Astrophysics of gravitational wave sources

Lecture 8: binary star evolution: Roche potential, mass transfer, common envelope

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FAILURE OF A NEUTRINO-DRIVEN EXPLOSION AFTER CORE-COLLAPSE MAY LEAD TO A THERMONUCLEAR SUPERNOVA

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ABSTRACT

We demonstrate that ∼10 s after the core-collapse of a massive star, a thermonuclear explosion of the outer shells is possible for some (tuned) initial density and composition profiles, assuming that the neutrinos failed to explode the star. The explosion may lead to a successful supernova, as first suggested by Burbidge et al. We perform a series of one-dimensional (1D) calculations of collapsing massive stars with simplified initial density profiles (similar to the results of stellar evolution calculations) and various compositions (not similar to 1D stellar evolution calculations). We assume that the neutrinos escaped with a negligible effect on the outer layers, which inevitably collapse. As the shells collapse, they compress and heat up adiabatically, enhancing the rate of thermonuclear burning. In some cases, where significant shells of mixed helium and oxygen are present with pre-collapsed burning times of $\lesssim 100$ s (≈ 10 times the free-fall time), a thermonuclear detonation wave is ignited, which unbinds the outer layers of the star, leading to a supernova. The energy released is small, $\lesssim 10^{50}$ erg, and negligible amounts of synthesized material (including ^{56}Ni) are ejected, implying that these 1D simulations are unlikely to represent typical core-collapse supernovae. However, they do serve as a proof of concept that the core-collapse-induced thermonuclear explosions are possible, and more realistic two-dimensional and three-dimensional simulations are within current computational capabilities.

Key words: hydrodynamics – methods: numerical – supernovae: general

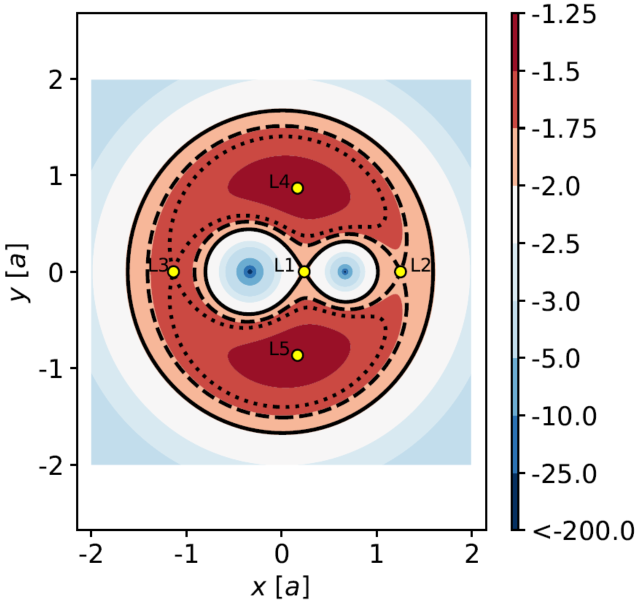
Roche potential

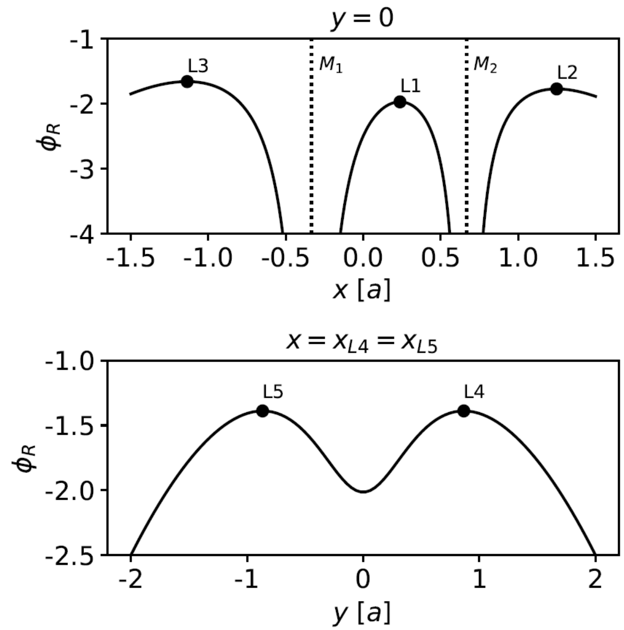
$$\ddot{\mathbf{r}} = -\nabla \phi_R(\mathbf{r}) - 2\boldsymbol{\omega} \times \dot{\mathbf{r}},$$

$$\phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r} - \mathbf{r_1}|} - \frac{GM_2}{|\mathbf{r} - \mathbf{r_2}|} + \frac{1}{2}|\boldsymbol{\omega} \times \mathbf{r}|^2$$

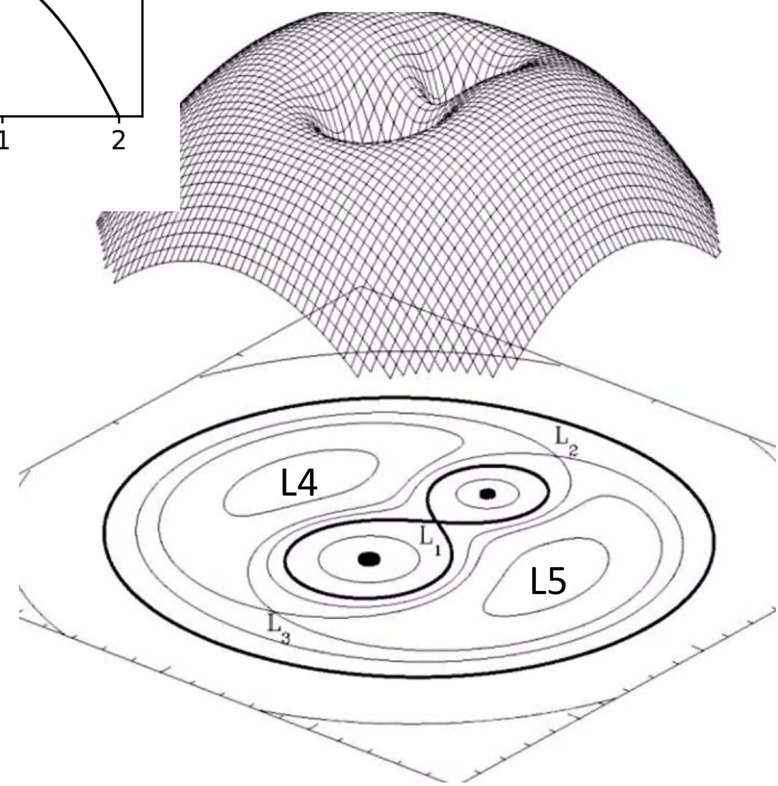
$$\omega^2 = \frac{GM}{a^3} = \left(\frac{2\pi}{T}\right)^2 \qquad q = \frac{M_2}{M_1} \qquad \mu = \frac{M_2}{M_1 + M_2} = \frac{q}{1+q}$$

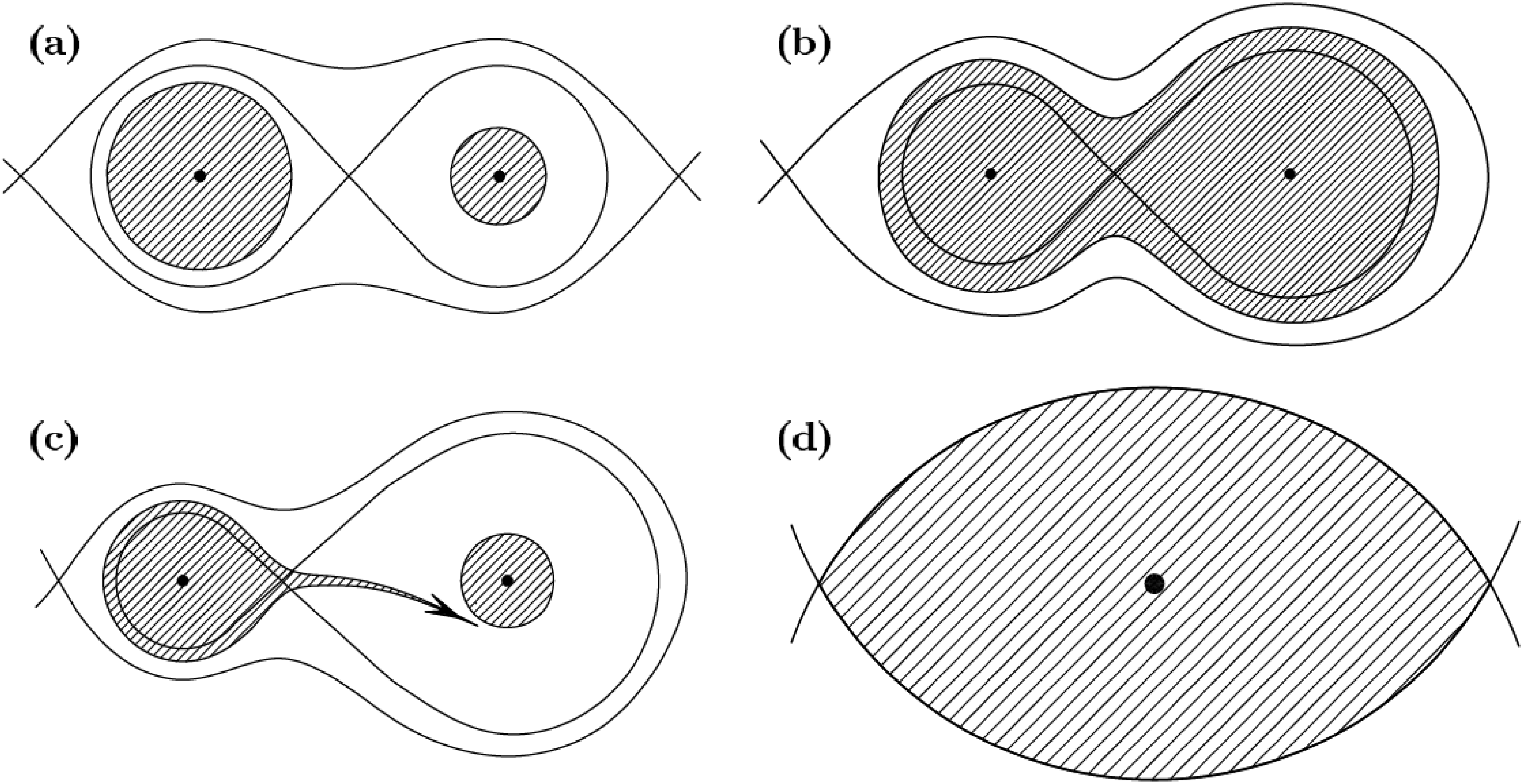
Roche potential





D. Hubová – Bc. thesis





Eggleton – Binary stars

Mass-radius relations of stars, evolutionary timescales

ZAMS:

$$\frac{R}{R_\odot} \simeq \left(\frac{M}{M_\odot}\right)^{0.7}$$

(Polytrope with γ = 5/3 has adiabatic $R \sim M^{-1/3}$)

$$\frac{L}{L_\odot} \simeq \left(\frac{M}{M_\odot}\right)^{3.8}$$

$$\tau_{\rm dyn} = \frac{R}{c_{\rm s}} \approx 0.04 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{R}{R_\odot}\right)^{3/2} \text{ day}$$

$$\tau_{\rm KH} = \frac{E_{\rm th}}{L} \approx \frac{GM^2}{2RL} \approx 1.5 \times 10^7 \left(\frac{M}{M_\odot}\right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \text{ yr}$$

$$\tau_{\rm nuc} = 0.007 \frac{M_{\rm core} c^2}{L} \approx 10^{10} \frac{M}{M_\odot} \frac{L_\odot}{L} \text{ yr}$$

Onno Pols' lecture notes http://www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/Binaries_ch6-8.pdf

Roche lobe overflow

$$\log R = \log R_0 + R'_{\mathrm{TE}} \log \frac{M_1}{M_0} + \frac{t}{t_{\mathrm{NE}}}$$

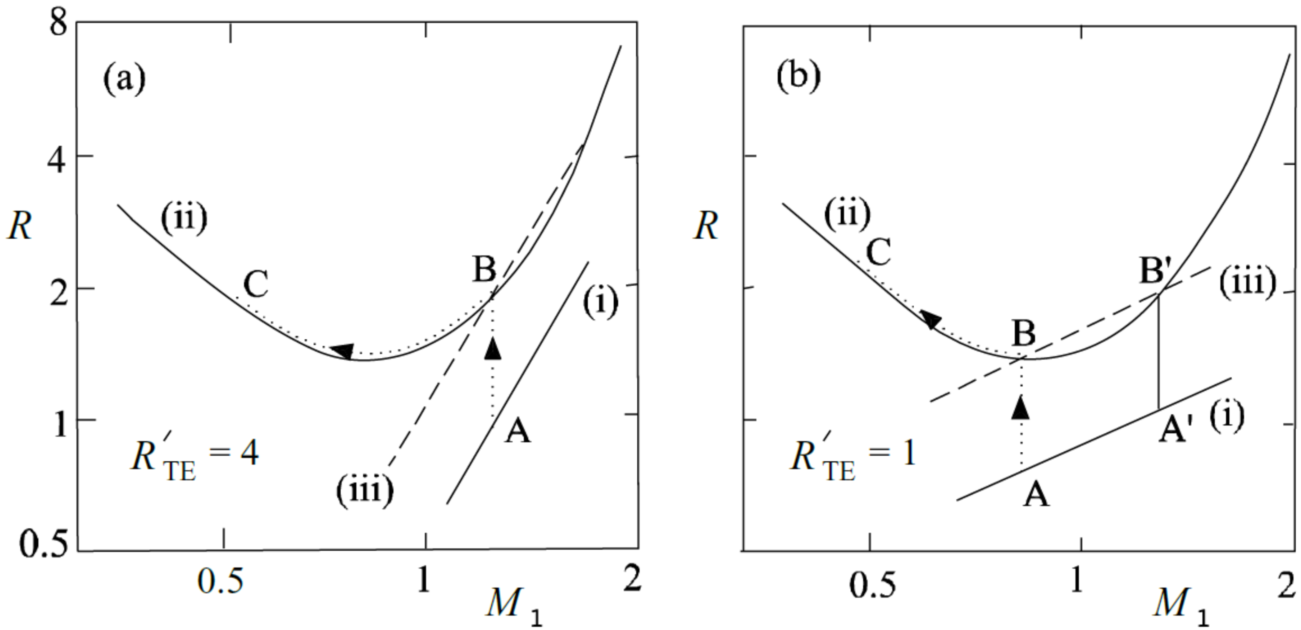


Figure 3.4 Schematic behaviour of Roche-lobe radius and stellar radius as functions of primary mass during evolution governed by the simplistic relation (3.52). Units are arbitrary, except that the total mass is 2 units. The curves are (i) the ZAMS radius, (ii) the Roche-lobe radius, (iii) the radius at time $t = t_{\mathrm{NE}} \log 2$. The star starts on curve (i), at point A or A′, and evolves vertically until it reaches curve (ii) at B or B′. From B in either panel, it can proceed to evolve along curve (ii) to C, losing mass while still evolving on a nuclear timescale. In (b) it cannot do this from point B′, since curve (ii) is steeper than curve (iii) there.

$$\frac{\mathrm{d} \log M_1}{\mathrm{d}t} = -\frac{1}{t_{\mathrm{NE}}} \cdot \frac{1}{R'_{\mathrm{TE}} - R'_{\mathrm{L}}}.$$

(Eggleton's book)

Logarithmic change of the Roche lobe radius with orbital angular momentum and total mass fixed:

$$R'_{\mathrm{L}} \equiv \frac{\mathrm{d}\log R_{\mathrm{L}}}{\mathrm{d}\log M_1} = (1+q)\cdot\left(\frac{\mathrm{d}\log R_{\mathrm{L}}/a}{\mathrm{d}\log q} + \frac{\mathrm{d}\log a}{\mathrm{d}\log q}\right)$$
$$\approx 2.13q - 1.67, \quad 0 < q \lesssim 50;$$

Polytrope with $\gamma = 5/3$ has adiabatic $R \sim M^{-1/3}$, which leads to critical q

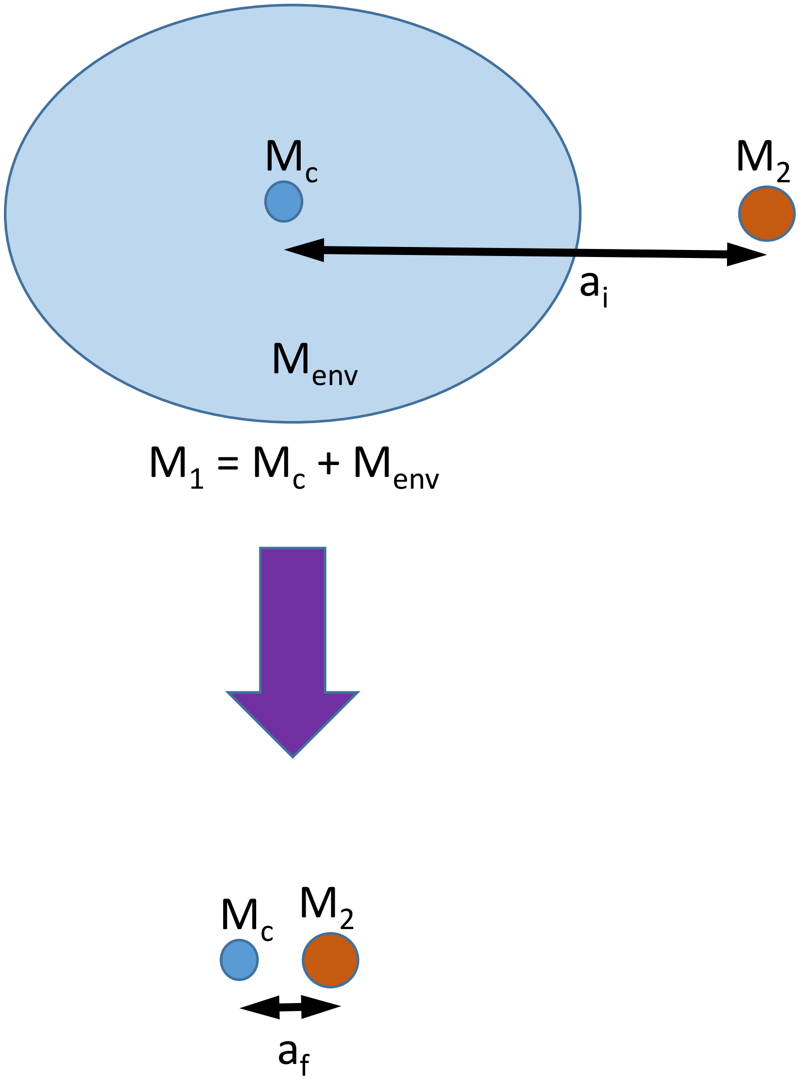
Dynamical instability -> total energy conserved

(Eggleton's book)

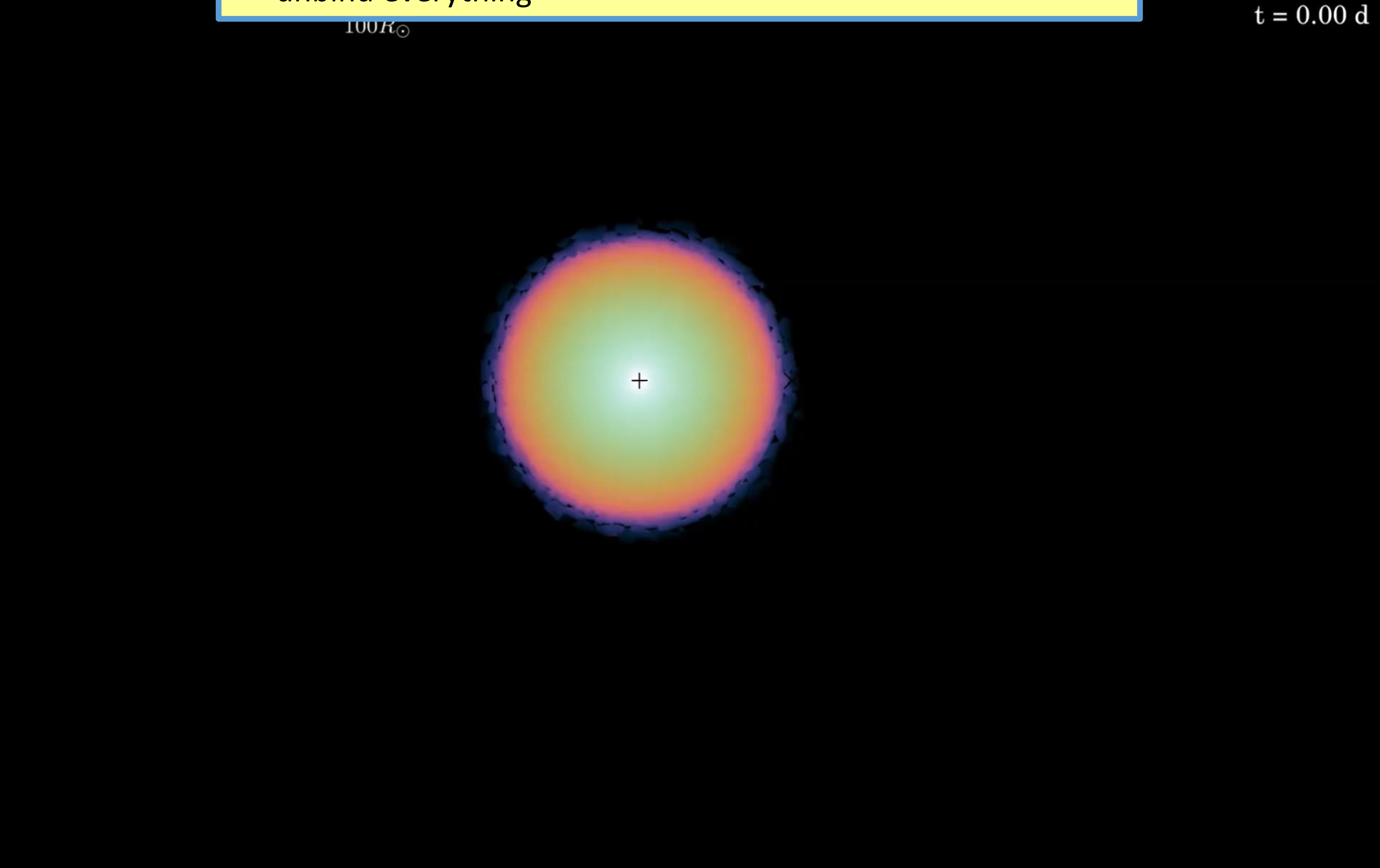
Roche lobe overflow

- Nuclear, thermal, dynamical timescale
- Conservative vs nonconservative evolution
- Nonconservative processes:
    - Stellar wind
    - Magnetic braking
    - Gravitational radiation
    - Tidal friction
    - Secular dynamics
    - (supernova, common envelope, cluster dynamics)

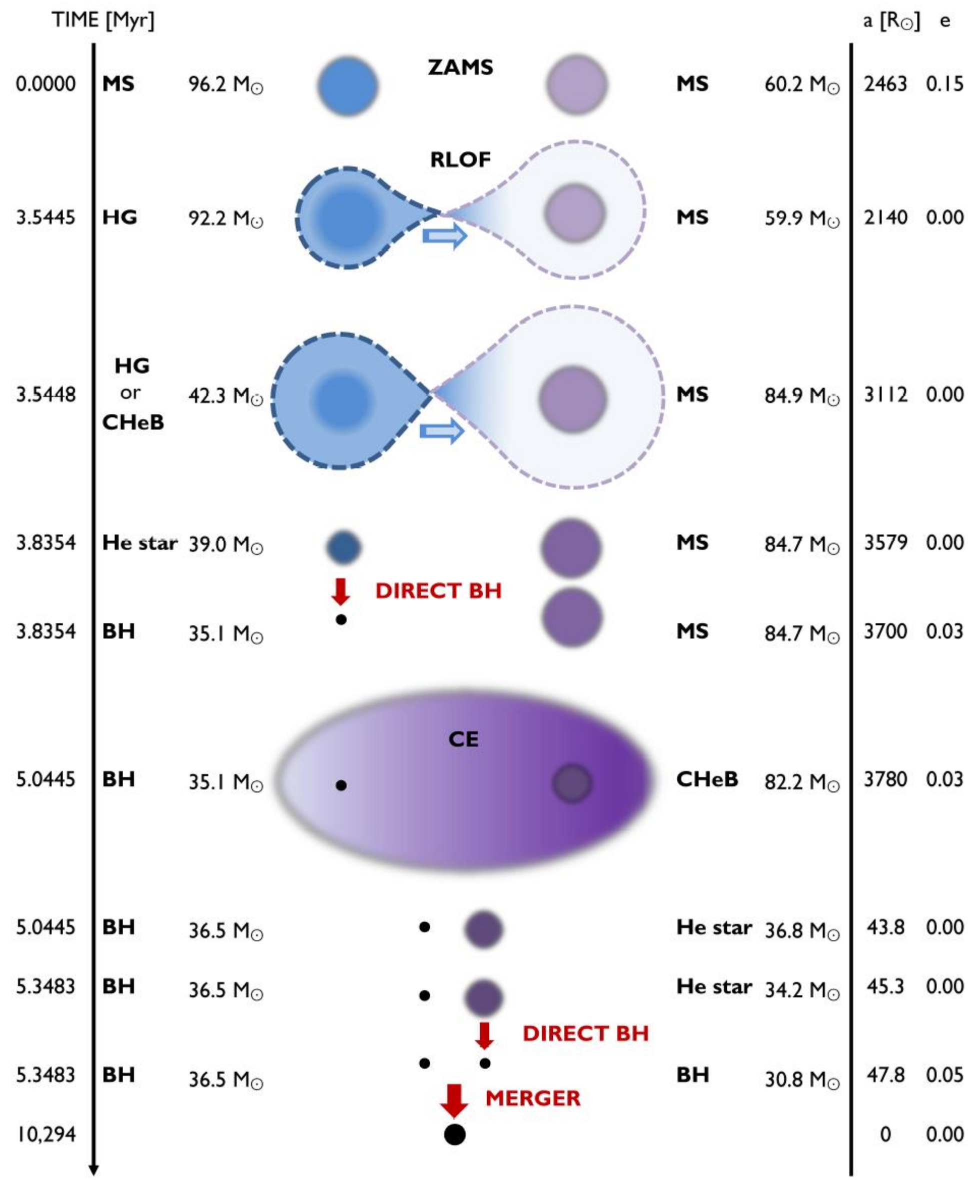
Common envelope - calculation of energy balance



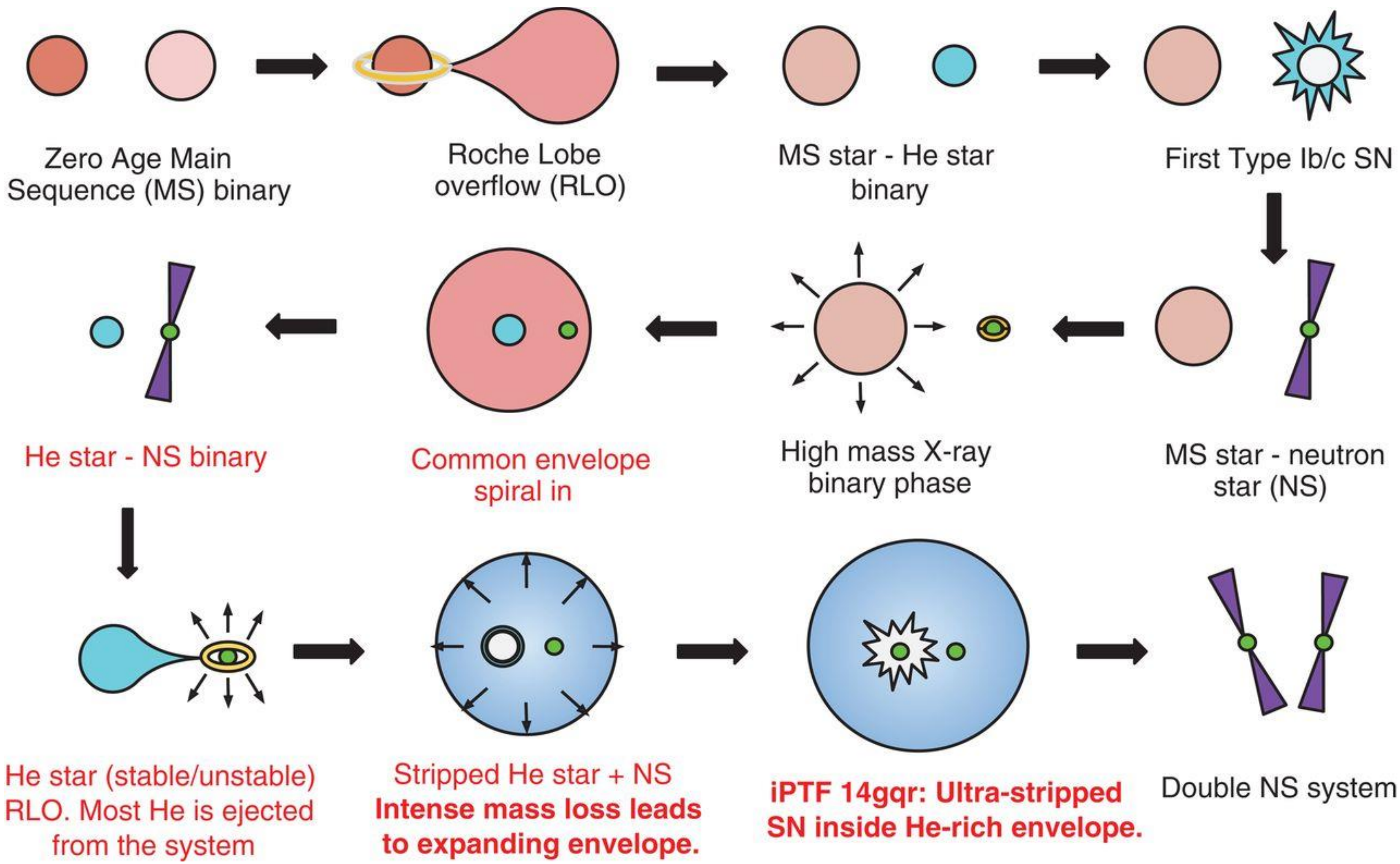
- Common envelope simulation lasts ~few orbital periods
- Unbinds only ~8% of the envelope, although expected to unbind everything



Ohlmann et al. (2016)



Belczynski et al. (2016)


Zero Age Main Sequence (MS) binary
Roche Lobe overflow (RLO)
MS star - He star binary
First Type Ib/c SN
He star - NS binary
Common envelope spiral in
High mass X-ray binary phase
MS star - neutron star (NS)
He star (stable/unstable) RLO. Most He is ejected from the system
Stripped He star + NS
Intense mass loss leads to expanding envelope.
iPTF 14gqr: Ultra-stripped SN inside He-rich envelope.
Double NS system

De et al. (2018)

THE INCIDENCE OF STELLAR MERGERS AND MASS GAINERS AMONG MASSIVE STARS

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ABSTRACT

Because the majority of massive stars are born as members of close binary systems, populations of massive main-sequence stars contain stellar mergers and products of binary mass transfer. We simulate populations of massive stars accounting for all major binary evolution effects based on the most recent binary parameter statistics and extensively evaluate the effect of model uncertainties. Assuming constant star formation, we find that $8^{+9}_{-4}\%$ of a sample of early-type stars are the products of a merger resulting from a close binary system. In total we find that $30^{+10}_{-15}\%$ of massive main-sequence stars are the products of binary interaction. We show that the commonly adopted approach to minimize the effects of binaries on an observed sample by excluding systems detected as binaries through radial velocity campaigns can be counterproductive. Systems with significant radial velocity variations are mostly pre-interaction systems. Excluding them substantially enhances the relative incidence of mergers and binary products in the non-radial velocity variable sample. This poses a challenge for testing single stellar evolutionary models. It also raises the question of whether certain peculiar classes of stars, such as magnetic O stars, are the result of binary interaction and it emphasizes the need to further study the effect of binarity on the diagnostics that are used to derive the fundamental properties (star-formation history, initial mass function, mass-to-light ratio) of stellar populations nearby and at high redshift.

Binary Interaction Dominates the Evolution of Massive Stars

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The presence of a nearby companion alters the evolution of massive stars in binary systems, leading to phenomena such as stellar mergers, x-ray binaries, and gamma-ray bursts. Unambiguous constraints on the fraction of massive stars affected by binary interaction were lacking. We simultaneously measured all relevant binary characteristics in a sample of Galactic massive O stars and quantified the frequency and nature of binary interactions. More than 70% of all massive stars will exchange mass with a companion, leading to a binary merger in one-third of the cases. These numbers greatly exceed previous estimates and imply that binary interaction dominates the evolution of massive stars, with implications for populations of massive stars and their supernovae.