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Binary compact objects as sources of gravitational waves

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Multimessenger Astrophysics, Asiago 14 – 23 January 2020

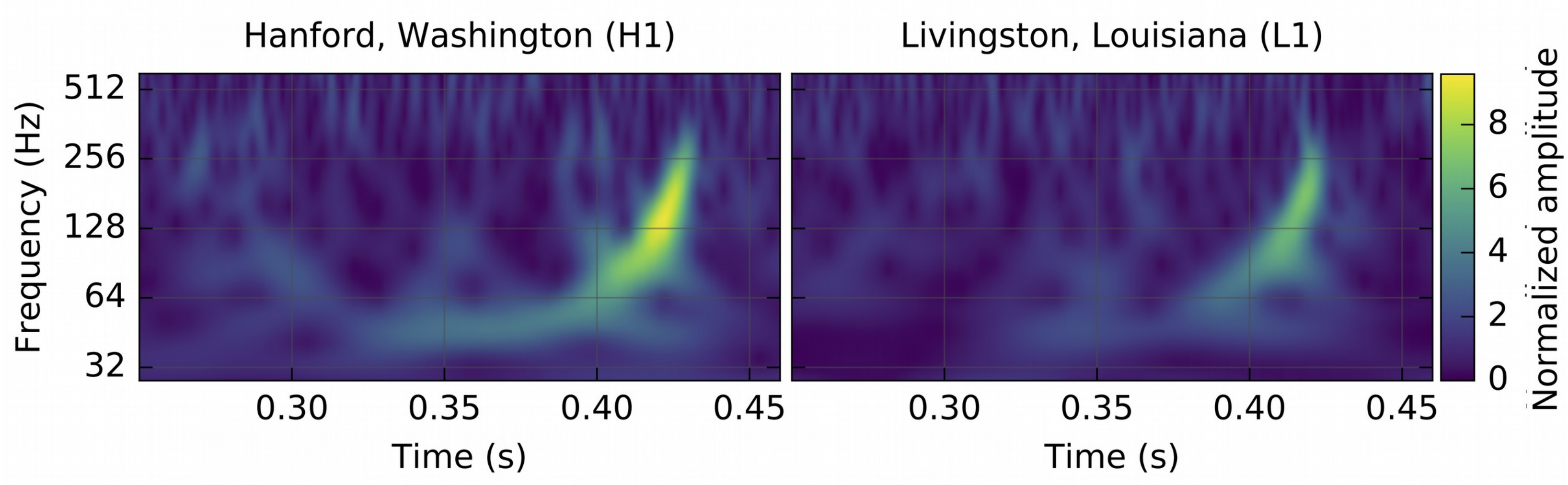
OUTLINE:

1. The formation of compact objects from stellar evolution and supernova explosions

2. Isolated formation of binary compact objects
   with EXERCISES on binary compact objects

3. Dynamical formation of binary compact objects

1. The formation of compact objects



Abbott+ 2016

What have astrophysicists learned from O1 + O2 detections?

1. Binary neutron star (BNS) mergers are associated with a gorgeous electromagnetic emission (Abbott+ 2017 on GW170817)

1. Binary black holes (BBHs) exist

(Tutukov & Yungelson 1973; Thorne 1987; Schutz 1989)

2. BBHs can merge in a Hubble time

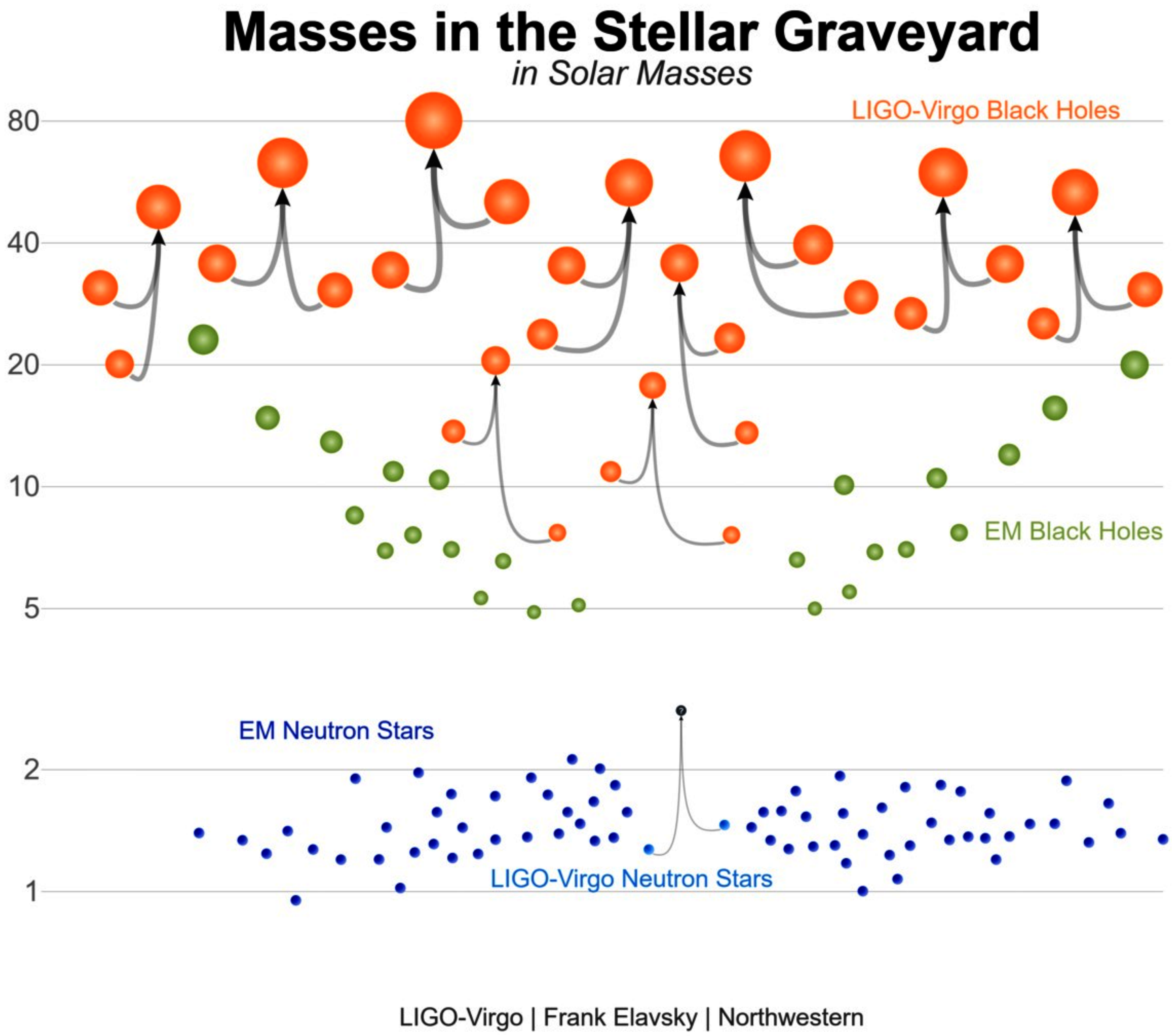
3. Massive black holes (BHs) exist i.e. stellar BHs with mass >20 M⊙

(Heger et al. 2003; MM et al. 2009, 2010; Belczynski+ 2010)

BHs in X-ray binaries < 20 M⊙ (Ozel+ 2010)

Most models of BH demography do not predict massive BH

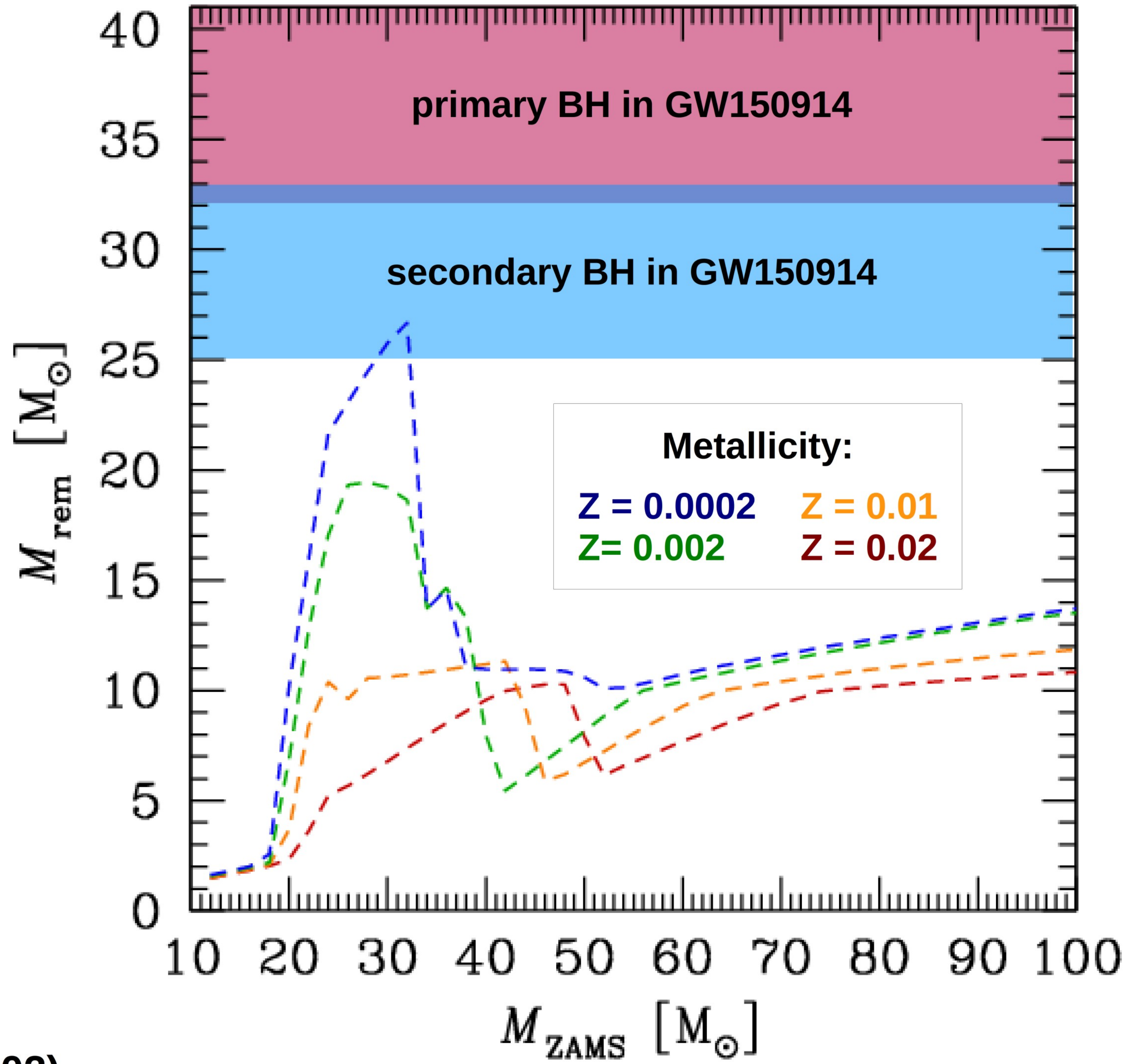
1. The formation of compact objects



1. The formation of compact objects

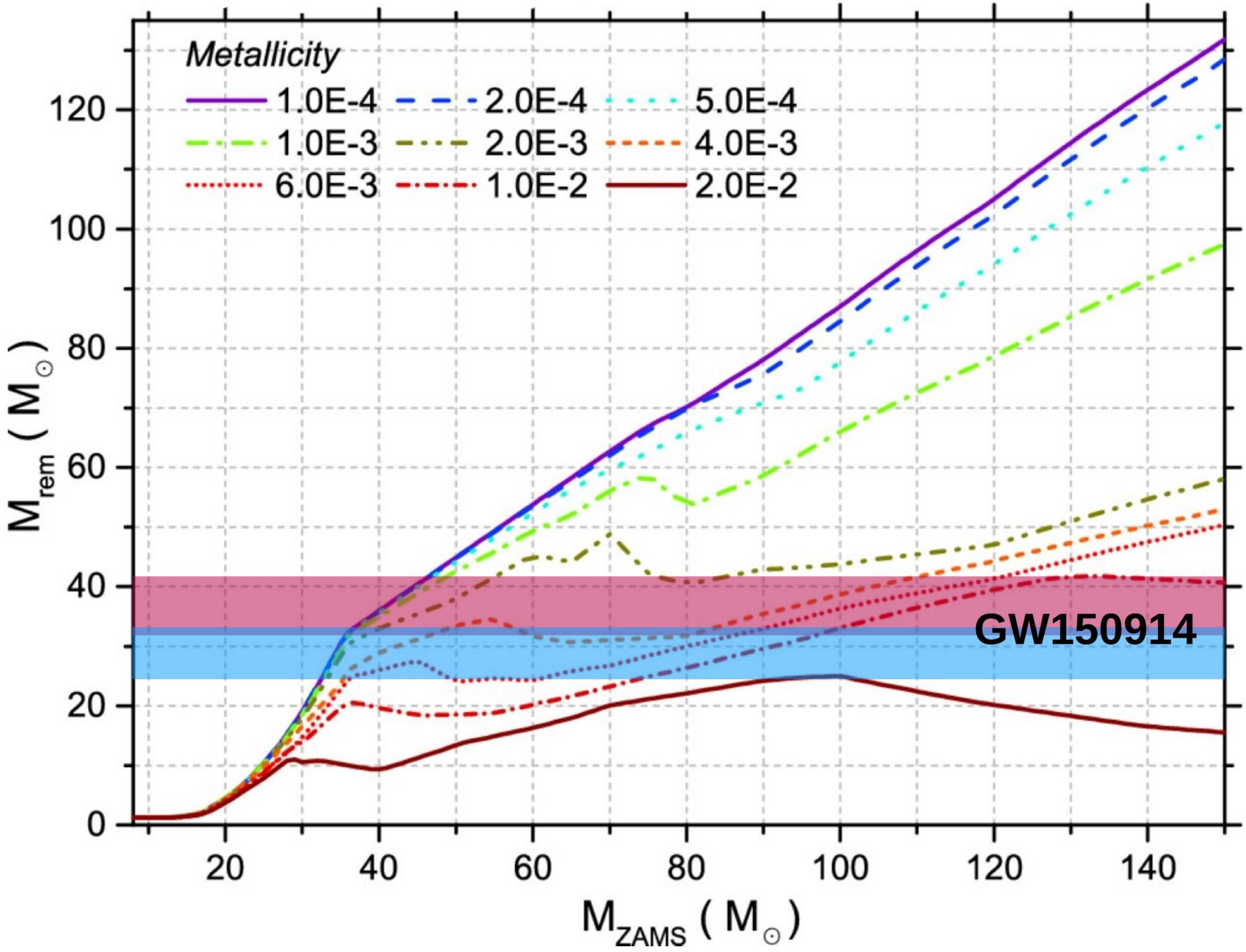
Most common remnant mass spectrum BEFORE GW150914 detection

cannot explain GW150914



(BSE code, Hurley+ 2002)

1. The formation of compact objects



From Spera, MM & Bressan 2015, MNRAS, 451, 4086

See also MM+ 2009, MNRAS, 395, L71; MM+ 2010, MNRAS, 408, 234; Belczynski+ 2010, ApJ, 714, 1217; Fryer+ 2012, ApJ, 749, 91; MM+ 2013, MNRAS, 429, 2298; Belczynski+ 2016, A&A, 594, 97; Spera & MM 2017, MNRAS, 470, 4739

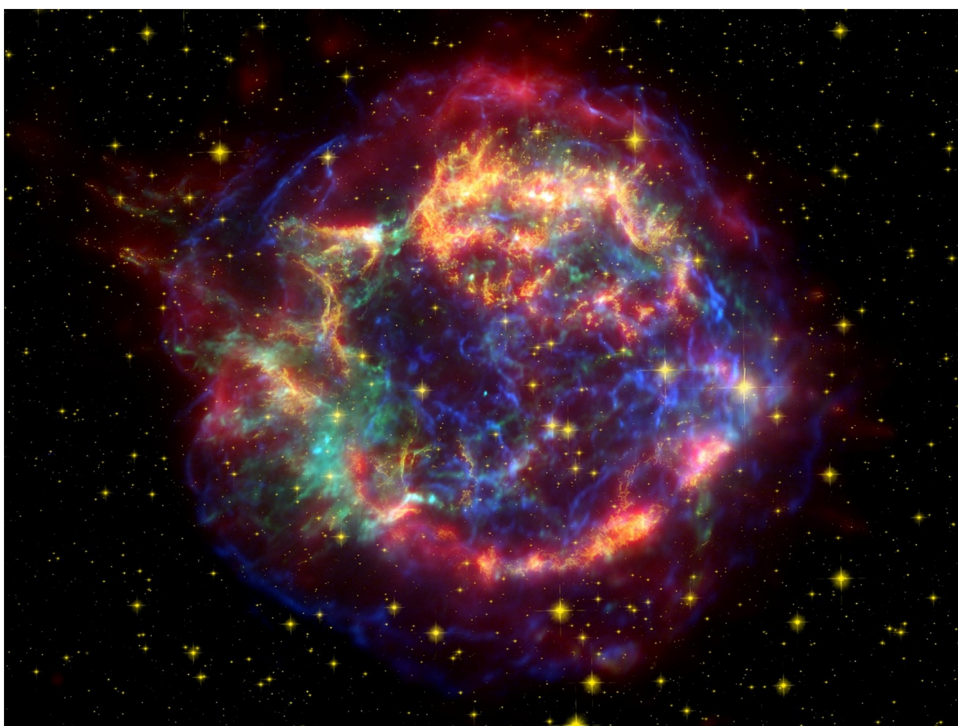
1. The formation of compact objects

Two critical ingredients:

1) **PROGENITOR STAR EVOLUTION (STELLAR WINDS)**

2) **SUPERNOVA (SN) EXPLOSION**

Winds ejected by Eta Carinae (HST, credits: NASA)



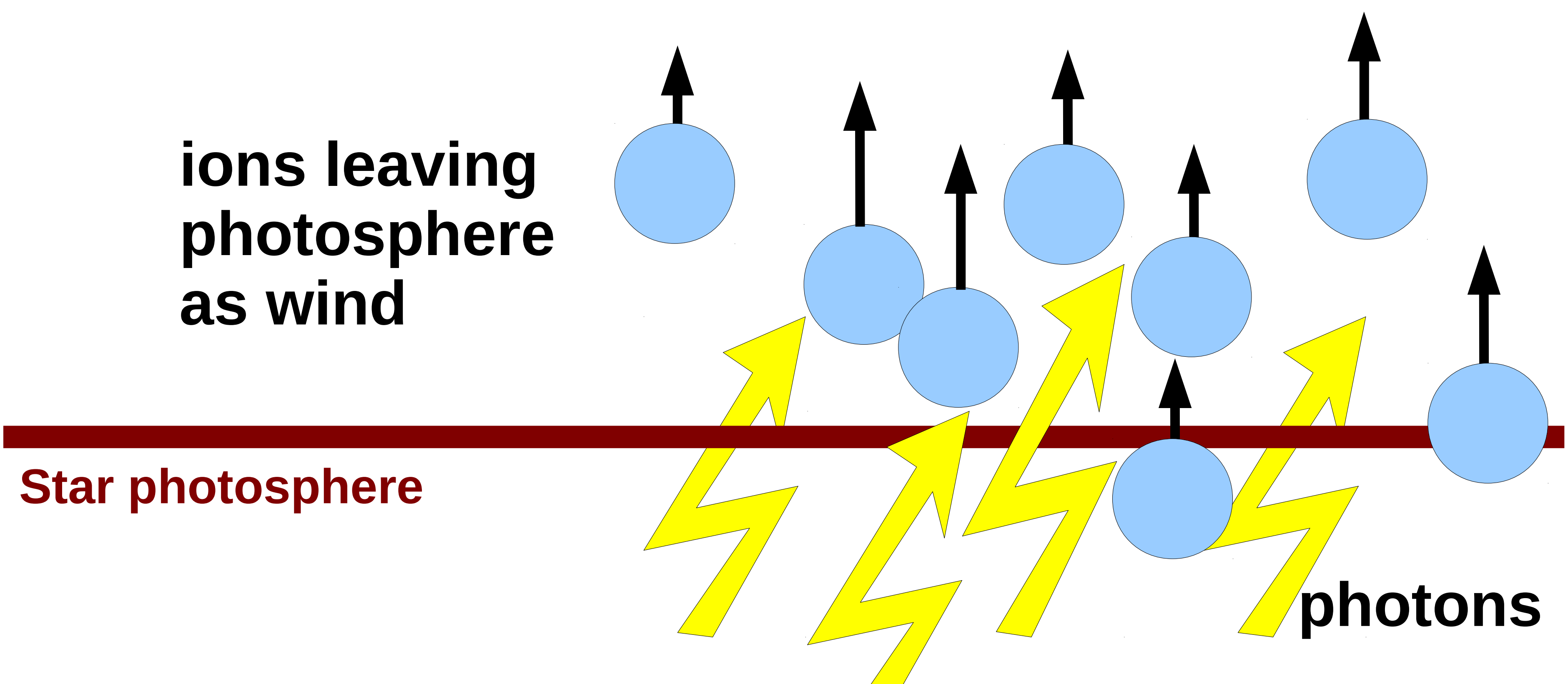
Chandra + HST + Spitzer Image of the SN remnant Cassiopeia A

1. The formation of compact objects: stellar winds

Massive stars (>30 Msun) might lose >50% mass by winds
Stellar wind models underwent major upgrade in last ~10 yr
(Vink+ 2001, 2005, 2011; see Vink+ 2016 for a short review)

Photons in atmosphere of a star couple with ions
→ transfer linear momentum to the ions and unbind them

Coupling through resonant METAL LINES (especially Fe lines)
→ MASS LOSS DEPENDS ON METALLICITY



How do we define metallicity in astrophysics?

Metallicity in astrophysics is NOT same as chemistry

Metals in Astro:
every element heavier than Helium

Measured with Z = FRACTION of elements heavier than He

$$X + Y + Z = 1.0$$

If M = total mass of system

$X = m_p / M$ $\quad$ $Y = m_{He} / M$ $\quad$ $Z = \sum_i m_i / M$

Cosmological values:
$X \sim 0.75$, $Y \sim 0.25$, $Z \sim 0$

Sun values:
$X \sim 0.73$, $Y \sim 0.25$, $Z \sim 0.02$

1. The formation of compact objects: stellar winds

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→ MASS LOSS DEPENDS ON METALLICITY

$$\boxed{\dot{M} \propto Z^{\alpha}} \qquad \alpha \sim 0.5 - 0.9$$

Metallicity dependence less important when STAR is CLOSE to electron-scattering EDDINGTON LIMIT
(RADIATION PRESSURE dominates)

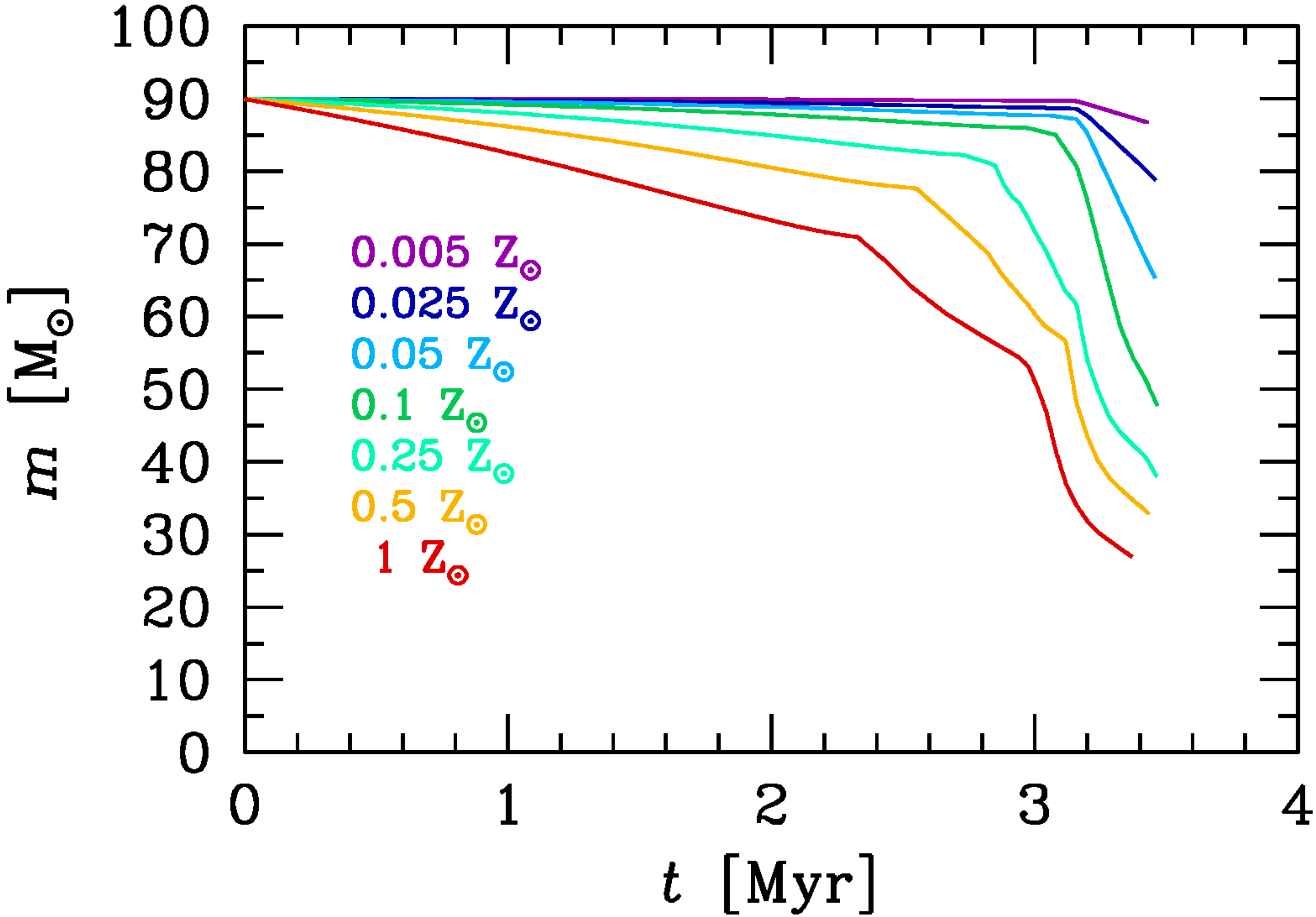
e.g. Graefener & Hamann 2008

$$\boxed{\Gamma = \frac{L_*}{L_{\rm Edd}}}$$

$$\alpha = 0.85 \qquad [\text{if } \Gamma < 2/3]$$

$$\alpha = 2.45 - 2.4\,\Gamma \quad [\text{if } \Gamma > 2/3]$$

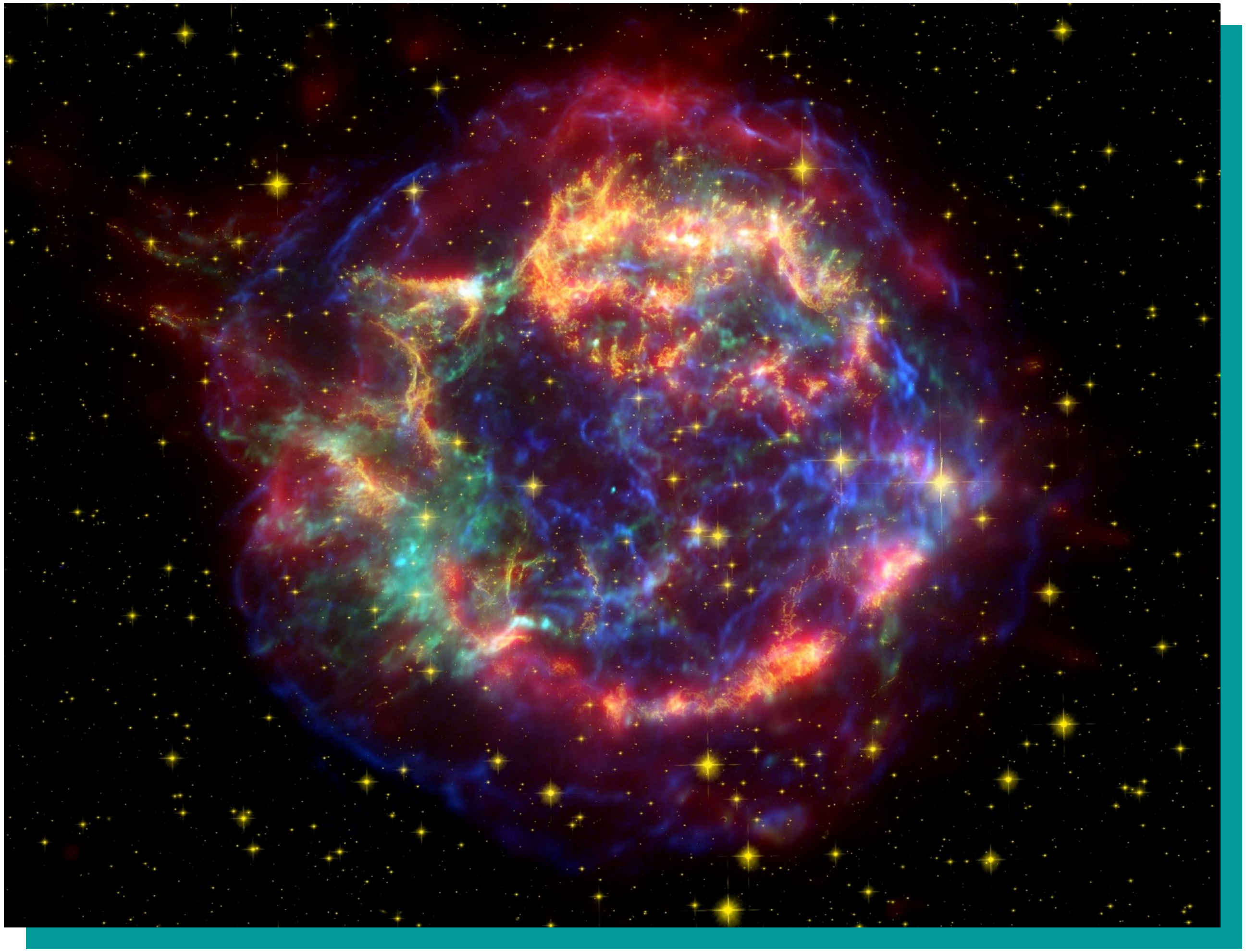
1. The formation of compact objects: stellar winds



Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015)

1. The formation of compact objects: supernova

Pre-supernova mass of a star is very important because affects the outcome of the SUPERNOVA



1. The formation of compact objects: supernova

When Fe core forms in a massive (> 8 Msun) star

1) Fe-group atoms (Ni-62, Fe-58, Fe-56) have maximum binding energy: no more energy released by fusion
→ core starts collapsing because pressure drops

2) electron degeneracy pressure tries to stop collapse but if core mass > Chandrasekhar mass (~1.4 Msun) electron + proton capture removes electrons
<u>→ electron pressure decreases</u>

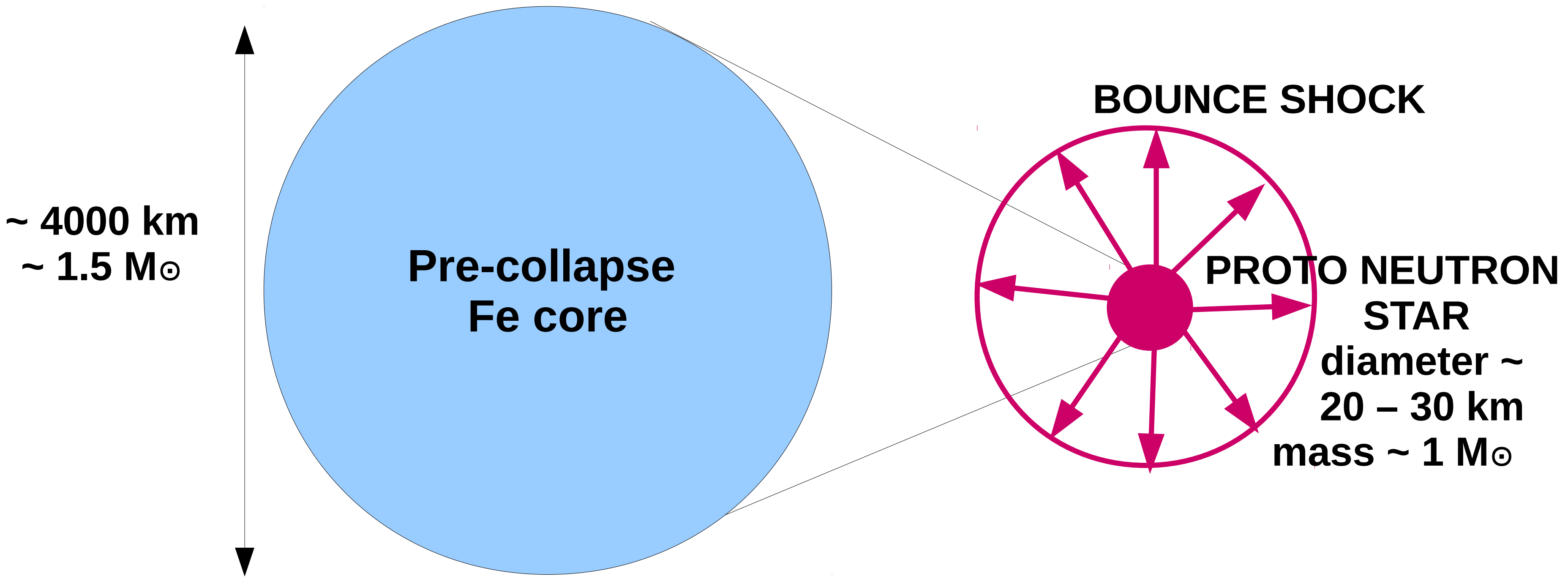
→ COLLAPSE to NUCLEAR DENSITY,
where <u>neutron degeneracy pressure</u> stops collapse

→ PROTO-NEUTRON STAR FORMS

1. The formation of compact objects: supernova

Collapse of the core to nuclear density produces BOUNCE SHOCK

Fraction of binding energy of core (Eb,c ~10^{53} erg) is converted into thermal energy (mostly of neutrinos)



1. The formation of compact objects: supernova

Collapse of the core to nuclear density produces BOUNCE SHOCK

Fraction of binding energy of core (Eb,c ~10^{53} erg)
is converted into thermal energy (mostly of neutrinos)

SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS

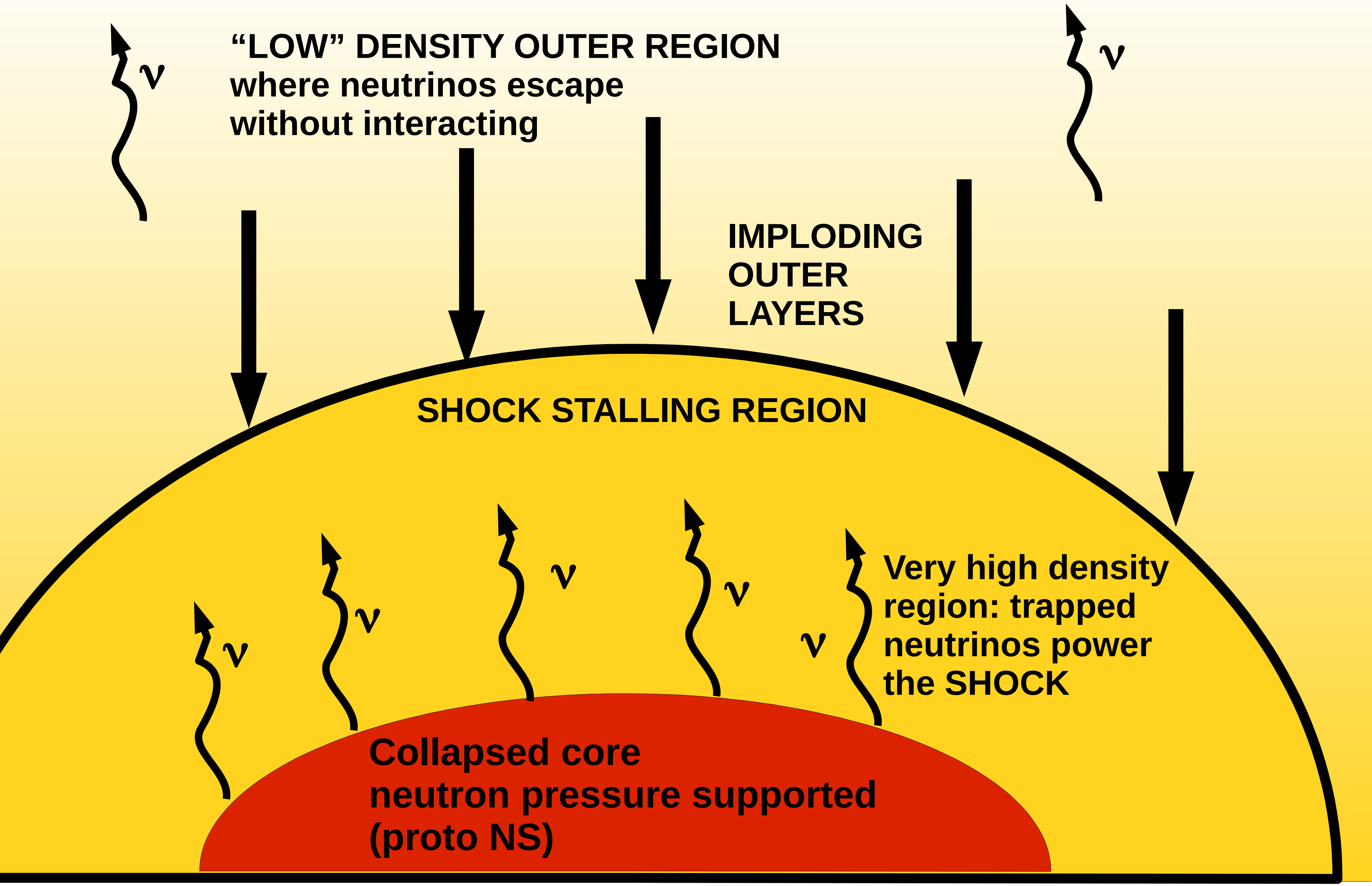
But density must be sufficiently high that neutrinos interact,
otherwise neutrinos leak away without transferring energy
→ SHOCK MIGHT STALL
→ SN FAILS

WHAT CAN REVIVE THE SHOCK?

STANDARD MODEL: CONVECTIVE ENGINE

Fryer 2014, http://pos.sissa.it/archive/conferences/237/004/FRAPWS2014_004.pdf

1. The formation of compact objects: supernova



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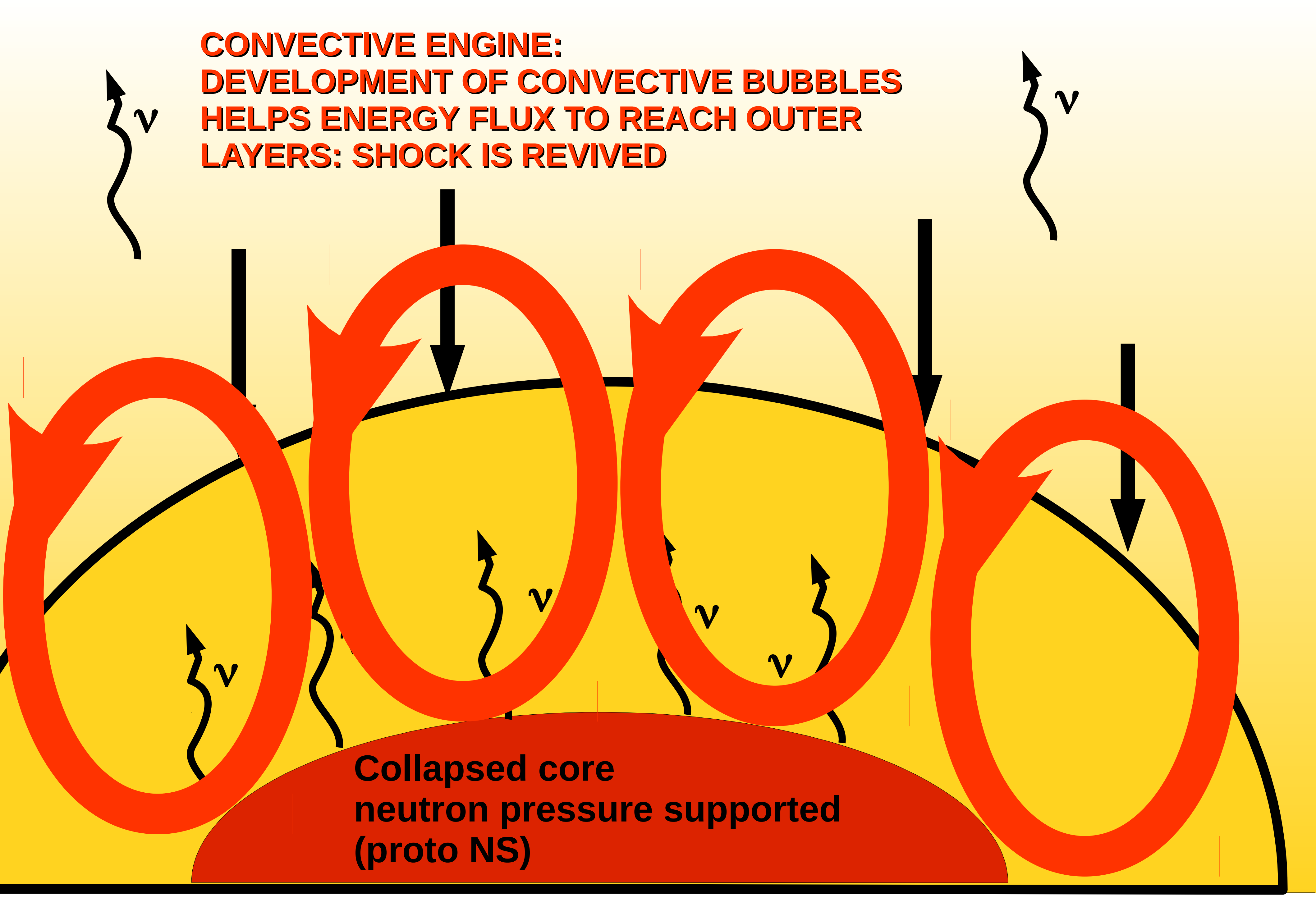


1. The formation of compact objects: supernova

Supernova shock stops anyway if BOUND MASS is too LARGE (Fryer 1999; Fryer & Kalogera 2001)

Back-of-the-envelope calculation to connect direct collapse and pre-supernova mass:

envelope mass

proto-NS ~ 1 Msun

$$E_{\rm SN} = \frac{G\,M_{\rm env}\,(M_{\rm env}+M_{\rm core})}{R_{\rm env}}$$

envelope radius

Star cannot explode if envelope binding energy > SN energy

$$M_{\rm env} \sim 50\,M_\odot \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{1/2} \left(\frac{R_{\rm env}}{10\,R_\odot}\right)^{1/2}$$

If $M_{\rm fin}$>50 Msun this SN fails and star collapses to a BH

1. The formation of compact objects: supernova

CRITERIA FOR COLLAPSE TO A REMNANT

depends on the "compactness" of the inner layers of the star

1. MASS OF CARBON-OXYGEN CORE
If Mco > 8 – 12 Msun SN FAILS
(Fryer+ 1999, 2012; Belczynski+ 2010)

2. COMPACTNESS

3. TWO-PARAMETER CRITERION

1. The formation of compact objects: supernova

Core-collapse (CC) SN depends on the "compactness" of the inner layers

COMPACTNESS (= ratio between mass and radius) of a given portion of the stellar core at the onset of collapse
(O'Connor & Ott 2011)

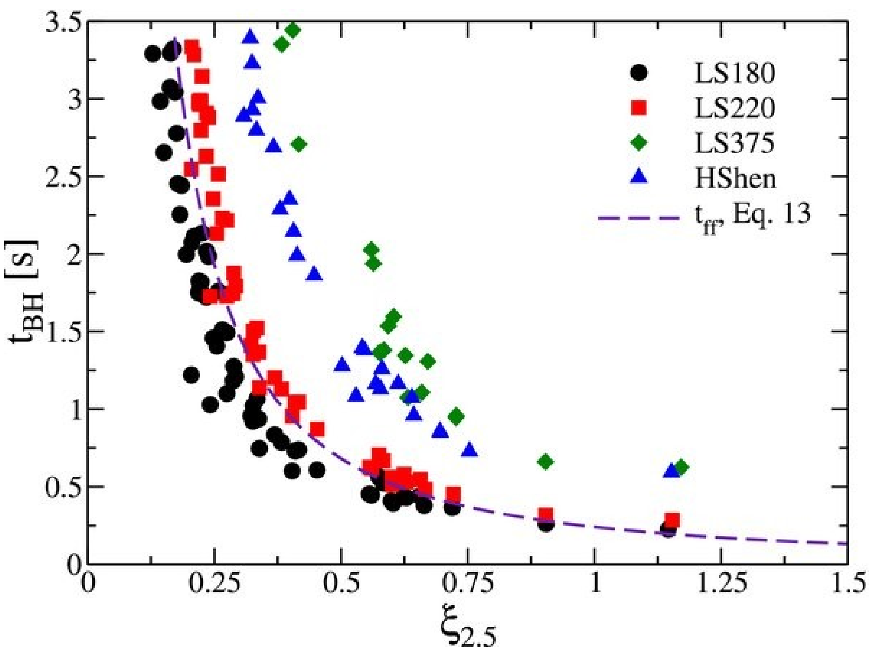
$$\xi_M \equiv \frac{M/\,\mathrm{M}_\odot}{R\,(M)\,/1000\,\mathrm{km}}$$

***M* = 2.5 M⊙ is usually adopted**

Star collapses if $\xi_{2.5} > 0.2$

(Ugliano+ 2012; Horiuchi+ 2012)

Figure from
O'Connor & Ott 2011



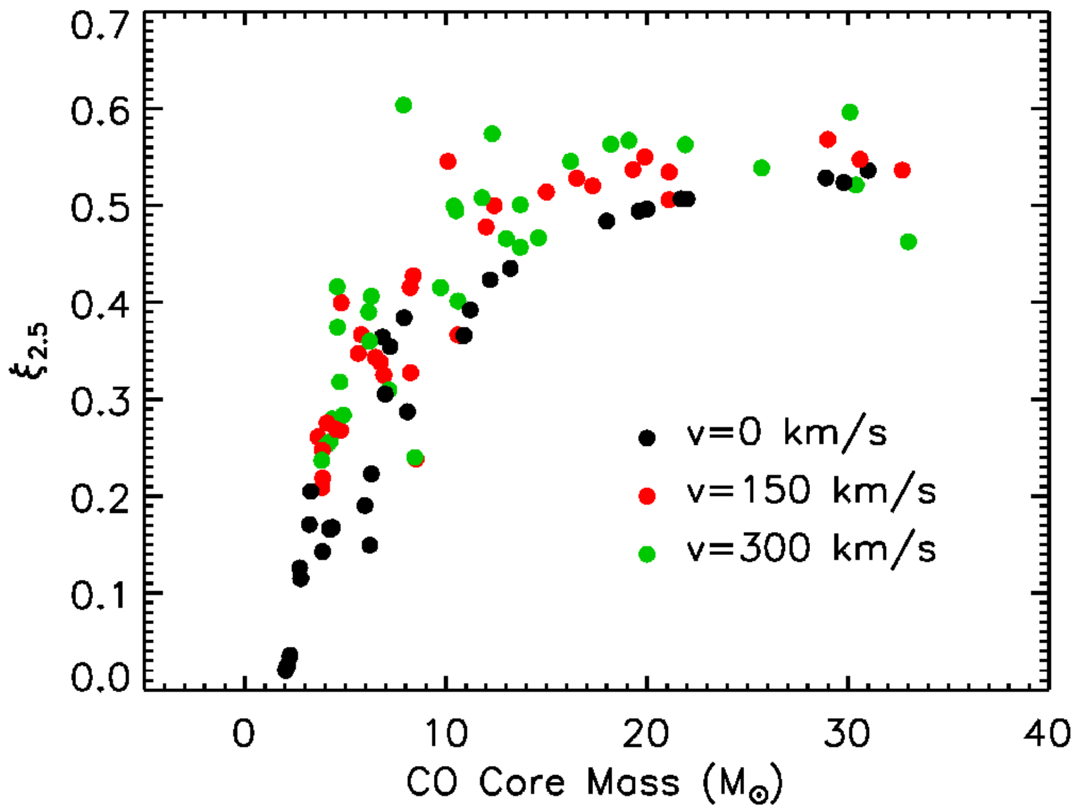
1. The formation of compact objects: supernova

Core-collapse (CC) SN depends on the "compactness" of the inner layers

Compactness correlates well with mass of CO core

→ compactness > 0.2 corresponds to CO core > 8 M⊙

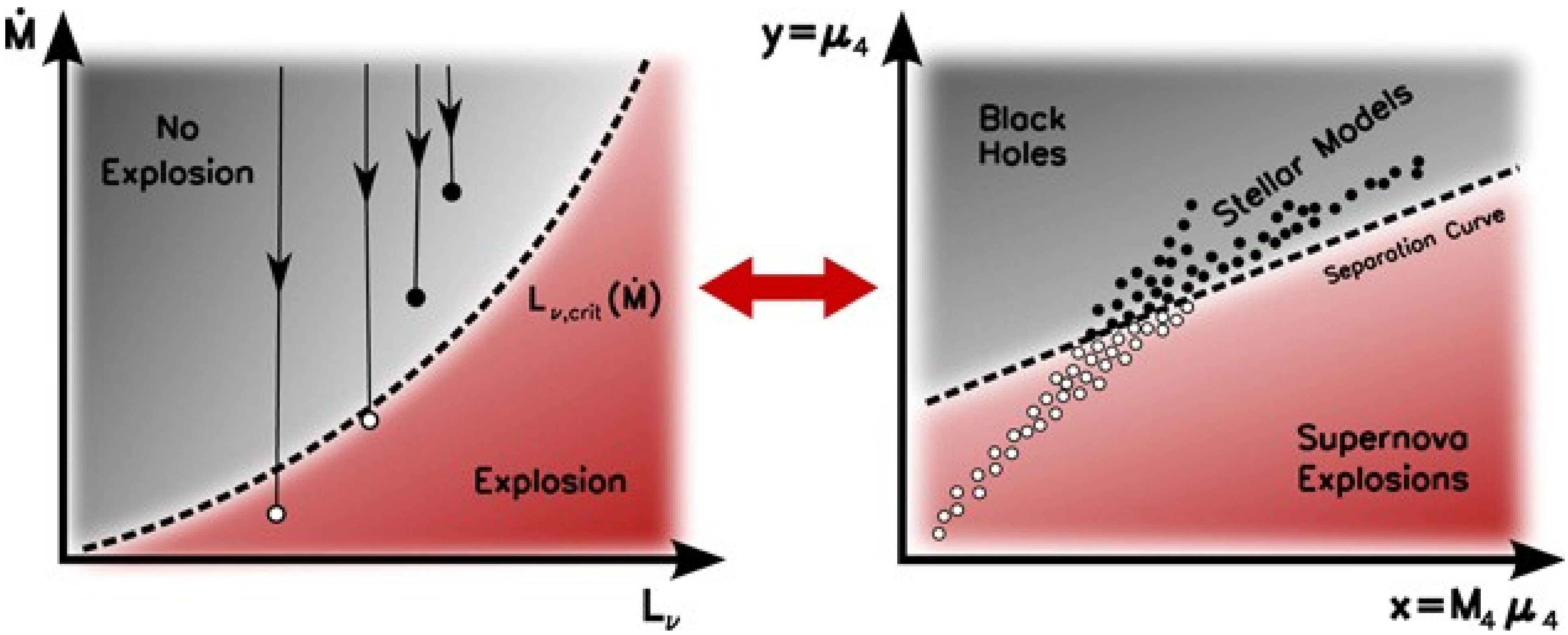
Figure from Limongi 2017 arXiv:1706.01913



1. The formation of compact objects: supernova

Core-collapse (CC) SN depends on the enclosed mass (M_4) and mass gradient (μ_4) at a dimensionless entropy per nucleon *s* = 4

$$M_4 = m(s=4)/M_\odot \qquad \mu_4 = \left[\frac{dm/M_\odot}{dr/1000\,\mathrm{km}}\right]_{s=4}$$



Ertl et al. 2016

1. The formation of compact objects: supernova

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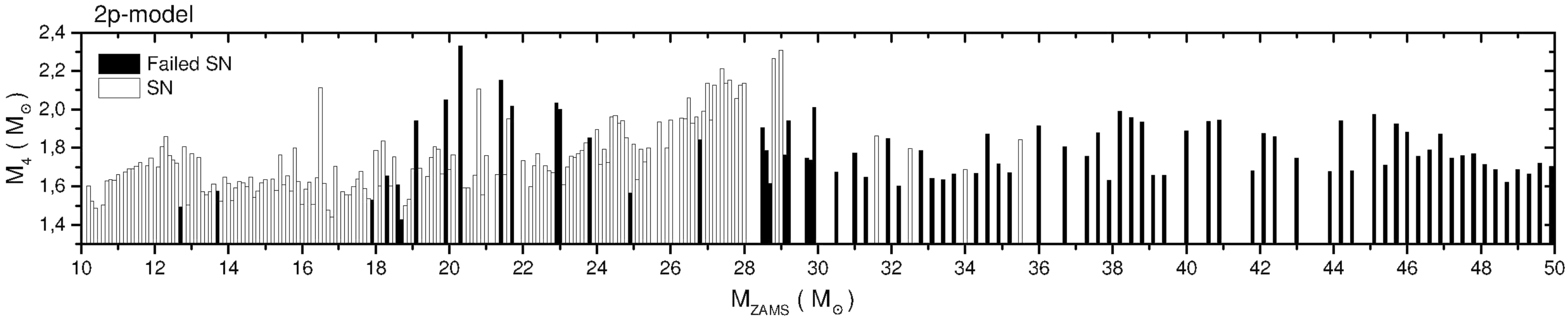


Fig. 21 **Spera, MM, Bressan 2015**

ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION

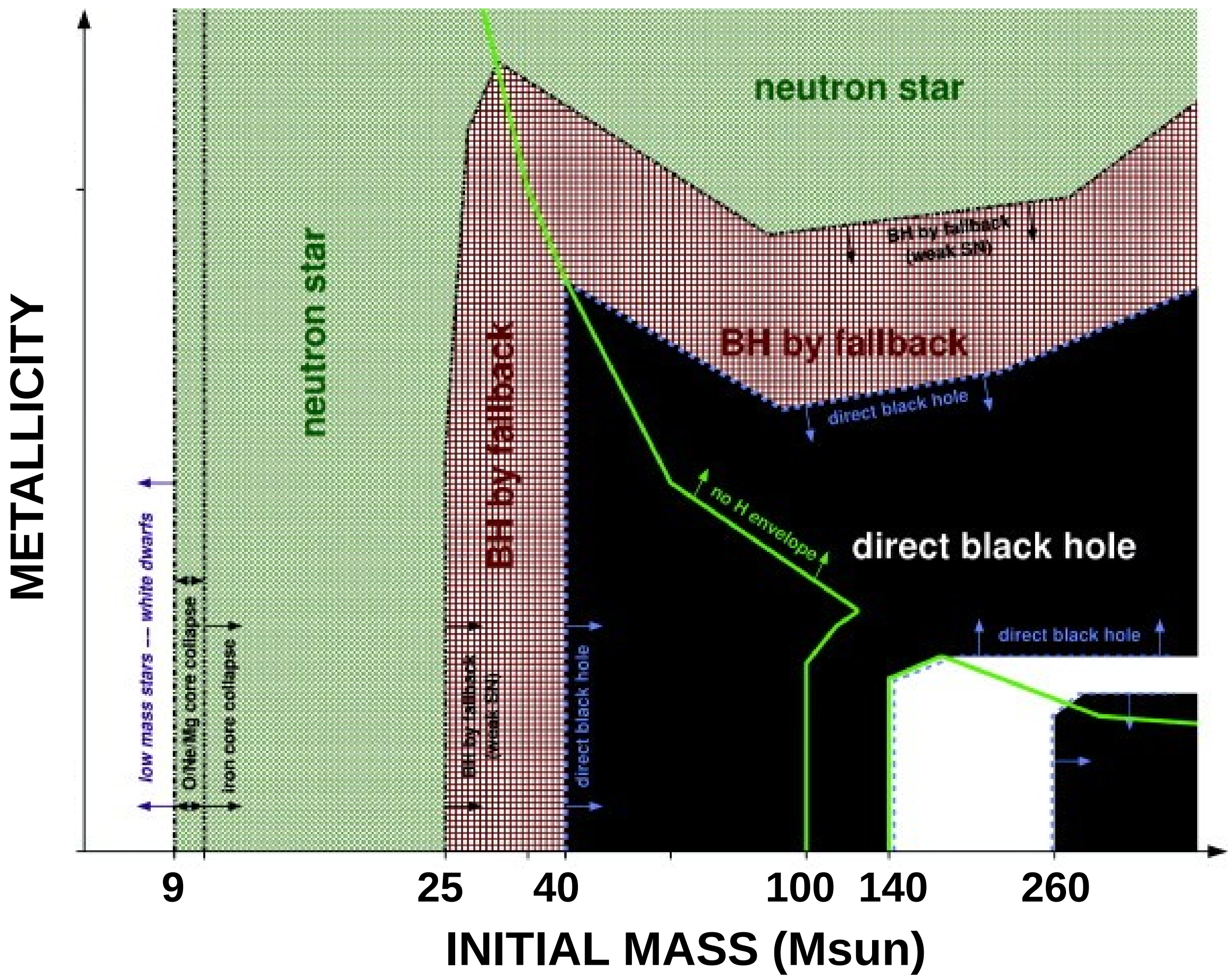
Concluding remark:
MANY MODELS of core-collapse SN EXPLOSION – REMNANT MASS CONNECTION BUT IF THE STAR IS VERY MASSIVE (>40 M⊙) THEY GIVE SIMILAR RESULT

1. The formation of compact objects: supernova

CC SN depends on the "fallback" of the outer layers of the star:

How much material falls back to the proto-NS after the SN

Barely constrained – depends on explosion energy,
angular momentum,
progenitor's mass/metallicity

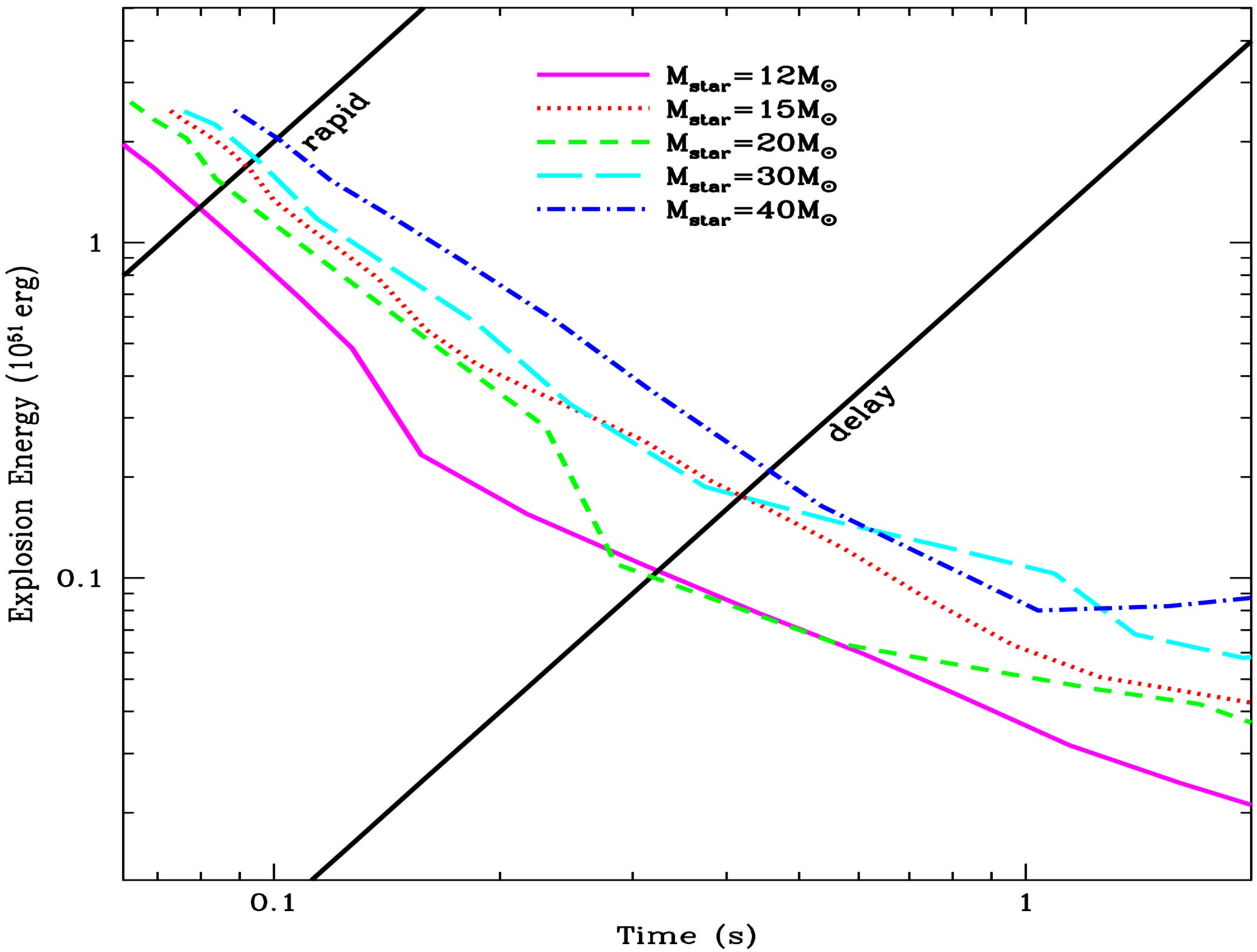


Heger 2003

1. The formation of compact objects: supernova

CC SN depends on the rapidity of the explosion:

(e.g. Fryer+ 2012; Fryer 2014)



RAPID (<250 ms after bounce): explosion energy >10^51 erg/s

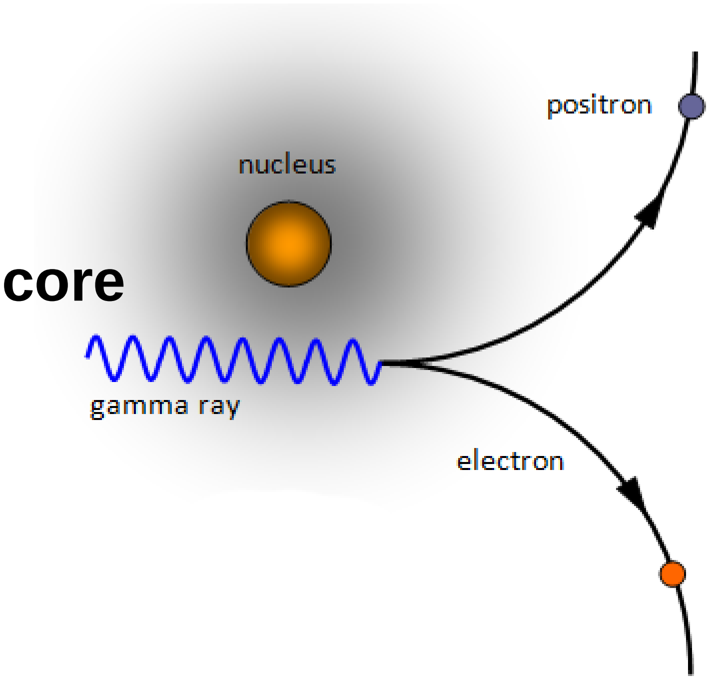
DELAYED (>500 ms after bounce): explosion energy <10^51 erg/s)

From Fryer 2014, http://pos.sissa.it/archive/conferences/237/004/FRAPWS2014_004.pdf

1. The formation of compact objects: supernova

PAIR-INSTABILITY SUPERNOVAE (PISNe)

If star is very massive,
Helium core mass > 64 $M_\odot$
→ central temperature > 7 x 10^8 K
→ efficient production of γ-ray radiation in core



➔ γ-ray photons scattering atomic nuclei produce electron-positron pairs (1 Mev)

The missing pressure of γ-ray photons produces dramatic collapse during O burning, without Fe core

→ high-Temperature collapse ignites all remaining species

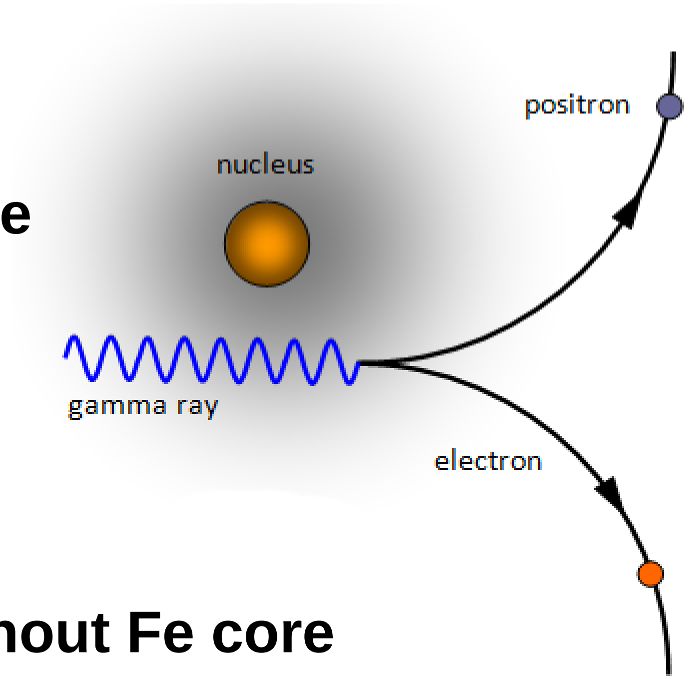
→ an explosion is induced that leaves NO remnant

Ober, El Eid & Fricke 1983; Bond, Arnett & Carr 1984; Heger et al. 2003; Woosley, Blinnikov & Heger 2007

1. The formation of compact objects: supernova

→ PULSATIONAL PAIR INSTABILITY (PPI)

If star is quite massive,
64 $M_\odot$ > Helium core mass > 32 $M_\odot$
→ some production of γ-ray radiation in core



➔ γ-ray photons scattering atomic nuclei produce electron-positron pairs (1 Mev)

The missing pressure of γ-ray photons produces contraction during O burning, without Fe core

→ enhancement of nuclear reaction restores pressure

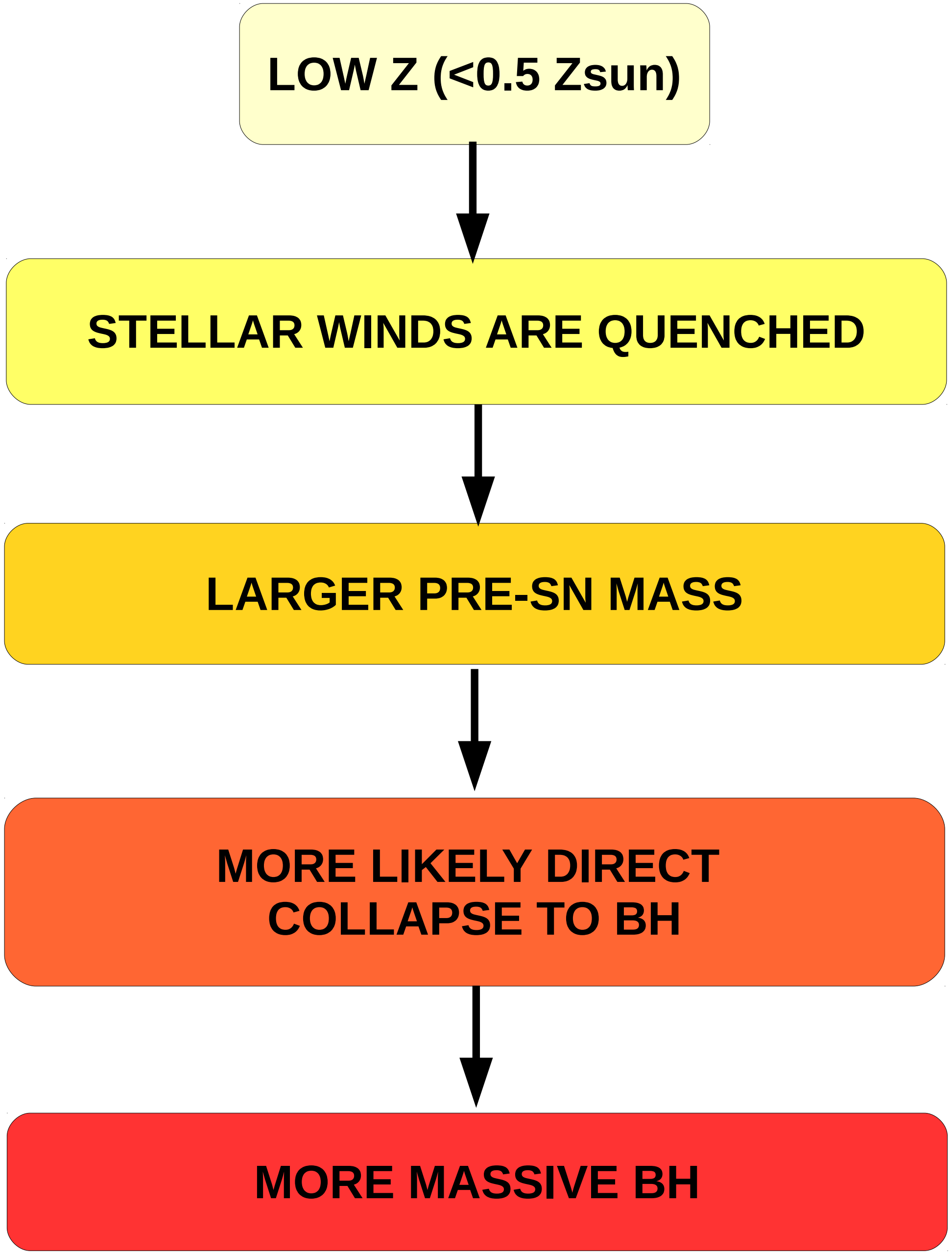
→ star gains equilibrium after one or more oscillations

→ oscillations enhance mass loss and final mass is lower

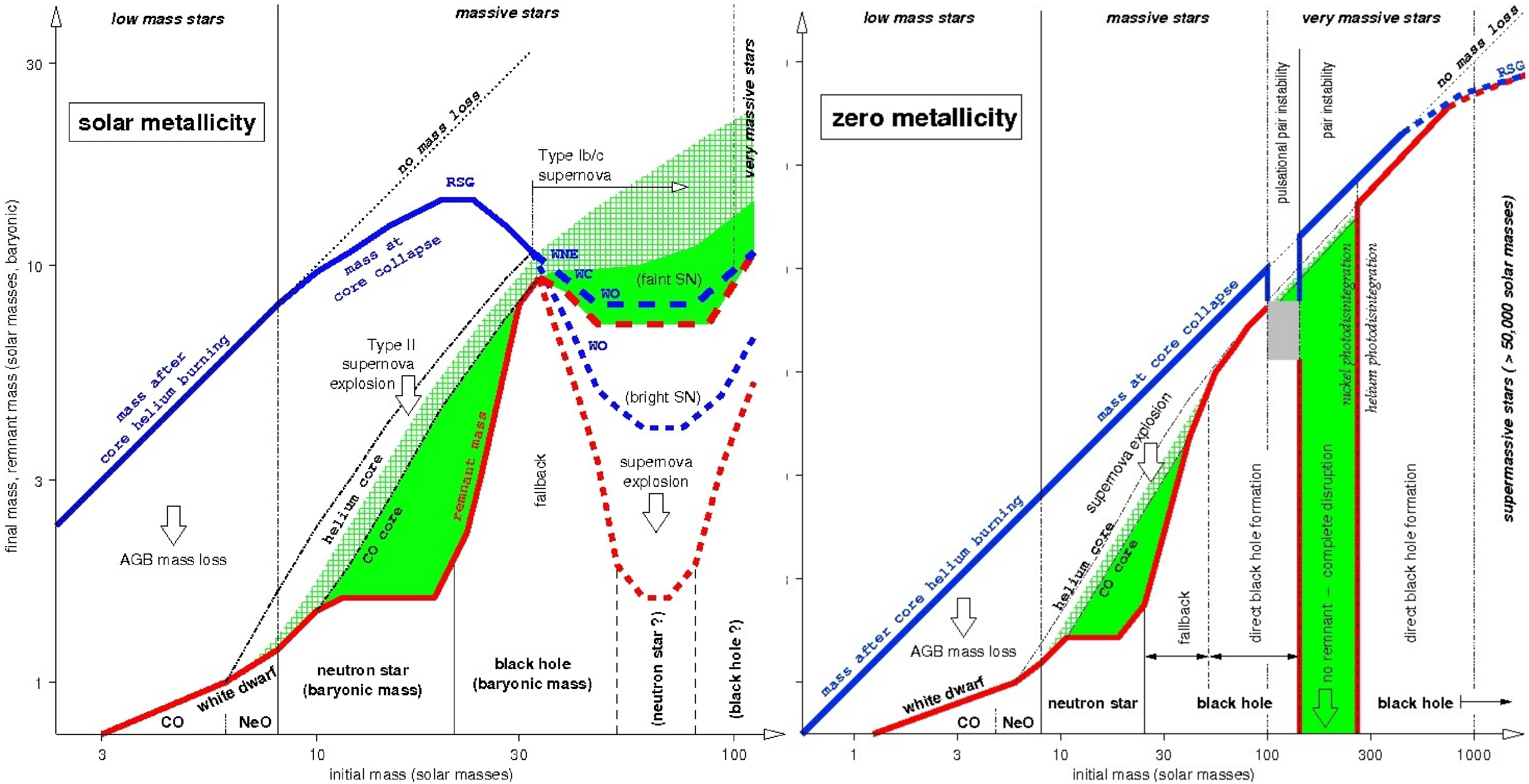
Barkat, Rakavy & Sack 1967; Woosley, Blinnikov & Heger 2007; Yoshida et al. 2016; Woosley 2017

1. The formation of compact objects: wrap up

Very complicated. However, as rule of thumb (MM+ 2009, 2013):

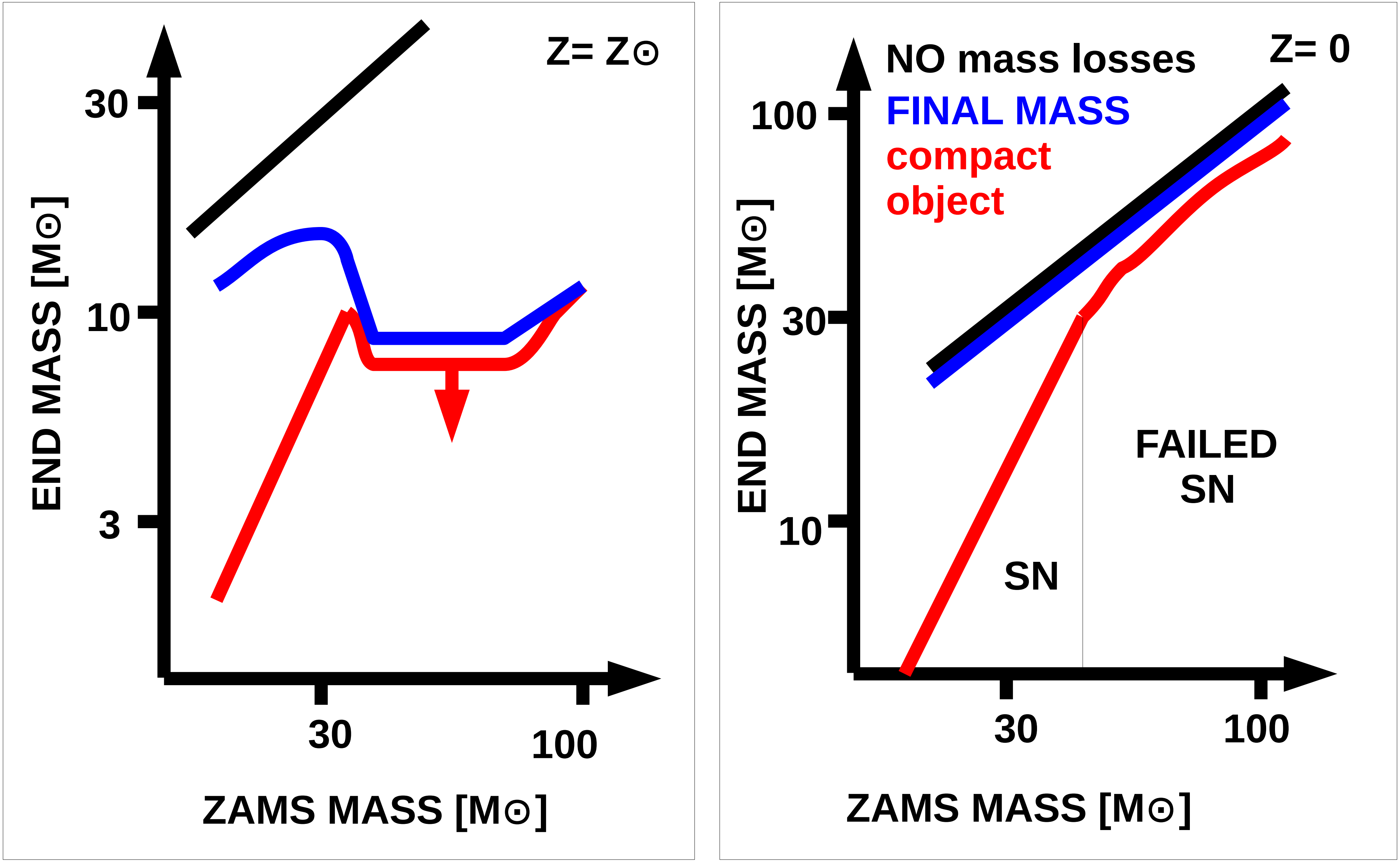


1. The formation of compact objects: wrap up



Heger et al. (2003)

1. The formation of compact objects: wrap up

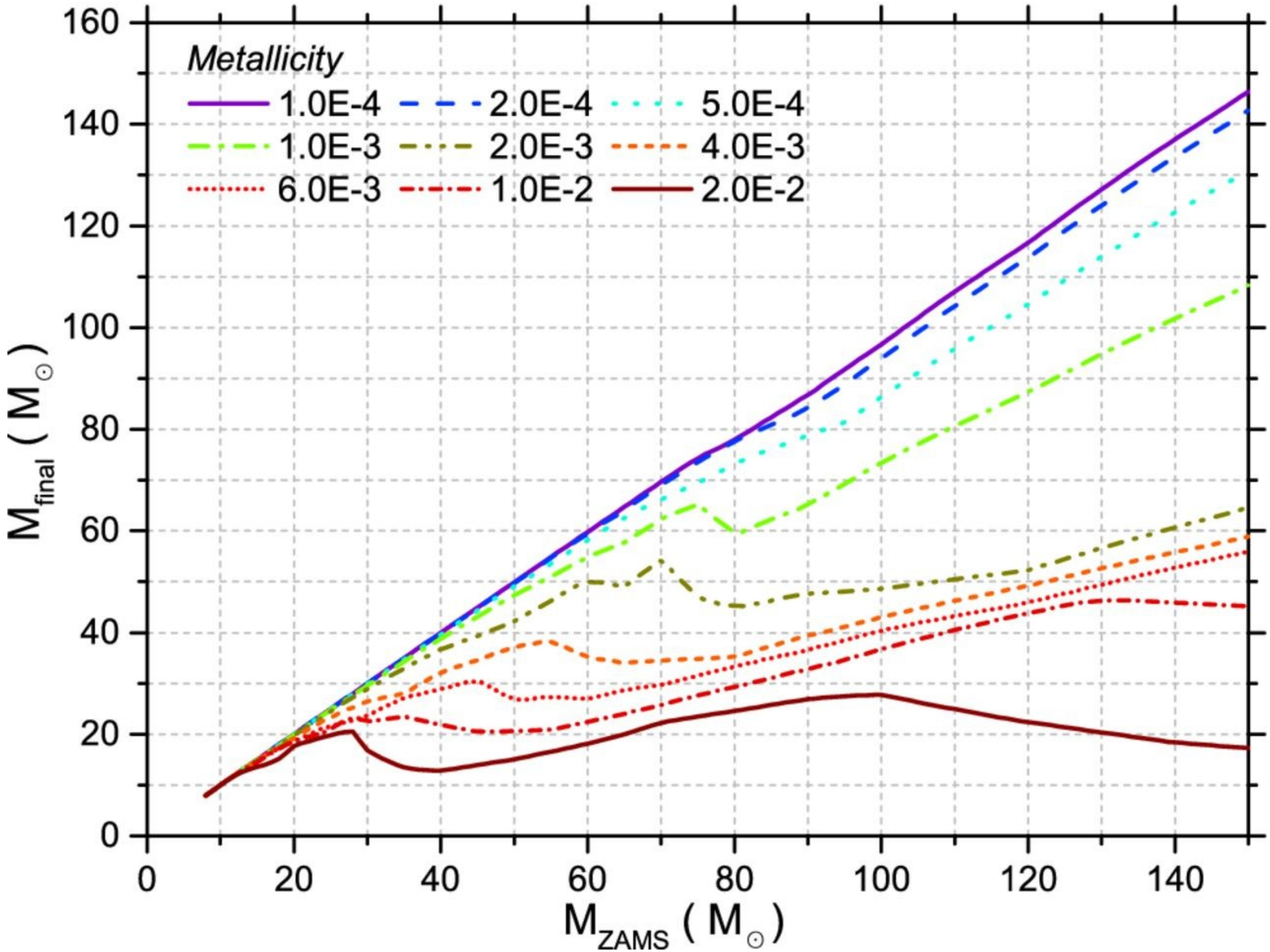


My cartoon from
Heger et al. (2003)

1. The formation of compact objects: wrap up

What about intermediate metallicities between 0 and solar?

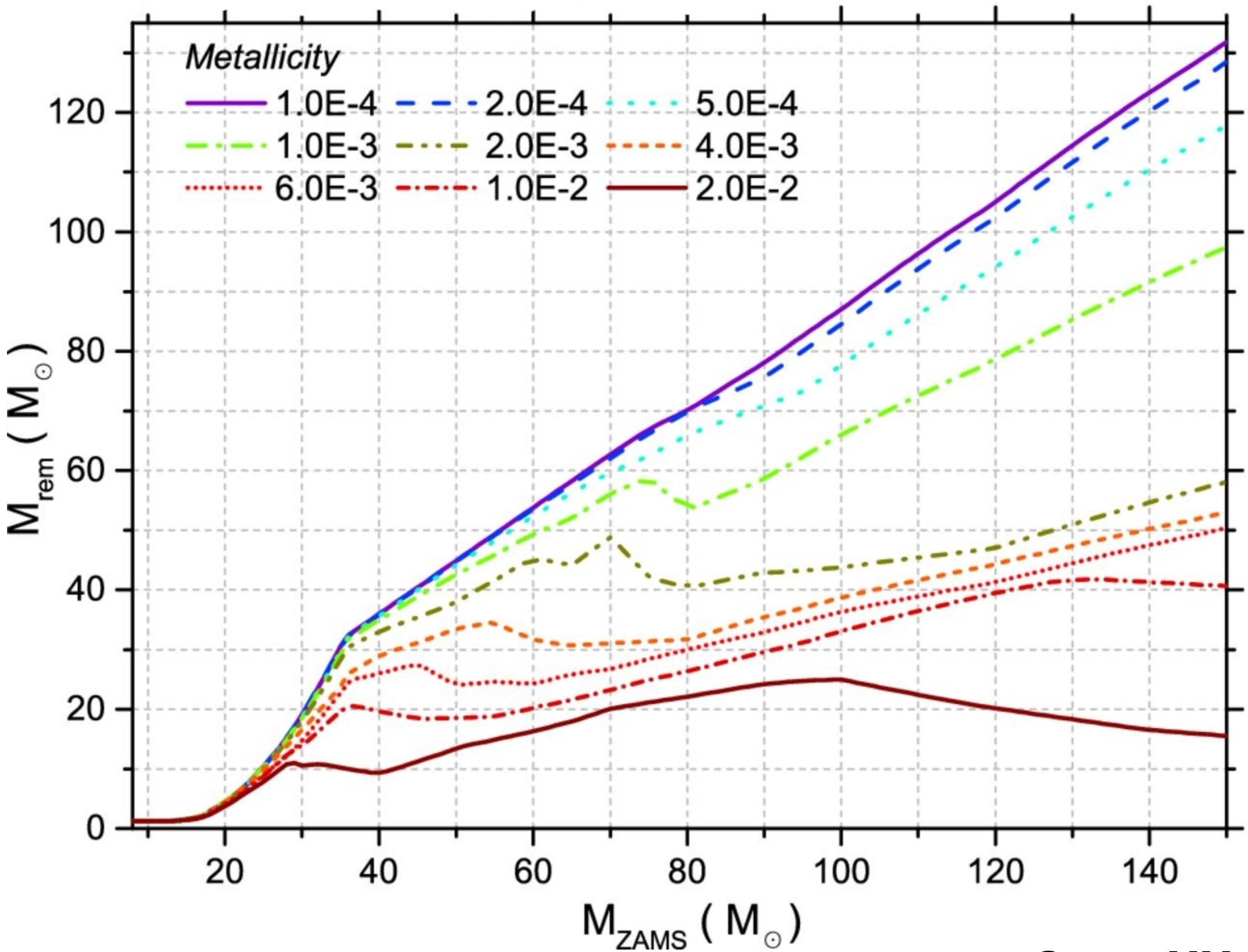
- more difficult because stellar winds are uncertain
- importance of final mass: pre-supernova mass of the star (when CO core built)



Spera, MM, Bressan 2015

1. The formation of compact objects: wrap up

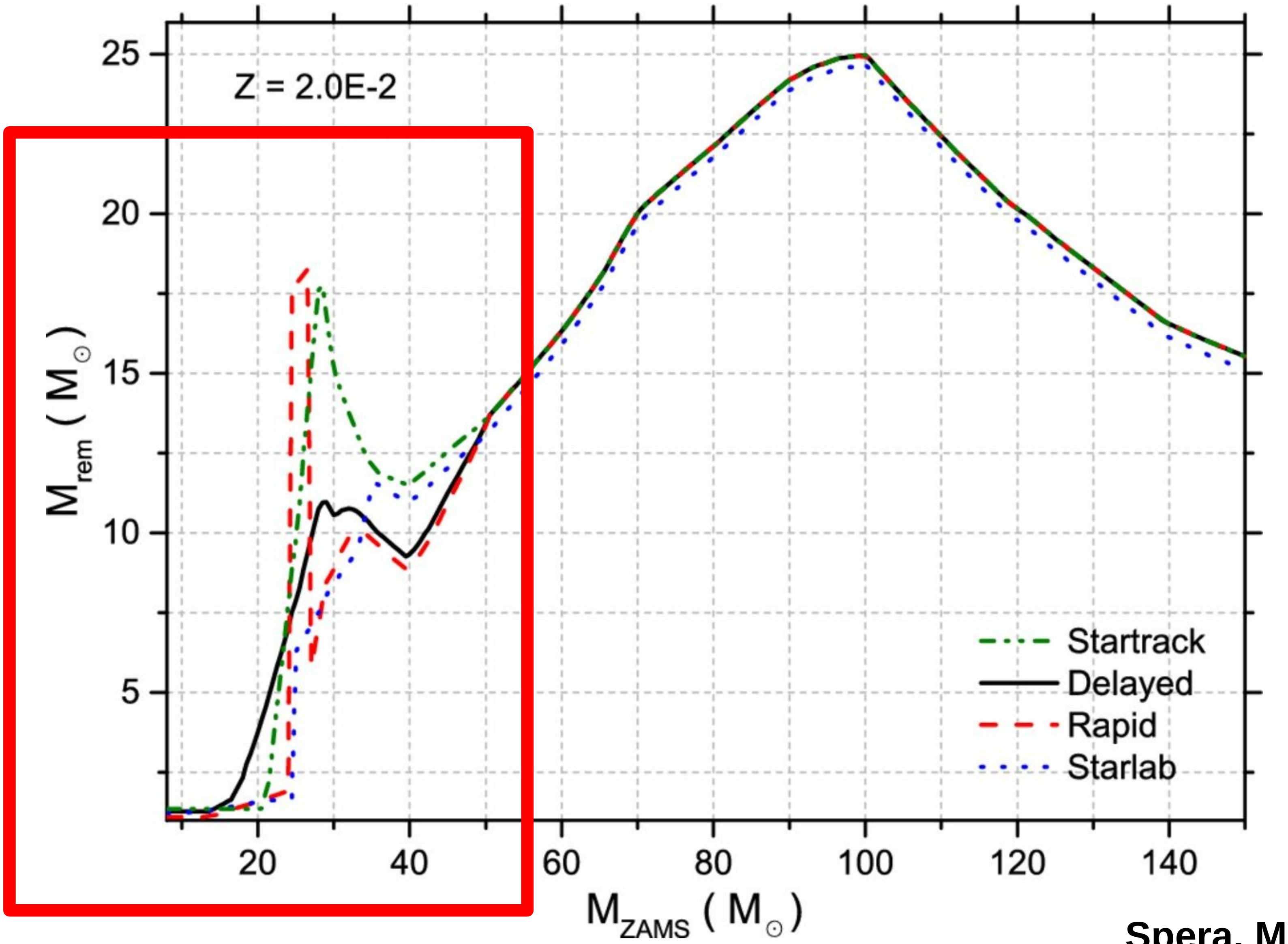
Remnant mass follows same trend as final mass
→ stellar winds are crucial



Spera, MM, Bressan 2015

1. The formation of compact objects: wrap up

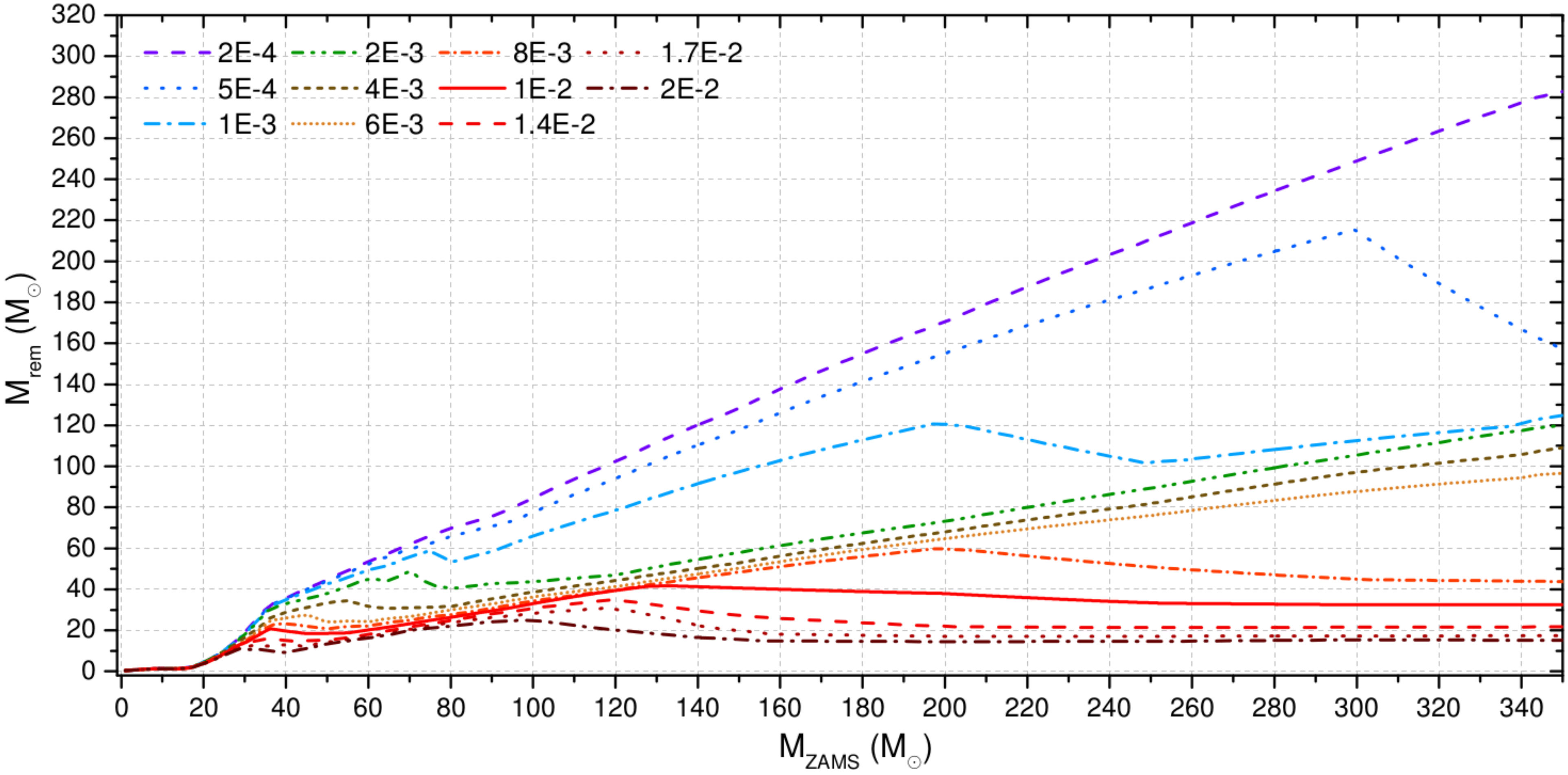
Importance of supernova model for "LOW" STAR MASSES (<40 M$_\odot$)



Spera, MM, Bressan 2015

1. The formation of compact objects: wrap up

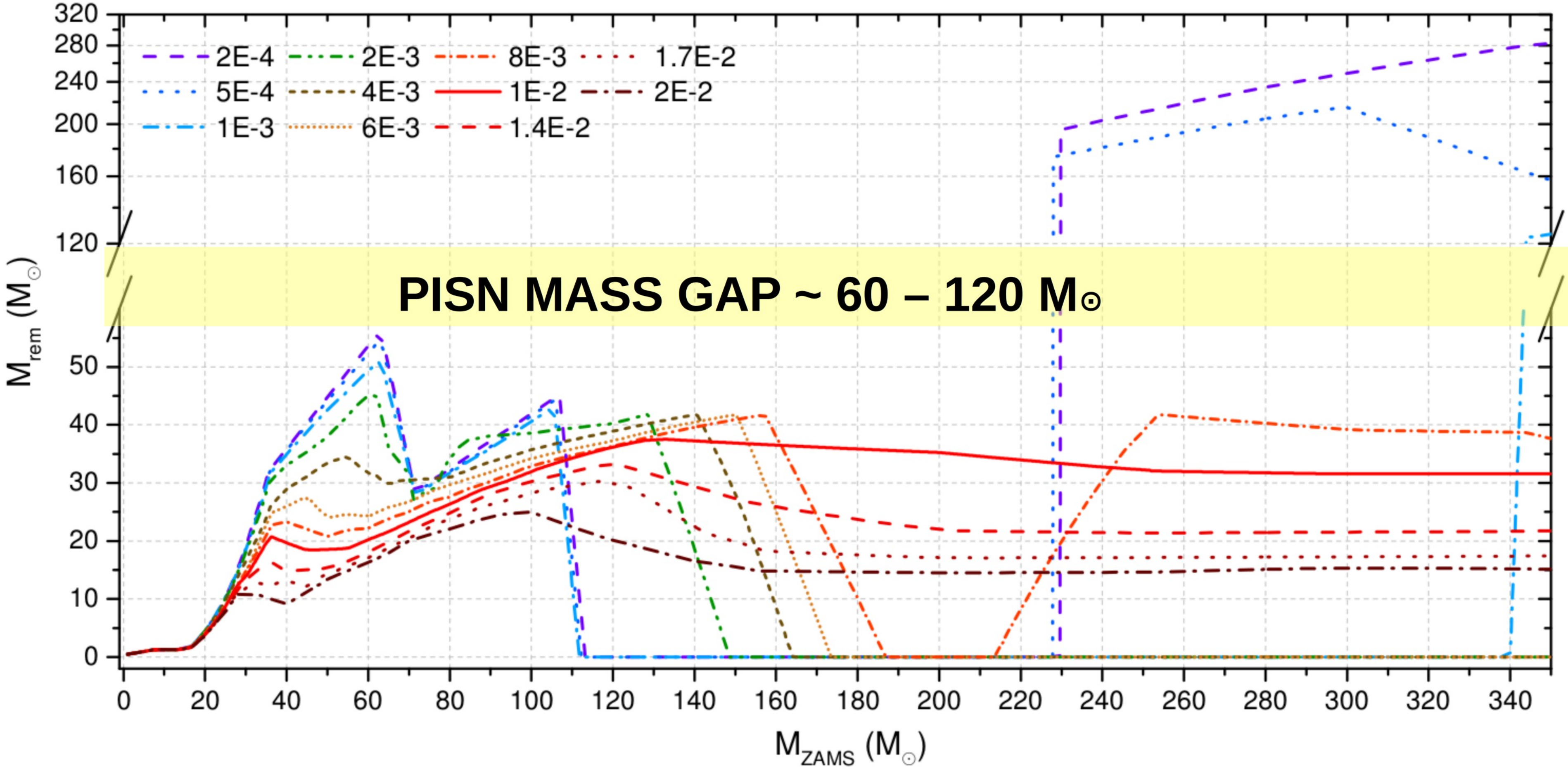
Evolution of very massive stars still uncertain
→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

1. The formation of compact objects: wrap up

Role of pulsational pair-instability and pair-instability supernovae (still missing in most models)

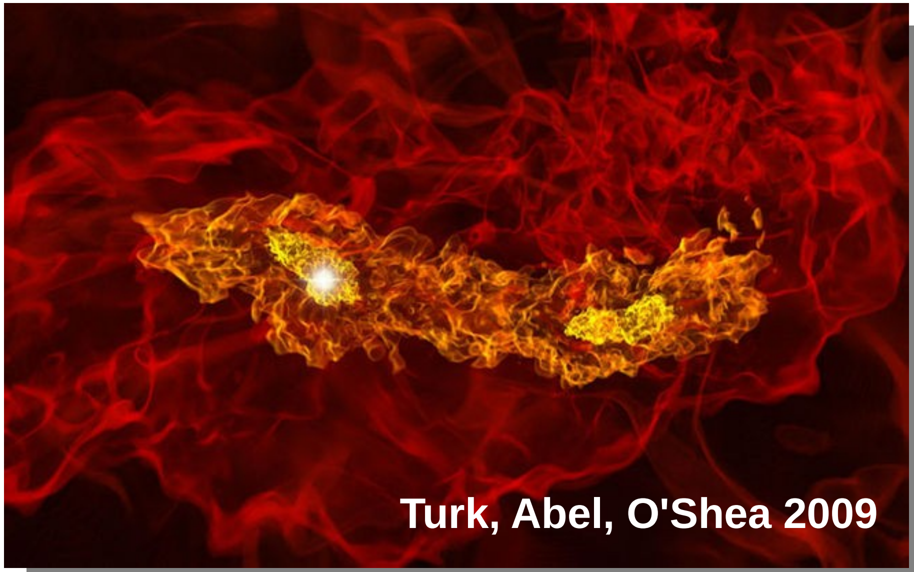


Spera & MM 2017

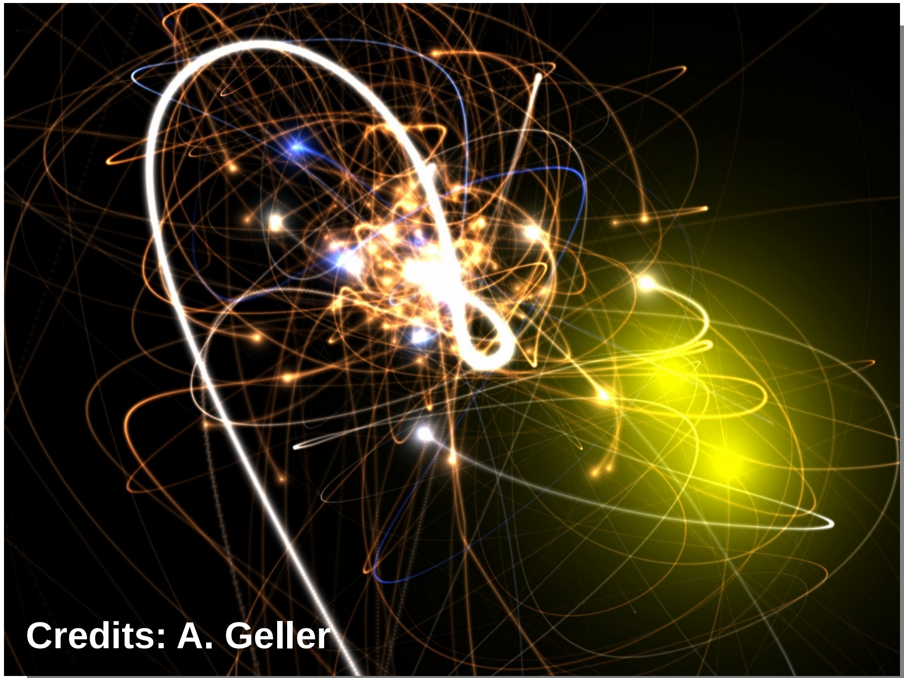
2. Binary compact objects

LIGO – Virgo observe compact object BINARIES

How do binary black holes or binary neutron stars or BH – NS form?



1) PRIMORDIAL BINARIES or ISOLATED BINARIES:
two stars form from same cloud and evolve into two black holes (BHs) gravitationally bound

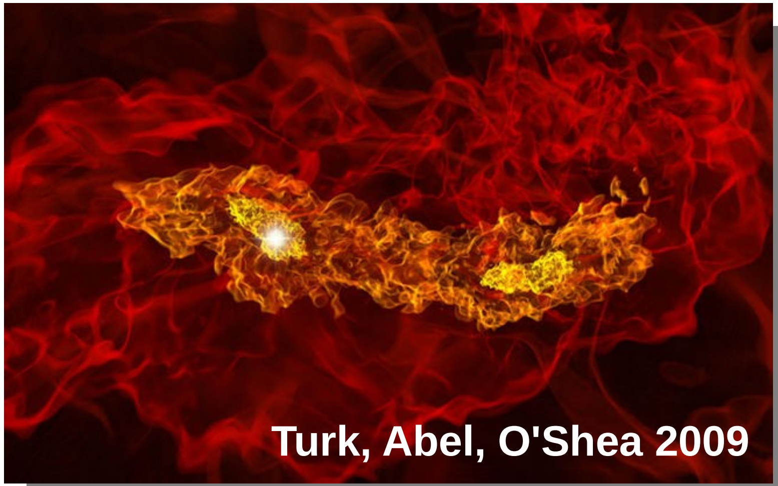


2) DYNAMICAL BINARIES:
BBH forms and/or evolves by dynamical processes

2. Binary compact objects

PRIMORDIAL BINARIES or ISOLATED BINARIES:

two stars form from same cloud and evolve into two black holes (BHs) gravitationally bound



MOST MASSIVE STARS ARE IN BINARY SYSTEMS (e.g. Sana et al. 2012; Moe & Di Stefano 2017)

NOT SO EASY:

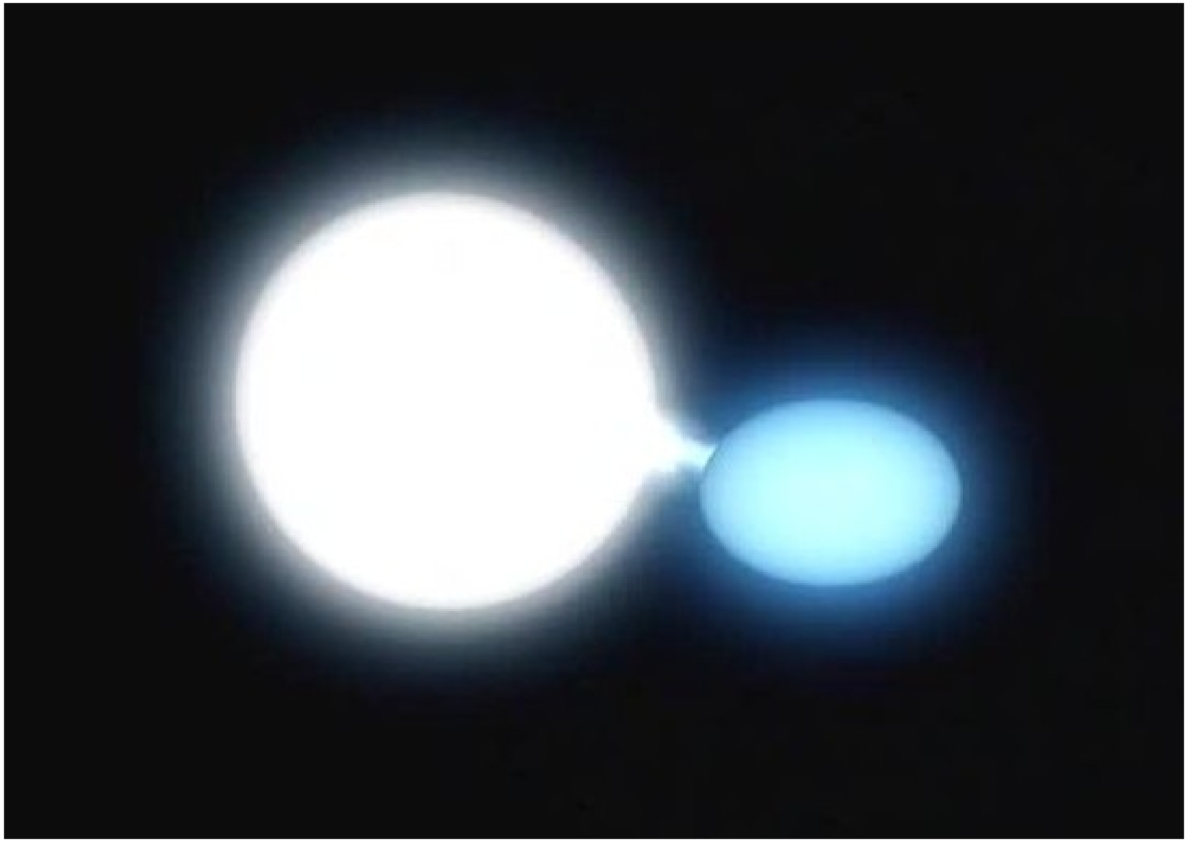
Many evolutionary processes can affect the binary

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

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

If two stars exchange mass (and some mass is lost from the system), the final mass of the black holes will be completely different from two single stars

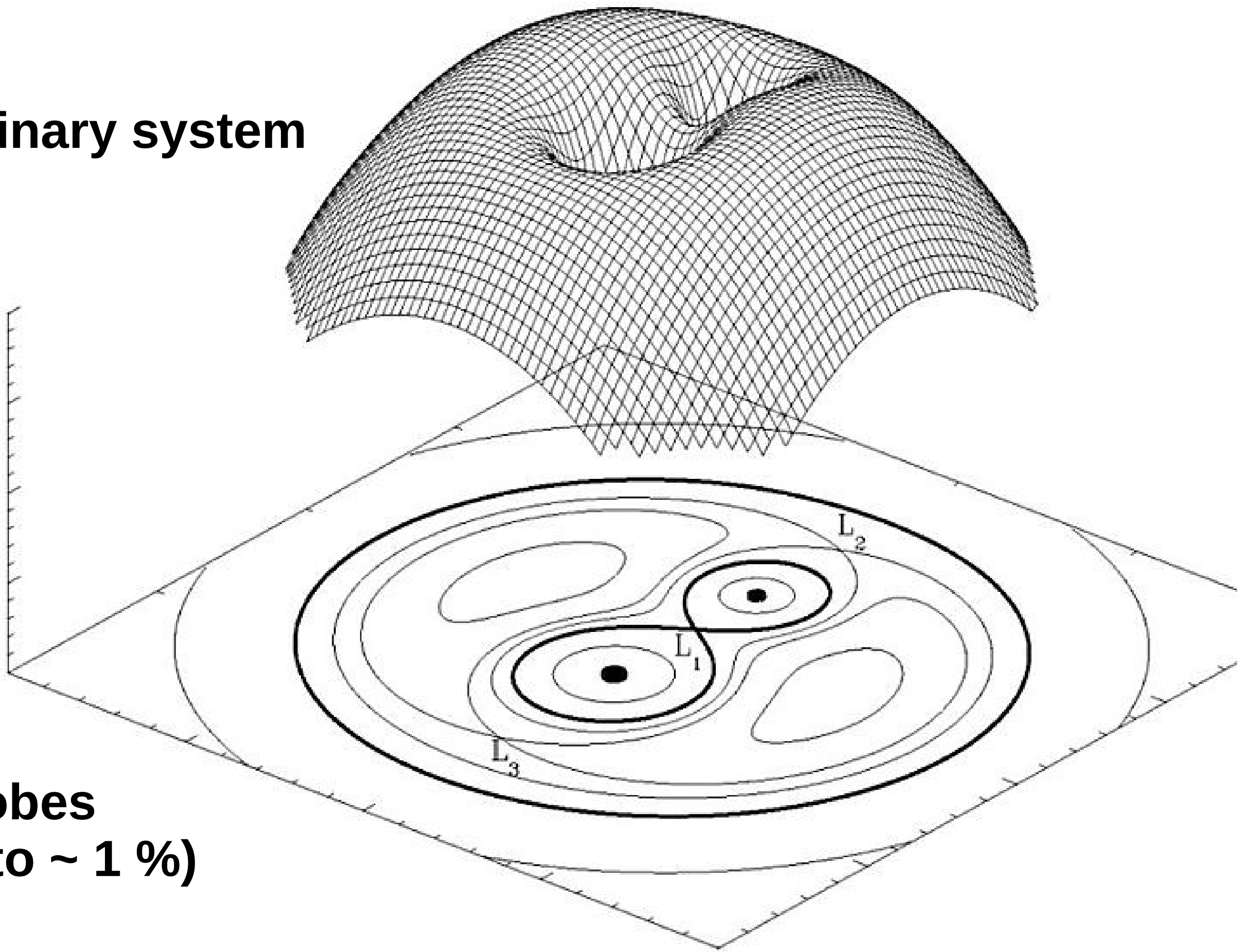
Mass transfer

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

2. Binary compact objects

Roche lobes

Equipotential surfaces in a binary system



For all *q > 0* exists a 8-shaped critical potential surface

The connecting point is L1 (inner Lagrangian point)

The two lobes are called ROCHE LOBES

Approximation assuming 2 lobes are perfect circles (accurate to ~ 1 %)

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

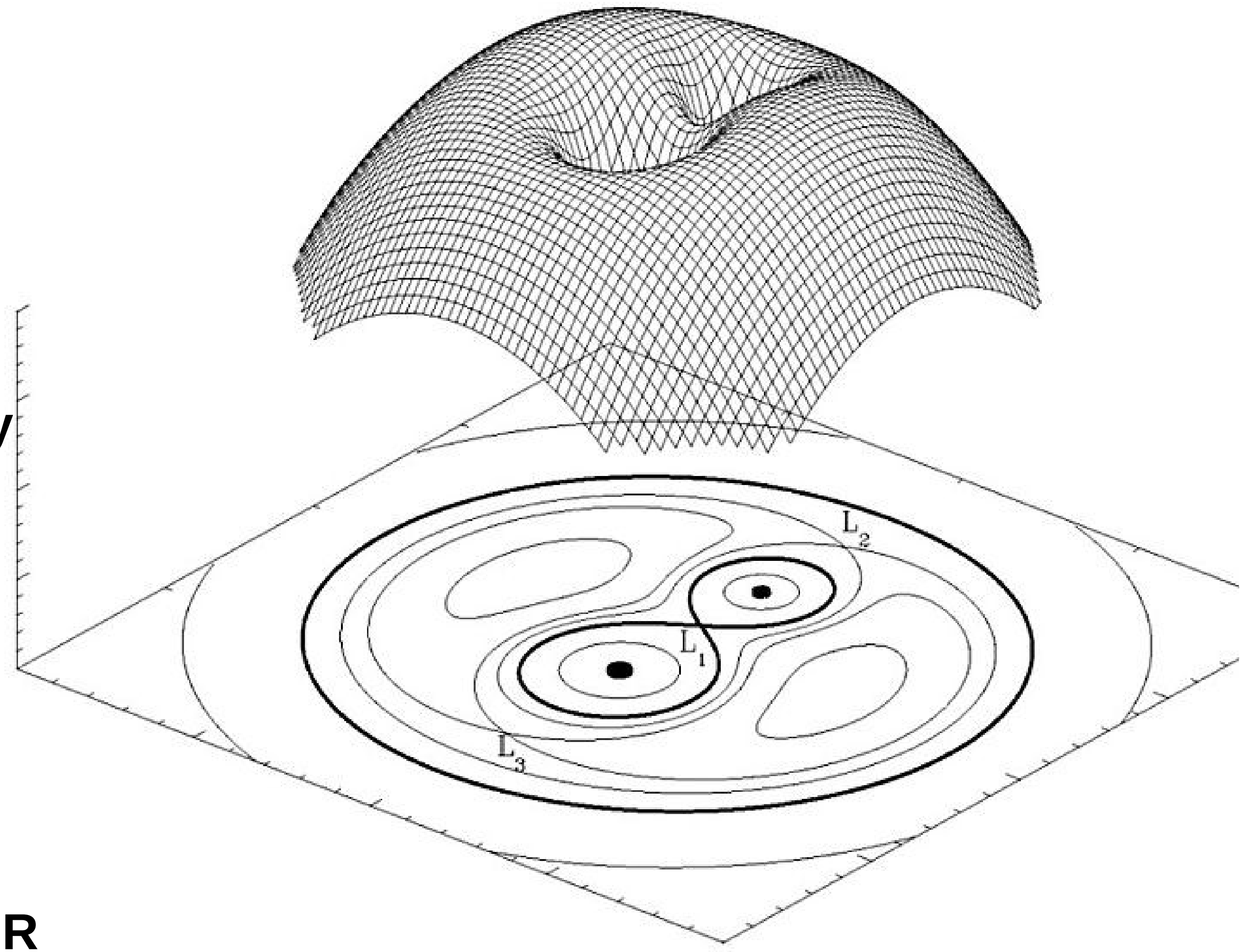
where a = semi-major axis

$$q = m_1/m_2$$

Eggleton 1983

2. Binary compact objects

Roche lobes



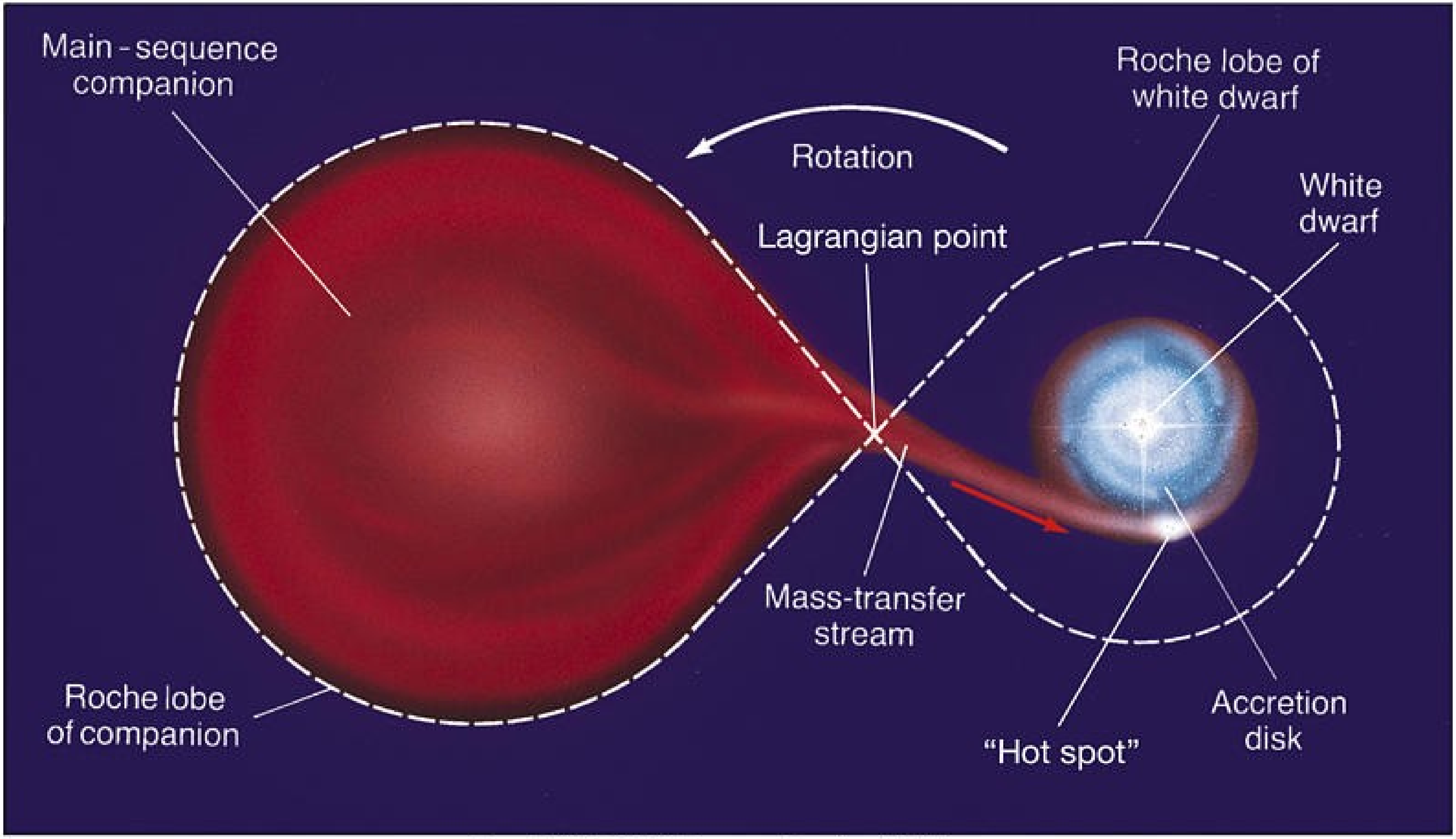
If a star fills its Roche lobe (:= if star radius is equal or larger than Roche lobe),

matter flows without energy change into the other star
→ MASS TRANSFER

called
ROCHE LOBE OVERFLOW

Star that fills the RL: DONOR
Star that receives (accretes) mass: ACCRETOR

2. Binary compact objects

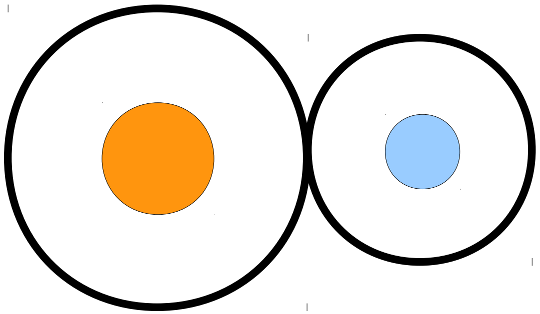


Note: accreting material gains angular momentum from Coriolis force and can form an accretion DISK around the accretor

2. Binary compact objects

Common envelope in binaries:

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

2. Binary compact objects

<u>Common envelope in binaries:</u>

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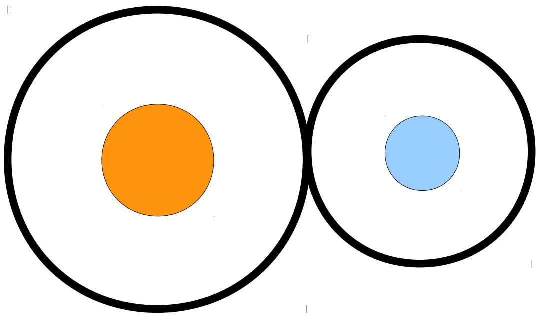
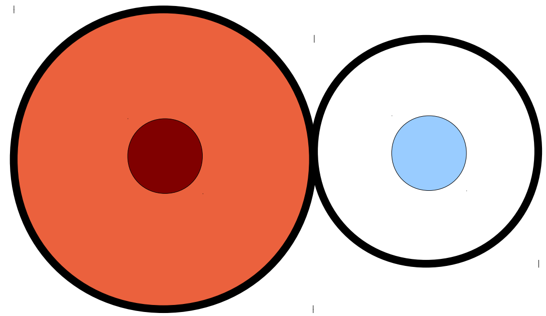




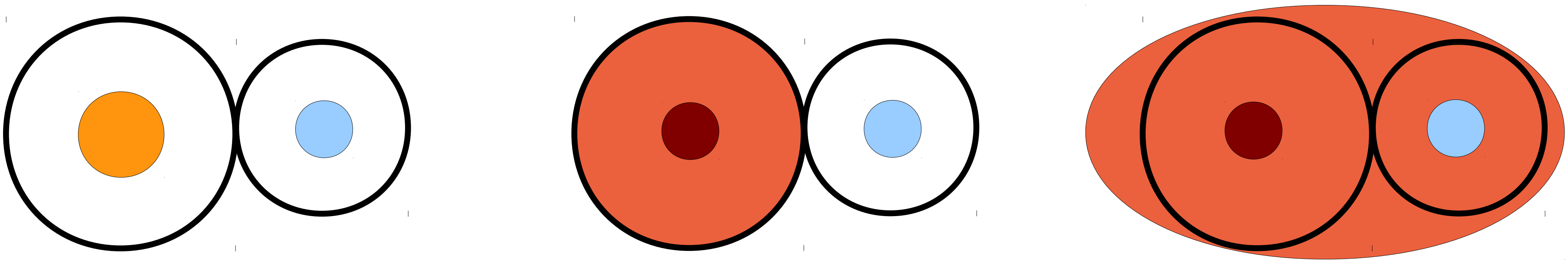
Two massive stars initially underfilling Roche lobe

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

2. Binary compact objects

Common envelope in binaries:

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

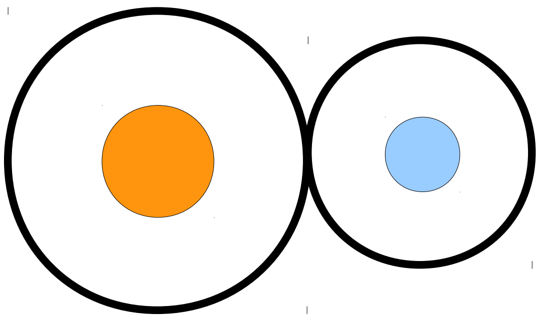
The first one evolves out of MS expands and start mass transfer onto the second

Mass transfer becomes unstable: CE phase

2. Binary compact objects

Common envelope in binaries:

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



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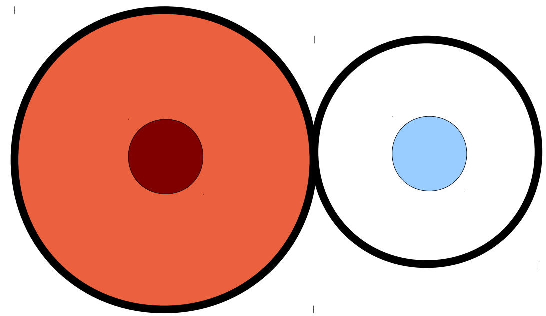

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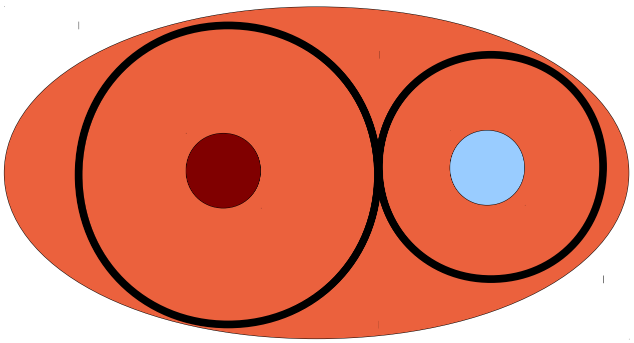
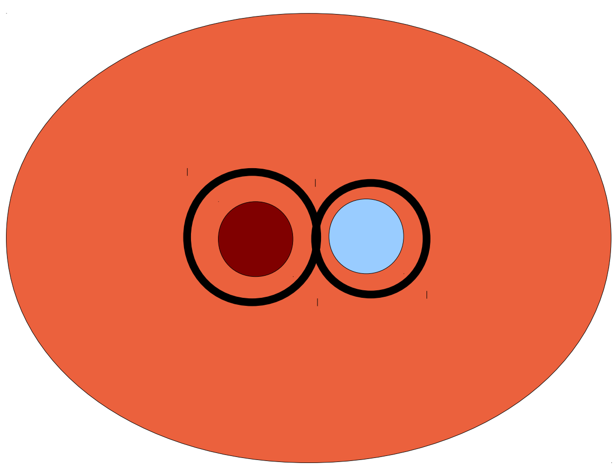


Mass transfer becomes unstable: CE phase



Drag by the envelope leads the two cores to spiral in

2. Binary compact objects

Common envelope in binaries:

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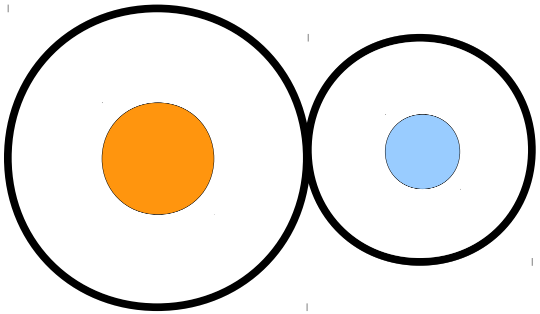
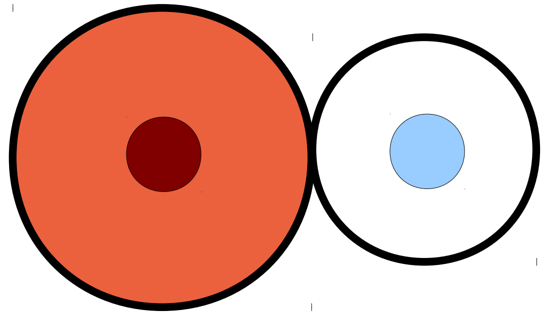


Two massive stars initially underfilling Roche lobe



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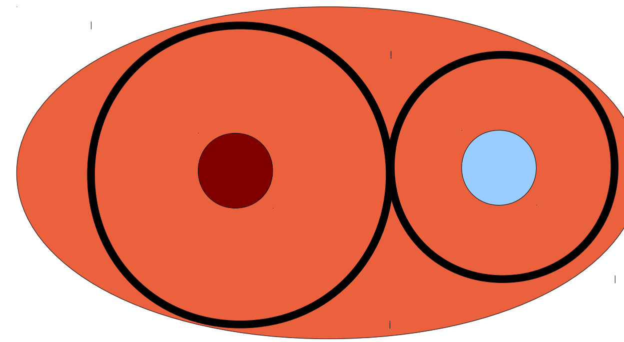
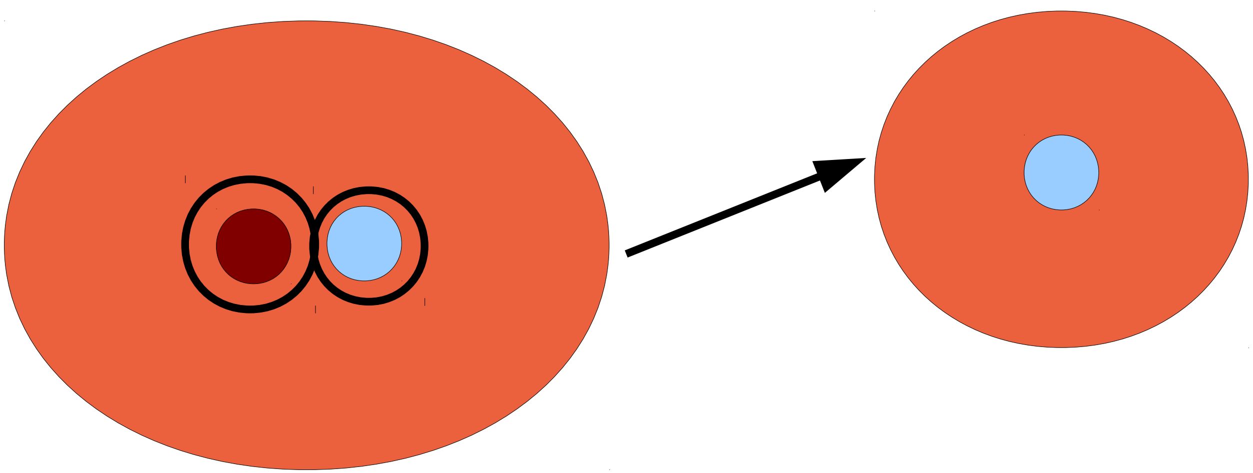


Mass transfer becomes unstable: CE phase



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

Drag by the envelope leads the two cores to spiral in

2. Binary compact objects

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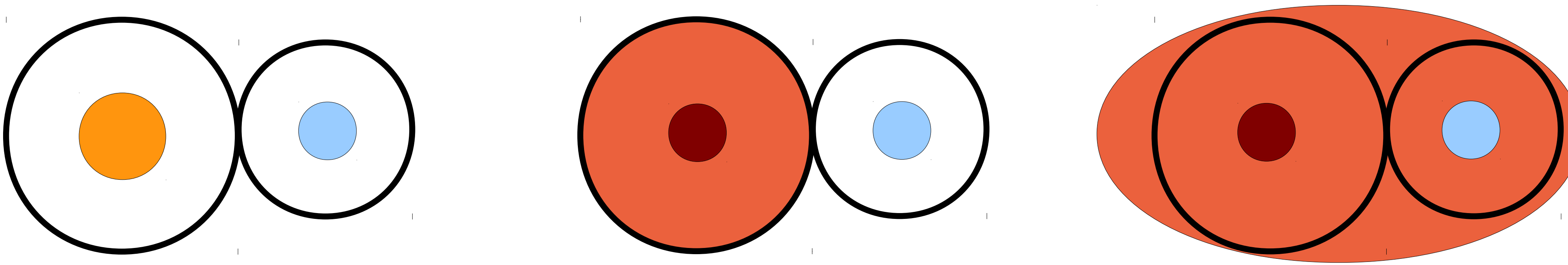

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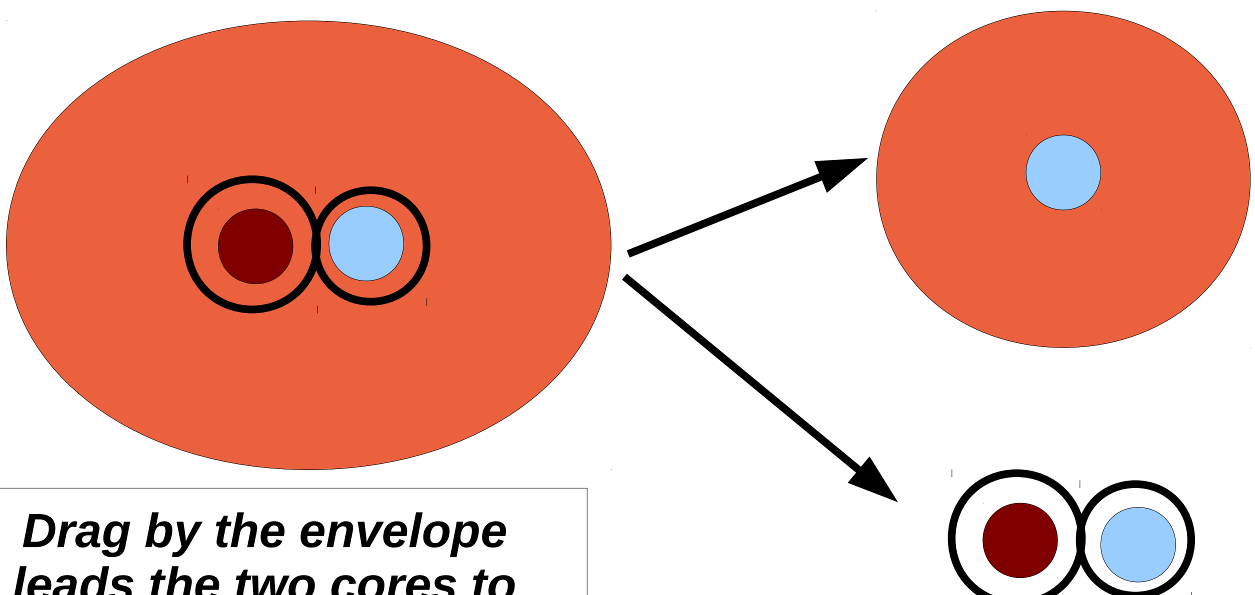


Drag by the envelope leads the two cores to spiral in

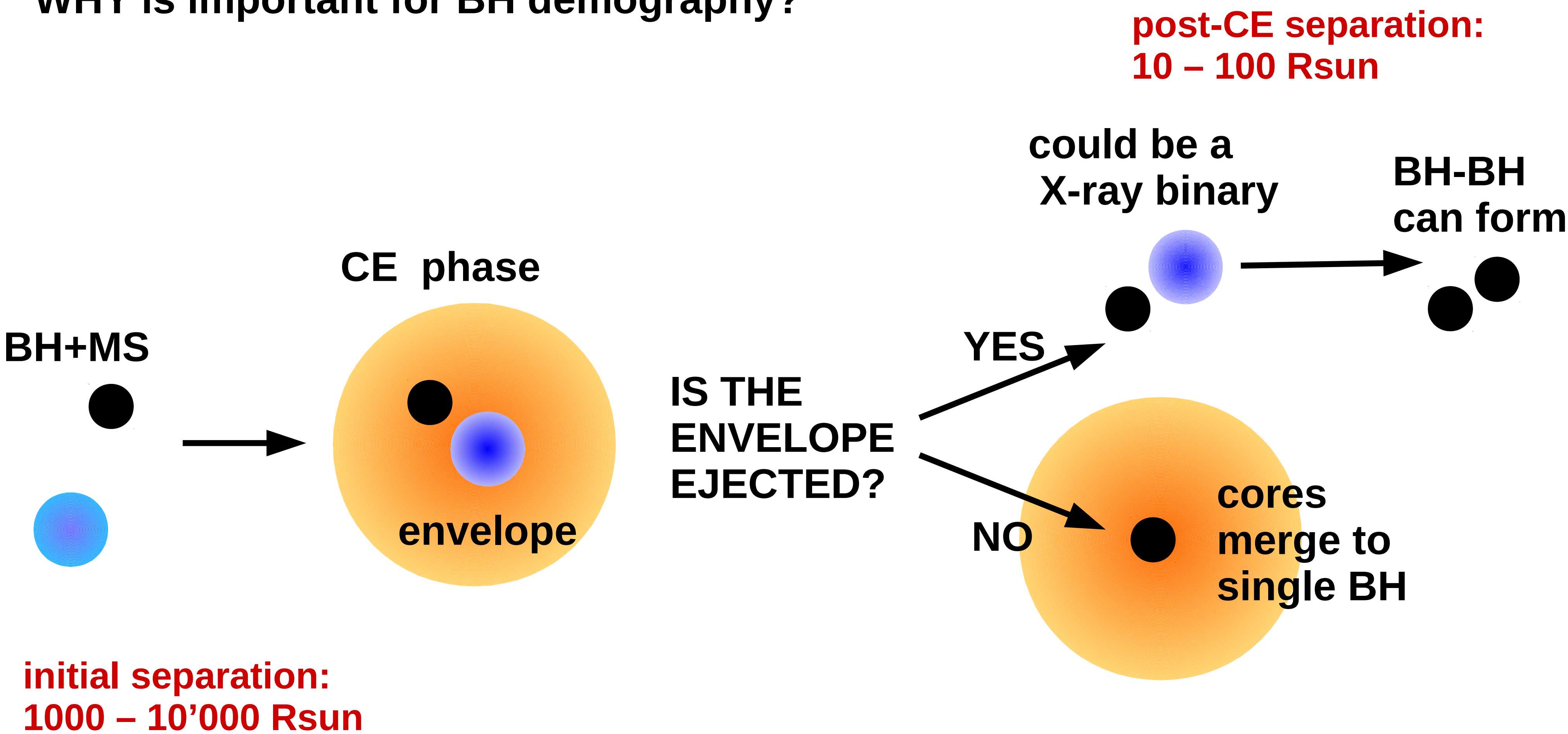
The two cores spiral in till they merge becoming a single star

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

2. Binary compact objects

Common envelope in binaries:

WHY is important for BH demography?



2. Binary compact objects

Common envelope in binaries:

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)

2. Binary compact objects

Common envelope in binaries:

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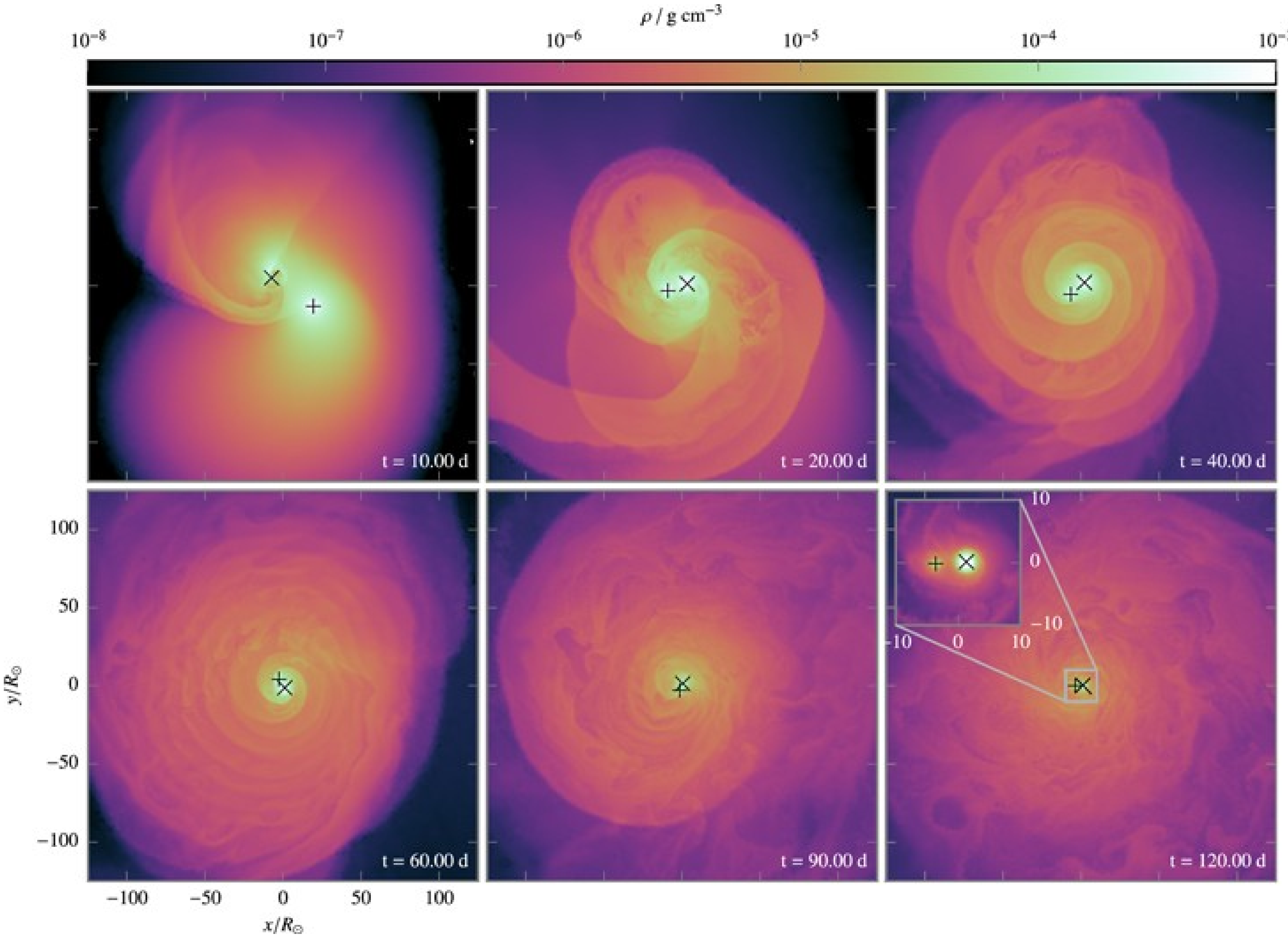
NOT YET MODELLED SELF-CONSISTENTLY (Ivanova et al. 2013)

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)

2. Binary compact objects



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

2. Binary compact objects

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POORLY UNDERSTOOD!!! WHAT REMOVES THE ENVELOPE?

2. Binary compact objects

Common envelope in binaries:

Probably the least understood process in binary evolution

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   POORLY UNDERSTOOD!!! WHAT REMOVES THE ENVELOPE?

4. **MERGER of the cores or EJECTION of ENVELOPE**

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

2. Binary compact objects

Common envelope in binaries:

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)

2. Binary compact objects

Common envelope in binaries:

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

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

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

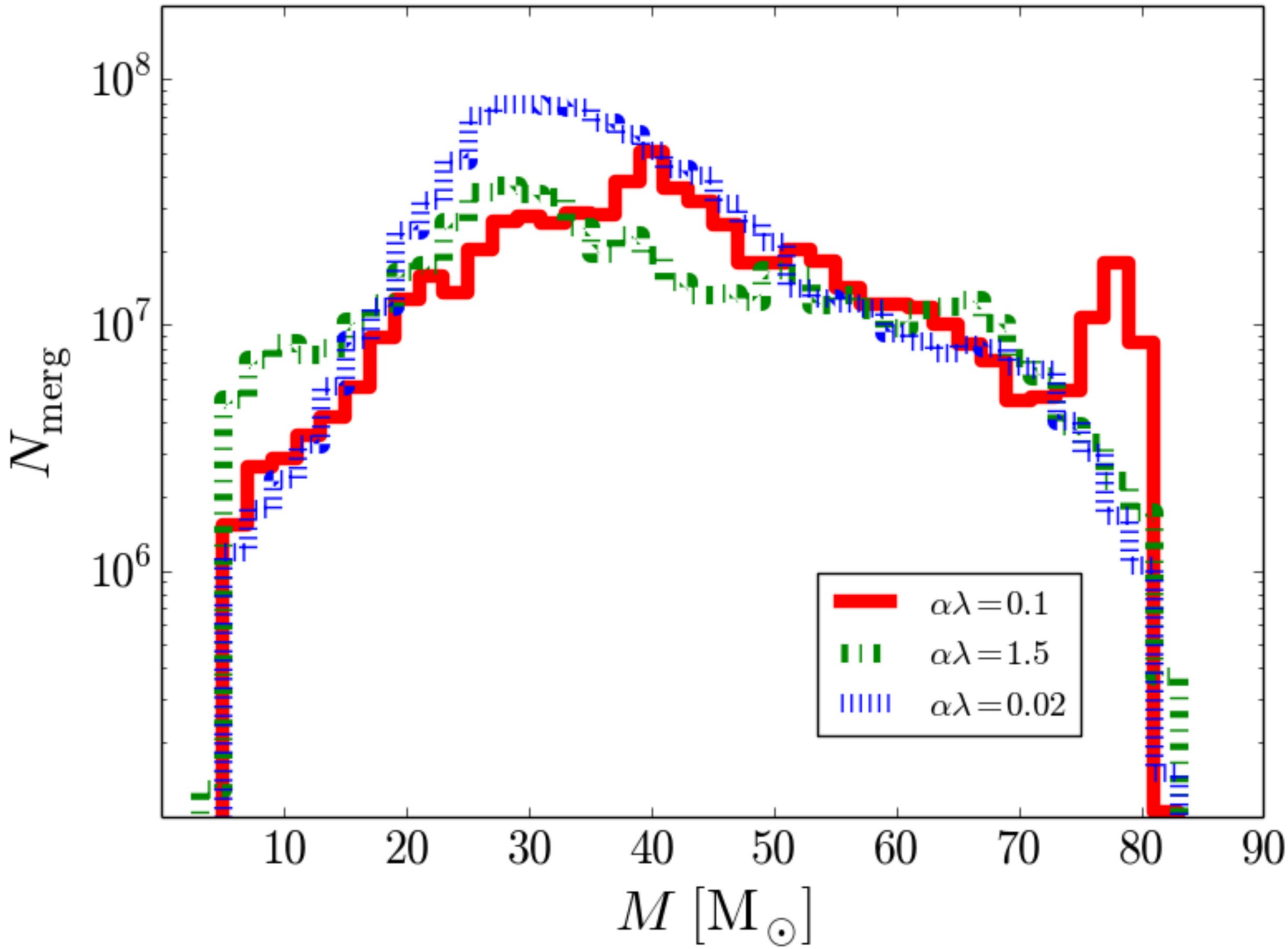
THEN the cores merge (Hurley+ 2002, MNRAS, 329, 897)

PROBLEM IS: HOW TO CONSTRAIN α and λ ?

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

2. Binary compact objects

Common envelope in binaries:



updated version of BSE (MM+ 2017, Giacobbo+ 2018)

2. Binary compact objects

Alternative to common envelope:

<u>chemically homogeneous evolution</u>

(Marchant+ 2016; Mandel & de Mink 2016; de Mink & Mandel 2016)

BASIC IDEA:

if stars are chemically homogeneous, their radii are smaller

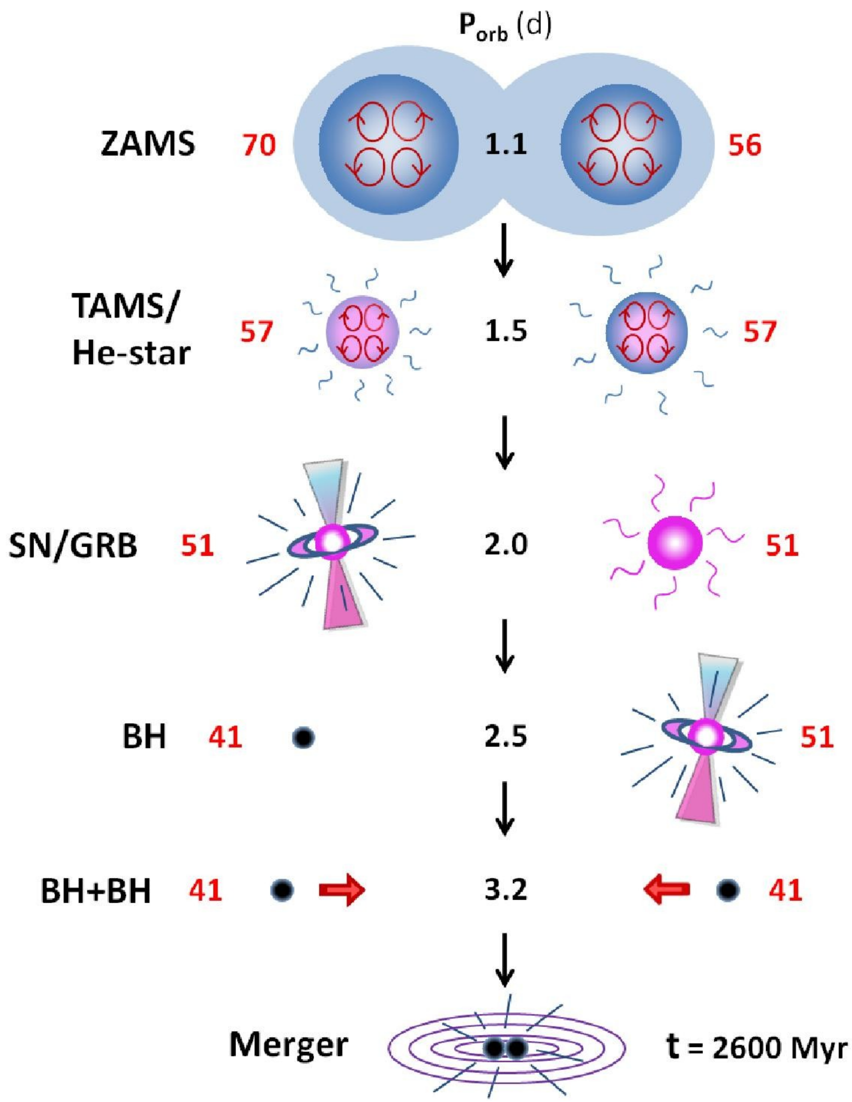
→ close binaries avoid common envelope and premature merger

To be chemically homogeneous, stars need to ROTATE fast

2. Binary compact objects

OVERCONTACT BINARIES (Marchant+ 2016):

Metal-poor fast rotating stars may OVERFILL ROCHE LOBE WITHOUT ENTERING COMMON ENVELOPE



Why?

Star rotation induces chemical mixing

Chemical mixing prevents star radius from growing significantly (efficient only if star is metal poor)

Predictions of this model:

*** nearly equal-mass BH-BH**

*** BH masses ~25 – 60, 130 – 230 Msun increasing with decreasing metallicity (no low-mass BHs!)**

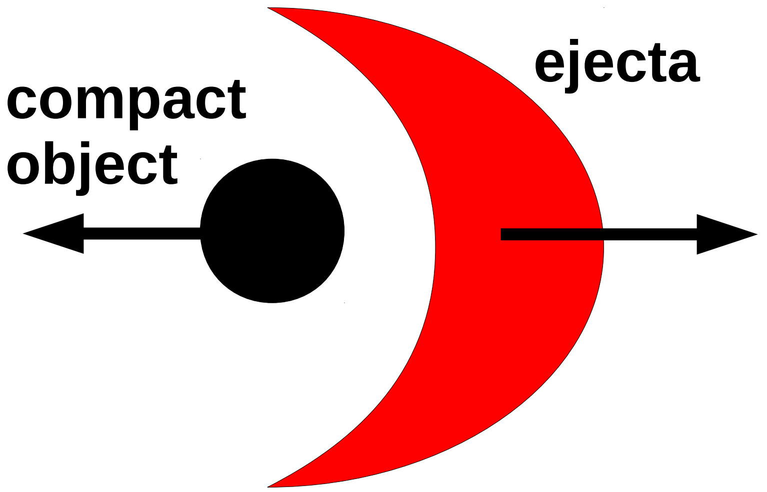
*** aligned spins unless SN reset them**

2. Binary compact objects

Supernova kicks and BH binaries:

A massive-star binary can become a BH-BH binary only if it is not unbound by SN kicks

WHY KICKS?



*** asymmetry in mass ejection during core collapse**

*** asymmetry in neutrino emission during core collapse**

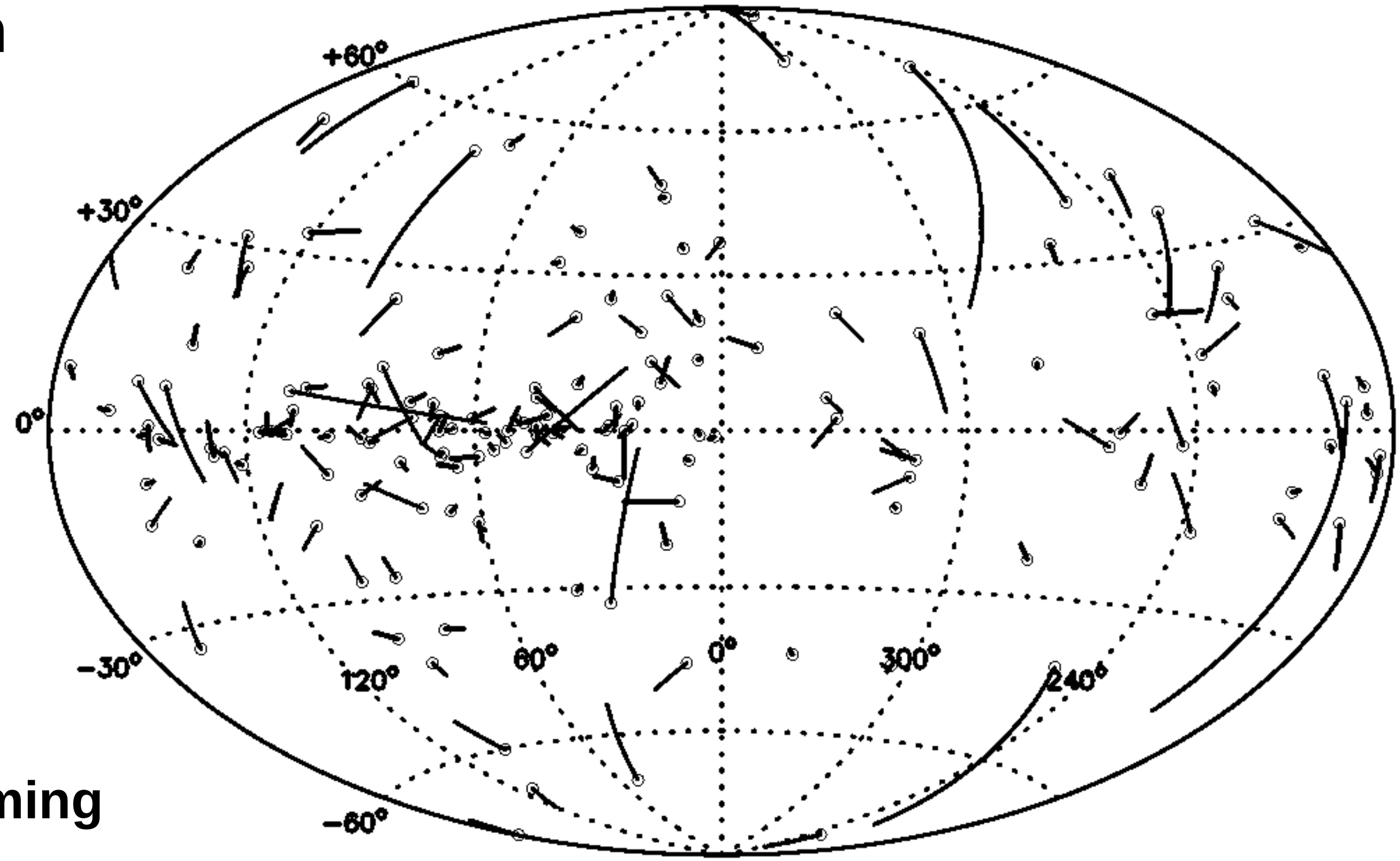
*** symmetric mass loss in a binary: breaks the binary only if pre-SN mass > companion mass (Blaauw mechanism, Blaauw 1961)**

2. Binary compact objects

Supernova kicks and BH binaries:

SN kicks for NSs constrained from velocity of PULSARS

Hobbs+ (2005):
sample of 233 pulsars with proper motion measurements



A pulsar is currently at the position indicated by a circle

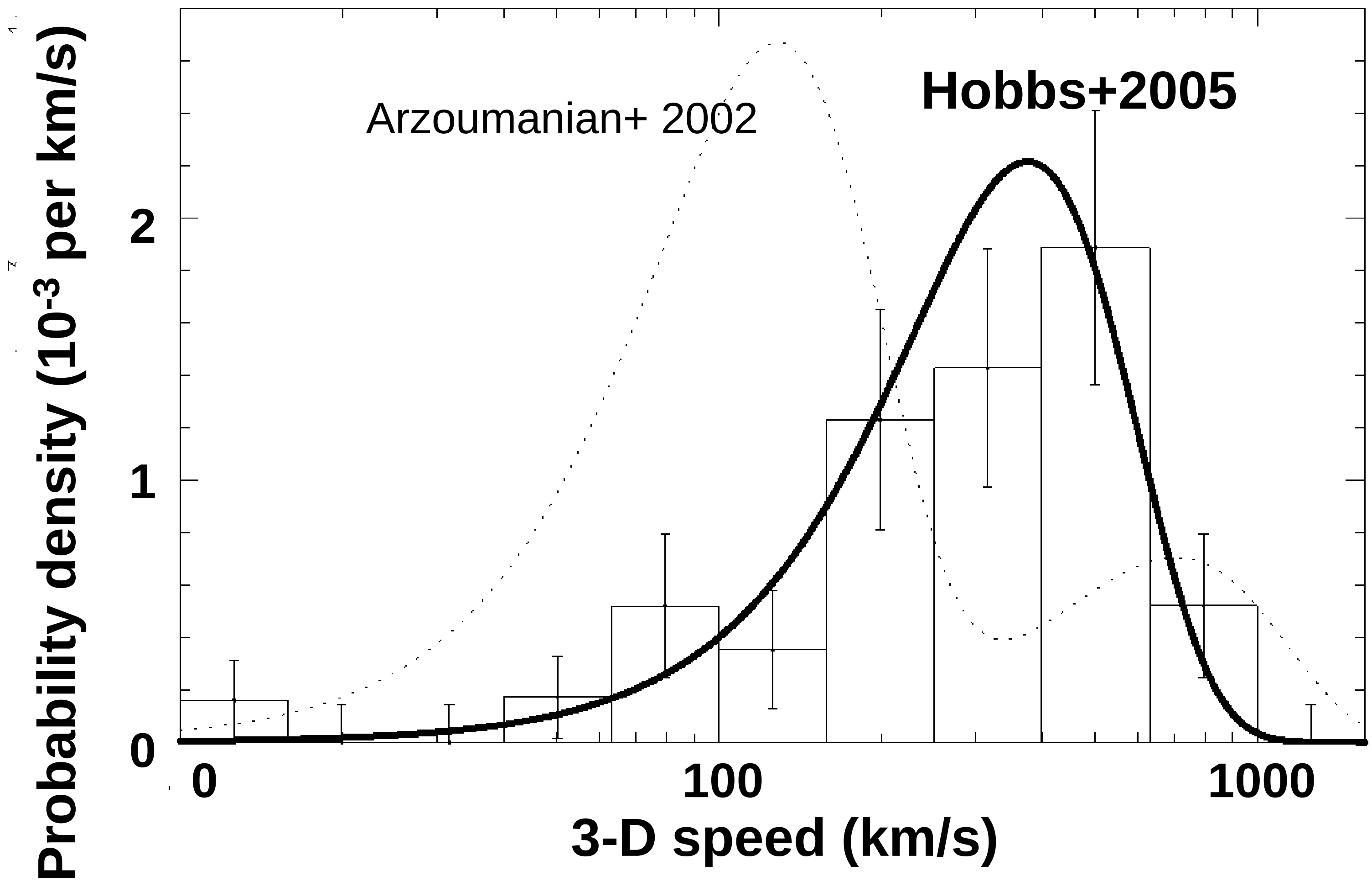
The track is its motion for the last 1 Myr assuming no radial velocity.

2. Binary compact objects

Supernova kicks and BH binaries:

Hobbs+ (2005): 3-D velocity distribution of pulsars obtained from the observed 2-D distributions of pulsars

→ Maxwellian distribution with sigma ~ 265 km/s



2. Binary compact objects

Supernova kicks and BH binaries:

High (>100 km/s) velocity kicks for NSs (with caveats!)

WHAT ABOUT BHs?

No reliable methods to measure. Then people assume

1. conservation of linear momentum

$$\boxed{v_{\mathrm{kick,\,BH}} = \frac{m_{\mathrm{NS}}}{m_{\mathrm{BH}}}\, v_{\mathrm{kick,\,NS}}}$$

2. BHs formed without SN (failed or direct collapse)
get NO KICK + kick modulated by FALLBACK

$$\boxed{v_{\mathrm{kick,\,BH}} = (1 - f_{\mathrm{fb}})\, v_{\mathrm{kick,\,NS}}}$$

2. Binary compact objects

Isolated binary evolution summary:

* possible Roche lobe

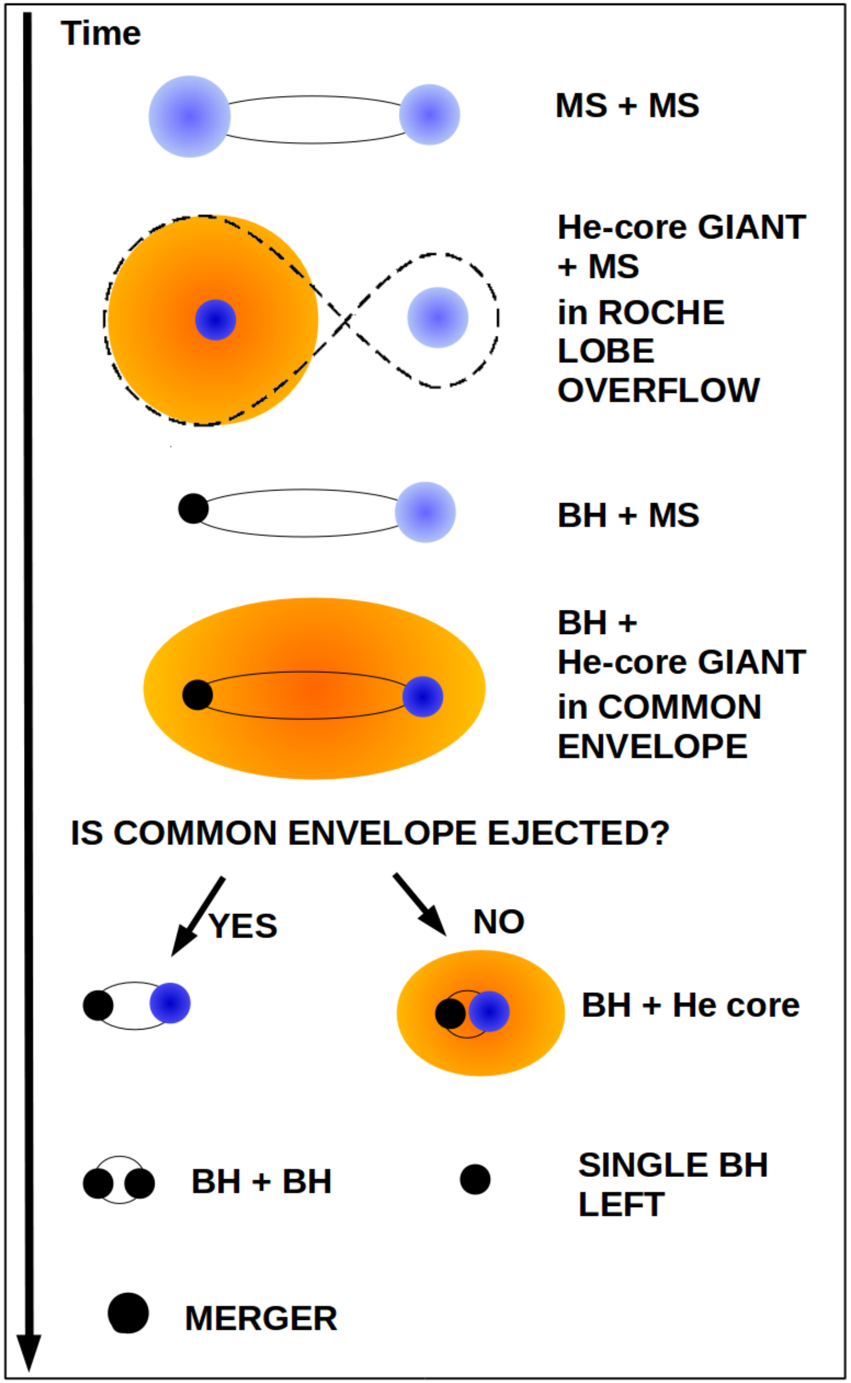
* 1st BH formation

* Common envelope
 BH – giant
 crucial to shrink the binary
 from >>100 Rsun
 to <100 Rsun

* If binary survives common
 envelope, formation of
 second BH

* BH – BH merger

cartoon from MM2018



2. Binary compact objects: EXERCISES

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 population-synthesis codes

BINARY_C (Izzard+ 2000)

BPASS (Eldridge+ 2017)

BSE/MOBSE (Hurley+ 2002; Mapelli+ 2017; Giacobbo+ 2018)

COMBINE (Kruckow+ 2018)

Seba (Portegies Zwart+ 2001; Mapelli+ 2013)

SEVN (Spera+ 2015, 2019; Spera & Mapelli 2017)

StarTrack (Belczynski+ 2007, 2010)

EXERCISE 1: follow the evolution of a binary

https://drive.google.com/open?id=1YIXgf_Q8qXO8hp5jEcNXGln3_F5jdo1P

Enter in folder BBH

File bbh_binary.txt contains the data of a simulation of a massive binary

The simulation was done with MOBSE (Giacobbo et al. 2018, https://ui.adsabs.harvard.edu/abs/2018MNRAS.474.2959G/)

The first line explains the content. In particular

col.1: time [Myr]
col.3: mass star1 [Msun]
col.6: log10(R1) [Rsun]

col.9: mass star2 [Msun]
col.12: log10(R2) [Rsun]

col.14: semi-major axis [Rsun]
col.15: eccentricity

EXERCISE 1: follow the evolution of a binary

Plot the following quantities:

1. Masses of the two stars as a function of time
2. Radii of the two stars and their Roche lobe radii as a function of time
3. Semi-major axis as a function of time

QUESTIONS YOU WANT TO TRY TO ANSWER WITH THESE PLOTS

* When do the two stars become black holes?

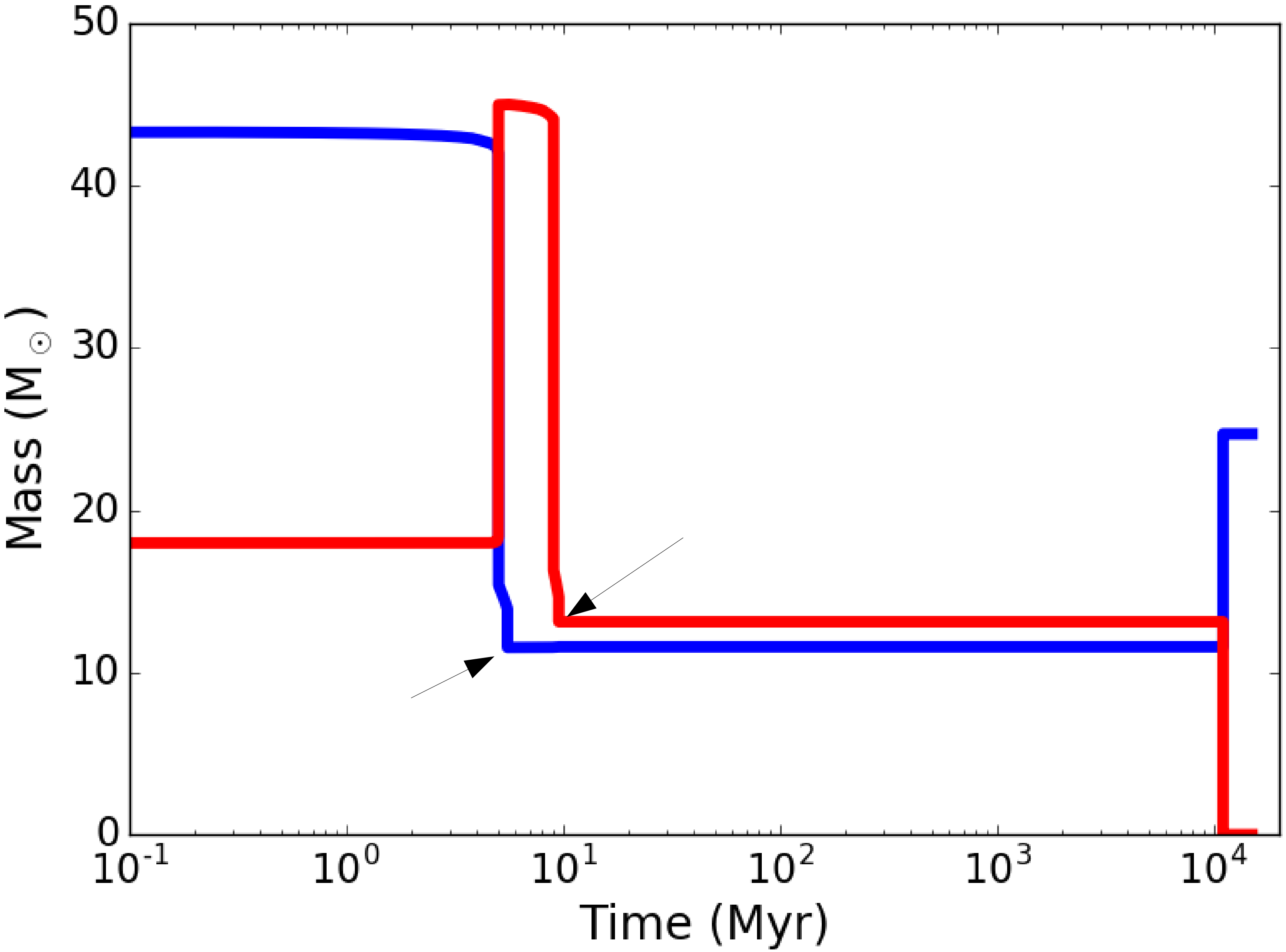
* Does the binary undergo Roche lobe overflow?

* Is there a common-envelope episode?

* Does the binary merges by gravitational-wave emission?

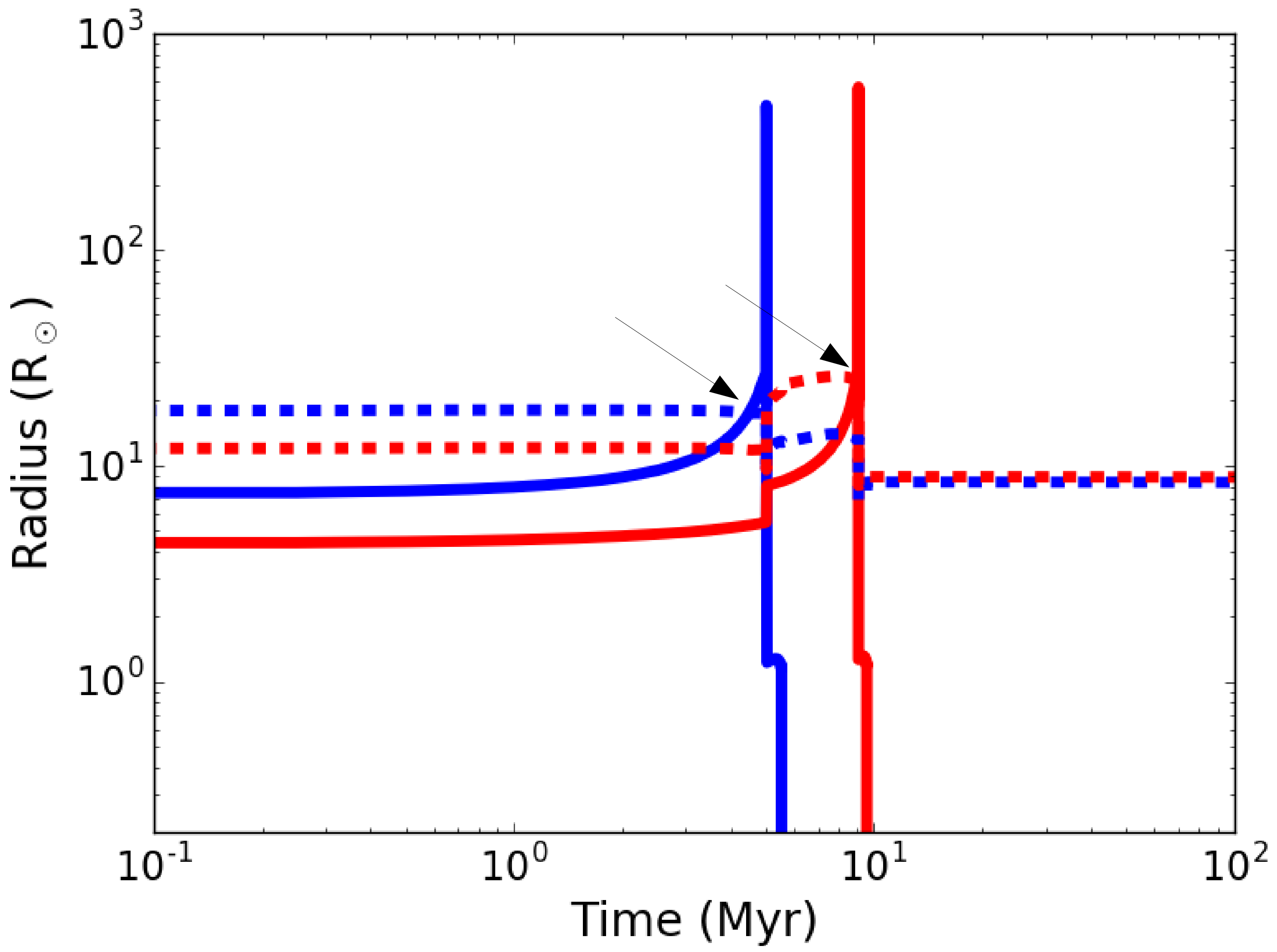
Note that in the directory BBH you find also the file bbh_binary_log.txt
which contains a useful log file of the simulation

EXERCISE 1: follow the evolution of a binary



*** When do the two stars become black holes?**

EXERCISE 1: follow the evolution of a binary



* Does the binary undergo Roche lobe overflow?
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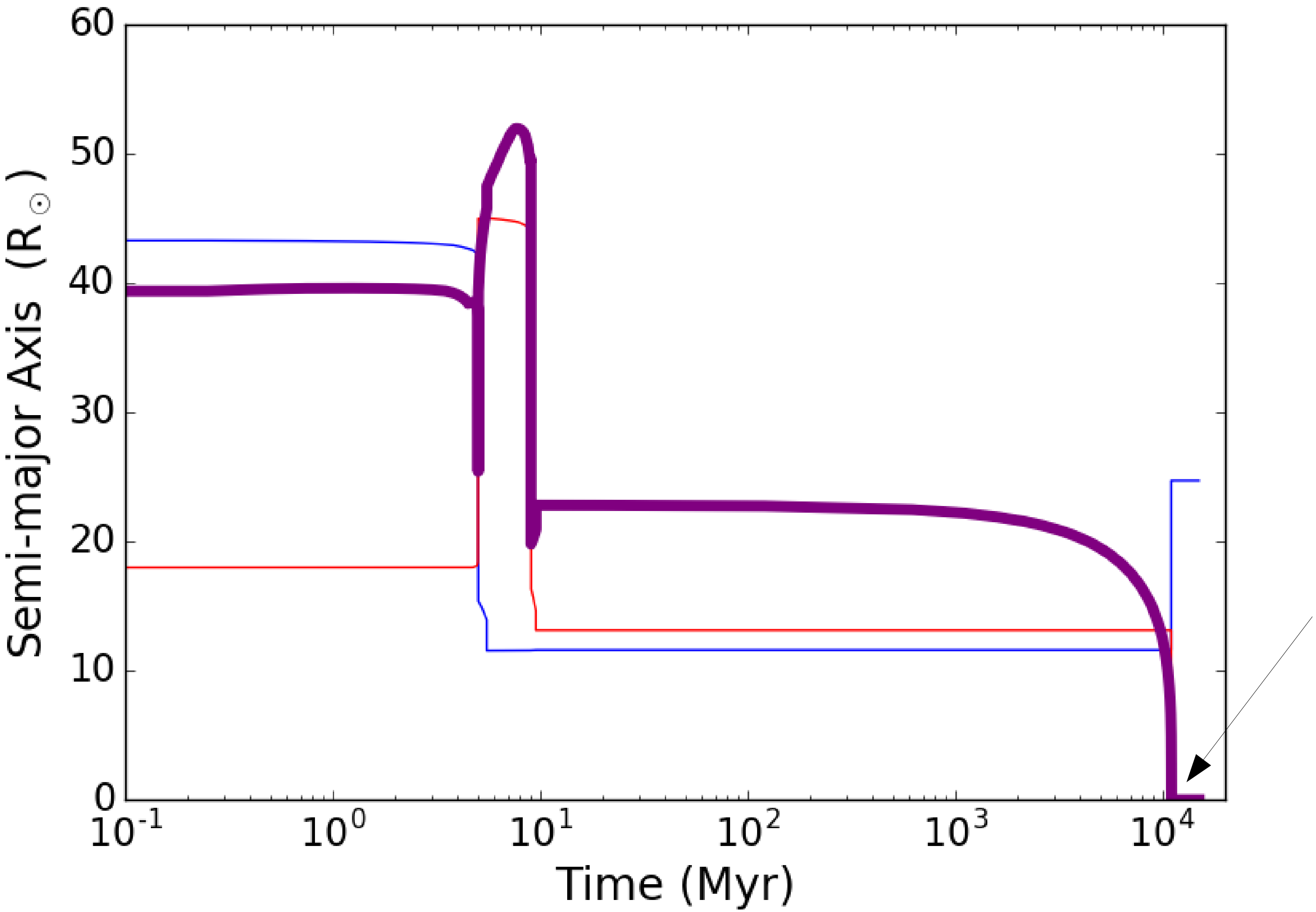
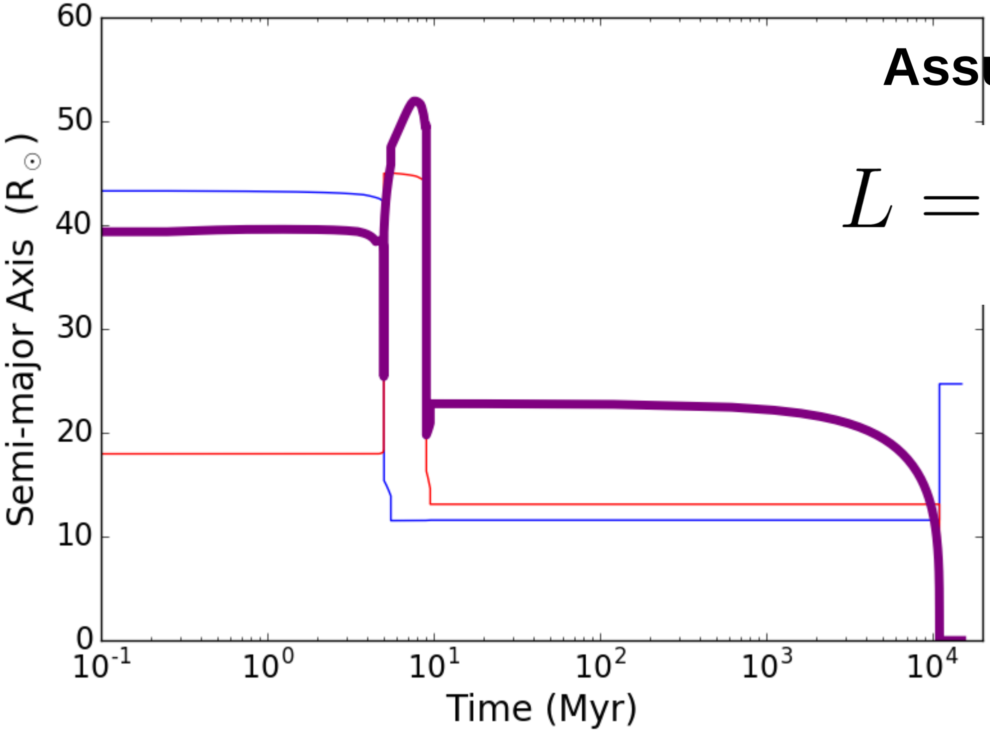


*** Does the binary merges by gravitational-wave emission?**

EXERCISE 1: follow the evolution of a binary



Assume mass transfer is CONSERVATIVE

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

L **= const,** ***m$_1$*****+*****m$_2$*** **= const**

$$(m_1 m_2)^2\, a = \text{const}$$

Semi-major axis has a minimum for $m_1 = m_2$

If initially Mdonor > Maccretor orbital separation decreases

If initially Mdonor < Maccretor orbital separation increases

Since $R_\mathrm{L} \propto a$ **when orbital sep. decreases RL shrinks**
when orbital sep. increases RL expands

EXERCISE 2: properties of a compact binary sample

https://drive.google.com/open?id=1YIXgf_Q8qXO8hp5jEcNXGln3_F5jdo1P

Enter in folder A5

The folder contains several files, which are catalogues of merging binary black holes, binary neutron stars and black hole – neutron star binaries

simulated with MOBSE (simulation named α5 in Giacobbo & MM 2018, https://ui.adsabs.harvard.edu/abs/2018MNRAS.480.2011G/)

File names are of type

data_BHBs_*.txt	**for binary black holes**
data_BHNS_*.txt	**for black hole – neutron star binaries**
data_DNSs_*.txt	**for binary neutron stars**

The number before .txt indicates the METALLICITY of the PROGENITOR STAR
Z = 0.02, 0.016, 0.012, 0.008, 0.006, 0.004, 0.002, 0.0016, 0.0012, 0.0008. 0.0004 and 0.0002

The first line of each file contains just two numbers: the total stellar mass which has been simulated and the number of merging compact binaries in the catalogue (ignore this line)

Each of the other lines is a single compact binary

EXERCISE 2: properties of a compact binary sample

https://drive.google.com/open?id=1YIXgf_Q8qXO8hp5jEcNXGln3_F5jdo1P

Description of the columns:

col. 1: identifier of the binary
col.2 : ZAMS mass of stellar progenitor 1 [Msun]
col. 3: ZAMS mass of stellar progenitor 2 [Msun]
col. 4: mass of compact object 1 [Msun] NOTE that compact object 1 is not necessarily more massive than compact object 2, it is just the compact object that forms from stellar progenitor 1
col. 5: mass of compact object 2 [Msun]
col. 6: mass of compact object 1 + mass of compact object 2 [Msun]
col. 7: delay time [Gyr]
col. 8: semi-major axis [Rsun] when the binary becomes double degenerates
col. 9: eccentricity when the binary becomes double degenerates

EXERCISE 2: properties of a compact binary sample

https://drive.google.com/open?id=1YIXgf_Q8qXO8hp5jEcNXGln3_F5jdo1P

1. Make a histogram plot of the delay times of files

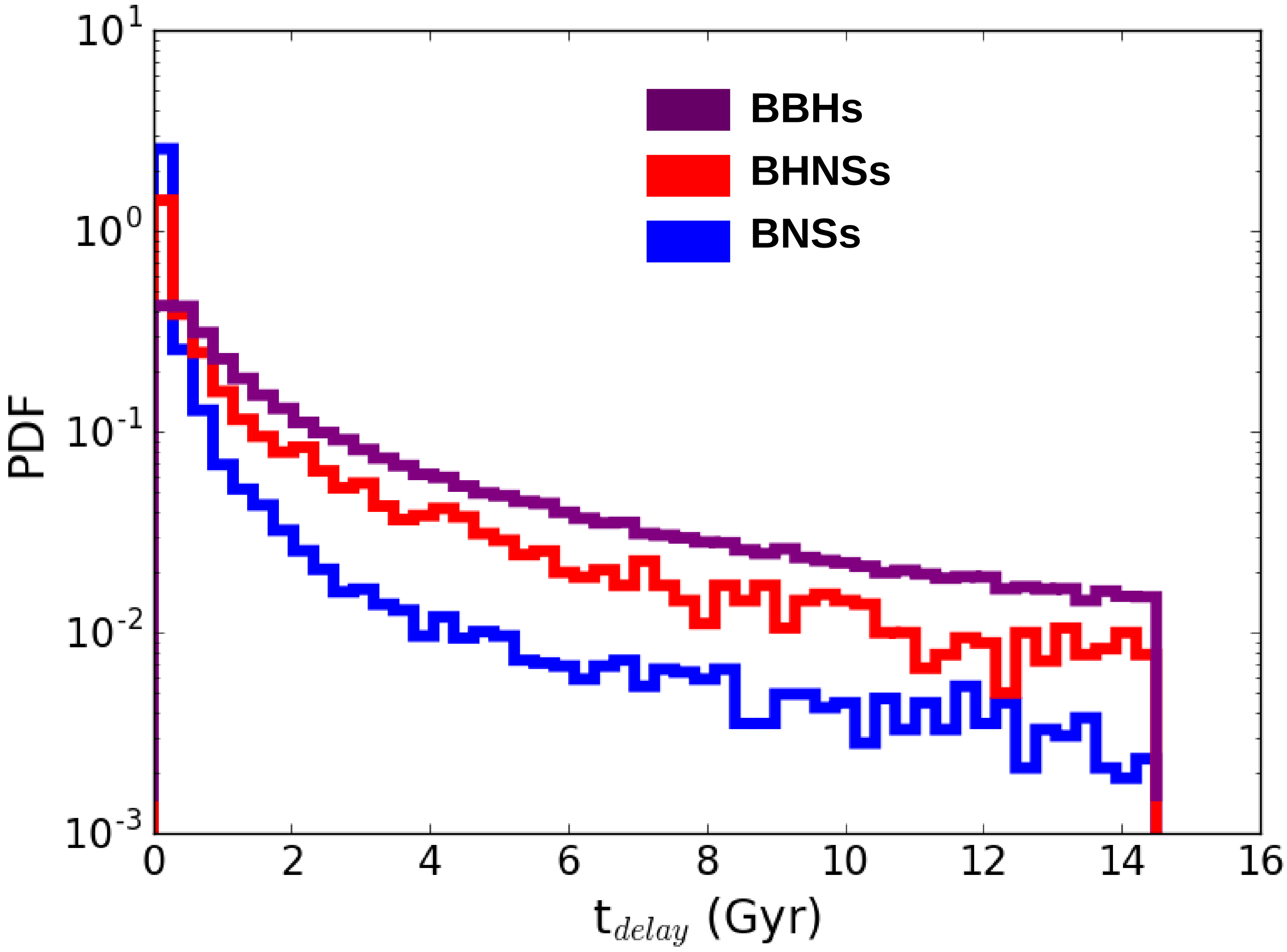
data_BHBs_0.0002.txt
data_BHNS_0.0002.txt
data_DNSs_0.0002.txt

WHAT IS THE TYPICAL TREND OF DELAY TIMES?
DO YOU SEE DIFFERENCES BETWEEN NEUTRON STARS AND BLACK HOLES?

2. Make a histogram plot of the masses of the black holes in binary black holes and black hole – neutron star binaries for several different metallicities
(it is not needed that you plot all of them)

WHAT IS THE MAXIMUM BLACK HOLE MASS?
HOW DOES IT DEPEND ON METALLICITY?

EXERCISE 2: properties of a compact binary sample



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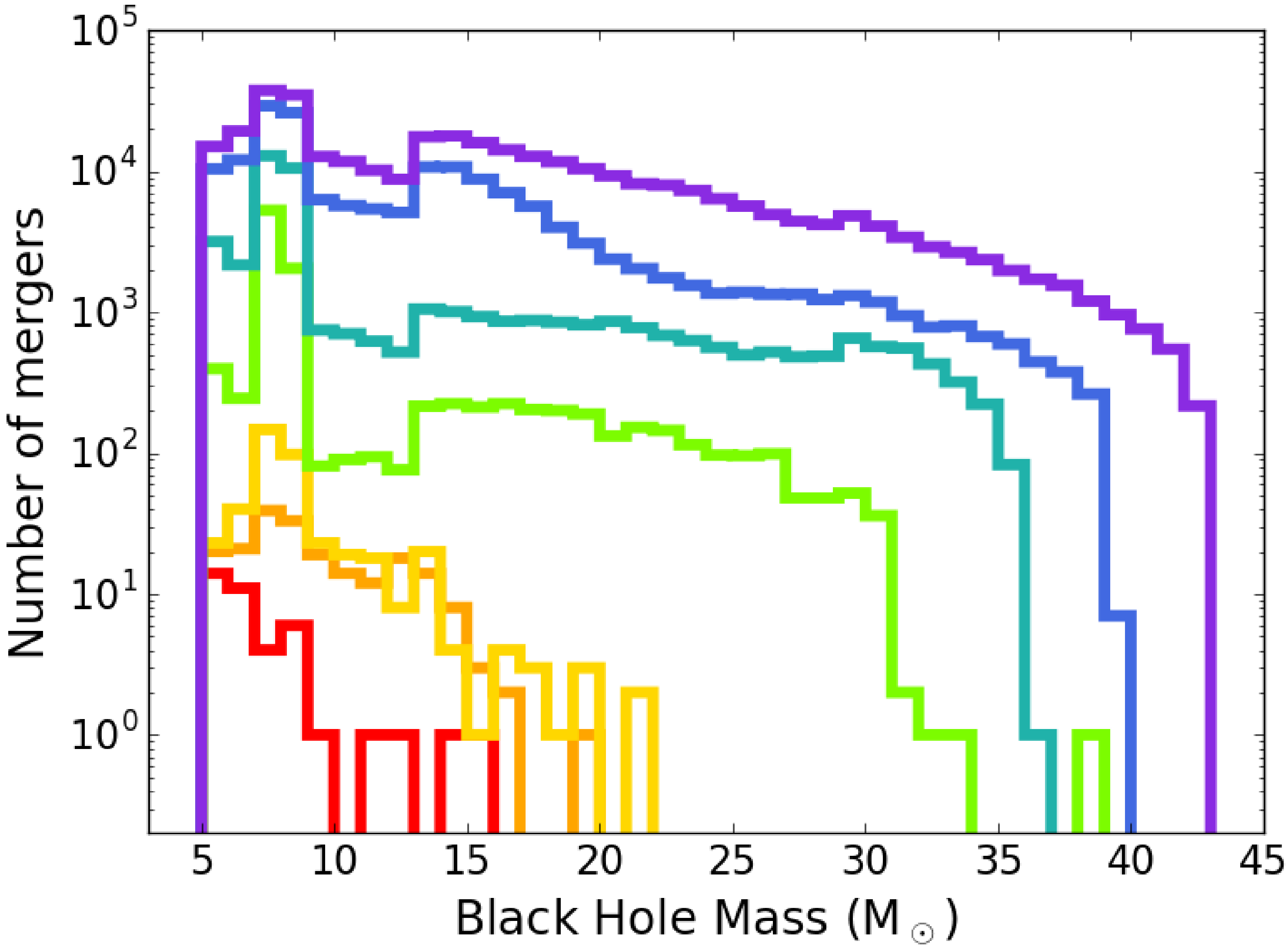
EXERCISE 2: properties of a compact binary sample

Black holes in BBHs:



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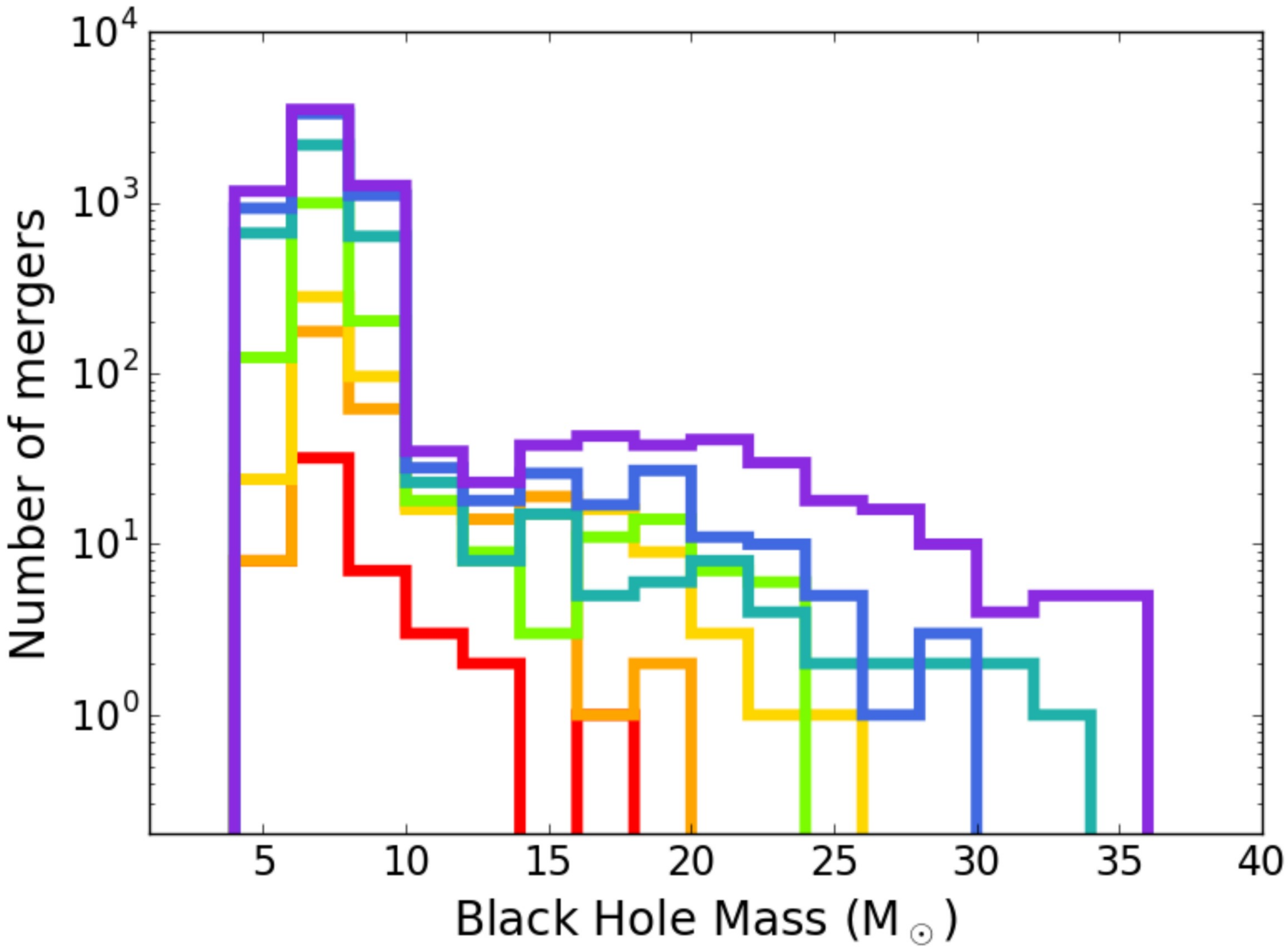
HOW DOES IT DEPEND ON METALLICITY?

EXERCISE 2: properties of a compact binary sample

Black holes in BHNS systems:

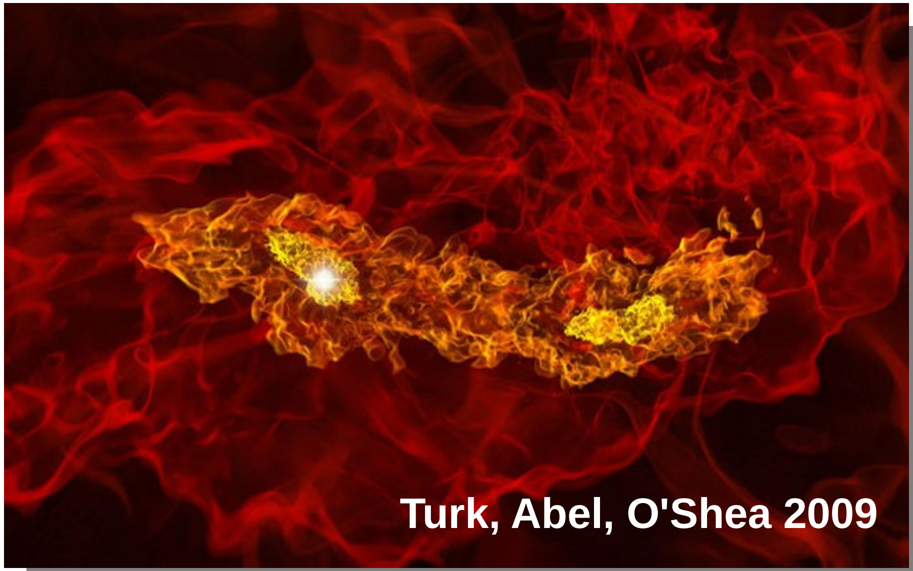


WHAT IS THE MAXIMUM BLACK HOLE MASS?
HOW DOES IT DEPEND ON METALLICITY?

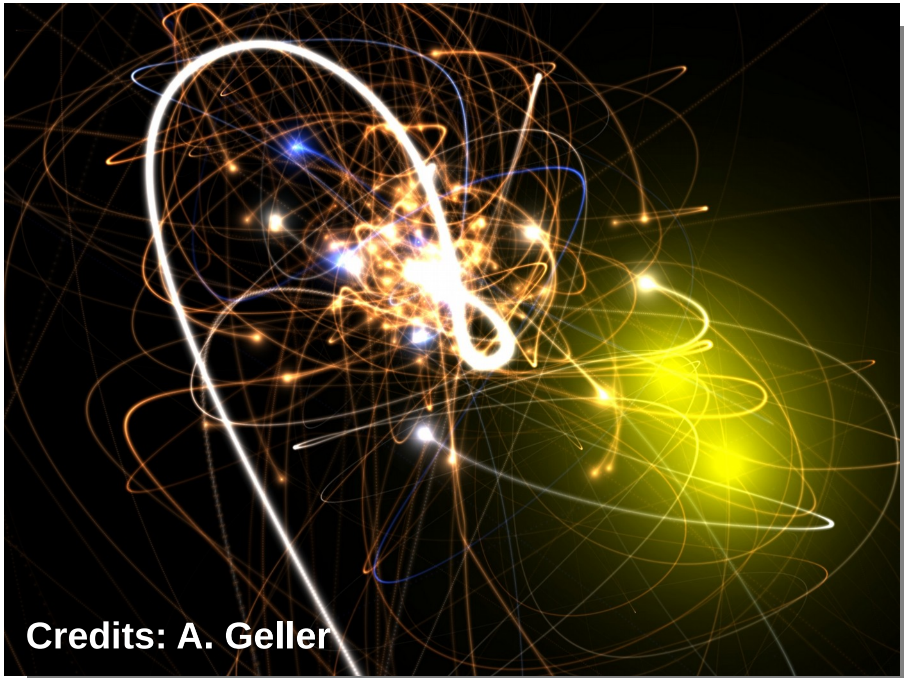
2. Binary compact objects

LIGO – Virgo observe compact object BINARIES

How do binary black holes or binary neutron stars or BH – NS form?



1) PRIMORDIAL BINARIES or ISOLATED BINARIES:
two stars form from same cloud and evolve into two black holes (BHs) gravitationally bound



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

3. The dynamics of black hole (BH) binaries:

DYNAMICS is IMPORTANT ONLY IF $\boxed{n > 10^3 \text{ stars pc}^{-3}}$

i.e. only in dense star clusters, where encounters are common

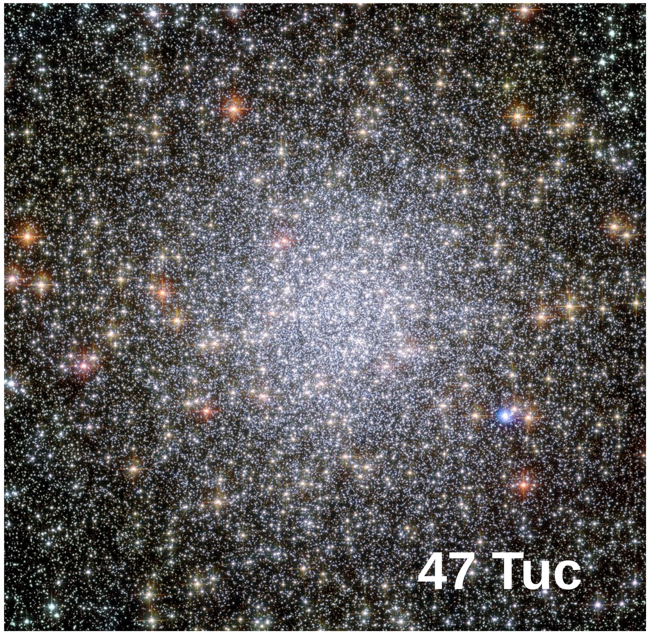
BUT massive stars (compact-object progenitors) form in star clusters

(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; see Portegies Zwart+ 2010 for a review)

R136 in the LMC

3. The dynamics of BH binaries:

There are many different flavours of star clusters



Globular clusters

- ✔ Formed mainly 12 Gyr ago
- ✔ Single-age stars
- ✔ Long lived
- ✔ Very massive (10^{4-6} M⊙)

3. The dynamics of BH binaries:

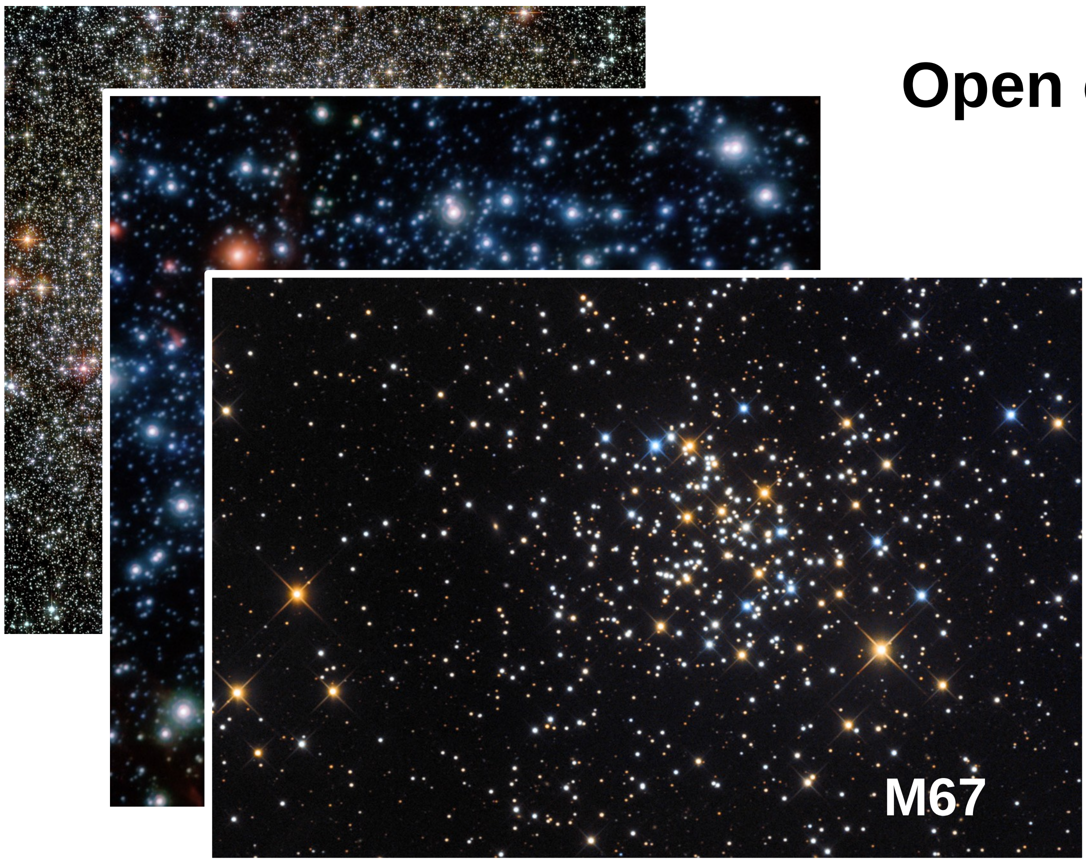
There are many different flavours of star clusters

Nuclear star clusters

- ✔ At center of galaxies
- ✔ Prolonged star formation still ongoing (3 Myr – 12 Gyr ago)
- ✔ Long lived
- ✔ Very massive ($>10^6$ M⊙)
- ✔ Sometimes coexist with super-massive black hole (eg in the Milky Way)

3. The dynamics of BH binaries:

There are many different flavours of star clusters



Open clusters

✔ Age from few Myr to several Gyr

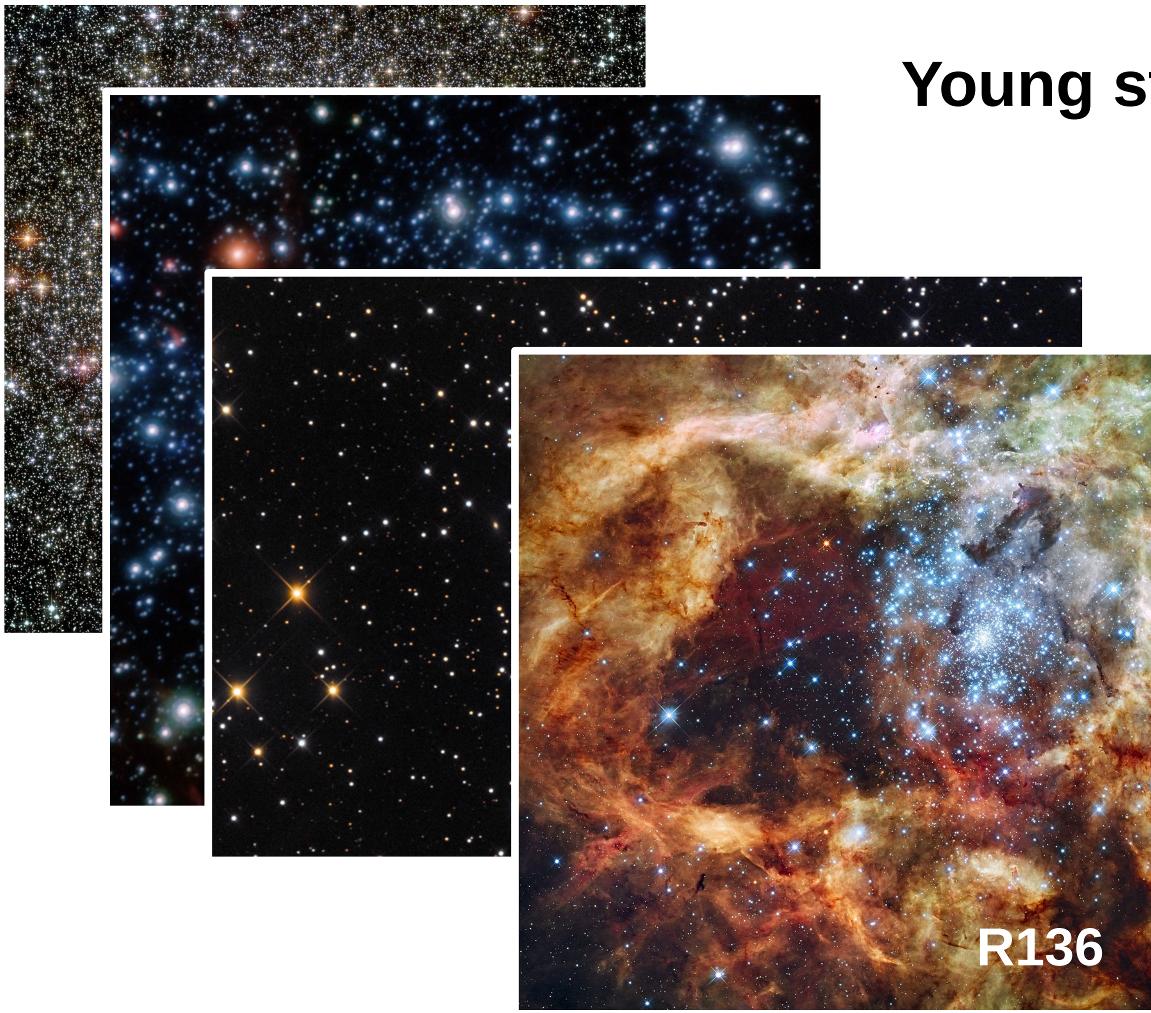
✔ Single-age stars

✔ Not so long lived:
when they die they release
stellar content in the field
→ building blocks of field

✔ Lower mass (10^{2-5} $M_\odot$)

3. The dynamics of BH binaries:

There are many different flavours of star clusters

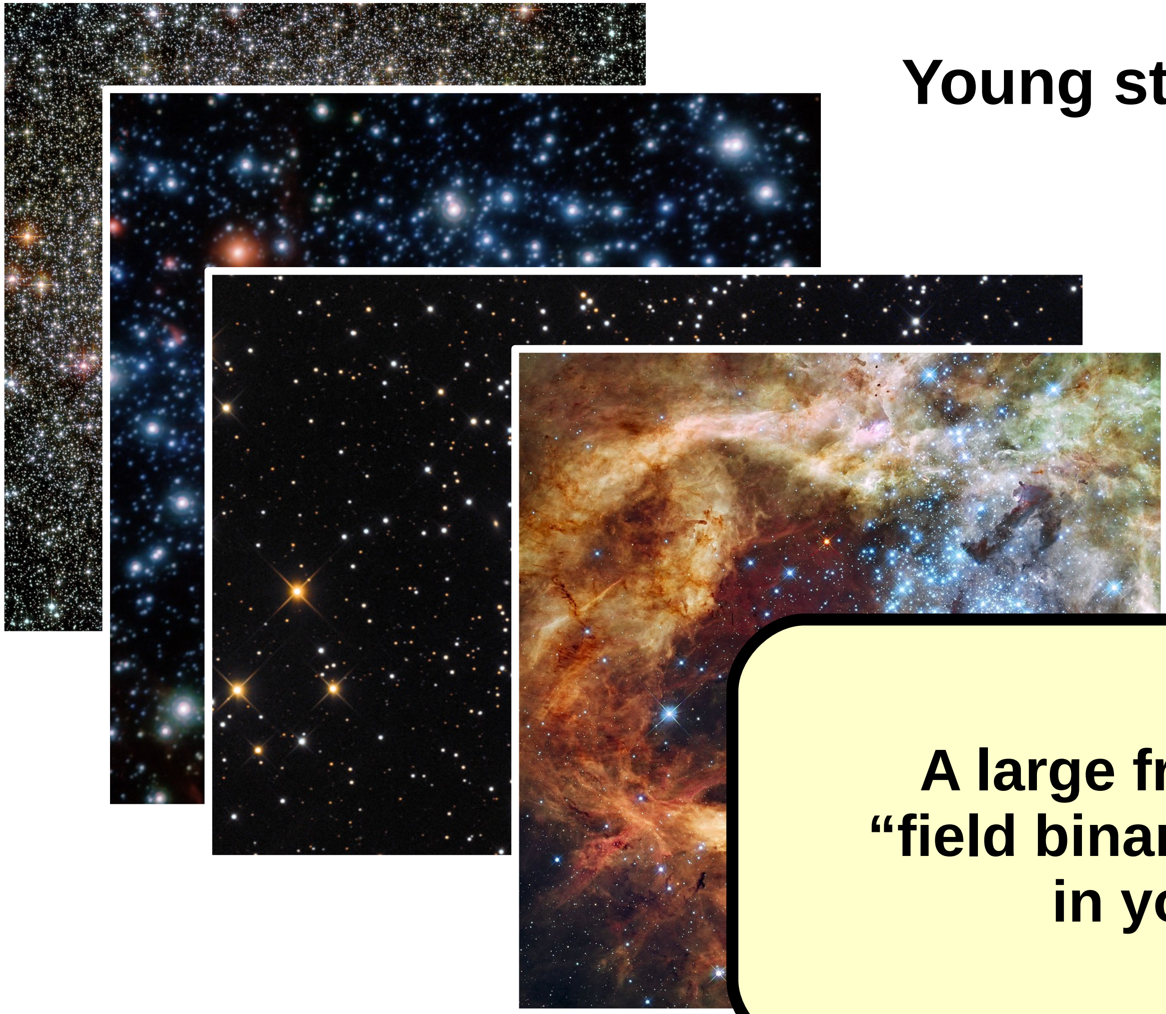


Young star clusters

- ✔ Young (<100 Myr)
- ✔ Not so long lived:
  when they die they
  release stellar content
  in the field
  → building blocks of field
- ✔ Spread of masses
  ($>10^{2-5}\ M_\odot$)
- ✔ Are the NURSERY of
  massive stars

3. The dynamics of BH binaries:

There are many different flavours of star clusters



Young star clusters

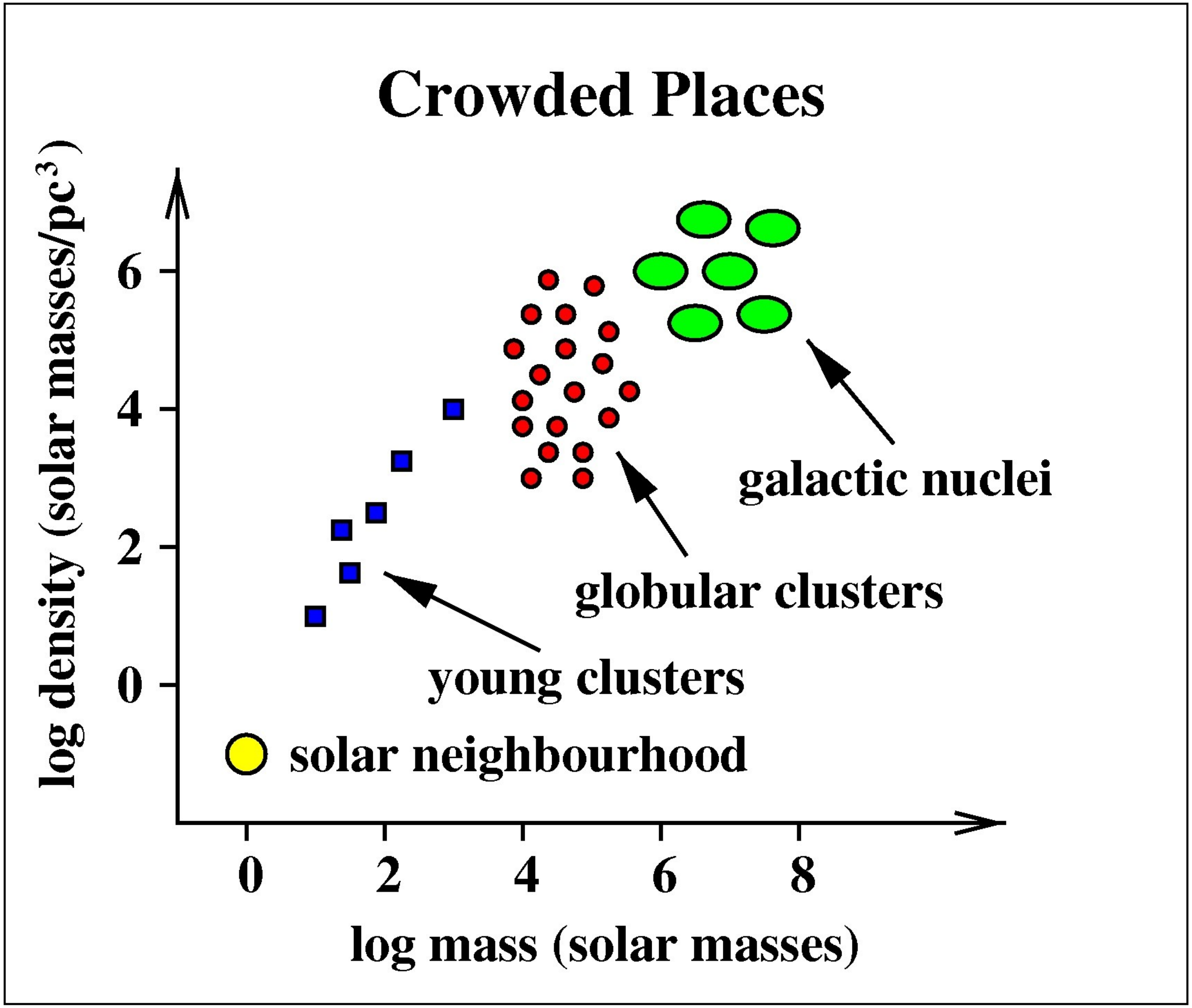
A large fraction of what we call “field binaries” might have formed in young star clusters

3. The dynamics of BH binaries:

What processes happen in star clusters which cannot happen in the field?

Central density
> 100 stars pc $^{-3}$

Stars and binaries undergo close encounters between each other



M. B. Davies 2002

3. The dynamics of stellar BH binaries: 3-body encounters

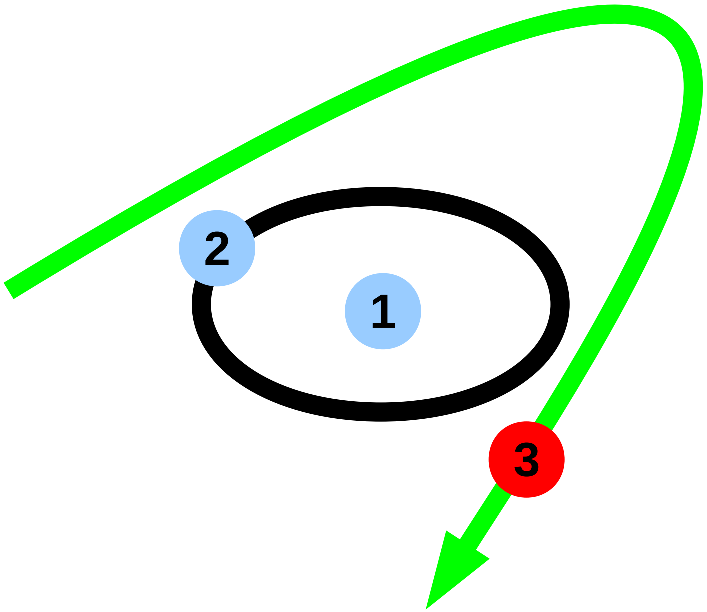
Binaries have a energy reservoir (internal energy)

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

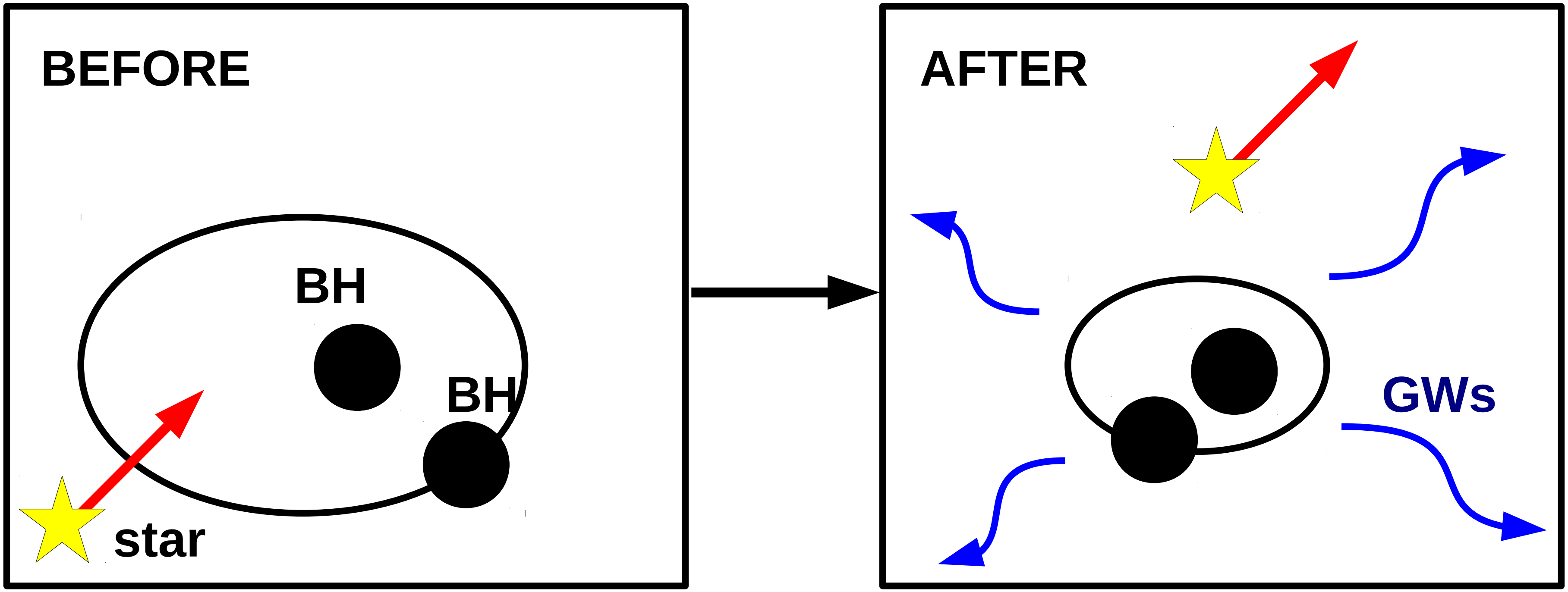
where m_1 and m_2 are the mass of the primary and secondary member of the binary,
μ is the reduced mass (:= $m_1\,m_2/(m_1+m_2)$), r and v are the relative separation and velocity.

$$E_{int} = -\frac{G\,m_1\,m_2}{2\,a} = -E_b$$

THE ENERGY RESERVOIR of BINARIES can be EXCHANGED with stars during a 3-BODY INTERACTION, i.e. an interaction between a binary and a single star



3. The dynamics of stellar BH binaries: FLYBYs

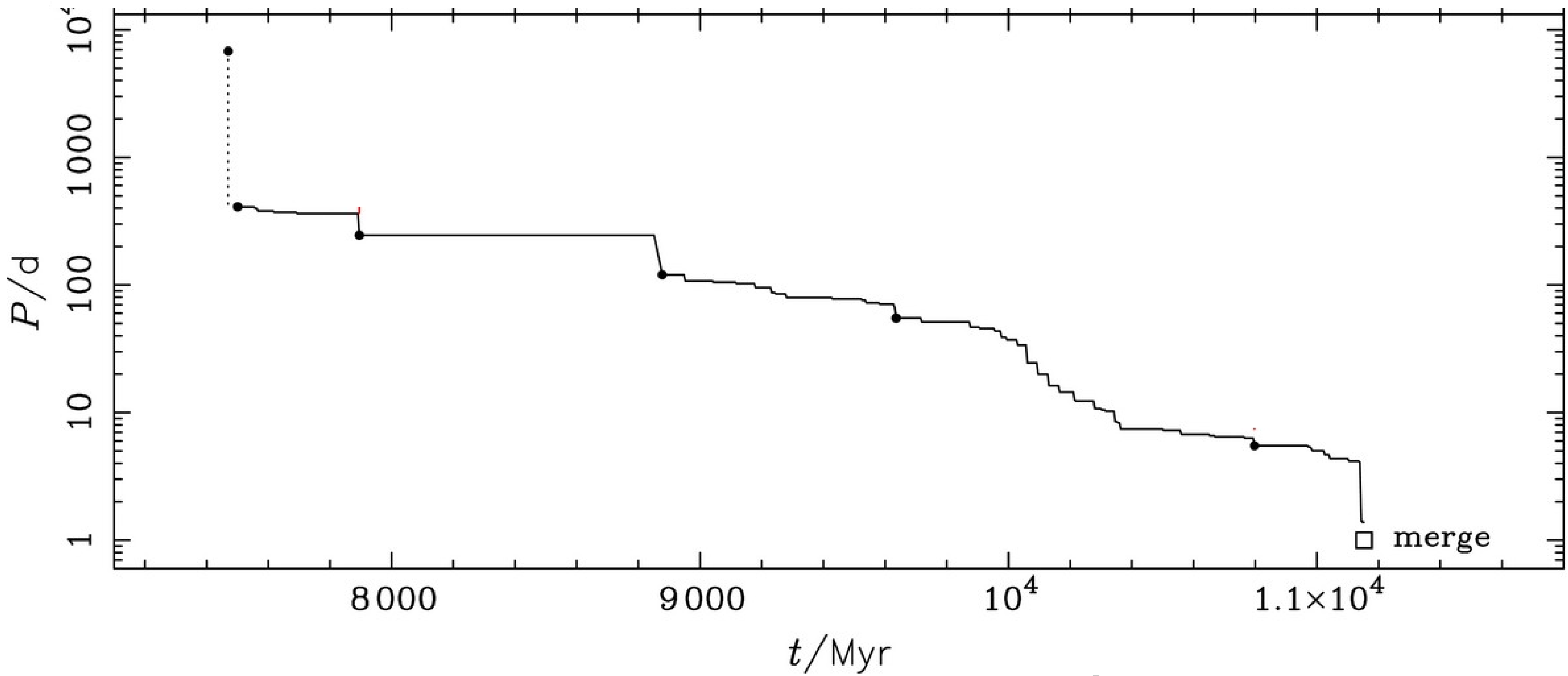


In a flyby, the star acquires kinetic energy from the binary

→ ***the binary shrinks***

→ ***shorter coalescence time***

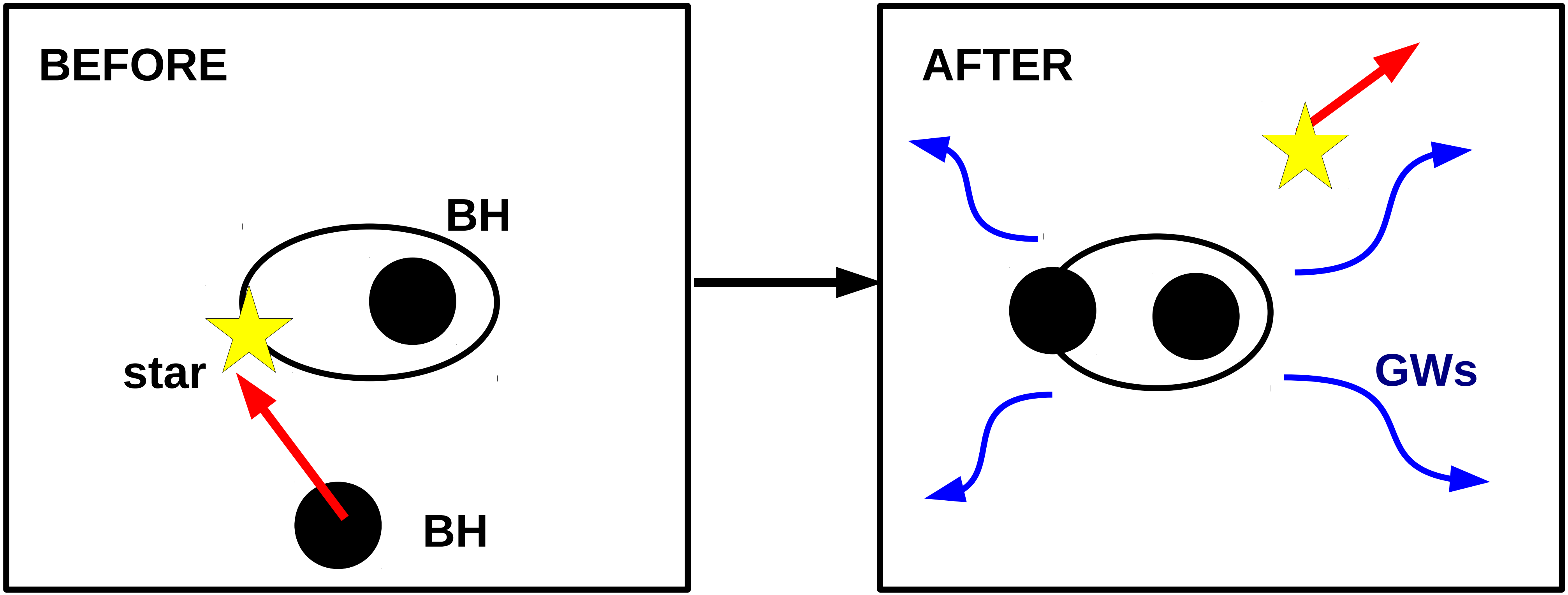
3. The dynamics of stellar BH binaries: FLYBYs



Hurley+ 2016, PASA, 33, 36

Hills 1992, AJ, 103, 1955; Sigurdsson & Hernquist 1993, Nature, 364, 423;
Portegies Zwart & McMillan 2000, ApJ, 528, L17; Aarseth 2012, MNRAS, 422, 841;
Breen & Heggie 2013, MNRAS, 432, 2779; MM+ 2013, MNRAS, 429, 2298;
Ziosi+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, PhRvL, 115, 1101;
Rodriguez+ 2016, PhRvD, 93, 4029; MM 2016, MNRAS, 459, 3432;
Banerjee 2017, MNRAS, 467, 524 and many others

3. The dynamics of stellar BH binaries: EXCHANGEs



Exchanges bring BHs in binaries

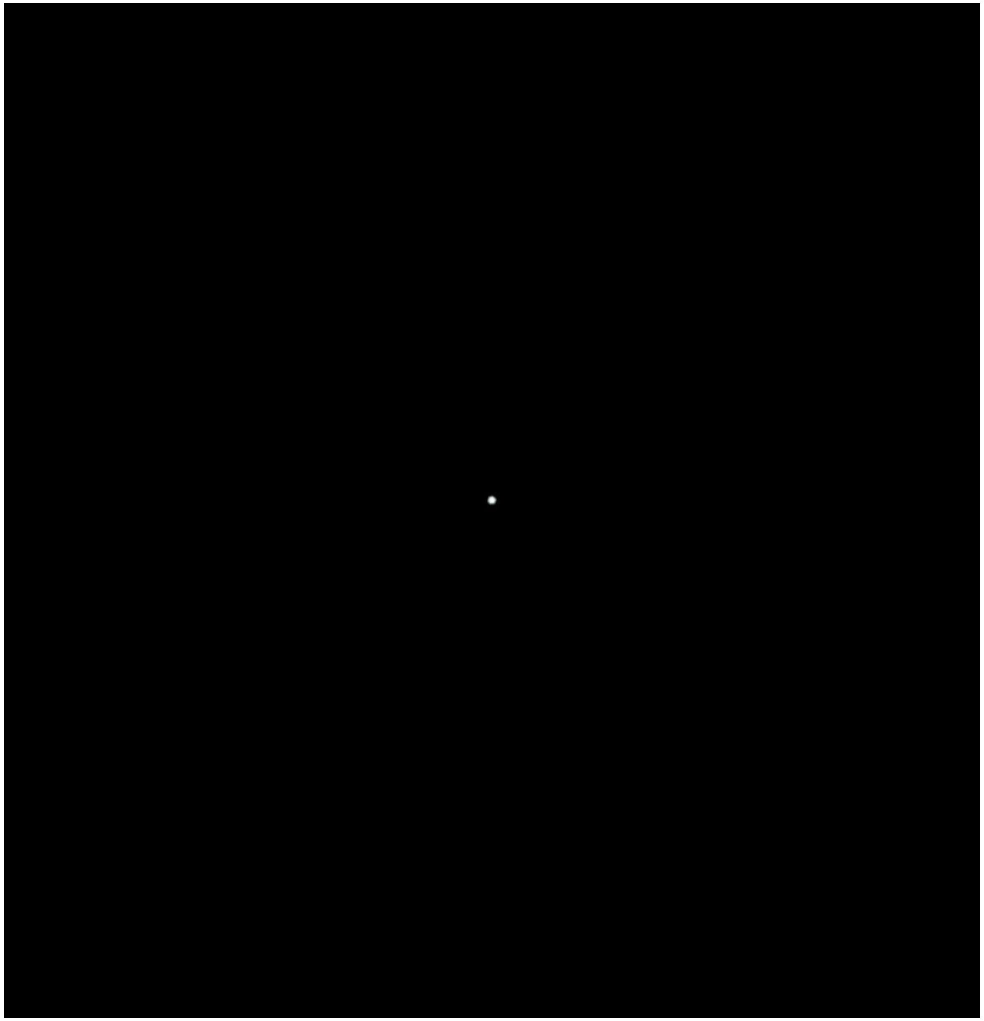
BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!

BH born from single star in the field never acquires a companion
BH born from single star in a cluster likely acquires companion from dynamics

NEUTRON STARs (NSs) are lighter → Dynamics is less important for NSs

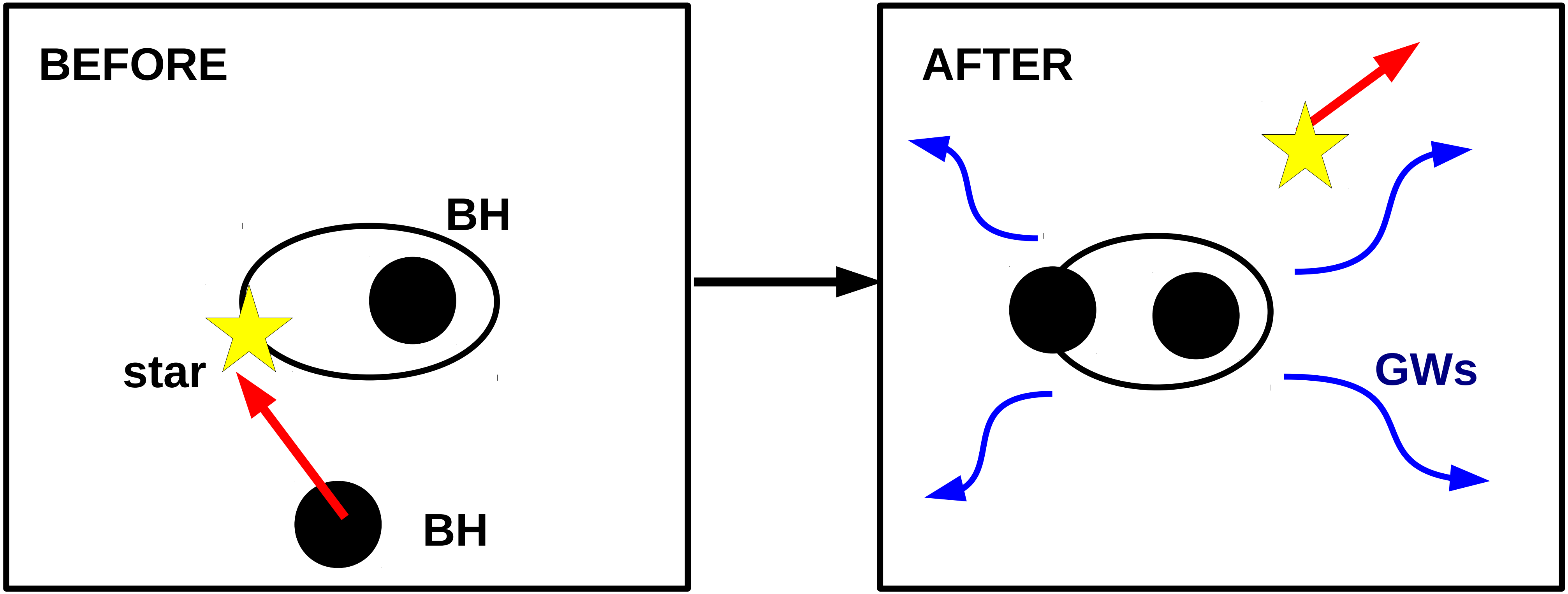
3. The dynamics of stellar BH binaries: EXCHANGEs

Credits: Aaron Geller @Northwestern



ciera.northwestern.edu/Research/visualizations/videos/Binary+single.mp4
ciera.northwestern.edu/Research/visualizations/videos/Binary+singleex.mp4
ciera.northwestern.edu/Research/visualizations/videos/Triple+binary.mp4

3. The dynamics of stellar BH binaries: EXCHANGEs



>90% BH-BH binaries in young star clusters form by exchange

(Ziosi, MM+ 2014, MNRAS, 441, 3703)

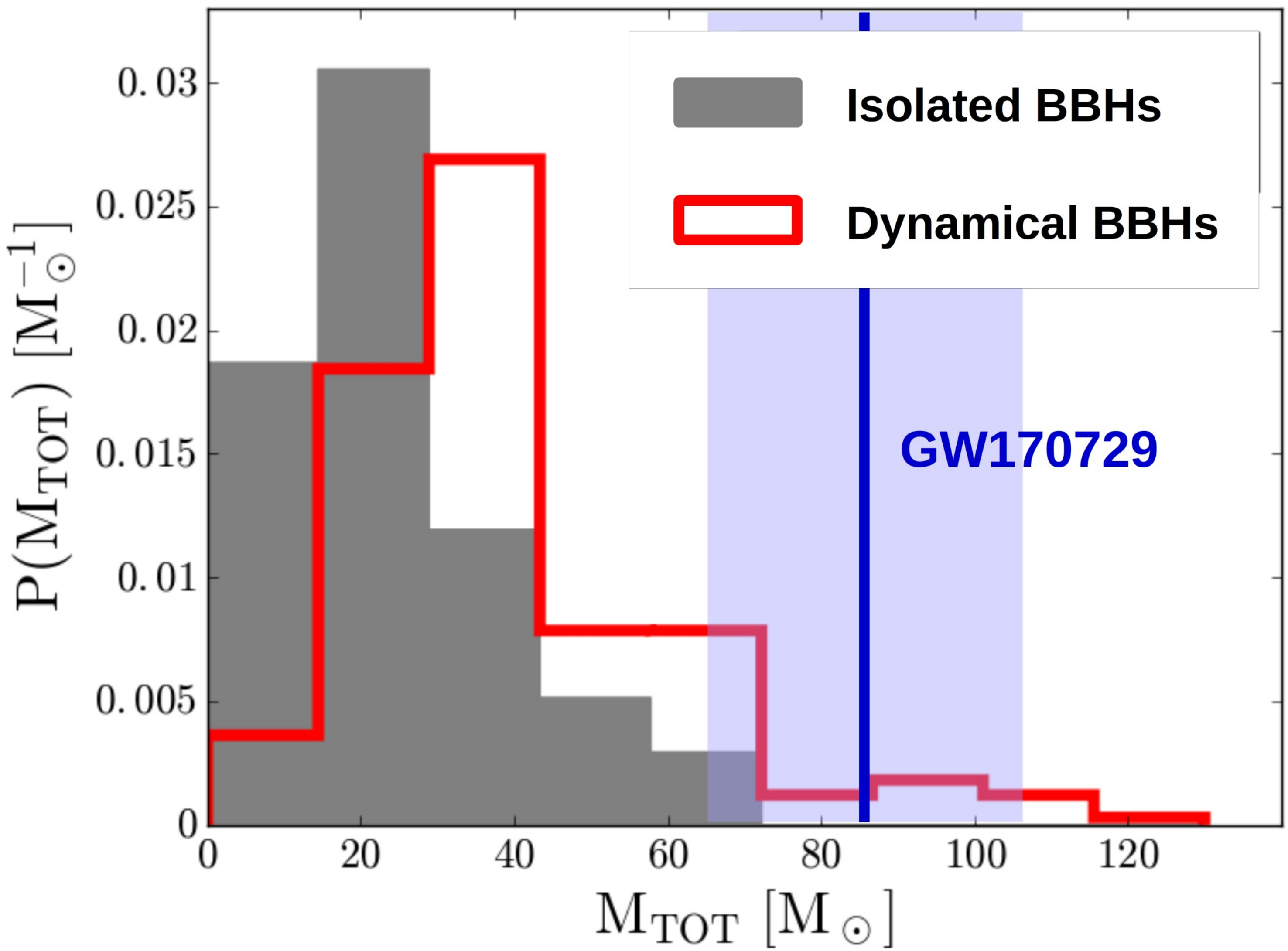
EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH

** THE MOST MASSIVE BHs*

** HIGH ECCENTRICITY*

** MISALIGNED BH SPINS*

3. The dynamics of stellar BH binaries: MASSEs



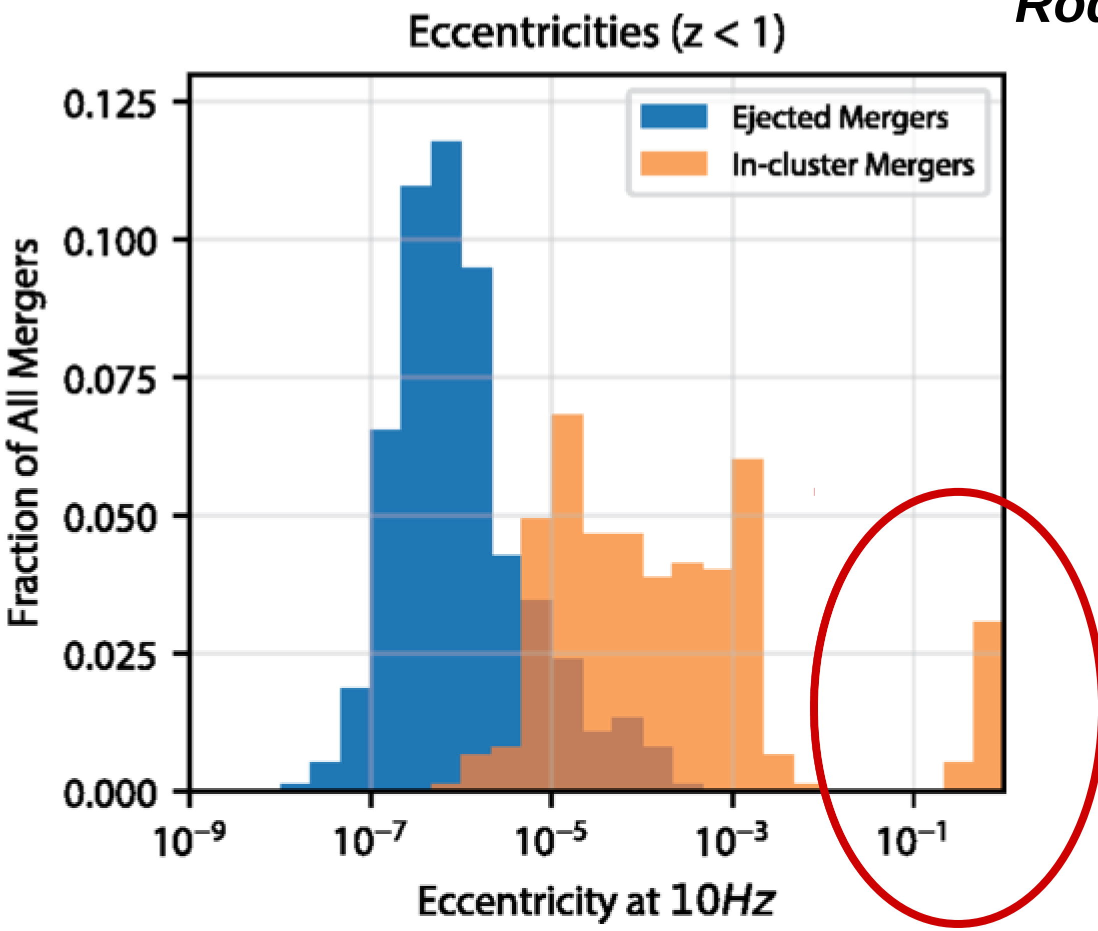
Metallicity
$Z = 0.1\ Z_\odot$

Di Carlo et al. 2019, arXiv:1901.00863

see also Banerjee+ 2010; Ziosi+ 2014; MM 2016; Kimpson+ 2016; Banerjee 2017, 2018; Rastello+ 2018; Kumamoto+ 2018

3. The dynamics of stellar BH binaries: ECCENTRICITY

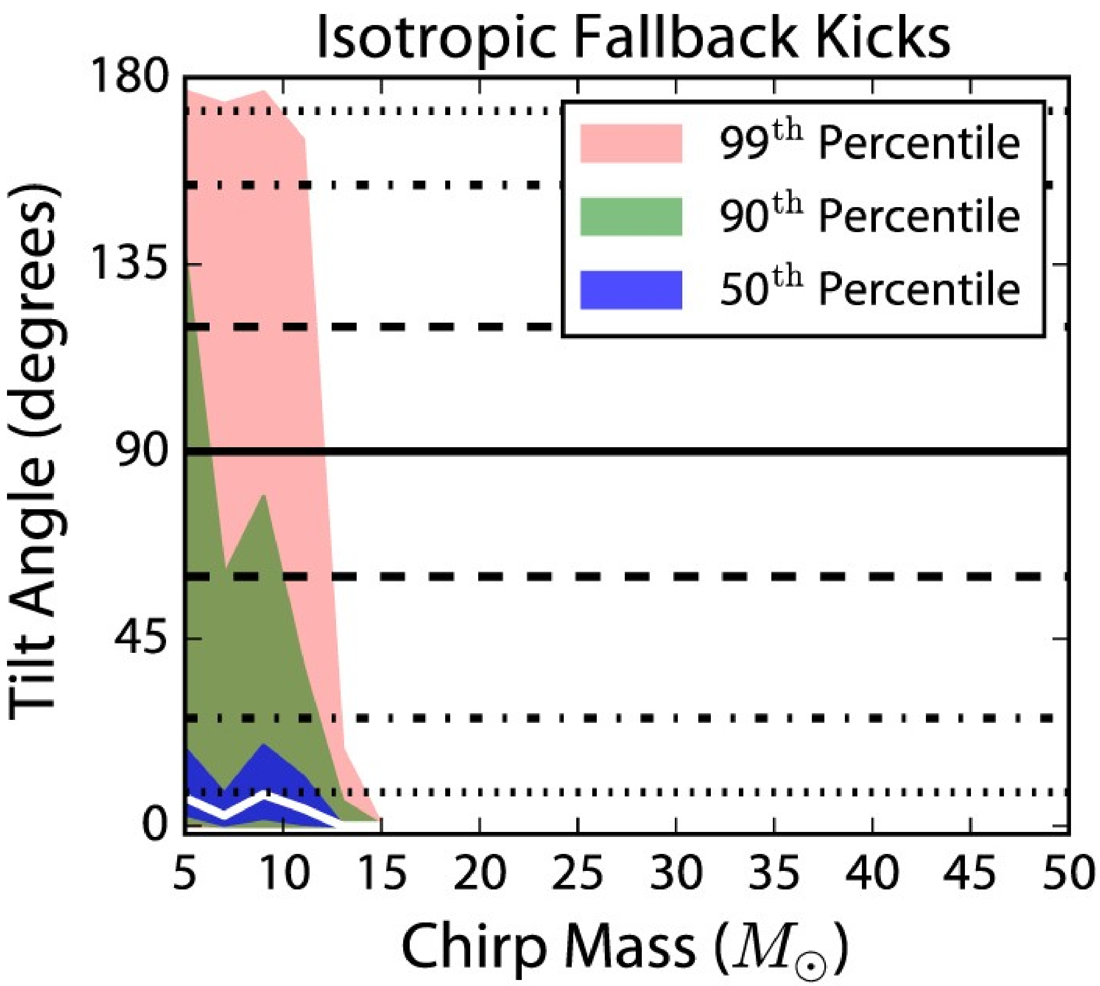
Rodriguez+ 2018, PhRvD, 120, 1101

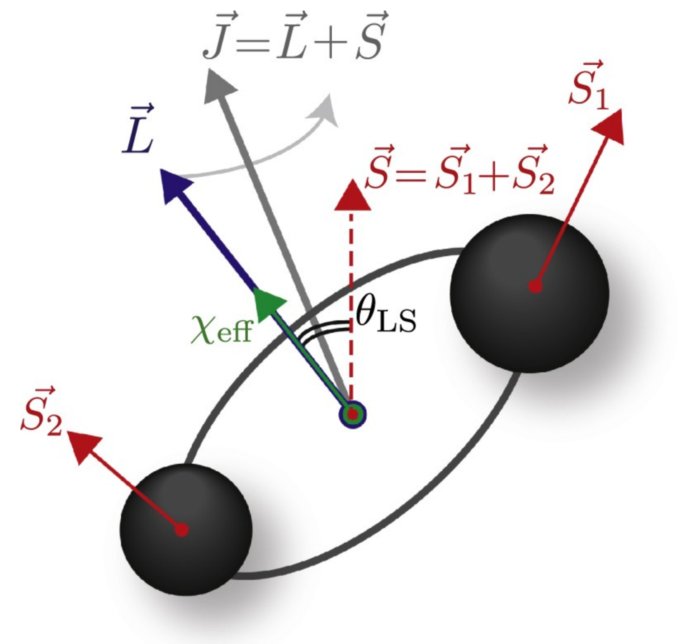


Extreme eccentricity in few systems that evolve in clusters

Ziosi, MM+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, Phys. Review Letter, 115, 1101; Hurley+ 2016, PASA, 33, 36; Askar+ 2017, MNRAS, 464, L36; Banerjee 2017, MNRAS, 467, 524 and many others

3. The dynamics of stellar BH binaries: SPINs





Colours: isolated BBHs
Dark horizontal lines: dynamically formed BBHs

Rodriguez+ 2016, ApJ, 832, L2

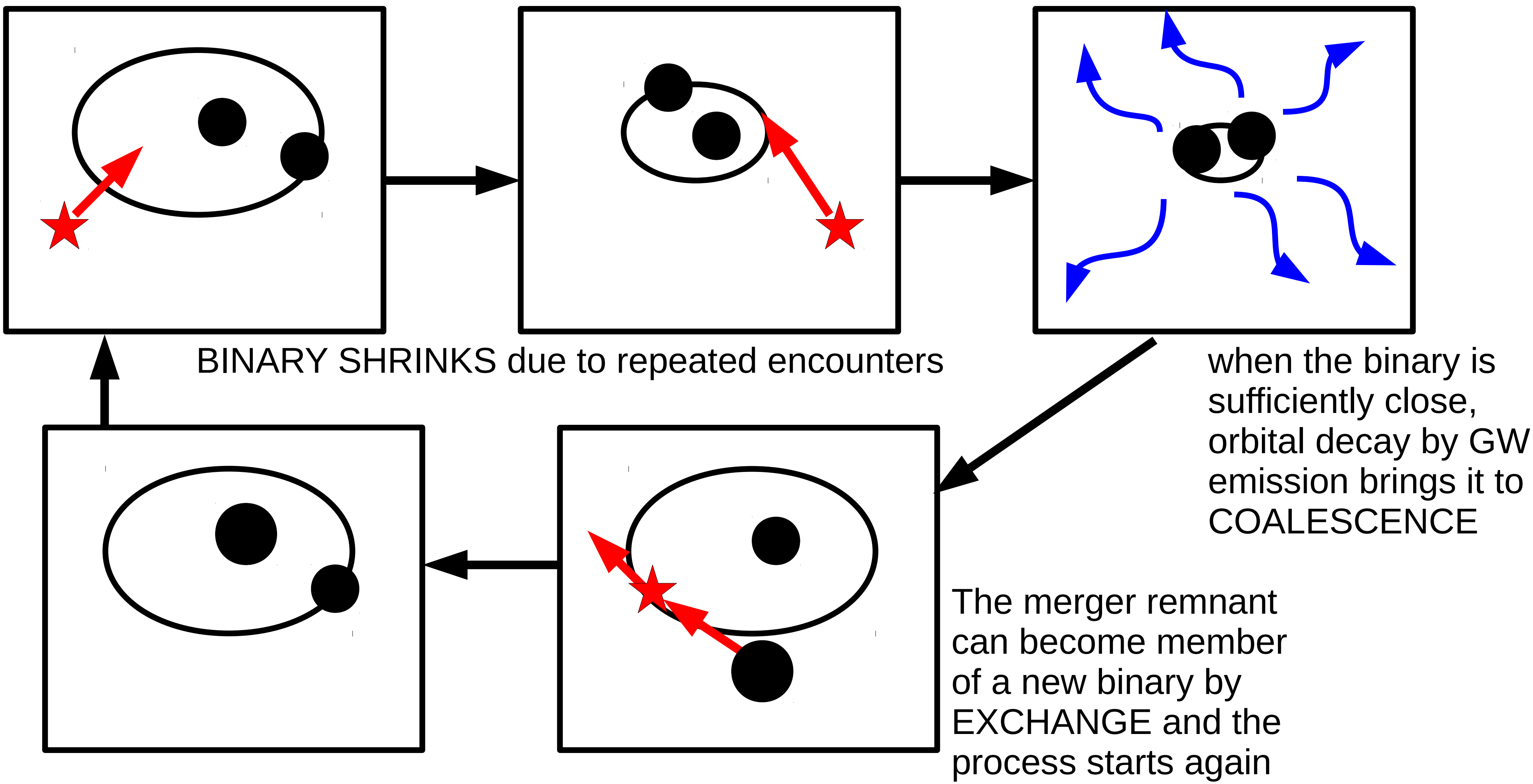
Spins of BBHs formed by exchange are ISOTROPICALLY distributed

Spins of BBHs formed from isolated binaries can be misaligned by SN kicks, but most remain aligned (especially massive binaries)

3. The dynamics of stellar BH binaries: intermediate-mass BHs (IMBHs)

<u>Formalism by Miller & Hamilton (2002) to form IMBHs (100 – 10’000 Msun)</u>

In a old cluster stellar BHs can grow in mass because of repeated mergers with the companion triggered by 3-body encounters



3. The dynamics of stellar BH binaries: wrap up

Dynamical binary evolution summary:

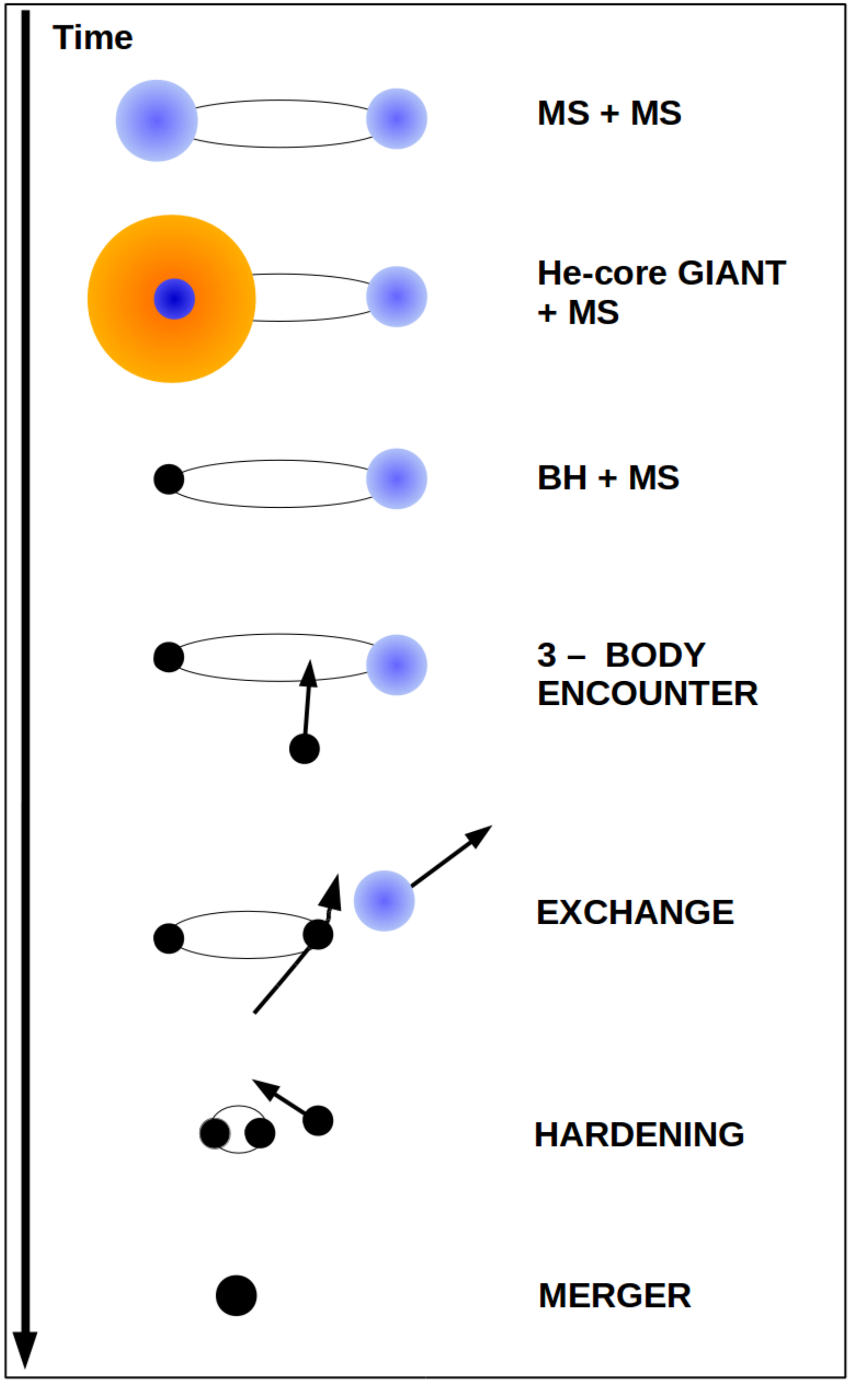
* no need for Roche lobe
  or common envelope
  (but might happen)

* exchanges build up
  more massive
  black hole binaries

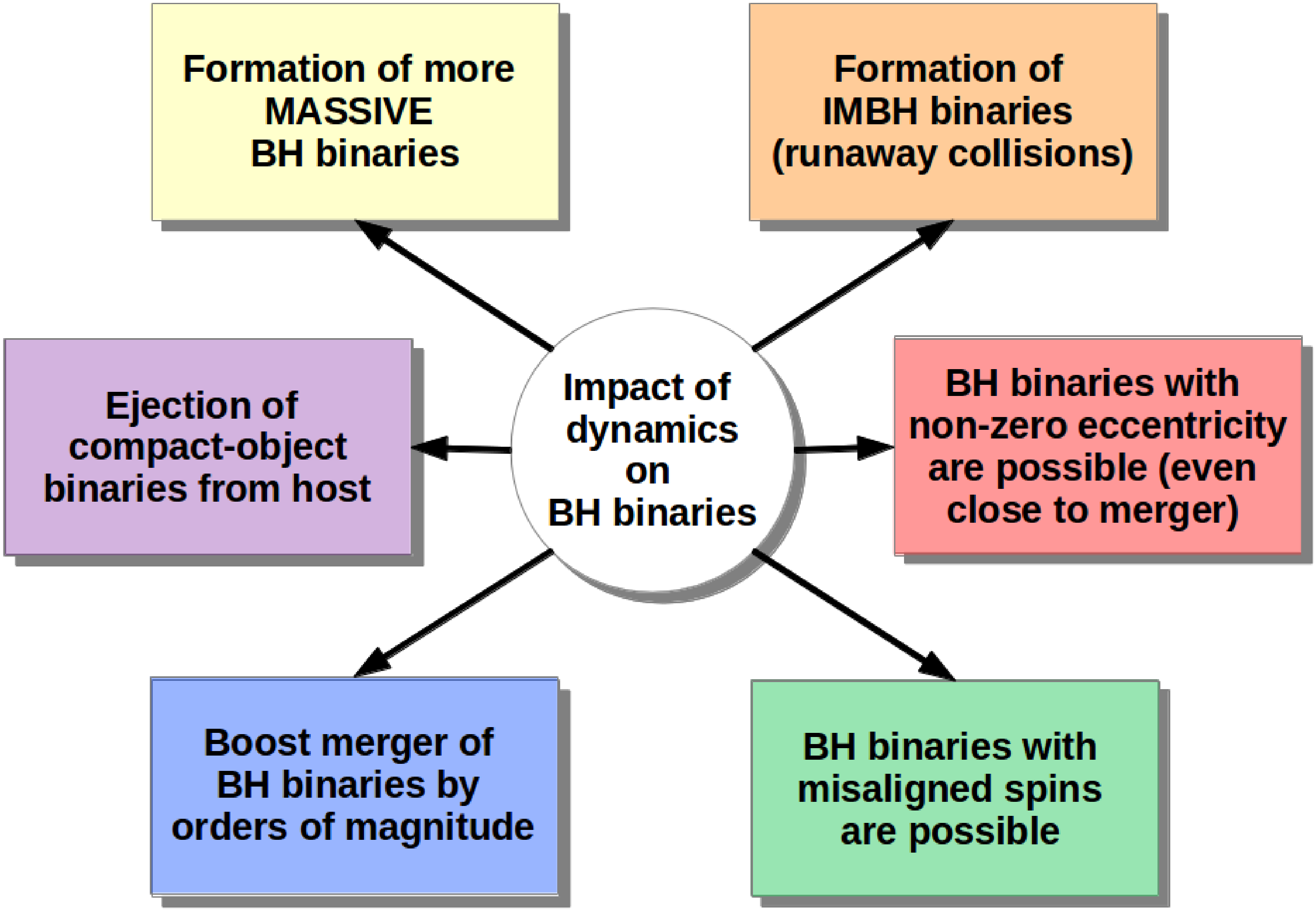
* hardening by three-body
  encounters favours
  the binary shrinking

* BH – BH merger

cartoon from MM 2018,
https://arxiv.org/abs/1809.09130



3. The dynamics of stellar BH binaries: wrap up



THANK YOU