White Dwarf mergers:
AM CVn, sdB and R CrB connections

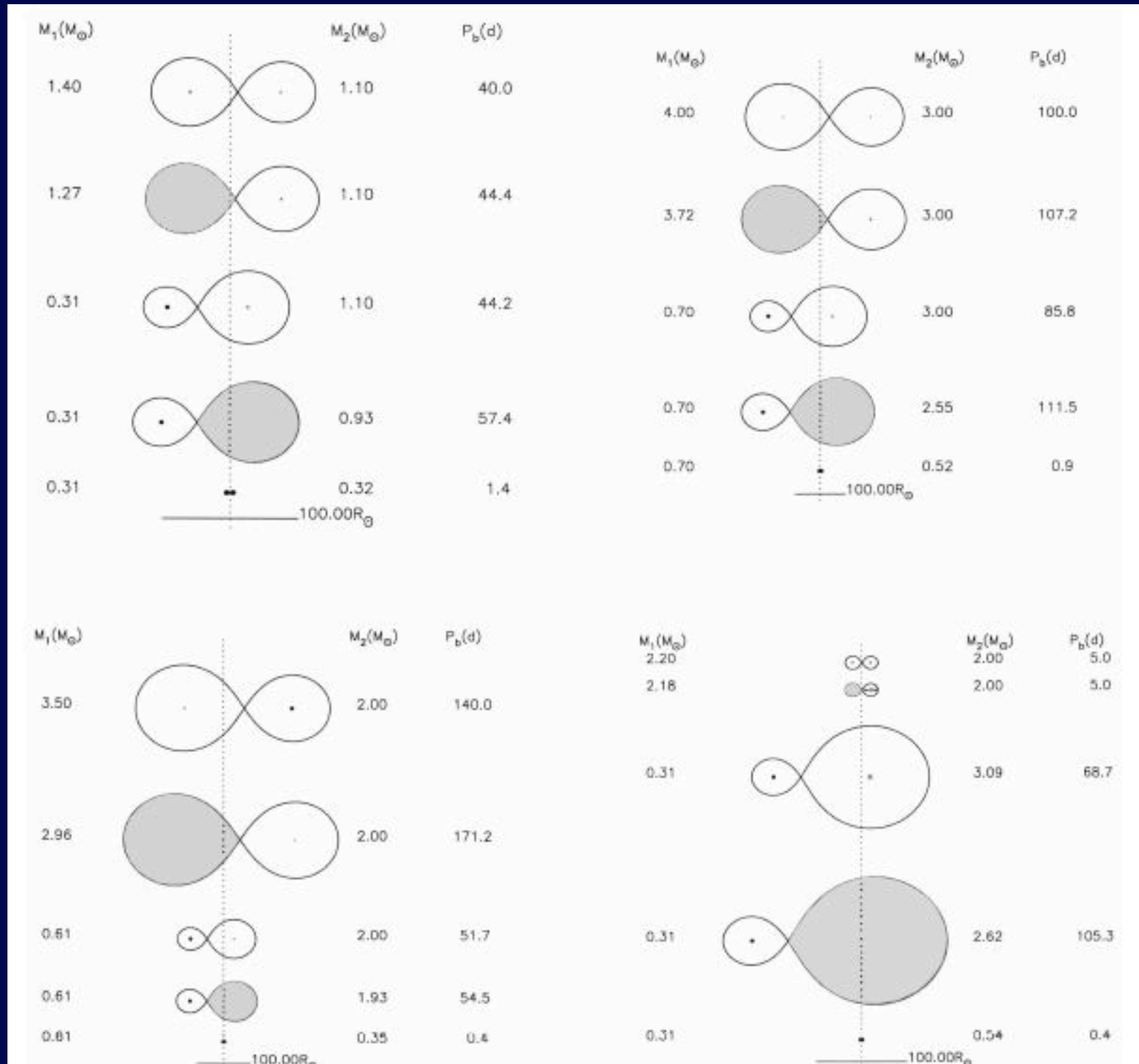
Simon Jeffery
Armagh Observatory

many, many colleagues, but principally:
Phil Hill, Uli Heber and Hideyuki Saio

White Dwarf mergers:
AM CVn, sdB and R CrB connections

- WD-WD binaries and WD-WD mergers
- AM CVn stars
- He+He WD mergers - EHe / sdB / sdO stars ?
- CO+He WD mergers - EHe / RCrB / SNIa ?
- CO+CO WD mergers - ?
- What *actually* happens in a WD merger ?
  - Angular Momentum ?
  - Disk / Envelope / Core ?
  - Hydrodynamics ?
  - Nucleosynthesis ?
- Lies, Damned Lies

Origin of Binary White Dwarfs



HE+HE

CO+CO

CO+HE

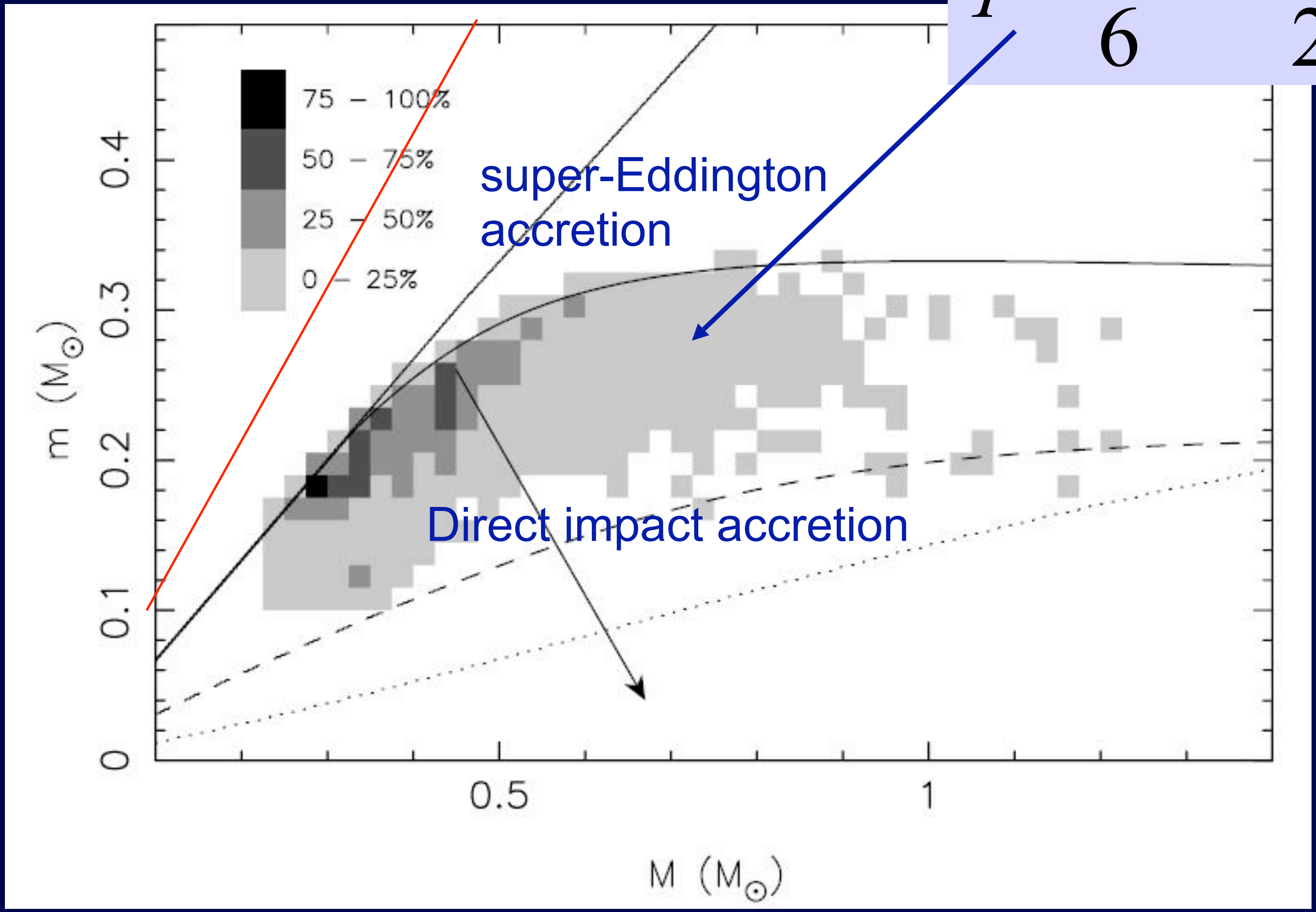
HE+CO

Nelemans et al. 2001 A&A 365, 491 (inter alia)

Binary White Dwarf Stability

Dynamically stable mass transfer for:

$$q < \frac{5}{6} + \frac{\varsigma(m)}{2}$$

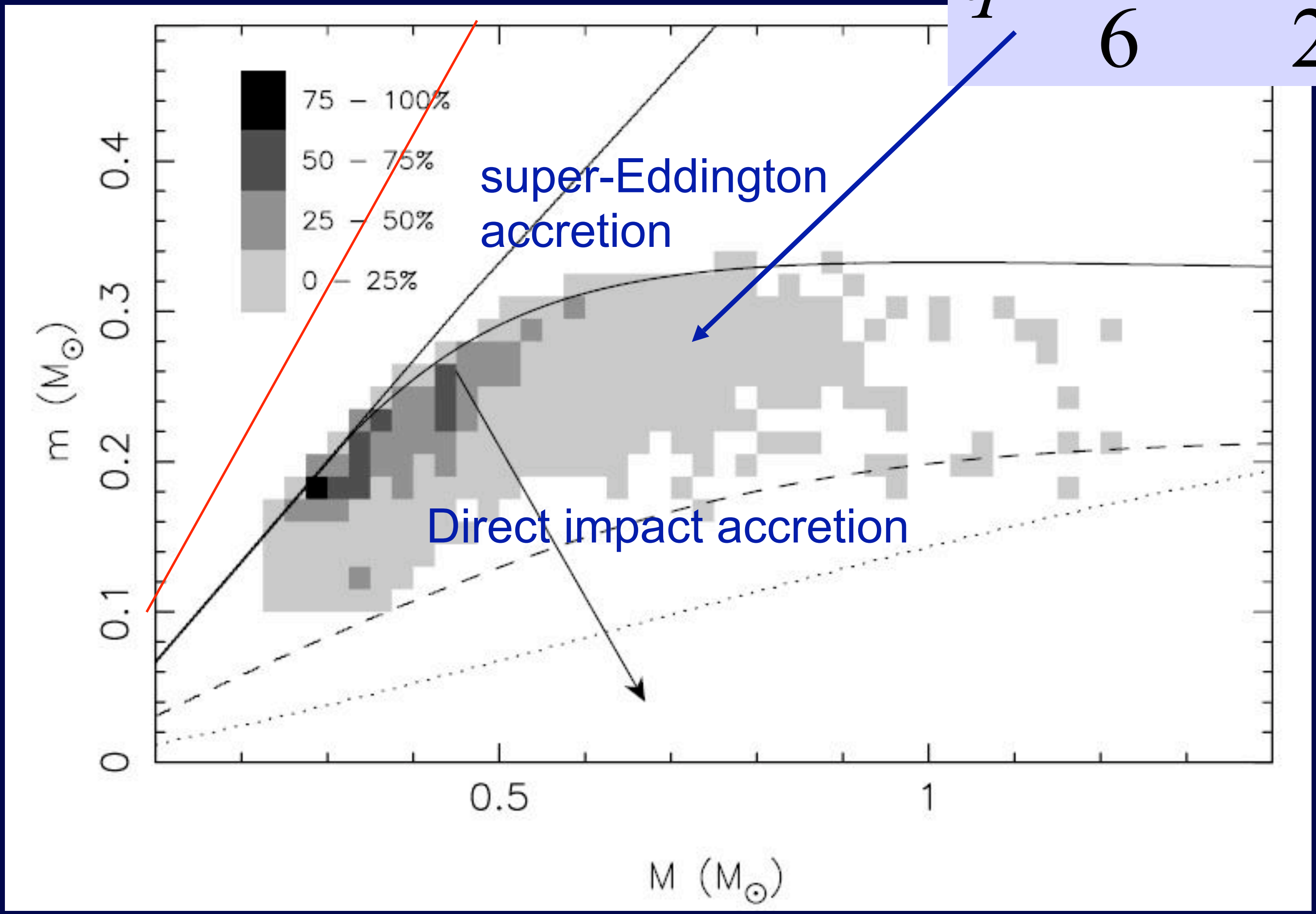


Nelemans et al. 2001 A&A 368, 939

Binary White Dwarf Stability

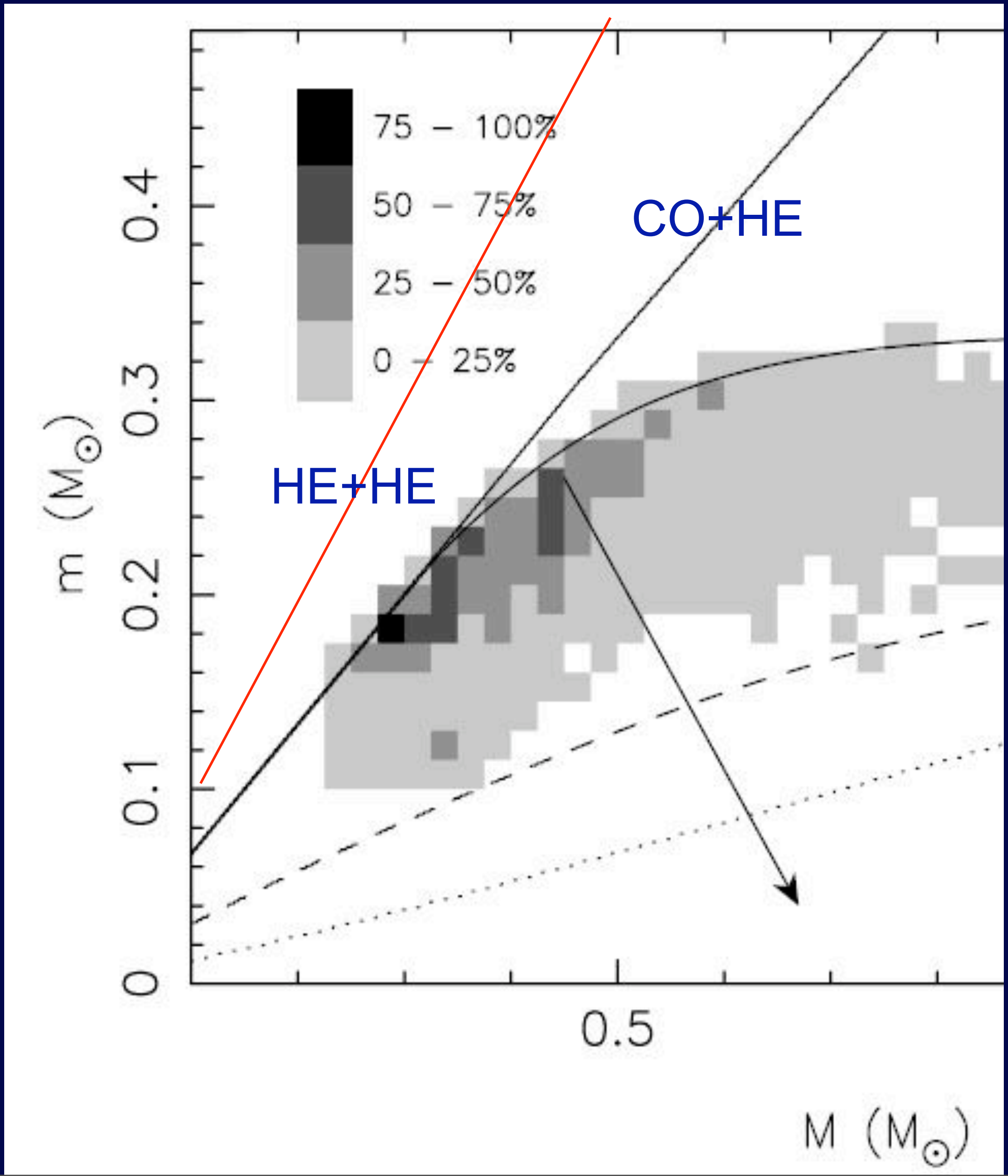
Allegedly

Dynamically stable mass transfer for: $q < \frac{5}{6} + \frac{\varsigma(m)}{2}$



Nelemans et al. 2001 A&A 368, 939

What happens in the unstable zone?



white-dwarf white-dwarf binaries

period distribution:

(Nelemans et al. 2001, Maxted et al. 2002, also Deloye's talk)

merger timescales:

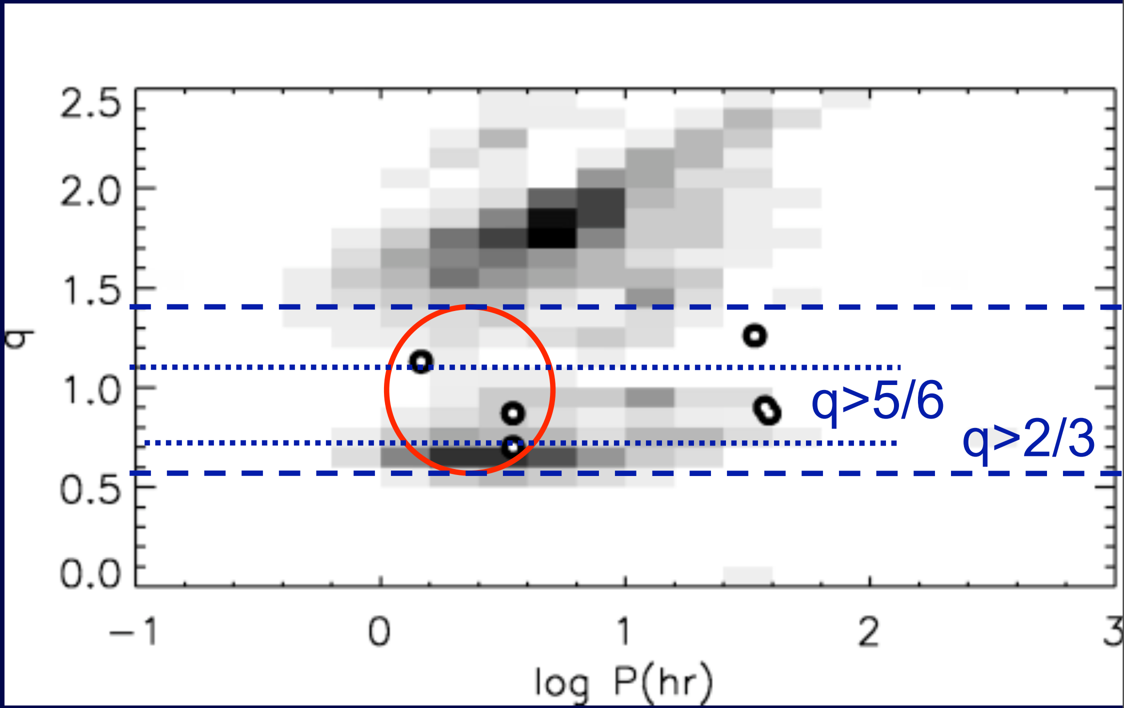
$\tau_m = 10^7\,(P/\mathrm{h})^{8/3}\,\mu^{-1}\,(M/M_\odot)^{-2/3}$ yr

(Landau & Lifshitz 1958)

CO+He merger frequency:

$\nu \sim 4.4\ 10^{-3}\ \mathrm{yr}^{-1}$ *(Neleman's et al. 2001)*

$\nu \sim 2.3\ 10^{-3}\ \mathrm{yr}^{-1}$ *(Iben et al.)*



white-dwarf merger models: old question!

- He+He $\Rightarrow$ He ignition $\Rightarrow$ HeMS or sdB star $\Rightarrow$ CO WD

  (Nomoto & Sugimoto 1977, Nomoto & Hashimoto 1987, Kawai, Saio & Nomoto 1987, 1988, Iben 1990)

- He+CO $\Rightarrow$ RCrB star OR SNIa ?

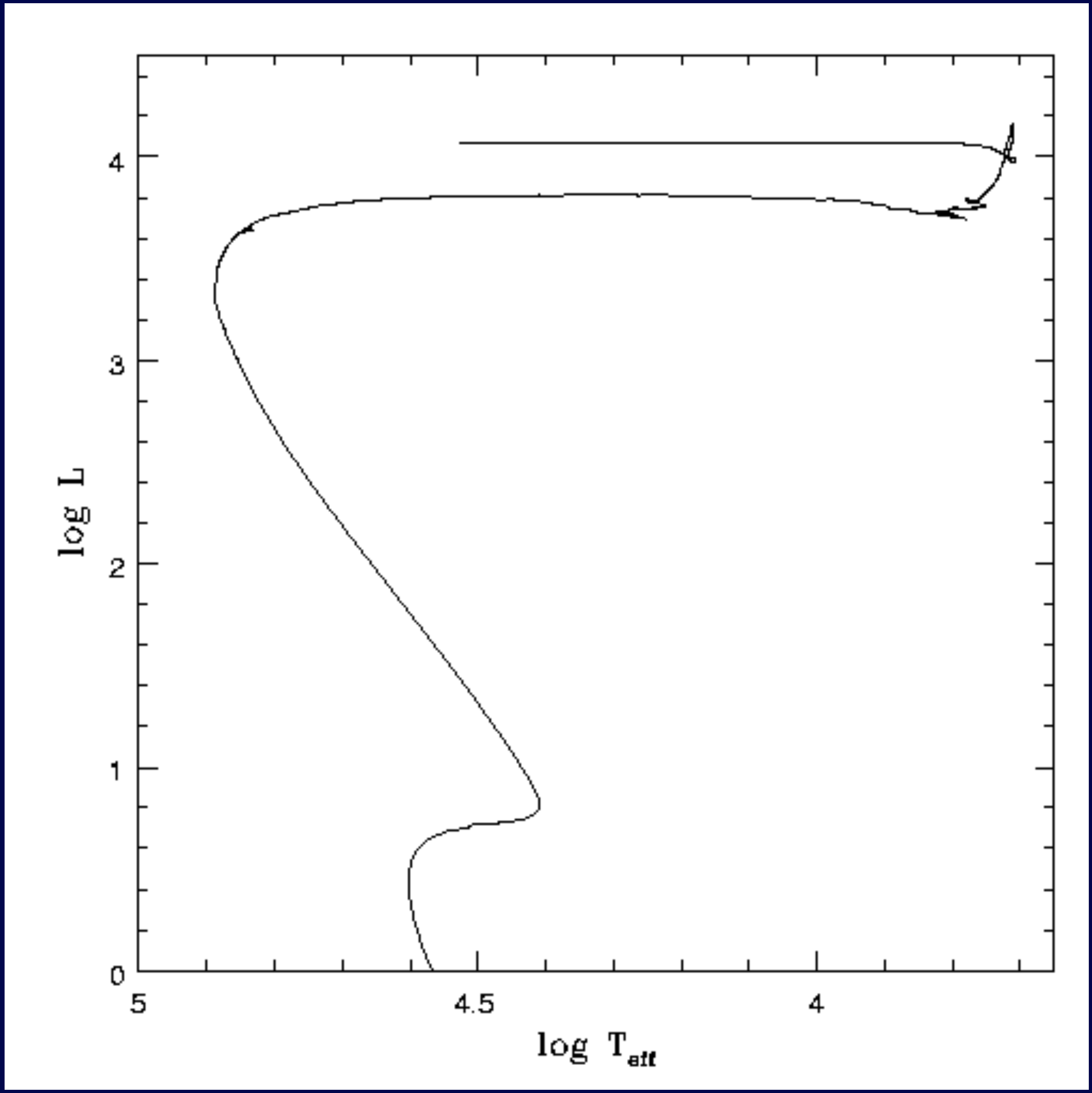
  (Webbink 1984, Iben & Tutukov 1984, Iben 1990)

- CO+CO $\Rightarrow$ C ignition $\Rightarrow$ O+Ne+Mg WD OR explosion ?

  (Hachisu et al. 1986a,b, Kawai, Saio & Nomoto 1987, 1988, Nomoto & Hashimoto 1987, Mochkovitch & Livio 1990, Saio & Nomoto 1998)

- results critically sensitive to WD temperature AND accretion rate
- what do the products look like between merger and end-state?

white dwarf merger models: basic approach



Saio & Jeffery ….

He+He WD mergers

hypothesis

He+He white dwarf formed

orbit decays

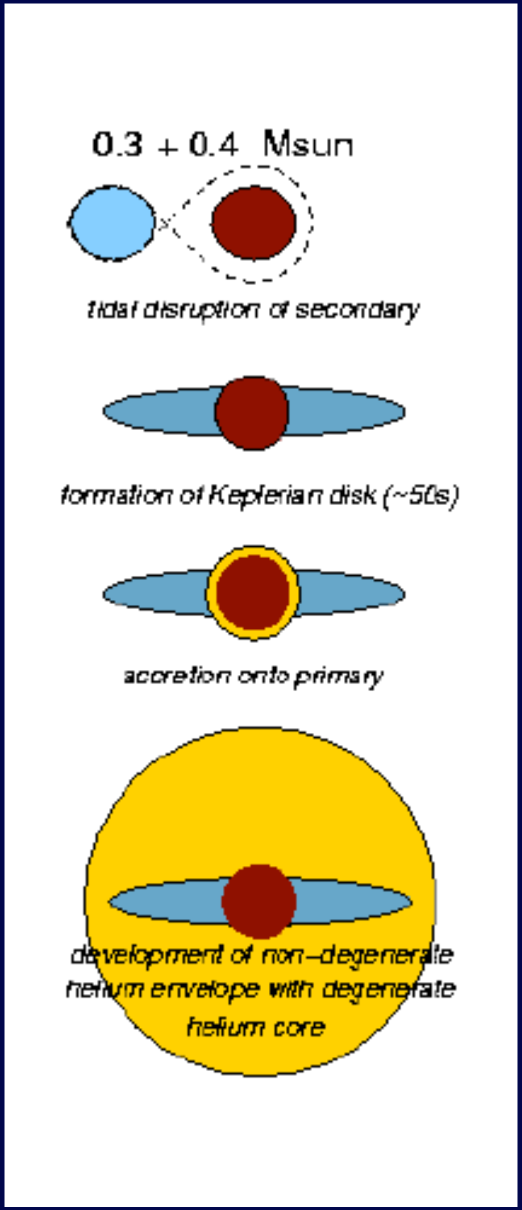
less massive WD disrupted when P_{orb} ~4 minutes

super-Eddington accretion:

forms thick disk?

more massive WD accretes material from disk

⇒model



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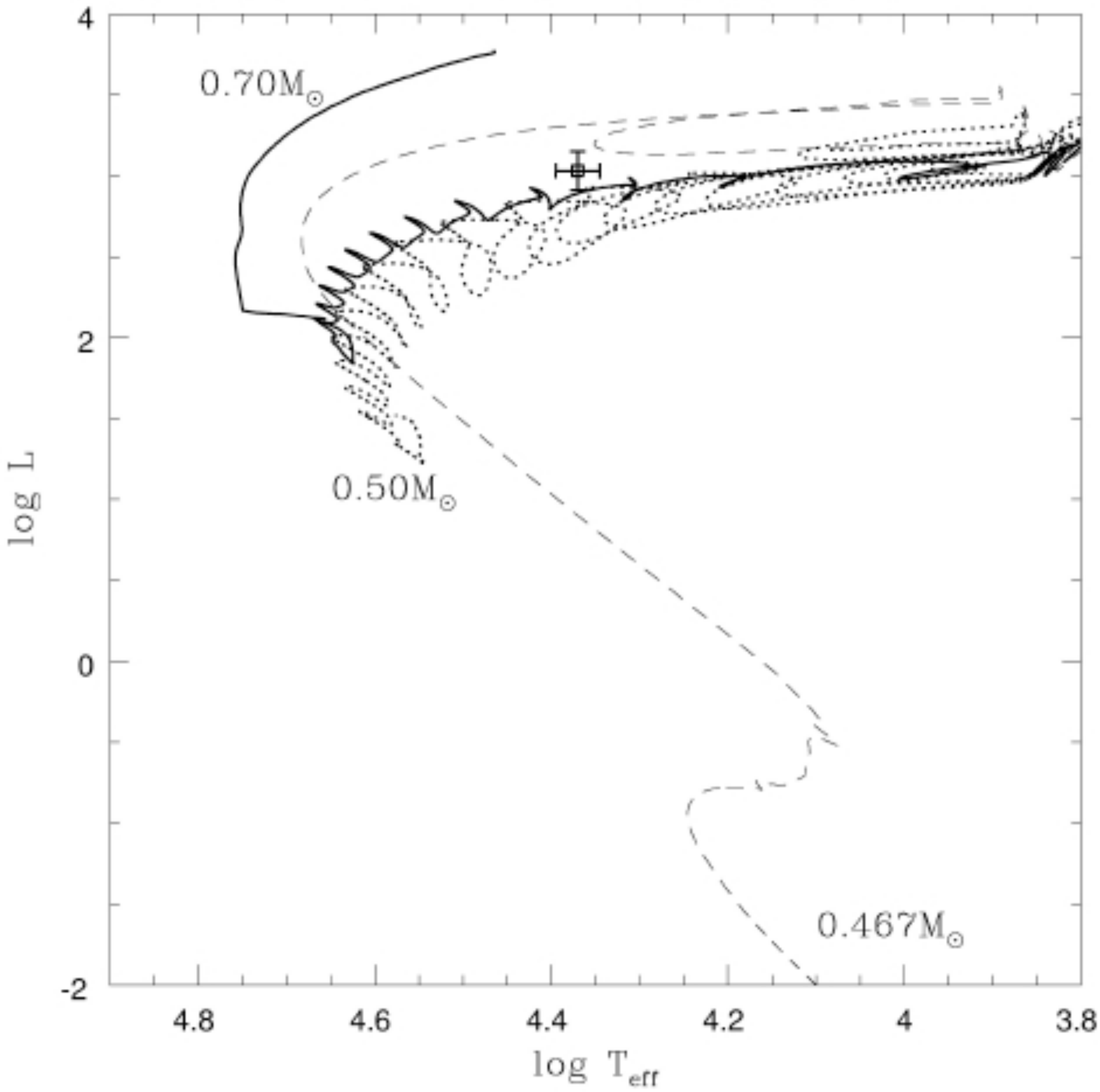

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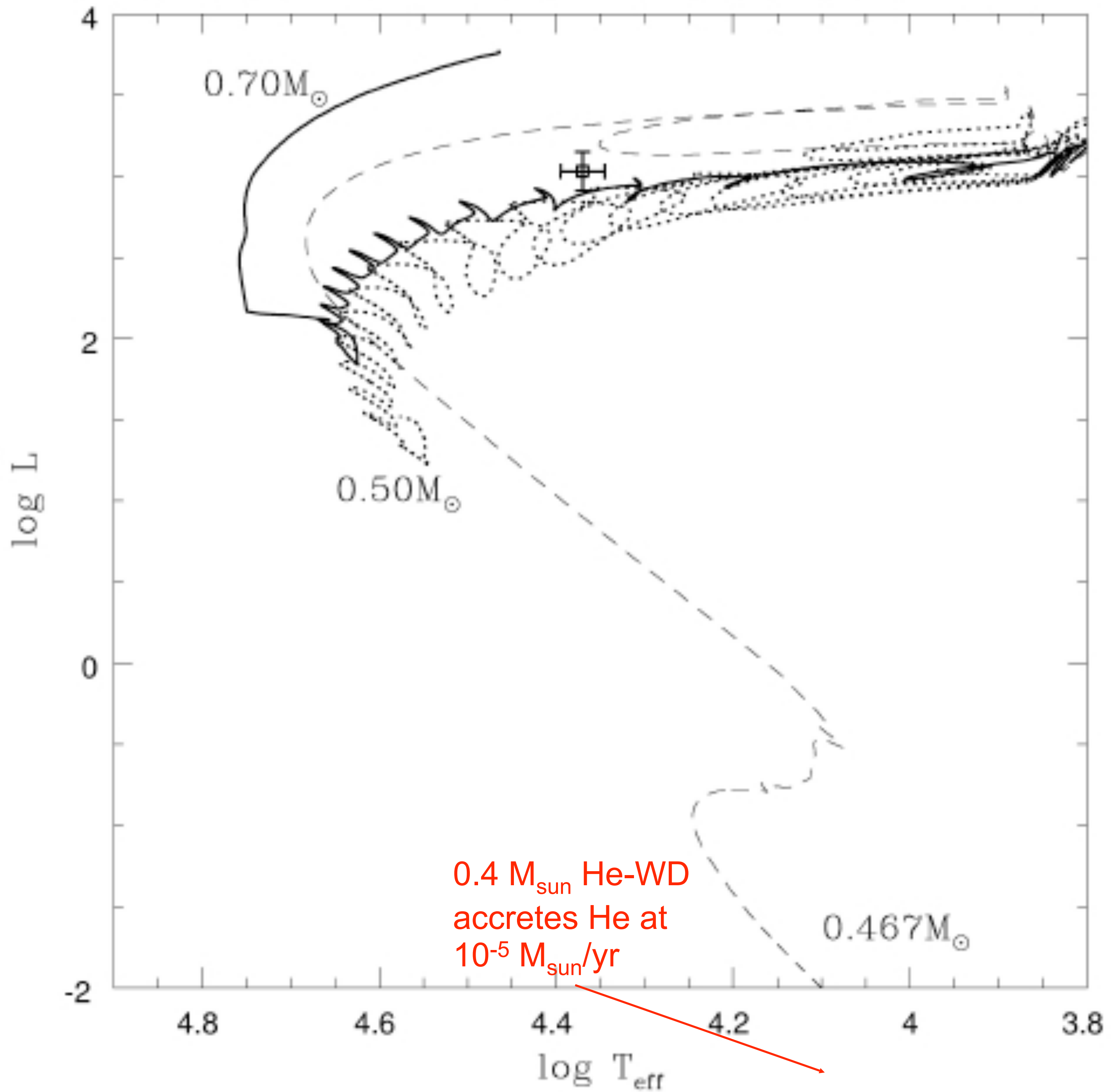

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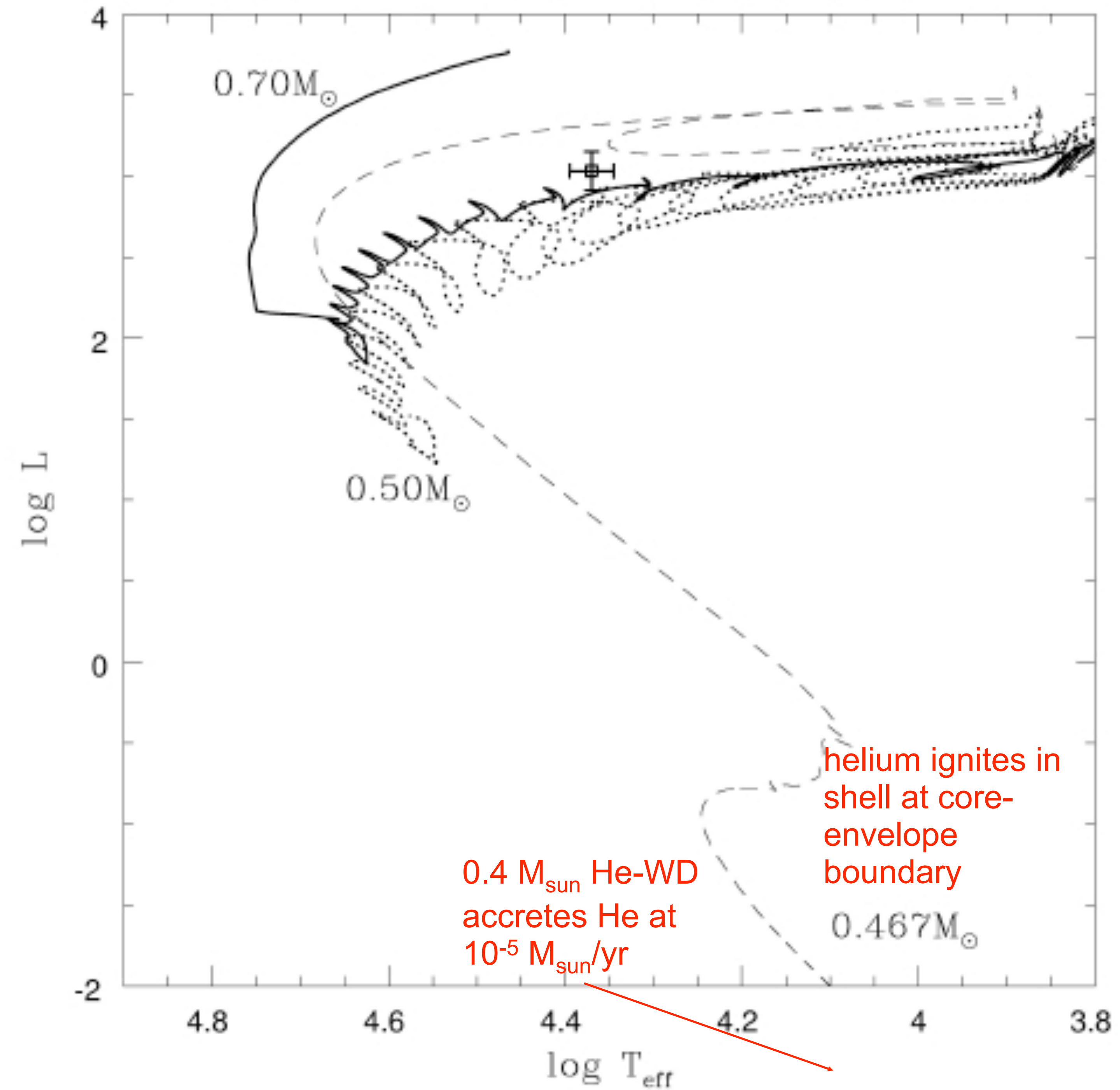

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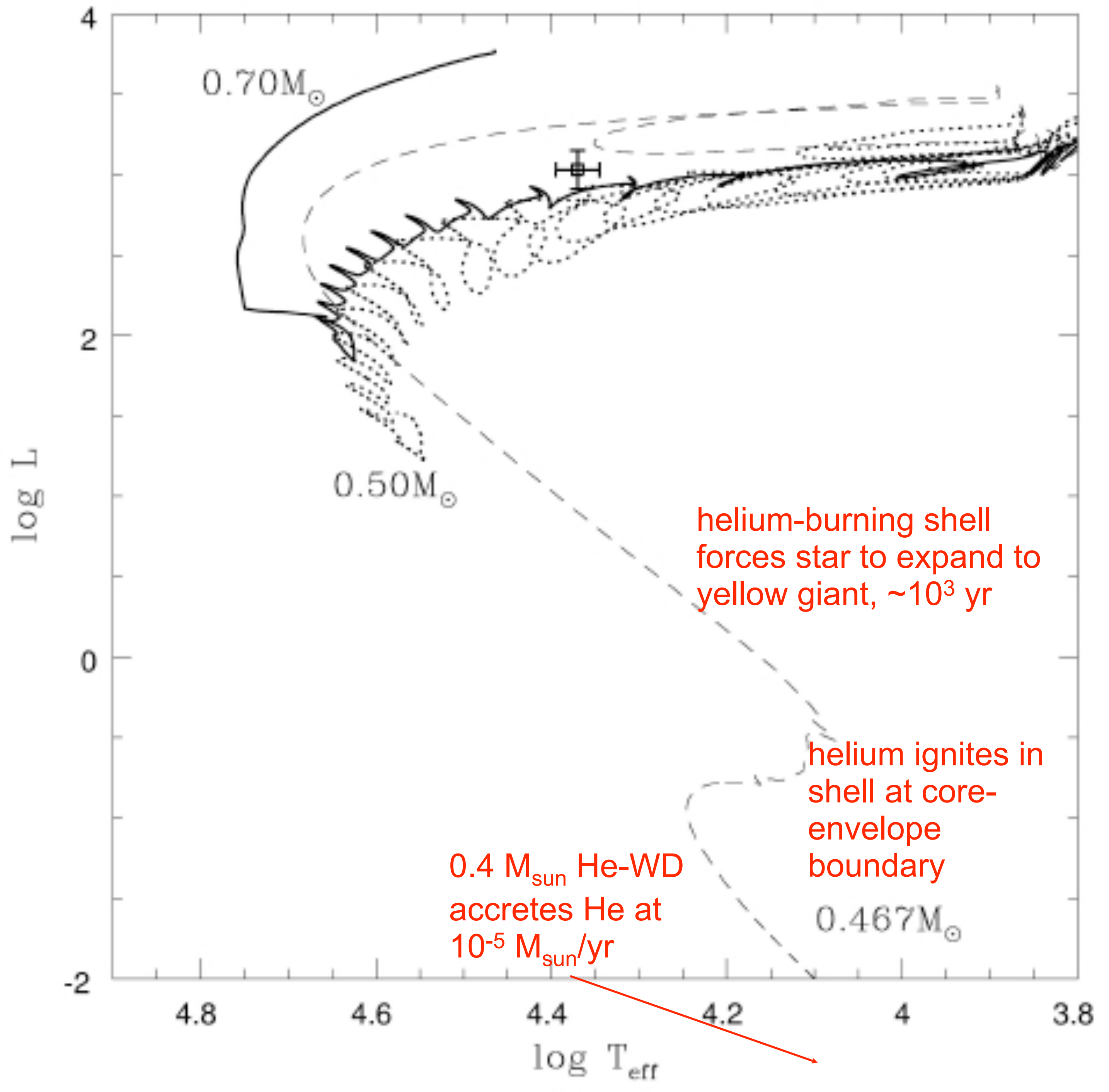

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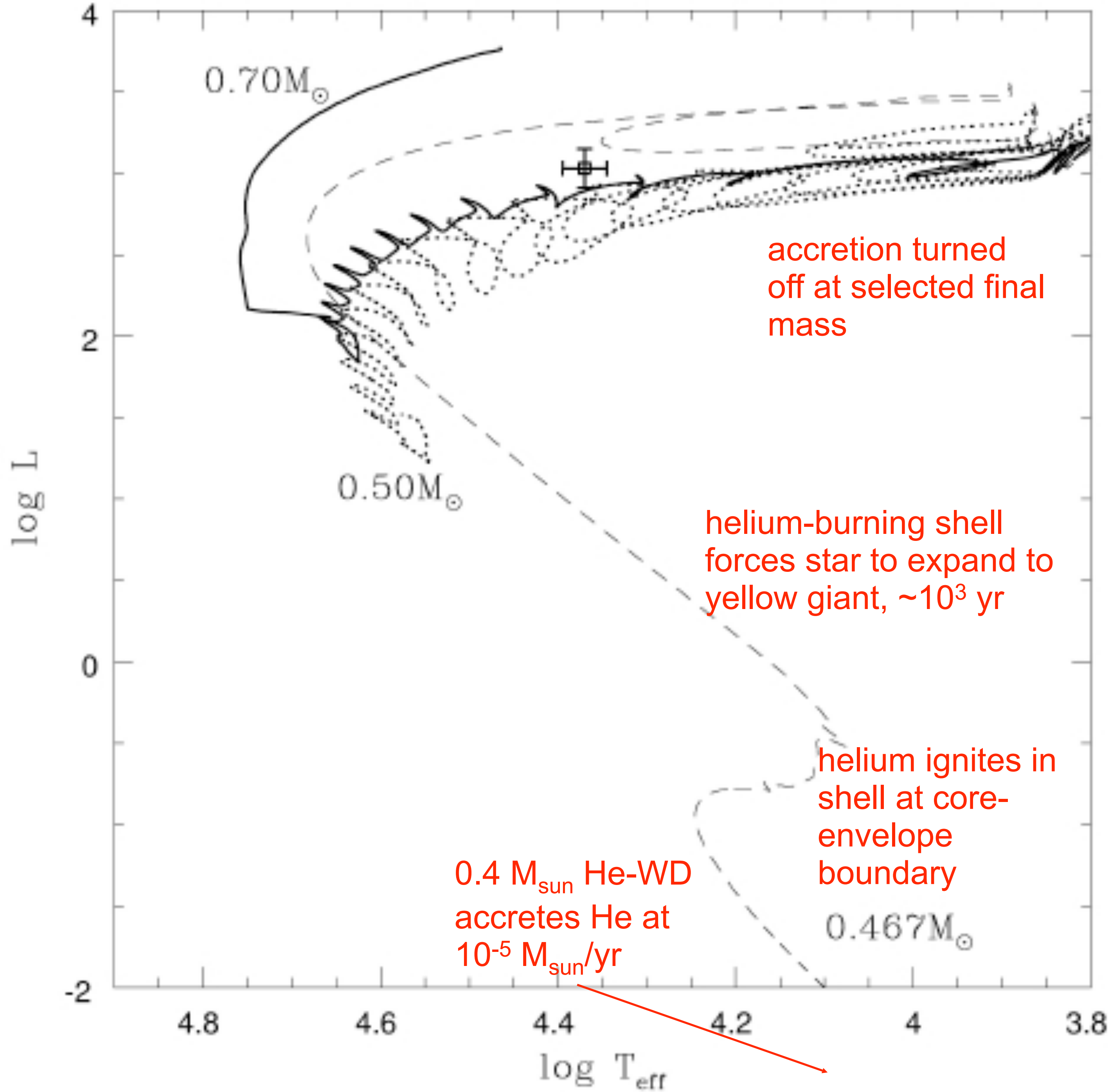

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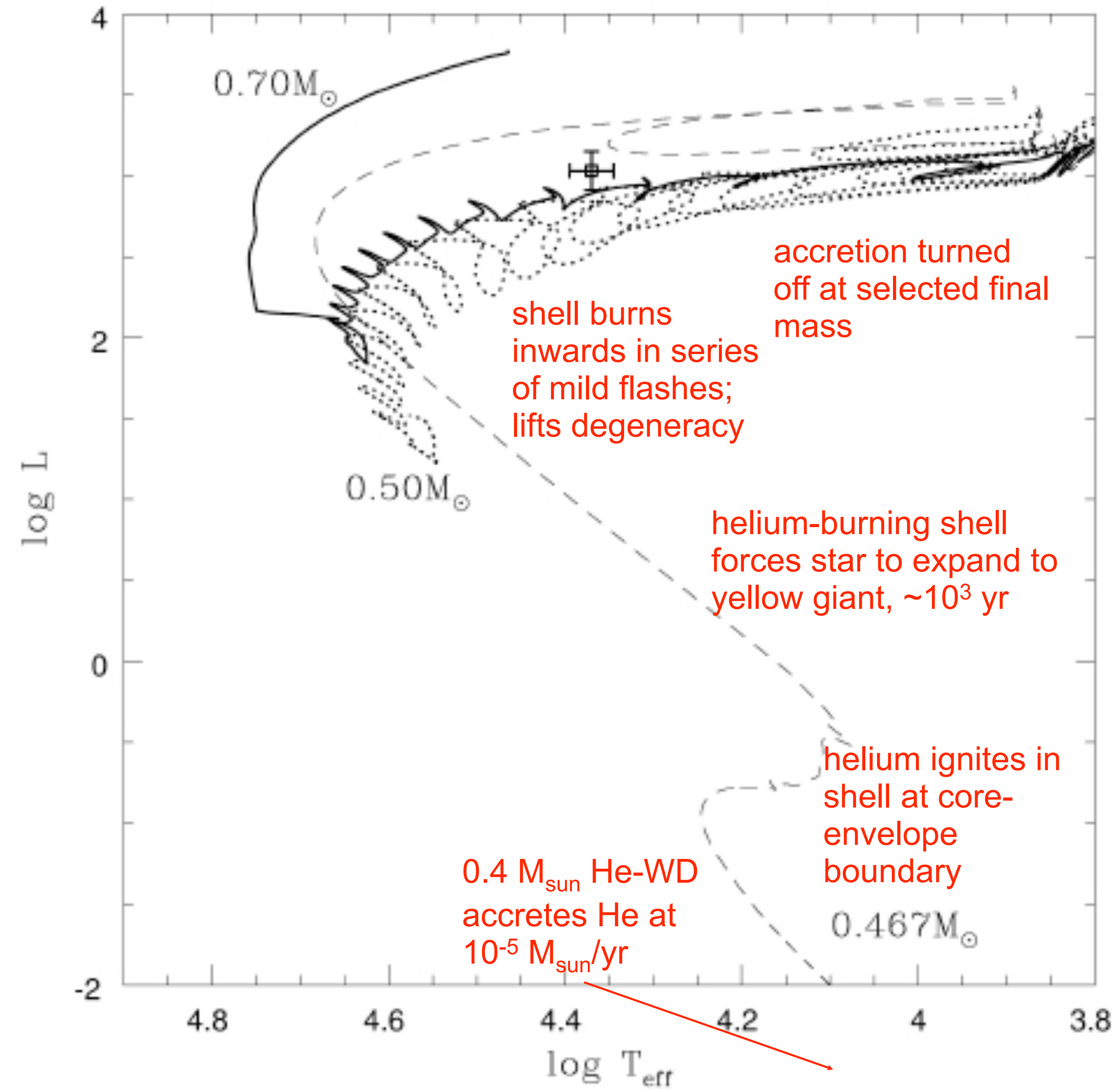

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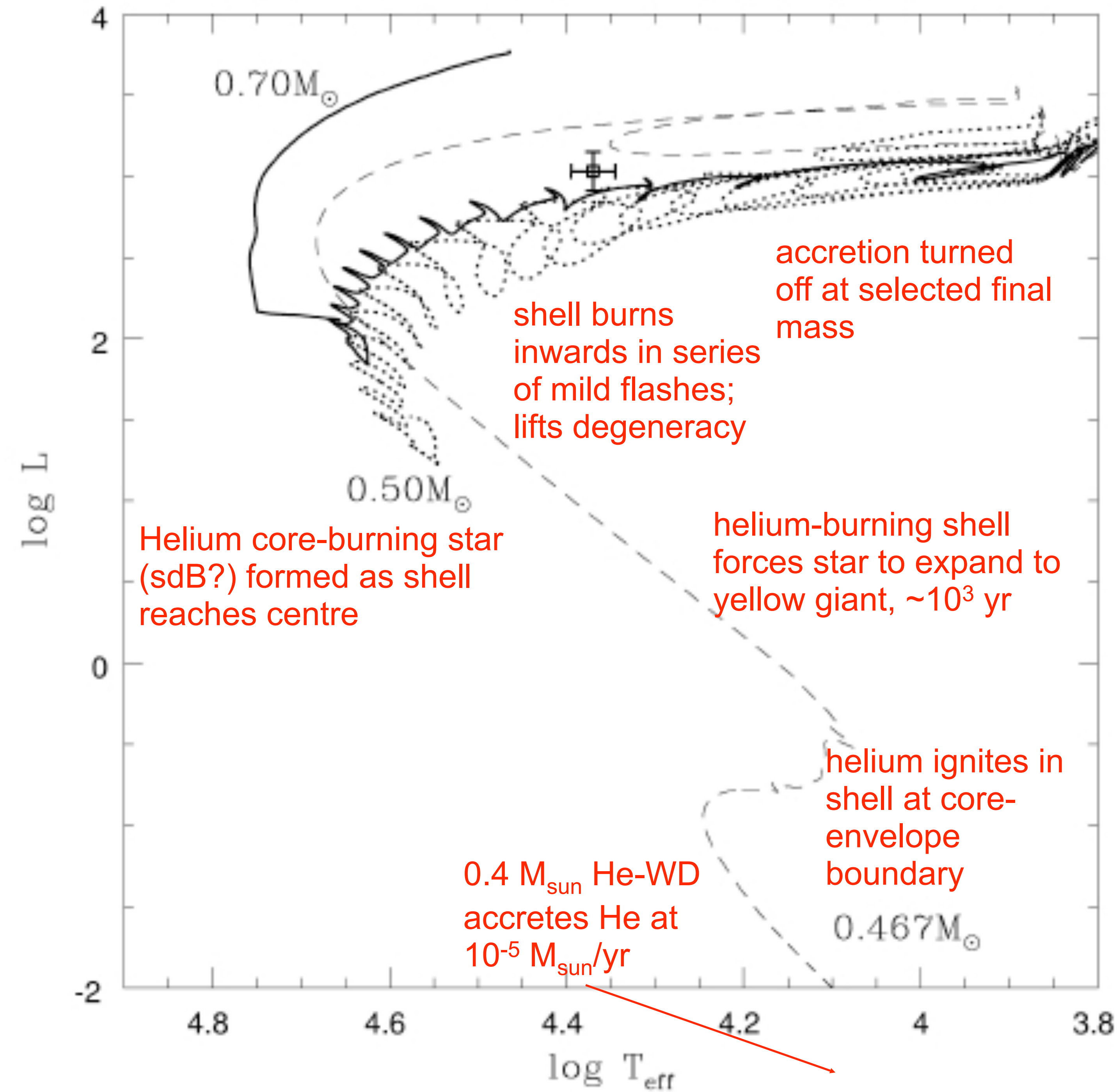
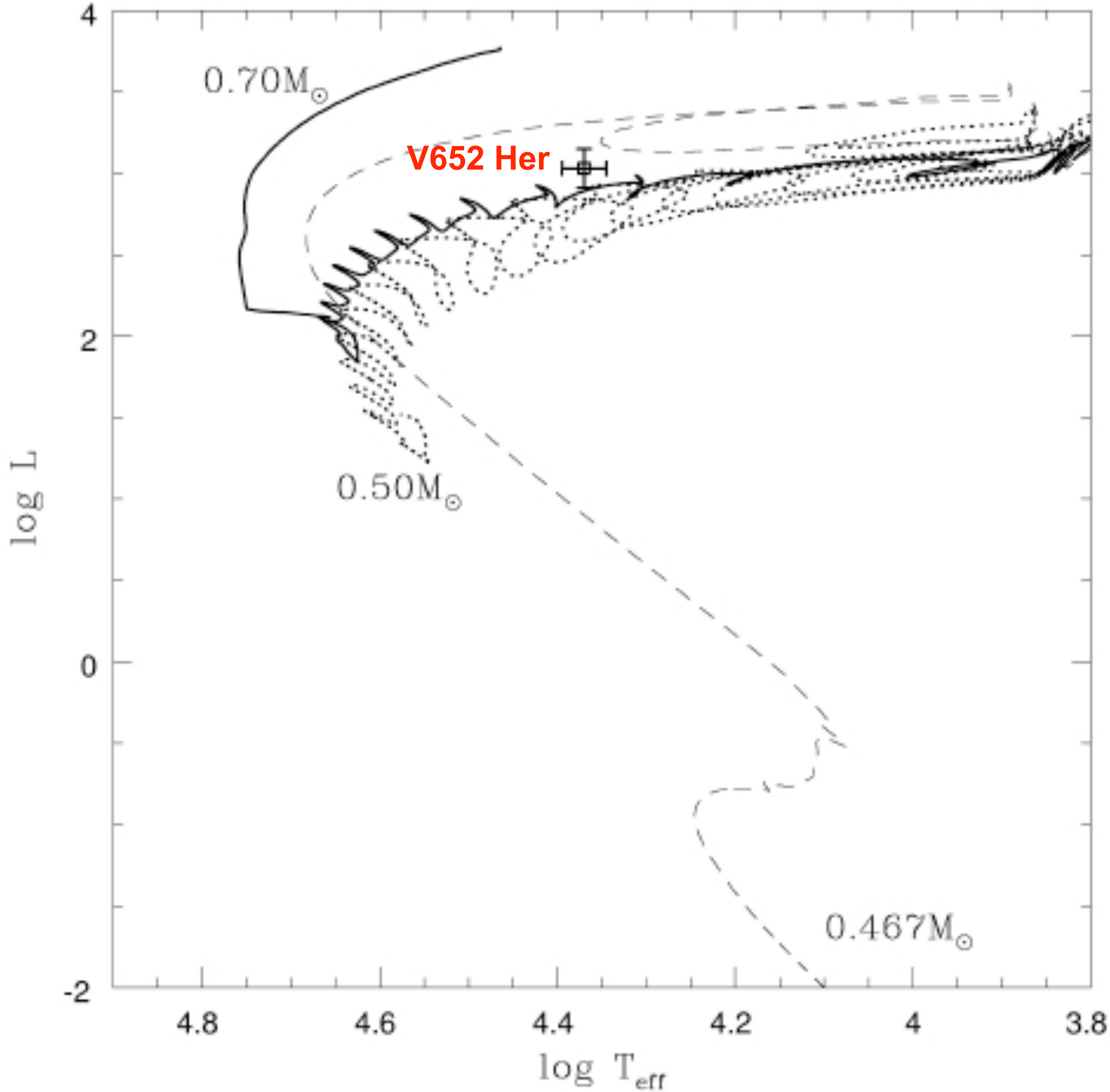


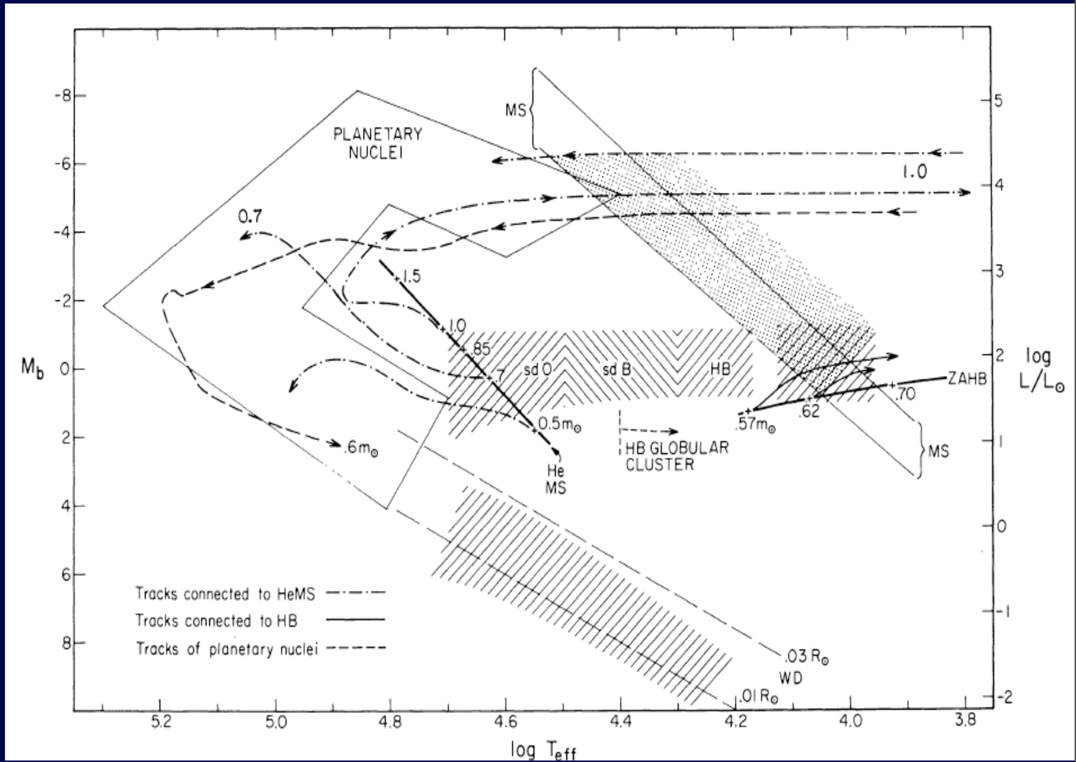


0.70M⊙
V652 Her
0.50M⊙
0.467M⊙
log L
log T_{eff}
4
2
0
-2
4.8
4.6
4.4
4.2
4
3.8

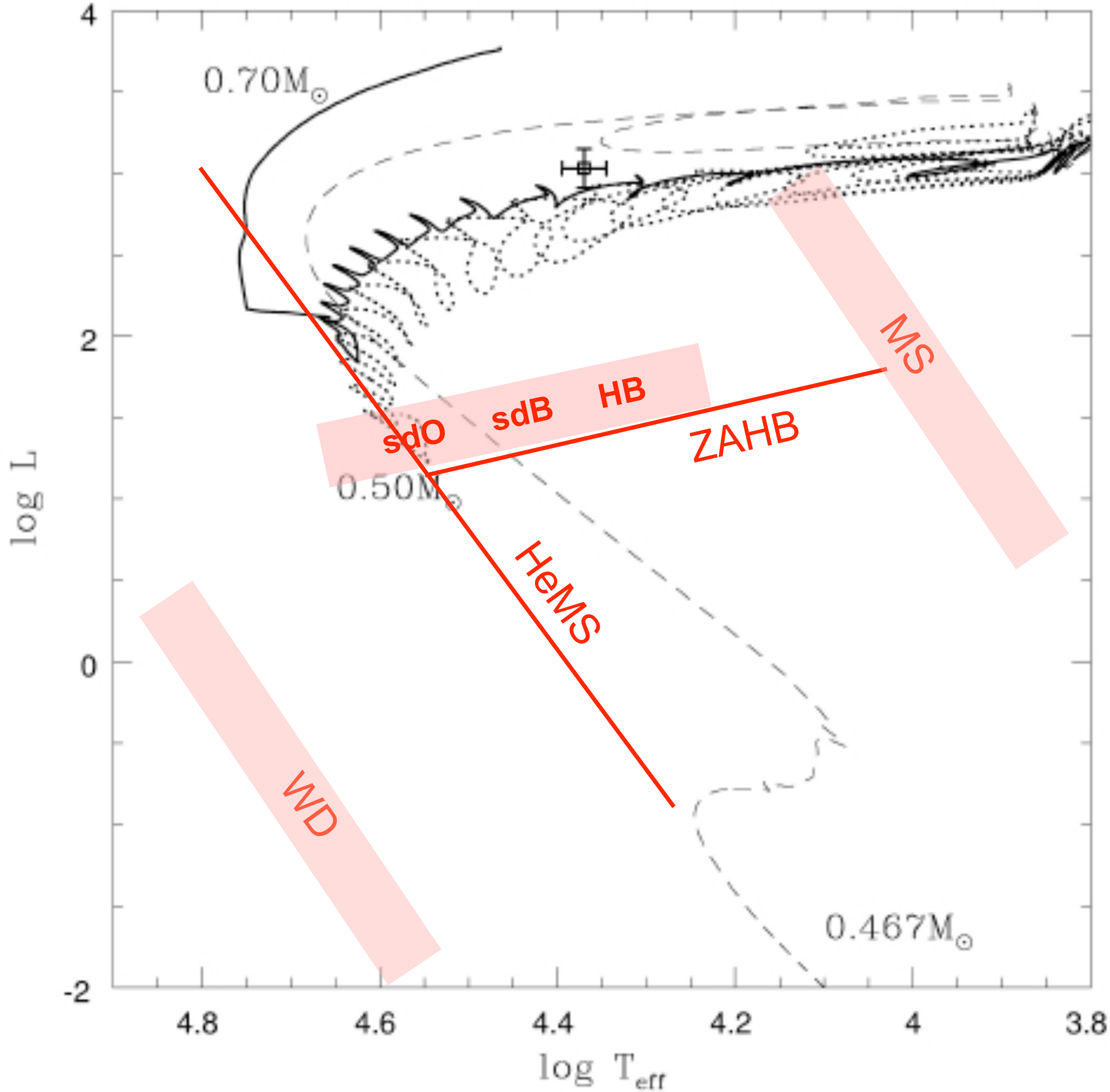
sdB stars

- Four types:
  - sdB+MS (F-G) long-period
  - sdB+MS (M) short-period
  - sdB+WD (He) short-period
  - sdB single

- Four origins:
  - Stable RLOF
  - CE
  - Stable RLOF + CE
  - HeWD+HeWD merger

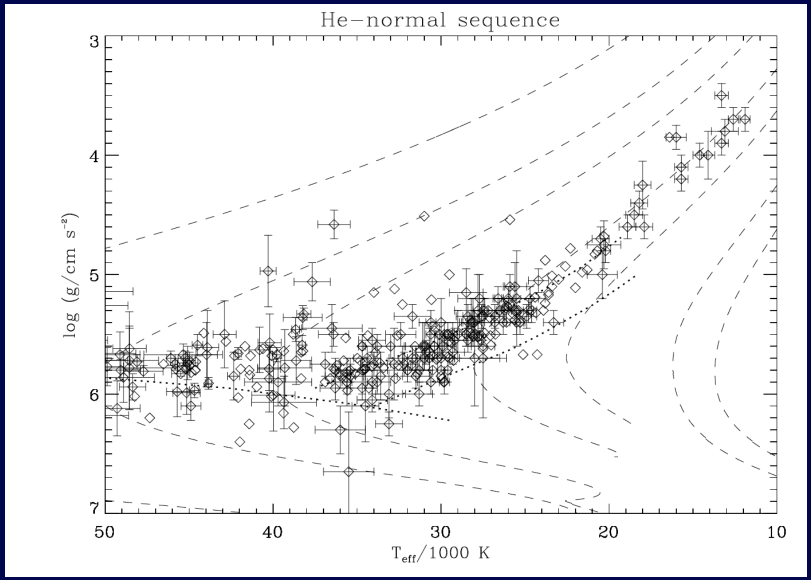


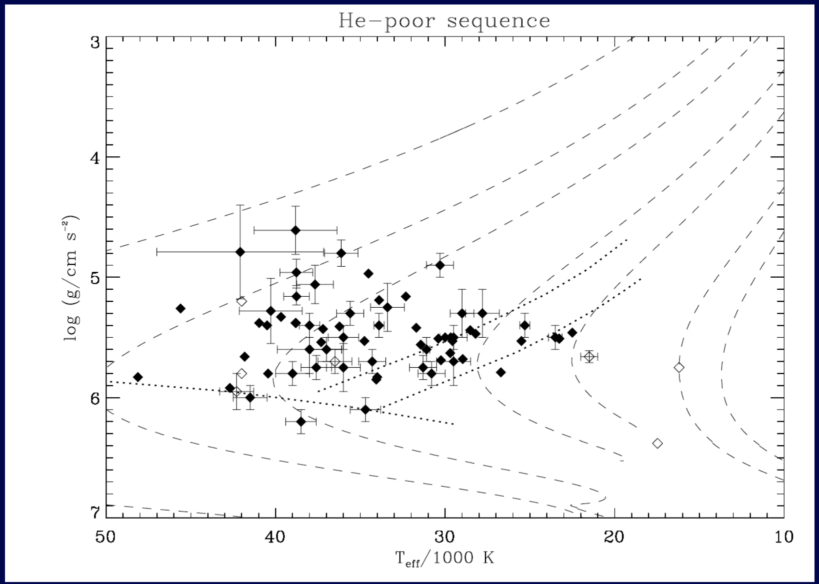
Greenstein & Sargent 1974



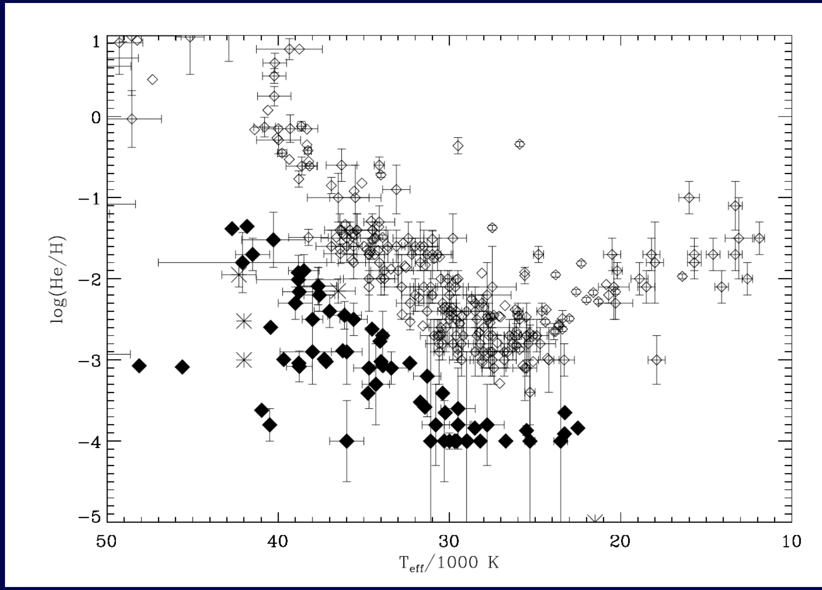
0.70M⊙
0.50M⊙
0.467M⊙
sdO
sdB
HB
ZAHB
MS
HeMS
WD
log L
log Teff
4
2
0
-2
4.8
4.6
4.4
4.2
4
3.8

sdB stars: helium abundance and He+He mergers ?





N_{He} ~ 0.001-0.10

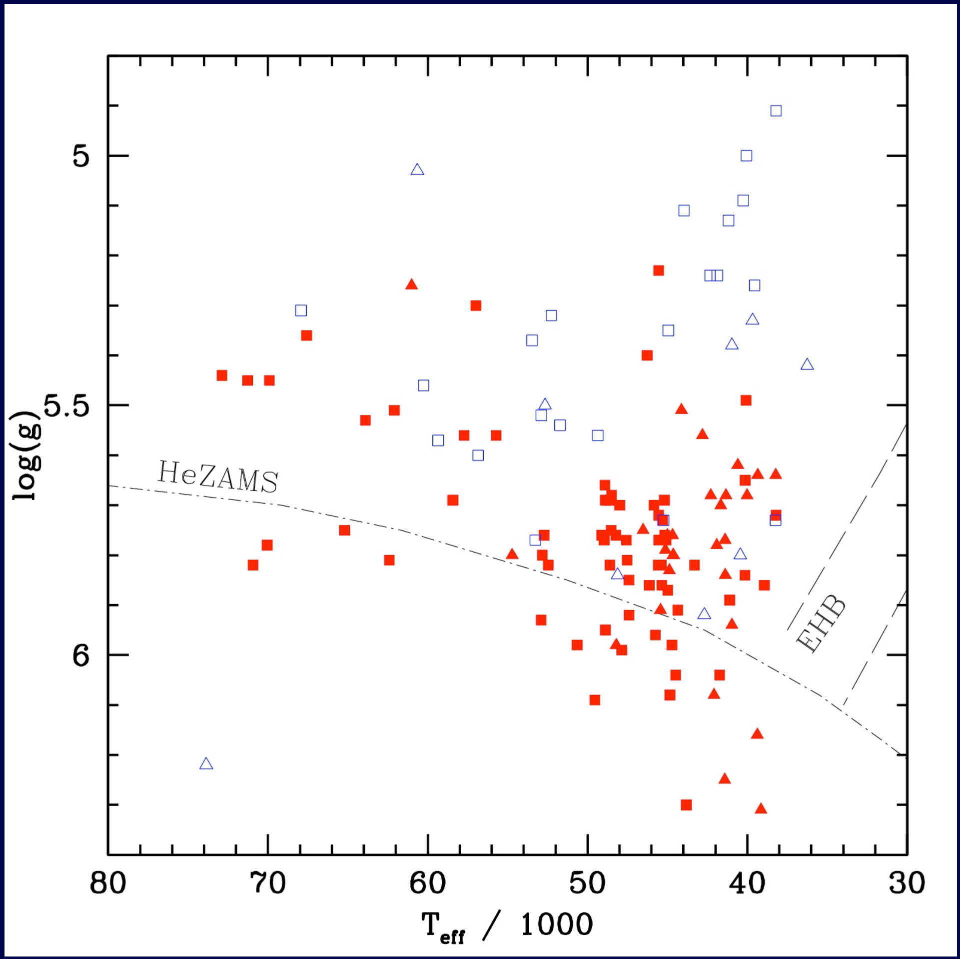


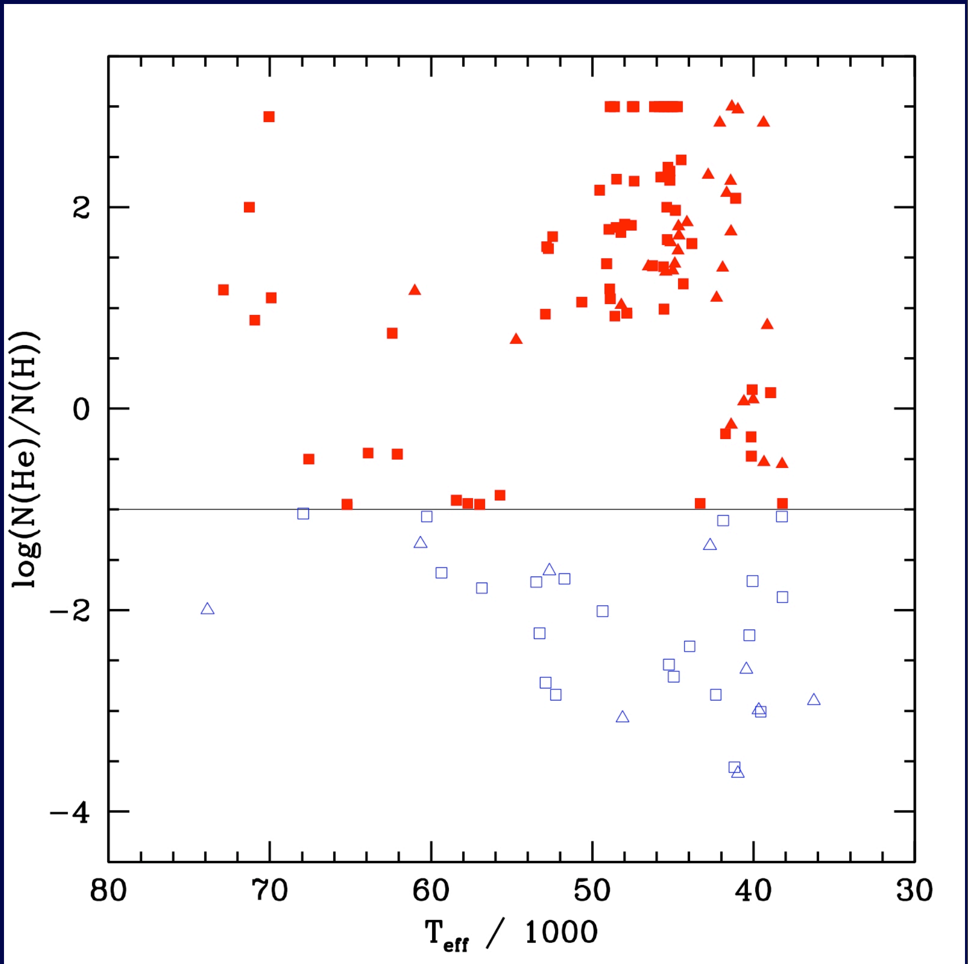
N_{He} ~ 0.0001-0.02

Edelmann et al. 2004,
Winter 2006,
O'Toole 2008

Helium-rich sdB/O's: He, C, and N abundances

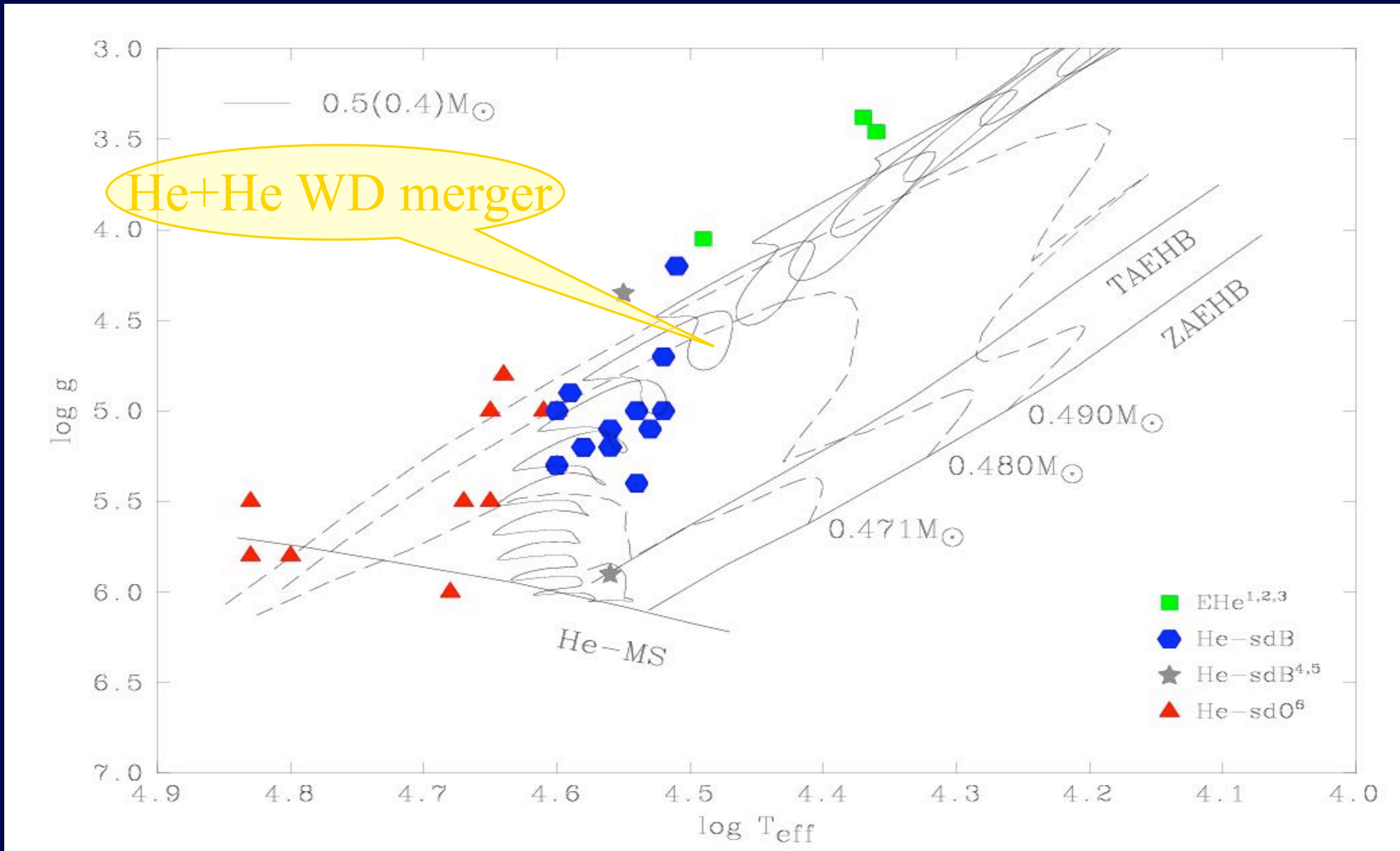
N_{He} ~ 0.1-0.99





Stroeer et al. 2004, Hirsch et al. 2008

He-sdB's: merger or flasher?



Ahmad et al. 2004, see also Justham et al. ???

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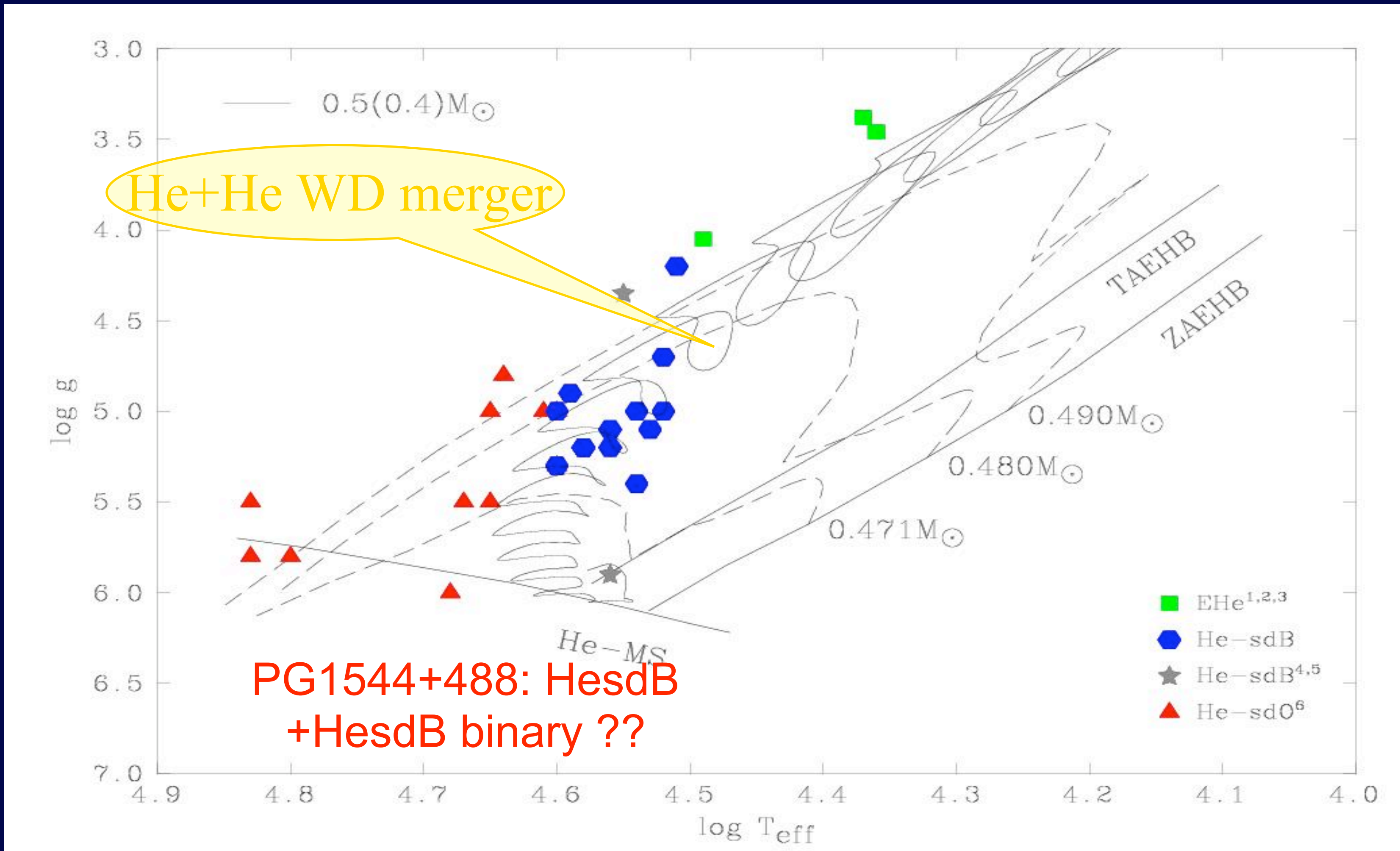
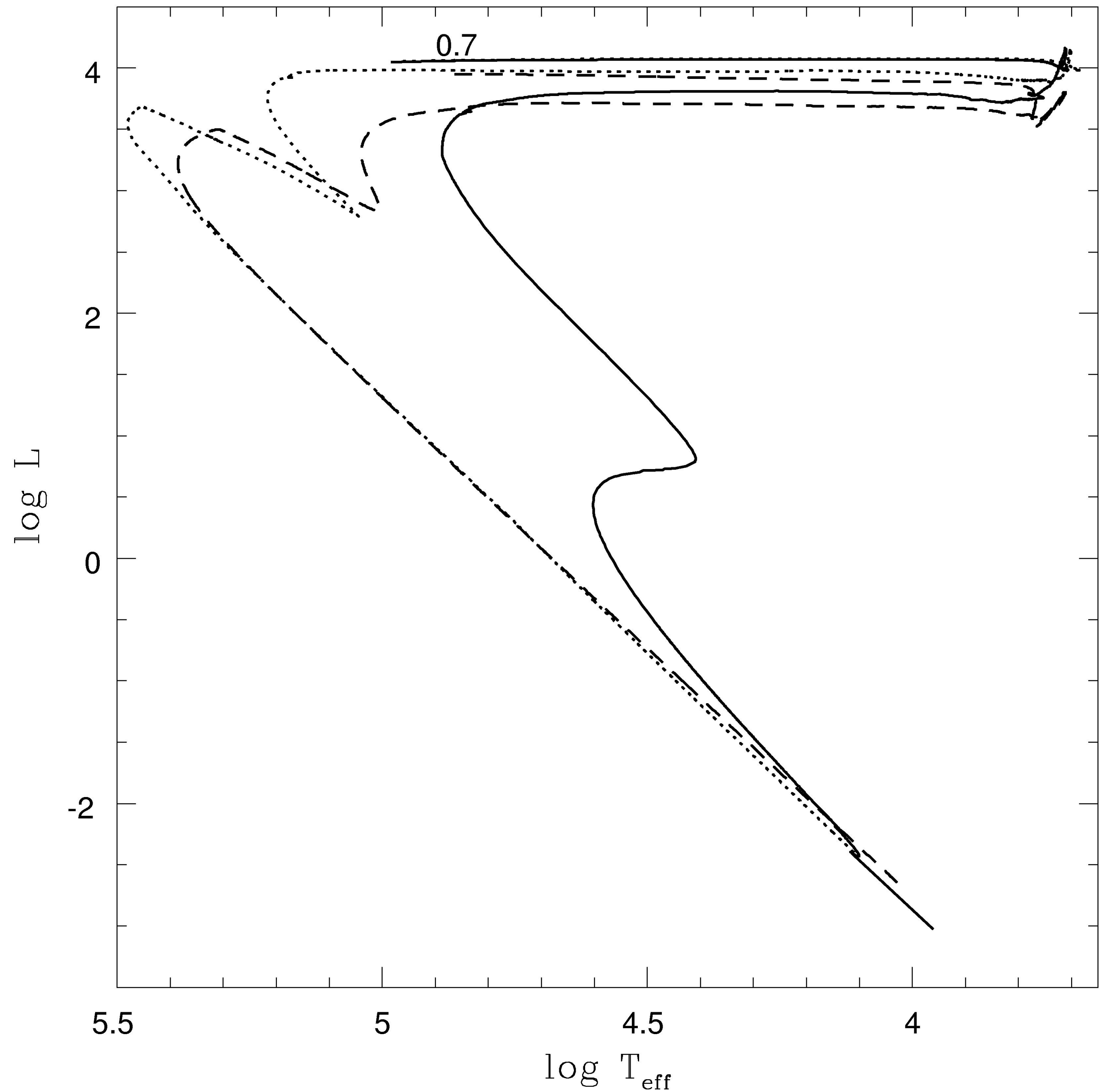
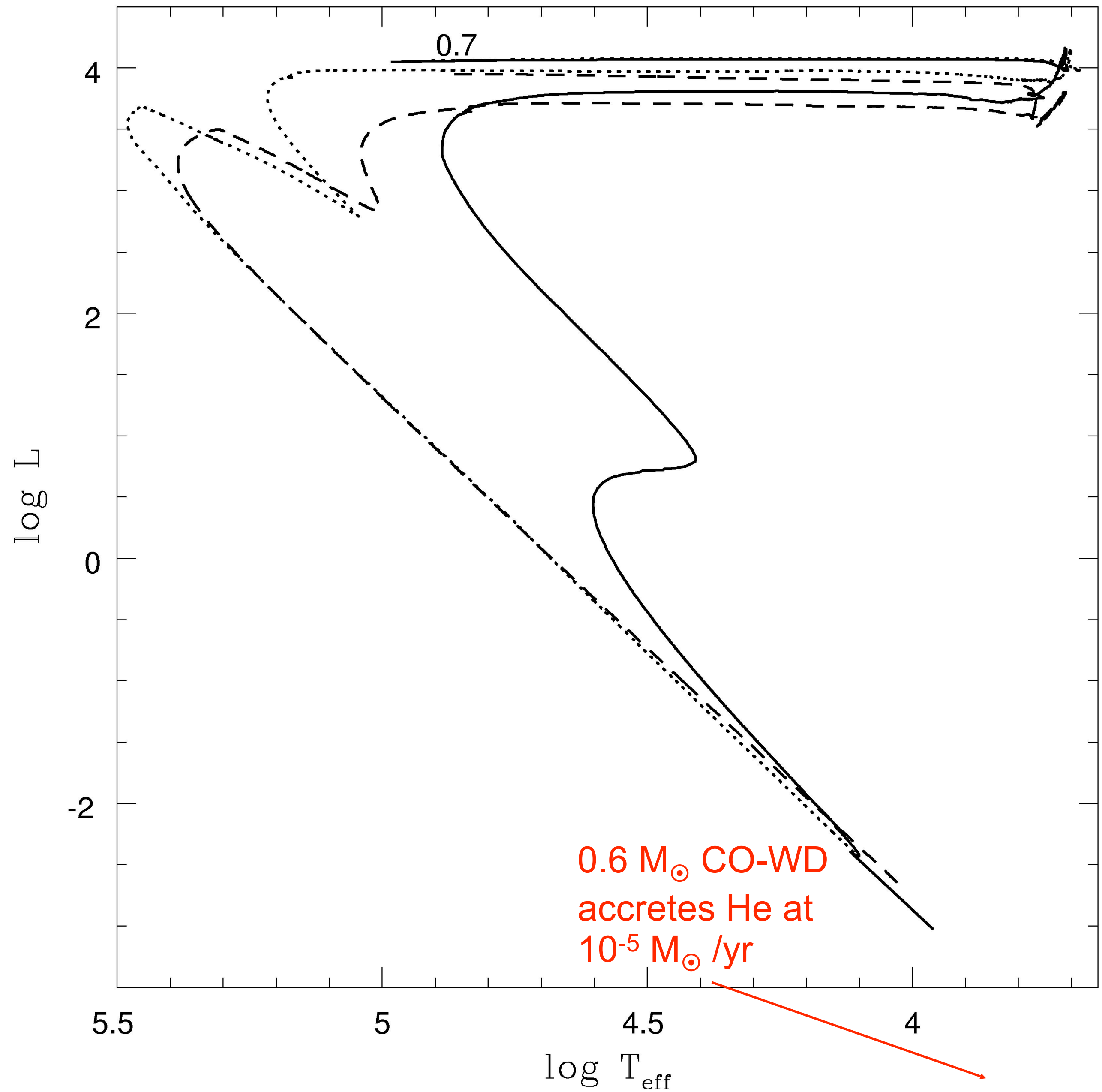


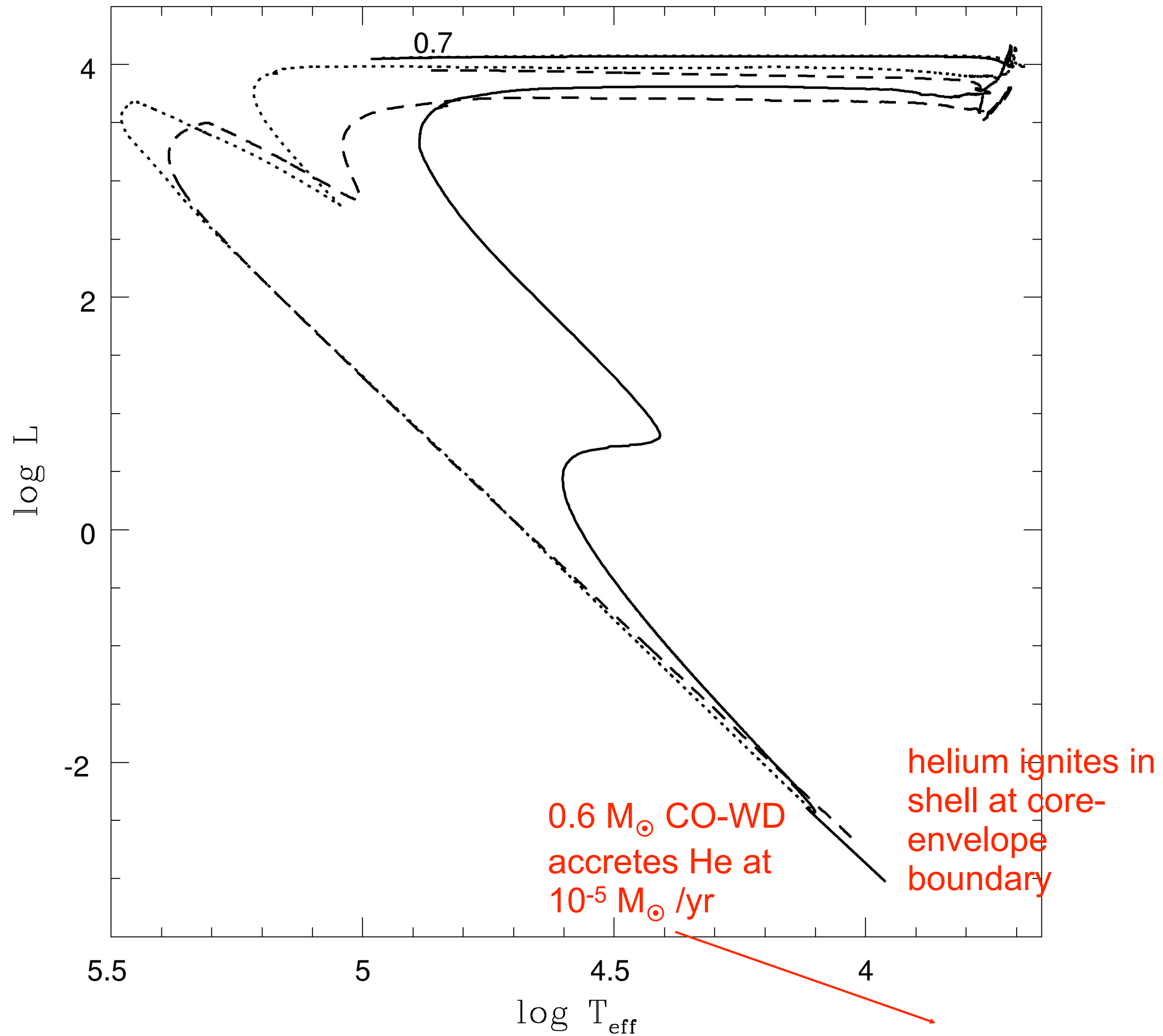
Ahmad et al. 2004, see also Justham et al. ???

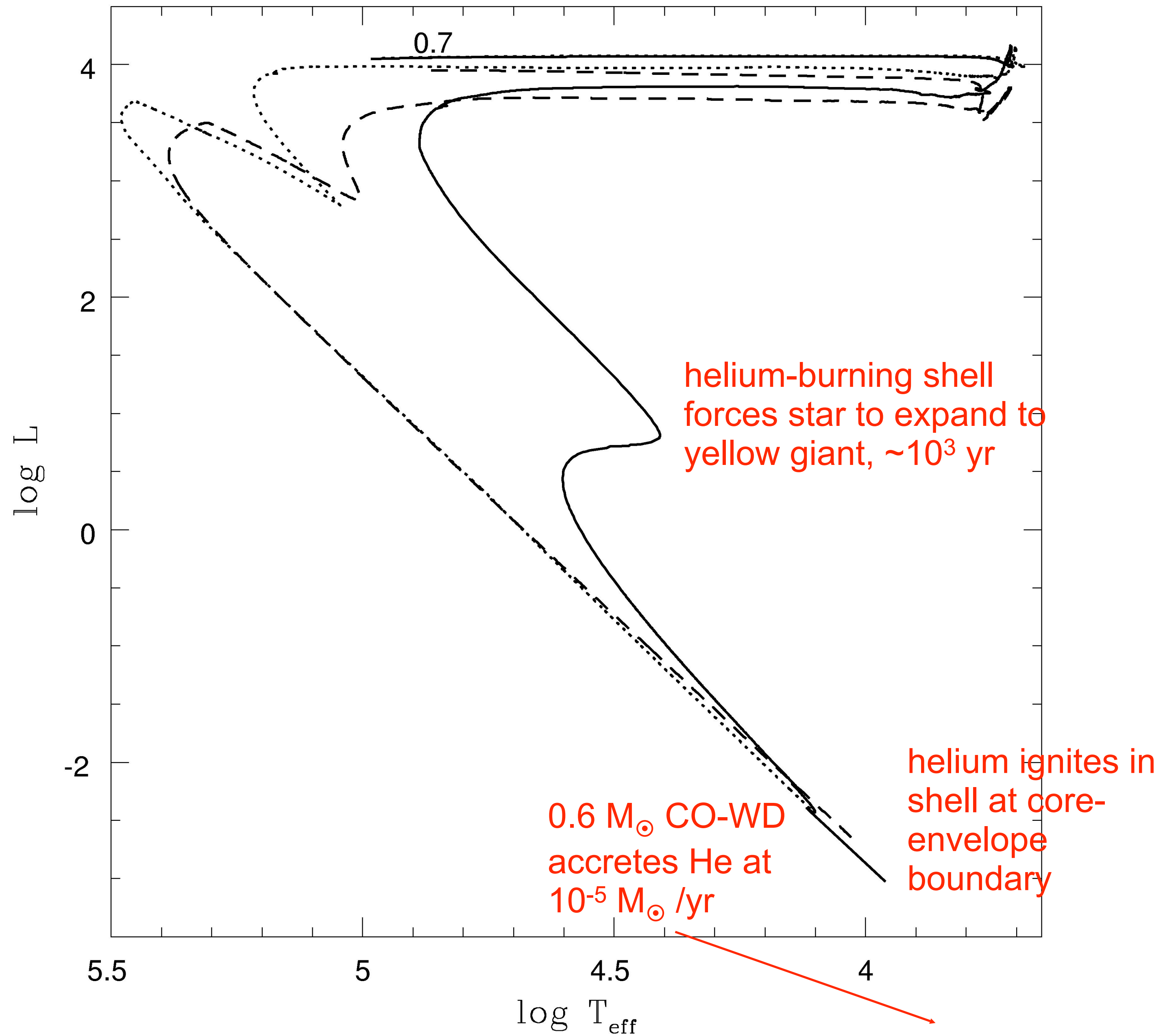
CO+He WD mergers

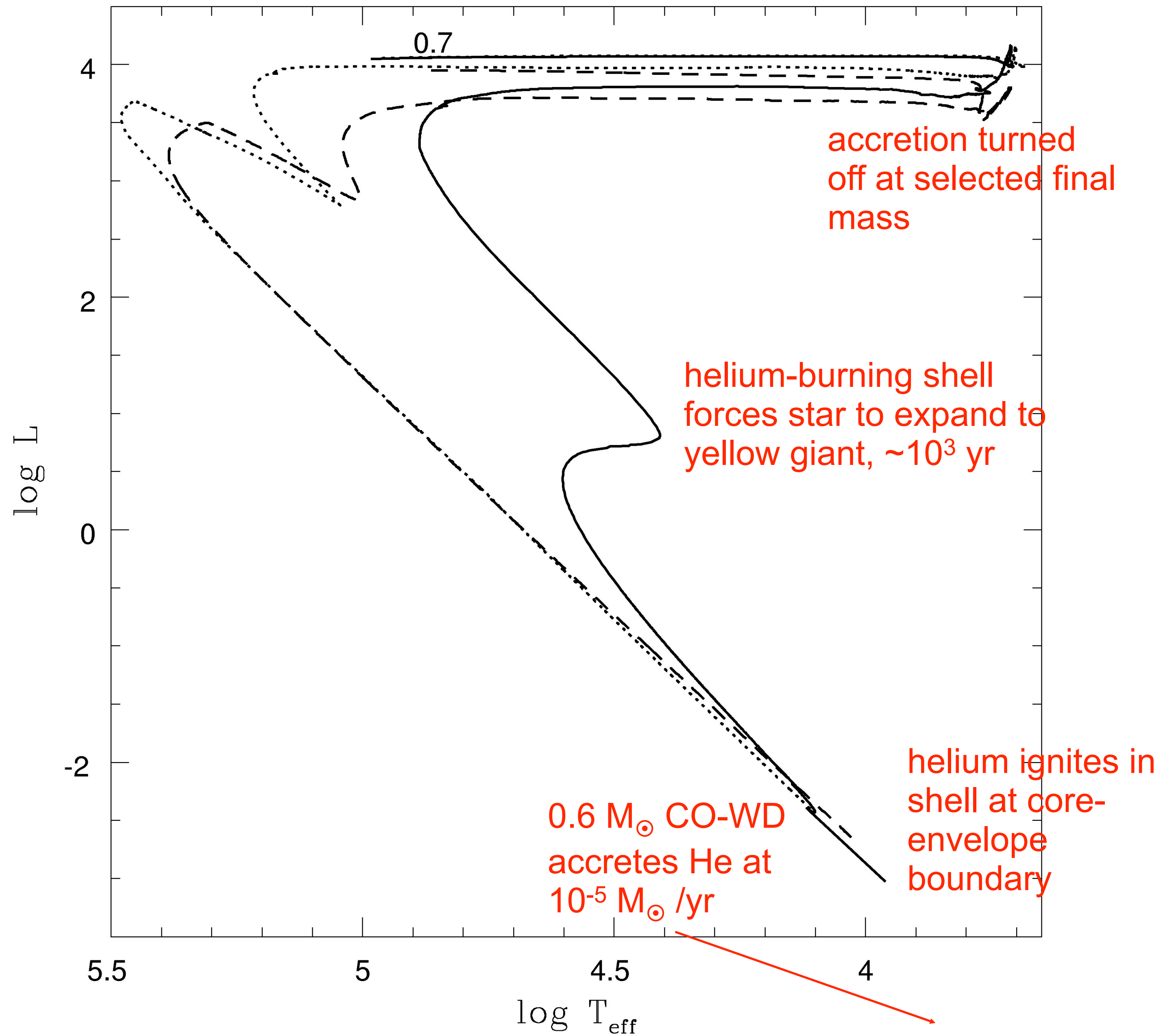


0.7
4
2
0
-2
log L
5.5
5
4.5
4
log T eff


0.7
4
2
0
-2
log L
5.5
5
4.5
4
log Teff
0.6 M⊙ CO-WD
accretes He at
10-5 M⊙ /yr


0.7
4
2
0
-2
log L
5.5
5
4.5
4
log T_eff
0.6 M⊙ CO-WD accretes He at 10-5 M⊙ /yr
helium ignites in shell at core-envelope boundary


0.7
4
2
0
-2
log L
5.5
5
4.5
4
log T_{eff}
helium-burning shell forces star to expand to yellow giant, ~10^3 yr
helium ignites in shell at core-envelope boundary
0.6 $M_\odot$ CO-WD accretes He at 10^{-5} $M_\odot$ /yr



0.7
4
2
0
-2
log L
5.5
5
4.5
4
log T_{eff}
accretion turned off at selected final mass
helium-burning shell forces star to expand to yellow giant, ~10^3 yr
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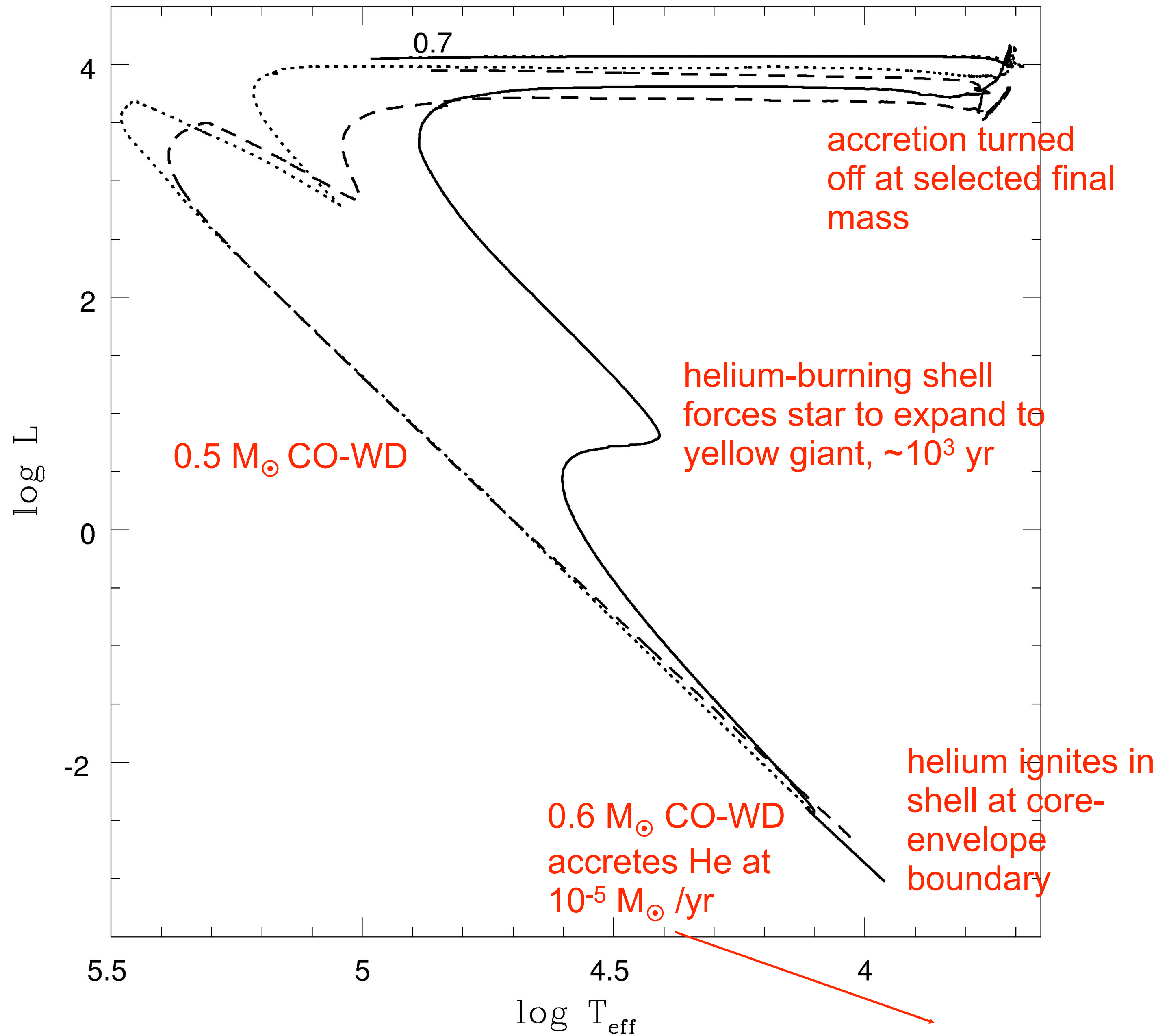
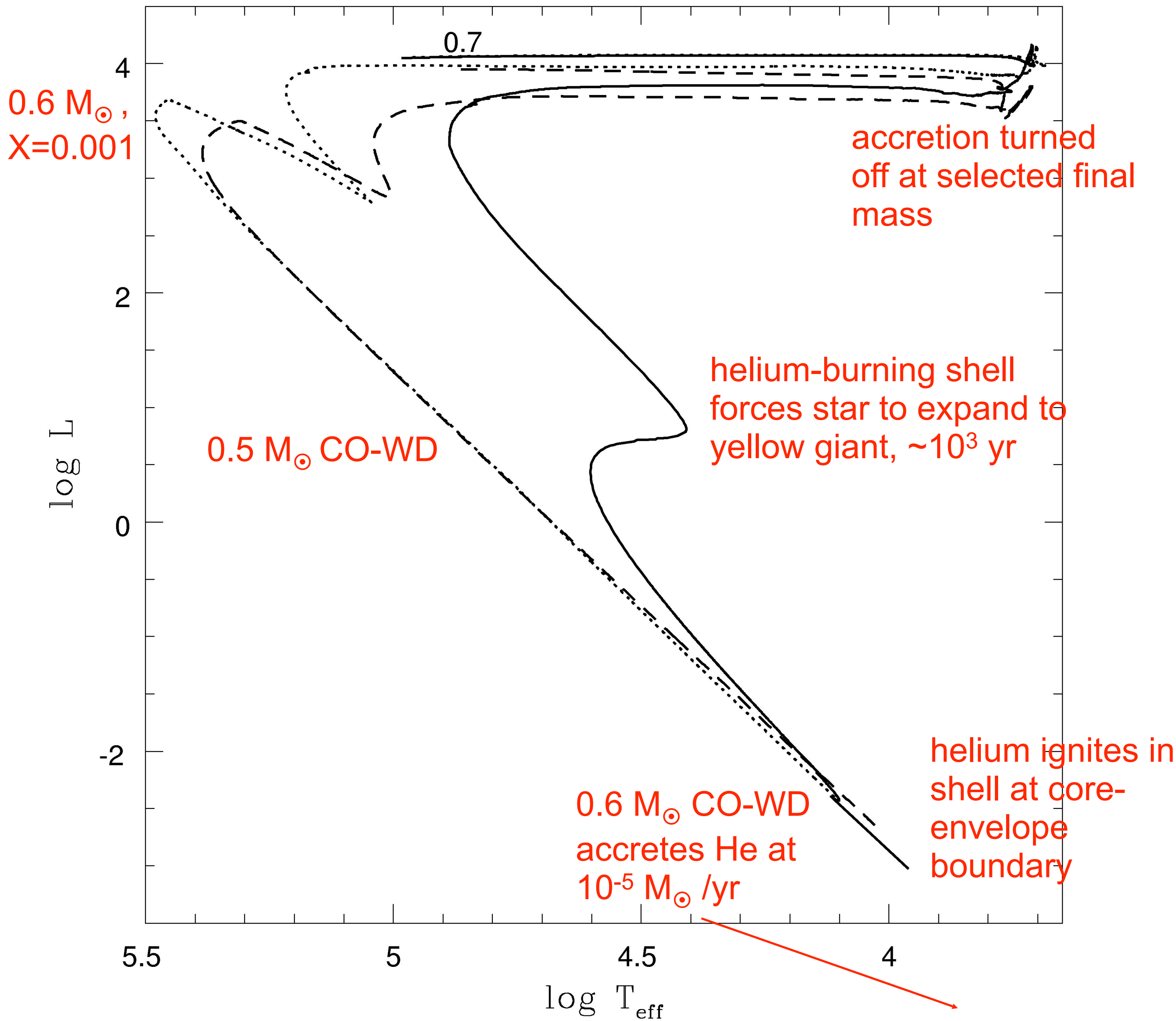
helium ignites in shell at core-envelope boundary



0.7
accretion turned off at selected final mass
helium-burning shell forces star to expand to yellow giant, ~10³ yr
0.5 M⊙ CO-WD
0.6 M⊙ CO-WD accretes He at 10⁻⁵ M⊙ /yr
helium ignites in shell at core-envelope boundary
log L
log T_eff
4
2
0
-2
5.5
5
4.5
4



0.6 M⊙ , X=0.001
0.7
accretion turned off at selected final mass
helium-burning shell forces star to expand to yellow giant, ~10³ yr
0.5 M⊙ CO-WD
0.6 M⊙ CO-WD accretes He at 10⁻⁵ M⊙ /yr
helium ignites in shell at core-envelope boundary
log L
log Teff
4
2
0
-2
5.5
5
4.5
4

CO+He merger: EHes and RCrBs

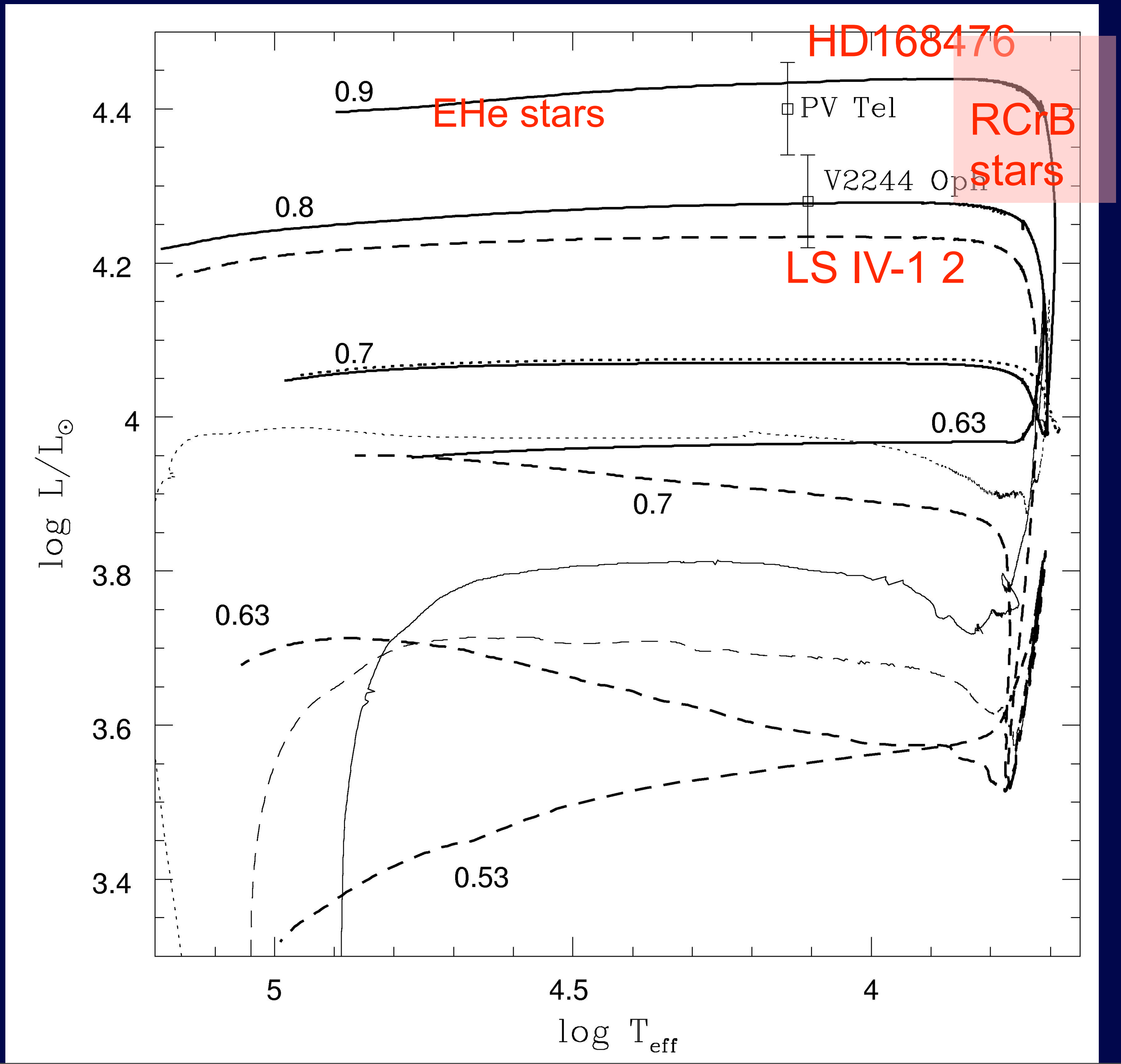
CO+He mergers

solid: $0.6M_{\odot}$CO+He
dashed: $0.5M_{\odot}$CO+He

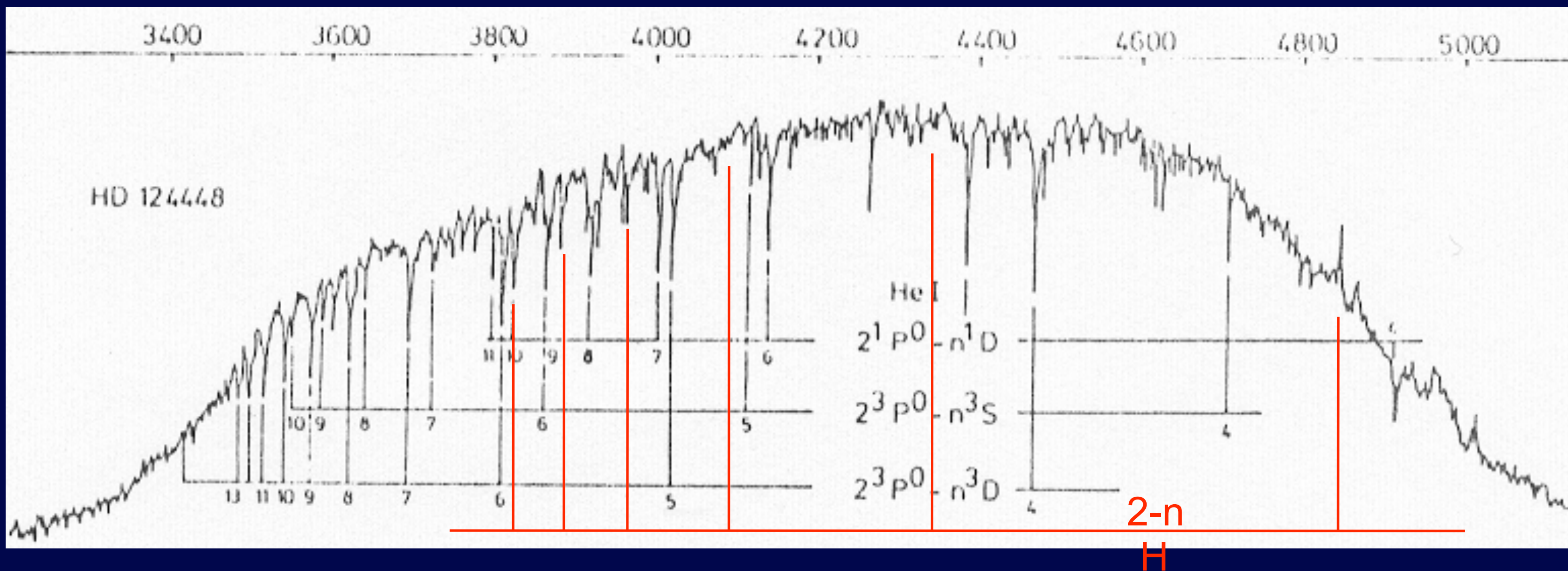
light: accretion
heavy: contraction

EHes

Baade radii from pulsating EHes



Extreme Helium Stars
R Coronae Borealis Stars
Hydrogen-Deficient Carbon Giants



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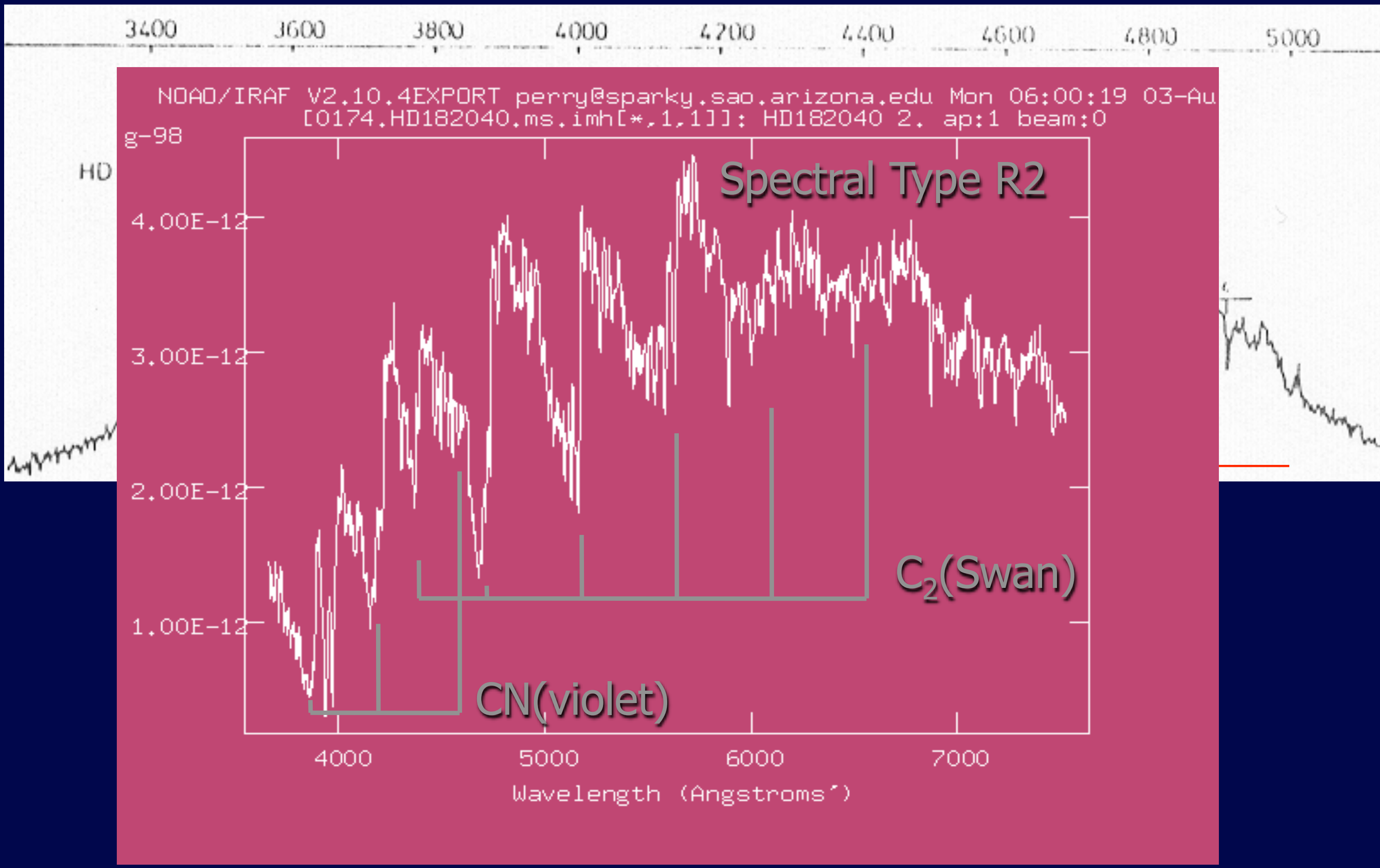


The RCrB – EHe – O(He) – WD sequence

- RCrB / HdC
- EHe
- HesdO+
- O(He)

Surface abundances:

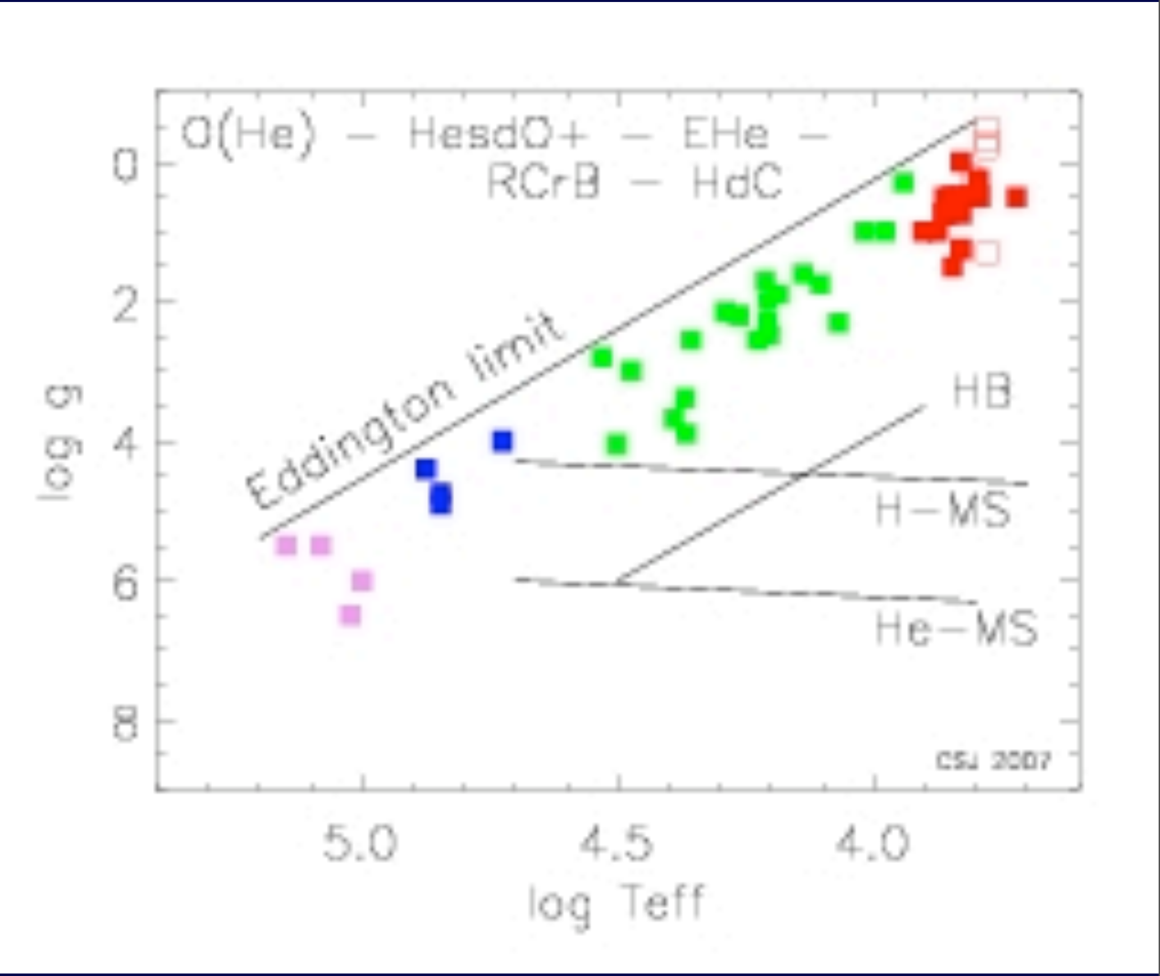
H < 1:10^5

N (from CNO cycle)

C (from 3α process)

O (α-capture on ^{12}C)

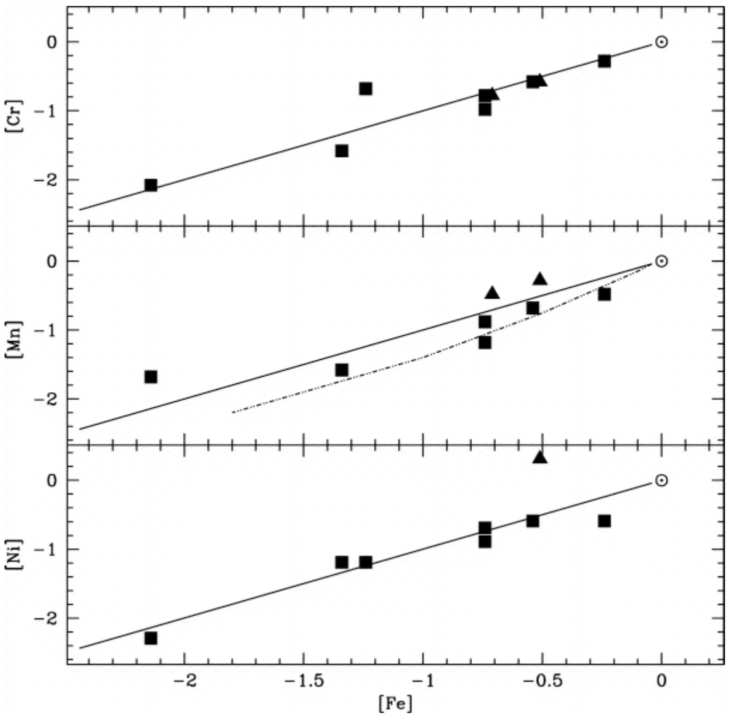
Ne (2α-capture on ^{14}N)

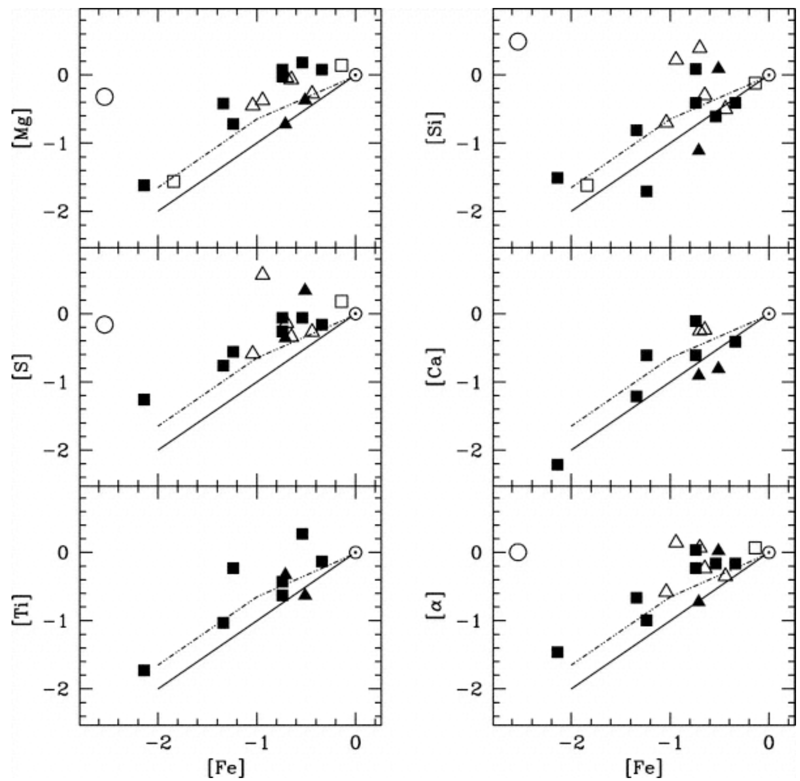


Photospheric Abundances

a) Proxies for metallicity (Ni,Mn,Cr,Fe) ⇒ -2 < [Fe/H] < 0

b) Overabundant light elements (Mg,Si,S,…) ??





Pandey, Lambert, Jeffery & Rao 2006, ApJ 638, 454

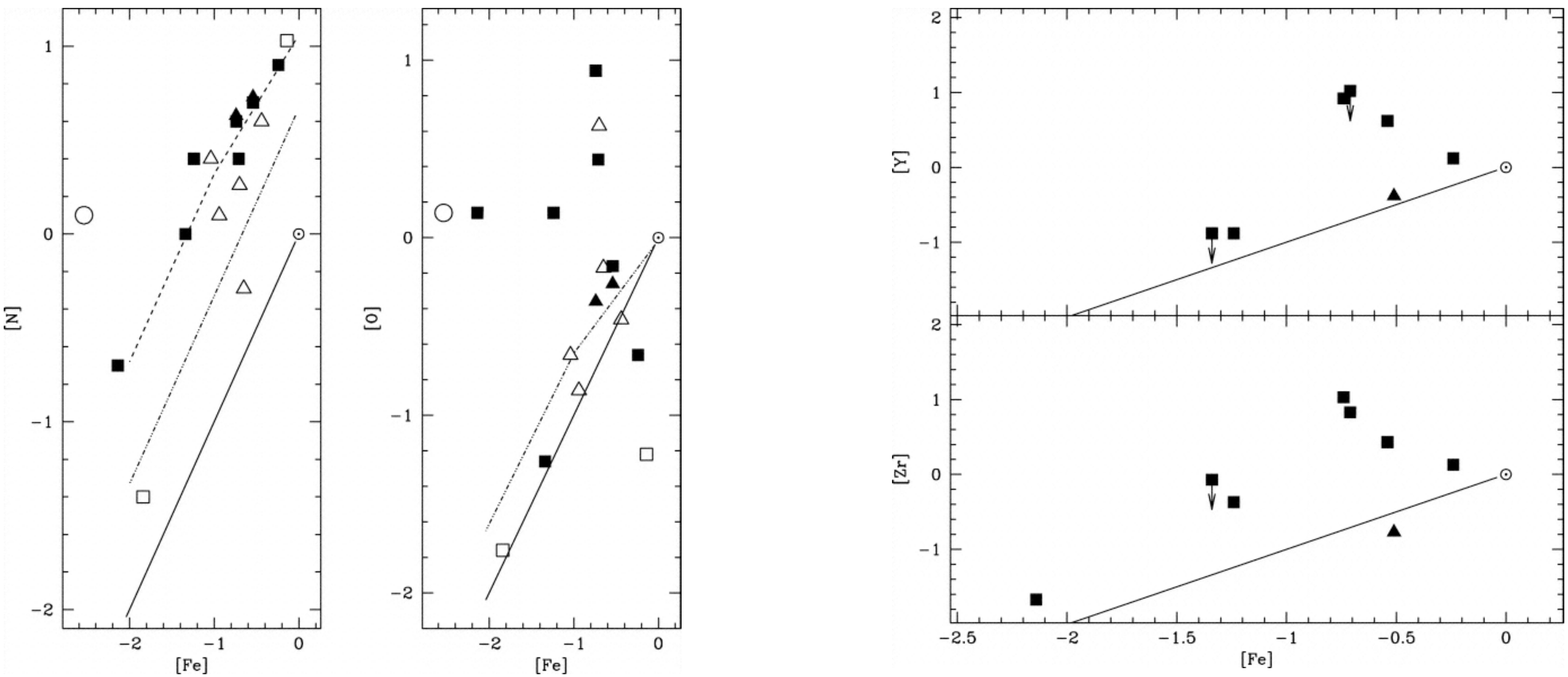
Photospheric Abundances

c) [N/Fe] ∝ [(C+N+O)/Fe] OK

d) [O/Fe] >> 0 ??

e) [s/Fe] >> 0 AGB intershell ??

f) [Ne/Fe] >> 0 ??



Pandey, Lambert, Jeffery & Rao 2006, ApJ 638, 454

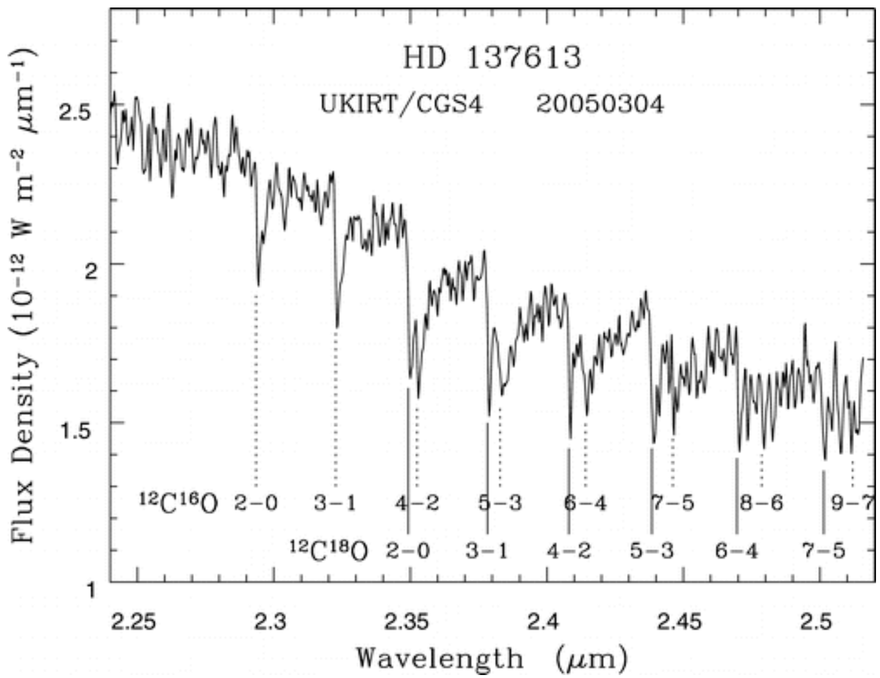
Photospheric Abundances

g) F ?? Pandey (2007)

h) Li ??

i) ^{18}O >> ^{16}O α-capture on N^{14} : but when? Clayton et al. (2007)

j) ^{12}C >> ^{13}C substantial 3α processing



Clayton et al. 2007

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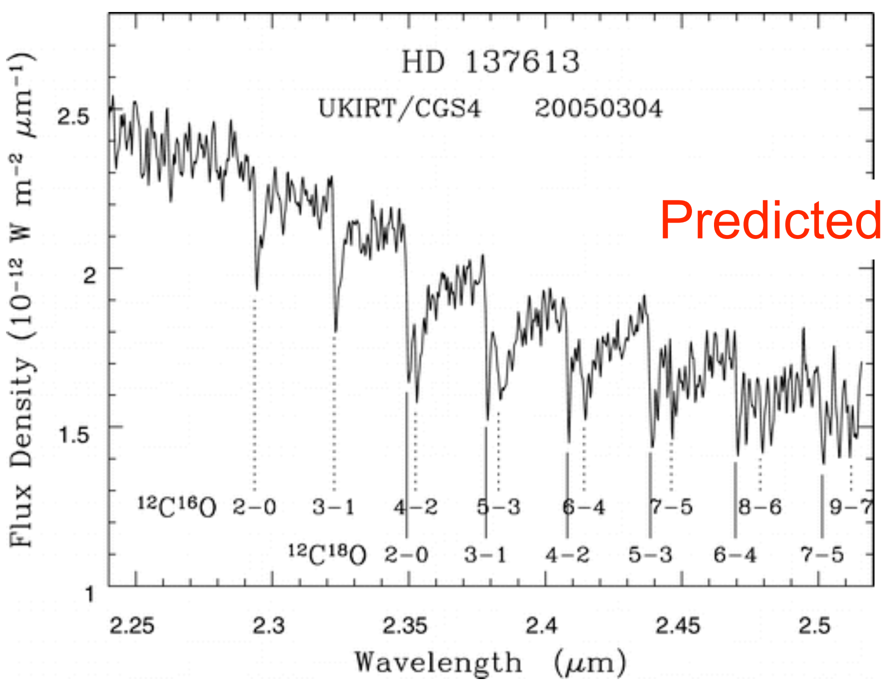


Predicted by Brian Warner in 1967 !!

Clayton et al. 2007

The merger process

Angular momentum

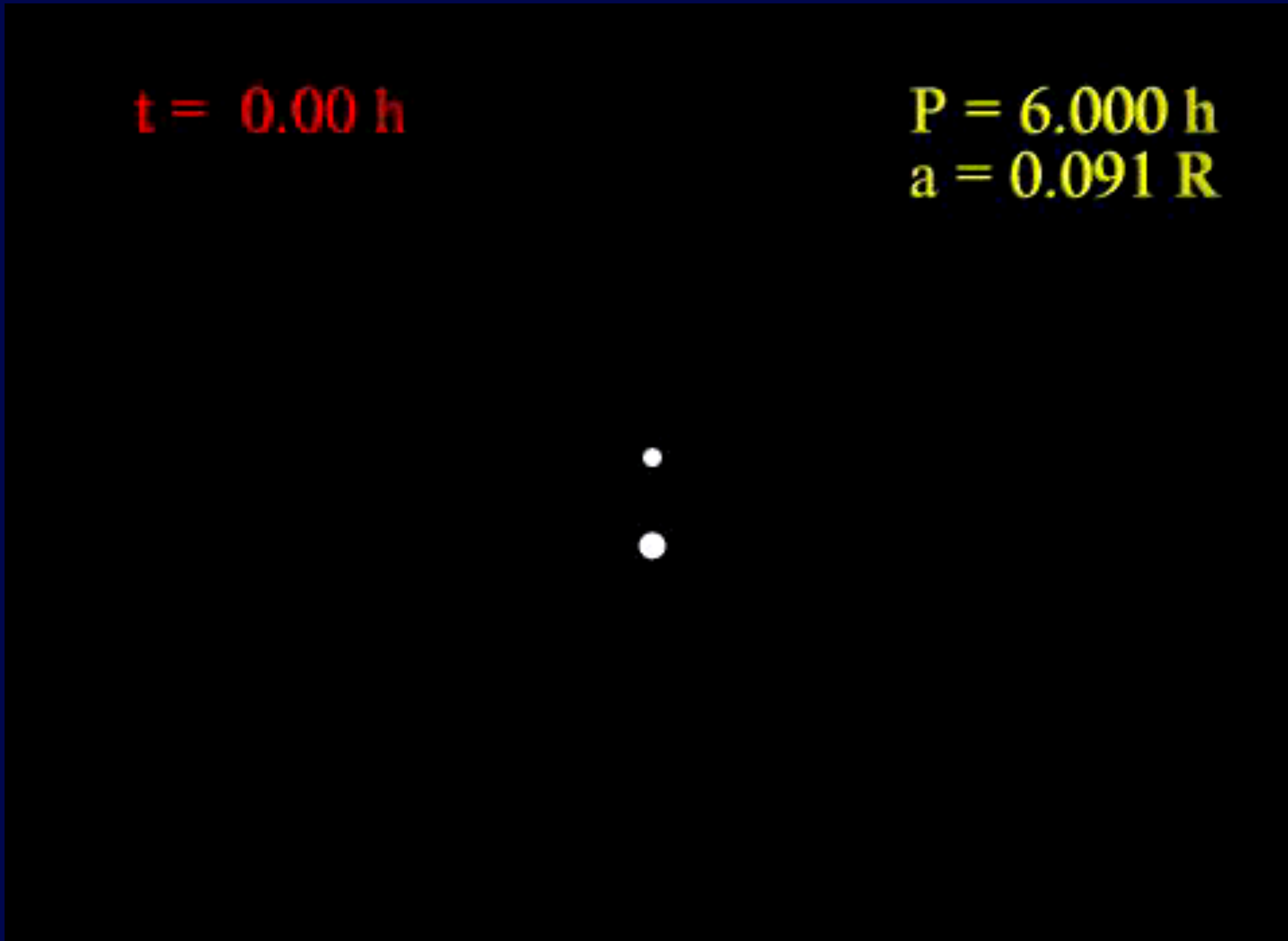
Disk / Envelope / Core

Hydrodynamics

Nucleosynthesis

What actually happens in a WD merger?

What actually happens in a WD merger?

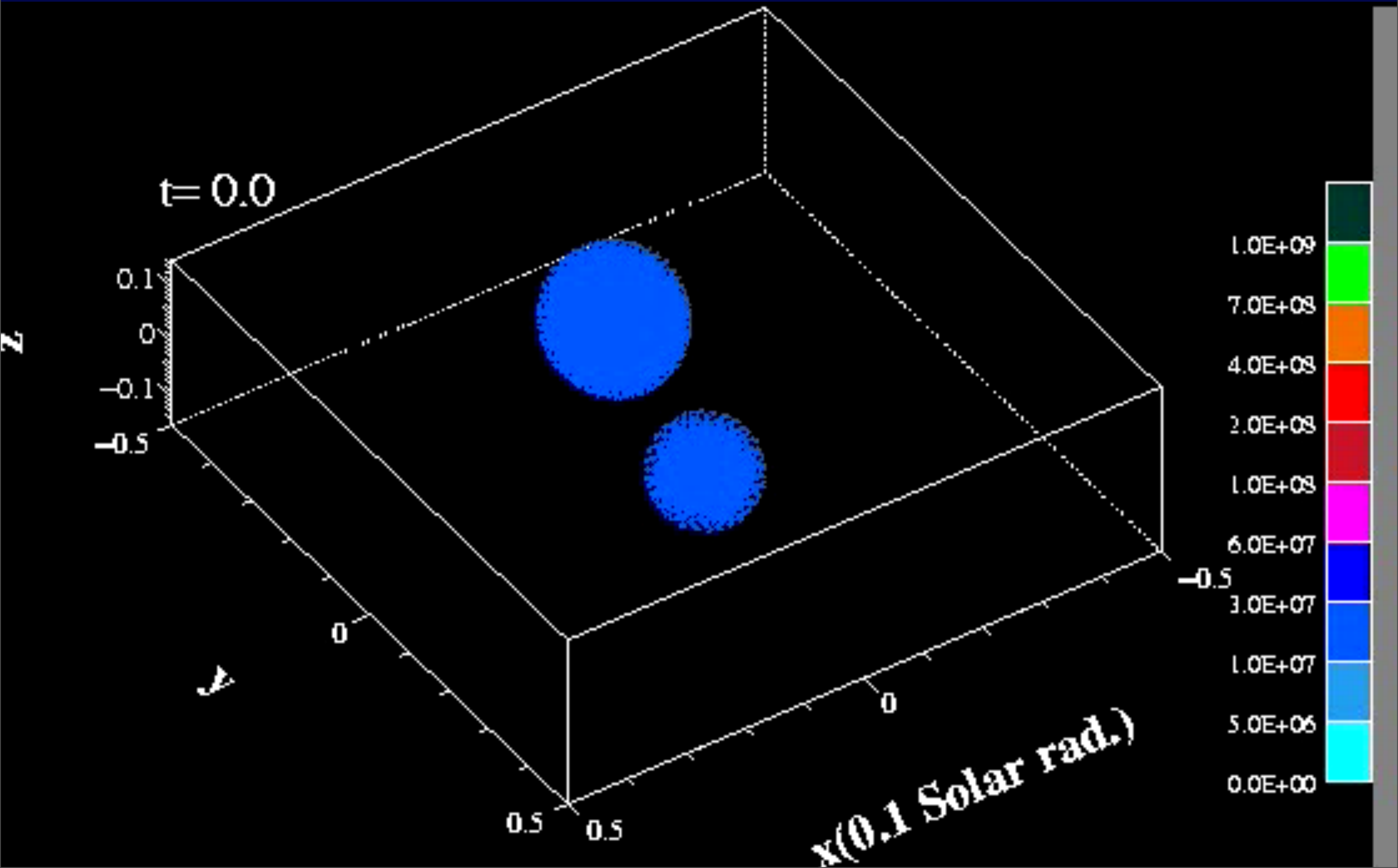


SPH Simulations: 0.8+0.6 T

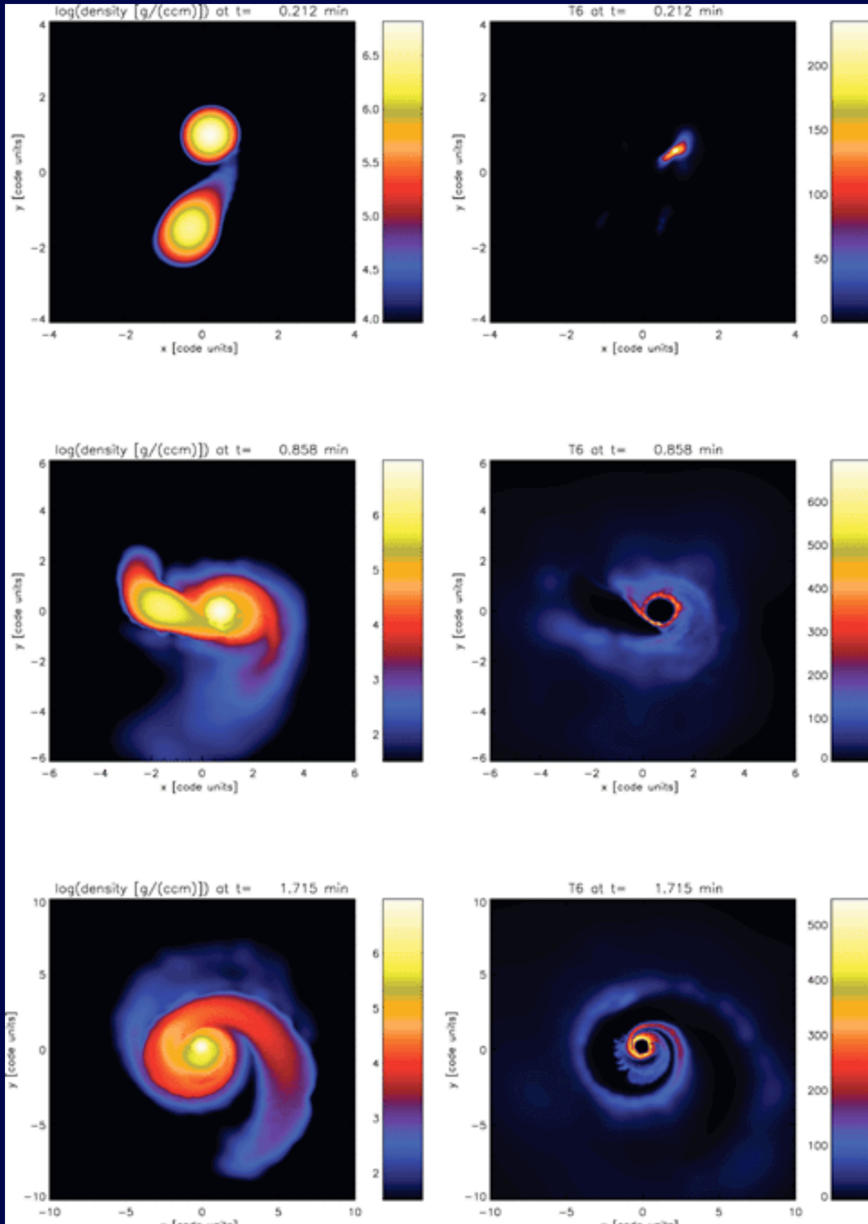
Isern & Guerrero 2002, WD13 Naples

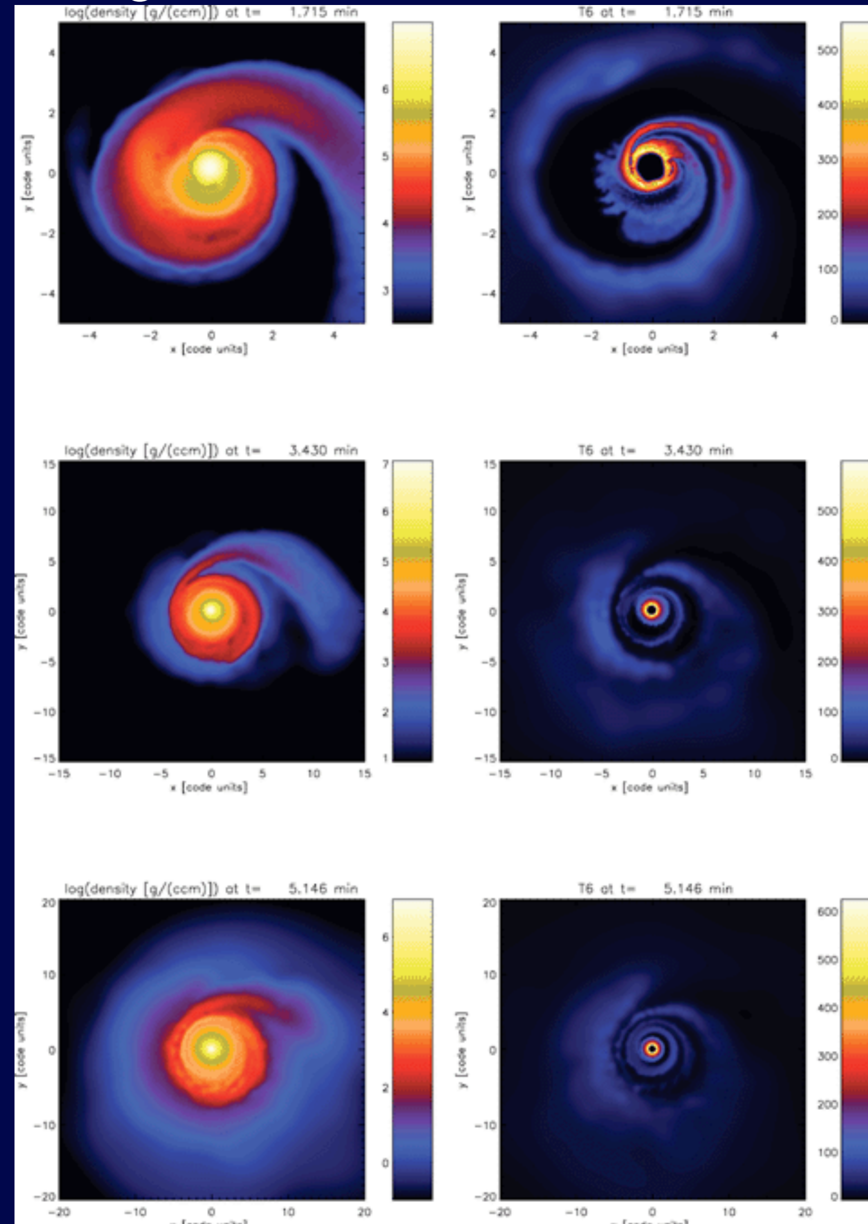
SPH Simulations: 0.8+0.6 T

Isern & Guerrero 2002, WD13 Naples

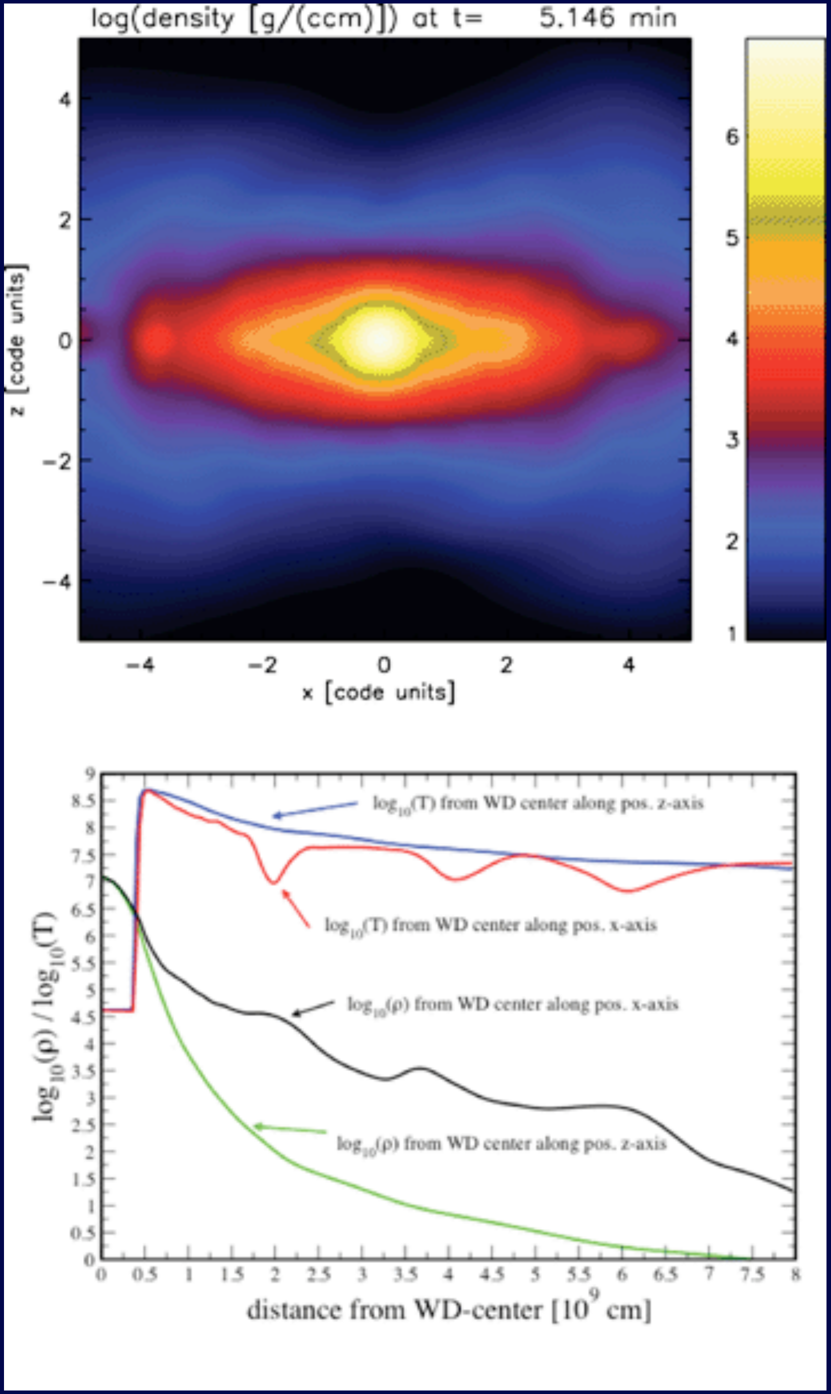


evolution of a 0.9+0.6 $M_\odot$ CO WD

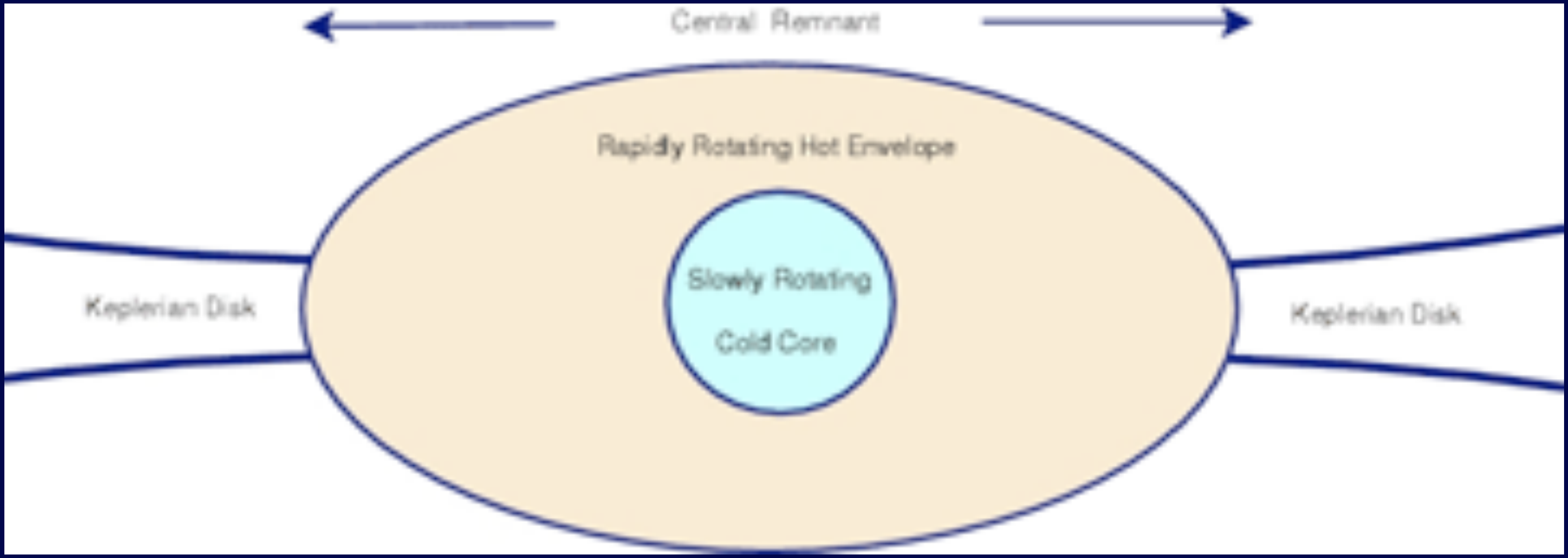




Yoon et al. 2007, Also Benz et al. 1990ab, Segretain et al. 1997



Yoon et al. 2007



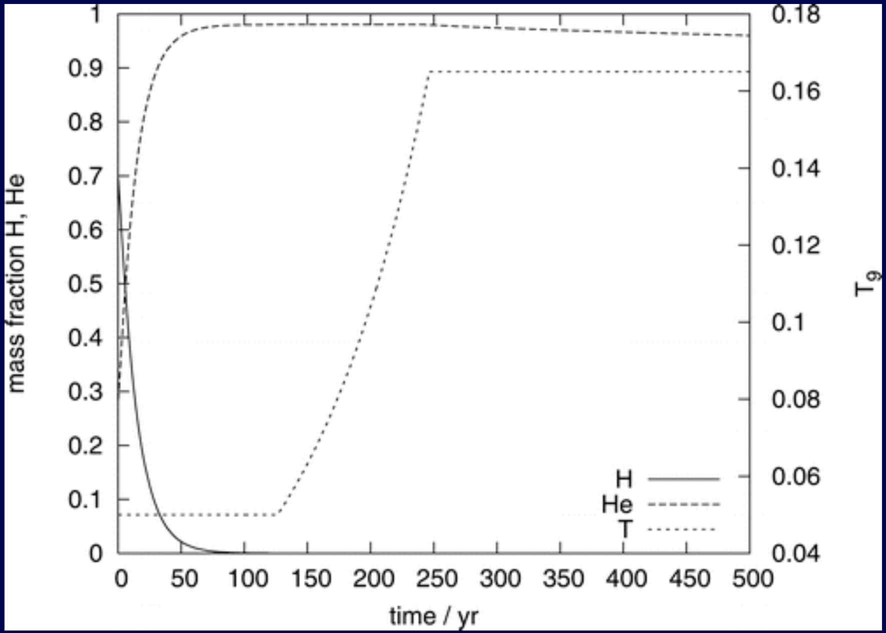
Yoon et al. 2007:

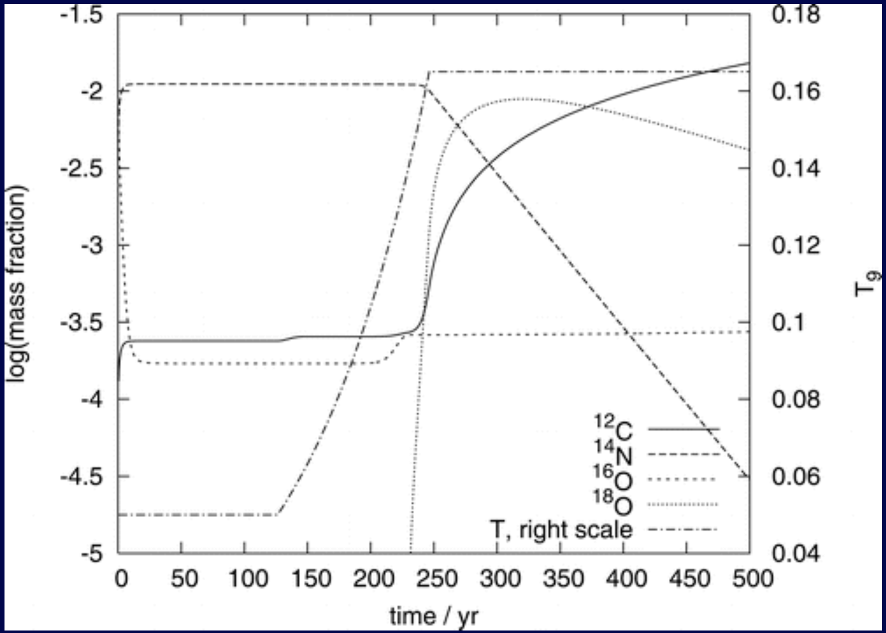
Clayton et al. 2007: evolution of a CO+He WD merger

Considered a one-zone high-entropy envelope, for two cases (M_{He} = 0.2 and 0.4 $M_\odot$).

Computed temperature, density from 1d hydrodynamic evolution, including nucleosynthesis.

Found dramatic production of ^{18}O.





Phases in a DD merger

- Tidal disruption
- "Disk" formation
- Prompt nucleosynthesis in disk?
- Angular momentum dissipation
- High-entropy envelope forms
- Envelope "accreted" onto primary: $dM_{env}/dt < dM_{edd}/dt$
- Helium (carbon) – burning starts
- Star expands, but high-S envelope remains
- Outer layers convective
- Accretion continues to completion

Lies, Damned Lies, and ….

Lies, Damned Lies, and …. Statistics

!! Warning !!

The statistics are due to Gijs Nelemans

The lies are entirely my own

All are still under discussion

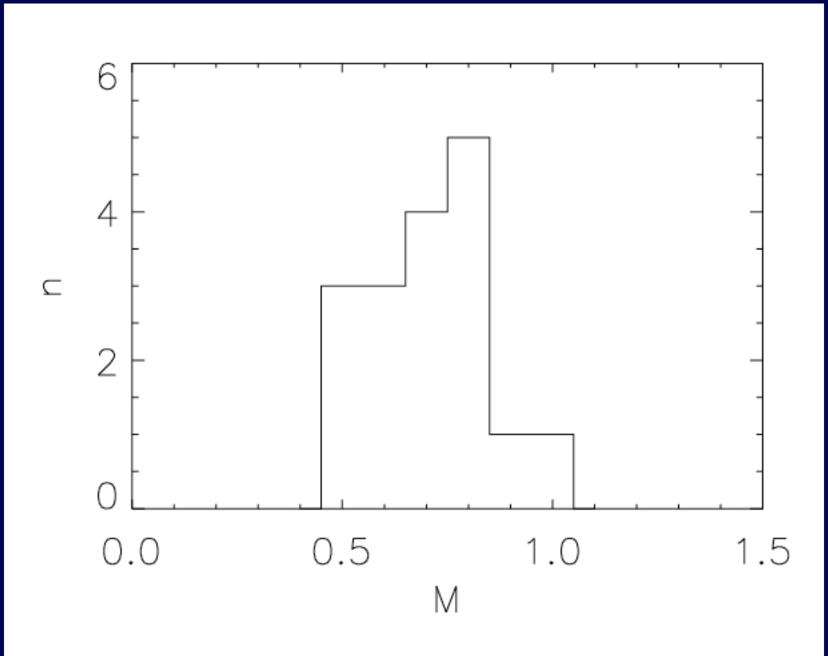
CO+He mergers: number densities

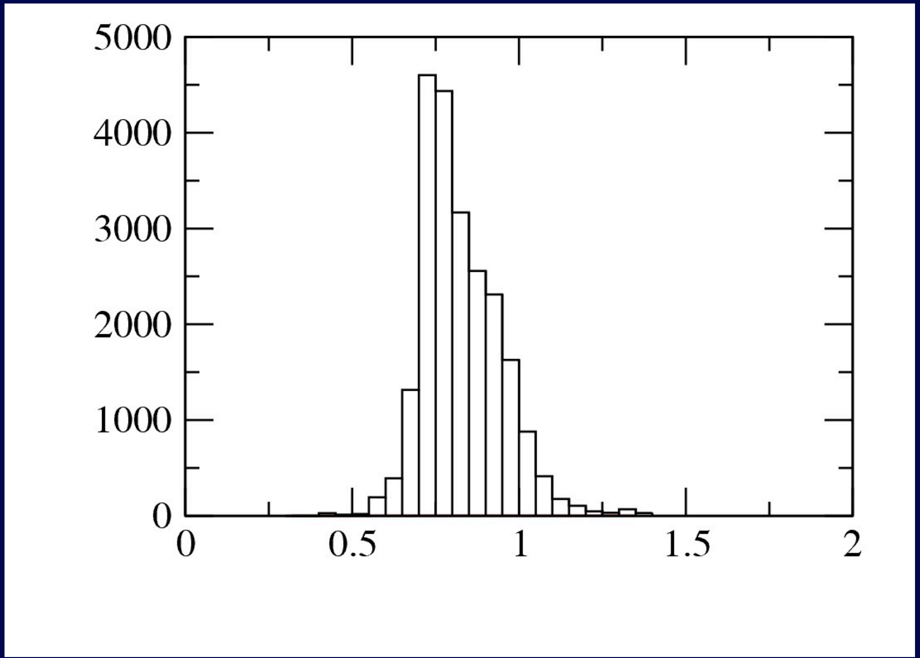
- 20% of all WD pairs include CO+He WD (Neleman's et al 2001)
- CO+He WD merger rate: $\nu \sim 4.4\ 10^{-3}\ \mathrm{yr}^{-1}$ (Neleman's et al. 2001) (Iben et al. give $2.3\ 10^{-3}\ \mathrm{yr}^{-1}$)
- Heating rates between 10 000 and 40 000 K are 10 - 100 K yr^{-1}, or evolution timescales: $\tau \sim 300 - 3000$ yr
- Merger rate × timescales gives number of EHes (N) in Galaxy between 1.3 and 13
- There are 17 known EHes in this temperature range
- Stars cooler than 10 000 K have $\tau \sim 10^5$ yr,

$\Rightarrow N = \nu\,\tau \sim 30 - 300$ cool CO+He merger products

- There are an estimated 200-1000 RCrBs in galaxy (Lawson et al. 1990), although only 33 are known (Alcock et al. estimate 3000 RCrBs)

Observed mass distribution Predicted



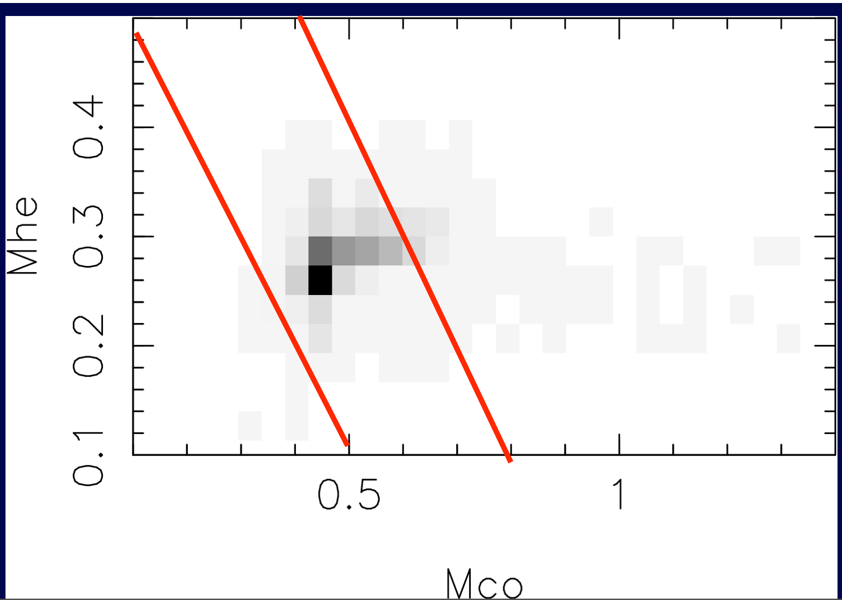


Mass distributions look OK

Galactic distribution ??

Observed – bulge and thick disk

Predicted – thin disk



Conclusions

- A significant number of DDs merge (a few/galaxy/century)
- He+He WDs $\Rightarrow$ EHe – sdO / sdB sequence
- CO+He WDs $\Rightarrow$ RCrB – EHe – O(He) – WD sequence

- Physics of merger is really really interesting
  – surface abundances require hot mergers

- Predicted birth-rates and mass-distribution compatible with observed numbers

Questions:

- Can observed merger products account for all DDs formed ?
- Are any DDs left over to become stellar AM CVne ?
- What happens to AM CVne when they ignite helium ?