How the Giant lost its mantle and became a Dwarf

or

Modelling the evolution of double white-dwarf systems

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Outline

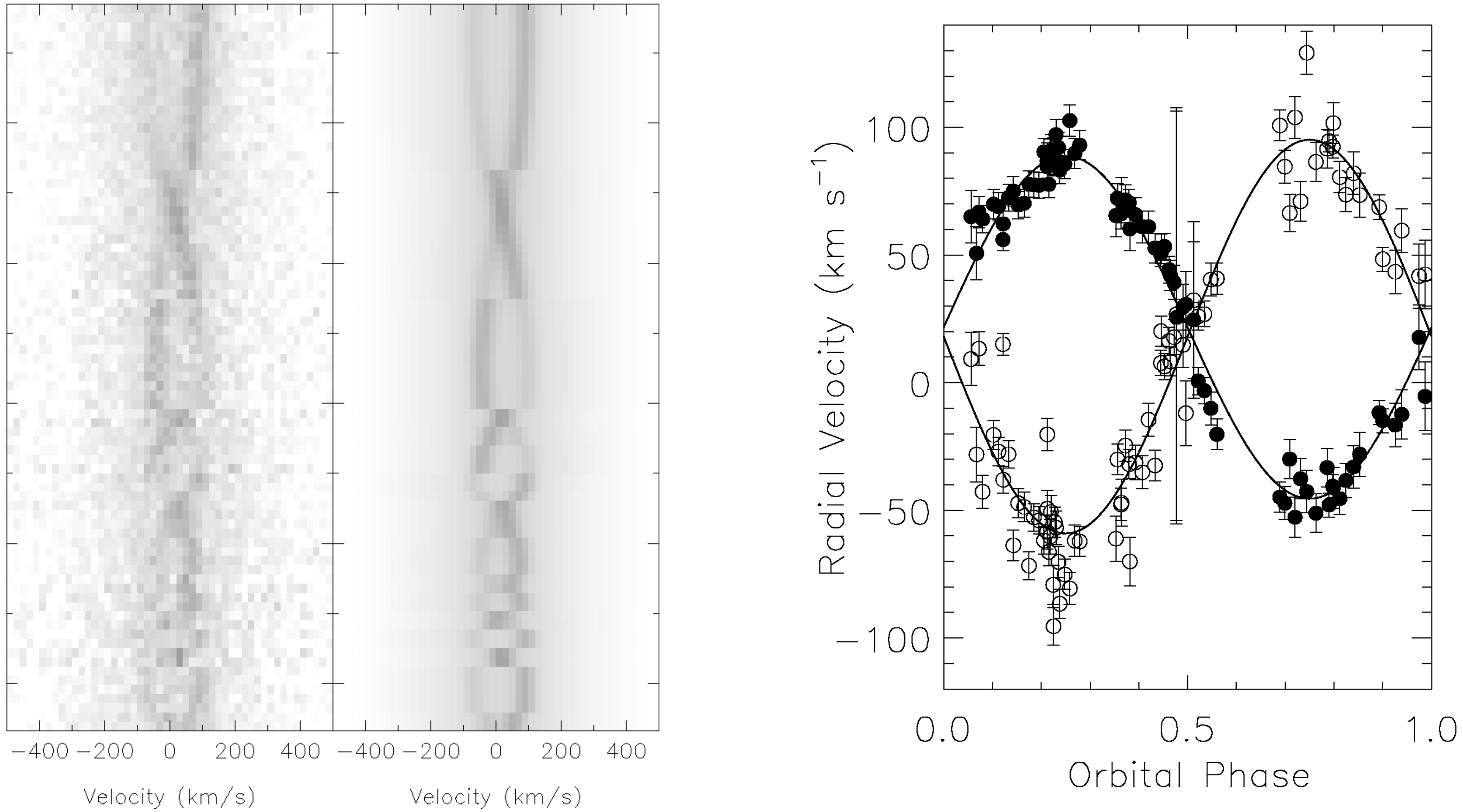
- Introduction and context
- Observed double white dwarfs
- Common envelope and spiral-in
- Stable first mass transfer
- Unstable first mass transfer
- Conclusions

Astrophysical context

- Possibly progenitors of Supernova type Ia
- Sources of low-frequency gravitational waves

- Binary evolution theory
- White dwarf cooling theory
- Population synthesis

Observed double white dwarfs



WD 0316+768, Adapted from Maxted et al., 2002

Observed double white dwarfs

System	P_{orb} (d)	a_{orb} ($R_\odot$)	M_1 ($M_\odot$)	M_2 ($M_\odot$)	$q_2 = M_2/M_1$	$\Delta\tau$ (Myr)
WD 0135–052	1.556	5.63	0.52 ± 0.05	0.47 ± 0.05	0.90 ± 0.04	350
WD 0136+768	1.407	4.99	0.37	0.47	1.26 ± 0.03	450
WD 0957–666	0.061	0.58	0.32	0.37	1.13 ± 0.02	325
WD 1101+364	0.145	0.99	0.33	0.29	0.87 ± 0.03	215
PG 1115+116	30.09	46.9	0.7	0.7	0.84 ± 0.21	160
WD 1204+450	1.603	5.74	0.52	0.46	0.87 ± 0.03	80
WD 1349+144	2.209	6.59	0.44	0.44	1.26 ± 0.05	—
HE 1414–0848	0.518	2.93	0.55 ± 0.03	0.71 ± 0.03	1.28 ± 0.03	200
WD 1704+481a	0.145	1.14	0.56 ± 0.07	0.39 ± 0.05	0.70 ± 0.03	-20
HE 2209–1444	0.277	1.88	0.58 ± 0.08	0.58 ± 0.03	1.00 ± 0.12	500

See references in: Maxted et al., 2002 and Nelemans & Tout, 2005.

Common envelope

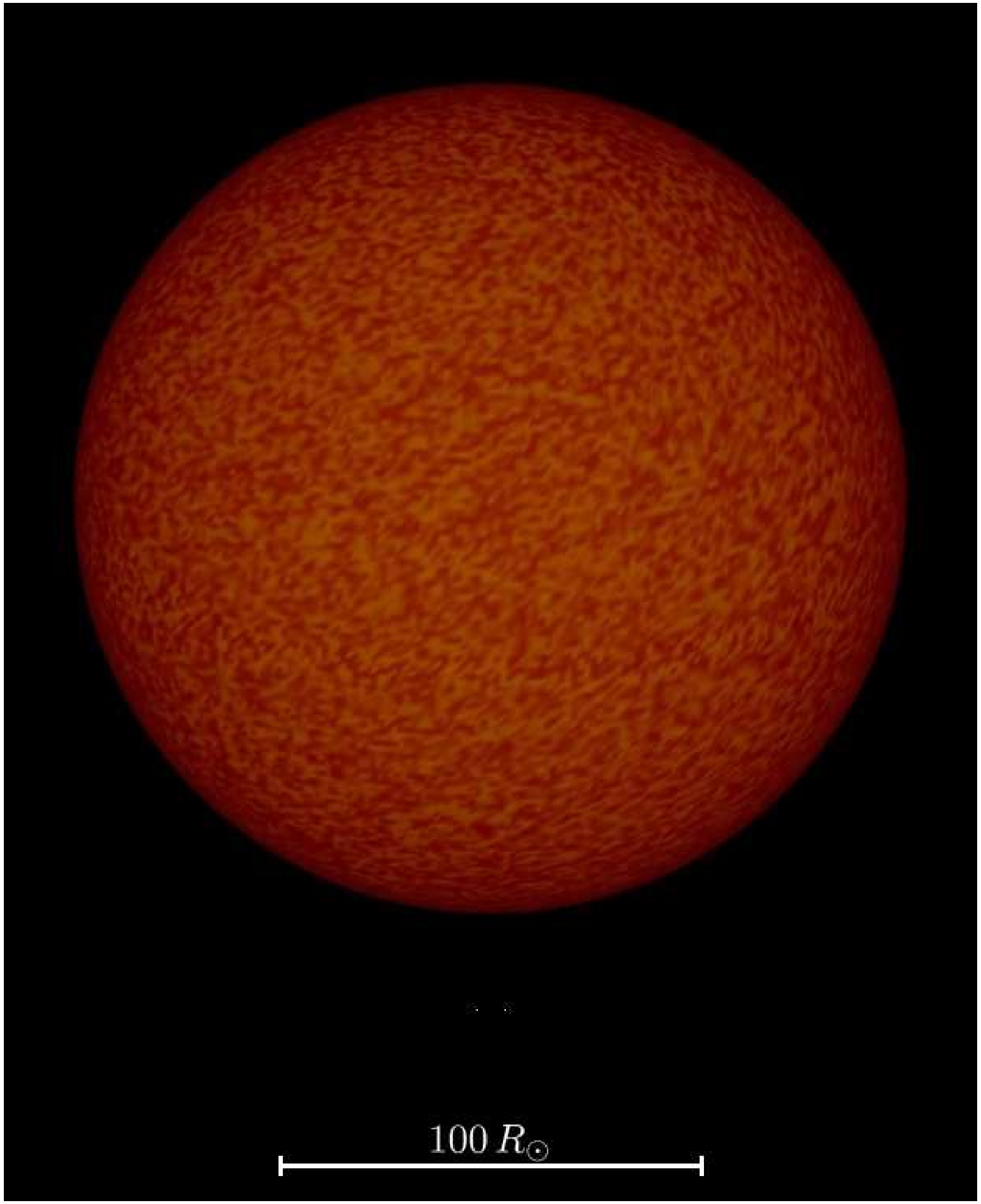
- Average orbital separation:

  $7\ R_\odot$

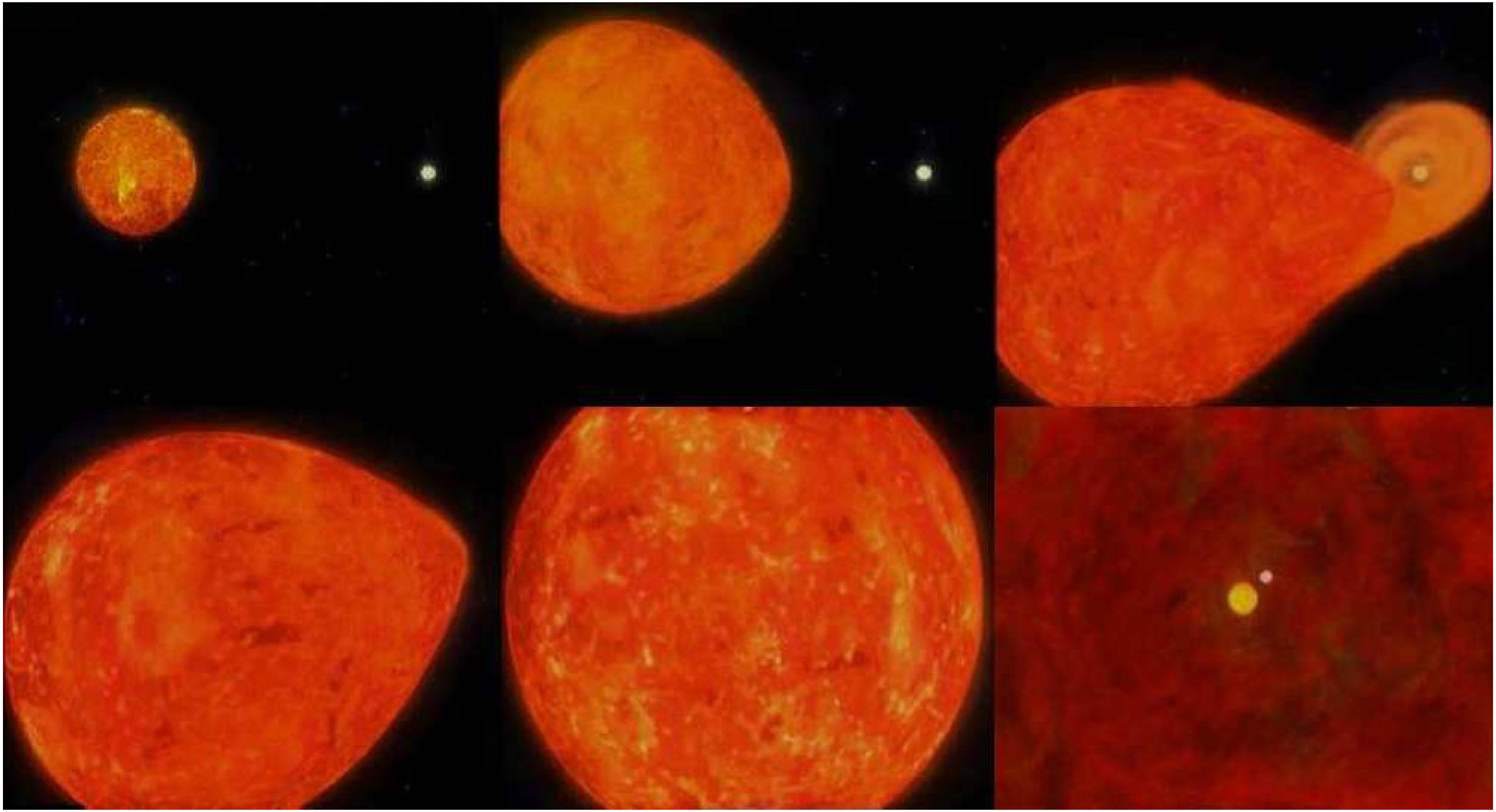
- Typical progenitor:

  $M_\mathrm{c} \gtrsim 0.3\,M_\odot$

  $R_* \sim 100\,R_\odot$



Common envelope



Envelope ejection

- Classical α-CE:

  Orbital energy is used to expel envelope:

$$U_{\mathrm{bind}} = \alpha_{\mathrm{CE}} \left[\frac{G\,M_{1\mathrm{f}}\,M_2}{2\,a_{\mathrm{f}}} - \frac{G\,M_{1\mathrm{i}}\,M_2}{2\,a_{\mathrm{i}}} \right]$$

(Webbink, 1984)

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with $\alpha_{\rm CE}$ the infamous Common Envelope parameter

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(Webbink, 1984)

- γ-EE:

  Envelope ejection with angular-momentum balance:

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} \;=\; \gamma\,\frac{M_{\rm 1i} - M_{\rm 1f}}{M_{\rm 1i} + M_2}$$

(Nelemans et al., 2000)

Envelope ejection

- EE much faster than nuclear evolution:
  - Core mass does not grow during EE
  - No accretion during EE

Envelope ejection

- EE much faster than nuclear evolution:
  - Core mass does not grow during EE
  - No accretion during EE
- Radius of the giant gives orbital period
- Envelope binding energy gives α_{CE}

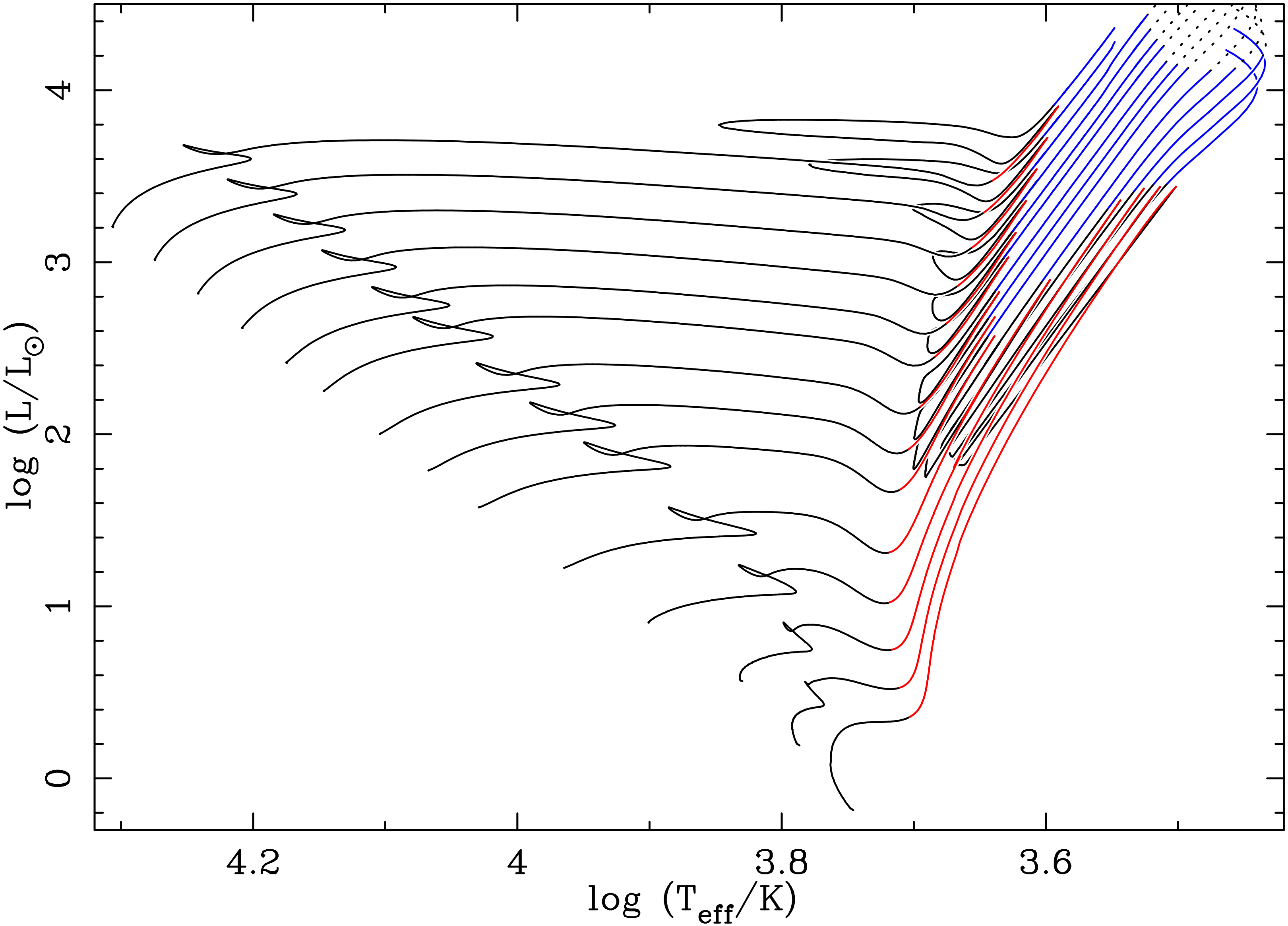
Progenitor models

199 models

0.8-10 $M_\odot$

RGB

AGB

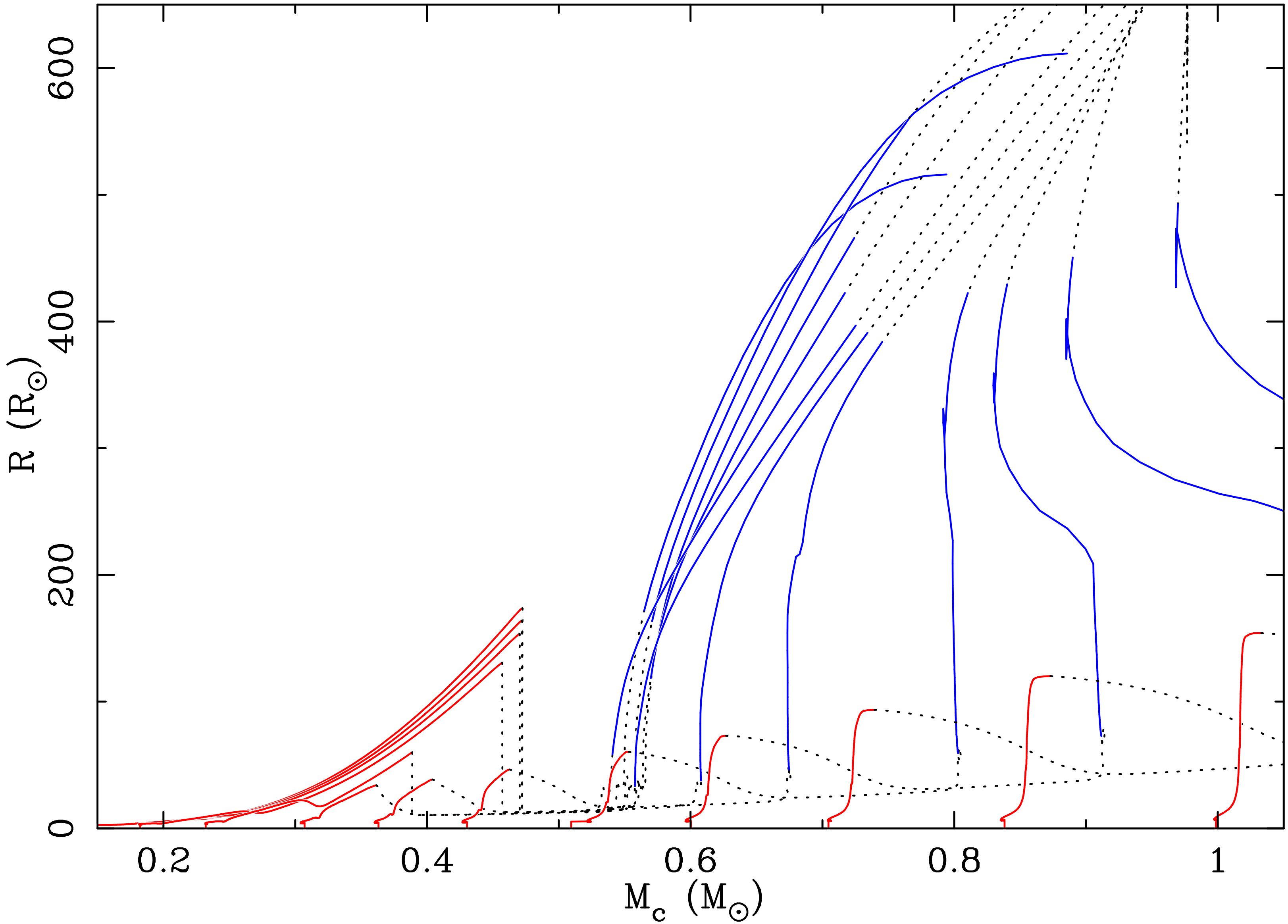


Progenitor models

R_* provides P_{orb} at onset of EE

RGB

AGB

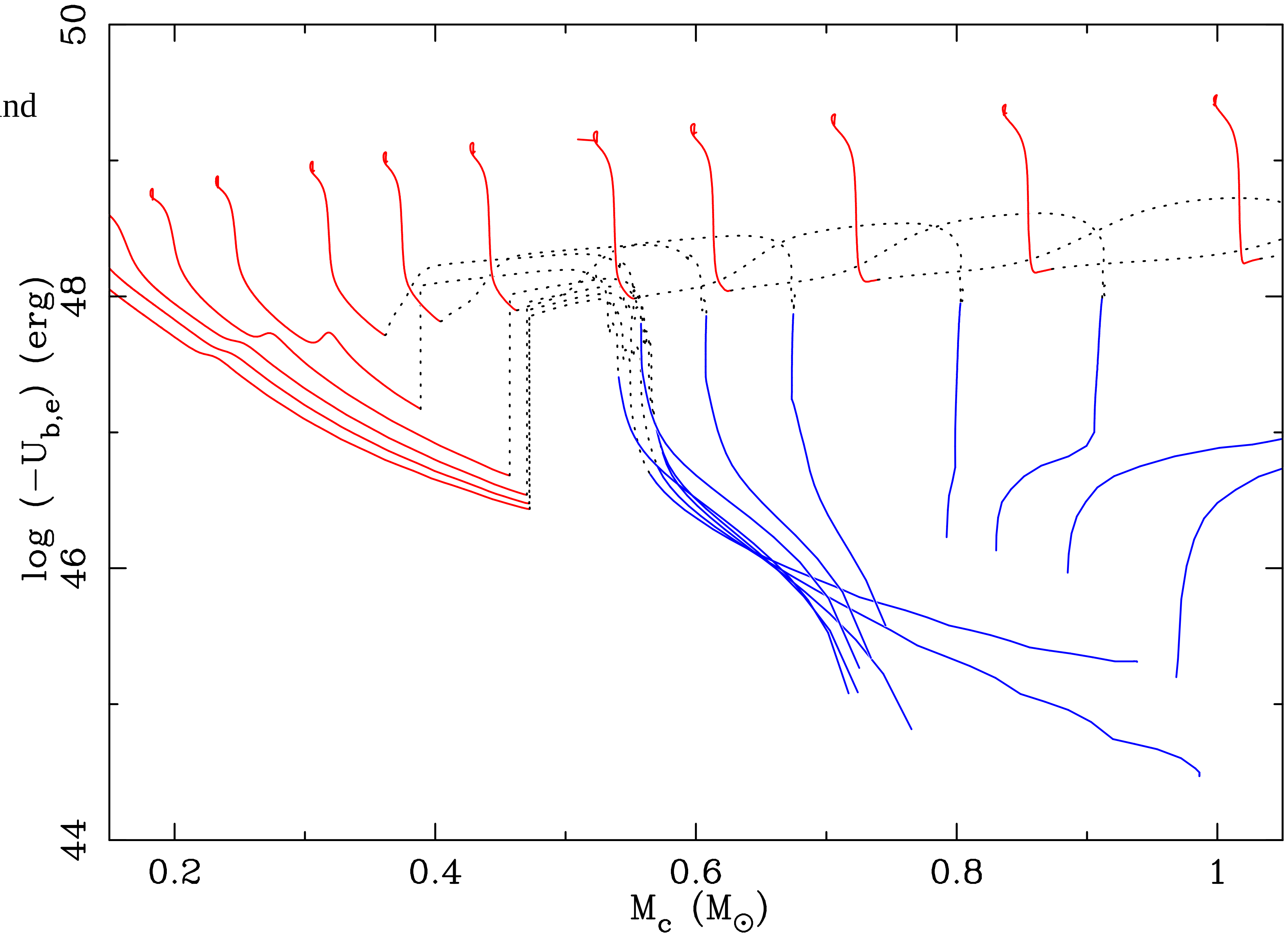


Progenitor models

Envelope U_{bind} provides α_{CE}

RGB

AGB



Evolutionary scenarios

MS + MS

↓ Stable M.T. (cons.) ↓

WD + MS

↓ Unstable M.T. (α-CE) ↓

WD + WD

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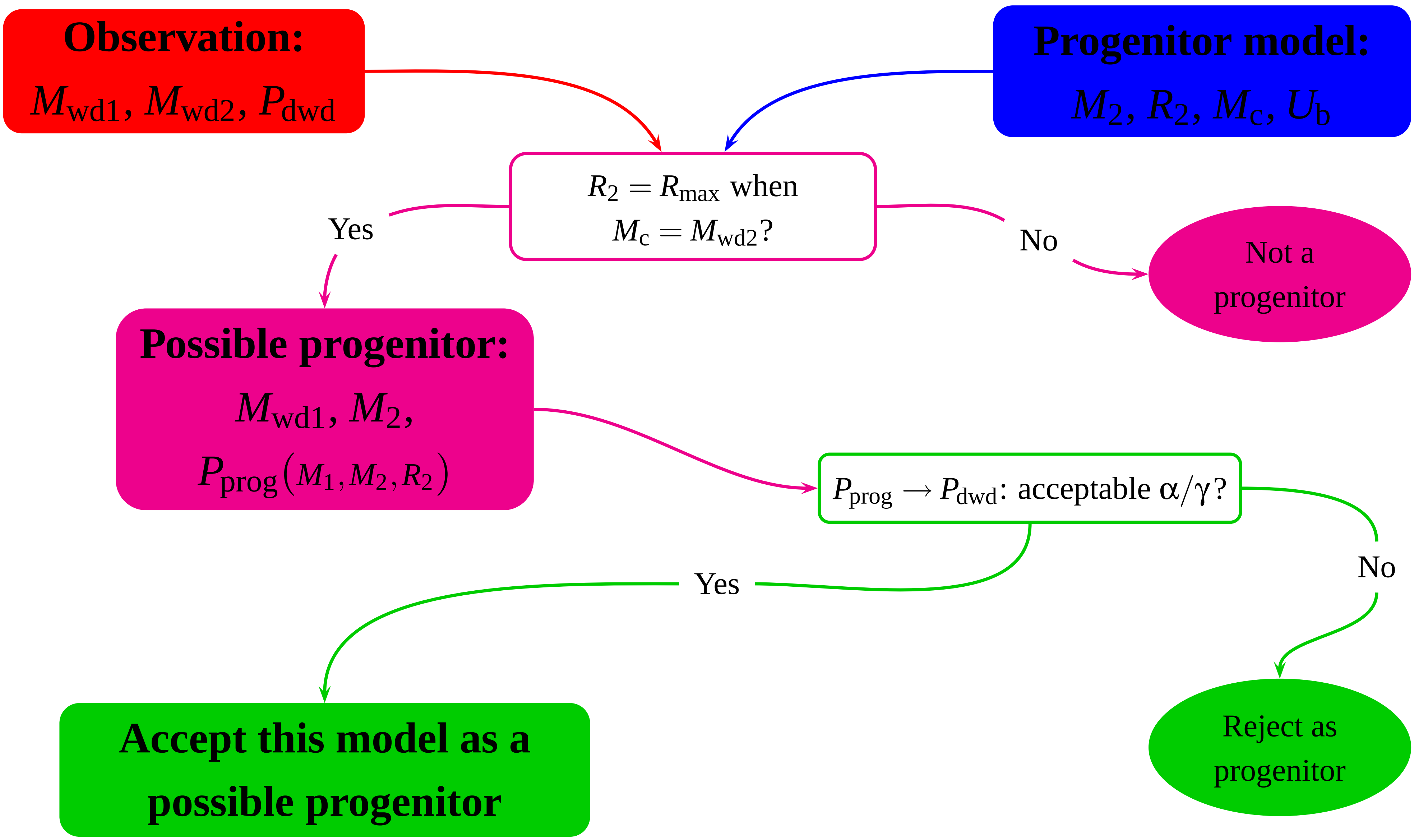
WD + MS

↓ Unstable M.T. (α,γ-EE) ↓

WD + WD

Confusogram

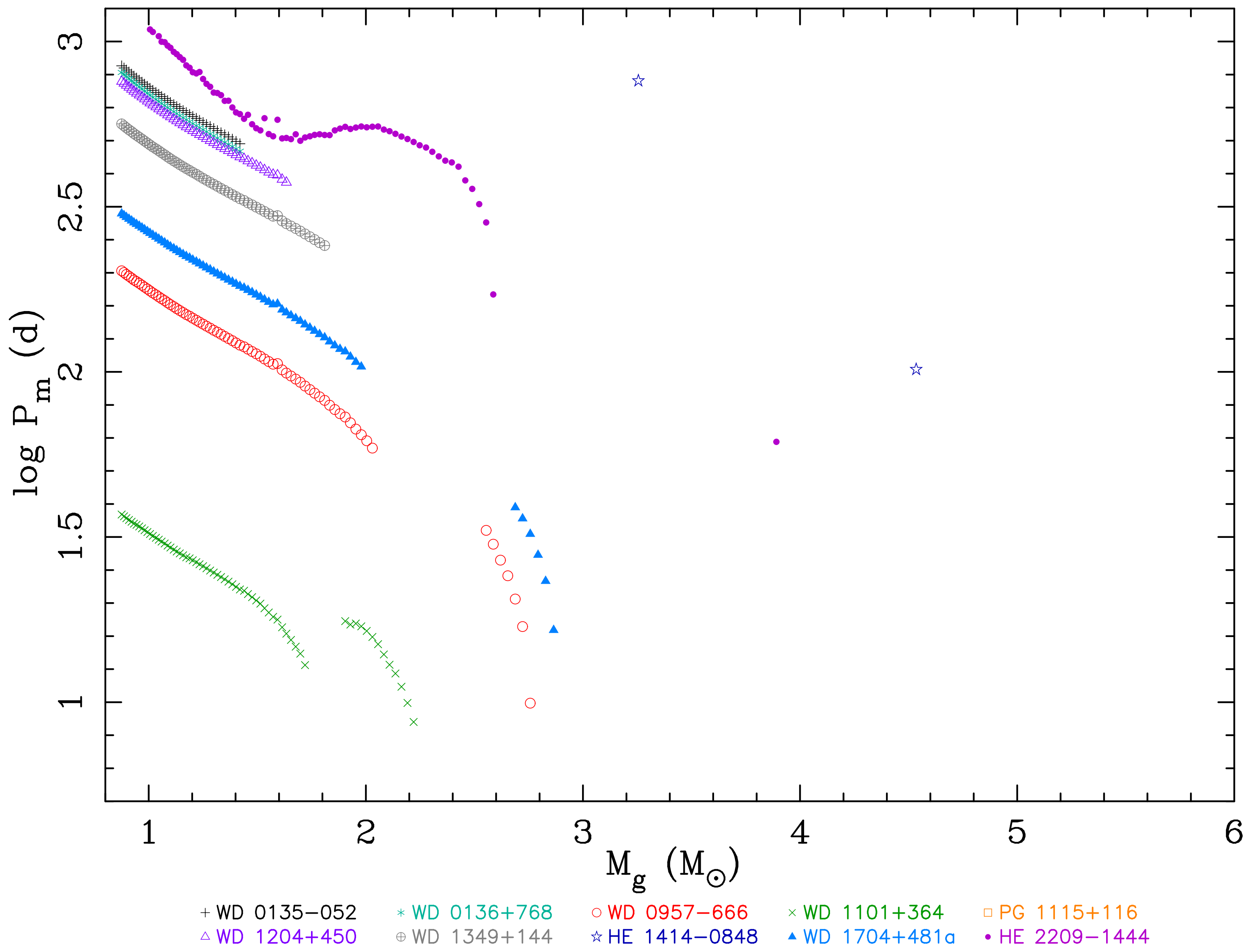


α-CE results

Accept

$0.1 < \alpha_{ce} < 10$

No errors
in observed
masses

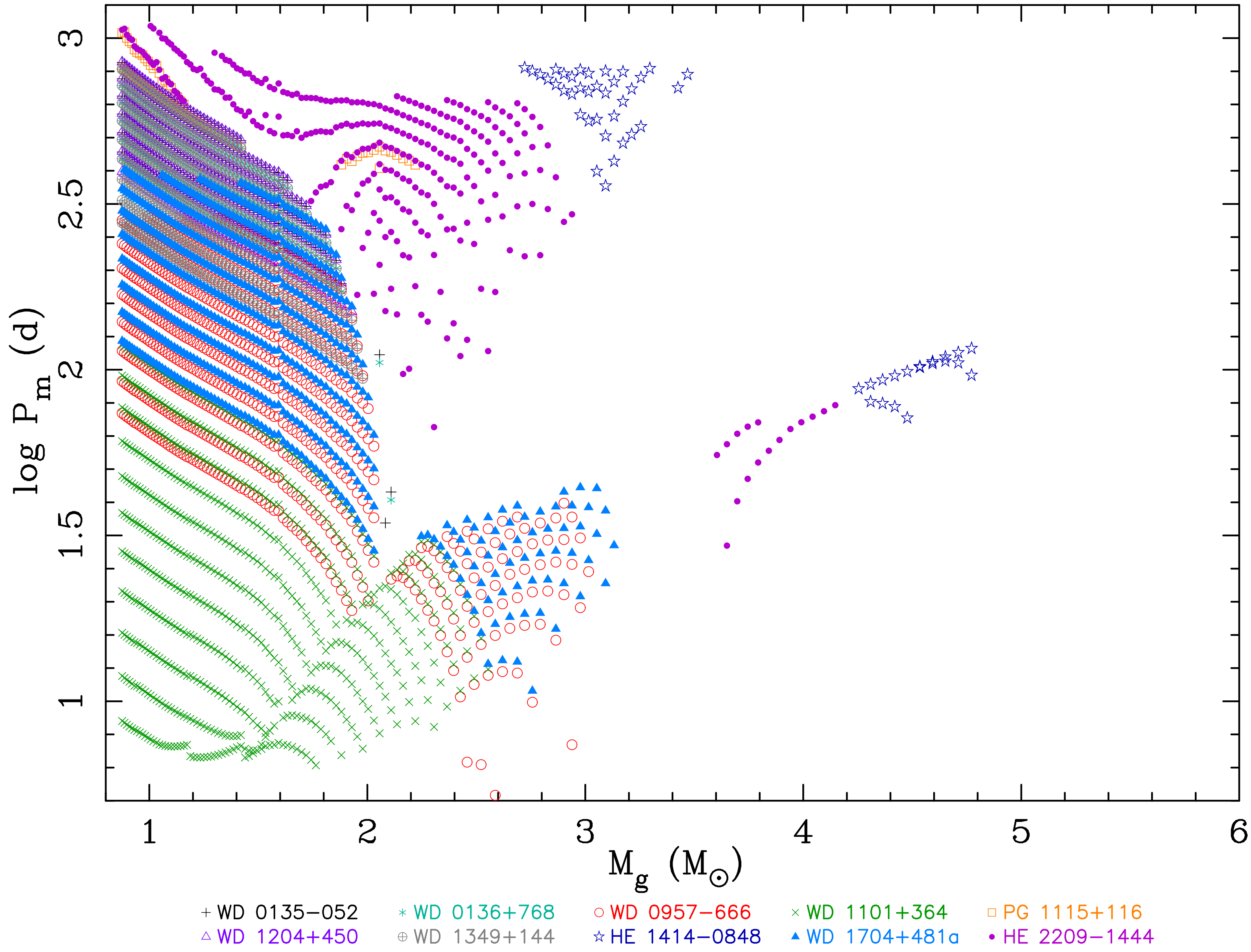


α-CE results

Accept

$0.1 < \alpha_{ce} < 10$

Introduce errors in observed masses: $\pm 0.05 M_{\odot}$

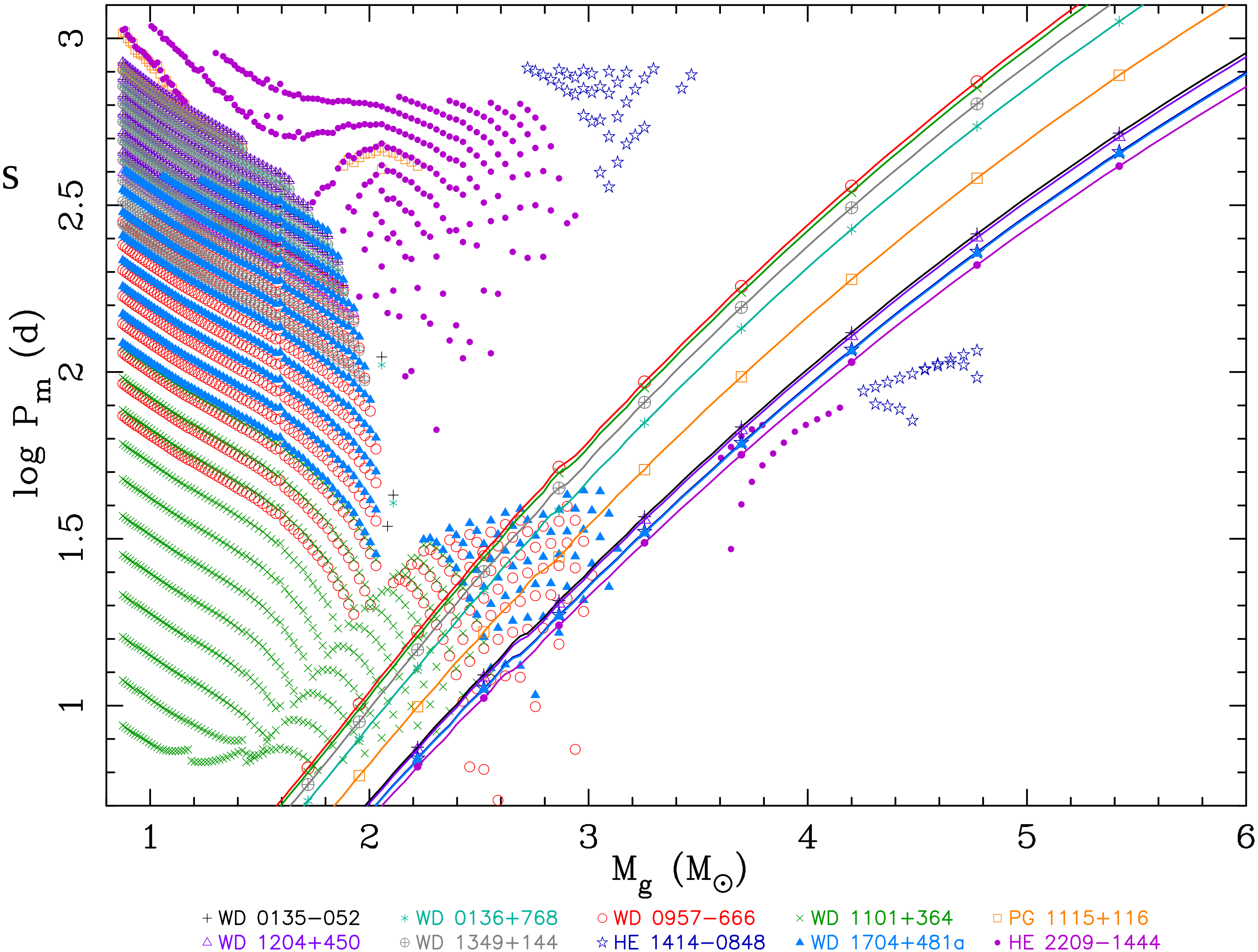


α-CE results

Maximum P_{orb} after stable mass transfer with $q_i = 0.62$

(Nelemans et al., 2000)

Only 5 systems have CE solutions with $P_{orb} < P_{max}$

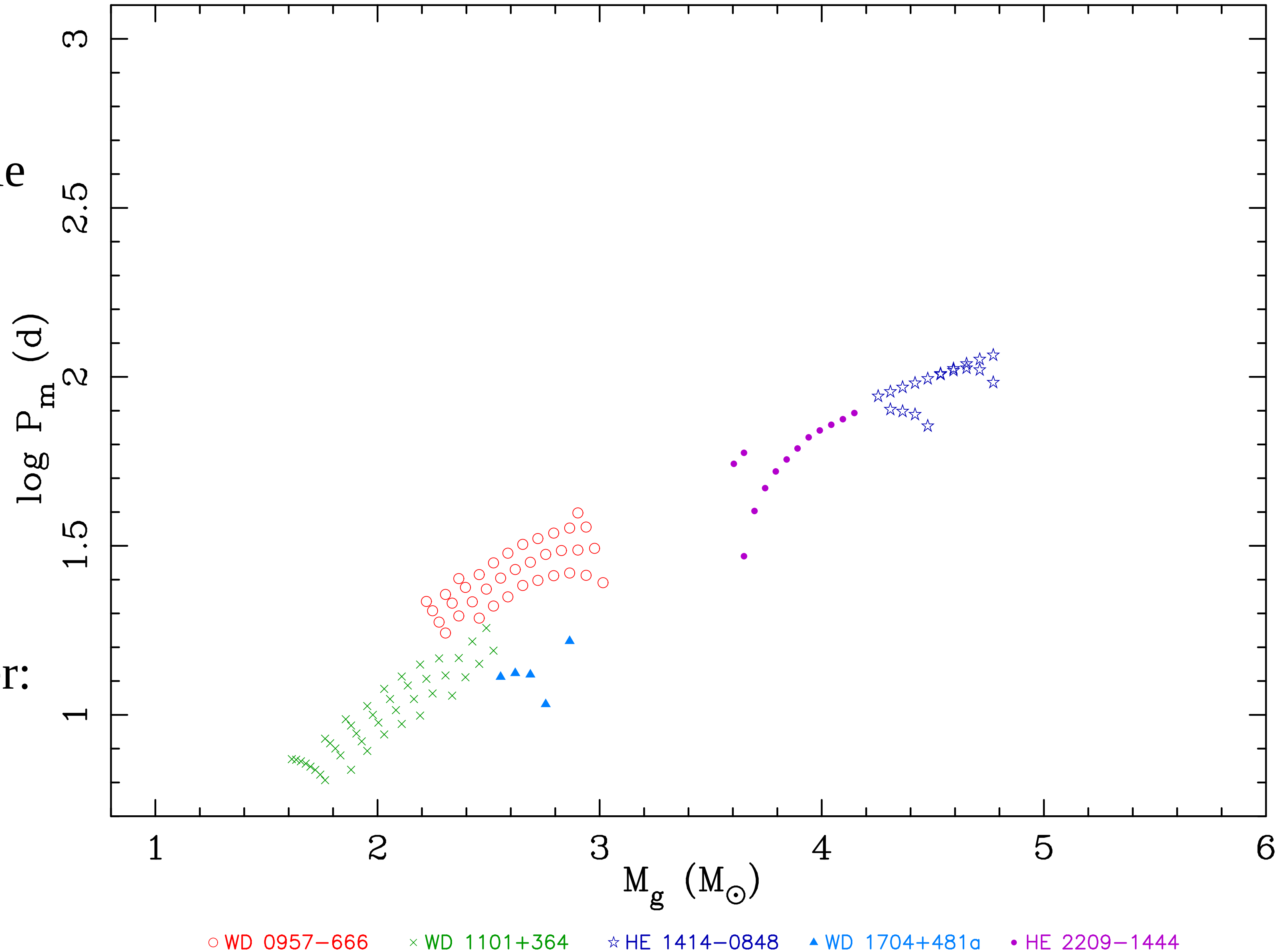


α-CE results

CE solutions that may be formed by stable mass transfer

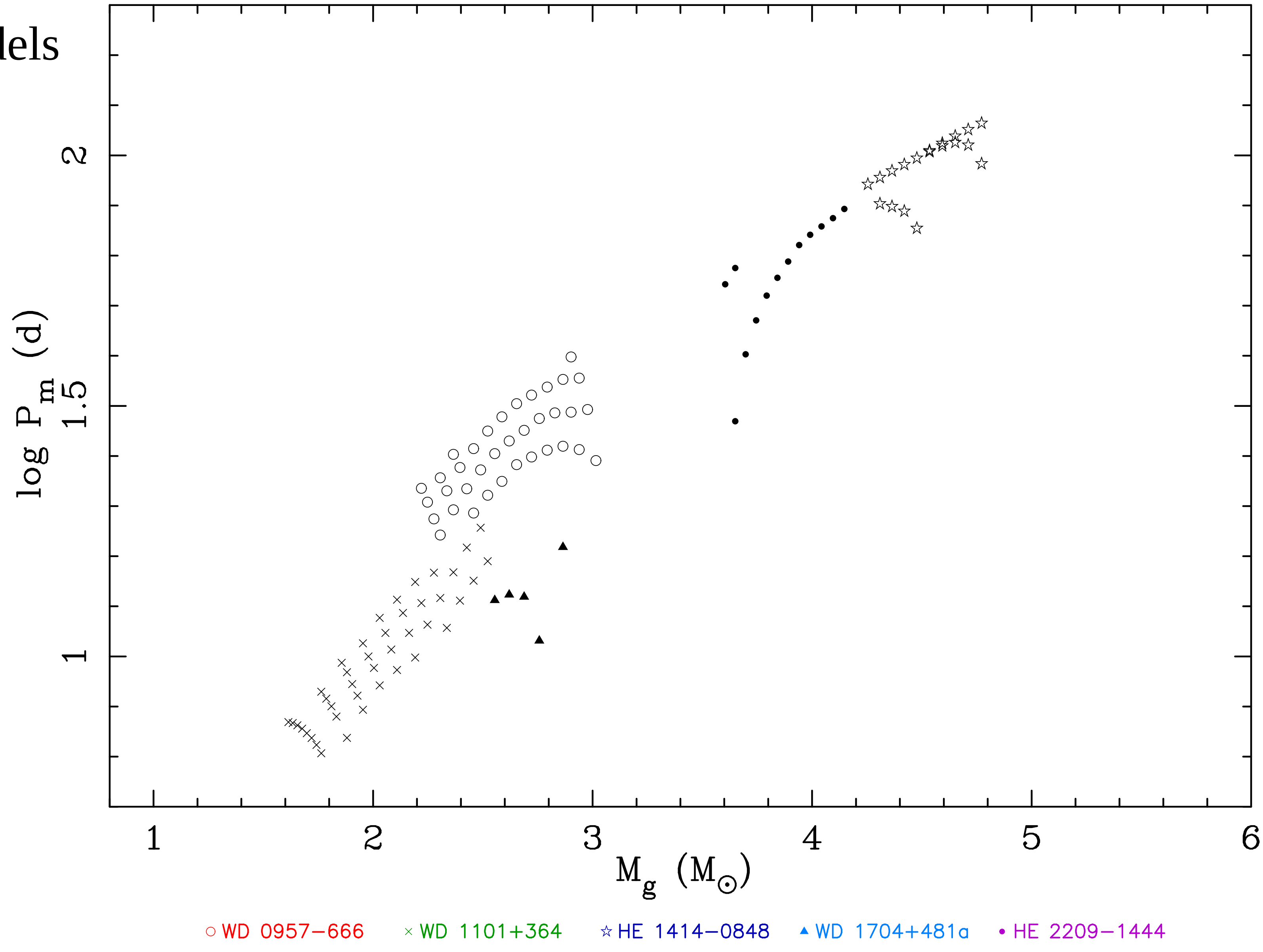
Conservative mass transfer: M_{tot} and J_{orb} fixed

1 free parameter: q_i



Conservative mass transfer

230 binary models calculated



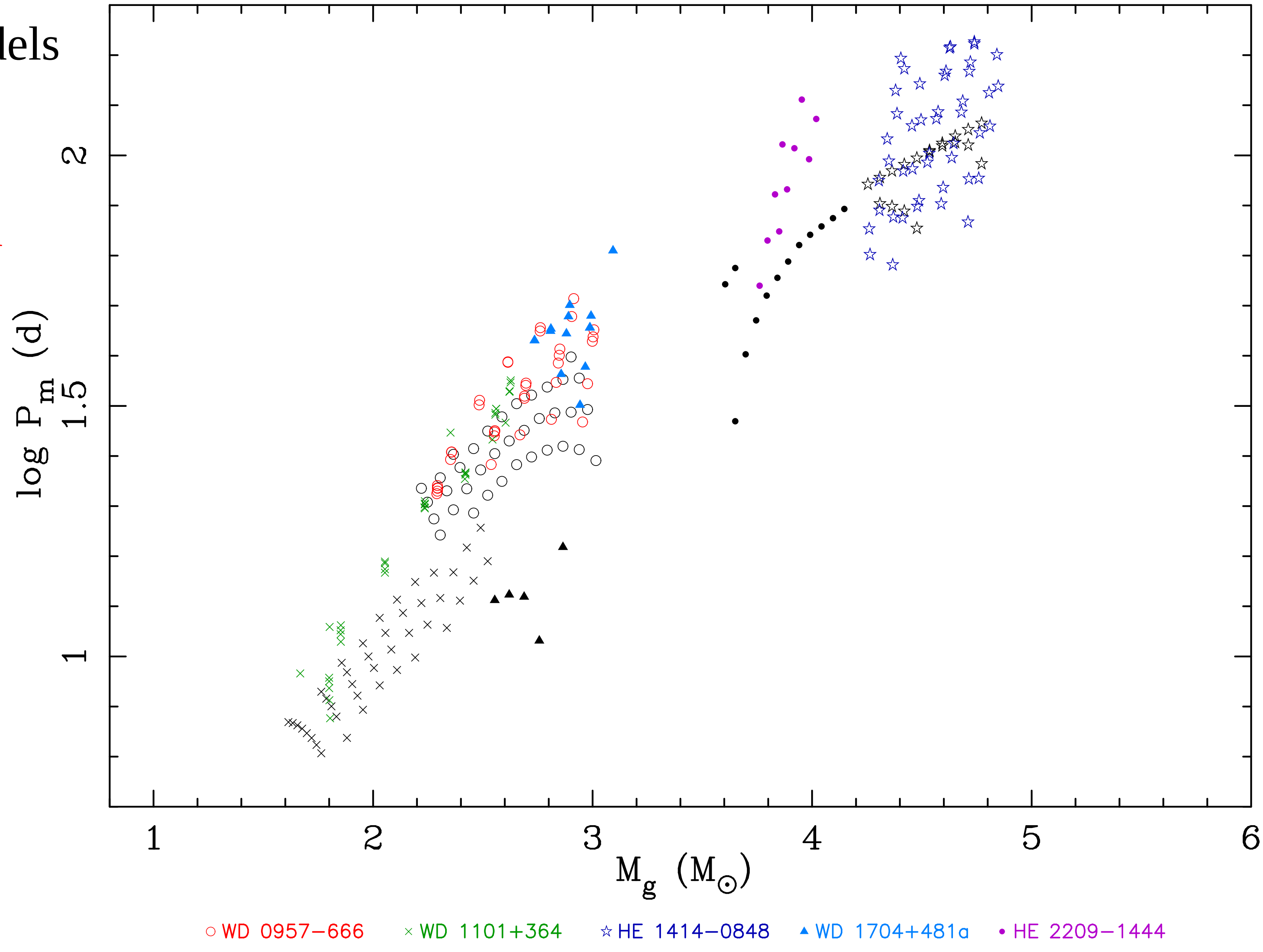
Conservative mass transfer

230 binary models calculated:

39% dynamical

18% contact

43% DWD



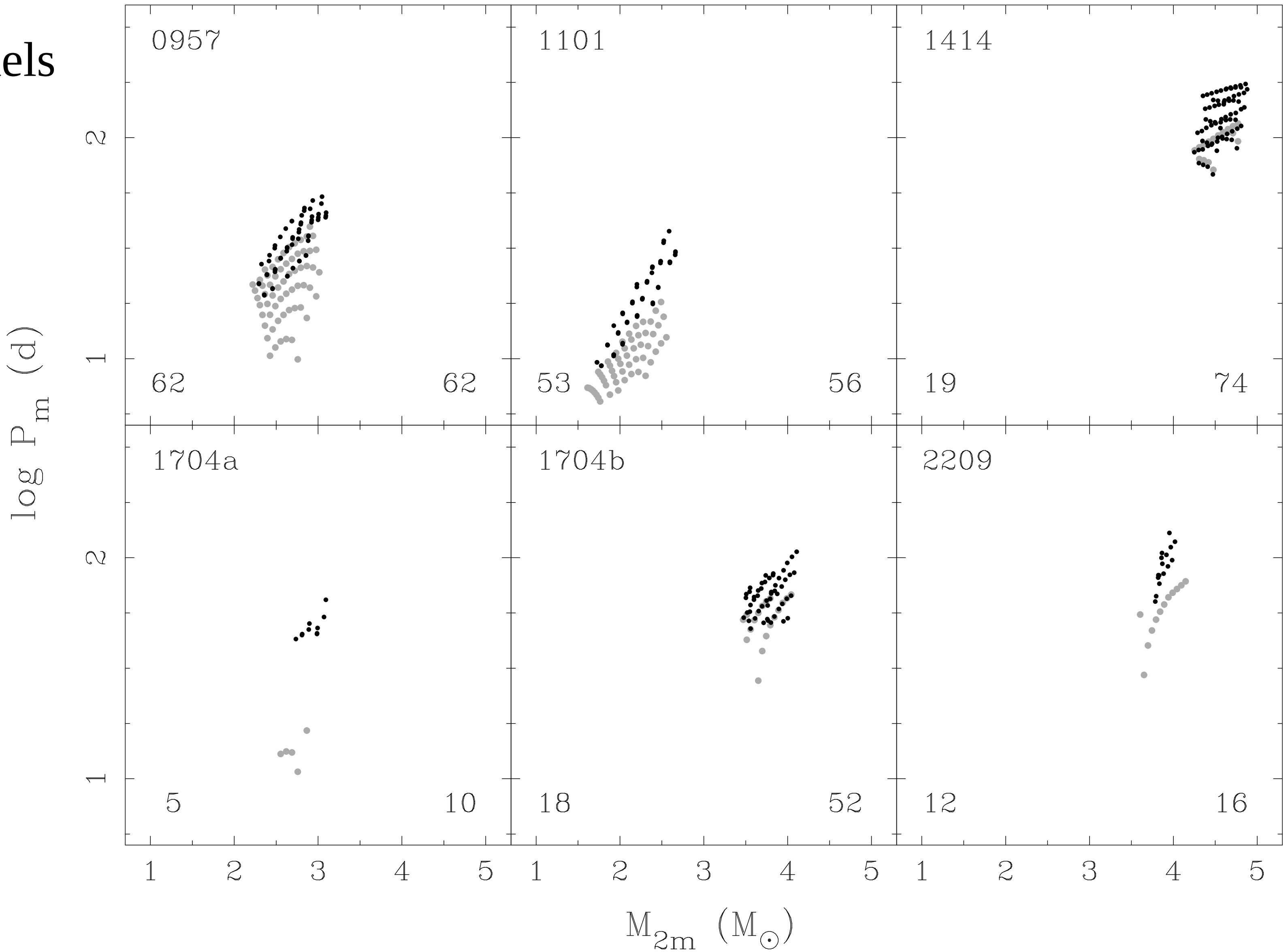
Conservative mass transfer

570 binary models calculated:

39% dynamical

18% contact

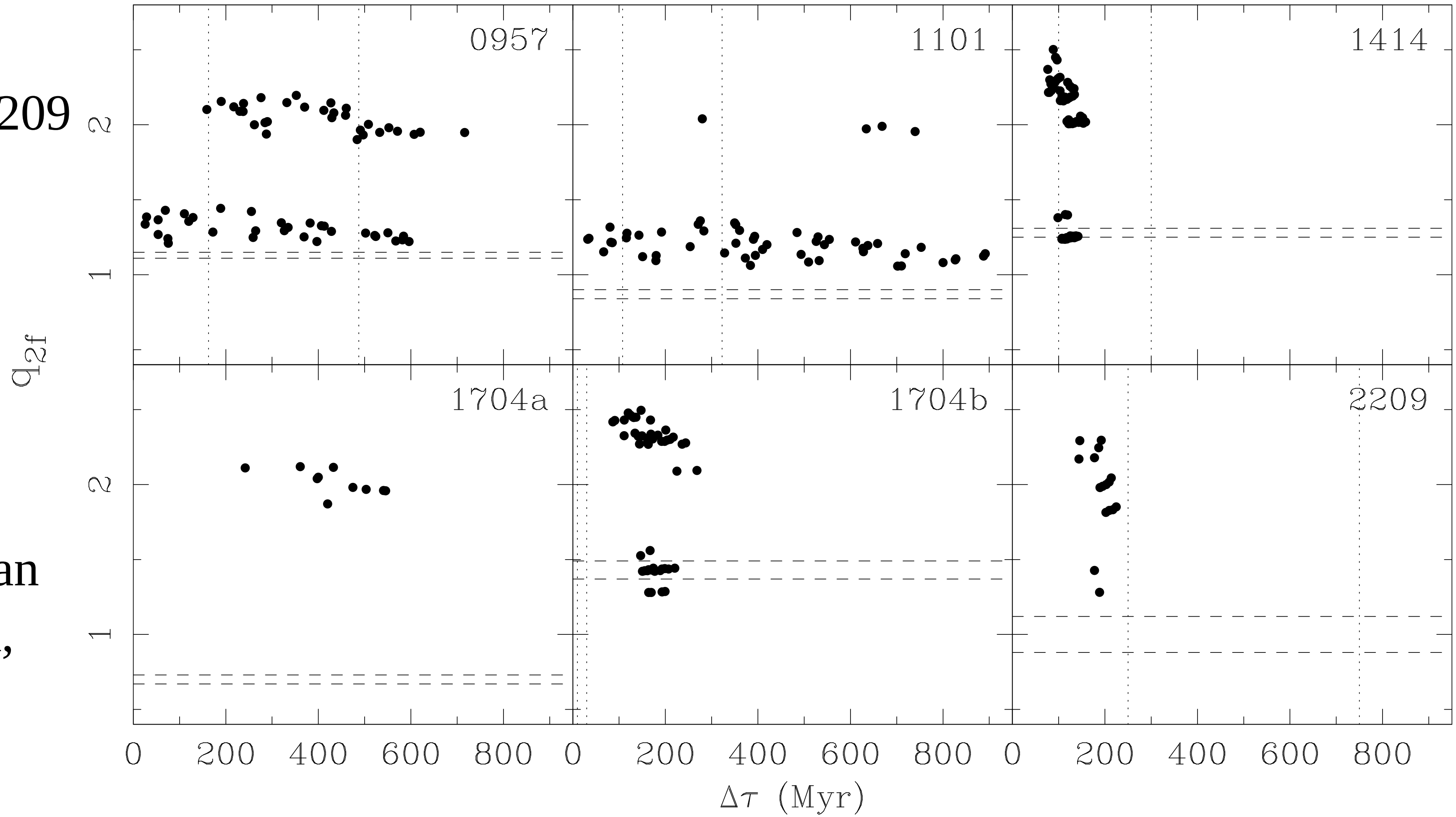
43% DWD



Conservative mass transfer

1414 fits
0957, 1101
1704b and 2209
are close

Out of ten
systems, 1 can
be explained,
4 are close



Conclusions for conservative MT

- More accurate models change α-CE only slightly
- White-dwarf primaries have too low mass, hence orbital periods too long
- We can reproduce perhaps 1–3 out of 10 systems, but with $\alpha_{\rm ce} > 1.6$
- **Conservative mass transfer cannot explain the observed double white dwarfs**

Evolutionary scenario

~~MS + MS~~

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MS + MS

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WD + WD

Angular-momentum balance

- Average specific angular momentum of the system:

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{s} \frac{M_{1\mathrm{i}} - M_{1\mathrm{f}}}{M_\mathrm{tot,i}}$$

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- Specific angular momentum of the accretor:

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{a} \left[1 - \frac{M_\mathrm{tot,i}}{M_\mathrm{tot,f}} \exp\left(\frac{M_\mathrm{1f} - M_\mathrm{1i}}{M_2}\right)\right]$$

- Specific angular momentum of the donor:

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{d} \frac{M_\mathrm{1i} - M_\mathrm{1f}}{M_\mathrm{tot,f}} \frac{M_\mathrm{2i}}{M_\mathrm{1i}}$$

Models

- Number of progenitor models:

  199 progenitor models, 10+1 observed systems

  11 variations in observed mass: $-0.05, -0.04, \ldots, +0.05\,M_{\odot}$

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- Filters:

  Dynamical MT: $R_* > R_{\mathrm{BGB}}$ and $q > q_{\mathrm{crit}}$

  Age: $\tau_1 < \tau_2 < 13\,\mathrm{Gyr}$

  EE-parameter: $0.1 < \alpha_{\mathrm{ce}}, \gamma < 10$

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  Age: $\tau_1 < \tau_2 < 13\,{\rm Gyr}$

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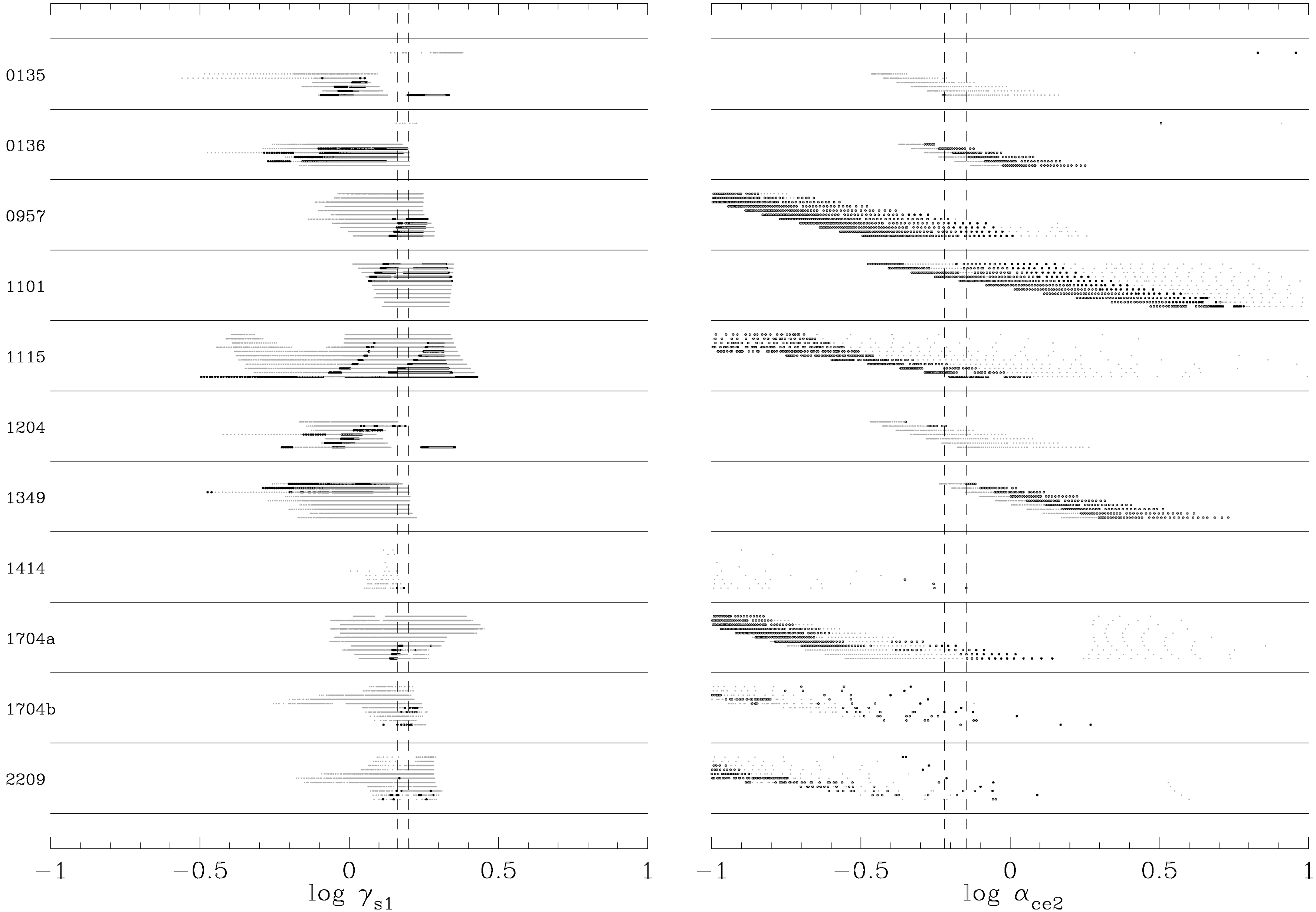
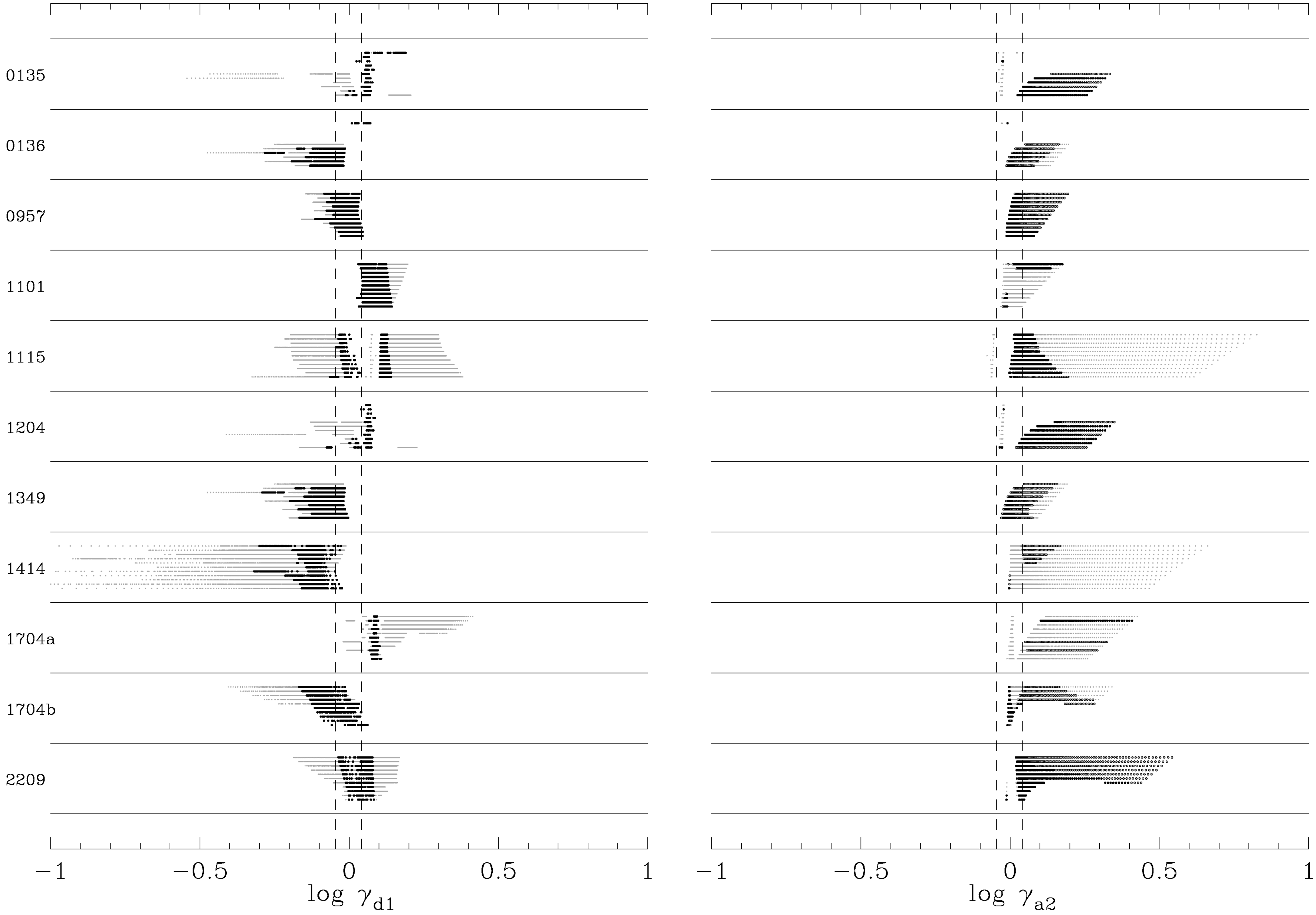
- Candidate progenitors left: $\sim$ 204 000

Results: $\gamma_s \alpha_{ce}$



Results: γdγa



Results: overview

$0.8 < \alpha_{ce} < 1.2, \quad 1.46 < \gamma_s < 1.79, \quad 0.9 < \gamma_{a,d} < 1.1$:

System	1: $\gamma_s\alpha_{ce}$	2: $\gamma_s\gamma_s$	3: $\gamma_a\alpha_{ce}$	4: $\gamma_a\gamma_a$	5: $\gamma_d\alpha_{ce}$	6: $\gamma_d\gamma_a$	Opt. res.	Best prescr.
0135	−	+	+	−	+	+	+	2,3,5,6
0136	+	+	+	+	+	+	+	1–6
0957	+	+	−	+	+	+	+	1,2,4,5,6
1101	+	+	+	−	+	+	+	1,2,3,5,6
1115	+	+	+	+	+	+	+	1–6
1204	−	+	+	+	+	+	+	2–6
1349	+	+	+	+	+	+	+	1–6
1414	−	+	−	+	−	+	+	2,4,6
1704a	+	+	−	−	−	−	+	1,2
1704b	+	+	−	+	+	+	+	1,2,4,5,6
2209	+	+	−	−	+	+	+	1,2,5,6

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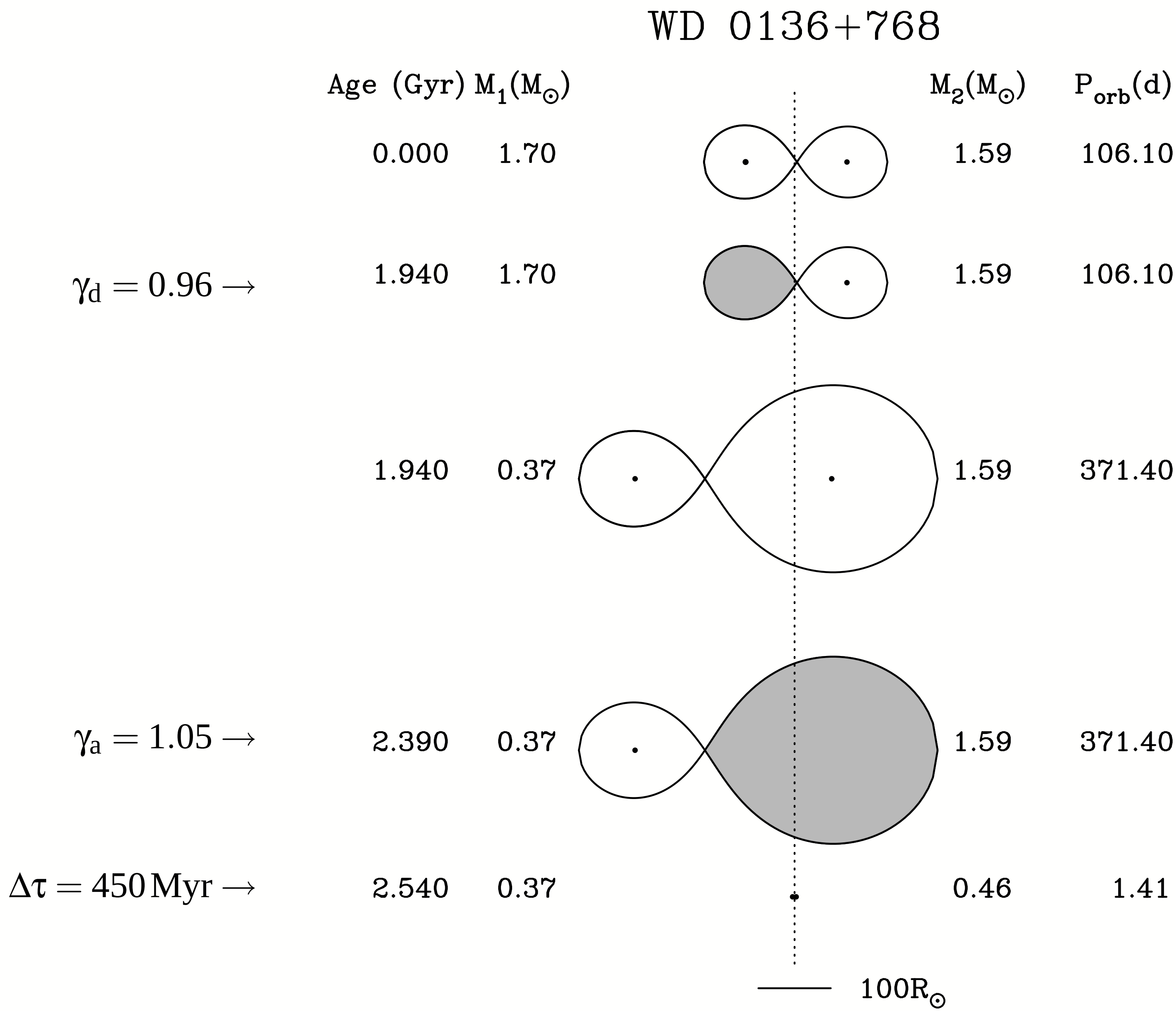
System	1: $\gamma_s\alpha_{ce}$	2: $\gamma_s\gamma_s$	3: $\gamma_a\alpha_{ce}$	4: $\gamma_a\gamma_a$	5: $\gamma_d\alpha_{ce}$	6: $\gamma_d\gamma_a$	Opt. res.	Best prescr.
0135	$-/-$	$+/\sim$	$+/\sim$	$-/-$	$+/\sim$	$+/\sim$	$+/\sim$	2,3,5,6
0136	$+/+$	$+/+$	$+/\sim$	$+/\sim$	$+/+$	$+/+$	$+/+$	1,2,5,6
0957	$+/+$	$+/+$	$-/-$	$+/-$	$+/+$	$+/+$	$+/+$	1,2,5,6
1101	$+/\sim$	$+/-$	$+/-$	$-/-$	$+/\sim$	$+/\sim$	$+/\sim$	1,5,6
1115	$+/\sim$	$+/+$	$+/\sim$	$+/\sim$	$+/+$	$+/+$	$+/+$	2,5,6
1204	$-/-$	$+/-$	$+/-$	$+/-$	$+/-$	$+/+$	$+/+$	6
1349	$+/+$	$+/+$	$+/+$	$+/+$	$+/+$	$+/+$	$+/+$	1–6
1414	$-/-$	$+/+$	$-/-$	$+/+$	$-/-$	$+/+$	$+/+$	2,4,6
1704a	$+/-$	$+/-$	$-/-$	$-/-$	$-/-$	$-/-$	$+/-$	1,2
1704b	$+/-$	$+/-$	$-/-$	$+/-$	$+/-$	$+/-$	$+/-$	1,2,4,5,6
2209	$+/+$	$+/+$	$-/-$	$-/-$	$+/\sim$	$+/+$	$+/+$	1,2,6

Results: example solution



Results: solutions

WD	Mthd.	γ_1	γ_2,	$\Delta\tau$ (Myr)		M_{1i}	M_{2i}	P_i	P_m	M_{1f}	M_{2f}	P_f
			α_{ce2}	Obs	Mdl	$M_\odot$	$M_\odot$	d	d	$M_\odot$	$M_\odot$	d
0135	$\gamma_d\gamma_a$	1.11	0.94	350	118	3.30	2.90	36.28	41.10	0.47	0.42	1.56
0136	$\gamma_d\gamma_a$	0.96	1.05	450	450	1.70	1.59	106.1	371.4	0.37	0.46	1.41
0957	$\gamma_d\gamma_a$	1.00	1.01	325	317	1.98	1.83	26.17	79.26	0.33	0.37	0.06
1101	$\gamma_d\gamma_a$	1.10	0.98	215	322	2.87	2.34	22.02	28.23	0.39	0.34	0.14
1115	$\gamma_d\gamma_a$	0.97	1.04	160	240	5.42	3.42	201.2	1012.	0.89	0.75	30.09
1204	$\gamma_d\gamma_a$	1.09	0.92	80	100	3.34	2.98	15.47	19.99	0.47	0.41	1.60
1349	$\gamma_d\gamma_a$	0.95	0.98	0	101	1.86	1.81	63.44	241.2	0.35	0.44	2.21
1414	$\gamma_d\gamma_a$	0.95	0.99	200	188	3.51	3.09	70.81	358.3	0.52	0.66	0.52
1704a	$\gamma_d\gamma_a$	1.11	1.13	-20	52	2.06	1.88	40.37	65.66	0.51	0.36	0.14
1704b	$\gamma_d\alpha_{ce}$	1.03	0.15	20	182	1.68	1.65	212.1	478.6	0.41	0.58	0.14
2209	$\gamma_d\gamma_a$	1.04	1.05	500	340	4.15	2.94	98.45	294.3	0.63	0.63	0.28

Conclusions

- Conservative mass transfer cannot explain the observed double white dwarfs
- Unstable envelope ejection can do this
- Several EE descriptions can reconstruct observed masses and periods
- $\gamma_s\gamma_s$ and $\gamma_d\gamma_a$ can in addition explain most observed cooling-time differences