Supplementary Information for:

Stereocontrolled Lactide Polymerisation Determined by the Nuclearity of the Yttrium Initiator

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Experimental Section

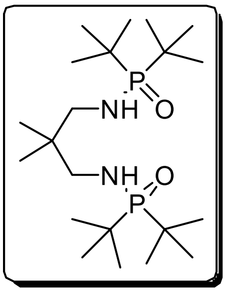
Materials and methods

All reactions were conducted under a nitrogen atmosphere, using either standard Schlenk techniques or in a nitrogen filled glovebox, unless stated otherwise. All solvents and reagents were obtained from commercial sources (Aldrich and Strem) and used as received unless stated otherwise. 2,2-Dimethyl-1,3-propane diamine was stirred over CaH_2, distilled and stored under nitrogen; *iso*-propanol was stirred over CaH_2, distilled, degassed and stored under nitrogen. Toluene, THF, pentane and hexane were distilled from sodium and stored under nitrogen. Dichloromethane and ethyl acetate were distilled from CaH_2 and stored under nitrogen. Benzene-d_6 was dried over potassium and and dichloromethane-d_2 was dried over CaH_2; in each case, performing three freeze-thaw cycles under vacuum, refluxing them for 1-2 days, distilling them under vacuum and storing them under nitrogen. *Rac*-lactide was generously donated by Purac Plc. and was recrystallised from anhydrous ethyl acetate or toluene and sublimed at 50 ºC three times under vacuum prior to use. [*Tris*{*N,N'*-*bis*(dimethylsilyl)amido}*bis*(tetrahydrofurano)]yttrium, $[Y\{N(SiHMe_2)_2\}_3(THF)_2]$ was prepared according to the literature procedure.[1]

Measurements

^1H and $^{13}C\{^1H\}$ NMR spectra were performed on a Bruker Av-400 instrument, unless otherwise stated. $^{31}P\{^1H\}$ NMR experiments were performed on a Bruker Av500 spectrometer equipped with a z-gradient bbo/5mm tuneable probe and a BSMS GAB 10 amp gradient amplifier providing a maximum gradient output of 5.35 G/cmA. To observe the complex P-Y coupling patterns, $^{31}P\{^1H\}$ spectra were collected at a frequency of 202.47 MHz using a 30 degree pulse, a spectral width of 8082 Hz (centred on 57.5 ppm) and 65536 data points with a relaxation delay of 2 s. The spectra were zero filled (0.12 Hz/point resolution) and processed with no apodization. Spectra were processed and analysed using Mestrenova software. Elemental analyses were determined by Mr Stephen Boyer at London Metropolitan University, North Campus, Holloway Road, London, N7. Mass spectra were performed on a Micromass Autospec Premier machine, using LSIMS (FAB) ion sources. Melting points were determined using a Reichert apparatus. IR spectra were acquired on a Perkin-Elmer Spectrum 100 FT-IR spectrometer, and the data was processed using Spectrum Express software.

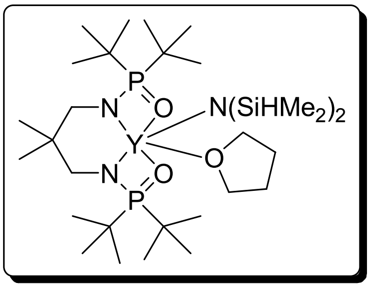
N,N′-1,3-*Bis*(*P,P′*-di-*tert*-butylphosphinoyl)-2,2-dimethylpropanediamine[2]



To a 250 mL round bottomed flask equipped with a stirrer bar was added 2,2-dimethyl-1,3-propylenediamine (0.24 mL, 2 mmol), triethylamine (1.40 mL, 10 mmol) and dichloromethane (25 mL). The flask was cooled to 0 ºC in an ice bath and chloro-di-*tert*-butyl phosphine (0.80 mL, 4.2 mmol) was added dropwise, *via* a syringe. The mixture was allowed to warm to room temperature and stirred for 20 h. The flask was opened to air and the mixture cooled to 0ºC in an ice bath. Hydrogen peroxide (1.03 mL of a 30 % w/v soln., 8 mmol) was added cautiously to the mixture. Stirring was continued at 0 ºC for 10 min and then at 25 ºC for a further 30 min. Sodium thiosulphate (20 mL of a 1 M soln., 20 mmol) was then added slowly. The aqueous and organic layers were separated, and the aqueous layer washed with dichloromethane (2 x 10 mL). The organic layers were collected, dried ($MgSO_4$) and the solvents removed under reduced pressure to leave a colourless residue. Recrystallisation from ethyl acetate gave the title product as a colourless, crystalline solid (0.80 g, 95%).

M. Pt. ºC: 185 – 187 (sublimed).^{1}H NMR (400 MHz, $CDCl_3$,) δ ppm: 3.08 (m, 2H, N*H*), 2.68 (t, 4H, $^3J_{HH}$ = 7.6 Hz, C*H*$_2$), 1.10 (d, 36H, $^3J_{HP}$ = 13.6 Hz, C(C*H*$_3$)$_3$), 0.71 (s, 6H, C(C*H*$_3$)$_2$). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$,) δ ppm: 46.2 (s, *C*H$_2$), 37.0 (s, *C*(CH$_3$)$_2$), 26.5 (d, $^1J_{PC}$ = 81.0 Hz, *C*H(CH$_3$)$_2$), 23.3 (s, *C*H$_3$), 16.2 (d, $^2J_{PC}$ = 2.1 Hz, CH(*C*H$_3$)$_2$), 15.9 (d, $^2J_{PC}$ = 2.3 Hz, CH(*C*H$_3$)$_2$). ^{31}P{^{1}H} NMR (162 MHz, $CDCl_3$) δ ppm: 54.0 (s). MS *m/z* (FAB$^+$): 423 [M+H]$^+$. IR (neat) υ cm^{-1}: 3215 (w, N-H), 3140 (w, N-H), 2944 (m, C-H), 2894 (m, C-H), 2862 (m, C-H), 1473 (m), 1387 (m), 1354 (m), 1153 (m), 1141 (s, P=O), 1086 (m), 1078 (m), 1015 (w), 934 (w), 819 (s), 656 (s). Anal. Calcd. for $C_{21}H_{48}N_2O_2P_2$: C, 59.69, H, 11.45, N, 6.63 %. Found: C, 59.59, H, 11.36, N, 6.55 %.

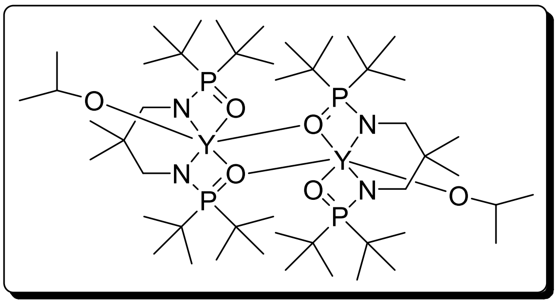
[{*N*,*N′*-1,3-*Bis*(*P*,*P′*-di-*tert*-butylphosphinoyl)-2,2-dimethylpropanediamido}(tetrahydrofurano){*bis*(dimethylsilyl)amido}]yttrium 1



To a Schlenk tube equipped with a stirrer bar were added *N*,*N′*-1,3-*bis*(*P*,*P′*-di-*tert*-butylphosphinoyl)-2,2-dimethylpropane diamine (0.422 g, 1.0 mmol) and [*tris*{*N,N′*-*bis*(dimethylsilyl)amido}*bis*(tetrahydrofurano)]yttrium, [Y{N(SiHMe$_2$)$_2$}$_3$(THF)$_2$], (0.630 g, 1.0 mmol). Toluene (20 mL) was added *via* a cannula and the resulting colourless solution was heated to 70 ºC for 16 h. The volatiles were removed *in vacuo* to leave a colourless residue. To this was added *n*-pentane (20 mL). The mixture was stirred for 10 min and the solvents removed *in vacuo* to leave a colourless solid. The product was recrystallised from *n*-pentane, at -35 ºC, to give the title product as a colourless, crystalline solid (0.42 g, 59 %).

^{1}H NMR (400 MHz, C$_6$D$_6$) δ ppm: 5.15 (m, 2H, Si*H*), 4.09 (m, 4H, OC*H*$_2$CH$_2$), 3.24 (dd, 2H, $^3J_{PH}$ = 6.4 Hz, $^2J_{HH}$ = 11.2 Hz, C*H*$_2$), 3.17 (dd, 2H, $^3J_{PH}$ = 5.6 Hz, $^2J_{HH}$ = 11.2 Hz, C*H*$_2$), 1.45 (m, 4H, OCH$_2$C*H*$_2$), 1.34 (d, 18H, $^3J_{PH}$ = 13.6 Hz, C(C*H*$_3$)$_3$), 1.32 (s, 3H, C*H*$_3$), 1.18 (d, 18H, $^3J_{PH}$ = 12.8 Hz, C(C*H*$_3$)$_3$), 0.94 (s, 3H, C*H*$_3$), 0.44 (d, 12H, $^3J_{HH}$ = 3.2 Hz, Si(CH$_3$)$_2$). ^{13}C{^{1}H} NMR (100 MHz, C$_6$D$_6$) δ ppm: 70.3 (s, O*C*H$_2$), 58.4 (d, $^2J_{CP}$ = 2.3 Hz, *C*H$_2$), 38.4 (d, $^1J_{CP}$ = 64.4 Hz, *C*(CH$_3$)$_3$), 38.3 (t, $^3J_{CP}$ = 13.7 Hz, *C*(CH$_3$)$_2$), 37.0 (d, $^1J_{CP}$ = 64.4 Hz, *C*(CH$_3$)$_3$), 28.3 (s, C(*C*H$_3$)$_3$), 28.0 (s, C(*C*H$_3$)$_2$), 27.3 (s, C(*C*H$_3$)$_2$), 26.1 (s, C(*C*H$_3$)$_2$), 25.3 (s, *C*H$_2$), 4.3 (s, Si(*C*H$_3$)$_2$). ^{31}P{^{1}H} NMR (162 MHz, C$_6$D$_6$) δ ppm: 59.3 (d, $^2J_{PY}$ = 4.37 Hz). IR (nujol mull, NaCl) υ cm^{-1}: 2100 (m, Si-H stretch), 2042 (m, Si-H stretch), 1615 (m, Si-H stretch), 1515 (m, Si-H stretch), 1388 (s), 1238 (s), 1207 (s), 1181 (s), 1152 (m), 1057 (s), 1023 (s), 989 (m). Anal. Calcd. for C$_{29}$H$_{68}$N$_3$O$_3$P$_2$Si$_2$Y: C, 48.79, H, 9.60, N, 5.89 %. Found: C, 48.67, H, 9.51, N, 5.94 %.

Di-µ-oxo-{[*N*,*N′*-1,3-*bis*(*P*,*P′*-di-*tert*-butylphosphinoyl)-2,2-dimethylpropanediamido](*iso*-propoxy)]yttrium} 2



To a solution of **1** (0.071 g, 0.1 mmol) in a minimum volume of C_6D_6, was added *iso*-propanol (7.6 µL, 0.1 mmol) *via* a microsyringe. Colourless crystals precipitated. These were filtered off to give the title product as a colourless, crystalline solid (0.020 g, 35 %)..

^{1}H NMR (400 MHz, C_6D_6) δ ppm: 4.58 (sept, $^3J_{HH}$ = 5.6 Hz, 2H, OC*H*(CH_3)$_2$), 3.21 (m, 8H, C*H*$_2$), 1.59 (d, $^3J_{PH}$ = 13.6 Hz, 18H, C(C*H*$_3$)$_3$), 1.57 (s, 6H, C*H*$_3$), 1.48 (d, $^3J_{PH}$ = 13.2 Hz, 18H, C(C*H*$_3$)$_3$), 1.41 (d, $^3J_{HH}$ = 5.6 Hz, 6H, CH(C*H*$_3$)), 1.39 (d, $^3J_{HH}$ = 5.6 Hz, 6H, CH(C*H*$_3$)), 1.31 (d, $^3J_{PH}$ = 12.8 Hz, 18H, C(C*H*$_3$)$_3$), 1.25 (d, $^3J_{PH}$ = 12.8 Hz, 18H, C(C*H*$_3$)$_3$), 0.86 (s, 6H, C*H*$_3$). ^{13}C{^{1}H} NMR (100 MHz, C_6D_6) δ ppm: 68.2 (s, O*C*H(CH_3)$_2$), 59.7 (s, *C*H$_2$), 58.8 (s, *C*H$_2$), 48.9 (s, *C*(CH_3)$_2$), 40.2 (d, $^1J_{CP}$ = 67.6 Hz, *C*(CH_3)$_3$), 37.9 (d, $^1J_{CP}$ = 65.1 Hz, *C*(CH_3)$_3$), 37.8 (d, $^1J_{CP}$ = 56.9 Hz, *C*(CH_3)$_3$), 36.8 (d, $^1J_{CP}$ = 61.3 Hz, *C*(CH_3)$_3$),29.1 (s, OCH(*C*H$_3$)$_2$), 29.0 (s, OCH(*C*H$_3$)$_2$), 28.3 (s, *C*H$_3$), 28.1 (s, C(*C*H$_3$)$_3$), 27.6 (s, C(*C*H$_3$)$_3$), 27.3 (s, C(*C*H$_3$)$_3$), 23.7 (s, *C*H$_3$). ^{31}P{^{1}H} NMR (162 MHz, C_6D_6) δ ppm: 67.0 (t, 1P, $^2J_{PY}$ = 4.37 Hz), 58.9 (d, 1P, $^2J_{PY}$ = 4.21 Hz). Anal. Calcd. for $C_{24}H_{53}N_2O_3P_2Y$: C, 50.70, H, 9.40, N, 4.93 %. Found: C, 48.70, H, 7.61, N, 5.49 %.

General Polymerisation Protocol

To a rapidly stirred solution of *rac*-lactide (144 mg, 1.0 mmol) in dichloromethane (1.75 mL), in a small glass vial equipped with a lid, in the glove box, was added a solution of the appropriate initiator in dichloromethane (0.25 mL of a 0.02 M solution, 0.005 mmol), such that the total reaction volume was 2.0 mL, with $[LA]_0$ = 0.5 M and [**1**,**2**] = 2.5 mM. The lid was replaced on the vial, and aliquots of ~0.1 mL were removed at known times *via* a syringe and quenched in 4 – 5 mL of cold hexane. Upon completion of the reaction, the quenched samples were dried *in vacuo* to yield colourless polymer.

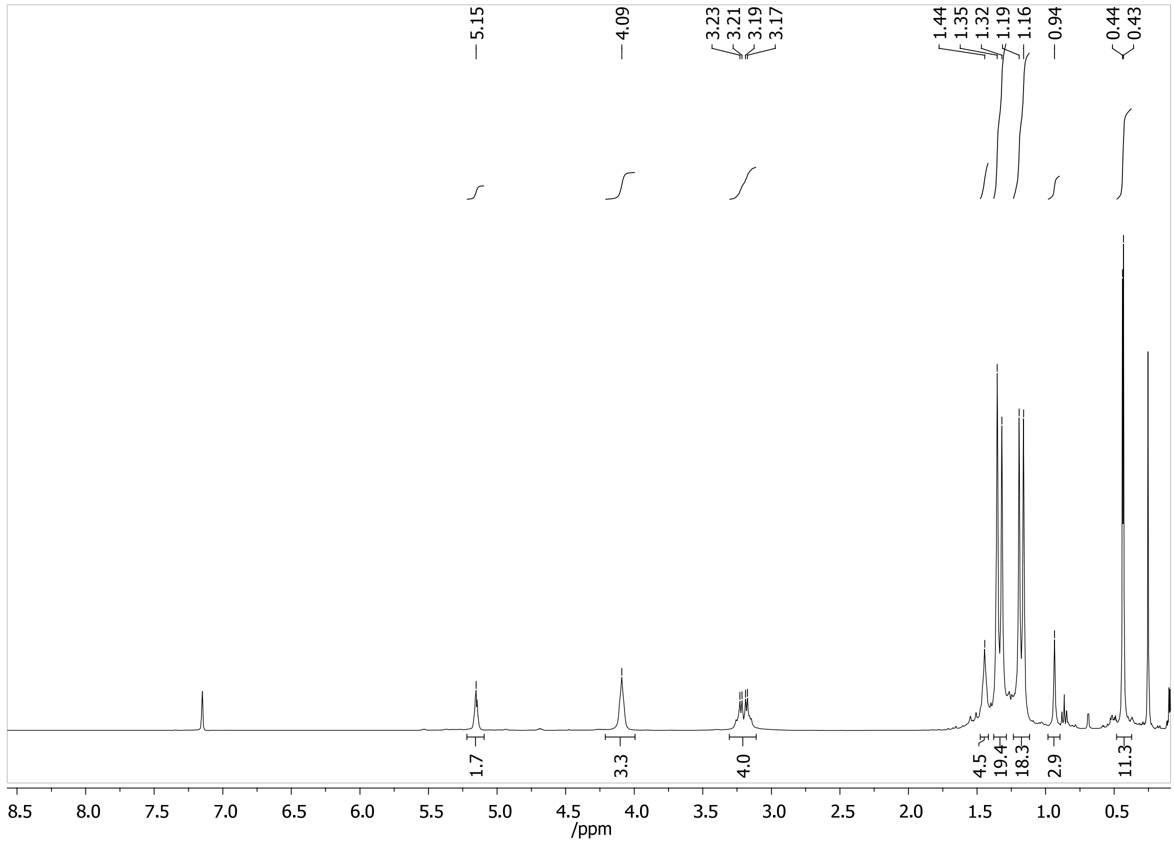


Fig. S1: ^{1}H NMR spectrum of **1** in benzene-d_6.

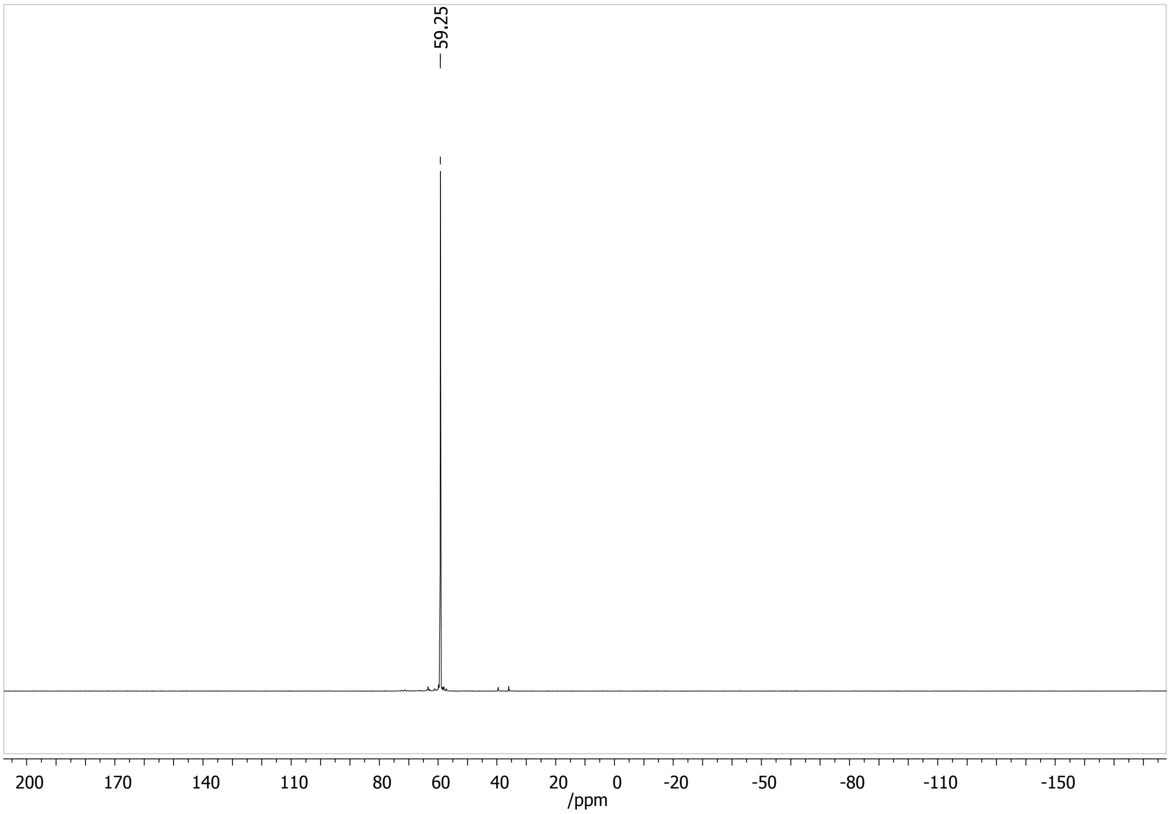


Fig. S2: $^{31}P\{^{1}H\}$ NMR spectrum of **1** in benzene-d_6.

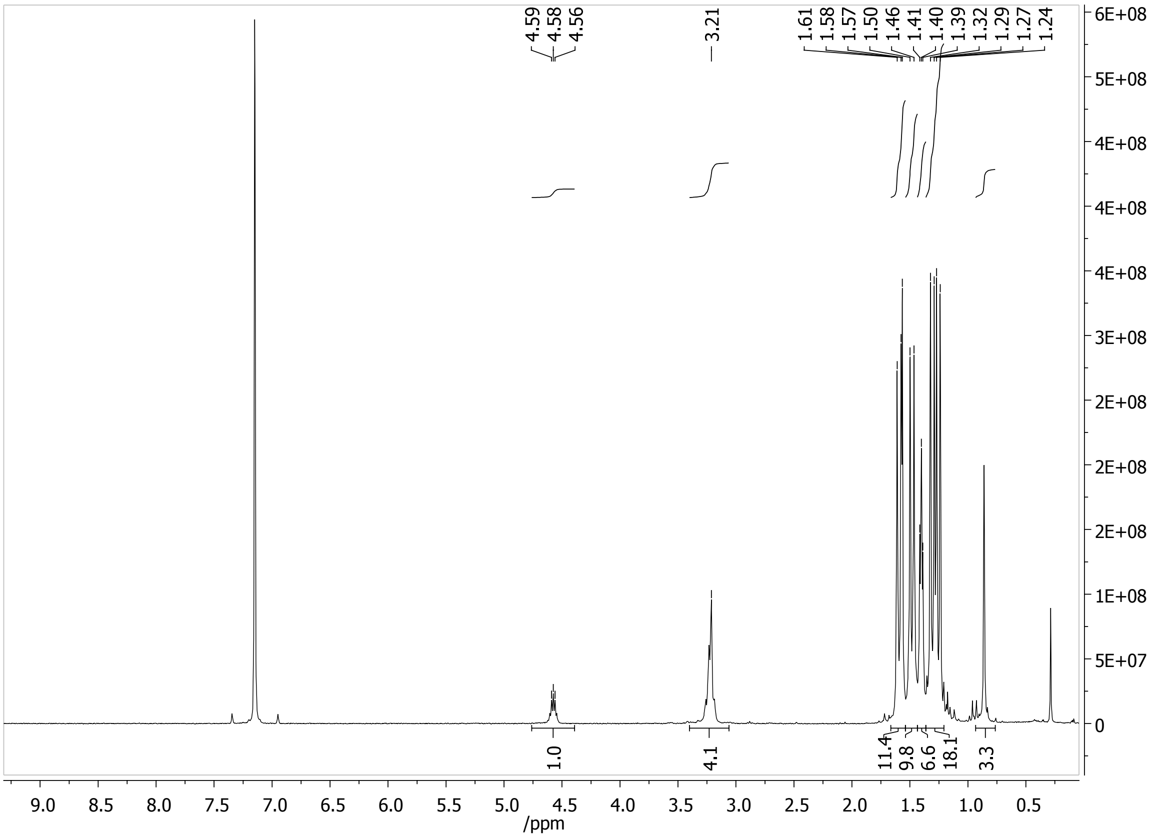


Fig. S3: ^{1}H NMR spectrum of **2** in benzene-d_6.

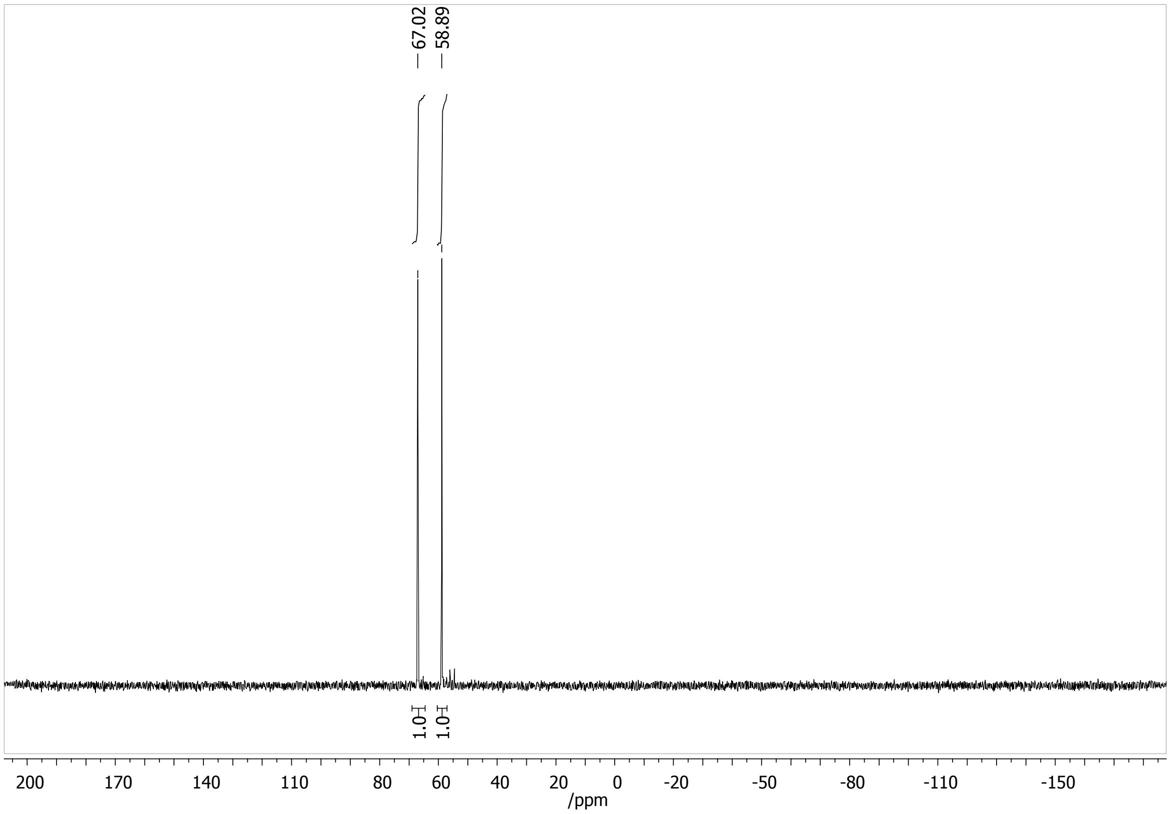


Fig. S4: ^{31}P{^{1}H} NMR spectrum of **2** in benzene-d_6.

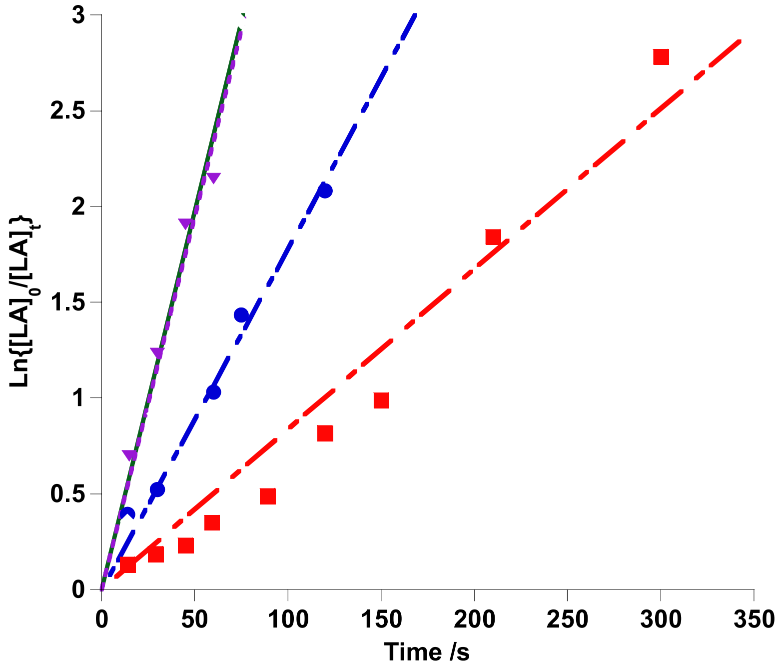


Fig. S5: Lactide polymerisation using complexes **1** (blue circles, CH_2Cl_2, k_{obs} = 17.8 x 10^{-3} s^{-1}, R = 0.994; red squares, THF, k_{obs} = 8.36 x 10^{-3} s^{-1}, R = 0.987) and **2** (purple triangles, THF, k_{obs} = 38.8 x 10^{-3} s^{-1}, R = 0.990).

Polymerisation Conditions: $[LA]_0$=0.5 M, $[\text{initiator}]_0$=2.5 mM, 25 °C, where initiator = **1**, **2**.

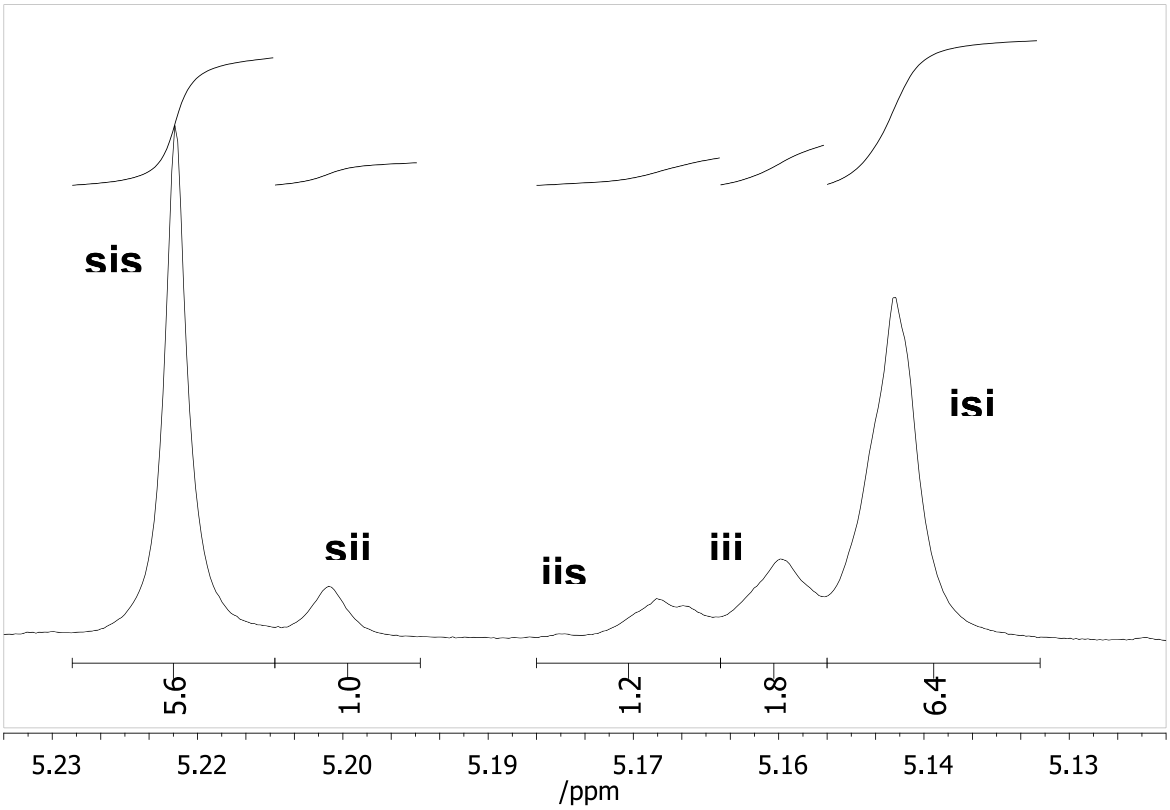


Fig. S6: ^{1}H NMR spectrum (homonuclear decoupled) showing the heterotactic bias in the PLA produced from *rac*-LA using initiator **1**. $P_r = 0.85$.[3]

Polymerisation Conditions: $[\mathrm{LA}]_0 = 0.5$ M, $[\mathrm{LA}]_0/[\mathbf{1}]_0 = 200$, THF, 25 ºC.

X-ray Crystallography

Crystal data for **1**: $C_{25}H_{60}N_3O_2P_2Si_2Y$, $M = 641.79$, monoclinic, Cc (no. 9), $a = 12.7563(4)$, $b = 18.5514(6)$, $c = 15.1861(6)$ Å, $\beta = 104.350(4)$°, $V = 3481.6(2)$ Å^3, $Z = 4$, $D_c = 1.224$ g cm^{-3}, μ(Mo-Kα) = 1.860 mm^{-1}, $T = 173$ K, colourless blocks, Oxford Diffraction Xcalibur 3 diffractometer; 7236 independent measured reflections ($R_{int} = 0.0435$), F^2 refinement, R_1(obs) = 0.035, wR_2(all) = 0.071, 5391 independent observed absorption-corrected reflections [$|F_o| > 4\sigma(|F_o|)$, $2\theta_{max} = 65°$], 316 parameters. The absolute structure of **1** was unambiguously determined by a combination of R-factor tests [$R_1^+ = 0.0353$, $R_1^- = 0.0764$] and by use of the Flack parameter [$x^+ = +0.000(5)$, $x^- = +1.008(5)$]. CCDC 720127.

Compound **1** crystallised in the polar space group, Cc, and the absolute structure of **1** was unambiguously determined by a combination of R-factor tests [$R_1^+ = 0.0353$, $R_1^- = 0.0764$] and by use of the Flack parameter [$x^+ = +0.000(5)$, $x^- = +1.008(5)$]. Whilst the Si(31)–H proton was located from a ΔF map, that on Si(34) could not be found. To maintain a consistency of approach, both Si–H protons were placed in idealised positions and allowed to ride on their parent silicon atoms with an Si–H distance of 1.45 Å.

Crystal data for **2:** $C_{48}H_{106}N_4O_6P_4Y_2$, $M = 1137.07$, triclinic, $P\bar{1}$ (no. 2), $a = 10.6592(3)$, $b = 12.4077(3)$, $c = 13.0174(4)$ Å, $\alpha = 71.981(3)$, $\beta = 89.831(3)$, $\gamma = 69.204(3)$°, $V = 1519.43(9)$ Å^3, $Z = 1$ [C_i symmetry], $D_c = 1.243$ g cm^{-3}, μ(Cu-Kα) = 3.884 mm^{-1}, $T = 173$ K, colourless plates, Oxford Diffraction Xcalibur PX Ultra diffractometer; 5825 independent measured reflections ($R_{int} = 0.0368$), F^2 refinement, R_1(obs) = 0.037, wR_2(all) = 0.106, 5175 independent observed absorption-corrected reflections [$|F_o| > 4\sigma(|F_o|)$, $2\theta_{max} = 143°$], 315 parameters. CCDC 720128.

In the structure of **2,** disorder was found in the C(20) and C(24) *tert*-butyl groups. In each case two orientations were identified, of *ca.* 89:11 and 85:15% partial occupancy respectively, with only the non-hydrogen atoms of the major occupancy orientations being refined anisotropically.

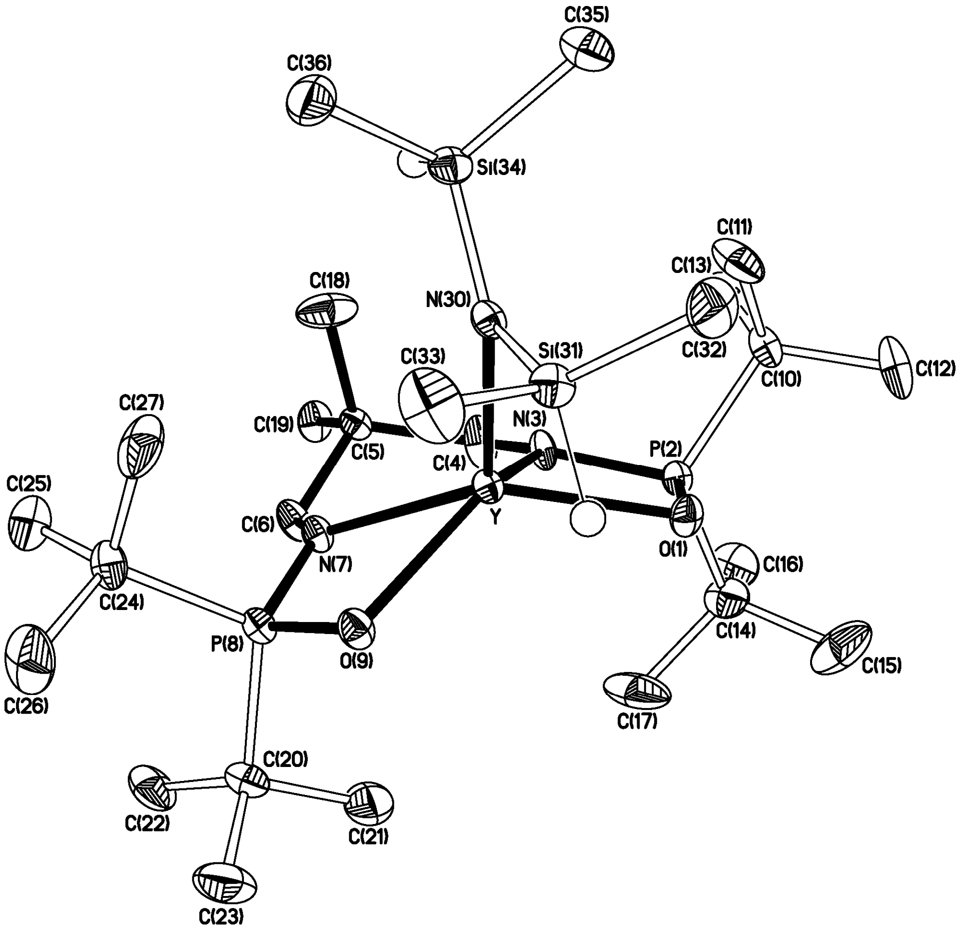


Fig. S7: The molecular structure of **1** (30% probability ellipsoids).

Table S1: Selected bond lengths (Å) and angles (°) for **1**.

Y–O(1)	2.266(2)	Y–N(3)	2.326(2)
Y–N(7)	2.331(2)	Y–O(9)	2.282(2)
Y–N(30)	2.262(2)		
O(1)–Y–N(3)	64.36(8)	O(1)–Y–N(7)	131.44(8)
O(1)–Y–O(9)	125.90(8)	O(1)–Y–N(30)	103.73(8)
N(3)–Y–N(7)	77.52(8)	N(3)–Y–O(9)	134.23(8)
N(3)–Y–N(30)	117.38(9)	N(7)–Y–O(9)	64.14(8)
N(7)–Y–N(30)	120.55(9)	O(9)–Y–N(30)	103.67(8)
Y–N(30)–Si(31)	101.05(12)	Y–N(30)–Si(34)	132.25(13)

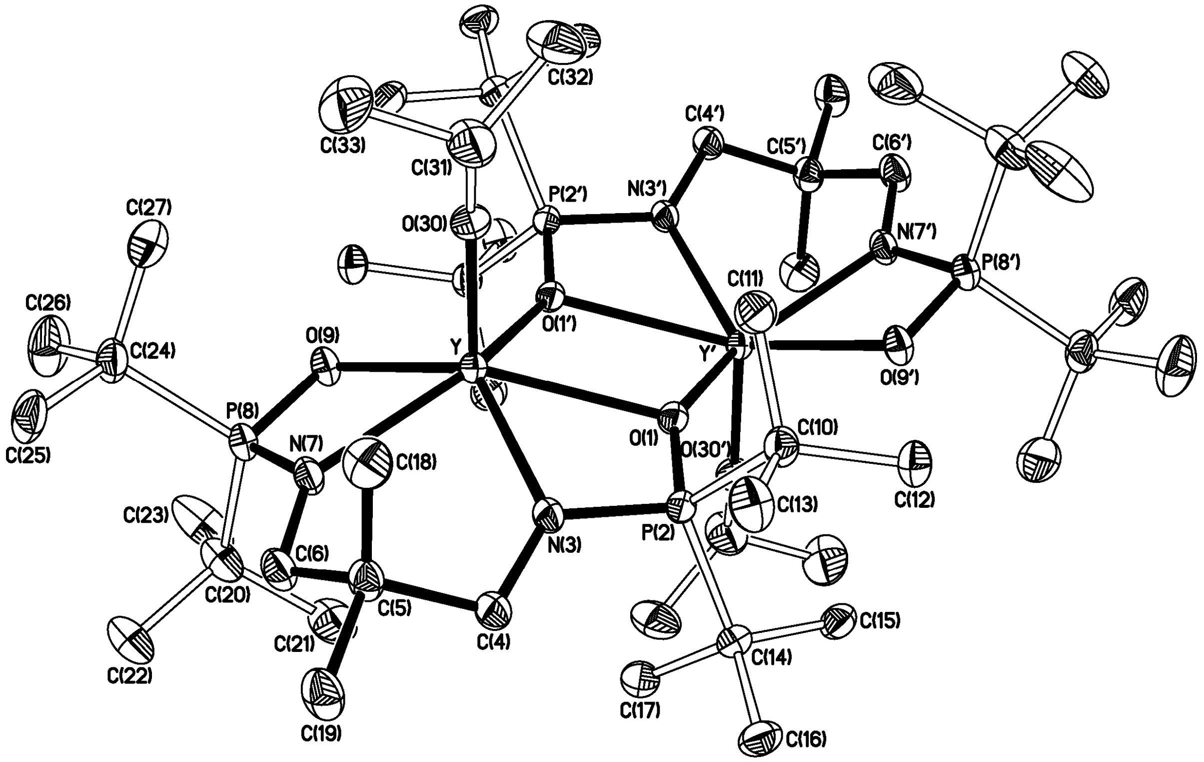


Fig. S8: The molecular structure of the C_i-symmetric complex **2** (30% probability ellipsoids).

Table S2: Selected bond lengths (Å) and angles (°) for **2.**

Y–O(1)	2.4661(17)	Y–N(3)	2.350(2)
Y–N(7)	2.379(2)	Y–O(9)	2.3196(18)
Y–O(30)	2.0551(19)	Y–O(1')	2.3640(17)
O(1)–Y–N(3)	60.97(7)	O(1)–Y–N(7)	131.88(7)
O(1)–Y–O(9)	135.58(6)	O(1)–Y–O(30)	104.83(7)
O(1)–Y–O(1')	68.81(7)	N(3)–Y–N(7)	75.70(8)
N(3)–Y–O(9)	131.25(7)	N(3)–Y–O(30)	104.07(8)
N(3)–Y–O(1')	128.00(7)	N(7)–Y–O(9)	62.72(7)
N(7)–Y–O(30)	105.09(8)	N(7)–Y–O(1')	138.74(7)
O(9)–Y–O(30)	110.14(8)	O(9)–Y–O(1')	78.42(6)
O(30)–Y–O(1')	100.64(7)	Y–O(1)–Y'	111.19(7)

References

1. W. A. Herrmann, J. Eppinger, M. Spiegler, O. Runte and R. Anwander, *Organometallics*, 1997, **16**, 1813-1815.
2. D. A. Watson, M. Chiu and R. G. Bergman, *Organometallics*, 2006, **25**, 4731-4733.
3. J. Coudane, C. Ustariz-Peyret, G. Schwach and M. Vert, *J. Polym. Sci., Polym. Chem.*, 1997, **35**, 1651-1658.