Giving a Second Chance to Ir/sulfoximine-based Catalysts for the Asymmetric Hydrogenation of Olefins Containing Poorly Coordinative Groups

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ABSTRACT: This work identifies a family of Ir/phosphite-sulfoximines catalysts that has been successfully used in the asymmetric hydrogenation of olefins with poorly coordinative or non-coordinative groups. In comparison with analogue Ir/phosphine-sulfoximines catalysts previously reported, the presence of a phosphite group extended the range of olefins than can be efficiently hydrogenated. High enantioselectivities, comparable to the best ones reported, have been achieved for a wide range of olefins containing relevant poorly coordinative groups such as α,β-unsaturated enones, esters, lactones and lactams as well as alkenylboronic esters.

Asymmetric hydrogenation (AH) is one of the most popular and straightforward catalyzed transformations for the preparation of chiral compounds. It has a perfect atom economy and a high functional group tolerance, which makes it very attractive for preparing complex chiral molecules (i.e. drugs, crop-protecting products …).[1] The development of chiral analogues of Crabtree catalysts opened the possibility of hydrogenating olefins with poorly coordinative groups or non-coordinative groups,[2] which is not feasible with classical Rh and Ru diphosphine catalysts.[3] Since then, many efforts have been devoted to extend the substrate scope by developing new catalyst types.[4] Bolm's group early found that Ir-catalysts with phosphine-sulfoximine ligands (Figure 1a) can efficiently hydrogenate α,β-unsaturated ketones[5] and non-olefinic substrates such as quinolines[6] and imines[7]. This important finding opened a direct, atom efficient path for preparing valuable optically pure ketones, whose synthesis up to then mainly relied on non-catalyzed methods with a limited substrate scope.[8] Nevertheless, the efficiency of those Ir/phosphine-sulfoximine catalysts depended highly on the substitution pattern of the enone and the steric constrains of the olefin substituents.[5a,b] Excellent enantioselectivities were only obtained for β,β'-disubstituted enones containing two large substituents (Figure 1b). This may be a reason why researchers have overlooked the use of sulfoximines-based ligands for the AH of olefins containing poorly or non-coordinative groups despite the high enantioselectivities achieved in other asymmetric transformations[9].
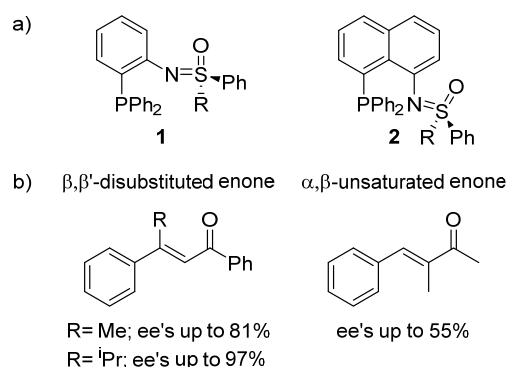

Figure 1. (a) Representative phosphine-sulfoximine ligands developed by Bolm's group. (b) Summary of the enantioselectivities achieved in the asymmetric hydrogenation of representative enones (data from refs. 5a,b).

Our group has contributed to the Ir-hydrogenation of olefins containing poorly or non-coordinative groups with new types of efficient P-N ligands. We have shown that biaryl phosphite groups improve the ligand's efficiency and substrate scope.[10] Here, we disclose whether the replacement of the phosphine moiety by a more adaptive biaryl phosphite group[11] can overcome the substrate scope limitation of Ir/phosphine-sulfoximines. For this purpose we report the synthesis of phosphite-sulfoximines ligands **L1**–**L3a**–**c** (Figure 2) with different biaryl phosphite groups (**a**–**c**). These new ligands are based on already reported phosphine-sulfoximines **1** and **2**.[5-7] Thus, ligands **L1** differ from **1** by having biaryl phosphite groups instead of a diphenylphosphine moiety. Ligands **L2** differ from **L1** by having bulky tBu groups in the Ph backbone ring. Ligands **L3** are a more rigid version of **L1** and **L2**.
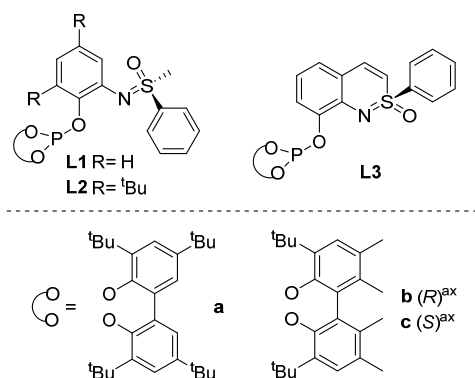
Figure 2. Phosphite-sulfoximine ligands **L1**–**L3a**–**c**.

Ir-catalyst precursors [Ir(cod)(**L1**–**L3a**–**c**)]BAr_F were synthesized in a few steps from the corresponding commercially available 1-bromo-phenols **3**–**5** (Scheme 1). Protection of the hydroxyl group with methoxymethyl chloride (MOMCl; step i), subsequent coupling with the enantiopure sulfoximine **9** (using either Cu/DMEDA[12] for **6** and **7** or Pd/BINAP[13] for **8**; steps ii and iii, respectively) and deprotection with HCl (step iv) provided hydroxyl-sulfoximines **13**–**15**. Compounds **13**–**15** were then converted into the corresponding phosphite-sulfoximines by treatment with the desired phosphorochloridite (ClP(OR)₂; (OR)₂= **a**–**c**; step v) under basic conditions.[14] Finally, treatment of the appropriate phosphite-sulfoximine ligand (**L1**–**L3a**–**c**) with [Ir(μ–Cl)(cod)]₂ in dichloromethane at 40 °C for 1 h, followed by insitu Cl⁻/BAr_F⁻ counterion exchange with sodium tetrakis[3,5-bis(trifluoromethyl)-phenyl]borate (NaBAr_F; 1 equiv) in water gave access to the desired [Ir(cod)(**L1**–**L3a**–**c**)]BAr_F catalyst precursors (step vi). They were obtained as air-stable orange solids. The HRMS-ESI spectra show the heaviest ions at m/z which correspond to the loss of the BAr_F anion from the parent molecular species. The spectral ¹H, ¹³C and ³¹P assignments, made using ¹H–¹H and ¹³C–¹H correlation measurements, were as expected for these C_1-symmetric iridium complexes. It should be noted, that for complexes containing ligands **L1** and **L2**, two species in solution were detected. The ²D DOSY

³¹P{¹H} NMR experiments showed that these two species have the same diffusion coefficient, which indicates that they must be isomers. This is likely due to the presence of two different stable conformations for the 6-membered chelate ring, since only a single isomer is formed for complexes containing ligands **L3** which has a more rigid backbone.

In a first set of experiments we tested [Ir(cod)(**L1**–**L3a**–**c**)]BAr_F catalyst precursors in the asymmetric hydrogenation of two benchmark α,β-unsaturated ketones with different substitution patterns, β,β'-disubstiued substrate 1,3-diphenylbut-2-en-1-one **S1** and α,β substituted 3-methyl-4-phenylbut-3-en-2-one **S2**. These substrates were selected because the previous Ir/sulfoximine-based catalysts **1**–**2** provided suboptimal enantioselectivities (Figure 1b).[5a,b] Improving those results we obtained higher enantioselectivities (>91% ee) for both substrates using the new Ir/phosphite-sulfoximine catalysts (Table 1; entries 2 and 6 vs. 7).

Table 1. Asymmetric hydrogenation of S1 and S2 using [Ir(cod)(L1–L3a–c)]BAr_F catalyst precursors[a]

		S1		S2	
Entry	L	% Conv[b]	% ee[c]	% Conv[b]	% ee[c]
1	**L1a**	100	70 (R)	85	13 (S)
2	**L1b**	100 (96)	91 (R)	90 (85)	76 (S)
3	**L1c**	100	7 (S)	80	57 (R)
4	**L2a**	70	61 (R)	24	11 (S)
5	**L3a**	89	17 (S)	100	73 (R)
6	**L3b**	100 (94)	30 (S)	100 (97)	96 (R)
7	**2**[d]	100	81 (S)[e]	100	55 (S)[f]

[a] Reactions conditions: 1 mol% Ir-catalyst precursor, substrate (0.5 mmol), DCM, rt for 18 h, H₂ (50 bar). [b] Conversions measured by ¹H-NMR. Isolated yields in parenthesis. [c] Enantioselectivies measured by chiral HPLC. [d] R=ⁱBu. [e] Data from ref 5a. [f] Data from ref 5b.

Scheme 1. Synthesis of [Ir(cod)(L1–L3a–c)]BAr_F catalyst precursors.
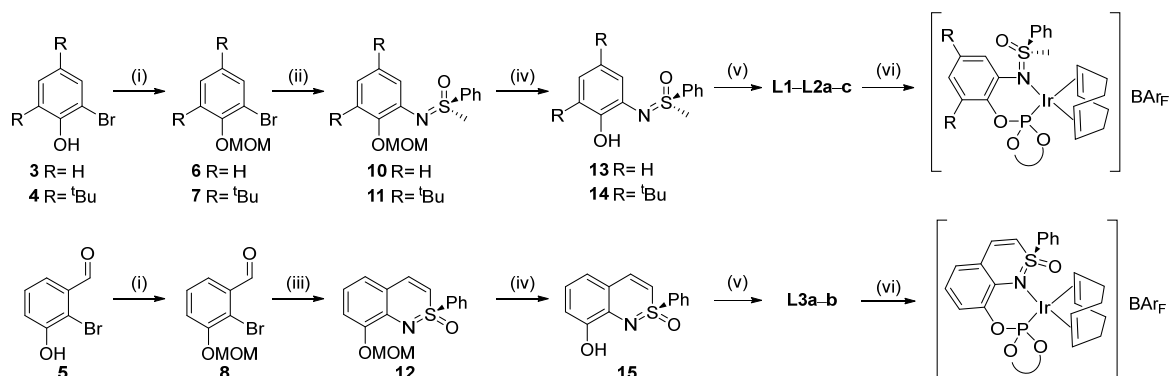
(i) MOMCl, NEt₃, THF, rt, 2-16 h; (ii) (S)-S-methyl-S-phenylsulfoximine (**9**), CuI, DMEDA, NaI, Cs₂CO₃, toluene, 110 °C, 40-80 h; (iii) **9**, Pd(OAc)₂, rac-BINAP, Cs₂CO₃, toluene, reflux, 48 h; (iv) ⁱPrOH/HCl/THF (2:1:1), rt, 3 h; (v) ClP(OR)₂; (OR)₂= **a**–**c**, Py, toluene, rt, 18 h. (vi) [Ir(μ-Cl)(cod)]₂, DCM, reflux, 1 h then NaBAr_F, H₂O, rt, 30 min.

Results also indicated that, as expected, each substrate requires a different ligand to maximize the enantioselectivity. Thus, while for the β,β'-disubstitued substrate **S1** enantioselectivities were best with the more flexible Ir-**L1b** catalyst, the more rigid Ir-**L3b** catalyst was better for substrate **S2**. Interestingly, for both substrate types the presence of a chiral *R*-biaryl phosphite moiety (**b**) in the ligand is needed to maximize enantioselectivities (e.g. entries 2 vs 3). This suggests a cooperative effect between the configurations of the sulfoximine and the phosphite groups.

We next studied the potential of the Ir-**L1b** and Ir-**L3b** catalytic systems to hydrogenate other enones (Figure 3). We found out that Ir-**L1b** is also able to hydrogenate β,β'-disubstituted enones containing two large substituents such as the 4-methyl-1,3-diphenylpent-2-en-1-one **S3** in high enantioselectivities. This overcome the previously observed dependence of the steric constrains of the β-substituents on enantioselectivity using catalysts **1** and **2** (Figure 1b). Interestingly, Ir-**L3b** was also able to hydrogenate other α,β-unsaturated enones (**S4–S9**) in high ee's regardless the different decorations at the phenyl group and the different substituents at the ketonic group.
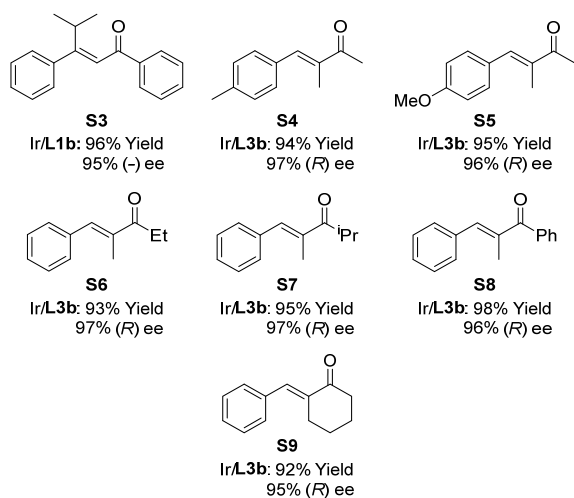

Figure 3. Asymmetric hydrogenation of α,β-unsaturated enones **S3–S9**. Typical reaction conditions: 1 mol% Ir-catalyst precursor, substrate (0.5 mmol), DCM, rt for 18 h, H_2 (50 bar). Full conversions were achieved in all cases.

Finally, we tested whether the high enantioselectivities can be maintained for olefins containing other relevant poorly coordinative groups than a ketone (Figure 4). We found that high enantioselectivities can also be achieved for a range of β,β'-disubstituted unsaturated esters (substrates **S10–S17**), α,β-unsaturated lactones (**S18–S19**) and lactams (**S20–S21**) and alkenylboronic ester **S22**. The efficient hydrogenation of olefins containing such a variety of functional groups is interesting because they are highly versatile building blocks for the synthesis of complex chiral molecules such as fragrances, natural products and pharmaceuticals. Interestingly, we also found that Ir-**L1b** is able to hydrogenate tri- and disubstituted olefins without an extra functional group (substrates **S23** and **S24**) in ee's as high as 93%.
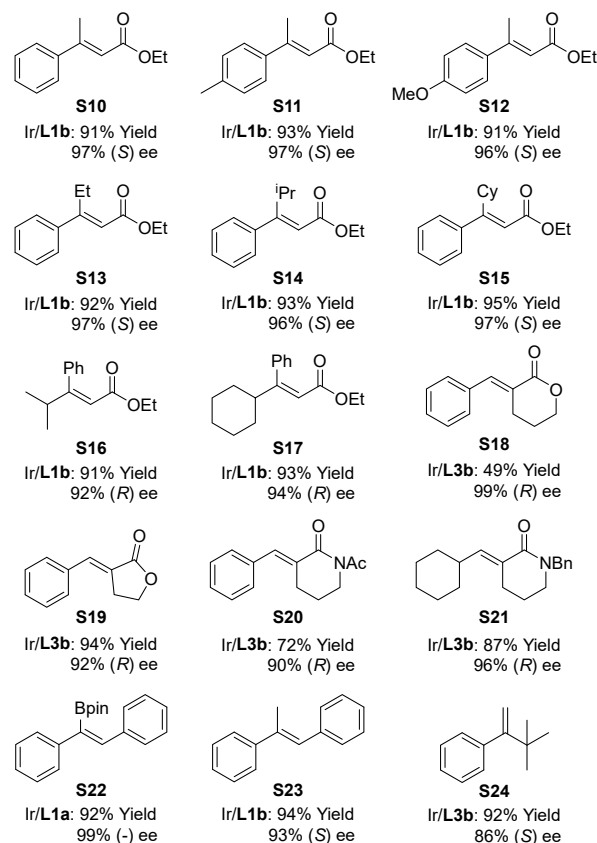

Figure 4. Asymmetric hydrogenation of α,β-unsaturated esters, lactones and lactams, alkenylboronic ester and unfunctionalized olefins **S10–S24**. Typical reaction conditions: 1 mol% Ir-catalyst precursor, substrate (0.5 mmol), DCM, rt for 18 h, H_2 (50 bar for **S10–S23** and 1 bar for **S24**). Full conversions were obtained in all cases (except for **S18** and **S20** with 56% conv and 81% conv, respectively)

In summary, we have demonstrated that sulfoximines, which are useful in other asymmetric transformations and in others areas such as medicinal and crop protecting chemistry,[15] can also be useful when combined with a biaryl phosphite group as ligands for the AH of the so-called minimally functionalized olefins. High enantioselectivities, comparable to the best ones reported,[16] have been therefore achieved in the hydrogenation of a wide range of olefins containing relevant poorly coordinative groups such as α,β-unsaturated enones, esters, lactones and lactams as well as alkenylboronic esters.

EXPERIMENTAL SECTION

General Methods. All reactions were carried out using standard Schlenk techniques under an argon atmosphere. Solvents were purified and dried by standard procedures. Hydroxyl-sulfoximine **15**[13] and sulfoximine **9**[12] were prepared as previously described. Phosphorochloridites are easily prepared in one step from the corresponding biaryls.[17] ^1H, ^{13}C, and ^{31}P NMR spectra were recorded using a 400 MHz spectrometer. Chemical shifts are relative to that of SiMe_4 (^1H and ^{13}C) as internal standard or H_3PO_4 (^{31}P) as external standard. ^1H, ^{13}C, and ^{31}P assignments were made on the basis of ^1H-^1H gCOSY, ^1H-^{13}C gHSQC and ^1H-^{31}P gHMBC experiments. Substrates **S2**,[18] **S3**,[5a] **S4–S8**,[5b] **S9**,[19] **S10–S12**,[20] **S13–S17**,[21] **S18–S21**[22] and **S24**[23] were prepared following the reported procedures, while

substrates **S1**, **S22** and **S23** were commercially available and used as received.

Preparation of compounds 6–7. A flame dried Schlenk flushed with argon was charged with compounds **3** or **4** (10 mmol, 1 eq.) which was dissolved in dry THF (25 mL) along with dry triethylamine (49.6 mmol, 6.8 mL, 5 eq.), and a stir bar. MOMCl (20 mmol, 1.5 mL, 2 eq.) was added dropwise resulting in the formation of a white precipitate. The reaction was allowed to stir during 4 h for compound **3**, and 16 h for compound **4**. The reaction was taken up in water (20 mL) and extracted with ethyl acetate (3 x 20 mL). The combined organic layers were washed with brine, dried with MgSO$_4$ and concentrated *in vacuo*. Purification by flash chromatography (94% (petroleum ether): 6% (ethyl acetate) for **6** and 100% (petroleum ether) for **7**).

1-Bromo-2-(methoxymethoxy)benzene (6). Yield: 1.73 g (80%). ^{1}H NMR (400 MHz, CDCl$_3$): δ= 3.52 (s, 3H, CH$_3$), 5.24 (s, 2H, CH$_2$), 6.88 (ddd, 1H, CH=, $^3J_{H-H}$= 7.9 Hz, $^3J_{H-H}$= 7.4 Hz, $^4J_{H-H}$= 1.5 Hz), 7.15 (dd, 1H, CH=, $^3J_{H-H}$= 8.3 Hz, $^4J_{H-H}$= 1.5 Hz), 7.24 (ddd, 1H, CH=, $^3J_{H-H}$= 8.3 Hz, $^3J_{H-H}$= 7.4 Hz, $^4J_{H-H}$= 1.6 Hz), 7.55 (dd, 1H, CH=, $^3J_{H-H}$= 7.9 Hz, $^4J_{H-H}$= 1.6 Hz). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 56.4 (CH$_3$), 95.0 (CH$_2$), 112.9 (C), 116.2 (CH=), 123.1 (CH=), 128.5 (CH=), 133.4 (CH=), 153.8 (C).

1-Bromo-3,5-di-tert-butyl-2-(methoxymethoxy)benzene (7). Yield: 1.97 g (60%). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.29 (s, 9H, CH$_3$, ^{t}Bu), 1.43 (s, 9H, CH$_3$, ^{t}Bu), 3.69 (s, 3H, CH$_3$), 5.21 (s, 2H, CH$_2$), 7.30 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz), 7.39 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 30.8 (CH$_3$, ^{t}Bu), 31.3 (CH$_3$, ^{t}Bu), 34.6 (C, ^{t}Bu), 35.9 (C, ^{t}Bu), 57.7 (CH$_3$), 99.3 (CH$_2$), 117.5 (C), 123.9 (CH=), 128.7 (CH=), 144.4 (CH=), 147.5 (CH=), 150.5 (C).

Preparation of compounds 10–11. Under an argon atmosphere a dry flamed Schlenk flask was charged with the MOM-protected hydroxyl-aryl bromide **6** or **7** (2.0 equiv, 5.0 mmol), CuI (0.1 equiv, 0.25 mmol, 47.5 mg), DMEDA (0.2 equiv, 0.5 mmol, 44.1 mg) and NaI (4.0 equiv, 10 mmol, 1.5 g). Then, degassed toluene (50 mL) was added, and the resulting heterogeneous mixture was heated to 110 °C for 20 h for **6** and 40 h for **7**. Then, sulfoximine **9** (1.0 equiv, 2.5 mmol, 0.4 g) and Cs$_2$CO$_3$ (2.5 equiv, 12.5 mmol, 4.0 g) were added and the mixture was kept at 110 °C for additional 20 h for **6**, and 40 h for **7**. Subsequently, the mixture was cooled to room temperature, and extracted with dichloromethane and an aqueous ammonia solution. The combined organic extracts were dried with MgSO$_4$, filtered and concentrated under reduced pressure. Purification by column chromatography on silica gel with 100% ethyl acetate afforded compounds **10–11**.

(S)-((2-(Methoxymethoxy)phenyl)imino)(methyl)(phenyl)-λ^6-sulfanone (10). Yield: 619.1 mg (85%). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 3.21 (s, 3H, CH$_3$), 3.48 (s, 3H, CH$_3$), 5.16 (d, 2H, CH$_2$, $^2J_{H-H}$= 6.6 Hz), 5.21 (d, 2H, CH$_2$, $^2J_{H-H}$= 6.6 Hz), 6.75 (td, 1H, CH=, $^3J_{H-H}$= 7.6 Hz, $^4J_{H-H}$= 1.5 Hz), 6.82 (td, 1H, CH=, $^3J_{H-H}$= 7.6 Hz, $^4J_{H-H}$= 1.7 Hz), 7.03 (dd, 1H, CH=, $^3J_{H-H}$= 8.0 Hz, $^4J_{H-H}$= 1.5 Hz), 7.08 (dd, 1H, CH=, $^3J_{H-H}$= 7.8 Hz, $^4J_{H-H}$= 1.7 Hz), 7.45-7.68 (m, 3H, CH=), 8.00 (dd, 2H, CH=, $^3J_{H-H}$= 8.4 Hz, $^4J_{H-H}$= 1.2 Hz). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 46.2 (CH$_3$), 56.1 (CH$_3$), 95.5 (CH$_2$), 116.9 (CH=), 122.5 (CH=), 122.7 (CH=), 124.6 (CH=), 128.4 (CH=), 129.4 (CH=), 133.1 (CH=), 135.0 (C), 140.1 (C), 150.7 (C).

(S)-((2,3-Di-tert-butyl-6-(methoxymethoxy)phenyl)imino)(methyl)-(phenyl)-λ^6-sulfanone (11). Yield: 585.2 mg (58%). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.11 (s, 9H, CH$_3$, ^{t}Bu), 1.41 (s, 9H, CH$_3$, ^{t}Bu), 3.24 (CH$_3$), 3.69 (CH$_3$), 5.31 (d, 1H, CH$_2$, $^2J_{H-H}$= 4.5 Hz), 5.44 (d, 1H, CH$_2$, $^2J_{H-H}$= 4.5 Hz), 6.87 (dd, 2H, CH=, $^3J_{H-H}$= 8.2 Hz, $^4J_{H-H}$= 2.4 Hz), 7.48-7.56 (m, 3H, CH=), 8.01-8.05 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 30.7 (CH$_3$, ^{t}Bu), 31.3 (CH$_3$, ^{t}Bu), 34.3 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 45.6 (CH$_3$), 57.5 (CH$_3$), 98.4 (CH$_2$), 117.5 (CH=), 119.4 (CH=), 128.5 (CH=), 129.4 (CH=), 133.1 (CH=), 137.0 (C), 139.6 (C), 141.8 (C), 145.2 (C), 147.1 (C).

Preparation of compounds 13–14. The corresponding compound **10** or **11** (1 equiv, 2.0 mmol) was added to a solution of 2-propanol (50 equiv, 7.7 mL, 100 mmol), HCl (25 equiv, 12.1 N, 4.1 mL, 50 mmol) and THF (25 equiv, 4.1 mL, 50 mmol). The mixture was stirred at room temperature for 3 h. The mixture was diluted with water (10 mL) and extracted with ether (3 × 10 mL). The combined organic layers were washed with 5% (w/w) NaHCO$_3$ and brine, dried (MgSO$_4$) and concentrated *in vacuo* affording pure hydroxy-sulfoximine **13–14**.

(S)-((2-Hydroxyphenyl)imino)(methyl)(phenyl)-λ^6-sulfanone (13). Yield: 474.8 mg (96%). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 3.32 (s, 3H, CH$_3$), 6.57 (td, 1H, CH=, $^3J_{H-H}$= 7.6 Hz, $^4J_{H-H}$= 1.6 Hz), 6.79-6.89 (m, 3H, CH=), 7.53-7.63 (m, 3H, CH=), 7.91-7.93 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 46.0 (CH$_3$), 113.9 (CH=), 119.9 (CH=), 120.9 (CH=), 122.8 (CH=), 128.4 (CH=), 129.8 (CH=), 131.8 (C), 133.7 (CH=), 138.2 (C), 149.9 (C). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{13}$H$_{13}$NO$_2$SNa 270.3012; Found: 270.3116.

(S)-((2,3-Di-tert-butyl-6-hydroxyphenyl)imino)(methyl)(phenyl)-λ^6-sulfanone (14). Yield: 675.9 mg (94%). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.14 (s, 9H, CH$_3$, ^{t}Bu), 1.26 (s, 9H, CH$_3$, ^{t}Bu), 4.11 (s, 3H, CH$_3$), 6.96 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz), 7.06 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz), 7.59 (t, 2H, CH=, $^3J_{H-H}$= 7.7Hz), 7.71 (t, 1H, CH=, $^3J_{H-H}$= 7.4 Hz), 8.16 (d, 2H, CH=, $^3J_{H-H}$= 7.9 Hz). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 29.3 (CH$_3$, ^{t}Bu), 31.3 (CH$_3$, ^{t}Bu), 34.1 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 42.5 (CH$_3$), 121.1 (CH=), 123.4 (CH=), 129.0 (CH=), 130.1 (CH=), 131.7 (C), 136.1 (CH=), 138.3 (C), 142.2 (C), 148.1 (C). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{21}$H$_{29}$NO$_2$SNa 382.5172; Found: 382.5177.

Preparation of ligands L1–L3a–c. To a solution of *in situ* generated phosphorochloridite (0.55 mmol) in dry toluene (3 mL), pyridine (0.08 mL, 1.0 mmol) was added. Then, this solution was placed in a -78 °C bath and a solution of the hydroxyl-sulfoximine (0.50 mmol) and pyridine (0.08 mL, 1.0 mmol) in toluene (3 mL) was added dropwise. The mixture was left to warm to room temperature and stirred overnight at this temperature. The precipitate formed was filtered under argon, and the solvent was evaporated under vacuum. The residue was purified by flash chromatography (under argon, using neutral alumina and dry toluene (1% NEt$_3$) as eluent system) to afford the corresponding phosphite-sulfoximine as white solids for **L1–L2a–c** or as yellow solids for **L3a–b**.

L1a. Yield: 174.9 mg (51%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 137.8 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.28 (s, 18H, CH$_3$, ^{t}Bu), 1.62 (s, 9H, CH$_3$, ^{t}Bu), 1.64 (s, 9H, CH$_3$, ^{t}Bu), 2.72 (s, 3H, CH$_3$), 6.52-6.58 (m, 2H, CH=), 6.79-6.91 (m, 4H, CH=), 6.91-7.01 (m, 3H, CH=), 7.63 (s, 2H, CH=), 7.98 (s, 2H, CH=). ^{13}C{^{1}H} NMR

(100.6 MHz, C$_6$D$_6$): δ = 31.1 (CH$_3$, ^{t}Bu), 31.2 (d, CH$_3$, ^{t}Bu, J_{C-P}= 2.6 Hz), 31.3 (CH$_3$, ^{t}Bu), 34.4 (d, C, ^{t}Bu, J_{C-P}= 3.0 Hz), 35.4 (C, ^{t}Bu), 45.0 (CH$_3$), 121.9-146.7 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{41}$H$_{52}$NO$_4$PSNa 708.3250; Found 708.3247.

L1b. Yield: 120.3 mg (40%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 133.0 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.54 (s, 9H, CH$_3$, ^{t}Bu), 1.72 (s, 9H, CH$_3$, ^{t}Bu), 1.75 (s, 3H, CH$_3$), 1.76 (s, 3H, CH$_3$), 2.07 (s, 6H, CH$_3$), 2.66 (s, 3H, CH$_3$), 6.49-6.53 (m, 1H, CH=), 6.57-6.60 (m, 1H, CH=), 6.82-6.84 (m, 1H, CH=), 6.89-6.91 (m, 3H, CH=), 7.02-7.31 (m, 1H, CH=), 7.32 (s, 1H, CH=), 7.41-7.43 (m, 1H, CH=), 7.92-7.94 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, C$_6$D$_6$): δ = 16.3 (CH$_3$), 16.5 (CH$_3$), 20.1 (CH$_3$), 31.1 (CH$_3$, ^{t}Bu, J_{C-P}= 5.1 Hz), 31.8 (CH$_3$, ^{t}Bu), 34.6 (C, ^{t}Bu), 34.9 (C, ^{t}Bu), 44.7 (CH$_3$), 122.0-146.1 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{37}$H$_{44}$NO$_4$PSNa 652.2624; Found 652.2621.

L1c. Yield: 66.2 mg (22%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 131.0 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.55 (s, 9H, CH$_3$, ^{t}Bu), 1.75 (s, 9H, CH$_3$, ^{t}Bu), 1.78 (s, 3H, CH$_3$), 1.80 (s, 3H, CH$_3$), 2.08 (s, 6H, CH$_3$), 2.68 (s, 3H, CH$_3$), 6.49-6.51 (m, 1H, CH=), 6.53-6.56 (m, 1H, CH=), 6.95-7.04 (m, 5H, CH=), 7.11-7.16 (m, 1H, CH=), 7.27 (s, 1H, CH=), 7.34 (s, 1H, CH=), 7.35-7.37 (m, 1H, CH=), 8.02-8.03 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, C$_6$D$_6$): δ = 16.4 (CH$_3$), 16.6 (CH$_3$), 20.0 (CH$_3$), 20.1 (CH$_3$), 31.2 (d, CH$_3$, ^{t}Bu, J_{C-P}= 5.5 Hz), 31.7 (s, CH$_3$, ^{t}Bu), 34.6 (C, ^{t}Bu), 35.0 (C, ^{t}Bu), 45.1 (CH$_3$), 121.9-145.7 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{37}$H$_{44}$NO$_4$PSNa 652.2621; Found 652.2623.

L2a. Yield: 39.9 mg (10%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 131.1 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.08 (s, 9H, CH$_3$, ^{t}Bu), 1.26 (s, 9H, CH$_3$, ^{t}Bu), 1.29 (s, 9H, CH$_3$, ^{t}Bu), 1.52 (s, 9H, CH$_3$, ^{t}Bu), 1.71 (s, 18H, CH$_3$, ^{t}Bu), 2.65 (s, 3H, CH$_3$), 6.90-7.04 (m, 4H, CH=), 7.26 (d, 1H, CH=, $^4J_{H-H}$= 2.2 Hz), 7.43 (d, 1H, $^4J_{H-H}$= 2.4 Hz), 7.57 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz), 7.67 (d, 1H, CH=, $^4J_{H-H}$= 2.5 Hz), 7.71 (d, 1H, CH=, $^4J_{H-H}$= 2.4 Hz), 7.94-7.97 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, C$_6$D$_6$): δ = 30.4 (CH$_3$, ^{t}Bu), 31.0 (CH$_3$, ^{t}Bu), 31.2 (CH$_3$, ^{t}Bu), 31.3 (CH$_3$, ^{t}Bu), 31.4 (CH$_3$, ^{t}Bu), 34.1 (C, ^{t}Bu), 34.3 (C, ^{t}Bu), 34.5 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 35.5 (C, ^{t}Bu), 35.6 (C, ^{t}Bu), 44.3 (CH$_3$), 116.8-150.3 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{49}$H$_{68}$NO$_4$PSNa 820.4499; Found 820.4501.

L3a. Yield: 160.0 mg (46%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 138.2 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.22 (s, 9H, CH$_3$, ^{t}Bu), 1.25 (s, 9H, CH$_3$, ^{t}Bu), 1.51 (s, 9H, CH$_3$, ^{t}Bu), 1.58 (s, 9H, CH$_3$, ^{t}Bu), 5.64 (d, 1H, CH=, $^3J_{H-H}$= 9.5 Hz), 6.60-6.69 (m, 2H, CH=), 6.75 (d, 1H, CH=, $^3J_{H-H}$= 9.5 Hz), 6.87-6.91 (m, 3H, CH=), 7.07-7.12 (m, 1H, CH=), 7.32 (dd, 2H, CH=, $^3J_{H-H}$= 6.5 Hz, $^4J_{H-H}$= 2.1 Hz), 7.56 (dd, 2H, CH=, $^3J_{H-H}$= 12.1 Hz, $^4J_{H-H}$= 2.1 Hz), 7.72 (dd, 2H, CH=, $^3J_{H-H}$= 7.3 Hz, $^4J_{H-H}$= 1.1 Hz). ^{13}C{^{1}H} NMR (100.6 MHz, C$_6$D$_6$): δ = 31.1 (CH$_3$, ^{t}Bu), 31.2 (d, CH$_3$, ^{t}Bu, J_{C-P}= 2.3 Hz), 34.3 (d, C, ^{t}Bu, J_{C-P}= 4.2 Hz), 35.4 (C, ^{t}Bu), 35.5 (C, ^{t}Bu), 110.8 (CH=), 117.7-146.5 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{42}$H$_{50}$NO$_4$PSNa 718.3090; Found 718.3092.

L3b. Yield: 165.2 mg (54%). ^{31}P NMR (161.9 MHz, C$_6$D$_6$): δ = 133.3 (s). ^{1}H NMR (400 MHz, C$_6$D$_6$): δ = 1.48 (s, 9H, CH$_3$, ^{t}Bu), 1.66 (s, 3H, CH$_3$), 1.68 (s, 9H, CH$_3$, ^{t}Bu), 1.70 (s, 3H, CH$_3$), 1.98 (s, 3H, CH$_3$), 2.00 (s, 3H, CH$_3$), 5.74 (d, 1H, CH=, $^3J_{H-H}$= 9.8 Hz), 6.62 (t, 1H, CH=, $^3J_{H-H}$= 7.1 Hz), 6.72 (d, 1H, CH=, $^3J_{H-H}$= 7.8 Hz), 6.83 (d, 1H, CH=, $^3J_{H-H}$= 9.8 Hz), 6.86-6.98 (m, 3H, CH=), 7.14 (s, 1H, CH=), 7.21 (s, 1H, CH=), 7.27 (d, 1H, CH=, $^3J_{H-H}$= 7.7 Hz), 7.78-7.80 (m, 2H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, C$_6$D$_6$): δ = 16.3 (CH$_3$), 16.5 (CH$_3$), 20.1 (CH$_3$), 31.2 (d, CH$_3$, ^{t}Bu, J_{C-P}= 5.2 Hz), 31.8 (CH$_3$, ^{t}Bu), 34.6 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 111.1 (CH=), 118.0-145.6 (aromatic carbons). HRMS (ESI-TOF) m/z: [M+Na]$^+$ Calcd for C$_{38}$H$_{42}$NO$_4$PSNa 662.2464; Found 662.2467.

Preparation of [Ir(cod)(L1–L3a–c)]BAr$_F$ catalyst precursors. The corresponding ligand (0.074 mmol) was dissolved in CH$_2$Cl$_2$ (5 mL) and [Ir(μ–Cl)(cod)]$_2$ (25.0 mg, 0.037 mmol) was added. The reaction mixture was heated to reflux at 40 °C for 1 h. After 5 min at rt, NaBAr$_F$ (77.2 mg, 0.080 mmol) and water (5 mL) were added and the reaction mixture was stirred vigorously for 30 min at rt. The phases were separated and the aqueous phase was extracted twice with CH$_2$Cl$_2$. The combined organic phases were dried with MgSO$_4$ filtered through a plug of Celite and the solvent was evaporated to give the corresponding products as orange solids.

[Ir(cod)(L1a)]BAr$_F$. Yield: 124 mg (91%). Major isomer (57%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 122.4 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.27 (s, 9H, CH$_3$, ^{t}Bu), 1.40 (s, 9H, CH$_3$, ^{t}Bu), 1.44 (s, 9H, CH$_3$, ^{t}Bu), 1.68 (s, 9H, CH$_3$, ^{t}Bu), 1.57-1.67 (m, 2H, CH$_2$, cod), 1.95-2.16 (m, 2H, CH$_2$, cod), 2.28-2.35 (m, 3H, CH$_2$, cod), 2.49-2.52 (m, 1H, CH$_2$, cod), 3.91 (m, 1H, CH=, cod), 3.95 (s, 3H, CH$_3$), 4.57 (m, 1H, CH=, cod), 5.42 (m, 1H, CH=, cod), 6.15 (m, 1H, CH=, cod), 6.39-8.45 (m, 25H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 25.9 (CH$_2$, cod), 29.8 (CH$_2$, cod), 31.1 (CH$_3$, ^{t}Bu), 31.2 (CH$_3$, ^{t}Bu), 31.5 (CH$_3$, ^{t}Bu), 32.3 (CH$_2$, cod), 34.9-35.8 (C, ^{t}Bu), 36.9 (CH$_2$, cod), 44.1 (CH$_3$), 65.3 (CH=, cod), 66.7 (CH=, cod), 99.8 (d, CH=, cod, J_{C-P}= 20.1 Hz), 109.2 (d, CH=, cod, J_{C-P}= 12.9 Hz), 117.8-150.2 (aromatic carbons), 162.1 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.8 Hz). Minor isomer (43%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 120.8 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.05-1.07 (m, 2H, CH$_2$, cod), 1.14 (s, 9H, CH$_3$, ^{t}Bu), 1.34 (s, 9H, CH$_3$, ^{t}Bu), 1.57 (s, 9H, CH$_3$, ^{t}Bu), 1.73 (s, 9H, CH$_3$, ^{t}Bu), 1.87-1.91 (m, 3H, CH$_2$, cod), 1.91 (m, CH=, cod), 2.08-2.24 (m, 2H, CH$_2$, cod), 2.50 (m, 1H, CH$_2$, cod), 3.12 (CH$_3$), 3.89 (m, 1H, CH=, cod), 4.41 (m, 1H, CH=, cod), 6.08 (m, 1H, CH=, cod), 7.11-8.02 (m, 25H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 24.6 (CH$_2$, cod), 29.0 (CH$_2$, cod), 30.1 (CH$_2$, cod), 30.9 (CH$_3$, ^{t}Bu), 31.1 (CH$_3$, ^{t}Bu), 31.5 (CH$_3$, ^{t}Bu), 33.2 (CH$_2$, cod), 34.9-35.8 (C, ^{t}Bu), 50.0 (CH$_3$), 54.5 (CH=, cod), 66.3 (CH=, cod), 99.7 (d, CH=, cod, J_{C-P}= 22.5 Hz), 108.1 (d, CH=, cod, J_{C-P}= 13.8 Hz), 117.8-150.2 (aromatic carbons), 162.1 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.8 Hz). HRMS (ESI-TOF) m/z: [M-BAr$_F$]$^+$ Calcd for C$_{49}$H$_{64}$IrNO$_4$PS 986.3923; Found 986.3919.

[Ir(cod)(L1b)]BAr$_F$. Yield: 122 mg (92%). Major isomer (80%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 121.4 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.15 (s, 9H, CH$_3$, ^{t}Bu), 1.43-1.46 (m, 1H, CH$_2$, cod), 1.62 (s, 9H, CH$_3$, ^{t}Bu), 1.70-1.82 (m, 1H, CH$_2$, cod), 1.72 (s, 3H, CH$_3$), 1.90 (s, 3H, CH$_3$), 2.05-2.08 (m, 1H, CH$_2$, cod), 2.25-2.33 (m, 3H, CH$_2$, cod), 2.28 (s, 3H, CH$_3$), 2.33 (s, 3H, CH$_3$), 2.50-2.54 (m, 1H, CH$_2$, cod), 2.33 (m, 1H, CH=, cod), 4.01 (s, 3H, CH$_3$), 4.32 (m, 1H, CH=, cod), 5.46 (m, 1H, CH=, cod), 6.58 (m, 1H, CH=, cod), 6.71-7.89 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 16.9 (CH$_3$), 17.0 (CH$_3$), 20.0 (CH$_3$), 20.6 (CH$_3$), 25.8 (CH$_2$, cod), 29.8 (CH$_2$, cod), 31.5 (CH$_3$, ^{t}Bu), 31.6 (CH$_3$, ^{t}Bu), 32.6 (CH$_2$, cod), 35.2 (C, ^{t}Bu), 35.3 (C, ^{t}Bu), 37.5 (CH$_2$, cod), 49.6 (CH$_3$), 54.9 (CH=, cod), 68.8 (CH=, cod), 100.0 (d, CH=, cod, J_{C-}

P= 21.3 Hz), 108.6 (d, CH=, cod, J_{C-P} = 14.1 Hz), 117.8-145.3 (aromatic carbons), 162.1 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.9 Hz). Minor isomer (20%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 119.3 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.28 (s, 9H, CH$_3$, ^{t}Bu), 1.57 (s, 9H, CH$_3$, ^{t}Bu), 1.70 (s, 3H, CH$_3$), 1.73-1.93 (m, 4H, CH$_2$, cod), 1.96 (s, 3H, CH$_3$), 2.00-2.30 (m, 4H, CH$_2$, cod), 2.30 (s, 3H, CH$_3$), 2.34 (s, 3H, CH$_3$), 3.54 (s, 3H, CH$_3$), 4.10 (m, 1H, CH=, cod), 4.14 (m, 1H, CH=, cod), 4.74 (m, 1H, CH=, cod), 5.89 (m, 1H, CH=, cod), 6.46-7.80 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 16.8 (CH$_3$), 16.9 (CH$_3$), 20.7 (CH$_3$), 20.9 (CH$_3$), 25.8 (CH$_2$, cod), 30.4 (CH$_2$, cod), 31.4 (CH$_3$, ^{t}Bu), 31.5 (CH$_3$, ^{t}Bu), 31.9 (CH$_2$, cod), 32.3 (CH$_2$, cod), 35.8 (C, ^{t}Bu), 44.6 (CH$_3$), 53.8 (CH=, cod), 63.1 (CH=, cod), 100.0 (CH=, cod), 109.0 (d, CH=, cod, J_{C-P}= 14.4 Hz), 121.8-147.3 (aromatic carbons), 162.1 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.9 Hz). HRMS (ESI-TOF) m/z: [M- BAr$_F$]$^+$ Calcd for C$_{45}$H$_{61}$IrNO$_4$PS 930.3297; Found 930.3293.

[**Ir(cod)(L1c)**]**BAr$_F$.** Yield: 126 mg (95%). Major isomer (80%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 121.4 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ =1.17-1.28 (m, 2H, CH$_2$, cod), 1.26 (s, 9H, CH$_3$, ^{t}Bu), 1.54 (m, 1H, CH=, cod), 1.69 (s, 9H, CH$_3$, ^{t}Bu), 1.74 (s, 3H, CH$_3$), 1.90-2.13 (m, 2H, CH$_2$, cod), 2.21-2.29 (m, 2H, CH$_2$, cod), 2.40-2.44 (m, 2H, CH$_2$, cod), 1.98 (s, 3H, CH$_3$), 2.31 (s, 3H, CH$_3$), 2.36 (s, 3H, CH$_3$), 3.87 (s, 3H, CH$_3$), 4.06 (m, 1H, CH=, cod), 5.31 (m, 1H, CH=, cod), 6.11 (m, 1H, CH=, cod), 6.53-8.50 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ =16.4 (CH$_3$), 16.5 (CH$_3$), 20.2 (CH$_3$), 20.5 (CH$_3$), 25.2 (CH$_2$, cod), 29.6 (CH$_2$, cod), 31.0 (CH$_3$, ^{t}Bu), 31.1 (CH$_3$, ^{t}Bu), 32.1 (CH$_2$, cod), 34.7 (C, ^{t}Bu), 34.8 (C, ^{t}Bu), 36.8 (CH$_2$, cod), 49.5 (CH$_3$), 55.1 (CH=, cod), 68.8 (CH=, cod), 99.6 (d, CH=, cod, J_{C-P}= 21.3 Hz), 108.0 (d, CH=, cod, J_{C-P}= 14.1 Hz), 117.4-144.9 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.9 Hz). Minor isomer (20%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 119.1 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.00-1.11 (m, 2H, CH$_2$, cod), 1.11 (s, 9H, CH$_3$, ^{t}Bu), 1.22-1.25 (m, 2H, CH$_2$, cod), 1.56 (s, 9H, CH$_3$, ^{t}Bu), 1.68-1.72 (m, 1H, CH$_2$, cod), 1.85 (s, 3H, CH$_3$), 2.10-2.21 (m, 3H, CH$_2$, cod), 2.24 (s, 3H, CH$_3$), 2.32 (s, 6H, CH$_3$), 3.08 (s, 3H, CH$_3$), 3.89 (m, 1H, CH=, cod), 4.26 (m, 1H, CH=, cod), 4.43 (m, 1H, CH=, cod), 6.05 (m, 1H, CH=, cod), 6.96-7.93 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 16.4 (CH$_3$), 20.2 (CH$_3$), 20.4 (CH$_3$), 25.5 (CH$_2$, cod), 28.2 (CH$_2$, cod), 29.3 (CH$_2$, cod), 30.9 (CH$_3$, ^{t}Bu), 31.7 (CH$_2$, cod), 34.9 (C, ^{t}Bu), 35.3 (C, ^{t}Bu), 36.8 (CH$_2$, cod), 44.1 (CH$_3$), 54.4 (CH=, cod), 68.4 (CH=, cod), 99.6 (CH=, cod), 108.3 (d, CH=, cod, J_{C-P}= 21.5 Hz), 121.2-146.8 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.9 Hz). HRMS (ESI-TOF) m/z: [M- BAr$_F$]$^+$ Calcd for C$_{45}$H$_{56}$IrNO$_4$PS 930.3297; Found 930.3294.

[**Ir(cod)(L2a)**]**BAr$_F$.** Yield: 138 mg (95%). Major isomer (78%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 117.4 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.15 (s, 9H, CH$_3$, ^{t}Bu), 1.17 (s, 9H, CH$_3$, ^{t}Bu), 1.31 (s, 9H, CH$_3$, ^{t}Bu), 1.37 (s, 9H, CH$_3$, ^{t}Bu), 1.40 (s, 9H, CH$_3$, ^{t}Bu), 1.70 (m, 1H, CH$_2$, cod), 1.74 (s, 9H, CH$_3$, ^{t}Bu), 1.92-2.00 (m, 3H, CH$_2$, cod), 2.03 (m, 1H, CH=, cod), 2.30-2.34 (m, 2H, CH$_2$, cod), 2.40-2.58 (m, 2H, CH$_2$, cod), 2.90 (s, 3H, CH$_3$), 3.97 (m, 1H, CH=, cod), 4.63 (m, 1H, CH=, cod), 6.20 (m, 1H, CH=, cod), 7.02-8.43 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 22.7 (CH$_2$, cod), 24.7 (CH$_2$, cod), 30.0 (CH$_2$, cod), 30.6 (CH$_3$, ^{t}Bu), 31.0 (CH$_3$, ^{t}Bu), 31.3 (CH$_3$, ^{t}Bu), 31.9 (CH$_3$, ^{t}Bu), 34.4 (C, ^{t}Bu), 34.8 (C, ^{t}Bu), 34.9 (C, ^{t}Bu), 35.1 (C, ^{t}Bu), 35.5 (C, ^{t}Bu), 35.9 (CH$_2$, cod), 43.3 (CH$_3$), 52.7 (CH=, cod), 66.4 (CH=, cod), 101.3 (d, CH=,

cod, J_{C-P}= 20.5 Hz), 107.9 (d, CH=, cod, J_{C-P}= 14.3 Hz), 117.4-149.7 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.7 Hz). Minor isomer (22%): ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 118.6 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.01 (s, 9H, CH$_3$, ^{t}Bu), 1.14-1.25 (m, 3H, CH$_2$, cod), 1.28 (s, 9H, CH$_3$, ^{t}Bu), 1.33 (s, 9H, CH$_3$, ^{t}Bu), 1.38 (s, 9H, CH$_3$, ^{t}Bu), 1.46 (s, 9H, CH$_3$, ^{t}Bu), 1.59 (s, 9H, CH$_3$, ^{t}Bu), 2.08-2.15 (m, 3H, CH$_2$, cod), 2.32-2.45 (m, 2H, CH$_2$, cod), 2.60 (m, 1H, CH=, cod), 3.97 (s, 3H, CH$_3$), 4.49 (m, 1H, CH=, cod), 5.72 (m, 1H, CH=, cod), 6.36 (m, 1H, CH=, cod), 6.39-7.81 (m, 23H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 22.6 (CH$_2$, cod), 25.7 (CH$_2$, cod), 29.5 (CH$_2$, cod), 29.7 (CH$_3$, ^{t}Bu), 30.8 (CH$_3$, ^{t}Bu), 31.4 (CH$_3$, ^{t}Bu), 31.6 (CH$_3$, ^{t}Bu), 34.4 (C, ^{t}Bu), 34.9 (C, ^{t}Bu), 35.2 (C, ^{t}Bu), 35.5 (C, ^{t}Bu), 35.6 (C, ^{t}Bu), 36.5 (CH$_2$, cod), 49.5 (CH$_3$), 55.4 (CH=, cod), 68.1 (CH=, cod), 103.3 (CH=, cod), 109.0 (CH=, cod), 1204-149.7 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.7 Hz). HRMS (ESI-TOF) m/z: [M- BAr$_F$]$^+$ Calcd for C$_{57}$H$_{80}$IrNO$_4$PS 1098.5175; Found 1098.5170 .

[**Ir(cod)(L3a)**]**BAr$_F$.** Yield: 125 mg (91%). ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 116.2 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.26-1.28 (m, 1H, CH$_2$, cod), 1.38 (s, 18H, CH$_3$, ^{t}Bu), 1.42 (s, 9H, CH$_3$, ^{t}Bu), 1.49 (s, 9H, CH$_3$, ^{t}Bu), 1.66-1.68 (m, 1H, CH$_2$, cod), 1.92-2.10 (m, 3H, CH$_2$, cod), 2.18-2.27 (m, 2H, CH$_2$, cod), 2.43-2.46 (m, 1H, CH$_2$, cod), 3.08 (m, 1H, CH=, cod), 3.54 (m, 1H, CH=, cod), 5.80 (m, 1H, CH=, cod), 6.49 (m, 1H, CH=, cod), 6.68-7.71 (m, 26H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 26.2 (CH$_2$, cod), 28.6 (CH$_2$, cod), 29.7 (CH$_2$, cod), 31.3 (CH$_3$, ^{t}Bu), 31.5 (CH$_3$, ^{t}Bu), 32.2 (CH$_3$, ^{t}Bu), 34.8 (d, C, ^{t}Bu, J_{C-P}= 4.2 Hz), 35.6 (d, C, ^{t}Bu, J_{C-P}= 7.1 Hz), 36.2 (CH$_2$, cod), 56.7 (CH=, cod), 61.6 (CH=, cod), 107.8 (d, CH=, cod, J_{C-P}= 16.9 Hz), 110.7 (d, CH=, cod, J_{C-P}= 14.1 Hz), 116.1 (CH=), 117.5-149.1 (aromatic carbons), 161.7 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.8 Hz). HRMS (ESI-TOF) m/z: [M- BAr$_F$]$^+$ Calcd for C$_{50}$H$_{62}$IrNO$_4$PS 996.3766; Found 996.3762.

[**Ir(cod)(L3b)**]**BAr$_F$.** Yield: 124 mg (94%). ^{31}P NMR (161.9 MHz, CDCl$_3$): δ = 113.7 (s). ^{1}H NMR (400 MHz, CDCl$_3$): δ = 1.28 (m, 1H, CH$_2$, cod), 1.36 (s, 9H, CH$_3$, ^{t}Bu), 1.45 (s, 9H, CH$_3$, ^{t}Bu), 1.79 (s, 3H, CH$_3$), 1.73-1.95 (m, 2H, CH$_2$, cod), 1.85 (s, 3H, CH$_3$), 2.13-2.22 (m, 3H, CH$_2$, cod), 2.30 (s, 3H, CH$_3$), 2.31 (s, 3H, CH$_3$), 2.42 (m, 1H, CH$_2$, cod), 3.02 (m, 1H, CH=, cod), 3.59 (m, 1H, CH=, cod), 5.76 (m, 1H, CH=, cod), 6.39 (m, 1H, CH=, cod), 6.66-7.73 (m, 26H, CH=). ^{13}C{^{1}H} NMR (100.6 MHz, CDCl$_3$): δ = 16.5 (CH$_3$), 16.6 (CH$_3$), 20.4 (CH$_3$), 26.1 (CH$_2$, cod), 28.6 (CH$_2$, cod), 31.2 (CH$_2$, cod) 31.6 (CH$_3$, ^{t}Bu), 32.4 (CH$_3$, ^{t}Bu), 34.9 (C, ^{t}Bu), 35.0 (C, ^{t}Bu), 36.2 (CH$_2$, cod), 56.8 (CH=, cod), 62.1 (CH=, cod), 107.4 (d, CH=, cod, J_{C-P}= 14.8 Hz), 109.4 (d, CH=, cod, J_{C-P}= 17.8 Hz), 115.8 (CH=), 117.5-144.7 (aromatic carbons), 161.6 (q, C-B, BAr$_F$, $^1J_{C-B}$= 49.8 Hz). HRMS (ESI-TOF) m/z: [M- BAr$_F$]$^+$ Calcd for C$_{46}$H$_{54}$IrNO$_4$PS 940.3140; Found: 940.3138.

General procedure for the asymmetric hydrogenation. The alkene (0.25 mmol) and Ir complex (1 mol%) were dissolved in CH$_2$Cl$_2$ (1.5 mL) and placed in a high-pressure autoclave. The autoclave was purged 4 times with hydrogen. Then, it was pressurized at the desired pressure. After the desired reaction time, the autoclave was depressurized, and the solvent evaporated off. The residue was dissolved in Et$_2$O (1.5 ml) and filtered through a short plug of Celite. Conversions were determined by ^{1}H NMR and enantiomeric excesses were determined by chiral HPLC or GC.

(R)-1,3-diphenylbutan-1-one.[5a] Yield: 54 mg (96%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=97/3, 0.5 mL/min, 220 nm). t_R 31.0 min (*R*); t_R 33.8 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.33 (d, 3H, *J*=6.7 Hz), 3.17 (m, 1H), 3.28 (m, 1H), 3.50 (m, 1H), 7.1-7.9 (m, 5H).

(R)-3-Methyl-4-phenylbutan-2-one.[5b] Yield: 39 mg (97%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=97/3, 1 mL/min, 220 nm). t_R 8.6 min (*S*); t_R 9.2 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.08 (d, 3H, *J*=6.8 Hz), 2.08 (s, 3H), 2.56 (m, 1H), 2.82 (m, 1H), 2.98 (m, 1H), 7.1-7.3 (m, 5H).

(-)-4-Methyl-1,3-diphenylpentan-1-one.[5a] Yield: 60 mg (96%). Enantiomeric excess determined by HPLC using Chiracel AD column (hexane/2-propanol=97/3, 0.5 mL/min, 220 nm). t_R 16.2 min (+); t_R 19.0 min (-). ^{1}H NMR (CDCl$_3$), δ: 0.78 (d, 3H, *J*=6.9 Hz), 0.97 (d, 3H, *J*=6.6 Hz), 1.93 (m, 1H), 3.15 (m, 1H), 3.35 (m, 1H), 7.1-7.5 (m, 8H), 7,86 (m, 2H).

(R)-4-(4-Methylphenyl)-3-methylbutan-2-one.[5b] Yield: 41 mg (94%). Enantiomeric excess determined by HPLC using Chiracel Lux-Amylose-1 column (hexane/2-propanol=97/3, 0.5 mL/min, 220 nm). t_R 11.0 min (*R*); t_R 11.6 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.04 (d, 3H, *J*=6.8 Hz), 2.06 (s, 3H), 2.50 (dd, 1H, *J*=7.4 Hz, *J*=13.4 Hz), 2.76 (m, 1H), 2.92 (dd, 1H, *J*=6.8 Hz, *J*=13.4 Hz), 3.77 (s, 3H), 6.80 (m, 2H), 7.0-7.3 (m, 2H).

(R)-4-(4-Methoxyphenyl)-3-methylbutan-2-one.[5b] Yield: 46 mg (95%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=95/5, 0.5 mL/min, 220 nm). t_R 25.5 min (*S*); t_R 27.8 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.07 (d, 3H, *J*=6.8 Hz), 2.08 (s, 3H), 2.52 (dd, 1H, *J*=7.4 Hz, *J*=13.4 Hz), 2.78 (m, 1H), 2.93 (dd, 1H, *J*=6.8 Hz, *J*=13.4 Hz), 3.77 (s, 3H), 6.82 (m, 2H), 7.0-7.3 (m, 2H).

(R)-2-Methyl-1-phenylpentan-3-one.[5b] Yield: 41 mg (93%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=99/1, 0.5 mL/min, 220 nm). t_R 15.2 min (*S*); t_R 16.2 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 0.96 (t, 3H, *J*=7.2 Hz), 1.07 (d, 3H, *J*=6.8 Hz), 2.21 (m, 1H), 2.43 (m, 1H), 2.57 (dd, 1H, *J*=7.0 Hz, *J*=13.4 Hz), 2.83 (m, 1H), 2.92 (dd, 1H, *J*=6.8 Hz, *J*=13.4 Hz), 7.1-7.3 (m, 5H).

(R)-2,4-Dimethyl-1-phenylpentan-3-one.[5b] Yield: 45 mg (95%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=99/1, 0.5 mL/min, 220 nm). t_R 15.2 (*S*); t_R 17.8 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 0.80 (d, 3H, *J*=6.8 Hz), 0.95 (d, 3H, *J*=6.8 Hz), 1.01 (d, 1H, *J*=6.8 Hz), 2.49 (m, 2H), 2.95 (m, 2H), 7.0-7.2 (m, 5H).

(R)-2-Methyl-1,3-diphenylpropan-1-one.[5b] Yield: 55 mg (98%). Enantiomeric excess determined by HPLC using Chiracel OB column (hexane/2-propanol=98.2, 0.5 mL/min, 220 nm). t_R 12.9 min (*S*); t_R 13.7 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.13 (d, 3H, *J*=6.8 Hz), 2.61 (dd, 1H, *J*=13.2 Hz, *J*=7.2 Hz), 3.09 (dd, 1H, *J*=13.2 Hz, *J*=6.4 Hz), 3.69 (m, 1H), 7.1-7.9 (m, 10H).

(R)-2-Benzylcyclohexanone.[5b] Yield: 43 mg (92%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=97/3, 1 mL/min, 210 nm). t_R 8.4 min (*S*); t_R 9.1 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.35 (m, 1H), 1.63 (m, 2H), 1.83 (m, 1H), 2.04 (m, 2H), 2.44 (m, 4H), 3.24 (dd, 1H, *J* = 14.0 Hz, *J*=4.6 Hz), 7.18 (m, 3H), 7.28 (m, 2H).

(S)-Ethyl 3-phenylbutanoate.[24] Yield: 44 mg (91%). Enantiomeric excess determined by HPLC using Chiracel IB column (hexane/2-propanol=99.5/0.5, 1 mL/min, 254 nm). t_R 10.6 min (*R*); t_R 18.5 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.16 (t, 3H, *J*=7.2 Hz), 1.30 (d, 3H, *J*=6.8 Hz), 2.54 (m, 2H), 3.28 (m, 1H), 4.08 (q, 2H, *J*=7.2 Hz), 7.2-7.3 (m, 5H).

(S)-Ethyl 3-(p-tolyl)butanoate.[25] Yield: 48 mg (93%). Enantiomeric excess determined by HPLC using Chiracel IB column (hexane/2-propanol=99.5/0.5, 0.5 mL/min, 254 nm). t_R 12.3 min (*R*); t_R 13.0 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.11 (t, 3H, *J*=7.2 Hz), 1.21 (d, 3H, *J*=6.0 Hz), 2.24 (s, 3H), 2.49 (m, 2H), 3.17 (m, 1H), 4.00 (q, 2H, *J*=7.2 Hz), 7.04 (m, 4H).

(S)-Ethyl 3-(4-methoxyphenyl)butanoate.[25] Yield: 51 mg (91%). Enantiomeric excess determined by HPLC using Chiracel IB column (hexane/2-propanol=99.5/0.5, 0.5 mL/min, 254 nm). t_R 18.5 min (*R*); t_R 19.5 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.11 (t, 3H, *J*= 7.2 Hz), 1.26 (d, 3H, *J*=6.4 Hz), 2.54 (m, 2H), 3.24 (m, 1H), 3.77 (s, 3H), 4.07 (q, 2H, *J*=7.2 Hz), 6.82 (m, 2H), 7.13 (m, 2H).

(S)-Ethyl 3-phenylpentanoate.[25] Yield: 46 mg (92%). Enantiomeric excess determined by HPLC using Chiracel IC column (hexane/2-propanol=99.5/0.5, 0.5 mL/min, 254 nm). t_R 11.6 min (*R*); t_R 12.0 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 0.79 (t, 3H, *J*=7.2 Hz), 1.13 (t, 3H, *J*=7.2 Hz), 1.62 (m, 2H), 2.60 (m, 2H), 2.99 (m, 1H), 4.03 (q, 2H, *J*=7.2 Hz), 7.17 (m, 2H), 7.26 (m, 3H).

(S)-Ethyl 4-methyl-3-phenylpentanoate.[26] Yield: 52 mg (93%). Enantiomeric excess determined by HPLC using Chiracel OD-H column (hexane/2-propanol=99/1, 0.5 mL/min, 254 nm). t_R 11.0 min (*R*); t_R 18.8 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 0.75 (d, 3H, *J*=6.0 Hz), 0.95 (d, 3H, *J*=6.0 Hz), 1.06 (t, 3H, *J*=6.8 Hz), 1.86 (m, 1H), 2.58 (m, 1H), 2.76 (m, 1H), 2.86 (m, 1H), 3.94 (q, 2H, *J*=6.8 Hz), 7.1-7.3 (m, 5H).

(S)-Ethyl 3-cyclohexyl-3-phenylpropanoate.[27] Yield: 61 mg (95%). Enantiomeric excess determined by HPLC using Chiracel OD-H column (hexane/2-propanol=99/1, 0.5 mL/min, 254 nm). t_R 10.3 min (*R*); t_R 17.9 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 0.92 (m, 1H), 0.93 (m, 1H), 1.06 (t, 3H, *J*=7.2 Hz), 1.12 (m, 1H), 1.24 (m, 2H), 1.42 (m, 2H), 1.60 (m, 2H), 1.72 (m, 1H), 1.80 (m, 1H), 2.54 (m, 1H), 2.78 (m, 1H), 2.89 (m, 1H), 3.92 (q, 2H, *J*= 7.2 Hz), 7.1-7.3 (m, 5H).

(R)-3-Benzyltetrahydro-2H-pyran-2-one.[16f] Yield: 23 mg (49%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=90/10, 1 mL/min, 210 nm). t_R 39.4 min (*R*); t_R 44.4 min (*S*). ^{1}H NMR (CDCl$_3$), δ: 1.51 (m, 1H), 1.83 (m, 3H), 2.71 (m, 2H), 3.35 (m, 1H), 4.26 (m, 2H), 7.1-7.3 (m, 5H).

(R)-3-Benzyldihydrofuran-2(3H)-one.[16f] Yield: 41 mg (94%). Enantiomeric excess determined by HPLC using Chiracel OD-H column (hexane/2-propanol=90/10, 1 mL/min, 254 nm). t_R 17.3 min (*S*); t_R 18.8 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.98 (m, 1H), 2.12 (m, 1H), 2.64 (m, 1H), 2.84 (m, 1H), 3.12 (m, 1H), 4.16 (m, 1H), 4.22 (m, 1H), 7.2-7.3 (m, 5H).

(R)-1-Acetyl-3-benzylpiperidin-2-one.[10e] Yield: 42 mg (72%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=80/20, 0.5 mL/min, 210 nm). t_R 21.5 min (*S*); t_R 23.6 min (*R*). ^{1}H NMR (CDCl$_3$), δ: 1.47 (m, 1H), 1.71 (m, 1H), 1.82 (m, 2H), 2.47 (s, 3H), 2.69 (m, 2H), 3.30 (m, 1H), 3.54 (m, 1H), 3.77 (m, 1H), 7.1-7.3 (m, 5H).

(R)-1-benzyl-3-(cyclohexylmethyl)piperidin-2-one.[10e] Yield: 62 mg (87%). Enantiomeric excess determined by HPLC using Chiracel IA column (hexane/2-propanol=90/10, 0.5 mL/min, 210 nm). t_R 16.3 min (*S*); t_R 19.1 min (*R*). [1H] NMR (CDCl$_3$), δ: 0.82 (m, 1H), 0.92 (m, 1H), 1.0-1.4 (m, 5H), 1.43 (m, 1H), 1.64 (m, 5H), 1.81 (m, 1H), 1.92 (m, 2H), 2.41 (m, 1H), 3.18 (m, 1H), 4.42 (m, 2H), 7.1-7.3 (m, 5H).

(-)-2-(1,2-Diphenylethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane.[16g] Yield: 71 mg (92%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=99/1, 0.5 mL/min, 254 nm). t_R 9.5 min (-); t_R 12.9 min (+). [1H] NMR (CDCl$_3$), δ: 1.02 (s, 6H), 1.09 (s, 6H), 2.67 (dd, 1H, *J*= 6.8 Hz, *J*= 10.0 Hz), 2.95 (dd, 1H, *J*= 7.0 Hz, *J*= 13.6 Hz), 3.15 (dd, 1H, *J*= 9.6 Hz, *J*= 13.6 Hz), 7.1-7.2 (m, 10H).

(S)-Propane-1,2-diyldibenzene.[24] Yield: 46 mg (94%). Enantiomeric excess determined by HPLC using Chiracel OJ-H column (hexane/2-propanol=99/1, 0.5 mL/min, 254 nm). t_R 12.7 min (*R*); t_R 17.5 min (*S*). [1H] NMR (CDCl$_3$), δ: 1.26 (d, 3H, *J*= 6.8 Hz), 2.78 (m, 1H), 3.00 (m, 2H), 7.10 (m, 2H), 7.2-7.3 (m, 8H).

(S)-(3,3-Dimethylbutan-2-yl)benzene.[24] Yield: 37 mg (92%). Enantiomeric excess determined by GC using Chiradex B-DM column (100 kPa H$_2$, 60 °C for 30 min, 3 °C/min until 175 °C). t_R 36.0 min (*S*); t_R 37.1 min (*R*). [1H] NMR (CDCl$_3$), δ: 0.86 (s, 9H), 1.25 (d, 3H, *J*= 6.8 Hz), 2.54 (q, 1H, *J*= 6.8 Hz), 7.1-7.3 (m, 5H).

ASSOCIATED CONTENT

Copies of NMR spectra of intermediates (**6**, **7**, **10**, **11**, **13** and **14**), ligands (**L1**–**L3a**–**c**), [[Ir(cod)(**L1**–**L3a**–**c**)]BAr$_F$ complexes. Copies of [1H]–NMR and GC/HPLC traces for all hydrogenated products. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

REFERENCES

(1) (a) *Asymmetric Catalysis in Industrial Scale: Challenges, Approaches and Solutions*, 2nd ed; Blaser, H.-U.; Federsel, H.-J., Eds.; Wiley: Weinheim, **2010**. (b) Shang, G.; Li, W.; Zhang, X. In *Catalytic Asymmetric Synthesis, 3rd Edition*; Ojima, I., Ed.; John Wiley & Sons, Inc.: Hoboken, **2000**, pp 343–436. (c) Brown, J. M. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N.; Pfaltz, A.; Yamamoto, H., Eds.; Springer-Verlag: Berlin, **1999**; Vol. I, pp 121–182. (d) *Asymmetric Catalysis in Organic Synthesis*; Noyori, R.; Ed.; Wiley: New York, **1994**; (e) *Applied Homogeneous Catalysis with Organometallic Compounds*, 2nd edition; Cornils, B.; Herrmann, W. A., Eds.; Wiley-VCH, Weinheim, **2002**.

(2) See for example: (a) Cui, X.; Burgess, K. Catalytic Homogeneous Asymmetric Hydrogenations of Largely Unfunctionalized Alkenes. *Chem.*

Rev. **2005**, *105*, 3272–3296. (b) Roseblade, S. J.; Pfaltz, A. Iridium-Catalyzed Asymmetric Hydrogenation of Olefins. *Acc. Chem. Res.* **2007**, *40*, 1402–1411. (c) Woodmansee, D. H.; Pfaltz, A. Asymmetric Hydrogenation of Alkenes Lacking Coordinating Groups. *Chem. Commun.* **2011**, *47*, 7912–7916. (d) Zhu, Y.; Burgess, K. Filling Gaps in Asymmetric Hydrogenation Methods for Acyclic Stereocontrol: Application to Chirons for Polyketide-Derived Natural Products. *Acc. Chem. Res.* **2012**, *45*, 1623–1636. (e) Verendel, J. J.; Pàmies, O.; Diéguez, M.; Andersson, P. G. Asymmetric Hydrogenation of Olefins Using Chiral Crabtree-type Catalysts: Scope and Limitations. *Chem. Rev.* **2014**, *114*, 2130–2169. (f) Margarita, C.; Andersson, P. G. Evolution and Prospects of the Asymmetric Hydrogenation of Unfunctionalized Olefins. *J. Am. Chem. Soc.* **2017**, *139*, 1346–1356.

(3) Ru- and Rh-diphosphine catalysts require the presence of a coordinating polar group adjacent to the C=C group. See for example: (a) Genêt, J. P. In *Modern Reduction Methods*; Andersson, P. G.; Munslow, I. J.; Eds.; Wiley-VCH, Weinheim, **2008**, pp 3–38. (b) Tang, W.; Zhang, X. New Chiral Phosphorus Ligands for Enantioselective Hydrogenation. *Chem. Rev.* **2003**, *103*, 3029–3069; (c) Kitamura, M.; Noyori, R. In *Ruthenium in Organic Synthesis*; Murahashi, S.-I., Ed.; Wiley-VCH, Weinheim, **2004**, pp 3–52. (d) Weiner, B.; Szymanski, W.; Janssen, D. B.; Minnaard, A. J.; Feringa, B. L. Recent Advances in the Catalytic Asymmetric Synthesis of β-Amino Acids. *Chem. Soc. Rev.* **2010**, *39*, 1656–1691.

(4) Researchers have mainly focused on Ir catalysts with P-oxazoline ligands, although P-thiazole/oxazole/pyridine, carbene-oxazoline and more recently P-O and P-thioether ligands have also provided comparable catalytic performances. See, ref. 2.

(5) (a) Lu, S.-M.; Bolm, C. Highly Chemo- and Enantioselective Hydrogenation of Linear α,β-Unsaturated Ketones. *Chem. Eur. J.* **2008**, *14*, 7513–7516; (b) Lu, S.-M.; Bolm, C. Highly Enantioselective Synthesis of Optically Active Ketones by Iridium-Catalyzed Asymmetric Hydrogenation. *Angew. Chem. Int. Ed.* **2008**, *47*, 8920–8923; (c) Engel, J.; Mersmann, S.; Norrby, P.-O.; Bolm, C. Mechanistic Insights into the Iridium-Catalyzed Hydrogenations of α,β-Unsaturated Ketones. *ChemCatChem* **2016**, *8*, 3099–3106.

(6) Lu, S.-M.; Bolm, C. Synthesis of Sulfoximine-Derived P,N Ligands and their Applications in Asymmetric Quinoline Hydrogenations. *Adv. Synth. Catal.* **2008**, *350*, 1101–1105.

(7) Moessner, C.; Bolm, C. Diphenylphosphanylsulfoximines as Ligands in Iridium-Catalyzed Asymmetric Imine Hydrogenations. *Angew. Chem. Int. Ed.* **2005**, *44*, 7564–7567.

(8) See for example: (a) Naodovice, M.; Yamamoto, H. Asymmetric Silver-Catalyzed Reactions. *Chem. Rev.* **2008**, *108*, 3132– 3148; (b) Caine, D. In *Comprehensive Organic Synthesis*, Vol. 3; Trost, B. M., Pleming, I., Eds.; Pergamon: Oxford, 1991, pp 1–63; (c) Job, A.; Janeck, C. F.; Bettray, W.; Peters, R.; Enders, D. The SAMP-/RAMP-Hydrazone Methodology in Asymmetric Synthesis. *Tetrahedron* **2002**, 58, 2253–2329; (d) Zagozda, M.; Plenkiewicz, J. Enantioselective Reduction of α,β-Unsaturated Ketones by *Geotrichum candidum*, *Mortierella isabellina* and *Rhodotorula rubra* Yeast. *Tetrahedron: Asymmetry* **2006**, *17*, 1958 – 1962.

(9) Bolm, C. In *Asymmetric Synthesis with Chemical and Biological Methods*; Enders, D., Jaeger, K.-E., Eds.; Wiley-VCH, Weinheim, 2007; pp 149–176.

(10) See for instance: (a) Diéguez, M.; Mazuela, J.; Pàmies, O.; Verendel, J. J.; Andersson, P. G. Chiral Pyranoside Phosphite−Oxazolines: A New Class of Ligand for Asymmetric Catalytic Hydrogenation of Alkenes. *J. Am. Chem. Soc.* **2008**, *130*, 7208–7209; (b) Diéguez, M.; Mazuela, J.; Pàmies, O.; Verendel, J. J.; Andersson, P. G. Biaryl phosphite-oxazolines from hydroxyl aminoacid derivatives: highly efficient modular ligands for Ir-catalyzed hydrogenation of alkenes. *Chem. Commun.* **2008**, 3888–3890. (c) Mazuela, J.; Verendel, J. J.; Coll, M.; Schäffner, B.; Börner, A.; Andersson, P. G.; Pàmies, O.; Diéguez, M. Iridium Phosphite−Oxazoline Catalysts for the Highly Enantioselective Hydrogenation of Terminal Alkenes. *J. Am. Chem. Soc.* **2009**, *131*, 12344–13353. (d) Mazuela, J.; Norrby, P.-O; Andersson, P. G.; Pàmies, O.; Diéguez, M. Pyranoside Phosphite−Oxazoline Ligands for the Highly Versatile and Enantioselective Ir-Catalyzed Hydrogenation of Minimally Functionalized Olefins. A Combined Theoretical and Experimental Study.

J. Am. Chem. Soc. **2011**, *133*, 13634–13645. (e) Biosca, M.; Magre, M.; Pàmies, O.; Diéguez, M. Asymmetric Hydrogenation of Disubstituted, Tri-substituted, and Tetrasubstituted Minimally Functionalized Olefins and Cyclic β-Enamides with Easily Accessible Ir–P,Oxazoline Catalysts. *ACS Catal.* **2018**, *8*, 10316–10320.

(11) Mechanistic studies have shown that the efficiency and broad substrate scope of catalysts containing biaryl phosphite–based ligands is due to the adaptability of the biaryl phosphite group that allows the catalyst to adjust to the structural demands of the substrate. See for example: ref 10d.

(12) (a) Arka, P.; Surojit, S.; Joyram, G. Direct N-Acylation of Sulfoximines with Aldehydes by N-Heterocyclic Carbene Catalysis under Oxidative Conditions. *Asian J. Org. Chem.* **2016**, *5*, 870–873; (b) Brandt, J.; Gais, H.-J. An Efficient Resolution of (±)-S-Methyl-S-phenylsulfoximine with (+)-10-Camphorsulfonic Acid by the Method of Half-Quantities. *Tetrahedron: Asymmetry* **1997**, *8*, 909–912.

(13) Note that the coupling of 2-bromo-3-(methoxymethoxy)benzaldehyde **8** with sulfoximine **9** is followed by a cyclization reaction leading to corresponding MOM-protected benzothiazine **12**. Harmata, M.; Calkins, N. L.; Baughman, R. G.; Barnes, C. L. New Chiral Benzothiazine Ligand and Its Use in the Synthesis of a Chiral Receptor. *J. Org. Chem.* **2006**, *71*, 3650–3652.

(14) Ligands were isolated as white or pale-yellow solids that were manipulated and stored in air due to its high stability to oxygen and to hydrolysis.

(15) Worch, C.; Mayer, A. C; Bolm, C. In *Organosulfur Chemistry in Asymmetric Synthesis*; Toru, T., Bolm, C., Eds.; Wiley-VCH, Weinheim, 2008; pp 209–232.

(16) For successful examples on the AH of α,β-unsaturated enones, see: (a) Lu, W.-J.; Chen, Y.-W.; Hou, X.-L. Iridium-Catalyzed Highly Enantioselective Hydrogenation of the C=C Bond of α,β-Unsaturated Ketones. *Angew. Chem., Int. Ed.* **2008**, *47*, 10133–10136; (b) Verendel, J. J.; Li, J.-Q.; Quan, X.; Peters, B.; Zhou, T.; Gautun, O. R.; Govender, T.; Andersson, P. G. Chiral Hetero- and Carbocyclic Compounds from the Asymmetric Hydrogenation of Cyclic Alkenes. *Chem. Eur. J.* **2012**, *18*, 6507–6513. For examples on AH of α,β-unsaturated esters, see: (c) Wang, X.; Han, Z.; Wang, Z.; Ding, K. Catalytic Asymmetric Synthesis of Aromatic Spiroketals by SpinPhox/Iridium(I)-Catalyzed Hydrogenation and Spiroketalization of α,α-Bis(2-hydroxyarylidene) Ketones. *Angew. Chem. Int. Ed.* **2012**, *51*, 936–940; (d) Biosca, M.; Magre, M.; Coll, M.; Pàmies, O.; Diéguez, M. Alternatives to Phosphinooxazoline (t-BuPHOX) Ligands in the Metal-Catalyzed Hydrogenation of Minimally Functionalized Olefins and Cyclic β-Enamides. *Adv. Synth. Catal.* **2017**, *359*, 2801–2814. For examples on AH of α,β-unsaturated lactones and lactams, see: (e) Yue, T.-Y.; Nugent, W. A. Enantioselective Hydrogenation of 3-Alkylidenelactams: High-Throughput Screening Provides a Surprising Solution. *J. Am. Chem. Soc.* **2002**, *124*, 13692–13693; (f) Liu, X.; Han, Z.; Wang, Z.; Ding, K. SpinPhox/Iridium(I)-Catalyzed Asymmetric Hydrogenation of Cyclic α-Alkylidene Carbonyl Compounds. *Angew. Chem. Int. Ed.* **2014**, *53*, 1978–1982. For examples on AH of alkenylboronic esters, see: (g) Ganič, A.; Pfaltz, A. Iridium-Catalyzed Enantioselective Hydrogenation of Alkenylboronic Esters. *Chem. Eur. J.* **2012**, *18*, 6724–6728; (h) Coll, M.; Pàmies, O.; Diéguez, M. A Modular Furanoside Thioether-Phosphite/Phosphinite/ Phosphine Ligand Library for Asymmetric Iridium-Catalyzed Hydrogenation of Minimally Functionalized Olefins: Scope and Limitations. *Adv. Synth. Catal.* **2013**, *355*, 143–160.

(17) Buisman, G. J. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Tetrahedron: Asymmetry* **1993**, *4*, 1625

(18) Too, P. C.; Noji, T.; Lim, Y. J.; Li, X.; Chiba, S. Rhodium(III)-Catalyzed Synthesis of Pyridines from α,β-Unsaturated Ketoximes and Internal Alkynes. *Synlett* **2011**, *2011*, 2789–2794.

(19) Galambos, J.; Wágner, G.; Nógrádi, K.; Bielik, A.; Molnár, L.; Bobok, A.; Horváth, A.; Kiss, B.; Kolok, S.; Nagy, J.; Kurkó, D.; Bakk, M. L.; Vastag, M.; Sághy, K.; Gyertyán, I.; Gál, K.; Greiner, I.; Szombathelyi, Z.; Keserű, G. M.; Domány, G. Carbamoyloximes as Novel Non-competitive mGlu5 Receptor Antagonists. *Bioorg. Med. Chem. Lett.* **2010**, *20*, 4371–4375.

(20) Chen, X.; Yang, H.; Ge, Y.; Feng, L.; Jia, J.; Wang, J. Synthesis, X-Ray Crystal Structure and Optical Properties of Novel 2-Aryl-3-ethoxycarbonyl-4-phenylpyrido[1,2-a]benzimidazoles. *Luminescence* **2012**, *27*, 382–389.

(21) Li, J.-Q.; Quan, X.; Andersson, P. G. Highly Enantioselective Iridium-Catalyzed Hydrogenation of α,β-Unsaturated Esters. *Chem. Eur. J.* **2012**, *18*, 10609–1061.

(22) Fengtao, T.; Dongmei, Y.; Yuanyuan, L.; Fang, X.; Wanbin, Z. Iridium-Catalyzed Highly Enantioselective Hydrogenation of Exocyclic α,β-Unsaturated Carbonyl Compounds. *Adv. Synth. Catal.* **2010**, *352*, 1841–1845.

(23) Biosca, M.; Paptchikhine, A.; Pàmies, O.; Andersson, P. G.; Diéguez, M. Extending the Substrate Scope of Bicyclic P-Oxazoline/Thiazole Ligands for Ir-Catalyzed Hydrogenation of Unfunctionalized Olefins by Introducing a Biaryl Phosphoroamidite Group. *Chem. Eur. J.* **2015**, *21*, 3455–3464.

(24) Källström, K.; Hedberg, C.; Brandt, P.; Bayer, P.; Andersson, P. G. Rationally Designed Ligands for Asymmetric Iridium-Catalyzed Hydrogenation of Olefins. *J. Am. Chem. Soc.* **2004**, *126*, 14308–14309.

(25) Lu, W.-J.; Chen, Y.-W.; Hou, X.-L. Highly Enantioselective Iridium-Catalyzed Hydrogenation of Trisubstituted Olefins, α,β-Unsaturated Ketones and Imines with Chiral Benzylic Substituted P,N Ligands. *Adv. Synth. Catal.* **2010**, *352*, 103–107.

(26) Hou, C.-J.; Guo, W.-L.; Hu, X.-P.; Deng, J.; Zheng, Z. Chiral Ferrocenyl Phosphine-Phosphoramidite Ligands for Cu-catalyzed Asymmetric Conjugate Reduction of α,β-Unsaturated Esters. *Tetrahedron: Asymmetry* **2011**, *22*, 195–199.

(27) Giese, B.; Lachhein, S. Zum cis-Effekt bei Radikalischen Additionen an Alkene. *Chem. Ber.* **1985**, *118*, 1616–1620.

Ir-cat / H$_2$

24 examples
ee's ranging 86-99%

Ph

BAr$_F$