Asymmetric Counteranion-Directed Lewis Acid Catalysis with α,β-Unsaturated Esters

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“To improve is to change; To perfect is to change often.”

Winston Churchill

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Ben

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Finally, I am deeply grateful to my family for their constant support throughout my education from the distance.

Table of Contents

Abstract

The fundamental substrate class of α,β-unsaturated esters offers extraordinary synthetic potential for carbon-carbon bond forming reactions, such as cycloadditions and conjugate additions, however is rarely applied in asymmetric catalysis due to its relatively low reactivity. By expanding the concept of silylium-ACDC to non-silicon transfer reactions (catalytic in silicon), the introduction of chiral C–H acids into asymmetric catalysis and the identification of two distinct families of imidodiphosphorimidates (IDPi) catalysts, we could report unprecedented highly enantio- and diastereoselective Diels–Alder and Mukaiyama–Michael reactions of simple α,β-unsaturated methyl esters. The developed extremely active chiral Lewis acids represent the most efficient catalysts for asymmetric Diels–Alder reactions of α,β-unsaturated esters to date while tolerating a very broad scope on a variable scale with catalyst loadings as low as 0.1 mol%.

Kurzzusammenfassung

Die grundlegende Substratklasse der α,β-ungesättigten Ester bietet herausragendes synthetisches Potential für Kohlenstoff-Kohlenstoff Bindungsknüpfungsreaktionen wie Cycloadditionen und konjugierte Additionen, wird jedoch in der asymmetrischen Katalyse aufgrund ihrer relativ niedrigen Reaktivität kaum angewendet. Durch die Erweiterung des Konzept der asymmetrischen Gegenanion-vermittelten Katalyse mit Silylium-Equivalenten (silylium-ACDC) hin zu Reaktionen mit katalytischen Mengen Silizium, die Einführung von chiralen C–H Säuren in die asymmetrische Katalyse und die Identifizierung von zwei separaten Familien an Imidodiphosphorimidat-Katalysatoren, konnten bisher beispiellose hoch enantio- und diastereoselektive Diels–Alder und Mukaiyama–Michael Reaktionen beschrieben werden. Die entwickelten chiralen Lewis Säuren stellen die bis dato effizientesten Katalysatoren für asymmetrische Diels–Alder Reaktionen von α,β-ungesättigten Estern dar und tolerieren trotzdem ein sehr breites Substratspektrum auf verschiedenen Reaktionsmaßstäben mit sehr niedrigen Katalysatorbeladungen von bis zu 0.1 mol%.

List of Abbreviations

*	designating chiral element
ACDC	asymmetric counteranion-directed catalysis
Alk	alkyl
Ar	aryl
aq.	aqueous
BINOL	1,1’-bi-2-naphthol
Bn	benzyl
Boc	*tert*-butyloxycarbonyl
br	broad
cat.	catalyst or catalytic
conc.	concentrated
conv.	conversion
d	doublet or day(s)
DCE	dichloroethane
DCM	dichloromethane
DFT	density functional theory
DMAP	4-dimethylaminopyridine
DMF	dimethylformamide
DMSO	dimethylsulfoxide
d.r.	diastereomeric ratio
Elec.	electrophile
EI	electron impact ionization
e.r.	enantiomeric ratio
equiv.	equivalents

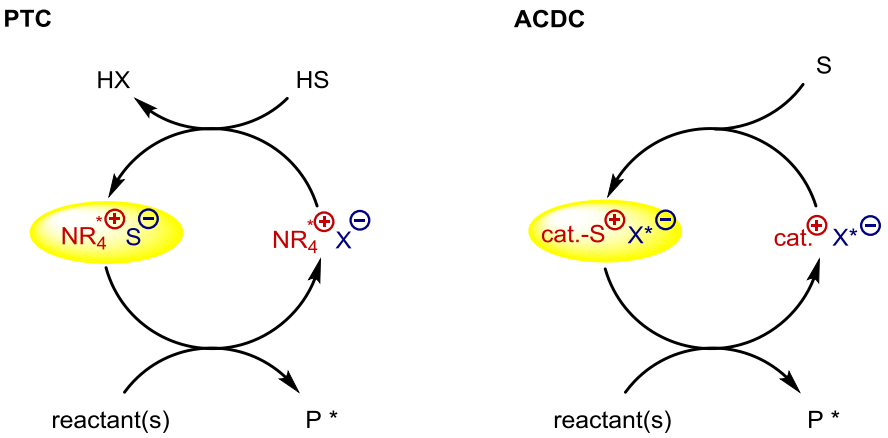
Et	ethyl
et al.	et alii/et aliae – and others
ESI	electrospray ionization
GC	gas chromatography (gas chromatography coupled with mass detection)
h	hour(s)
HPLC	high performance liquid chromatography
HRMS	high resolution mass spectrometry
HX*	designating chiral Brønsted acids, e.g. chiral phosphoric acid diesters
i	iso
m	meta
m	multiplet
M	molar or metal
Me	methyl
MS	mass spectrometry or molecular sieves
MTBE	methyl *tert*-butyl ether
MW	molecular weight
NMR	nuclear magnetic resonance (spectroscopy)
NOE	nuclear Overhauser effect
NuH/Nuc.	nucleophile
o	ortho
P	product
p	para
Ph	phenyl
Pr	propyl
quant.	quantitative
quint	quintet
rac	racemic

r.t.	room temperature
sat.	saturated
t	*tert*, tertiary
t	triplet
T	temperature
Tf	trifluoromethylsulfonyl
THF	tetrahydrofuran
TLC	thin layer chromatography
TMP	2,2,6,6-tetramethyl piperidine
TMS	trimethylsilyl
TON	turnover number
TRIP	3,3'-bis(2,4,6-triisopropylphenyl)-1,1'-binaphthyl-2,2'-diyl-hydrogen phosphate
TsOH	*para*-toluenesulfonic acid

1 Introduction & Objective

1.1 Background

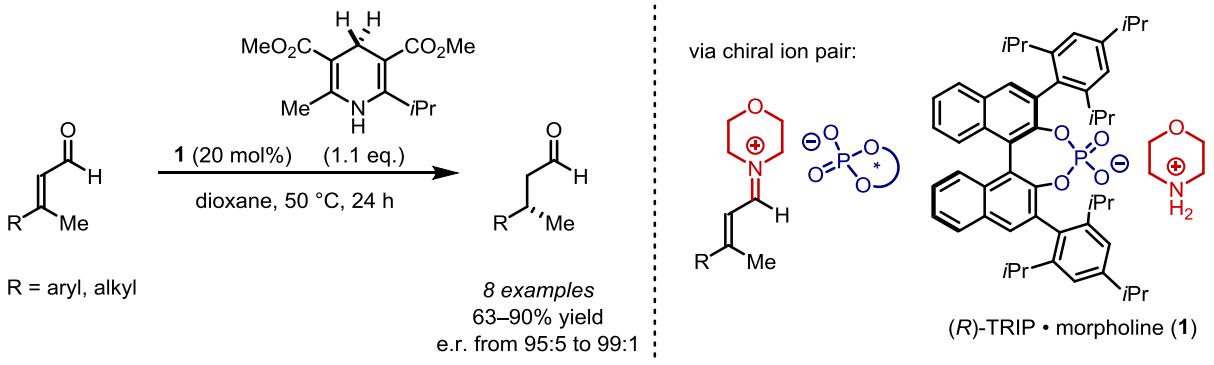
In asymmetric catalysis, the majority of reactions proceed through partially charged or completely ionic intermediates. When anionic intermediates are involved such as negatively charged nucleophiles, chiral enantiopure countercations can render subsequent transformations enantioselective upon sufficient association of the ion pair (Scheme 1.1). This principle has widely been applied in enantioselective phase-transfer catalysis (PTC).[1] Asymmetric induction upon ion-pair formation may also proceed with a crucial anionic partner. In the concept of asymmetric counteranion-directed catalysis (ACDC), a cationic species, such as a protonated intermediate, forms an ion pair with a chiral anion, which directs enantiotopos/-face-differentiation or enantiomer-differentiation.[2,3]



Scheme 1.1 Schematic representation of ion pairs in enantioselective catalysis: phase-transfer catalysis with chiral countercations (PTC) and asymmetric counteranion-directed catalysis (ACDC) with chiral counteranions. P = product; S = substrate; X = anion; NR_4^- = chiral ammonium ion; cat. = cation (H^+).

A general definition of ACDC is given as: “Asymmetric counteranion-directed catalysis refers to the induction of enantioselectivity in a reaction proceeding through a cationic intermediate by means of ion pairing with a chiral, enantiomerically pure anion provided by the catalyst.”[2] The term *ion pair* is further defined according to Anslyn and Dougherty: “An ion pair is defined to exist when a cation and anion are close enough in space that the energy associated with their electrostatic attraction is larger than the thermal energy (RT)

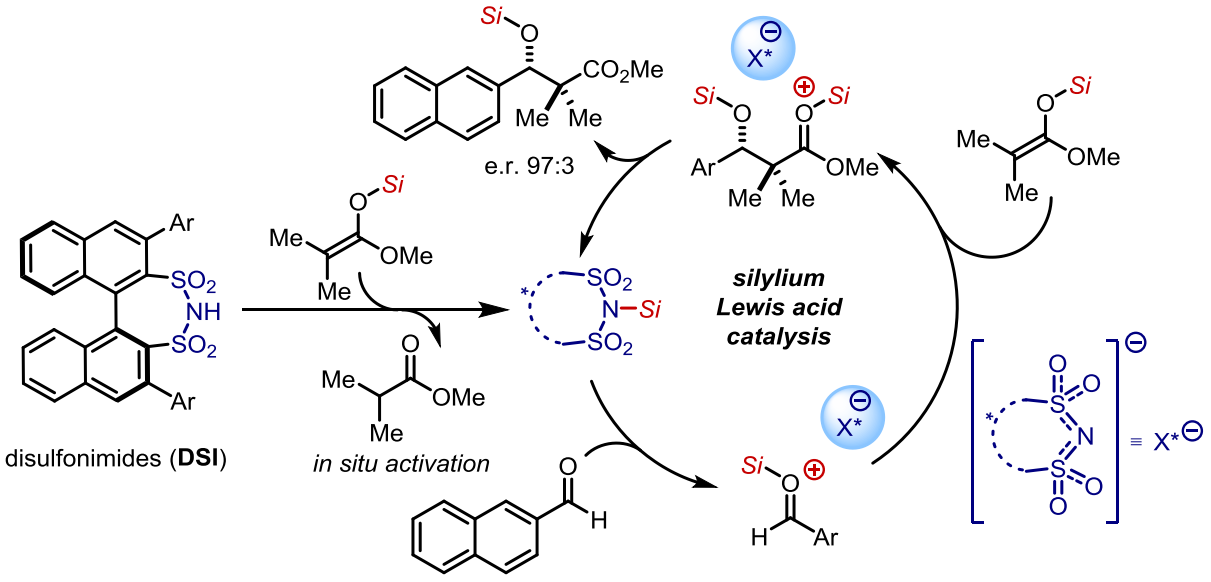
available to separate them."[4] Further attractive interactions, in addition to the Coulomb attraction, between cation and anion may be involved in the context of ACDC.[2] The term *ion-pair catalysis* is understood in a broader sense merging the concepts of phase-transfer-catalysis and asymmetric counteranion-directed catalysis.[5] Thus, catalyzed reactions proceeding through ion pairs in general are categorized into this class of catalytic processes. A proof-of-principle on the feasibility of ACDC as a powerful strategy for asymmetric catalysis beyond Brønsted acid catalysis was delivered by List and coworkers in 2006 for the highly enantioselective transfer hydrogenations of enals using a Hantzsch ester as the reductant (Scheme 1.2).[6] The morpholinium salt of TRIP phosphoric acid (**1**) forms a chiral ion pair upon condensation with the enal substrate. The chiral anion directs the approach of the hydride source to the reactive iminium intermediate by enantiofacial steric shielding. The chiral ion pair intermediate as being present in the enantiodetermining step renders this reaction a clear showcase of ACDC. The high potential of this concept was rapidly realized and let to many applications in enantioselective organocatalysis but also in transition-metal catalysis featuring chiral enantiopure anions.[2-5-7]



Scheme 1.2 Proof-of-principle for asymmetric counteranion-directed catalysis (ACDC): The catalytic asymmetric transfer hydrogenation of enals with the salt of morpholine and TRIP phosphoric acid.

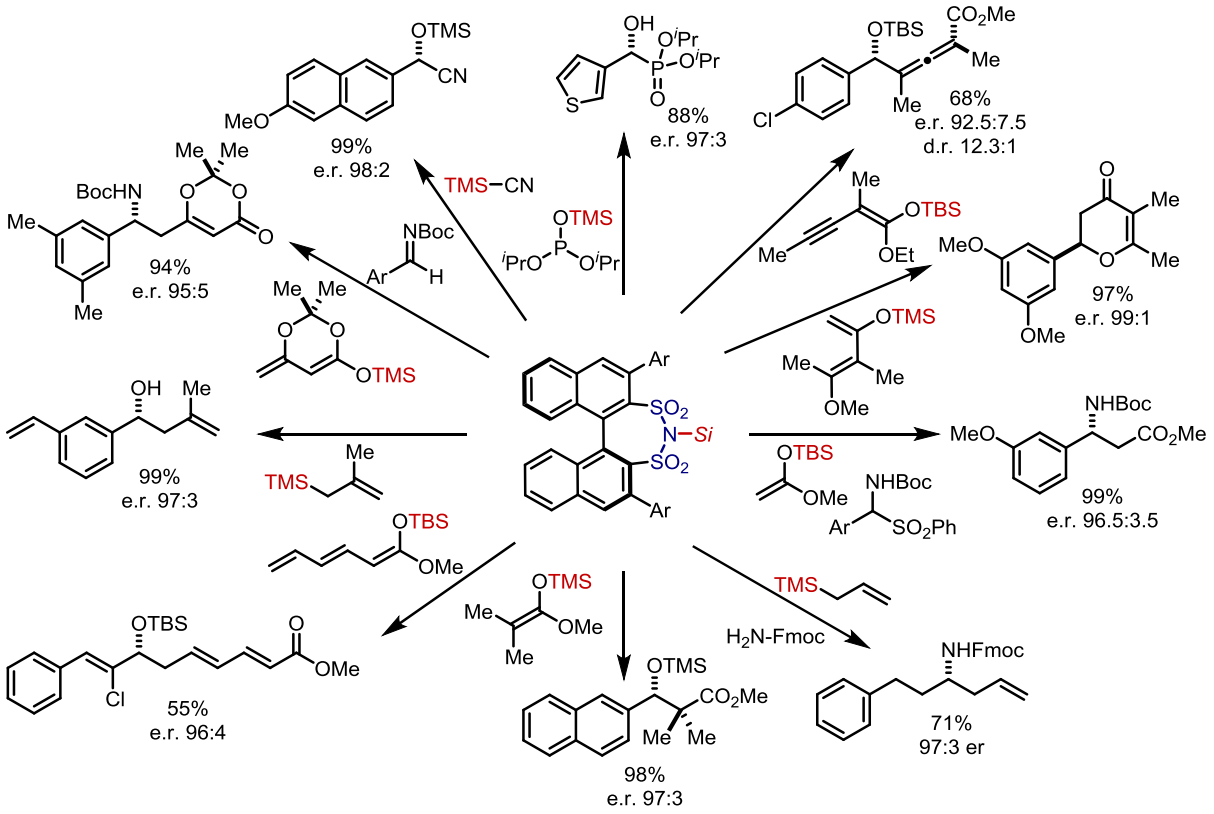
While enantioselective Brønsted acid catalysis is particularly successful for relatively electrophilic and/or basic substrates, such as imines, Brønsted acidic activation of substrates such as aldehydes, ketones, unsaturated carboxylic acid derivatives and olefins is profoundly more challenging. Thus, the focus shifted towards organic Lewis acids as potential catalysts for activating such substrates. In the presence of silylating agents, Brønsted acids such as triflic acid (TfOH) and triflimide (Tf_2NH) can be converted into their silylated analogues, which are very potent Lewis acids.[8-9] As indicated by trends in pK_a values, triflimide

($pK_a = -11.9$ in DCE; $pK_a = 0.3$ in MeCN)[10] is turned into a much stronger Lewis acid upon silylation then triflic acid ($pK_a = -11.4$ in DCE; $pK_a = 0.7$ in MeCN) rendering TMS-NTf_2 a promising motif for chiral organic Lewis acids.[11] For previously reported metal-based Lewis acid-catalyzed asymmetric transformations, such as Mukaiyama–Aldol reactions, a major issue was competition between the desired enantioselective Lewis acid catalysis and a non-enantioselective pathway catalyzed by silylium ions.[12-13] By taking advantage of silylium ions/equivalents as potent Lewis acid, it was envisioned that a combination with a suitable chiral anion may render this pathway enantioselective through ACDC. In 2009, List and coworkers reported the first realization of this concept featuring chiral disulfonimide (**DSI**) catalysts in Mukaiyama–Aldol reactions of aromatic aldehydes with silyl ketene acetals to give excellent yields and enantioselectivities.[14] Disulfonimides as Brønsted-acidic pre-catalysts are silylated to form the active species (Scheme 1.3). Residual water in the reaction mixture is transformed into TMS_2O via catalyst hydrolysis and re-silylation by the silylated reagent, which is present in excess. In the dormant phase of the reaction, this process is continued until all water is consumed into TMS_2O.[15] The highly relevant ability of catalyst regeneration after hydrolysis under silylating conditions is referred as self-healing or self-regeneration. Aldehyde substrates are activated through complexation of the silyl group forming a chiral ion pair which allows effective enantiofacial differentiation. Upon nucleophilic attack of the silyl ketene acetal, the primary reaction product collapses to give the product and to regenerate the silylated catalyst.



Scheme 1.3 General catalytic cycle for asymmetric Lewis acid catalysis with silylium ion equivalents and chiral counteranions.

The existence of underlying Lewis acid catalysis was supported by experiments in the presence of 2,6-di-tert-butyl-4-methyl pyridine as a Brønsted acid scavenger, which did not suppress the reaction. The shown catalytic cycle is considered to be general for the activation of aldehydes in reactions with silylated nucleophiles. This concept and the novel class of chiral Brønsted acids led to a renaissance of asymmetric Lewis acid catalysis for transformations of carbon electrophiles, such as aldehydes and imines, with silylated nucleophiles (Scheme 1.4).[16-17] Aromatic aldehydes and imines are preferred substrates for silylated DSI catalysts and have subsequently been used for a series of other transformations with various silylated nucleophiles resulting in consistently high enantioselectivities. In analogy to the common Mukaiyama–Aldol reaction with silyl ketene acetals, a vinylogous, a bis-vinylogous[18] and an alkynylogous[19] variant have been developed. Combination with Danishefsky-type dienes gave hetero-Diels–Alder products after cyclization with trifluoroacetic acid (TFA),[20] while treatment with (2-methylallyl)trimethylsilanes (N = 4.41)[21] afforded the corresponding methallylation products.[22]



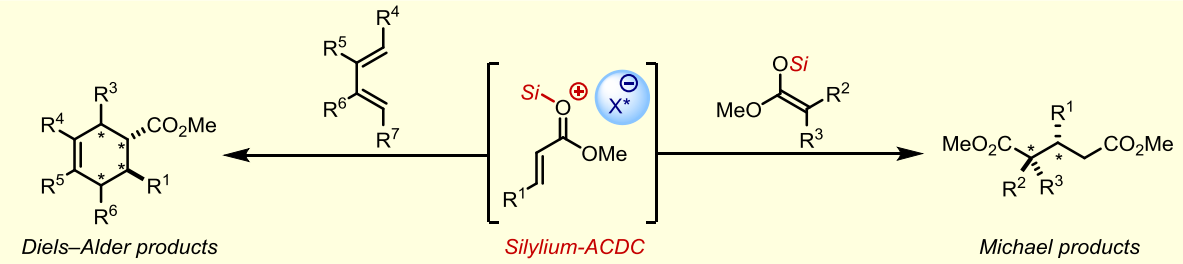
Scheme 1.4 Overview on applications of DSI catalysts in enantioselective Lewis acid-catalyzed reactions of aromatic aldehydes and imines.

The corresponding Hosomi–Sakurai reaction employing allyltrimethylsilane as a very simple allylating reagent proved to be challenging due to its very low nucleophilicity (N = 1.68)[23] and required higher reaction temperatures, resulting in only moderate enantioselectivity. However, if *in situ* generated *N*-fluorenylmethoxycarbonyl (Fmoc) imines were used as electrophiles, the allylation with allyltrimethylsilane proceeds with excellent enantioselectivity in all examined cases.[24] Aliphatic aldehydes, which gave only low to moderate enantioselectivities in previous transformations, could be employed as well without loss of selectivity. With *N*-butyloxycarbonyl (Boc) imines formed *in situ* from *N*-Boc amino sulfone precursors, an asymmetric Mukaiyama–Mannich reaction with silyl ketene acetal nucleophiles has been developed.[25] Consuming one equivalent of SKA, the imine substrate is generated and Mannich products were afforded after the subsequent step with excellent yields and enantioselectivities. A vinylogous variant yielding versatile δ-amino-β-ketoesters could be achieved using silyloxydienes.[26] With TMS-CN, the cyanosilylation of aldehydes has been possible with catalyst loadings as low as 0.005 mol% (50 ppm),[15] while the asymmetric catalytic Abramov reaction with silylated phosphites gave access to highly enantioenriched α-hydroxy phosphonates.[27]

1.2 Objective

While aldehydes and aldimines as reactive substrates became routinely accessible with silylated DSI catalysts, more challenging electrophiles, such as ketones and unsaturated carboxylic acid derivatives, became attractive targets. In particular, α,β-unsaturated esters represent an underdeveloped substrate class for asymmetric catalysis despite their prominent role as dienophiles for Diels–Alder reactions and as versatile Michael acceptors. α,β-Unsaturated esters, and cinnamates in particular, have recently been ranked among the very least electrophilic Michael acceptors via quantitative measurements by Mayr and coworkers.[28] Also for Diels–Alder reactions, α,β-unsaturated esters have been determined to be a relatively unreactive class of dienophiles through empirical observations in asymmetric catalysis and by computational studies.[29-30] Thus, the main objectives of the doctoral studies presented herein were:

1. Proof-of-principle for the activation of α,β-unsaturated esters with chiral silylium Lewis acids and the development of enantioselective methodology.
2. Broadening the concept of silylium-ACDC by introducing transformations catalytic in silicon.
3. Overcoming current limitations of catalytic asymmetric Diels–Alder reactions of simple α,β-unsaturated esters in scope and scale.



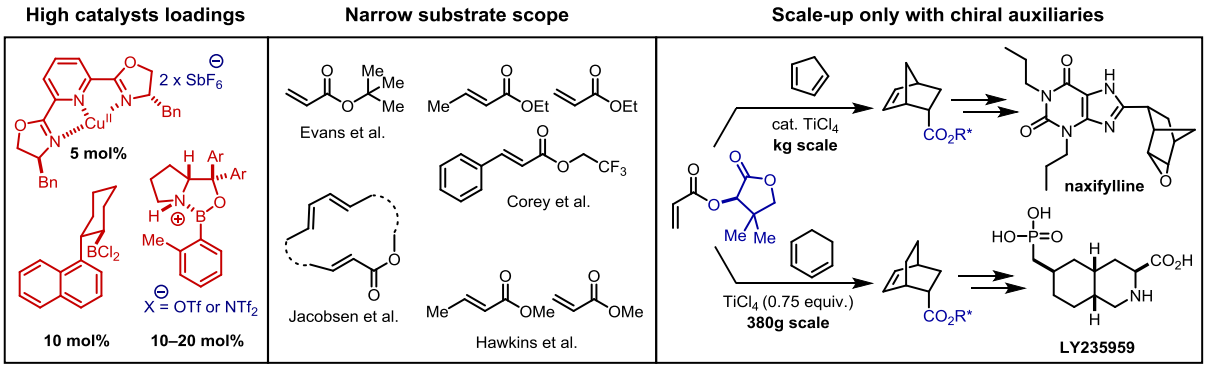
Scheme 1.5 Enantioselective access to Diels–Alder and Mukaiyama–Michael products.

Preliminary results on the activation and application of α,β-unsaturated esters for enantioselective Diels–Alder and Mukaiyama–Michael reactions have been obtained in my Master thesis conducted in the List laboratory.[31] By further exploration of catalyst structures and the optimization of reaction conditions, we aimed for very high enantioselectivities over a broad substrate scope for these transformations.

As described in the previous chapter, enantioselective catalysis with chiral disulfonimides was applicable to a variety of silylated reagents acting as both activators for the catalyst and as nucleophiles in the reactions with aldehydes and aldimines (Scheme 1.4). In these silicon-transfer reactions, the silyl group of the nucleophiles is always attached to the primary reaction product, while cleaved off in some cases by the workup or treatment with appropriate reagents. In contrast, no example for a reaction employing a non-silylated nucleophile or reactant has been described in silylium-ACDC. The use of only catalytic amounts of a silylating reagent, solely for the activation of the catalyst, would lead to a significant broadening of this concept, allowing for example its application in pericyclic reactions, such as the Diels–Alder reaction.

Asymmetric catalytic Diels–Alder reactions have been developed for many activated α,β-unsaturated carboxylic acid derivatives, such as *N*-acyl oxazolidinones[32-39] and *N*-acyl pyrazoles.[40-42] These ester surrogates, however, exhibit the inherent disadvantage of featuring a stereocontrolling and electrophilicity enhancing group that has to be attached and subsequently be cleaved off the molecule of interest. For simple α,β-unsaturated esters as highly desirable dienophiles only a limited number of examples have been reported. Evans et al. described the highly enantioselective Diels–Alder reactions of *tert*-butyl acrylate with cyclopentadiene with a bis(oxazolinyl)pyridine copper complex.[34] Using a chiral alkyldichloroborane Lewis acid, Hawkins and coworkers obtained very good results in Diels–Alder reactions of methyl acrylate and crotonate with cyclopentadiene.[43-45] The broadest scope for α,β-unsaturated esters and different dienes to date was achieved with cationic oxazaborolidines introduced by Corey et al..[30,46-50] For most transformations, however, more reactive trifluoroethyl ester substrates were used and a diene scope was only reported for readily reactive trifluoroethyl acrylate. In addition to the severe limitations in scope, catalyst loadings for all applicable chiral Lewis acids are generally high (5–20 mol%), while catalyst recycling or regeneration has never been demonstrated. Such a high demand of chiral catalyst currently prevents the use of asymmetric catalysis of the Diels–Alder reaction on a

larger scale as the authors of a recent review on the industrial application of the Diels–Alder reaction stated: “To our knowledge, no example of a catalytic asymmetric DA reaction carried out on a large scale has so far appeared in the literature.”[51] For asymmetric synthesis of Diels–Alder products, the chiral auxiliary approach is currently the method of choice, e.g. for the large-scale synthesis of adenosine receptor agonist **naxifylline**[52-54] or **LY235959**,[55] a potential agent for the treatment of neurodegenerative disorders. We therefore aimed for the development of new highly enantioselective methodology applying simple α,β-unsaturated methyl esters and various dienes with only very low catalyst loadings (≤1 mol%), potentially also enabling future application of asymmetric catalysis for the Diels–Alder reaction on an industrial scale.



Scheme 1.6 Current limitations in asymmetric Diels–Alder chemistry.

2. Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid

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Authors	Tim Gatzenmeier, Manuel van Gemmeren, Youwei Xie, Denis Höfler, Markus Leutzsch, Benjamin List

Content

Silylium ion equivalents have shown promise as Lewis acid catalysts for a range of important C–C bond-forming reactions. Here we describe chiral C–H acids that upon in situ silylation, generate silylium-carbanion pairs, which are extremely active Lewis acid catalysts for enantioselective Diels–Alder reactions of cinnamates with cyclopentadiene. Enantiomeric ratios of up to 97:3 and diastereomeric ratios of more than 20:1 are observed across a diverse set of substitution patterns with 1 mole percent (mol %) of C–H acid catalyst and 10 mol % of a silylating reagent. The results show promise for broad applications of such C–H acid–derived silylium ion equivalents in asymmetric Lewis acid catalysis.

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repair by homologous recombination for maintenance of the stability of the genome, which also requires the coordinated involvement of several additional partners.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/351/6276/943/suppl/DC1
Materials and Methods
Figs. S1 to S18
Tables S1 and S2
References (*31*–*33*)

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REPORTS

ORGANIC LEWIS ACIDS

Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid

Tim Gatzenmeier,* Manuel van Gemmeren,* Youwei Xie, Denis Höfler, Markus Leutzsch, Benjamin List†

Silylium ion equivalents have shown promise as Lewis acid catalysts for a range of important C–C bond-forming reactions. Here we describe chiral C–H acids that upon in situ silylation, generate silylium-carbanion pairs, which are extremely active Lewis acid catalysts for enantioselective Diels–Alder reactions of cinnamates with cyclopentadiene. Enantiomeric ratios of up to 97:3 and diastereomeric ratios of more than 20:1 are observed across a diverse set of substitution patterns with 1 mole percent (mol %) of C–H acid catalyst and 10 mol % of a silylating reagent. The results show promise for broad applications of such C–H acid–derived silylium ion equivalents in asymmetric Lewis acid catalysis.

Lewis acid catalysis enables key reactions in chemical synthesis, such as the Diels–Alder, Friedel–Crafts, and various aldol, Mannich, and Michael reactions. Consequently, substantial efforts have been directed toward enantiopure Lewis acids, which have enabled important asymmetric variations of such reactions (*1*, *2*). Despite the plethora of elegant catalysts and methodologies developed in this context, a key limitation of enantioselective Lewis acid catalysis is the frequent need for relatively high catalyst loadings, which result from issues such as insufficient Lewis acidity (keeping some substrate classes completely out of reach), product inhibition, hydrolytic instability, and the competition with nonenantioselective background catalysis (*3*, *4*). With respect to these issues, we are now envisioning an alternative approach to asymmetric Lewis acid catalysis (Fig. 1). Conventional chiral Lewis acids typically consist of a metal (loid) complex with chiral ligands or substituents (*5*–*9*). Their activity can often be increased by rendering the complexes cationic and combining them with weakly coordinating, achiral counteranions. By inverting the chiral entities within the ion pair, a conceptually different strategy results.

We have recently developed in situ silylated disulfonimide Lewis acid organocatalysts for highly enantioselective Mukaiyama-type reactions involving silylated nucleophiles with catalyst loadings as low as 10 parts per million (ppm) (*10*–*15*). As an example of asymmetric counteranion-directed catalysis (ACDC) (*16*–*19*), these reactions proceed via silylation of an electrophile, generating a cationic reactive species that ion pairs with an enantiopure counteranion and reacts with a silylated nucleophile. We became interested in expanding this silylium ion–ACDC to, in principle, all types of Lewis acid–catalyzed reactions, including those that do not involve stoichiometric amounts of silylated reagents. We hypothesized that the use of a suitable enantiopure precatalyst and a catalytic amount of a silylating reagent should effect the formation of a catalytically competent silylium ion equivalent. If successful, silylium ion–ACDC, catalytic in silicon, would provide an efficient approach to alleviating challenges in modern asymmetric Lewis acid catalysis. Here we report the realization of this idea. We have developed chiral C–H acids that, upon in situ silylation, become extremely active Lewis acid catalysts for highly enantioselective Diels–Alder reactions of cinnamates with cyclopentadiene.

Enantioselective Diels–Alder reactions of α,β-unsaturated ester dienophiles are generally challenging, and only a few have been reported. For example, Ghosez applied chiral silylium ion equivalents in combination with triflimide as achiral counteranion to catalyze Diels–Alder reactions of α,β-unsaturated esters with moderate enantioselectivity (*6*, *7*). Corey has reported that triflimide-activated chiral oxazaborolidine Lewis acids (*8*, *9*) give excellent results with acrylates and crotonates as dienophiles. Cinnamates, with their highly conjugated π-electron system, represent an even more challenging substrate class for asymmetric Diels–Alder reactions, and in a reported example, activated trifluoroethyl cinnamate required 20 mole percent (mol %) of the protonated oxazaborolidine catalyst to react (*9*, *20*).

Given the superb reactivity observed in silylium ion–ACDC in Mukaiyama-type reactions (*10*, *13*), we were curious to explore if our strategy would also be suitable for the activation of cinnamates in enantioselective Diels–Alder reactions. We anticipated that a highly Brønsted-acidic precatalyst

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would be activated in situ with a catalytic amount of a silylating reagent such as a silyl ketene acetal. The resulting silylium ion equivalent would then activate the cinnamate, while he chiral counteranion would induce the enantioselectivity.

We began our studies by exploring various previously developed chiral disulfonimide precatalysts in the reaction of cinnamate **1a** with cyclopentadiene **2** (Fig. 2A). Disappointingly, their observed high activity was insufficient toward this substrate class, indicating that catalysts of even higher Lewis acidity would be required (see table S3 for further details). Inspired by the activity trends known for achiral silylium ion equivalents in solution (Fig. 2B), which indicate that the use of a carbon-centered counteranion leads to higher Lewis acidities (*21*), we became interested in developing chiral, enantiopure C–H acids as precatalysts. After considerable synthetic efforts, we accessed compounds of sufficient C–H acidity and could identify binaphthyl-allyl-tetrasulfones (BALTs) as promising candidates for the enantioselective catalysis of our target reaction (Fig. 2C). These catalysts were designed based on the notion that the Lewis acidity of the silylium ion equivalent should increase on rendering the catalyst-derived counteranion less Lewis basic. This goal was achieved by exploiting the principle of vinylogy: In BALT anions, the negative charge is highly delocalized (onto eight oxygen atoms and two carbon atoms), leading to a low charge density and thus Lewis basicity on every position of the anionic substructure, and therefore to the excellent catalytic activities observed with this catalyst class.

The optimized reaction conditions involve the use of a 9-fluoroenylmethyl cinnamate ester, which enables higher stereoselectivities but is not required for catalytic activity; 9-phenanthryl groups as 3,3′-substituents on the catalyst; and the use of only 1 mol % of catalyst **6b**, alongside 10 mol % of silyl ketene acetal **4b** to effect the initial catalyst silylation. The Brønsted acidic catalyst **6b** itself was found to be inactive for this transformation (see table S9 for further details). Under the optimal conditions, our model reaction proceeded smoothly, giving the desired product **3a** in 94% yield and an enantiomeric ratio (e.r.) of 97:3 (Fig. 3). Using these conditions, we proceeded to explore the scope of the reaction. We found that the transformation proceeds smoothly in the presence of both strongly electron-donating substituents (**3b**: 93%; e.r. = 95:5), as well as strongly electron-withdrawing groups (**3c**: 90%; e.r. = 95:5). Halide substituents were well tolerated, and the corresponding products **3d–3g** were all obtained in high to excellent yields and with excellent stereocontrol. We proceeded to assess the influence of regioisomeric substitution on the cinnamate substrate and found that methyl substituents in para, meta, and ortho position are tolerated, and the corresponding products **3h–j** were obtained with yields ≥90% and enantiomeric

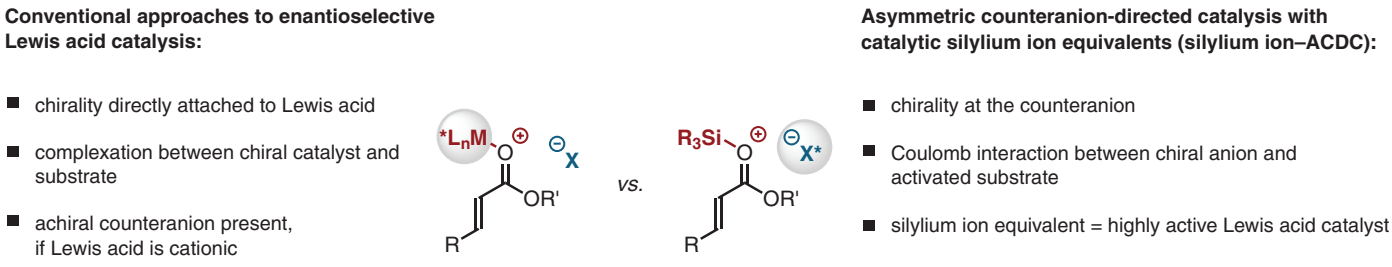


Fig. 1. Comparing silylium ion–ACDC with conventional approaches to enantioselective Lewis acid catalysis.

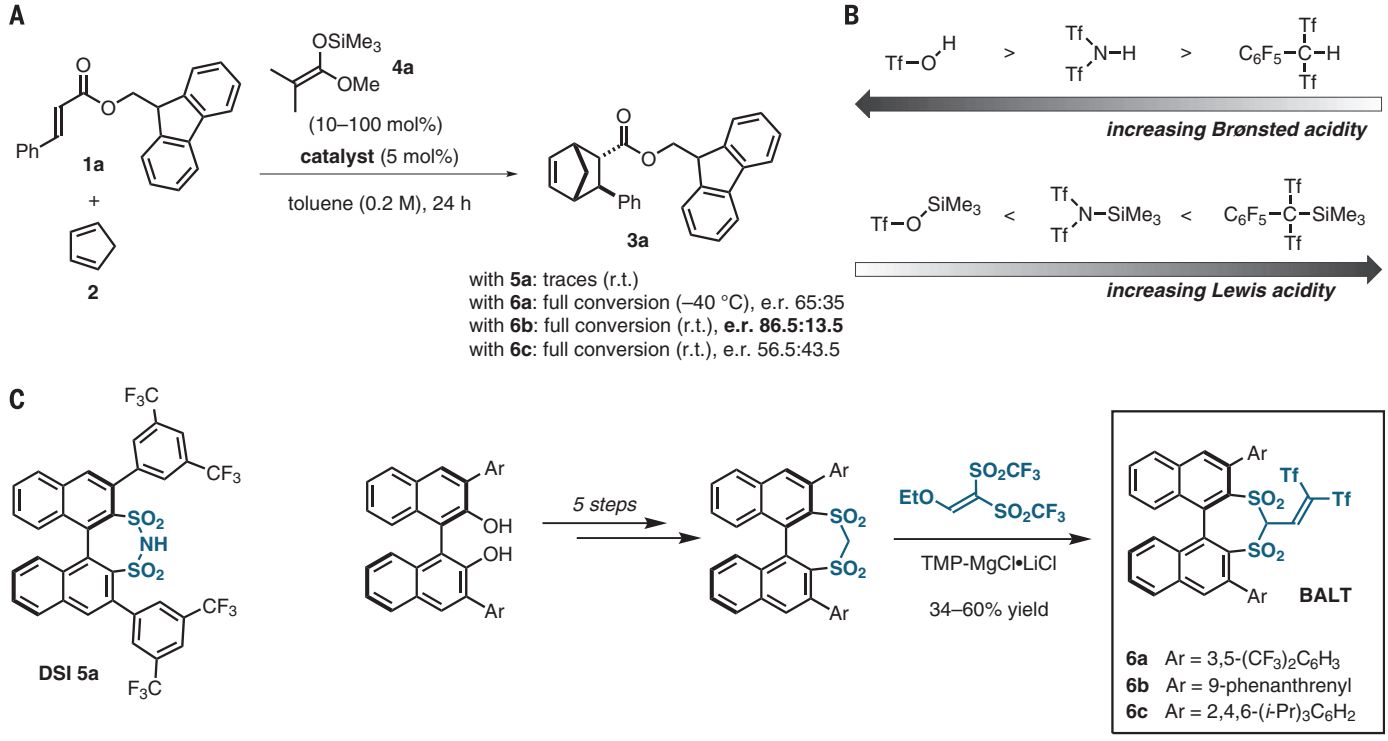


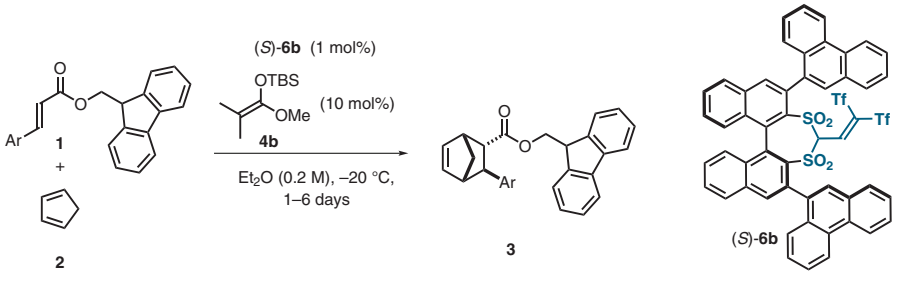
Fig. 2. Initial catalyst screening and optimization. (**A**) Model reaction of an unactivated cinnamate ester **1a** with cyclopentadiene **2**. (**B**) Trends of Lewis and Brønsted acidities in solution for silylium ion equivalents bearing CF_3SO_2 (Tf)–substituted O-, N-, and C-centered counteranions and the corresponding Brønsted acids (*21*). (**C**) Precatalysts: disulfonimides (DSI) and chiral C–H acids (BALTs).

ratios ≥95.5:4.5. To further demonstrate the tolerance of substituents in various positions of the aryl-ring, the meta-nitro-substituted product **3k** was prepared in 91% yield and with an e.r. of 97:3, a result that compares very well to the one obtained for the para-substituted analog **3c**. Furthermore, we studied substrates with extended π-surfaces, and the corresponding 1- and 2-naphthyl–substituted products (**3l** and **3m**) were obtained with excellent results. Finally, we synthesized the 2-furyl– and 2-thiophenyl–substituted products **3n** and **3o**, which were both obtained in good yields and with high stereoselectivities, thus revealing that our methodology can be applied to hetero-aromatic substrates. All Diels–Alder adducts described in this work were obtained with excellent endo-diastereoselectivities (d.r. >25:1 in virtually all cases).

Having studied the scope of our reaction, we were interested in probing the mode of action proposed at the outset of our studies. To do so, we applied ^{1}H nuclear magnetic resonance (NMR) spectroscopy to monitor the in situ activation of the BALT catalyst, using the 3,3′-unsubstituted variant **6d** and silyl ketene acetal **4a** as model compounds (Fig. 4A). We found that over a period of ~70 min, the signals corresponding to the precatalyst disappeared, and a new species emerged lacking the signal corresponding to the acidic proton (H-1). In comparison to the precatalyst (two diastereotopic naphthyl groups with sharp ^{1}H NMR signals), the newly formed species showed relatively broad signals at room temperature. Increasing the temperature to 55°C allowed us to observe pseudohomotopic naphthyl groups in the activated species, an observation in good agreement with expectations for the formation of a silylium BALT–anion pair such as **7d**. The anionic character of the BALT motif in this activated species was corroborated by the spectral similarities to the features observed for a BALT-derived tetraalkyl ammonium salt (see fig. S6 for further details).

On the basis of these observations and previous studies (*22*–*25*), we propose a catalytic cycle (Fig. 4B), which involves ionic species and thus represents a case of asymmetric counteranion-directed catalysis.

After the initial catalyst activation, achieved via protodesilylation of a catalytic amount of silyl ketene acetal **4**, the resulting silylium BALT–anion pair **7** could exchange the Lewis base, thus forming species **9**, which is activated by lowering of the lowest unoccupied molecular orbital (LUMO-lowering). Traces of water that may be present in the reaction mixture will presumably immediately hydrolyze ion pair **7**, furnishing C–H acid **6**, which in turn is reactivated by silyl ketene acetal **4**. The Diels–Alder reaction of **9** with cyclopentadiene (**2**), proceeding through a transition state such as **A**$^{\neq}$, would then result in



3a, 94% (15 h)
e.r. 97:3
d.r. >25:1

3b, 93% (6 days in $CHCl_3$)[a]
e.r. 95:5
d.r. >25:1

3c, 90% (2 days in $CHCl_3$)
e.r. 95:5
d.r. >25:1

3d, 91% (3 days)
e.r. 95:5
d.r. >25:1

3e, 94% (0 °C, 10 h)
e.r. 95:5
d.r. >20:1

3f, 97% (4 days)
e.r. 96:4
d.r. >25:1

3g, 89% (3 days)
e.r. 95.5:4.5
d.r. >25:1

3h, 96% (24 h)
e.r. 95.5:4.5
d.r. >25:1

3i, 92% (10 h)
e.r. 95.5:4.5
d.r. >25:1

3j, 90% (3 days)
e.r. 96:4
d.r. >25:1

3k, 91% (36 h)
e.r. 97:3
d.r. >25:1

3l, 93% (24 h)
e.r. 96:4
d.r. >25:1

3m, 93% (2 days)
e.r. 96.5:3.5
d.r. >25:1

3n, 91% (3 days)
e.r. 95.5:4.5
d.r. >25:1

3o, 88% (0 °C, 3 days)
e.r. 92.5:7.5
d.r. >25:1

3o (x-ray structure)

Fig. 3. Scope of the Diels–Alder reaction (Tf: SO_2CF_3; Fm: fluorenylmethyl; TBS: tert-butyldimethylsilyl). All yields are isolated. Enantiomeric ratios (e.r.) were determined via high-performance liquid chromatography (HPLC). Diastereomeric ratios (d.r.) were determined by ^{1}H-NMR. *Using 3 instead of 1 mol % of catalyst loading gave full conversion after 3 days with identical enantiomeric and diastereomeric ratios.

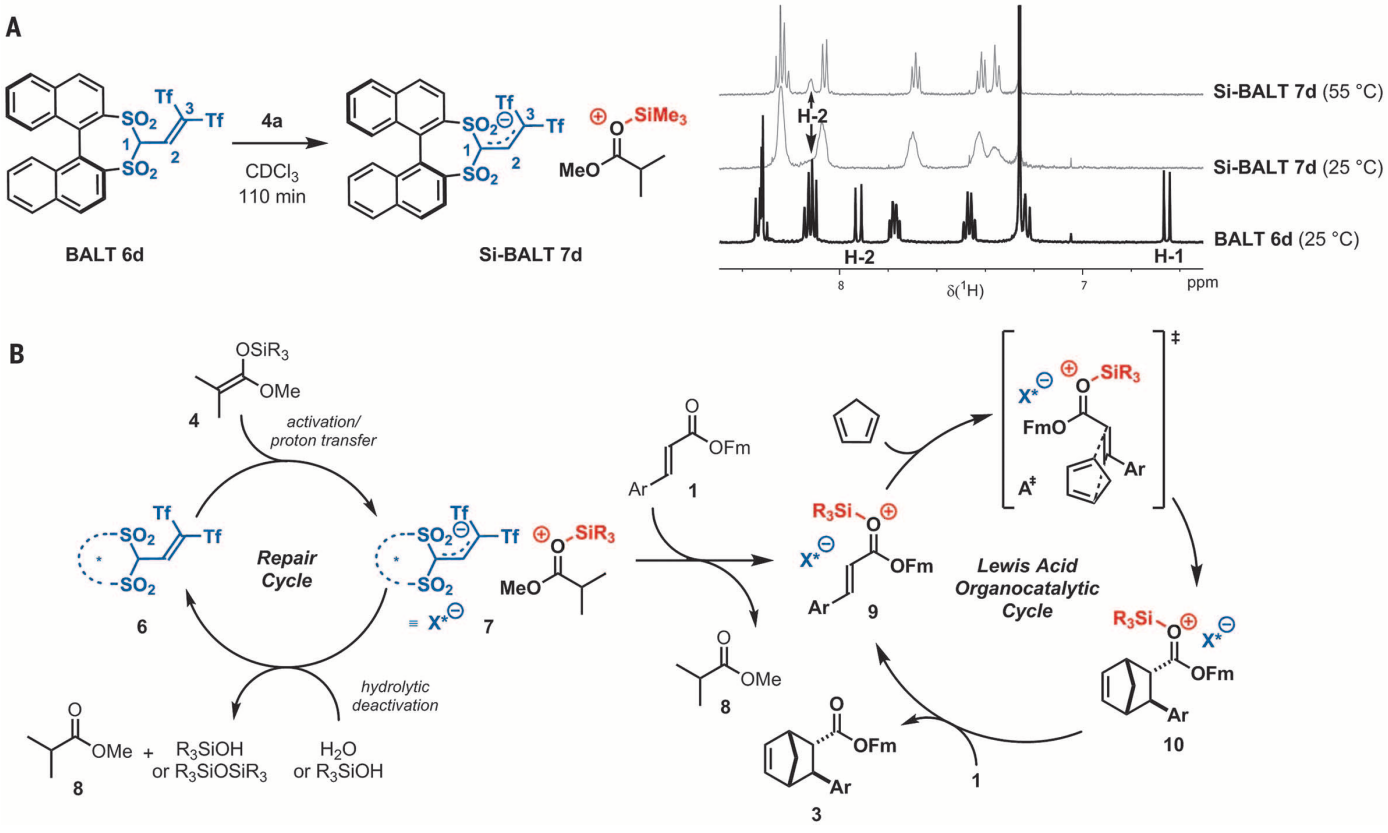


Fig. 4. Proposed catalytic cycle and mechanistic considerations. (**A**) In situ NMR spectroscopic study of catalyst activation. 3,3′-Unsubstituted BALT catalyst **6d** was treated with an excess of silyl ketene acetal **4a** to give the silylium BALT–anion pair **7d**. (Right) ^{1}H-NMR spectra of the starting material and of the product at different temperatures. (**B**) Catalyst activation and proposed catalytic cycle.

a product complex **10**. The asymmetric induction in transition state $\mathbf{A}^{\neq}$ would result largely from the stereochemical communication between the achiral cationic moiety and the enantiopure BALT anion. After the enantio-determining step, the final product ***3*** could be liberated by direct Lewis base exchange with another molecule of substrate **1**, or via the intermediate formation of the activated complex **7** with **8**, in both cases resulting in the concomitant closing of the catalytic cycle.

An important and unique feature of our silylium ion–ACDC approach arises from the possibility of a repair pathway upon hydrolytic deactivation of the Lewis acid catalyst, enabled by simply adjusting the amount of the silylating reagent. The valuable source of chirality is hydrolytically stable and can only switch between the anionic state (active Lewis acid) and the Brønsted acidic state, thus allowing very low catalyst loadings.

Our findings immediately suggest widespread applications of this activation mode to other reactions susceptible to Lewis acid catalysis. Furthermore, our studies constitute a proof of principle for the feasibility of enantioselective C–H acid catalysis and likely pave the way for the application of such catalysts in enantioselective Brønsted acid catalysis. We believe that our C–H acid-based catalyst design may furnish solutions for addressing limitations remaining with current O–H– and N–H–based organocatalysts, and in ACDC in general.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/351/6276/949/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S7
Tables S1 to S14
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Analytical Data

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Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid

Tim Gatzenmeier, Manuel van Gemmeren, Youwei Xie, Denis Höfler, Markus Leutzsch and Benjamin List

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Silicon marries a chiral counterion

Acid is among the oldest and most versatile of chemical catalysts, but its symmetrical protons can't guide reactions to favor a product over its mirror image. Chemists have resolved this shortcoming through the use of chiral conjugate bases. While the proton activates the substrate, the nearby counterion asymmetrically biases the space around it. Gatzenmeier *et al.* extend this approach to Lewis acid catalysis by silyl cations, which can activate a variety of substrates in complementary fashion to protons (see the Perspective by Dumoulin and Masson). By pairing these silyl groups with chiral carbon-based anions, they achieve highly enantioselective catalysis of Diels-Alder reactions.

Science, this issue p. 949; see also p. 918

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Supplementary Materials for

Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid

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Asymmetric Lewis Acid Organocatalysis of the Diels–Alder Reaction by a Silylated C–H Acid

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[+]The authors contributed equally.

General Information

Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. Unless otherwise stated, solvents were used without prior degassing or drying. Freshly cracked 1,3-cyclopentadiene was stored in a Schlenk flask under Argon at -78 °C. Reactions were monitored by thin layer chromatography (TLC) on silica gel pre-coated plastic sheets (0.2 mm, Macherey-Nagel). Visualization was accomplished by irradiation with UV light at 254 nm and/or phosphomolybdic acid (PMA) stain and/or Cerium Ammonium Molybdate (CAM) stain and/or permanganate stain. Column chromatography was performed on Merck silica gel (60, particle size 0.040-0.063 mm). Optical rotations were measured on an Autopol IV automatic polarimeter (Rudolph Research Analytical) at 589 nm, 25°C. Data are reported as: $[\alpha]_D^t$, concentration (c in g/100 mL), and solvent. The absolute configurations were determined by comparing the optical rotations with reported values when such values were available in literature and by x-ray crystallography– all other products were assigned by analogy. Proton and carbon NMR spectra were recorded on Bruker Avance III 500 MHz spectrometer in deuterated solvents. Proton chemical shifts are reported in ppm (δ) relative to tetramethylsilane (TMS) with the solvent resonance employed as the internal standard (CD_2Cl_2, δ = 5.32 ppm; $CDCl_3$ δ = 7.26 ppm, DMSO δ = 2.50 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, triplet = t, q = quartet, m = multiplet, b = broad), coupling constants (Hz) and integration. ^{13}C chemical shifts are reported in ppm (δ) from tetramethylsilane (TMS) with the solvent resonance as the internal standard (CD_2Cl_2, δ = 53.8 ppm; $CDCl_3$, δ = 77.16 ppm, DMSO δ = 39.52 ppm). High resolution mass spectra were determined on a Bruker APEX III FTMS (7 T magnet). The enantiomeric ratios were determined by HPLC analysis employing a chiral stationary phase column specified in the individual experiment (HPLC traces analysis), by comparing the samples with the appropriate racemic mixtures. Unless otherwise stated, diastereomeric ratios were determined by ^1H-NMR.

Substrate Synthesis & Characterization

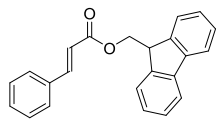
All ester substrates have been prepared from commercially available cinnamic acids purchased from Sigma-Aldrich, Alfa Aesar, Acros Organics, AK Scientific, Apollo Scientific, Key Organics and Aronis.

General procedure A: Preparation of 9-fluorenylmethyl cinnamates:

A literature procedure reported by Trost et al. was applied with slight modifications.(*26*)

A mixture of 9-fluorenylmethanol (2.16 g, 11 mmol, 1.1 equiv.), the appropriate cinnamic acid (10 mmol), pTSA (172 mg, 1 mmol, 10 mol%) in toluene (50 mL) was heated to reflux in a Dean-Stark trap and the reaction progress was controlled by TLC. After full conversion (typically after 1-2d), the reaction mixture was allowed to cool to room temperature, diluted with MTBE or diethylether (100 mL), washed with saturated $NaHCO_3$ (50 mL) and brine (50 mL), dried over $MgSO_4$, and concentrated under reduced pressure. Purification by flash column chromatography on silica gel followed by recrystallization gave the corresponding esters as solid, crystalline compound.

(*E*)-(9*H*-Fluoren-9-yl)methyl cinnamate (1a)



To a solution of cinnamic acid (1.63g, 11.0 mmol) under argon in dry CH_2Cl_2 (100 mL) at r.t., 9-fluorenylmethanol (2.38 g, 12.1 mmol, 1.1 equiv.), EDC hydrochloride (2.11 g, 12.1 mmol, 1.1 equiv.) and DMAP (134 mg, 1.1 mmol, 10 mol%) were added in this order. The reaction mixture was stirred at r.t. overnight, subsequently transferred to a separation funnel and washed with diluted HCl solution (10%, 50 mL), water (50 mL) and brine (50 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 40:1 → 20:1) affording **1a** as a colorless, crystalline solid (2.14 g, 66%).

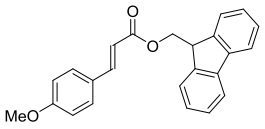
^{1}H-NMR (300 MHz, $CDCl_3$): δ = 4.33 (t, *J* = 7.2 Hz, 1H), 4.53 (d, *J* = 7.2 Hz, 2H), 6.54 (d, *J* = 16.0 Hz, 1H), 7.30–7.38 (m, 2H), 7.39–7.47 (m, 5H), 7.53–7.62 (m, 2H), 7.63–7.69 (m, 2H), 7.71–7.84 (m, 3H) ppm.

^{13}C NMR (75 MHz, $CDCl_3$): δ = 47.1, 66.7, 118.0, 120.2, 125.3, 127.3, 128.0, 128.3, 129.1, 130.6, 134.5, 141.5, 144.1, 145.4, 167.0 ppm.

MS (EI) *m/z* (%):178 (100%), 131 (29%).

HRMS (ESIpos) m/z calculated for $C_2H_{18}NaO_2^+$: 349.1199; found 349.1198.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-methoxycinnamate (1b)



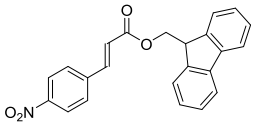
The product was synthesized according to the general procedure A employing *p*-methoxycinnamic acid (1.78g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 98:2 → 90:10) to give a solid (2.60 g, 73%), which was further purified by precipitation from toluene by addition of hexanes, affording **1b** as a colorless, powder.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 3.85 (s, 3H), 4.34 (t, *J* = 7.3 Hz, 1H), 4.53 (d, *J* = 7.3 Hz, 2H), 6.43 (d, *J* = 15.9 Hz, 1H), 6.90 – 6.97 (m, 2H), 7.36 (td, *J* = 7.4, 1.0 Hz, 2H), 7.44 (t, *J* = 7.4 Hz, 2H), 7.50 – 7.55 (m, 2H), 7.65 – 7.70 (m, 2H), 7.74 (d, *J* = 15.9 Hz, 1H), 7.78 – 7.83 (m, 2H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 47.0, 55.5, 66.5, 114.4, 115.3, 120.1, 125.2, 127.1, 127.2, 127.8, 129.9, 141.4, 144.0, 145.0, 161.6, 167.3.

HRMS (ESIpos) m/z calculated for $C_{24}H_{20}NaO_3^+$: 379.1305; found 379.1305

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-nitrocinnamate (1c)



The product was synthesized according to the general procedure A employing *p*-nitrocinnamic acid (1.93g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/CH_2Cl_2 90:10 → 40:60) to give a solid (3.57 g, 96%), which was further purified by recrystallization from EtOAc/hexanes (5:3), affording **1c** as a pale brownish powder.

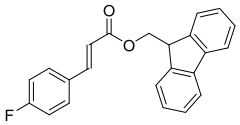
^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.31 (t, *J* = 7.0 Hz, 1H), 4.56 (d, *J* = 7.1 Hz, 2H), 6.62 (d, *J* = 16.0 Hz, 1H), 7.35 (td, *J* = 7.5, 0.9 Hz, 2H), 7.43 (t, *J* = 7.5 Hz, 2H), 7.64 (d, *J* = 7.5 Hz,

2H), 7.66 – 7.70 (m, 2H), 7.73 (d, *J* = 16.1 Hz, 1H), 7.80 (d, *J* = 7.6 Hz, 2H), 8.22 – 8.28 (m, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$) δ 46.9, 66.9, 120.2, 122.1, 124.3, 125.1, 127.3, 128.0, 128.9, 140.5, 141.4, 142.4, 143.7, 148.6, 166.0 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}NNaO_4^+$: 394.1050; found 394.1050.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-fluorocinnamate (1d)



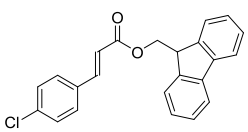
The product was synthesized according to the general procedure A employing *p*-fluorocinnamic acid (1.66, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 95:5) to give a solid (3.23 g, 94%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1d** as a colorless solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.34 (t, *J* = 7.2 Hz, 1H), 4.55 (d, *J* = 7.2 Hz, 2H), 6.47 (d, *J* = 15.9 Hz, 1H), 7.10 (t, *J* = 8.6 Hz, 2H), 7.37 (td, *J* = 7.4, 1.1 Hz, 2H), 7.45 (tm, *J* = 7.3 Hz, 2H), 7.51 – 7.58 (m, 2H), 7.68 (dq, *J* = 7.6, 1.0 Hz, 2H), 7.73 (d, *J* = 16.0 Hz, 1H), 7.82 (dm, *J* = 7.6 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.9, 66.6, 116.0, 116.2, 117.6, 117.6, 120.1, 125.1, 127.2, 127.9, 130.1, 130.2, 130.6, 130.6, 141.4, 143.9, 144.0, 163.0, 165.0, 166.8 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}FNaO_2^+$: 367.1105; found 367.1105.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-chlorocinnamate (1e)



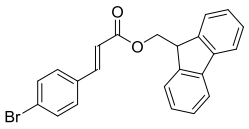
The product was synthesized according to the general procedure A employing *p*-chlorocinnamic acid (1.83, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 96:4) to give a solid (3.61 g, >99%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1e** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.33 (t, *J* = 7.2 Hz, 1H), 4.55 (d, *J* = 7.2 Hz, 2H), 6.51 (d, *J* = 16.0 Hz, 1H), 7.33 – 7.40 (m, 4H), 7.41 – 7.51 (m, 4H), 7.64 – 7.74 (m, 3H), 7.81 (dm, *J* = 7.6 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.9, 66.6, 118.4, 120.2, 125.1, 127.2, 127.9, 129.2, 129.4, 132.8, 136.4, 141.4, 143.9, 166.7 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}ClNaO_2^+$: 383.0809; found 383.0809.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-bromocinnamate (1f)



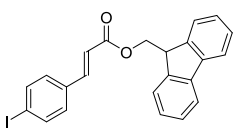
The product was synthesized according to the general procedure A employing *p*-bromocinnamic acid (2.27, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 90:10) to give a solid (4.05 g, 99%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1f** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.32 (t, *J* = 7.2 Hz, 1H), 4.53 (d, *J* = 7.2 Hz, 2H), 6.52 (d, *J* = 16.0 Hz, 1H), 7.35 (td, *J* = 7.5, 1.1 Hz, 2H), 7.38 – 7.47 (m, 4H), 7.52 – 7.56 (m, 2H), 7.63 – 7.70 (m, 3H), 7.80 (dm, *J* = 7.5 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.9, 66.7, 118.5, 120.2, 124.8, 125.2, 127.2, 127.9, 129.6, 132.2, 133.3, 141.4, 143.9, 144.0, 166.7 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}BrNaO_2^+$: 427.0304; found 427.0304.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-iodocinnamate (1g)



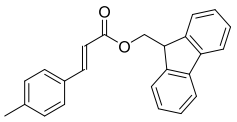
The product was synthesized according to the general procedure A employing *p*-iodocinnamic acid (822 mg, 3 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 94:6) to give a solid (1.14 g, 84%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1g** as a colorless powder.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.34 (t, *J* = 7.2 Hz, 1H), 4.56 (d, *J* = 7.2 Hz, 2H), 6.55 (d, *J* = 16.0 Hz, 1H), 7.29 (dm, *J* = 8.4 Hz, 2H), 7.38 (td, *J* = 7.4, 1.0 Hz, 2H), 7.46 (t, *J* = 7.4 Hz, 2H), 7.65 – 7.70 (m, 3H), 7.76 (dm, *J* = 8.4 Hz, 2H), 7.83 (d, *J* = 7.5 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.9, 66.7, 96.8, 118.6, 120.2, 125.1, 127.2, 127.9, 129.7, 133.8, 138.2, 141.4, 143.9, 144.1, 166.6 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}INaO_2^+$: 475.0165; found 475.0165.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*p*-methylcinnamate (1h)



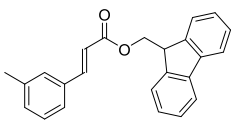
The product was synthesized according to the general procedure A employing *p*-methylcinnamic acid (1.62 g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 96:4) to give a solid (3.30 g, 97%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1h** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 2.40 (s, 3H), 4.33 (t, *J* = 7.2 Hz, 1H), 4.52 (d, *J* = 7.3 Hz, 2H), 6.52 (d, *J* = 15.9 Hz, 1H), 7.23 (d, *J* = 7.8 Hz, 2H), 7.35 (t, *J* = 7.6 Hz, 2H), 7.44 (t, *J* = 7.4 Hz, 2H), 7.48 (d, *J* = 7.8 Hz, 2H), 7.67 (d, *J* = 7.4 Hz, 2H), 7.75 (d, *J* = 16.0 Hz, 1H), 7.81 (d, *J* = 7.5 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 21.6, 47.0, 66.6, 116.8, 120.2, 125.2, 127.2, 127.9, 128.3, 129.8, 131.7, 141.0, 141.4, 144.0, 145.4, 167.2 ppm.

HRMS (ESIpos) m/z calculated for $C_{24}H_{20}NaO_2^+$: 363.1356; found 363.1355.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*m*-methylcinnamate (1i)



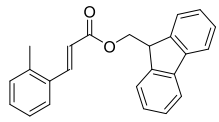
The product was synthesized according to the general procedure A employing *m*-methylcinnamic acid (1.62 g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 96:4) affording **1i** as a colorless, crystalline solid (3.33 g, 98%).

^{1}H NMR (501 MHz, $CDCl_3$): δ 2.46 (s, 3H), 4.42 (t, *J* = 6.3 Hz, 1H), 4.65 (d, *J* = 6.6 Hz, 2H), 6.66 (d, *J* = 16.0 Hz, 1H), 7.24 – 7.40 (m, 2H), 7.40 – 7.59 (m, 6H), 7.79 (d, *J* = 6.9 Hz, 2H), 7.84 – 7.94 (m, 3H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 21.2, 46.8, 66.3, 117.4, 120.0, 125.0, 125.3, 127.0, 127.7, 128.7, 128.7, 131.2, 134.1, 138.4, 141.2, 143.8, 145.3, 166.7 ppm.

HRMS (ESIpos) m/z calculated for $C_{24}H_{20}NaO_2^+$: 363.1356; found 363.1355.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*o*-methylcinnamate (1j)



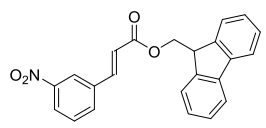
The product was synthesized according to the general procedure A employing *o*-methylcinnamic acid (1.62 g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 95:5) to give a solid (3.37 g, 99%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1j** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 2.50 (s, 3H), 4.37 (t, *J* = 7.2 Hz, 1H), 4.59 (d, *J* = 7.2 Hz, 2H), 6.50 (d, *J* = 15.9 Hz, 1H), 7.24 – 7.32 (m, 2H), 7.35 (td, *J* = 7.4, 1.4 Hz, 1H), 7.39 (td, *J* = 7.4, 1.2 Hz, 2H), 7.47 (tm, *J* = 7.4 Hz, 2H), 7.65 (d, *J* = 7.8 Hz, 1H), 7.70 – 7.74 (m, 2H), 7.84 (d, *J* = 7.5 Hz, 2H), 8.08 (d, *J* = 15.9 Hz, 1H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 19.9, 47.0, 66.5, 118.8, 120.2, 125.2, 126.5, 127.2, 127.9, 130.3, 130.9, 133.3, 137.8, 141.4, 143.0, 144.0, 166.9 ppm.

HRMS (ESIpos) m/z calculated for $C_{24}H_{20}NaO_2^+$: 363.1356; found 363.1355.

(*E*)-(9*H*-Fluoren-9-yl)methyl-*m*-nitrocinnamate (1k)



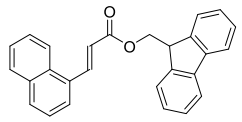
The product was synthesized according to the general procedure A employing *m*-nitrocinnamic acid (1.93g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/CH_2Cl_2 90:10 → 40:60), affording **1k** as a colorless powder (3.53 g, 95%).

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.28 (t, *J* = 6.8 Hz, 1H), 4.53 (d, *J* = 7.0 Hz, 2H), 6.59 (d, *J* = 16.0 Hz, 1H), 7.35 (t, *J* = 7.4 Hz, 2H), 7.42 (t, *J* = 7.5 Hz, 2H), 7.49 (t, *J* = 7.9 Hz, 1H), 7.60 – 7.83 (m, 6H), 8.17 (d, *J* = 7.7 Hz, 1H), 8.33 (s, 1H).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.7, 66.6, 120.0, 120.7, 122.3, 124.5, 124.9, 127.1, 127.8, 129.8, 133.6, 135.8, 141.2, 142.2, 143.6, 148.4, 165.9 ppm.

HRMS (ESIpos) m/z calculated for $C_{23}H_{17}NNaO_4^+$: 394.1050; found 349.1050.

(*E*)-(9*H*-Fluoren-9-yl)methyl-3-(1-naphthalenyl)acrylate (1l)



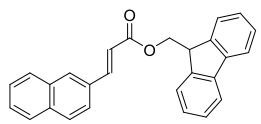
The product was synthesized according to the general procedure A employing 3-(1-naphthalenyl)acrylic acid (1.98 g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/CH_2Cl_2 90:10 → 40:60) to give a solid (3.50 g, 93%), which was further purified by recrystallization from hexanes/EtOAc (5:1), affording **1l** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, Chloroform-*d*): δ = 4.37 (t, *J* = 7.1 Hz, 1H), 4.60 (d, *J* = 7.1 Hz, 2H), 6.62 (d, *J* = 15.8 Hz, 1H), 7.36 (tm, *J* = 7.5 Hz, 2H), 7.44 (t, *J* = 7.4 Hz, 2H), 7.52 (t, *J* = 7.7 Hz, 1H), 7.56 (ddd, *J* = 8.0, 6.8, 1.2 Hz, 1H), 7.62 (ddd, *J* = 8.4, 6.7, 1.4 Hz, 1H), 7.70 (d, *J* = 7.4 Hz, 2H), 7.81 (d, *J* = 7.4 Hz, 3H), 7.90 (d, *J* = 8.2 Hz, 1H) , 7.93 (d, *J* = 8.2 Hz, 1H), 8.18 (d, *J* = 8.4 Hz, 1H), 8.57 (d, *J* = 15.7 Hz, 1H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 47.1, 66.7, 120.2, 120.5, 123.4, 125.2, 125.2, 125.6, 126.4, 127.1, 127.3, 127.9, 128.9, 130.8, 131.5, 131.7, 133.8, 141.5, 142.3, 144.0, 166.8 ppm.

HRMS (ESIpos) m/z calculated for $C_{27}H_{20}NaO_2^+$: 399.1356; found 399.1355.

(*E*)-(9*H*-Fluoren-9-yl)methyl-3-(2-naphthalenyl)acrylate (1m)



The product was synthesized according to the general procedure A employing 3-(2-naphthalenyl)acrylic acid (1.98 g, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/CH_2Cl_2 90:10 → 40:60) followed by to give a solid (3.61 g,

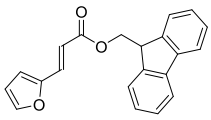
96%), which was further purified from hexanes/EtOAc (2:1), affording **1m** as a colorless, crystalline solid.

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.37 (t, *J* = 7.2 Hz, 1H), 4.59 (d, *J* = 7.3 Hz, 2H), 6.68 (d, *J* = 16.0 Hz, 1H), 7.39 (td, *J* = 7.5, 1.2 Hz, 2H), 7.47 (t, *J* = 7.3 Hz, 2H), 7.52 – 7.58 (m, 2H), 7.72 (dt, *J* = 8.4, 1.4 Hz, 3H), 7.81 – 7.91 (m, 5H), 7.95 (d, *J* = 16.0 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 47.0, 66.6, 118.0, 120.2, 123.6, 125.2, 126.8, 127.2, 127.4, 127.9, 127.9, 128.7, 128.8, 130.2, 131.9, 133.3, 134.4, 141.4, 144.0, 145.4, 167.0 ppm.

HRMS (ESIpos) m/z calculated for $C_{27}H_{20}NaO_2^+$: 399.1356; found 399.1356.

(*E*)-(9*H*-Fluoren-9-yl)methyl-3-(2-furanyl)acrylate (1n)



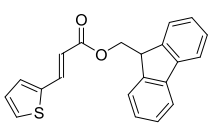
The product was synthesized according to the general procedure A employing 3-(2-furanyl)acrylic acid (1.38, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 99:1 → 95:5), affording **1n** as a colorless powder (1.04g, 33%).

^{1}H NMR (501 MHz, $CDCl_3$): δ = 4.31 (t, *J* = 7.4 Hz, 1H), 4.49 (d, *J* = 7.4 Hz, 2H), 6.44 (d, *J* = 15.7 Hz, 1H), 6.50 (dd, *J* = 3.5, 1.8 Hz, 1H), 6.66 (d, *J* = 3.5 Hz, 1H), 7.31 – 7.37 (m, 2H), 7.43 (t, *J* = 7.5 Hz, 2H), 7.50 (d, *J* = 15.8 Hz, 2H), 7.65 (d, *J* = 7.4 Hz, 2H), 7.79 (d, *J* = 7.5 Hz, 2H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 47.0, 66.7, 112.5, 115.3, 115.5, 120.2, 125.3, 127.2, 127.9, 131.6, 141.4, 144.0, 145.0, 151.0, 167.1 ppm.

HRMS (ESIpos) m/z calculated for $C_{21}H_{16}NaO_3^+$: 339.0992; found 339.0992.

(*E*)-(9*H*-Fluoren-9-yl)methyl-3-(2-thiophenyl)acrylate (1o)



The product was synthesized according to the general procedure A employing 3-(2-thiophenyl)acrylic acid (1.54, 10 mmol) as starting material. The crude product was purified by flash column chromatography (eluent hexane/EtOAc 98:2 → 92:8) to give a solid (3.12 g, 94%), which was further purified by recrystallization from hexanes/EtOAc (15:1), affording **1o** as a pale yellow powder.

^{1}H NMR (501 MHz, Chloroform-*d*): δ = 4.33 (t, *J* = 7.3 Hz, 1H), 4.54 (d, *J* = 7.3 Hz, 2H), 6.37 (d, *J* = 15.7 Hz, 1H), 7.08 (dd, *J* = 5.1, 3.6 Hz, 1H), 7.30 (d, *J* = 3.6 Hz, 1H), 7.37 (td, *J* = 7.4, 1.1 Hz, 2H), 7.41 (dm, *J* = 5.1 Hz, 1H), 7.45 (tm, *J* = 7.3 Hz, 2H), 7.68 (dm, *J* = 7.5 Hz, 2H), 7.82 (dm, *J* = 7.5 Hz, 2H), 7.88 (dm, *J* = 15.7 Hz, 1H) ppm.

^{13}C NMR (126 MHz, $CDCl_3$): δ = 46.9, 66.6, 116.5, 120.1, 125.2, 127.2, 127.9, 128.2, 128.7, 131.3, 137.7, 139.5, 141.4, 143.9, 166.8 ppm.

HRMS (ESIpos) m/z calculated for $C_{21}H_{16}NaO_2S^+$: 355.0763; found 355.0763.

Synthesis of Chiral C-H Acids

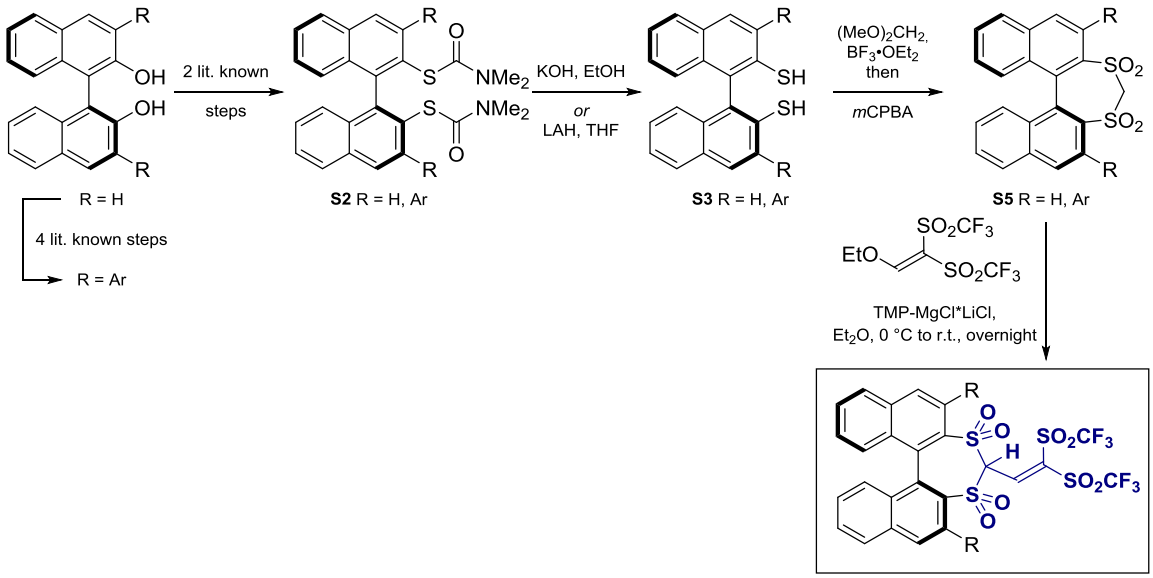
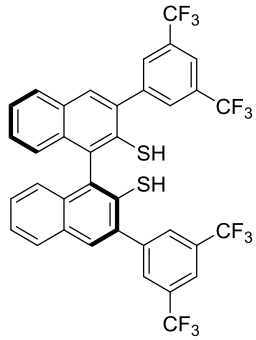


Fig. S1. Synthetic route to chiral C–H acids.

Synthesis of Disulfones from BINOLs

(*S*)-3,3′-Bis(3,5-bis(trifluoromethyl)phenyl)-[1,1′-binaphthalene]-2,2′-dithiol (S3a):



To a flame dried flask under Ar, *(S)*-(3,3′-Bis(3,5-bis(trifluoromethyl)phenyl)-[1,1′-binaphthalene]- 2,2′diyl-*S*,*S*′-bis(*N*,*N*-dimethylthiocarbamate)(*10*) (10.4 g, 11.7 mmol) and KOH (9.8 g, 0.18 mol, 15 equiv.) were added and the solids were set under Ar by 3 cycles of evacuation and Ar-flushing. Degassed (30 min Ar bubbling)

EtOH (120 mL) was added and the reaction mixture was stirred at 70 °C for 36 h. After cooling to room temperature the reaction mixture was partitioned between degassed aq. HCl sol. (10%, 400 mL) and CH_2Cl_2 (400 mL). The organic layer was separated, dried over Na_2SO_4 and concentrated under reduced pressure. The obtained crude product was purified by column chromatography (5% EtOAc in hexanes) giving the title compound (9.1 g, >99%) as a yellow powder.

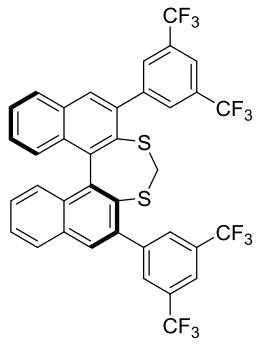
^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 3.26 (s, 2H), 7.07 (d, *J* = 8.5 Hz, 2H), 7.40 (dd, *J* = 8.5 Hz, 6.8 Hz, 2H), 7.52 (dd, *J* = 8.3 Hz, 6.8 Hz, 2H), 7.91 (s, 2H), 7.94 (d, *J* = 8.3 Hz, 2H), 7.98 (br s, 2H), 8.08 (s, 4H) ppm.

^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 122 (m), 124.3, 125.0, 126.6, 128.5, 128.6, 130.0, 130.3, 130.8, 131.6, 131.7, 132.1, 133.2, 136.2, 142.4 ppm.

MS (ESIneg) m/z: 741 (M–H).

HRMS (ESIneg) m/z: calculated (M–H = $C_{36}H_{17}F_{12}S_2$) 741.0586, found 741.0589.

(*S*)-2,6-Bis(3,5-bis(trifluoromethyl)phenyl)dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine (S4a):



(*S*)-3,3′-Bis(3,5-bis(trifluoromethyl)phenyl)- [1,1′-binaphthalene]-2,2′-dithiol **S3a** (4.4 g, 5.9 mmol) was placed in a flame dried flask under Ar and dissolved in CH_2Cl_2 (30 mL). $H_2C(OMe)_2$ (0.52 mL, 5.9 mmol, 1.0 equiv.) was added, followed by BF_3•OEt_2 (0.75 mL, 5.9 mmol, 1.0 equiv.). The resulting mixture was stirred for 24 h, after which identical quantities of both reagents were added. After another 24 h the reaction was quenched by addition to aq. KOH sol. (2%, 100 mL) and diluted with further CH_2Cl_2 (100 mL). The organic phase was washed with aq. KOH sol. (2%, 50 mL) and brine (50 mL), dried over $MgSO_4$ and concentrated under reduced pressure. After purification by column chromatography (2% EtOAc in hexanes), the title compound (4.1 g, 92%) was obtained as a yellow powder.

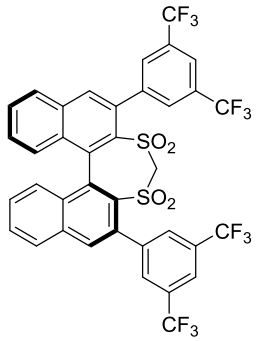
^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 3.90 (s, 2H), 7.19 (d, *J* = 8.5 Hz, 2H), 7.37 (ddd, *J* = 8.5 Hz, 6.9 Hz, 1.3 Hz 2H), 7.61 (ddd, *J* = 8.2 Hz, 6.9 Hz, 1.0 Hz, 2H), 7.96 (s, 2H), 8.01 (s, 4H), 8.04 (d, *J* = 8.2 Hz, 2H), 8.11 (s, 2H) ppm.

^{13}C-NMR ($CDCl_3$, 100 MHz): δ = 48.2, 121.4 (sept., $J_{C–F}$ = 3.5 Hz), 123.5 (q, $J_{C–F}$ = 273.0 Hz), 127.5, 127.6, 127.9, 128.6, 130.3, 130.4 (m), 131.2 (q, $J_{C–F}$ = 32.8 Hz), 132.1, 133.7, 140.4, 143.1, 144.7 ppm. (Not all C-signals could be detected, presumably due to overlap of several signals in the designated multipletts.) **^{19}F-NMR** ($CDCl_3$, 376 MHz): δ = –62.6 ppm.

MS (EI) m/z: 754 (21%), 740 (22%), 721 (61%), 708 (100%), 494 (18%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{37}H_{18}F_{12}S_2Na$) 777.0551, found 777.0554.

(*S*)-2,6-Bis(3,5-bis(trifluoromethyl)phenyl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide (S5a):



(*S*)-2,6-Bis(3,5-bis(trifluoromethyl)phenyl)dinaphtho [2,1-*d*:1′,2′-*f*][1,3]dithiepine **S4a** (5.4 g, 7.1 mmol) was placed in a flame dried flask under Ar and dissolved in $CHCl_3$ (70 mL). *m*CPBA (9.8 g, 57 mmol, 8.0 equiv.) was added at 0 °C. The resulting mixture was stirred at 40 °C for 36 h. The reaction mixture was diluted with CH_2Cl_2 (400 mL) and washed with aq. KOH sol. (2%, 3 × 80 mL), H_2O (20 mL) and brine (20 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. After purification by column chromatography (20–80% gradient of CH_2Cl_2 in hexanes), the title compound (6.4 g, 75%) was obtained as light orange foam.

^{1}H-NMR ($CDCl_3$, 400 MHz): δ = 4.59 (s, 2H), 7.17 (d, *J* = 8.5 Hz, 2H), 7.53 (ddd, *J* = 8.5 Hz, 7.0 Hz, 1.2 Hz, 2H), 7.80 (ddd, *J* = 8.2 Hz, 7.0 Hz, 1.0, 2H), 7.91 (s, 2H), 7.96 (s, 2H), 7.98 (s, 2H), 8.09 (s, 2H), 8.09 (d, *J* = 8.2 Hz, 2H) ppm.

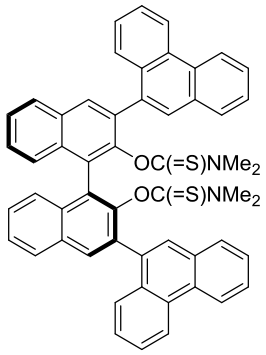
^{13}C-NMR ($CDCl_3$, 100 MHz): δ = 84.2, 121.9 (sept, J_{C-F} = 3.8 Hz), 123.3 (q, J_{C-F} = 273.0 Hz), 123.4 (q, J_{C-F} = 273.0 Hz), 127.9, 128.1 (m), 128.7, 129.5, 130.1, 130.5 (sept, J_{C-F} = 33.6 Hz), 130.9, 131.4 (m), 130.5 (sept, J_{C-F} = 33.8 Hz), 132.7, 134.4, 134.8, 135.0, 141.0, 141.2 ppm.

^{19}F-NMR ($CDCl_3$, 376 MHz): δ = –62.5, –62.6 ppm.

MS (ESIpos) m/z: 841 (M+Na).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{37}H_{18}O_4F_{12}S_2Na$) 841.0347, found 841.0339.

(*S*)-(3,3′-Bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′-diyl)-*O,O′*-bis(*N,N*-dimethylthiocarbamate) (S1b):



The title compound was prepared following the procedure previously described by our group.(*10*)

(*S*)-(3,3′-Bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′-diol (16.5 g, 25.8 mmol)(*27*) was placed in a flame dried flask under Ar and dissolved in DMF (150 mL). The solution was cooled to 0 °C and NaH (60% dispersion in oil, 4.10 g, 103 mmol, 4.0 equiv.) was added portionwise. The cooling bath was removed and the reaction was stirred at room temperature for 5 min. *N,N*-dimethyl thiocarbamoylchloride (16.0 g, 130 mmol, 5.0 equiv.) was added and the resulting mixture was stirred at 85 °C for 36 h. The reaction mixture was allowed to cool to 40 °C and aq. KOH sol. (2%, 300 mL) was added. The resulting precipitate was separated by filtration, washed with aq. KOH sol. (2%, 200 mL) and taken up in CH_2Cl_2 (500 mL). The solution was washed with H_2O (1 × 100 mL) and brine (1 × 50 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The resulting crude product was subjected to column chromatography (gradient from 20% to 50% of CH_2Cl_2 in hexanes) giving partially purified compound and revealing an instability of the title compound upon prolonged exposure to silica, which was further confirmed by 2D-TLC. A second purification step was thus conducted, which was optimized for short contact to silica (hexanes/CH_2Cl_2 = 3/2) giving the title compound (7.97 g, 38%) as yellow foam.

Due to the presence of rotamers of the thiocarbamate groups and the 9-phenanthryl substituents, several signal sets could be observed for the title compound. NMR-characterization of the major conformer, amounting to approx. 43% of the overall compound is given below:

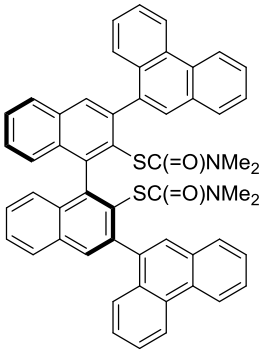
^{1}H-NMR ($CDCl_3$, 400 MHz): δ = 2.07 (s, 6H), 2.71 (s, 6H), 7. (dd, *J* = 7.0 Hz, 1.1 Hz, 1H), 7.23 (dd, *J* = 6.8 Hz, 1.0 Hz, 1H), 7.36 (ddd, *J* = 8.4 Hz, 6.8 Hz, 1.2 Hz, 2H), 7.49 (ddd, *J* = 8.2 Hz, 7.0 Hz, 1.0 Hz, 2H), 7.52–7.57 (m, 3H), 7.62–7.73 (m, 5H), 7.50 (d, *J* = 8.6 Hz, 2H), 7.91 (d, *J* = 7.8 Hz, 2H), 7.98 (dd, *J* = 7.8 Hz, 1.2 Hz, 2H), 8.05 (s, 2H), 8.12 (s, 2H), 8.70–8.76 (m, 4H) ppm.

^{13}C-NMR ($CDCl_3$, 100 MHz): δ = 37.5, 42.6, 122.4, 122.9, 125.9, 126.05, 126.1, 126.2, 126.9, 127.0, 127.7, 129.2, 129.4, 129.9, 130.1, 130.5, 131.4, 131.6, 132.0, 132.1, 133.1, 133.7, 133.8, 148.8, 186.6 ppm. (The list of ^{13}C-signals is incomplete, as only those signals clearly corresponding to the major conformer as judged by signal intensity were included.)

MS (ESIpos) m/z: 835 (M+Na)

HRMS (ESIpos) m/z: calculated (M+H = $C_{54}H_{41}N_2O_2S_2$) 813.2604, found 813.2600.

***(S)*-(3,3′-Bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′diyl-*S,S′*-bis(*N,N*-dimethylthiocarbamate) (S2b):**



The title compound was prepared following a modified form of the procedure previously described by our group.(*10*)

(*S*)-(3,3′-Bis(9-phenanthryl)- [1,1′-binaphthalene]-2,2′-diyl)- *O,O′*-bis(*N,N*-dimethylthiocarbamate) **S1a** (7.95 g, 6.10 mmol) was split into 5 approximately equal batches, which were placed in Ar-flushed dram glass vials equipped with a magnetic stirring bar. The vials were placed in a preheated (250 °C) stirring plate equipped with an aluminum heating block and stirred at this temperature for 120 min. The vials were removed from the heating block and allowed to reach room temperature. The obtained crude products were taken up in CH_2Cl_2 (20 mL for each vial), combined and concentrated onto silica. Analysis of the crude product by 2D-TLC revealed the presence of rotamers, which were partially stable on the chromatography time scale but equilibrated upon storage in solid state or solution. On a small scale one of the two rotamers could be separated by column chromatography (CH_2Cl_2) and analyzed by ^{1}H-NMR spectroscopy.

After storage of this sample for 3d, a ^{1}H-NMR spectrum was again recorded and found to be identical to the spectrum obtained for the unseparated rotamers. Likewise both rotamers could be detected again by TLC.

A comparison of the aromatic region of spectra obtained for the purified least polar symmetric rotamer (top), the remaining rotamer(s) (middle) and the spectrum obtained for both samples after 3 d (bottom) is shown below.

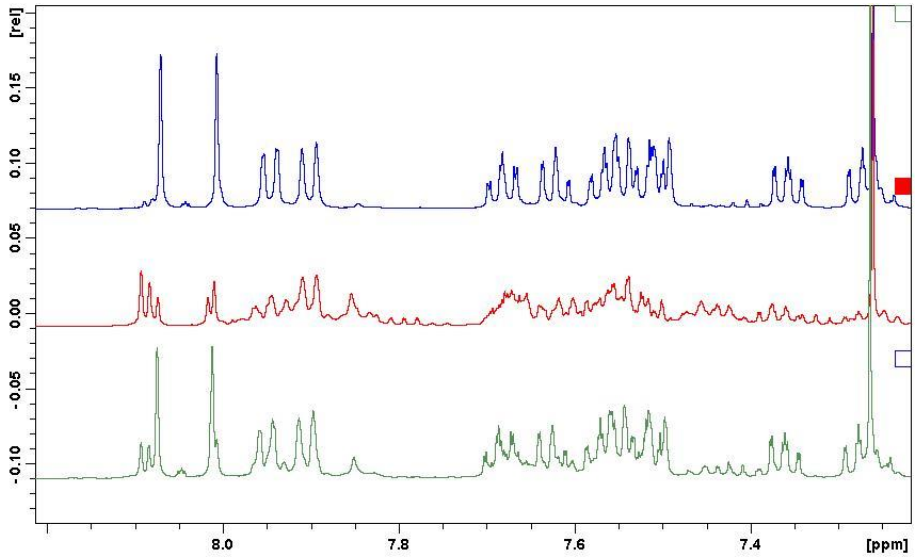


Fig. S2. Comparison of NMR spectra of the different rotamers.

Thus no attempt to separate these rotamers on a large scale was undertaken. The crude product was purified by column chromatography (CH_2Cl_2), giving the mixture of rotamers of the title compound (6.69 g, 84%) as a yellow foam.

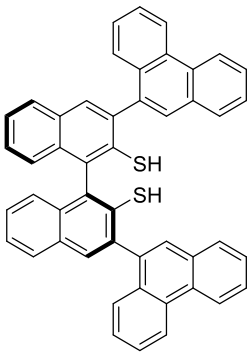
^{1}H-NMR ($CDCl_3$, 400 MHz): δ = 2.25 (br s, 12H), 7.27–7.30 (m, 1H), 7.34–7.46 (m, 3H), 7.50–7.70 (m, 12H), 7.82–7.98 (m, 5H), 8.00–8.02 (m, 1H), 8.06–8.10 (m, 2H), 8.72–8.78 (m, 4H) ppm. (Due to the overlap of signals belonging to different rotamers, the integrations are non-integer and have been rounded to best account for the overall number of protons.)

^{13}C-NMR ($CDCl_3$, 101 MHz): δ = 165.5, 144.5, 144.1, 142.8, 142.6, 142.3, 137.6, 137.5, 133.9, 133.87, 133.5, 133.4, 132.7, 132.66, 132.3, 132.1, 132.0, 131.6, 131.4, 130.5, 130.3, 130.2, 130.1, 130.0, 129.9, 129.7, 129.0, 128.8, 128.7, 127.9, 127.6, 127.5, 127.3, 127.26, 127.2, 127.14, 127.0, 126.7, 126.6, 126.57, 126.5, 126.48, 126.4, 126.3, 126.2, 126.0, 125.95, 122.6, 122.5, 122.43, 122.40, 36.6 ppm.

MS (ESIpos) m/z: 835 (M+Na).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{54}H_{40}N_2O_2S_2Na$) 835.2423, found 835.22425.

(*S*)-3,3′-Bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′-dithiol (S3b):



In a flame dried flask under Ar, *(S)*-(3,3′-bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′diyl-*S*,*S*′-bis(*N*,*N*-dimethylthiocarbamate) **S2b** (6.6 g, 8.1 mmol) was dissolved in THF (80 mL) and $LiAlH_4$ (1.54 g, 40.6 mol, 5.0 equiv.) was added. The reaction mixture was stirred at 65 °C overnight. After cooling to room temperature, degassed aq. HCl sol. (10%, 50 mL) was added and the aqueous phase was extracted with CH_2Cl_2 (3 × 80 mL). The combined organic phases were separated, dried over Na_2SO_4 and concentrated under reduced pressure. The obtained crude product (5.5 g, >99%) was analyzed and used in the next step without further purification. As expected from the preceding experiments, the title compound was obtained as a mixture of rotamers.

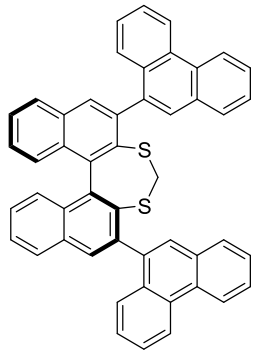
^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 3.28 + 3.30 + 3.34 + 3.36 (4 × s, 2H), 7.31 (t, *J* = 8.4 Hz, 1H), 7.38 (t, *J* = 8.0 Hz, 1H), 7.41–7.46 (m_{Ar}, 2H), 7.46–7.55 (m_{Ar}, 3H), 7.59–7.76 (m_{Ar}, 8H), 7.78 (d, *J* = 8.3 Hz, 1H), 7.87–7.97 (m_{Ar}, 5H), 7.98–8.02 (m_{Ar}, 1H), 8.03–8.06 (m_{Ar}, 2H), 8.76–8.85 (m_{Ar}, 4H) ppm. (Due to the overlap of signals belonging to different rotamers, the integrations are non-integer and have been rounded to best account for the overall number of protons.)

^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 122.7, 122.8, 123.0, 123.1, 124.9, 125.2, 125.9, 125.95, 126.0, 126.8, 126.9, 126.95, 127.0, 127.05 (3C), 127.1, 127.15 (3C), 127.2, 127.6, 127.65 (2C), 127.7, 128.4,128.45, 128.5, 128.6, 128.8, 129.0 (2C), 129.05, 129.1, 130.4, 130.5, 130.55 (2C), 130.6 (2C), 130.8, 131.1, 131.6, 131.7, 131.75, 131.8, 132.15, 132.2, 132.4, 132.8, 132.85, 133.7, 133.9 (2C), 136.8, 136.85, 137.1, 137.5, 137.7 ppm.

MS (EI) m/z: 670 (21%), 636 (100%), 459 (21%), 334 (12%), 318 (12%), 302 (12%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{48}H_{30}S_2Na$) 693.1681, found 693.1685.

(*S*)-2,6-Bis(9-phenanthryl)dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine (S4b):



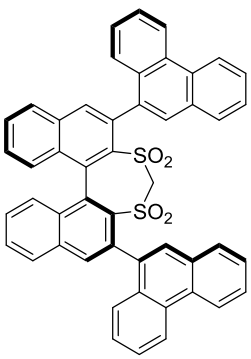
In a flame dried flask under Ar, (*S*)-3,3′-bis(9-phenanthryl)-[1,1′-binaphthalene]-2,2′-dithiol **S3b** (5.5 g, 8.1 mmol) was dissolved in CH_2Cl_2 (40 mL). Dimethoxymethane (820 µL, 705 mg, 9.30 mmol, 1.1 equiv.) and BF_3•OEt_2 (2.84 mL, 2.47 g, 17.4 mmol, 2.1 equiv.) were added and the reaction mixture was stirred at room temperature overnight. The reaction mixture was diluted with CH_2Cl_2 (200 mL) and washed with aq. KOH sol. (2%, 4 × 50 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was purified by column chromatography (gradient form 30% to 40% of CH_2Cl_2 in hexanes) giving the title compound (4.38 g, 79%) as a mixture of interconverting rotamers.

^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 3.62, 3.65 + 3.68 + 3.70 + 3.72 (5 × s, 2H), 7.21–7.25 (m_{Ar}, 4H), 7.45–7.50 (m_{Ar}, 2H), 7.51–7.74 (m_{Ar}, 10H), 7.80–7.87 (m_{Ar}, 2H), 7.91–7.92 (m_{Ar}, 1H), 7.96–7.99 (m_{Ar}, 1H), 8.00–8.06 (m_{Ar}, 2H), 8.16–8.18 (m_{Ar}, 1H), 8.20–8.24 (m_{Ar}, 1H), 8.74–8.85 (m_{Ar}, 4H) ppm. (Due to the overlap of signals belonging to different rotamers, the integrations are non-integer and have been rounded to best account for the overall number of protons. Based on the experience from previous steps, no ^{13}C-NMR was recorded, as the assignment of signals had generally proven impossible in the obtained mixtures of rotamers.)

MS (EI) m/z: 682 (38%), 649, (97%), 636 (100%), 458 (9%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{49}H_{30}S_2Na$) 705.1681, found 705.1678.

(*S*)-2,6-Bis(9-phenanthryl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide (S5b):



(*S*)-2,6-Bis(3,5-bis(9-phenanthryl) dinaphtho [2,1-d:1′,2′-f] [1,3] dithiepine **S4b** (4.5 g, 6.4 mmol) was placed in a flame dried flask under Ar and dissolved in CH_2Cl_2 (250 mL). *m*CPBA (70%, 8.8 g, 51 mmol, 8.0 equiv.) was added at 0 °C. The resulting mixture was stirred at room temperature for 36 h. The reaction mixture was diluted with CH_2Cl_2 (500 mL) and washed with aq. KOH sol. (2%, 3×250 mL) and brine (100 mL). The organic phase was dried over $MgSO_4$ and concentrated

under reduced pressure. Column chromatography (hexanes/CH_2Cl_2 = 4/6 to pure CH_2Cl_2) gave a yellowish powder (3.14 g, 66%) as a mixture of three different rotamers.

Separation of 1.5 g of this rotamer mixture was achieved with column chromatography (pure toluene). The least polar rotamer was obtained as a yellow powder, which could be precipitated from CH_2Cl_2/hexanes to give a colorless powder (0.4 g).

^{1}H-NMR (CD_2Cl_2, 500 MHz): δ = 4.46 (s, 2H), 7.31 (dm, *J* = 8.7 Hz, 2H), 7.51 (ddd, *J* = 8.2, 6.1, 1.2 Hz, 6H), 7.65 (ddd, *J* = 8.3, 6.1, 2.2 Hz, 2H), 7.69 (ddd, *J* = 7.8, 7.0, 1.2 Hz, 2H), 7.74 (ddd, *J* = 8.3, 7.0, 1.5 Hz, 2H), 7.79 (ddd, *J* = 8.2, 6.9, 1.1 Hz, 2H), 7.92 (s, 2H), 7.98 (dd, *J* = 7.8, 1.5 Hz, 2H),f 8.07 (d, *J* = 8.2 Hz, 2H), 8.22 (d, *J* = 0.8 Hz, 2H), 8.78 (d, *J* = 8.3 Hz, 2H), 8.81 (d, *J* = 8.3 Hz, 2H) ppm.

^{13}C NMR (CD_2Cl_2, 126 MHz): δ = 82.2, 123.1, 123.6, 126.7, 126.9, 127.3, 127.5, 127.5, 128.5, 128.6, 128.7z.8, 129.0, 130.3, 130.5, 130.7, 131.6, 132.5, 132.9, 132.9, 134.7, 135.7, 136.0, 136.7, 140.0 ppm.

MS (EI) m/z: 746 (100%), 708 (11%), 615 (14%), 439 (20%), 373 (17%), 315 (43%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{49}H_{30}O_4S_2Na$) 769.1478, found 769.1474.

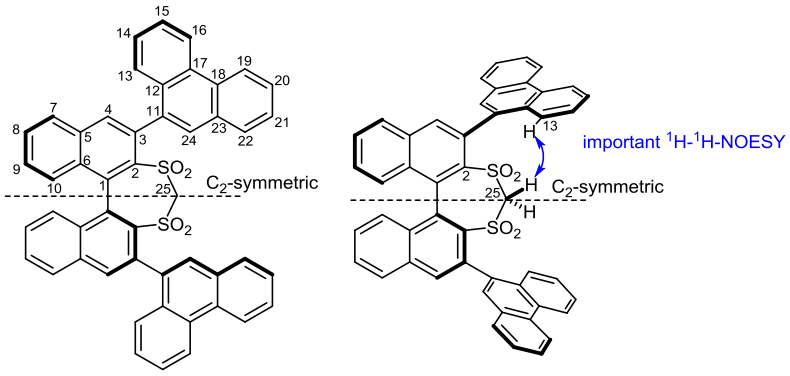
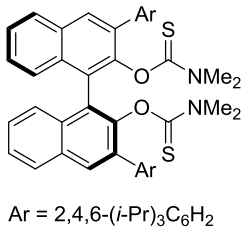


Table S1. Overview of NMR chemical shifts of all atoms of **S5b** and the correspoinding 2D correlations used for assignment.

Atom	Chemical Shift [ppm]	J [Hz]	Cross-peaks			
			COSY	HSQC	HMBC	NOESY
1 C	140.01				4, 10	
1' C						
2 C	132.47				25, 4	
2' C						
3 C	136.68				4, 24	
3' C						
4 C	134.69			4	4, 7, 24	
H	8.22	0.80(10)	10	4	2, 1, 3, 11, 5, 4, 6, 7	13, 24, 7
4' C						
H						
5 C	135.68				4, 7, 8, 10	
5' C						
6 C	132.89				9, 7, 4	
6' C						
7 C	128.84			7	4, 9	
H	8.07	8.20(8), 1.20(9)	8	7	5, 4, 6, 9	4, 8
7' C						
H						
8 C	130.65			8	10	
H	7.79	8.20(7), 1.10(10), 6.90(9)	7, 9	8	5, 10	9, 7
8' C						
H						
9 C	128.73	162.00(9H)		9	7	
H	7.52	1.20(7), 6.90(8), 162.00(9C), 8.70(10)	8, 10	9	6, 7	8, 10
9' C						
H						
10 C	128.55			10	8	
H	7.31	0.80(4), 1.10(8), 8.70(9)	9, 4	10	1, 5, 8	9
10' C						
H						
11 C	136.04				4, 24, 13	
11' C						
12 C	132.88				16, 24, 15, 14	
12' C						
13 C	126.71	159.00(13H)		13	15	
H	7.53	159.00(13C), 8.20(14), 2.20(15)		13	11, 17, 15	25, 4
13' C						

H						
14 C	127.51			14	16, 15, 14	
H	7.5	1.20(16), 6.10(15), 8.20(13)	15	14	12, 14, 16	15
14' C						
H						
15 C	126.95			15	15, 13	
H	7.65	6.10(14), 8.30(16), 2.20(13)	16, 14	15	12, 17, 14, 15, 13	16, 14
15' C						
H						
16 C	123.6			16	16, 14	
H	8.81	1.20(14), 8.30(15)	15	16	12, 18, 14, 16	19, 15
16' C						
H						
17 C	130.31				19, 15, 13	
17' C						
18 C	130.45				16, 22, 24, 20	
18' C						
19 C	123.06			19	19, 21	
H	8.78	1.20(21), 8.30(20)	20	19	23, 17, 21, 19	16, 20
19' C						
H						
20 C	127.33			20	22	
H	7.74	8.30(19), 7.00(21), 1.50(22)	19	20	18, 22	19
20' C						
H						
21 C	127.5			21	19	
H	7.69	1.20(19), 7.80(22), 7.00(20)	22	21	23, 19	22
21' C						
H						
22 C	129.01			22	24, 20	
H	7.98	7.80(21), 1.50(20)	21	22	18, 24, 20	21, 24
22' C						
H						
23 C	131.62				19, 21, 24	
23' C						
24 C	128.52			24	22	
H	7.92			24	3, 11, 4, 12, 23, 18, 22	4, 22
24' C						
H						
25 C	82.25	146.00(25H)		25		
H2	4.46	146.00(25C)		25	2	13

(*S*)-(3,3′-Bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′-diyl)-*O,O′*-bis(*N,N*-dimethylthiocarbamate) (S1d):



Ar = 2,4,6-(*i*-Pr)$_3$C$_6$H$_2$

(*S*)-(3,3′-Bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′-diol(*28*) (1.44 g, 2.00 mmol) was placed in a flame dried flask under Ar and dissolved in DMF (8 mL). The solution was cooled to 0 °C and NaH (60% dispersion in oil, 320 mg, 8.00 mmol, 4.0 equiv.) was added portionwise. The cooling bath was removed and the reaction was stirred at room temperature for 5 min. A solution of *N,N*-dimethyl thiocarbamoylchloride (1.23 g, 10.0 mmol, 5.0 equiv.) in DMF (1.4 mL) was added and the resulting mixture was heated to 85 °C for 2 d. The reaction mixture was allowed to cool to 40 °C and aq. KOH sol. (2%, 50 mL) was added. The resulting precipitate was separated by filtration, washed with aq. KOH sol. (2%, 50 mL) and taken up in CH_2Cl_2 (200 mL). The solution was washed with H_2O (10 mL) and brine (10 mL), dried over $MgSO_4$ and concentrated under reduced pressure. The resulting crude product was purified by column chromatography (1% to 5% EtOAc in hexanes) giving the title compound (1.22 g, 71%) as yellow foam.

Due to the presence of rotamers of the thiocarbamate groups, several signal sets could be observed for the title compound. NMR-characterization of the major rotamer is given below:

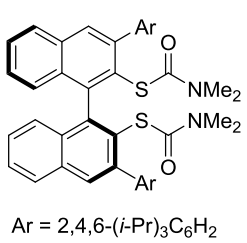
^{1}H-NMR ($CDCl_3$, 400 MHz): δ = 1.10 (d, *J* = 7.1 Hz, 6H), 1.12 (d, *J* = 6.9 Hz, 6H), 1.16 (d, *J* = 6.8 Hz, 6H), 1.27 (d, *J* = 7.0 Hz, 18H), 2.39 (s, 6H), 2.87 (s, 6H) superimposed with 2.85–2.97 (m, 4H), 3.00–3.10 (m, 2H), 6.98 (d, *J* = 1.7 Hz, 2H), 7.07 (d, *J* = 1.7 Hz, 2H), 7.23 (ddd, *J* = 8.3 Hz, 6.8 Hz, 1.4 Hz, 2H), 7.40 (ddd, *J* = 8.1 Hz, 7.0 Hz, 1.1 Hz, 2H), 7.64 (d, *J* = 8.7 Hz, 2H), 7.75 (s, 2H) overlays one part of 7.77 (d, *J* = 7.6 Hz, 2H) ppm.

^{13}C-NMR ($CDCl_3$, 100 MHz): δ = 22.9, 23.9, 24.2, 24.4, 25.3, 26.8, 30.5, 30.8, 34.5, 37.8, 42.6, 119.7, 121.1, 124.9, 125.5, 127.3, 127.9, 130.5, 131.1, 131.8, 132.3, 133.0, 134.0, 147.0, 148.4, 148.5, 148.6, 185.5 ppm.

MS (EI) m/z: 864 (26%), 792 (48%), 760 (18%), 677 (22%), 88 (100%), 72 (58%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{56}H_{68}S_2O_2Na$) 887.4614, found 887.4608.

(*S*)-(3,3′-Bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′diyl-*S*,*S*′-bis(*N*,*N*-dimethylthiocarbamate) (S2d):



Ar = 2,4,6-(*i*-Pr)$_3$C$_6$H$_2$

(*S*)-(3,3′-Bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′-diyl)-*O*,*O*′-bis(*N*,*N*-dimethylthiocarbamate) **S1d** (1.22 g, 1.41 mmol) was placed in an Ar-flushed dram glass vial equipped with a magnetic stirring bar. The vial was placed on a preheated (250 °C) stirring plate equipped with an aluminum heating block and stirred at this temperature for 120 min. The vial was removed from the heating block and allowed to reach room temperature. The obtained crude product was taken up in CH_2Cl_2 (20 mL) and concentrated onto silica. The crude product from six separate experiments was combined and purified by column chromatography (5% to 10% EtOAc in hexanes), giving the title compound (894 mg, 73%) as a yellow foam.

^{1}H-NMR ($CDCl_3$, 400 MHz): δ = 0.85 (d, *J* = 6.8 Hz, 6H), 1.09 (d, *J* = 6.7 Hz, 6H), 1.18 (d, *J* = 6.8 Hz, 6H), 1.21 (d, *J* = 6.8 Hz, 6H), 1.28 (d, *J* = 6.9 Hz, 12H), 2.28 (s, 12H), 2.73 (sept, *J* = 6.9 Hz, 2H), 2.92 (sept, *J* = 6.8 Hz, 2H), 3.03 (sept, *J* = 6.8 Hz, 2H), 6.99 (d, *J* = 1.7 Hz, 2H), 7.06 (d, *J* = 1.7 Hz, 2H), 7.30 (ddd, *J* = 8.3 Hz, 6.8 Hz, 1.1 Hz, 2H), 7.40 (ddd, *J* = 8.0 Hz, 6.9 Hz, 1.1 Hz, 2H), 7.55 (d, *J* = 8.4 Hz, 2H), 7.80 (d, *J* = 8.2 Hz, 2H), 7.83 (s, 2H) ppm. (The symmetry of the aliphatic H-signals and the number of aliphatic C-atoms detected indicate that the two CH_3-parts of the *ortho-i* Pr substituents are magnetically non-equivalent, while the two CH_3-parts of the *para-i* Pr substituents are magnetically equivalent.)

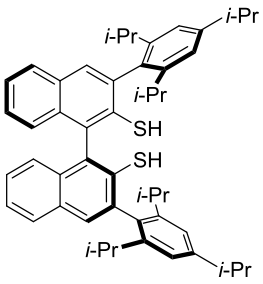
^{13}C-NMR ($CDCl_3$, 100 MHz):[a] δ = 23.3, 23.8, 24.2, 24.3, 25.6, 26.6, 30.5, 34.3, 36.6, 120.1, 120.9, 125.5, 126.9, 127.2, 129.6, 129.7, 129.8, 132.3, 133.5, 135.9, 142.8, 145.6, 147.1, 147.7, 147.8, 165.0 ppm.

MS (EI) m/z: 864 (16%), 792 (36%), 760 (11%), 677 (13%), 72 (100%).

HRMS (ESIpos) m/z: calculated (M+H = $C_{56}H_{69}S_2O_2$) 865.4795, found 865.4800.

a

(*S*)-3,3′-Bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′-dithiol (S3d):



In a flame dried flask under Ar, *(S)*-(3,3′-bis(3,5-bis(2,4,6-triisopropylphenyl)- [1,1′-binaphthalene]-2,2′diyl- *S*,*S*′-bis(*N*,*N*-dimethylthiocarbamate) **S2d** (894 mg, 1.04 mmol) was dissolved in THF (13 mL) and $LiAlH_4$ (280 mg, 7.38 mol, 7.0 equiv.) was added. The reaction mixture was heated to 65 °C overnight. After cooling to room temperature, degassed aq. HCl sol. (10%, 10 mL) was added and the aqueous phase was extracted with CH_2Cl_2 (3 × 20 mL). The combined organic phases were separated, dried over Na_2SO_4 and concentrated under reduced pressure. The obtained crude product (732 mg, 98%) was found to be of sufficient purity without further purification.

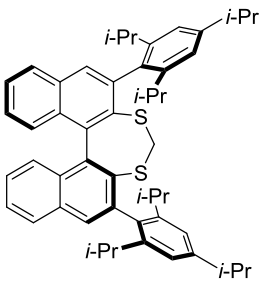
^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 1.05 (d, *J* = 6.8 Hz, 6H), 1.16 (d, *J* = 6.8 Hz, 6H), 1.20 (d, *J* = 6.8 Hz, 12H), 1.34 (d, *J* = 6.9 Hz, 12H), 2.66 (sept, *J* = 6.8 Hz, 2H), 2.79 (sept, *J* = 6.8 Hz, 2H), 2.98 (sept, *J* = 6.9 Hz, 2H), 3.17 (s, 2H), 7.12–7.19 (m_{Ar}, 6H), 7.34 (ddd, *J* = 8.3 Hz, 6.9 Hz, 1.2 Hz, 2H), 7.45 (ddd, *J* = 8.0 Hz, 6.9 Hz, 1.2 Hz, 2H), 7.78 (s, 2H), 7.88 (d, *J* = 8.1 Hz, 2H) ppm.

^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 23.7, 23.8, 24.1, 24.2, 24.9, 27.1, 30.8, 31.1, 34.4, 121.2, 121.4, 124.8, 125.5, 127.0, 128.3, 129.3, 131.6, 131.8, 132.1, 134.8, 135.4, 137.4, 147.0, 147.5, 149.2 ppm.

MS (EI) m/z: 722 (100%), 637 (9%), 595 (10%), 520 (6%).

HRMS (ESIneg) m/z: calculated (M–H = $C_{50}H_{57}S_2$) 721.3907, found 721.3909.

(*S*)-2,6-Bis(2,4,6-triisopropylphenyl)dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine (S4d):



In a flame dried flask under Ar, (*S*)-3,3′-bis(2,4,6-triisopropylphenyl)-[1,1′-binaphthalene]-2,2′-dithiol **S3d** (196 mg, 0.270 mmol) was dissolved in CH_2Cl_2 (0.8 mL). Dimethoxymethane (21 mg, 0.27 mmol, 1.0 equiv.) and BF_3•OEt_2 (40 µL, 44 mg, 0.27 mmol, 1.0 equiv.) were added and the reaction mixture was stirred at room temperature for 6 h. The reaction mixture was diluted with CH_2Cl_2 (10 mL) and washed with aq. KOH sol. (2%, 4 × 3 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. The crude product (185 mg, 93%) was found to be of sufficient purity to be used without further purification.

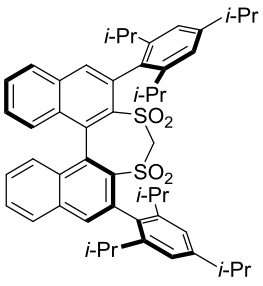
^{1}H-NMR ($CDCl_3$, 300 MHz): δ = 1.10–1.25 (m, 24H), 1.38 (d, *J* = 6.8 Hz, 12H), 2.63 (apparent octet, presumably superimposition of 2 × sept, *J* = 6.8 Hz, 4H), 3.02 (sept, *J* = 6.9 Hz, 2H), 4.02 (s, 2H), 7.10–7.20 (m_{Ar}, 6H), 7.31 (dd, *J* = 8.1 Hz, 6.9 Hz, 2H), 7.54 (dd, *J* = 8.0 Hz, 7.0 Hz, 2H), 7.93 (s, 2H) overlays with one part of 7.95 (d, *J* approx. 8 Hz, 2H), ppm.

^{13}C-NMR ($CDCl_3$, 76 MHz): δ = 23.3, 23.8, 24.1, 24.9, 25.9, 30.7, 31.1, 34.3, 47.2, 120.6, 120.7, 126.2, 126.8, 127.4, 128.2, 129.9, 130.5, 131.9, 133.7, 135.7, 141.7, 143.3, 146.2, 147.1, 148.2 ppm. (The number of aliphatic C-atoms detected indicates that the two CH_3-parts of the *ortho*-*i*-Pr substituents are magnetically non-equivalent, while the two CH_3-parts of the *para*-*i*-Pr substituents are magnetically equivalent.)

MS (EI) m/z: 734 (100%), 701 (28%), 691 (98%), 649 (35%), 373 (36%).

HRMS (ESIpos) m/z: calculated (M+Na = $C_{51}H_{58}S_2Na$) 757.3872, found 757.3877.

(*S*)-2,6-Bis(2,4,6-triisopropylphenyl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide (S5d):



(*S*)-2,6-Bis(3,5-bis(2,4,6-triisopropylphenyl) dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine **S4d** (185 mg, 0.250 mmol) was placed in a flame dried flask under Ar and dissolved in $CHCl_3$ (3 mL). *m*CPBA (70%, 350 mg, 2.02 mmol, 5.6 equiv) was added at 0 °C. The resulting mixture was stirred at room temperature for 6 h. The reaction mixture was diluted with CH_2Cl_2 (10 mL) and washed with aq. KOH sol. (2%, 3 × 4 mL) and brine (2 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. After several purification steps by column chromatography (20% to 80% gradient of CH_2Cl_2 in hexanes), the title compound (107 mg, 54%) was obtained as yellowish powder.

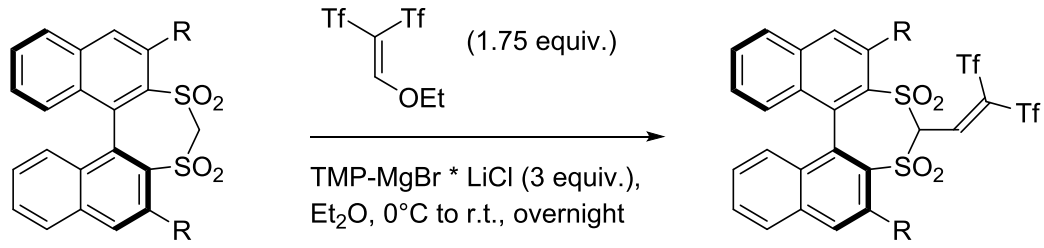
^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 1.16 (d, *J* = 6.9 Hz, 6H), 1.19 (d, *J* = 6.8 Hz, 12H), 1.25 (d, *J* = 6.9 Hz, 6H), 1.35 (d, *J* = 6.9 Hz, 12H), 2.67 (sept, *J* = 6.9 Hz, 4H), 3.00 (sept, *J* = 6.9 Hz, 2H), 4.56 (s, 2H), 7.06 (d. *J* = 8.6 Hz, 2H), 7.09–7.13 (m_{Ar}, 4H), 7.41 (ddd, *J* = 8.4 Hz, 6.9 Hz, 1.1 Hz, 2H), 7.68 (ddd, *J* = 8.0 Hz, 6.9 Hz, 0.9 Hz, 2H), 7.96 (d, *J* = 8.0 Hz, 2H), 7.97 (s, 2H) ppm.

^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 23.5, 23.53, 24.15, 24.2, 24.6, 25.3, 31.4, 34.3, 83.0, 120.5, 120.6, 127.7, 128.1, 128.3, 129.9, 132.1, 132.4, 133.38, 133.4, 135.2, 136.5, 139.5, 145.6, 146.6, 148.6 ppm.

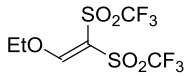
MS (EI) m/z: 798 (100%), 783 (7%), 649 (8%), 587 (4%).

HRMS (ESIneg) m/z: calculated (M–H = $C_{51}H_{58}O_4S_2$) 798.3777, found 798.3781.

Synthesis of C-H Acid Catalysts



2-Ethoxy-1,1-bis((trifluoromethyl)sulfonyl)ethane (S6):



Bis(trifuluoromethanesulfonyl)methane (0.60 g, 2.1 mmol) and triethyl orthoformate (0.39 mL, 0.35 g, 2.4 mmol, 1.1 equiv.) were placed in a flame dried flask under argon and dissolved in Ac_2O (7.5 mL). The solution was stirred at room temperature for 1 h and then heated to 60 °C for 6 h. The reaction mixture was allowed to cool below 40 °C and subsequently concentrated under reduced pressure. Complete removal of all volatiles was achieved by dissolving in dry CH_2Cl_2 (3 × 3 mL) and subsequent evaporation to dryness. The title compound was obtained as a yellow powder (689 mg, 98%).

^{1}H-NMR ($CDCl_3$, 300 MHz): δ = 1.55 (t, *J* = 7.2 Hz, 3H), 4.70 (q, *J* = 7.2 Hz, 2H), 8.42 (s, 1H) ppm.

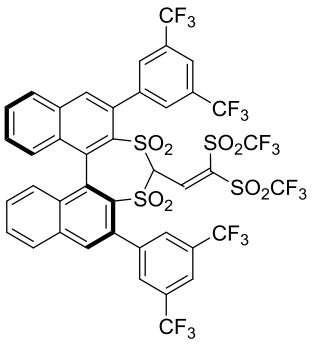
^{13}C-NMR ($CDCl_3$, 75.5 MHz): δ = 15.1, 80.1, 107.2 (m), 119.4 (q, $J_{C–F}$ = 325.3 Hz), 119.6 (q, $J_{C–F}$ = 326.3 Hz), 180.0 ppm.

^{19}F-NMR ($CDCl_3$, 282 MHz): δ = –76.4, –77.7 ppm.

MS (EI) m/z: 267 (41%), 239 (75%), 127 (16%), 69 (66%), 29 (100%).

HRMS (ESIpos) m/z: calculated (M+H = $C_6H_7O_5F_6S_2$) 336.9634, found 336.9635.

(*S*)-4-(2,2-Bis((trifluoromethyl)sulfonyl)vinyl)-2,6-bis(3,5-bis(trifluoromethyl)phenyl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine-3,3,5,5-tetraoxide (6a):



(*S*)-2,6-Bis(3,5-bis(trifluoromethyl)phenyl)- 4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine-3,3,5,5-tetraoxide **S5a** (0.20 g, 0.25 mmol) and 2-ethoxy-1,1-bis((trifluoromethyl)sulfonyl) ethane **S6** (0.12 g, 0.38 mmol, 1.5 equiv.) were placed in a flame dried flask under Ar

and dissolved in Et_2O (1.5 mL). The resulting solution was cooled to 0 °C and TMPMgBr•LiCl (1M sol. in toluene, 0.75 mL, 0.75 mmol, 3.0 equiv.) was added dropwise. The reaction mixture was allowed to slowly reach room temperature and stirred overnight. 6 mL of a saturated NH_4Cl solution and CH_2Cl_2 (20 mL) were added subsequently. The reaction mixture was washed three times with a 6 M aq. HCl solution. The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. After purification by column chromatography (0.5% to 4% gradient of MeOH in CH_2Cl_2 and 1% of AcOH), and acidification (shaking of CH_2Cl_2 solution with 6M aq. HCl) the title compound (165 mg, 60%, 69% brsm) was obtained as off-white powder. A significant amount of starting material could also be re-isolated, the yields varying between 25% and 50% in different experiments.

^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 6.37 (d, *J* = 12.2 Hz, 1H), 7.24 (d, *J* = 8.6 Hz, 2H), 7.54 (d, *J* = 12.2 Hz, 1H), 7.57–7.62 (m, 2H), 7.79 (s, 1H), 7.85–7.90 (m, 3H), 7.95 (d, *J* = 10.0 Hz, 2H), 7.97 (s, 1H), 8.07 (s, 1H), 8.12 (d, *J* = 8.3 Hz, 1H), 8.14 (d, *J* = 8.3 Hz, 1H), 8.16 (s, 2H) ppm.

^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 90.6, 118.8 (q, $J_{C–F}$ = 329 Hz), 119.0 (q, $J_{C–F}$ = 328 Hz), 122.2 (m), 123.2 (q, $J_{C–F}$ = 273 Hz), 123.3 (q, $J_{C–F}$ = 272 Hz), 123.5, 127.3, 127.95, 127.98, 128.0, 128.3 (m), 128.9, 129.0, 129.3, 130.0, 130.4 (m), 130.7, 130.8, 131.1, 131.6, 131.8, 131.9, 132.1, 132.4, 142.5, 132.6, 134.8, 135.3, 135.35, 135.4, 135.7, 140.4, 140.9, 141.7 (m), 152.4 ppm. (Not all C-signals could be detected, presumably due to overlap of several signals in the designated multiplets.)

^{19}F-NMR ($CDCl_3$, 282 MHz): δ = –62.7, –62.8, –62.9, –72.8, –73.0 ppm.

MS (EI) m/z: 1108 (22%), 740 (100%), 676 (59%), 606 (13%), 126 (29%).

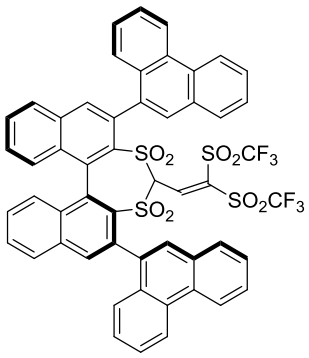
MS (ESIneg) m/z: 1107 (M–H).

HRMS (ESIneg) m/z: calculated (M–H = $C_{41}H_{18}O_8F_{18}S_4$) 1106.9524, found 1106.9529.

Elemental analysis (CHS):

Element:	C	H	S
Calculated	44.91	1.729	11.18
Found	44.91	1.725	11.39

(*S*)-4-(2,2-Bis((trifluoromethyl)sulfonyl)vinyl)-2,6-bis(9-phenanthryl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine-3,3,5,5-tetraoxide (6b):



(*S*)-2,6-bis(9-phenanthryl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide (220 mg, 0.29 mmol) and 2-ethoxy-1,1-bis((trifluoromethyl) sulfonyl)ethene **S6** (190 mg, 0.55 mmol, 1.9 equiv.) were placed in a three times flame dried 50 mL Schlenk flask under Ar and dissolved in Et_2O (4.6 mL). The resulting solution was cooled to –5°C and TMPMgCl•LiCl (1M sol. in toluene, 1.0 mL, 1.0 mmol, 3.4 equiv.) was added dropwise. The reaction mixture was allowed to slowly reach room temperature and was stirred overnight. 6 mL of a saturated NH_4Cl solution and CH_2Cl_2 (20 mL) were added subsequently. The reaction mixture was washed three times with a 6 M aq. HCl solution. The organic phase was dried over $MgSO_4$, concentrated under reduced pressure, and was purified via flash chromatography (SiO2, stepwise gradient from 0.5% MeOH, 0.5% AcOH in DCM to 4% MeOH, 1% AcOH in DCM). The desired fractions were acidified (washing of a methyl *tert*-butyl ether solution with 6 M HCl) and the desired compound was obtained as an orange to red solid (104 mg, 34%).

^{1}H NMR (CD_2Cl_2, 600 MHz): δ = 6.35 (d, *J* = 12.6 Hz, 1H), 7.24 (d, *J* = 8.6 Hz, 1H), 7.29 (d, *J* = 8.7 Hz, 1H), 7.47 (d, *J* = 8.0 Hz, 1H), 7.53 – 7.59 (m, 3H), 7.61 (d, *J* = 12.6 Hz, 1H), 7.63 – 7.70 (m, 5H), 7.71 – 7.76 (m, 3H), 7.77 (d, *J* = 8.2 Hz, 1H), 7.81 – 7.88 (m, 2H), 7.90 (d, *J* = 8.7 Hz, 1H), 7.91 (s, 1H), 7.96 (d, *J* = 7.7 Hz, 1H), 8.08 (d, *J* = 8.2 Hz, 1H), 8.13 (d, *J* = 8.3 Hz, 1H), 8.26 (s, 1H), 8.31 (s, 1H), 8.78 (d, *J* = 8.6 Hz, 3H), 8.81 (d, *J* = 9.3 Hz, 1H) ppm.

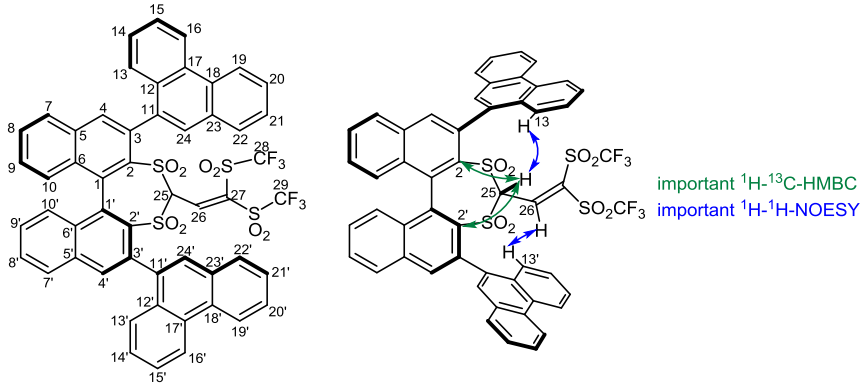
^{13}C NMR (CD_2Cl_2, 151 MHz): δ = 90.6, 118.2, 118.5, 122.8, 122.9, 123.3, 123.4, 125.8, 126.1, 127.0, 127.0, 127.3, 127.4, 127.4, 127.4, 128.1, 128.2, 128.2, 128.4, 128.5, 128.8, 128.8, 128.9, 128.9, 129.2, 129.3, 130.1, 130.2, 130.3, 130.3, 130.5, 130.5, 130.9, 131.1, 131.1, 131.3, 131.5, 132.4, 132.5, 132.6, 134.2, 134.8, 135.2, 135.4, 135.9, 136.0, 136.4, 136.6, 140.0, 140.6, 140.9, 153.4 ppm.

^{19}F NMR (CD_2Cl_2, 282 MHz): δ = -74.8, -72.4.

MS (ESIneg) m/z: 1035 (M–H)

HRMS (ESIneg) m/z: calculated (M–H = $C_{53}H_{29}O_8F_6S_4$) 1035.0655, found 1035.0663.

Table S2. Overview of NMR chemical shifts of all atoms of **6b** and the correspoinding 2D correlations used for assignment.



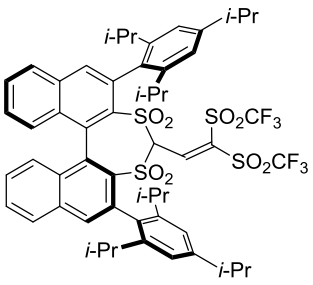
Atom	Chemical Shift [ppm]	J [Hz]	Cross-peaks COSY	HSQC	HMBC	NOESY
1 C	139.97				4, 10	
1' C	140.65				4', 10'	
2 C	131.06				4, 25	
2' C	130.46				4', 25	
3 C	136.43				4, 24	
3' C	136.56				4', 24'	
4 C	135.37			4	4, 7, 24	
H	8.31		10, 7	4	1, 3, 5, 4, 11, 6, 2, 7	24, 7, 13
4' C	135.91			4'	4', 7', 24'	
H	8.26		10', 7'	4'	1', 3', 4', 5', 11', 6', 2', 7'	24', 7', 13'
5 C	136.01				4, 7, 8, 10	
5' C	135.22				7', 4', 8', 10'	
6 C	132.62				4, 7, 9	
6' C	132.49				4', 7', 9'	
7 C	128.89			7	9, 4, 7	
H	8.13	8.30(8), 1.20(9)	4, 9, 8	7	5, 4, 6, 7, 9	4, 8
7' C	128.77			7'	9', 4', 7'	
H	8.08		4', 8', 9'	7'	4', 5', 6', 7', 9'	4', 8'
8 C	131.48			8	10	
H	7.87	8.30(7), 1.00(10), 7.00(9)	10, 7, 9	8	5, 10	7, 9
8' C	131.27			8'	10'	
H	7.83		9', 10', 7'	8'	5', 10'	7', 9'
9 C	129.30			9	7	
H	7.58	1.20(7), 7.00(8), 8.70(10)	10, 7, 8	9	6, 7	8, 10
9' C	129.17			9'	7'	
H	7.57		8', 10', 7'	9'	6', 7'	10', 8'
10 C	128.20			10	8, 10	
H	7.24	1.00(8), 8.70(9)	4, 9, 8	10	1, 5, 8, 10	9, 10'
10' C	128.14			10'	8', 10'	

H	7.29		4', 9', 8'	10'	1', 5', 8', 10'	9', 10
11 C	134.77				4, 24, 13	
11' C	134.18				4', 13', 24'	
12 C	132.36				16, 14, 24	
12' C	131.27				16', 14', 24'	
13 C	125.82			13	13, 14, 15	
H	7.47	8.20(14)	15, 14	13	11, 17, 14, 13, 15	25, 4
13' C	126.13			13'	13', 14', 15'	
H	7.77		15', 14'	13'	11', 17', 14', 13', 15'	4', 14', 26
14 C	128.22			14	16, 13, 14	
H	7.55	8.20(13), 7.00(15), 1.10(16)	13, 15, 16	14	12, 14, 13, 16	25
14' C	128.39			14'	16', 13', 14', 15'	
H	7.63		13', 15', 16'	14'	12', 14', 13', 16'	13'
15 C	126.99			15	13	
H	7.65	8.30(16), 7.00(14)	13, 14, 16	15	17, 13	16
15' C	127.05			15'	13'	
H	7.69		13', 14', 16'	15'	17', 14', 13'	16'
16 C	123.41			16	14, 16	
H	8.80	8.30(15), 1.10(14)	15, 14	16	12, 18, 14, 16	15, 19
16' C	123.34			16'	14', 16'	
H	8.82		15', 14'	16'	12', 18', 14', 16'	15', 19'
17 C	130.08				13, 15, 19	
17' C	130.54				13', 15', 19'	
18 C	130.31				22, 20, 24, 16	
18' C	130.20				20', 22', 24', 16'	
19 C	122.94			19	21, 19	
H	8.78	8.30(20), 1.20(21)	24, 20, 21	19	23, 17, 21, 19	16, 20
19' C	122.83			19'	21', 19'	
H	8.78		24', 20', 21'	19'	23', 17', 21', 19'	16', 21
20 C	127.32			20	22	
H	7.74	8.30(19), 1.30(22), 6.30(21)	22, 21, 19	20	18, 22	19
20' C	127.37			20'	22'	
H	7.73		22', 21', 19'	20'	18'	
21 C	127.38			21	19	
H	7.68	1.20(19), 6.30(20), 8.00(22)	22, 20, 19	21	23, 19	22, 19'
21' C	127.36			21'	19'	
H	7.65		22', 20', 19'	21'	23', 19'	22'
22 C	128.83			22	20, 24	
H	7.96	1.30(20), 8.00(21)	21, 20	22	18, 24, 20	24, 21
22' C	128.87			22'	22', 24'	

H	7.90		21', 20'	22'	24', 18', 22', 20'	24', 21'
23 C	131.11				19, 24, 21	
23' C	130.92				19', 24', 21'	
24 C	128.54			24	22	
H	7.91		19	24	3, 4, 11, 12, 23, 18, 22	4, 22
24' C	130.27			24'	22'	
H	7.74		19'	24'	3', 4', 11', 12', 23', 18', 22'	4', 22'
25 C	90.59	154.00(25H)		25	25, 26	
H	6.35	12.50(26), 154.00(25C)	26	25	25, 26, 27, 2, 2'	26, 14, 13
26 C	153.43	171.00(26H)		26	25, 26	
H	7.61	12.50(25), 171.00(26C)	25	26	25, 26, 27, 29	25, 13'
27 C	140.93				25, 26	
28 C	118.15	328.00(?)*				
29 C	118.48	328.00(?)*			26	

*could not be unambiguously assigned

(*S*)-4-(2,2-Bis((trifluoromethyl)sulfonyl)vinyl)-2,6-bis(2,4,6-triisopropylphenyl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine-3,3,5,5-tetraoxide (6c):



(*S*)-2,6-Bis(2,4,6-triisopropylphenyl)- 4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide **S5d** (107 mg, 0.130 mmol) and 2-ethoxy-1,1-bis((trifluoromethyl)sulfonyl)ethene **S6** (45 mg, 0.13 mmol, 1.0 equiv.) were placed in a flame dried flask under Ar and dissolved in Et_2O (0.4 mL). The resulting solution was cooled to –78 °C and TMPMgCl•LiCl (1M sol. in toluene, 0.4 mL, 3.0 equiv.) was added dropwise. The reaction mixture was slowly allowed to reach room temperature and stirred overnight. The reaction mixture was diluted with CH_2Cl_2 (5 mL) and washed with aq. HCl sol. (10%, 2 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. After several purification steps by column chromatography (2.5% of MeOH in CH_2Cl_2) and acidification (shaking of CH_2Cl_2 solution with 6M aq. HCl), the title compound (67 mg, 48%) was obtained as brownish powder. An unquantified amount of starting material was isolated as the only other major component of the reaction mixture.

^{1}H-NMR ($CDCl_3$, 500 MHz): δ = 0.97 (d, *J* = 6.7 Hz, 3H), 1.00 (d, *J* = 6.7 Hz, 3H), 1.04 (d, *J* = 6.8 Hz, 3H), 1.05 (d, *J* = 6.8 Hz, 3H), 1.08 (d, *J* = 6.6 Hz, 3H), 1.13 (d, *J* = 6.8 Hz, 3H), 1.14 (d, *J* = 6.9 Hz, 3H), 1.16 (d, *J* = 7.0 Hz, 3H), 1.27–1.32 (m, 12H), 2.49 (sept, *J* = 6.9 Hz, 1H), 2.60 (apparent oct, presumably 2 × sept, *J* = 6.9 Hz, 2H), 2.70 (sept, *J* = 7.0 Hz, 1H), 2.87–3.00 (m, 2H), 6.83 (d, *J* = 8.6 Hz, 1H), 6.99 (m, 2H) 7.01 (d, *J* = 1.6 Hz, 1H), 7.05 (d, *J* = 1.6 Hz, 1H), 7.15–7.20 (m, 1H), 7.26–7.31 (m, 2H), 7.38 (ddd, *J* = 8.5 Hz, 6.8 Hz, 0.6 Hz, 1H), 7.54–7.62 (m, 2H), 7.70 (s, 1H), 7.82–7.91 (m, 4H) ppm.

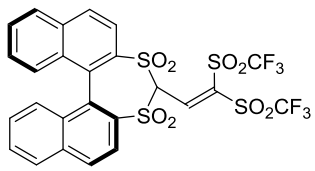
^{13}C-NMR ($CDCl_3$, 125 MHz): δ = 23.4, 23.5, 23.6, 23.7, 24.0, 24.1, 24.25, 24.3, 24.6, 25.0, 25.3, 25.5, 31.0, 31.1, 31.4, 31.8, 34.1, 34.6, 119.6, 120.3, 120.6, 120.8, 120.5 (q, $J_{C–F}$ = 331.2 Hz), 123.7 (q, $J_{C–F}$ = 323.9 Hz), 127.4, 127.45, 127.5, 128.0, 128.28, 128.3, 128.5, 129.0, 129.1, 130.5 (m), 132.1, 132.6, 133.6, 134.1, 134.2, 134.3, 134.7, 135.8, 136.0, 136.3, 136.6, 138.1, 138.8, 139.3, 145.3, 145.6, 146.4, 146.5, 147.9, 148.1, 186.3 ppm.

^{19}F-NMR ($CDCl_3$, 282 MHz): δ = –66.6, –74.6 ppm.

MS (ESIneg) m/z: 1087 (M–H).

HRMS (ESIneg) m/z: calculated (M–H = $C_{55}H_{57}F_6O_8S_4$) 1087.2846, found 1087.2849.

(*S*)-4-(2,2-Bis((trifluoromethyl)sulfonyl)vinyl)-4*H*-dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide (6d):



(*S*)-4*H*-Dinaphtho[2,1-*d*:1′,2′-*f*][1,3]dithiepine 3,3,5,5-tetraoxide **S5c** (197 mg, 0.500 mmol) and 2-ethoxy-1,1-bis((trifluoromethyl)sulfonyl)ethene **S6** (168 mg, 0.600 mmol, 1.0 equiv.) were placed in a flame dried flask under Ar and dissolved in Et_2O (1.5 mL). The resulting solution was cooled to –78 °C and TMPMgBr•LiCl (1M sol. in toluene, 1.5 mL, 1.5 mmol, 3.0 equiv.) was added dropwise. The reaction mixture was allowed to slowly reach room temperature and stirred overnight. The reaction mixture was diluted with CH_2Cl_2 (20 mL) and washed with aq. HCl sol. (10%, 5 mL). The organic phase was dried over $MgSO_4$ and concentrated under reduced pressure. After several purification steps by column chromatography (0% to 5% gradient of MeOH in CH_2Cl_2) and acidification (shaking of CH_2Cl_2 solution with 6M aq. HCl), the title compound (110 mg, 0.16 mmol, 32%) was obtained as a brownish foam.

^{1}H-NMR ($CDCl_3$, 300 MHz): δ = 6.66 (d, *J* = 12.4 Hz, 1H), 7.19–7.28 (m_{Ar}, 2H), 7.40–7.52 (m_{Ar}, 2H), 7.72–7.82 (m_{Ar}, 2H), 7.93 (d, *J* = 12.4 Hz, 1H), 8.07–8.17 (m_{Ar}, 3H), 8.26–8.37 (m_{Ar}, 3H) ppm.

^{13}C-NMR ($CDCl_3$, 76 MHz): δ = 91.0, 124.0, 124.8, 128.0, 128.95, 129.0, 129.1, 130.7, 131.1, 131.4, 131.7, 132.3, 132.5, 136.7, 136.9, 137.15, 137.2, 154.5 ppm. (The signals corresponding to the CF_3 groups could not be detected, presumably due to the low signal intensity caused by coupling. The number of aromatic C-atoms detected is between the one expected for a C_2-symmetric backbone and the one expected for an non-symmetric backbone. As the signals in the ^{1}H-spectrum indicate a non-symmetric structure, this can be rationalized by the superimposition of signals or the low signal intensity for some C-atoms.)

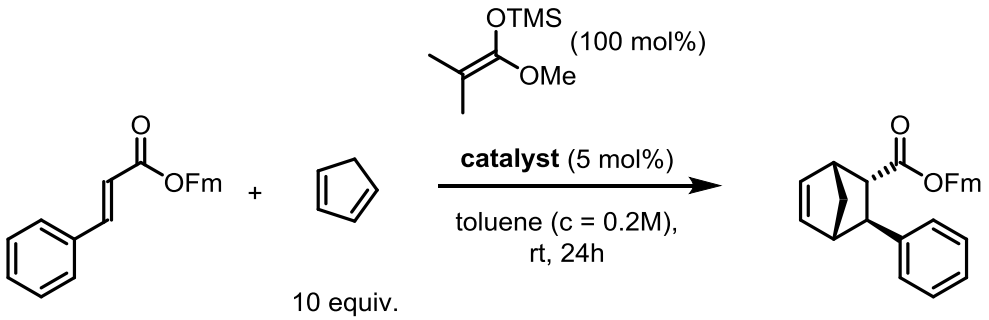
^{19}F-NMR ($CDCl_3$, 282 MHz): δ = –72.8, –73.6 ppm.

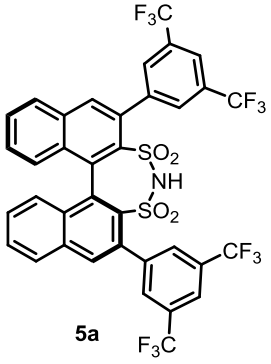
MS (EI) m/z: 684 (37%), 556 (8%), 316 (100%), 289 (28%), 252 (32%).

HRMS (EI) m/z: calculated (M = $C_{25}H_{14}O_8F_6S_4$) 683.9476, found 683.9477.

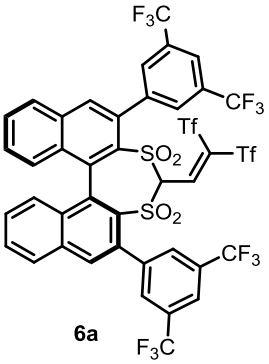
Reaction Development & Screening of Reaction Conditions

Table S3. Catalyst screening.

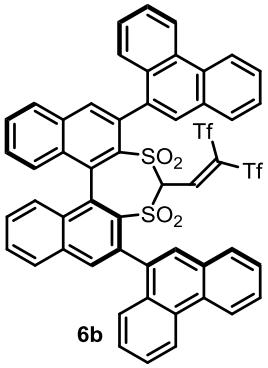




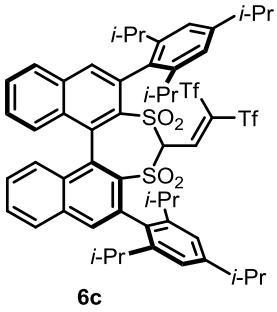
5a



6a



6b



6c

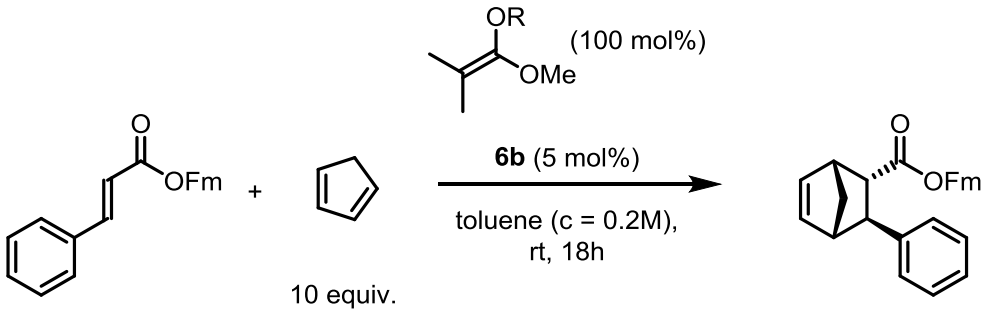
catalyst	**conversion**[*]	**d.r.**[†]	**e.r.**[‡]
5a	traces	/	/
6a	full	13 : 1	56 : 44
6a	full (-40°C)	18 : 1	65 : 35
6b	**full**	**18 : 1**	**86.5 : 13.5**
6c	full	13 : 1	56.5 : 43.5

[*] conversions were determined by ^{1}H-NMR

[†] diastereomeric ratios were determined by HPLC

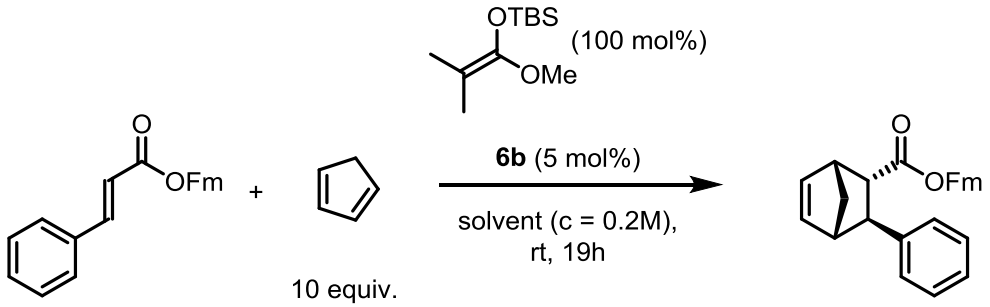
[‡] enantiomeric ratios were determined by HPLC with a chiral stationary phase

Table S4. Screening of silyl ketene acetals.



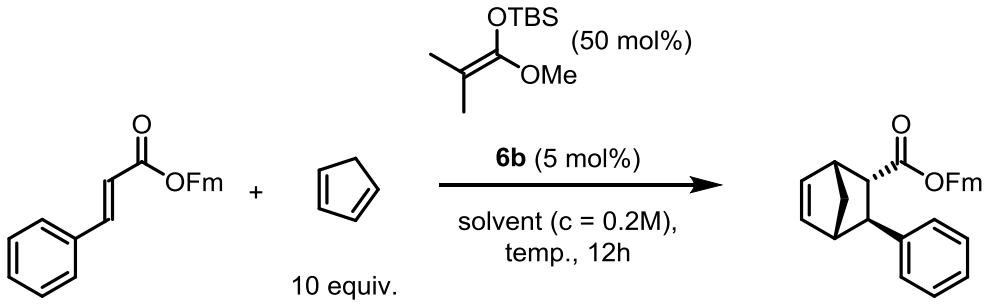
SKA (R =)	**conversion**	**d.r.**	**e.r.**
TMS (4a)	full	18:1	86.5 : 13.5
TBS (4b)	full	16:1	**89.5 : 10.5**
TES (4c)	full	13:1	87.5 : 12.5
TIPS (4d)	full	6:1	87.5 : 12.5

Table S5. Solvent screening.



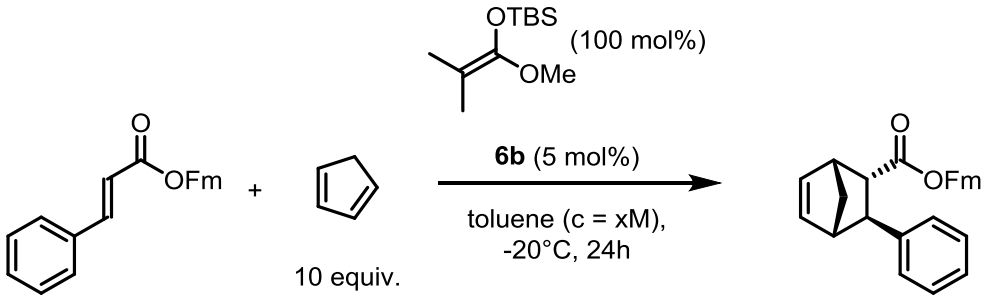
solvent	**conversion**	**d.r.**	**e.r.**	**solvent**	**conversion**	**d.r.**	**e.r.**
Et_2O	**full**	**17:1**	**94 : 6**	Benzene	full	16:1	89 : 11
MTBE	**full**	**14:1**	**93.5 : 6.5**	Toluene	full	16:1	89.5 : 10.5
Dioxane	full	15:1	91.5 : 8.5	o-Xylene	full	18:1	90 : 10
TMS_2O	>95%	11:1	81.5 : 18.5	m-Xylene	full	19:1	90 : 10
$CHCl_3$	**>95%**	**16:1**	**91.5 : 8.5**	p-Xylene	full	18:1	89.5 : 10.5
CCl_4	>95%	14:1	90 : 10	Mesitylene	full	18:1	90 : 10
EtOAc	**full**	**18:1**	**93.5 : 6.5**	n-Hexane	full	11:1	79.5 : 20.5
MeCN	no product	/	/	Cyclohexane	full	14:1	87 : 13

Table S6. Temperature screening.



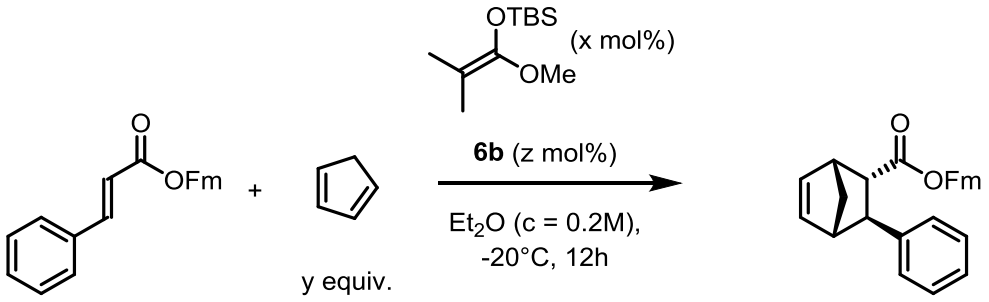
solvent	**temp.**	**conversion**	**d.r.**	**e.r.**
Et_2O	0°C	full	31:1	95.5 : 4.5
	-20°C	**>95%**	**39:1**	**96 : 4**
MTBE	0°C	>95%	28:1	95.5 : 4.5
	-20°C	full	30:1	94 : 6
$CHCl_3$	0°C	>95%	24:1	93.5 : 6.5
	-20°C	>95%	31:1	95 : 5
EtOAc	0°C	>75%	31:1	95.5 : 4.5
	-20°C	40%	36:1	97 : 3

Table S7. Concentration screening.



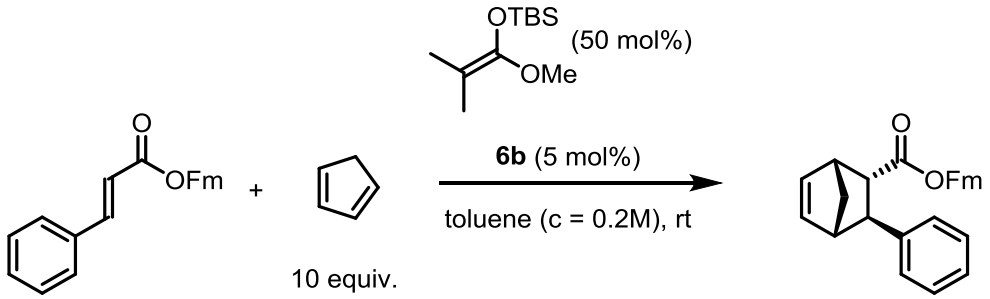
concentration	**conversion**	**d.r.**	**e.r.**
1M	full	30:1	91 : 9
0.5M	full	32:1	91 : 9
0.2M	**full**	**32:1**	**91.5 : 8.5**
0.1M	>95%	31:1	92 : 8
0.05M	>95%	33:1	92 : 8
0.025M	>95%	33:1	92.5 : 7.5

Table S8. Catalyst loading and screening of reagents.



catalyst loading (x)	**equiv. of Cp (y)**	loading silyl ketene acetal (z)	**conversion**	**d.r.**	**e.r.**
5 mol%	10	50 mol%	full (in GC-vial under Ar)	33 : 1	96 : 4
1 mol%	10	50 mol%	full (in GC-vial under Ar)	35 : 1	97 : 3
1 mol%	5	50 mol%	>95% (in GC-vial under Ar)	36 : 1	97 : 3
1 mol%	5	20 mol%	92% (in GC-vial under Ar)	27 : 1	97 : 3
1 mol%	5	10 mol%	0 % (in GC-vial under Ar)	/	/
1 mol%	**5**	**10 mol%**	**full (15h, in Schlenk under Ar); 94% isolated yield**	**>25 : 1**	**96.75 : 3.25**

Table S9. Control experiments.



conditions	**time**	**conversion**	**d.r.**	**e.r.**
no catalyst, no silyl ketene acetal	5d	3%	/	/
no catalyst	5d	1%	/	/
no silyl ketene acetal	5d	5%	/	/
with catalyst and silyl ketene acetal	18h	full	16:1	89.5 : 10.5

General Procedure for the Catalytic, Asymmetric Diels-Alder Reaction:

A flame-dried Schlenk flask was charged with unsaturated ester (0.1 mmol), catalyst (*S*)-**6b** (0.001 mmol, 1.04 mg) and a magnetic stir bar under Argon and further dried under high vacuum overnight. After addition of Et_2O and cyclopentadiene (0.05 mmol, 42 µL), the reaction mixture was cooled to -20 °C. Methyl *tert*-butyldimethylsilyl dimethylketene acetal **4b** (0.01 mmol, 2.5 µL) was added and the reaction mixture was stirred at -20 °C for 1-6 d. After complete conversion was detected by TLC analysis, the reaction was quenched with NEt_3 (one drop) and concentrated under reduced pressure. The crude product was purified by flash column chromatography (SiO_2, stepwise gradient from 1% to 5% ethyl acetate in hexanes) affording Diels-Alder cycloadducts.

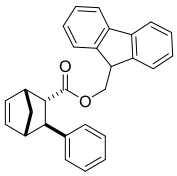
General Procedure for the Preparation of Racemic Products:

A GC-vial was charged with the appropriate unsaturated ester (0.04 mmol) and cyclopentadiene (30 equiv., 0.1 mL) in toluene (0.1 mL). The reaction mixture was heated to 120 °C overnight. A racemic mixture of the endo- and exo-product was obtained after purification of the crude material by preparative TLC. Under these conditions, the exo-cycloadduct is typically the main product.

Racemic **3j** was obtained by applying the general procedure for the catalytic Diels-Alder reaction at room temperature using the *R/S* mixture of **6b**.

Characterization of Diels-Alder Products

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3a)



The product was synthesized according to the general procedure employing substrate **1a** (15h). **3a** was obtained as a yellow powder (36.9 mg, 94%, d.r. >25:1).

^{1}H-NMR (300 MHz, $CDCl_3$) δ = 1.52-1.59 (m, 1H), 1.74-1.80 (m, 1H), 2.94-2.98 (m, 3H), 3.21 (br. s, 1H), 4.19 (t, *J* = 6.3 Hz, 1H), 4.49 (d, *J* = 6.3 Hz, 2H), 5.92 (dd, *J* = 5.6, 2.8 Hz, 1H), 6.34 (dd, *J* = 5.6, 3.2 Hz, 1H), 7.15-7.33 (m, 7H), 7.38-7.45 (m, 2H), 7.56 (d, *J* = 7.6 Hz, 2H), 7.77 (d, *J* = 7.6 Hz, 2H) ppm.

^{13}C-NMR (75 MHz, $CDCl_3$) δ = 46.4, 47.26, 47.3, 47.7, 48.5, 52.4, 53.6, 66.1, 120.2, 120.25, 125.09, 125.1, 126.3, 127.29, 127.3, 127.7, 127.9, 128.0 128.7, 134.7, 139.2, 141.6, 141.63, 144.0, 144.1, 144.3, 174.4 ppm.

MS (EI) m/z: 178 (100%), 66 (2%), 327 (2%).

HRMS (ESIpos) m/z: calculated for $C_{28}H_{24}NaO_2^+$: 415.1668; found 415.1671.

$[\alpha]_D^{25}$: +82.6° (c=0.78, CH_2Cl_2).

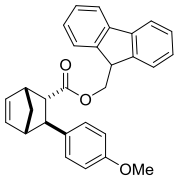
Optical rotation for the corresponding carboxylic acid obtained by basic deprotection:

$[\alpha]_D^{25}$: +186° (c=0.3, CH_2Cl_2).

Literature value: **$[\alpha]_D^{25}$**: +126.0° (c=1.0, CH_2Cl_2).(*29*)

HPLC: Daicel Chiralcel OD-3R, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 17.6 min (major) and 40.4 min (minor); t_R (exo-Diels Alder product) = 23.5 min and 27.4 min. e.r = 97:3

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-methoxyphenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3b)



The product was synthesized according to the general procedure employing substrate **1b** in $CHCl_3$ for 6d. **3b** was obtained as a colorless solid (39.3 mg, 93%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.54 (dm, *J* = 8.8 Hz, 1H), 1.75 (d, *J* = 8.7 Hz, 1H), 2.94-2.98 (m, 3H), 3.19 (br. s, 1H), 3.80 (s, 3H), 4.19 (t, *J* = 6.2 Hz, 1H), 4.48 (d, *J* = 6.4 Hz, 2H), 5.90 (dd, *J* = 5.6, 2.7 Hz, 1H), 6.32 (dd, *J* = 5.6, 3.2 Hz, 1H), 6.80-6.85 (m, 2H), 7.13-7.18 (m, 2H), 7.30 (dddd, *J* = 7.5, 7.5, 3.4, 1.1 Hz, 2H), 7.41 (ddd, *J* = 7.5, 7.5, 2.6 Hz, 2H), 7.56 (d, *J* = 7.5 Hz, 2H), 7.77 (d, *J* = 7.5 Hz, 2H) ppm.

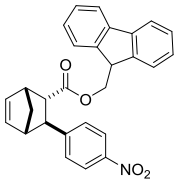
^{13}C-NMR (125 MHz, $CDCl_3$) δ = 46.1, 46.9, 47.06, 47.1, 48.6, 52.4, 55.3, 65.8, 113.9, 120.0, 120.1, 124.9, 124.95, 127.1, 127.1,4, 127.75, 127.8, 128.4, 134.5, 136.2, 139.1, 141.4, 141.45, 143.85, 143.9, 157.9, 174.3 ppm.

HRMS (ESIpos) m/z: calculated for $C_{29}H_{26}NaO_3^+$: 445.1774; found 445.1777.

$[\alpha]_D^{25}$: +82.1° (c=0.98, CH_2Cl_2).

HPLC: Daicel Chiralcel OD-3R, acetonitrile:water = 70:30, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 43.9 min (major) and 86.6 min (minor); t_R (exo-Diels Alder product) = 58.2 min and 60.2 min. e.r = 95:5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-nitrophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3c)



The product was synthesized according to the general procedure employing substrate **1c** for 2d in $CHCl_3$. **3c** was obtained as a colorless solid (39.4 mg, 90%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.57 (dm, *J* = 8.9 Hz, 1H), 1.64 (d, *J* = 8.9 Hz, 1H), 2.83 (dd, *J* = 5.1, 3.7 Hz, 1H), 2.92 (dm, *J* = 5.1 Hz, 1H), 2.98-3.01 (m, 1H), 3.18 (br. s, 1H), 4.19 (t, *J* = 5.5 Hz, 1H), 4.59 (dd, *J* = 11.0, 5.5 Hz, 1H), 4.61 (dd, *J* = 11.0, 5.7 Hz, 1H), 5.88 (dd, *J* = 5.7, 2.8 Hz, 1H), 6.27 (dd, *J* = 5.7, 3.2 Hz, 1H), 7.26-7.29 (m, 2H), 7.33 (dddd, *J* = 7.5, 7.5, 4.4, 1.1 Hz, 2H), 7.42 (dddm, *J* = 7.5, 7.5, 4.2 Hz, 2H), 7.56 (dm, *J* = 7.6 Hz, 2H), 7.77 (dm, *J* = 7.6 Hz, 2H), 8.06-8.10 (m, 2H) ppm.

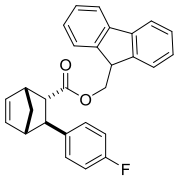
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.1, 47.1, 47.15, 47.5, 47.7, 52.7, 65.6, 120.07, 120.1, 123.6, 124.7, 124.72, 127.17, 127.2, 127.8, 127.9, 128.2, 135.1, 138.6, 141.5, 141.5, 143.7, 143.71, 146.3, 152.1, 173.5 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}NNaO_4^+$: 460.1519; found 460.1522.

$[\alpha]_D^{25}$: +107.5° (c=0.96, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 21.8 min (minor) and 39.0 min (major); t_R (exo-Diels Alder product) = 19.7 min and 28.7 min. e.r = 95:5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-fluorophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3d)



The product was synthesized according to the general procedure employing substrate **1d** (3d). **3d** was obtained as a colorless solid (37.4 mg, 91%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.55 (dm, *J* = 8.7 Hz, 1H), 1.71 (d, *J* = 8.7 Hz, 1H), 2.89 (dd, *J* = 5.0, 3.5 Hz, 1H), 2.92 (dm, *J* = 5.0 Hz, 1H), 2.94-2.97 (m, 1H), 3.19 (br. s, 1H), 4.19 (t, *J* = 6.1 Hz, 1H), 4.53 (d, *J* = 6.1 Hz, 2H), 5.90 (dd, *J* = 5.6, 2.8 Hz, 1H), 6.31 (dd, *J* = 5.6, 3.2 Hz, 1H), 6.92-7.00 (m, 2H), 7.13-7.19 (m, 2H), 7.32 (dddd, *J* = 7.5, 7.5, 2.8, 1.1 Hz, 2H), 7.42 (dddm, *J* = 7.5, 7.5, 3.2 Hz, 2H), 7.56 (dm, *J* = 7.6 Hz, 2H), 7.78 (dm, *J* = 7.6 Hz, 2H) ppm.

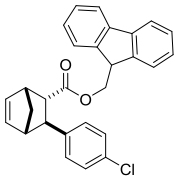
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.2, 46.9, 47.1, 47.2, 48.3, 52.6, 65.8, 115.1, 115.3, 120.1, 120.11, 124.85, 124.9, 127.15, 127.2, 127.8, 127.85, 128.8, 128.9, 134.7, 139.0, 139.85, 139.9, 141.5, 141.52, 143.8, 143.9, 160.3, 162.3, 174.1 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}FNaO_2^+$: 433.1574; found 433.1572.

$[\alpha]_D^{25}$: +73.9° (c=0.71, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 70:30, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 35.1 min (major) and 56.2 min (minor); t_R (exo-Diels Alder product) = 41.9 min and 44.2 min. e.r = 95:5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-chlorophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3e)



The product was synthesized according to the general procedure employing substrate **1e** (0 °C, 10h). **3e** was obtained as a pale yellow, crystalline solid (40.0 mg, 94%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.55 (dm, *J* = 8.9 Hz, 1H), 1.70 (d, *J* = 8.9 Hz, 1H), 2.89 (dd, *J* = 5.0, 3.4 Hz, 1H), 2.90 (dm, *J* = 5.1 Hz, 1H), 2.94-2.97 (m, 1H), 3.19 (br. s, 1H), 4.19 (t, *J* = 6.1 Hz, 1H), 4.53 (d, *J* = 6.0 Hz, 2H), 5.90 (dd, *J* = 5.6, 2.7 Hz, 1H), 6.30 (dd, *J* = 5.6, 3.3 Hz, 1H), 7.11-7.15 (m, 2H), 7.21-7.26 (m, 2H), 7.32 (dddd, *J* = 7.5, 7.5, 2.9, 0.8 Hz, 2H), 7.42 (dddm, *J* = 7.5, 7.5, 3.9 Hz, 2H), 7.56 (dm, *J* = 7.5 Hz, 2H), 7.78 (dm, *J* = 7.5 Hz, 2H) ppm.

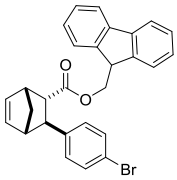
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.1, 47.0, 47.1, 47.15, 48.1, 52.5, 65.8, 120.07, 120.1, 124.8, 124.9, 127.1, 127.2, 127.8, 127.85, 128.5, 128.8, 131.8, 134.7, 138.9, 141.46, 141.5, 142.7, 143.8, 174.0 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}ClNaO_2^+$: 449.1279; found 449.1280.

$[\alpha]_D^{25}$: +82.3° (c=1.0, CH_2Cl_2).

HPLC: Daicel Chiralcel OD-3R, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 29.3 min (major) and 42.4 min (minor); t_R (exo-Diels Alder product) = 31.8 min and 35.1 min. e.r = 95:5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3f)



The product was synthesized according to the general procedure employing substrate **1f** (4d). **3f** was obtained as a yellowish syrup (45.7 mg, 97%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.54 (dm, *J* = 8.7 Hz, 1H), 1.68 (d, *J* = 8.7 Hz, 1H), 2.86-2.90 (m, 2H), 2.92-2.96 (m, 1H), 3.18 (br. s, 1H), 4.18 (t, *J* = 6.0 Hz, 1H), 4.52 (d, *J* = 6.0 Hz, 2H), 5.89 (dd, *J* = 5.7, 2.9 Hz, 1H), 6.29 (dd, *J* = 5.7, 3.3 Hz, 1H), 7.04-7.10 (m, 2H), 7.32 (dddd, *J* = 7.5, 7.5, 4.2, 3.1 Hz, 2H), 7.36-7.40 (m, 2H), 7.42 (dddm, *J* = 7.5, 7.5, 4.1 Hz, 2H), 7.56 (dm, *J* = 7.6 Hz, 2H), 7.77 (dm, *J* = 7.6 Hz, 2H) ppm.

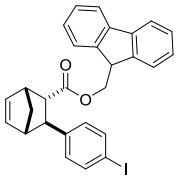
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.1, 47.1, 47.15, 48.1, 52.4, 65.8, 119.8, 120.1, 120.12, 124.8, 124.9, 127.15, 127.2, 127.8, 127.9, 129.2, 131.5, 134.8, 138.9, 141.47, 141.5, 143.2, 143.8, 174.0 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}BrNaO_2^+$: 493.0774; found 493.0775.

$[\alpha]_D^{25}$: +76.3° (c=0.92, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 70:30, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 61.9 min (major) and 89.6 min (minor); t_R (exo-Diels Alder product) = 64.4 min and 75.0 min. e.r = 96:4

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(4-iodophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3g)



The product was synthesized according to the general procedure employing substrate **1g** (3d). The crude product was purified by flash column chromatography affording **3g** as a colorless solid (46.1 mg, 89%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.54 (dm, *J* = 8.9 Hz, 1H), 1.67 (d, *J* = 8.9 Hz, 1H), 2.84-2.90 (m, 2H), 2.92-2.96 (m, 1H), 3.18 (br. s, 1H), 4.18 (t, *J* = 6.1 Hz, 1H), 4.52 (dm, *J* = 6.1 Hz, 2H), 5.89 (dd, *J* = 5.6, 2.8 Hz, 1H), 6.29 (dd, *J* = 5.6, 3.2 Hz, 1H), 6.93-6.97 (m, 2H), 7.32 (dddd, *J* = 7.5, 7.5, 3.0, 1.1 Hz, 2H), 7.42 (dddm, *J* = 7.5, 7.5, 4.1 Hz, 2H), 7.56 (dm, *J* = 7.5 Hz, 2H), 7.56-7.60 (m, 2H), 7.77 (dm, *J* = 7.5 Hz, 2H) ppm.

^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.1, 47.1, 47.15, 47.2, 48.1, 52.4, 65.8, 91.2, 120.0, 120.1, 124.8, 124.9, 127.15, 127.2, 127.8, 127.9, 129.6, 134.7, 137.5, 138.9, 141.47, 141.5, 143.8, 143.9, 173.9 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}INaO_2^+$: 541.0635; found 541.0637.

$[\alpha]_D^{25}$: +68.4° (c=0.92, CH_2Cl_2).

HPLC:

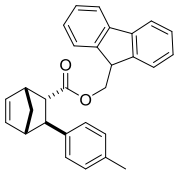
Diastereomer separation:

YMC Triart ExRS, acetonitrile:water = 85:15, flow: 0.5 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 5.56 min; t_R (exo-Diels Alder product) = 5.78 min

Enantiomer separation:

Kromasil Cellucoat RP, acetonitrile:methanol = 5:95, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 33.7 min (major) and 34.7 min (minor). e.r = 95.5:4.5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(*p*-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3h)



The product was synthesized according to the general procedure employing substrate **1h** (1d). **3h** was obtained as a yellowish syrup (39.0 mg, 96%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.55 (dm, *J* = 8.7 Hz, 1H), 1.78 (d, *J* = 8.7 Hz, 1H), 2.35 (s, 3H), 2.94-3.03 (m, 3H), 3.22 (br. s, 1H), 4.20 (t, *J* = 6.3 Hz, 1H), 4.48 (dm, *J* = 6.3 Hz, 2H), 5.90-5.95 (m, 1H), 6.33-6.37 (m, 1H), 7.12 (d, *J* = 7.9 Hz, 2H), 7.16 (d, *J* = 7.9 Hz, 2H), 7.29-7.35 (m, 2H), 7.39-7.45 (m, 2H), 7.58 (d, *J* = 7.5 Hz, 2H), 7.78 (d, *J* = 7.5 Hz, 2H) ppm.

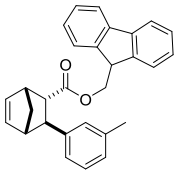
^{13}C-NMR (125 MHz, $CDCl_3$) δ 21.0, 46.2, 47.1, 47.3, 48.6, 52.2, 65.9, 120.0, 120.1, 124.95, 125.0, 127.1, 127.14, 127.4, 127.75, 127.8, 129.2, 134.5, 135.6, 139.1, 141.1, 141.4, 141.5, 143.9, 143.95, 174.3 ppm.

HRMS (ESIpos) m/z: calculated for $C_{29}H_{26}NaO_2^+$: 429.1825; found 429.1828.

$[\alpha]_D^{25}$: +83.8° (c=0.78, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 15.1 min (major) and 30.9 min (minor); t_R (exo-Diels Alder product) = 20.3 min and 22.2 min. e.r = 95.5:4.5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(*m*-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3i)



The product was synthesized according to the general procedure employing substrate **1i** (10h). **3i** was obtained as a colorless powder (37.4 mg, 92%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.57 (dm, *J* = 8.8 Hz, 1H), 1.80 (d, *J* = 8.8 Hz, 1H), 2.36 (s, 3H), 3.00-3.07 (m, 3H), 3.23 (br. s, 1H), 4.21 (t, *J* = 6.4 Hz, 1H), 4.49 (d, *J* = 6.4 Hz, 2H), 5.93 (dd, *J* = 5.7, 2.8 Hz, 1H), 6.36 (dd, *J* = 5.7, 3.2 Hz, 1H), 7.05 (d, *J* = 7.6 Hz, 1H), 7.09 (d, *J* = 7.6 Hz, 1H), 7.12 (s, 1H), 7.21 (dd, *J* = 7.6, 7.6 Hz, 2H), 7.32 (dddd, *J* = 7.5, 7.5, 2.6, 1.1 Hz, 2H), 7.43 (ddm, *J* = 7.5, 7.5 Hz, 2H), 7.59 (dm, *J* = 7.5 Hz, 2H), 7.79 (dm, *J* = 7.5 Hz, 2H) ppm.

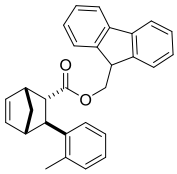
^{13}C-NMR (125 MHz, $CDCl_3$) δ 21.6, 46.3, 47.1, 47.2, 47.5, 48.6, 53.1, 67.0, 120.0, 120.1, 124.5, 124.95, 125.0, 126.9, 127.1, 127.2, 127.8, 127.81, 128.4, 128.43, 134.5, 138.1, 139.2, 141.4, 141.5, 143.9, 144.0, 144.1, 174.3 ppm.

HRMS (ESIpos) m/z: calculated for $C_{29}H_{26}NaO_2^+$: 429.1825; found 429.1827.

$[\alpha]_D^{25}$: +88.1° (c=0.90, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 12.8 min (major) and 31.2 min (minor); t_R (exo-Diels Alder product) = 17.9 min and 20.6 min. e.r = 95.5:4.5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(*o*-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3j)



The product was synthesized according to the general procedure employing substrate **1j** (3d). **3j** was obtained as a colorless solid (36.6 mg, 90%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.53 (dm, *J* = 8.8 Hz, 1H), 1.84 (d, *J* = 8.8 Hz, 1H), 2.28 (s, 3H), 2.82 (br.s, 1H), 3.14-3.20 (m, 2H), 3.22 (br. s, 1H), 4.17 (t, *J* = 6.5 Hz, 1H), 4.42 (dd, *J* = 10.9, 6.4 Hz, 1H), 4.47 (dd, *J* = 10.9, 6.7 Hz, 1H), 5.88-5.92 (m, 1H), 6.37-6.41 (m, 1H), 7.14-7.25 (m, 3H), 7.27-7.33 (m, 3H), 7.42 (dd, *J* = 7.5, 7.5 Hz, 2H), 7.53 (dd, *J* = 7.6 Hz, 2H), 7.78 (d, *J* = 7.6 Hz, 2H) ppm.

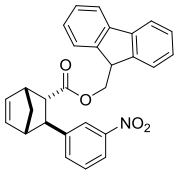
^{13}C-NMR (125 MHz, $CDCl_3$) δ 20.3, 44.5, 46.7, 46.9, 47.0, 49.5, 49.55, 65.9, 120.0, 124.9,, 125.0, 125.4, 126.0, 126.2, 127.1, 127.14, 127.76, 127.8, 130.7, 134.2, 137.2, 138.9, 141.4, 141.45, 141.7, 143.8, 144.0, 174.4 ppm.

HRMS (ESIpos) m/z: calculated for $C_{29}H_{26}NaO_2^+$: 429.1825; found 429.1825.

$[\alpha]_D^{25}$: +106.4° (c=0.91, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 70:30, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 30.6 min (major) and 60.4 min (minor); t_R (exo-Diels Alder product) = 42.5 min and 50.8 min. e.r = 96:4

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(3-nitrophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3k)



The product was synthesized according to the general procedure employing substrate **1k** (36h). **3k** was obtained as a colorless solid (39.8 mg, 91%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.59 (dm, *J* = 9.0 Hz, 1H), 1.68 (d, *J* = 9.0 Hz, 1H), 2.90 (dd, *J* = 5.0, 3.6 Hz, 1H), 2.97 (dm, *J* = 5.0 Hz, 1H), 2.99-3.02 (m, 1H), 3.20 (br. s, 1H), 4.19 (t, *J* = 5.8 Hz, 1H), 4.57 (d, *J* = 5.8 Hz, 2H), 5.88 (dd, *J* = 5.8, 2.9 Hz, 1H), 6.29 (dd, *J* = 5.7, 3.2 Hz, 1H), 7.32 (ddd, *J* = 7.5, 7.5, 0.8 Hz, 2H), 7.38-7.43 (m, 3H), 7.48 (dm, *J* = 7.7 Hz, 1H), 7.57 (dm, *J* = 7.6 Hz, 2H), 7.76 (d, *J* = 7.6 Hz, 2H) 8.04 (dm, *J* = 8.2 Hz, 1H), 8.08-8.12 (m, 2H) ppm.

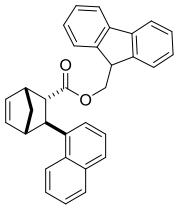
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.1, 47.0, 47.2, 47.3, 48.0, 52.4, 65.8, 120.06, 120.1, 121.3, 121.7, 124.7, 124.8, 127.17, 127.2, 127.8, 127.9, 129.3, 134.4, 135.0, 138.6, 141.5, 141.52, 143.7, 143.8, 146.4, 148.5, 173.5 ppm.

HRMS (ESIpos) m/z: calculated for $C_{28}H_{23}NNaO_4^+$: 460.1519; found 460.1520.

$[\alpha]_D^{25}$: +85.4° (c=0.99, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 60:40, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 113.3 min (major) and 143.0 min (minor); t_R (exo-Diels Alder product) = 100.3 min and 105.7 min. e.r = 97:3

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(1-naphthalenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3l)



The product was synthesized according to the general procedure employing substrate **1l** (24h). **3l** was obtained as a colorless, crystalline solid (41.2 mg, 93%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.61 (dm, *J* = 8.8 Hz, 1H), 1.86 (d, *J* = 8.8 Hz, 1H), 3.04-3.07 (m, 1H), 3.25-3.29 (m, 1H), 3.31 (dd, *J* = 5.0, 3.7 Hz, 1H), 3.78 (dm, *J* = 5.0 Hz, 1H), 4.16 (t, *J* = 6.5 Hz, 1H), 4.43 (dd, *J* = 10.8, 6.4 Hz, 1H), 4.52 (dd, *J* = 10.8, 6.7 Hz, 1H), 6.00 (dd, *J* = 5.6, 2.6 Hz, 1H), 6.54 (dd, *J* = 5.6, 3.1 Hz, 1H), 7.24 (ddd, *J* = 7.5, 7.5, 1.1 Hz, 1H), 7.16 (ddd, *J* = 7.5, 7.5, 0.8 Hz, 1H), 7.38 (dd, *J* = 7.5, 7.5 Hz, 1H), 7.45-7.51 (m, 4H), 7.50-7.56 (m, 2H), 7.75 (d, *J* = 7.5 Hz, 2H), 7.78 (dd, *J* = 7.2, 1.6 Hz, 1H) 7.88-7.92 (m, 1H), 8.12-8.18 (m, 1H) ppm.

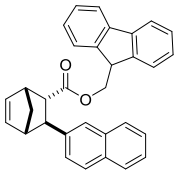
^{13}C-NMR (125 MHz, $CDCl_3$) δ 44.0, 46.7, 47.0, 47.6, 49.7, 49.73, 66.1, 120.0, 122.7, 124.0, 125.0, 125.3, 125.7, 126.2, 127.0, 127.09, 127.1, 127.7, 127.73, 128.9, 132.6, 134.0, 134.6, 138.7, 139.5, 141.4, 143.8, 143.9, 174.5 ppm.

HRMS (ESIpos) m/z: calculated for $C_{32}H_{26}NaO_2^+$: 465.1825; found 465.1825.

$[\alpha]_D^{25}$: +66.9° (c=0.82, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 23.1 min (major) and 43.7 min (minor); t_R (exo-Diels Alder product) = 35.0 min and 36.7 min. e.r 96:4

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(2-naphthalenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3m)



The product was synthesized according to the general procedure employing substrate **1m** (2d). **3m** was obtained as a colorless solid (41.2 mg, 93%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.63 (dm, *J* = 8.7 Hz, 1H), 1.87 (d, *J* = 8.7 Hz, 1H), 3.12-3.17 (m, 2H), 3.21 (d, *J* = 4.8 Hz, 1H), 3.28 (br s, 1H), 4.22 (t, *J* = 6.3 Hz, 1H), 4.54 (dm, *J* = 6.4 Hz, 1H), 5.98 (dd, *J* = 5.7, 2.8 Hz, 1H), 6.42 (dd, *J* = 5.7, 3.2 Hz, 1H), 7.27-7.33 (m, 2H), 7.39-7.45 (m, 3H), 7.45-7.52 (m, 2H), 7.60 (d, *J* = 7.6 Hz, 2H), 7.71 (br s, 1H) 7.78 (d, *J* = 7.5 Hz, 2H), 7.79 (d, *J* = 8.5 Hz, 1H), 7.80-7.86 (m, 2H) ppm.

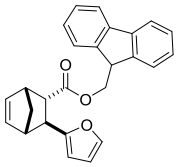
^{13}C-NMR (125 MHz, $CDCl_3$) δ 46.4, 47.1, 47.2, 47.8, 48.4, 52.1, 66.0,120.0, 120.1, 124.8, 124.9, 125.0, 125.5, 126.1, 127.1, 127.13, 127.15, 127.6, 127.77, 127.8, 128.1, 132.1, 133.6, 134.7, 139.1, 141.4, 141.5, 141.7, 143.85, 143.9 174.2 ppm.

HRMS (ESIpos) m/z: calculated for $C_{32}H_{26}NaO_2^+$: 465.1825; found 465.1826.

$[\alpha]_D^{25}$: +109.6° (c=0.81, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 23.0 min (major) and 57.0 min (minor); t_R (exo-Diels Alder product) = 32.0 min and 33.8 min. e.r = 96.5:3.5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(2-furanyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3n)



The product was synthesized according to the general procedure employing substrate **1n** (3d). **3n** was obtained as a yellowish syrup (34.8 mg, 91%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.51 (dm, *J* = 8.7 Hz, 1H), 1.75 (d, *J* = 8.7 Hz, 1H), 2.97-3.00 (m, 1H), 3.02 (d, *J* = 4.6 Hz, 1H), 3.15 (dd, *J* = 4.8, 3.8 Hz, 1H), 3.20 (br s, 1H), 4.19 (t, *J* = 6.5 Hz, 1H), 4.42 (dd, *J* = 10.8, 6.4 Hz, 1H),), 4.46 (dd, *J* = 10.8, 6.8 Hz, 1H), 5.90 (dd, *J* = 5.6, 2.8 Hz, 1H), 6.05 (dm, *J* = 3.2 Hz, 1H), 6.30 (dd, *J* = 5.6, 3.2 Hz, 1H), 6.32 (dd, *J* = 3.1, 1.9 Hz, 1H), 7.29-7.35 (m, 3H), 7.42 (dd, *J* = 7.5,7.5 Hz, 2H), 7.59 (dd, *J* = 8.9,7.5 Hz, 2H), 7.78 (d, *J* = 7.6 Hz, 1H) ppm.

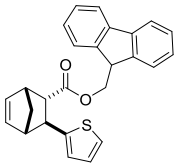
^{13}C-NMR (125 MHz, $CDCl_3$) δ 41.9, 45.8, 47.5, 48.5, 49.9, 66.1, 105.1, 110.2, 120.1, 125.0, 125.05, 127.15, 127.2, 127.8, 127.82, 134.4, 138.1, 141.3, 141.4, 141.5, 143.8, 144.0, 157.6, 173.7 ppm.

HRMS (ESIpos) m/z: calculated for $C_{26}H_{22}NaO_3^+$: 405.1461; found 405.1463.

$[\alpha]_D^{25}$: +104.4° (c=0.86, CH_2Cl_2).

HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 265 nm, t_R (endo-Diels Alder product) = 10.1 min (major) and 23.6 min (minor); t_R (exo-Diels Alder product) = 12.9 min and 14.3 min. e.r = 95.5:4.5

(9H-fluoren-9-yl)methyl (1R,2S,3S,4S)-3-(2-thiophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3o)



The product was synthesized according to the general procedure employing substrate **1o** (0 °C, 3d). **3o** was obtained as a colorless powder (35.1 mg, 88%, d.r. >25:1).

^{1}H-NMR (500 MHz, $CDCl_3$) δ = 1.59 (dm, *J* = 8.9 Hz, 1H), 1.82 (d, *J* = 8.9 Hz, 1H), 2.97-3.01 (m, 1H), 3.08 (dd, *J* = 4.7, 3.8 Hz, 1H), 3.19-3.23 (m, 2H), 4.20 (t, *J* = 6.4 Hz, 1H), 4.47 (dd, *J* = 10.8, 6.3 Hz, 1H),), 4.50 (dd, *J* = 10.8, 6.6 Hz, 1H), 5.92 (dd, *J* = 5.6, 2.7 Hz, 1H), 6.31 (dd, *J* = 5.6, 3.1 Hz, 1H), 6.83 (dm, *J* = 3.5 Hz, 1H), 6.94 (dd, *J* = 5.1, 3.5 Hz, 1H), 7.16 (dd, *J* = 5.2, 1.2 Hz, 1H), 7.32 (dd, *J* = 7.5,7.5 Hz, 2H), 7.42 (dd, *J* = 7.5, 7.5 Hz, 2H), 7.58 (dd, *J* = 7.5, 3.8 Hz, 2H), 7.78 (d, *J* = 7.5 Hz, 2H) ppm.

^{13}C-NMR (125 MHz, $CDCl_3$) δ 43.8, 46.0, 47.1, 47.5, 50.6, 53.7, 66.0, 120.05, 120.1, 123.2, 123.9, 124.96, 125.0, 126.8, 127.15, 127.2, 127.8, 127.82, 134.4, 138.3, 141.4, 141.5, 143.8, 143.9, 148.5, 173.6 ppm.

HRMS (ESIpos) m/z: calculated for $C_{26}H_{22}NaO_2S^+$: 421.1233; found 421.1233.

$[\alpha]_D^{25}$: +86.1° (c=0.84, CH_2Cl_2).

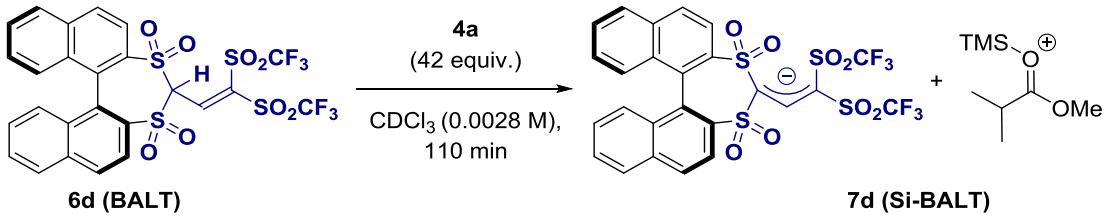
HPLC: Kromasil Cellucoat RP, acetonitrile:water = 80:20, flow: 1 mL/min, 25°C, absorption at 220 nm, t_R (endo-Diels Alder product) = 13.0 min (major) and 34.3 min (minor); t_R (exo-Diels Alder product) = 16.9 min and 19.8 min. e.r = 92.5:7.5

Mechanistic NMR Studies

Kinetic Studies of C–H Acid Catalyst Activation

To investigate the activation of catalyst **6d**, we studied the disappearance of the protonated BALT **6d** in the presence of an excess of silyl ketene acetal **4a** (Fig S3). Catalyst **6d** and the $SiMe_3$-derived silyl ketene acetal **4a** were chosen in order to facilitate the analysis of the mixtures obtained during the activation process.

Accordingly, C-H acid **6d** (0.8 mg, 12 µmol) was dissolved in 0.5 mL dry $CDCl_3$ under an argon atmosphere in a 5mm NMR tube. The sample was analyzed by ^{1}H-NMR spectroscopy to obtain the point t = 0s. Then, (1-methoxy-2-methyl-1-propenyloxy)trimethylsilane **4a** (10 µL, 49 µmol) was added under argon and the sample was, after shaking, transferred back to the NMR instrument. Every 10 min, a ^{1}H-NMR spectrum was acquired and the obtained kinetic NMR data was analyzed with the reaction monitoring module of MNova 10.0.2 (Mestrelab Research, Santiago de Compostela**,** Spain) (Fig. S4).



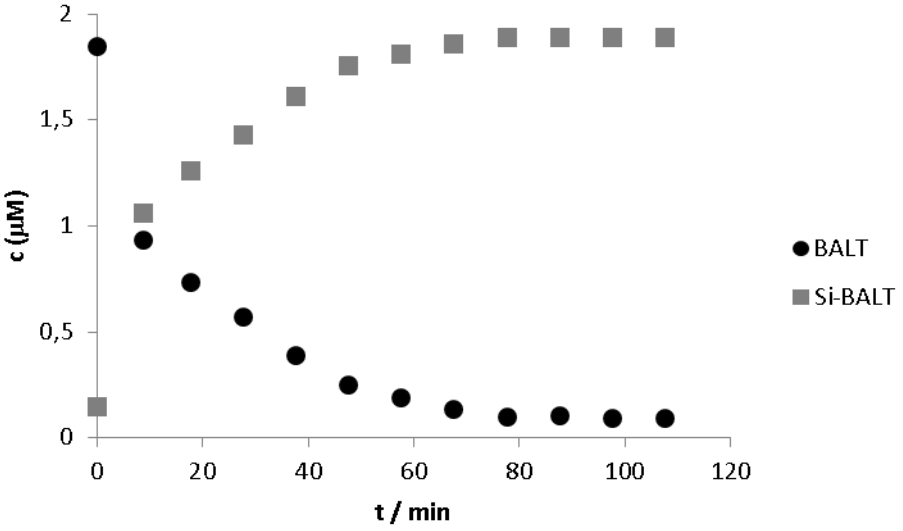


Fig. S3. ^{1}H-NMR spectroscopic analysis of reaction kinetics. The integration regions that were used to obtain the plot are shown in Fig. S4 (green fields).

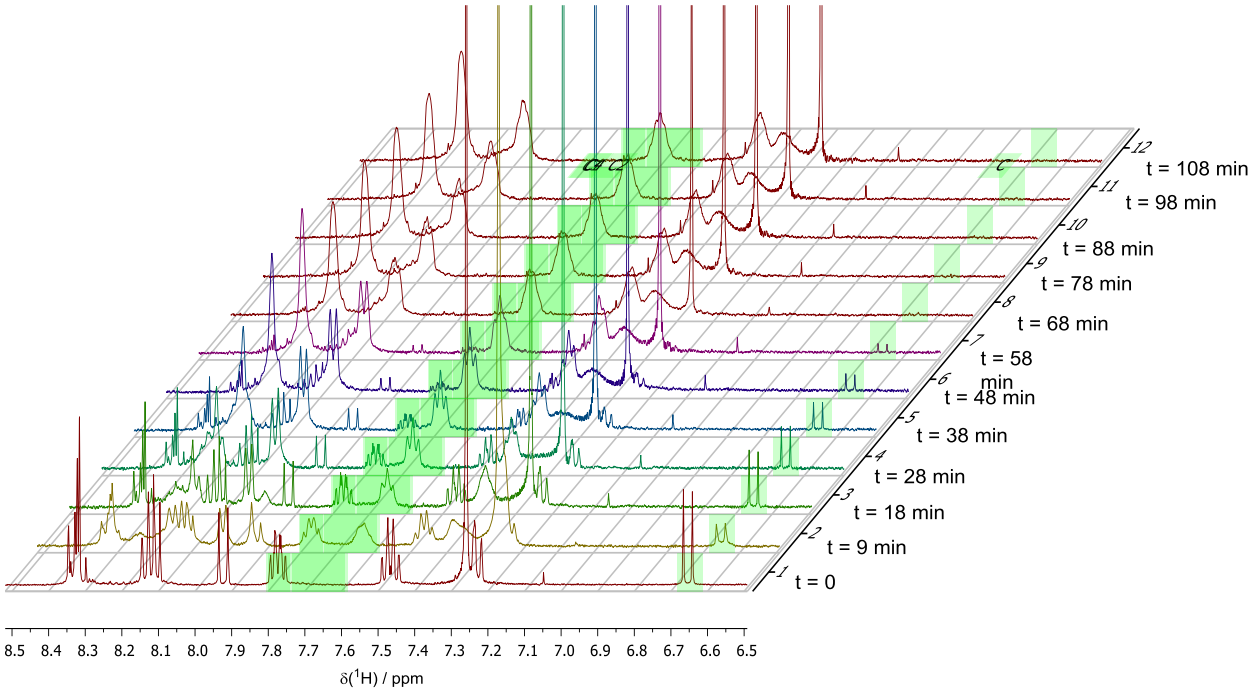


Fig. S4. Stack plot of different ^{1}H-NMR spectra which were measured at different time points in the course of the reaction.

Characterization of C–H Acid-Derived Ion Pairs

The sample obtained from the previous measurements was used to analyze the activated catalyst by ^{1}H and ^{19}F NMR spectroscopy at several temperatures (Fig S5). At high temperatures, the ^{1}H-NMR signals of the two naphthalene rings are pseudo homotopic. This observation can be explained with the anionic nature of the compound. At lower temperatures at least two different species could be detected in the ^{1}H and the ^{19}F-NMR spectra.

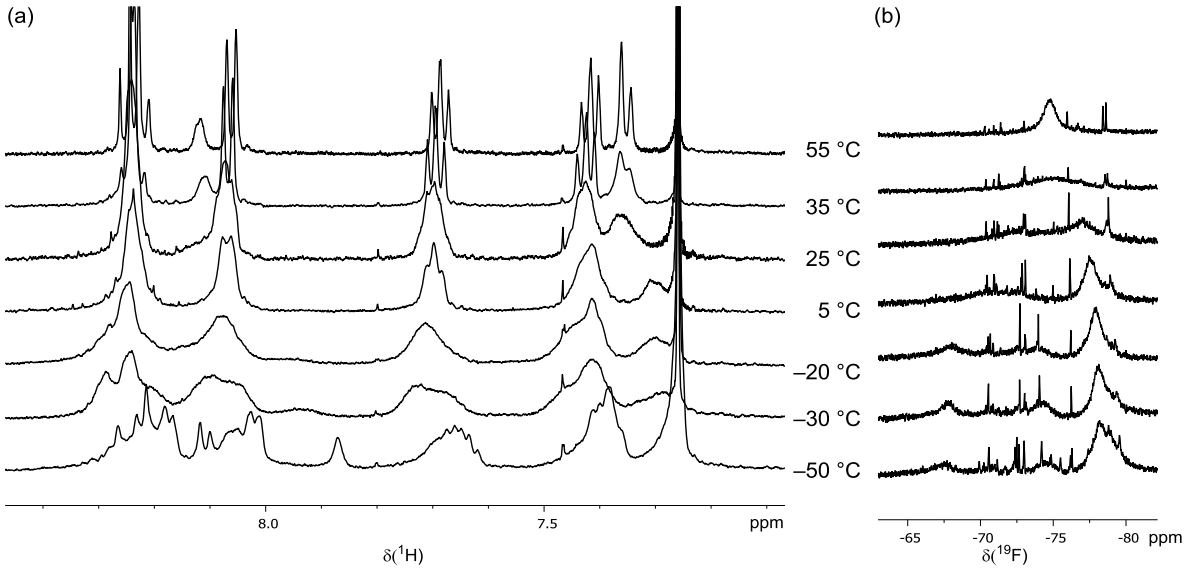


Fig. S5. (a) ^{1}H- and (b) ^{19}F-NMR spectra of **7d** at various temperatures.

In order to further support the identification of the detected species as the catalyst-derived anion, we compared the obtained NMR spectra to those of the tetraethyl-ammonium-salt of BALT **6d**. The NMR sample of this salt was prepared by dissolving **6d** in a $(NEt_4)_2CO_3$-solution (10 mM in CH_2Cl_2). After removing of the solvent under reduced pressure, the residue was dissolved in $CDCl_3$ (0.5 mL).

The direct comparison of the ^{19}F- and ^{1}H-NMR spectra (Fig. S6) reveals the involvement of very similar species, as well as similar temperature dependent behaviors, thus underscoring the largely anionic character of the BALT-derived activated species formed under the reaction conditions.

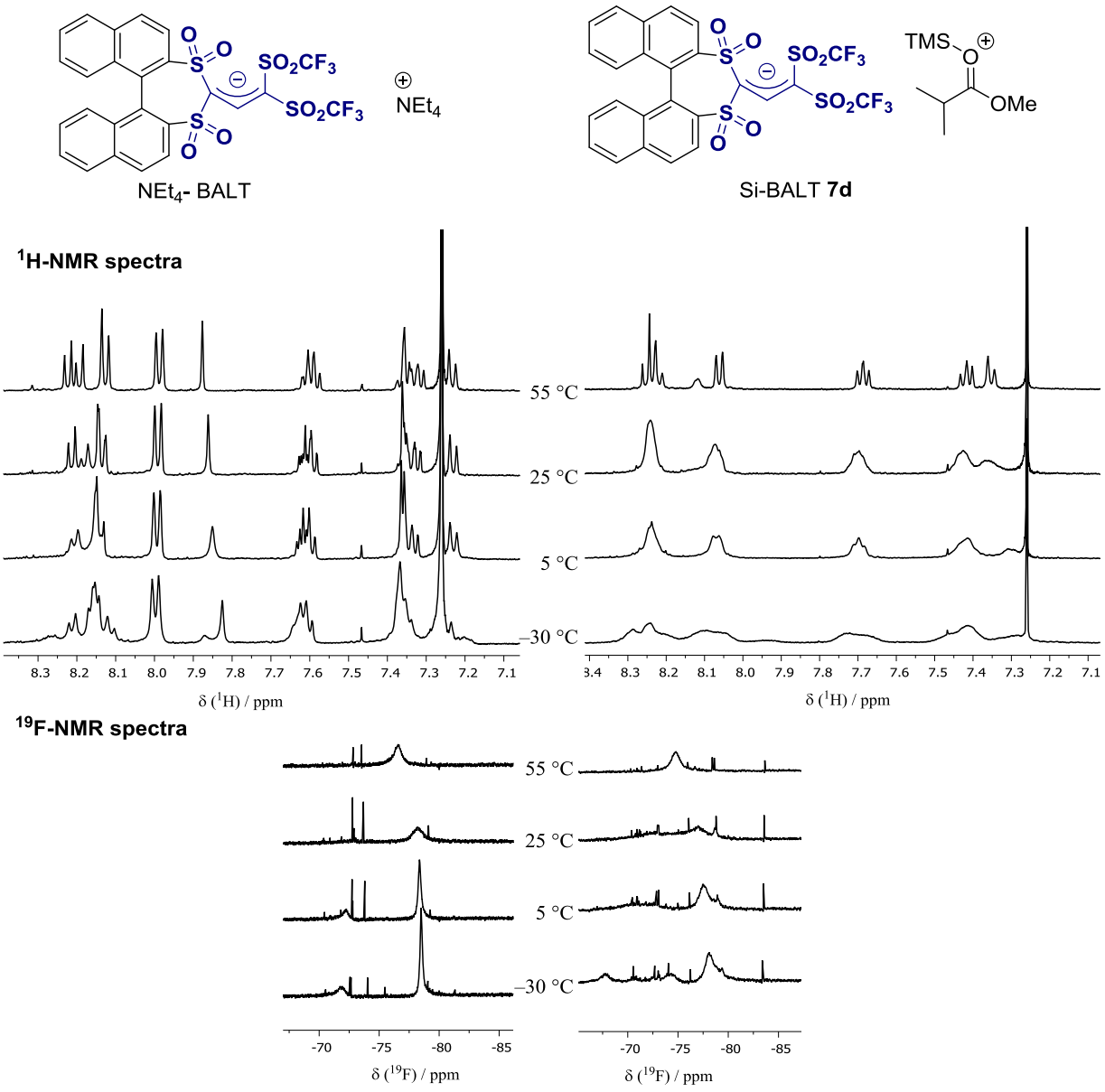


Fig. S6. Comparison of the ^{1}H- and ^{19}F-NMR spectra of NEt_4-BALT and Si-BALT **7d** at various temperatures.

The temperature dependence of the NMR signals can likely be explained by the exchange between different conformers or isomers of the allyl anion, which is probably non-planar due to the steric demand of the SO_2-groups.(*30*)

X-Ray data

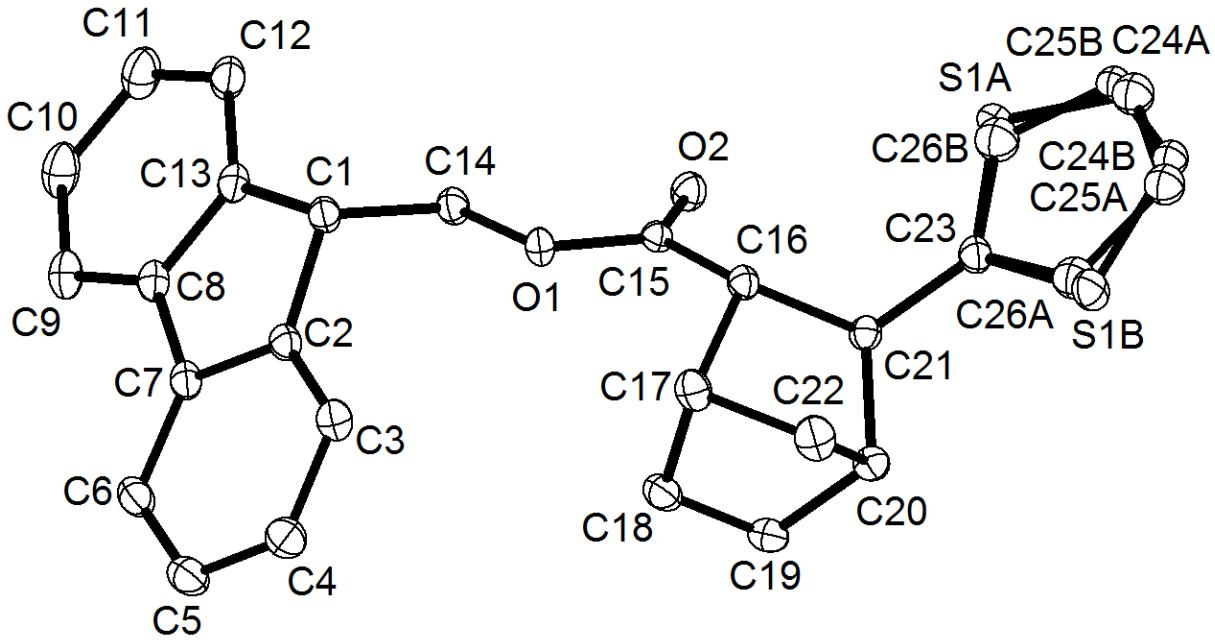


Fig. S7. X-Ray structural analysis parameter for **3o**.

Table S10. Crystal data and structure refinement of **3o**.

Identification code	9782	
Empirical formula	$C_{26}\ H_{22}\ O_2\ S$	
Color	colourless	
Formula weight	398.49 $g \cdot mol^{-1}$	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	monoclinic	
Space group	$P\ 2_1$, (no. 4)	
Unit cell dimensions	a = 8.6044(3) Å	α= 90°.
	b = 7.9270(7) Å	β= 102.446(3)°.
	c = 14.7952(7) Å	γ = 90°.
Volume	985.42(11) $Å^3$	
Z	2	
Density (calculated)	1.343 $Mg \cdot m^{-3}$	
Absorption coefficient	0.185 mm^{-1}	
F(000)	420 e	

Crystal size	0.16 x 0.10 x 0.07 mm^3	
θ range for data collection	4.953 to 33.168°.	
Index ranges	$-13 \le h \le 13$, $-12 \le k \le 12$, $-22 \le l \le 22$	
Reflections collected	35604	
Independent reflections	7482 [R_{int} = 0.0467]	
Reflections with I>2σ (I)	7156	
Completeness to θ = 25.242°	98.9 %	
Absorption correction	Gaussian	
Max. and min. transmission	0.98903 and 0.97287	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	7482 / 1 / 269	
Goodness-of-fit on F^2	1.042	
Final R indices [I>2σ (I)]	R_1 = 0.0337	wR^2 = 0.0883
R indices (all data)	R_1 = 0.0361	wR^2 = 0.0904
Absolute structure parameter	-0.05(3)	
Extinction coefficient	0	
Largest diff. peak and hole	0.325 and -0.322 e·$Å^{-3}$	

Table S11. Atomic coordinates and equivalent isotropic displacement parameters ($Å^2$). U_{eq} is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U_{eq}
C(1)	0.2163(2)	0.6744(2)	0.2009(1)	0.015(1)
C(2)	0.0501(2)	0.6054(2)	0.1963(1)	0.015(1)
C(3)	-0.0434(2)	0.6145(2)	0.2619(1)	0.018(1)
C(4)	-0.1913(2)	0.5337(2)	0.2435(1)	0.021(1)
C(5)	-0.2454(2)	0.4479(2)	0.1601(1)	0.022(1)
C(6)	-0.1539(2)	0.4426(2)	0.0928(1)	0.020(1)
C(7)	-0.0058(2)	0.5218(2)	0.1120(1)	0.016(1)
C(8)	0.1169(2)	0.5313(2)	0.0567(1)	0.017(1)
C(9)	0.1220(2)	0.4631(2)	-0.0294(1)	0.022(1)
C(10)	0.2604(2)	0.4835(2)	-0.0629(1)	0.026(1)
C(11)	0.3906(2)	0.5712(3)	-0.0118(1)	0.027(1)
C(12)	0.3849(2)	0.6422(2)	0.0737(1)	0.021(1)
C(13)	0.2474(2)	0.6214(2)	0.1078(1)	0.017(1)
C(14)	0.3449(2)	0.5962(2)	0.2766(1)	0.016(1)

C(15)	0.4189(2)	0.5792(2)	0.4389(1)	0.013(1)
C(16)	0.3731(2)	0.6170(2)	0.5296(1)	0.014(1)
C(17)	0.1903(2)	0.6140(2)	0.5267(1)	0.018(1)
C(18)	0.1329(2)	0.4392(2)	0.4931(1)	0.020(1)
C(19)	0.1936(2)	0.3300(2)	0.5605(1)	0.020(1)
C(20)	0.2908(2)	0.4304(2)	0.6407(1)	0.017(1)
C(21)	0.4437(2)	0.4865(2)	0.6071(1)	0.014(1)
C(22)	0.1952(2)	0.5968(2)	0.6311(1)	0.021(1)
C(23)	0.5749(2)	0.5560(2)	0.6819(1)	0.016(1)
O(1)	0.3086(1)	0.6329(1)	0.3656(1)	0.015(1)
O(2)	0.5425(1)	0.5129(1)	0.4313(1)	0.017(1)
S(1A)	0.7577(1)	0.5935(1)	0.6622(1)	0.019(1)
C(24A)	0.8301(4)	0.6579(4)	0.7748(2)	0.022(1)
C(25A)	0.7187(4)	0.6506(3)	0.8270(2)	0.020(1)
C(26A)	0.5702(6)	0.5914(7)	0.7740(3)	0.023(1)
S(1B)	0.5619(2)	0.5907(3)	0.7905(2)	0.020(1)
C(24B)	0.7579(7)	0.6545(6)	0.8236(3)	0.016(1)
C(25B)	0.8383(6)	0.6527(6)	0.7549(4)	0.015(1)
C(26B)	0.7320(11)	0.5927(16)	0.6697(8)	0.024(2)

Table S12. Bond lengths [Å] and angles [°].

C(1)-C(13)	1.5181(19)	C(1)-C(2)	1.5187(19)
C(1)-C(14)	1.5264(19)	C(2)-C(3)	1.3903(18)
C(2)-C(7)	1.4025(18)	C(3)-C(4)	1.398(2)
C(4)-C(5)	1.397(2)	C(5)-C(6)	1.397(2)
C(6)-C(7)	1.394(2)	C(7)-C(8)	1.470(2)
C(8)-C(9)	1.3944(19)	C(8)-C(13)	1.406(2)
C(9)-C(10)	1.394(2)	C(10)-C(11)	1.394(3)
C(11)-C(12)	1.395(2)	C(12)-C(13)	1.392(2)
C(14)-O(1)	1.4475(16)	C(15)-O(2)	1.2131(16)
C(15)-O(1)	1.3468(15)	C(15)-C(16)	1.5077(17)
C(16)-C(17)	1.5645(18)	C(16)-C(21)	1.5664(18)
C(17)-C(18)	1.519(2)	C(17)-C(22)	1.542(2)
C(18)-C(19)	1.338(2)	C(19)-C(20)	1.522(2)
C(20)-C(22)	1.545(2)	C(20)-C(21)	1.5675(19)
C(21)-C(23)	1.5048(19)	C(23)-C(26A)	1.400(4)
C(23)-C(26B)	1.432(9)	C(23)-S(1B)	1.658(3)
C(23)-S(1A)	1.6873(18)	S(1A)-C(24A)	1.725(3)
C(24A)-C(25A)	1.355(4)	C(25A)-C(26A)	1.427(6)
S(1B)-C(24B)	1.728(6)	C(24B)-C(25B)	1.348(7)
C(25B)-C(26B)	1.468(12)		
C(13)-C(1)-C(2)	102.01(11)	C(13)-C(1)-C(14)	108.18(11)
C(2)-C(1)-C(14)	114.42(11)	C(3)-C(2)-C(7)	120.45(12)
C(3)-C(2)-C(1)	129.11(12)	C(7)-C(2)-C(1)	110.43(11)
C(2)-C(3)-C(4)	118.61(13)	C(5)-C(4)-C(3)	120.79(13)
C(6)-C(5)-C(4)	120.78(14)	C(7)-C(6)-C(5)	118.21(13)
C(6)-C(7)-C(2)	121.12(13)	C(6)-C(7)-C(8)	130.15(13)
C(2)-C(7)-C(8)	108.70(12)	C(9)-C(8)-C(13)	120.62(14)
C(9)-C(8)-C(7)	131.04(14)	C(13)-C(8)-C(7)	108.29(12)
C(10)-C(9)-C(8)	118.49(15)	C(11)-C(10)-C(9)	120.91(14)
C(10)-C(11)-C(12)	120.76(15)	C(13)-C(12)-C(11)	118.63(15)
C(12)-C(13)-C(8)	120.57(13)	C(12)-C(13)-C(1)	128.73(13)
C(8)-C(13)-C(1)	110.56(12)	O(1)-C(14)-C(1)	108.78(11)
O(2)-C(15)-O(1)	122.84(12)	O(2)-C(15)-C(16)	124.81(12)
O(1)-C(15)-C(16)	112.31(11)	C(15)-C(16)-C(17)	115.24(10)
C(15)-C(16)-C(21)	112.67(10)	C(17)-C(16)-C(21)	103.81(10)

C(18)-C(17)-C(22)	100.61(12)	C(18)-C(17)-C(16)	106.10(11)
C(22)-C(17)-C(16)	99.45(10)	C(19)-C(18)-C(17)	107.41(13)
C(18)-C(19)-C(20)	107.64(13)	C(19)-C(20)-C(22)	100.53(12)
C(19)-C(20)-C(21)	104.98(11)	C(22)-C(20)-C(21)	101.30(11)
C(23)-C(21)-C(16)	114.05(11)	C(23)-C(21)-C(20)	114.70(11)
C(16)-C(21)-C(20)	101.54(10)	C(17)-C(22)-C(20)	93.80(10)
C(26A)-C(23)-C(21)	128.0(2)	C(26B)-C(23)-C(21)	124.1(5)
C(26B)-C(23)-S(1B)	110.6(5)	C(21)-C(23)-S(1B)	125.26(12)
C(26A)-C(23)-S(1A)	110.8(2)	C(21)-C(23)-S(1A)	121.14(10)
C(15)-O(1)-C(14)	114.58(10)	C(23)-S(1A)-C(24A)	92.37(13)
C(25A)-C(24A)-S(1A)	112.6(2)	C(24A)-C(25A)-C(26A)	111.1(3)
C(23)-C(26A)-C(25A)	113.0(4)	C(23)-S(1B)-C(24B)	93.3(2)
C(25B)-C(24B)-S(1B)	114.3(4)	C(24B)-C(25B)-C(26B)	109.0(5)
C(23)-C(26B)-C(25B)	112.8(7)		

Symmetry transformations used to generate equivalent atoms:

Table S13. Anisotropic displacement parameters ($Å^2$).

The anisotropic displacement factor exponent takes the form:
$-2\pi^2[h^2a^{*2}U_{11} + ... + 2 h k a^* b^* U_{12}]$.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	0.016(1)	0.016(1)	0.014(1)	0.000(1)	0.001(1)	0.000(1)
C(2)	0.015(1)	0.014(1)	0.014(1)	0.000(1)	0.001(1)	0.001(1)
C(3)	0.017(1)	0.020(1)	0.016(1)	-0.001(1)	0.003(1)	0.002(1)
C(4)	0.016(1)	0.023(1)	0.023(1)	0.001(1)	0.004(1)	0.002(1)
C(5)	0.016(1)	0.021(1)	0.026(1)	0.000(1)	0.001(1)	-0.002(1)
C(6)	0.019(1)	0.019(1)	0.020(1)	-0.001(1)	-0.002(1)	-0.002(1)
C(7)	0.017(1)	0.014(1)	0.013(1)	0.000(1)	0.000(1)	0.001(1)
C(8)	0.020(1)	0.017(1)	0.013(1)	0.001(1)	0.000(1)	0.003(1)
C(9)	0.026(1)	0.024(1)	0.014(1)	-0.002(1)	0.001(1)	0.004(1)
C(10)	0.029(1)	0.035(1)	0.015(1)	0.000(1)	0.005(1)	0.008(1)
C(11)	0.024(1)	0.039(1)	0.017(1)	0.004(1)	0.007(1)	0.006(1)
C(12)	0.019(1)	0.029(1)	0.016(1)	0.005(1)	0.002(1)	0.002(1)
C(13)	0.018(1)	0.018(1)	0.013(1)	0.002(1)	0.001(1)	0.002(1)
C(14)	0.016(1)	0.018(1)	0.013(1)	-0.001(1)	0.002(1)	-0.001(1)
C(15)	0.014(1)	0.012(1)	0.014(1)	0.000(1)	0.001(1)	-0.002(1)
C(16)	0.014(1)	0.013(1)	0.014(1)	0.000(1)	0.001(1)	0.001(1)
C(17)	0.014(1)	0.020(1)	0.019(1)	-0.001(1)	0.002(1)	0.004(1)
C(18)	0.015(1)	0.024(1)	0.019(1)	-0.002(1)	0.003(1)	-0.003(1)
C(19)	0.017(1)	0.022(1)	0.021(1)	0.000(1)	0.004(1)	-0.005(1)
C(20)	0.016(1)	0.020(1)	0.015(1)	0.000(1)	0.004(1)	-0.002(1)
C(21)	0.014(1)	0.013(1)	0.014(1)	0.001(1)	0.002(1)	0.001(1)
C(22)	0.018(1)	0.028(1)	0.020(1)	-0.003(1)	0.006(1)	0.004(1)
C(23)	0.016(1)	0.015(1)	0.014(1)	0.001(1)	0.001(1)	0.001(1)
O(1)	0.015(1)	0.018(1)	0.011(1)	0.000(1)	0.000(1)	0.001(1)
O(2)	0.016(1)	0.019(1)	0.016(1)	0.002(1)	0.003(1)	0.002(1)
S(1A)	0.014(1)	0.023(1)	0.018(1)	0.002(1)	0.002(1)	-0.004(1)
S(1B)	0.020(1)	0.025(1)	0.015(1)	-0.004(1)	0.004(1)	-0.001(1)

Table S14. Hydrogen coordinates and isotropic displacement parameters ($Å^2$).

	x	y	z	U_{eq}
H(1)	0.2171	0.8001	0.2065	0.019
H(3)	-0.0075	0.6744	0.3182	0.022
H(4)	-0.2557	0.5371	0.2881	0.025
H(5)	-0.3457	0.3926	0.1491	0.026
H(6)	-0.1916	0.3866	0.0355	0.024
H(9)	0.0331	0.4040	-0.0646	0.026
H(10)	0.2661	0.4371	-0.1213	0.031
H(11)	0.4842	0.5828	-0.0355	0.032
H(12)	0.4730	0.7035	0.1080	0.026
H(14A)	0.3485	0.4727	0.2676	0.019
H(14B)	0.4502	0.6436	0.2738	0.019
H(16)	0.4149	0.7314	0.5507	0.017
H(17)	0.1273	0.7109	0.4945	0.021
H(18)	0.0661	0.4123	0.4350	0.023
H(19)	0.1787	0.2112	0.5585	0.024
H(20)	0.3094	0.3748	0.7028	0.021
H(21)	0.4857	0.3875	0.5779	0.017
H(22A)	0.0882	0.5835	0.6449	0.026
H(22B)	0.2534	0.6901	0.6682	0.026
H(24A)	0.9365	0.6945	0.7978	0.026
H(25A)	0.7371	0.6810	0.8905	0.024
H(26A)	0.4778	0.5774	0.7986	0.027
H(24B)	0.8051	0.6879	0.8851	0.019
H(25B)	0.9463	0.6850	0.7606	0.018
H(26B)	0.7641	0.5797	0.6125	0.029

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3. The Catalytic Asymmetric Mukaiyama–Michael Reaction of Silyl Ketene Acetals with α,β-Unsaturated Methyl Esters

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Content

α,β-Unsaturated esters are readily available but challenging substrates to activate in asymmetric catalysis. We now describe an efficient, general, and highly enantioselective Mukaiyama–Michael reaction of silyl ketene acetals with α,β-unsaturated methyl esters that is catalyzed by a silylium imidodiphosphorimidate (IDPi) Lewis acid.

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The Catalytic Asymmetric Mukaiyama–Michael Reaction of Silyl Ketene Acetals with α,β-Unsaturated Methyl Esters

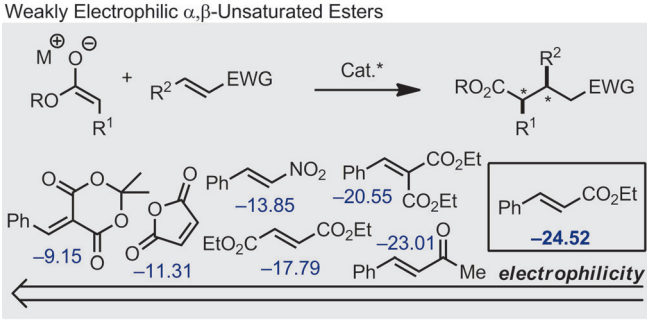
*Tim Gatzenmeier, Philip S. J. Kaib, Julia B. Lingnau, Richard Goddard, and Benjamin List**

Abstract: *α,β-Unsaturated esters are readily available but challenging substrates to activate in asymmetric catalysis. We now describe an efficient, general, and highly enantioselective Mukaiyama–Michael reaction of silyl ketene acetals with α,β-unsaturated methyl esters that is catalyzed by a silylium imidodiphosphorimidate (IDPi) Lewis acid.*

Michael additions of enolate equivalents to α,β-unsaturated carbonyl compounds are widely applied carbon–carbon bond-forming reactions, and the development of catalytic asymmetric variants has been the subject of intensive research over the past decades.[1] Whereas α,β-unsaturated aldehydes and ketones readily engage in various catalytic enantioselective Michael additions by iminium ion, Brønsted acid, or Lewis acid catalysis,[2–4] α,β-unsaturated esters—the original substrates in Michael's seminal study from 1887[5]—have proven to be particularly challenging substrates for such reactions. Very recently, Mayr and co-workers provided an explanation for their low reactivity by systematically quantifying the electrophilicity of a wide range of common Michael acceptors.[6] Indeed, α,β-unsaturated esters in general, and cinnamates in particular, rank among the very least electrophilic substrates (Figure 1 A). However, because α,β-unsaturated esters are naturally abundant, industrially relevant, and inexpensive or readily available, they are highly attractive substrates for Michael additions. Herein, we show that a silylium imidodiphosphorimidate (IDPi) Lewis acid catalyzes a highly enantioselective catalytic Mukaiyama–Michael addition of silyl ketene acetals to a range of simple α,β-unsaturated methyl esters.

In contrast to the desired Michael additions of enolate equivalents, elegant and useful catalytic asymmetric conjugate additions to α,β-unsaturated esters have previously been developed. Examples include Feringa's copper phosphoramidite catalyzed conjugate additions of Grignard reagents,[7] Hayashi's rhodium-catalyzed 1,4-additions of boronic acids,[8] and Pfaltz' cobalt-catalyzed conjugate reductions.[9] Organocatalytic enantioselective Stetter reactions with α,β-unsaturated esters have also been described.[10] Furthermore, to circumvent the poor reactivity of α,β-unsaturated esters, more electrophilic α,β-unsaturated *N*-acyl oxazolidinones, *N*-acyl imides, *N*-acyl imidazolides, thioamides, α-ketophosphonates, alkylidene malonates, or perfluorinated esters[11] have been suggested as ester surrogates in Michael-type additions, but such reagents are inherently less atom- and step-economic. To activate α,β-unsaturated esters themselves, only few Lewis acidic catalysts have been reported, including Corey's oxazaborolidines or bifunctional hydrogen-bonding catalysts.[12,13]

A. The Challenge: Catalytic Asymmetric Michael Addition of Enolates to Weakly Electrophilic α,β-Unsaturated Esters



B. This Work: Asymmetric Mukaiyama–Michael Reaction of Silyl Ketene Acetals to α,β-Unsaturated Methyl Esters

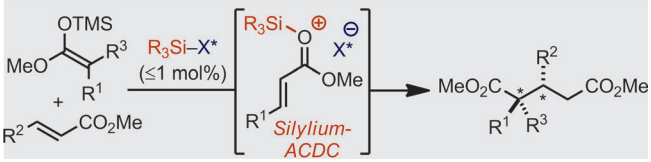


Figure 1. Asymmetric catalysis of the Michael reaction.

Within our research program of exploring the potential of asymmetric counteranion-directed silylium Lewis acid catalysis (silylium-ACDC),[14,15] we recently focused our attention on the activation of α,β-unsaturated esters in catalytic asymmetric Diels–Alder reactions with cyclopentadiene.[16] While these studies suggested sufficient reactivity of our silylium Lewis acid catalysts, high enantioselectivities were only obtained with 9-fluorenylmethyl esters. These substrates are electronically non-activated, but prone to strong dispersion interactions.[17] Striving to make the simplest and most readily available methyl esters accessible as substrates, we became highly interested in exploring their utility in silylium-ACDC and specifically in the asymmetric Mukaiyama–Michael reaction (Figure 1 B).

We began our study with the asymmetric conjugate addition reaction of methyl *trans*-cinnamate (**1a**) with commercial silyl ketene acetal (SKA) **2a** (Table 1).[18] In preliminary studies of this model reaction, we found that Lewis acids derived from our chiral disulfonimides (DSIs),[15] or binaphthyl allyl tetrasulfone (BALT) C–H acids,[16] were either insufficiently reactive as catalysts or gave very low

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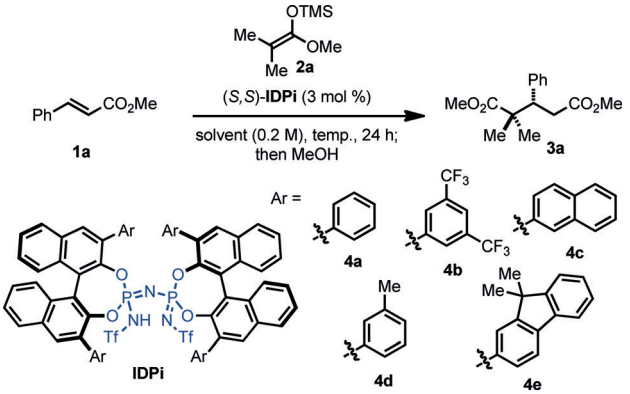
Table 1: Reaction development.[a]



Entry	Cat.	Solvent	Temp.	Conv. [%][b]	e.r.[c]
1	**4a**	toluene	RT	full	73.5:26.5
2	**4b**	toluene	RT	full	54.5:45.5
3	**4c**	toluene	RT	full	14:86
4	**4d**	toluene	RT	full	83:17
5	**4e**	toluene	RT	full	93:7
6	**4e**	Et_2O	RT	43	92:8
7	**4e**	$CHCl_3$	RT	80	77:23
8	**4e**	cyclohexane	RT	52	95.5:4.5
9[d,e]	**4e**	cyclohexane	RT	full	95.5: 4.5
10[d,e]	**4e**	cyclohexane	10 °C	full	96.5:3.5
11[d,e,f]	**4e**	**cyclohexane**	**0 °C**	**full**	**97:3**

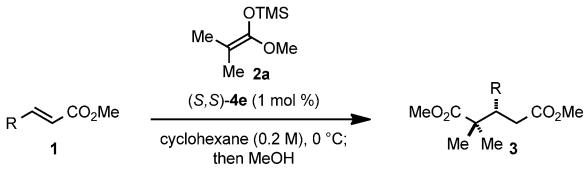
[a] Reactions were performed on 0.02 mmol scale. [b] Determined by ^{1}H NMR analysis. [c] Determined by HPLC analysis on a chiral stationary phase. [d] Freshly prepared and purified SKA **2a** was used. [e] With 1 mol% of the catalyst. [f] 12 h reaction time.

enantioselectivities (see the Supporting Information for further details). In contrast, encouraging results were obtained with our recently developed IDPi acids[19] **4a–e** (Table 1, entries 1–5). This catalyst motif combines very high acidity with a confined three-dimensional structure, and generates a C_2-symmetric anion upon deprotonation.

Of the investigated IDPi acids, **4e** was identified as the best catalyst (entry 5). Further optimization resulted in very high enantioselectivity but only moderate conversion (entry 8). A remarkable enhancement in reactivity was observed when freshly synthesized and purified reagent was used instead of commercially available SKA **2a**.[20] This allowed us to obtain full conversion with only 1 mol% of catalyst at 0 °C after 12 h (entry 11). With the commercial reagent, the conversion was only 52% at room temperature with 3 mol% of the catalyst after a reaction time of 24 h (entry 8). We attribute this effect to trace impurities of diisopropylamine in the commercially available SKA, which potentially deactivate the catalyst.

With optimized reaction conditions in hand, we next investigated the scope of the reaction by employing a variety of 3-aryl and 3-alkyl methyl *trans*-acrylates (Table 2). With model substrate **1a**, the catalyst loading could even be lowered to 0.25 mol% (entries 1–3), giving consistently excellent yields of product **3a** with prolonged reaction times. Differently substituted arenes (**3b–d**, **3h**) as well as halogenated substrates (**3e–g**) gave the desired products in excellent yields and enantioselectivities. Furthermore, both

Table 2: Ester scope.[a]



Entry	R =	Product	Time	Yield [%][b]	e.r.[c]
1		**3a**	14 h	97 (1 mol%)	97:3
2		**3a**	5 d	98 (0.5 mol%)	97:3
3		**3a**	5 d	98 (0.25 mol%)	96.5:3.5
4	Me	**3b**	14 h	95	97:3
5	Me	**3c**	14 h	95	98:2
6	Me	**3d**	5 d	92	96.5:3.5
7	F	**3e**	14 h	99	97.5:2.5
8	Cl	**3f**	14 h	97	97.5:2.5
9	Br	**3g**	14 h	98	98:2
10		**3h**	2 d	92	94.5:5.5
11	MeO	**3i**	24 h	95	95.5:4.5
12[d]	NC	**3j**	14 h	89	97.5:2.5
13[e]	O_2N	**3k**	4 d	76	95:5
14[f]	O O	**3l**	3 d	84	97:3
15	O	**3m**	14 h	94	94.5:5.5
16[g]		**3n**	24 h	92	97:3
17[g]	Me	**3o**	2 d	94	95:5
18[h]	Me Me	**3p**	24 h	27% conv.[i]	84.5:15.5
19[h]		**3q**	24 h	no reaction	–

[a] Reactions were performed on 0.2 mmol scale with 3.0 equiv of SKA **2a** for the specified period of time. [b] Yield of isolated product. [c] Determined by HPLC analysis on a chiral stationary phase. [d] In *p*-xylene. [e] In toluene/1,4-dioxane (3:1) at RT. [f] In *m*-xylene. [g] In methylcyclohexane at −40 °C. [h] With 5 mol% of the catalyst at 40 °C. [i] Determined by ^{1}H NMR analysis.

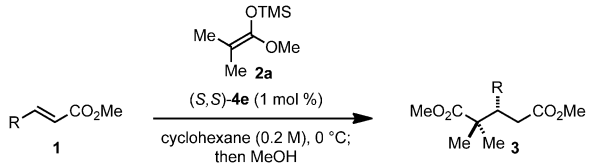
electron-rich (**3i**, **3l**) and electron-deficient substrates (**3j**, **3k**) were well tolerated under slightly modified conditions. Heterocyclic product **3m** could also be obtained with good results. As linear 3-alkyl *trans*-acrylates are generally more reactive than cinnamates,[6,12b] it was necessary to decrease the

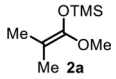
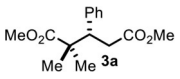
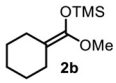
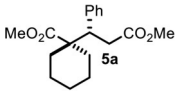
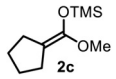
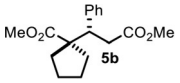
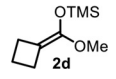
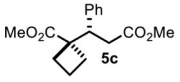
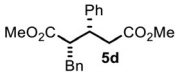
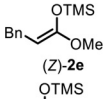
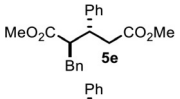
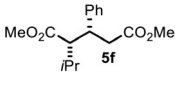
reaction temperature to obtain the desired products with high enantiocontrol (**3n**, **3o**). γ-Branched substrates (entries 18 and 19) were found to be very unreactive, and only very low or no conversion was detected even at increased catalyst loadings and temperatures.

We also studied other cinnamates, including the corresponding ethyl and benzyl esters, free cinnamic acid, cinnamoyl chloride, and methyl *cis*-cinnamate. Interestingly, ethyl *trans*-cinnamate gave strongly diminished enantioselectivity (e.r. 77.5:22.5) and reactivity (89% yield, 3 d reaction time). When methyl *cis*-cinnamate ($Z/E > 99{:}1$) was used, only very low conversion (55% yield) was detected after 5 days, and the opposite enantiomer was enriched (e.r. 62.5:37.5). All other tested substrates gave no conversion. These results are consistent with a scenario in which catalyst **4e** exhibits an ideally shaped chiral pocket to accommodate the geometry of trimethylsilylated α,β-unsaturated *trans*-methyl esters. While modifications of the 3-position are well-tolerated, distortion of this geometry would result in either decelerated or complete shutdown of catalysis.

The scope with respect to the silyl ketene acetals was explored next (Table 3). With cyclic SKA nucleophiles (**2b–d**), the corresponding products were obtained with high yields and enantioselectivities. With α-monosubstituted silyl ketene acetals, the reaction outcome was found to significantly depend on the type of SKA employed. The two isomeric SKAs (*E*)-**2e** (*E*/*Z* 4:1) and (*Z*)-**2e** (*E*/*Z* 1:19) both gave excellent enantioselectivities (e.r. ≥98.5:1.5) while favoring opposite diastereomers: (*E*)-**2e** afforded *syn* product **5d** (d.r. 12:1) whereas (*Z*)-**2e** predominantly gave the corresponding *anti* product **5e** (d.r. 1.6:1). Intriguingly, the reaction failed to provide any increased diastereoselectivity with all SKA variants when triflimide ($HNTf_2$) was used as an achiral catalyst, highlighting an additional benefit of the confined reaction environment beyond enantiocontrol (see the Supporting Information for further details). The isopropyl-substituted SKA (*E*)-**2g** was found to provide product **5f** with excellent diastereoselectivity and enantioselectivity (entry 7). The observed preference for the *syn* or *anti* diastereomer in relation to the *E* or *Z* enolate geometry is in agreement with that observed by Evans and co-workers in their Mukaiyama–Michael reactions of α,β-unsaturated *N*-acyl oxazolidinones.[21]

Table 3: Silyl ketene acetal (SKA) scope.[a]



Entry	SKA	Product	Yield [%][b]	e.r. (d.r.)[c]
1			97	97:3
2[d]			95	98:2
3			97	96:4
4			99	96.5:3.5
5			98	99:1 (12:1)
6[e]			96	98.5:1.5 (1.6:1)
7			98	99.5:0.5 (24:1)

[a] Reactions were performed on 0.2 mmol scale with 3.0 equiv of the SKA. [b] Yield of isolated product. [c] e.r. and d.r. determined by HPLC analysis on a chiral stationary phase. [d] With 2 mol% of the catalyst. [e] With 5 mol% of the catalyst.

Towards understanding the reaction mechanism, we became interested in the nature of the initial reaction product before methanolysis. Aside from the previously reported [2+2] or [4+2] intermediates[22,21a] with ketene acetals, we also anticipated an open-chain intermediate as proposed in other silylium Lewis acid catalyzed reactions.[18c,23] Indeed, by monitoring the reaction by NMR spectroscopy, we were able to identify and characterize silyl ketene acetal **D** (Figure 2) as the initial reaction product. Interestingly, the Z/E ratio of product **D** was determined to be $> 99{:}1$, which is consistent with an s-*cis* conformation for the reacting α,β-unsaturated ester in the carbon–carbon bond-forming transition state. Accordingly, a tentative catalytic cycle is suggested, which is initiated by the protonation of the SKA with the IDPi precatalyst, furnishing silylated ester **A**. Silicon transfer to the substrate then leads to the activated chiral ion pair **B**, which reacts with the nucleophile to provide the doubly silylated intermediate **C**. Silylation of the next substrate molecule could then occur either directly or via other esters of the generic type **A**. As intermediate **D** is a potential nucleophile itself, we tested whether reduced amounts of the starting SKA **2a** would cause oligomerizations

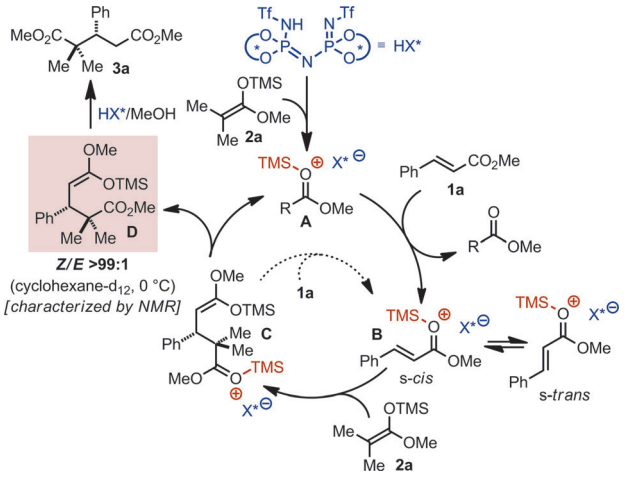


Figure 2. Proposed reaction mechanism.

by subsequent Michael addition of intermediate **D** to unsaturated ester **1a**. However, we found that even only 1.1 equivalents of SKA **2a** gave a clean reaction profile and the same yield after prolonged reaction time. Also sub-stoichiometric amounts of **2a** did not result in any significant side product formation even after prolonged reaction times at room temperature. Increased steric hindrance at silyl ketene acetal **D**, and as a consequence lower reactivity, may account for this observation. Generally, the yield of isolated product correlated well with the employed amount of SKA (see the Supporting Information for further details), and the self-healing features of silylium Lewis acid catalysis[15b,16] also allowed us to conduct the reaction in non-dried solvent and without an inert gas atmosphere. Product **3a** was isolated in identical yield and enantioselectivity under these conditions.

As differentiation of the two product ester groups would be highly attractive for further transformations, we investigated possibilities for selective derivatization (Figure 3). Gratifyingly, we found that simple saponification with aqueous NaOH provided a very high degree of selectivity for the less sterically hindered ester group. Thus both products **3a** and **5d** were converted smoothly into the corresponding mono-carboxylic acids **6** and **7** in quantitative yield and, in the case of product **5d**, without epimerization. An alternative and complementary approach for differentiating the two ester groups of our products would involve the direct utilization of silyl ketene acetal intermediate **D**. Indeed, we found that adding LAH instead of methanol to the reaction mixture selectively gave lactol **8**. Reduction of product **3a** with LAH gave the corresponding diol, which cyclizes under acidic conditions to furnish tetrahydropyran **9**.

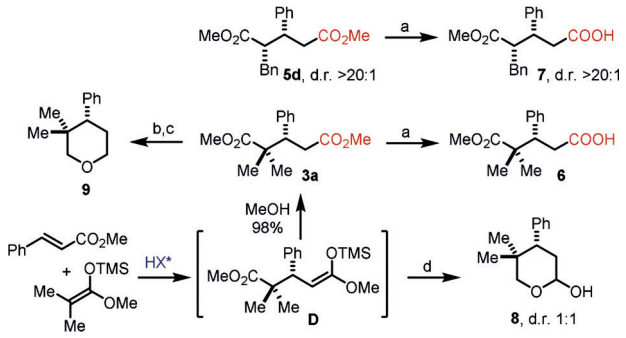


Figure 3. Selective product derivatizations. Reagents and conditions: a) aq. NaOH (5 equiv), MeOH/THF (2:1), 0 °C to RT, 1 h, quant.; b) LAH (1.5 equiv), THF, 0 °C to RT, 3 h, quant.; c) TsOH (20 mol %), $MgSO_4$, toluene, 120 °C, 16 h, 97 %; d) LAH (1.5 equiv), 0 °C, 3 h, 75 %.

In summary, we have developed the first asymmetric Mukaiyama–Michael reaction of α,β-unsaturated methyl esters. This reaction is enabled by the use of chiral silylium ion based Lewis acids and delivers high enantio- and diastereoselectivity with a broad scope of different substrates. Without catalysis, the reaction half-life of our model reaction would instead exceed 35 million years.[24] Future work will focus on further applications of this catalytic system and its reaction intermediates for asymmetric synthesis.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: Brønsted acids · cinnamates · Mukaiyama–Michael reaction · organocatalysis · silyl ketene acetals

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[24] Calculated by applying formulas: $\log k_{20\,^\circ C} = s_N(N + E)$, and $t_{1/2} = \ln(2)/k_{20\,^\circ C}$. E (ethyl cinnamate) = −24.52 (Ref. [6]); N (SKA **2a**) = 9.00; s_N (SKA **2a**) = 0.98 (Mayr's Database Of Reactivity Parameters).

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Supporting Information

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Contents

General Information and Instrumentation

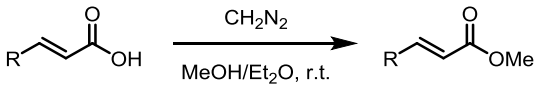
Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. For all reactions under argon, dried and degassed solvents were used. Dry argon was purchased from Air Liquide with >99.5% purity. All reported yields, unless otherwise specified, refer to spectroscopically and chromatographically pure compounds. Nomenclature follows the suggestions proposed by the computer program ChemBioDraw of CBD/Cambridgesoft. The enantiomeric ratios were determined by HPLC analysis employing a chiral stationary phase column specified in the individual experiment (HPLC traces analysis), by comparing the samples with the appropriate racemic mixtures. Diastereoselectivities were determined by HPLC analysis of the combined diastereomeric mixture after purification.

Thin-layer chromatography (TLC) was performed using silica gel pre-coated plastic sheets (Polygram SIL G/UV254, 0.2 mm, with fluorescent indicator; Macherey-Nagel), which were visualized with a UV lamp (254 or 366 nm) and/or phosphomolybdic acid (PMA) stain and/or $KMnO_4$ stain. Preparative thin-layer chromatography (PrepTLC) was performed on silica gel pre-coated glass plates SIL G-25 UV254 and SIL G-100 UV254 with 0.25 mm and 1.0 mm SiO_2 layers (Macherey-Nagel). Flash column chromatography was performed on Merck silica gel (60, particle size 0.040–0.063 mm). ^{1}H, ^{13}C, ^{19}F, ^{31}P nuclear magnetic resonance (NMR) spectra were recorded on a Bruker AV-500, AV-400 or DPX-300 spectrometer in a suitable deuterated solvent. The solvents employed and respective measuring frequencies are indicated for each experiment. The resonance multiplicity is described as s (singlet), d (doublet), t (triplet), q (quadruplet), p (pentet), hept (heptet), m (multiplet), and br (broad). All spectra were recorded at 298 K unless otherwise noted, processed with Bruker TOPSPIN or MestReNova suits of programs, and coupling constants are reported as observed. The residual deuterated solvent signal relative to tetramethylsilane was used as the internal reference in ^{1}H NMR spectra (e.g. $CDCl_3$ = 7.26 ppm), and are reported as follows: chemical shift δ in ppm (multiplicity, coupling constant *J* in Hz, number of protons). ^{13}C, ^{19}F, ^{31}P NMR spectra were referenced according to Ξ-values (IUPAC recommendations 2008)[1] relative to the internal references set in ^{1}H NMR spectra (e.g. ^{13}C: Me_4Si, ^{19}F: CCl_3F, ^{31}P: H_3PO_4 each 0.00 ppm). All spectra are broadband decoupled unless otherwise noted. Electron impact (EI) mass spectrometry (MS) was performed on a Finnigan MAT 8200 (70 eV) or MAT 8400 (70 eV) spectrometer. Electrospray ionization (ESI) mass spectrometry was conducted on a Bruker ESQ 3000 spectrometer. High resolution mass spectrometry (HRMS) was performed on a Finnigan MAT 95 (EI) or Bruker APEX III FTMS (7 T magnet, ESI). The ionization method and mode of detection employed is indicated for the respective experiment. High performance liquid chromatography (HPLC) was performed on a Shimadzu LC-20AD liquid chromatograph (SIL-20AC auto sampler, CMB-20A communication bus module, DGU-20A5 degasser, CTO-20AC column oven, SPD-M20A diode array detector), Shimadzu LC-20AB liquid chromatograph (SIL-20ACHT auto sampler, DGU-20A5 degasser, CTO-20AC column oven, SPD-M20A diode array detector), or Shimadzu LC-20AB liquid chromatograph (reversed phase, SIL-20ACHT auto sampler, CTOS3 20AC column oven, SPD-M20A diode array detector) using Daicel columns with a chiral stationary phase. All solvents used were commercial HPLC-grade quality. The column employed and the respective solvent mixture is indicated for each experiment. Optical rotations were measured on an Autopol IV automatic polarimeter (Rudolph Research Analytical) at 589 nm (sodium D line), 25 °C. Data are reported as: $[\alpha]_D^t$, concentration (c in g/100 mL), and in the corresponding solvent.

Synthesis and Characterization of Substrates

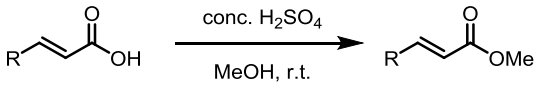
Commercially available α,β-unsaturated carboxylic acids were purchased from Sigma-Aldrich, Alfa Aesar, Acros Organics, AK Scientific, Apollo Scientific, Key Organics and Aronis. *E*/*Z* ratios were >99:1, unless stated otherwise. *p*-Tolylsulfonylmethylnitrosamide (Diazald®) was purchased from Sigma-Aldrich.

General Procedure A: Methylation with Diazomethane



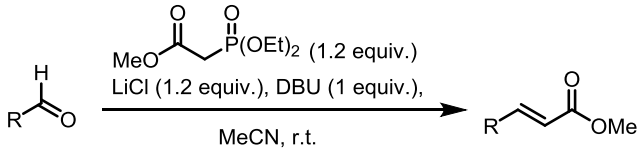
An ethereal solution of diazomethane was prepared from *p*-tolylsulfonylmethylnitrosamide (Diazald®) following a reported procedure.[2] A stirring solution/suspension of the appropriate α,β-unsaturated carboxylic acid (2.0 mmol) in MeOH (10 mL) was treated portionwise with an ethereal solution of diazomethane (~0.1 M) at room temperature using a graduated pipette (vigorous gas development) until the light green color of the diazomethane persisted in the reaction solution. The reaction mixture was stirred for additional 15 min, then quenched by dropwise addition of AcOH until disappearance of the light green color and concentrated *in vacuo*. Filtration of the crude material through a plug of silica gel with DCM gave the corresponding esters.

General Procedure B: Methylation with H_2SO_4/Methanol



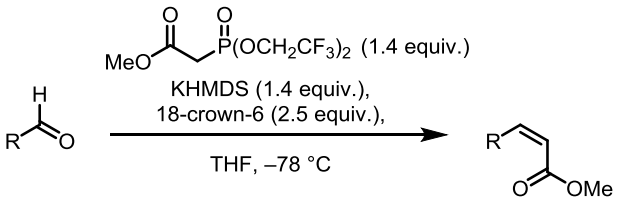
Following a typical protocol,[3] a solution/suspension of α,β-unsaturated carboxylic acid (2.0 mmol) in MeOH (10 mL) was treated with conc. H_2SO_4 (0.4 mL, 7.5 mmol, 3.8 equiv.), stirred at room temperature for 24 h and then concentrated *in vacuo*. Filtration of the crude material through a plug of silica gel with DCM gave the corresponding esters.

General Procedure C: Masamune-Roush Olefination



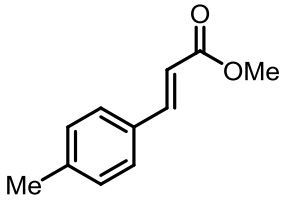
Following a typical protocol,[4] to a solution of anhydrous LiCl (305 mg, 7.2 mmol, 1.2 equiv.) in MeCN (72 mL) under argon methyl diethylphosphonoacetate (1.33 mL, 7.2 mmol, 1.2 equiv.) was added, followed by 1,8-diazabicyclo[5.4.0]undec-7-en (DBU; 0.90 mL, 6.0 mmol, 1.0 equiv.) and appropriate aldehyde (6.0 mmol, 1.0 equiv.), and the mixture was stirred at room temperature for 3 d. The reaction mixture was diluted EtOAc, washed with water and brine, dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by column chromatography on silica gel.

General Procedure D: Still-Gennari Olefination

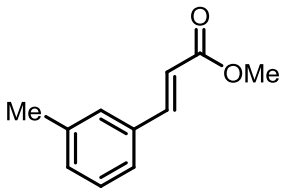


Following a typical protocol,[5] a solution of methyl *P*,*P*-bis(2,2,2-trifluoroethyl)phosphonoacetate (1.78 mL, 8.4 mmol, 1.40 equiv.) and 18-crown-6 (3.96 g, 15 mmol, 2.50 equiv.) in THF (120 mL) under argon was treated with KHMDS (0.5 M in toluene, 16.8 mL, 8.4 mmol, 1.40 equiv.) at –78 °C and was stirred for 30 min at this temperature. To this suspension, a solution of appropriate aldehyde (6 mmol, 1.0 equiv.) in THF (2 mL) was added dropwise, and the reaction mixture was stirred at –78 °C until full consumption of starting material was indicated by TLC (typically 2 . The reaction was quenched with sat. NH_4Cl solution and the organic phase was washed with water and brine, dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by column chromatography on silica gel.

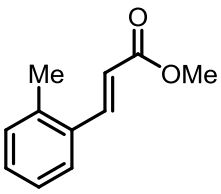
(*E*)-methyl 3-(*p*-tolyl)acrylate (1b): Prepared according to general procedure A from (*E*)-3-(*p*-tolyl)acrylic acid (324 mg, 2.0 mmol) and obtained as a colorless solid (318 mg, 1.81 mmol, 90%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.67 (d, *J* = 16.0 Hz, 1H), 7.47 – 7.38 (m, 2H), 7.19 (d, *J* = 7.8 Hz, 2H), 6.40 (d, *J* = 16.0 Hz, 1H), 3.80 (s, 3H), 2.37 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.8, 145.0, 140.9, 131.8, 129.8, 128.2, 116.8, 51.8, 21.6; **HRMS** (ESI) calculated for $C_{11}H_{12}O_2Na^+$ $[M+Na]^+$: 199.0729; found 199.0727.



(*E*)-methyl 3-(*m*-tolyl)acrylate (1c): Prepared according to general procedure A from (*E*)-3-(*m*-tolyl)acrylic acid (324 mg, 2.0 mmol) and obtained as a colorless liquid (331 mg, 1.88 mmol, 94%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.67 (d, *J* = 16.0 Hz, 1H), 7.33 (d, *J* = 6.4 Hz, 2H), 7.30 – 7.25 (m, 1H), 7.20 (d, *J* = 7.7 Hz, 1H), 6.43 (d, *J* = 16.0 Hz, 1H), 3.81 (s, 3H), 2.37 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.6, 145.2, 138.7, 134.5, 131.3, 128.9, 128.9, 125.4, 117.7, 51.8, 21.5; **HRMS** (ESI) calculated for $C_{11}H_{12}O_2Na^+$ $[M+Na]^+$: 199.0729; found 199.0727.



(*E*)-methyl 3-(*o*-tolyl)acrylate (1d): Prepared according to general procedure A from (*E*)-3-(*o*-tolyl)acrylic acid (324 mg, 2.0 mmol) and obtained as a colorless liquid (344 mg, 1.95 mmol, 97%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.99 (d, *J* = 15.9 Hz, 1H), 7.59 – 7.50 (m, 1H), 7.30 – 7.25 (m, 1H), 7.21 (t, *J* = 7.2 Hz, 2H), 6.36 (d, *J* = 15.9 Hz, 1H), 3.81 (s, 3H), 2.44 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.6, 142.7, 137.8, 133.5, 130.9, 130.2, 126.5, 126.5, 119.0, 51.8, 19.9; **HRMS** (ESI) calculated for $C_{11}H_{12}O_2Na^+$ $[M+Na]^+$: 199.0729; found 199.0727.



(*E*)-methyl 3-(4-fluorophenyl)acrylate (1e): Prepared according to general procedure A from (*E*)-3-(4-fluorophenyl)acrylic acid (332 mg, 2.0 mmol) and obtained as a colorless solid (325 mg, 1.80 mmol, 90%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.66 (d, *J* = 16.1 Hz, 1H), 7.55 – 7.47 (m, 2H), 7.16 – 7.02 (m, 2H), 6.36 (d, *J* = 16.0 Hz, 1H), 3.81 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.3, 164.9, 162.9, 143.6, 130.6 (d, *J* = 3.3 Hz), 129.9 (d, *J* = 8.6 Hz), 117.6 (d, *J* = 2.3 Hz), 116.0 (d, *J* = 22.0 Hz), 51.7; **^{19}F NMR** (471 MHz, $CDCl_3$) δ –109.6; **HRMS** (ESI) calculated for $C_{10}H_9O_2FNa^+$ $[M+Na]^+$: 203.0479; found 203.0476.

(*E*)-methyl 3-(4-chlorophenyl)acrylate (1f): Prepared according to general procedure A from (*E*)-3-(4-chlorophenyl)acrylic acid (365 mg, 2.0 mmol) and obtained as a colorless solid (387 mg, 1.97 mmol, 98%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.64 (d, *J* = 16.0 Hz, 1H), 7.52 – 7.42 (m, 2H), 7.41 – 7.32 (m, 2H), 6.41 (d, *J* = 16.0 Hz, 1H), 3.81 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.3, 143.6, 136.4, 133.0, 129.4, 129.3, 118.5, 51.9; **HRMS** (EI) calculated for $C_{10}H_9O_2Cl$: 196.0291; found 196.0292.

(*E*)-methyl 3-(4-bromophenyl)acrylate (1g): Prepared according to general procedure A from (*E*)-3-(4-bromophenyl)acrylic acid (473 mg, 2.1 mmol) and obtained as a colorless solid (460 mg, 1.91 mmol, 92%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.61 (d, *J* = 16.0 Hz, 1H), 7.51 (d, *J* = 8.5 Hz, 2H), 7.37 (d, *J* = 8.4 Hz, 2H), 6.42 (d, *J* = 16.0 Hz, 1H), 3.80 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.2, 143.5, 133.4, 132.2, 129.5, 124.6, 118.6, 51.9; **HRMS** (ESI) calculated for $C_{10}H_9BrO_2Na^+$ $[M+Na]^+$: 262.9678; found 262.9679.

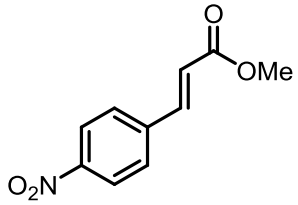
(*E*)-methyl 3-(naphthalen-1-yl)acrylate (1h): Prepared according to general procedure A from (*E*)-3-(naphthalen-1-yl)acrylic acid (396 mg, 2.0 mmol) and obtained as a pale yellow, viscous oil (372 mg, 1.75 mmol, 88%, *E/Z* 98:2); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.54 (d, *J* = 15.8 Hz, 1H), 8.20 (d, *J* = 7.9 Hz, 1H), 7.89 (t, *J* = 8.7 Hz, 2H), 7.76 (d, *J* = 7.2 Hz, 1H), 7.58 (ddd, *J* = 8.4, 6.8, 1.5 Hz, 1H), 7.54 (ddd, *J* = 8.0, 6.9, 1.2 Hz, 1H), 7.51 – 7.47 (m, 1H), 6.54 (d, *J* = 15.8 Hz, 1H), 3.86 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.5, 142.1, 133.8, 131.9, 131.5, 130.7, 128.9, 127.0, 126.4, 125.6, 125.2, 123.5, 120.6, 51.9; **HRMS** (ESI) calculated for $C_{14}H_{12}O_2Na^+$ $[M+Na]^+$: 235.0729; found 235.0726.

(*E*)-methyl 3-(4-methoxyphenyl)acrylate (1i): Prepared according to general procedure A from (*E*)-3-(4-methoxyphenyl)acrylic acid (356 mg, 2.0 mmol) and obtained as a colorless solid (371 mg, 1.93 mmol, 96%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.65 (d, *J* = 15.9 Hz, 1H), 7.58 – 7.40 (m, 2H), 6.98 – 6.82 (m, 2H), 6.31 (d, *J* = 16.0 Hz, 1H), 3.84 (s, 3H), 3.79 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.8, 161.4, 144.5, 129.7, 127.1, 115.3, 114.3, 55.38, 51.6; **HRMS** (ESI) calculated for $C_{11}H_{12}O_3Na^+$ $[M+Na]^+$: 215.0679; found 215.0675.

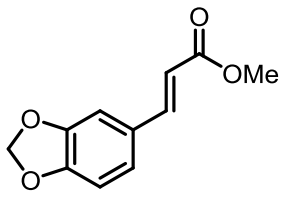
(*E*)-methyl 3-(4-cyanophenyl)acrylate (1j): Prepared according to general procedure B from (*E*)-3-(4-cyanophenyl)acrylic acid (346 mg, 2.0 mmol) and obtained as a colorless solid (300 mg, 1.60 mmol, 80%, *E/Z* >99:1); **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.77 – 7.54 (m, 5H), 6.51 (d, *J* = 16.1 Hz, 1H), 3.82 (s, 3H); **^{13}C NMR** (75 MHz, $CDCl_3$) δ 166.7, 142.5, 138.8, 132.8, 128.5,

121.5, 118.4, 113.6, 52.1; **HRMS** (ESI) calculated for $C_{11}H_9NO_2Na^+$ $[M+Na]^+$: 210.0525; found 210.0524.

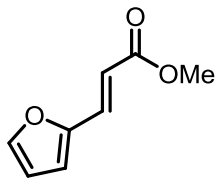
(*E*)-methyl 3-(4-nitrophenyl)acrylate (1k): Prepared according to general procedure B from (*E*)-4-nitrocinnamic acid (368 mg, 2.0 mmol) and obtained as a pale yellow solid (389 mg, 1.88 mmol, 94%, *E/Z* 99:1); **^{1}H NMR** (300 MHz, $CDCl_3$) δ 8.32 – 8.17 (m, 2H), 7.72 (d, *J* = 16.2 Hz, 1H), 7.69 – 7.64 (m, 2H), 6.56 (d, *J* = 16.0 Hz, 1H), 3.84 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 166.6, 148.7, 142.0, 140.6, 128.8, 124.3, 122.2, 52.2; **HRMS** (EI) calculated for $C_{10}H_9NO_4$: 207.0532; found 207.0532.



(*E*)-methyl 3-(benzo[d][1,3]dioxol-5-yl)acrylate (1l): Prepared according to general procedure A from (*E*)-3-(benzo[d][1,3]dioxol-5-yl)acrylic acid (384 mg, 2.0 mmol) and obtained as a colorless solid (411 mg, 1.99 mmol, 99%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.59 (d, *J* = 15.9 Hz, 1H), 7.02 (d, *J* = 1.7 Hz, 1H), 6.99 (dd, *J* = 8.0, 1.7 Hz, 1H), 6.80 (d, *J* = 8.0 Hz, 1H), 6.26 (d, *J* = 15.9 Hz, 1H), 6.00 (s, 2H), 3.78 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.7, 149.7, 148.5, 144.7, 128.9, 124.5, 115.9, 108.7, 106.6, 101.7, 51.8; **HRMS** (ESI) calculated for $C_{11}H_{10}O_4Na^+$ $[M+Na]^+$: 229.0471; found 229.0469.

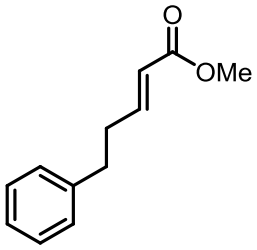


(*E*)-methyl 3-(furan-2-yl)acrylate (1m): Prepared according to general procedure A from (*E*)-3-(furan-2-yl)acrylic acid (276 mg, 2.0 mmol) and obtained as an acid labile, colorless liquid (277 mg, 1.82 mmol, 91%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.49 – 7.46 (m, 1H), 7.43 (d, *J* = 15.8 Hz, 1H), 6.60 (d, *J* = 3.4 Hz, 1H), 6.46 (dd, *J* = 3.4, 1.8 Hz, 1H), 6.31 (d, *J* = 15.7 Hz, 1H), 3.78 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.6, 151.0, 144.9, 131.3, 115.6, 114.9, 112.4, 51.8; **HRMS** (EI) calculated for $C_8H_8O_3$: 152.0473; found 152.0472.

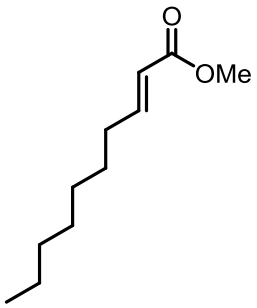


NOTE: Co-evaporation with reagent grade $CHCl_3$ to remove solvent impurities, resulted in an orange decomposition product.

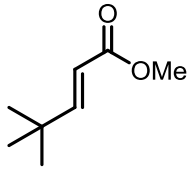
(*E*)-methyl 5-phenylpent-2-enoate (1n): Prepared according to general procedure C from 3-phenylpropionaldehyde (0.79 mL, 6.0 mmol) and obtained after column chromatography (hexane/Et_2O 15:1) as a colorless oil (704 mg, 3.70 mmol, 62%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.29 (t, *J* = 7.5 Hz, 2H), 7.23 – 7.16 (m, 3H), 7.01 (dt, *J* = 15.7, 6.9 Hz, 1H), 5.85 (dt, *J* = 15.8, 1.6 Hz, 1H), 3.72 (s, 3H), 2.78 (t, *J* = 7.7 Hz, 2H), 2.59 – 2.47 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.1, 148.5, 140.9, 128.6, 128.5, 126.3, 121.6, 51.6, 34.5, 34.0; **HRMS** (ESI) calculated for $C_{12}H_{14}O_2Na^+$ $[M+Na]^+$: 213.0886; found 213.0882.



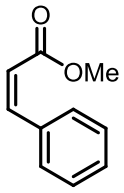
(*E*)-methyl dec-2-enoate (1o): Prepared according to general procedure C from octanal (0.73 mL, 6.0 mmol) and obtained after column chromatography (hexane/Et_2O 15:1) as a colorless oil (597 mg, 3.24 mmol, 54%, *E/Z* 98:2); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.97 (dt, *J* = 15.7, 7.0 Hz, 1H), 5.81 (dt, *J* = 15.6, 1.6 Hz, 1H), 3.72 (s, 3H), 2.19 (qd, *J* = 7.2, 1.6 Hz, 2H), 1.49 – 1.40 (m, 2H), 1.32 – 1.23 (m, 8H), 0.90 – 0.85 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.6, 150.2, 121.2, 51.8, 32.6, 32.1, 29.5, 29.5, 28.4, 23.0, 14.5; **HRMS** (ESI) calculated for $C_{11}H_{20}O_2Na^+$ $[M+Na]^+$: 207.1355; found 207.1357.



(*E*)-methyl 4,4-dimethylpent-2-enoate (1q): Prepared according to general procedure C from pivaldehyde (0.65 mL, 6.0 mmol) and obtained after column chromatography (pentane/Et_2O 20:1) as colorless oil (383 mg, 2.69 mmol, 45%, *E/Z* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.98 (d, *J* = 15.9 Hz, 1H), 5.74 (d, *J* = 15.9 Hz, 1H), 3.73 (s, 3H), 1.08 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 167.9, 159.5, 116.4, 51.6, 33.9, 28.8; **HRMS** (ESI) calculated for $C_8H_{14}O_2Na^+$ $[M+Na]^+$: 165.0886; found 165.0884.

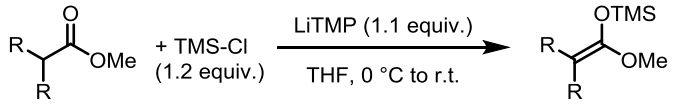


(*Z*)-methyl 3-phenylacrylate: Prepared according to general procedure D from benzaldehyde (0.61 mL, 6.0 mmol) and obtained after column chromatography (eluent hexane/EtOAc 90:10) as colorless oil (962 mg, 5.93 mmol, 98%, *Z/E* >99:1); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.63 – 7.54 (m, 2H), 7.42 – 7.30 (m, 3H), 6.96 (dd, *J* = 12.6, 0.8 Hz, 1H), 5.96 (d, *J* = 12.6 Hz, 1H), 3.72 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 166.7, 143.5, 134.9, 129.8, 129.2, 128.2, 119.4, 51.5; **HRMS** (ESI) calculated for $C_{10}H_{10}O_2Na^+$ $[M+Na]^+$: 185.0573; found 185.0570.



Synthesis and Characterization of Silyl Ketene Acetals

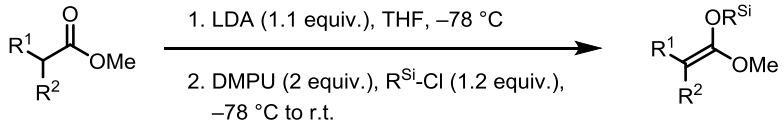
General Procedure A:



R = alkyl

To a stirring solution of freshly distilled 2,2,6,6-tetramethylpiperidine (TMP; 6.0 mL, 36 mmol, 1.2 equiv.) in THF (35 mL) under argon cooled to 0 °C with an ice bath, *n*-BuLi (2.45 M solution in hexane, 13.5 mL, 33 mmol, 1.1 equiv.) was added dropwise and the reaction mixture was stirred for 15 min. Then, a solution of ester (30 mmol, 1.0 equiv.) and Me_3SiCl (4.6 mL, 33 mmol, 1.2 equiv.) in THF (12 mL) under argon was added at 0 °C. The ice bath was removed after complete addition and the reaction solution was stirred overnight at room temperature. The reaction mixture was concentrated *in vacuo* to remove THF. Hexane (50 mL) and sat. $NaHCO_3$ solution (50 mL) were added to the residue and the organic layer was further washed with water (50 mL), sat. $CuSO_4$ solution (3 × 50 mL), water (50 mL) and brine (50 mL) in this order. After drying over $MgSO_4$ and concentration, the crude product was purified by distillation under reduced pressure to afford the silyl ketene acetals as colorless liquids, which were stored in Schlenk flasks under argon.

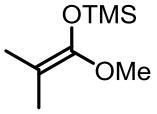
General Procedure B:



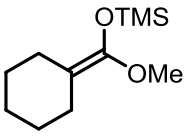
R^{Si} = trimethylsilyl (TMS), triethylsilyl (TES), *tert*-butyldimethylsilyl (TBS), triisopropylsilyl (TIPS)
$R^{1,2}$ = H or alkyl

Following a reported protocol,[6] to a stirring solution of freshly distilled *i*-Pr_2NH (4.2 mL, 30 mmol, 1.2 equiv.) in THF (30 mL) under argon cooled to 0 °C, *n*-BuLi (2.5 M solution in hexane, 11 mL, 28mmol, 1.1 equiv.) was added dropwise and the reaction mixture was stirred at 0 °C for 15 mins. The reaction was subsequently cooled to –78 ºC and neat methyl isobutyrate (2.9 mL, 25 mmol, 1.0 equiv.) was added dropwise. The reaction mixture was stirred for 30 min at –78 ºC, followed by the addition of 1,3-dimethyl-3,4,5,6,-tetrahydro-2(1H)-pyrimidinone (DMPU; 6.0 mL, 50 mmol, 2.0 equiv.) and the corresponding silyl chloride (30 mmol, 1.2 equiv.; added neat if liquid, or in 15 mL THF if solid). The reaction was allowed to warm up to room temperature (removal of dry-ice bath) and stirred overnight. The reaction mixture was then concentrated *in vacuo* (NOTE: The pressure on the rotavap was reduced to <50 mbar at 40 °C water bath temperature to remove the majority of solvent and *i*-Pr_2NH). Further workup and purification identical to procedure A was applied.

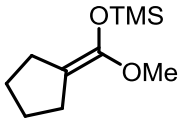
((1-methoxy-2-methylprop-1-en-1-yl)oxy)trimethylsilane (2a): Prepared according to general procedure A from methyl isobutyrate (11.5 mL, 100 mmol) and obtained after distillation (bp 35 °C at 10 mbar) as a colorless liquid (11.1 g, 64.0 mmol, 64%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.50 (s, 3H), 1.57 (s, 3H), 1.52 (s, 3H), 0.20 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 149.5, 91.0, 56.7, 17.0, 16.3, 0.2; **HRMS** (GC-EI) calculated for $C_8H_{18}O_2Si$: 174.1071; found 174.1071.



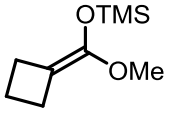
(cyclohexylidene(methoxy)methoxy)trimethylsilane (2b): Prepared according to general procedure A from methyl cyclohexanecarboxylate (4.29 mL, 30.0 mmol) and obtained after distillation (bp 40 °C at 0.3 mbar) as a colorless liquid (5.58 g, 22.6 mmol, 87%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.50 (s, 3H), 2.14 – 2.06 (m, 2H), 2.06 – 1.99 (m, 2H), 1.52 – 1.40 (m, 6H), 0.20 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 147.3, 99.6, 57.1, 27.9, 27.4, 27.2, 27.0, 26.8, 0.1; **HRMS** (GC-EI) calculated for $C_{11}H_{22}O_2Si$: 214.1384; found 214.1381.



(cyclopentylidene(methoxy)methoxy)trimethylsilane (2c): Prepared according to general procedure A from methyl cyclopentanecarboxylate (3.90 mL, 30.0 mmol) and obtained after distillation (bp 34 °C at 0.5 mbar) as a colorless liquid (4.84 g, 19.4 mmol, 80%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.52 (s, 3H), 2.23 – 2.15 (m, 2H), 2.16 – 2.08 (m, 2H), 1.64 – 1.55 (m, 4H), 0.21 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 147.2, 100.8, 56.1, 28.5, 27.5, 27.2, 27.0, 0.3; **HRMS** (GC-EI) calculated for $C_{10}H_{20}O_2Si$: 200.1227; found 200.1226.

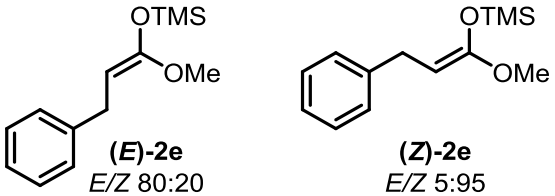


(cyclobutylidene(methoxy)methoxy)trimethylsilane (2d): Prepared according to general procedure A from methyl cyclobutanecarboxylate (3.31 mL, 30.0 mmol) and obtained after distillation (bp 30 °C at 0.5 mbar) as a colorless liquid (2.52 g, 6.12 mmol, 45%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.55 (s, 3H), 2.79 – 2.69 (m, 2H), 2.61 – 2.55 (m, 2H), 1.97 – 1.87 (m, 2H), 0.19 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 147.9, 92.8, 56.2, 26.9, 26.6, 17.8, 0.4; **HRMS** (GC-EI) calculated for $C_9H_{18}O_2Si$: 186.1071; found 186.1068.



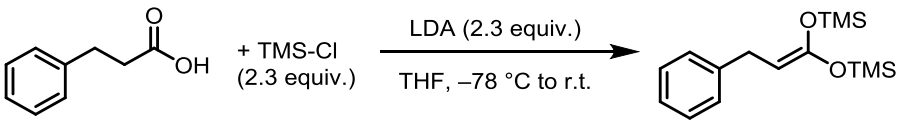
NOTE: Obtained as a mixture of 82% silyl ketene acetal and 18% α-C-silylated methyl ester.

Silyl ketene acetals **(*E*)-2e** and **(*Z*)-2e** were prepared according to a reported protocol[7] and were obtained as *E/Z* mixtures of 80:20 and 5:95, respectively.



(*E*)-2e *E/Z* 80:20 **(*Z*)-2e** *E/Z* 5:95

2,2,6,6-tetramethyl-4-(2-phenylethylidene)-3,5-dioxa-2,6-disilaheptane (2f):

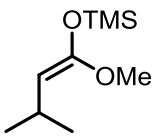


To a solution of hydrocinnamic acid (5.0 g, 33.3 mmol) and TMS-Cl (9.70 mL, 76.6 mmol, 2.3 equiv.) in THF (40 mL) under argon at –78 ºC, a freshly prepared solution of LDA in THF

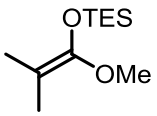
(76.6 mmol, 2.3 equiv.) was added via a cannula. The reaction mixture was subsequently allowed to warm up to room temperature and stirred for 2 h. Concentration of the reaction mixture *in vacuo* (NOTE: The pressure on the rotavap was reduced to reach <50 mbar at 40 °C water bath temperature to remove the majority of solvent and *i*-Pr_2NH) and dilution of the residue with hexane (50 mL) gave a suspension, which was filtered through a pad of celite. After evaporation of the solvent, the remaining yellow oil was purified by distillation (bp 90 °C at 0.06 mbar) to afford the title compound in 79% purity as a colorless liquid (5.98 g, 20.3 mmol, 61%), which was stored in a Schlenk flask under argon. **^{1}H NMR** (500 MHz, CD_2Cl_2) δ 7.28 – 7.24 (m, 2H), 7.23 – 7.18 (m, 2H), 7.17 – 7.12 (m, 1H), 3.78 (t, *J* = 7.3 Hz, 1H), 3.28 (d, *J* = 7.3 Hz, 2H), 0.25 (s, 9H), 0.21 (s, 9H); **^{13}C NMR** (126 MHz, CD_2Cl_2) δ 151.9, 143.9, 128.6, 128.6, 125.9, 82.3, 31.9, 0.7, 0.1; **HRMS** (ESI) calculated for $C_{15}H_{27}O_2Si_2$ $[M+H]^+$: 295.1544; found 295.1545.

NOTE: The obtained material contained 14% of the trimethylsilyl ester and 7% of the α-C-silylated trimethylsilyl ester.

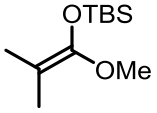
(*E*)-((1-methoxy-3-methylbut-1-en-1-yl)oxy)trimethylsilane (2g): Prepared according to general procedure B without DMPU from methyl isovalerate (3.96 mL, 30.0 mmol) and obtained after distillation (bp 47 °C at 10 mbar) as a colorless liquid (4.20 g, 22.3 mmol, 74%, *E/Z* 96:4); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.56 (d, *J* = 8.9 Hz, 1H), 3.51 (s, 3H), 2.51 (dp, *J* = 8.9, 6.7 Hz, 1H), 0.94 (s, 3H), 0.93 (s, 3H), 0.22 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 152.4, 93.9, 55.1, 24.8, 24.3, –0.1; **HRMS** (GC-EI) calculated for $C_9H_{20}O_2Si$: 188.1227; found 188.1226.



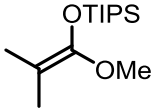
triethyl((1-methoxy-2-methylprop-1-en-1-yl)oxy)silane (2h): Prepared according to general procedure B without DMPU from methyl isobutyrate (3.44 mL, 30 mmol) and obtained after distillation (bp 60 °C at 2 mbar) as a colorless liquid (4.44 g, 20.5 mmol, 68%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.52 (s, 3H), 1.56 (s, 3H), 1.54 (s, 3H), 0.99 (t, *J* = 7.9 Hz, 9H), 0.69 (q, *J* = 7.9 Hz, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 150.0, 91.1, 57.2, 17.0, 16.3, 6.7, 5.1; **HRMS** (GC-EI) calculated for $C_{11}H_{24}O_2Si$: 216.1540; found 216.1539.



***tert*-butyl((1-methoxy-2-methylprop-1-en-1-yl)oxy)dimethylsilane (2i):** Prepared according to general procedure B from methyl isobutyrate (4.59 mL, 40 mmol) and obtained after distillation (bp 60 °C at 6 mbar) as a colorless liquid (6.80 g, 31.4 mmol, 79%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.51 (s, 3H), 1.57 (s, 3H), 1.53 (s, 3H), 0.96 (s, 9H), 0.15 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 149.9, 91.5, 57.2, 25.9, 18.2, 17.0, 16.4, –4.5; **HRMS** (GC-EI) calculated for $C_{11}H_{24}O_2Si$: 216.1540; found 216.1538.



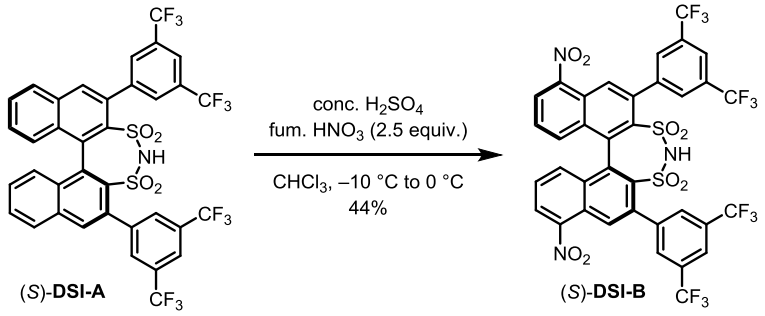
triisopropyl((1-methoxy-2-methylprop-1-en-1-yl)oxy)silane (2j): Prepared according to general procedure B from methyl isobutyrate (2.87 mL, 25 mmol) and obtained after distillation (bp 50 °C at 0.1 mbar) as a colorless liquid (5.51 g, 21.3 mmol, 85%); **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.56 (s, 3H), 1.57 (s, 6H), 1.21 – 1.13 (m, 3H), 1.11 (s, 12H), 1.09 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 150.9, 91.2, 58.3, 18.0, 17.2, 16.5, 12.9; **HRMS** (GC-EI) calculated for $C_{14}H_{30}O_2Si$: 258.2010; found 258.2006.



Synthesis and Characterization of Catalysts

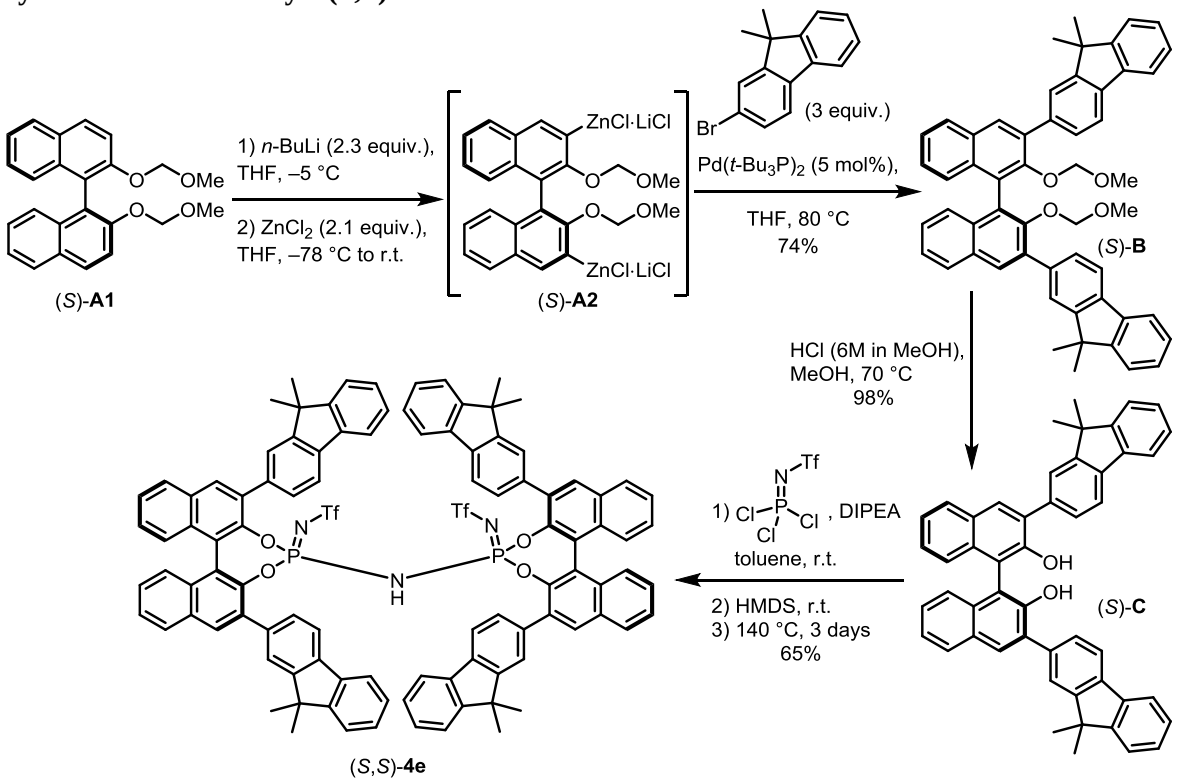
Synthesis of nitrated disulfonimide catalyst (*S*)-DSI-B

A nitrated version of (*S*)-**DSI-A**[8] was synthesized according to a described protocol.[9]



To a solution of (*S*)-**DSI-A** (478 mg, 0.58 mmol) in a mixture of $CHCl_3$ (2.4 mL) and conc. sulfuric acid (6 mL) cooled to –10 °C using a cryostat, fuming nitric acid (65 µL, 1.45 mmol, 2.5 equiv.) was added. The reaction mixture was allowed to warm up to 0 °C and stirred at this temperature until TLC indicated full conversion of the starting material (typically 1 h). The reaction mixture was subsequently poured in ice water, slowly neutralized inside a separation funnel using a sat. Na_2CO_3 solution, and extracted with EtOAc (3 × 50 mL). The combined organic layers were dried over $MgSO_4$ and concentrated to afford a mixture of product regioisomers (3 distinct spots on TLC, 50:50 Hex/EtOAc; R_f^1 = 0.37, R_f^2 = 0.27, R_f^2 = 0.25). Purification of the least polar regioisomer was accomplished via repeated column chromatography on silica gel (80:20→65:35→50:50 Hex/EtOAc). The salt product was dissolved in DCM and acidified twice with aq. HCl (6 M). Evaporation of the organic phase and drying on high vaccum gave the acidified title compound as a brown solid (234 mg, 44%). **^{1}H NMR** (500 MHz, acetone-d_6) δ 8.84 (d, *J* = 0.9 Hz, 2H), 8.58 (dd, *J* = 7.4, 1.2 Hz, 2H), 8.23 (s, 4H), 8.17 (s, 2H), 7.82 (dt, *J* = 8.7, 1.2 Hz, 2H), 7.77 (dd, *J* = 8.7, 7.4 Hz, 2H); **^{13}C NMR** (126 MHz, acetone-d_6) δ 148.1, 142.2, 139.2, 137.4, 135.3, 135.0, 134.1, 132.0 (br), 130.5, 130.2 (br), 129.0, 128.5, 127.7, 127.0, 125.5, 123.4, 122.8 (m); **^{19}F NMR** (471 MHz, acetone-d_6) δ –63.1, –63.2; **HRMS** (ESI) calculated for $C_{36}H_{14}N_3O_8F_{12}S_2$ $[M–H]^-$: 908.0036; found 908.0045.

Synthesis of IDPi catalyst (*S*,*S*)-4e



(*S*)-A2

To a solution of MOM-protected BINOL (*S*)-**A1** (5.92 g, 15.8 mmol) in THF (30 mL) under argon at –5 °C, *n*-BuLi in hexane (2.45 M, 22.6 mL, 55.3 mmol, 3.5 equiv.) was added over a period of 5 min (NOTE: The temperature was kept between –10 °C and –5 °C during the addition. The color changed from light yellow to deep red). The reaction was stirred between –10 °C and –5 °C for 4 h, during which the color changed from deep red to red-brownish. Then, the reaction mixture was cooled to –78 °C and a solution of $ZnCl_2$ in THF (0.96 M, 34.7 mL, 33.2 mmol, 2.1 equiv.) was added over a period of 20 min. The dry-ice bath was removed and the reaction was allowed to warm up to r.t. and stirred for additional 45 min, during which the color changed from red-brownish to light yellow. Then, the solvent was removed from the reaction vessel under reduced pressure by using a cooling trap with liquid nitrogen (NOTE: A voluminous foam is formed). Upon dryness, the organozinc compound was afforded as a pale yellow solid and dried on high vaccum overnight. A stock solution (0.29 M) in THF (54 mL) under argon was prepared and stored in a fridge at –20 °C.

(*S*)-B

In a flame-dried 2-neck flask under argon, 2-bromo-9,9-dimethyl-9H-fluorene (2.46 g, 9.0 mmol) and Pd(*t*-$Bu_3P)_2$ (77 mg, 0.15 mmol) were dissolved in THF (60 mL). Then, a solution of organozinc BINOL (*S*)-**A2** in THF (0.29 M, 10.2 mL, 3.0 mmol) was added at r.t. under stirring and the resulting reaction mixture was refluxed under argon for 18 h. The cooled reaction mixture was quenched with sat. NH_4Cl solution (30 mL) and extracted with MTBE (3 × 50 mL). The combined organic layers were washed with brine, dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by column chromatography on silica (20:1→10:1 Hex/EtOAc) to afford the title compound as a colorless solid (1.68 g, 74%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.03 (s, 2H), 7.93 (d, *J* = 8.2 Hz, 2H), 7.84 – 7.81 (m, 4H), 7.77 (td, *J* = 8.0, 1.3 Hz, 4H), 7.48 (dd, *J* = 6.5, 1.2 Hz, 2H), 7.44 (ddd, *J* = 8.1, 6.1, 1.8 Hz, 2H), 7.39 – 7.28 (m, 8H), 4.54 – 4.40 (m, 4H), 2.39 (s, 6H), 1.60 (s, 6H), 1.55 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.1, 154.0, 151.6, 139.1, 138.5, 138.3, 136.0, 133.8, 131.0, 130.7, 128.9, 128.0, 127.4, 127.2, 126.7, 126.6, 126.4, 125.3, 124.0,

122.8, 120.2, 120.0, 98.7, 56.1, 47.2, 27.4, 27.3; **HRMS** (EI) calculated for $C_{54}H_{46}O_4$: 758.3396; found 758.3395.

(*S*)-C

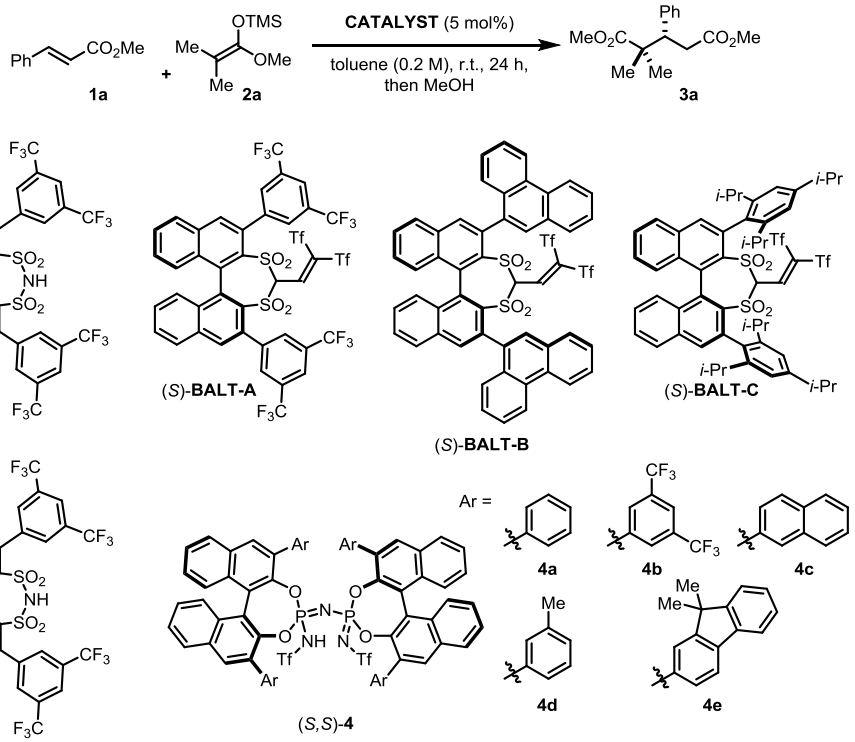
To a solution of MOM-protected BINOL (*S*)-**B** (1.68 g, 2.22 mmol) in MeOH (30 mL), HCl in MeOH (12 mL, 1.25 M, 15 mmol) was added and the reaction solution was refluxed overnight. After evaporation of the solvent, the crude product was purified by column chromatography on silica gel (20:1→10:1 Hex/EtOAc) to give the title compound as a colorless solid (1.46 g, 98%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.10 (s, 2H), 7.96 (d, *J* = 8.1 Hz, 2H), 7.84 (d, *J* = 7.9 Hz, 2H), 7.82 (d, *J* = 1.4 Hz, 2H), 7.79 – 7.76 (m, 2H), 7.73 (dd, *J* = 7.8, 1.6 Hz, 2H), 7.48 – 7.44 (m, 2H), 7.41 (ddd, *J* = 8.1, 6.8, 1.3 Hz, 2H), 7.38 – 7.32 (m, 6H), 7.28 (d, *J* = 8.5 Hz, 2H), 5.47 (s, 2H), 1.55 (s, 12H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.1, 154.0, 150.3, 139.1, 139.0, 136.5, 133.2, 131.4, 131.2, 129.7, 128.7, 128.6, 127.6, 127.4, 127.2, 124.5, 124.5, 124.1, 122.8, 120.3, 120.2, 112.8, 47.2, 27.4; **HRMS** (ESI) calculated for $C_{50}H_{37}O_2$ $(M–H)^-$: 669.2799; found 669.2805.

(*S*,*S*)-4e

An reported protocol for the synthesis of imidodiphosphorimidate Brønsted acids was applied.[10] In a flamed-dried Schlenk tube, a suspension of 3,3'-substituted BINOL (*S*)-**9** (704 mg, 1.05 mmol) in toluene (2.5 mL) under argon was treated with *N*-triflylphosphorimidoyl trichloride (168 µL, 298 mg, 1.05 mmol) and DIPEA (1.38 mL, 8.0 mmol). The reaction mixture was stirred for 15 min at r.t., until neat hexamethyldisilazane (HMDS, 104 µL, 0.5 mmol) was added dropwise. The reaction mixture was further stirred for 15 min at r.t.. The Schlenk tube was subsequently sealed and heated to 140 °C for 3 days. After cooling, aq. HCl (1 M) was added and the mixture was extracted with DCM. The combined organic layers were washed with water and brine, dried over $MgSO_4$ and concentrated. The crude material was purified by column chromatography on silica gel (90:10→80:20→70:30→60:40→50:50 hexane/MTBE) to afford the desired product as a salt. The free acid was obtained after acidification in DCM with aq. HCl (6 M), evaporation followed by drying under high vacuum as a colorless solid (557 mg, 65%). **^{1}H NMR** (500 MHz, CD_2Cl_2): δ 8.12 (s, 2H), 8.08 (dd, *J* = 8.3, 3.4 Hz, 4H), 7.92 – 7.84 (m, 4H), 7.73 (ddd, *J* = 8.3, 6.7, 1.3 Hz, 2H), 7.64 – 7.59 (m, 4H), 7.53 (d, *J* = 1.6 Hz, 2H), 7.48 – 7.40 (m, 10H), 7.36 – 7.32 (m, 2H), 7.29 (td, *J* = 7.4, 1.2 Hz, 2H), 7.25 – 7.21 (m, 8H), 7.09 (s, 2H), 6.79 (d, *J* = 8.0 Hz, 2H), 6.60 (dd, *J* = 8.0, 1.6 Hz, 2H), 6.41 (d, *J* = 7.7 Hz, 2H), 1.50 (s, 6H), 1.42 (s, 6H), 1.25 (s, 6H), 1.17 (s, 6H); **^{13}C NMR** (126 MHz, CD_2Cl_2): δ 154.6, 154.4, 154.1, 144.4 (m), 143.3 (br), 139.7, 139.1, 139.0, 135.4, 134.9, 134.9, 134.3, 132.7, 132.4, 132.3, 132.3, 132.2, 132.0, 129.8, 129.3, 129.3, 129.2, 128.1, 127.7, 127.6, 127.5, 127.4, 127.3, 127.3, 127.2, 127.1, 124.3, 124.0, 123.8, 123.1, 123.0, 122.4, 120.7, 120.2, 119.7, 119.4, 47.5, 47.4, 27.8, 27.4, 27.1, 26.8 (other signals not detected or observed); **^{19}F NMR** (282 MHz, CD_2Cl_2): δ −78.6; **^{31}P NMR** (122 MHz, CD_2Cl_2): δ −9.9, −17.0; **HRMS** (ESI) calculated for $C_{102}H_{72}N_3O_8F_6P_2S_2$ $(M–H)^-$: 1706.4146; found: 1706.4162.

Reaction Development & Optimization

Table S1. Catalyst screening[a]

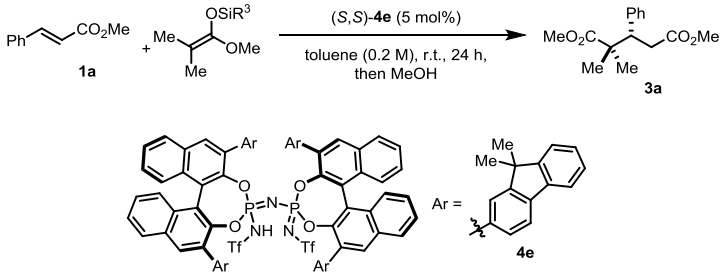


entry	catalyst	conv. (%)[b]	e.r.[c]
1	**(*S*)-DSI-A**	traces	/
2[e]	**(*S*)-DSI-B**	60	29:71
3[f]	**(*S*)-BALT-A**	full	50:50
4	**(*S*)-BALT-B**	full	48:52
5	**(*S*)-BALT-A**	full	50:50
6[d]	**(*S,S*)-4a**	full	26.5:73.5
7[d]	**(*S,S*)-4b**	full	45.5:54.5
8[d]	**(*S,S*)-4c**	full	86:14
9[d]	**(*S,S*)-4d**	full	17:83
10[d]	**(*S,S*)-4e**	full	7:93

[a]Reactions were performed on a 0.02 mmol scale with 1.5 equiv. of commercial SKA **2a** for the specified period of time and quenched with 5 equiv. of MeOH. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on chiral stationary phase. [d]3 mol% of catalyst. [e]48 h of reaction time. [f]at –40 °C.

NOTE: Silyl ketene acetal **2a** was purchased from Alfa Aesar and used without further purification. (*S*)-**BALT** catalysts **A-B** have been reported previously.[11]

Table S2. Screening of silyl ketene acetals[a]

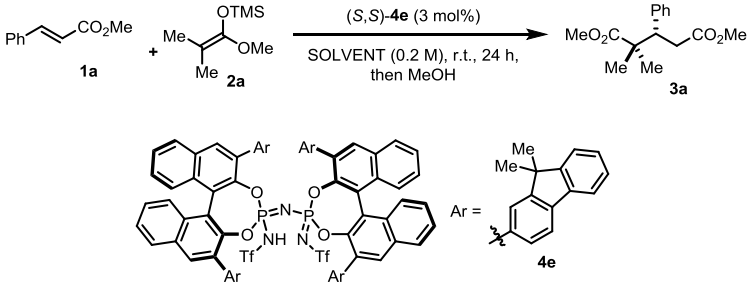


entry	SiR^3	conv. (%)[b]	e.r.[c]
1	TMS (2a)	83	6:94
2	TES (2h)	full	13.25:86.75
3	TBS (2i)	76	14.5:85.5
4	TIPS (2j)	full	34:66

[a]Reactions were performed on a 0.02 mmol scale with 1.5 equiv. of silyl ketene acetal for the specified period of time and quenched with 5 equiv. of MeOH. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on chiral stationary phase.

NOTE: Silyl ketene acetal **2a** was purchased from Alfa Aesar and used without further purification. Silyl ketene acetals **2h-j** were prepared and purified as described above.

Table S3. Solvent screening[a]

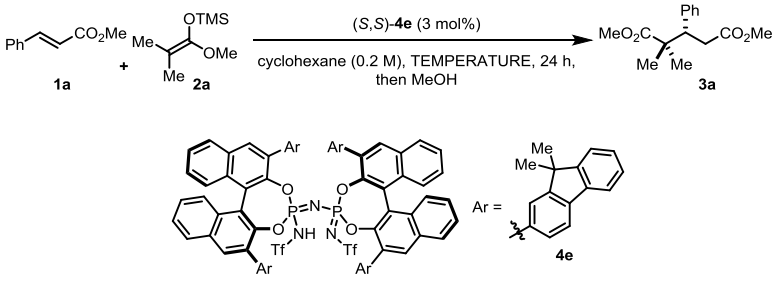


entry	solvent	conv. (%)[b]	e.r.[c]
1	Et_2O	43	7.75:92.25
2	MTBE	0	/
3	1,4-dioxane	56	6.75:93.25
4	TMS_2O	98	20.5:79.5
5	CH_2Cl_2	full	46:54
6	$CHCl_3$	80	22.75:77.25
7	CCl_4	80	4:96
8	EtOAc	5	19.25:80.75
9	MeCN	72	50:50
10	$MeNO_2$	full	49.5:50:5
11	benzene	87	6.5:93.5
12	toluene	91	5.75:94.25
13	*o*-xylene	95	6:94
14	*m*-xylene	94	5.5:94.5
15	*p*-xylene	72	5.25:94.75
16	*n*-hexane	30	10.25:89.75
17	cyclohexane	52	3.75:96.25

[a]Reactions were performed on a 0.02 mmol scale with 3.0 equiv. of commercial SKA **2a** for the specified period of time and quenched with 5 equiv. of MeOH. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on chiral stationary phase.

NOTE: Silyl ketene acetal **2a** was purchased from Alfa Aesar and used without further purification.

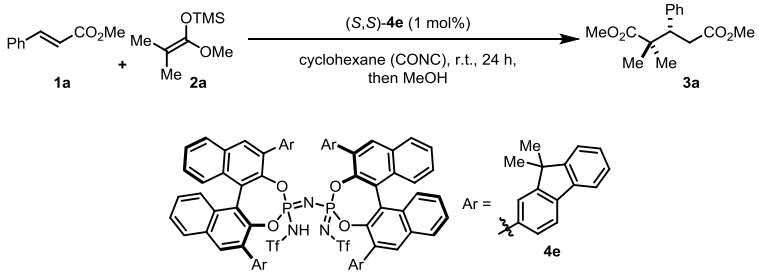
Table S4. Temperature screening[a]



entry	temperature	conv. (%)[b]	e.r.[c]
1[d]	r.t.	52	3.75:96.25
2[e]	r.t.	full	4.25:95.75
3[e]	10 °C	full	4.5:95.5
4[e]	0 °C	full	3:97
5[e,f]	0 °C	full	3:97

[a]Reactions were performed on a 0.02 mmol scale with 3.0 equiv. of SKA **2a** for the specified period of time and quenched with 5 equiv. of MeOH. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on chiral stationary phase. [d]commercial SKA **2a** was used. [e]freshly prepared and purified SKA **2a** and 1 mol% catalyst used. [f]12 h reaction time.

Table S5. Screening of concentration effects[a]



entry	concentration	conv. (%)[b]	e.r.[c]
1	0.5 M	full	4.5:95.5
2	0.2 M	full	4.25:95.75
3	0.1 M	92	4:96
4	0.05 M	0	/
5	0.025 M	0	/

[a]Reactions were performed on a 0.02 mmol scale with 3.0 equiv. of freshly prepared and purified SKA **2a** for the specified period of time and quenched with 5 equiv. of MeOH. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on chiral stationary phase.

General Procedure for the Catalytic, Asymmetric Mukaiyama-Michael Reaction

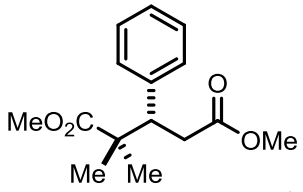
A 4 mL vial was charged with a magnetic stirrer bar, the appropriate α,β-unsaturated ester (0.2 mmol) and (*S*,*S*)-**4e** (3.4 mg, 2 μmol, 1 mol%), and the reactants were dissolved in cyclohexane (1 mL) under argon. The vial was cooled to 0 °C in a cryostat, at which temperature the reaction mixture is a half-liquid slurry. Upon addition of the appropriate silyl ketene acetal (0.6 mmol) and mixing, the reaction mixture becomes a homogeneous solution and was stirred at 0 °C for the specified period of time. After complete conversion indicated by TLC, the reaction was quenched with MeOH (1 mmol, 40 μL). Purification by column chromatography on silica gel and drying in high vaccum overnight gave the pure Mukaiyama–Michael addition products.

General Procedure for the Preparation of Racemic Products

In a flame-dried Schlenk tube, the appropriate α,β-unsaturated ester (0.2 mmol) and the appropriate silyl ketene acetal (0.6 mmol) were dissolved in DCM (1 mL) under argon. A stock solution of $HNTf_2$ (0.2 M in 1,2-dichloroethane, 10 μL, 2 μmol) was added at –78 °C and the reaction was stirred until TLC indicated full conversion (typically 10 to 20 min). The reaction was quenched by adding MeOH (1 mmol, 40 μL) at –78 °C. The racemic product was obtained by purification via preparative TLC.

Characterization of Products

dimethyl (*S*)-2,2-dimethyl-3-phenylpentanedioate (3a): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (51 mg, 97% yield), which solidified to a colorless solid upon cooling. The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.27 (ddt, *J* = 7.5, 6.5, 1.1 Hz, 2H), 7.25 – 7.20 (m, 1H), 7.19 – 7.15 (m, 2H), 3.66 (s, 3H), 3.54 (dd, *J* = 11.3, 4.2 Hz, 1H), 3.49 (s, 3H), 2.86 (dd, *J* = 15.7, 11.3 Hz, 1H), 2.68 (dd, *J* = 15.7, 4.2 Hz, 1H), 1.16 (s, 3H), 1.10 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.5, 172.6, 139.5, 129.3, 128.0, 127.1, 52.0, 51.7, 49.0, 46.2, 35.8, 24.4, 21.7; **HRMS** (GC-EI) calculated for $C_{15}H_{20}O_4$: 264.1356; found 264.1358; **$[\alpha]_D^{25}$** = –11.6° (c = 0.92, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor) = 7.7 min, t_R (major) = 9.2 min; e.r. = 97:3.



Reactions with lower catalyst loadings were performed using **1a** and 3 equiv. of SKA **2a** at 0 °C in cyclohexane with increasing concentrations.

entry	scale	catalyst loading	concentration	time	isolated yield (%)	e.r.
1	0.2 mmol	1 mol%	0.2 M	12 h	97	97:3
2	0.4 mmol	0.5 mol%	0.4 M	5 d	98	97:3
3	0.8 mmol	0.25 mol%	0.8 M	5 d	98	96.5:3.5

Reactions with lower amounts of SKA **2a** were performed with **1a** (0.20 mmol) and 1 mol% (*S*,*S*)-**4e** in 1 mL cyclohexane (0.2 M) at 0 °C. For entry 4 and 5, the reactions were run for 3 days at 0 °C, and further stirred for 1 week at room temperature.

entry	equiv. of **2a**	time	conv. (%)[a]	isolated yield (%)	e.r.
1	2	24 h	full	98	97:3
2	1.5	3.5 d	full	98	97:3
3	1.1	3.5 d	full	98	97:3
4	0.5	10 d (0 °C→r.t.)	46	45	97:3
5	0.2	10 d (0 °C→r.t.)	16	13	97:3

[a]Determined by ^{1}H NMR analysis.

For an experiment under non-dried conditions and without inert gas, **1a** (0.20 mmol, 32 mg) and (*S*,*S*)-**4e** (3.4 mg, 2 μmol) were dissolved in non-dried cyclohexane in an open vial. SKA **2a** (122 μL, 0.60 mmol) was added at room temperature. The vial was subsequently sealed and placed in a cryostat at 0 °C. After stirring for 3.5 days, the reaction was quenched with MeOH (40 μL, 1 mmol, 5 equiv.). Product **3a** was obtained in 96% yield after usual purification (e.r. = 97.5:2.5).

The reaction with (*Z*)-methyl cinnamate (**1s**, 0.20 mmol, 32 mg) as starting material was performed according to the general procedure with 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 5 days resulting in 70% conversion as detected ^{1}H NMR analysis. The product was obtained after usual purification in 55% yield with (*R*)-**3a** being the major enantiomer (e.r. 62.5:37.5).

dimethyl (*S*)-2,2-dimethyl-3-(p-tolyl)pentanedioate (3b): Prepared according to the general procedure using (*E*)-methyl 3-(*p*-tolyl)acrylate (**1b**, 0.20 mmol, 35 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (53 mg, 95% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.11 – 6.99 (m, 4H), 3.65 (s, 3H), 3.49 (dd, *J* = 11.4, 4.3 Hz, 1H), 3.49 (s, 3H), 2.83 (dd, *J* = 15.7, 11.3 Hz, 1H), 2.64 (dd, *J* = 15.7, 4.1 Hz, 1H), 2.30 (s, 3H), 1.14 (s, 3H), 1.08 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.6, 172.7, 136.6, 136.3, 129.2, 128.8, 51.9, 51.7, 48.6, 46.2, 35.9, 24.4, 21.7, 21.2; **HRMS** (GC-EI) calculated for $C_{16}H_{22}O_4$: 278.1513; found 278.1513; **$[\alpha]_D^{25}$** = –11.8° (c = 0.51, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 4.8 min, t_R (minor) = 7.2 min; e.r. = 97.25:2.75.

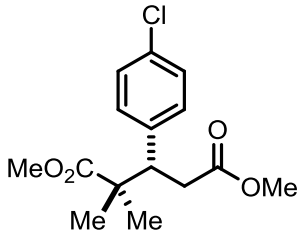
dimethyl (*S*)-2,2-dimethyl-3-(m-tolyl)pentanedioate (3c): Prepared according to the general procedure using (*E*)-methyl 3-(*m*-tolyl)acrylate (**1c**, 0.20 mmol, 35 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless solid (53 mg, 95% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.15 (t, *J* = 7.6 Hz, 1H), 7.02 (d, *J* = 7.4 Hz, 1H), 6.95 (d, *J* = 8.0 Hz, 2H), 3.65 (s, 3H), 3.49 (s, 3H), 3.49 (dd, *J* = 11.2, 4.2 Hz, 1H), 2.84 (dd, *J* = 15.8, 11.2 Hz, 1H), 2.66 (dd, *J* = 15.8, 4.2 Hz, 1H), 2.31 (s, 3H), 1.14 (s, 3H), 1.09 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.6, 172.7, 139.4, 137.4, 130.2, 127.9, 127.9, 126.3, 51.9, 51.7, 48.9, 46.2, 35.8, 24.4, 21.7, 21.7; **HRMS** (GC-EI) calculated for $C_{16}H_{22}O_4$: 278.1513; found 278.1515; **$[\alpha]_D^{25}$** = –15.4° (c = 0.26, $CHCl_3$); **HPLC** Daicel Chiralpak AS-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 4.6 min, t_R (minor) = 5.6 min; e.r. = 98.25:1.75.

dimethyl (*S*)-2,2-dimethyl-3-(o-tolyl)pentanedioate (3d): Prepared according to the general procedure using (*E*)-methyl 3-(*o*-tolyl)acrylate (**1d**, 0.20 mmol, 35 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 5 days. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (51 mg, 92% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.16 – 7.06 (m, 4H), 3.90 (dd, *J* = 11.4, 3.9 Hz, 1H), 3.67 (s, 3H), 3.46 (s, 3H), 2.83 (dd, *J* = 15.9, 11.4 Hz, 1H), 2.69 (dd, *J* = 15.8, 3.9 Hz, 1H), 2.44 (s, 3H), 1.18 (s, 3H), 1.12 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.7, 172.8, 138.5, 138.1, 130.6, 127.1, 126.7, 125.7, 52.0, 51.6, 46.8, 42.7, 37.1, 24.7, 21.5, 20.7; **HRMS** (GC-EI) calculated for $C_{16}H_{22}O_4$: 278.1513; found 278.1514; **$[\alpha]_D^{25}$** = –13.2° (c = 0.59, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor) = 7.6 min, t_R (major) = 8.9 min; e.r. = 96.5:3.5.

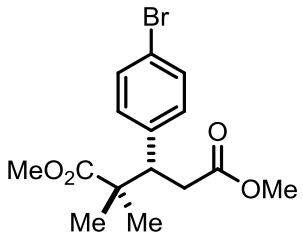
dimethyl (*S*)-3-(4-fluorophenyl)-2,2-dimethylpentanedioate (3e): Prepared according to the general procedure using (*E*)-methyl 3-(4-fluorophenyl)acrylate (**1e**, 0.20 mmol, 36 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (56 mg, 99% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.18 – 7.10 (m, 2H), 7.03 – 6.91 (m, 2H), 3.64 (s,

3H), 3.51 (dd, *J* = 11.5, 4.2 Hz, 1H), 3.49 (s, 3H), 2.80 (dd, *J* = 15.7, 11.5 Hz, 1H), 2.66 (dd, *J* = 15.7, 4.1 Hz, 1H), 1.14 (s, 3H), 1.09 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.3, 172.5, 163.0, 161.0, 135.2, 135.2, 130.8, 130.7, 115.1, 114.9, 52.0, 51.7, 48.4, 46.2, 35.9, 24.2, 21.9; **^{19}F NMR** (471 MHz, $CDCl_3$) δ –115.8; **HRMS** (GC-EI) calculated for $C_{15}H_{19}O_4F$: 282.1262; found 282.1262; **$[\alpha]_D^{25}$** = –14.5° (c = 0.51, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 4.9 min, t_R (minor) = 6.9 min; e.r. = 97.5:2.5.

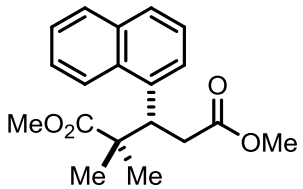
dimethyl (*S*)-3-(4-chlorophenyl)-2,2-dimethylpentanedioate (3f): Prepared according to the general procedure using (*E*)-methyl 3-(4-chlorophenyl)acrylate (**1f**, 0.20 mmol, 39 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (58 mg, 97% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.26 – 7.22 (m, 2H), 7.13 – 7.07 (m, 2H), 3.65 (s, 3H), 3.51 (dd, *J* = 11.6, 4.2 Hz, 1H), 3.49 (s, 3H), 2.80 (dd, *J* = 15.8, 11.5 Hz, 1H), 2.66 (dd, *J* = 15.9, 4.1 Hz, 1H), 1.13 (s, 3H), 1.08 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.2, 172.4, 138.1, 133.0, 130.6, 128.3, 52.1, 51.8, 48.5, 46.1, 35.7, 24.2, 21.8; **HRMS** (GC-EI) calculated for $C_{15}H_{19}O_4Cl$: 298.0966; found 298.0962; **$[\alpha]_D^{25}$** = –10.6° (c = 0.53, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 5.0 min, t_R (minor) = 6.8 min; e.r. = 97.5:2.5.



dimethyl (*S*)-3-(4-bromophenyl)-2,2-dimethylpentanedioate (3g): Prepared according to the general procedure using (*E*)-methyl 3-(4-bromophenyl)acrylate (**1g**, 0.20 mmol, 48 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (67 mg, 98% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.42 – 7.36 (m, 2H), 7.08 – 7.01 (m, 2H), 3.65 (s, 3H), 3.49 (s, 3H), 3.49 (dd, *J* = 11.4, 4.1 Hz, 1H), 2.80 (dd, *J* = 15.8, 11.5 Hz, 1H), 2.66 (dd, *J* = 15.9, 4.1 Hz, 1H), 1.13 (s, 3H), 1.08 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.2, 172.4, 138.6, 131.2, 131.0, 121.2, 52.1, 51.8, 48.5, 46.0, 35.6, 24.2, 21.8; **HRMS** (GC-EI) calculated for $C_{15}H_{19}O_4Br$: 342.0461; found 342.0461; **$[\alpha]_D^{25}$** = –7.8° (c = 0.46, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 5.4 min, t_R (minor) = 7.2 min; e.r. = 98:2.

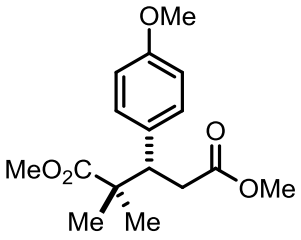


dimethyl (*S*)-2,2-dimethyl-3-(naphthalen-1-yl)pentanedioate (3h): Prepared according to the general procedure using (*E*)-methyl 3-(naphthalen-1-yl)acrylate (**1h**, 0.20 mmol, 42 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 2 days. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless wax (58 mg, 92% yield), which solidified to a colorless solid upon cooling. The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.36 (d, *J* = 8.6 Hz, 1H), 7.82 (d, *J* = 8.6 Hz, 1H), 7.74 (d, *J* = 8.1 Hz, 1H), 7.54 (ddd, *J* = 8.5, 6.8, 1.4 Hz, 1H), 7.46 (ddd, *J* = 7.9, 6.9, 1.0 Hz, 1H), 7.44 – 7.40 (m, 1H), 7.34 (dd, *J* = 7.3, 1.0 Hz, 1H), 4.67 (dd, *J* = 11.1, 4.2 Hz, 1H), 3.63 (s, 3H), 3.37 (s, 3H), 3.02 (dd, *J* = 15.9, 11.1 Hz, 1H), 2.85 (dd, *J* = 15.9, 4.2 Hz, 1H), 1.21 (s, 3H), 1.05 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.7, 172.6, 136.5, 133.9, 133.6, 128.9, 127.8, 126.1, 125.5, 125.1, 124.9, 124.2, 52.1, 51.6, 47.0, 41.0, 37.2, 25.2, 21.4; **HRMS** (GC-EI) calculated for $C_{19}H_{22}O_4$: 314.1513; found 314.1512; **$[\alpha]_D^{25}$** = –74.0° (c = 0.60,

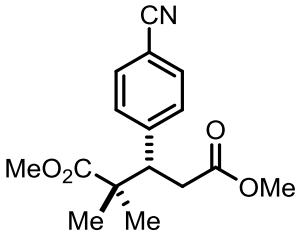


$CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor) = 9.8 min, t_R (major) = 14.8 min; e.r. = 94.5:5.5

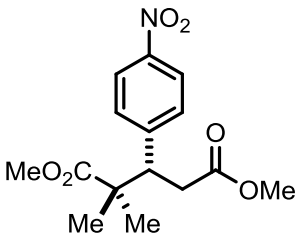
dimethyl (*S*)-3-(4-methoxyphenyl)-2,2-dimethylpentanedioate (3i): Prepared according to the general procedure using (*E*)-methyl 3-(4-methoxyphenyl)acrylate (**1i**, 0.20 mmol, 38 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 24 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (59 mg, 95% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.11 – 7.03 (m, 2H), 6.84 – 6.75 (m, 2H), 3.77 (s, 3H), 3.64 (s, 3H), 3.48 (s, 3H), 3.46 (dd, *J* = 11.4, 4.2 Hz, 1H), 2.80 (dd, *J* = 15.6, 11.4 Hz, 1H), 2.63 (dd, *J* = 15.6, 4.1 Hz, 1H), 1.13 (s, 3H), 1.08 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.6, 172.7, 158.6, 131.4, 130.3, 113.4, 55.2, 52.0, 51.7, 48.3, 46.3, 36.0, 24.3, 21.7; **HRMS** (GC-EI) calculated for $C_{16}H_{22}O_5$: 294.1462; found 294.1465; **$[\alpha]_D^{25}$** = –9.6° (c = 0.50, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 8.8 min, t_R (minor) = 11.1 min; e.r. = 95.75:4.25



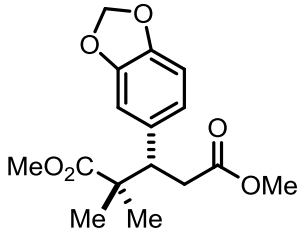
dimethyl (*S*)-3-(4-cyanophenyl)-2,2-dimethylpentanedioate (3j): Prepared according to a modified general procedure (*p*-xylene instead of cyclohexane) using (*E*)-methyl 3-(4-cyanophenyl)acrylate (**1j**, 0.20 mmol, 37 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (10:1→5:1→3:1 hexane/EtOAc) as a colorless oil (58 mg, 89% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.60 – 7.55 (m, 2H), 7.31 – 7.27 (m, 2H), 3.65 (s, 3H), 3.58 (dd, *J* = 11.5, 4.0 Hz, 1H), 3.49 (s, 3H), 2.84 (dd, *J* = 16.2, 11.5 Hz, 1H), 2.72 (dd, *J* = 16.1, 4.0 Hz, 1H), 1.15 (s, 3H), 1.10 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.7, 172.1, 145.4, 131.9, 130.1, 118.8, 111.2, 52.2, 51.9, 49.1, 46.1, 35.4, 24.2, 22.1; **HRMS** (GC-EI) calculated for $C_{16}H_{19}NO_4$: 289.1309; found 289.1310; **$[\alpha]_D^{25}$** = –10.5° (c = 0.42, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 95/5, 1 mL/min, 25 °C, 220 nm, t_R (major) = 9.2 min, t_R (minor) = 11.0 min; e.r. = 97.5:2.5.



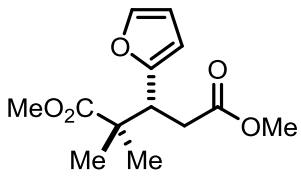
dimethyl (*S*)-3-(4-nitrophenyl)-2,2-dimethylpentanedioate (3k): Prepared according to a modified general procedure (toluene/1,4-dioxane 3:1 instead of cyclohexane) using (*E*)-methyl 3-(4-nitrophenyl)acrylate (**1k**, 0.20 mmol, 41 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at room temperature for 4 days. The product was obtained after column chromatography on silica gel (9:1→4:1→2:1 hexane/EtOAc) as an orange oil (47 mg, 76% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.18 – 8.12 (m, 2H), 7.40 – 7.31 (m, 2H), 3.66 (s, 3H), 3.65 (dd, *J* = 11.5, 4.0 Hz, 1H), 3.50 (s, 3H), 2.88 (dd, *J* = 16.2, 11.5 Hz, 1H), 2.75 (dd, *J* = 16.2, 3.9 Hz, 1H), 1.17 (s, 3H), 1.12 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.7, 172.0, 147.6, 147.2, 130.2, 123.3, 52.2, 51.9, 48.9, 46.1, 35.5, 24.2, 22.2; **HRMS** (GC-EI) calculated for $C_{15}H_{19}NO_6$: 309.1207; found 309.1205; **$[\alpha]_D^{25}$** = –13.5° (c = 0.64, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 95/5, 1 mL/min, 25 °C, 220 nm, t_R (major) = 8.3 min, t_R (minor) = 10.0 min; e.r. = 95.25:4.75.



dimethyl (*S*)-3-(benzo[d][1,3]dioxol-5-yl)-2,2-dimethylpentanedioate (3l): Prepared according to a modified general procedure (*m*-xylene instead of cyclohexane) using (*E*)-methyl 3-(benzo[d][1,3]dioxol-5-yl)acrylate (**1l**, 0.20 mmol, 42 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 3 days. The product was obtained after column chromatography on silica gel (10:1 hexane/EtOAc) as a colorless oil (52 mg, 84% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.71 (d, *J* = 8.0 Hz, 1H), 6.67 – 6.60 (m, 2H), 5.92 (q, *J* = 1.5 Hz, 2H), 3.65 (s, 3H), 3.52 (s, 3H), 3.45 (dd, *J* = 11.4, 4.1 Hz, 1H), 2.76 (dd, *J* = 15.7, 11.4 Hz, 1H), 2.63 (dd, *J* = 15.8, 4.1 Hz, 1H), 1.14 (s, 3H), 1.09 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.5, 172.6, 147.4, 146.6, 133.2, 122.6, 109.5, 107.9, 101.1, 52.0, 51.7, 48.8, 46.3, 36.0, 24.3, 21.9; **HRMS** (GC-EI) calculated for $C_{16}H_{20}O_6$: 308.1254; found 308.1256; **$[\alpha]_D^{25}$** = –10.6° (c = 0.49, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 9.7 min, t_R (minor) = 14.9 min; e.r. = 97:3.

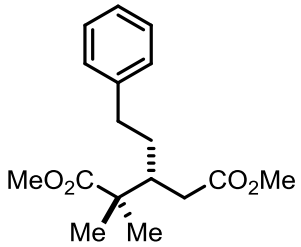


dimethyl (*R*)-3-(furan-2-yl)-2,2-dimethylpentanedioate (3m): Prepared according to the general procedure using (*E*)-methyl 3-(furan-2-yl)acrylate (**1m**, 0.20 mmol, 30 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a acid-labile, colorless oil (48 mg, 94% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, CD_2Cl_2) δ 7.33 (dd, *J* = 1.9, 0.8 Hz, 1H), 6.30 (dd, *J* = 3.2, 1.8 Hz, 1H), 6.09 (dt, *J* = 3.2, 0.7 Hz, 1H), 3.66 (s, 3H), 3.65 (dd, *J* = 11.4, 3.7 Hz, 1H), 3.55 (s, 3H), 2.77 (dd, *J* = 15.9, 11.5 Hz, 1H), 2.53 (dd, *J* = 15.9, 3.6 Hz, 1H), 1.16 (s, 3H), 1.08 (s, 3H); **^{13}C NMR** (126 MHz, CD_2Cl_2) δ 177.4, 172.7, 154.7, 142.0, 110.6, 108.2, 52.4, 52.1, 46.4, 43.1, 34.7, 24.3, 21.8; **HRMS** (GC-EI) calculated for $C_{13}H_{18}O_5$: 254.1149; found 254.1147; **$[\alpha]_D^{25}$** = –4.4° (c = 0.49, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 99/1, 1 mL/min, 25 °C, 220 nm, t_R (major) = 7.7 min, t_R (minor) = 9.3 min; e.r. = 94.5:5.5.

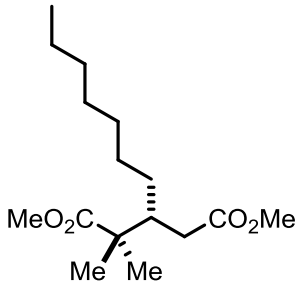


NOTE: Co-evaporation with reagent grade $CHCl_3$ to remove solvent impurities, resulted in an orange decomposition product.

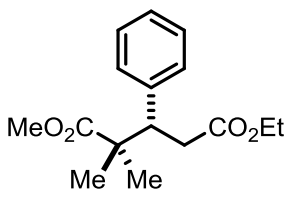
dimethyl (*R*)-2,2-dimethyl-3-phenethylpentanedioate (3n): Prepared according to a modified general procedure using (*E*)-methyl 5-phenylpent-2-enoate (**1n**, 0.21 mmol, 40 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at –40 °C in methylcyclohexane (1 mL) for 24 hours. The product was obtained after chromatography on silica gel (20:1→10:1→5:1 hexane/EtOAc) as a colorless oil (56 mg, 92% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.30 – 7.25 (m, 2H), 7.20 – 7.13 (m, 3H), 3.70 (s, 3H), 3.62 (s, 3H), 2.65 (ddd, *J* = 13.5, 10.9, 5.1 Hz, 1H), 2.51 (ddd, *J* = 13.6, 10.7, 6.3 Hz, 1H), 2.47 (dd, *J* = 15.6, 4.8 Hz, 1H), 2.41 – 2.35 (m, 1H), 2.24 (dd, *J* = 15.6, 6.9 Hz, 1H), 1.66 (dddd, *J* = 13.8, 10.9, 6.3, 2.9 Hz, 1H), 1.46 (dddd, *J* = 14.0, 10.6, 9.4, 5.1 Hz, 1H), 1.13 (s, 3H), 1.12 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.9, 174.1, 142.2, 128.5, 128.5, 126.0, 51.9, 51.9, 46.2, 42.0, 35.9, 34.7, 34.3, 23.1, 21.7; **HRMS** (ESI) calculated for $C_{17}H_{24}O_4Na$ $(M+Na)^+$: 315.1567; found 315.1569; **$[\alpha]_D^{25}$** = –7.4° (c=0.71, $CHCl_3$); **HPLC:** Chiralpak OD-3, *n*-heptane/IPA = 99/1, 1 mL/min, 25 °C, 220 nm, t_R (major) = 8.9 min; t_R (minor) = 9.8 min, e.r. = 97:3



dimethyl (*R*)-3-heptyl-2,2-dimethylpentanedioate (3o): Prepared according to the general procedure using (*E*)-methyl dec-2-enoate (**1o**, 0.23 mmol, 43 mg), (*S,S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at –40 °C for 48 hours. The product was obtained after chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (66 mg, 95% yield). The enantiomeric ratio was determined by derivatization to the corresponding 1,5-dicarboxylic acid and GC analysis on a chiral stationary phase (see 3-heptyl-2,2-dimethylpentanedioic acid). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.66 (s, 3H), 3.65 (s, 3H), 2.37 (dd, *J* = 15.7, 4.9 Hz, 1H), 2.26 (ddq, *J* = 9.6, 4.9, 2.6 Hz, 1H), 2.12 (dd, *J* = 15.6, 6.9 Hz, 1H), 1.34 – 1.16 (m, 12H), 1.12 (s, 3H), 1.10 (s, 3H), 0.86 (t, *J* = 7.0 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 178.1, 174.3, 51.8, 51.7, 46.2, 42.2, 35.9, 31.9, 31.9, 29.9, 29.3, 28.2, 23.2, 22.8, 21.7, 14.2; **HRMS** (ESI) calculated for $C_{16}H_{31}O_4$ $(M+H)^+$: 287.2217; found 287.2217; **$[\alpha]_D^{25}$** = –5.9° (c=0.74, $CHCl_3$).

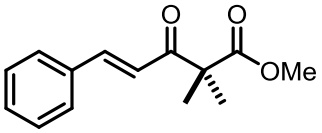


dimethyl (*S*)-3-isopropyl-2,2-dimethylpentanedioate (3p): (*E*)-methyl 4-methylpent-2-enoate (*E/Z* 97:3, purchased from Alfa Aesar; 0.20 mmol, 28 μL) was tested as substrate using a modified general procedure with 5 mol% (*S,S*)-**4e** (17.1 mg, 10 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 40 °C for 16 h. A conversion of 27% was determined by ^{1}H NMR analysis. The enantiomeric ratio was determined by GC on a chiral stationary phase. Rac-**3p** could be isolated by using $HNTf_2$ as the catalyst. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 3.67 (s, 3H), 3.66 (s, 3H), 2.37 (dd, *J* = 15.3, 5.4 Hz, 1H), 2.34 – 2.29 (m, 1H), 2.26 (dd, *J* = 15.3, 5.8 Hz, 1H), 1.82 (heptd, *J* = 6.9, 2.6 Hz, 1H), 1.16 (s, 3H), 1.15 (s, 3H), 0.90 (d, *J* = 7.0 Hz, 3H), 0.80 (d, *J* = 6.8 Hz, 3H). **^{13}C NMR** (126 MHz, $CDCl_3$) δ 178.3, 175.0, 51.8, 47.4, 46.3, 31.1, 28.7, 24.8, 23.9, 22.4, 18.3; **HRMS** (ESI) calculated for $C_{12}H_{22}O_4Na$ $(M+Na)^+$: 253.1410; found 253.1412; **GC** column: C-DEXTRIN H G 632, 25.0 m, temperature: 230 90 62 MIN ISO 8/MIN 170 3 MIN ISO 350, gas: 0.40 bar H_2, sample size: 1.0 mL, t_R (minor) = 53.58 min, t_R (major) = 55.47 min, e.r. = 85.5:15.5.



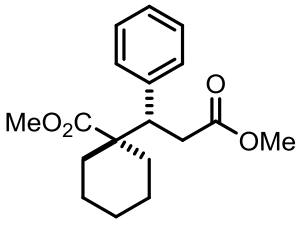
5-ethyl 1-methyl (*S*)-2,2-dimethyl-3-phenylpentanedioate: Prepared according to a modified general procedure using (*E*)-ethyl cinnamate (0.20 mmol, 34 μL), 1 mol% (*S,S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2a** (0.12 mL, 0.60 mmol) at 0 °C for 5 days to reach full conversion. The 1,2-addition product (see below) was obtained after column chromatography on silica gel (20:1 hexane/EtOAc) as a colorless oil (*E/Z* 93:7, 4 mg, 9% yield). Further elusion gave the desired Mukaiyama–Michael product (title compound) as a colorless oil (50 mg, 89% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.21 (tt, *J* = 6.7, 1.1 Hz, 2H), 7.18 – 7.14 (m, 1H), 7.13 – 7.10 (m, 2H), 3.87 (qq, *J* = 10.8, 7.1 Hz, 2H), 3.60 (s, 3H), 3.47 (dd, *J* = 11.5, 4.3 Hz, 1H), 2.79 (dd, *J* = 15.5, 11.5 Hz, 1H), 2.60 (dd, *J* = 15.5, 4.2 Hz, 1H), 1.11 (s, 3H), 1.05 (s, 3H), 0.96 (t, *J* = 7.1 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.5, 172.2, 139.5, 129.5, 128.0, 127.1, 60.4, 52.0, 49.1, 46.2, 36.0, 24.3, 21.8, 14.1; **HRMS** (ESI) calculated for $C_{16}H_{23}O_4$ $(M+H)^+$: 279.1591; found 279.1591; **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor) = 5.6 min, t_R (major) = 6.3 min; e.r. = 77.5:22.5. **$[\alpha]_D^{25}$** = –9.5° (c=0.74, $CHCl_3$).

methyl (*E*)-2,2-dimethyl-3-oxo-5-phenylpent-4-enoate:

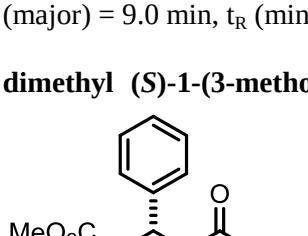


^{1}H NMR (500 MHz, $CDCl_3$) δ 7.72 (d, *J* = 15.7 Hz, 1H), 7.58 – 7.52 (m, 2H), 7.43 – 7.37 (m, 3H), 6.85 (d, *J* = 15.6 Hz, 1H), 3.73 (s, 3H), 1.46 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 196.5, 174.6, 144.2, 134.6, 130.8, 129.1, 128.6, 120.9, 55.0, 52.7, 22.1; **HRMS** (ESI) calculated for $C_{14}H_{16}O_3Na$ $(M+Na)^+$: 255.0992; found 255.0990.

dimethyl (*S*)-1-(3-methoxy-3-oxo-1-phenylpropyl)cyclohexane-1-carboxylate (5a): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 2 mol% (*S*,*S*)-**4e** (6.8 mg, 4 μmol) and 3 equiv. of SKA **2b** (0.14 mL, 0.60 mmol) at 0 °C for 14 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (58 mg, 95% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.28 – 7.23 (m, 2H), 7.22 – 7.18 (m, 1H), 7.11 – 7.06 (m, 2H), 3.63 (s, 3H), 3.46 (s, 3H), 3.28 (dd, *J* = 9.2, 6.3 Hz, 1H), 2.86 – 2.76 (m, 2H), 2.26 – 2.14 (m, 1H), 2.02 – 1.91 (m, 1H), 1.67 – 1.51 (m, 3H), 1.38 – 0.98 (m, 5H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.7, 173.0, 139.6, 129.3, 127.9, 127.1, 51.6, 51.5, 51.2, 50.7, 35.4, 33.3, 31.6, 25.6, 23.8, 23.5; **HRMS** (GC-EI) calculated for $C_{18}H_{24}O_4$: 304.1669; found 304.1670; **$[\alpha]_D^{25}$** = +8.9° (c = 0.81, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (major) = 9.0 min, t_R (minor) = 19.4 min; e.r. = 98:2.

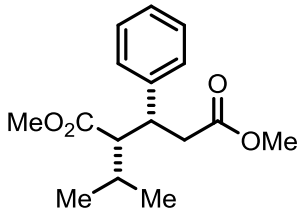


dimethyl (*S*)-1-(3-methoxy-3-oxo-1-phenylpropyl)cyclopentane-1-carboxylate (5b): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2c** (0.13 mL, 0.60 mmol) at 0 °C for 16 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (56 mg, 97% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.28 – 7.23 (m, 2H), 7.22 – 7.18 (m, 1H), 7.15 – 7.11 (m, 2H), 3.62 (s, 3H), 3.49 (s, 3H), 3.49 (dd, *J* = 11.1, 4.1 Hz, 1H), 2.91 (dd, *J* = 15.9, 11.2 Hz, 1H), 2.80 (dd, *J* = 16.0, 4.1 Hz, 1H), 2.21 – 2.11 (m, 1H), 2.11 – 2.02 (m, 1H), 1.61 – 1.45 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.9, 172.9, 140.5, 128.8, 128.1, 127.1, 59.1, 51.9, 51.7, 48.6, 37.1, 35.1, 33.5, 24.3, 24.2; **HRMS** (GC-EI) calculated for $C_{17}H_{22}O_4$: 290.1513; found 290.1514; **$[\alpha]_D^{25}$** = +24.4° (c = 0.76, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 99/1, 1 mL/min, 25 °C, 220 nm, t_R (major) = 11.5 min, t_R (minor) = 12.9 min; e.r. = 96:4.

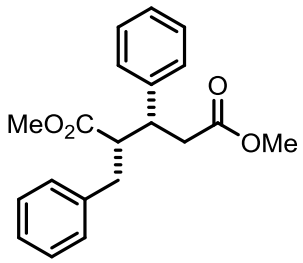


dimethyl (*S*)-1-(3-methoxy-3-oxo-1-phenylpropyl)cyclobutane-1-carboxylate (5c): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA **2d** (0.15 mL, 82%, 0.60 mmol) at 0 °C for 16 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (55 mg, 99% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.30 – 7.22 (m, 2H), 7.23 – 7.19 (m, 1H), 7.17 – 7.12 (m, 2H), 3.64 (s, 3H), 3.54 (dd, *J* = 10.8, 4.3 Hz, 1H), 3.51 (s, 3H), 2.88 (dd, *J* = 16.0, 10.8 Hz, 1H), 2.80 (dd, *J* = 16.0, 4.3 Hz, 1H), 2.39 – 2.29 (m, 2H), 2.19 – 2.04 (m, 2H), 1.80 (dtt, *J* = 11.5, 9.4, 7.3 Hz, 1H), 1.68 (dtt, *J* = 11.4, 9.4, 5.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.7, 172.9, 139.7, 128.5, 128.3, 127.2, 52.2, 51.8, 51.7, 48.0, 35.6, 30.0, 28.4, 15.5; **HRMS** (ESI) calculated for $C_{16}H_{20}O_4Na$ $(M+Na)^+$: 299.1254; found 299.1257; **$[\alpha]_D^{25}$** = +26.5° (c = 0.51, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor) = 6.5 min, t_R (major) = 8.6 min; e.r. = 96.5:3.5.

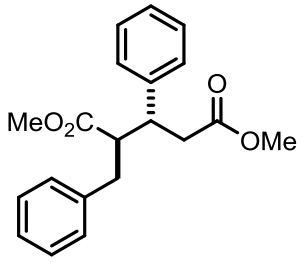
dimethyl (2*S*,3*R*)-2-isopropyl-3-phenylpentanedioate (5f): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA (*E*)-**2g** (0.13 mL, 0.60 mmol) at 0 °C for 20 hours. The product was obtained after column chromatography on silica gel (20:1→10:1 hexane/EtOAc) as a colorless oil (54 mg, 98% yield). The enantiomeric and diastereomeric ratio was determined by HPLC on a chiral stationary phase. The relative stereochemistry was assigned in analogy to **5d**. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.31 – 7.27 (m, 2H), 7.24 – 7.16 (m, 3H), 3.66 (s, 3H), 3.56 – 3.49 (m, 1H), 3.47 (s, 3H), 2.71 – 2.57 (m, 3H), 1.61 (pd, *J* = 6.9, 5.5 Hz, 1H), 0.89 (d, *J* = 6.9 Hz, 3H), 0.86 (d, *J* = 6.8 Hz, 4H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.3, 172.2, 141.4, 128.7, 128.0, 127.1, 57.1, 51.6, 51.3, 42.0, 39.0, 28.0, 21.6, 17.7; **HRMS** (ESI) calculated for $C_{16}H_{22}O_4Na$: 301.1410; found 301.1410; **$[\alpha]_D^{25}$** = +19.8° (c = 0.61, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor, *syn*) = 5.0 min, (minor, *anti*) = 5.6 min, t_R (major, *syn*) = 6.6 min, t_R (major, *anti*) = 7.5 min; e.r. = 99.5:0.5 (*syn*), e.r. 96.5:3.5 (*anti*), d.r. (*syn*/*anti*) = 96:4.



dimethyl (2*S*,3*R*)-2-benzyl-3-phenylpentanedioate (5d): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 1 mol% (*S*,*S*)-**4e** (3.4 mg, 2 μmol) and 3 equiv. of SKA (*E*)-**2e** (0.15 mL, 0.60 mmol) at 0 °C for 20 hours. The product was obtained after column chromatography on silica gel (40:1→20:1→10:1 hexane/EtOAc) as a colorless solid (65 mg, 98%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **$[\alpha]_D^{25}$** = +0.8° (c = 0.53, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor, *syn*) = 9.0 min, (minor, *anti*) = 12.1 min, t_R (major, *anti*) = 15.2 min, t_R (major, *syn*) = 18.3 min; e.r. = 99:1 (*syn*), e.r. 94:6 (*anti*), d.r. (*syn*/*anti*) = 92:8.



dimethyl (2*R*,3*R*)-2-benzyl-3-phenylpentanedioate (5e): Prepared according to the general procedure using (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg), 5 mol% (*S*,*S*)-**4e** (17 mg, 10 μmol) and 1.5 equiv. of SKA (*Z*)-**2e** (80 μL, 0.30 mmol) at 0 °C for 24 hours. The product was obtained after column chromatography on silica gel (40:1→20:1→10:1 hexane/EtOAc) as a colorless solid (63 mg, 96%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **$[\alpha]_D^{25}$** = +11.9° (c = 0.51, $CHCl_3$); **HPLC** Daicel Chiralpak OD-3, *n*-heptane/IPA = 98/2, 1 mL/min, 25 °C, 220 nm, t_R (minor, *syn*) = 9.0 min, (minor, *anti*) = 12.1 min, t_R (major, *anti*) = 15.2 min, t_R (major, *syn*) = 18.3 min; e.r. 94:6 (*syn*), e.r. = 98.5:1.5 (*anti*), d.r. (*syn*/*anti*) = 38:62.



A racemic mixture of diastereomers **5d** (*syn*) and **5e** (*anti*) was separated by preparative HPLC and pure single diastereomers were characterized as follows:

syn-diastereomer (**5d**): **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.40 – 7.34 (m, 2H), 7.31 – 7.25 (m, 3H), 7.25 – 7.19 (m, 2H), 7.19 – 7.14 (m, 1H), 7.04 – 6.98 (m, 2H), 3.55 (s, 3H), 3.52 (s, 3H), 3.47 (td, *J* = 9.9, 5.3 Hz, 1H), 2.96 (ddd, *J* = 11.2, 10.1, 3.9 Hz, 1H), 2.78 – 2.65 (m, 3H), 2.55 (dd, *J* = 13.7, 3.9 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.7, 171.8, 141.1, 139.1, 128.9, 128.6, 128.4, 128.1, 127.4, 126.5, 54.0, 51.6, 51.6, 44.8, 39.4, 37.2; **HRMS** (ESI) calculated for $C_{20}H_{22}O_4Na$ $(M+Na)^+$: 349.1410; found 349.1410.

anti-diastereomer (**5e**): **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.45 – 7.40 (m, 2H), 7.40 – 7.35 (m, 3H), 7.35 – 7.29 (m, 3H), 7.28 – 7.23 (m, 2H), 3.70 (s, 3H), 3.69 – 3.65 (m, 1H), 3.46 (s, 3H), 3.19 (ddd,

J = 10.0, 7.5, 5.2 Hz, 1H), 3.11 (dd, *J* = 15.9, 5.8 Hz, 1H), 3.05 (dd, *J* = 13.5, 10.1 Hz, 1H), 3.00 (dd, *J* = 13.6, 5.2 Hz, 1H), 2.92 (dd, *J* = 15.8, 9.2 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 173.8, 172.3, 140.8, 139.1, 128.9, 128.5, 128.5, 128.1, 127.2, 126.5, 53.3, 51.8, 51.3, 44.2, 37.8, 35.9; **HRMS** (ESI) calculated for $C_{20}H_{22}O_4Na$ $(M+Na)^+$: 349.1410; found 349.1411.

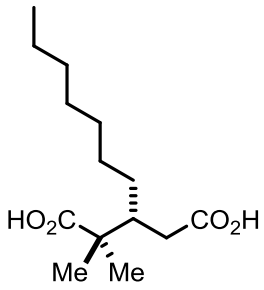
Different silyl ketene acetals (*E*)-**2e**, (*Z*)-**2e** and **2f** have been compared with respect to diastereoselectivity in the Mukaiyama–Michael reaction with **1a**. Reactions with $HNTf_2$ were conducted at –78 °C in DCM (entries 1-3). The reactions with **2f** were performed under the conditions specified in the general procedure. The product was obtained after methylation with K_2CO_3 and MeI.

entry	silyl ketene acetal	catalyst (loading)	d.r. (*syn*/*anti*)	e.r. (*syn*)	e.r. (*anti*)
1	(*E*)-**2e**	$HNTf_2$ (5 mol%)	69:31	/	/
2	(Z)-**2e**	$HNTf_2$ (5 mol%)	76:24	/	/
3	2f	$HNTf_2$ (5 mol%)	69:31	/	/
4	(*E*)-**2e**	(*S*,*S*)-**4e** (1 mol%)	92:8	99:1	94:6
5	(Z)-**2e**	(*S*,*S*)-**4e** (5 mol%)	38:62	94:6	98.5:1.5
6	2f	(*S*,*S*)-**4e** (1 mol%)	33:67	80.5:19.5	90:10

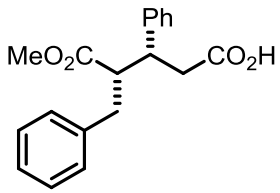
Product Derivatizations & Assignment of Absolute and Relative Stereochemistry

Product Derivatizations

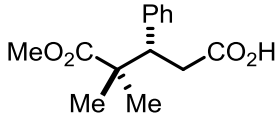
(*R*)-3-heptyl-2,2-dimethylpentanedioic acid: To a solution of diester **3o** (42 mg, 0.15 mmol) in methanol (0.3 mL) in a vial, aq. NaOH (50%, 10 equiv., 0.12 mL) was added and the resulting reaction mixture was heated under stirring to 80 °C overnight. Aq. HCl (10%) was added after cooling to r.t. and the reaction mixture was extracted with DCM. The organic phase was washed with brine, drying over $MgSO_4$, filtering and concentration gave the pure dicarboxylic acid as a colorless oil (37 mg, quant.). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 2.43 – 2.32 (m, 2H), 2.24 (dddd, *J* = 10.8, 8.6, 4.1, 2.2 Hz, 1H), 1.51 (ddq, *J* = 12.8, 7.9, 2.6 Hz, 1H), 1.42 (ddt, *J* = 17.9, 10.3, 5.2 Hz, 1H), 1.37 – 1.25 (m, 10H), 1.25 (s, 3H), 1.09 (s, 3H), 0.88 (t, *J* = 6.9 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 185.1, 180.5, 44.7, 42.1, 35.4, 32.0, 29.7, 29.4, 29.3, 28.2, 24.8, 22.8, 18.2, 14.2.; **HRMS** (ESI) calculated for $C_{14}H_{25}O_4$ $(M-H)^-$: 257.1758; found 257.1760; **$[\alpha]_D^{25}$** = –28.2° (c=0.44, $CHCl_3$). **GC** column: IVADEX 1/PS086 G 662, 25.0 m, temperature: 230 80 1/MIN 220 10 MIN ISO 350, gas: 0.50 bar H_2, sample size: 1.0 µL, t_R (major) = 136.34 min, t_R (minor) = 136.61 min, e.r. = 95:5



***rac*-(3*R*,4*S*)-4-benzyl-5-methoxy-5-oxo-3-phenylpentanoic acid (7):** To a solution of diester *rac*-**5d** (21 mg, 0.06 mmol, d.r. >20:1) in 2:1 methanol/THF (0.24 mL+0.12mL) at 0 °C, aq. NaOH (50%, 5 equiv., 30 µL) was added dropwise, subsequently allowed to warm up to r.t. and stirred for 1 h in total. After full conversion was indicated by TLC, aq. HCl (10%) was added and the reaction mixture was extracted with DCM. The organic phase was washed with brine, drying over $MgSO_4$, filtering and concentration gave the pure monocarboxylic acid as a colorless solid (20 mg, quant., d.r. >20:1). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.38 – 7.30 (m, 2H), 7.28 – 7.17 (m, 5H), 7.17 – 7.12 (m, 1H), 7.01 – 6.95 (m, 2H), 3.50 (s, 3H), 3.40 (td, *J* = 9.6, 5.6 Hz, 1H), 2.92 (ddd, *J* = 11.2, 10.1, 4.0 Hz, 1H), 2.77 – 2.64 (m, 3H), 2.51 (dd, *J* = 13.6, 4.0 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.0, 174.7, 140.9, 139.0, 128.9, 128.7, 128.5, 128.1, 127.5, 126.5, 54.0, 51.7, 44.4, 39.1, 37.2; **HRMS** (ESI) calculated for $C_{19}H_{20}O_4Na$ $(M+Na)^+$: 335.1254; found 335.1254.



***rac*-5-methoxy-4,4-dimethyl-5-oxo-3-phenylpentanoic acid (6):** Prepared according to a modified previous procedure (4 h reaction time, extraction with EtOAc instead of DCM) from *rac*-**3a** (56 mg, 0.21 mmol) to give the title compound as a colorless oil (53 mg, quant.). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.30 – 7.18 (m, 3H), 7.17 – 7.10 (m, 2H), 3.61 (s, 3H), 3.47 (dd, *J* = 11.0, 4.1 Hz, 1H), 2.83 (dd, *J* = 16.1, 11.0 Hz, 1H), 2.67 (dd, *J* = 16.2, 4.1 Hz, 1H), 1.12 (s, 3H), 1.06 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 177.9, 177.4, 139.2, 129.4, 128.1, 127.3, 52.0, 48.6, 46.2, 35.8, 24.4, 21.6; **HRMS** (ESI) calculated for $C_{14}H_{18}O_4Na$ $(M+Na)^+$: 273.1097; found 273.1099.



(4*S*)-5,5-dimethyl-4-phenyltetrahydro-2H-pyran-2-ol (8): According to the general procedure for the asymmetric Mukaiyama–Michael reaction, (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg) was reacted at 0 °C for 14 hours. Then, $LiAlH_4$ (1 M in Et_2O, 0.3 mL, 0.3 mmol) was added to the reaction mixture and the resulting suspension was stirred for 3 h at 0 °C. A sat. solution of Rochelle's salt (1 mL) was added at 0 °C and the mixture stirred for 1 h at r.t.. The mixture was extracted with EtOAc, the organic layer washed with brine, dried over $MgSO_4$ and concentrated. Purification by column chromatography on silica gel (90:10→80:20→65:35→50:50 hexane/MTBE) gave the title compound as mixture of diastereomers (31 mg, 75% yield, d.r. 1:1, colorless solid). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 4H), 7.26 – 7.21 (m, 2H), 7.19 – 7.12 (m, 4H), 5.46 (t, *J* = 2.8 Hz, 1H), 4.85 (ddd, *J* = 9.4, 6.0, 2.4 Hz, 1H), 3.96 (d, *J* = 11.0 Hz, 1H), 3.65 (d, *J* = 6.1 Hz, 1H), 3.61 (d, *J* = 11.5 Hz, 1H), 3.41 (d, *J* = 11.5 Hz, 1H), 3.20 (d, *J* = 11.0 Hz, 1H), 3.08 (dd, *J* = 13.6, 3.8 Hz, 1H), 2.99 (t, *J* = 2.4 Hz, 1H), 2.64 (dd, *J* = 13.4, 3.6 Hz, 1H), 2.32 (tdd, *J* = 13.7, 3.7, 1.9 Hz, 1H), 2.08 (td, *J* = 13.2, 9.4 Hz, 1H), 1.88 (ddd, *J* = 13.0, 3.7, 2.4 Hz, 1H), 1.73 (ddd, *J* = 13.7, 3.7, 1.1 Hz, 1H), 0.93 (s, 3H), 0.92 (s, 3H), 0.72 (s, 3H), 0.72 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 141.1, 140.7, 129.4, 129.2, 127.9, 127.8, 126.8, 126.6, 97.3, 92.1, 77.7, 71.0, 49.9, 44.2, 34.8, 34.3, 34.0, 31.7, 25.1, 24.4, 19.0, 18.3; **$[\alpha]_D^{25}$** = +102.9° (c=0.49, $CHCl_3$); **HRMS** (ESI) calculated for $C_{13}H_{18}O_2Na$ $(M+Na)^+$: 229.1199; found 229.1201.

Assignment of Absolute Stereochemistry

(*S*)-2,2-dimethyl-3-phenylpentane-1,5-diol:

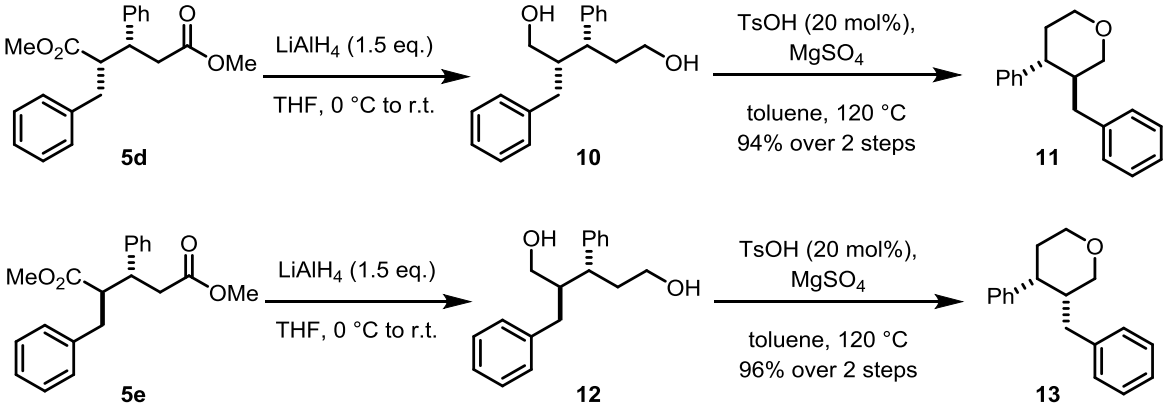
An ice-cooled solution of (*S*)-**3a** (407 mg, 1.54 mmol) in THF (15 mL) under argon was treated with $LiAlH_4$ (1 M in Et_2O, 2.3 mL, 2.3 mmol). The ice-bath was removed and the reaction was stirred for 2 h at r.t.. A sat. solution of Rochelle's salt (20 mL) was added at 0 °C and the mixture stirred for 1 h at r.t.. Extraction with EtOAc, drying of the organic layer over $MgSO_4$ and concentration gave the title compound as a colorless, crystalline solid (310 mg, 99% yield) without further purification. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.31 – 7.26 (m, 2H), 7.24 – 7.18 (m, 3H), 3.51 (ddd, *J* = 10.9, 6.9, 4.3 Hz, 1H), 3.42 (d, *J* = 10.9 Hz, 1H), 3.35 (ddd, *J* = 10.3, 8.6, 6.0 Hz, 1H), 3.21 (d, *J* = 10.9 Hz, 1H), 2.83 (dd, *J* = 11.8, 3.0 Hz, 1H), 2.04 (dddd, *J* = 13.7, 8.6, 6.9, 3.0 Hz, 1H), 1.95 (dddd, *J* = 13.7, 11.7, 6.0, 4.3 Hz, 1H), 1.71 (s, 2H), 0.94 (s, 3H), 0.81 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 141.9, 129.7, 128.2, 126.5, 71.0, 61.9, 47.4, 38.6, 32.3, 22.6, 22.2; **$[\alpha]_D^{25}$** = +1.0° (c=0.21, $CHCl_3$); **HRMS** (ESI) calculated for $C_{13}H_{20}O_2Na$ $(M+Na)^+$: 231.1355; found 231.1357.

(*S*)-3-(4-bromophenyl)-2,2-dimethylpentane-1,5-diol: Prepared according to previous procedure from (*S*)-**3g** (137 mg, 1.54 mmol) to give the title compound as a colorless solid (113 mg, 98% yield). **^{1}H NMR** (500 MHz, acetone-d_6) δ 7.51 – 7.39 (m, 2H), 7.23 – 7.17 (m, 2H), 3.65 (t, *J* = 5.3 Hz, 1H), 3.39 (t, *J* = 5.1 Hz, 1H), 3.33 (ddt, *J* = 10.4, 8.0, 4.5 Hz, 1H), 3.28 (dd, *J* = 10.5, 5.1 Hz, 1H), 3.19 (dddd, *J* = 10.2, 8.2, 6.9, 5.4 Hz, 1H), 3.13 (dd, *J* = 10.5, 5.6 Hz, 1H), 2.89 (dd, *J* = 12.1, 3.0 Hz, 1H), 2.04 – 1.98 (m, 1H), 1.91 (dddd, *J* = 13.4, 12.0, 7.0, 4.1 Hz, 1H), 0.91 (s, 3H), 0.75 (s, 3H); **^{13}C NMR** (126 MHz, acetone-d_6) δ 142.9, 132.7, 131.4, 120.1, 70.4, 61.4, 47.6, 38.9, 33.0, 22.8, 22.7; **$[\alpha]_D^{25}$** = +9.2° (c=0.45, $CHCl_3$); **HRMS** (ESI) calculated for $C_{13}H_{19}O_2BrNa$ $(M+Na)^+$: 309.0461; found 309.0461.

Both 1,5-diols were crystallized from DCM/hexane to afford single-crystals suitable for X-ray structure analysis (see below). All other products were assigned by analogy.

(*S*)-3,3-dimethyl-4-phenyltetrahydro-2H-pyran (9): A seal-cap vial was charged with (*S*)-2,2-dimethyl-3-phenylpentane-1,5-diol (42 mg, 0.2 mmol), *p*-toluenesulfonic acid (8 mg, 0.04 mmol) and $MgSO_4$ (40 mg). The reactants were dissolved in toluene (2 mL), the vial was sealed and the suspension was heated to 120 °C overnight. Purification by column chromatography on silica gel (10:1 hexane/EtOAc) gave the title compound as a colorless solid (37 mg, 97% yield). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.33 – 7.28 (m, 2H), 7.25 – 7.21 (m, 1H), 7.20 – 7.14 (m, 2H), 4.13 (ddt, *J* = 11.3, 4.8, 1.2 Hz, 1H), 3.56 (dd, *J* = 11.2, 0.9 Hz, 1H), 3.50 (ddd, *J* = 12.2, 11.3, 2.5 Hz, 1H), 3.26 (dd, *J* = 11.1, 1.0 Hz, 1H), 2.58 (dd, *J* = 13.0, 3.6 Hz, 1H), 2.30 (tdd, *J* = 13.2, 12.4, 4.8 Hz, 1H), 1.49 (dddd, *J* = 13.5, 3.9, 2.4, 1.5 Hz, 1H), 0.93 (s, 3H), 0.70 (s, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 141.8, 129.3, 127.8, 126.5, 80.3, 69.3, 51.5, 34.8, 28.2, 25.1, 19.0; **$[\alpha]_D^{25}$** = +57.9° (c=0.76, $CHCl_3$); **HRMS** (GC-EI) calculated for $C_{13}H_{18}O$: 191.1430; found 191.1431.

Assignment of Relative Stereochemistry

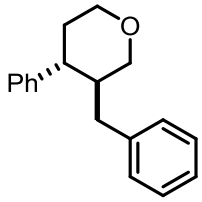


A racemic mixture of diastereomers **5d** (*syn*) and **5e** (*anti*) was separated by preparative HPLC and the single diastereomers were subsequently derivatized to tetrahydropyrans **11** and **13**, respectively.

***rac*-(2*S*,3*R*)-2-benzyl-3-phenylpentane-1,5-diol (10):** Prepared according to previous procedure from *rac*-**5d** (48 mg, 0.15 mmol) to give the title compound as a colorless solid (40 mg, quant.). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.31 – 7.22 (m, 2H), 7.21 – 7.11 (m, 5H), 7.11 – 7.03 (m, 1H), 7.02 – 6.96 (m, 2H), 3.64 (dd, *J* = 11.3, 3.5 Hz, 1H), 3.49 (ddd, *J* = 10.9, 6.4, 4.7 Hz, 1H), 3.41 – 3.30 (m, 2H), 2.94 (ddd, *J* = 10.7, 8.2, 3.9 Hz, 1H), 2.47 (dd, *J* = 13.7, 3.8 Hz, 1H), 2.28 (dd, *J* = 13.7, 10.8 Hz, 1H), 2.17 – 2.05 (m, 3H), 1.92 (ddq, *J* = 12.0, 8.1, 3.9 Hz, 1H), 1.83 (ddt, *J* = 13.7, 10.5, 5.1 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.3, 141.3, 129.1, 128.7, 128.7, 128.4, 126.6, 126.0, 61.2, 61.0, 48.1, 42.7, 35.7, 35.0; **HRMS** (ESI) calculated for $C_{18}H_{22}O_2Na$ $(M+Na)^+$: 293.1512; found 293.1513.

***rac*-(2*R*,3*R*)-2-benzyl-3-phenylpentane-1,5-diol (12):** Prepared according to the previous procedure from *rac*-**5e** (46 mg, 0.14 mmol) to give the title compound as a colorless solid (38 mg, quant.). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 2H), 7.30 – 7.20 (m, 5H), 7.20 – 7.16 (m, 1H), 7.16 – 7.11 (m, 2H), 3.54 (ddd, *J* = 11.0, 6.9, 4.5 Hz, 1H), 3.46 – 3.36 (m, 2H), 3.27 (dd, *J* = 11.2, 4.4 Hz, 1H), 2.99 (ddd, *J* = 11.0, 6.9, 3.7 Hz, 1H), 2.85 (dd, *J* = 13.7, 4.6 Hz, 1H), 2.54 (dd, *J* = 13.7, 9.9 Hz, 1H), 2.24 – 2.14 (m, 1H), 2.03 (dq, *J* = 6.7, 4.9 Hz, 1H), 1.96 (h, *J* = 6.7, 5.9 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 142.9, 140.8, 129.2, 128.7, 128.5, 128.5, 126.6, 126.1, 62.0, 61.3, 48.2, 42.6, 34.6, 34.5; **HRMS** (ESI) calculated for $C_{18}H_{22}O_2Na$ $(M+Na)^+$: 293.1512; found 293.1512.

***rac*-(3*S*,4*R*)-3-benzyl-4-phenyltetrahydro-2H-pyran (11):** Prepared analogously to (*S*)-**9** from diol *rac*-**10** (40 mg, 0.15 mmol) to give the pure title compound as a colorless solid (35 mg, 94% yield). For **^{1}H NMR** and **^{13}C NMR**, see below; **HRMS** (GC-EI) calculated for $C_{18}H_{20}O$: 252.1509; found 252.1510.



***rac*-(3*R*,4*R*)-3-benzyl-4-phenyltetrahydro-2H-pyran (13):** Prepared according to the previous procedure from diol *rac*-**12** (38 mg, 0.14 mmol) to give the pure title compound as a colorless solid (34 mg, 96% yield). For **^{1}H NMR** and **^{13}C NMR**, see below; **HRMS** (GC-EI) calculated for $C_{18}H_{20}O$: 252.1509; found 252.1510.

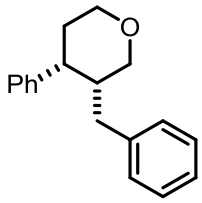
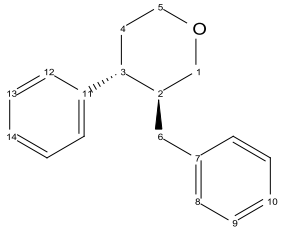


Table S6. Peak table compound **11**. ^{1}H NMR (500 MHz, $CDCl_3$), ^{13}C NMR (126 MHz, $CDCl_3$).



Atom	δ	J	COSY	HSQC	HMQC	NOESY
1 C	72,63			1ax, 1eq	5ax, 5eq, 1ax, 1eq, 6a, 6b, 2, 3	
Hax	3,168	11.5(1eq), 10.6(2)	1eq, 2, 6a, 6b	1	1, 5, 3, 2, 6	8, 1eq, 5ax, 6b, 3
Heq	3,917	11.5(1ax), 0.9(5eq), 4.2(2)	5eq, 2, 1ax, 6b	1	11, 1, 5, 3, 2	8, 6b, 1ax, 2
2 C	43,20			2	1ax, 1eq, 6a, 6b, 2, 3, 4ax, 4eq	
H	2,192	10.6(1ax), 4.2(1eq), 10.5(6b), 11.0(3), 3.2(6a)	1eq, 3, 6a, 1ax, 6b	2	7, 1, 3, 2, 6	8, 12, 1eq, 4ax, 6a
3 C	48,51			3	12, 5ax, 5eq, 1ax, 1eq, 6a, 6b, 3, 2, 4ax, 4eq	
H	2,491	11.0(2), 12.0(4ax), 4.0(4eq)	4eq, 2, 4ax, 12, 6b	3	11, 12, 1, 5, 3, 2, 6, 4	12, 5ax, 1ax, 4eq, 6b, 6a
4 C	35,48			4ax, 4eq	5eq, 3, 4ax, 4eq	
Hax	1,892	12.0(3), 4.6(5eq), 13.7(4eq), 12.3(5ax)	5eq, 5ax, 3, 4eq	4	11, 5, 3, 2, 4	12, 5eq, 2
Heq	1,765	4.0(3), 13.7(4ax), 1.7(5eq), 2.3(5ax)	5eq, 5ax, 3, 4ax	4	3, 2, 4	12, 5eq, 5ax, 3
5 C	68,69			5ax, 5eq	5ax, 5eq, 1ax, 1eq, 3, 4ax	
Hax	3,498	12.3(4ax), 2.3(4eq), 11.4(5eq)	5eq, 4eq, 4ax	5	1, 5, 3	5eq, 1ax, 4eq, 3
Heq	4,043	0.9(1eq), 4.6(4ax), 1.7(4eq), 11.4(5ax)	4eq, 1eq, 5ax, 4ax	5	1, 5, 3, 4	4ax, 5ax, 4eq
6 C	36,68			6a, 6b	8, 1ax, 6a, 6b, 2, 3	
Ha	2,597	3.2(2), 13.9(6b)	2, 8, 9, 10, 1ax, 6b	6	7, 12, 8, 1, 3, 2, 6	8, 12, 6b, 2, 3
Hb	2,050	10.5(2), 13.9(6a)	3, 2, 8, 6a, 1ax, 1eq	6	7, 8, 1, 3, 2, 6	8, 12, 1eq, 1ax, 3, 6a
7 C	139,91				9, 6a, 6b, 2	
8 C	128,87			8	8, 10, 6a, 6b	
H	6,986	m	9, 10, 6a, 6b	8	10, 8, 6	6b, 12, 1eq, 1ax, 2, 6a
9 C	128,33			9	9	
H	7,219	m	10, 8, 6a	9	7, 9	
10 C	126,03			10	8	
H	7,148	m	9, 8, 6a	10	8	
11 C	144,41				13, 3, 4ax, 1eq	
12 C	127,80			12	12, 14, 3, 6a	
H	7,297	m	13, 14, 3	12	14, 12, 3	6b, 4ax, 8, 4eq, 3, 2, 6a
13 C	128,84			13	13	
H	7,375	m	14, 12	13	11, 13	
14 C	126,70			14	12	
H	7,263	m	13, 12	14	12	

Assignment of stereochemistry:
The relative stereochemistry was determined to be *anti* based on coupling constants of adjacent hydrogen atoms of **11** as shown below, and NOESY signals.

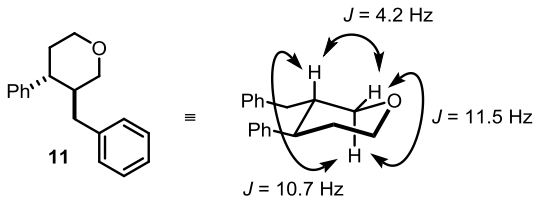
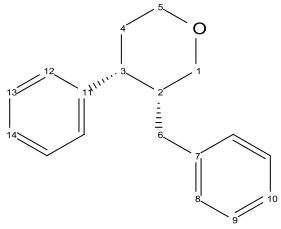


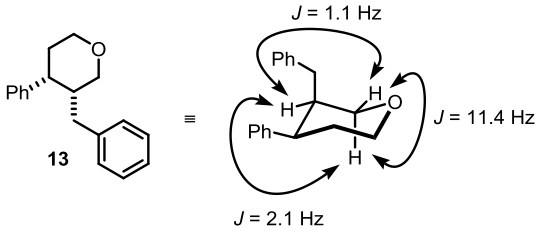
Table S7. Peak table compound **13**. ^{1}H NMR (500 MHz, $CDCl_3$), ^{13}C NMR (126 MHz, $CDCl_3$).



Atom	δ	J	COSY	HSQC	HMQC	NOESY
1 C	69,67			1ax, 1eq	5eq, 6a, 6b, 1eq	
Hax	3,496	Ddd 11.5(1eq), 2.4/1.6(2; 6b)	1eq, 6b, 2	1	6	2, 3
Heq	3,817	Dt 11.5(1ax), 1.3(2; 5eq)	5eq, 1ax, 2	1	3, 2, 5, 1, 6	8, 2, 6a
2 C	43,61			2	6a, 6b, 1eq	
H	2,025	Dm 11.8(6a)	1eq, 1ax, 3, 6a, 6b	2		8, 1ax, 1eq, 6b, 3, 12
3 C	43,98			3	12, 5eq, 3, 1eq, 4ax	
H	3,211	Dt 12.9(4ax), 3.9(4eq; 2)	12, 4ax, 4eq, 2	3	11, 12, 3, 4, 6	4eq, 2, 5ax, 1ax, 12
4 C	25,63			4ax, 4eq	3, 4ax	
Hax	2,303	DDDd 13.3(4eq), 12.9(3), 12.2(5ax), 4.7(5eq)	4eq, 5eq, 5ax, 3	4	3, 5, 4	5eq, 4eq, 6a, 12
Heq	1,704	Dm 13.3(4ax)	4ax, 5eq, 5ax, 3	4		5eq, 5ax, 4ax, 3, 12
5 C	68,85			5ax, 5eq	5eq, 1eq, 4ax	
Hax	3,591	DDd 12.2(4ax), 11.3(5eq), 2.4(4eq)	5eq, 4ax, 4eq	5		5eq, 4eq, 3
Heq	4,222	Dddm 11.3(5ax), 4.7(4ax), 1.8(4eq)	4ax, 4eq, 1eq, 5ax	5	3, 5, 1	5ax, 4ax, 4eq
6 C	30,60			6a, 6b	8, 1ax, 1eq, 3, 6a, 6b	
Ha	2,755	DD 13.3(6b), 11.8(2)	8, 6b, 2	6	7, 8, 9, 2, 1, 6	8, 4ax, 6b, 1eq, 12
Hb	2,249	Dm 13.3(6a)	8, 1ax, 6a, 2	6	7, 8, 2, 1, 6	8, 2, 6a
7 C	141,49				9, 6a, 6b	
8 C	129,31			8	8, 10, 6a, 6b	
H	6,995	m	9, 6b, 6a	8	10, 8, 6	1eq, 6b, 2, 6a
9 C	128,33			9	9, 6a	
H	7,209	m	10, 8	9	7, 9	
10 C	125,80			10	8	
H	7,133	m	9	10	8	
11 C	143,85				13, 3	
12 C	127,37			12	12, 14, 3	
H	7,294	m	13, 3	12	14, 12, 3	4ax, 4eq, 2, 3, 6a
13 C	128,60			13	13	
H	7,398	m	14, 12	13	13, 11	
14 C	126,43			14	12	
H	7,273	m	13	14	12	

Assignment of stereochemistry:

The relative stereochemistry was determined to be *syn* based on coupling constants of adjacent hydrogen atoms of **13** as shown below, and NOESY signals.



X-ray Crystallography Data

Single-Crystal X-ray Structure Analysis of (*S*)-2,2-dimethyl-3-phenyl-pentane-1,5-diol

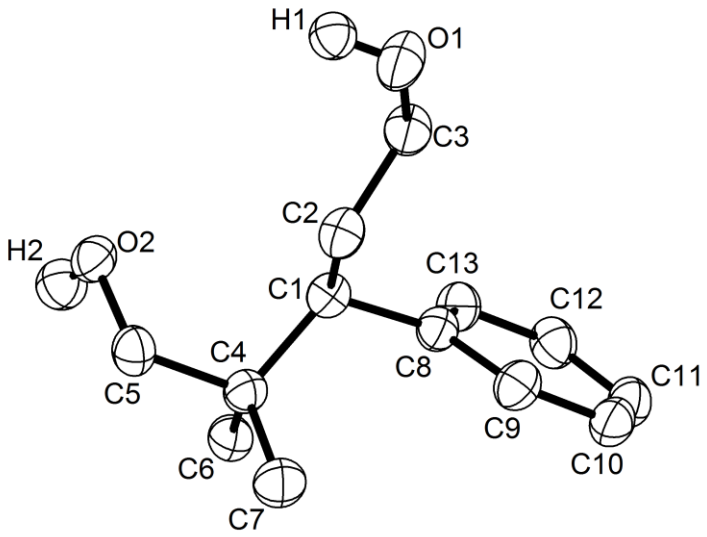


Figure S1. The molecular structure of (*S*)-2,2-dimethyl-3-phenyl-pentane-1,5-diol. Phenyl, methyl and methylene H atoms are removed for clarity.

Table S8. Crystal data and structure refinement.

Identification code	GAT-GB-597 (10566)	
Empirical formula	$C_{13}H_{20}O_2$	
Color	colourless	
Formula weight	208.29 g·mol^{-1}	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	monoclinic	
Space group	*P* 2_1, (no. 4)	
Unit cell dimensions	a = 6.2186(7) Å	α= 90°.
	b = 7.6511(8) Å	β= 96.281(2)°.
	c = 12.8993(14) Å	γ = 90°.
Volume	610.05(11) Å^3	
Z	2	
Density (calculated)	1.134 Mg·m^{-3}	
Absorption coefficient	0.587 mm^{-1}	
F(000)	228 e	
Crystal size	0.290 x 0.201 x 0.080 mm^3	
θ range for data collection	3.447 to 72.168°.	
Index ranges	$-7 \le h \le 7$, $-9 \le k \le 9$, $-15 \le l \le 15$	
Reflections collected	14442	
Independent reflections	2371 [R_{int} = 0.0306]	

Reflections with I>2σ(I)	2250	
Completeness to θ = 67.679°	100.0 %	
Absorption correction	Gaussian	
Max. and min. transmission	0.96413 and 0.89095	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2371 / 3 / 147	
Goodness-of-fit on F^2	1.173	
Final R indices [I>2σ(I)]	R_1 = 0.0480	wR^2 = 0.1336
R indices (all data)	R_1 = 0.0497	wR^2 = 0.1350
Absolute structure parameter	0.035(132) 972 selected quotients (Parsons' method)	
Extinction coefficient	0.045(6)	
Largest diff. peak and hole	0.191 and -0.182 e·$Å^{-3}$	

Table S9. Atomic coordinates and equivalent isotropic displacement parameters ($Å^2$).

U_{eq} is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U_{eq}
C(1)	0.7817(4)	0.4438(4)	0.2212(2)	0.030(1)
C(2)	0.7684(5)	0.6048(4)	0.1500(2)	0.034(1)
C(3)	0.9495(5)	0.7339(4)	0.1792(2)	0.037(1)
C(4)	0.6230(4)	0.2929(4)	0.1836(2)	0.032(1)
C(5)	0.6558(5)	0.2387(4)	0.0717(2)	0.035(1)
C(6)	0.6700(5)	0.1337(4)	0.2544(2)	0.036(1)
C(7)	0.3852(5)	0.3433(5)	0.1822(3)	0.044(1)
C(8)	0.7696(4)	0.4914(4)	0.3350(2)	0.030(1)
C(9)	0.6075(5)	0.5966(4)	0.3686(2)	0.036(1)
C(10)	0.5942(5)	0.6251(5)	0.4742(2)	0.038(1)
C(11)	0.7438(5)	0.5505(4)	0.5483(2)	0.039(1)
C(12)	0.9105(5)	0.4512(4)	0.5167(2)	0.037(1)
C(13)	0.9231(5)	0.4227(4)	0.4111(2)	0.033(1)
O(1)	0.9636(4)	0.8644(3)	0.1008(2)	0.048(1)
O(2)	0.8751(4)	0.2001(3)	0.0580(2)	0.035(1)

The absolute structure determination of two further crystals was undertaken:
1st crystal
Flack parameter x = 0.005(553) by classical fit to all intensities
0.013(255) from 1004 selected quotients (Parsons' method)
2nd crystal
Flack parameter x = 0.068(445) by classical fit to all intensities
0.039(194) from 977 selected quotients (Parsons' method)

Table S10. Bond lengths [Å] and angles [°].

C(1)-C(8)	1.521(4)	C(1)-C(2)	1.533(4)
C(1)-C(4)	1.561(4)	C(1)-H(1A)	1.0000
C(2)-C(3)	1.514(4)	C(2)-H(2A)	0.9900
C(2)-H(2B)	0.9900	C(3)-O(1)	1.430(4)
C(3)-H(3A)	0.9900	C(3)-H(3B)	0.9900
C(4)-C(7)	1.527(4)	C(4)-C(6)	1.531(4)
C(4)-C(5)	1.537(4)	C(5)-O(2)	1.425(4)
C(5)-H(5A)	0.9900	C(5)-H(5B)	0.9900
C(6)-H(6A)	0.9800	C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800	C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800	C(7)-H(7C)	0.9800
C(8)-C(9)	1.395(4)	C(8)-C(13)	1.395(4)
C(9)-C(10)	1.391(4)	C(9)-H(9)	0.9500
C(10)-C(11)	1.383(5)	C(10)-H(10)	0.9500
C(11)-C(12)	1.382(4)	C(11)-H(11)	0.9500
C(12)-C(13)	1.389(4)	C(12)-H(12)	0.9500
C(13)-H(13)	0.9500	O(1)-H(1)	0.90(3)
O(2)-H(2)	0.89(3)		
C(8)-C(1)-C(2)	112.4(2)	C(8)-C(1)-C(4)	112.4(2)
C(2)-C(1)-C(4)	114.7(2)	C(8)-C(1)-H(1A)	105.5
C(2)-C(1)-H(1A)	105.5	C(4)-C(1)-H(1A)	105.5
C(3)-C(2)-C(1)	112.7(2)	C(3)-C(2)-H(2A)	109.1
C(1)-C(2)-H(2A)	109.1	C(3)-C(2)-H(2B)	109.1
C(1)-C(2)-H(2B)	109.1	H(2A)-C(2)-H(2B)	107.8
O(1)-C(3)-C(2)	112.4(2)	O(1)-C(3)-H(3A)	109.1
C(2)-C(3)-H(3A)	109.1	O(1)-C(3)-H(3B)	109.1
C(2)-C(3)-H(3B)	109.1	H(3A)-C(3)-H(3B)	107.9
C(7)-C(4)-C(6)	109.2(3)	C(7)-C(4)-C(5)	106.5(2)
C(6)-C(4)-C(5)	108.0(2)	C(7)-C(4)-C(1)	113.3(3)
C(6)-C(4)-C(1)	109.3(2)	C(5)-C(4)-C(1)	110.3(2)
O(2)-C(5)-C(4)	113.5(2)	O(2)-C(5)-H(5A)	108.9
C(4)-C(5)-H(5A)	108.9	O(2)-C(5)-H(5B)	108.9
C(4)-C(5)-H(5B)	108.9	H(5A)-C(5)-H(5B)	107.7

C(4)-C(6)-H(6A)	109.5	C(4)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5	C(4)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5	H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5	C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5	C(4)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5	H(7B)-C(7)-H(7C)	109.5
C(9)-C(8)-C(13)	117.4(3)	C(9)-C(8)-C(1)	123.4(2)
C(13)-C(8)-C(1)	119.1(3)	C(10)-C(9)-C(8)	121.1(3)
C(10)-C(9)-H(9)	119.4	C(8)-C(9)-H(9)	119.4
C(11)-C(10)-C(9)	120.3(3)	C(11)-C(10)-H(10)	119.8
C(9)-C(10)-H(10)	119.8	C(12)-C(11)-C(10)	119.5(3)
C(12)-C(11)-H(11)	120.3	C(10)-C(11)-H(11)	120.3
C(11)-C(12)-C(13)	120.0(3)	C(11)-C(12)-H(12)	120.0
C(13)-C(12)-H(12)	120.0	C(12)-C(13)-C(8)	121.6(3)
C(12)-C(13)-H(13)	119.2	C(8)-C(13)-H(13)	119.2
C(3)-O(1)-H(1)	109(4)	C(5)-O(2)-H(2)	107(3)

Table S11. Anisotropic displacement parameters ($Å^2$).

The anisotropic displacement factor exponent takes the form:
$-2\pi^2[\ h^2a^{*2}U_{11} + ... + 2\ h\ k\ a^*\ b^*\ U_{12}\ ]$.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	0.030(1)	0.030(1)	0.029(1)	0.002(1)	0.003(1)	0.004(1)
C(2)	0.041(2)	0.033(2)	0.028(1)	0.004(1)	0.004(1)	0.006(1)
C(3)	0.051(2)	0.028(2)	0.034(2)	0.004(1)	0.010(1)	0.001(1)
C(4)	0.028(1)	0.036(2)	0.031(1)	-0.003(1)	0.004(1)	0.000(1)
C(5)	0.036(2)	0.037(2)	0.032(2)	-0.005(1)	0.000(1)	0.001(1)
C(6)	0.043(2)	0.033(2)	0.033(2)	-0.002(1)	0.009(1)	-0.006(1)
C(7)	0.030(2)	0.053(2)	0.049(2)	-0.007(2)	0.005(1)	0.000(1)
C(8)	0.032(1)	0.029(2)	0.028(1)	-0.001(1)	0.005(1)	0.001(1)
C(9)	0.038(2)	0.036(2)	0.034(1)	0.002(1)	0.006(1)	0.005(1)
C(10)	0.043(2)	0.034(2)	0.039(2)	-0.003(1)	0.013(1)	0.002(1)
C(11)	0.049(2)	0.038(2)	0.030(1)	-0.004(1)	0.009(1)	-0.006(1)
C(12)	0.045(2)	0.037(2)	0.030(1)	0.001(1)	0.001(1)	-0.003(1)
C(13)	0.036(1)	0.033(2)	0.030(1)	-0.001(1)	0.002(1)	0.002(1)
O(1)	0.079(2)	0.029(1)	0.040(1)	0.005(1)	0.026(1)	0.004(1)
O(2)	0.041(1)	0.031(1)	0.035(1)	0.001(1)	0.012(1)	0.001(1)

Table S12. Hydrogen coordinates and isotropic displacement parameters ($Å^2$).

	x	y	z	U_{eq}
H(1A)	0.9301	0.3951	0.2184	0.035
H(2A)	0.7740	0.5665	0.0770	0.041
H(2B)	0.6278	0.6638	0.1538	0.041
H(3A)	0.9254	0.7916	0.2456	0.045
H(3B)	1.0885	0.6700	0.1904	0.045
H(5A)	0.5659	0.1344	0.0525	0.042
H(5B)	0.6043	0.3344	0.0236	0.042
H(6A)	0.5766	0.0364	0.2285	0.054
H(6B)	0.6415	0.1631	0.3256	0.054
H(6C)	0.8219	0.0995	0.2545	0.054
H(7A)	0.3537	0.4433	0.1355	0.066
H(7B)	0.3553	0.3750	0.2528	0.066
H(7C)	0.2940	0.2442	0.1574	0.066
H(9)	0.5044	0.6496	0.3184	0.043
H(10)	0.4818	0.6963	0.4955	0.046
H(11)	0.7321	0.5673	0.6205	0.046
H(12)	1.0164	0.4024	0.5671	0.045
H(13)	1.0389	0.3549	0.3903	0.040
H(1)	1.003(8)	0.814(7)	0.043(3)	0.083(16)
H(2)	0.899(9)	0.090(4)	0.078(4)	0.097(19)

INTENSITY STATISTICS FOR DATASET

Resolution	#Data	#Theory	%Complete	Redundancy	Mean I	Mean I/s	Rmerge	Rsigma
Inf - 3.28	36	36	100.0	8.33	231.93	82.46	0.0163	0.0102
3.28 - 2.24	83	84	98.8	7.10	91.97	73.12	0.0213	0.0123
2.24 - 1.77	125	125	100.0	5.31	62.43	60.85	0.0210	0.0155
1.77 - 1.52	118	118	100.0	5.24	22.95	50.67	0.0255	0.0168
1.52 - 1.40	114	114	100.0	6.45	23.18	53.18	0.0256	0.0155
1.40 - 1.29	120	120	100.0	6.47	21.96	53.90	0.0254	0.0161
1.29 - 1.22	116	116	100.0	5.87	19.63	45.08	0.0225	0.0174
1.22 - 1.16	123	123	100.0	5.73	22.25	46.05	0.0214	0.0177
1.16 - 1.10	128	128	100.0	5.45	18.00	44.59	0.0235	0.0188
1.10 - 1.06	111	111	100.0	4.81	11.60	36.05	0.0309	0.0235
1.06 - 1.02	142	142	100.0	5.85	11.16	35.63	0.0434	0.0234
1.02 - 0.99	101	101	100.0	8.38	9.45	31.63	0.0732	0.0257
0.99 - 0.96	141	141	100.0	8.94	6.83	23.35	0.0976	0.0354
0.96 - 0.94	99	100	99.0	8.16	4.13	16.13	0.1204	0.0541
0.94 - 0.91	149	149	100.0	6.56	4.57	13.68	0.1169	0.0627
0.91 - 0.89	101	101	100.0	6.21	3.06	9.95	0.1512	0.0894
0.89 - 0.87	133	133	100.0	6.14	3.81	11.27	0.1301	0.0692
0.87 - 0.85	150	152	98.7	5.44	3.01	10.55	0.1476	0.0816
0.85 - 0.84	71	71	100.0	5.25	2.42	8.92	0.1503	0.0898
0.84 - 0.82	155	157	98.7	4.17	2.56	8.97	0.1393	0.0886
0.82 - 0.81	64	91	70.3	1.56	2.14	6.99	0.0967	0.1214
0.91 - 0.81	674	705	95.6	4.88	2.93	9.73	0.1404	0.0845
Inf - 0.81	2380	2413	98.6	6.00	19.72	32.56	0.0306	0.0196
0.75 - 0.65	1502	1505	99.8	4.57	5.8	13.24	0.0855	0.0586
Inf - 0.65	4402	4412	99.8	6.19	18.7	28.84	0.0368	0.0226

The structure was solved by direct methods and refined by full-matrix least-squares against F^2 to R_1 = 0.048 [$I > 2\sigma(I)$], wR_2 = 0.135, 147 parameters. The C-H H atoms were refined using a riding model with a U_H = 1.2 x U_C. The O-H H atoms were refined with isotropic atomic displacement parameters and the O-H bond distances were restrained to be 0.84 Å with an estimated standard deviation of 0.02. S = 1.175, residual electron density 0.19 (1.35 Å from C11)/ -0.18 (0.48 from H12) e Å^{-3}. Three crystals were investigated and their absolute configurations determined. The respective Flack parameters (Parson's method) are 0.035(132) [972 quotients], 0.039(194) [977 quotients] and 0.013(255) [1004 quotients]. In addition, the absolute configuration of two crystals of the 4-bromyl-phenyl derivative were determined (see below). **CCDC-1550399**.

Single-Crystal X-ray Structure Analysis of (*S*)-2,2-dimethyl-3-(4-bromo-phenyl)-pentane-1,5-diol

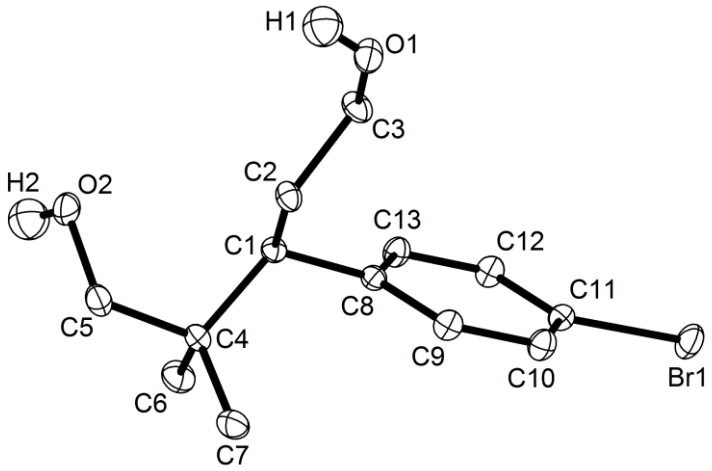


Figure S2. The molecular structure of (*S*)-2,2-dimethyl-3-(4-bromo-phenyl)-pentane-1,5-diol. Phenyl, methyl and methylene H atoms are removed for clarity.

Table S13. Crystal data and structure refinement.

Identification code	GAT-GB-611-01 (10742)	
Empirical formula	C_{13} H_{19} Br O_2	
Color	colourless	
Formula weight	287.19 g·mol^{-1}	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	orthorhombic	
Space group	P 2_1 2_1 2_1, (no. 19)	
Unit cell dimensions	a = 7.6003(11) Å	α= 90°.
	b = 10.0962(5) Å	β= 90°.
	c = 17.0161(15) Å	γ = 90°.
Volume	1305.7(2) Å^3	
Z	4	
Density (calculated)	1.461 Mg·m^{-3}	
Absorption coefficient	3.133 mm^{-1}	
F(000)	592 e	

Crystal size	0.33 x 0.09 x 0.08 mm^3	
θ range for data collection	3.563 to 33.071°.	
Index ranges	$-11 \le h \le 11$, $-15 \le k \le 15$, $-26 \le l \le 26$	
Reflections collected	29594	
Independent reflections	4949 [R_{int} = 0.0396]	
Reflections with I>2σ(I)	4560	
Completeness to θ = 25.242°	99.6 %	
Absorption correction	Gaussian	
Max. and min. transmission	0.80490 and 0.44130	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4949 / 0 / 151	
Goodness-of-fit on F^2	1.103	
Final R indices [I>2σ(I)]	R_1 = 0.0261	wR^2 = 0.0537
R indices (all data)	R_1 = 0.0323	wR^2 = 0.0560
Absolute structure parameter	-0.009(4) [1826 quotients]	
Extinction coefficient	0	
Largest diff. peak and hole	0.378 and -0.424 e·$Å^{-3}$	

Table S14. Atomic coordinates and equivalent isotropic displacement parameters ($Å^2$).

U_{eq} is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U_{eq}
C(1)	0.6271(3)	0.4764(2)	0.6021(1)	0.012(1)
C(2)	0.7695(2)	0.5829(2)	0.5938(1)	0.014(1)
C(3)	0.8997(3)	0.5496(2)	0.5295(1)	0.017(1)
C(4)	0.4826(3)	0.5112(2)	0.6636(1)	0.014(1)
C(5)	0.4054(3)	0.6481(2)	0.6446(1)	0.018(1)
C(6)	0.3356(3)	0.4081(2)	0.6596(1)	0.021(1)
C(7)	0.5527(3)	0.5183(2)	0.7479(1)	0.021(1)
C(8)	0.7099(3)	0.3411(2)	0.6141(1)	0.012(1)
C(9)	0.8440(3)	0.3205(2)	0.6687(1)	0.015(1)
C(10)	0.9276(3)	0.1992(2)	0.6760(1)	0.016(1)
C(11)	0.8748(2)	0.0962(2)	0.6282(1)	0.014(1)
C(12)	0.7415(3)	0.1118(2)	0.5740(1)	0.015(1)
C(13)	0.6603(3)	0.2342(2)	0.5673(1)	0.015(1)
Br(1)	0.9879(1)	-0.0706(1)	0.6354(1)	0.021(1)
O(1)	1.0288(2)	0.6503(2)	0.5202(1)	0.020(1)
O(2)	0.3636(2)	0.6629(2)	0.5636(1)	0.021(1)

Table S15. Bond lengths [Å] and angles [°].

C(1)-C(8)	1.518(3)	C(1)-C(2)	1.532(3)
C(1)-C(4)	1.557(3)	C(1)-H(1A)	1.0000
C(2)-C(3)	1.514(3)	C(2)-H(2A)	0.9900
C(2)-H(2B)	0.9900	C(3)-O(1)	1.421(2)
C(3)-H(3A)	0.9900	C(3)-H(3B)	0.9900
C(4)-C(6)	1.528(3)	C(4)-C(7)	1.532(3)
C(4)-C(5)	1.535(3)	C(5)-O(2)	1.422(3)
C(5)-H(5A)	0.9900	C(5)-H(5B)	0.9900
C(6)-H(6A)	0.9800	C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800	C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800	C(7)-H(7C)	0.9800
C(8)-C(13)	1.393(3)	C(8)-C(9)	1.394(3)
C(9)-C(10)	1.386(3)	C(9)-H(9)	0.9500
C(10)-C(11)	1.380(3)	C(10)-H(10)	0.9500
C(11)-C(12)	1.380(3)	C(11)-Br(1)	1.8947(19)
C(12)-C(13)	1.385(3)	C(12)-H(12)	0.9500
C(13)-H(13)	0.9500	O(1)-H(1)	0.74(3)
O(2)-H(2)	0.74(3)		
C(8)-C(1)-C(2)	110.55(15)	C(8)-C(1)-C(4)	113.92(16)
C(2)-C(1)-C(4)	113.68(16)	C(8)-C(1)-H(1A)	106.0
C(2)-C(1)-H(1A)	106.0	C(4)-C(1)-H(1A)	106.0
C(3)-C(2)-C(1)	111.92(17)	C(3)-C(2)-H(2A)	109.2
C(1)-C(2)-H(2A)	109.2	C(3)-C(2)-H(2B)	109.2
C(1)-C(2)-H(2B)	109.2	H(2A)-C(2)-H(2B)	107.9
O(1)-C(3)-C(2)	111.89(17)	O(1)-C(3)-H(3A)	109.2
C(2)-C(3)-H(3A)	109.2	O(1)-C(3)-H(3B)	109.2
C(2)-C(3)-H(3B)	109.2	H(3A)-C(3)-H(3B)	107.9
C(6)-C(4)-C(7)	109.13(17)	C(6)-C(4)-C(5)	108.91(17)
C(7)-C(4)-C(5)	106.70(16)	C(6)-C(4)-C(1)	109.37(16)
C(7)-C(4)-C(1)	113.24(17)	C(5)-C(4)-C(1)	109.39(16)
O(2)-C(5)-C(4)	112.54(17)	O(2)-C(5)-H(5A)	109.1
C(4)-C(5)-H(5A)	109.1	O(2)-C(5)-H(5B)	109.1
C(4)-C(5)-H(5B)	109.1	H(5A)-C(5)-H(5B)	107.8
C(4)-C(6)-H(6A)	109.5	C(4)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5	C(4)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5	H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5	C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5	C(4)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5	H(7B)-C(7)-H(7C)	109.5
C(13)-C(8)-C(9)	117.59(18)	C(13)-C(8)-C(1)	120.54(17)
C(9)-C(8)-C(1)	121.77(17)	C(10)-C(9)-C(8)	121.79(18)
C(10)-C(9)-H(9)	119.1	C(8)-C(9)-H(9)	119.1
C(11)-C(10)-C(9)	118.65(18)	C(11)-C(10)-H(10)	120.7
C(9)-C(10)-H(10)	120.7	C(12)-C(11)-C(10)	121.44(18)
C(12)-C(11)-Br(1)	118.57(15)	C(10)-C(11)-Br(1)	119.98(15)
C(11)-C(12)-C(13)	118.94(18)	C(11)-C(12)-H(12)	120.5
C(13)-C(12)-H(12)	120.5	C(12)-C(13)-C(8)	121.59(18)
C(12)-C(13)-H(13)	119.2	C(8)-C(13)-H(13)	119.2
C(3)-O(1)-H(1)	109.5	C(5)-O(2)-H(2)	109.5

Table S16. Anisotropic displacement parameters ($Å^2$).

The anisotropic displacement factor exponent takes the form:
$-2\pi^2[h^2a^{*2}U_{11} + ... + 2 h k a^* b^* U_{12}]$.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	0.011(1)	0.012(1)	0.013(1)	0.000(1)	0.000(1)	-0.001(1)
C(2)	0.012(1)	0.012(1)	0.019(1)	-0.001(1)	0.002(1)	0.000(1)
C(3)	0.014(1)	0.016(1)	0.022(1)	0.000(1)	0.005(1)	-0.002(1)
C(4)	0.012(1)	0.016(1)	0.015(1)	0.000(1)	0.002(1)	0.001(1)
C(5)	0.016(1)	0.018(1)	0.020(1)	0.000(1)	0.003(1)	0.004(1)
C(6)	0.016(1)	0.022(1)	0.024(1)	0.003(1)	0.004(1)	-0.003(1)
C(7)	0.020(1)	0.027(1)	0.014(1)	-0.001(1)	0.002(1)	0.004(1)
C(8)	0.011(1)	0.013(1)	0.013(1)	0.001(1)	0.001(1)	-0.001(1)
C(9)	0.016(1)	0.014(1)	0.015(1)	-0.002(1)	-0.003(1)	-0.001(1)
C(10)	0.016(1)	0.016(1)	0.015(1)	-0.001(1)	-0.004(1)	0.000(1)
C(11)	0.016(1)	0.013(1)	0.014(1)	0.002(1)	0.001(1)	0.002(1)
C(12)	0.017(1)	0.013(1)	0.016(1)	-0.002(1)	-0.003(1)	0.000(1)
C(13)	0.014(1)	0.015(1)	0.015(1)	-0.001(1)	-0.004(1)	0.001(1)
Br(1)	0.027(1)	0.015(1)	0.019(1)	0.000(1)	-0.004(1)	0.008(1)
O(1)	0.013(1)	0.017(1)	0.030(1)	0.007(1)	0.003(1)	-0.001(1)
O(2)	0.013(1)	0.025(1)	0.024(1)	0.008(1)	0.001(1)	0.004(1)

Table S17. Hydrogen coordinates and isotropic displacement parameters ($Å^2$).

	x	y	z	U_{eq}
H(1A)	0.5658	0.4723	0.5501	0.014
H(2A)	0.7131	0.6689	0.5818	0.017
H(2B)	0.8330	0.5920	0.6443	0.017
H(3A)	0.9588	0.4649	0.5422	0.021
H(3B)	0.8358	0.5377	0.4793	0.021
H(5A)	0.2976	0.6617	0.6763	0.022
H(5B)	0.4913	0.7172	0.6599	0.022
H(6A)	0.2852	0.4072	0.6066	0.031
H(6B)	0.2438	0.4307	0.6977	0.031
H(6C)	0.3836	0.3205	0.6719	0.031
H(7A)	0.5929	0.4304	0.7643	0.031
H(7B)	0.4588	0.5484	0.7831	0.031
H(7C)	0.6513	0.5808	0.7502	0.031
H(9)	0.8790	0.3917	0.7017	0.018
H(10)	1.0194	0.1871	0.7132	0.019
H(12)	0.7059	0.0398	0.5417	0.019
H(13)	0.5687	0.2455	0.5299	0.018
H(1)	0.9893(19)	0.708(3)	0.4998(17)	0.030
H(2)	0.268(5)	0.650(3)	0.5576(4)	0.031

INTENSITY STATISTICS FOR DATASET

Resolution	#Data	#Theory	%Complete	Redundancy	Mean I	Mean I/s	Rmerge	Rsigma
Inf - 2.64	75	80	93.8	11.36	144.63	101.41	0.0308	0.0101
2.64 - 1.77	176	176	100.0	9.49	85.24	76.37	0.0257	0.0102
1.77 - 1.40	253	253	100.0	8.58	53.40	67.36	0.0269	0.0122
1.40 - 1.22	261	261	100.0	8.02	42.27	54.21	0.0275	0.0139
1.22 - 1.11	245	245	100.0	7.67	34.87	50.74	0.0294	0.0157
1.11 - 1.03	258	258	100.0	7.28	23.99	41.46	0.0353	0.0194
1.03 - 0.97	241	241	100.0	7.03	21.90	38.07	0.0387	0.0215
0.97 - 0.92	258	258	100.0	6.60	18.12	30.63	0.0423	0.0254
0.92 - 0.88	269	269	100.0	6.26	14.17	26.27	0.0525	0.0306
0.88 - 0.84	276	276	100.0	5.97	15.09	25.44	0.0536	0.0320
0.84 - 0.82	189	189	100.0	5.68	12.30	21.53	0.0604	0.0375
0.82 - 0.79	287	287	100.0	5.40	9.92	18.36	0.0735	0.0457
0.79 - 0.77	221	221	100.0	5.24	10.02	17.63	0.0744	0.0474
0.77 - 0.75	255	255	100.0	4.86	8.45	14.88	0.0924	0.0576
0.75 - 0.73	263	263	100.0	4.87	7.64	13.72	0.1011	0.0631
0.73 - 0.71	304	304	100.0	4.56	6.09	10.92	0.1161	0.0785
0.71 - 0.70	177	177	100.0	4.44	5.50	9.81	0.1275	0.0861
0.70 - 0.68	368	368	100.0	4.25	5.81	10.10	0.1229	0.0872
0.68 - 0.67	183	183	100.0	3.97	4.90	8.36	0.1450	0.1062
0.67 - 0.66	202	202	100.0	3.94	5.24	8.68	0.1346	0.1019
0.66 - 0.65	216	217	99.5	3.75	4.26	7.15	0.1699	0.1254
0.75 - 0.65	1713	1714	99.9	4.29	5.75	10.05	0.1238	0.0874
Inf - 0.65	4977	4983	99.9	5.96	20.58	28.28	0.0393	0.0256

The structure was solved by direct methods and refined by full-matrix least-squares against F^2 to R_1 = 0.026 [$I > 2\sigma(I)$], wR_2 = 0.056, 151 parameters. The H atoms were refined using a riding model with U_H = 1.5 x U_x for the methyl and hydroxyl groups, otherwise U_H = 1.2 x U_C. S = 1.103, residual electron density 0.38 (0.75 Å from C3)/ -0.42 (0.60 from Br1) e Å^{-3}. The Flack parameter (Parson's method) is -0.009(4) [1826 quotients]. The absolute structure of a second crystal was determined (Flack parameter -0.008(4) [1519 quotients]). **CCDC-1550400**.

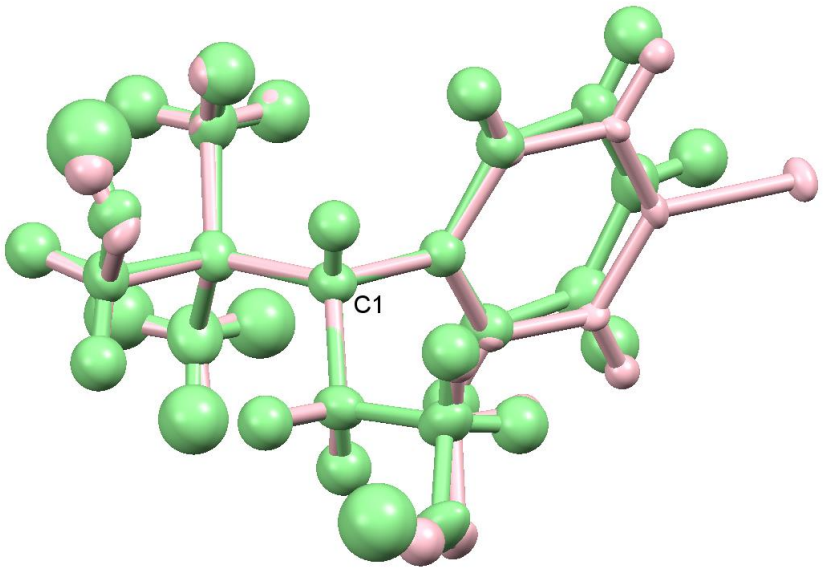
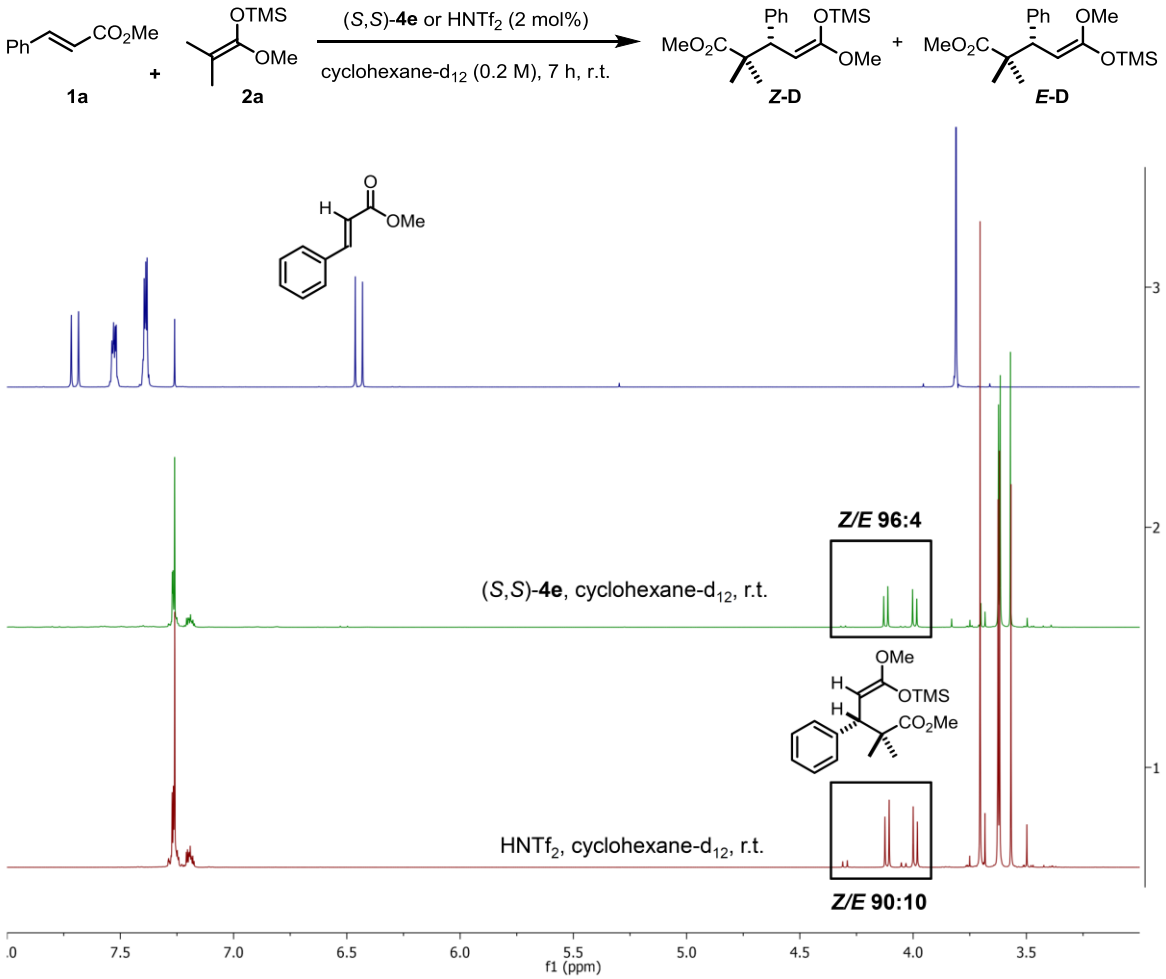


Figure S3. Superposition of the molecular structures of (*S*)-2,2-dimethyl-3-phenyl-pentane-1,5-diol (green) and (*S*)-2,2-dimethyl-3-(4-bromo-phenyl)-pentane-1,5-diol (pink).

Mechanistic NMR Studies

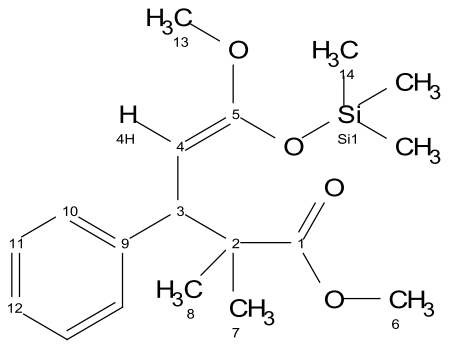
Reaction Intermediate

To identify the initial reaction product before protonolysis, Mukaiyama–Michael reactions of methyl cinnamate **1a** (19.5 mg, 0.12 mmol) and SKA **2a** (50 μL, 0.24 mmol) with (*S*,*S*)-**4e** (4.0 mg, 2.4 μmol) or $HNTf_2$ (24 μL, 0.2 M in DCE, 2.4 μmol) were conducted in an NMR tube in cyclohexane-d_{12} (0.6 mL) at r.t. for 7 h (>99% conversion).



The initial reaction intermediates ***E*/*Z*-D** were characterized from the reaction mixture after full conversion. The *E*/*Z* rations were determined to be 4:96 (with **4e**) and 10:90 (with $HNTf_2$). We observed slow *E*/*Z* isomerization when the reaction mixture was kept at r.t. after completion.

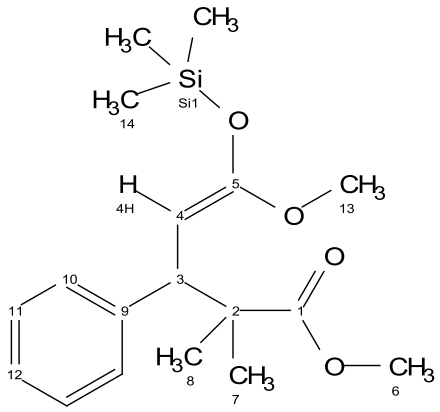
Table S18. Peak table intermediate ***Z*-D**



Atom	Chemical Shift	J	COSY	HSQC	HMBC	Si-HMQC	NOESY
Si1	19,15					14	
1 C	176,80				3, 7, 8, 6		
2 C	47,48				3, 4, 7, 8		
3 C	50,13			3	3, 4, 7, 8, 10		
3 H	3,83	d 9.3(4 H)	4, 13	3	5, 9, 4, 2, 1, 7, 8, 3, 10		8, 7, 14, 10
4 C	76,16			4	3, 4		
4 H	3,95	d 9.3(3 H)	13, 3	4	5, 9, 4, 2, 13, 3		8, 7, 14, 13, 10
5 C	158,27				4, 3, 13		
6 C	50,96			6	6		
6 H	3,45	s		6	6, 1		8, 7, 14, 10
7 C	23,76			7	3, 8		
7 H	1,08	s	8	7	2, 1, 8, 3		3, 6, 13, 14, 4, 10
8 C	23,08			8	3, 7		
8 H	1,10	s	7	8	2, 1, 7, 3		3, 6, 13, 14, 4, 10
9 C	143,99				3, 4		
10 C	130,07				3		
10 H	7.13 - 6.99	m			3		3, 8, 7, 4, 6
11 C	127,86						
11 H	7.13 - 6.99	m					
12 C	126,37						
12 H	7.13 - 6.99	m					
13 C	54,45			13	4		
13 H	3,46	s	4, 3	13	5		8, 7, 14, 4
14 C	0,31			14	14		
14 H	0,02	s		14	14	Si1	3, 6, 7, 8, 13, 4

Reaction intermediate ***Z*-D** was identified from the reaction mixture with catalyst (*S*,*S*)-**4e** (*E*/*Z* 4:96). The geometry of the double bond was assigned due to characteristic NOESY correlation between 4-H and 13-H (red circle in Table S18).

Table S19. Peak table intermediate ***E*-D**

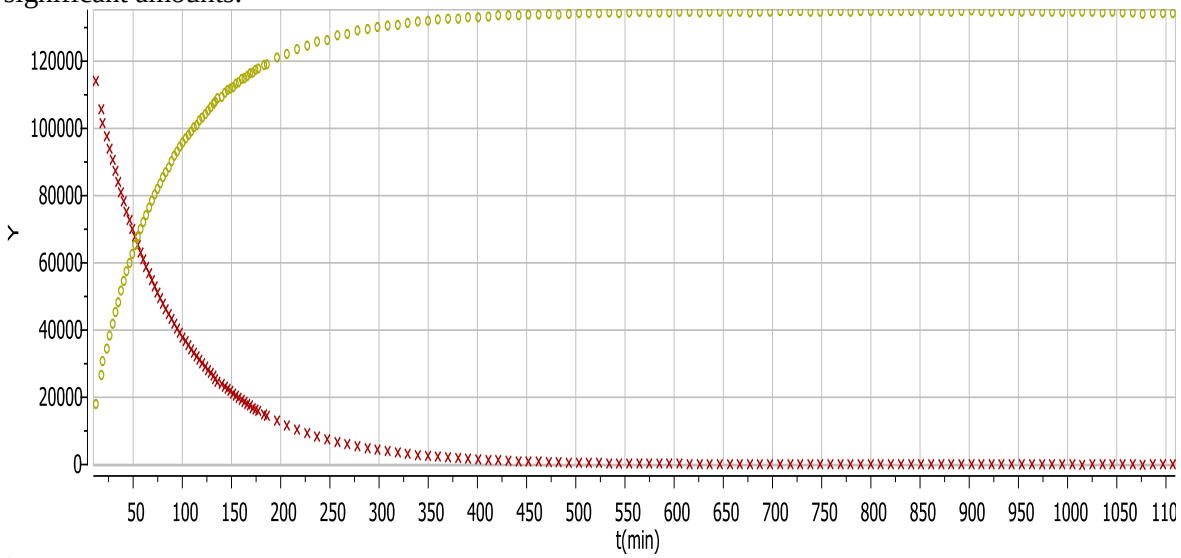


Atom	Chemical Shift	J	COSY	HSQC	HMBC	Si-HMQC	NOESY
Si1	19,43					14	
1 C	176,73				3, 6, 7, 8		
2 C	47,48				3, 4, 7, 8		
3 C	49,72			3	3, 7, 8, 10		
3 H	3,88	d 10.2(4 H)	4	3	1, 5, 9, 4, 2, 7, 8, 3, 10		10, 7, 8
4 C	84,58			4	3, 4		
4 H	4,14	d 10.2(3 H)	3, 13	4	5, 9, 4, 2		10, 7, 8, 14
5 C	154,80				3, 4, 13		
6 C	50,92			6	6		
6 H	3,46	s		6	1, 6		7, 8
7 C	23,80			7	3, 8		
7 H	1,06	s	8	7	1, 2, 8, 3		3, 4, 6, 13, 10
8 C	23,02			8	3, 7		
8 H	1,08	s	7	8	1, 2, 7, 3		3, 4, 6, 13, 10
9 C	143,61				3, 4		
10 C	129,80				3		
10 H	7.13 - 6.99	m			3		3, 4, 7, 8
11 C	127,93						
11 H	7.13 - 6.99	m					
12 C	126,43						
12 H	7.13 - 6.99	m					
13 C	54,10			13			
13 H	3,33	s	4	13	5		7, 8, 14
14 C	-0,05			14	14		
14 H	0,22	s		14	14	Si1	4, 13

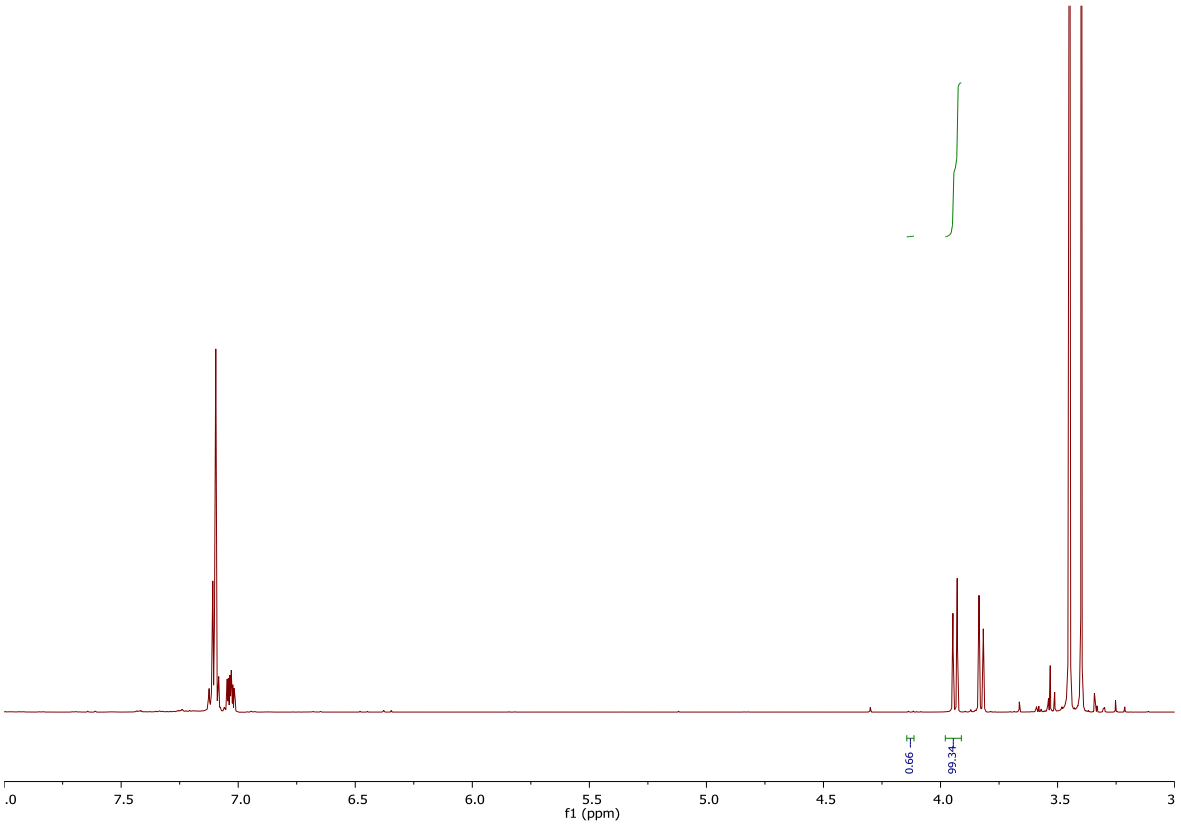
Reaction intermediate ***E*-D** was identified from the reaction mixture with catalyst (*S*,*S*)-**4e** (*E*/*Z* 4:96).

Preliminary Kinetic Study

In order to follow the course of the reaction under standard conditions, we conducted the Mukaiyama–Michael reaction of methyl cinnamate **1a** (19.5 mg, 0.12 mmol), SKA **2a** (75 µL, 0.36 mmol) and (*S*,*S*)-**4e** (2.0 mg, 1.2 µmol) in an NMR tube in cyclohexane-d_{12} (0.6 mL) at 0 °C. The integrals of olefinic protons of **1a** (red) and ***Z*-D** (yellow) were plotted against time (graph below). After 8 h (480 min) reaction time, the starting material is converted to >99% of product. The *Z*/*E* ratio was determined to be >99:1. No other reaction intermediates could be detected in significant amounts:



^{1}H NMR after 8 h reaction time:



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4. A Scalable and Highly Diastereo- and Enantioselective Catalytic Diels–Alder Reaction of α,β-Unsaturated Methyl Esters

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Authors Tim Gatzenmeier, Mathias Turberg, Diana Yepes, Youwei Xie, Frank Neese, Giovanni Bistoni, Benjamin List

NMR spectra, HPLC and GC traces were omitted.

Content

Despite tremendous advances in enantioselective catalysis of the Diels–Alder reaction, the use of simple α,β-unsaturated esters as one of the most abundant and useful class of dienophiles is still severely limited in scope due to their low reactivity. We report here a catalytic asymmetric Diels–Alder methodology for a large variety of α,β-unsaturated methyl esters and different dienes based on extremely reactive silylium imidodiphosphorimidate (IDPi) Lewis acids. Mechanistic insights from accurate domain-based local pair natural orbital coupled-cluster (DLPNO-CCSD(T)) calculations rationalize catalyst control and stereochemical outcome.

A Scalable and Highly Diastereo- and Enantioselective Catalytic Diels–Alder Reaction of α,β-Unsaturated Methyl Esters

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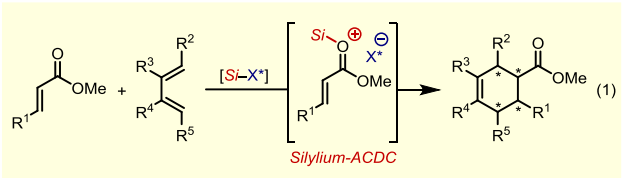
Supporting Information Placeholder

ABSTRACT: Despite tremendous advances in enantioselective catalysis of the Diels–Alder reaction, the use of simple α,β-unsaturated esters as one of the most abundant and useful class of dienophiles is still severely limited in scope due to their low reactivity. We report here a catalytic asymmetric Diels–Alder methodology for a large variety of α,β-unsaturated methyl esters and different dienes based on extremyl reactive silylium imidodiphosphorimidate (IDPi) Lewis acids. Mechanistic insights from accurate domain-based local pair natural orbital coupled-cluster (DLPNO-CCSD(T)) calculations rationalize catalyst control and stereochemical outcome.

The discovery of the Diels–Alder reaction by Kurt Alder and Otto Diels is regarded as one of the transforming events in organic chemistry.[1] The power and efficiency to rapidly build up complexity by forming up to four stereocenters at once was quickly realized and led to many important and elegant applications in the chemical synthesis of complex natural products,[2] agrochemicals, pharmaceuticals and fragrances.[3] In the historical development of stereoselective synthesis, the Diels–Alder reaction has served as one of the most prominent platforms and α,β-unsaturated carboxylic acid derivatives have been a widely applied class of dienophiles. In fact, a very early approach to asymmetric synthesis has been the Lewis acid-mediated Diels–Alder reaction of enantiopure acrylates with cyclopentadiene.[4] Within the area of asymmetric Lewis acid catalysis, chiral complexes based on aluminum, titanium, copper, boron and others have emerged,[5] which enabled high enantioselectivities with α,β-unsaturated *N*-acyl oxazolidinones, aldehydes, ketones, and trifluoroethyl esters as dienophiles. Also some simple, unactivated α,β-unsaturated esters, such as methyl or ethyl acrylate and crotonate, in combination with cyclopentadiene can engage in highly enantioselective Diels–Alder reactions catalyzed either by chiral alkyldichloroboranes introduced by Hawkins[6] or Corey's cationic oxazaborolidines (CBS),[5c,7] which undoubtedly represent the most versatile family of chiral Lewis acids to date. Also various organocatalytic approaches have been described for α,β-unsaturated aldehydes and ketones via asymmetric iminium ion or Brønsted acid catalysis.[8,9] Despite these examples, the application of simple α,β-unsaturated esters as a highly abundant and fundamental class of dienophiles is still severely limited in scope due to their particularly low reactivity.[10]

In our efforts to overcome existing challenges in asymmetric Lewis acid catalysis, we have recently proposed a new strategy to catalyze the Diels–Alder reaction of α,β-unsaturated esters with an achiral, cationic silylium ion and an enantiopure counteranion (Eq. 1).[11] This asymmetric counteranion-directed silylium Lewis acid catalysis (silylium-ACDC)[12] differs conceptually from



conventional enantioselective Lewis acid catalysis, which typically utilizes metal(loid) complexes with chiral ligands or substituents.[13] Rendering such complexes cationic and combining them with weakly coordinating, achiral counteranions is often a powerful measure to increase their activity. In contrast, the inversion of the chiral entities within the ion pair, as provided with silylium-ACDC, allows for the unique feature in silylium catalysis of possessing a repair pathway upon hydrolytic deactivation:[11,14] The source of chirality is hydrolytically stable, converts back to the Brønsted acidic state, and can be re-activated in the presence of a suitable silylating reagent. Providing a slight excess of the silylating reagent compared to the chiral Brønsted acid then allows for very low catalyst loadings of the chiral Brønsted acid precatalyst. In addition, the logic of designing more stabilized and weaker coordinating enantiopure anions also applies here and leads to higher activity of the corresponding cationic silylium species.

After demonstrating this concept for the catalytic asymmetric Diels–Alder reactions of 9-fluorenylmethyl cinnamate esters with a chiral C–H acid as Lewis acid precursor,[11] we were recently able to utilize simple α,β-unsaturated methyl esters in highly enantioselective Mukaiyama–Michael reactions with silyl ketene acetals (SKA) and highly acidic and confined imidodiphosphorimidate (IDPi) catalysts.[15] We now report the development of a catalytic asymmetric Diels–Alder methodology for a large variety of α,β-unsaturated methyl esters and different dienes, including normally unreactive substrate combinations.

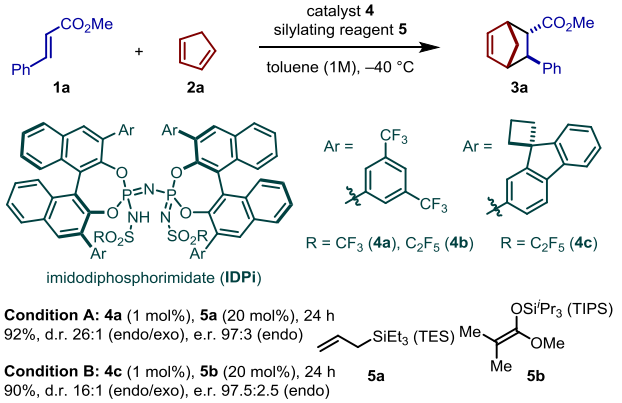


Figure 1. Reaction Development and Catalyst Systems.

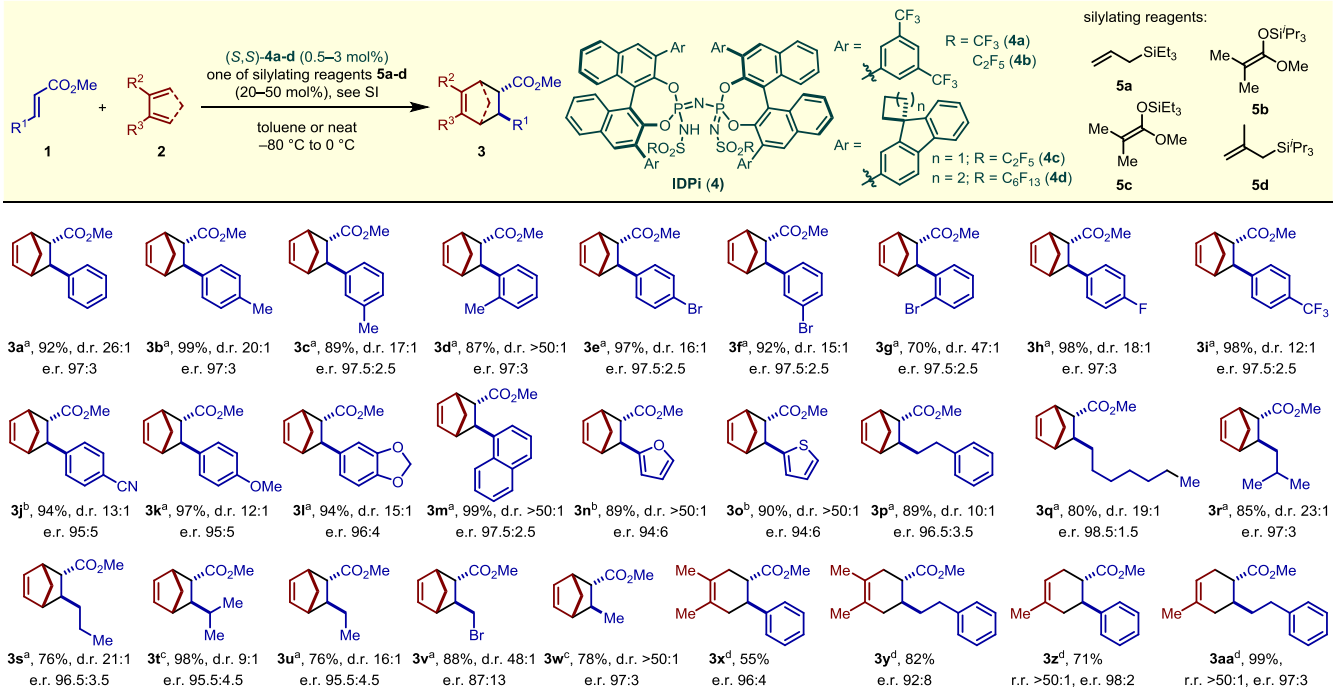


Figure 2. Substrate and Diene Scope. Reactions of α,β-unsaturated methyl esters with cyclopentadiene **2a**, 2,3-dimethylbutadiene **2b** and isoprene **2c**. [a]with catalyst **4a**. [b]with catalyst **4b**. [c]with catalyst **4c**. [d]with catalyst **4d** (3 mol%). Yields refer to isolated material. d.r., diastereomeric ratio; e.r., enantiomeric ratio. For details, see the supplementary material.

We chose the Diels–Alder reaction between only weakly reactive methyl *trans*-cinnamate (**1a**) and cyclopentadiene (**2a**) as our model reaction (Fig. 1) and conducted an extensive catalyst evaluation. We found that our IDPi acids provided both sufficient activity and promising enantioselectivities compared to other chiral acids tested (for more details, see the supplementary material). Gratifyingly, we could identify two distinct families of IDPi catalysts, which after optimization gave very high enantio- and diastereoselectivities in our model reaction. Catalysts **4a** and **4b** possess 3,5-trifluoromethylphenyl substituents, while IDPi **4c** features cyclobutyl-derivatized 3-fluorenyl substituents on the BINOL backbone. In general, inner core modification toward longer perfluoroalkyl groups (e.g. R = C_2F_5)[15e-15h] increased catalytic activity, while the impact on enantioselectivity varied. The type of silylating reagent (**5**) suitable to activate the IDPi Brønsted acid precursors to the silylium-Lewis acids depends on catalyst acidity and activation temperature. We investigated silyl ketene acetals (SKA), methallylsilanes, and allylsilanes as activators and found that their silylating power decreased in this order. While the type of reagent had no effect on enantioselectivity, the impact of the silyl group on both reaction rate and stereoselectivity was quite significant. Independent reaction optimization for our two privileged catalyst lead structures revealed triethyl allylsilane **5a** as the optimal activator of catalyst **4a** (condition A), while catalyst **4c** performed best with triisopropylsilyl (TIPS) SKA **5b** (condition B). Both catalyst systems gave equally high yields and enantioselectivities (e.r. ≥ 97:3) in our model reaction using only 1 mol% of IDPi and a sub-stoichiometric amount of silylating reagent at -40 °C.

With this flexibility and optional fine-tuning in hand, we proceeded to explore the scope of α,β-unsaturated esters as dienophiles with cyclopentadiene (**2a**) (Fig. 2). As condition A provided higher reactivity and increased diastereoselectivity, we tested methyl- and bromo-substituted cinnamates with catalyst **4a** and found that ortho-, meta- or para-substitution is well tolerated, and the desired products (**3b-g**) were obtained in high yields, excellent enantioselectivities, and high diastereoselectivities. Similar results were achieved for para-fluoro- or trifluoromethyl-substituted products **3h** and **3i** under the same conditions. For stronger electron-deficient substrates such as cinnamate **1j** and 3-heteroaryl-substituted acrylates **1n** and **1o**, we used catalyst **4b** to efficiently catalyze the reaction and achieved high enantioselectivities. When electron-rich substrates were tested to afford products **3k** and **3i**, increased catalyst loading (3 mol% of **4a**) and temperature (–20 °C) provided sufficient reactivity to obtain high yields and stereoselectivity. As 3-alkyl acrylates were empirically found to be more reactive than 3-aryl acrylates,[5c] both available catalyst systems were explored at decreased temperatures (–80 °C) and gave product **3p** in comparably excellent yields and enantioselectivities (for more details, see the supplementary material). Using catalyst **4a**, we tested substrates with various alkyl substitutions and could isolate the corresponding products (**3q-s**, **3u-v**) with consistently very high levels of stereocontrol, while the enantioselectivities slightly decreased with shorter chains lengths. With γ-branched methyl 4-methylpent-2-enoate (**1t**) and methyl crotonate (**1w**), however, only diminished enantioselectivities were obtained. Switching to catalyst **4c** in combination with the triethylsilyl (TES) group under neat conditions instead gave excellent results for both Diels–Alder products (**3t** and **3w**). In light of the extremely high activity of our silylium-Lewis acids, we proceeded to explore less reactive dienes. We selected 2,3-dimethylbutadiene (k_{rel} = 4.9) and isoprene (k_{rel} = 2.3) as representatives as these dienes have been determined to be orders of magnitude less reactive than cyclopentadiene (k_{rel} = 1350) in reference to butadiene (k_{rel} = 1).[16] During optimization, we found that IDPi's of the 3-fluorenyl substitution family were generally superior to the bistrifluoromethylphenyl derivatives (**4a** and **4b**) in enantiodiscrimination, while the latter exhibited significantly higher activity. This issue could be solved by attaching a longer, linear perfluoroalkyl chain (R = C_6F_{13}) to the inner core sulfonyl groups, which led to the identification of cyclopentyl-derived **4d** as the optimal catalyst in combination with TIPS methallylsilane **5d** as the activator. With this catalyst system, Diels–Alder reactions of two representative dienophiles covering a broad range of reactivity (**1a** and **1p**) with both

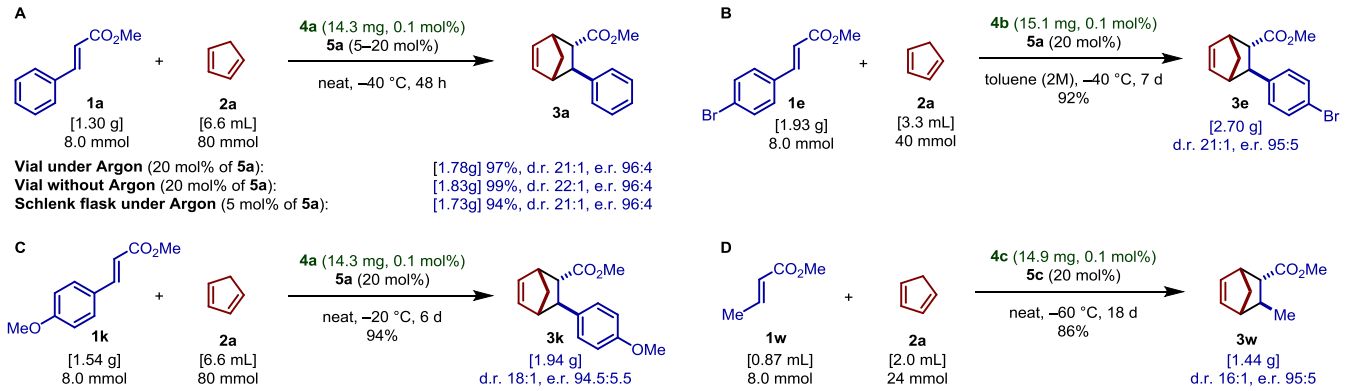


Figure 3. Scale-Up Experiments. Preparative scale reactions with reduced catalyst loadings. For details, see the supplementary material.

2,3-dimethylbutadiene and isoprene were enabled highly enantioselectively and with good yields, under neat conditions. Increasing the reaction temperature to above 0 °C was found to be deleterious for the reaction rate as catalyst methylation was observed presumably due to a collapse of the chiral ion pair consisting of silylated methyl ester substrate and counteranion.

We wer also able to lower the catalyst loading of IDPi **4a** to only 0.1 mol% and to conduct our model reaction on a gram-scale under neat conditions to furnish product **3a** in nearly quantitative yield and with an e.r. of 95:5 (Fig. 3A). Importantly, only small amounts of cyclopentadiene polymerization products were formed and could be easily filtered off during workup. As our silylium Lewis acid strategy conveniently provides self-drying conditions,[11,15g] we could also run this gram-scale reaction without inert gas atmosphere to give essentially identical results. In contrast, strictly anhydrous conditions in a Schlenk flask allowed us to lower the loading of silylating reagent to only 5 mol%. Further gram-scale experiments with methyl crotonate **1w** and substituted cinnamates (**1e** and **1k**, Fig. 3B-D) and with 0.1 mol% of catalyst gave equally high yields and enantioselectivities after prolonged reaction time.

In order to obtain deeper insight into reaction mechanism and the catalyst's mode of action, we investigated the reaction profile for methyl cinnamate **1a**, cyclopentadiene **2a** and (*S*,*S*)-**4a** at the DLPNO-CCSD(T)/def2-TZVP + C-PCM(toluene) // PBE-D3 (BJ)/def2-SVP level of theory (for details, see the supplementary material).[17] Silylation of the IDPi acid with allylsilane **5a** to give the active catalyst occurs instantaneously at r.t. as observed by NMR and propene formation was detected (Fig. 4A). Subsequently, the silyl group is transferred onto the carbonyl group of cinnamate **1a** to form a chiral ion pair (CIP, Fig. 4B) in an endothermal process (ΔG = 7.4 kcal/mol) with the *s*-trans conformation as the most stable intermediate. Interaction of cyclopentadiene with the CIP gives a reactant complex ($RC_{s\text{-trans}}$) as a subsequent intermediate towards the Diels–Alder transition states. The competing transition states for each of the endo-enantiomers ($TS_{s\text{-trans}}$; marked in black and blue) are predicted to give an e.r. of 93:7 ($\Delta\Delta G^{\ddagger}$=1.2 kcal/mol), which is in good agreement with the experimental data (e.r. 97:3, $\Delta\Delta G^{\ddagger}$=1.6 kcal/mol). The most stable TS features two stabilizing non-classical C-H···O hydrogen bonds (between an oxygen atom of the SO_2CF_3 group of the catalyst and the C-H groups of the cyclopentadiene) that are missing in the other TS structures. Subsequently, de-silylation and release of the product is thermodynamically favored rendering the silylated IDPi as the resting state within the catalytic cycle. We further investigated the CIP in greater detail to understand the origin of enantioselectivity (Fig. 4C). The electrostatic potential maps revealed that the most favorable interaction mode (ΔG = –23.8 kcal/mol) for this structure orients the phenyl ring of ester **1a** far from the counteranion, consistent with the high enantioselectivities observed for various substitutions at the 3-position. In addition, the methyl group of the substrate is pointing inside the chiral pocket of the IDPi moiety, overall resulting in a striking geometrical match of the ion pair. In this context, we also tested ethyl and benzyl *trans*-cinnamate as substrates, but not only detected sluggishly reactivity with catalyst **4a**, but also significantly diminished enantioselectivities (e.r. 75:25 with ethyl cinnamate; e.r. 57.5:42.5 with benzyl cinnamate, which can be rationalized by an improper fit with such bulkier groups.

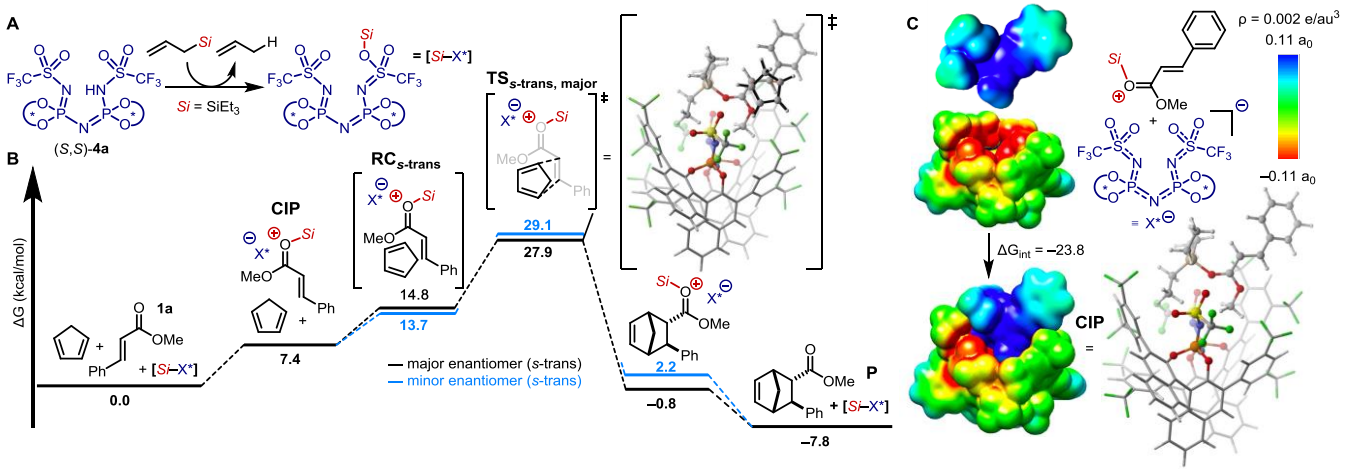


Figure 4. Computational Studies. A Catalyst activation. **B** Diels–Alder reaction profiles. **C** Interaction within the chiral ion pair (CIP); Geometry optimizations with PBE-D3(BJ)/def2-SVP; single-point energies with DLPNO-CCSD(T)/def2-TZVP+C-PCM(toluene). For more details, see the supplementary material.

In summary, we report the development of a catalytic asymmetric Diels–Alder methodology for a large variety of poorly reactive α,β-unsaturated methyl esters and different dienes to give the cycloaddition products in excellent yields, enantio- and diastereoselectivities. Many of the products have previously been inaccessible with known chiral Lewis acids, while the corresponding Diels–Alder reactions can now be accomplished with very low catalyst loadings of only 0.1-3 mol%. Future work will focus on overcoming remaining challenges in catalytic asymmetric Diels–Alder reactions and on synthetic applications towards important target structures.

ASSOCIATED CONTENT

Supporting Information

Additional detailed synthetic protocols, analytical data for all compounds and the computational strategy. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare the following competing interest: Patent WO2017037141 (A1) has been filed by the MPI für Kohlenforschung covering the IDPi catalyst class and their applications in asymmetric synthesis.

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Supporting Information

A Scalable and Highly Diastereo- and Enantioselective Catalytic Diels–Alder Reaction of α,β-Unsaturated Methyl Esters

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Contents

General Information and Instrumentation

Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. For all reactions under argon, dried and degassed solvents were used. Dry argon was purchased from Air Liquide with >99.5% purity. All reported yields, unless otherwise specified, refer to spectroscopically and chromatographically pure compounds. Nomenclature follows the suggestions proposed by the computer program ChemBioDraw of CBD/Cambridgesoft. The enantiomeric ratios were determined by HPLC or GC analysis employing a chiral stationary phase column specified in the individual experiment, by comparing the samples with the appropriate racemic mixtures. The diastereomeric ratios were determined by HPLC analysis or ^{1}H NMR analysis and specified in the individual experiment. The absolute configurations were determined by comparing the optical rotations with reported values available in literature. All other products were assigned by analogy.

Thin-layer chromatography (TLC) was performed using silica gel pre-coated plastic sheets (Polygram SIL G/UV254, 0.2 mm, with fluorescent indicator; Macherey-Nagel), which were visualized with a UV lamp (254 or 366 nm) and/or phosphomolybdic acid (PMA) stain and/or permanganate stain. Preparative thin-layer chromatography (PrepTLC) was performed on silica gel pre-coated glass plates SIL G-25 UV254 and SIL G-100 UV254 with 0.25 mm and 1.0 mm SiO_2 layers (Macherey-Nagel). Flash column chromatography was performed on Merck silica gel (60, particle size 0.040-0.063 mm). ^{1}H, ^{13}C, ^{19}F, ^{31}P nuclear magnetic resonance (NMR) spectra were recorded on a Bruker AV-500, AV-400 or DPX-300 spectrometer in a suitable deuterated solvent. The solvents employed and respective measuring frequencies are indicated for each experiment. The resonance multiplicity is described as s (singlet), d (doublet), t (triplet), q (quadruplet), p (pentet), hept (heptet), m (multiplet), and br (broad). All spectra were recorded at 298 K unless otherwise noted, processed with Bruker TOPSPIN or MestReNova suits of programs, and coupling constants are reported as observed. The residual deuterated solvent signal relative to tetramethylsilane was used as the internal reference in ^{1}H and ^{13}C NMR spectra (e.g. $CDCl_3$ = 7.26 ppm for ^{1}H, 77.160 ppm for ^{13}C), and are reported as follows: chemical shift in ppm (multiplicity, coupling constant *J* in Hz, number of protons). All spectra are broadband decoupled unless otherwise noted. Electron impact (EI) mass spectrometry (MS) was performed on a Finnigan MAT 8200 (70 eV) or MAT 8400 (70 eV) spectrometer. Electrospray ionization (ESI) mass spectrometry was conducted on a Bruker ESQ 3000 spectrometer. High resolution mass spectrometry (HRMS) was performed on a Finnigan MAT 95 (EI) or Bruker APEX III FTMS (7T magnet, ESI). The ionization method and mode of detection employed is indicated for the respective experiment. High performance liquid chromatography (HPLC) was performed on Shimadzu LC-20AD liquid chromatograph (SIL-20AC auto sampler, CMB-20A communication bus module, DGU-20A5 degasser, CTO-20AC column oven, SPD-M20A diode array detector), Shimadzu LC-20AB liquid chromatograph (SIL-20ACHT auto sampler, DGU-20A5 degasser, CTO-20AC column oven, SPD-M20A diode array detector), or Shimadzu LC-20AB liquid chromatograph (reversed phase, SIL-20ACHT auto sampler, CTOS3 20AC column oven, SPD-M20A diode array detector) using Daicel columns with a chiral stationary phase. All solvents used were HPLC-grade solvents purchased from Sigma-Aldrich. The column employed and the respective solvent mixture is indicated for each experiment. Optical rotations were measured on an Autopol IV automatic polarimeter (Rudolph Research Analytical) at 589 nm (sodium D line), 25 °C. Data are reported as: $[\alpha]_D^t$, concentration (c in g/100 mL), and in the corresponding solvent.

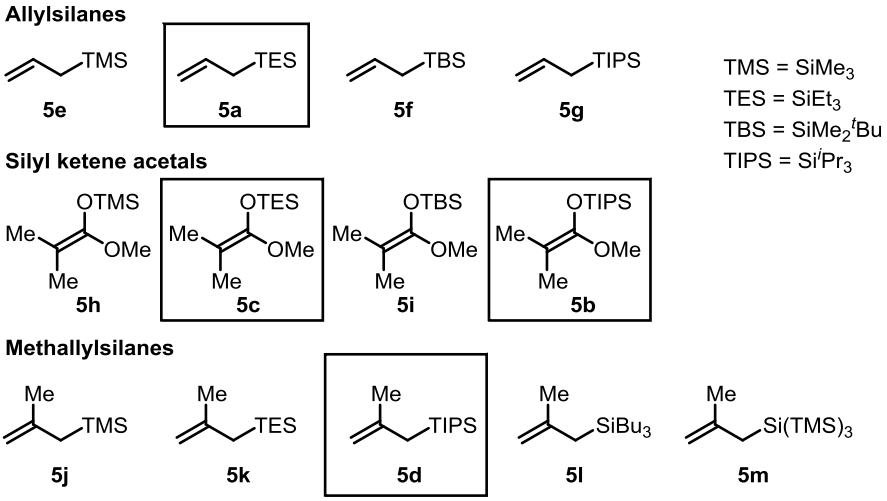
If available, α,β-unsaturated methyl esters have been purchased from commercial sources and the *E*/*Z* ratios were >99:1, unless stated otherwise. Other α,β-unsaturated methyl esters have been prepared as described previously with *E*/*Z* ratios of >99:1.[1]

Purification and storage of dienes

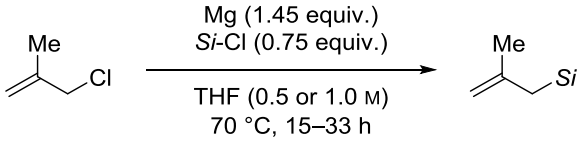
1,3-Cyclopentadiene was prepared by pyrolysis of dicyclopentadiene[2] and was stored in a Schlenk flask under argon at –78 °C. Other commercial dienes were washed several times with 1M NaOH, water and brine to remove the inhibitor (mostly BHT = 3,5-di-*tert*-butyl-4-hydroxytoluol). The dienes were then dried over $MgSO_4$, subsequently distilled under argon from $NaBH_4$ and stored in a Schlenk flask under argon at –20 °C. In some initial screening experiments, unpurified dienes were used as specified.

Synthesis and Characterization of Silylating Reagents

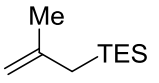
The following silylating reagents have been tested during the reaction development. Reagents **5a-d** were found optimal for individual combinations of substrate and catalyst.



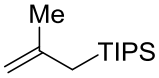
Allylsilanes **5e**, **5a**, **5f** and **5g** were purchased from commercial sources and used without further purification. Silyl ketene acetals (SKA) **5h**, **5c**, **5l**, **5b** were synthesized and purified as described previously.[1] Methallylsilane **5j** was purchased from commercial sources and used without further purification. Methallylsilane **5k**, **5d**, **5l**, **5m** were synthesized and purified according to a slightly modified literature procedure[3] and stored in Schlenk flasks under argon in a fridge at 5 °C.



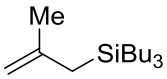
triethyl(2-methylallyl)silane (5k): To a 50 mL two-neck Schlenk-flask under argon equipped with a magnetic stirring bar and a reflux condenser was added magnesium (705 mg, 29.0 mmol). The apparatus was evacuated and purged with argon three times. Then, THF (2.00 mL) was added and to the resulting suspension was added one grain of iodine to initiate the reaction. A solution of 3-chloro-2-methylpropene (1.97 mL, 1.81 g, 20.0 mmol) and triethylsilyl chloride (2.52 mL, 2.26 g, 15.0 mmol) in THF (13.0 mL) was added dropwise using a syringe pump over 35 min (total volume 17.5 mL, 20 mL syringe, diameter 20 mm, pump rate: 0.50 mL · min^{-1}) to the reaction mixture under reflux (NOTE: a color change from yellow to a cloudy/turbid colorless suspension was immediately visible upon addition of the methallylchloride/silyl chloride solution). After the addition was complete, the reaction mixture was heated under reflux for an additional 33 h at 75 °C (oil bath temperature). The formed colorless precipitate was filtrated off and the residue was extracted with hexane (2 × 50 mL). The combined filtrate and extracts were concentrated under reduced pressure and triethyl(2-methylallyl)silane **5k** was obtained by distillation under reduced pressure (bp 48–52 °C at 3.3–5.3 mbar) as a colorless oil (1.80 g, 10.6 mmol, 71%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 4.61–4.56 (m, 1H), 4.53–4.48 (m, 1H), 1.73 (s, 3H), 1.56 (s, 2H), 0.96 (t, *J* = 7.9 Hz, 9H), 0.56 (q, *J* = 7.9 Hz, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ (mixture of rotamers) 144.2, 144.1, 108.3, 108.3, 25.4, 25.4, 23.3, 23.3, 7.5, 7.5, 3.7, 3.7;



^{29}Si NMR (99 MHz, $CDCl_3$) δ 5.4; **HRMS** (CI, ammonia) calculated for $C_{10}H_{26}NSi^+$ $[M+NH_4]^+$: 188.1829; found: 188.1828.

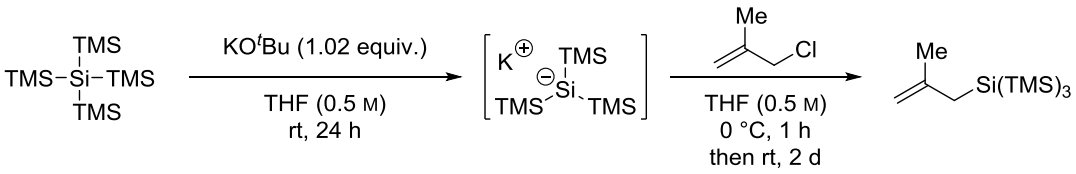
triisopropyl(2-methylallyl)silane (5d): 

Magnesium (705 mg, 29.0 mmol) was transferred to a 50 mL two neck round-bottom flask under argon equipped with a magnetic stirring bar and a reflux condenser. THF (2 m L) and a small amount of iodine were added to initiate the reaction and the light-brown solution was heated to 70 °C (oil bath temperature). A solution of 3-chloro-2-methylpropene (1.97 mL, 1.81 g, 20.0 mmol) and triisopropylsilyl chloride (3.21 mL, 2.89 g, 15 mmol) in THF (13.0 mL) was dropwise added over 30 min to the reaction mixture at reflux (NOTE: a color change from yellow to colorless was observed; formation of a colorless off-white precipitate was also observed during the addition). The reaction mixture was heated under reflux for an additional 15 h when the addition was complete. The precipitate was filtered off and the residue was extracted with hexane (2 × 50 mL). The combined filtrate and extracts were first distilled in a Vigreux column (7 cm) under atmospheric pressure to remove the excess of organic solvents. Triisopropyl(2-methylallyl)silane **5d** was obtained by distillation (Vigreux column, 7 cm) under reduced pressure (bp 85–87 °C at 12.6 mbar) as a colorless oil (2.15 g, 10.1 mmol, 50%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 4.63–4.59 (m, 2H), 1.79 (app t, J = 1.1 Hz, 3H), 1.67–1.62 (m, 2H), 1.11–1.02 (m, 21H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 144.6, 109.5, 25.8, 20.9, 18.9, 11.7; **^{29}Si NMR** (99 MHz, $CDCl_3$) δ 4.6; **HRMS** (CI, ammonia) calculated for $C_{13}H_{29}Si^+$ $[M+H]^+$: 213.2033; found: 213.2032.

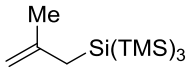
tributyl(2-methylallyl)silane (5l): 

To a 50 mL two-neck Schlenk-flask under argon equipped with a magnetic stirring bar and a reflux condenser was added magnesium (705 mg, 29.0 mmol). The apparatus was evacuated and purged with argon three times. Then, THF (2.00 mL) was added and to the resulting suspension was added one crystal of iodine to initiate the reaction. A solution of 3-chloro-2-methylpropene (1.97 mL, 1.81 g, 20.0 mmol) and triethylsilyl chloride (2.52 mL, 2.26 g, 15.0 mmol) in THF (13.0 mL) was added dropwise using a syringe pump over 35 min (total volume 17.5 mL, 20 mL syringe, diameter 20 mm, pump rate: 0.50 mL min^{-1}) to the reaction mixture under reflux (NOTE: a color change from yellow to a cloudy/turbid colorless suspension was immediately visible upon addition of the methallylchloride/silyl chloride solution). After the addition was complete, the reaction mixture was heated under reflux for an additional 33 h at 75 °C (oil bath temperature). The formed colorless precipitate was filtered off and the residue was extracted with *iso*-hexane (2 × 50 mL). The combined filtrate and extracts were concentrated under reduced pressure and tributylsilyl(2-methallyl)silane **5l** was obtained by distillation under reduced pressure (bp 104–107 °C at 3.3 mbar) as a colorless oil (2.73 g, 10.7 mmol, 71%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 4.58 (dq, J = 2.8, 1.4 Hz, 1H), 4.49 (dq, J = 2.0, 0.9 Hz, 1H), 1.73 (t, J = 1.1 Hz, 3H), 1.55 (d, J = 1.0 Hz, 2H), 1.37–1.24 (m, 12H), 0.89 (t, J = 7.1 Hz, 9H), 0.61–0.48 (m, 6H);); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 144.2, 108.4, 27.0, 26.2, 25.5, 24.3, 13.9, 12.5; **^{29}Si NMR** (99 MHz, $CDCl_3$) δ 1.7; **HRMS** (EI) calculated for $C_{16}H_{34}Si$: 254.2430; found: 254.2428.

Tris(trimethylsilyl)silylmethallylsilane **5m** was prepared according to a slightly modified procedure reported in the literature.[4]



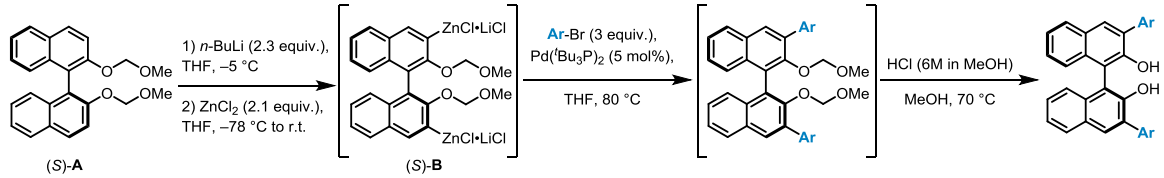
1,1,1,3,3,3-hexamethyl-2-(2-methylallyl)-2-(trimethylsilyl)trisilane (5m):



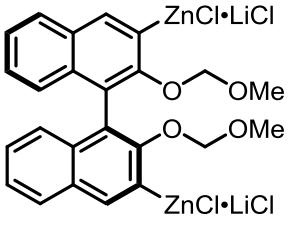
Tetrakis(trimethylsilyl)silane (160 mg, 0.50 mmol, 1.0 equiv.) was transferred to a 10 mL Schlenk-tube under argon and KO*t*Bu (1.0 M solution in THF, 58.2 mg, 0.52 mL, 0.52 mmol, 1.04 equiv.) was added at r.t.. The solution was stirred for 24 h at r.t. (NOTE: slow color change from colorless to yellow-orange was observed), then the solution of tris(trimethylsilyl)potassium was cooled to 0 °C and 3-chloro-2-methyl-1-propene (2.4 mL, 24 mmol) was added. The mixture was stirred for 1 h at 0° C, the ice bath was removed and the reaction was further stirred at r.t. (2 d), then treated at 0 °C with sat. aq. NH_4Cl (0.5 mL). The organic layer was separated and the aqueous layer was extracted with Et_2O (2 × 5 mL). The combined extracts were dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was filtered through a short pad of silica (using pentane as eluent), to afford the **5m** as a white waxy solid (134.2 mg, 0.44 mmol, 89%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 4.60 (s, 1H), 4.56 (s, 1H), 1.79 (s, 2H), 1.76 (s, 3H), 0.19 (s, 27H)); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 146.2, 109.0, 25.0, 18.6, 1.3; **HRMS** (EI) calculated for $C_{13}H_{34}Si_4$: 302.1732; found: 302.1727. The analytical data was in agreement with the data reported in the literature.[4]

Synthesis and Characterization of Catalysts

Synthesis of BINOL derivatives

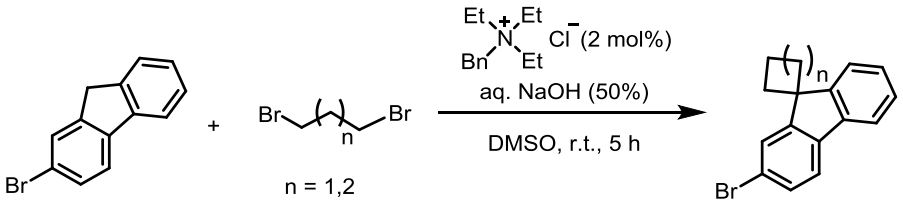


3,3'-zincated MOM-protected BINOL **(*S*)-B:**

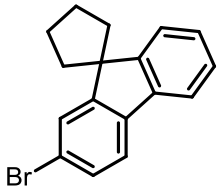


To a solution of MOM-protected BINOL (*S*)-**A** (5.92 g, 15.8 mmol) in THF (40 mL) under argon at –5 °C, *n*-BuLi in hexane (2.45 M, 22.6 mL, 55.3 mmol, 3.5 equiv.) was added over a period of 5 min (NOTE: The temperature was kept between –10 °C and –5 °C during the addition. The color changed from light yellow to deep red). The reaction was stirred between -10 °C and -5 °C for 4 h, during which the color changed from deep red to red-brownish. Then, the reaction mixture was cooled to –78 °C and a solution of $ZnCl_2$ in THF (0.96 M, 34.7 mL, 33.2 mmol, 2.1 equiv.) was added over a period of 20 min. The dry-ice bath was removed and the reaction was allowed to warm up to r.t. and stirred for additional 45 min, during which the color changed from red-brownish to light yellow. Then, the solvent was removed from the reaction vessel under reduced pressure by using a cooling trap with liquid nitrogen (NOTE: A voluminous foam results). Upon dryness, the organozinc compound was afforded as a pale yellow solid and dried on high vaccum overnight. A stock solution (0.27 M) in THF under argon was prepared (54 mL total volume) and stored in a fridge at –20 °C. The concentration was determined through deuterium incorporation after treatment with D_2O as analyzed by ^{1}H-NMR (~93%) with respect to the total volume and the initial molarity of (*S*)-**A** (15.8 mmol).

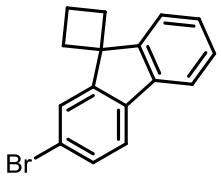
Representative procedure for derivatization of 2-bromo-9*H*-fluorene:



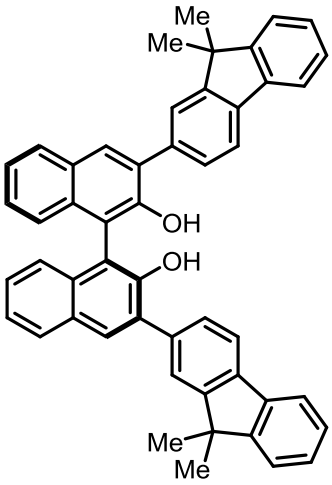
2'-bromospiro[cyclopentane-1,9'-fluorene]: Following a reported procedure,[5] aq. NaOH (50%, 8.8 mL, 110 mmol, 5.5 equiv.) was added dropwise to the mixture of 2-bromo-9*H*-fluorene (4.90 g, 20.0 mmol, 1.0 equiv.) and benzyl-triethylammonium chloride (91.1 g, 0.4 mmol, 2 mol%) in DMSO (20 mL) under argon at r.t. (NOTE: rapid color change from yellow to red). After the subsequent addition of 1,4-dibromobutane (2.4 mL, 20.0 mmol, 1.0 equiv.) (NOTE: color change from red to beige), the reaction was stirred for 5 hours at r.t.. Then, water (100 mL) and toluene (100 mL) were added and the organic layer was separated, dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was purified by column chromatography (hexanes) to yield 2'-bromospiro[cyclopentane-1,9'-fluorene] as a light yellow solid (3.70 g, 12.4 mmol, 62%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.69 – 7.63 (m, 1H), 7.59 – 7.52 (m, 2H), 7.47 – 7.39 (m, 2H), 7.35 – 7.29 (m, 2H), 2.19 – 2.04 (m, 8H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 156.51, 154.07, 138.65, 138.58, 129.91, 128.01, 127.04, 126.43, 123.02, 121.25, 121.06, 119.77, 57.94, 39.83, 27.07; **HRMS** (GC-EI) calculated for $C_{15}H_{11}Br$: 298.0357; found: 298.0356.



2'-bromospiro[cyclobutane-1,9'-fluorene]: Prepared according to the representative procedure on a 30 mmol scale for to give the title compound as a colorless viscous oil (3.0 g, 10.6 mmol, 35%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.90 (d, *J* = 1.7 Hz, 1H), 7.76 (dt, *J* = 7.7, 0.9 Hz, 1H), 7.64 (dt, *J* = 7.2, 1.0 Hz, 1H), 7.53 (d, *J* = 8.1 Hz, 1H), 7.46 (dd, *J* = 8.0, 1.8 Hz, 1H), 7.39 (td, *J* = 7.4, 1.3 Hz, 1H), 7.34 (td, *J* = 7.4, 1.2 Hz, 1H), 2.72 – 2.57 (m, 4H), 2.48 – 2.34 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.5, 152.0, 138.5, 138.4, 130.2, 128.1, 127.3, 126.3, 122.9, 121.4, 121.0, 119.7, 52.1, 33.3, 17.1; **HRMS** (GC-EI): calculated for $C_{16}H_{13}Br$: 284.0195; found: 284.0193.

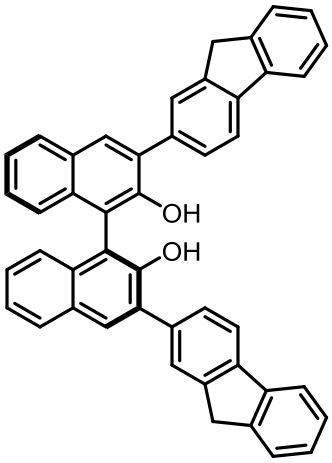


Representative procedure for Negishi cross-coupling reactions and subsequent MOM-deprotections: (*S*)-3,3'-bis(9,9-dimethyl-9H-fluoren-2-yl)-[1,1'-binaphthalene]-2,2'-diol

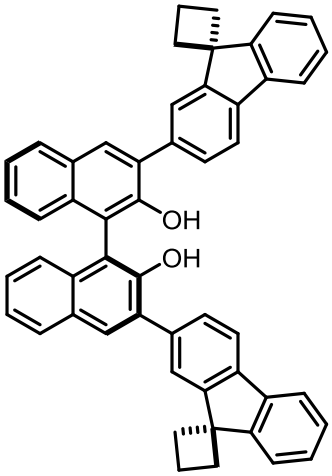


In a 2-neck flask under argon, 2-bromo-9,9-dimethyl-9H-fluorene (2.46 g, 9.0 mmol) and $Pd(^tBu_3P)_2$ (77 mg, 0.15 mmol) were dissolved in THF (60 mL). Then, a solution of organozinc BINOL (*S*)-**B** in THF (0.27 M, 11.1 mL, 3.0 mmol) was added at r.t. under stirring and the resulting reaction mixture was refluxed under argon for 18 h. The cooled reaction mixture was treated with sat. aq. NH_4Cl (30 mL) and extracted with MTBE (3 × 50 mL). The combined organic layers were washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The crude product was dissolved in MeOH or dioxane (30 mL), HCl in MeOH (12 mL, 1.25 M, 15 mmol) was added and the reaction solution was refluxed overnight. After evaporation of the solvent, the crude product was purified by column chromatography on silica gel (Hex/EtOAc 20:1→10:1) to give the title compound as an off-white solid (1.46 g, 72% over two steps). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.10 (s, 2H), 7.96 (d, *J* = 8.1 Hz, 2H), 7.84 (d, *J* = 7.9 Hz, 2H), 7.82 (d, *J* = 1.4 Hz, 2H), 7.79 – 7.76 (m, 2H), 7.73 (dd, *J* = 7.8, 1.6 Hz, 2H), 7.48 – 7.44 (m, 2H), 7.41 (ddd, *J* = 8.1, 6.8, 1.3 Hz, 2H), 7.38 – 7.32 (m, 6H), 7.28 (d, *J* = 8.5 Hz, 2H), 5.47 (s, 2H), 1.55 (s, 12H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.1, 154.0, 150.3, 139.1, 139.0, 136.5, 133.2, 131.4, 131.2, 129.7, 128.7, 128.6, 127.6, 127.4, 127.2, 124.5, 124.5, 124.1, 122.8, 120.3, 120.2, 112.8, 47.2, 27.4; **HRMS** (ESI) calculated for $C_{50}H_{37}O_2$ $(M-H)^-$: 669.2799; found 669.2805.

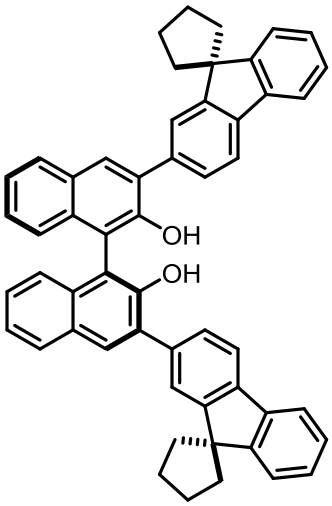
(*S*)-3,3'-di(9H-fluoren-2-yl)-[1,1'-binaphthalene]-2,2'-diol: Prepared according to the representative procedure on a 3 mmol scale for (*S*)-**B** with 2-bromo-9H-fluorene (2.57 g, 10.5 mmol) to give the title compound as an off-white solid (1.10 g, 59% over two steps). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.10 (s, 2H), 7.98 – 7.93 (m, 4H), 7.91 (d, *J* = 7.9 Hz, 2H), 7.85 (dt, *J* = 7.6, 0.9 Hz, 2H), 7.77 (dd, *J* = 7.9, 1.6 Hz, 2H), 7.58 (dt, *J* = 7.4, 1.0 Hz, 2H), 7.42 (ddt, *J* = 8.5, 7.4, 1.5 Hz, 4H), 7.38 – 7.32 (m, 4H), 7.29 (dd, *J* = 8.5, 1.2 Hz, 2H), 5.46 (s, 2H), 3.99 (s, 4H).; **^{13}C NMR** (126 MHz, $CDCl_3$) δ 150.3, 143.7, 141.5, 141.5, 136.0, 133.1, 131.4, 131.1, 129.7, 128.6, 128.5, 127.4, 127.0, 127.0, 126.4, 125.2, 124.5, 124.5, 120.2, 120.0, 112.7, 37.2; **HRMS** (ESI) calculated for $C_{46}H_{29}O_2$ $[M-H]^-$: 613.2173; found: 613.2170.



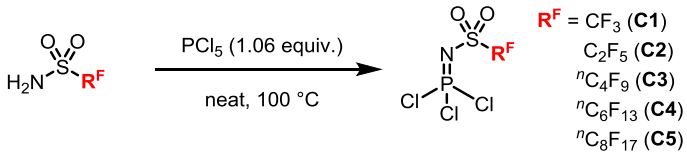
(*S*)-3,3'-di(spiro[cyclobutane-1,9'-fluoren]-2'-yl)-[1,1'-binaphthalene]-2,2'-diol: Prepared according to the representative procedure on a 3 mmol scale for (*S*)-**B** with 2'-bromospiro[cyclobutane-1,9'-fluorene] (3.0 g, 10.6 mmol) to give the title compound as an off-white solid (1.66 g, 80% over two steps). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.22 – 8.13 (m, 4H), 8.00 (d, *J* = 8.0 Hz, 2H), 7.88 – 7.80 (m, 4H), 7.79 – 7.72 (m, 4H), 7.48 – 7.42 (m, 2H), 7.42 – 7.36 (m, 6H), 7.34 (d, *J* = 8.4 Hz, 2H), 5.55 (s, 2H), 2.83 – 2.72 (m, 4H), 2.73 – 2.64 (m, 4H), 2.45 (p, *J* = 9.0, 8.5 Hz, 4H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 152.8, 152.7, 150.3, 139.2, 139.1, 136.8, 133.2, 131.4, 131.2, 129.7, 128.7, 128.6, 127.9, 127.4, 127.2, 124.6, 124.5, 124.2, 122.8, 119.8, 119.7, 112.8, 77.4, 52.2, 33.4, 33.4, 17.2.; **HRMS** (ESI) calculated for $C_{52}H_{37}O_2$ $[M\text{-}H]^-$: 693.2799; found: 693.2800.



(*S*)-3,3'-di(spiro[cyclopentane-1,9'-fluoren]-2'-yl)-[1,1'-binaphthalene]-2,2'-diol: Prepared according to the representative procedure on a 3.5 mmol scale for (*S*)-**B** with 2'-bromospiro[cyclopentane-1,9'-fluorene] (3.1 g, 10.4 mmol) to give the title compound as an off-white solid (2.11 g, 84% over two steps). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.16 (s, 2H), 8.04 – 7.98 (m, 2H), 7.89 (d, *J* = 1.5 Hz, 2H), 7.86 (d, *J* = 7.8 Hz, 2H), 7.79 (dd, *J* = 6.6, 1.8 Hz, 2H), 7.76 (dd, *J* = 7.8, 1.6 Hz, 2H), 7.52 (dd, *J* = 6.7, 1.8 Hz, 2H), 7.45 (ddd, *J* = 8.1, 6.7, 1.3 Hz, 2H), 7.41 – 7.34 (m, 6H), 7.30 (d, *J* = 8.4 Hz, 2H), 5.61 (s, 2H), 2.24 – 2.14 (m, 16H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.69, 154.63, 150.34, 139.18, 139.06, 136.73, 133.14, 131.22, 129.64, 128.48, 128.37, 127.72, 127.18, 126.83, 124.33, 124.31, 124.29, 123.01, 119.75, 119.56, 112.87, 57.89, 39.91, 39.87, 26.96; **HRMS** (ESI) calculated for $C_{52}H_{37}O_2$ $[M\text{-}H]^-$: 693.2799; found: 693.2800.

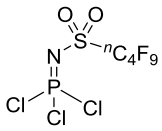


Synthesis of phosphorimidoyl trichlorides



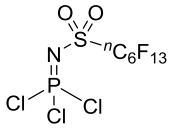
The syntheses of ((trifluormethyl)sulfonyl)phosphorimidoyl trichloride[6] **C1**, ((perfluoroethyl)sulfonyl)phosphorimidoyl trichloride[7] **C2** have been described previously. 1,1,2,2,3,3,4,4,4 nonafluoro-n-butanesulfonamide was synthesized as reported in the literature[8] and purified by recrystallization from toluene. 1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexane-1-sulfonamide and 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctane-1-sulfonamide were purchased from commercial sources and recrystallized twice from toluene to removed impurities of branched perfluoroalkylsulfonamides.

Representative procedure: ((Perfluoro-n-butyl)sulfonyl)phosphorimidoyl trichloride (C3)



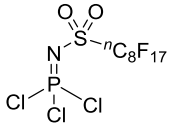
In a Schlenk flask under Argon equipped with a magnetic stirring bar connected to a two-neck flask containing NaOH pellets and a vacuum pump in this order, a mixture of sulfonamide (2.50 g, 8.36 mmol, 1.0 equiv) and PCl_5 (1.84 g, 8.86 mmol, 1.06 equiv) was heated to 100 °C under Argon for 1 h. The reaction was monitored by ^{1}H, ^{19}F, and ^{31}P NMR to ensure full consumption of sulfonamide. Removal of the excess amount of PCl_5 by prolonged evacuation in vacuum afforded the title compound in quantitative yield as colorless oil, which was stored in a Schlenk flask under argon. **^{19}F NMR** (471 MHz, CD_2Cl_2) δ -81.1 (t, *J* = 10.1 Hz, 3F), -112.6 (t, *J* = 14.2 Hz, 2F), -120.7 – -121.6 (m, 2F), -125.8 – -126.7 (m, 2F); **^{31}P NMR** (203 MHz, CD_2Cl_2) δ 17.0; **HRMS** (CI [DE] i-butane) calculated for $C_4H_1N_1O_2Cl_3F_9P_1S_1$ [M+H]: 433.8387; found: 433.8390.

((Perfluoro-n-hexyl)sulfonyl)phosphorimidoyl trichloride (C4):



Obtained as a colorless oil, which became a solid upon storage in a fridge at 4 °C. **^{19}F NMR** (471 MHz, $CDCl_3$) δ -80.7 (t, *J* = 9.9 Hz, 3F), -111.9 (tdt, *J* = 12.3, 6.7, 3.3 Hz, 2F), -120.0 (ddt, *J* = 19.6, 14.2, 6.6 Hz, 2F), -121.7 (p, *J* = 13.9 Hz, 2F), -122.4 – -122.9 (m, 2F), -126.1 (ttd, *J* = 13.1, 6.7, 6.1, 3.0 Hz, 2F); **^{31}P NMR** (203 MHz, $CDCl_3$) δ 15.3; **HRMS** (CI [DE] i-butane) calculated for $C_6H_1N_1O_2Cl_3F_{13}P_1S_1$ [M+H]: 533.8318; found: 533.8321.

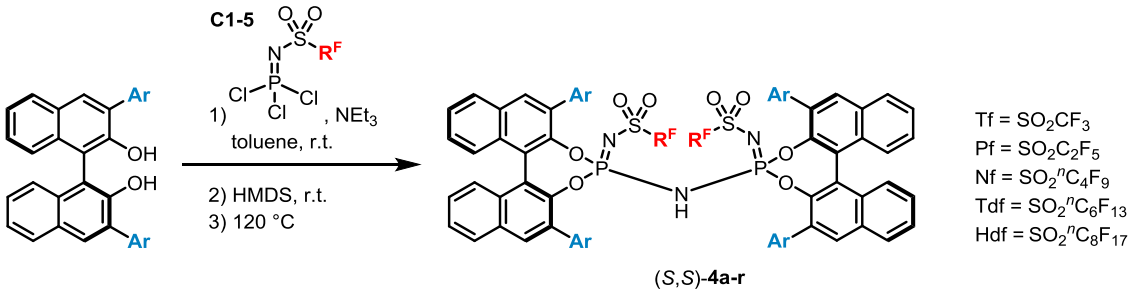
((Perfluoro-n-octyl)sulfonyl)phosphorimidoyl trichloride (C5):



Obtained as a colorless solid. **^{19}F NMR** (471 MHz, $CDCl_3$) δ -80.7 (t, *J* = 9.8 Hz, 3F), -111.9 (t, *J* = 15.4 Hz, 2F), -119.6 – -120.4 (m, 2F), -121.3 – -121.5 (m, 2F), -121.5 – -121.7 (m, 2F), -121.7 – -122.0 (m, 2F), -122.4 – -122.9 (m, 2F), -125.8 – -126.3 (m, 2F); **^{31}P NMR** (203 MHz, $CDCl_3$) δ 15.3; **HRMS** (CI [DE] i-butane) calculated for $C_8H_1N_1O_2Cl_3F_{17}P_1S_1$ [M+H]: 633.8260; found: 633.8255.

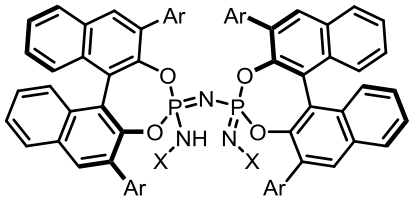
NOTE: ^{13}C spectra could not be obtained due to very low signal intensity.

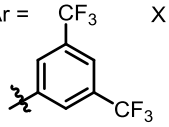
General Procedure for IDPi Synthesis



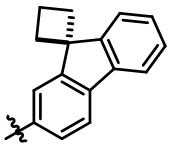
An improved protocol for the synthesis of imidodiphosphorimidate Brønsted acids was applied.[6] In a Schlenk tube under argon, a suspension of 3,3'-substituted (*S*,*S*)-BINOL (1.05 mmol, 2.1 equiv.) in toluene (2.5 mL) was treated with phosphorimidoyl trichloride **C1-5** (1.05 mmol, 2.1 equiv.) and then NEt_3 (1.12 mL, 8.0 mmol, 16 equiv.). The reaction mixture was stirred for 15 min at r.t., until neat hexamethyldisilazane (HMDS, 104 µL, 0.5 mmol, 1 equiv.) was added dropwise. The reaction mixture was stirred for additional 15 min at r.t., the Schlenk tube was subsequently sealed and heated to 120 °C for 3 days. After cooling to r.t., aq. HCl (10%) was added and the mixture was extracted with DCM or Et_2O. The combined organic layers were washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The crude material was purified by column chromatography on silica gel (hexane/MTBE 90:10→80:20→70:30→60:40→50:50 and/or 0.5–5% EtOAc in DCM) to afford the desired product as a salt. The corresponding IDPi Brønsted acids (*S*,*S*)-**4a-r** were obtained after acidification in DCM or Et_2O with aq. HCl (6 M) and evaporation of the solvent followed by drying under high vacuum as typically off-white solids.

The following IDPi catalysts have been prepared during the course of this work:

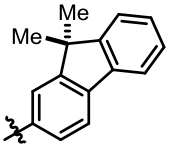


Ar = 

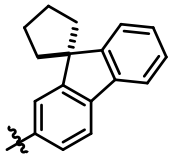
X = SO_2CF_3 (**4a**)
$SO_2C_2F_5$ (**4b**)
$SO_2C_4F_9$ (**4e**)
$SO_2C_6F_{13}$ (**4f**)
$SO_2C_8F_{17}$ (**4g**)



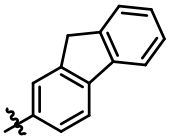
X = SO_2CF_3 (**4h**)
$SO_2C_2F_5$ (**4c**)
$SO_2C_4F_9$ (**4i**)
$SO_2C_6F_{13}$ (**4j**)
$SO_2C_8F_{17}$ (**4k**)



X = SO_2CF_3 (**4o**)
$SO_2C_2F_5$ (**4p**)

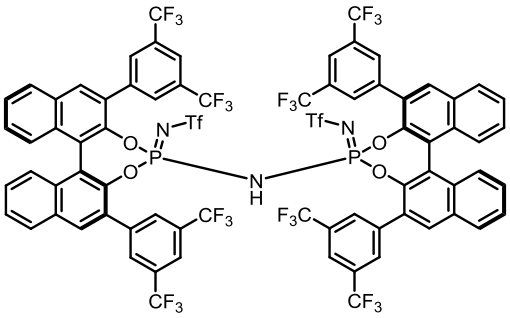


X = SO_2CF_3 (**4l**)
$SO_2C_2F_5$ (**4m**)
$SO_2C_4F_9$ (**4n**)
$SO_2C_6F_{13}$ (**4d**)



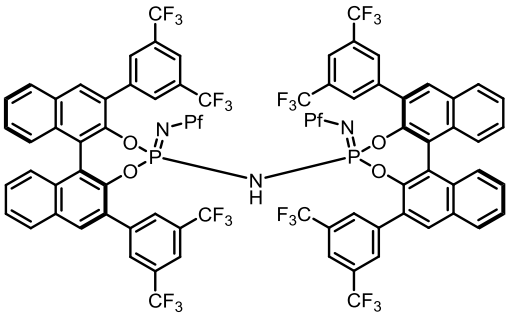
X = SO_2CF_3 (**4q**)
$SO_2C_2F_5$ (**4r**)

(*S*,*S*)-4a:



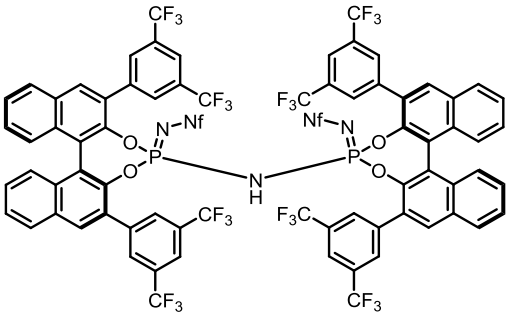
Prepared according to the general procedure on a 1.0 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/Et_2O 80:20 → 70:30 → 60:40 → 50:50; second: DCM/EtOAc 99:1 → 98:2 → 97:3 → 96:4 → 95:5). Off-white solid (914 mg, 0.51 mmol, 51%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.19 – 8.04 (m, 4H), 7.98 – 7.89 (m, 4H), 7.86 (s, 4H), 7.82 – 7.70 (m, 4H), 7.68 – 7.57 (m, 6H), 7.38 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 2H), 7.33 (s, 4H), 7.15 (d, *J* = 8.6 Hz, 2H), 6.66 (s, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.7 (t, *J* = 5.6 Hz), 141.6 (t, *J* = 4.9 Hz), 138.0, 137.7, 133.3, 132.5, 132.3, 132.2, 132.2, 132.1, 132.1, 132.0, 132.0, 131.9, 131.8, 131.7, 131.5, 131.3, 130.8, 130.5, 130.0, 129.9, 129.9, 129.5, 129.3, 128.8, 128.1, 127.4, 127.3, 126.7, 126.4, 126.3, 124.2, 124.1, 123.7, 122.1, 121.9, 121.3, 120.1, 119.9, 119.8, 117.5 (other signals not detected or observed); **^{19}F NMR** (280 MHz, $CDCl_3$) δ -62.5 (s, 12F), -63.1 (s, 12F), -79.0 (s, 6F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -15.4; **HRMS** (ESI) calculated for $C_{74}H_{32}N_3O_8F_{30}P_2S_2$ $(M\text{-}H)^-$: 1786.0633; found: 1786.0641.

(*S*,*S*)-4b:



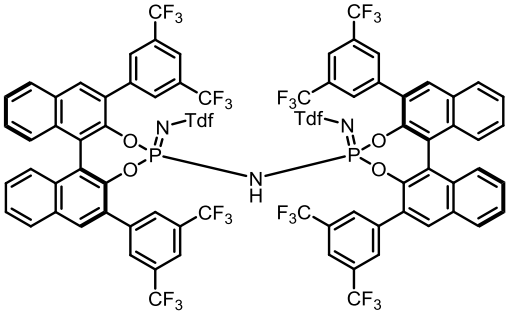
Prepared according to the general procedure on a 0.33 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/Et_2O 80:20 → 70:30 → 60:40 → 50:50; second: DCM/EtOAc 99:1 → 98:2 → 97:3 → 96:4 → 95:5). Off-white solid (329 mg, 0.174 mmol, 52%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.07 (t, *J* = 4.0 Hz, 4H), 7.96 – 7.88 (m, 4H), 7.86 (s, 2H), 7.83 (s, 2H), 7.79 (d, *J* = 8.5 Hz, 2H), 7.73 (ddd, *J* = 8.3, 5.9, 2.0 Hz, 2H), 7.64 (s, 4H), 7.63 – 7.59 (m, 2H), 7.38 (ddd, *J* = 8.4, 6.8, 1.3 Hz, 2H), 7.32 (s, 4H), 7.17 (d, *J* = 8.6 Hz, 2H), 6.64 (s, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.7 (t, *J* = 5.3 Hz), 141.9 (t, *J* = 5.1 Hz), 138.2, 137.9, 133.3, 132.3, 132.2, 132.1, 132.0, 132.0, 131.9, 131.8, 131.8, 131.7, 131.5, 131.4, 131.2, 130.9, 130.7, 129.9, 129.9, 129.5, 129.3, 128.7, 128.0, 127.3, 127.2, 126.8, 126.4, 126.3, 124.3, 124.1, 123.7, 122.1, 122.0, 122.0, 121.9, 121.9, 121.6, 119.9, 119.8, 118.5, 118.3, 118.0, 116.2, 116.0, 115.7, 111.5, 111.1 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -62.5 (s, 12F), -63.1 (s, 12F), -79.1 (s, 6F), -117.0 (s, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -14.7; **HRMS** (ESI) calculated for $C_{76}H_{32}N_3O_8P_2S_2F_{34}$ $(M\text{-}H)^-$: 1886.0569; found: 1886.0573.

(*S*,*S*)-4e:



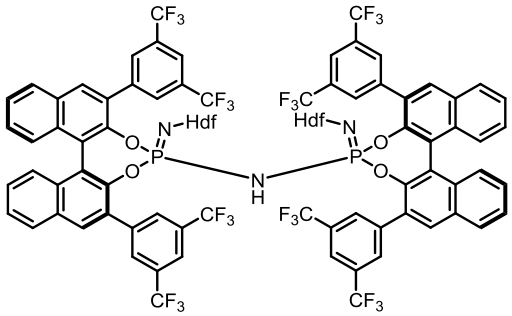
Prepared according to the general procedure on a 0.255 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/MTBE 90:10 → 80:20 → 70:30 → 60:40 → 50:50 → 40:60 → 30:70; second: DCM/EtOAc 99:1 → 98:2 → 97:3). Off-white solid (369 mg, 0.177 mmol, 69%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.15 (s, 2H), 8.10 (d, *J* = 8.2 Hz, 2H), 7.96 – 7.89 (m, 4H), 7.86 (s, 2H), 7.83 – 7.77 (m, 4H), 7.73 (ddd, *J* = 8.4, 5.3, 2.7 Hz, 2H), 7.67 – 7.59 (m, 6H), 7.39 (ddd, *J* = 8.2, 6.9, 1.0 Hz, 2H), 7.33 (s, 4H), 7.17 (d, *J* = 8.6 Hz, 2H), 6.65 (s, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.4 (t, *J* = 5.3 Hz), 141.7 (t, *J* = 5.0 Hz), 138.2, 137.4, 133.3, 132.5, 132.4, 132.2, 132.2, 132.2, 132.1, 132.0, 132.0, 132.0, 131.9, 131.7, 131.6, 131.2, 130.7, 130.5, 129.9, 129.4, 129.4, 129.4, 128.8, 128.1, 127.4, 127.3, 127.3, 126.7, 126.4, 126.2, 124.2, 124.1, 123.8, 122.2, 122.2, 122.2, 122.1, 121.9, 121.9, 121.7, 119.9, 119.7, 116.0 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -62.5 (s, 12F), -63.35 (s, 12F), -80.98 (t, *J* = 10.1 Hz, 6F), -112.47 (d, *J* = 261.2 Hz, 2F), -113.30 (d, *J* = 264.6 Hz, 2F), -120.91 (s, 4F), -125.87 (d, *J* = 296.8 Hz, 2F), -126.71 (d, *J* = 297.4 Hz, 2F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -15.1; **HRMS** (ESI) calculated for $C_{80}H_{32}F_{42}N_3O_8P_2S_2$ $(M\text{-}H)^-$: 2086.0441; found: 2086.0427.

(*S*,*S*)-4f:



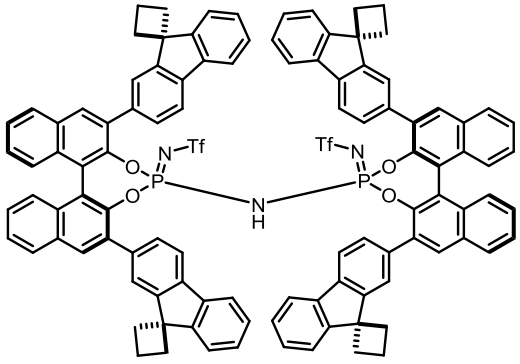
Prepared according to the general procedure on a 0.174 mmol scale (with respect to HMDS), purified by column chromatography (first: hexane/MTBE 90:10 → 80:20 → 70:30 → 60:40 → 50:50 → 40:60 → 30:70; second: DCM/EtOAc 99:1 → 98:2) and acidified in Et_2O instead of DCM. Off-white solid (237 mg, 0.104 mmol, 60%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.15 (s, 2H), 8.10 (d, *J* = 8.2 Hz, 2H), 7.96 – 7.88 (m, 4H), 7.86 (s, 2H), 7.82 – 7.76 (m, 4H), 7.73 (ddd, *J* = 8.4, 5.4, 2.5 Hz, 2H), 7.66 – 7.58 (m, 6H), 7.39 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 2H), 7.33 (s, 4H), 7.17 (d, *J* = 8.5 Hz, 2H), 6.65 (s, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.4 (t, *J* = 5.6 Hz), 141.7 (t, *J* = 4.6 Hz), 138.2, 137.4, 133.3, 132.5, 132.4, 132.2, 132.2, 132.2, 132.1, 132.0, 132.0, 132.0, 131.9, 131.7, 131.6, 131.2, 130.7, 130.5, 129.9, 129.4, 129.4, 128.8, 128.1, 127.3, 127.3, 126.7, 126.4, 126.2, 124.2, 124.1, 123.8, 122.3, 122.2, 122.2, 122.2, 122.2, 122.0, 121.9, 121.9, 121.8, 121.8, 121.8, 121.7, 119.9, 119.7 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -62.6 (s, 12F), -63.4 (s, 12F), -81.0 (t, *J* = 9.6 Hz, 6F), -112.3 (d, *J* = 256.1 Hz, 2F), -113.2 (d, *J* = 259.1 Hz, 2F), -120.1 (d, *J* = 61.2 Hz, 4F), -122.1 (s, 4F), -123.0 (s, 4F), -126.4 (d, *J* = 13.6 Hz, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -15.1; **HRMS** (ESI) calculated for $C_{84}H_{32}F_{50}N_3O_8P_2S_2$ $(M\text{-}H)^-$: 2286.0313; found: 2286.0296.

(*S*,*S*)-4g:



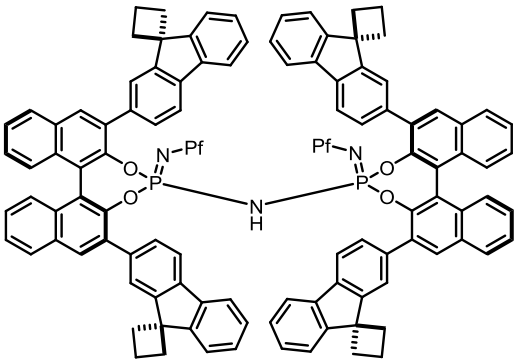
Prepared according to the general procedure on a 0.236 mmol scale (with respect to HMDS), purified by column chromatography (first: hexane/MTBE 90:10 → 80:20 → 70:30 → 60:40 → 50:50 → 40:60 → 30:70; second: DCM/EtOAc 99.5:0.5 → 99:1 → 98:2) and acidified in Et_2O instead of DCM. Off-white solid (85 mg, 0.034 mmol, 15%). **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.15 (s, 2H), 8.10 (d, *J* = 8.2 Hz, 2H), 7.96 – 7.88 (m, 4H), 7.85 (s, 2H), 7.82 – 7.76 (m, 4H), 7.73 (ddd, *J* = 8.3, 5.8, 2.1 Hz, 2H), 7.67 – 7.59 (m, 6H), 7.39 (ddd, *J* = 8.4, 6.9, 1.3 Hz, 2H), 7.33 (s, 4H), 7.17 (d, *J* = 8.6 Hz, 2H), 6.65 (s, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.5 (t, *J* = 5.0 Hz), 141.8 (t, *J* = 5.3 Hz), 138.2, 137.5, 133.3, 132.5, 132.4, 132.2, 132.2, 132.2, 132.1, 132.0, 131.9, 131.9, 131.8, 131.7, 131.6, 131.2, 130.7, 130.5, 129.9, 129.9, 129.9, 129.4, 129.3, 128.8, 128.1, 127.3, 126.7, 126.4, 126.3, 124.2, 124.1, 123.8, 122.2, 122.2, 122.1, 122.1, 121.9, 121.8, 121.8, 121.8, 119.9, 119.8 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -62.6 (s, 12F), -63.4 (s, 12F), -80.9 (t, *J* = 10.0 Hz, 6F), -112.3 (d, *J* = 258.7 Hz, 2F), -113.2 (d, *J* = 260.5 Hz, 2F), -120.0 (d, *J* = 51.2 Hz, 4F), -121.1 – -122.8 (m, 12F), -122.9 (s, 4F), -126.3 (s, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -14.8; **HRMS** (ESI) calculated for $C_{88}H_{32}F_{58}N_3O_8P_2S_2$ $(M\text{-}H)^-$: 2486.0186; found: 2486.0164.

(*S*,*S*)-4h:



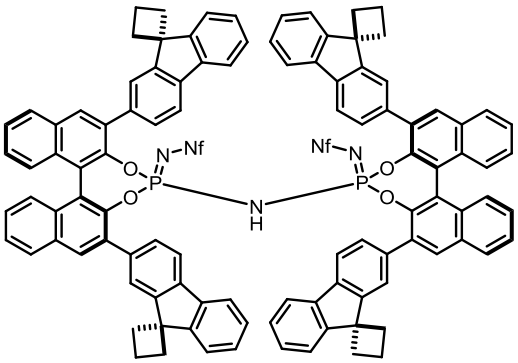
Prepared according to the general procedure on a 0.15 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 20:1 → 9:1 → 4:1 → 2:1). Off-white solid (112 mg, 0.064 mmol, 43%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.14 – 8.05 (m, 6H), 7.93 – 7.82 (m, 4H), 7.82 – 7.79 (m, 4H), 7.70 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 2H), 7.66 – 7.62 (m, 2H), 7.62 – 7.58 (m, 4H), 7.50 (dd, *J* = 8.1, 5.7 Hz, 4H), 7.41 (ddd, *J* = 8.4, 6.7, 1.3 Hz, 2H), 7.33 (dd, *J* = 7.2, 1.4 Hz, 2H), 7.30 (td, *J* = 7.5, 1.1 Hz, 2H), 7.26 – 7.15 (m, 10H), 6.55 (d, *J* = 8.0 Hz, 2H), 6.44 (dd, *J* = 7.9, 1.6 Hz, 2H), 6.09 (dd, *J* = 7.9, 1.6 Hz, 2H), 2.84 – 2.76 (m, 2H), 2.68 – 2.53 (m, 8H), 2.42 – 2.33 (m, 8H), 2.29 – 2.15 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.0, 152.9, 152.5, 151.9, 144.0 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 139.5, 139.0, 138.8, 138.6, 135.1, 135.0, 134.5, 134.4, 132.3, 132.0, 132.0, 131.9, 131.8, 131.4, 129.1, 128.9, 128.9, 128.7, 128.1, 127.6, 127.4, 127.3, 127.1, 127.0, 126.9, 126.7, 126.6, 124.1, 123.6, 122.6, 122.5, 121.9, 120.1, 119.8, 119.2, 118.7, 118.3, 117.5, 52.1, 52.1, 33.7, 33.1, 32.8, 32.7, 17.1 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -78.3 (s, 6F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.6; **HRMS** (ESI) calculated for $C_{106}H_{72}N_3O_8F_6P_2S_2$ $(M\text{-}H)^-$: 1754.4146; found: 1754.4158.

(*S*,*S*)-4c:



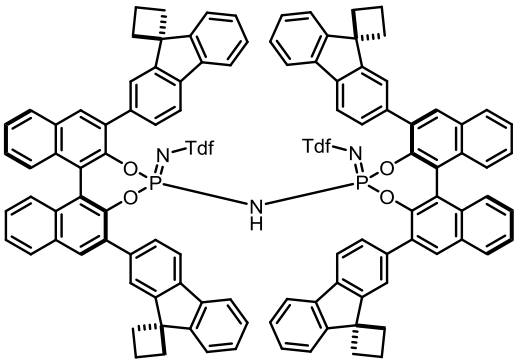
Prepared according to the general procedure on a 0.071 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 10:1 → 4:1 → 2:1 → 1:1). Off-white solid (95 mg, 0.051 mmol, 72%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.09 (s, 2H), 8.06 (dd, *J* = 8.4, 5.8 Hz, 4H), 7.92 – 7.84 (m, 4H), 7.83 – 7.77 (m, 4H), 7.71 (ddd, *J* = 8.3, 6.9, 1.3 Hz, 2H), 7.66 – 7.63 (m, 2H), 7.59 (ddd, *J* = 8.2, 6.6, 1.3 Hz, 2H), 7.56 (d, *J* = 1.6 Hz, 2H), 7.53 (dt, *J* = 7.6, 0.9 Hz, 2H), 7.47 – 7.43 (m, 2H), 7.40 (ddd, *J* = 8.5, 6.7, 1.3 Hz, 2H), 7.35 (d, *J* = 7.9 Hz, 2H), 7.31 – 7.27 (m, 4H), 7.25 – 7.19 (m, 4H), 7.19 – 7.16 (m, 2H), 7.09 (s, 2H), 6.49 (d, *J* = 8.0 Hz, 2H), 6.38 (dd, *J* = 8.0, 1.6 Hz, 2H), 6.33 (dd, *J* = 7.9, 1.6 Hz, 2H), 2.84 – 2.76 (m, 2H), 2.67 – 2.52 (m, 8H), 2.41 – 2.23 (m, 13H), 2.18 – 2.11 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.1, 153.0, 152.4, 151.9, 144.1 (t, *J* = 5.0 Hz), 143.0 t, *J* = 5.0 Hz), 139.7, 139.1, 138.8, 138.6, 135.1, 135.1, 134.5, 134.2, 132.3, 132.1, 131.9, 131.8, 131.7, 131.5, 129.3, 129.0, 128.9, 128.9, 128.1, 127.5, 127.3, 127.1, 127.0, 126.9, 126.8, 126.7, 126.5, 124.0, 123.6, 122.5, 122.4, 121.8, 119.9, 119.2, 118.7, 118.3, 52.1, 52.1, 33.5, 33.0, 32.8, 17.1, 17.0 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -79.0 (s, 6F), -114.8 – -116.8 (m, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -17.5; **HRMS** (ESI) calculated for $C_{108}H_{72}N_3O_8F_{10}P_2S_2$ $(M\text{-}H)^-$: 1854.4082; found: 1854.4089.

(*S*,*S*)-4i:



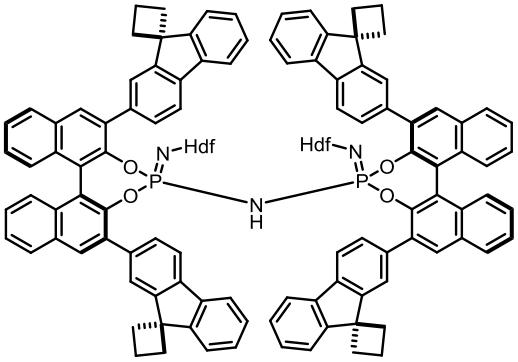
Prepared according to the general procedure on a 0.076 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1). Off-white solid (99 mg, 0.048 mmol, 67%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.08 (s, 2H), 8.06 (d, *J* = 8.3 Hz, 2H), 8.03 (dd, *J* = 8.6, 1.3 Hz, 2H), 7.88 (td, *J* = 5.9, 5.2, 1.4 Hz, 4H), 7.81 (d, *J* = 1.6 Hz, 2H), 7.77 (d, *J* = 7.5 Hz, 2H), 7.72 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 2H), 7.67 – 7.64 (m, 2H), 7.60 – 7.54 (m, 6H), 7.41 (d, *J* = 8.0 Hz, 2H), 7.40 – 7.35 (m, 4H), 7.32 – 7.27 (m, 4H), 7.24 (dd, *J* = 7.4, 1.3 Hz, 2H), 7.20 (td, *J* = 7.5, 1.2 Hz, 4H), 7.05 (s, 2H), 6.60 (dd, *J* = 7.9, 1.6 Hz, 2H), 6.55 (d, *J* = 8.0 Hz, 2H), 6.34 (dd, *J* = 7.9, 1.6 Hz, 2H), 2.81 – 2.74 (m, 2H), 2.69 – 2.54 (m, 8H), 2.38 – 2.21 (m, 12H), 2.17 – 2.08 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.1, 152.9, 152.3, 152.1, 144.2 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 139.7, 139.1, 138.9, 138.6, 135.1, 135.0, 134.4, 133.9, 132.3, 132.1, 131.8, 131.7, 131.3, 129.5, 129.1, 128.9, 128.7, 128.1, 127.4, 127.3, 127.3, 127.1, 127.0, 126.8, 126.6, 126.5, 123.8, 123.7, 123.6, 122.4, 121.8, 119.8, 119.3, 118.7, 118.3, 52.1, 52.0, 33.2, 33.1, 32.7, 17.1, 17.0 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -81.0 (t, *J* = 10.1 Hz, 3F), -111.0 – -112.6 (m, 2F), -121.1 (q, *J* = 11.1 Hz, 2F), -125.1 – -126.9 (m, 2F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.8; **HRMS** (ESI) calculated for $C_{112}H_{72}N_3O_8F_{18}P_2S_2$ $(M\text{-}H)^-$: 2054.3954; found: 2054.3944.

(*S*,*S*)-4j:



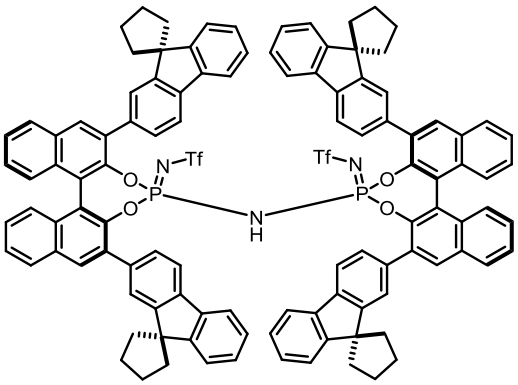
Prepared according to the general procedure on a 0.5 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1). Off-white solid (205 mg, 0.091 mmol, 64%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.10 (s, 2H), 8.07 (d, *J* = 8.3 Hz, 2H), 8.04 – 8.00 (m, 2H), 7.91 – 7.84 (m, 4H), 7.81 (d, *J* = 1.6 Hz, 2H), 7.76 (d, *J* = 7.5 Hz, 2H), 7.72 (ddd, *J* = 8.2, 6.8, 1.3 Hz, 2H), 7.63 (d, *J* = 7.5 Hz, 2H), 7.58 (ddd, *J* = 8.2, 5.9, 2.1 Hz, 2H), 7.56 – 7.51 (m, 4H), 7.42 – 7.37 (m, 6H), 7.30 (d, *J* = 7.4 Hz, 2H), 7.28 (d, *J* = 8.0 Hz, 2H), 7.23 (td, *J* = 7.4, 1.2 Hz, 2H), 7.21 – 7.18 (m, 2H), 7.18 – 7.15 (m, 2H), 7.07 (s, 2H), 6.60 (d, *J* = 8.0 Hz, 4H), 6.37 (dd, *J* = 7.9, 1.6 Hz, 2H), 2.83 – 2.73 (m, 2H), 2.68 – 2.52 (m, 8H), 2.38 – 2.22 (m, 12H), 2.18 – 2.08 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.1, 152.9, 152.3, 152.1, 144.2 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 139.7, 139.1, 139.0, 138.6, 135.1, 134.9, 134.3, 134.0, 132.3, 132.1, 131.8, 131.7, 131.3, 129.4, 129.1, 128.9, 128.7, 128.1, 127.4, 127.3, 127.1, 127.0, 126.8, 126.6, 126.5, 126.5, 123.8, 123.7, 123.6, 122.4, 122.4, 122.0, 119.7, 119.2, 118.7, 118.4, 52.1, 52.0, 33.2, 33.1, 33.1, 32.6, 17.1, 17.0 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -80.8 (t, *J* = 9.7 Hz, 6F), -110.4 – -112.6 (m, 4F), -120.1 (dt, *J* = 32.4, 14.4 Hz, 4F), -121.8 (p, *J* = 13.1 Hz, 4F), -122.6 – -123.2 (m, 4F), -126.2 (t, *J* = 14.6 Hz, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.8; **HRMS** (ESI) calculated for $C_{116}H_{72}N_3O_8F_{26}P_2S_2$ $(M\text{-}H)^-$: 2254.3827; found: 2254.3809.

(*S*,*S*)-4k:



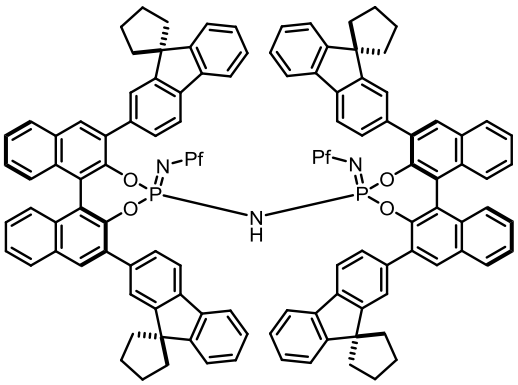
Prepared according to the general procedure on a 0.22 mmol scale (with respect to HMDS) and purified by column chromatography (first: hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1; second: DCM/EtOAc 99.5:0.5 → 99:1 → 98:2). Off-white solid (50 mg, 0.02 mmol, 9%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.11 (s, 2H), 8.05 (dd, *J* = 20.2, 8.3 Hz, 4H), 7.88 (d, *J* = 8.1 Hz, 4H), 7.82 (s, 2H), 7.80 – 7.69 (m, 4H), 7.64 (d, *J* = 7.5 Hz, 2H), 7.61 – 7.51 (m, 6H), 7.39 (q, *J* = 8.3 Hz, 6H), 7.30 (dd, *J* = 17.3, 7.4 Hz, 4H), 7.24 – 7.14 (m, 6H), 7.08 (s, 2H), 6.61 (dd, *J* = 8.2, 3.0 Hz, 4H), 6.39 (d, *J* = 7.9 Hz, 2H), 2.85 – 2.75 (m, 2H), 2.71 – 2.51 (m, 8H), 2.40 – 2.23 (m, 12H), 2.19 – 2.10 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.1, 152.9, 152.3, 152.1, 144.2 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 139.7, 139.1, 139.0, 138.6, 135.1, 134.8, 134.3, 134.0, 132.3, 132.1, 131.9, 131.8, 131.7, 131.3, 129.5, 129.1, 128.9, 128.7, 128.1, 127.4, 127.3, 127.1, 127.0, 126.8, 126.6, 126.5, 126.5, 123.8, 123.7, 122.4, 122.4, 122.0, 119.7, 119.3, 118.7, 118.4, 52.1, 52.0, 33.3, 33.1, 33.1, 32.6, 17.1, 17.0 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -80.8 (t, *J* = 9.8 Hz, 6F), -110.5 – -112.8 (m, 4F), -120.1 (p, *J* = 12.8, 11.4 Hz, 4F), -121.6 (m, 4F), -121.8 – -122.3 (m, 8F), -122.8 (dd, *J* = 22.3, 11.9 Hz, 4F), -126.1 (t, *J* = 14.2 Hz, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.7; **HRMS** (ESI) calculated for $C_{120}H_{72}N_3O_8F_{34}P_2S_2$ $(M\text{-}H)^-$: 2454.3699; found: 2454.3676.

(*S*,*S*)-4l:



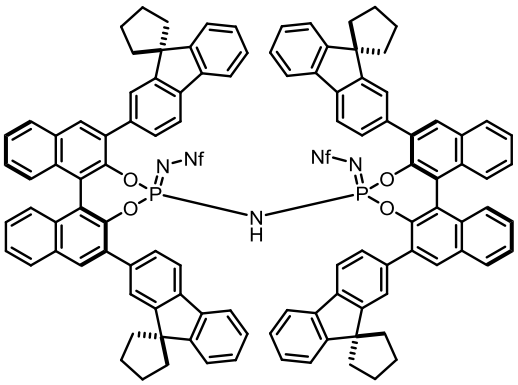
Prepared according to the general procedure on a 0.066 mmol scale (with respect to HMDS) and purified by column chromatography (5% EtOAc, 20% DCM, 75% hexanes). Off-white solid (106 mg, 0.058 mmol, 88%). **^{1}H NMR** (500 MHz, CD_2Cl_2): δ 8.12 (s, 2H), 8.08 (t, *J* = 8.1 Hz, 4H), 7.86 (t, *J* = 7.5 Hz, 2H), 7.80 (d, *J* = 8.5 Hz, 2H), 7.69 (dd, *J* = 8.5, 6.9 Hz, 2H), 7.61 (ddd, *J* = 8.1, 6.3, 1.5 Hz, 2H), 7.58 – 7.52 (m, 4H), 7.47 – 7.43 (m, 4H), 7.43 – 7.36 (m, 6H), 7.34 (dt, *J* = 7.0, 3.0 Hz, 2H), 7.28 – 7.23 (m, 4H), 7.23 – 7.17 (m, 6H), 7.16 (s, 2H), 6.68 (d, *J* = 7.9 Hz, 2H), 6.51 (dd, *J* = 7.9, 1.6 Hz, 2H), 6.30 – 6.22 (m, 2H), 2.22 (qd, *J* = 10.6, 9.1, 5.4 Hz, 2H), 2.17 – 1.91 (m, 22H), 1.88 – 1.60 (m, 8H); **^{13}C NMR** (126 MHz, CD_2Cl_2) δ 154.82, 154.75, 154.47, 153.79, 139.53, 138.85, 138.82, 138.64, 134.96, 134.52, 134.39, 133.87, 132.15, 131.78, 131.56, 131.36, 129.13, 128.67, 128.54, 128.43, 127.76, 127.48, 127.30, 126.84, 126.81, 126.77, 126.54, 126.41, 123.85, 123.65, 123.27, 122.85, 122.72, 121.87, 119.66, 119.11, 118.69, 118.24, 57.89, 57.77, 39.94, 39.84, 39.04, 38.87, 26.94, 26.73, 26.57, 26.41 (other signals not detected or observed); **^{19}F NMR** (470 MHz, CD_2Cl_2) δ -78.7 (s, 6F); **^{31}P NMR** (200 MHz, CD_2Cl_2) δ -16.9; **HRMS** (ESI) calculated for $C_{110}H_{80}N_3O_8F_6P_2S_2$ $(M-H)^-$: 1810.4772; found: 1810.4779.

(*S*,*S*)-4m:



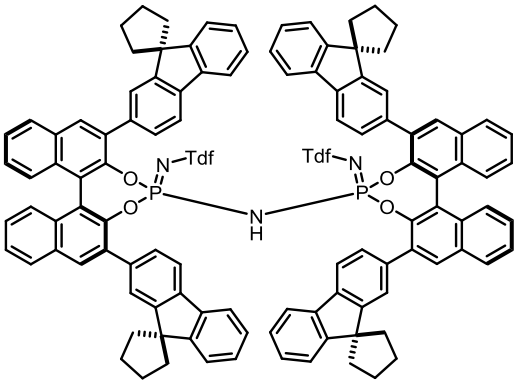
Prepared according to the general procedure on a 0.25 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 20:1 → 9:1 → 4:1 → 2:1). Off-white solid (238 mg, 0.124 mmol, 50%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.03 (q, *J* = 8.3 Hz, 6H), 7.86 – 7.81 (m, 4H), 7.68 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 2H), 7.58 (ddd, *J* = 8.2, 6.4, 1.5 Hz, 2H), 7.54 (d, *J* = 7.5 Hz, 2H), 7.51 (d, *J* = 1.6 Hz, 2H), 7.43 – 7.37 (m, 8H), 7.31 (ddd, *J* = 7.9, 4.9, 2.1 Hz, 4H), 7.25 – 7.14 (m, 10H), 7.02 (s, 2H), 6.59 (d, *J* = 8.0 Hz, 2H), 6.47 (dd, *J* = 8.0, 1.6 Hz, 2H), 6.30 (dd, *J* = 7.9, 1.7 Hz, 2H), 2.29 – 2.19 (m, 2H), 2.13 – 1.95 (m, 22H), 1.86 – 1.69 (m, 8H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 155.3, 155.2, 154.6, 154.2, 144.3 (t, *J* = 5.0 Hz), 143.3 (t, *J* = 5.0 Hz), 140.2, 139.5, 139.3, 138.9, 135.3, 134.7, 134.5, 132.5, 132.3, 132.2, 132.0, 132.0, 131.8, 129.5, 129.1, 128.9, 128.2, 127.7, 127.5, 127.4, 127.3, 127.3, 127.1, 127.0, 126.7, 126.7, 124.1, 124.0, 123.8, 123.1, 123.0, 122.0, 120.3, 119.6, 119.0, 118.7, 58.2, 58.2, 40.4, 40.0, 39.3, 27.3, 27.1, 26.9 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -78.9 (s, 6F), -114.8 – -116.5 (m, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -17.3; **HRMS** (ESI) calculated for $C_{112}H_{80}N_3O_8F_{10}P_2S_2$ $(M-H)^-$: 1910.4708; found: 1910.4713.

(*S*,*S*)-4n:



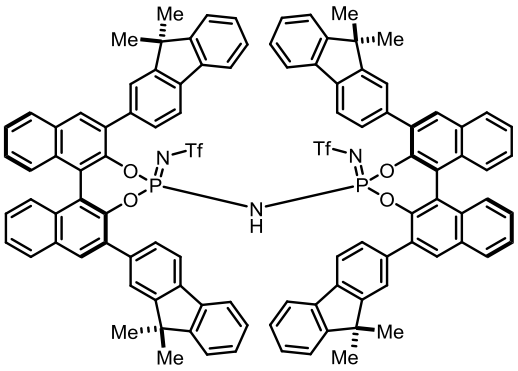
Prepared according to the general procedure on a 0.086 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 20:1 → 9:1 → 4:1 → 2:1). Off-white solid (57 mg, 0.027 mmol, 32%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 7.98 – 7.92 (m, 4H), 7.89 (d, *J* = 8.2 Hz, 2H), 7.77 (t, *J* = 7.5 Hz, 2H), 7.71 (d, *J* = 8.6 Hz, 2H), 7.60 (ddd, *J* = 8.3, 6.7, 1.3 Hz, 2H), 7.49 (ddd, *J* = 7.7, 6.1, 2.0 Hz, 4H), 7.43 (d, *J* = 1.6 Hz, 2H), 7.37 (d, *J* = 7.9 Hz, 2H), 7.32 (d, *J* = 7.4 Hz, 2H), 7.30 – 7.25 (m, 4H), 7.25 – 7.21 (m, 4H), 7.17 – 7.12 (m, 4H), 7.12 – 7.07 (m, 6H), 6.88 (s, 2H), 6.50 (t, *J* = 7.8 Hz, 4H), 6.33 (dd, *J* = 7.9, 1.6 Hz, 2H), 2.07 – 1.86 (m, 24H), 1.75 – 1.68 (m, 2H), 1.66 – 1.48 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 155.0, 154.8, 154.4, 153.9, 144.3 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 140.0, 139.3, 139.1, 138.7, 135.1, 135.0, 134.3, 133.9, 132.3, 132.1, 131.8, 131.7, 131.7, 131.3, 129.5, 128.8, 128.6, 127.8, 127.3, 127.1, 127.0, 126.7, 126.5, 126.4, 126.3, 124.0, 123.6, 123.4, 122.9, 122.6, 121.7, 120.0, 119.3, 118.7, 118.4, 58.1, 57.9, 39.7, 39.6, 39.3, 39.0, 27.1, 26.8, 26.6, 26.5 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -80.9 (t, *J* = 10.1 Hz, 6F), -110.9 – -112.7 (m, 4F), -121.0 (q, *J* = 10.7 Hz, 4F), -125.2 – -126.9 (m, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.7; **HRMS** (ESI) calculated for $C_{116}H_{80}N_3O_8F_{18}P_2S_2$ $(M\text{-}H)^-$: 2110.4580; found: 2110.4574.

(*S*,*S*)-4d:



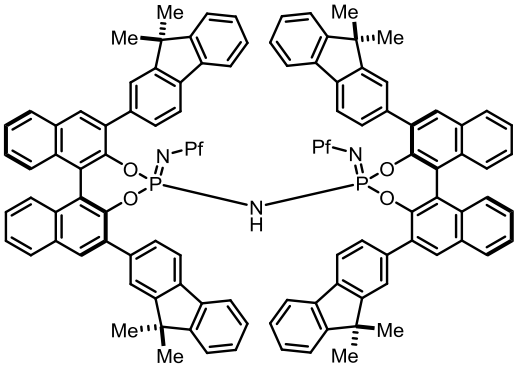
Prepared according to the general procedure on a 0.12 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 10:1 → 5:1 → 2:1 → 1:1). Off-white solid (141 mg, 0.061 mmol, 50%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.04 (d, *J* = 7.2 Hz, 4H), 7.98 (d, *J* = 8.2 Hz, 2H), 7.84 (t, *J* = 7.5 Hz, 2H), 7.79 (d, *J* = 8.5 Hz, 2H), 7.70 – 7.64 (m, 2H), 7.56 (ddd, *J* = 15.3, 6.4, 1.9 Hz, 4H), 7.51 (d, *J* = 1.6 Hz, 2H), 7.41 (dd, *J* = 11.6, 7.7 Hz, 4H), 7.37 – 7.34 (m, 4H), 7.32 – 7.29 (m, 4H), 7.23 (d, *J* = 1.5 Hz, 2H), 7.22 – 7.13 (m, 8H), 6.99 (s, 2H), 6.64 (d, *J* = 8.0 Hz, 2H), 6.56 (d, *J* = 7.9 Hz, 2H), 6.45 (dd, *J* = 8.0, 1.6 Hz, 2H), 2.16 – 1.93 (m, 24H), 1.82 – 1.75 (m, 2H), 1.73 – 1.63 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 155.0, 154.8, 154.4, 153.9, 144.2 (t, *J* = 5.0 Hz), 143.1 (t, *J* = 5.0 Hz), 139.9, 139.3, 139.1, 138.7, 135.0, 134.3, 134.0, 132.3, 132.1, 131.8, 131.7, 131.7, 131.3, 129.4, 128.9, 128.5, 127.8, 127.3, 127.1, 127.1, 127.0, 126.7, 126.5, 126.4, 126.3, 124.0, 123.6, 123.4, 122.9, 122.6, 121.8, 119.9, 119.3, 118.7, 118.4, 58.1, 57.9, 39.7, 39.7, 39.3, 39.0, 27.1, 26.7, 26.6, 26.5 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -80.8 (t, *J* = 10.0 Hz, 6F), -110.5 – -113.0 (m, 4F), -120.0 (dt, *J* = 48.6, 14.6 Hz, 4F), -121.4 – -122.1 (m, 4F), -122.6 – -123.2 (m, 4F), -125.9 – -126.5 (m, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.6; **HRMS** (ESI) calculated for $C_{120}H_{80}N_3O_8F_{26}P_2S_2$ $(M\text{-}H)^-$: 2310.4452; found: 2310.4438.

(*S*,*S*)-4o:



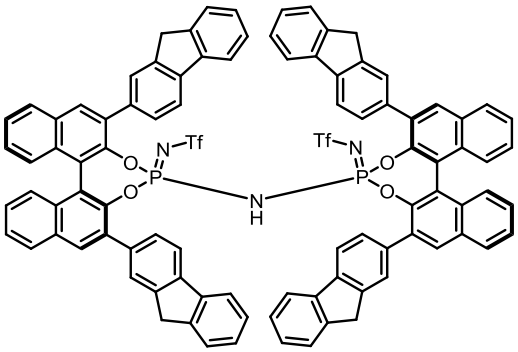
Prepared according to the general procedure on a 0.5 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1). Off-white solid (557 mg, 0.325 mmol, 65%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.09 – 8.02 (m, 6H), 7.89 – 7.82 (m, 4H), 7.70 (ddd, *J* = 8.2, 6.8, 1.2 Hz, 2H), 7.62 – 7.56 (m, 4H), 7.50 (d, *J* = 1.4 Hz, 2H), 7.45 – 7.41 (m, 4H), 7.41 – 7.37 (m, 6H), 7.31 – 7.27 (m, 4H), 7.24 – 7.23 (m, 2H), 7.23 – 7.18 (m, 6H), 7.08 (s, 2H), 6.73 (d, *J* = 7.9 Hz, 2H), 6.62 (dd, *J* = 8.0, 1.6 Hz, 2H), 6.25 (dd, *J* = 7.9, 1.7 Hz, 2H), 1.50 (s, 6H), 1.42 (s, 6H), 1.26 (s, 6H), 1.22 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.3, 154.2, 153.9, 153.7, 144.1 (t, *J* = 5.0 Hz), 142.9 (t, *J* = 5.0 Hz), 139.4, 138.8, 138.8, 138.6, 134.9, 134.8, 134.3, 134.2, 132.2, 132.2, 131.9, 131.8, 131.5, 129.2, 129.0, 128.8, 128.7, 127.7, 127.6, 127.3, 127.2, 127.1, 127.0, 126.9, 126.8, 126.7, 126.6, 123.8, 123.6, 123.5, 122.6, 122.5, 121.8, 120.4, 119.8, 119.2, 119.1, 47.1, 47.1, 27.6, 27.1, 27.0, 26.6 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -78.2 (s, 6F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.8; **HRMS** (ESI) calculated for $C_{102}H_{72}N_3O_8F_6P_2S_2$ $(M–H)^-$: 1706.4146; found: 1706.4162.

(*S*,*S*)-4p:



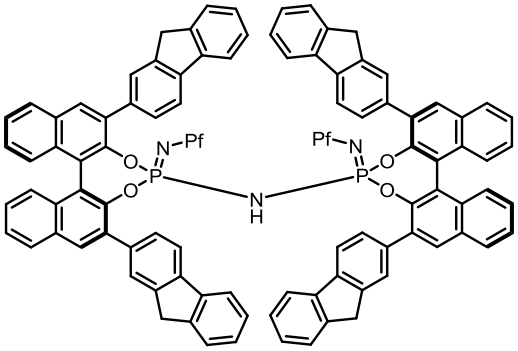
Prepared according to the general procedure on a 0.10 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 20:1 → 9:1 → 4:1 → 2:1). Off-white solid (62 mg, 0.034 mmol, 34%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.06 – 8.01 (m, 6H), 7.89 – 7.83 (m, 4H), 7.71 (ddd, *J* = 8.4, 6.8, 1.3 Hz, 2H), 7.61 – 7.56 (m, 4H), 7.50 (d, *J* = 1.6 Hz, 2H), 7.45 (d, *J* = 7.9 Hz, 2H), 7.42 – 7.37 (m, 6H), 7.33 (ddd, *J* = 20.0, 5.8, 3.3 Hz, 4H), 7.28 – 7.26 (m, 1H), 7.25 (d, *J* = 1.2 Hz, 1H), 7.24 – 7.18 (m, 8H), 6.99 (s, 2H), 6.69 (d, *J* = 8.0 Hz, 2H), 6.57 (dd, *J* = 7.9, 1.6 Hz, 2H), 6.43 (dd, *J* = 7.9, 1.6 Hz, 2H), 1.51 (s, 6H), 1.45 (s, 6H), 1.26 (s, 6H), 1.18 (s, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.3, 154.2, 153.9, 153.8, 144.2 (t, *J* = 5.0 Hz), 143.2 (t, *J* = 5.0 Hz), 139.5, 138.9, 138.8, 138.5, 134.9, 134.3, 134.1, 132.3, 132.2, 131.9, 131.8, 131.7, 131.6, 129.3, 128.9, 127.7, 127.5, 127.3, 127.3, 127.1, 127.0, 126.9, 126.7, 126.5, 123.7, 123.7, 123.6, 122.5, 122.4, 121.8, 120.4, 119.8, 119.2, 119.0, 47.2, 47.1, 29.9, 27.6, 27.1, 26.6, 22.6 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -78.9 (s, 6F), -114.9 – -116.4 (m, 4F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -17.3; **HRMS** (ESI) calculated for $C_{104}H_{72}N_3O_8F_{10}P_2S_2$ $(M-H)^-$: 1806.4082; found: 1806.4084.

(*S*,*S*)-4q:



Prepared according to the general procedure on a 0.076 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1). Off-white solid (42 mg, 0.026 mmol, 34%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.11 (d, *J* = 8.1 Hz, 2H), 8.03 (d, *J* = 8.5 Hz, 2H), 8.00 (s, 2H), 7.94 – 7.84 (m, 4H), 7.78 – 7.68 (m, 4H), 7.62 – 7.55 (m, 4H), 7.53 (d, *J* = 7.9 Hz, 2H), 7.50 – 7.43 (m, 4H), 7.42 – 7.36 (m, 4H), 7.31 – 7.26 (m, 2H), 7.25 – 7.22 (m, 4H), 7.21 – 7.17 (m, 2H), 7.14 (d, *J* = 7.9 Hz, 2H), 7.09 (d, *J* = 13.9 Hz, 4H), 6.95 (s, 2H), 6.73 (d, *J* = 7.8 Hz, 2H), 6.55 (d, *J* = 7.9 Hz, 2H), 3.75 (d, *J* = 21.9 Hz, 2H), 3.53 – 3.33 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 143.8, 143.6, 143.1, 142.9, 141.7, 141.2, 141.2, 134.8, 134.0, 133.9, 133.6, 132.1, 131.9, 131.9, 131.8, 130.9, 129.1, 128.9, 128.6, 128.5, 127.5, 127.4, 127.3, 127.2, 127.1, 127.0, 126.9, 126.6, 126.5, 126.4, 126.2, 125.1, 124.8, 123.5, 121.6, 120.2, 119.9, 119.0, 118.9, 36.9, 36.3 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -78.6 (s, 6F); **^{31}P NMR** (200 MHz, $CDCl_3$) δ -16.8; **HRMS** (ESI) calculated for $C_{94}H_{56}N_3O_8F_6P_2S_2$ $(M–H)^-$: 1594.2894; found: 1594.2910.

(*S*,*S*)-4r:



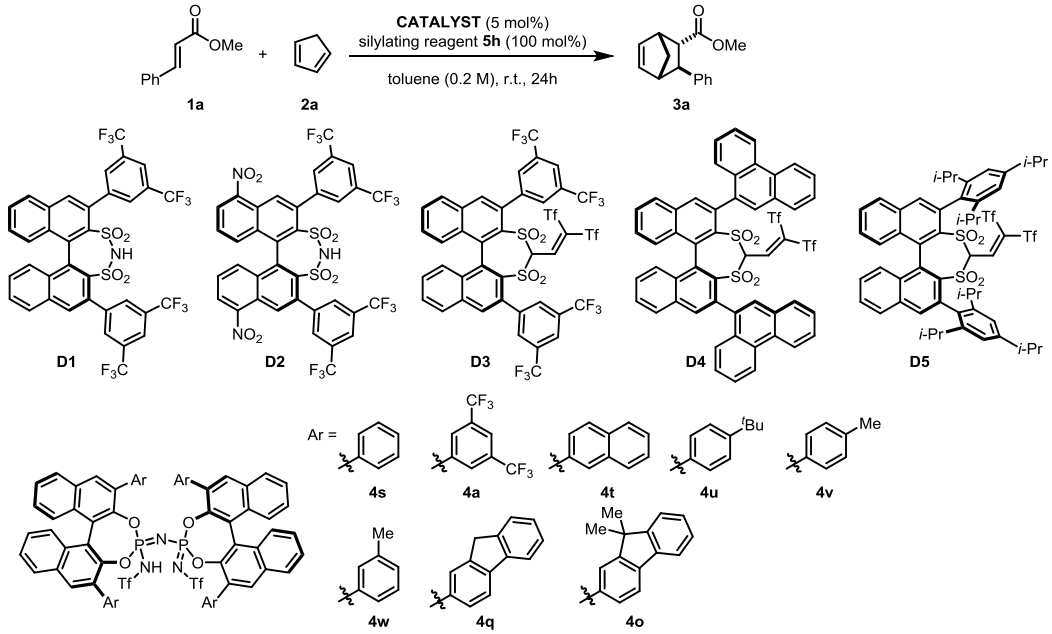
Prepared according to the general procedure on a 0.048 mmol scale (with respect to HMDS) and purified by column chromatography (hexane/MTBE 9:1 → 4:1 → 2:1 → 1:1). Off-white solid (47 mg, 0.028 mmol, 58%). **^{1}H NMR** (500 MHz, $CDCl_3$): δ 8.09 (d, *J* = 8.4 Hz, 2H), 8.03 (d, *J* = 8.2 Hz, 2H), 7.99 (s, 2H), 7.93 – 7.86 (m, 4H), 7.80 – 7.72 (m, 4H), 7.59 (ddd, *J* = 8.1, 6.6, 1.3 Hz, 2H), 7.55 (dd, *J* = 7.8, 5.3 Hz, 4H), 7.52 (d, *J* = 7.3 Hz, 2H), 7.44 (d, *J* = 8.4 Hz, 2H), 7.42 – 7.39 (m, 2H), 7.37 (d, *J* = 7.3 Hz, 2H), 7.30 (td, *J* = 7.4, 1.2 Hz, 2H), 7.26 – 7.24 (m, 2H), 7.20 (td, *J* = 7.4, 1.2 Hz, 2H), 7.15 (s, 2H), 7.08 – 7.03 (m, 4H), 7.00 (s, 2H), 6.72 (d, *J* = 7.8 Hz, 2H), 6.59 (d, *J* = 7.9 Hz, 2H), 3.76 (d, *J* = 21.9 Hz, 2H), 3.54 – 3.36 (m, 6H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 144.2 (t, *J* = 5.0 Hz), 143.8, 143.6, 143.1, 142.9, 141.7, 141.3, 141.2, 134.8, 133.9, 133.7, 132.1, 132.1, 131.9, 131.7, 131.0, 129.2, 128.9, 128.6, 128.4, 127.5, 127.4, 127.3, 127.2, 127.1, 126.9, 126.8, 126.6, 126.5, 126.4, 126.4, 126.1, 125.1, 124.8, 123.5, 121.5, 120.3, 119.8, 119.0, 118.9, 36.8, 36.4 (other signals not detected or observed); **^{19}F NMR** (470 MHz, $CDCl_3$) δ -79.3 (s, 6F), -116.3 (d, *J* = 50.1 Hz, 4F).; **^{31}P NMR** (200 MHz, $CDCl_3$) δ -17.1; **HRMS** (ESI) calculated for $C_{96}H_{56}N_3O_8F_{10}P_2S_2$ $(M–H)^-$: 1694.2830; found: 1694.2849.

Reaction Development

Optimization for Dienophiles

Table S1 Initial Catalyst screening

Initial catalyst screening experiments were performed on an analytical scale (0.02 mmol) in argonated GC-vial at r.t. with commercial SKA **5h** (1 equiv.) as the silylating reagent for the specified period of time. The reaction mixtures were analyzed by ^{1}H NMR and the desired product was isolated by preparative TLC. Chiral DSIs (**D1** and **D2**) and C−H acids (**D3-5**) gave either insufficient reactivity or no enantioselectivity. IDPi catalyst **4a** and **4o**, however, both catalyzed the reaction with high efficiency and promising enantioselectivity. Further, the reaction conditions were optimized independently with **4a** and 3-fluorenyl-substituted IDPis, such as **4o**.

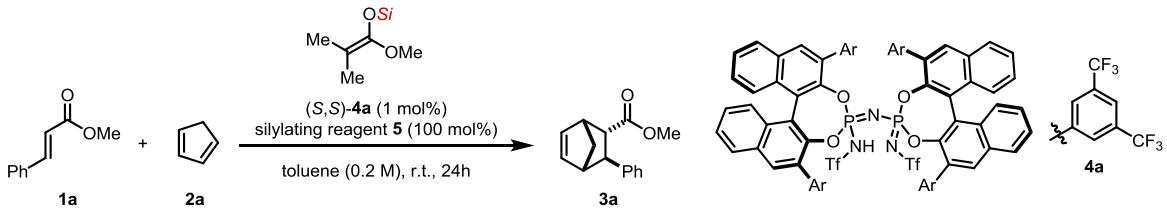


entry	CATALYST	conv.(%)[a]	e.r.$_{endo}$[b]	d.r. (endo/exo)[b]
1	**D1**	traces	/	/
2	**D2**	60% (traces of product)[c]	50:50	1:1
3[d]	**D3**	>99%	52.5:47.5	26:1
4	**D4**	82%	51:49	9:1
5	**D5**	71% (traces of product)[c]	n.d.	n.d.
6	**4s**	>99%	70:30	14:1
7	**4a**	>99%	85:15	11:1
8	**4t**	>99%	26.5:73.5	10:1
9	**4u**	>99%	25:75	6:1
10	**4v**	>99%	54:46	8:1
11	**4w**	>99%	73:27	11:1
12	**4q**	>99%	74:26	7:1
13	**4o**	>99%	85:15	8:1

[a]Determined by ^{1}H NMR analysis. [b]Determined by HPLC on a chiral stationary phase. [c]Mukaiyama-Michael adduct was the major product. [d] -40 °C.

Table S2 Screening of silyl groups with **4a**.[a]

The influence of the silyl group on conversion and stereoselectivity was tested by employing various silyl ketene acetal (SKA) reagents. The triethylsilyl (TES) group gave the best result.

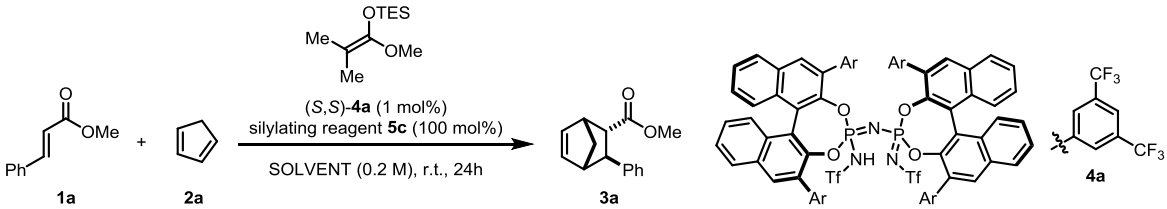


entry	SiR_3	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	TMS (**5h**)	90%	86.5:13.5	82:18	11:1
2	TES (**5c**)	>99%	88:12	86.5:13.5	9:1
3	TBS (**5i**)	>95%	87.5:12.5	83.5:16.5	11:1
4	TIPS (**5b**)	>99%	87:13	87:13	6:1

[a]Reactions were performed on a 0.02 mmol scale and 5 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Table S3 Screening of solvents with **4a**.[a]

The influence of the solvent was evaluated and many non-protic, apolar solvents were found to give equally good results. Toluene was chosen due to good solubility of reactants and substrates.

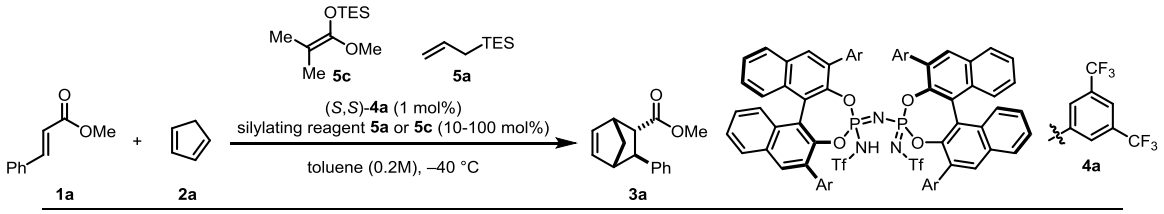


entry	SOLVENT	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	Et_2O	>99%	86.75:13.25	84.5:15.5	9:1
2	MTBE	38%	79.5:20.5	n.d.	2.6:1
3	1,4-dioxane	>95%	85.5:14.5	82.75:17.25	9:1
4	TMS_2O	>99%	89.75:10.25	87.5:12.5	8:1
5	CH_2Cl_2	>95%	72:28	69:31	8.5:1
6	$CHCl_3$	90%	81.25:18.75	77.5:22.5	7:1
7	CCl_4	>95%	89.75:10.25	87.5:12.5	8:1
8	EtOAc	70%	82.25:17.75	75.5:24.4	7:1
9	MeCN	36%	52.5:47.5	50:50	1:1
10	benzene	>95%	87.25:12.75	84.75:15.25	8:1
11	toluene	>95%	88:12	86:14	8:1
12	*o*-xylene	>95%	88.5:11.5	86.75:13.25	9:1
13	*m*-xylene	>95%	87.75:12.25	86.75:13.25	9:1
14	*p*-xylene	>95%	88.5:11.5	87.25:12.75	9:1
15	mesitylene	>95%	87.75:12.25	87:13	9:1
16	*n*-hexane	>99%	90:10	89:11	9:1
17	cyclohexane	>99%	89.75:10.25	89:11	10:1

[a]Reactions were performed on a 0.02 mmol scale and 5 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Table S4 Evaluation of other silylating reagent with **4a**.[a]

We found that lowering the temperature to −40°C gave excellent enantio- and diastereoselectivity for product **3a**, however, the use of SKA **5c** in high quantities caused the formation of Mukaiyama−Michael side products. Thus, allylsilane **5a** was tested as an alternative reagent to silylate the catalyst. Reagent loadings of as low as 10 mol% of **5a** were found to be sufficient to activate the catalyst and fully prevent side product formation. However, the reaction time for reaching full converstion of **1a** was very long (6 days).

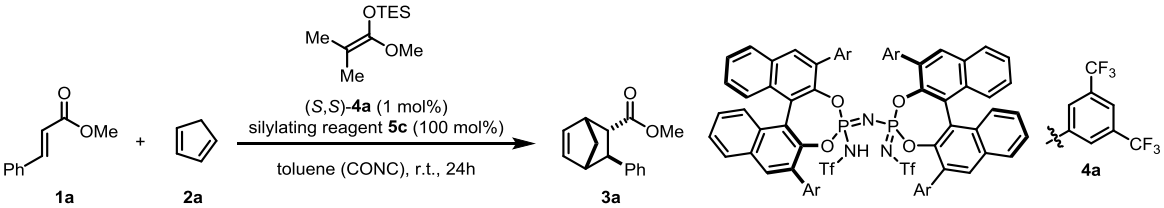


entry	silylating reagent	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	**5c** (100 mol%)	>99%[d]	96.75:3.25	n.d.	22:1
2	**5a** (100 mol%)	>99%[e]	97:3	94.5:5.5	22:1
3	**5a** (50 mol%)	>95%[e]	97:3	n.d.	20:1
4	**5a** (30 mol%)	>99%[e]	96.75:3.25	95.5:4.5	21:1
5	**5a** (20 mol%)	>99%[e]	97:3	95.5:4.5	19:1
6	**5a** (10 mol%)	>99%[e]	96.75:3.25	94.25:5.75	21:1

[a]Reactions were performed on a 0.02 mmol scale and 5 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on a chiral stationary phase. [d]24 h reaction time, Mukaiyama−Michael adduct is the major product. [e]6d reaction time.

Table S5 Evaluation of concentration effects at r.t. with **4a**.[a]

We tested the effect of concentration on the reaction at r.t. and detected only small deviations in stereoselectivities, but a strong deceleration with dilution.

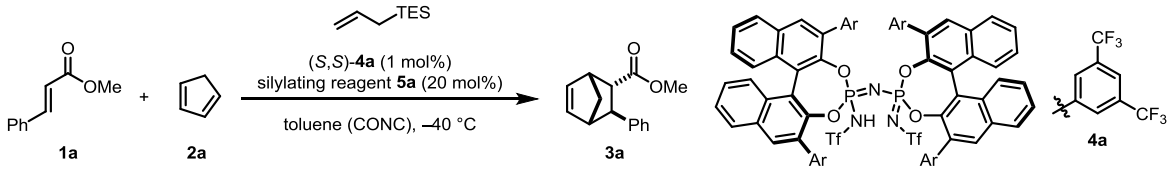


entry	concentration	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	1M	>99%	86.5:13.5	85.25:14.75	8:1
2	0.5M	>99%	87:13	85.25:14.75	8:1
3	0.2M	>95%	87.5:12.5	85:15	8:1
4	0.1M	93%	87.5:12.5	84.25:15.75	8:1
5	0.05M	78%	87.75:12.25	82:18	7:1
6	0.025M	47%	87.5:12.5	74.5:25.5	6:1
7	0.01M	10%	88.75:11.25	n.d.	3:1

[a]Reactions were performed on a 0.02 mmol scale and 5 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Table S6 Evaluation of concentration effects at low temperature with **4a**.[a]

A study on concentration effects was repeated with silylating agent **5a** at decreased temperature (−40°C) and the reaction time to achieve full conversion was evaluated. At 1M concentration, the reaction completed within 24 h using 1 mol% catalyst. For these optimal conditions, we derived a corresponding general procedure for the catalytic, asymmetric Diels−Alder reaction (vide infra).

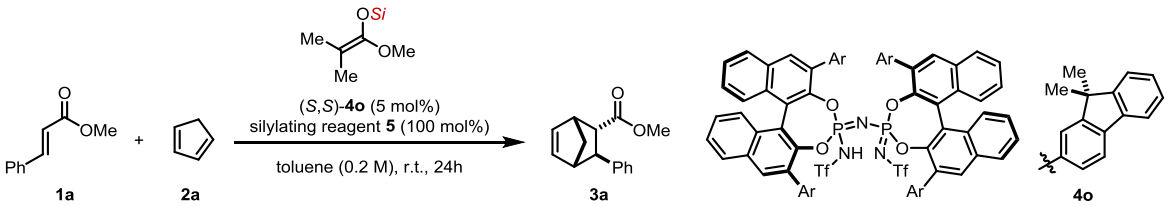


entry	concentration	reaction time[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	0.2M	6d	97:3	93.25:6.75	21:1
2	0.4M	2d	96.75:3.25	96:4	20:1
3	1M	<24h	96.5:3.5	95.5:4.5	19:1
4	2M	<24h	95.5:4.5	95.25:4.75	17:1

[a]Reactions were performed on a 0.02 mmol scale and 10 equiv. of CP **2a**. [b]for the reaction to reach full conversion. [c]Determined by HPLC on a chiral stationary phase.

Table S7 Screening of silyl groups with **4o**.[a]

For the second catalyst lead structure **4o**, the influence of the silyl group on conversion and stereoselectivity was re-evaluated. In this case, the triisopropylsilyl (TIPS) group was found optimal. In addition, only small amounts of Mukaiyama-Michael side products were detected with SKA **5b**.

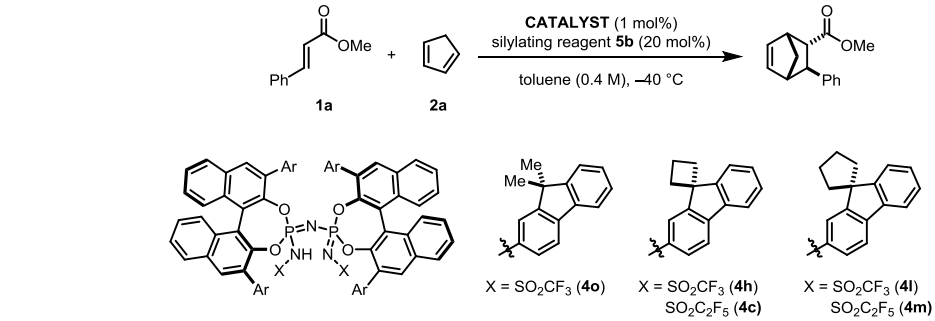


entry	SiR_3	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	TMS (**5h**)	83%	85.75:14.25	86.5:13.5	7.5:1
2	TES (**5c**)	>99%	87.5:12.5	86.75:13.25	7.5:1
3	TBS (**5i**)	76%	86.25:13.75	85:15	9:1
4	TIPS (**5b**)	>99%	88.25:11.75	88.25:11.75	5.5:1

[a]Reactions were performed on a 0.02 mmol scale and 10 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Table S8 Screening of other 3-fluorenyl-derived IDPi catalysts.[a]

Although promising results were obtained with **4o**, reactivity was significantly lower than with **4a**. Thus, we tested more 3-fluorenyl-derived IDPi catalysts including the corresponding inner-core modified derivatives (X = SO_2CF_3, $SO_2C_2F_5$) to achieve higher reactivity and/or enantioselectivity. We found that using corresponding cyclobutyl-derivatives **4h** and **4c** resulted in increased stereoinduction, while the latter was significantly more active due to the inner-core modification (X = $SO_2C_2F_5$). Product **3a** was isolated in 90% yield after 12 h of reaction time (entry 3). These conditions were used in a corresponding general procedure for the catalytic, asymmetric Diels−Alder reaction (vide infra).



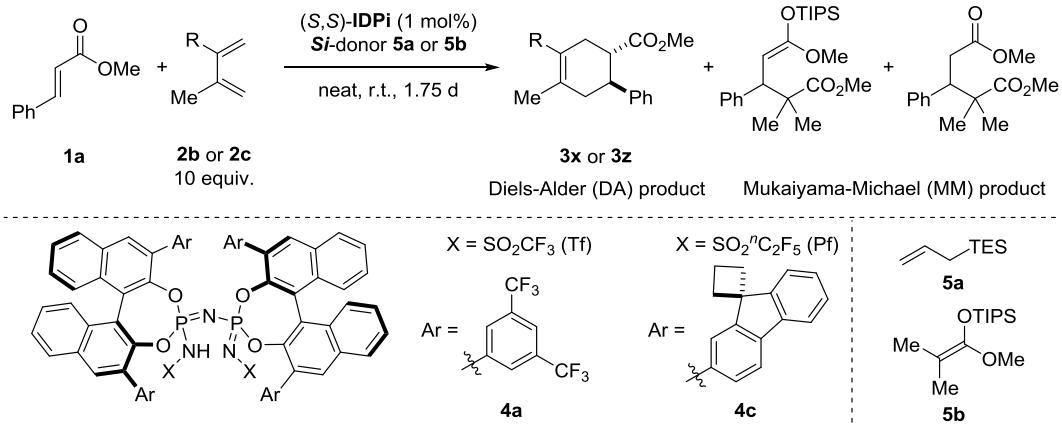
entry	CATALYST	conv.(%)[b]	e.r.$_{endo}$[c]	e.r.$_{exo}$[c]	d.r. (endo/exo)[c]
1	**4o**	84% (64h)	94.75:5.25	95.5:4.5	7:1
2	**4h**	92% (64h)	97:3	92:8	12:1
3[d]	**4c**	>99% (<12h)	97.5:2.5	91.5:8.5	16:1
4	**4l**	89% (64h)	95:5	95.75:4.25	7:1
5	**4m**	>99% (64h)	97:3	94.75:5.25	12.5:1

[a]Reactions were performed on a 0.02 mmol scale and 10 equiv. of CP **2a**. [b]Determined by ^{1}H NMR analysis after the specified reaction time. [c]Determined by HPLC on a chiral stationary phase. [d]at 1M concentration using 5 equiv. of CP **2a**.

Optimization for Dienes

General procedure for the screening experiments:
The experiments were conducted on a 0.08 mmol or 0.1 mmol scale. An oven-dried 2.0 mL screw-cap glass vial was charged with the corresponding (*S*,*S*)-IDPi catalyst (0.8 µmol or 1.0 µmol, 1 mol%) and the appropriate α,β-unsaturated methyl ester (0.08 mmol or 0.1 mmol). A Teflon-coated magnetic stirring bar was added, the vial was closed with a screw-cap containing a PTFE/rubber septum and sealed with parafilm. The reaction vial was evacuated and purged with argon (3 ×). The silyl donor (30–50 mol%) was transferred to the reaction mixture and the reaction mixture was stirred for 5 min at r.t.. Then, the diene was transferred to the reaction vial and the colorless solution was stirred at the indicated temperature for the specified reaction time until sufficient conversion was observed. The reaction was monitored by TLC and ^{1}H NMR spectroscopy and treated with triethylamine. The desired Diels–Alder product was obtained by preparative TLC.

Table S9. Catalyst screening[a]

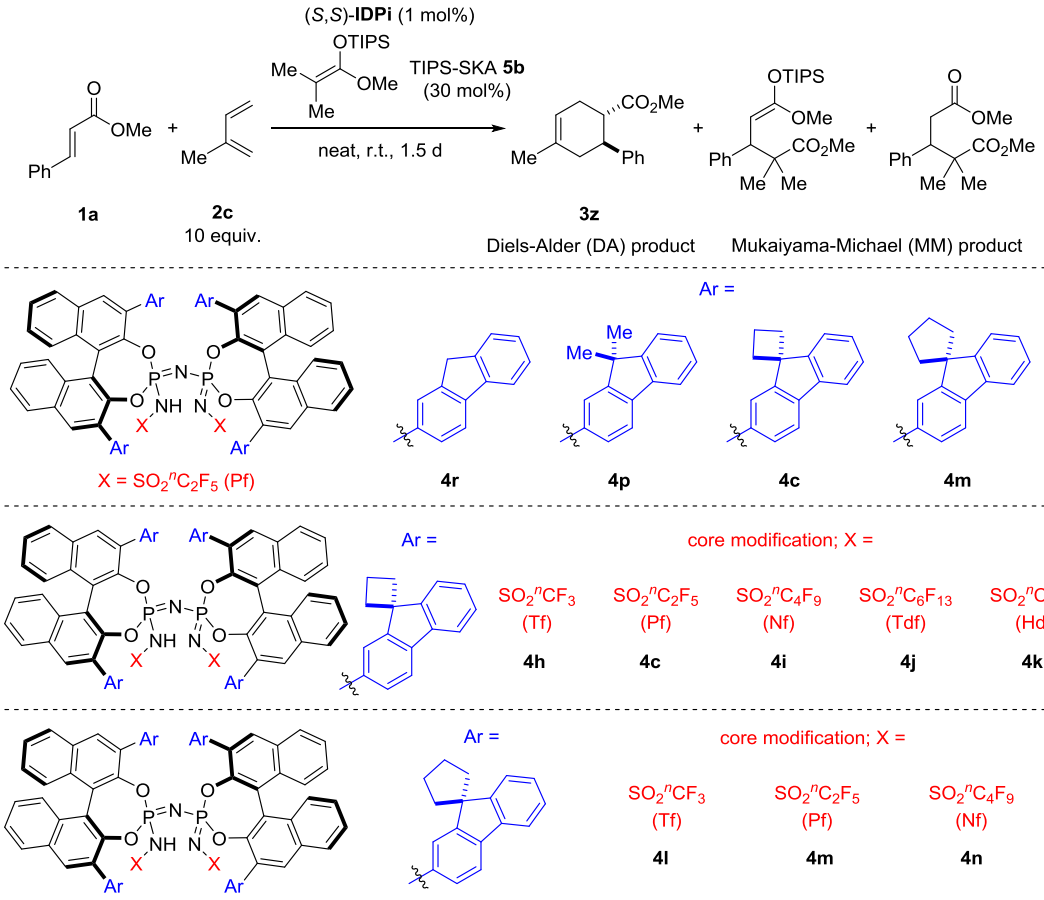


entry	catalyst	silyl donor	conversion(%)[b]	ratio[b] **3**:[MM]	e.r.[c] **3x** or **3z**
			diene substrate: isoprene (**2c**)		
1	**4a**	**5a**	24	n.a.	67.4:32.6
2	**4c**	**5b**	34	15:85	95.3:4.7
			diene substrate: 2,3-dimethylbuta-1,3-diene (**2b**)		
3	**4a**	**5a**	16	n.a.	51.4:48.6
4	**4c**	**5b**	34	10:90	78.3:21.7

[a]Reactions were performed on a 0.08 mmol scale with 50 mol% of **5a** or 30 mol% of **5b** and 1 mol% of catalyst for 1.75 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^{1}H NMR analysis; n.a.: not applicable. [c]Determined by HPLC on a chiral stationary phase.

An initial catalyst screening (Table S9) of representative examples of both catalyst families used for the dienophile scope indicated that 3-fluorenyl-derived IDPi (**4c**) provided the Diels–Alder products with higher enantiomeric ratios for both dienes compared to the more acidic trifluoromethylphenyl derivative (**4a**). Therefore, further IDPi catalyst derivatives of the 3-fluorenyl substitution family with different core modifications and substituents in the 3,3'-position of the BINOL backbone were investigated (Table S10).

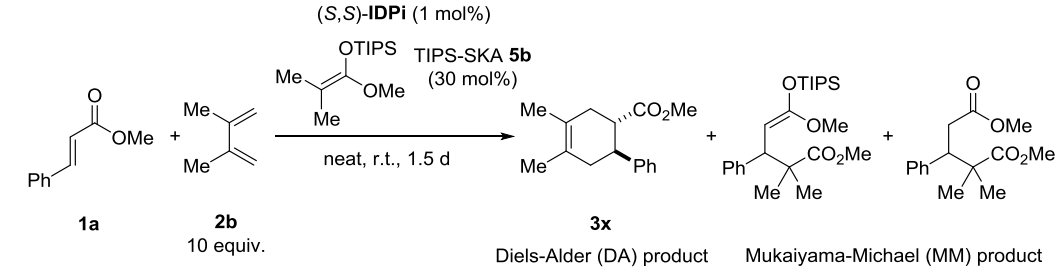
Table S10. Catalyst screening with isoprene[a]

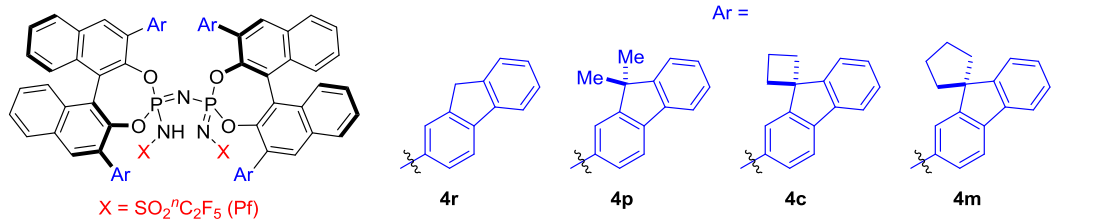


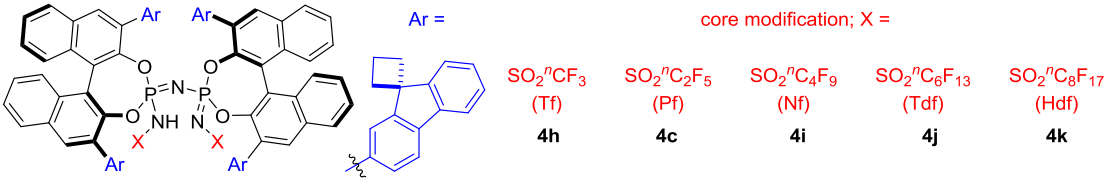
diene substrate: isoprene (**2c**)				
entry	catalyst	conversion (%)[b]	ratio[b] **3z**:[MM]	e.r.[c] **3z**
1	**4r**	35	18:82	54.6:45.4
2	**4p**	28	6:94	91.9:8.1
3	**4c**	34	21:79	94.3:5.7
4	**4m**	34	40:60	96.7:3.3
5[d]	**4h**	34	4:96	94.4:5.6
6[e]	**4c**	43	17:83	95.1:4.9
7[e]	**4i**	61	21:79	95.2:4.8
8[e]	**4j**	63	27:73	95.5:4.5
9[e]	**4k**	64	21:79	96.8:3.2
10[d]	**4l**	34	25:75	95.3:4.7
11[e]	**4m**	34	40:60	96.7:3.3
12	**4n**	37	42:58	97.2:2.8

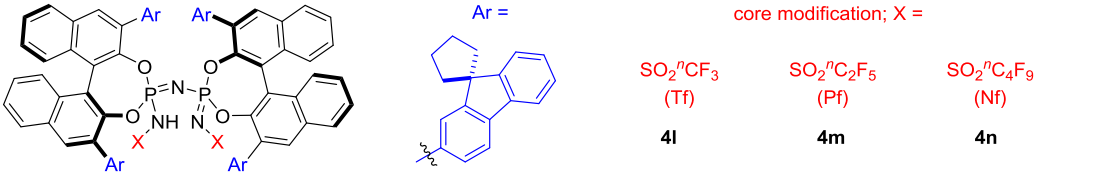
[a]Reactions were performed on a 0.08 mmol scale with 30 mol% of SKA and 1 mol% of catalyst for 1.5 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase. [d]3.5 days reaction time. [e]50 mol% TIPS-SKA (**5b**) were used.

Table S11. Catalyst screening with 2,3-dimethylbutadiene[a]









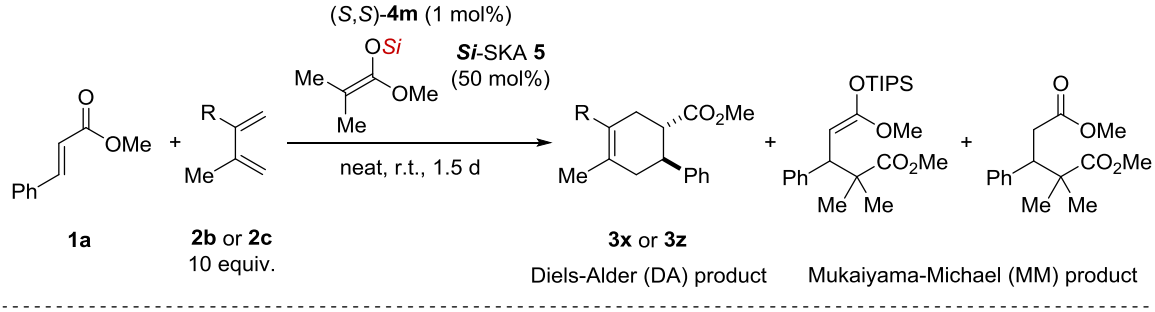
diene substrate: 2,3-dimethylbuta-1,3-diene (**2b**)				
entry	catalyst	conversion (%)[b]	ratio[b] **3x**:[MM]	e.r.[c] **3x**
1	**4r**	56	31:69	55.4:44.6
2	**4p**	37	2:98	84.3:15.7
3	**4c**	44	22:78	78.3:21.7
4	**4m**	52	24:76	93.6:6.4
5[d]	**4h**	32	5:95	89.4:10.6
6[e]	**4c**	35	10:90	75.6:24.4
7[e]	**4i**	57	20:80	92.7:7.3
8[e]	**4j**	55	22:78	92.7:7.3
9[e]	**4k**	62	18:82	92.3:7.7
10[d]	**4l**	36	18:82	92.7:7.3
11	**4m**	52	24:76	93.6:6.4
12	**4n**	50	14:86	95.2:4.8

[a]Reactions were performed on a 0.08 mmol scale with 30 mol% of SKA and 1 mol% of catalyst for 1.5 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase. [d]3.5 days reaction time. [e]50 mol% TIPS-SKA (**5b**) were used.

Increasing the size of the 3-fluorenyl substituent from 9H-fluorenyl to 3-cyclopentylfluorenyl proved to be beneficial for the enantiomeric ratio with both tested dienes (**2b** and **2c**, see Table S10, entries 1–4, and Table S11, entries 1–4). Inner-core modifications bearing longer perfluoroalkyl substituents provided an improvement in both reactivity and selectivity towards the desired Diels–Alder product, while maintaining or slightly improving the enantiomeric ratio (Tables S10 and S11, entries 5–12). The IDPi catalysts bearing 3-cyclopentylfluorenyl substituents were identified as the best catalyst system for both dienes. With this catalyst subgroup in hand, the effect of the silyl group on both enantioselectivity and conversion was investigated. Changing the silyl group from the initially used TIPS group to TMS, TES or TBS was found to be deleterious for conversion, chemo- and enantioselectivity (Table S12).

Screening of silyl ketene acetals (SKA) as silyl donors

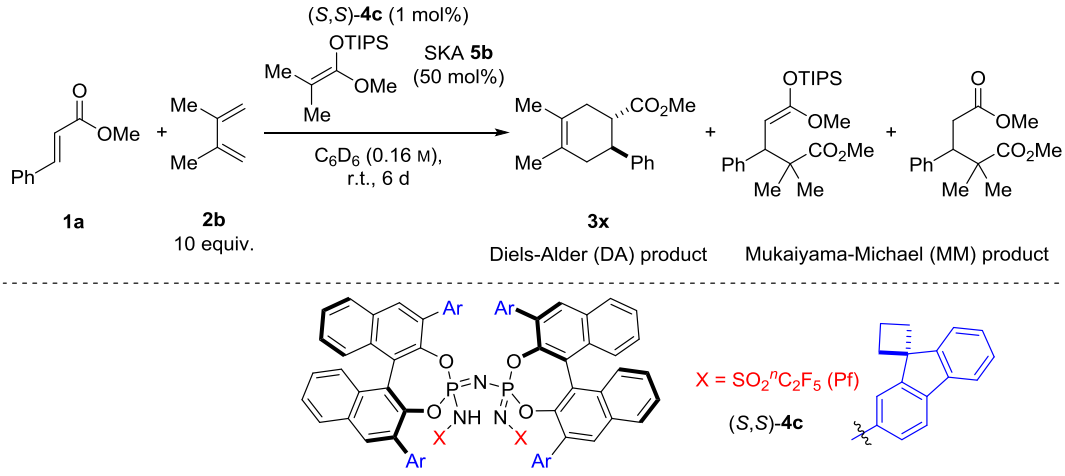
Table S12. Screening silyl groups with silyl ketene acetals[a]



entry	SKA 5	conversion (%)[b]	ratio[b] 3:[MM]	e.r.[c] 3x or 3z
diene substrate: isoprene (**2c**)				
1	**TMS-SKA (5h)**	37	5:95	90.3:9.7
2	**TES-SKA (5c)**	51	7:93	94.4:5.6
3	**TBS-SKA (5i)**	28	3:97	94.3:5.7
4	**TIPS-SKA (5b)**	53	15:85	96.7:3.3
diene substrate: 2,3-dimethylbuta-1,3-diene (**2b**)				
5	**TMS-SKA (5h)**	49	4:96	78.8:21.2
6	**TES-SKA (5c)**	49	5:96	86.4:13.6
7	**TBS-SKA (5i)**	44	1:99	91.4:6.6
8	**TIPS-SKA (5b)**	56	11:89	94.4:5.6

[a]Reactions were performed on a 0.08 mmol scale with 50 mol% of SKA and 1 mol% of catalyst for 1.5 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

In contrast to Diels–Alder reactions with cyclopentadiene, using SKAs as silylating reagents with less reactive dienes is the competing Mukaiyama–Michael reaction and the corresponding product is usually observed as the major product species in the crude reaction mixture. In addition, incomplete conversion was observed, even after prolonged reaction times suggesting deactivation of the catalyst. In order to clarify this issue, a mixture of **1a** (0.08 mmol), **2b** (0.8 mmol, 10 equiv.), SKA **5b** (24 µmol, 30 mol%) and IDPi catalyst **4c** (0.8 µmol, 1 mol%) was dissolved in 0.5 mL C_6D_6 and transferred to a 5 mm NMR tube under argon. ^{1}H and ^{31}P NMR spectra were collected periodically until full consumption of SKA **5b** was observed.



The ^{31}P NMR spectra indicate complete silylation long as **5b** is present in the reaction mixture. However, as the sub-stoichiometric amount of silylating reagent **5b** is gradually consumed in the competing Mukaiyama–Michael reaction, deactivation of the catalyst due to slow hydrolysis occures. Consequently, the formed silylated Mukaiyama–Michael product does not silylate (or significantly slower than silyl ketene acetal **5b**) the IDPi catalyst as suggested by the ^{31}P NMR spectrum of the reaction mixture after 6 days (Figure S1).

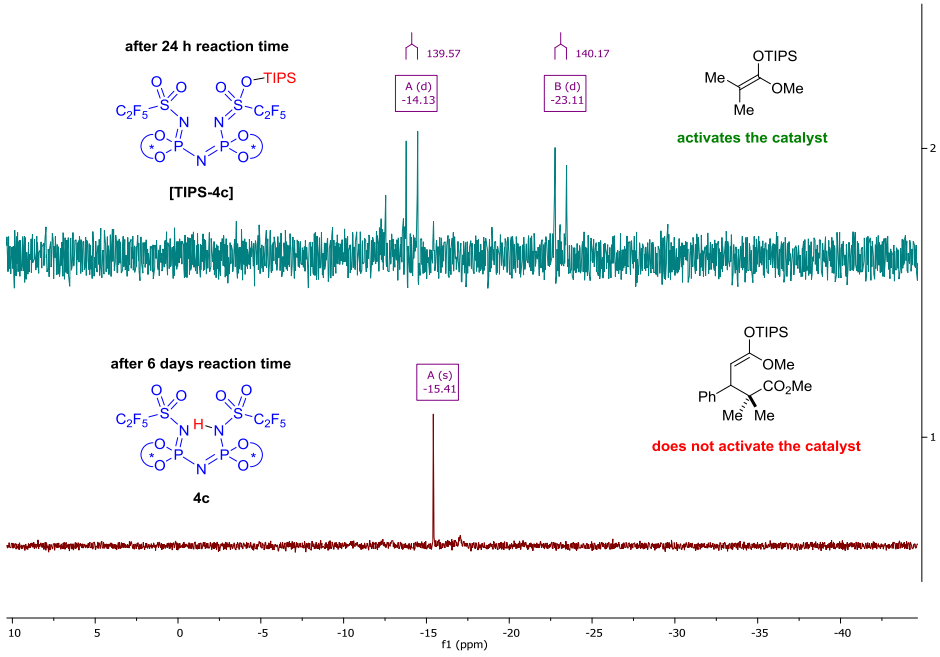


Figure S1: Stacked ^{31}P NMR spectra of the reaction mixture after 24 h reaction time and 6 days reaction time using 30 mol% of **5b** as silylating reagent.

Representative ^{1}H NMR spectrum for the analysis of the reaction mixture:

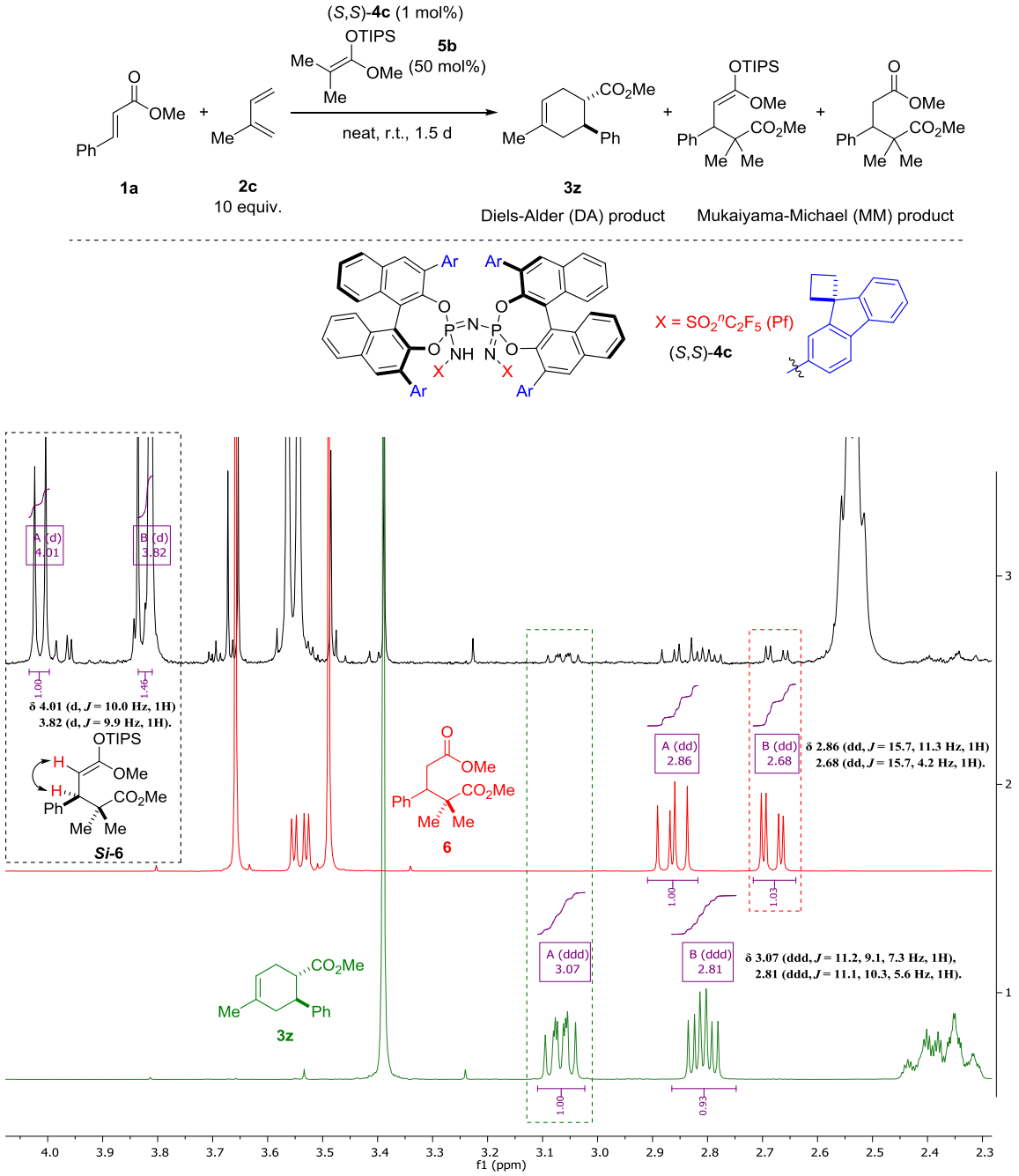
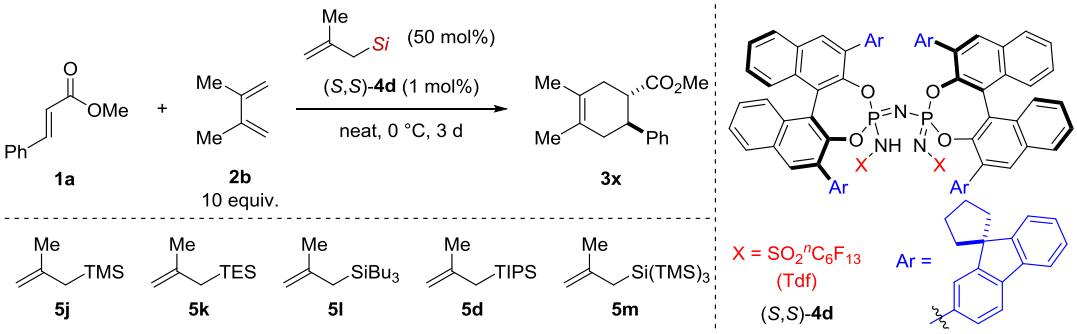


Figure S2. Representative stacked ^{1}H NMR spectra of the reaction mixture described above (upper spectrum), the purified Mukaiyama–Michael product (middle spectrum) and the purified Diels–Alder product. The proton signals chosen for integration to determine the conversion are highlighted in the dashed boxes.

Screening of methallylsilanes as silyl donors

Due to the observed competing Mukaiyama–Michael reaction with silyl ketene acetals as silylating reagents, allylsilanes and (2-methallyl)silanes were tested as alternative silyl donors for the activation of 3-fluorenyl-derived IDPi's.

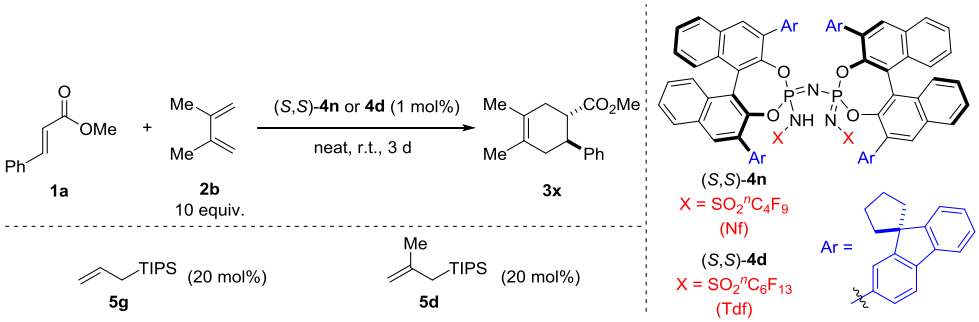
Table S13. Screening of (2-methallyl)silanes as silylating reagents.[a]



entry	*Si*-(2-methallyl)silane	conversion (%)[b]	remaining silyl *Si*-(2-methallyl)silane	e.r.[c]
1	**TMS (5j)**	8	14	75:25
2	**TES (5k)**	16	20	86:14
3	**$SiBu_3$ (5l)**	24	19	76:24
4	**TIPS (5d)**	22	20	96:4
5	**$Si(TMS)_3$ (5m)**	8	36	94:6

[a]Reactions were performed on a 0.1 mmol scale with 50 mol% of (2-methallyl)silanes **5** and 1 mol% of catalyst (*S*,*S*)-**4d** for 3 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Table S14. Screening of allylsilanes and (2-methallyl)silanes as silylating reagents.[a]



entry	catalyst	silylating reagent	conversion (%)[b]	e.r.[c]
1	**4n**	**5g**	~ 5	n.d.
2	**4d**	**5g**	~ 5	n.d.
3[d]	**4n**	**5g**	8	93.9:6.1
4	**4n**	**5d**	12	94.1:5.9
5	**4d**	**5d**	13	94.5:5.5

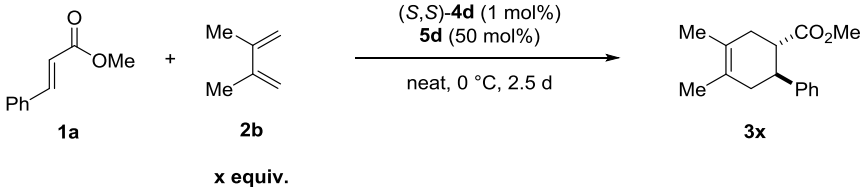
[a]Reactions were performed on a 0.1 mmol scale with 50 mol% of silylating reagent and 1 mol% of IDPi catalyst for 3 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase; n.d.: not determined.[d]3.75 d reaction time using 50 mol% **5g**.

Several (2-methallyl)silanes bearing different silyl groups were prepared and used in the enantioselective Diels–Alder reactions in order to investigate the effect of the silyl group on conversion and enantioselectivity. In consistency with the results obtained with silyl ketene acetals, the TIPS group delivered the desired Diels–Alder product with an excellent enantiomeric ratio (96:4; Table S13, entry 4). A direct comparison between allylsilanes and (2-methallyl)silanes indicated an accelerated silylation of the catalyst with (2-methallyl)silanes, thus resulting in a shorter induction/dormant period of the catalytic system (Table S14).

Screening of concentration effects

As the reaction was conducted under neat conditions, we expected a concentration on effect stereoselectivity and conversion with different equivalents of diene. In general, lower concentrations resulted in an increased enantiomeric ratio of Diels–Alder product **3x**, whereas higher conversion was observed at 0.02 M concentration (corresponding to 4 equiv. of diene, see Table S15). Thus, in the preparative scale experiments, either 4 or 5 equivalents of the diene were used to achieve an acceptable balance of conversion and enantioselectivity.

Table S15. Screening of different concentrations.[a]

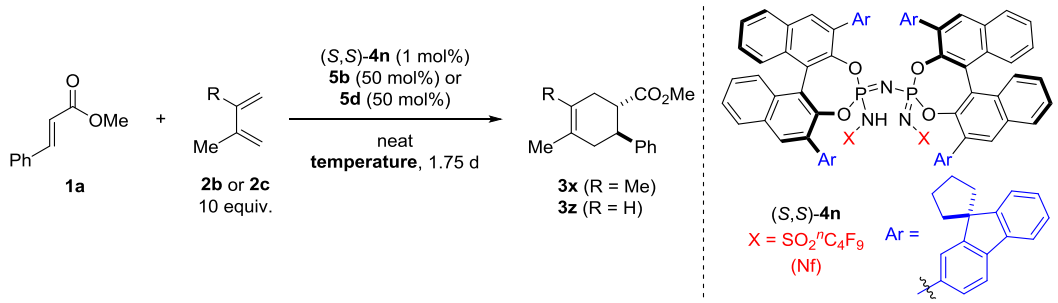


entry	**2b**/equiv.	concentration (M)	conversion (%)[b]	e.r.[c]
1	2	0.044	7	92.4:7.6
2	3	0.029	19	93.5:6.5
3	4	0.022	24	94.7:5.3
4	5	0.018	17	95.3:4.7
5	10	0.009	14	95.9:4.1

[a]Reactions were performed on a 0.1 mmol scale with 50 mol% of **5d** and 1 mol% of catalyst (*S*,*S*)-**4d** for 2.5 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase.

Temperature screening

Table S16. Screening of different reaction temperatures.[a]



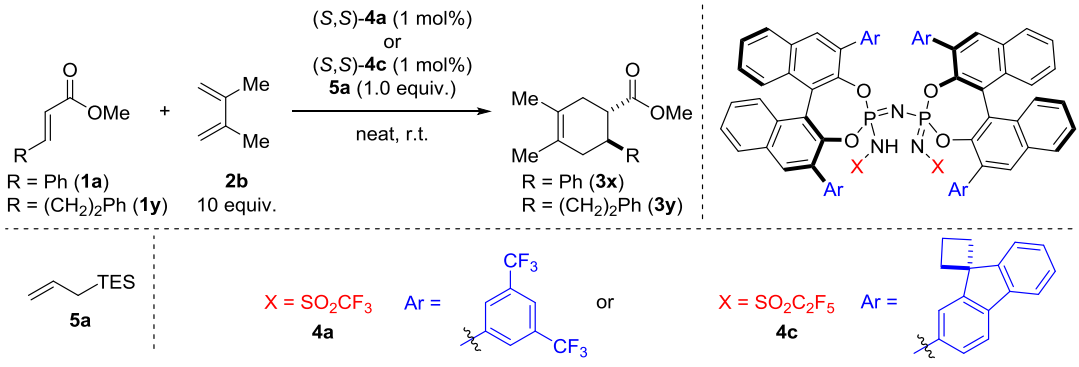
entry	diene	silyl donor	temperature(°C)	conversion(%)[b]	e.r.[c]
1	**2b**	**5b**	40	6	92:8
2[d]	**2b**	**5d**	60	12	62:38
3	**2c**	**5b**	40	5	95:5
4[d]	**2c**	**5d**	60	10	79:21

[a]Reactions were performed on a 0.1 mmol scale with 50 mol% of **5d** and 1 mol% of catalyst (*S*,*S*)-**4n** for 1.75 d and quenched with 1.1 equiv. of NEt_3. [b]Determined by ^1H NMR analysis. [c]Determined by HPLC on a chiral stationary phase. [d]8.5 d reaction time.

We tested if increasing the temperature (40 °C and 60 °C) would improve the conversion of the Diels–Alder reaction with catalyst (*S*,*S*)-**4n**, however surprisingly found that this proved to be detrimental for both conversion and enantioselectivity (Table S16). In contrast, for the preparation of racemates using $HNTf_2$ as catalyst this effect was not observed and increasing temperatures usually provided full conversion of the starting materials.

Preliminary kinetic studies

A possible explanation accounting for these results could involve a deactivation pathway with IDPi catalysts at increased temperatures. Therefore, we followed the course of the catalytic enantioselective Diels–Alder reaction at r.t. over time with substrates **1a** and **1y** and 2,3-dimethylbutadiene **2b** (see below). One member of each catalyst family was chosen to compare both electronic and steric effects.



To an oven dried 2 mL screw-cap glass vial were added the IDPi catalyst (1.43 mg, 0.80 μmol, 1.0 equiv.) and the appropriate α,β-unsaturated methyl ester (80 μmol, 1.0 equiv.). A Teflon-coated magnetic stirring bar was added, the vial was sealed, evacuated and purged with argon (3 ×). Allyltriethylsilane (16 μL, 80 μmol, 1.0 equiv.) and 2,3-dimethyl-1,3-butadiene (91 μL, 0.8 mmol, 10 equiv.) were transferred to the reaction vial and the resulting pale yellow solution was stirred at 25 °C. At the indicated time, a 5 μL aliquot was taken, quenched with triethylamine (12 μL, 1 equiv.), dissolved in 0.5 mL $CDCl_3$ and the conversion of the reaction was determined by ^{1}H NMR spectroscopy (integration of the methoxy groups of starting material and product; see Figure S3 with representative stacked ^{1}H NMR spectra depicted below).

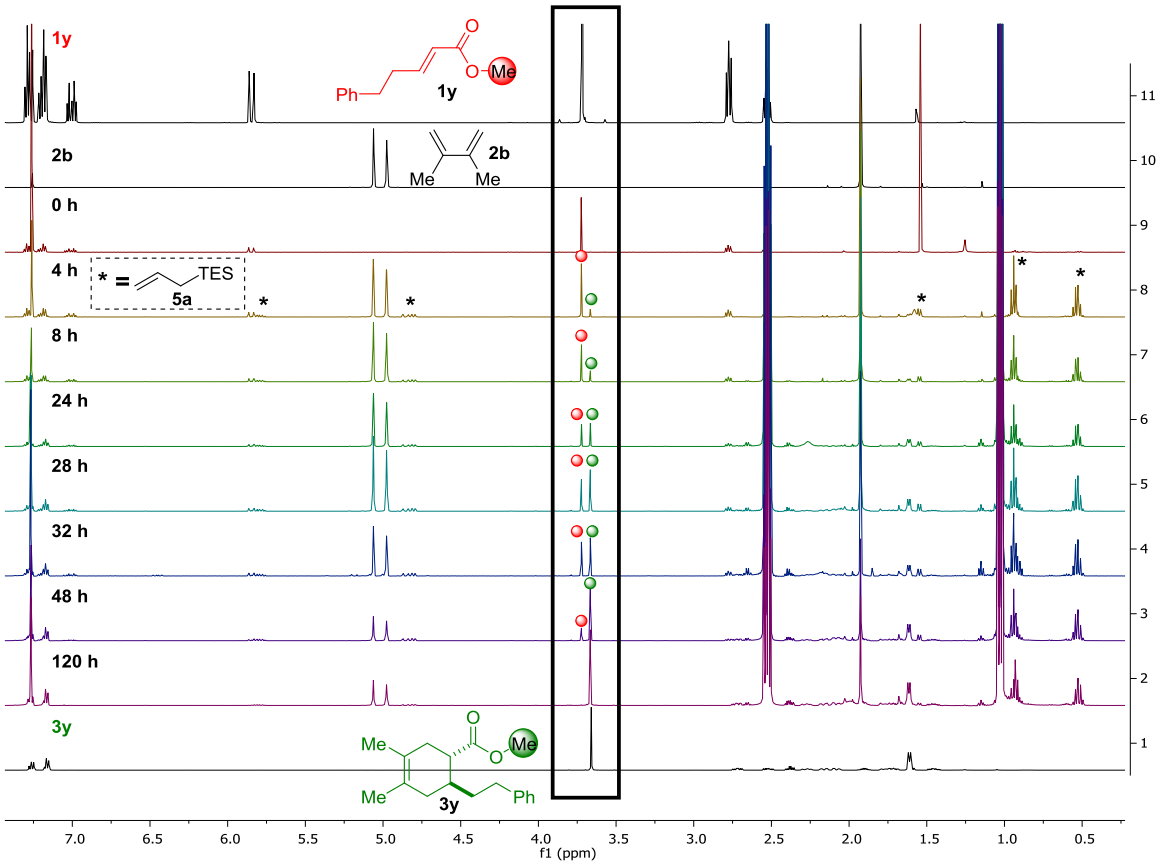


Figure S3. Stacked ^{1}H NMR spectra of starting materials, the kinetic study (^{1}H NMR spectra from each collected data point) and the Diels–Alder product **3y**.

With (*S*,*S*)-**4a**, higher conversions were observed then with (*S*,*S*)-**4c** for both substrates, however full conversion was only obtained with substrate **1y** (see plots in Figure S4a-d). In all other cases, the reaction stopped after a certain amount of time and only partial conversion was obtained. These preliminary kinetic data suggests that catalyst inhibition or deactivation for certain substrates and catalyst combinations is indeed an inhibitory pathway.

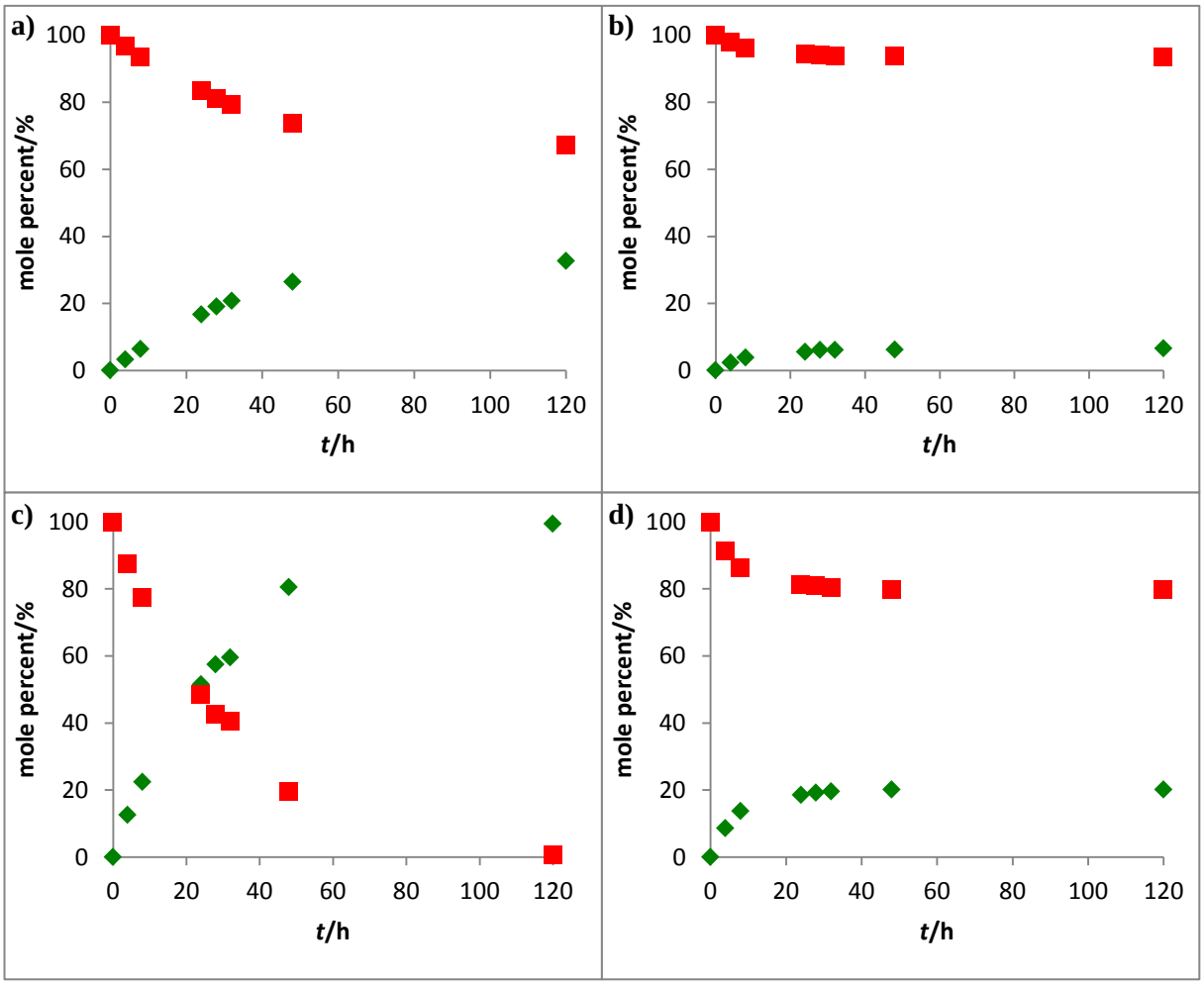


Figure S4. a) Preliminary kinetic data obtained for the reaction of dienophile **1a** with catalyst (*S*,*S*)-**4a**. b) Reaction of dienophile **1a** with catalyst (*S*,*S*)-**4c**. c) Reaction of dienophile **1y** with catalyst (*S*,*S*)-**4a**. d) Reaction of dienophile **1y** with catalyst (*S*,*S*)-**4c**.

Methylation of the catalyst

In consequence to these preliminary kinetic studies, we carefully re-examined reactions at higher temperature than r.t. (Table S16). Upon isolation of the Diels–Alder product by preparative TLC, we detected a less polar IDPi derivative in significant amounts (Figure S5B). This compound was identified as the methylated IDPi (methyl-[*S*,*S*]-**4n**) by HRMS (ESI): calculated for $C_{117}H_{83}N_3O_8F_{18}P_2S_2Na$ $(M+Na)^+$: 2148.4702; found: 2148.4717. In further studies at various temperatures, we qualitatively observed increasing catalyst methylation with higher temperatures. We reason that this inhibitory pathway accounts for the observed partial conversions at r.t. and rationalize it via collapse of the chiral ion pair (CIP) consisting of silylated substrate and chiral counteranion (Figure S5A). Thus, methyl cinnamate **1a** acts as a methyl group donor to give a silyl ester side product. For catalyst derivatives with longer perfluoroalkyl groups as inner-modifications, we qualitatively observed less catalyst methylation. For IDPi **4d** ($X = SO_2C_6F_{13}$) essentially no methylation was detected ≤0 °C. We therefore reason that the stability of the chiral ion pair depends not only on the reaction temperature, but also on the nucleophilicity of the chiral counteranion and on methyl ester substrate. For the optimized conditions, we selected 3 mol% of IDPi **4d** ($X = SO_2C_6F_{13}$), 0 °C as reaction temperature and 3 equiv. of diene (see general procedures), for which we obtained full conversion with both substrates after 3.5 to 5.5 days.

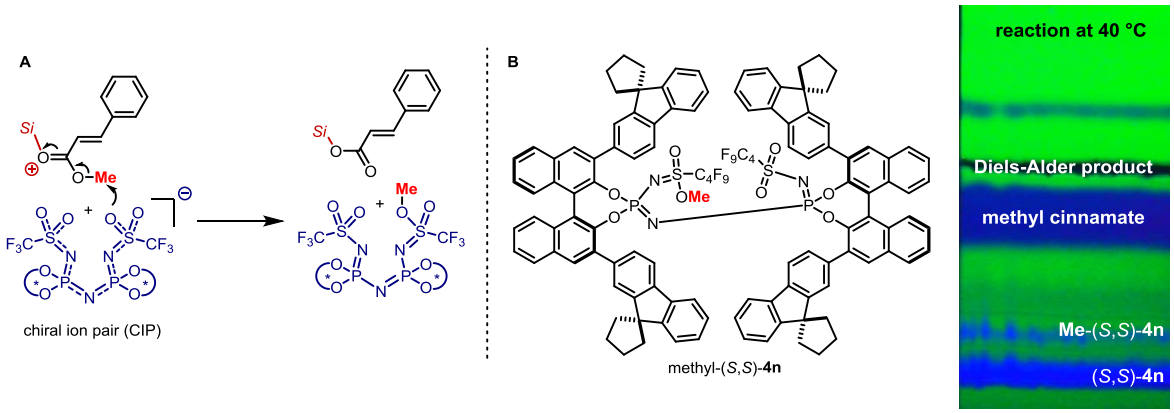


Figure S5. A Proposed methylation pathway of IDPi catalysts; **B** Qualitative analysis of a representative preparative TLC plate (silica gel; hexane/EtOAc 19:1, one elution, 254 nm) indicating catalyst methylation at 40 °C.

General Procedures

Catalytic, Asymmetric Diels-Alder Reactions

Procedure A: Catalyst activation with allylsilanes

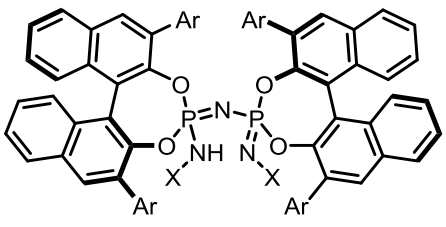
A 4 mL vial with a septum lid was charged with a magnetic stirrer bar, the appropriate α,β-unsaturated ester (0.2 mmol) and (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%) under argon. The reagents were dissolved in dry toluene (0.2 mL) and triethylallylsilane **5a** (40 μmol, 8 μL, 20 mol%) was added. The reaction mixture was stirred at r.t. for 5 min, subsequently cooled to the appropriate temperature and cyclopentadiene was added (1 mmol, 84 μL, 5 equiv.). Some parafilm was wrapped around the lid to seal the vial and the reaction was stirred at the appropriate temperature until TLC or NMR analysis indicated full consumption of the starting material. The reaction was then treated with a mixture of methanol/triethylamine (5:1, 50 μL) and diluted with hexanes, which caused precipitation of eventual cyclopentadiene polymers. The reaction mixture was filtered through cotton directly onto an equilibrated silica flash column and elution with the specified solvent mixture afforded the pure Diels-Alder products.

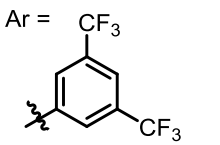
Procedure B: Catalyst activation with silyl ketene acetals

A 4 mL vial with a septum lid was charged with a magnetic stirrer bar, the appropriate α,β-unsaturated ester (0.2 mmol) and (*S*,*S*)-**4c** (2 μmol, 3.7 mg, 1 mol%) under argon. The reagents were dissolved in dry toluene (0.2 mL) and the reaction mixture was cooled to the appropriate temperature. Then, silyl ketene acetal **5b** (40 μmol, 12 μL, 20 mol%) and cyclopentadiene (1 mmol, 84 μL, 5 equiv.) were added in this order. The following steps were identical to those described in procedure A.

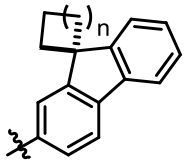
Procedure C: Neat reaction conditions
A 4 mL vial with a septum lid was charged with a magnetic stirrer bar, the appropriate α,β-unsaturated ester (0.2 mmol) and (*S*,*S*)-**4a-c** (2 μmol, 1 mol%) under argon. The sealed vial was cooled to the appropriate temperature and cyclopentadiene (2 mmol, 180 μL, 10 equiv.) was added. The reaction was stirred for 10 min to correctly adjust the temperature, before silylating agent **5a-d** (40 μmol, 20 mol%) was added. The following steps were identical to those described in procedure A.

NOTE: We found that catalysts with highly fluorinated 3,3'-substituents, such as **4a** and **4b**, generally tend to be more active, however also cause a certain level of cyclopentadiene polymerization. These catalysts can be activated with both, silyl ketene acetals or allyl silanes with the exception of triisopropylallylsilane reacting very sluggishly with these IDPi acids. With catalysts possessing 3-fluorene-derivated 3,3'-substituents, such as **4c**, cyclopentadiene polymerization is significantly suppressed or not detected at all depending on the reaction temperature. These IDPi derivatives are conveniently activated with silyl ketene acetals, while they generally react only slowly with allyl silanes.





X = SO_2CF_3 (**4a**)
$SO_2C_2F_5$ (**4b**)



n = 1; X = $SO_2C_2F_5$ (**4c**)
n = 2; X = $SO_2C_6F_{13}$ (**4d**)

Procedure D: Reactions with alternative dienes at 0 °C

An oven-dried 2.0 mL screw-cap glass vial was charged with (*S*,*S*)-**4d** (13.9 mg, 6 µmol, 3 mol%) and the appropriate α,β-unsaturated methyl ester (0.2 mmol). A Teflon-coated magnetic stirring bar was added, the vial was closed with a screw-cap containing a PTFE/rubber septum and sealed with parafilm. The reaction vial was evacuated, purged with argon (3 ×) and subsequently placed into an aluminum block submerged in an ice/acetone bath at −10 °C. The diene was transferred to the reaction vial and the colorless solution was kept at this temperature for 5 min. After the elapsed time, triisopropyl(2-methallyl)silane (**5d**, 23 µL, 0.1 mmol, 50 mol%) was added to the reaction mixture to initiate the reaction. Then, the vial was placed into an aluminum block in a cryostat at 0 °C and stirred at this temperature for the indicated time. The reaction was monitored by TLC and ^{1}H NMR spectroscopy and quenched with triethylamine (5 µL, 0.2 equiv.).

Procedure E: Reactions with alternative dienes at −20 °C and −40 °C

An oven-dried 2.0 mL screw-cap glass vial was charged with (*S*,*S*)-**4d** (13.9 mg, 6 µmol, 3 mol%) and the appropriate α,β-unsaturated methyl ester (0.2 mmol). A Teflon-coated magnetic stirring bar was added, the vial was closed with a screw-cap containing a PTFE/rubber septum and sealed with parafilm. Then, the reaction vial was evacuated, purged with argon (3 ×) and subsequently placed into an aluminum block submerged in a dry-ice/isopropanol bath at −77 °C. The diene was transferred to the reaction vial and the colorless solution was kept at this temperature for 5 min. After the elapsed time, triisopropyl(2-methallyl)silane (**5d**, 23 µL, 0.1 mmol, 50 mol%) was added to the reaction mixture to initiate the reaction. Then, the vial was placed into an aluminum block in a cryostat at 0 °C and stirred at this temperature for the indicated time.

Preparation of racemic Diels-Alder Products

Procedure A: with $HNTf_2$ as catalyst using Schlenk technique

In a flame-dried Schlenk flask, appropriate α,β-unsaturated ester (8 mmol) and trimethylallylsilane (0.8 mmol, 0.13 mL, 10 mol%) were dissolved in dry DCM (8 mL) under argon. The reaction solution was cooled to -78 °C and a stock solution of $HNTf_2$ (0.2 M in DCM, 40 µL, 8 µmol, 0.1 mol%) was added. Then, cyclopentadiene (40 mmol, 3.4 mL, 5 equiv.) was added and the reaction mixture was warmed up to 0 °C. Upon completion of the reaction indicated by TLC (typically within a few hours), the reaction was quenched with triethylamine (0.5 mL) and diluted with hexanes. Precipitated cyclopentadiene polymers were removed by filtration through celite and subsequent column chromatography on silica gel gave the racemic Diels-Alder products.

NOTE: This procedure was used for sensitive substrates such as methyl acrylate and methyl crotonate, which are prone to decomposition or polymerization. Higher amounts of silylating reagent were necessary in some cases to prevent extensive cyclopentadiene polymerization.

Procedure B: with $HNTf_2$ as catalyst in a vial

In a 4 mL vial with a septum lid with a magnetic stirrer bar, the appropriate α,β-unsaturated ester (0.2 mmol) was dissolved in dry toluene (0.2 mL) under argon. Trimethylallylsilane (0.1 mmol, 15 µL, 50 mol%) and a stock solution of $HNTf_2$ (0.2 M in DCM, 10 µL, 2 µmol, 1 mol%) was added in this order at r.t.. Then, cyclopentadiene (1 mmol, 84 µL, 5 equiv.) was added and the reaction mixture was stirred at r.t. until TLC indicated complete reaction (typically within a few hours). Triethylamine (10 µL) was added and the solvent was removed under reduced pressure. The residue oil was diluted with methanol and the precipitated cyclopentadiene polymers were filtered off through cotton. Concentration under reduced pressure gave the crude racemic Diels-Alder product, which were used for analytics without further purification.

Procedure C: thermal Diels-Alder reaction

A microwave reaction vial was charged with the appropriate unsaturated ester (0.2 mmol) and cyclopentadiene (2.4 mmol, 0.2 mL). The vial was sealed and heated to 120 °C overnight. Racemic Diels-Alder products were obtained after purification of the crude material by preparative TLC.

NOTE: Under these conditions, the exo-cycloadduct is typically the major diastereomer.

Characterization of Products

methyl (1*R*,2*S*,3*S*,4*S*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3a): Prepared according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), (*E*)-methyl cinnamate (**1a**, 0.20 mmol, 32 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 12 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (42 mg, 92%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. $[\alpha]_D^{25}$ = +127.1 (*c* 0.65, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 90/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 7.6 min, t_R (major, *exo*) = 8.8 min, t_R (minor, *exo*) = 9.5 min, t_R (minor, *endo*) = 11.9 min; $e.r._{endo}$ = 97:3, $e.r._{exo}$ = 96.5:3.5, d.r. (*endo*/*exo*) = 26:1.

The performance of catalysts **4a-c** was compared at a reaction temperature of −40 °C and a reaction time of 12 hours following the appropriate procedure A or B respectively:

entry	catalyst	silyl group	procedure	yield (%)	$e.r._{endo}$	$e.r._{exo}$	d.r. (endo/exo)
1	**4a**	TES	A	92	97:3	96.5:3.5	26:1
2	**4b**	TES	A	90	95.5:4.5	95:5	19:1
3	**4c**	TIPS	B	90	97.5:2.5	91.5:8.5	16:1

An enantioenriched mixture of endo/exo diastereomers (d.r. 9:1, $e.r._{endo}$ = 95.5:4.5, $e.r._{exo}$ = 95:5) was separated by preparative HPLC and the pure diastereomers were characterized as followed:

endo-diastereomer: **methyl (1*R*,2*S*,3*S*,4*S*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate ($3a_{endo}$)**:

≡

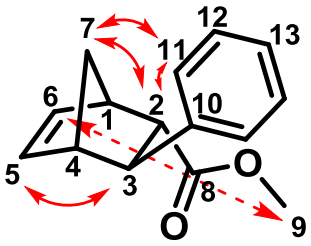
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.22 – 7.18 (m, 1H), 6.42 (dd, *J* = 5.6, 3.1 Hz, 1H), 6.12 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.67 (s, 3H), 3.32 – 3.25 (m, 1H), 3.11 (dd, *J* = 5.0, 1.8 Hz, 1H), 3.07 – 3.03 (m, 1H), 3.01 (dd, *J* = 5.0, 3.6 Hz, 1H), 1.81 – 1.76 (dm, *J* = 8.7 Hz, 1H), 1.61 – 1.55 (dm, *J* = 8.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.0, 144.4, 139.2, 134.7, 128.6, 127.6, 126.2, 77.4, 77.2, 76.9, 52.2, 51.9, 48.5, 47.6, 47.3, 46.4; $[\alpha]_D^{25}$ = +114.8 (*c* 0.77, $CHCl_3$); Lit.:[9] $[\alpha]_D^{20}$ = +126.8 (*c* 0.401, $CHCl_3$) for $e.r._{endo}$ = 98.5:1.5, d.r. (*endo*/*exo*) = 99:1; **HRMS** (ESI) calculated for $C_{15}H_{16}O_2Na$ $(M+Na)^+$: 251.1042; found 251.1044.

exo-diastereomer: **methyl (1*S*,2*S*,3*S*,4*R*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate ($3a_{exo}$)**:

≡

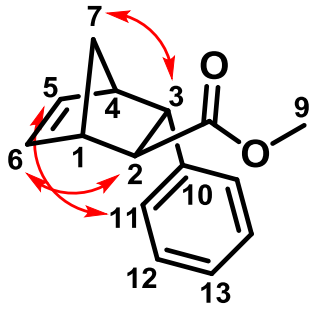
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.28 – 7.23 (m, 2H), 7.21 – 7.15 (m, 3H), 6.31 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.03 (dd, *J* = 5.7, 2.9 Hz, 1H), 3.72 (s, 3H), 3.70 (dd, *J* = 5.3, 3.5 Hz, 1H), 3.20 – 3.13 (m, 2H), 2.52 (dd, *J* = 5.3, 1.8 Hz, 1H), 1.90 (dm, *J* = 8.6 Hz, 1H), 1.56 (dm, *J* = 8.6 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.2, 143.2, 136.7, 136.1, 128.2, 128.0, 127.9, 126.3, 77.4, 77.2, 76.9, 52.1, 50.6, 48.8, 48.4, 48.2, 48.1; $[\alpha]_D^{25}$ = +247.5 (*c* 0.54, $CHCl_3$); **HRMS** (ESI) calculated for $C_{15}H_{16}O_2Na$ $(M+Na)^+$: 251.1042; found 251.1043.

Table S17. Peak table for methyl (1*R*,2*S*,3*S*,4*S*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate (**3a**$_{endo}$). Red arrows and circles indicate the characteristic NOESY signals for the assignment of stereochemistry.



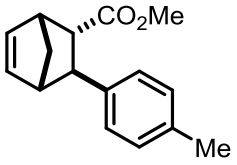
Atom	δ	J	COSY	HSQC	HMBC	NOESY
C1	46,40			1	1, 2, 4, 5, 6, 7', 7"	
H1	3,289	m	6, 7', 7"	1	1, 4, 5	2, 6, 7', 7"
C2	52,15			2	2, 4, 7"	
H2	3,005	dd 3.6(H1), 5.0(H3)	3, 4	2	1, 2, 3, 6, 8, 10	1, 7', 9, 11
C3	47,65			3	2, 3, 7", 11	
H3	3,113	dd 5.0(H2), 1.8(H7" anti)	2, 7", 11	3	3, 4, 5, 7, 8, 10, 11	5, 9, 11
C4	48,49			4	1, 3, 4, 5, 6, 7', 7"	
H4	3,042	m	2, 5, 7', 7"	4	1, 2, 4, 6	5, 7', 7", 11
C5	139,24			5	1, 3, 5, 6, 7'	
H5	6,424	dd 3.1(H4), 5.6(H6)	4, 6	5	1, 4, 5, 6, 7	3, 4, H7"
C6	134,70			6	2, 4, 5, 6, 7'	
H6	6,122	dd 2.8(H1), 5.6(H5)	1, 5	6	1, 4, 5, 6, 7	1, 9, H7"
C7	47,32			7', 7"	3, 5, 6, 7', 7"	
H7' syn	1,786	dm 8.7(H7" anti)	1, 4, 7"	7	1, 4, 5, 6, 7	1, 2, 4, 11
H7" anti	1,579	dm 8.7(H7' syn)	1, 3, 4, 7'	7	1, 2, 3, 4, 7, 8	1, 4, 5, 6
C8	174,96				2, 3, 7", 9	
C9	51,87			9	9	
H9	3,672	s		9	8, 9	2, 3, 6
C10	144,38				2, 3, 12	
C11	127,61			11	3, 11, 13	
H11	7,328	m	3	11	3, 11, 13	2, 3, 4, 7'
C12	128,60			12	12	
H12	7,308	m		12	10, 12	
C13	126,19			13	11	
H13	7,200	m		13	11	

Table S18. Peak table for methyl (1*S*,2*S*,3*S*,4*R*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate **(3a$_{exo}$)**. Red arrows and circles indicate the characteristic NOESY signals for the assignment of stereochemistry.



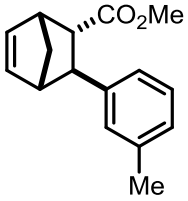
Atom	δ	J	COSY	HSQC	HMBC	NOESY
C1	48,24			1	1, 2, 4, 5, 6, 7'	
H1	3,149	m	6, 7', 7"	1	1, 3, 4, 5	2, 6, 7', 7"
C2	50,57			2	2, 3, 4, 5, 7"	
H2	2,520	dd 5.3(3), 1.8(7"anti)	3, 7"	2	1, 2, 3, 6, 7, 8, 10	1, 6, 11
C3	48,85			3	1, 2, 3, 6, 7', 7", 11	
H3	3,702	dd 3.5(4), 5.3(2)	2, 4, 11	3	2, 3, 4, 5, 8, 10, 11	4, 7', 11
C4	48,41			4	1, 3, 4, 5, 6, 7'	
H4	3,180	m	3, 5, 7', 7"	4	1, 2, 4, 6	3, 5, 7', 7", 11
C5	136,06			5	1, 3, 5, 6, 7', 7"	
H5	6,026	dd 2.9(4), 5.6(6)	4, 6, 7'	5	1, 2, 4, 5, 6, 7	4, 7", 11
C6	136,73			6	2, 4, 5, 6, 7', 7"	
H6	6,314	dd 3.2(1), 5.6(5)	1, 5, 7'	6	1, 3, 4, 5, 6, 7	1, 2, 7"
C7	48,11			7', 7"	2, 5, 6, 7', 7"	
H7' syn	1,897	dm 8.6(7"anti)	1, 4, 5, 6, 7"	7	1, 3, 4, 5, 6, 7	1, 3, 4
H7" anti	1,557	dm 8.6(7'syn)	1, 2, 4, 7'	7	2, 3, 5, 6, 7, 10	1, 4, 5, 6
C8	176,21				2, 3, 9	
C9	52,05			9	9	
H9	3,716	s		9	8, 9	
C10	143,17				2, 3, 7", 12	
C11	127,97			11	3, 11, 13	
H11	7,178	m	3	11	3, 11, 13	2, 3, 4, 5
C12	128,18			12	12	
H12	7,255	m		12	10, 12	
C13	126,29			13	11	
H13	7,176	m		13	11	

methyl (1*R*,2*S*,3*S*,4*S*)-3-(p-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3b): Prepared



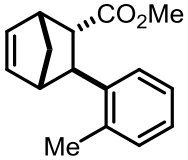
according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(p-tolyl)acrylate (**1b**, 0.20 mmol, 35.4 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (48 mg, 99%). The enantiomeric ratios were determined by HPLC on a chiral stationary phase. The diastereomeric ratio was determined by ^{1}H NMR. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.22 (d, *J* = 8.1 Hz, 2H), 7.12 (d, *J* = 7.9 Hz, 2H), 6.42 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.67 (s, 3H), 3.28 (dtq, *J* = 4.1, 2.2, 1.1 Hz, 1H), 3.07 (dd, *J* = 5.1, 1.7 Hz, 1H), 3.03 – 2.97 (m, 2H), 2.33 (s, 3H), 1.78 (dt, *J* = 8.6, 1.5 Hz, 1H), 1.56 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.0, 141.3, 139.2, 135.7, 134.6, 129.3, 127.5, 52.1, 51.8, 48.7, 47.4, 47.3, 46.3, 21.1; **HRMS** (EI) calculated for $C_{16}H_{18}O_2$: 242.1301; found 242.1301; **$[\alpha]_D^{25}$** = +118.5 (*c* 0.53, $CHCl_3$); **HPLC** (Heartcut) 1. 50 mm Zorbax Eclipse PAH, 4.6 mm, methanol/water – gradient 50 % B - 5` - 80 % B -5` - 80% - 1` - 100% B, 1.0 mL/min, 38.5 MPa, 308 K, 220 nm; 2. 150mm Chiralcel OJ-3R, 4.6 mm, methanol, 1.0 mL/min, 298 K, 17.7 MPa, 220 nm; t_R (major, *exo*) = 5.3 min, t_R (major, *endo*) = 5.5 min, t_R (minor, *exo*) = 7.0 min, t_R (minor, *endo*) = 9.5 min; $e.r._{endo}$ = 97:3, $e.r._{exo}$ = 96:4, d.r. (*endo*/*exo*) = 20:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(m-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3c): Prepared



according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(m-tolyl)acrylate (**1c**, 0.20 mmol, 35.9 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (44 mg, 89%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.20 (t, *J* = 7.5 Hz, 1H), 7.16 – 7.10 (m, 2H), 7.02 (d, *J* = 7.4 Hz, 1H), 6.42 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.67 (s, 3H), 3.32 – 3.25 (m, 1H), 3.08 (dd, *J* = 5.1, 1.8 Hz, 1H), 3.05 – 2.98 (m, 2H), 2.35 (s, 3H), 1.79 (dt, *J* = 8.8, 1.5 Hz, 1H), 1.57 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.0, 144.3, 139.3, 138.1, 134.6, 128.5, 128.5, 126.9, 124.5, 52.0, 51.8, 48.6, 47.6, 47.4, 46.4, 21.7; **HRMS** (EI) calculated for $C_{16}H_{18}O_2$: 242.1301; found 242.1302; **$[\alpha]_D^{25}$** = +128.1 (*c* 0.51, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 90/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 7.7 min, t_R (minor, *exo*) = 9.5 min, t_R (major, *exo*) = 10.6 min, t_R (minor, *endo*) = 11.8 min; $e.r._{endo}$ = 97.5:2.5, $e.r._{exo}$ = 98:2, d.r. (*endo*/*exo*) = 17:1.

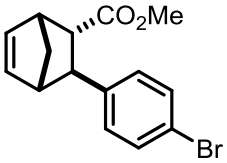
methyl (1*R*,2*S*,3*S*,4*S*)-3-(o-tolyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3d): Prepared



according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(o-tolyl)acrylate (**1d**, 0.20 mmol, 36.0 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (43 mg, 87%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.31 – 7.27 (m, 1H), 7.21 – 7.16 (m, 2H), 7.18 – 7.09 (m, 2H), 6.47 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.10 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.64 (s, 3H), 3.30 (dddt, *J* = 4.0, 3.2, 2.3, 1.1 Hz, 1H), 3.20 (dd, *J* = 5.2, 1.7 Hz, 1H), 3.12 (dd, *J* = 5.1, 3.6 Hz, 1H), 2.84 (dq, *J* = 3.2, 1.6 Hz, 1H), 2.32 (s, 3H), 1.85 (dt, *J* = 8.7, 1.5 Hz, 1H), 1.55 (dd, *J* = 8.8, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.1, 142.0, 139.1, 137.2, 134.2, 130.7, 126.2, 126.1, 125.5, 51.8, 49.6, 49.5, 47.2, 46.8, 44.6, 20.4; **HRMS** (EI) calculated for $C_{16}H_{18}O_2$: 242.1301; found 242.1302; **$[\alpha]_D^{25}$** = +150.3 (*c* 0.64, $CHCl_3$); **HPLC** (Heartcut) 1. 50 mm Eclipse Plus C18, 3.0 mm, methanol/water – gradient 50% B - 5` - 70 % B - 5` - 70 % B - 1`- 100% B, 0.5 mL/min, 34.8 MPa, 308 K, 220 nm; 2. 150 mm Chiralcel OJ3R, 4.6 mm, methanol/water = 90:10, 1.0 mL/min, 25.6 MPa, 308 K, 220 nm; t_R (minor, *exo*) =

4.2 min, t_R (major, *exo*) = 4.9 min, t_R (minor, *endo*) = 5.7 min, t_R (major, *endo*) = 6.1 min; e.r.$_{endo}$ = 97:3, e.r.$_{exo}$ = not given due to weak signal, d.r. (*endo*/*exo*) = >50:1.

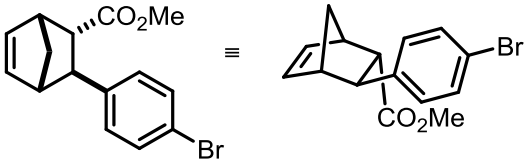
methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3e): Prepared



according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(4-bromophenyl)acrylate (**1e**, 0.20 mmol, 48.5 mg) and cyclopentadiene (2 mmol, 180 μL) at −40 °C for 24 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (60 mg, 97%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **HPLC** Daicel Chiralcel OJ-3R, MeCN/H_2O = 60/40, 1 mL/min, 25 °C, 220 nm, t_R (major, *exo*) = 8.9 min, t_R (major, *endo*) = 9.7 min, t_R (minor, *exo*) = 10.5 min, t_R (minor, *endo*) = 12.3 min; e.r.$_{endo}$ = 97.5:2.5, e.r.$_{exo}$ = 97.5:2.5, d.r. (*endo*/*exo*) = 16:1; $[\alpha]_D^{25}$ = +102.2 (*c* 0.64, $CHCl_3$).

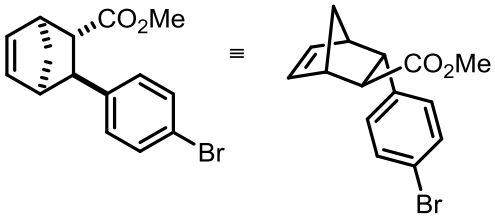
An enantioenriched mixture of endo/exo diastereomers (d.r. 17:1, e.r.$_{endo}$ = 95.5:4.5, e.r.$_{exo}$ = 91:9) was separated by preparative HPLC on a chiral stationary phase to give optically pure diastereomers, which were characterized as followed:

endo-diastereomer: **methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3e$_{endo}$)**:



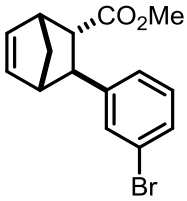
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.44 – 7.39 (m, 2H), 7.22 – 7.17 (m, 2H), 6.40 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.67 (s, 3H), 3.33 – 3.26 (m, 1H), 3.05 (dd, *J* = 5.0, 1.8 Hz, 1H), 3.03 – 2.96 (m, 1H), 2.92 (dd, *J* = 5.0, 3.6 Hz, 1H), 1.72 (d, *J* = 8.8 Hz, 1H), 1.58 (d, *J* = 8.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.7, 143.5, 139.1, 134.9, 131.6, 129.4, 120.0, 52.4, 52.0, 48.2, 47.3, 47.2, 46.3; $[\alpha]_D^{25}$ = +101.1 (*c* 0.73, $CHCl_3$); **HRMS** (ESI) calculated for $C_{15}H_{15}O_2BrNa$ $(M+Na)^+$: 329.0148; found 329.0151.

exo-diastereomer: **methyl (1*S*,2*S*,3*S*,4*R*)-3-(4-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3e$_{exo}$)**:



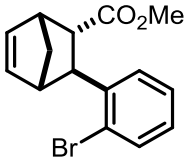
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.39 – 7.33 (m, 1H), 7.07 – 7.01 (m, 1H), 6.31 (dd, *J* = 5.7, 3.1 Hz, 1H), 5.99 (dd, *J* = 5.7, 2.9 Hz, 1H), 3.71 (s, 2H), 3.64 (dd, *J* = 5.3, 3.4 Hz, 1H), 3.16 – 3.14 (m, 1H), 3.14 – 3.11 (m, 0H), 2.44 (dd, *J* = 5.3, 1.7 Hz, 1H), 1.86 (dtt, *J* = 8.7, 1.6, 0.7 Hz, 1H), 1.56 (dq, *J* = 8.7, 1.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.9, 142.2, 137.0, 135.8, 131.2, 129.7, 120.1, 52.1, 50.7, 48.4, 48.2, 48.2; $[\alpha]_D^{25}$ = +260.2 (*c* 0.625, $CHCl_3$); **HRMS** (ESI) calculated for $C_{15}H_{15}O_2BrNa$ $(M+Na)^+$: 329.0148; found 329.0151.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(3-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3f): Prepared



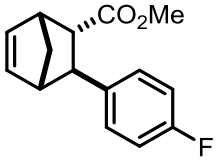
according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(3-bromophenyl)acrylate (**1f**, 0.20 mmol, 48.4 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (57 mg, 92%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.46 (d, *J* = 2.0 Hz, 1H), 7.33 (dt, *J* = 8.0, 1.4 Hz, 1H), 7.27 – 7.23 (m, 1H), 7.17 (t, *J* = 7.8 Hz, 1H), 6.40 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.68 (s, 3H), 3.33 – 3.26 (m, 1H), 3.07 (dd, *J* = 5.1, 1.8 Hz, 1H), 3.02 (dq, *J* = 3.2, 1.5 Hz, 1H), 2.95 (dd, *J* = 5.0, 3.6 Hz, 1H), 1.74 (dt, *J* = 8.8, 1.5 Hz, 1H), 1.59 (dq, *J* = 8.8, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.6, 146.9, 139.0, 134.9, 130.6, 130.1, 129.3, 126.4, 122.8, 52.3, 52.0, 48.2, 47.3, 47.3, 46.4; **HRMS** (EI) calculated for $C_{15}H_{15}O_2Br$: 306.0250; found 306.0245; $[\alpha]_D^{25}$ = +104.1 (*c* 0.58, $CHCl_3$); **HPLC** Daicel Chiralpak AD-3R, MeOH/H_2O = 80/20, 1 mL/min, 25 °C, 220 nm, t_R (minor, *exo*) = 14.6 min, t_R (minor, *endo*) = 15.8 min, t_R (major, *endo*) = 18.3 min, t_R (major, *exo*) = 20.6 min; $e.r._{endo}$ = 97.5:2.5, $e.r._{exo}$ = 97.5:2.5, d.r. (*endo*/*exo*) = 15:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(2-bromophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3g): Prepared



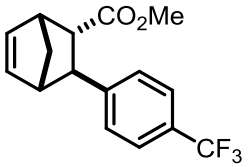
according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(2-bromophenyl)acrylate (**1g**, 0.20 mmol, 48.2 mg) and cyclopentadiene (2 mmol, 180 μL) at −40 °C for 24 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (43 mg, 70%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.60 (dd, *J* = 7.9, 1.3 Hz, 1H), 7.32 (dd, *J* = 7.9, 1.7 Hz, 1H), 7.28 (td, *J* = 7.7, 1.2 Hz, 1H), 7.08 (td, *J* = 7.7, 1.8 Hz, 1H), 6.49 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.14 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.64 (s, 3H), 3.38 (dd, *J* = 5.2, 1.7 Hz, 1H), 3.31 (dddt, *J* = 4.1, 3.3, 2.4, 1.1 Hz, 1H), 3.14 (dd, *J* = 5.2, 3.6 Hz, 1H), 2.93 – 2.88 (m, 1H), 1.71 (dddd, *J* = 8.8, 2.2, 1.4, 0.6 Hz, 1H), 1.52 (dq, *J* = 8.8, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.6, 142.6, 138.8, 134.6, 133.5, 127.8, 127.5, 127.4, 126.4, 51.9, 50.0, 49.1, 48.3, 46.7, 46.6; **HRMS** (ESI) calculated for $C_{15}H_{16}O_2Br$ $(M+H)^+$: 307.0328; found 307.0329; $[\alpha]_D^{25}$ = +95.6 (*c* 0.55, $CHCl_3$); **HPLC** (2D-Separation) 1. 50 mm Eclipse PAH 1.8 μm, 3.0 mm, methanol/water – gradient 60% - 5' - 90% B, 0.5 mL/min, 38.5 MPa, 308 K; 2. 150 mm 3-CelluCoat RP, 4.6 mm, methanol/water – gradient 70% - 5' - 90% B, 1.0 ml/min, 35.3 MPa, 298 K; t_R (major, *endo*) = 10.4 min, t_R (minor, *endo*) = 10.7 min, t_R (*exo*) = 39.6 min, t_R (*exo*) = 39.8 min; $e.r._{endo}$ = 97.5:2.5, $e.r._{exo}$ = not given due to weak signal, d.r. (*endo*/*exo*) = 47:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-fluorophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3h): Prepared

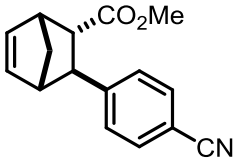


according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(4-fluorophenyl)acrylate (**1h**, 0.20 mmol, 36.5 mg) and cyclopentadiene (2 mmol, 180 μL) at −40 °C for 24 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (49 mg, 98%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.32 – 7.23 (m, 2H), 7.04 – 6.95 (m, 2H), 6.41 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.67 (s, 3H), 3.32 – 3.26 (m, 1H), 3.07 (d, *J* = 4.7 Hz, 1H), 3.00 (dq, *J* = 3.3, 1.7 Hz, 1H), 2.93 (dd, *J* = 5.1, 3.5 Hz, 1H), 1.74 (dt, *J* = 8.7, 1.5 Hz, 1H), 1.59 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.8, 162.4, 160.4, 140.1, 140.0, 139.1, 134.8, 129.0, 128.9, 115.4, 115.2, 52.5, 51.9, 48.4, 47.2, 47.0, 46.3; **HRMS** (ESI) calculated for $C_{15}H_{15}O_2F_1Na$ $(M+Na)^+$: 269.0948; found 269.0948; $[\alpha]_D^{25}$ = +103.3 (*c* 0.79, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 90/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 6.1 min, t_R (major, *exo*) =

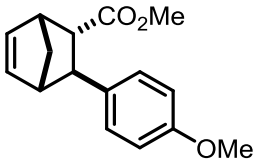
6.9 min, t_R (minor, *exo*) = 7.3 min, t_R (minor, *endo*) = 8.9 min; e.r.$_{endo}$ = 97:3, e.r.$_{exo}$ = 95.5:4.5, d.r. (*endo*/*exo*) = 18:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-(trifluoromethyl)phenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3i): 

Prepared according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(4-(trifluoromethyl)phenyl)acrylate (**1i**, 0.20 mmol, 45.9 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as a colorless oil (58 mg, 98%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.56 (d, *J* = 8.1 Hz, 2H), 7.44 (d, *J* = 8.1 Hz, 2H), 6.43 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.14 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.68 (s, 3H), 3.32 (s, 1H), 3.16 (d, *J* = 4.8 Hz, 1H), 3.06 (dt, *J* = 3.3, 1.7 Hz, 1H), 2.96 (dd, *J* = 5.1, 3.6 Hz, 1H), 1.74 (dt, *J* = 8.8, 1.5 Hz, 1H), 1.62 (dq, *J* = 8.8, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.5, 148.6, 139.0, 135.0, 127.9, 125.5 (q, *J* = 3.7 Hz), 52.4, 52.0, 48.1, 47.6, 47.3, 46.4; **^{19}F NMR** (471 MHz, $CDCl_3$) δ -62.4; **HRMS** (ESI) calculated for $C_{16}H_{15}O_2F_3Na$ $(M+Na)^+$: 319.0916; found 319.0919; **$[\alpha]_D^{25}$** = +93.1 (*c* 0.64, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 75/25, 1 mL/min, 25 °C, 220 nm, t_R (major, *exo*) = 20.7 min, t_R (major, *endo*) = 21.9 min, t_R (minor, *exo*) = 24.0 min, t_R (minor, *endo*) = 29.6 min; e.r.$_{endo}$ = 97.5:2.5, e.r.$_{exo}$ = 98.5:1.5, d.r. (*endo*/*exo*) = 12:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-cyanophenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3j): Prepared 

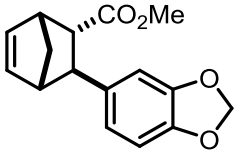
according to procedure A with catalyst (*S*,*S*)-**4b** (6 μmol, 11.3 mg, 3 mol%), methyl (*E*)-3-(4-cyanophenyl)acrylate (**1j**, 0.20 mmol, 37.8 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 3 days. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 2:1→1:1→1:2→1:4) as a colorless wax (48 mg, 94%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.62 – 7.57 (m, 2H), 7.46 – 7.41 (m, 2H), 6.41 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.14 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.68 (s, 3H), 3.32 (dddd, *J* = 4.6, 2.7, 2.0, 1.1 Hz, 1H), 3.15 (dd, *J* = 5.2, 1.9 Hz, 1H), 3.06 (dq, *J* = 3.1, 1.5 Hz, 1H), 2.92 (dd, *J* = 5.1, 3.6 Hz, 1H), 1.70 (dddd, *J* = 8.8, 2.2, 1.4, 0.6 Hz, 1H), 1.62 (dq, *J* = 8.9, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.3, 150.2, 138.9, 135.1, 132.4, 128.4, 119.1, 110.1, 52.5, 52.1, 47.9, 47.8, 47.3, 46.4; **HRMS** (ESI) calculated for $C_{16}H_{15}NO_2Na$ $(M+Na)^+$: 276.0995; found 276.0997; **$[\alpha]_D^{25}$** = +125.8 (*c* 0.48, $CHCl_3$); **HPLC** (2D-Separation) 1. 50 mm Eclipse PAH 1.8 μm, 3.0 mm, methanol/water – gradient 40% - 5' - 60% B, 0.5 mL/min, 308 K, 32.7 MPa; 2. 150 mm AmyCoat RP, 4.6 mm, methanol/water = 90:10, 1.0 mL/min, 298 K, 21.0 MPa, 220 nm; t_R (major, *exo*) = 12.5 min, t_R (minor, *exo*) = 13.5 min, t_R (minor, *endo*) = 36.2 min, t_R (major, *endo*) = 24.8 min; e.r.$_{endo}$ = 95:5, e.r.$_{exo}$ = 64.5:35.5, d.r. (*endo*/*exo*) = 13:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(4-methoxyphenyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3k): 

Prepared according to procedure A with catalyst (*S*,*S*)-**4a** (6 μmol, 10.8 mg, 3 mol%), methyl (*E*)-3-(4-methoxyphenyl)acrylate (**1k**, 0.20 mmol, 38.3 mg), triethylallylsilane (0.1 mmol, 20 μL, 50 mol%) and cyclopentadiene (2 mmol, 180 μL) at −20 °C for 2 days. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 2:1→1:1) as a colorless oil (50 mg, 97%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.26 – 7.21 (m, 2H), 6.88 – 6.83 (m, 2H), 6.41 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.11 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.79 (s, 3H), 3.66 (s, 3H), 3.27 (dddt, *J* = 4.0, 3.1, 2.2, 1.1 Hz, 1H), 3.04 (dd, *J* = 5.1, 1.8 Hz, 1H), 2.98 (dq, *J* = 3.3, 1.7 Hz, 1H), 2.95 (dd, *J* = 5.0, 3.6 Hz, 1H), 1.80 – 1.73 (m, 1H), 1.56 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.0, 158.0, 139.2, 136.4, 134.6, 128.5, 114.0, 55.4, 52.3, 51.8, 48.7, 47.3, 47.0, 46.3; **HRMS** (ESI) calculated for $C_{16}H_{19}O_3$ $(M+H)^+$: 259.1329; found

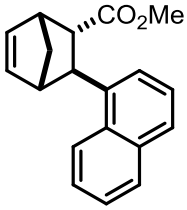
259.1333; $[\alpha]_D^{25}$ = +112.6 (*c* 0.57, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeCN/H_2O = 70/30, 1 mL/min, 25 °C, 220 nm, t_R (major, *exo*) = 4.4 min, t_R (major, *endo*) = 4.9 min, t_R (minor, *exo*) = 5.4 min, t_R (major, *endo*) = 6.6 min; $e.r._{endo}$ = 95:5, $e.r._{exo}$ = n.d., d.r. (*endo*/*exo*) = 12:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(benzo[d][1,3]dioxol-5-yl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3l):



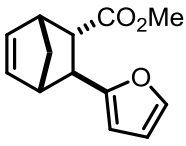
Prepared according to procedure A with catalyst (*S*,*S*)-**4a** (6 μmol, 10.8 mg, 3 mol%), methyl (*E*)-3-(benzo[d][1,3]dioxol-5-yl)acrylate (**1l**, 0.20 mmol, 41.6 mg), triethylallylsilane (0.1 mmol, 20 μL, 50 mol%) and cyclopentadiene (2 mmol, 180 μL) at −20 °C for 2 days. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 2:1→1:1) as a colorless oil (51 mg, 94%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.84 (d, *J* = 1.6 Hz, 1H), 6.77 (ddd, *J* = 8.1, 1.7, 0.7 Hz, 1H), 6.74 (d, *J* = 8.0 Hz, 1H), 6.39 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.10 (dd, *J* = 5.7, 2.8 Hz, 1H), 5.92 (s, 2H), 3.67 (s, 3H), 3.26 (dddt, *J* = 4.2, 3.2, 2.4, 1.2 Hz, 1H), 3.02 (dd, *J* = 5.0, 1.8 Hz, 1H), 2.97 (dq, *J* = 3.2, 1.6 Hz, 1H), 2.91 (dd, *J* = 5.0, 3.5 Hz, 1H), 1.75 (ddd, *J* = 9.5, 1.9, 1.2 Hz, 1H), 1.60 – 1.55 (m, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.9, 147.8, 145.9, 139.2, 138.4, 134.7, 120.2, 108.3, 101.0, 52.6, 51.9, 48.6, 47.5, 47.3, 46.3; **HRMS** (ESI) calculated for $C_{16}H_{16}O_4Na$ $(M+Na)^+$: 295.0941; found 295.0940; $[\alpha]_D^{25}$ = +102.3 (*c* 0.58, $CHCl_3$); **HPLC** Kromasil AmyCoat RP, MeOH/H_2O = 85/15, 1 mL/min, 25 °C, 254 nm, t_R (minor, *exo*) = 11.6 min, t_R (minor, *endo*) = 13.2 min, t_R (major, *endo*) = 18.8 min, t_R (minor, *exo*) = 22.2 min; $e.r._{endo}$ = 96:4, $e.r._{exo}$ = 91:9, d.r. (*endo*/*exo*) = 15:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(naphthalen-1-yl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3m):



Prepared according to procedure A with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), methyl (*E*)-3-(naphthalen-1-yl)acrylate (**1m**, 0.20 mmol, 42.4 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 48 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (55 mg, 99%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 8.16 (d, *J* = 8.4 Hz, 1H), 7.86 (dd, *J* = 7.9, 1.7 Hz, 1H), 7.74 (d, *J* = 7.5 Hz, 1H), 7.51 (dddd, *J* = 17.8, 8.0, 6.8, 1.4 Hz, 2H), 7.47 – 7.42 (m, 2H), 6.60 (dd, *J* = 5.7, 3.1 Hz, 1H), 6.19 (dd, *J* = 5.6, 2.8 Hz, 1H), 3.80 (dd, *J* = 5.1, 1.1 Hz, 1H), 3.66 (s, 3H), 3.34 (dtd, *J* = 3.6, 1.8, 0.9 Hz, 1H), 3.21 (dd, *J* = 5.1, 3.6 Hz, 1H), 3.08 (dt, *J* = 3.3, 1.7 Hz, 1H), 1.88 (d, *J* = 8.7 Hz, 1H), 1.63 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.2, 139.9, 138.9, 134.6, 134.1, 132.7, 128.9, 127.1, 126.1, 125.7, 125.4, 124.2, 122.8, 51.9, 49.8, 49.8, 47.8, 47.0, 43.9; **HRMS** (ESI) calculated for $C_{19}H_{18}O_2Na$ $(M+Na)^+$: 301.1199; found 301.1200; $[\alpha]_D^{25}$ = +89.8 (*c* 0.53, $CHCl_3$); **HPLC** (2D-Separation) 1. 50 mm Eclipse PAH 1.8 μm, 3.0 mm, methanol/water – gradient 60% - 5' - 90% B, 0.5 mL/min, 37.0 MPa, 308 K; 2. 150 mm 3-AmyCoat RP, 4.6 mm, acetonitrile/water = 50:50, 1.0 ml/min, 18.6 MPa, 298 K, 220 nm; t_R (*exo*) = 15.0 min, t_R (*exo*) = 16.1 min, t_R (major, *endo*) = 36.2 min, t_R (minor, *endo*) = 37.5 min; $e.r._{endo}$ = 97.5:2.5, $e.r._{exo}$ = not given due to weak signal, d.r. (*endo*/*exo*) = >50:1.

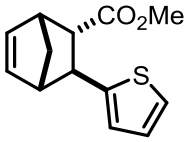
methyl (1*R*,2*S*,3*S*,4*S*)-3-(furan-2-yl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3n):



Prepared according to procedure A with catalyst (*S*,*S*)-**4b** (6 μmol, 11.3 mg, 3 mol%), methyl (*E*)-3-(furan-2-yl)acrylate (**1n**, 0.20 mmol, 30.4 mg) and cyclopentadiene (2 mmol, 180 μL) at −40 °C for 14 hours. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1→1:1) as an orange oil (39 mg, 89%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.33 – 7.30 (m, 1H), 6.34 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.29 (dd, *J* = 3.2, 1.8 Hz, 1H), 6.10 – 6.05 (m, 2H), 3.65 (s, 3H), 3.29 – 3.26 (m, 1H), 3.11 (dd, *J* = 4.8, 3.6 Hz, 1H), 3.06 (dd, *J* = 5.0, 1.8 Hz, 1H), 3.01 – 2.98 (m, 1H), 1.74 (dt, *J* = 8.6, 1.6 Hz, 1H), 1.51 (dq, *J* = 8.7, 1.8 Hz, 1H); **^{13}C**

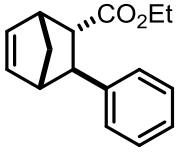
NMR (126 MHz, $CDCl_3$) δ 174.3, 157.7, 141.3, 138.3, 134.4, 110.3, 105.0, 51.9, 49.8, 48.6, 47.7, 46.0, 41.9; **HRMS** (EI) calculated for $C_{13}H_{14}O_3$ (M): 218.0937; found 218.0937; $[\alpha]_D^{25}$ = +120.0 (*c* 0.42, $CHCl_3$); **HPLC** (Heartcut) 1. 50 mm YMC Triart C18 ExRS, 3.0 mm, methanol/water – gradient 50 % B - 5` - 70 % B -5` - 70% - 1` - 100% B, 0.5 mL/min, 58.7 MPa, 308 K, 220 nm; 2. 150mm Chiralcel OJ-3R, 4.6 mm, methanol/water = 90:10, 1.0 mL/min, 298 K, 26.5 MPa, 220 nm; t_R (major, *exo*) = 4.7 min, t_R (minor, *exo*) = 5.0 min, t_R (major, *endo*) = 5.0 min, t_R (minor, *endo*) = 6.6 min; $e.r._{endo}$ = 94:6, $e.r._{exo}$ = not given due to weak signal, d.r. (*endo*/*exo*) = >50:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(thiophen-2-yl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3o): Prepared



according to procedure A with catalyst (*S*,*S*)-**4b** (6 µmol, 11.3 mg, 3 mol%), methyl (*E*)-3-(thiophen-2-yl)acrylate (**1o**, 0.20 mmol, 34.3 mg) and cyclopentadiene (1 mmol, 90 µL) at −40 °C for 3 days. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 2:1→1:1→1:2) as a colorless oil (43 mg, 90%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.14 (dd, *J* = 5.1, 1.2 Hz, 1H), 6.94 (dd, *J* = 5.1, 3.5 Hz, 1H), 6.90 (dt, *J* = 3.5, 1.1 Hz, 1H), 6.38 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.11 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.67 (s, 3H), 3.33 – 3.25 (m, 2H), 3.07 (dd, *J* = 4.8, 3.6 Hz, 1H), 3.01 (ddq, *J* = 3.2, 1.6, 0.8 Hz, 1H), 1.83 (dtt, *J* = 9.0, 1.5, 0.7 Hz, 1H), 1.60 (dq, *J* = 8.9, 1.8 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.3, 148.7, 138.5, 134.5, 126.9, 123.8, 123.3, 53.6, 51.9, 50.7, 47.6, 46.1, 43.9; **HRMS** (ESI) calculated for $C_{13}H_{14}O_2SNa$ $(M+Na)^+$: 257.0607; found 257.0606; $[\alpha]_D^{25}$ = +117.7 (*c* 0.53, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeCN/H_2O = 40/60, 1 mL/min, 25 °C, 220 nm, t_R (minor, *exo*) = 35.6 min, t_R (major, *endo*) = 38.2 min, t_R (minor, *endo*) = 42.9 min, t_R (minor, *exo*) = 45.1 min; $e.r._{endo}$ = 94:6, $e.r._{exo}$ = 90:10, d.r. (*endo*/*exo*) = >50:1.

ethyl (1*R*,2*S*,3*S*,4*S*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate: Prepared according to

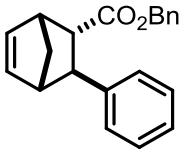


procedure B with catalyst (*S*,*S*)-**4d** (2 µmol, 3.7 mg, 1 mol%), silyl ketene acetal **5b** (0.04 mmol, 12 µL, 20 mol%), ethyl (*E*)-cinnamate (0.20 mmol, 35.7 mg) and cyclopentadiene (1 mmol, 90 µL) at −40 °C for 7 days. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (49 mg, 99%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.37 – 7.28 (m, 4H), 7.23 – 7.18 (m, 1H), 6.43 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.12 (dd, *J* = 5.7, 2.8 Hz, 1H), 4.13 (p, *J* = 7.1 Hz, 2H), 3.29 (tdq, *J* = 3.1, 2.2, 1.1 Hz, 1H), 3.12 (dd, *J* = 5.2, 1.8 Hz, 1H), 3.05 (dt, *J* = 3.3, 1.7 Hz, 1H), 2.99 (dd, *J* = 5.0, 3.6 Hz, 1H), 1.79 (dt, *J* = 8.6, 1.5 Hz, 1H), 1.60 – 1.56 (m, 1H), 1.26 (t, *J* = 7.1 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 174.4, 144.5, 139.2, 134.6, 128.6, 127.6, 126.1, 60.5, 52.4, 48.4, 47.5, 47.3, 46.4, 14.5; **HRMS** (ESI) calculated for $C_{16}H_{19}O_2$ $(M+H)^+$: 243.1380; found 243.1384; $[\alpha]_D^{25}$ = +89.0 (*c* 0.54, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 90/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 8.7 min, t_R (minor, *exo*) = 10.2 min, t_R (major, *exo*) = 10.8 min, t_R (minor, *endo*) = 12.0 min; $e.r._{endo}$ = 88:12, $e.r._{exo}$ = 82:18, d.r. (*endo*/*exo*) = 14:1.

The performance of catalysts **4a** and **4c** was compared at a reaction temperature of −40 °C and a reaction time of 7 days following the appropriate procedure A or B respectively:

entry	catalyst	procedure	yield (%)	d.r. (endo:exo)	e.r. (endo)	e.r. (exo)
1	**4a**	A	99	15:1	73.5:26.5	75:25
2	**4c**	B	99	14:1	88:12	82:18

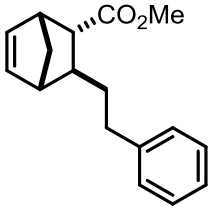
benzyl (1*R*,2*S*,3*S*,4*S*)-3-phenylbicyclo[2.2.1]hept-5-ene-2-carboxylate: Prepared according to procedure B with catalyst (*S*,*S*)-**4d** (2 μmol, 3.7 mg, 1 mol%), silyl ketene acetal **5b** (0.04 mmol, 12 μL, 20 mol%), benzyl (*E*)-cinnamate (0.20 mmol, 47.7 mg) and cyclopentadiene (1 mmol, 90 μL) at −40 °C for 3 weeks. The conversion was determined by ^{1}H-NMR to be approx. 10% and isolation of the product for stereochemical analysis was performed by preparative TLC. The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (300 MHz, $CDCl_3$): δ = 7.42–7.13 (m, 10H), 6.42 (dd, *J* = 5.6, 3.2 Hz, 1H), 6.06 (dd, *J* = 5.6, 3.2 Hz, 1H), 5.11 (q, *J* = 12.4, 6.9 Hz, 2H), 3.32 (s, 1H), 3.15 (dd, *J* = 7.3, 2.0 Hz, 2H), 3.05 (dd, *J* = 4.9, 3.6 Hz, 2H), 1.89 (d, *J* = 8.6 Hz, 1H), 1.80 (d, *J* = 8.7 Hz, 2H), 1.61–1.55 (m, 2H); **^{13}C NMR** (75 MHz, $CDCl_3$) δ 174.2, 144.4, 139.3, 136.8, 134.6, 128.7, 128.6, 128.2, 128.0, 127.6, 126.2, 66.6, 52.4, 48.5, 47.7, 47.4, 46.6; **HRMS** (ESI) calculated for $C_{21}H_{20}O_2Na$ $(M+Na)^+$: 327.1354; found 327.1355; **HPLC** Daicel Chiralcel OJ-3R, MeOH/MeCN/H_2O = 45/45/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 6.2 min, t_R (major, *exo*) = 6.5 min, t_R (minor, *endo*) = 8.3 min, t_R (minor, *exo*) = 14.5 min; $e.r._{endo}$ = 84:16, $e.r._{exo}$ = 80:20, d.r. (*endo*/*exo*) = 32:1.



The performance of catalysts **4a** and **4c** was compared at a reaction temperature of −40 °C and a reaction time of 3 weeks following the appropriate procedure A or B respectively:

entry	catalyst	procedure	conversion (%)	d.r. (endo:exo)	e.r. (endo)	e.r. (exo)
1	**4a**	A	<5	21:1	58.5:41.5	57.5:42.5
2	**4c**	B	10	32:1	84:16	80:20

methyl (1*R*,2*S*,3*S*,4*S*)-3-phenethylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3p): Prepared according to procedure B with catalyst (*S*,*S*)-**4a** (2 μmol, 3.6 mg, 1 mol%), silyl ketene acetal **5c** (0.04 mmol, 10 μL, 20 mol%), methyl (*E*)-5-phenylpent-2-enoate **1p** (0.20 mmol, 38.4 mg) and cyclopentadiene (1 mmol, 90 μL) at −80 °C for 30 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (46 mg, 89%). The enantiomeric and diastereomeric ratios were determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.32 – 7.26 (m, 2H), 7.22 – 7.16 (m, 3H), 6.26 (dd, *J* = 5.7, 3.1 Hz, 1H), 6.01 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.64 (s, 3H), 3.15 – 3.12 (m, 1H), 2.77 – 2.67 (m, 2H), 2.67 – 2.63 (m, 1H), 2.49 (t, *J* = 3.8 Hz, 1H), 1.89 – 1.80 (m, 2H), 1.80 – 1.73 (m, 1H), 1.56 – 1.52 (m, 1H), 1.46 (dq, *J* = 8.8, 1.7 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.2, 142.6, 138.6, 133.7, 128.4, 128.4, 125.9, 51.6, 51.4, 47.2, 46.6, 46.0, 43.7, 38.2, 35.2; **HRMS** (EI) calculated for $C_{17}H_{20}O_2$: 256.1458; found 256.1457; **$[\alpha]_D^{25}$** = +83.2 (*c* 0.62, $CHCl_3$); **HPLC** Daicel Chiralcel OJ-3R, MeOH/H_2O = 90/10, 1 mL/min, 25 °C, 220 nm, t_R (major, *endo*) = 6.7 min, t_R (major, *exo*) = 7.2 min, t_R (minor, *exo*) = 7.7 min, t_R (minor, *endo*) = 8.5 min; $e.r._{endo}$ = 96.5:3.5, $e.r._{exo}$ = 97:3, d.r. (*endo*/*exo*) = 10:1.



The performance of catalysts **4a** and **4c** was compared at a reaction temperature of −80 °C and a reaction time of 24 hours following procedure B:

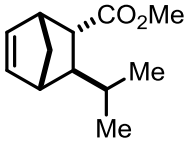
entry	catalyst	silyl group	yield (%)	d.r. (endo:exo)	e.r. (endo)	e.r. (exo)
1	**4a**	TES	89	10:1	96.5:3.5	97:3
2	**4c**	TIPS	(46% conv.)	5:1	98:2	92:8

methyl (1*R*,2*S*,3*S*,4*S*)-3-heptylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3q): Prepared according to procedure B with catalyst (*S*,*S*)-**4a** (4 μmol, 7.2 mg, 1 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 μL, 20 mol%), methyl (*E*)-dec-2-enoate **1q** (0.40 mmol, 77.5 mg) and cyclopentadiene (2 mmol, 180 μL) at −80 °C for 30 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (84 mg, 80%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.24 (dd, *J* = 5.7, 3.1 Hz, 1H), 5.97 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.61 (s, 3H), 3.09 (tdd, *J* = 3.9, 2.7, 1.6 Hz, 1H), 2.58 (h, *J* = 1.6 Hz, 1H), 2.40 (dd, *J* = 4.5, 3.5 Hz, 1H), 1.74 – 1.69 (m, 1H), 1.52 – 1.19 (m, 14H), 0.89 – 0.85 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.4, 138.7, 133.5, 51.6, 51.3, 47.0, 46.6, 45.9, 43.8, 36.2, 32.0, 29.9, 29.4, 28.8, 22.8, 14.2; **HRMS** (EI) calculated for $C_{16}H_{26}O_2$: 250.1927; found 250.1925; **$[\alpha]_D^{25}$** = +68.8 (*c* 0.63, $CHCl_3$); **GC** column: BGB 176/BGB 15 G 618, 30.0 m, temperature: 230 140 60 MIN ISO 9/MIN 220 2 MIN ISO 350, gas: 0.50 bar H_2, sample size: 1.0 μL, t_R (minor, *exo*) = 53.63 min, t_R (major, *exo*) = 56.83 min, t_R (minor, *endo*) = 58.37 min, t_R (major, *endo*) = 59.78 min; $e.r._{endo}$ = 97.5:2.5, $e.r._{exo}$ = 98.5:1.5, d.r. (*endo*/*exo*) = 19:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-isobutylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3r): Prepared according to procedure B with catalyst (*S*,*S*)-**4a** (4 μmol, 7.2 mg, 1 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 μL, 20 mol%), methyl (*E*)-5-methylhex-2-enoate **1r** (0.44 mmol, 64.1 mg, *E*/*Z* 96:4) and cyclopentadiene (2 mmol, 180 μL) at −80 °C for 30 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (77 mg, 85%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.25 (dd, *J* = 5.7, 3.2 Hz, 1H), 5.97 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.61 (s, 3H), 3.12 – 3.05 (m, 1H), 2.54 (dq, *J* = 3.4, 1.7 Hz, 1H), 2.40 (dd, *J* = 4.5, 3.5 Hz, 1H), 1.83 (tdd, *J* = 7.8, 4.5, 1.7 Hz, 1H), 1.63 (dp, *J* = 13.2, 6.5 Hz, 1H), 1.51 (dt, *J* = 8.7, 1.5 Hz, 1H), 1.41 (dq, *J* = 8.7, 1.7 Hz, 1H), 1.38 – 1.21 (m, 2H), 0.91 (d, *J* = 3.1 Hz, 3H), 0.89 (d, *J* = 3.0 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.4, 138.7, 133.5, 51.6, 51.4, 47.4, 46.6, 46.1, 45.7, 41.4, 27.0, 23.2, 22.8; **HRMS** (EI) calculated for $C_{13}H_{20}O_2$: 208.1458; found 208.1457; **$[\alpha]_D^{25}$** = +69.5 (*c* 0.57, $CHCl_3$); **GC** column: BGB 176/BGB 15 G 618, 30.0 m, temperature: 230 110 50 MIN ISO 9/MIN 220 3 MIN ISO 350, gas: 0.60 bar H_2, sample size: 1.0 μL, t_R (minor, *exo*) = 25.49 min, t_R (major, *exo*) = 28.01 min, t_R (major, *endo*) = 28.79 min, t_R (minor, *endo*) = 29.38 min; $e.r._{endo}$ = 97:3, $e.r._{exo}$ = n.d., d.r. (*endo*/*exo*) = 23:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-propylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3s): Prepared according to procedure B with catalyst (*S*,*S*)-**4a** (4 μmol, 7.2 mg, 1 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 μL, 20 mol%), methyl (*E*)-hex-2-enoate **1s** (0.44 mmol, 57 mg, *E*/*Z* 98:2) and cyclopentadiene (2 mmol, 180 μL) at −80 °C for 30 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (64 mg, 76%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.24 (dd, *J* = 5.7, 3.2 Hz, 1H), 5.97 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.61 (s, 3H), 3.11 – 3.06 (m, 1H), 2.57 (dq, *J* = 3.3, 1.6 Hz, 1H), 2.40 (dd, *J* = 4.5, 3.5 Hz, 1H), 1.73 (tdd, *J* = 6.7, 4.6, 1.8 Hz, 1H), 1.53 – 1.30 (m, 6H), 0.93 – 0.88 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.5, 138.7, 133.5, 51.6, 51.2, 47.0, 46.6, 45.9, 43.5, 38.5, 21.9, 14.4; **HRMS** (EI) calculated for $C_{12}H_{18}O_2$: 194.1301; found 194.1302; **$[\alpha]_D^{25}$** = +79.7 (*c* 0.65, $CHCl_3$); **GC** column: G-TA 0.25 G/448, 30.0 m, temperature: 230 80 30 MIN ISO 9/MIN 170 2 MIN ISO 350, gas: 0.90 bar H_2, sample size: 1.0 μL, t_R (minor, *exo*) = 23.89 min, t_R (major, *exo*) = 24.68 min, t_R (major, *endo*) = 26.09 min, t_R (minor, *endo*) = 28.72 min; $e.r._{endo}$ = 96.5:3.5, $e.r._{exo}$ = 99:1, d.r. (*endo*/*exo*) = 21:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-isopropylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3t): Prepared



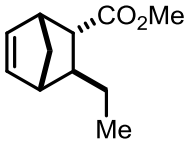
according to procedure C with catalyst (*S*,*S*)-**4c** (4 μmol, 7.4 mg, 1 mol%), silyl ketene acetal **5c** (0.16 mmol, 40 μL, 40 mol%), methyl (*E*)-4-methylpent-2-enoate **1t** (0.42 mmol, 56 mg, *E*/*Z* 97:3) and cyclopentadiene (4 mmol, 340 μL) at −60 °C for 48 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (80 mg, 98%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.27 (dd, *J* = 5.7, 3.2 Hz, 1H), 5.94 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.62 (s, 3H), 3.11 (dddt, *J* = 4.1, 3.3, 2.4, 1.2 Hz, 1H), 2.77 (dq, *J* = 3.4, 1.7 Hz, 1H), 2.52 (t, *J* = 3.8 Hz, 1H), 1.49 – 1.36 (m, 4H), 0.99 (d, *J* = 6.0 Hz, 3H), 0.94 (d, *J* = 6.2 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.5, 139.2, 133.4, 51.6, 51.4, 49.7, 46.8, 46.4, 45.2, 33.1, 22.3, 22.0; **HRMS** (ESI) calculated for $C_{12}H_{19}O_2$ $(M+H)^+$: 195.1380; found 195.1381; **$[\alpha]_D^{25}$** = +48.9 (*c* 0.56, $CHCl_3$); **GC** column: G-TA 0.25 G/448, 30.0 m, temperature: 230 80 25 MIN ISO g/MIN 170 3 MIN ISO 350, gas: 0.90 bar H_2, sample size: 1.0 μL, t_R (major, *exo*) = 19.59 min, t_R (minor, *exo*) = 20.12 min, t_R (major, *endo*) = 21.25 min, t_R (minor, *endo*) = 22.63 min; $e.r._{endo}$ = 95.5:4.5, $e.r._{exo}$ = 92:8, d.r. (*endo*/*exo*) = 9:1.

The stereoselectivity for **3t** was optimized by comparing catalysts and reactions conditions:

entry	catalyst	temp.	silyl group	yield	d.r. (endo:exo)	$e.r._{endo}$	$e.r._{exo}$
1	**4a**	−20°C	TES	(19% conv.)[a,b]	3.7:1	84:16	89:11
2	**4c**	−20°C	TIPS	(93% conv.)[b]	1.3:1	92.5:7.5	92:8
3	**4c**	−40°C	TES	(70% conv.)[c,d]	3.1:1	94.5:5.5	90:10
4	**4c**	−60°C	TES	98%[d,e]	9:1	95.5:4.5	92:8

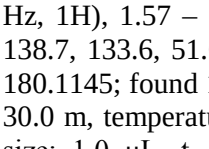
[a]extensive cyclopentadiene polymerization was observed. [b]18 h reaction time. [c]12 h reaction time. [d]The reaction was performed neat with 10 eq. of cyclopentadiene. [e]48 h reaction time.

methyl (1*R*,2*S*,3*S*,4*S*)-3-ethylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3u): Prepared according to



procedure B with catalyst (*S*,*S*)-**4a** (4 μmol, 7.2 mg, 1 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 μL, 20 mol%), methyl (*E*)-pent-2-enoate **1u** (0.41 mmol, 49 mg, *E*/*Z* 98:2) and cyclopentadiene (2 mmol, 180 μL) at −80 °C for 30 h. The product was obtained as a diastereomeric mixture after column chromatography (pentane/DCM 4:1→2:1) as a colorless oil (56 mg, 76%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.24 (dd, *J* = 5.7, 3.1 Hz, 1H), 5.97 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.61 (s, 3H), 3.09 (dp, *J* = 5.1, 1.7 Hz, 1H), 2.60 (h, *J* = 1.6 Hz, 1H), 2.40 (dd, *J* = 4.5, 3.5 Hz, 1H), 1.64 (tdd, *J* = 7.6, 4.5, 1.7 Hz, 1H), 1.57 – 1.39 (m, 4H), 0.96 (t, *J* = 7.4 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.4, 138.7, 133.6, 51.6, 51.1, 46.6, 46.5, 45.9, 45.7, 28.9, 13.2; **HRMS** (EI) calculated for $C_{11}H_{16}O_2$: 180.1145; found 180.1146; **$[\alpha]_D^{25}$** = +75.5 (*c* 0.54, $CHCl_3$); **GC** column: BGB 176/BGB 15 G 618, 30.0 m, temperature: 230 100 40 MIN ISO 9/MIN 220 3 MIN ISO 350, gas: 0.50 bar H_2, sample size: 1.0 μL, t_R (minor, *exo*) = 24.70 min, t_R (major, *exo*) = 27.41 min, t_R (minor, *endo*) = 27.90 min, t_R (major, *endo*) = 28.34 min; $e.r._{endo}$ = 95.5:4.5, $e.r._{exo}$ = 97.5:2.5, d.r. (*endo*/*exo*) = 16:1.

methyl (1*R*,2*S*,3*S*,4*S*)-3-(bromomethyl)bicyclo[2.2.1]hept-5-ene-2-carboxylate (3v): Prepared



according to procedure B with catalyst (*S*,*S*)-**4a** (4 μmol, 7.2 mg, 1 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 μL, 20 mol%), methyl (*E*)-4-bromobut-2-enoate **1v** (0.40 mmol, 84 mg, *E*/*Z* 96:4, >80% purity, freshly distilled) and cyclopentadiene (2 mmol, 180 μL) at −80 °C for 30 h. NOTE: After full conversion, the reaction was treated with a mixture of hexane/triethylamine(5:1, 50 μL) and a drop of water. The standard treatment resulted in product decomposition. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as

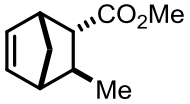
a colorless oil (81 mg, 88%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.28 (dd, *J* = 5.7, 3.2 Hz, 1H), 6.04 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.64 (s, 3H), 3.56 (dd, *J* = 9.9, 7.2 Hz, 1H), 3.40 (dd, *J* = 9.9, 8.8 Hz, 1H), 3.21 – 3.18 (m, 1H), 2.86 (dt, *J* = 3.4, 1.7 Hz, 1H), 2.54 (dd, *J* = 4.7, 3.6 Hz, 1H), 2.26 (dddd, *J* = 8.7, 7.1, 4.7, 1.4 Hz, 1H), 1.53 – 1.46 (m, 2H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 173.9, 138.3, 134.4, 51.9, 51.0, 46.5, 46.5, 46.3, 46.2, 37.2; **HRMS** (ESI) calculated for $C_{10}H_{13}O_2BrNa$ $(M+Na)^+$: 266.9991; found 266.9994; **$[\alpha]_D^{25}$** = +36.1 (*c* 0.62, $CHCl_3$); **GC** column: LIPODEX E G644, 25.0 m, temperature: 230 110 45 MIN ISO 8/MIN 220 3 MIN ISO350, gas: 0.40 bar H_2, sample size: 1.0 µL, t_R (minor, *exo*) = 24.35 min, t_R (major, *exo*) = 25.52 min, t_R (major, *endo*) = 30.81 min, t_R (minor, *endo*) = 31.89 min; $e.r._{endo}$ = 87:13, $e.r._{exo}$ = 90:10, d.r. (*endo*/*exo*) = 48:1.

The stereoselectivity for **3v** with catalysts **4a** and **4c** was compared following procedure B:

entry	catalyst	temp.	silyl group	yield	d.r. (endo:exo)	$e.r._{endo}$	$e.r._{exo}$
1	**4a**	−80°C	TES	98%[a]	48:1	87:13	90:10
2	**4c**	−80°C → −60°C	TES	(66% conv.)[b,c]	1.2:1	95:5	74:26

[a]30 h reaction time. [b]The reaction was performed neat with 10 eq. of cyclopentadiene. [c]The reaction was set up at −80 °C, warmed up to −60 °C after 18 h due to insufficient conversion, and stopped after 5d at −60 °C.

methyl (1*R*,2*R*,3*S*,4*S*)-3-methylbicyclo[2.2.1]hept-5-ene-2-carboxylate (3w): Prepared



according to procedure C with catalyst (*S*,*S*)-**4c** (2 µmol, 3.7 mg, 0.5 mol%), silyl ketene acetal **5c** (0.08 mmol, 20 µL, 20 mol%), methyl crotonate **1w** (0.41 mmol, 41.5 mg) and cyclopentadiene (4 mmol, 340 µL) at −80 °C for 18 h. The product was obtained as a diastereomeric mixture after column chromatography (hexane/DCM 4:1→2:1) as a colorless oil (52 mg, 78%). The enantiomeric and diastereomeric ratios were determined by GC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 6.26 (dd, *J* = 5.7, 3.2 Hz, 1H), 5.98 (dd, *J* = 5.7, 2.8 Hz, 1H), 3.61 (s, 3H), 3.10 (dh, *J* = 3.4, 1.6 Hz, 1H), 2.46 (td, *J* = 3.3, 1.6 Hz, 1H), 2.36 (dd, *J* = 4.5, 3.5 Hz, 1H), 1.82 (qdd, *J* = 6.8, 4.5, 1.7 Hz, 1H), 1.57 – 1.49 (m, 1H), 1.42 (dq, *J* = 8.7, 1.8 Hz, 1H), 1.17 (d, *J* = 7.0 Hz, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.3, 138.8, 133.4, 52.5, 51.6, 49.0, 46.1, 46.0, 38.0, 21.1; **HRMS** (EI) calculated for $C_{10}H_{14}O_2$: 166.0988; found 166.0986; **$[\alpha]_D^{25}$** = +112.4 (*c* 0.64, $CHCl_3$); **GC** column: BGB 176/BGB 15 G 618, 30.0 m, temperature: 230 85 60 MIN ISO 9/MIN 220 3 MIN ISO 350, gas: 0.50 bar H_2, sample size: 1.0 µL, t_R (minor, *exo*) = 28.93 min, t_R (major, *exo*) = 31.23 min, t_R (minor, *endo*) = 32.42 min, t_R (major, *endo*) = 34.90 min; $e.r._{endo}$ = 97:3, $e.r._{exo}$ = 95:5, d.r. (*endo*/*exo*) = >50:1.

The stereoselectivity for **3w** was optimized by comparing catalysts and reactions conditions following procedure B:

entry	catalyst	temp.	silyl group	yield	d.r. (endo:exo)	$e.r._{endo}$	$e.r._{exo}$
1	**4a**	−80°C	TES	(full conv.)[a]	26:1	85.5:14.5	92.5:7.5
2	**4a**	−100°C	TES	(>95% conv.)[a]	38:1	88.5:12.5	93.75:6.25
3	**4c**	−80°C	TIPS	(18% conv.)[a]	5:1	96.5:3.5	95:5
4	**4c**	−100°C	TIPS	(<5%)[a]	n.d.	n.d.	n.d.
5	**4c**	−80°C	TMS	(>95% conv.)[a,b]	5:1	93.5:6.5	94.5:5.5
6	**4c**	−80°C	TES	(full conv.)[a,b]	21:1	97:3	95:5
7	**4c**	−80°C	TBS	(full conv.)[a,b]	26:1	95:5	94.5:5.5
8	**4c**	−80°C	TIPS	(59% conv.)[a,b]	6:1	96:4	95:5
9	**4c**	−80°C	TES	78%[b,c]	>50:1	97:3	95:5

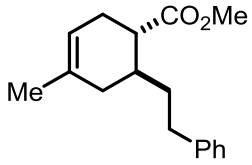
[a]24 h reaction time. [b]The reaction was performed neat with 10 eq. of cyclopentadiene. [c]18 h reaction time and 0.5 mol% of **4d**.

methyl (1*S*,6*S*)-3,4,6-trimethylcyclohex-3-ene-1-carboxylate (3x): Prepared according to procedure D with catalyst (*S*,*S*)-**4d** (6 µmol, 13.9 mg, 3 mol%), triisopropylmethallylsilane **5d** (0.1 mmol, 23.4 µL, 50 mol%), methyl (*E*)-cinnamate **1a** (0.2 mmol, 32.4 mg) and 2,3-dimethyl-1,3-butadiene **2b** (1 mmol, 113 µL, 5 equiv.) at 0 °C for 5.5 days. Purification by column chromatography on silica gel (hexane→hexane/EtOAc 19:1) afforded the title compound as a colorless oil (26.8 mg, 0.11 mmol, 55% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.29–7.26 (m, 2H), 7.23–7.15 (m, 3H), 3.39 (s, 3H), 3.02 (ddd, *J* = 11.6, 9.8, 6.8 Hz, 1H), 2.86 (ddd, *J* = 11.5, 10.7, 5.2 Hz, 1H), 2.46–2.38 (m, 1H), 2.25–2.21 (m, 1H), 2.21–2.15 (m, 2H), 1.69–1.66 (m, 3H), 1.66–1.63 (m, 3H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.8, 144.2, 128.5, 127.5, 126.6, 125.4, 123.8, 51.4, 47.0, 43.7, 40.2, 35.6, 18.8, 18.7; **HRMS** (EI) calculated for $C_{16}H_{20}O_2$: 244.1458; found: 244.1457; **$[\alpha]_D^{25}$** = +77.4 (*c* 0.78, $CHCl_3$); **HPLC** Daicel Chiralcel OD-3R, MeOH/H_2O = 80:20, 1 mL/min, 25 °C, 220 nm, t_R (major) = 10.7 min, t_R (minor) = 12.2 min; e.r. = 96:4.

methyl (1*S*,6*S*)-3,4-dimethyl-6-phenethylcyclohex-3-ene-1-carboxylate (3y): Prepared according to procedure E with catalyst (*S*,*S*)-**4d** (6 µmol, 13.9 mg, 3 mol%), triisopropyl(2-methallyl)silane **5d** (0.1 mmol, 23 µL, 50 mol%), methyl (*E*)-5-phenylpent-2-enoate **1p** (0.2 mmol, 38.0 mg) and 2,3-dimethyl-1,3-butadiene **2b** (0.8 mmol, 91 µL, 4 equiv.) at −20 °C for 3.5 days. Purification by column chromatography on silica gel (hexane → hexane/EtOAc 19:1) afforded the title compound as a colorless oil (44.8 mg, 0.17 mmol, 82% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.30–7.26 (m, 2H), 7.22–7.14 (m, 3H), 3.67 (s, 3H), 2.73 (ddd, *J* = 13.6, 11.0, 5.1 Hz, 1H), 2.53 (ddd, *J* = 13.7, 10.9, 6.0 Hz, 1H), 2.39 (td, *J* = 10.3, 5.2 Hz, 1H), 2.32–2.25 (m, 1H), 2.18 (dd, *J* = 17.1, 5.3 Hz, 1H), 2.10 (dd, *J* = 17.0, 5.2 Hz, 1H), 1.96–1.88 (m, 1H), 1.83–1.77 (m, 1H), 1.73 (dddd, *J* = 13.4, 11.0, 6.0, 3.8 Hz, 1H), 1.63 (s, 3H), 1.62 (s, 3H), 1.47 (dddd, *J* = 13.4, 10.9, 9.1, 5.1 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.7, 142.6, 128.4, 128.4, 125.8, 124.6, 123.7, 51.6, 46.5, 36.9, 36.2, 35.9, 35.0, 33.0, 19.1, 18.7; **HRMS** (EI) calculated for $C_{18}H_{24}O_2$: 272.1771; found: 272.1771; **$[\alpha]_D^{25}$** = +82.0 (*c* 0.49, $CHCl_3$); **HPLC** Daicel Chiralcel IC-3R, MeOH/H_2O = 80:20, 1 mL/min, 25 °C, 220 nm, t_R (major) = 12.1 min, t_R (minor) = 14.3 min; e.r. = 92:8.

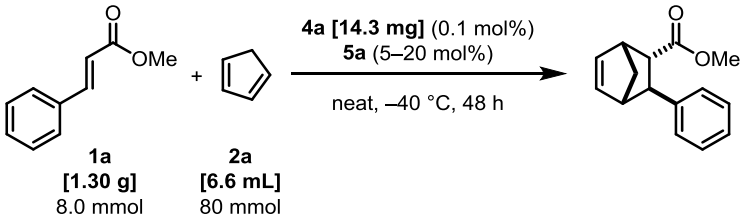
methyl (1*S*,2*S*)-5-methyl-1,2,3,6-tetrahydro-[1,1'-biphenyl]-2-carboxylate (3z): Prepared according to procedure D with catalyst (*S*,*S*)-**4d** (6 µmol, 13.9 mg, 3 mol%), triisopropyl(2-methallyl)silane **5d** (0.1 mmol, 23 µL, 50 mol%), methyl (*E*)-cinnamate **1a** (0.2 mmol, 32.7 mg) and isoprene **2c** (1 mmol, 100 µL, 5 equiv.) at 0 °C for 5.5 days. Purification by column chromatography on silica gel (hexane → hexane/EtOAc 19:1) afforded the title compound as a colorless oil (32.4 mg, 0.14 mmol, 71% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. The regioisomeric ratio was determined by ^{1}H NMR spectroscopy. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.32–7.24 (m, 2H), 7.24–7.15 (m, 3H), 5.45 (ddq, *J* = 5.9, 3.3, 1.6 Hz, 1H), 3.39 (s, 3H), 3.07 (ddd, *J* = 11.2, 9.1, 7.3 Hz, 1H), 2.81 (ddd, *J* = 11.1, 10.3, 5.6 Hz, 1H), 2.45–2.37 (m, 1H), 2.33 (dddd, *J* = 15.6, 6.9, 3.6, 1.7 Hz, 1H), 2.20 (d, *J* = 8.0 Hz, 2H), 1.70 (dt, *J* = 2.7, 1.3 Hz, 3H).**^{13}C NMR** (126 MHz, $CDCl_3$) δ 175.9, 144.2, 133.8, 128.5, 127.5, 126.6, 119.0, 51.4, 46.2, 43.3, 38.4, 29.5, 23.3; **HRMS** (EI) calculated for $C_{15}H_{18}O_2$: 230.1301; found: 230.1303; **$[\alpha]_D^{25}$** = +74.1 (*c* 0.95, $CHCl_3$); **HPLC** Daicel Chiralcel OD-3R, MeOH/H_2O = 75:25, 1 mL/min, 25 °C, 220 nm, t_R (major) = 13.7 min, t_R (minor) = 15.4 min; e.r. = 98:2; r.r. (*para*/*meta*) > 50:1.

methyl (1*S*,6*S*)-4-methyl-6-phenethylcyclohex-3-ene-1-carboxylate (3aa): Prepared according to procedure E with catalyst (*S*,*S*)-**4d** (6 µmol, 13.9 mg, 3 mol%), triisopropyl(2-methallyl)silane **5d** (0.1 mmol, 23 µL, 50 mol%), methyl (*E*)-5-phenylpent-2-enoate **1p** (0.2 mmol, 38.0 mg) and isoprene **2c** (0.8 mmol, 80 µL, 4 equiv.) at −20 °C for 3.5 days. Purification by column chromatography on silica gel (*iso*-hexane → *iso*-hexane/ethyl acetate 19:1) afforded the title compound as a colorless oil (51.6 mg, 0.20 mmol, 99% yield). The enantiomeric ratio was determined by HPLC on a chiral stationary phase. The regioisomeric ratio was determined by ^{1}H NMR spectroscopy. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.33–7.26 (m, 2H), 7.22–7.13 (m, 3H), 5.37 (ddq, *J* = 4.1, 2.9, 1.5 Hz, 1H), 3.68 (s, 3H), 2.74 (ddd, *J* = 13.6, 11.0, 5.1 Hz, 1H), 2.55 (ddd, *J* = 13.6, 10.8, 6.0 Hz, 1H), 2.36 (td, *J* = 9.7, 5.3 Hz, 1H), 2.32–2.25 (m, 1H), 2.24–2.15 (m, 2H), 1.98 (qdd, *J* = 9.6, 5.4, 3.9 Hz, 1H), 1.80–1.71 (m, 2H), 1.70–1.65 (m, 3H), 1.50 (dddd, *J* = 13.4, 10.9, 9.1, 5.1 Hz, 1H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 176.7, 142.5, 133.0, 128.5, 128.4, 125.9, 118.9, 51.6, 45.5, 36.2, 35.5, 35.1, 32.9, 28.7, 23.6; **HRMS** (EI) calculated for $C_{17}H_{22}O_2$: 258.1614; found: 258.1616; **$[\alpha]_D^{25}$** = +86.1 (*c* 0.60, $CHCl_3$); **HPLC** Daicel Chiralcel IC-3R, MeOH/H_2O = 70:30, 1 mL/min, 25 °C, 220 nm, t_R (major) = 31.8 min, t_R (minor) = 36.2 min; e.r. = 97:3; r.r. (*para*/*meta*) > 50:1.



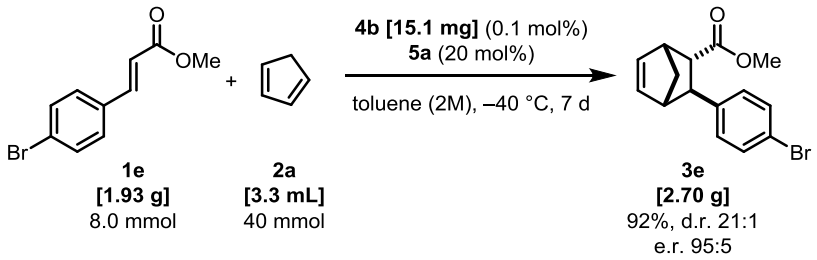
Scale-Up Experiments

Following a modified procedure C, a 15 mL vial was charged with (*E*)-methyl cinnamate (**1a**, 8 mmol, 1.3 g), (*S*,*S*)-**4a** (8 µmol, 14.3 mg, 0.1 mol%) and a magnetic stirrer bar. The vial was sealed with a screw-cap containing a PTFE/rubber septum and was either evacuated by purged with argon (3 ×) or left under air. After addition of triethylallylsilane **5a** (320 µmol, 20 mol%) at r.t., the vial was cooled in a cryostat at −40 °C under stirring for 10 min. Then, neat cyclopentadiene (80 mmol, 6.6 mL) was added via a syringe, the cap sealed with parafilm. After 48 h, TLC indicated full conversion. Work-up and purification was performed as described before. In case of entry 3, a flame-dried Schlenk flask under argon was used in combination with 5 mol% triethylallylsilane **5a** (80 µL).



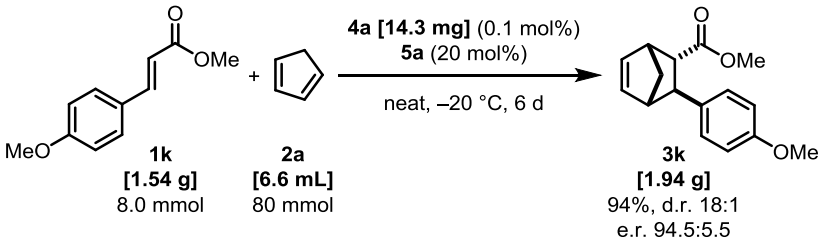
entry	container	atmosphere	loading **5a**	yield (%)	e.r.$_{endo}$	d.r. (endo/exo)
1	vial	argon	20 mol%	97	96.25:3.75	21:1
2	vial	air	20 mol%	99	96:4	22:1
3	Schlenk	argon	5 mol%	94	96:4	21:1

Following a modified procedure A, a 15 mL vial was charged with methyl (*E*)-3-(4-bromophenyl)acrylate (**1e**, 8 mmol, 48.5 mg), (*S*,*S*)-**4b** (8 µmol, 15.1 mg, 0.1 mol%) and a magnetic stirrer bar. The vial was sealed with a screw-cap containing a PTFE/rubber septum and was either evacuated by purged with argon (3 ×). Dry toluene (4 mL) and triethylallylsilane **5a** (320 µmol, 20 mol%) were added at r.t. and the reaction was cooled to −40 °C. Then, neat cyclopentadiene (40 mmol, 3.3 mL) was added via a syringe, the cap sealed with parafilm. After 7 days, TLC indicated full conversion. Work-up and purification was performed as described before. Product **3e** was isolated in 92% yield (2.70 g, e.r.$_{endo}$ = 95:5, d.r. [*endo*/*exo*] = 21:1).



NOTE: Attempts to perform this example under neat conditions at −40 °C or −20 °C resulted in extensive polymerization of cyclopentadiene and consequently very low conversion, presumably due to the very low solubility of **1e** in cyclopentadiene.

Following a modified procedure C, a 15 mL vial was charged with methyl (*E*)-3-(4-methoxyphenyl)acrylate (**1k**, 8 mmol, 1.54 g), (*S*,*S*)-**4a** (8 μmol, 14.3 mg, 0.1 mol%) and a magnetic stirrer bar. The vial was sealed with a screw-cap containing a PTFE/rubber septum and was either evacuated by purged with argon (3 ×). After addition of triethylallylsilane **5a** (320 μmol, 20 mol%) at r.t., the vial was cooled in a cryostat at −20 °C under stirring for 10 min. Then, neat cyclopentadiene (80 mmol, 6.6 mL) was added via a syringe, the cap sealed with parafilm. After 6 days, TLC indicated full conversion. Work-up and purification was performed as described before. Product **3k** was isolated in 94% yield (1.94 g, e.r.$_{endo}$ = 94.5:5.5, d.r. [*endo*/*exo*] = 18:1).

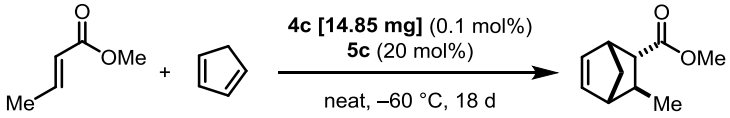


1k **[1.54 g]** 8.0 mmol

2a **[6.6 mL]** 80 mmol

3k **[1.94 g]** 94%, d.r. 18:1 e.r. 94.5:5.5

Following a modified procedure C, a 15 mL vial was charged with *S*,*S*)-**4c** (8 μmol, 14.9 mg, 0.1 mol%) and a magnetic stirrer bar. The vial was sealed with a screw-cap containing a PTFE/rubber septum and was either evacuated by purged with argon (3 ×). The vial was cooled in a cryostat at −60 °C. Then, neat cyclopentadiene (24 mmol, 2.0 mL) was added via a syringe followed by silyl ketene acetal **5c** (400 μL, 20 mol%) and methyl crotonate **1w** (8 mmol, 0.87 mL) in this order. The cap was sealed with parafilm and the reaction mixture was stirred at −60 °C for 18 days, after which ^{1}H NMR analysis indicated full conversion. Work-up and purification was performed as described before. Product **3w** was isolated in 86% yield (1.44 g, e.r.$_{endo}$ = 95:5, d.r. [*endo*/*exo*] = 16:1).



1w **[0.87 mL]** 8.0 mmol

2a **[2.0 mL]** 24 mmol

3w **[1.44 g]** 86%, d.r. 16:1 e.r. 95:5

Computational Studies

Computational Details

All calculations presented in this paper were carried out with the development version of the ORCA suite of programs base on version 4.0.[10] All molecular geometries were optimized in the gas-phase using the PBE functional[11] in conjunction with the D3 version of Grimme's dispersion correction with Becke-Johnson damping function,[12] using the resolution of identity approximation. The def2-SVP basis set was used for all atoms with matching auxiliary basis.[13] In all cases, a fine integration grid (grid7) was used. Analytic frequency calculations were performed to verify the nature of all stationary points (minima and transition states) and to calculate free energies and enthalpies at 233 K by using the rigid-rotor harmonic oscillator (RRHO) approximation, as implemented in ORCA, combined with B3LYP-D3(BJ)/def2-TZVP single-point energies.[14] Single-point energies taking into account solvation effects (toluene) were also carried out via the conductor like polarizable continuum model (C-PCM)[15] at B3LYP-D3(BJ)/def2-TZVP level. The gas phase electronic energies were also refined using single-point DLPNO-CCSD(T)/def2-TZVP[16] calculations with NormalPNO settings and tighten TCutPairs threshold (10^{-5}). Solvation, entropy and thermal corrections were kept at DFT level. This protocol is denoted as (DLPNO-CCSD(T) + C-PCM(toluene))//PBE-D3(BJ)/def2-SVP.

Conformational sampling

Due to the conformational flexibility of the substrate and the catalyst, two different strategies were used to localize the most stable transition states (TS) for both enantiomers. First, the conformers of the silylated methyl cinnamate **1a** (Figure S6) together with different conformers of the (*S*,*S*)-**4a** counteranion (18 different conformers located by scanning the rotation of the SO_2CF_3 and 3,5-trifluoromethylphenyl substituents) were used to explore several structures for the chiral ion pair (CIP). Although, this particular type of catalyst has a highly delocalized negative charge, the electrostatic potential map (see Fig. 4 in the manuscript) evidenced that the negative region is confined into a chiral pocket adopted by the anion. Consequently, the electrostatic interaction with the cationic substrate can be highly directional. In total, 9 CIP were found and used as a starting point for the endo-attack of cyclopentadiene on both faces of the silylated-**1a**. 16 different transition states were located: 9 for the favoured and 7 for the disfavoured enantiomer.

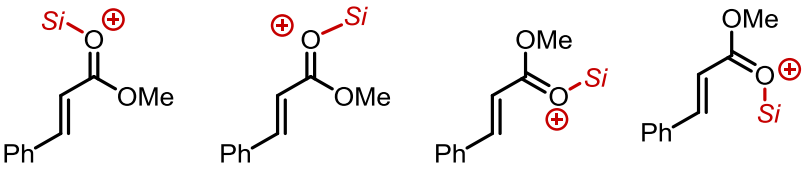


Figure S6. Conformational possibilities for the silylated methyl cinnamate silylated-**1a**: the carbonyl group can be placed either *s-trans* or *s-cis* to the olefin, while the silyl group is bonded *syn* or *anti* to the ester fragment. The *anti s-trans* conformation is often most stable.[17]

The two lowest-lying TS leading to both enantiomers of the endo-cycloadduct have *s*-trans conformation of silylated-**1a** (Figure S7). Both transition states originate from the same CIP and have different non-classical C-H···O and C-H···F hydrogen bonds assisting the cyclopentadiene addition. As visualized in Fig S7, the $TS_{s\text{-}trans}$ structure leading to the favoured enantiomer has two stabilizing C-H···O hydrogen bonds between an oxygen atom of the SO_2CF_3 group of the catalyst and the C-H groups of the cyclopentadiene (2.506 Å and 2.651 Å), that are lacked in the other TS. Thus, these interactions allow the discrimination of both TSs, guiding to the high enantioselectivity.

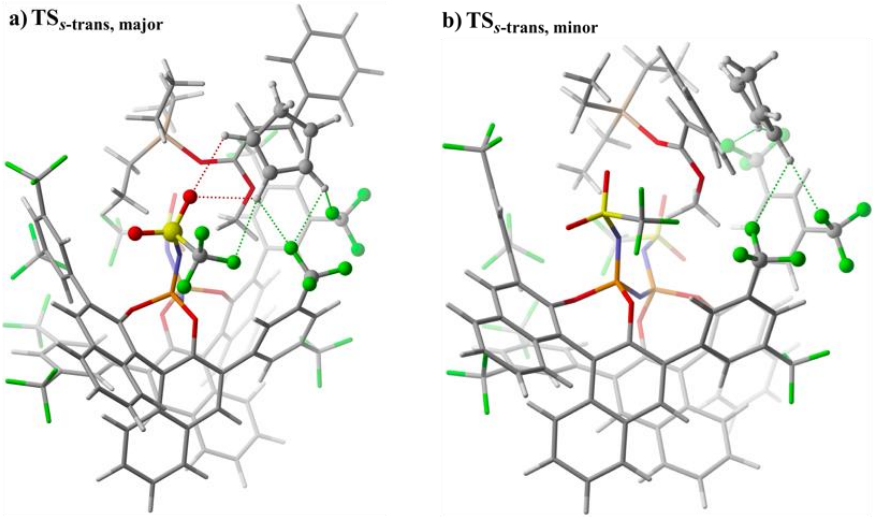


Figure S7. Close-up of the non-classical C-H···O (dotted red lines) and C-H···F (dotted green lines) hydrogen bonds assisting the cyclopentadiene attack for both enantiodetermining TS structures. Distances shorter than 3 Å are shown.

Cartesian coordinates and electronic energies

Cartesian coordinates (in Å) and electronic energies (in a. u.) of all the stationary points discussed in the text. Calculations reported at PBE-D3(BJ)/def2-SVP level.

1a (methyl cinnamate)

E = -536.508893432386

C	3.167405	-2.240044	0.596801
C	1.981376	-1.605171	0.411591
C	1.843926	-0.192442	0.004229
O	0.773230	0.371700	-0.162589
H	1.013776	-2.109466	0.554478
H	4.083181	-1.648838	0.428754
O	3.045638	0.428984	-0.173839
C	2.964095	1.798471	-0.571692
H	2.424154	2.402321	0.186271
H	4.005626	2.152713	-0.673705
H	2.425539	1.902030	-1.536002
C	3.372916	-3.632402	0.997605
C	4.697031	-4.113447	1.138768
C	2.305867	-4.529262	1.252985
C	4.949780	-5.437448	1.519809
H	5.535935	-3.427079	0.943362
C	2.557912	-5.850591	1.633261
H	1.266415	-4.183954	1.151328
C	3.880339	-6.311482	1.768626
H	5.987215	-5.789774	1.623366
H	1.715883	-6.532261	1.827227
H	4.074148	-7.352569	2.068202

Cyclopentadiene

E = -193.710286707175

C	0.448150	-0.593955	-0.134747
C	1.810381	-0.544452	-0.134769
C	2.244175	0.858213	-0.134861
C	1.147724	1.668099	-0.134886
H	-0.179379	-1.495363	-0.134688
H	2.490591	-1.408233	-0.134730
H	3.293261	1.187182	-0.134898
H	1.138630	2.766391	-0.134948
C	-0.087365	0.810865	-0.134813
H	-0.735921	1.011391	-1.019477
H	-0.735864	1.011480	0.749872

Catalyst [Si-X*]

E = -8593.59563547091

P	0.960999	-1.153585	-0.218729
O	2.458345	-0.776130	0.366389
O	0.583893	-2.472576	0.715302
C	3.375817	-1.743024	0.750989
C	4.535292	-1.916061	-0.064318
C	5.486628	-2.832886	0.362922
C	5.301909	-3.618123	1.533549
C	6.274197	-4.582263	1.931894
C	6.065303	-5.392145	3.036687
C	4.859477	-5.277100	3.776507
C	3.898746	-4.340146	3.422743
C	4.097982	-3.465583	2.314043
C	3.141968	-2.459398	1.923828
C	1.905467	-2.202303	2.712819
C	1.951955	-1.856939	4.112918
C	3.175318	-1.604085	4.803244
C	3.180796	-1.281385	6.153111
C	1.966669	-1.217223	6.886564
C	0.759661	-1.434582	6.240498
C	0.716471	-1.725455	4.844990
C	-0.521905	-1.902372	4.170273
C	-0.581243	-2.179291	2.807902
C	0.653748	-2.286936	2.093911
C	4.680057	-1.183472	-1.344010
H	6.406311	-2.968982	-0.226017
H	7.191815	-4.678589	1.331211
H	6.822275	-6.134549	3.330658
H	4.680038	-5.941988	4.634738
H	2.965805	-4.273308	3.998277
H	4.121223	-1.659438	4.251449
H	4.137798	-1.083453	6.658928
H	1.986759	-0.990129	7.963326

H	-0.191344	-1.374921	6.789627
H	-1.455085	-1.838636	4.750690
C	-1.890134	-2.462489	2.163660
C	4.391989	0.189173	-1.438837
C	4.510261	0.860259	-2.664708
C	4.924778	0.179613	-3.814654
C	5.194152	-1.196663	-3.729957
C	5.071476	-1.873466	-2.511608
C	-3.008529	-1.639854	2.417661
C	-4.276880	-2.003065	1.941493
C	-4.455022	-3.194798	1.218381
C	-3.345523	-4.006435	0.950750
C	-2.068461	-3.634904	1.400626
H	4.060556	0.741526	-0.552676
H	5.016957	0.711339	-4.771158
H	5.229621	-2.959100	-2.474662
H	-2.881220	-0.710340	2.989636
H	-5.449837	-3.487915	0.859692
H	-1.208242	-4.285860	1.193021
N	0.097042	0.092469	0.260552
P	-0.829657	1.271438	-0.144636
O	-0.580860	2.608007	0.787425
O	-2.356150	0.830150	0.282293
C	-0.654460	2.370508	2.164071
C	0.572597	2.258013	2.887748
C	0.485381	1.943248	4.240119
C	-0.765588	1.728497	4.881345
C	-0.829586	1.405488	6.268817
C	-2.043286	1.142835	6.884291
C	-3.243375	1.189434	6.127426
C	-3.220019	1.538770	4.784267
C	-1.990408	1.839792	4.126448
C	-1.917824	2.216850	2.735632
C	-3.136309	2.435766	1.903691
C	-4.135678	3.401562	2.289333
C	-3.973105	4.278611	3.402245
C	-4.963921	5.186647	3.747281
C	-6.167684	5.264243	2.999022
C	-6.345132	4.447124	1.894277
C	-5.338694	3.515848	1.502214
C	-5.492762	2.716887	0.337459
C	-4.502398	1.841085	-0.090123
C	-3.325096	1.731731	0.711294
C	1.885418	2.520886	2.243025
H	1.405628	1.865143	4.838750
H	0.111644	1.353710	6.835136
H	-2.078451	0.889590	7.954650
H	-4.204055	0.953731	6.609338
H	-4.156389	1.576052	4.215002
H	-3.043720	4.238664	3.985828
H	-4.811100	5.856800	4.606543
H	-6.948998	5.982707	3.288374

H	-7.263228	4.512271	1.290290
H	-6.423917	2.800476	-0.243295
C	-4.675450	1.057798	-1.339522
C	2.073608	3.665647	1.442464
C	3.336343	3.966591	0.907898
C	4.427391	3.123748	1.152078
C	4.246066	1.978815	1.946807
C	2.988520	1.674327	2.487343
C	-5.130519	1.699282	-2.512637
C	-5.358112	0.965031	-3.683781
C	-5.148378	-0.423894	-3.710643
C	-4.665132	-1.055988	-2.559861
C	-4.420559	-0.325576	-1.385938
H	1.232596	4.347117	1.259430
H	5.411097	3.358310	0.724783
H	2.856643	0.765751	3.091381
H	-5.272658	2.788077	-2.514715
H	-5.320911	-1.000715	-4.629075
H	-4.028743	-0.841933	-0.501040
N	0.854198	-1.482464	-1.775686
N	-0.709511	1.800484	-1.685680
S	1.570587	-2.762279	-2.500459
O	1.982973	-2.392837	-3.867497
O	2.499871	-3.509621	-1.618159
S	-1.408206	3.042324	-2.336712
O	-1.442469	2.776837	-3.877576
O	-2.678859	3.572746	-1.822495
C	-0.185219	4.497751	-2.309296
C	0.084339	-3.913509	-2.715387
F	0.060166	4.811809	-1.036532
F	0.938843	4.157465	-2.930487
F	-0.757125	5.529011	-2.930925
F	-0.535481	-4.086301	-1.539035
F	0.515044	-5.096393	-3.165684
F	-0.782408	-3.396430	-3.599354
C	5.456834	1.123419	2.246431
C	3.509783	5.234484	0.097508
C	4.156439	2.324505	-2.699343
C	5.554345	-1.939910	-4.994875
F	6.167651	0.855366	1.122976
F	5.124873	-0.063928	2.807646
F	6.297792	1.751187	3.103652
F	2.943023	6.290446	0.734563
F	2.916395	5.151979	-1.118351
F	4.811276	5.529245	-0.107079
F	5.079852	3.086427	-2.053581
F	2.968338	2.541680	-2.073611
F	4.051255	2.808288	-3.958829
F	6.605110	-1.348376	-5.622626
F	5.893691	-3.225840	-4.757446
F	4.525959	-1.942103	-5.875789
C	-3.517957	-5.324570	0.221152

C	-5.496642	-1.163381	2.242254
C	-4.356264	-2.534332	-2.557889
C	-5.742088	1.662053	-4.966677
F	-6.130398	2.938594	-4.765014
F	-4.685541	1.693632	-5.831812
F	-6.744250	1.017430	-5.606310
F	-5.227462	-3.225653	-1.776527
F	-4.418625	-3.077217	-3.795755
F	-3.114888	-2.756025	-2.068326
F	-5.172477	0.076660	2.690550
F	-6.272067	-0.998616	1.140533
F	-6.275027	-1.738578	3.189125
F	-2.994396	-5.299506	-1.024267
F	-4.821886	-5.666328	0.107287
F	-2.889929	-6.322961	0.891602
Si	-0.759352	1.392062	-4.852283
C	-1.647022	-0.162653	-4.286425
H	-2.540062	0.156444	-3.710948
H	-0.984306	-0.684976	-3.564362
C	-1.281334	2.037692	-6.540429
H	-2.387951	2.129365	-6.532592
H	-1.049037	1.244204	-7.284325
C	1.099560	1.333158	-4.629228
H	1.323213	1.009218	-3.592211
H	1.537719	2.343736	-4.755993
C	1.691800	0.334067	-5.640994
H	2.793223	0.275661	-5.550066
H	1.327691	-0.695864	-5.457373
H	1.461526	0.613737	-6.690323
C	-2.058774	-1.095614	-5.436201
H	-2.549791	-2.009715	-5.051078
H	-2.768408	-0.599505	-6.129626
H	-1.183021	-1.428909	-6.029796
C	-0.619062	3.366932	-6.929831
H	-0.973144	3.728257	-7.916696
H	-0.841191	4.160157	-6.186930
H	0.484837	3.273205	-6.990262

CIP (*s*-trans)

E = -9130.13585176186

P	0.953790	-0.466206	-0.632019
O	2.438547	-0.291037	0.072043
O	0.534429	-1.990269	-0.104793
C	3.335325	-1.350123	0.045352
C	4.435593	-1.283402	-0.862139
C	5.332463	-2.343742	-0.856387
C	5.161869	-3.467388	-0.000530
C	6.079222	-4.558947	-0.026588
C	5.887256	-5.672636	0.775826
C	4.756887	-5.740664	1.631771

C	3.850021	-4.691743	1.689317
C	4.031032	-3.521605	0.895438
C	3.119495	-2.407910	0.923994
C	1.925846	-2.377332	1.814361
C	2.038091	-2.442258	3.247827
C	3.297514	-2.395406	3.915409
C	3.369346	-2.417632	5.300878
C	2.188505	-2.519054	6.083391
C	0.948227	-2.558290	5.463899
C	0.836000	-2.491231	4.043612
C	-0.432915	-2.475252	3.400615
C	-0.553105	-2.355220	2.019094
C	0.651282	-2.248843	1.254498
C	4.565428	-0.133446	-1.787681
H	6.200989	-2.320140	-1.532141
H	6.941841	-4.502318	-0.708441
H	6.601472	-6.508955	0.742320
H	4.594388	-6.635280	2.251710
H	2.974093	-4.760481	2.348726
H	4.214334	-2.309570	3.317263
H	4.350675	-2.352030	5.793714
H	2.260219	-2.559081	7.180781
H	0.024781	-2.629145	6.058007
H	-1.339783	-2.569413	4.017176
C	-1.887003	-2.438614	1.367156
C	4.356689	1.181497	-1.328481
C	4.400018	2.262513	-2.218312
C	4.701208	2.063386	-3.571208
C	4.926855	0.756604	-4.032115
C	4.845068	-0.336088	-3.154804
C	-2.988036	-1.727716	1.883363
C	-4.274732	-1.929877	1.354049
C	-4.483252	-2.835176	0.304980
C	-3.387365	-3.535631	-0.222362
C	-2.099062	-3.331614	0.292262
H	4.128377	1.360294	-0.270484
H	4.731183	2.914783	-4.262756
H	4.936062	-1.360025	-3.541561
H	-2.837606	-1.012855	2.705516
H	-5.489340	-2.990768	-0.103012
H	-1.250900	-3.890926	-0.124737
N	0.074164	0.629742	0.074132
P	-0.741223	1.969700	-0.113011
O	-0.500846	2.943549	1.206246
O	-2.324543	1.490833	0.101919
C	-0.698060	2.328355	2.438069
C	0.454280	1.929501	3.186091
C	0.238927	1.215784	4.361572
C	-1.068564	0.879401	4.807824
C	-1.268858	0.107505	5.990246
C	-2.542629	-0.267205	6.390274
C	-3.669713	0.126106	5.621382

C	-3.511940	0.913666	4.489580
C	-2.216241	1.320855	4.054064
C	-2.007662	2.102651	2.861548
C	-3.145325	2.632177	2.059822
C	-4.118864	3.521735	2.641030
C	-3.991862	4.042919	3.962701
C	-4.947323	4.901057	4.488163
C	-6.078134	5.281983	3.719628
C	-6.220865	4.810046	2.424150
C	-5.251686	3.936099	1.850911
C	-5.379048	3.468231	0.513116
C	-4.417553	2.655495	-0.066068
C	-3.282389	2.282440	0.715309
C	1.829904	2.316069	2.780704
H	1.099809	0.906744	4.973644
H	-0.384324	-0.195613	6.570012
H	-2.682357	-0.872497	7.298742
H	-4.678205	-0.196633	5.919320
H	-4.389417	1.209410	3.900811
H	-3.115132	3.767000	4.564319
H	-4.822051	5.295313	5.507929
H	-6.830886	5.960183	4.148636
H	-7.083540	5.111434	1.809913
H	-6.262700	3.761957	-0.073839
C	-4.577695	2.139989	-1.453960
C	2.116151	3.632692	2.358280
C	3.440148	4.037887	2.135144
C	4.498651	3.132559	2.294033
C	4.218615	1.815484	2.686985
C	2.896826	1.406063	2.926482
C	-4.502117	3.001261	-2.567382
C	-4.671058	2.490430	-3.863168
C	-4.935874	1.127211	-4.070126
C	-4.998586	0.269846	-2.964843
C	-4.816144	0.769194	-1.664502
H	1.298834	4.355957	2.235341
H	5.532561	3.455609	2.121889
H	2.690290	0.370174	3.232384
H	-4.258796	4.060490	-2.413064
H	-5.070414	0.731566	-5.085703
H	-4.859429	0.091860	-0.801064
N	0.958025	-0.492981	-2.229455
N	-0.449358	2.800952	-1.450698
S	1.320082	-1.656487	-3.279211
O	1.083084	-1.113169	-4.639601
O	2.555369	-2.421427	-3.002648
S	-1.198521	4.175969	-1.880458
O	-1.397636	4.200215	-3.348503
O	-2.326467	4.564438	-0.992954
C	0.124668	5.480617	-1.532711
C	-0.084963	-2.934581	-3.072288
F	0.554826	5.359529	-0.270902

F	1.159066	5.353272	-2.372267
F	-0.425323	6.690547	-1.697733
F	0.257820	-3.887263	-2.199021
F	-0.329521	-3.508415	-4.262290
F	-1.205703	-2.323014	-2.648404
C	5.343546	0.825418	2.874939
C	3.718305	5.488754	1.799501
C	4.070551	3.632667	-1.678784
C	5.273193	0.518630	-5.482105
F	6.558745	1.412083	2.823544
F	5.327926	-0.143882	1.916858
F	5.248357	0.185576	4.068799
F	3.261798	6.298540	2.790546
F	3.102979	5.881509	0.662388
F	5.040656	5.732391	1.656765
F	5.027203	4.069944	-0.815623
F	2.903724	3.600372	-0.989877
F	3.953893	4.559025	-2.655128
F	6.609749	0.383038	-5.662321
F	4.694752	-0.610408	-5.960939
F	4.871142	1.548566	-6.275222
C	-3.618174	-4.605616	-1.267558
C	-5.443862	-1.173889	1.941068
C	-5.177654	-1.215066	-3.152714
C	-4.459618	3.371836	-5.071534
F	-4.514079	4.681633	-4.779617
F	-3.237998	3.124864	-5.635114
F	-5.377861	3.119001	-6.039448
F	-6.148722	-1.715370	-2.352491
F	-5.482509	-1.550441	-4.427980
F	-4.027805	-1.882680	-2.836149
F	-5.527515	-1.343969	3.282929
F	-5.328338	0.168335	1.724803
F	-6.623783	-1.557413	1.406599
F	-3.592713	-5.839898	-0.705495
F	-2.667985	-4.602409	-2.237579
F	-4.817188	-4.474093	-1.884823
C	-1.521960	-0.067702	-5.543297
H	-1.473223	-1.085878	-7.462713
O	-2.046453	-0.100212	-4.351374
O	-0.797169	0.935559	-5.851610
C	-1.640928	0.911169	-3.387854
H	-0.564481	0.787717	-3.177625
H	-2.235994	0.689419	-2.489133
H	-1.850933	1.921746	-3.776959
Si	0.297774	1.635333	-7.072209
C	0.622874	3.299514	-6.271321
H	-0.360985	3.749006	-6.013700
H	1.076527	3.963367	-7.041202
C	1.807754	0.528670	-7.161570
H	2.171166	0.418425	-6.119493
H	2.582841	1.124739	-7.694140

C	-0.705936	1.704544	-8.670264
H	-0.755706	0.679548	-9.100199
H	-0.076518	2.280933	-9.386393
C	1.510863	3.222889	-5.018777
H	1.046921	2.604020	-4.225287
H	1.675853	4.224892	-4.579823
H	2.501427	2.783982	-5.249565
C	1.651382	-0.861867	-7.787353
H	2.634621	-1.370837	-7.844748
H	1.232963	-0.827739	-8.815339
H	1.003179	-1.502974	-7.158008
C	-2.107065	2.322660	-8.565299
H	-2.599522	2.385781	-9.556876
H	-2.077512	3.345871	-8.141138
H	-2.769874	1.729713	-7.903828
H	-2.785885	-2.235117	-4.886893
C	-2.879327	-3.468214	-6.658040
C	-3.506630	-4.500022	-5.913168
C	-2.635933	-3.672344	-8.040025
C	-3.877099	-5.698903	-6.531504
H	-3.687190	-4.349675	-4.837815
C	-3.009566	-4.869855	-8.653480
H	-2.150212	-2.884236	-8.634582
C	-3.630846	-5.885491	-7.901490
H	-4.359126	-6.493338	-5.942777
H	-2.817045	-5.020112	-9.726232
H	-3.922263	-6.827852	-8.389641
C	-1.842160	-1.163882	-6.430919
C	-2.510768	-2.256397	-5.952276

RC (*s*-trans, major)

E = -9323.86539073144

P	0.849311	-0.815285	-0.739578
O	2.354885	-0.317630	-0.247771
O	0.698099	-2.250175	0.074271
C	3.400110	-1.208667	-0.034261
C	4.559891	-1.078804	-0.863338
C	5.590062	-1.992190	-0.677848
C	5.514900	-3.029708	0.290433
C	6.562425	-3.986606	0.431770
C	6.475082	-5.006475	1.366096
C	5.324088	-5.111378	2.190090
C	4.293196	-4.188206	2.085605
C	4.361111	-3.113558	1.150548
C	3.311891	-2.134740	1.010029
C	2.153558	-2.120064	1.948492
C	2.324664	-1.978769	3.371711
C	3.588810	-1.700726	3.970061
C	3.708504	-1.547492	5.344030
C	2.577301	-1.702239	6.188381

C	1.332493	-1.963981	5.635928
C	1.163807	-2.072885	4.223469
C	-0.125006	-2.252957	3.648244
C	-0.314326	-2.314473	2.269990
C	0.856912	-2.228295	1.449012
C	4.692122	0.020059	-1.851322
H	6.502291	-1.902734	-1.287247
H	7.441367	-3.902331	-0.225889
H	7.288693	-5.740870	1.462506
H	5.244540	-5.935539	2.914996
H	3.403279	-4.289376	2.721407
H	4.469736	-1.582826	3.326024
H	4.689537	-1.303090	5.777478
H	2.689596	-1.605858	7.278861
H	0.445444	-2.075519	6.277217
H	-0.990638	-2.339179	4.322168
C	-1.664734	-2.480479	1.672320
C	4.354855	1.342877	-1.511354
C	4.501535	2.377694	-2.448756
C	4.973084	2.113936	-3.739663
C	5.298884	0.792873	-4.086066
C	5.173458	-0.241651	-3.150856
C	-2.795107	-1.874651	2.262084
C	-4.076671	-2.069445	1.720523
C	-4.258348	-2.845922	0.566632
C	-3.137639	-3.441566	-0.027923
C	-1.859663	-3.277932	0.522463
H	3.960491	1.568148	-0.512015
H	5.055728	2.922739	-4.477584
H	5.391110	-1.274513	-3.450358
H	-2.674424	-1.234069	3.147390
H	-5.258988	-2.991534	0.140046
H	-1.008416	-3.779956	0.048734
N	-0.156034	0.227889	-0.119098
P	-0.975339	1.555320	-0.364734
O	-0.637133	2.671871	0.816041
O	-2.540524	1.114450	-0.005936
C	-0.740899	2.227889	2.129080
C	0.464641	2.022226	2.870106
C	0.353210	1.467055	4.141664
C	-0.907022	1.119731	4.700870
C	-1.004610	0.526177	5.993972
C	-2.234368	0.159788	6.519576
C	-3.418972	0.383867	5.769328
C	-3.361412	0.999628	4.526991
C	-2.113194	1.391991	3.959769
C	-2.011326	2.008564	2.661108
C	-3.217773	2.430734	1.899484
C	-4.151464	3.364521	2.479009
C	-3.914208	4.024095	3.722019
C	-4.838341	4.915887	4.246798
C	-6.047871	5.194642	3.558314

C	-6.298166	4.590198	2.336645
C	-5.361867	3.680201	1.764503
C	-5.592110	3.085207	0.494117
C	-4.661896	2.245746	-0.100213
C	-3.456311	1.956097	0.607136
C	1.783816	2.503506	2.385601
H	1.260139	1.313705	4.746039
H	-0.077184	0.357987	6.560850
H	-2.295056	-0.305866	7.514890
H	-4.392589	0.067076	6.171571
H	-4.282547	1.168570	3.955392
H	-2.977454	3.831176	4.261595
H	-4.626244	5.417678	5.202897
H	-6.774856	5.900076	3.987818
H	-7.221465	4.812486	1.779396
H	-6.529109	3.310392	-0.037841
C	-4.969433	1.649116	-1.433932
C	1.919139	3.816434	1.884352
C	3.189450	4.356208	1.637743
C	4.342806	3.583882	1.837120
C	4.211440	2.264585	2.293659
C	2.943754	1.725866	2.569846
C	-4.854410	2.421394	-2.606264
C	-5.250306	1.887798	-3.842398
C	-5.786970	0.596120	-3.923417
C	-5.887272	-0.181171	-2.760312
C	-5.475449	0.337258	-1.521517
H	1.024394	4.434874	1.728022
H	5.333872	4.009060	1.638512
H	2.852066	0.695869	2.942894
H	-4.439788	3.435534	-2.543725
H	-6.130745	0.202286	-4.889690
H	-5.574021	-0.265268	-0.608907
N	0.633861	-1.185907	-2.276126
N	-0.782772	2.242731	-1.799765
S	1.429609	-2.084431	-3.346803
O	0.651571	-2.074559	-4.608364
O	2.889826	-1.859620	-3.396408
S	-1.547594	3.579783	-2.296661
O	-1.919194	3.440036	-3.726714
O	-2.560659	4.109457	-1.345234
C	-0.163058	4.866257	-2.251236
C	1.274419	-3.866747	-2.711299
F	0.351231	4.921019	-1.017918
F	0.804531	4.561151	-3.127711
F	-0.680154	6.058677	-2.570831
F	2.094310	-4.060472	-1.670500
F	1.609897	-4.703574	-3.699274
F	0.009437	-4.130671	-2.329179
C	5.437435	1.415613	2.533356
C	3.301545	5.812978	1.237291
C	4.103390	3.774464	-2.043061

C	5.645273	0.472284	-5.519211
F	6.583923	2.080246	2.278960
F	5.435894	0.300687	1.750200
F	5.494968	0.979466	3.819126
F	2.796364	6.609572	2.215935
F	2.607613	6.091775	0.112122
F	4.584055	6.188358	1.035089
F	5.014092	4.334880	-1.201487
F	2.918228	3.757517	-1.383550
F	3.973884	4.603520	-3.101404
F	6.344711	1.472916	-6.107048
F	6.374104	-0.660530	-5.630858
F	4.517305	0.294636	-6.265233
C	-3.282297	-4.223725	-1.311114
C	-5.275676	-1.416264	2.366882
C	-6.397680	-1.595205	-2.880213
C	-5.064939	2.669437	-5.121778
F	-4.821685	3.972608	-4.910307
F	-4.016848	2.167257	-5.844352
F	-6.155578	2.571295	-5.923674
F	-6.792920	-2.108198	-1.692783
F	-7.447780	-1.683559	-3.737124
F	-5.433754	-2.424848	-3.373279
F	-5.220716	-1.475785	3.717613
F	-5.364231	-0.093811	2.034353
F	-6.436980	-1.988806	1.977232
F	-4.553688	-4.630848	-1.528527
F	-2.488811	-5.315784	-1.335338
F	-2.926224	-3.450954	-2.378671
C	-2.416014	-0.391197	-5.579624
C	-3.118356	-0.738774	-6.792629
C	-4.356298	-1.322822	-6.750766
C	-3.691227	-4.236300	-6.848959
C	-2.004037	-3.705465	-5.366651
C	-3.399253	-4.108304	-5.516977
C	-1.433820	-3.583791	-6.602361
H	-2.132230	-4.849411	-8.226697
H	-0.389840	-3.308189	-6.797450
H	-1.498330	-3.521567	-4.412816
H	-4.091760	-4.265712	-4.679366
H	-4.652723	-4.532350	-7.289162
C	-2.451588	-3.950972	-7.647276
H	-2.607446	-3.159262	-8.415092
H	-2.643964	-0.430333	-7.733193
O	-2.963150	-0.767766	-4.454287
O	-1.343619	0.303658	-5.529996
C	-2.346528	-0.357760	-3.209175
H	-2.257780	0.742507	-3.186071
H	-3.019570	-0.726483	-2.420678
H	-1.341818	-0.810169	-3.116632
Si	-0.169607	1.155912	-6.593986
C	0.795223	2.177342	-5.368554

H	1.479119	2.822535	-5.967006
H	0.061519	2.863675	-4.897658
C	-1.174611	2.231442	-7.785650
H	-0.595480	2.268626	-8.736333
H	-2.121556	1.709365	-8.042461
C	0.835682	-0.210781	-7.406817
H	1.819502	0.257499	-7.638614
H	1.048296	-0.953344	-6.606404
C	1.557183	1.396827	-4.295069
H	2.336070	0.733609	-4.719484
H	2.051351	2.086416	-3.585756
H	0.866872	0.775843	-3.698194
C	-1.474204	3.652137	-7.277673
H	-2.091979	4.214316	-8.007490
H	-2.017682	3.641261	-6.313619
H	-0.541925	4.230596	-7.118836
C	0.247642	-0.882112	-8.654130
H	0.947186	-1.629601	-9.081914
H	-0.691435	-1.424125	-8.421736
H	0.020247	-0.150361	-9.457420
H	-4.749571	-1.578550	-5.756143
C	-5.254846	-1.559391	-7.871695
C	-6.556957	-2.048285	-7.597359
C	-4.897648	-1.303396	-9.218942
C	-7.469922	-2.275324	-8.632869
H	-6.841268	-2.244390	-6.551413
C	-5.810034	-1.536241	-10.252243
H	-3.896277	-0.915273	-9.459087
C	-7.097729	-2.024488	-9.964157
H	-8.478303	-2.650041	-8.402707
H	-5.519365	-1.332610	-11.293882
H	-7.813033	-2.204738	-10.780716

RC (s-trans, minor)

E = -9323.86377638752

P	0.782125	-0.681975	-0.895618
O	2.283797	-0.463960	-0.227388
O	0.373791	-2.173283	-0.293596
C	3.189966	-1.514993	-0.137781
C	4.355473	-1.463892	-0.962403
C	5.254923	-2.517160	-0.875493
C	5.026254	-3.633507	-0.025589
C	5.935288	-4.731400	0.012572
C	5.681983	-5.840411	0.804397
C	4.496850	-5.894957	1.583353
C	3.599409	-4.836434	1.579919
C	3.841956	-3.670263	0.796154
C	2.936426	-2.549205	0.763165
C	1.734456	-2.501209	1.640644
C	1.844840	-2.576585	3.073823

C	3.100926	-2.547197	3.749304
C	3.165286	-2.616280	5.133632
C	1.980588	-2.751167	5.905748
C	0.743788	-2.764442	5.278925
C	0.639314	-2.641254	3.861414
C	-0.625845	-2.562211	3.218399
C	-0.747907	-2.397713	1.839649
C	0.464146	-2.362763	1.077285
C	4.578368	-0.335904	-1.897348
H	6.169149	-2.495614	-1.487916
H	6.839892	-4.685250	-0.613328
H	6.388391	-6.683854	0.819565
H	4.282679	-6.787235	2.190841
H	2.680391	-4.898438	2.178228
H	4.022704	-2.449540	3.160795
H	4.144434	-2.567712	5.632796
H	2.046799	-2.834953	7.001002
H	-0.183180	-2.850136	5.865437
H	-1.531520	-2.626905	3.839909
C	-2.088781	-2.283110	1.207450
C	4.427002	0.996738	-1.471786
C	4.638015	2.055862	-2.366504
C	5.009846	1.809469	-3.693403
C	5.142862	0.481089	-4.128123
C	4.928962	-0.583963	-3.241187
C	-3.120492	-1.597016	1.882166
C	-4.421673	-1.558628	1.356353
C	-4.716230	-2.175318	0.133039
C	-3.689175	-2.838432	-0.557475
C	-2.391854	-2.902453	-0.027756
H	4.127420	1.208505	-0.437067
H	5.150203	2.644082	-4.392054
H	4.965986	-1.619748	-3.603500
H	-2.905396	-1.084943	2.830983
H	-5.736274	-2.152963	-0.271297
H	-1.615666	-3.456117	-0.568478
N	-0.137523	0.404711	-0.231064
P	-0.766763	1.851063	-0.323265
O	-0.291912	2.767795	0.977404
O	-2.378970	1.579247	-0.009356
C	-0.457363	2.182443	2.228438
C	0.703594	1.718437	2.923272
C	0.505708	1.034588	4.120327
C	-0.792927	0.799554	4.647602
C	-0.978672	0.069624	5.858657
C	-2.250516	-0.189617	6.346235
C	-3.388302	0.283231	5.640265
C	-3.238984	1.035685	4.483729
C	-1.944814	1.323655	3.958182
C	-1.748063	2.076116	2.744613
C	-2.885635	2.735322	2.050127
C	-3.702607	3.696425	2.748700

C	-3.374481	4.187964	4.047423
C	-4.187234	5.111627	4.688836
C	-5.370497	5.589570	4.067289
C	-5.706449	5.148678	2.796976
C	-4.884874	4.210543	2.106821
C	-5.207794	3.766527	0.795250
C	-4.379612	2.906681	0.090214
C	-3.188185	2.436191	0.719314
C	2.083215	2.053531	2.489185
H	1.377574	0.684958	4.693790
H	-0.086724	-0.294775	6.389062
H	-2.381002	-0.763348	7.276394
H	-4.398907	0.052719	6.008443
H	-4.124914	1.396726	3.947088
H	-2.455328	3.838021	4.536556
H	-3.906389	5.482338	5.686272
H	-6.009443	6.317881	4.588789
H	-6.610615	5.524644	2.293654
H	-6.135288	4.125567	0.323803
C	-4.810139	2.426736	-1.257205
C	2.410229	3.366589	2.086774
C	3.749206	3.742202	1.904858
C	4.781920	2.807752	2.070752
C	4.458947	1.490407	2.429365
C	3.122600	1.113581	2.636973
C	-4.543207	3.158914	-2.427453
C	-5.074095	2.734455	-3.657626
C	-5.885539	1.593715	-3.736792
C	-6.149607	0.861387	-2.567732
C	-5.611562	1.270752	-1.338843
H	1.614273	4.112699	1.958384
H	5.827511	3.107536	1.929058
H	2.882599	0.081916	2.931482
H	-3.924886	4.063988	-2.365038
H	-6.328568	1.292852	-4.696482
H	-5.848207	0.716504	-0.422466
N	0.729142	-0.801064	-2.497208
N	-0.457770	2.647398	-1.678806
S	1.361355	-1.958692	-3.429891
O	1.214744	-1.534964	-4.841572
O	2.644665	-2.539954	-2.975409
S	-1.091821	4.088425	-2.064789
O	-1.367606	4.141360	-3.517998
O	-2.133379	4.568930	-1.114863
C	0.346405	5.284796	-1.763750
C	0.148383	-3.415424	-3.275848
F	0.867159	5.070008	-0.549435
F	1.302617	5.144238	-2.690870
F	-0.134042	6.532743	-1.824516
F	0.454315	-4.197873	-2.235224
F	0.207575	-4.147353	-4.398484
F	-1.108030	-2.956535	-3.121113

C	5.546586	0.462654	2.635665
C	4.068281	5.198698	1.636197
C	4.414043	3.462472	-1.870137
C	5.506599	0.196385	-5.566006
F	6.783254	0.998423	2.559983
F	5.481327	-0.532489	1.709138
F	5.433709	-0.138227	3.849633
F	3.723032	5.958849	2.709263
F	3.385748	5.687332	0.577838
F	5.385530	5.400015	1.410597
F	5.377064	3.836654	-0.985616
F	3.226531	3.555998	-1.224131
F	4.412480	4.371515	-2.870389
F	6.842425	0.035435	-5.728357
F	4.913064	-0.934438	-6.021417
F	5.128009	1.210625	-6.389892
C	-4.003829	-3.460958	-1.899073
C	-5.512019	-0.843080	2.119289
C	-7.039979	-0.355454	-2.646543
C	-4.736891	3.500802	-4.915200
F	-4.534624	4.807652	-4.686350
F	-3.590803	3.006996	-5.485297
F	-5.706322	3.382469	-5.855306
F	-7.451850	-0.769584	-1.422833
F	-8.141406	-0.121602	-3.393812
F	-6.396630	-1.413209	-3.218134
F	-5.466344	-1.118613	3.443524
F	-5.401053	0.514093	1.998181
F	-6.745034	-1.169519	1.672527
F	-3.214481	-4.527977	-2.174241
F	-3.821290	-2.564579	-2.911998
F	-5.287231	-3.877390	-1.973429
C	-1.472828	-0.479695	-5.558949
C	-1.423750	-1.624994	-6.430490
C	-2.028869	-2.801052	-6.081653
C	-4.761551	-2.326394	-7.233837
C	-4.367840	-0.076981	-6.920868
C	-4.901166	-1.305565	-6.334076
C	-3.898673	-0.342033	-8.177530
H	-4.827984	-1.902509	-9.365357
H	-3.455720	0.382207	-8.874140
H	-4.336461	0.899963	-6.421165
H	-5.320432	-1.387534	-5.322394
H	-5.062666	-3.372684	-7.093211
C	-4.143508	-1.790352	-8.491987
H	-3.220363	-2.341790	-8.779489
H	-0.785719	-1.530024	-7.317560
O	-2.259135	-0.552203	-4.516100
O	-0.796145	0.593967	-5.727262
C	-2.212821	0.502231	-3.519967
H	-1.219125	0.483612	-3.037353
H	-3.009565	0.250108	-2.800522

H	-2.384529	1.487857	-3.986758
Si	0.398547	1.340125	-6.837893
C	0.870394	2.822414	-5.800205
H	-0.055798	3.330490	-5.454697
H	1.399316	3.545255	-6.461343
C	1.886232	0.242150	-7.167654
H	2.312986	-0.037447	-6.184698
H	2.607236	0.965975	-7.615725
C	-0.590275	1.710725	-8.402237
H	-1.022581	0.752470	-8.767530
H	0.157981	2.003130	-9.173532
C	1.741755	2.440294	-4.593273
H	1.219476	1.735006	-3.916055
H	2.005246	3.329648	-3.992725
H	2.685520	1.957161	-4.911036
C	1.771509	-1.009476	-8.043849
H	2.777659	-1.383820	-8.323020
H	1.210579	-0.832646	-8.986563
H	1.278640	-1.828986	-7.484419
C	-1.676390	2.786646	-8.267483
H	-2.211702	2.952165	-9.225449
H	-1.245549	3.760686	-7.958613
H	-2.432019	2.520575	-7.503653
H	-2.598751	-2.812773	-5.142133
C	-1.897347	-4.081216	-6.759156
C	-2.426166	-5.230615	-6.121557
C	-1.221654	-4.239906	-7.994345
C	-2.288921	-6.496553	-6.701216
H	-2.925873	-5.113204	-5.147083
C	-1.091807	-5.504806	-8.574919
H	-0.784647	-3.363863	-8.496669
C	-1.625721	-6.636728	-7.931819
H	-2.695264	-7.380946	-6.188018
H	-0.562277	-5.614407	-9.533098
H	-1.516673	-7.631449	-8.389710

TS (s-trans, major)

E = -9323.85434826665

P	0.852586	-0.809522	-0.742533
O	2.355070	-0.307852	-0.246114
O	0.699581	-2.239985	0.079168
C	3.400858	-1.199314	-0.035668
C	4.556977	-1.072828	-0.870230
C	5.584116	-1.991042	-0.690349
C	5.508819	-3.029854	0.276514
C	6.550846	-3.994110	0.409060
C	6.461935	-5.016194	1.340825
C	5.315539	-5.115312	2.171950
C	4.290662	-4.184500	2.076887
C	4.359824	-3.108429	1.143602
C	3.314629	-2.124759	1.009222
C	2.158958	-2.107100	1.950733
C	2.332458	-1.965767	3.373716
C	3.598762	-1.693929	3.970219
C	3.721144	-1.541906	5.344104
C	2.590247	-1.689840	6.190013
C	1.343268	-1.944817	5.639366
C	1.172364	-2.054603	4.227329
C	-0.117648	-2.233679	3.654391
C	-0.307735	-2.299955	2.276781
C	0.861639	-2.214551	1.453434
C	4.687477	0.025589	-1.858743
H	6.493679	-1.905083	-1.304133
H	7.426430	-3.914295	-0.253643
H	7.270715	-5.756835	1.429900
H	5.234646	-5.941186	2.894710
H	3.404162	-4.280970	2.718194
H	4.479388	-1.580218	3.324949
H	4.704223	-1.303761	5.776405
H	2.704657	-1.594147	7.280301
H	0.456533	-2.051882	6.281836
H	-0.982916	-2.317519	4.329061
C	-1.655994	-2.477804	1.679022
C	4.343838	1.347680	-1.521722
C	4.487145	2.381149	-2.460846
C	4.963037	2.117548	-3.750206
C	5.296680	0.797696	-4.093175
C	5.173313	-0.235758	-3.156556
C	-2.792126	-1.870251	2.254887
C	-4.070064	-2.080714	1.709908
C	-4.242094	-2.875234	0.566726
C	-3.114669	-3.473546	-0.012500
C	-1.840715	-3.293302	0.540767
H	3.947128	1.573731	-0.523544
H	5.042825	2.925456	-4.489422
H	5.396725	-1.267909	-3.454225

H	-2.678842	-1.216292	3.131438
H	-5.239760	-3.031691	0.137117
H	-0.983927	-3.796354	0.078329
N	-0.157581	0.235640	-0.137049
P	-0.980774	1.560857	-0.388052
O	-0.646621	2.678998	0.792501
O	-2.544758	1.113621	-0.029739
C	-0.754013	2.237771	2.105852
C	0.449527	2.033077	2.850767
C	0.334059	1.479614	4.122682
C	-0.927981	1.133284	4.678393
C	-1.029110	0.539747	5.971242
C	-2.260327	0.173815	6.493761
C	-3.442912	0.398919	5.740613
C	-3.381895	1.014481	4.498316
C	-2.132055	1.405700	3.933819
C	-2.026176	2.019763	2.634165
C	-3.230853	2.437223	1.866592
C	-4.168022	3.371701	2.439030
C	-3.933604	4.040275	3.677726
C	-4.860502	4.933466	4.195380
C	-6.069975	5.204326	3.503581
C	-6.317843	4.590120	2.286264
C	-5.379017	3.678210	1.721621
C	-5.608587	3.069936	0.457344
C	-4.675606	2.229515	-0.130987
C	-3.466499	1.953687	0.576909
C	1.770243	2.513320	2.369413
H	1.238811	1.326696	4.730451
H	-0.103023	0.371350	6.540410
H	-2.323665	-0.291942	7.488874
H	-4.417727	0.082964	6.140510
H	-4.301393	1.183939	3.924309
H	-2.996626	3.853250	4.219207
H	-4.650657	5.442557	5.148180
H	-6.799110	5.911137	3.927142
H	-7.241293	4.805759	1.726772
H	-6.548026	3.284535	-0.074581
C	-4.987568	1.607171	-1.452579
C	1.906289	3.824249	1.863162
C	3.176961	4.364289	1.619185
C	4.330327	3.593807	1.825427
C	4.198522	2.276121	2.286631
C	2.930330	1.737510	2.560918
C	-4.857402	2.343374	-2.646911
C	-5.247636	1.774419	-3.869198
C	-5.789342	0.482968	-3.916528
C	-5.910117	-0.255333	-2.730912
C	-5.508168	0.299281	-1.504586
H	1.011654	4.441109	1.700282
H	5.321723	4.019157	1.628598
H	2.838455	0.708900	2.937731

H	-4.434625	3.355618	-2.612946
H	-6.120397	0.059958	-4.875296
H	-5.622128	-0.273150	-0.574722
N	0.646700	-1.197153	-2.277101
N	-0.785035	2.244673	-1.822830
S	1.435527	-2.104129	-3.341294
O	0.627759	-2.152956	-4.584409
O	2.887391	-1.846507	-3.437975
S	-1.560670	3.573875	-2.326206
O	-1.928382	3.428856	-3.755801
O	-2.580708	4.095721	-1.377734
C	-0.184805	4.869576	-2.281698
C	1.338304	-3.875547	-2.665314
F	0.328041	4.931796	-1.047769
F	0.785656	4.567965	-3.155843
F	-0.709357	6.057678	-2.605260
F	2.160907	-4.025751	-1.620401
F	1.699784	-4.723306	-3.635945
F	0.079238	-4.171035	-2.281831
C	5.424559	1.428994	2.532600
C	3.288807	5.820068	1.214874
C	4.081673	3.776867	-2.058590
C	5.651112	0.475793	-5.524008
F	6.571336	2.094464	2.281778
F	5.427601	0.312742	1.750986
F	5.477542	0.994776	3.819197
F	2.788676	6.619094	2.194214
F	2.589995	6.096724	0.092326
F	4.570748	6.193992	1.006526
F	4.990643	4.343770	-1.219351
F	2.897273	3.755687	-1.398255
F	3.947389	4.602106	-3.119153
F	6.342613	1.481166	-6.112769
F	6.392265	-0.650111	-5.628309
F	4.528352	0.283169	-6.273655
C	-3.242790	-4.278733	-1.281686
C	-5.275114	-1.427248	2.345085
C	-6.426439	-1.669133	-2.811487
C	-5.059394	2.510116	-5.175479
F	-4.726067	3.800050	-5.010785
F	-4.074708	1.918280	-5.917893
F	-6.183667	2.462111	-5.933941
F	-6.836208	-2.143386	-1.612391
F	-7.466801	-1.781953	-3.675810
F	-5.459493	-2.519345	-3.265842
F	-5.234197	-1.491651	3.696028
F	-5.357839	-0.103600	2.016634
F	-6.433173	-1.996386	1.941024
F	-4.509694	-4.693969	-1.508996
F	-2.446111	-5.369699	-1.277360
F	-2.873458	-3.526306	-2.360228
C	-2.336006	-0.557484	-5.501664

C	-2.911927	-1.082027	-6.694079
C	-4.200836	-1.691126	-6.680623
C	-3.842185	-3.703077	-6.757787
C	-2.021030	-3.625571	-5.342247
C	-3.390628	-3.949842	-5.433380
C	-1.566156	-3.246114	-6.608754
H	-2.371347	-4.683066	-7.955681
H	-0.535364	-2.942334	-6.832212
H	-1.427291	-3.578136	-4.423292
H	-4.033349	-4.214435	-4.583694
H	-4.803185	-4.080737	-7.137290
C	-2.599227	-3.642059	-7.621454
H	-2.666960	-3.023662	-8.535592
H	-2.454994	-0.746189	-7.632652
O	-2.917999	-0.896095	-4.371624
O	-1.321359	0.232696	-5.439835
C	-2.380055	-0.377657	-3.133043
H	-2.356235	0.725291	-3.170423
H	-3.062454	-0.738948	-2.348707
H	-1.355392	-0.762866	-2.974817
Si	-0.220841	1.073597	-6.571620
C	0.757319	2.153308	-5.406049
H	1.422970	2.784866	-6.038216
H	0.028015	2.845163	-4.937055
C	-1.306056	2.070797	-7.762150
H	-0.789465	2.073409	-8.748345
H	-2.255698	1.517479	-7.929708
C	0.836523	-0.259847	-7.391661
H	1.840011	0.209013	-7.508265
H	0.987262	-1.051206	-6.624630
C	1.548242	1.407897	-4.327434
H	2.320610	0.734632	-4.748727
H	2.055690	2.119589	-3.650039
H	0.874012	0.801747	-3.697054
C	-1.605379	3.508212	-7.304565
H	-2.281614	4.021934	-8.018017
H	-2.085680	3.534228	-6.307942
H	-0.677879	4.111558	-7.234793
C	0.371147	-0.838850	-8.733892
H	1.089120	-1.588856	-9.125226
H	-0.611760	-1.347768	-8.655677
H	0.265820	-0.054148	-9.511247
H	-4.690377	-1.684244	-5.696691
C	-5.158991	-1.527529	-7.804998
C	-6.537496	-1.709609	-7.546227
C	-4.762185	-1.195456	-9.119064
C	-7.487372	-1.565171	-8.565608
H	-6.861796	-1.964996	-6.524134
C	-5.712229	-1.055709	-10.139819
H	-3.699777	-1.025705	-9.350951
C	-7.077749	-1.240559	-9.868795
H	-8.555491	-1.703723	-8.339956

H	-5.383374	-0.790873	-11.156114
H	-7.821639	-1.125207	-10.671215

TS (s-trans, minor)

E = -9323.85080394122

P	0.776751	-0.690212	-0.895570
O	2.281820	-0.480484	-0.232949
O	0.370059	-2.184837	-0.299919
C	3.183125	-1.535620	-0.149562
C	4.344127	-1.487824	-0.980268
C	5.242873	-2.541831	-0.895300
C	5.019447	-3.653604	-0.038139
C	5.932267	-4.748140	0.003659
C	5.687450	-5.851344	0.806093
C	4.506392	-5.903687	1.591402
C	3.604745	-4.848672	1.583519
C	3.839288	-3.687485	0.789887
C	2.932050	-2.567676	0.754872
C	1.730974	-2.516497	1.633708
C	1.841287	-2.587300	3.067142
C	3.097196	-2.553789	3.742826
C	3.161289	-2.614760	5.127599
C	1.976506	-2.746404	5.900190
C	0.739912	-2.764598	5.273055
C	0.635640	-2.648492	3.854893
C	-0.629421	-2.570110	3.211665
C	-0.751693	-2.406218	1.832786
C	0.460549	-2.375596	1.070405
C	4.570654	-0.357715	-1.911704
H	6.154632	-2.522082	-1.511472
H	6.833721	-4.702922	-0.626864
H	6.397876	-6.691337	0.825416
H	4.299311	-6.791255	2.208179
H	2.689451	-4.908876	2.187603
H	4.018940	-2.458100	3.153926
H	4.140201	-2.561616	5.626826
H	2.042440	-2.822981	6.996025
H	-0.187109	-2.847053	5.859931
H	-1.534806	-2.633172	3.833649
C	-2.092903	-2.284653	1.201900
C	4.431225	0.974266	-1.479991
C	4.655094	2.035616	-2.369113
C	5.027865	1.791647	-3.696068
C	5.147146	0.464007	-4.137192
C	4.920115	-0.602985	-3.256281
C	-3.122182	-1.602219	1.884552
C	-4.424687	-1.557175	1.362896
C	-4.723385	-2.162660	0.135334
C	-3.699082	-2.820243	-0.564107
C	-2.400132	-2.891687	-0.038930

H	4.132032	1.184251	-0.444830
H	5.177052	2.627969	-4.390928
H	4.947101	-1.637136	-3.623980
H	-2.904409	-1.098298	2.837031
H	-5.744755	-2.136430	-0.265305
H	-1.626672	-3.441862	-0.587422
N	-0.135765	0.394235	-0.214546
P	-0.768511	1.837919	-0.320522
O	-0.298698	2.762056	0.977170
O	-2.382259	1.567440	-0.008938
C	-0.461338	2.177235	2.228662
C	0.700596	1.713920	2.922180
C	0.504662	1.030945	4.119941
C	-0.793073	0.796635	4.649661
C	-0.976450	0.069554	5.862711
C	-2.247268	-0.188251	6.353597
C	-3.386409	0.283036	5.648813
C	-3.239378	1.032458	4.489953
C	-1.946275	1.319081	3.961074
C	-1.751406	2.069348	2.745831
C	-2.889535	2.725954	2.049687
C	-3.706278	3.688857	2.745890
C	-3.377071	4.184362	4.042827
C	-4.188128	5.111610	4.681092
C	-5.370915	5.589162	4.058330
C	-5.708519	5.143566	2.790100
C	-4.888593	4.201670	2.103152
C	-5.212724	3.752949	0.793572
C	-4.384116	2.891978	0.090381
C	-3.191399	2.424177	0.719061
C	2.079412	2.047925	2.485059
H	1.377463	0.681446	4.692009
H	-0.083440	-0.293250	6.392295
H	-2.375819	-0.759344	7.285612
H	-4.396257	0.053928	6.020003
H	-4.126324	1.392680	3.954367
H	-2.458097	3.834982	4.532599
H	-3.906097	5.485748	5.676837
H	-6.008082	6.321003	4.577046
H	-6.612365	5.518936	2.285657
H	-6.141045	4.109724	0.321958
C	-4.818434	2.407792	-1.254272
C	2.406643	3.361398	2.084446
C	3.745476	3.735681	1.899039
C	4.777441	2.799578	2.059913
C	4.453992	1.481806	2.416395
C	3.117849	1.106193	2.627573
C	-4.540063	3.127438	-2.429683
C	-5.080170	2.704275	-3.656303
C	-5.911300	1.577105	-3.725243
C	-6.182496	0.853795	-2.552452
C	-5.636255	1.262573	-1.327161

H	1.610941	4.108591	1.960468
H	5.822858	3.098376	1.915286
H	2.877168	0.074227	2.920455
H	-3.907372	4.023086	-2.373321
H	-6.368414	1.281239	-4.679848
H	-5.878951	0.717197	-0.407041
N	0.712529	-0.792370	-2.495200
N	-0.458887	2.629392	-1.678485
S	1.321738	-1.936654	-3.458726
O	1.164377	-1.482169	-4.858779
O	2.601733	-2.539457	-3.022942
S	-1.088269	4.068957	-2.073360
O	-1.364901	4.115069	-3.527316
O	-2.129455	4.559506	-1.127826
C	0.356063	5.260055	-1.782061
C	0.086657	-3.373759	-3.334731
F	0.879041	5.048802	-0.568158
F	1.308007	5.108520	-2.711507
F	-0.117885	6.510338	-1.847964
F	0.348668	-4.163100	-2.285829
F	0.165590	-4.102420	-4.455623
F	-1.165717	-2.891981	-3.213425
C	5.541127	0.452114	2.615400
C	4.065271	5.191929	1.630248
C	4.440828	3.442197	-1.868277
C	5.508547	0.184463	-5.576631
F	6.778154	0.986608	2.537030
F	5.471350	-0.539855	1.685812
F	5.432035	-0.152742	3.827796
F	3.716167	5.953183	2.701350
F	3.386456	5.679565	0.569018
F	5.383199	5.393247	1.408863
F	5.402942	3.806270	-0.978325
F	3.251384	3.543398	-1.226685
F	4.450425	4.354819	-2.865205
F	6.846370	0.045337	-5.744969
F	4.930840	-0.954846	-6.029382
F	5.110636	1.193302	-6.398144
C	-4.022000	-3.427697	-1.910255
C	-5.512837	-0.846049	2.132600
C	-7.094126	-0.347192	-2.625600
C	-4.737093	3.457232	-4.920499
F	-4.511317	4.761063	-4.703938
F	-3.605955	2.938355	-5.497874
F	-5.716471	3.347388	-5.854163
F	-7.483960	-0.772913	-1.400152
F	-8.208658	-0.085538	-3.344837
F	-6.482512	-1.407971	-3.229473
F	-5.459658	-1.121955	3.456154
F	-5.407950	0.511645	2.011027
F	-6.747355	-1.176536	1.691859
F	-3.225785	-4.481776	-2.209763

F	-3.863393	-2.513834	-2.912709
F	-5.302757	-3.856052	-1.976289
C	-1.550087	-0.398458	-5.649526
C	-1.675189	-1.471038	-6.579202
C	-2.367855	-2.664176	-6.212267
C	-4.227224	-2.448928	-6.968283
C	-4.344960	-0.158086	-6.731940
C	-4.773823	-1.388284	-6.192334
C	-3.583572	-0.411027	-7.878401
H	-4.698975	-1.855406	-8.968666
H	-3.117755	0.355248	-8.512690
H	-4.480327	0.828618	-6.274636
H	-5.321654	-1.513235	-5.249123
H	-4.602305	-3.480664	-6.897011
C	-3.812513	-1.833202	-8.289625
H	-2.986530	-2.336642	-8.823885
H	-0.993024	-1.442713	-7.436415
O	-2.304867	-0.464974	-4.574107
O	-0.793431	0.633922	-5.780380
C	-2.155515	0.539860	-3.539470
H	-1.156131	0.424760	-3.081937
H	-2.951681	0.316623	-2.809455
H	-2.262446	1.556277	-3.956862
Si	0.424748	1.356095	-6.858698
C	0.939060	2.810437	-5.798329
H	0.024434	3.344664	-5.460938
H	1.502579	3.523670	-6.441061
C	1.867911	0.206272	-7.214914
H	2.322847	-0.055114	-6.239768
H	2.597290	0.882077	-7.720194
C	-0.515436	1.818703	-8.431571
H	-0.906862	0.883849	-8.891400
H	0.259428	2.181091	-9.144654
C	1.775943	2.384674	-4.582898
H	1.219490	1.687993	-3.925081
H	2.059558	3.257016	-3.966896
H	2.707460	1.874675	-4.893081
C	1.660613	-1.073740	-8.031381
H	2.635770	-1.517683	-8.318066
H	1.088133	-0.904489	-8.968657
H	1.134529	-1.836506	-7.424384
C	-1.624946	2.865384	-8.263446
H	-2.129853	3.091099	-9.225339
H	-1.222632	3.820595	-7.869987
H	-2.401394	2.539130	-7.544321
H	-2.666712	-2.707621	-5.156101
C	-1.972739	-3.991872	-6.754355
C	-2.349610	-5.148211	-6.033822
C	-1.229985	-4.155146	-7.943683
C	-2.007055	-6.425553	-6.493255
H	-2.897930	-5.032036	-5.085401
C	-0.887675	-5.434124	-8.404551

H	-0.888402	-3.275840	-8.510523
C	-1.278495	-6.574237	-7.684744
H	-2.302966	-7.312130	-5.912344
H	-0.300852	-5.539935	-9.329472
H	-1.005819	-7.577076	-8.046247

P (s-trans, major)

E = -9323.89299227211

P	0.855760	-0.748004	-0.718468
O	2.367142	-0.277711	-0.224982
O	0.698538	-2.199059	0.063907
C	3.399922	-1.189886	-0.038819
C	4.544237	-1.077698	-0.890910
C	5.561180	-2.010927	-0.727900
C	5.485080	-3.050905	0.237600
C	6.517452	-4.027510	0.355321
C	6.427595	-5.051031	1.285303
C	5.290067	-5.139264	2.129927
C	4.274641	-4.196846	2.049288
C	4.345210	-3.119185	1.117882
C	3.310457	-2.123114	0.998020
C	2.156031	-2.102588	1.940456
C	2.329211	-1.970011	3.363889
C	3.596673	-1.708492	3.962139
C	3.718406	-1.561714	5.336644
C	2.585085	-1.703282	6.180495
C	1.336936	-1.948238	5.627781
C	1.167317	-2.054564	4.215324
C	-0.122279	-2.226977	3.639534
C	-0.311847	-2.284946	2.261313
C	0.858781	-2.197263	1.440411
C	4.670685	0.020253	-1.879807
H	6.463755	-1.935244	-1.353239
H	7.386223	-3.955593	-0.317132
H	7.228746	-5.801203	1.362686
H	5.208584	-5.966000	2.851650
H	3.394955	-4.284448	2.701144
H	4.478049	-1.597417	3.317341
H	4.702492	-1.331924	5.771181
H	2.698585	-1.610399	7.271113
H	0.448485	-2.050307	6.268738
H	-0.988618	-2.312133	4.312567
C	-1.660162	-2.457420	1.662670
C	4.331654	1.343324	-1.541071
C	4.460622	2.374372	-2.484462
C	4.921983	2.107822	-3.778655
C	5.252959	0.787482	-4.122656
C	5.140566	-0.243909	-3.182678
C	-2.797258	-1.865258	2.252208
C	-4.075963	-2.077780	1.710237

C	-4.247619	-2.857312	0.556728
C	-3.118579	-3.435185	-0.040303
C	-1.844141	-3.254785	0.511108
H	3.948773	1.571854	-0.538251
H	4.992256	2.914038	-4.520778
H	5.359159	-1.276557	-3.482444
H	-2.685529	-1.223127	3.137625
H	-5.246369	-3.017786	0.131818
H	-0.986728	-3.744787	0.036436
N	-0.136790	0.292983	-0.073611
P	-0.983382	1.597196	-0.365949
O	-0.682959	2.734204	0.803036
O	-2.549651	1.137283	-0.030897
C	-0.788270	2.284656	2.115591
C	0.415286	2.071176	2.857618
C	0.298039	1.505144	4.123724
C	-0.964568	1.153662	4.674885
C	-1.065724	0.545671	5.961006
C	-2.297086	0.174570	6.479500
C	-3.479521	0.408079	5.728812
C	-3.418279	1.034284	4.491768
C	-2.168482	1.431265	3.931525
C	-2.060687	2.054292	2.636190
C	-3.263946	2.458258	1.858576
C	-4.214782	3.383875	2.421970
C	-3.992864	4.060969	3.658298
C	-4.931152	4.947645	4.166465
C	-6.140117	5.201990	3.467467
C	-6.377090	4.577185	2.253342
C	-5.426488	3.671686	1.698277
C	-5.646103	3.048634	0.439356
C	-4.700636	2.216787	-0.141422
C	-3.487184	1.965623	0.569625
C	1.737752	2.543957	2.374892
H	1.202176	1.343561	4.730110
H	-0.139700	0.370032	6.528194
H	-2.360695	-0.302355	7.469291
H	-4.454396	0.088680	6.125817
H	-4.337689	1.206860	3.918541
H	-3.056541	3.885808	4.205008
H	-4.731184	5.464337	5.117281
H	-6.878114	5.904063	3.883415
H	-7.300924	4.778938	1.689367
H	-6.589072	3.242913	-0.094135
C	-5.011761	1.563237	-1.449179
C	1.880383	3.850950	1.860587
C	3.153277	4.380916	1.606548
C	4.302581	3.604663	1.813246
C	4.164281	2.290976	2.284183
C	2.893844	1.761626	2.565978
C	-4.856552	2.254669	-2.667429
C	-5.234575	1.641654	-3.872973

C	-5.786237	0.354337	-3.879745
C	-5.942546	-0.334752	-2.669438
C	-5.554829	0.262156	-1.459163
H	0.989106	4.472469	1.697247
H	5.295907	4.022373	1.609638
H	2.797230	0.734687	2.946585
H	-4.422220	3.262789	-2.664920
H	-6.098970	-0.101427	-4.829218
H	-5.693266	-0.270969	-0.509721
N	0.630712	-1.079497	-2.262100
N	-0.773719	2.251698	-1.812539
S	1.338108	-1.970719	-3.391089
O	0.428987	-2.013067	-4.564899
O	2.772394	-1.693368	-3.611228
S	-1.562811	3.553738	-2.361506
O	-1.909040	3.364091	-3.792103
O	-2.604598	4.083359	-1.441772
C	-0.206451	4.870597	-2.334606
C	1.316642	-3.749442	-2.732530
F	0.307701	4.954434	-1.103054
F	0.766161	4.571896	-3.207788
F	-0.748768	6.046627	-2.671780
F	2.198743	-3.886910	-1.734858
F	1.646671	-4.575967	-3.731568
F	0.088714	-4.078318	-2.287320
C	5.386456	1.438057	2.529537
C	3.271562	5.832286	1.188983
C	4.054352	3.769724	-2.080419
C	5.592080	0.465288	-5.557119
F	6.536399	2.101459	2.287859
F	5.389405	0.327254	1.739572
F	5.432490	0.994589	3.812889
F	2.785451	6.643434	2.165205
F	2.564071	6.102643	0.069965
F	4.553866	6.195711	0.965556
F	4.968908	4.341862	-1.251802
F	2.876080	3.746360	-1.409403
F	3.906266	4.591487	-3.142647
F	6.309815	1.454981	-6.141102
F	6.299296	-0.680548	-5.673105
F	4.461006	0.312188	-6.304257
C	-3.249948	-4.209563	-1.330124
C	-5.282100	-1.439751	2.358432
C	-6.503424	-1.734411	-2.718224
C	-5.020642	2.311439	-5.210161
F	-4.650713	3.597518	-5.105716
F	-4.042685	1.654126	-5.912821
F	-6.135876	2.257031	-5.977728
F	-6.843449	-2.200970	-1.493268
F	-7.607690	-1.803516	-3.503275
F	-5.601701	-2.607188	-3.246273
F	-5.227991	-1.504443	3.708749

F	-5.382643	-0.115616	2.032312
F	-6.437503	-2.020370	1.964595
F	-4.500752	-4.687068	-1.520659
F	-2.397381	-5.257400	-1.385037
F	-2.960708	-3.409199	-2.394361
C	-2.158308	-0.749011	-5.395953
C	-2.525080	-1.610548	-6.552028
C	-4.018700	-2.060967	-6.586647
C	-3.879926	-3.625268	-6.855402
C	-2.095064	-3.807686	-5.394982
C	-3.380814	-4.198951	-5.543023
C	-1.727214	-2.996164	-6.618659
H	-2.257113	-4.713883	-7.903142
H	-0.650798	-2.854422	-6.809796
H	-1.456658	-3.917226	-4.511639
H	-4.011399	-4.688607	-4.788321
H	-4.801025	-4.063445	-7.280577
C	-2.593119	-3.678613	-7.701292
H	-2.655542	-3.113517	-8.654597
H	-2.258585	-1.041707	-7.461663
O	-2.738846	-1.033497	-4.274413
O	-1.335212	0.218296	-5.442189
C	-2.378103	-0.287210	-3.081353
H	-2.424902	0.794260	-3.291960
H	-3.109853	-0.593944	-2.319894
H	-1.348788	-0.571845	-2.792732
Si	-0.257542	1.032390	-6.652930
C	0.692361	2.194329	-5.547758
H	1.339672	2.801362	-6.222040
H	-0.046722	2.895396	-5.108303
C	-1.436834	1.908227	-7.844455
H	-0.968765	1.871800	-8.853553
H	-2.365380	1.302417	-7.929595
C	0.824739	-0.308197	-7.424355
H	1.833185	0.158980	-7.494286
H	0.944238	-1.101202	-6.654000
C	1.511488	1.524808	-4.439741
H	2.262274	0.810392	-4.829786
H	2.049254	2.282851	-3.841279
H	0.853211	0.980703	-3.738484
C	-1.778613	3.356482	-7.456838
H	-2.517417	3.792131	-8.159541
H	-2.205245	3.424532	-6.438106
H	-0.878482	4.003210	-7.478431
C	0.416340	-0.879380	-8.788187
H	1.141042	-1.641600	-9.139648
H	-0.577425	-1.372711	-8.765821
H	0.365841	-0.093375	-9.569225
H	-4.458627	-1.941536	-5.579912
C	-4.916326	-1.331962	-7.563613
C	-6.291165	-1.235712	-7.254762
C	-4.472320	-0.773109	-8.778873

C	-7.186001	-0.581424	-8.112199
H	-6.661729	-1.688082	-6.320145
C	-5.365874	-0.121848	-9.643891
H	-3.411154	-0.833496	-9.065355
C	-6.724285	-0.016369	-9.311406
H	-8.249501	-0.507781	-7.838643
H	-4.991923	0.312821	-10.583250
H	-7.420663	0.505928	-9.984287

P (s-trans, minor)

E = -9323.89022570158

P	0.868969	-0.746806	-0.783113
O	2.409799	-0.535081	-0.210871
O	0.498982	-2.239353	-0.159551
C	3.299020	-1.597749	-0.104107
C	4.438578	-1.594533	-0.964334
C	5.321444	-2.661736	-0.875145
C	5.104428	-3.743009	0.022144
C	5.992938	-4.857259	0.064906
C	5.752471	-5.929427	0.909780
C	4.602186	-5.927857	1.741335
C	3.725863	-4.851843	1.733996
C	3.954882	-3.723589	0.892552
C	3.064817	-2.591033	0.846756
C	1.891020	-2.495132	1.757754
C	2.037782	-2.499290	3.189194
C	3.310364	-2.448785	3.830538
C	3.408247	-2.434736	5.214662
C	2.241399	-2.502879	6.021852
C	0.989185	-2.541322	5.427260
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C	-0.586790	-2.378944	2.008952
C	0.609265	-2.378167	1.218704
C	4.672153	-0.486279	-1.921315
H	6.214320	-2.676388	-1.518663
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H	6.442153	-6.786592	0.927951
H	4.397981	-6.790512	2.393468
H	2.833493	-4.870631	2.374090
H	4.217181	-2.395621	3.213876
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H	-1.317264	-2.502812	4.039331
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C	4.889652	1.894357	-2.402893
C	5.195537	1.616862	-3.740186
C	5.213530	0.281216	-4.173621

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C	-4.309693	-1.728168	1.571282
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H	4.903354	-1.800375	-3.633121
H	-2.816007	-1.189653	3.043485
H	-5.598863	-2.369840	-0.058633
H	-1.420903	-3.429375	-0.407185
N	0.005008	0.347201	-0.049965
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C	-0.955738	0.223081	6.011760
C	-2.211781	-0.079430	6.514755
C	-3.372230	0.291603	5.785473
C	-3.262709	0.984900	4.588114
C	-1.986393	1.317972	4.046083
C	-1.828741	2.015556	2.793756
C	-2.998158	2.549329	2.043067
C	-3.902217	3.481622	2.669955
C	-3.650433	4.058213	3.950892
C	-4.546551	4.949408	4.523136
C	-5.741872	5.309519	3.847378
C	-6.004765	4.787426	2.591043
C	-5.095799	3.881943	1.970014
C	-5.333636	3.378739	0.662286
C	-4.422834	2.553807	0.019719
C	-3.237650	2.171050	0.717542
C	2.006053	2.158545	2.528087
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H	-0.045505	-0.062237	6.559664
H	-2.311818	-0.608452	7.474631
H	-4.369291	0.027555	6.167763
H	-4.166797	1.265408	4.034097
H	-2.724003	3.801116	4.481757
H	-4.323055	5.387354	5.507618
H	-6.447041	6.013141	4.314514
H	-6.915647	5.074150	2.043005
H	-6.255196	3.672433	0.136976
C	-4.721032	2.087202	-1.367891
C	2.304239	3.463892	2.079980
C	3.632542	3.848512	1.842340
C	4.680374	2.931798	2.012280
C	4.385752	1.622811	2.419659

C	3.060431	1.234733	2.673460
C	-4.462573	2.930908	-2.464666
C	-4.820331	2.527845	-3.760563
C	-5.462620	1.302166	-3.976461
C	-5.736812	0.466405	-2.883505
C	-5.357712	0.848042	-1.586073
H	1.494628	4.197041	1.962404
H	5.717794	3.240202	1.836816
H	2.841175	0.208343	3.001370
H	-3.964405	3.894433	-2.295531
H	-5.751641	1.000093	-4.991400
H	-5.578319	0.196964	-0.730142
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N	-0.502478	2.470956	-1.633856
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O	1.377234	-1.265038	-4.757830
O	2.518452	-2.647321	-2.923181
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O	-1.402022	3.948926	-3.486426
O	-2.122313	4.448105	-1.082679
C	0.378468	5.068253	-1.800491
C	-0.023155	-3.181321	-3.592845
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F	1.279010	4.887018	-2.775397
F	-0.054917	6.333098	-1.838707
F	-0.100431	-3.953136	-2.500626
F	0.240888	-3.947562	-4.656876
F	-1.204684	-2.563089	-3.780048
C	5.497390	0.620503	2.622610
C	3.933152	5.292271	1.491686
C	4.753672	3.317268	-1.918641
C	5.496075	-0.021265	-5.625806
F	6.721221	1.180232	2.517071
F	5.437807	-0.388291	1.708205
F	5.419409	0.034051	3.845134
F	3.414682	6.123857	2.432461
F	3.397839	5.662365	0.307930
F	5.263130	5.530107	1.429534
F	5.631651	3.594989	-0.917907
F	3.510183	3.529869	-1.419022
F	4.961386	4.221519	-2.900041
F	6.824255	-0.132755	-5.871962
F	4.917294	-1.178992	-6.023420
F	5.026973	0.964571	-6.439009
C	-3.783987	-3.494945	-1.741423
C	-5.438501	-1.062486	2.322788
C	-6.522375	-0.796542	-3.145628
C	-4.459690	3.378100	-4.953951
F	-4.236501	4.660872	-4.640810
F	-3.329982	2.896710	-5.562299
F	-5.434172	3.343726	-5.905391
F	-6.628624	-1.583196	-2.049557

F	-7.782226	-0.507142	-3.554872
F	-5.963415	-1.544824	-4.135517
F	-5.340848	-1.249918	3.659527
F	-5.448836	0.286796	2.111690
F	-6.648201	-1.522853	1.930906
F	-2.878444	-4.431261	-2.101231
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F	-5.010460	-4.056787	-1.839690
C	-1.853889	-0.105892	-5.841302
C	-2.334282	-0.960490	-6.968430
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C	-4.398646	0.370636	-7.549318
C	-5.206211	-0.685460	-7.298116
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H	-2.464345	0.521494	-8.680283
H	-4.580082	1.426734	-7.311785
H	-6.182265	-0.679486	-6.793226
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H	-1.409451	-1.367425	-7.422459
O	-2.524409	-0.158890	-4.735913
O	-0.838867	0.651406	-5.909275
C	-2.038811	0.579071	-3.571945
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C	1.113894	2.661228	-5.537700
H	0.238876	3.258056	-5.197655
H	1.781734	3.372870	-6.075330
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H	1.158858	1.377522	-3.752678
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H	2.699796	1.433241	-4.641036
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H	0.737481	-1.792118	-7.214664
C	-1.369462	3.266690	-8.100223
H	-1.659707	3.773269	-9.043003
H	-1.065277	4.051137	-7.378532
H	-2.279242	2.796704	-7.681527
H	-3.770375	-1.886742	-5.598758

C	-2.724667	-3.496358	-6.501177
C	-3.199621	-4.362650	-5.494343
C	-1.744003	-3.982529	-7.389465
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C	-1.730080	-6.138570	-6.260888
H	-3.077856	-6.313315	-4.558801
H	-0.483798	-5.648580	-7.974085
H	-1.335327	-7.161037	-6.163843

P

E = -730.258169480856

C	-0.929654	3.395982	1.217870
C	0.578645	3.494349	1.303629
C	1.228018	4.908886	1.304489
C	2.304380	4.775849	0.136735
C	0.873125	3.520456	-1.178612
C	1.494994	4.720624	-1.146817
C	1.280581	2.770200	0.079423
H	3.400117	2.970065	-0.539781
H	1.119246	1.676930	0.082838
H	0.117540	3.178728	-1.899864
H	1.346645	5.565710	-1.834327
H	3.098752	5.542070	0.193250
C	2.719469	3.296124	0.270936
H	3.162788	3.041050	1.254098
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C	-2.932990	4.455814	0.577391
H	-3.429526	4.230253	1.542552
H	-3.248830	5.444966	0.200806
H	-3.208805	3.660200	-0.144169
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C	1.829322	5.383142	2.612484
C	1.798796	6.763764	2.906469
C	2.470885	4.530515	3.535234
C	2.391120	7.277371	4.068420
H	1.294590	7.445983	2.203122
C	3.065521	5.038784	4.700643
H	2.504935	3.445554	3.354024
C	3.030591	6.414633	4.972453
H	2.348204	8.358408	4.272126
H	3.557124	4.349809	5.404546
H	3.494365	6.812245	5.887868

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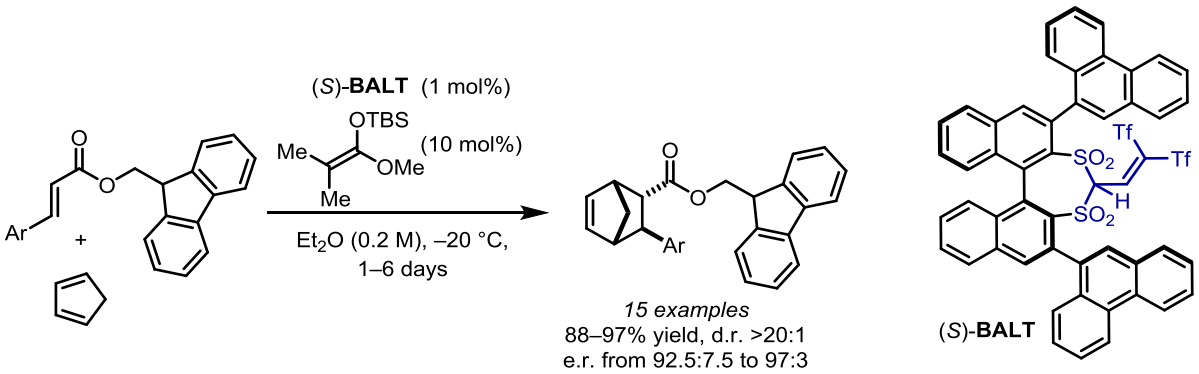
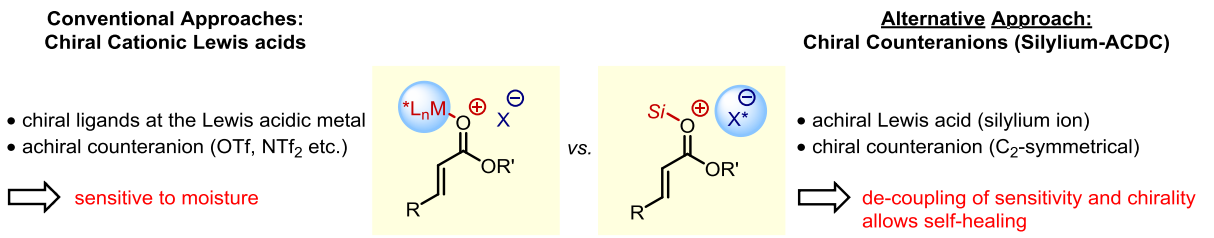
5. Summarizing Discussion

During the course of this work, the activation and application of α,β-unsaturated esters in highly enantioselective transformations has been studied. While this fundamental substrate class is highly abundant, economical and displays diverse synthetic potential, α,β-unsaturated esters, especially cinnamates, demonstrate particularly low reactivity as electrophiles in catalytic asymmetric reactions, despite recent successes in enantioselective catalysis with chiral Brønsted and Lewis acids. Gratifyingly, through the identification of novel and extremely active Lewis acid catalysts, we were able to overcome some of the major synthetic challenges associated with this class of compounds.

Specifically, the design of catalysts with enhanced activity through a highly acidified C–H bond led to the synthesis of binaphthyl-allyl-tetrasulfones (**BALT**).[56] Upon silylation, these chiral C–H acids become extremely active Lewis acid catalysts. With the appropriate catalyst derivative, we could affect a Diels–Alder reaction between typically unreactive cinnamates and cyclopentadiene with very high yields and excellent enantio- and diastereoselectivities using only 1 mol% catalyst loading and a catalytic amount of a silyl ketene acetal (Scheme 5.1).[57] This example represents the first highly enantioselective transformation involving an unambiguous chiral C–H acid as the catalyst. Mechanistic studies indicated the involvement of ionic species and a catalytic cycle based on the concept of asymmetric counteranion-directed catalysis (ACDC). Conceptually, this strategy differs from conventional chiral Lewis acid catalysis typically involving a metal(loid) complex with chiral ligands or substituents (Scheme 5.2). Their activity can often be increased by rendering the complexes cationic and combining them with weakly coordinating, achiral counteranions.



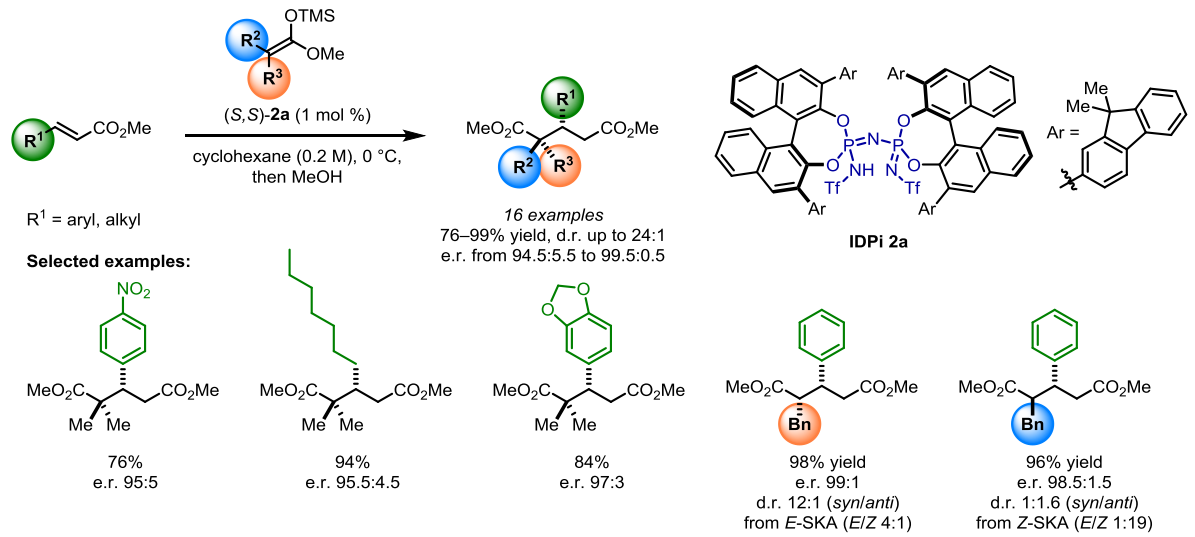
Scheme 5.1 Catalytic asymmetric Diels-Alder reactions of 9-fluorenylmethyl cinnamates catalyzed by a chiral C–H acid.



Scheme 5.2 Conventional approaches and silylium ion–ACDC in enantioselective Lewis acid catalysis.

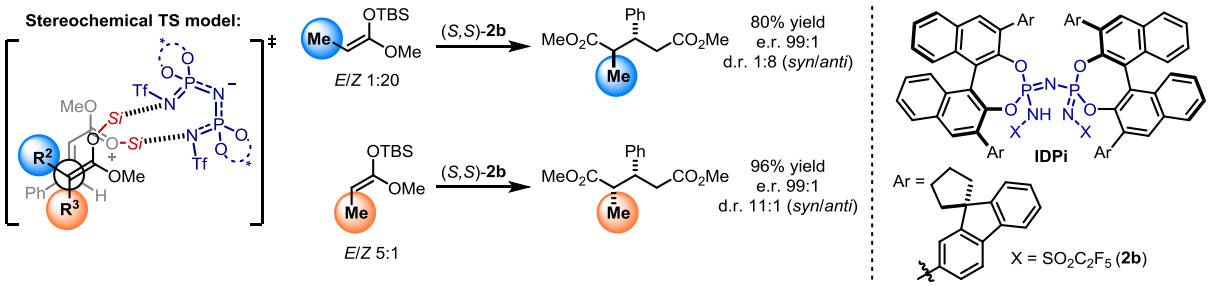
In contrast, an inversion of the chiral entities within the ion pair can be achieved by combining an achiral Lewis acidic silylium ion with a chiral counteranion. The important and unique feature of this silylium ion–ACDC approach arises from the possibility of a repair pathway upon hydrolytic deactivation of the Lewis acid catalyst, enabled by simply adjusting the amount of the silylating reagent. The valuable source of chirality is hydrolytically stable and can only switch between the anionic state (active Lewis acid) and the Brønsted acidic state, thus allowing extremely low catalyst loadings. A limitation of our studies involved the requirement of the 9-fluorenylmethyl ester group, which does not result in electrophilic activation, however was crucial to obtain high enantioselectivities. A subsequent computational study by Wheeler and coworkers concluded that the high stereoselectivities arise from stabilizing π–stacking interactions of the 9-fluorenylmethyl group with the 9-phenanthrenyl substituent.[58]

As we reasoned that such an achiral auxiliary group could ultimately be made obsolete with the right catalyst design, our subsequent efforts in catalyst and reaction development aimed for accessing simple and most readily available α,β-unsaturated methyl esters. These substrates, and cinnamates in particular, have been quantified among the very least electrophilic Michael acceptors by Mayr and coworkers,[28] and very little precedence for their activation has been reported so far. We found that our recently developed confined imidodiphosphorimidate (**IDPi**) acids were exceptionally high performing catalysts for asymmetric Mukaiyama–Michael reactions of silyl ketene acetals (SKA) to α,β-unsaturated methyl esters.[59] Very high enantio- and diastereoselectivities with only 1 mol% of **2a** could be achieved with a large variety of substrates and different nucleophiles (Scheme 5.3). In addition, our chiral catalyst controls the diastereomeric outcome of the reaction depending on the geometry of the SKA applied: *E*-SKAs afford *syn*-products, whereas *Z*-SKAs pre-



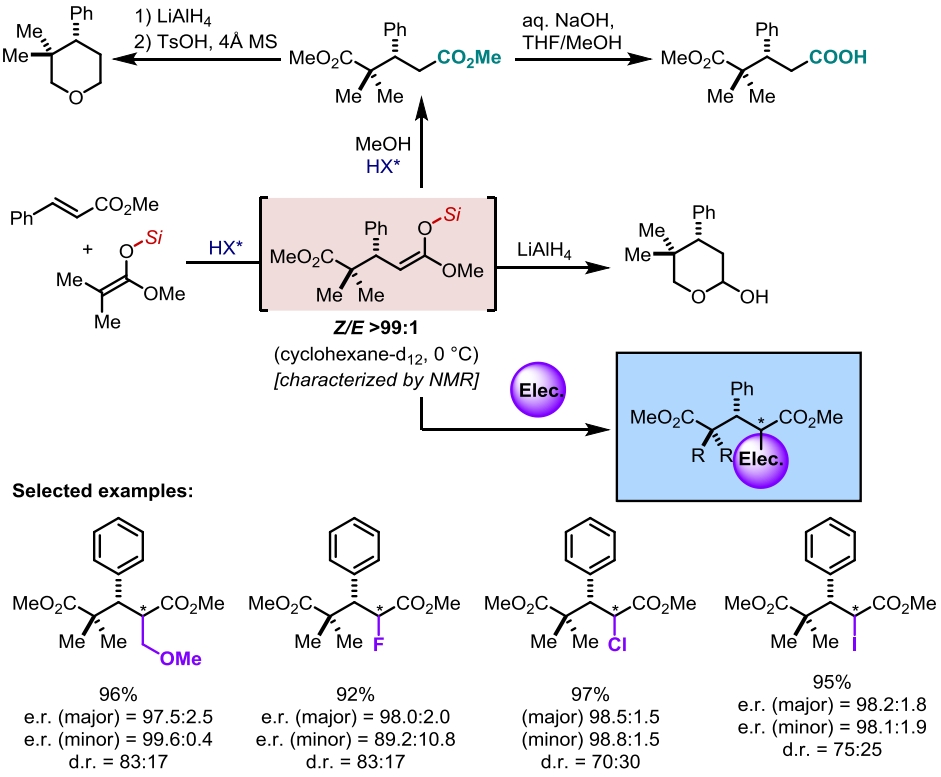
Scheme 5.3 Catalytic asymmetric Mukaiyama–Michael reaction of silyl ketene acetals with α,β-unsaturated methyl esters.

dominantly give the corresponding *anti*-products. Intriguingly, achiral triflimide ($HNTf_2$) as catalyst failed to provide any increased diastereoselectivity with all SKA variants. Further catalyst optimization resulted in IDPi derivative **2b**, which allowed us to obtain very high enantio- and diastereoselectivities for both the *syn*- and the *anti*-stereoisomer with methyl cinnamate as substrate (Scheme 5.4).[60] From these results, we were able to derive a transition state model which rationalizes the stereochemical outcome of the reaction and predicts the stereochemistry for a desired product based on the configuration of the catalyst and the *E*/*Z*-geometry of the SKA. Through mechanistic and kinetic studies, we identified and characterized an open-chain silyl ketene acetal intermediate as the initial reaction product with *Z*/*E* ratio of >99:1 (Scheme 5.5). Direct utilization of this intermediate in a LAH reduction allowed selective differentiating the two ester groups, while treatment of the Mukaiyama–Michael product with aq. NaOH resulted in selective saponification of the less



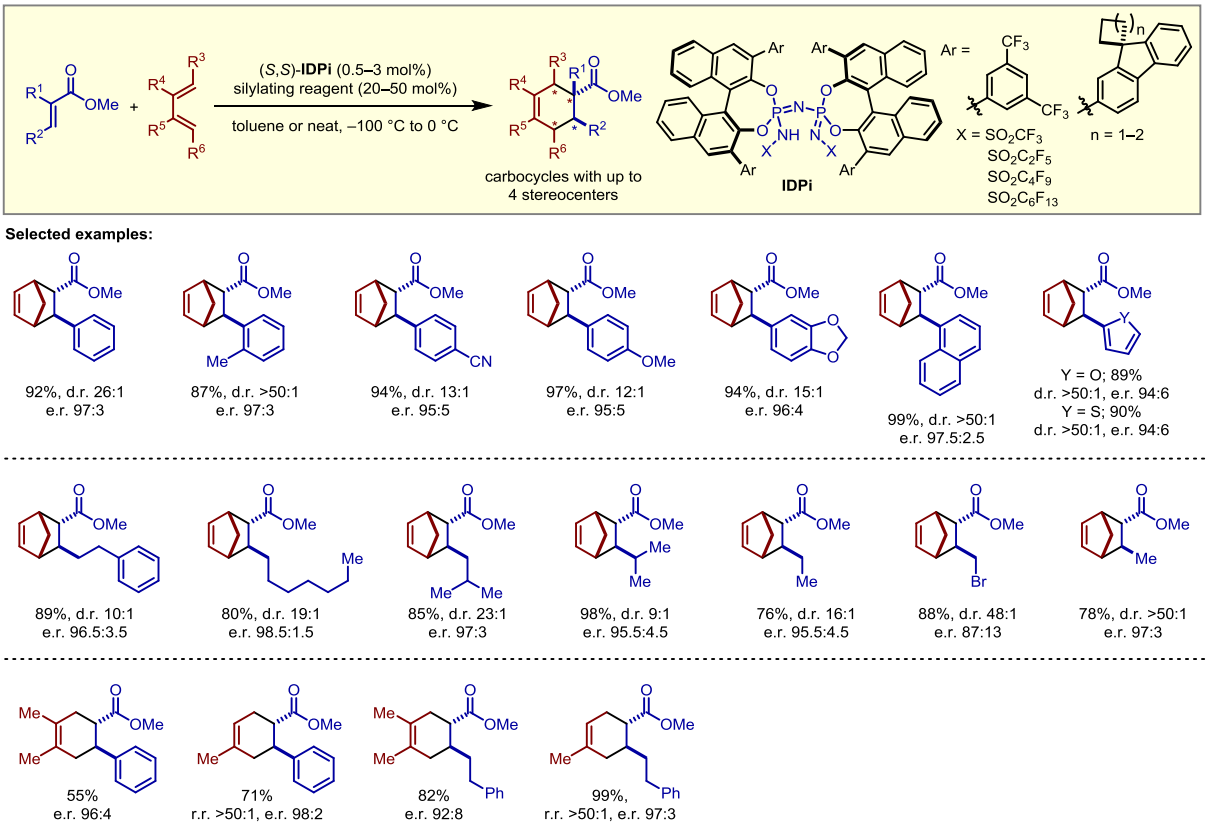
Scheme 5.4 Stereochemical model for the enantio- and diastereocontrol by the catalyst and the *E*/*Z*-geometry of the SKA.

sterically hindered ester group. Together with Master student Vanda Daskova, we further envisioned to employ the silyl ketene acetal intermediate as a nucleophile in a subsequent reaction with appropriate electrophiles. Indeed, we found that such tandem Mukaiyama–Michael reactions could successfully be conducted with various halogenating agents and carbon electrophiles to afford α-functionalized products with excellent enantioselectivities and promising diastereoselectivities.[60]



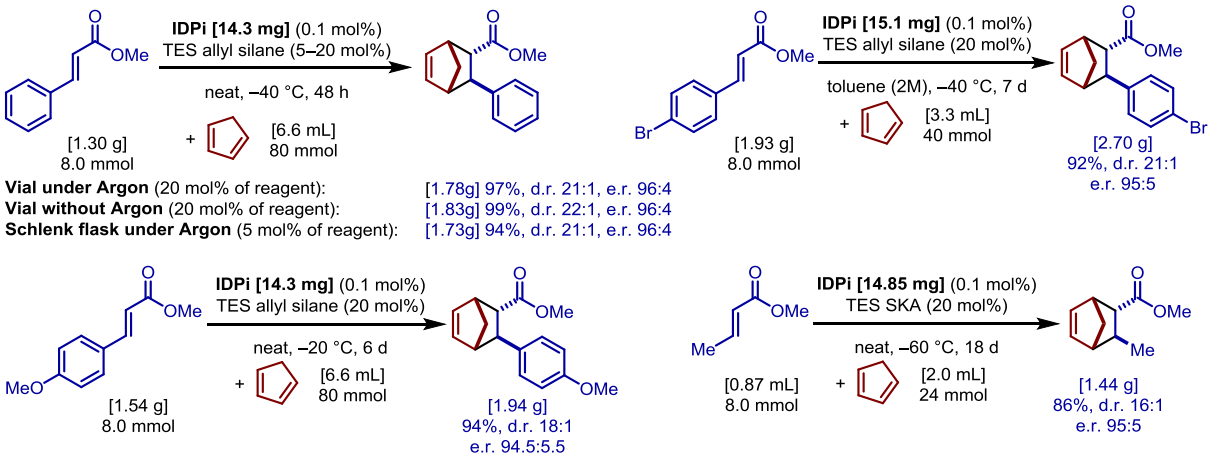
Scheme 5.5 Selective transformations of the silyl ketene acetal reaction intermediate and tandem α-functionalizations.

Towards a general Diels–Alder methodology for simple α,β-unsaturated methyl esters as dienophiles, we could identify two distinct families of IDPi catalysts for very high enantio- and diastereoselectivities, each of which giving optimal results in combination with a different silyl group (Scheme 5.6).[61] 3,5-trifluoromethylphenyl substituted catalyst performed optimal with the triethylsilyl (TES) group, while 3-fluorene derivatives at the 3,3'-position of the BINOL backbone interacted best with the triisopropylsilyl (TIPS) group. This flexibility in our catalytic system and the optional fine-tuning allowed us to employ an extraordinary broad scope of both 3-aryl- and 3-alkyl-substituted α,β-unsaturated methyl esters as substrates. Diels–Alder adducts with cyclopentadiene were isolated in excellent yields, enantio- and diastereoselectivities using only 0.5–3 mol% of catalyst. We also tested



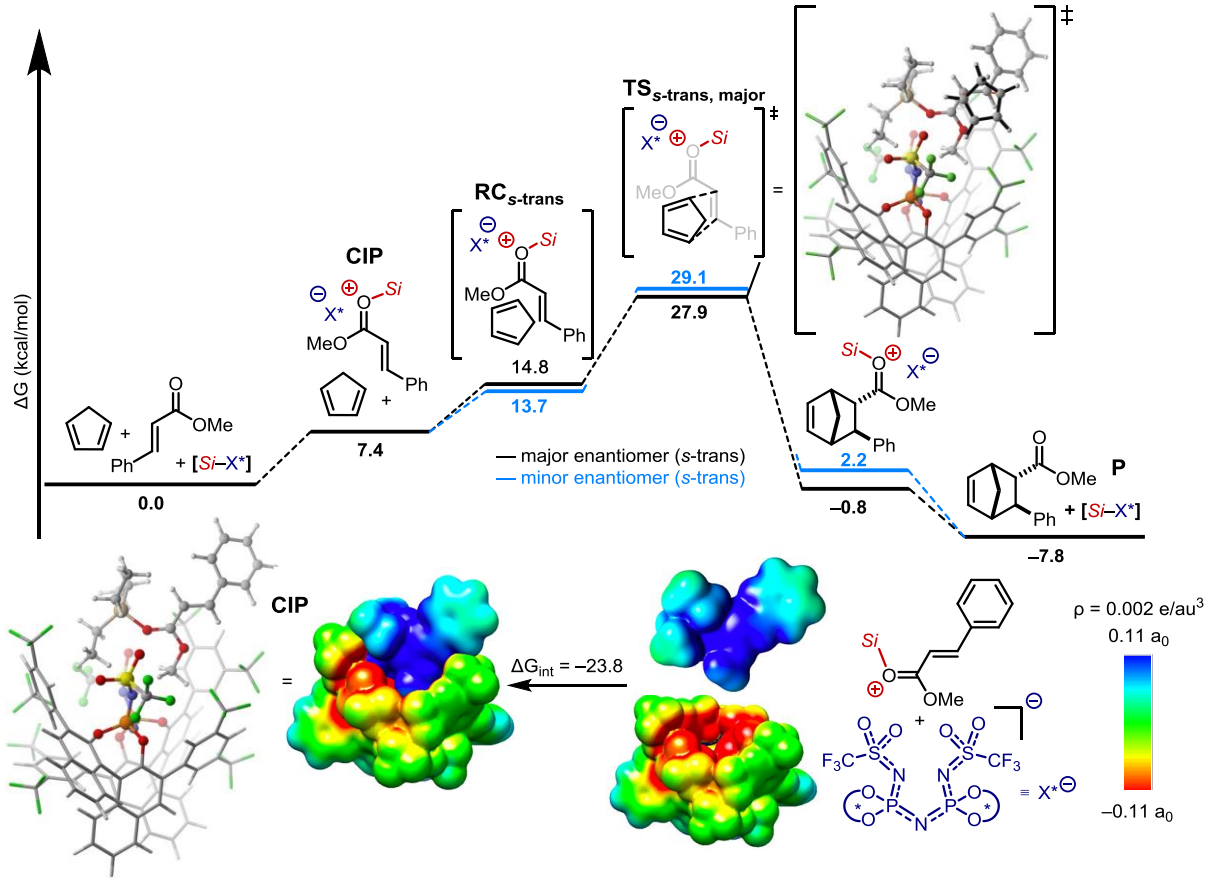
Scheme 5.6 A general catalytic asymmetric Diels–Alder methodology of α,β-unsaturated methyl esters and different dienes.

less reactive dienes in comparison to cyclopentadiene (k_{rel} = 1350), such as 2,3-dimethylbutadiene (k_{rel} = 4.9) and isoprene (k_{rel} = 2.3), as referenced to butadiene (k_{rel} = 1) by Sauer et al..[62] Under optimized conditions, high yield, regio- and enantioselectivities were obtained for the corresponding products. In order to demonstrate practical applicability, catalytic asymmetric Diels–Alder reactions with four different dienophiles were performed on a preparative scale and even reduced catalyst loadings of 0.1 mol% giving near quantitative yields and very high enantioselectivities (Scheme 5.7). We found that our catalytic system even tolerates neat reaction conditions with the diene acting as the solvent and observed only low levels of polymerization. Another practical aspect of this methodology arises from the self-drying properties of the reaction conditions, which allowed us to conduct the reaction in a standard vial without inert gas or dry solvents. The reaction profile was investigated in detail for methyl cinnamate and cyclopentadiene at the DLPNO-CCSD(T)/def2-TZVP + C-PCM(toluene) // PBE-D3 (BJ)/def2-SVP level of theory in cooperation with the Neese research group. Transfer of the silyl group from the activated catalyst to the ester substrate as the first step was calculated to be endothermic (ΔG = 7.4 kcal/mol) and



Scheme 5.7 Gram-scale experiments with four different substrates and reduced catalyst loadings.

the corresponding *s*-trans conformation was found to be more stable over the *s*-cis conformation. Detailed analysis of the resulting chiral ion pair (CIP) revealed a strong geometrical match between the chiral counteranion and silylated methyl cinnamate



Scheme 5.8 Computational studies on the Diels–Alder reaction profile and the interaction within the chiral ion pair (CIP).

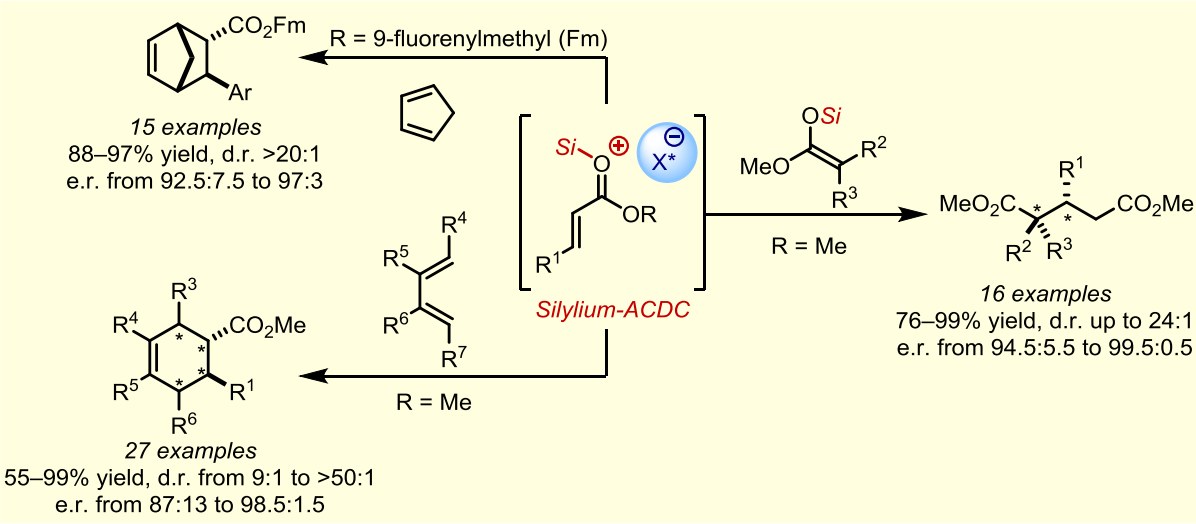
accounting for the obtained high enantioselectivities and the high tolerance at the 3-position of the substrate. Calculation of the transition states leading to both enantiomers featuring the structure of the chiral ion pair as the starting point resulted in a theoretical enantiomeric ratio (e.r. 93:7; $\Delta\Delta G^{\ddagger}$ = 1.2 kcal/mol), which was in good agreement with the experimental data.

6. Summary & Outlook

By addressing the first objective of the present work, silylium-ACDC enabled the activation of various α,β-unsaturated esters, among them unreactive cinnamates, in combination with appropriately strong chiral Brønsted pre-catalysts. Through the first example of highly enantioselective catalysis with a chiral C–H acid previously inaccessible Diels–Alder adducts derived from cinnamates could be obtained. The identification of 3-fluorenyl-derived IDPi's as privileged catalyst family of catalysts for efficient enantiodiscrimination of α,β-unsaturated methyl esters led to a highly enantio- and diastereoselective Mukaiyama–Michael reaction with SKAs and a second-generation Diels–Alder methodology.

The expansion of silylium-ACDC to non-silicon transfer reactions (catalytic in silicon) was successfully achieved for both developed Diels–Alder methodologies while the ability of self-healing was maintained and side-reactions were excluded.

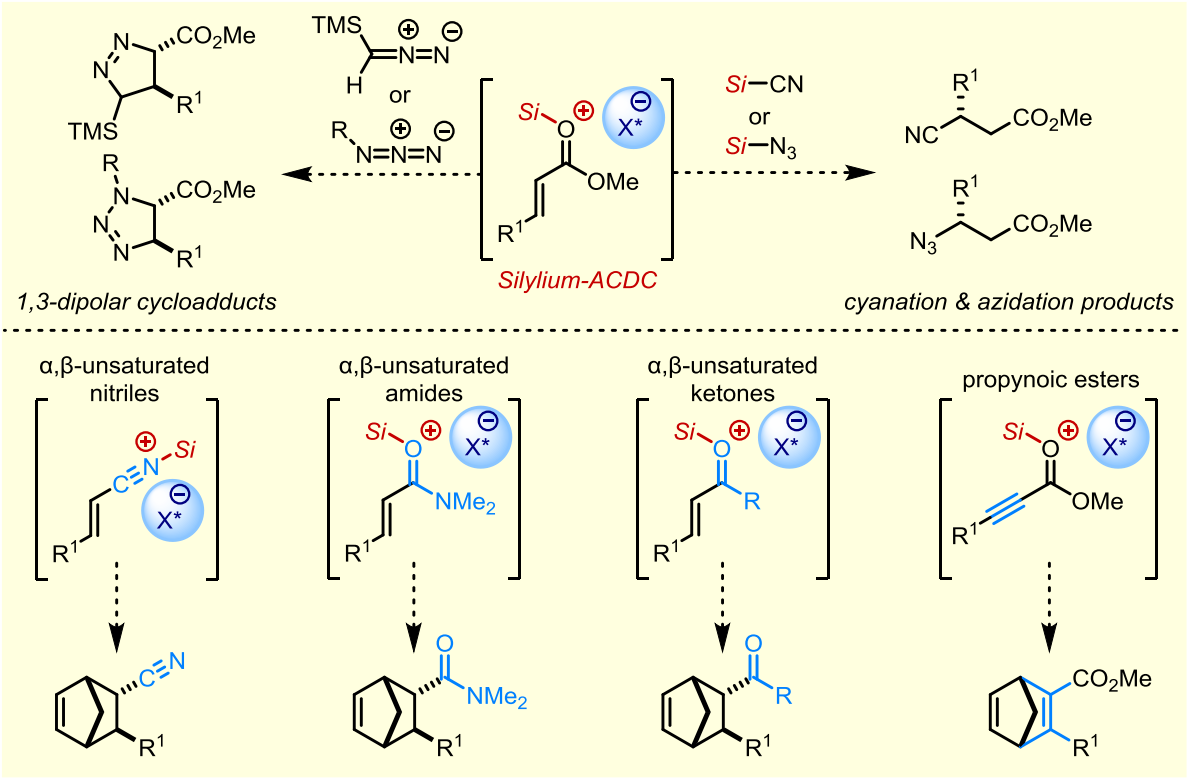
The severe limitation of high catalyst loadings for asymmetric Diels–Alder reactions was fully overcome via self-healing and the extremely high activity of the employed acids. With catalyst loadings as low as 0.1 mol%, it can be argued that the most efficient catalyst system for asymmetric Diels–Alder reactions to date has been introduced. Intriguingly, the reaction conditions still tolerate a broad variety of functional groups and residual amounts of moisture. In addition, the scope of accessible Diels–Alder products has significantly been expanded for both dienophiles and dienes. Gram-scale experiments under neat conditions indicated the extraordinary potential for future large-scale applications.



Scheme 6.1 Summary of the developed asymmetric catalytic methodology applying silylium-ACDC with α,β-unsaturated esters.

Continued efforts in the development of catalytic asymmetric Diels–Alder methodology should comprise the expansion of the substrate scope to methyl acrylate and derivatives with different dienes, the expansion of the diene scope to silylated dienes, the investigation of high-pressure conditions on stereoselectivity and reaction rate, further scale-up (up to kilogram scale) and catalyst recycling to demonstrate industrial applicability, as well as the enantioselective synthesis of attractive target molecules, such as norbornene-derived pharmaceuticals[63-68] and natural products of the dihydrochalcone family.[69-72]

Further, efficient enantiodiscrimination of α,β-unsaturated methyl esters by silylated IDPi catalysts could be exploited for other catalytic asymmetric pericyclic reactions, such as 1,3-dipolar cycloaddition reactions with substituted azides or diazomethane derivatives as 1,3-dipols. Catalytic asymmetric conjugate addition reactions of silylated nucleophiles, such as silylazides and silylcyanides, hold great promise for the asymmetric synthesis of pharmaceutically relevant structures through the introduction of nitrogen-containing groups. In addition, the concept of silylium-ACDC catalytic in silicon could be expanded to other attractive, though rarely applied substrate classes, such as α,β-unsaturated nitriles, amides, ketones and propynoic esters for future catalytic asymmetric Diels–Alder reactions.



Scheme 6.2 Outlook of further applications of silylium-ACDC with α,β-unsaturated methyl esters and other potential substrate classes.

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8. Appendix

8.1 Eigene Beiträge an den zu Grunde liegenden Veröffentlichungen/Own contribution to the incorporated publications

1) “Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid” T. Gatzenmeier, M. van Gemmeren, Y. Xie, D. Höfler, M. Leutzsch, B. List, *Science* **2016**, *351*, 949−952.

Eigenanteile: Projektplanung, hauptsächlicher Anteil an der Katalysatoroptimierung, Design, Entwicklung und Optimierung der Diels–Alder Reaktion, überwiegender Anteil an der Explorierung des Substratspektrums, Planung und Koordinierung mechanistischer NMR-Studien, anteiliger Beitrag am Verfassen des Manuskripts.

2) “The Catalytic Asymmetric Mukaiyama–Michael Reaction of Silyl Ketene Acetals with α,β-Unsaturated Methyl Esters” T. Gatzenmeier, P. S. J. Kaib, J. B. Lingnau, R. Goddard, B. List, *Angew. Chem. Int. Ed.* **2018**, *57*, 2464−2468.

Eigenanteile: Projektplanung, Design, Entwicklung und Optimierung der Mukaiyama–Michael Reaktion, Explorierung des Substratspektrums, Planung und Koordinierung mechanistischer NMR-Studien, hauptsächlicher Anteil am Verfassen des Manuskripts.

3) *“*A Scalable and Highly Diastereo- and Enantioselective Catalytic Diels−Alder Reaction of α,β-Unsaturated Methyl Esters *”*; T. Gatzenmeier, M. Turberg, D. Yepes, Y. Xie, F. Neese, G. Bistoni, B. List, *Manuskript in Begutachtung.*

Eigenanteile: Projektplanung, hauptsächlicher Anteil an der Katalysatoroptimierung, Design, Entwicklung und Optimierung der Diels–Alder Reaktion, überwiegender Anteil an der Explorierung des Substratspektrums, Durchführung der Skalierungsexperimente, Planung und Koordinierung mechanistischer NMR- und theoretischer Studien, hauptsächlicher Anteil am Verfassen des Manuskripts.

8.2. Erklärung/Declaration

“Ich versichere, dass ich die von mir vorgelegte Dissertation selbständig angefertigt, die benutzten Quellen und Hilfsmittel vollständig angegeben und die Stellen der Arbeit – einschließlich Tabellen, Karten und Abbildungen – , die anderen Werken im Wortlaut oder dem Sinn nach entnommen sind, in jedem Einzelfall als Entlehnung kenntlich gemacht habe; dass diese Dissertation noch keiner anderen Fakultät oder Universität zur Prüfung vorgelegen hat; dass sie – abgesehen von unten angegebenen Teilpublikationen – noch nicht veröffentlicht worden ist sowie, dass ich eine solche Veröffentlichung vor Abschluss des Promotionsverfahrens nicht vornehmen werde. Die Bestimmungen der Promotionsordnung sind mir bekannt. Die von mir vorgelegte Dissertation ist von Herrn Professor Dr. Benjamin List betreut worden.“

Mülheim an der Ruhr, September 2018

_____

(Tim Gatzenmeier)

Bisher sind folgende Teilpublikationen veröffentlich worden:

1) “Asymmetric Lewis acid organocatalysis of the Diels–Alder reaction by a silylated C–H acid” T. Gatzenmeier, M. van Gemmeren, Y. Xie, D. Höfler, M. Leutzsch, B. List, *Science* **2016**, *351*, 949−952.

2) “The Catalytic Asymmetric Mukaiyama–Michael Reaction of Silyl Ketene Acetals with α,β-Unsaturated Methyl Esters” T. Gatzenmeier, P. S. J. Kaib, J. B. Lingnau, R. Goddard, B. List, *Angew. Chem. Int. Ed.* **2018**, *57*, 2464−2468.

Eine weitere Teilpublikation befindet sich zum Zeitpunkt der Abgabe der Dissertation im Begutachtungsprozess:

3) *“*A Scalable and Highly Diastereo- and Enantioselective Catalytic Diels−Alder Reaction of α,β-Unsaturated Methyl Esters *”*; T. Gatzenmeier, M. Turberg, D. Yepes, Y. Xie, F. Neese, G. Bistoni, B. List, *Manuskript in Begutachtung.*

8.3. Lebenslauf/CV

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