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Formation and evolution of merging black-hole binaries

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Outline

1. The GW detections

2. The black hole mass spectrum

3. Formation channels of black hole binaries

4. Conclusions

GW detections of merging black holes

GW150914

$$m_1 = 35.4^{+5.0}_{-3.4}\ \mathrm{M}_\odot$$

$$m_2 = 29.8^{+3.3}_{-4.3}\ \mathrm{M}_\odot$$

GW151226

$$m_1 = 14.2^{+8.3}_{-3.7}\ \mathrm{M}_\odot$$

$$m_2 = 7.5^{+2.3}_{-2.3}\ \mathrm{M}_\odot$$

GW170104

$$m_1 = 31.2^{+8.4}_{-6.0}\ \mathrm{M}_\odot$$

$$m_2 = 19.4^{+5.3}_{-5.9}\ \mathrm{M}_\odot$$

GW170608

$$m_1 = 12.0^{+7.0}_{-2.0}\ \mathrm{M}_\odot$$

$$m_2 = 7.0^{+2.0}_{-2.0}\ \mathrm{M}_\odot$$

GW170814

$$m_1 = 30.5^{+5.7}_{-3.0}\ \mathrm{M}_\odot$$

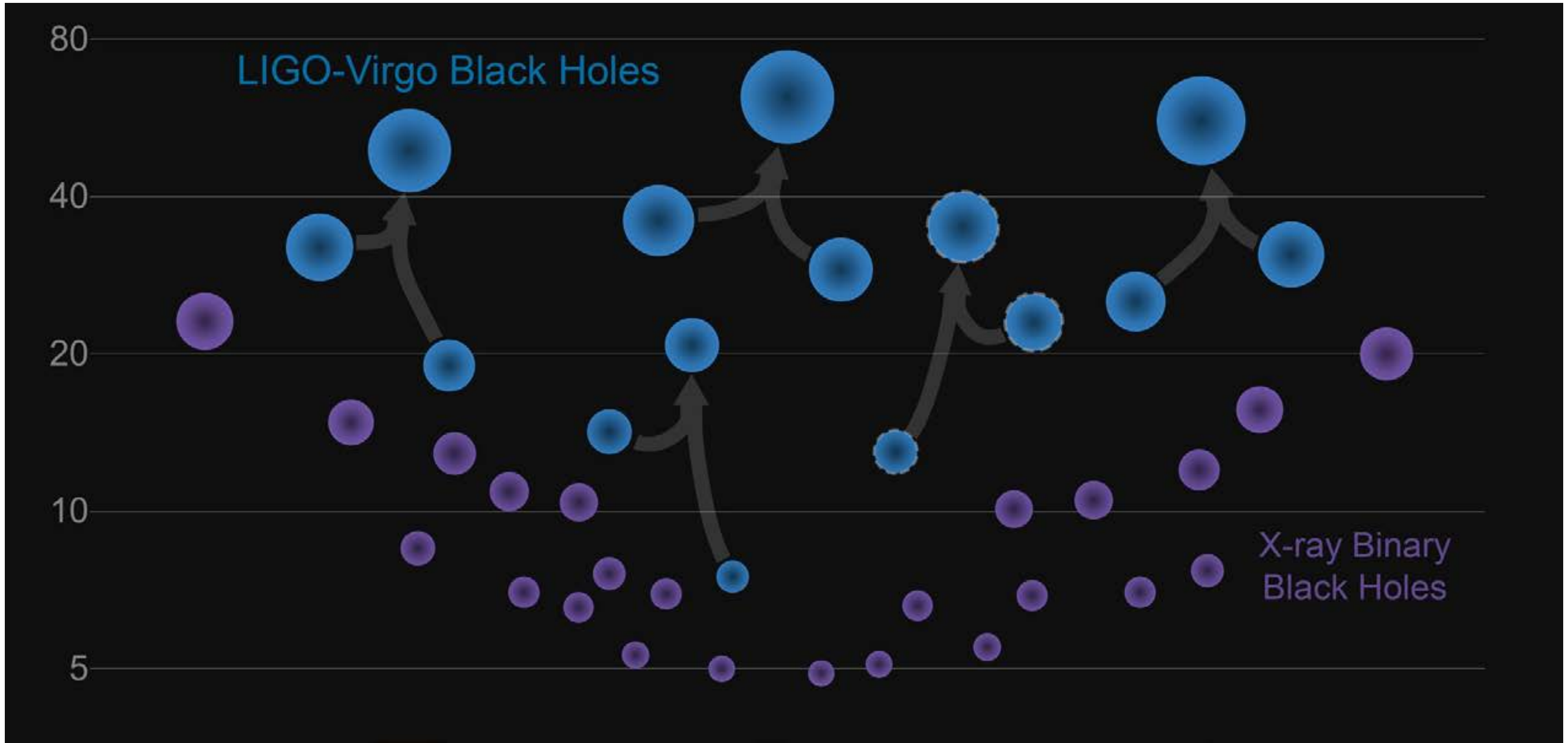
$$m_2 = 25.3^{+2.8}_{-4.2}\ \mathrm{M}_\odot$$

Implications for the BH mass spectrum

✓ **BINARY** black holes exist

$\checkmark$ **MASSIVE** black holes exist $(m > 25\ \mathrm{M}_{\odot})$

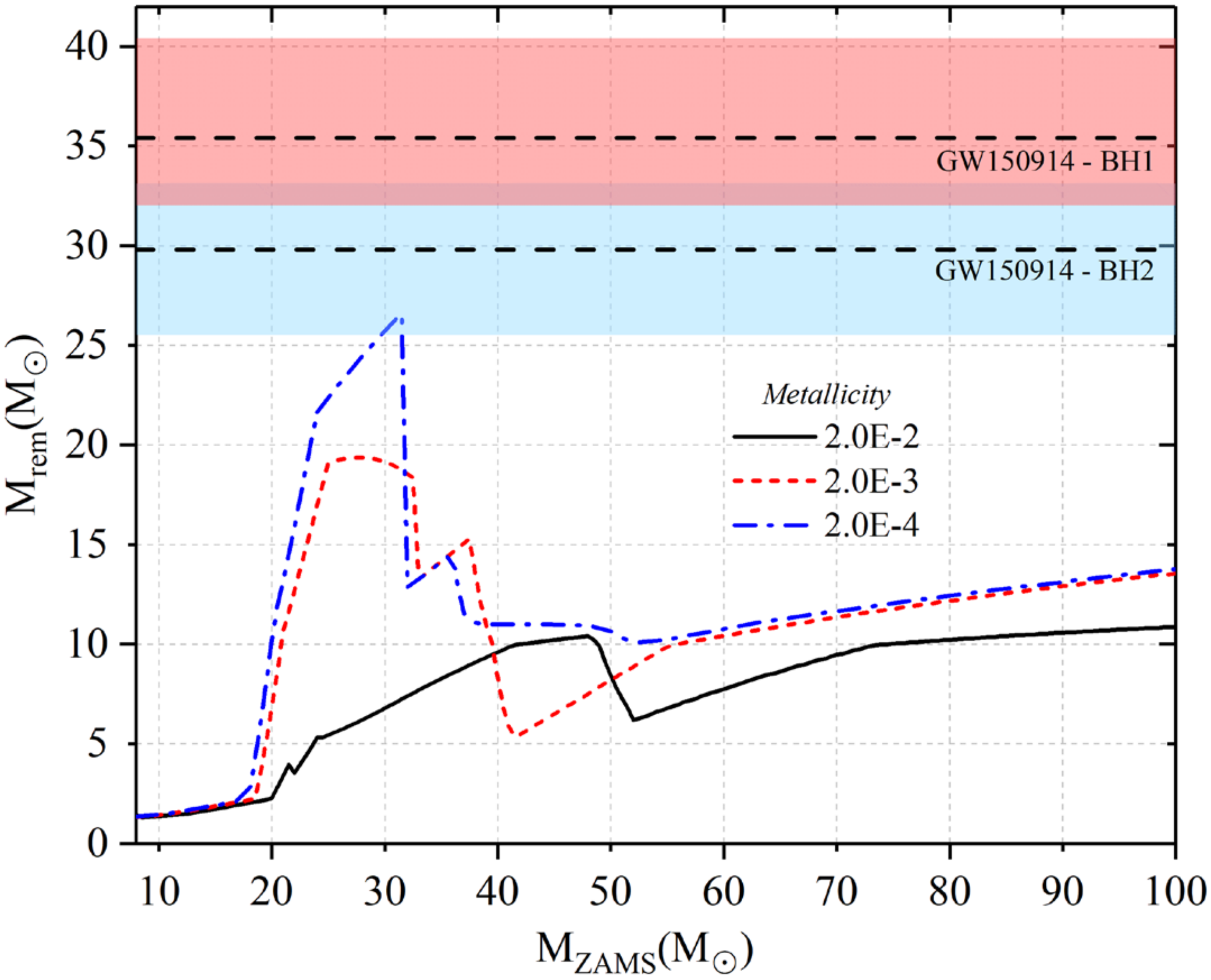
✓ Binary black holes can **MERGE** within a Hubble time



www.ligo.caltech.edu

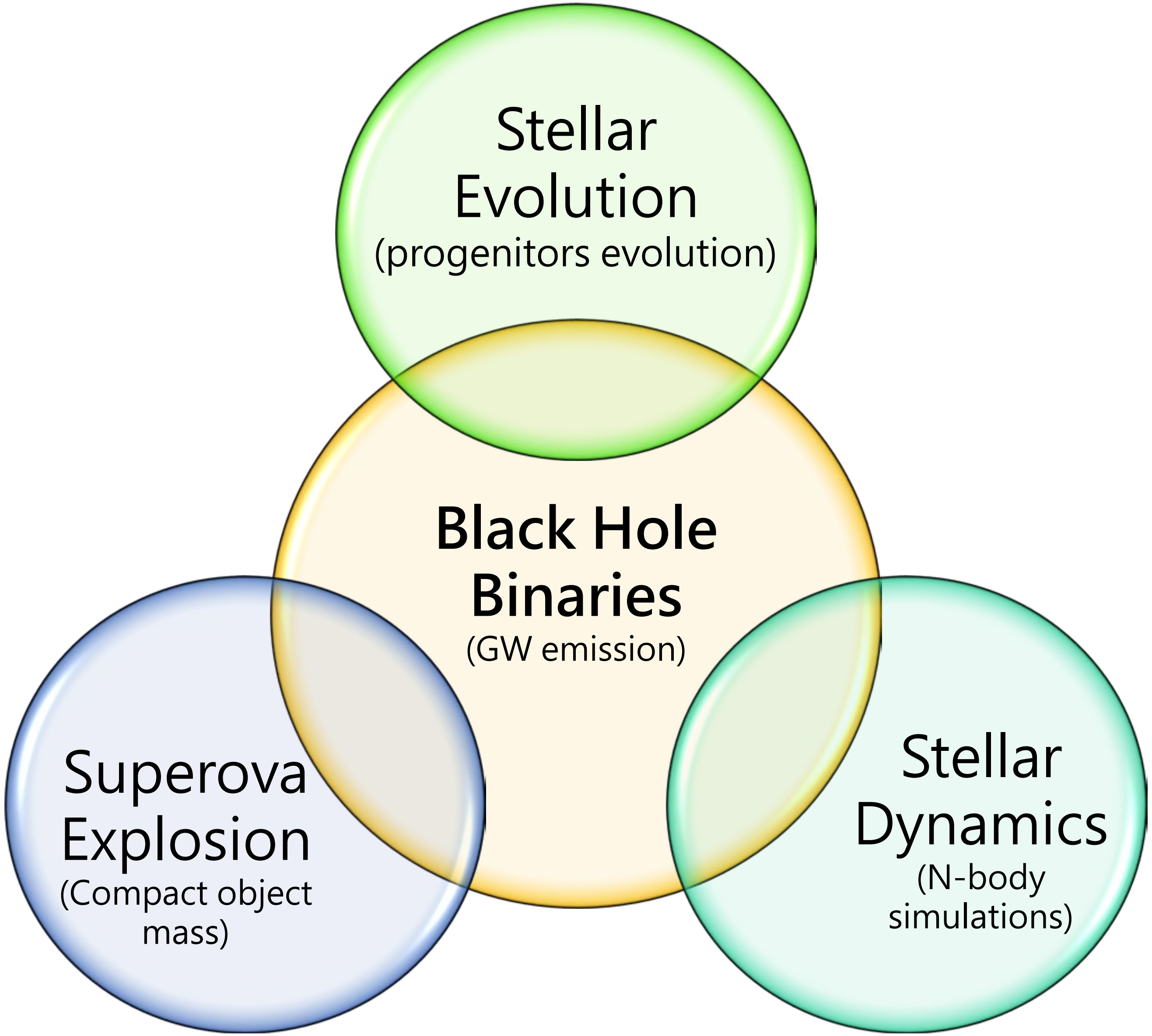
Models of BH mass spectrum (before GW150914)

*Models from the **BSE** code (Hurley+ 2002)*



Most models of BH mass spectrum were not able to explain GW150914

Understanding black holes: ingredients



BH mass spectrum: physical processes

Stellar evolution → stellar winds

Stars lose mass

(Vink+ 2001, 2005, Bressan+ 2012, Tang, Bressan+ 2014, Chen, Bressan+ 2015)

Wind from WR star WR 124, Sagitta, HST

✓ Mass-loss depends on **mass** and **metallicity**

$$\frac{dM}{dt} \propto Z^{\alpha} \qquad (\alpha \in [0.5; 0.9])$$

✓ The amount of mass-loss for massive stars can be conspicuous

Wolf-Rayet star WR 124

$$M_{\text{initial}} \simeq 30M_{\odot} \xrightarrow{\text{stellar winds}} \simeq 10M_{\odot}$$

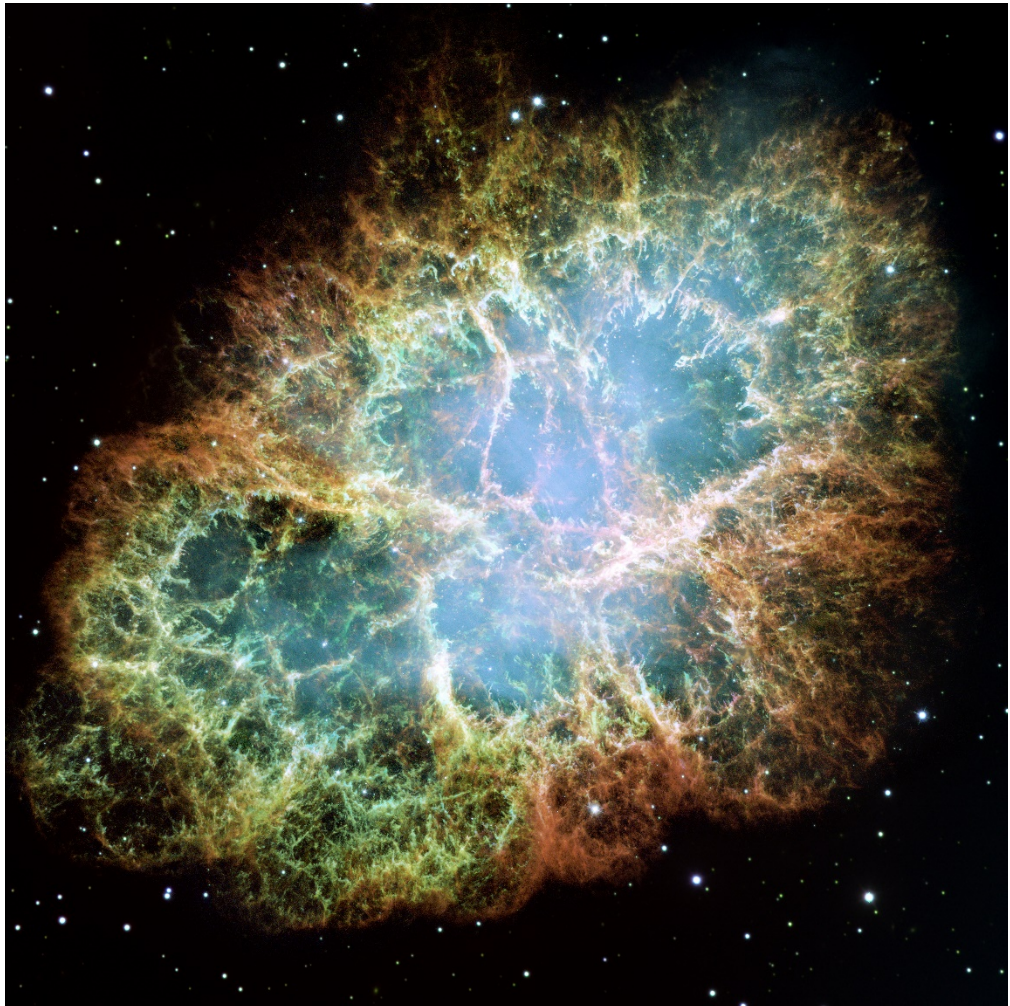
BH mass spectrum: physical processes

Supernova explosion

BHs form after supernovae

(Fryer+ 1999, 2001, 2012, Heger+ 2003, Mapelli+ 2009, 2010)

Crab Nebula, HST

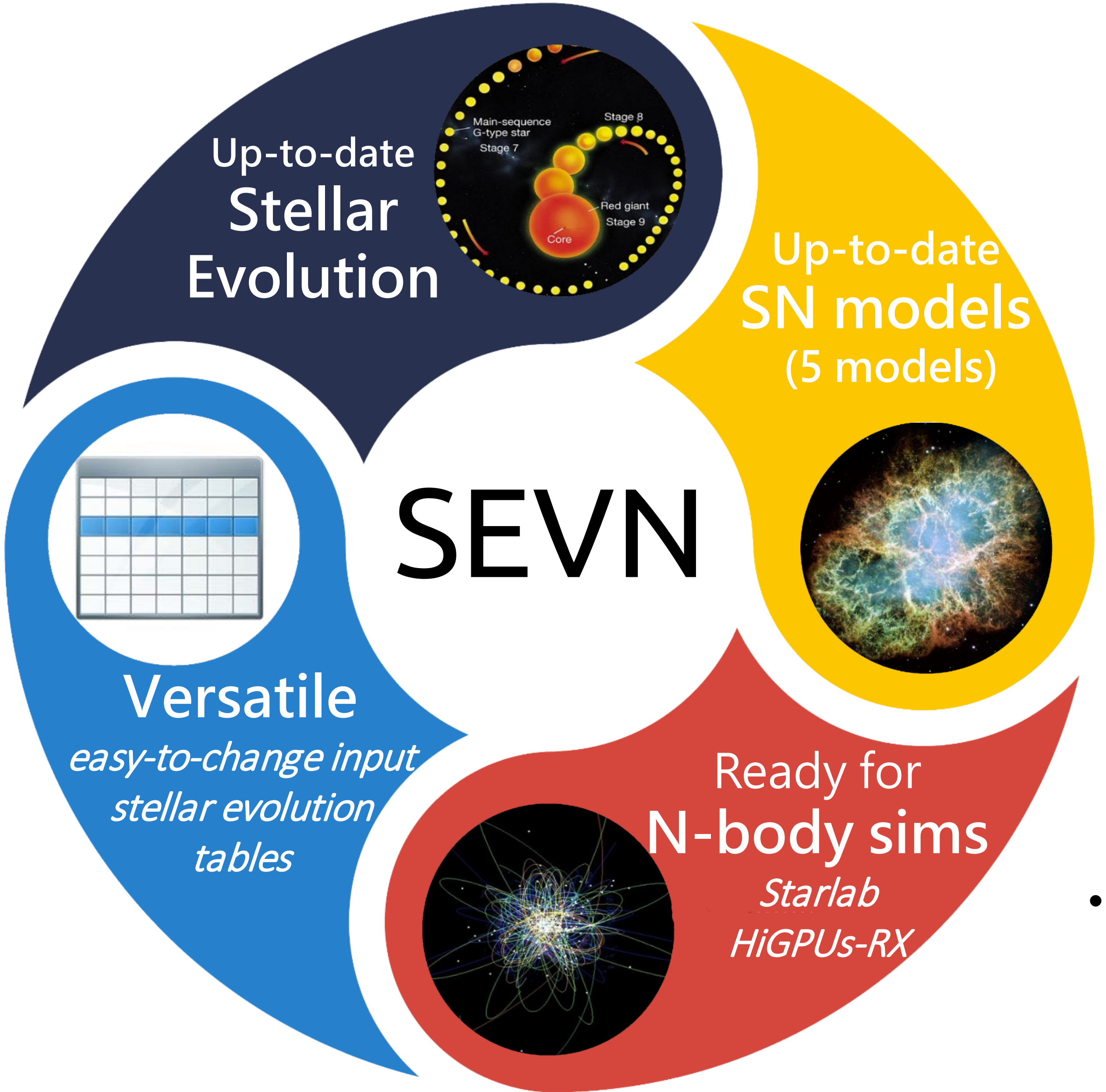


- ✓ Supernova remnant (BH/NS) depends on the **final mass** of the star
- ✓ It depends on the **compactness** of the star
- ✓ It depends on the **rapidity** of the explosion
- ✓ It depends on **fallback**

✓ $M_{\rm final} \gtrsim 30 M_{\odot}$: the SN explosion may fail → direct collapse → massive black hole

The SEVN code

Stellar EVolution for N-body



- *MS, Mapelli, Bressan, 2015, MNRAS, 451, 4086*
- *MS & Mapelli, 2017, MNRAS, 470, 4739*

- Stellar evolution through **look-up tables**.
  a. Versatile approach.
  b. Default: tables from the PARSEC code (Bressan+ 2012, Chen+ 2015)

- Several up-to-date **SN explosion** models
  a. CO-based criteria
  b. Compactness-based criteria

- Already coupled with some **N-body codes**

- SEVN is **publicly available**
  - https://gitlab.com/mario.spera/SEVN
  - http://web.pd.astro.it/mapelli/SEVN.tar.gz

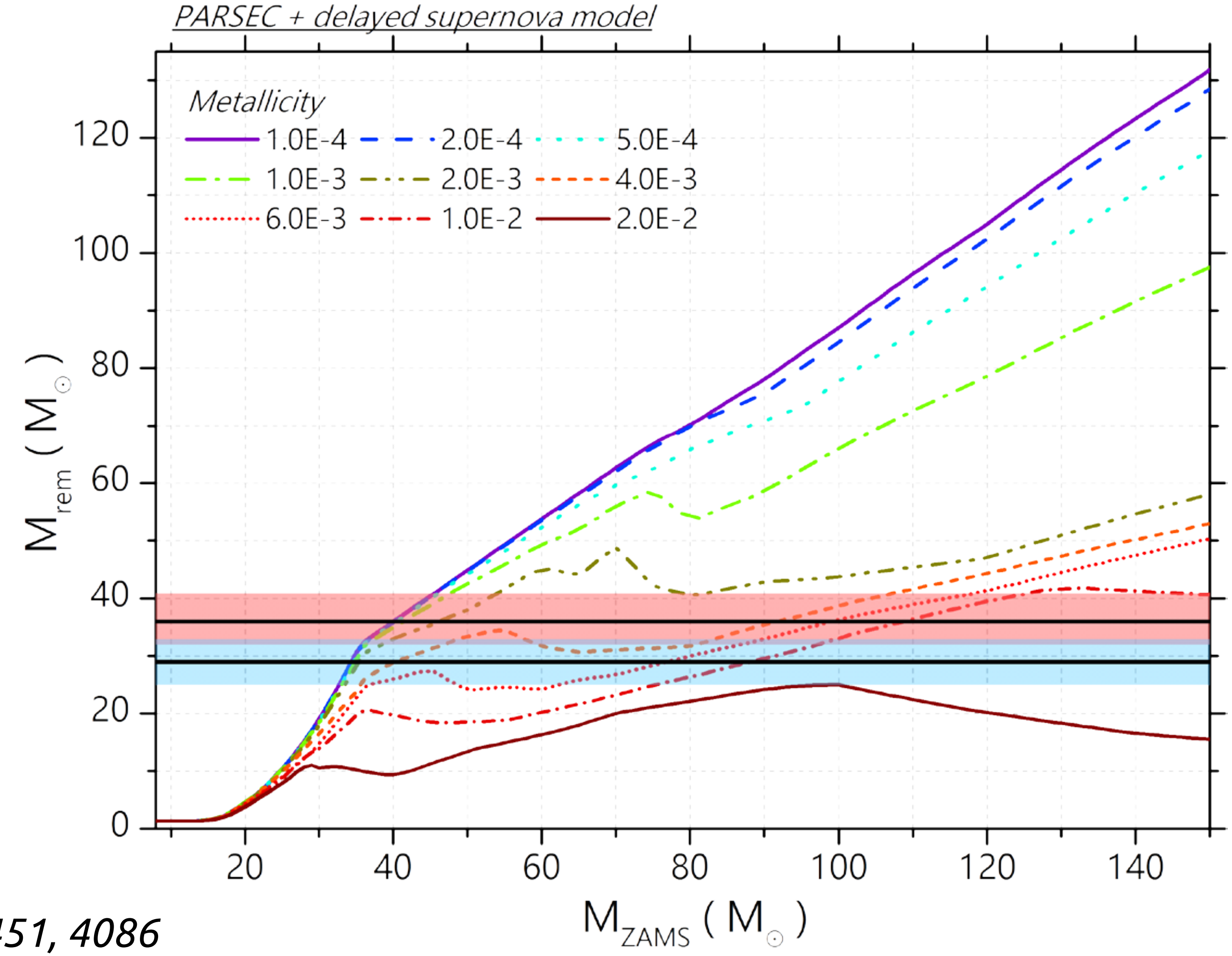
The BH mass spectrum with the SEVN code

Massive ($> 30M_\odot$) stellar black holes:

Low metallicity

+

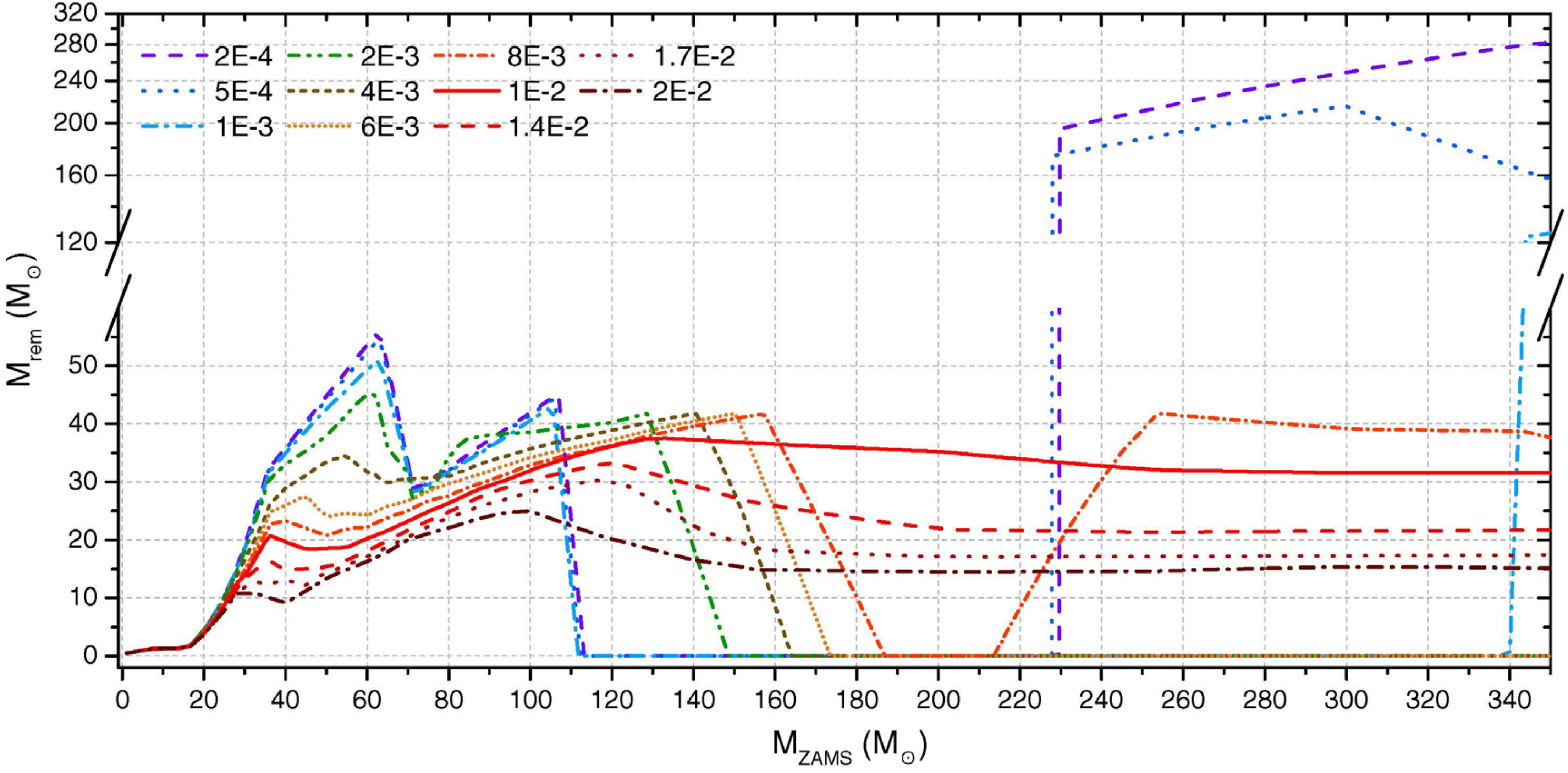
direct collapse



- *MS, Mapelli, Bressan, 2015, MNRAS, 451, 4086*
- *Abbott+ 2016 ApJL, 818, L22 (Fig. 1)*

The role of pair-instability SNe

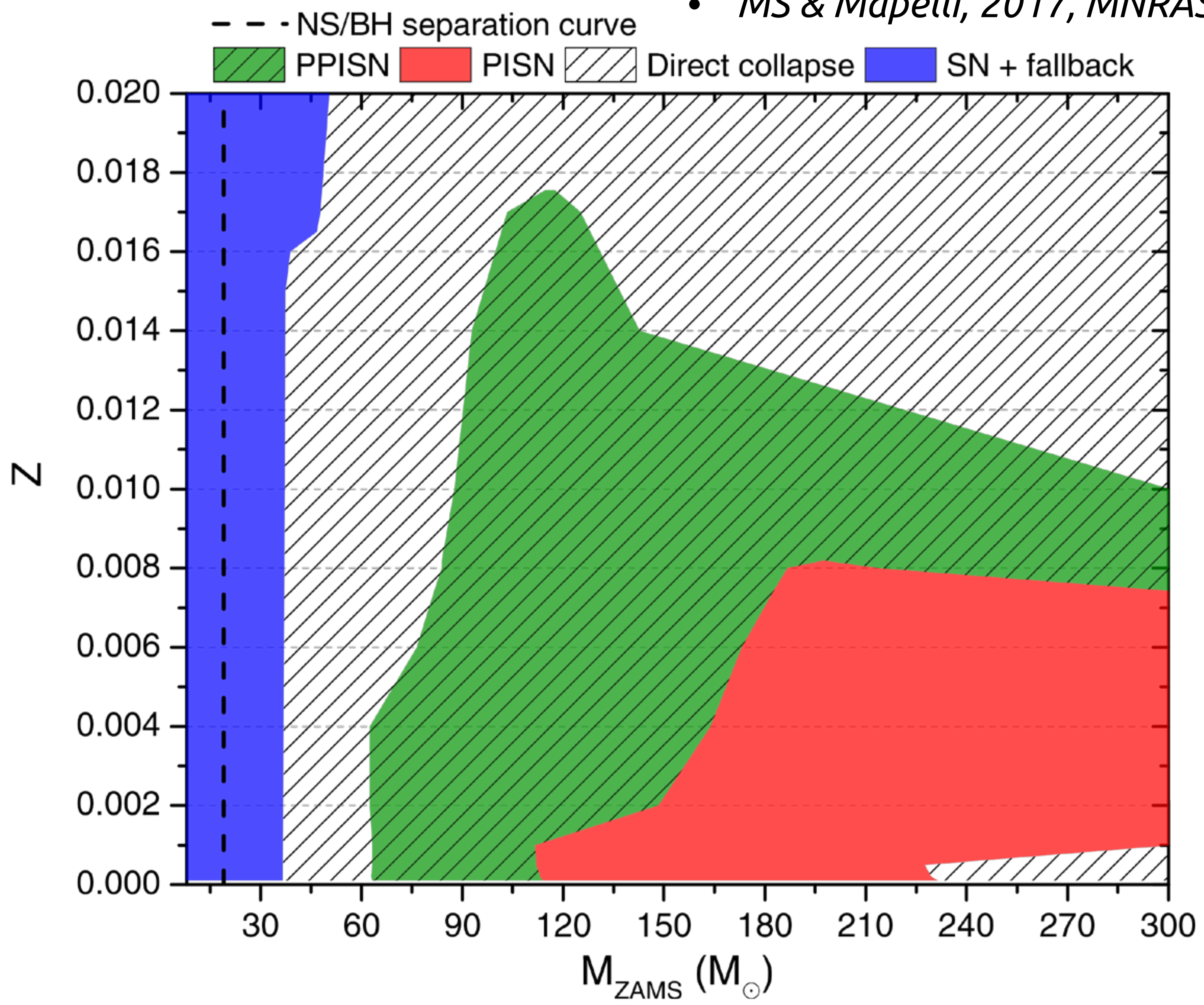
Pulsational- and pair-instability SNe are missing in most population-synthesis codes



- *MS & Mapelli, 2017, MNRAS, 470, 4739*

PISN/PPISN: a schematic view

- *MS & Mapelli, 2017, MNRAS, 470, 4739*



PISN/PPISN: a schematic view

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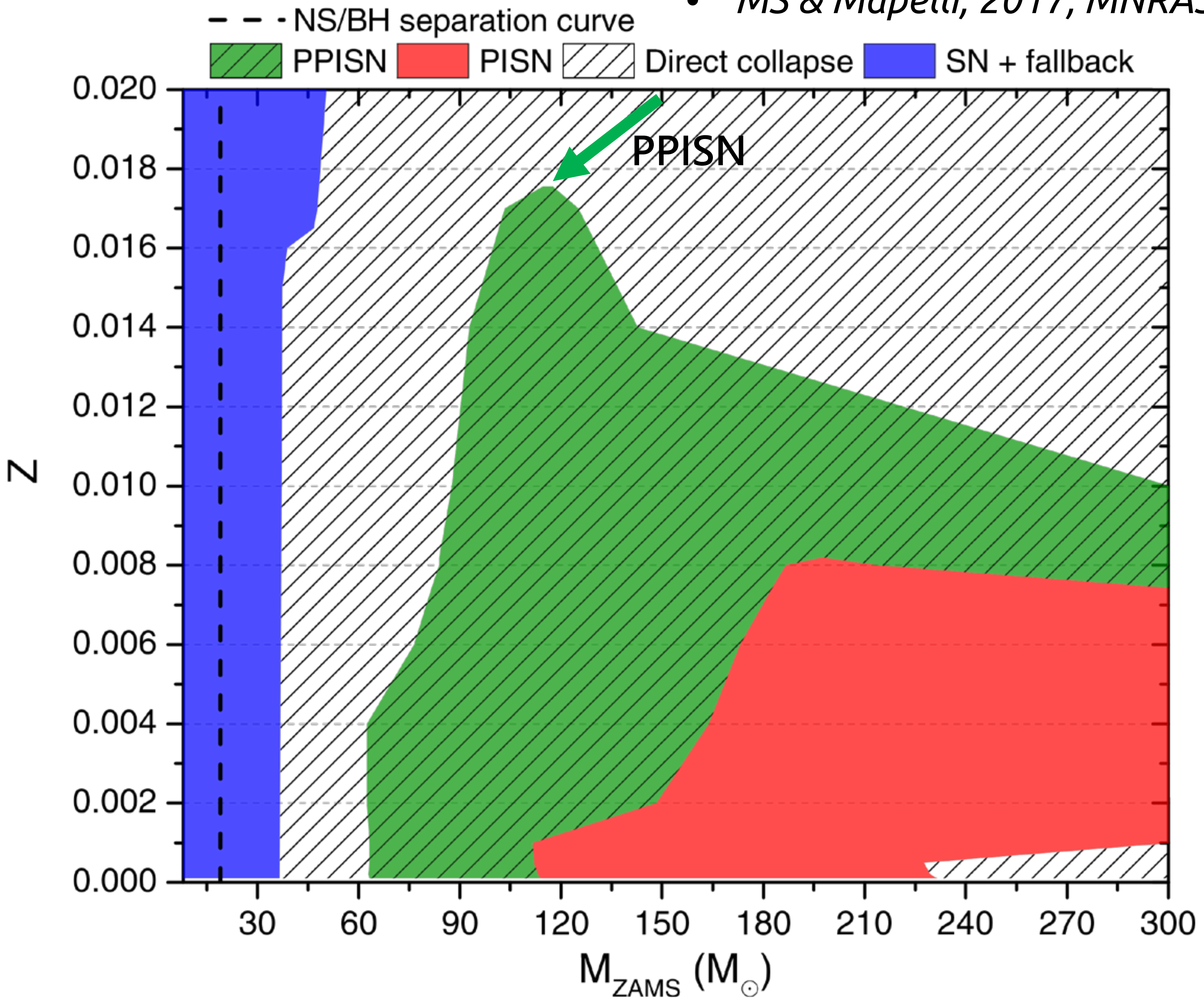

PPISN: $Z \lesssim 0.017 \simeq Z_\odot$

PISN/PPISN: a schematic view

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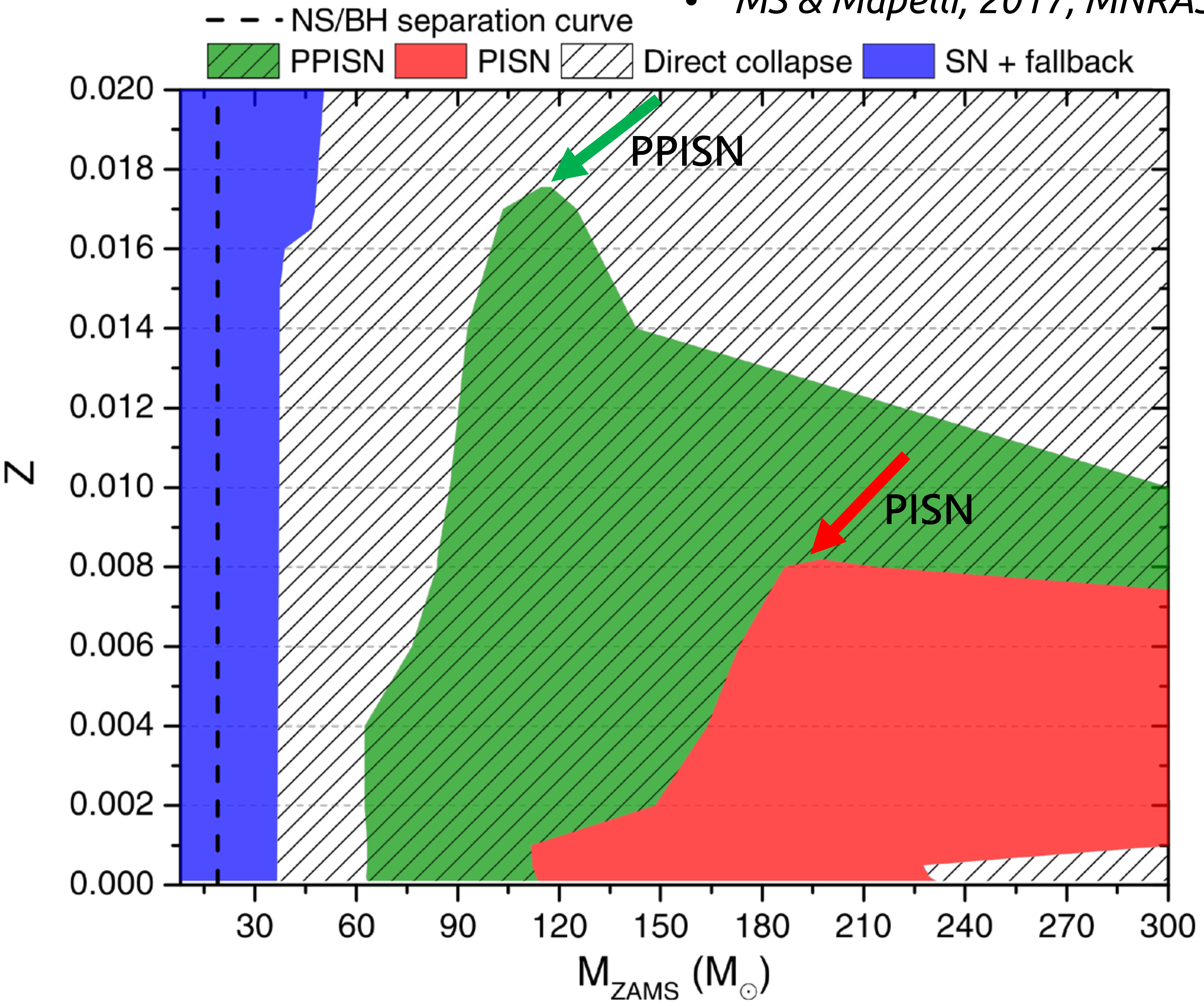

PPISN: $Z \lesssim 0.017 \simeq Z_\odot$

PISN: $Z \lesssim 0.008 \simeq 0.5 Z_\odot$

PISN/PPISN: a schematic view

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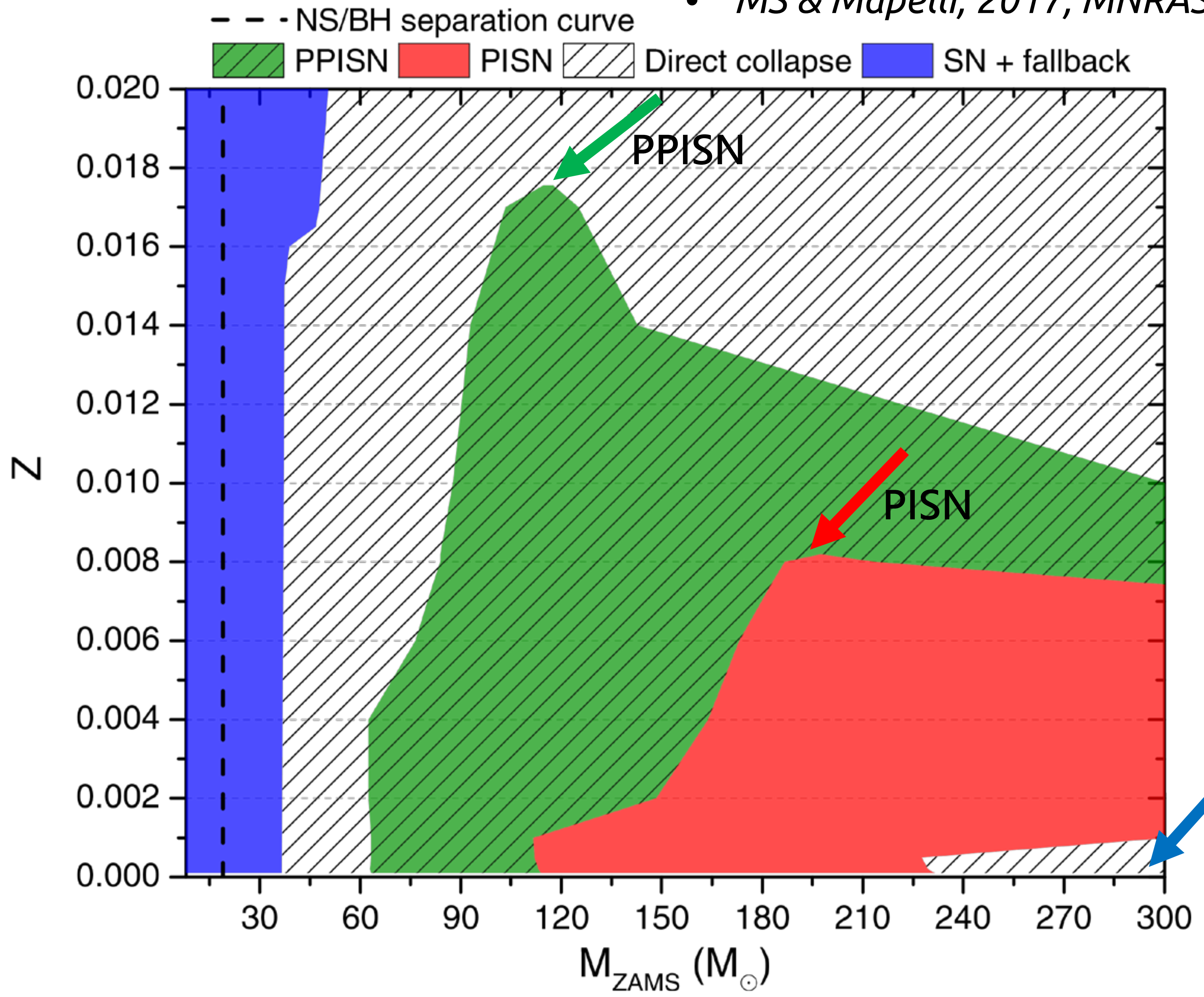


PPISN: $Z \lesssim 0.017 \simeq Z_\odot$

PISN: $Z \lesssim 0.008 \simeq 0.5 Z_\odot$

Direct collapse

$M_{ZAMS} \gtrsim 230 M_\odot$

$Z \lesssim 0.001 \simeq \frac{1}{20} Z_\odot$

$M_{BH} \gtrsim 200 M_\odot$

What about black-hole BINARIES?

Formation channels

Primordial binary

Two stars **are bound** since the **beginning** of their life.

Dynamically formed binary

Two stars **become bound** after one (or more) **gravitational encounters**

Primordial binaries

Two stars **are bound** since the **beginning** of their life.

Question: can primordial binaries become black-hole binaries?

Not so easy → **Binary stellar evolution processes**
(mass transfer, common envelope, tidal dissipation, supernova kicks)

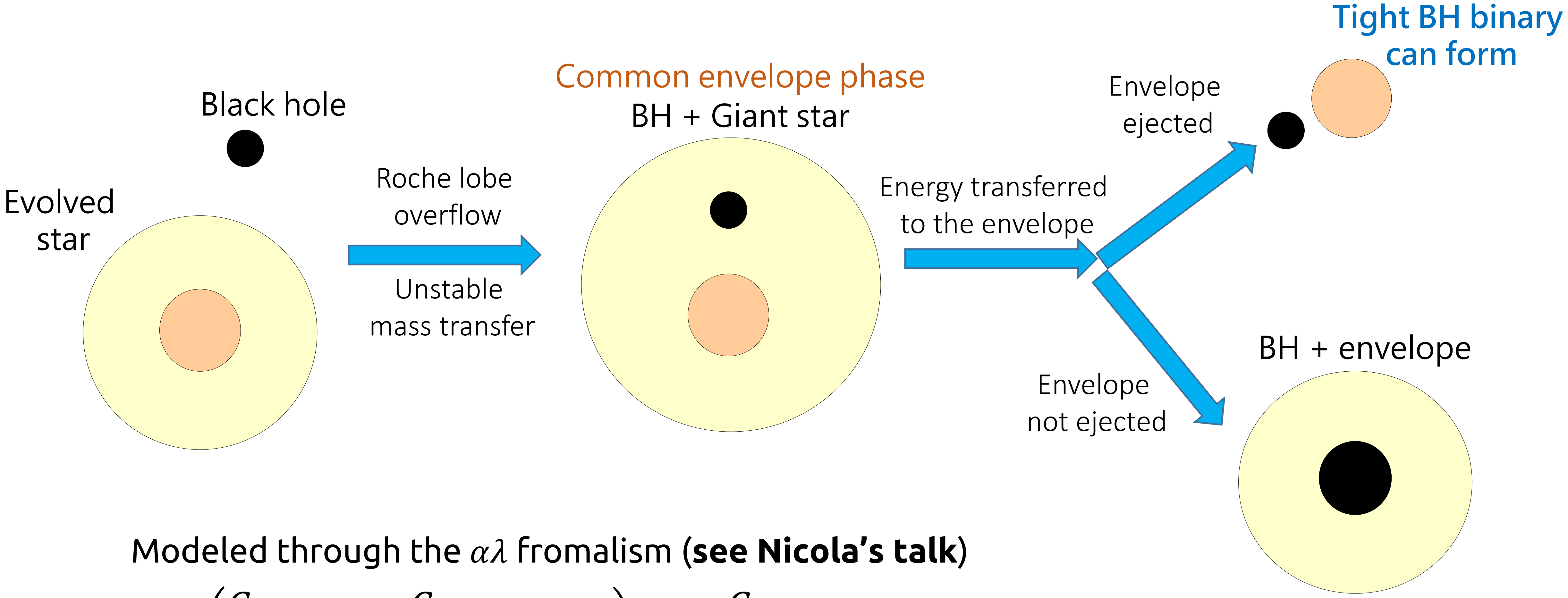
Question: if a BH binary is formed, can it merge within a Hubble time?

Not so easy → **BHs must be very close to each other (tens of $R_{\odot}$)**

Question: is there any process that brings the compact remnants close to each other?

Common envelope evolution

Two compact objects orbit in a **shared envelope**



Modeled through the $\alpha\lambda$ fromalism (**see Nicola's talk**)

$$\boldsymbol{\alpha}\left(\frac{Gm_1m_2}{2a_i}-\frac{Gm_{1,\mathrm{core}}m_2}{2a_f}\right)=-\frac{Gm_1m_{1,\mathrm{env}}}{\boldsymbol{\lambda}R_1}$$

See Ivanova et al. 2012 for a review

The BH mass spectrum with the SEVN code

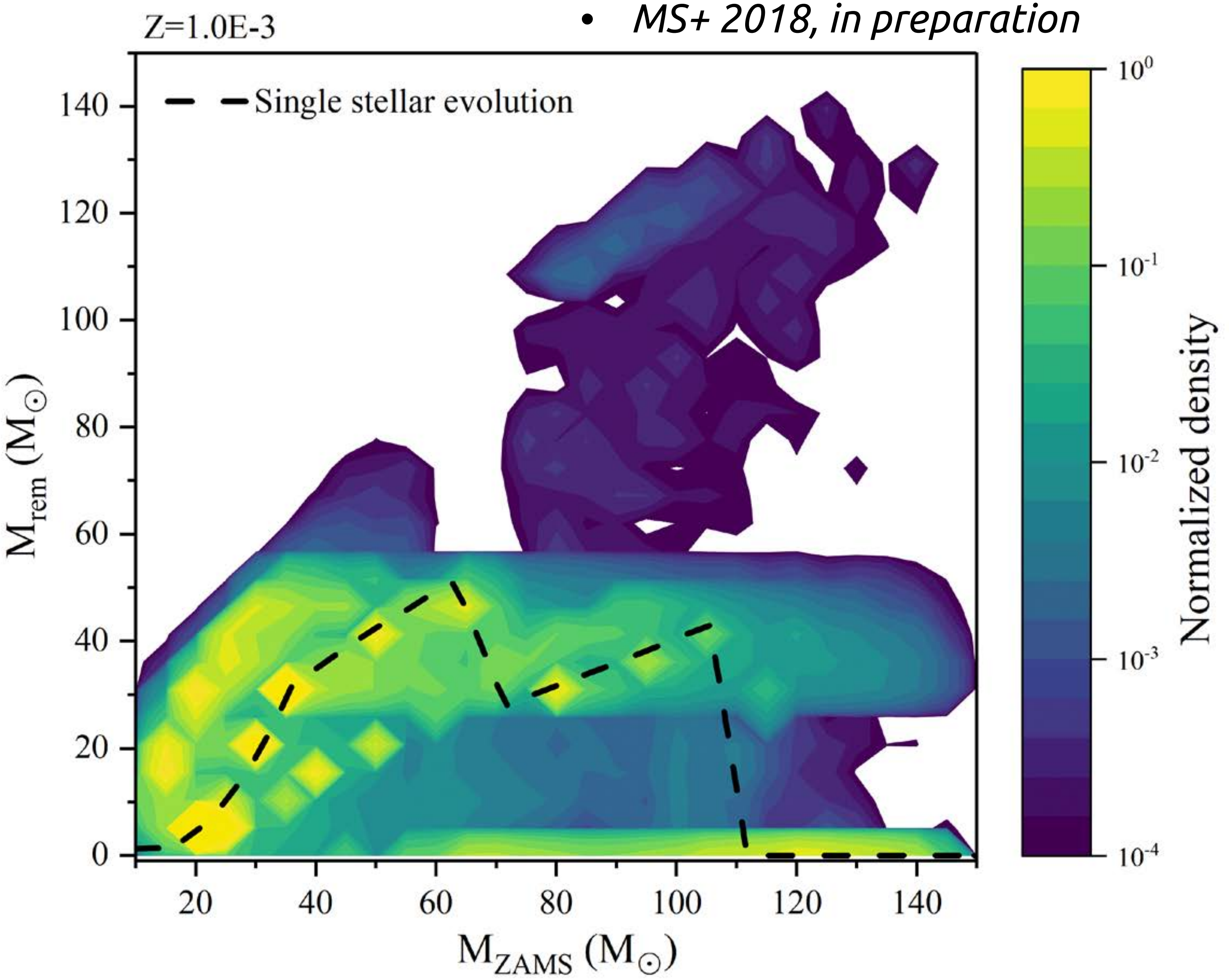
The effect of binary stellar evolution

- *MS+ 2018, in preparation*

10M binary systems

Power-law initial mass function (Kroupa 2001)

Initial period and eccentricity distributions as in Sana+2012



Dynamically formed binaries

Young star cluster R136, Large Magellanic Cloud, HST

Two stars become bound after one (or more) **gravitational encounters**

Gravitational encounters: are they common?

YES, in dense stellar environments

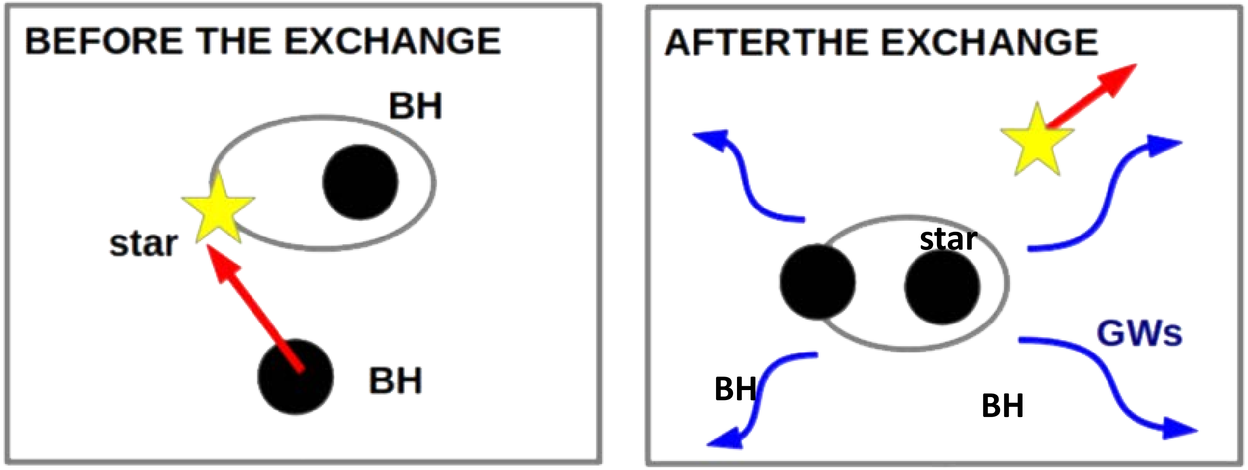
Dense means $n \gtrsim 10^3$ stars pc^{-3}

Is it common to find stars in dense environments?

The majority of stars form in dense stellar environments *(Lada & Lada 2003)*

We MUST care about dynamics

An example: Gravitational exchanges



BHs born from single stars in a star cluster
likely **acquire a companion** thanks to dynamics

Exchanges favour the formation of massive BH-BH binaries, with
high eccentricity and misaligned spins

$> 90\%$ BH-BH binaries form dynamically in star clusters *(Ziosi, Mapelli+ 2014)*

See also Elisa's talk

An example: Gravitational exchanges

Take home message:
we need to constrain stellar dynamics better

BHs born from single stars in a star cluster
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$>$ 90% BH-BH binaries form dynamically in star clusters *(Ziosi, Mapelli+ 2014)*

See also Elisa’s talk

Conclusions

1. Models of BH formation are hampered by uncertainties on stellar winds and supernova explosion *(Mapelli+ 2009, 2010)*

2. Recent population-synthesis models show that BHs may have mass $\gg 20 M_{\odot}$ if progenitor is metal poor *(Mapelli+ 2013; MS+ 2015; MS+ 2017)*

3. BH binaries can form both from primordial binaries and from dynamically evolved binaries – there is a strong degeneracy

4. Binary stelar evolution can dramatically affect the BH mass psectrum

5. **Dynamics can affect the formation and evolution of BH-BH binaries in many ways**
    a. dynamical exchanges (Ziosi, Mapelli+ 2014)
    b. Spitzer Instability (MS+ 2016)
    c. Kozai resonance (Kimpson, MS+ 2016)
    d. Runaway growth of IMBHs(Mapelli 2016)