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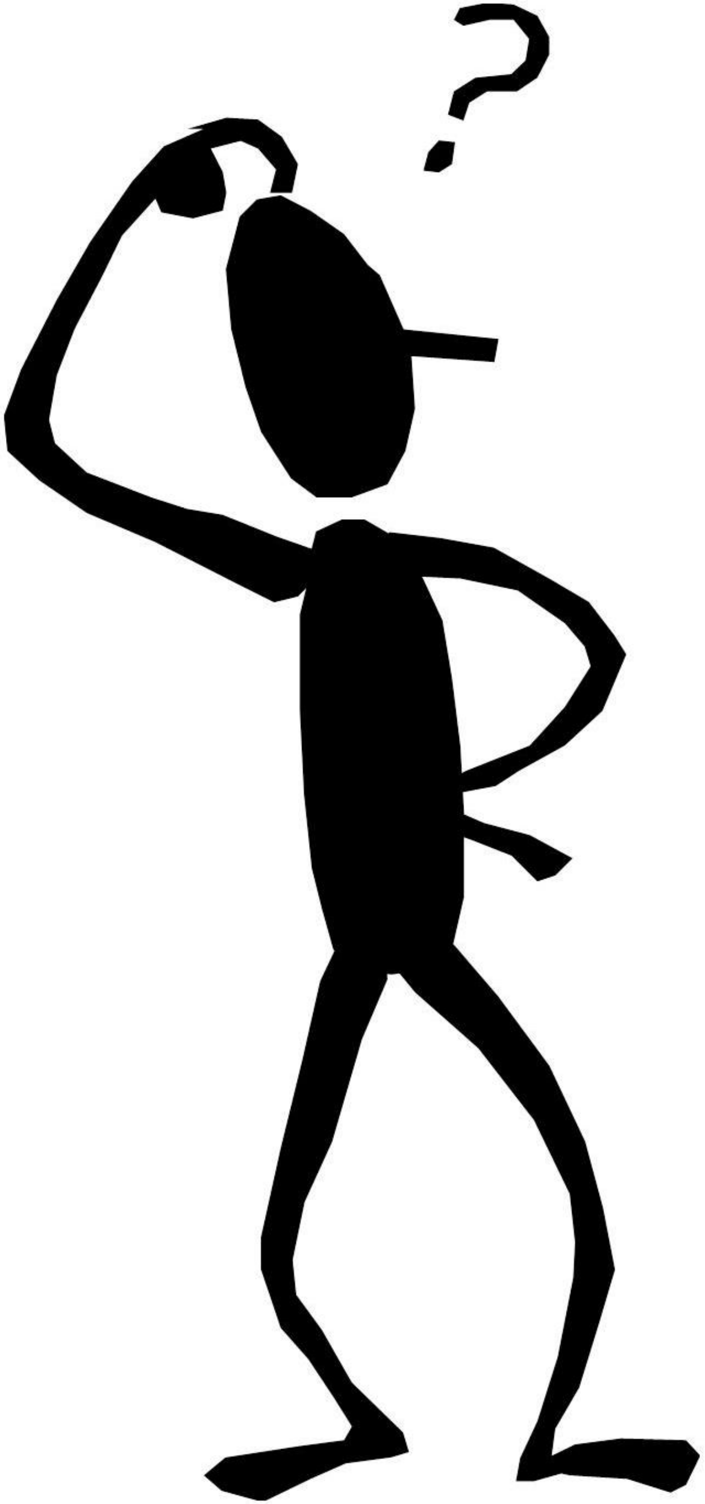
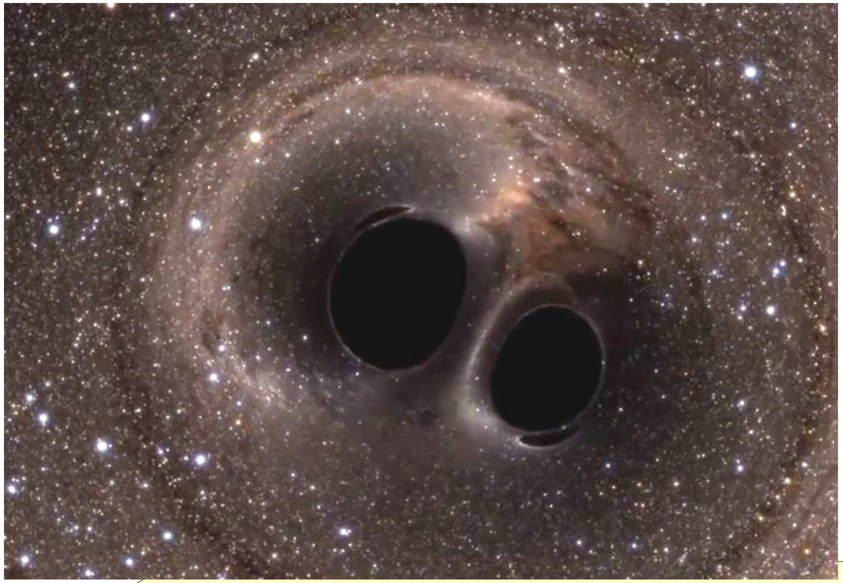
2012 FIRB fellow
2015 MERAC prize

Stellar black hole (astro-) physics

Collaborators: Mario Spera, Nicola Giacobbo, Alessandro A. Trani, Sandro Bressan, Elisa Bortolas, Alessandro Ballone, Ugo N. Di Carlo, Marica Branchesi

Enrico Fermi School, Varenna, July 2 – 12 2017





TWO OPEN QUESTIONS:

1. What are the progenitors of merging binaries observed by LIGO?

2. Do LIGO/Virgo observations help us constraining the astrophysical properties and formation channels of black holes (BHs)?

OUTLINE:

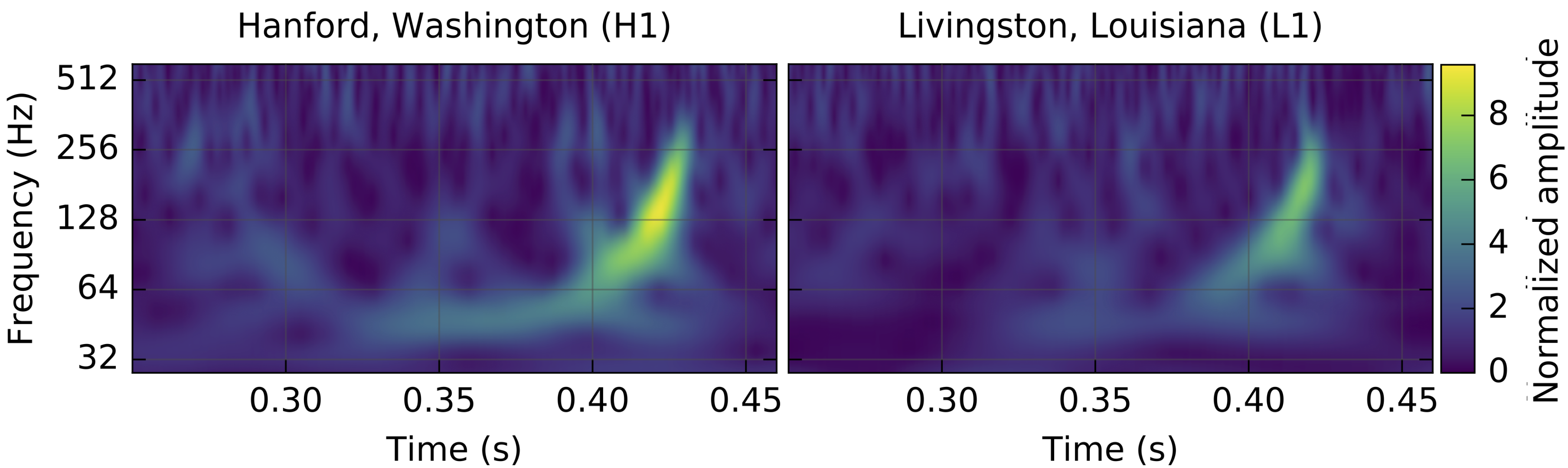
1. The formation of compact remnants from stellar evolution and supernova explosions

2. Binaries of stellar black holes (BHs)

3. The dynamics of BH binaries

4. BH binaries in cosmological context

1. The formation of compact remnants



What have astrophysicists learned from first 3 detections?

1. double black hole (BH) binaries exist

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

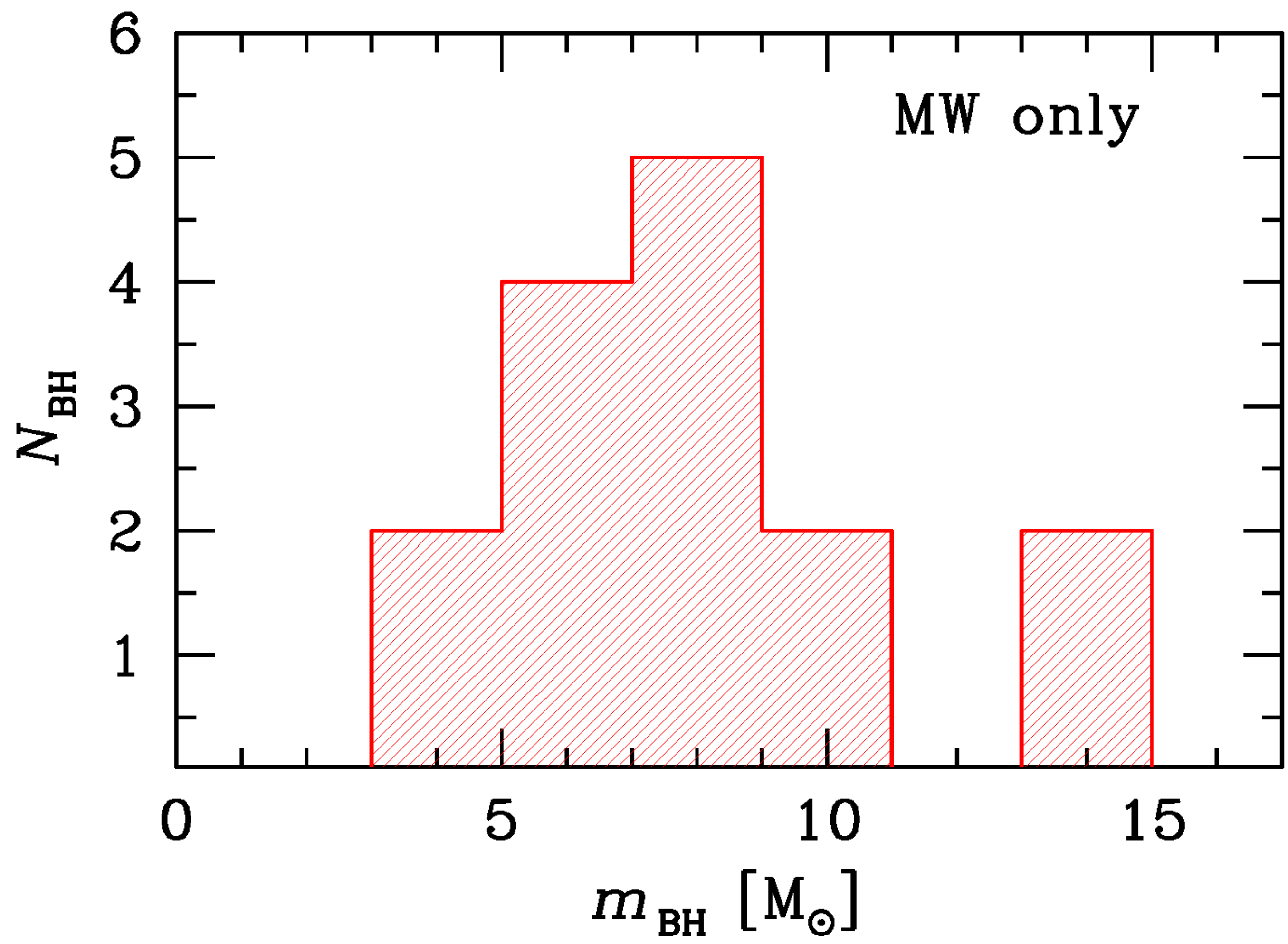
2. can merge in a Hubble time

3. massive BHs exist i.e. stellar-mass 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 remnants

Dynamical measurements of ~10 BH masses in Milky Way X-ray binaries

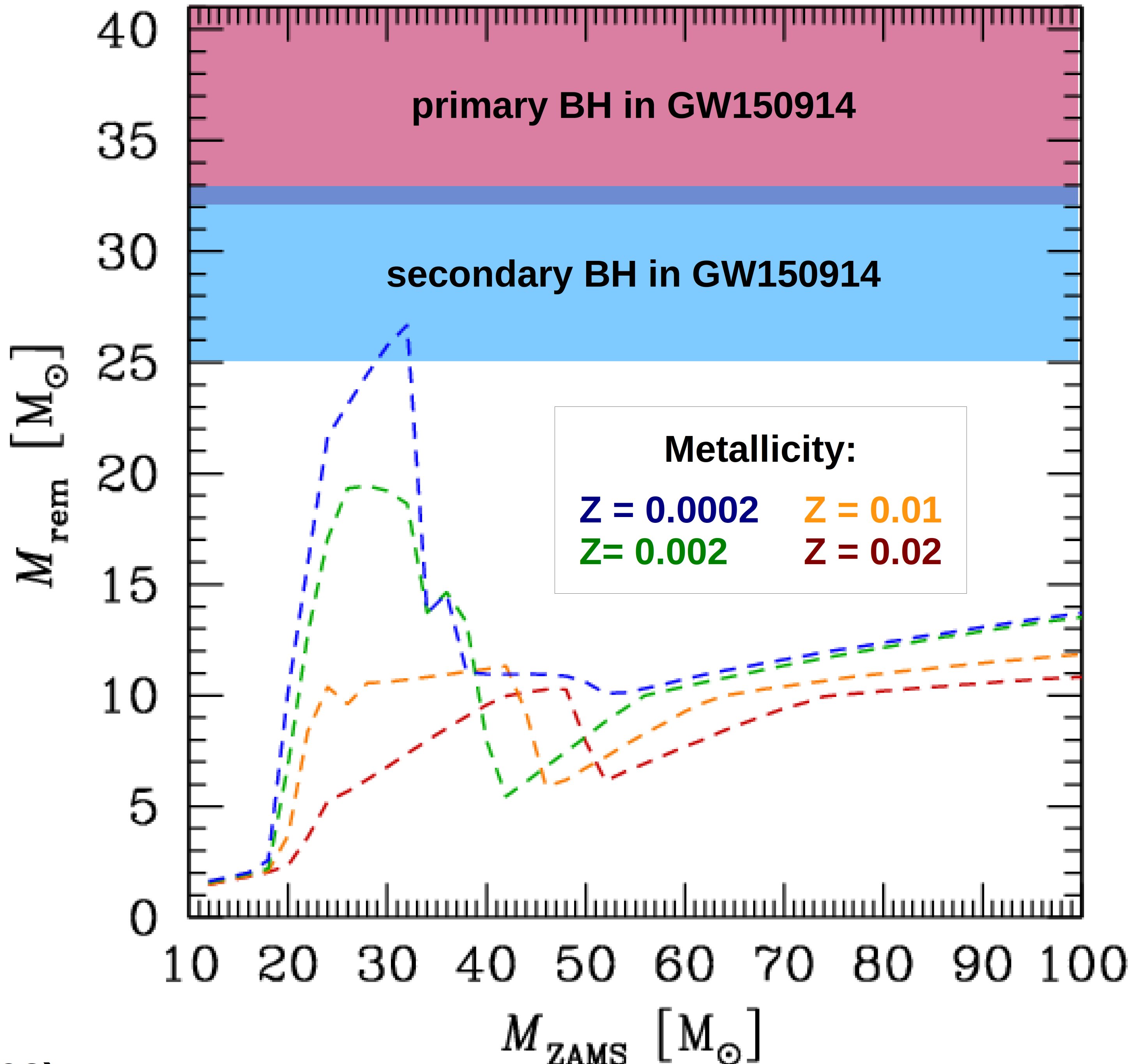


compilation from
Orosz+ 2003,
Ozel+ 2010

1. The formation of compact remnants

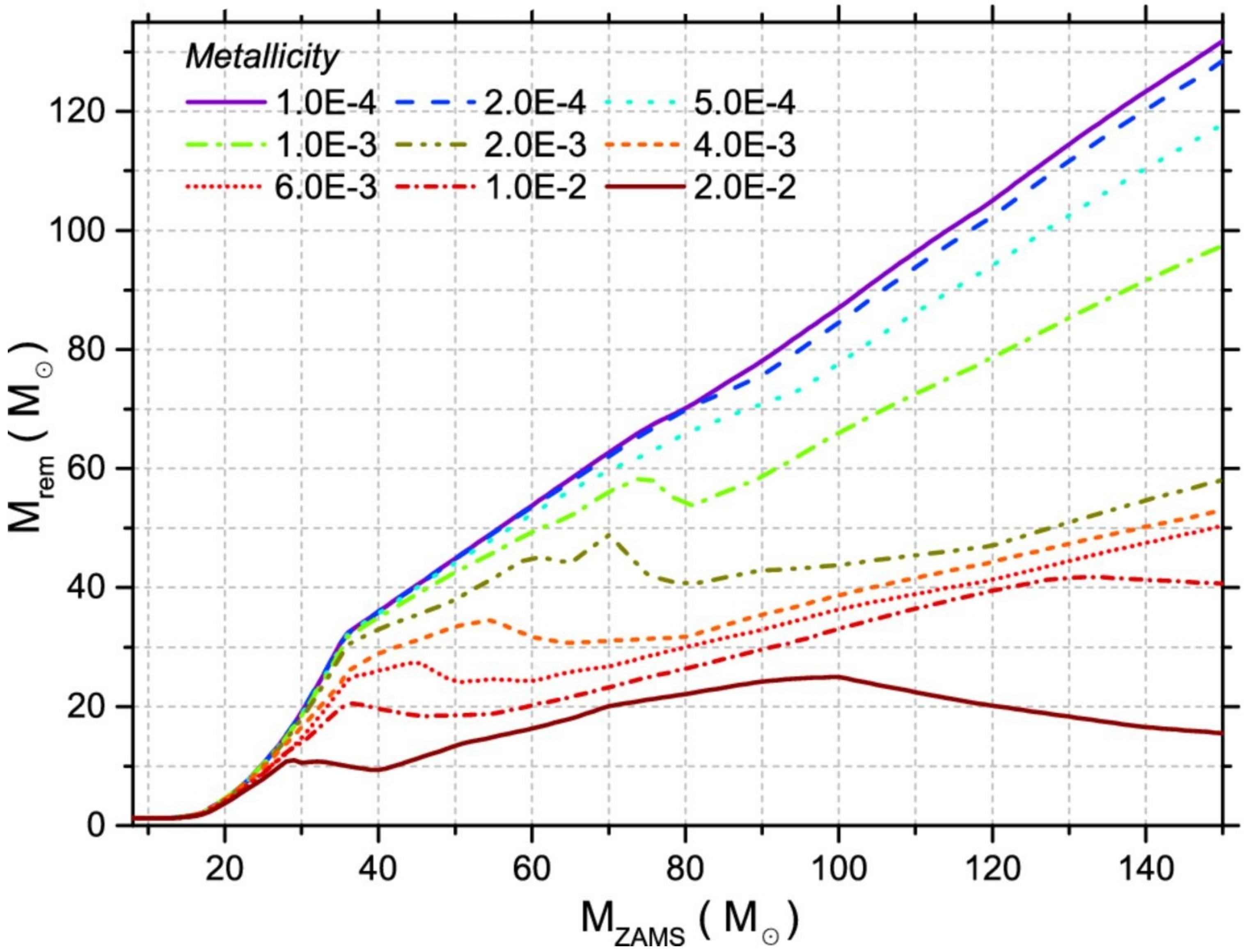
Most common remnant mass spectrum BEFORE GW150914 detection

cannot explain GW150914



(BSE code, Hurley+ 2002)

1. The formation of compact remnants



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

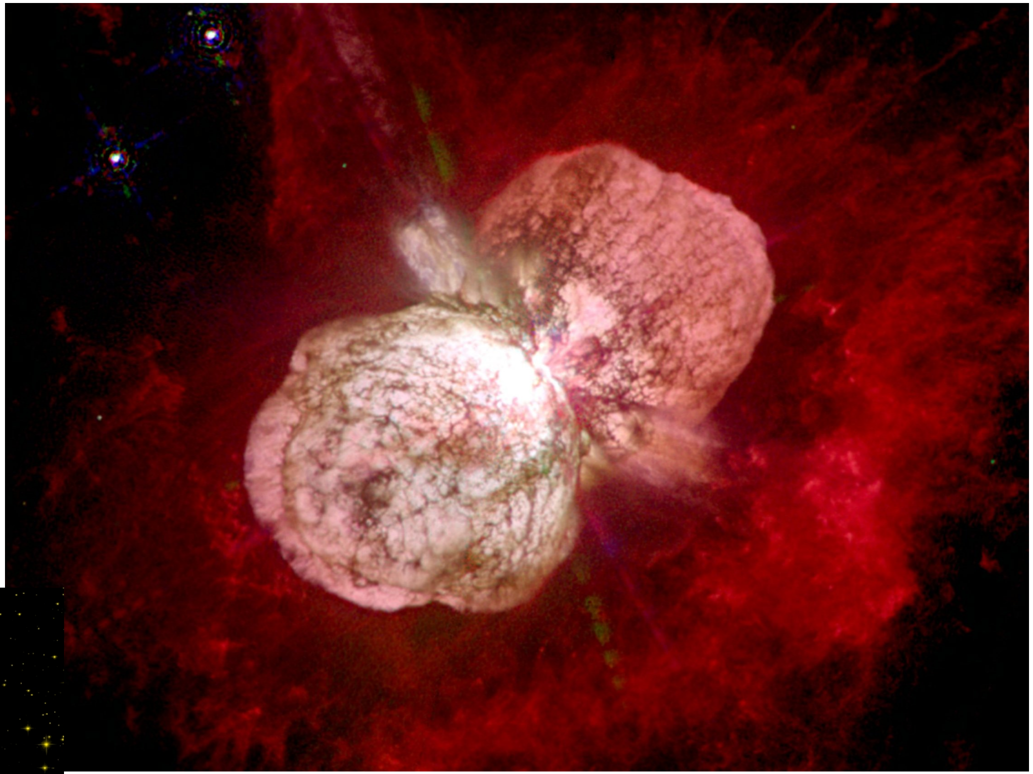
See also MM+ 2009, MNRAS, 395, L71; MM+ 2010, MNRAS, 408, 234; Belczynski+ 2010, ApJ, 714, 1217; Fryer+ 2012, ApJ, 749, 91; MM+ 2013, MNRAS, 429, 2298; Belczynski+ 2016, A&A, 594, 97; Spera & MM 2017, MNRAS, in press, arXiv:1706.06109

1. The formation of compact remnants

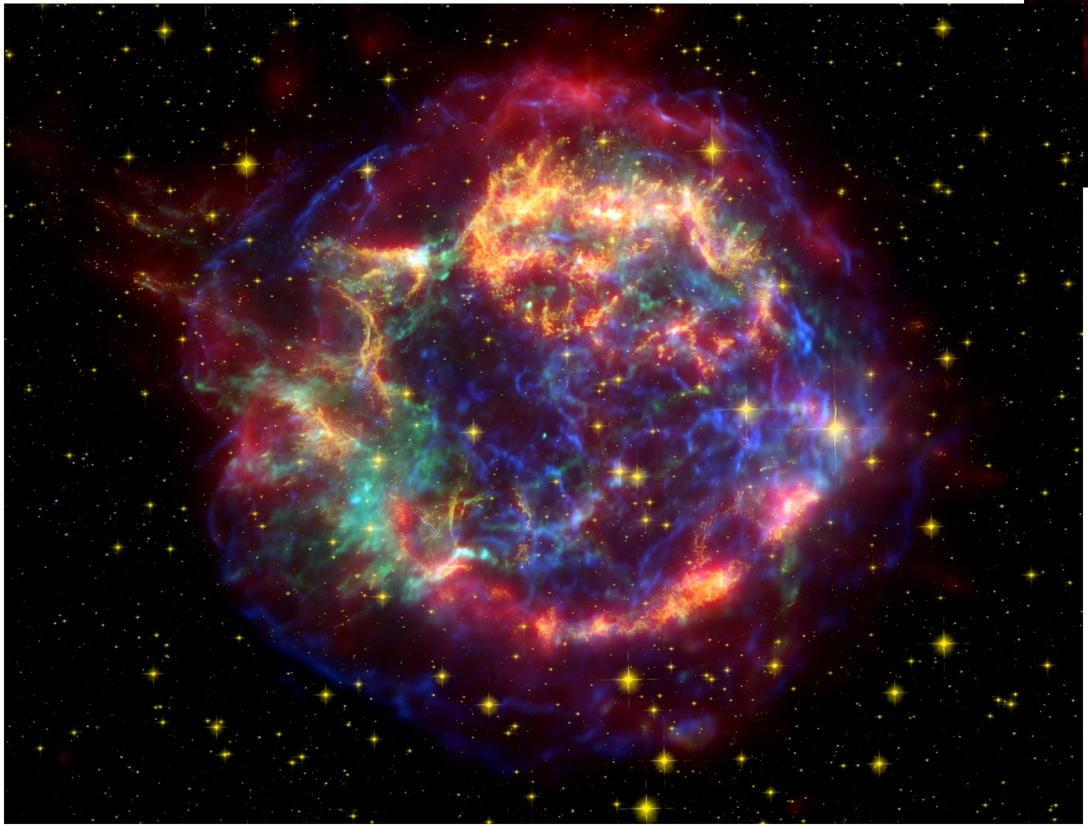
Two critical ingredients:

1) STELLAR WINDS

2) SUPERNOVA (SN) EXPLOSION



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



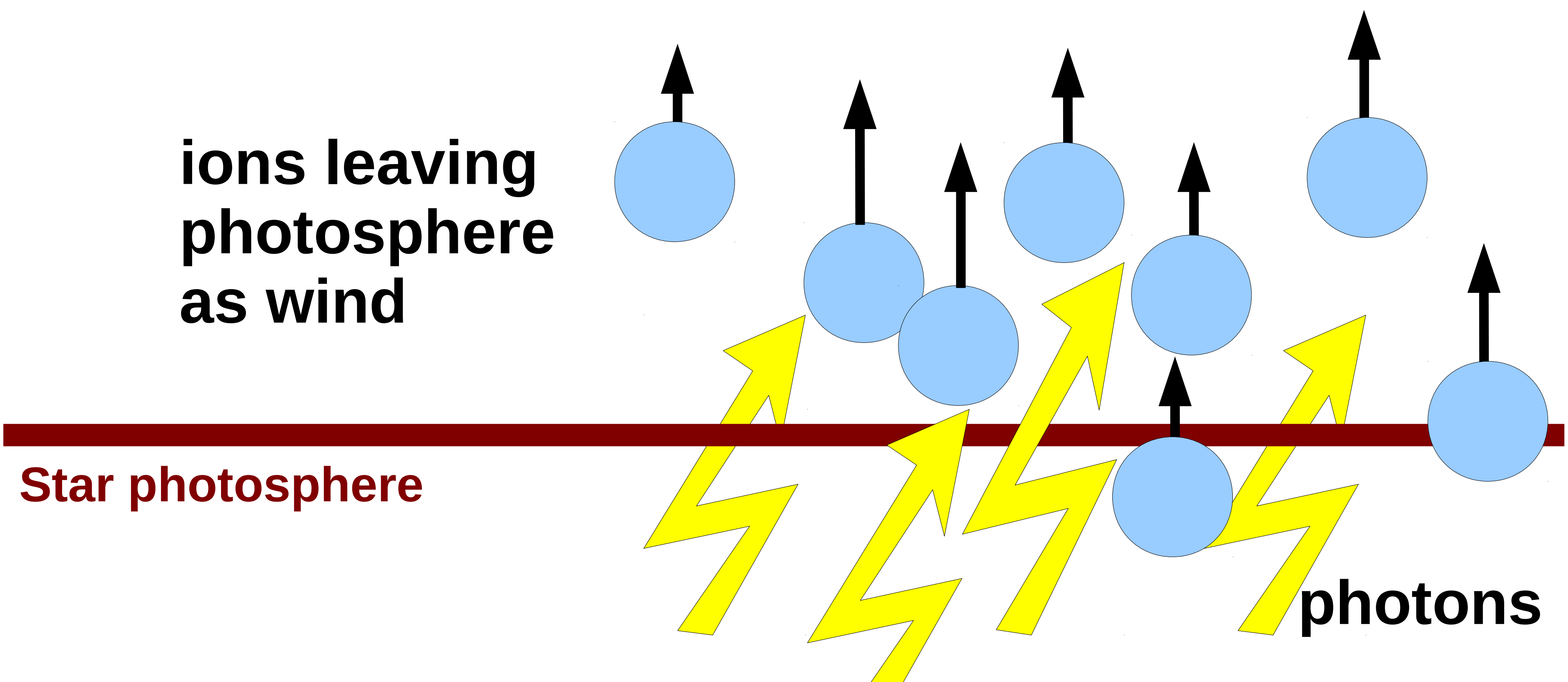
Chandra + HST + Spitzer Image of the SN remnant Cassiopeia A

1. The formation of compact remnants: 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:
$X \sim 0.73$, $Y \sim 0.25$, $Z \sim 0.02$

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

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

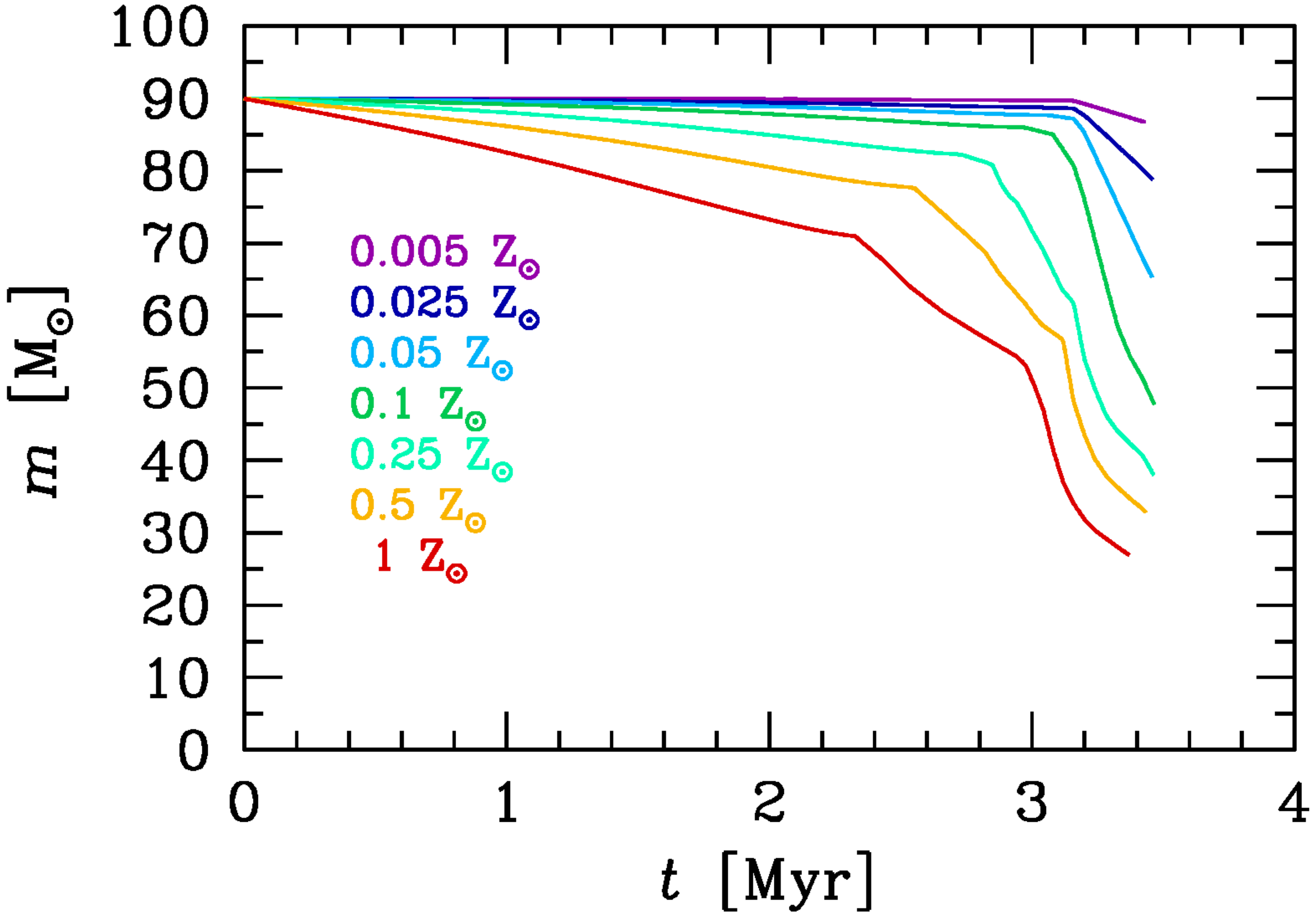
e.g. Graefener & Hamann 2008

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

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

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

1. The formation of compact remnants: stellar winds



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

1. The formation of compact remnants: stellar winds

Mass loss depends on metallicity

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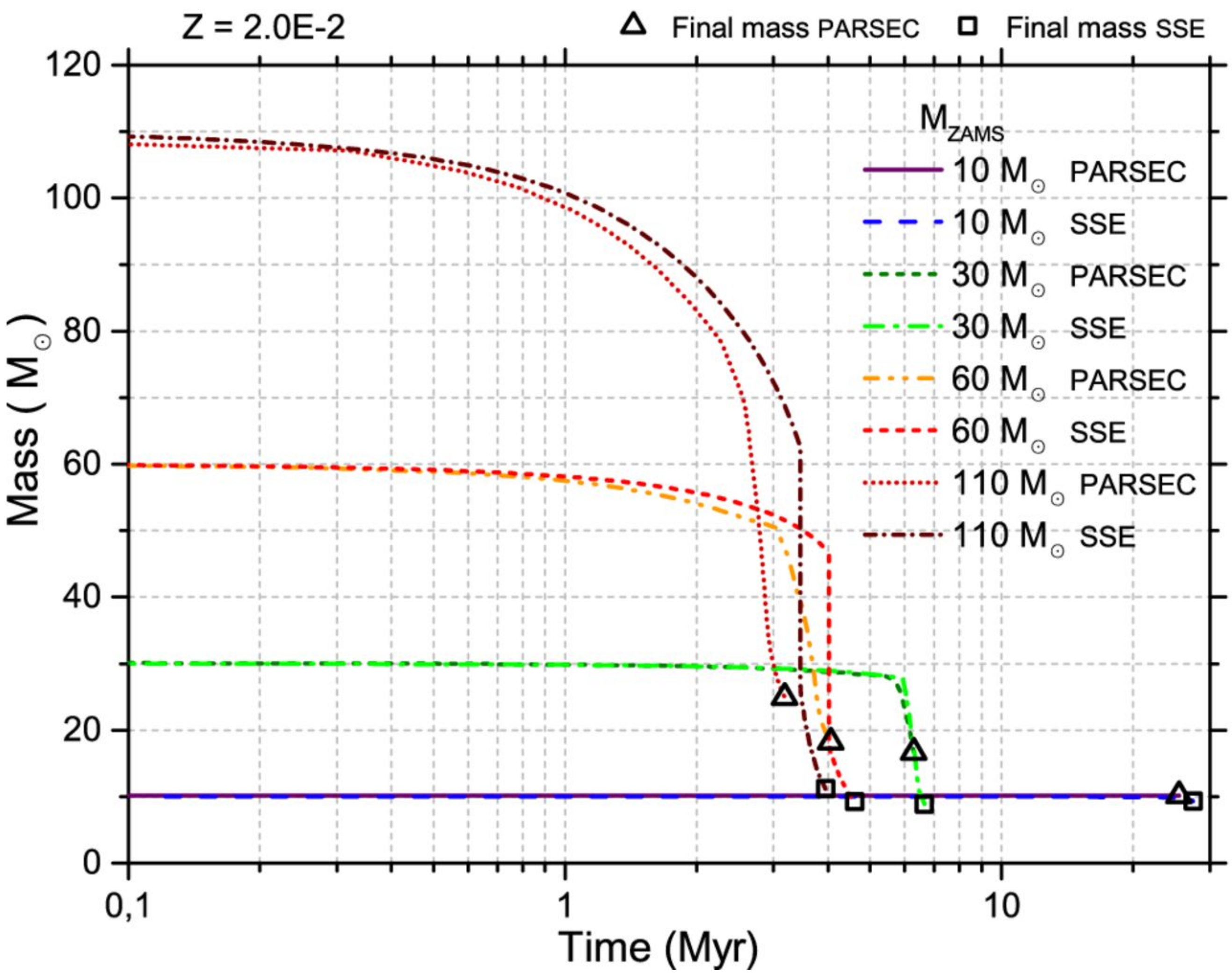
Z = 1 Zsun



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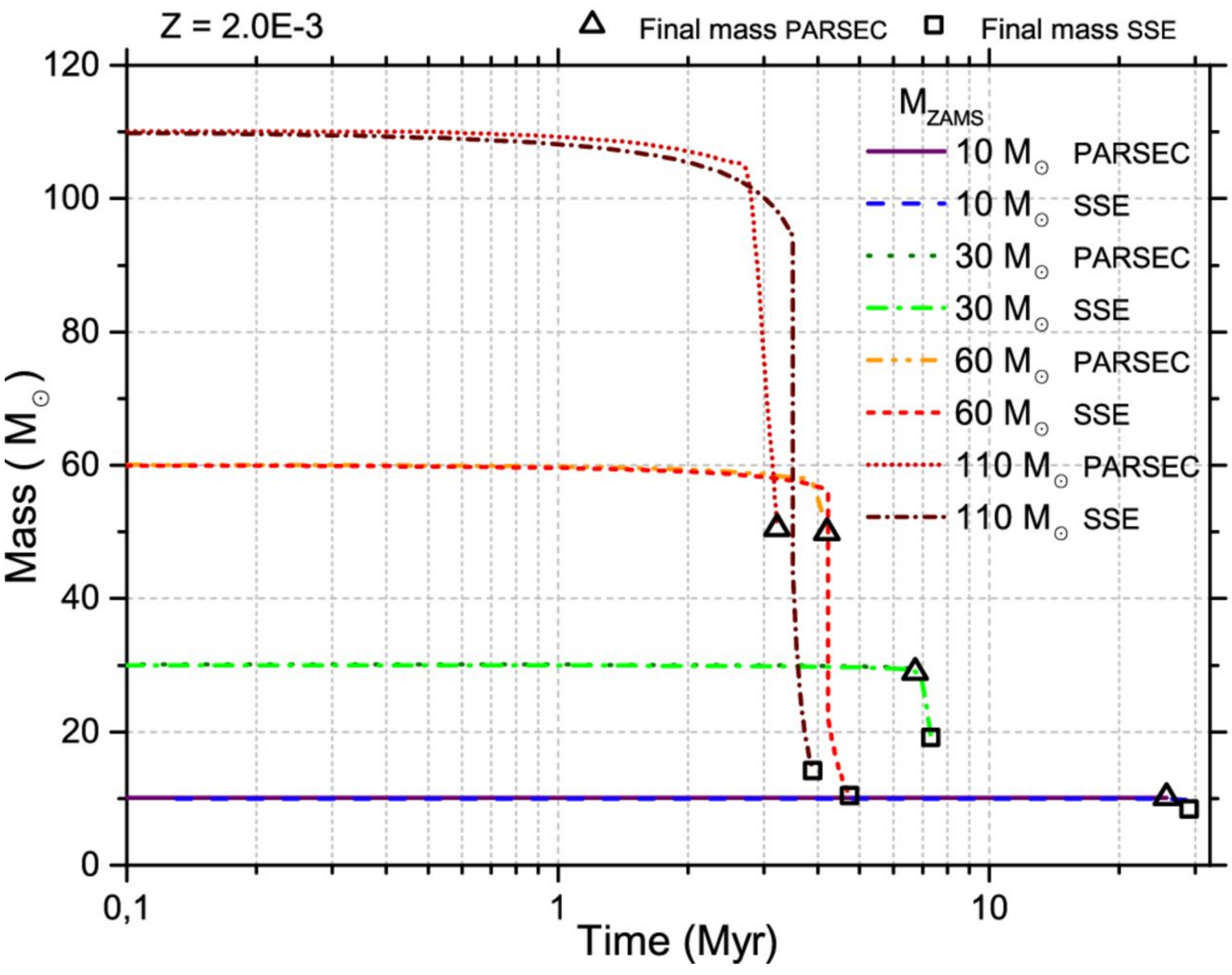

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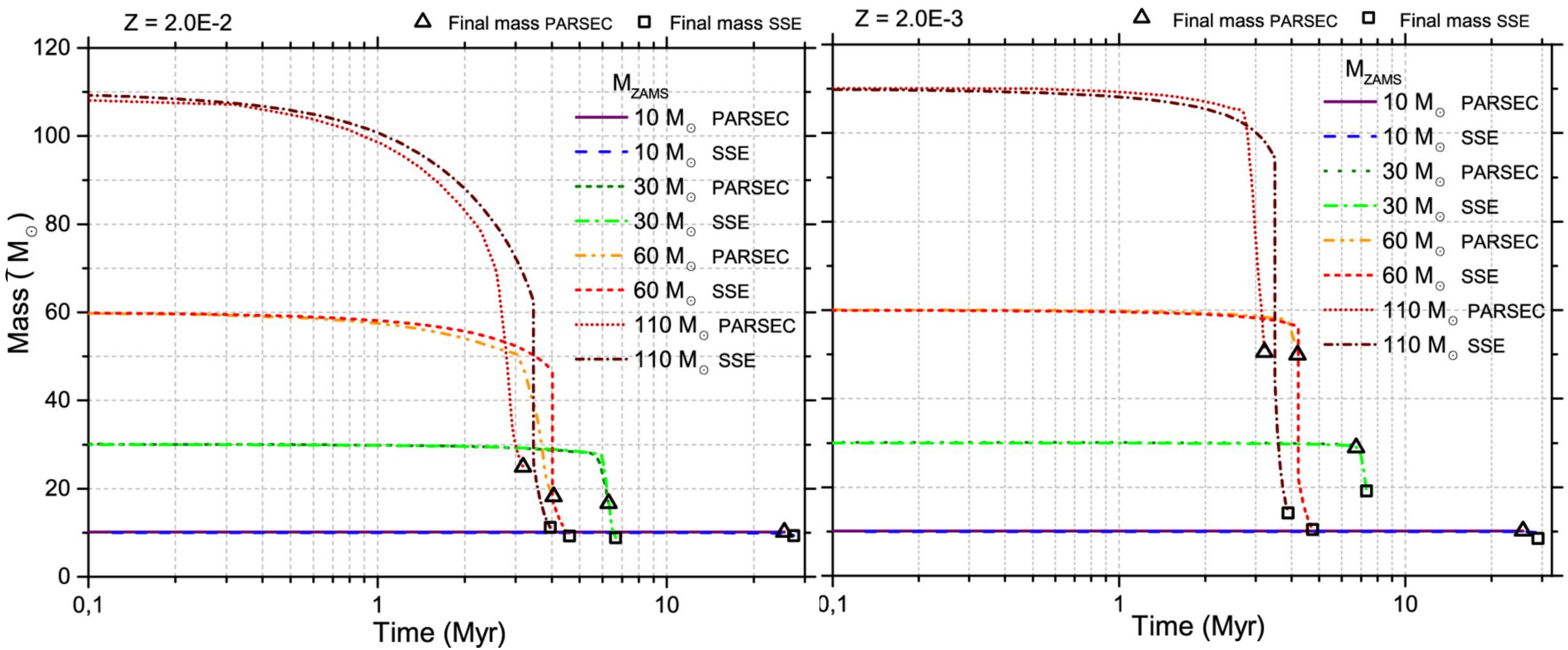
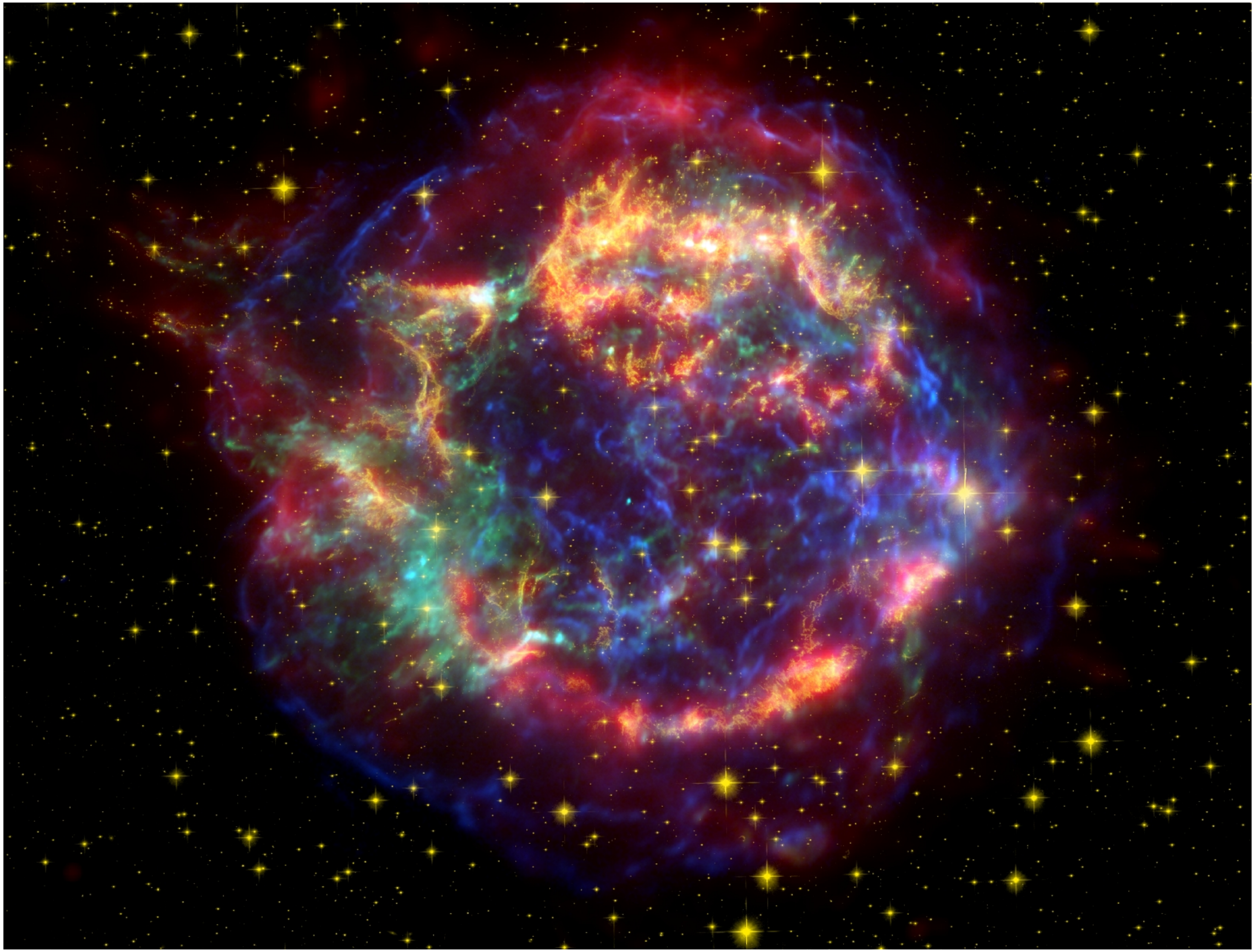


Pre-supernova mass of a star depends on metallicity

Models from PARSEC stellar evolution code (Bressan+ 2012; Tang+ 2014; Chen, Bressan+ 2015) vs SSE population synthesis code (Hurley+ 2000, 2002)

1. The formation of compact remnants: supernova

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



1. The formation of compact remnants: 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 remnants: supernova

Fraction of binding energy of core (Eb,c ~10^{53} erg)
used to launch a SHOCK : = supernova explosion

MECHANISM that converts binding energy into shock is UNKNOWN

STANDARD MODEL: CONVECTIVE ENGINE

Potential energy is converted into thermal energy
(mostly thermal energy of neutrinos)
and core bounces driving shocks

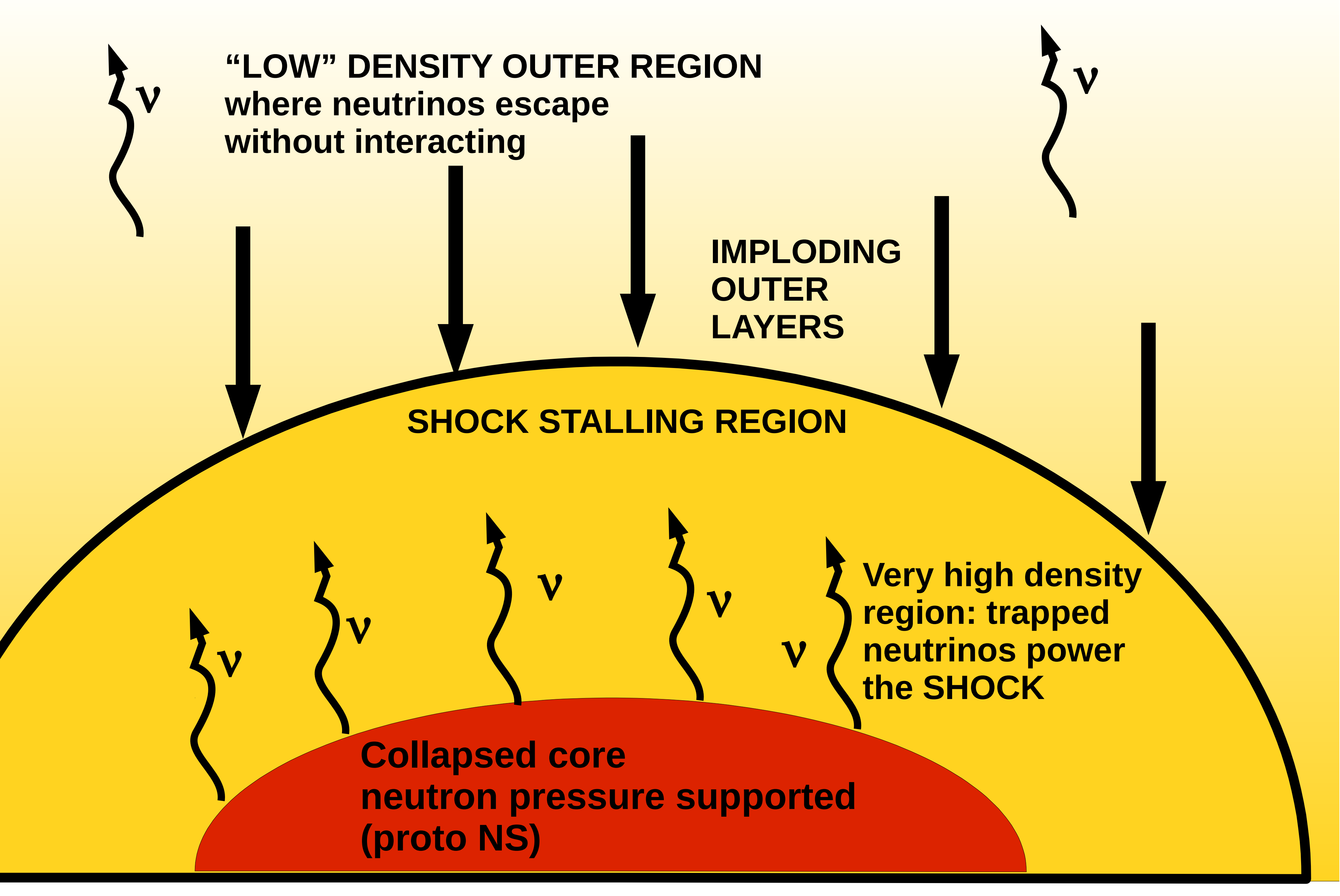
SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS

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

<u>WHEN DOES THE SHOCK STALL and the SN FAILS?</u>

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

1. The formation of compact remnants: supernova



1. The formation of compact remnants: supernova

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

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

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

envelope mass ($M_{\rm env}$)

proto-NS ~ 1 Msun ($M_{\rm core}$)

envelope radius ($R_{\rm env}$)

Star cannot explode if envelope binding energy > SN energy

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

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

1. The formation of compact remnants: supernova

NOT SO EASY (1):
it depends on the "compactness" of the inner layers of the star

STAR COLLAPSES TO BH DIRECTLY IF

1. MASS OF CARBON-OXYGEN CORE
If Mco > 7 Msun   SN FAILS
(Fryer+ 1999, 2012; Belczynski+ 2010)

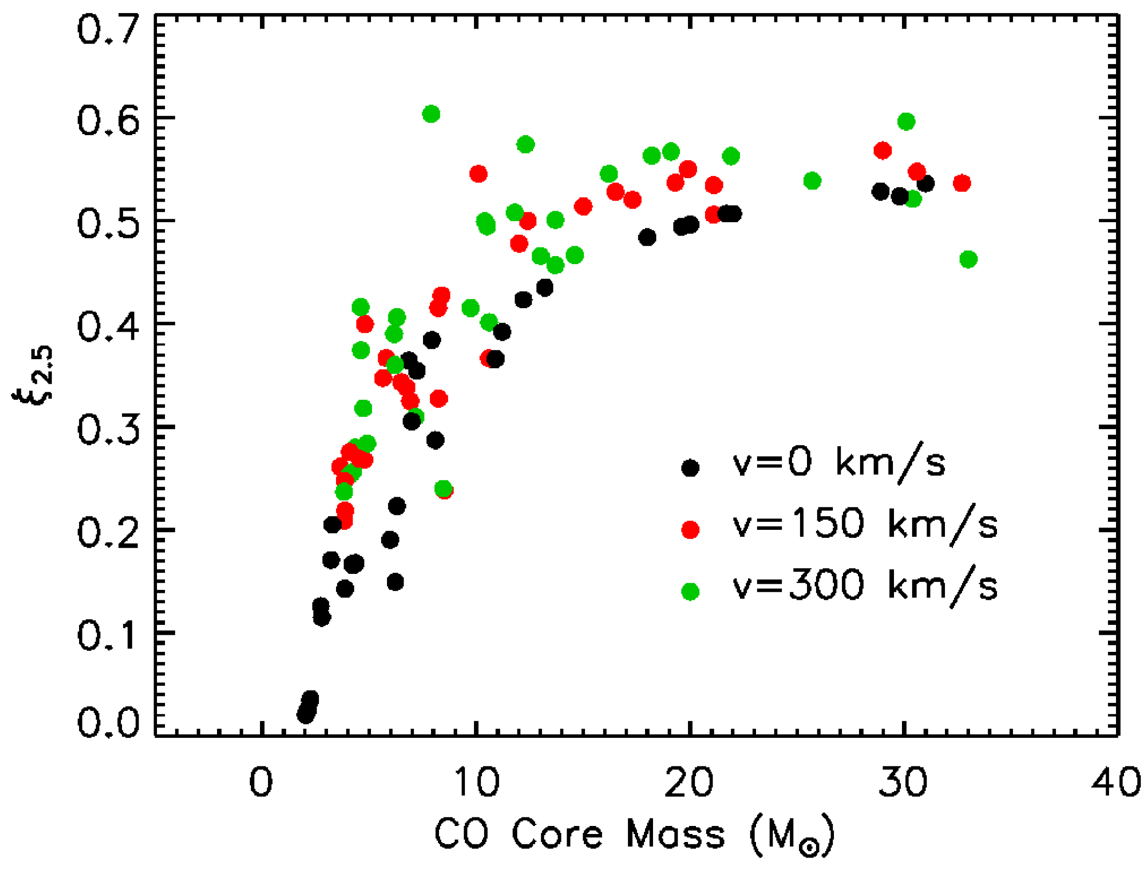
1. The formation of compact remnants: supernova

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

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

Star collapses if $\xi_{2.5} > 0.2$ **(*M* = 2.5 M⊙ is usually adopted)**

Figure from Limongi 2017 arXiv:1706.01913



1. The formation of compact remnants: supernova

3. enclosed mass (M_4) and mass gradient (μ_4) at a dimensionless entropy per nucleon *s* = 4 (Ertl+ 2016)

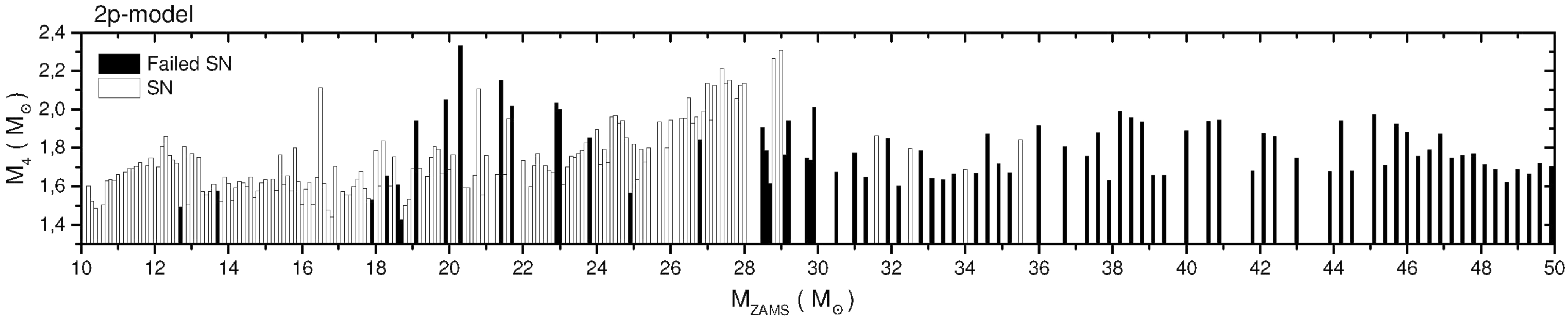


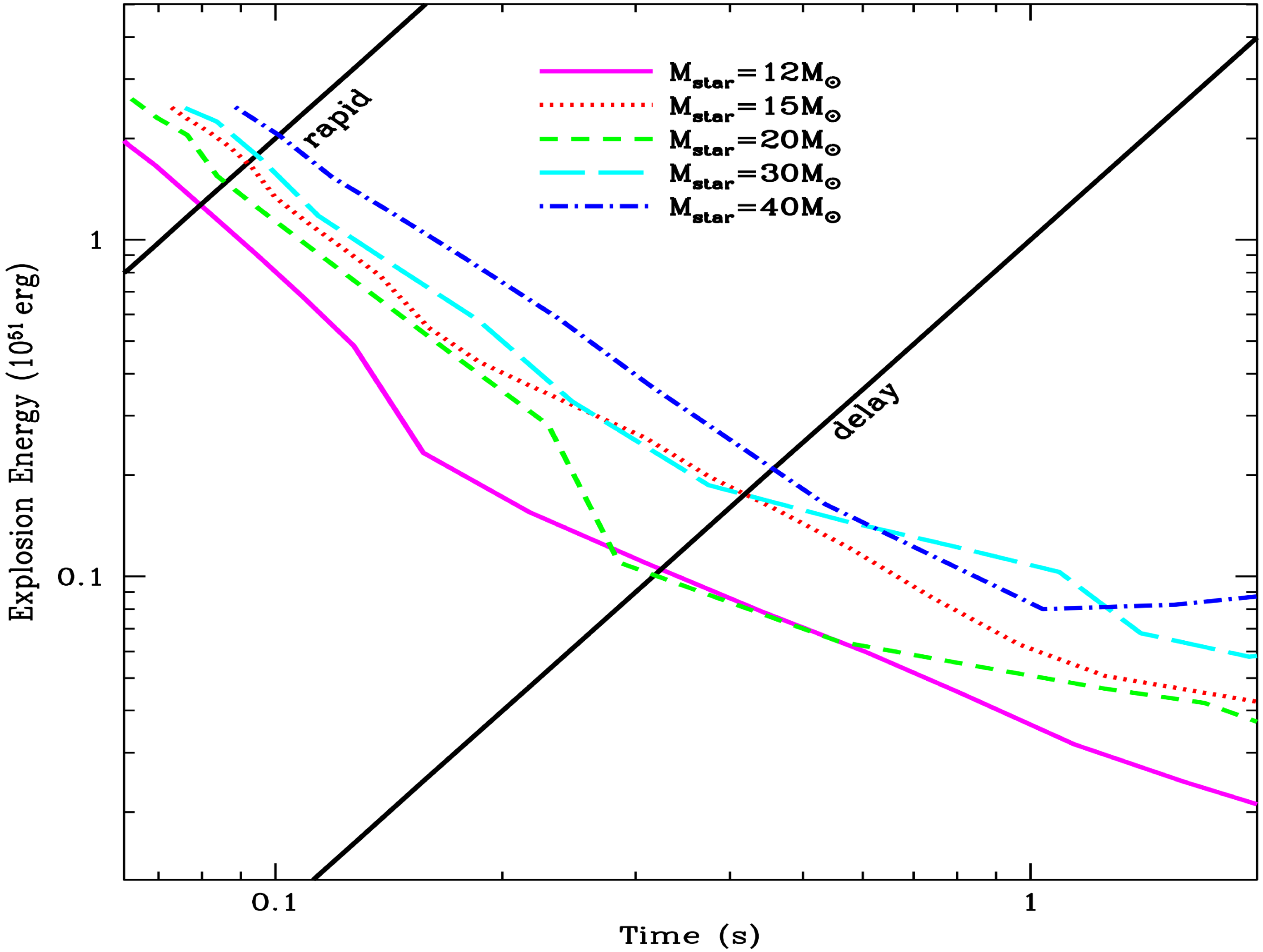
Fig. 21 Spera, MM, Bressan 2015

ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION

Concluding remark:
MANY MODELS of SN EXPLOSION – REMNANT MASS CONNECTION
BUT IF THE STAR IS VERY MASSIVE (>40 $M_\odot$)
THEY GIVE SIMILAR RESULT

1. The formation of compact remnants: supernova

NOT SO EASY (2):
it depends on the "rapidity" of the explosion
(e.g. Fryer+ 2012; Fryer 2014)



RAPID
(<200 ms
after bounce):
explosion
energy >10^51 erg/s

DELAYED
(>200 ms
after bounce):
explosion
energy <10^51 erg/s)

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

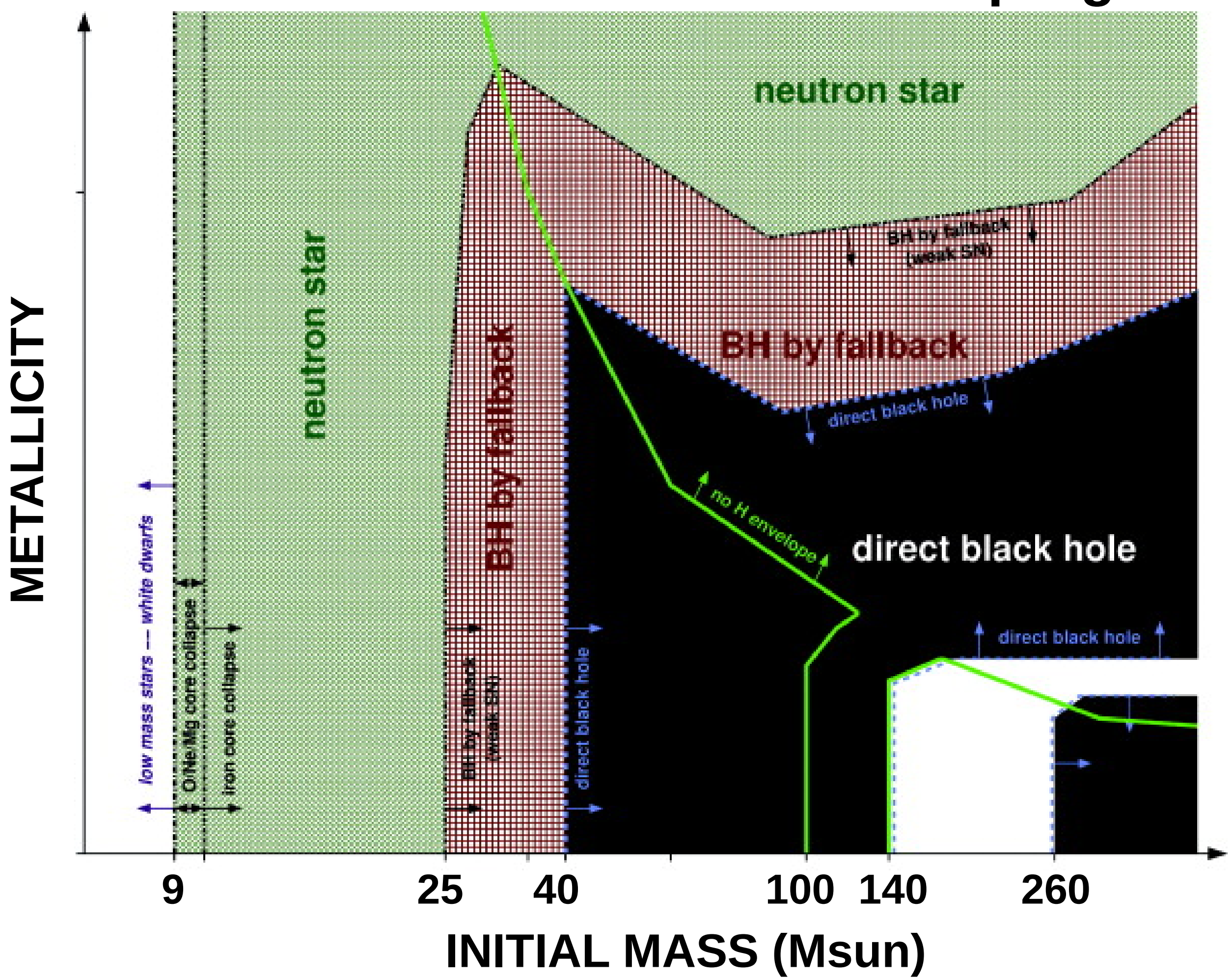
1. The formation of compact remnants: supernova

NOT SO EASY (3):

it 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

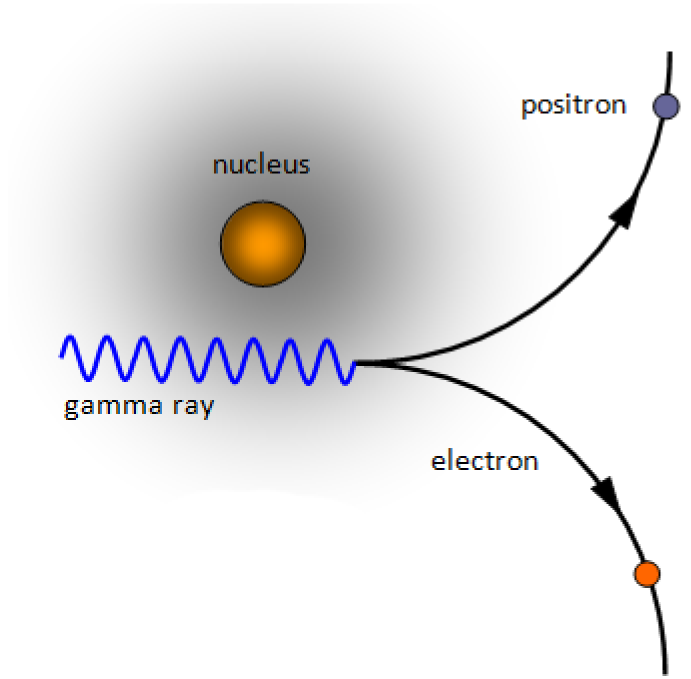


Heger 2003

1. The formation of compact remnants: supernova

NOT SO EASY (4): PAIR-INSTABILITY SUPERNOVAE

If star is very massive
(=produces 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

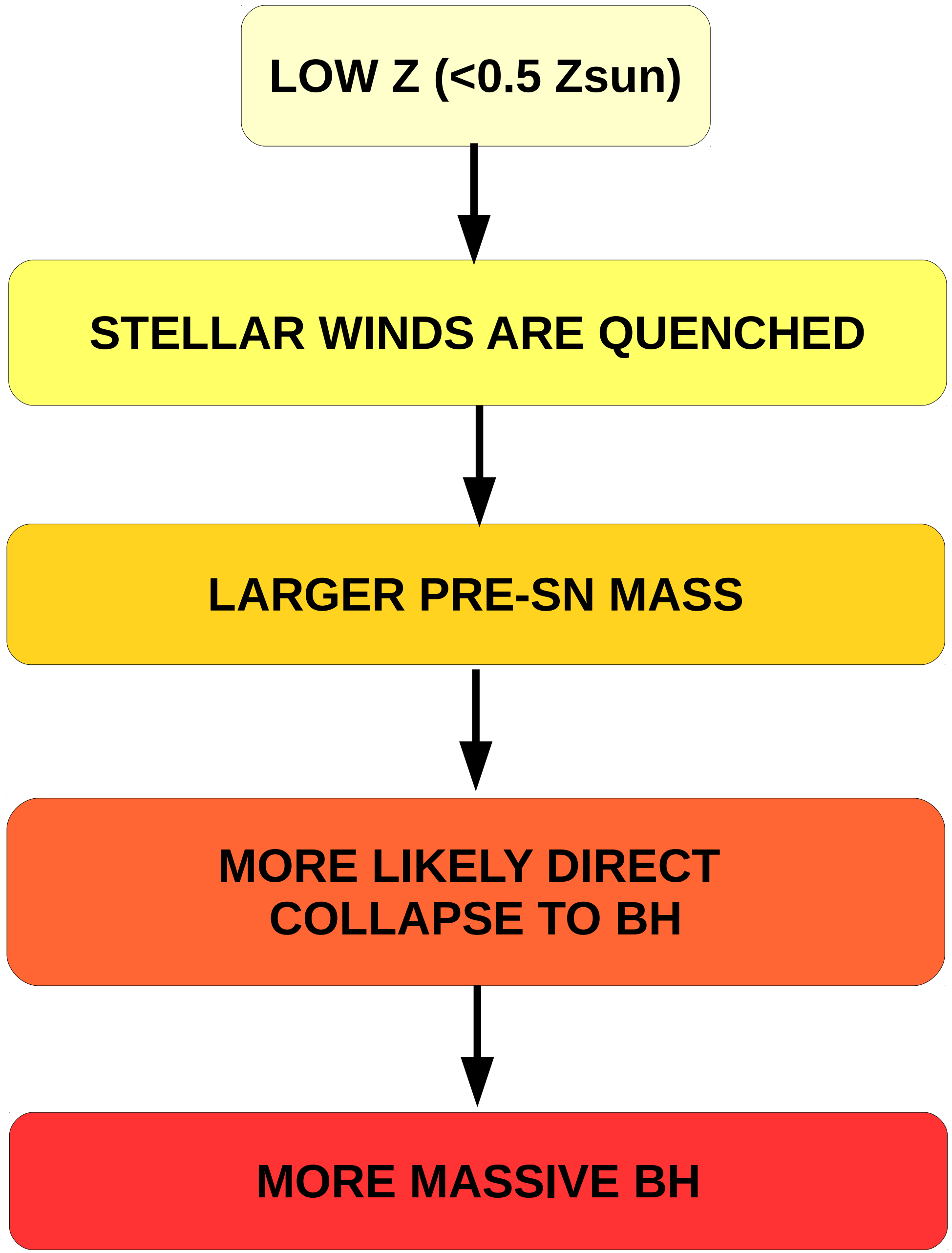
→high-Temperature collapse ignites all remaining species

→ an explosion is induced that leaves NO remnant

!! Strongly depends on progenitor mass/metallicity and
neutrino physics (eg Belczynski+ 2016)

1. The formation of compact remnants: wrap up

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



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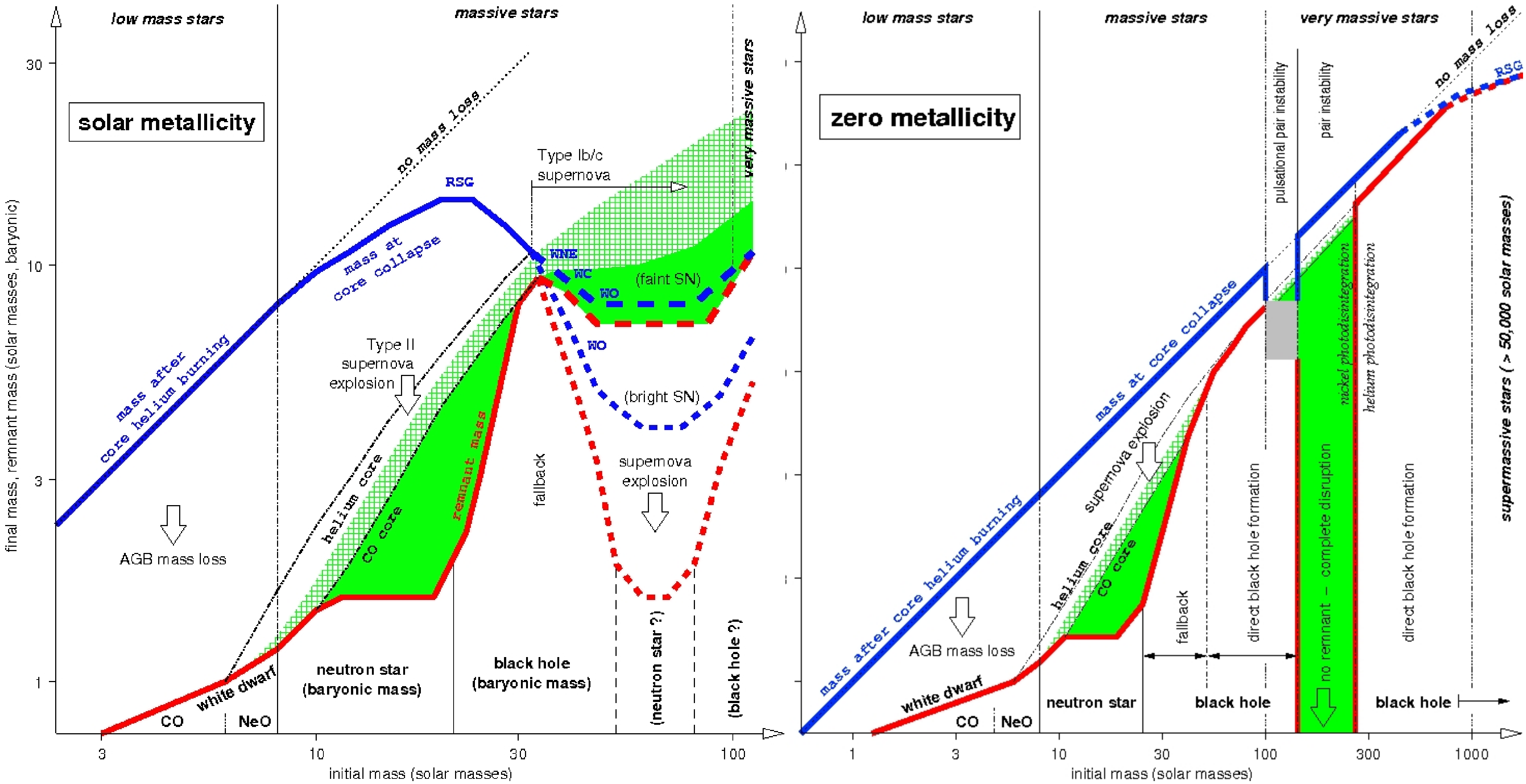
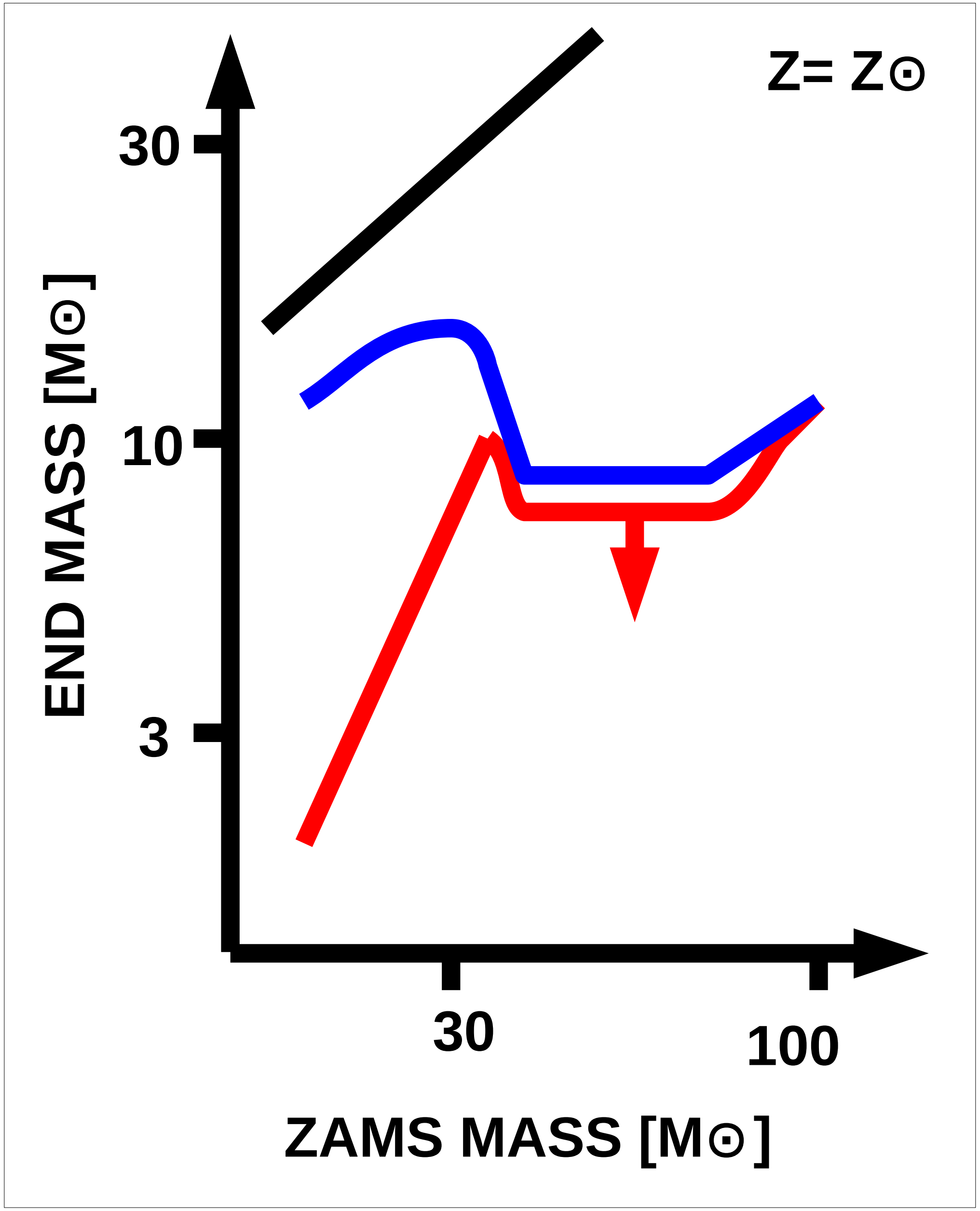
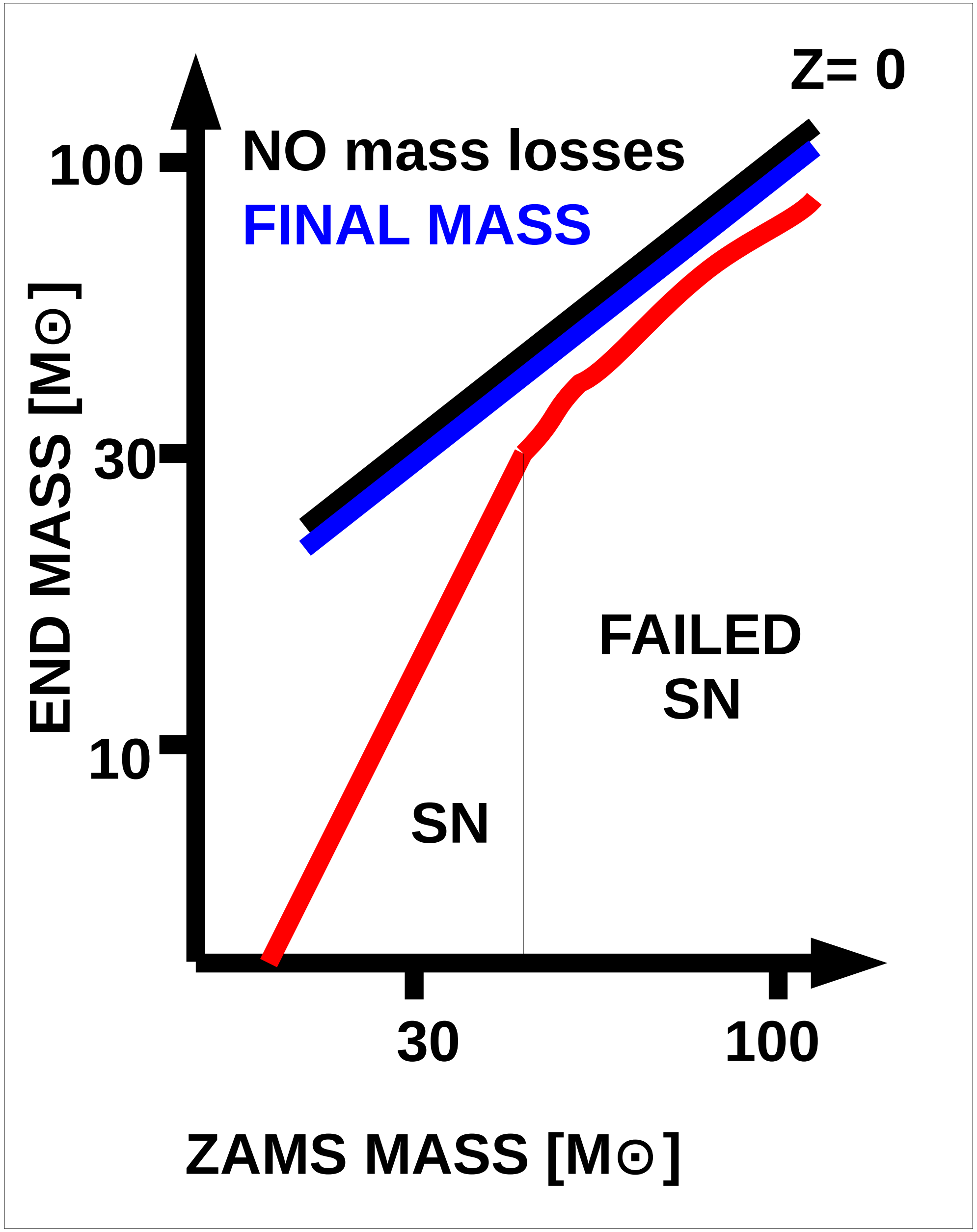


Heger et al. (2003)

1. The formation of compact remnants: wrap up



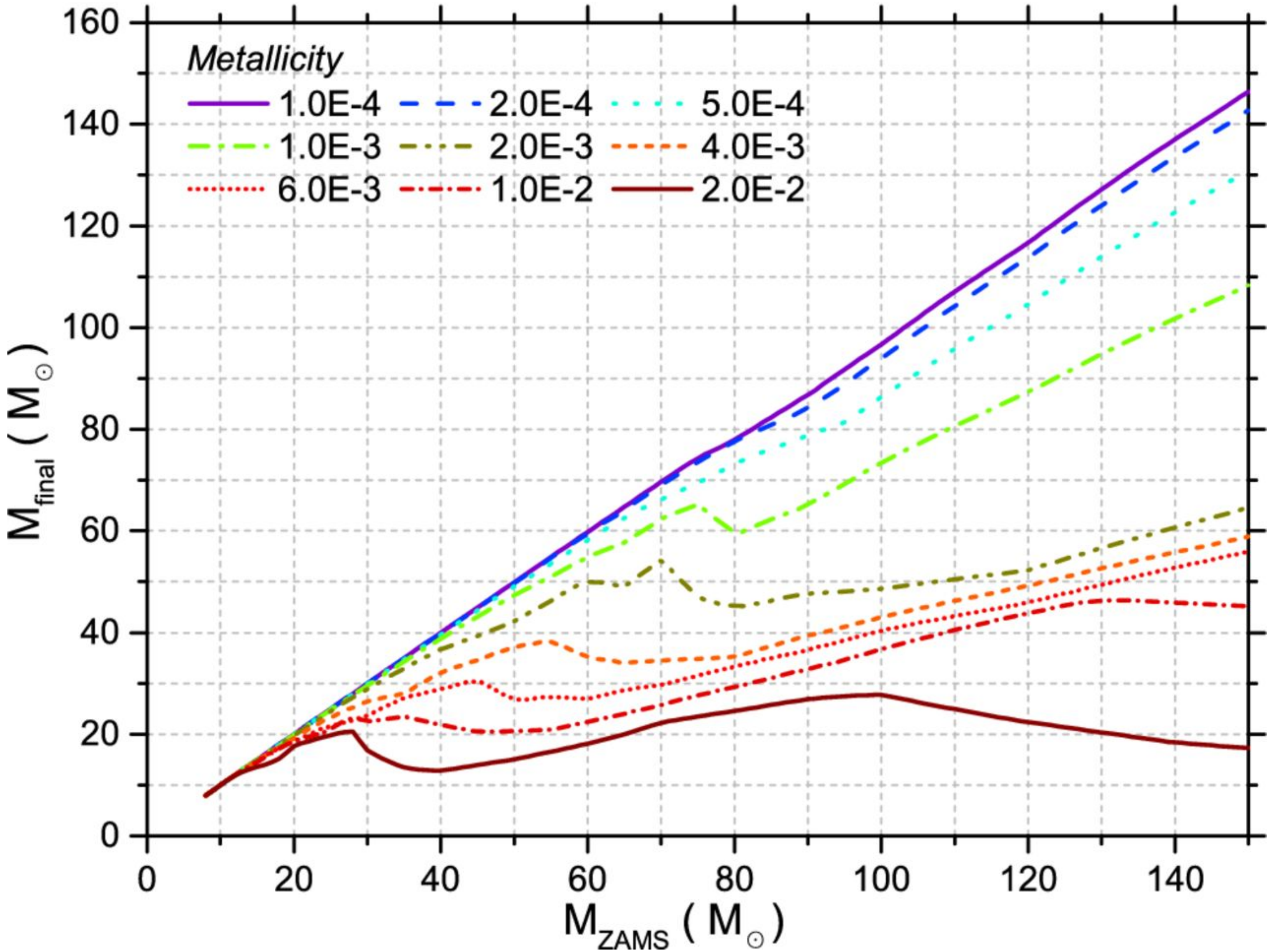


My cartoon from
Heger et al. (2003)

1. The formation of compact remnants: wrap up

What about intermediate metallicities between 0 and solar?

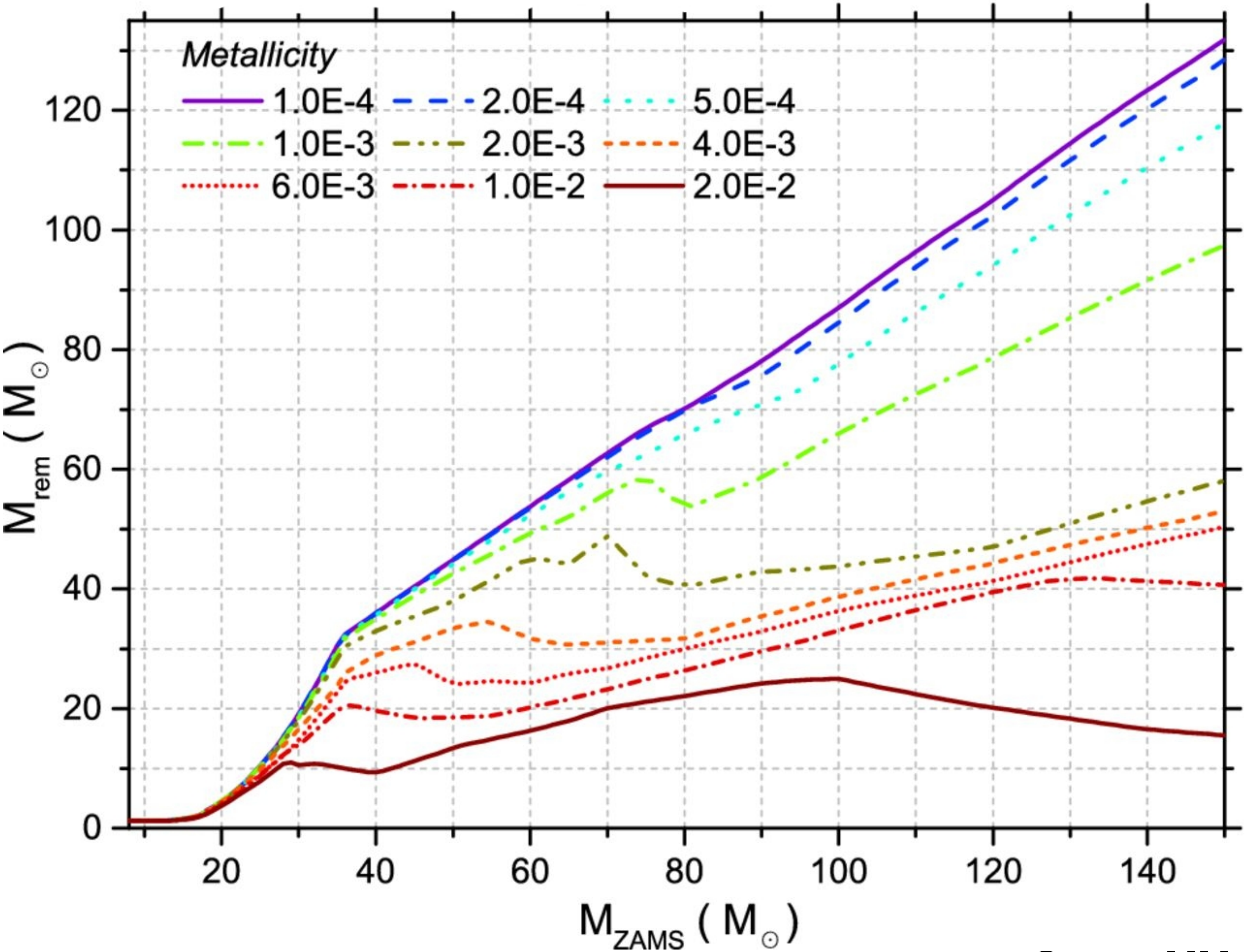
- **more difficult because stellar winds are uncertain**
- **importance of final mass: pre-supernova mass of the star (when CO core built)**



Spera, MM, Bressan 2015

1. The formation of compact remnants: wrap up

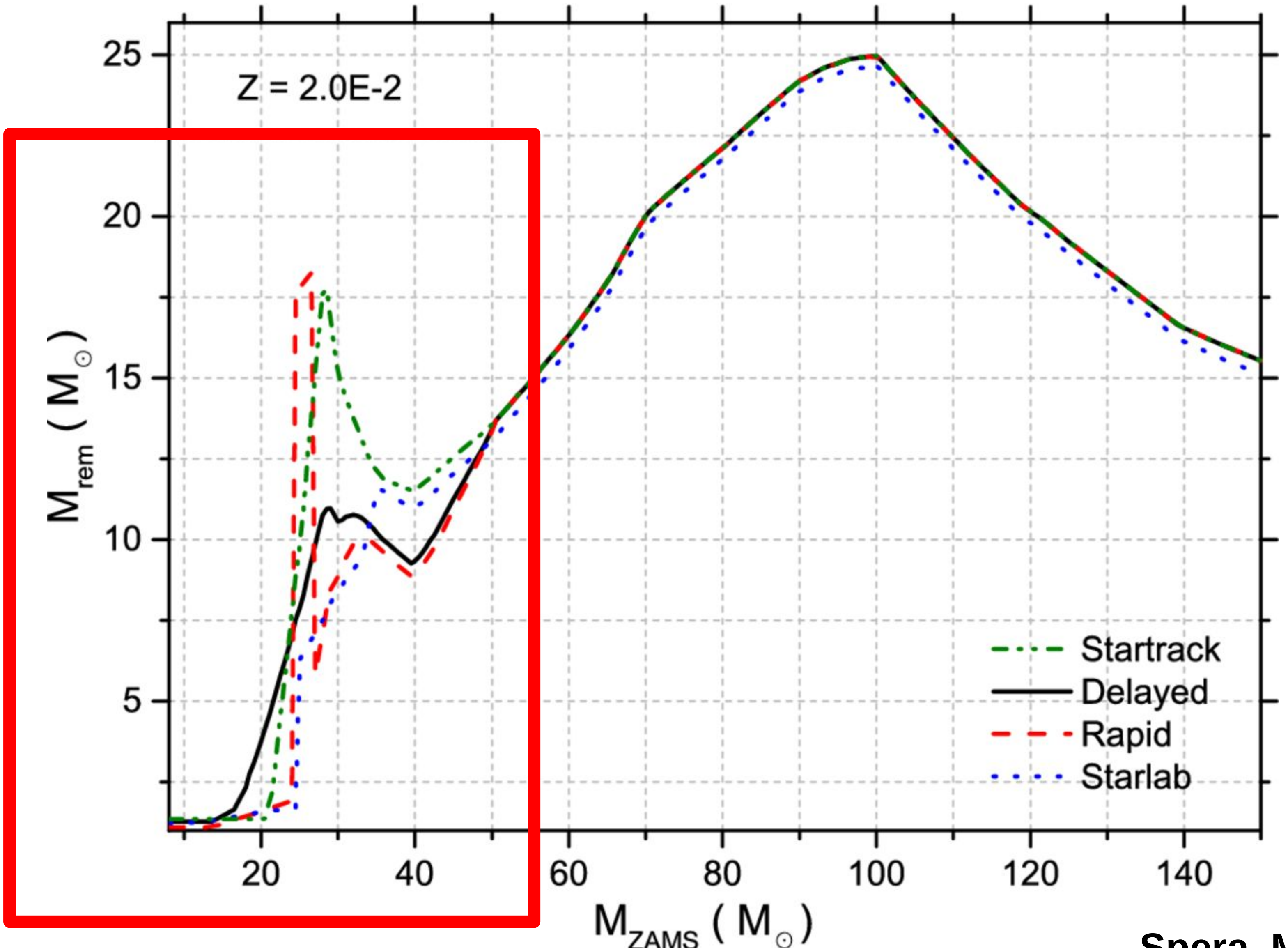
Remnant mass follows same trend as final mass
→ stellar winds are crucial



Spera, MM, Bressan 2015

1. The formation of compact remnants: wrap up

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



Spera, MM, Bressan 2015

1. The formation of compact remnants: wrap up

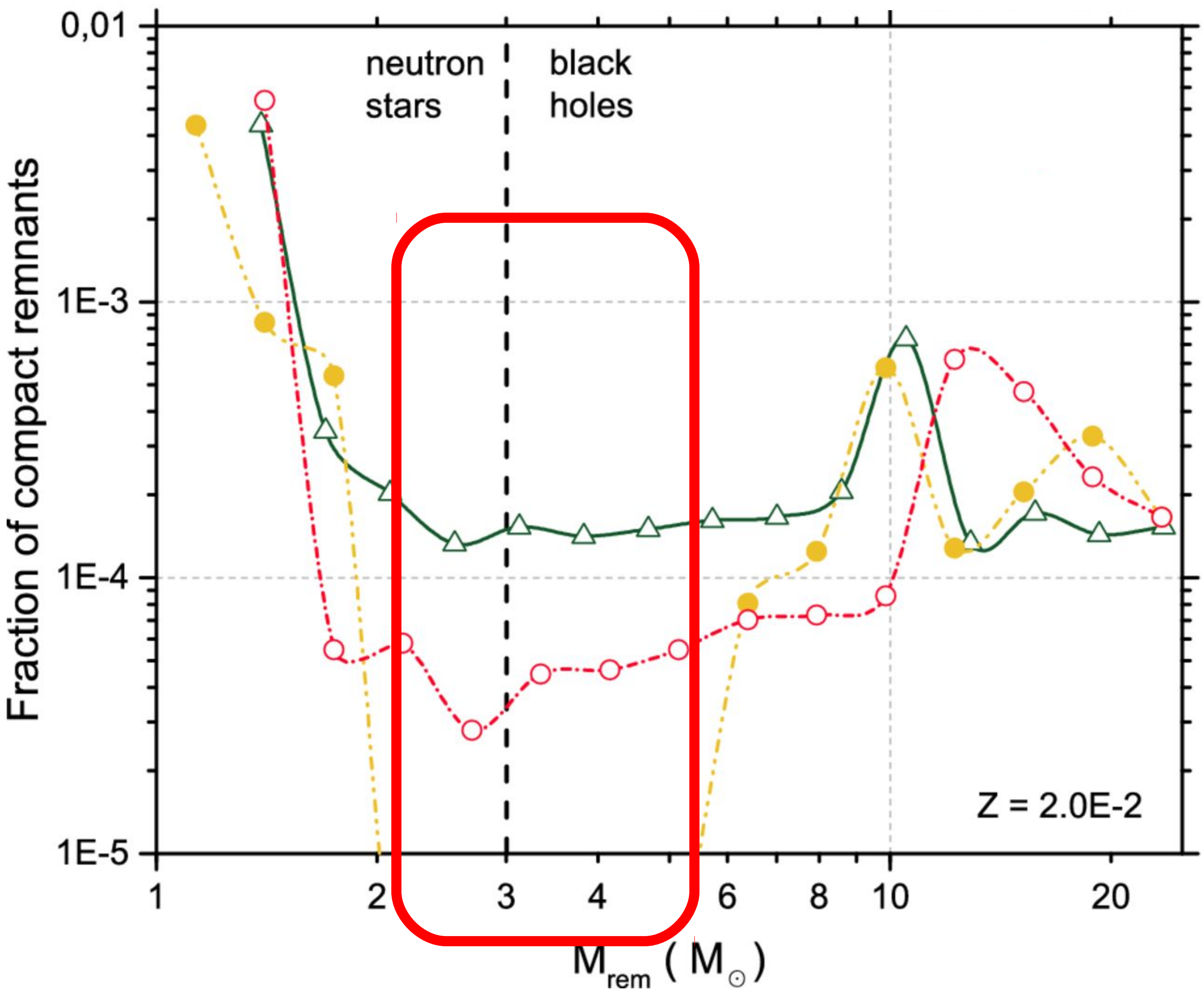
Importance of supernova model for LOW STAR MASSES (<40 M☉)

Solar metallicity

GREEN: DELAYED SN (Fryer+ 2012)

RED: DELAYED SN (MM+ 2013)

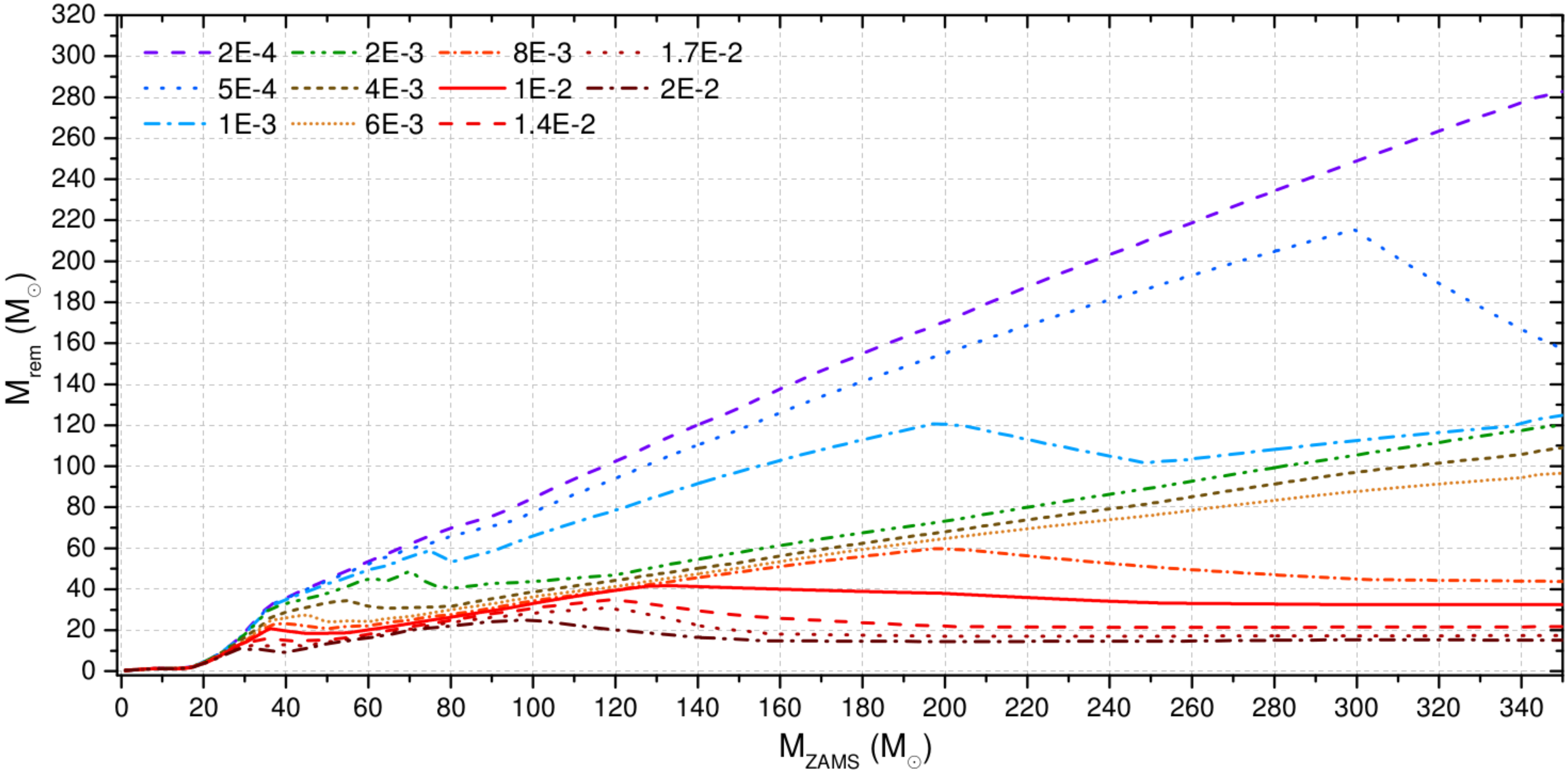
YELLOW: PROMPT SN (Fryer+ 2012)



Spera, MM, Bressan 2015

1. The formation of compact remnants: wrap up

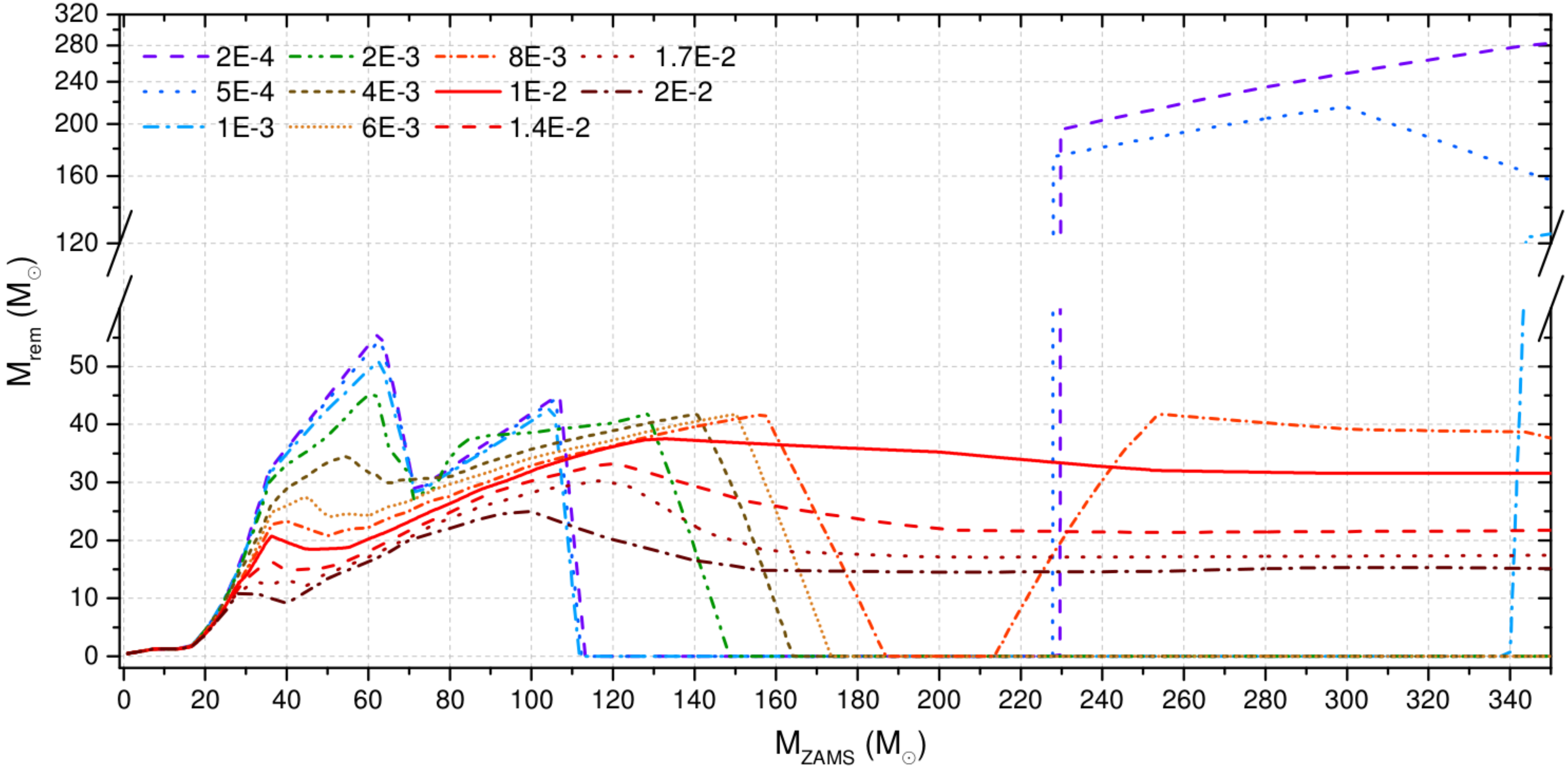
Evolution of very massive stars still uncertain
→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

1. The formation of compact remnants: wrap up

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

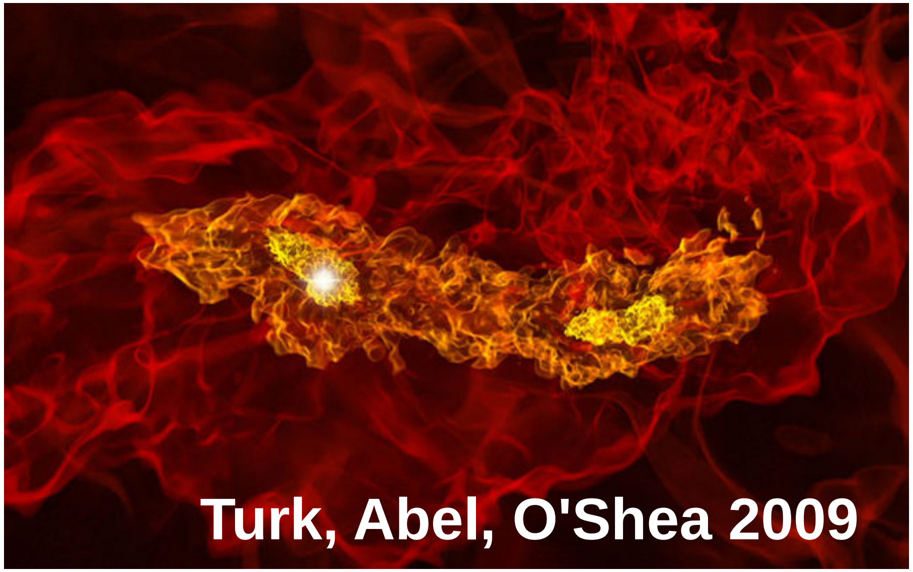


Spera & MM 2017

2. Binaries of stellar black holes (BHs)

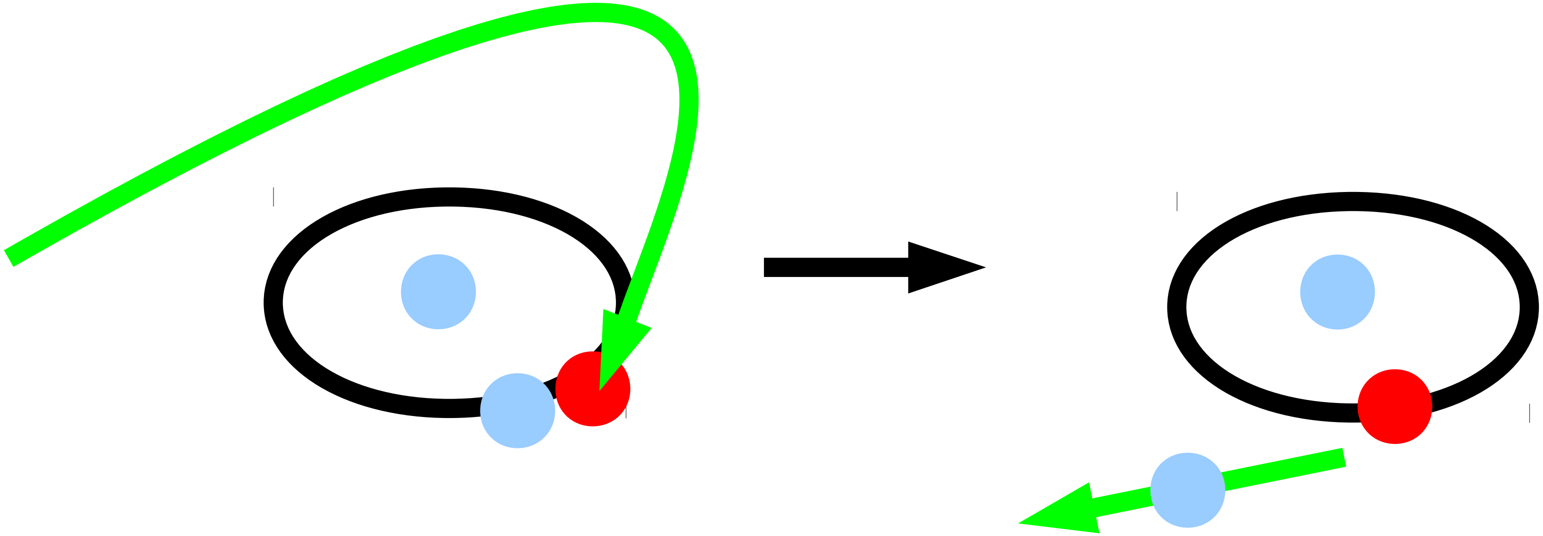
LIGO observed a BH-BH BINARY

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



1) PRIMORDIAL BINARY

2) DYNAMICALLY FORMED BINARY



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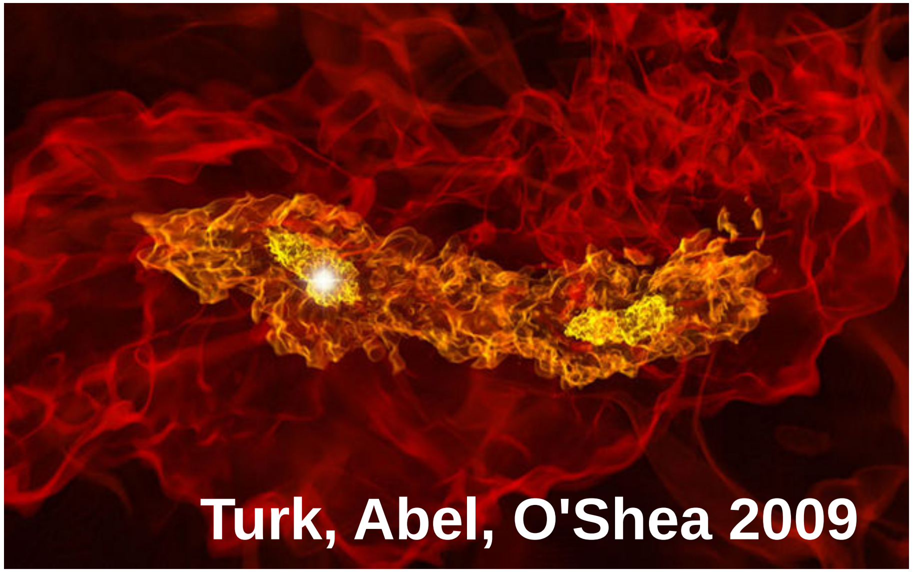


1) PRIMORDIAL BINARY:

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

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)

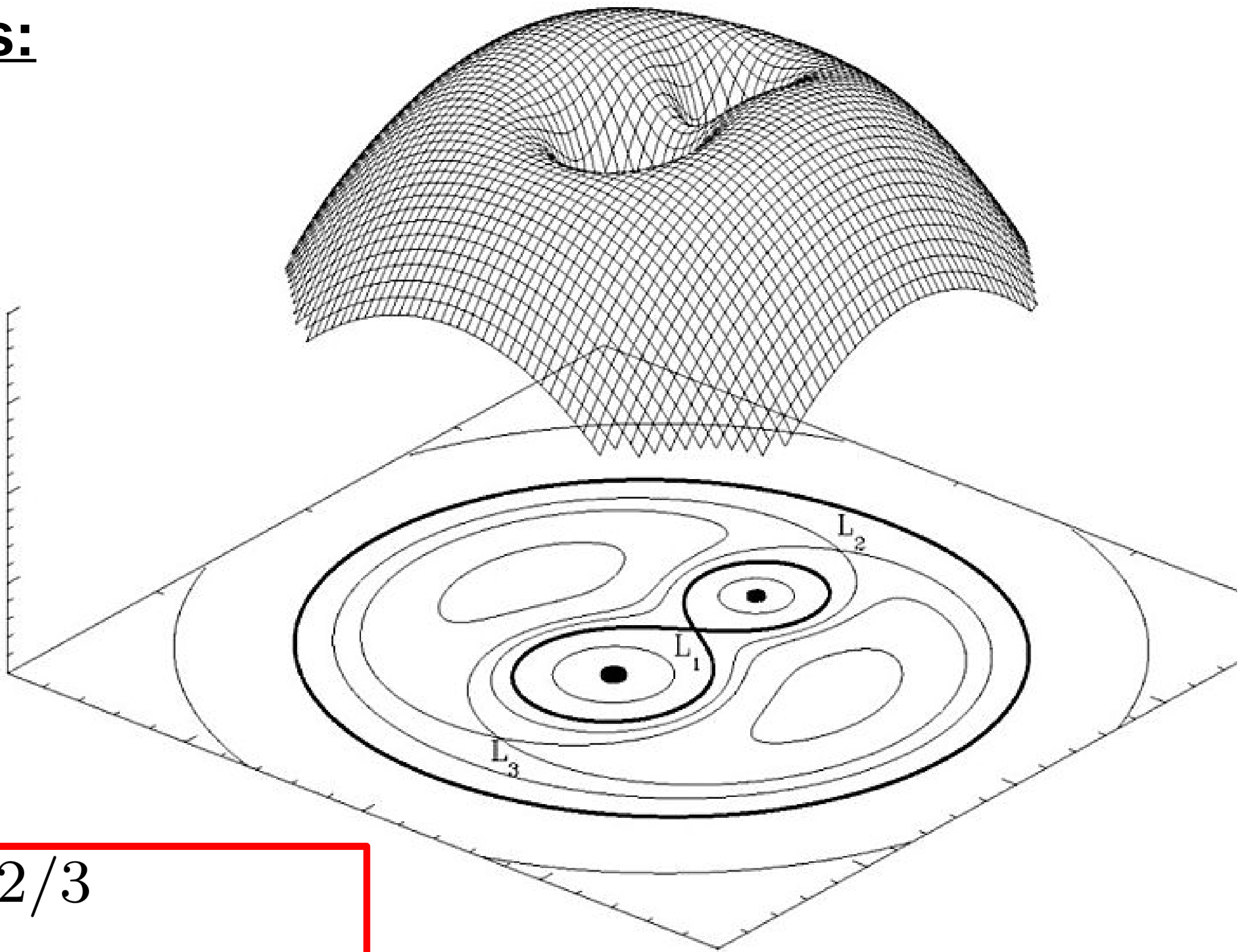
2. Binaries of stellar black holes (BHs)

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

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

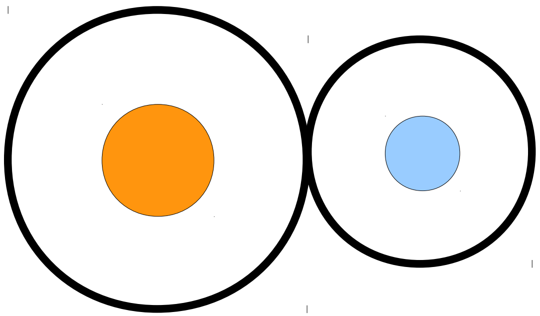
where $\boldsymbol{a}$ **= semi-major axis**

$\boldsymbol{q = M_1/M_2}$

2. Binaries of stellar black holes (BHs)

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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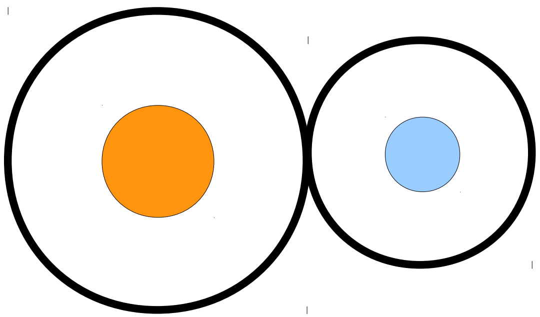

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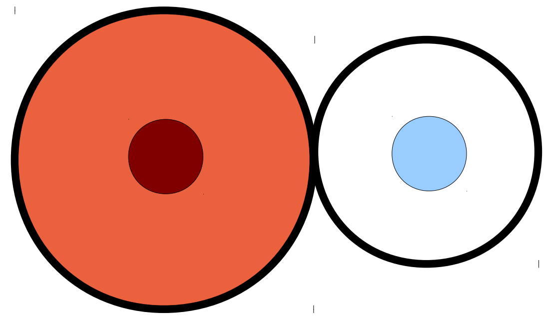

The first one evolves out of MS expands and start mass transfer onto the second

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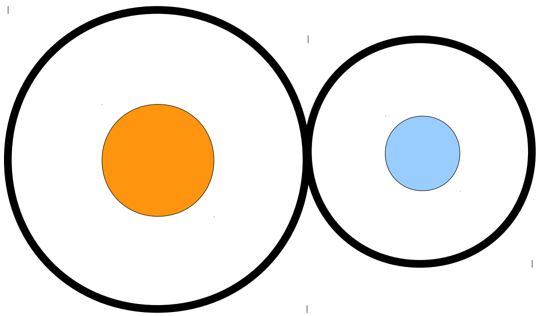

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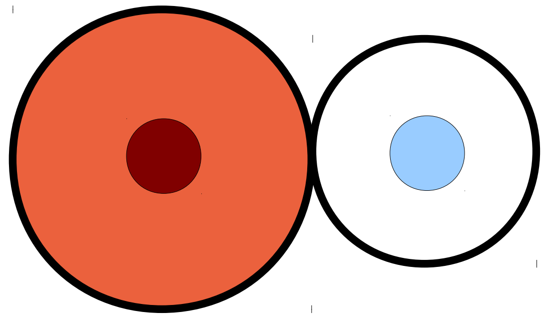

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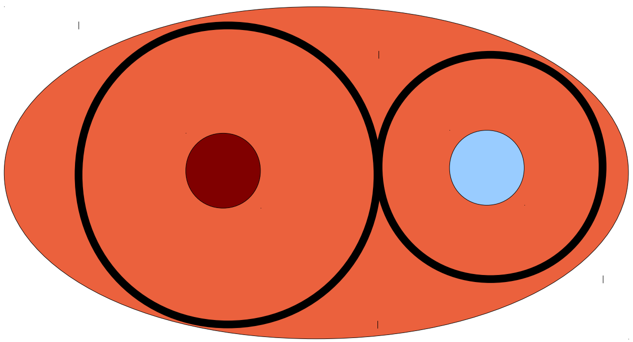
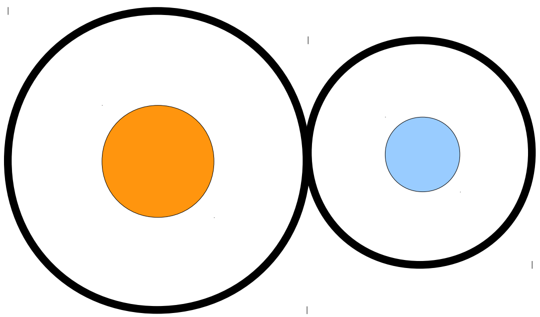


Mass transfer becomes unstable: CE phase

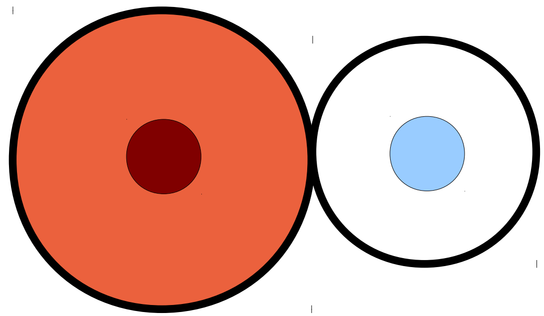
2. Binaries of stellar black holes (BHs)

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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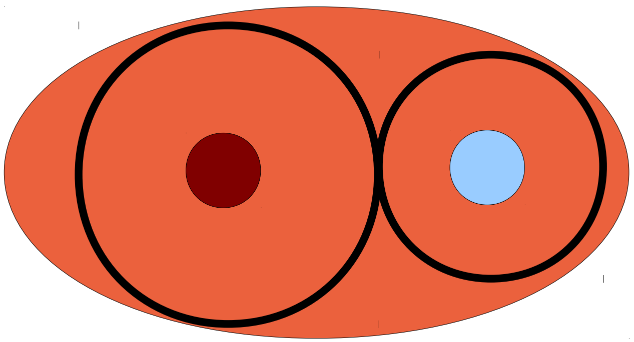

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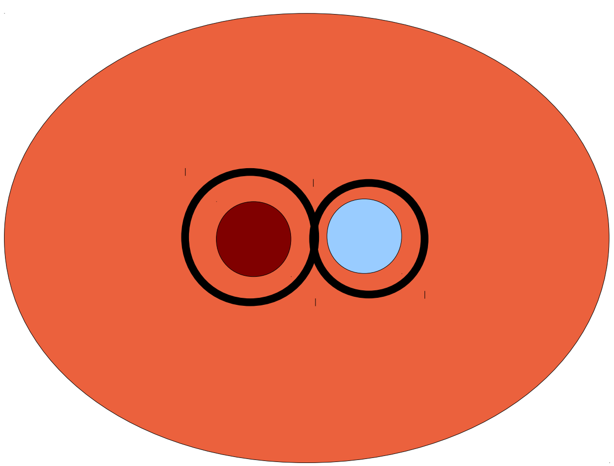

Drag by the envelope leads the two cores to spiral in

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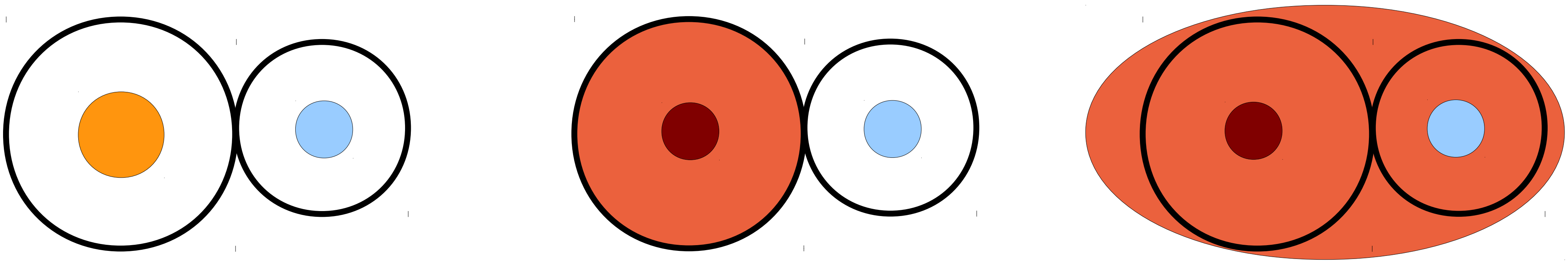

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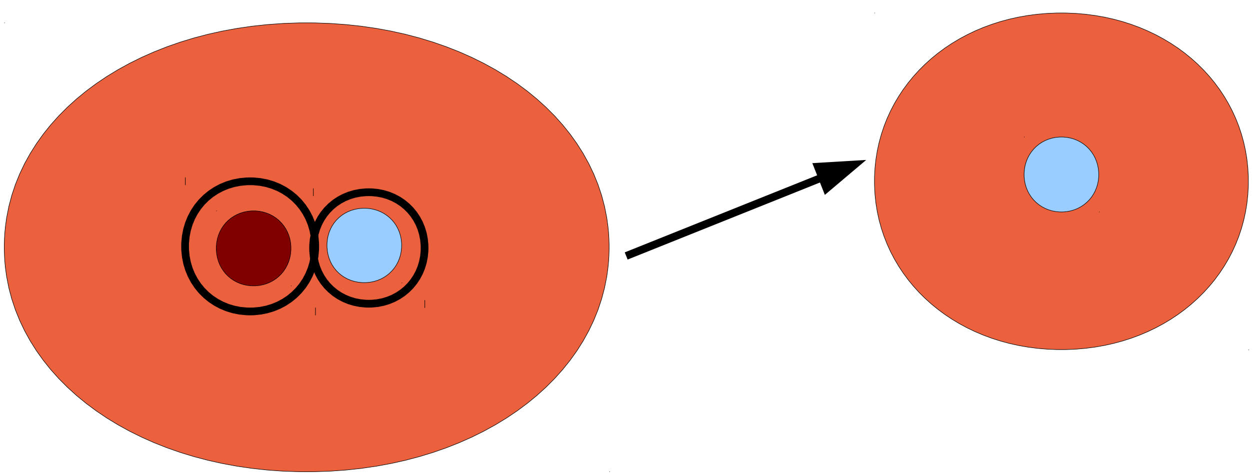

The two cores spiral in till they merge becoming a single star

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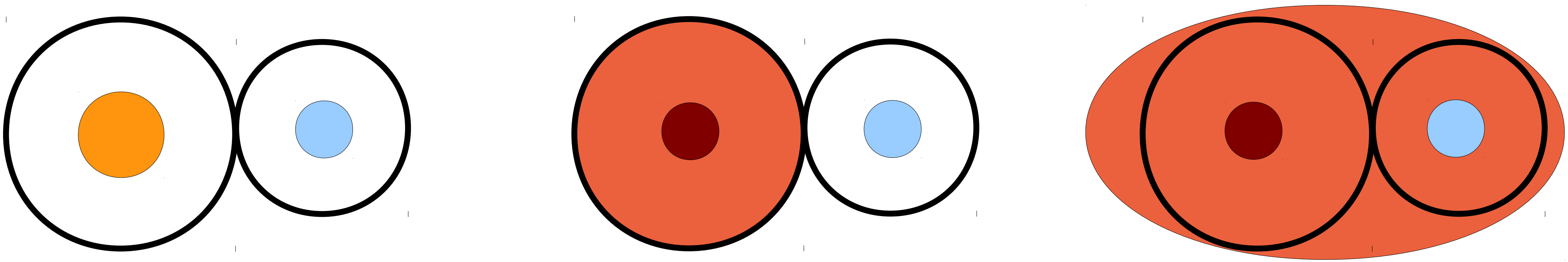

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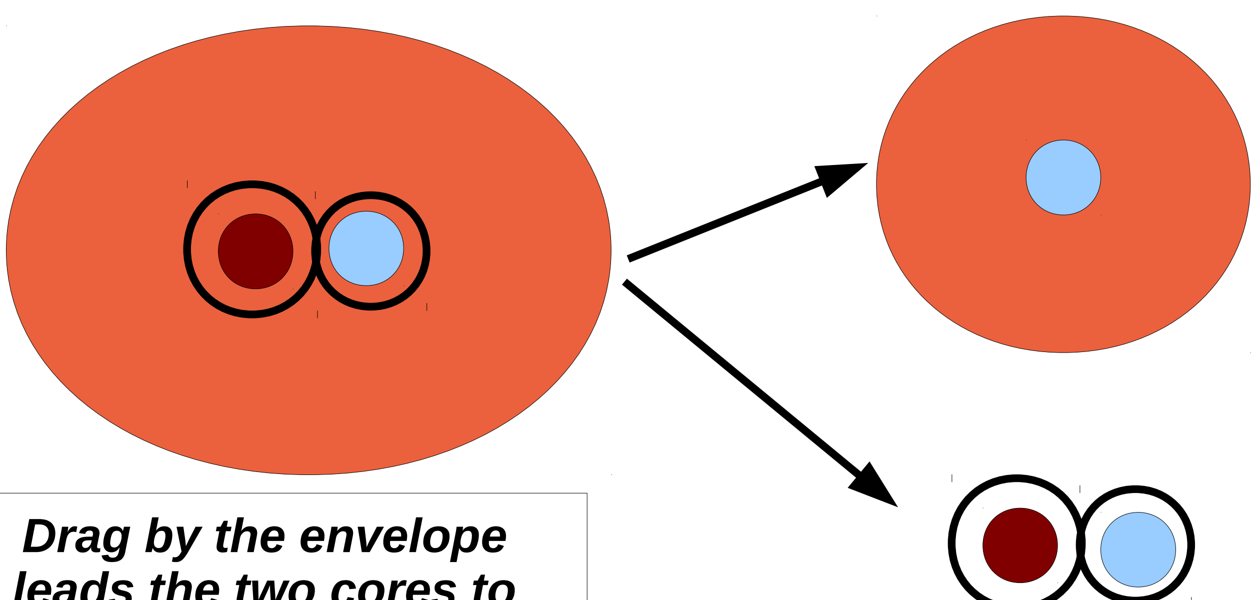


The two cores spiral in till they merge becoming a single star

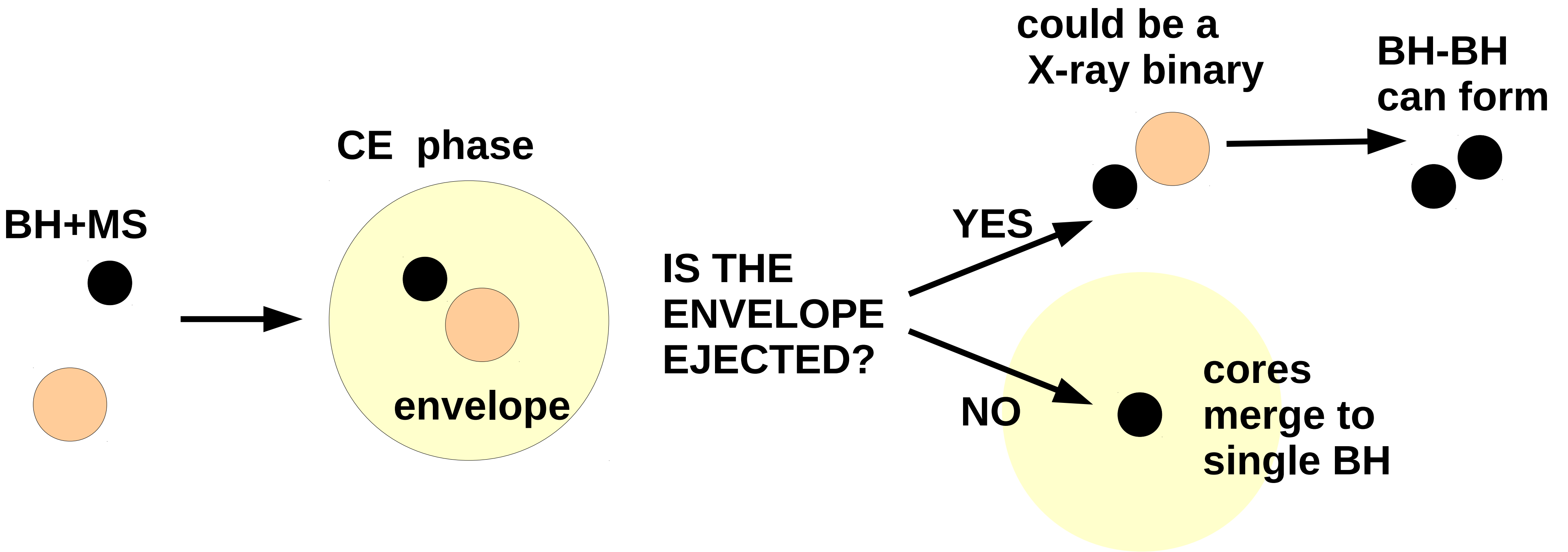
Drag by the envelope leads the two cores to spiral in

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

2. Binaries of stellar black holes (BHs)

Common envelope in binaries:

WHY is important for BH demography?



2. Binaries of stellar black holes (BHs)

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)

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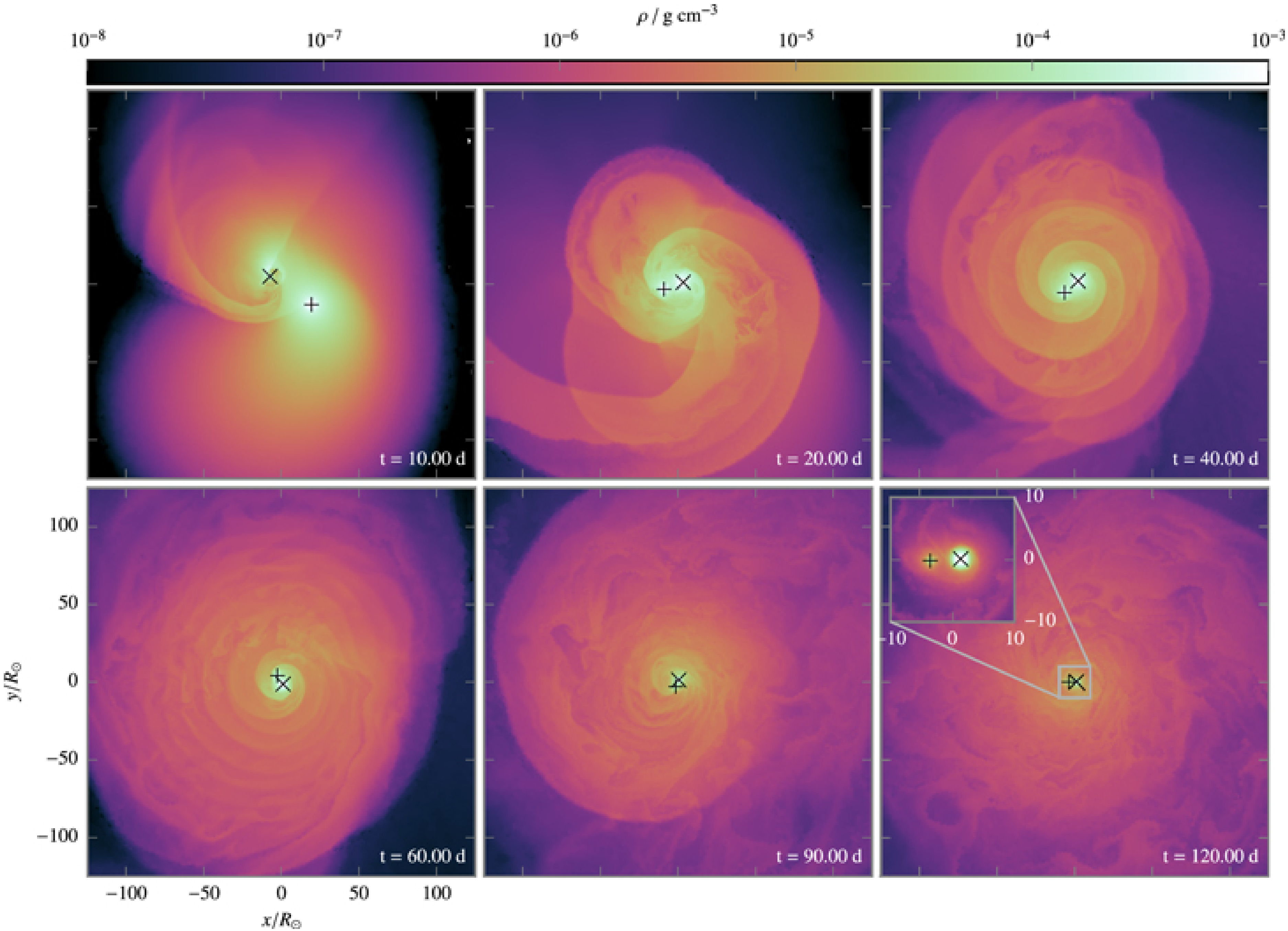
on dynamical time scale (~100d) – SIMULATED IN 3D
(Ricker & Taam 2008, 2012; Passy et al. 2012; Ohlmann+ 2016)

2. Binaries of stellar black holes (BHs)



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

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POORLY UNDERSTOOD!!! WHAT REMOVES THE ENVELOPE?

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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. Binaries of stellar black holes (BHs)

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:

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

α is second free parameter (energy removal efficiency)

2. Binaries of stellar black holes (BHs)

Common envelope in binaries:

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

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

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

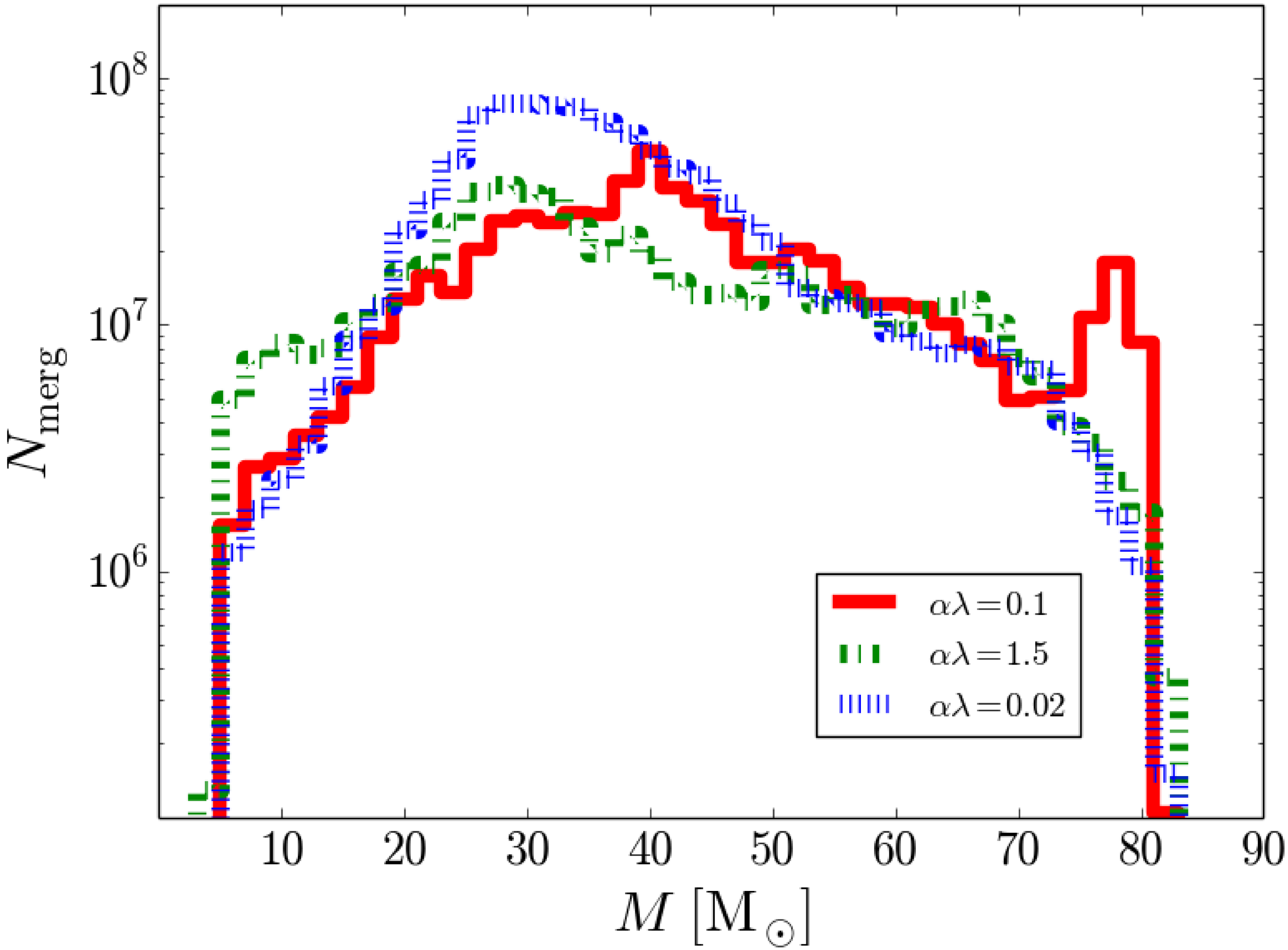
THEN the cores merge (Hurley+ 2002, MNRAS, 329, 897)

PROBLEM IS: HOW TO CONSTRAIN α and λ ?

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

2. Binaries of stellar black holes (BHs)

Common envelope in binaries:



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

2. Binaries of stellar black holes (BHs)

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

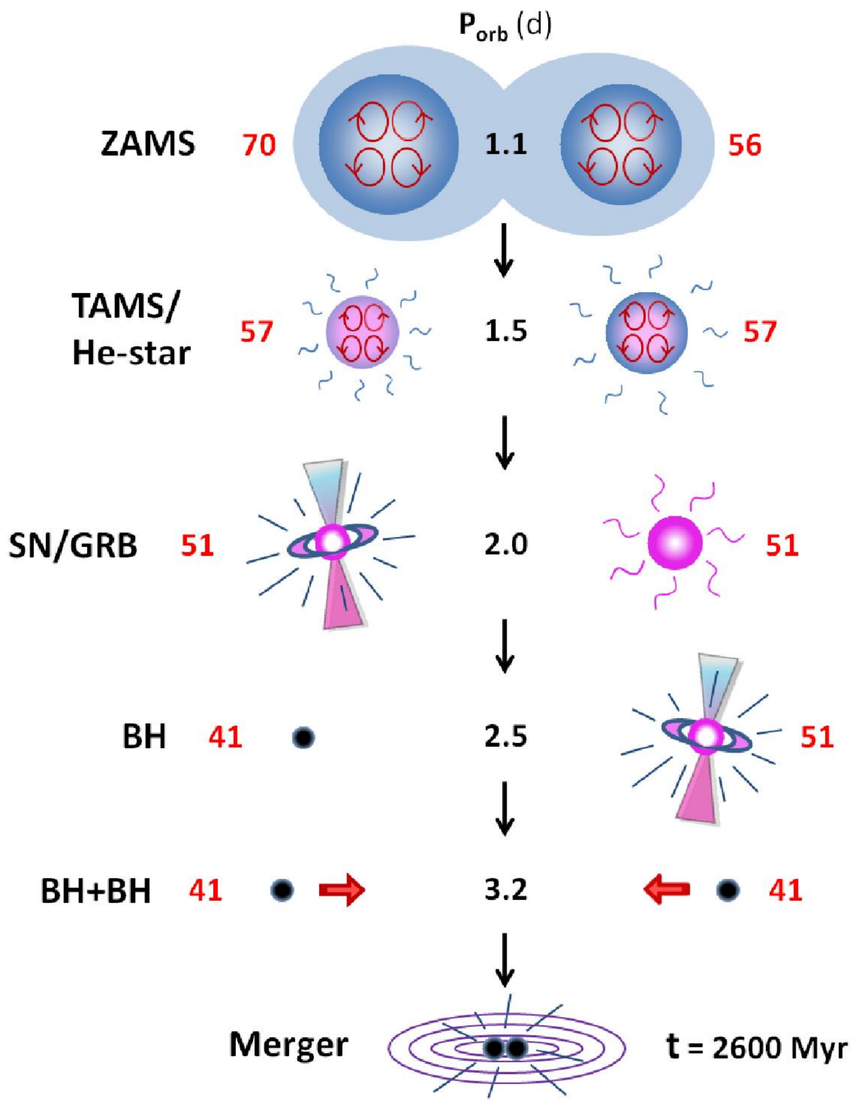
→ close binaries avoid common envelope and premature merger

To be chemically homogeneous, stars need to ROTATE fast

2. Binaries of stellar black holes (BHs)

OVERCONTACT BINARIES (Marchant+ 2016):

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



Predictions:

* 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

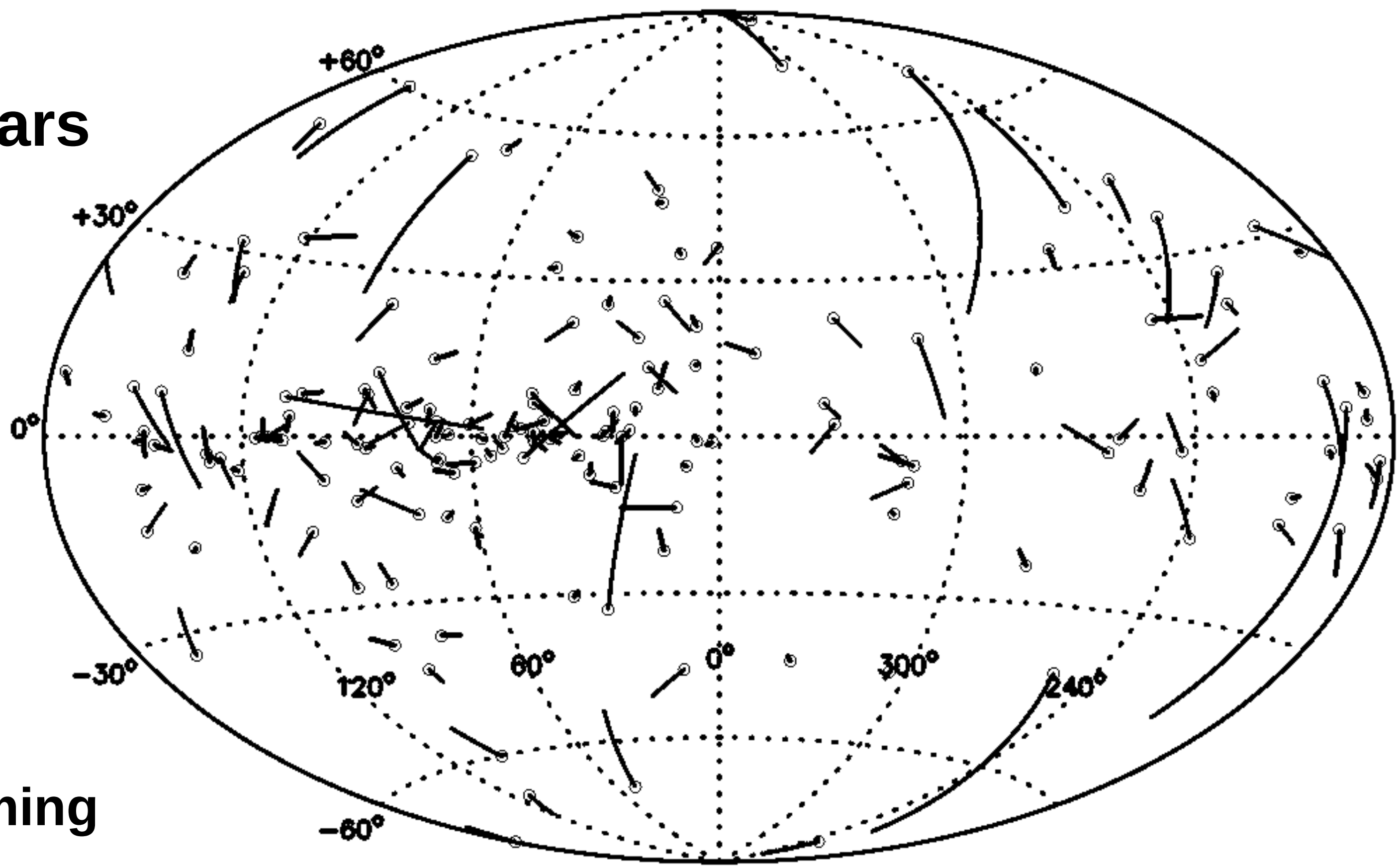
2. Binaries of stellar black holes (BHs)

Supernova kicks and BH binaries:

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

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

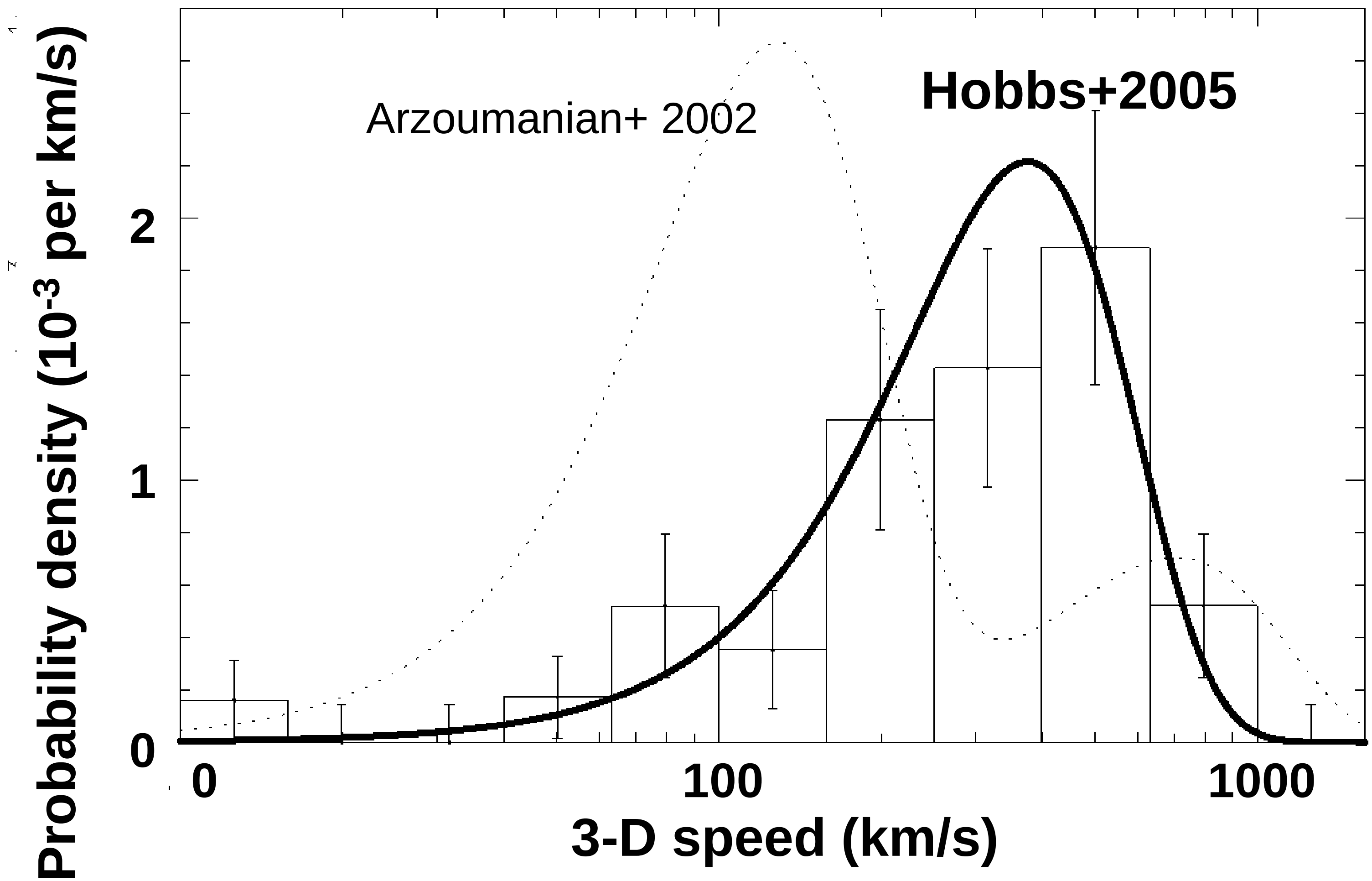
The track is its motion for the last 1 Myr assuming no radial velocity.

2. Binaries of stellar black holes (BHs)

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 stellar black holes (BHs)

Supernova kicks and BH binaries:

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

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

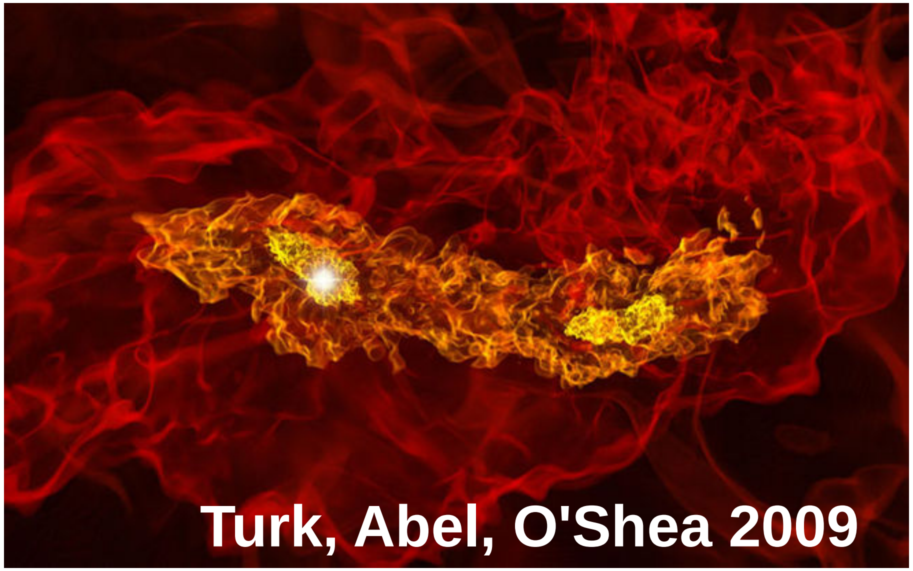
$$v_{\rm kick,\,BH} = (1 - f_{\rm fb})\,v_{\rm kick,\,NS}$$

2. Binaries of stellar black holes (BHs)

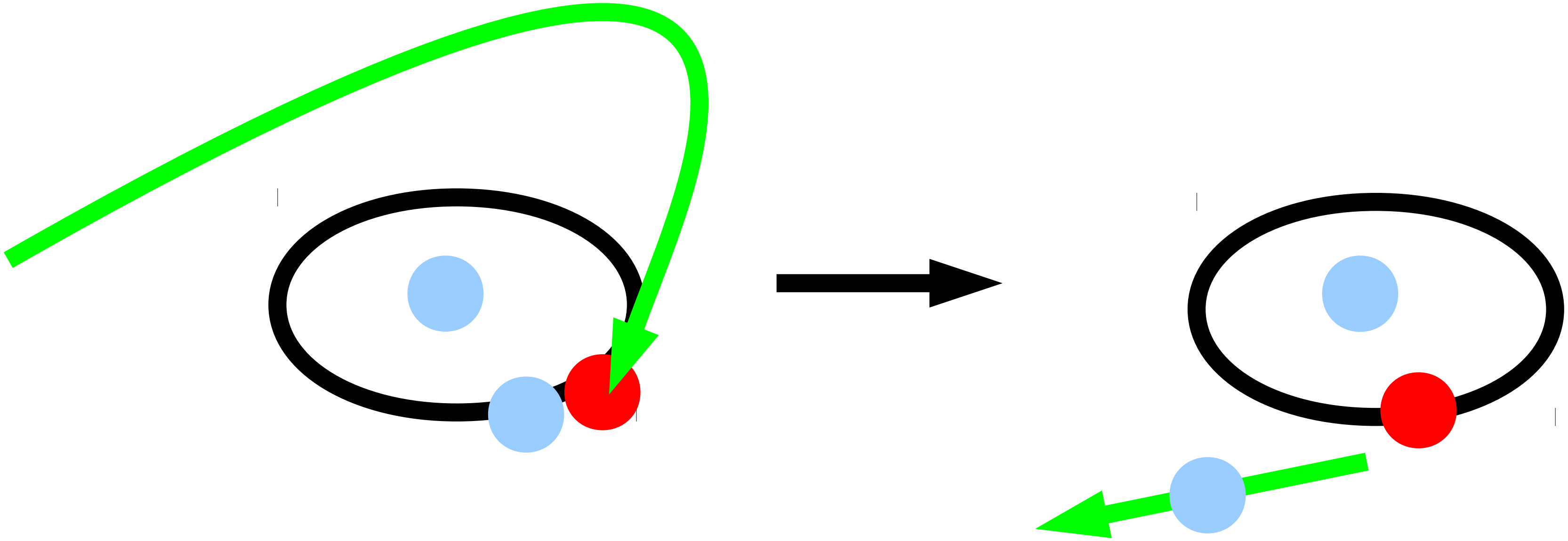
LIGO observed a BH-BH BINARY

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

1) PRIMORDIAL BINARY



2) DYNAMICALLY FORMED BINARY



3. The dynamics of 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)

3. The dynamics of BH binaries:

WHY DYNAMICS???????

Massive stars (BH progenitors) form in STAR CLUSTERS

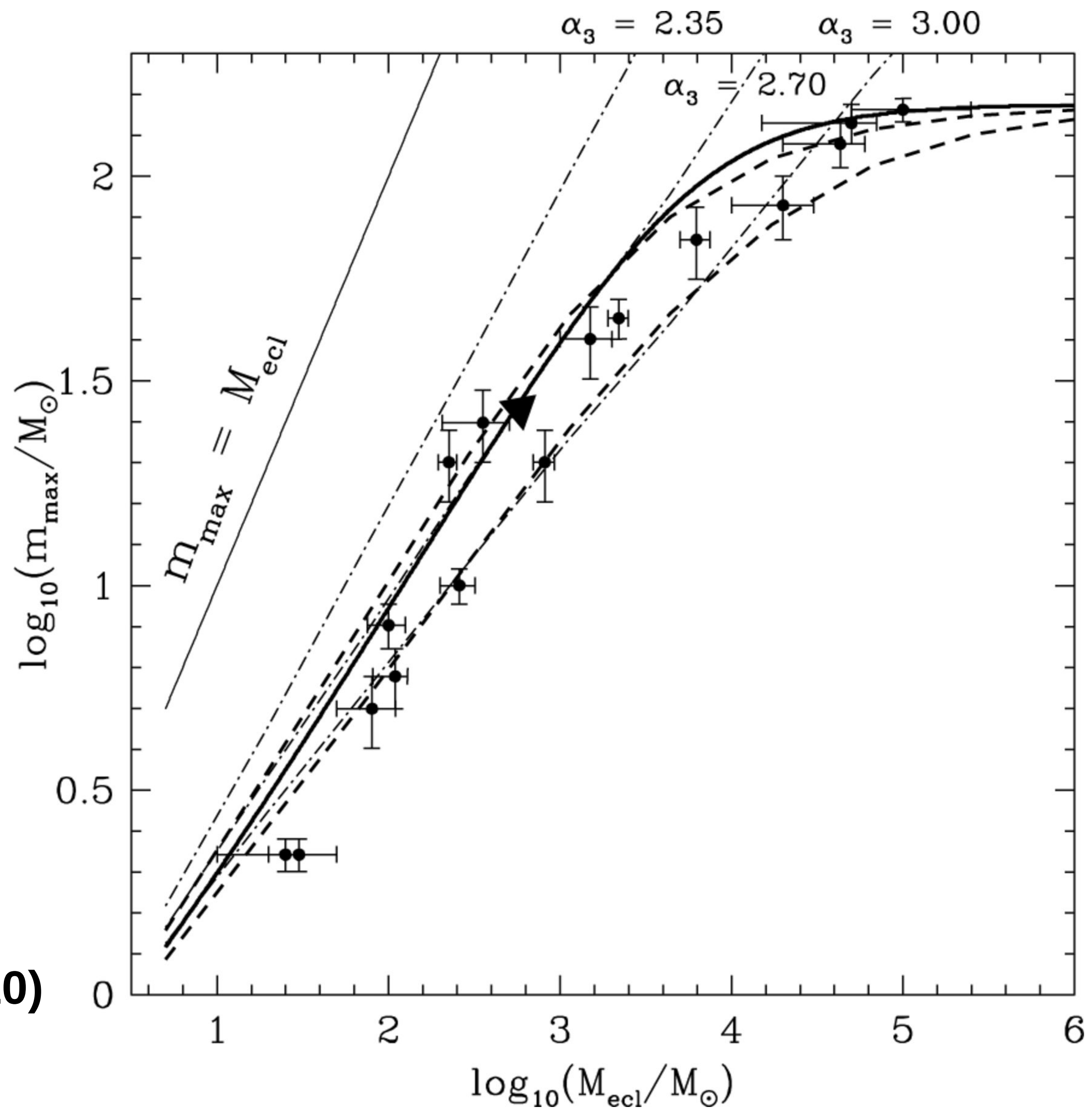


Figure from Weidner & Kroupa (2006)

Data points: observed star clusters

Lines: theoretical fits

See also Weidner, Kroupa & Bonnell (2010)

3. The dynamics of BH binaries:

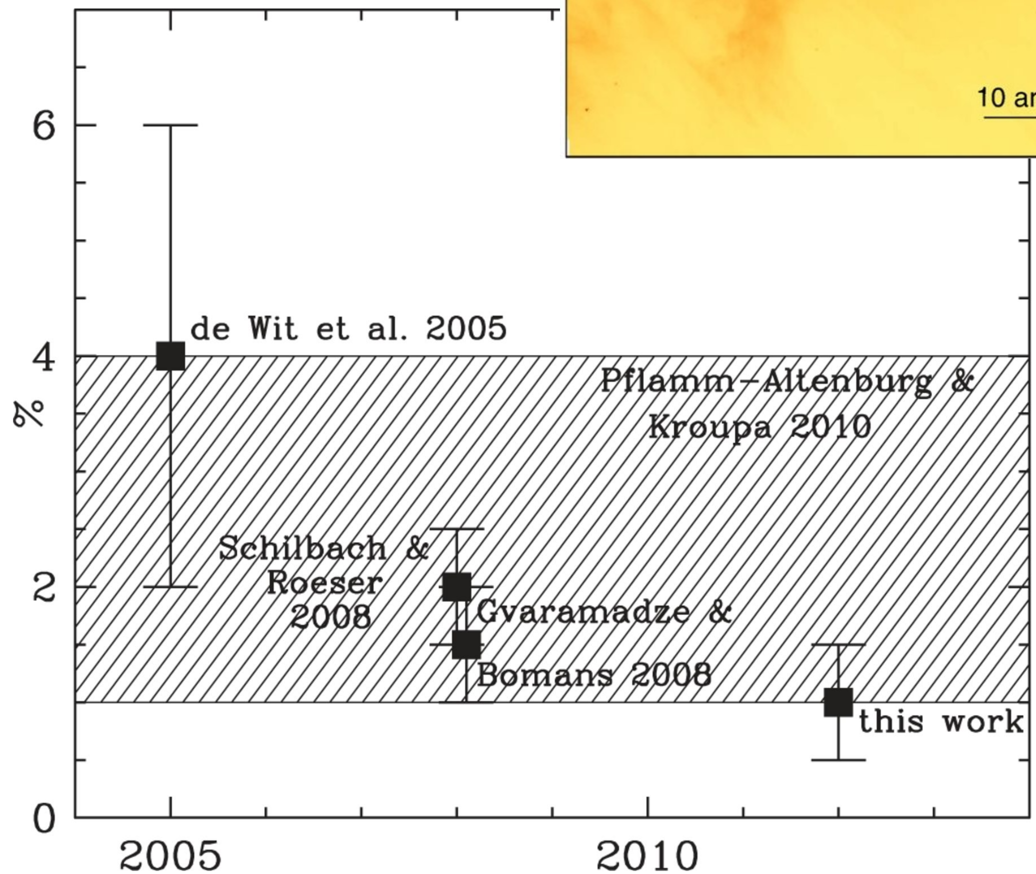
WHY DYNAMICS???????

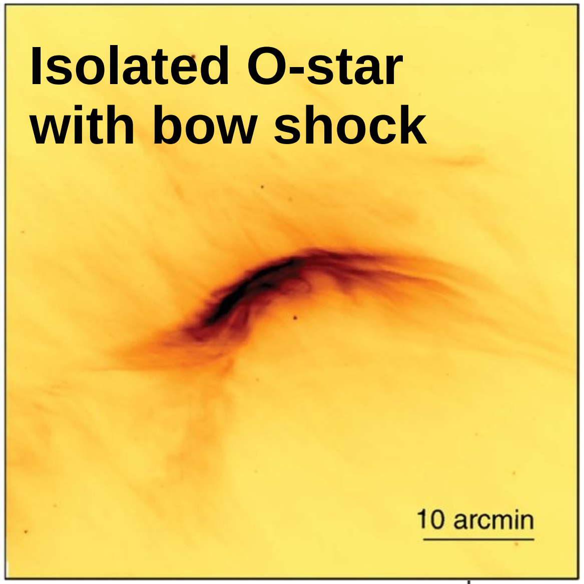
O-type stars in the field are mostly RUNAWAY from star clusters (as we see from bow shocks)

Figures from Gvaramadze et al. (2012)

See also
De Wit et al. (2004, 2005)
Schilbach & Roeser (2008)

Percentage of genuine field O stars





1. Why dynamics?

FIELD:

*** NO dynamics (density in solar neighborhood <1 star pc^-3)**

GLOBULAR CLUSTERS:

*** dynamics**

*** long-lived (12 Gyr)**

*** < 1 % baryonic mass of the Universe**

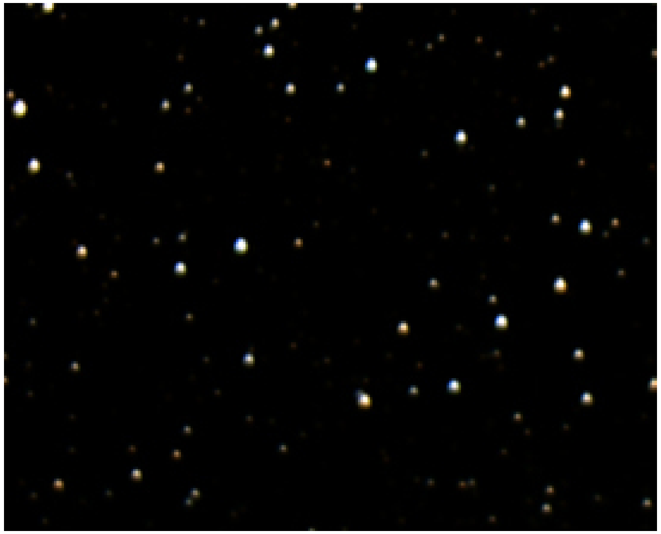


Image credit: Jim Mazur’s Astrophotography, via http://www.skyledge.net/.

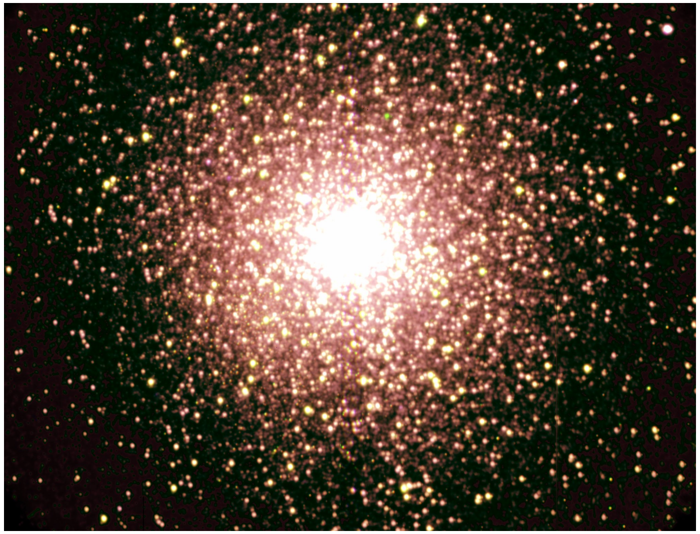


Image credit: HST

1. Why dynamics?

FIELD:

* NO dynamics (density in solar neighborhood <1 star pc^-3)

YOUNG STAR CLUSTERS and OPEN CLUSTERS:

* dynamics
* short-lived (0.01 – 1 Gyr)
* cradle of massive stars (80% star formation)

GLOBULAR CLUSTERS:

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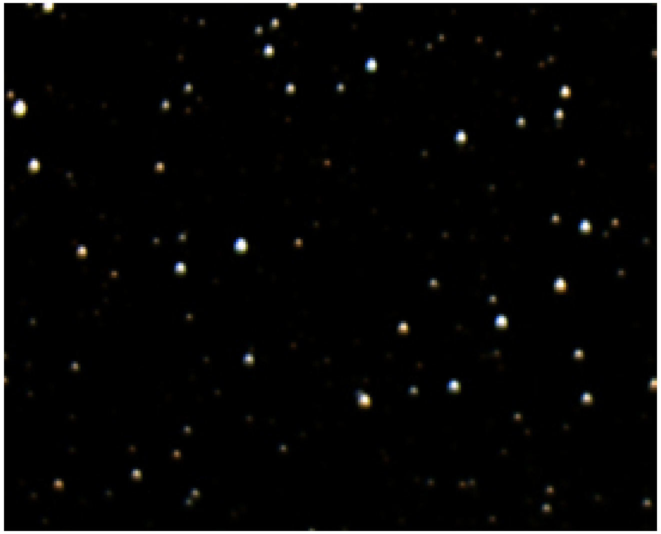

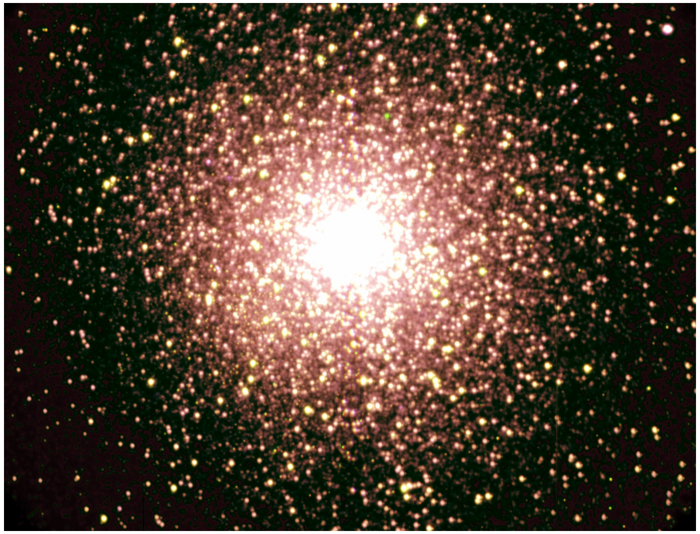

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*** dynamics**

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*** < 1 % baryonic mass of the Universe**

provide stars (and compact objects) to the field

share dynamical properties with globular clusters

1. Why dynamics?

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YOUNG STAR CLUSTERS and OPEN CLUSTERS:

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GLOBULAR CLUSTERS:

* dynamics
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* < 1 % baryonic mass of the Universe

NUCLEAR STAR CLUSTERS:

* dynamics
* long-lived (12 Gyr)
* host SUPER-MASSIVE BHs

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

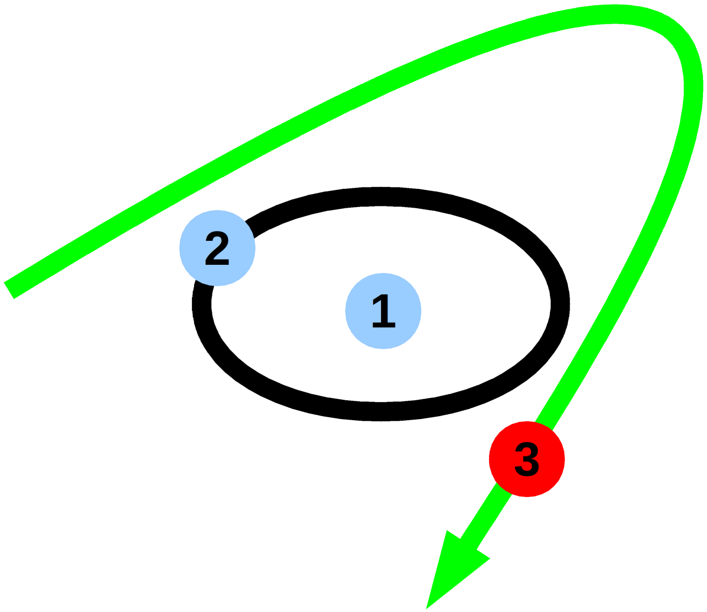
Binaries have a energy reservoir (internal energy)

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

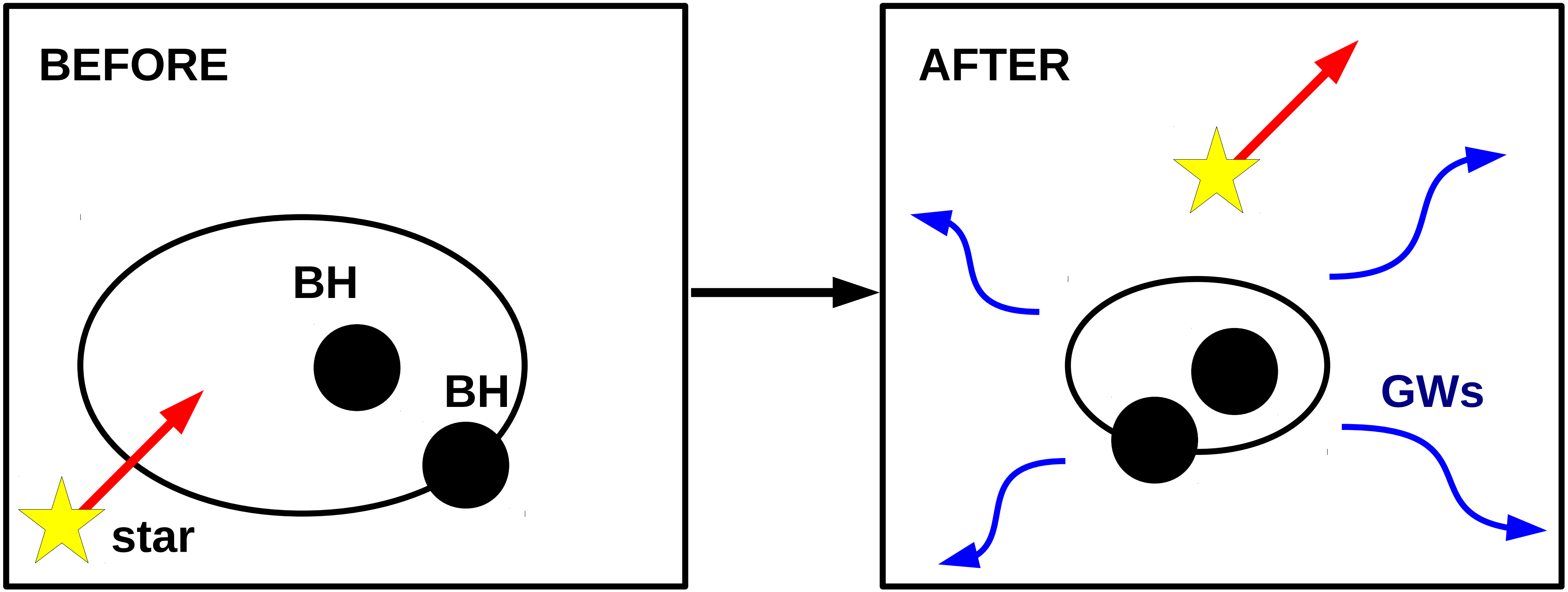
where m_1 and m_2 are the mass of the primary and secondary member of the binary,
μ is the reduced mass (:= $m_1\, m_2/(m_1+m_2)$), r and v are the relative separation and velocity.

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

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

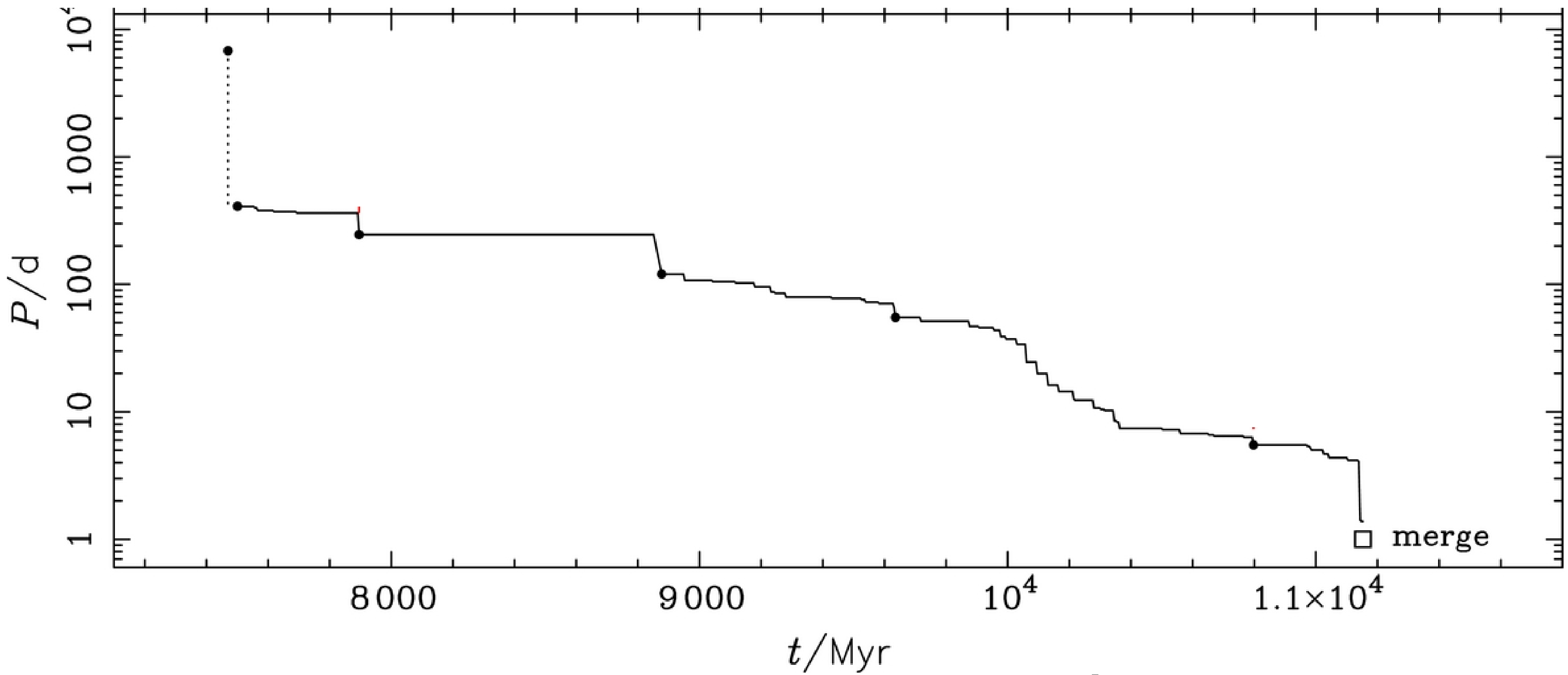


In a flyby, the star acquires kinetic energy from the binary

→ 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
(e.g. Colpi+ 2003)

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

GRAVITATIONAL WAVE (GW) TIMESCALE (Peters 1964)

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

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

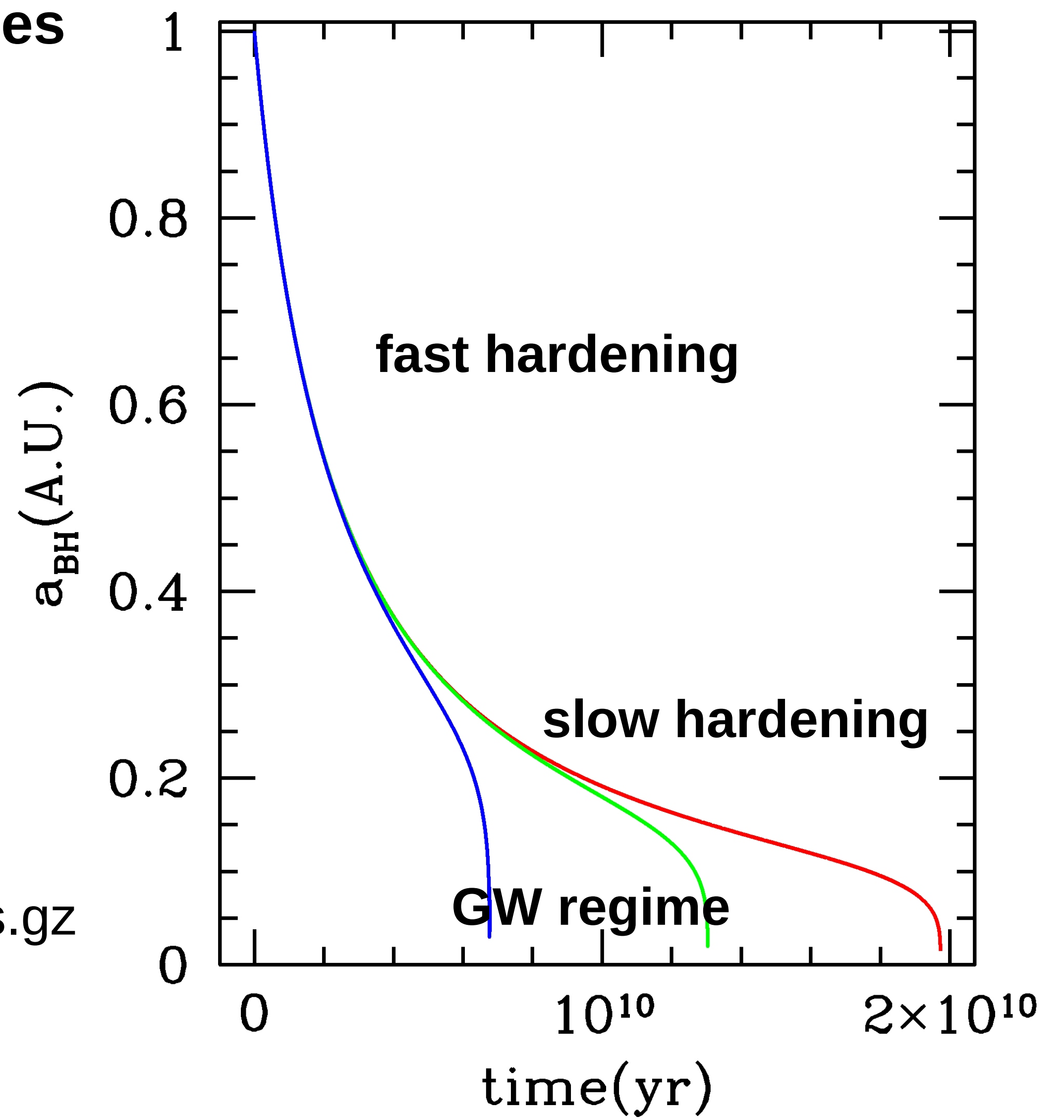
$$a_{GW} = \left[\frac{256}{5}\,\frac{G^2\,m_1\,m_2\,(m_1+m_2)\,\sigma}{2\,\pi\xi\,\left(1-e^2\right)^{7/2}\,c^5\,\rho}\right]^{1/5}$$

3. The dynamics of stellar BH binaries

* blue
m_1=200 $M_\odot$ m_2=10 $M_\odot$

* green
m_1=50 $M_\odot$ m_2=10 $M_\odot$

* red
m_1=30 $M_\odot$ m_2=3 $M_\odot$



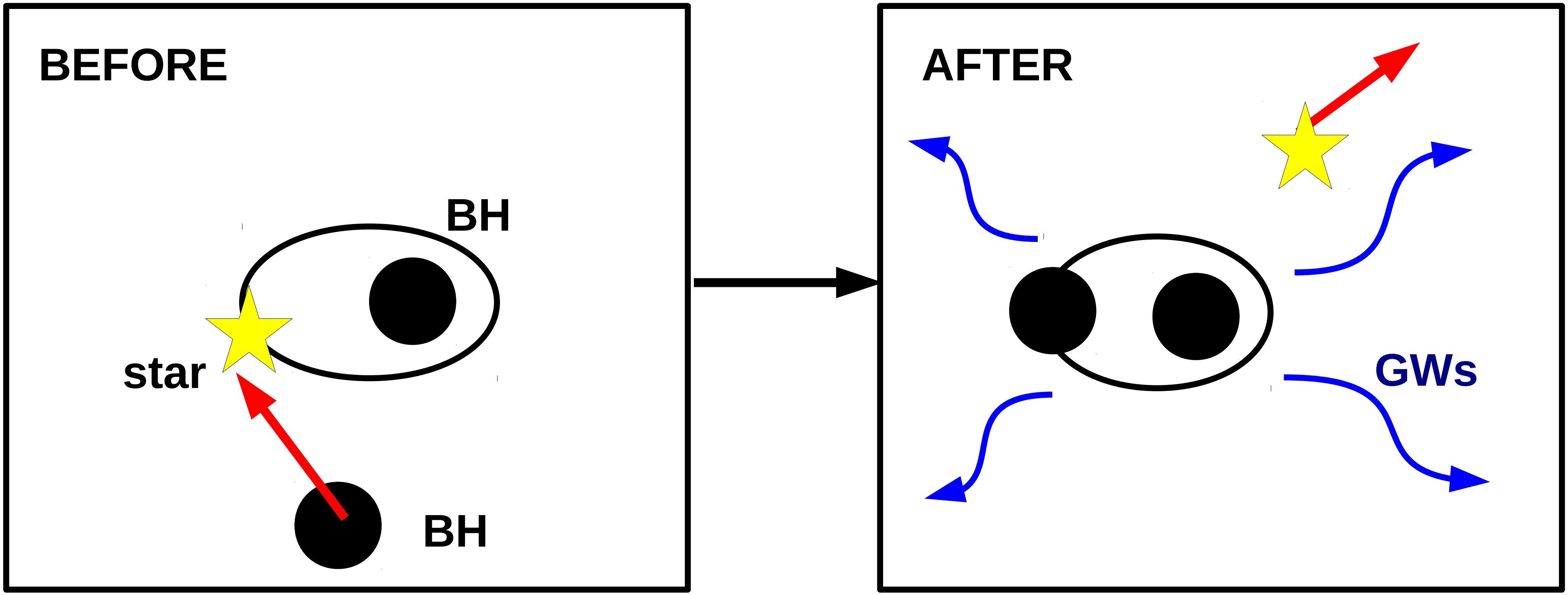
See
http://web.pd.astro.it/mapelli/images/tesi.ps.gz
and **Colpi, MM, Possenti 2003**

$$\frac{da}{dt} = \underbrace{-2\,\pi\,\xi\,\frac{G\,\rho}{\sigma}\,a^2}_{\text{Binary shrinking by hardening}} \underbrace{-\,\frac{64}{5}\,\frac{G^3\,m_1\,m_2\,(m_1+m_2)}{c^5\,(1-e^2)^{7/2}}\,a^{-3}}_{\text{Binary shrinking by GWs (Peters 1964)}}$$

Binary shrinking by hardening

Binary shrinking by GWs (Peters 1964)

3. The dynamics of stellar BH binaries: EXCHANGEs



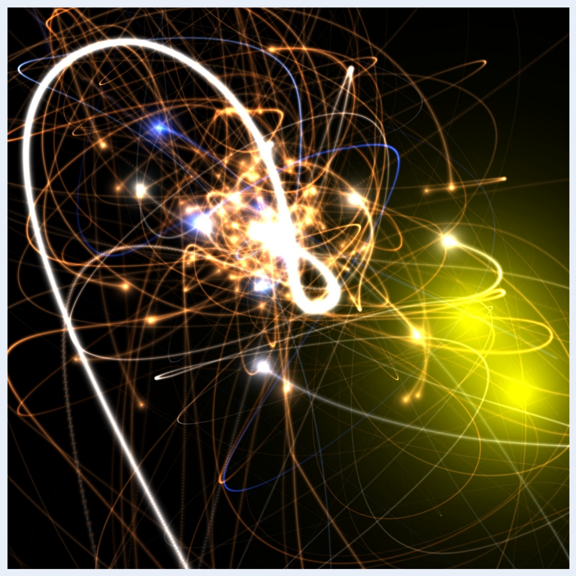
Exchanges bring BHs in binaries

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

3. The dynamics of stellar BH binaries: EXCHANGEs

Credits: Aaron Geller (@Northwestern):

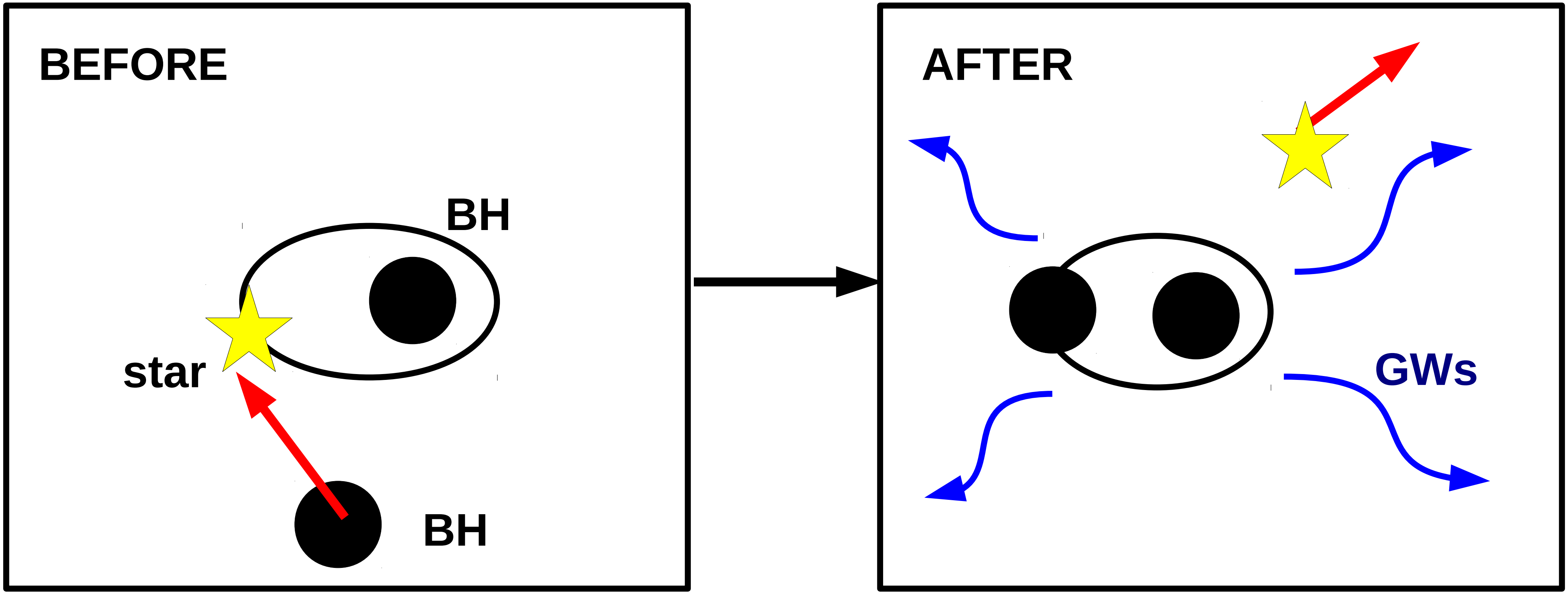


Movie 2 : binary – single interaction
ciera.northwestern.edu/Research/visualizations/videos/Binary+single.mp4

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)

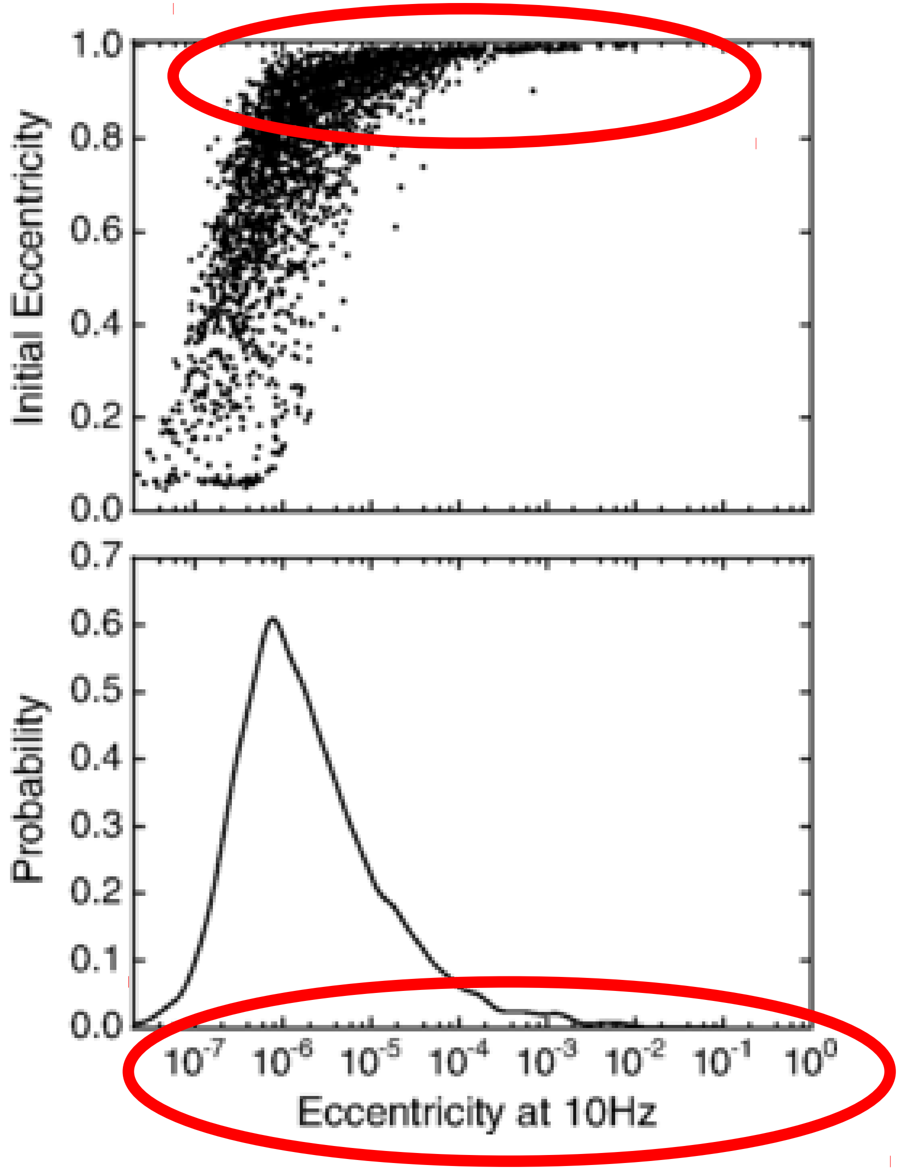
EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH

** THE MOST MASSIVE BHs*

** HIGH ECCENTRICITY*

** MISALIGNED BH SPINS*

3. The dynamics of stellar BH binaries: EXCHANGEs



Rodriguez+ 2016, PhRvD, 93, 4029

- high eccentricity at formation

- small eccentricity when reaching LIGO-Virgo range

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

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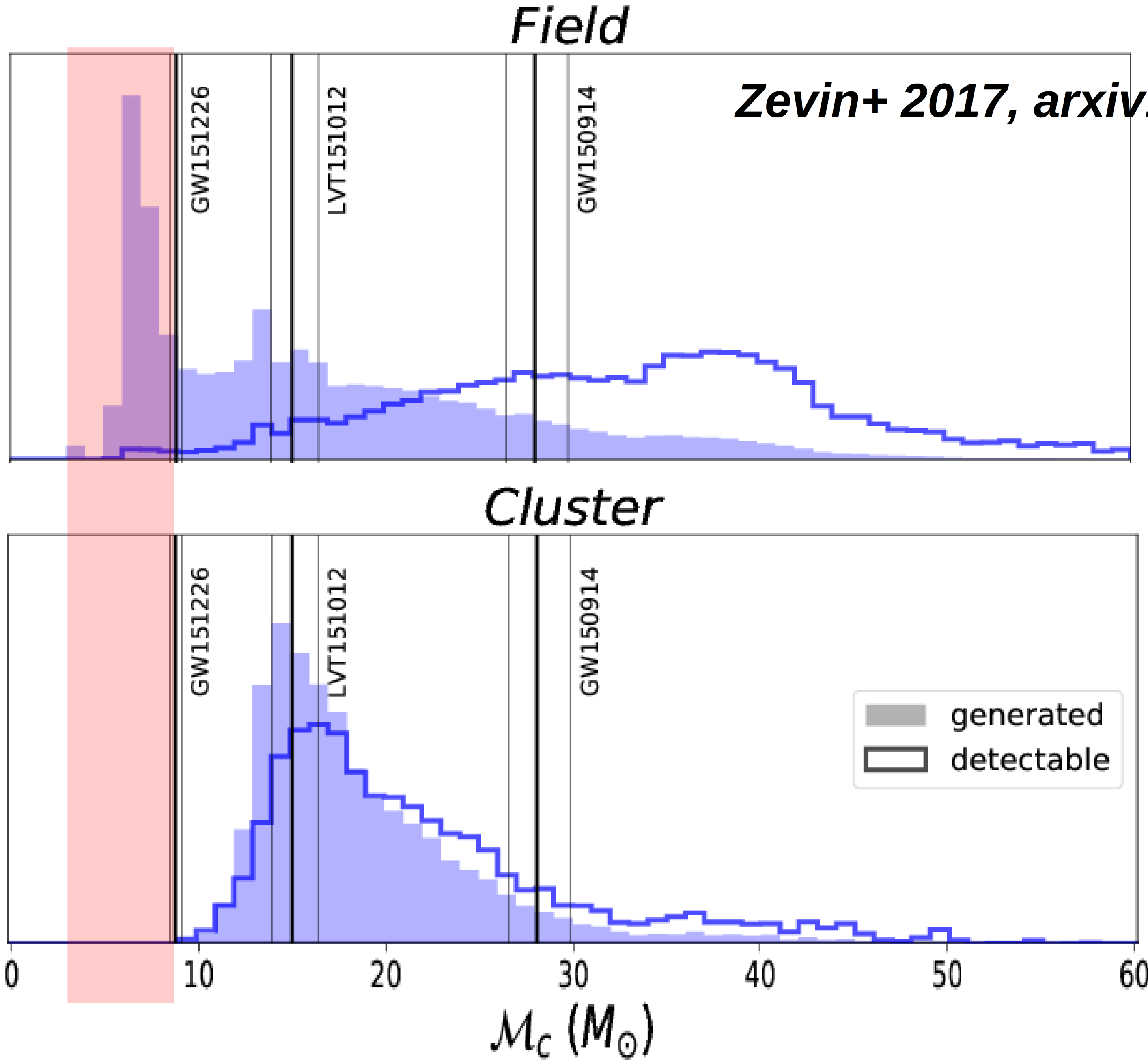
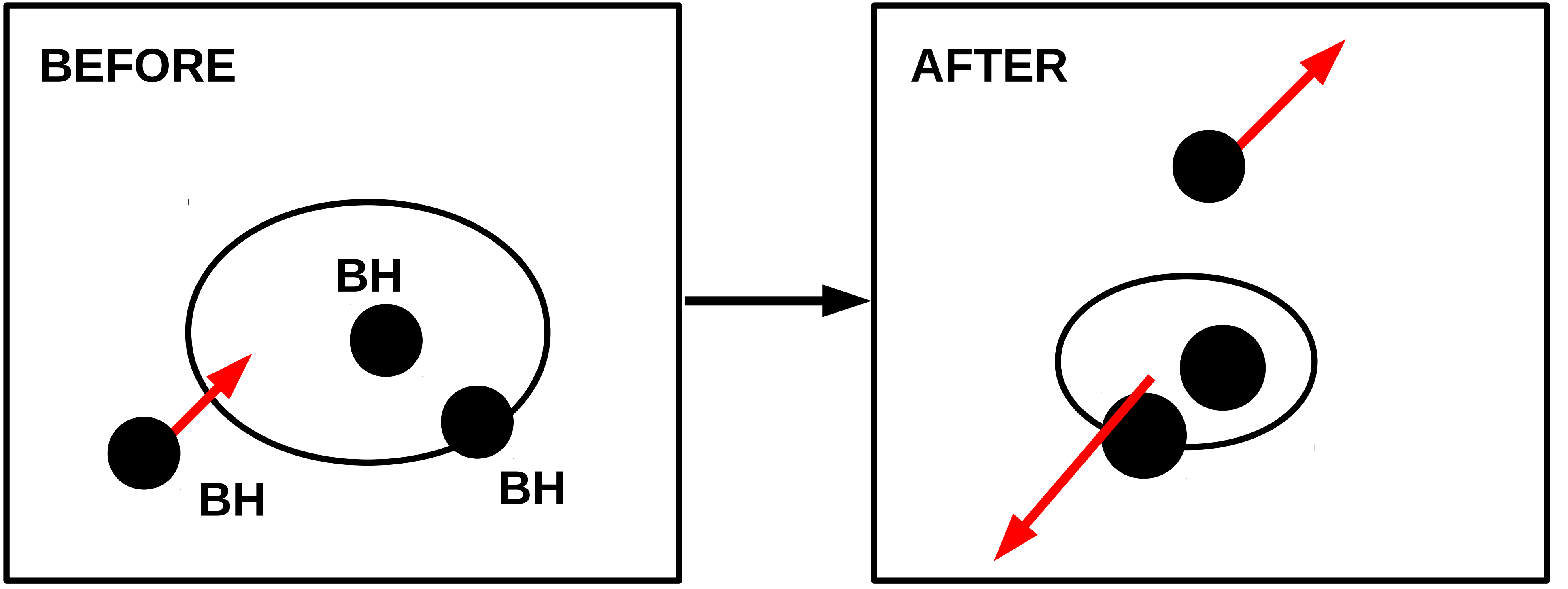


Zevin+ 2017, arxiv1704.07379

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: ejections



Internal energy is extracted from the binary

→ **converted into KINETIC ENERGY of the INTRUDER AND of the CM of the BINARY**

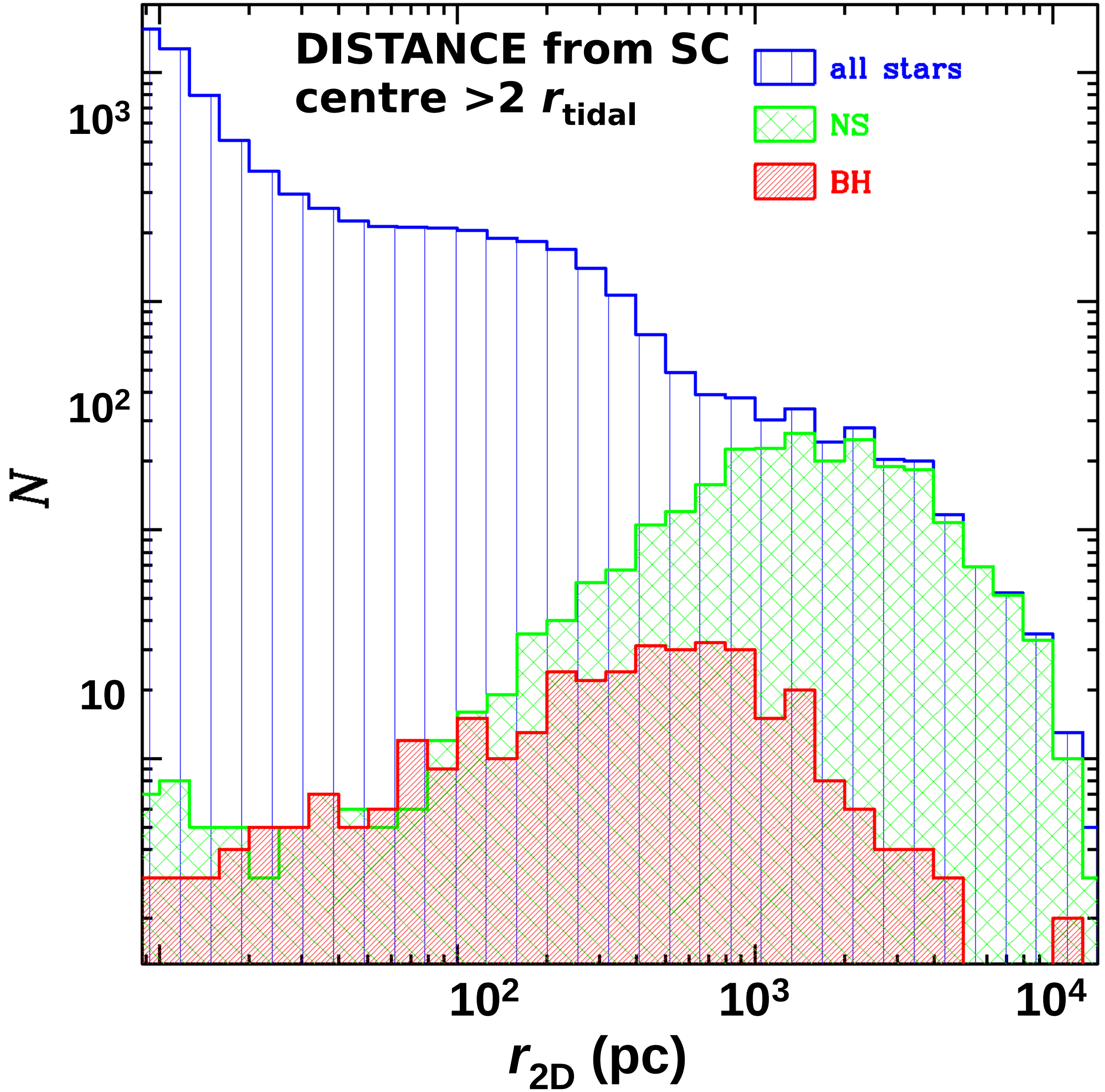
→ **BOTH RECOIL and can be ejected from SC**

IMPORTANT NOT ONLY FOR BHs but also for BH-NS and NS-NS!!

3. The dynamics of stellar BH binaries: ejections

BHs and NSs are ejected from host star clusters by DYNAMICS and NATAL (SN) KICKS

Simulations of young star clusters @ t=100 Myr



~80-90% NS is ejected (mainly by SN)

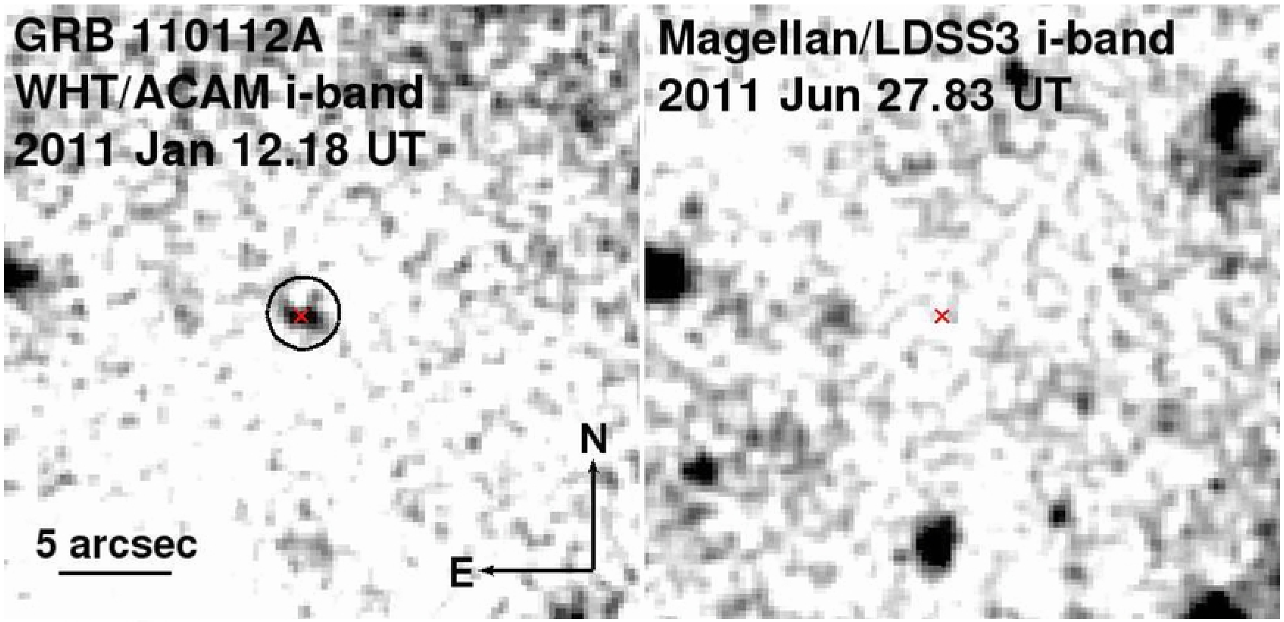
~40% BH is ejected (1/2 by SN, 1/2 by 3body)

PREDICTED MERGERS OCCUR MOSTLY IN THE FIELD

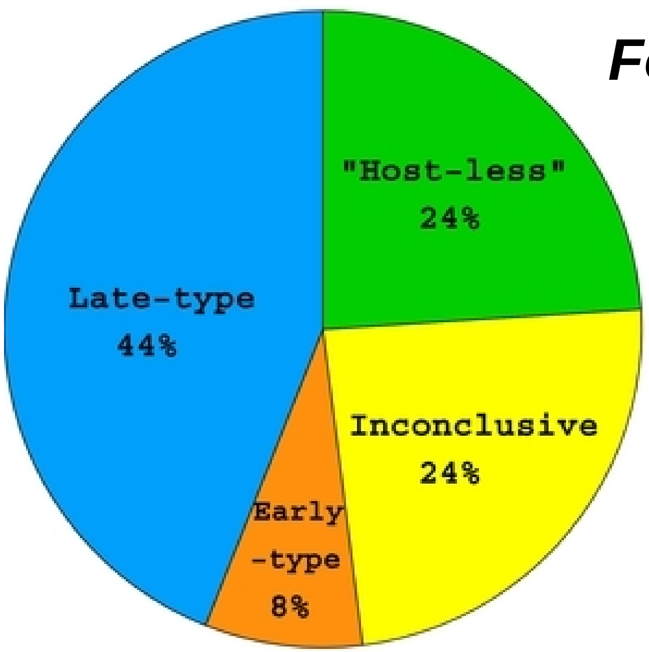
Downing+ 2011, MNRAS, 416, 133
MM + 2013, MNRAS, 429, 2298

3. The dynamics of stellar BH binaries: ejections

Are host-less short GRBs associated with dynamical ejections?



Fong+ 2013, ApJ, 769, 56



ISSUE: dynamical kicks 0 – 200 km/s

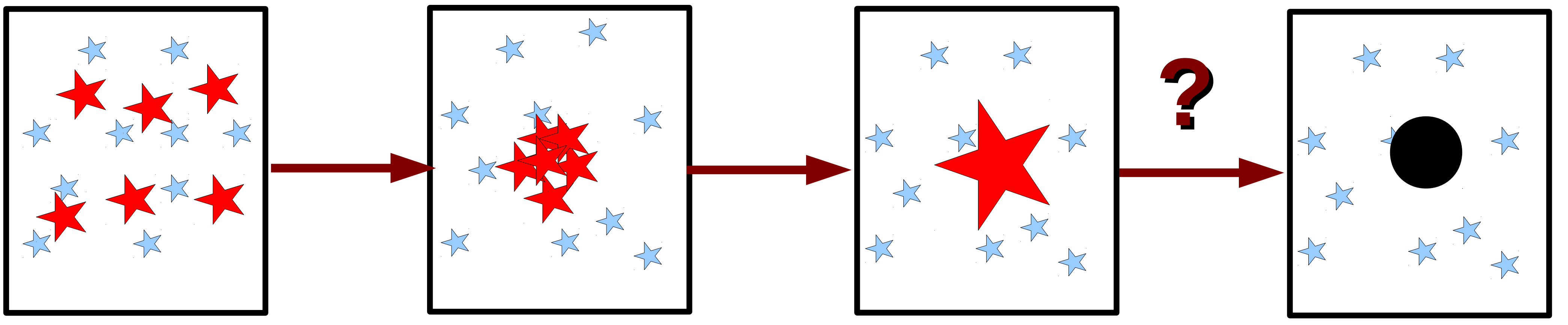
not enough to unbind system from host galaxy

3. The dynamics of stellar BH binaries: runaway collisions

Mass segregation fast in young star clusters:

$$t_{\rm DF}(25M_\odot) \sim 2{\rm Myr}\,\left(\frac{t_{\rm rlx}}{50{\rm Myr}}\right) < t_{\rm SN}$$

Massive stars segregate to the centre where collide with each other



Massive super-star forms and possibly collapses to IMBH

What is the final mass of the collision product?

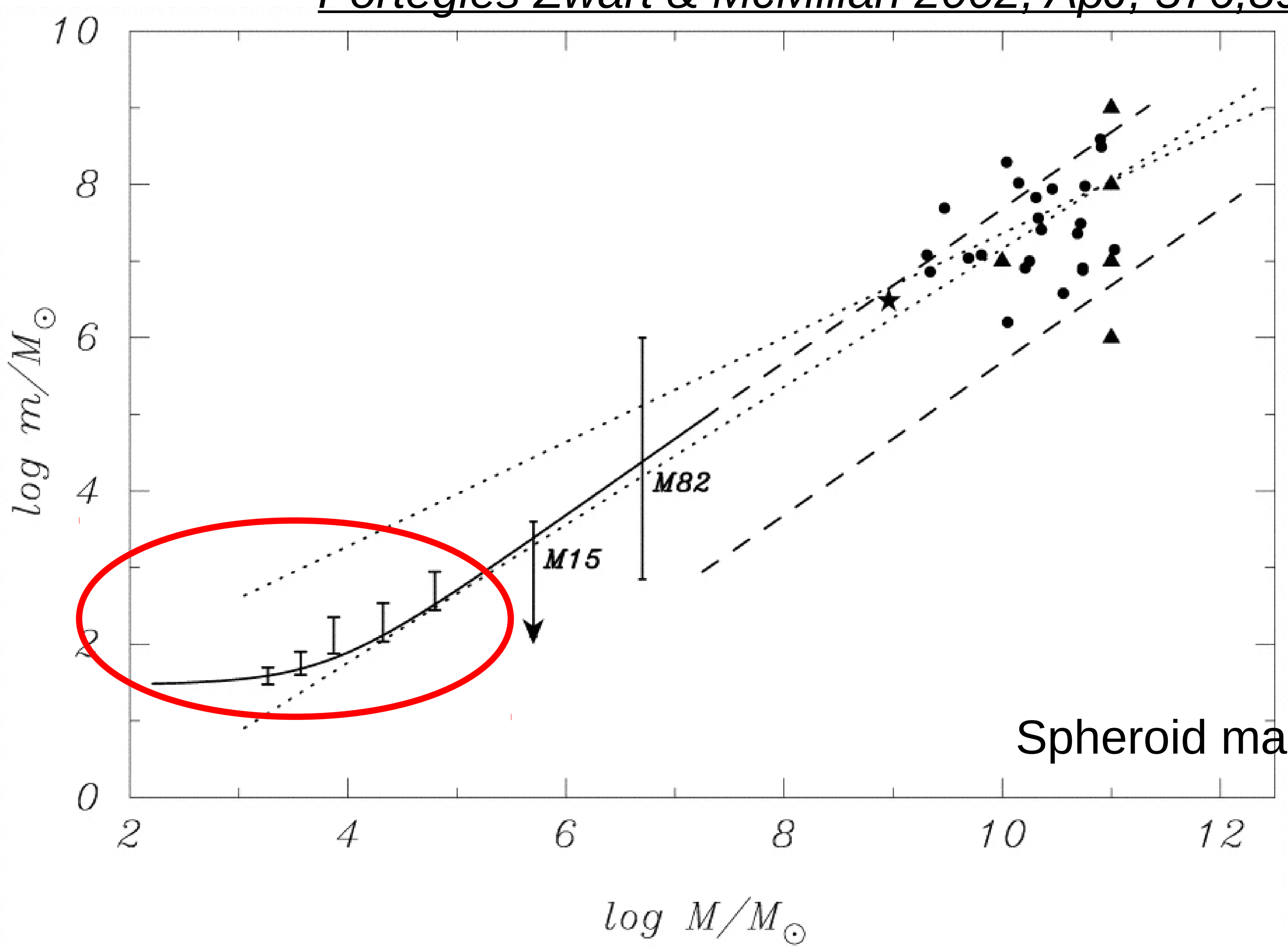
Colgate 1967, ApJ, 150, 163; Sanders 1970, ApJ, 162, 791; Portegies Zwart+ 1999, A&A, 348, 117; Portegies Zwart & McMillan 2002, ApJ, 576, 899; Portegies Zwart+ 2004, Nature, 428, 724; Gurkan+ 2006, ApJ, 640, L39; Freitag+ 2006, MNRAS, 368, 141; Giersz+ 2015, MNRAS, 454, 3150; MM 2016, MNRAS, 459, 3432 and many many others

3. The dynamics of stellar BH binaries: runaway collisions

Early studies without stellar evolution suggest IMBH mass ~ 10^-3 star cluster mass

Portegies Zwart & McMillan 2002, ApJ, 576,899

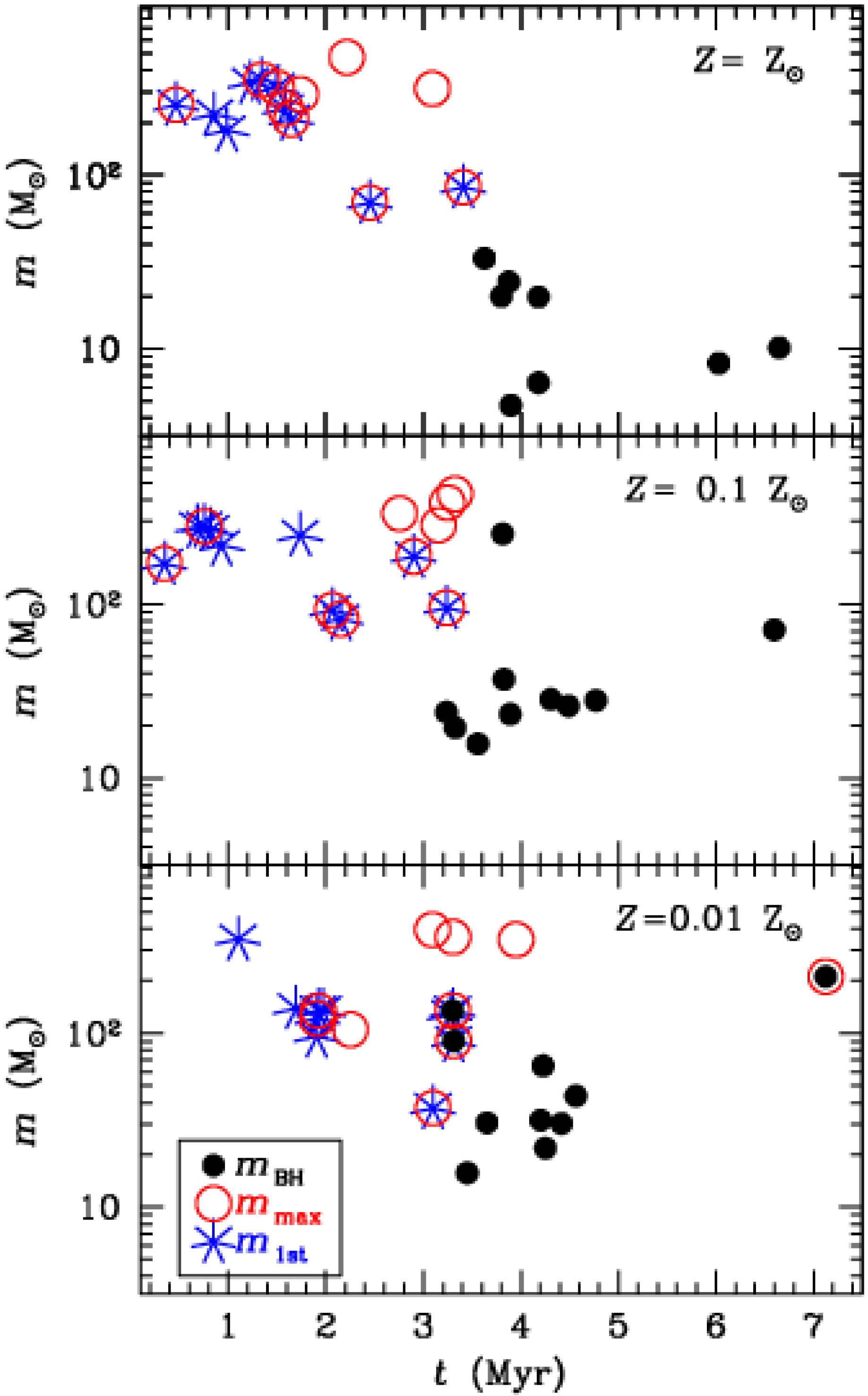
BH mass



Spheroid mass

BUT stellar evolution CANNOT be neglected!!

3. The dynamics of stellar BH binaries: runaway collisions



<u>**N-body simulations with star evolution**</u>

Masses of runaway collision products:

*** no IMBHs at Zsun**
because stellar winds are too strong

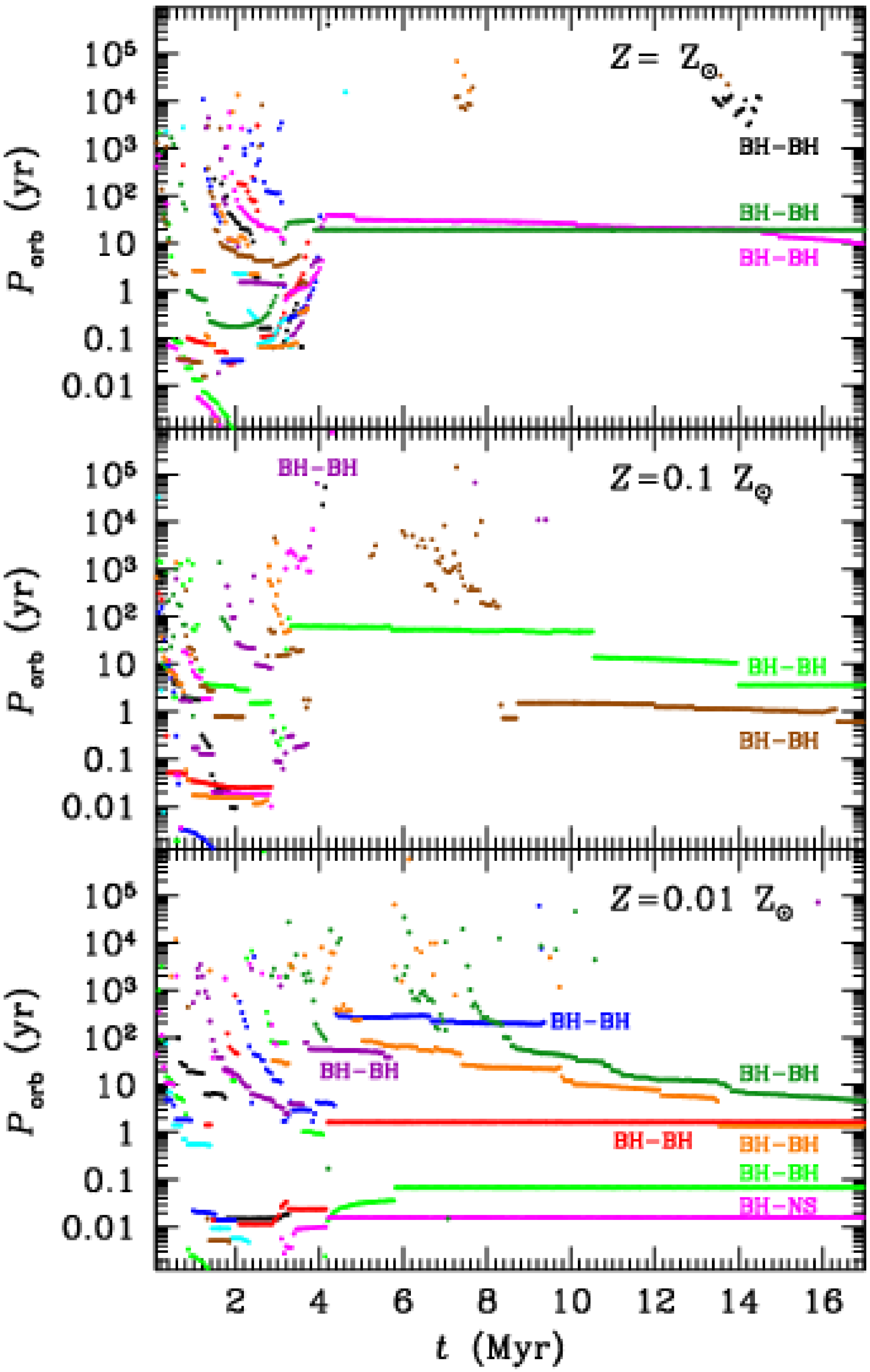
*** 10% BHs in the IMBH regime**
(>100 Msun) at Z = 0.01 – 0.1 Zsun

*** CAVEAT 1: uncertainties in the evolution of very massive stars**

*** CAVEAT 2: uncertainties in mass-loss during/after collisions**

MM 2016, MNRAS, 459, 3432

3. The dynamics of stellar BH binaries: runaway collisions



N-body simulations with star evolution

Collision products form stable binaries with other BHs:

4 BH-BH at Z = 0.01 Zsun
1 BH-NS at Z = 0.01 Zsun
2 BH-BH at Z = 0.1 Zsun
2 BH-BH at Z = 1 Zsun

PERIOD from few hours to few years

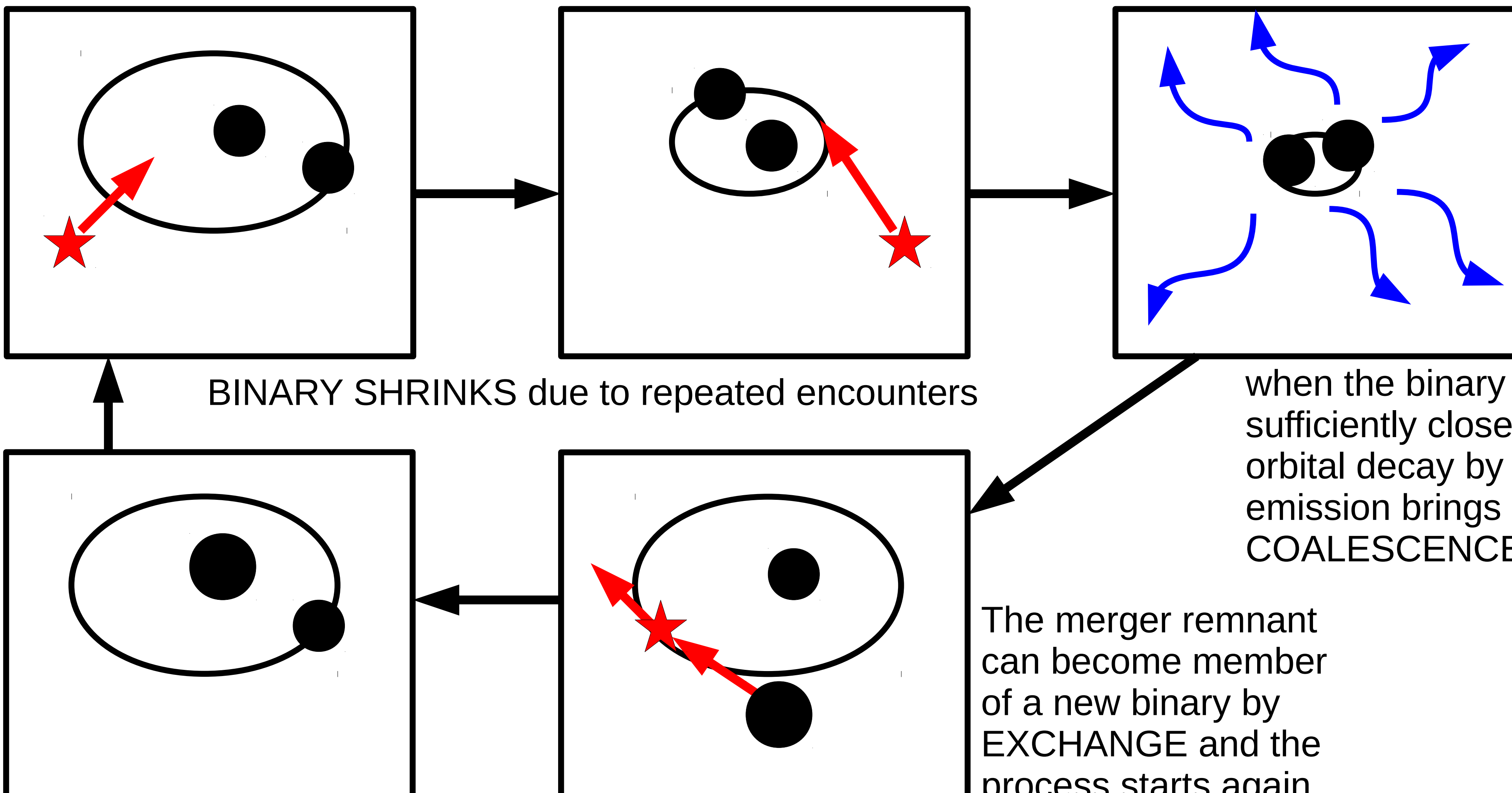
Possibly JOINT SOURCES for LISA and for LIGO-Virgo

MM 2016, MNRAS, 459, 3432

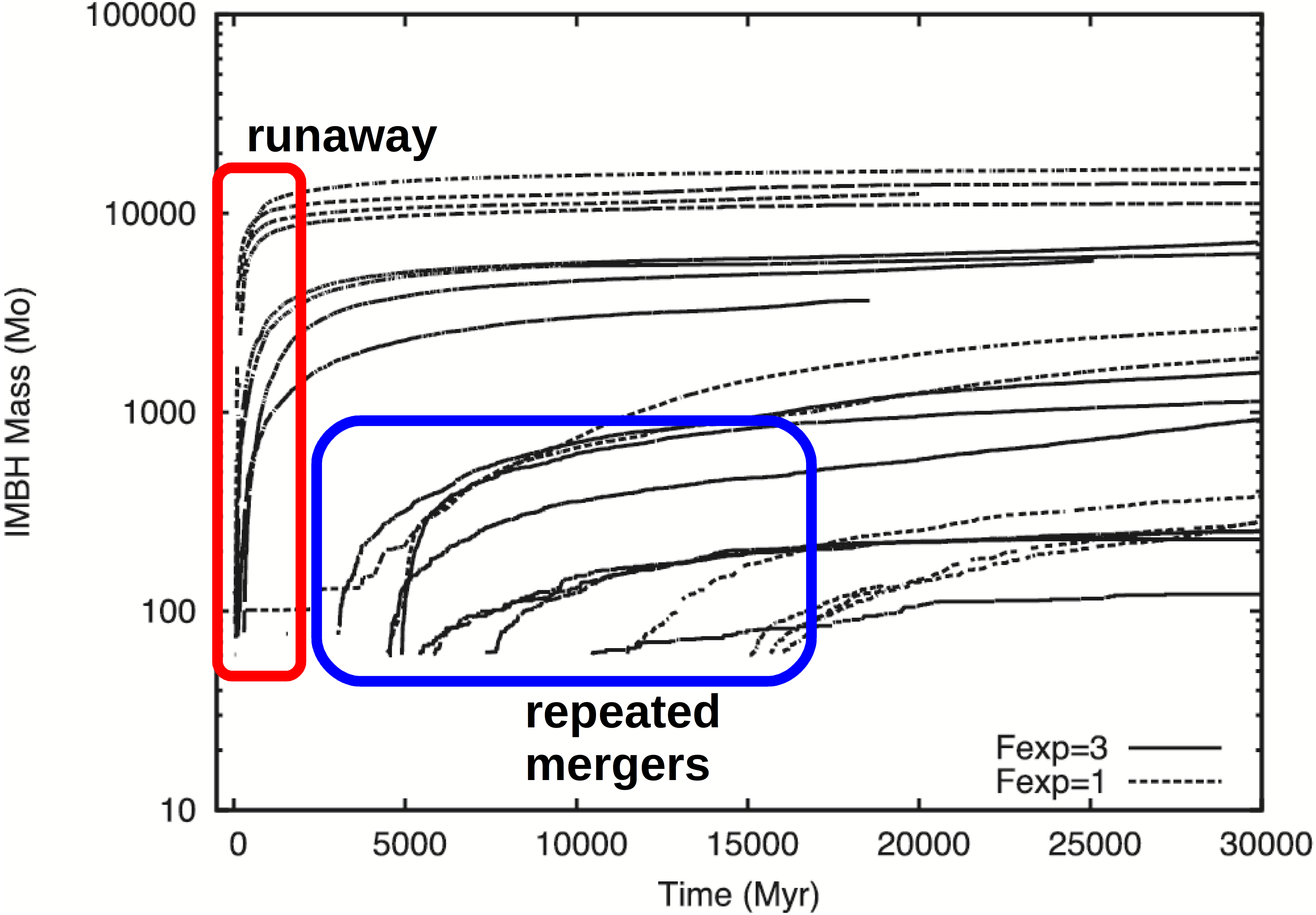
3. The dynamics of stellar BH binaries: repeated mergers

<u>Formalism by Miller & Hamilton (2002)</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: repeated mergers

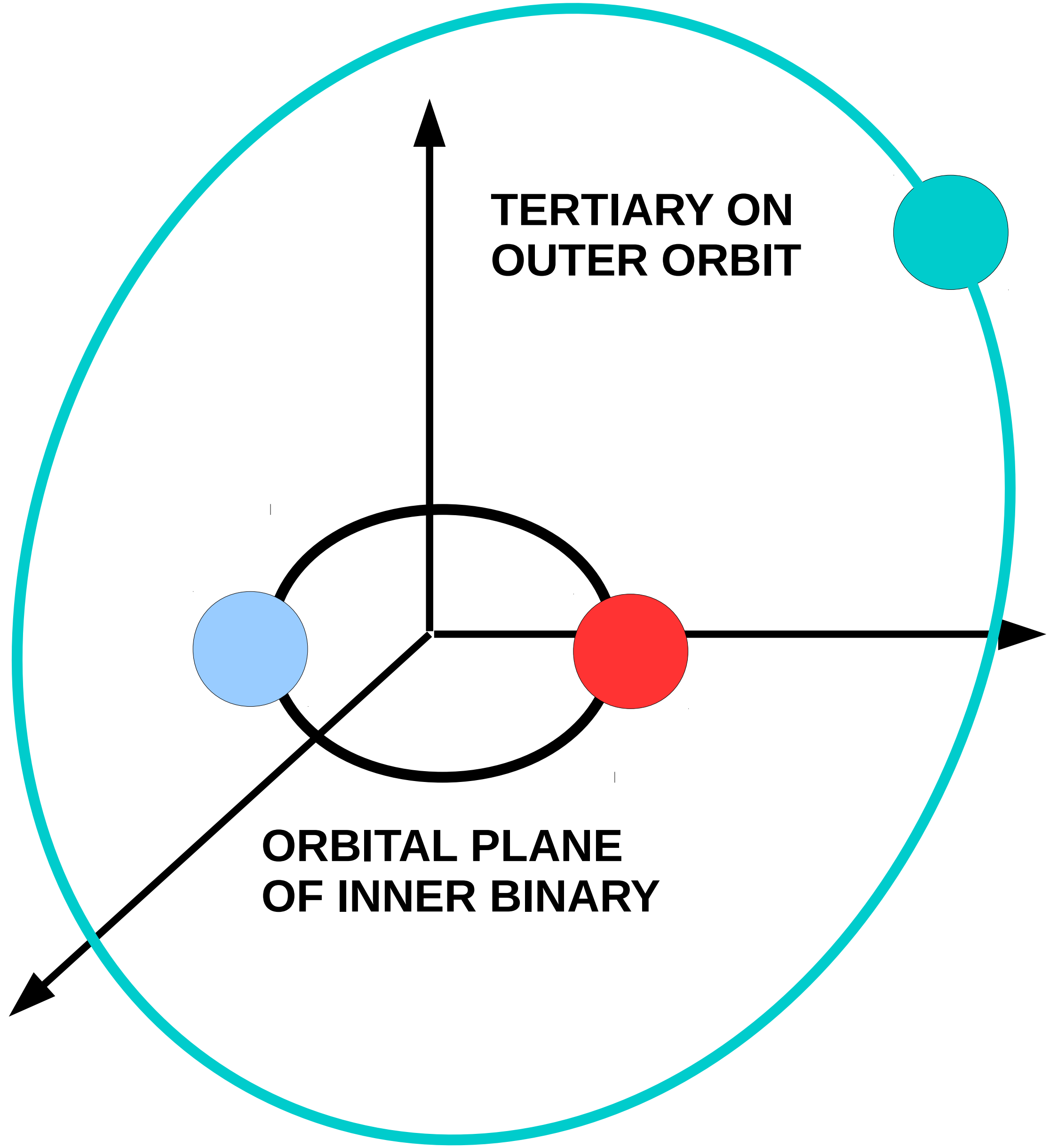


Giersz +2015, MNRAS, 454, 3150

3. The dynamics of stellar BH binaries: Kozai resonance

ONLY DYNAMICAL PROCESS COMMON ALSO IN THE FIELD

~ 15% stars are in triple (e.g. Raghavan+ 2010)



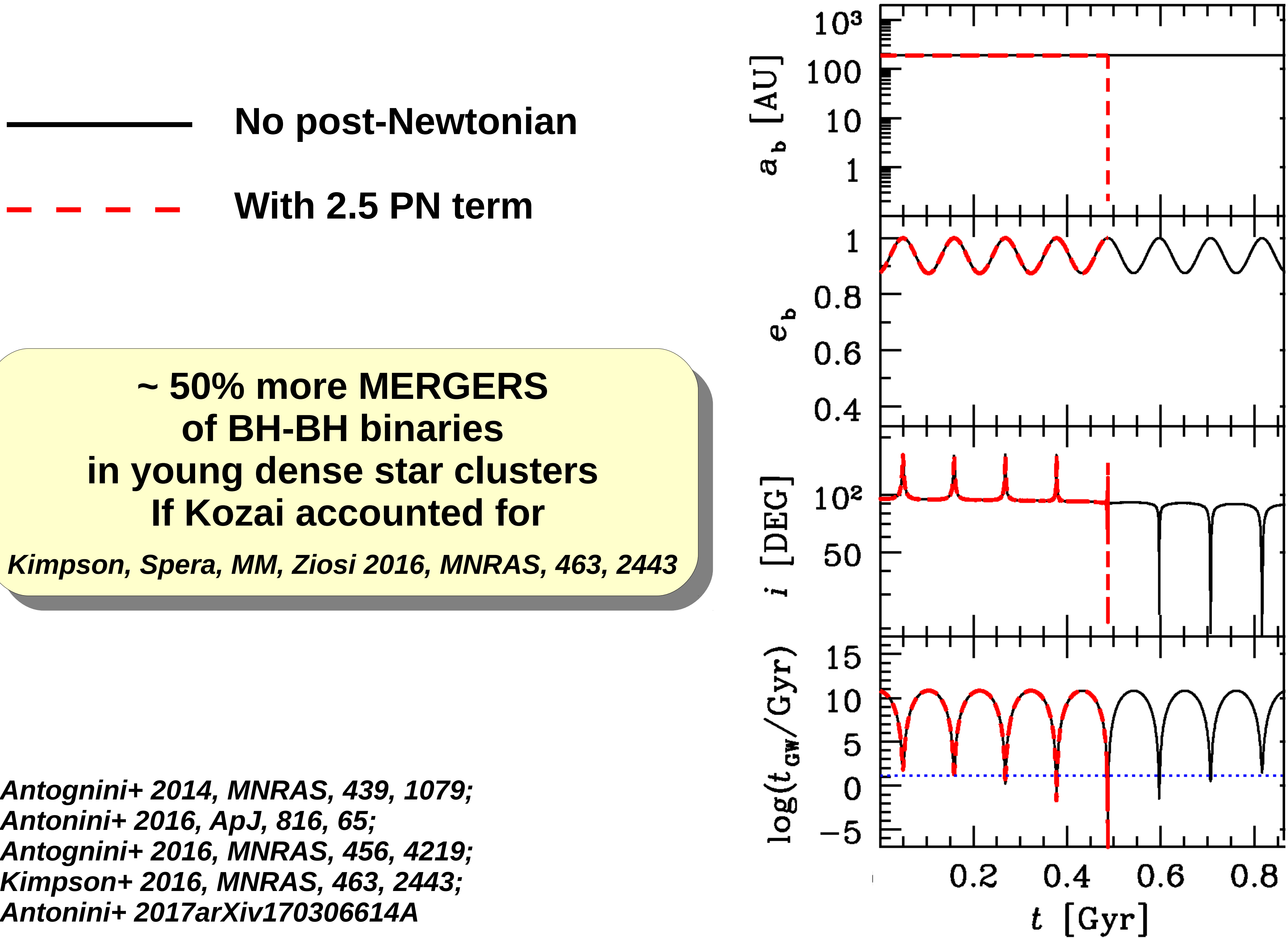
IN A HIERARCHICAL TRIPLE ECCENTRICITY AND INCLINATION OSCILLATE

TRIGGERING MERGERS / COLLISIONS between binary members

Antognini+ 2014, MNRAS, 439, 1079;
Antonini+ 2016, ApJ, 816, 65;
Antognini+ 2016, MNRAS, 456, 4219;
Kimpson+ 2016, MNRAS, 463, 2443;
Antonini+ 2017arXiv170306614A

Kozai 1962, AJ, 67, 591
Lidov 1962, P&SS, 9, 719

3. The dynamics of stellar BH binaries: Kozai resonance



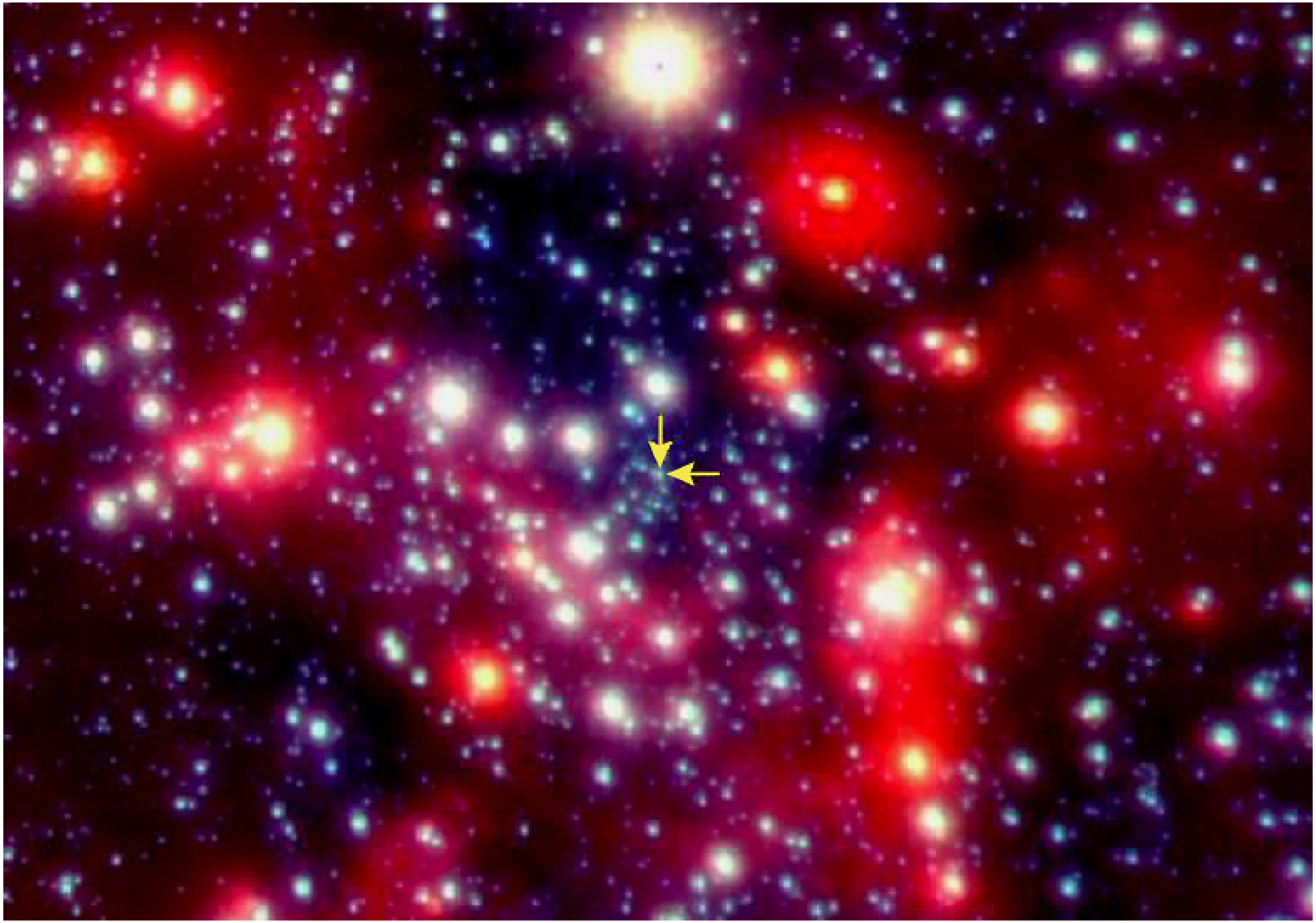
~ 50% more MERGERS
of BH-BH binaries
in young dense star clusters
If Kozai accounted for

Kimpson, Spera, MM, Ziosi 2016, MNRAS, 463, 2443

Antognini+ 2014, MNRAS, 439, 1079;
Antonini+ 2016, ApJ, 816, 65;
Antognini+ 2016, MNRAS, 456, 4219;
Kimpson+ 2016, MNRAS, 463, 2443;
Antonini+ 2017arXiv170306614A

3. The dynamics of stellar BH binaries: Kozai resonance

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:



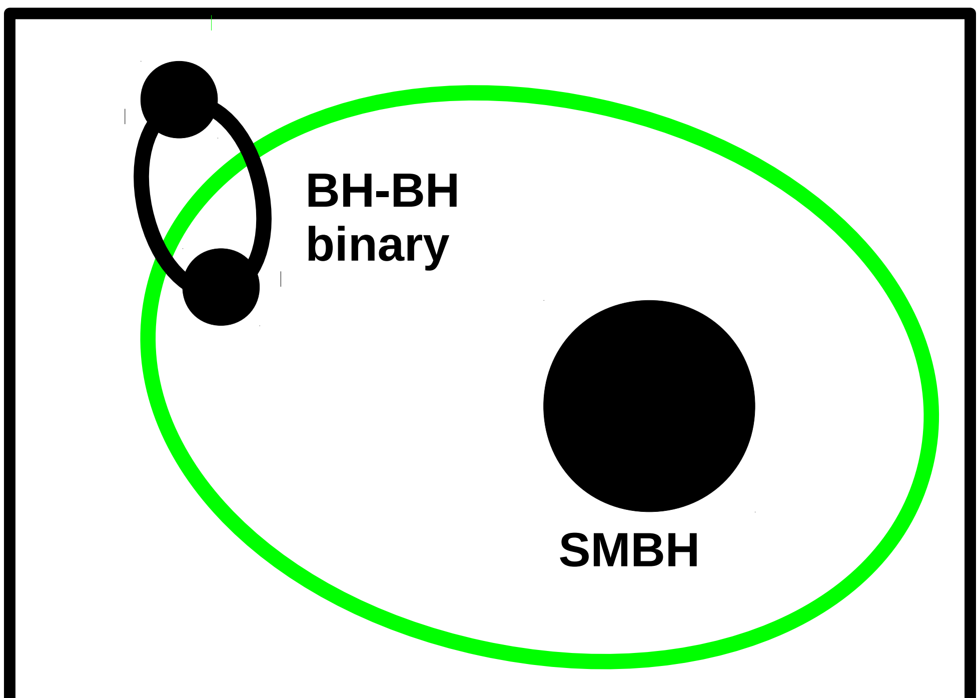
Schoedel et al. 2002, Nature, 419, 694

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

3. The dynamics of stellar BH binaries: Kozai resonance

KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:

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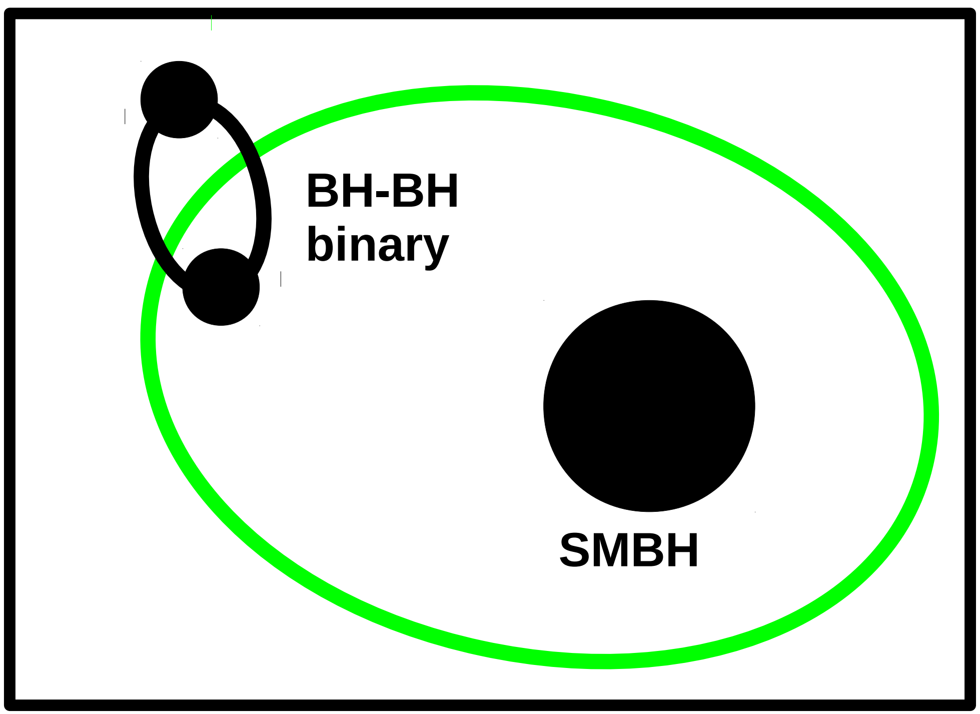
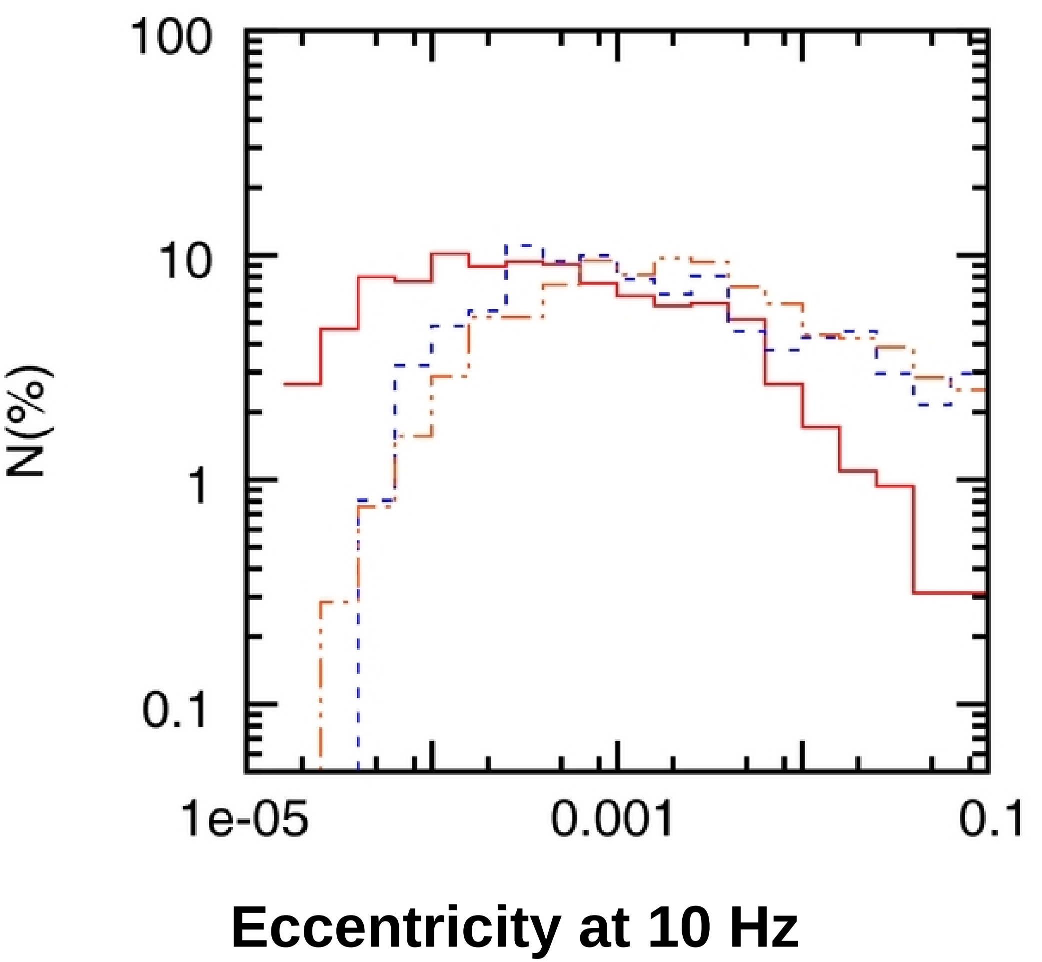
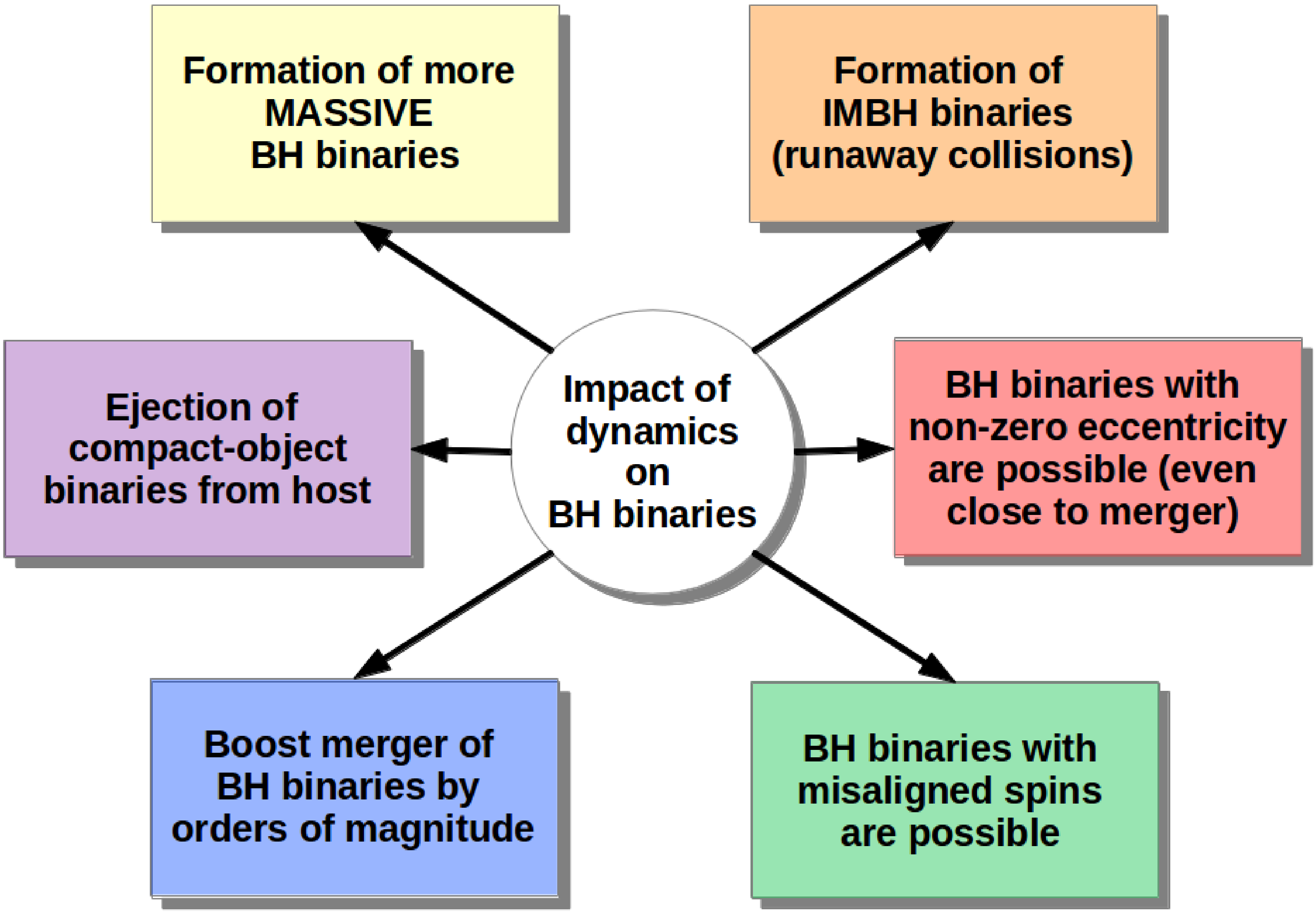




Antonini & Perets 2012, ApJ, 757, 27

3. The dynamics of stellar BH binaries: wrap up

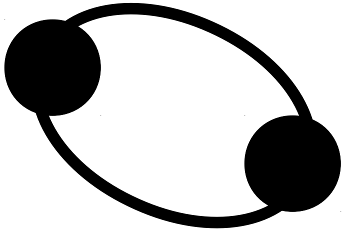


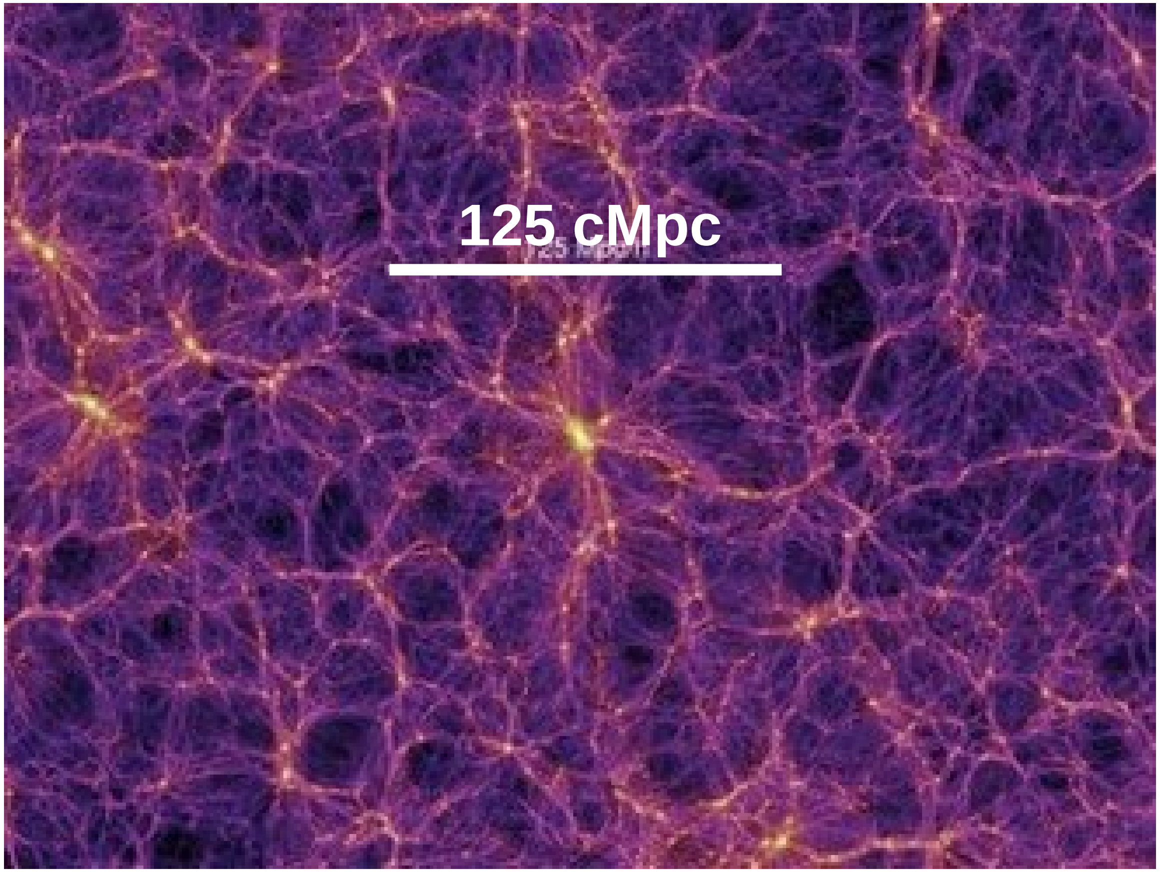
4. BH binaries in cosmological context

How do merging BHB binaries populate galaxies?

CHALLENGING:

Scale of a BHB < few AU





Scale of cosmic structures ~ tens of Mpc

4. BH binaries in cosmological context

TWO MAIN ESCAMOTAGES:

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

Dominik+ 2013, 2015
Belczynski+ 2016
***Lamberts+ 2016**
(*use 1 ingredient from simulations)

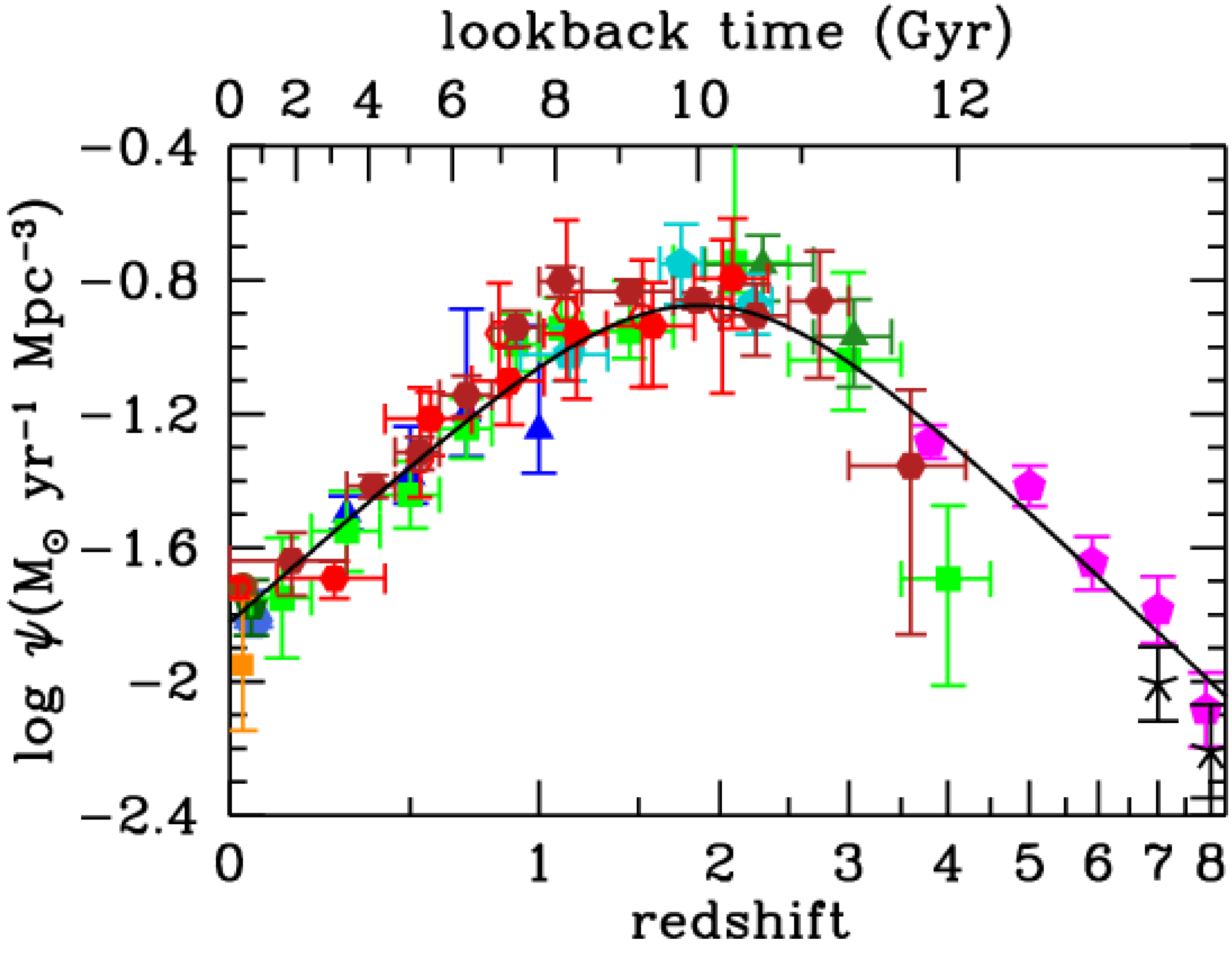
- cosmological simulations + binary population synthesis simulations through Monte Carlo procedure

O'Shaughnessy+ 2017
Schneider+ 2017
MM+ 2017

4. BH binaries in cosmological context

MAIN INGREDIENTS: cosmic star formation rate density

BH-BH binaries depend on it because BHs form from massive stars

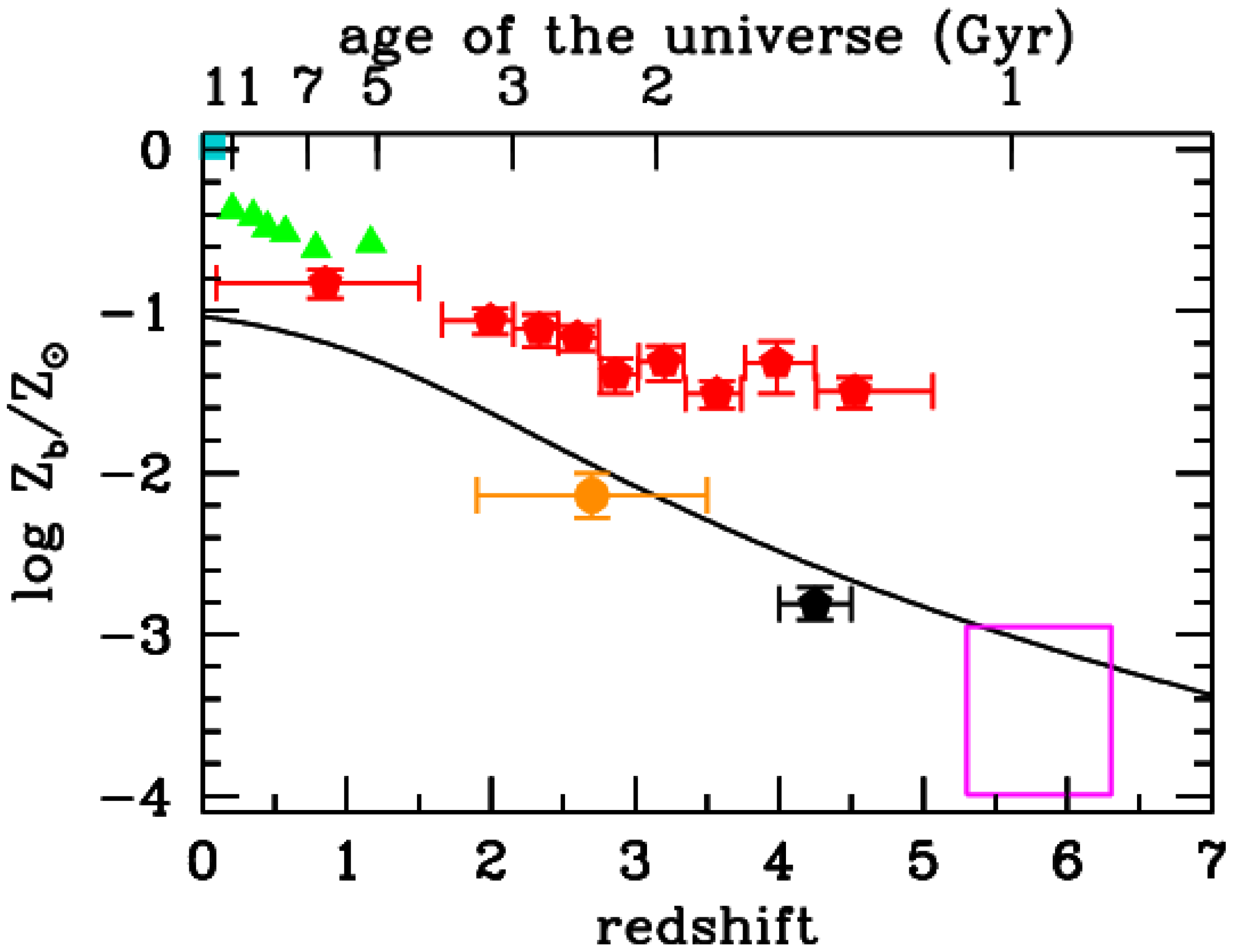


(FUV+ IR data, Fig. 9 of Madau & Dickinson 2014)

4. BH binaries in cosmological context

MAIN INGREDIENTS: metallicity evolution

Mass of BHs depends on metallicity

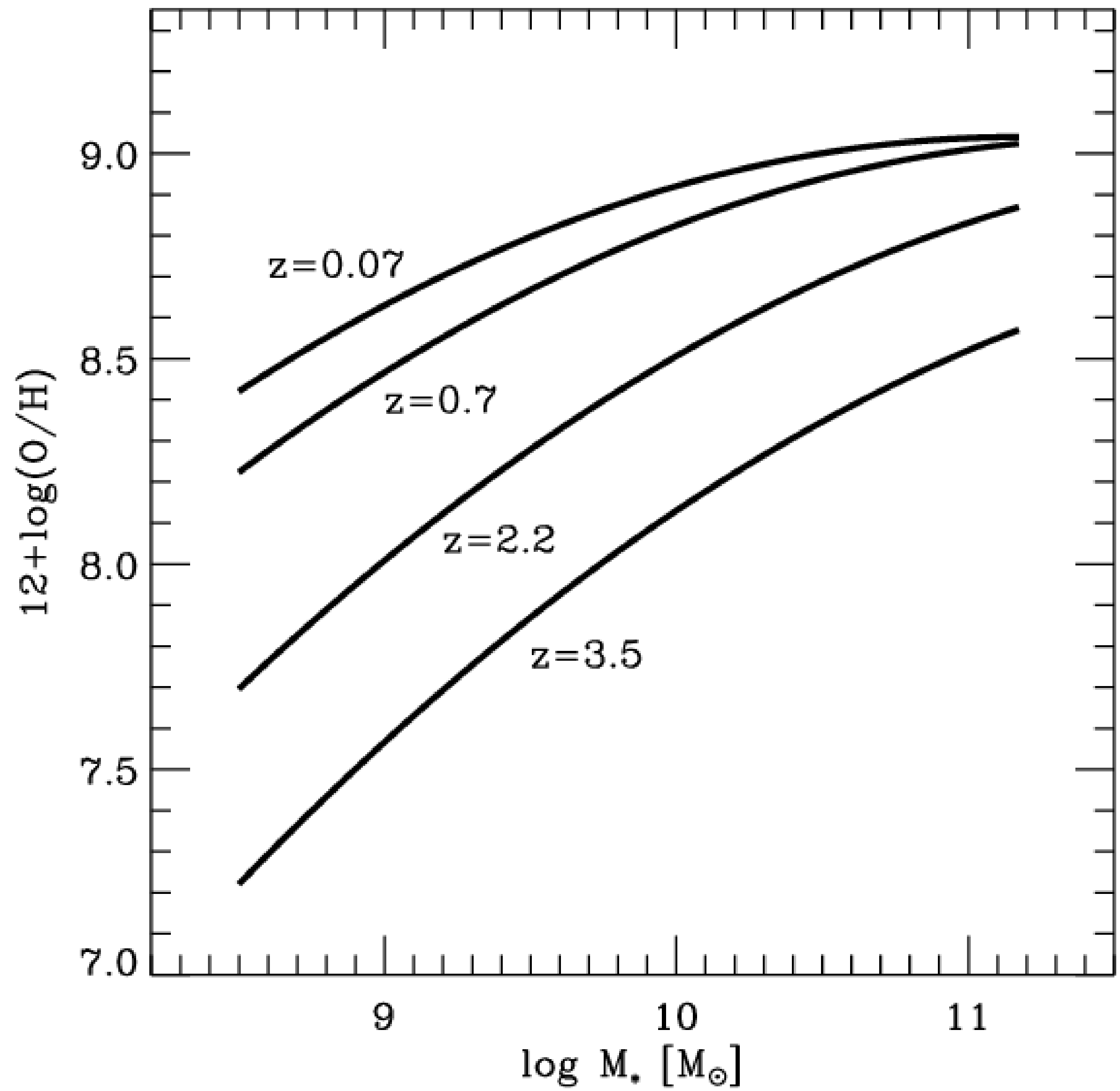


(Fig. 14 of Madau & Dickinson 2014)

4. BH 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

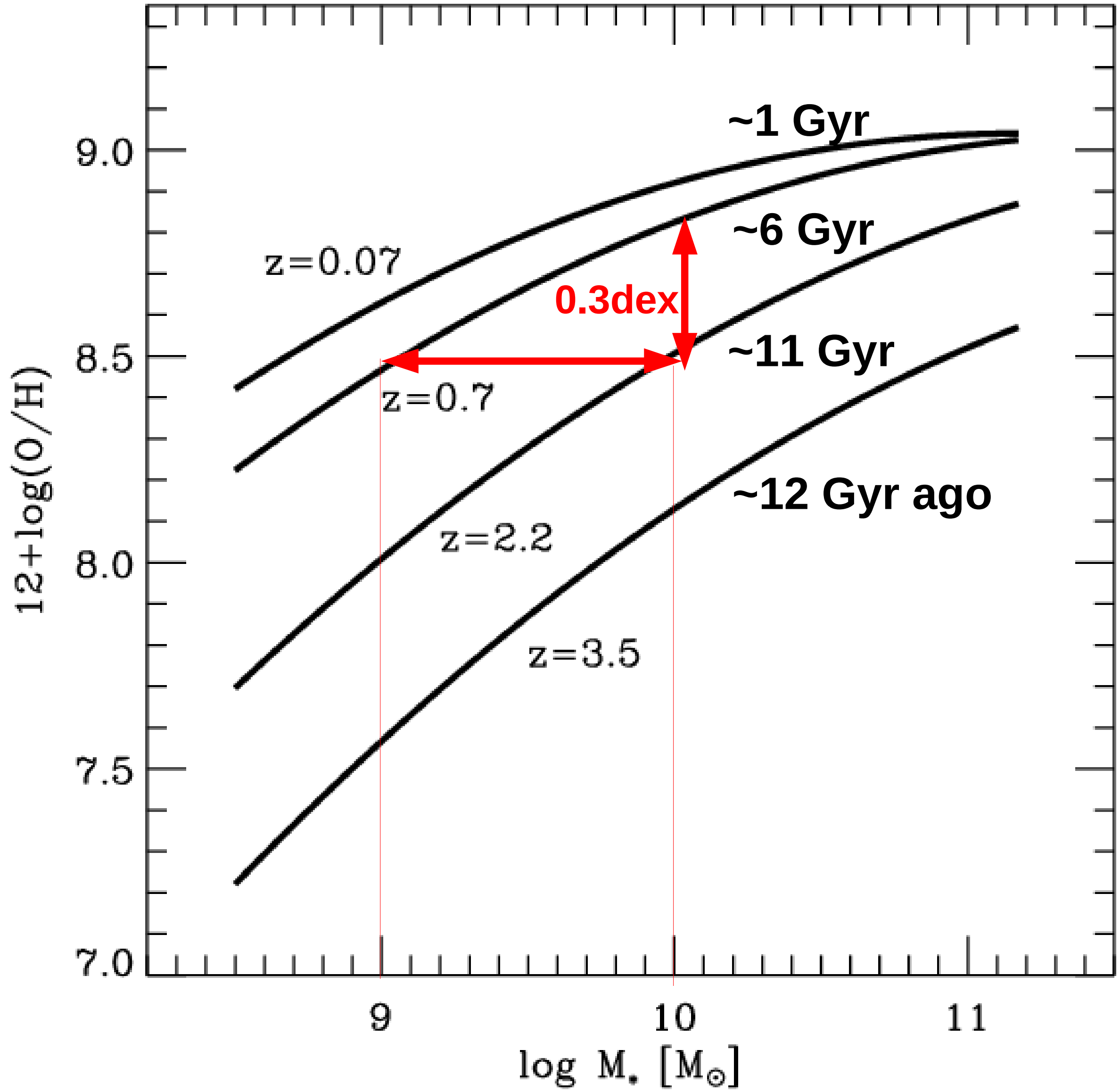
4. BH binaries in cosmological context

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

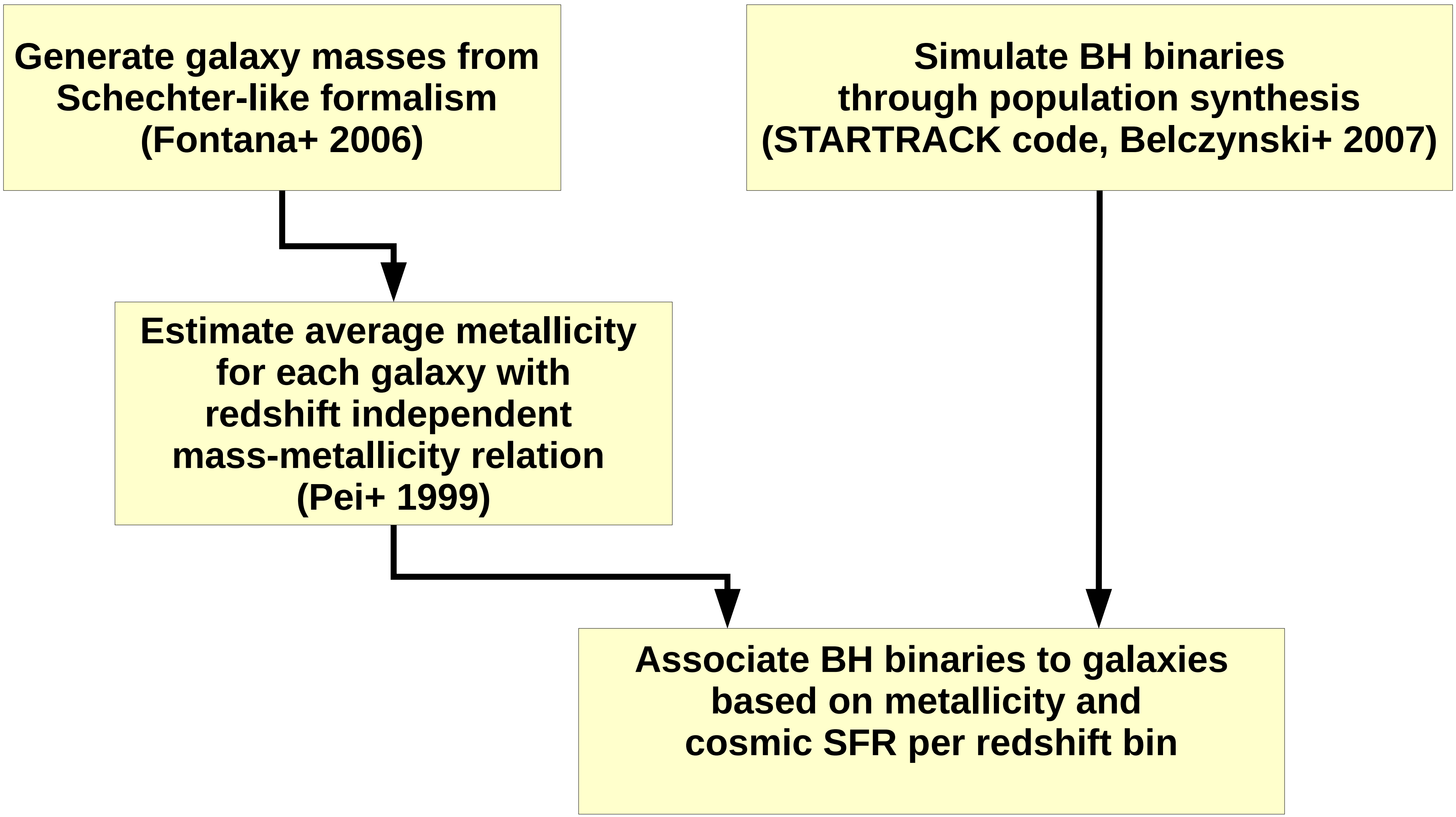
Between 10^9 and 10^10 M⊙ observed metallicity changes ~0.3 dex for fixed redshift (~0.7)



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

4. BH binaries in cosmological context

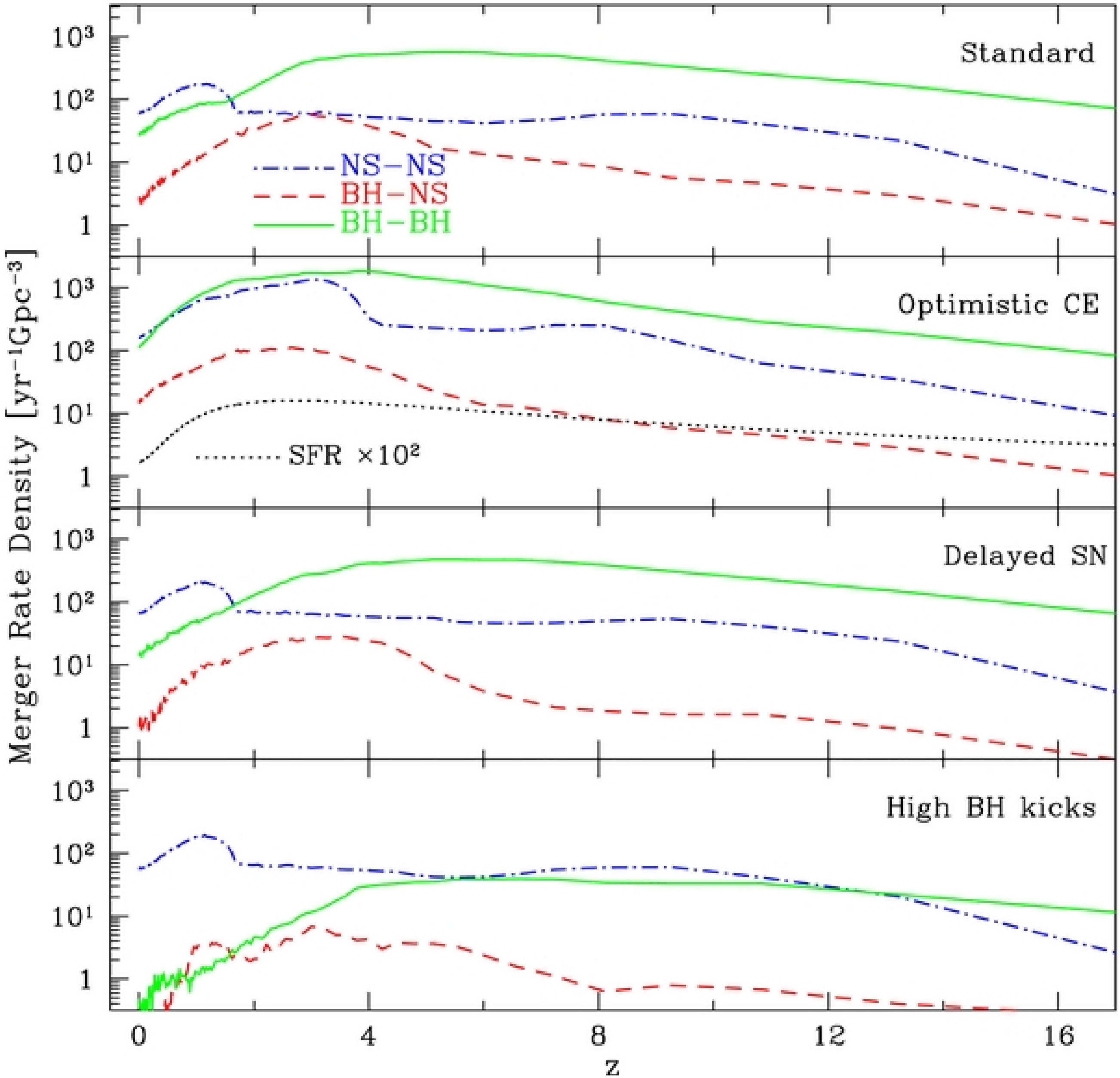
Dominik+ 2013



Issues: all stars in a galaxy have same metallicity,
does not recover mass-metallicity-star formation rate relation

4. BH binaries in cosmological context

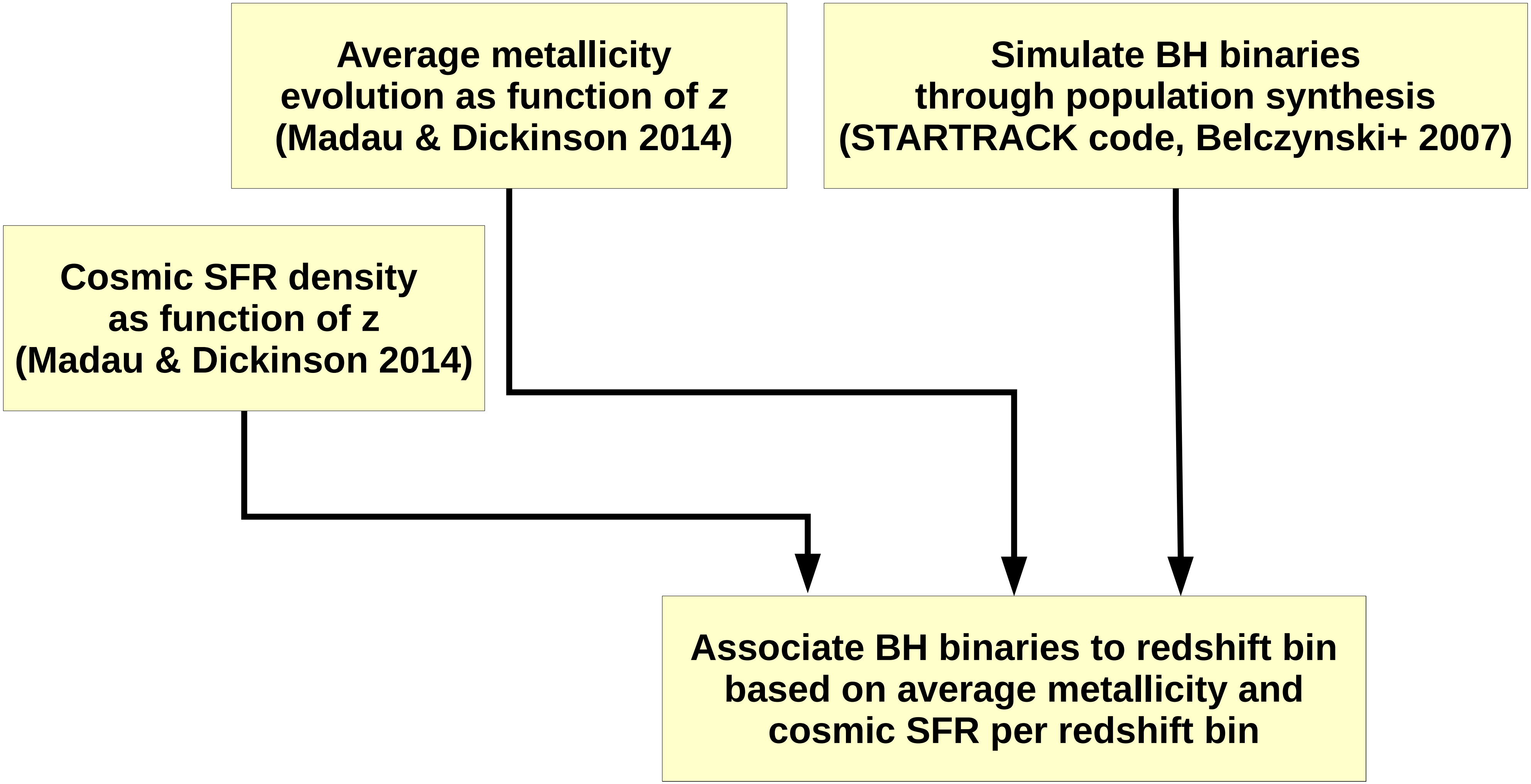
Dominik+ 2013



Issues: * all stars in a galaxy have same metallicity,
*** does not recover mass-metallicity relation!!**

4. BH binaries in cosmological context

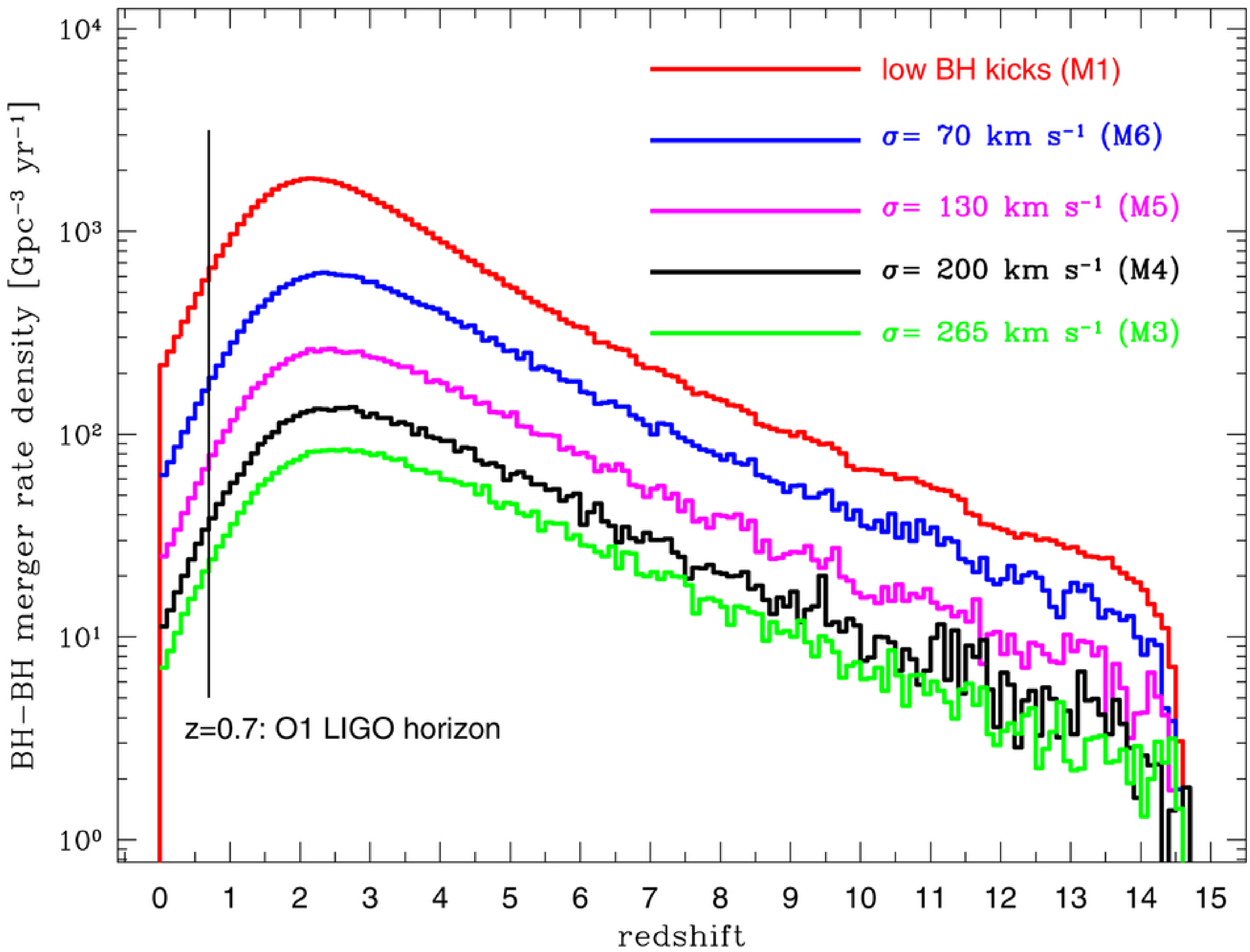
Belczynski+ 2016



Issues: does not recover mass-metallicity rate relation!!!
No information on host galaxies

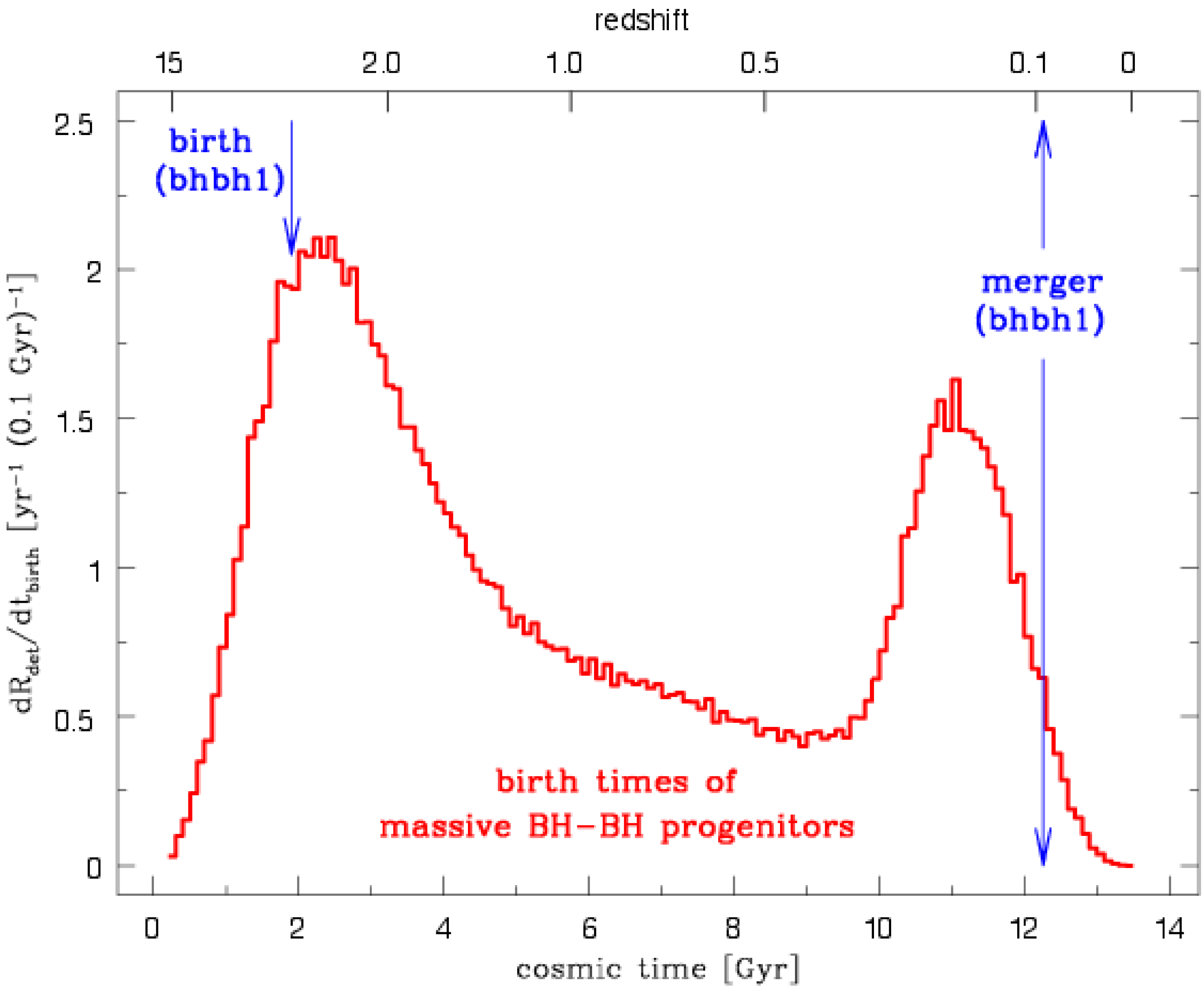
4. BH binaries in cosmological context

Belczynski+ 2016



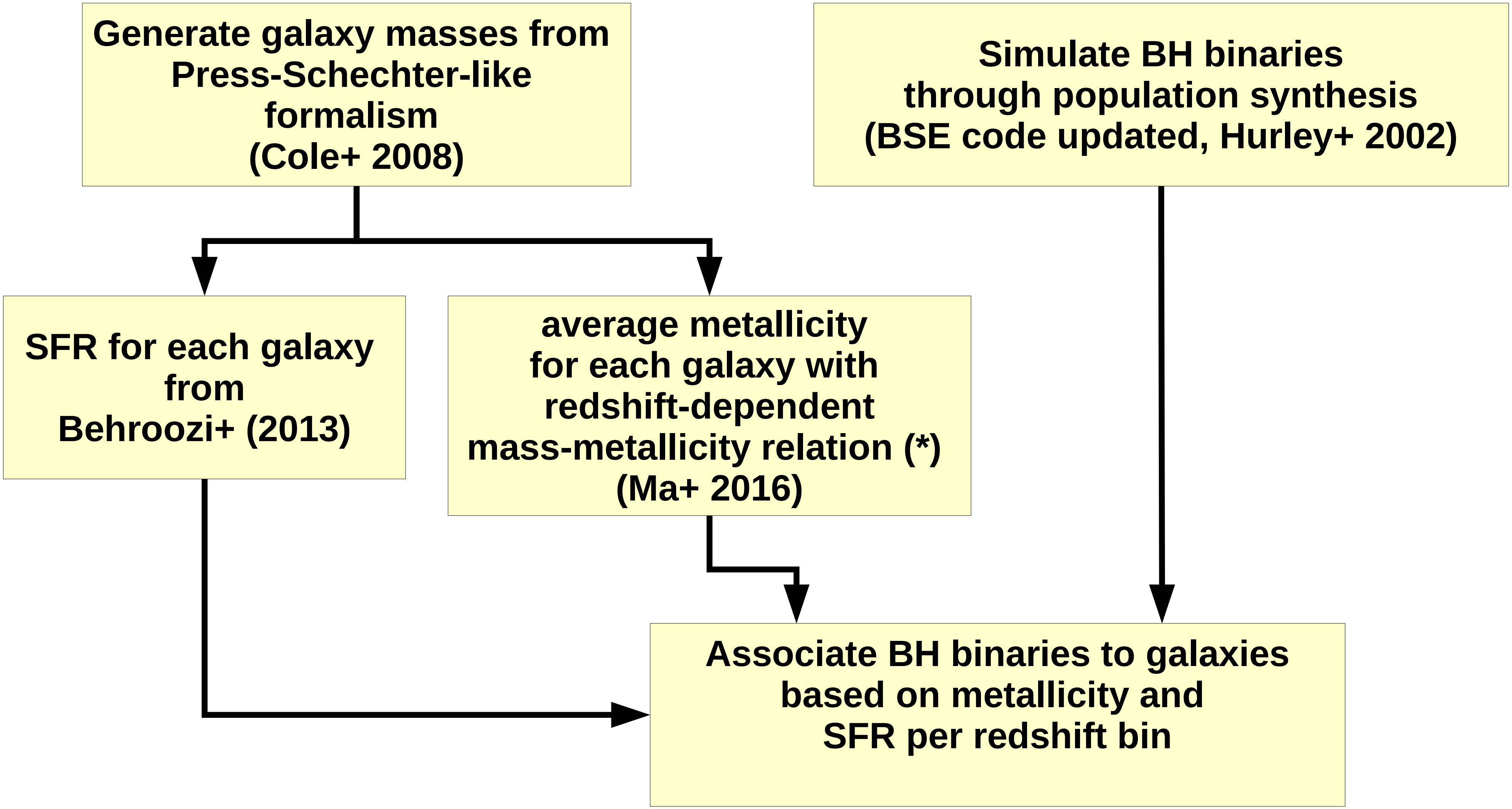
4. BH binaries in cosmological context

Belczynski+ 2016



4. BH binaries in cosmological context

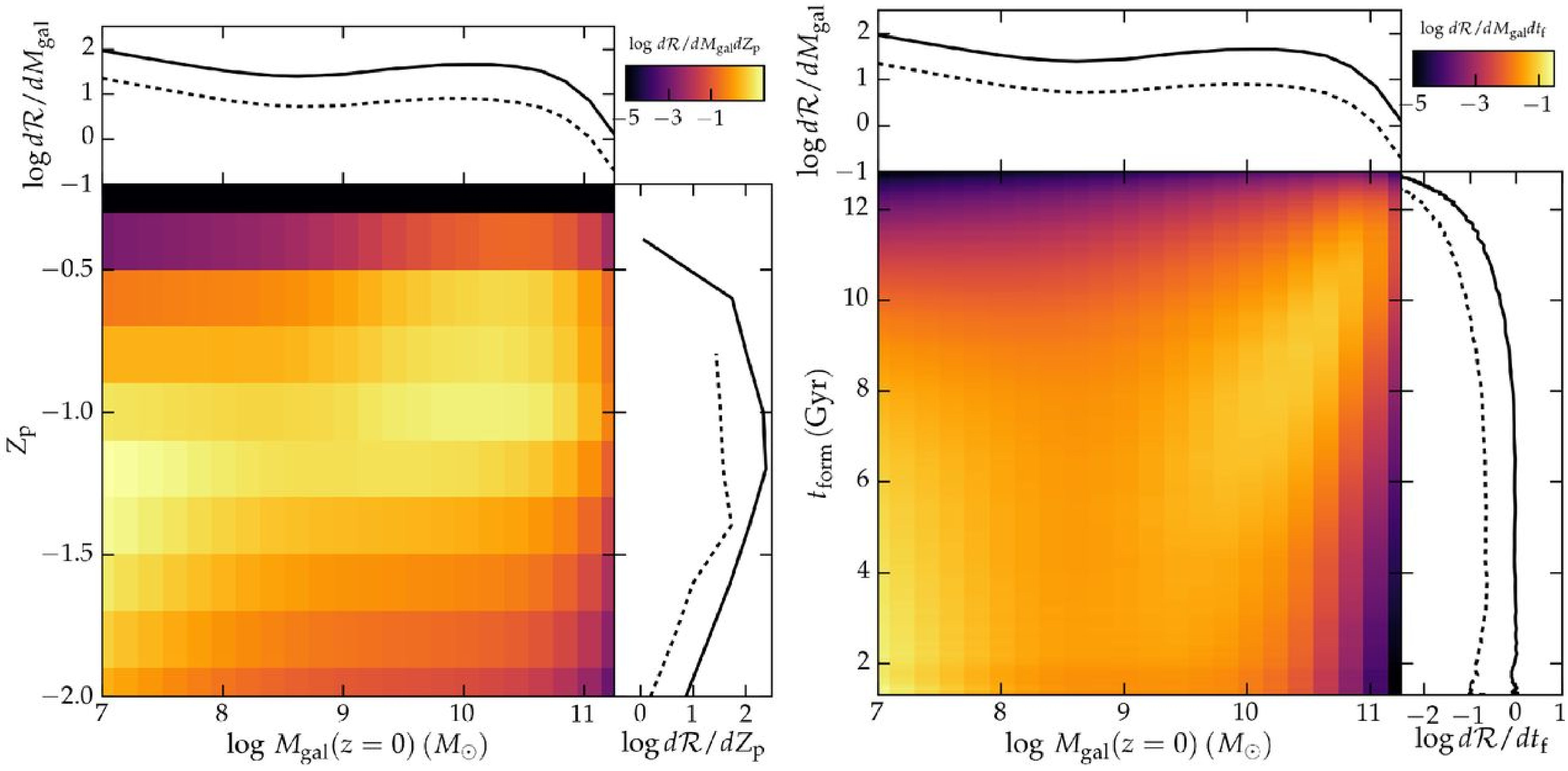
Lamberts+ 2016



Does recover mass-metallicity-star formation rate relation
(*) this mass-metallicity relation comes from cosmological simulations!!!

4. BH binaries in cosmological context

Lamberts+ 2016



Issue: BHB merger rate ~ 850 Gpc^-3 yr^-1

4. BH binaries in cosmological context

O'Shaughnessy+ 2017

Six galaxies extracted from cosmological SPH simulation and re-simulated with high-res: 2 dwarfs and 4 Milky Ways

Simple assumption for BH binaries: uniform mass distribution from 5 Msun to max mass

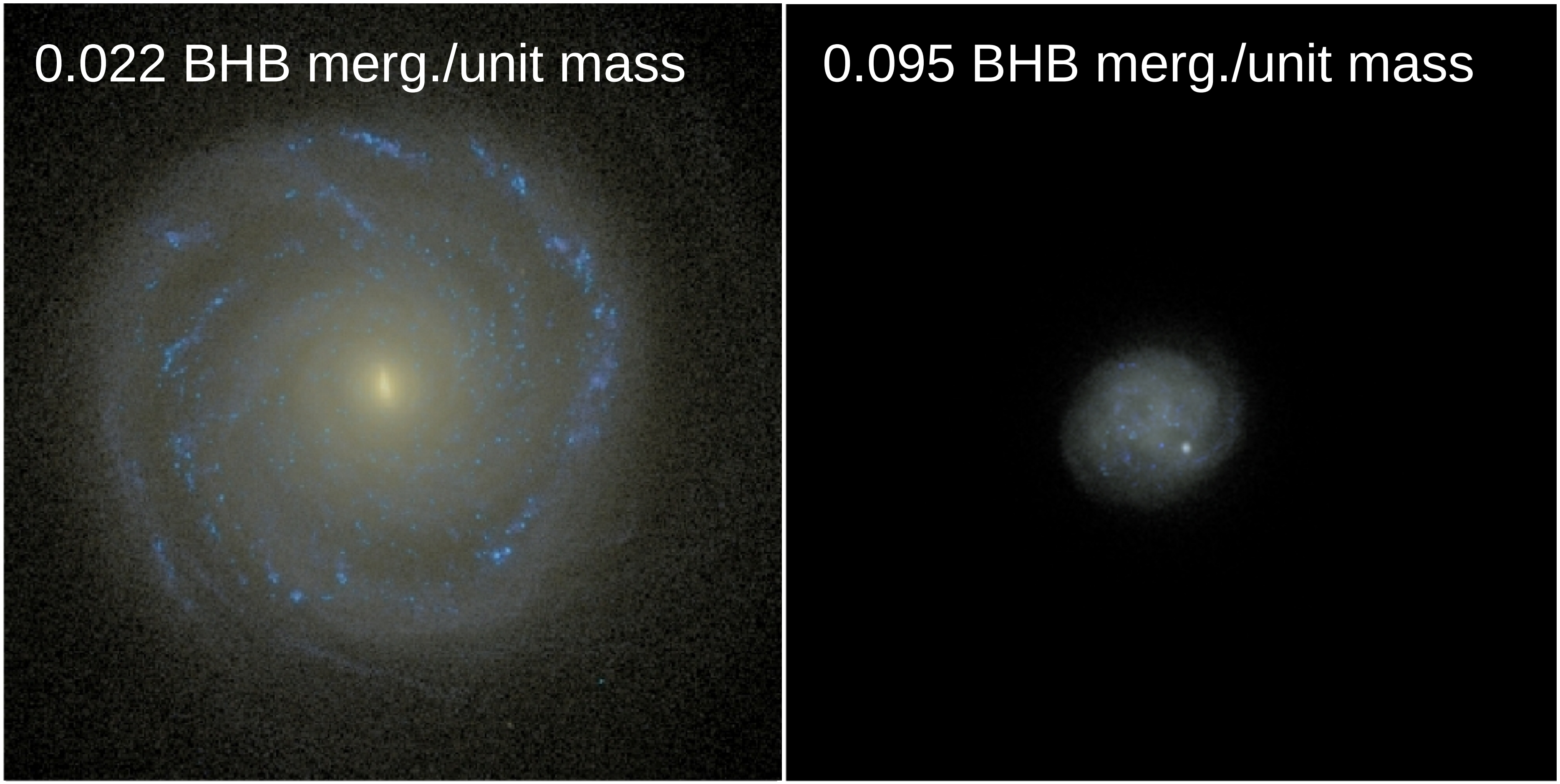
Metallicity evolution and SF are already included in simulations

Associate BH binaries to simulate galaxies based on metallicity and SF

Does include information on hosts

4. BH binaries in cosmological context

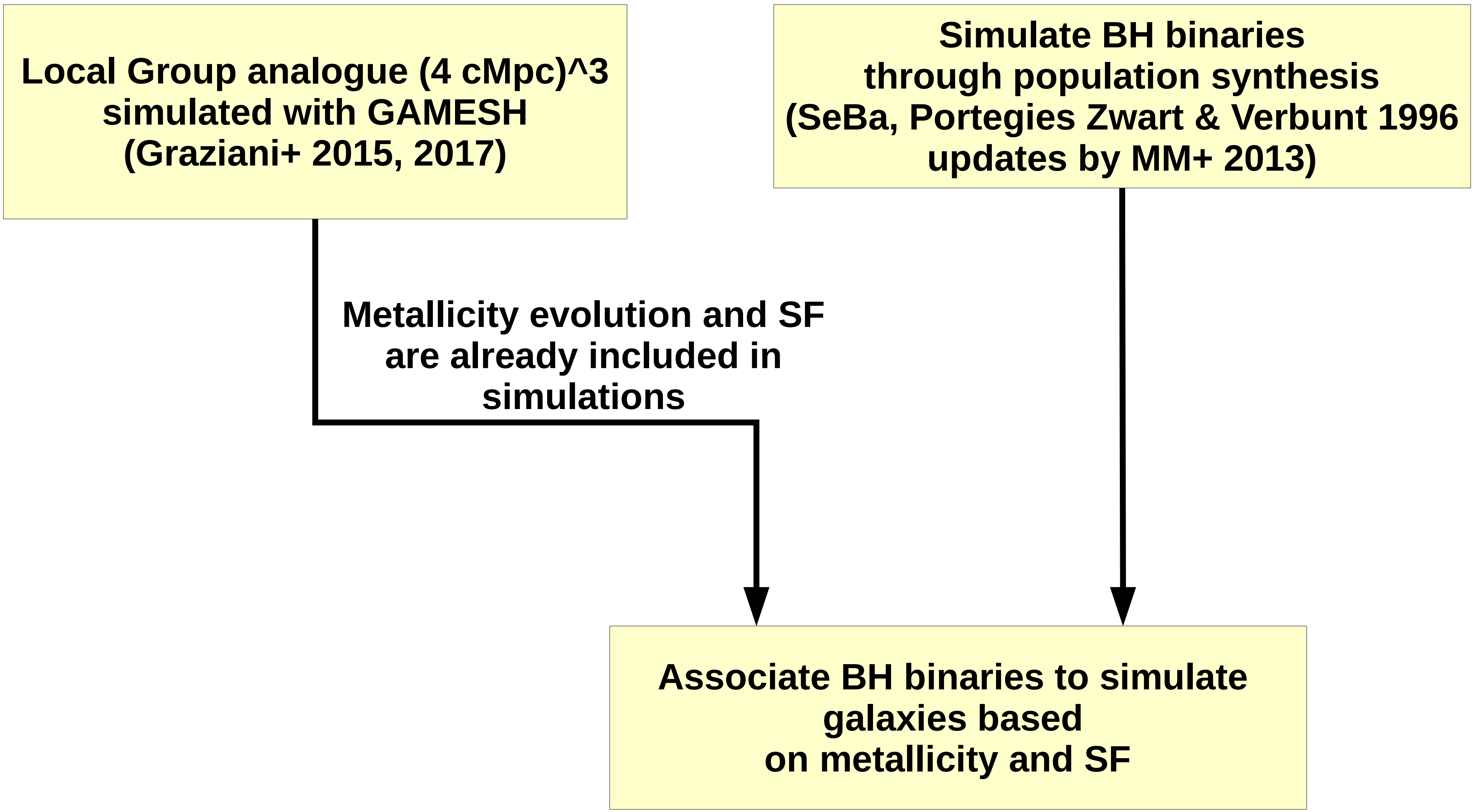
O'Shaughnessy+ 2017



MAIN RESULT: merger rate per unit mass double in DWARFS wrt Milky Ways

4. BH binaries in cosmological context

Schneider+ 2017

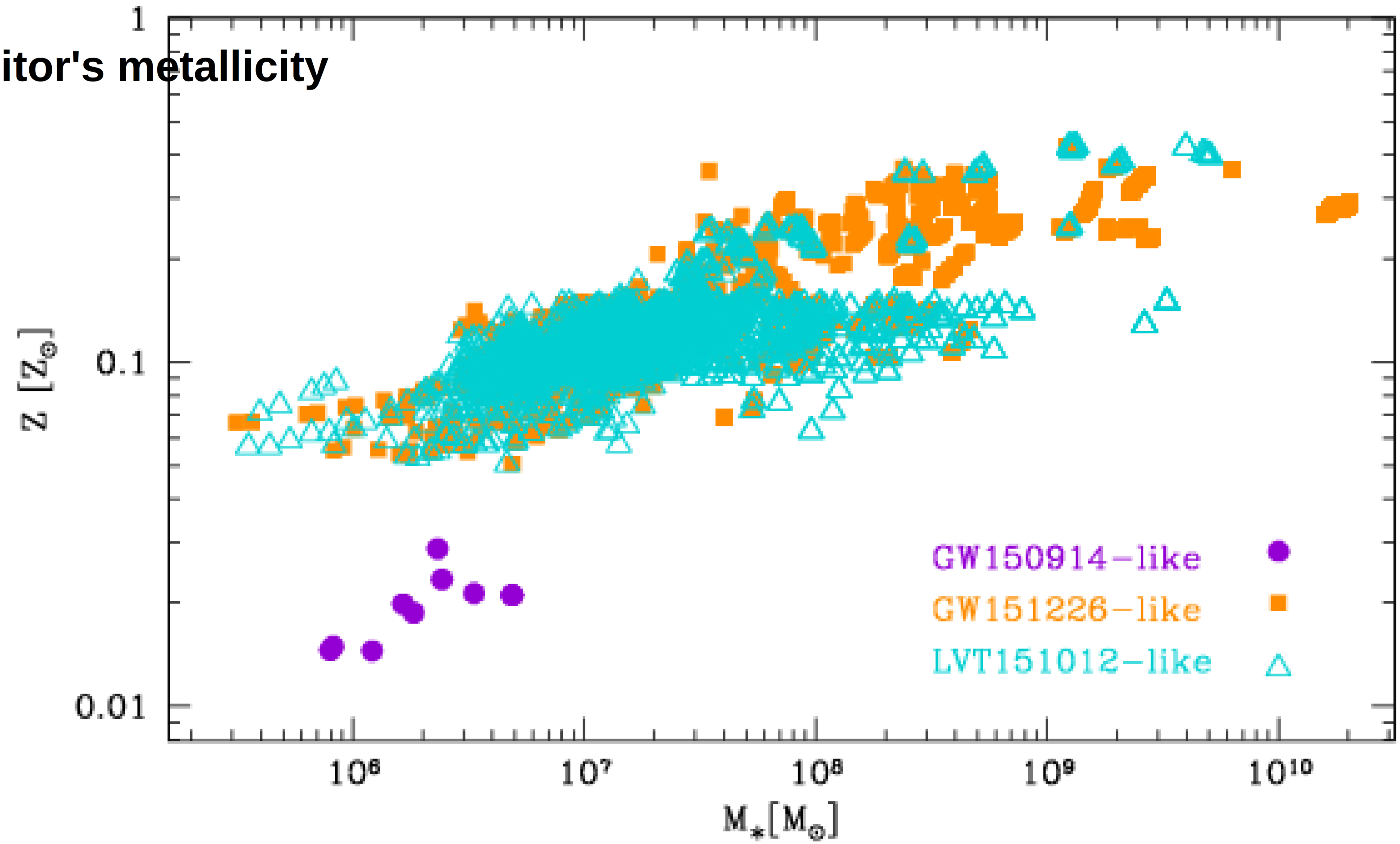


Does include information on hosts
Does recover mass-metallicity-star formation rate relation

4. BH binaries in cosmological context

Schneider+ 2017

Progenitor's metallicity

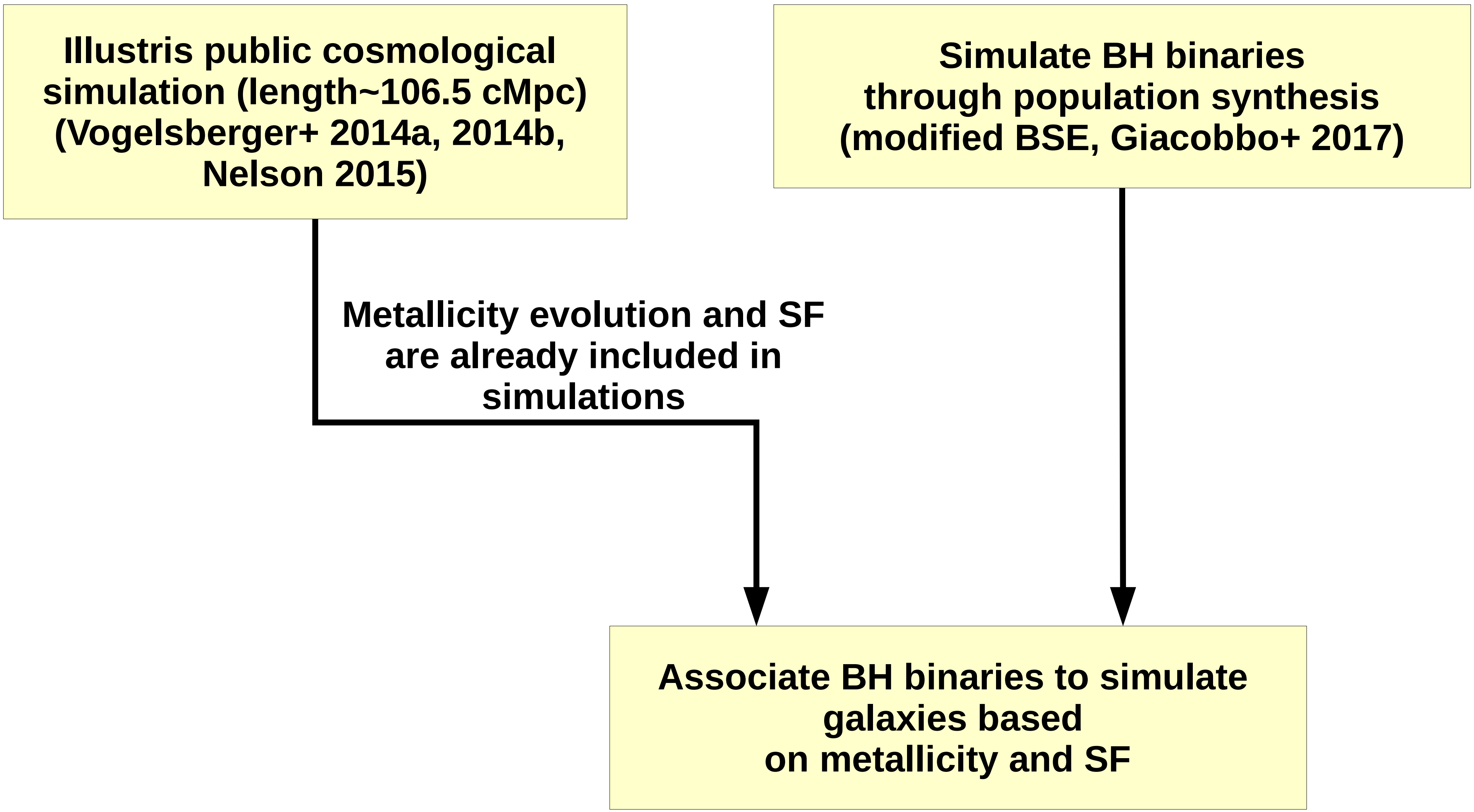


Stellar mass of the host galaxy (at merger)

- **host of GW150914 : small and metal poor galaxies**
- **host of GW151226 and LVT151012 : all possible galaxy mass**

4. BH binaries in cosmological context

MM, Giacobbo, Ripamonti, Spera 2017

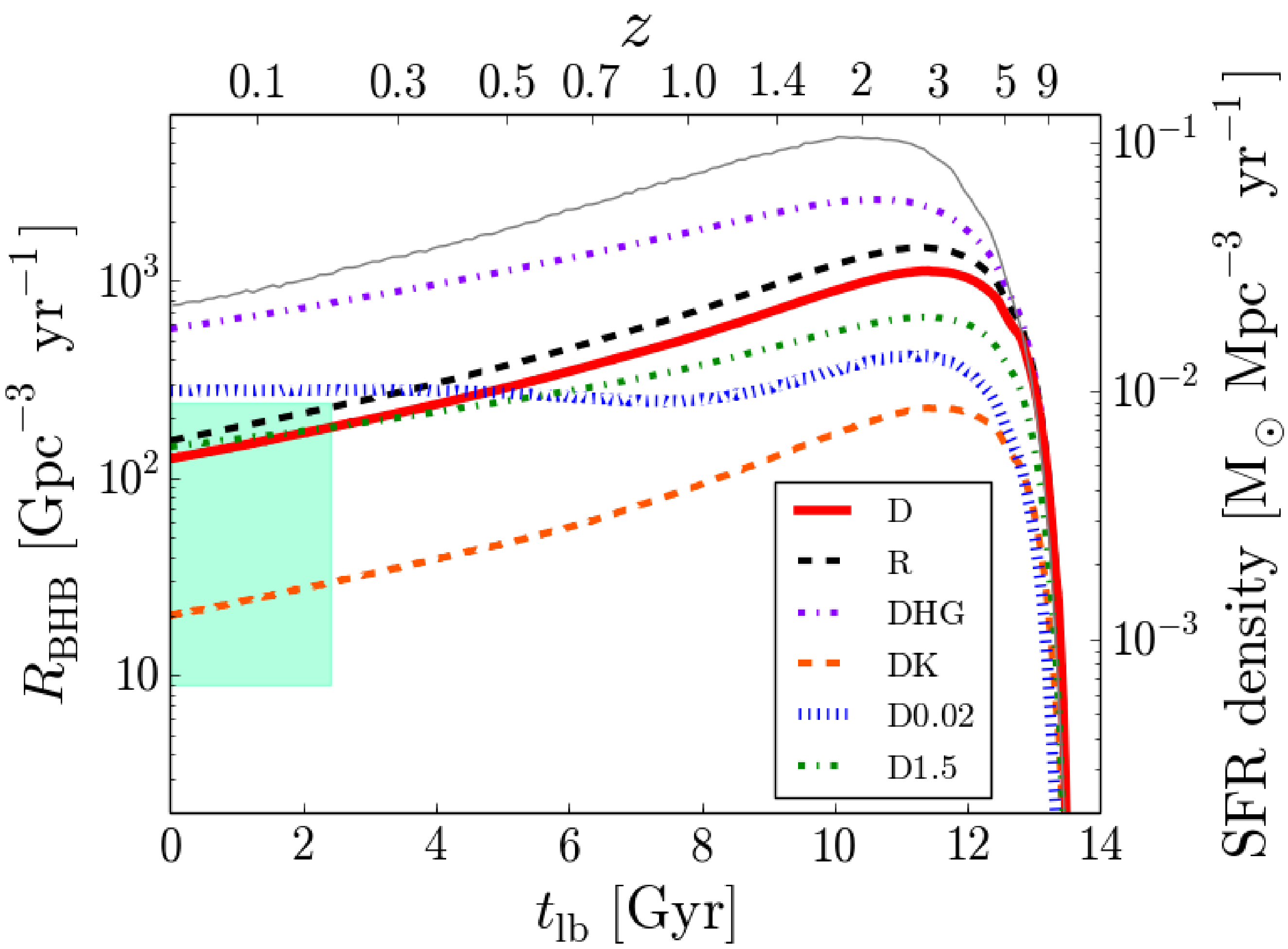


Does include information on hosts
Does recover mass-metallicity-star formation rate relation

4. BH binaries in cosmological context

MM, Giacobbo, Ripamonti, Spera 2017

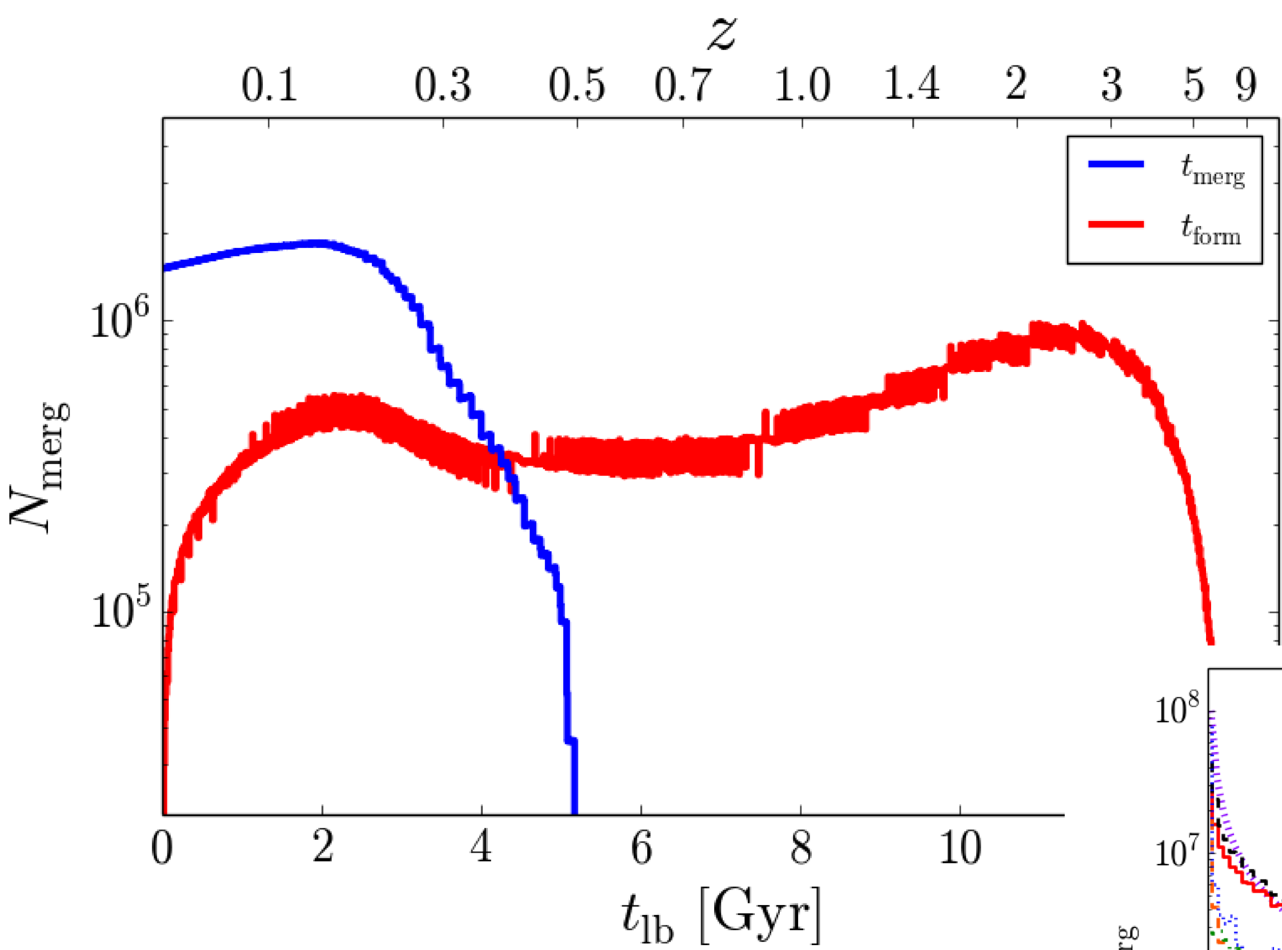
BHB merger rate density in comoving frame



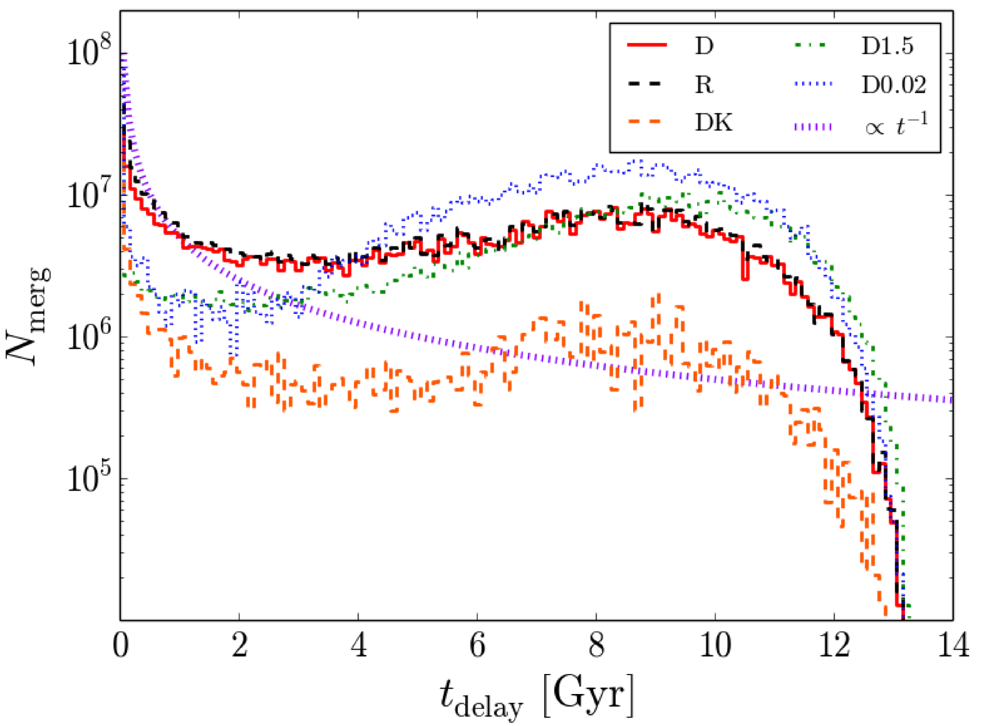
- Future detections will discriminate between models
- BHB merger rate scales with cosmic SFR density

4. BH binaries in cosmological context

Properties of BHs merging in LIGO's 2015-2016 horizon (MM+ 2017)

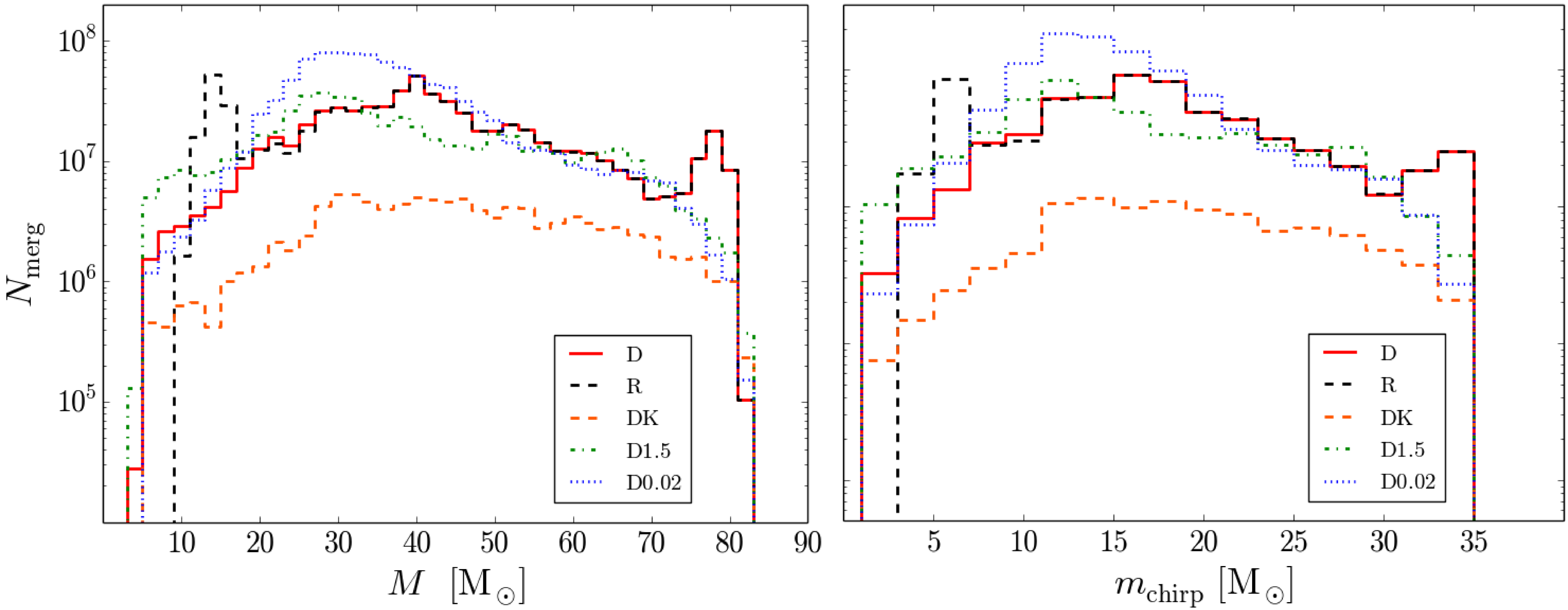


Horizon depends on BH mass!



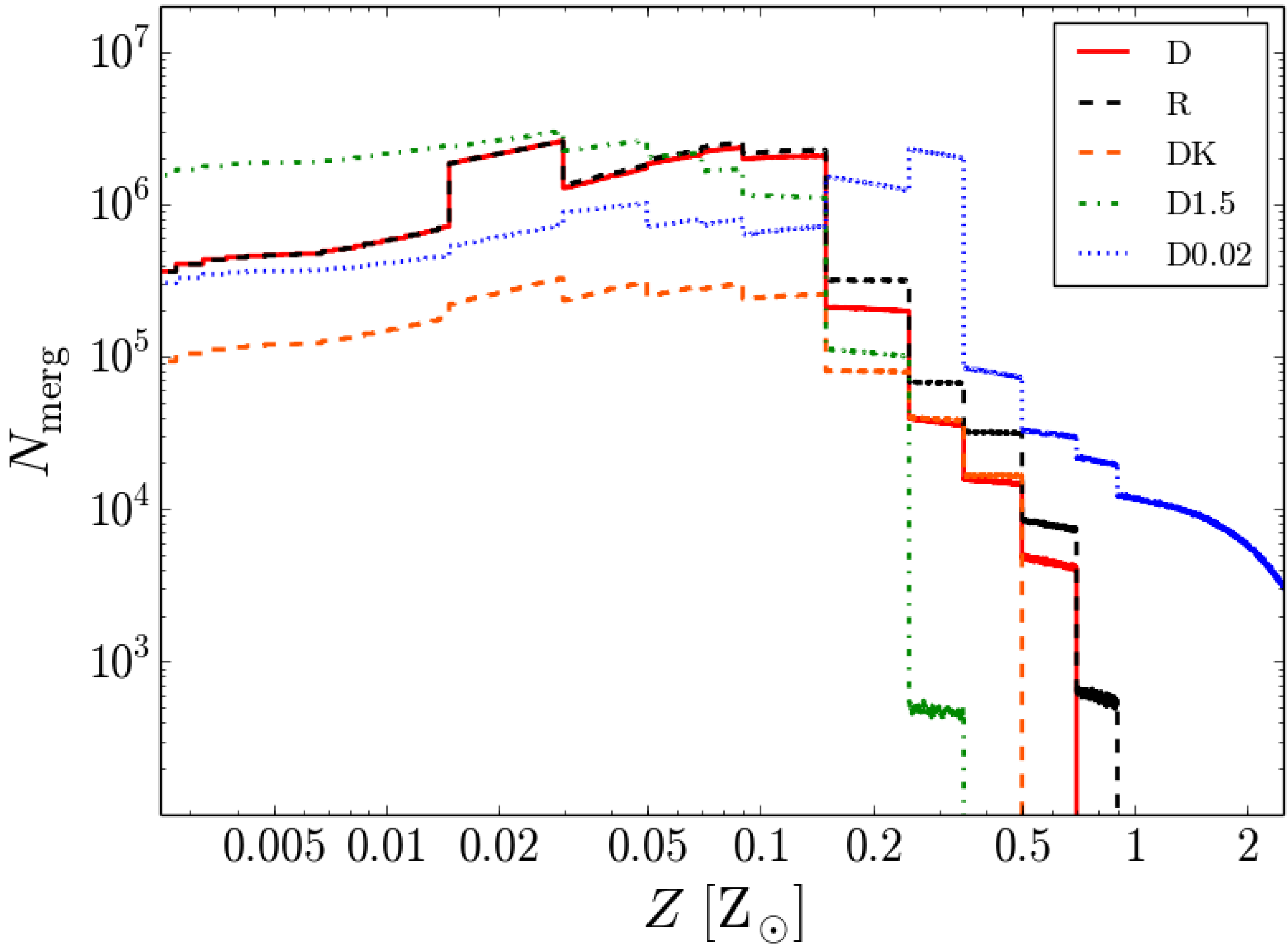
4. BH binaries in cosmological context

Properties of BHs merging in LIGO's 2015-2016 horizon (MM+ 2017)



4. BH binaries in cosmological context

Properties of BHs merging in LIGO's 2015-2016 horizon (MM+ 2017)



4. BH binaries in cosmological context

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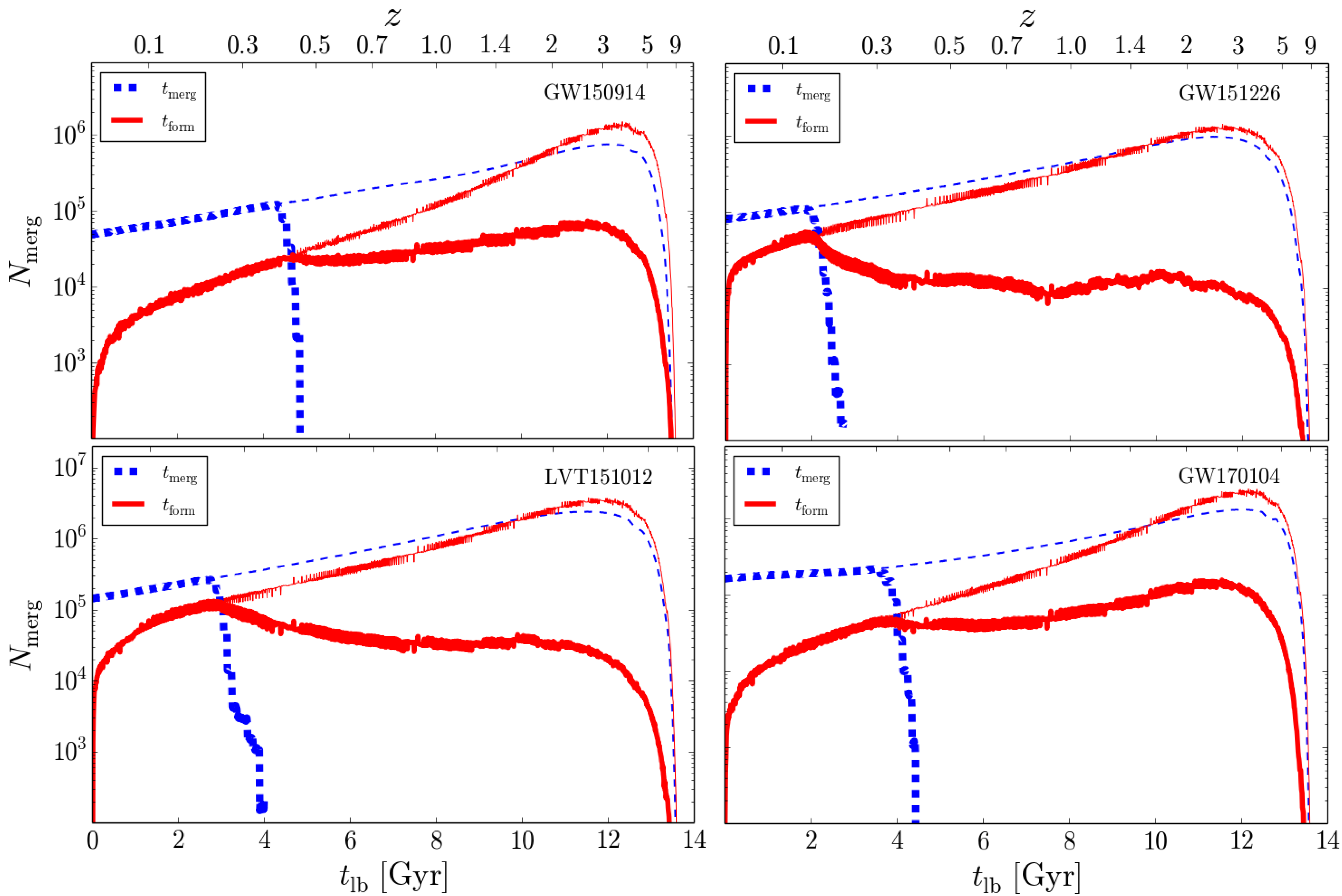

THANK YOU!