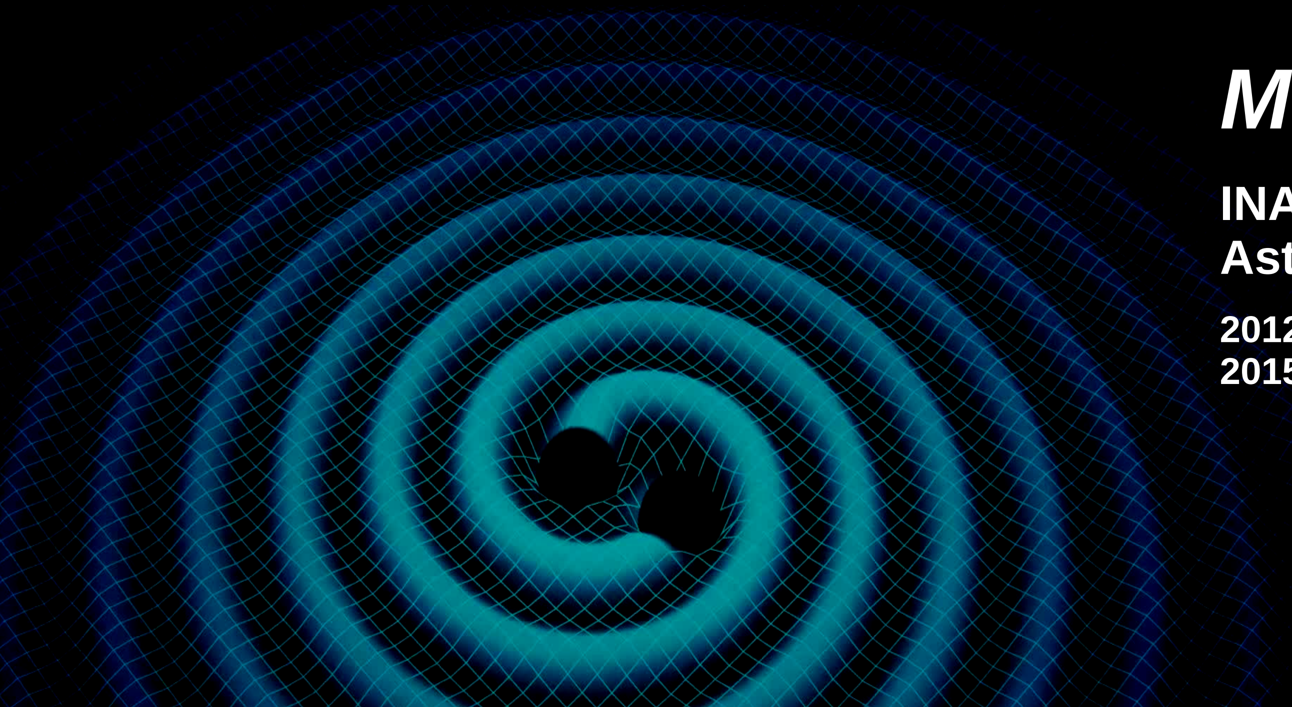
Michela Mapelli

INAF-Osservatorio Astronomico di Padova

2012 FIRB fellow
2015 MERAC prize



Astrophysics of black hole binaries: what is new after 3 detections?

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

Amaldi12, Pasadena, July 9 – 14 2017

OUTLINE:

1. Information from current detections

2. Implications for the mass spectrum of black holes

3. Field or dynamical origin?

4. The cosmological context

5. Conclusions

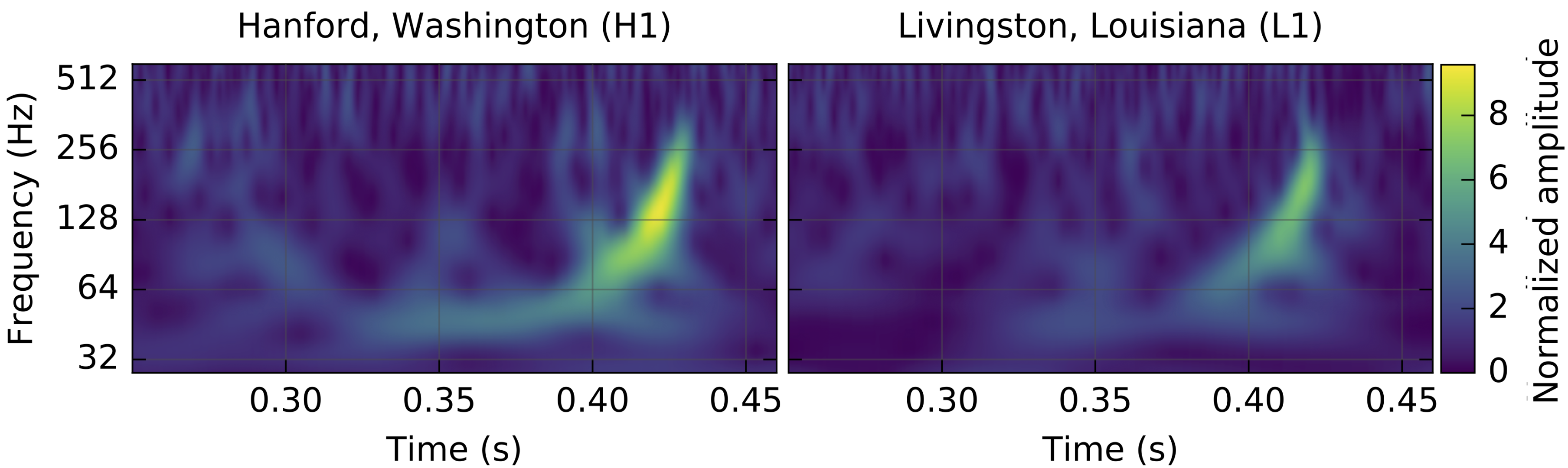
1. Information from current detections

	GW150914	GW151226	GW170104
TOTAL MASS* (Msun)	65.3 [+4.1,-3.4]	21.8 [+5.9,-1.7]	50.7 [+5.9,-5.0]
EFF. SPIN	–0.06 [+/-0.14]	0.21 [+0.20,-0.10]	–0.12 [+0.21,-0.30]
DIST. (Mpc)	420 [+150,-180]	440 [+180,-190]	880 [+450,-390]

*and of course also chirp mass and mass ratio

What can we learn from these quantities?

1. Information from current detections



What have astrophysicists learned from the first 3 detections?

1. double black hole (BH) binaries exist

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

2. can merge in a Hubble time

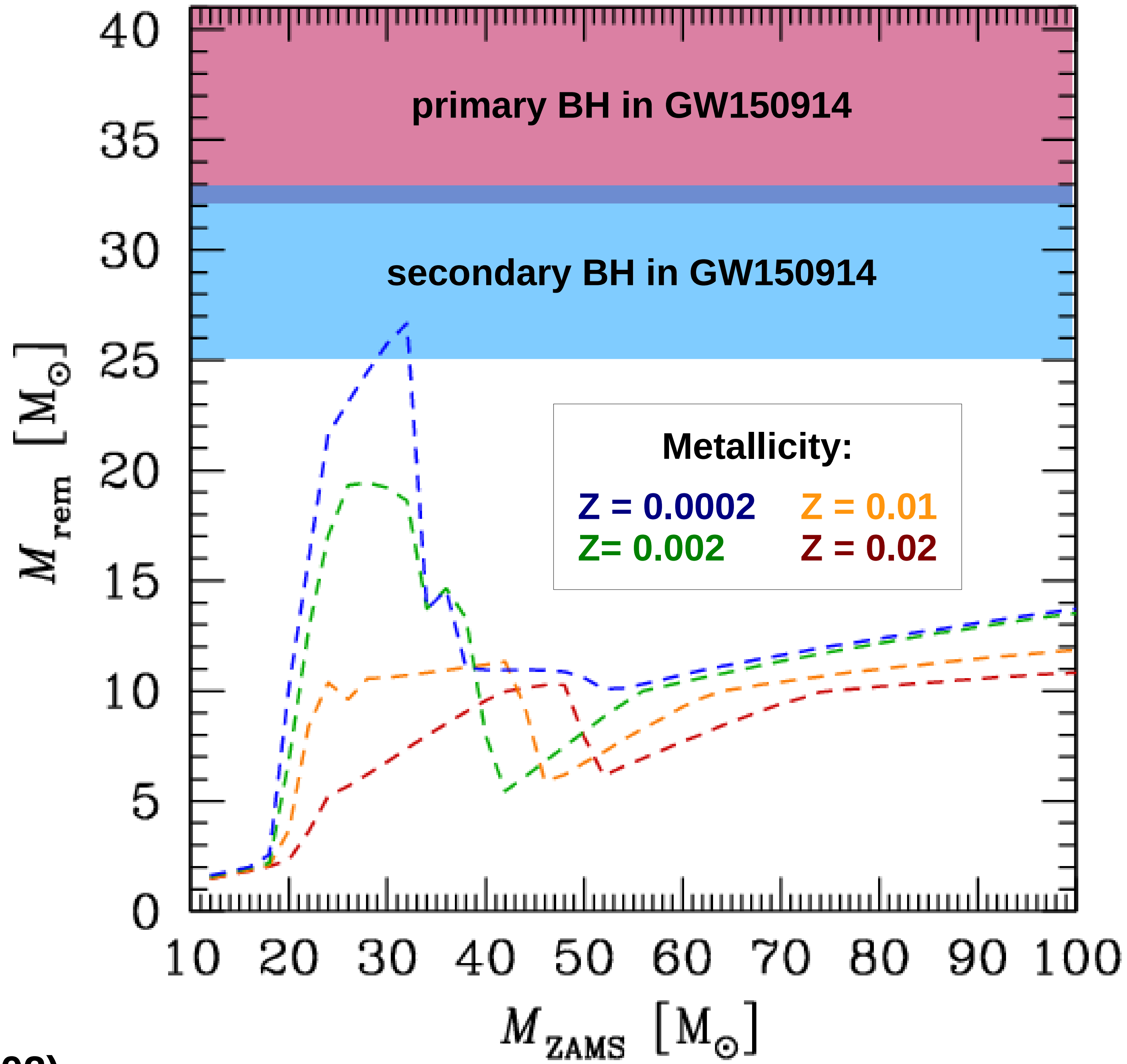
3. massive BHs exist i.e. stellar-mass BHs with mass >20 M⊙
(Heger et al. 2003; MM et al. 2009, 2010; Belczynski+ 2010)

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

2. Implications for the mass spectrum of black holes

Most common remnant mass spectrum BEFORE GW150914 detection

cannot explain GW150914



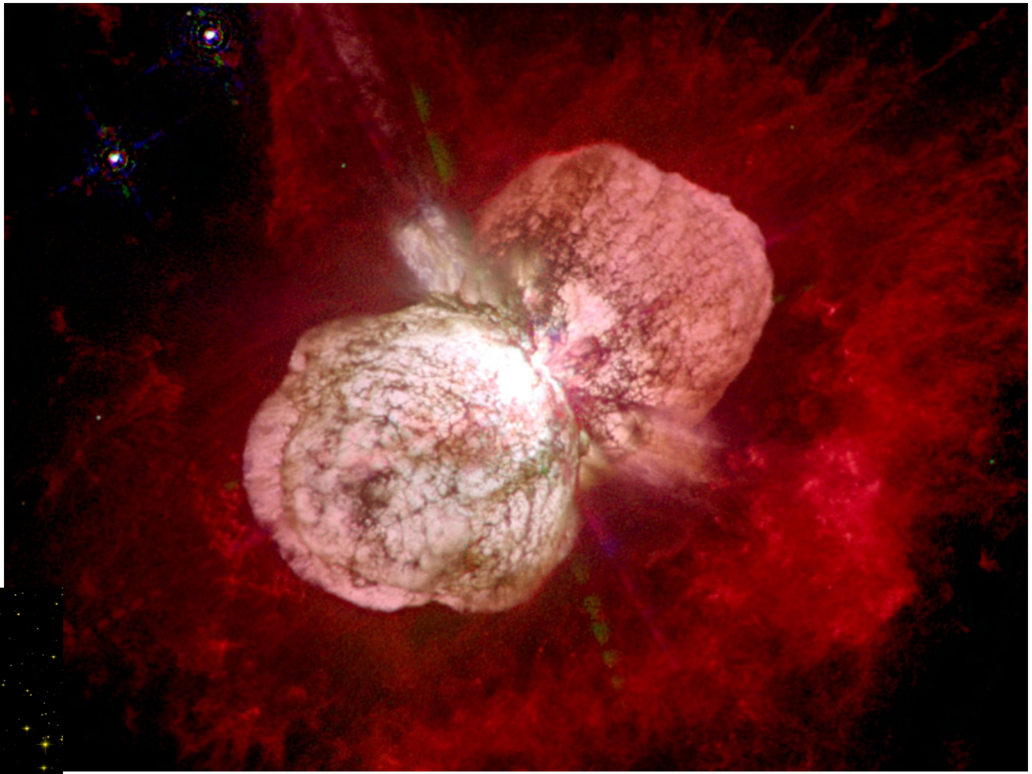
(BSE code, Hurley+ 2002)

2. Implications for the mass spectrum of black holes

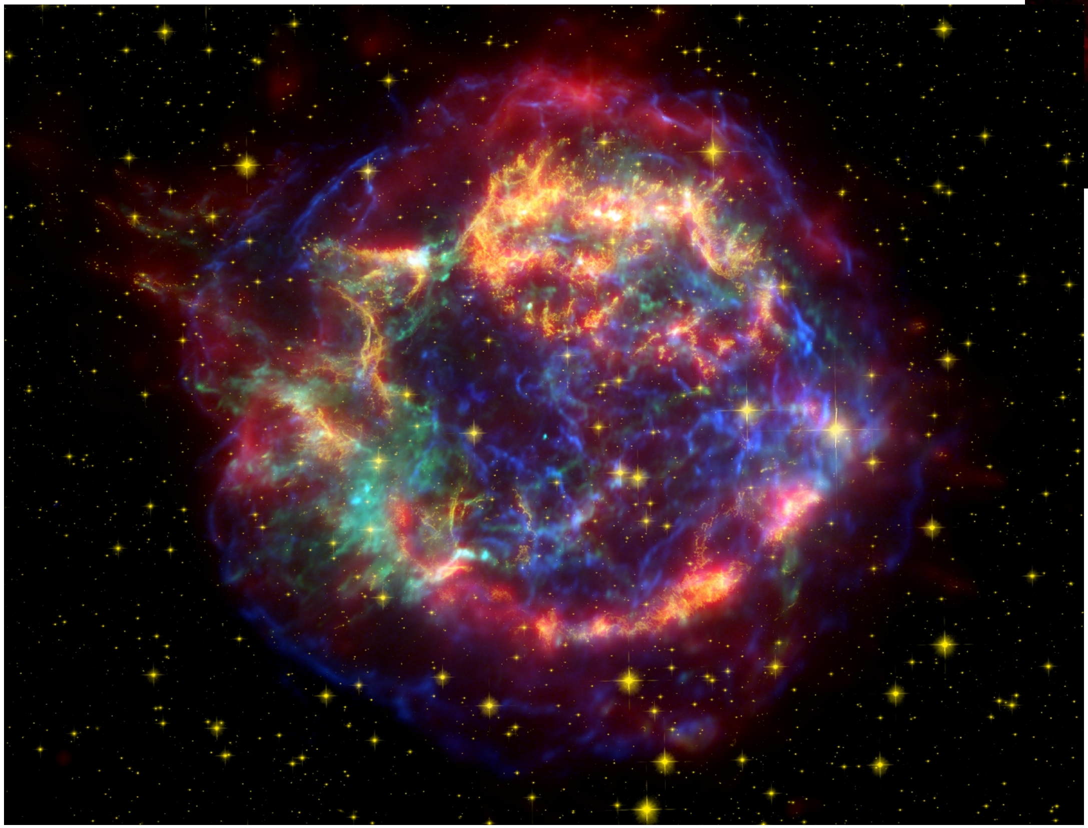
Two critical ingredients determine remnant mass:

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

2. Implications for the mass spectrum of black holes

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)

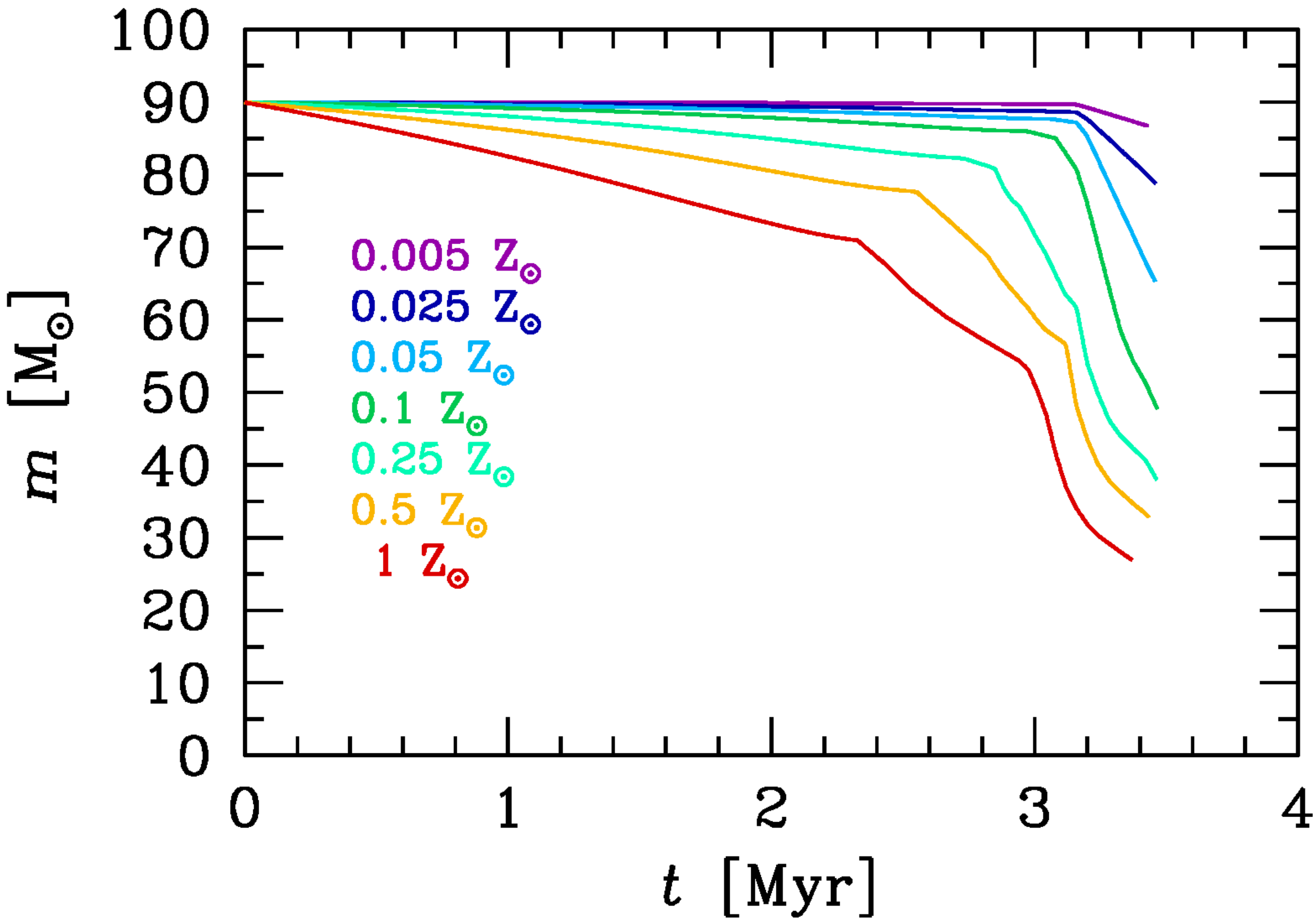
$$\dot{M} \propto Z^{\alpha}$$

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

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

Tang, Bressan+ 2014; Chen, Bressan+ 2015

2. Implications for the mass spectrum of black holes



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

2. Implications for the mass spectrum of black holes

* 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. Implications for the mass spectrum of black holes

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

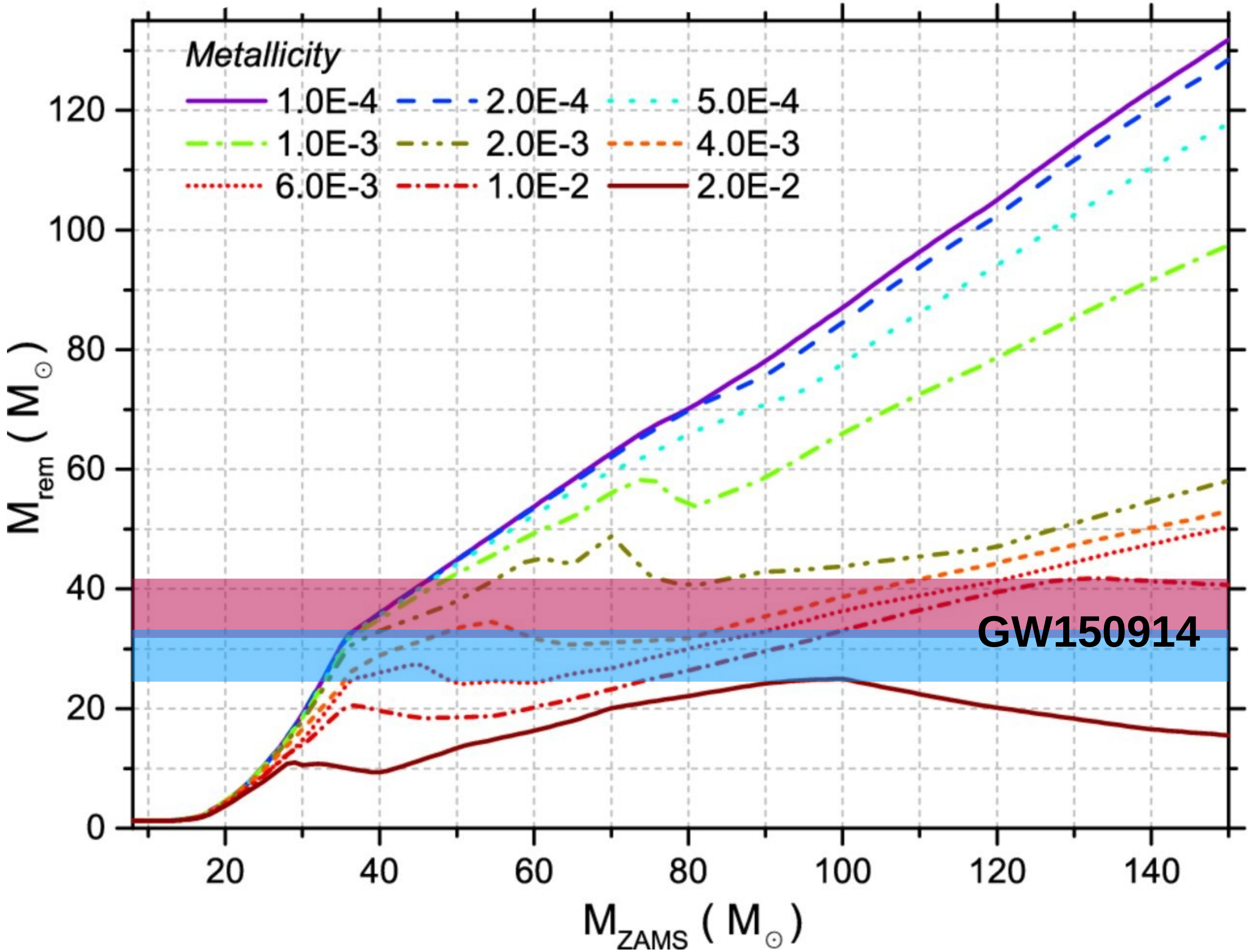
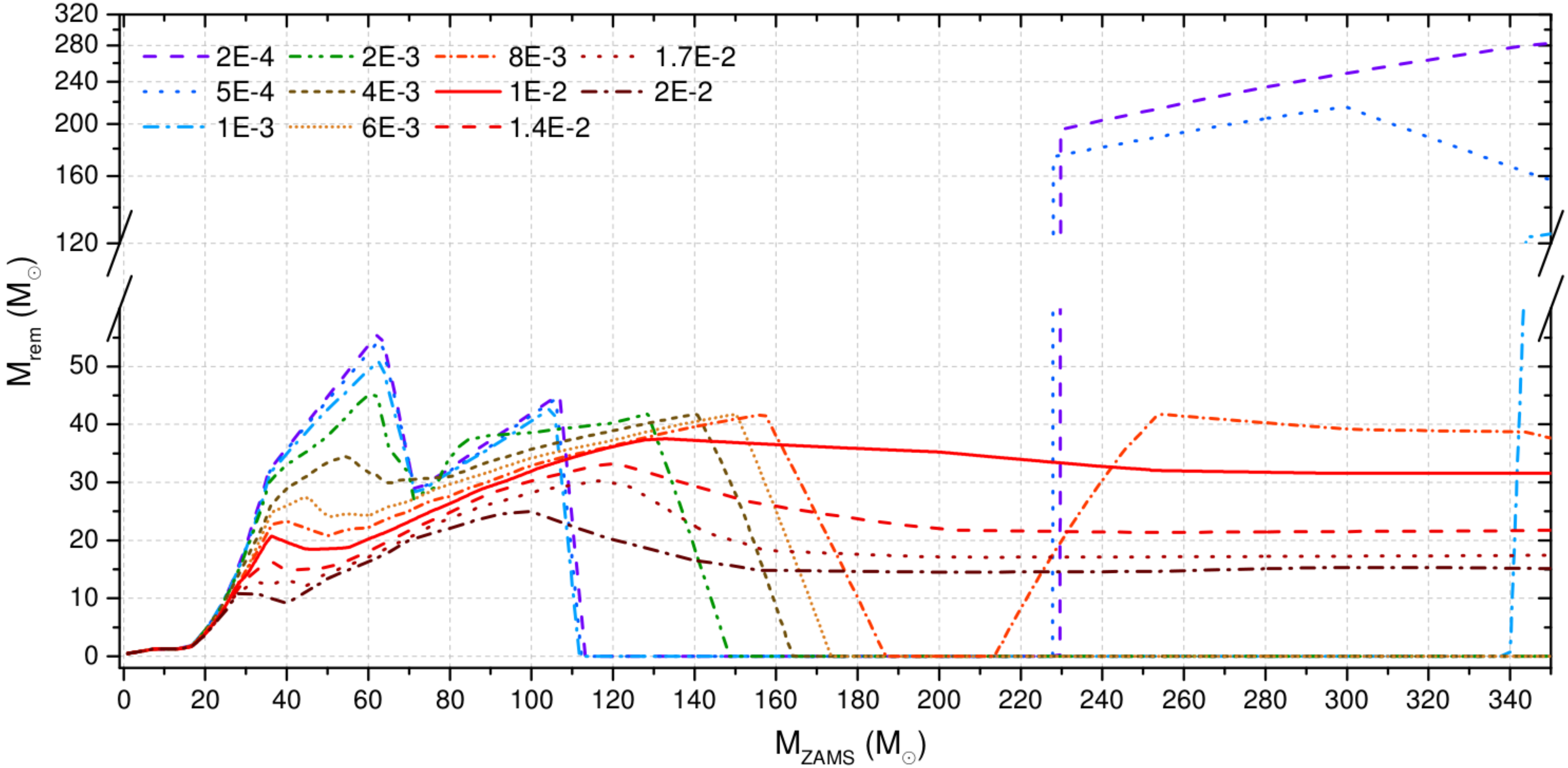


Figure from Spera, MM & Bressan 2015
see also MM+ 2009; Belczynski+ 2010; Fryer+ 2012; MM+ 2013, 2014

2. Implications for the mass spectrum of black holes

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



Belczynski+ 2016
Woosley 2017
Spera & MM 2017

Take home message for BH masses:

Dependence of BH mass on metallicity is necessary to account for GW150914 and GW170104
(e.g. Abbott+ 2016; Belczynski+ 2016; MM 2016; Spera & MM 2017)

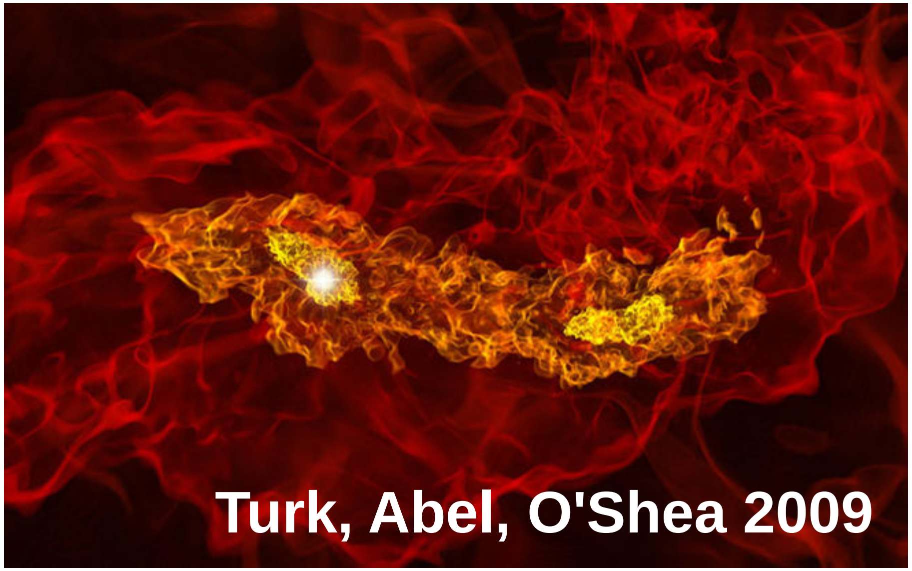
UNLESS we require PRIMORDIAL BHs (NO STELLAR ORIGIN!!!)
(e.g. Bird+ 2016; Carr+ 2016; Inomata+ 2016; Magee & Hanna 2017)

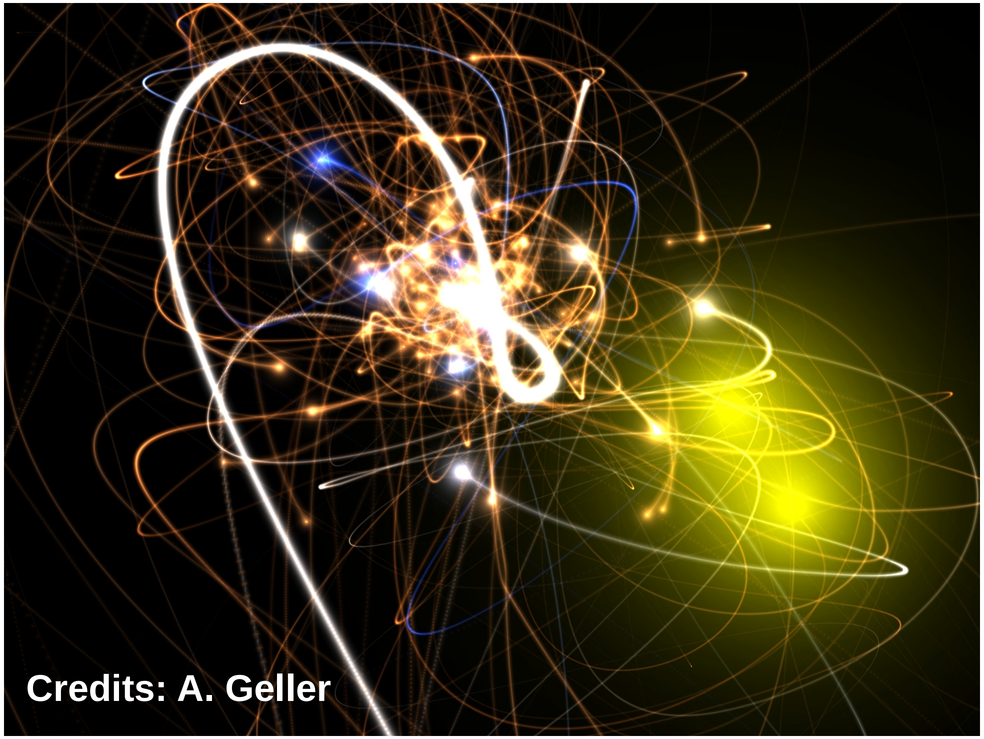
or BHs from previous mergers
(Gerosa & Berti 2017; see talk by Davide Gerosa)

3. Field or dynamical origin?

1) PRIMORDIAL BINARIES:

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

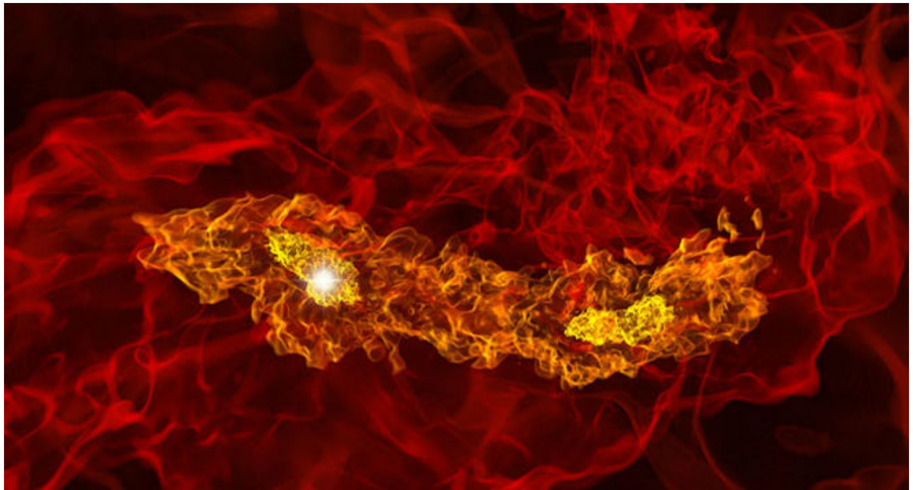




2) DYNAMICAL BINARIES:

BH binary forms and/or evolves by dynamical processes

3. Field or dynamical origin?


Turk, Abel, O'Shea 2009

1) PRIMORDIAL BINARIES:

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

NOT SO EASY:
Many evolutionary processes can affect the binary

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

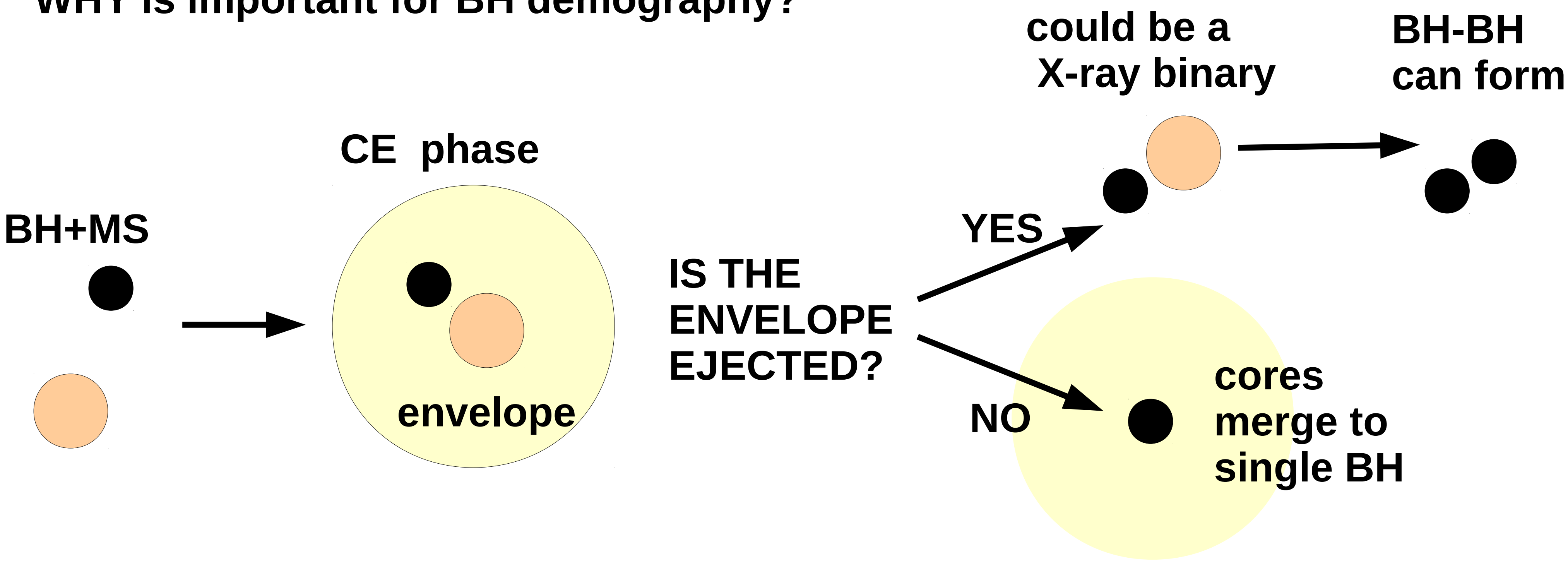
Binary evolution studied via POPULATION SYNTHESIS CODES:

→ - BSE (Hurley+ 2002; Giacobbo, MM+ in prep.)
→ - Seba in Starlab (Portegies Zwart+ 2001; MM+2013)
→ - SEVN (Spera, MM & Bressan 2015; Spera & MM 2017)
- StarTrack (Belczynski+ 2007, 2010)

3. Field or dynamical origin?

Common envelope in binaries:

WHY is important for BH demography?

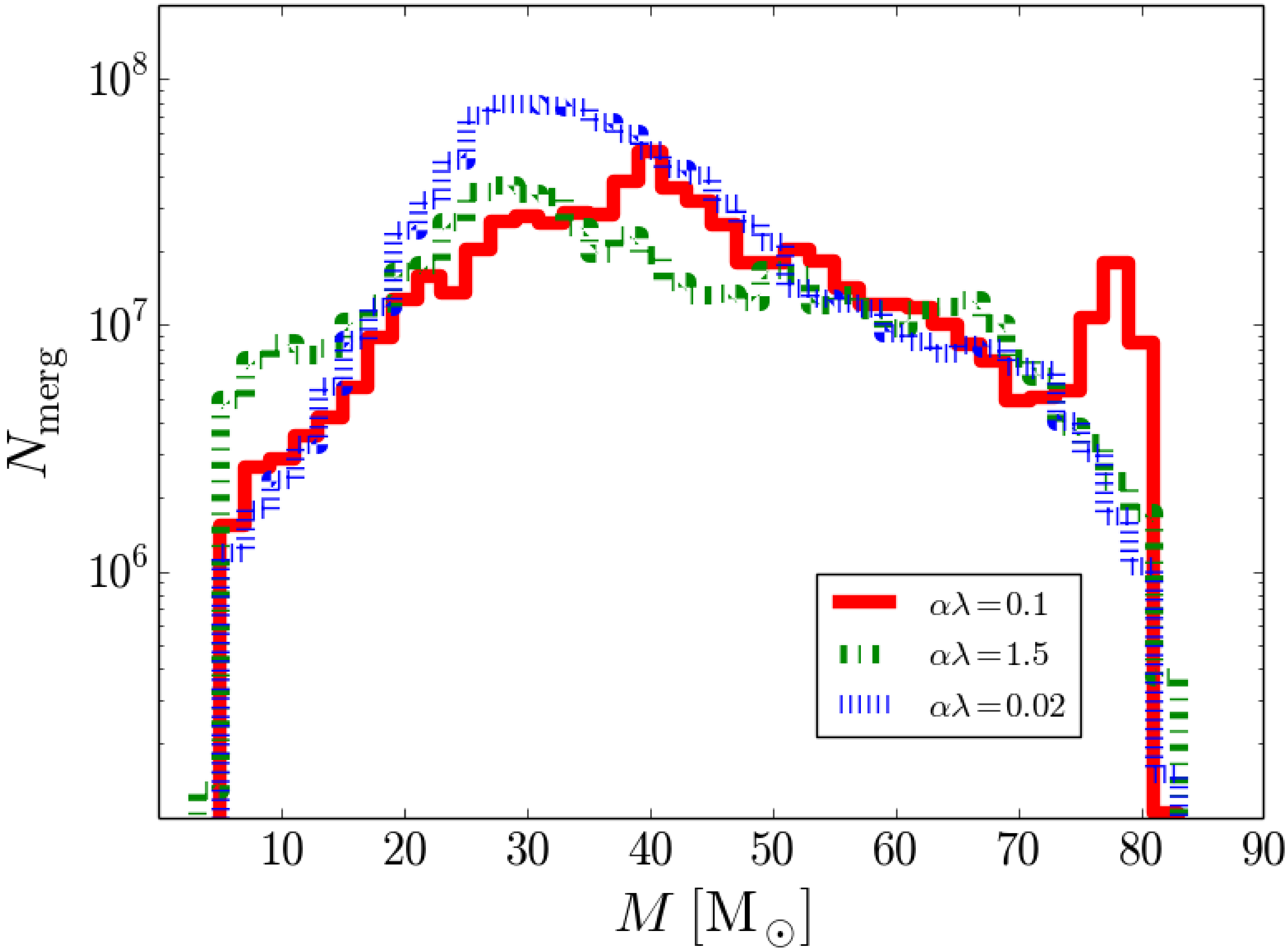


COMMONLY USED α λ formalism does not capture all physics

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

3. Field or dynamical origin?

Total mass distribution of BH binaries with population synthesis



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

3. Field or dynamical origin?

Alternative to common envelope:

chemically homogeneous evolution

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

BASIC IDEA:

if stars are chemically homogeneous, their radii are smaller

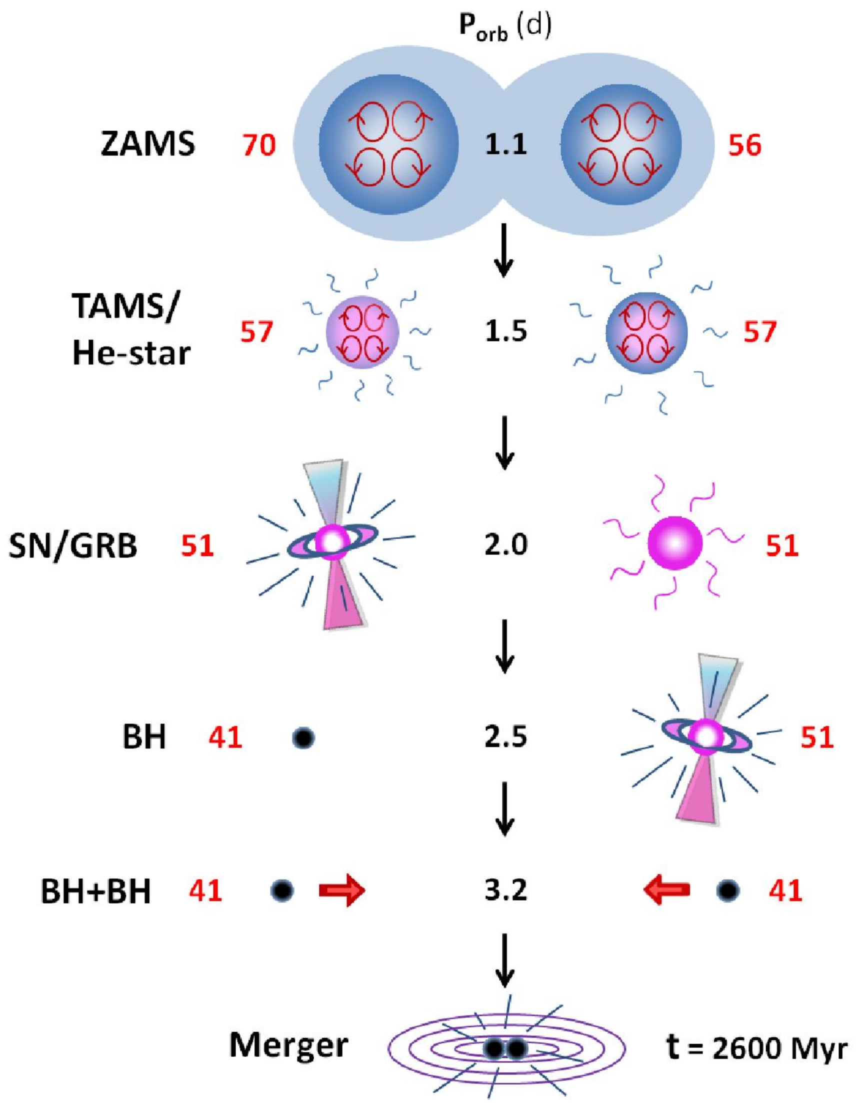
→ close binaries avoid common envelope and premature merger

To be chemically homogeneous, stars need to ROTATE fast

3. Field or dynamical origin?

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

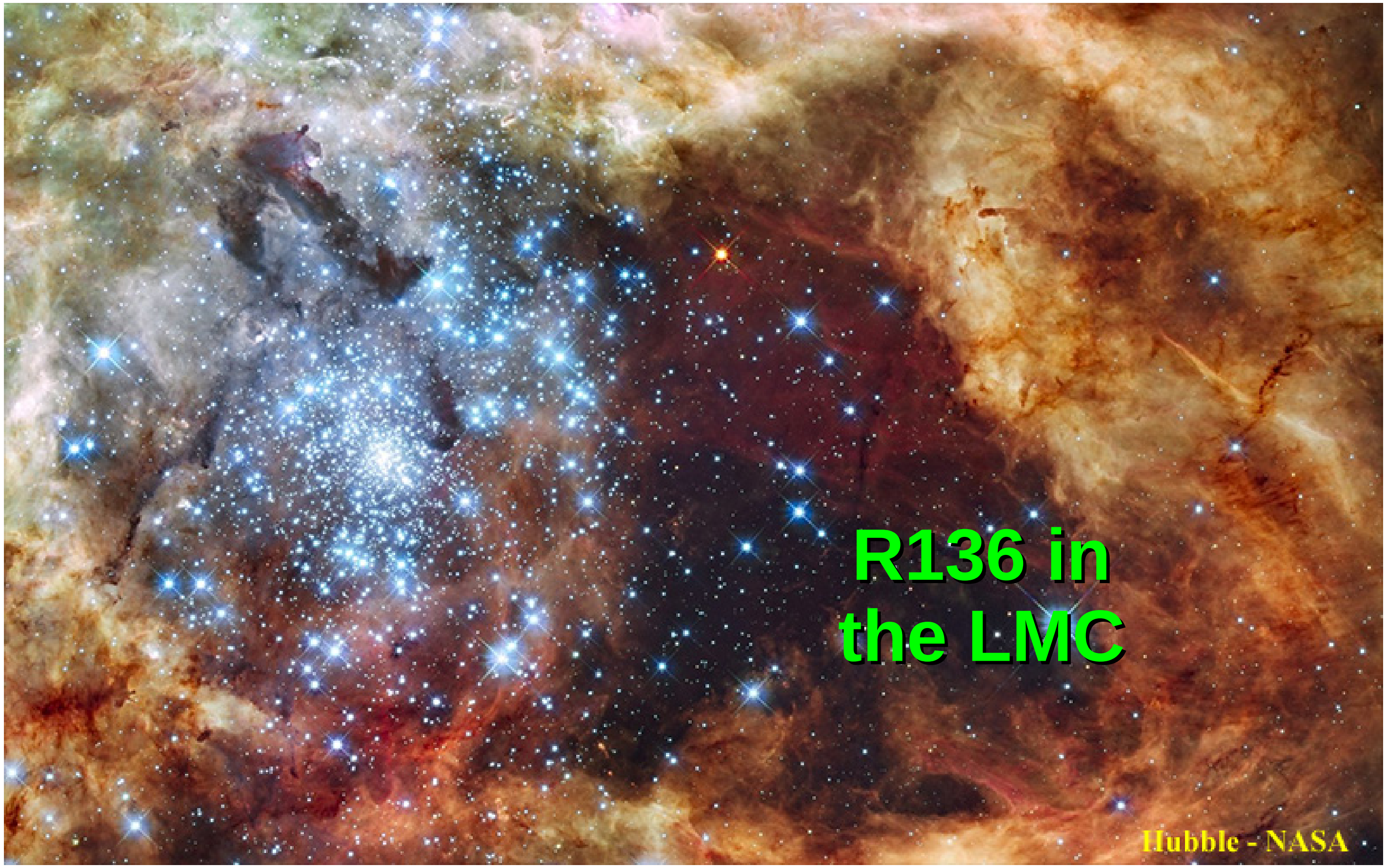
3. Field or dynamical origin?

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*)**



3. Field or dynamical origin?

FIELD:

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

GLOBULAR CLUSTERS:

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

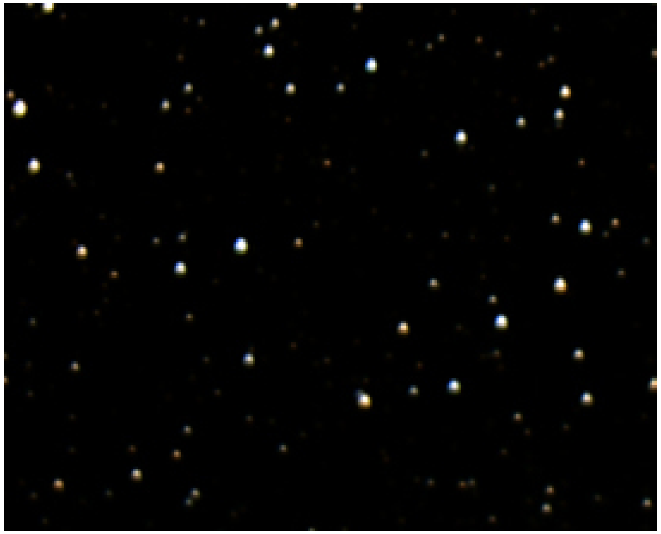


Image credit: Jim Mazur’s Astrophotography, via http://www.skyledge.net/.

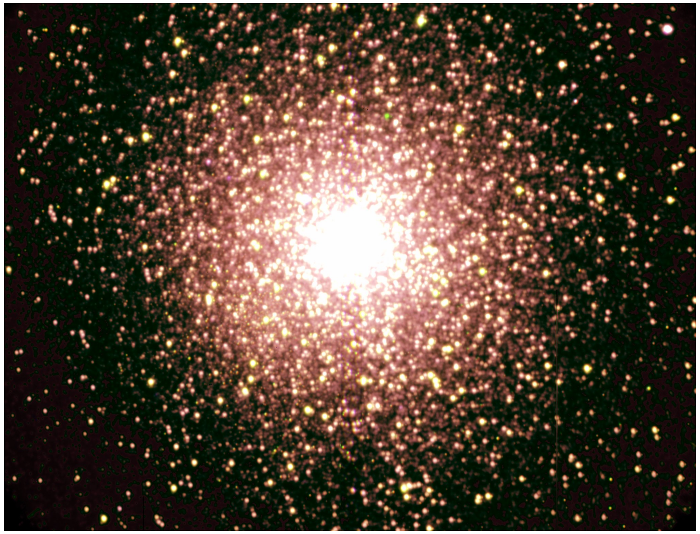


Image credit: HST

3. Field or dynamical origin?

FIELD:

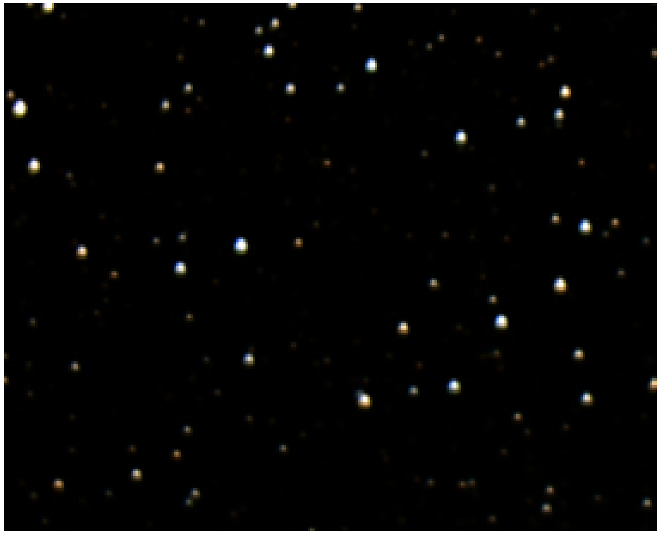
* NO dynamics (density in solar neighborhood <1 star pc^-3)

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



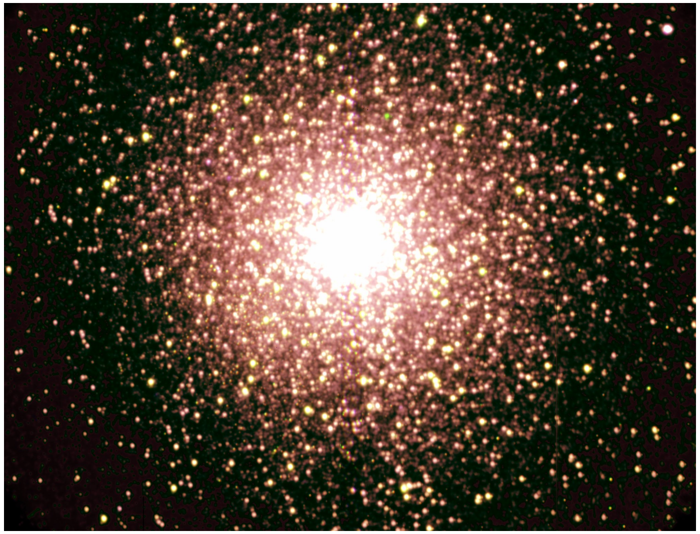


Image credit: Jim Mazur’s Astrophotography, via http://www.skyledge.net/.

Image credit: HST

3. Field or dynamical origin?

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**

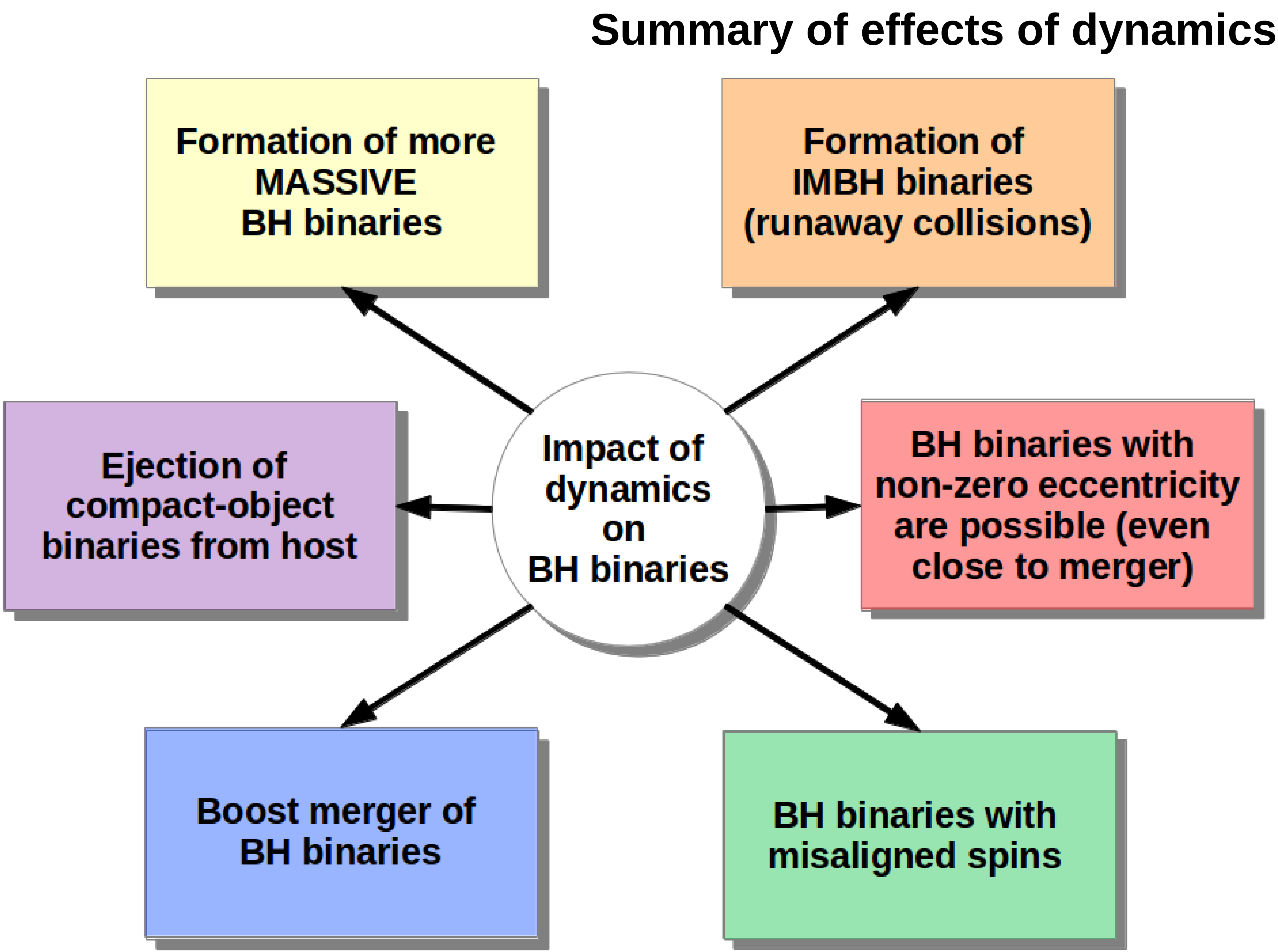
*** long-lived (12 Gyr)**

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

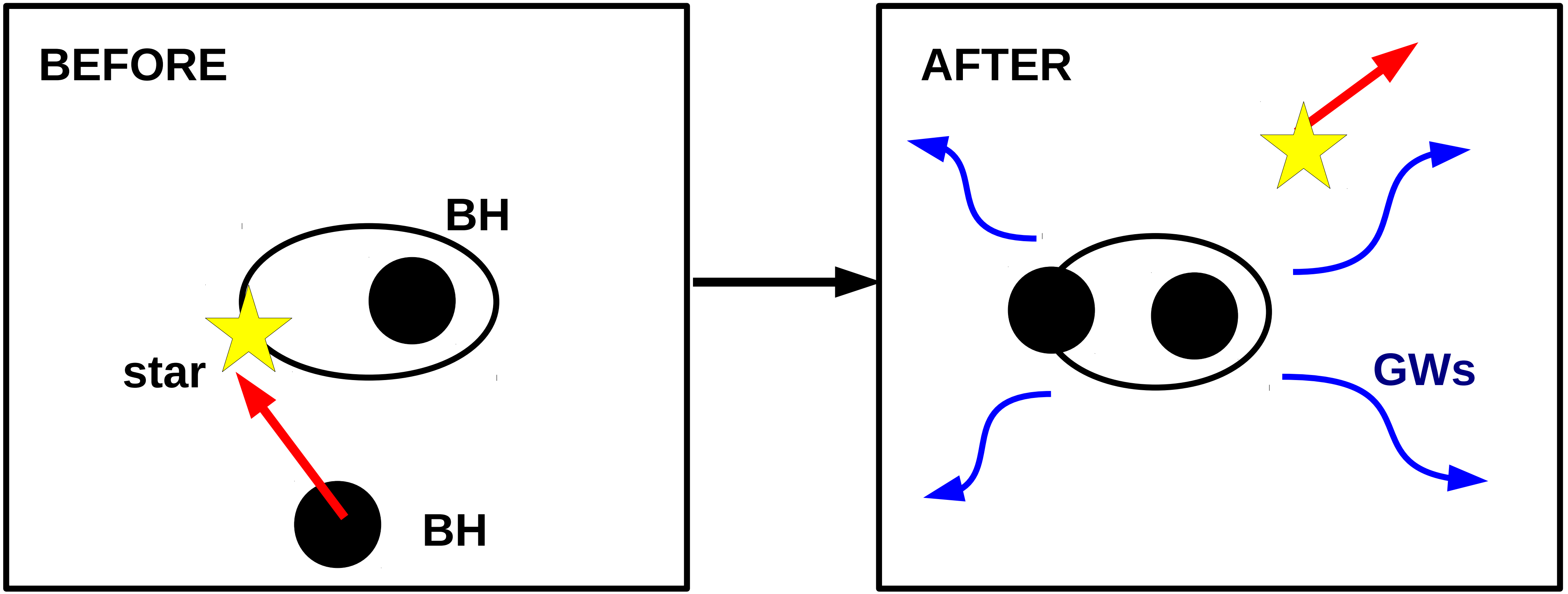
provide stars (and compact objects) to the field

share dynamical properties with globular clusters

3. Field or dynamical origin?



3. Field or dynamical origin?

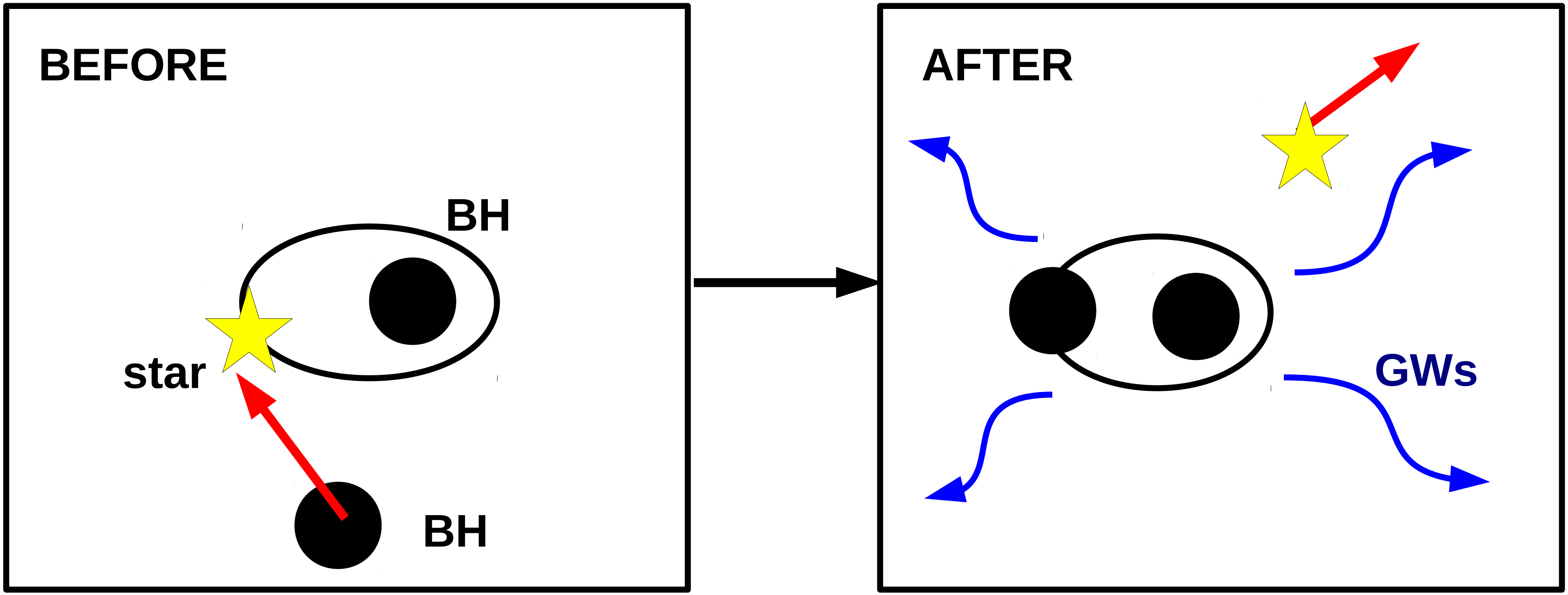


Exchanges bring BHs in binaries

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. Field or dynamical origin?



>90% BH-BH binaries in young star clusters form by exchange
(Ziosi, MM+ 2014, MNRAS, 441, 3703)

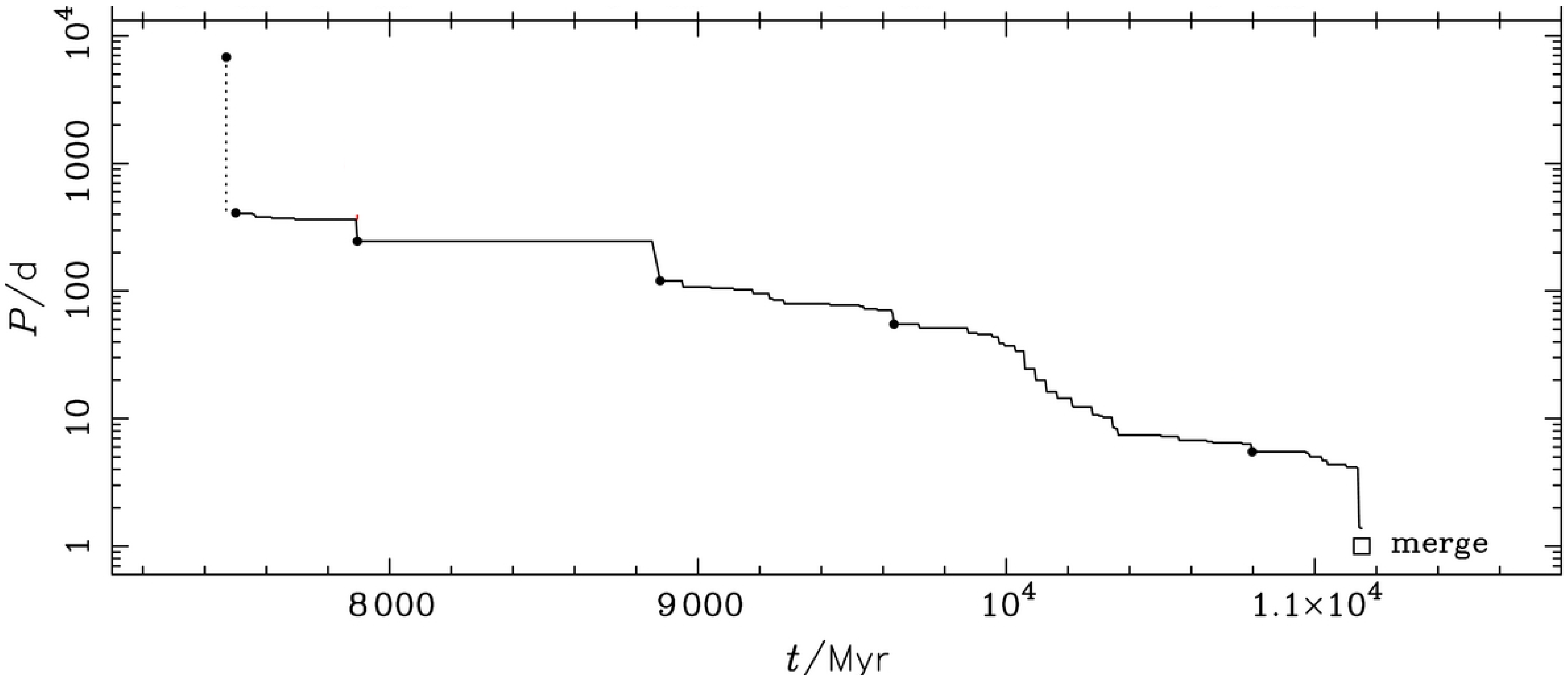
EXCHANGES FAVOUR THE FORMATION of BH-BH BINARIES WITH

** THE MOST MASSIVE BHs*

** HIGH ECCENTRICITY*

** MISALIGNED BH SPINS (see talk by Davide Gerosa)*

3. Field or dynamical origin?



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; Ziosi, MM+ 2014, MNRAS, 441, 3703;
Rodriguez+ 2015, Phys. Review Letter, 115, 1101; Rodriguez+ 2016, PhRvD, 93, 4029;
MM 2016, MNRAS, 459, 3432; Askar+ 2017, MNRAS, 464, L36; Banerjee 2017, MNRAS, 467, 524; Samsing+ 2017, arXiv170603776S, and many others

3. Field or dynamical origin?

INFERRED BHB merger rate from LIGO ~ 12 – 213 Gpc $^{-3}$ yr $^{-1}$

(Abbott+ 2016, Phys. Rev. X, 6, 041015; Abbott+ 2017; Phys. Rev. L., 118, 1101)

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 CLUSTERS: ~ 1 – 2 Gpc $^{-3}$ yr $^{-1}$

(Antonini & Rasio 2016, ApJ, 2016, 831, L187; see B.-M. Hoang poster)

Issue: only preliminary result

3. Field or dynamical origin? Issues with dynamics

1- Dynamical models start from spherical, virialized clusters,
<u>WITHOUT GAS</u>

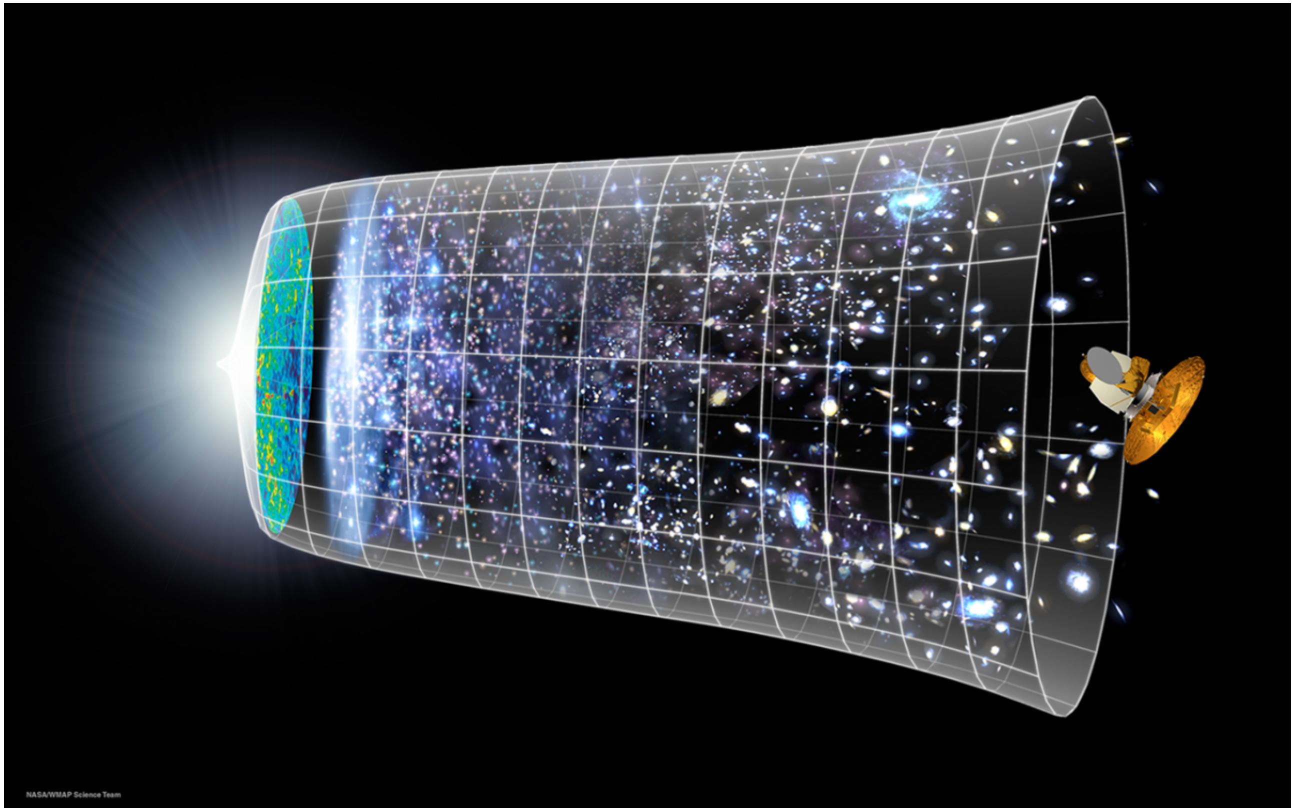
Trapezium
credits: Hubble - Nasa

3. Field or dynamical origin? Issues with dynamics

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

2- Objects that merge at $z \sim 0.1$ might have formed at $z \gg 0.1$

We must put star cluster dynamics in COSMOLOGICAL CONTEXT



3. Field or dynamical origin? Issues with 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

3- Will GW data be able to discriminate between ISOLATED BINARIES and DYNAMICAL BINARY FORMATION?
HOW MANY DETECTIONS DO WE NEED?

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

3. Field or dynamical origin? Issues with dynamics

1- Dynamical models start from spherical, virialized clusters,
<u>WITHOUT GAS</u>

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

We must put star cluster dynamics in <u>COSMOLOGICAL CONTEXT</u>

3- Will GW data be able to discriminate between ISOLATED BINARIES and DYNAMICAL BINARY FORMATION?
HOW MANY DETECTIONS DO WE NEED?

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

Are we accounting for dynamics in the proper way?

3. Field or dynamical origin?

Take home message for field vs dynamics:

MASSES and SPINS from GW DETECTIONS may disentangle FIELD vs DYNAMICAL BINARIES

(e.g. from dynamics we expect more massive binaries with uniform spin distribution)

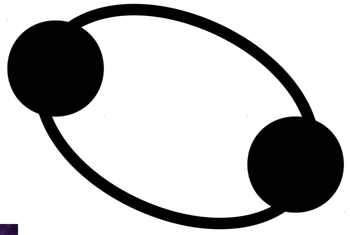
BUT still too many issues and uncertainties affect DYNAMICS SIMULATIONS

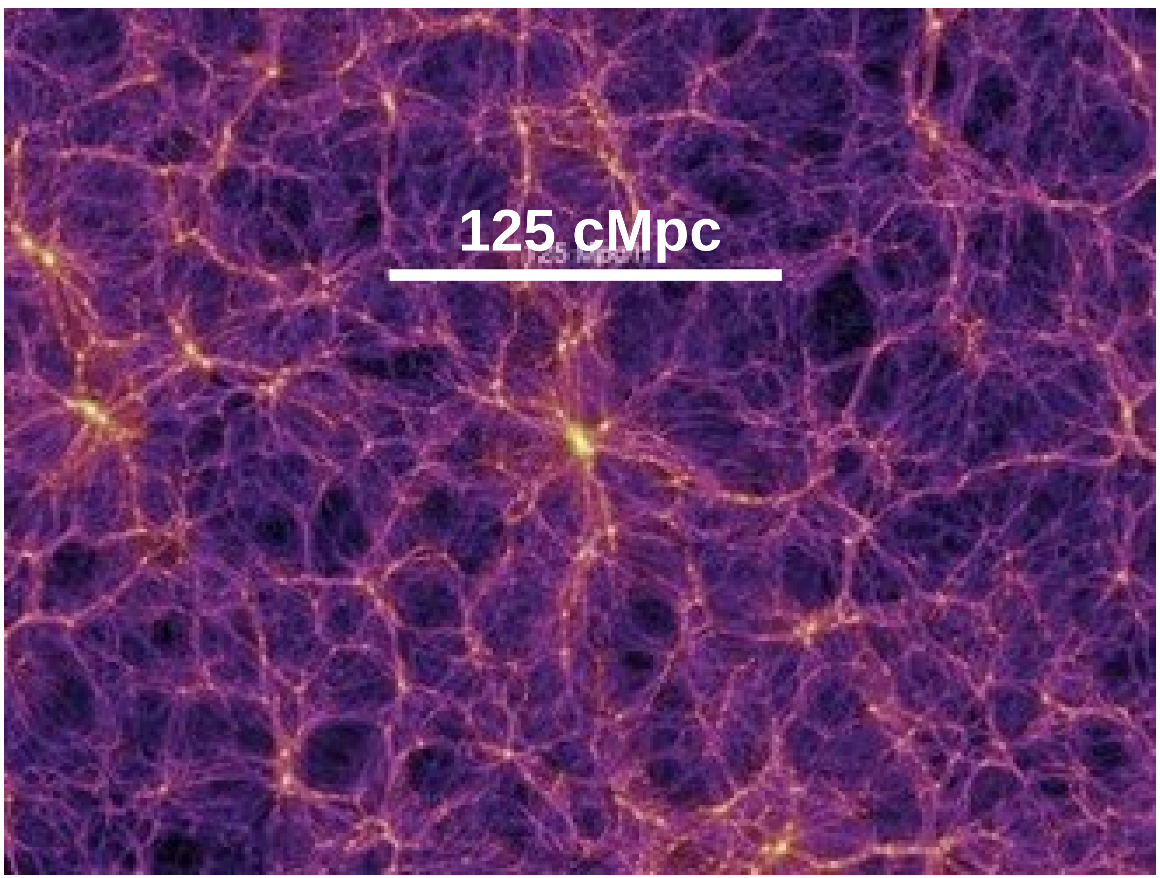
4. The cosmological context

How do merging BH binaries populate galaxies?

CHALLENGING: humongous physical range

Scale of a BHB < few AU





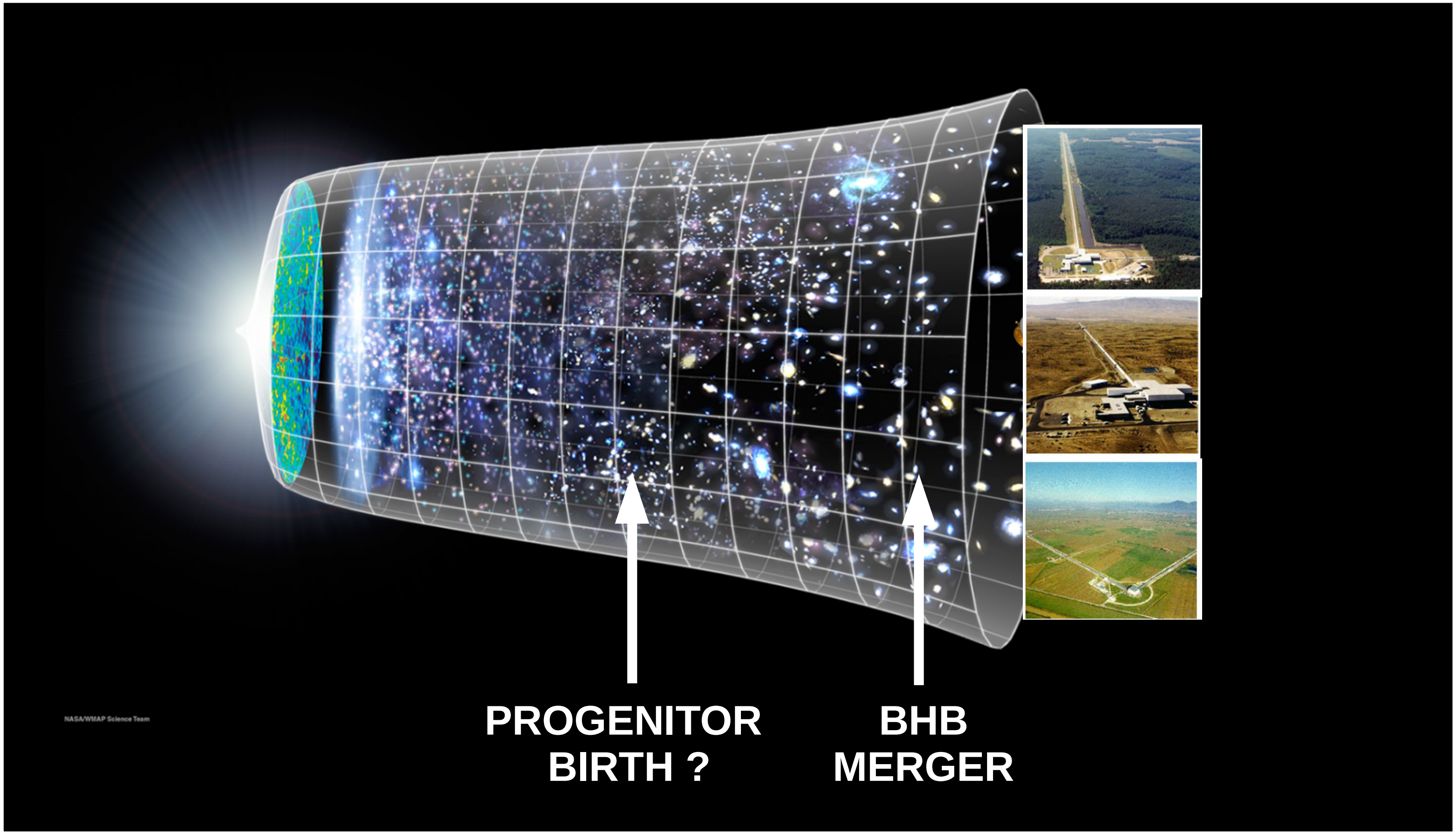
Scale of
cosmic structures
~ tens of Mpc

4. The cosmological context

How do merging BH binaries populate galaxies?

CHALLENGING: humongous physical range

BUT NECESSARY:
binary merging at z~0.1 might have formed at z>>0.1



4. The cosmological context

TWO MAIN APPROACHES:

- analytic formalism
+ binary population synthesis simulations through Monte Carlo procedure

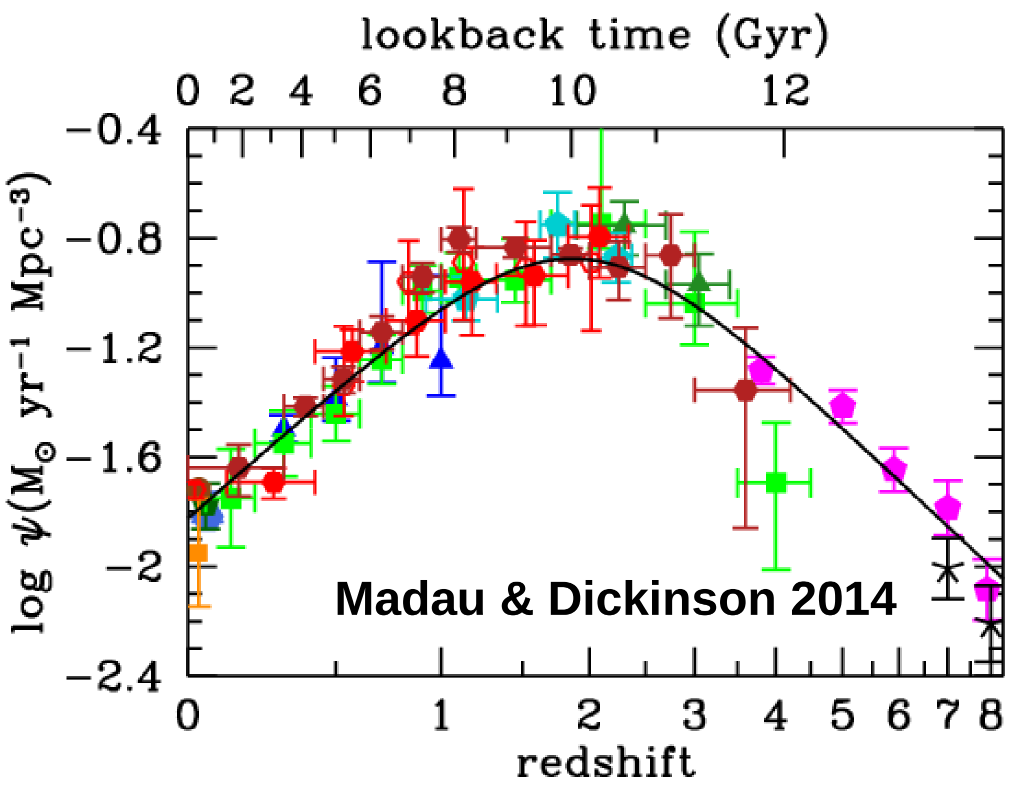
Dominik+ 2013, 2015
Belczynski+ 2016
Lamberts+ 2016

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

O'Shaughnessy+ 2017
Schneider+ 2017
MM+ 2017

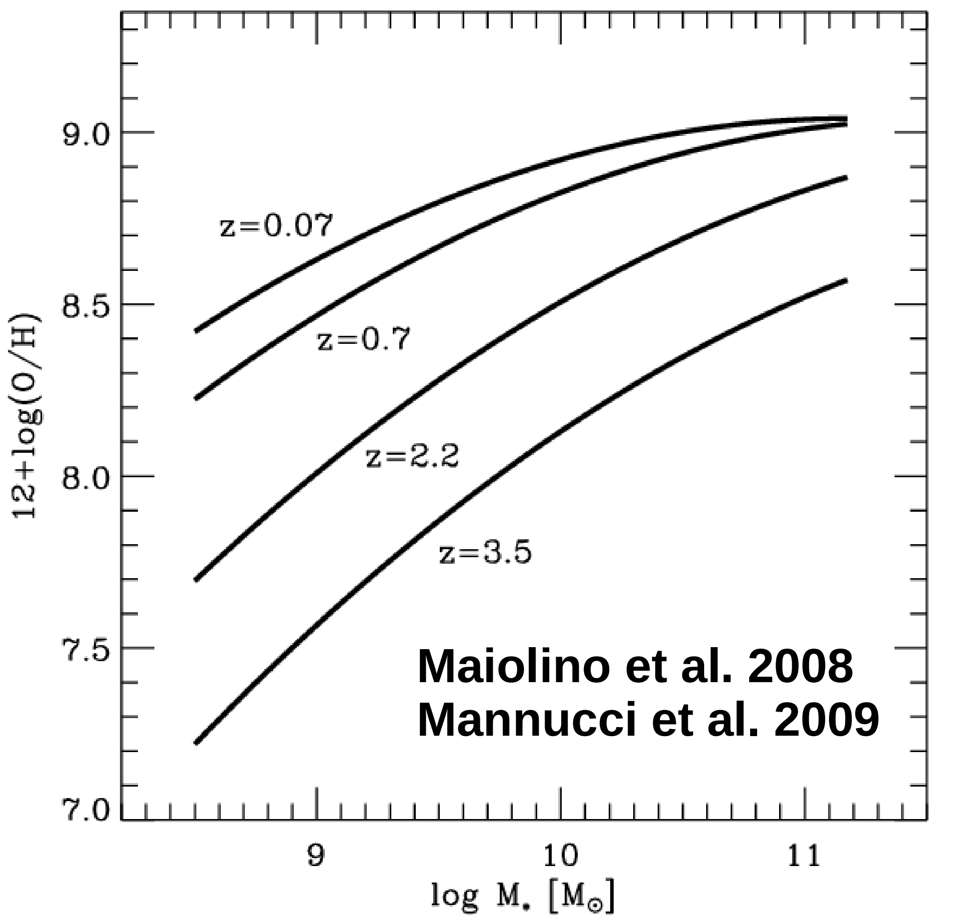
4. The cosmological context: crucial ingredients

Cosmic star formation rate



Affects mainly number of mergers

Redshift-dependent mass – metallicity relation

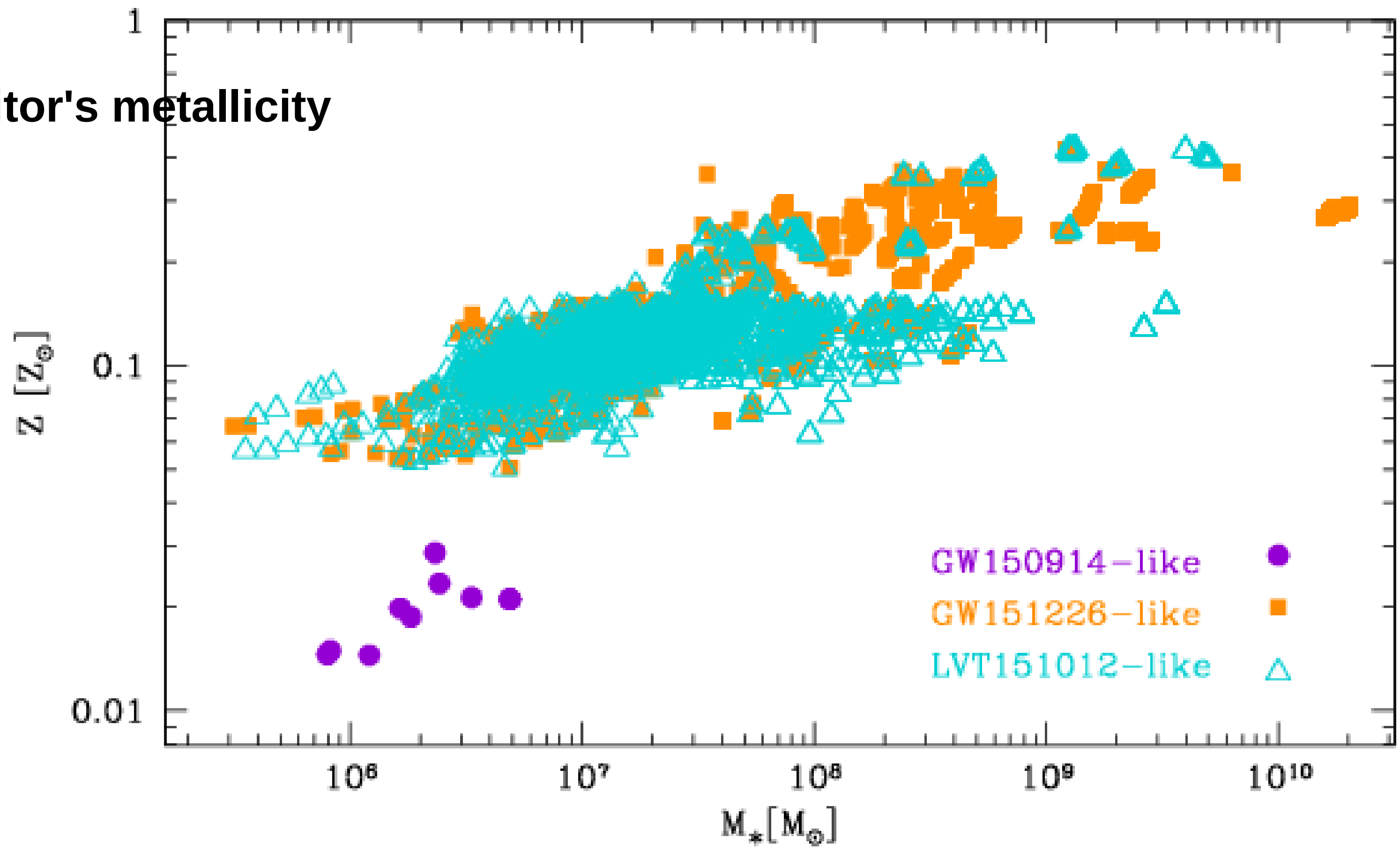


Affects mainly mass of merging systems

4. The cosmological context: Schneider et al. 2017

(4 cMpc)^3 GAMESH cosmological simulation (Graziani+ 2015, 2017)
+ SeBa simulations of BH binaries (MM+ 2013)
+ Monte Carlo approach

Progenitor's metallicity

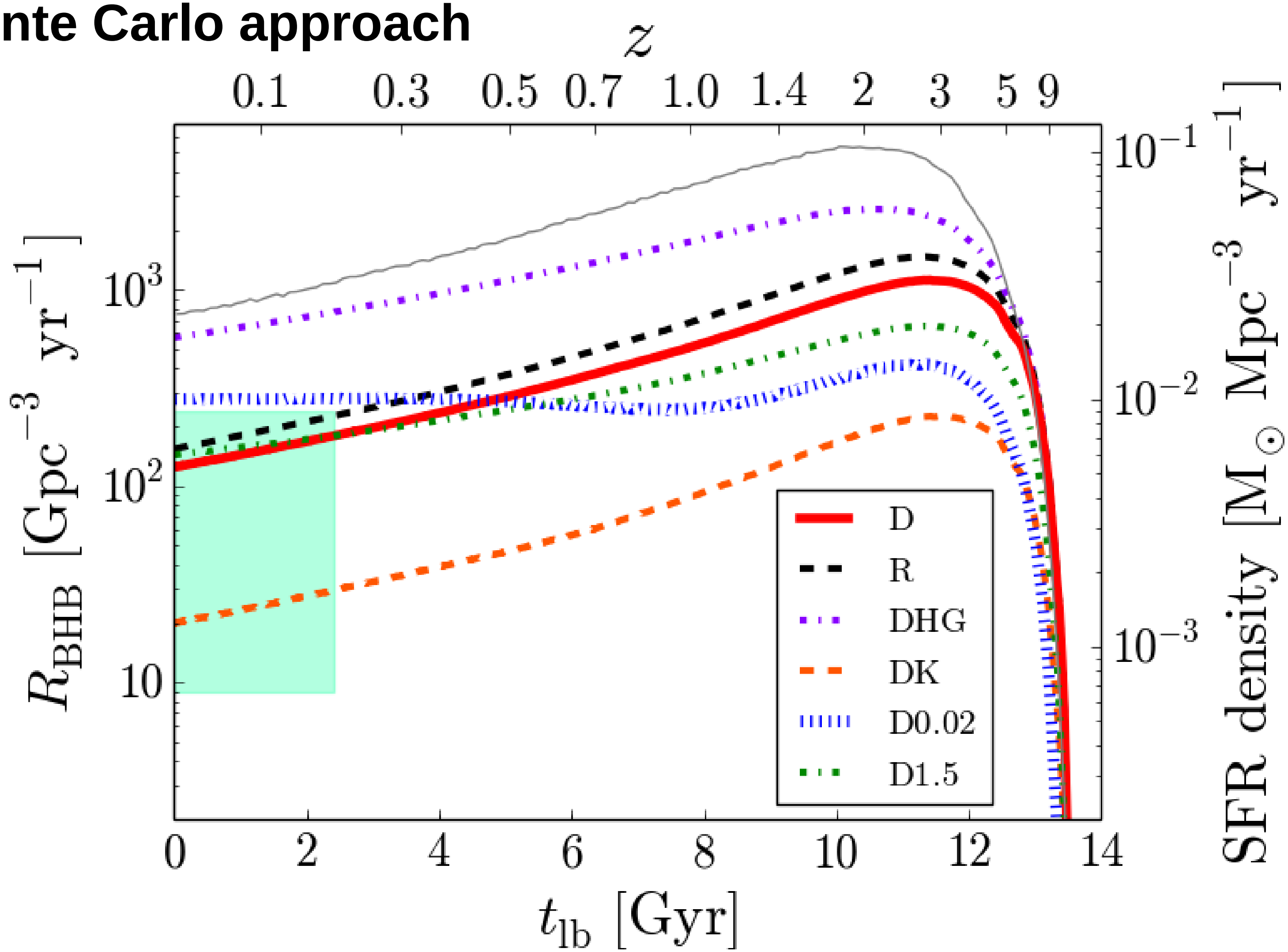


Stellar mass of the host galaxy (at birth)

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

4. The cosmological context: MM et al. 2017

(106.5 cMpc)^3 Illustris cosmological simulation (Vogelsberger+ 2014)
+ BSE simulations of BH binaries (Giacobbo+ 2017)
+ Monte Carlo approach



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

4. The cosmological context

Take home message from cosmology:

DISTANCE DISTRIBUTION of GW DETECTIONS may give us constraints on BH formation:

Stellar-born BHs follow cosmic star formation rate
vs
Primordial BHs do not follow cosmic star formation

BUT how many detections do we need?
Is full Advanced LIGO-Virgo sensitivity enough or should we wait for 3rd generation detectors?

5. Conclusions

* The masses of three observed events were a major breakthrough for astrophysics: already rejected most popular models of BH mass

* Dependence of BH mass on metallicity is necessary to account for GW150914 and GW170104
(e.g. MM, Colpi & Zampieri 2009; Belczynski+ 2010; Spera, MM & Bressan 2015; Belczynski+ 2016; Spera & MM 2017)

* Further detections might disentangle common-envelope from chemically homogeneous (Marchant+ 2016; Mandel & de Mink 2017) evolution thanks to predictions on mass, spin, and redshift

* Dynamics leads to more massive BH binaries, with misaligned spins
(e.g. Ziosi+ 2014; Rodriguez+ 2015, 2016; Hurley+ 2016; MM 2016; Askar+ 2017; Zevin+ 2017)

* A breakthrough in models of dynamical binary formation is needed to disentangle isolated binary evolution from dynamical evolution!!

* Redshift distribution of GW events might disentangle between stellar BHs (which follow cosmic star formation rate) and primordial BHs
(e.g. Dominik+ 2013, 2015; Belczynski+ 2016; Lamberts+ 2016; O'Shaughnessy+ 2017; Schneider+ 2017; MM+ 2017)

THANK YOU!