White-Dwarf-Merger Outcomes

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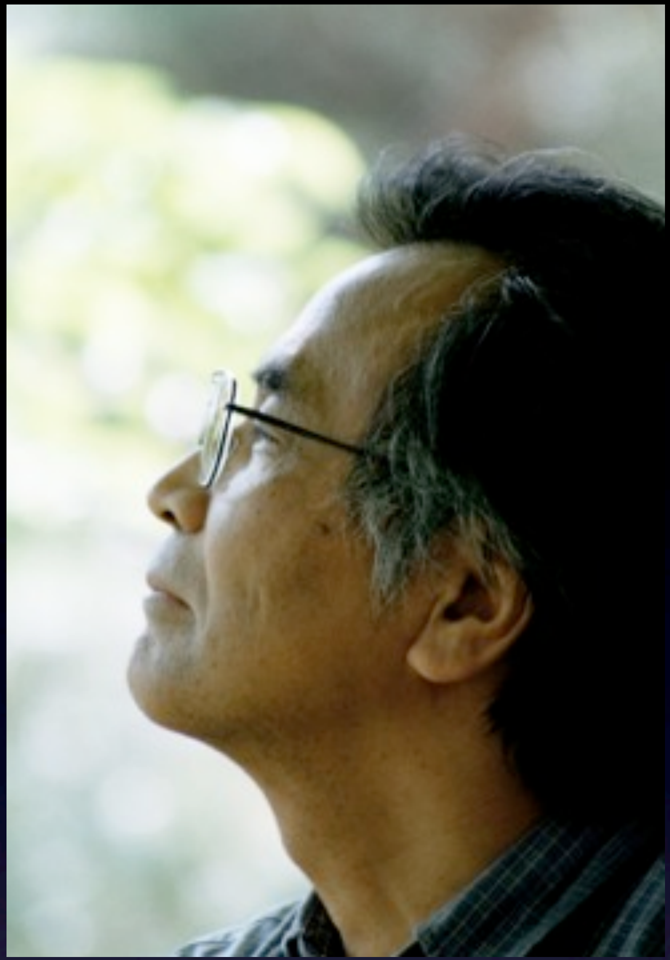


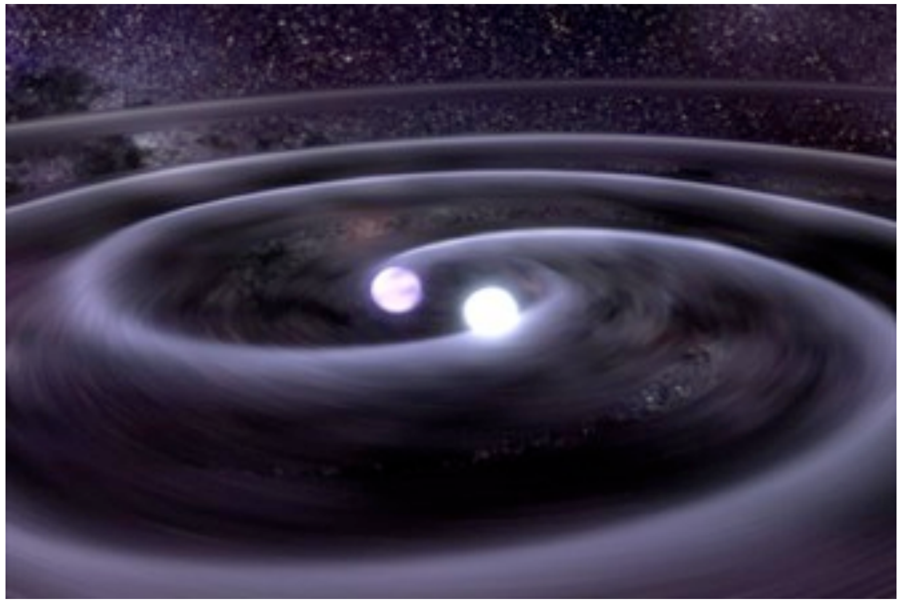
Double-White-Dwarf Mergers and Connections Between Extreme Helium Stars, R CrB stars, Hot Subdwarfs, and, Possibly, Type Ia Supernovae

mostly with Karakas, Zhang, Yu and Saio

Outline

- Double-White-Dwarf Binaries
- Double-White-Dwarf Mergers
- Hydrogen-Deficient Stars
- CO+He mergers
- He+He Mergers [Xianfei Zhang]
- Some Statistics
- Other DD Merger outcomes

Double White Dwarf Binaries



- Binary star evolution produces DWDs
- Gravitational-wave radiation implies orbit shrinks

- What happens next?
  - i) violent interaction
  - ii) stable interaction
- Keys:
  - stability, efficiency, progenitors

- Can we identify the products?

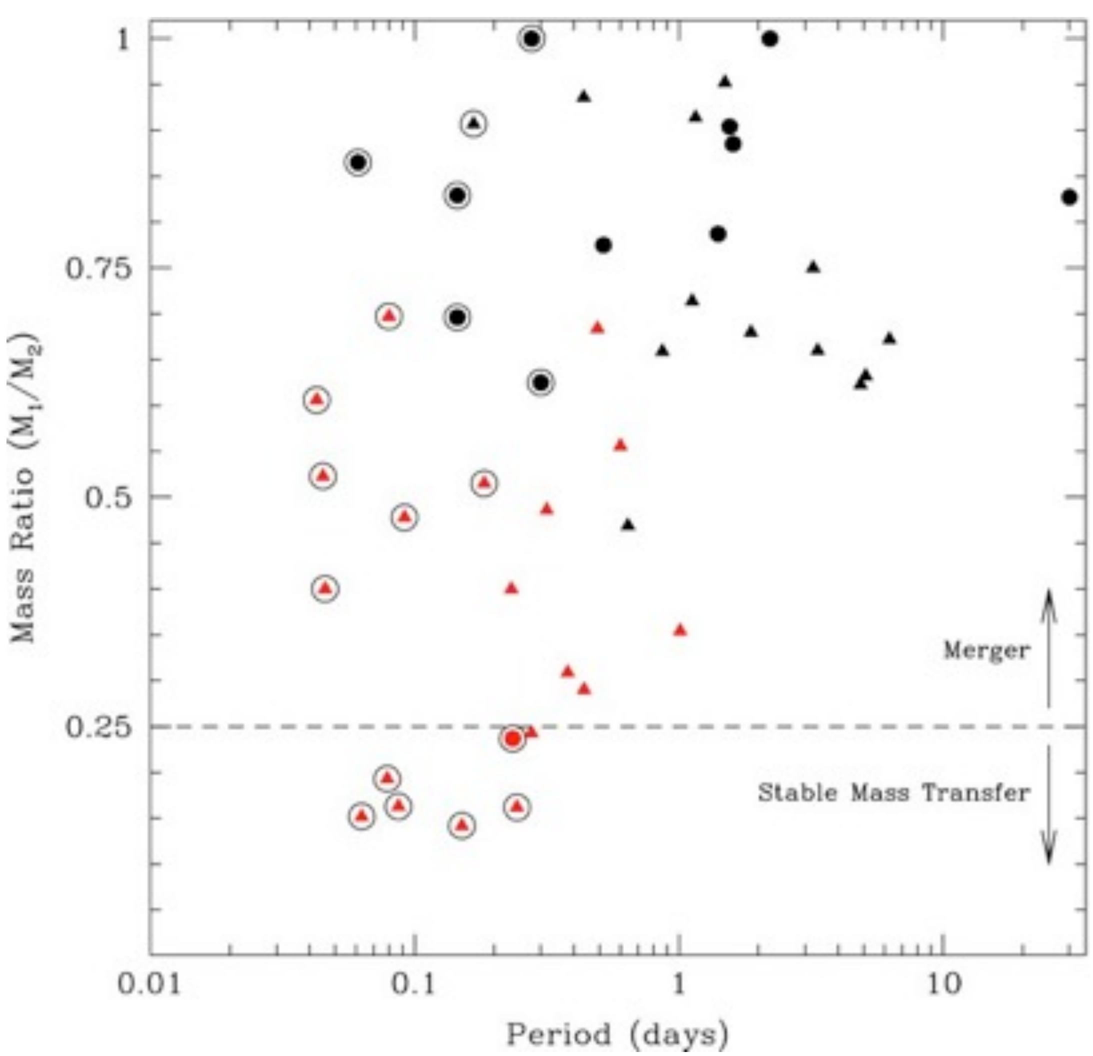
Low-mass DWDs

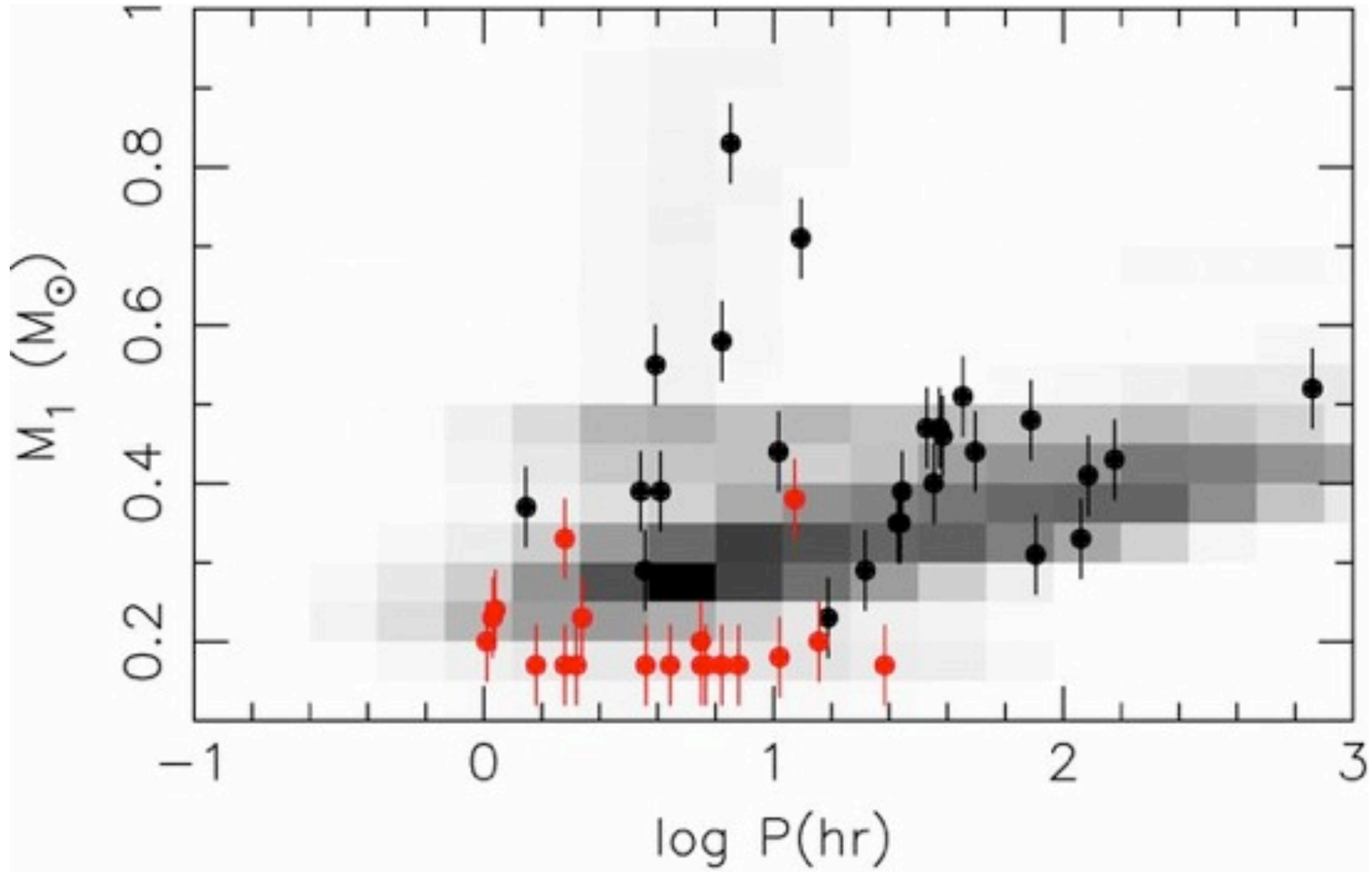
Many new DWD binaries found (Kilic et al. 2011, Marsh et al. , Brown et al., ...).

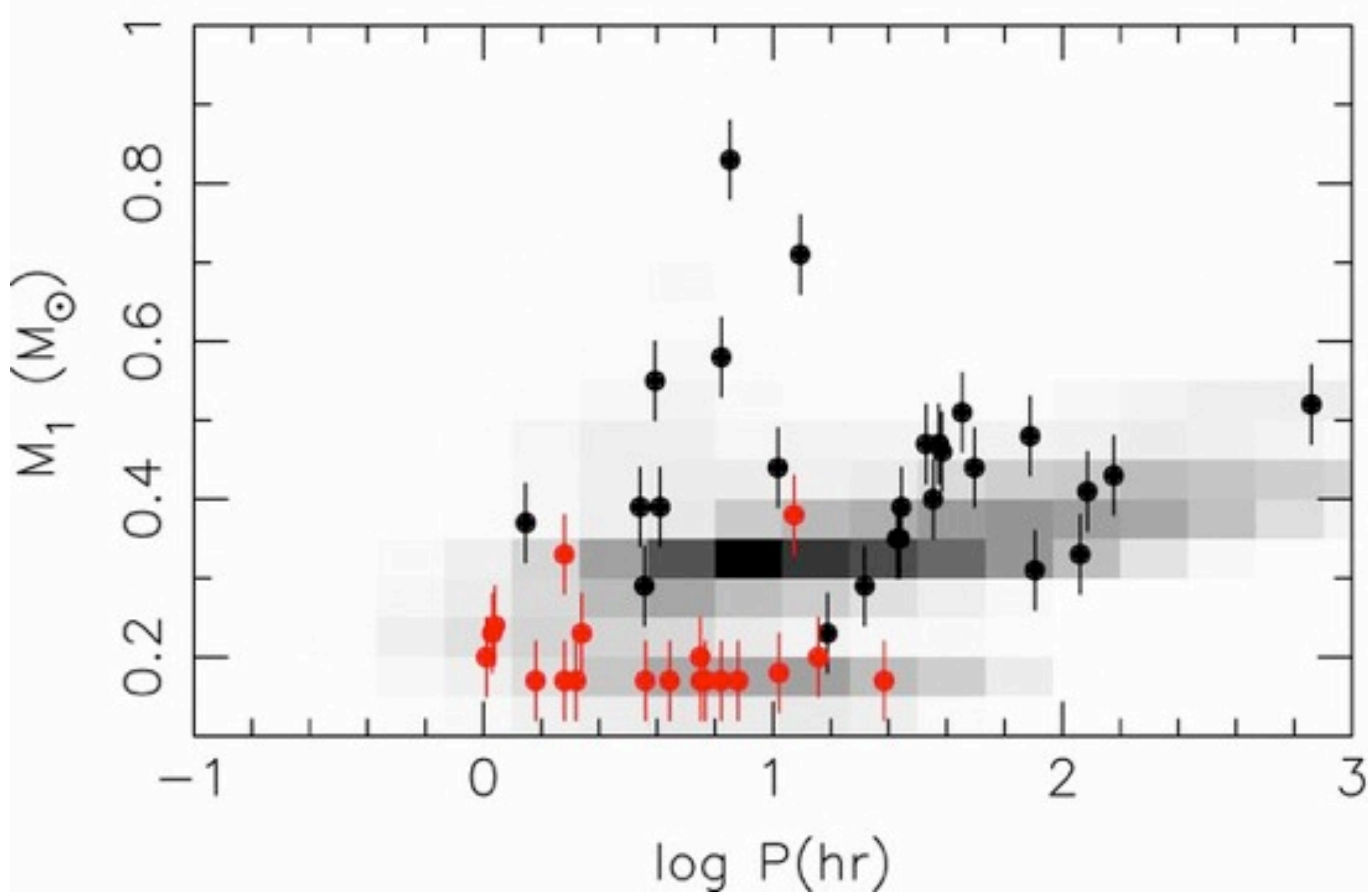
Discrepancies about stability.

Predicted mass-period distribution sensitive to physics (eg WD cooling).

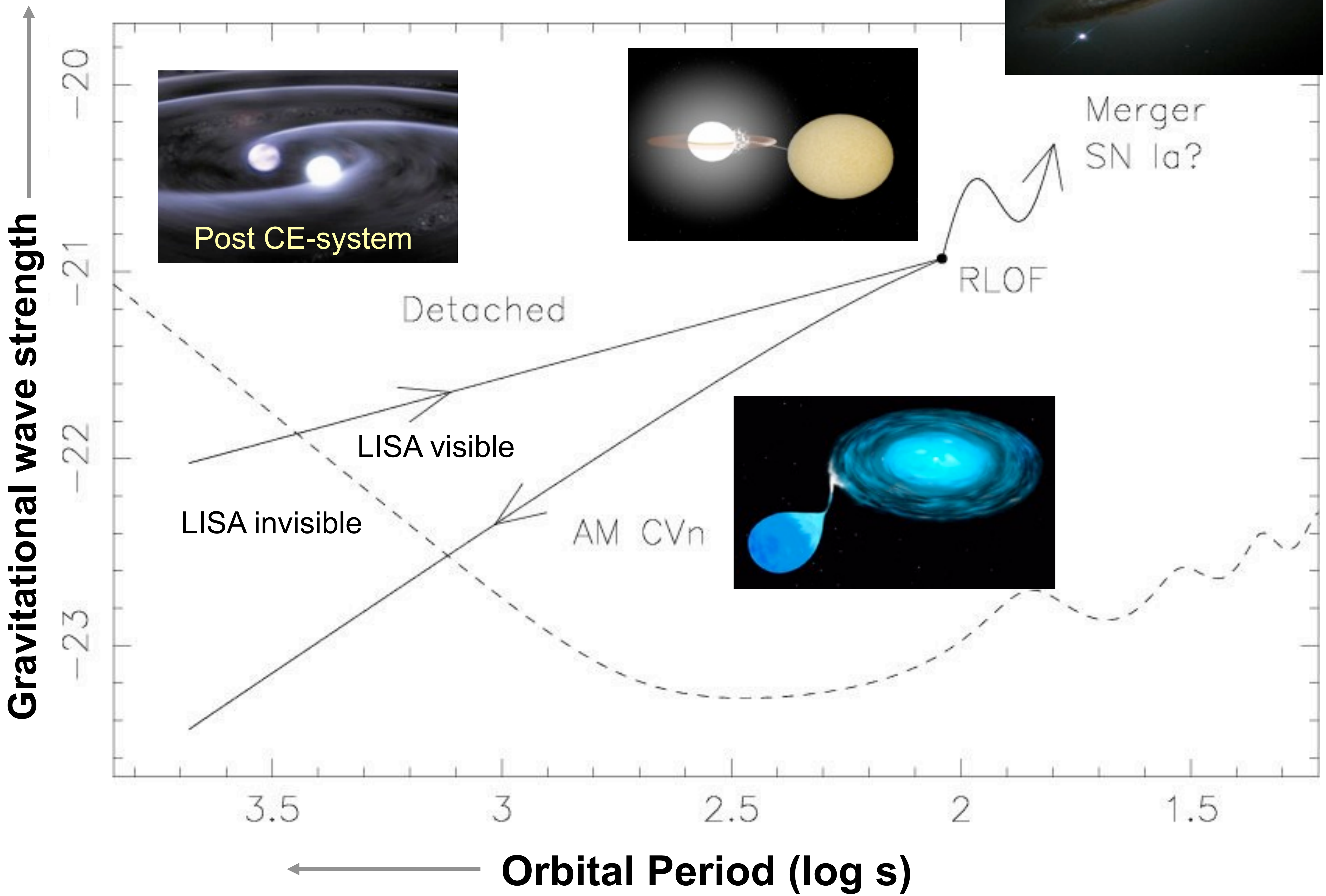
All agree many short-period systems will merge. What happens next?



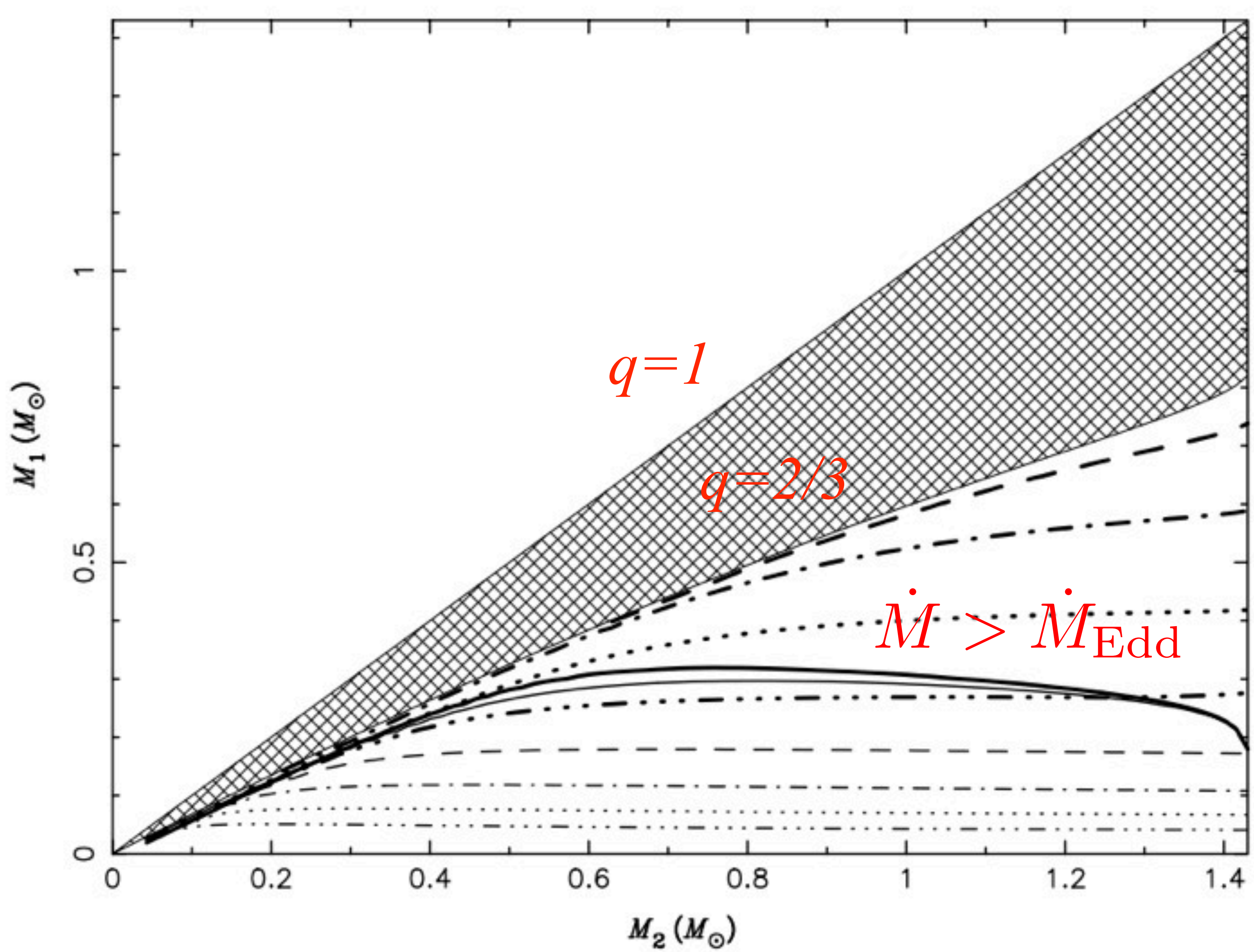




Gravitational wave evolution



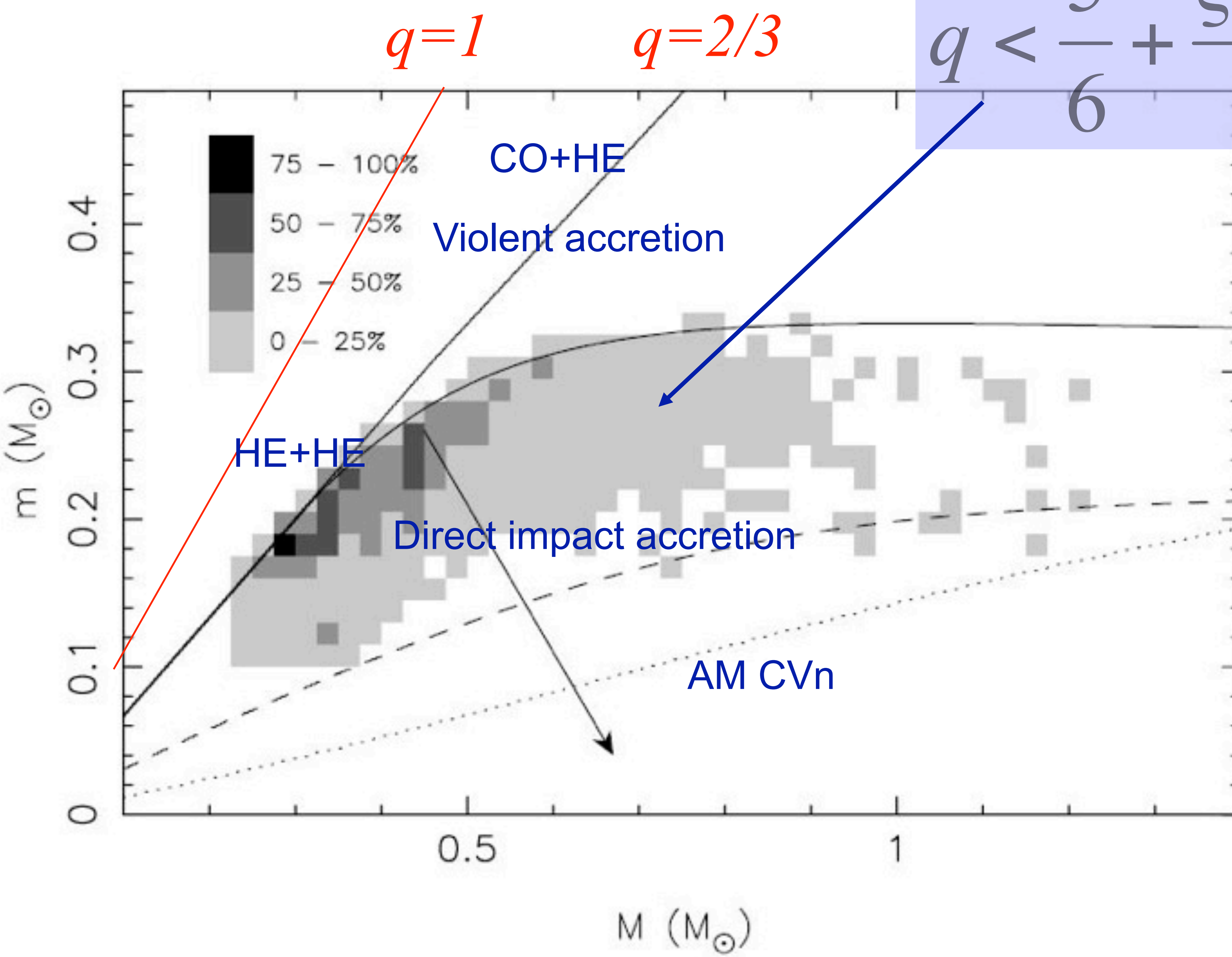
Reflections on stability - Mdot



Han & Webbink 1999

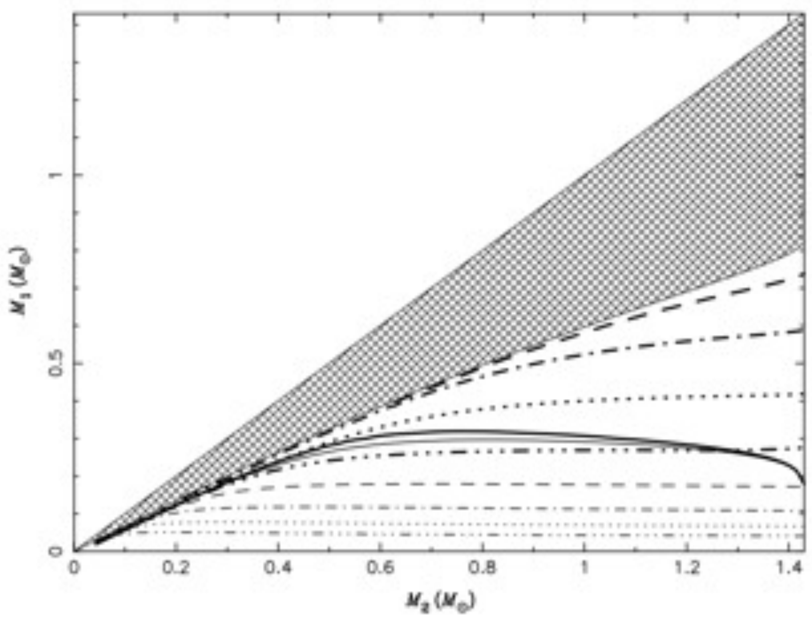
Reflections on stability: progenitor stats

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



Nelemans 2001

Reflections on stability: pyrotechnics



What happens when accretion rates

< “violent” ?

Piersanti et al. 2011, IAU Symp 281

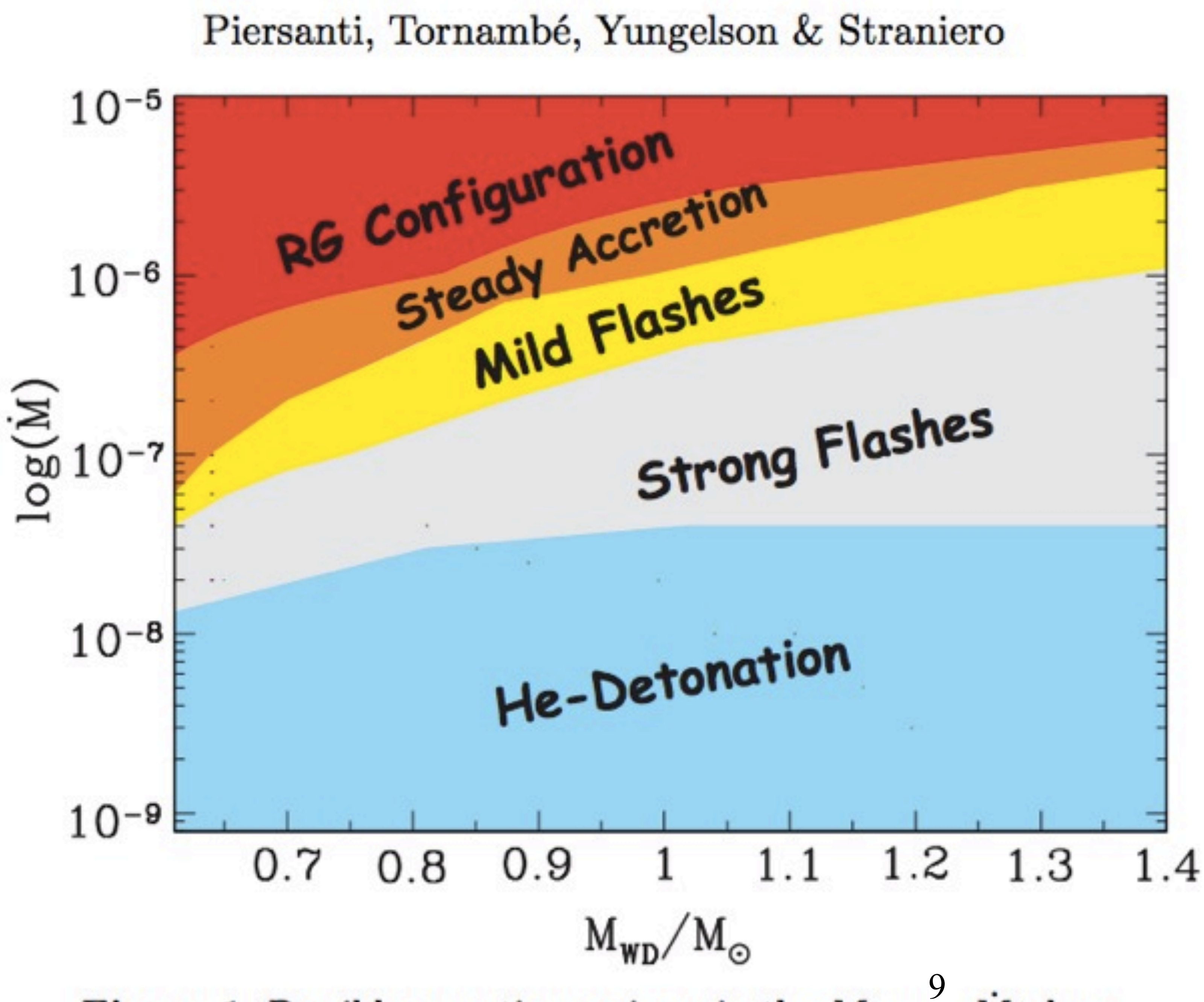
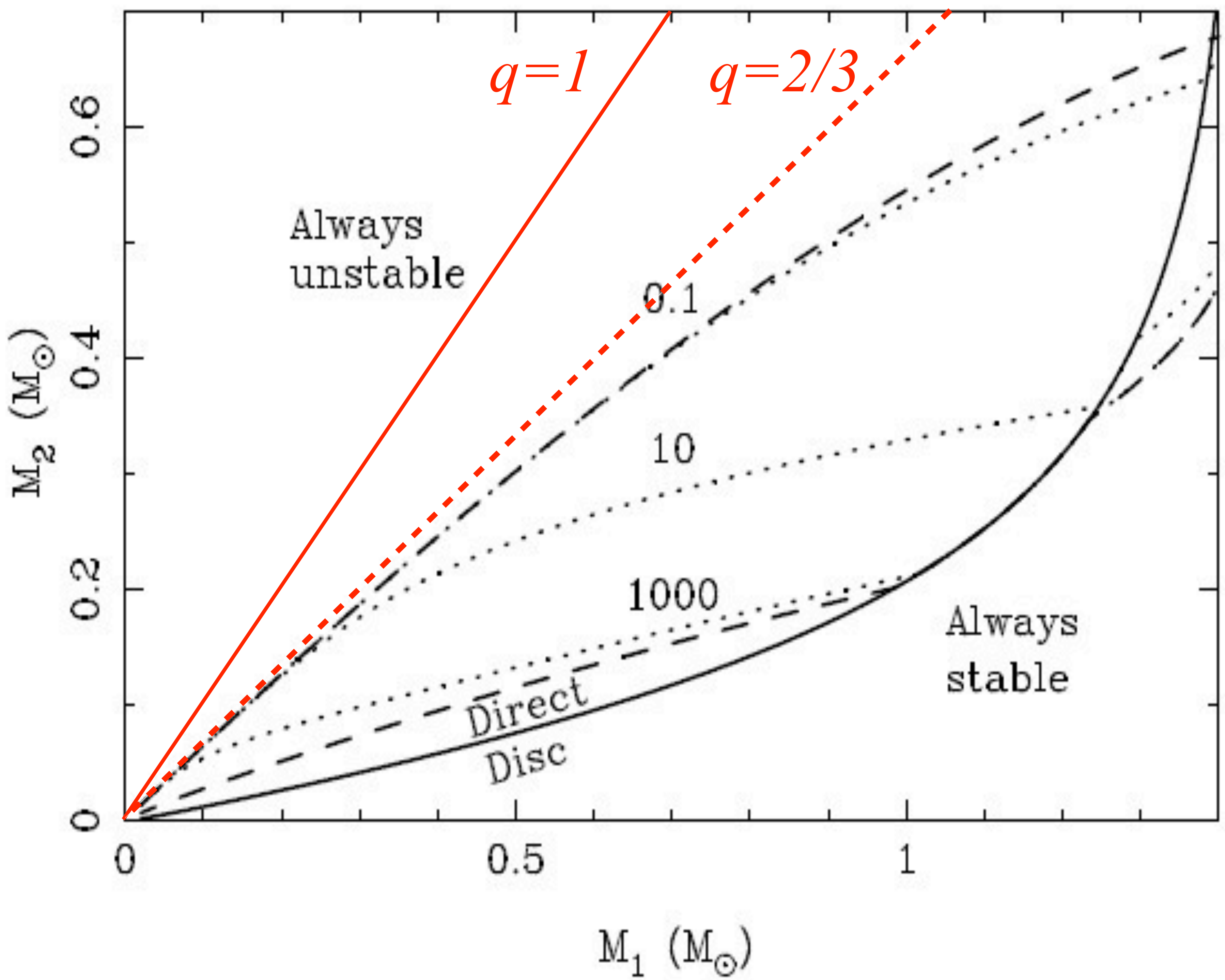


Figure 1. Possible accretion regimes in the $M_{WD} - \dot{M}$ plane.

Reflections on stability: synchronization



Marsh et al. 2004 (but see talk by Sepinsky)

Reflections on efficiency

Han & Webbink 1999

Assume spherical symmetry and require $\dot{M} < \dot{M}_{\rm Edd}$

Marcello's talk:

Hydro simulation non-spherical

β≈1 for *q=0.4*

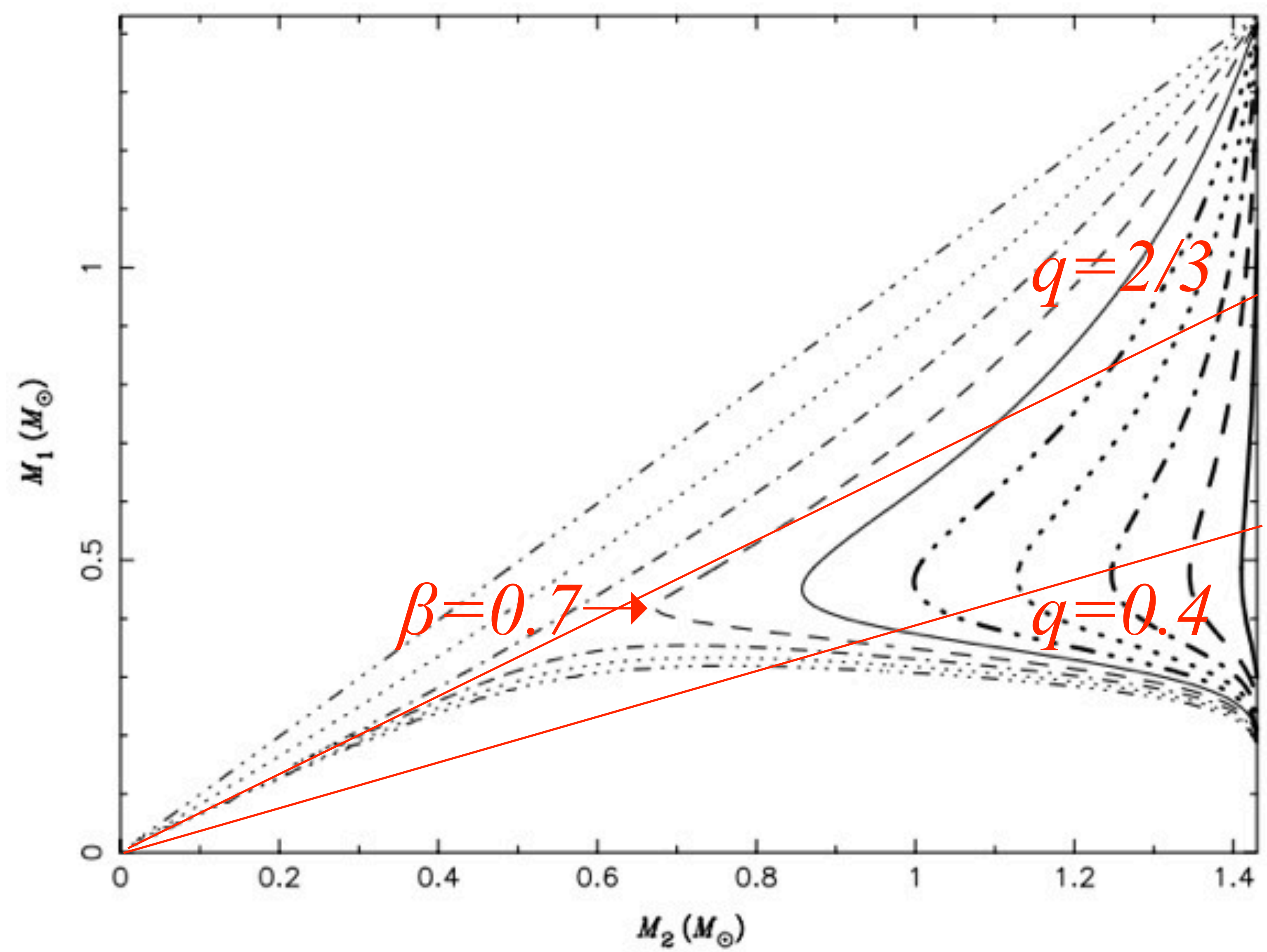
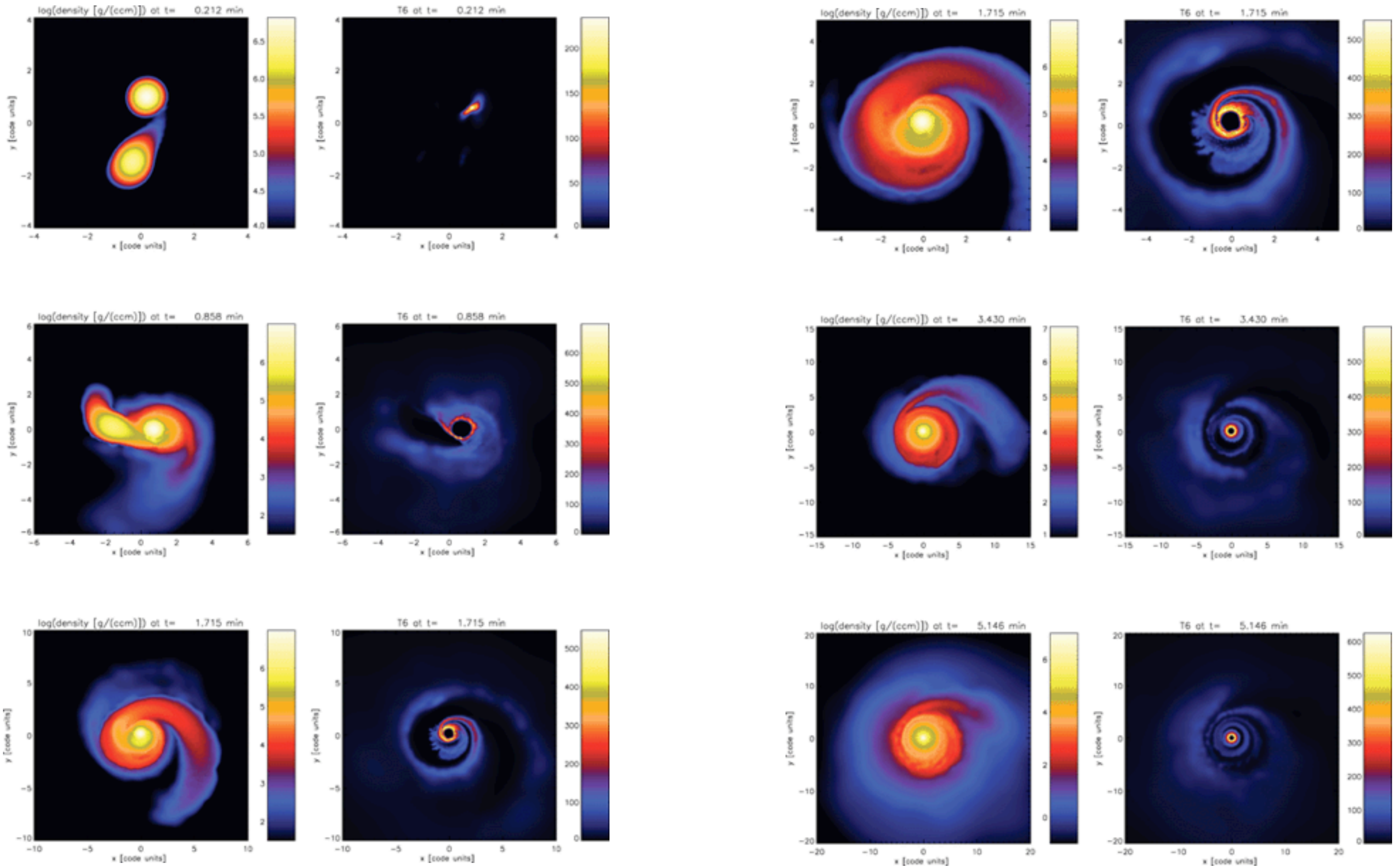


Fig. 3. Ejected mass fraction $(1 - \beta)$ of an interacting DWD (Eq. [22]). Contours mark, from left to right, $1 - \beta = 0.0, 0.1, \ldots, 0.9$, respectively.

Double White Dwarf Mergers

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



Yoon et al. 2007.

Also: Benz et al. 1990ab, Segretain et al. 1997, Guerrero et al. 2004, Loren-Aguilar et al. 2009, Marcello et al. 2012...

Groot 2012: Post-Merger systems

- What are they?
  Single massive WD, R CorBor, sdB, NS, low-mass BH?
- Where are they?
  Are they lurking in our knowledge/archives?
- How do we recognize them?
  How do we tie them to their DD past?

Potential Products

- He+He ⇒ He ignition ⇒ sdO/B star ⇒ He/CO WD
  (Nomoto & Sugimoto 1977, Nomoto & Hashimoto 1987, Kawai, Saio & Nomoto 1987, 1988, Iben 1990, Saio & Jeffery 2000, Zhang & Jeffery 2012)

- ?? He/CO+He ⇒ He ignition ⇒ sdO star ⇒ CO WD
  (Justham et al. 2010)

- He+CO ⇒ RCrB / EHe star ⇒ CO WD OR explosion ?
  (Webbink 1984, Iben & Tutukov 1984, Iben 1990, Saio & Jeffery 2002)
  (Wang et al. 2010)

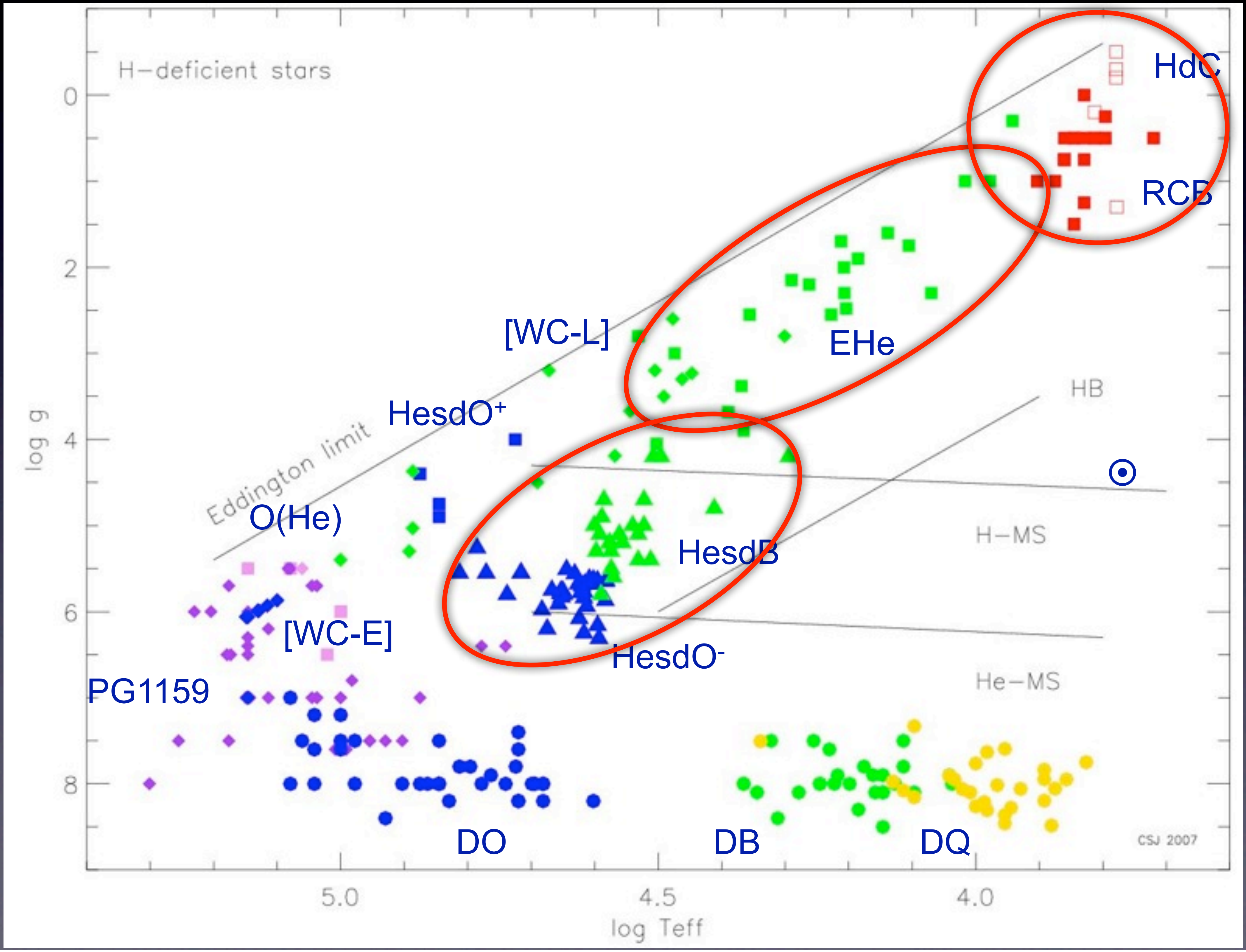
- CO+CO ⇒ C ignition ⇒ ONe WD OR collapse/explosion ?
  (Hachisu et al. 1986a,b, Kawai, Saio & Nomoto 1987, 1988, Nomoto & Hashimoto 1987, Mochkovitch & Livio 1990, Saio & Nomoto 1998)

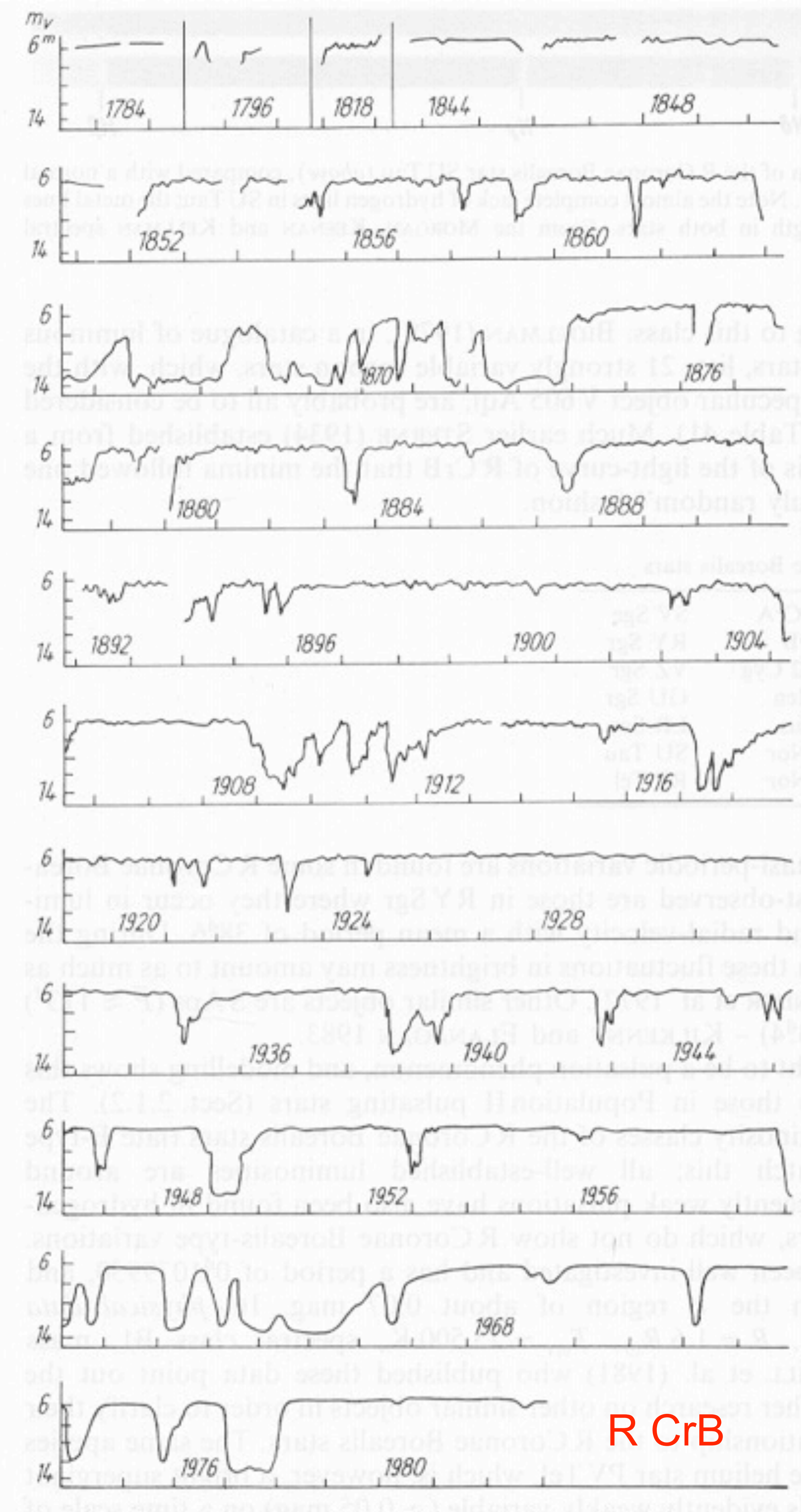
- ONe+CO ⇒ collapse/explosion ?

- Need proper calculations of merger
- Need proper calculations of evolution

  – *Results sensitive to WD temperature AND accretion rate*

DWD mergers are unlikely to be hydrogen-rich !

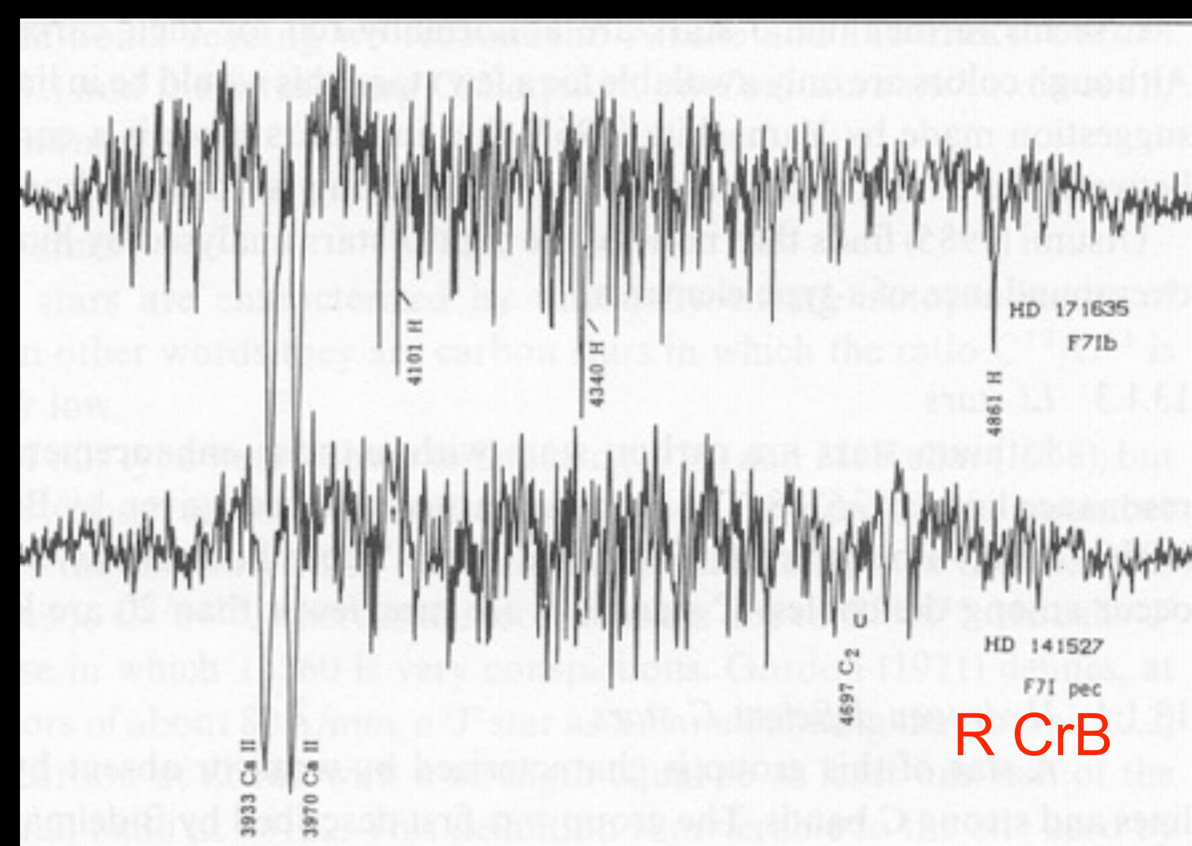


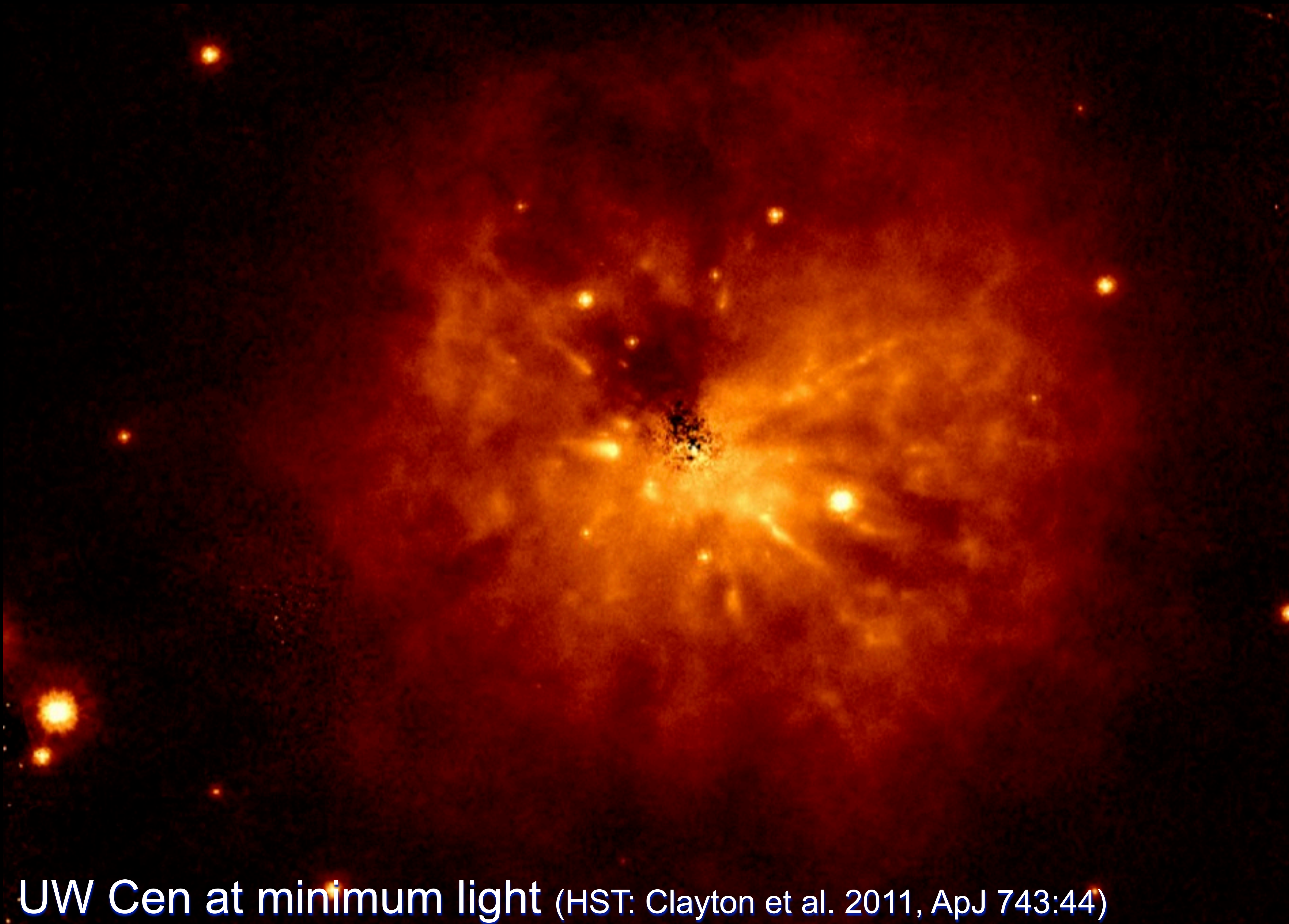


R Coronae Borealis variables

90 in MACC ??

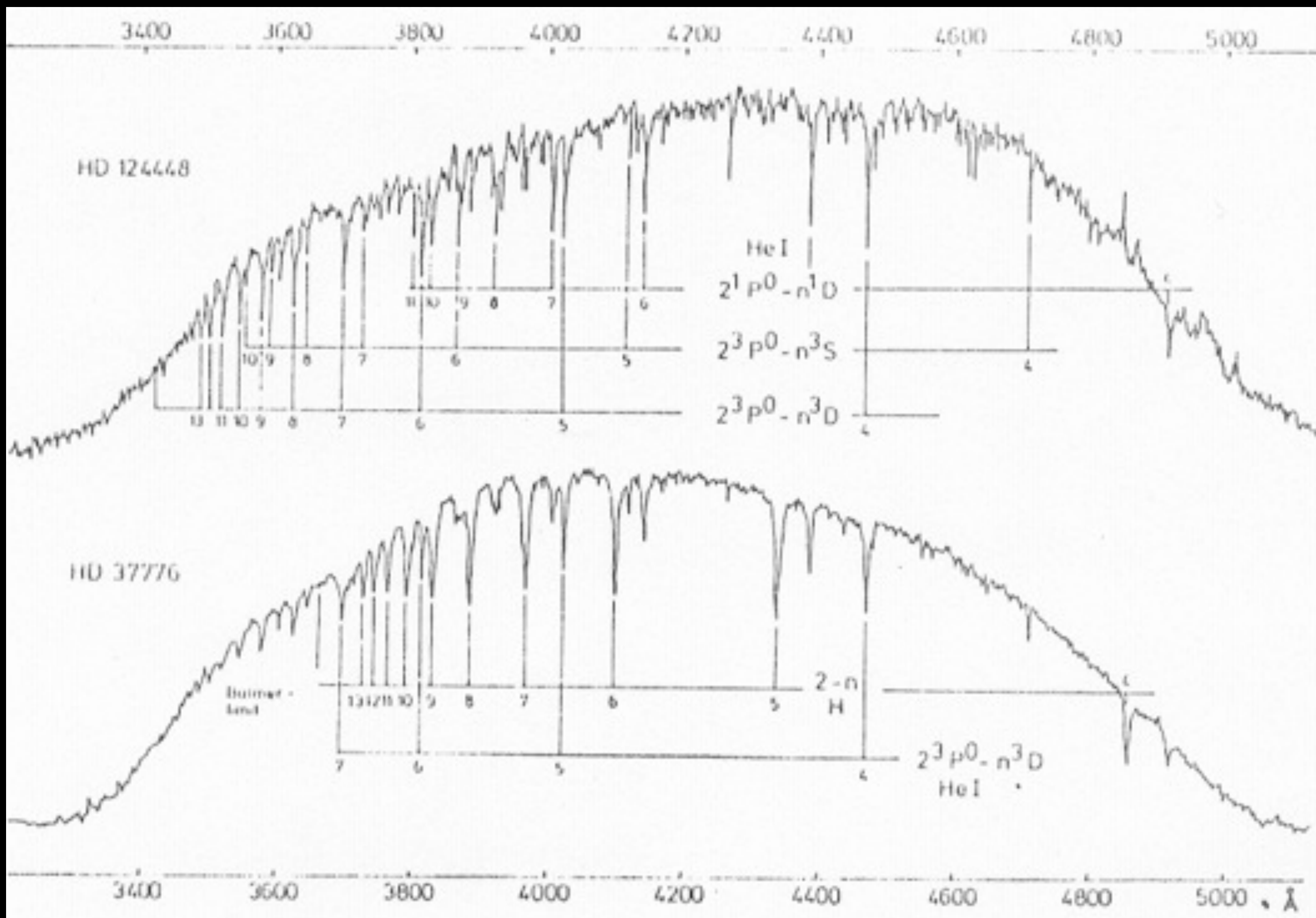
- ~ 35 known in galaxy, 17 in the LMC *(Clayton's web page)*
- Irregular light fades (5^m)
- Low-amplitude pulsations
- Hydrogen-deficient spectrum
- Infrared excess





UW Cen at minimum light (HST: Clayton et al. 2011, ApJ 743:44)

Extreme Helium stars



Comparison of spectrum of an extreme helium star with a helium-rich B star.

Jaschek & Jaschek, 1987, The classification of stars, Cambridge

- Approx. 17 known in galaxy
- Spectrum: A- and B-
  - Strong HeI
  - Narrow lines: supergiant
  - No Balmer lines
  - Strong N and C
- Origin? - clues from
  - distribution
  - chemical composition
  - low-amplitude pulsations

Helium-rich subdwarfs

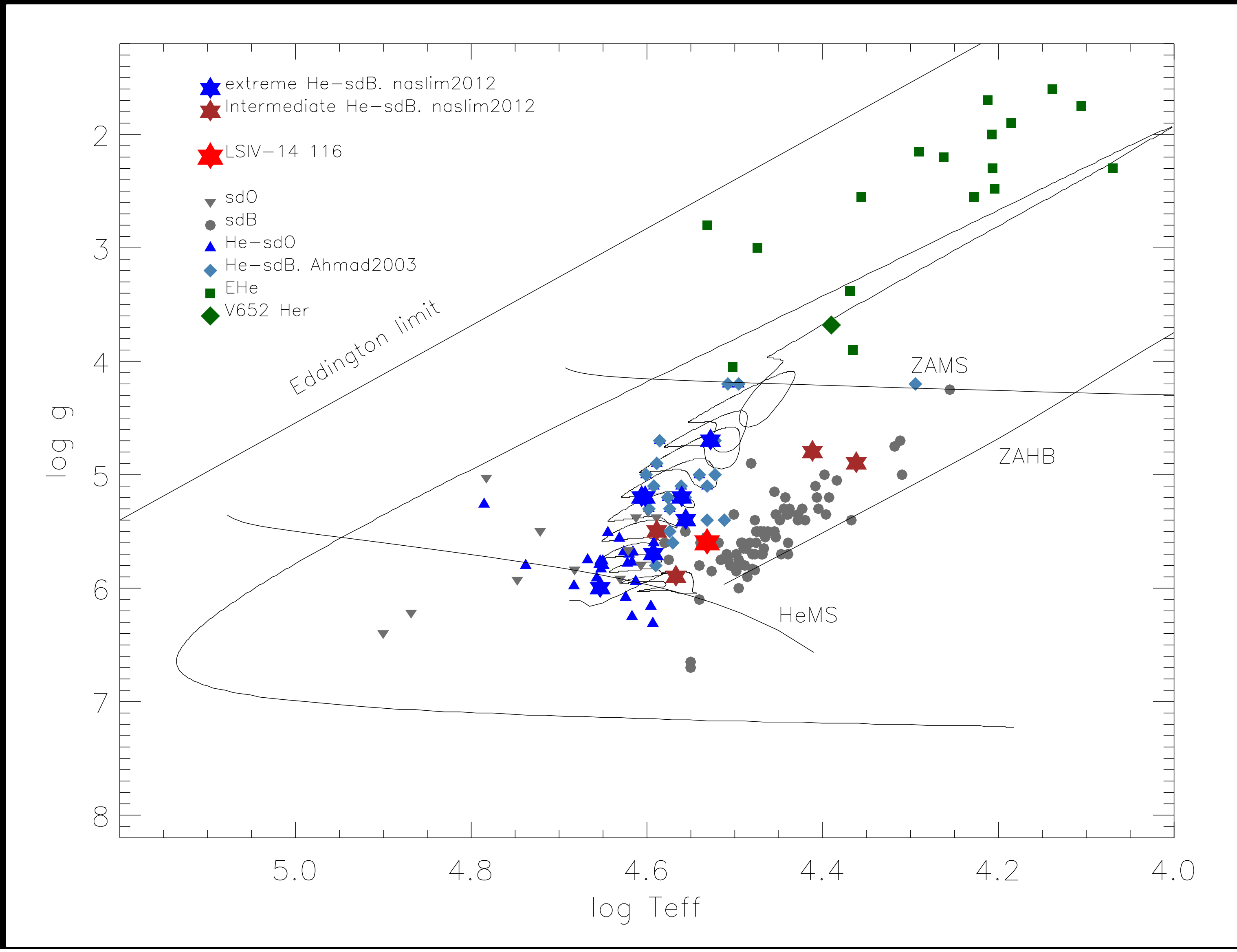
Palomar-Green survey of faint-blue objects finds many hot subdwarfs.

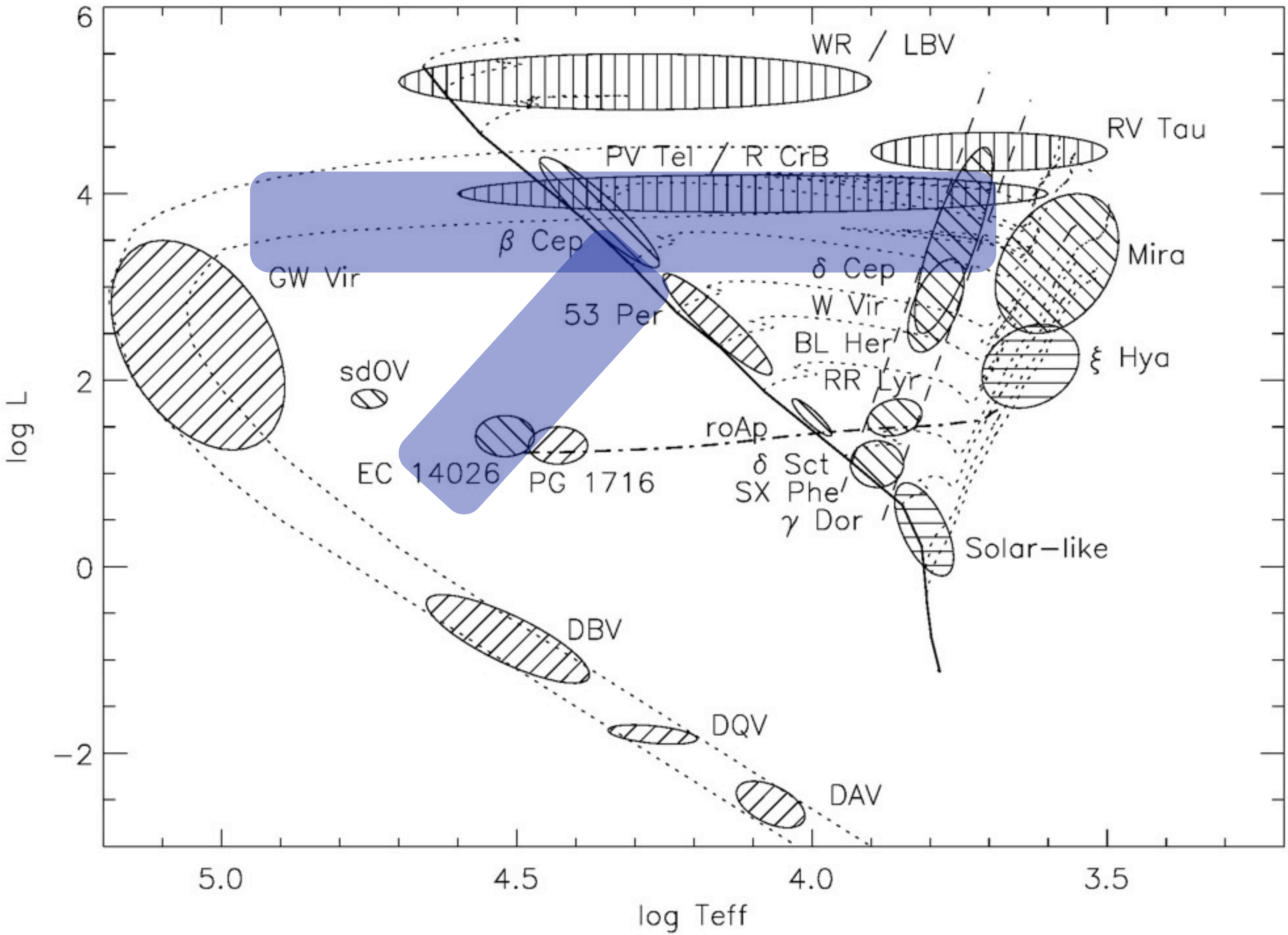
1) sdB: He<1%
> 2000 analyzed

2) sdO, sdOB,
sdOC = He-sdO,
sdOD = He-sdB

+SDSS+EC+HE:
> 170 He-sds.

3) Spectroscopic analysis →
extreme: H<10%
intermediate: 10%<H<99%



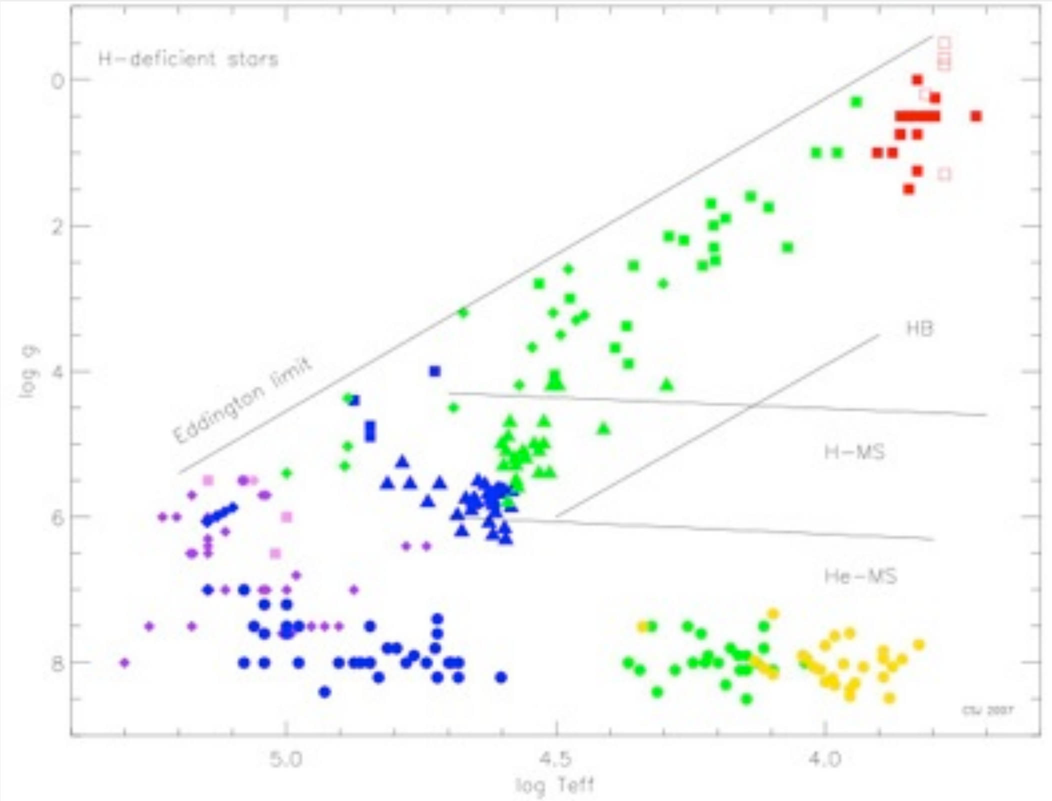


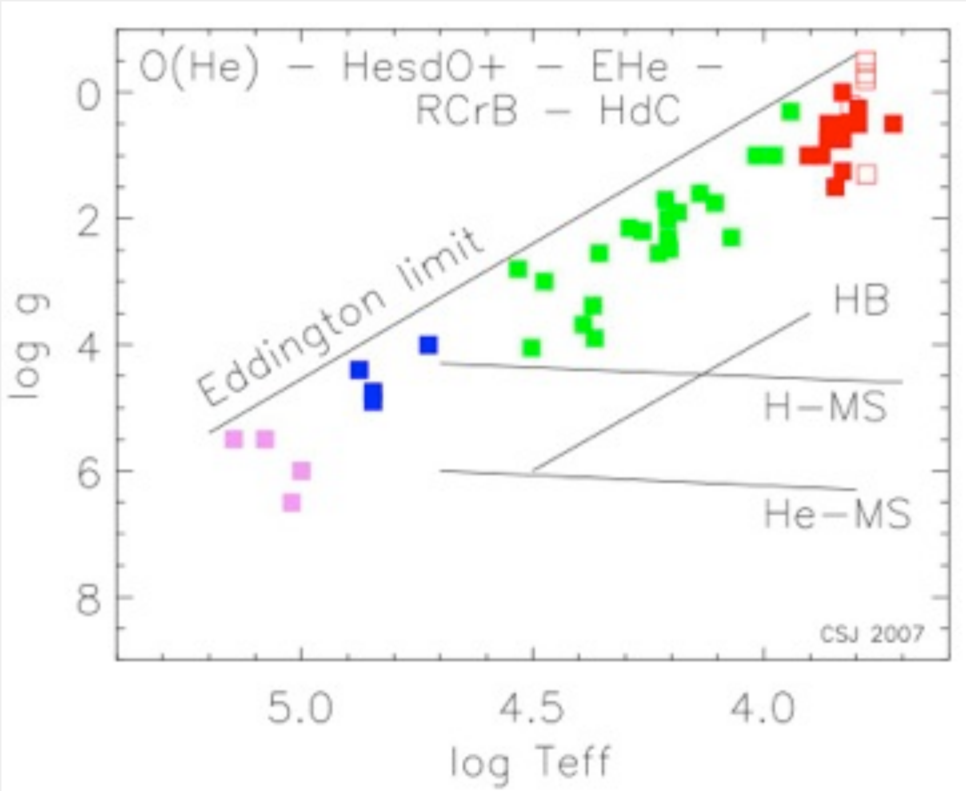
log L
log Teff
6
4
2
0
−2
5.0
4.5
4.0
3.5
WR / LBV
RV Tau
PV Tel / R CrB
β Cep
GW Vir
Mira
δ Cep
W Vir
53 Per
BL Her
ξ Hya
sdOV
RR Lyr
roAp
EC 14026
δ Sct
PG 1716
SX Phe
γ Dor
Solar−like
DBV
DQV
DAV

EHEs as merger products?

DWD Merger products will be H-deficient

CO+He → RCrB → EHe → HesdO$^+$ → O(He)??





CO+He WD mergers

hypothesis

CO+He WD binary formed

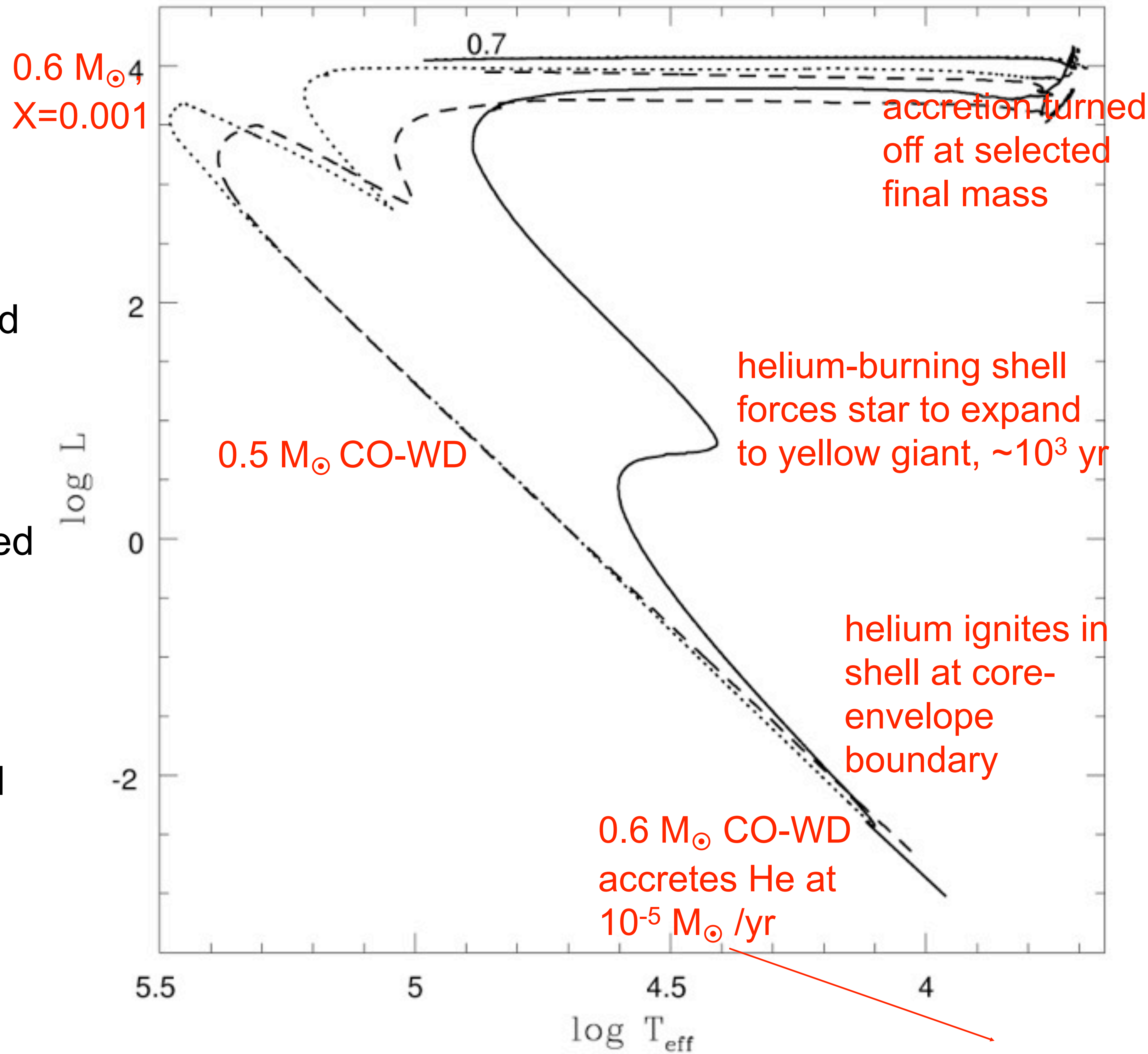
orbit decays

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

forms thick disk?

CO WD accretes material from disk

⇒model



Saio & Jeffery, 2002, MNRAS

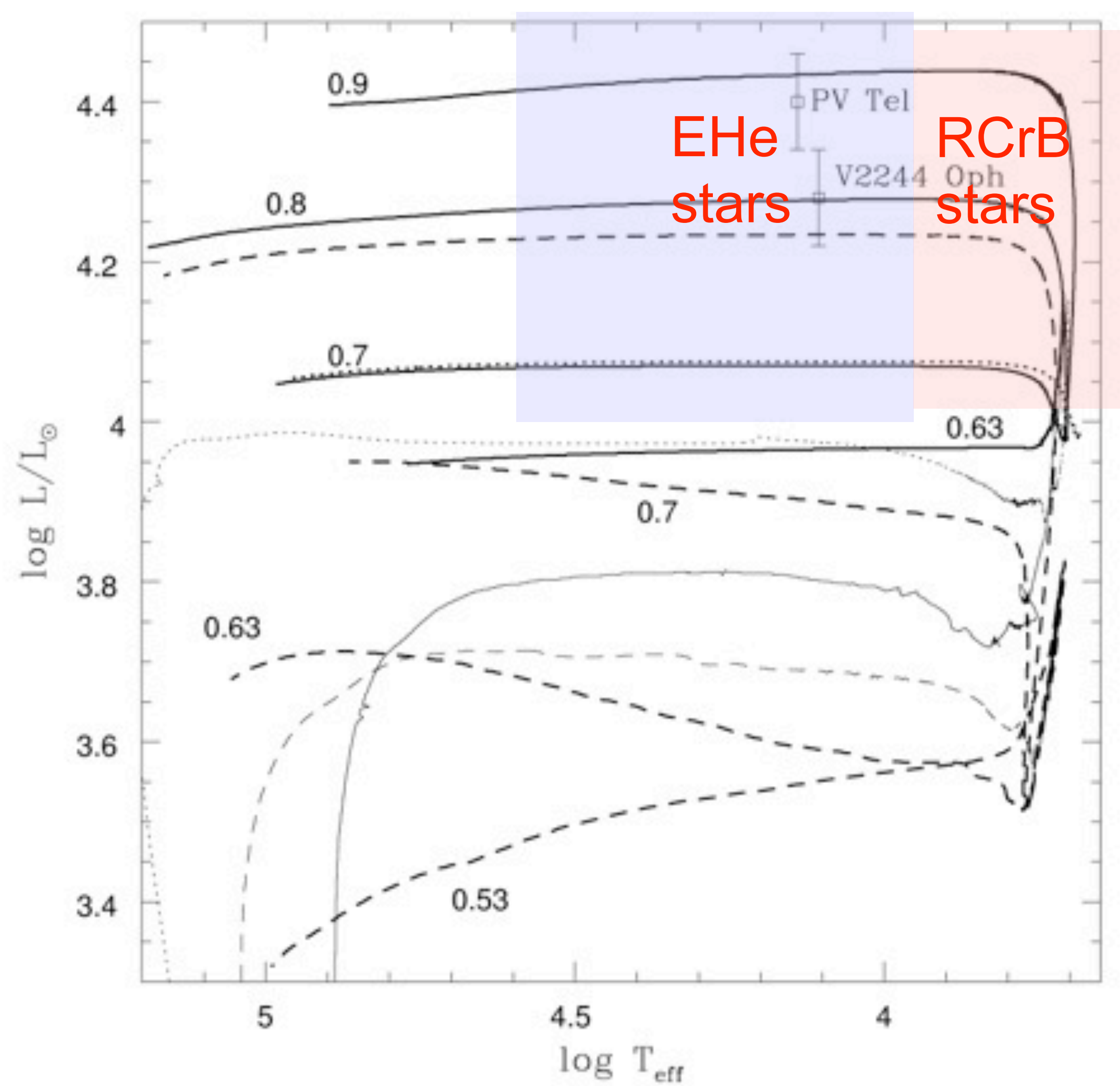
CO+He merger: EHes and RCrBs

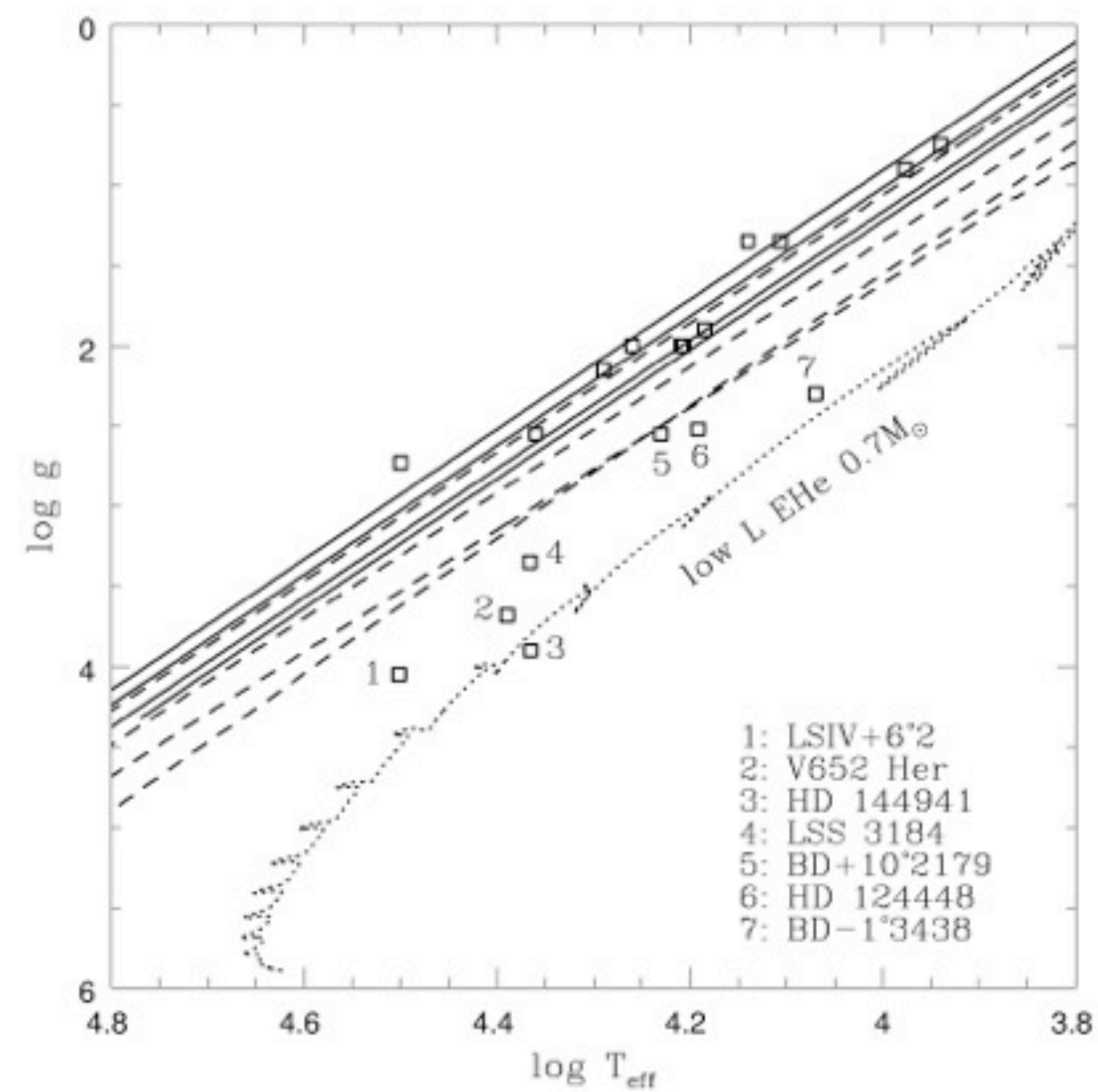
CO+He mergers
solid: 0.6$M_\odot$CO+ x $M_\odot$ He
dashed: 0.5$M_\odot$CO+ x $M_\odot$ He

light: accretion
heavy: contraction

CO+He mergers
solid: 0.6 $M_\odot$ CO + x $M_\odot$ He
dashed: 0.5 $M_\odot$ CO + x $M_\odot$ He

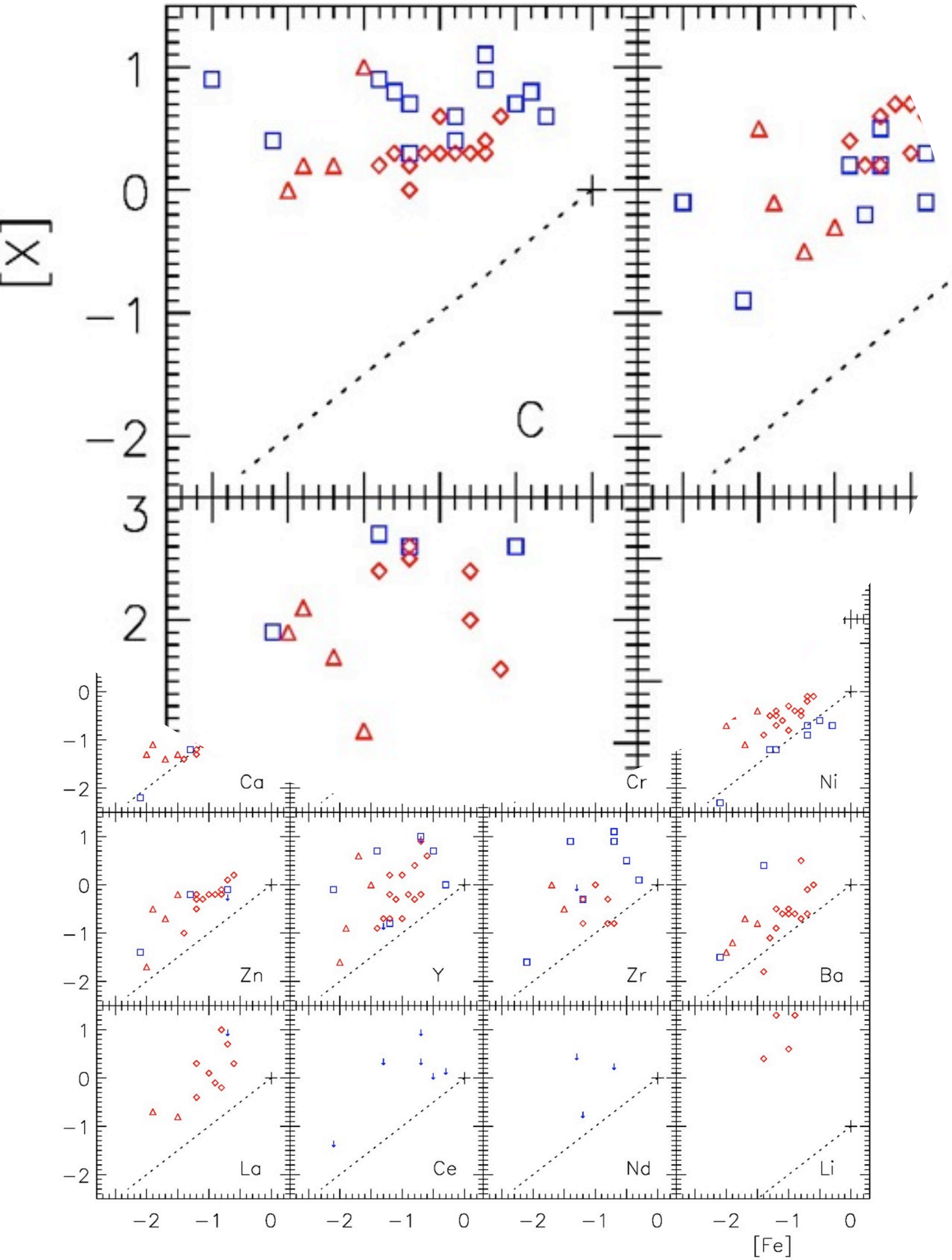
He+He merger
dotted: 0.7 $M_\odot$ He+He





(Saio & Jeffery, 2002, MNRAS)

Chemical Clues

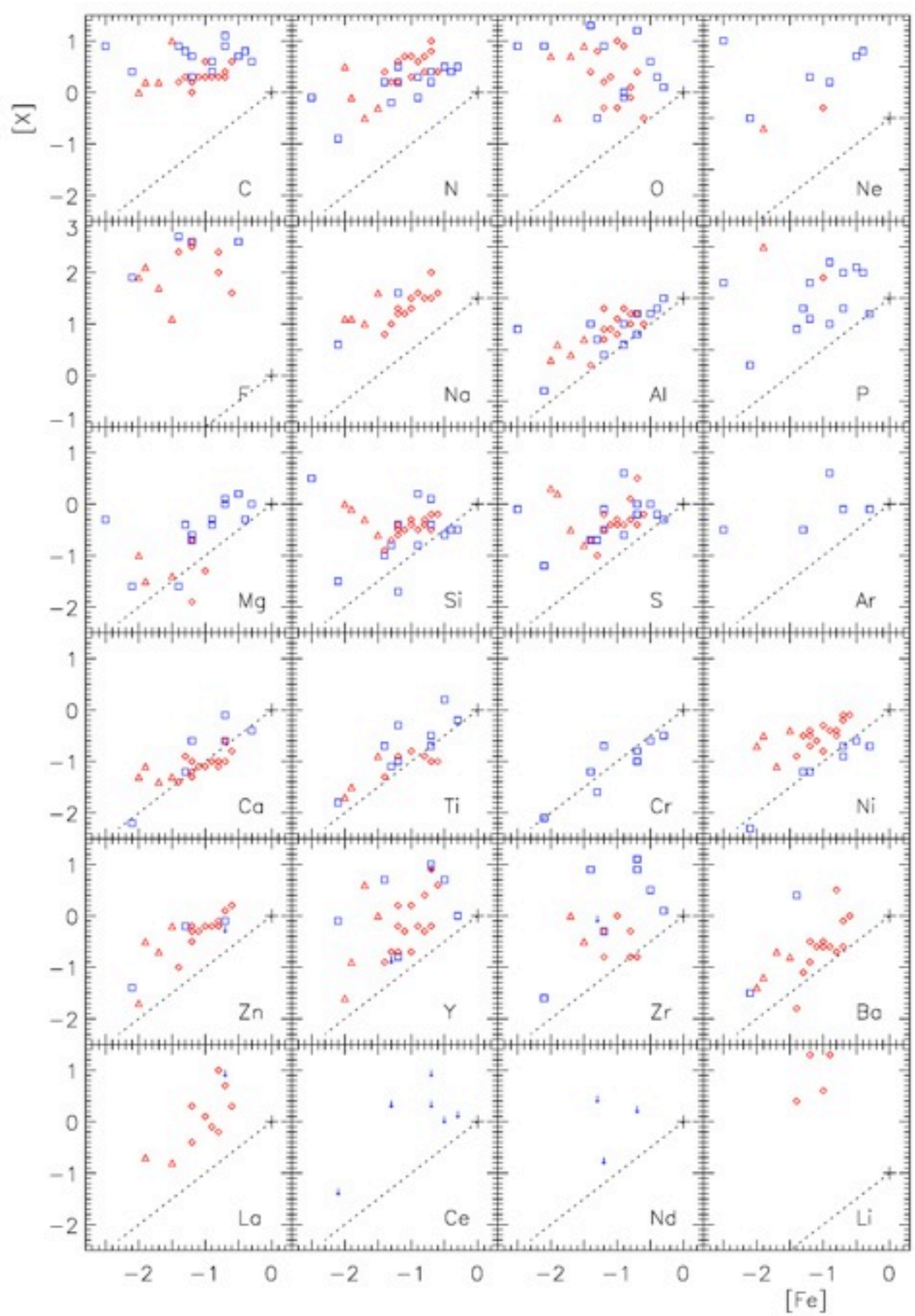


Extreme Helium Star and RCrB star surface abundances from spectroscopic analyses.

Each panel shows abundance of one element relative to iron, where 0,0 represents the solar value.

Blue Squares: Extreme Helium Stars
Red Diamonds: RCrB (majority)
Red Triangles: RCrB (minority)

(Jeffery, Heber, Pandey, Asplund, Lambert, ...1993 - 2011)

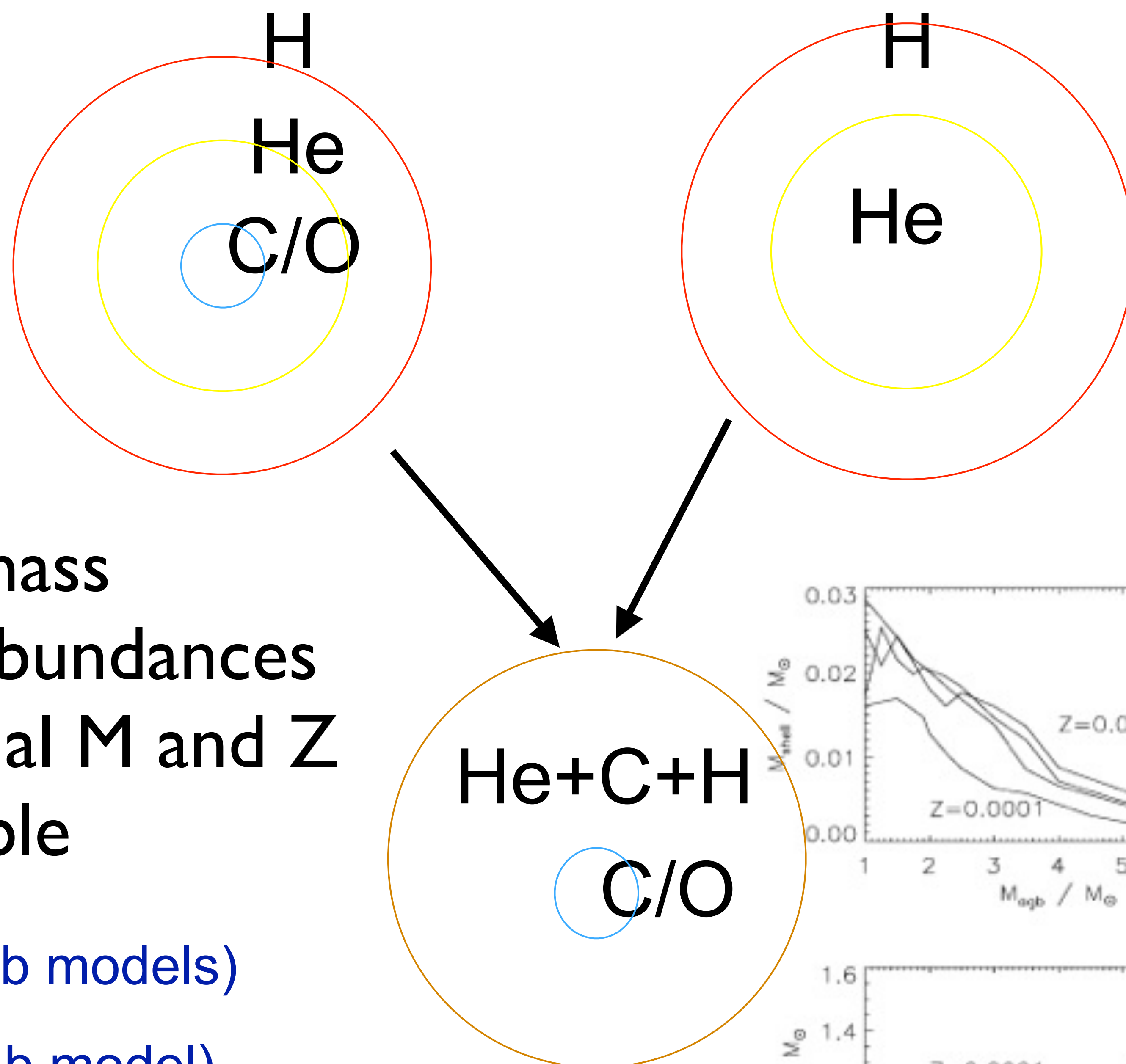


Astroarchaeology: a star digs up its past.

Object: deduce previous evolution from present chemical composition of stellar surface

a)	H (not shown)	relic
b)	Ca,Ti,Cr,Mn,(Ni) ~ ∝ Fe	OK
c)	[N/Fe] ∝ [(C+N+O)/Fe]	CNO
d)	[C/Fe] >> 0, ^{12}C >> ^{13}C	3α
e)	[O/Fe] >> 0, ^{18}O ≈ ^{16}O	^{14}N+α?
f)	[Ne/Fe] >> 0	^{14}N+2α
g)	Mg,Si,S,…	X + α
h)	[F/Fe]>>0	^{18}O+p?
i)	[s/Fe] >> 0	AGB ?
j)	[P/Fe] >> 0	AGB ?
k)	Li present	??

Understanding EHe abundances: the simple recipe: Mk II



CO WD

from AGB star
CO core mass
He intershell mass
He intershell abundances
depend on initial M and Z
H mass negligible

He WD

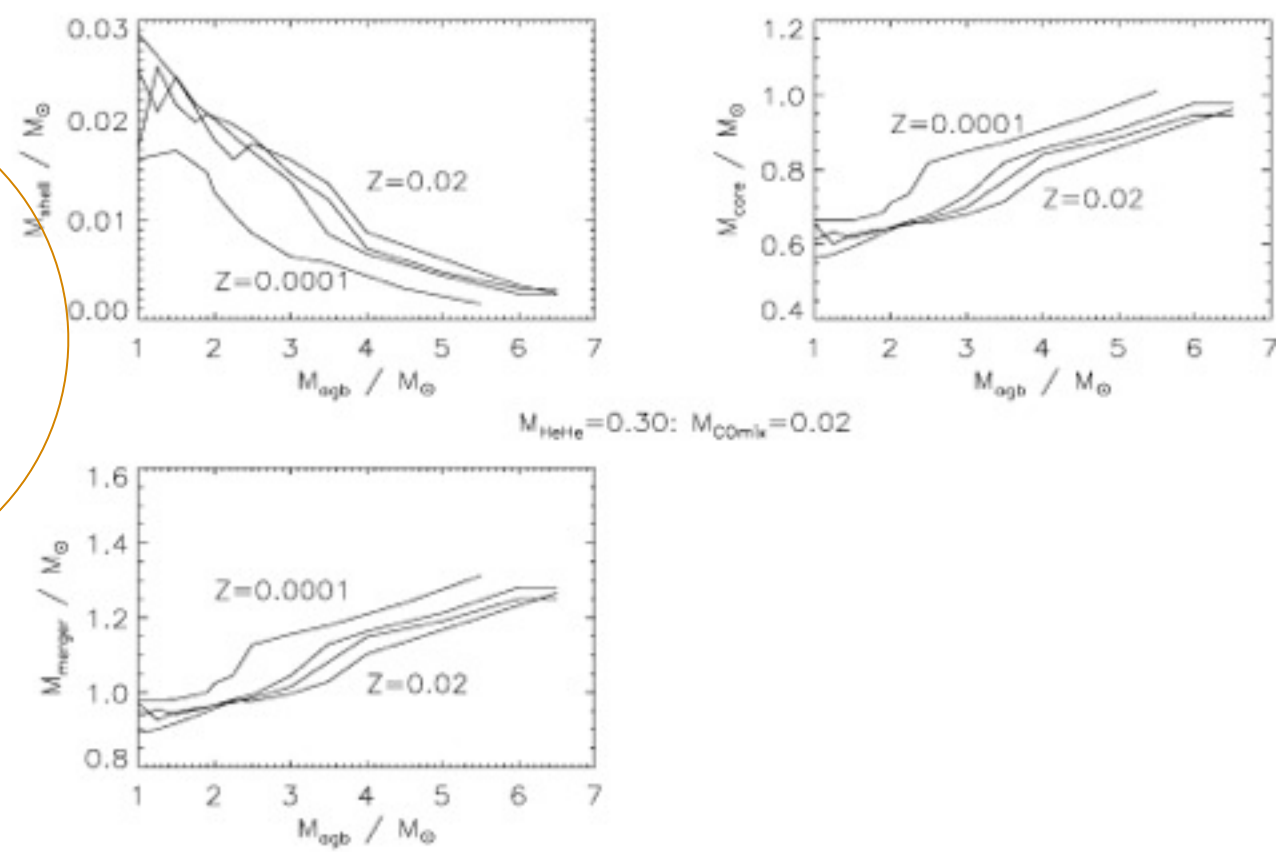
from post-MS star
He core abundances
from CNO burning
H mass negligible

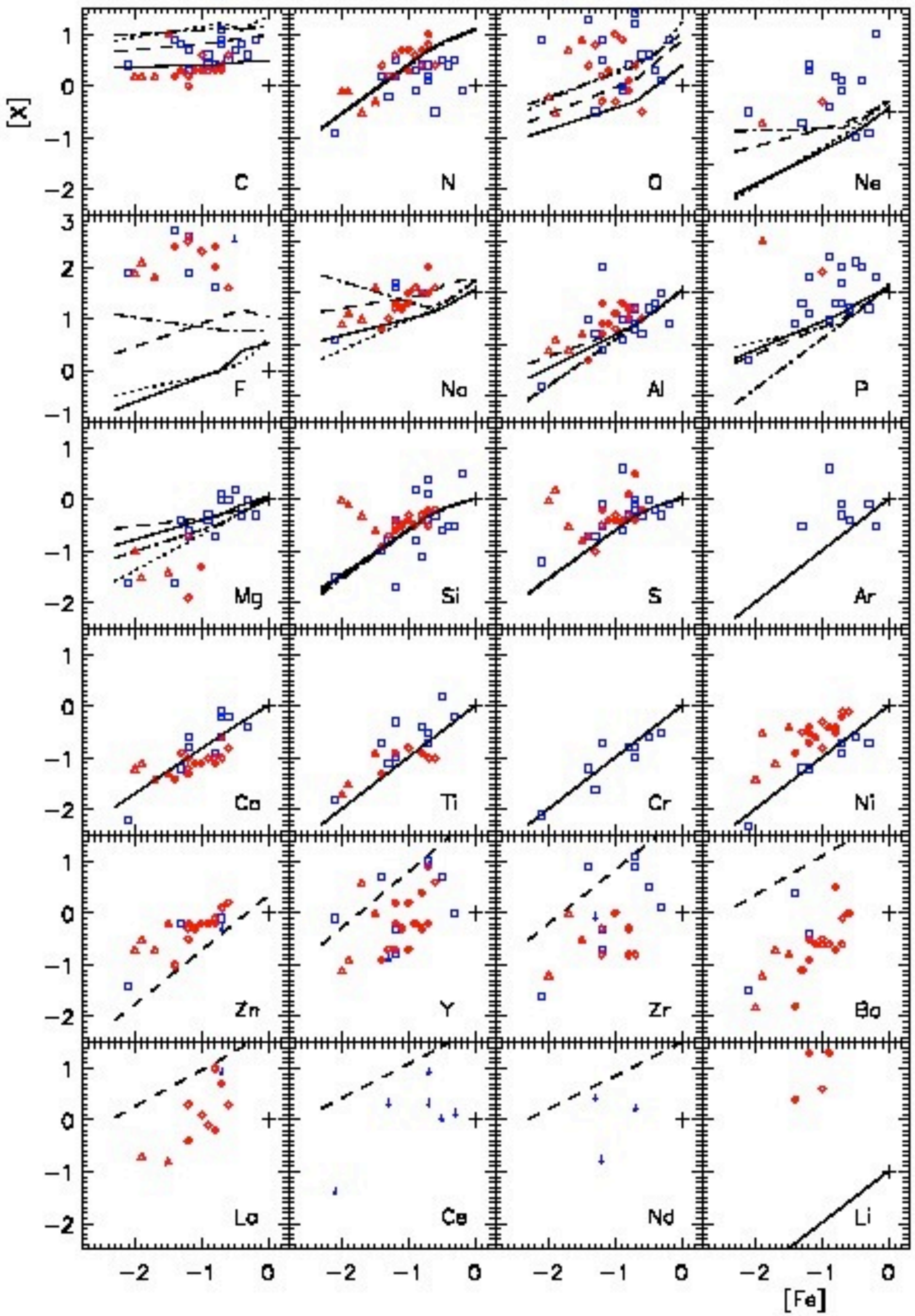
$M_{core} \sim f(M_i,Z)$ (agb models)

$M_{shell} \sim f(M_i,Z)$ (agb model)

$M_{merger} \sim (1 + q_{crit}) * (M_{core}+M_{shell})$

q_{crit}: defined by $\frac{\mathrm{d}r}{\mathrm{d}m} > \frac{\mathrm{d}a}{\mathrm{d}q}$





Simple CO+He merger models for AGB stars with initial masses: 1.0, 1.9, 3.0, and 5.0 $M_\odot$

The mass of the AGB progenitor has a strong influence on the composition of the intershell and, hence, possibly, on the surface composition of any subsequent WD merger.

What clues do surface abundances provide about previous evolution?

[N/Fe] ∝ [(C+N+O)/Fe]	OK
[C/Fe] >> 0	fixed
[O/Fe] >> 0	^{18}O pocket
[Ne/Fe] >> 0	??
Mg,Si,S,…	OK
[F/Fe]>>0	M_{agb}~2-3$M_\odot$?
[s/Fe] >> 0	not modelled
[P/Fe] >> 0	M_{agb}~2-3$M_\odot$?
Li	??

So far, not so good ☹, we still need:

- s-process yields from the AGB grids
- experiment with hot merger models

^{18}O: Signature of a hot or cold merger?

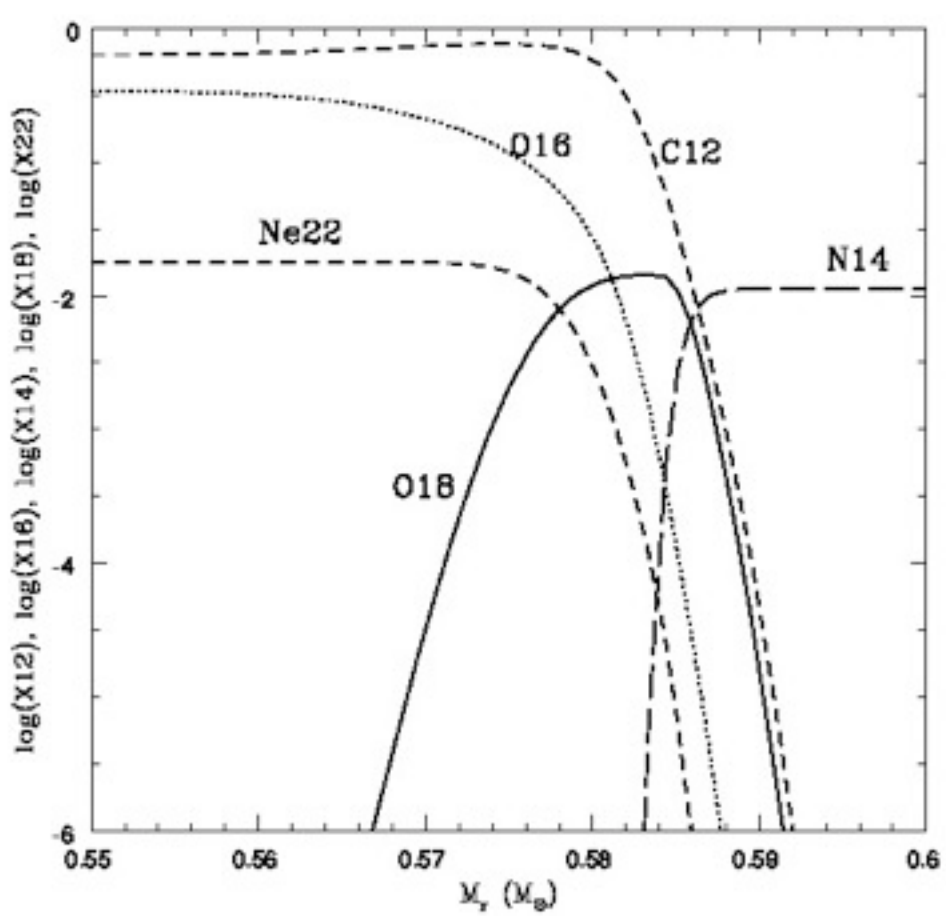
Cold merger

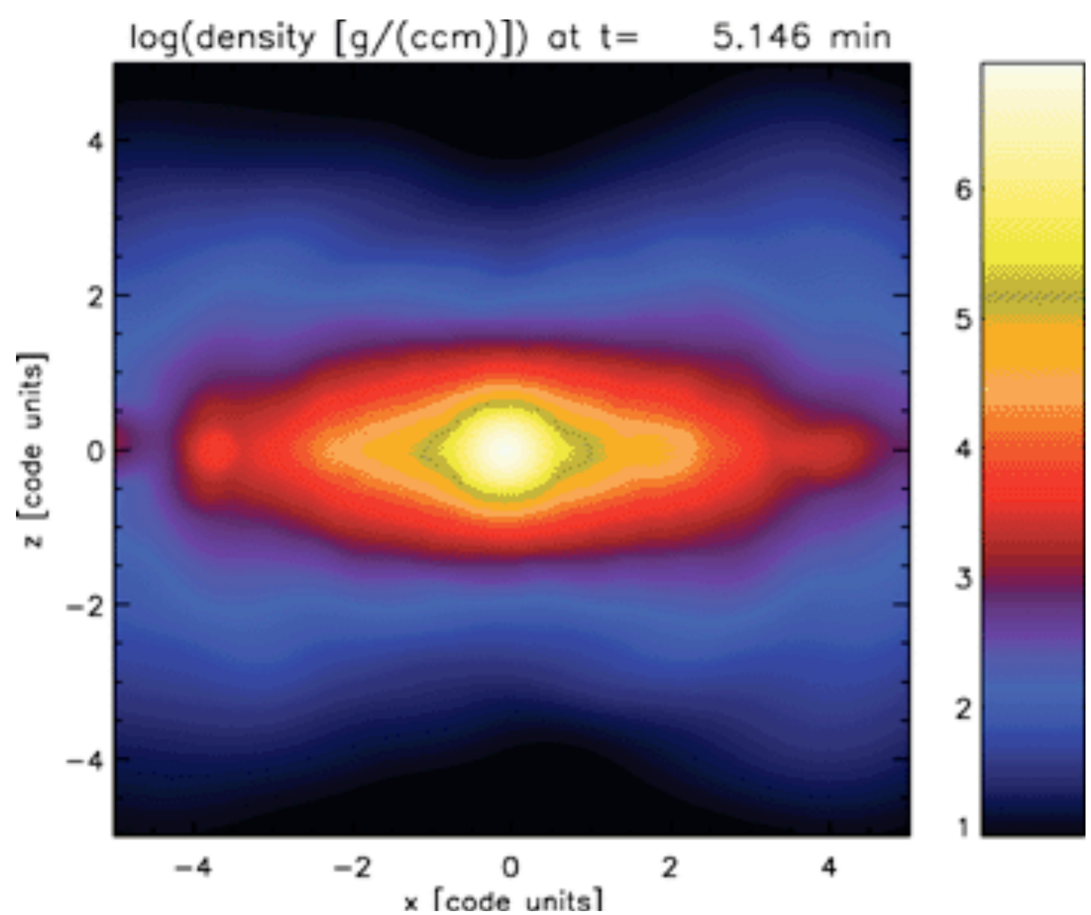
^{18}O from pocket at CO/He boundary in CO WD
-- needs mixing over boundary, but it works.
Can give some ^{19}F from AGB.

Hot merger (Clayton et al. 2007),

^{18}O from partial α-burning of ^{14}N

Could produce extra ^{19}F





Progenitor and final masses?

Observations (pulsation, distribution):

$M_{EHe} \approx 0.7 - 0.9\ M_\odot$

Thick Disk / Bulge

AGB evolution:

^{19}F, ^{31}P: $M_1 \approx 2 - 3\ M_\odot$

$M_{COWD} \approx 0.55 - 0.65\ M_\odot$

If $M_{HeWD} \approx 0.25 - 0.3\ M_\odot$

$\Rightarrow M_{merger} \approx 0.85 - 1.0\ M_\odot$

(Jeffery et al. 2011)

Population Synthesis ??

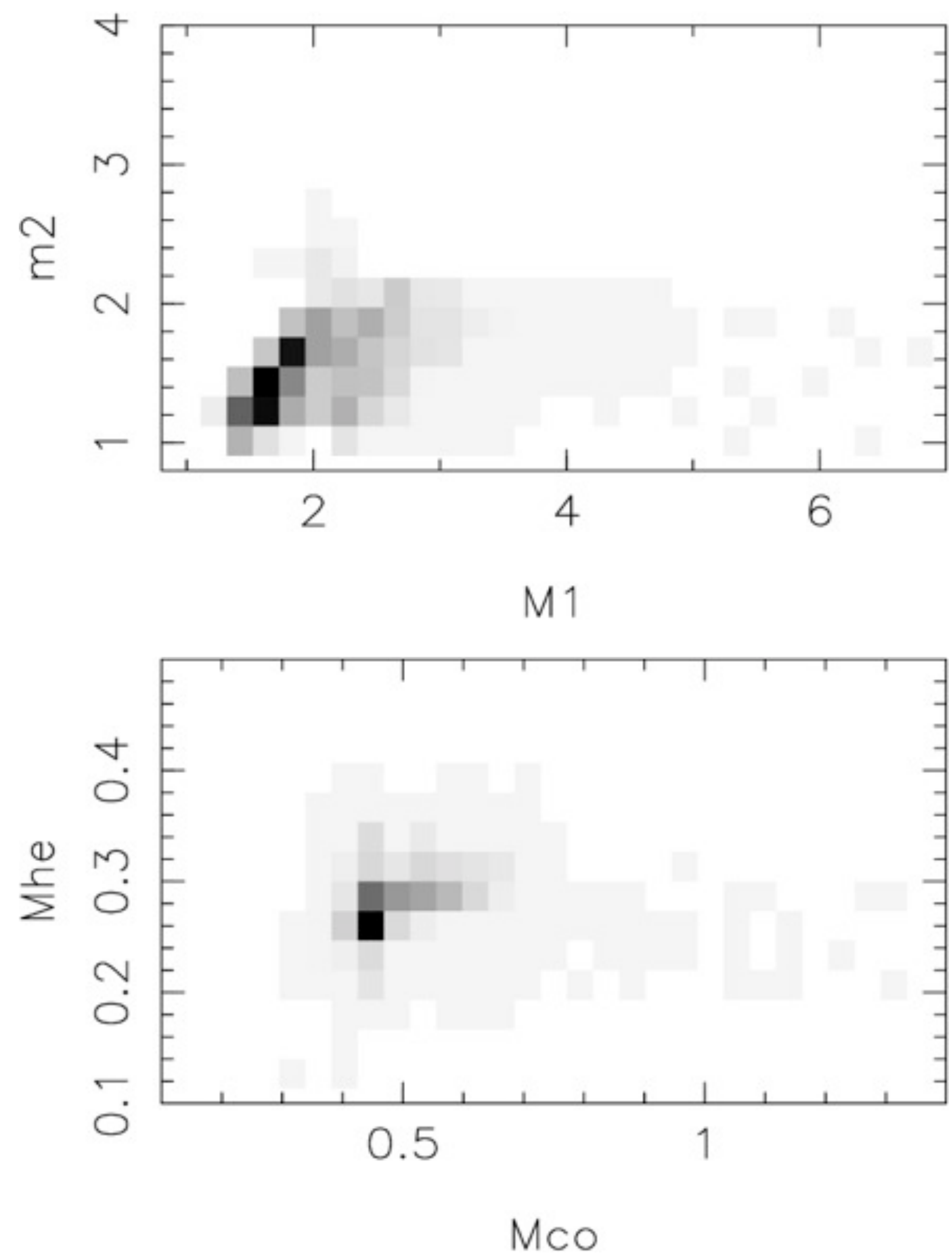
$M_1 \approx 1.4 - 3\ M_\odot$

$M_{HeWD} \approx 0.25 - 0.35\ M_\odot$

$M_{COWD} \approx 0.4 - 0.65\ M_\odot$

$\Rightarrow M_{merger} \approx 0.65 - 1.0\ M_\odot$

Thin Disk ?



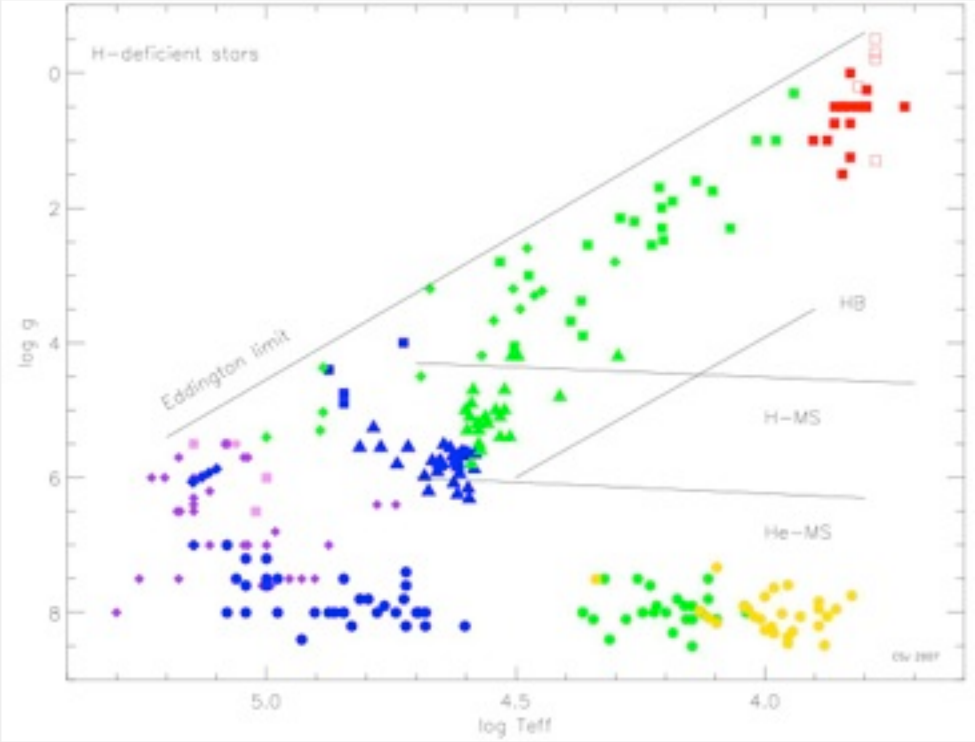
HesdBs as merger products ?

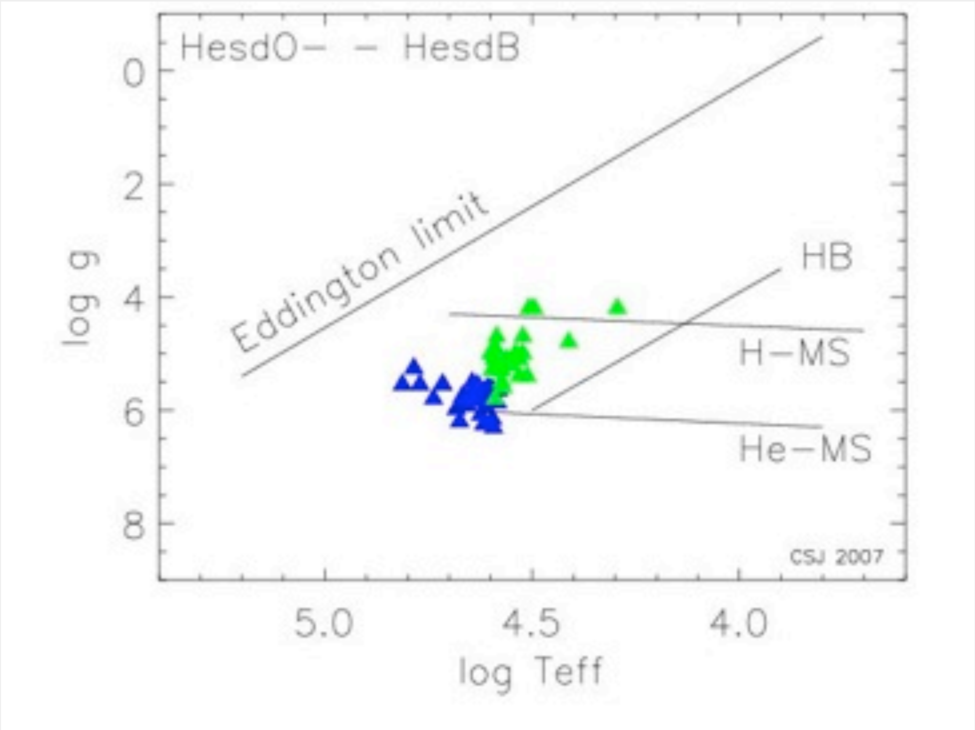
Merger products will be extremely H-deficient

He+He → EHe → HesdB → He-sdO/B

→ sdB?

see talk by Xianfei Zhang



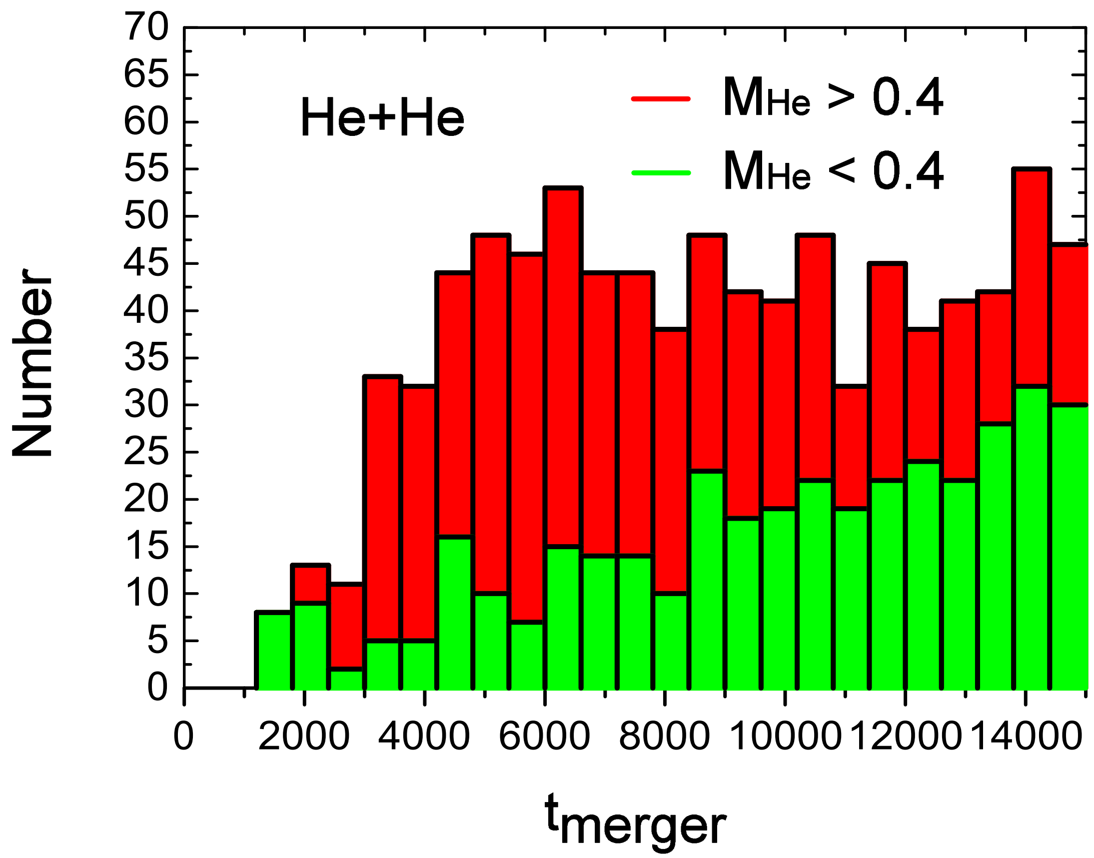


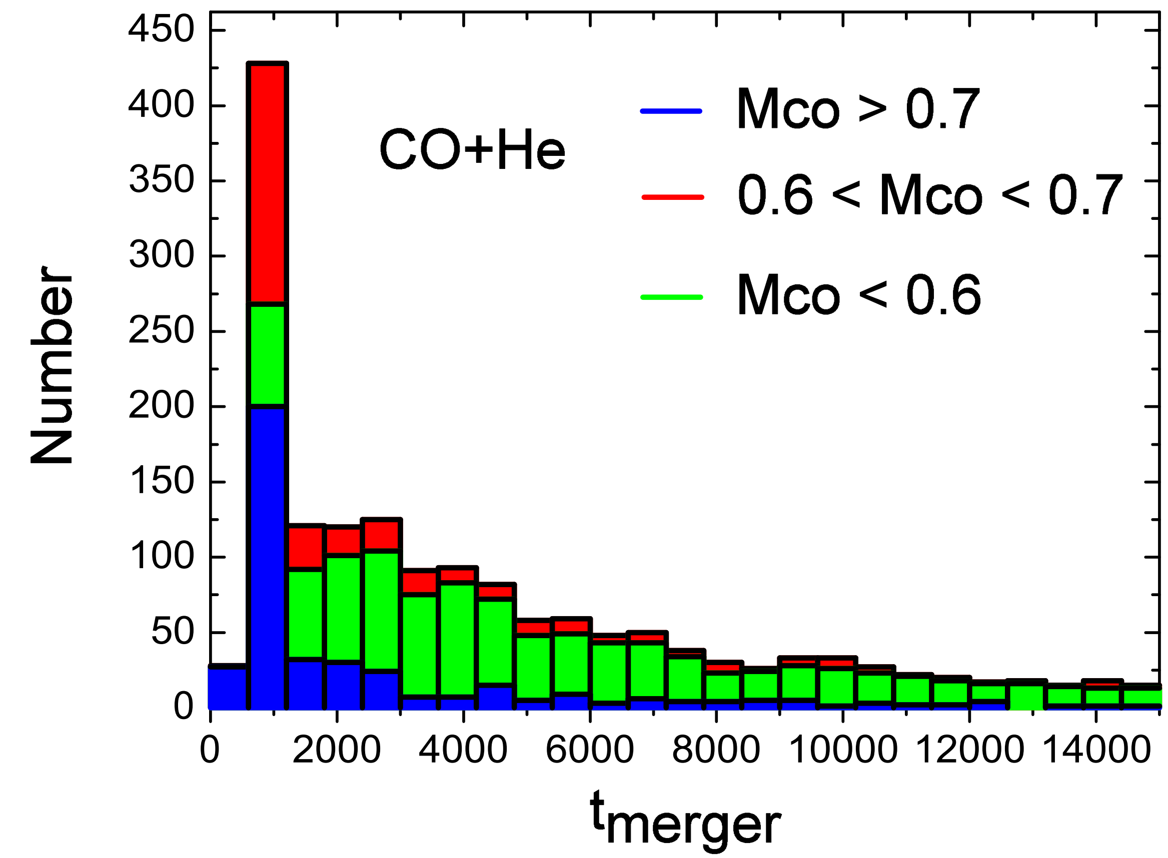
Merger statistics

- Do DWDs occur in the right period and mass ranges to produce mergers?
- Do they come from old stellar populations or recent star formation?
- What are there progenitors?
- Do mergers occur at the right frequency to explain populations of "products"?
- Some preliminary findings....
(with Yu and Nelemans, ...)

Population Synthesis

- Code: modified Hurley (Yu & Jeffery 2010)
- Sample: 1,000,000 binaries
- IMF: Kroupa 1993 (broken power law)
- Mass transfer: $\alpha_\lambda=1$
- Mass ratio: $dN/dq = 1$
- Separation: $dN/d \log a$ = constant (Han 1998)
- Eccentricity: $dN/de = 2e$
- $Z=0.02$
- Initial-final mass relation: Hurley (2002)
- No star formation convolution





Number distribution for DWDs as a function of time to merger (Myr)

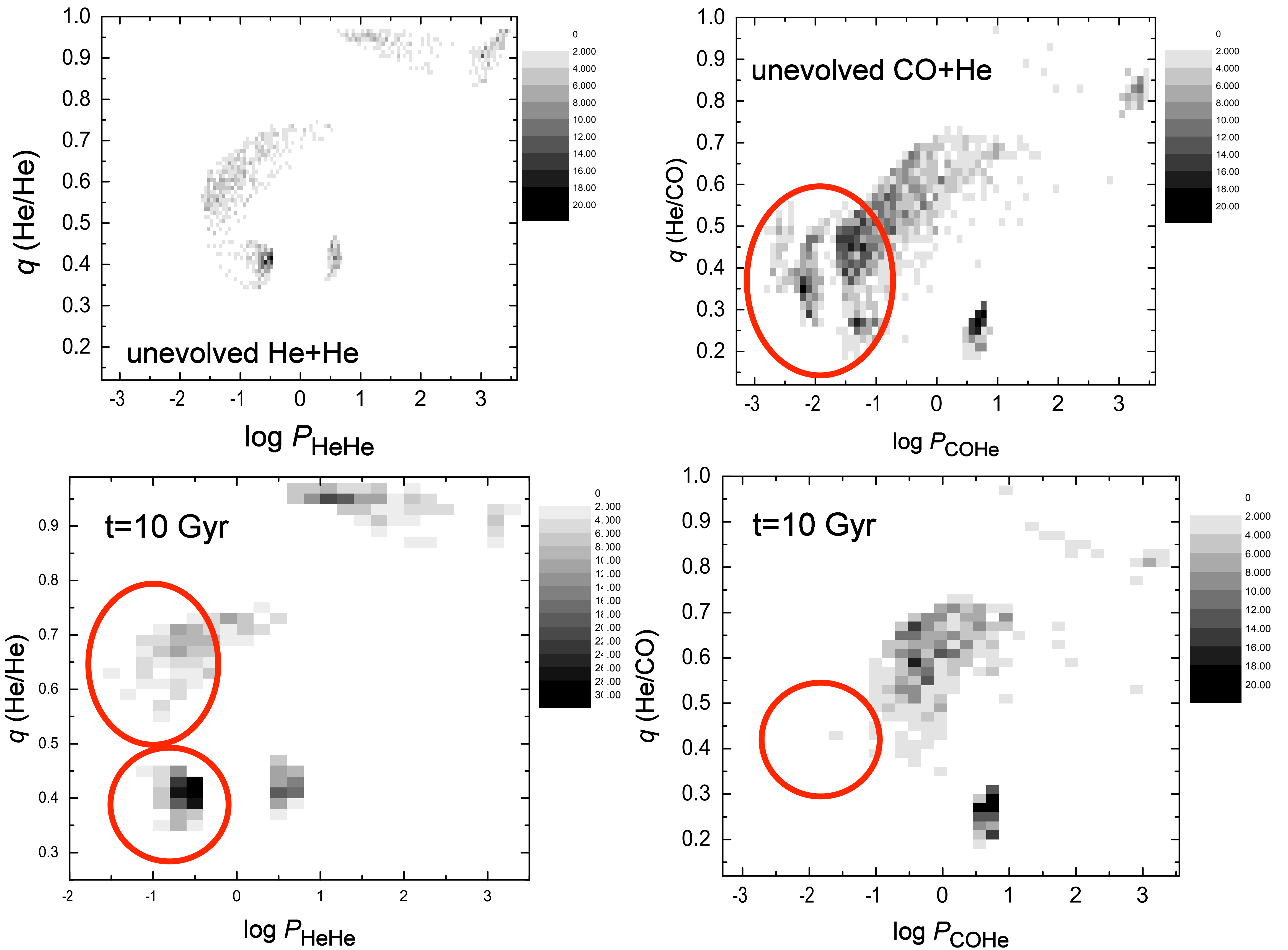
He+He:

old environments (thick disk, bulge, halo) -- OK

CO+He:

Mco>0.6 young environments (thin disk)

Mco<0.6 older environments (thick disk ?)



Mass-ratio / period distribution for DWDs

Interim Results

- Most CO+He mergers from recent star formation (~1 Gyr)
  - *contradicts galactic distribution of EHe+RCrB*
- CO+He mergers from 1.5 - 3 $M_\odot$ progenitors
  - *supported by nucleosynthesis and abundances in EHe+RCrB*
- Most high-mass He+He mergers from 4 - 8 Gyr
- Most low-mass He+He mergers from >8 Gyr
  - *supported by thick disk location of sdBs*
- He+He mergers from 1.0 - 1.5 $M_\odot$ progenitors

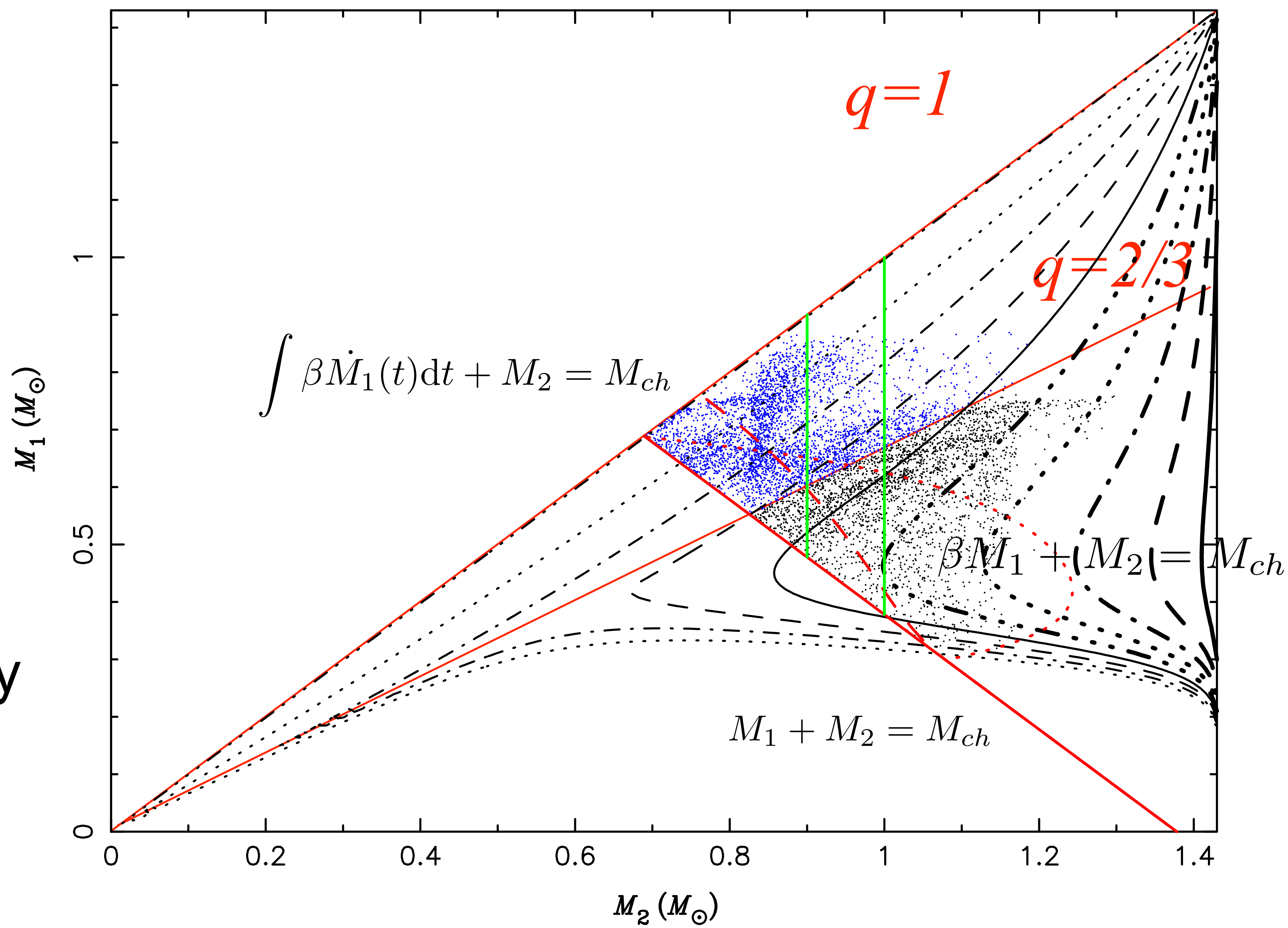
DD mergers and M_{ch}

i) Include non-conservative mass transfer in merger

ii) Require *$M_2/M_1>1.5$* and *$M_2>0.9(1.0)$* in order to avoid AIC (Pakmor et al. 2010,11,12)

SNIa rates reduced by factors between 2/3 and 1/6

(Chen et al. in prep)



DD merger outcomes: $q > q_{crit}$

He+He

HesdO/B stars

? EHe stars

CO+He

RCrB + EHe stars

? ONe WDs

CO+CO

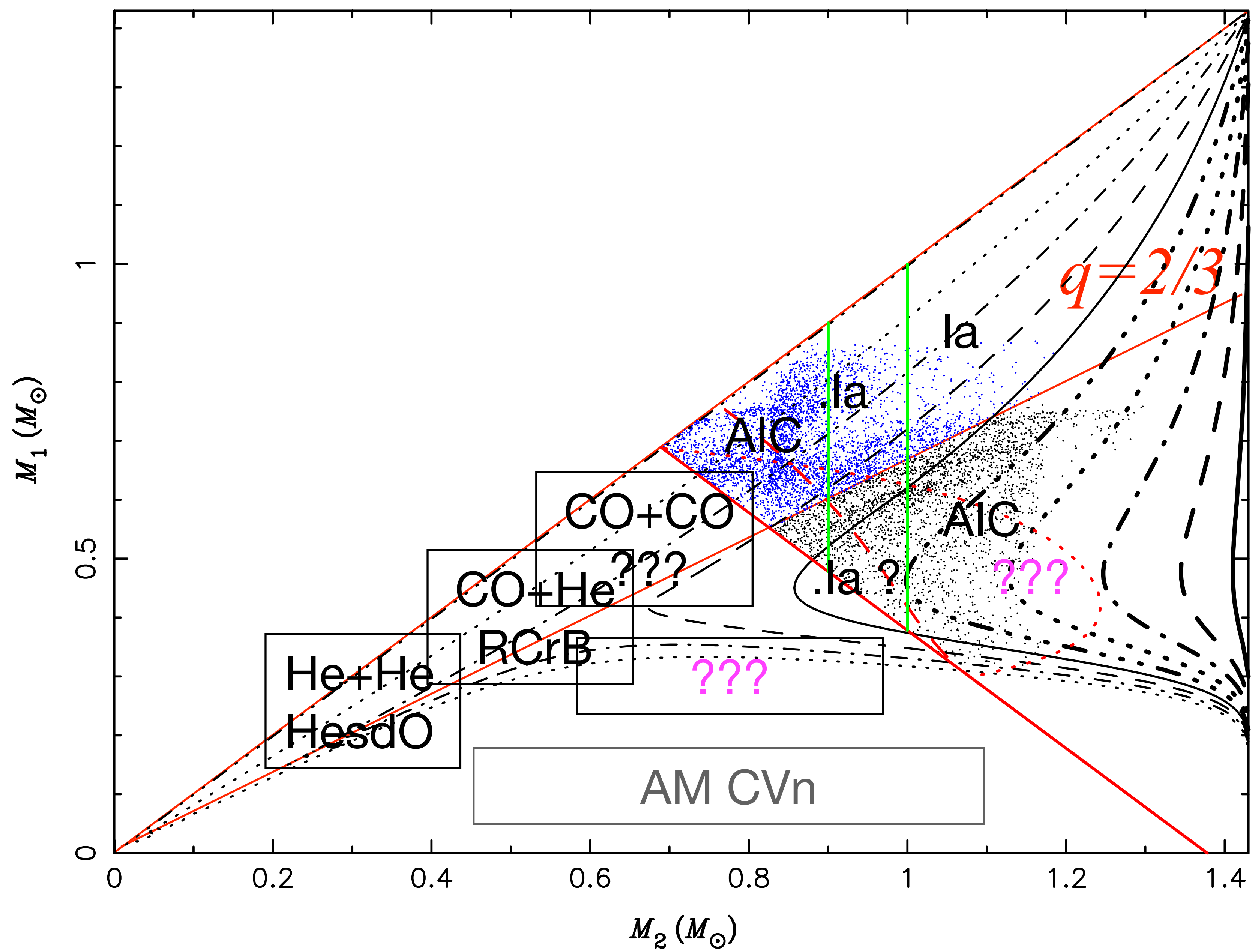
$M_{tot} > M_{ch}$ & $M_2 > 1.0$: SN Ia

$M_{tot} > M_{ch}$ & $M_2 < 0.9$: AIC

$M_{tot} < M_{ch}$: sub Chandra Ia?

...

? neutron stars



Conclusions

- EHe+RCB abundances consistent with CO+He merger. Require some boundary layer mixing and a hot merger. Progenitors 2 - 3 $M_\odot$
- He-sdO/B abundances consistent with He+He merger. Require a composite (corona+disk) process. The most massive mergers are C-rich.
- EHe+RCB distribution suggests an old population. Binary Pop Synth suggests CO+He DWDs primarily young (~1 Gyr). Progenitors 1.5 - 3 $M_\odot$
- He+He DWDs generally much older (4-8 Gyr) Progenitors 1 - 1.5 $M_\odot$