INAF – Osservatorio Astronomico di Padova

Modeling the formation of compact remnants in star clusters

Mario Spera (mario.spera@oapd.inaf.it) (mario.spera@live.it)
Postdoctoral fellow at Astronomical Observatory of Padova

Collaborators: **Michela Mapelli**, Alessandro A. Trani, Nicola Giacobbo, Adam Dakroury, Alessandro Bressan

Talk @ Stellar aggregates over mass and spatial scales
December 5 - 9 2016, Physikzentrum Bad Honnef, Germany

Outline

Stellar mass black holes

1. Observations
   X-ray binaries, GW150914, GW151226, LVT151012 (what we know)

2. Mass spectrum: ingredients
   mass loss, supernova explosions

3. Black hole mass spectrum from SEVN
   up to $300M_{\odot}$ including pair instability

4. Conclusions

(Direct) Observations of merging black holes

GW150914

$$m_1 = 35^{+5}_{-3}\ \mathrm{M}_\odot$$

$$m_2 = 30^{+3}_{-4}\ \mathrm{M}_\odot$$

GW151226

$$m_1 = 14^{+8}_{-4}\ \mathrm{M}_\odot$$

$$m_2 = 7.5^{+2}_{-2}\ \mathrm{M}_\odot$$

LVT151012

$$m_1 = 23^{+18}_{-6}\ \mathrm{M}_\odot$$

$$m_2 = 13^{+5}_{-5}\ \mathrm{M}_\odot$$

What are they telling us?

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

✓ **BINARY** BHs exit

✓ They can **MERGE** within a Hubble time

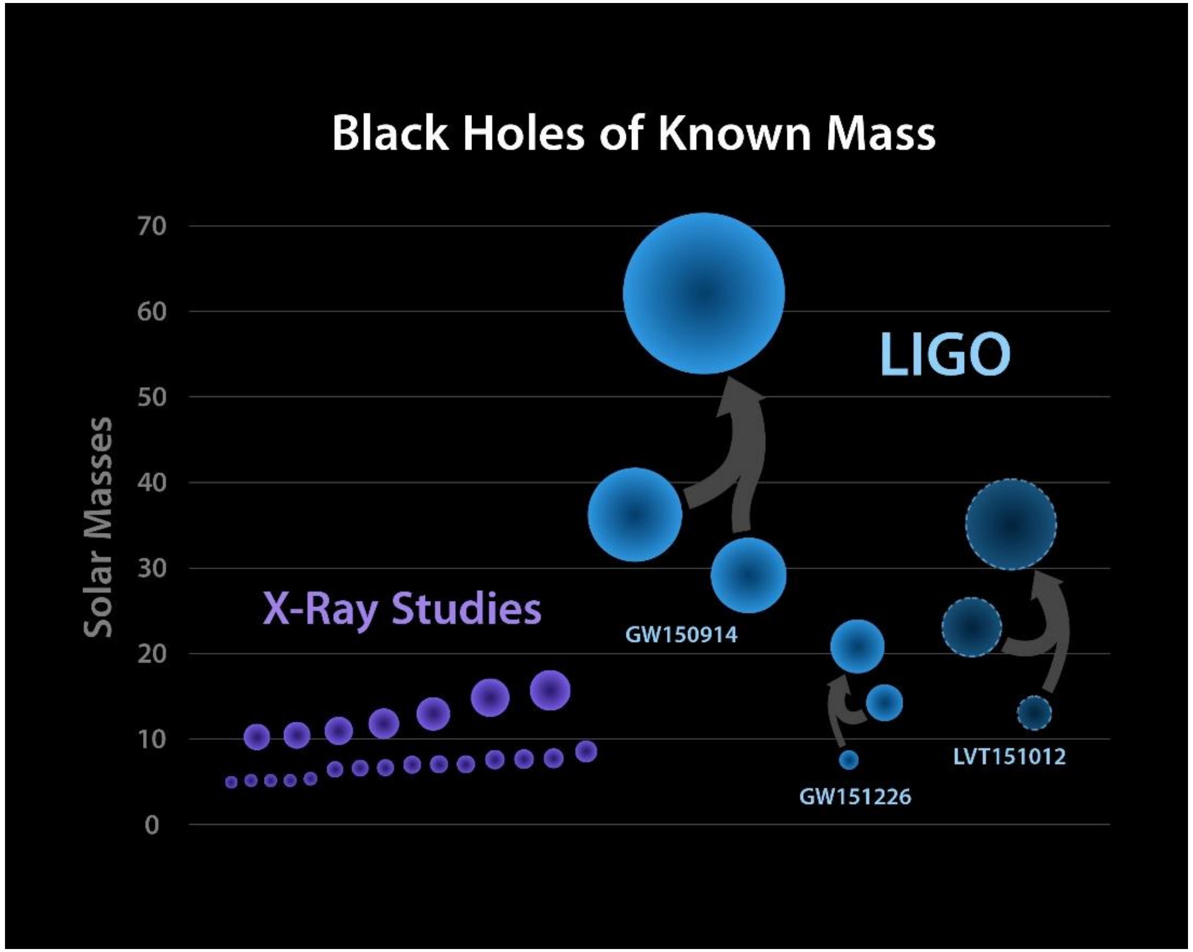
Stellar black holes and their masses

✓ Massive BHs exist ($m > 25\ \mathrm{M}_\odot$) → is that surprising?

Before GW events
~15 BH masses in Milky Way X-ray binaries

Milky Way: all BHs have $m < 15\ \mathrm{M}_\odot$

We used to deal with "light" BHs



https://www.ligo.caltech.edu/image/ligo20160615e

Stellar black holes and their masses

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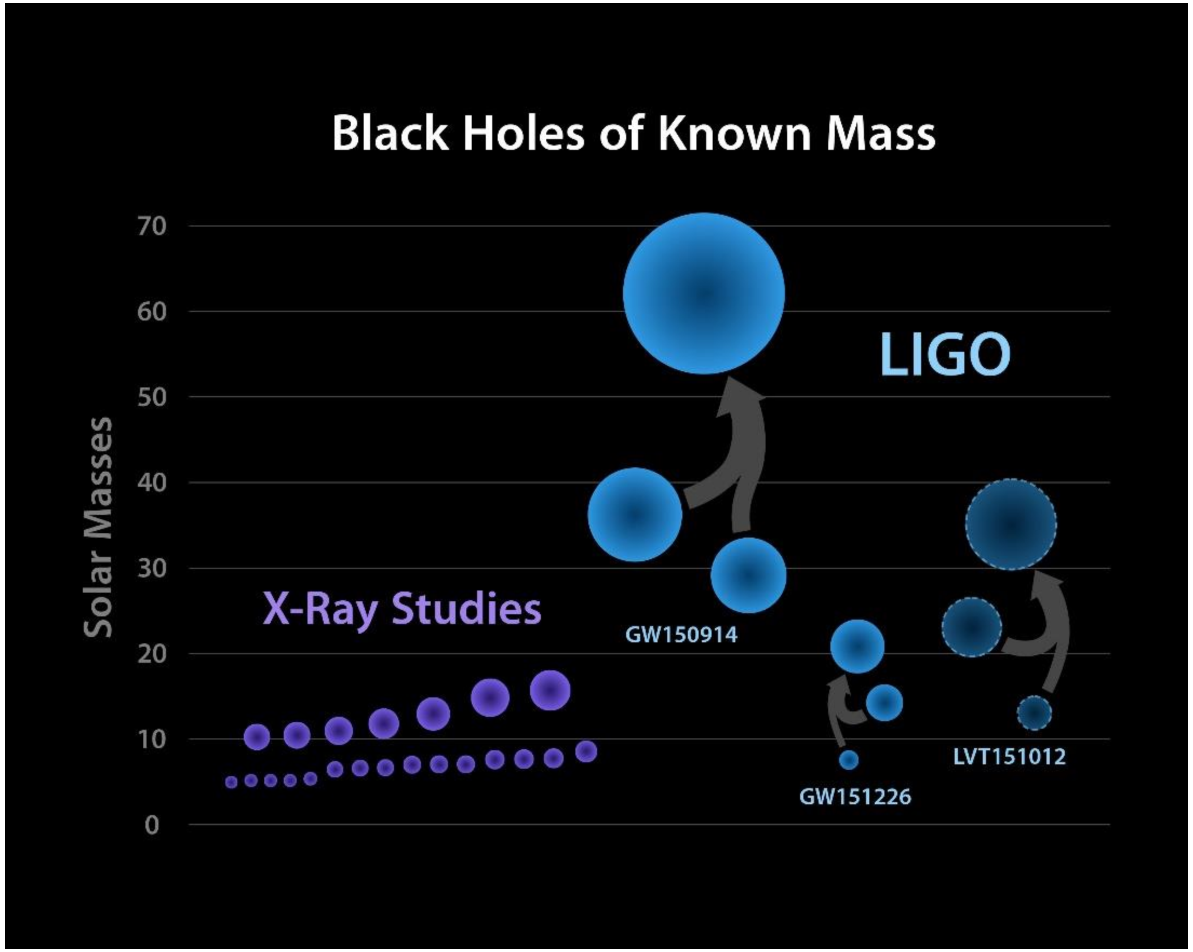
After GW events

LIGO/Virgo events constrain the
BHs mass spectrum

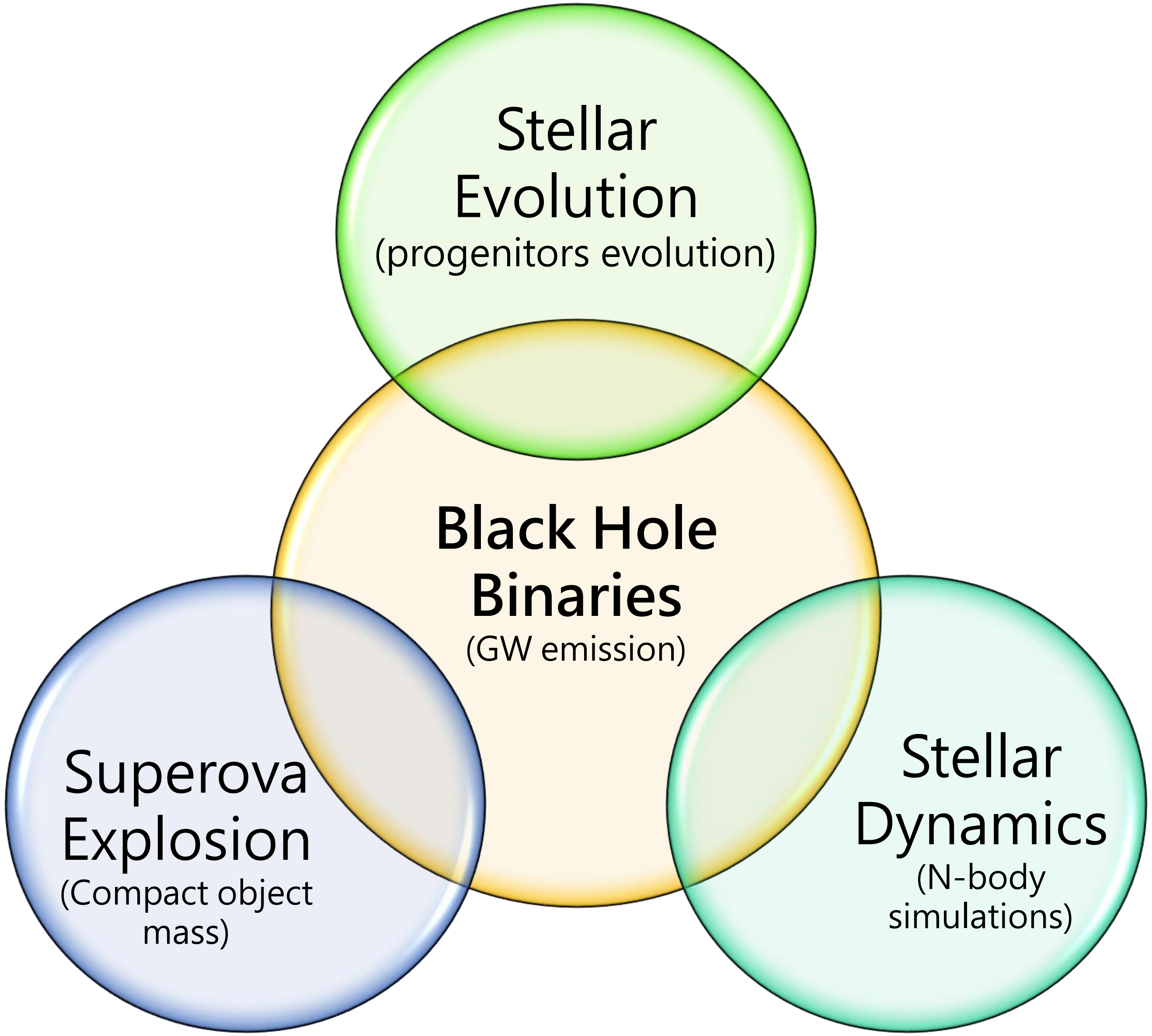
Even with just few detections



https://www.ligo.caltech.edu/image/ligo20160615e

Understanding BHs: ingredients

From a theoretical point of view



Understanding BHs: ingredients

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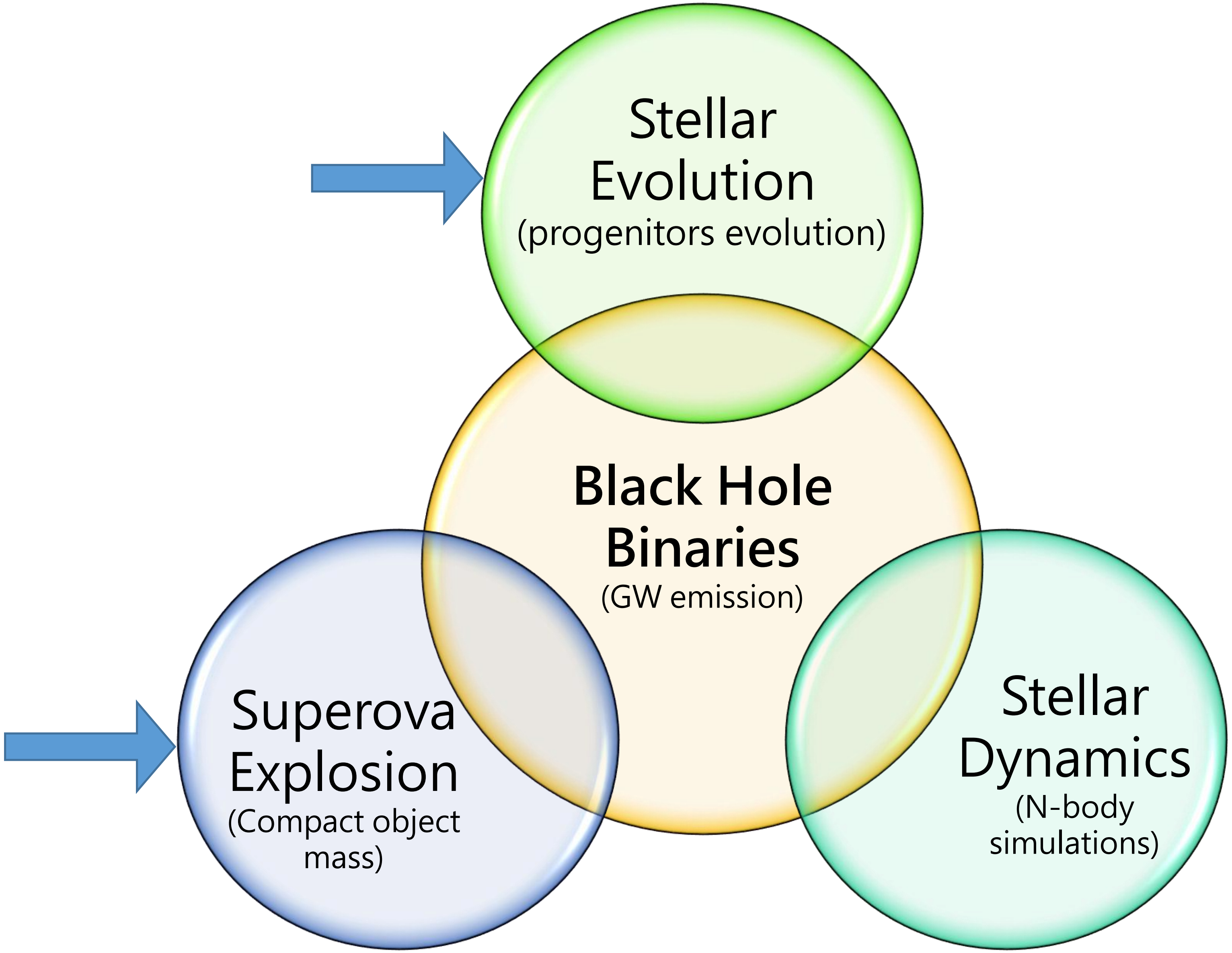

BH mass spectrum: physical processes

Stellar evolution → stellar winds

Stars lose mass

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

- ✓ Mass loss depends on **mass** and **metallicity**
- ✓ The amount of mass loss for massive stars can be conspicuous

$$\frac{dM}{dt} \propto Z^{\alpha}$$

$(\alpha \in [0.5; 0.9])$

Supernova explosion

BHs form after supernovae

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

- ✓ **Final mass** of the star
- ✓ **Compactness** of the pre-SN star
- ✓ **Rapidity** of the explosion
- ✓ **Fallback mass**

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

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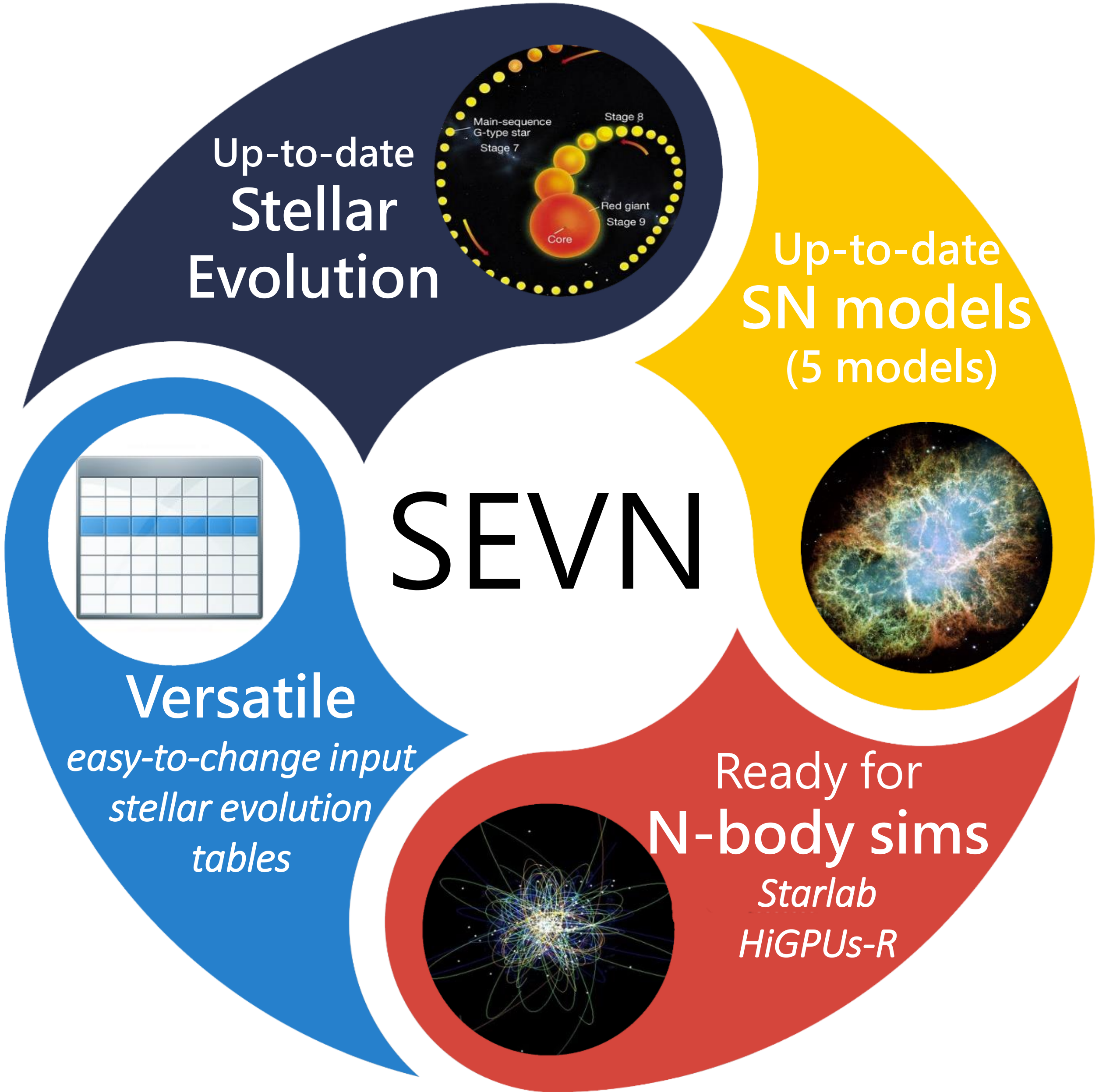
Putting it all together: our code SEVN

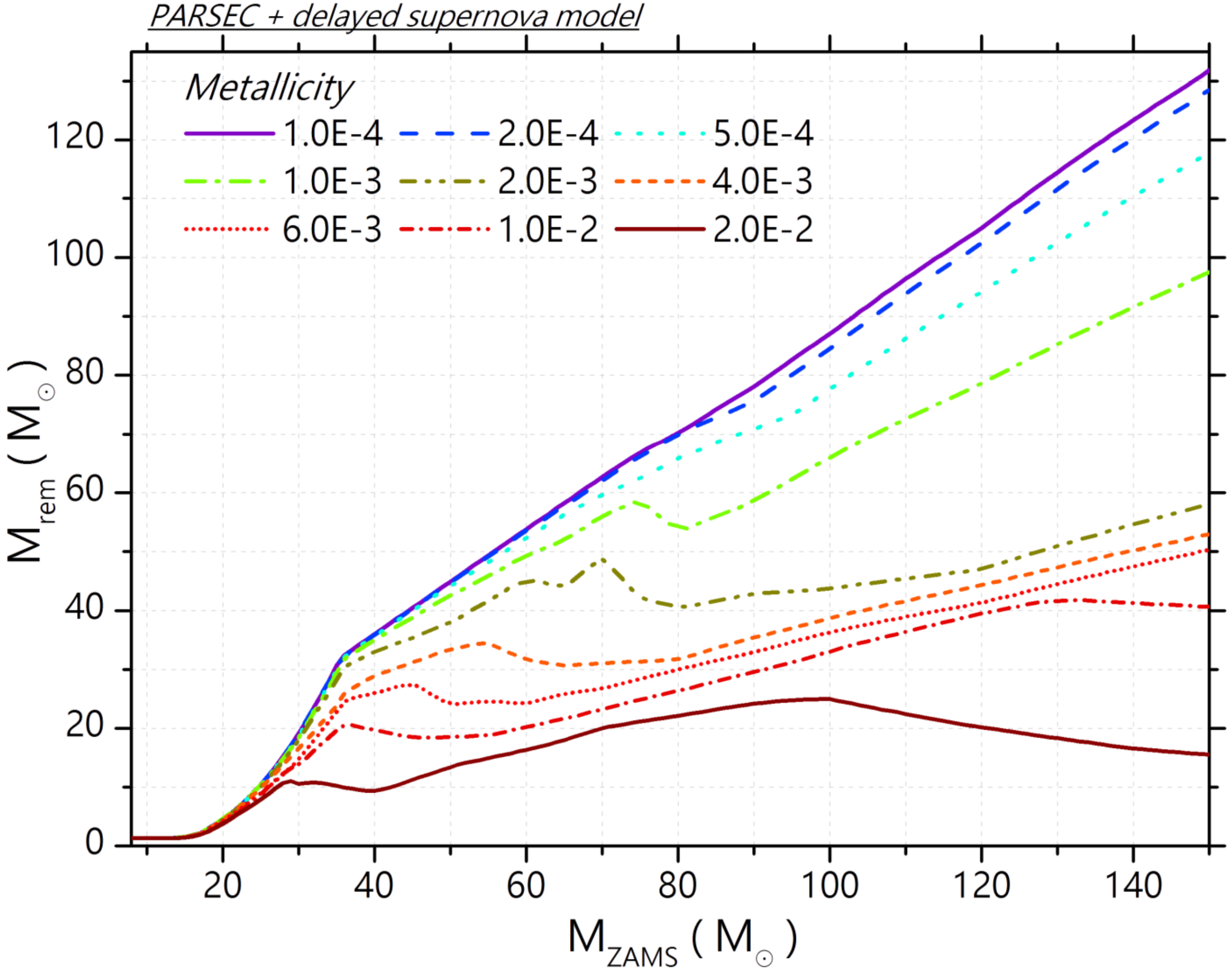
Stellar EVolution for N-body codes. MS, Mapelli, Bressan 2015 MNRAS, 451, 4086



Putting it all together: BH mass spectrum

SEVN: new population synthesis code

Mapelli+ 2009,2010,2013
MS, Mapelli, Bressan 2015 MNRAS, 451, 4086



Putting it all together: BH mass spectrum

SEVN: new population synthesis code

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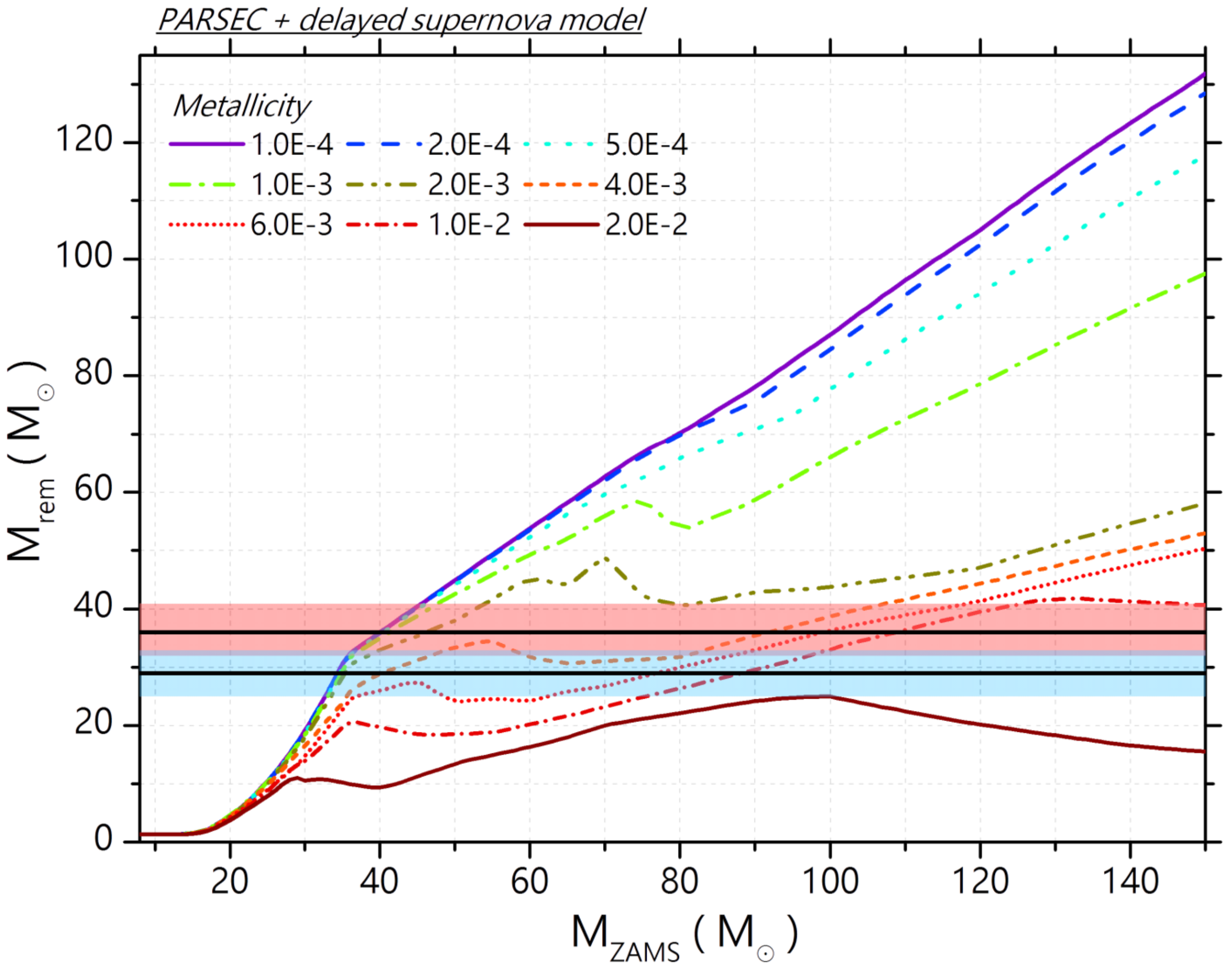
MS, Mapelli, Bressan 2015 MNRAS, 451, 4086

Abbott+ 2016 ApJL, 818, L22 (Fig. 1)

Below $Z \simeq 0.5Z_{\odot}$ and possibly below $Z \simeq 0.25Z_{\odot}$

High metallicity stars lose more mass than metal poor stars

Key points: low Z + direct collapse



Putting it all together: BH mass spectrum

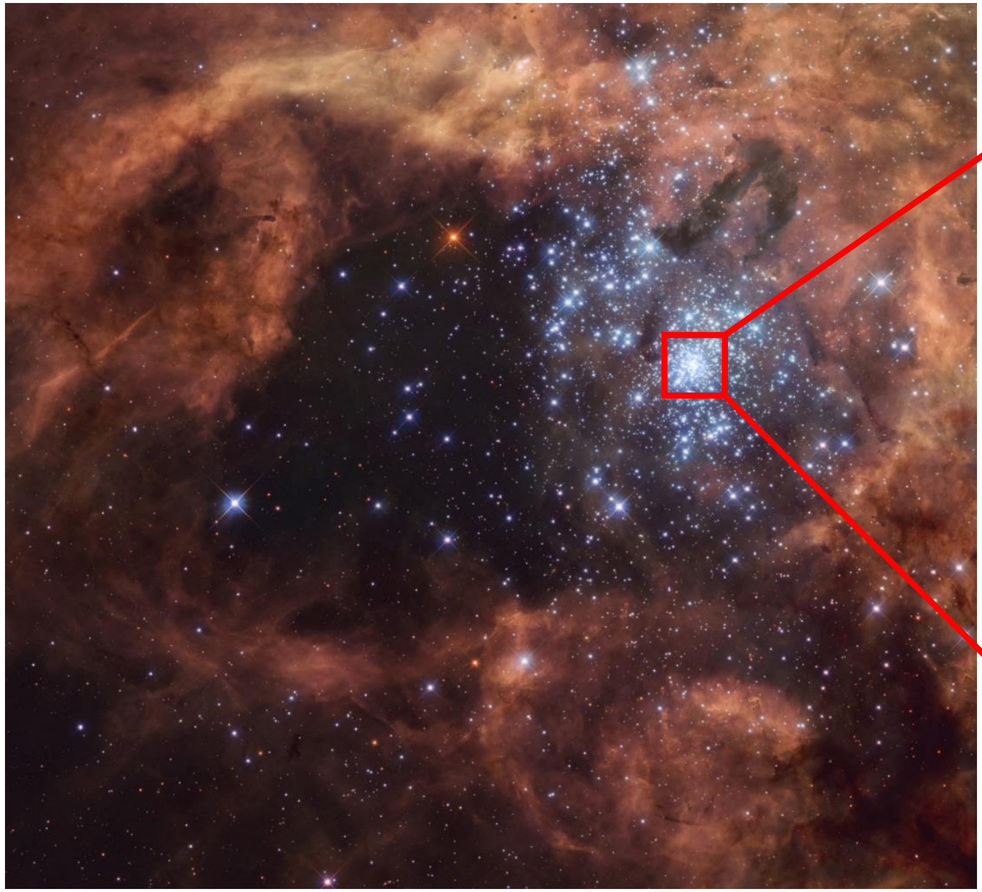
MS, Giacobbo, Mapelli 2016; MS & Mapelli, in preparation

MS+ 2015 → limited to $M_{\rm ZAMS} = 150 M_{\odot}$

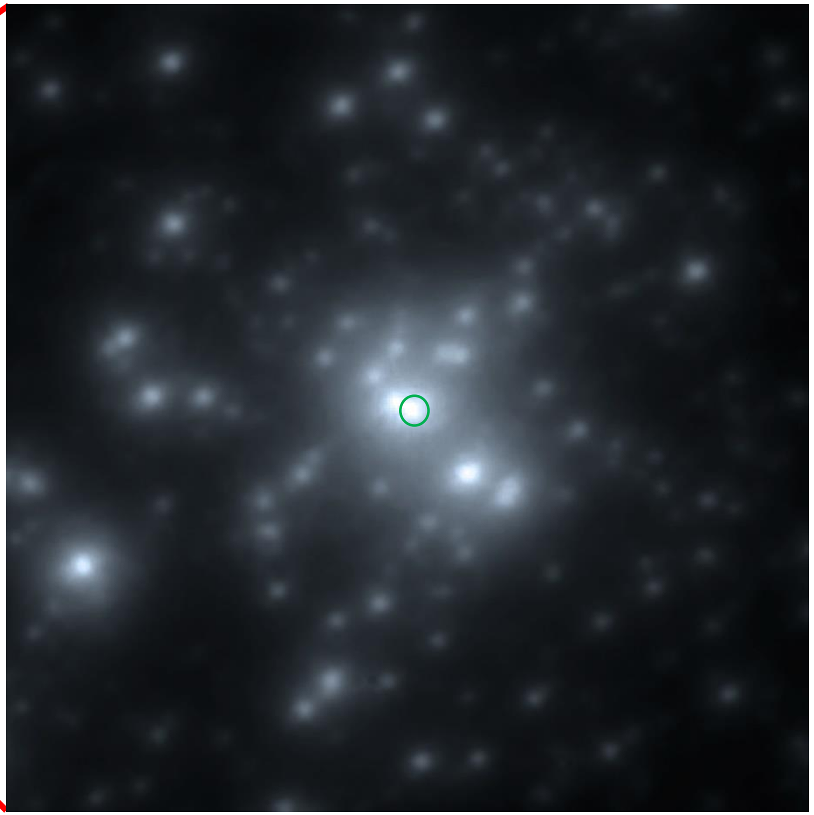
Stars up to $\sim 300 M_{\odot}$ exist *Crowther+ 2016*

Still to be studied in details

Young star cluster R136, Large Magellanic Cloud, HST



○ R136a1: $\sim 300 M_{\odot}$



ESO/VLT http://www.eso.org/public/images/eso1030d/

Putting it all together: BH mass spectrum

MS, Giacobbo, Mapelli 2016; *MS & Mapelli, in preparation*

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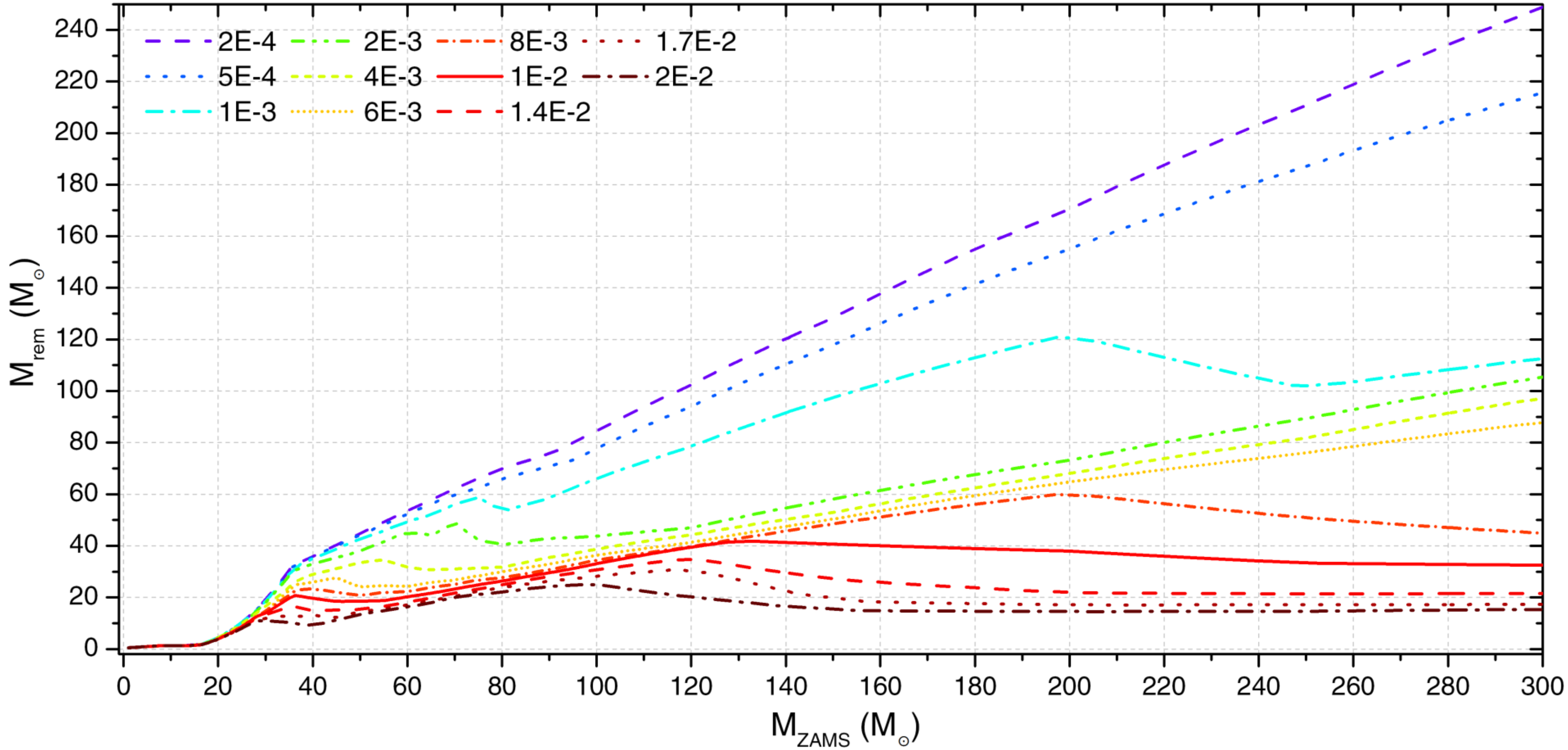
Compact remnant mass spectrum extended up to $\sim 300 M_{\odot}$



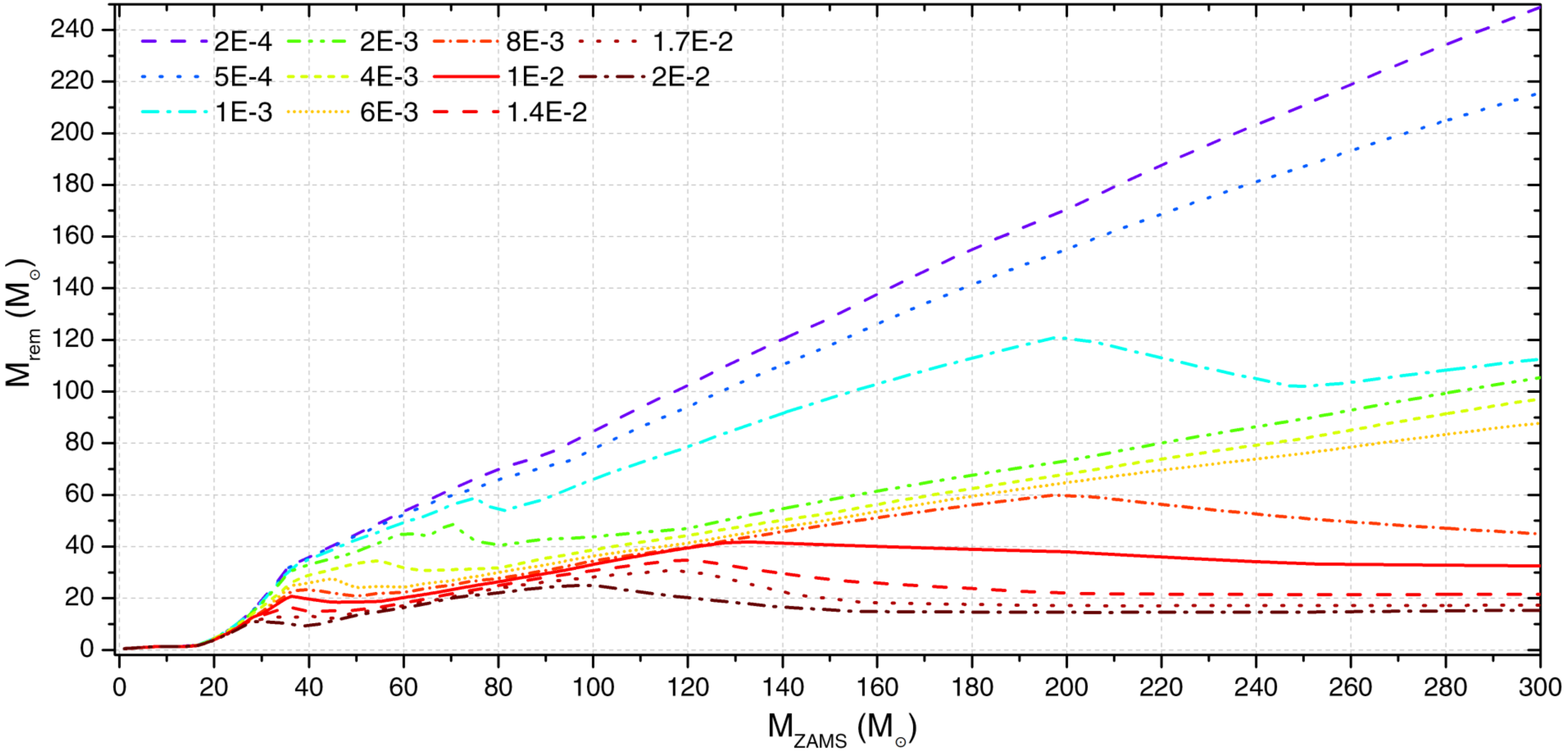
Putting it all together: BH mass spectrum

MS & Mapelli, in preparation; Woosley 2016

The role of pulsational (PPISN) and pair-instability (PISN) supernovae

Pre-SN He core ∈ $[\sim 30; \sim 65]M_{\odot}$ → pair production → several pulses → enhanced mass loss

Pre-SN He core ∈ $[\sim 65; \sim 135]M_{\odot}$ → pair production → 1 violent pulse → disruption



NO PPISN PISN

Putting it all together: BH mass spectrum

MS & Mapelli, in preparation; Woosley 2016

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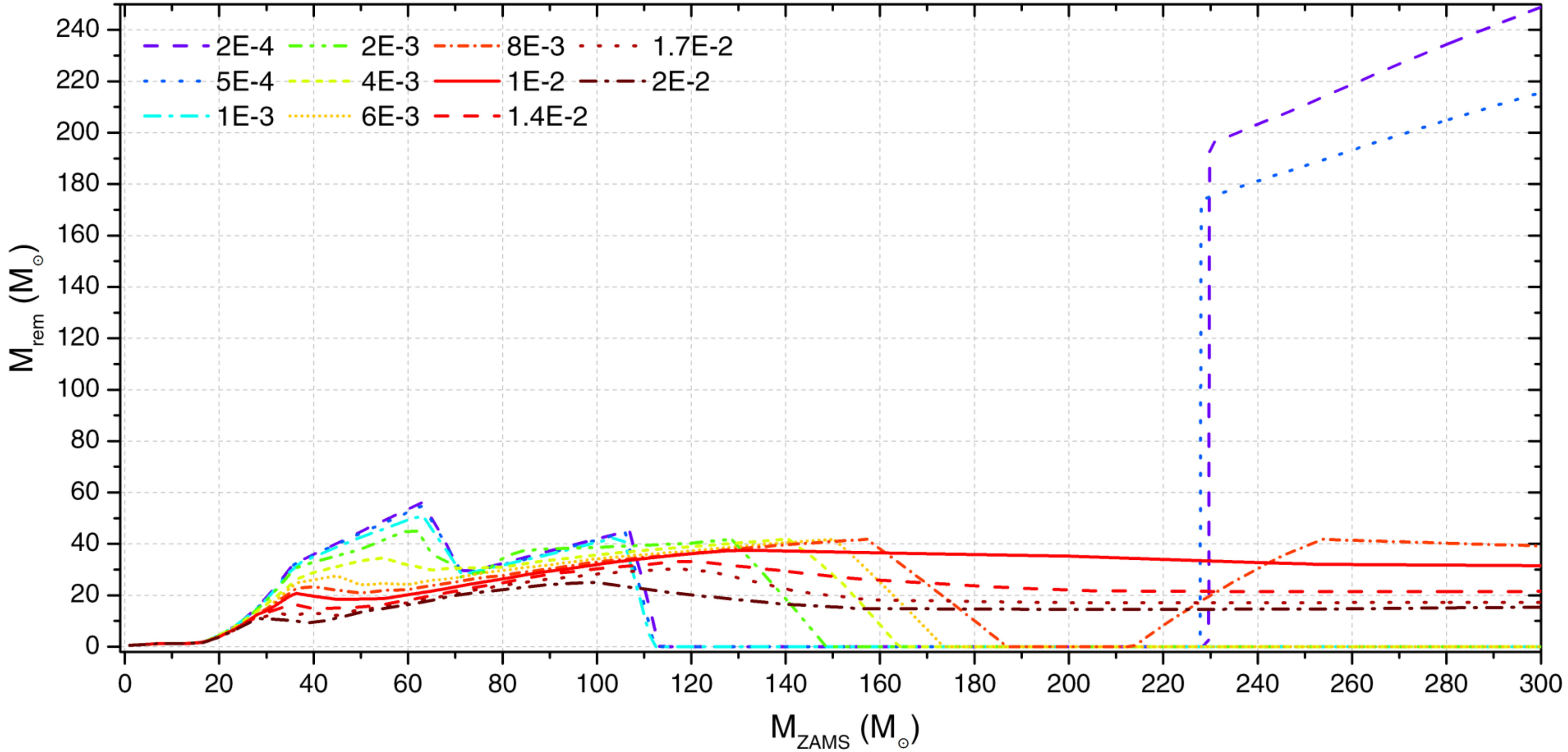
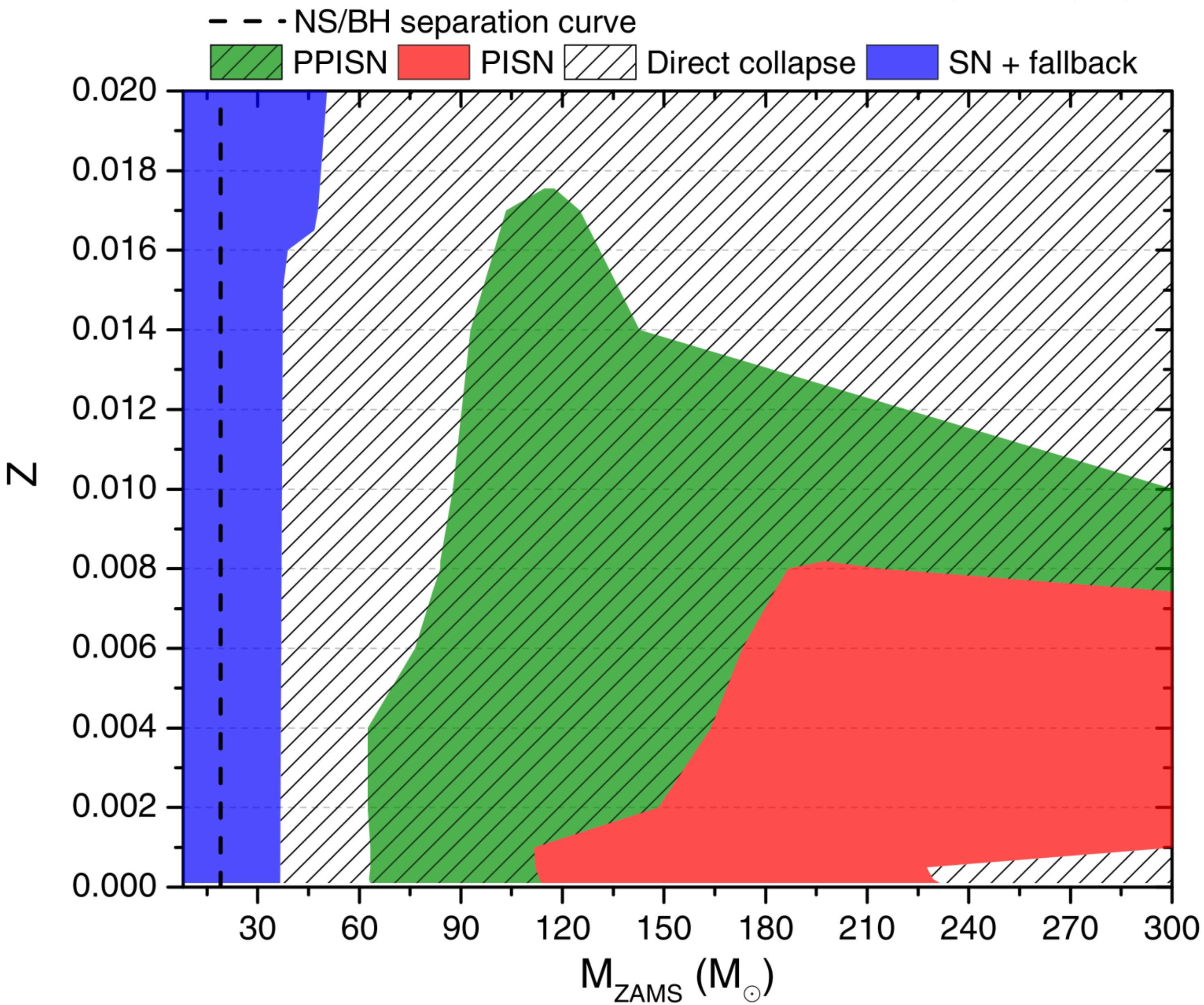


PPISN
+
PISN

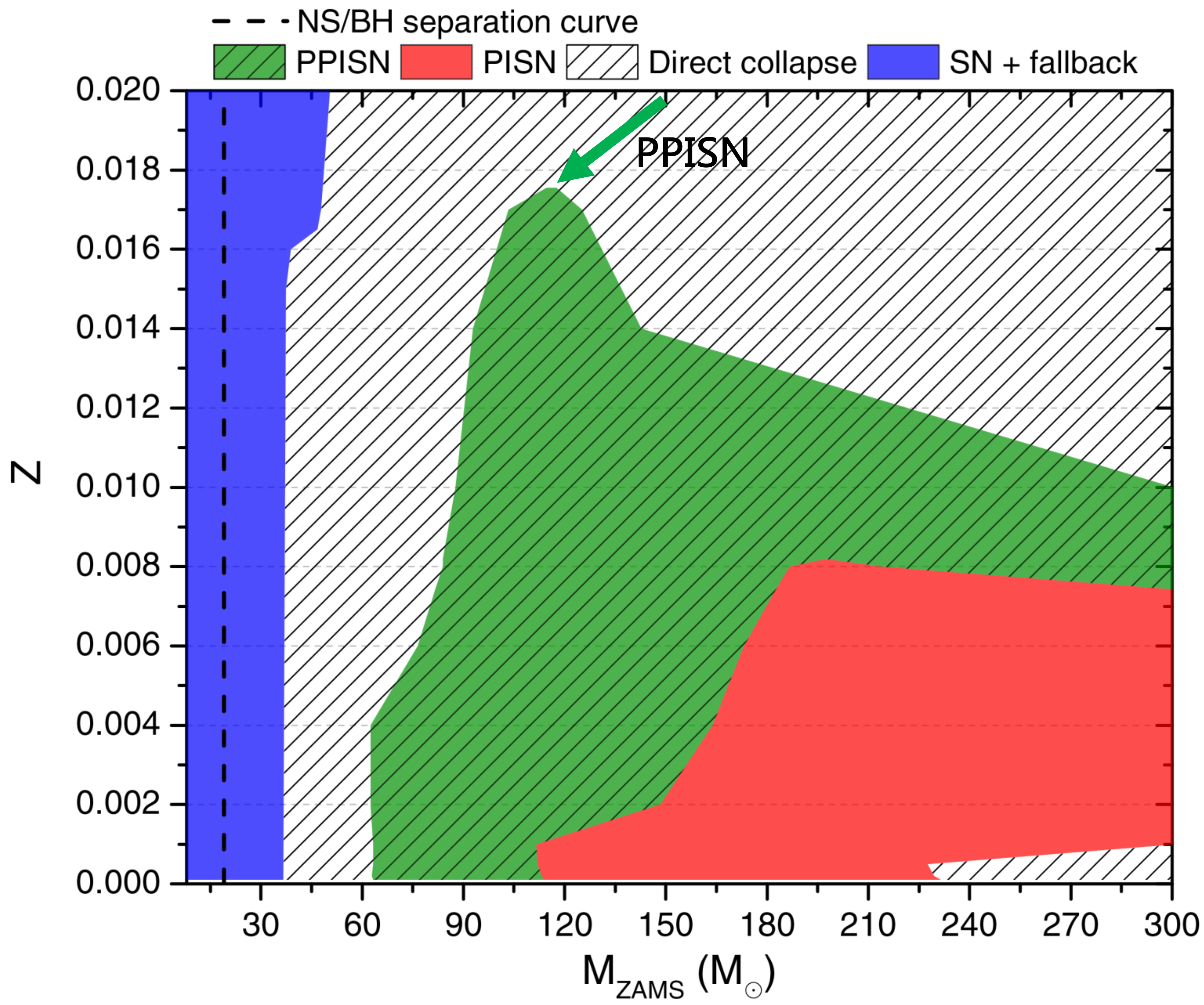
PISN/PPISN: a schematic view

MS & Mapelli, in preparation



PISN/PPISN: a schematic view

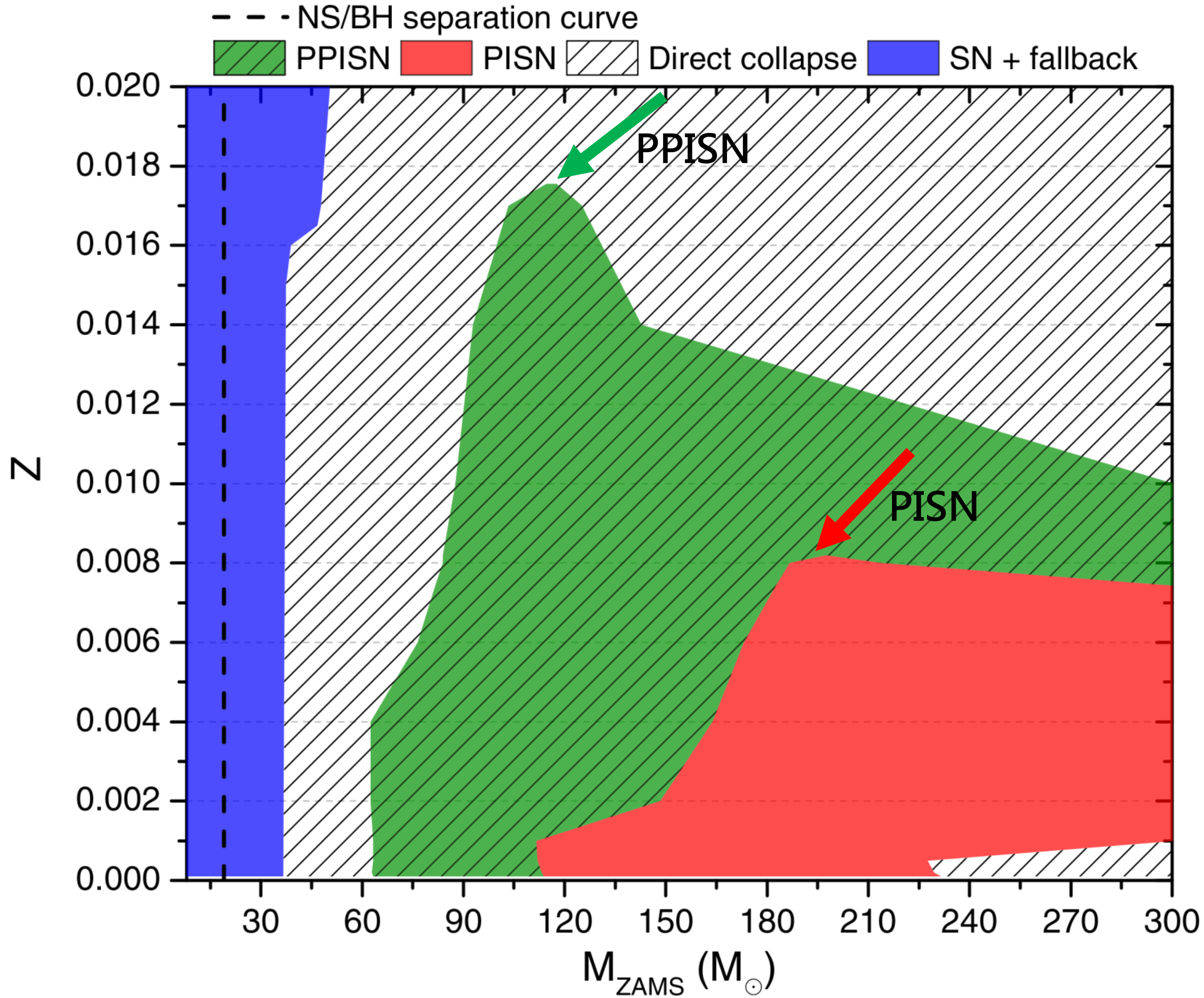
MS & Mapelli, in preparation



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

PISN/PPISN: a schematic view

MS & Mapelli, in preparation

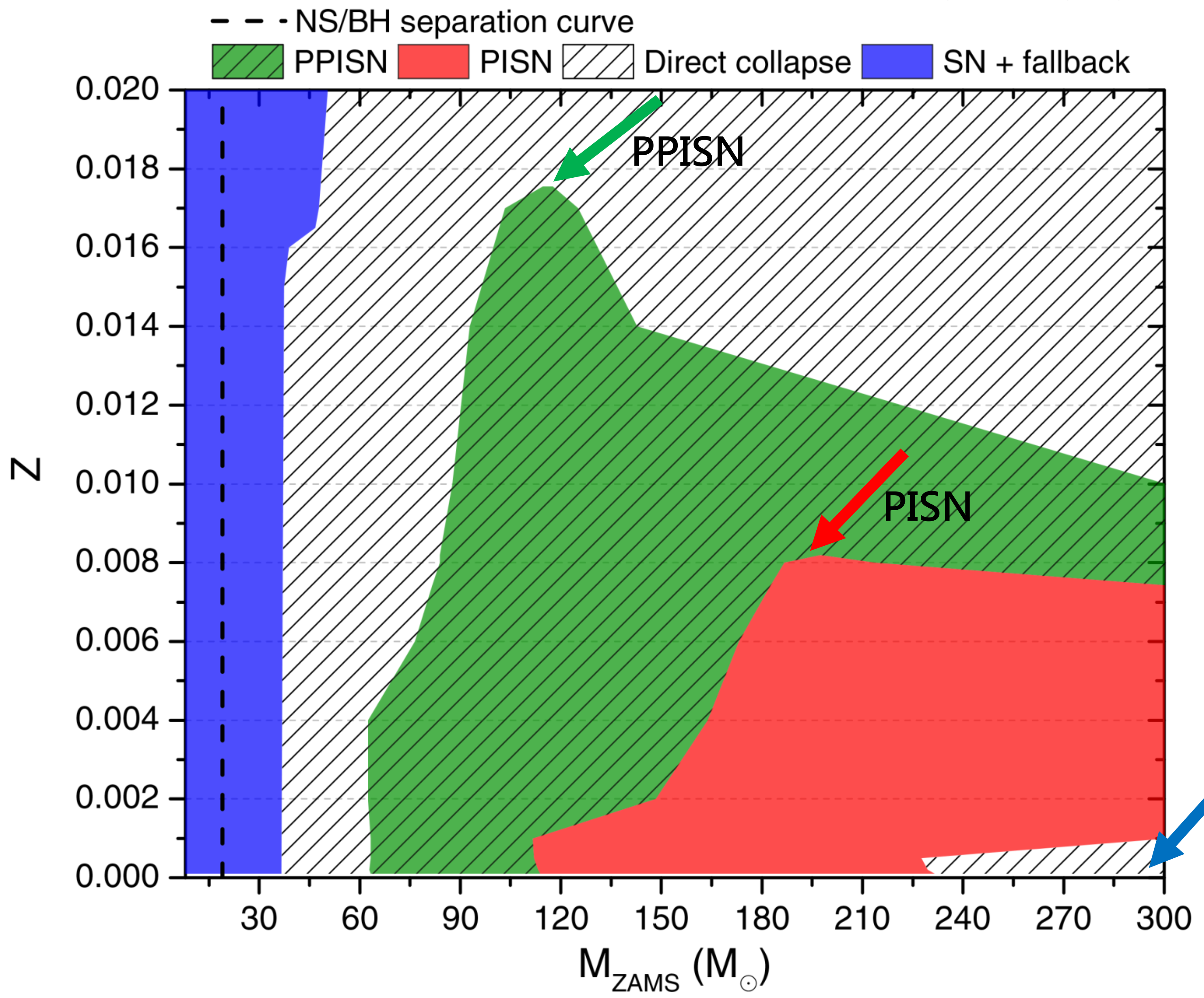


PPISN: $Z \lesssim 0.017 \simeq Z_{\odot}$

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

PISN/PPISN: a schematic view

MS & Mapelli, in preparation



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

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

Direct collapse

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

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

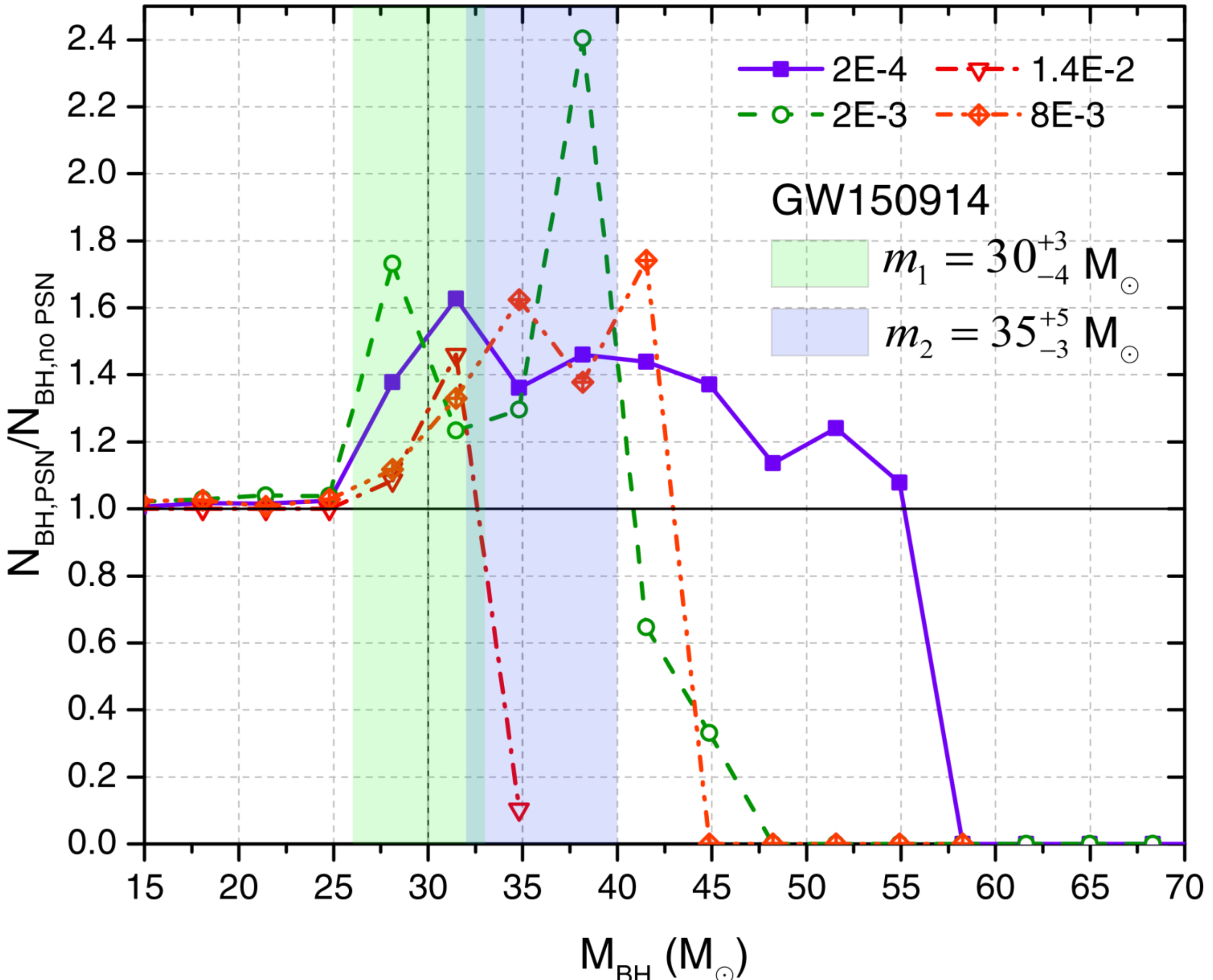
$M_{BH} \gtrsim 200 M_\odot$

BH mass distribution: effects of PPISN/PISN

MS & Mapelli, in preparation

Population synthesis simulations
(with and without PPISN/PISN)

$\mathrm{N} = 10^7$
Kroupa IMF $m \in [0.1, 150]\mathrm{M}_\odot$



BH mass distribution: effects of PPISN/PISN

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Population synthesis simulations
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$\mathrm{N} = 10^7$
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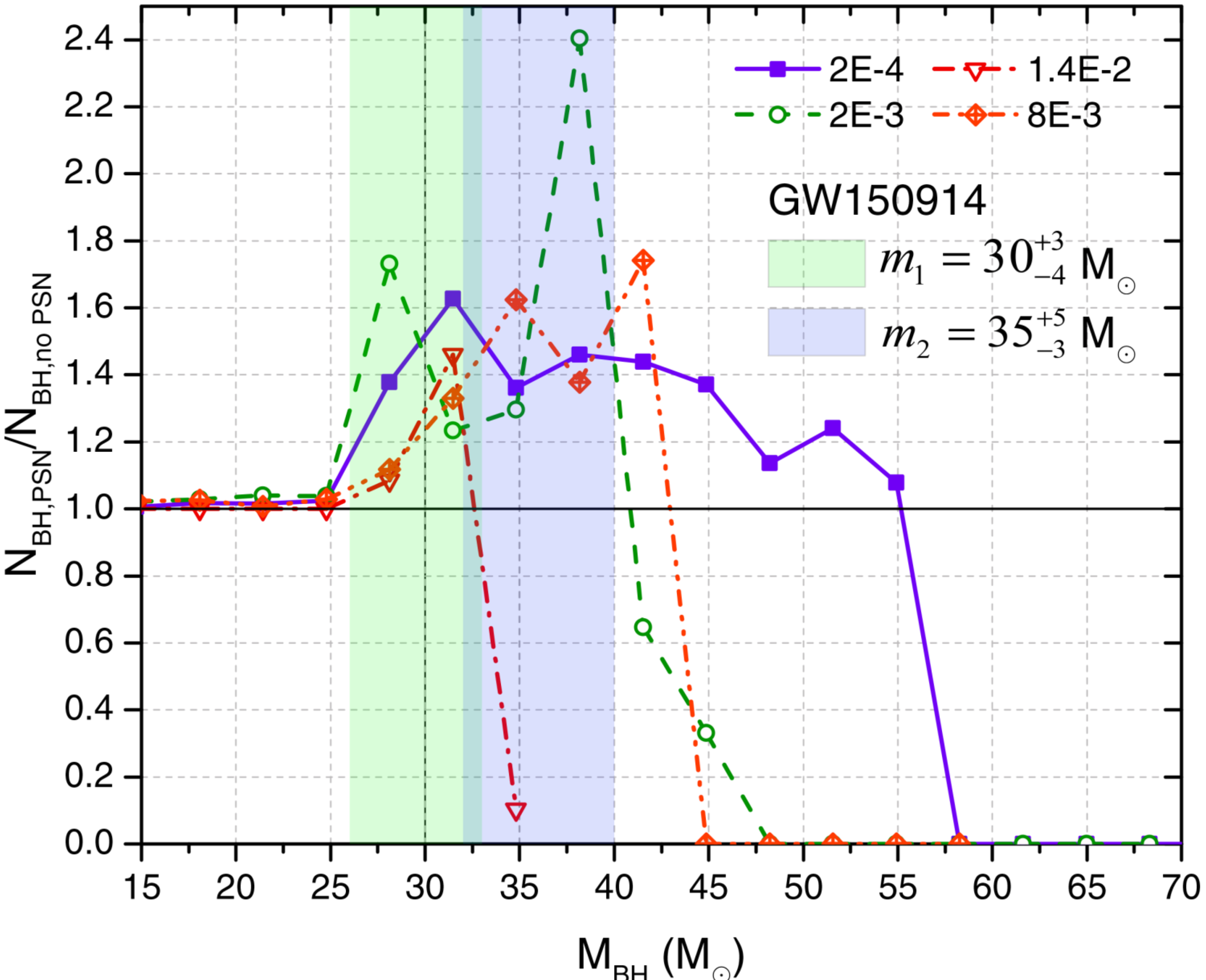
With PPISN/PISN we form more GW150914-like black holes

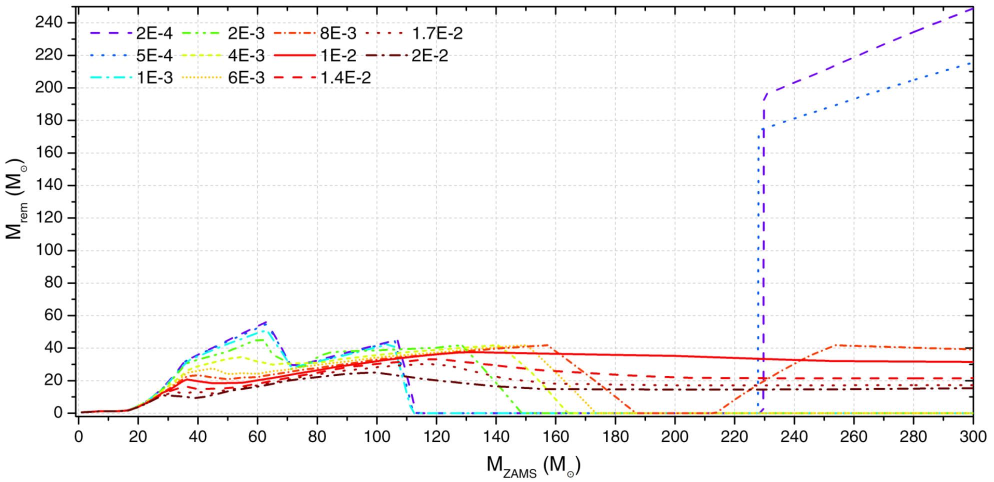


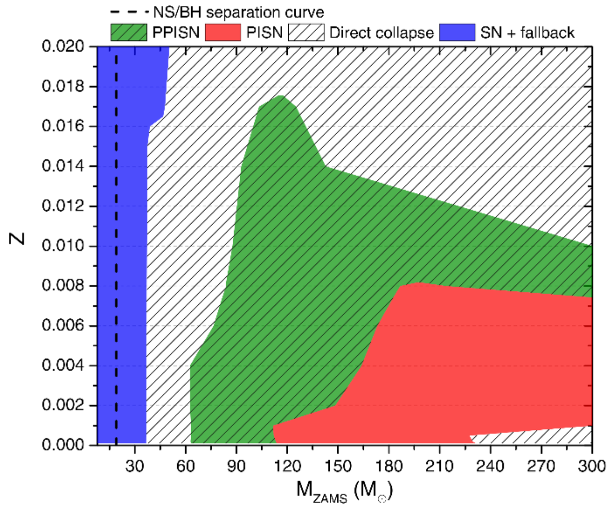
Conclusions

1. LIGO – Virgo detections show that BH-BH binaries exist, can merge in a Hubble time, and can be massive

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

3. The BH mass spectrum form SEVN *(MS+2015; MS+ 2016; MS & Mapelli in prep.)*





4. **PPISN/PISN** → avoid BHs with $m \gtrsim 60 M_{\odot}$ for $Z \gtrsim 0.001$
   → favour GW150914-like BHs
   → for $Z \lesssim 0.001$ are ineffective *(we can still form BHs with $m \gtrsim 200 M_{\odot}$)*

Credits for infographic: Freepik @ http://www.freepik.com/free-vector/rounded-infographic-business_831592.htm