 Michela Mapelli

Binary evolution processes I

Formation of black hole and neutron star binaries

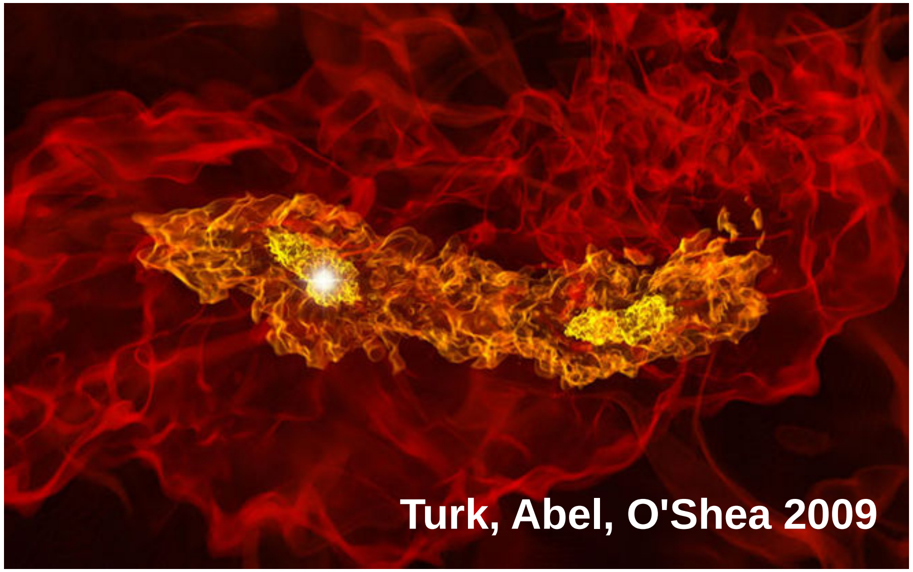
Lecture 3: how black holes and neutron stars form from SINGLE massive stars

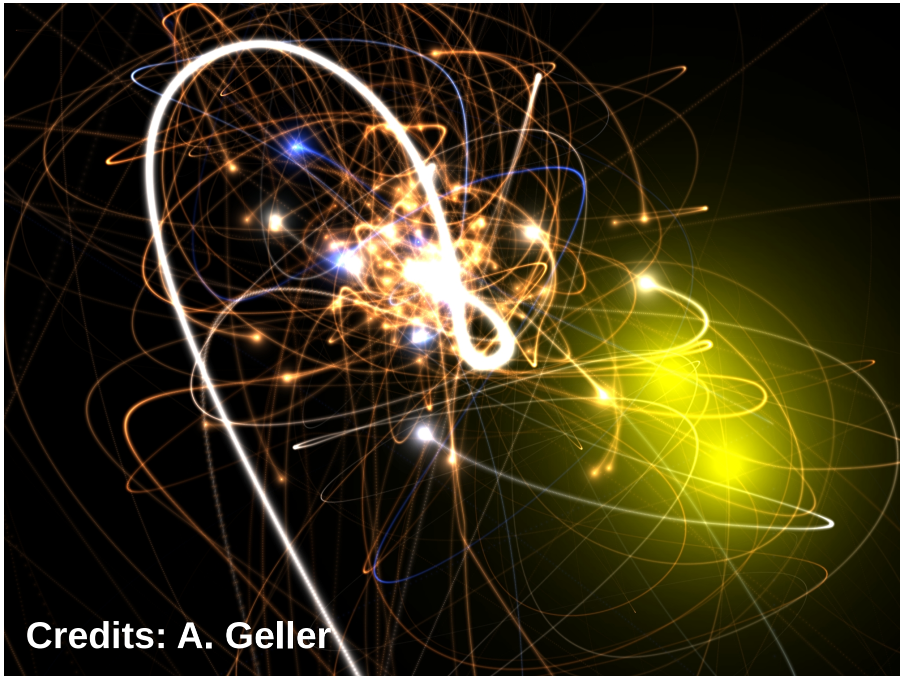
BUT LIGO-Virgo observed the merger of black holes and neutron stars in binaries

WHAT ARE THE FORMATION CHANNELS OF NEUTRON STAR AND BLACK HOLE BINARIES ?

Formation of black hole and neutron star binaries

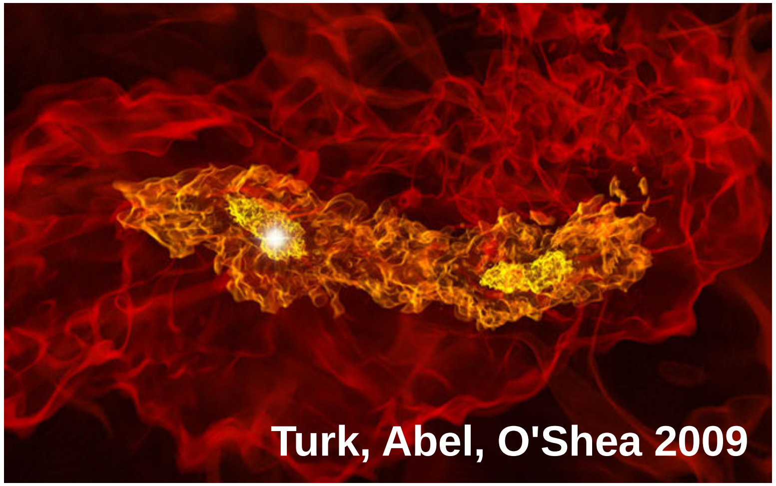
1) PRIMORDIAL BINARIES:
two stars form from same cloud and evolve into two BHs gravitationally bound





2) DYNAMICAL BINARIES:
BH binary forms and/or evolves by dynamical processes

Formation of black hole and neutron star binaries



PRIMORDIAL BINARIES:

Two stars form from same cloud and
evolve into two BHs gravitationally bound

NOT SO EASY:

Many evolutionary processes can affect the binary

SN kick	tidal evolution
wind mass transfer	magnetic braking
Roche lobe mass transfer	orbital evolution
common envelope	gravitational wave decay

Population-synthesis codes

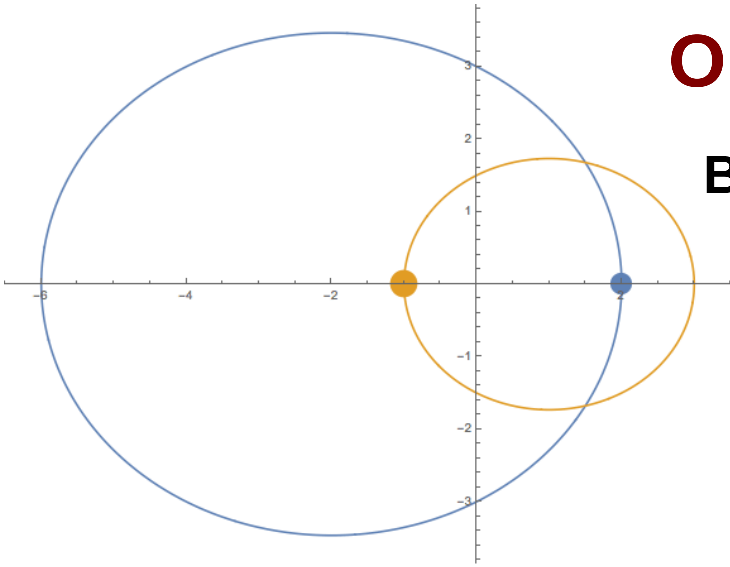
Binary evolution studied via POPULATION SYNTHESIS CODES:

* include models of stellar evolution in a simplified way
* include prescriptions for supernova explosions
* include treatment of binary evolution processes
* based on a Monte Carlo approach
 (direct integration would be too expensive)

Examples of used population-synthesis codes

→	BSE	(Hurley+ 2002; Giacobbo+ 2018)
→	Seba	(Portegies Zwart+ 2001; Mapelli+ 2013)
→	SEVN	(Spera, Mapelli & Bressan 2015; Spera & Mapelli 2017)
	StarTrack	(Belczynski+ 2007, 2010)

By the end of these lectures you will learn how to use BSE



Orbital properties

Binaries follow Kepler laws

Orbit as function of true anomaly

$$r(\theta) = \frac{a\,(1-e^2)}{1+e\,\cos\theta}$$

Orbital period

$$P = 2\,\pi\left(\frac{a^3}{G\,(m_1+m_2)}\right)^{1/2}$$

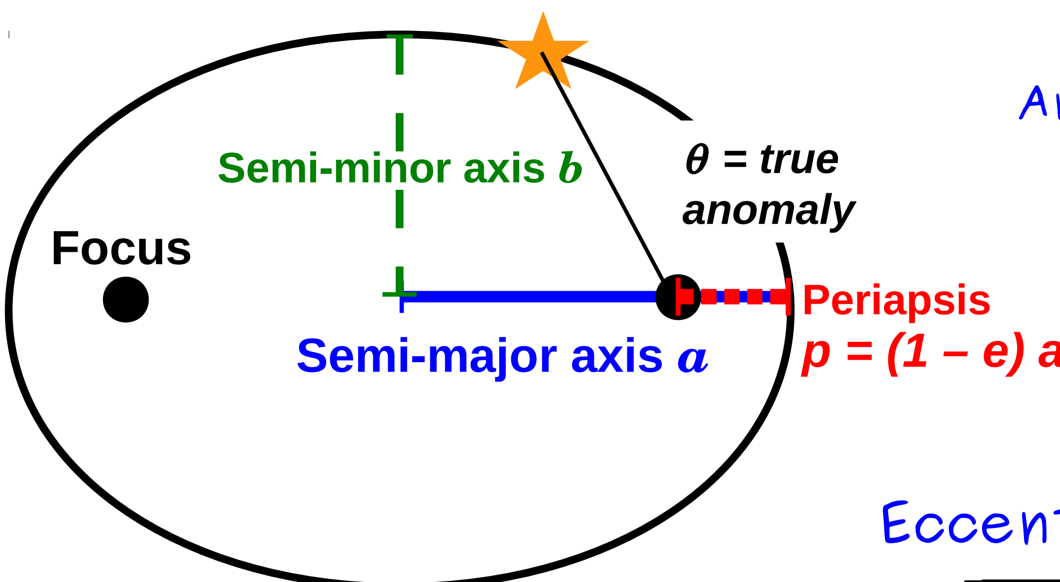
Energy

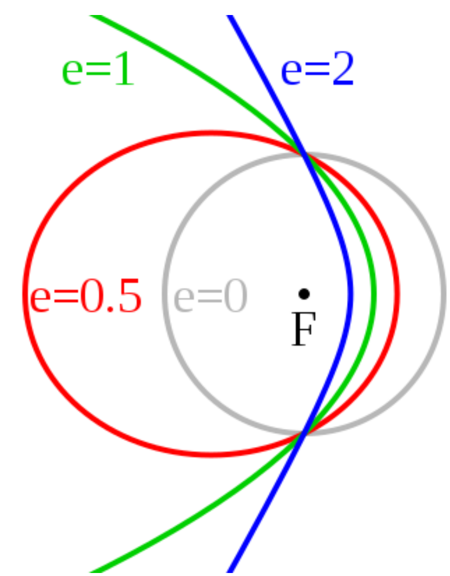
$$E = \frac{1}{2}\,\mu\,v^2 - \frac{G\,m_1\,m_2}{r}$$

Angular momentum

$$L = \mu\,\sqrt{G\,(m_1+m_2)\,a}$$

In the reduced particle + CoM frame





reduced mass:

$$\mu = \frac{m_1\,m_2}{(m_1+m_2)}$$

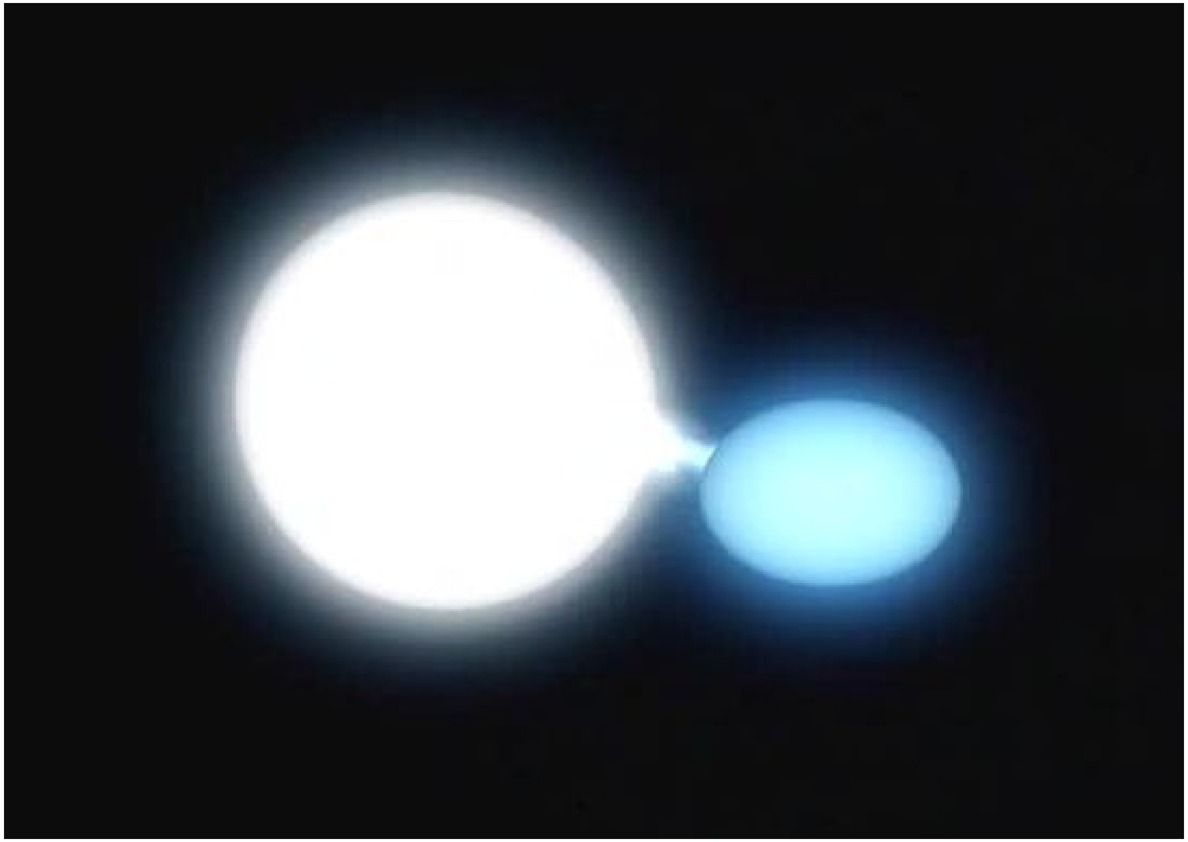
Eccentricity:

$$e = \sqrt{1+\frac{2\,E\,L^2}{\mu^3\,G^2\,(m_1+m_2)^2}}$$

Mass transfer

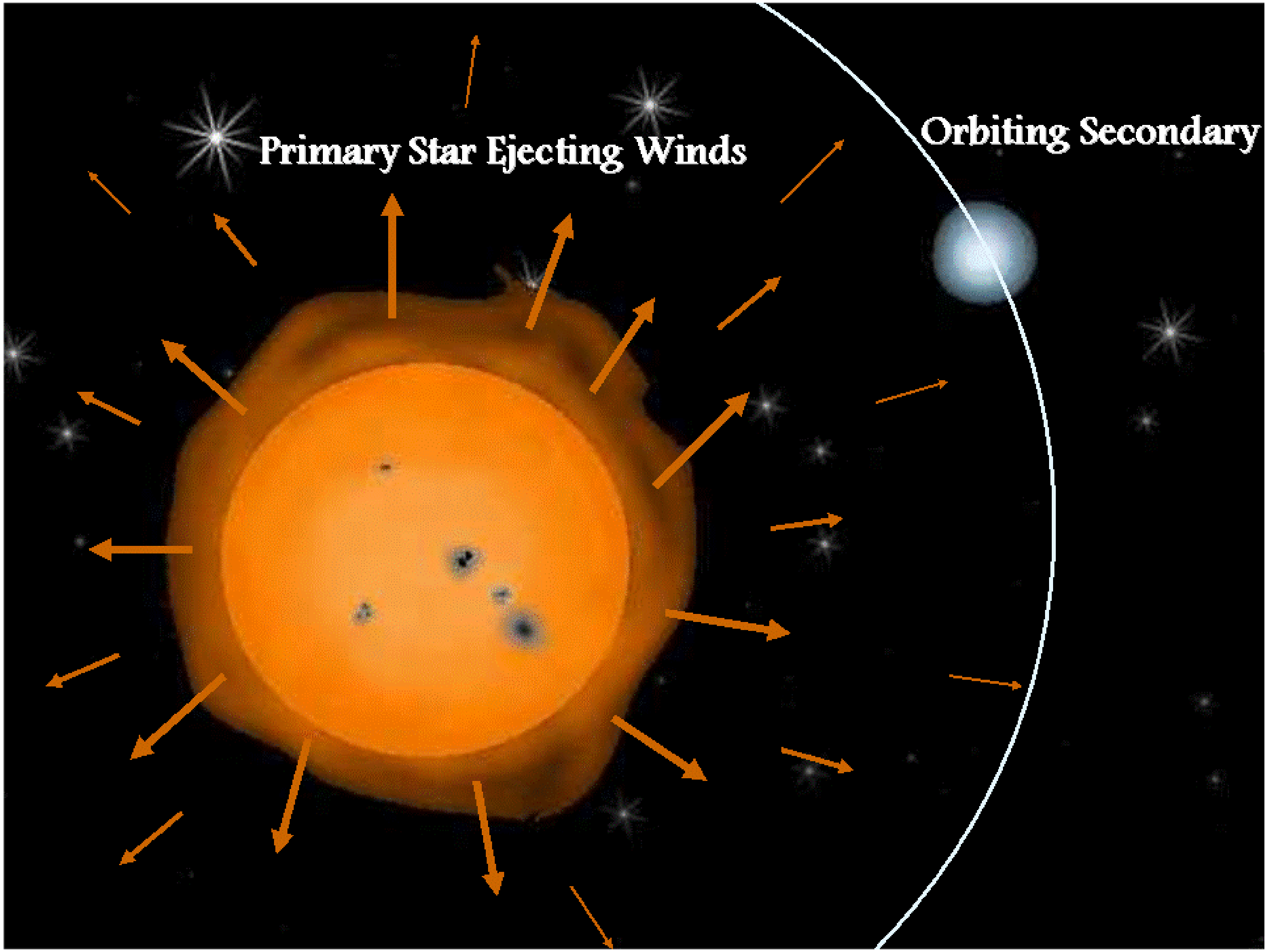
Two stars in a binary might exchange mass

1. wind mass transfer
2. Roche lobe overflow
3. common envelope



Credits: ESO/L. Calçada/M. Kornmesser/S.E. de Mink

Wind mass transfer



Wind mass transfer

* primary loses mass by stellar winds as $\dot{M}_{1W}$

* secondary acquires a part of it as (Bondi & Hoyle 1944)

$$\dot{M}_{2A} = -\frac{1}{\sqrt{1-e^2}}\left(\frac{G\,M_2}{v_W^2}\right)^2\frac{\alpha_W}{2\,a^2}\,\frac{1}{(1+v^2)^{3/2}}\,\dot{M}_{1W}$$

where

$$v^2 = \frac{v_{\rm orb}^2}{v_W^2} \qquad v_{\rm orb}^2 = \frac{G\,(M_1+M_2)}{a} \qquad v_W^2 = 2\,\beta_W\,\frac{G\,M_1}{R_1}$$

$$\alpha_W \sim 1.5 \quad \beta_W \sim 0.125 - 7$$

* non-conservative mass transfer induces orbital angular momentum loss

$$L = \mu\,\sqrt{G\,(M_1+M_2)\,a}$$

* mass transfer induces spin change (see tide discussion)

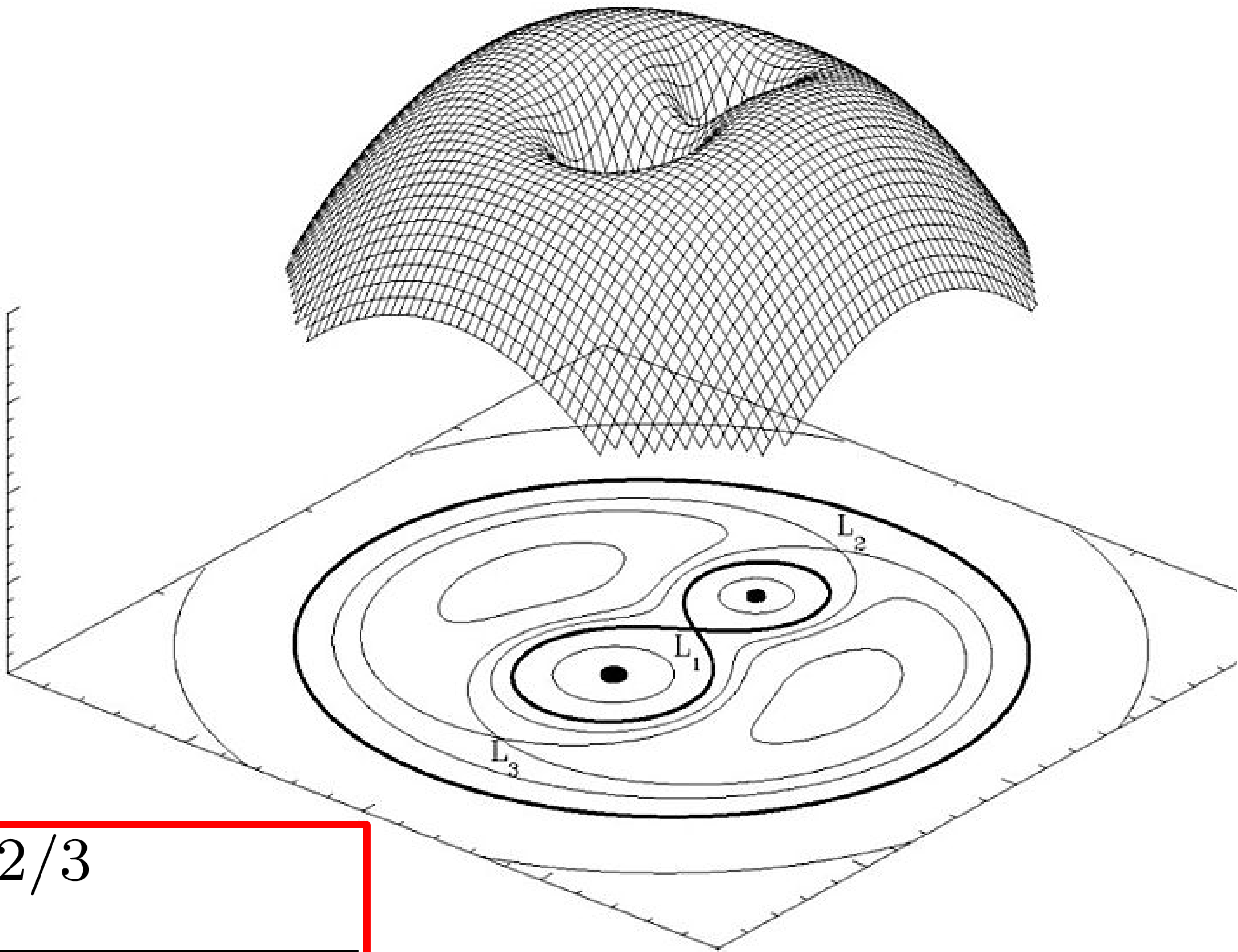
* VERY INEFFICIENT

Roche lobe overflow

Equipotential surfaces in a binary system

Roche lobe: minimum contact equip. surface (L1 Lagrangian point)

If a star fills its Roche lobe matter flows without energy change into the other star → MASS TRANSFER



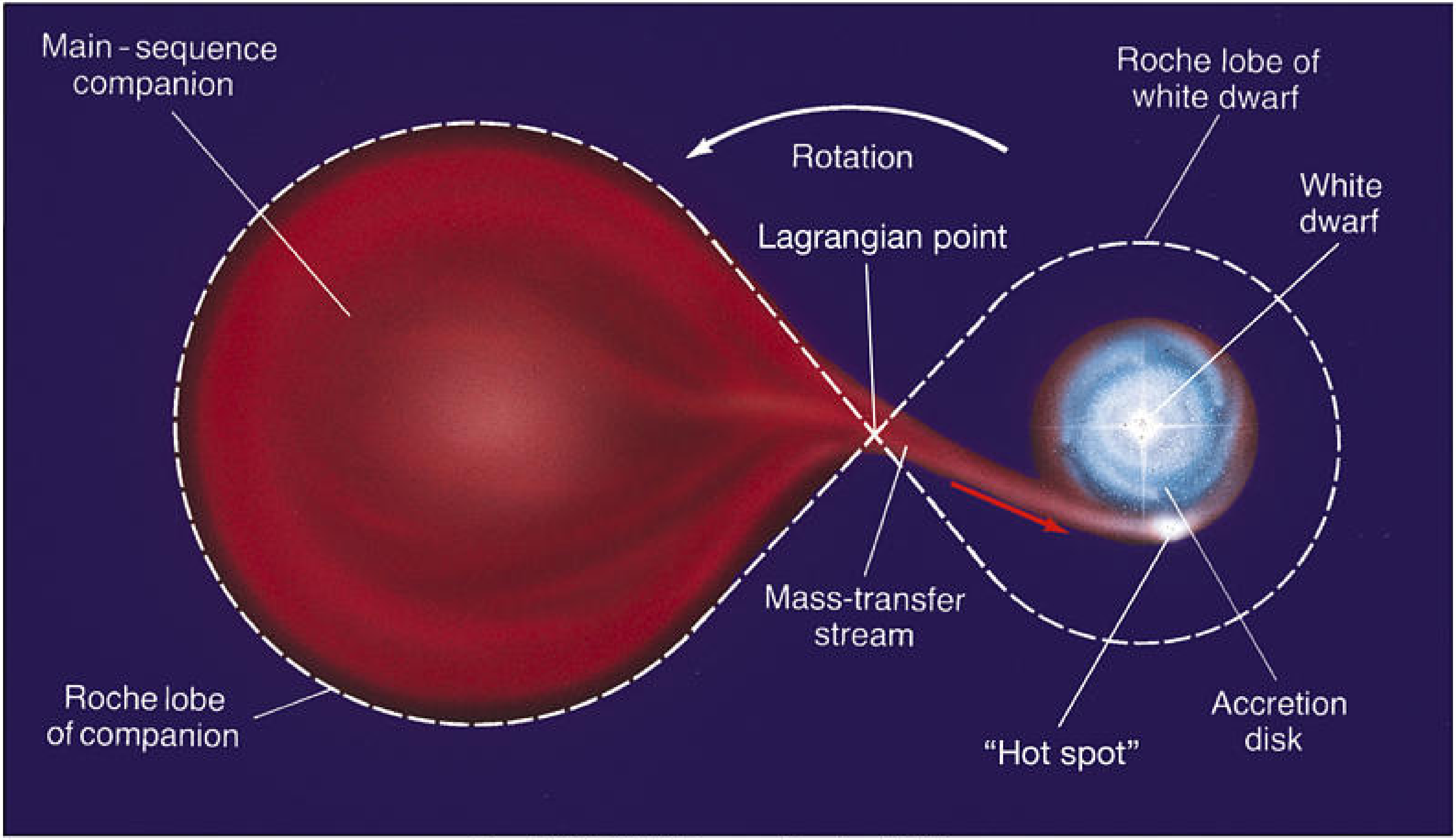
$$\boxed{\frac{r_1}{a} = \frac{0.49\, q^{2/3}}{0.6\, q^{2/3} + \ln\left(1 + q^{1/3}\right)}}$$

Eggleton 1983

where a **= semi-major axis**

$q = M_1/M_2$

Roche lobe overflow



Roche lobe overflow (un)stability

Important to decide on which timescale mass transfer is stable/unstable (Webbink 1985)

$$\zeta_{\rm ad} = \left(\frac{d\ln R}{d\ln M}\right)_{\rm ad} \quad \zeta_{\rm th} = \left(\frac{d\ln R}{d\ln M}\right)_{\rm th} \quad \zeta_{\rm L} = \left(\frac{d\ln R_L}{d\ln M}\right)$$

Change of radius (due to mass loss of the donor) to adiabatically adjust to new hydrostatic equilibrium (NO thermal eq.)

Change of radius (due to mass loss of the donor) to adjust to new thermal equilibrium

Change of Roche lobe radius (due to mass loss of the donor)

Hurley et al. 2002

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Change of radius (due to mass loss of the donor) to adjust to new thermal equilibrium

Change of Roche lobe radius (due to mass loss of the donor)

1. If $\zeta_{\rm L} > \zeta_{\rm ad}$ mass transfer dynamically unstable
   i.e. UNSTABLE on a DYNAMICAL TIMESCALE
   No equilibrium is possible → **COMMON ENVELOPE**
2. If $\zeta_{\rm ad} > \zeta_{\rm L} > \zeta_{\rm th}$ mass transfer thermally unstable
   i.e. unstable on a Kelvin-Helmholtz timescale
3. If $\zeta_{\rm ad} > \zeta_{\rm th} > \zeta_{\rm L}$ mass transfer evolves on the evolution time of the star
   i.e. nuclear reactions must change the radius of the star to change the mass transfer conditions

Hurley et al. 2002

Roche lobe overflow (un)stability

How much mass is transferred from the DONOR?

3. If $\zeta_{\rm ad} > \zeta_{\rm th} > \zeta_{\rm L}$ mass transfer evolves on the evolution time of the star

$$dM = 3 \times 10^{-6} M_\odot \, (M/M_\odot)^2 \, (\ln R/R_L)^3$$

2. If $\zeta_{\rm ad} > \zeta_{\rm L} > \zeta_{\rm th}$ mass transfer thermally unstable
dM minimum between

$$dM = 3 \times 10^{-6} M_\odot \, (M/M_\odot)^2 \, (\ln R/R_L)^3 \quad \text{and} \quad dM = (M\,/\tau_{\rm KH})\, dt$$

How much mass is accreted by the ACCRETOR?

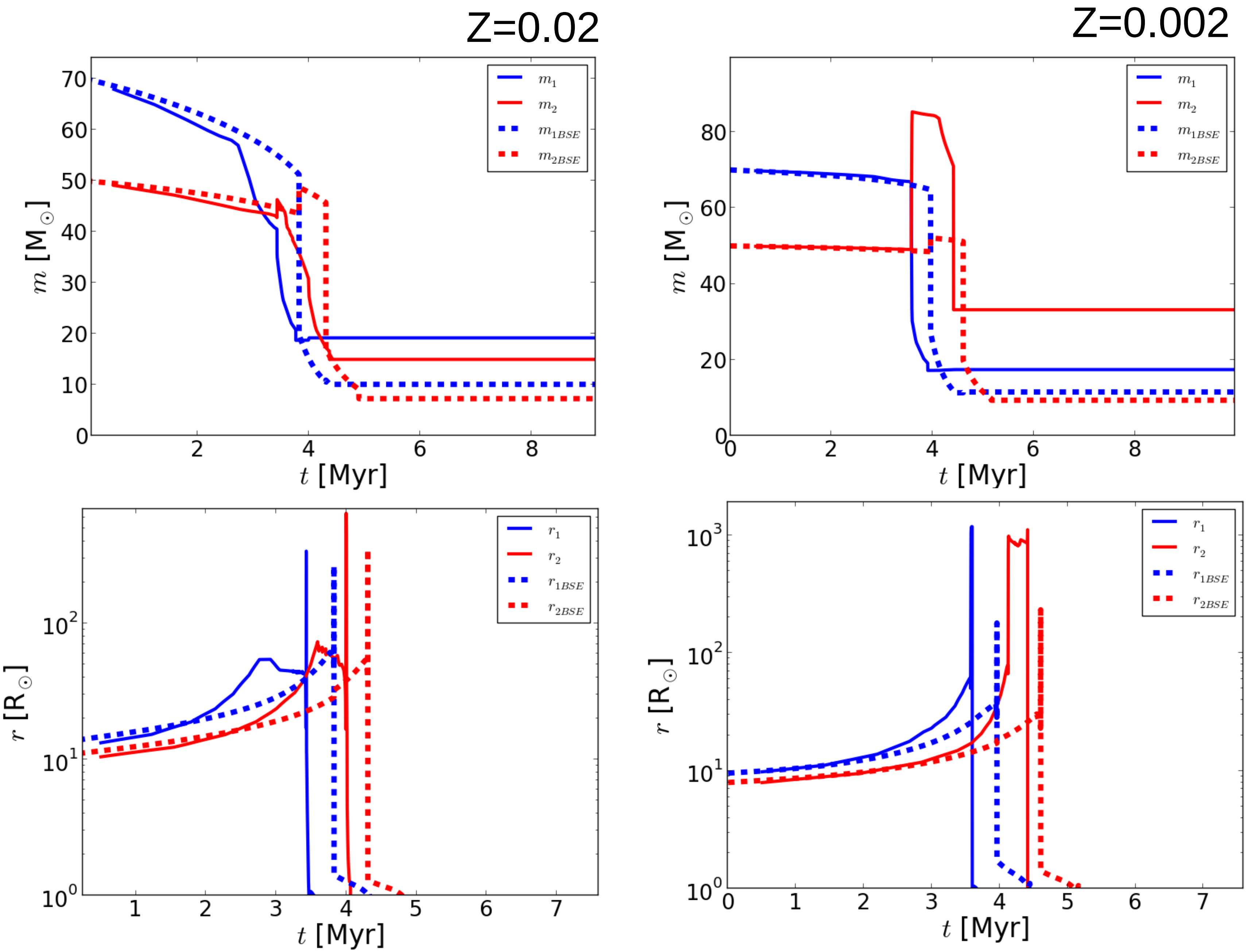
CONSERVATIVE: all transferred mass is accreted

NON CONSERVATIVE: accretion is limited by response of secondary

$$dM_2 = \min\left(\xi\,\frac{M_2}{dM}\,\frac{dt}{\tau_{\rm KH2}},\,1\right) dM$$

Hurley et al. 2002

Roche lobe overflow examples



Orbital changes induced by Roche lobe overflow

1. CONSERVATIVE

$$L = \mu \sqrt{G\,(M_1 + M_2)\,a}$$

Ang. Mom. is conserved

If M_donor > M_accretor orbital separation decreases

If M_accretor > M_donor orbital separation increases

Orbital changes induced by Roche lobe overflow

1. NON CONSERVATIVE: mass is lost from the system

$$L = \mu \sqrt{G\,(M_1 + M_2)\,a}$$

Ang. Mom. diminishes

Orbital separation should diminish too but details depend on donor/accretor mass

$$\frac{\langle \Delta a \rangle}{a} = -\frac{\Delta M_1}{M_1 + M_2} - \left(\frac{2 - e^2}{M_2} + \frac{1 + e^2}{M_1 + M_2} \right) \frac{\langle \Delta M_2 \rangle}{1 - e^2}$$

$$\frac{\langle \Delta e \rangle}{e} = -\langle \Delta M_2 \rangle \left(\frac{1}{M_1 + M_2} + \frac{1}{2\,M_2} \right)$$

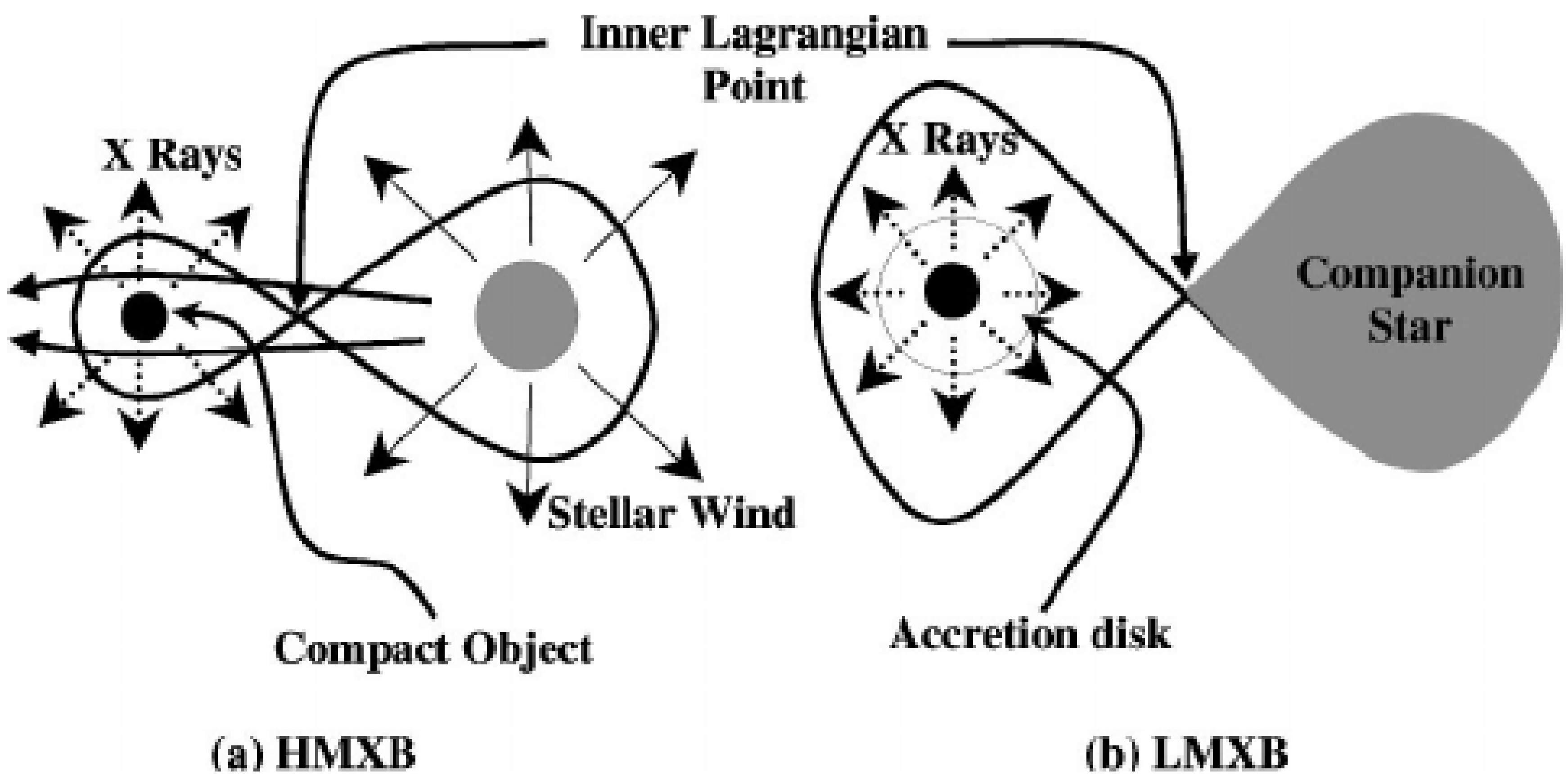
$$\frac{\langle \Delta L \rangle}{L} = \frac{\Delta M_1\,M_2 - \langle \Delta M_2 \rangle\,M_1}{M_1\,(M_1 + M_2)}$$

Hurley et al. 2002

Wind accretion versus Roche lobe overflow

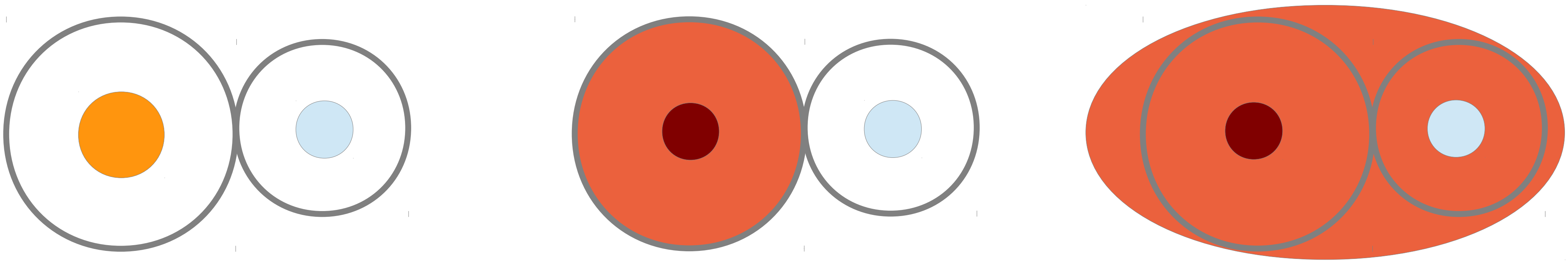
Wind accretion: no disk, usually High Mass X-ray binaries

Roche lobe : accretion disk, usually Low Mass X-ray binaries



Common Envelope

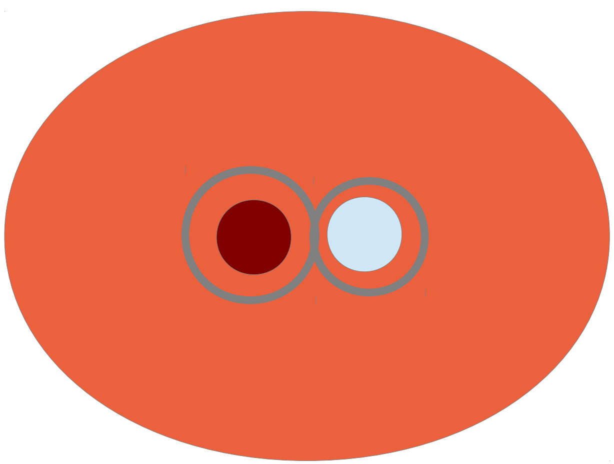
If mass transfer becomes unstable (e.g. both stars fill Roche lobe), COMMON ENVELOPE (CE) phase = Two stars, one envelope



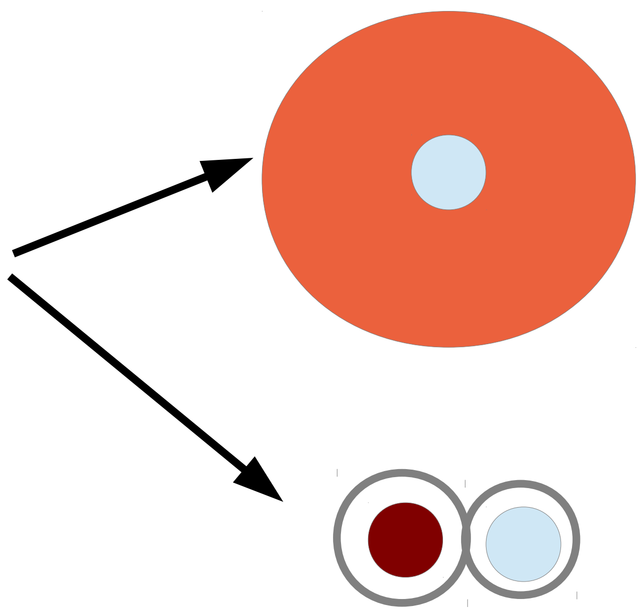
Two massive stars initially underfilling Roche lobe

The first one evolves out of MS expands and start mass transfer onto the second

Mass transfer becomes unstable: CE phase



Drag by the envelope leads the two cores to spiral in



The two cores spiral in till they merge becoming a single star

The energy released during the spiral in removes the envelope: The two cores form a new tighter binary

Common Envelope

Probably the least understood process in binary evolution

Four STAGES (with different physics):

1. loss of COROTATION: instable mass transfer prevents the envelope to co-rotate with the core

NOT YET MODELLED SELF-CONSISTENTLY (Ivanova et al. 2013)

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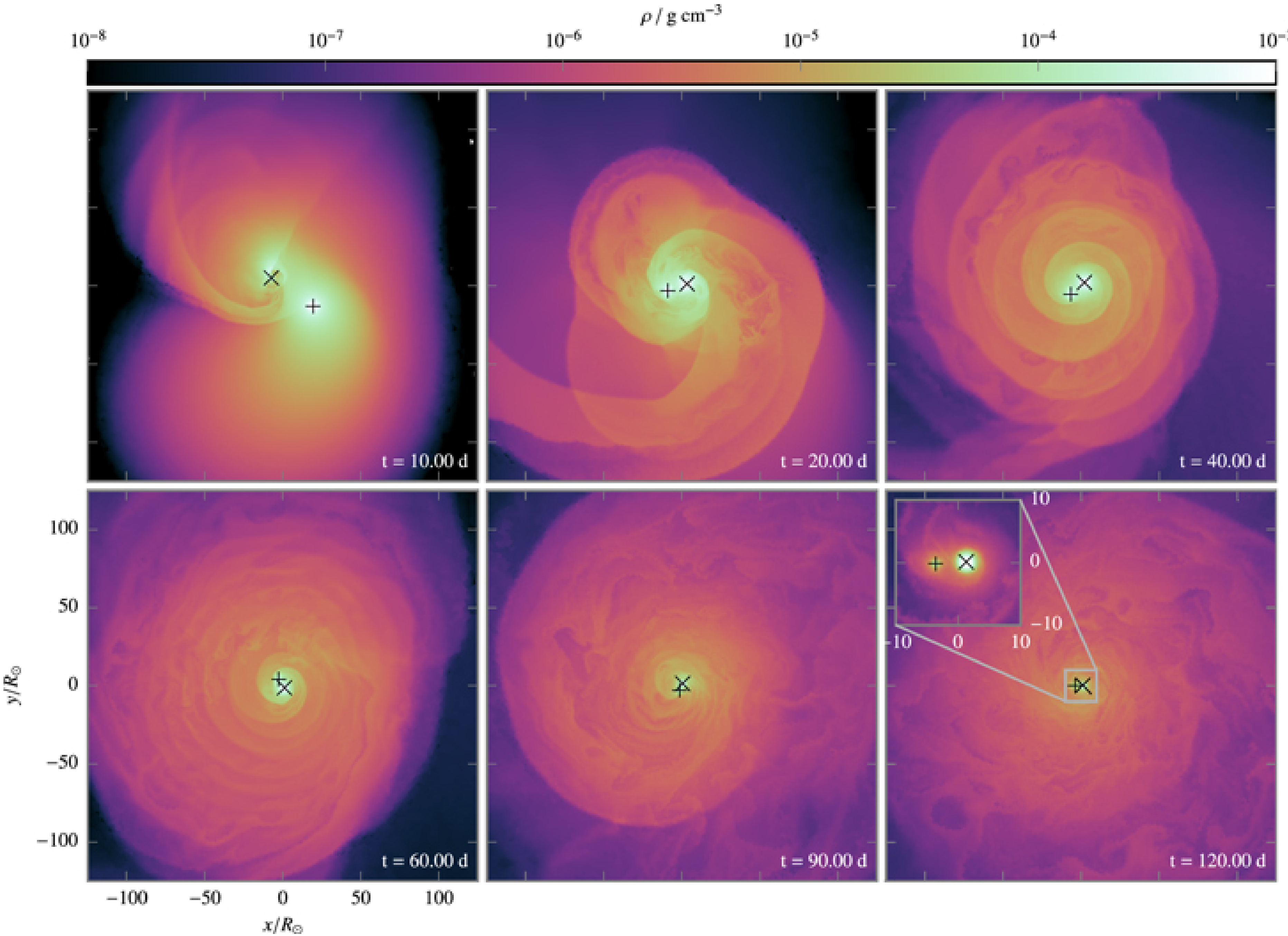
2. fast SPIRAL IN: two cores spiral in – they lose kinetic energy by drag with the gas and heat the gaseous envelope –
on dynamical time scale (~100d) – SIMULATED IN 3D
(Ricker & Taam 2008, 2012; Passy et al. 2012; Ohlmann+ 2016)



From Ohlmann et al. 2016, ApJ, 816, L9

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3. **slow SPIRAL IN: when two cores are close spiral-in slows down before envelope is ejected – Kelvin-Helmoltz timescale of envelope (~10^3-5 yr)**
   POORLY UNDERSTOOD!!! WHAT REMOVES THE ENVELOPE?

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4. MERGER of the cores or EJECTION of ENVELOPE

SEE IVANOVA ET AL. 2013, A&ARv, 21, 59 for a review

Common Envelope

Most used analytic formalism (αλ, Webbink 1984) does not capture physics. In its version by Hurley+ (2002, MNRAS, 329, 897) the αλ formalism is:

1. initial binding energy of envelope (λ = free parameter, geometrical factor)

$$E_{\rm bind,i} = -\frac{G}{\lambda}\left(\frac{M_1\,M_{\rm env,1}}{r_1}+\frac{M_2\,M_{\rm env,2}}{r_2}\right)$$

2. orbital energy of the cores

$$E_{\rm orb} = -\frac{1}{2}\,\frac{G\,M_{\rm c,1}\,M_{\rm c,2}}{a}$$

3. change of orbital energy needed to unbind the envelope:

$$E_{\rm bind,i} = \Delta E_{\rm orb} = \alpha\,(E_{\rm orb,f} - E_{\rm orb,i})$$

α is second free parameter (energy removal efficiency)

Common Envelope

4. if $$a_{\rm f} < (r_{\rm c,1} + r_{\rm c,2})$$

or $$r_{\rm c,i} < r_{\rm L,i}$$

i.e. any of the two cores fills Roche lobe before envelope ejection

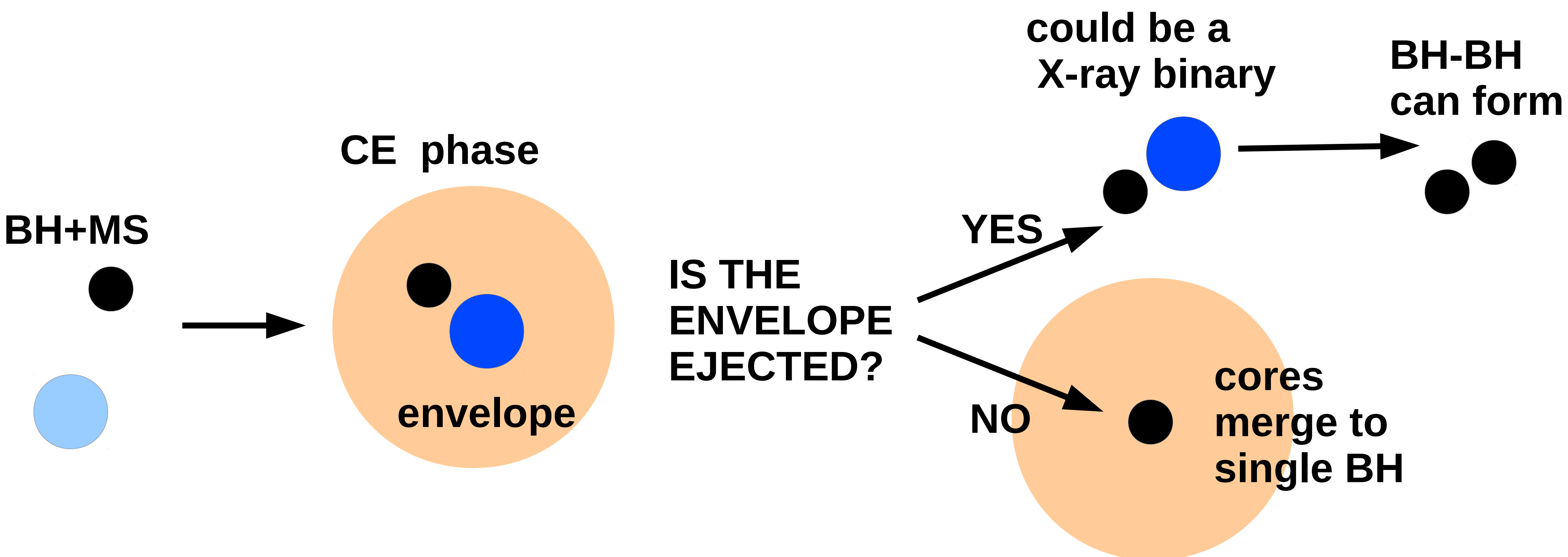
THEN the cores merge (Hurley+ 2002, MNRAS, 329, 897)

PROBLEM IS: HOW TO CONSTRAIN α and λ ?

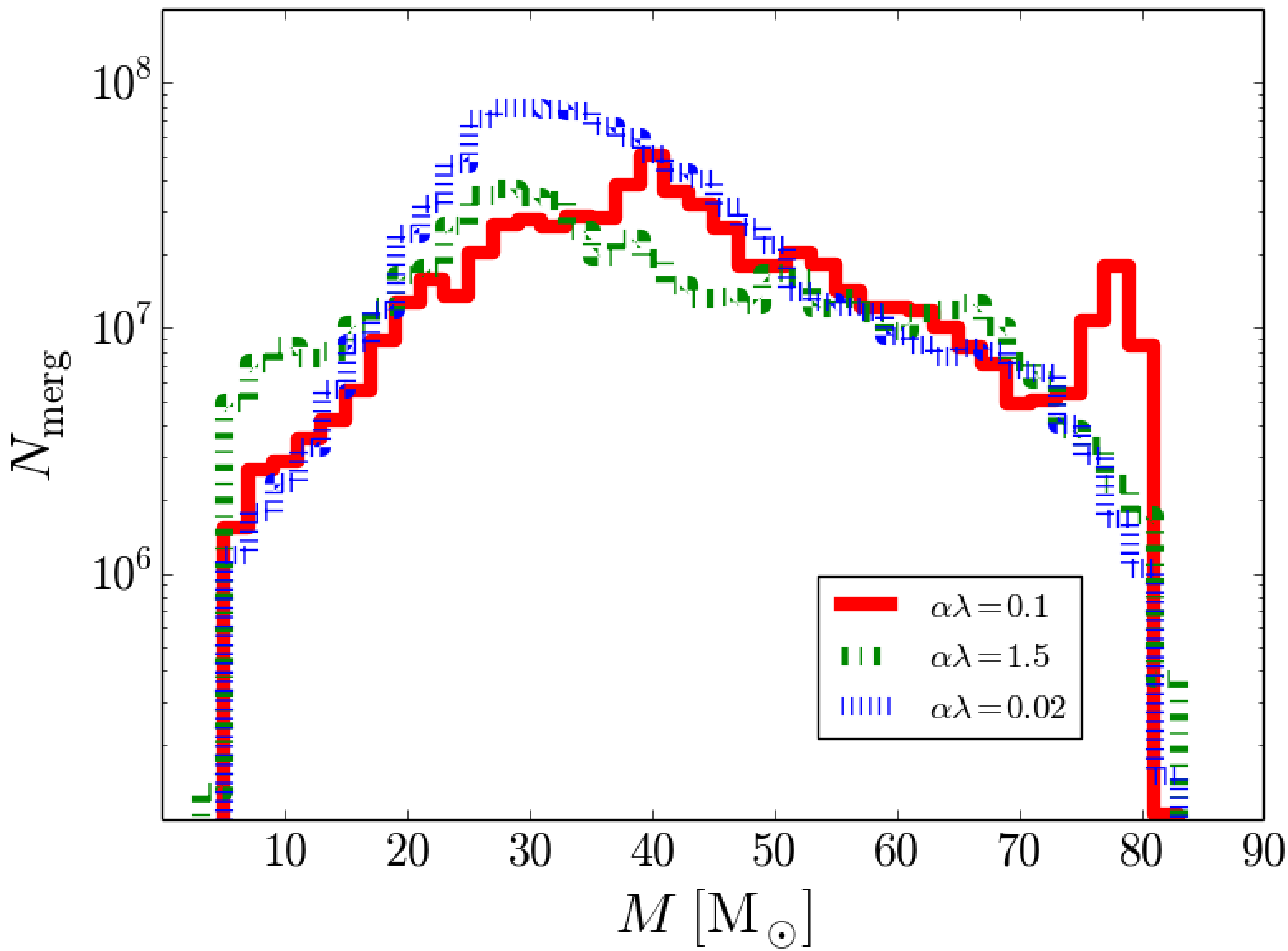
Observations of WD binaries, NS binaries, SNIa, now gravitational wave events, ….

Common Envelope

WHY is important for BH demography?



Common Envelope

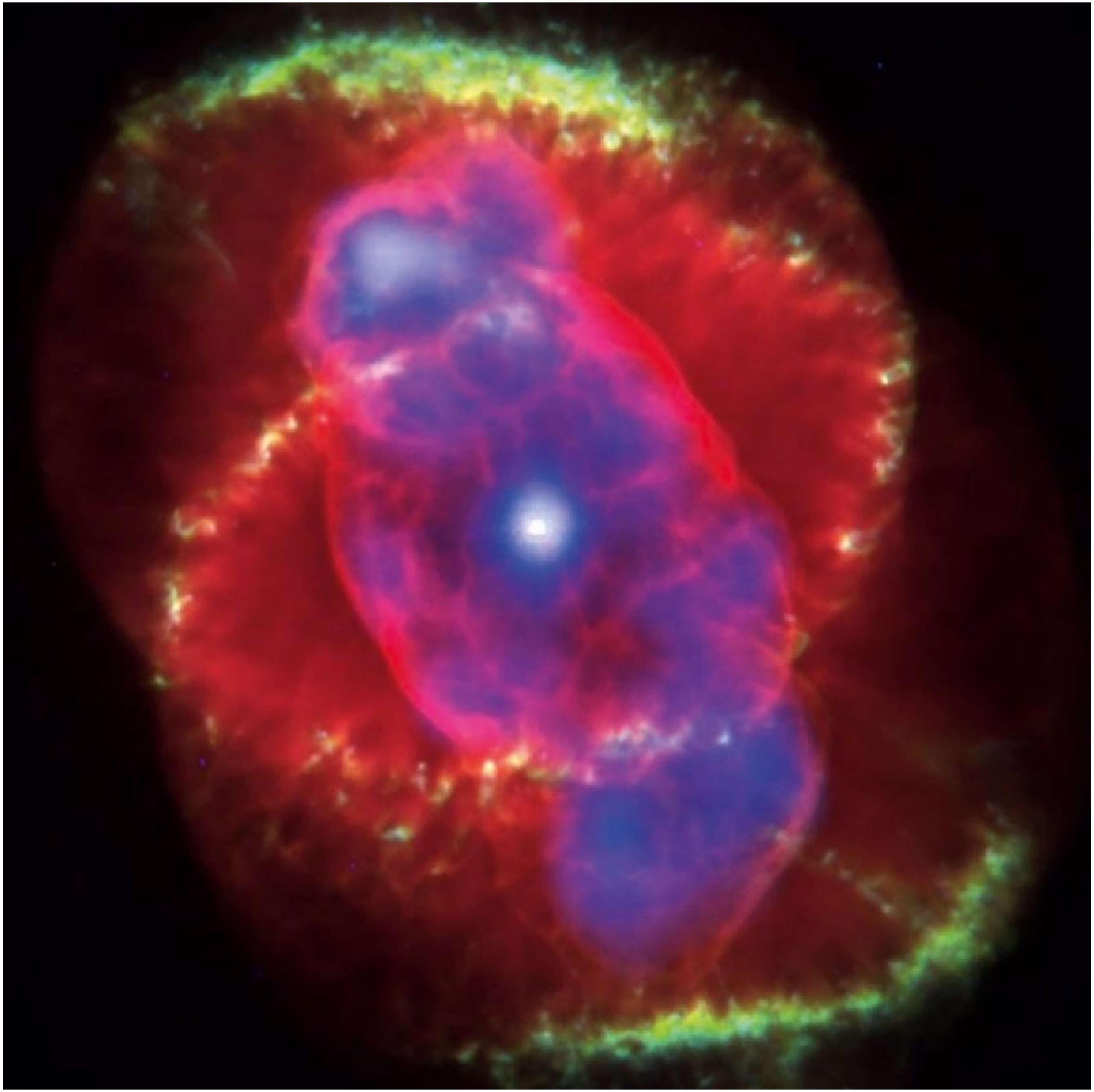


updated version of BSE (MM+ submitted, Giacobbo+ in prep.)

Common Envelope

observed post-CE systems

e.g. Cat's eye nebula



THANK YOU