EVOLUTIONARY PATHS OF LOW AND INTERMEDIATE MASS CLOSE BINARIES

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Why not ALL binary stars produce SN Ia progenitors?

REPETITION IS THE MOTHER OF LEARNING

The aims of the binary star evolution theory:

to understand how very different binary stars, e.g. , CV, X-ray binaries or progenitors of SN form from the pairs of stars that differ initially in the masses of components and their separations only;

to explain the observational manifestations of the inhabitants of the binary star zoo;

to estimate the number distribution of different binaries at any epoch of the galactic (cosmic) history, their distributions over basic observable parameters, the occurrence rate of different events, e.g., SNIa, Novae;

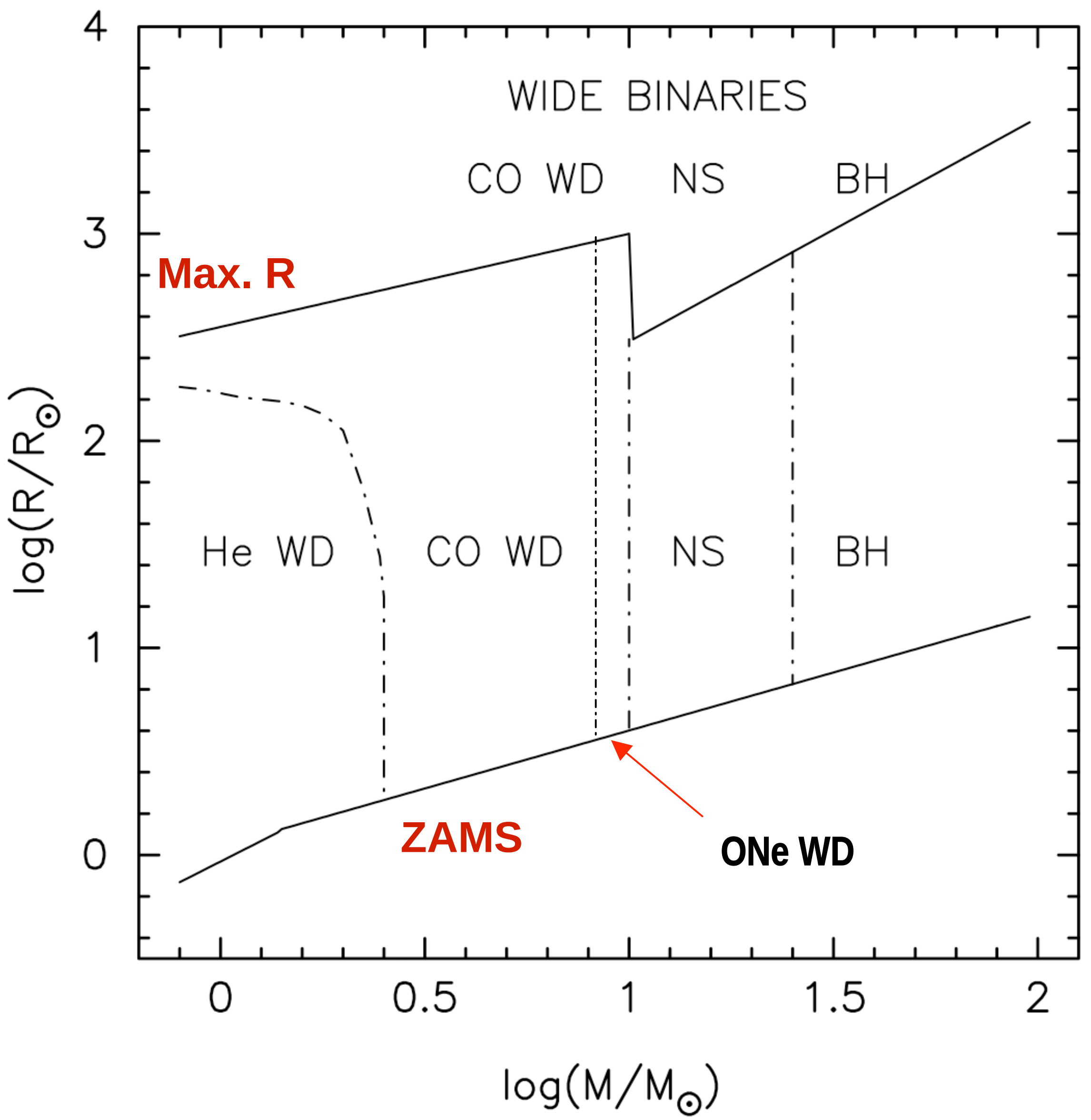
to understand the selection effects that form the observable ensembles of stars of different sorts.

The tool - population synthesis - a convolution of evolutionary scenarios for binaries with statistical data on SFR(t), binarity rate, distributions over initial masses of components and their separations

Evolutionary scenario - the sequence of transformations of a binary star with a given initial set of M_{10}, M_{20}, a_0 that it experiences in a Hubble time.

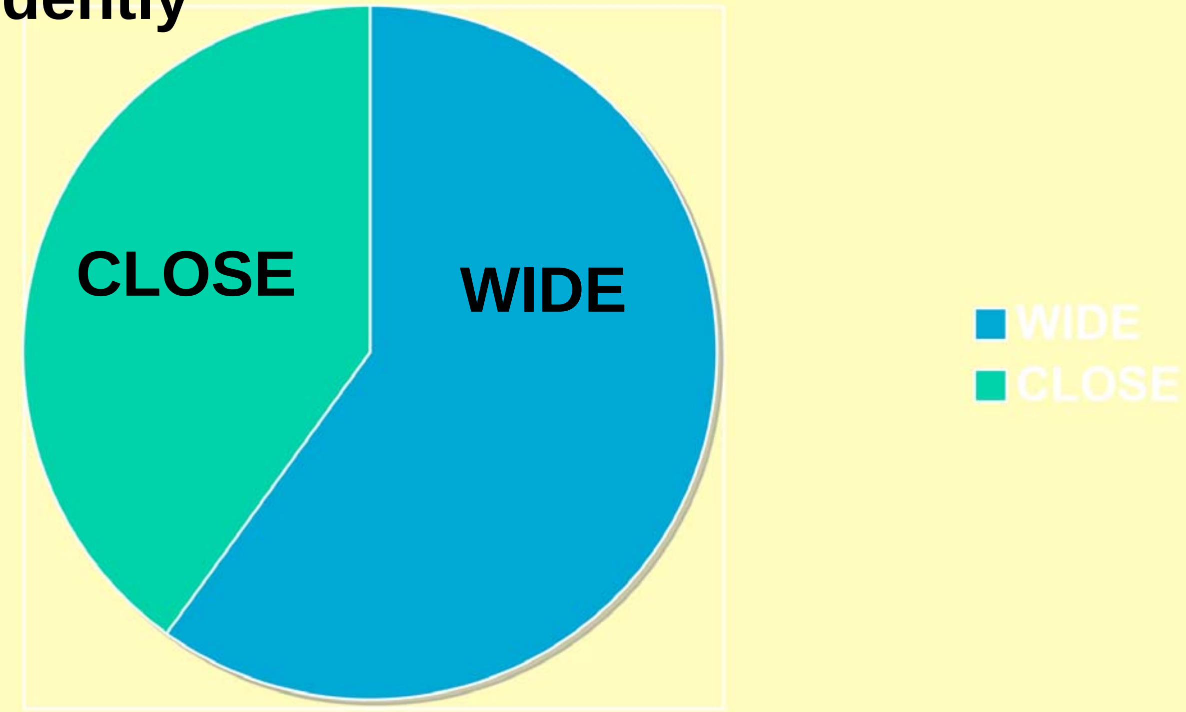
The term “evolutionary scenario”
was coined by Ed van den Heuvel in 70ties

Products of mass loss depending on R at RLOF



"Close binary" - the primary overflows Roche lobe at some instant of its evolution

Among all binaries (if dn~dlog(a))
~40% - close - components interact
~60% - wide - components evolve independently



Among “close” ~90% have low/intermediate mass (~1 to ~10 solar)

Ingredients of scenarios provided by stellar evolution theory:

- the timescales of evolutionary stages;

- the rates of stellar wind in different evolutionary stages
  (mass loss prior to RLOF);

- the rates of mass-exchange upon RLOF for stars in different evolutionary stages and for different donor/accretor combinations
  (stable vs. unstable mass exchange);

- the nature of the products of mass-exchange or mass-loss stages (He-stars, WD) and initial - final mass relations;

- response of stars to accretion (formation of common envelopes? response of compact objects to accretion - erosion or growth?)

- transformation of separations of components under different assumptions on mass and momentum loss

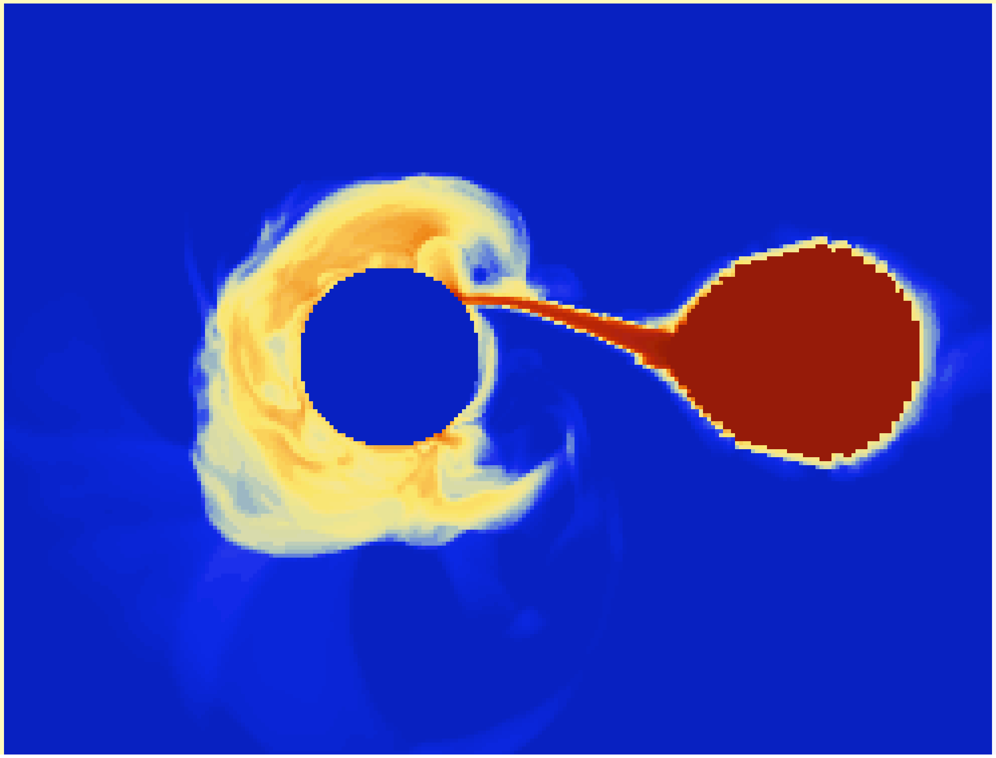
…

Input from statistics:

- binarity rate - 50 to 100% (changes only normalisation)
- SFR(t) - flat or peaking at T=0 or …
- IMF - Salpeter, Miller-Scalo, …
- mass ratio distribution $f(q)=Cq^a$
- distribution over semimajor axes of orbits $f(a) \sim a^{-1}$
- distribution over eccentricities of orbits (sometimes)
- normalisation of SFR - e. g., 1 wd is born per yr in the Galaxy

Mass and momentum loss: necessity for their account was noticed already in the first attempts to compare results of computations for CBS with observations (Paczynski, Ziolkowski, Weigert, Refsdal … , late 60ties)

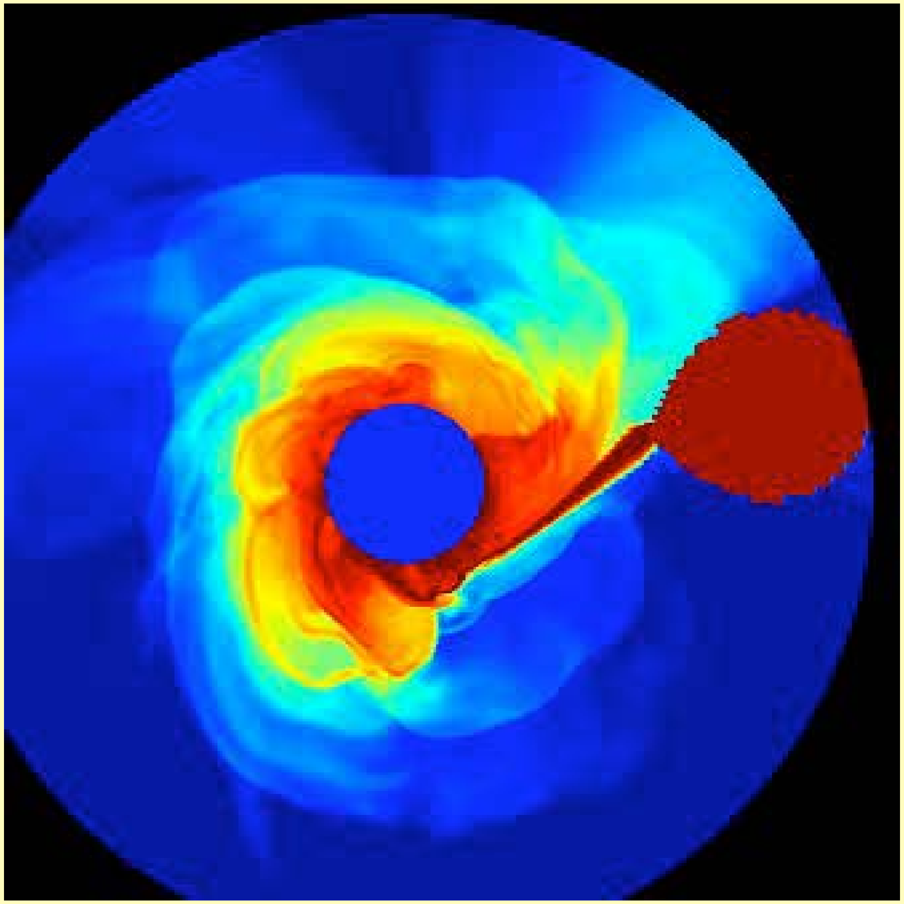
But we still do not understand how mass and momentum are lost even from the simplest binaries like Algols and are unable to reproduce their distributions over P and q and have to **parameterize** mass and momentum loss using observations of well-studied binaries



M.Richards & M. Ratliff

3/10/07

Model of the Algol binary



http://wonka.physics.ncsu.edu/Astro/Research/Algol/algol.mpeg

Sinks of momentum: "Ordinary" stellar wind, GWR, MSW, circumbinary disks

THE MOST MYSTERIOUS STAGE -- COMMON ENVELOPE

May arise due to

- * tidal instability, if mass ratio >5-6
- * inability of accretor to "swallow" all mass transferred by the donor, i.e., mass-transfer timescale is important
- * super-Eddington accretion rate

Mass exchange timescale depends, primarily, on the mass ratio of components and the structure of the donor.

Mass-exchange is unstable (dynamical timescale), if the donor has a deep convective envelope or $q \geq 2$.

As a result , 1 to 4 CE episodes in the lifetime of a binary.

Most commonly used: Webbink 1984; de Kool 1990

$$\frac{GM_{\rm donor}M_{\rm env}}{\lambda a_{\rm i} r_{\rm L}} = \eta_{\rm CE}\left[\frac{GM_{\rm core}M_2}{2a_{\rm f}} - \frac{GM_{\rm donor}M_2}{2a_{\rm i}}\right]$$

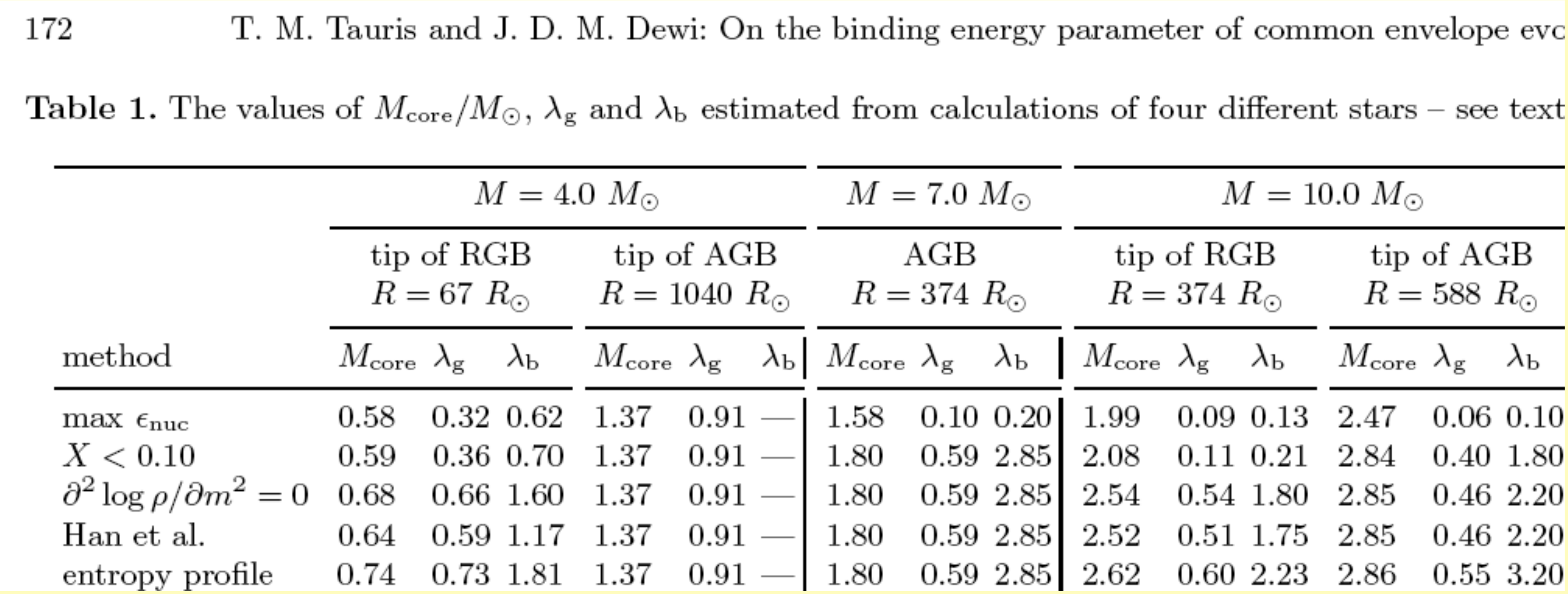
$$\frac{a_{\rm f}}{a_{\rm i}} = \frac{M_{\rm core}M_2}{M_{\rm donor}}\frac{1}{M_2 + 2M_{\rm env}/(\eta_{\rm CE}\lambda r_{\rm L})}.$$

Han, 1994

$$E_{\rm bind} = \int_{M_{\rm core}}^{M_{\rm donor}} \left(-\frac{GM(r)}{r} + U\right) dm$$

U is the internal thermodynamic energy

$$E_{\rm env} = -\int_{M_{\rm core}}^{M_{\rm donor}} \frac{GM(r)}{r} dm + \alpha_{\rm th}\int_{M_{\rm core}}^{M_{\rm donor}} U\, dm$$



172 T. M. Tauris and J. D. M. Dewi: On the binding energy parameter of common envelope evc

Table 1. The values of $M_{\rm core}/M_\odot$, $\lambda_{\rm g}$ and $\lambda_{\rm b}$ estimated from calculations of four different stars – see text

	$M = 4.0\ M_\odot$						$M = 7.0\ M_\odot$			$M = 10.0\ M_\odot$					
	tip of RGB $R = 67\ R_\odot$			tip of AGB $R = 1040\ R_\odot$			AGB $R = 374\ R_\odot$			tip of RGB $R = 374\ R_\odot$			tip of AGB $R = 588\ R_\odot$		
method	$M_{\rm core}$	$\lambda_{\rm g}$	$\lambda_{\rm b}$	$M_{\rm core}$	$\lambda_{\rm g}$	$\lambda_{\rm b}$	$M_{\rm core}$	$\lambda_{\rm g}$	$\lambda_{\rm b}$	$M_{\rm core}$	$\lambda_{\rm g}$	$\lambda_{\rm b}$	$M_{\rm core}$	$\lambda_{\rm g}$	$\lambda_{\rm b}$
max $\epsilon_{\rm nuc}$	0.58	0.32	0.62	1.37	0.91	—	1.58	0.10	0.20	1.99	0.09	0.13	2.47	0.06	0.10
$X < 0.10$	0.59	0.36	0.70	1.37	0.91	—	1.80	0.59	2.85	2.08	0.11	0.21	2.84	0.40	1.80
$\partial^2 \log \rho / \partial m^2 = 0$	0.68	0.66	1.60	1.37	0.91	—	1.80	0.59	2.85	2.54	0.54	1.80	2.85	0.46	2.20
Han et al.	0.64	0.59	1.17	1.37	0.91	—	1.80	0.59	2.85	2.52	0.51	1.75	2.85	0.46	2.20
entropy profile	0.74	0.73	1.81	1.37	0.91	—	1.80	0.59	2.85	2.62	0.60	2.23	2.86	0.55	3.20

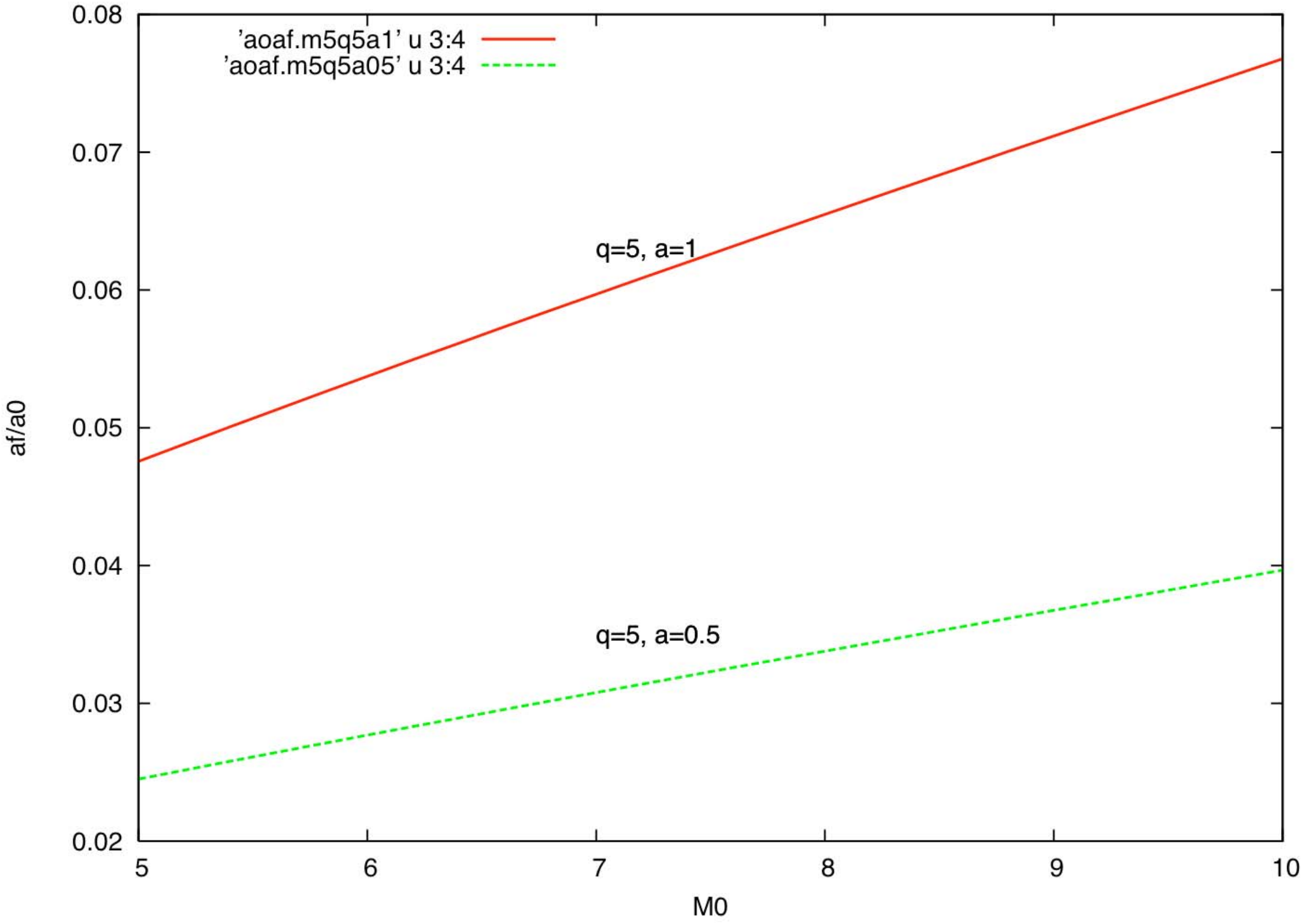
The value of λ is different in different evolutionary stages, depends on the definition of the "core=mass of the donor remnant" and on the terms included in the consideration of binding energy: gravitational energy only or (a fraction of) thermodynamic energy too.

Are there other energy sources that can contribute to η_{CE} ?

η_{CE} may be >1, it is not a universal constant

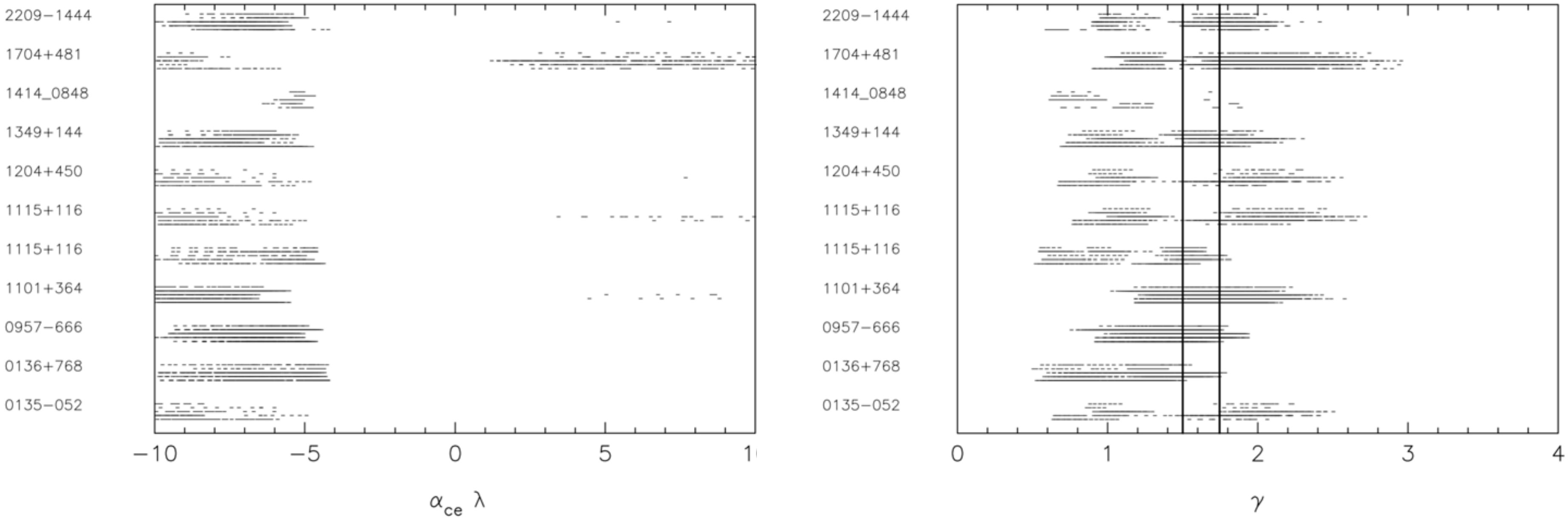
CE may be avoided in some cases by ejection of matter on expense of accretion luminosity?

Relative reduction of separation in common envelope



“Standard” common envelope formalism may be not valid for the first unstable RLOF in the systems with comparable masses of components

(Nelemans et al. 2000, Nelemans & Tout 2004).

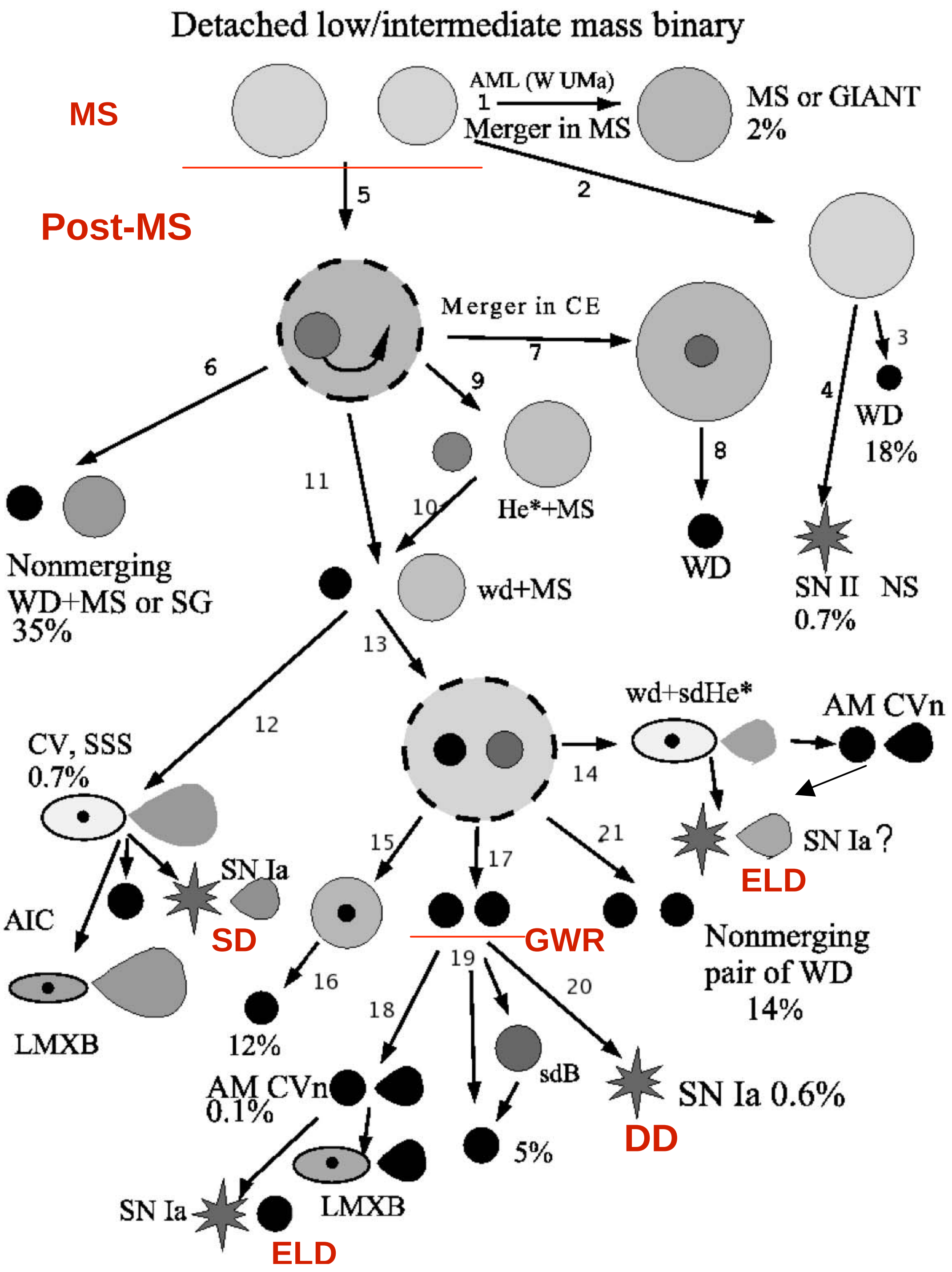


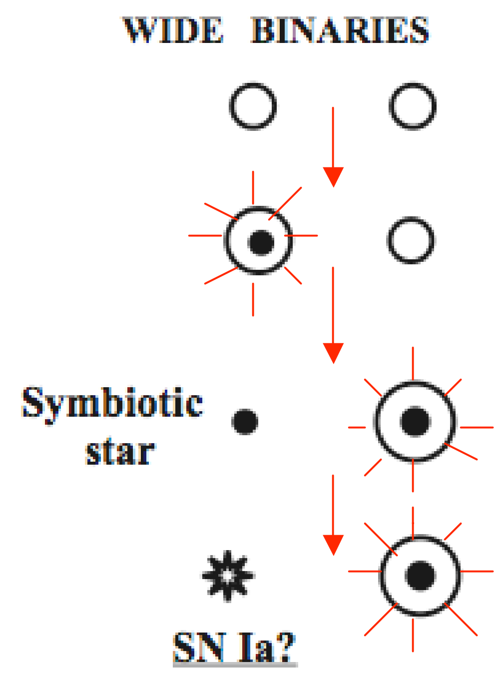
Common envelope formalism may be replaced, e.g., by the “angular momentum balance” formalism (Nelemans et al., 2000), but a parameter still remains

$$\frac{\Delta J}{J} = \gamma \frac{\Delta M}{M_d + M_a}$$

A run of a population synthesis code for ~6e6 binaries (this gives sufficient resolution in “M1 - M2 - a” space) with M1= 0.8 to 10 Msun produces ~600 different scenarios. Some have up to 15-20 stages.

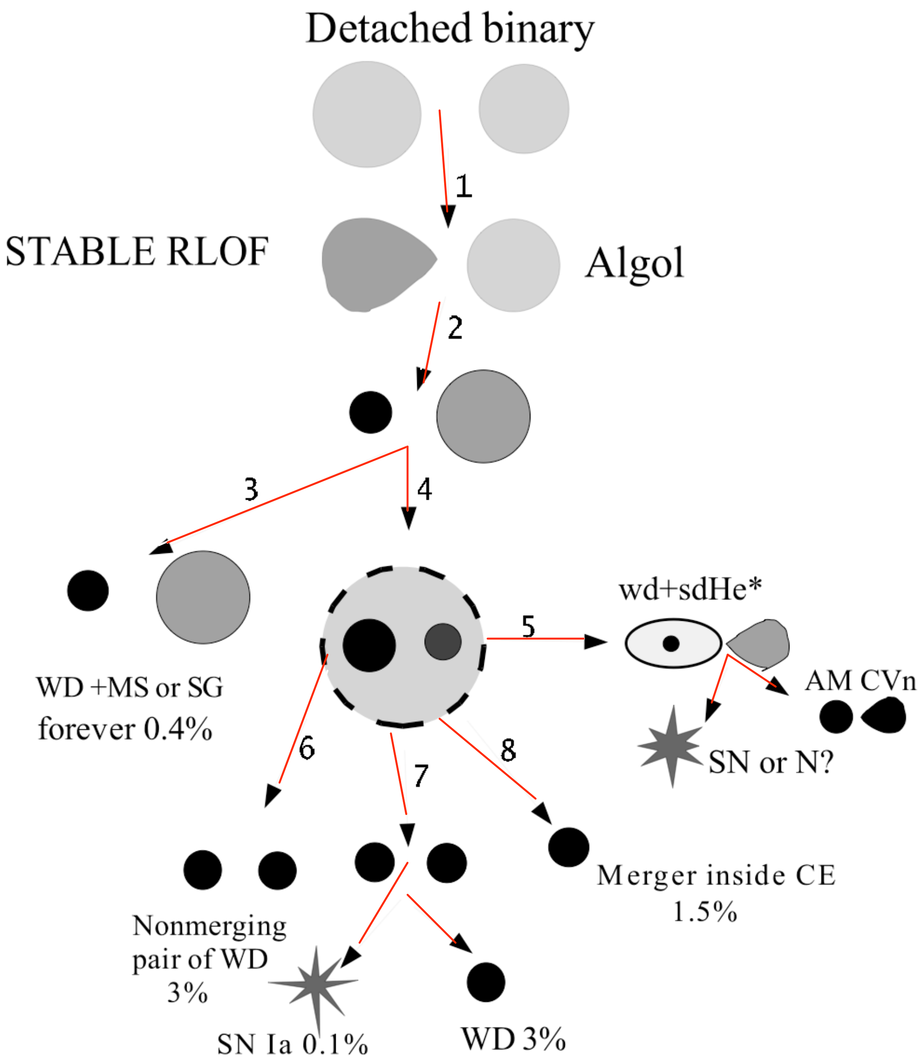
~90% of them have unstable first ME episode.



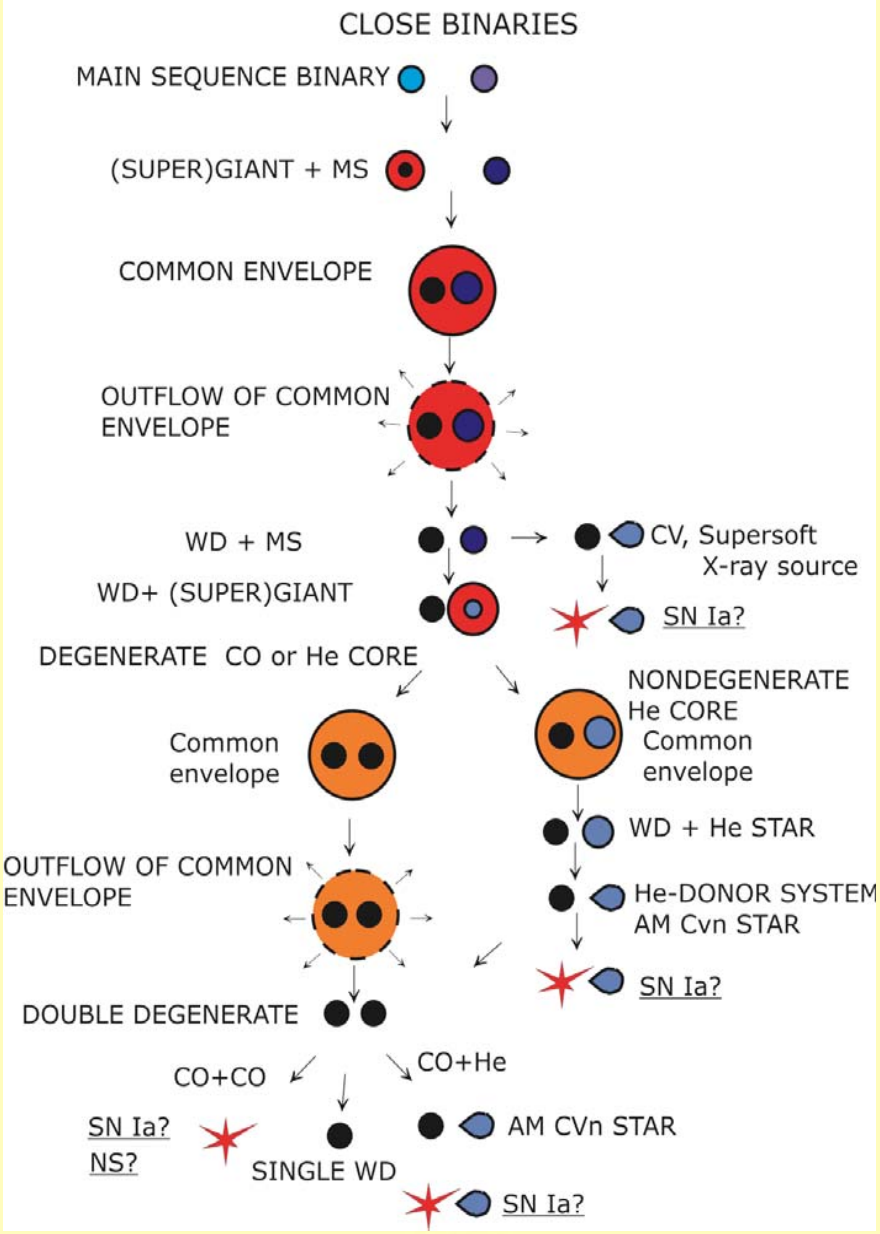


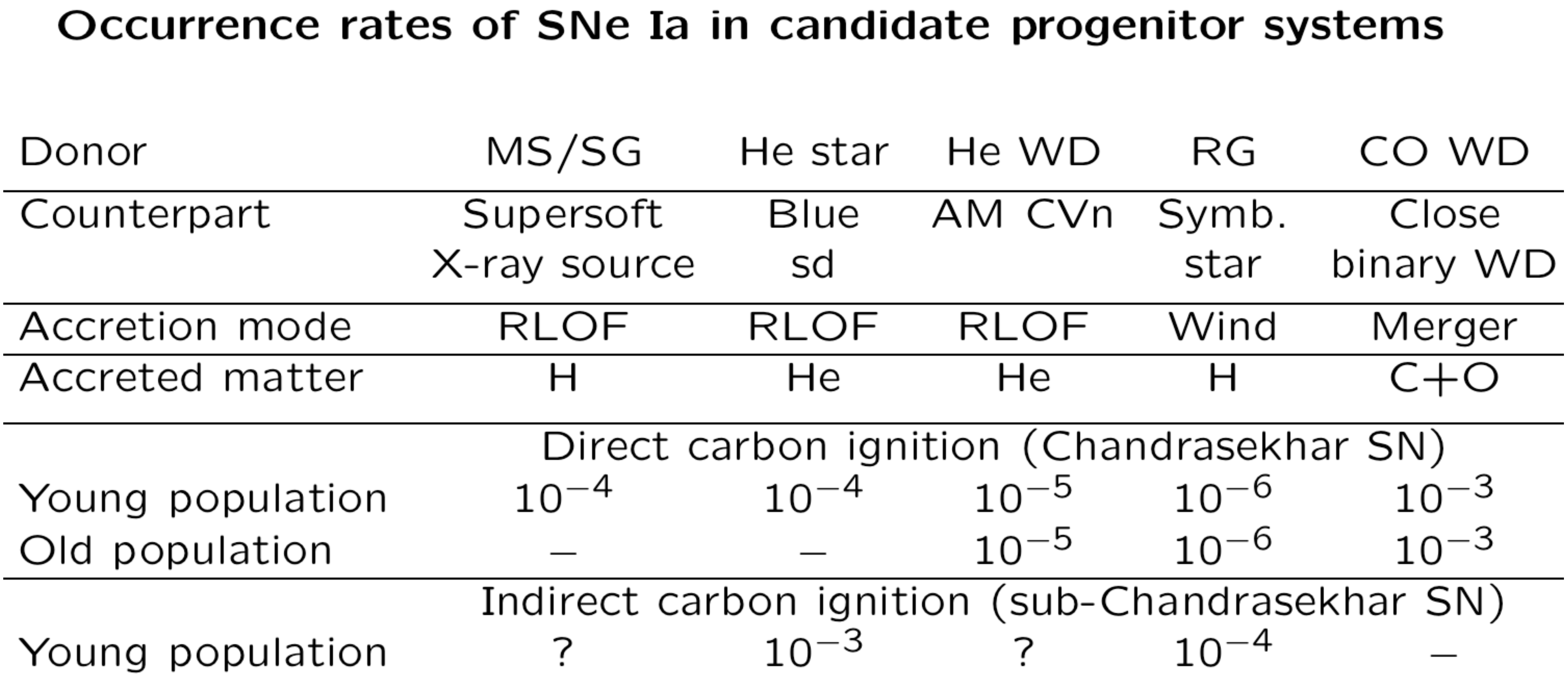
What may happen to a close binary in 13 Gyr?

Close binaries with stable first RLOF



A summary of scenarios for formation of potential SN Ia progenitors in close binaries





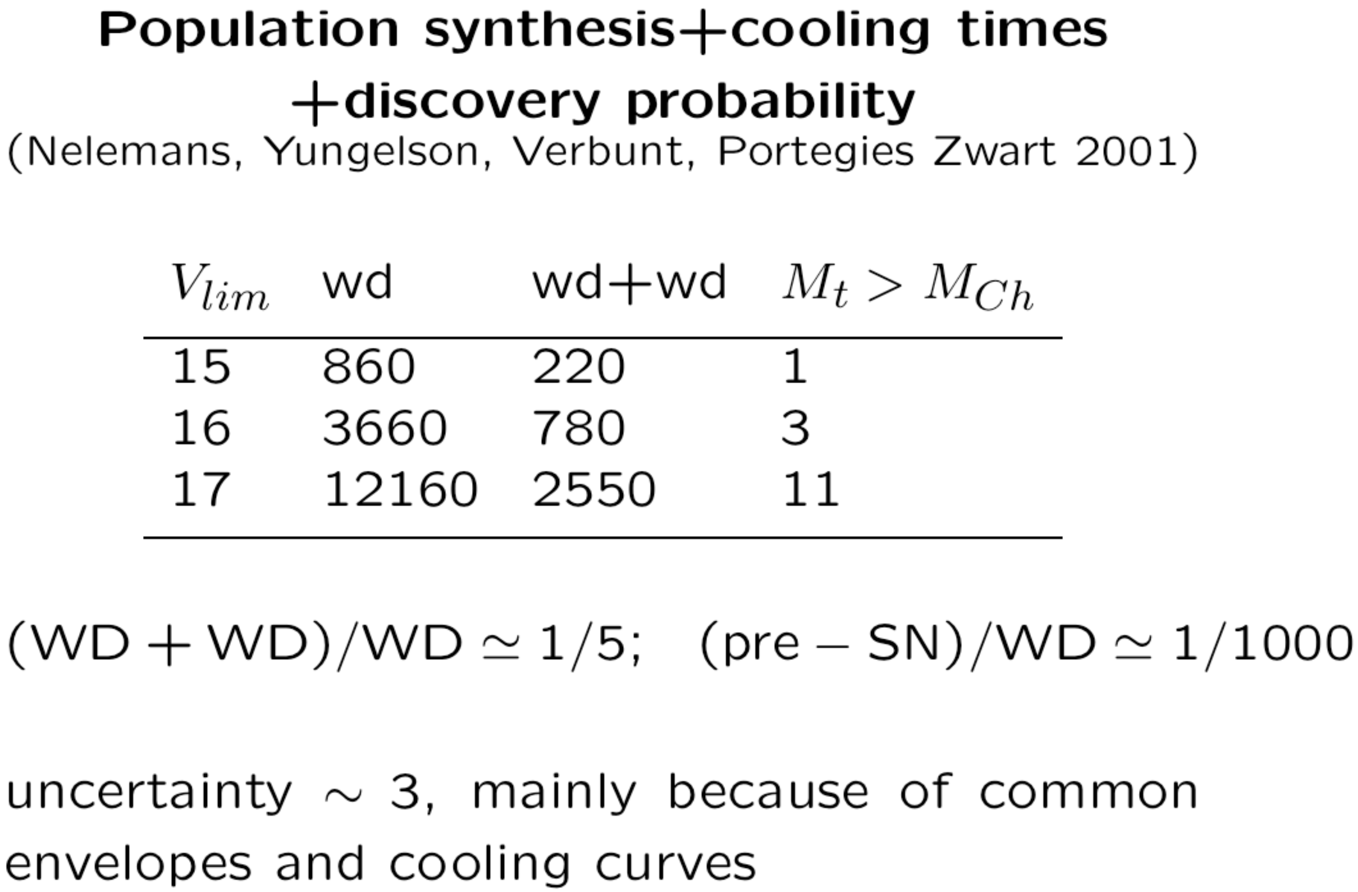
Occurrence rates of SNe Ia in candidate progenitor systems

Donor	MS/SG	He star	He WD	RG	CO WD
Counterpart	Supersoft X-ray source	Blue sd	AM CVn	Symb. star	Close binary WD
Accretion mode	RLOF	RLOF	RLOF	Wind	Merger
Accreted matter	H	He	He	H	C+O
	Direct carbon ignition (Chandrasekhar SN)				
Young population	10^{-4}	10^{-4}	10^{-5}	10^{-6}	10^{-3}
Old population	–	–	10^{-5}	10^{-6}	10^{-3}
	Indirect carbon ignition (sub-Chandrasekhar SN)				
Young population	?	10^{-3}	?	10^{-4}	–

Observationally inferred Galactic rate - 4±2 per 1000 yr

(Cappellaro et al. 1999)

Model predictions for the magnitude-limited sample of wd that has to be surveyed for binarity In order to find a super-Chandrasekhar total mass pair



Population synthesis+cooling times +discovery probability

(Nelemans, Yungelson, Verbunt, Portegies Zwart 2001)

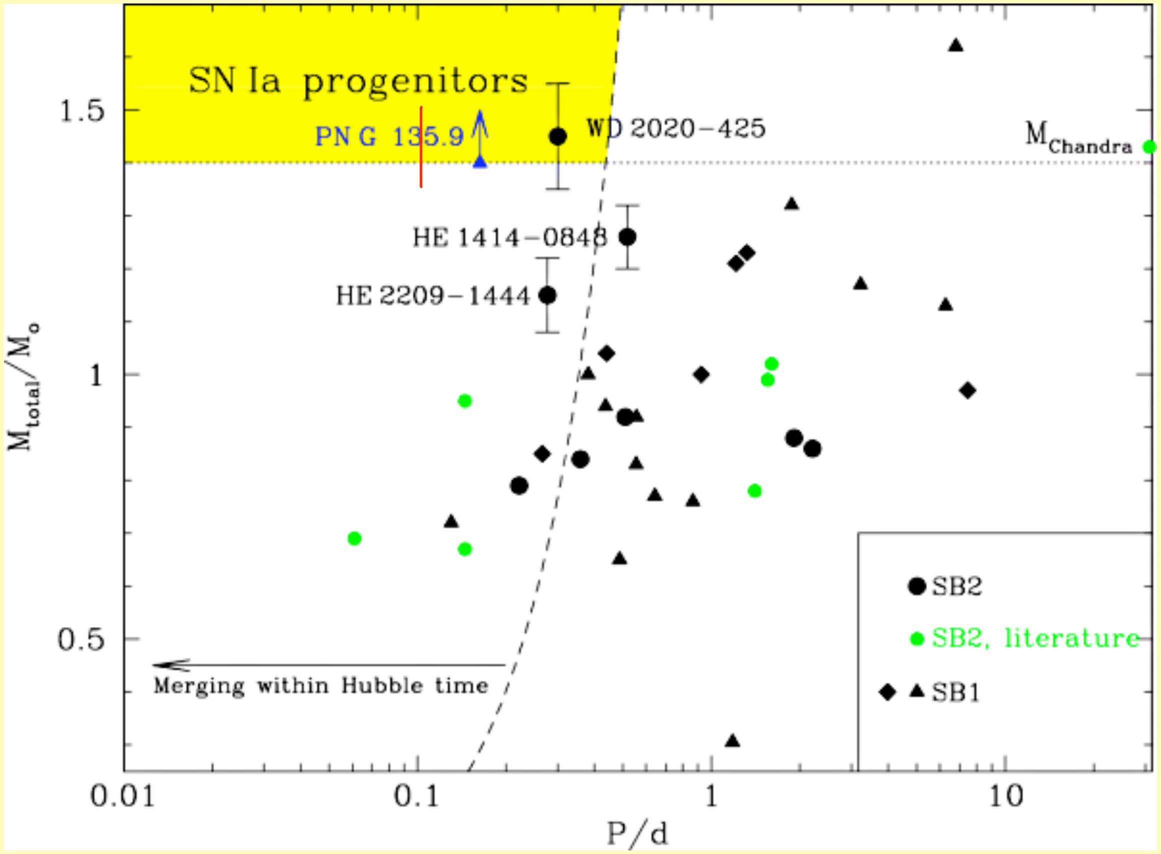
V_{lim}	wd	wd+wd	$M_t > M_{Ch}$
15	860	220	1
16	3660	780	3
17	12160	2550	11

$$(\mathrm{WD}+\mathrm{WD})/\mathrm{WD} \simeq 1/5; \quad (\mathrm{pre}-\mathrm{SN})/\mathrm{WD} \simeq 1/1000$$

uncertainty $\sim$ 3, mainly because of common envelopes and cooling curves

ESO Supernovae Progenitor surveY = SPY

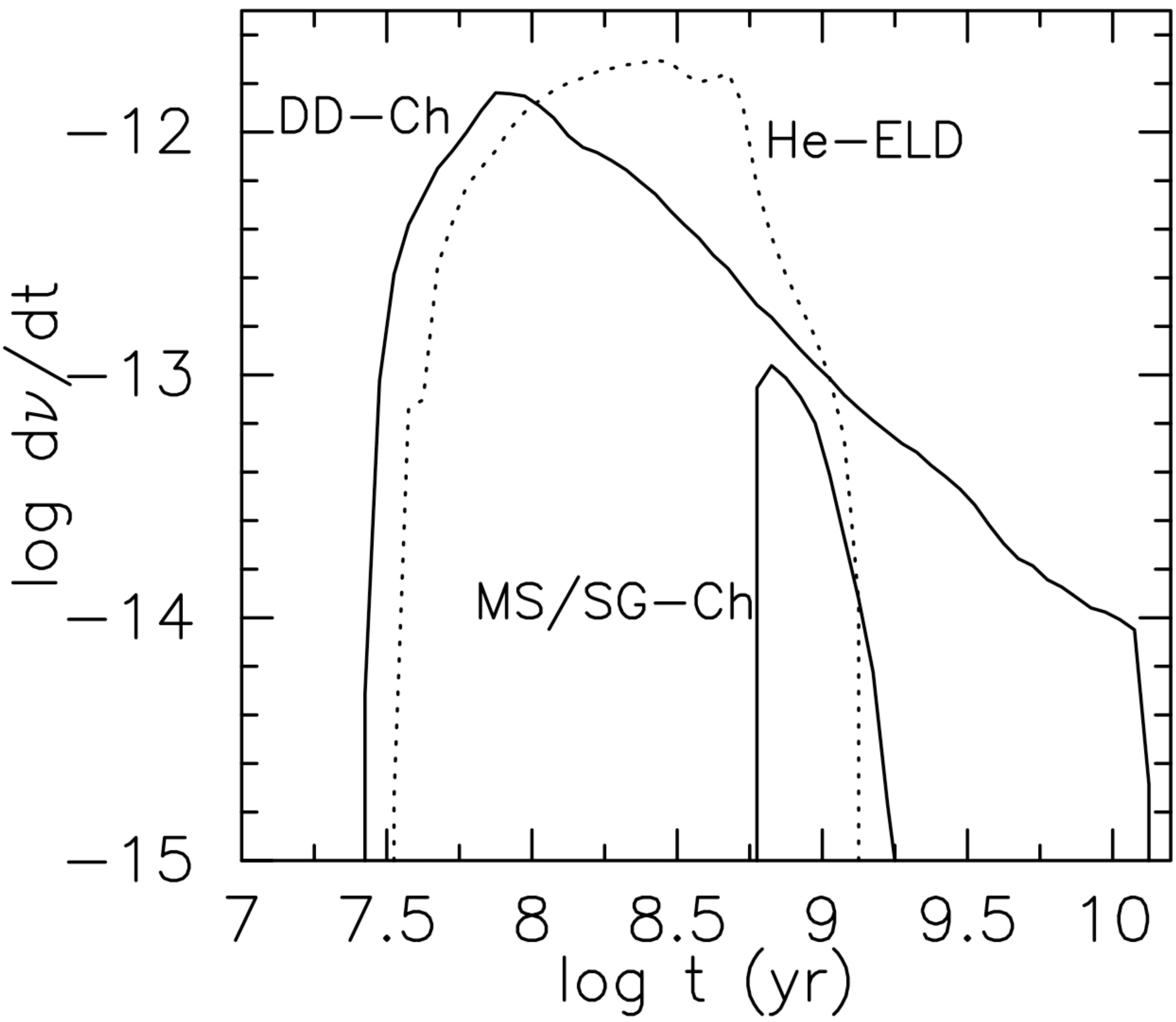
(a survey for radial velocity variations of ~1000 wd brighter than B≈16.5; ΔRV>2km/s)

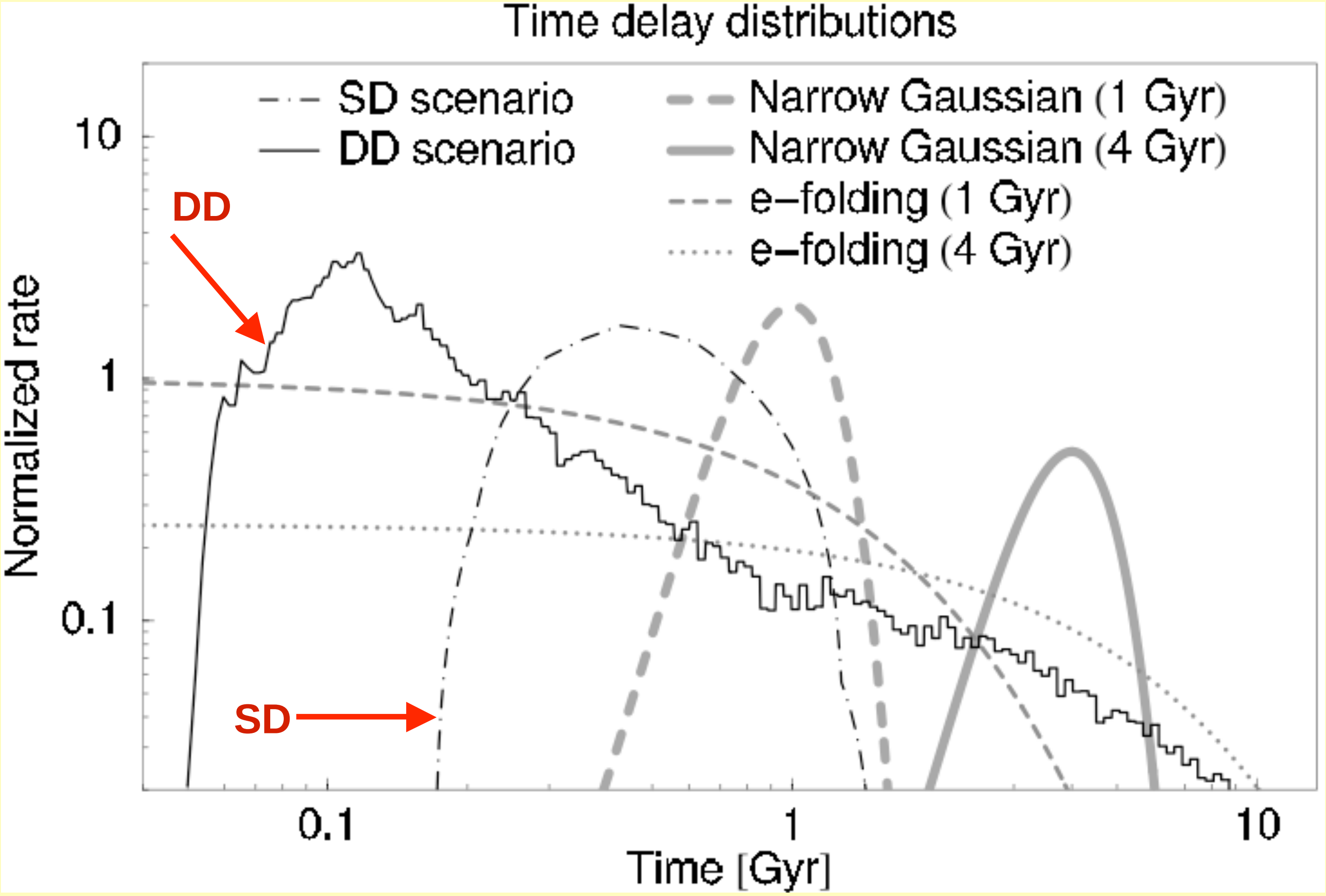


R. Napiwotzki, fall 2005

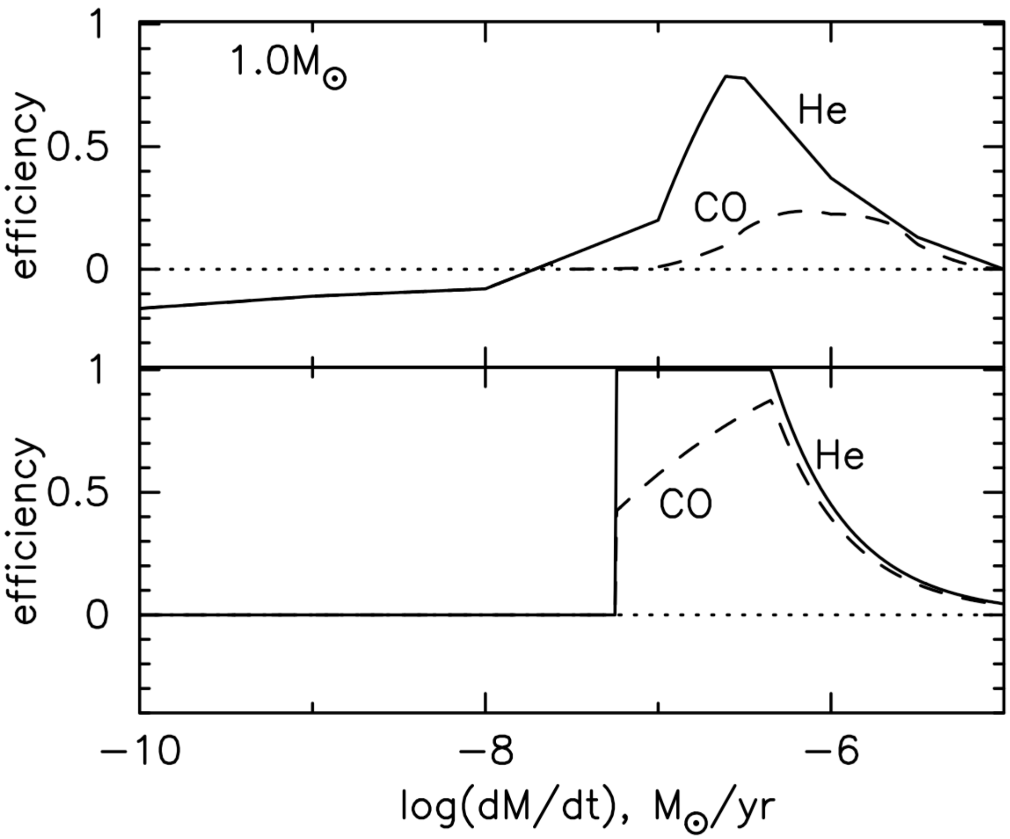
— KPD1930+2752 (Geier et al. 2007) - sdB+wd - nascent wd+wd

PN G135.9+55.9 (Tovmassian et al. 2004) - binary nucleus of PN - nascent wd (0.85Msun)+ce


DD−Ch
He−ELD
MS/SG−Ch
−12
−13
−14
−15
log dν/dt
7
7.5
8
8.5
9
9.5
10
log t (yr)



Foerster, Wolf, Podsiadlowski, Han, 2006



TY: wind for steady burners, mass loss from RG-type envelopes,
possibility of erosion (PK95)
ν(SD) ~0.1ν(DD)

HP: no wind, no erosion, no mass-loss from RG-type envelopes
ν(SD) >ν(DD)

Different estimates of the effect of He-flashes

Comparison of matter accumulation efficiencies in different population synthesis codes:
Tutukov & Yungelson vs. Han & Podsiadlowski

CONCLUSION

- Evolutionary links between many of close binary stars are, at least qualitatively, understood.

- Quantitative results are very strongly dependent on input parameters, especially, on common envelope formalism; in the absence of theoretical models, some parameters may be constrained by studies of formation of individual observed close binaries.

There are some very important problems to solve:

- mass and angular momentum loss from the close binaries;
- evolution in common envelopes;
- merger of stars, from MS-stars through relativistic objects;
- evolution of merger products;
- response of accreting stars to accretion depending on the nature of accretors, accretion rate and chemical composition of accreted matter;

…