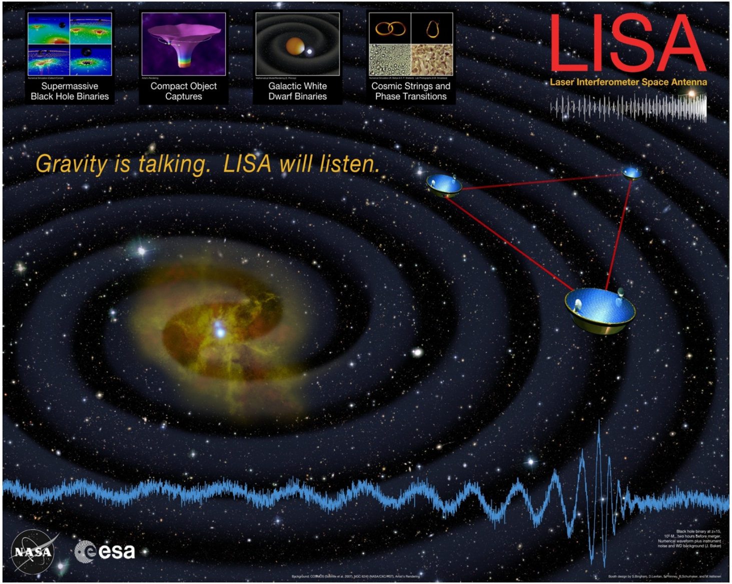
# The formation of (double-lined) double white dwarfs and other GW sources

Marc van der Sluys

Nikhef / Utrecht University / Virgo

Andrew Loveridge, Vicky Kalogera
Tyrone Woods, Natasha Ivanova
Gijs Nelemans, Sweta Shah
Mónica Zorotovic, Matthias Schreiber, Alberto Rebassa-Mansergas

# Laser Interferometer Space Antenna (LISA)



# LISA: verification binaries

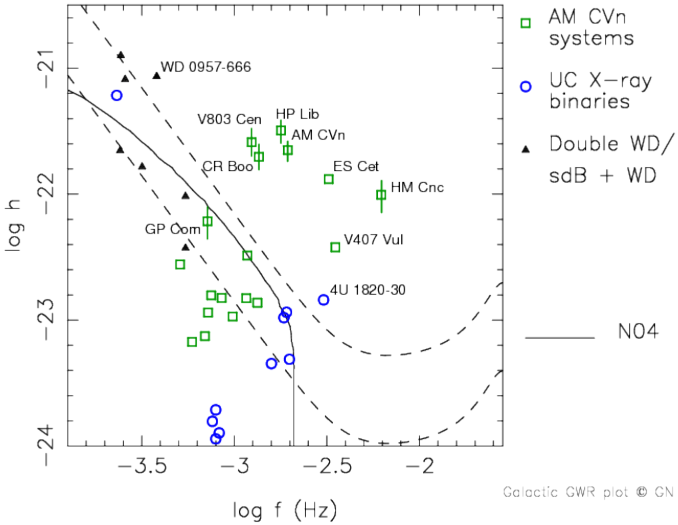
**Properties of known binaries:**

| Type | Number | $P$ (min) | $M_1\,(M_\odot)$ | $M_2\,(M_\odot)$ | $d$ (pc) |
|---|---|---|---|---|---|
| AM CVn | 27 | 5.4 – 65.1 | 0.55 – 1.2 | 0.006 – 0.27 | 100 – 2600 |
| DWDs | 15 | 12.8 – 209 | $>$0.1 – 0.8 | 0.17 – 0.39 | 100 – 1100 |
| UCXBs | 8 | 11.4 – 42 | $\sim$ 1.4? | $\geq$ 0.02 – 0.06 | 5k – 12k |
| CVs | 7 | 55 – 85 | $\gtrsim$ 0.7 | 0.10 – 0.15 | 43 – 200 |
| dNSs | 1 | 147 | 1.34 | 1.25 | $\sim$ 1.2k |

https://www.astro.ru.nl/~nelemans/dokuwiki/doku.php?id=lisa_wiki

- $\dot{P}$ measured for:
  - AM CVns: RX J0806.3+1527 and V407 Vul
  - LMXBs: 4U 1820–30
- 4 out of 8 UCXBs are in globular clusters

# LISA: verification binaries



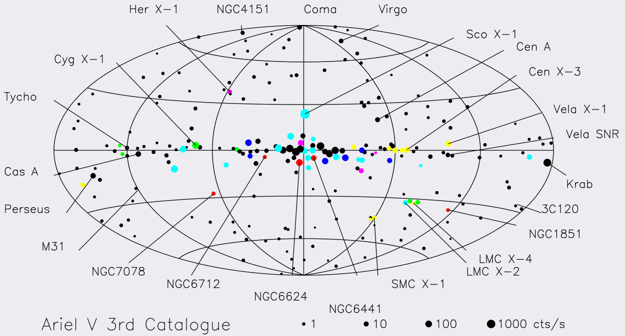

Nelemans, 2009; Roelofs et al., 2007, 2010

# Ultracompact X-ray binaries

## X-ray binaries

- Bright X-ray sources: in Galactic plane, concentrated towards Galactic centre
- 14 bright X-ray sources in globular clusters
- Binaries with $P_{\mathrm{orb}} \lesssim 60$ min are called *ultra-compact*

## Ariel V X-ray map of the sky

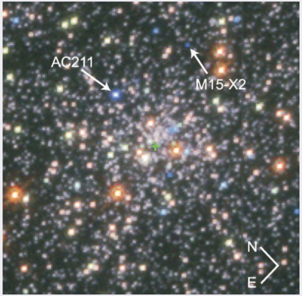



## XRBs are overabundant in GCs

- 1 in $10^9$ stars in Galaxy is an XRB
- 1 in $10^6$ stars in globular clusters is an XRB

# Direct period measurement

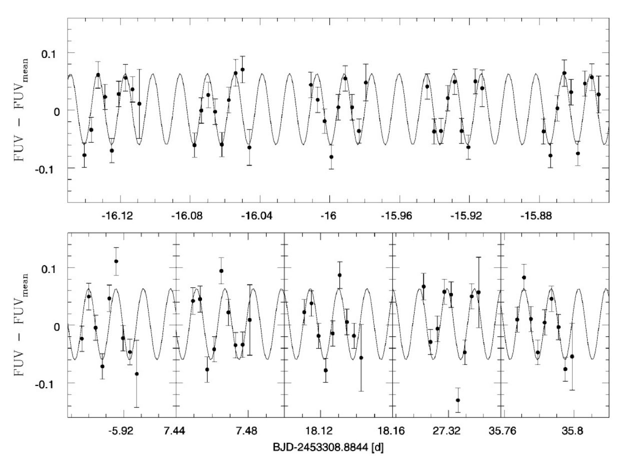
## M 15-X2




White & Angelini, 2001; Guhathakurta, 1996

- FUV study (less crowding)
- Magnitude modulation: 0.06m
- $>$ 3000 cycles
- Period: 22.6 min.

## Magnitude modulation



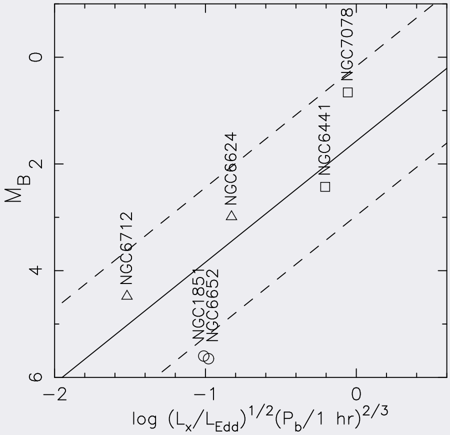

Dieball et al., 2005

# Indirect period indication (1)

## Optical vs. X-ray flux

- Optical flux from reprocessed X-rays in disc
- Scales with X-ray flux and size of disc
- Hence, $f_{\mathrm{opt}}/f_{\mathrm{X}} \propto R_{\mathrm{disc}} \propto a_{\mathrm{orb}}$

Van Paradijs & McClintock, 1994



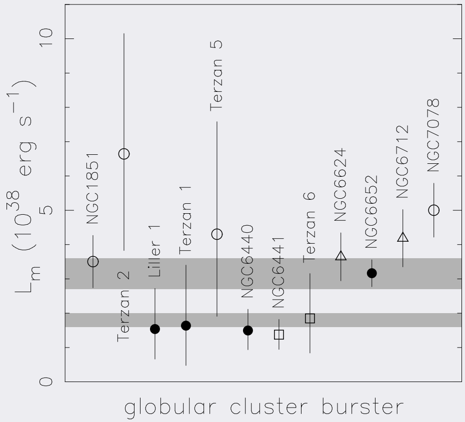

□ normal P △ ultra-short P O unknown P

Verbunt & Lewin (2006)

# Indirect period indication (2)

## Burst maximum

- Maximum luminosity during burst is Eddington luminosity: $L_{\rm Edd} = \frac{4\pi cGM}{\sigma_{\rm T}}$
- Electron scattering cross section depends on hydrogen content: $\sigma_{\rm T} = 0.2\ (1 + X)\ \ \frac{\rm cm^2}{\rm g}$
- Compact donor $\rightarrow$ low $X$ $\rightarrow$ small $\sigma_{\rm T}$ $\rightarrow$ high $L_{\rm edd}$ $\rightarrow$ (ultra)compact binary

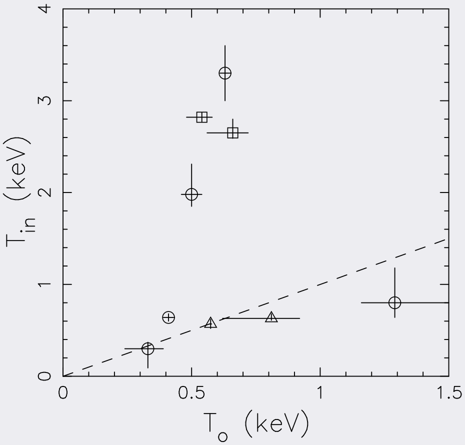



Kuulkers et al. (2003)

# Indirect period indication (3)

## X-ray spectrum

- Temperature $T_0$ of the seed photons comes from a Compton model
- Temperature $T_{\rm in}$ is observed from the inner disc
- Ultracompacts show $T_0 \sim T_{\rm in}$




□ normal P △ ultra-short P O unknown P

Adapted from Sidoli et al. (2001)

# X-ray sources in globular clusters

## Known period information

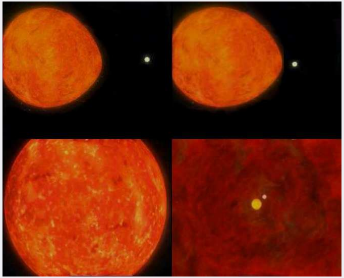
| Cluster | Position | $P_{orb}$ | Indirect indication | | |
|---|---|---|---|---|---|
| | | | low $f_{opt}/f_x$ | burst max. | spectrum |
| NGC 1851 | 0512–40 | ? | U | U | U |
| NGC 6440 | 1745–20 | 8.7 hr | — | — | N |
| NGC 6440 | 1748–20 | 57.3 min | — | — | — |
| NGC 6441 | 1746–37 | 5.7 hr | — | N | N |
| NGC 6624 | 1820–30 | 11.4 min | U | U | U |
| NGC 6652 | 1836–33 | ? | U | U | U |
| NGC 6712 | 1850–09 | 21/13 min | U | U | U |
| NGC 7078 | 2127+12b | 17.1 hr | — | — | — |
| NGC 7078 | 2127+12a | 22.6 min | — | U | — |
| Terzan 1 | 1732–30 | ? | — | — | — |
| Terzan 2 | 1724–31 | ? | — | U | N |
| Terzan 5 | 1745–25 | ? | — | — | U |
| Terzan 6 | 1751–31 | 12.4 hr | — | — | N |
| Liller 1 | 1730–33 | ? | — | — | — |

- Up to 7 of the 14 X-ray binaries in globular clusters are ultra-compact!
- **11-min system (1820-30 in NGC 6624) has negative $\dot{P}$**

# Overabundance in globular clusters: direct collisions

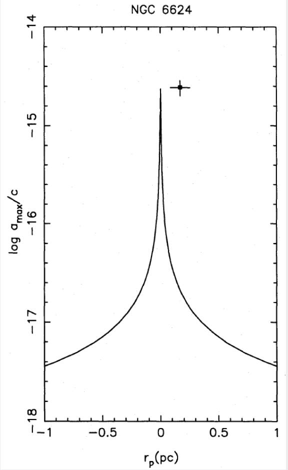
## Star collisions occur in GCs

- Stellar density up to $10^6$ times higher than in solar neighbourhood
- Probability of collisions $10^{12}$ times higher
- Direct collisions most likely for subgiants
- Binary with NS and core of subgiant is formed; envelope is expelled



## After the collision

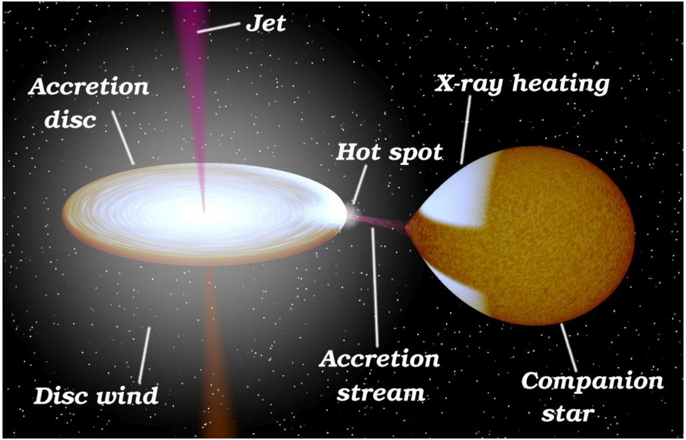
- A NS-WD binary is formed
- Gravitational radiation shrinks the orbit
- Orbital period increases as soon as mass transfer starts
- Observed X-ray binaries should always have positive $\dot{P}$
- The 11-min system has a measured $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15}\mathrm{s}^{-1}$
  - this cannot be explained by gravitational acceleration:




Van der Klis et al., 1993

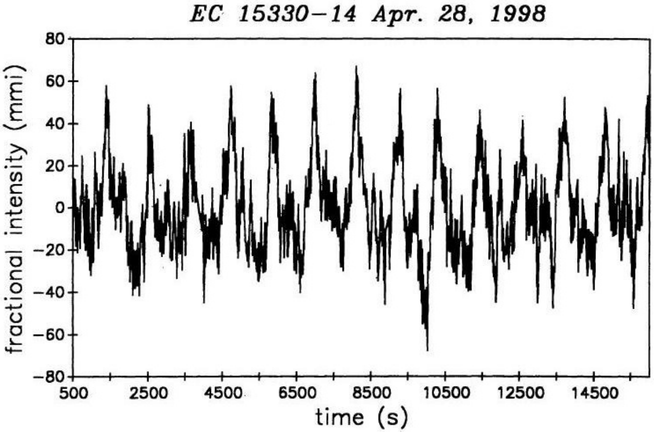
# Cataclysmic variables

BinSim,
R. Hynes



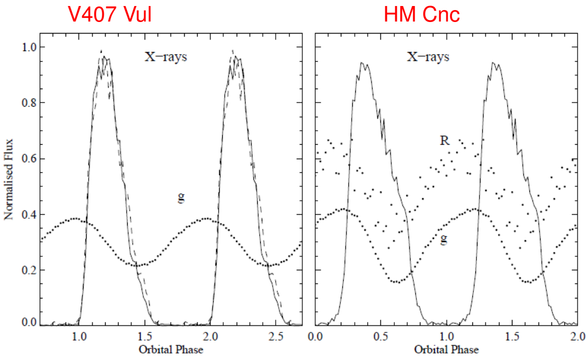

- “LMXBs with a WD accretor”
- Optical emission comes from *hot spot*
- Accretion speed, hence luminosity, varies, sometimes dramatically

# Photometric variability

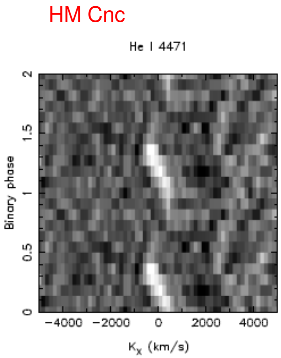



**HP Lib** (Seetha et al., 2000)

# First ultracompact systems



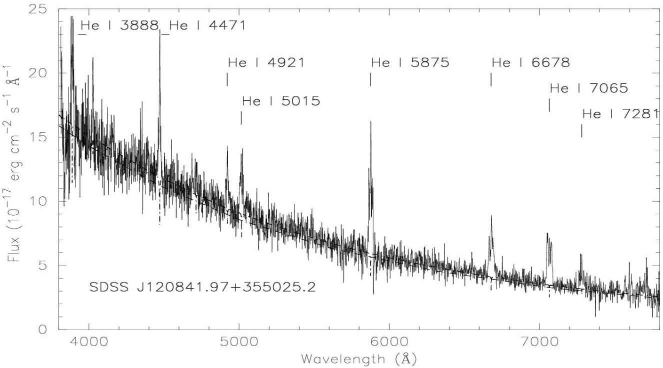

(Motch et al. 1996; Israel et al., 1999; Burwitz & Reinsch 2001)




(Roelofs et al. 2010)

- Two systems previously known from X-ray emission
- Ultrashort periods confirmed using 10 m Keck-telescope:
  - HM Cnc: shortest known period: 5.4 min

# Systematic search for new ultracompacts: SDSS



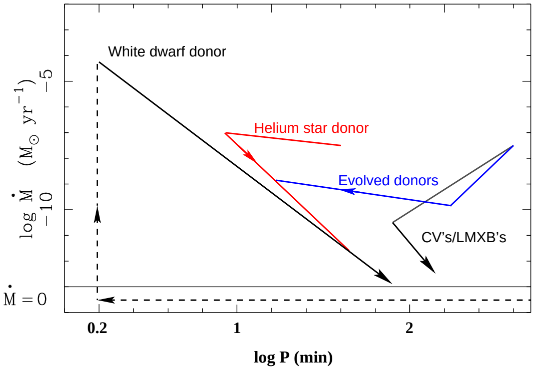

- H poor $\rightarrow$ strong He lines in spectrum
- SDSS spectroscopy and follow-up yielded 13 new systems

(Roelofs et al. 2005, 2009, Anderson et al. 2005, 2008, Rau et al. 2009)

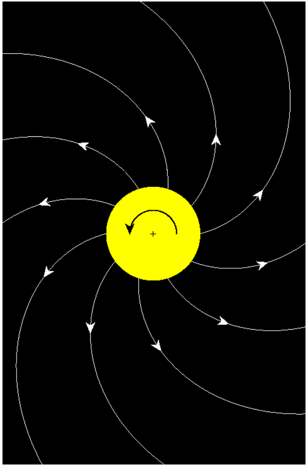
- Newly discovered systems help determine space density
- Problem: there are $\sim 10\times$ fewer AM CVn systems than theory predicts

# AM CVn systems

- $\sim$ 30 known
- He-dominated spectra:
  - CVs without H signature
  - H/He $\lesssim 10^{-5}$
  - H-poor donor fits in tighter orbit
- Short orbital periods: $\sim$ 5–65 min
- Main guaranteed LISA sources
- Possible donors:
  - He/hybrid He-CO white dwarf
  - helium star
  - evolved main-sequence star



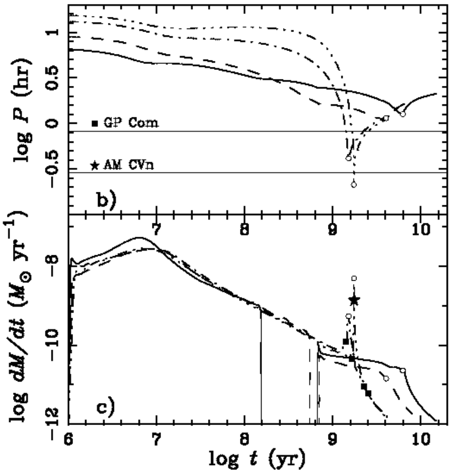
# Magnetic capture



1. Donor star fills Roche lobe around TAMS
2. Magnetic braking on donor removes AM from orbit
3. H-rich envelope is transferred until processed core surfaces
4. AM loss due to GWs takes over at short orbital periods
5. Periods below 70–80 min possible

*e.g.* Pylyser & Savonije 1988,89, Podsiadlowski et al., 2002,03, MvdS et al., 2005a,b

# Podsiadlowski et al., 2003




Podsiadlowski et al., 2003

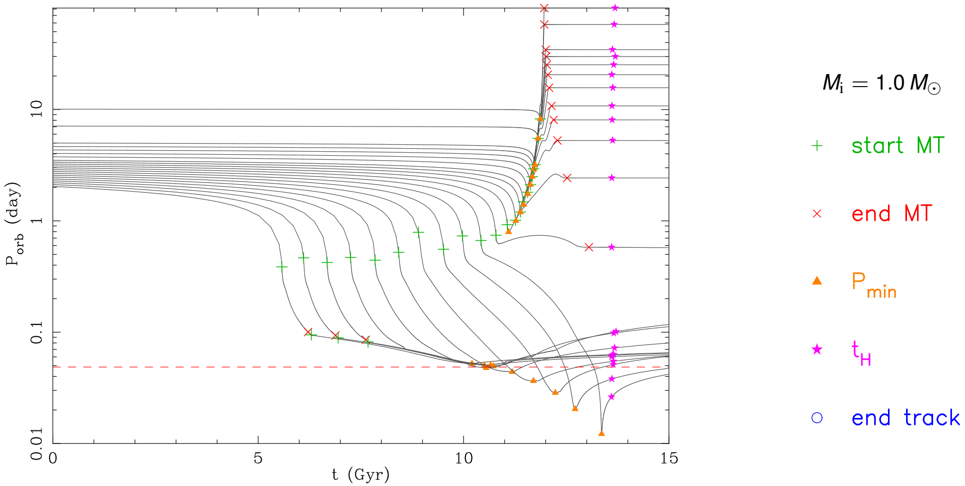
- MB: Verbunt & Zwaan, 1981; Rappaport, Verbunt & Joss, 1983
- $M_{\rm WD}$ : 0.6 – 1.0 $M_{\odot}$
- $M_{2,\rm i}$ : 0.8 – 1.4 $M_{\odot}$
- $t_{\rm RLOF} \sim 7 - 11$ Gyr
- $t_{P_{\rm min}} \sim$ few Gyr
- $P_{\rm min}$ down to $\sim 10$ min
- $X_{\rm H} \sim 1 - 20\%$

# Binary-evolution models

## Grids of detailed binary-evolution models

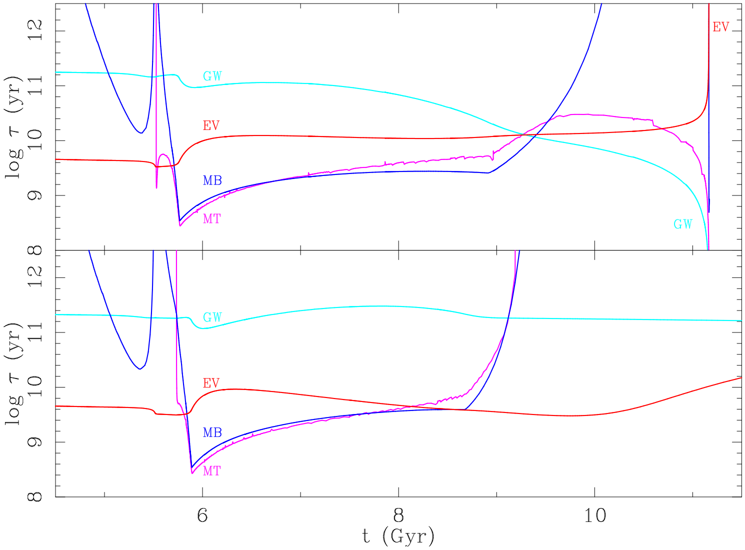
- Eggleton's *TWIN* binary-evolution code (Eggleton 1971, 1972, etc., Pols et al., 1995)
- MB: Rappaport, Verbunt & Joss, 1983; $\gamma = 4$:
  - MB decreases as $\exp\left(1 - \frac{0.02}{q_{\rm conv}}\right)$ for $q_{\rm conv} \equiv \frac{M_{\rm conv}}{M_*} < 0.02$ (Podsiadlowski et al., 2002)
  - No MB if $q_{\rm conv} = 1$
- Analytic GW evolution after $P_{\rm min}$
- Mass transfer fully non-conservative
- $M_{\rm WD} = 1.0\,M_\odot$; $M_{2,i} = 0.7 - 1.5\,M_\odot$
- $P_{\rm i} \sim 0.4 - 5.5$ days; $\sim$20–40 models per $M_{2,\rm i}$

# Period evolution




MvdS et al. (2005a)

# Convergence vs. divergence: relevant timescales




Two models with $M_i = 1.1\ M_\odot$, similar $P_i$:

1. GWs take over where MB weakens → **convergence**
2. GWs do **not** take over where MB weakens → **divergence**

**Timescales:**

EV: Nuclear evolution

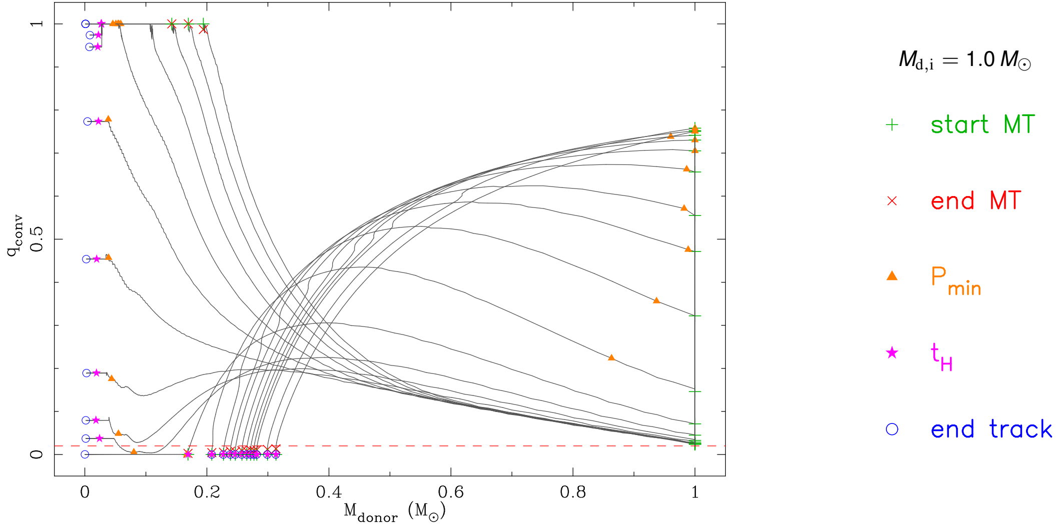
MT: Mass transfer

MB: Magnetic braking

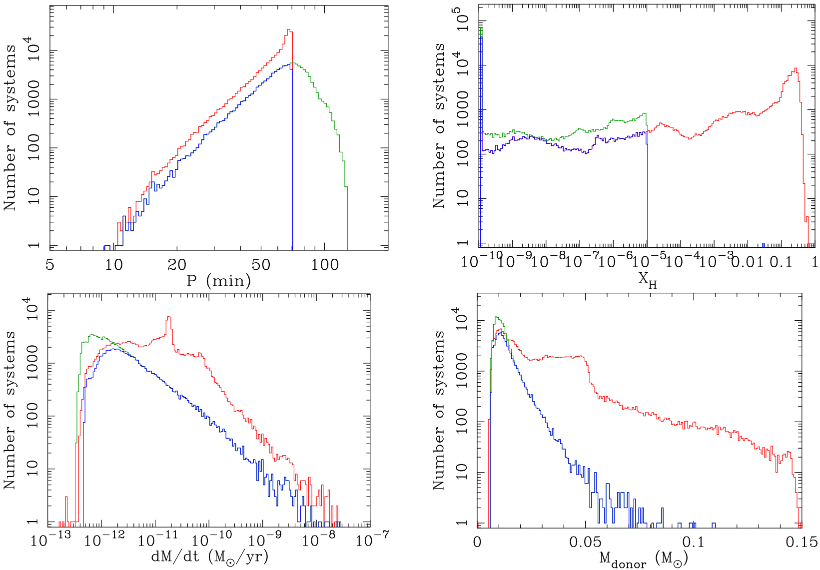
GW: Gravitational waves

MvdS et al. (2005a)

# Convective mass fraction



# Ultracompact/AM CVn population




$P < 70$ min:
174 448 systems

$X_{\rm H} < 10^{-5}$:
103 900 systems

$P < 70$ min **AND** $X_{\rm H} < 10^{-5}$:
61 713 systems

MvdS et al. (2005a)

# Choice of magnetic-braking prescription

## Rappaport, Verbunt & Joss

$$\frac{dJ_{\rm MB}}{dt} = -3.8\times 10^{-30}\,\eta\left(\frac{M}{M_\odot}\right)\left(\frac{R}{R_\odot}\right)^4\omega^3 \quad {\rm dyn\,cm}$$

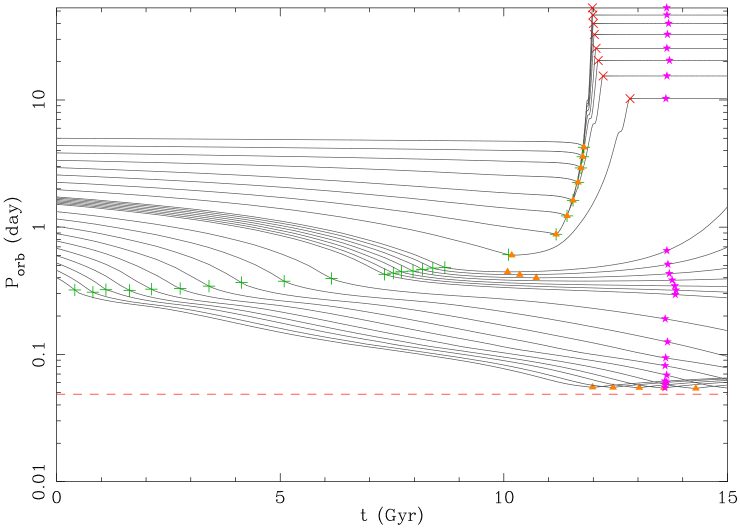
## **Saturated magnetic braking:** Sills et al., 2000; Andronov et al., 2003

$$\begin{aligned}\frac{dJ_{\rm MB}}{dt} &= -K\left(\frac{R}{R_\odot}\right)^{0.5}\left(\frac{M}{M_\odot}\right)^{-0.5}\omega^3, && \omega\le\omega_{\rm crit};\\ &= -K\left(\frac{R}{R_\odot}\right)^{0.5}\left(\frac{M}{M_\odot}\right)^{-0.5}\omega\,\omega_{\rm crit}^2, && \omega>\omega_{\rm crit},\end{aligned}$$

$$K = 2.7\times 10^{47}\,{\rm g\,cm^2\,s};\quad \omega_{\rm crit} = \omega_{{\rm crit},\odot}\left(\frac{\tau_{\rm to}}{\tau_{{\rm to},\odot}}\right)^{-1};\quad \omega_{{\rm crit},\odot}\approx 2.5\,{\rm day}.$$

- MB becomes saturated at some critical $\omega$;
- $\omega_{\rm crit}$ depends on the convective-turnover timescale $\tau_{\rm to}$.

# Saturated magnetic braking




$M_{d,i} = 1.0\,M_\odot$

+ start MT

× end MT

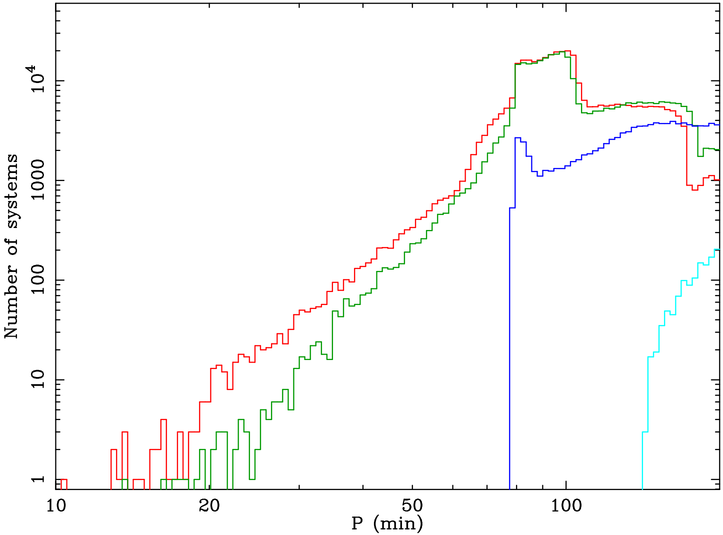
▲ $P_{min}$

★ $t_H$

○ end track

**No systems with P $\lesssim$ 70 min!**

# Effect of magnetic-braking prescription




Rappaport, Verbunt & Joss; $\eta = 1.00$

Rappaport, Verbunt & Joss; $\eta = 0.25$

Sills et al.; Andronov et al.

GWs only

MvdS et al. (2005b)

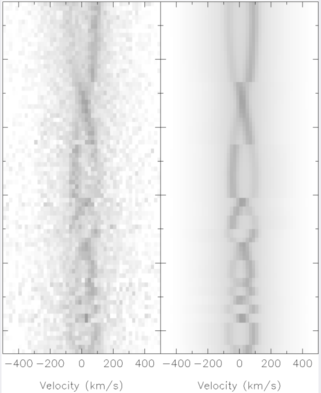
# Conclusions

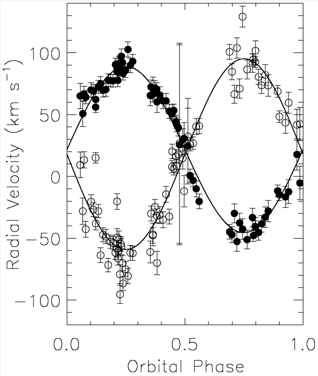
## Conclusions

1. With the magnetic-capture scenario, a relatively large number of ultracompact CVs can be produced
2. A sizable fraction of these have $X_{\mathrm{H}} < 10^{-5}$ and would be observed as AM CVn stars
3. For each H-poor ultracompact CV (AM CVn), we would expect 1–10 H-rich ultracompact CVs
4. For each $\sim$10-minute system, we would expect $\sim$10 20-minute systems and $\sim$100 30-minute systems
5. A saturated magnetic-braking prescription increases the minimum period found from $\sim$ 10 min to $\sim$ 75 min
   - this is still $\sim 2\times$ lower than can be achieved with GWs alone
6. The 11.4-minute system with the negative $\dot{P}$ 1820-30 probably has a He-star donor

# Observed double-lined double white dwarfs

## WD 0136+768




Adapted from Maxted et al. (2002)

- well determined: $P_{\rm orb}$, $q$
- model-dependent: $M_1$, $M_2$, $\tau_{\rm cool}$

# Observed double-lined double white dwarfs

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

† star 2 is supposedly the latest-formed WD

* unclear which white dwarf is older

See references in Maxted et al. (2002), Nelemans & Tout (2005) and MvdS et al. (2006)

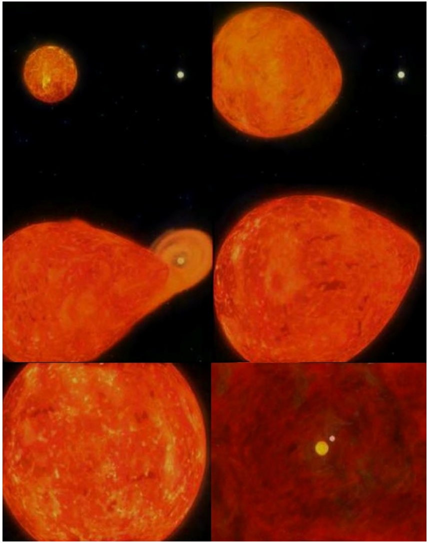
- WD masses $\sim 0.3 - 0.7\ M_\odot$
- Orbital separations $\sim 0.5 - 6\ R_\odot$ (and $47\ R_\odot$)
- $q \sim 0.70 - 1.28$ (mean: 1.01)

# Double white dwarf vs. red giant

**Properties of observed white dwarfs**

- Current DWD system:
  - $a_{\rm orb}$: mean: 7 $R_\odot$, median: 4 $R_\odot$
  - $q$: $\sim 1$
- Typical progenitor star:
  - $M_{\rm c} \gtrsim 0.3\,M_\odot$
  - $R_* \sim 100\,R_\odot$

# Common envelopes (CEs)



## CE Assumptions

- Donor core and companion spiral in, $E_{\rm orb}$ heats up and expels envelope
- Envelope ejection occurs much faster than nuclear evolution ($\tau \lesssim 1000\,$yr?), hence:
  - core mass does not grow during envelope ejection
  - no accretion by companion during envelope ejection
- CE occurs when MT is dynamically unstable, *i.e.* if $q_1 > q_{\rm crit} \sim 0.65$ (Hurley et al., 2002)
- But what if the timescale is longer than the dynamical timescale?

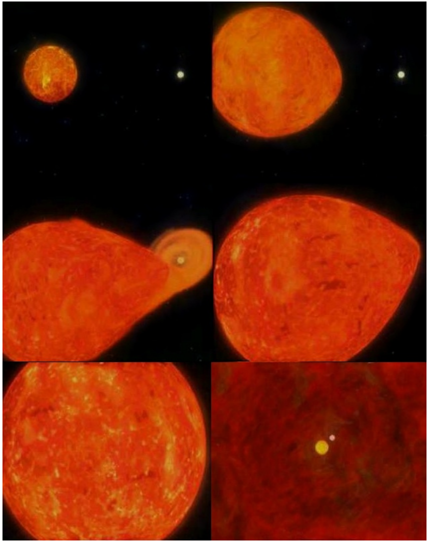
## Classical $\alpha$-common envelope (CE):

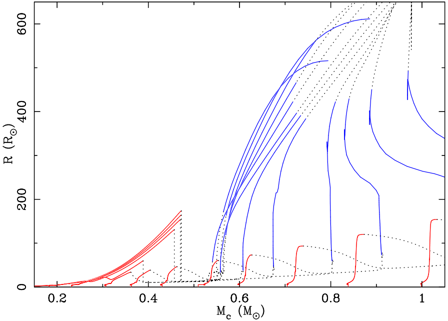
- orbital energy is used to expel envelope (Webbink, 1984):

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

- $\alpha_{\rm CE} \sim 1$ (0.3?) is the common-envelope efficiency parameter
- usually, $a_{\rm orb,f} \ll a_{\rm orb,i}$: spiral-in

# First mass-transfer phase: common envelope (CE)?

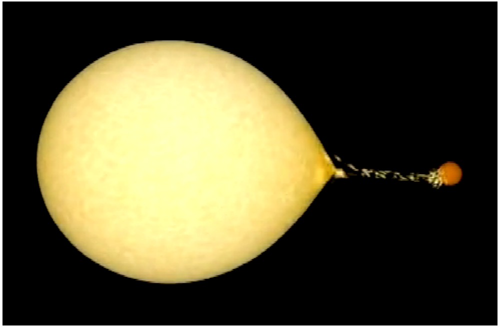




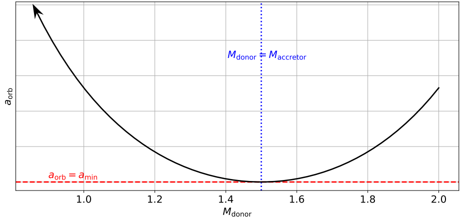

## Outcome of a CE as first MT phase

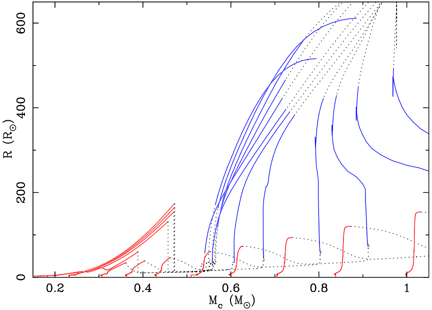
1. Orbit shrinks a lot
2. Secondary has a much smaller Roche lobe
3. Secondary fills Roche lobe at much smaller radius $\rightarrow$ core mass
4. Second WD **less massive** than first WD: $\mathbf{q \not\sim 1}$

# First mass-transfer phase: stable (and conservative)?



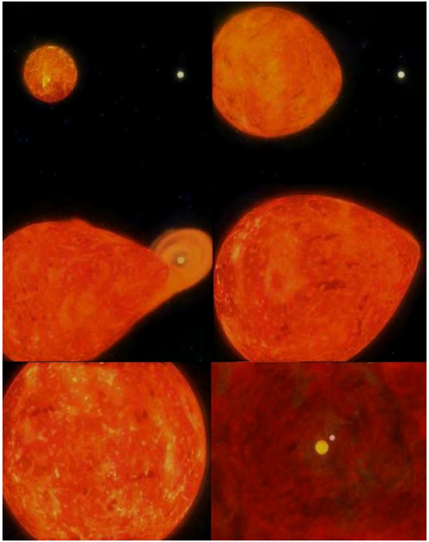
TWIN → BinSim, R. Hynes: `http://www.phys.lsu.edu/~rih/binsim/`




1. Orbit typically grows (but: non-conservative MT?)
2. Secondary becomes more massive → larger Roche lobe
3. Secondary fills Roche lobe at larger radius → core mass
4. Second WD **more massive** than first WD: **$q \not\approx 1$**

# Common envelope (CE) and Envelope ejection (EE)



## Classical $\alpha$-common envelope (CE):

- orbital energy is used to expel envelope (Webbink, 1984):

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

- $\alpha_{\rm CE} \sim 1$ (0.3?) is the common-envelope efficiency parameter
- usually, $a_{\rm orb,f} \ll a_{\rm orb,i}$: spiral-in

## $\gamma$-envelope ejection (EE):

- envelope ejection with angular-momentum balance:

$$\frac{J_{\rm i} - J_{\rm f}}{J_{\rm i}} = \gamma_{\rm EE} \frac{M_{\rm 1i} - M_{\rm 1f}}{M_{\rm 1i} + M_2}$$

- $\gamma_{\rm EE} \approx 1.5$ is the efficiency parameter (Nelemans et al., 2000)
- $a_{\rm orb,f}$ may be $\sim a_{\rm orb,i}$; spiral-in not necessary
- But what does $\gamma_{\rm EE}$ mean? Why 1.5?

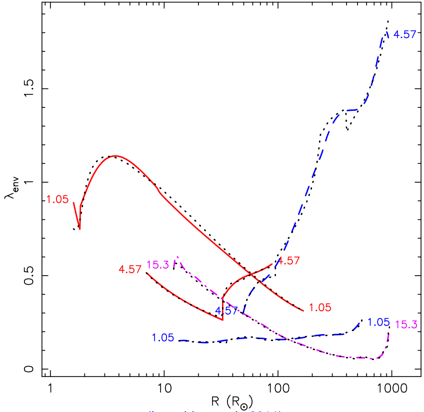
# Envelope-structure parameter

- Detailed stellar model is needed to compute $E_{\rm bind}$
- Use $\lambda_{\rm env}$ to approximate $E_{\rm bind}$ from basic parameters (Webbink, 1984; De Kool et al., 1987)

$$\lambda_{\rm env} \equiv \frac{G\,M\,M_{\rm env}}{R\,E_{\rm bind,env}}$$

$$-\frac{G\,M\,M_{\rm env}}{R} = \alpha_{\rm CE}\,\lambda_{\rm env}\,\Delta E_{\rm orb}$$

- Smaller $\lambda_{\rm env}$ indicates more centrally concentrated envelope
- Often, a constant value for $\lambda_{\rm env}$ is assumed in population-synthesis codes:
  - $\lambda_{\rm env} = 0.5$ (*e.g.* De Kool 1987; Nelemans et al., 2000; Hurley et al., 2002)
  - $\alpha_{\rm CE}\lambda_{\rm env} = 0.5, 1.0$ (*e.g.* Belczynski et al., 2008)
- Value of $\lambda_{\rm env}$ is far from constant (*e.g.* Dewi & Tauris, 2000; MvdS et al., 2006)



(Loveridge et al., 2011)

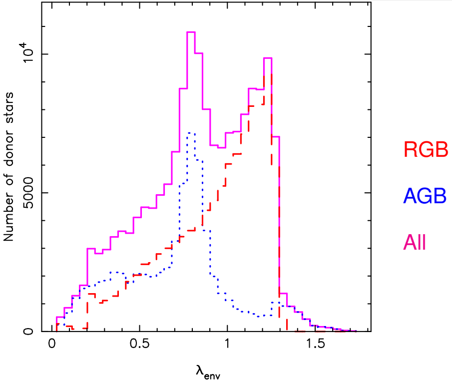
## Determine typical values for $\lambda_{\rm env}$

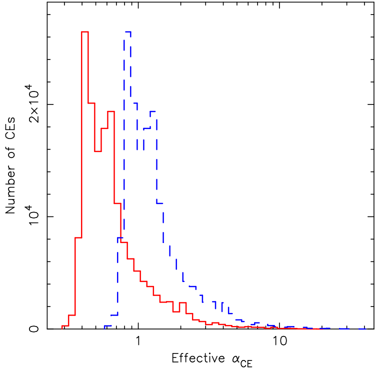
- Grid of 116 detailed stellar-evolution models; 32 brown-dwarf models
- Generate **10$^6$** random ZAMS binaries; $M_* < 20\,M_\odot$; uniform $P(\log P_{\rm orb})$,$P(q)$; $M_{\rm c} \equiv M(X = 0.1)$
- Follow donor stars from ZAMS to CE; record properties at RLOF: 165,007 CEs

# Envelope-structure parameter

## Properties of 165,007 CEs

| | RGB | AGB | Total |
|---|---|---|---|
| **Survivors** | 16.1% | 31.8% | 48.0% |
| **Mergers** | 45.4% | 6.6% | 52.0% |
| **Total** | 61.5% | 38.5% | 100.0% |

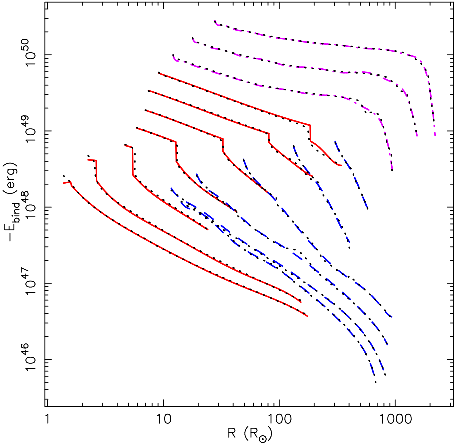



If $\alpha_{CE}\,\lambda_{env}$ = 0.5, 1.0, then implicitly $\alpha_{CE} > 1$ for 16% and 64% of CEs

MvdS et al. (2010)

# Fits for the binding energy




low-mass RGB low-mass AGB high-mass GB
dots: models, coloured lines: fits

$$E_{\text{bind}} = \int_{M_c}^{M_s} \left( E_{\text{int}}(m) - \frac{Gm}{r(m)} \right) \mathrm{d}m$$

$$\log\left(\frac{-E_{\text{bind}}}{\text{erg}}\right) \approx E_0 + \Lambda(M_0, M) \times \sum_{m,r} \alpha_{m,r} \left[\log\left(\frac{M}{M_\odot}\right)\right]^m \left[\log\left(\frac{R}{R_\odot}\right)\right]^r$$

- ev / STARS / TWIN (Eggleton 1971, 1972, ...)
- 73 models, $0.8\,M_\odot \leq M \leq 100\,M_\odot$
- fit as a function of ZAMS mass, current mass and current radius
- 6 different metallicities ($Z = 10^{-4} - 0.03$)
- $\Lambda$ correction factor for wind mass loss
- separate fits for recombination energy

# Conclusions for the binding energies

## Envelope binding energies:

- $\lambda_{\mathrm{env}}$ varies wildly as a function of stellar mass and evolutionary stage
- Simplified assumptions for $\lambda_{\mathrm{env}}$ may imply unphysical values for $\alpha_{\mathrm{CE}}$
- Loveridge et al. (2011) provide accurate fits for $E_{\mathrm{bind}}$
  - electronic data files and routines online
  - $\lambda_{\mathrm{env}}$ no longer needed

## Population-synthesis codes:

- Fits are (being) implemented in:
  - StarTrack (Belczynski et al.)
  - SeBa (Toonen)
  - BSE (Hurley et al.; Zorotovic)

## However:

- Massive stars:
  - uncertainty in core-envelope boundary
  - possible deviations for strong stellar winds

# Formation channels

### Stable + unstable MT

**MS + MS**
↓ Stable M.T. (partly? conservative) ↓
**WD + MS**
↓ Unstable M.T. ($\alpha$-CE) ↓
**WD + WD**

### Unstable + unstable MT

**MS + MS**
↓ Unstable M.T. ($\gamma$-EE) ↓
**WD + MS**
↓ Unstable M.T. ($\alpha$-CE, $\gamma$-EE) ↓
**WD + WD**

### Envelope ejection with angular-momentum conservation

- Average specific angular momentum of the system (Nelemans et al., 2000):

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{s} \frac{M_\mathrm{1i} - M_\mathrm{1f}}{M_\mathrm{tot,i}} \qquad (\gamma_\mathrm{s} \sim 1.5)$$

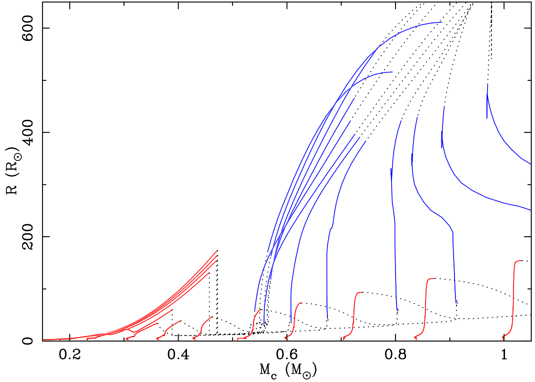
- Specific angular momentum of the donor (MvdS et al., 2006):

$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{d} \frac{M_\mathrm{1i} - M_\mathrm{1f}}{M_\mathrm{tot,f}} \frac{M_\mathrm{2i}}{M_\mathrm{1i}} \qquad (\gamma_\mathrm{d} \sim 1.0)$$

- Specific angular momentum of the accretor (MvdS et al., 2006):

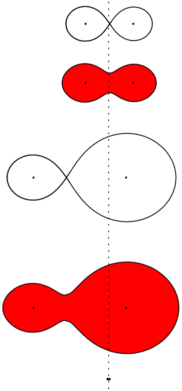
$$\frac{J_\mathrm{i} - J_\mathrm{f}}{J_\mathrm{i}} = \gamma_\mathrm{a} \left[1 - \frac{M_\mathrm{tot,i}}{M_\mathrm{tot,f}} \exp\left(\frac{M_\mathrm{1f} - M_\mathrm{1i}}{M_2}\right)\right] \qquad (\gamma_\mathrm{a} \sim 1.0)$$

# Formation models: reconstruction of second mass-transfer phase




- 199 single-star models
- 0.8–10.0 $M_\odot$
- CEs at RGB or AGB

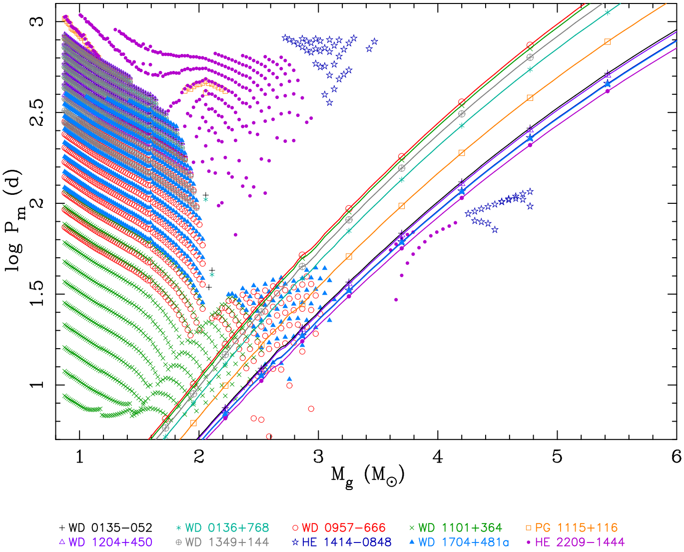
- $M_c = M_{WD}$
- $R_* = R_{RLOF} \rightarrow P_{orb}$



## Reconstructing the second mass-transfer phase: CE

- White-dwarf mass sets core mass (evolutionary state) of progenitor
- Giant radius determines orbital period of progenitor
- Envelope binding energy dictates what $\alpha_{CE}$ is needed for $\Delta P_{orb}$
- **Unknown:** progenitor mass $\rightarrow$ try them all!

# First mass-transfer phase: stable, conservative MT

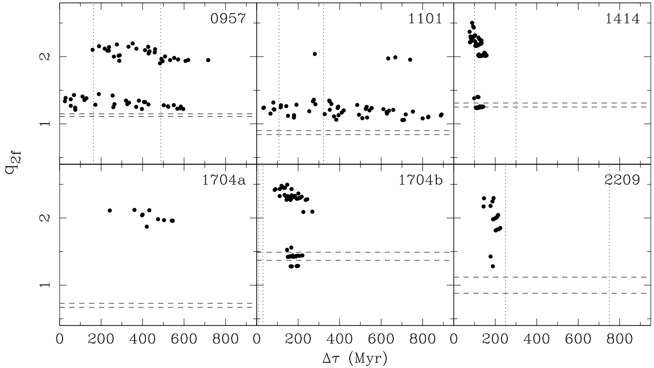



Stable MT:
$R_* < R_{\rm BGB}$ or
$q < q_{\rm crit}$
(Hurley et al., 2002)

Maximum $P_{\rm orb}$ after stable, conservative mass transfer with $q_{\rm i} = 0.62$
(Nelemans et al., 2000)

Only **five** systems have CE solutions with $P_{\rm orb} < P_{\rm max}$

# Conservative mass transfer: mass ratios and cooling-age differences




- **1414** fits
- **0957, 1101, 1704b** and **2209** nearly fit

- Out of ten systems, only **one** can be explained, while four are close
- Mwah...

# Models for unstable MT + unstable MT

## Number of progenitor models:

- 10+1 observed systems
- 199 progenitor models in our grid
- 11 variations in observed mass: $-0.05, -0.04, \ldots, +0.05\ M_\odot$
- Total: $11 \times 11 \times \sum_{n=1}^{198} n \approx$ 2.4 million

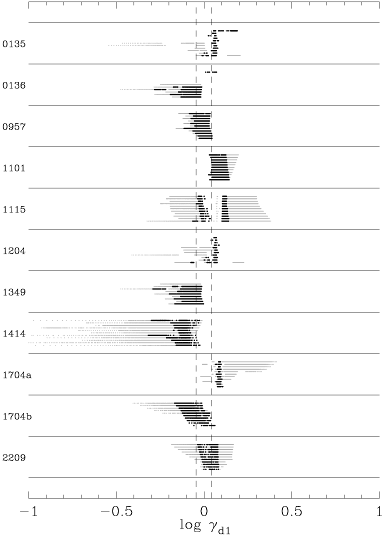
## Filters:

- Unstable MT: $R_* > R_{\rm BGB}$ and $q > q_{\rm crit}$
  - $q_{\rm crit} \approx 0.64 + 0.94 \left(\frac{M_{\rm c}}{M_*}\right)^5 (Z = 0.02)$ (Hurley et al., 2002)
- Age: $\tau_1 < \tau_2 < 13\,{\rm Gyr}$
- CE/EE-parameter: $0.1 < \alpha_{\rm CE}, \gamma_{\rm s,d,a} < 10$

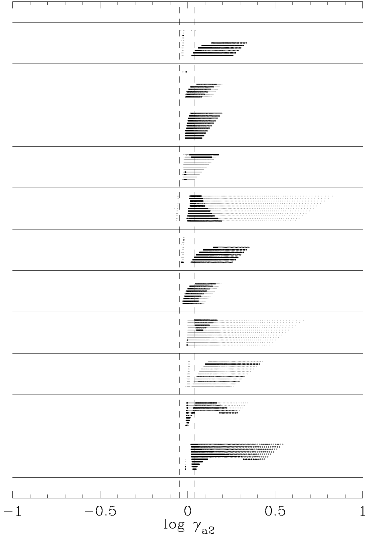
## Result:

- Candidate progenitors left: $\sim$204 000

# Results for $\gamma_d + \gamma_a$




- **system inside range in other panel**
- system outside range in other panel



# Unstable MT results: overview

Select systems with:

- $0.8 < \alpha_{CE} < 1.2$
- $1.46 < \gamma_s < 1.79$
- $0.9 < \gamma_{a,d} < 1.1$

| 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: $\gamma_d\gamma_a$ | Best: |
|---|---|---|---|---|---|---|---|
| 0135 | $-/-$ | $+/\sim$ | $+/\sim$ | $-/-$ | $+/\sim$ | $+/\sim$ | 2,3,5,6 |
| 0136 | $+/+$ | $+/+$ | $+/\sim$ | $+/\sim$ | $+/+$ | $+/+$ | 1,2,5,6 |
| 0957 | $+/+$ | $+/+$ | $-/-$ | $+/-$ | $+/+$ | $+/+$ | 1,2,5,6 |
| 1101 | $+/\sim$ | $+/-$ | $+/-$ | $-/-$ | $+/\sim$ | $+/\sim$ | 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 |
| Best | 7× | 9× | 2× | 3× | 7× | 10× | |

Column 1: $+$: $\alpha, \gamma$ within range, $-$: $\alpha, \gamma$ outside range
Column 2: $+$: $\Delta(\Delta t) < 50\%$, $\sim$: $50\% < \Delta(\Delta t) < 500\%$, $-$: $\Delta(\Delta t) > 500\%$

# DWD summary/conclusions so far

## Stable, conservative mass transfer:

- Nelemans et al. (2000); MvdS et al. (2006)
- Analytic models and detailed binary-evolution models give qualitatively same results
- We can reproduce perhaps 1–4 out of 10 systems, all with $\alpha_{\rm CE} > 1.6$
- **Conservative MT + CE cannot explain the observed double white dwarfs**

## Unstable mass transfer:

- Unstable envelope ejection **can explain** most observed double white dwarfs
- Several EE descriptions can reconstruct observed masses and periods
- In addition, $\gamma_{\rm s}\gamma_{\rm s}$ and $\gamma_{\rm d}\gamma_{\rm a}$ can explain most observed cooling-age differences

## But:

- What do $\gamma_{\rm s,d,a}$ mean?
- Is $q_{\rm crit}$ a good condition for stabilty of MT?
- What about stable, *partly-conservative* MT?
- What is the influence of stellar winds?

# System mass loss during stable mass transfer

## Mass loss during mass transfer:

- “stable, non-conservative mass transfer [. . . ] would stabilise the mass transfer.” (MvdS et al., 2006)
- “[the DWDs] evidently evolved through quasi-conservative mass transfer.” (Webbink, 2008)

## This leads to:

- stable MT can be initiated at longer orbital periods ($q_{\rm crit}$ changes)
- stable MT can be initiated for almost equal-mass binaries
- MT can be stable from more-massive donor stars
- shorter post-MT orbits due to AM loss

## Hence:

- more massive primaries
- less massive secondaries
- more (low-mass) DWDs with $q \sim 1$

# Stability of and conservation factor during mass transfer

## Critical mass ratio:

CE occurs when MT is dynamically unstable, *i.e.* if $q_1 > q_{\rm crit} \sim 0.65$ (Hurley et al., 2002)

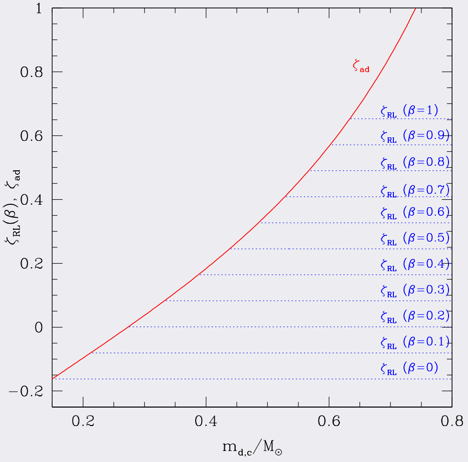
## Response of donor star and Roche lobe to mass loss:

$$\zeta_{\rm ad} \equiv \left(\frac{d\log R_*}{d\log M_*}\right)_{\rm ad} = f\left(\frac{M_{\rm c}}{M_*}\right)$$

$$\zeta_{\rm Rl} \equiv \frac{d\log R_{\rm Rl}}{d\log M_*} = f(q, \beta)$$

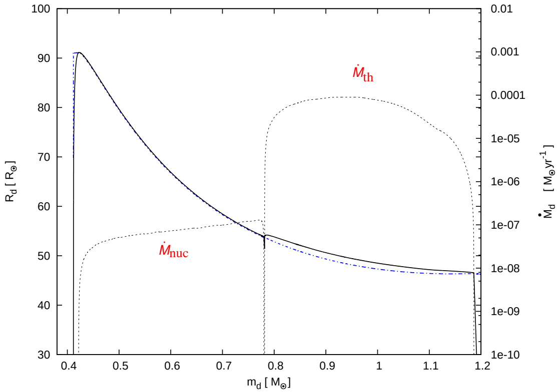
- If $\zeta_{\rm ad} \gtrsim \zeta_{\rm Rl}$ (*i.e.*, $\dot{R}_* \lesssim \dot{R}_{\rm Rl}$), mass transfer is dynamically stable (Hjellming & Webbink, 1987)
- $\beta \in [0, 1]$: mass-conservation factor; $\dot{M}_2 = -\beta \dot{M}_1$

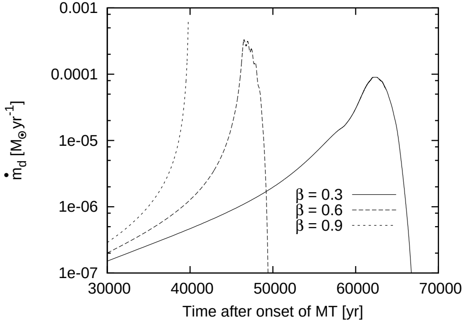
## $M_1 = 1.2\,M_\odot$, $M_2 = 1.1\,M_\odot$




Woods et al., 2012

# Thermal and nuclear mass transfer



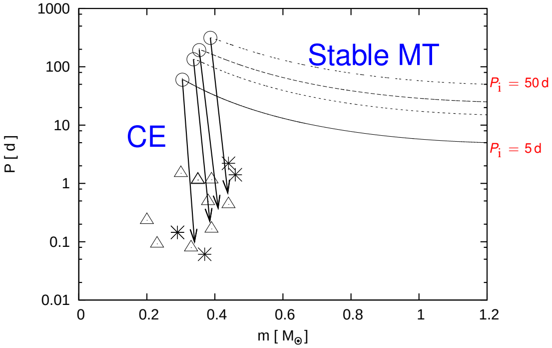



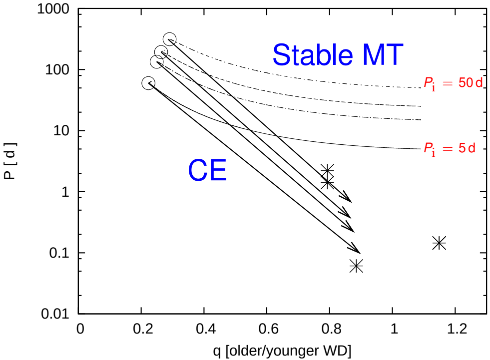

## Default system:

- $M_i = 1.2 + 1.1\, M_\odot \quad (q_i \approx 1.09)$
- $P_i = 100\,\mathrm{d} \quad (M_{c,1} \approx 0.35\, M_\odot)$
- $\beta = 0.3$

Woods et al., 2012

# Formation of low-mass DWDs through stable mass transfer




**Initial systems:**

- $M_\mathrm{i}$ = 1.2 + 1.1 $M_\odot$ $\quad (q_\mathrm{i} \approx 1.09)$
- $P_\mathrm{i}$ = 5, 15, 25, 50 d
- $\beta = 0.3$

∗ DWD (double lined)
△ WD binary (single lined)

Woods et al., 2012

# Population synthesis

## Caveat

**Work in progress!!!**

## BSE

- BSE/popbin (Hurley et al., 2000, 2002)
- Updated stability criterion ($\zeta$ instead of $q_{\rm crit}$) for (sub)giants

## Initial population

- 10 million ZAMS binaries; constant star-formation rate
- Kroupa IMF, $0.8\,M_\odot \leq M_1 \leq 10\,M_\odot$
- Uniform $q_i$ distribution; $0.1\,M_\odot \leq M_2 \leq M_1$
- Uniform distribution in $\log(a_i)$, $5\,R_\odot \leq a \leq 10^4\,R_\odot$; $e = 0$

## Assumptions

- $\alpha_{\rm CE} = 1.0$, $\lambda$: simple fit
- MT conservation factor $\beta$ ($\beta = 1$: conservative)
  1. constant $0.0 \leq \beta \leq 1.0$
  2. variable $\beta$:

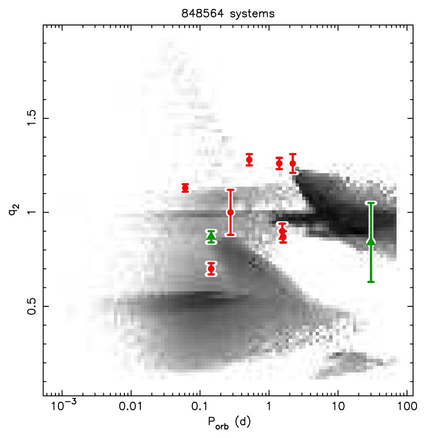
$$\begin{cases} \beta_{\rm nuc} & = \min\left[10 \times \frac{M_{\rm a}/\tau_{\rm th,a}}{M_{\rm d}/\tau_{\rm nuc,d}}, 1\right] \quad (\sim 1) \\ \beta_{\rm th} & = \min\left[10 \times \frac{M_{\rm a}/\tau_{\rm th,a}}{M_{\rm d}/\tau_{\rm th,d}}, 1\right] \quad (\sim 0.01) \end{cases}$$

## Match with observed systems

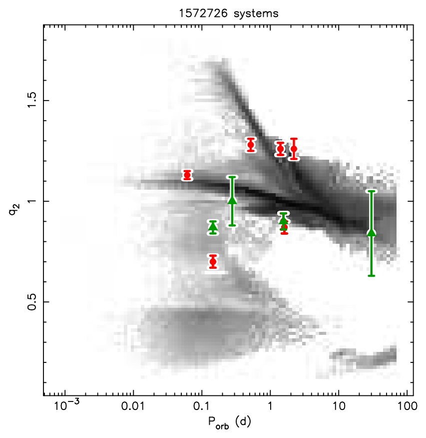
- $M_2$ within observed uncertainty ($\Delta M_{2,\rm min} = 0.05\,M_\odot$)
- $q_2$ within observed uncertainty
- $P_{\rm orb}$ within 1% from observed
- simple double-linedness criterion:
  1. $T_{\rm eff,1,2} > 6000\,$K;
  2. $T_{\rm hot}/T_{\rm cool} < 2.5$; **and**
  3. $P_{\rm orb} < 70\,$days.

# Population synthesis: $q - P_{\rm orb}$

## Conservative MT




## Non-conservative MT

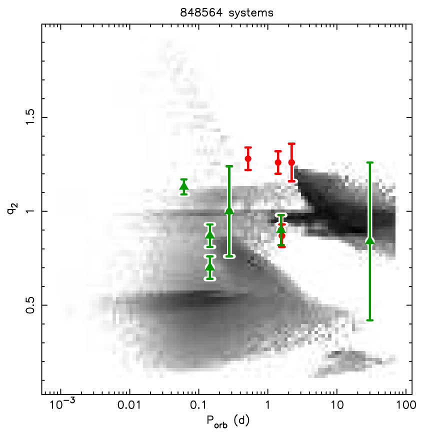



MvdS et al., in preparation

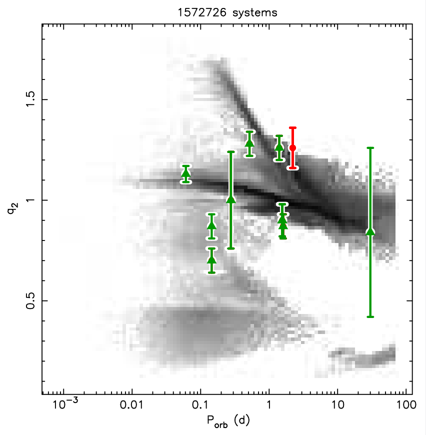
- $\beta =$ variable & $\zeta$s

# Population synthesis: $q - P_{\rm orb}$

## Conservative MT




## Non-conservative MT

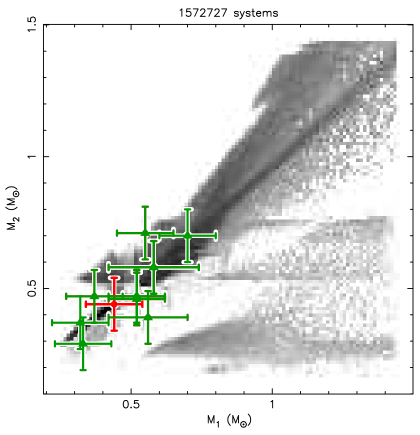



- $\beta =$ variable & $\zeta$s
- allow twice observed uncertainty "2-$\sigma$"

MvdS et al., in preparation

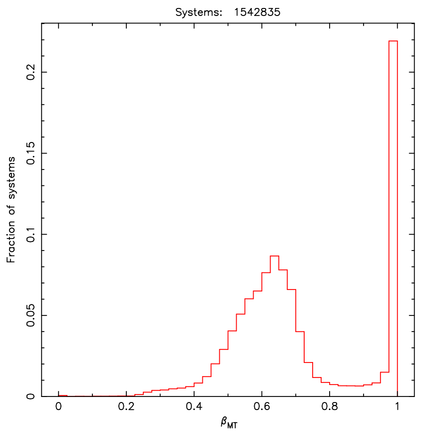
# Population synthesis: $M_1 - M2, \beta$

## Masses




MvdS et al., in preparation

## Mass-conservarion factor $\beta$




- $\beta =$ variable & $\zeta$s
- allow twice observed uncertainty "2-$\sigma$"

# Cheating(?) with errors

### Interpretation of errors: "1$\sigma$" $\rightarrow$ "2$\sigma$"

- $\Delta M$: $1\times \rightarrow 2\times$ min(observed uncertainty, 0.05 $M_\odot$)
- $\Delta q_2$: $1\times \rightarrow 2\times$ observed uncertainty
- $P_{\rm orb}$ within 1% $\rightarrow$ 2% from observed

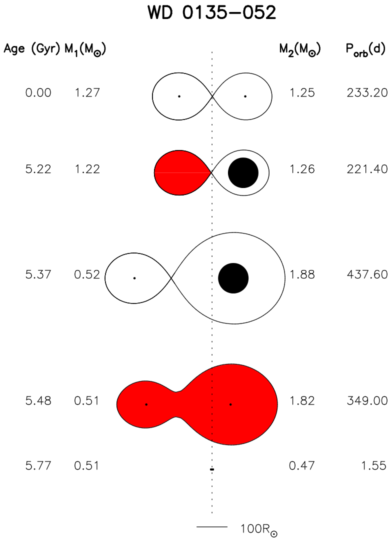
### Original models

- $10^7$ ZAMS binaries
- 713 723 ZA DWDs
- DWD recycling: 25x $\rightarrow$ evolve 17 843 075 ZA DWDs to present day
- 1 572 727 present-day DWDs
- 856 solutions matching **9**/10 observed systems ("2$\sigma$")

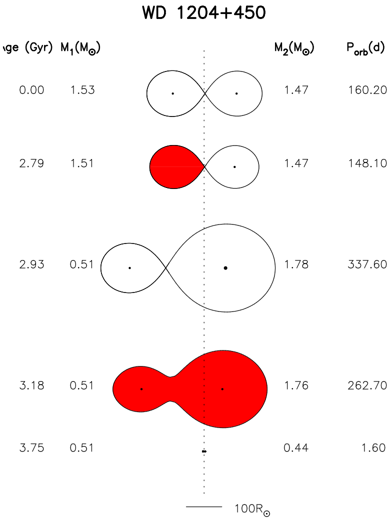
### Number of explained DWDs

| uncertainty | expected | conservative | non-conservative |
|---|---|---|---|
| 1$\sigma$ | 6.8 | 2 | 4 |
| 2$\sigma$ | 9.5 | 6 | 9 |
| 3$\sigma$ | 10.0 | 7 | 10 |

# Results: example solutions




$\beta = 0.7$



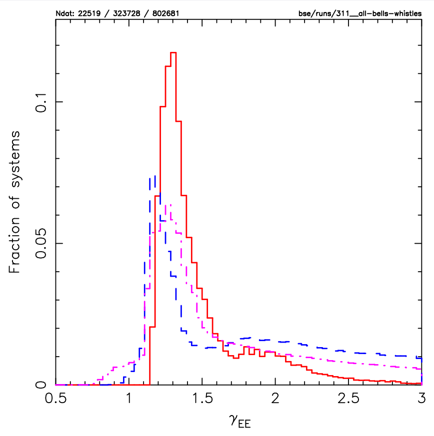

$\beta = 0.3$

# Match with observed double-lined double white dwarfs

| System | Observed | | | | Reconstructed | | | | Initial | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $q_2$ | $P_{orb}$ (d) | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $q_2$ | $P_{orb}$ (d) | $M_{1i}$ ($M_\odot$) | $M_{2i}$ ($M_\odot$) | $P_i$ (d) | $\beta$ |
| WD 0135 | 0.52 | 0.47 | 0.90 | 1.556 | 0.514 | 0.461 | 0.897 | 1.549 | 1.37 | 1.36 | 180 | 1.00 |
| WD 0136 | 0.37 | 0.47 | 1.26 | 1.407 | 0.438 | 0.533 | 1.217 | 1.377 | 1.34 | 1.31 | 84.3 | 0.67 |
| WD 0957 | 0.32 | 0.37 | 1.13 | 0.061 | 0.312 | 0.352 | 1.128 | 0.061 | 1.26 | 1.22 | 12.6 | 0.73 |
| WD 1101 | 0.33 | 0.29 | 0.87 | 0.145 | 0.355 | 0.304 | 0.856 | 0.144 | 1.10 | 1.10 | 130 | dCE |
| PG 1115 | 0.7 | 0.7 | 0.84 | 30.09 | 0.842 | 0.701 | 0.833 | 0.041 | 3.58 | 2.00 | 3409 | 0.95 |
| WD 1204 | 0.52 | 0.46 | 0.87 | 1.603 | 0.509 | 0.438 | 0.861 | 1.624 | 1.19 | 1.18 | 338 | 0.41 |
| WD 1349 | 0.44 | 0.44 | 1.26 | 2.209 | 0.446 | 0.509 | 1.141 | 2.205 | 1.12 | 1.12 | 342 | |
| HE 1414 | 0.55 | 0.71 | 1.28 | 0.518 | 0.514 | 0.645 | 1.255 | 0.509 | 1.93 | 1.91 | 32.2 | 1.00 |
| WD 1704 | 0.56 | 0.39 | 0.70 | 0.145 | 0.361 | 0.537 | 1.488 | 0.139 | 1.99 | 1.86 | 247 | 0.51 |
| HE 2209 | 0.58 | 0.58 | 1.00 | 0.277 | 0.555 | 0.551 | 0.993 | 0.276 | 2.20 | 2.20 | 374 | dCE |

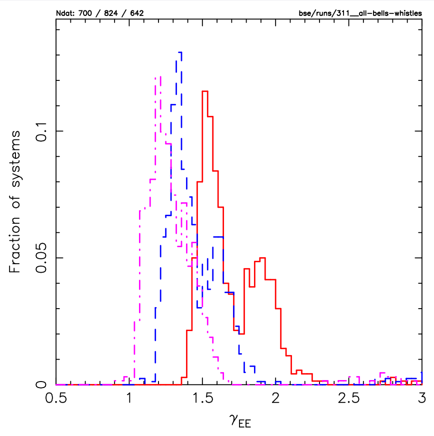
# $\gamma$-values for non-conservative MT

## Non-conservative MT




all binaries — all DWDs — double-lined DWDs

## Non-conservative MT




$\beta = 0.5$ — $\beta = 0.6$ — $\beta = 0.7$

# DWD conclusions

## Stable, non-conservative mass transfer + CE

- Can explain 4/9/10 of 10 observed DWDs ($q$, $P_{\rm orb}$, $M_1$, $M_2$, $\Delta\tau$)
- Forms fewer DWDs through CE, but many more through stable MT
- Crux is adapted stability criterion, not AM loss
- System mass loss is naturally explained by thermal-timescale mass transfer

**Progenitors:**

- Equal-mass systems in double CE ($\beta$ independent)
- Near-equal-mass systems + $\beta < 1$

## $\gamma_{\rm EE}$

- $\gamma_{\rm EE} \sim 1.5$ may indicate stable, non-conservative mass transfer

## To do:

- Consider mass loss through $L_2$

The End