A facile 2H-chromene dimerization through an ortho-quinone methide intermediate catalyzed by a sulfonyl derived MIL-101 MOF

Xin Du, a Xiujuan Li, a Houliang Tang, b Wenyu Wang, c Daniele Ramella d and Yi Luan a,*

a School of Materials Science and Engineering, University of Science and Technology Beijing, 30 Xueyuan Road, Haidian District, Beijing 100083, P. R. China, E-mail: yiluan@ustb.edu.cn.
b Department of Chemistry, Southern Methodist University, 3215 Daniel Avenue, Dallas, 75275, TX, USA
c The Broad Institute, 415 Main Street, Cambridge, MA02142, USA.
d Department of chemistry, Temple University-Beury Hall, 1901, N. 13th Street Philadelphia PA 19122, United States.
Fig. S1 SEM image of recycled MIL-101-SO$_3$H.
Fig. S2 XRD pattern of recycled MIL-101-SO$_3$H.
General procedure used for the preparation of homodimers 2 by MIL-101-SO$_3$H catalyst (Table 2).

To a reaction vessel equipped with stir bar in air was added 2H-chromene 1a (134 mg, 0.5 mmol) and MIL-101-SO$_3$H catalyst (1 mol%) in 10 mL dichloromethane. The mixture was stirred at room temperature for 2 hours. Then the crude product was subjected to $^1$H-NMR analysis for the determination of diastereoselectivity. The reaction was purified without work-up by flash chromatography over silica gel column (elution with 98:2 – 95:5, hexanes:EtOAc) to afford the product 2a as a single diastereomer (white solid, 263 mg, 98% yield).

(E)-3,10-dimethoxy-6-(4-methoxyphenyl)-7-(4-methoxystyrlyl)-6,6a,7,12a-tetrahydrochromeno[4,3-b]chromene (2a)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. Yield: 263 mg, 98%. Single diastereomer. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.28 – 7.11 (m, 9H), 7.12 (d, J = 1.5 Hz, 1H), 6.91 – 6.83 (m, 2H), 6.80 – 6.68 (m, 3H), 6.51 (ddd, J = 8.4, 2.5, 1.3 Hz, 1H), 6.43 (dd, J = 8.3, 2.0 Hz, 3H), 6.03 (ddd, J = 15.7, 6.3, 1.3 Hz, 1H), 5.91 (d, J = 15.7 Hz, 1H), 5.01 (t, J = 1.8 Hz, 1H), 4.93 (d, J = 10.7 Hz, 1H), 3.78 (d, J = 1.4 Hz, 3H), 3.77 – 3.60 (m, 9H), 3.07 (d, J = 6.3 Hz, 1H), 2.40 (dq, J = 10.8, 2.0 Hz, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 161.59 , 159.89 , 159.81 , 159.07 , 155.91 , 153.53 , 131.30 , 131.20 , 131.09 , 131.07 , 130.69 , 129.61 , 128.68 , 127.37 , 114.14 , 113.92 , 113.67 , 112.39 , 108.32 , 108.04 , 101.30 , 101.24 , 76.56 , 67.27 , 55.37 , 55.34 , 55.28 , 41.59 , 38.02 . IR (thin film, cm$^{-1}$): 3006, 2956, 2909, 2836, 1618, 1587, 1511, 1464, 1443, 1303, 1251, 1160, 1112, 1034, 833, 755. HRMS m/z 537.2277 [(M + H$^+$) calc’d for C$_{34}$H$_{32}$O$_6$H$^+$: 537.2278].
(E)-6-(4-methoxyphenyl)-7-(4-methoxystyryl)-6,6a,7,13a-tetrahydro-[1,3]dioxolo[4',5':6,7]chromeno[4,3-b][1,3]dioxolo[4,5-g]chromene (2b)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 90:10, hexanes:EtOAc. Yield: 259 mg, 92%. Single diastereomer. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.22 – 7.11 (m, 6H), 6.91 – 6.83 (m, 2H), 6.75 (s, 2H), 6.81 – 6.69 (m, 2H), 6.39 (q, $J = 1.4$ Hz, 2H), 6.37 – 6.28 (m, 1H), 6.06 – 5.93 (m, 2H), 5.95 – 5.76 (m, 5H), 4.93 – 4.84 (m, 2H), 3.80 – 3.67 (m, 6H), 3.03 – 2.96 (m, 1H), 2.39 – 2.26 (m, 1H), 1.17 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 159.85 , 150.14 , 147.38 , 147.20 , 141.80 , 131.10 , 131.01 , 130.65 , 129.47 , 128.60 , 127.37 , 114.12 , 113.93 , 112.69 , 111.98 , 108.69 , 108.64 , 101.17 , 100.95 , 98.60 , 98.57 , 67.64 , 55.33 , 55.28 , 41.37 , 38.60. IR (thin film, cm$^{-1}$): 3010, 2903, 1610, 1511, 1480, 1439, 1248, 1152, 1076, 1037, 755. HRMS $m/z$ 565.1862 [(M + H$^+$) calc’d for C$_{34}$H$_{28}$O$_8$H$^+$: 565.1860].
(6R,6aS,7R,12aS)-3,10-dimethoxy-6-phenyl-7-((E)-styrly)-6a,12a-dihydro-6H,7H-
chromeno[4,3-b]chromene (2c)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. Yield: 193 mg, 81%. Single diastereomer. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.26 – 7.08 (m, 5H), 6.90 – 6.82 (m, 2H), 6.84 – 6.68 (m, 3H), 6.65 – 6.38 (m, 2H), 6.41 (s, 2H), 6.02 (ddd, $J = 15.7, 6.3, 1.5$ Hz, 1H), 5.90 (d, $J = 15.7$ Hz, 1H), 5.00 (t, $J = 1.9$ Hz, 1H), 4.92 (d, $J = 10.8$ Hz, 1H), 3.06 (d, $J = 6.2$ Hz, 1H), 2.39 (dq, $J = 10.9, 2.0$ Hz, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 161.59, 155.91, 153.53, 131.30, 131.20, 131.09, 131.07, 130.69, 129.61, 128.68, 127.37, 114.14, 113.92, 113.67, 112.39, 108.32, 108.04, 101.30, 101.24, 67.27, 55.37, 55.28, 41.59, 38.02. IR (thin film, cm$^{-1}$): 3004, 2951, 2901, 1611, 1582, 1465, 1442, 1301, 1254, 1108, 1031, 829, 748. HRMS m/z 477.2066 [(M + Na$^+$) calc’d for C$_{32}$H$_{28}$O$_4$H$^+$: 477.2068].
(6R,6aS,7R,13aS)-6-phenyl-7-((E)-styryl)-6a,13a-dihydro-6H,7H-
[1,3]dioxolo[4',5':6,7]chromeno[4,3-b][1,3]dioxolo[4,5-g]chromene (2d)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 90:10, hexanes:EtOAc. **Yield:** 259 mg, 86%. **Single diastereomer.** ¹H NMR (400 MHz, CDCl₃) δ 7.61 – 7.52 (s, 1H), 7.51 – 7.48 (d, 1H), δ 7.32 – 7.12 (m, 7H), 6.91 – 6.83 (m, 2H), 6.75 – 6.62 (m, 2H), 6.43 – 6.28 (s, 2H), 6.05 – 5.91 (m, 1H), 5.90 – 5.84 (m, 3H), 5.01 (t, J = 1.8 Hz, 1H), 4.93 (s, 1H), 3.01 (d, J = 6.3 Hz, 1H), 2.38 (d, J = 10.8, 2.0 Hz, 1H). ¹³C NMR (101 MHz, CDCl₃) δ 149.15 , 147.22 , 141.81 , 131.11 , 131.02 , 130.66 , 129.48 , 128.60 , 127.45 , 127.38 , 114.13 , 113.93 , 112.70 , 111.99 , 108.70 , 108.65 , 101.17 , 100.96 , 98.61 , 98.57 , 76.45 , 67.64 , 41.38 , 38.61 . **IR** (thin film, cm⁻¹): 3010, 2903, 1610, 1511, 1480, 1456, 1439, 1248, 1152, 1076, 1037, 755. **HRMS m/z** 505.1651 [(M + H⁺) calc’d for C₃₂H₂₄O₆H⁺: 505.1652].
The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. **Yield:** 214 mg, 90%. **D.r.:** 5:1. **\(^1\)H NMR** (400 MHz, CDCl\(_3\), both diastereomers reported) Major: \(\delta\) 7.53 – 6.77 (m, 16H), 6.37 (d, \(J = 15.7\) Hz, 1H), 5.91 (dd, \(J = 15.7, 9.3\) Hz, 1H), 3.82 (s, 3H), 3.78 (s, 3H), 3.51 (dd, \(J = 9.9\) Hz, \(J = 9.9\) Hz, 1H), 2.91 – 2.56 (m, 3H). Minor: \(\delta\) 7.53 – 6.77 (m, 16H), 6.37 (d, \(J = 15.6\) Hz, 1H), 6.15 (dd, \(J = 15.7, 9.3\) Hz, 1H), 3.81 (s, 3H), 3.78 (s, 3H), 3.51 (m, 1H), 2.91 – 2.56 (m, 3H). **\(^{13}\)C NMR** (101 MHz, CDCl\(_3\), both diastereomers reported) \(\delta\) 159.91, 159.85, 159.33, 159.28, 152.97, 152.35, 151.81, 151.46, 133.74, 133.52, 132.76, 132.52, 129.62, 129.57, 129.36, 129.10, 128.71, 128.07, 128.03, 127.82, 127.53, 127.50, 127.46, 127.28, 127.22, 125.85, 123.67, 122.24, 121.68, 121.57, 121.37, 121.12, 119.36, 117.13, 116.98, 116.55, 116.48, 114.09, 114.07, 113.99, 113.86, 101.09, 100.83, 55.36, 55.26, 42.24, 40.08, 38.11, 37.19, 27.43, 23.19. **IR** (thin film, cm\(^{-1}\)): 3008, 2933, 2836, 1609, 1584, 1512, 1486, 1455, 1249, 1177, 1054, 754. **HRMS** m/z 477.2066 [(M + H\(^{+}\)) calc’d for C\(_{32}\)H\(_{28}\)O\(_4\)H\(^{+}\): 477.2069].
\((E)-2,9\text{-dibromo-5a-(4-methoxyphenyl)-11-(4-methoxystyryl)-5a,11,11a,12-tetrahydrochromeno}[2,3-b]chromene\) (2f)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. **Yield:** 269 mg, 85%. **D.r.:** 5:1. **\(^1\)H NMR** (400 MHz, CDCl\(_3\), both diastereomers reported) Major: \(\delta\) 7.65 – 6.65 (m, 14H), 6.40 (d, \(J = 15.7\) Hz, 1H), 5.85 (dd, \(J = 15.6, 9.4\) Hz, 1H), 3.83 (s, 3H), 3.78 (s, 3H), 3.41 (dd, 1H), 2.98 – 2.69 (m, 1H), 2.70 – 2.47 (m, 2H). Minor: \(\delta\) 7.65 – 6.65 (m, 14H), 6.47 (d, \(J = 15.7\) Hz, 1H), 6.05 (dd, \(J = 15.6, 9.4\) Hz, 1H), 3.83 (s, 3H), 3.82 (s, 3H), 3.50 (dd, 1H), 2.98 – 2.69 (m, 1H), 2.70 – 2.47 (m, 2H). **\(^13\)C NMR** (101 MHz, CDCl\(_3\), both diastereomers reported) \(\delta\) 160.14, 160.08, 159.56, 159.52, 151.94, 151.31, 150.82, 150.48, 150.43, 134.63, 134.51, 132.16, 131.92, 131.82, 131.75, 131.71, 131.54, 131.16, 131.12, 130.54, 129.13, 129.06, 127.67, 127.64, 127.12, 127.08, 126.40, 125.80, 124.45, 124.25, 123.12, 121.42, 119.00, 118.78, 118.38, 118.32, 114.23, 114.14, 114.12, 114.01, 113.86, 113.71, 113.71, 101.26, 101.00, 55.38, 55.30, 42.22, 40.13, 37.51, 36.62, 27.27, 23.04. **IR** (thin film, cm\(^{-1}\)): 3009, 2957, 1608, 1512, 1475, 1249, 1177, 1034, 971, 816. **HRMS** \(m/z\) 633.0276 [(M + H\(^+\)) calc’d for C\(_{32}\)H\(_{26}\)Br\(_2\)O\(_4\)H\(^+\): 633.0258].
(E)-3,8-dichloro-5a-(4-methoxyphenyl)-11-(4-methoxystyryl)-5a,11,11a,12-tetrahydrochromeno[2,3-b]chromene (2g)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. **Yield:** 250 mg, 92%. **D.r.:** 5:1. ¹H NMR (400 MHz, CDCl₃, both diastereomers reported) Major: δ 6.80 – 7.52 (m, 14H), 6.38 (d, J = 15.7 Hz, 1H), 5.86 (dd, J = 15.7, 9.3 Hz, 1H), 3.83 (s, 3H), 3.80 (s, 3H), 3.42 (dd, 1H), 2.92 – 2.74 (m, 1H), 2.74 – 2.48 (m, 2H). Minor: δ 6.80 – 7.52 (m, 14H), 6.48 (d, J = 15.7 Hz, 1H), 6.07 (dd, J = 15.7, 9.4 Hz, 1H), 3.83 (s, 3H), 3.80 (s, 3H), 3.42 (dd, 1H), 2.92 – 2.74 (m, 1H), 2.74 – 2.48 (m, 2H). ¹³C NMR (101 MHz, CDCl₃, both diastereomers reported) δ 160.15, 160.09, 159.50, 159.46, 153.40, 152.78, 152.19, 151.87, 134.30, 134.15, 133.93, 133.32, 133.25, 132.63, 131.74, 131.51, 130.55, 130.40, 130.22, 129.25, 129.17, 127.53, 127.14, 127.08, 126.82, 124.74, 122.13, 122.08, 121.96, 121.87, 120.84, 119.42, 117.82, 117.32, 117.24, 116.75, 116.60, 114.13, 114.00, 101.42, 101.22, 55.36, 55.33, 55.31, 55.29, 41.86, 39.73, 37.71, 36.88, 26.95, 22.71. **HRMS** m/z 545.1286 [(M + H⁺) calc’d for C₃₂H₂₆Cl₂O₄H⁺: 545.1290]. **IR** (thin film, cm⁻¹): 3009, 2957, 2934, 2837, 1607, 1577, 1512, 1484, 1409, 1296, 1252, 1177, 1033, 998, 758.
(E)-2,9-dimethoxy-5a-(4-methoxyphenyl)-11-(4-methoxystyryl)-5a,11,11a,12-tetrahydrochromeno[2,3-b]chromene (2h)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. **Yield:** 243 mg, 91%. **D.r.:** 5:1. 1H NMR (400 MHz, CDCl₃, both diastereomers reported) Major: δ 7.46 – 6.27 (m, 14H), 6.32 (d, J = 15.6 Hz, 1H), 5.83 (dd, J = 15.7, 9.4 Hz, 4H), 3.74 (s, 3H), 3.69 (s, 3H), 3.66 (s, 3H), 3.62 (s, 3H), 3.49 – 3.28 (dd, 1H), 2.89 – 2.65 (m, 1H), 2.60 – 2.44 (m, 2H). Minor: δ 7.46 – 6.27 (m, 14H), 6.39 (d, J = 15.7 Hz, 2H), 6.05 (dd, J = 15.7, 9.4 Hz, 2H), 3.73 (s, 3H), 3.70 (s, 3H), 3.65 (s, 3H), 3.61 (s, 3H), 3.49 – 3.28 (dd, 1H), 2.89 – 2.65 (m, 1H), 2.60 – 2.44 (m, 2H). 13C NMR (101 MHz, CDCl₃, both diastereomers reported) δ 158.81, 158.75, 158.31, 158.26, 153.26, 153.12, 153.02, 152.97, 145.94, 145.33, 144.78, 144.44, 132.78, 132.57, 131.80, 131.59, 128.56, 128.50, 126.71, 126.48, 126.47, 126.30, 126.25, 124.67, 123.43, 121.93, 120.74, 118.92, 116.69, 116.54, 116.13, 116.08, 113.22, 113.18, 113.05, 113.03, 113.01, 112.98, 112.91, 112.84, 112.79, 112.65, 112.48, 99.87, 99.63, 54.70, 54.65, 54.62, 54.57, 54.33, 54.31, 54.24, 54.23, 41.53, 39.53, 37.00, 36.09, 26.83, 22.67. IR (thin film, cm⁻¹): 2934, 2835, 1653, 1512, 1455, 1457, 1251, 1199, 1177, 1055, 1035. HRMS m/z 537.2277 [(M + Na⁺) calc’d for C₃₄H₂₉O₆H⁺: 537.2288].
1,3,4,8,10,11-hexamethoxy-6-phenyl-7-((E)-styryl)-6,6a,7,12a-tetrahydrochromeno[4,3-b]chromene, dependensin (7)

To a reaction vessel equipped with stir bar in air was added 5,7,8-trimethoxyflav-3-ene 6 (150 mg, 0.50 mmol) and MIL-101-SO₃H catalyst (1 mol%) in 10 mL dichloromethane. The mixture was stirred at room temperature for 12 hours. The crude mixture was purified without work-up by flash chromatography over silica gel column (elution with 95:5 – 90:10, hexanes:EtOAc) to afford the dependensin 7 as a single diastereomer (white solid, 232 mg, 74% yield).
Mechanistic evidence for $2H$-chromene and vinyl ortho-quinone methide equilibrium

$\text{(E)-}8$ and $1b$ homodimerize into the same product $2a$ in similar yield and the same diastereoselectivity. This observation suggested the equilibrium between chromene $1h$ and vinyl $\omega$QM $\text{(E)-}8$. 

(Reproduced with permission.)
The crude mixture was purified by flash column chromatography with elution by 98:2, hexanes:EtOAc. **Yield:** 250 mg, 71%. **D.r.:** >99:1. **$^1$H NMR** (500 MHz, CDCl$_3$) $\delta$ 7.25 – 7.16 (m, 2H), 6.96 – 6.90 (m, 1H), 6.84 – 6.73 (m, 2H), 6.46 – 6.39 (m, 1H), 6.42 (s, 1H), 6.19 (d, $J$ = 15.7 Hz, 1H), 5.98 (dd, $J$ = 15.7, 7.6 Hz, 1H), 5.28 (d, $J$ = 2.6 Hz, 1H), 4.02 – 3.94 (m, 1H), 3.80 – 3.62 (m, 6H), 3.42 – 3.35 (m, 1H), 1.98 (s, 1H), 1.71 – 1.55 (m, 2H). **$^{13}$C NMR** (101 MHz, CDCl$_3$) $\delta$ 159.61, 153.12, 131.27, 130.67, 130.21, 129.72, 127.37, 113.95, 113.90, 107.99, 101.27, 95.43, 63.44, 55.31, 41.59, 37.26, 23.94, 23.27. **IR** (thin film, cm$^{-1}$): 2943, 1618, 1583, 1511, 1250, 1164, 1132, 1037, 987, 910, 832. **HRMS** m/z 353.1753 [(M + H$^+$) calc’d for 353.1756].

**(E)-8-methoxy-5-(4-methoxystyril)-2,3,4,4a,5,10a-hexahydropyrano[2,3-b]chromene (9a)**
(E)-7-methoxy-2-(4-methoxyphenyl)-4-(4-methoxystyril)chroman (9b)

The crude mixture was purified by flash column chromatography with elution by 98:2, hexanes:EtOAc. **Yield:** 326 mg, 81%. **D.r.:** 2:1. **1H NMR** (400 MHz, CDCl₃, both diastereomers reported) Major: δ 7.53 – 6.71 (m, 11H), 6.46 (m, 1H), 5.97 – 5.77 (m, 1H), 5.10 – 4.88 (m, 1H), 3.78 – 3.62 (3MeO, 9H), 3.61 – 3.49 (m, 1H), 2.08 – 1.88 (m, 2H). Minor: δ 7.53 – 6.71 (m, 11H), 6.30 – 6.58 (m, 1H), 5.10 – 4.88 (m, 1H), 3.78 – 3.62 (3MeO, 9H), 3.61 – 3.49 (m, 1H), 2.08 – 1.88 (m, 2H). **13C NMR** (101 MHz, CDCl₃, both diastereomers reported) δ 159.54, 159.50, 159.47, 159.30, 159.06, 159.02, 155.82, 155.71, 133.53, 133.35, 131.96, 131.20, 131.11, 130.65, 130.26, 129.95, 129.93, 129.81, 127.51, 127.45, 127.37, 127.32, 116.52, 115.17, 114.01, 113.99, 113.96, 113.93, 107.70, 107.56, 101.55, 101.40, 77.62, 73.71, 55.31, 40.42, 37.87, 37.11, 35.69. **IR** (thin film, cm⁻¹): 3001, 2954, 2835, 1613, 1511, 1248, 1157, 1033, 831. **HRMS m/z 403.1909 [(M + H⁺) calc’d for C₂₆H₂₆O₄: 403.1906].
(E)-3,10-dimethoxy-7-(4-methoxystyryl)-6,6a,7,12a-tetrahydro-5H-benzo[c]xanthene (9c)

The crude mixture was purified by flash column chromatography with elution by 98:2, hexanes:EtOAc. **Yield:** 377 mg, 88%. Single diastereomer.  

**$^1$H NMR** (400 MHz, CDCl$_3$) $\delta$ 7.29 – 6.08 (m, 12H), 4.94 (d, $J = 2.2$ Hz, 3H), 3.72 (s, 6H), 3.67 (s, 3H), 3.33 (dd, $J = 5.0$, 2.5 Hz, 1H), 2.84 (dd, $J = 21.5$, 11.6 Hz, 2H), 2.22 – 2.02 (m, 1H), 1.87 (ddd, $J = 19.1$, 12.4, 6.9 Hz, 1H), 1.73 – 1.57 (m, 1H).  

**$^{13}$C NMR** (101 MHz, CDCl$_3$) $\delta$ 159.70, 159.40, 158.97, 154.30, 138.56, 132.12, 131.39, 131.36, 130.34, 129.93, 127.66, 127.33, 113.93, 113.69, 112.34, 107.80, 101.15, 71.11, 55.29, 55.24, 55.23, 43.11, 37.51, 28.86, 23.28.  

**IR** (thin film, cm$^{-1}$): 2933, 2834, 1616, 1585, 1442, 1251, 1156, 1120, 1033.  

**HRMS** $m/z$ 429.2066 [(M + H$^+$) calc’d for C$_{28}$H$_{36}$O$_4$: 429.2065].
(E)-2,7-dimethoxy-10-(4-methoxystyryl)-4b,10a,11-tetrahydroindeno[1,2-b]chromene (9d)

The crude mixture was purified by flash column chromatography with elution by 98:2, hexanes:EtOAc. Yield: 315 mg, 76%. D.r.: 7:1. Major $^1$H NMR (400 MHz, CDCl$_3$, major diastereomer) $\delta$ 7.42 – 6.23 (m, 10H), 6.18 – 6.05 (m, 1H), 5.43 (d, $J = 13.2$, 1H), 3.74 (s, 3H), 3.73 (s, 3H), 3.68 (s, 3H), 3.28 – 3.13 (m, 1H), 3.02 – 2.90 (m, 1H), 2.90 – 2.77 (m, 1H), 2.75 – 2.66 (m, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 160.48, 159.40, 159.06, 155.54, 144.04, 134.83, 131.26, 129.90, 129.63, 129.36, 127.39, 125.82, 117.18, 113.97, 112.93, 110.26, 107.21, 102.10, 79.90, 55.27, 44.23, 41.25, 35.97. Minor $^1$H NMR (400 MHz, CDCl$_3$, minor diastereomer) $\delta$ 7.36 – 6.23 (m, 10H), 6.02 (dd, $J = 15.7$, 9.4 Hz, 1H), 5.42 (t, $J = 10.1$ Hz, 1H), 3.87 (m, 1H), 3.75 (s, 3H), 3.71 (s, 3H), 3.64 (s, 3H), 3.00 (dd, $J = 13.6$, 6.6 Hz, 1H), 2.82 (m, 2H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 160.68, 159.23, 159.12, 156.04, 145.79, 134.70, 132.18, 129.99, 128.69, 127.53, 127.40, 126.12, 116.76, 114.01, 112.89, 110.04, 107.05, 102.22, 81.31, 54.28, 33.86. IR (thin film, cm$^{-1}$): 2934, 2834, 1616, 1510, 1464, 1251, 1156, 1122, 1033. HRMS $m/z$ 415.1909 [(M + H$^+$) calc’d for C$_{27}$H$_{26}$O$_4$: 415.1901].
(E)-5a-(4-methoxyphenyl)-11-(4-methoxystyril)-5a,11,11a,12-tetrahydrochromeno[2,3-b]chromene (9e)

The crude mixture was purified by flash column chromatography with elution by 98:2 – 95:5, hexanes:EtOAc. **Yield:** 428 mg, 90%. **D.r.:** 4:1. **$^1$H NMR** (400 MHz, CDCl$_3$, both diastereomers reported) Major: $\delta$ 7.53 – 6.77 (m, 16H), 6.37 (d, $J$ = 15.7 Hz, 1H), 5.91 (dd, $J$ = 15.7, 9.3 Hz, 1H), 3.82 (s, 3H), 3.78 (s, 3H), 3.51 (dd, $J$ = 9.9 Hz, 9.9 Hz, 1H), 2.91 – 2.56 (m, 3H). Minor: $\delta$ 7.53 – 6.77 (m, 16H), 6.37 (d, $J$ = 15.6 Hz, 1H), 6.15 (dd, $J$ = 15.7, 9.3 Hz, 1H), 3.81 (s, 3H), 3.78 (s, 3H), 3.51 (m, 1H), 2.91 – 2.56 (m, 3H). **$^{13}$C NMR** (101 MHz, CDCl$_3$, both diastereomers reported) $\delta$ 159.91, 159.85, 159.33, 159.28, 152.97, 152.35, 151.81, 151.46, 133.74, 133.52, 132.76, 132.52, 129.62, 129.57, 129.36, 129.10, 128.71, 128.07, 128.03, 127.82, 127.50, 127.46, 127.28, 127.22, 125.85, 123.67, 122.24, 121.68, 121.57, 121.37, 121.12, 119.36, 117.13, 116.98, 116.55, 116.48, 114.09, 114.07, 113.99, 113.86, 101.09, 100.83, 55.36, 55.26, 42.24, 40.08, 38.11, 37.19, 27.43, 23.19. **IR** (thin film, cm$^{-1}$): 3008, 2933, 2836, 1609, 1584, 1512, 1486, 1455, 1249, 1177, 1054, 754. **HRMS m/z** 507.2171 [(M + H$^+$) calc’d for C$_{32}$H$_{28}$O$_4$H$^+$: 507.2165].
Preparation of vinyl ortho-quinone methide (E)-8

Modified Jurd synthesis\textsuperscript{1} of ortho-quinone methide. A solution of (E)-6-(3-(4-methoxyphenyl) allyl)benzo[d][1,3]dioxol-5-ol (1.0 g) in ether (50 mL) was added silver oxide (3.0 g) then stirred overnight. The solution was filtered, then concentrated to 20 mL, cooled, and red crystals were collected (0.54 g). The product is acid and heat sensitive.

\textsuperscript{1} L. Jurd, Tetrahedron 1977, 33, 163–168.