Electronic Supplementary Material (ESI) for Chemical Communications

Synergistic Lewis base and anion-binding catalysis for the enantioselective vinylogous addition of deconjugated butenolides to allenoates

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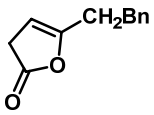
SUPPORTING INFORMATION: PART A

General: Organic solvents used for carrying out reactions were dried using standard methods. Unless stated otherwise, all reactions were carried out with distilled and dried solvents under an atmosphere of nitrogen or argon, oven (120 °C) dried glassware with standard vacuum line techniques. All work up and purification were carried out with reagent grade solvents in air. Thin layer chromatography was performed using Merck silica gel 60 F254 pre-coated plates (0.25 mm). Column chromatography was performed using silica gel (230-400 or 100-200 mesh). Infrared (FT-IR) spectra were recorded on a Perkin Elmer Spectrum BX spectrophotometer in cm^{-1} and the bands are characterized as broad (br), strong (s), medium (m), and weak (w). NMR spectra were recorded on Bruker Ultrashield spectrometer at 400 MHz (for ^{1}H-NMR) and 100 MHz (for^{13}C-NMR). Chemical shifts are reported in ppm from tetramethylsilane with the solvent resonance as internal standard ($CDCl_3$: δ 7.26, DMSO-d_6: δ 2.50 for ^{1}H-NMR and $CDCl_3$: δ 77.16, DMSO-d_6: δ 39.5 for ^{13}C-NMR). For ^{1}H-NMR, data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, dd = double doublet, t =triplet, q = quartet, br = broad, m = multiplet), coupling constants (Hz) and integration. High resolution mass spectrometry was performed on Micromass Q-TOF Micro instrument. Optical rotations were measured on JASCO P-1020 and P-2000 polarimeters. Melting points were measured using ANALAB μ-Thermocal 10 melting point apparatus. All melting points were measured in open glass capillary and values are uncorrected. Enantiomeric ratios were determined by HPLC analysis using chiral columns in comparison with authentic racemic materials.

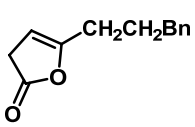
Preparation of β, γ-unsaturated butenolides:

α-Angelica lactone **1a** was obtained from Alfa Aesar and used without any further purification. Other β,γ-unsaturated butenolides **1b-h**, **1k-l** and **1o** have already been reported in literature and

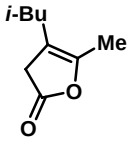
prepared accordingly.[1] The spectral data obtained are in accordance with those described in the literature.[1,2] Following the same procedure butenolides **1i-j** were also synthesized.[1a] Butenolides **1m** and **1n** were prepared according to literature procedure.[1b]



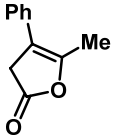
5-Phenethylfuran-2(3*H*)-one (1i): ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.31-7.27 (m; 2H), 7.22-7.17 (m; 3H), 5.08 (s; 1H), 3.14-3.13 (m; 2H), 2.87 (d, *J* = 7.6 Hz, 2H), 2.62-2.58 (m; 2H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 176.9, 156.2, 140.4, 128.6, 128.4, 126.4, 99.1, 34.0, 32.1, 30.2.



5-(3-Phenylpropyl)furan-2(3*H*)-one (1j): ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.31-7.25 (m; 2H), 7.21-7.17 (m; 3H), 5.11 (s; 1H), 3.17-3.15 (m; 2H), 2.67 (t, *J* = 7.6 Hz, 2H), 2.33-2.30 (m; 2H), 1.93-1.86 (m; 2H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 177.0, 156.9, 141.5, 128.55, 128.53, 126.1, 98.7, 35.2, 34.0, 27.8, 27.4.



4-Isobutyl-5-methylfuran-2(3*H*)-one (1m): ^{1}H-NMR (400 MHz, $CDCl_3$): δ 3.08-3.07 (m; 2H), 1.97-1.93 (m; 5H), 1.72-1.62 (m; 1H), 0.89 (d, *J* = 6.6 Hz; 6H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 176.4, 147.1, 111.6, 36.3, 34.9, 27.6, 22.4, 11.2.



5-Methyl-4-phenylfuran-2(3*H*)-one (1n): ^{1}H-NMR (400 MHz, $CDCl_3$): δ 7.40-7.36 (m; 2H), 7.29-7.24 (m; 3H), 3.55-3.54 (m; 2H), 2.23 (s; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 175.1, 148.0, 132.5, 128.9, 127.4, 127.0, 113.3, 36.5, 13.2.

Preparation of allenoates:

Methyl 2,3-butadienoate, ethyl 2,3-butadienoate, isobutyl 2,3-butadienoate, and benzyl 2,3-butadienoate are known compounds prepared using a published procedure.[3] Allenoates are prepared according to the literature procedure. The spectral data obtained are in accordance with those described in the literature.

Synthesis of thiourea catalysts: Catalysts **I-III** and **V** were prepared by following the procedure described below. Catalyst **IV** was prepared according to reported procedure and the spectral data are consistent with those reported in the literature.[4]

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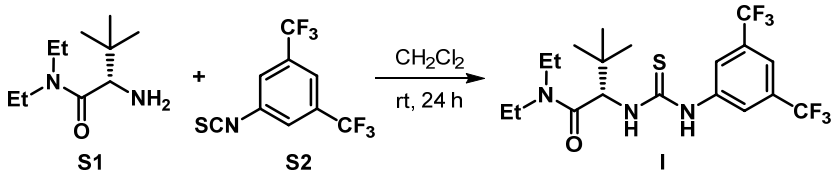
[1] (a) M. S. Manna, V. Kumar and S. Mukherjee, *Chem. Commun.*, 2012, **48**, 5193. (b) Y. Wu, R. P. Singh and L. Deng, *J. Am. Chem. Soc.*, 2011, **133**, 12458. (c) V. M. Sonpatki, M. R. Herbert, L. M. Sandvoss and A. J. Seed, *J. Org. Chem.* 2001, **66**, 7283. (d) N. A. Osman, A. H. Mahmoud, M. Allarà, R. Niess, K. A. Abouzid, V. D. Marzo and A. H. Abadi, *Bioorg. Med. Chem.* 2010, **18**, 8463.

[2] (a) W. E. Fristad, J. R. Peterson and A. B. E., *J. Org. Chem.* 1985, **50**, 3143. (b) M. E. Muratore, C. A. Holloway, A. W. Pilling, R. I. Storer, G. Trevitt and D. J. Dixon, *J. Am. Chem. Soc.*, 2009, **131**, 10796.

[3] X.-F. Zhu , C. E. Henry , J. Wang , T. Dudding and O. Kwon, *Org. Lett.*, 2005, **7**, 1387.

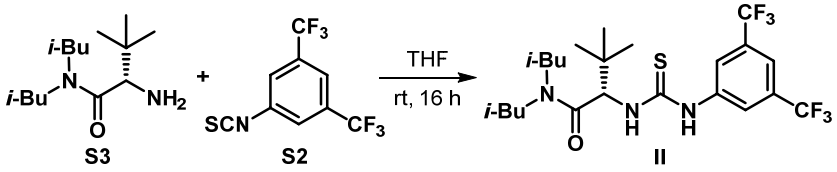
[4] I. T. Raheem, P. S. Thiara, E. A. Peterson and E. N. Jacobsen, *J. Am. Chem. Soc.*, 2007, **129**, 13404

(*S*)-2-(3-(3,5-Bis(trifluoromethyl)phenyl)thioureido)-*N*,*N*-diethyl-3,3-dimethylbutanamide (I):



Method A: To a solution of **S1** (378mg, 2.03 mmol) in DCM (1.5 mL) was added a solution of **S2** (605 mg, 2.23 mmol) in DCM (4 mL) at room temperature under argon atmosphere. The resulting mixture was stirred at rt for 24 h and concentrated under reduced pressure. The residue was purified by flash column chromatography on silica gel using EtOAc/Pet ether (1:9) as eluent to afford an off-white solid (426 mg, 0.93 mmol, 46% yield). **m.p.** 50-52 °C. **FT-IR (thin film):** 3431 (br), 2970 (w), 2874 (w), 1637 (m), 1629 (m), 1534 (m), 1458 (m), 1384 (m), 1277 (m), 1179 (m), 1133 (m). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 9.45 (s; 1H), 7.97 (s; 2H), 7.82 (d, *J* = 9.2 Hz; 1H), 7.62 (brs; 1H), 5.77 (d, *J* = 9.2 Hz; 1H), 3.88-3.79 (m; 1H), 3.75-3.66 (m; 1H), 3.38-3.29 (m; 1H), 2.98-2.89 (m; 1H), 1.31 (t, *J* = 7.2 Hz; 3H), 1.11 (s; 9H), 1.05 (t, *J* = 7.2 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 181.8, 171.6, 140.4, 131.9 (q, *J* = 33.4 Hz), 124.5, 124.4, 123.3 (q, *J* = 272.4 Hz), 118.61, 118.57, 118.53, 60.3, 43.5, 40.3, 36.8, 27.3, 14.5, 12.7. **HRMS (ESI+):** Calcd for $C_{19}H_{25}F_6N_3OSNa$ ($[M+Na]^+$): 480.1520, Found: 480.1520. **Specific rotation:** $[\alpha]_D^{24}$ –21.8 (*c* 2.0, $CHCl_3$).

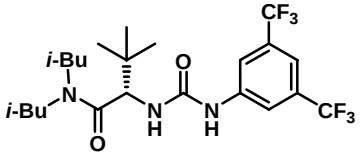
(*S*)-2-(3-(3,5-Bis(trifluoromethyl)phenyl)thioureido)-*N*,*N*-diisobutyl-3,3-dimethylbutanamide (II):



Method B: To a solution of **S3** in THF (2 mL) at rt was added **S2** in dropwise manner and the resulting mixture was stirred at rt for 16 h. After that reaction mixture was concentrated under reduced pressure to a residue which was purified by column chromatography on silica gel (100-200 mesh) using EtOAc/CH_2Cl_2 (1:9) as eluent to obtain **II** as a white amorphous solid (390 mg, 0.76 mmol, 78% yield). **m.p.** 55-57 °C. **FT-IR (KBr):** 3324 (br), 2965 (m), 2876 (w), 1606 (m), 1532 (m), 1470 (m), 1385 (m), 1278 (s), 1136 (s). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 9.42 (s; 1H), 7.97 (s; 2H), 7.82 (d, *J* = 8.8 Hz; 1H), 7.65 (s; 1H), 5.80 (d, *J* = 9.6 Hz; 1H), 3.66 (dd, *J* = 7.2, 13.2 Hz; 1H), 3.57 (dd, *J* = 8.4, 14.4 Hz; 1H), 3.06 (dd, *J* = 6.8, 14.4 Hz; 1H), 2.53 (dd, *J* = 7.6, 13.6 Hz; 1H), 2.14-2.05 (m; 1H), 1.95-1.85 (m; 1H), 1.11 (s; 9H), 0.95 (d, *J* = 6.4 Hz; 3H), 0.91

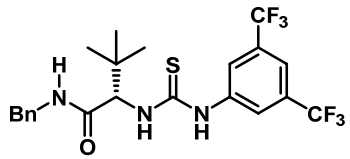
(d, *J* = 6.8 Hz; 3H), 0.81 (d, *J* = 6.4 Hz; 3H), 0.73 (d, *J* = 6.4 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 181.1, 172.5, 140.2, 132.3 (q, *J* =33.7 Hz), 124.5, 123.2 (q, *J* = 273.6 Hz), 118.8, 60.4, 56.7, 53.8, 37.8, 28.1, 27.4, 26.6, 20.7, 20.5, 20.4, 19.7. **HRMS (ESI+):** Calcd for $C_{23}H_{33}F_6N_3OSNa$ ($[M+Na]^+$): 536.2146, Found: 536.2148. **Specific rotation:** $[\alpha]_D^{23}$ –33.5 (*c* 1.0, $CHCl_3$).

(*S*)-2-(3-(3,5-Bis(trifluoromethyl)phenyl)ureido)-*N*,*N*-diisobutyl-3,3-dimethylbutanamide



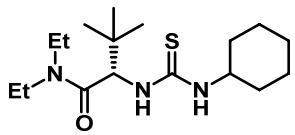
(III): Method B was adopted to obtain **III** as white amorphous solid (250 mg, 0.503 mmol, 52% yield). **m.p.**182-184 °C; **FT-IR (KBr):** 3691 (br), 3347 (m), 2965 (m), 2876 (w), 1666 (m), 1626 (m), 1574 (m), 1473 (m), 1388 (m), 1280 (s), 1183 (m), 1134 (s); **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 8.46 (s; 1H), 7.83 (s; 2H), 7.44 (s; 1H), 6.63 (d, *J* = 9.2 Hz; 1H), 4.96 (d, *J* = 9.2 Hz; 1H), 3.72 (dd, *J* = 6.8, 13.2 Hz; 1H), 3.54 (dd, *J* = 8.8, 14.0 Hz; 1H), 3.09 (dd, *J* = 6.0, 14.4 Hz; 1H), 2.66 (dd, *J* = 7.6, 13.2 Hz; 1H), 2.03-1.96 (m; 2H), 1.09 (s; 9H), 0.95 (d, *J* = 6.4 Hz; 3H), 0.90-0.87 (m; 6H), 0.78 (d, *J* = 6.4 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 173.3, 154.7, 141.3, 132.3 (q, *J* = 34.7 Hz), 123.4 (q, *J* = 273.7 Hz), 118.8, 115.5, 57.0, 56.0, 54.1, 36.8, 27.8, 27.1, 26.9, 20.6, 20.5, 20.3, 19.4. **HRMS (ESI+):** Calcd for $C_{23}H_{33}F_6N_3O_2Na$ ($[M + Na]^+$): 520.2375, Found: 520.2375. **Specific rotation:** $[\alpha]_D^{21}$ –11.4 (*c* 1.0, $CHCl_3$).

(*S*)-*N*-Benzyl-2-(3-(3,5-bis(trifluoromethyl)phenyl)thioureido)-3,3-dimethylbutanamide (V):



Method A was adopted to obtain **V** as off-white amorphous solid (163 mg, 0.33 mmol, 51% yield). **m.p.** 70-72 °C. **FT-IR (KBr):** 3435 (br), 2925 (m), 1646 (m), 1537 (w), 1385 (m), 1278 (m), 1179 (m), 1133 (m). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 9.11 (s; 1H), 7.94 (d, *J* = 8.4 Hz; 1H), 7.89 (s; 2H), 7.57 (s; 1H), 7.24-7.17 (m; 5H), 6.51 (s; 1H), 5.07 (d, *J* = 8.8 Hz; 1H), 4.47 (dd, *J* = 6.4, 14.8 Hz; 1H), 4.26 (dd, *J* = 4.8, 14.4 Hz; 1H), 1.12 (s; 9H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 182.1, 172.2, 140.1, 136.5, 131.8 (q, *J* = 33.4 Hz), 128.9, 128.8, 128.7, 128.0, 127.8, 127.6, 127.5, 124.4, 123.3 (q, *J* = 271.6 Hz), 118.6, 66.4, 44.2, 35.3, 27.3. **HRMS (ESI+):** Calcd for $C_{22}H_{23}F_6N_3OSNa$ ($[M+Na]^+$): 514.1364, Found: 514.1364. **Specific rotation:** $[\alpha]_D^{22}$ -6.8 (*c* 2, $CHCl_3$).

(*S*)-2-(3-Cyclohexylthioureido)-*N*,*N*-diethyl-3,3-dimethylbutanamide: Method A was adopted

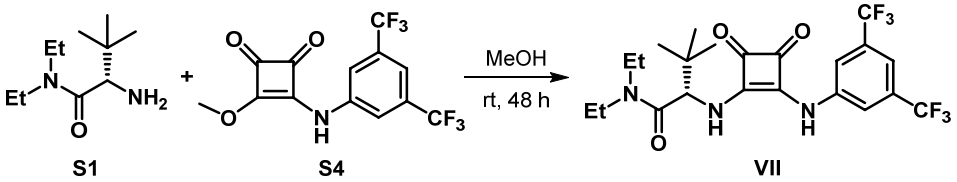


to obtain white amorphous solid (113 mg, 0.35 mmol, 58% yield), **m.p.** 153-155°C; **FT-IR (KBr):** 3328 (m), 2929 (s), 2855 (m), 1608 (m), 1538 (s), 1455 (m), 1084 (m); **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 6.55 (brs; 1H), 6.11 (d, *J* = 7.2 Hz; 1H), 5.61 (d, *J* = 9.6 Hz; 1H), 3.83-3.67 (m; 3H), 3.39-3.30 (m; 1H), 3.05-2.96 (m; 1H), 2.02-1.99 (m; 2H), 1.74-1.60 (m; 4H), 1.37-1.30 (m; 5H), 1.20-1.11 (m; 5H), 1.03 (s; 9H); **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 181.1, 171.4, 59.9, 52.7, 43.0, 40.0, 36.5, 33.0, 32.9, 27.1, 25.6,24.94, 24.88, 14.7, 12.9; **HRMS (ESI+):** Calcd for

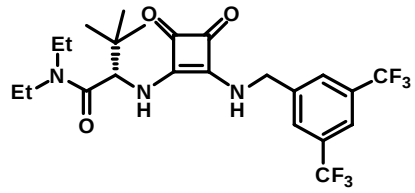
$C_{17}H_{33}N_3OSNa$ ([M + Na]$^+$): 350.2242, Found: 350.2242; **Specific rotation:** $[\alpha]_D^{21}$ –26.8 (*c* 1, $CHCl_3$).

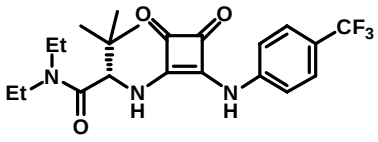
(2*S*)-*N*-Adamantan-1-yl)-2-(3-(3,5-bis(trifluoromethyl)phenyl)thioureido)-3,3-dimethylbutanamide: Method A was adopted to obtain white amorphous solid (189 mg, 0.35 mmol, 54% yield). **m.p.** 203-205°C. **FT-IR (KBr):** 3407 (br), 2913 (m), 2854 (w), 1648 (m), 1533 (m), 1385 (m), 1277 (m), 1132 (m). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 8.74 (brs; 1H), 8.11 (d, *J* = 7.6 Hz; 1H), 7.91 (brs; 2H), 7.55 (brs; 1H), 5.63 (brs; 1H), 4.89 (d, *J* = 9.2 Hz; 1H), 2.05-1.99 (m; 9H), 1.67-1.59 (m; 6H), 1.12 (s; 9H); **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 181.8, 171.6, 140.0, 131.7 (q, *J* = 33.5 Hz), 124.23, 124.22, 123.2 (q, *J* = 271.2 Hz), 118.5, 118.4, 67.1, 53.6, 41.8, 36.2, 35.0, 29.4, 27.6. **HRMS (ESI+):** Calcd for $C_{25}H_{31}F_6N_3OSNa$ ([M + Na]$^+$): 558.1990, Found: 558.1991. **Specific rotation:** $[\alpha]_D^{21}$ –36.8 (*c* 1, $CHCl_3$).

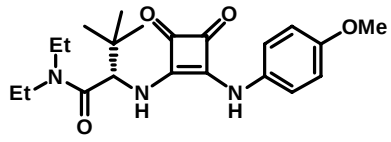
(*S*)-2-((2-((3,5-Bis(trifluoromethyl)phenyl)amino)-3,4-dioxocyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethylbutanamide (VII):

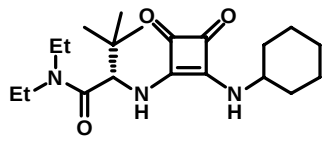


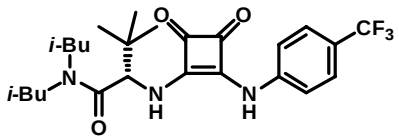
Method C: A solution of **S1** (79 mg, 0.42 mmol) in MeOH (0.6 mL) was added to a solution of **S4** (120 mg, 0.35 mmol) in MeOH (0.7 mL) at room temperature. Reaction mixture was stirred at rt till completion of reaction (48 h). Reaction mixture was concentrated under reduced pressure. The residue was purified by flash column chromatography on silica gel using EtOAc/Pet ether (7:18) as eluent to afford a light orange solid (151 mg, 0.31 mmol, 86% yield). **m.p.** 101-103 °C. **FT-IR (KBr):** 3447 (br), 3291 (m), 2969 (m), 1779 (m), 1604 (s), 1559 (s), 1438 (m), 1380 (s), 1278 (s), 1182 (m), 1134 (m); **^{1}H-NMR (400 MHz, DMSO-d_6):** δ 10.48 (s; 1H), 8.34 (d, *J* = 10.0 Hz; 1H), 8.07 (s; 2H), 7.66 (s; 1H), 5.05 (d, *J* = 10.0 Hz; 1H), 3.68-3.57 (m; 2H), 3.30-3.21 (m; 1H), 3.09-3.00 (m; 1H), 1.10 (t, *J* = 7.2 Hz; 3H), 1.06 (t, *J* = 7.2 Hz; 3H), 0.99 (s; 9H); **^{13}C-NMR (100 MHz, DMSO-d_6):** δ 184.6, 180.7, 169.1, 168.9, 162.9, 141.5, 131.8 (q, *J* = 32.7 Hz), 123.5 (q, *J* = 271.2 Hz), 118.4, 115.1, 59.1, 42.7, 36.5, 26.2, 14.9, 13.2. **HRMS (ESI+):** Calcd for $C_{22}H_{26}F_6N_3O_3$ ([M+H]$^+$): 494.1879, Found: 494.1879. **Specific rotation:** $[\alpha]_D^{21}$ –123.1 (*c* 1, $CHCl_3$).

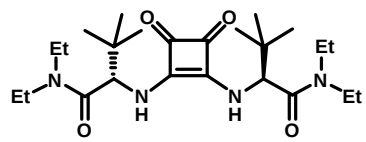
(*S*)-2-((2-((3,5-Bis(trifluoromethyl)benzyl)amino)-3,4-dioxocyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethylbutanamide (VIII):  Method C was adopted to obtain **VIII** as white solid (161 mg, 0.32 mmol, 86% yield). **m.p.** 247-249 °C. **FT-IR (KBr):** 3310 (m), 2972 (m), 1800 (w), 1664 (m), 1642 (m), 1578 (s), 1467 (w), 1345 (w), 1278 (s), 1177 (m), 1131 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 8.07-8.05 (m; 4H), 7.96 (d, *J* = 10.0 Hz; 1H), 5.03-4.86 (m; 3H), 3.64-3.50 (m; 2H), 3.29-3.20 (m; 1H), 3.05-2.96 (m; 1H), 1.07 (t, *J* = 6.8 Hz; 3H), 1.03 (t, *J* = 7.2 Hz; 3H), 0.93 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 182.94, 182.88, 169.2, 167.7, 167.5, 142.8, 130.9 (q, *J* = 32.4 Hz), 128.98, 128.95, 123.7 (q, *J* = 273.8 Hz), 121.71, 121.68, 58.4, 46.2, 42.6, 36.3, 27.6, 26.3, 14.9, 13.2. **HRMS (ESI+):** Calcd for $C_{23}H_{27}F_6N_3O_3Na$ ([M + Na]$^+$): 530.1854, Found: 530.1852. **Specific rotation:** $[\alpha]_D^{21}$ –75.9 (*c* 1, $CHCl_3$).

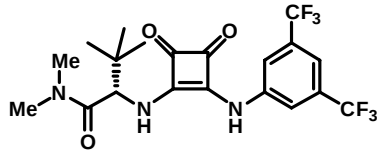
(*S*)-2-((3,4-Dioxo-2-((4-(trifluoromethyl)phenyl)amino)cyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethylbutanamide (IX):  Method C was adopted to obtain **IX** as off-white amorphous solid (152 mg, 0.36 mmol, 88% yield). **m.p.** 104-106 °C. **FT-IR (KBr):** 3449 (br s), 2966 (m), 1625 (m), 1441 (m), 1320 (m), 1262 (w), 1117 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.24 (s; 1H), 8.33 (d, *J* = 9.2 Hz; 1H), 7.69-7.62 (d, *J* = 8.6 Hz; 4H), 5.07 (d, *J* = 9.6 Hz; 1H), 3.62-3.59 (m; 2H), 3.28-3.21 (m; 1H), 3.05-3.01 (m; 1H), 1.09-1.03 (m; 6H), 0.98 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.6, 180.5, 169.0, 168.9, 163.4, 143.0, 127.1, 127.0, 124.9 (q, *J* = 271.0 Hz), 122.9 (q, *J* = 31.8 Hz), 118.4, 59.0, 42.7, 36.5, 26.3, 14.9, 13.2. **HRMS (ESI+):** Calcd for $C_{21}H_{26}F_3N_3O_3Na$ ([M + Na]$^+$): 448.1824, Found: 448.1828. **Specific rotation:** $[\alpha]_D^{24}$ –134.5 (*c* 1, $CHCl_3$).

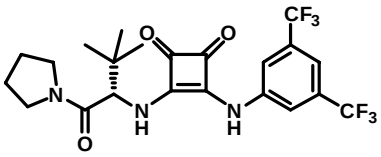
(*S*)-*N*,*N*-Diethyl-2-((2-((4-methoxyphenyl)amino)-3,4-dioxocyclobut-1-en-1-yl)amino)-3,3-dimethylbutanamide (X):  Method C was adopted to obtain **X** as light brown solid (119 mg, 0.31 mmol, 90% yield). **m.p.** 63-65 °C. **FT-IR (KBr):** 3501 (br), 2965 (m), 2873 (w), 1793 (m), 1682 (s), 1615 (s), 1515 (s), 1447 (m), 1369 (m), 1320 (m), 1245 (m), 1180 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 9.86 (s; 1H), 8.14 (d, *J* = 9.2 Hz; 1H), 7.37 (d, *J* = 8.8 Hz; 2H), 6.91 (d, *J* = 8.8 Hz; 2H), 5.08 (d, *J* = 10.0 Hz; 1H), 3.72 (s; 3H), 3.66-3.54 (m; 2H), 3.29-3.20 (m; 1H), 3.06-2.98 (m; 1H), 1.10-1.02 (m; 6H), 0.97 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 183.3, 180.7, 169.1, 168.3, 163.9, 155.7, 132.7, 120.0, 115.0, 58.8, 55.7, 42.7, 36.4, 26.3, 15.0, 13.3. **HRMS (ESI+):** Calcd for $C_{21}H_{29}N_3O_4Na$ ([M + Na]$^+$): 410.2056, Found: 410.2056. **Specific rotation:** $[\alpha]_D^{22}$ –132.6 (*c* 1, $CHCl_3$).

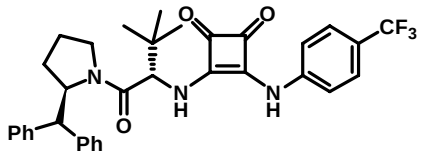
(*S*)-2-((2-(Cyclohexylamino)-3,4-dioxocyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethyl-butanamide (XI):  Method C was adopted to obtain **XI** as light brown solid (109 mg, 0.30 mmol, 63% yield). **m.p.** >250 °C. **FT-IR (KBr):** 3460 (br), 2933 (m), 2855 (m), 1798 (m), 1644 (s), 1574 (s), 1455 (m), 1368 (w), 1262 (m), 1094 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 7.80 (d, *J* = 10.0 Hz; 1H), 7.72 (d, *J* = 7.6 Hz; 1H), 5.01 (d, *J* = 10.0 Hz; 1H), 3.76-3.75 (m; 1H), 3.64-3.51 (m; 2H), 3.28-3.19 (m; 1H), 3.03-2.95 (m; 1H), 1.89-1.86 (m; 2H), 1.65 (brs; 2H), 1.34-1.24 (m; 6H), 1.08-1.01 (m; 6H), 0.93 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 182.5, 182.2, 169.4, 167.2, 167.1, 58.3, 52.2, 42.6, 36.2, 34.0, 33.9, 26.3, 25.2, 24.2, 15.0, 13.2. **HRMS (ESI+):** Calcd for $C_{20}H_{34}N_3O_3$ ([M + H]$^+$): 364.2600, Found: 364.2605. **Specific rotation:** $[\alpha]_D^{22}$ –128.9 (*c* 1, $CHCl_3$).

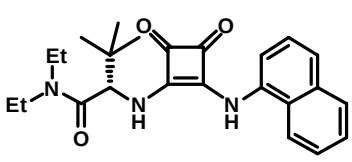
(*S*)-2-((3,4-Dioxo-2-((4-(trifluoromethyl)phenyl)amino)cyclobut-1-en-1-yl)amino)-*N*,*N*-diis-obutyl-3,3-dimethylbutanamide (XII):  Method C was adopted to obtain **XII** as off-white amorphous solid (158 mg, 0.33 mmol, 89% yield). **m.p.** 97-99 °C. **FT-IR (KBr):** 3275 (w), 2963 (m), 2874 (w), 1793 (w), 1616 (s), 1541 (s), 1437 (s), 1320 (s), 1246 (m), 1118 (s). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.27 (s; 1H), 8.35 (d, *J* = 9.6 Hz; 1H), 7.68 (d, *J* = 8.8 Hz; 2H), 7.62 (d, *J* = 8.4 Hz; 2H), 5.14 (d, *J* = 9.6 Hz; 1H), 3.71 (dd, *J* = 6.8, 13.2 Hz; 1H), 3.37 (dd, *J* = 8.8, 14.4 Hz; 1H), 3.06 (dd, *J* = 6.0, 14.4 Hz; 1H), 2.60 (dd, *J* = 7.6, 13.2 Hz; 1H), 1.98-1.81 (m; 2H), 0.97 (s; 9H), 0.89-0.87 (m; 6H), 0.83 (d, *J* = 6.4 Hz; 3H), 0.72 (d, *J* = 6.8 Hz; 3H); **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.6, 180.5, 170.2, 169.1, 163.4, 143.0, 127.07, 127.04, 124.9 (q, *J* = 269.6 Hz), 122.9 (q, *J* = 31.8 Hz), 118.4, 59.2, 56.0, 53.2, 36.9, 27.8, 26.7, 26.3, 20.8, 20.7, 20.2, 19.2. **HRMS (ESI+):** Calcd for $C_{25}H_{35}F_3N_3O_3$ ([M + H]$^+$): 482.2631, Found: 482.2633. **Specific rotation:** $[\alpha]_D^{21}$ –68.3 (*c* 1, $CHCl_3$).

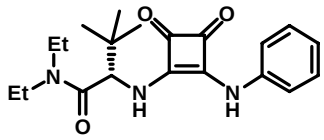
(2*S*,2'*S*)-2,2'-((3,4-Dioxocyclobut-1-ene-1,2-diyl)bis(azanediyl))bis(*N*,*N*-diethyl-3,3-dimethyl-butanamide) (XIII):  Method C was adopted to obtain **XIII** as light orange color solid (152 mg, 0.34 mmol, 96% yield). **m.p.** 189-191 °C. **FT-IR (KBr):** 3481 (m), 2969 (m), 2875 (m), 1800 (m), 1684 (m), 1622 (s), 1598 (s), 1522 (s), 1459 (m), 1363 (w), 1230 (w), 1123 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 8.20 (d, *J* = 10.0 Hz; 2H), 5.05 (d, *J* = 10.0 Hz; 2H), 3.73-3.65 (m; 2H), 3.62-3.53 (m; 2H), 3.29-3.20 (m; 2H), 3.00-2.92 (m; 2H), 1.10-1.00 (m; 12H), 0.95 (s; 18H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 182.2, 168.8, 166.6, 57.9, 42.2, 36.1, 25.9, 14.6, 12.8. **HRMS (ESI+):** Calcd for $C_{24}H_{43}N_4O_4$ ([M + H]$^+$): 451.3284, Found: 451.3281. **Specific rotation:** $[\alpha]_D^{21}$ –140.7 (*c* 1, $CHCl_3$).

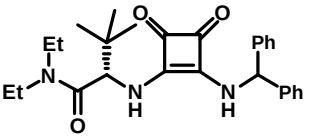
(*S*)-2-((2-((3,5-Bis(trifluoromethyl)phenyl)amino)-3,4-dioxocyclobut-1-en-1-yl)amino)-*N*,*N*,3,3-tetramethylbutanamide: 
Method C was adopted to obtain white amorphous solid (105 mg, 0.23 mmol, 77% yield). **m.p.** 130-132 °C. **FT-IR (KBr):** 3448 (br), 2925 (w), 1638 (m), 1375 (m), 1281 (m), 1274 (m), 1129 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.47 (s; 1H), 8.30 (d, *J* = 10.0 Hz; 1H), 8.07 (s; 2H), 7.66 (s; 1H), 5.17 (d, *J* = 10.0 Hz; 1H), 3.10 (s; 3H), 2.90 (s; 3H), 0.98 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.8, 180.7, 169.8, 169.2, 162.9, 141.5, 131.8 (q, *J* = 32.7 Hz), 123.6 (q, *J* = 271.3 Hz), 118.4, 115.2, 58.9, 38.2, 36.4, 35.4, 26.2. **HRMS (ESI+):** Calcd for $C_{20}H_{22}F_6N_3O_3$ ([M + H]$^+$): 466.1565, Found: 466.1565. **Specific rotation:** $[\alpha]_D^{26}$ +69.8 (*c* 1, MeOH).

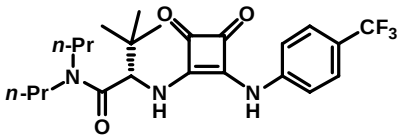
(*S*)-3-((3,5-Bis(trifluoromethyl)phenyl)amino)-4-((3,3-dimethyl-1-oxo-1-(pyrrolidin-1-yl)butan-2-yl)amino)cyclobut-3-ene-1,2-dione: 
Method C was adopted to obtain off-white amorphous solid (117 mg, 0.24 mmol, 81% yield). **m.p.** 149-151 °C. **FT-IR (KBr):** 3448 (br), 2967 (m), 2880 (w), 1795 (m), 1701 (m), 1607 (s), 1560 (s), 1481 (m), 1381 (m), 1279 (s), 1182 (s), 1133 (s). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.43 (s; 1H), 8.29 (d, *J* = 10.0 Hz; 1H), 8.05 (s; 2H), 7.64 (s; 1H), 4.89 (d, *J* = 10.0 Hz; 1H), 3.59-3.33 (m; 4H), 1.89-1.77 (m; 4H), 0.98 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.8, 180.7, 169.3, 168.1, 162.9, 141.5, 131.8 (q, *J* = 32.6 Hz), 123.5 (q, *J* = 271.2 Hz), 118.42, 118.39, 115.1, 61.6, 47.4, 45.9, 36.2, 26.1, 26.0, 24.2. **HRMS (ESI+):** Calcd for $C_{22}H_{24}F_6N_3O_3$ ([M + H]$^+$): 492.1722, Found: 492.1726. **Specific rotation:** $[\alpha]_D^{25}$ –10.8 (*c* 1, MeOH).

3-(((*S*)-1-((*R*)-2-Benzhydrylpyrrolidin-1-yl)-3,3-dimethyl-1-oxobutan-2-yl)amino)-4-((4-(trifluoromethyl)phenyl)amino)cyclobut-3-ene-1,2-dione: 
Method C was adopted to obtain light brown solid (47 mg, 0.08 mmol, 83% yield). **FT-IR (KBr):** 3276 (br), 2962 (w), 1794 (w), 1612 (m), 1578 (m), 1437 (m), 1320 (s), 1268 (w), 1118 (m), 1068 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.21 (s; 1H), 8.03(d, *J* = 10.0 Hz; 1H), 7.77-7.70 (m; 4H), 7.20-7.11 (m; 9H), 6.96 (t, *J* = 6.8 Hz; 1H), 4.98 (t, *J* = 6.8 Hz; 1H), 4.79 (d, *J* = 10.4 Hz; 1H), 4.46 (d, *J* = 6.8 Hz; 1H), 3.59-3.52 (m; 1H), 2.04-1.96 (m; 2H), 1.79-1.75 (m; 2H), 1.46-1.38 (m; 1H), 0.99 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.6, 180.5, 169.05, 169.0, 163.4, 143.0, 127.1, 127.0, 124.9 (q, *J*= 269.4 Hz), 122.9 (q, *J* = 32.1 Hz), 118.4, 59.0, 42.7, 36.5, 26.3, 14.9, 13.2. **HRMS (ESI+):** $C_{34}H_{34}F_3N_3O_3Na$ ([M + Na]$^+$): 612.2450, Found: 612.2451. **Specific rotation:** $[\alpha]_D^{22}$ –207.2 (*c* 0.5, $CHCl_3$).

(*S*)-*N*,*N*-Diethyl-3,3-dimethyl-2-((2-(naphthalen-1-ylamino)-3,4-dioxocyclobut-1-en-1-yl)amino)butanamide:  Method C was adopted to obtain light brown solid (156 mg, 0.38 mmol, 97% yield). **m.p.** 188-190 °C. **FT-IR (KBr):** 3282 (m), 2963 (m), 2868 (m), 1794 (m), 1677 (m), 1642 (m), 1582 (s), 1534 (s), 1437 (m), 1398 (m), 1140 (w), 1070 (w). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.07 (s; 1H), 8.54 (d, *J* = 9.2 Hz; 1H), 8.17 (d, *J* = 8.4 Hz; 1H), 7.97 (d, *J* = 8.0 Hz; 1H), 7.71-7.48 (m; 5H), 5.17 (d, *J* = 9.6 Hz; 1H), 3.70-3.61 (m; 2H), 3.30-3.26 (m; 1H), 3.07-3.02 (m; 1H), 1.13 (t, *J* = 7.2 Hz; 3H), 1.08 (t, *J* = 7.2 Hz; 3H), 1.03 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 185.0, 180.5, 169.3, 169.2, 164.5, 134.1, 133.7, 128.8, 126.8, 126.6, 126.2, 125.7, 124.2, 122.2, 117.9, 58.8, 42.7, 36.5, 26.4, 15.0, 13.3. **HRMS (ESI+):** Calcd for $C_{24}H_{29}N_3O_3Na$ ([M + Na]$^+$): 430.2107, Found: 430.2110. **Specific rotation:** $[\alpha]_D^{20}$ -119.1 (*c* 1, $CHCl_3$).

(*S*)-2-((3,4-Dioxo-2-(phenylamino)cyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethylbutanamide:  Method C was adopted to obtain off-white amorphous solid (92 mg, 0.26 mmol, 83% yield). **m.p.** 111-113 °C. **FT-IR (KBr):** 3468 (br), 2966 (m), 2872 (w), 1797 (m), 1694 (m), 1683 (m), 1622 (m), 1581 (m), 1538 (s), 1455 (s), 1435 (s), 1258 (w), 1111 (w). **^{1}H-NMR (400 MHz,DMSO-d$_6$):** δ 9.98 (s; 1H), 8.25 (d, *J* = 9.6 Hz; 1H), 7.46 (d, *J* = 8.0 Hz; 2H), 7.34 (t, *J* = 7.7 Hz; 2H), 7.02 (t, *J* = 7.2 Hz; 1H), 5.09 (d, *J* = 10.0 Hz; 1H), 3.67-3.55 (m; 2H), 3.30-3.21 (m; 1H), 3.07-2.99 (m; 1H), 1.09 (t, *J* = 6.8 Hz; 3H), 1.05 (t, *J* = 7.2 Hz; 3H), 0.98 (s; 9H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 183.5, 180.2, 168.7, 168.2, 163.5, 139.0, 129.4, 122.7, 118.0, 58.4, 42.3, 36.0, 25.9, 14.6, 12.9. **HRMS (ESI+):** Calcd for $C_{20}H_{27}N_3O_3Na$ ([M + Na]$^+$): 380.1950, Found: 380.1952. **Specific rotation:** $[\alpha]_D^{21}$ –167.9 (*c* 1, $CHCl_3$).

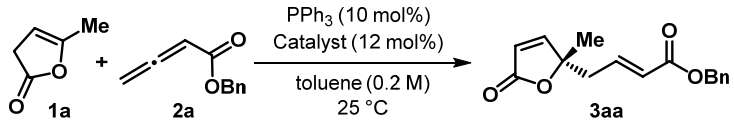
(*S*)-2-((2-(Benzhydrylamino)-3,4-dioxocyclobut-1-en-1-yl)amino)-*N*,*N*-diethyl-3,3-dimethylbutanamide:  Method C was adopted to obtain off-white amorphous solid (112 mg, 0.25 mmol, 73% yield). **m.p.** 216-218 °C. **FT-IR (KBr):** 3455 (br s), 2965 (w), 2870 (w), 1648 (m), 1591 (m), 1443 (w), 1356 (w), 1235 (w), 1123 (w). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 8.53 (d, *J* = 8.8 Hz; 1H), 7.92 (d, *J* = 10.0 Hz; 1H), 7.42-7.29 (m; 10H), 6.38 (d, *J* = 8.8 Hz; 1H), 5.01 (d, *J* = 10.0 Hz; 1H), 3.66-3.54 (m; 2H), 3.28-3.21 (m; 1H), 3.03-2.94 (m; 1H), 1.09-1.02 (m; 6H), 0.95 (s; 9H); **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 183.0, 182.6, 169.3, 167.5, 166.8, 142.6, 142.3, 129.25, 129.22, 128.0, 127.9, 127.3, 127.1, 60.8, 58.4, 42.6, 36.4, 26.3, 14.9, 13.2. **HRMS (ESI+):** Calcd for $C_{27}H_{33}N_3O_3Na$ ([M + Na]$^+$): 470.2420, Found: 470.2421. **Specific rotation:** $[\alpha]_D^{21}$ –91.3 (*c* 1, $CHCl_3$).

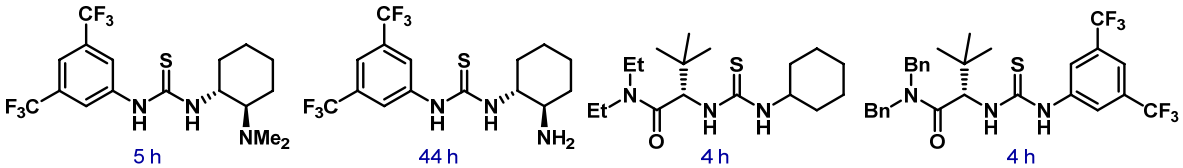
(*S*)-2-((3,4-Dioxo-2-((4-(trifluoromethyl)phenyl)amino)cyclobut-1-en-1-yl)amino)-3,3-dimethyl-*N*,*N*-dipropylbutanamide: 

Method C was adopted to obtain off-white amorphous solid (140 mg, 0.31 mmol, 84% yield). **m.p.** 92-94 °C. **FT-IR (KBr):** 3445 (br), 2964 (m), 2876 (w), 1798 (w), 1615 (m), 1539 (m), 1446 (m), 1320 (s), 1118 (m), 1068 (m). **^{1}H-NMR (400 MHz, DMSO-d$_6$):** δ 10.25 (s; 1H), 8.35 (d, *J* = 10.0 Hz; 1H), 7.69 (d, *J* = 8.8 Hz; 2H), 7.63 (d, *J* = 8.8 Hz; 2H), 5.10 (d, *J* = 10.0 Hz; 1H), 3.66-3.62 (m; 1H), 3.51-3.47 (m; 1H), 3.17-3.12 (m; 1H), 2.91-2.84 (m; 1H), 1.58-1.39 (m; 4H), 0.98 (s; 9H), 0.87-0.81 (m. 6H). **^{13}C-NMR (100 MHz, DMSO-d$_6$):** δ 184.6, 180.5, 169.4, 169.1, 163.4, 143.0, 127.09, 127.05, 124.9 (q, *J* = 270.0 Hz), 122.9 (q, *J* = 32.0 Hz), 118.4, 59.0, 50.1, 47.4, 36.6, 26.3, 22.6, 20.9, 11.8, 11.1. **HRMS (ESI+):** Calcd for $C_{23}H_{30}F_3N_3O_3Na$ ($[M + Na]^+$): 476.2137, Found: 476.2130. **Specific rotation:** $[\alpha]_D^{22}$ –75.1 (*c* 1, $CHCl_3$).

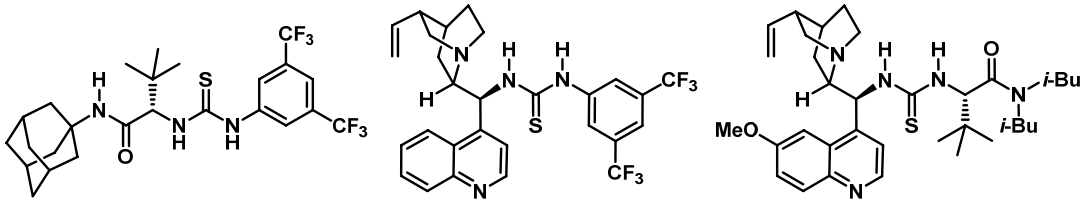
- **Catalyst optimization for enantioselective vinylogous addition of deconjugated butenolides to allenoates:**

1. Screening of thiourea catalysts



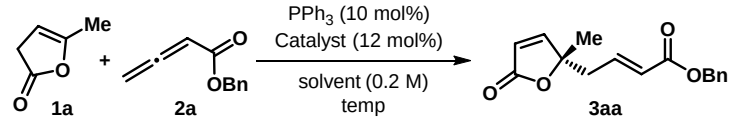


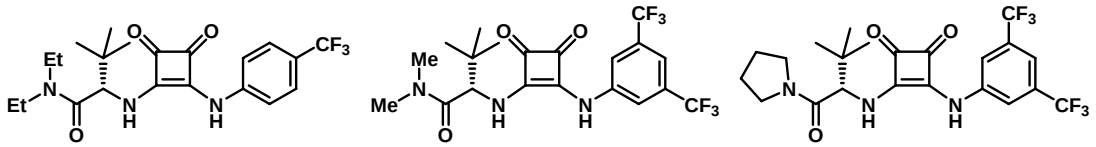
5 h, 50:50 er | 44 h, 50:50 er | 4 h, 64.5:35.5 er | 4 h, 60:40 er



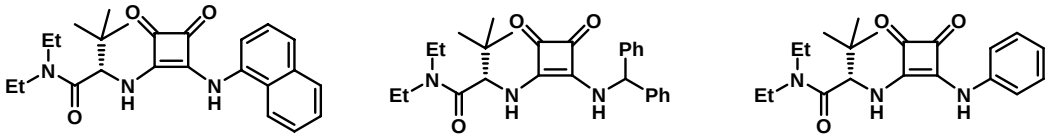
12 h, 59:41 er | 3 h, 51.5:48.5 er | 72 h, 56:44 er

2. Screening of squaramide catalysts

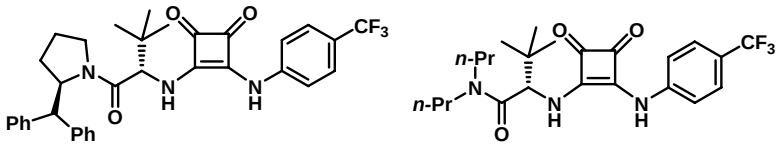




toluene, 25 °C, 7 h, 81.5:18.5 er | toluene, 10 °C, 8 h, 79.5:20.5 er | toluene, 10 °C, 6 h, 80:20 er

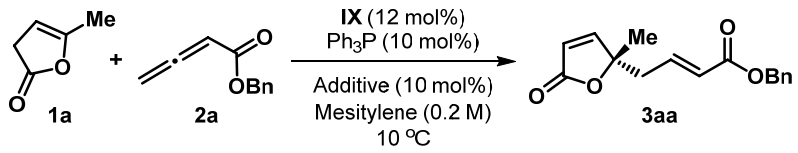


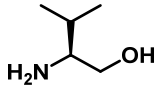
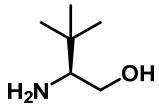
toluene, 25 °C, 7 h, 81.5:18.5 er | toluene, 25 °C, 6 h, 81:19 er | toluene, 25 °C, 8 h, 80.5:19.5 er



toluene, 25 °C, 9 h, 67.5:32.5 er | mesitylene, 10 °C, >48 h, 87.5:12.5 er

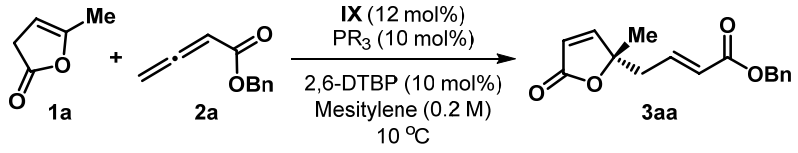
3. Screening of additives:



Entry	Additive	Time (h)	er
1	C_6H_5OH	12	85.5:14.5
2	**2,6-DTBP**[a]	**10**	**88.5:11.5**
3	2-ClC_6H_4OH	10	84.5:15.5
4	$C_6H_5CH_2OH$	10	86.5:13.5
5	2-$OHC_6H_4CH_2OH$	10	86.5:13.5
6	2-$MeOC_6H_4OH$	10	85:15
7	2-$H_2NC_6H_4OH$	10	88:12
8	8-Hydroxyquinoline	10	88:12
9	$C_6H_5NH_2$	10	87.5:12.5
10	CF_3CH_2OH	10	87.5:12.5
11	*t*-BuOH	>18[b]	87.5:12.5
12		10	87:13
13		22	87:13
14	Cupreine	22	88:12

[a] 2,6-DTBP = 2,6-di-*tert*-butylphenol. [b] Reaction not complete.

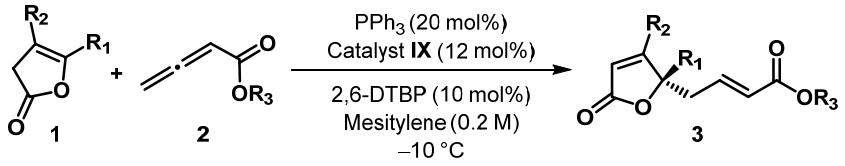
4. Screening of phosphines:



S.N.	PR_3	Time (h)	er
1	$(2\text{-}MeC_6H_4)_3P$	24	–[a]
2	$(4\text{-}MeC_6H_4)_3P$ (20 mol%)	21	79:21
3	$(4\text{-}FC_6H_4)_3P$ (20 mol%)	21	90.5:9.5
4	$(4\text{-}FC_6H_4)_3P$ (20 mol%)[b]	48	91:9
5	Ph_3P (20 mol%)[b]	72	91:9

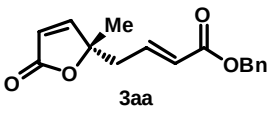
[a] No reaction. [b] Reaction was performed at –10 °C

Typical procedure for the enantioselective vinylogous addition of deconjugated butenolides to allenoates



In an oven dried reaction tube, **1** (0.15 mmol), **2** (0.225 mmol), **IX** (0.018 mmol) and 2,6-di-*tert*-butylphenol (0.015 mmol) were taken in mesitylene (0.45 mL). The tube was degassed in vacuum and cooled to –10 °C under argon. After 15 min a solution of PPh_3 (0.015 mmol) in mesitylene (0.3 mL) was added. The resulting solution was stirred at –10°C. After consumption of PPh_3 (typically after 24 h), a second batch of PPh_3 (0.015 mmol) was added in one portion as solid and reaction mixture was allowed to stir at the same temperature. After the completion of reaction, reaction mixture was directly loaded on a pre-packed column without any work-up. Purification was achieved by column chromatography on silica gel (230-400 mesh) using petroleum ether/EtOAc mixture as eluent.

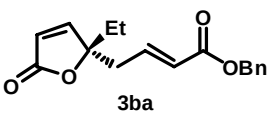
Benzyl (*S*,*E*)-4-(2-methyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3aa): Purification by silica gel (230-400 mesh) column chromatography (28% EtOAc in pet ether) afforded pure **3aa** as colorless oil (28 mg, 0.102 mmol, 68% yield).



3aa

FT-IR (thin film): 2960 (w), 2925 (m), 1755 (s), 1716 (s), 1658 (m), 1262 (s), 1109 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.38-7.33 (m; 6H), 6.86-6.78 (m; 1H), 6.07 (d, *J* = 5.6 Hz; 1H), 5.96 (d, *J* = 15.6 Hz; 1H), 5.17 (s; 2H), 2.69-2.59 (m; 2H), 1.49 (s; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.8, 165.5, 159.4, 141.1, 135.8, 128.7, 128.40, 128.37, 125.9, 121.5, 87.4, 66.5, 41.2, 23.9. **HRMS (ESI+):** Calcd for $C_{16}H_{16}O_4Na$ ($[M + Na]^+$): 295.0946, Found: 295.0944. **Specific rotation:** $[\alpha]_D^{21}$ +29.2 (*c* 1, $CHCl_3$) for a sample with 91:9 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 8.5 min, τ_{minor} = 9.3 min). See Supporting Information: Part B for HPLC chromatograms.

Benzyl (*S*,*E*)-4-(2-ethyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ba): Purification by silica gel (230-400 mesh) column chromatography (26% EtOAc in pet ether) afforded pure **3ba** as colorless oil (33 mg, 0.115 mmol, 77% yield).

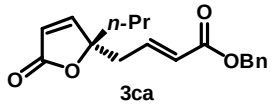


3ba

FT-IR (thin film): 2974 (w), 2883 (w), 1763 (s), 1720 (s), 1657 (w), 1267 (m), 1078 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.37-7.32 (m; 5H), 7.30 (d, *J* = 5.6 Hz; 1H), 6.84-6.76 (m; 1H), 6.11 (d, *J* = 5.6 Hz; 1H), 5.95 (dt, *J* = 1.2, 15.6 Hz; 1H), 5.16 (s; 2H), 2.71-2.60 (m; 2H), 1.94-1.85 (m; 1H), 1.82-1.73 (m; 1H), 0.86 (t, *J* = 7.4 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.5, 158.1, 141.2, 135.9, 128.7, 128.40, 128.38, 125.8, 122.5, 90.2, 66.5, 39.8, 29.8, 7.7. **HRMS (ESI+):** Calcd for $C_{17}H_{18}O_4Na$ ($[M + Na]^+$): 309.1103, Found: 309.1102.

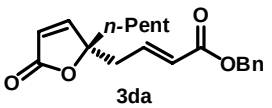
Specific rotation: $[\alpha]_D^{21}$ +38.8 (*c* 2, $CHCl_3$) for a sample with 90:10 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 7.9 min, τ_{minor} = 8.9 min). See Supporting Information: Part B for HPLC chromatograms.

Benzyl (*S*,*E*)-4-(5-oxo-2-propyl-2,5-dihydrofuran-2-yl)but-2-enoate (3ca): Purification by silica gel (230-400 mesh) column chromatography (24% EtOAc in pet ether) afforded pure **3ca** as colorless oil (33.6 mg, 0.112 mmol, 75% yield). **FT-IR (thin film):** 2961 (w), 2875 (w), 1752 (s), 1720 (s), 1656 (w), 1266 (m), 1016 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.37-7.31 (m; 6H), 6.84-6.77 (m; 1H), 6.09 (d, *J* = 6.0 Hz; 1H), 5.95 (dt, *J* = 1.2, 15.6 Hz; 1H), 5.17 (s; 2H), 2.67-2.63 (m; 2H), 1.83-1.79 (m; 1H), 1.74-1.70 (m; 1H), 1.29-1.23 (m; 2H), 0.91 (t, *J* = 7.2 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.5, 158.4, 141.2, 135.9, 128.7, 128.40, 128.38, 125.8, 122.2, 90.0, 66.5, 40.1, 38.8, 16.8, 14.1. **HRMS (ESI+):** Calcd for $C_{18}H_{20}O_4Na$ ($[M + Na]^+$): 323.1259, Found: 323.1254. **Specific rotation:** $[\alpha]_D^{21}$ +26.9 (*c* 2, $CHCl_3$) for a sample with 90:10 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 12.0 min, τ_{minor} = 17.4 min). See Supporting Information: Part B for HPLC chromatograms.



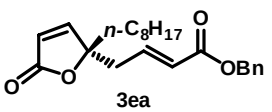
3ca

Benzyl (*S*,*E*)-4-(5-oxo-2-pentyl-2,5-dihydrofuran-2-yl)but-2-enoate (3da): Purification by silica gel (230-400 mesh) column chromatography (24% EtOAc in pet ether) afforded pure **3da** as colorless oil (37 mg, 0.113 mmol, 75% yield). **FT-IR (thin film):** 2953 (m), 2860 (w), 1752 (s), 1720 (s), 1656 (w), 1266 (m), 1018 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.37-7.30 (m; 6H), 6.84-6.76 (m; 1H), 6.09 (d, *J* = 5.6 Hz; 1H), 5.94 (dt, *J* = 1.2, 15.6 Hz; 1H), 5.17 (s; 2H), 2.67-2.63 (m; 2H), 1.83-1.79 (m; 1H), 1.73-1.67 (m; 1H), 1.29-1.17 (m; 6H), 0.86 (t, *J* = 6.8 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.5, 158.4, 141.2, 135.9, 128.7, 128.40, 128.38, 125.8, 122.2, 90.0, 66.5, 40.1, 36.7, 31.7, 23.0, 22.5, 14.0. **HRMS (ESI+):** Calcd for $C_{20}H_{24}O_4Na$ ($[M + Na]^+$): 351.1572, Found: 351.1572. **Specific rotation:** $[\alpha]_D^{21}$ +24.7 (*c* 2, $CHCl_3$) for a sample with 89:11 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 7.2 min, τ_{minor} = 9.1 min). See Supporting Information: Part B for HPLC chromatograms.



3da

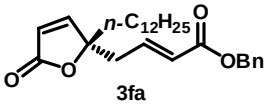
Benzyl (*S*,*E*)-4-(2-octyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ea): Purification by silica gel (230-400 mesh) column chromatography (22% EtOAc in pet ether) afforded pure **3ea** as colorless oil (37 mg, 0.0998 mmol, 67% yield). **FT-IR (thin film):** 2927 (w), 2855 (w), 1751 (s), 1723 (s), 1266 (m), 1168 (m), 1016 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.37-7.30 (m; 6H), 6.84-6.76 (m; 1H), 6.09 (d, *J* = 6.0 Hz; 1H), 5.95 (dt, *J* = 1.2, 16.8 Hz; 1H), 5.17 (s; 2H), 2.67-2.63 (m; 2H), 1.83-1.80 (m; 1H),



3ea

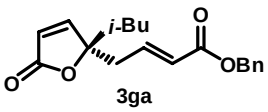
1.73-1.70 (m; 1H), 1.30-1.16 (m; 12H), 0.87 (t, J = 6.8 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.6, 158.4, 141.2, 135.9, 128.7, 128.43, 128.40, 125.8, 122.2, 90.0, 66.5, 40.2, 36.8, 31.9, 29.6, 29.4, 29.2, 23.4, 22.7, 14.2. **HRMS (ESI+):** Calcd for $C_{23}H_{30}O_4Na$ ($[M + Na]^+$): 393.2042, Found: 393.2040. **Specific rotation:** $[\alpha]_D^{21}$ +16.5 (*c* 2, $CHCl_3$) for a sample with 92:8 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (90:10 *n*-Hexane/EtOH, 1.5 mL/min, 20 °C, 210 nm, τ_{major} = 11.6 min, τ_{minor} = 12.9 min). See Supporting Information: Part B for HPLC chromatograms.

Benzyl (*S*,*E*)-4-(2-dodecyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3fa): Purification by silica gel (230-400 mesh) column chromatography (18% EtOAc in pet ether) afforded pure **3fa** as colorless oil (61 mg, 0.143 mmol, 95% yield). **FT-IR (thin film):** 2925 (s), 2854 (m), 1750 (s), 1733 (s), 1267 (m), 1004 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.36-7.31 (m; 6H), 6.84-6.76 (m; 1H), 6.09 (d, J = 5.6 Hz; 1H), 5.95 (d, J = 15.6 Hz; 1H), 5.17 (s; 2H), 2.70-2.60 (m; 2H), 1.87-1.80 (m; 1H), 1.74-1.71 (m; 1H), 1.29-1.24 (m; 20H), 0.88 (t, J = 6.4 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.5, 158.4, 141.2, 135.9, 128.7, 128.41, 128.38, 125.8, 122.2, 90.0, 66.5, 40.2, 36.8, 32.0, 29.73, 29.68, 29.62, 29.58, 29.47, 29.44, 23.4, 22.8, 14.2. **HRMS (ESI+):** Calcd for $C_{27}H_{38}O_4Na$ ($[M + Na]^+$): 449.2668, Found: 449.2669. **Specific rotation:** $[\alpha]_D^{22}$ +13.2 (*c* 2, $CHCl_3$) for a sample with 91.5:8.5 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (90:10 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 13.9 min, τ_{minor} = 16.0 min). See Supporting Information: Part B for HPLC chromatograms.



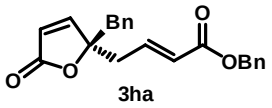
3fa

Benzyl (*S*,*E*)-4-(2-isobutyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ga): Purification by silica gel (230-400 mesh) column chromatography (22% EtOAc in pet ether) afforded pure **3ga** as colorless oil (38.4 mg, 0.122 mmol, 81% yield). **FT-IR (thin film):** 2956 (w), 2924 (w), 1751 (s), 1719 (s), 1655 (w), 1265 (m), 1010 (w). **^{1}H-MR (400 MHz, $CDCl_3$):** δ 7.37-7.32 (m; 6H), 6.82-6.75 (m; 1H), 6.09 (d, J = 5.6 Hz; 1H), 5.94 (dt, J = 1.6, 15.6 Hz; 1H), 5.17 (s; 2H), 2.66-2.60 (m; 2H), 1.84-1.79 (m; 1H), 1.64-1.56 (m; 2H), 0.91-0.89 (m; 6H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.5, 158.7, 141.2, 135.9, 128.7, 128.40, 128.36, 125.9, 122.1, 90.1, 66.5, 45.4, 40.9, 24.3, 24.1, 23.9. **HRMS (ESI+):** Calcd for $C_{19}H_{22}O_4Na$ ($[M + Na]^+$): 337.1416, Found: 337.1411. **Specific rotation:** $[\alpha]_D^{21}$ +34.3(*c* 2, $CHCl_3$) for a sample with 90:10 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{minor} = 11.6 min, τ_{major} = 16.5 min). See Supporting Information: Part B for HPLC chromatograms.



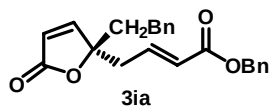
3ga

Benzyl (*R*,*E*)-4-(2-benzyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ha): Purification by silica gel (230-400 mesh) column chromatography (24% EtOAc in pet ether) afforded pure **3ha** as colorless thick oil (44 mg, 0.126 mmol, 84% yield). **FT-IR (thin film):** 2921(w), 2852 (w), 1751 (s), 1718 (s), 1654 (m), 1264 (m), 1090 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.35-7.23 (m; 9H), 7.13 (d, *J* = 6.8 Hz; 2H), 6.86-6.78 (m; 1H), 5.98-5.93 (m; 2H), 5.17 (s; 2H), 3.13 (d, *J* = 14.0 Hz; 1H), 3.04 (d, *J* =14.0 Hz; 1H), 2.76-2.62 (m; 2H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.6, 165.5, 157.8, 140.9, 135.9, 133.9, 130.4, 128.7, 128.6, 128.41, 128.37, 127.5, 126.1, 122.7, 89.4, 66.5, 43.7, 39.6. **HRMS (ESI+):** Calcd for $C_{22}H_{20}O_4Na$ ($[M + Na]^+$): 371.1259, Found: 371.1257. **Specific rotation:** $[\alpha]_D^{22}$ –3.97 (*c* 1.5, $CHCl_3$) for a sample with 82:18 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 9.2 min, τ_{minor} = 10.9 min). See Supporting Information: Part B for HPLC chromatograms.



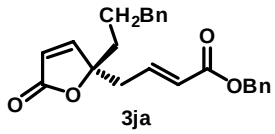
3ha

Benzyl (*S*,*E*)-4-(5-oxo-2-phenethyl-2,5-dihydrofuran-2-yl)but-2-enoate (3ia): Purification by silica gel (230-400 mesh) column chromatography (24% EtOAc in pet ether) afforded pure **3ia** as colorless oil (38 mg, 0.105 mmol, 70% yield). **FT-IR (thin film):** 2920 (w), 2851 (w), 1731 (s), 1720 (s), 1633 (s), 1258 (w), 1016 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.36-7.11 (m; 11H), 6.85-6.78 (m; 1H), 6.12 (d, *J* = 5.6 Hz; 1H), 5.96 (d, *J* = 15.6 Hz; 1H), 5.17 (s; 2H), 2.71-2.57 (m; 3H), 2.53-2.48 (m; 1H), 2.21-2.15 (m; 1H), 2.07-201 (m; 1H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.9, 165.5, 158.1, 140.8, 140.4, 135.9, 128.75, 128.70, 128.43, 128.39, 126.5, 126.1, 122.5, 89.5, 66.5, 40.3, 38.5, 29.7. **HRMS (ESI+):** Calcd for $C_{23}H_{22}O_4Na$ ($[M + Na]^+$): 385.1416, Found: 385.1418. **Specific rotation:** $[\alpha]_D^{25}$ +0.3 (*c* 2, $CHCl_3$) for a sample with 86.5:13.5 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (90:10 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 254 nm, τ_{major} = 21.3 min, τ_{minor} = 22.7 min). See Supporting Information: Part B for HPLC chromatograms.



3ia

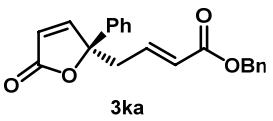
Benzyl (*S*,*E*)-4-(5-oxo-2-(3-phenylpropyl)-2,5-dihydrofuran-2-yl)but-2-enoate (3ja): Purification by silica gel (230-400 mesh) column chromatography (28% EtOAc in pet ether) afforded pure **3ja** as colorless oil (52.6 mg, 0.140 mmol, 93% yield). **FT-IR (thin film):** 2925 (w), 2855 (w), 1751 (s), 1735 (s), 1265 (m), 1018 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.38-7.34 (m; 5H), 7.28-7.25 (m; 3H), 7.20-7.11 (m; 3H), 6.79-6.73 (m; 1H), 6.08 (d, *J* = 5.6 Hz; 1H), 5.93 (d, *J* = 15.6 Hz; 1H), 5.17 (s; 2H), 2.65-2.58 (m; 4H), 1.89-1.85 (m; 1H), 1.77-1.70 (m; 1H), 1.65-1.59 (m; 1H), 1.54-1.48 (m; 1H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.9, 165.5, 158.2, 141.3, 140.9, 135.9, 128.7, 128.6, 128.42, 128.39, 126.2, 125.9, 122.4, 89.7, 66.5, 40.1, 36.2, 35.6, 25.2. **HRMS (ESI+):** Calcd for $C_{24}H_{24}O_4Na$ ($[M + Na]^+$): 399.1572, Found: 399.1573. **Specific**



3ja

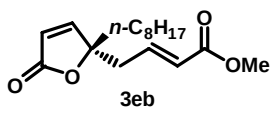
rotation: $[\alpha]_D^{26}$ +12.5 (*c* 2, $CHCl_3$) for a sample with 90:10 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 10.4 min, τ_{minor} = 13.2 min). See Supporting Information: Part B for HPLC chromatograms.

Benzyl (*S*,*E*)-4-(5-oxo-2-phenyl-2,5-dihydrofuran-2-yl)but-2-enoate (3ka): Purification by silica gel (230-400 mesh) column chromatography (4% EtOAc in toluene) afforded pure **3ka** as thick oil (23 mg, 0.069 mmol, 45% yield). **FT-IR (thin film):** 2955 (w), 2925 (w), 1747 (s), 1224 (s), 1100 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.66 (d, *J* = 5.6 Hz; 1H), 7.42-7.34 (m; 10H), 6.79-6.71 (m, 1H), 6.13 (d, *J* = 5.6 Hz; 1H), 5.92 (d, *J* = 15.6 Hz; 1H), 5.14 (s; 2H), 3.06-3.01 (m; 1H), 2.93-2.88 (m; 1H). **^{13}C-NMR (100 MHz, CDCl3):** δ 171.6, 165.5, 158.2, 140.6, 138.0, 135.9, 129.2, 128.8, 128.7, 128.4, 128.3, 126.1, 125.1, 121.1, 90.1, 66.5, 42.5. **HRMS (ESI+):** Calcd for $C_{21}H_{18}O_4Na$ ([M + Na]$^+$): 357.1103, Found: 357.1107. **Specific rotation:** $[\alpha]_D^{24}$ –11.5 (*c* 1, $CHCl_3$) for a sample with 61:39 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 9.2 min, τ_{minor} = 12.6 min). See Supporting Information: Part B for HPLC chromatograms.



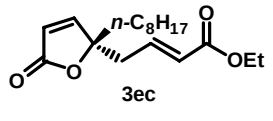
3ka

Methyl (*S*,*E*)-4-(2-octyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3eb): Purification by silica gel (230-400 mesh) column chromatography (22% EtOAc in pet ether) afforded pure**3eb** as colorless oil (32 mg, 0.109 mmol, 72% yield). **FT-IR (thin film):** 2927 (s), 2855 (m), 1757 (s), 1734 (s), 1654 (w), 1274 (m), 1018 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.31 (d, *J* = 4.8 Hz; 1H), 6.78-6.70 (m; 1H), 6.08 (d, *J* = 5.2 Hz; 1H), 5.89 (d, *J* = 15.6 Hz; 1H), 3.71 (s; 3H), 2.70-2.62 (m; 2H), 1.85-1.80 (m; 1H), 1.73-1.66 (m; 1H), 1.27-1.18 (m; 12H), 0.86 (t, *J* = 6.4 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 166.2, 158.4, 140.8, 125.7, 122.2, 90.0, 51.8, 40.1, 36.8, 31.9, 29.6, 29.4, 29.2, 23.4, 22.7, 14.2. **HRMS (ESI+):** Calcd for $C_{17}H_{26}O_4Na$ ([M + Na]$^+$): 317.1729, Found: 317.1727. **Specific rotation:** $[\alpha]_D^{25}$ +18.7 (*c* 1, $CHCl_3$) for a sample with 91:9 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (90:10 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{minor} = 15.4 min, τ_{major} = 17.3 min). See Supporting Information: Part B for HPLC chromatograms.



3eb

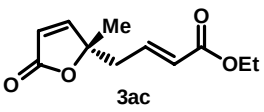
Ethyl (*S*,*E*)-4-(2-octyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ec): Purification by silica gel (230-400 mesh) column chromatography (20% EtOAc in pet ether) afforded pure **3ec** as colorless oil (32 mg, 0.104 mmol, 69% yield). **FT-IR (thin film):** 2927 (s), 2855 (m), 1758 (s), 1724 (s), 1267 (m), 1040 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.32 (d, *J* = 5.6 Hz; 1H), 6.78-6.70 (m; 1H), 6.09 (d, *J* = 5.6 Hz; 1H), 5.88 (d, *J* = 15.6 Hz; 1H), 4.17 (q, *J* = 6.8 Hz; 2H), 2.69-2.58 (m; 2H), 1.86-1.80 (m; 1H), 1.73-1.69 (m; 1H), 1.29-1.23 (m; 15H), 0.86 (t, *J* = 7.0 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ



3ec

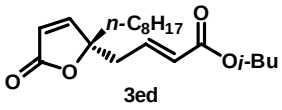
172.1, 165.8, 158.5, 140.5, 126.2, 122.2, 90.0, 60.7, 40.1, 36.8, 31.9, 29.6, 29.4, 29.2, 23.4, 22.7, 14.3, 14.2. **HRMS (ESI+):** Calcd for $C_{18}H_{28}O_4Na$ ($[M + Na]^+$): 331.1885, Found: 331.1883. **Specific rotation:** $[\alpha]_D^{25}$ +16.4 (*c* 1.5, $CHCl_3$) for a sample with 91:9 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (90:10 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 210 nm, τ_{minor} = 12.7 min, τ_{major} = 13.8 min). See Supporting Information: Part B for HPLC chromatograms.

Ethyl (*S*,*E*)-4-(2-methyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ac): Purification by silica gel (230-400 mesh) column chromatography (28% EtOAc in pet ether) afforded pure **3ac** as colorless oil (26 mg, 0.124 mmol, 62% yield). **FT-IR (thin film):** 2938 (w), 1757 (s), 1717 (s), 1655 (w), 1270 (m), 1043 (w); **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.38 (d, *J* = 5.6 Hz; 1H), 6.79-6.71 (m; 1H), 6.06 (d, *J* = 5.6 Hz; 1H), 5.89 (d, *J* = 16.0 Hz; 1H), 4.17 (q, *J* = 7.2 Hz; 2H), 2.68-2.57 (m; 2H), 1.49 (s; 3H), 1.27 (t, *J* = 7.1 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.9, 165.7, 159.4, 140.4, 126.3, 121.5, 87.5, 60.7, 41.2, 23.9, 14.3. **HRMS (ESI+):** Calcd for $C_{11}H_{14}O_4Na$ ($[M + Na]^+$): 233. 0790, Found: 233. 0795. **Specific rotation:** $[\alpha]_D^{22}$ +43.2 (*c* 1, $CHCl_3$) for a sample with 91:9 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 6.8 min, τ_{minor} = 7.8 min). See Supporting Information: Part B for HPLC chromatograms.



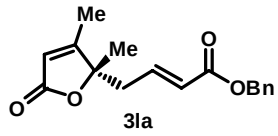
3ac

Isobutyl (*S*,*E*)-4-(2-octyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ed): Purification by silica gel (230-400 mesh) column chromatography (12% EtOAc in pet ether) afforded pure **3ed** as colorless oil (30.6 mg, 0.091 mmol, 61% yield). **FT-IR (thin film):** 2927 (s), 2856 (m), 1766 (s), 1722 (s), 1275 (w), 1020 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.32 (d, *J* = 5.6 Hz; 1H), 6.77-6.70 (m; 1H), 6.08 (d, *J* = 5.6 Hz; 1H), 5.90 (d, *J* = 15.6 Hz; 1H), 3.89 (d, *J* = 6.8 Hz; 2H), 2.69-2.58 (m; 2H), 1.99-1.89 (m; 1H), 1.86-1.79 (m; 1H), 1.73-1.67 (m; 1H), 1.27-1.17 (m; 12H), 0.92 (d, *J* = 6.7 Hz; 6H), 0.86 (t, *J* = 7.2 Hz; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 172.1, 165.8, 158.5, 140.5, 126.1, 122.2, 90.0, 70.8, 40.1, 36.8, 31.9, 29.6, 29.4, 29.2, 27.8, 23.4, 22.7, 19.2, 14.2. **HRMS (ESI+):** Calcd for $C_{20}H_{32}O_4Na$ ($[M + Na]^+$): 359.2198, Found: 359.2196. **Specific rotation:** $[\alpha]_D^{24}$ +19.6 (*c* 1.5, $CHCl_3$) for a sample with 93:7 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH,, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 4.8 min, τ_{minor} = 5.2 min). See Supporting Information: Part B for HPLC chromatograms.



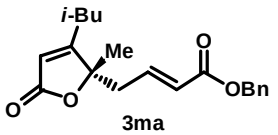
3ed

Benzyl (*S*,*E*)-4-(2,3-dimethyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3la): Purification by silica gel (230-400 mesh) column chromatography (24% EtOAc in pet ether) afforded pure **3la** as colorless oil (34.3 mg, 0.119 mmol, 80% yield). **FT-IR (thin film):** 2926 (w), 1750 (s), 1735 (s), 1654 (m), 1263 (m), 1018 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.35-7.30 (m; 5H), 6.79-6.71 (m; 1H), 5.94 (d, *J* = 15.6 Hz; 1H), 5.76 (s; 1H), 5.15 (s; 2H), 2.72 (dd, *J* = 7.6, 14.4 Hz; 1H), 2.49 (dd, *J* = 7.6, 14.8 Hz; 1H), 2.01 (s; 3H), 1.46 (s; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.6, 170.9, 165.5, 140.9, 135.9, 128.7, 128.4, 125.6, 117.3, 88.1, 66.4, 39.7, 23.5, 13.2. **HRMS (ESI+):** Calcd for $C_{17}H_{18}O_4Na$ ($[M + Na]^+$): 309.1103, Found: 309.1103. **Specific rotation:** $[\alpha]_D^{25}$ +16.6 (*c* 1, $CHCl_3$) for a sample with 93.5:6.5 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH,, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 12.4 min, τ_{minor} = 16.5 min). See Supporting Information: Part B for HPLC chromatograms.



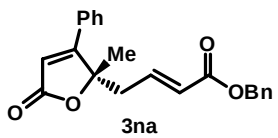
3la

Benzyl (*S*,*E*)-4-(3-isobutyl-2-methyl-5-oxo-2,5-dihydrofuran-2-yl)but-2-enoate (3ma): Purification by silica gel (230-400 mesh) column chromatography (20% EtOAc in pet ether) afforded pure **3ma** as colorless oil (42.2 mg, 0.128mmol, 85% yield). **FT-IR (thin film):** 2932 (w), 1752 (s), 1719 (s), 1658 (m), 1262 (m), 1042 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.38-7.31 (m; 5H), 6.78-6.71 (m; 1H), 5.93 (d, *J* = 15.6 Hz; 1H), 5.76 (s; 1H), 5.15 (s; 2H), 2.71 (dd, *J* = 7.6, 14.8 Hz; 1H), 2.47 (dd, *J* = 7.2, 14.4 Hz; 1H), 2.08 (d, *J* = 6.4 Hz; 2H), 2.03-1.95 (m; 1H), 1.44 (s; 3H), 0.99-0.97 (m; 6H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 174.6, 171.8, 165.4, 141.0, 135.9, 128.7, 128.34, 128.31, 125.6, 115.9, 88.2, 66.4, 39.9, 36.5, 26.4, 23.7, 22.7. **HRMS (ESI+):** Calcd for $C_{20}H_{24}O_4Na$ ($[M + Na]^+$): 351.1572, Found: 351.1573. **Specific rotation:** $[\alpha]_D^{21}$ +5.9 (*c* 2, $CHCl_3$) for a sample with 95:5 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 10.3 min, τ_{minor} = 15.1 min). See Supporting Information: Part B for HPLC chromatograms.



3ma

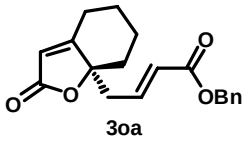
Benzyl (*S*,*E*)-4-(2-methyl-5-oxo-3-phenyl-2,5-dihydrofuran-2-yl)but-2-enoate (3na): Purification by silica gel (230-400 mesh) column chromatography (22% EtOAc in pet ether) afforded pure **3na** as colorless oil (17.7 mg, 0.051 mmol, 88% yield). **FT-IR (thin film):** 2926 (m), 2855 (w), 1751 (s), 1734 (s), 1261 (m), 1020 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.49-7.48 (m; 5H), 7.37-7.30 (m; 5H), 6.80-6.73 (m; 1H), 6.27 (s; 1H), 5.88 (d, *J* =15.6 Hz; 1H), 5.13 (s; 2H), 2.93 (dd, *J* = 8.0, 14.8 Hz; 1H), 2.78 (dd, *J* = 7.2, 14.8 Hz; 1H), 1.74 (s; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 171.0, 170.0, 165.5, 140.9, 135.9, 131.2, 130.1, 129.4, 128.7, 128.4, 128.3, 127.6, 125.9, 116.4, 88.2, 66.4, 41.1, 25.3. **HRMS (ESI+):** Calcd for $C_{22}H_{20}O_4Na$ ($[M + Na]^+$):



3na

371.1259, Found: 371.1256. **Specific rotation:** $[\alpha]_D^{21}$ –10.2 (*c* 1.0, $CHCl_3$) for a sample with 88.5:11.5 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak AD-H column (75:25 *n*-Hexane/EtOH, 1.0 mL/min, 20 °C, 254 nm, τ_{major} = 17.4 min, τ_{minor} = 19.5 min). See Supporting Information: Part B for HPLC chromatograms.

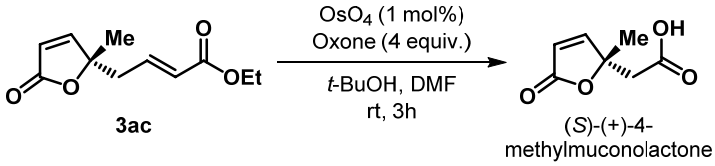
Benzyl (*S*,*E*)-4-(2-oxo-4,5,6,7-tetrahydrobenzofuran-7a(2*H*)-yl)but-2-enoate (3oa):



3oa

Purification by silica gel (230-400 mesh) column chromatography (32% EtOAc in pet ether) afforded pure **3oa** as colorless oil (26.7 mg, 0.085 mmol, 85% yield). **FT-IR (thin film):** 2923 (w), 1733 (s), 1716 (s), 1647 (m), 1262 (m), 1018 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.39-7.32 (m; 5H), 6.82-6.74 (m; 1H), 5.95 (d, *J* = 15.6 Hz; 1H), 5.73 (s; 1H), 5.16 (s; 2H), 2.83-2.73 (m; 2H), 2.60-2.55 (m; 1H), 2.33 (d, *J* = 9.2 Hz; 1H), 2.23-2.15 (m; 1H), 2.08 (d, *J* = 6.0 Hz; 1H), 1.84 (brs; 1H), 1.67 (brs; 1H), 1.47 (d, *J* = 9.2 Hz; 1H), 1.39-1.33 (m; 1H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 173.8, 172.1, 165.5, 141.1, 135.9, 128.7, 128.4, 125.6, 113.8, 87.1, 66.4, 38.4, 36.9, 27.55, 27.51, 22.4. **HRMS (ESI+):** Calcd for $C_{19}H_{20}O_4Na$ ($[M + Na]^+$): 335.1259, Found: 335.1252. **Specific rotation:** $[\alpha]_D^{21}$ –36.9 (*c* 1.0, $CHCl_3$) for a sample with 93:7 er. The enantiomeric ratio was determined by HPLC with a Daicel Chiralpak ID column (50:50 *n*-Hexane/*i*-PrOH,, 1.0 mL/min, 20 °C, 210 nm, τ_{major} = 19.3 min, τ_{minor} = 24.2 min). See Supporting Information: Part B for HPLC chromatograms.

Determination of absolute configuration through the synthesis of (*S*)-(+)-4-methylmuconolactone:



To a stirred solution of compound **3ac** (68 mg, 0.323 mmol) in DMF (1.6 mL), was added OsO_4 (0.82 mg, 0.0032 mmol) followed by *t*-BuOH (0.034 mL).[5] After 5 min, Oxone® (398 mg, 1.295 mmol) was added and the resulting mixture was allowed to stir at room temperature. After completion of reaction (3 h), sodium sulfite (528 mg) was added to it and the resulting mixture was allowed to stir for further 1 h. This was then diluted with ethyl acetate (5 mL) and 1 N HCl was added to make it acidic (pH ~ 4). Organic layer was separated and the aqueous phase was extracted with ethyl acetate (3 × 5 mL). Combined organic layer was dried (Na_2SO_4) and concentrated under reduced pressure to a residue which was purified by preparative TLC with diisopropyl ether/formic acid/water (200:7:3) to give acid (8.1 mg, 0.052 mmol, 16%). **FT-IR**

[5] B. R. Travis , R. S. Narayan and B. Borhan, *J. Am. Chem. Soc.*, 2002, **124**, 3824.

(thin film): 3442 (s), 2924 (w), 2853 (w), 1746 (s), 1711 (s), 1178 (m), 1106 (w). **^{1}H-NMR (400 MHz, $CDCl_3$):** δ 7.67 (d, *J* = 5.6 Hz; 1H), 6.09 (d, *J* = 5.6 Hz; 1H), 2.97 (d, *J* = 16.0 Hz; 1H), 2.75 (d, *J* = 16.0 Hz; 1H), 1.60 (s; 3H). **^{13}C-NMR (100 MHz, $CDCl_3$):** δ 173.7, 172.1, 159.6, 121.0, 85.7, 43.1, 24.0. **HRMS (ESI+):** Calcd for $C_7H_8O_4Na$ ($[M+Na]^+$): 179.0320, Found: 179.0320. **Specific rotation:** $[\alpha]_D^{21}$ +29.4 (*c* 0.66, H_2O) for a sample with 91:9 er [lit.[6] $[\alpha]_D^{20}$ +36 (*c* 1.32, H_2O) possibly for an enantiopure sample isolated from natural source].

[6] A. A. Freer, G. W. Kirby, G. V. Rao and R. B. Cain, *J. Chem. Soc., Perkin Trans. 1 ,* 1996 , 2111