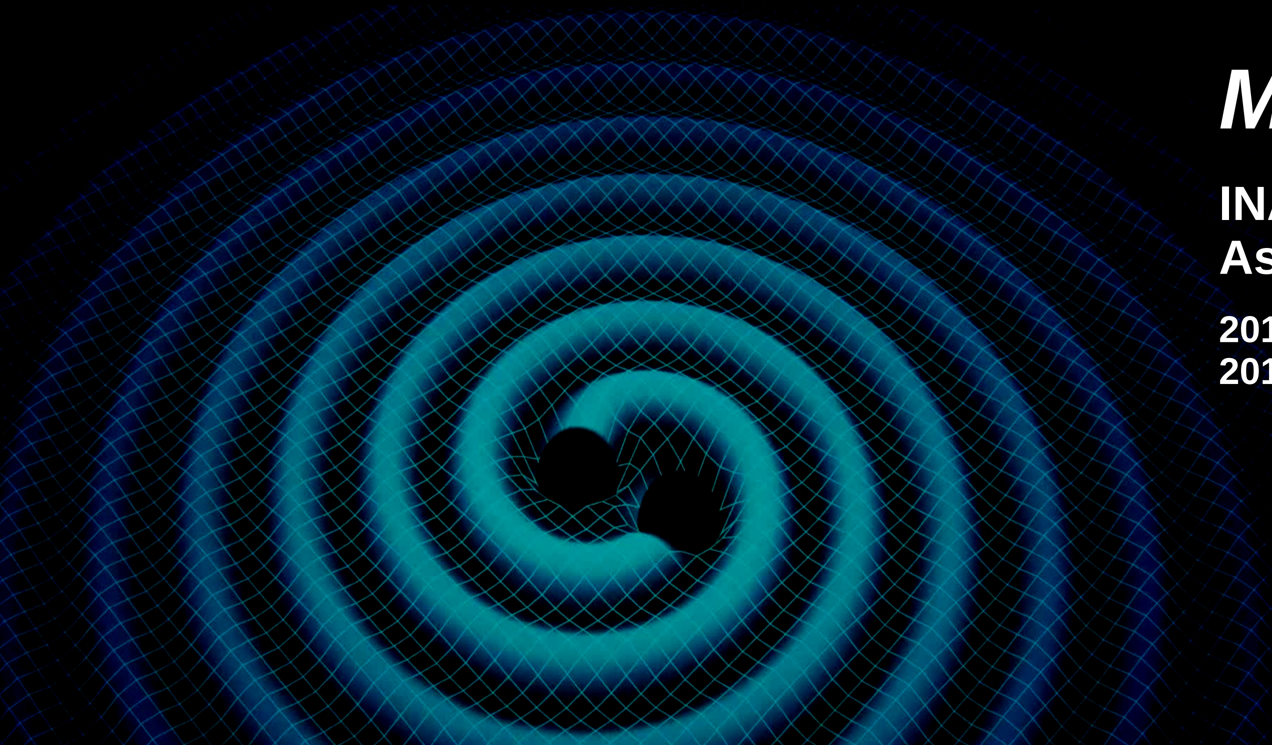


Michela Mapelli

INAF-Osservatorio Astronomico di Padova

2012 FIRB fellow
2015 MERAC prize

The mass spectrum and dynamics of BH-BH binaries

Collaborators: Mario Spera, Nicola Giacobbo, Sandro Bressan, Alessandro A. Trani, Tom O. Kimpson, Elisa Bortolas, Brunetto M. Ziosi, Marica Branchesi

“New Frontiers in Gravitational-Wave Astrophysics, Rome, June 18 – 22 2017

OUTLINE:

BH MASS

1. What influences black hole (BH) mass
2. The mass spectrum of black holes
3. BH binaries

BH – BH DYNAMICS

4. Why dynamics?
5. Exchanges and flybys
6. Intermediate-mass black holes (IMBHs)
7. Kozai-Lidov resonance
8. Effects of dynamics on merger rate
9. Issues about dynamics

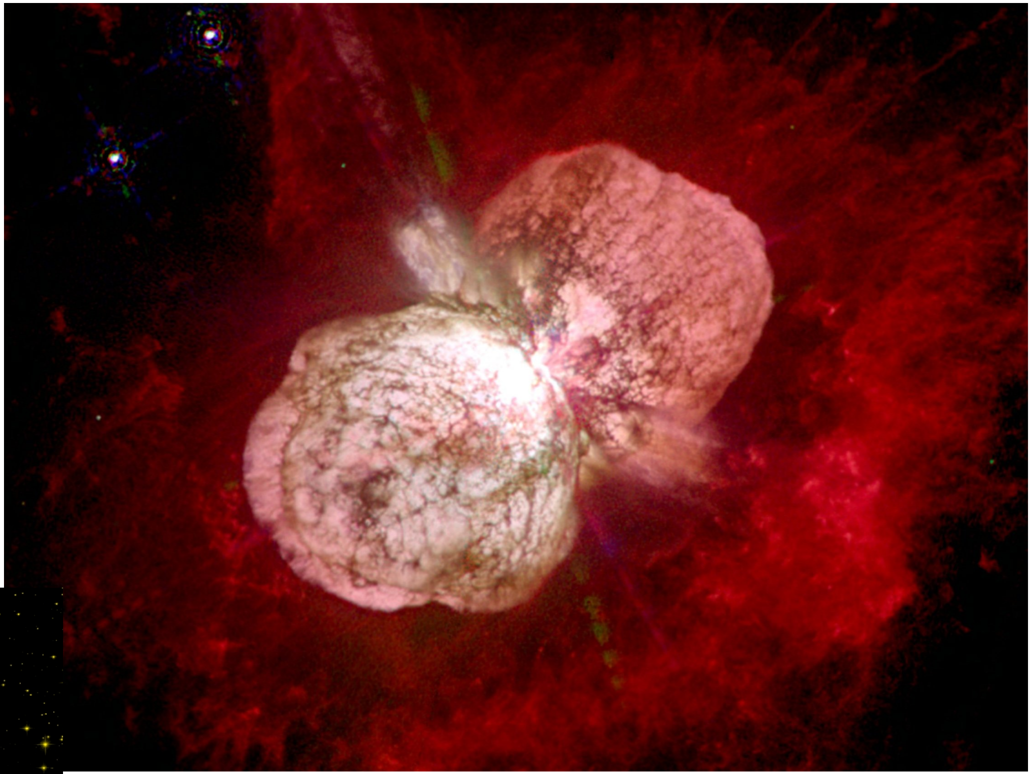
10. Conclusions

1. What influences BH mass

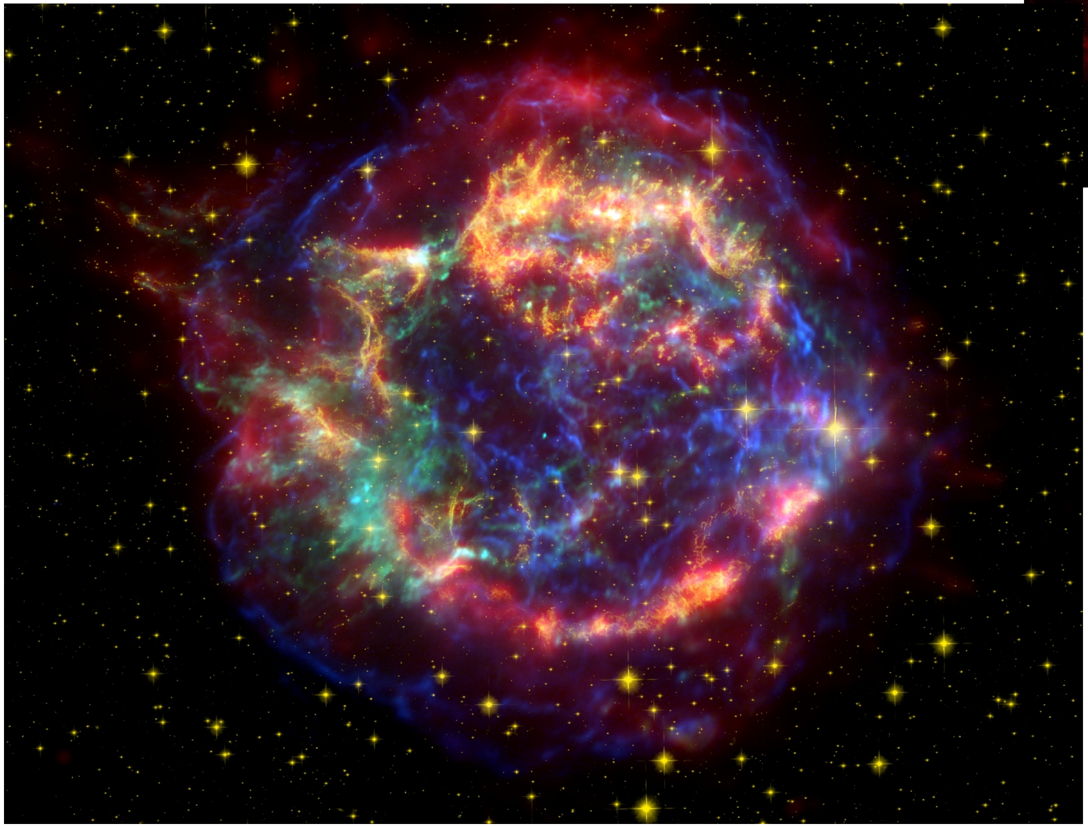
Two critical ingredients determine remnant mass:

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. What influences BH mass: stellar winds

Theory of massive star evolution deeply changed in last decade

* **METALLICITY DEPENDENT WINDS for massive stars (Vink+ 2001; Vink & de Koter 2005; Vink+ 2011)**

* **Metallicity dependence less important when STAR is CLOSE to electron-scattering EDDINGTON LIMIT (e.g. Graefener & Hamann 2008; Vink+ 2011; Vink 2016)**

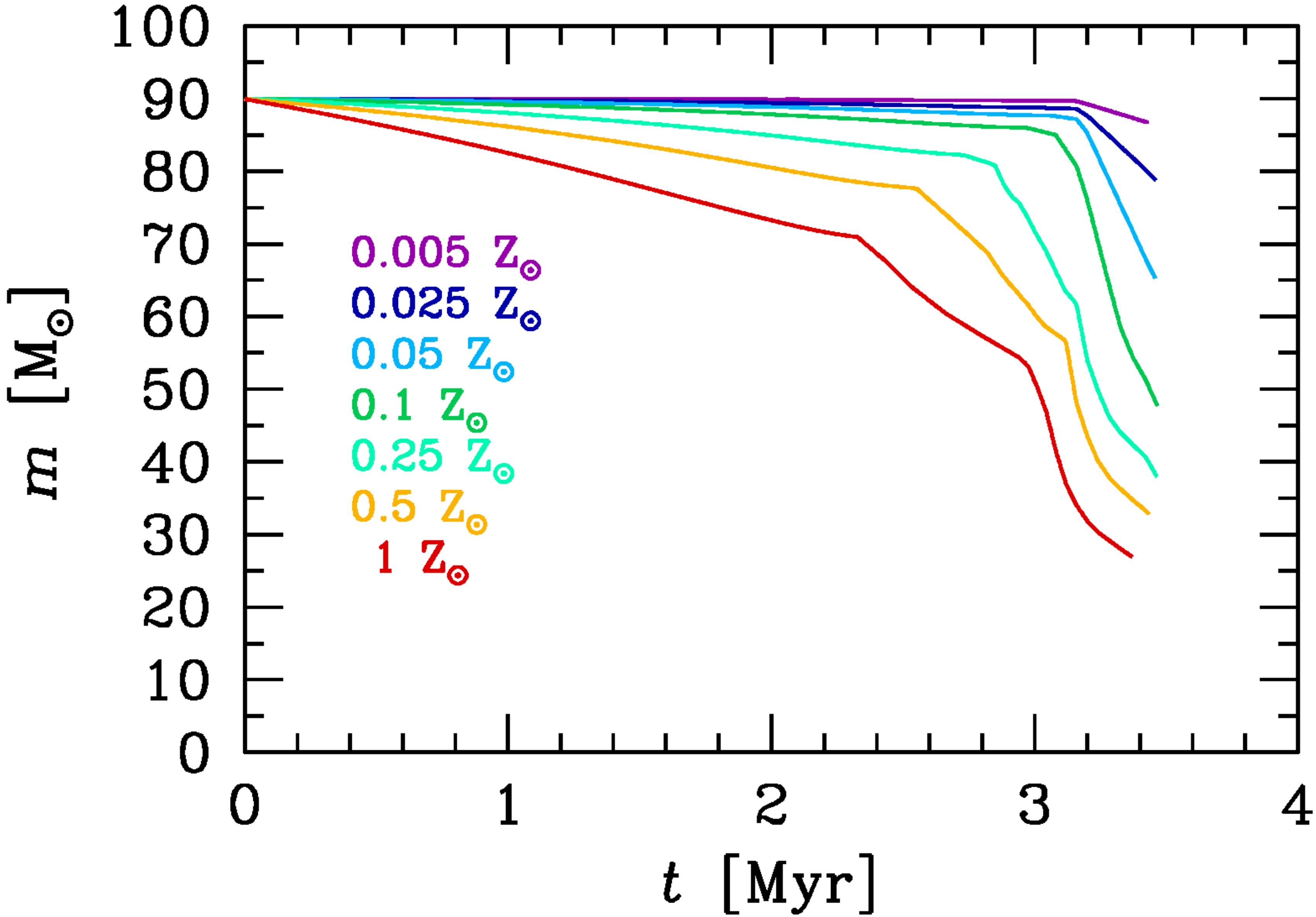
$$\dot{M} \propto Z^{\alpha}$$

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

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

Tang, Bressan+ 2014; Chen, Bressan+ 2015

1. What influences BH mass: stellar winds



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

1. What influences BH mass: core collapse supernova (SN)

* Very uncertain processes drive core-collapse SN
  (Fryer et al. 2012; Ugliano et al. 2012; Janka 2012; Sukhbold & Woosley 2014)

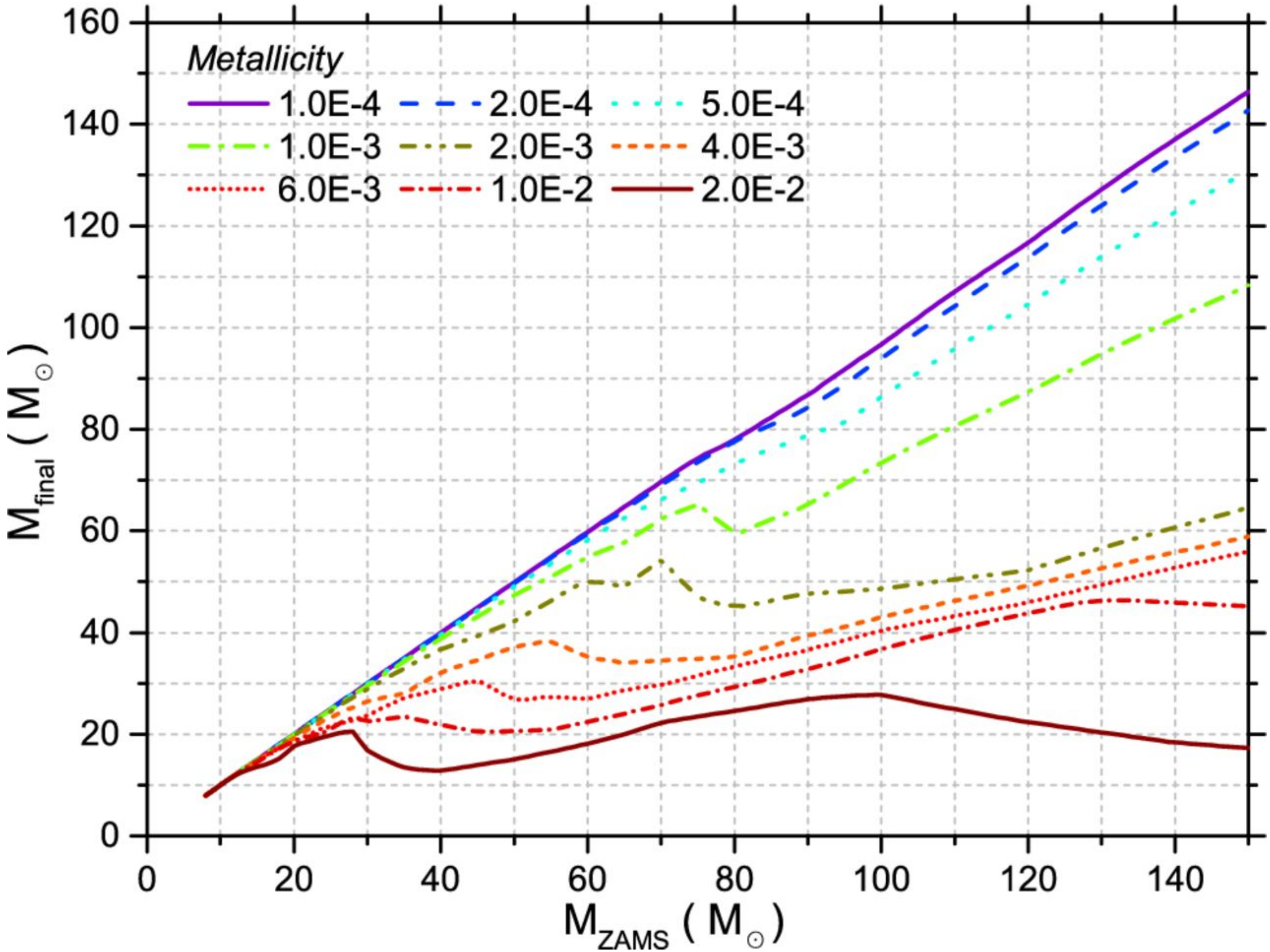
* If mass bound before onset of SN is sufficiently large,
  star can avoid SN and directly collapse to BH
  (Fryer 1999; Fryer & Kalogera 2001; Heger+ 2003; MM, Colpi & Zampieri 2009)

* If remnant forms by direct collapse its mass is larger

* Since metal-poor stars have larger pre-SN masses,
  they are more likely to directly collapse to BH
  and to produce more massive BHs
  (MM, Colpi & Zampieri 2009; Belczynski et al. 2010; Fryer et al. 2012)

2. The mass spectrum of BHs

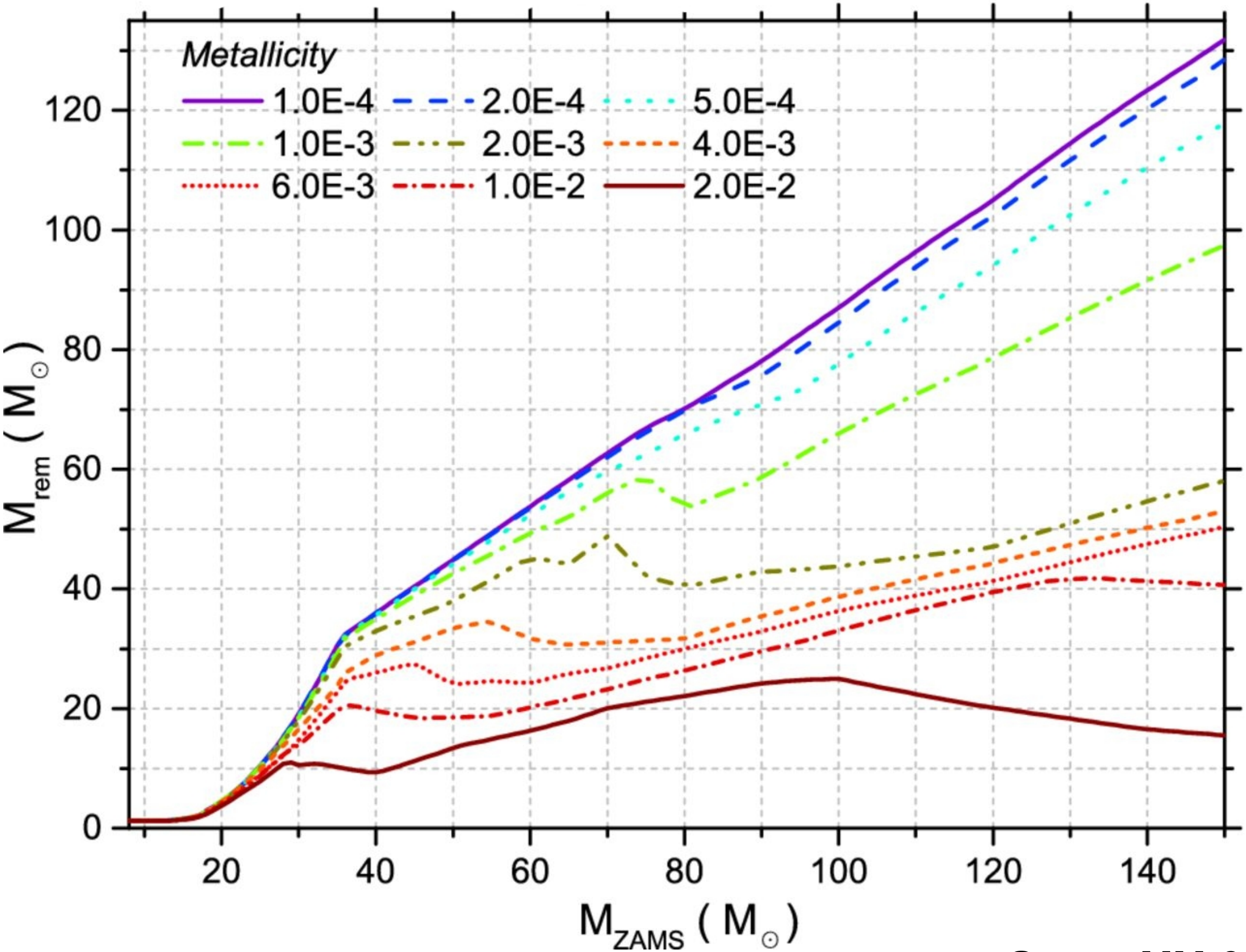
Final mass: pre-supernova mass of the star (when CO core built)



Spera, MM & Bressan 2015

2. The mass spectrum of BHs

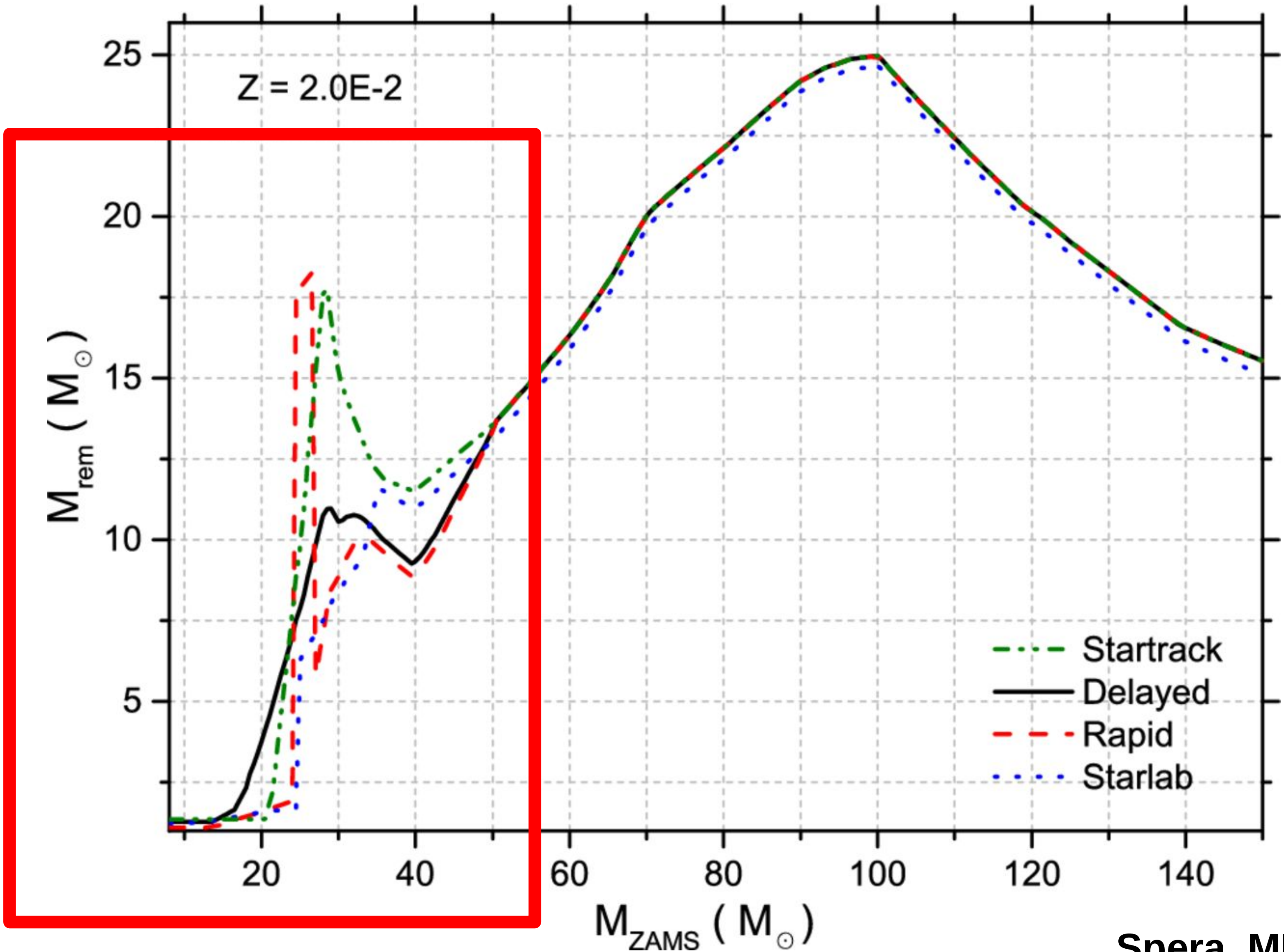
Remnant mass follows same trend as final mass
→ stellar winds are crucial



Spera, MM & Bressan 2015

2. The mass spectrum of BHs

Importance of supernova model only for LOW REMNANT MASSES



Spera, MM & Bressan 2015

2. The mass spectrum of BHs

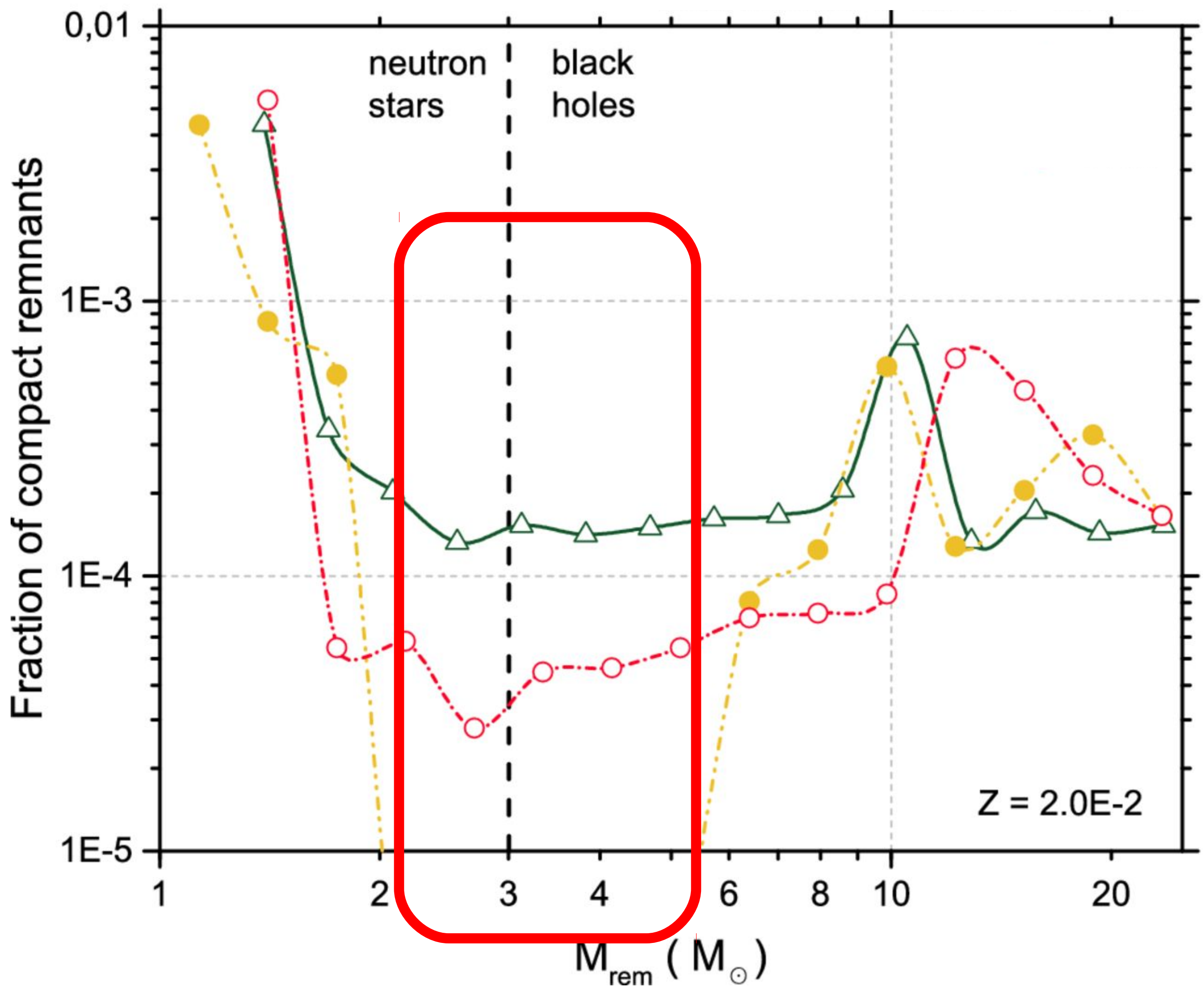
Importance of supernova model only for LOW REMNANT MASSES

Solar metallicity

GREEN:
DELAYED
SN (Fryer+ 2012)

RED:
DELAYED
SN (MM+ 2013)

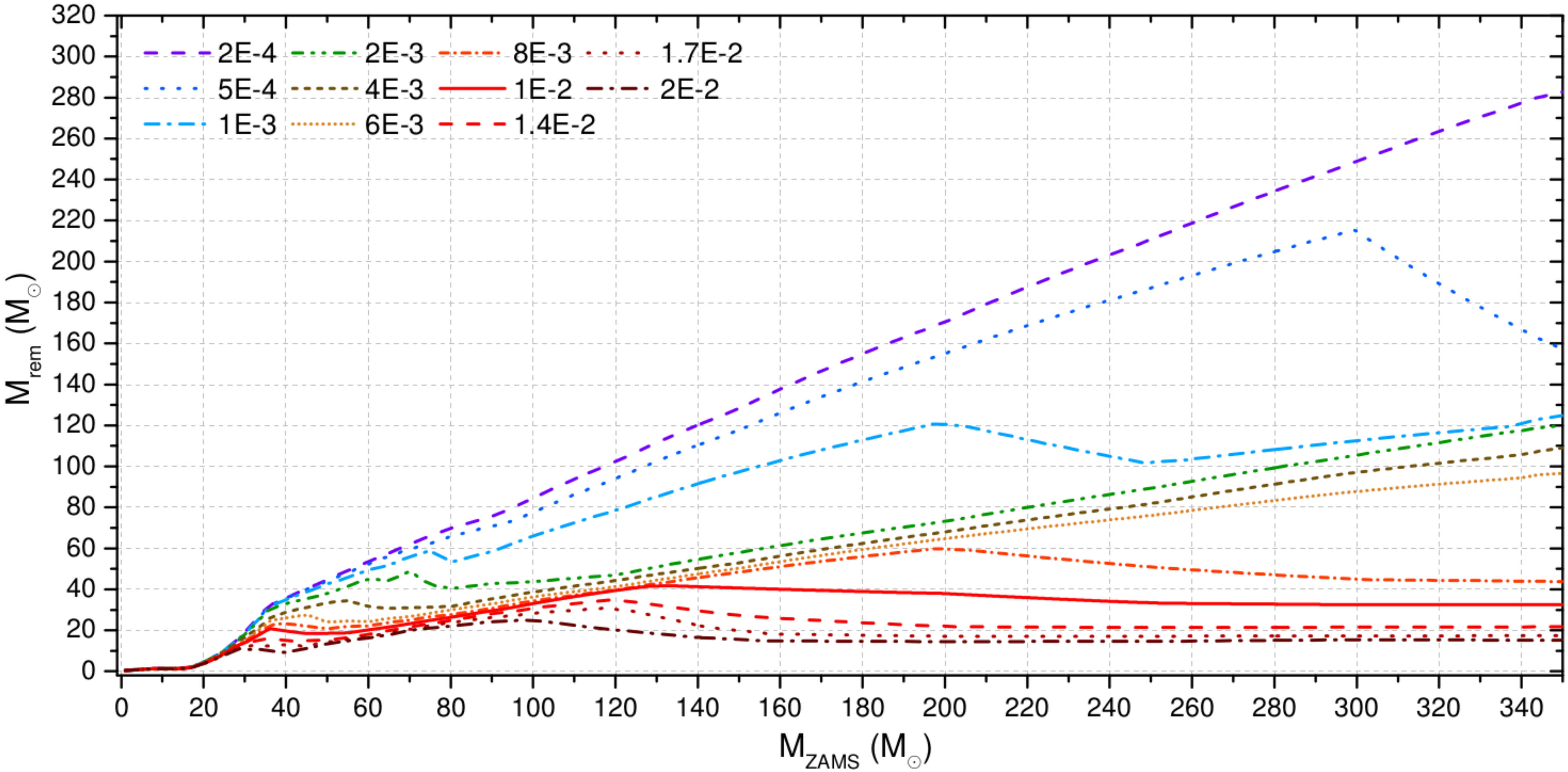
YELLOW:
PROMPT SN
(Fryer+ 2012)



Spera, MM & Bressan 2015

2. The mass spectrum of BHs

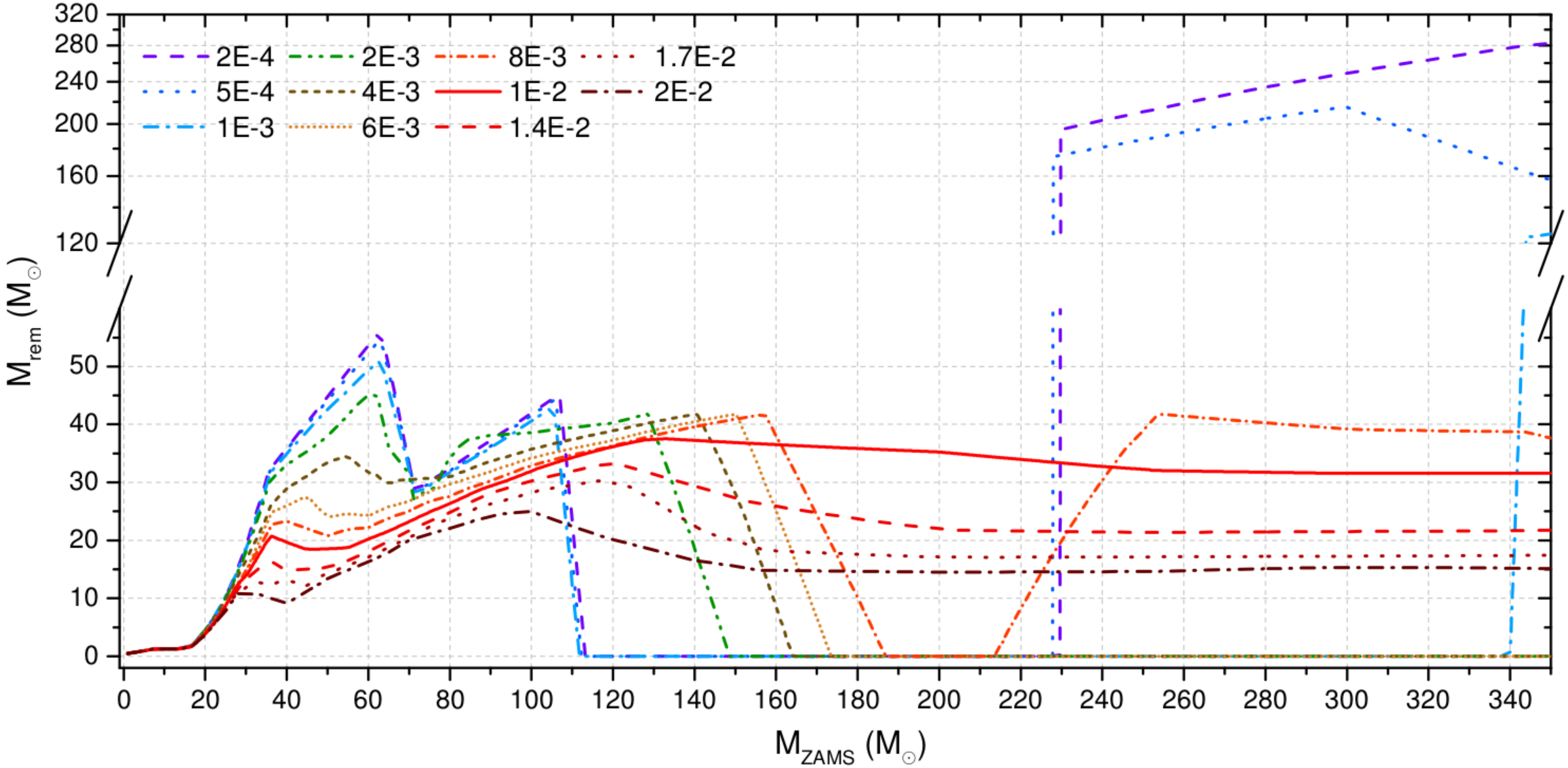
Evolution of very massive stars still uncertain
→ stellar winds are Eddington-limited rather than metallicity dependent



Spera & MM 2017

2. The mass spectrum of BHs

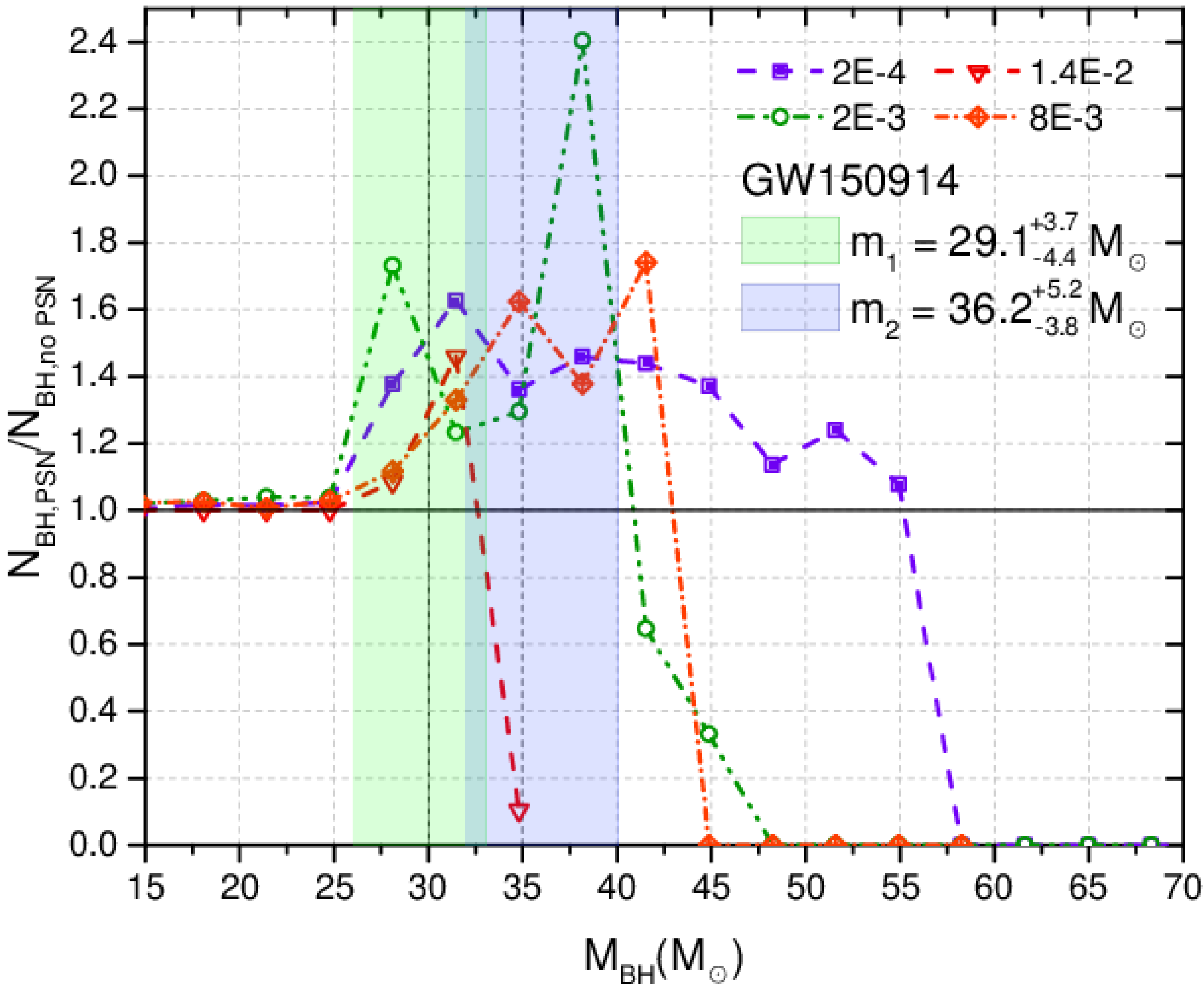
Role of pulsational pair-instability and pair-instability supernovae (still missing in most models)



Spera & MM 2017

2. The mass spectrum of BHs

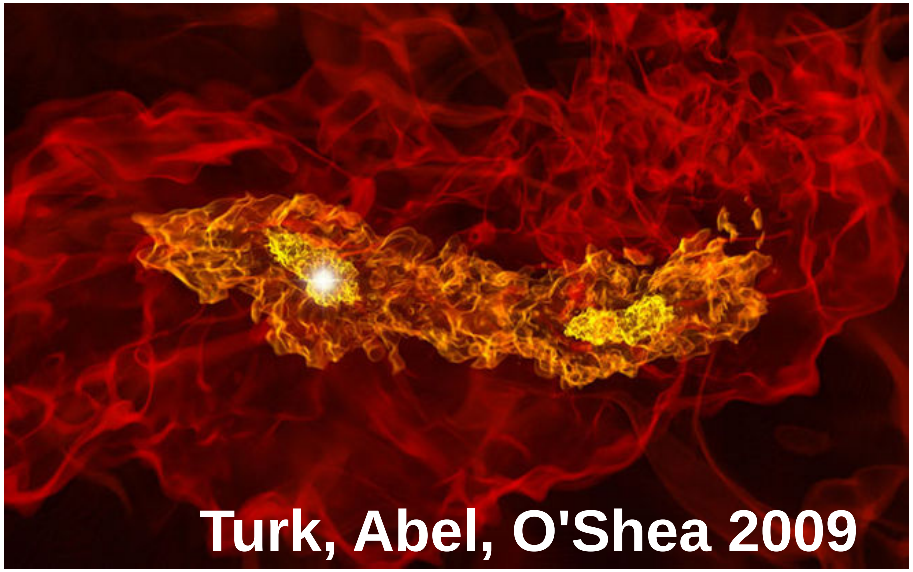
Effect of PISNe and PPISNe on the formation of GW150914



Spera & MM 2017

3. BH binaries

SIMPLE IDEA: 2 stars form from same gas cloud and evolve into 2 BHs gravitationally bound


Turk, Abel, O'Shea 2009

NOT SO EASY:

Many evolutionary processes can affect the binary

- single star evolution (stellar winds)
- supernova and remnant formation
- wind mass transfer
- Roche lobe mass transfer
- common envelope
- tidal evolution
- magnetic braking
- orbital evolution
- supernova kick
- gravitational wave decay
- gravitational wave kick

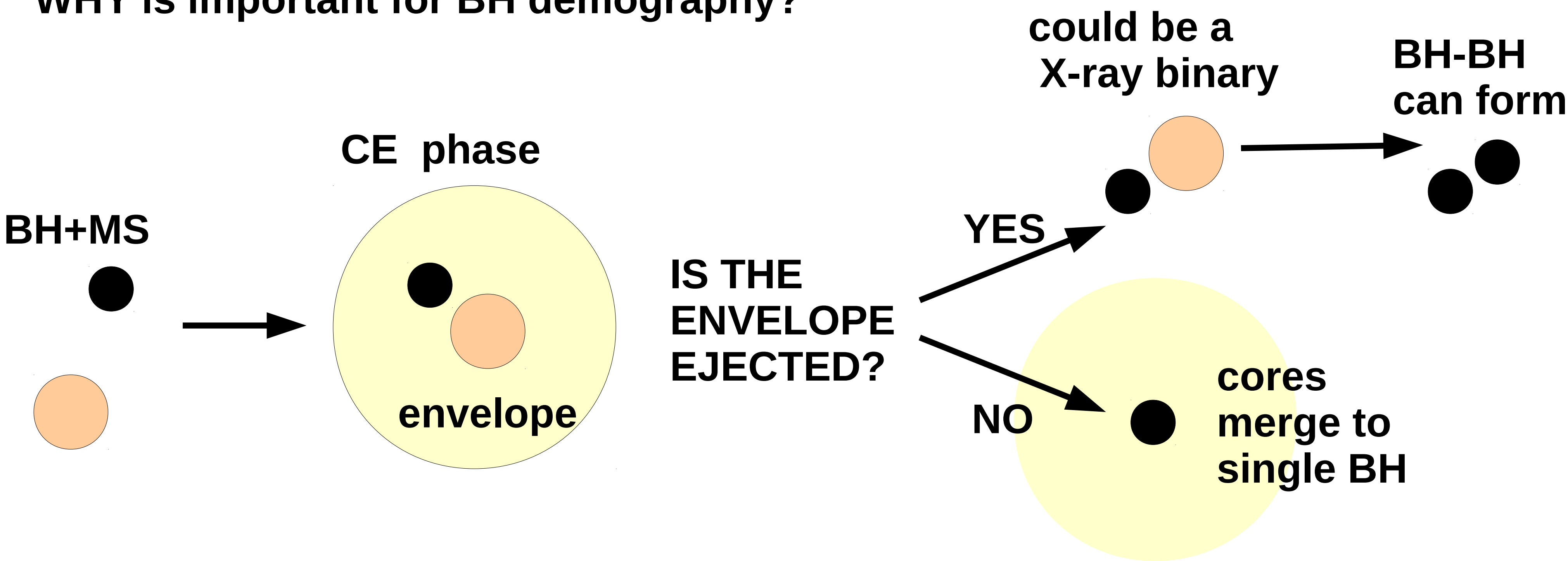
Binary evolution studied via POPULATION SYNTHESIS CODES:

- Seba in Starlab (Portegies Zwart+ 2001; MM+2013)
- BSE (Hurley+ 2002; Giacobbo, MM+ in prep.)
- StarTrack (Belczynski+ 2010)
- SEVN (Spera, MM & Bressan 2015; Spera & MM 2017)

3. BH binaries

Common envelope in binaries:

WHY is important for BH demography?

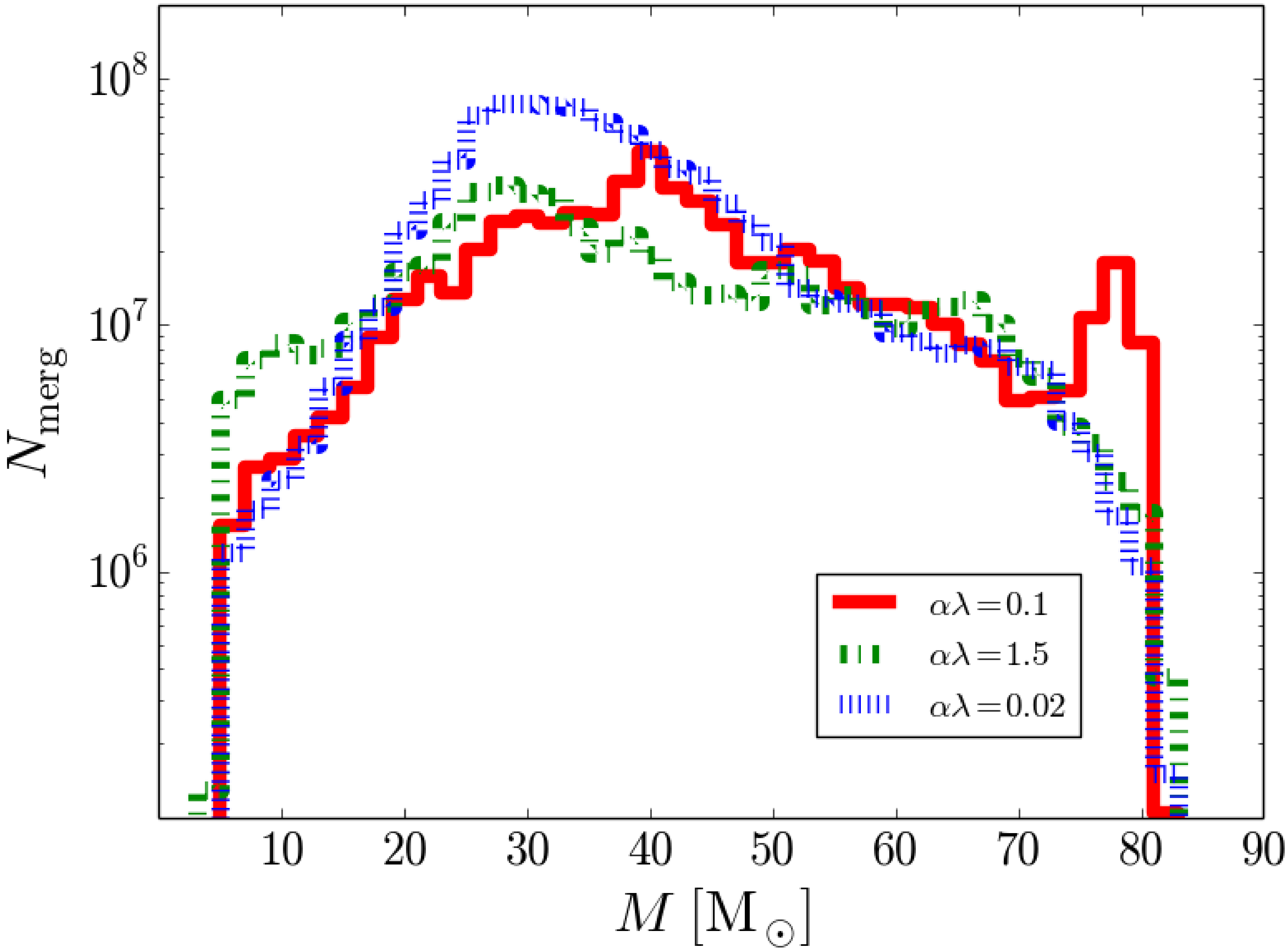


COMMONLY USED α λ formalism does not capture physics

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

3. BH binaries

Total mass distribution of BH binaries with population synthesis



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

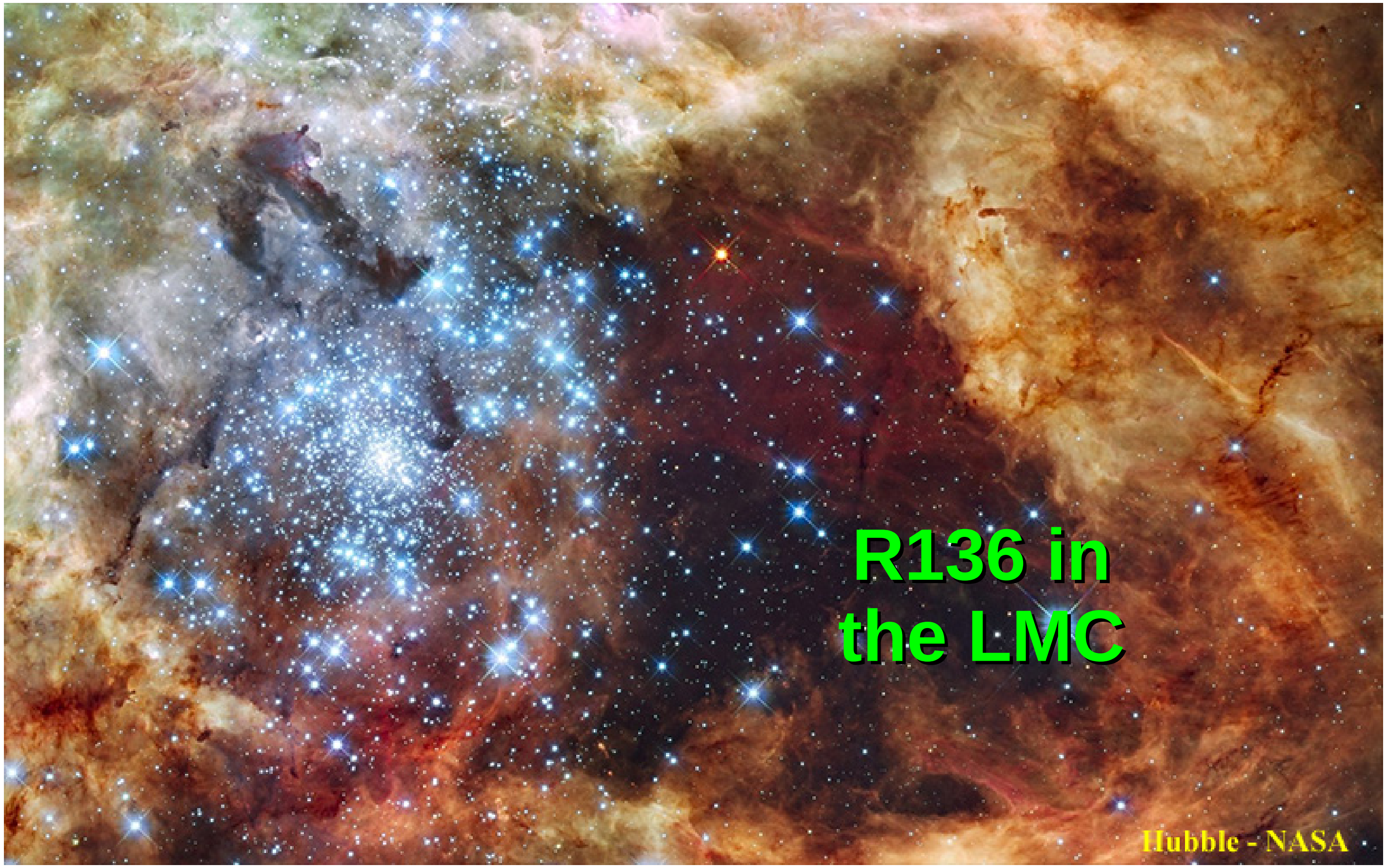
4. Why dynamics?

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

i.e. only in dense star clusters

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*)**



4. Why dynamics?

FIELD:

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

GLOBULAR CLUSTERS:

*** dynamics**

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

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

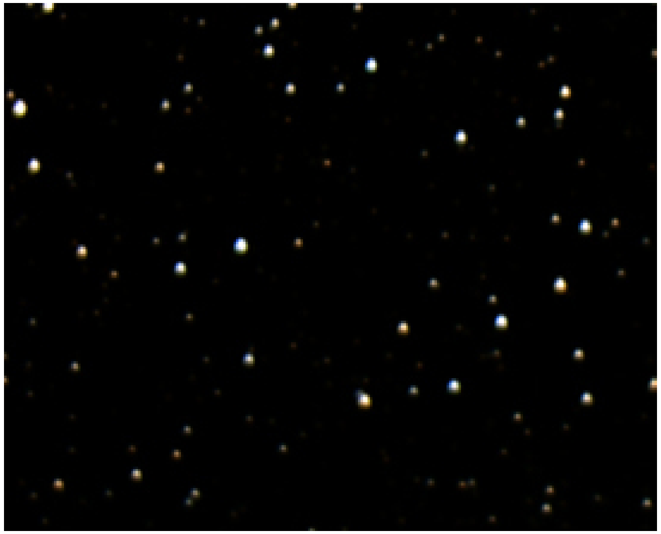


Image credit: Jim Mazur's Astrophotography, via http://www.skyledge.net/.

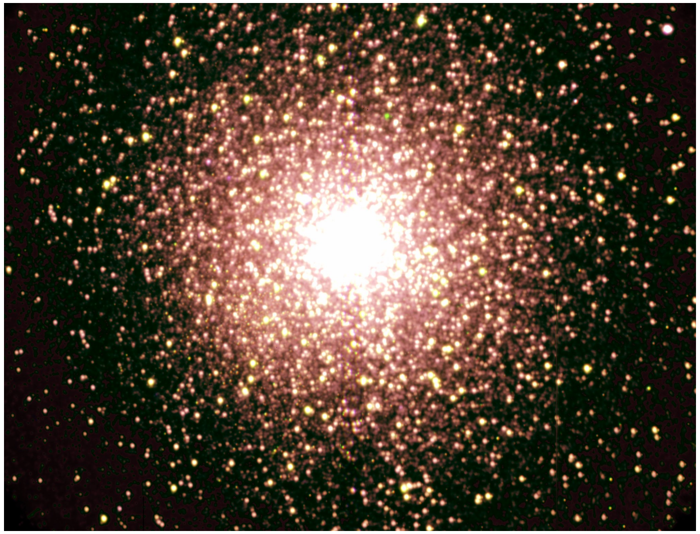


Image credit: HST

4. Why dynamics?

FIELD:

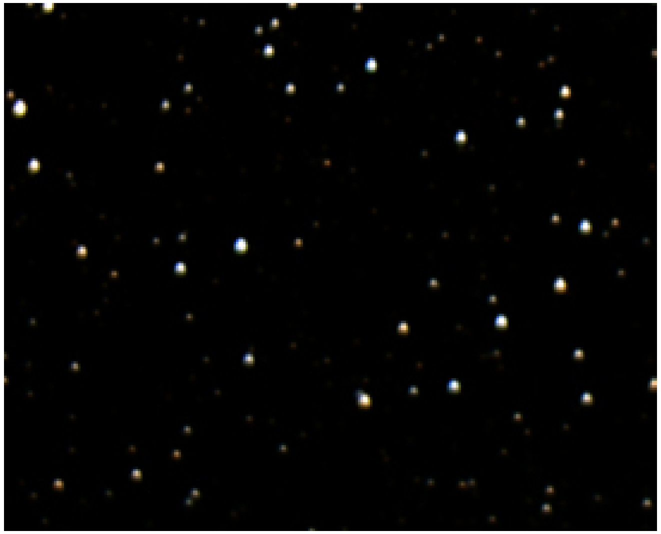
* NO dynamics (density in solar neighborhood <1 star pc^-3)

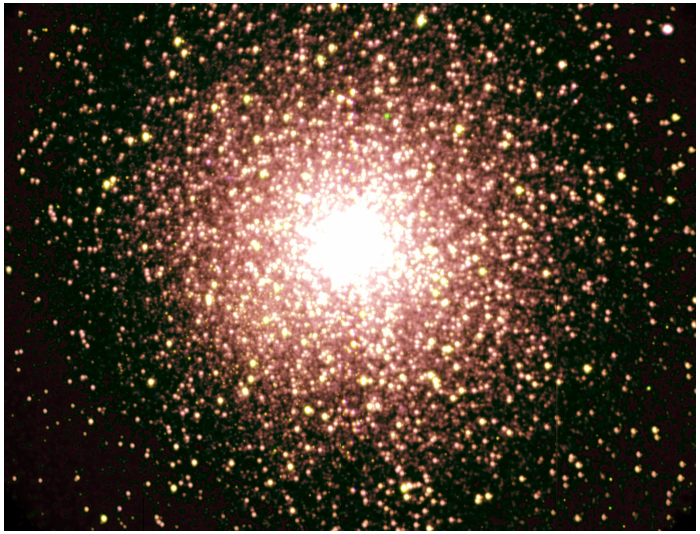
YOUNG STAR CLUSTERS and OPEN CLUSTERS:

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

GLOBULAR CLUSTERS:

* dynamics
* long-lived (12 Gyr)
* < 1 % baryon mass of the Universe





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GLOBULAR CLUSTERS:

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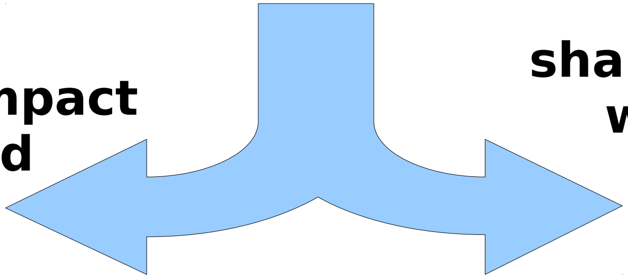
*** long-lived (12 Gyr)**

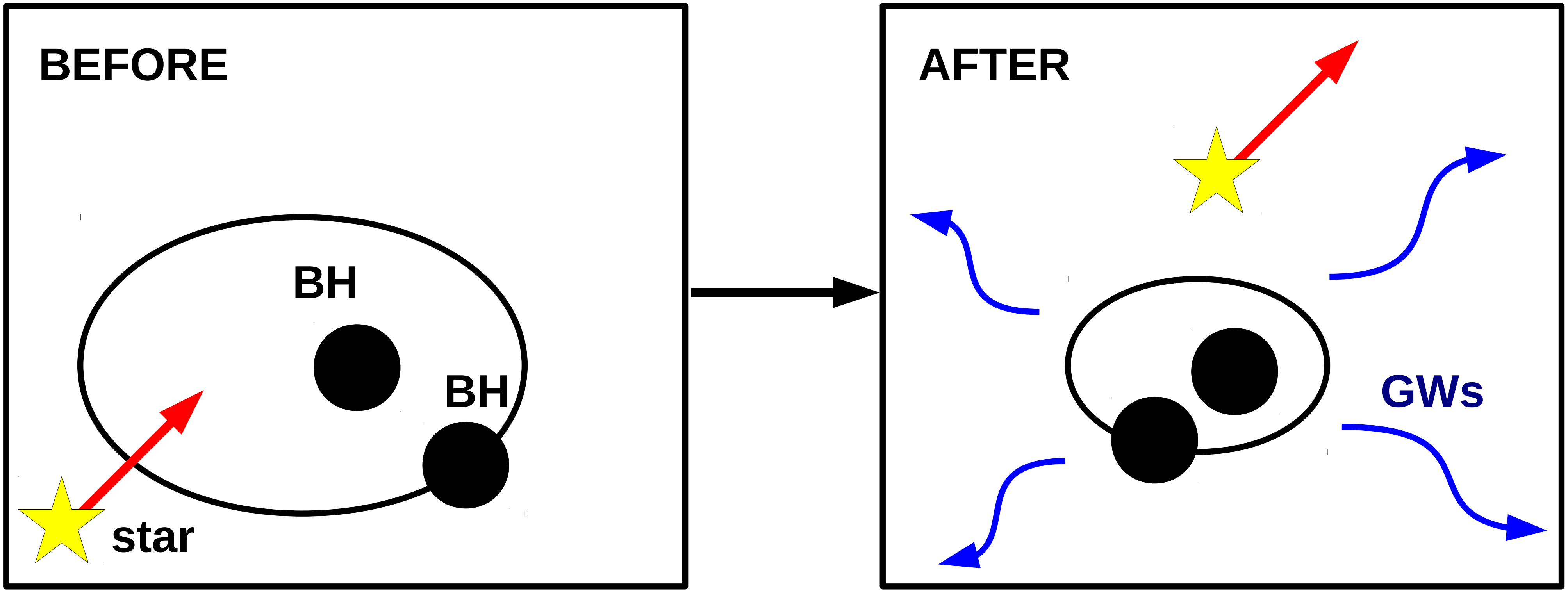
*** < 1 % baryon mass of the Universe**

provide stars (and compact objects) to the field



share dynamical properties with globular clusters

5. Exchanges and flybys

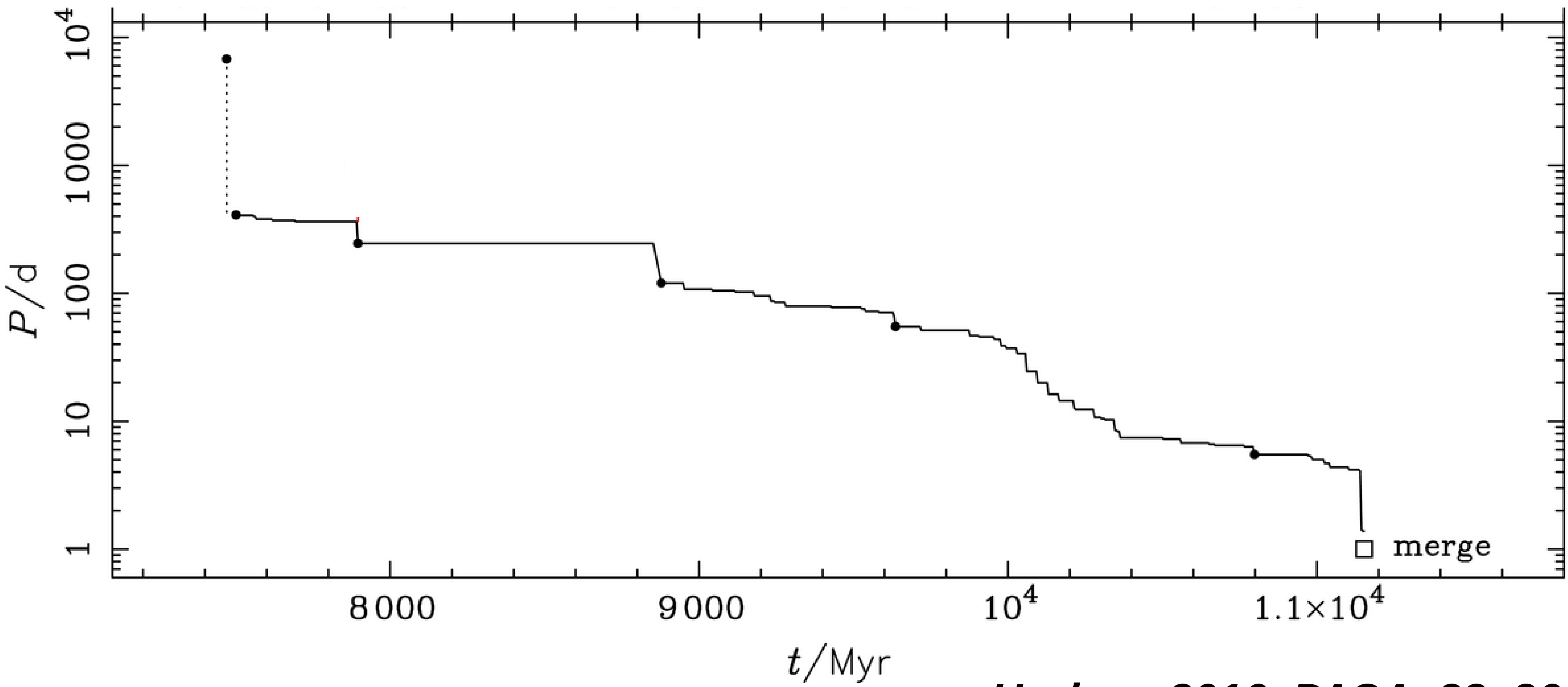


In a flyby, the star acquires kinetic energy from the binary

→ ***the binary shrinks***

→ ***shorter coalescence time***

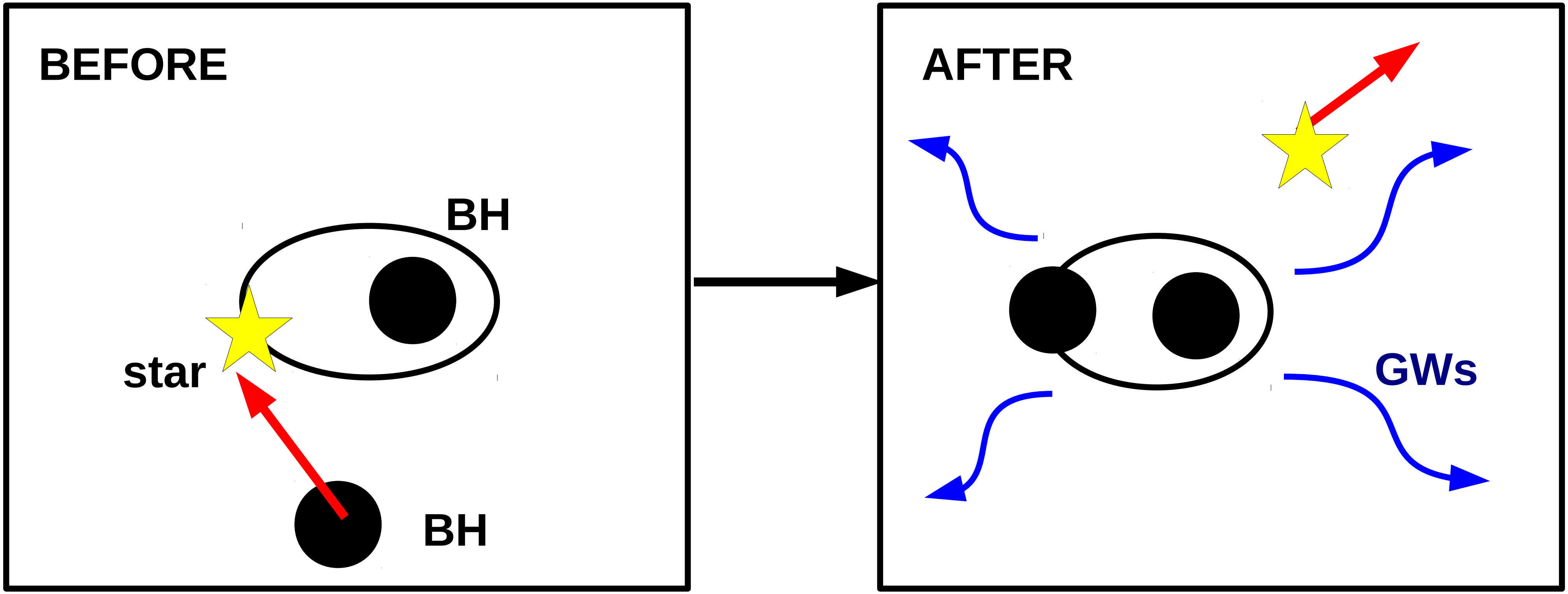
5. Exchanges and flybys



Hurley+ 2016, PASA, 33, 36

Hills 1992, AJ, 103, 1955; Kulkarni+ 1993, Nature, 364, 421; Sigurdsson & Hernquist 1993, Nature, 364, 423; Portegies Zwart & McMillan 2000, ApJ, 528, L17; Aarseth 2012, MNRAS, 422, 841; Breen & Heggie 2013, MNRAS, 432, 2779 ETC ETC...

5. Exchanges and flybys

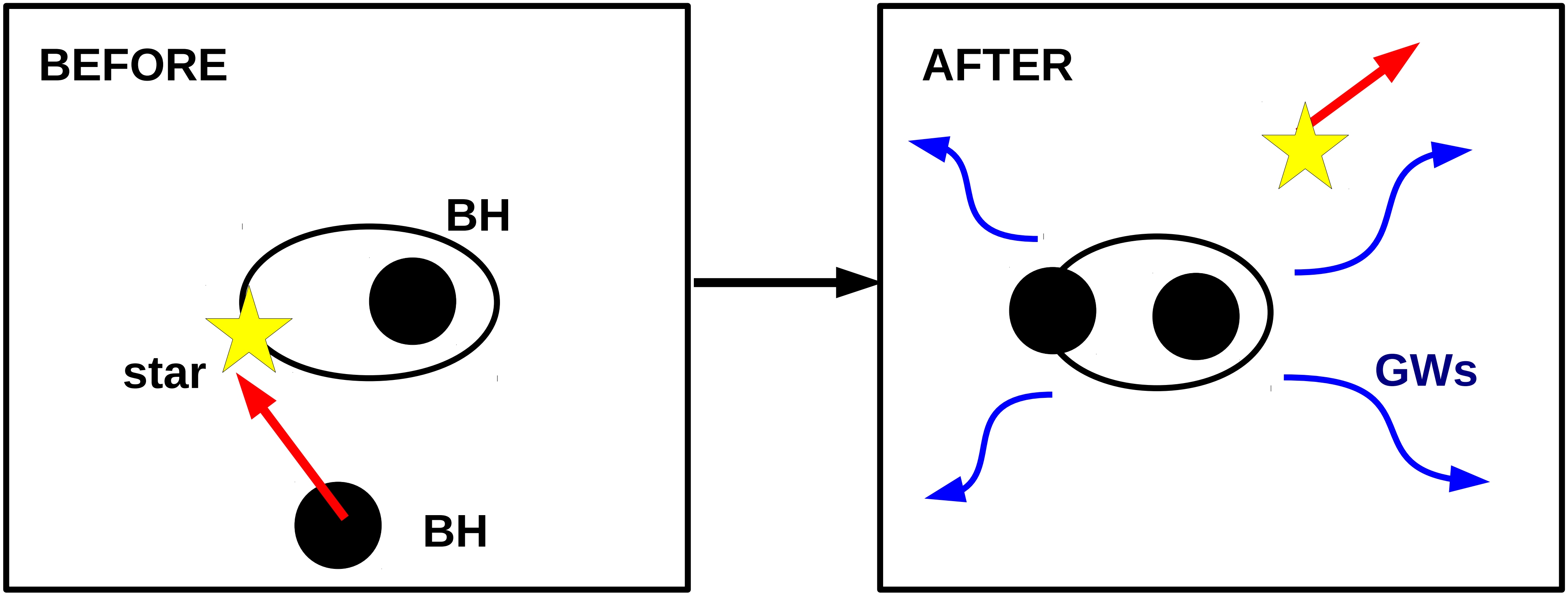


Exchanges bring BHs in binaries

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

5. Exchanges and flybys



>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

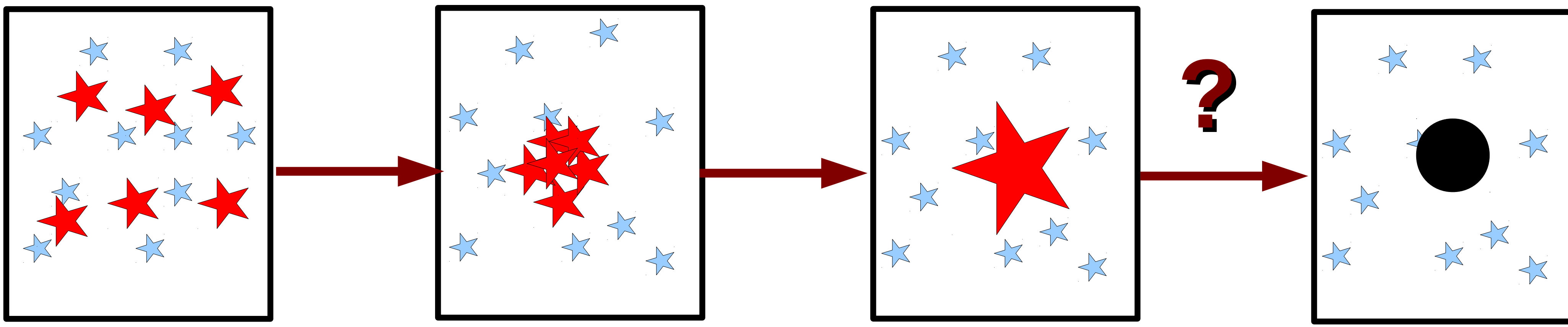
- *THE MOST MASSIVE BHs*
- *HIGH ECCENTRICITY*
- *MISALIGNED BH SPINS*

6. Intermediate-mass black holes (IMBHs): 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

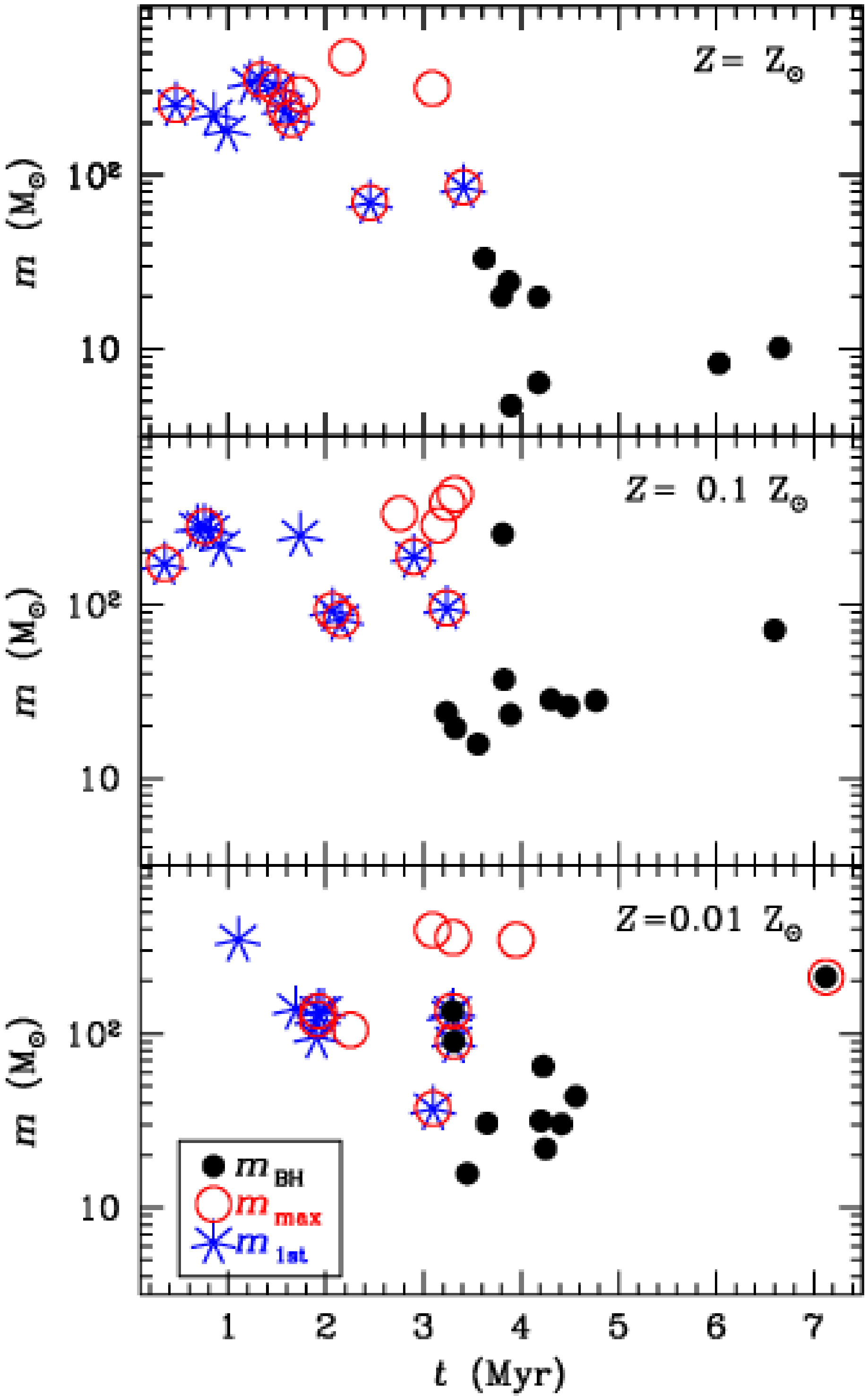


Massive super-star forms and possibly collapses to IMBH

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

6. Intermediate-mass black holes (IMBHs): runaway collisions



N-body simulations with star evolution

Masses of runaway collision products:

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

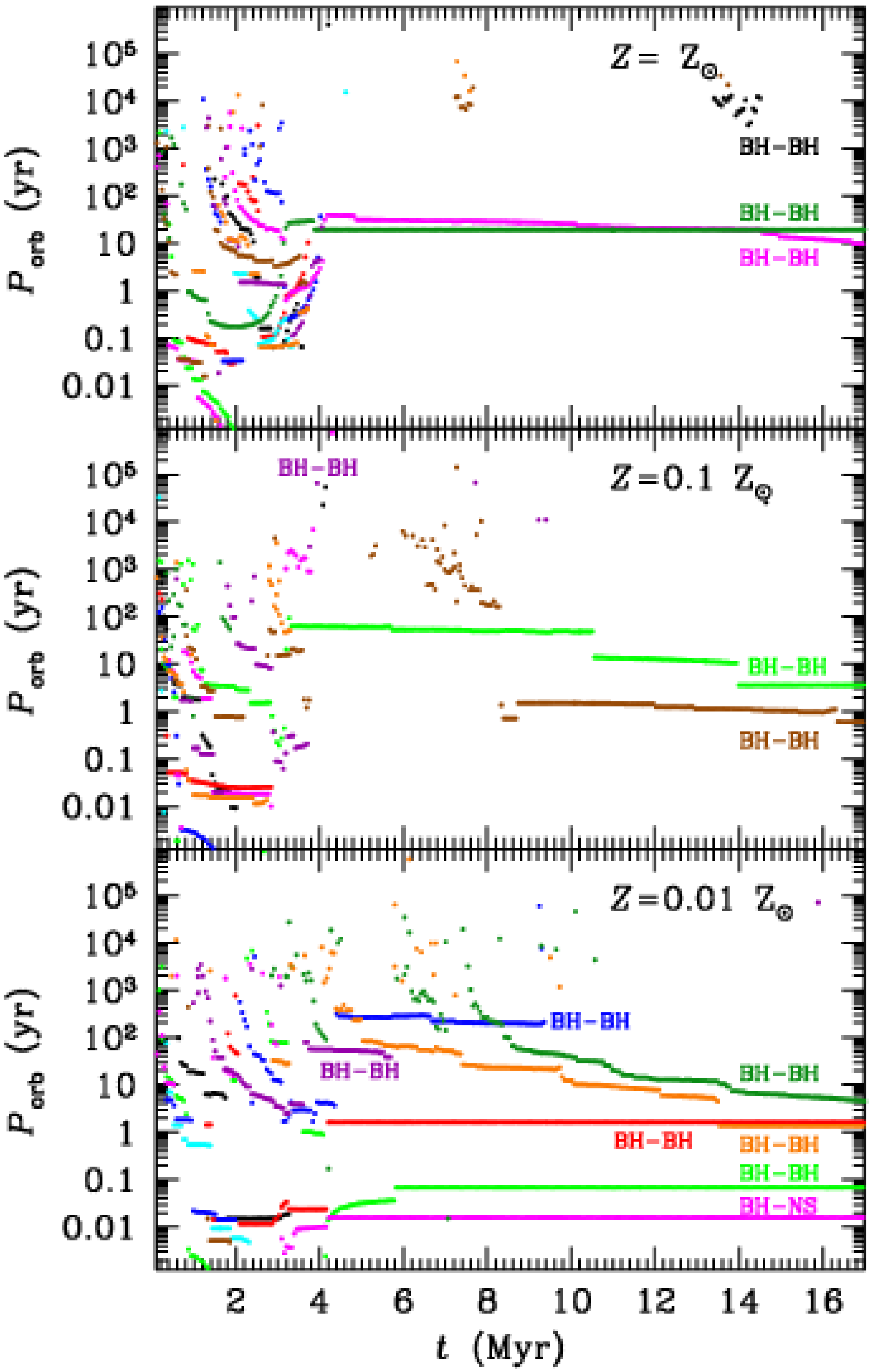
*** 10% BHs in the IMBH regime**
(>100 Msun) at Z = 0.01 – 0.1 Zsun

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

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

MM 2016, MNRAS, 459, 3432

6. Intermediate-mass black holes (IMBHs): 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

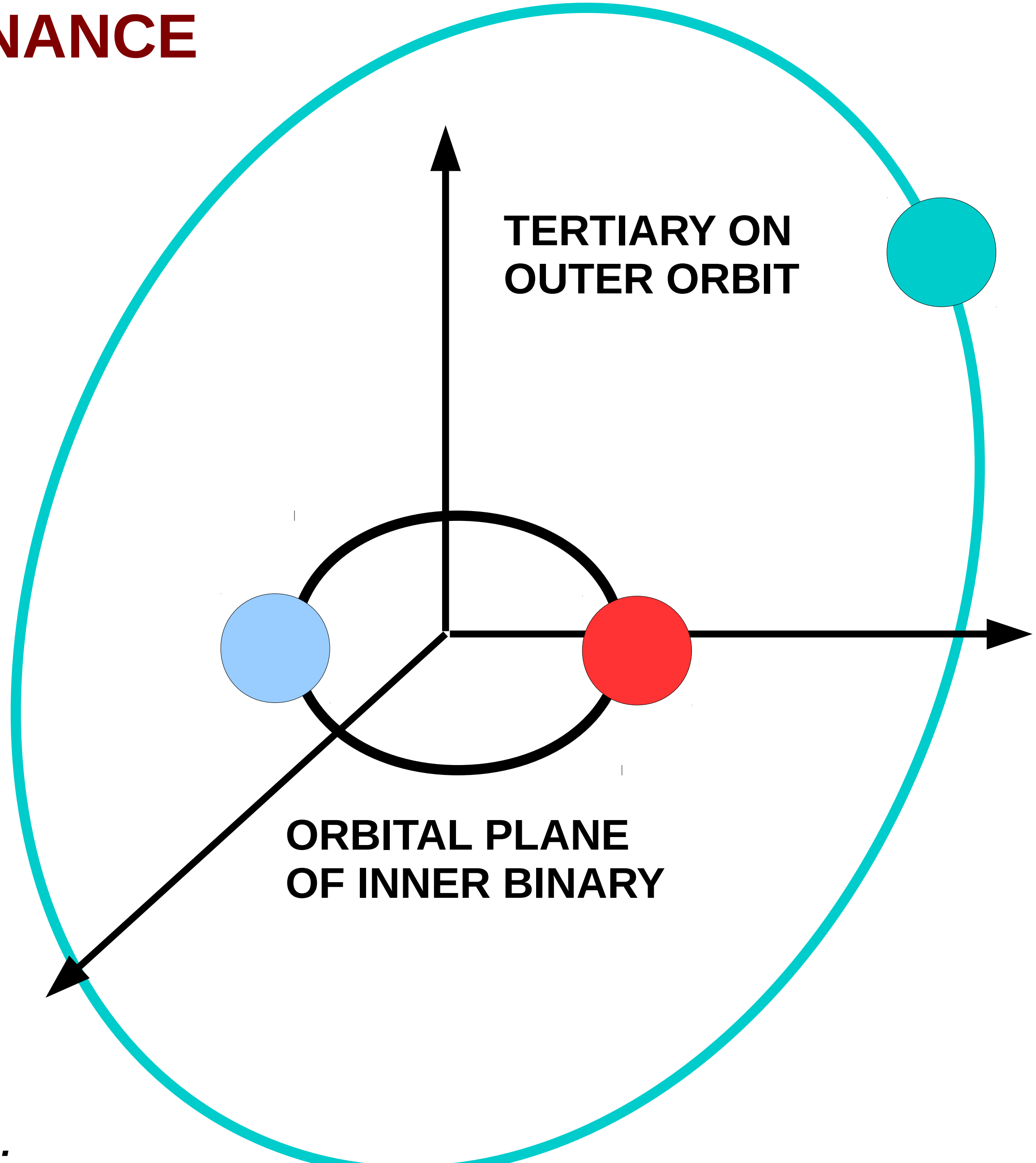
7. KOZAI-LIDOV RESONANCE

ONLY DYNAMICAL PROCESS COMMON ALSO IN THE FIELD

IN A HIERARCHICAL TRIPLE

ECCENTRICITY AND INCLINATION OSCILLATE

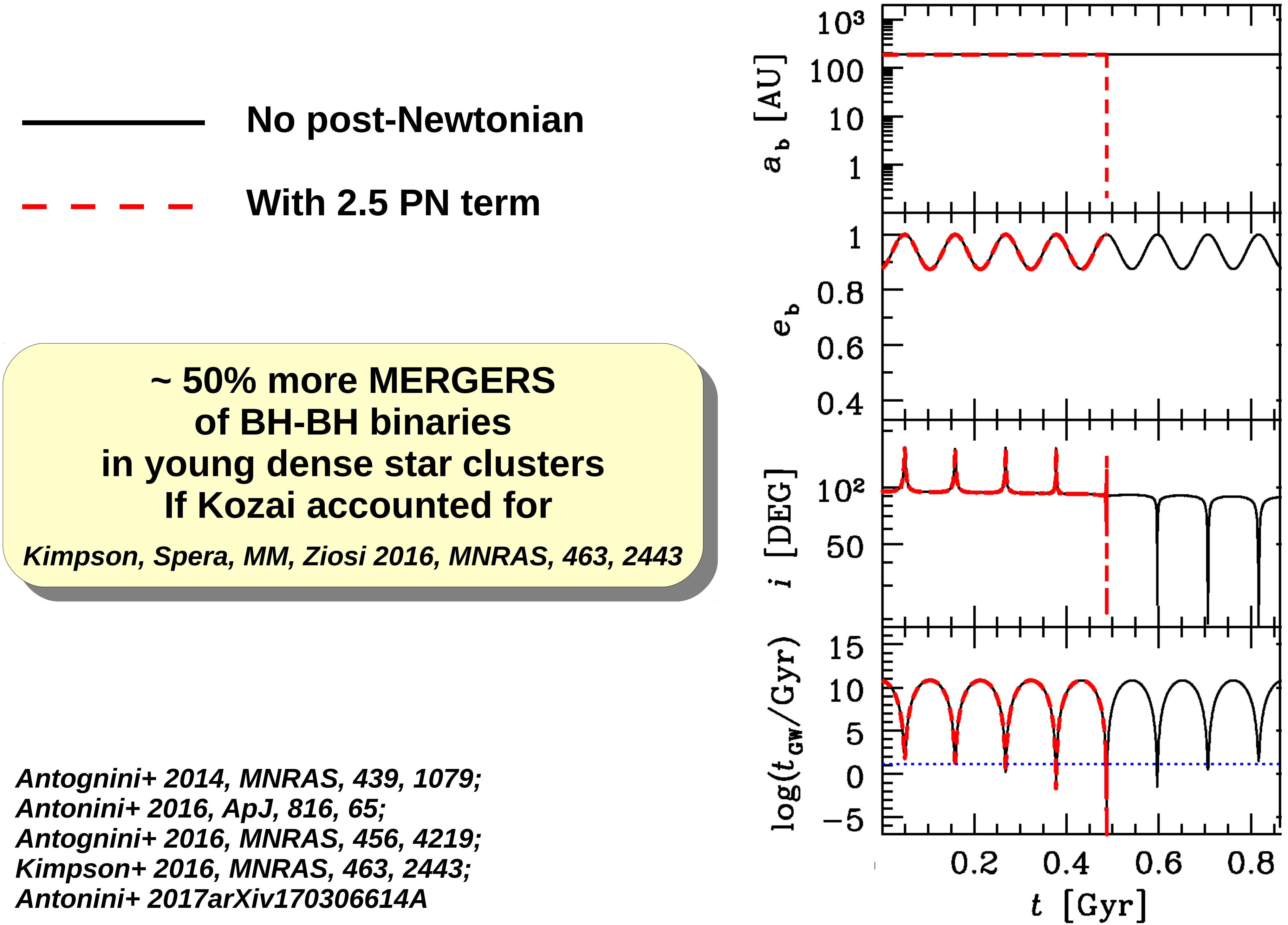
TRIGGERING MERGERS / COLLISIONS
between binary members



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

7. KOZAI-LIDOV 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

8. EFFECT OF DYNAMICS ON MERGER RATE

INFERRED BHB merger rate from LIGO ~ 9 – 240 Gpc $^{-3}$ yr $^{-1}$

(Abbott+ 2016, Physical Review X, 6, 041015)

BHB merger rate for GLOBULAR CLUSTERS ~ 5 Gpc $^{-3}$ yr $^{-1}$

(*Rodriguez+ 2016, PhRvD, 93, 4029; Askar+ 2017, MNRAS, 464, L36)*

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

BHB merger rate for YOUNG 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

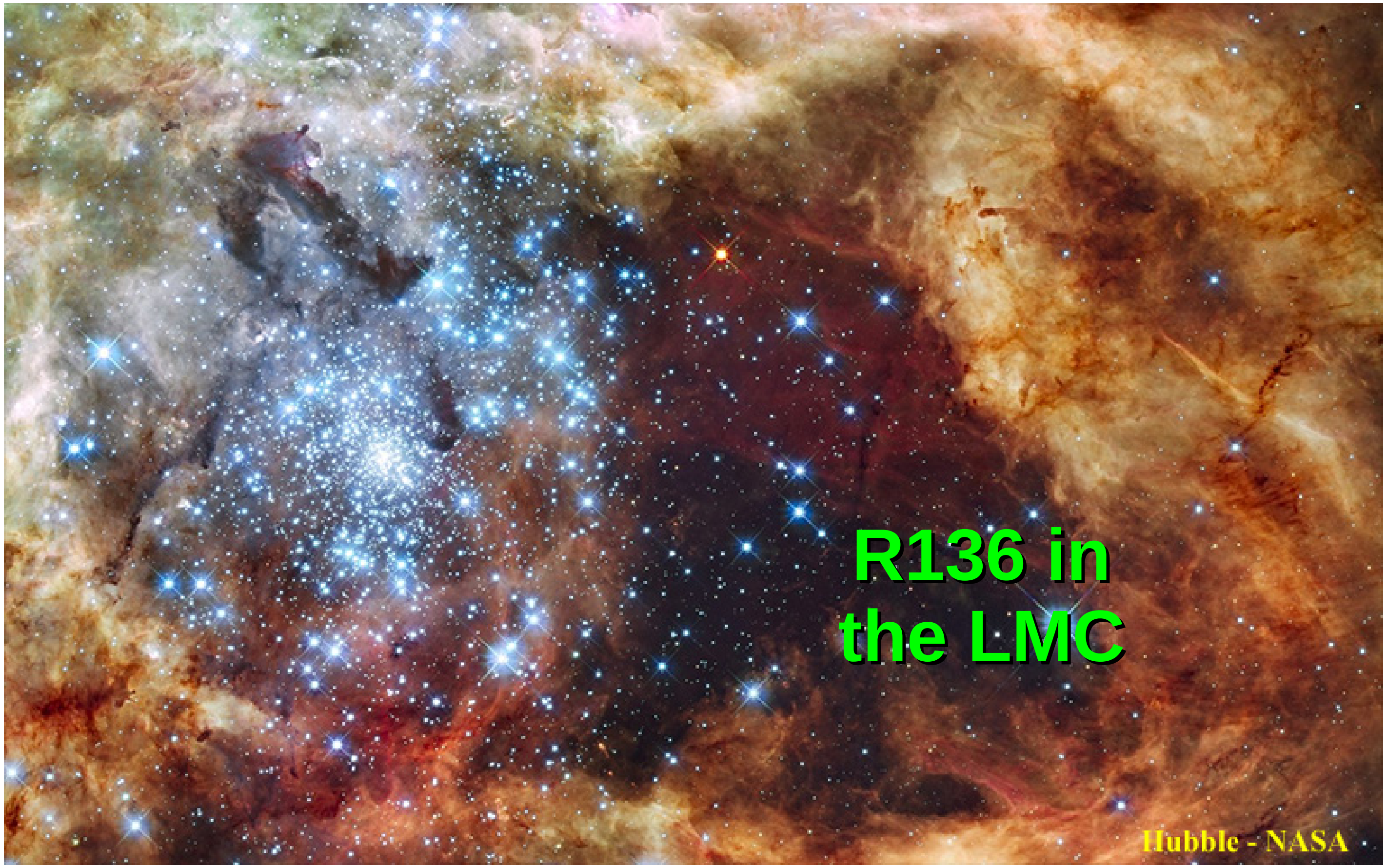
BHB merger rate for NUCLEAR STAR CLUSTERS: ~ 1.5 Gpc $^{-3}$ yr $^{-1}$

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

Issue: only preliminary result

9. issues about dynamics

1- Dynamical models start from spherical, virialized clusters, **WITHOUT GAS**

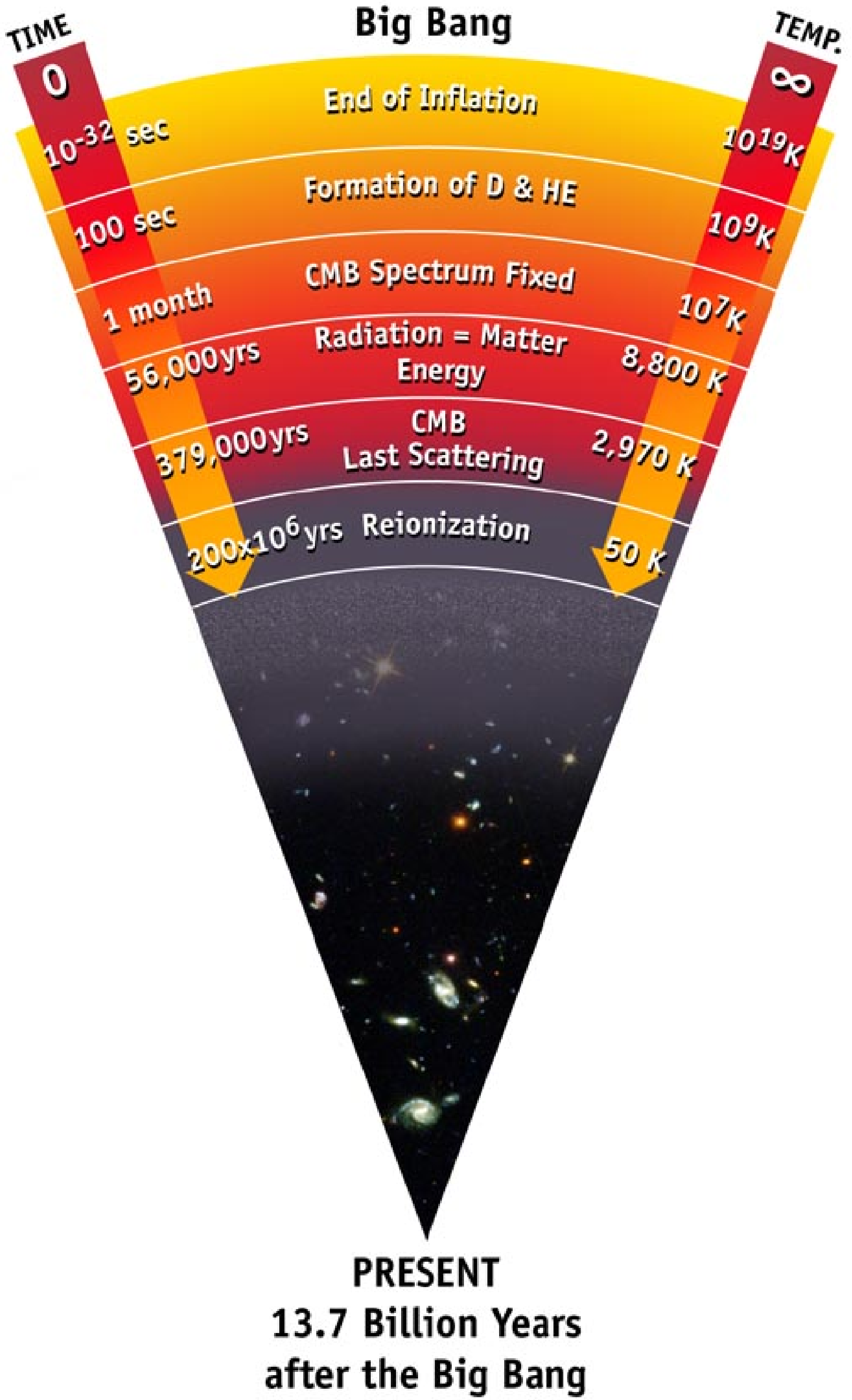


9. issues about dynamics

1- Dynamical models start from spherical, virialized clusters, WITHOUT GAS

2- Objects that merge at z ~ 0.1 might have formed at z >> 0.1

We must put star cluster dynamics in COSMOLOGICAL CONTEXT



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3- Will GW data be able to discriminate between ISOLATED BINARIES and DYNAMICAL BINARY FORMATION?

See Zevin+ 2017 arxiv1704.07379 for an attempt with Bayesian statistics

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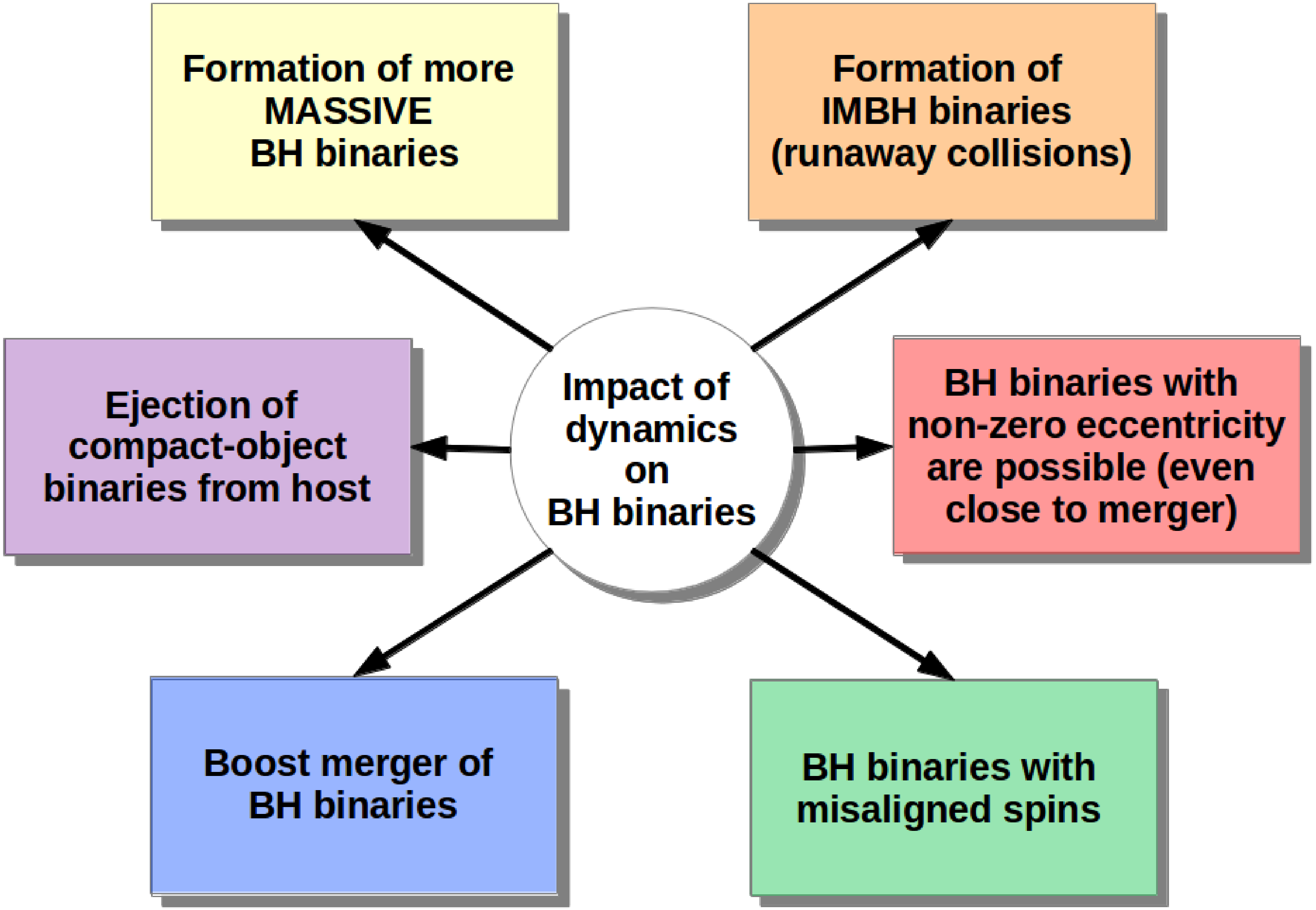
3- Will GW data be able to discriminate between ISOLATED BINARIES and DYNAMICAL BINARY FORMATION?

See Zevin+ 2017 arxiv1704.07379 for an attempt with Bayesian statistics

Are we accounting for dynamics in the proper way?

10. Conclusions



THANK YOU