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Gravitational – Wave Astrophysics

Main collaborators: M. Celeste Artale, Alessandro Ballone, Yann Bouffanais, Ugo N. Di Carlo, Nicola Giacobbo, Enrico Montanari, Mario Pasquato, Sara Rastello, Filippo Santoliquido, Mario Spera

ISAPP School, Heidelberg, June 4th 2019

What is Gravitational – Wave (GW) Astrophysics?

*** Astrophysical characterization of GW sources**

*** Young and fast evolving**

*** Boosted by GW detections**

*** Mostly (but not only) about binary black holes (BBHs), binary neutron stars (BNSs) and neutron star – black hole binaries (NSBHs)**

*** Want to know more?**
J. Creighton & W. G. Anderson,
Gravitational-Wave Physics and Astronomy: An Introduction to Theory, Experiment and Data Analysis,
ISBN-13: 978-3527408863

MM, *Astrophysics of stellar black holes,*
http://adsabs.harvard.edu/abs/2018arXiv180909130M

OPEN QUESTION:

What are the formation channels of merging binaries observed by gravitational-wave interferometers?

OUTLINE:

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

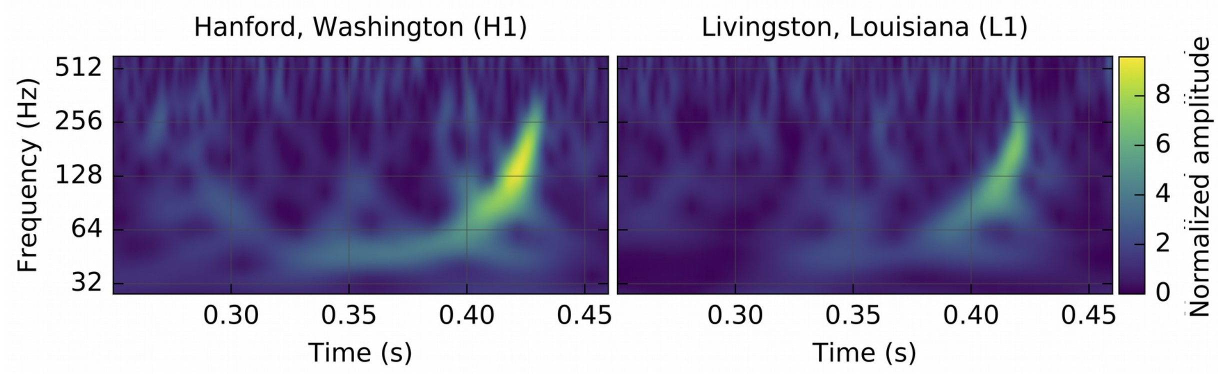
2. Binaries of compact objects

3. The dynamics of black hole (BH) binaries

4. Compact binaries in cosmological context

1. The formation of compact objects

GW150914: the first binary black hole (BBH)



Abbott et al. 2016, PhRvL, 116, 1102

O1 + O2: 10 BBHs and 1 binary neutron star (BNS)

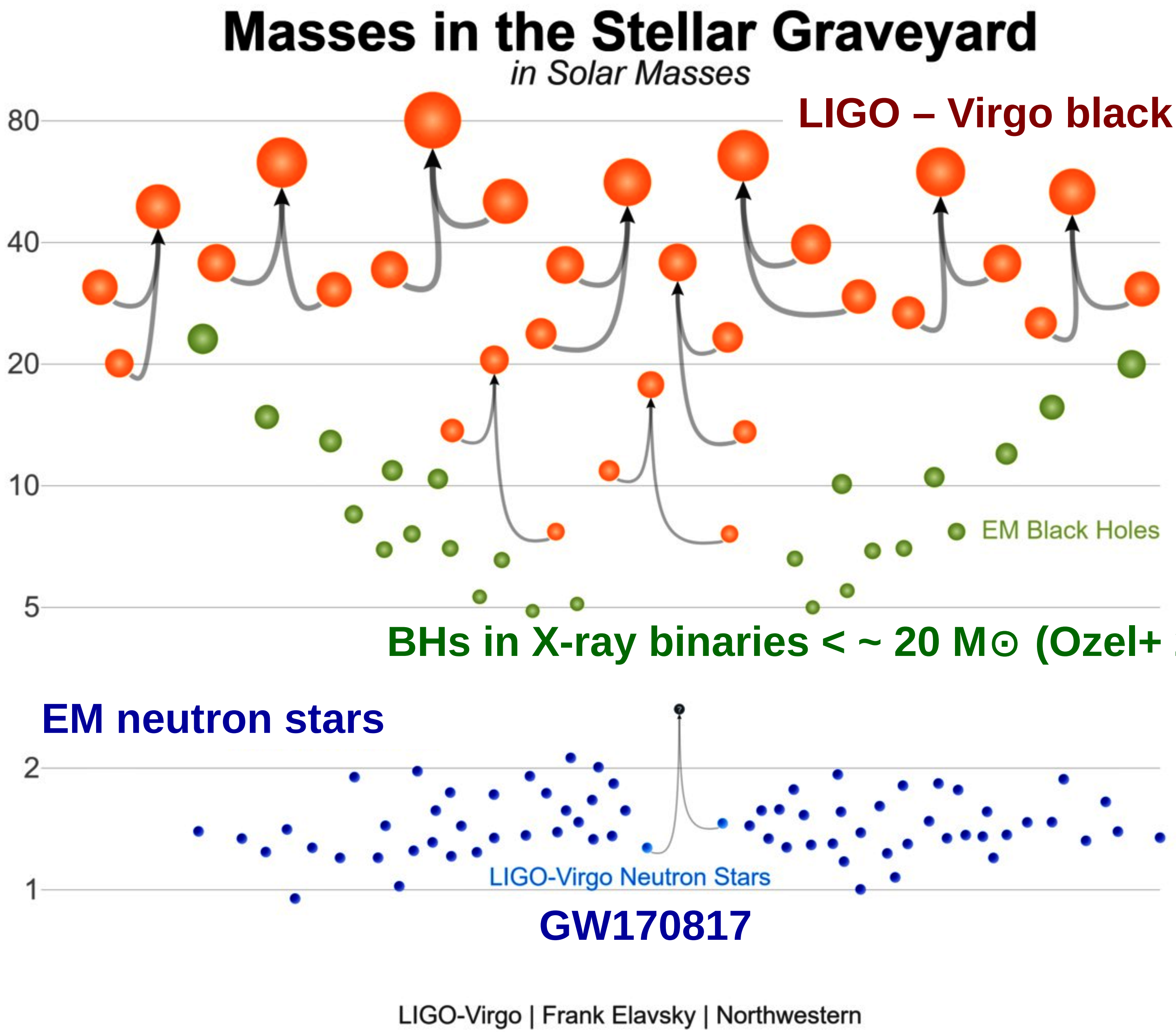
(Abbott et al. 2019, arXiv:1811.12907)

O3 ongoing → DAWN of GRAVITATIONAL WAVE ASTRONOMY

Lesson learned from GW events

1. **BNS mergers are associated with electromagnetic emission (Abbott+ 2017 on GW170817)**
2. **BBHs exist (Tutukov & Yungelson 1973; Thorne 1987; Schutz 1989)**
3. **BBHs can merge in a Hubble time**
4. **Massive BHs exist i.e. stellar-mass BHs with mass >20 $M_\odot$**

1. The formation of compact objects



LIGO – Virgo black holes

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

EM neutron stars

GW170817

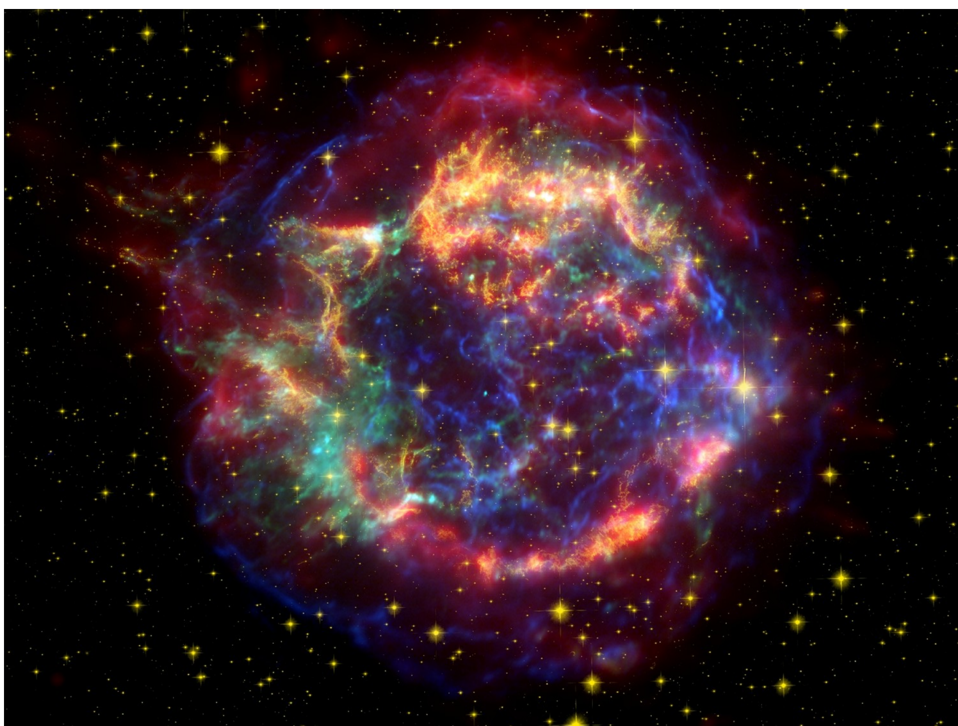
1. The formation of compact objects

Two critical ingredients:

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

2) **SUPERNOVA (SN) EXPLOSION**

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



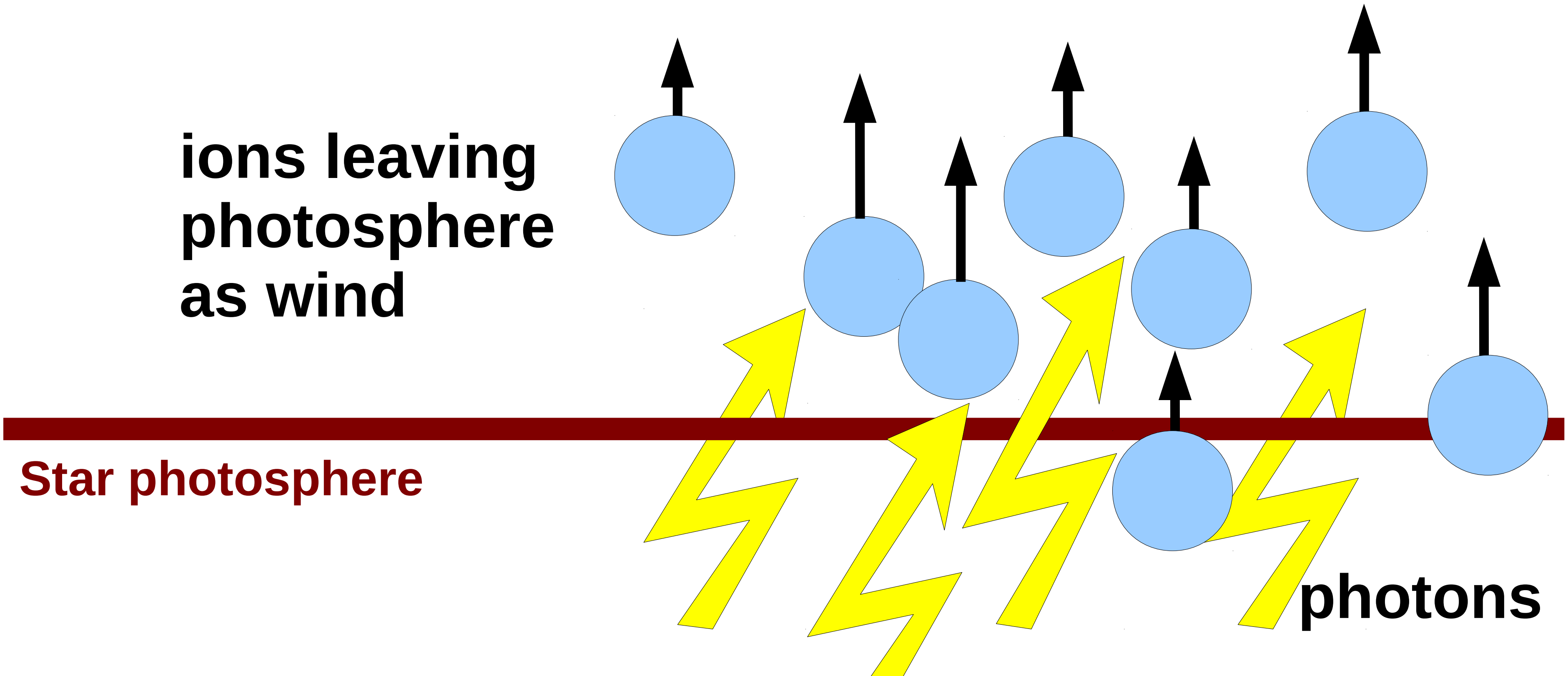
Chandra + HST + Spitzer Image of the SN remnant Cassiopeia A

1. The formation of compact objects: stellar winds

Massive stars (>30 M☉) 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

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

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

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

e.g. Graefener & Hamann 2008

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

$$\alpha = 0.85 \qquad [\text{if } \Gamma < 2/3]$$
$$\alpha = 2.45 - 2.4\,\Gamma \quad [\text{if } \Gamma > 2/3]$$

What is the Eddington limit?

Radiation pressure = Gravity force

Gravity force:

$$F_{grav} = \frac{G\,M}{r^2}$$

Energy flux:

$$Flux = \frac{dE}{dt\,dA} = \frac{L}{4\,\pi\,r^2}$$

Momentum of energy flux:

$$\frac{dp}{dt\,dA} = \frac{dE}{dt\,dA}\frac{1}{c} = \frac{L}{4\,\pi\,r^2\,c}$$

Accounting for absorption (opacity):

$$F_{rad} = \kappa\,\frac{dp}{dt\,dA} = \kappa\,\frac{dE}{dt\,dA}\frac{1}{c} = \kappa\,\frac{L}{4\,\pi\,r^2\,c}$$

What is the Eddington limit?

Radiation pressure = Gravity force

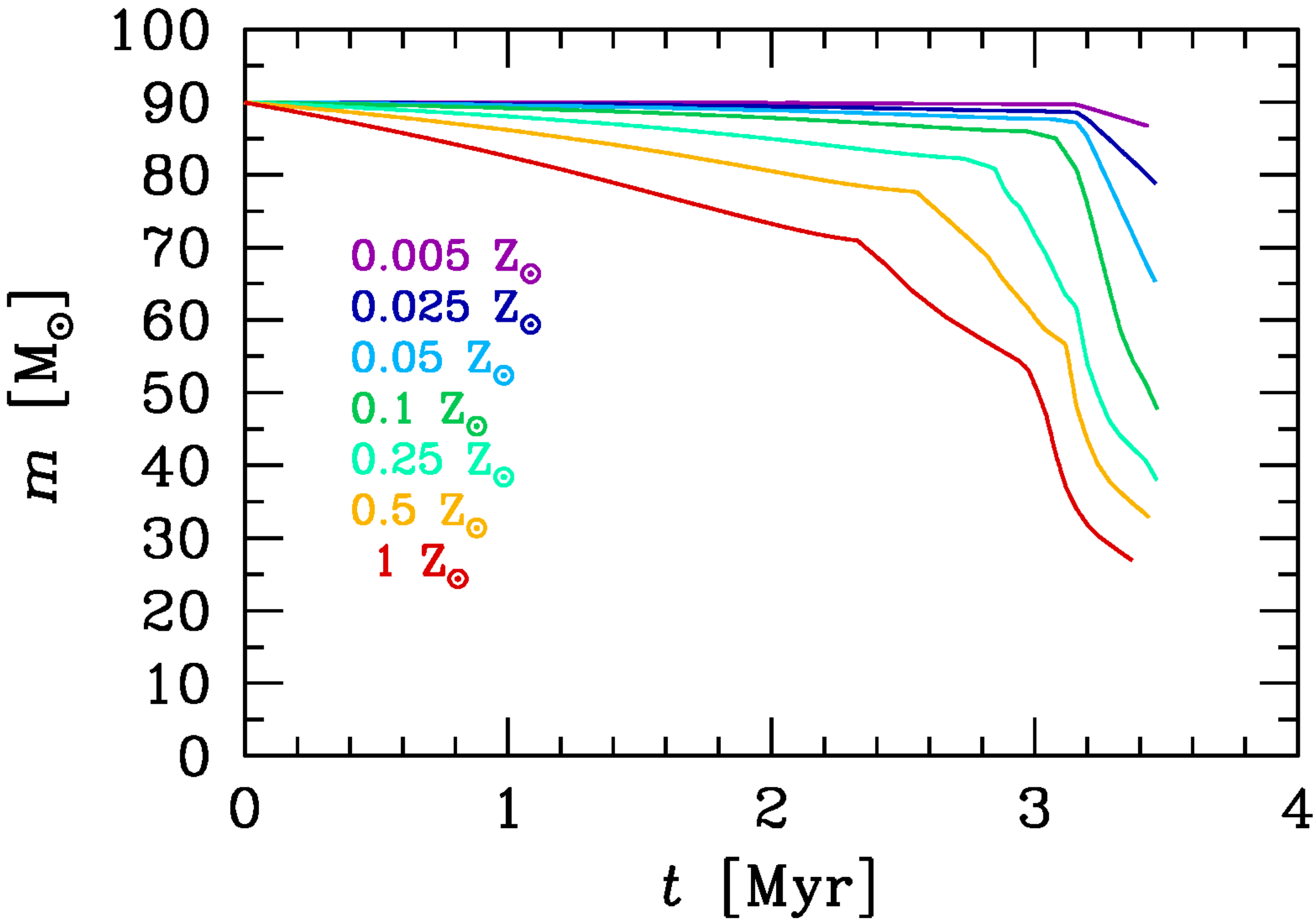
Gravity force: $$F_{grav} = \frac{G\,M}{r^2}$$

Radiation force: $$F_{rad} = \kappa\,\frac{L}{4\,\pi\,r^2\,c}$$

$$L = \frac{4\,\pi\,c\,G\,M}{\kappa}$$

$$\kappa \sim \frac{\sigma_T}{m_p}$$

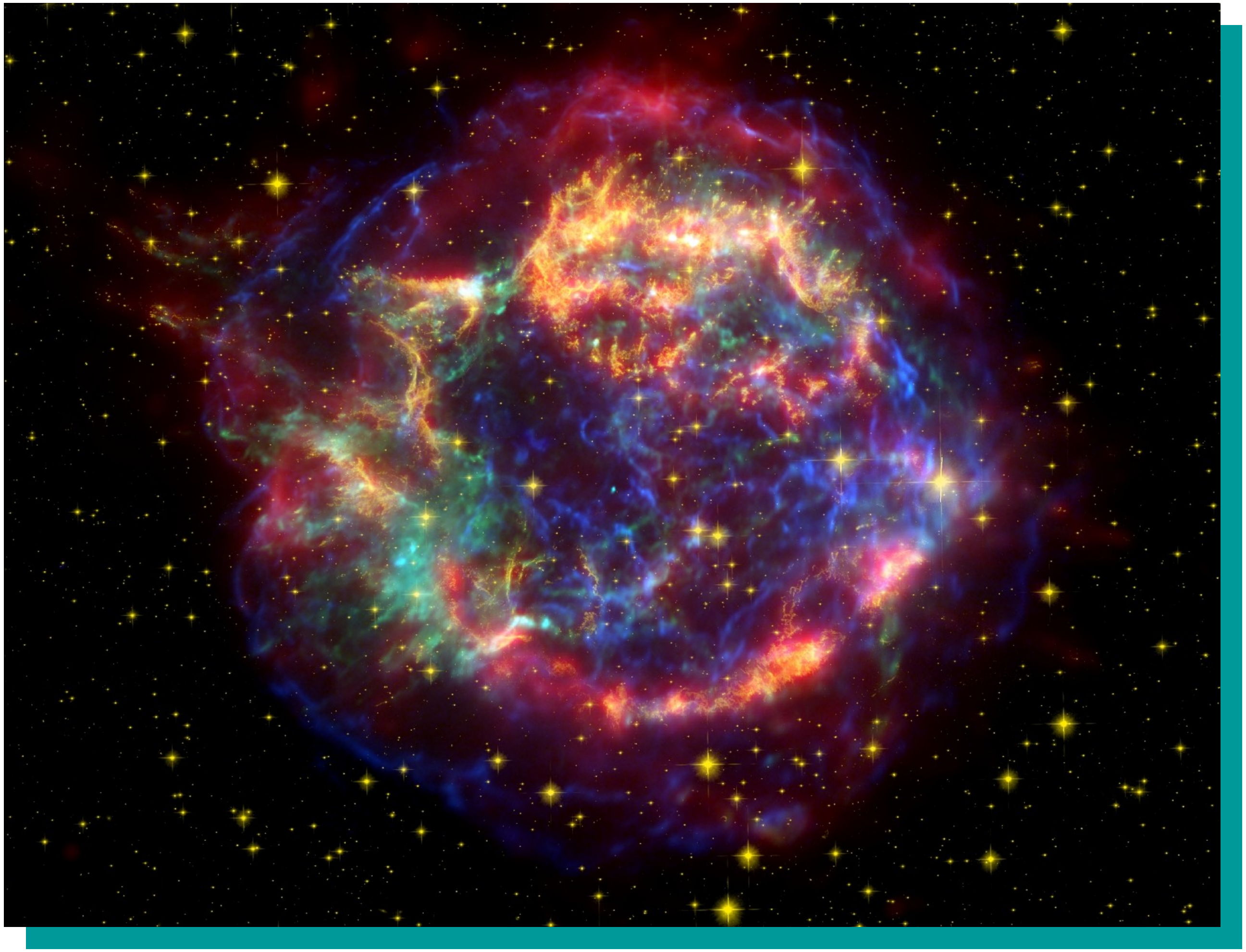
1. The formation of compact objects: stellar winds



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

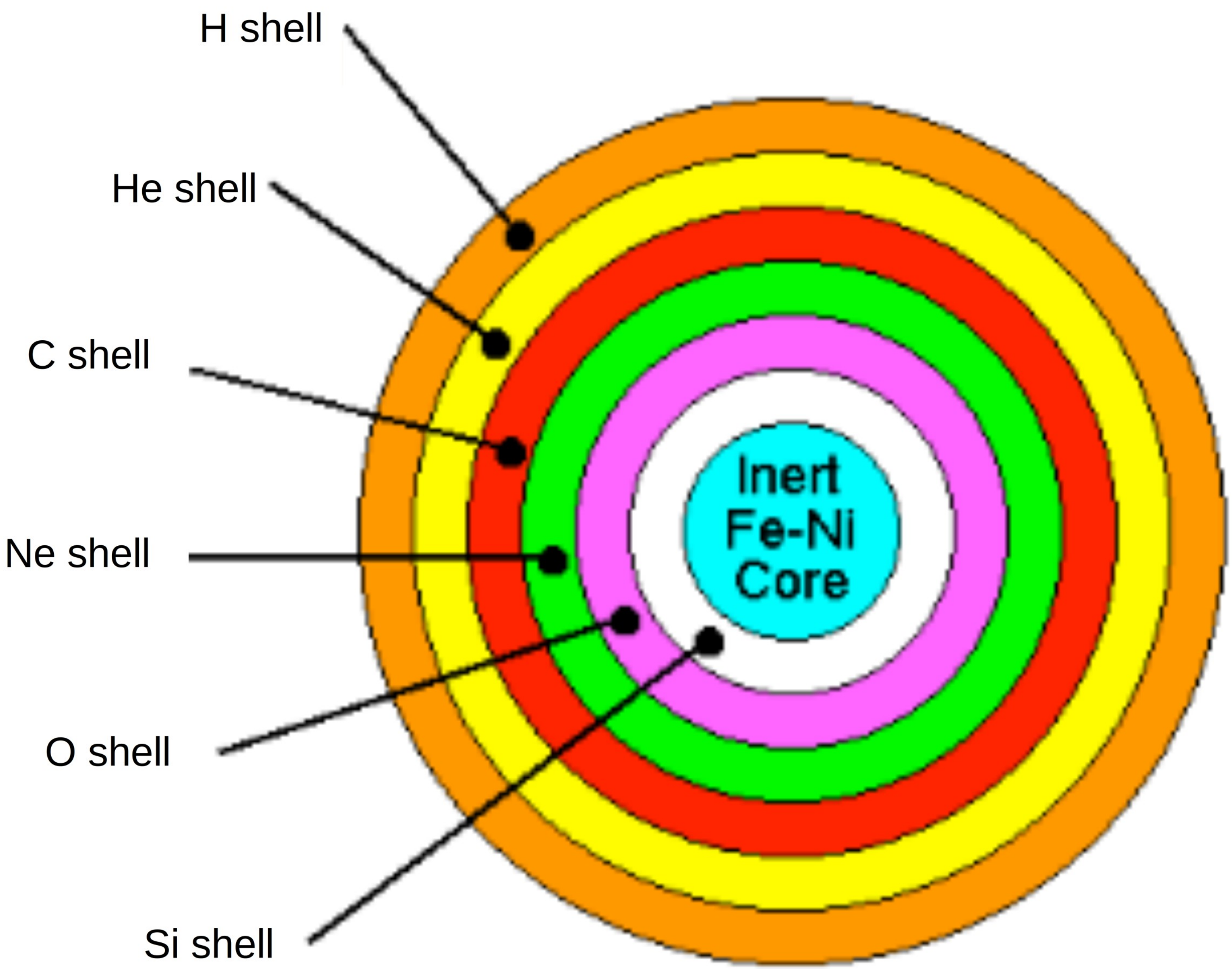
1. The formation of compact objects: supernova

Final mass of a star is very important, because it affects the outcome of a core-collapse (CC) SUPERNOVA



1. The formation of compact objects: supernova

Scheme of nuclear burning in a star



1. The formation of compact objects: supernova

When Fe core forms in a massive (> 8 $M_\odot$) 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 $M_\odot$)
electron + proton capture removes electrons
→ <u>electron pressure decreases</u>

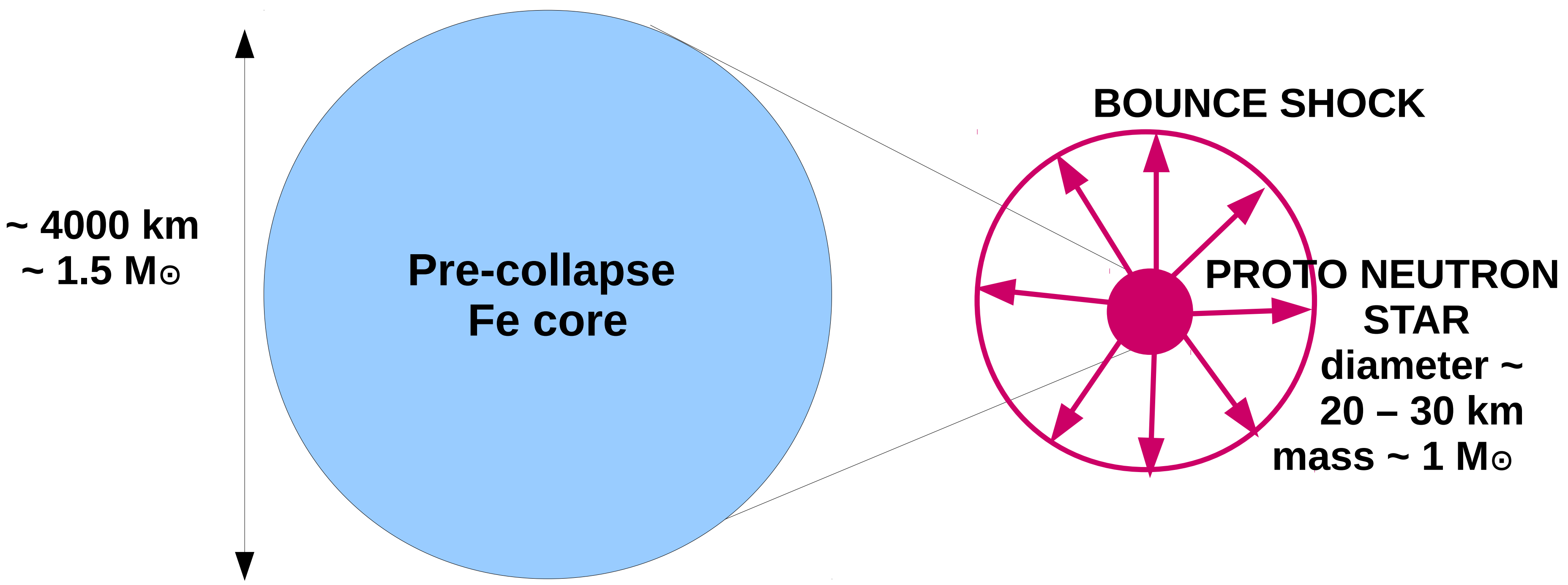
→ COLLAPSE to NUCLEAR DENSITY (~10^{17} kg m^{-3}), where <u>neutron degeneracy pressure</u> stops collapse

→ 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

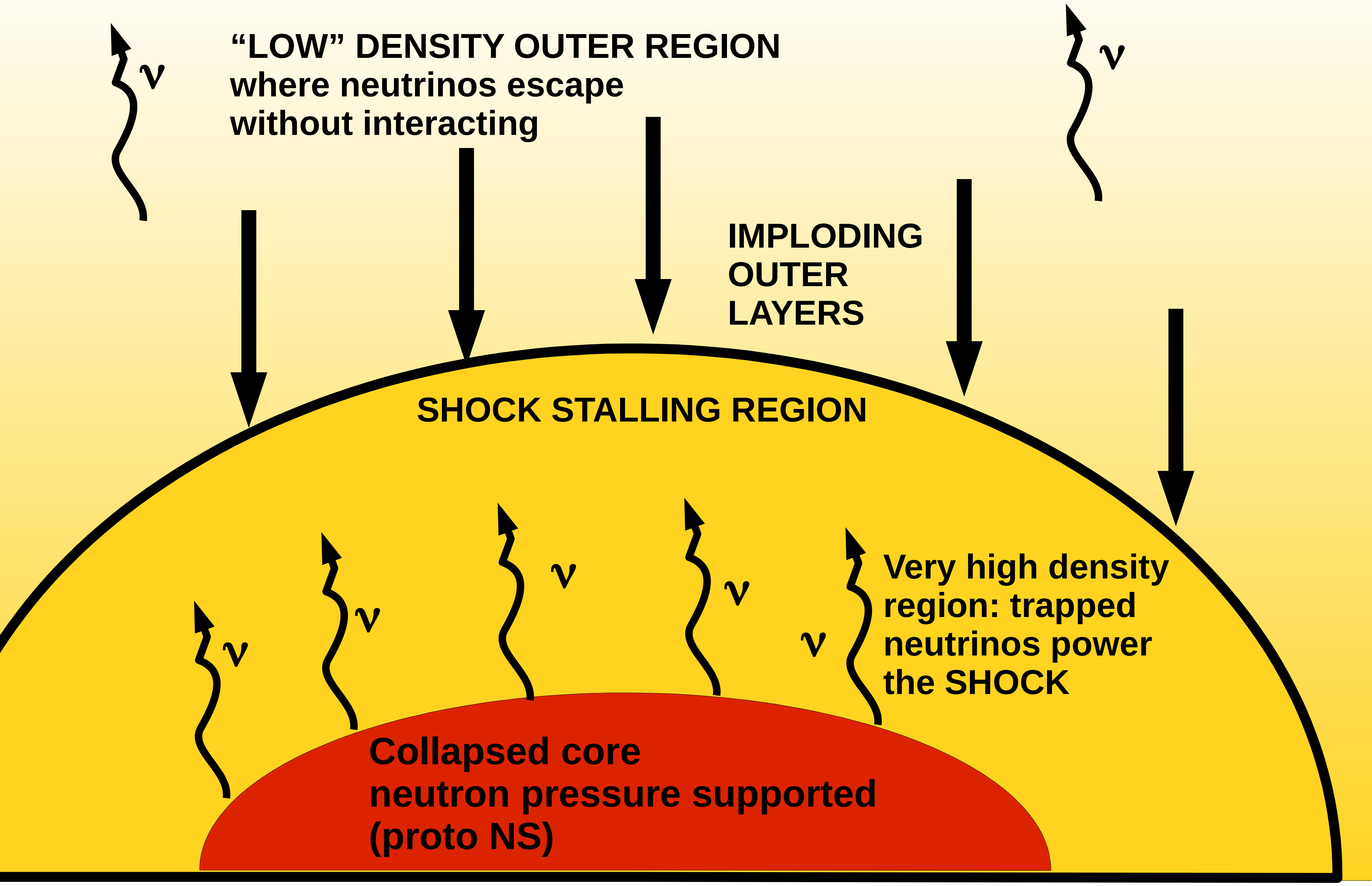
→ **SHOCK MIGHT STALL**
→ **SN FAILS**

WHAT CAN REVIVE THE SHOCK?

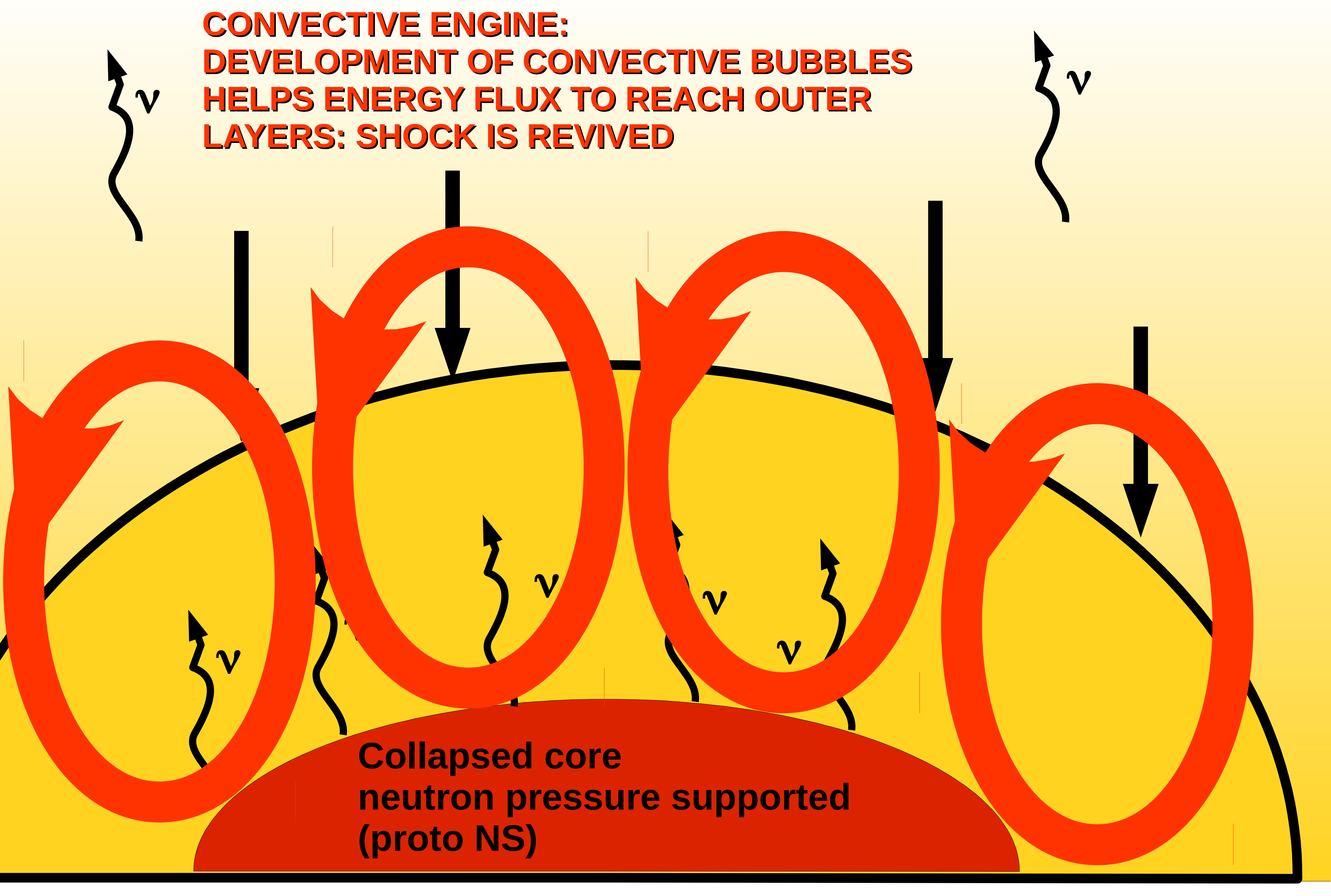
STANDARD MODEL: CONVECTIVE ENGINE

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

1. The formation of compact objects: supernova



1. The formation of compact objects: supernova



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 $M_\odot$ this SN fails and star collapses to a BH

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)

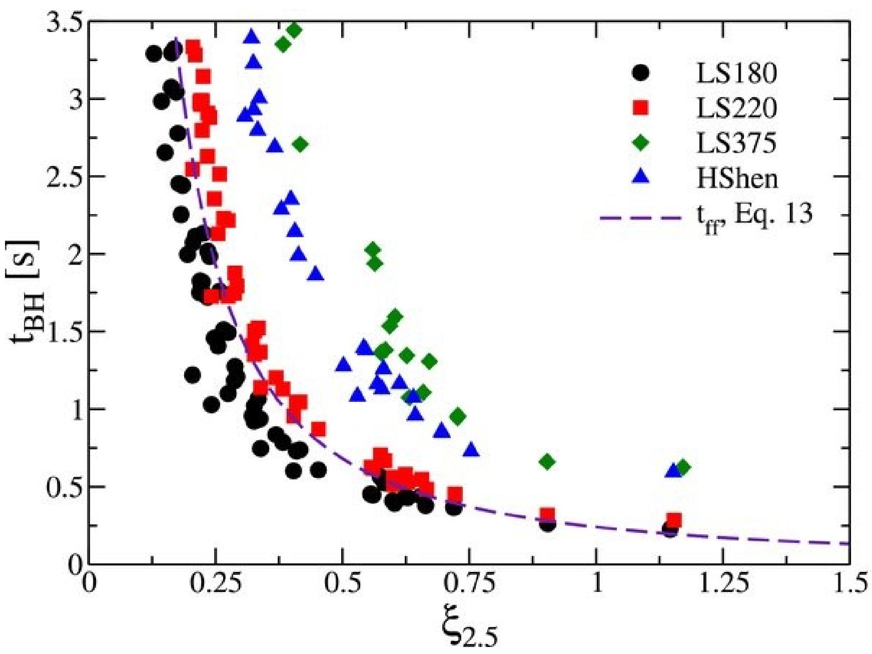


Figure from
O'Connor & Ott 2011

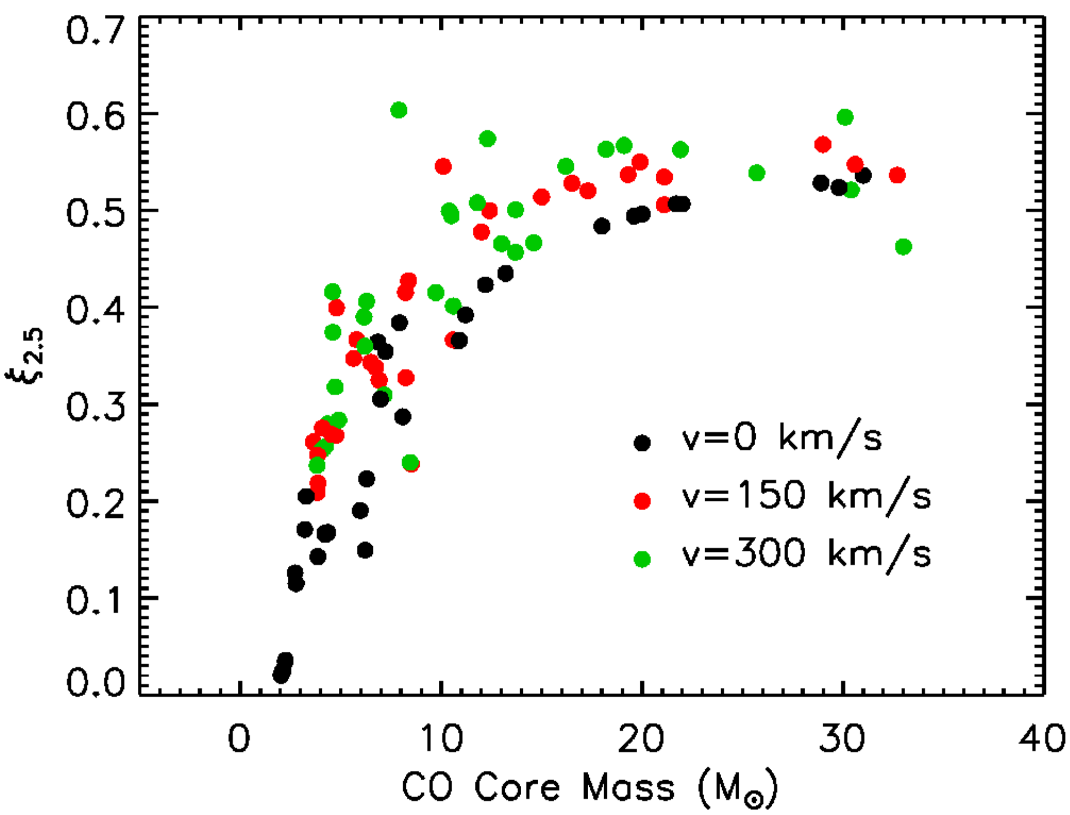
1. The formation of compact objects: supernova

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

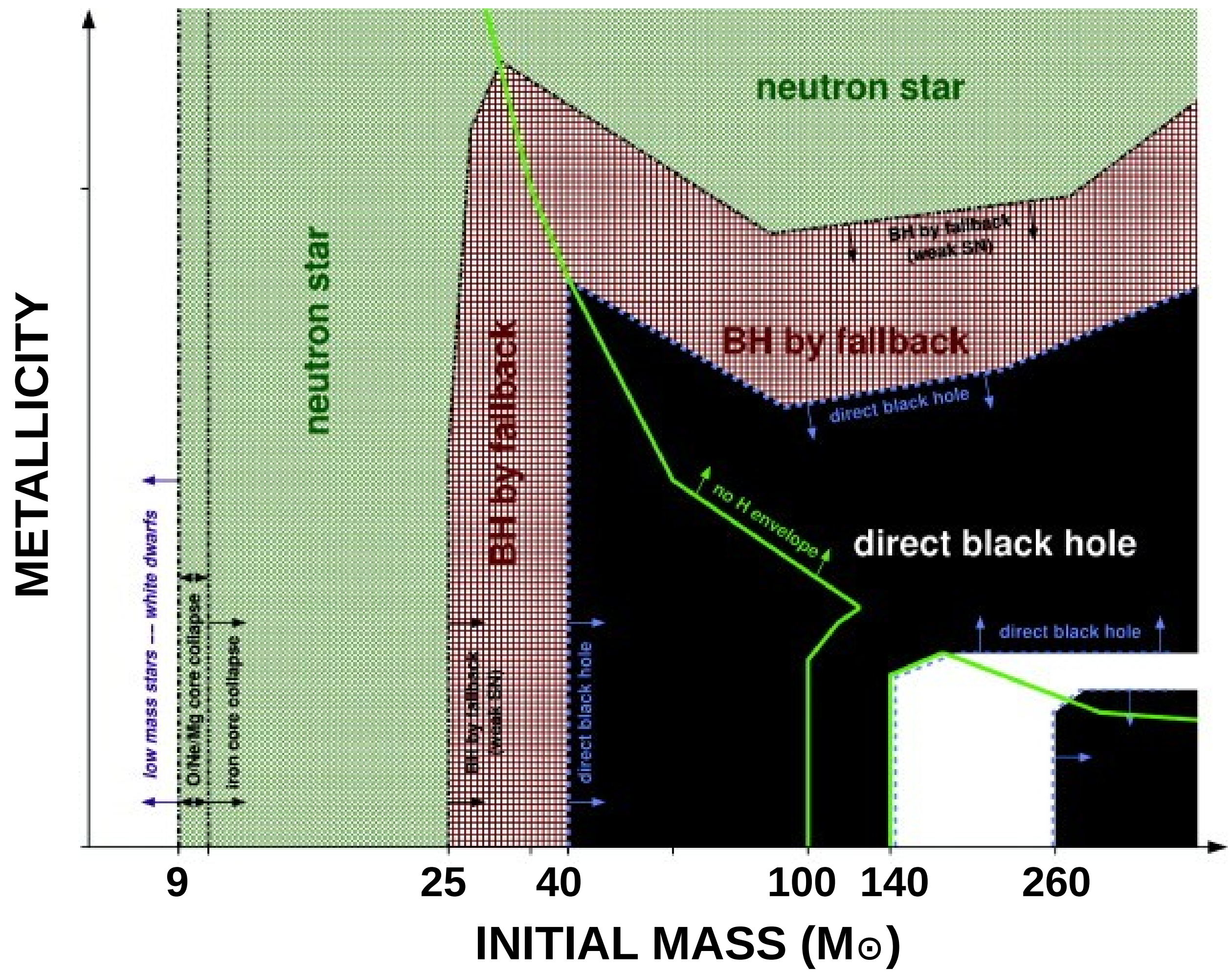


1. The formation of compact objects: supernova

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

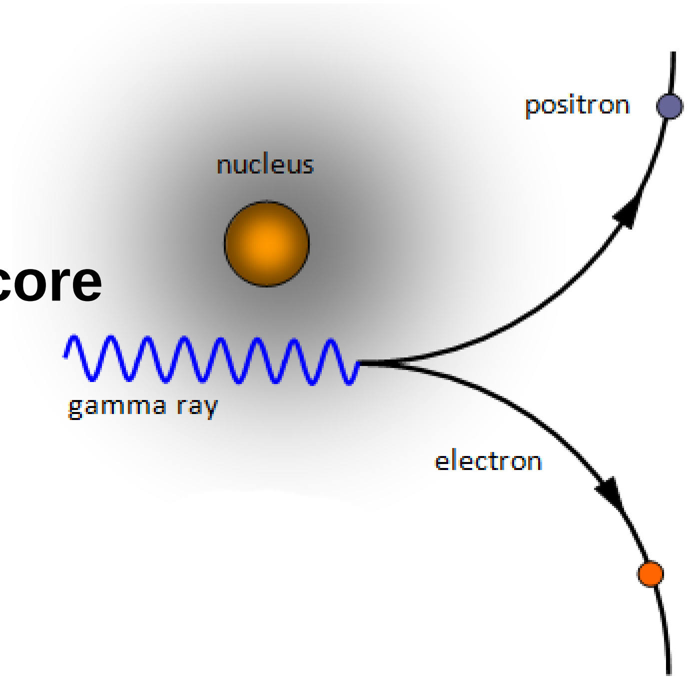
Barely constrained – depends on explosion energy,
angular momentum,
progenitor's mass/metallicity



Heger et al. 2003

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

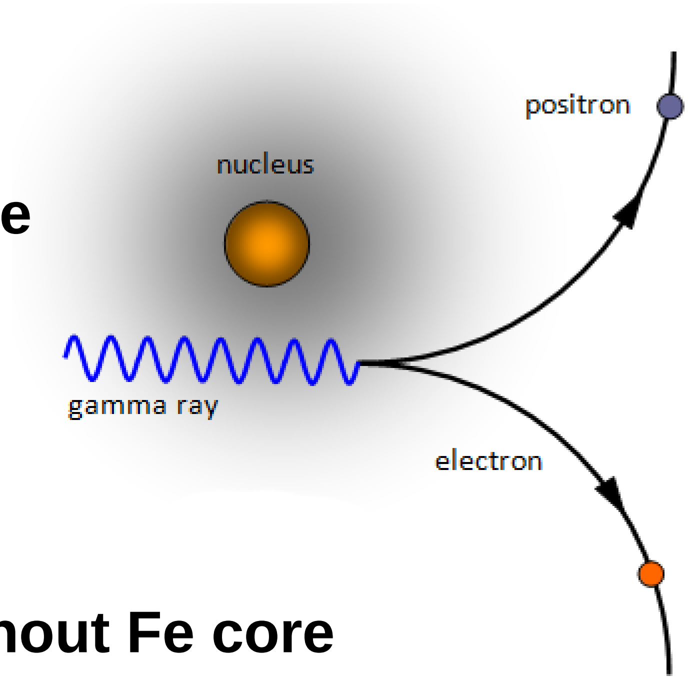
→ an explosion is induced that leaves NO remnant

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

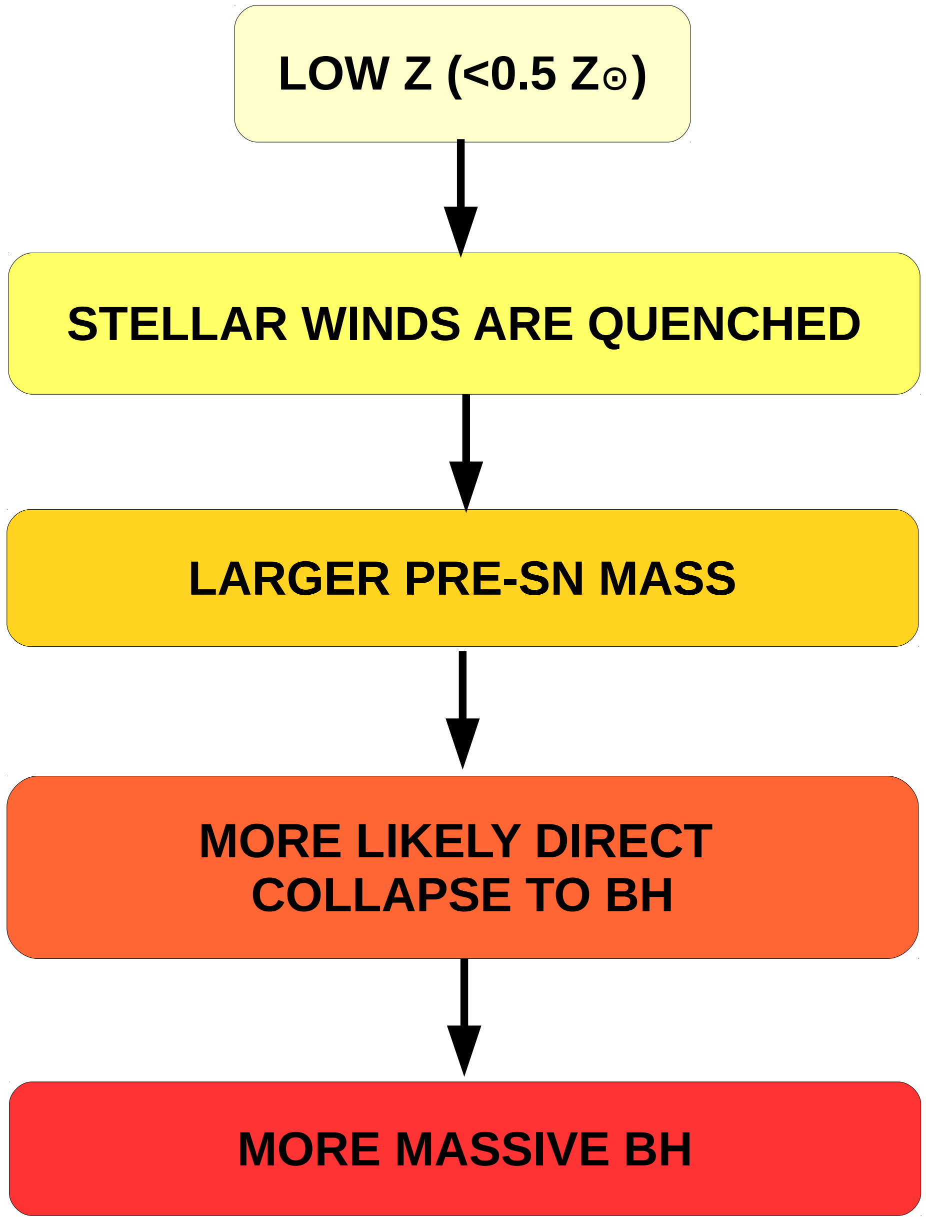
→ star gains equilibrium after one or more oscillations

→ 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):



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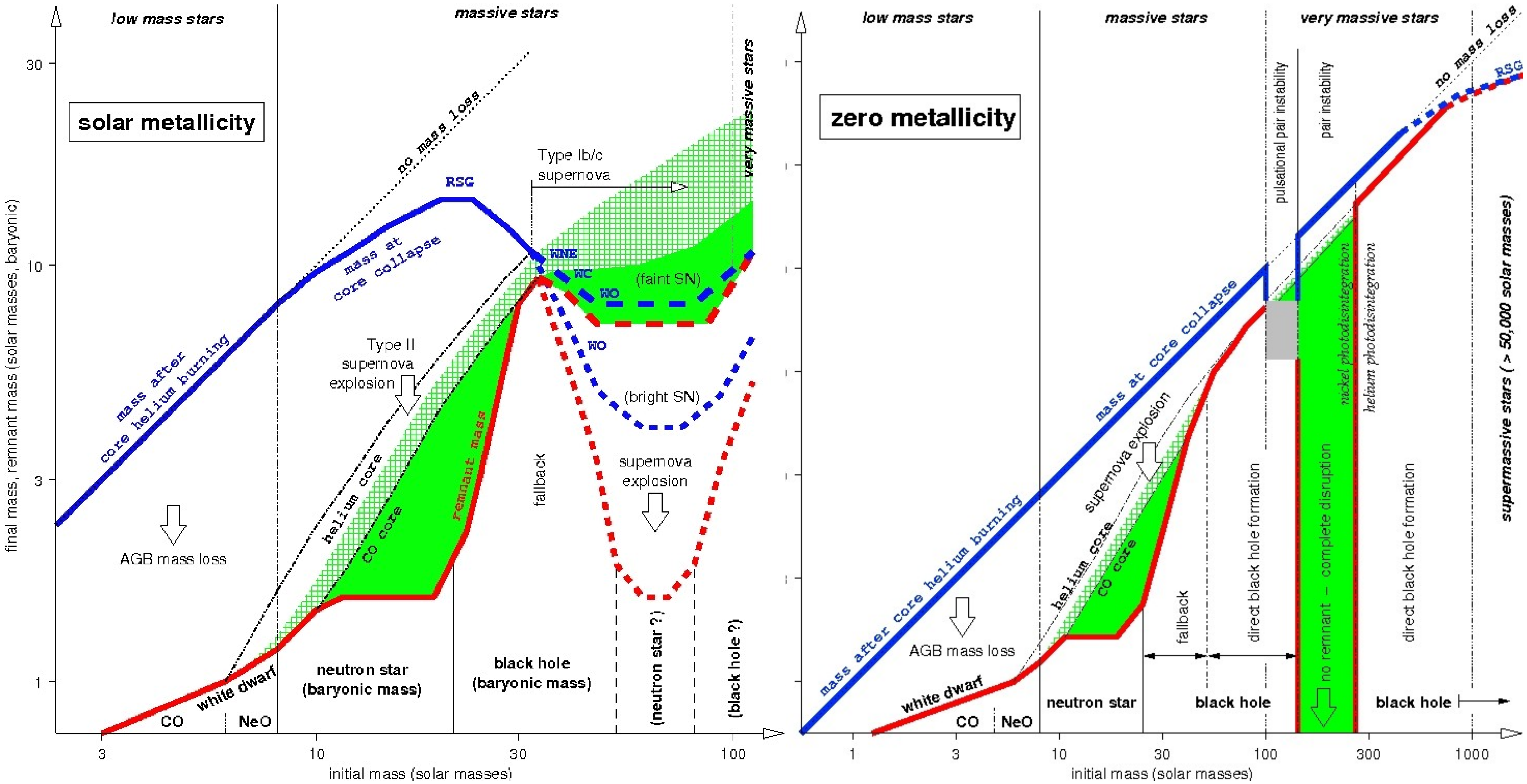
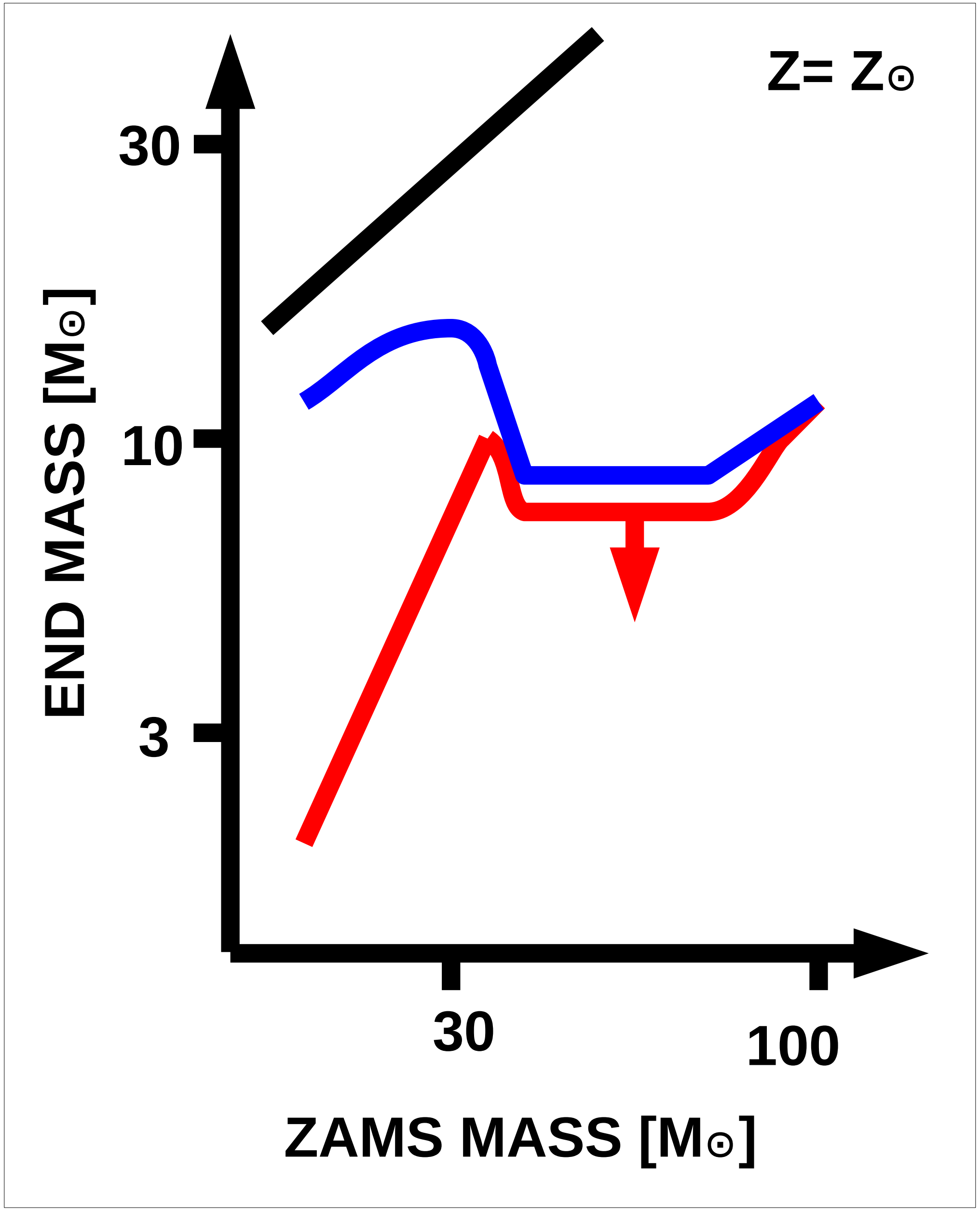
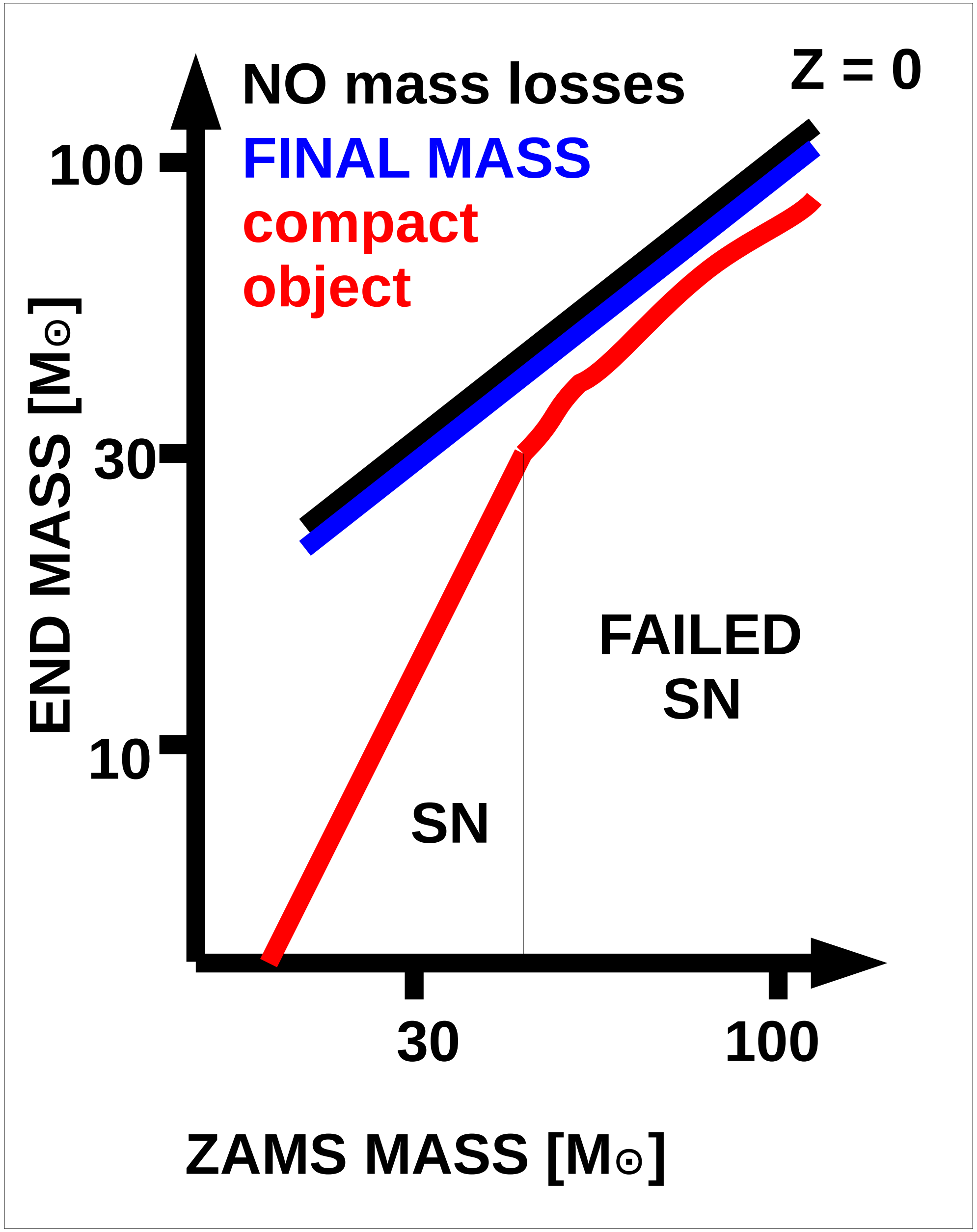


Heger et al. (2003)

1. The formation of compact objects: wrap up



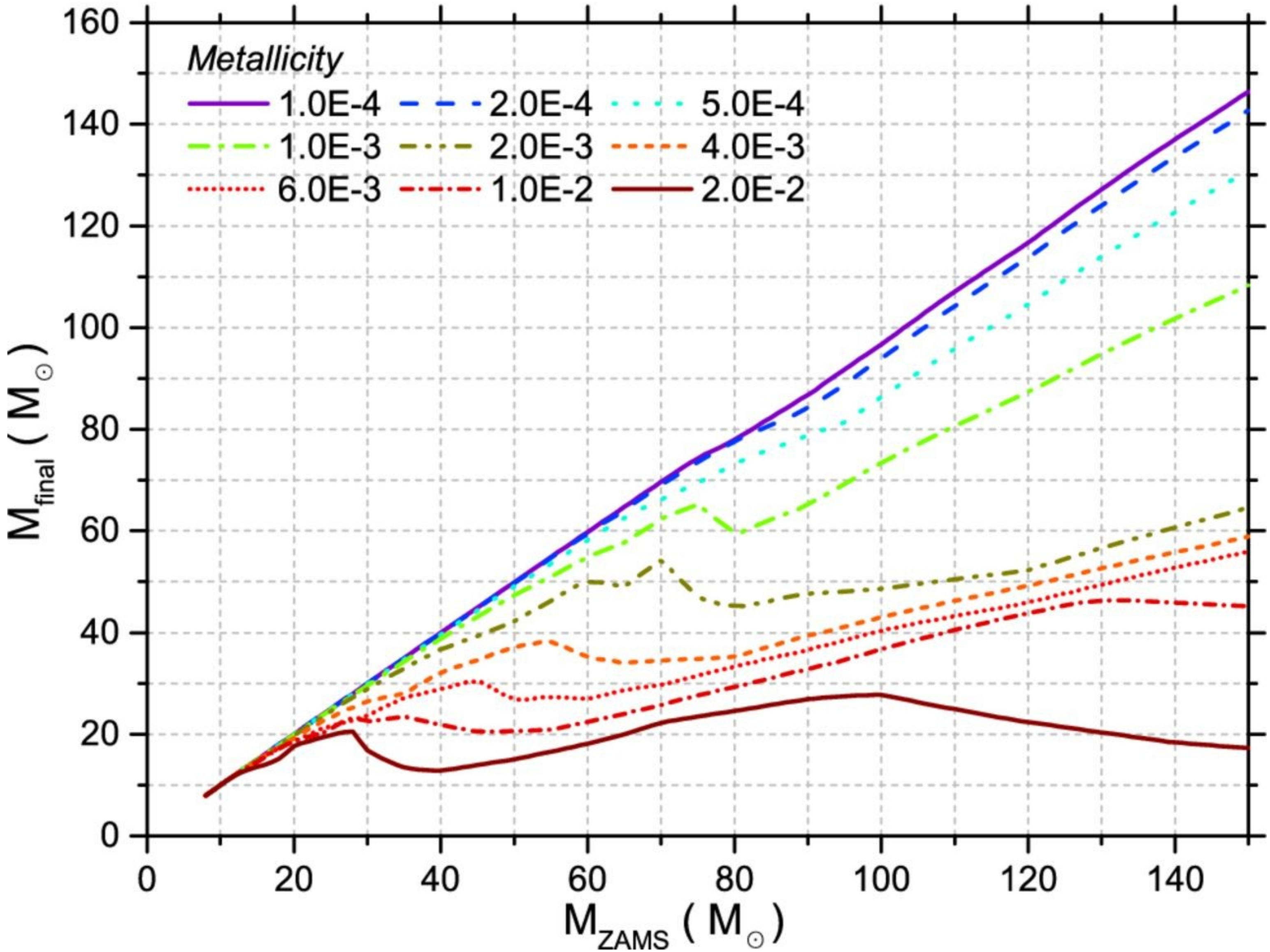


My cartoon from
Heger et al. (2003)

1. The formation of compact objects: wrap up

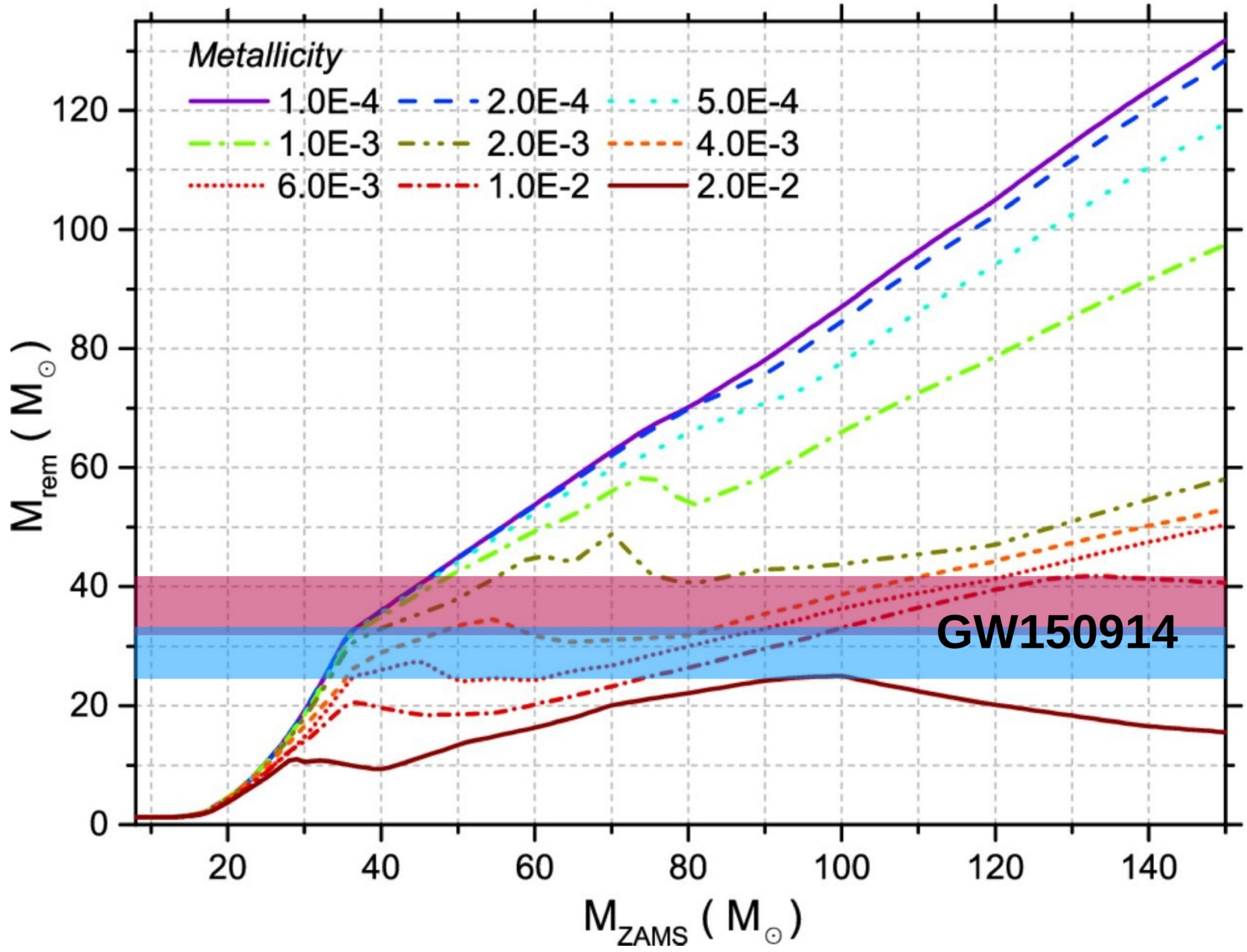
What about intermediate metallicities between 0 and solar?

- 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



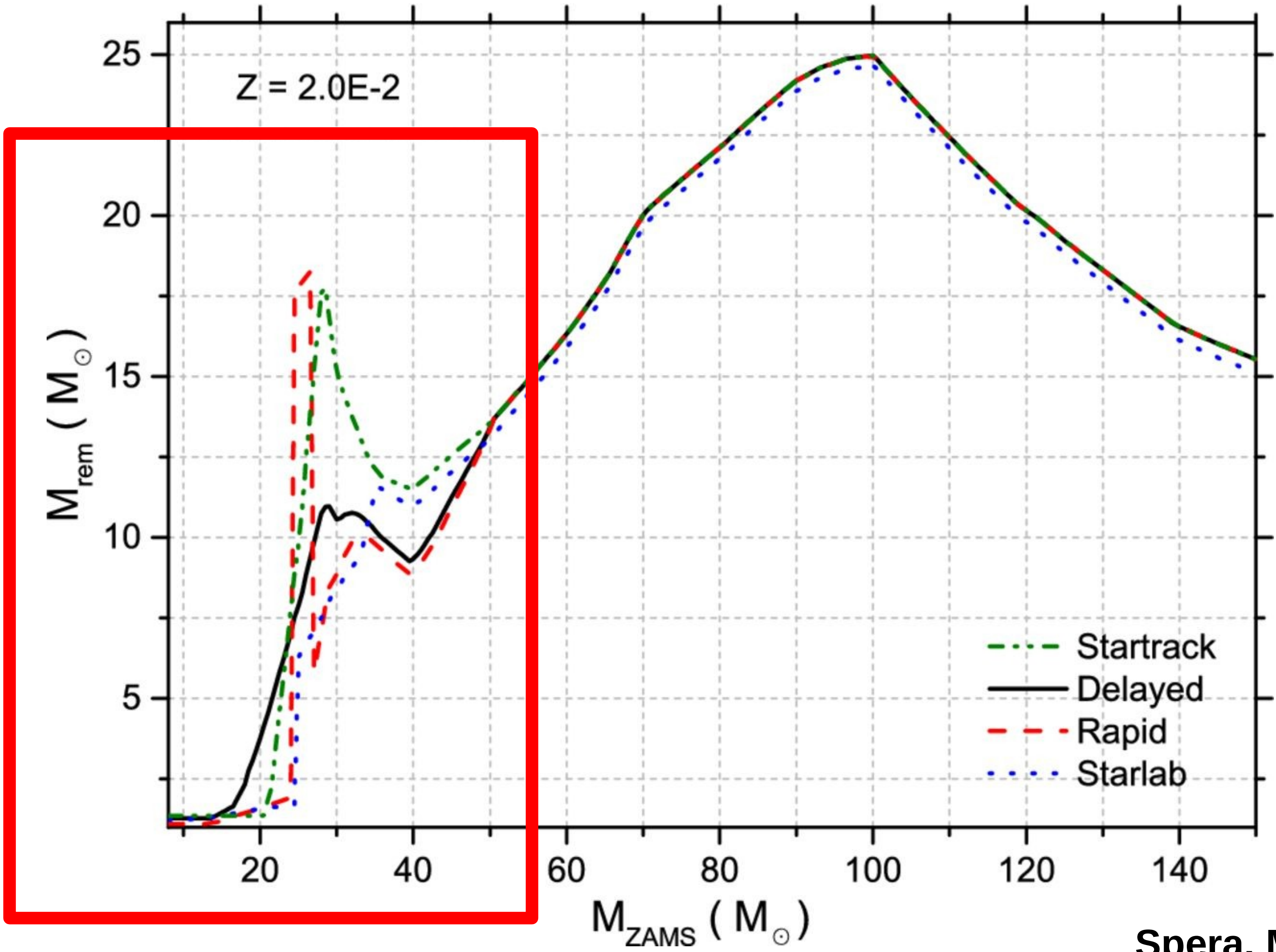
Remnant mass follows same trend as final mass → stellar winds are crucial

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: wrap up

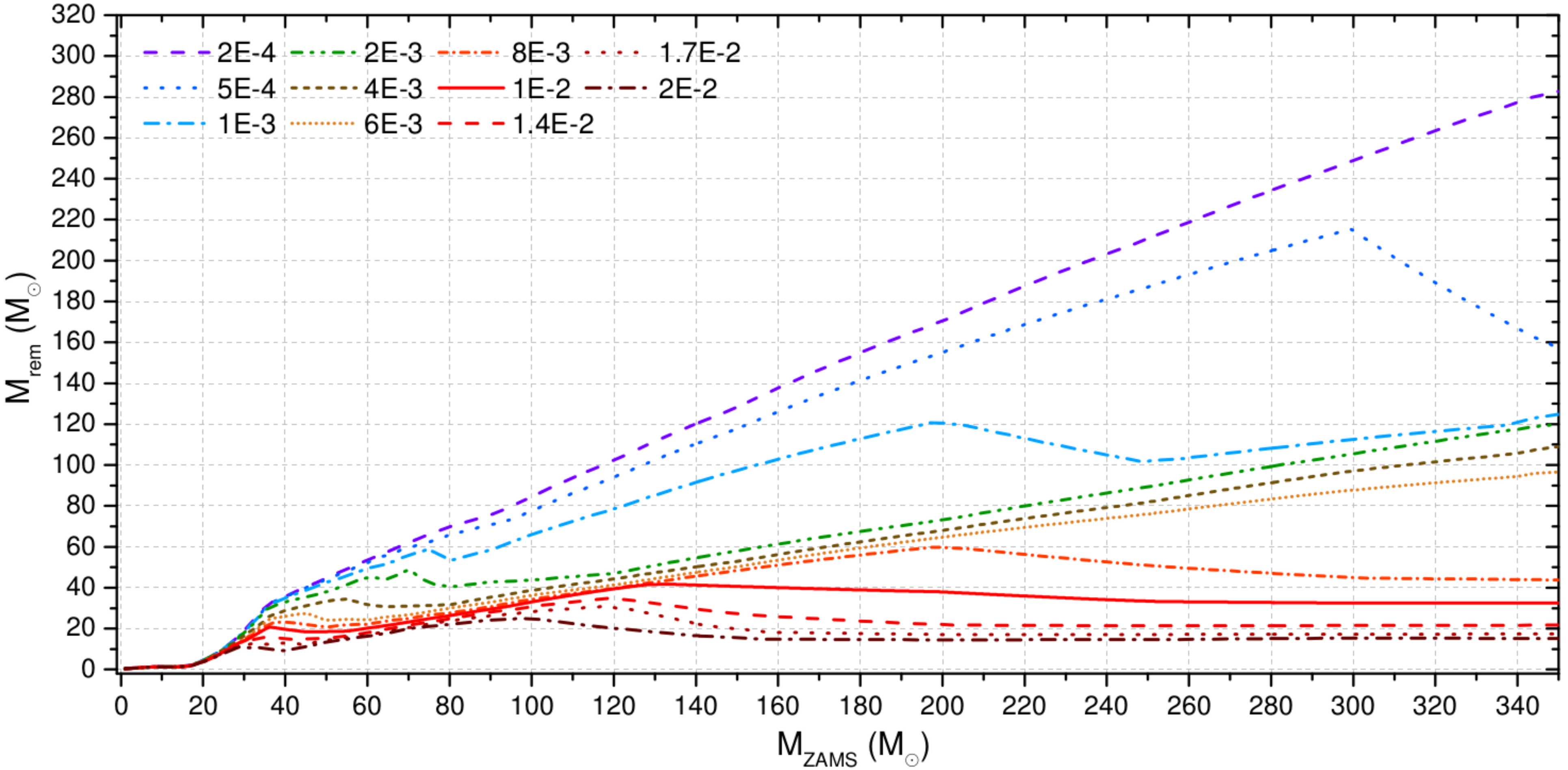
Importance of supernova model for “LOW” STAR MASSES (<40 M⊙)



Spera, MM, Bressan 2015

1. The formation of compact objects: wrap up

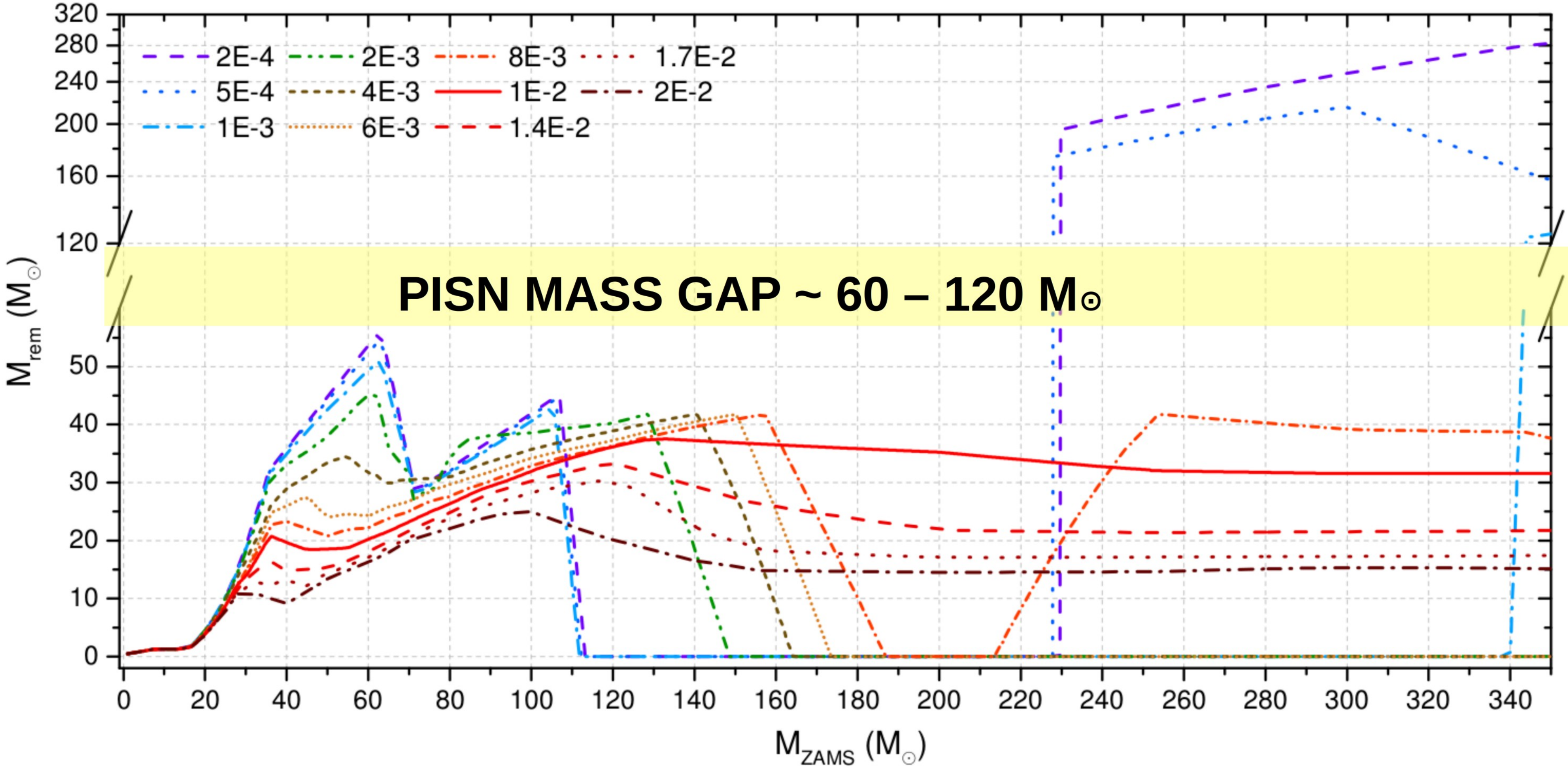
Evolution of very massive stars still uncertain
→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

1. The formation of compact objects: wrap up

Role of pulsational pair-instability and pair-instability supernovae



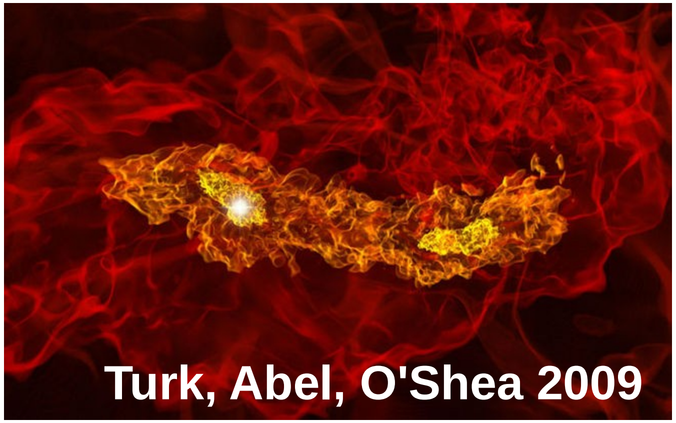
Spera & MM 2017

2. Binaries of compact objects

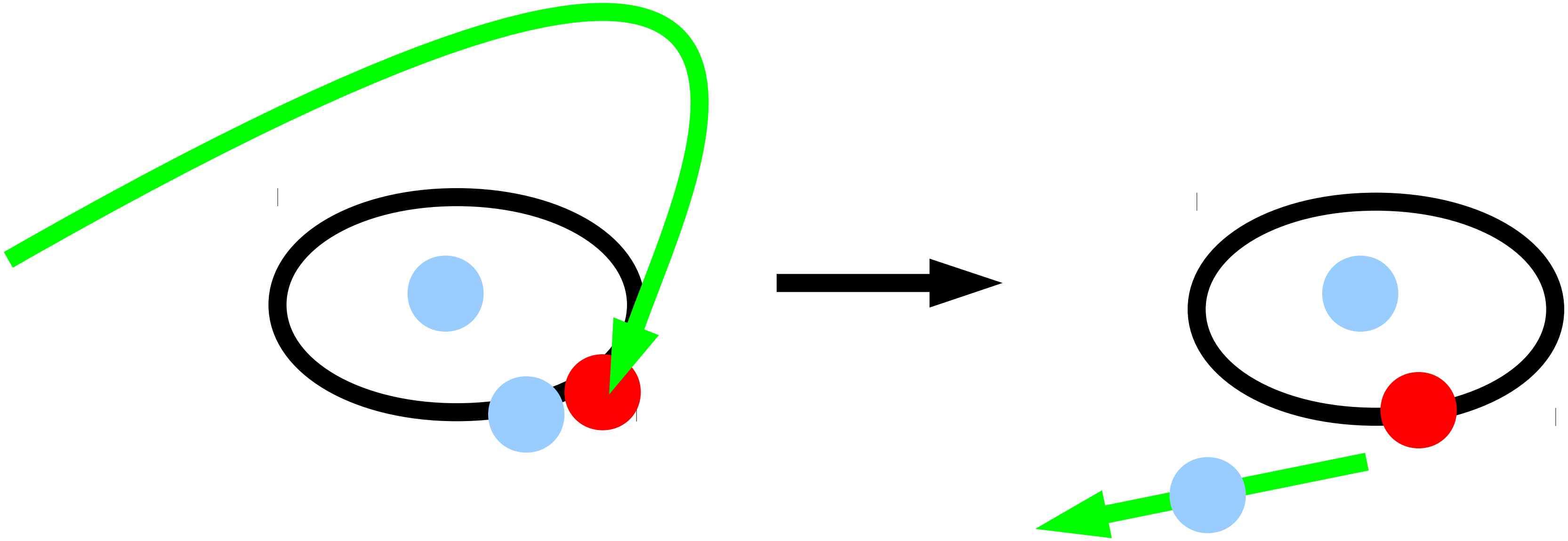
LIGO – Virgo observe compact object BINARIES

How do BH-BH (or BH-NS, NS-NS) binaries form?

1) ISOLATED BINARY



2) DYNAMICALLY FORMED BINARY



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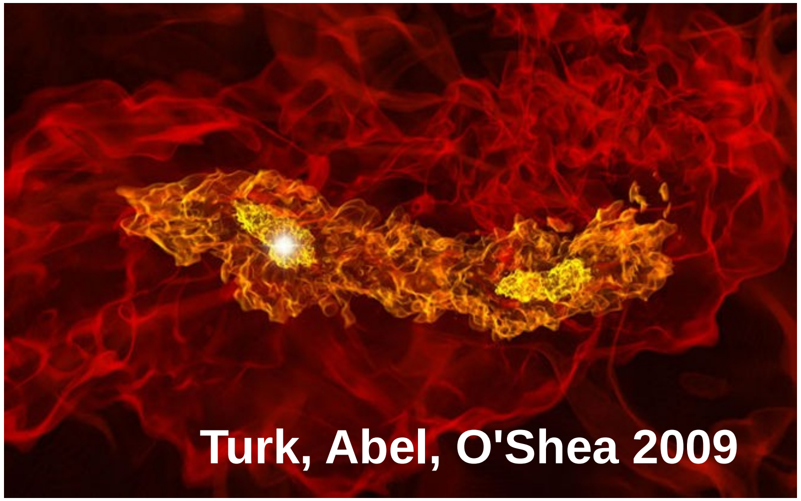


2 stars form from same gas cloud and evolve into 2 BHs or NSs

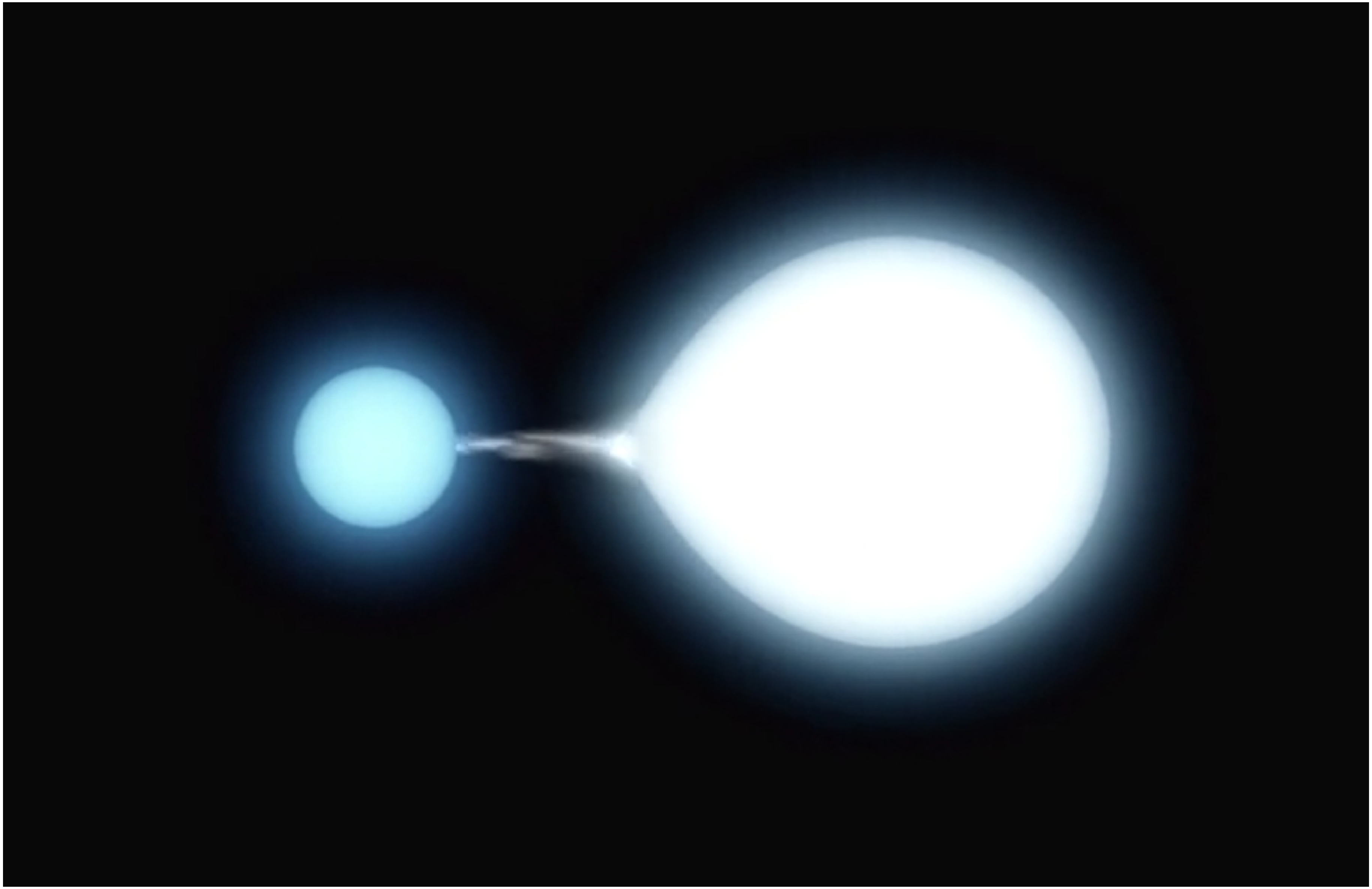
NOT SO EASY:

Many evolutionary processes can affect the binary

e.g. mass transfer, common envelope, SN kicks

Studied via POPULATION SYNTHESIS CODES:
integration of ISOLATED binaries
(Starlab, Portegies Zwart+ 2001; MM+2013; BSE, Hurley+ 2002; StarTrack, Belczynski+ 2010; SEVN, Spera+ 2015)

2. Binaries of compact objects



Movie1 (credits: ESO)

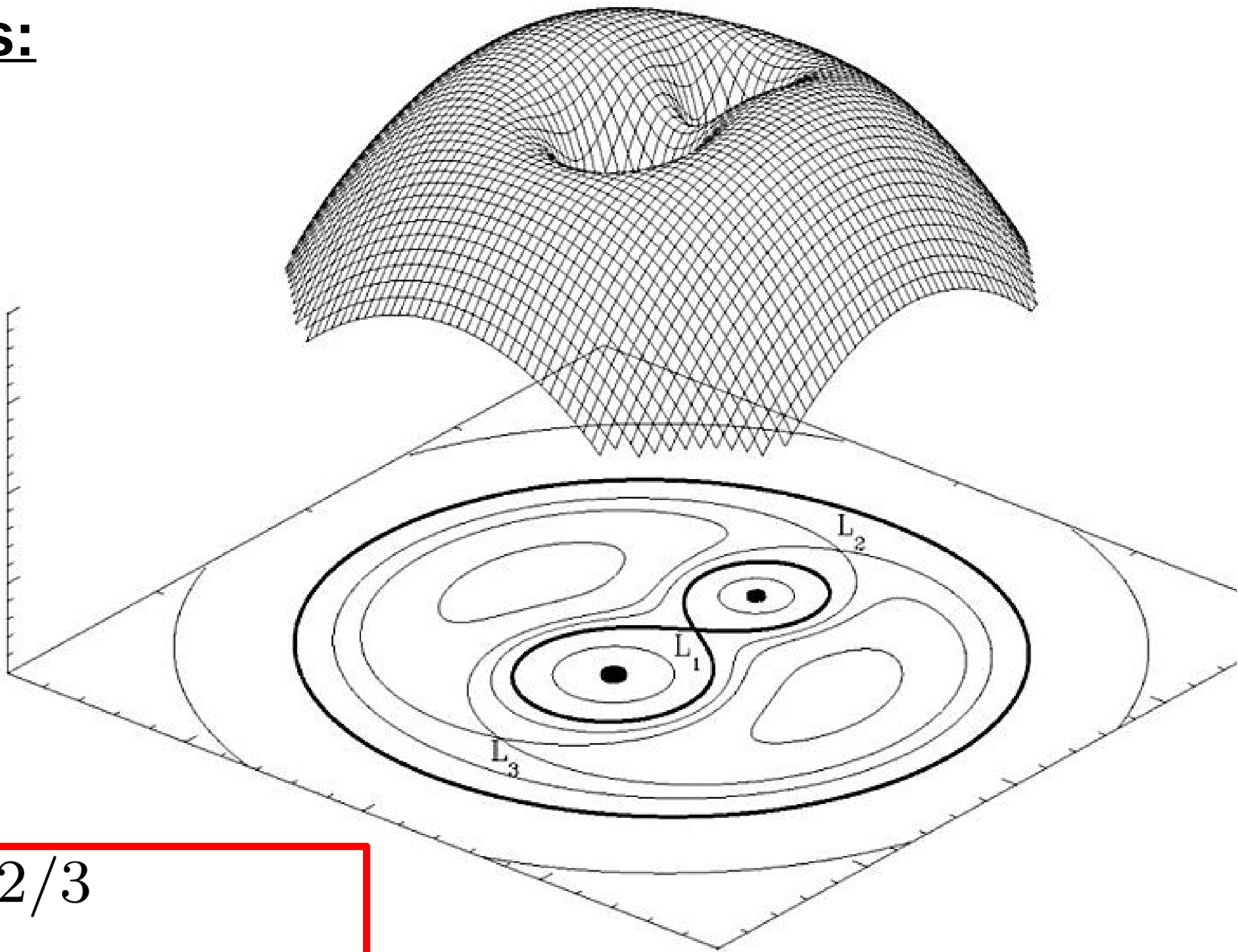
2. Binaries of compact objects

Mass transfer in binaries:

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



By Marc van der Sluys

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

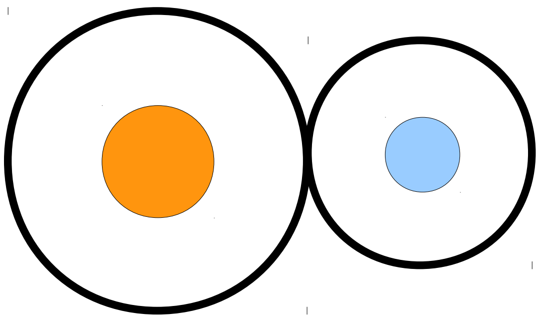
where a = **semi-major axis**

$q = M_1/M_2$

2. Binaries of 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

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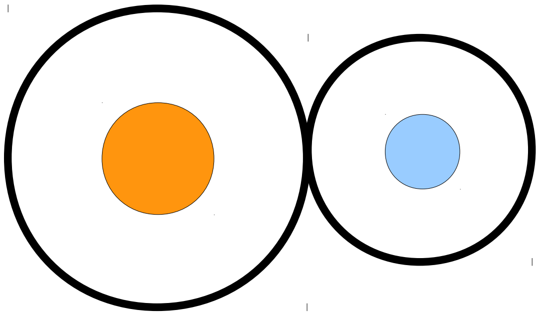

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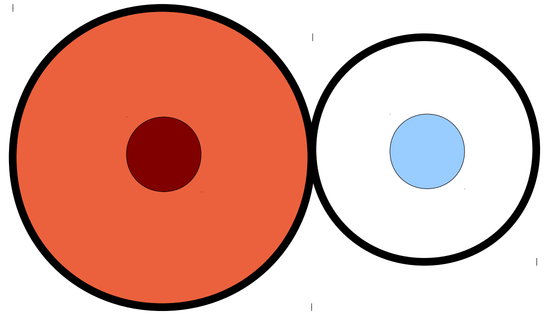
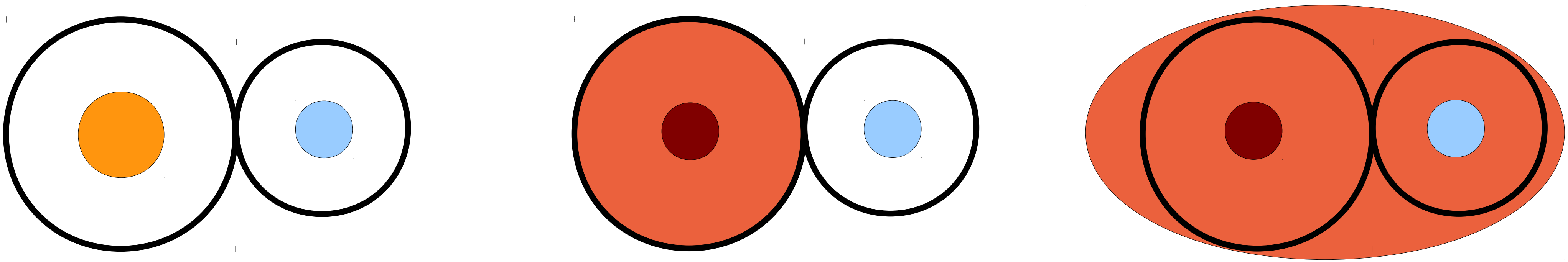


The first one evolves out of MS expands and start mass transfer onto the second

2. Binaries of compact objects

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

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. Binaries of compact objects

Common envelope in binaries:

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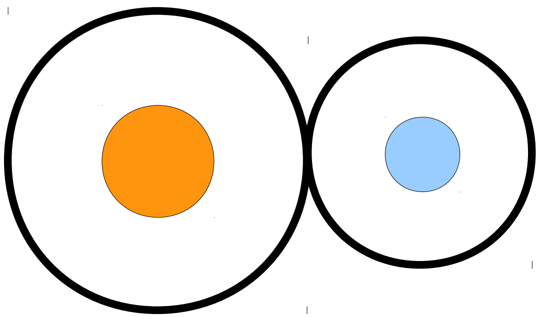
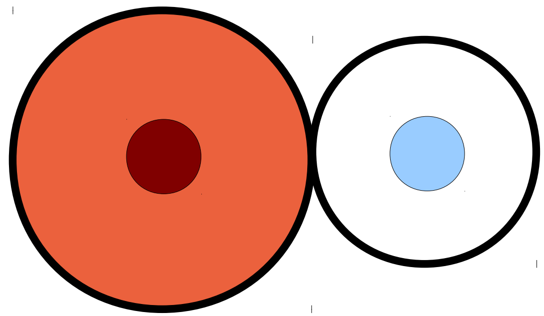


Two massive stars initially underfilling Roche lobe



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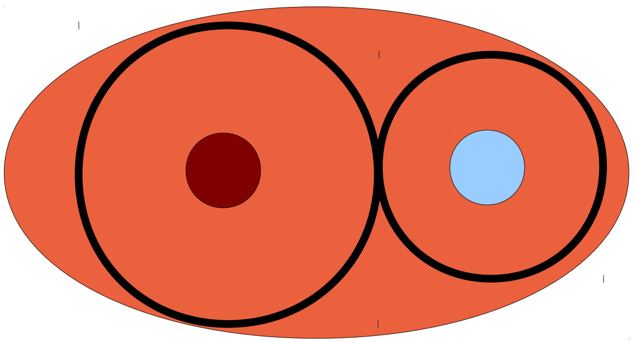
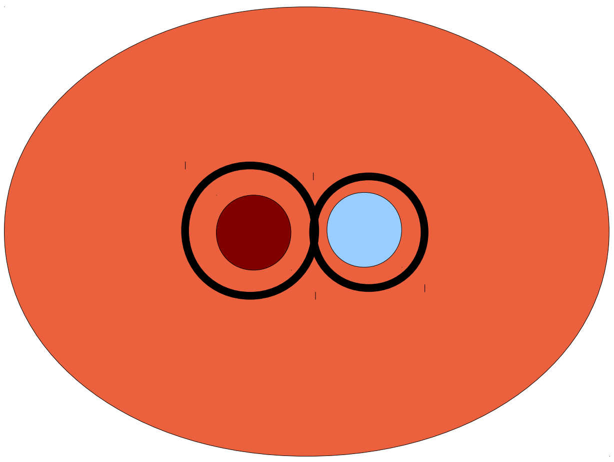


Mass transfer becomes unstable: CE phase

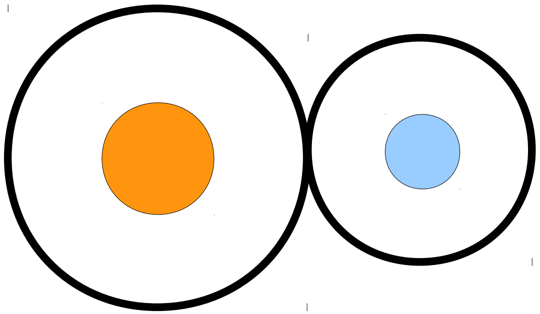


Drag by the envelope leads the two cores to spiral in

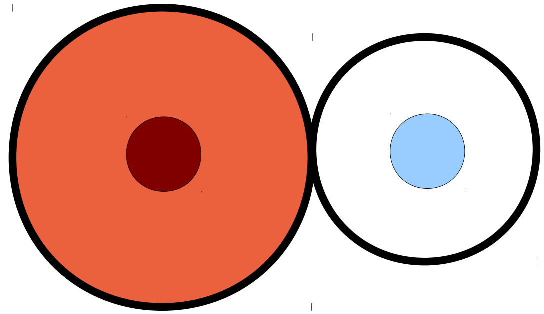
2. Binaries of compact objects

Common envelope in binaries:

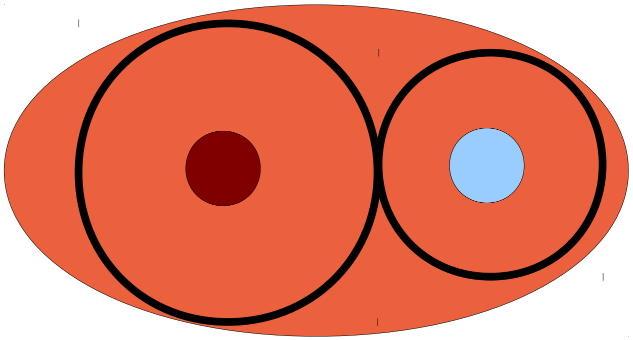
If mass transfer becomes unstable (e.g. both stars fill Roche lobe), COMMON ENVELOPE (CE) phase = Two stars, one envelope



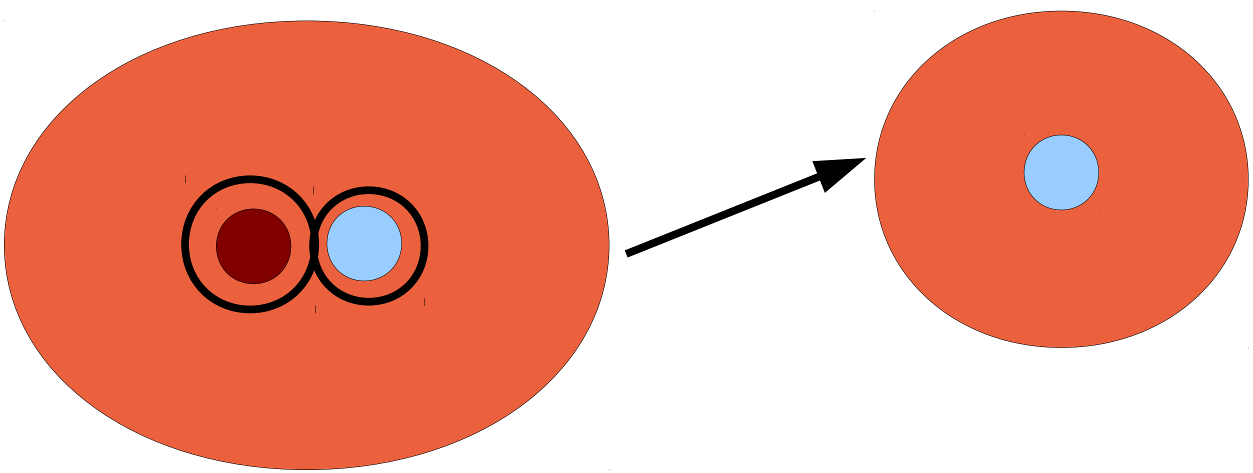
Two massive stars initially underfilling Roche lobe



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



Mass transfer becomes unstable: CE phase



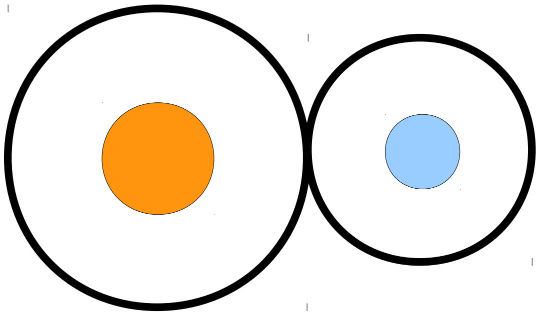
The two cores spiral in till they merge becoming a single star

Drag by the envelope leads the two cores to spiral in

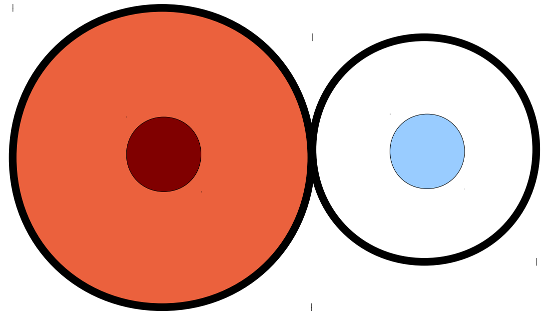
2. Binaries of compact objects

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



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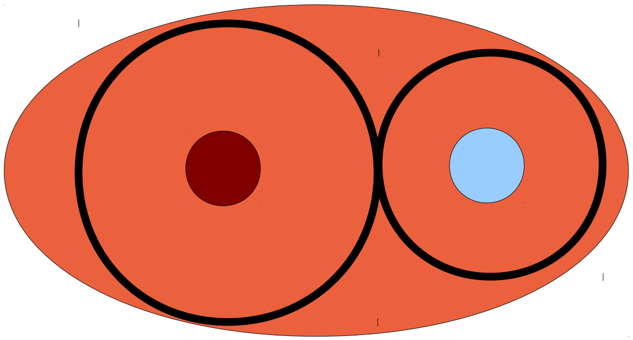
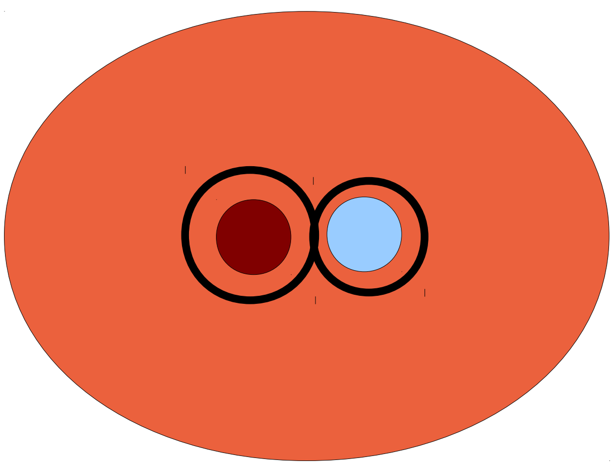
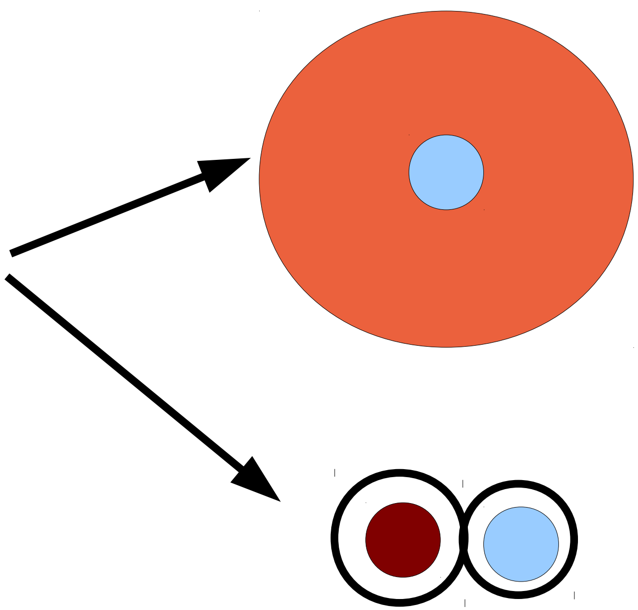


Mass transfer becomes unstable: CE phase



Drag by the envelope leads the two cores to spiral in



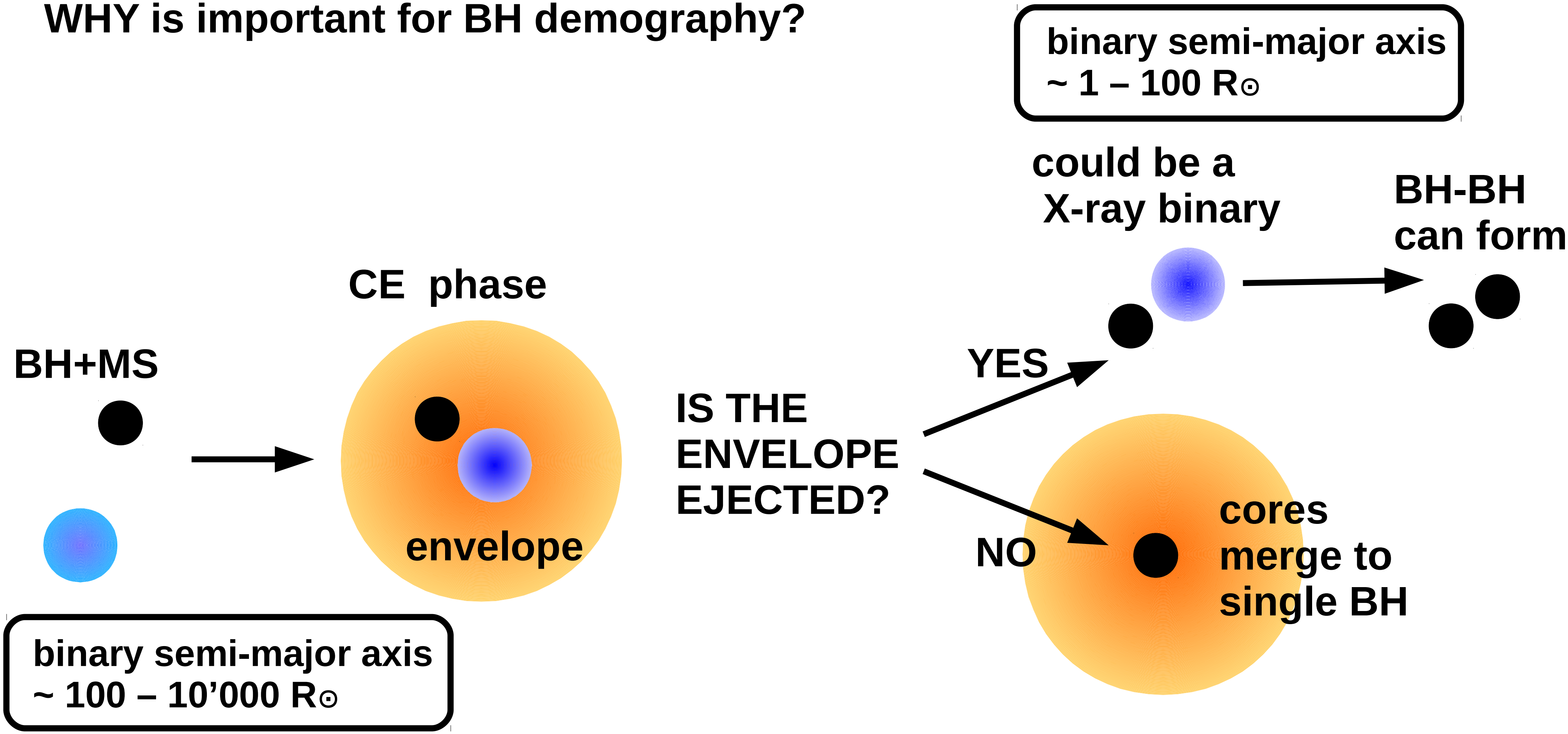
The two cores spiral in till they merge becoming a single star

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

2. Binaries of compact objects

Common envelope in binaries:

WHY is important for BH demography?



2. Binaries of 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

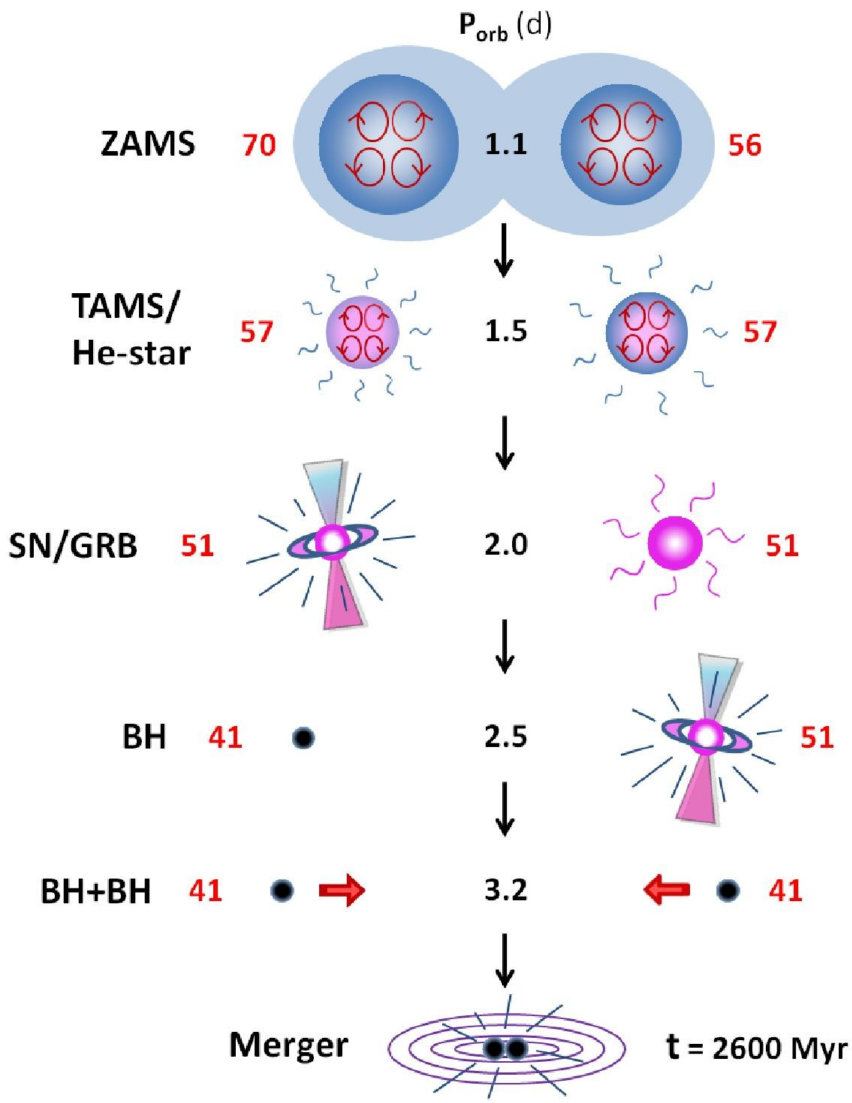
→ close binaries avoid common envelope and premature merger

To be chemically homogeneous, stars need to ROTATE fast

2. Binaries of 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 $M_\odot$ increasing with decreasing metallicity (no low-mass BHs!)**

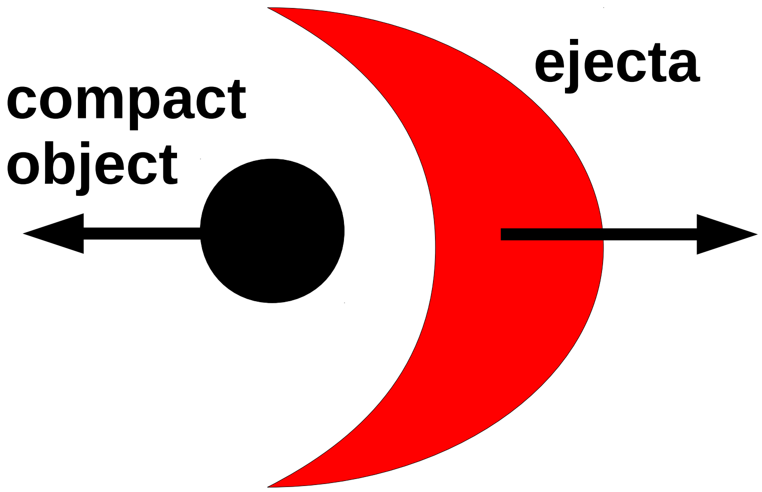
*** aligned spins unless SN reset them**

2. Binaries of 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**

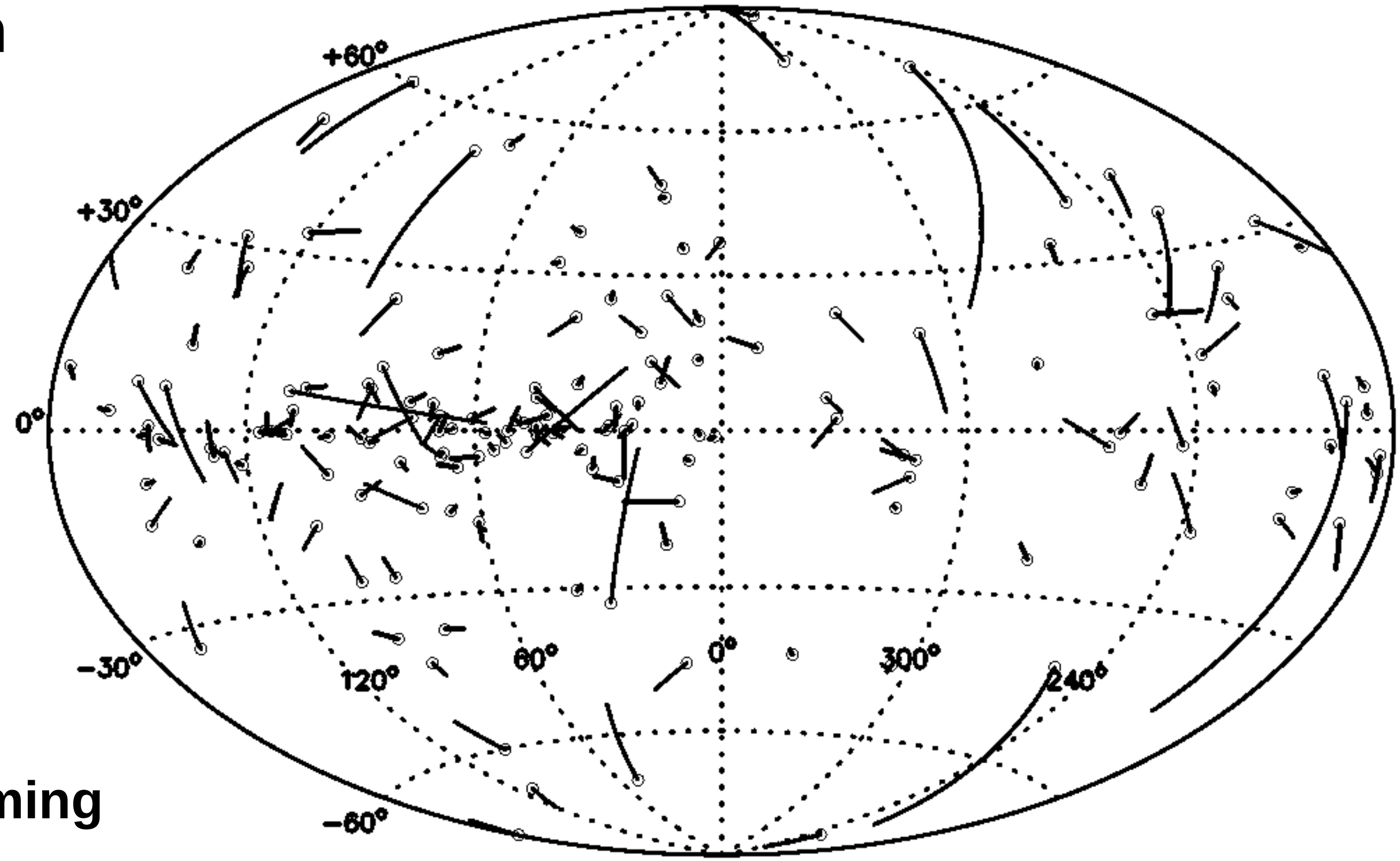
- **symmetric mass loss in a binary: breaks the binary only if pre-SN mass > companion mass (Blaauw mechanism, Blaauw 1961)**

2. Binaries of 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

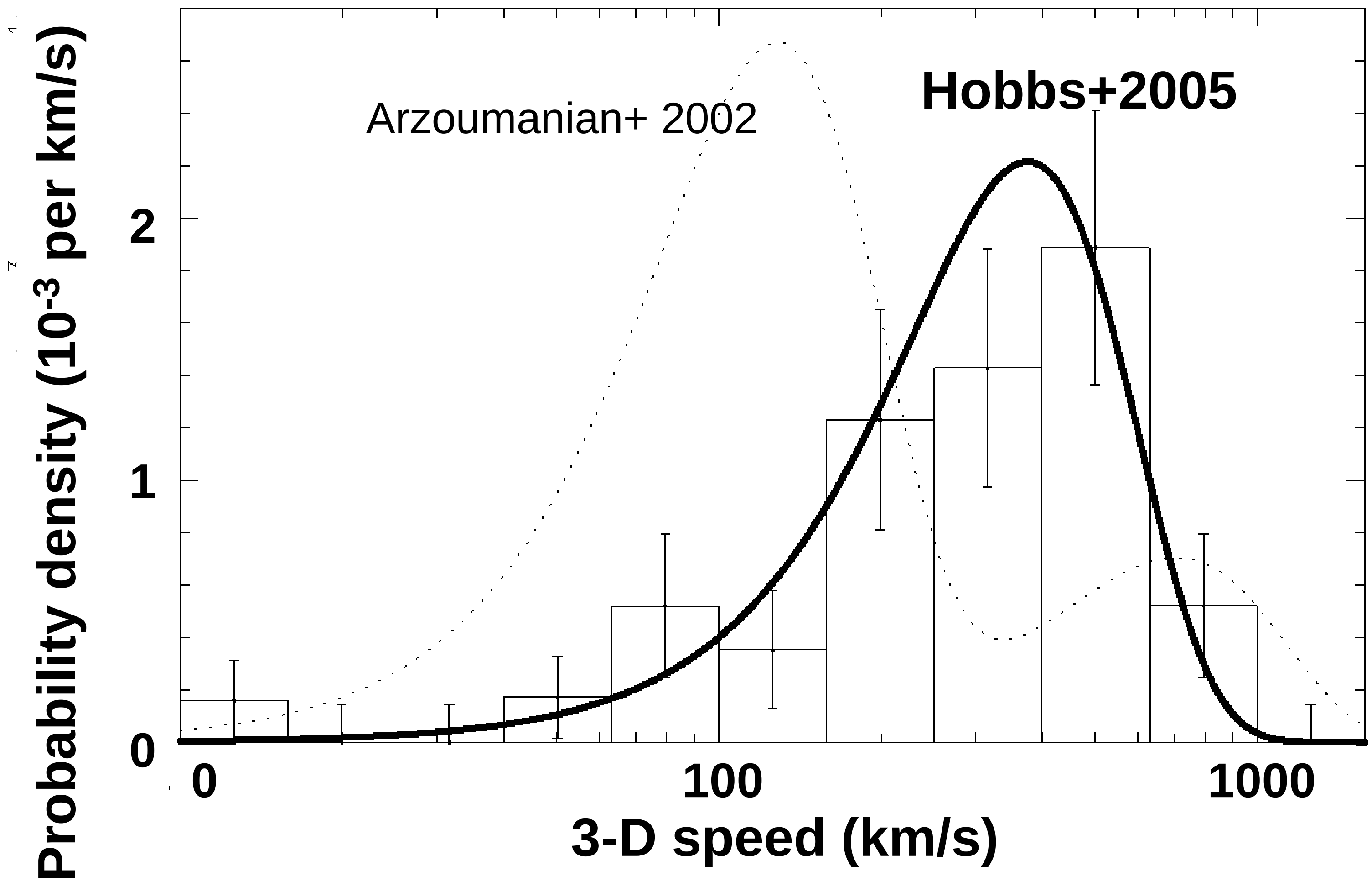
The track is its motion for the last 1 Myr assuming no radial velocity.

2. Binaries of 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. Binaries of 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

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

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

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

2. Binaries of compact objects

Isolated binary evolution summary:

* possible Roche lobe

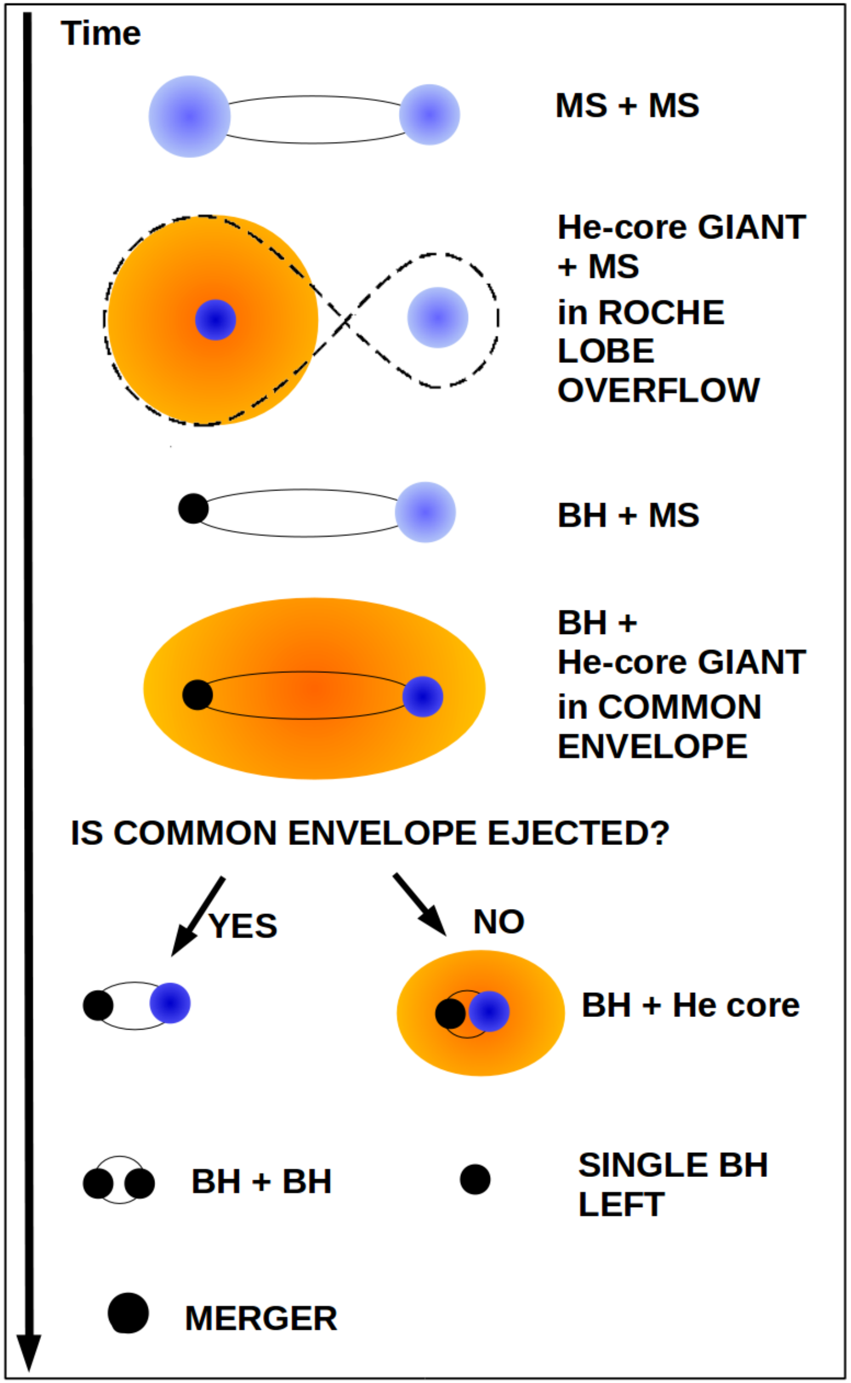
* 1st BH formation

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

* If binary survives common envelope, formation of second BH

* BH – BH merger

cartoon from MM2018

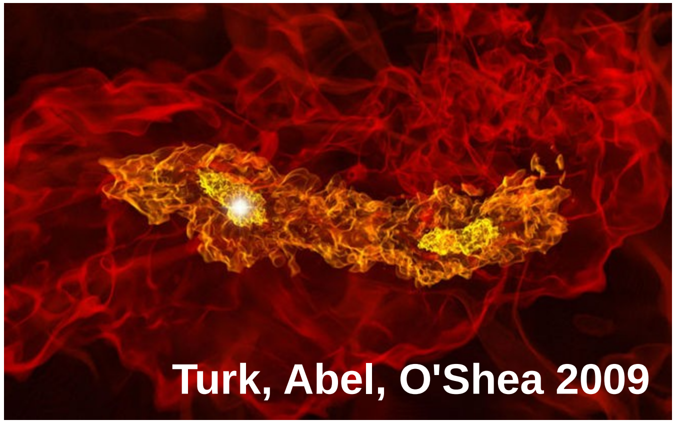


2. Binaries of compact objects

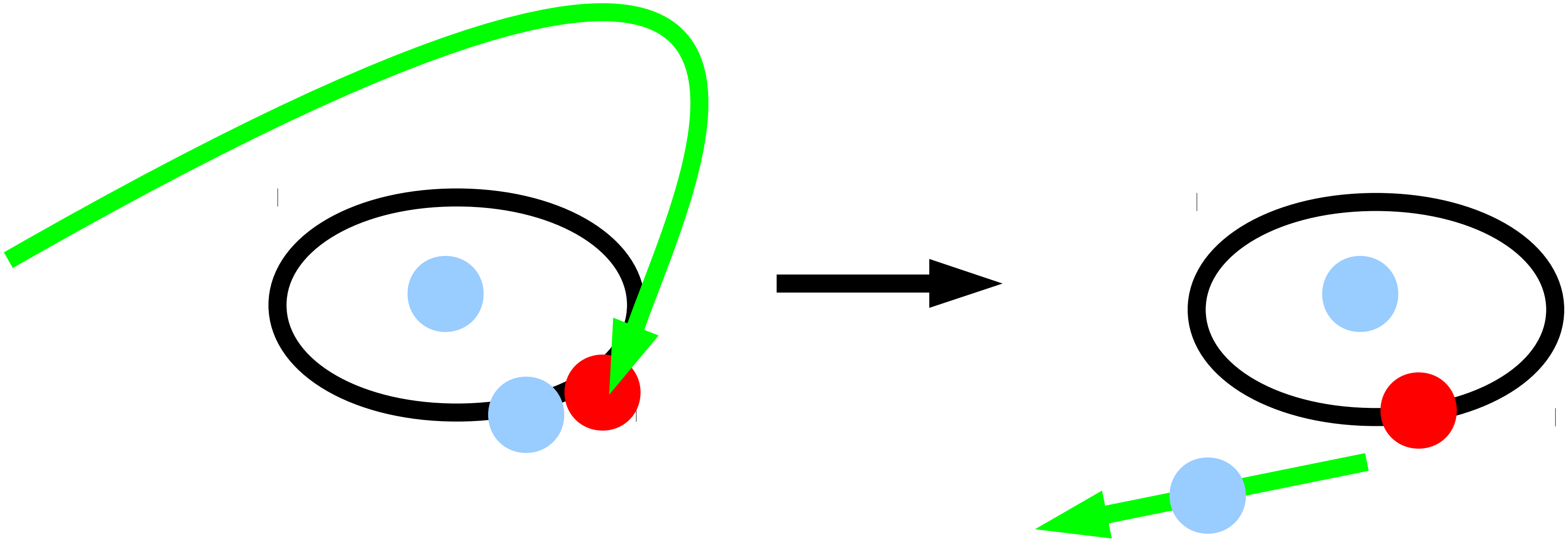
LIGO – Virgo observe compact object BINARIES

How do BH-BH (or BH-NS, NS-NS) binaries form?

1) ISOLATED BINARY



2) DYNAMICALLY FORMED BINARY



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

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

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

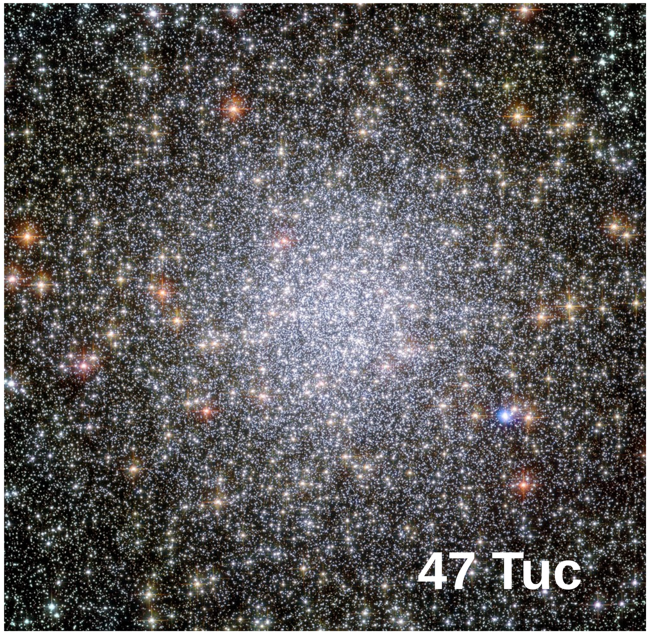
BUT massive stars (compact-object progenitors) form in star clusters

***(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:

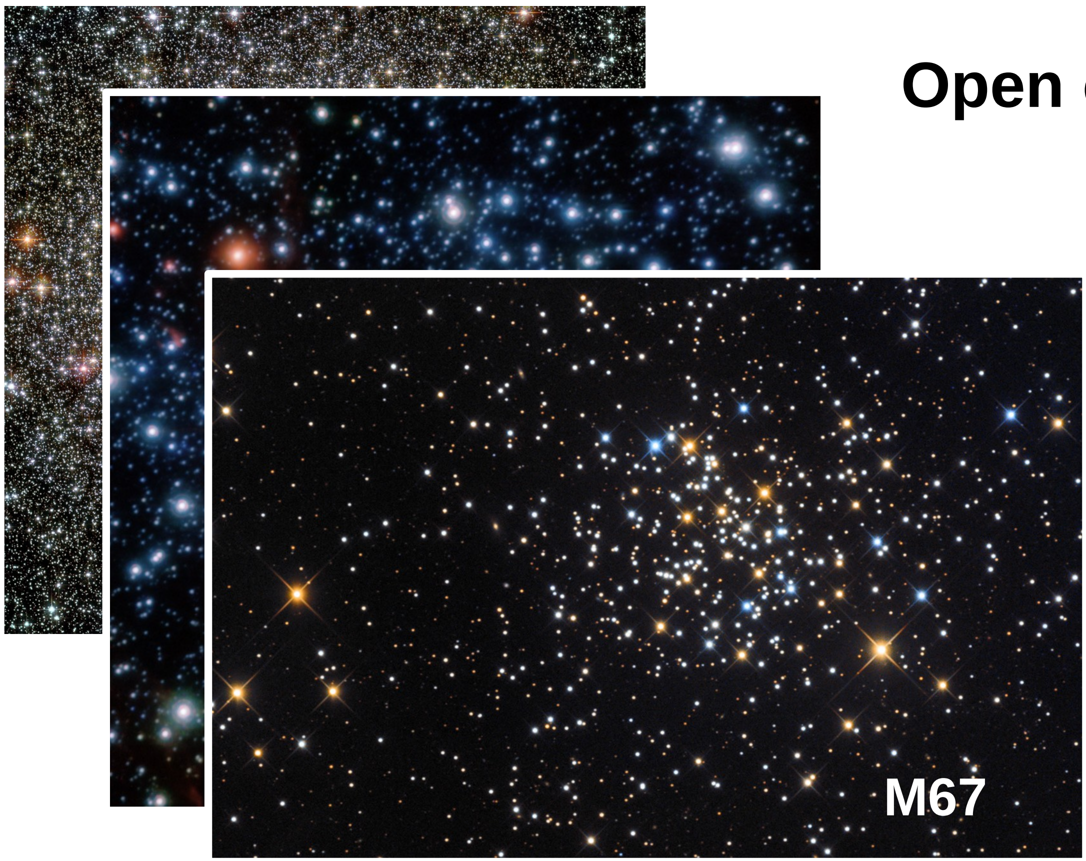
There are many different flavours of star clusters

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

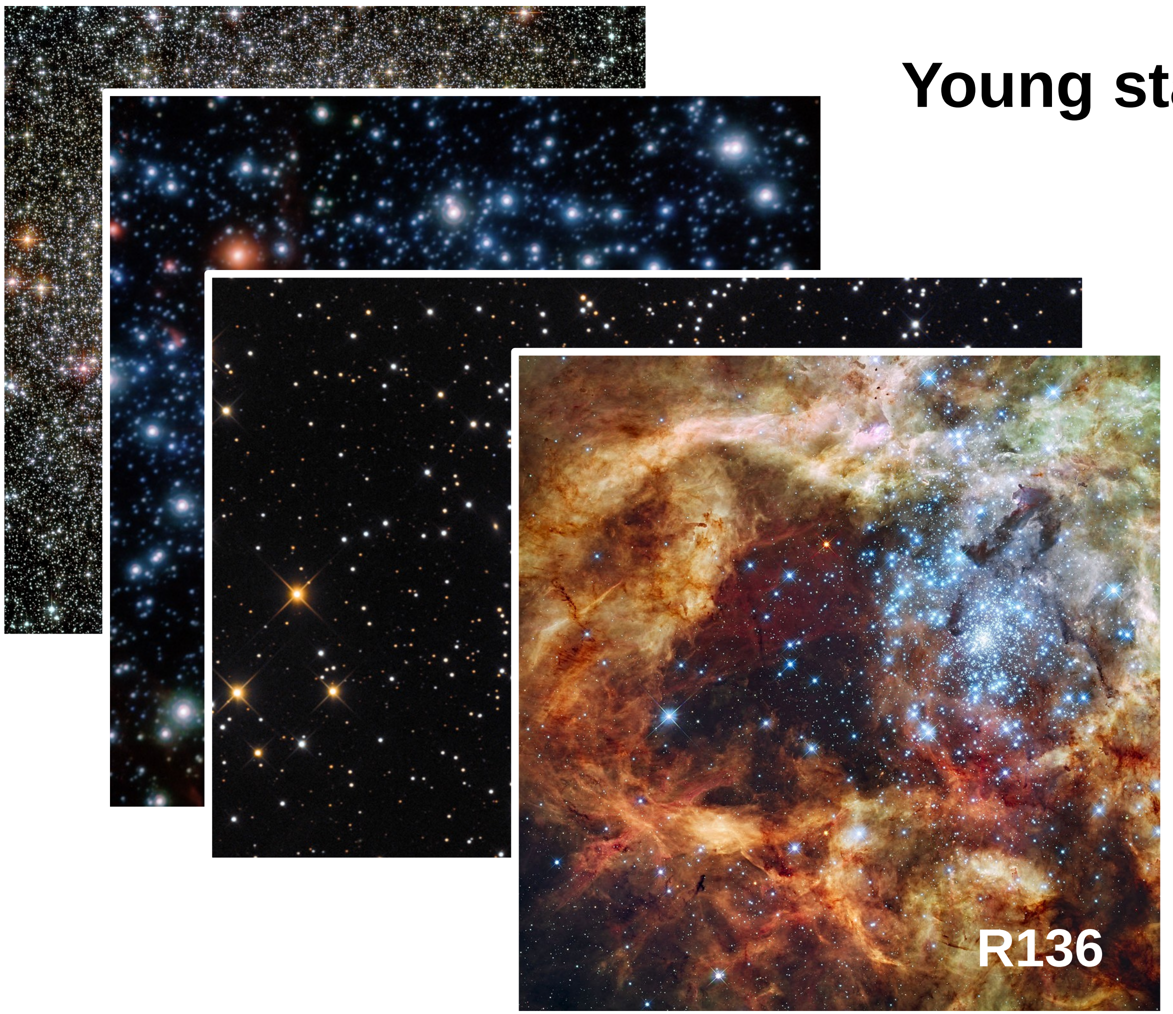


Open clusters

- ✔ 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☉)

3. The dynamics of BH binaries:

There are many different flavours of star clusters

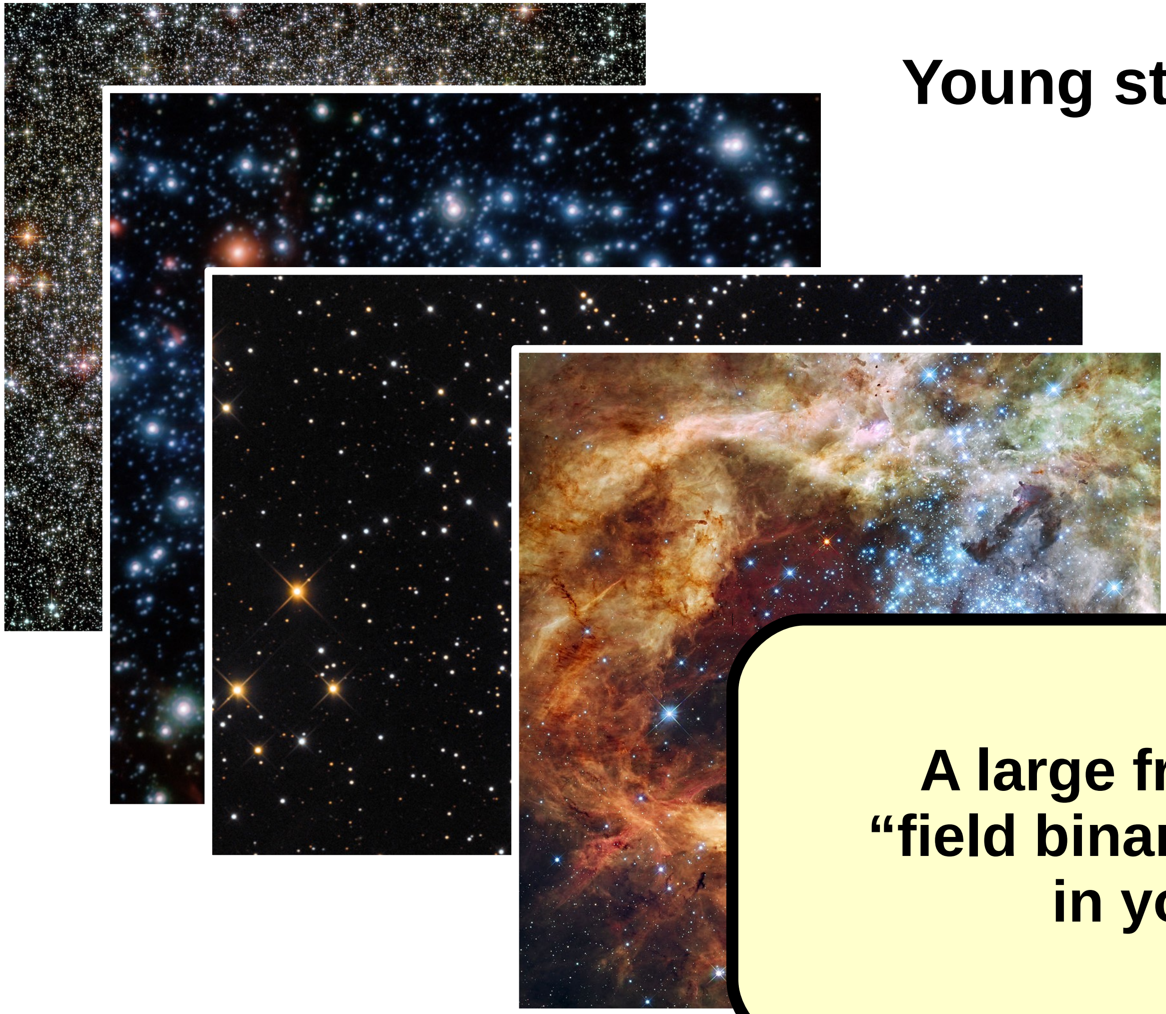


Young star clusters

- ✔ 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⊙)
- ✔ 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

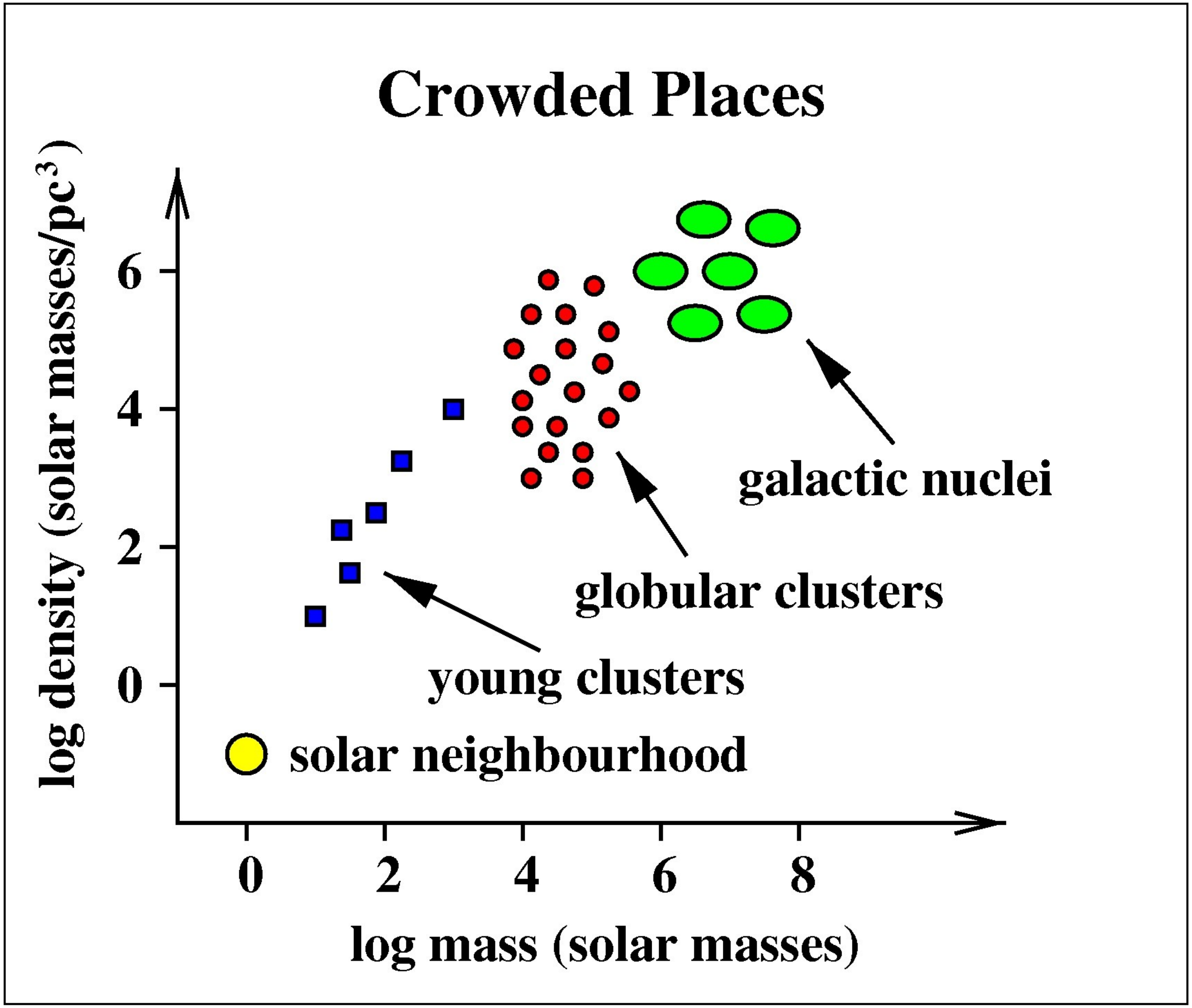
3. The dynamics of BH binaries:

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

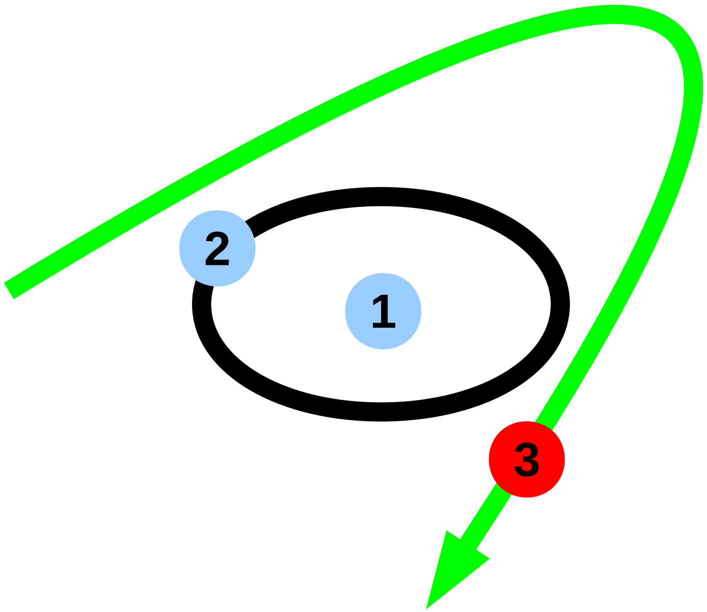
Binaries have a energy reservoir (internal energy)

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

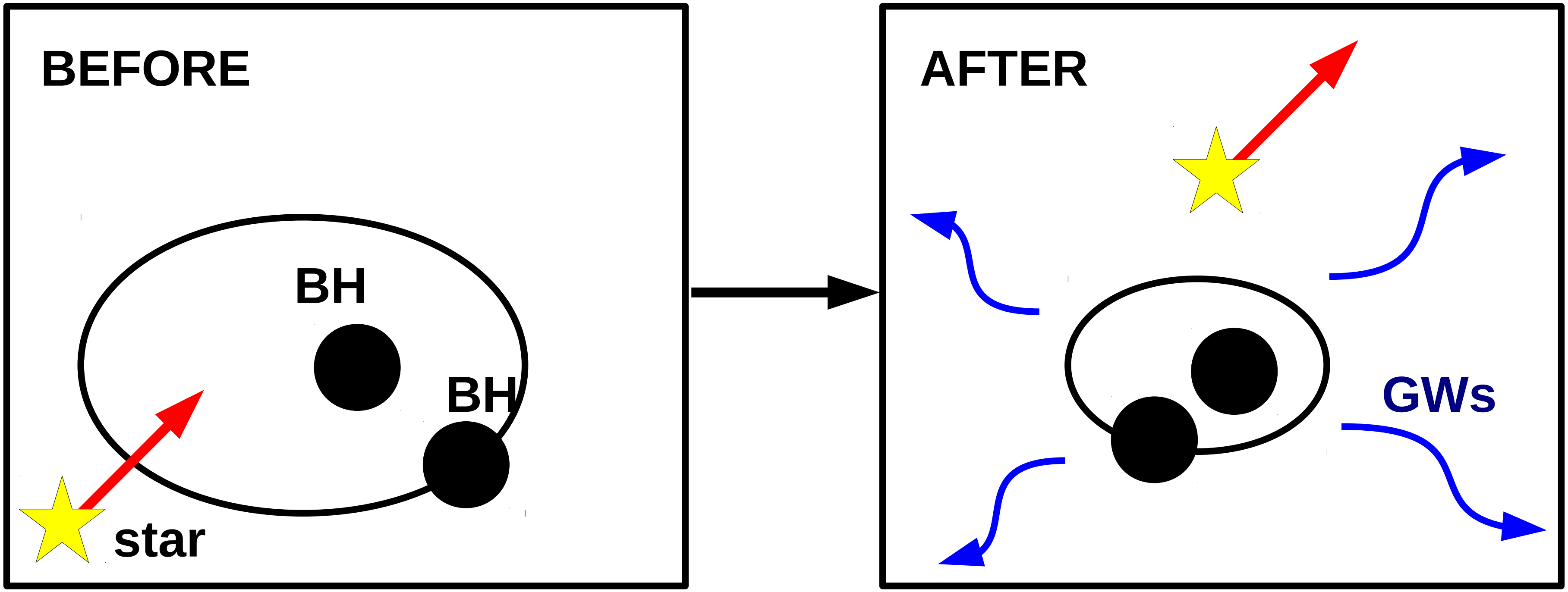
where m_1 and m_2 are the mass of the primary and secondary member of the binary,
μ is the reduced mass (:= $m_1\,m_2/(m_1+m_2)$), r and v are the relative separation and velocity.

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

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

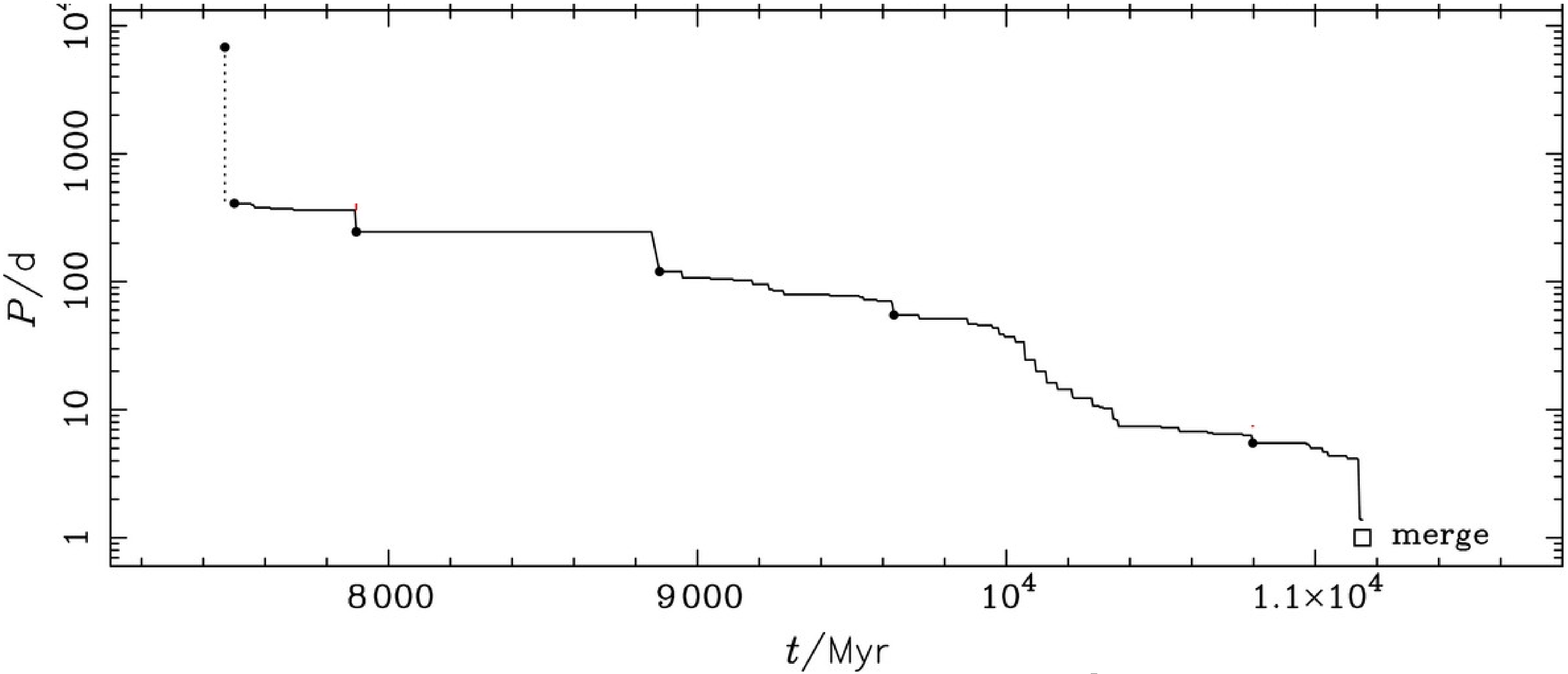


In a flyby, the star acquires kinetic energy from the binary

→ ***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: FLYBYs

HARDENING TIMESCALE

$$t_h = \left|\frac{a}{\dot{a}}\right| = \frac{1}{2\,\pi\,G\,\xi}\,\frac{\sigma}{\rho}\,\frac{1}{a}$$

GRAVITATIONAL WAVE (GW) TIMESCALE (Peters 1964)

$$t_{GW} = \frac{5}{256}\,\frac{c^5\,a^4\,(1-e^2)^{7/2}}{G^3\,m_1\,m_2\,(m_1+m_2)}$$

Combining 1) and 2) we can find the maximum semi-major axis for GWs to dominate evolution

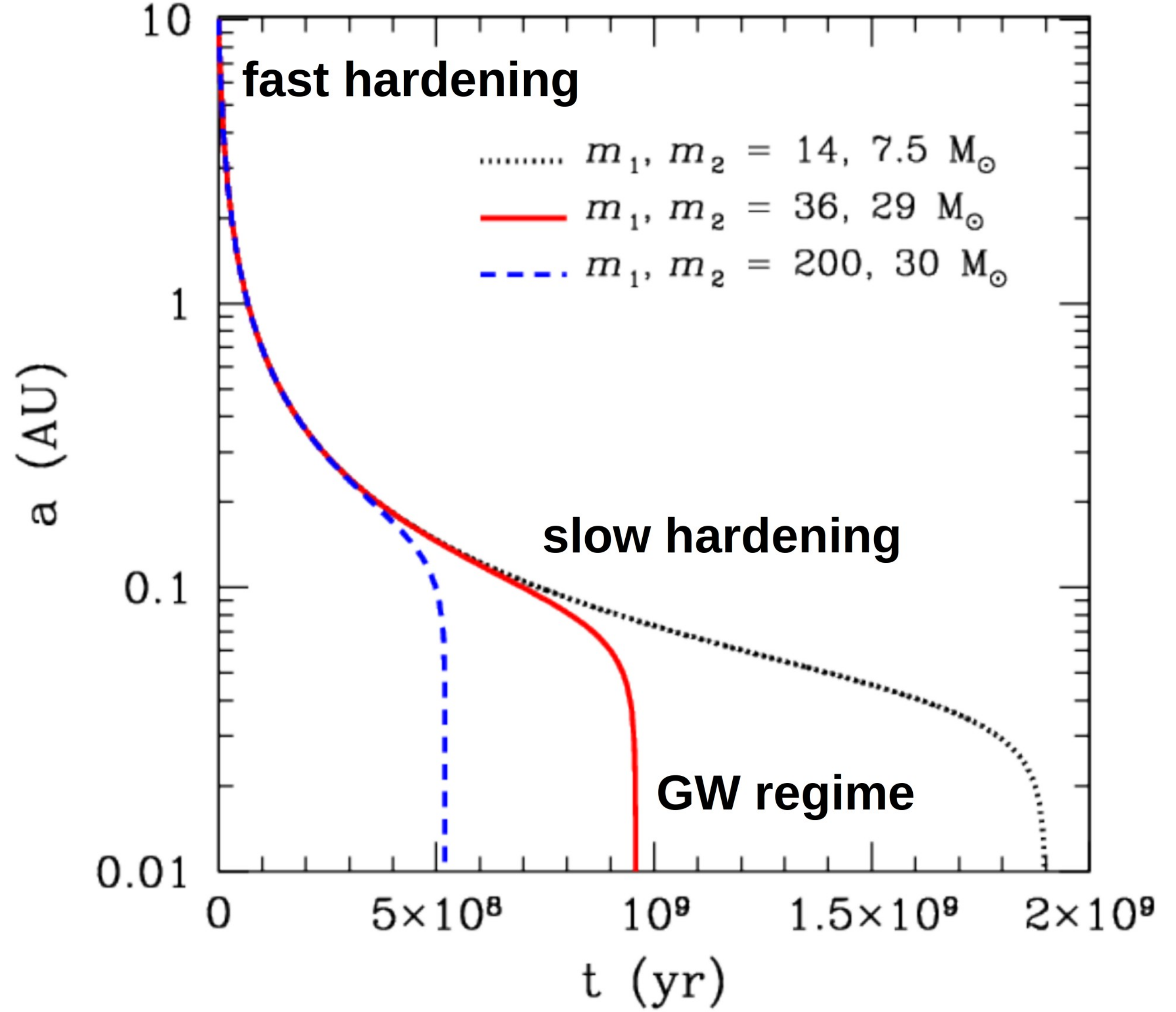
$$a_{GW} = \left[\frac{256}{5}\,\frac{G^2\,m_1\,m_2\,(m_1+m_2)\,\sigma}{2\,\pi\xi\,(1-e^2)^{7/2}\,c^5\,\rho}\right]^{1/5}$$

3. The dynamics of stellar BH binaries: FLYBYs

$$\frac{da}{dt} = -2\,\pi\,\xi\,\frac{G\,\rho}{\sigma}\,a^2 - \frac{64}{5}\,\frac{G^3\,m_1\,m_2\,(m_1+m_2)}{c^5\,(1-e^2)^{7/2}}\,a^{-3}$$

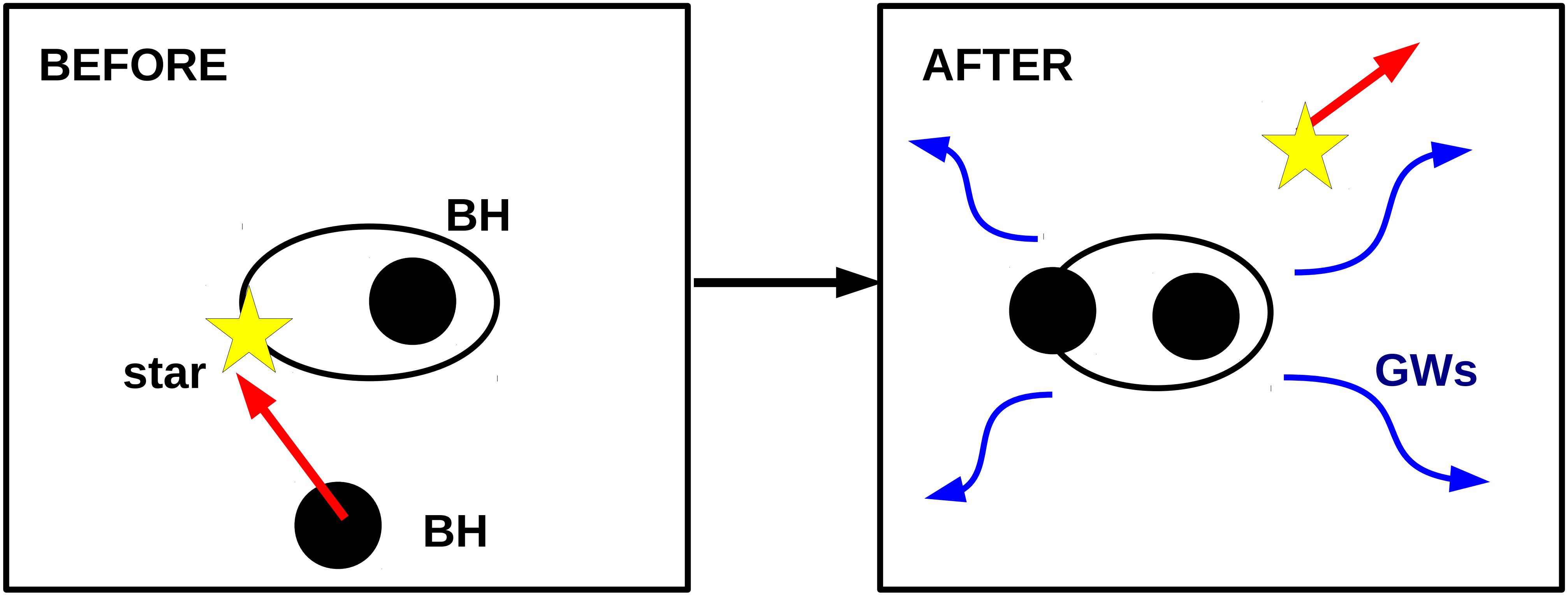
Binary shrinking by hardening

Binary shrinking by GWs (Peters 1964)



See MM 2018,
https://arxiv.org/abs/1809.09130

3. The dynamics of stellar BH binaries: EXCHANGEs



Exchanges bring BHs in binaries

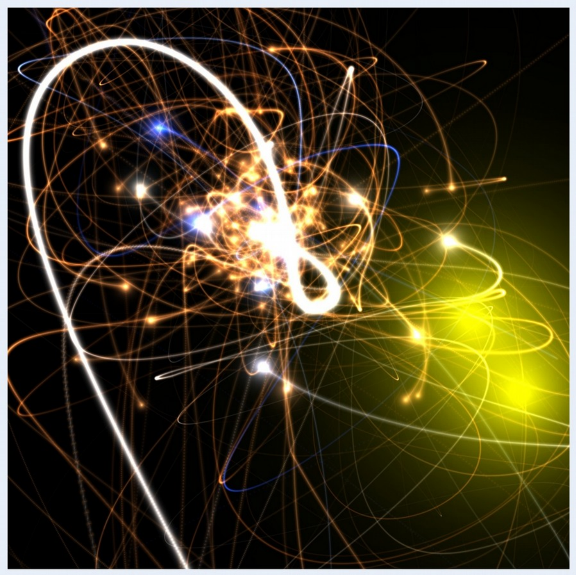
BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!

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):

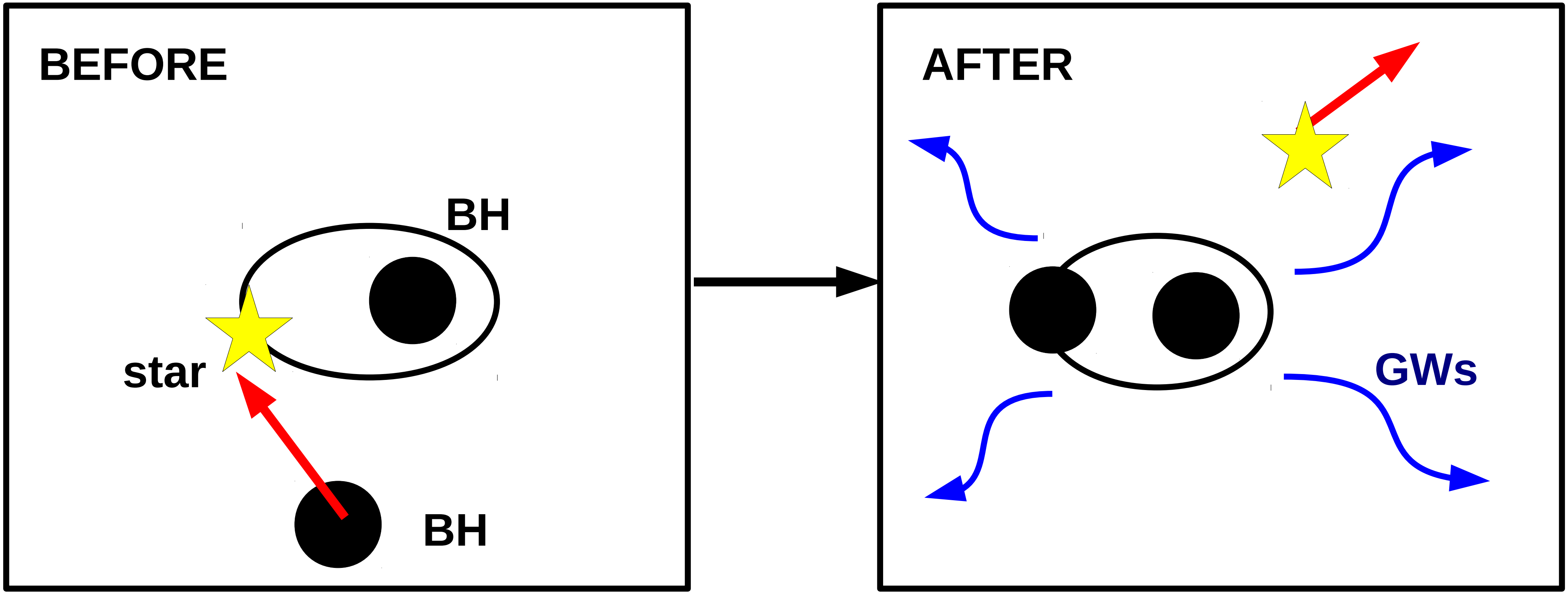


Movie 2 : binary – single interaction
ciera.northwestern.edu/Research/visualizations/videos/Binary+single.mp4

Movie 3 : dynamical exchange
ciera.northwestern.edu/Research/visualizations/videos/Binary+singleex.mp4

Movie 4: 5-body interaction (leads to a COLLISION!)
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

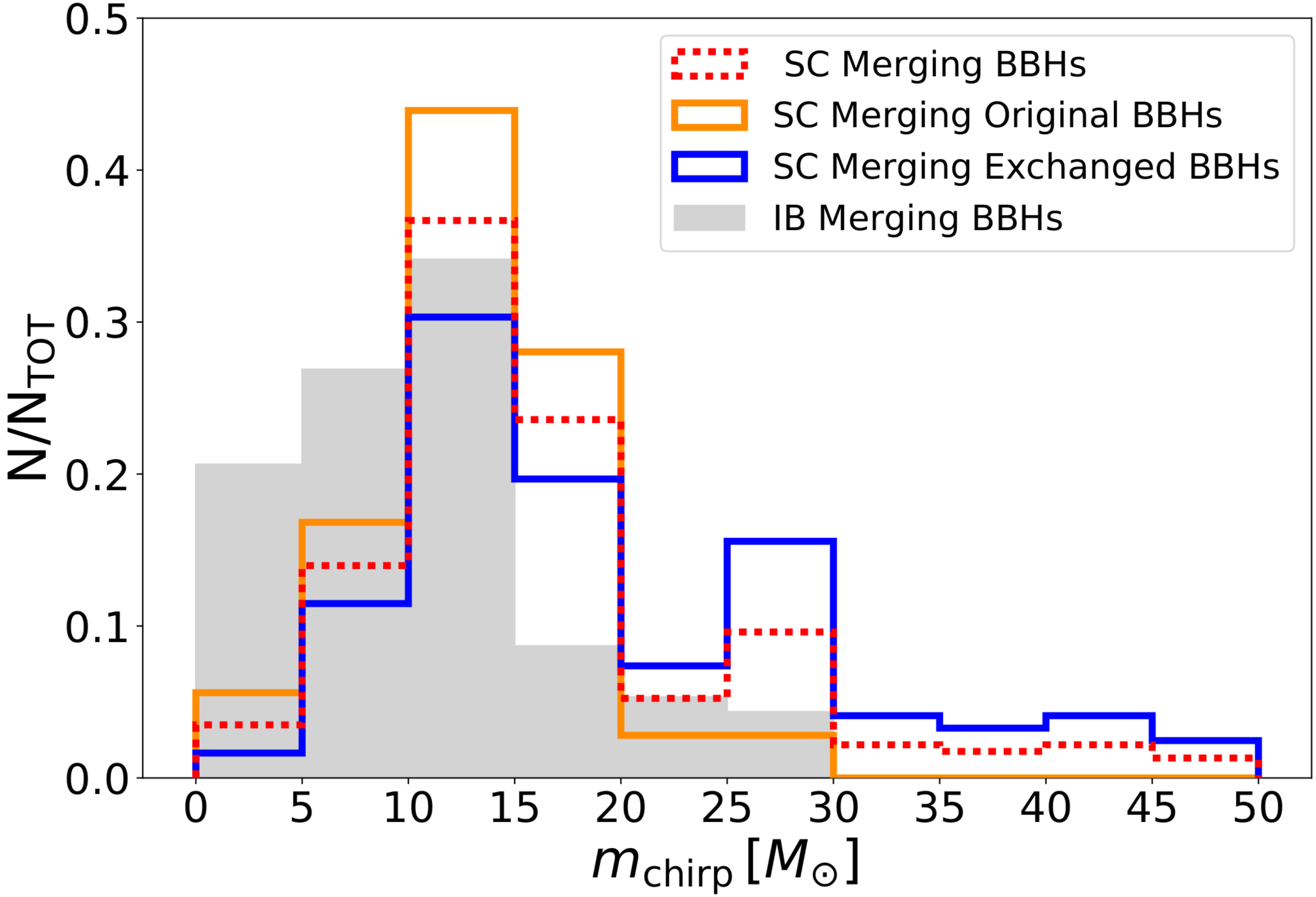
** THE MOST MASSIVE BHs*

** HIGH ECCENTRICITY*

** MISALIGNED BH SPINS*

3. The dynamics of stellar BH binaries: MASSEs

MOBSE + direct N-body code (Nbody6++GPU)



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: MASSEs

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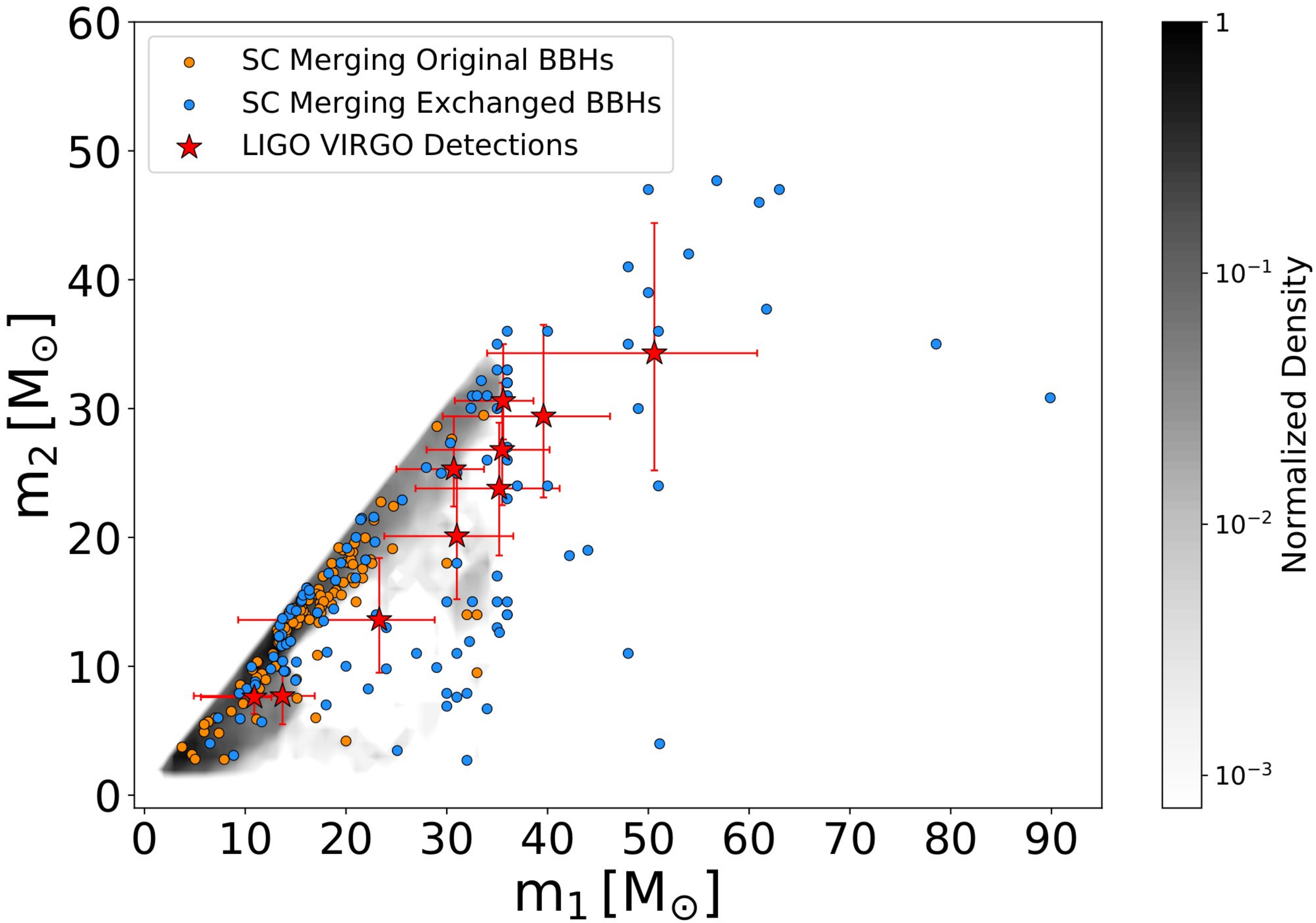

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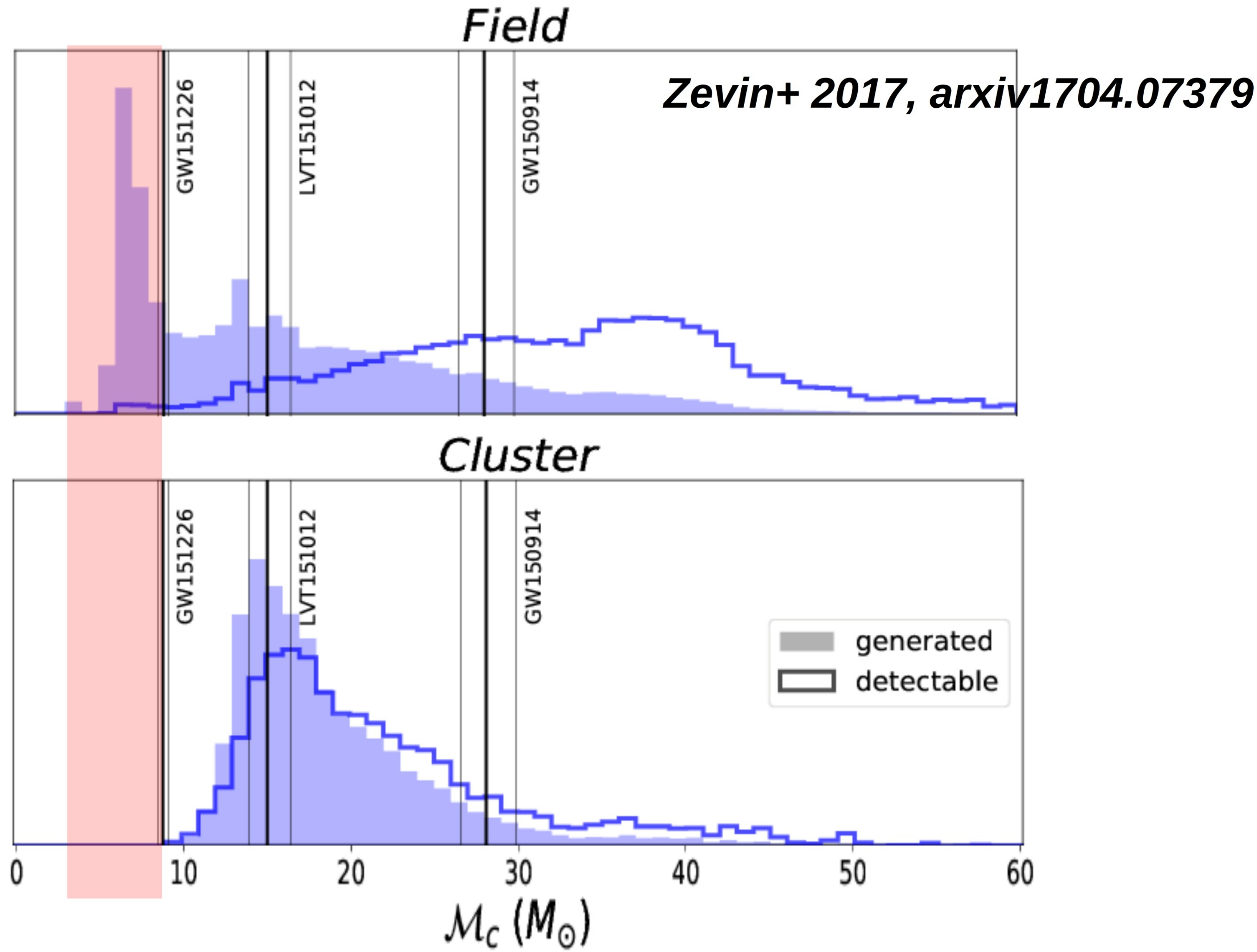
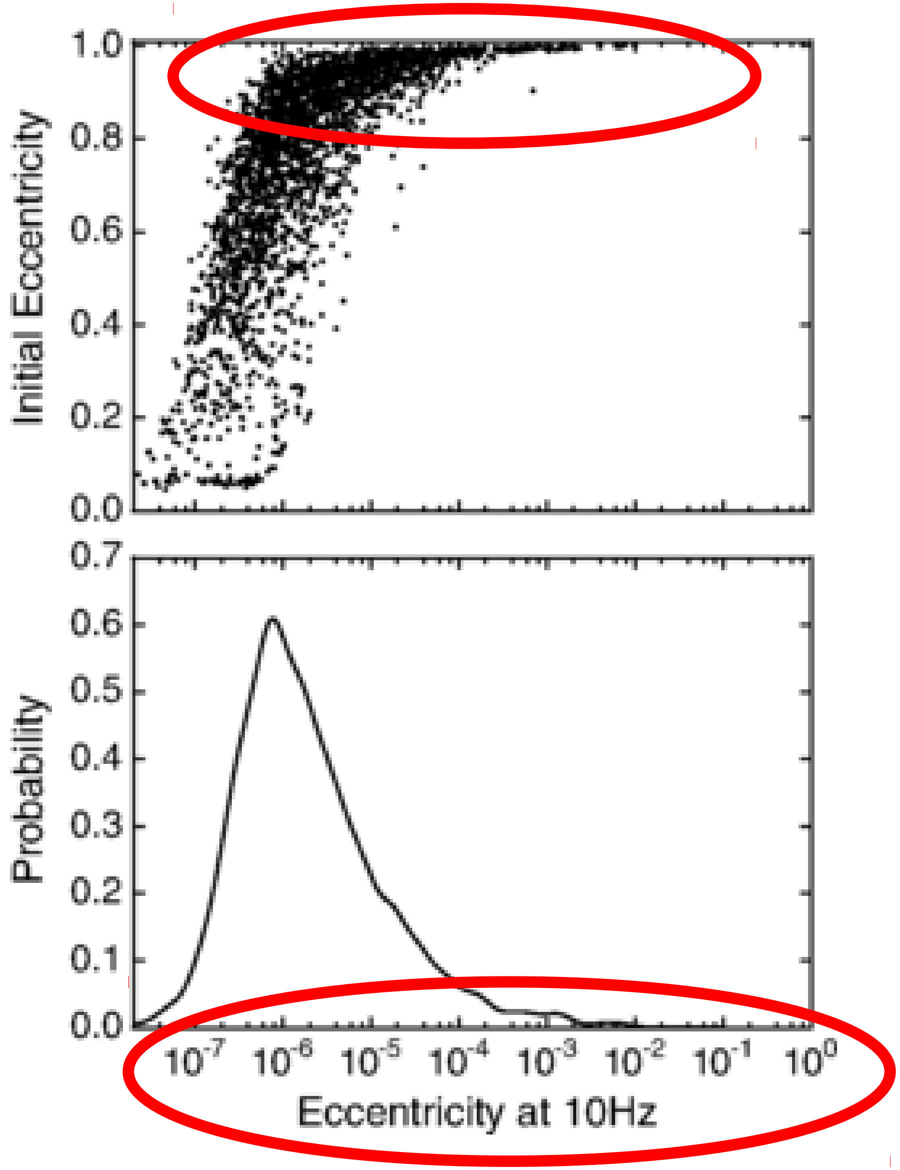


Ziosi, MM+ 2014, MNRAS, 441, 3703; Rodriguez+ 2015, Phys. Review Letter, 115, 1101; Hurley+ 2016, PASA, 33, 36; Askar+ 2017, MNRAS, 464, L36; Banerjee 2017, MNRAS, 467, 524 and many others

3. The dynamics of stellar BH binaries: ECCENTRICITY



Rodriguez+ 2016, PhRvD, 93, 4029

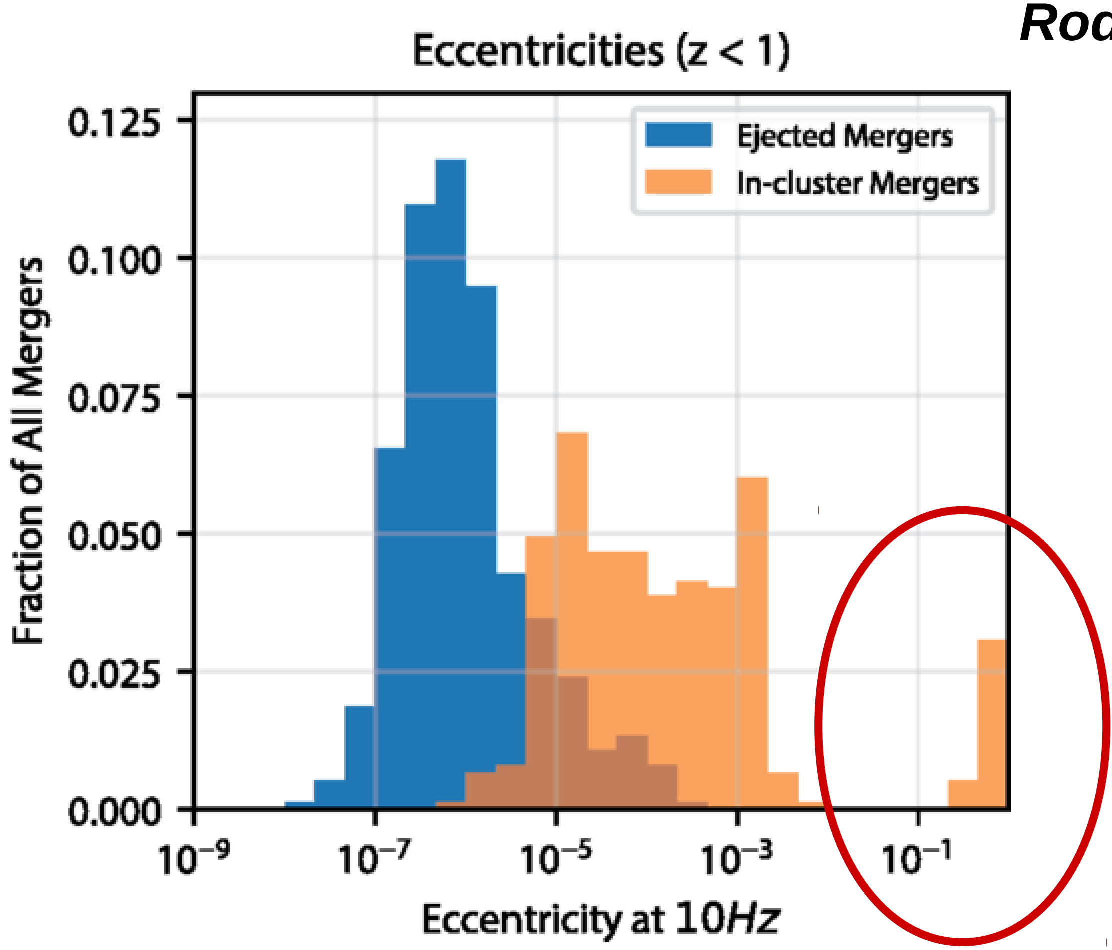
Initial eccentricity of ejected BBHs is very high

Even eccentricity in LIGO-Virgo band is non zero for a number of systems

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: ECCENTRICITY

Rodriguez+ 2018, PhRvD, 120, 1101



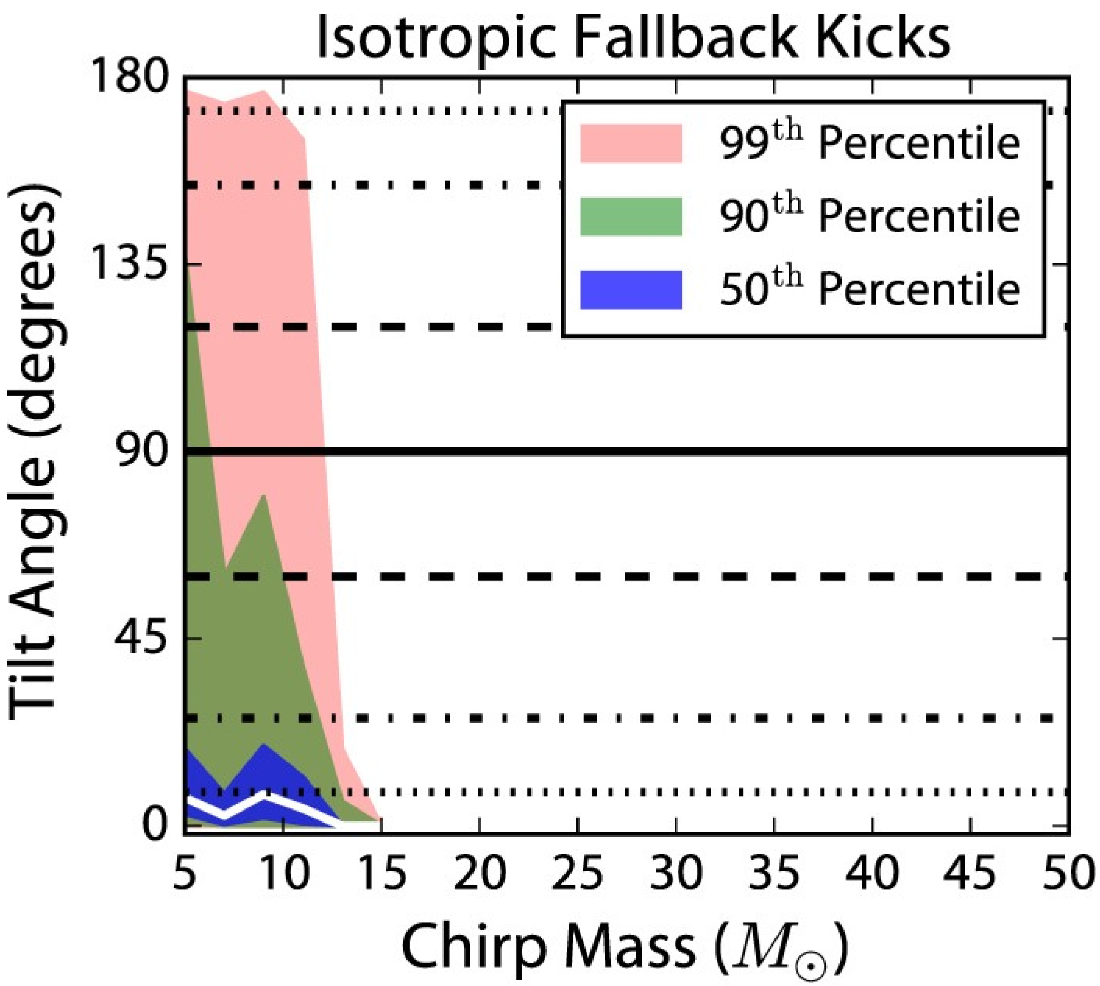
Initial eccentricity of ejected BBHs is very high

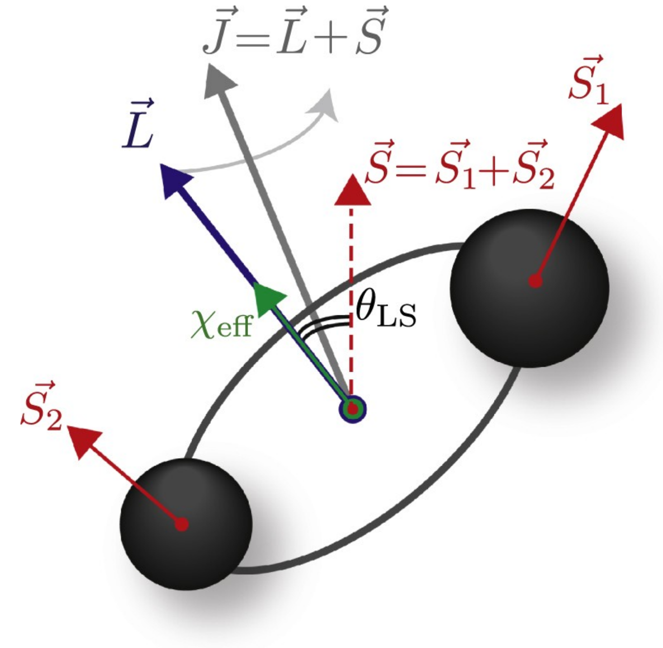
Even eccentricity in LIGO-Virgo band is non zero for a number of systems

Eccentricity of non-ejected BBHs is even higher!

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

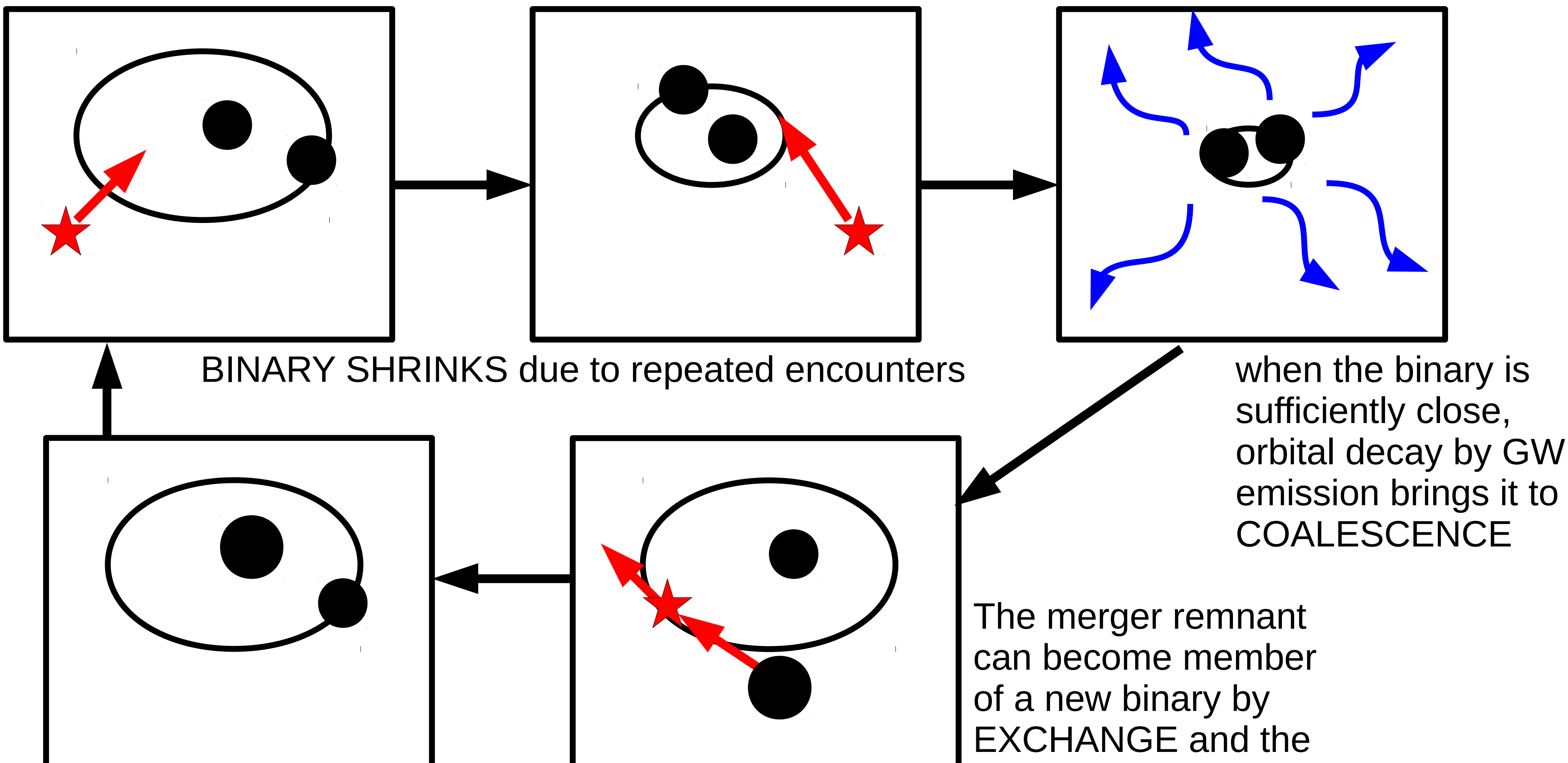
Spins of BBHs formed by exchange are ISOTROPICALLY distributed

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

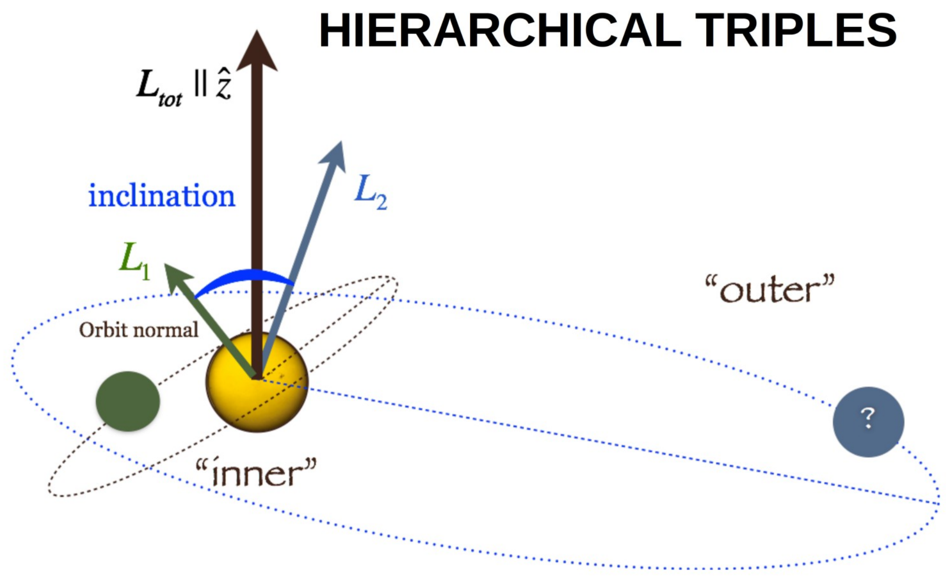
3. The dynamics of stellar BH binaries: repeated mergers

Formalism by Miller & Hamilton (2002)

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

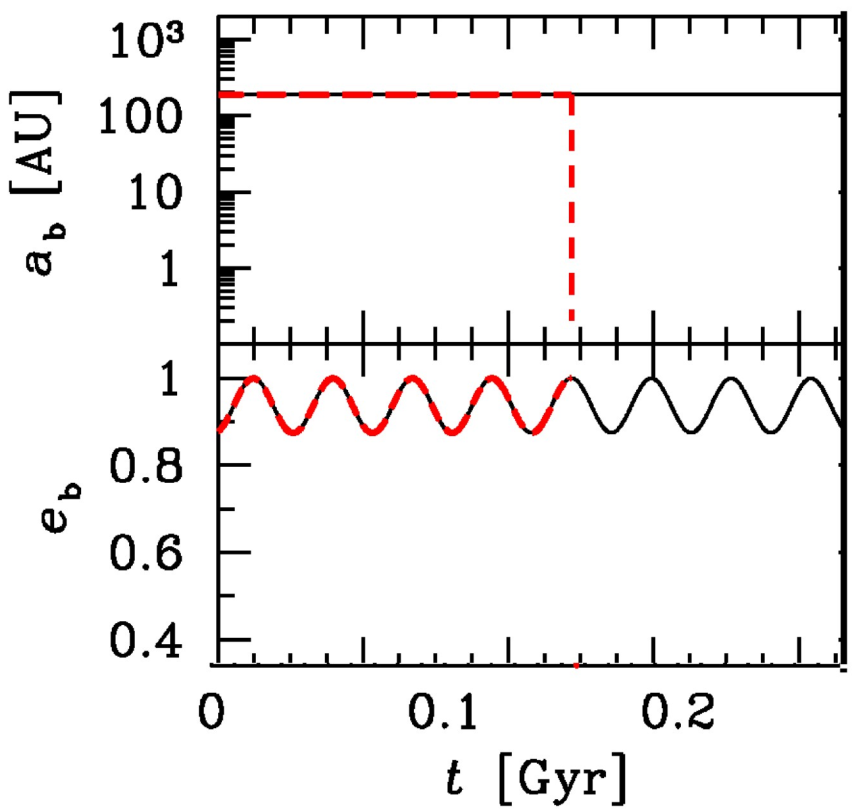


3. The dynamics of stellar BH binaries: Kozai resonance



Kozai 1962, AJ, 67, 591
Lidov 1962, P&SS, 9, 719
Figure credits: Smadar Naoz

ONLY DYNAMICAL PROCESS COMMON ALSO IN THE FIELD



ECCENTRICITY of the inner binary OSCILLATES

TRIGGERING MERGERS between binary members

No general relativity
With relativistic correction (2.5 Post-Newtonian)

Kimpson+ 2016, MNRAS, 463, 2443

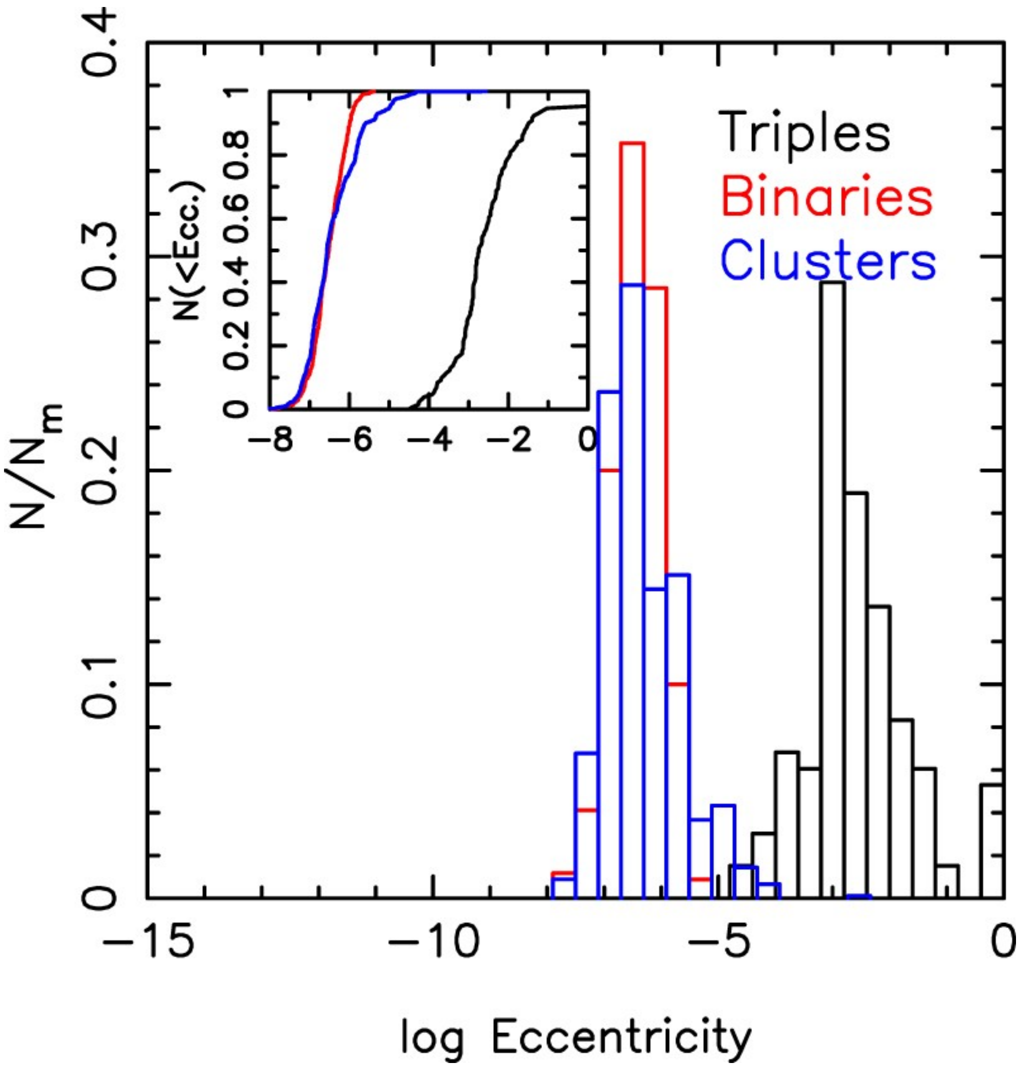
3. The dynamics of stellar BH binaries: Kozai resonance

~ 25% massive stars are in TRIPLES (Sana+ 2014)

KL FAVOURS BBH MERGERs
Antognini+ 2014, MNRAS, 439, 1079;
Antonini+ 2016, ApJ, 816, 65;
Antognini+ 2016, MNRAS, 456, 4219;
Kimpson+ 2016, MNRAS, 463, 2443;
Antonini+ 2017, ApJ, 841, 77

Eccentricity in banda LIGO-Virgo of KL systems is tremendously higher (e.g. Antonini+ 2017)!

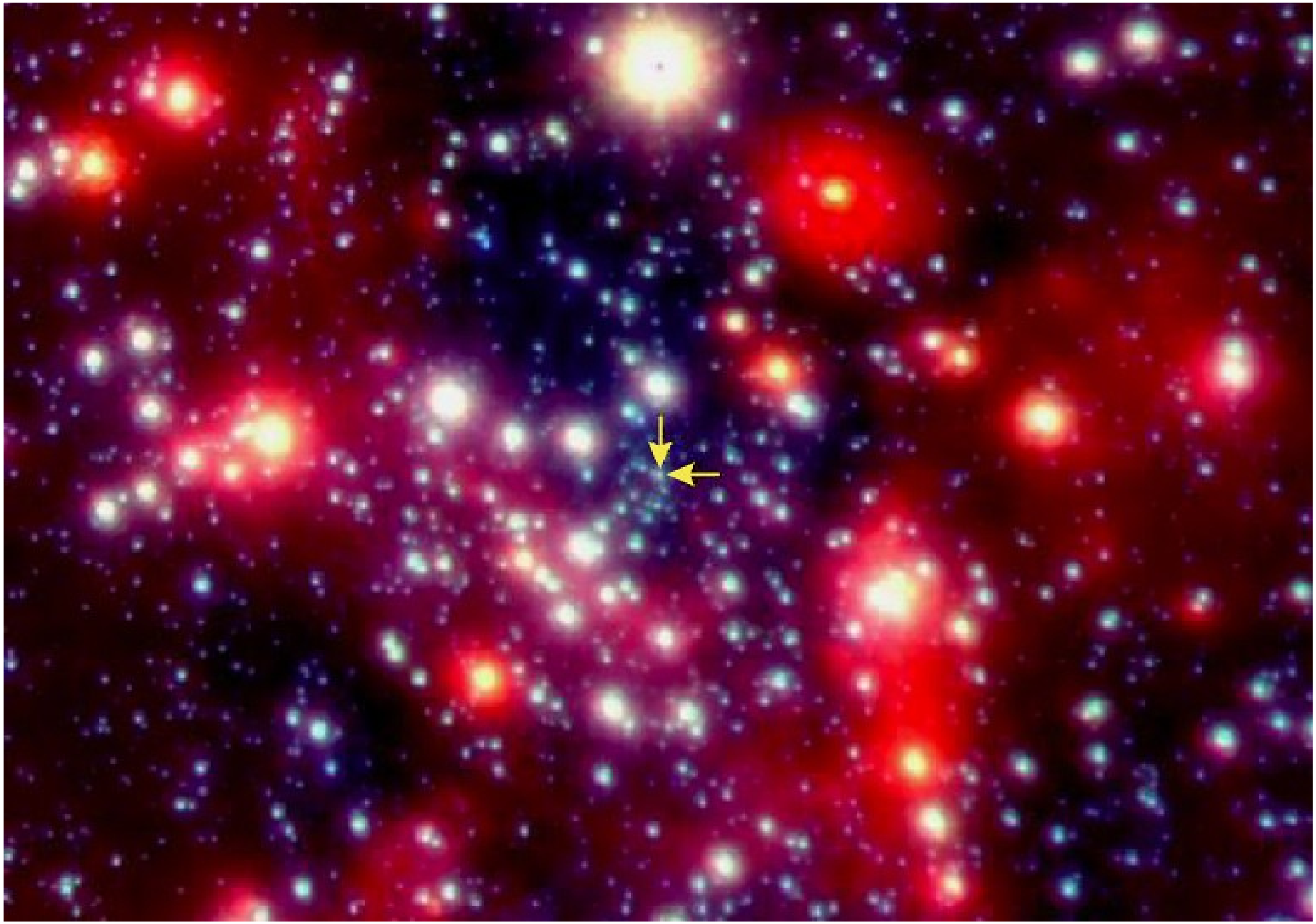
Merger rate from KL systems is low (<2.5 Gpc $^{-3}$ yr $^{-1}$)



Antonini+ 2017, ApJ, 841, 77

3. The dynamics of stellar BH binaries: Kozai resonance

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:



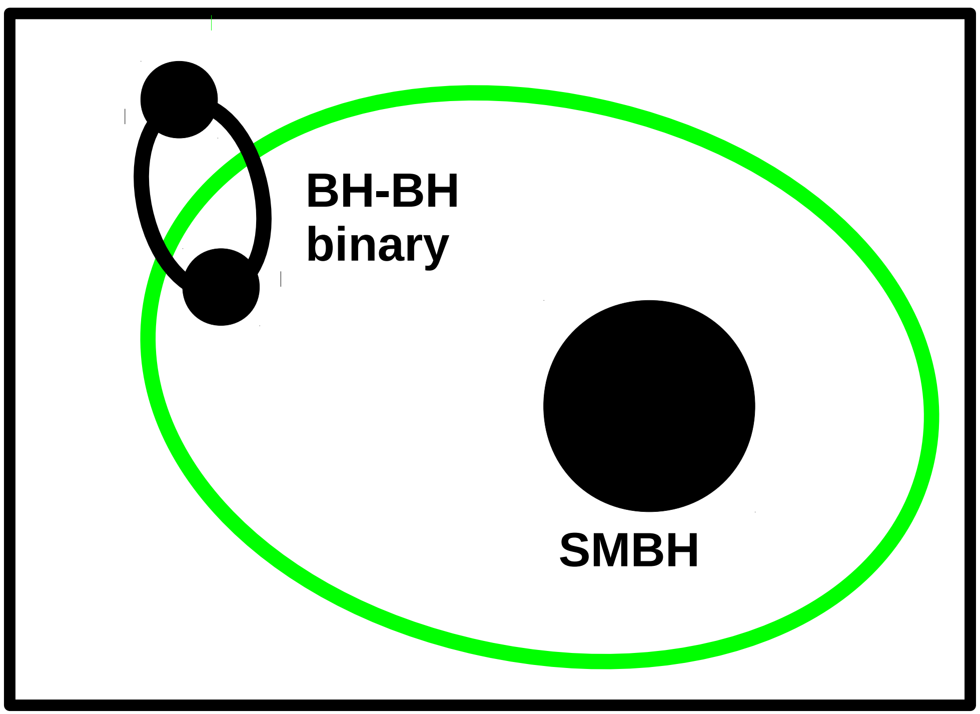
Schoedel et al. 2002, Nature, 419, 694

3. The dynamics of stellar BH binaries: Kozai resonance

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:

* high escape velocity
  (BHs are retained)

* triple might be with SMBH



Antonini & Perets 2012, ApJ, 757, 27

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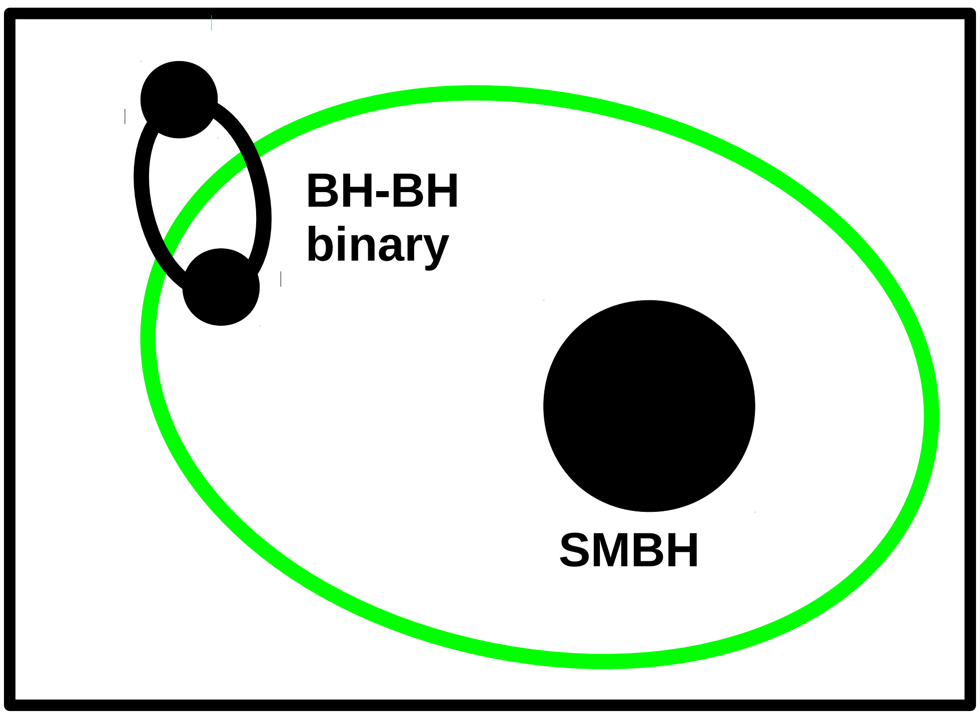
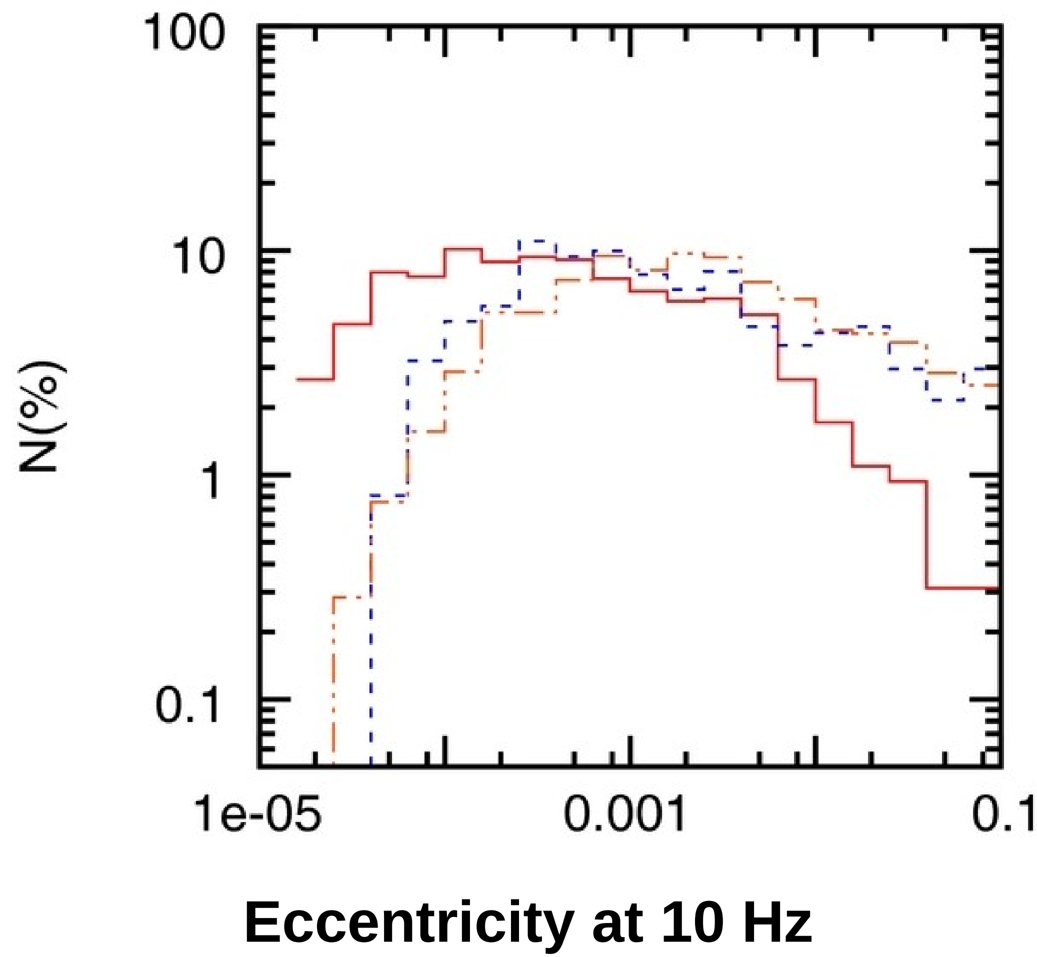




Antonini & Perets 2012, ApJ, 757, 27

3. The dynamics of stellar BH binaries: merger rates

INFERRED BBH merger rate from LIGO ~ 24 – 112 Gpc^{-3} yr^{-1}

(Abbott+ 2018, arXiv:1811.12907, arXiv:1811.12940)

Merger rate for GLOBULAR CLUSTERS ~ 4 – 20 Gpc^{-3} yr^{-1}

(Rodriguez+ 2016, PhRvD, 93, 4029; Askar+ 2017, MNRAS, 464, L36; Rodriguez & Loeb 2018, ApJ, 866, L5)

Globular clusters are tiny fraction of baryons in Universe (~1%) but produce high rate

Possible issue: Monte Carlo codes used by different groups adopt similar recipes

Merger rate for NUCLEAR CLUSTERS: ~ 1 – 2 Gpc^{-3} yr^{-1}

(Antonini & Rasio 2016, ApJ, 2016, 831, L187)

Issue: only preliminary results

Merger rate for YOUNG & OPEN CLUSTERS: ~ 0.1 – 100 Gpc^{-3} yr^{-1}

(Ziosi, MM+ 2014, MNRAS, 441, 3703; MM 2016, MNRAS, 459, 3432)

Issue: large uncertainty because difficult statistics but see recent result by Di Carlo et al. 2019

3. The dynamics of stellar BH binaries: wrap up

Dynamical binary evolution summary:

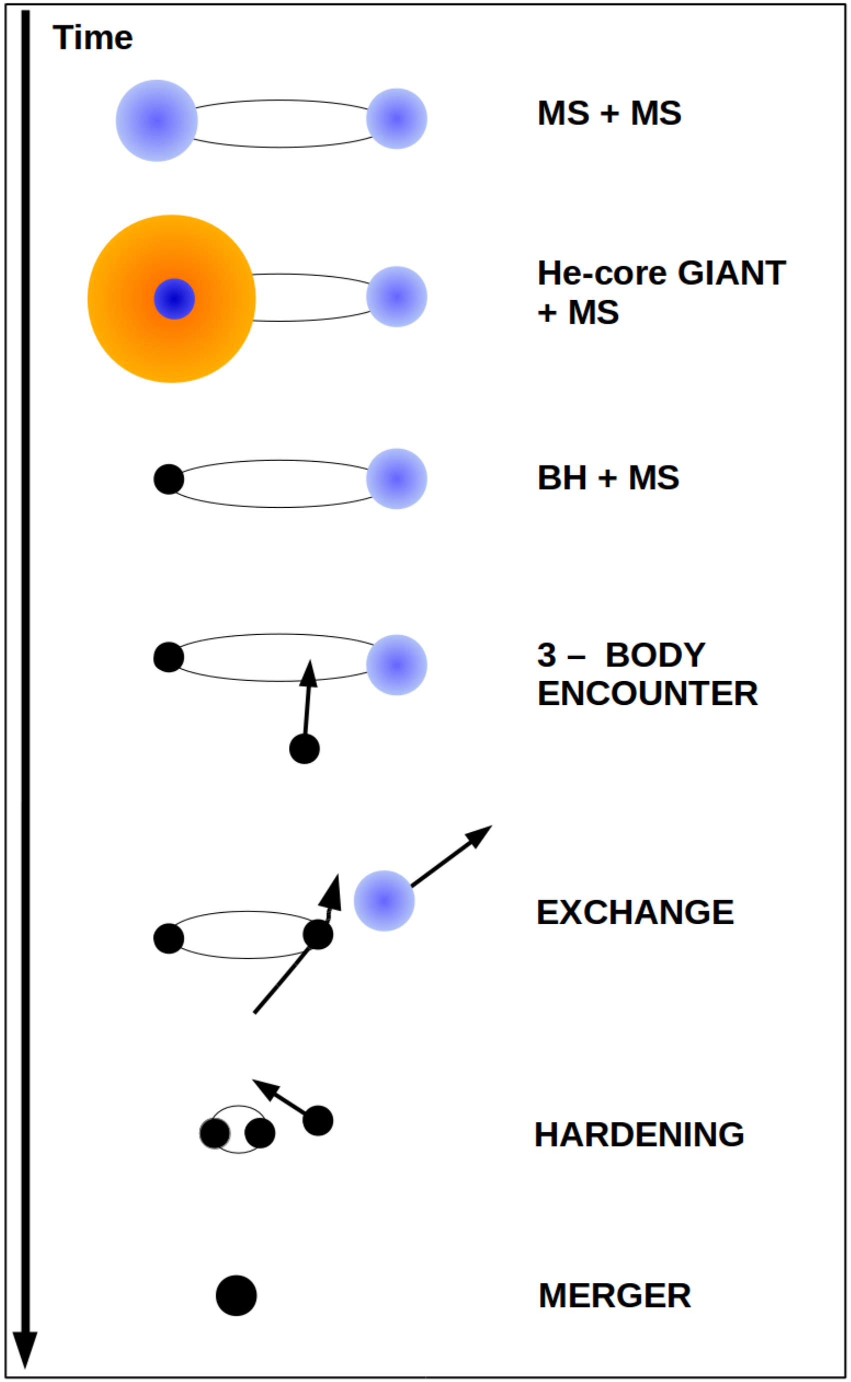
* no need for Roche lobe or common envelope (but might happen)

* exchanges build up more massive black hole binaries

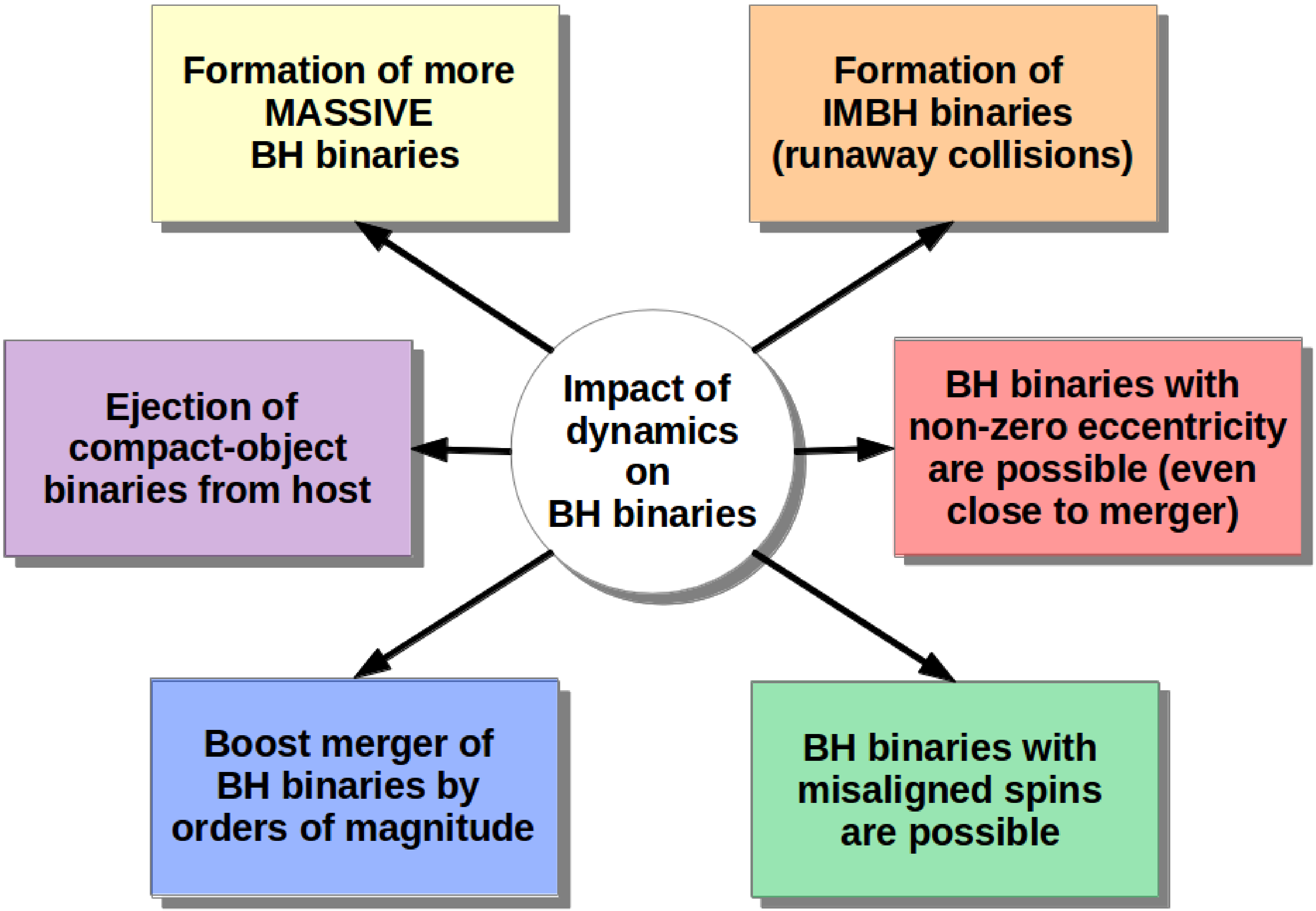
* hardening by three-body encounters favours the binary shrinking

* BH – BH merger

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



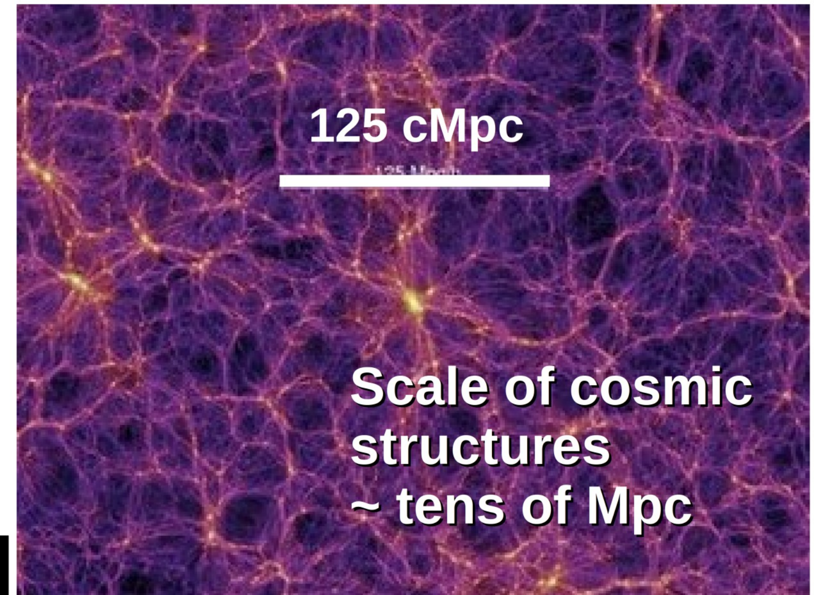
3. The dynamics of stellar BH binaries: wrap up

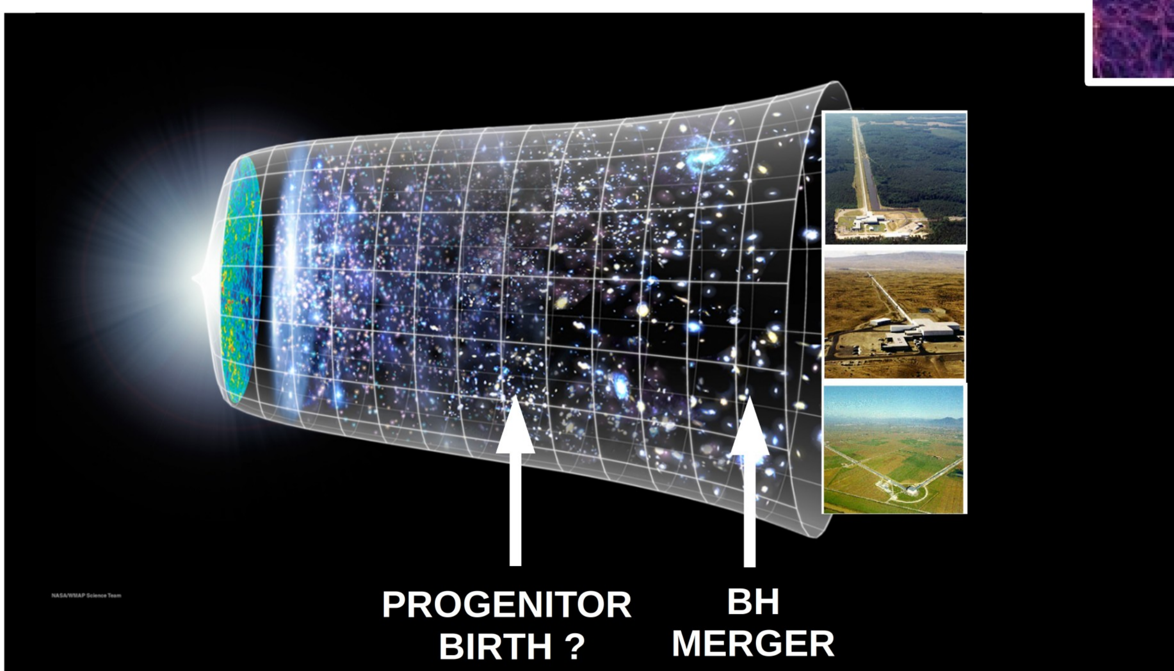


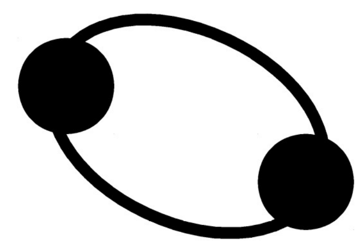
4. Compact binaries in cosmological context

NECESSARY:
binary merging at $z \sim 0.1$
might have formed at $z \gg 0.1$

BUT CHALLENGING:
humongous physical range







Scale of a compact object binary < AU

4. Compact binaries in cosmological context

TWO MAIN ESCAMOTAGES:

- analytic formalism + binary population synthesis sims. through Monte Carlo procedure

O'Shaughnessy+ 2010
Dominik+ 2013, 2015
Belczynski+ 2016
*Lamberts+ 2016
Giacobbo & MM 2018
Chruslinska+ 2019
(* use 1 ingredient from simulations)

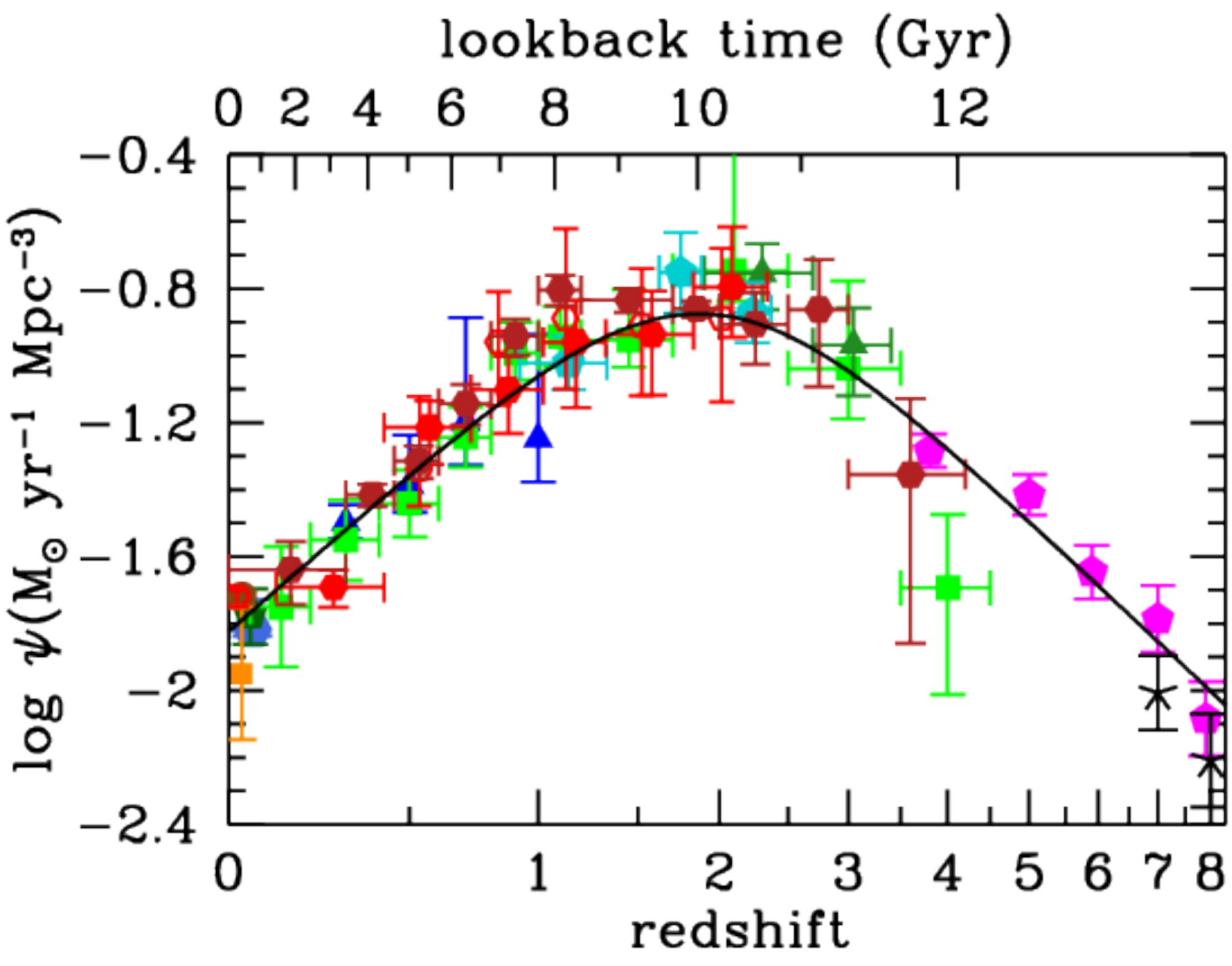
- cosmological simulations + binary population synthesis simulations through Monte Carlo procedure

O'Shaughnessy+ 2017
Schneider+ 2017
MM+ 2017, 2018, 2019
MM & Giacobbo 2018
Artale+ 2019
Marassi+ 2019

4. Compact binaries in cosmological context

MAIN INGREDIENTS: cosmic star formation rate density

Compact binaries depend on it because form from massive stars

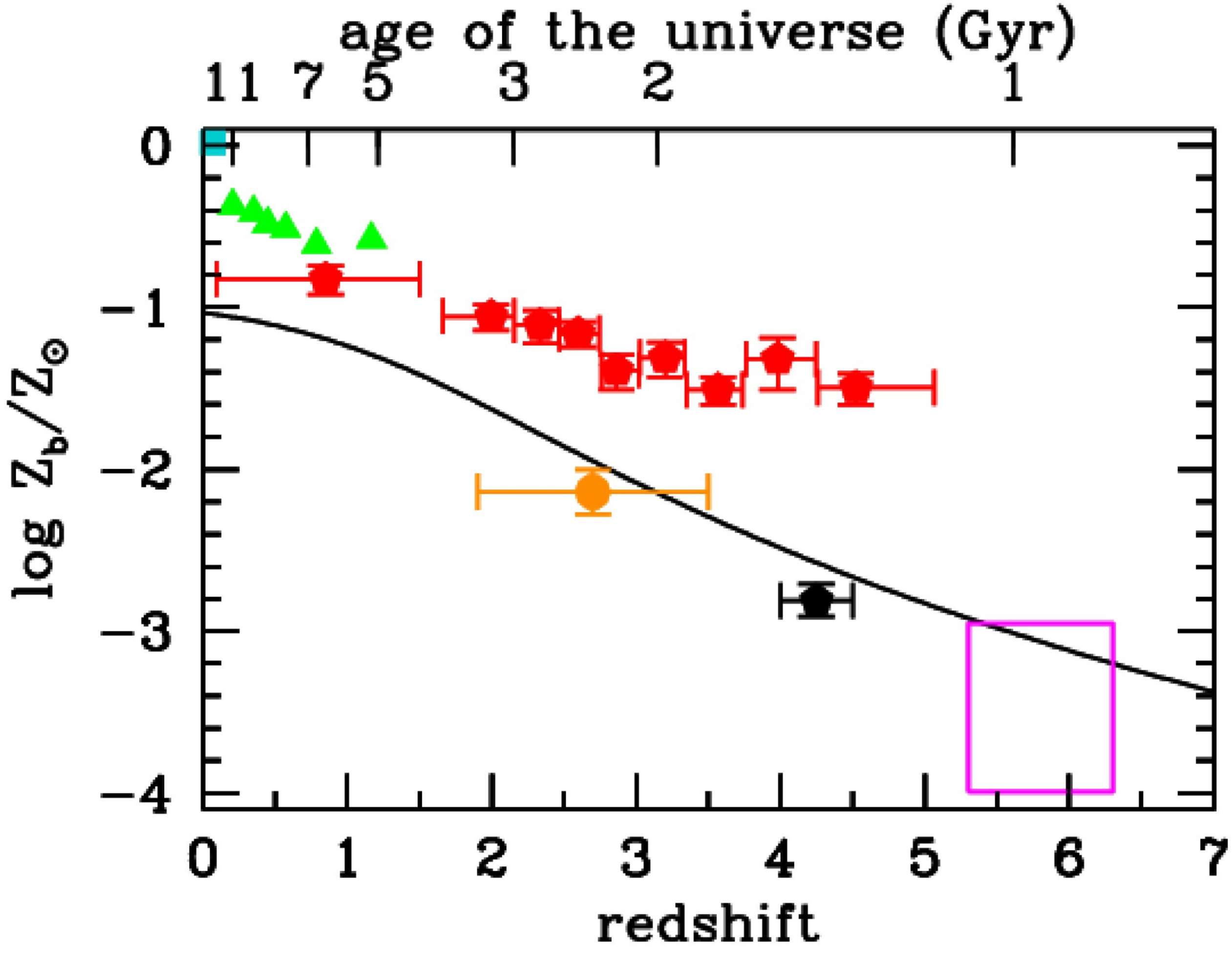


(FUV+ IR data, Fig. 9 of Madau & Dickinson 2014)

4. Compact binaries in cosmological context

MAIN INGREDIENTS: metallicity evolution

Mass of BHs (not neutron stars!) depends on metallicity

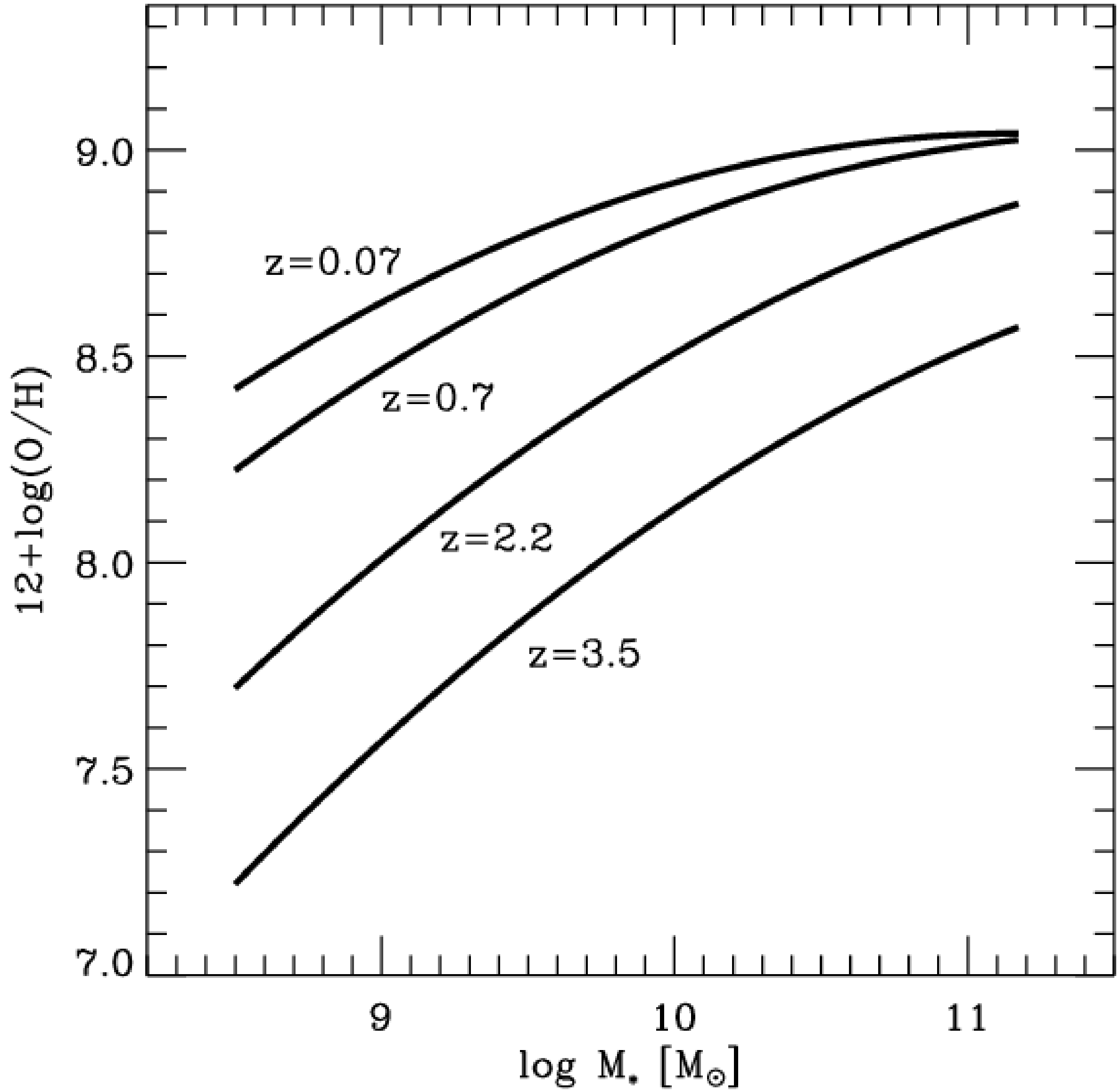


(Fig. 14 of Madau & Dickinson 2014)

4. Compact binaries in cosmological context

MAIN INGREDIENTS: galaxy mass – metallicity relation (Maiolino+ 2008, Mannucci+ 2011)

Links mass of host galaxy, metallicity and cosmic SFR



Maiolino et al. 2008, A&A 488, 463-479

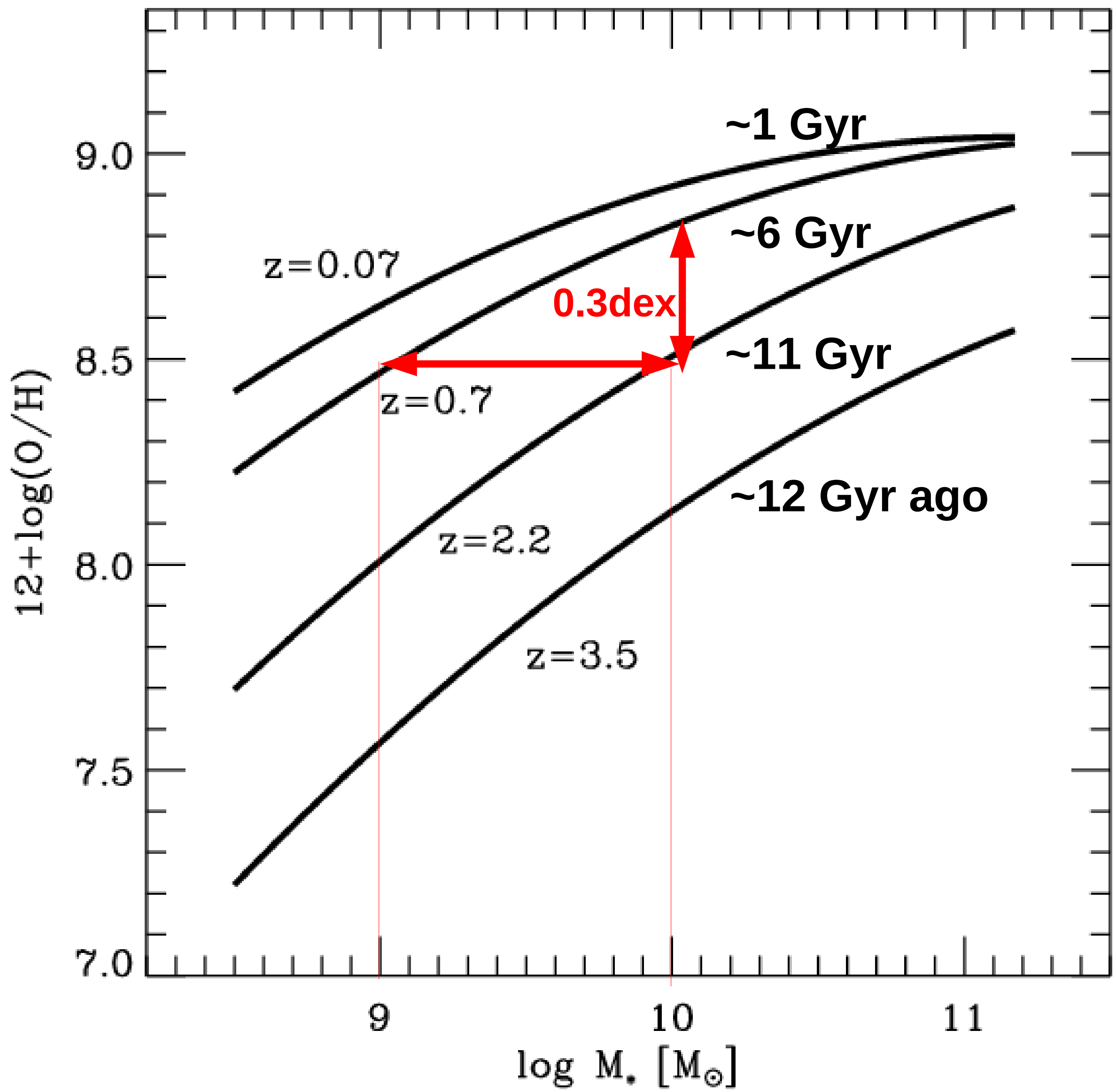
4. Compact binaries in cosmological context

MAIN INGREDIENTS: galaxy mass – metallicity relation (Maiolino+ 2008, Mannucci+ 2011)

Links mass of host galaxy, metallicity and cosmic SFR

Between 11 and 6 Gyr ago observed metallicity changed ~0.3 dex for fixed galaxy mass

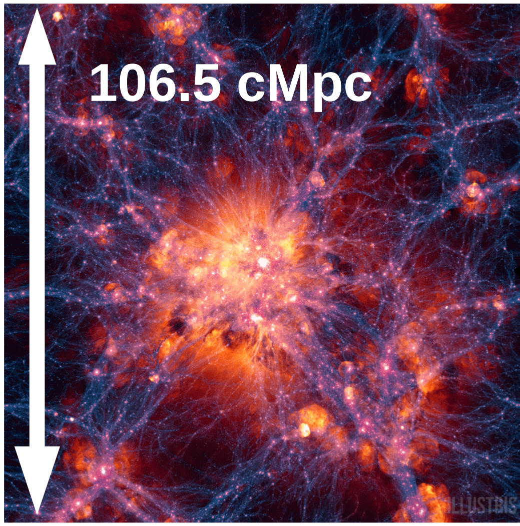
Between 10^9 and 10^{10} $M_\odot$ observed metallicity changes ~0.3 dex for fixed redshift (~0.7)



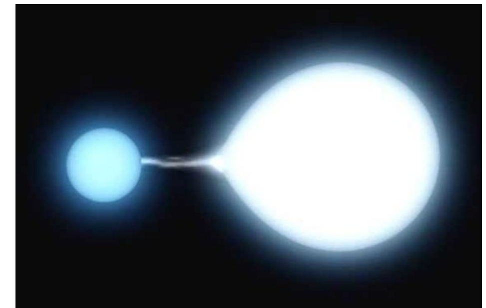
Maiolino et al. 2008, A&A 488, 463-479

4. Compact binaries in cosmological context

Cosmological simulation or data-driven approach



Pop. synthesis of isolated binaries

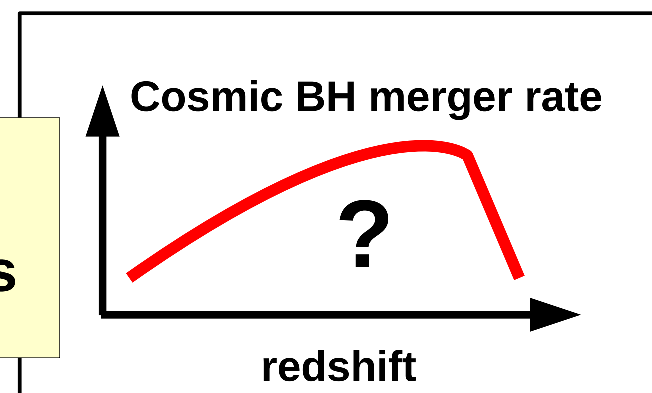


star formation and metallicity in galaxies

catalogues of isolated BH binaries

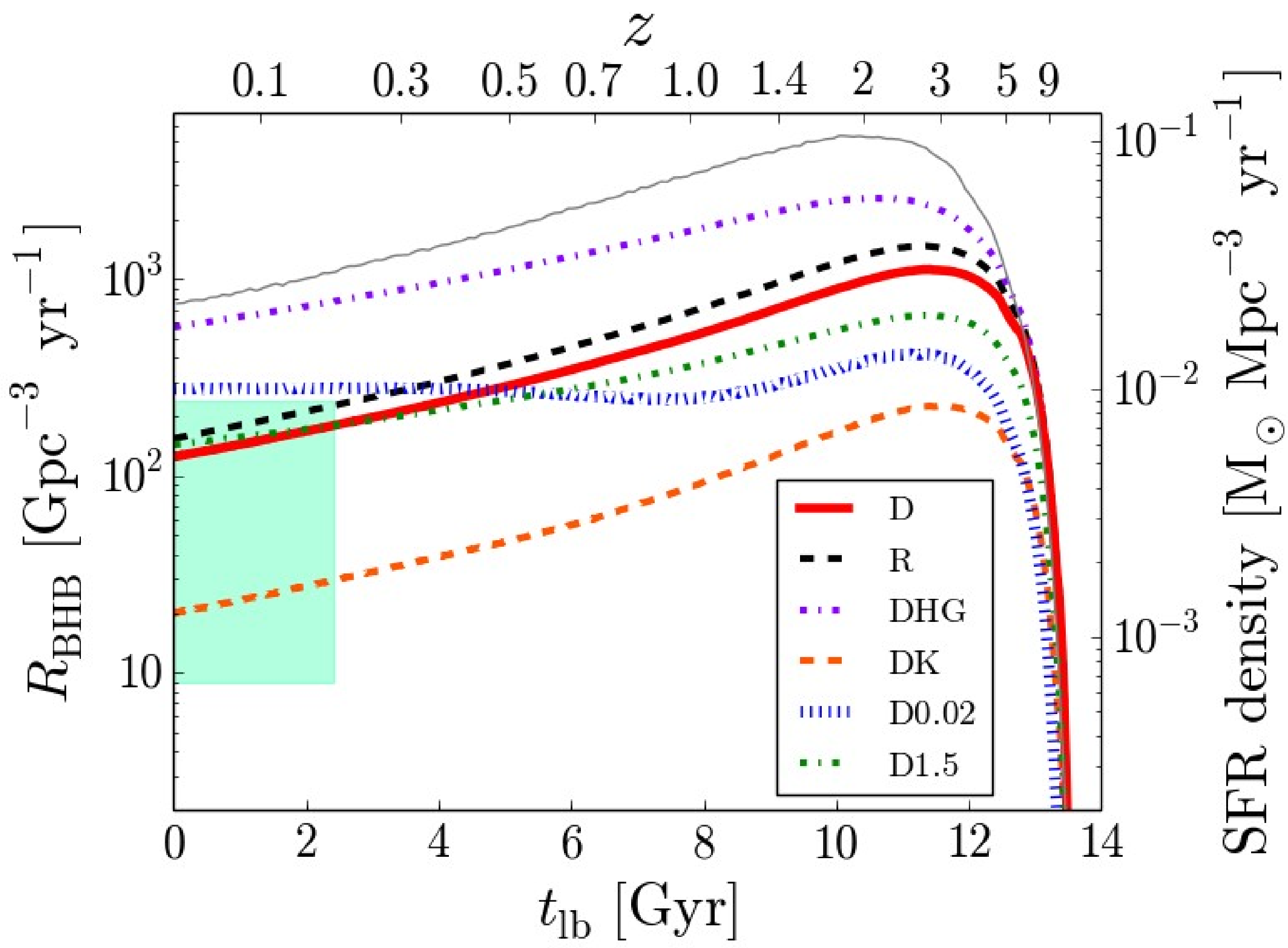
Monte Carlo code
to plant BH binaries in galaxies

Cosmic BH merger rate & host galaxy properties



4. Compact binaries in cosmological context

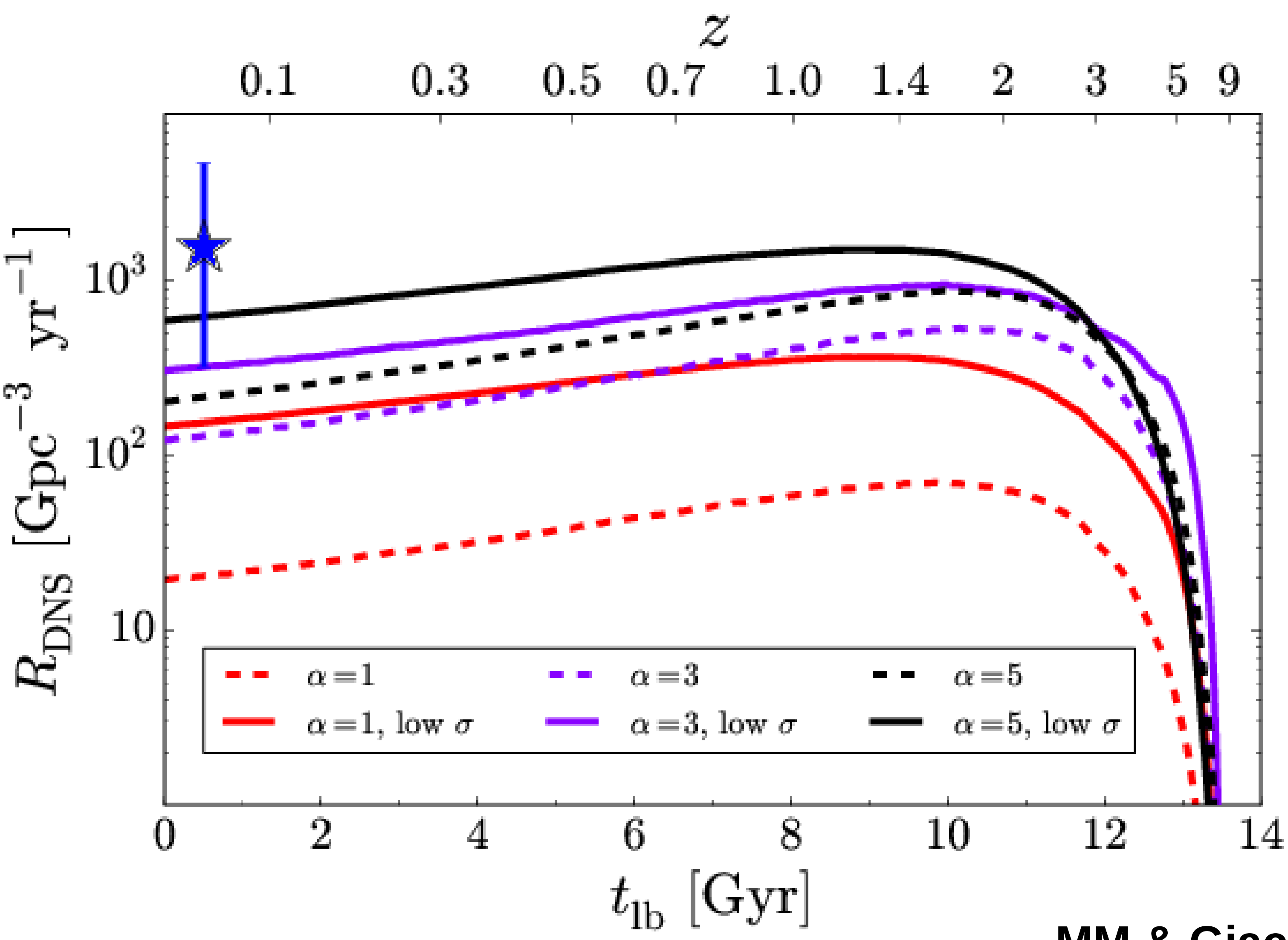
Black hole merger rate density in comoving frame



MM, Giacobbo, Ripamonti, Spera 2017

4. Compact binaries in cosmological context

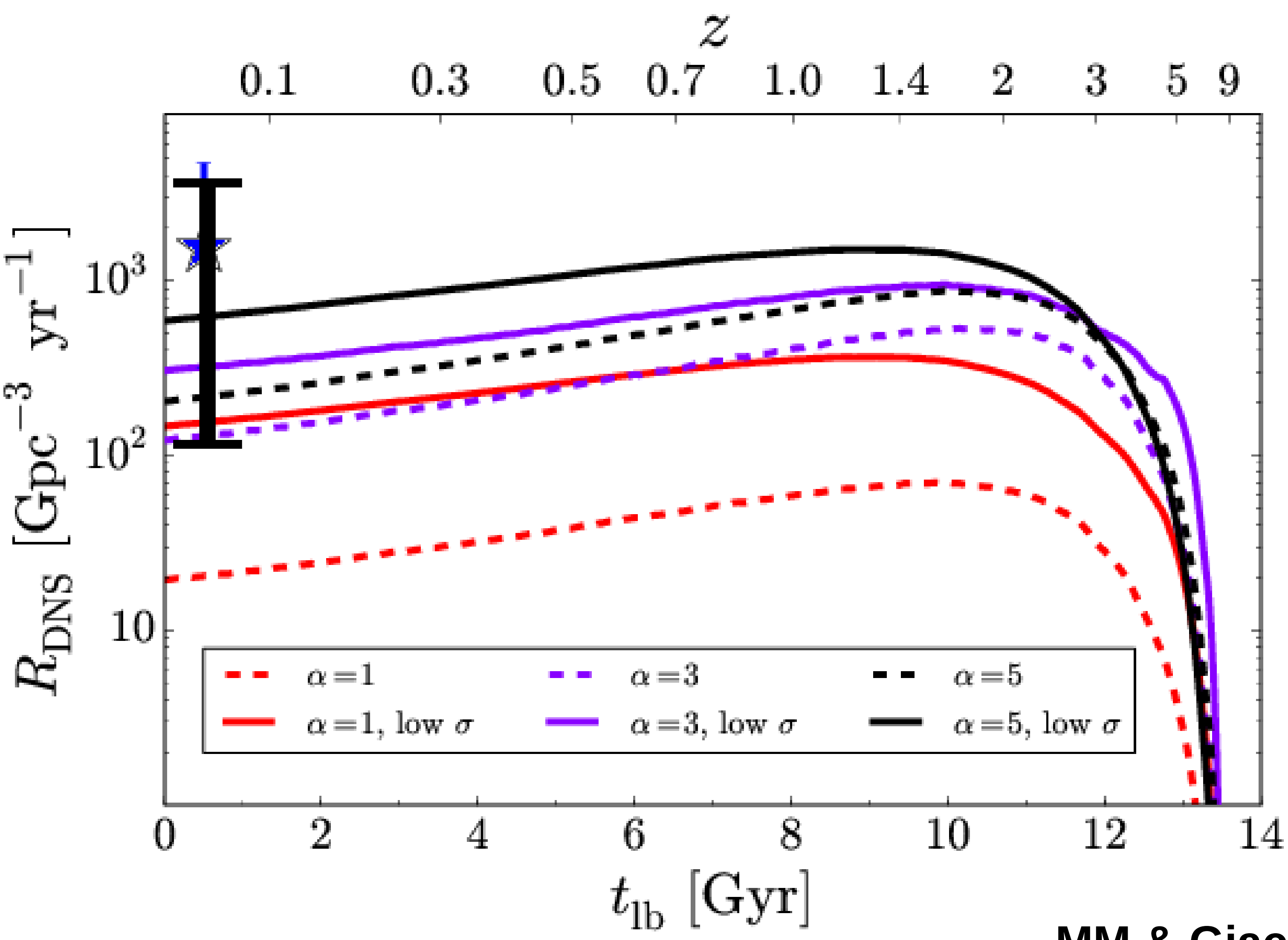
Double neutron star merger rate density in comoving frame



MM & Giacobbo 2018

4. Compact binaries in cosmological context

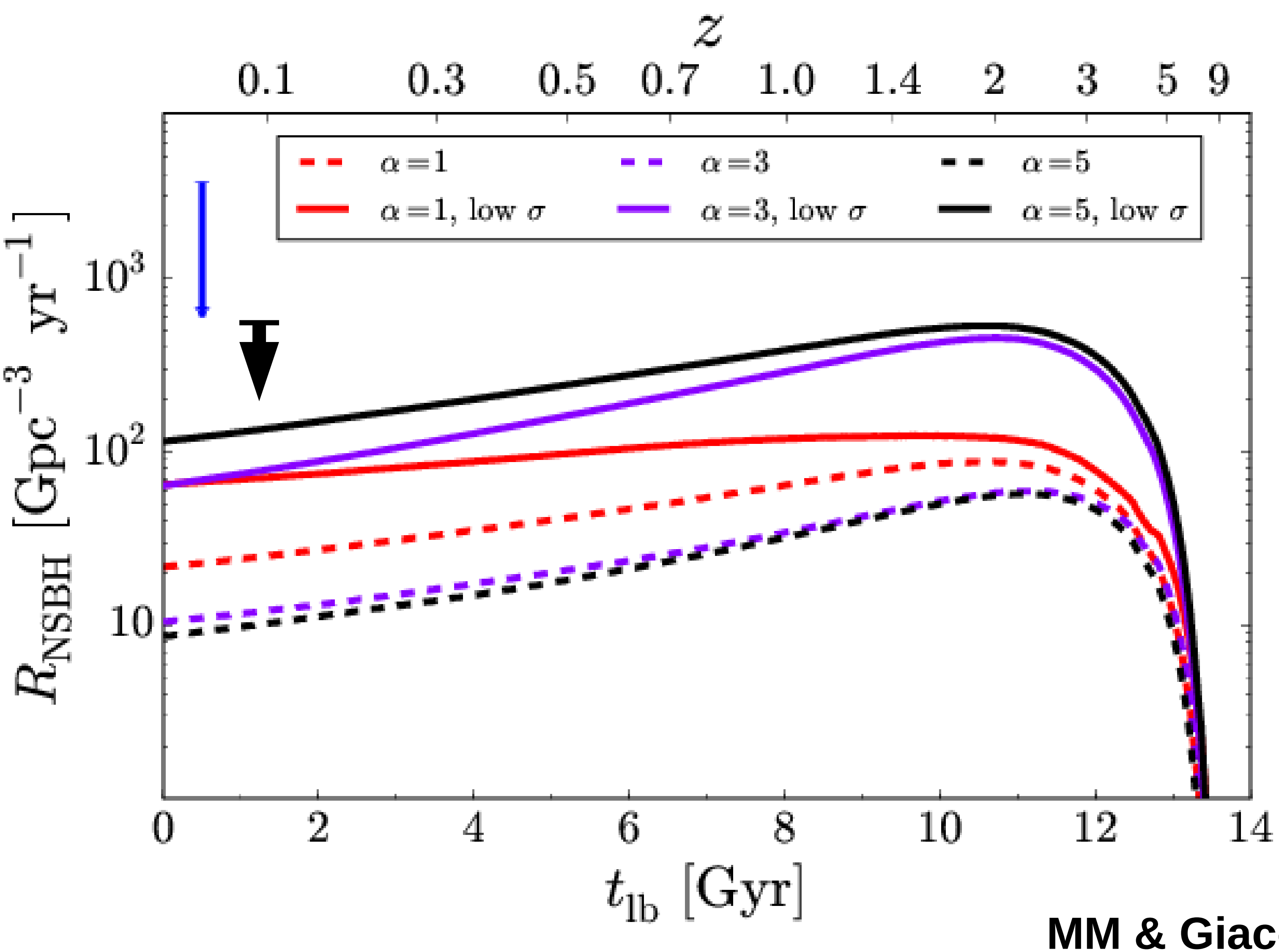
Double neutron star merger rate density in comoving frame



MM & Giacobbo 2018

4. Compact binaries in cosmological context

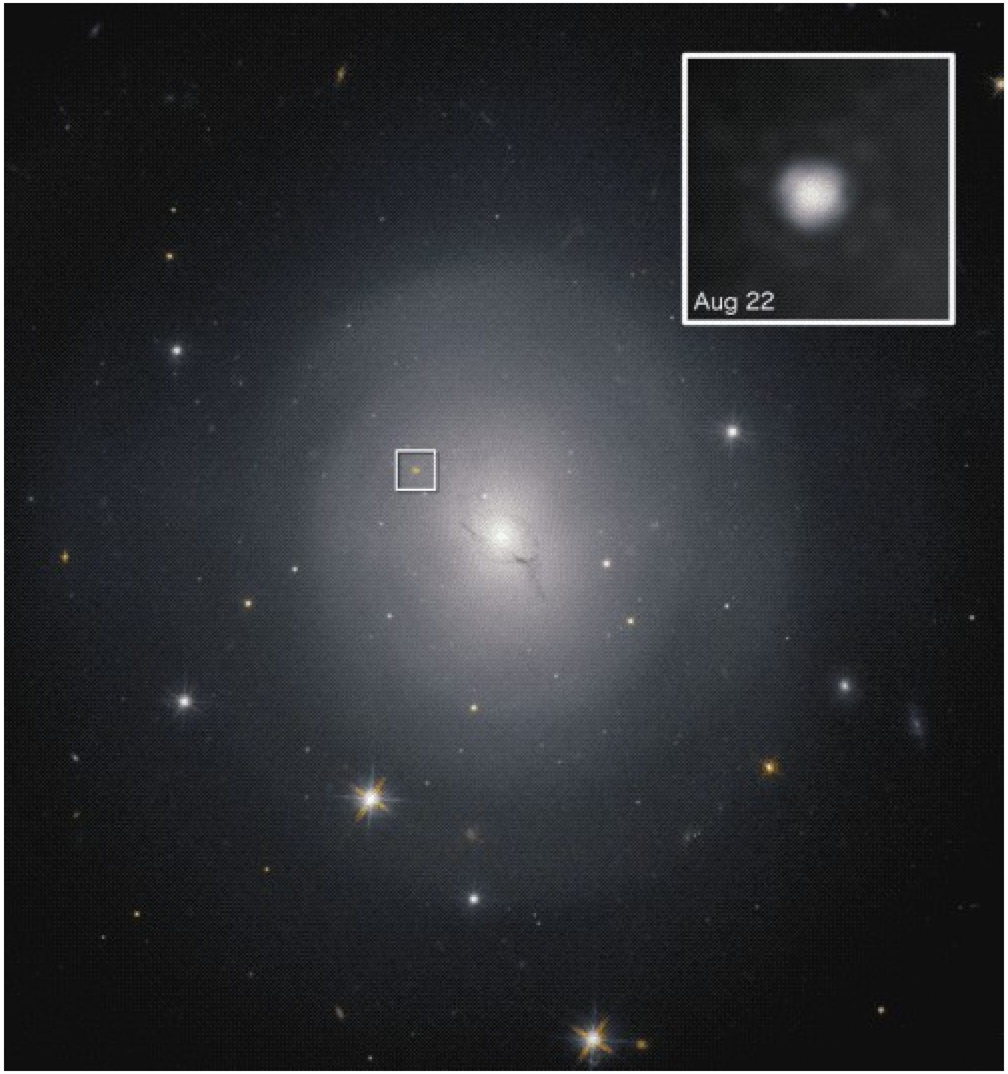
Black hole - neutron star merger rate density in comoving frame



MM & Giacobbo 2018

4. Compact binaries in cosmological context

Host galaxies: only for GW170817 (Abbott+ 2017)



- Early-type (S0) galaxy

- Mostly old stars
  (~ 10 Gyr; Blanchard et al. 2017)

- z ~ 0.0098
  (Levan et al. 2017)

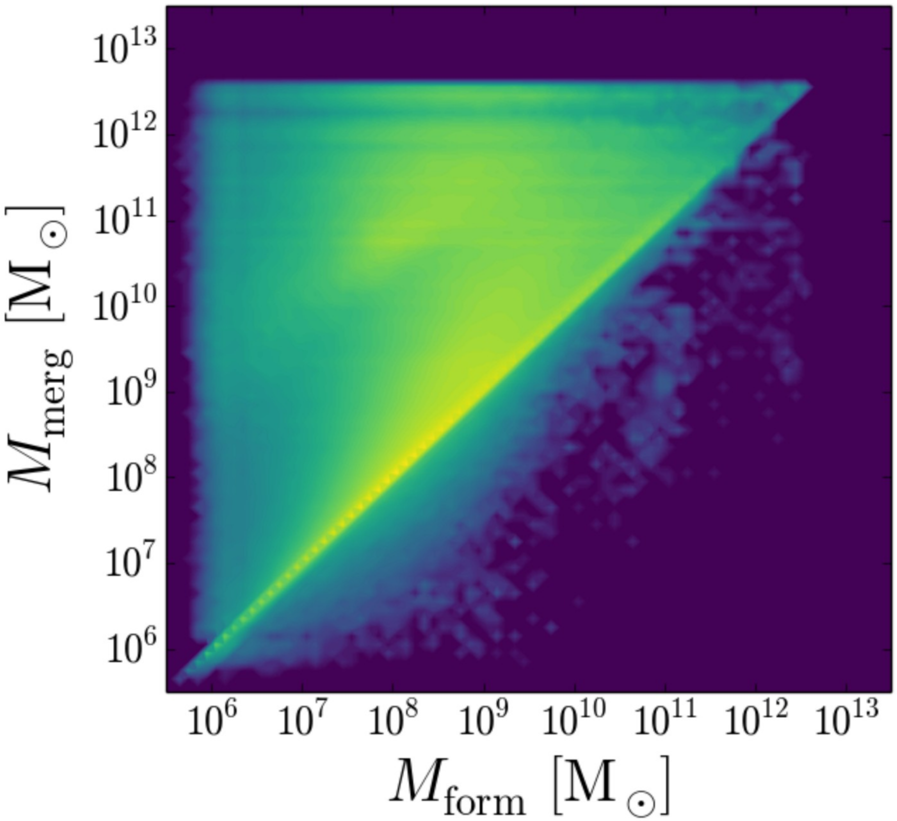
- stellar mass
  ~ 10^{10-11} $M_\odot$
  (Im et al. 2017)

- indications of a merger

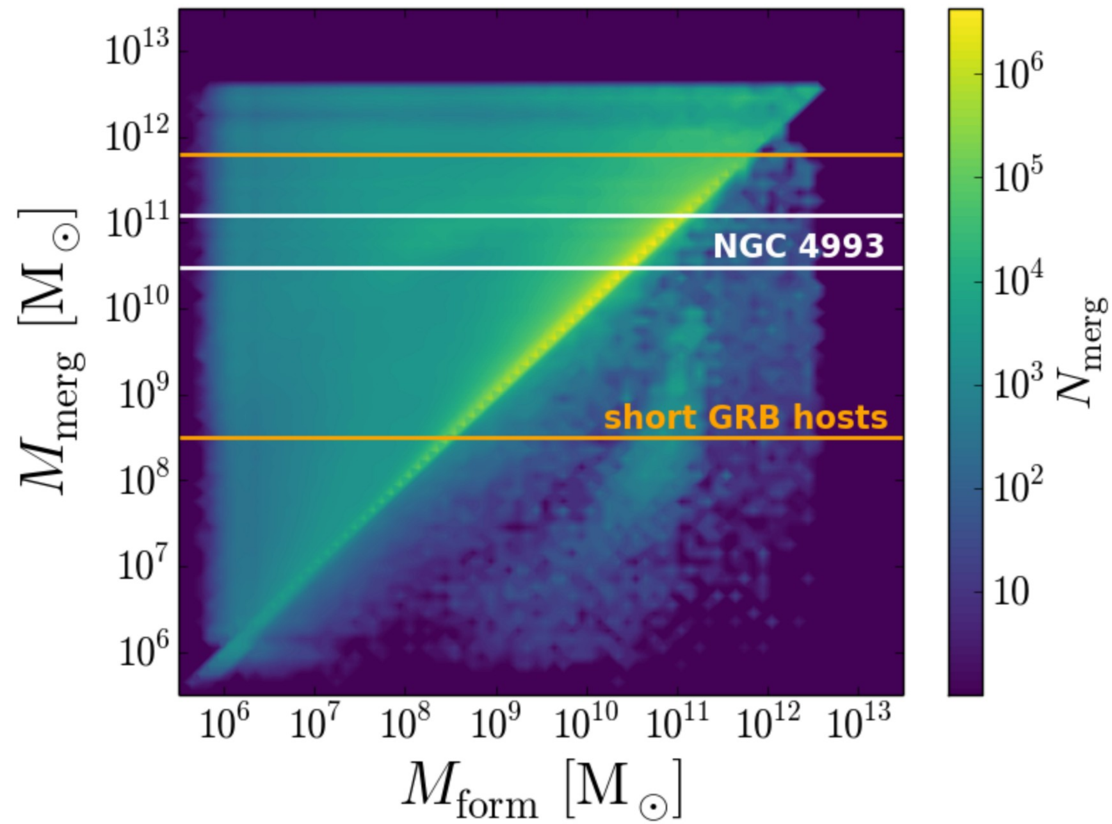
- with cosmo. simulations we can try to characterize them

4. Compact binaries in cosmological context

Double BHs merging at $z < 0.1$



Double NSs merging at $z < 0.1$



BH binaries form mostly in <10^{10} M⊙ galaxies and merge in both small and large galaxies

NS binaries form mostly in 10^9 – 10^{12} M⊙ galaxies and tend to merge where form

→ match GW170817 and short GRB hosts

MM et al. 2018

5. SUMMARY

The era of gravitational-wave astrophysics has just begun ;-)

Still a lot of work to do to understand

- *** the evolution of compact binaries (in isolation and in star clusters)**
- *** the environment, host galaxies and redshift evolution of binary populations**

THANK YOU!