Astrophysics of gravitational wave sources

Lecture 11: Binary and multiple stars & their evolution

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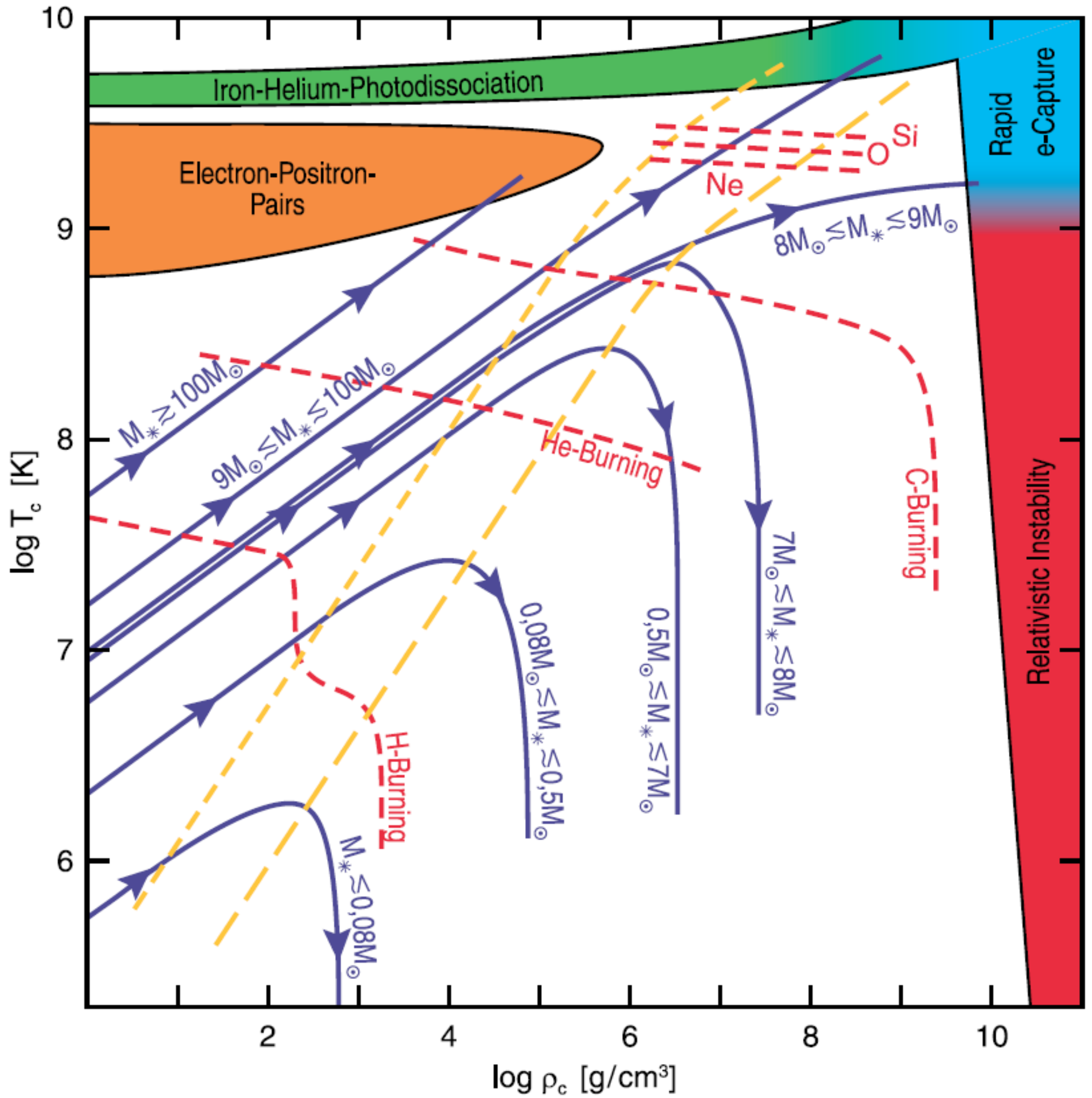
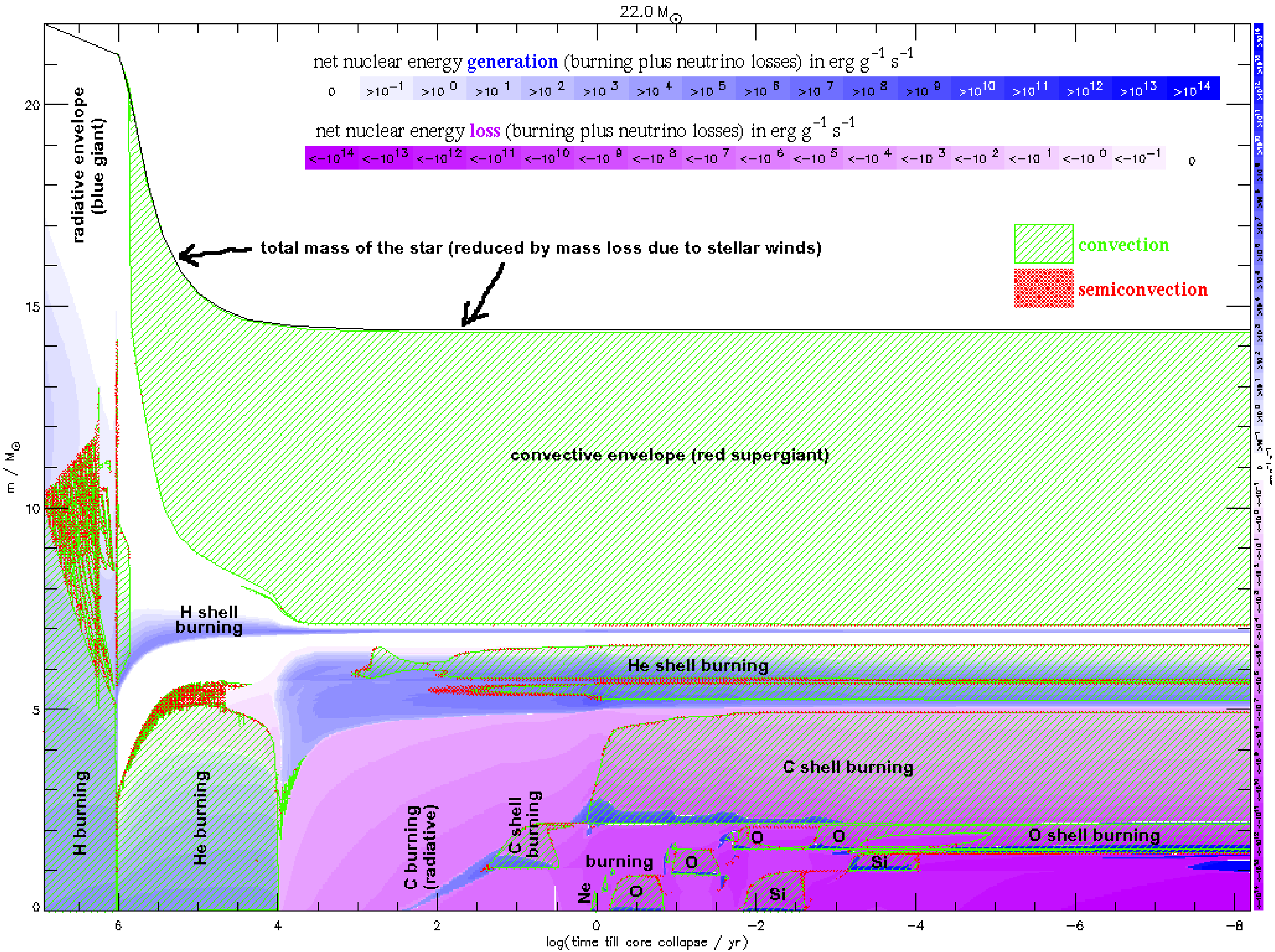
Single star evolution before core-collapse

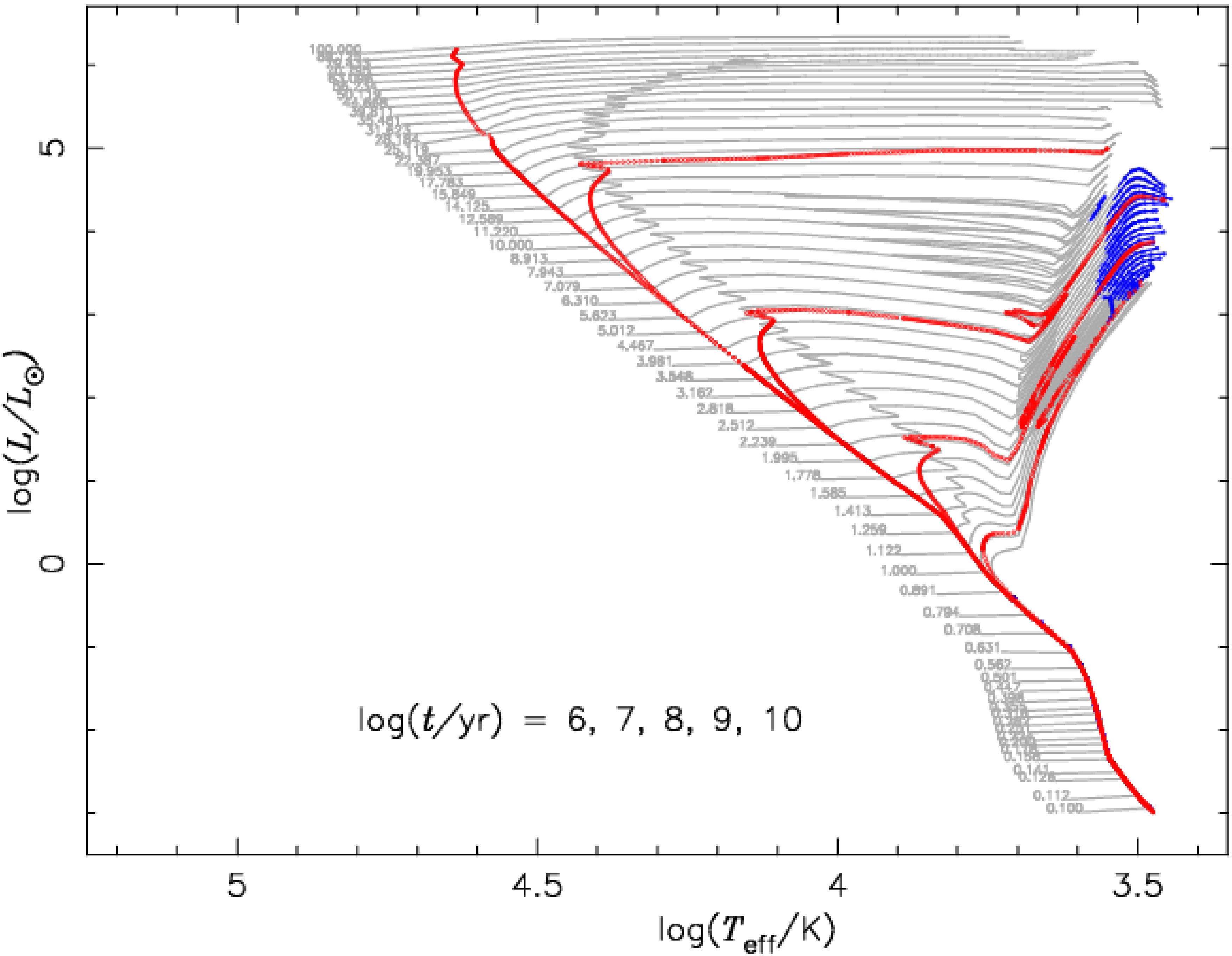
Central temperature and pressure



Janka (2012)

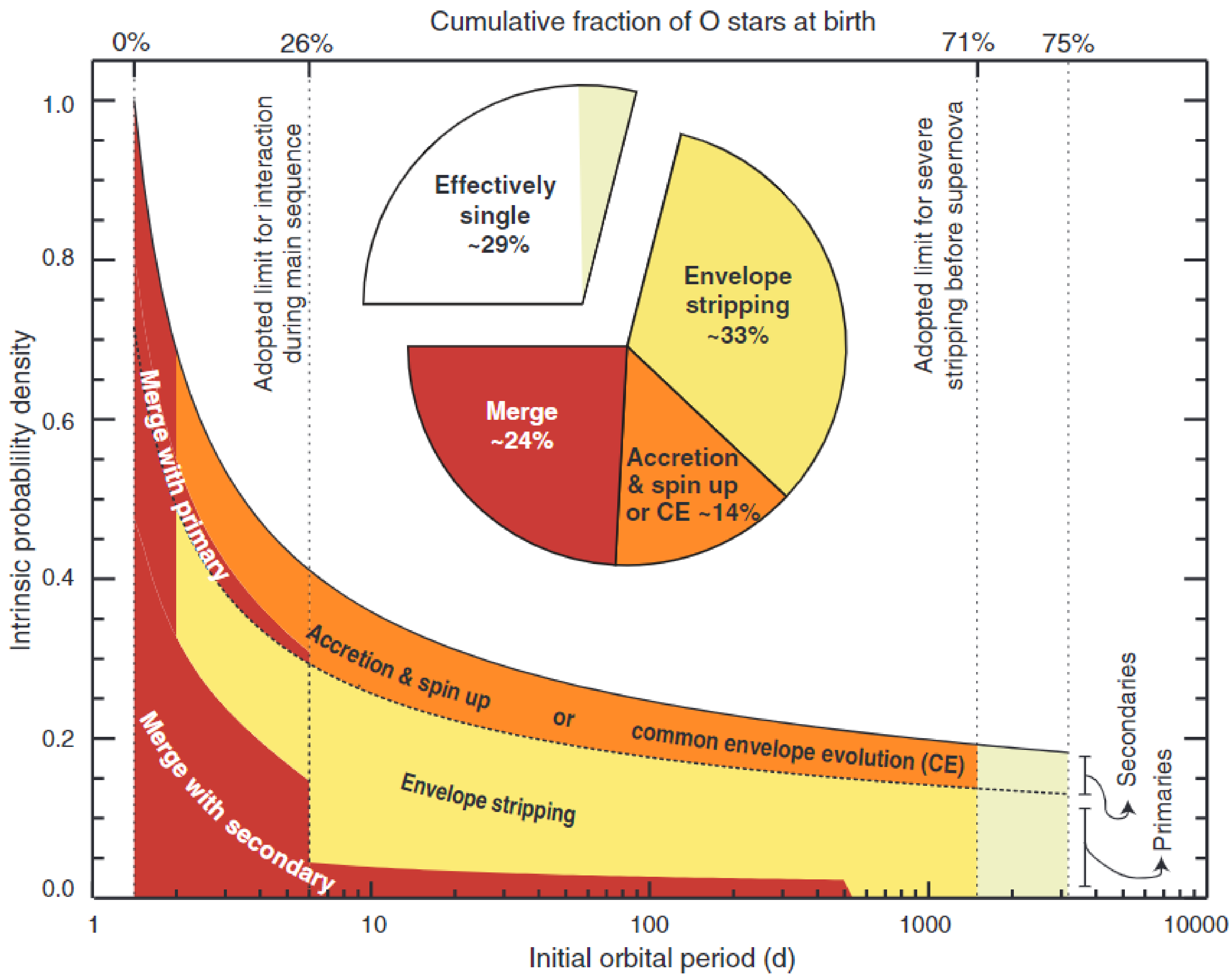


A. Heger website 2sn.org



log(L/L⊙)
5
0
log(Teff/K)
5
4.5
4
3.5
log(t/yr) = 6, 7, 8, 9, 10
100.000
19.953
17.783
15.849
14.125
12.589
11.220
10.000
8.913
7.943
7.079
6.310
5.623
5.012
4.467
3.981
3.548
3.162
2.818
2.512
2.239
1.995
1.778
1.585
1.413
1.259
1.122
1.000
0.891
0.794
0.708
0.631
0.562
0.501
0.447
0.112
0.100

Binary star interaction dominates the evolution of massive stars



Sana et al. (2012)

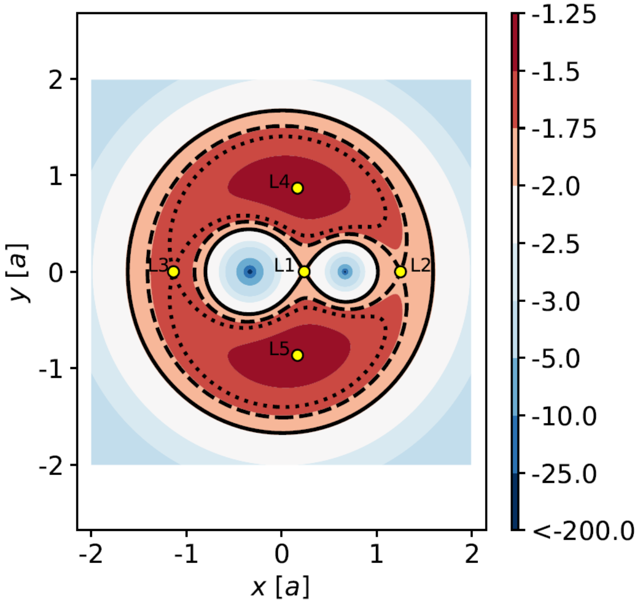
Binary stars - Roche potential

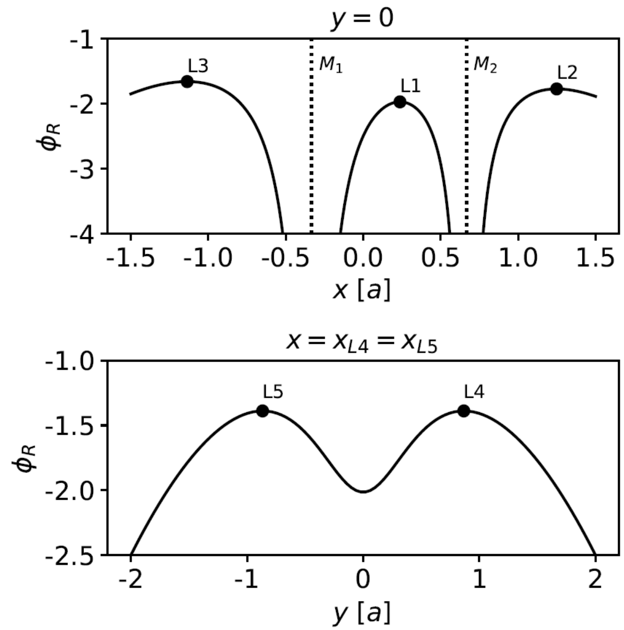
$$\ddot{\mathbf{r}} = -\nabla\phi_R(\mathbf{r}) - 2\boldsymbol{\omega} \times \dot{\mathbf{r}},$$

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

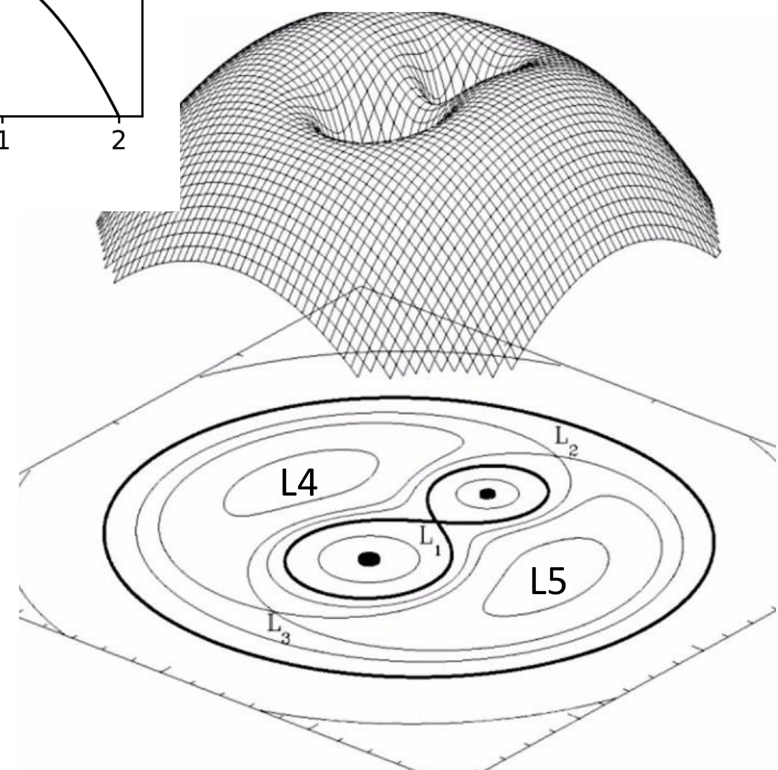
$$\omega^2 = \frac{GM}{a^3} = \left(\frac{2\pi}{T}\right)^2 \qquad q = \frac{M_2}{M_1} \qquad \mu = \frac{M_2}{M_1 + M_2} = \frac{q}{1+q}$$

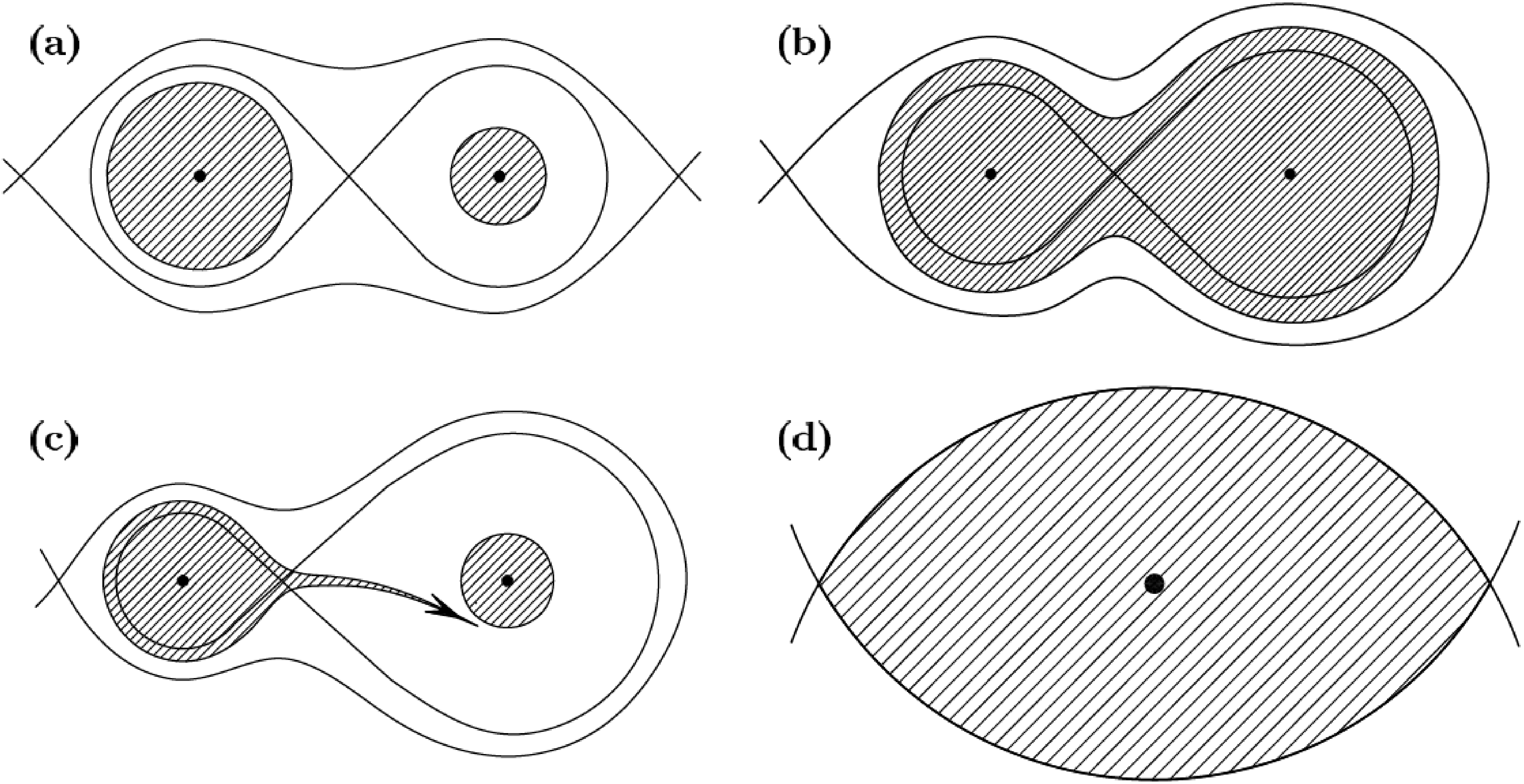
Roche potential





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 $R \sim M^{-1/3}$)

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

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

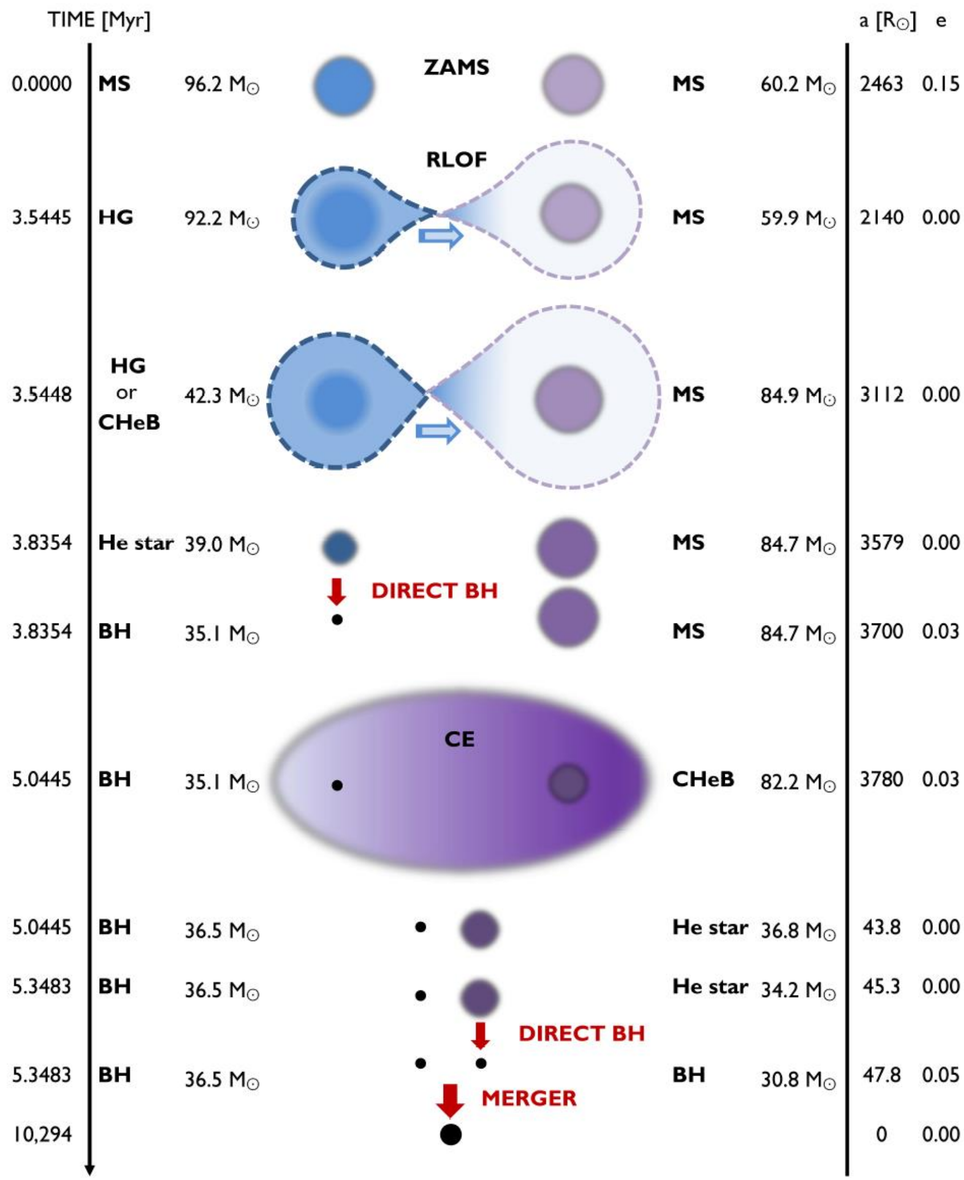
$$\tau_{\rm KH} = \frac{E_{\rm th}}{L} \approx \frac{GM^2}{2RL} \approx 1.5 \times 10^7 \left(\frac{M}{M_\odot}\right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \text{ yr}$$

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

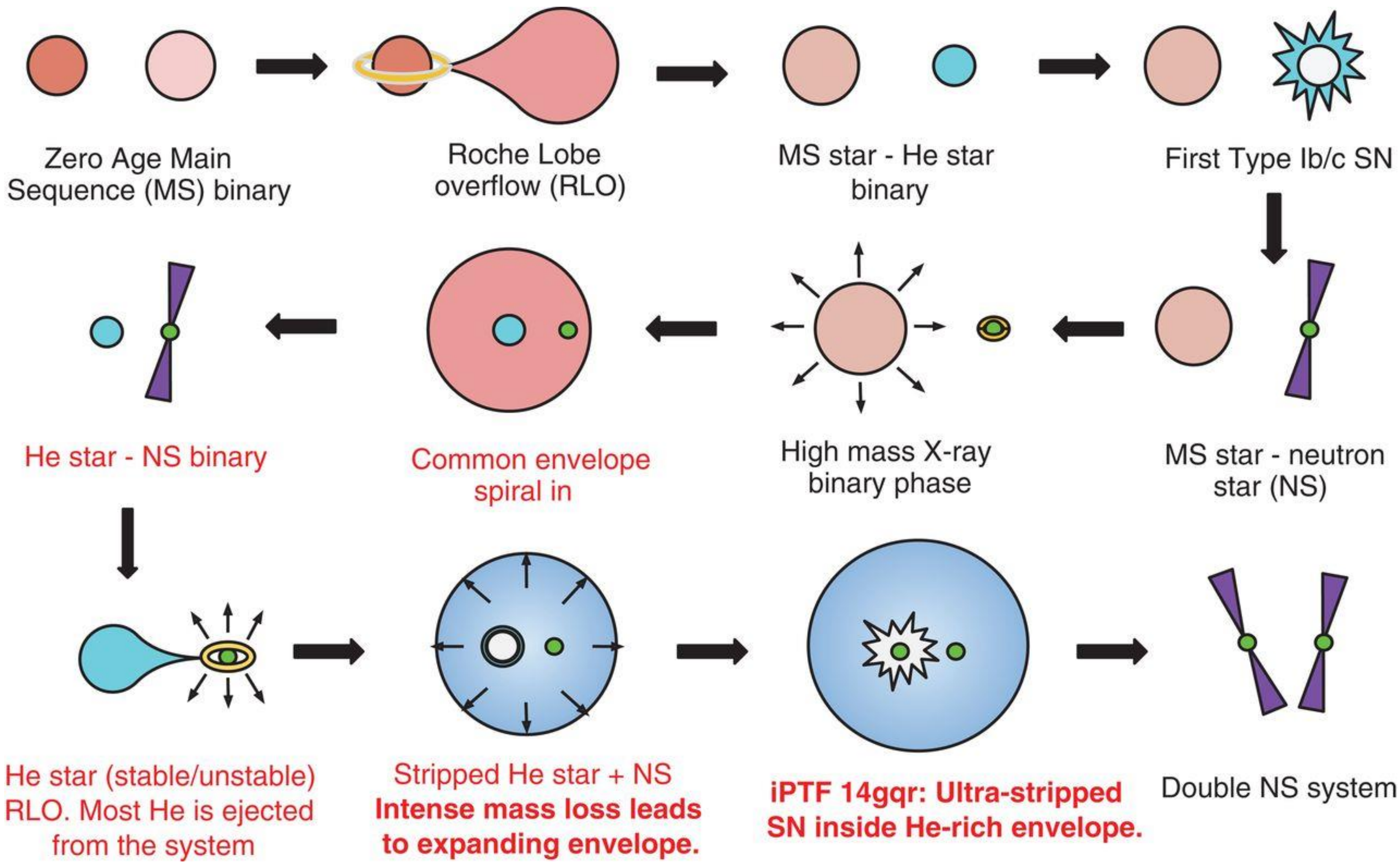
Onno Pols' lecture notes http://www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/Binaries_ch6-8.pdf

Roche lobe overflow

- 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)



Belczynski et al. (2016)


Zero Age Main Sequence (MS) binary
Roche Lobe overflow (RLO)
MS star - He star binary
First Type Ib/c SN
MS star - neutron star (NS)
High mass X-ray binary phase
Common envelope spiral in
He star - NS binary
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)

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

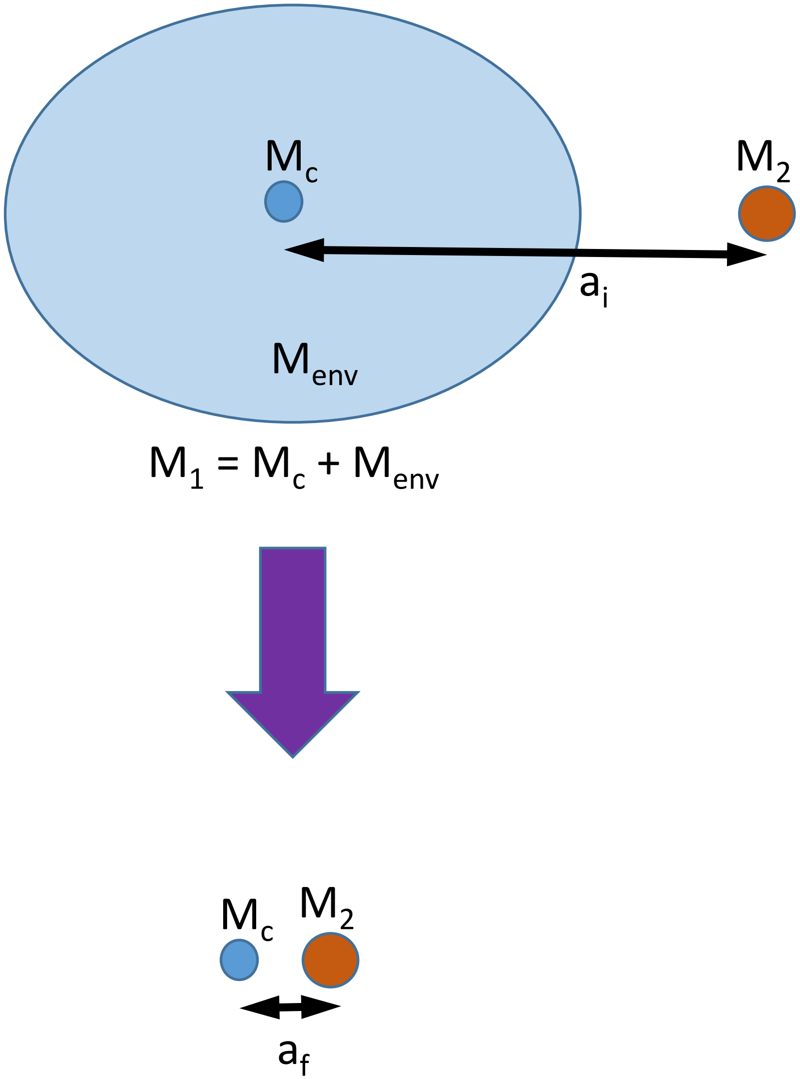
$$R'_{\mathrm{L}} \equiv \frac{\mathrm{d}\log R_{\mathrm{L}}}{\mathrm{d}\log M_1} = (1+q)\cdot\left(\frac{\mathrm{d}\log R_{\mathrm{L}}/a}{\mathrm{d}\log q} + \frac{\mathrm{d}\log a}{\mathrm{d}\log q}\right)$$
$$\approx 2.13q - 1.67, \quad 0 < q \lesssim 50;$$

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)

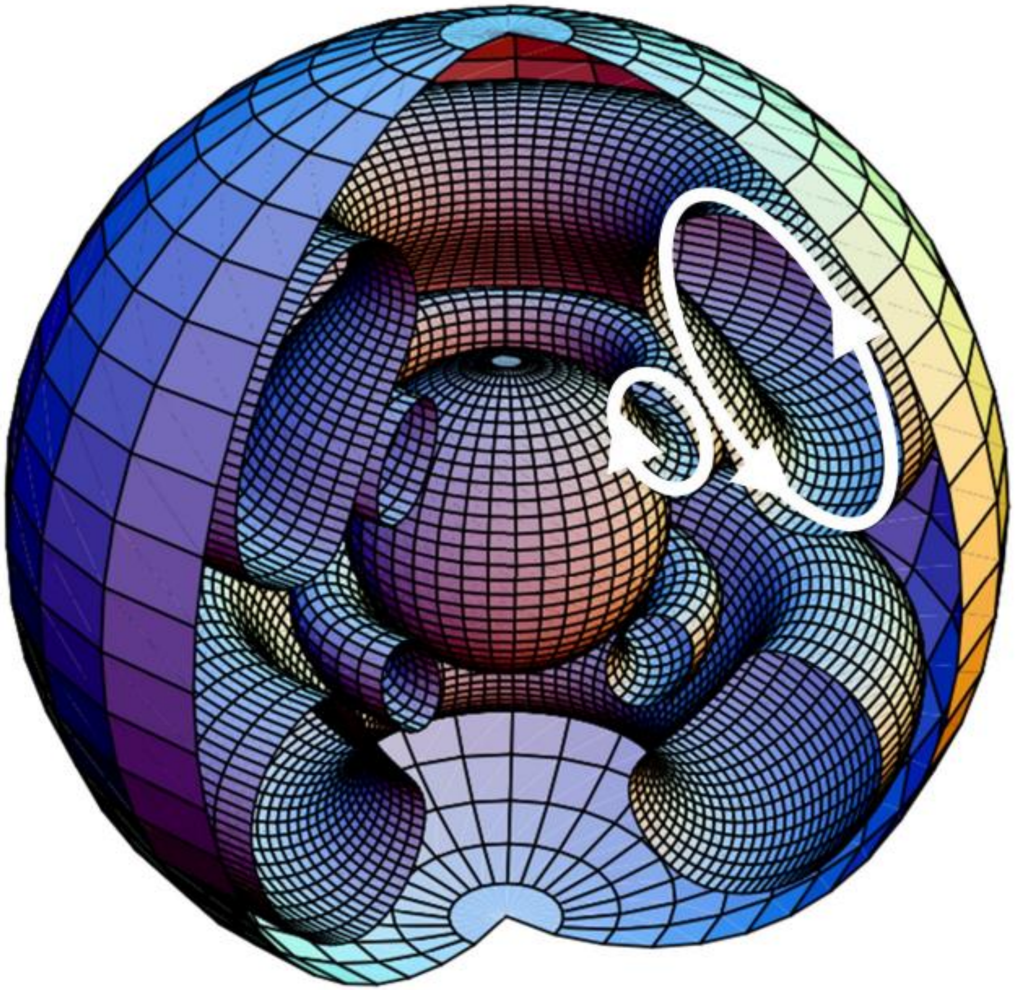
Common envelope - calculation of energy balance



Chemically-homogeneous evolution

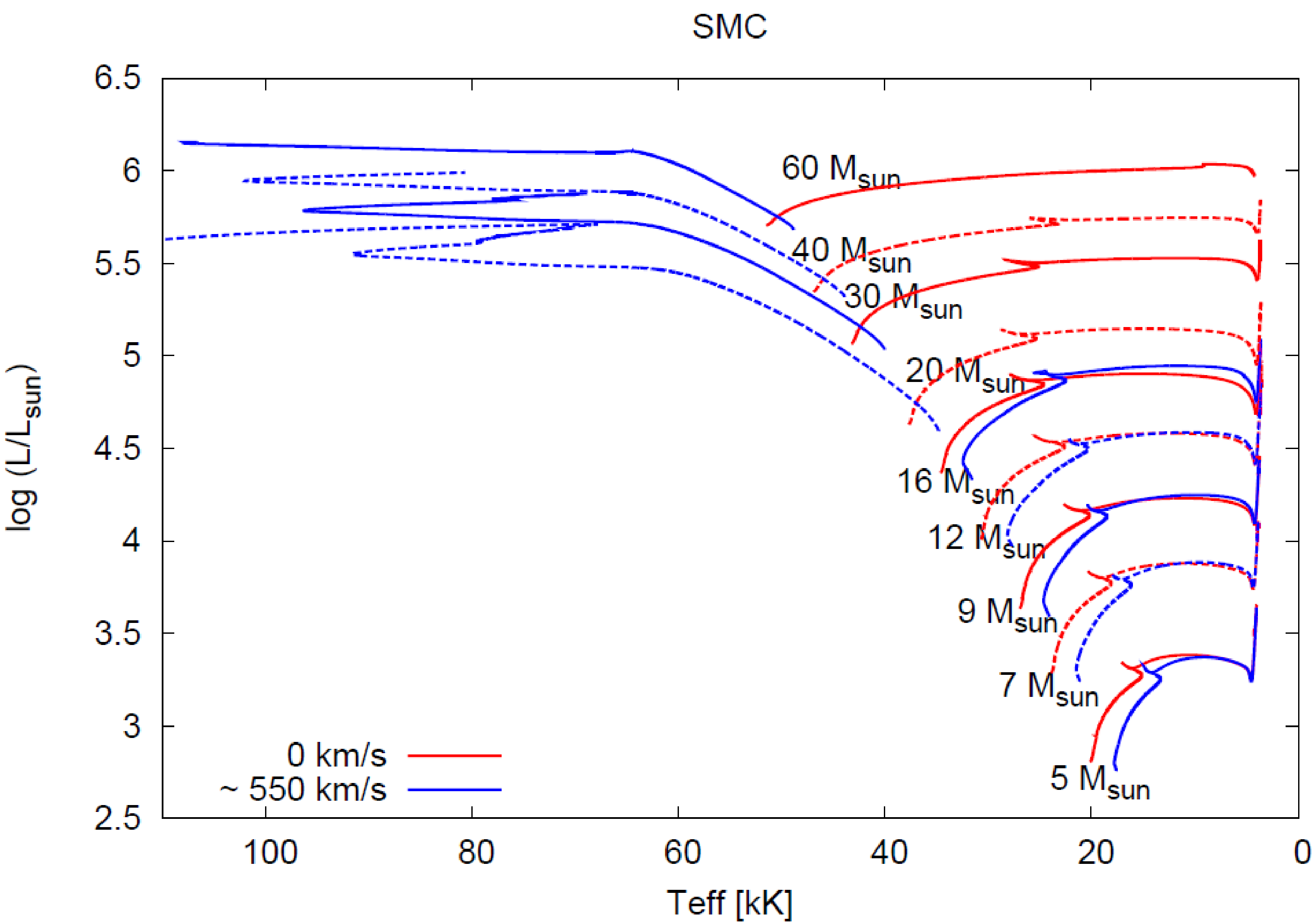
What drives evolutionary expansion of stars?

Rotation in stars



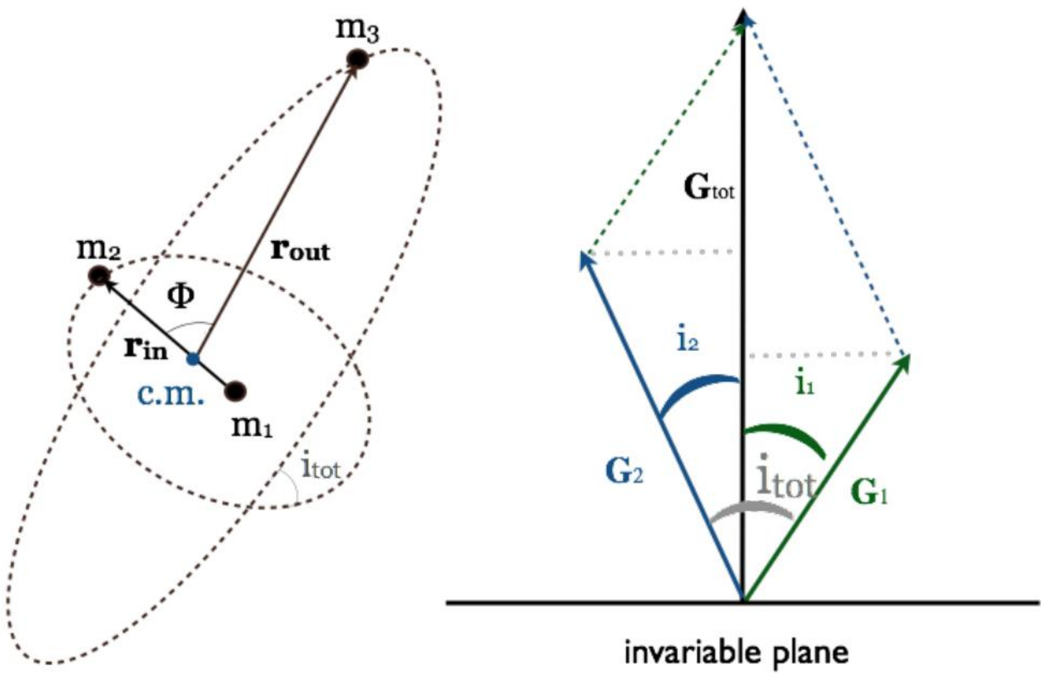
https://astro.uni-bonn.de/~nlanger/thesis/abel.pdf

Chemically-homogeneous evolution



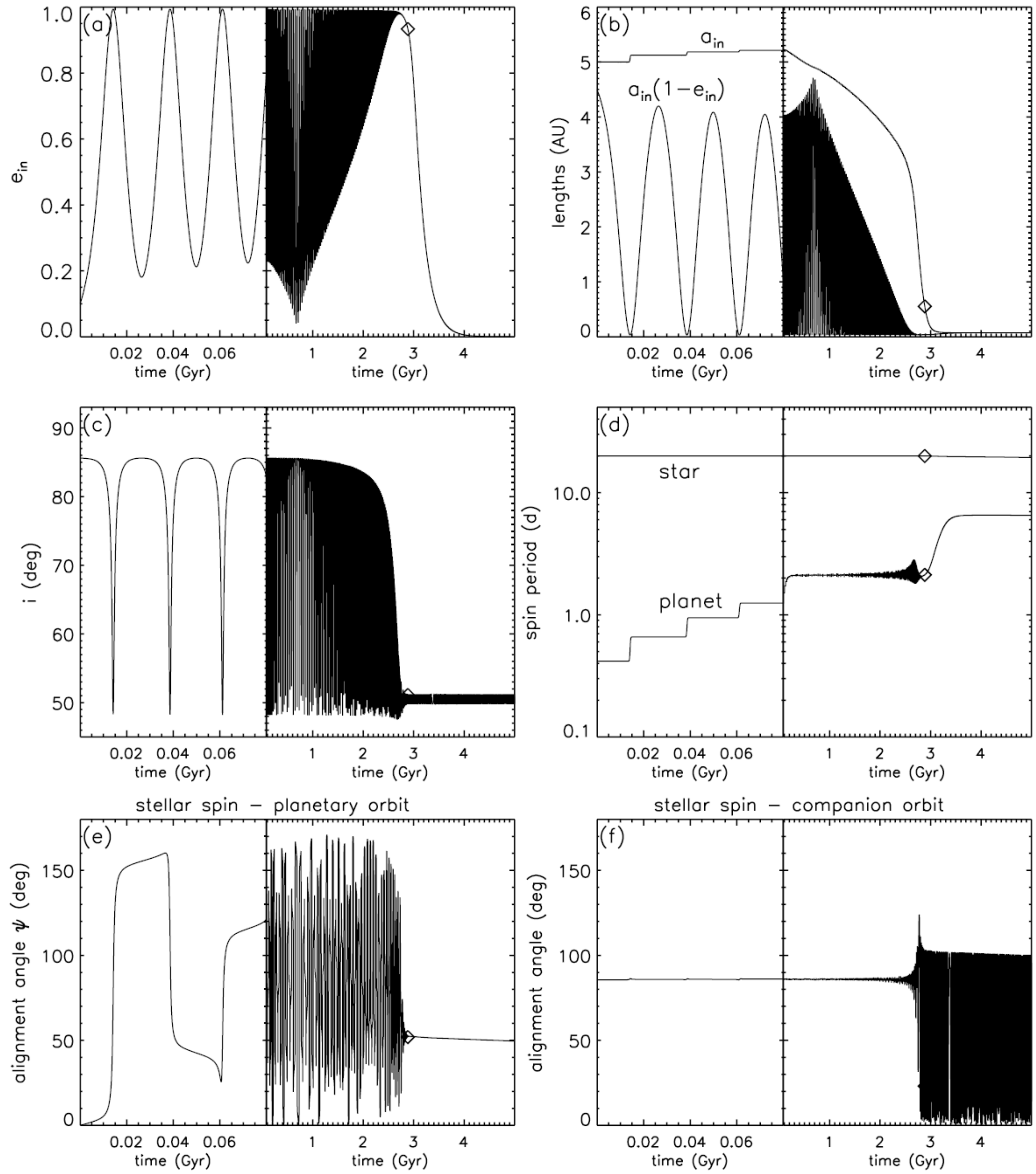
Brotts et al. (2011)

von Zeipel-Lidov-Kozai



The secular approximation (i.e., phase averaged, long term evolution) can be applied, where the interactions between two non-resonant orbits is equivalent to treating the two orbits as massive wires. Here, the line-density is inversely proportional to orbital velocity and the two orbits torque each other and exchange angular momentum, but not energy. Therefore the orbits can change shape and orientation (on timescales much longer than their orbital periods), but not semi-major axes of the orbits.

Naoz (2016)



Fabrycky & Tremaine (2007)

Cluster dynamics

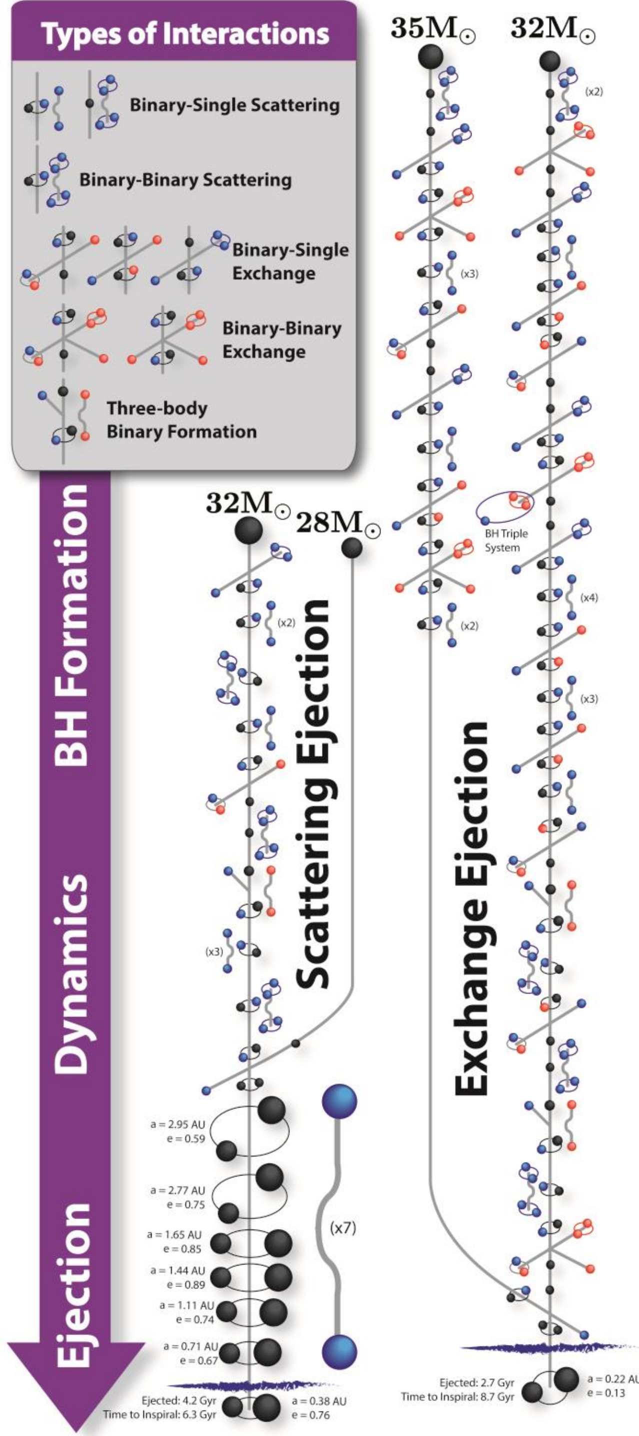
$$t_{\mathrm{relax}} \simeq \frac{N}{8 \ln \Lambda} t_{\mathrm{dyn}}$$

$$t_{\mathrm{dyn}} \simeq (G\bar{\rho})^{-1/2}$$

$$\ln \Lambda = \ln(b_{\mathrm{max}}/b_{\mathrm{min}})$$

$$b_{\mathrm{min}} = 2Gm/\sigma^2$$

Dehnen & Read (2011)



Rodriguez et al. (2016)

Cool videos

- https://www.youtube.com/watch?v=qJMom80Qdc8
- https://www.youtube.com/watch?v=3L3iSWRCtuA
- https://ciera.northwestern.edu/gallery/
- Also worth: Adler planetarium