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# Gravitational – Wave Astrophysics

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Mario Pasquato, Sara Rastello, Filippo Santoliquido, Mario Spera**

**Multimessenger physics and astrophysics with compact binaries,
Jena, 11 – 15 March 2019**

# What is Gravitational – Wave (GW) Astrophysics?

*** Astrophysical characterization of GW sources**

*** Young and continuously evolving NO TEXT BOOK**

*** Boosted by GW detections**

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

# OPEN QUESTION:

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

# OUTLINE:

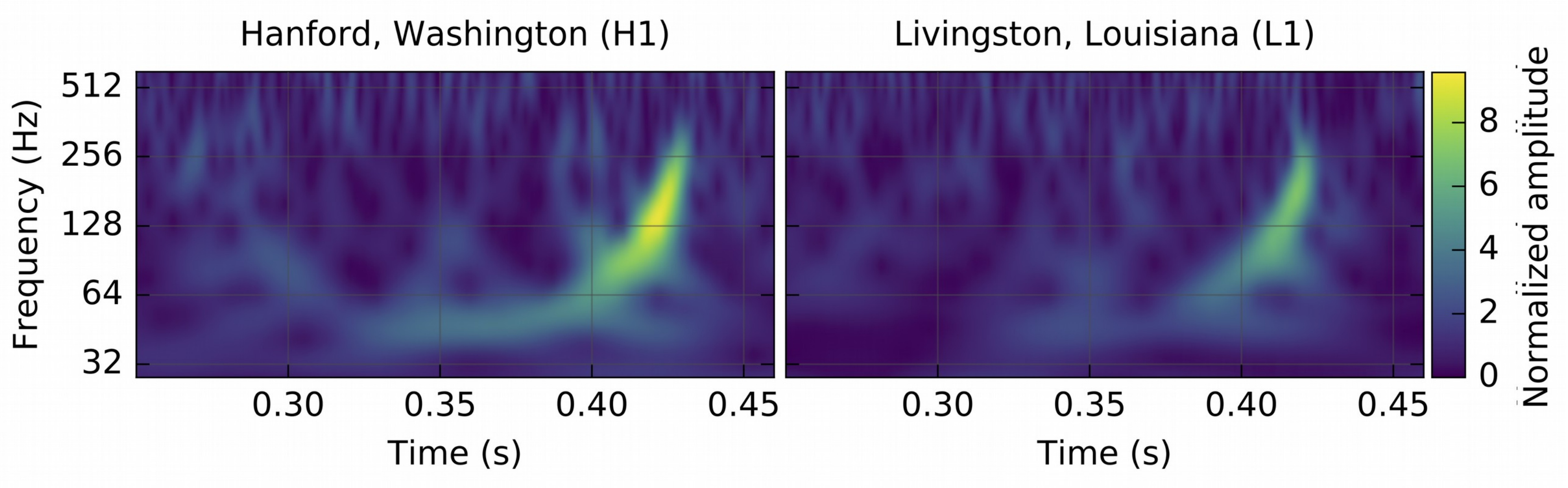
1. The formation of compact objects from stellar evolution and supernova explosions

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



**Abbott+ 2016**

## What have astrophysicists learned from O1 + O2 detections?

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

**1. Binary black holes (BBHs) exist**

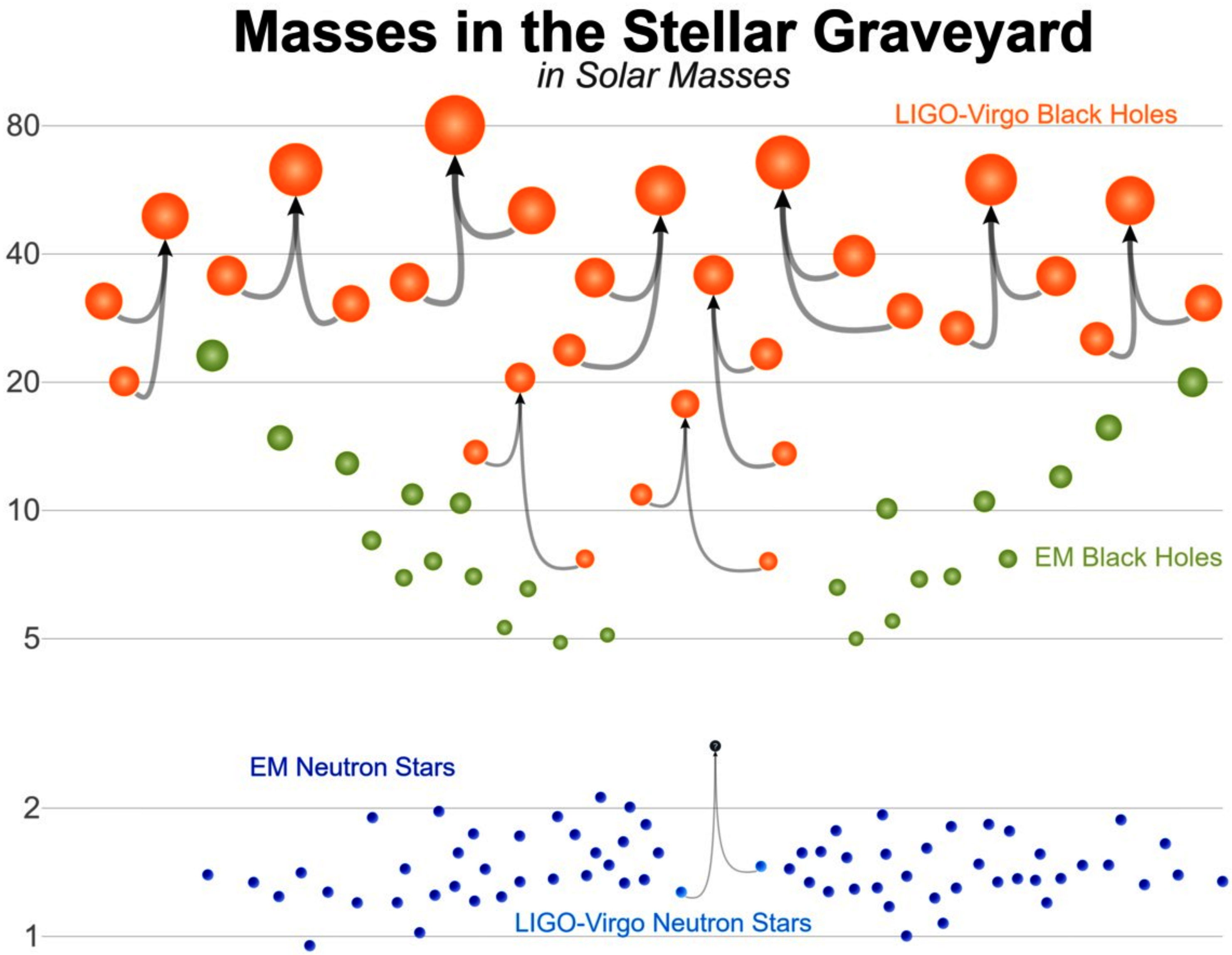
**(Tutukov & Yungelson 1973; Thorne 1987; Schutz 1989)**

**2. BBHs can merge in a Hubble time**

**3. Massive black holes (BHs) exist i.e. stellar BHs with mass >20 M⊙**
**(Heger et al. 2003; MM et al. 2009, 2010; Belczynski+ 2010)**

**BHs in X-ray binaries < 20 M⊙ (Ozel+ 2010)**
**Most models of BH demography do not predict massive BH**

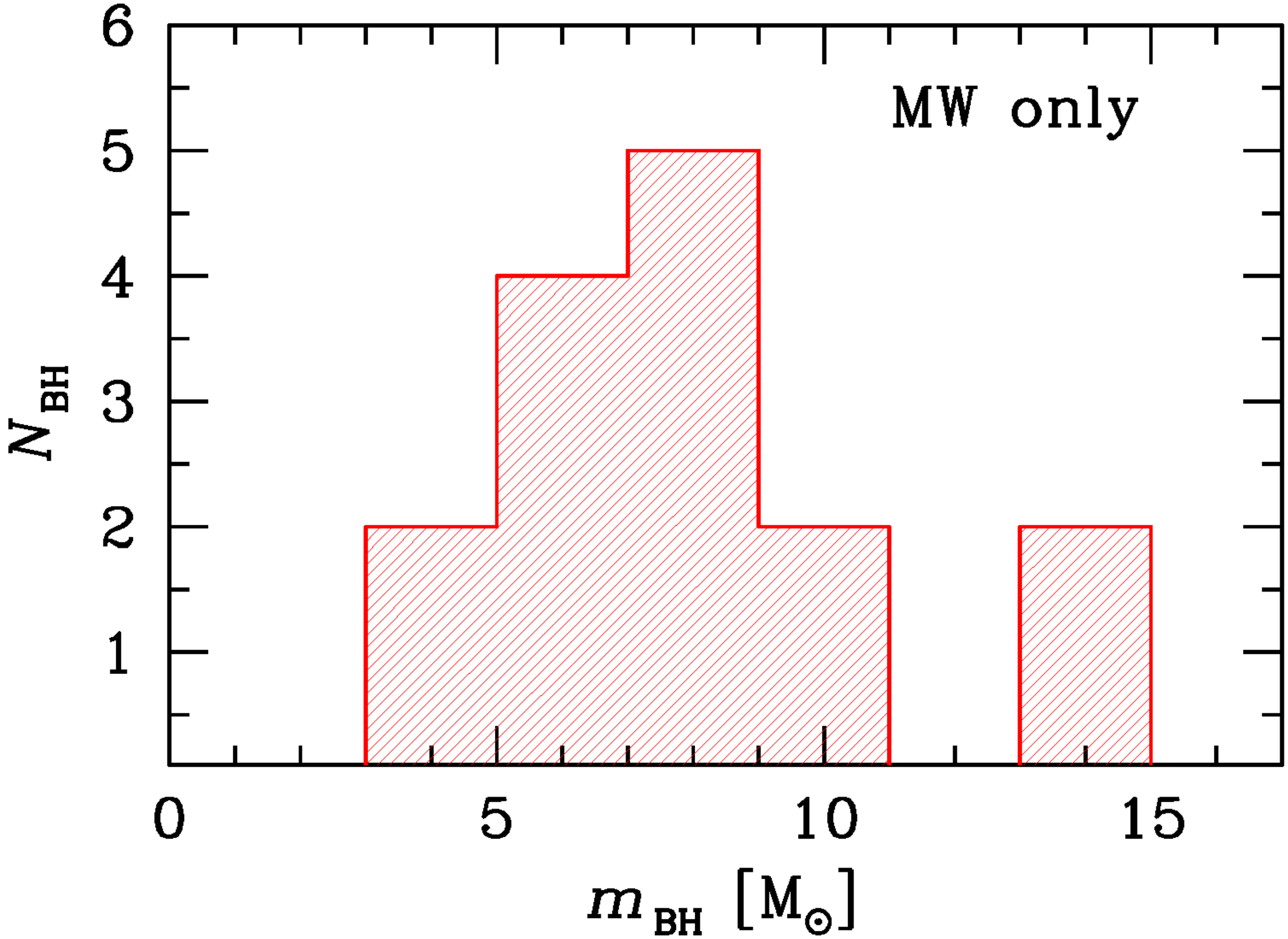
# 1. The formation of compact objects



LIGO-Virgo | Frank Elavsky | Northwestern

# 1. The formation of compact objects

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

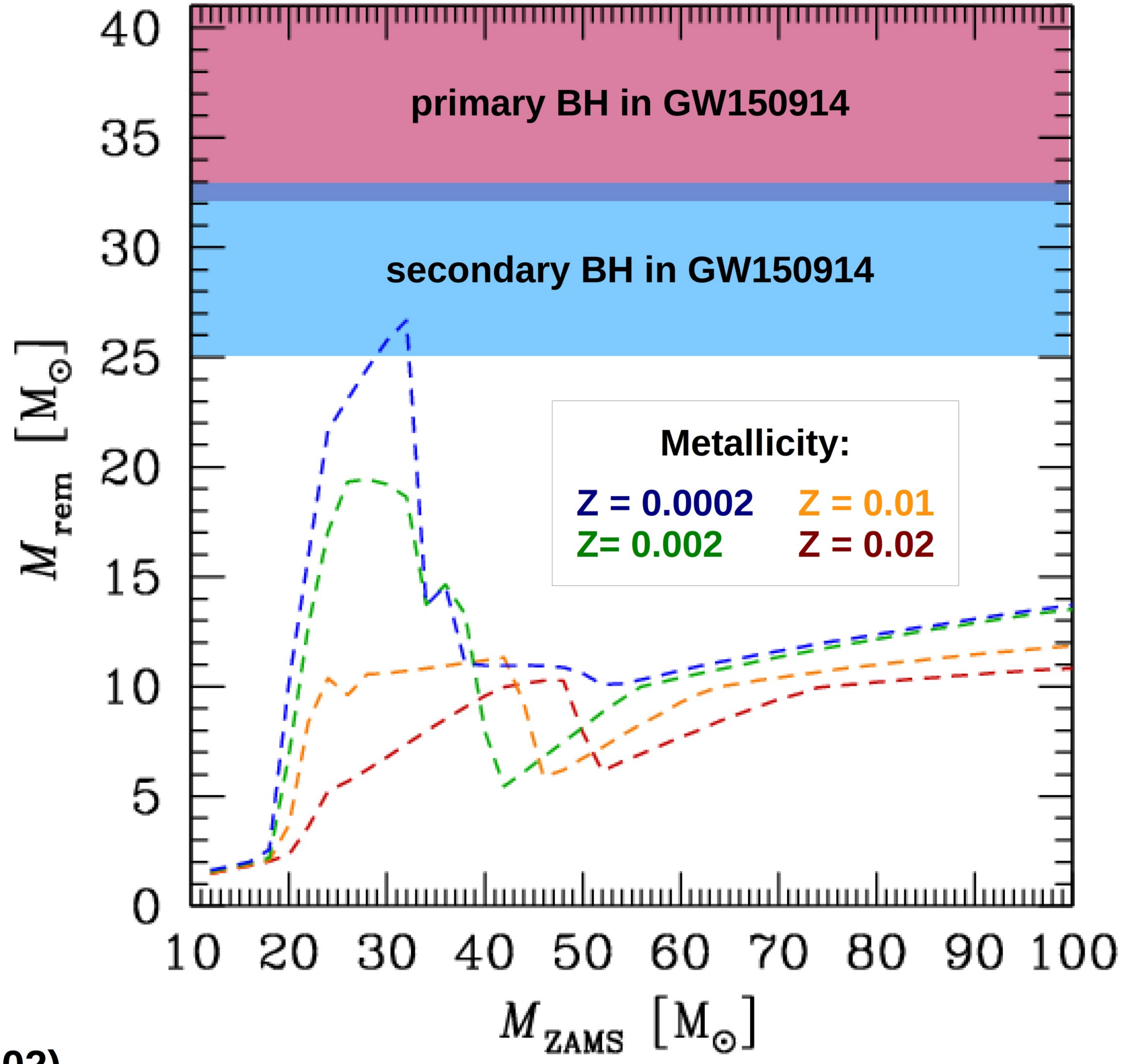


**compilation from
Orosz+ 2003,
Ozel+ 2010**

# 1. The formation of compact objects

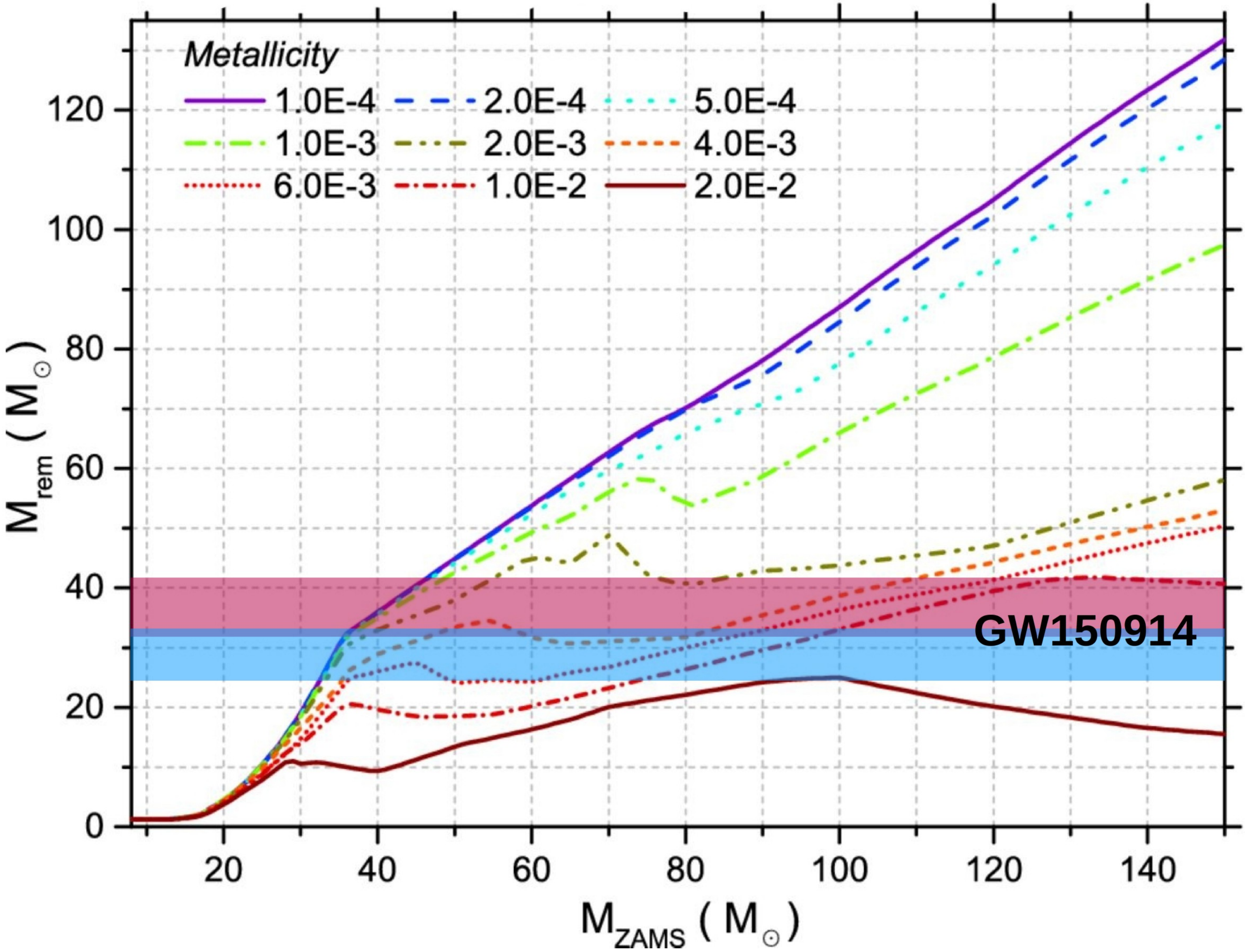
**Most common remnant mass spectrum BEFORE GW150914 detection**

**cannot explain GW150914**



**(BSE code, Hurley+ 2002)**

# 1. The formation of compact objects



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

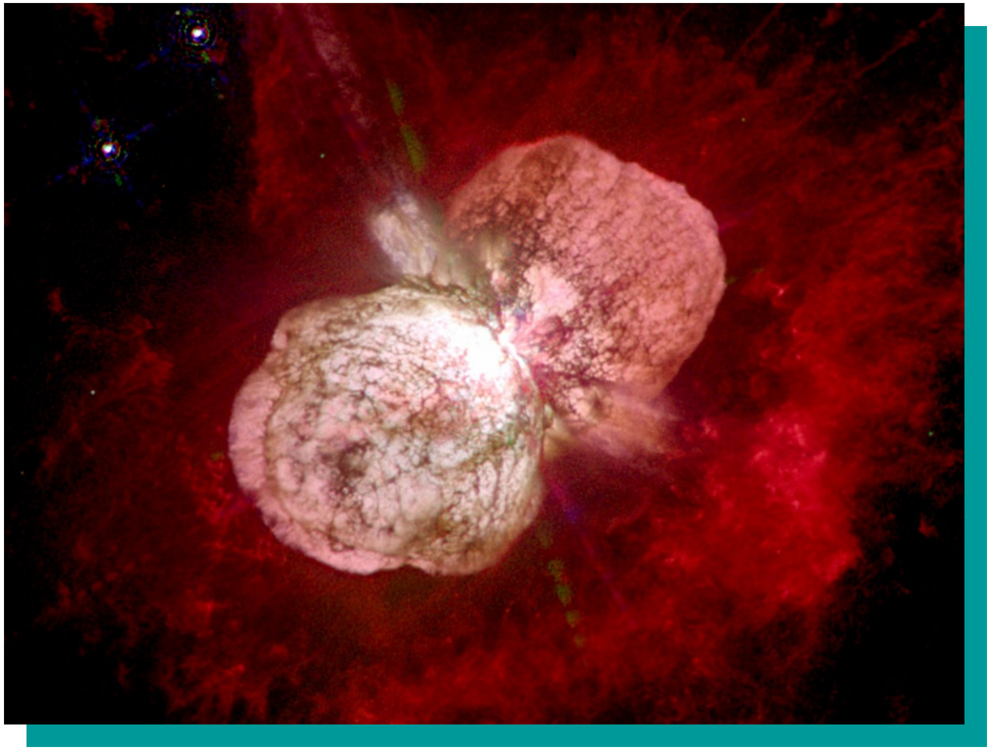
**See also MM+ 2009, MNRAS, 395, L71; MM+ 2010, MNRAS, 408, 234; Belczynski+ 2010, ApJ, 714, 1217; Fryer+ 2012, ApJ, 749, 91; MM+ 2013, MNRAS, 429, 2298; Belczynski+ 2016, A&A, 594, 97; Spera & MM 2017, MNRAS, 470, 4739**

# 1. The formation of compact objects

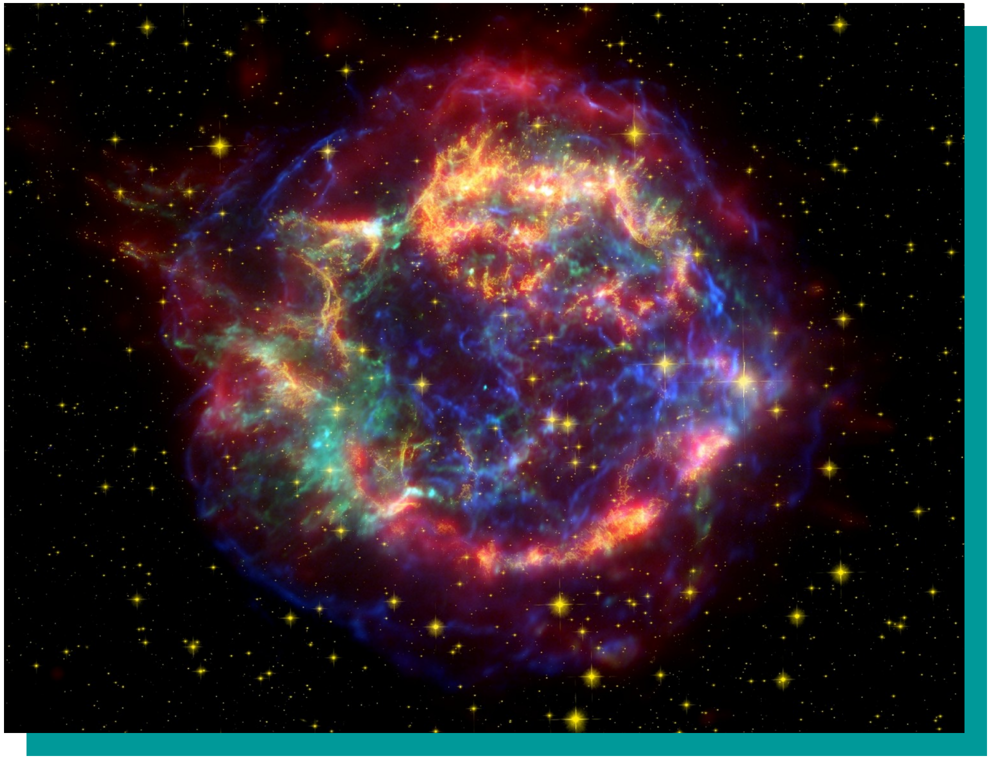
**Two critical ingredients:**

1) PROGENITOR STAR EVOLUTION (STELLAR WINDS)

2) SUPERNOVA (SN) EXPLOSION



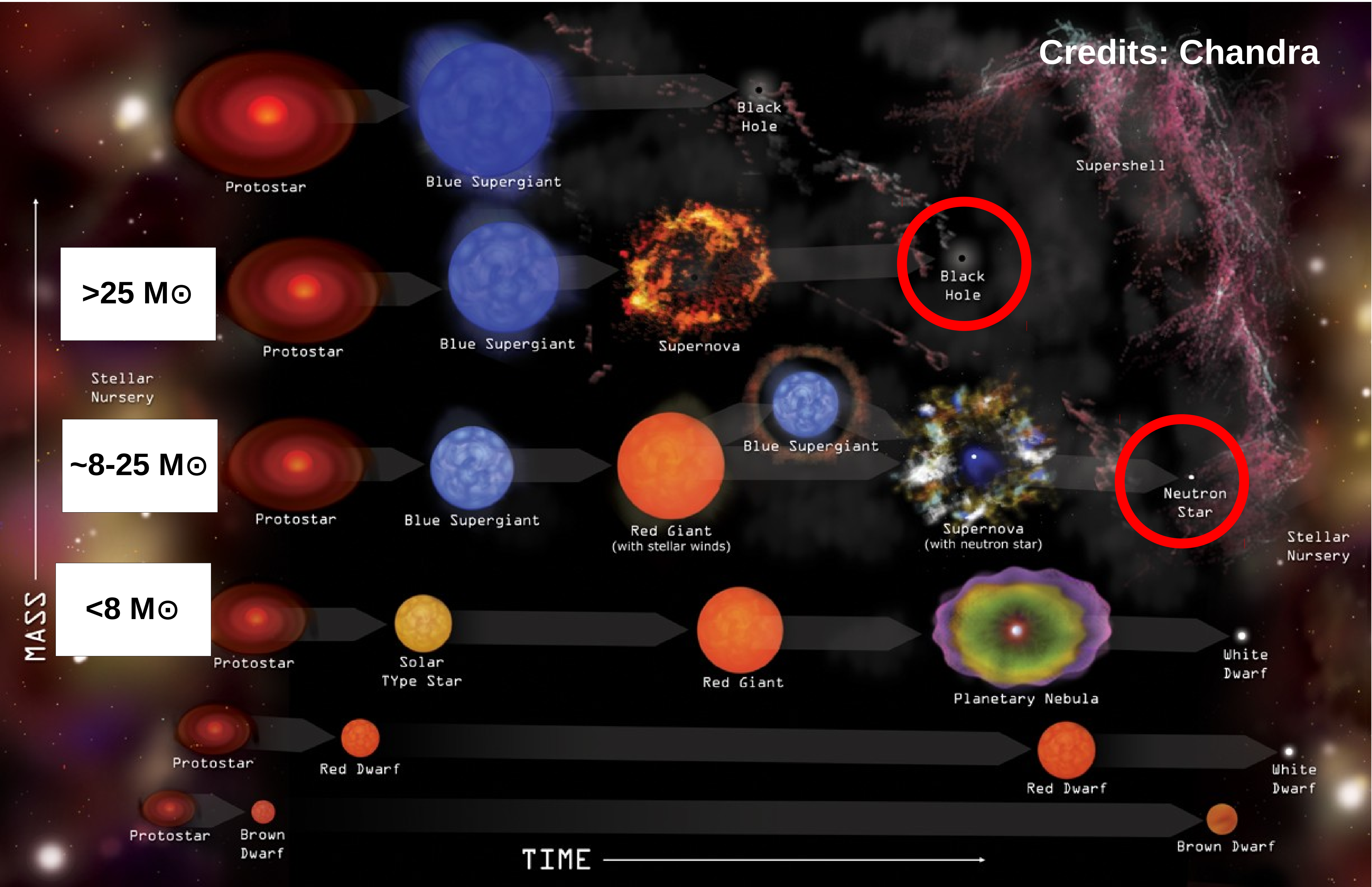
*Winds ejected by Eta Carinae (HST, credits: NASA)*



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

# 1. The formation of compact objects

**BHs and NSs are result of the evolution of most massive stars**

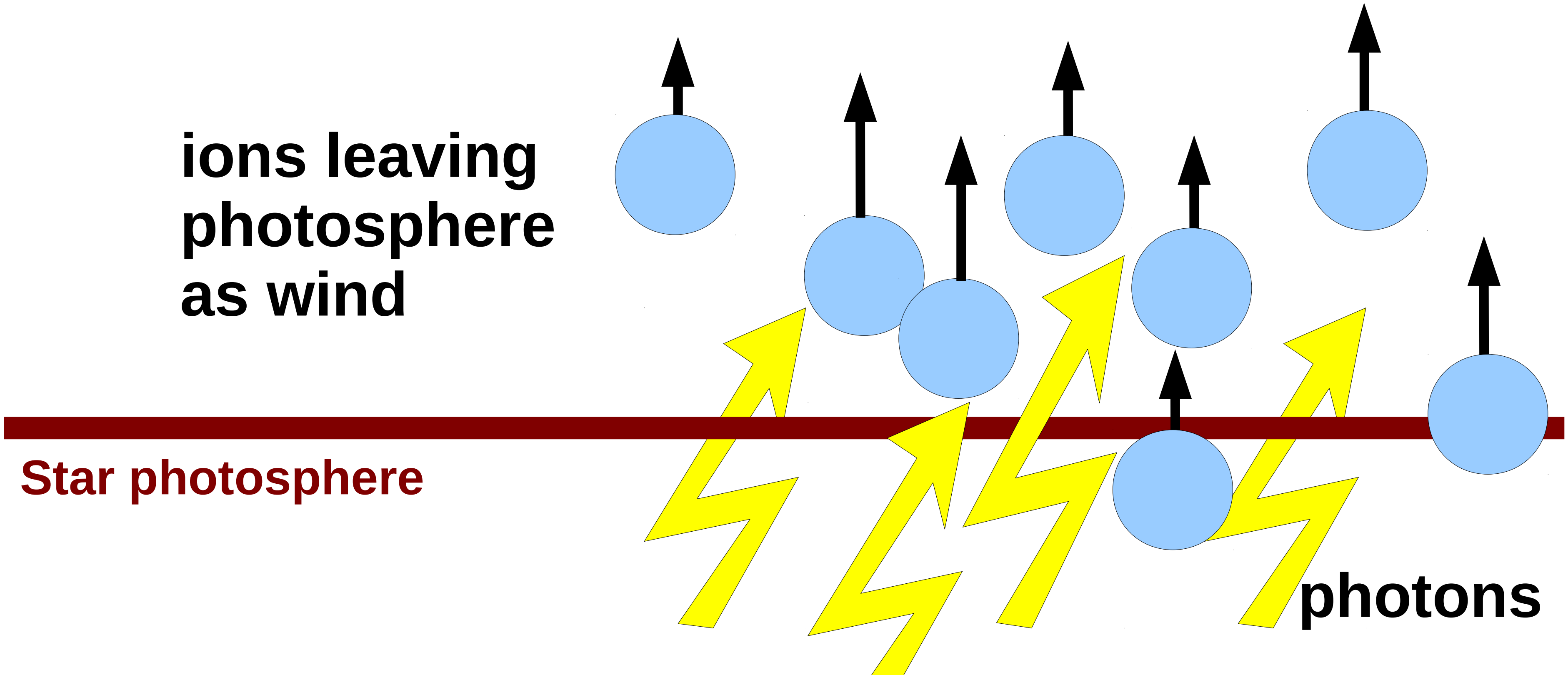

Credits: Chandra

# 1. The formation of compact objects: stellar winds

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

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

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



**How do we define metallicity in astrophysics?**

**Metallicity in astrophysics is NOT same as chemistry**

**Metals in Astro:**
**every element heavier than Helium**

**Measured with *Z* = FRACTION of elements heavier than He**

$$X + Y + Z = 1.0$$

**If M = total mass of system**

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

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

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

# 1. The formation of compact objects: stellar winds

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**→ MASS LOSS DEPENDS ON METALLICITY**

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

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

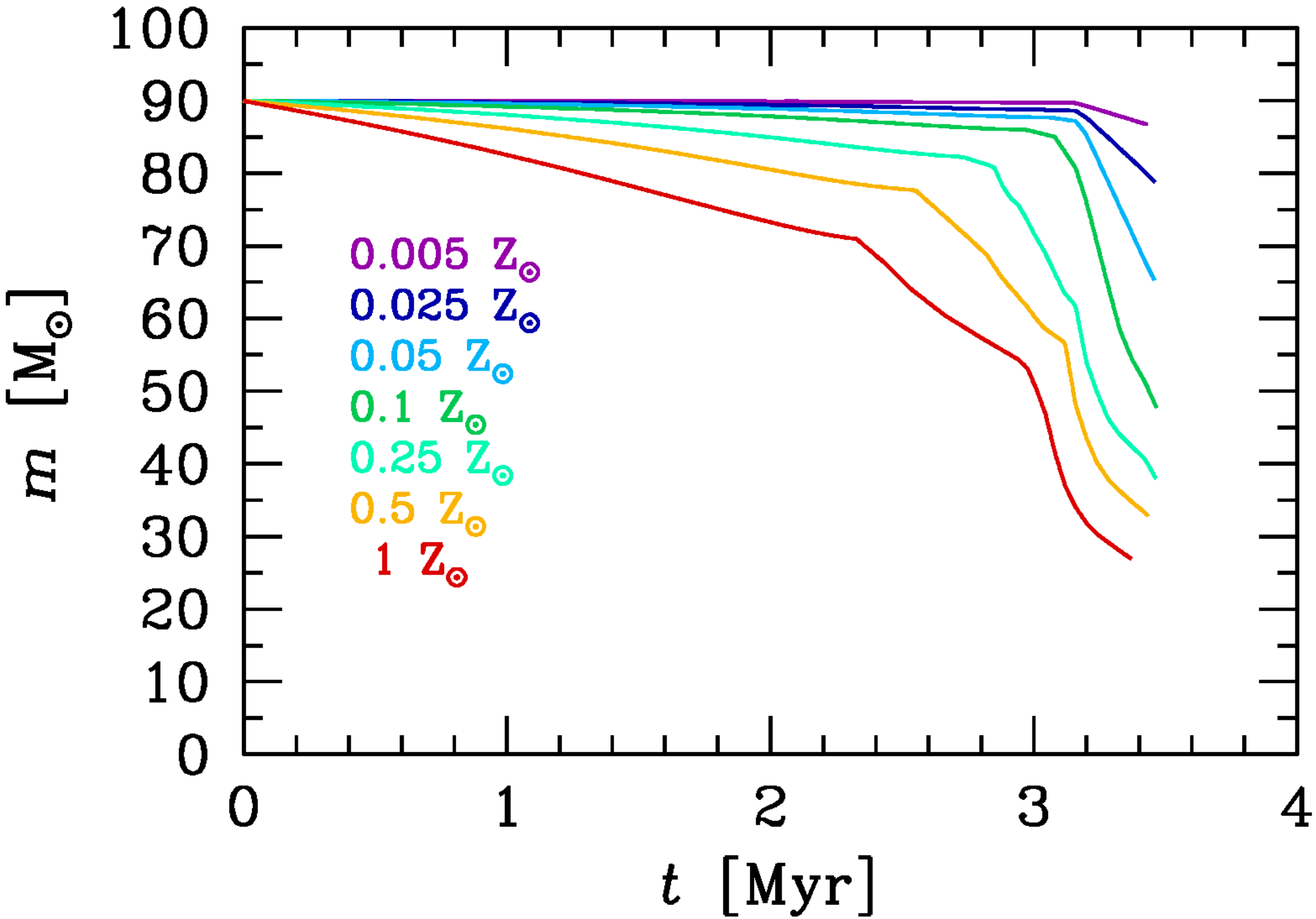
**e.g. Graefener & Hamann 2008**

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

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

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

# 1. The formation of compact objects: stellar winds



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

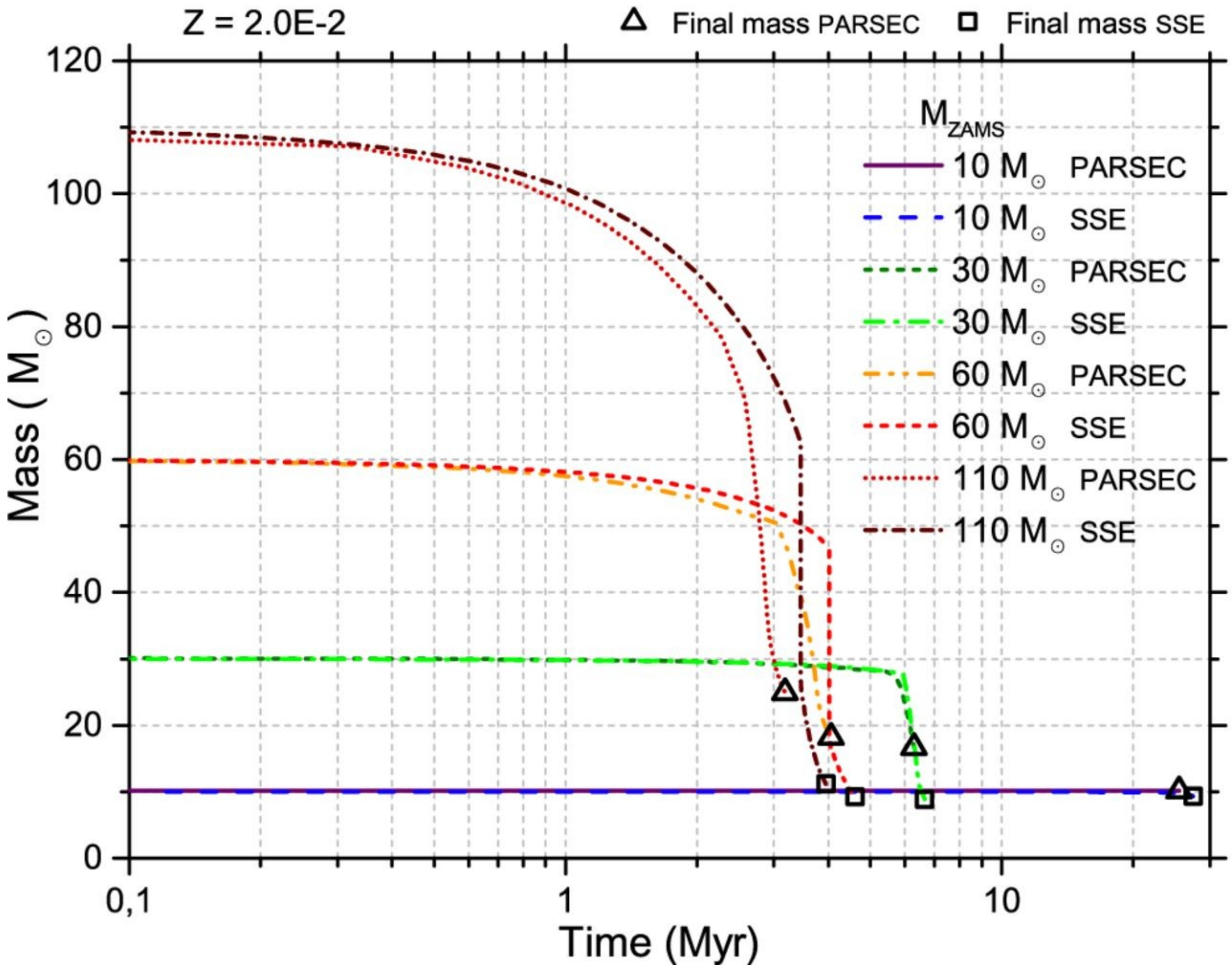
# 1. The formation of compact objects: stellar winds

**Mass loss depends on metallicity**

$$\dot{M} \propto Z^{\alpha}$$

$$\alpha \sim 0.5 - 0.9$$

**Z = 1 Zsun**



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

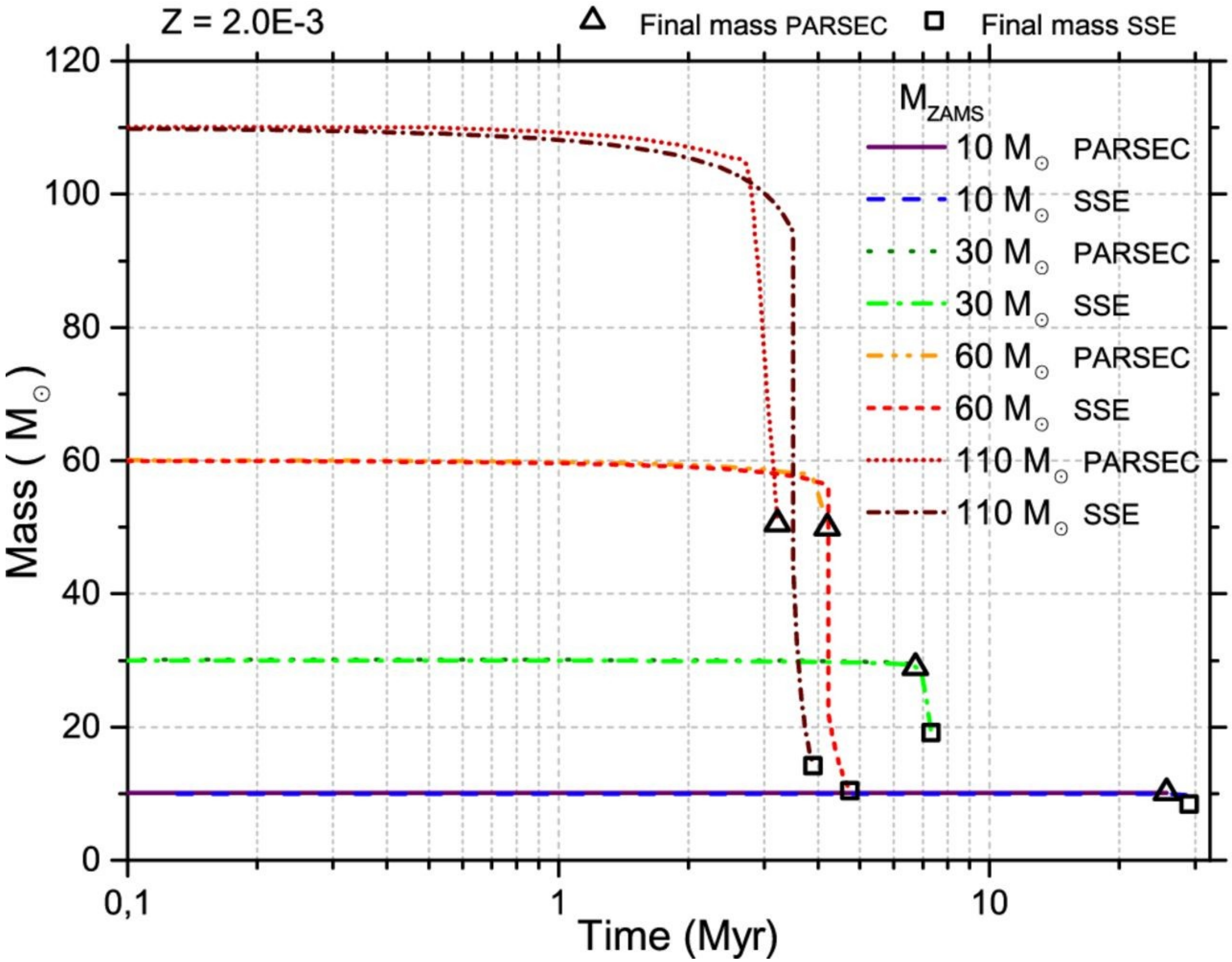
# 1. The formation of compact objects: stellar winds

**Mass loss depends on metallicity**

$$\dot{M} \propto Z^{\alpha}$$

$$\alpha \sim 0.5 - 0.9$$

**Z = 0.1 Zsun**



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# 1. The formation of compact objects: stellar winds

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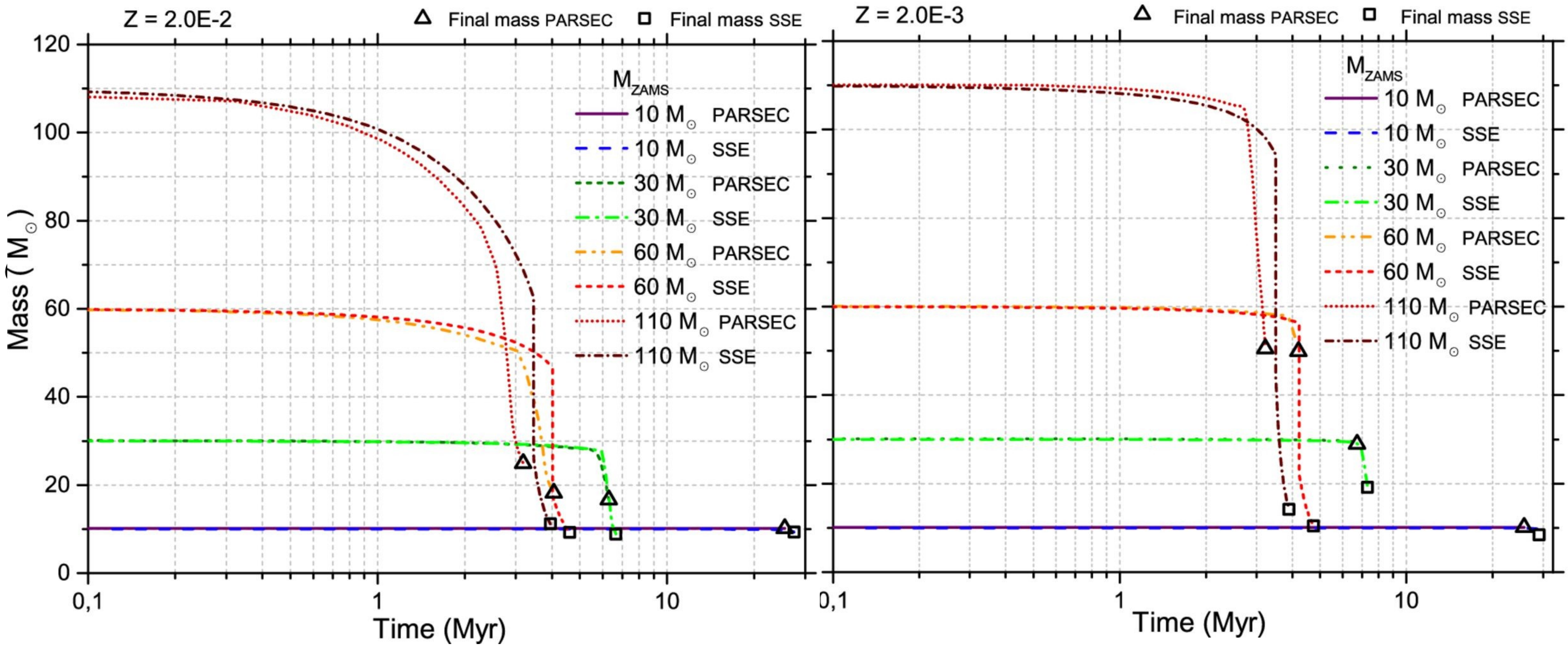
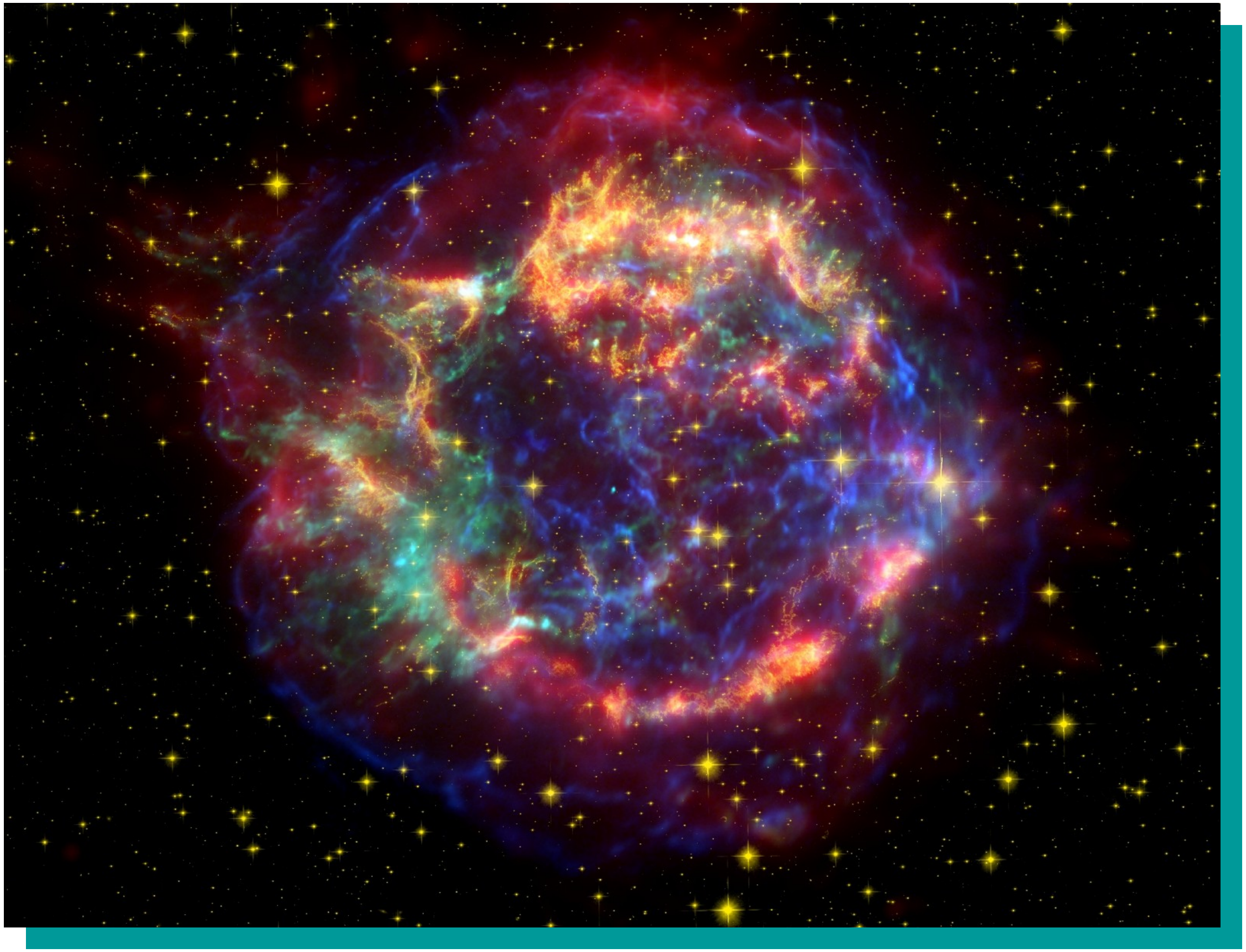


**Pre-supernova mass of a star depends on metallicity**

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

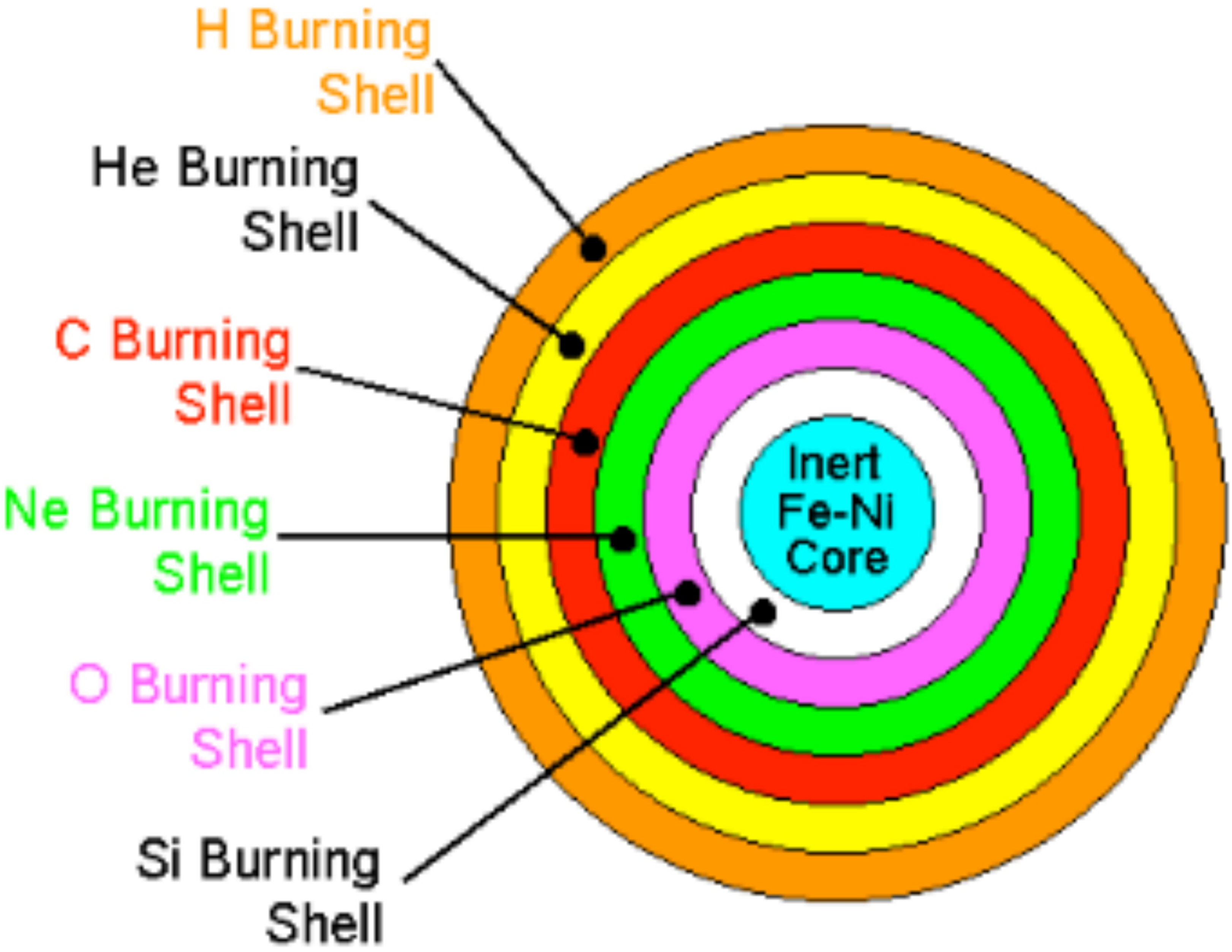
# 1. The formation of compact objects: supernova

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



# 1. The formation of compact objects: supernova

## Scheme of nuclear burning in a star



# 1. The formation of compact objects: supernova

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

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

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

**→ COLLAPSE to NUCLEAR DENSITY,**
**where neutron degeneracy pressure stops collapse**

**→ PROTO-NEUTRON STAR FORMS**

# 1. The formation of compact objects: 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**

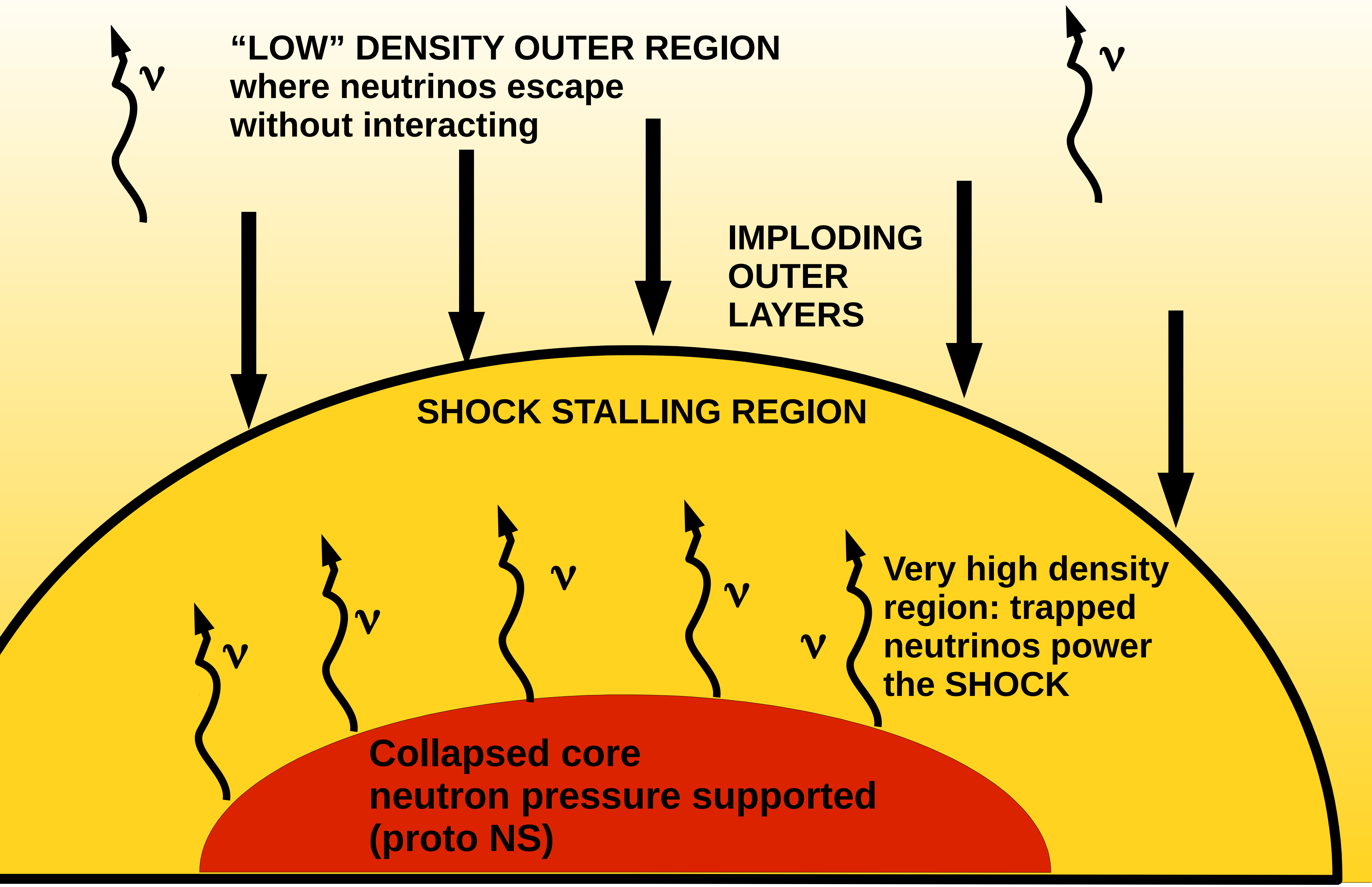
**SHOCK MUST REVERSE COLLAPSE OF OUTER LAYERS**

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

**WHEN DOES THE SHOCK STALL and the SN FAILS?**

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

# 1. The formation of compact objects: supernova



“LOW” DENSITY OUTER REGION
where neutrinos escape
without interacting

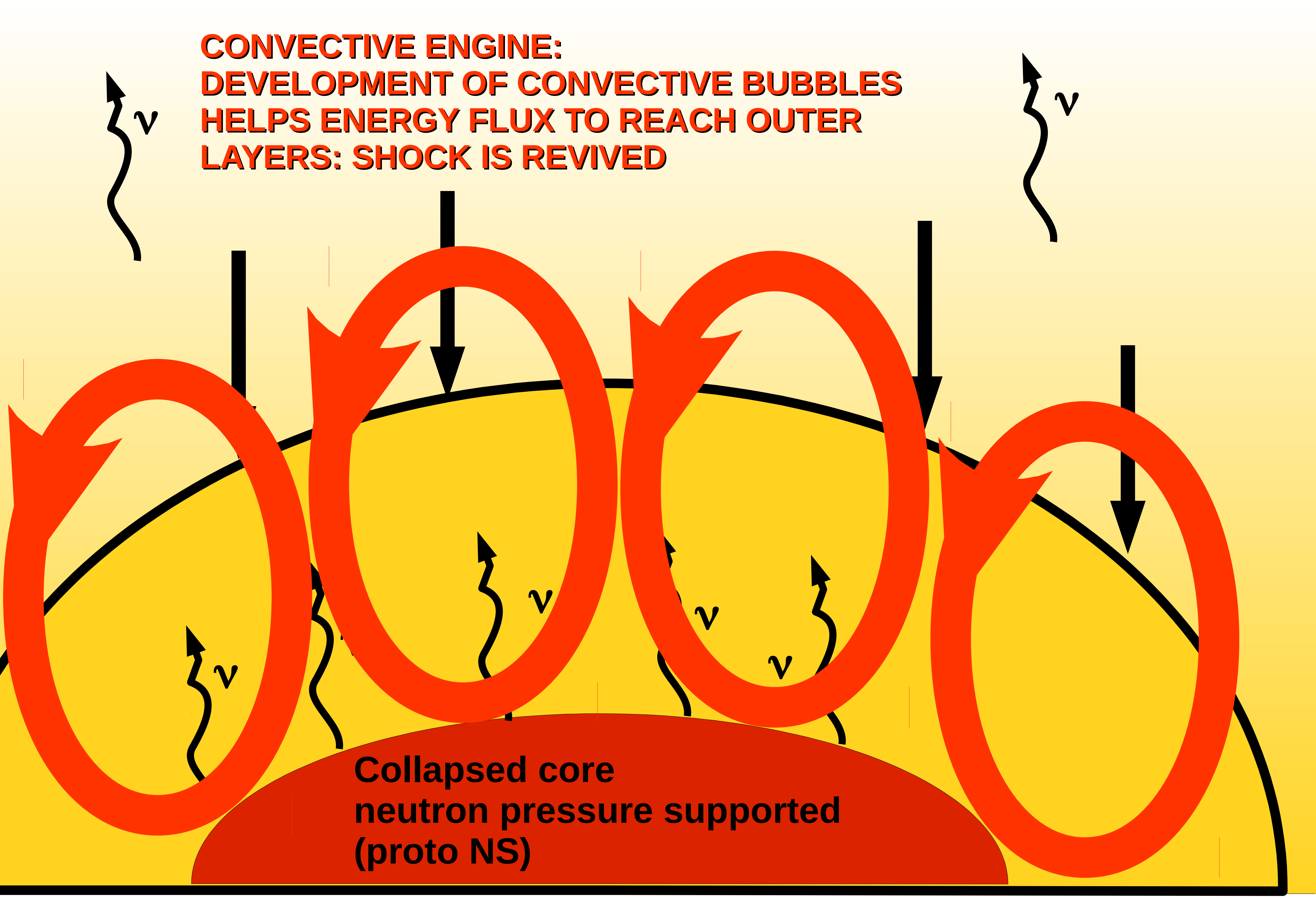
IMPLODING
OUTER
LAYERS

SHOCK STALLING REGION

Very high density
region: trapped
neutrinos power
the SHOCK

Collapsed core
neutron pressure supported
(proto NS)

# 1. The formation of compact objects: supernova



CONVECTIVE ENGINE:
DEVELOPMENT OF CONVECTIVE BUBBLES
HELPS ENERGY FLUX TO REACH OUTER
LAYERS: SHOCK IS REVIVED

Collapsed core
neutron pressure supported
(proto NS)

# 1. The formation of compact objects: supernova

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

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

**envelope mass**

**proto-NS ~ 1 Msun**

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

**envelope radius**

**Star cannot explode if envelope binding energy > SN energy**

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

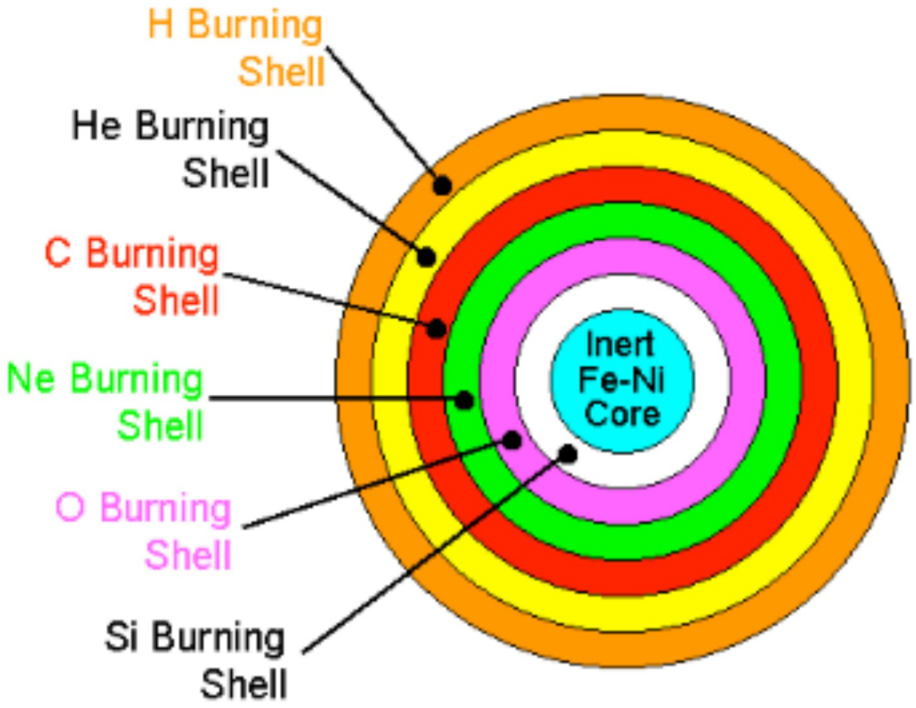
**If $M_{\rm fin}$>50 Msun this SN fails and star collapses to a BH**

# 1. The formation of compact objects: supernova

**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 > 8 Msun    SN FAILS**
**(Fryer+ 1999, 2012; Belczynski+ 2010)**



# 1. The formation of compact objects: 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)**

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

***M* = 2.5 M⊙ is usually adopted**

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

**(Ugliano+ 2012; Horiuchi+ 2012)**

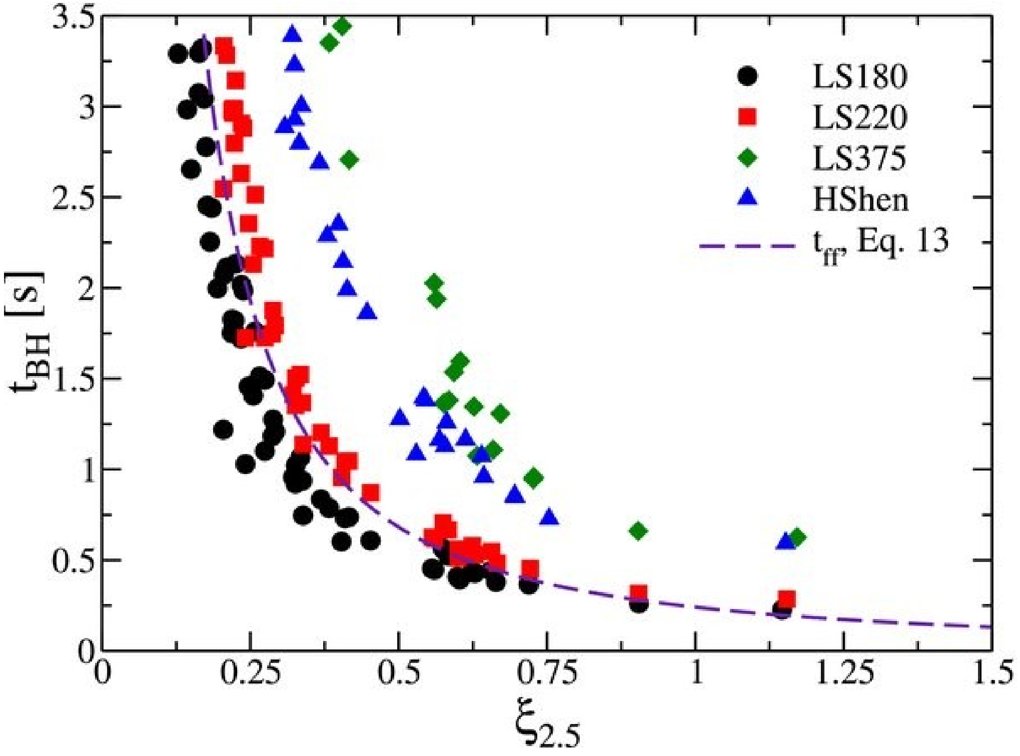


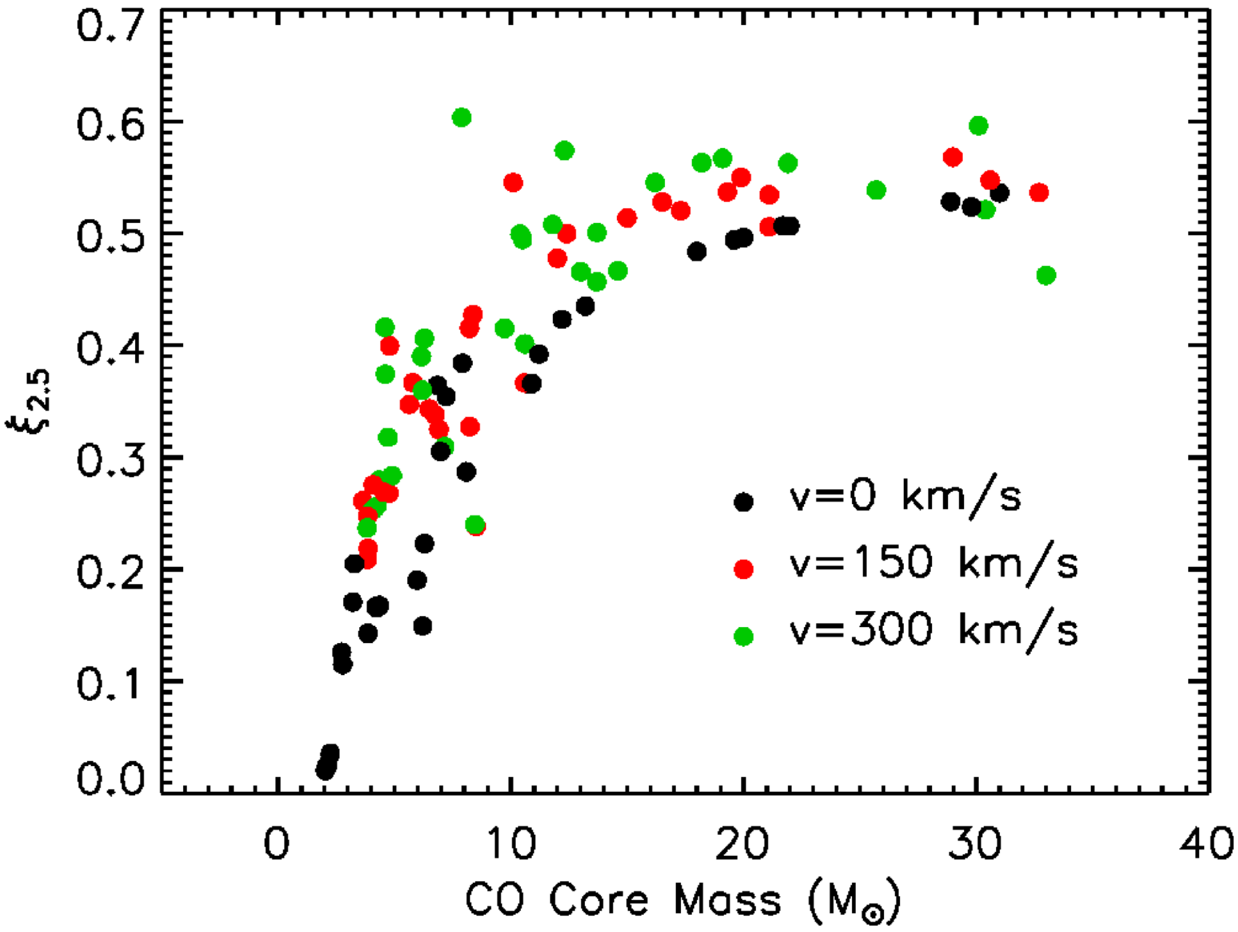
**Figure from O'Connor & Ott 2011**

# 1. The formation of compact objects: supernova

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

**Correlates well with mass of CO core**

**Figure from Limongi 2017 arXiv:1706.01913**

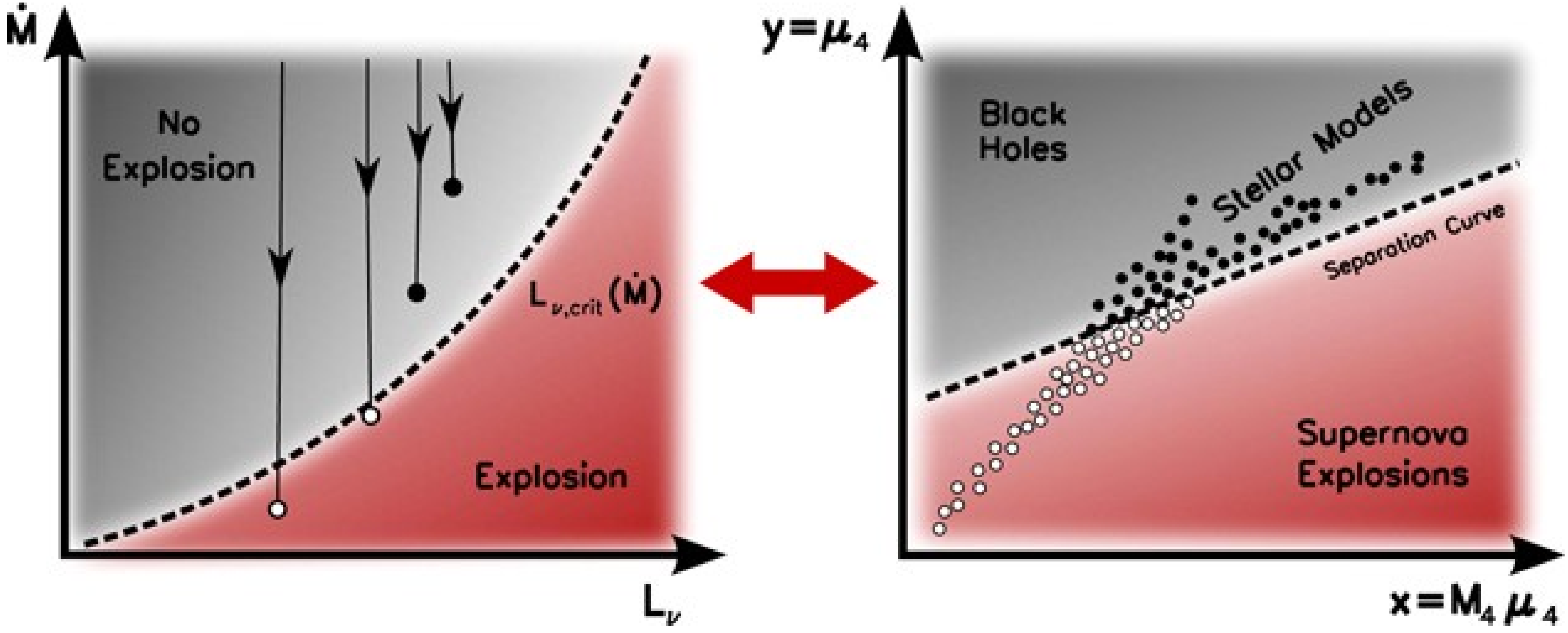


# 1. The formation of compact objects: supernova

**3. enclosed mass ($M_4$) and mass gradient ($\mu_4$) at a dimensionless entropy per nucleon *s* = 4 (Ertl+ 2016)**

$$M_4 = m(s=4)/M_\odot$$

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



# 1. The formation of compact objects: supernova

## 3. enclosed mass ($M_4$) and mass gradient ($\mu_4$) at a dimensionless entropy per nucleon $s = 4$ (Ertl+ 2016)

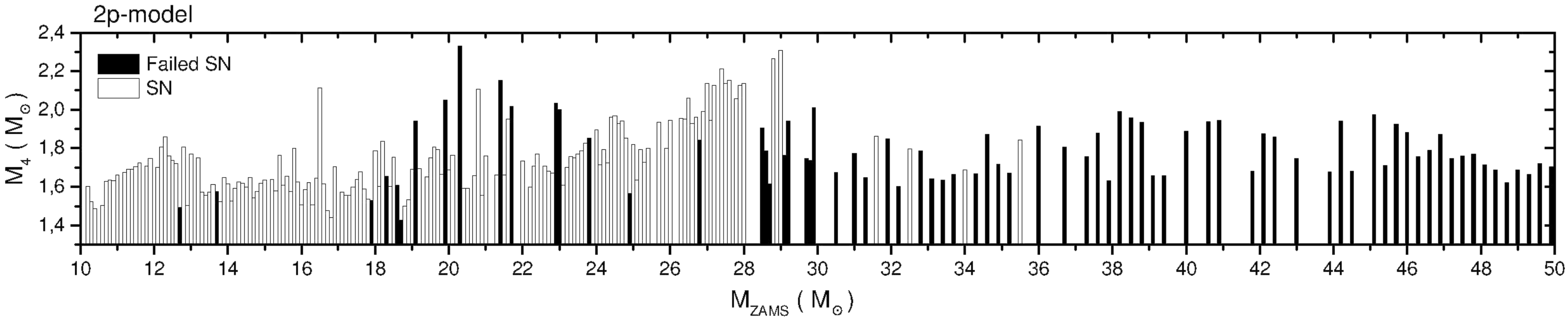


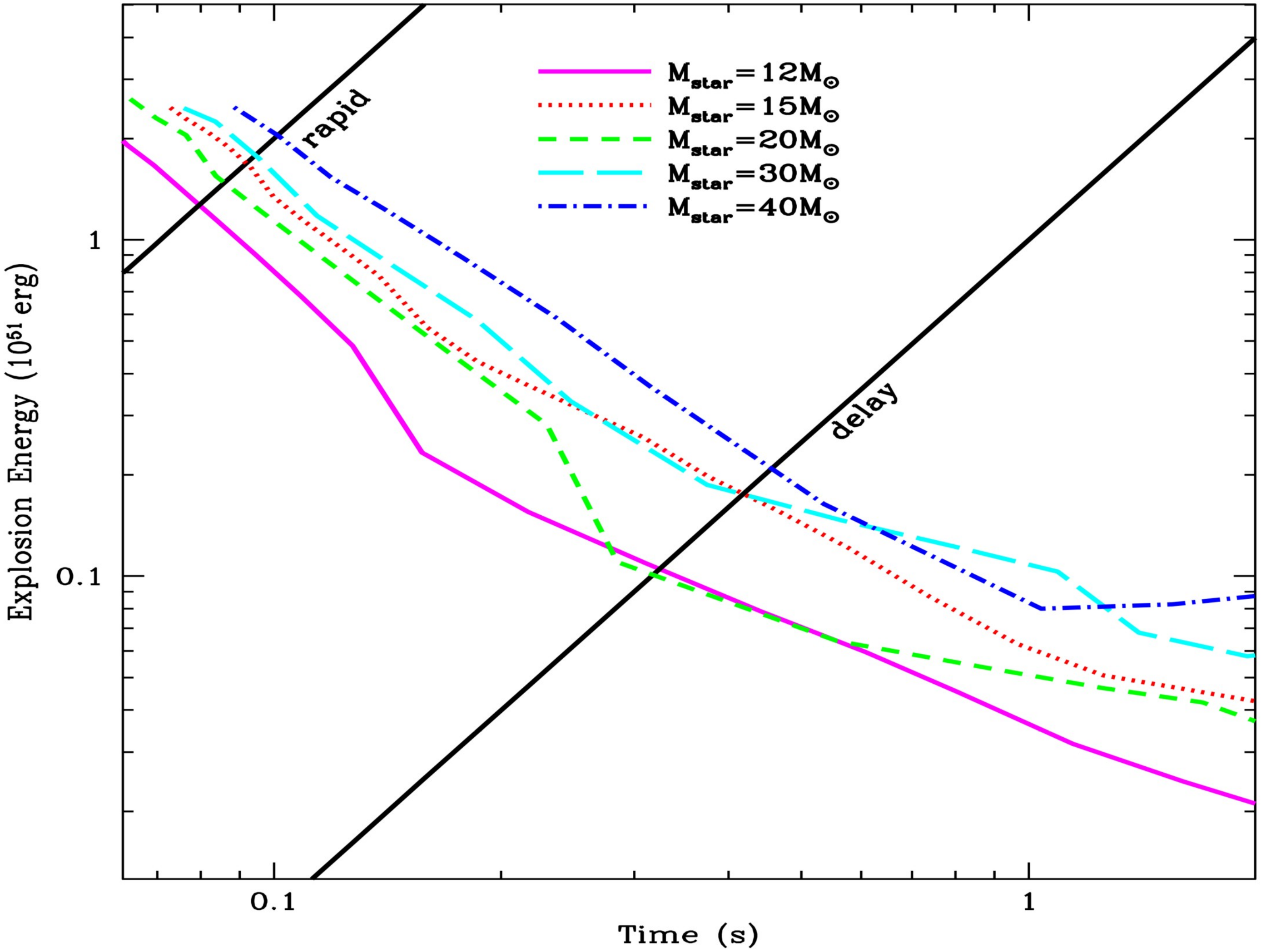
**Fig. 21 Spera, MM, Bressan 2015**

**ISLANDS OF DIRECT COLLAPSE AND SN EXPLOSION**

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

# 1. The formation of compact objects: 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**

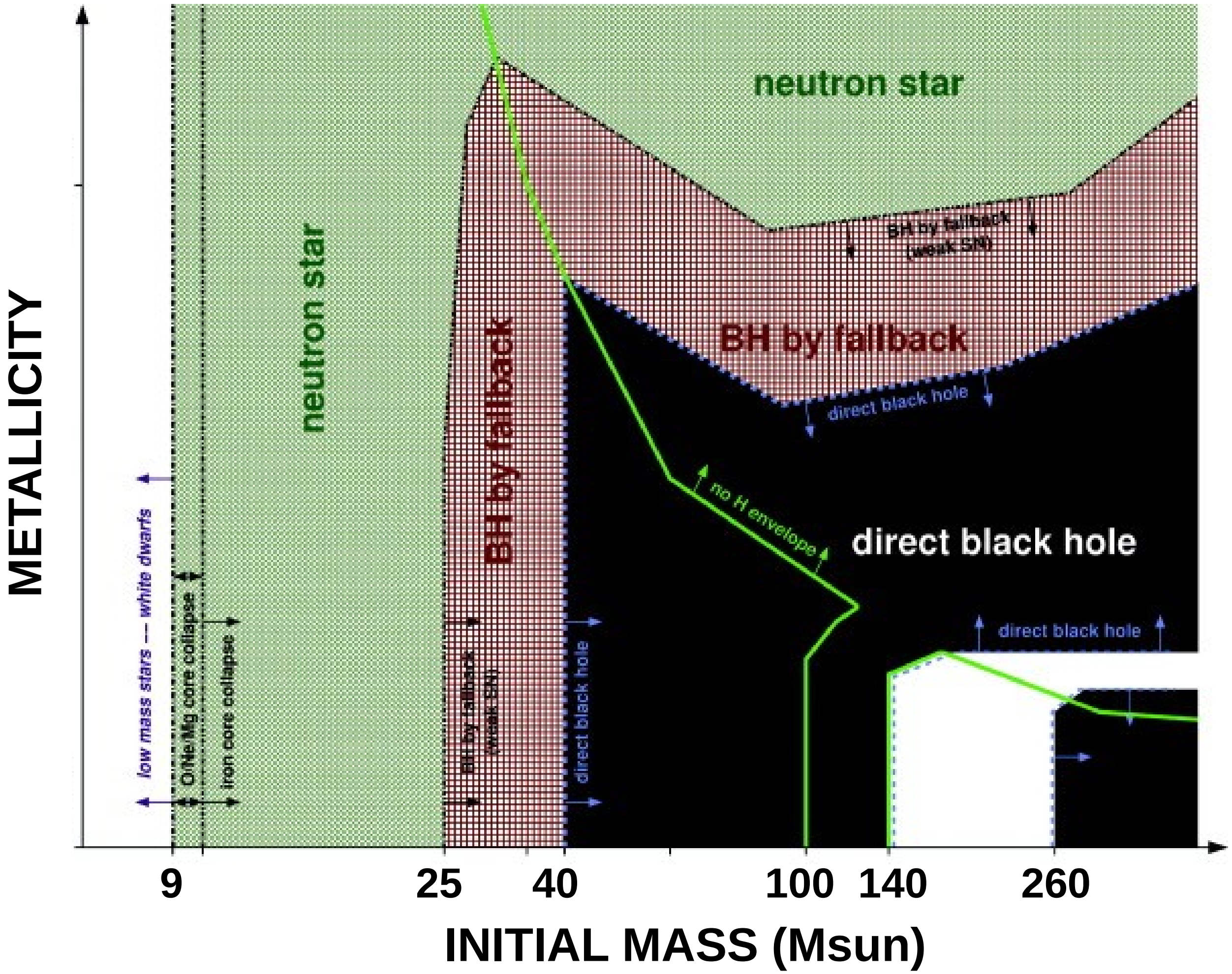
# 1. The formation of compact objects: supernova

**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**

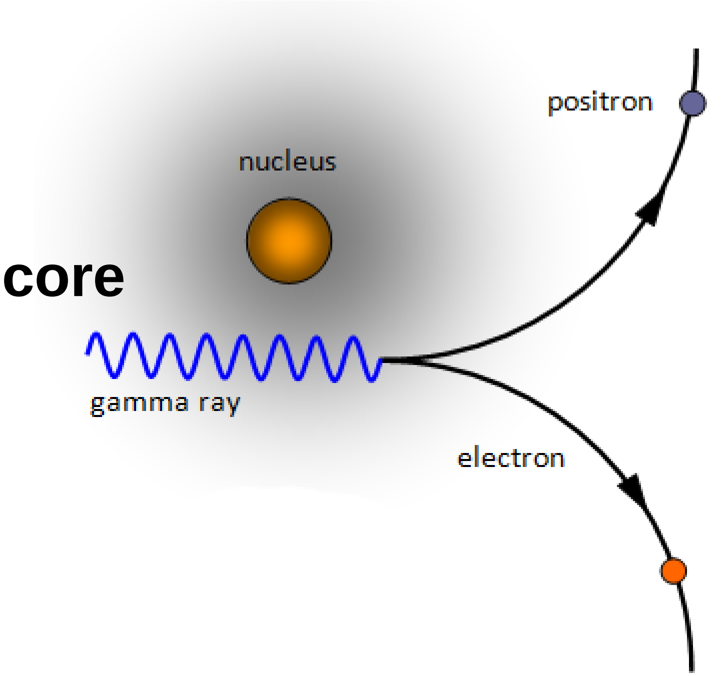
**Barely constrained – depends on explosion energy,**
**angular momentum,**
**progenitor's mass/metallicity**



**Heger 2003**

# 1. The formation of compact objects: supernova

## NOT SO EASY (4): PAIR-INSTABILITY SUPERNOVAE (PISNe)



**If star is very massive,**
**Helium core mass > 64 Msun**
**→ 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**

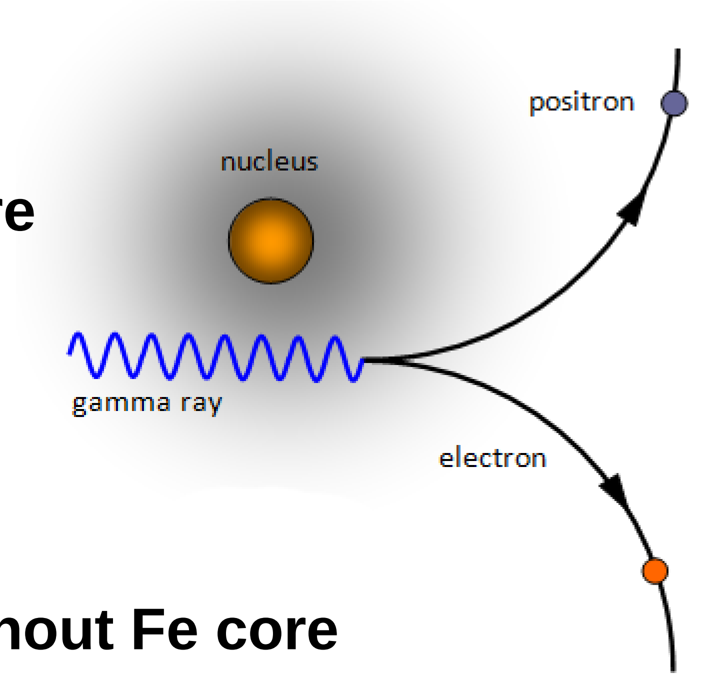
**→high-Temperature collapse ignites all remaining species**

**→ 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

→ **NOT SO EASY (5): PULSATIONAL PISNe**



**If star is quite massive,**
**64 Msun> Helium core mass > 32 Msun**
**→ 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):**

LOW Z (<0.5 Zsun)

↓

STELLAR WINDS ARE QUENCHED

↓

LARGER PRE-SN MASS

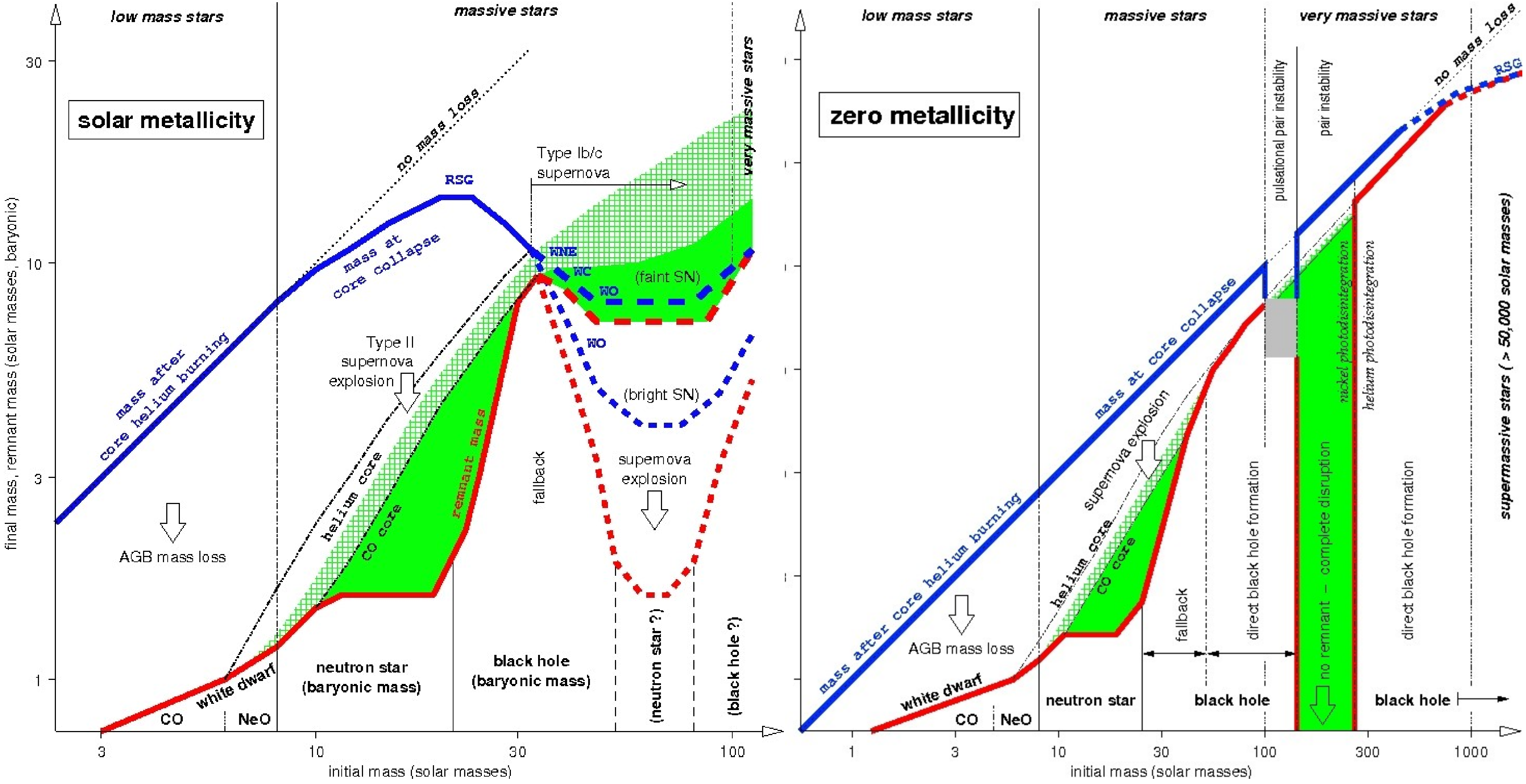
↓

MORE LIKELY DIRECT COLLAPSE TO BH

↓

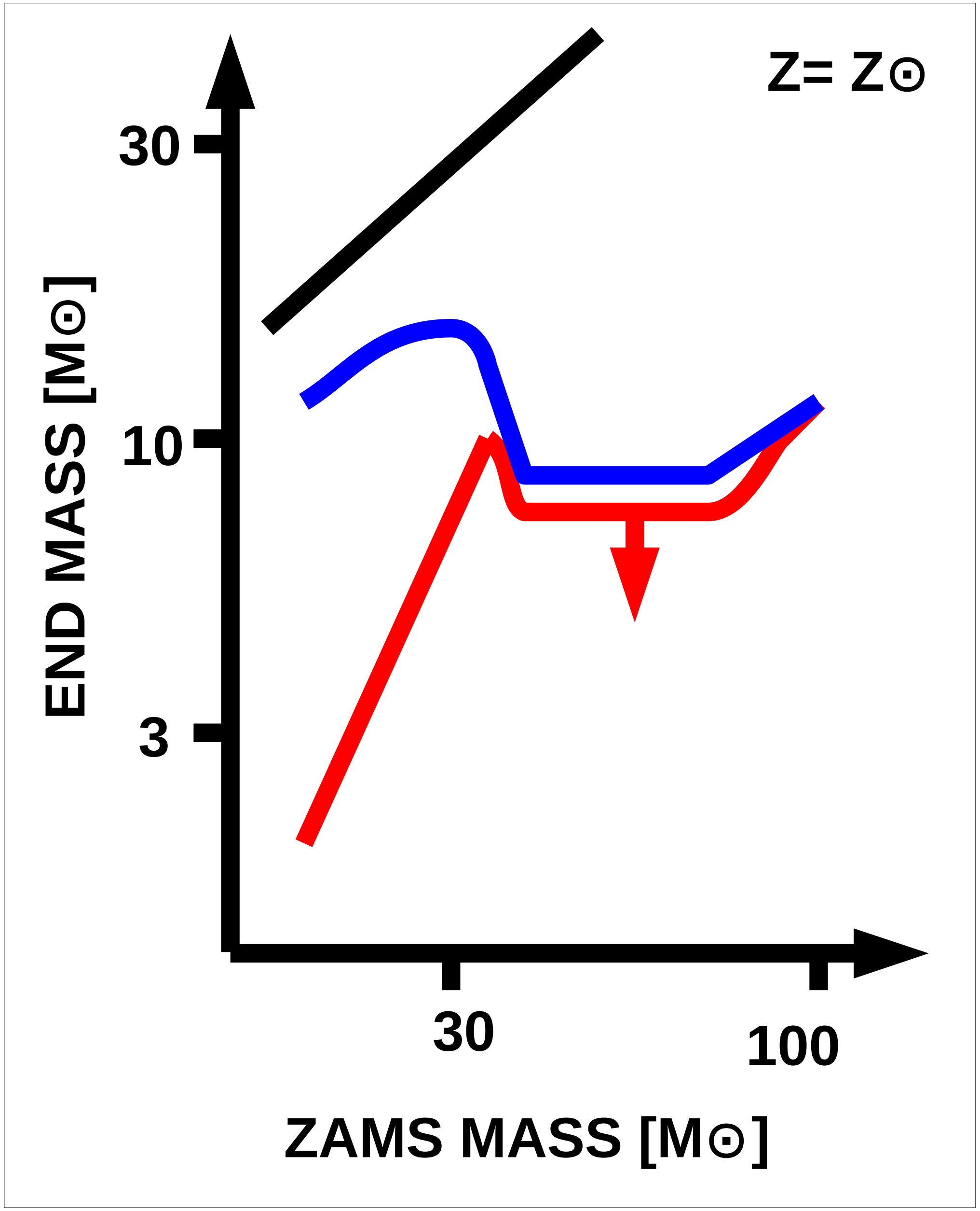
MORE MASSIVE BH

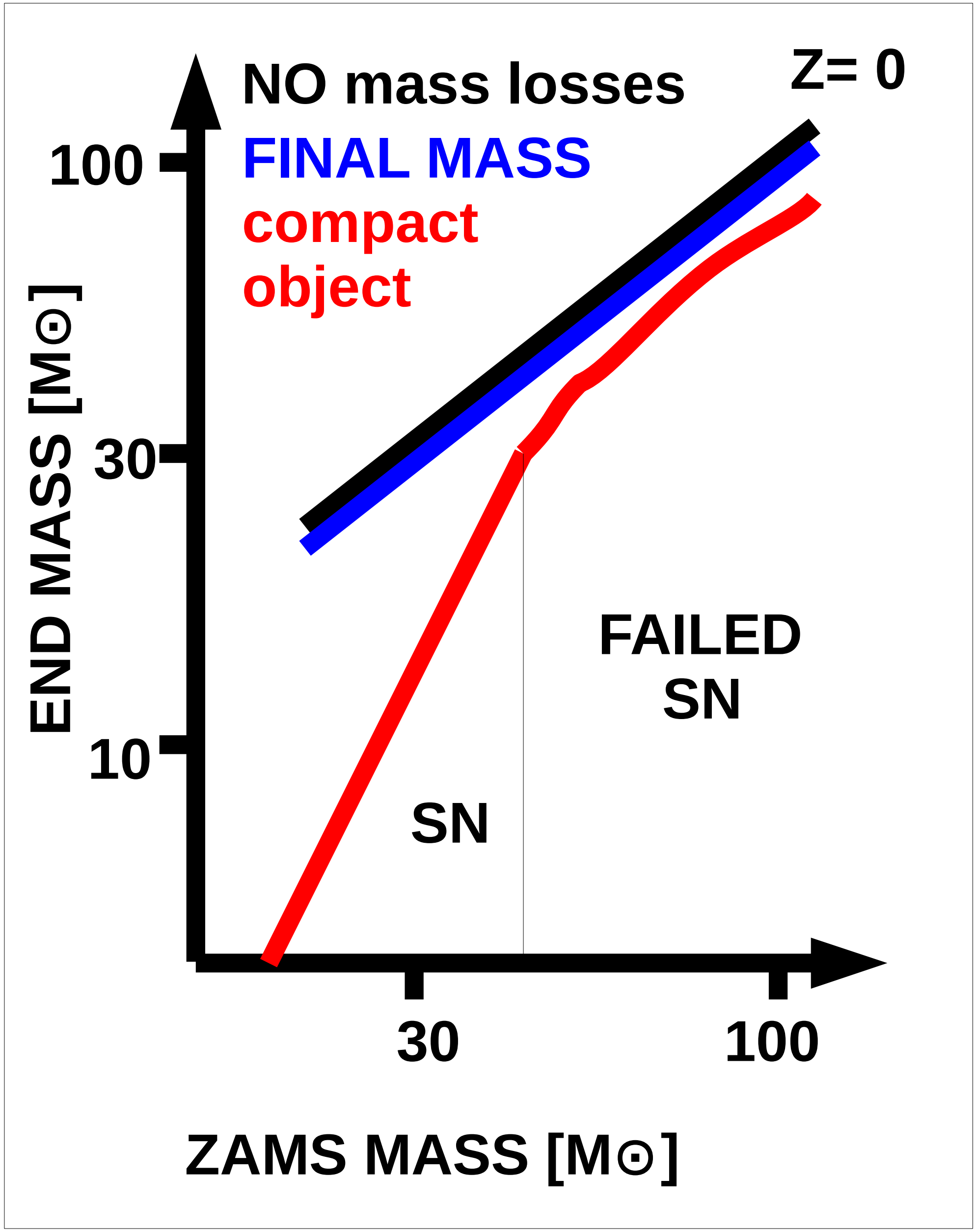
# 1. The formation of compact objects: wrap up



**Heger et al. (2003)**

# 1. The formation of compact objects: wrap up



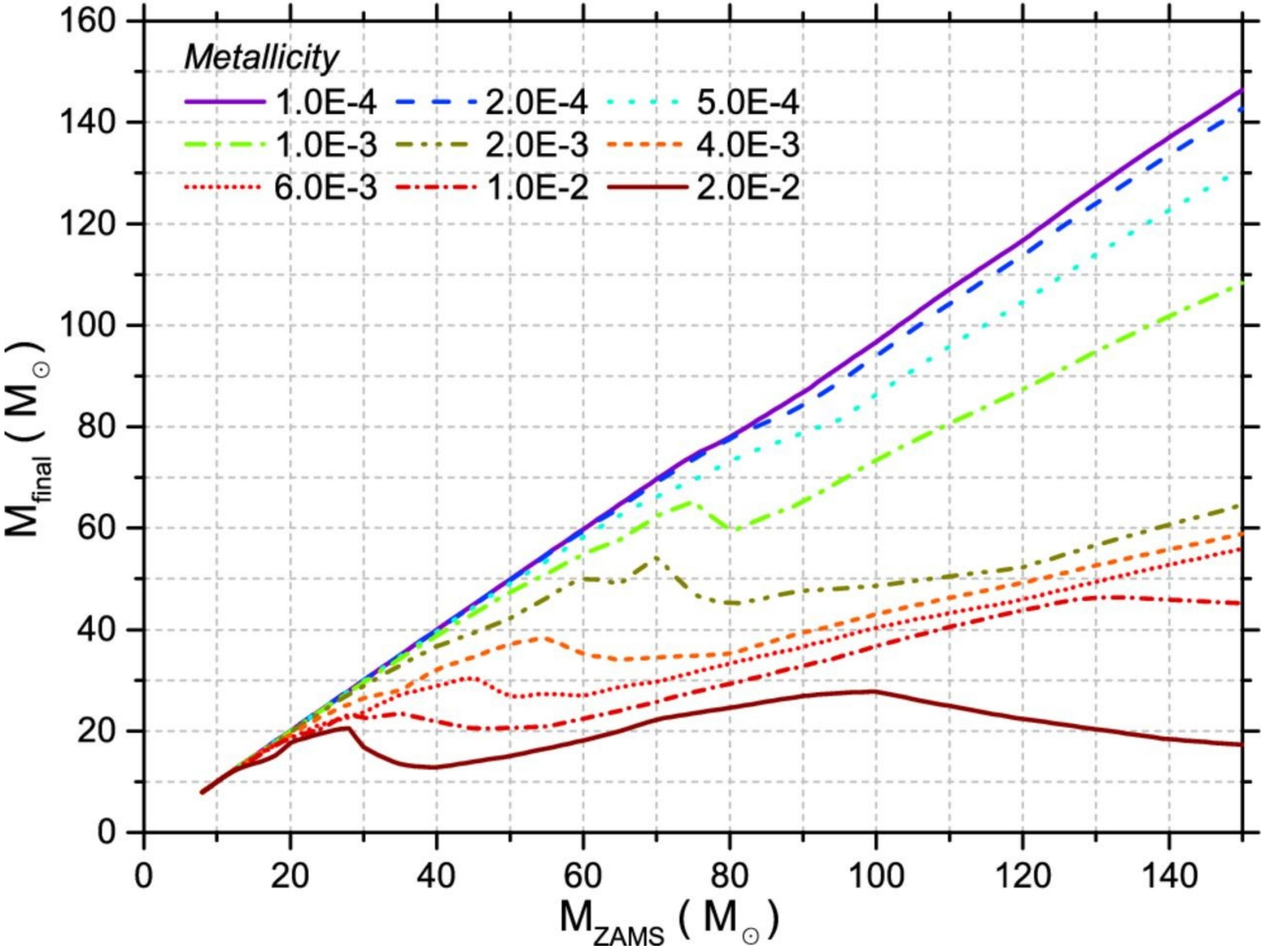


My cartoon from
Heger et al. (2003)

# 1. The formation of compact objects: wrap up

**What about intermediate metallicities between 0 and solar?**

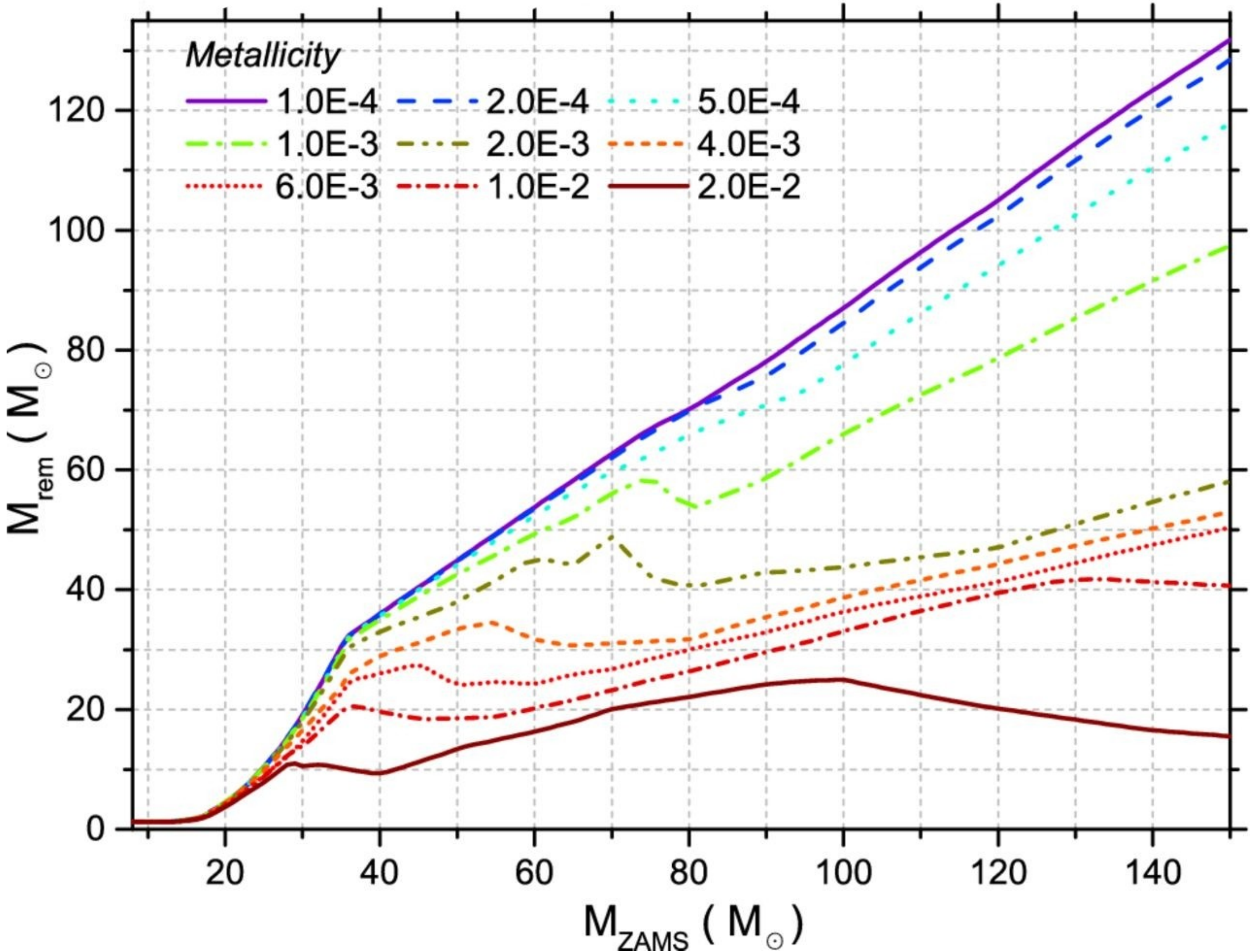
**- more difficult because stellar winds are uncertain**
**- importance of final mass: pre-supernova mass of the star (when CO core built)**



**Spera, MM, Bressan 2015**

# 1. The formation of compact objects: wrap up

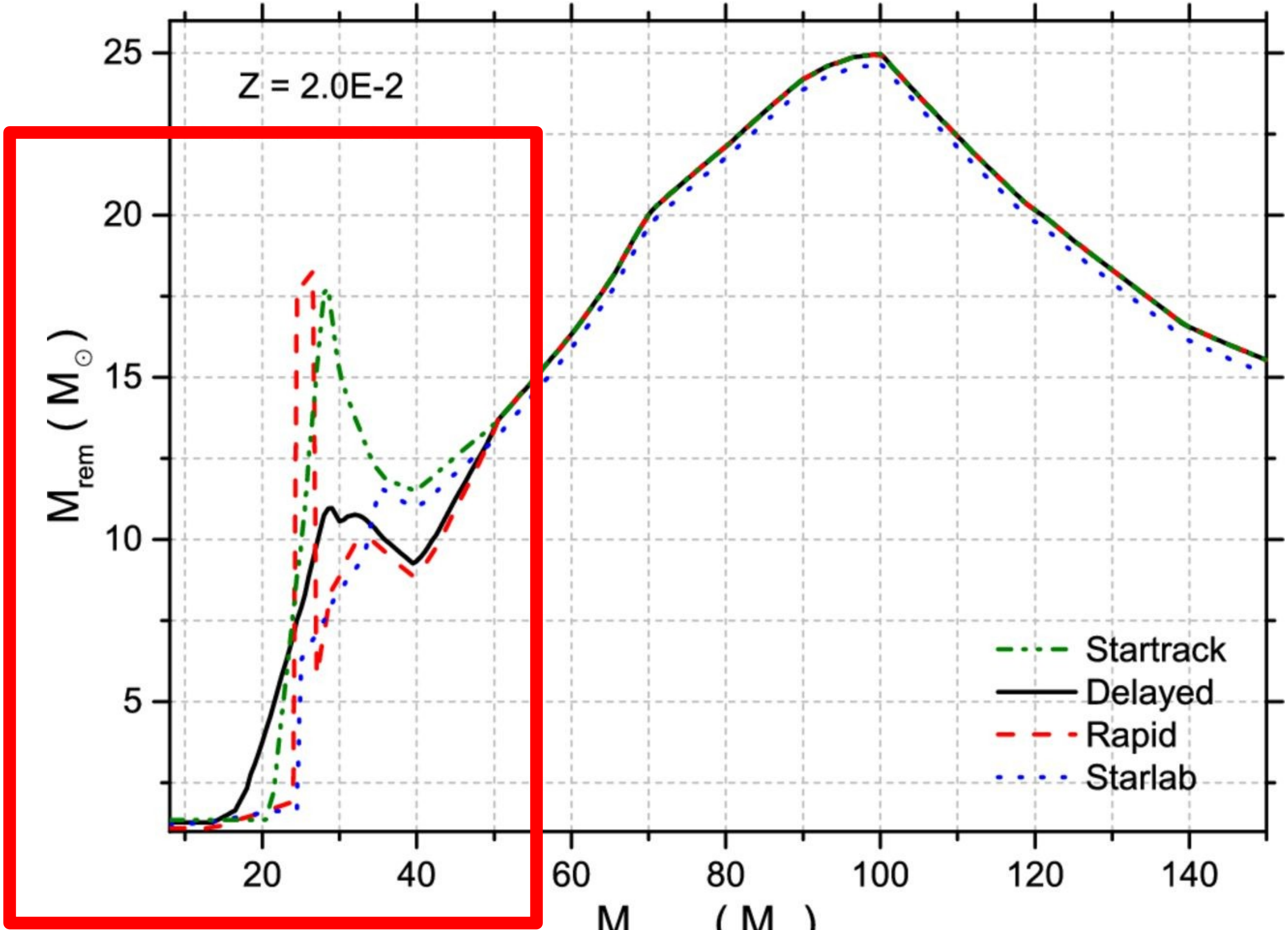
**Remnant mass follows same trend as final mass**
**→ stellar winds are crucial**



**Spera, MM, Bressan 2015**

# 1. The formation of compact objects: wrap up

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



**Spera, MM, Bressan 2015**

# 1. The formation of compact objects: wrap up

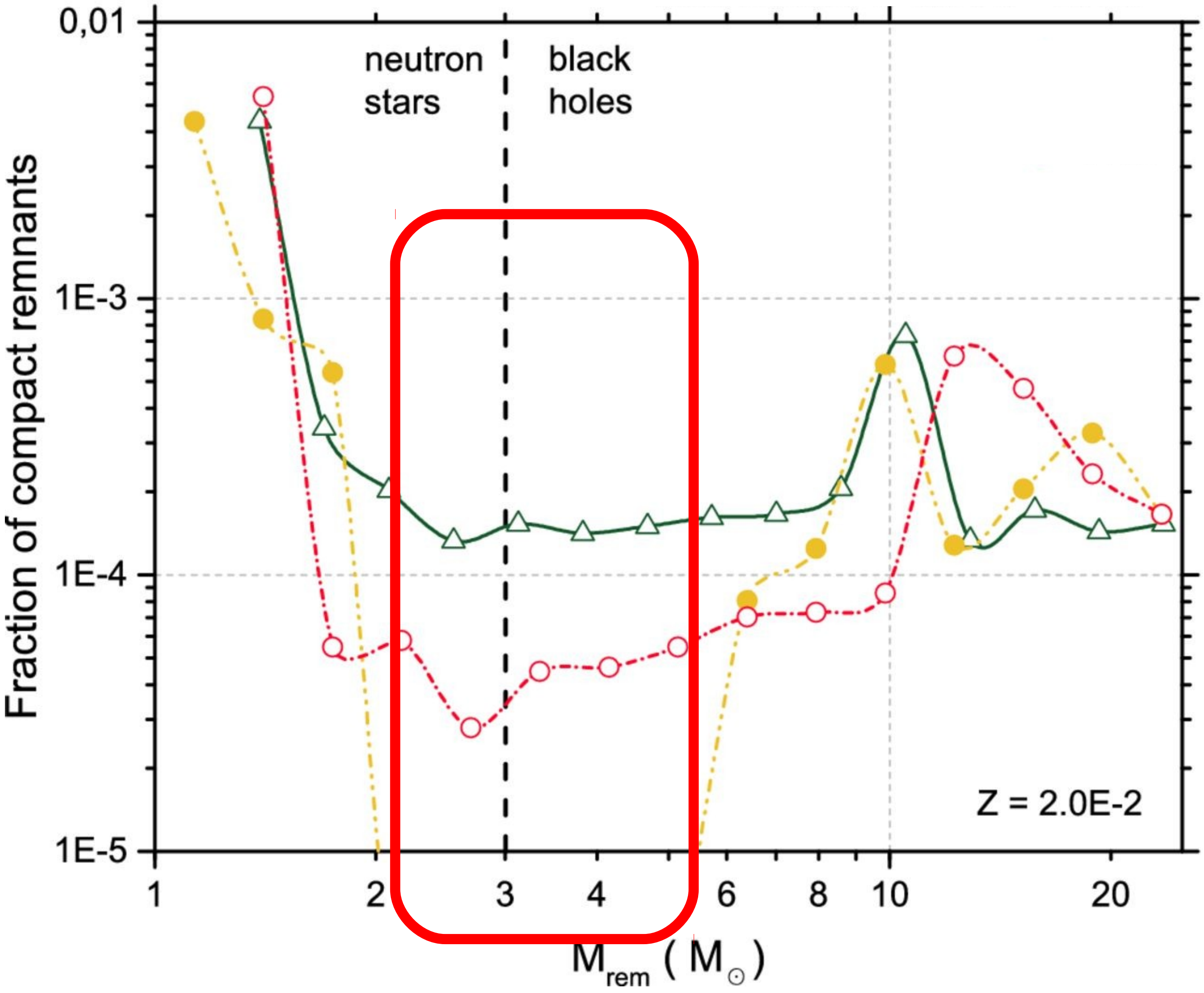
**Importance of supernova model for LOW STAR MASSES (<40 M⊙)**

**Solar metallicity**

**GREEN:**
**DELAYED**
**SN (Fryer+ 2012)**

**RED:**
**DELAYED**
**SN (MM+ 2013)**

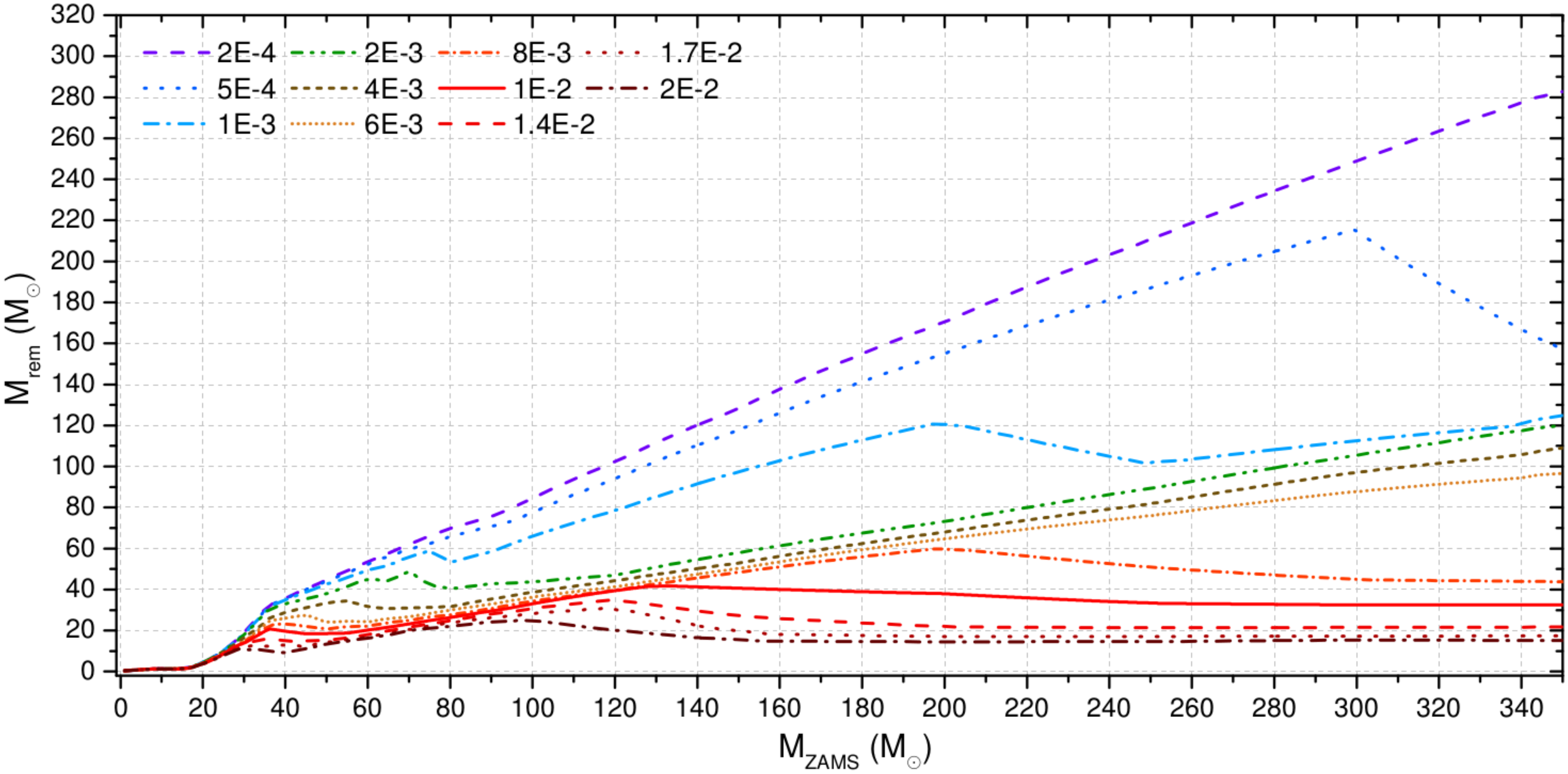
**YELLOW:**
**PROMPT SN**
**(Fryer+ 2012)**



**Spera, MM, Bressan 2015**

# 1. The formation of compact objects: wrap up

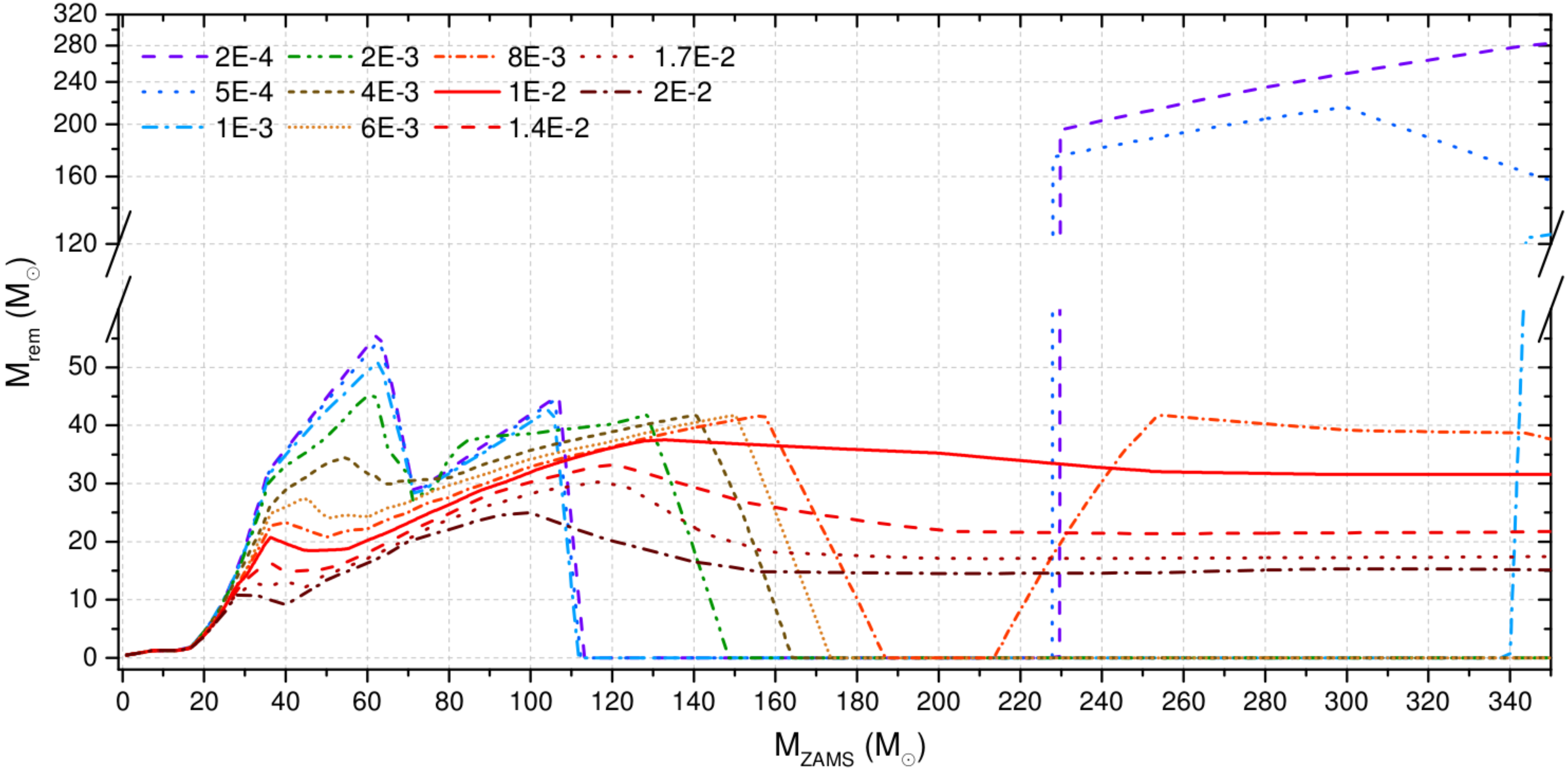
**Evolution of very massive stars still uncertain**
**→ stellar winds are Eddington-limited rather than metallicity dependent**



**Spera & MM 2017**

# 1. The formation of compact objects: wrap up

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



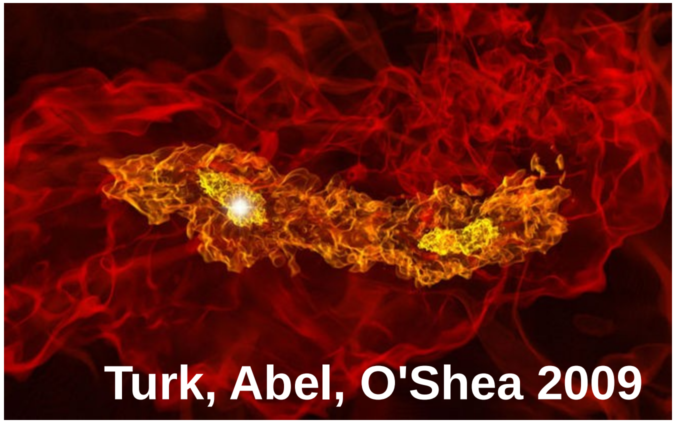
**Spera & MM 2017**

# 2. Binaries of compact objects

**LIGO – Virgo observe compact object BINARIES**

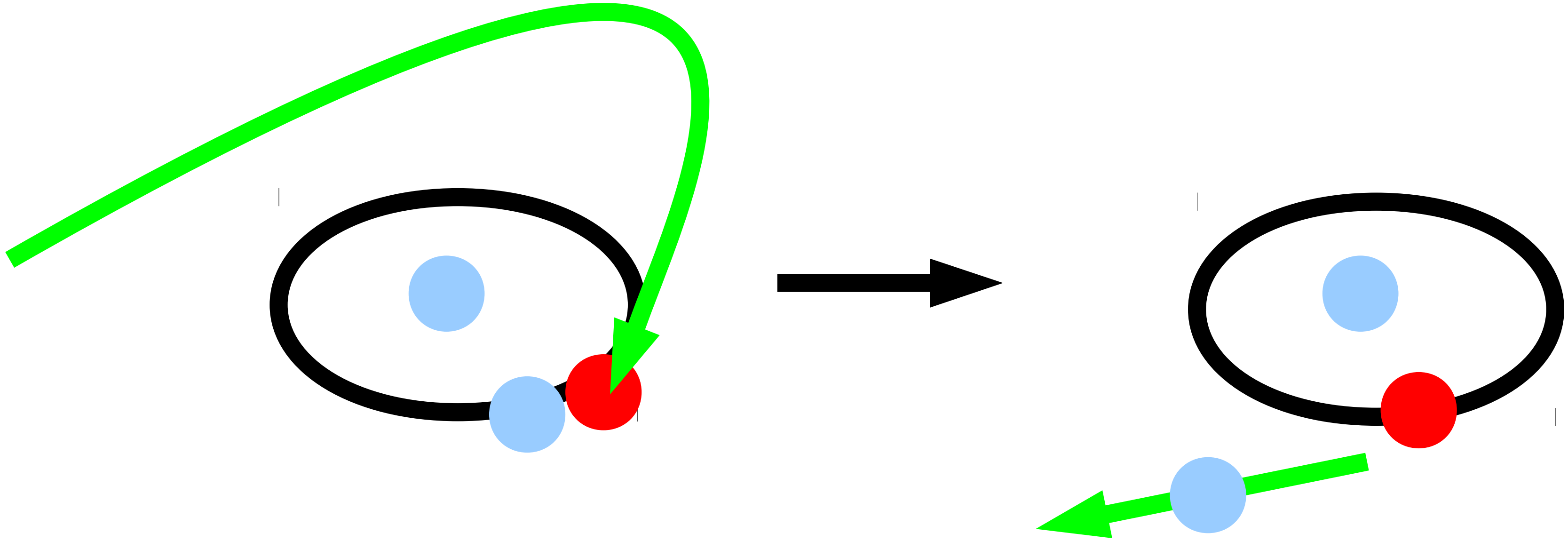
**How do BH-BH (or BH-NS, NS-NS) binaries form?**

**1) PRIMORDIAL BINARY**



Turk, Abel, O'Shea 2009

**2) DYNAMICALLY FORMED BINARY**

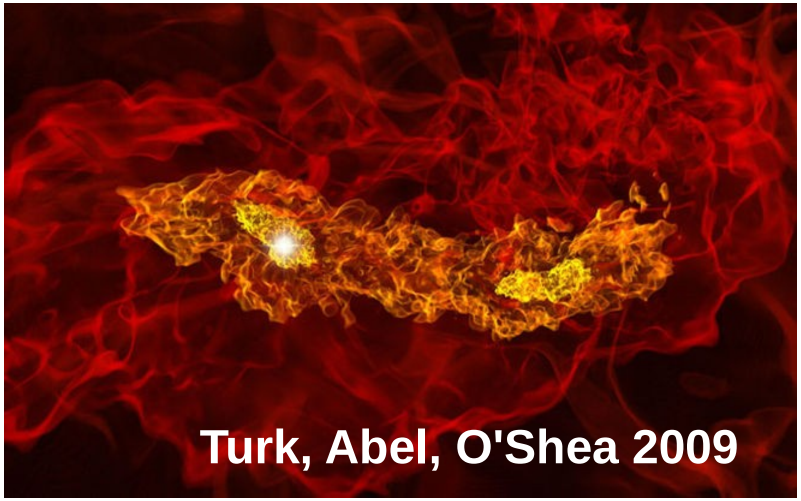


# 2. Binaries of compact objects

**LIGO – Virgo observe compact object BINARIES**
**How do BH-BH (or BH-NS, NS-NS) binaries form?**

## 1) PRIMORDIAL BINARY:

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


Turk, Abel, O'Shea 2009

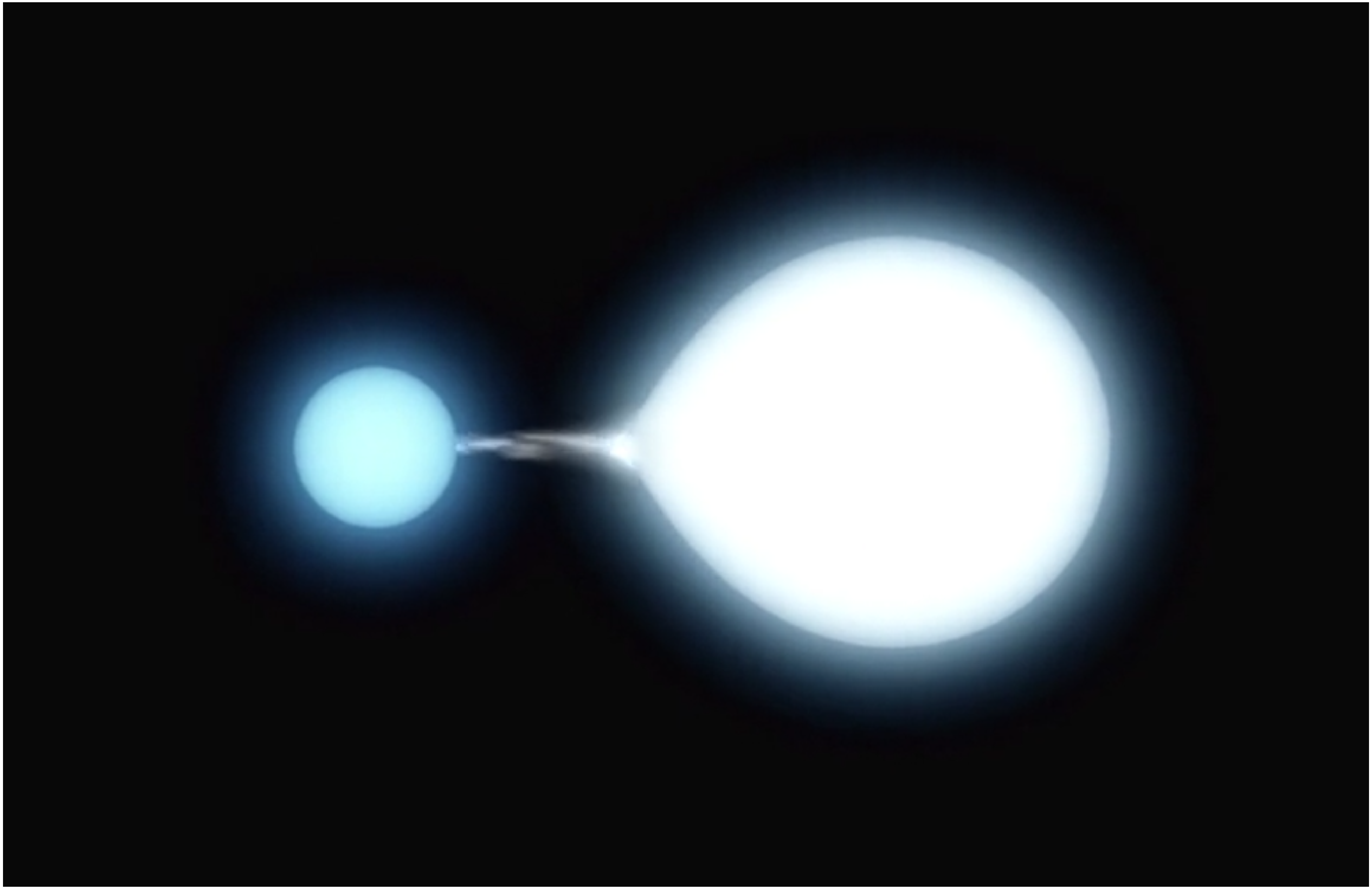
**NOT SO EASY:**

**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)**

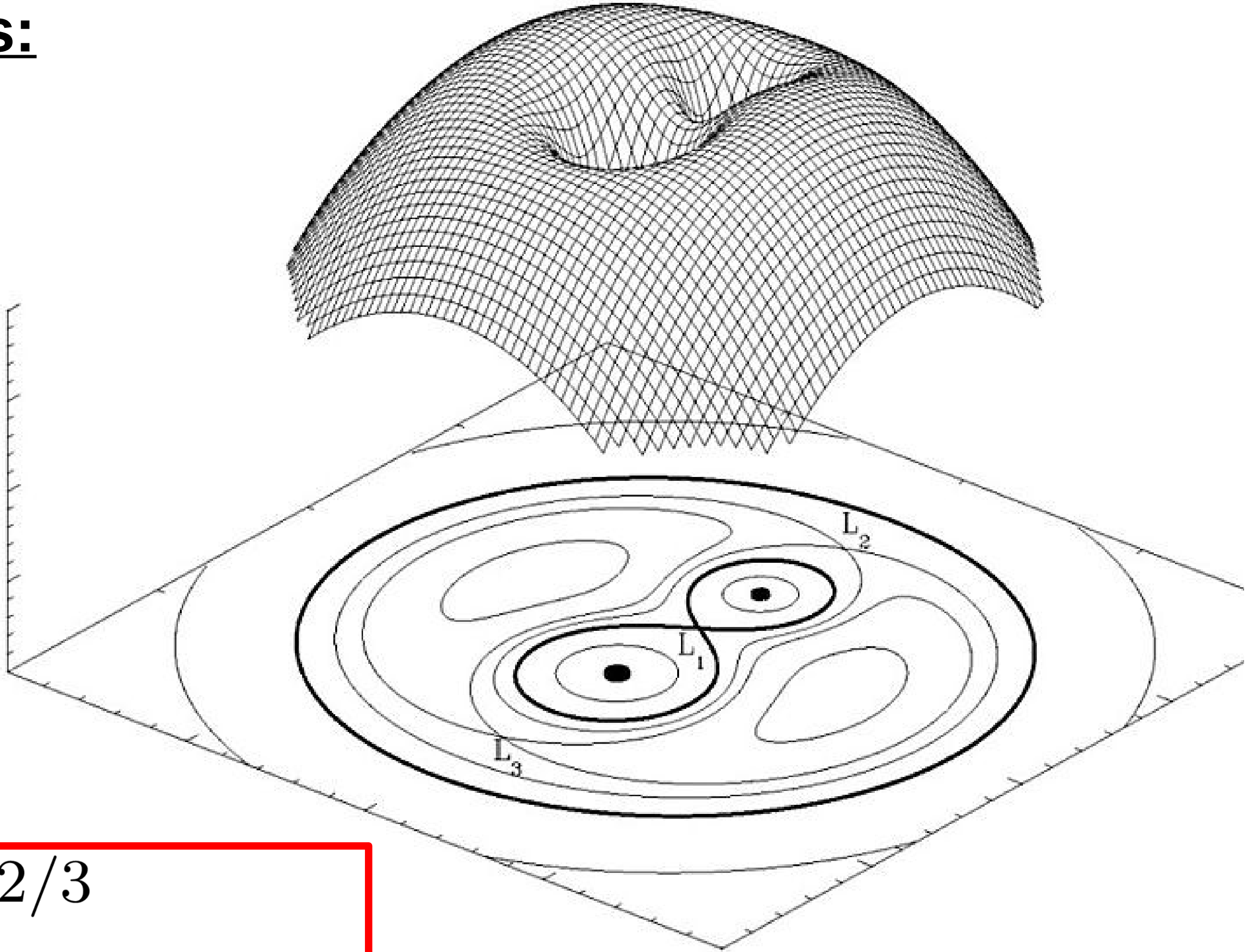
# 2. Binaries of compact objects

## 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

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

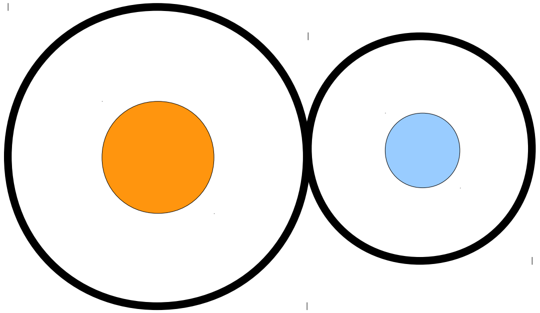
**where** $a$ **= semi-major axis**

$q = M_1/M_2$

# 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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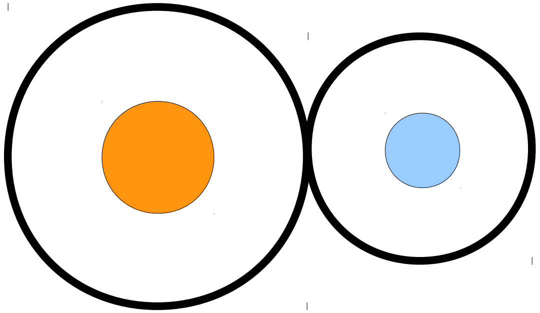
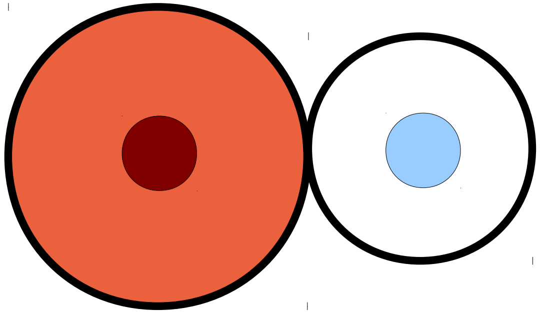


*Two massive stars initially underfilling Roche lobe*



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

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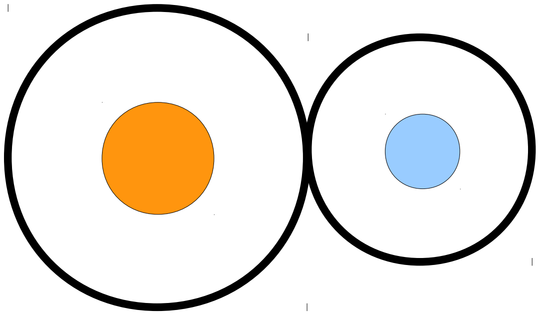

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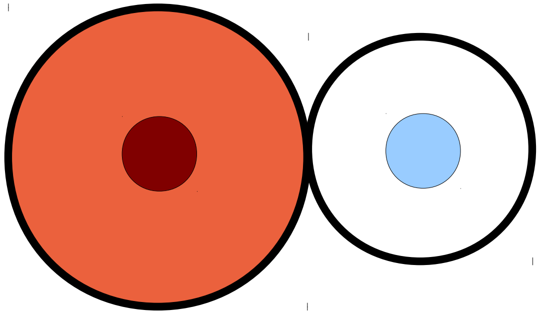

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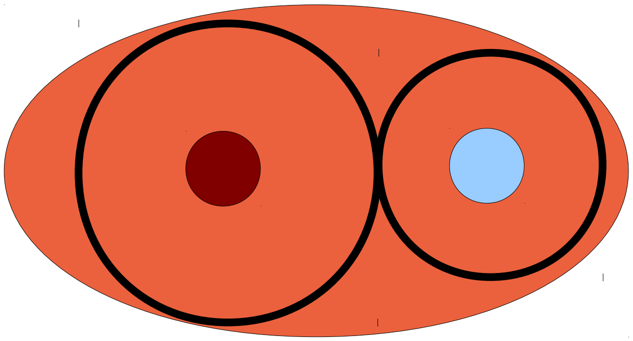

***Mass transfer becomes unstable: CE phase***

# 2. Binaries of compact objects

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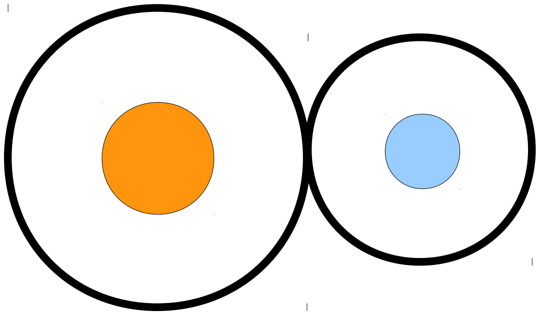

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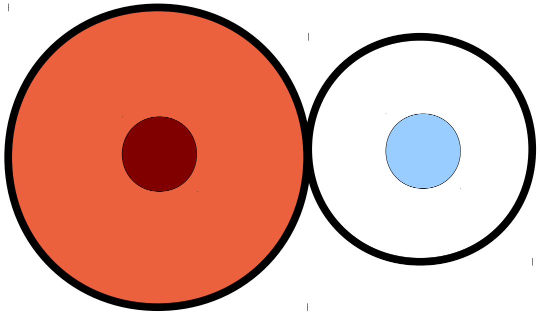

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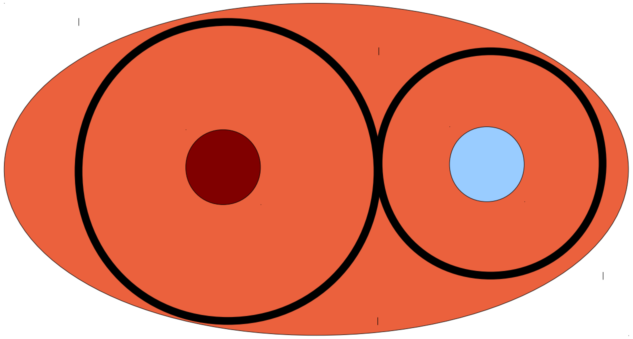

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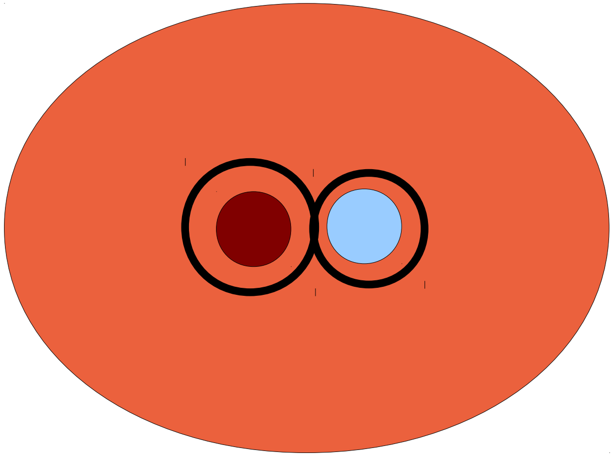

***Drag by the envelope leads the two cores to spiral in***

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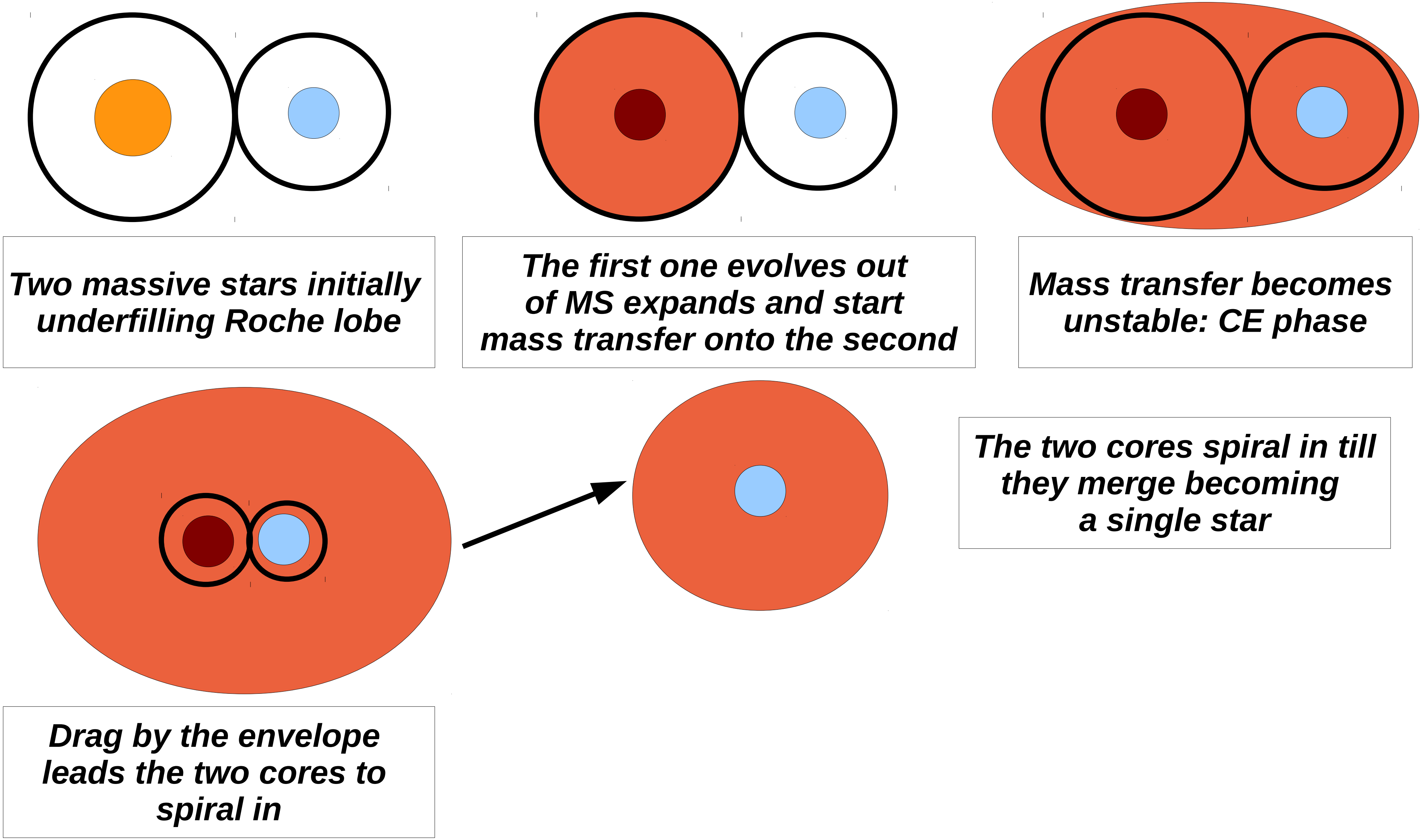

***Two massive stars initially underfilling Roche lobe***

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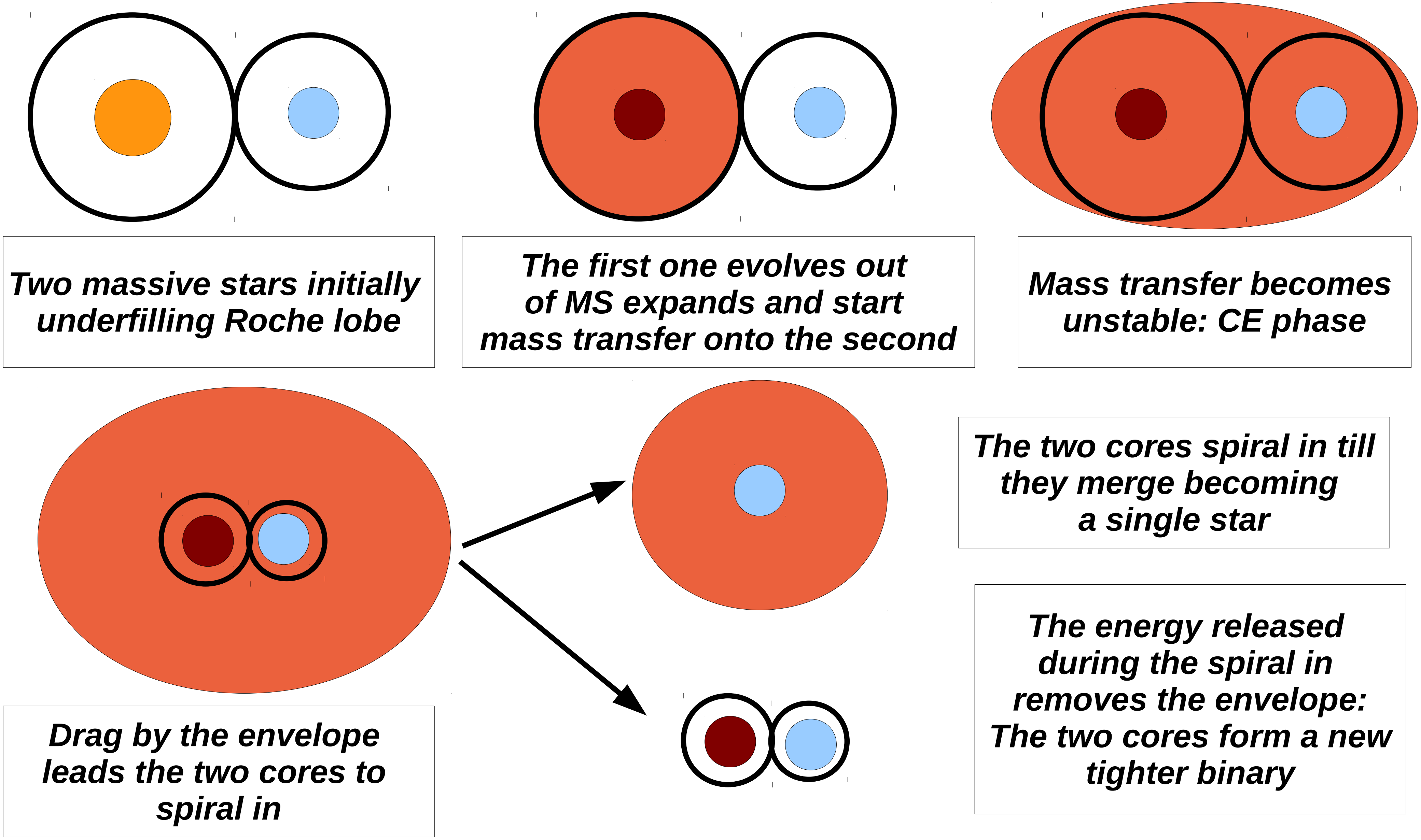

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***The first one evolves out of MS expands and start mass transfer onto the second***

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***Drag by the envelope leads the two cores to spiral in***

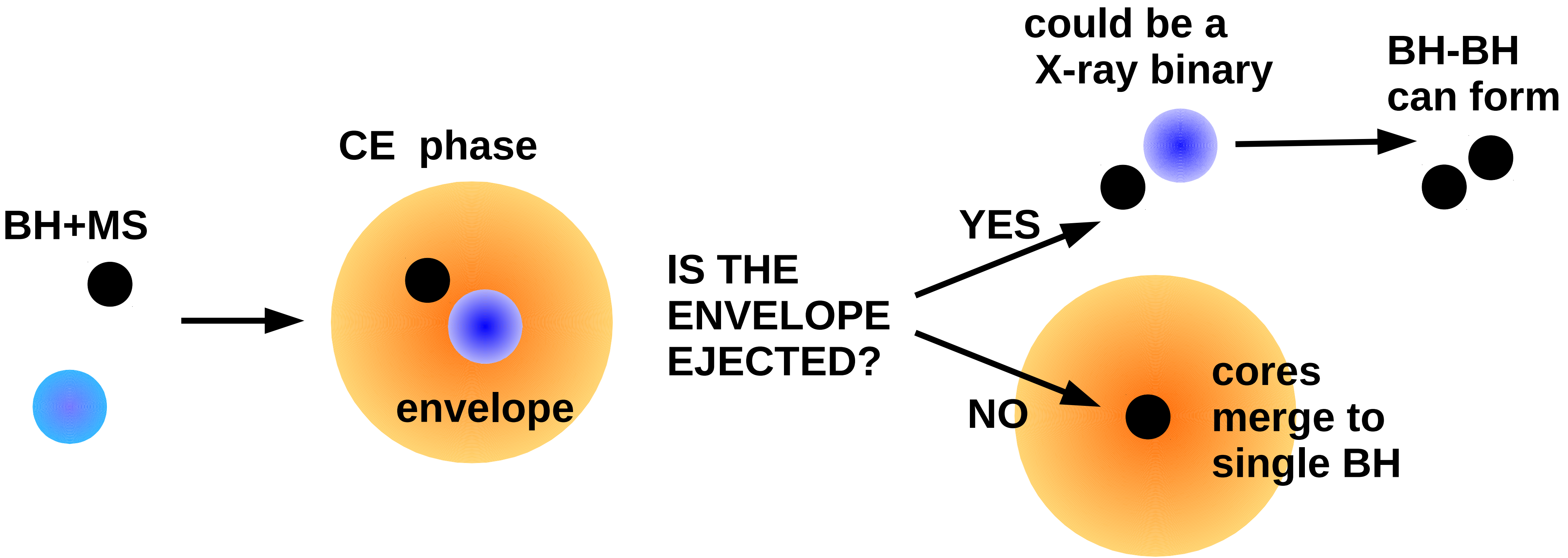
***The two cores spiral in till they merge becoming a single star***

***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

## 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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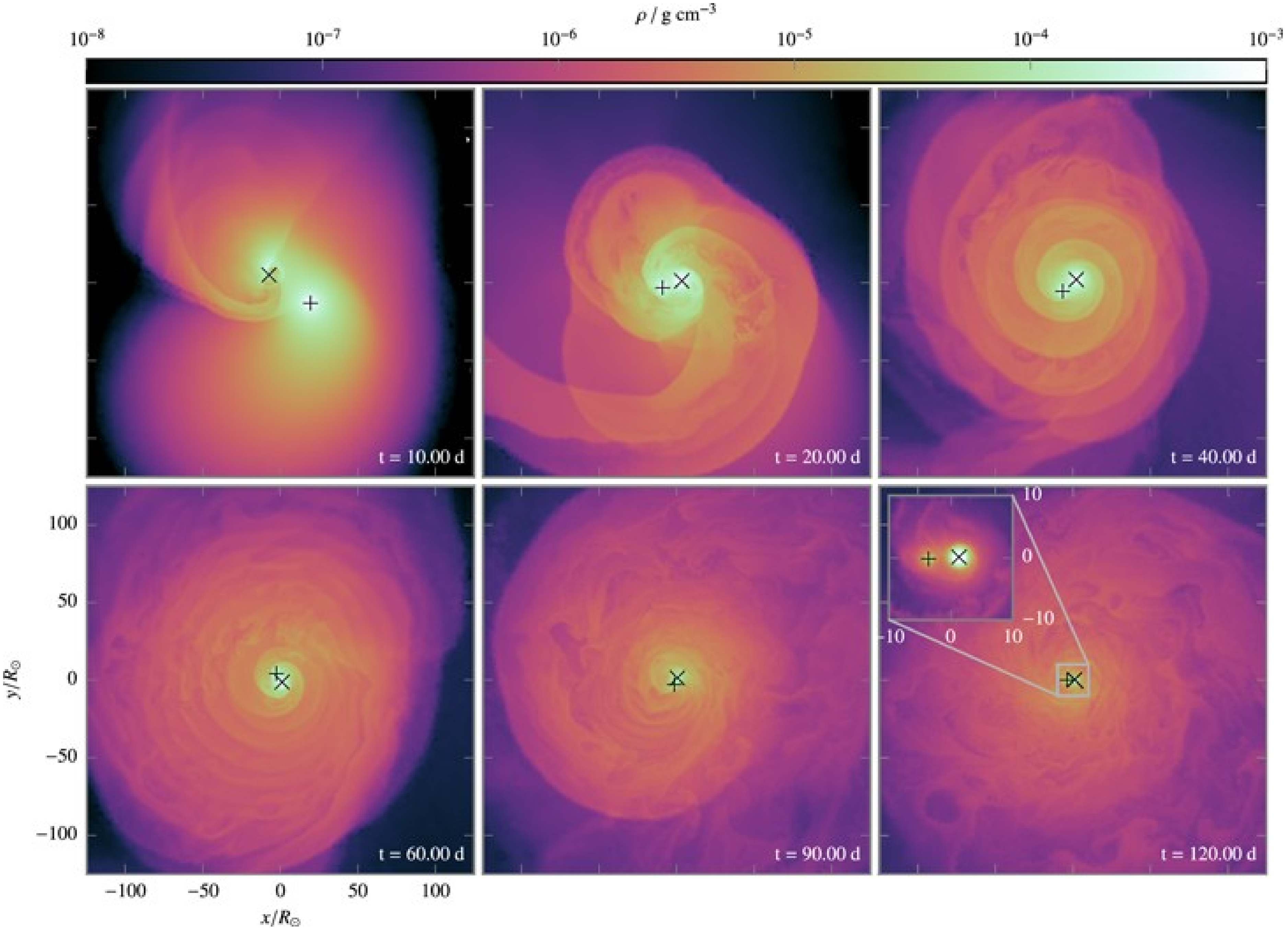
**(Ricker & Taam 2008, 2012; Passy et al. 2012; Ohlmann+ 2016)**

# 2. Binaries of compact objects



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 compact objects

## Common envelope in binaries:

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

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

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

**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:**

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

**α is second free parameter (energy removal efficiency)**

# 2. Binaries of compact objects

**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**

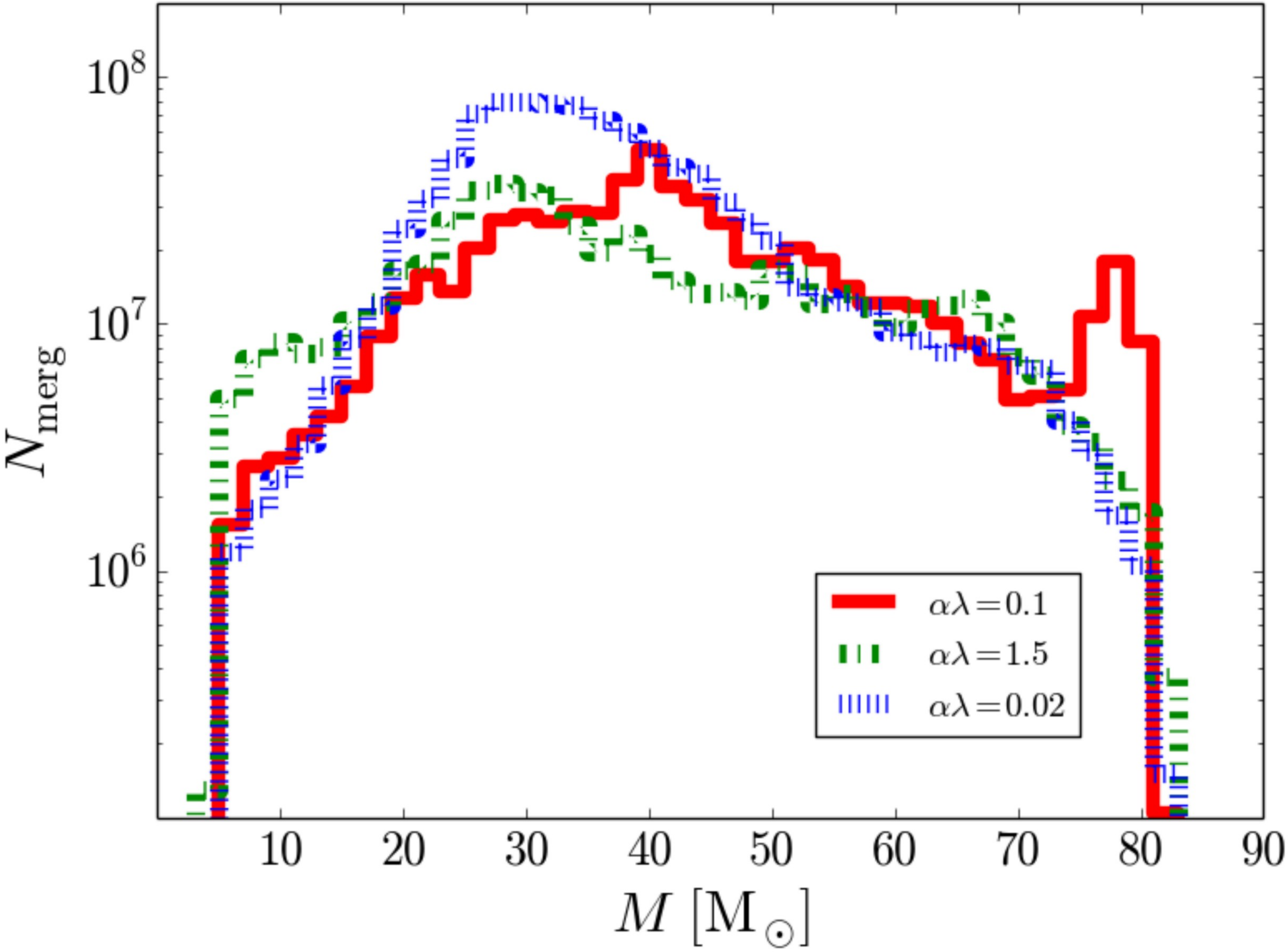
**THEN the cores merge (Hurley+ 2002, MNRAS, 329, 897)**

**PROBLEM IS: HOW TO CONSTRAIN $\alpha$ and $\lambda$ ?**

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

# 2. Binaries of compact objects

## Common envelope in binaries:



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

# 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**

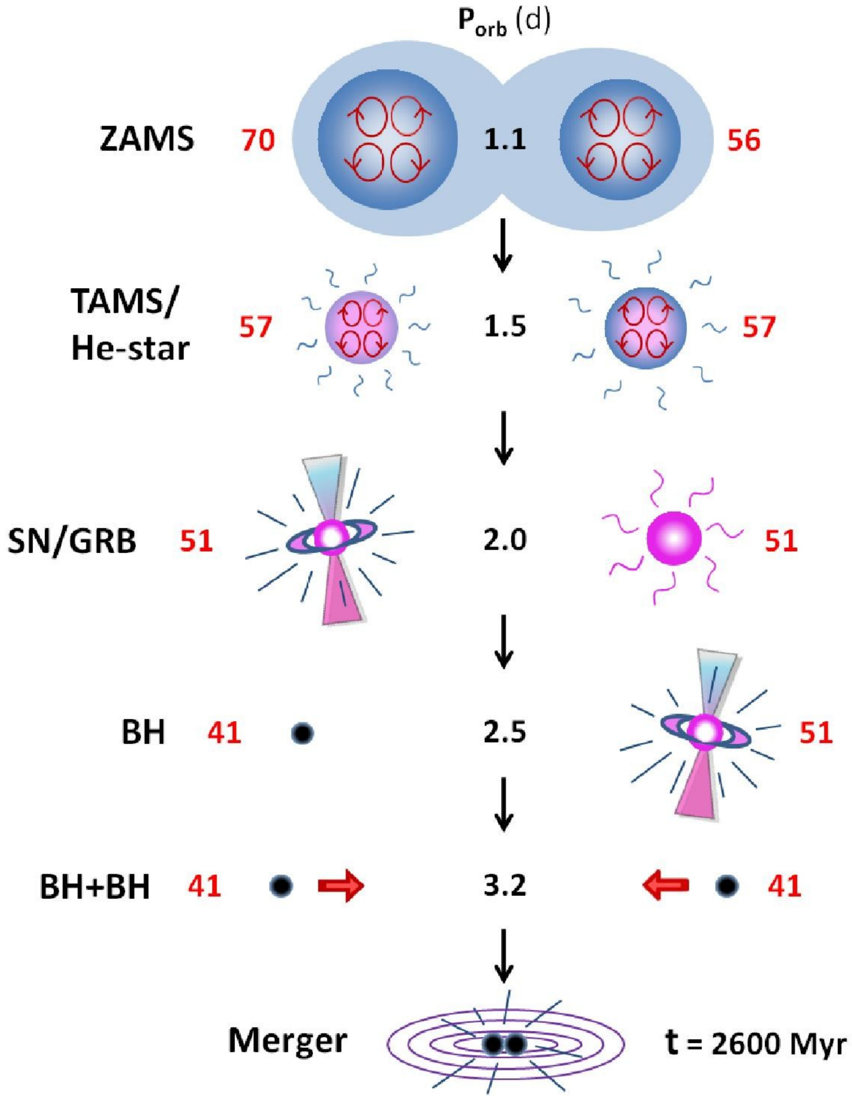
**→ close binaries avoid common envelope and premature merger**

**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 Msun**
**increasing with decreasing metallicity**
**(no low-mass BHs!)**

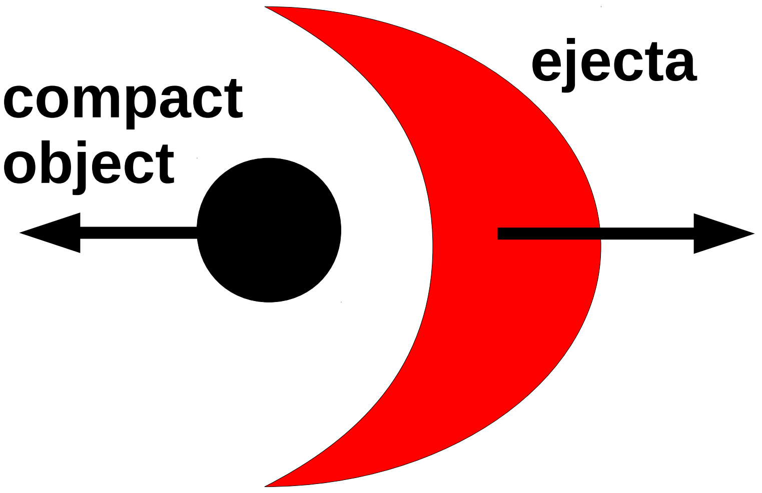
*** aligned spins unless SN reset them**

# 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**

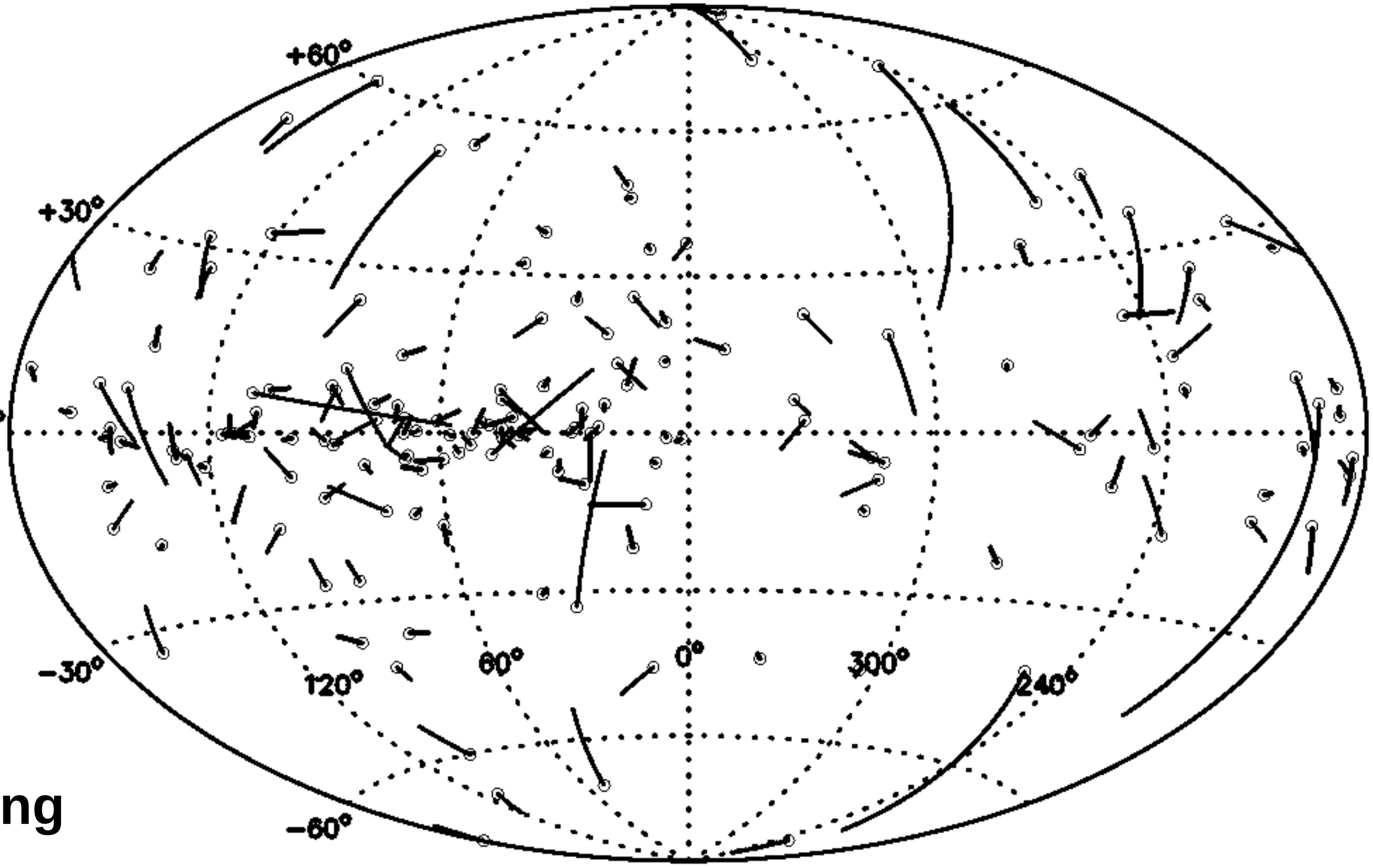
- **symmetric mass loss in a binary:**
  **breaks the binary only if pre-SN mass > companion mass**
  **(Blaauw mechanism, Blaauw 1961)**

# 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**

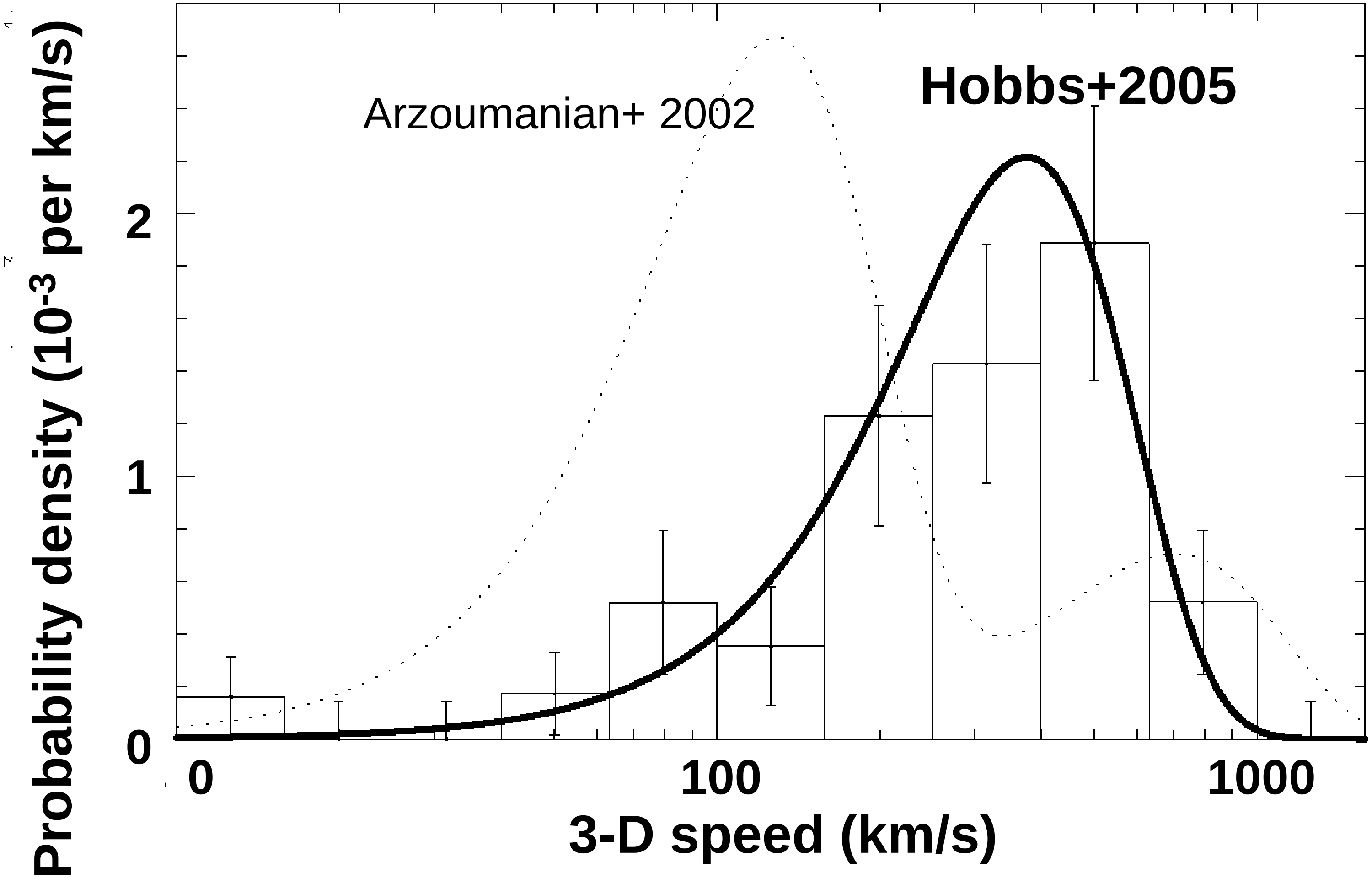
**The track is its motion for the last 1 Myr assuming no radial velocity.**

# 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**

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

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

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

# 2. Binaries of compact objects

## Isolated binary evolution summary:

* possible Roche lobe

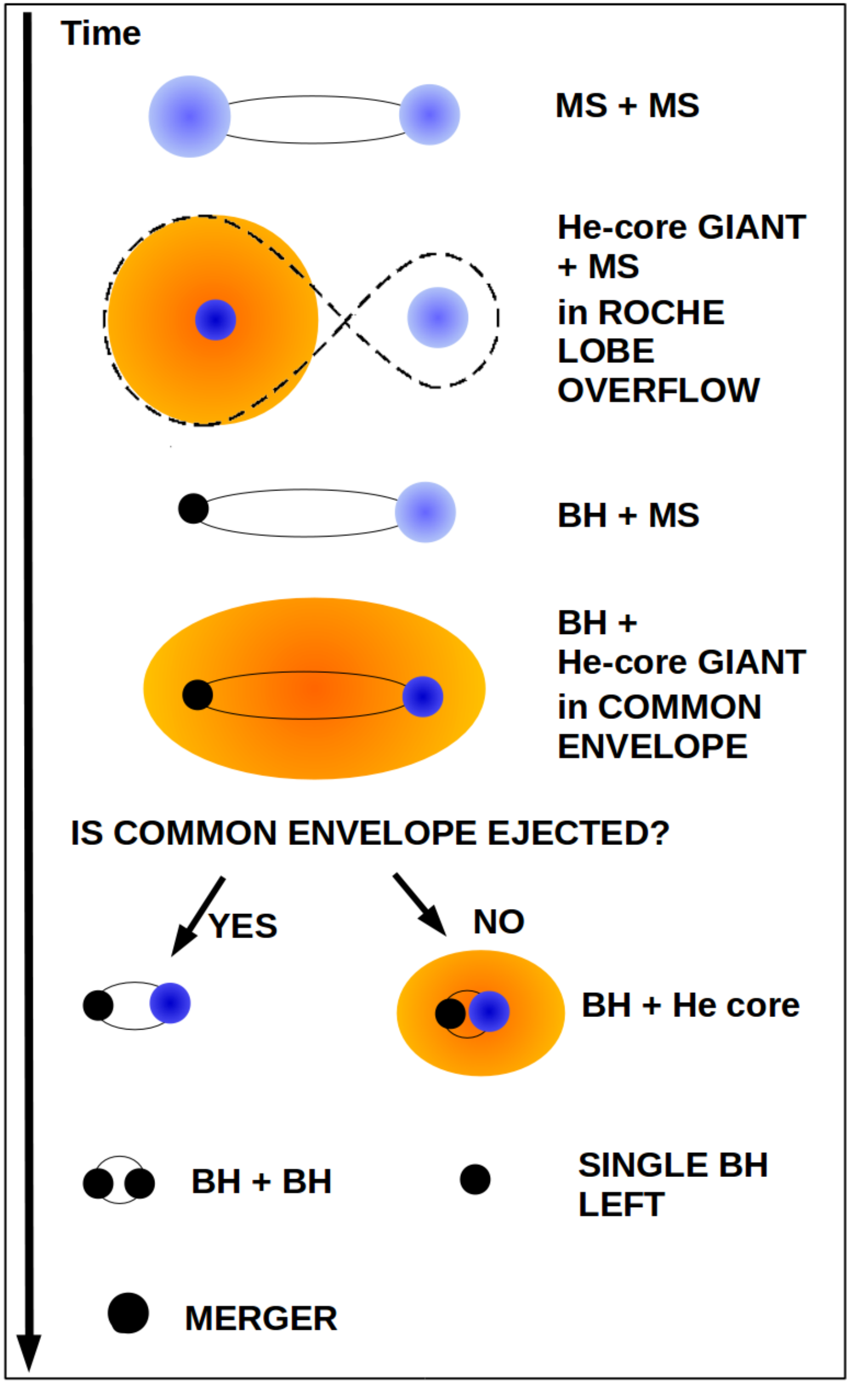
* 1st BH formation

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

* If binary survives common
envelope, formation of
second BH

* BH – BH merger

cartoon from MM2018



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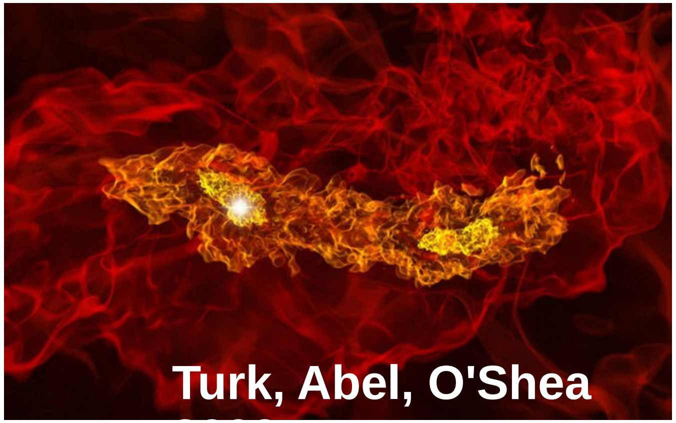
Turk, Abel, O'Shea

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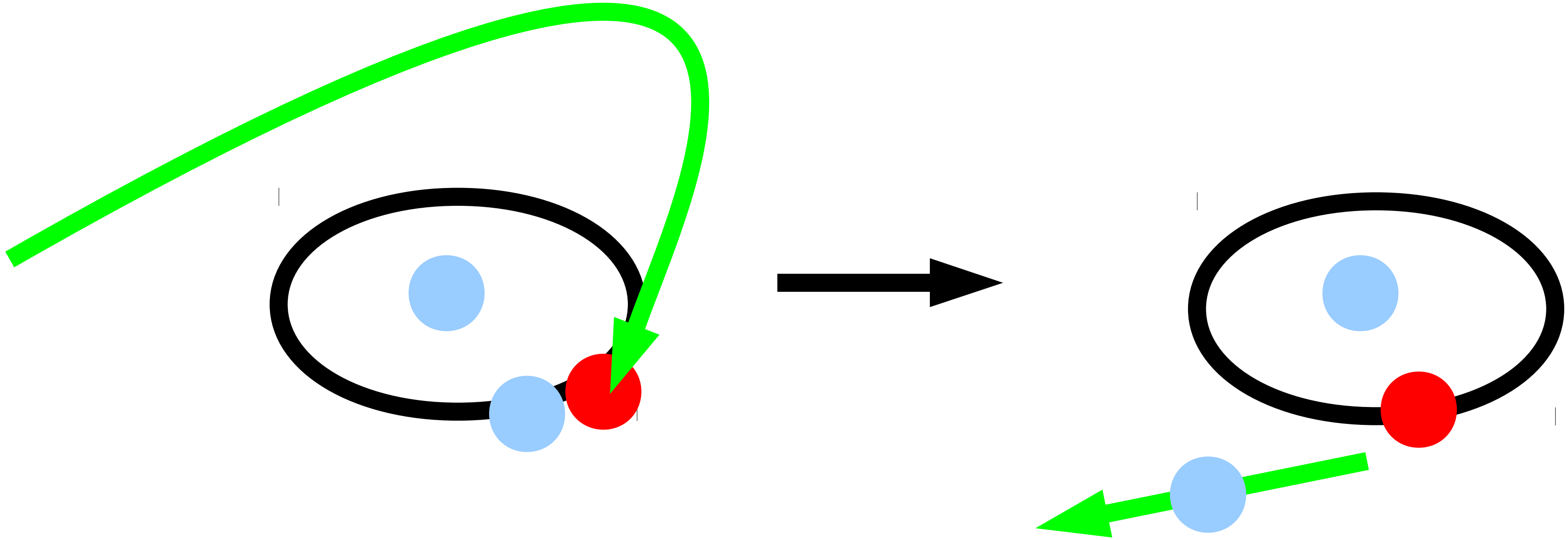


# 3. The dynamics of black hole (BH) binaries:

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

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

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

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

**R136 in the LMC**

# 3. The dynamics of BH binaries:

## WHY DYNAMICS???????

**Massive stars
(BH progenitors)
form in
STAR CLUSTERS**

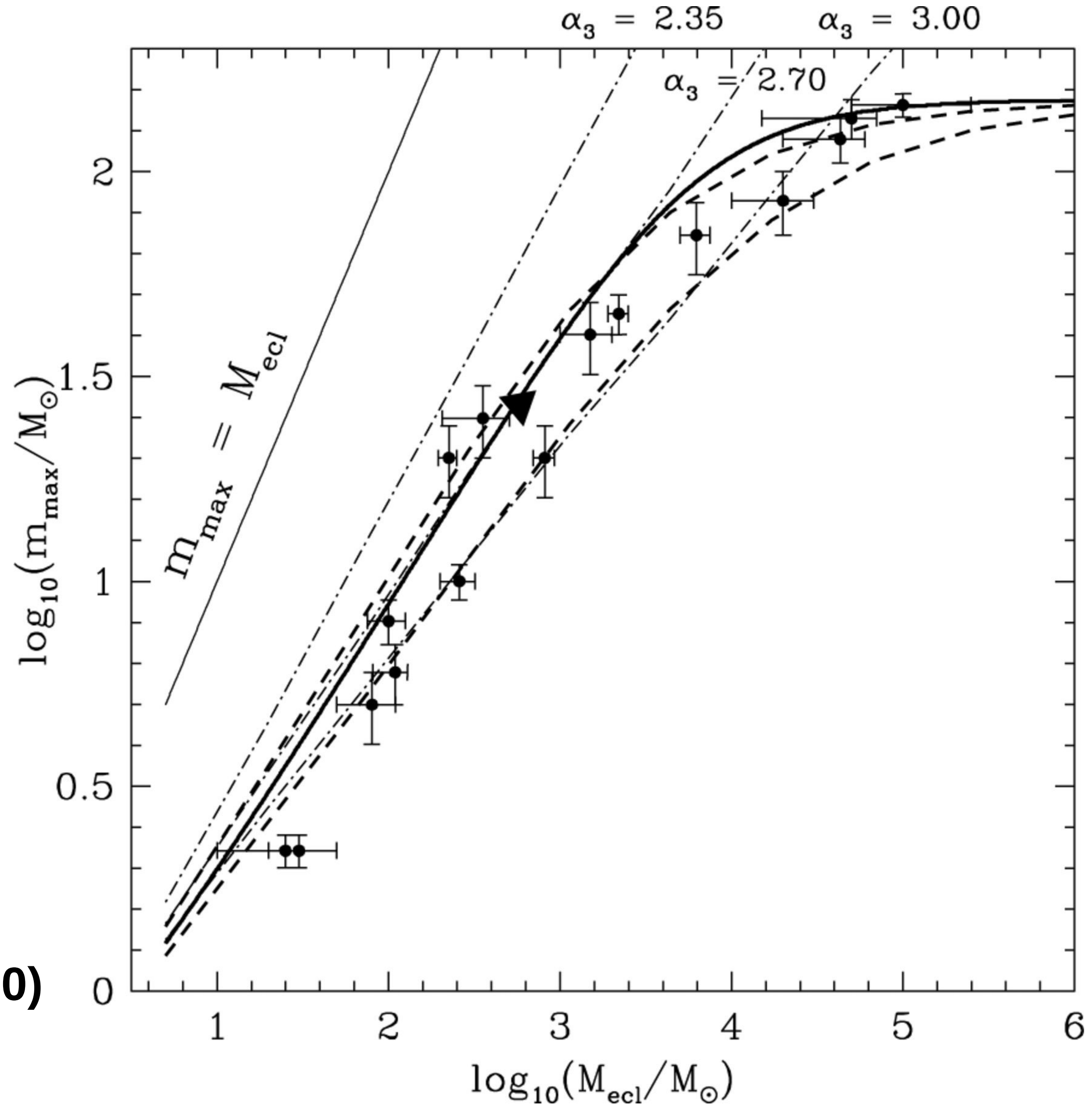


**Figure from
Weidner & Kroupa (2006)**

**Data points:
observed star clusters**

**Lines: theoretical fits**

**See also
Weidner, Kroupa & Bonnell (2010)**

# 3. The dynamics of BH binaries:

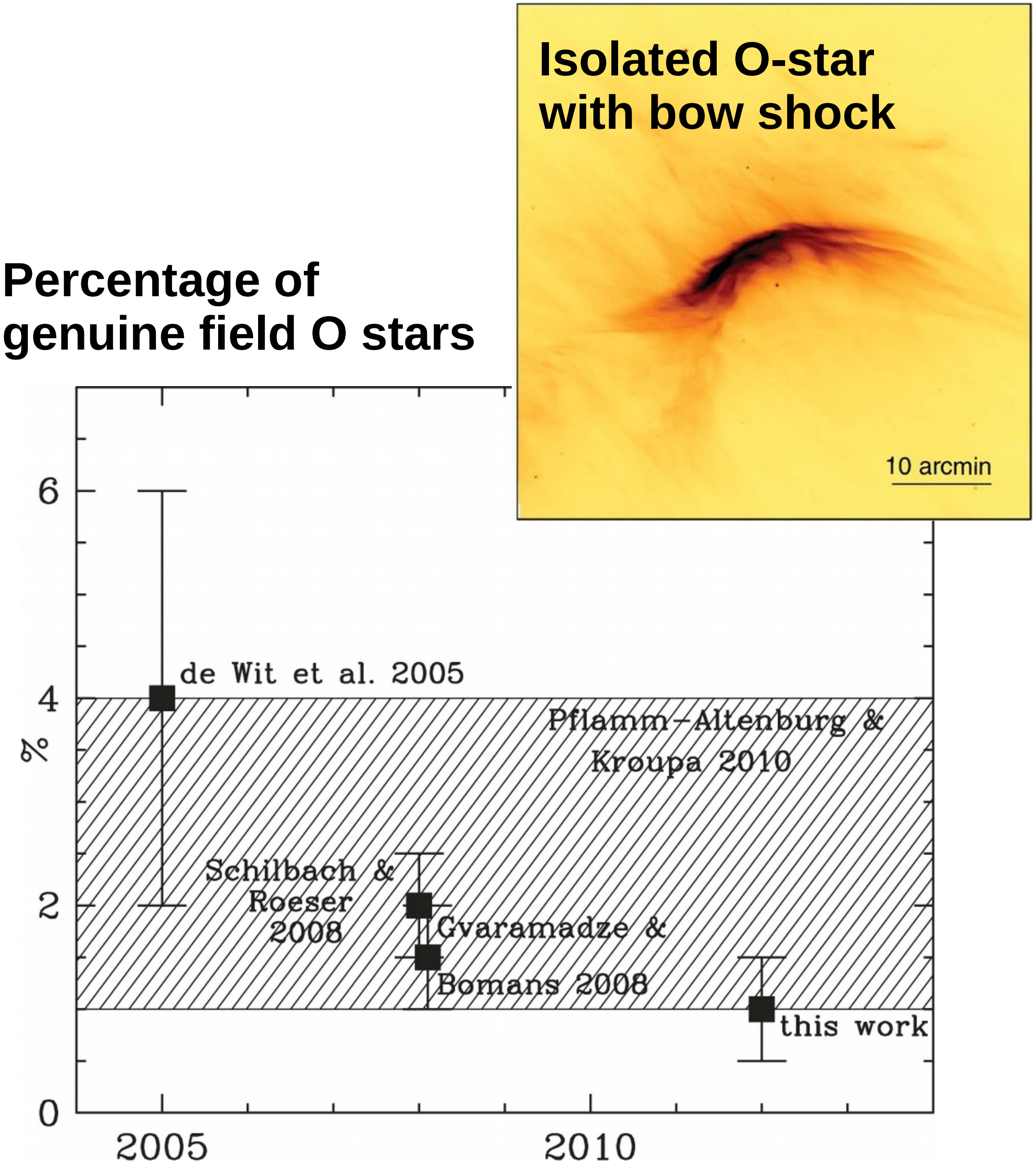
## WHY DYNAMICS????????

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

**Figures from Gvaramadze et al. (2012)**

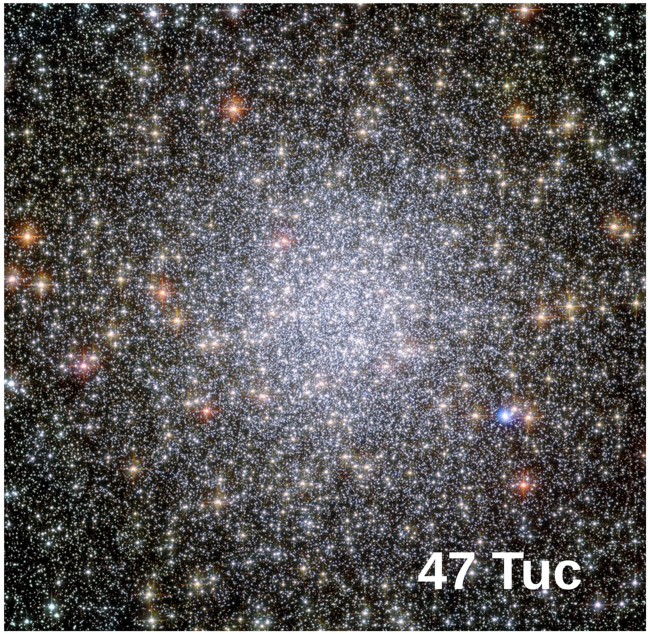
**See also**
**De Wit et al. (2004, 2005)**
**Schilbach & Roeser (2008)**

**Percentage of genuine field O stars**



# 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)

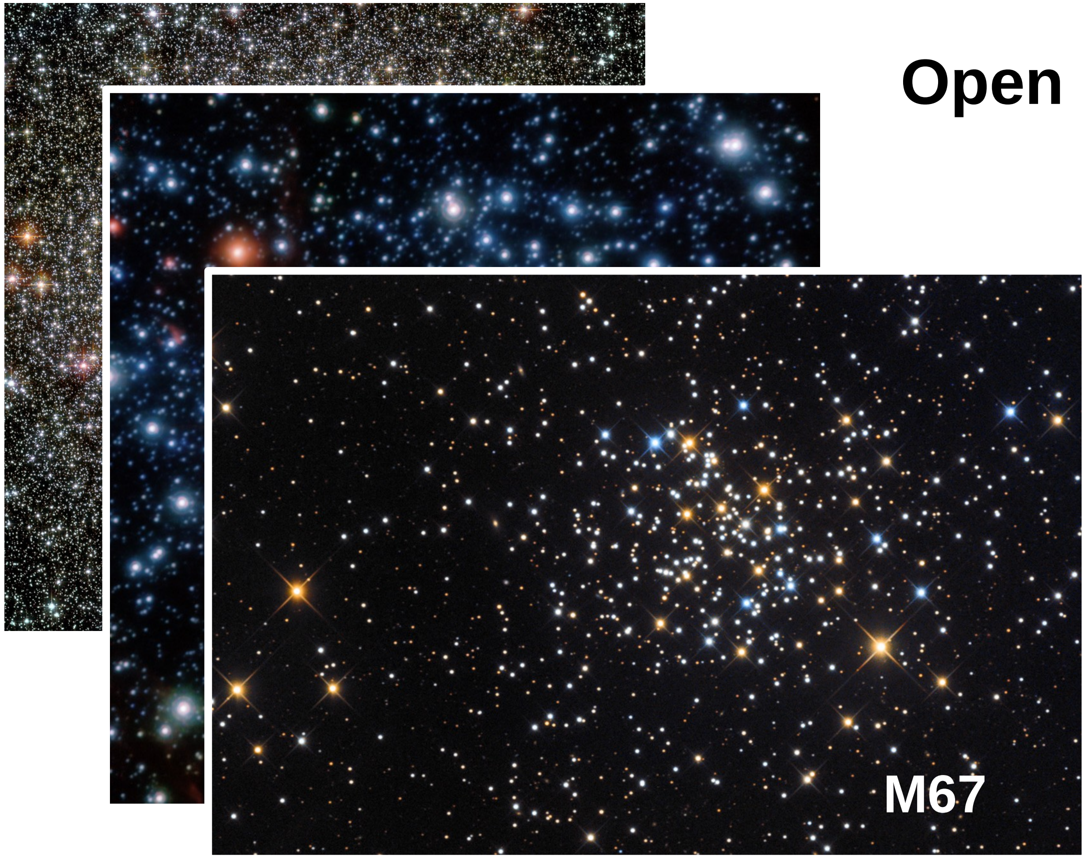
✔ Long lived

✔ Very massive ($>10^6\ M_\odot$)

✔ Sometimes coexist with super-massive black hole (eg in the Milky Way)

# 3. The dynamics of BH binaries:

**There are many different flavours of star clusters**

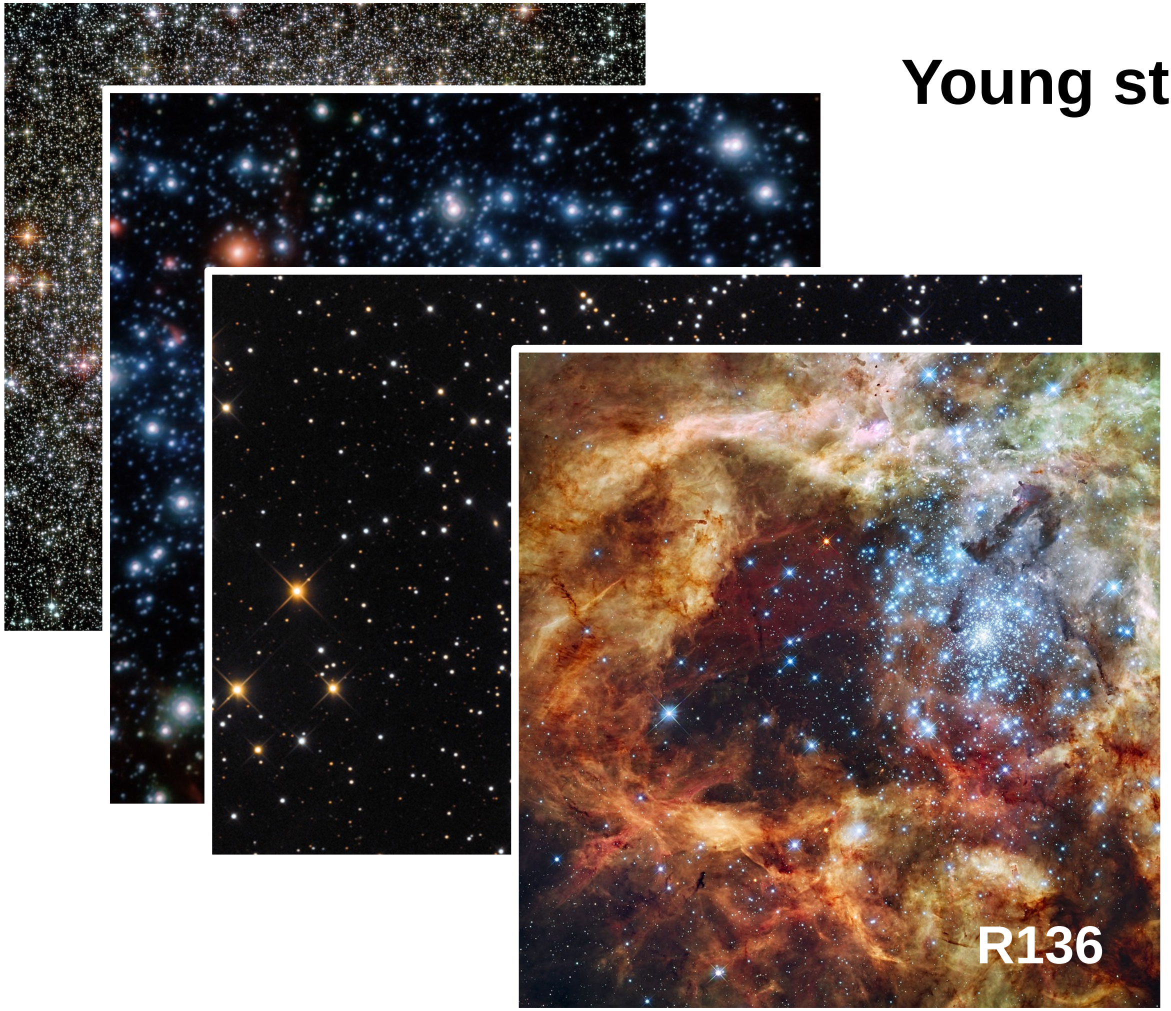


## Open clusters

- ✔ Age from few Myr to several Gyr
- ✔ Single-age stars
- ✔ Not so long lived:
  when they die they release stellar content in the field
  → building blocks of field
- ✔ Lower mass ($10^{2-5}\,M_\odot$)

# 3. The dynamics of BH binaries:

**There are many different flavours of star clusters**

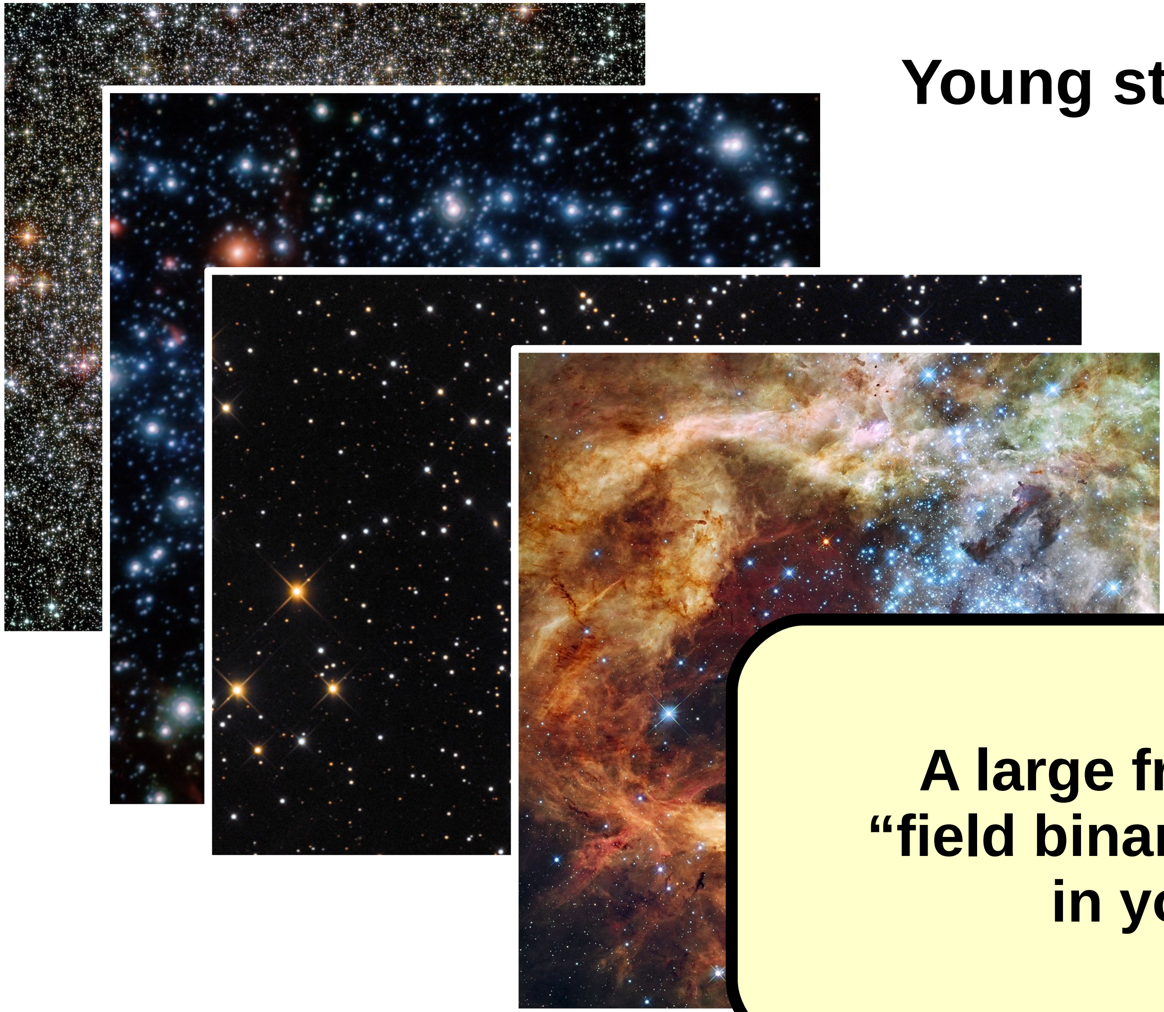


## Young star clusters

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

# 3. The dynamics of BH binaries:

There are many different flavours of star clusters



Young star clusters

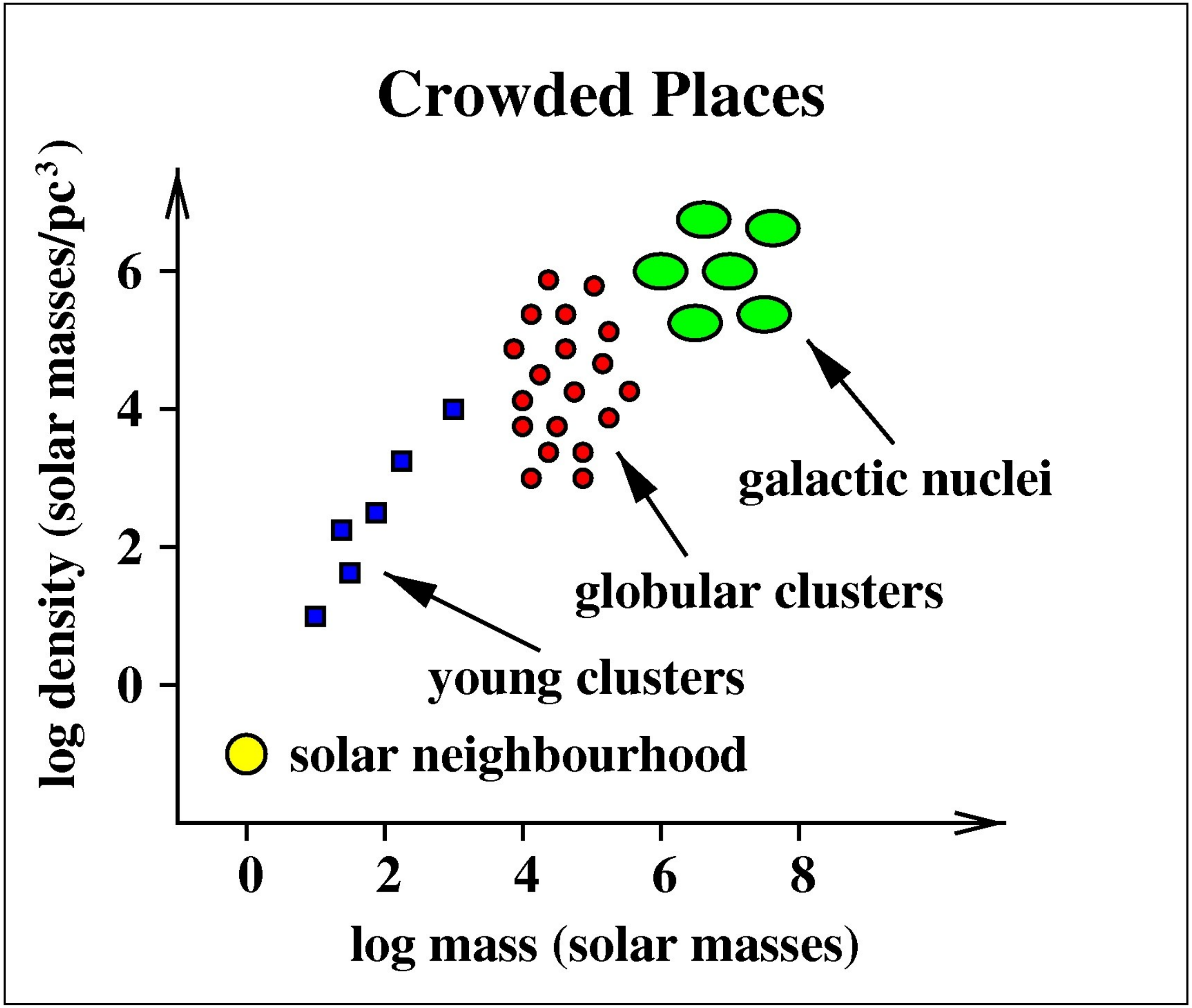
A large fraction of what we call “field binaries” might have formed in young star clusters

# 3. The dynamics of BH binaries:

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

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

**Stars and binaries**
**undergo close**
**encounters**
**between each other**



M. B. Davies 2002

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

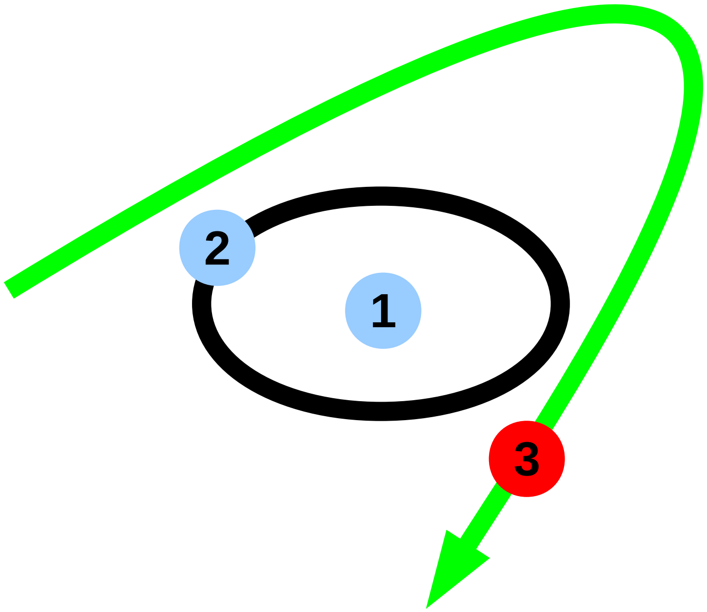
## Binaries have a energy reservoir (internal energy)

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

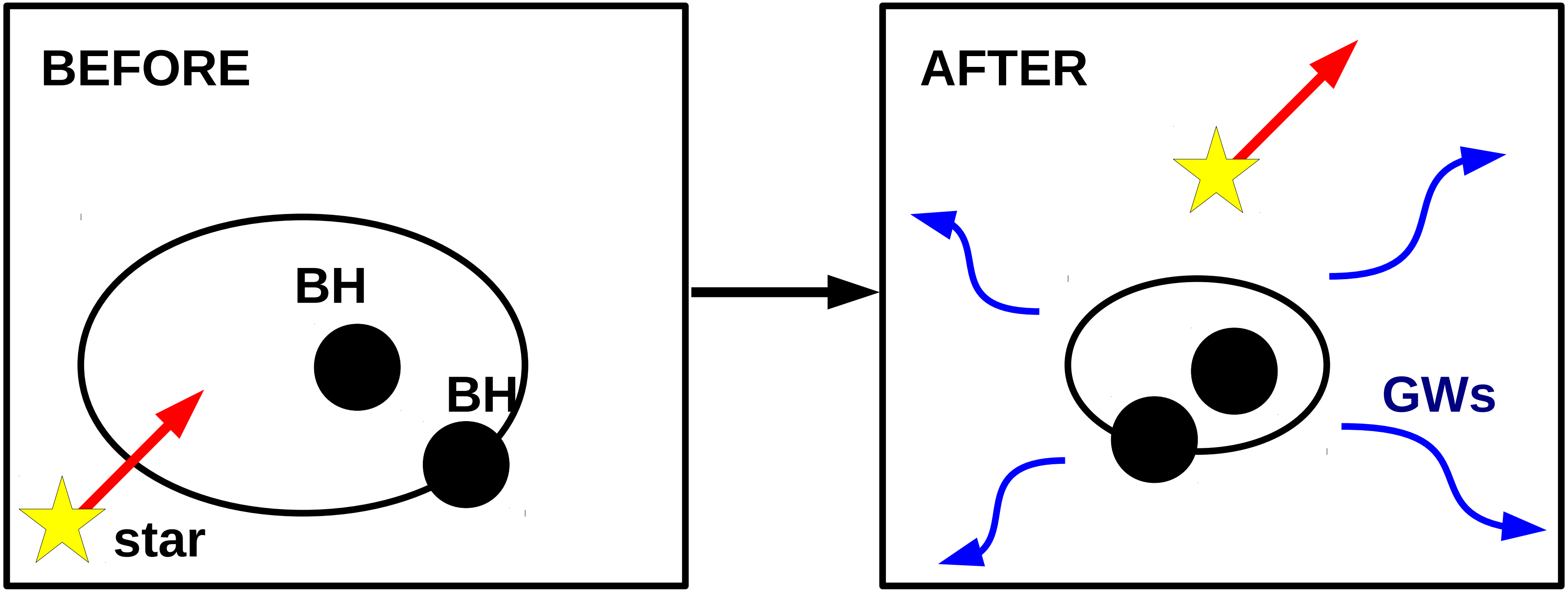
where $m_1$ and $m_2$ are the mass of the primary and secondary member of the binary,
$\mu$ is the reduced mass (:= $m_1\,m_2/(m_1+m_2)$), $r$ and $v$ are the relative separation and velocity.

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

***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

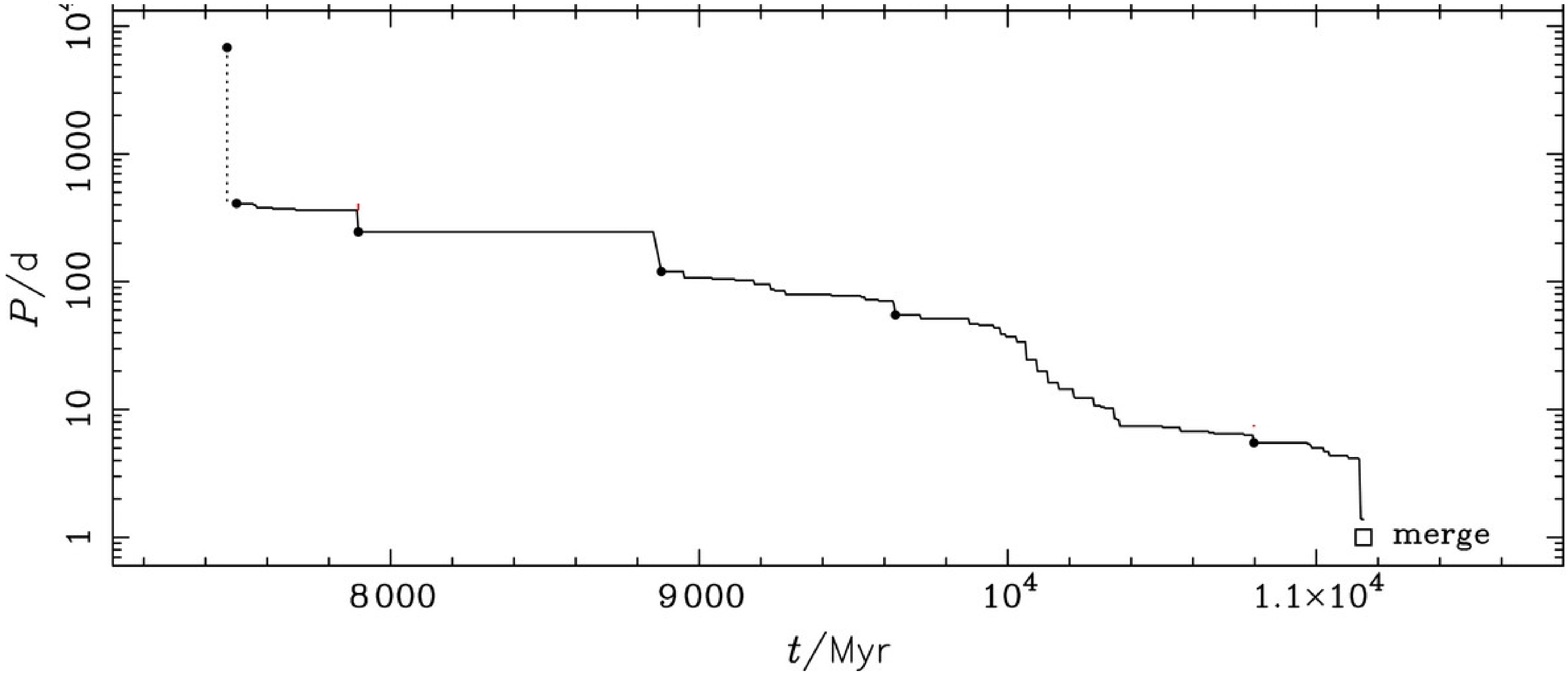


***In a flyby, the star acquires kinetic energy from the binary***

→ ***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**

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

**GRAVITATIONAL WAVE (GW) TIMESCALE (Peters 1964)**

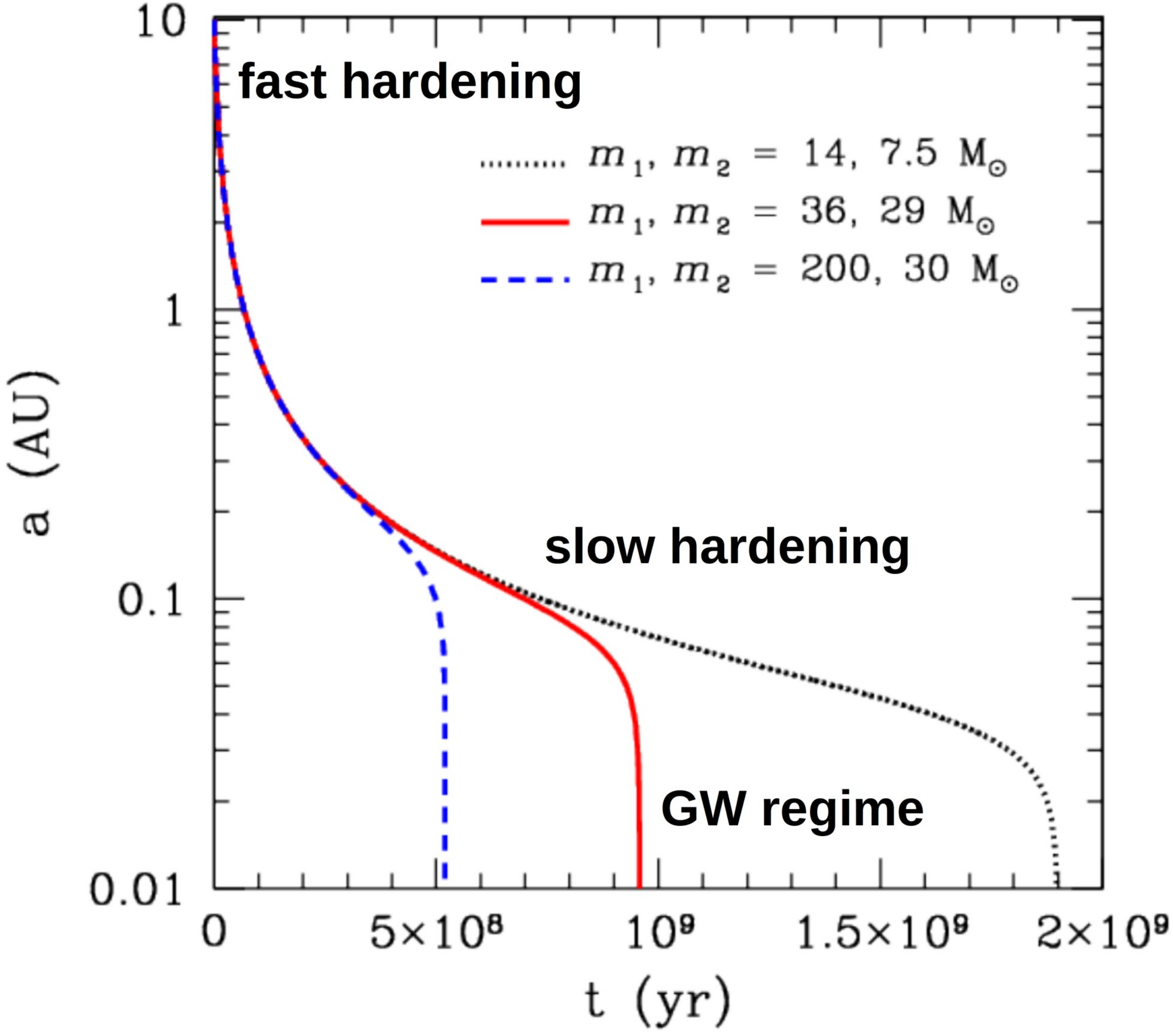
$$\boxed{t_{GW} = \frac{5}{256}\,\frac{c^5\,a^4\,\left(1-e^2\right)^{7/2}}{G^3\,m_1\,m_2\,(m_1+m_2)}}$$

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

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

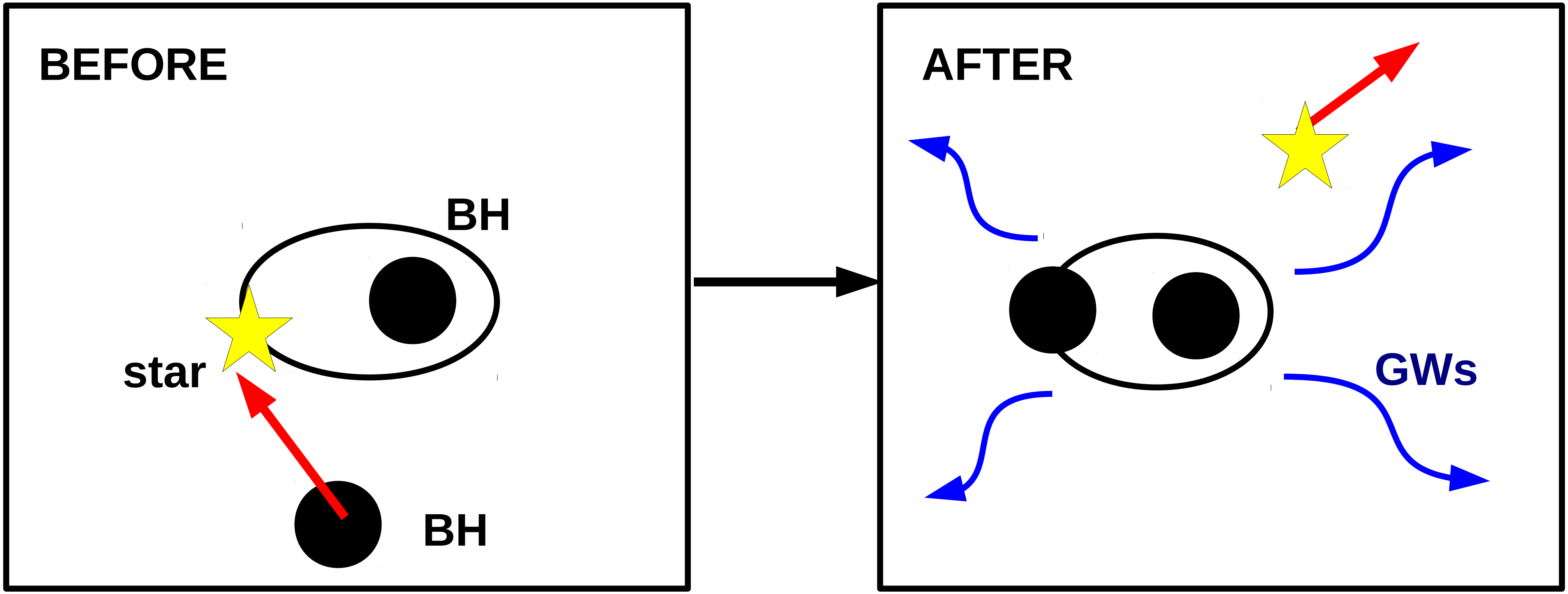
# 3. The dynamics of stellar BH binaries: FLYBYs

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



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

# 3. The dynamics of stellar BH binaries: EXCHANGEs



***Exchanges bring BHs in binaries***

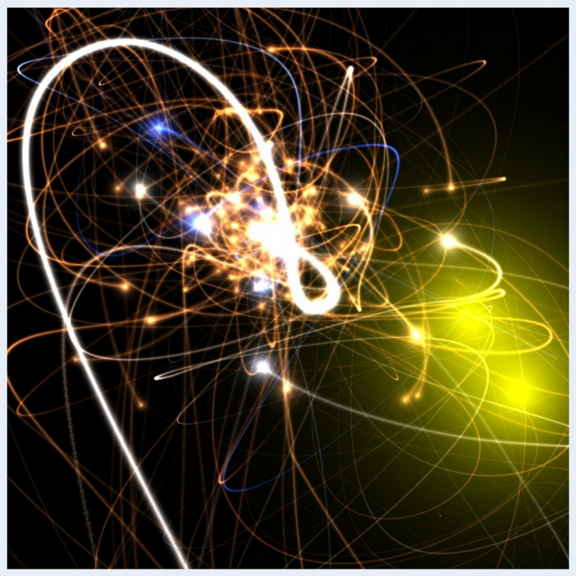
***BHs are FAVOURED BY EXCHANGES BECAUSE THEY ARE MASSIVE!***

***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):

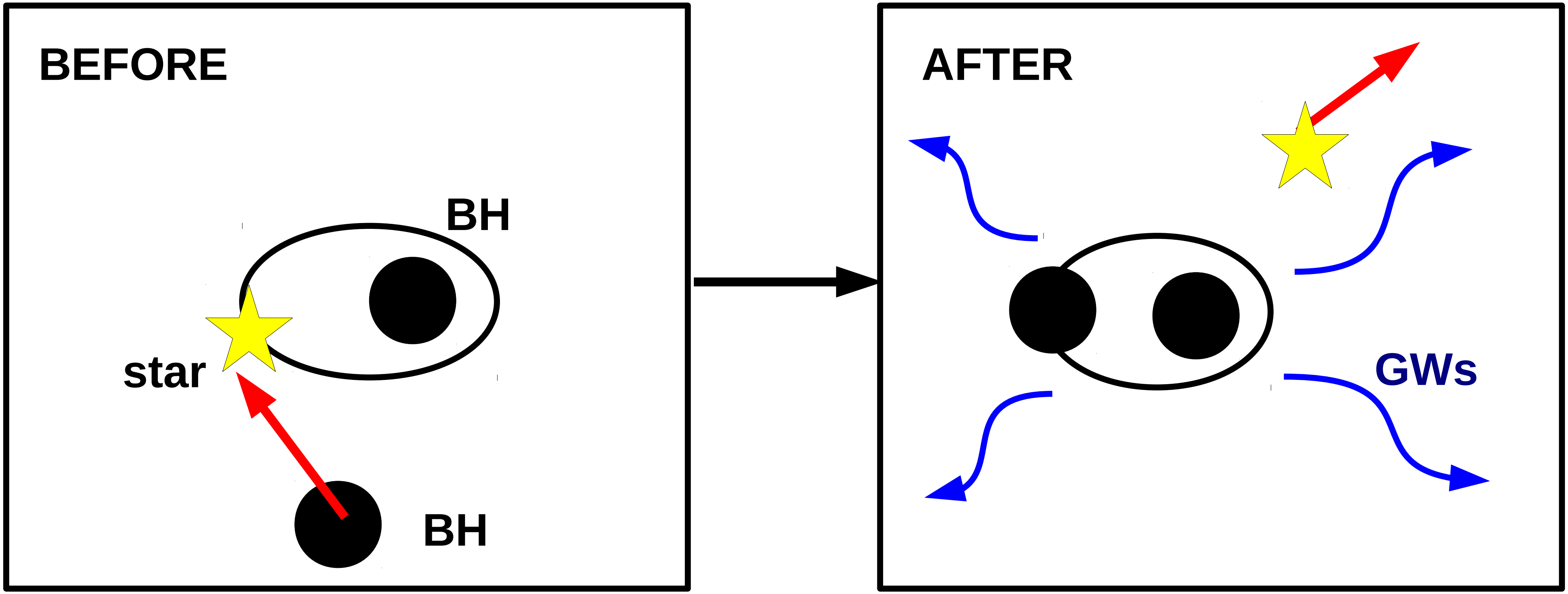


**Movie 2 :** binary – single interaction
ciera.northwestern.edu/Research/visualizations/videos/Binary+single.mp4

**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*

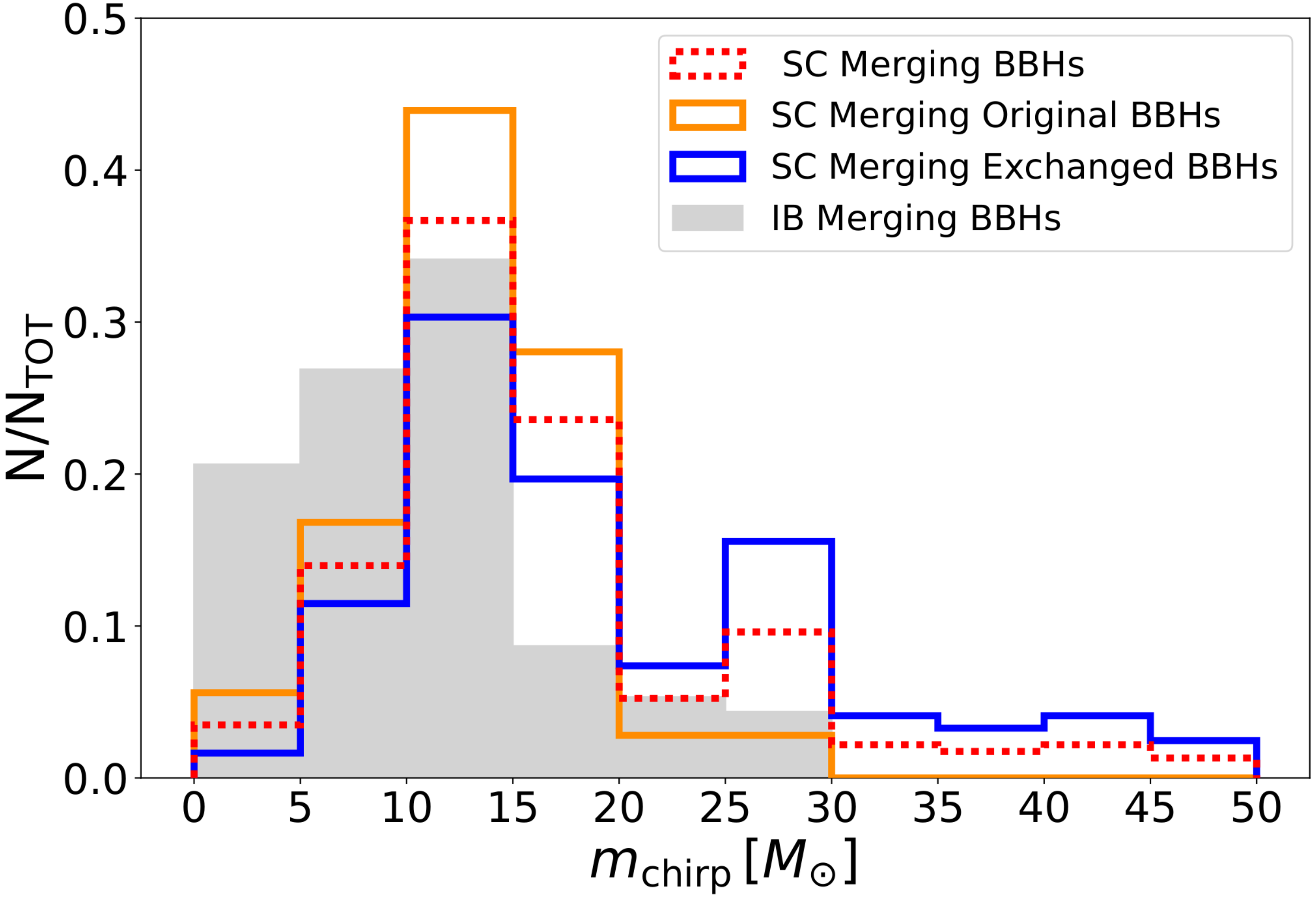
*(Ziosi, MM+ 2014, MNRAS, 441, 3703)*

*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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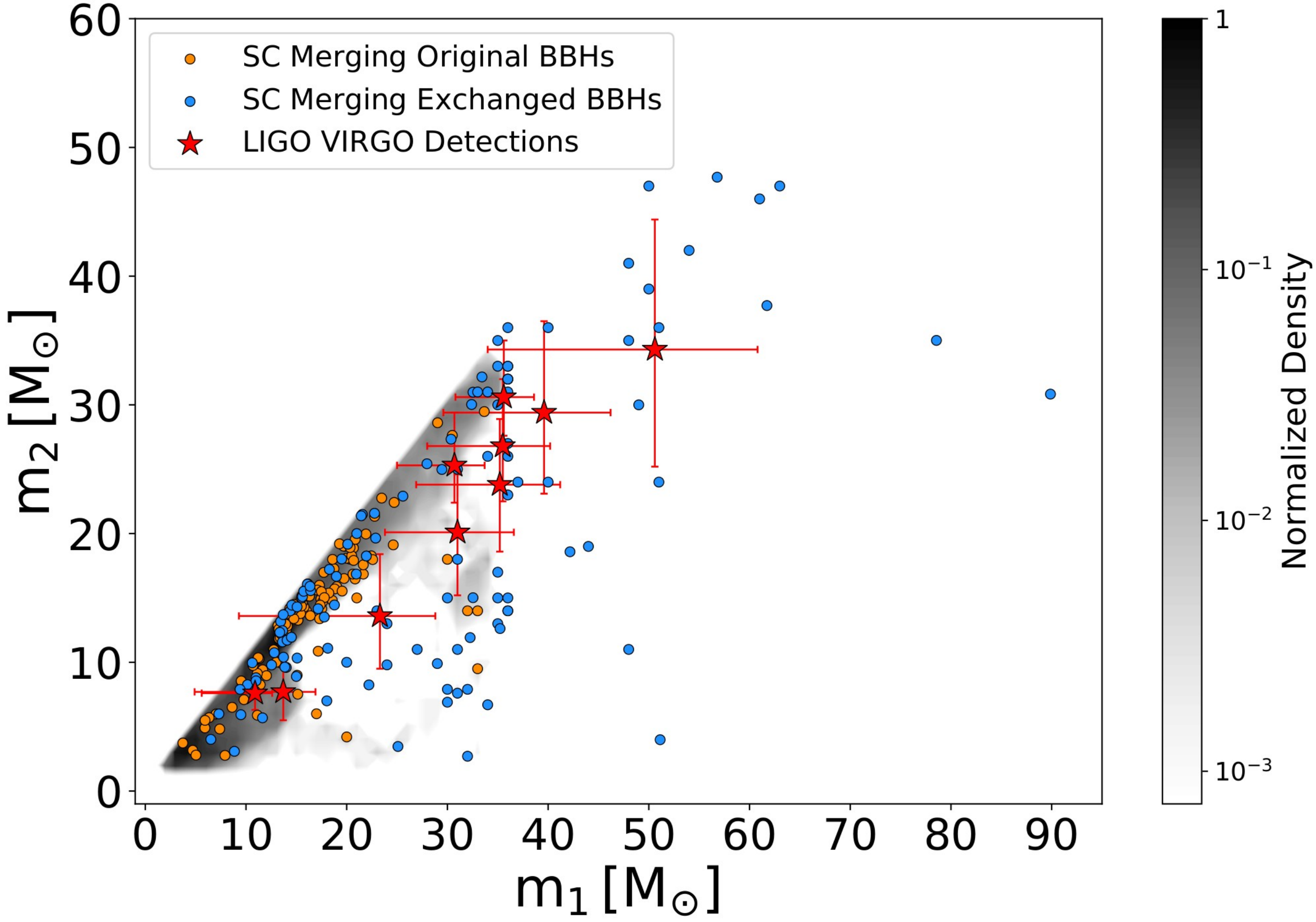

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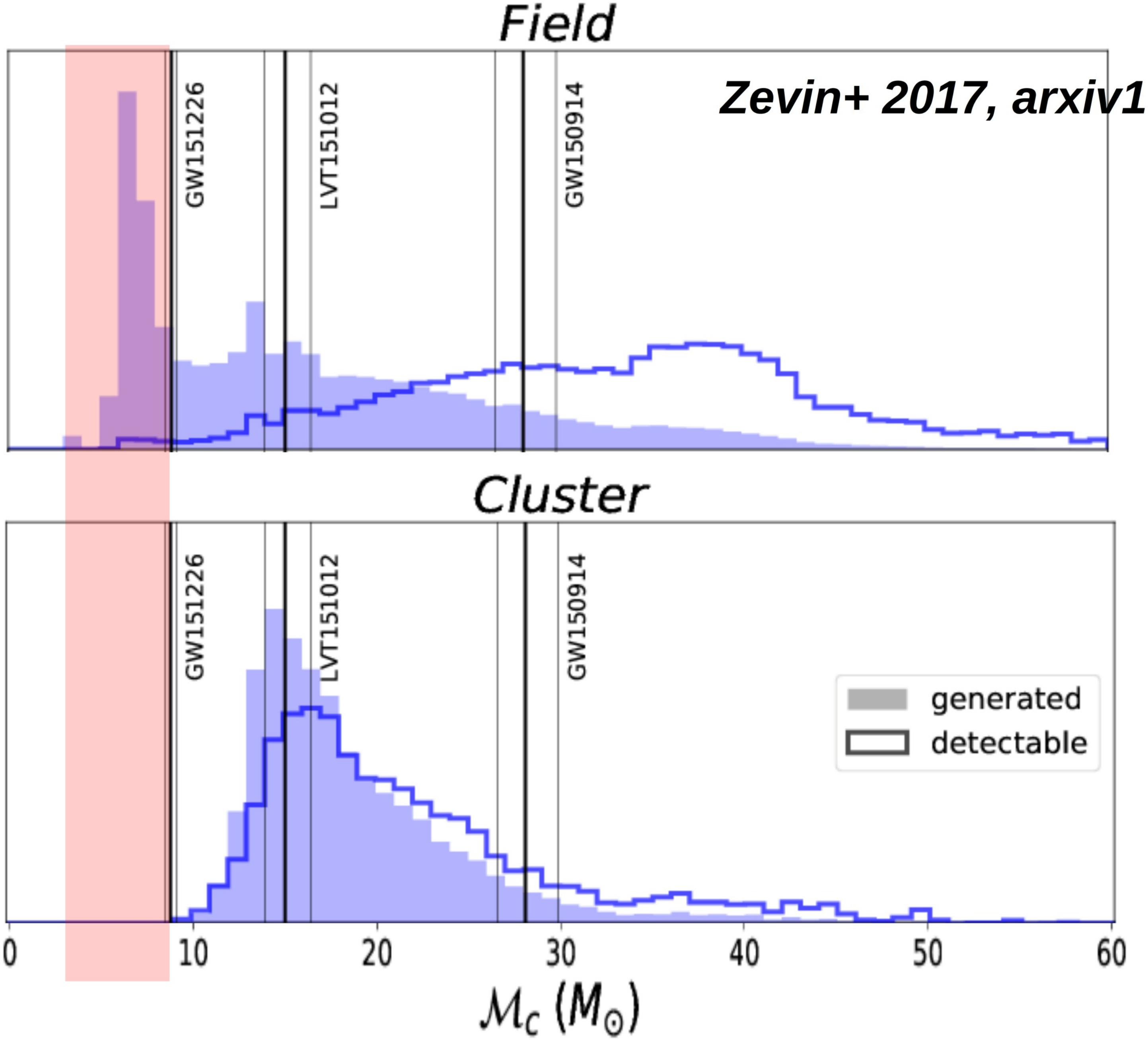
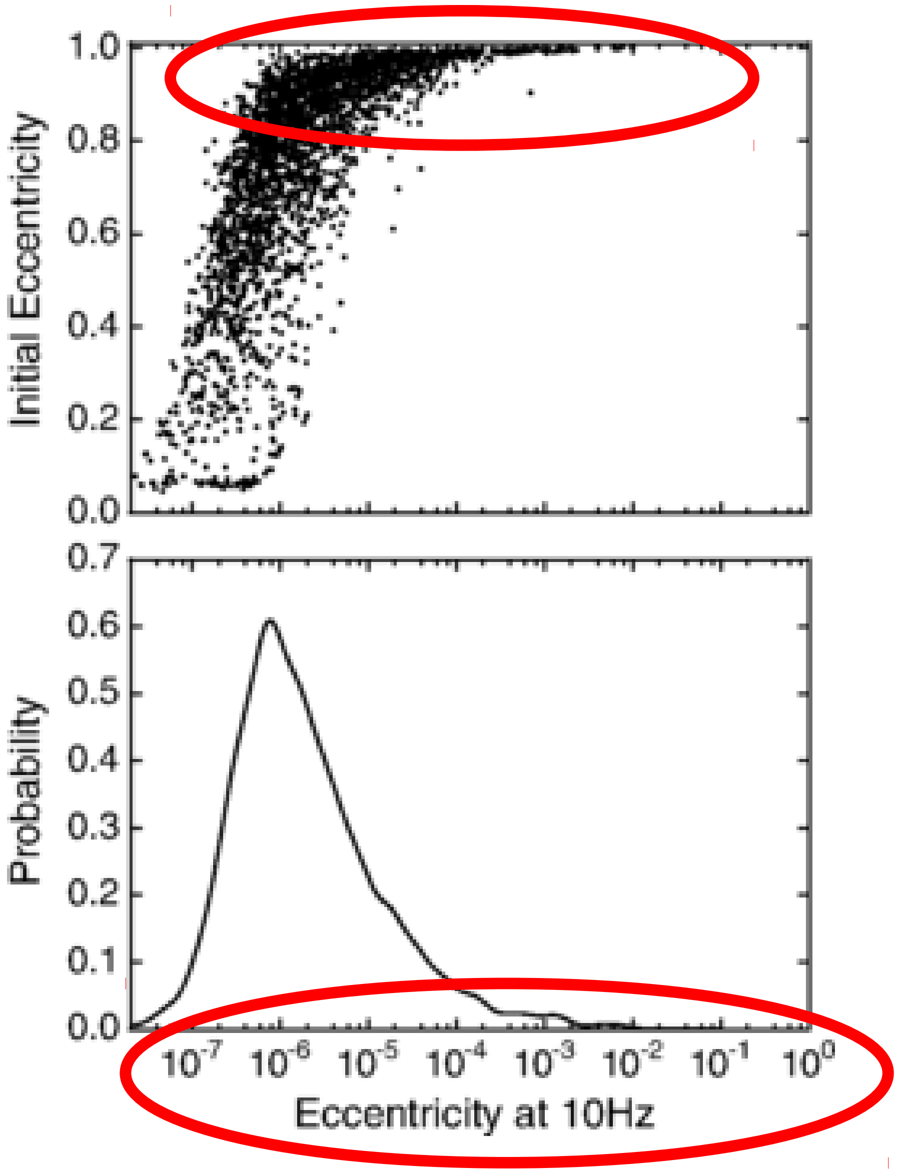
# 3. The dynamics of stellar BH binaries: MASSEs



***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: ECCENTRICITY



***Rodriguez+ 2016, PhRvD, 93, 4029***

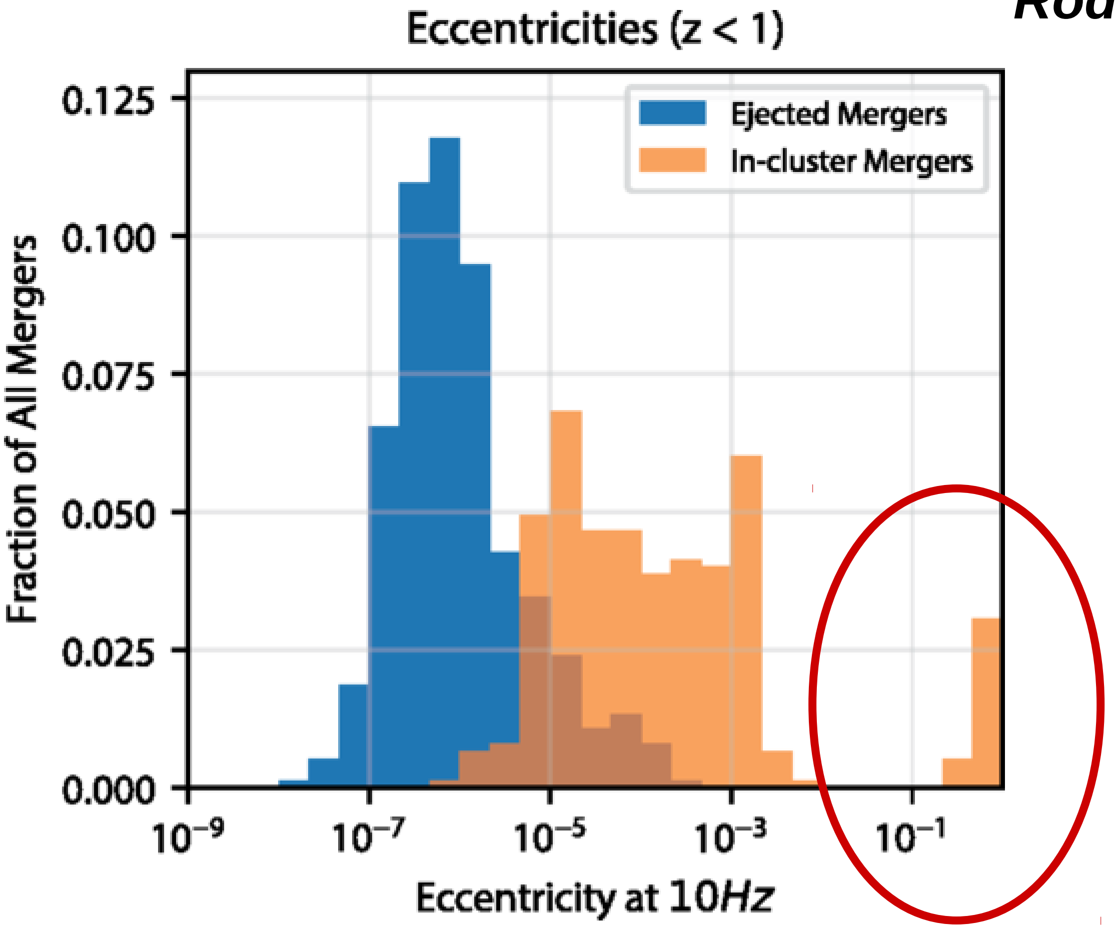
**Initial eccentricity of ejected BBHs is very high**

**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*



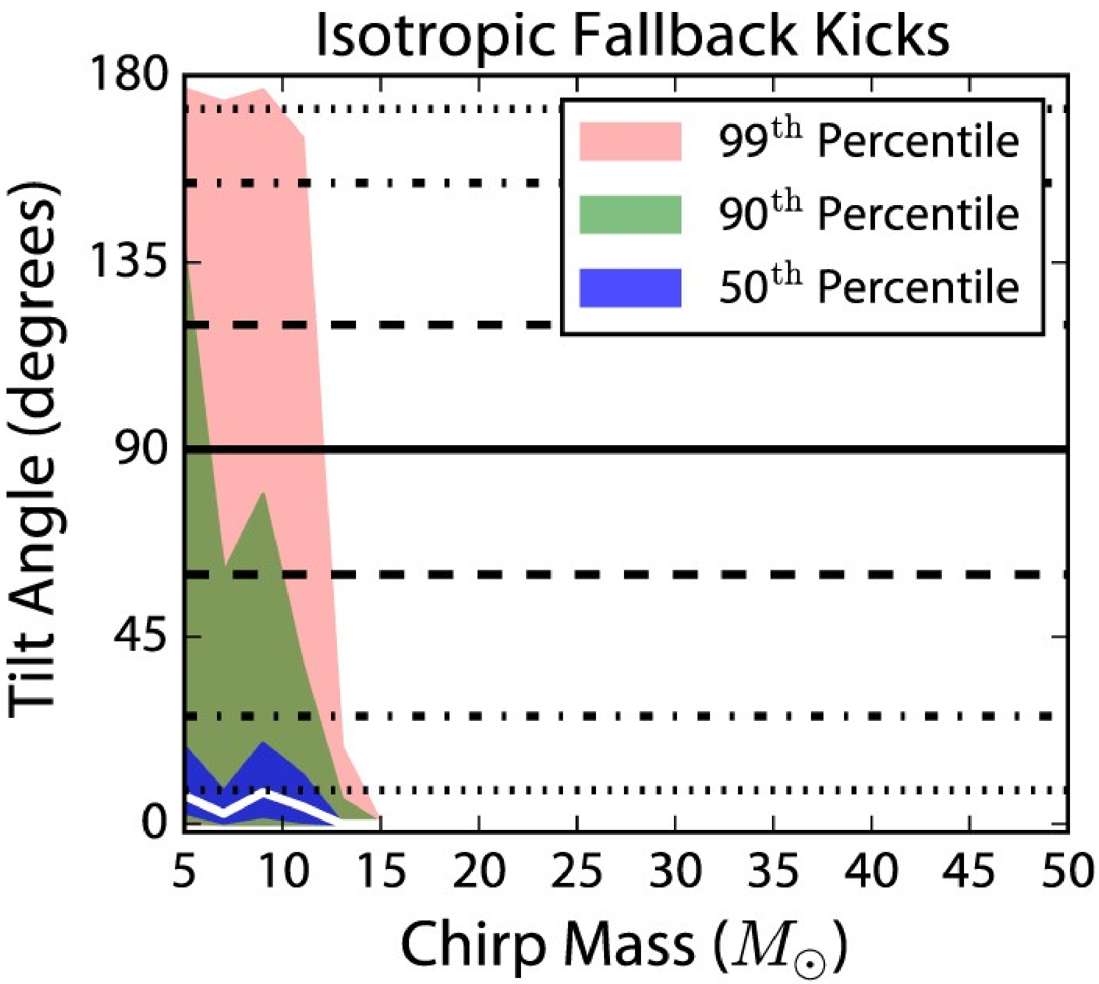
**Initial eccentricity of ejected BBHs is very high**

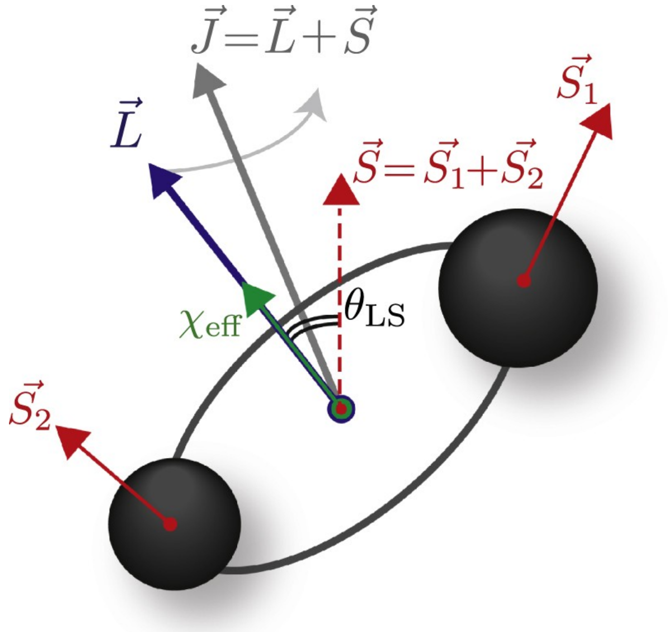
**Even eccentricity in LIGO-Virgo band is non zero for a number of systems**

**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





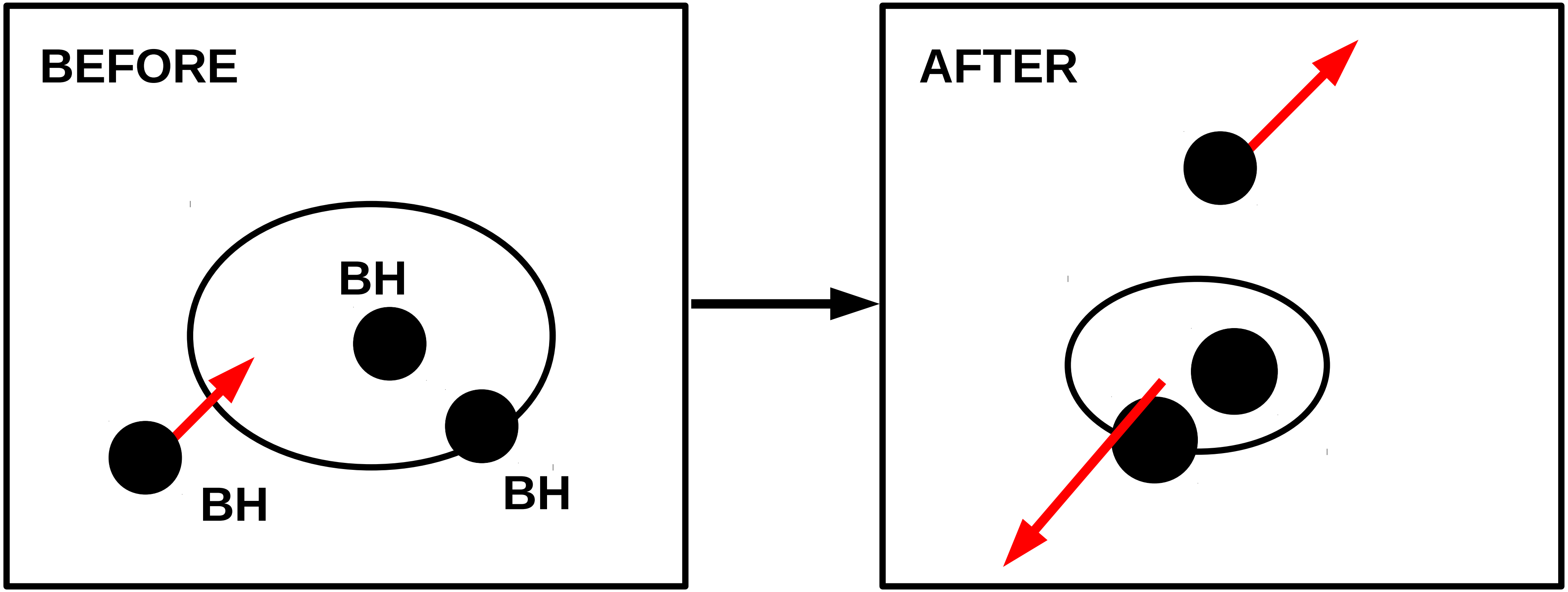
**Colours: isolated BBHs**
**Dark horizontal lines: dynamically formed BBHs**

**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: ejections



**Internal energy is extracted from the binary**

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

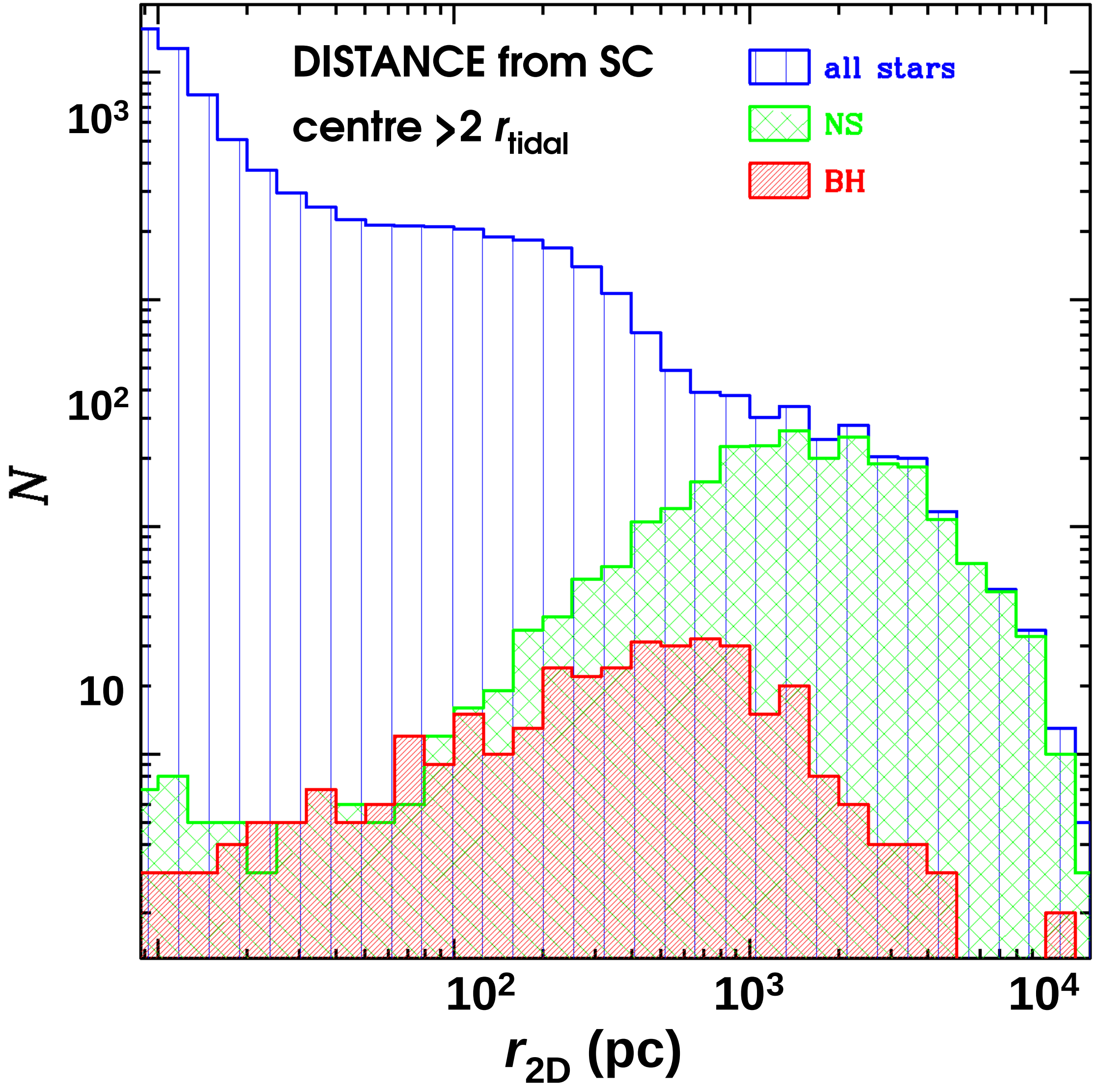
→ **BOTH RECOIL and can be ejected from SC**

**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)**

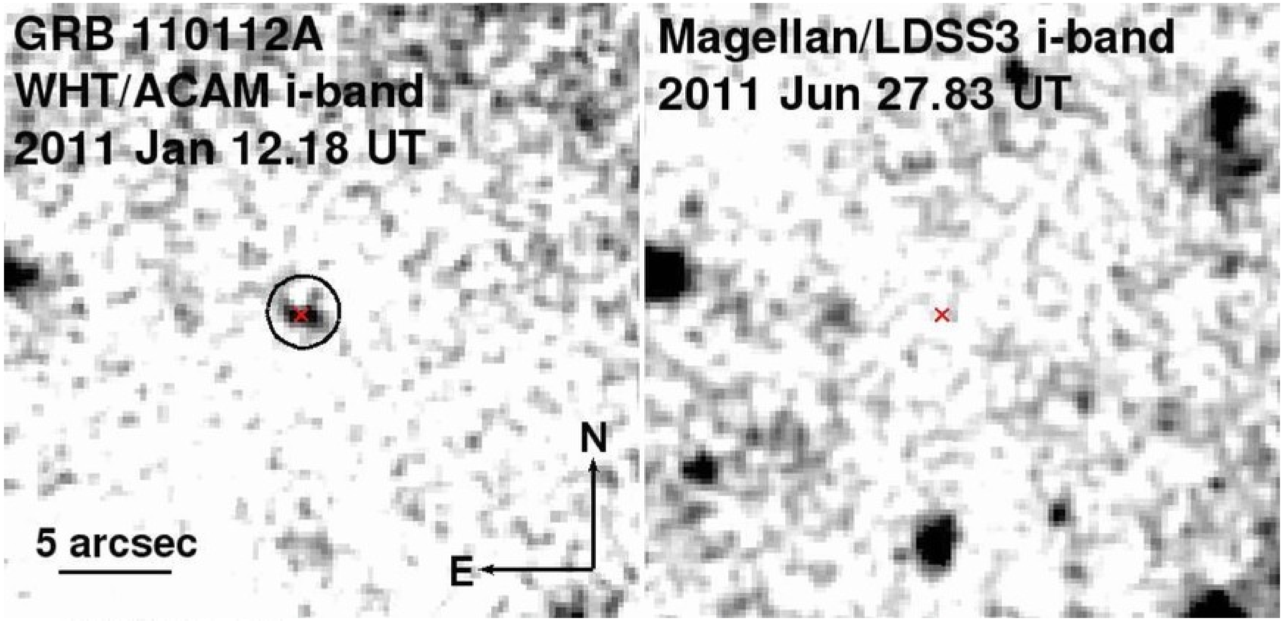
**~40% BH is ejected (1/2 by SN, 1/2 by 3body)**

**PREDICTED MERGERS OCCUR MOSTLY IN THE FIELD**

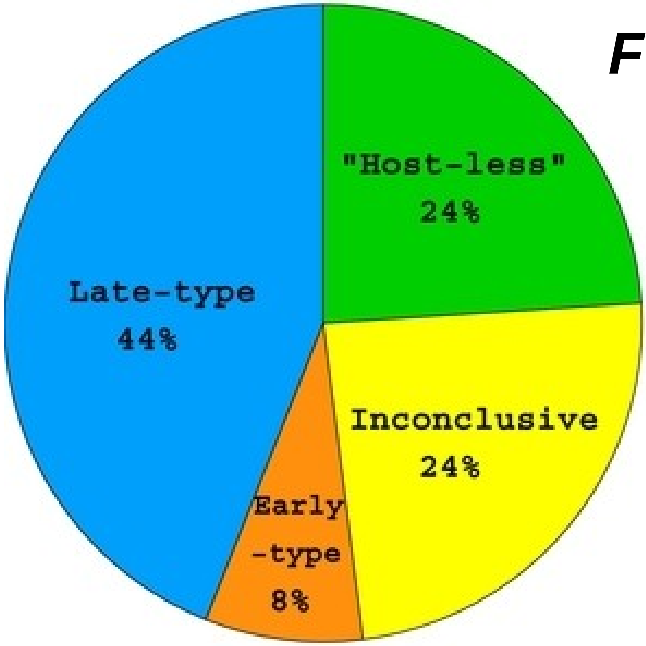
*Downing+ 2011, MNRAS, 416, 133*
*MM + 2013, MNRAS, 429, 2298*

# 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: Spitzer’s instability

## SPITZER’S INSTABILITY OR MASS STRATIFICATION INSTABILITY:

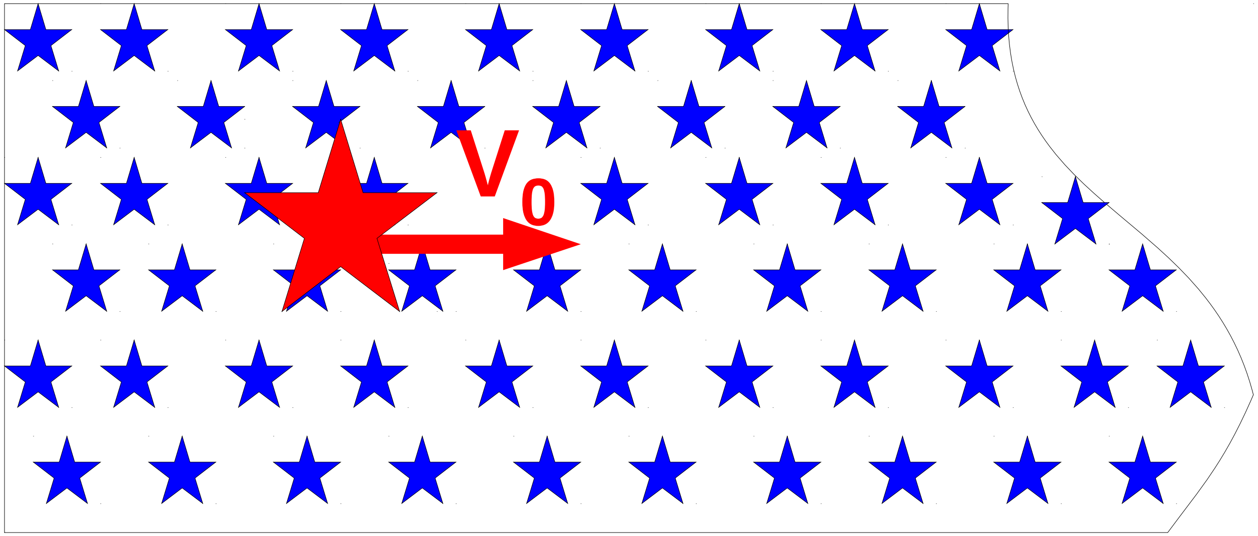
**IT IS NOT ALWAYS POSSIBLE TO REACH EQUIPARTITION in a STAR CLUSTER (Spitzer 1969)**

1. What does it mean?
2. What are the effects on BHs?

# 3. The dynamics of stellar BH binaries: Spitzer's instability

## DYNAMICAL FRICTION TIMESCALE

**A body of mass *M*, traveling through an infinite & homogeneous sea of bodies (mass *m*) suffers a steady deceleration: the dynamical friction**



**infinite & homogeneous sea:** otherwise the body M would be deflected

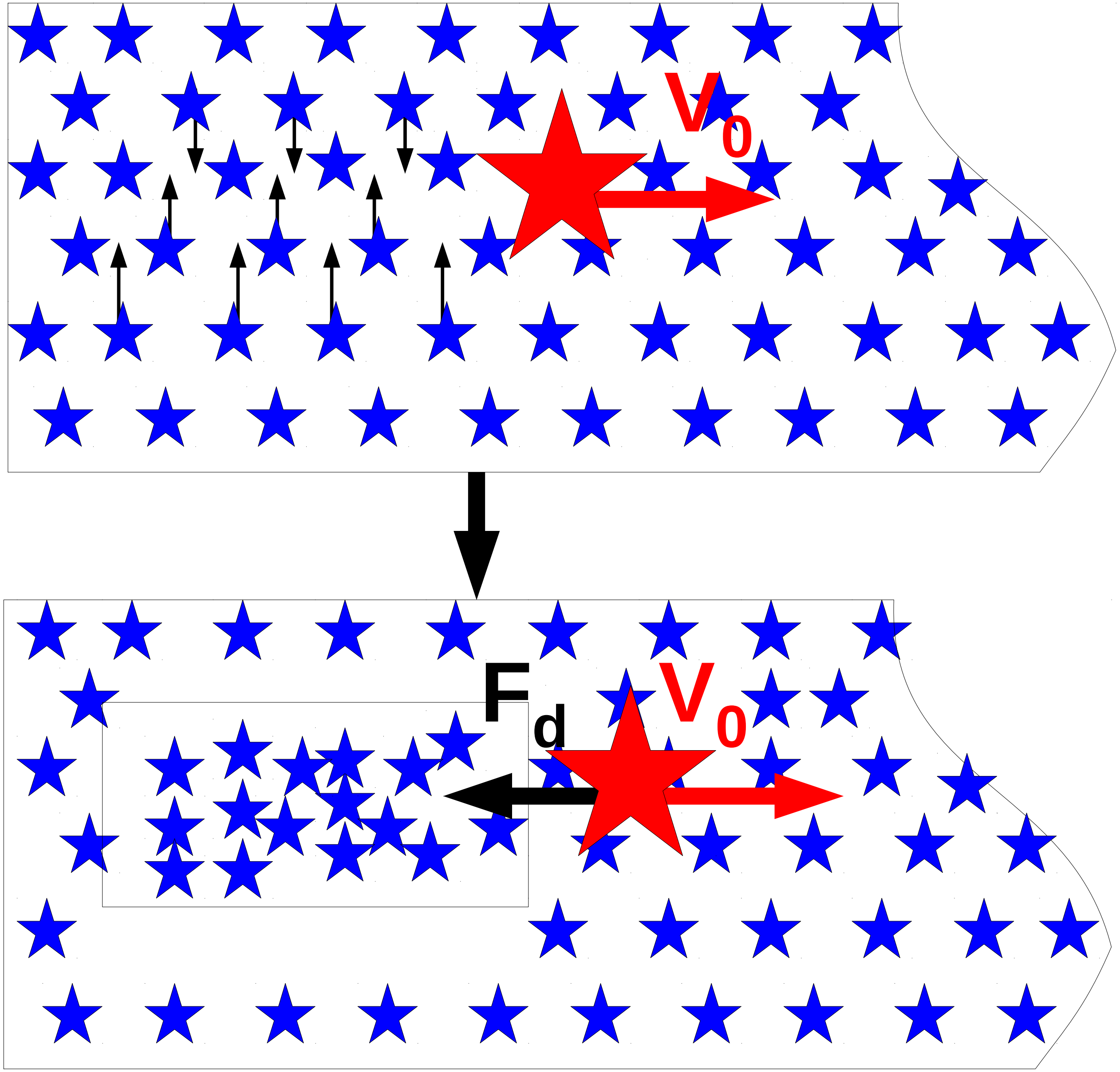
The sea exerts a force **parallel and opposite** to the velocity $V_0$ of the body

It can be shown that DYNAMICAL FRICTION TIMESCALE is

$$t_{df} = \frac{3}{4\,(2\,\pi)^{1/2}\,G^2\,\ln\Lambda}\,\frac{\sigma^3(r)}{M\,\rho(r)}$$

# 3. The dynamics of stellar BH binaries: Spitzer’s instability

## DYNAMICAL FRICTION TIMESCALE



The heavy body *M* attracts the lighter particles.

When lighter particles approach, the body *M* has already moved and leaves a local overdensity behind it.

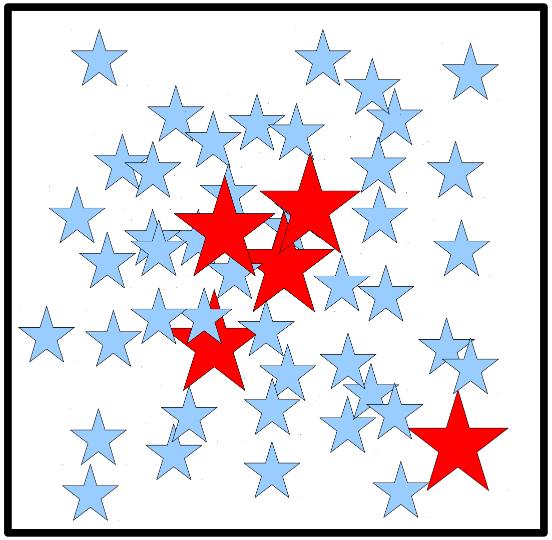
The overdensity attracts the heavy body (with force $F_d$) and slows it down.

3. The dynamics of stellar BH binaries: Spitzer’s instability

# MASS SEGREGATION:

Dynamical friction leads MASSIVE STARS
to SLOW DOWN wrt light stars

→ MASSIVE STARS SINK to the CENTRE of
the CLUSTER (= centre of the potential well)



The result is a cluster where the relative frequency
of massive stars is higher in the core
than in the outskirts:

a MASS STRATIFIED or MASS SEGREGATED cluster

<u>BOTTOM LINE: mass segregation indicates the state of the cluster</u>

<u>The physical process driving mass segregation is dynamical friction</u>

# 3. The dynamics of stellar BH binaries: Spitzer's instability

## EQUIPARTITION

**Theorem of statistical mechanics (Boltzmann 1876):**

**If a system of ideal gas particles is in thermal equilibrium, energy is shared equally by all particles**

**Stellar systems can be considered the same as gas particles if temperature is defined as**

$$\frac{1}{2}\,m\,\langle v^2\rangle = \frac{3}{2}\,\kappa_B\,T$$

**EQUIPARTITION for stellar systems:** if a stellar system is in thermal equilibrium, **PARTICLES TEND TO HAVE THE SAME KINETIC ENERGY**

# 3. The dynamics of stellar BH binaries: Spitzer's instability

## EQUIPARTITION

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**EQUIPARTITION for stellar systems:** if a stellar system is in thermal equilibrium, **PARTICLES TEND TO HAVE THE SAME KINETIC ENERGY**

**If particles have different masses:** $m_i\,\langle v_i^2\rangle = m_j\,\langle v_j^2\rangle$

$$\boxed{\text{if}\quad m_i > m_j \Rightarrow \langle v_i^2\rangle < \langle v_j^2\rangle}$$

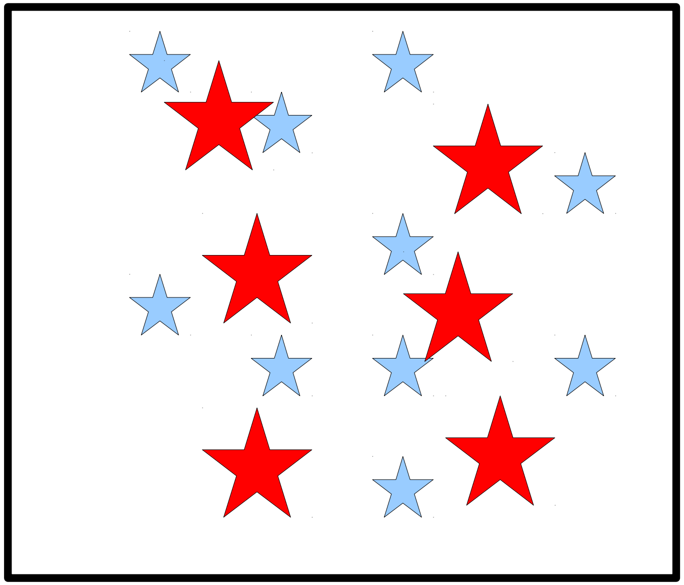
During two-body encounters, massive stars transfer kinetic energy to light stars. Massive stars slow down, light stars move to higher velocities.

# 3. The dynamics of stellar BH binaries: Spitzer’s instability

## SPITZER’S INSTABILITY

***It is not always possible to reach equipartition in a multi-mass system.***

*Let us suppose that there are two populations with two different masses:*



$$m_2 > m_1$$

★ *HEAVY POPULATION*
$m_2$ *(total mass* $M_2$*)*

☆ *LIGHT POPULATION*
$m_1$ *(total mass* $M_1$*)*

$$M_2 \sim M_1$$

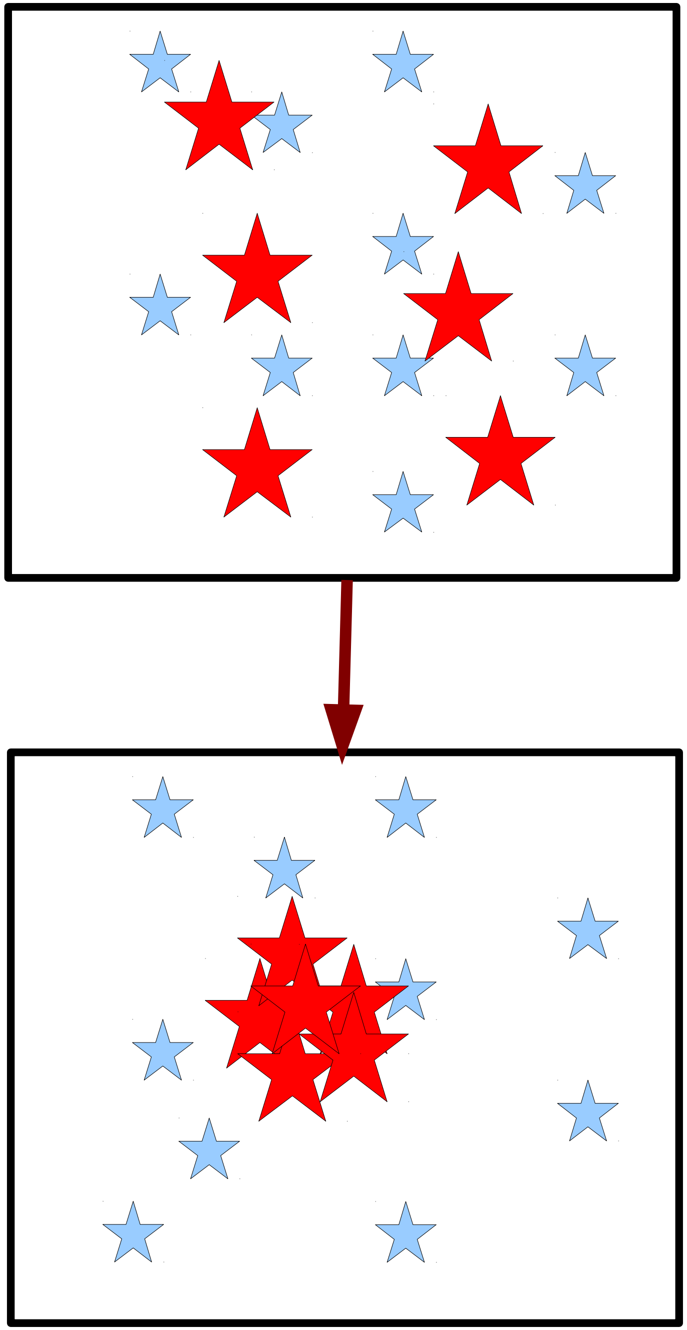
*If the total mass of the heavy population is similar to the total mass of the light population, equipartition is not possible:*

$$M_2 \langle v_2^2 \rangle >> M_1 \langle v_1^2 \rangle$$

*THE LIGHT POPULATION CANNOT ABSORB ALL THE KINETIC ENERGY THAT MUST BE TRANSFERRED FROM THE HEAVY POPULATION TO REACH EQUIPARTITION*

# 3. The dynamics of stellar BH binaries: Spitzer’s instability

## SPITZER’S INSTABILITY



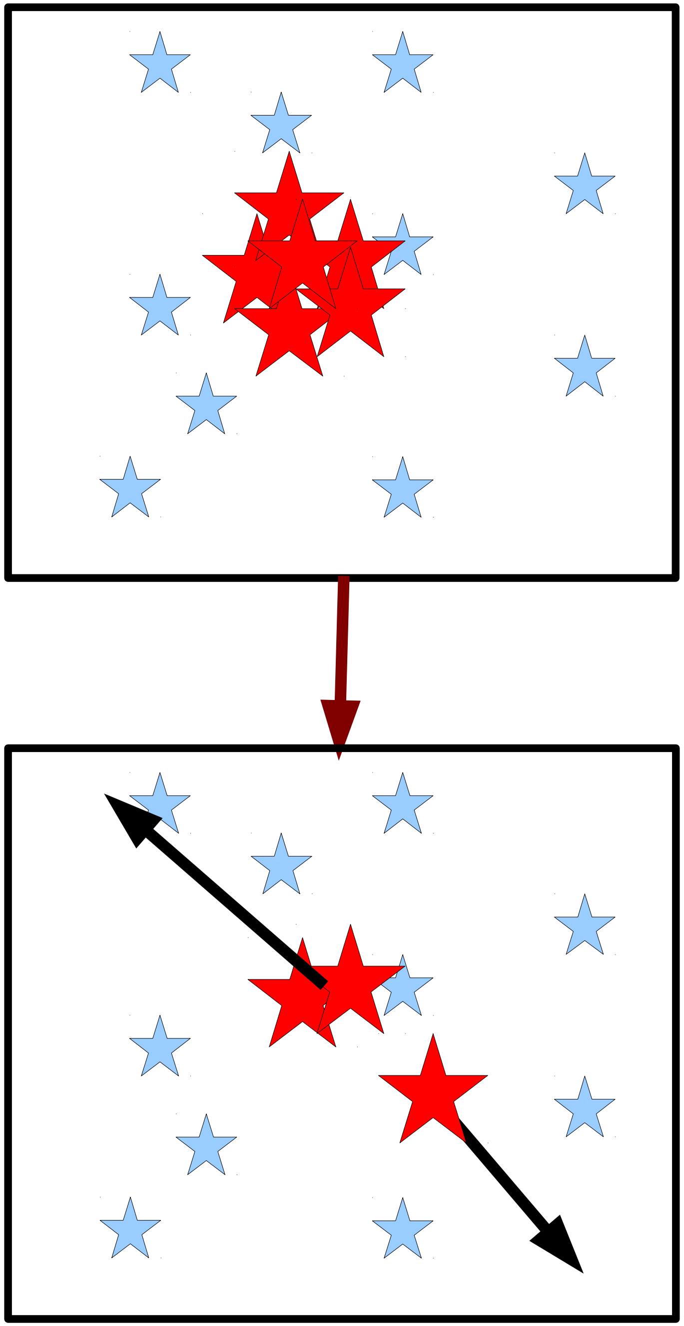
The heavy population forms a
CLUSTER WITHIN THE CLUSTER
(sub-cluster at the centre of the cluster),
DYNAMICALLY DECOUPLED
from the rest of the cluster.

The massive stars in the sub-cluster keep transferring kinetic energy to the lighter stars but cannot reach equipartition:

the core of massive stars continues to
CONTRACT TILL INFINITE DENSITY!

# 3. The dynamics of stellar BH binaries: Spitzer’s instability

## SPITZER’S INSTABILITY



*The contraction stops*

*– when most of the massive stars eject each-other from the SC by 3-body encounters*

*SPITZER INSTABILITY ENHANCES THE EJECTION OF MASSIVE OBJECTS (E.G. BLACK HOLES) FROM SCs*

# 3. The dynamics of stellar BH binaries: Spitzer's instability

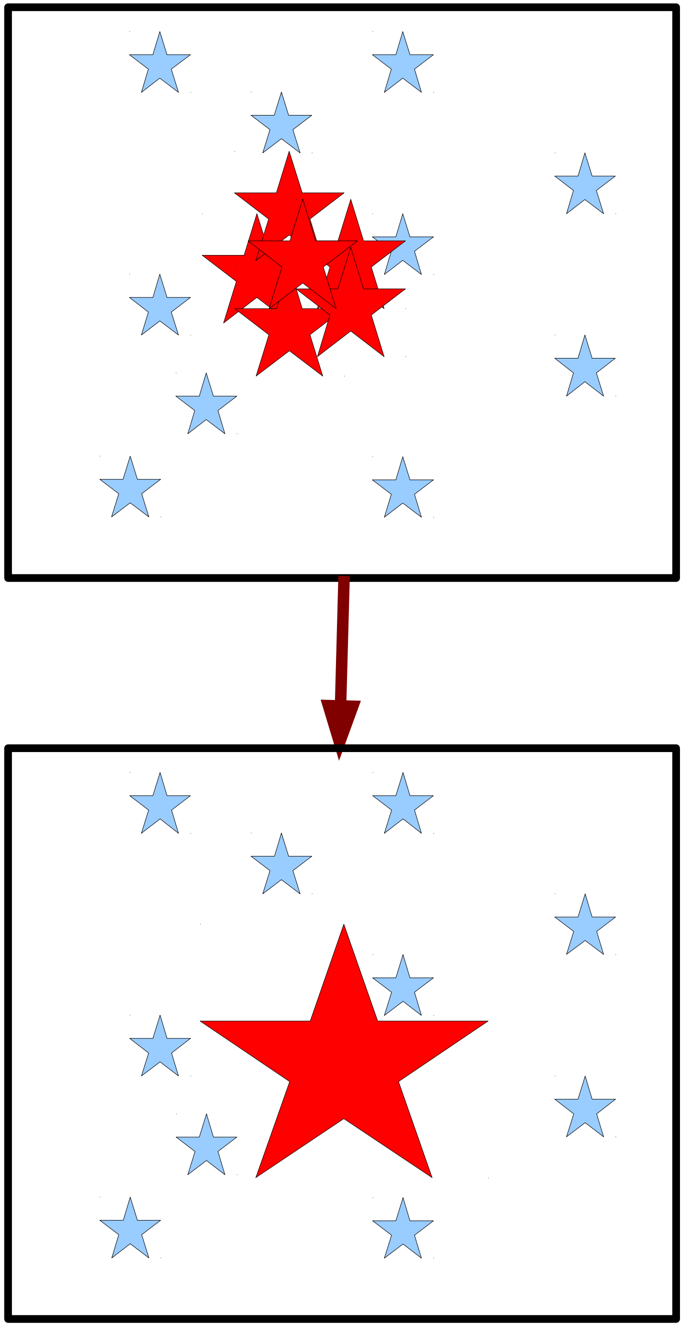
## SPITZER'S INSTABILITY

*The contraction stops*

*– when most of the massive stars eject each-other from the SC by 3-body encounters*

*SPITZER INSTABILITY ENHANCES THE EJECTION OF MASSIVE OBJECTS (E.G. BLACK HOLES) FROM SCs*

*– or when most of the massive stars collapse into a single object*

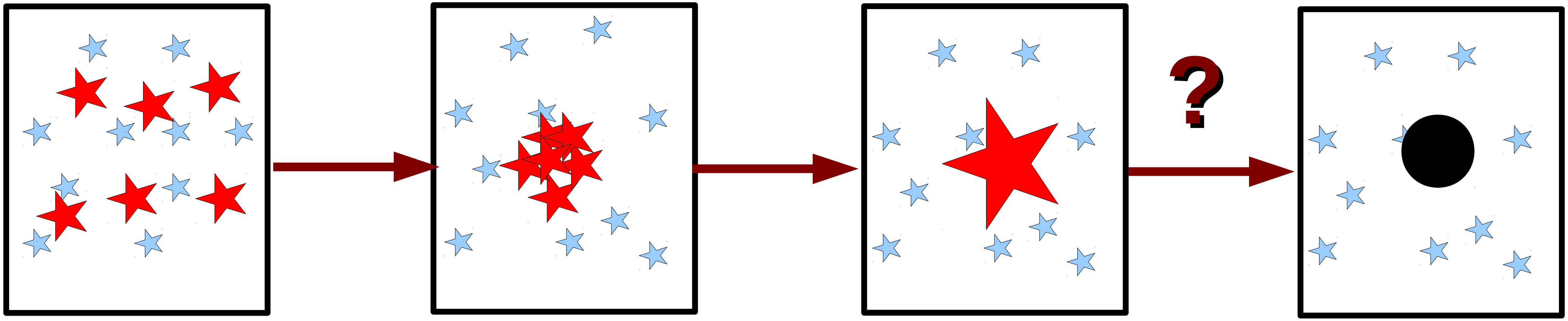


# 3. The dynamics of stellar BH binaries: runaway collisions

**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**

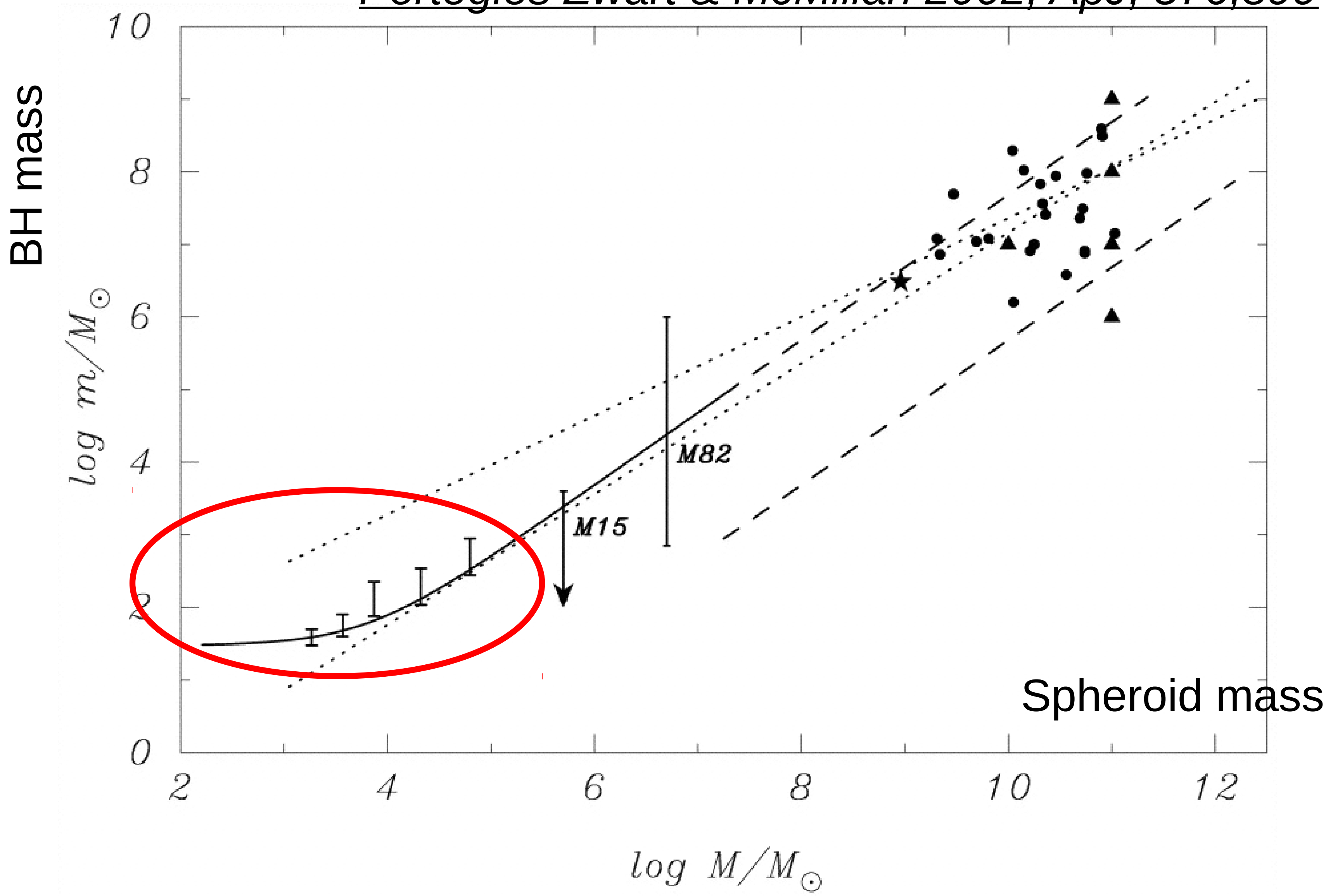
**What is the final mass of the collision product?**

***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 others***

# 3. The dynamics of stellar BH binaries: runaway collisions

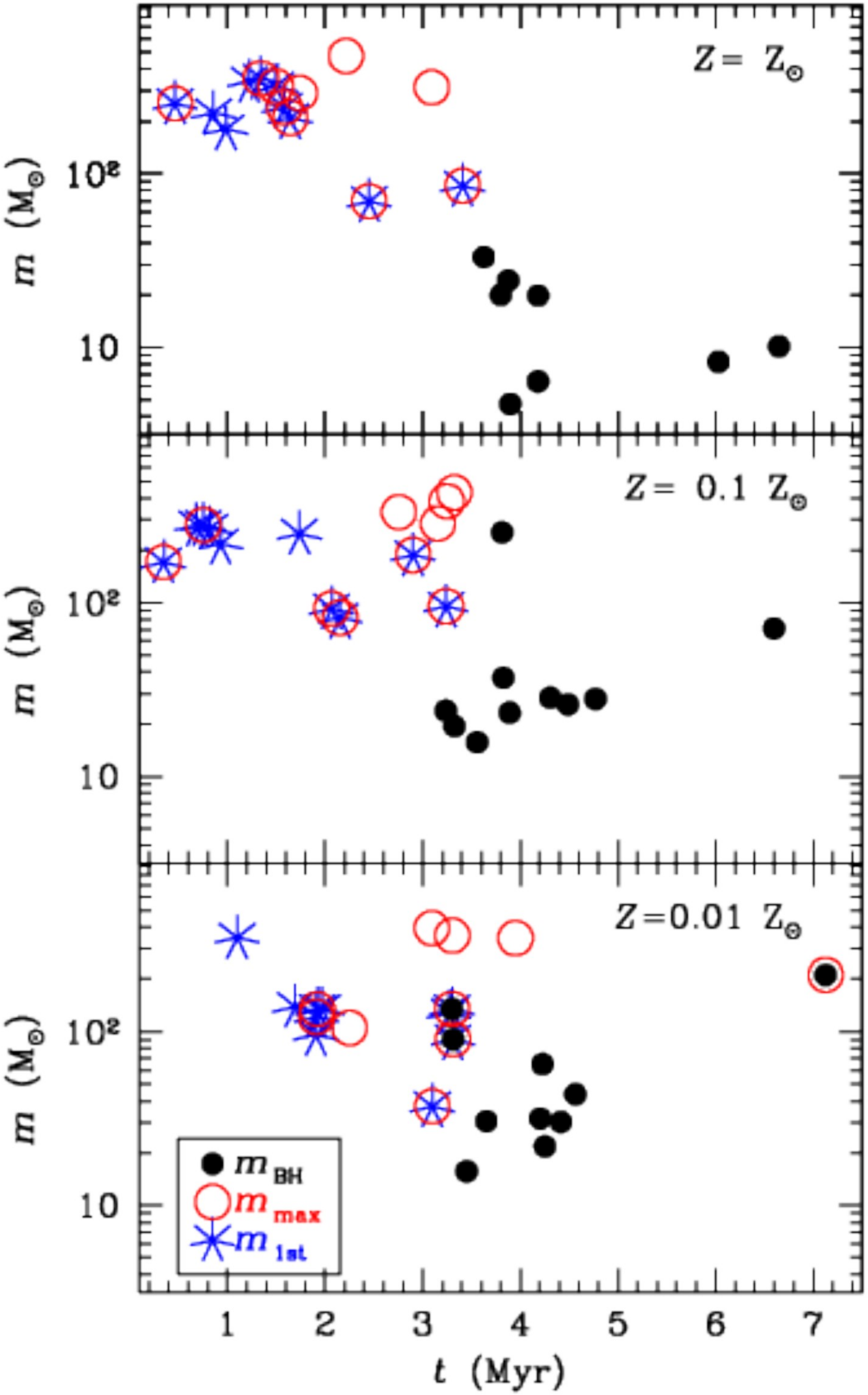
**Early studies without stellar evolution suggest IMBH mass ~ 10^-3 star cluster mass**

Portegies Zwart & McMillan 2002, ApJ, 576,899



**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**

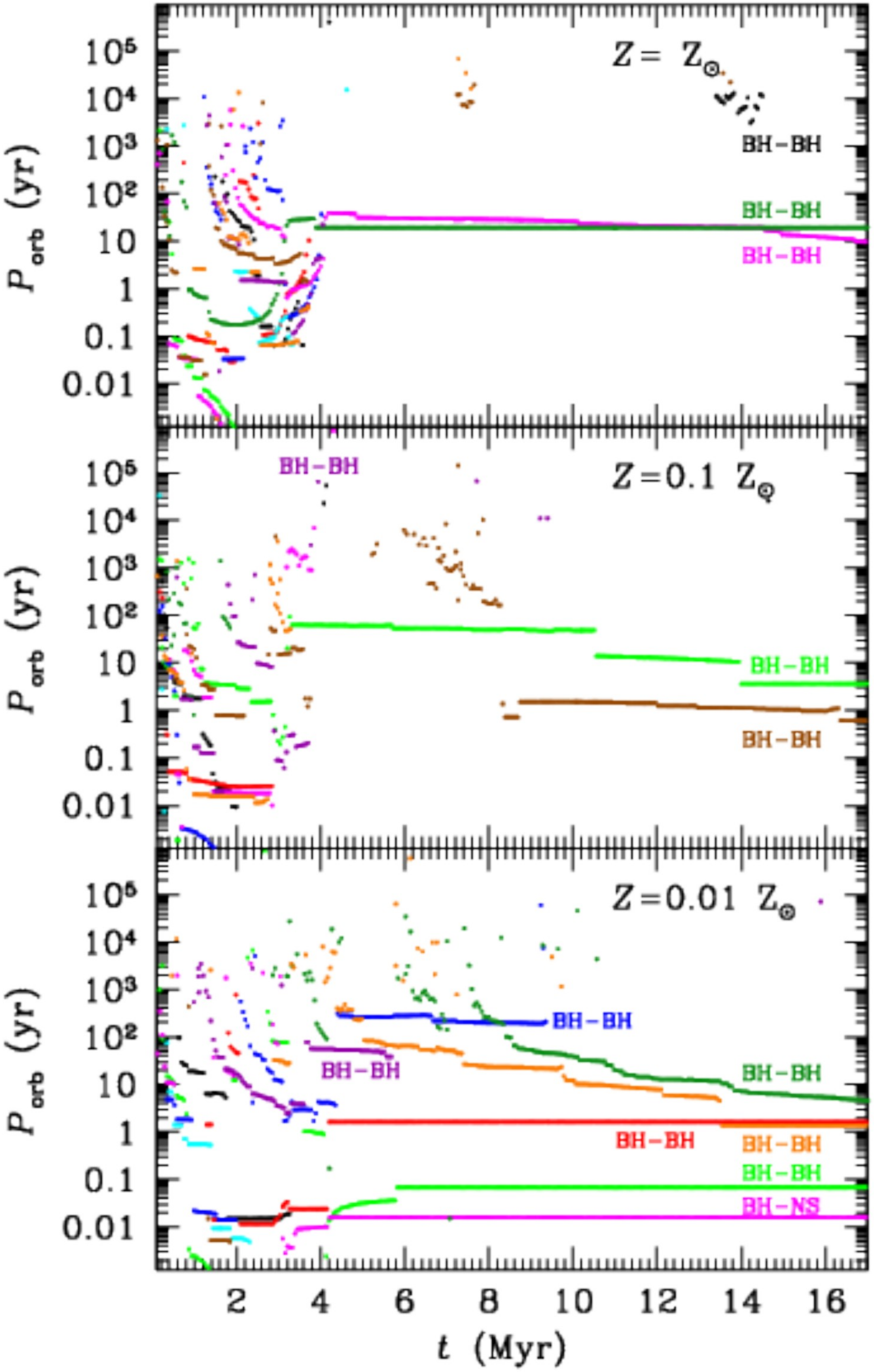
*** 10% BHs in the IMBH regime
(>100 Msun) at Z = 0.01 – 0.1 Zsun**

*** 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**

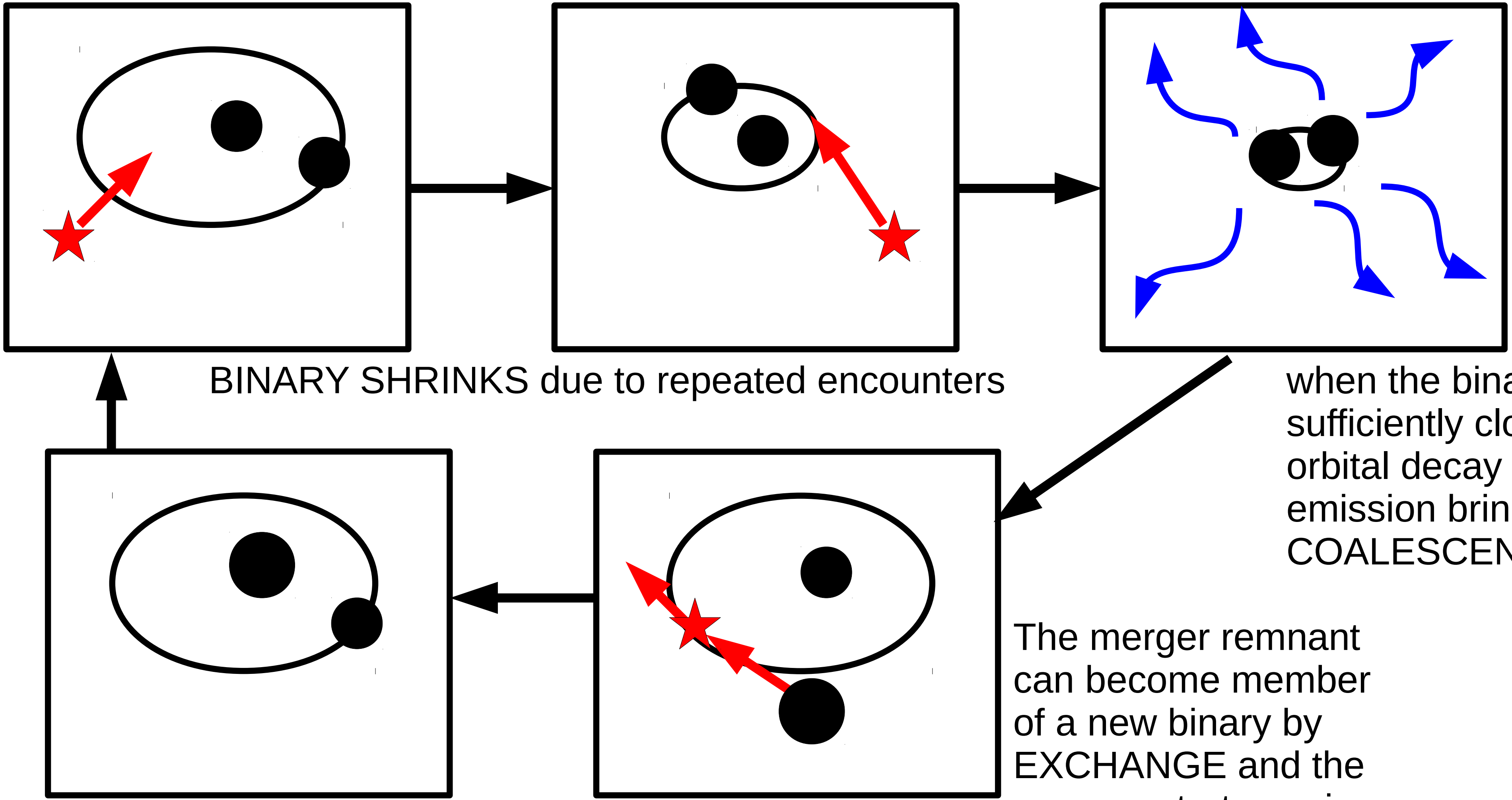
**Possibly JOINT SOURCES for LISA and for LIGO-Virgo**

***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

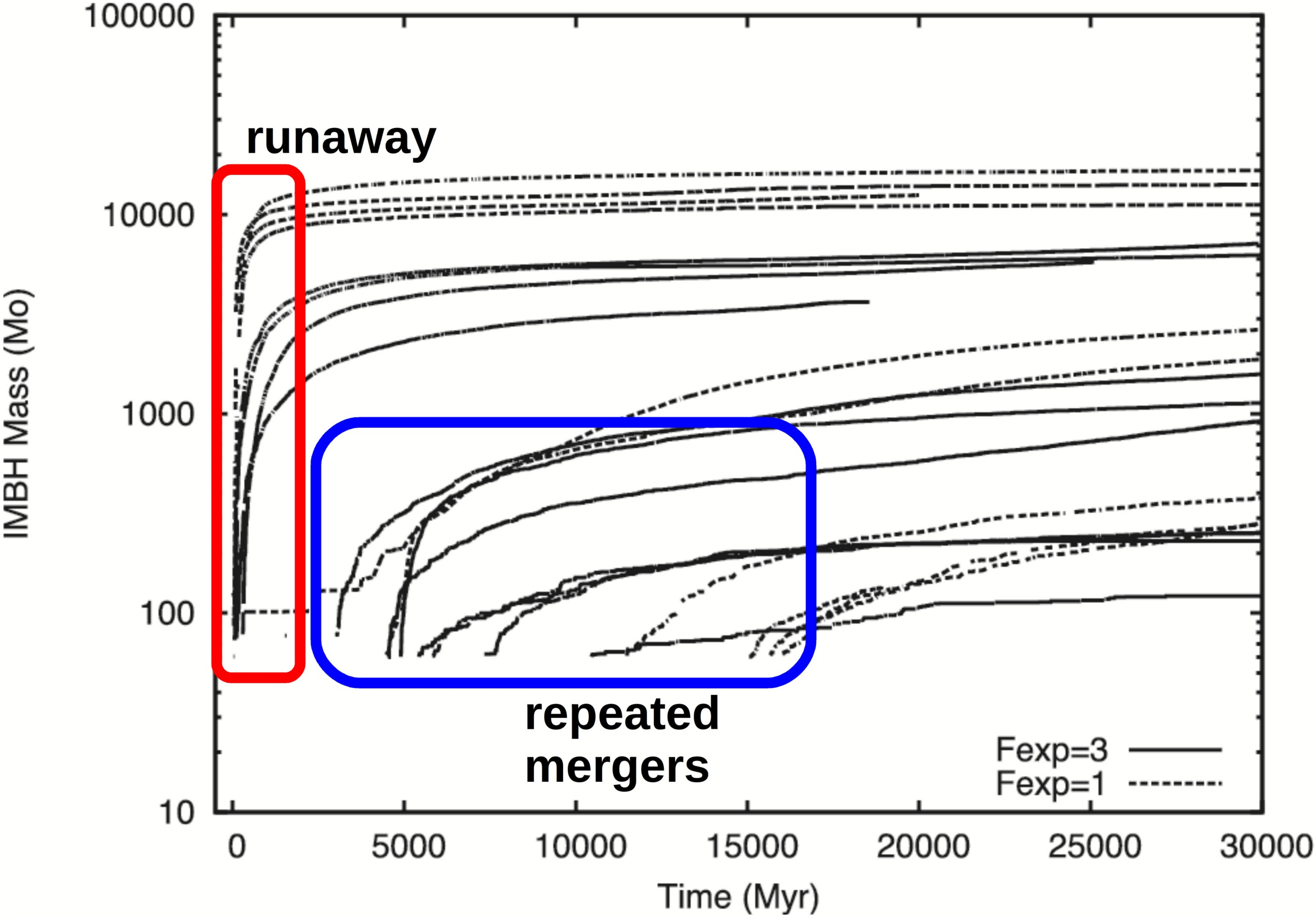


BINARY SHRINKS due to repeated encounters

when the binary is sufficiently close, orbital decay by GW emission brings it to COALESCENCE

The merger remnant can become member of a new binary by EXCHANGE and the process starts again

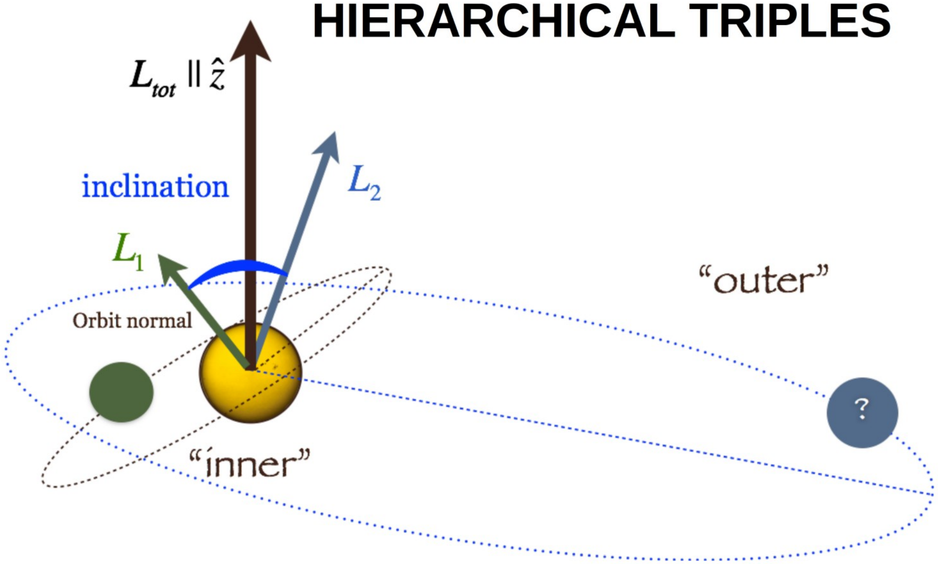
# 3. The dynamics of stellar BH binaries: repeated mergers



Giersz +2015, MNRAS, 454, 3150

# 3. The dynamics of stellar BH binaries: Kozai resonance

HIERARCHICAL TRIPLES

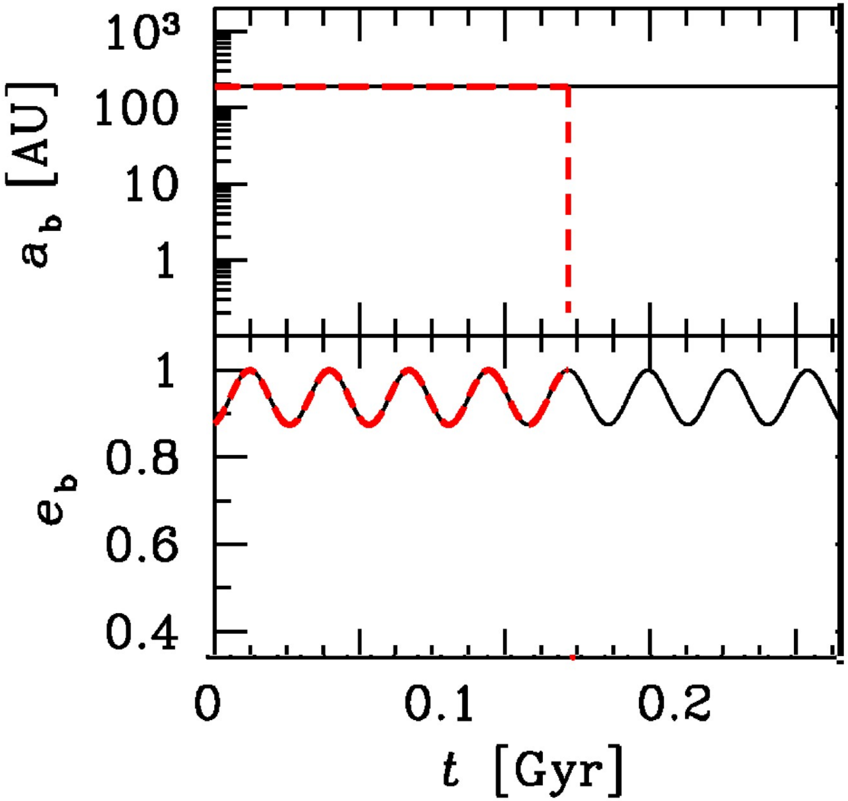


*Kozai 1962, AJ, 67, 591*
*Lidov 1962, P&SS, 9, 719*
*Figure credits: Smadar Naoz*

**ECCENTRICITY of the inner binary OSCILLATES**

**TRIGGERING MERGERS between binary members**

**ONLY DYNAMICAL PROCESS COMMON ALSO IN THE FIELD**



**No general relativity**
**With 2.5 Post-Newtonian**

*Kimpson+ 2016, MNRAS, 463, 2443*

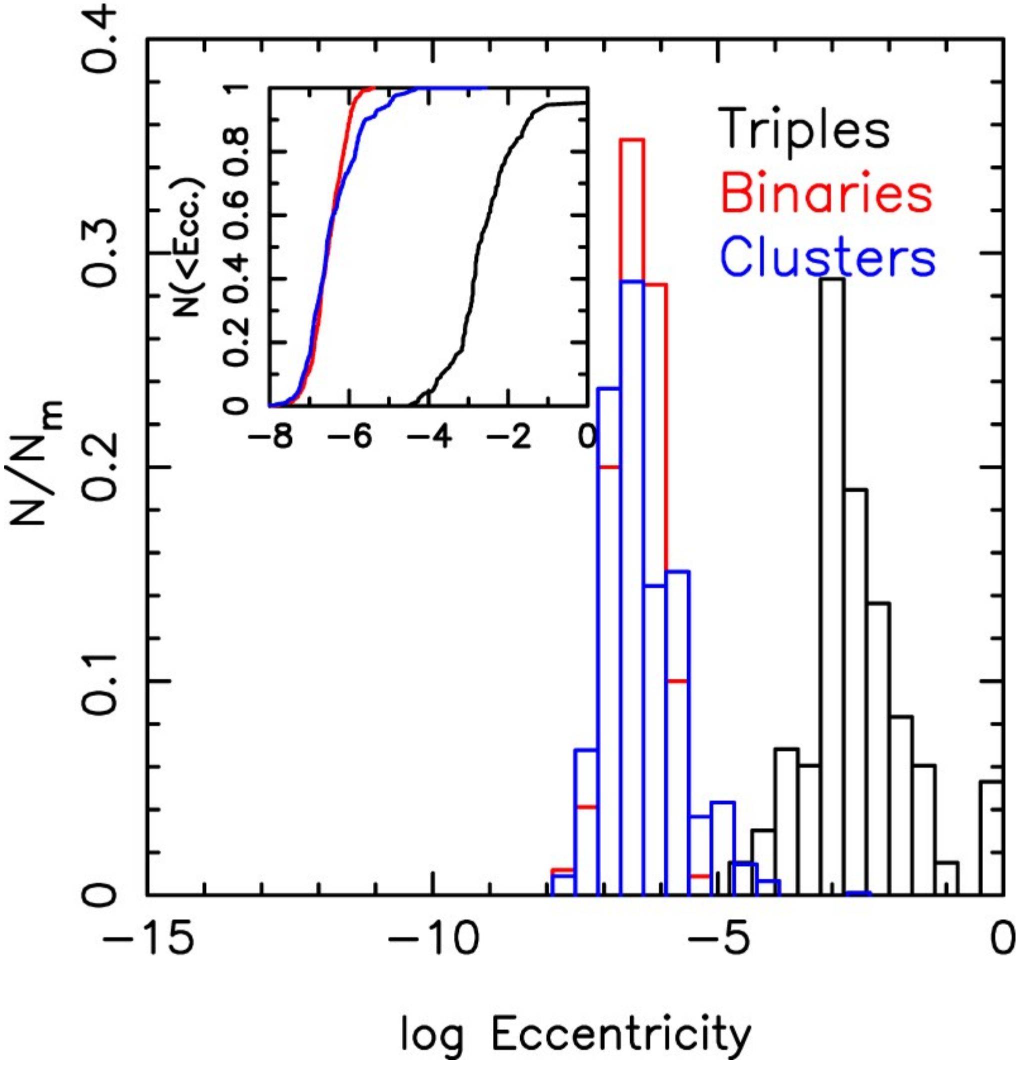
# 3. The dynamics of stellar BH binaries: Kozai resonance

**~ 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)!**

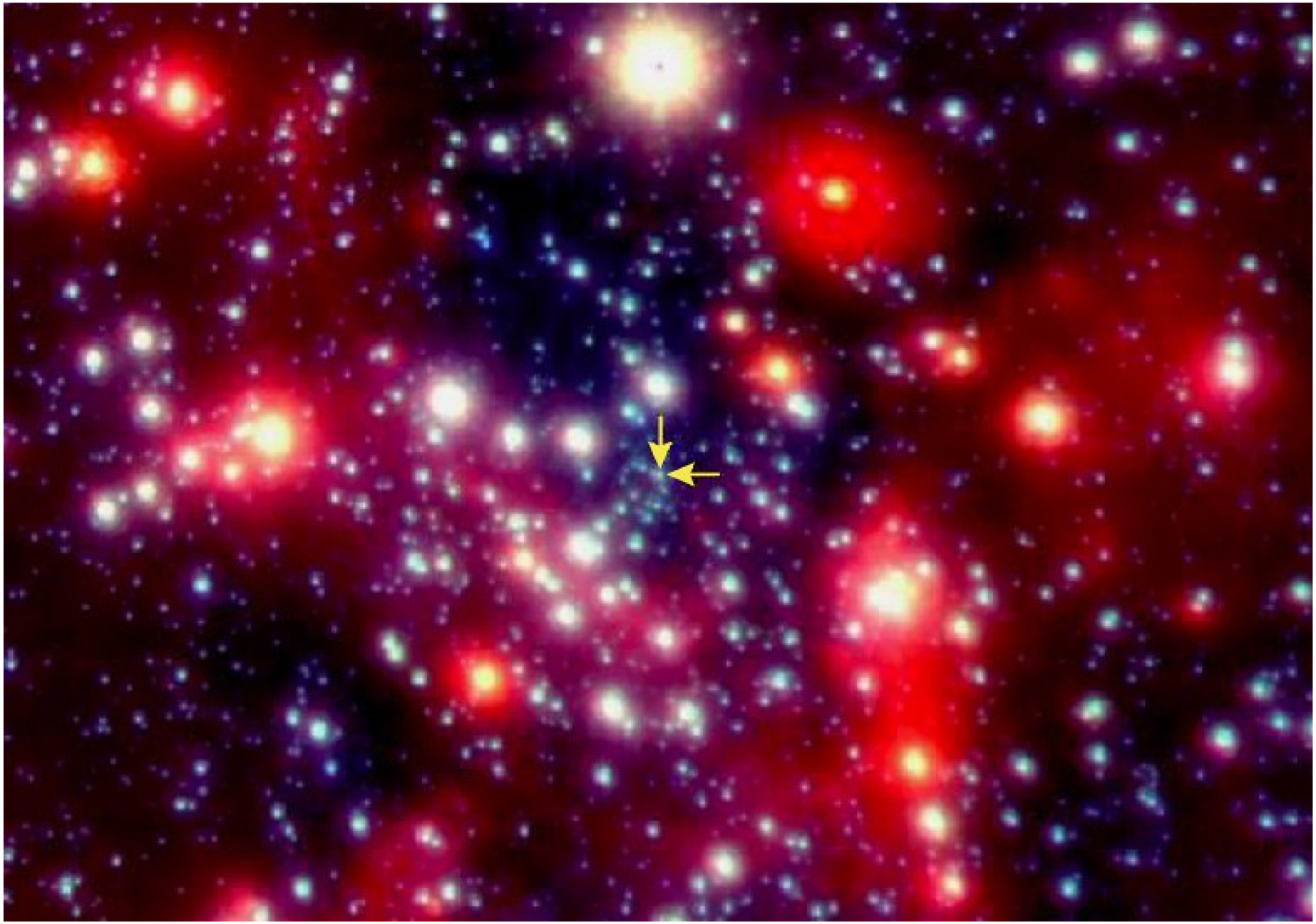
**Merger rate from KL systems is low (<2.5 Gpc$^{-3}$ yr$^{-1}$)**



**Antonini+ 2017, ApJ, 841, 77**

# 3. The dynamics of stellar BH binaries: Kozai resonance

## KOZAI-LIDOV particularly efficient in NUCLEAR STAR CLUSTERS:



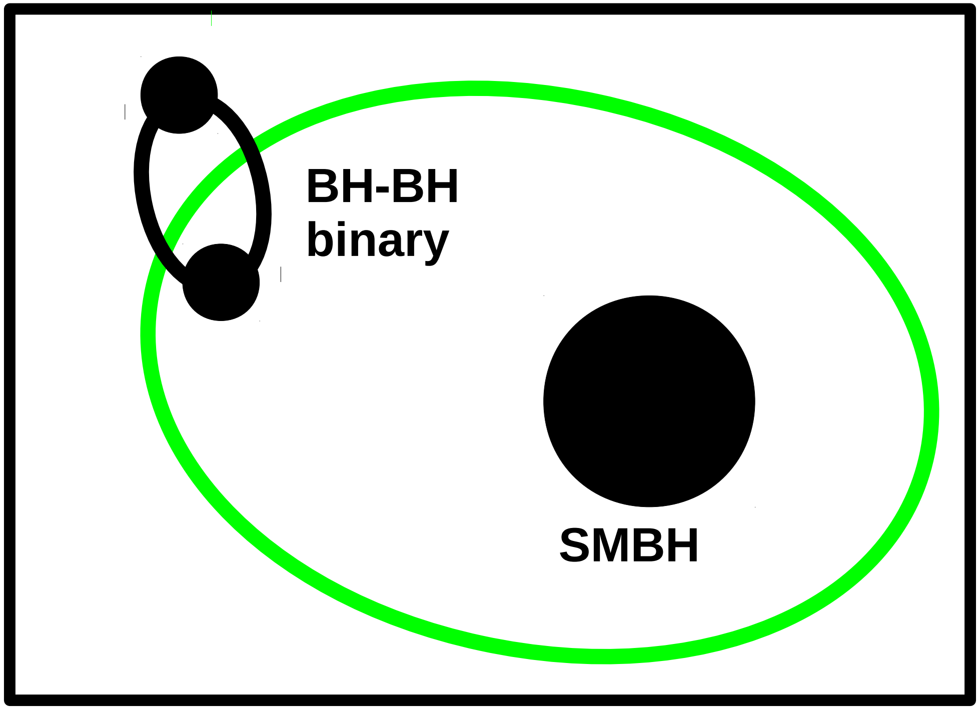
*Schoedel et al. 2002, Nature, 419, 694*

# 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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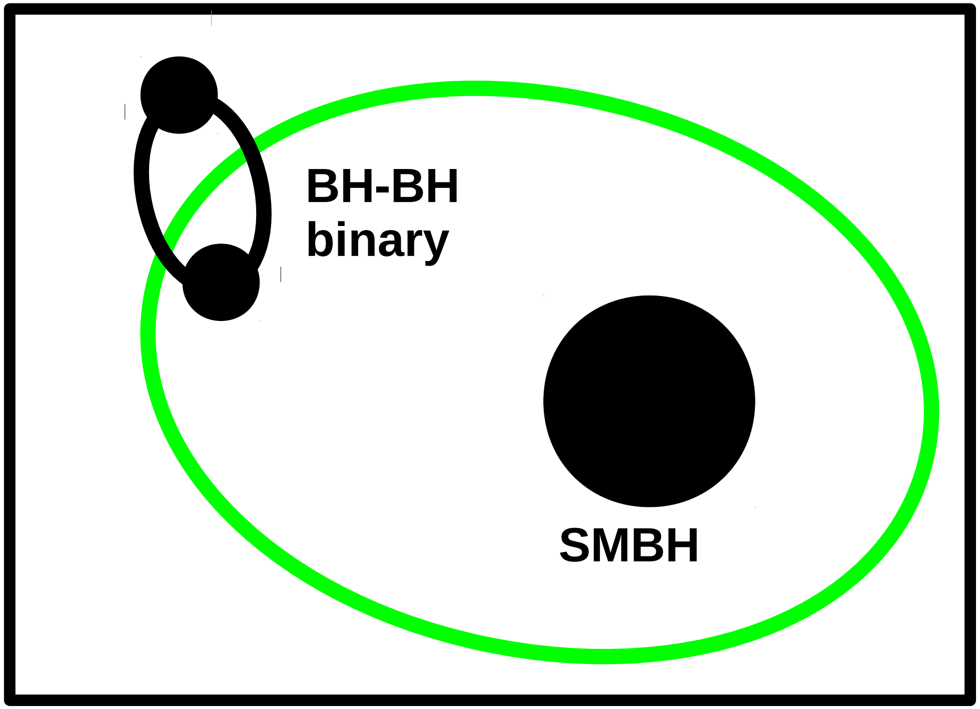
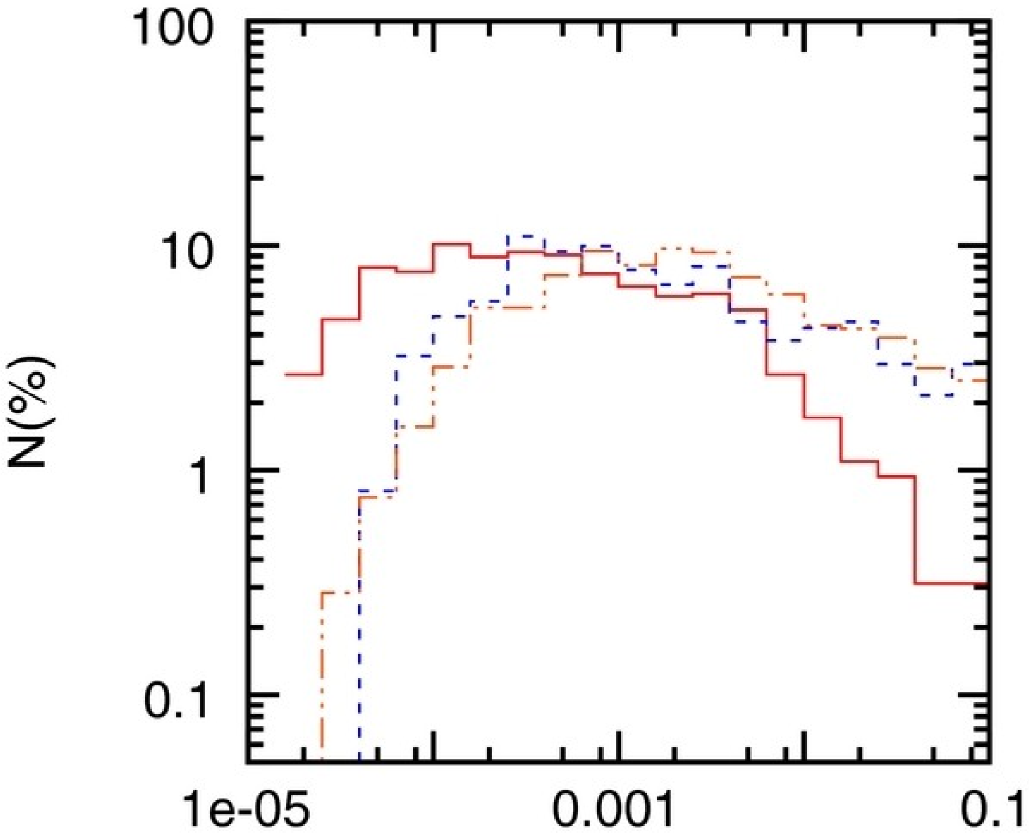




**Eccentricity at 10 Hz**

*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**

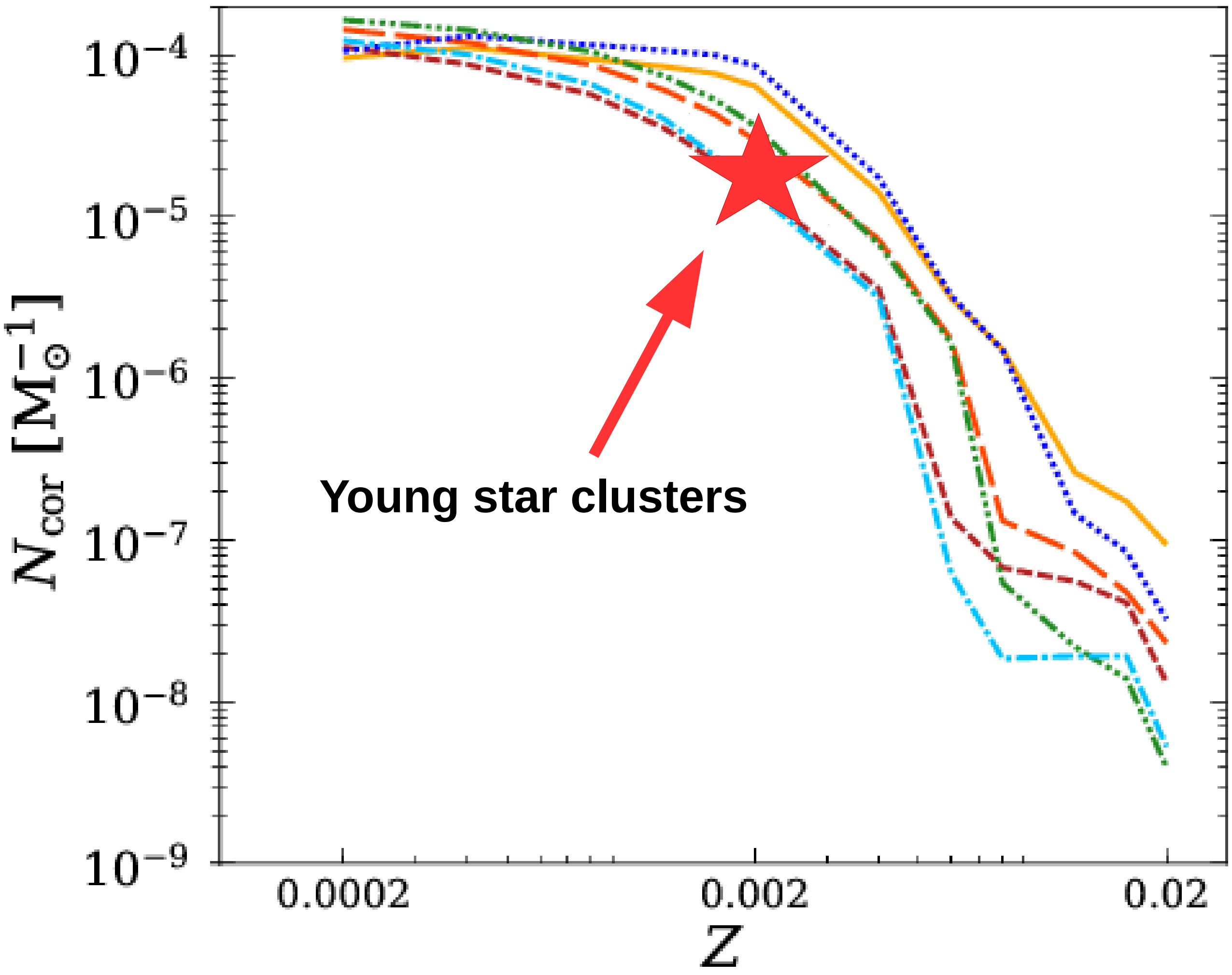
**Merger rate for YOUNG & OPEN CLUSTERS: ~ 0.1 – 100 Gpc $^{-3}$ yr $^{-1}$**

***(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: merger rates

## Number of BH mergers per unit stellar mass



Young star clusters

**Lines: isolated binaries from Giacobbo & MM 2018**

**Star: dynamical simulations Di Carlo et al. 2019**

**Dynamics in young star clusters does NOT affect the MERGER RATE (while it strongly affects the mass of the systems)**

**Di Carlo et al. 2019, arXiv:1901.00863**

# 3. The dynamics of stellar BH binaries: wrap up

## Dynamical binary evolution summary:

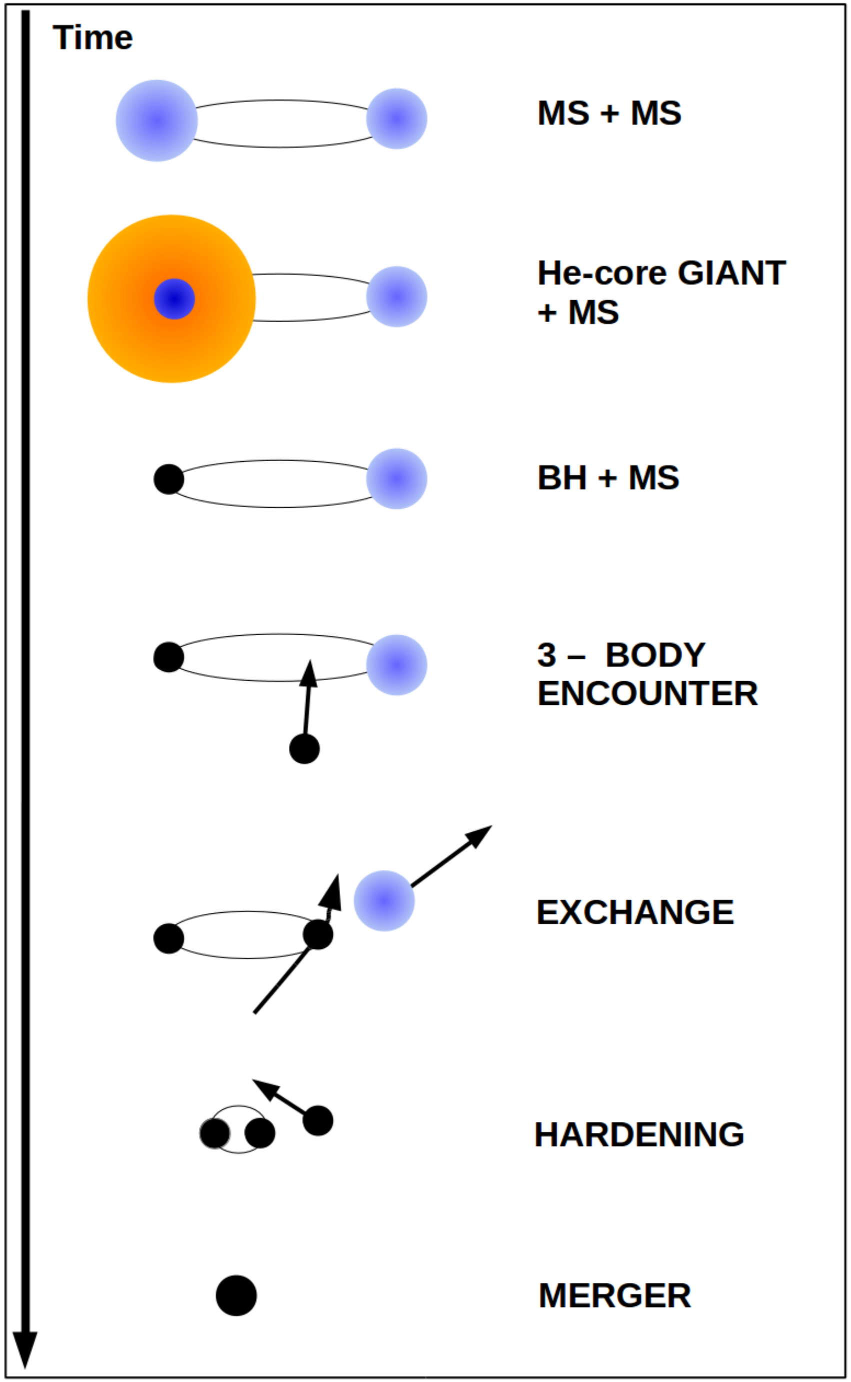
* no need for Roche lobe
or common envelope
(but might happen)

* exchanges build up
more massive
black hole binaries

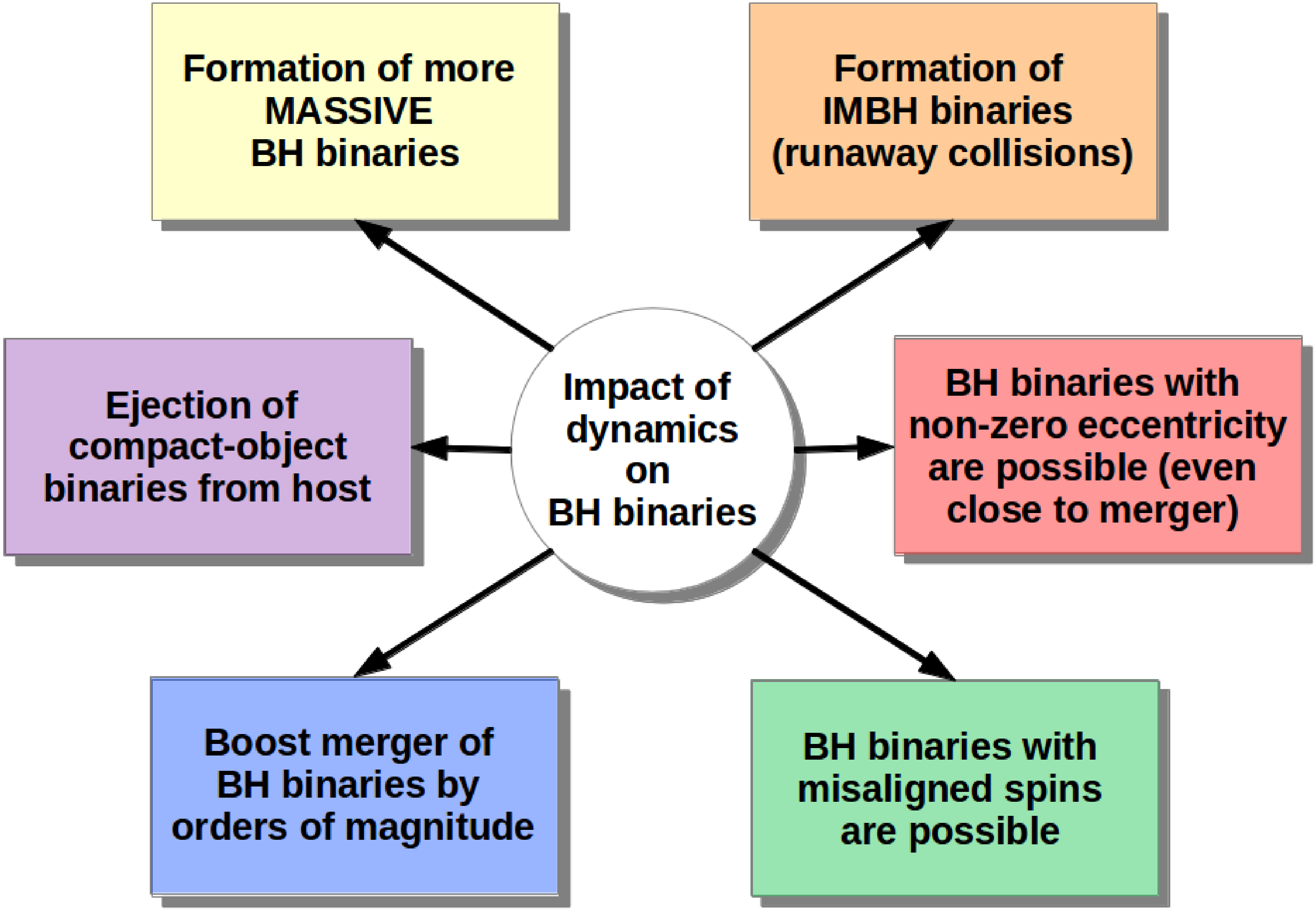
* hardening by three-body
encounters favours
the binary shrinking

* BH – BH merger

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



# 3. The dynamics of stellar BH binaries: wrap up



Impact of
dynamics
on
BH binaries

Formation of more
MASSIVE
BH binaries

Formation of
IMBH binaries
(runaway collisions)

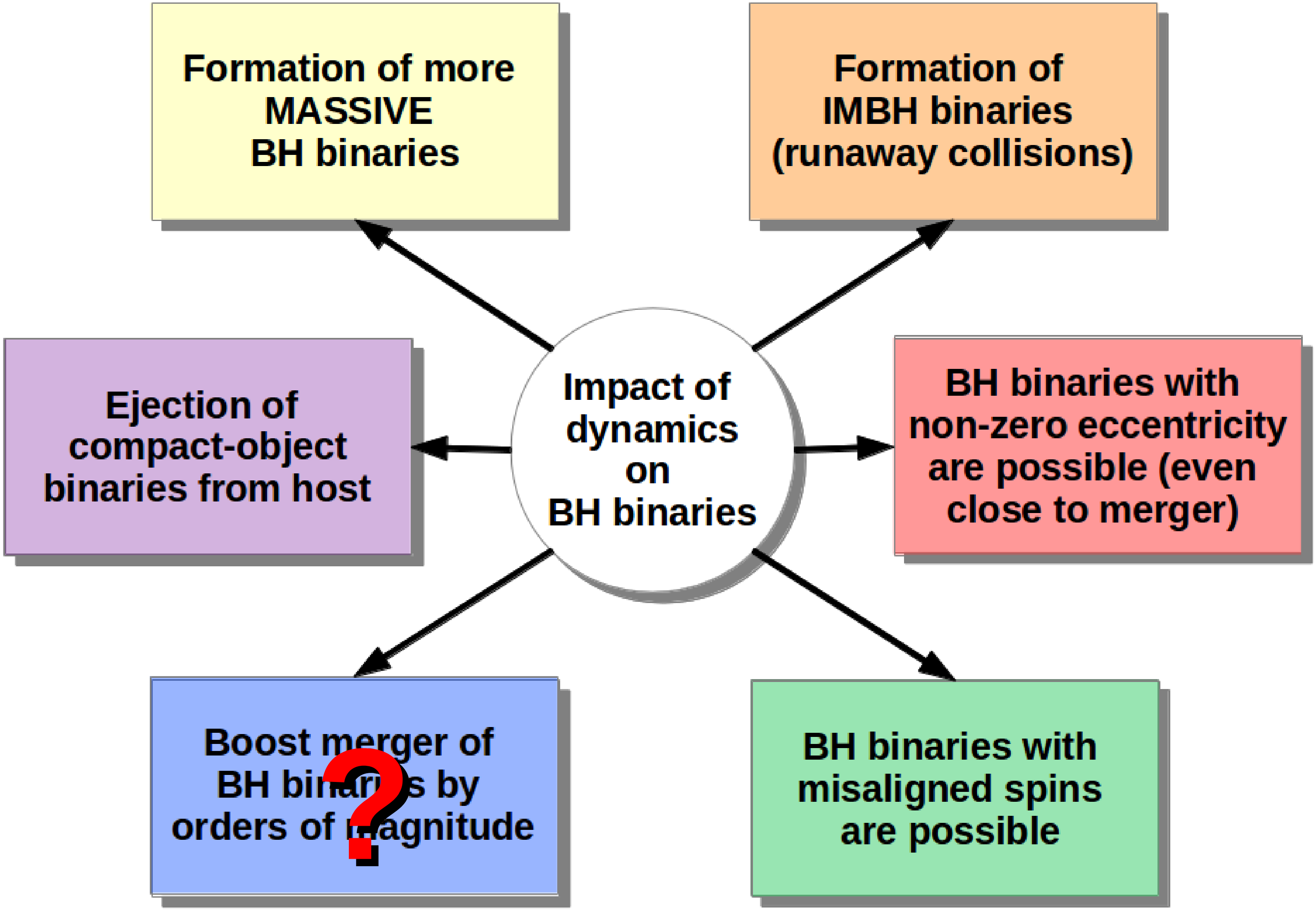
Ejection of
compact-object
binaries from host

BH binaries with
non-zero eccentricity
are possible (even
close to merger)

Boost merger of
BH binaries by
orders of magnitude

BH binaries with
misaligned spins
are possible

# 3. The dynamics of stellar BH binaries: wrap up



Impact of dynamics on BH binaries

Formation of more MASSIVE BH binaries

Formation of IMBH binaries (runaway collisions)

Ejection of compact-object binaries from host

BH binaries with non-zero eccentricity are possible (even close to merger)

Boost merger of BH binaries by orders of magnitude

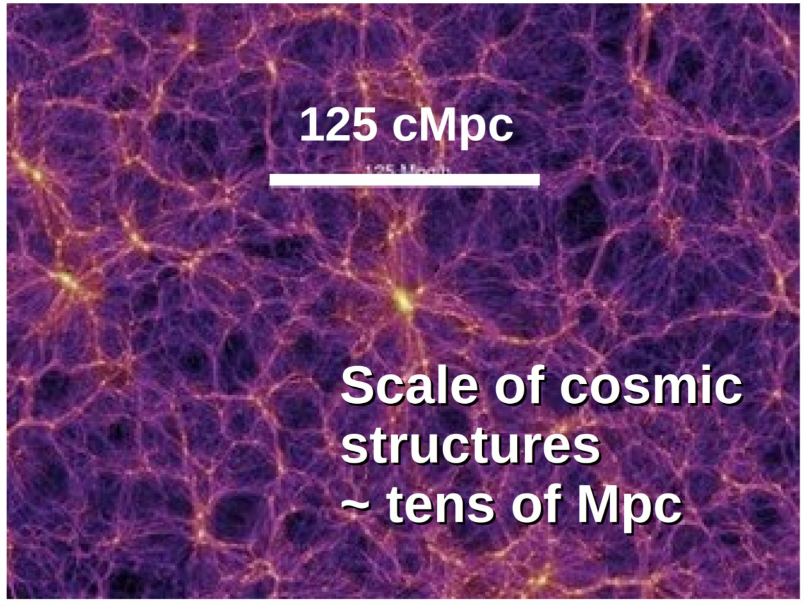
?

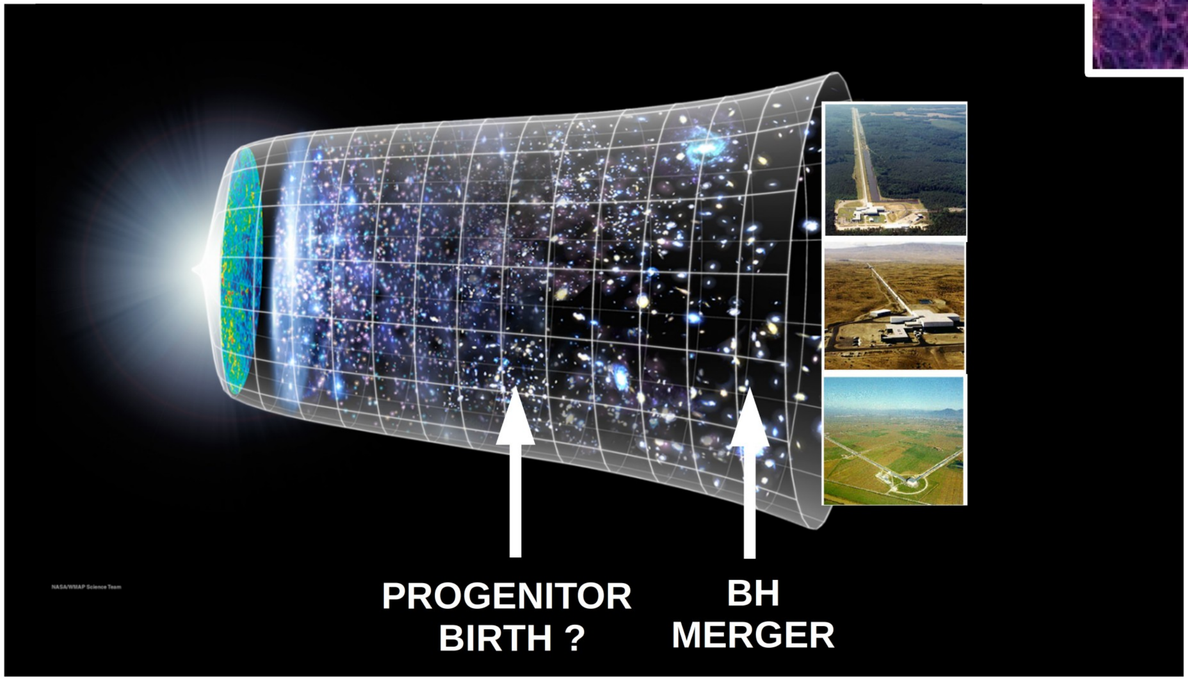
BH binaries with misaligned spins are possible

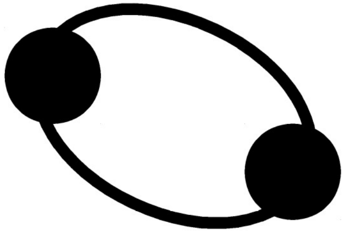
# 4. Compact binaries in cosmological context

**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)**

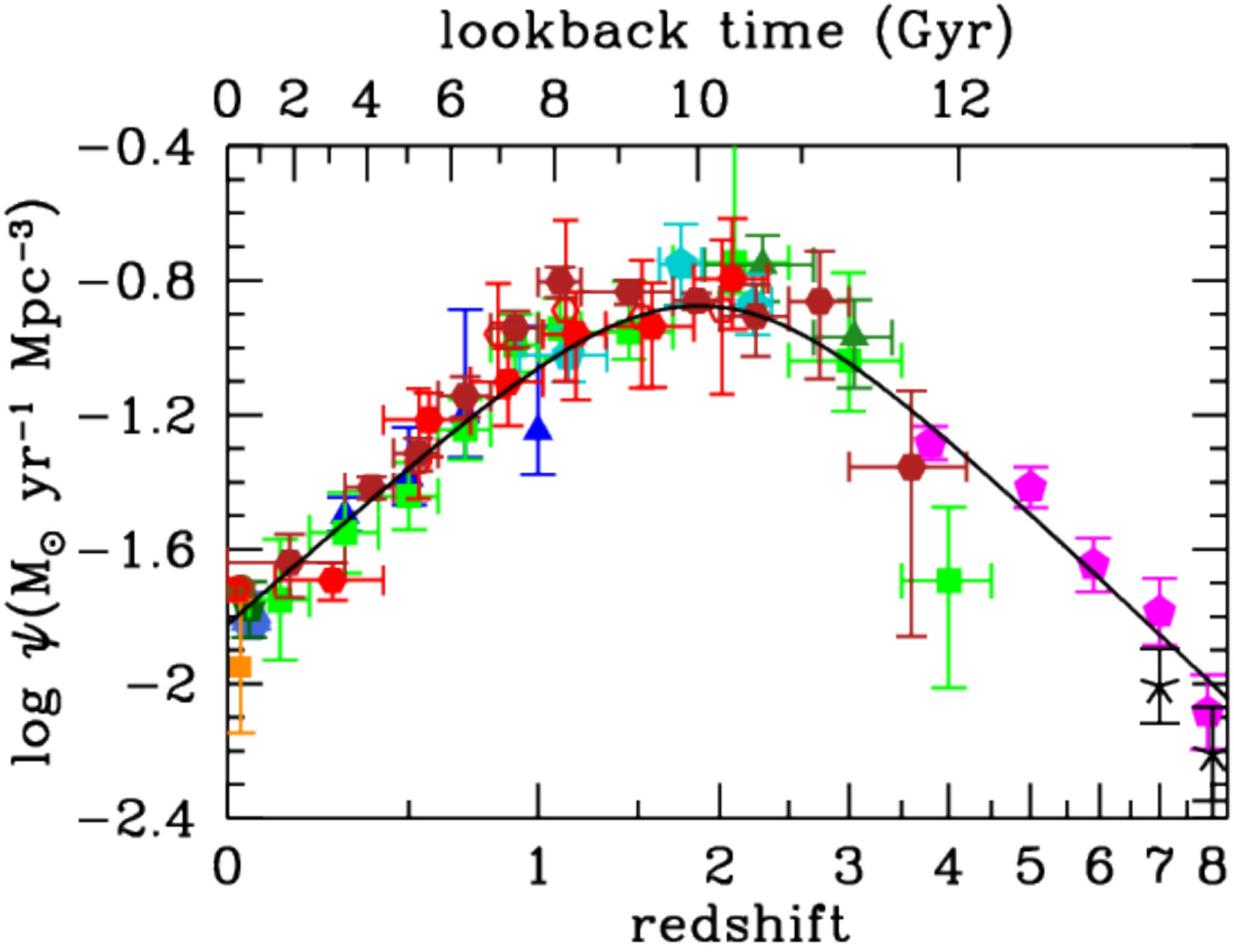
- **cosmological simulations + binary population synthesis simulations through Monte Carlo procedure**

**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**

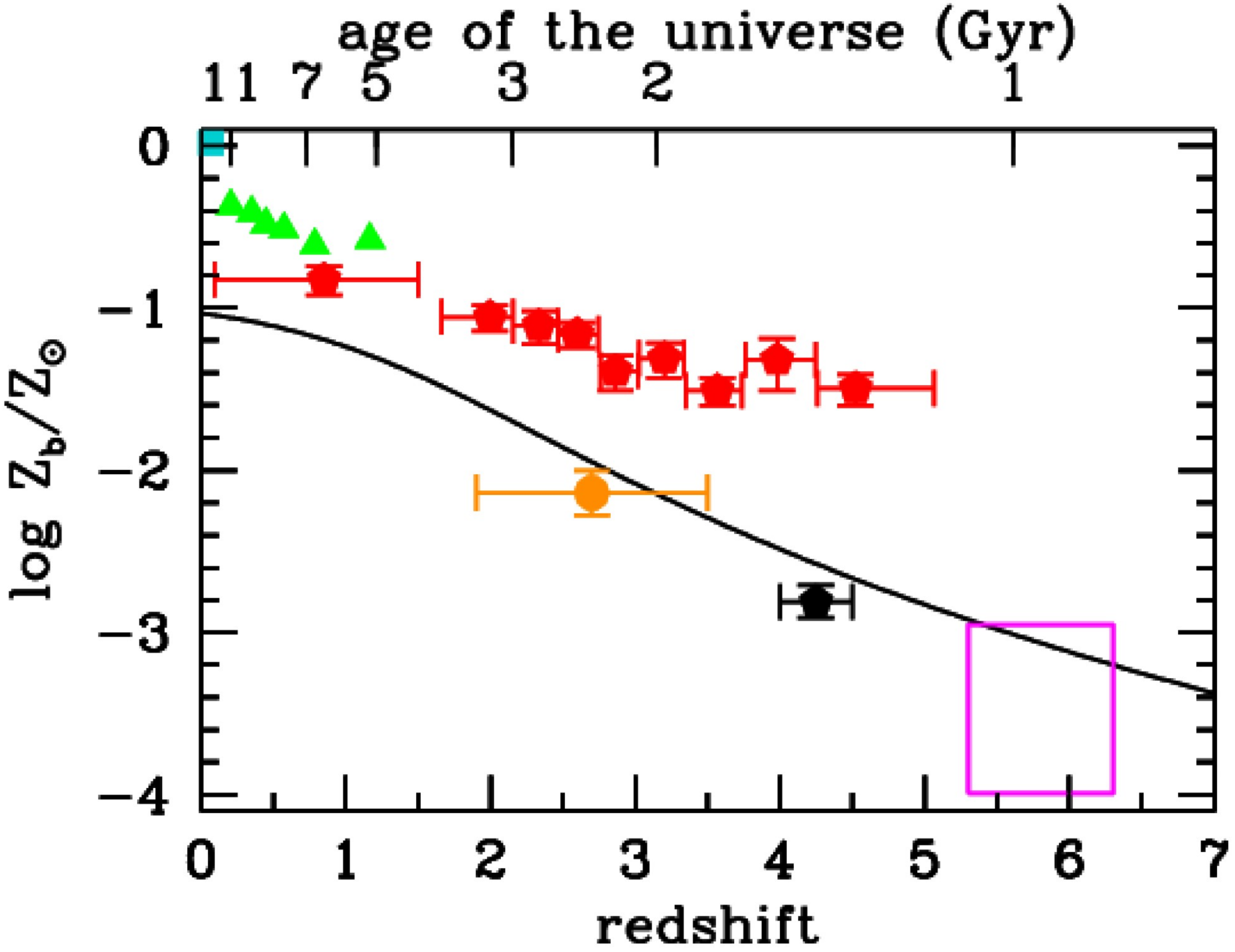


**(FUV+ IR data, Fig. 9 of Madau & Dickinson 2014)**

# 4. Compact binaries in cosmological context

## MAIN INGREDIENTS: metallicity evolution

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

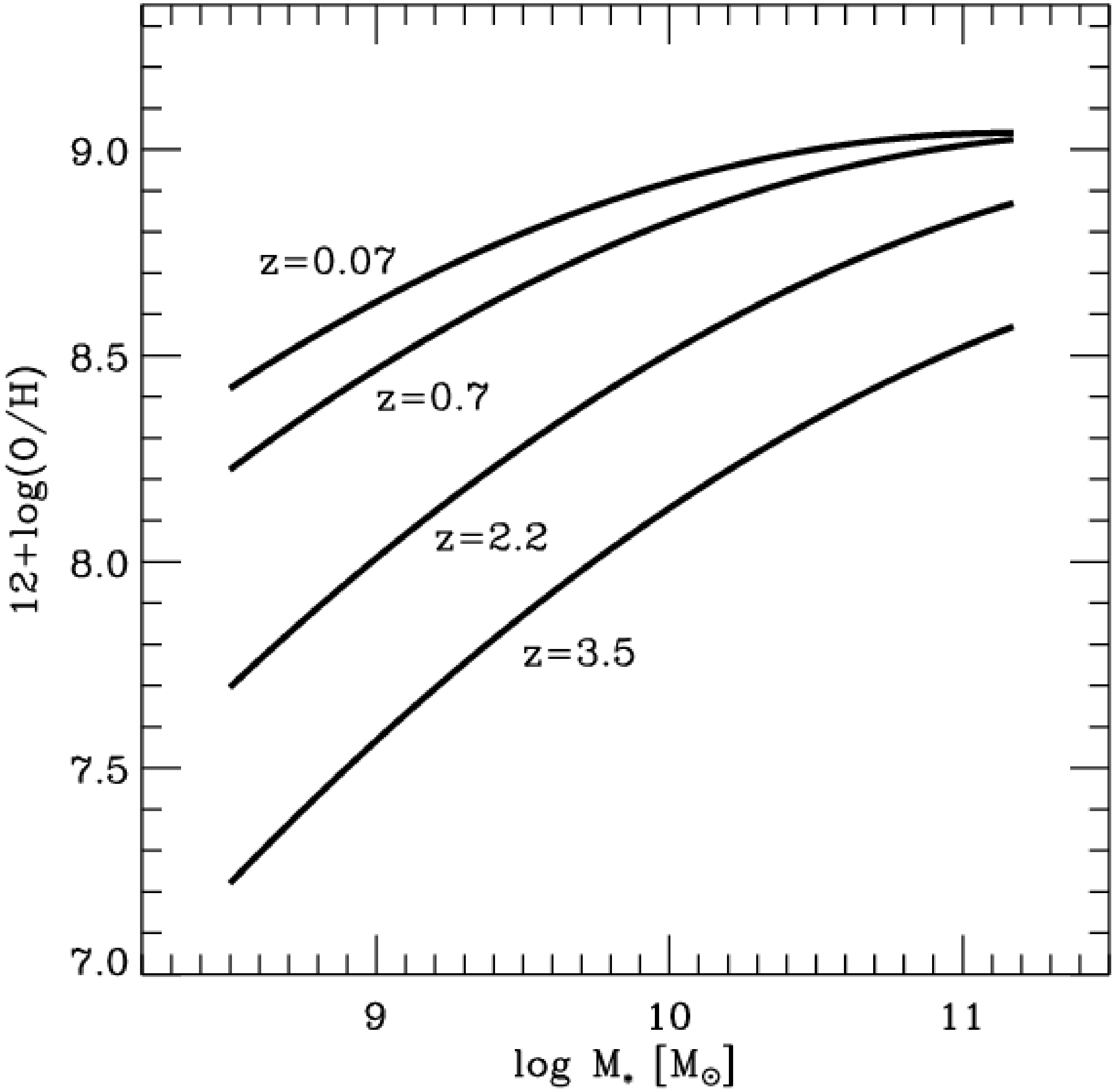


**(Fig. 14 of Madau & Dickinson 2014)**

# 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**

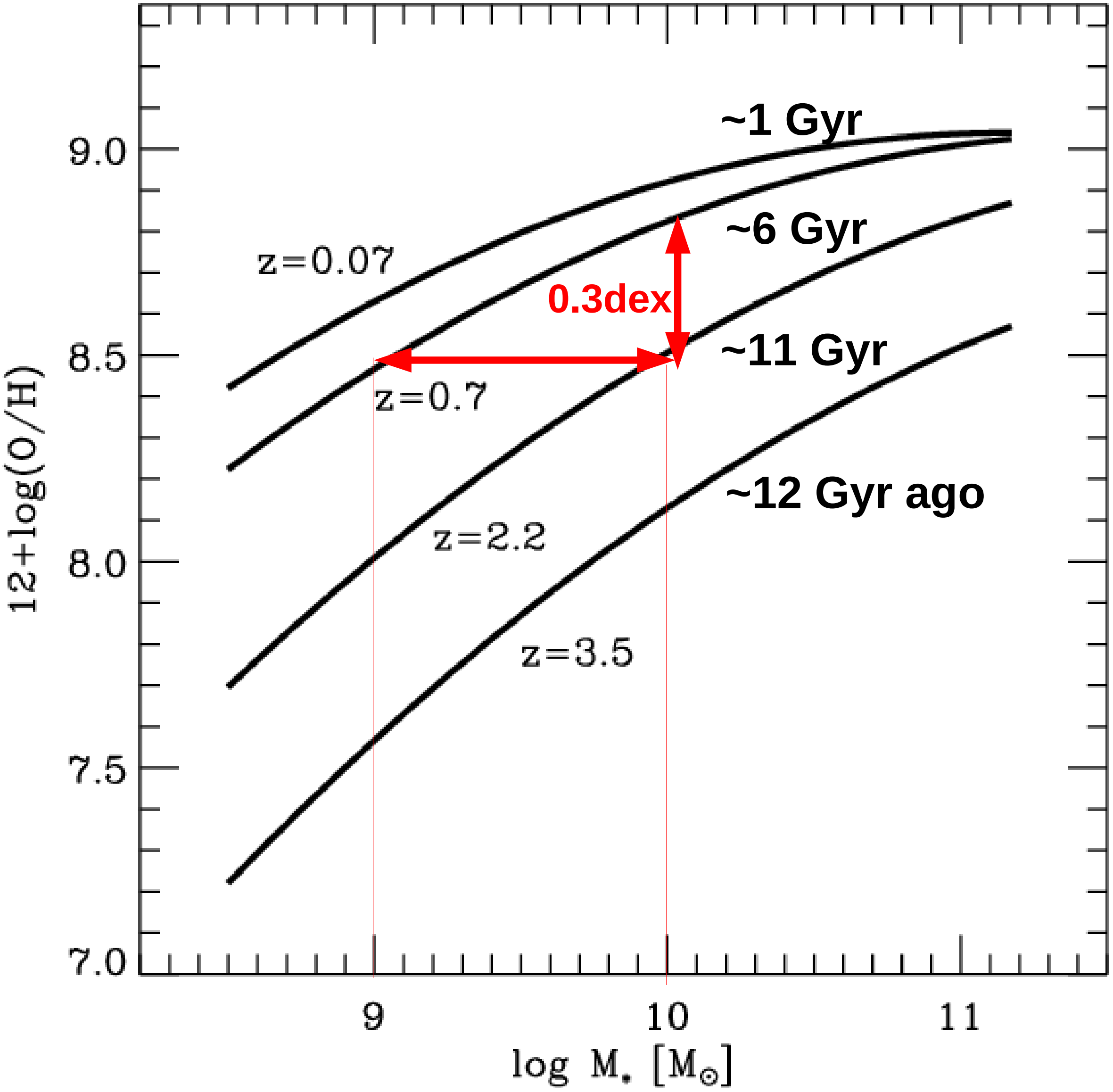
# 4. Compact binaries in cosmological context

## 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

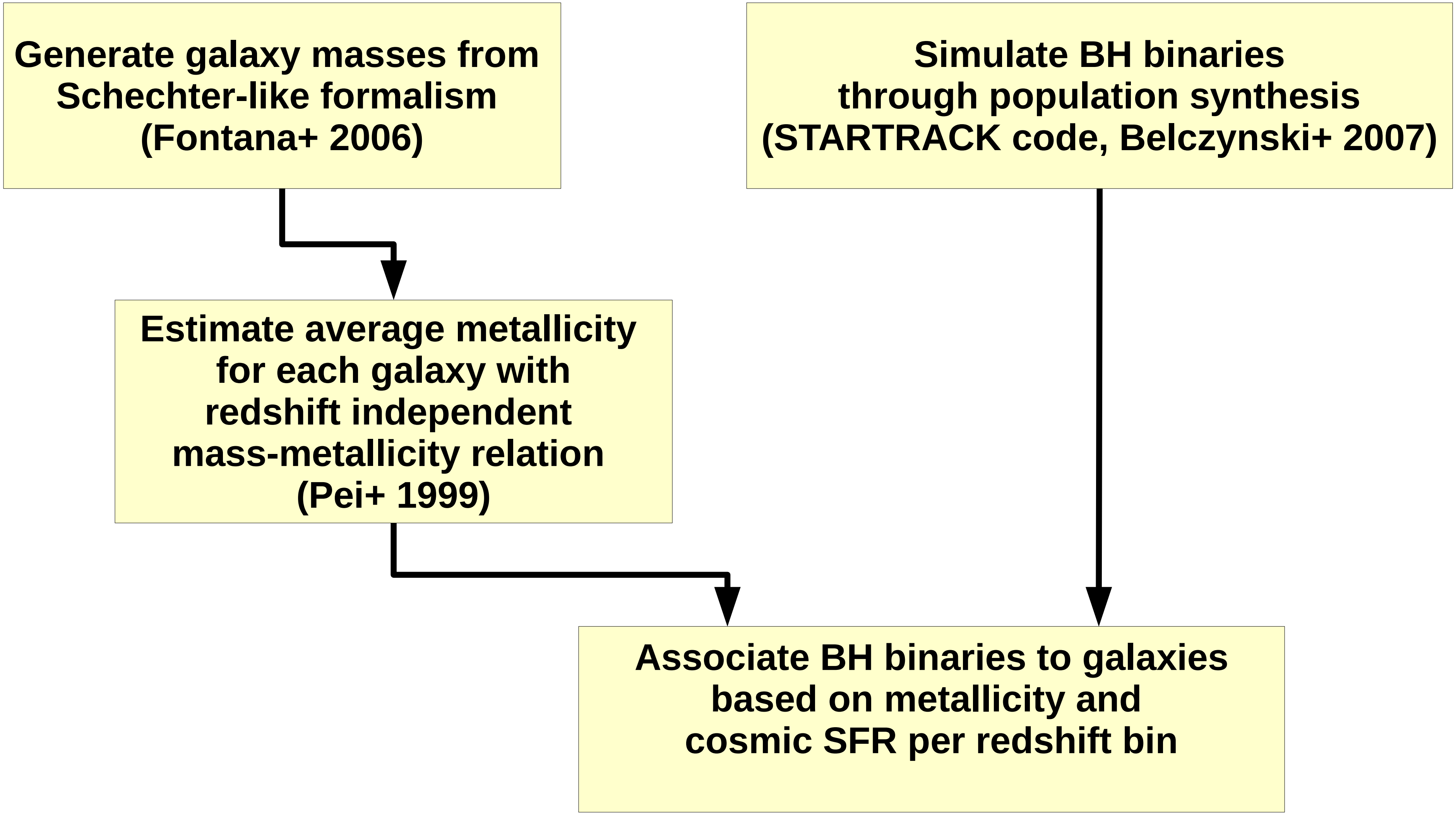
Between 10^9 and 10^10 M⊙ observed metallicity changes ~0.3 dex for fixed redshift (~0.7)



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

# 4. Compact binaries in cosmological context

## Dominik+ 2013



Generate galaxy masses from
Schechter-like formalism
(Fontana+ 2006)

Simulate BH binaries
through population synthesis
(STARTRACK code, Belczynski+ 2007)

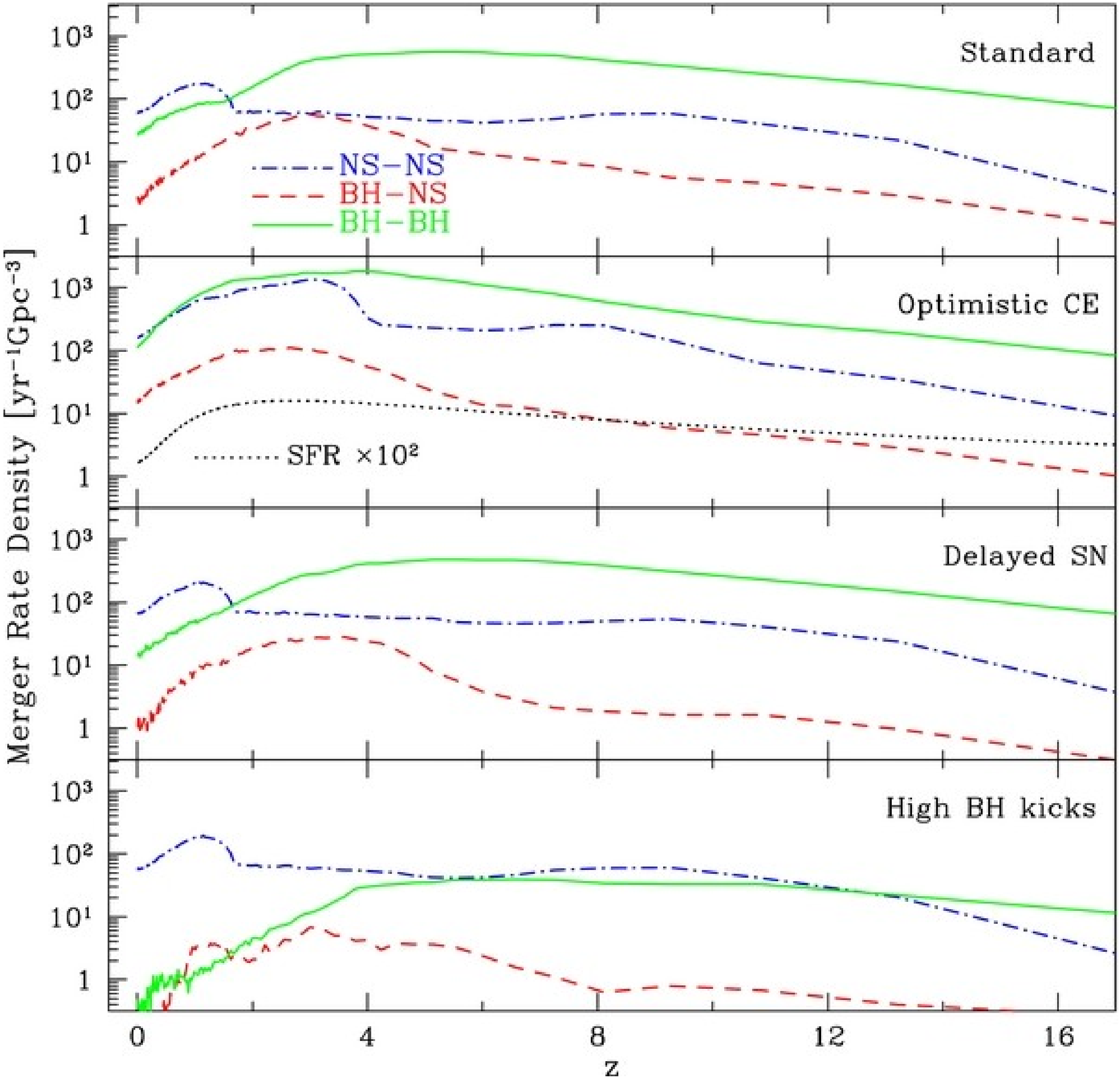
Estimate average metallicity
for each galaxy with
redshift independent
mass-metallicity relation
(Pei+ 1999)

Associate BH binaries to galaxies
based on metallicity and
cosmic SFR per redshift bin

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

# 4. Compact binaries in cosmological context

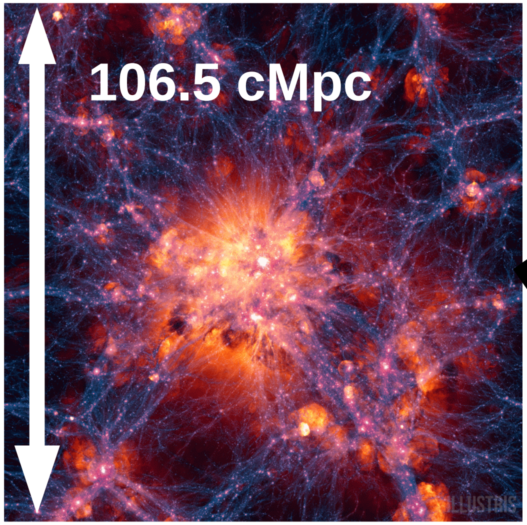
**Dominik+ 2013**



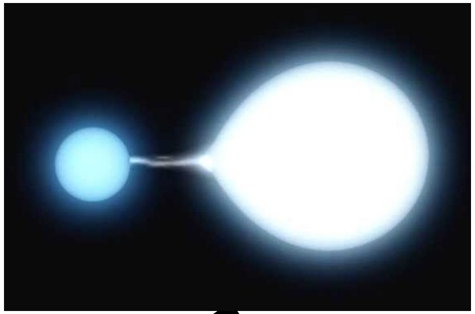
**Issues:** * all stars in a galaxy have same metallicity,
* does not recover mass – metallicity relation

# 4. Compact binaries in cosmological context

**Cosmological simulation**



**Pop. synthesis of isolated binaries**

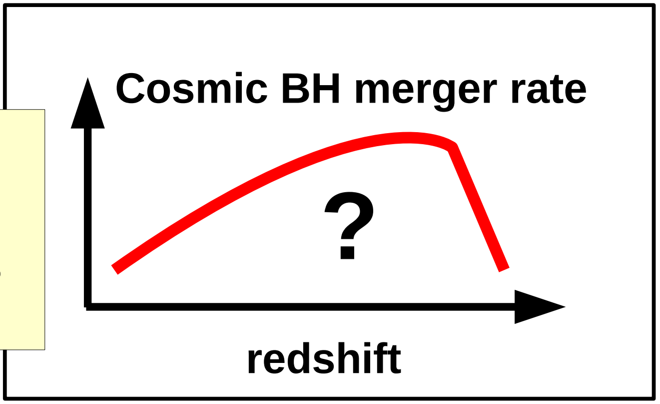


**star formation and metallicity in galaxies**

**catalogues of isolated BH binaries**

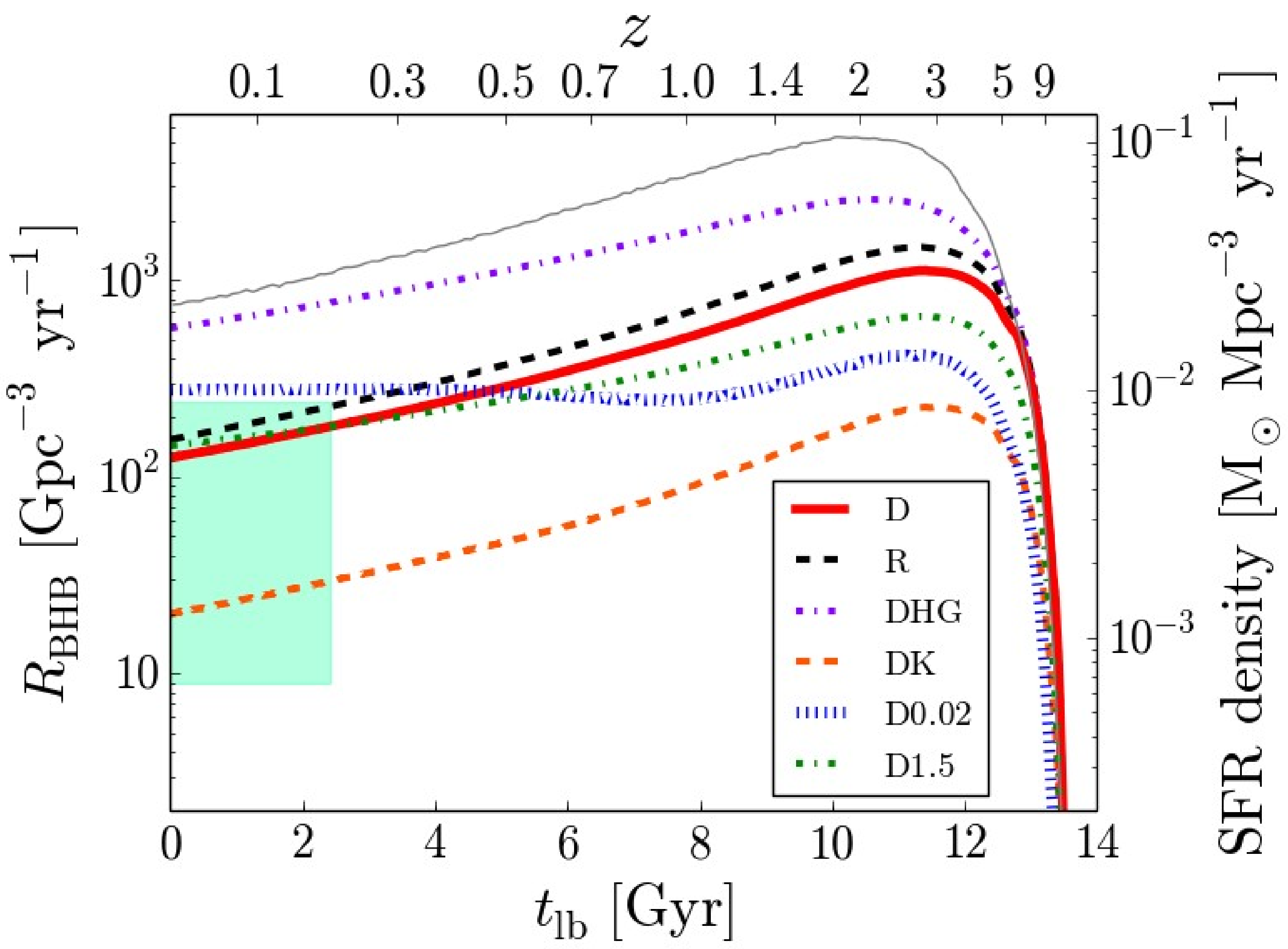
**Monte Carlo code**
**to plant BH binaries in galaxies**

**Cosmic BH merger rate & host galaxy properties**



# 4. Compact binaries in cosmological context

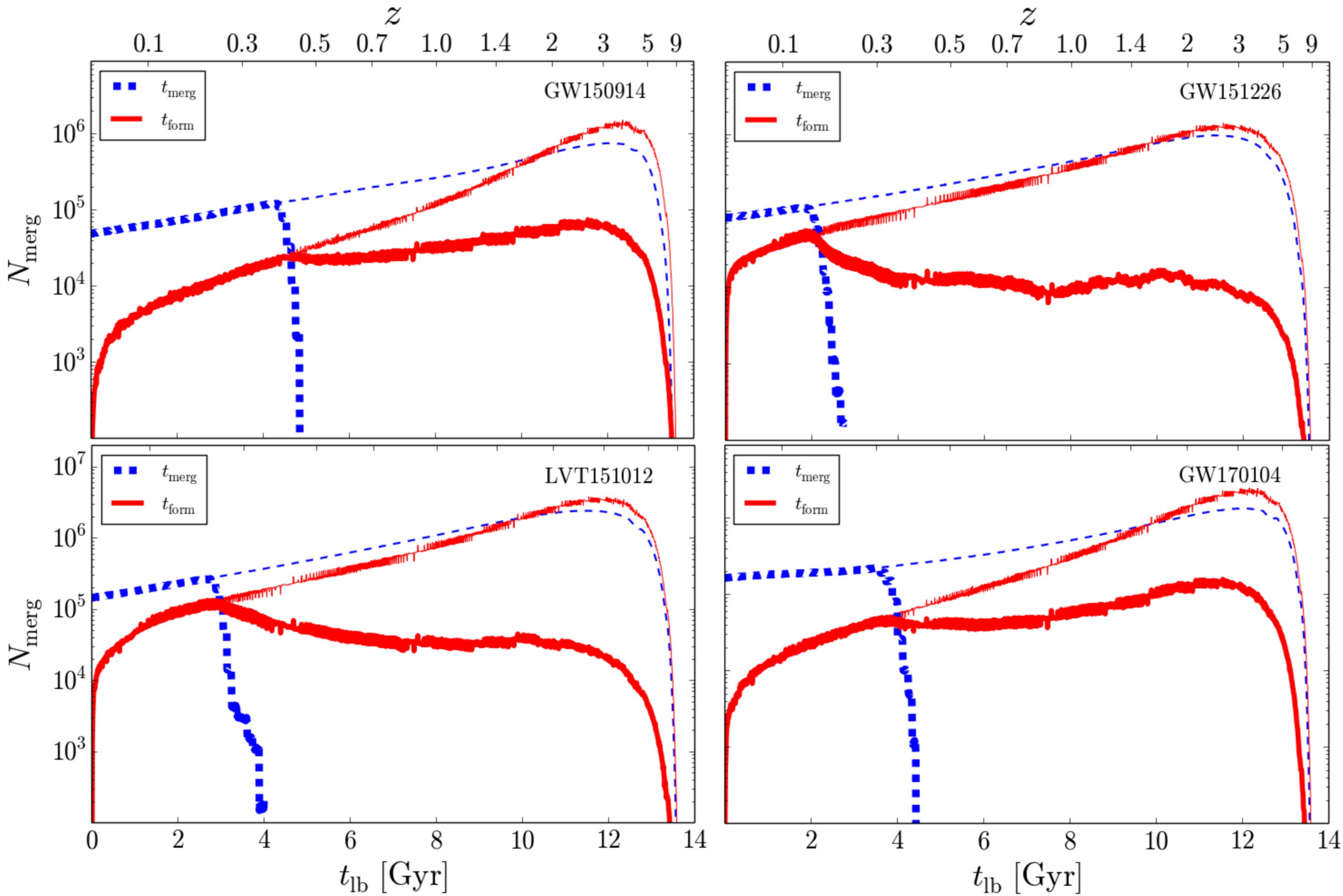
**Black hole merger rate density in comoving frame**



**MM, Giacobbo, Ripamonti, Spera 2017**

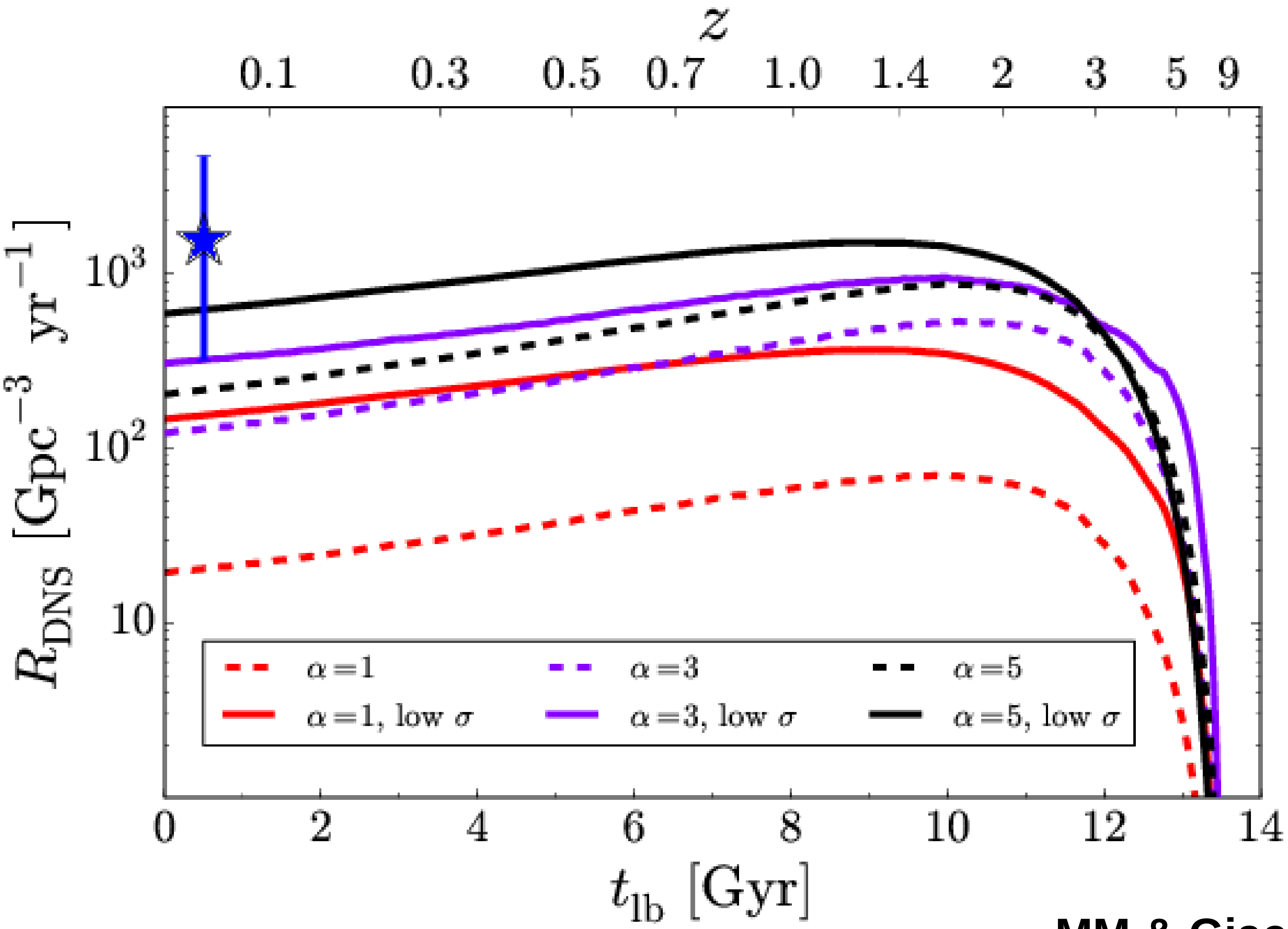
# 4. Compact binaries in cosmological context

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

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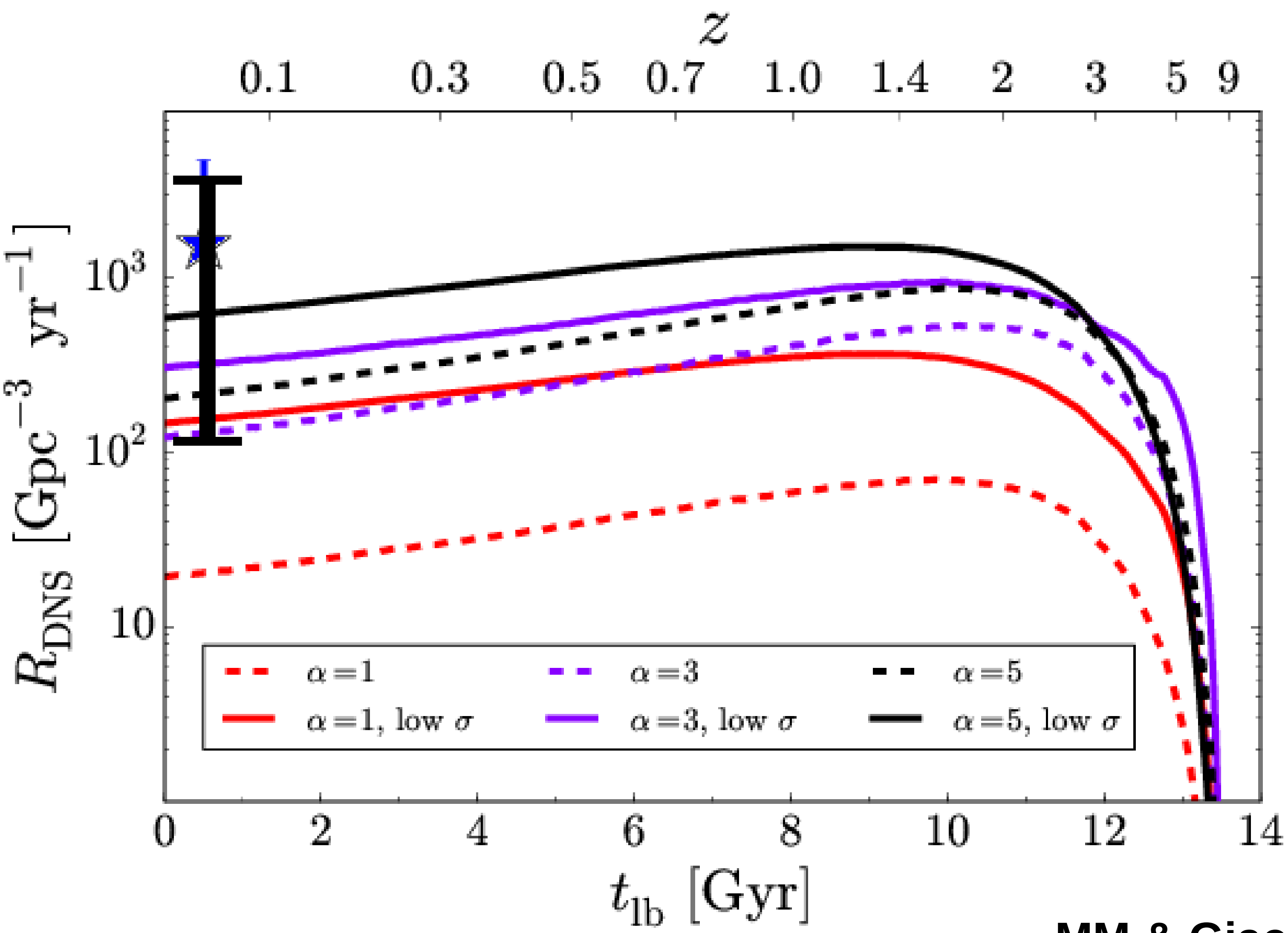
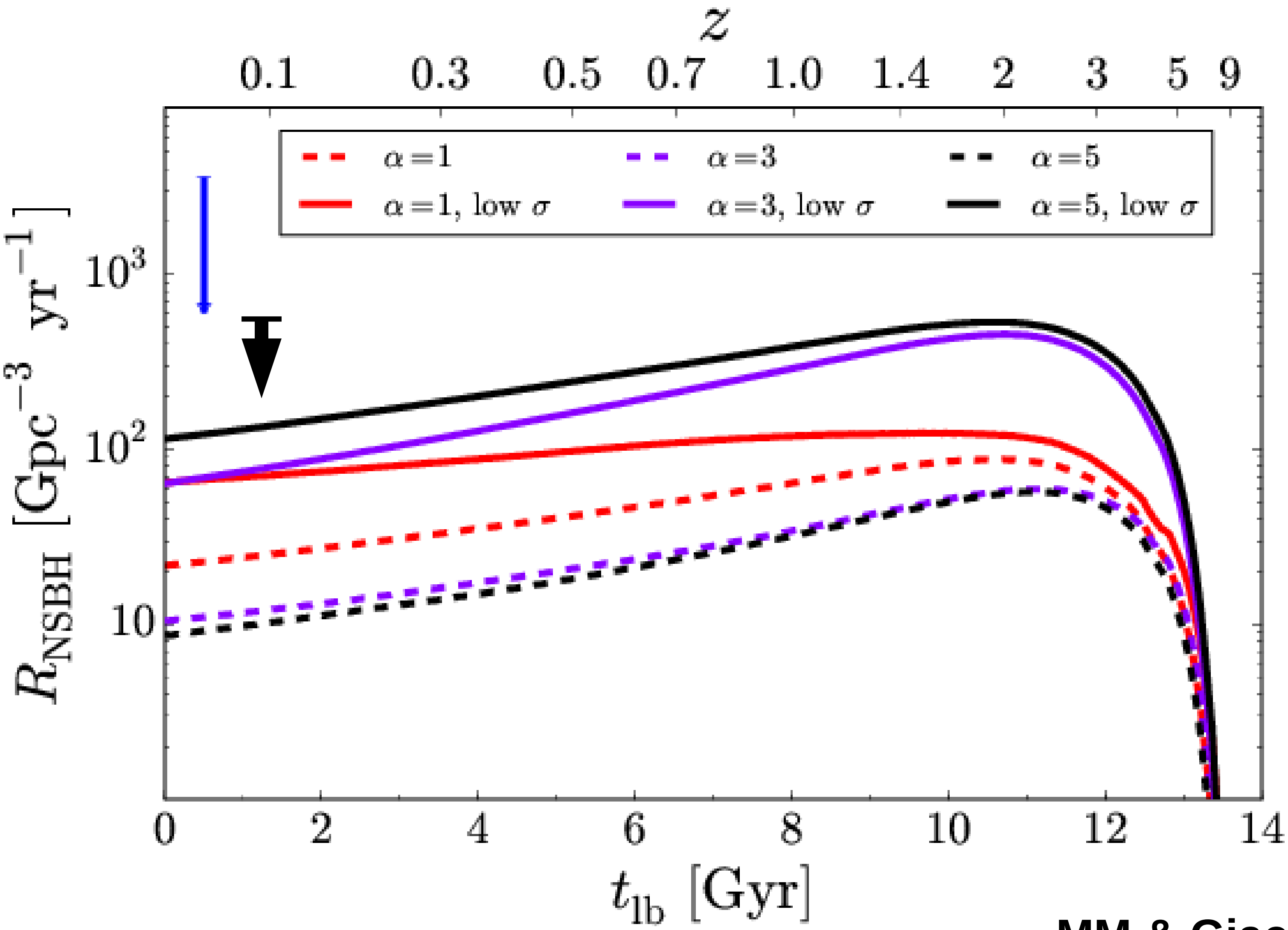


**MM & Giacobbo 2018**

# 4. Compact binaries in cosmological context

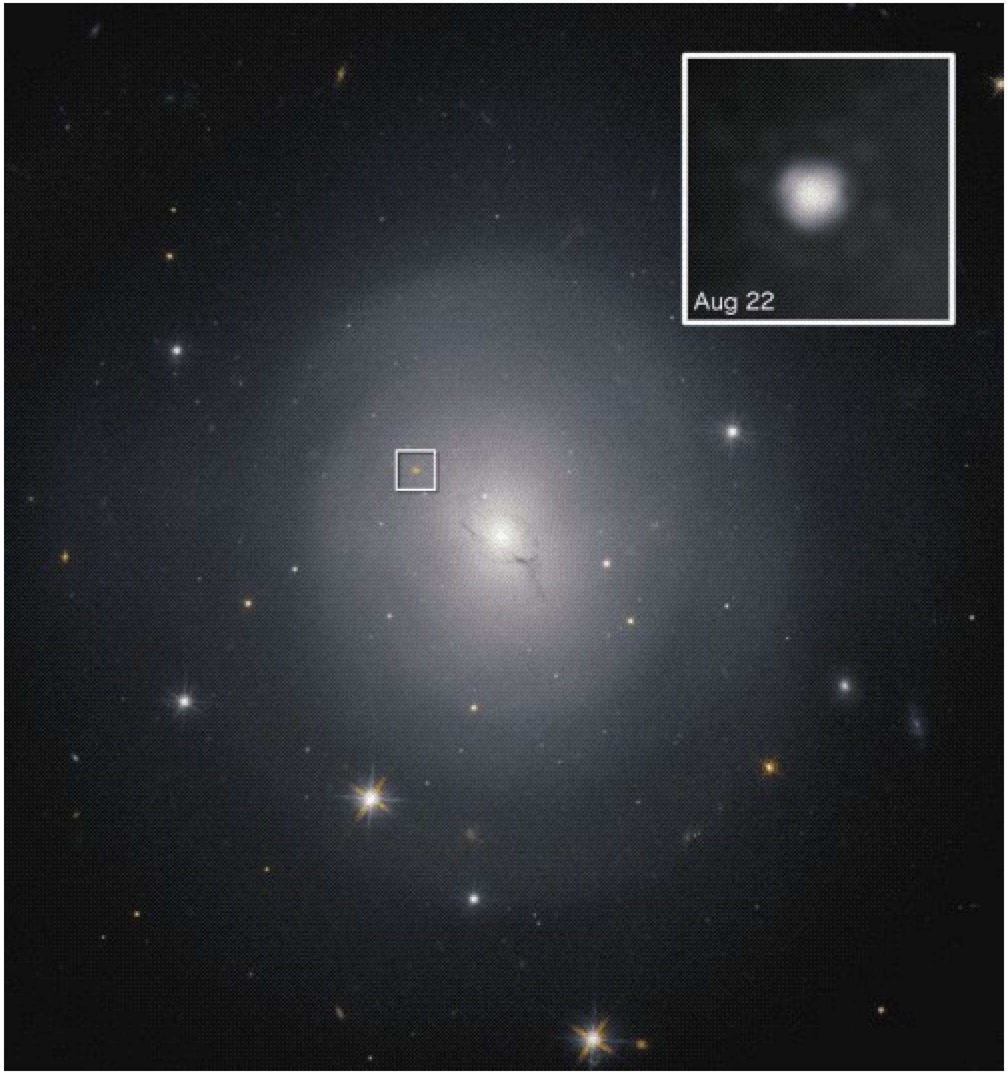
Black hole - neutron star merger rate density in comoving frame



**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)

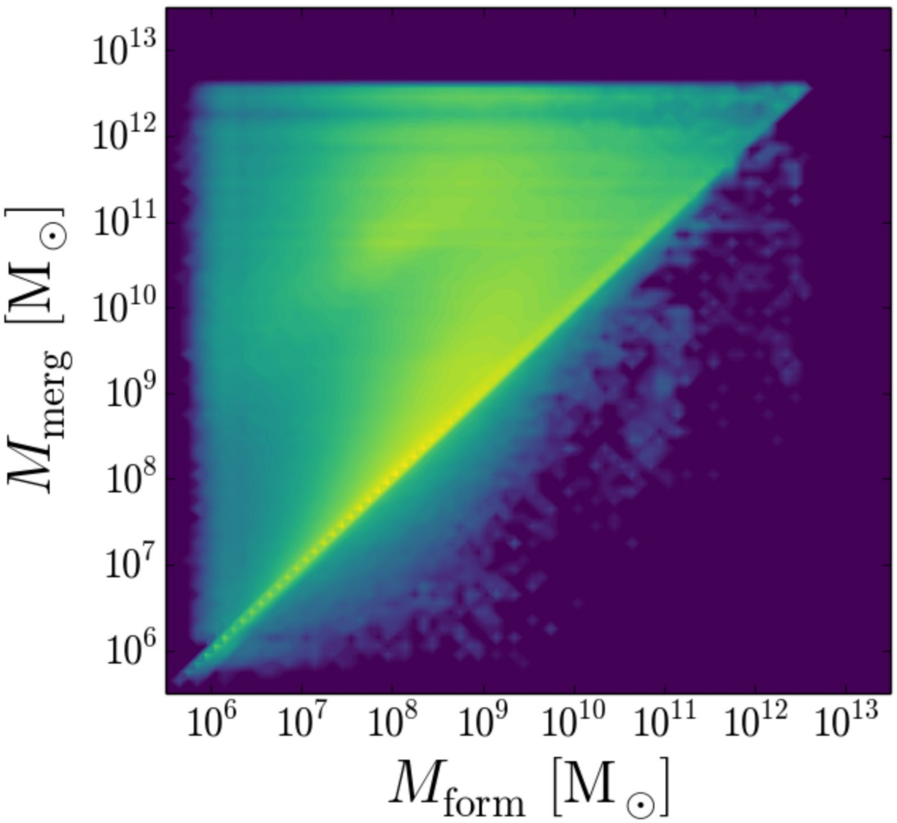
- stellar mass
  ~ $10^{10-11}$ Msun
  (Im et al. 2017)

- indications of a merger

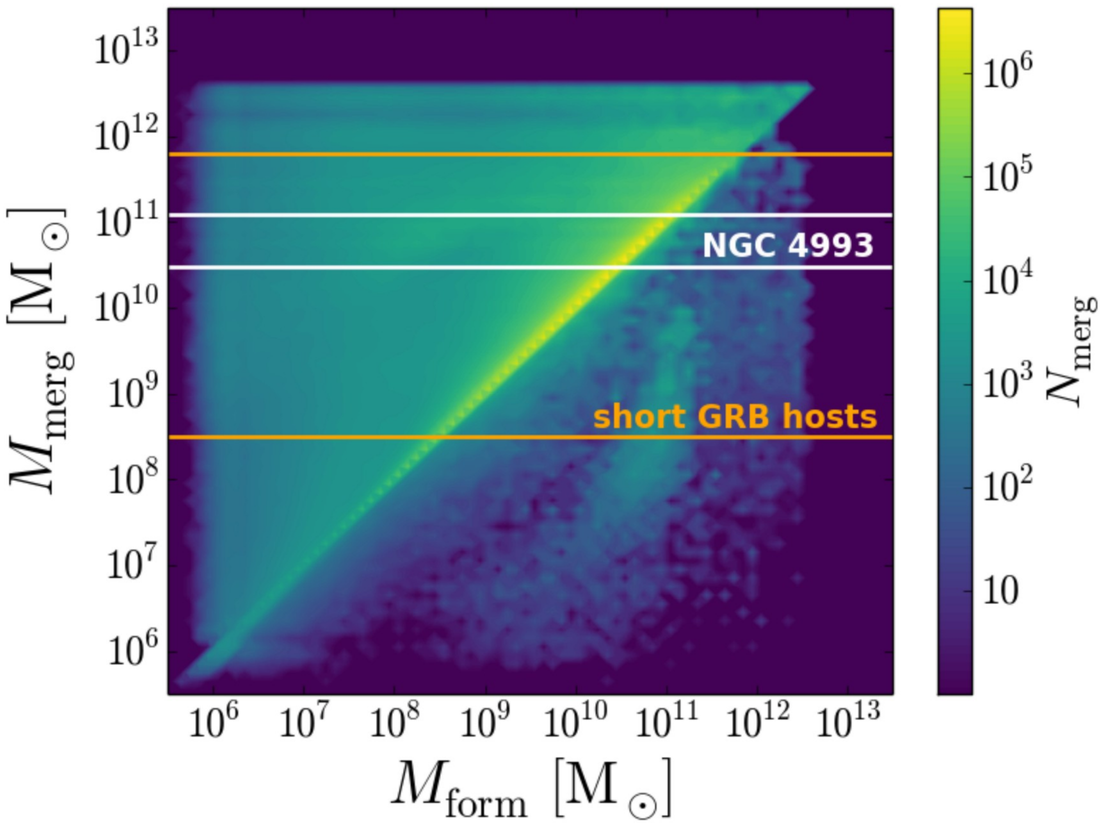
- with cosmo. simulations we can try to characterize them

# 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!