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MERAC 2015 prize

Massive stellar black holes: formation and dynamics

Collaborators: Mario Spera, Sandro Bressan, Brunetto Ziosi, Marica Branchesi, Alessandro Trani, Elisa Bortolas, Paolo Esposito, Luca Zampieri

Roma, April 11th 2016

OUTLINE:

1. **the masses of GW150914: why are they important?**

2. **the main ingredients: stellar winds and direct collapse**

3. **dynamics plays `gooseberry'**

4. **what has been done?**

5. **what has still to be done?**

5. **technical issues!**

1. the masses of GW150914: why are they important?

36 (+5,-4) Msun
29 (+4,-4) Msun

Abbott+2016a,b,c..

GW150914 shows that

1. BH-BH binaries exist

2. they can merge in a Hubble time

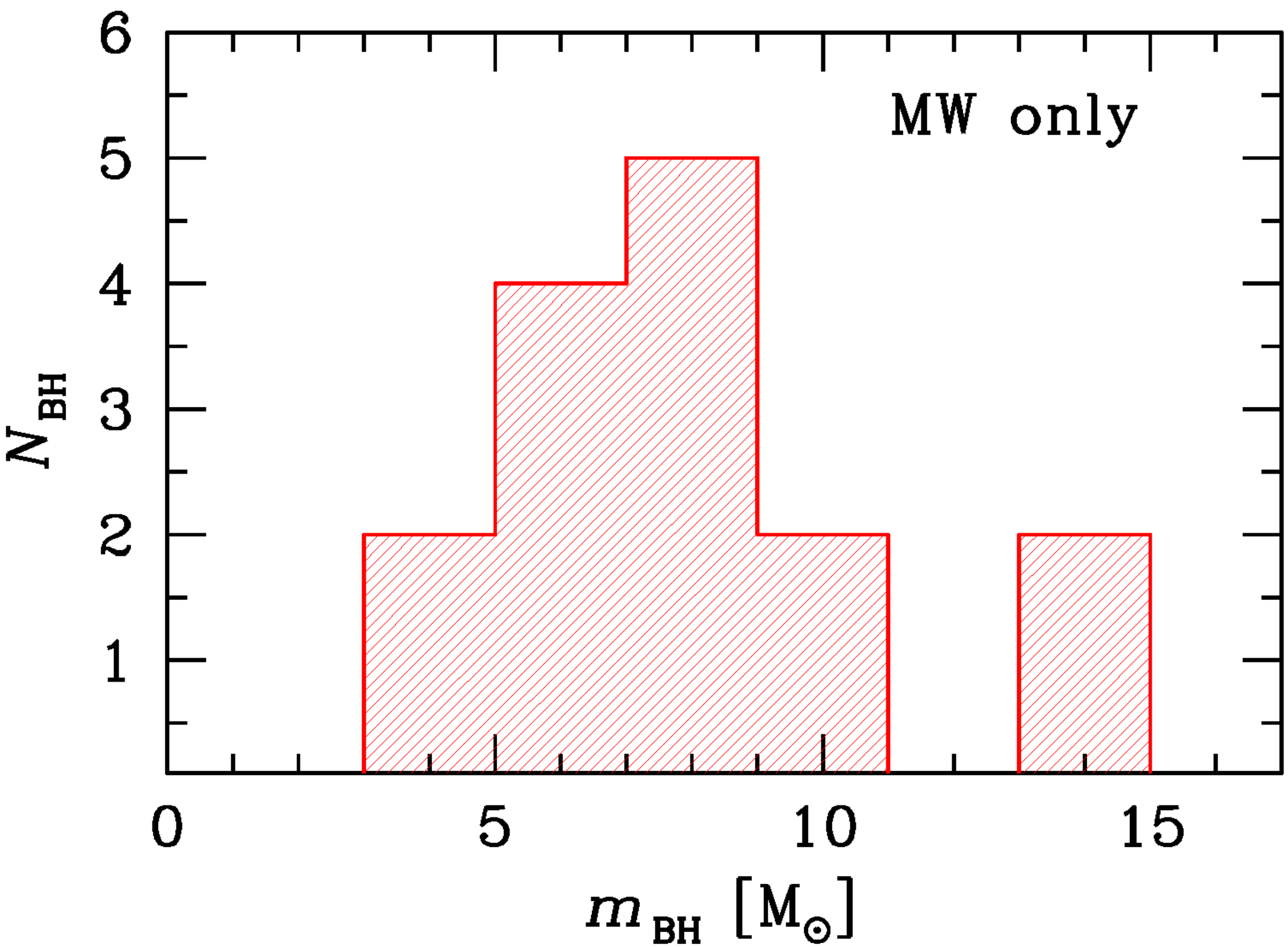
3. massive stellar BHs exist i.e. stellar BHs with mass >25 Msun (Mapelli+ 2009)

1. the masses of GW150914: why are they important?

Massive stellar BHs exist
i.e. stellar BHs with mass >25 Msun
(Mapelli+ 2009)

Dynamical mass measurements of ~10 BH masses in MW X-ray binaries

compilation from Orosz+ 2003, Ozel+ 2010



Massive stellar BHs exist
i.e. stellar BHs with mass >25 Msun
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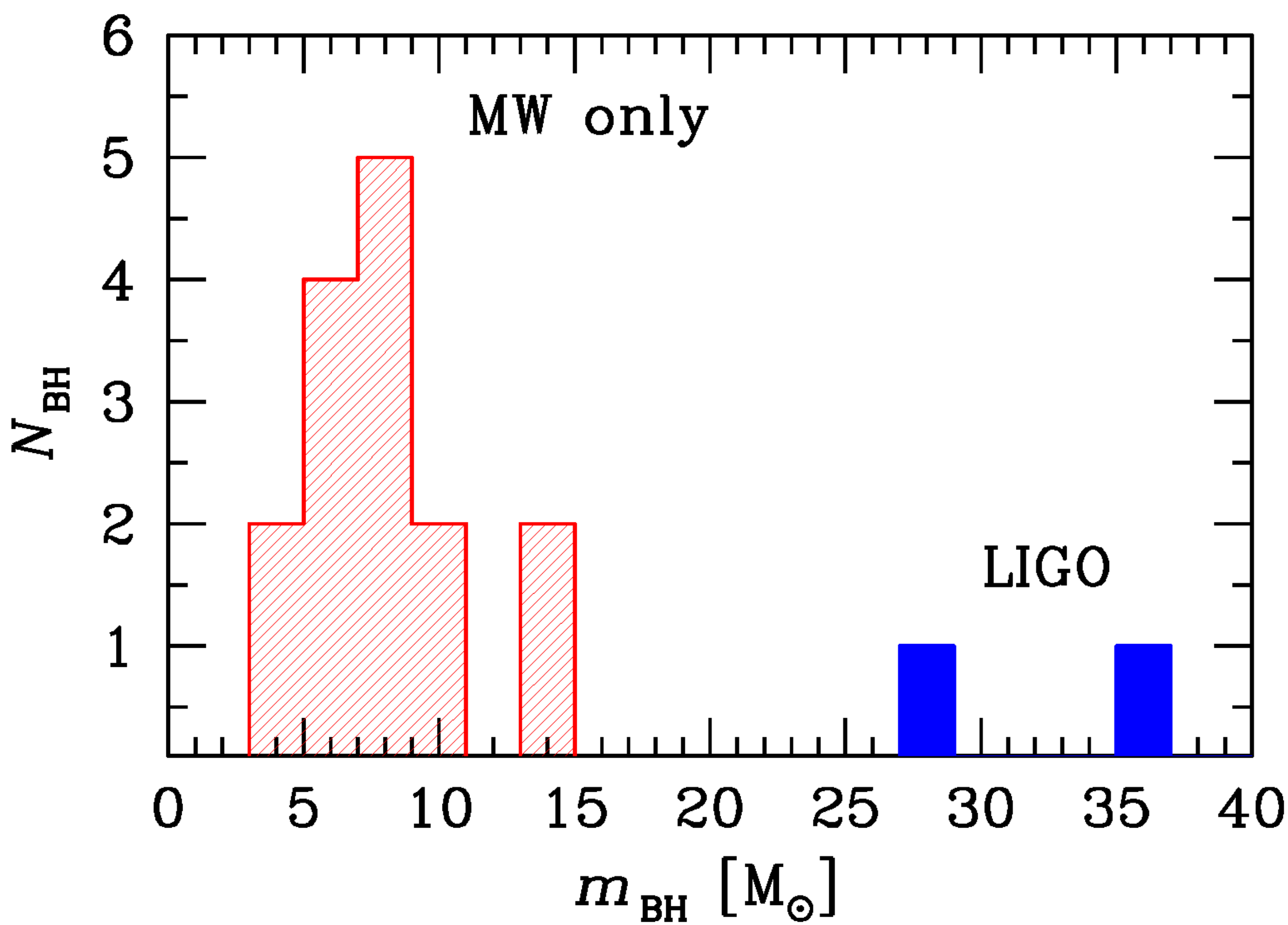


2. the main ingredients: stellar winds and direct collapse

THEORETICAL MODELS of BH MASS DEPEND ON:

1. 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; Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)

Mass loss depends on metallicity

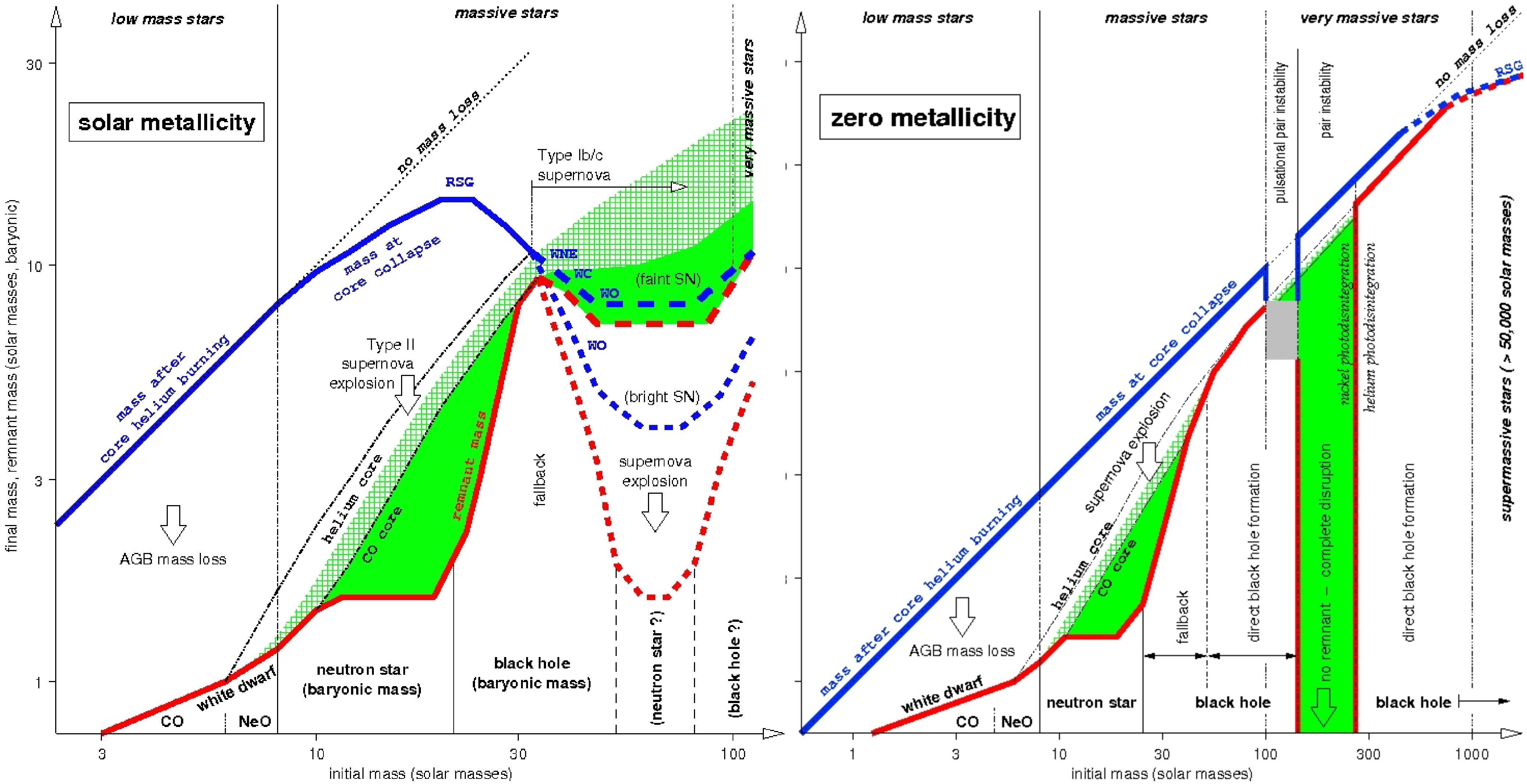
$$\dot{M} \propto Z^{\alpha} \qquad \alpha \sim 0.5 - 0.9$$

2. SUPERNOVA:

Direct collapse: if final mass of star >30-40 Msun
there is no supernova and most star mass becomes BH
(Fryer+ 1999, 2001; Heger+ 2003; Mapelli+ 2009)

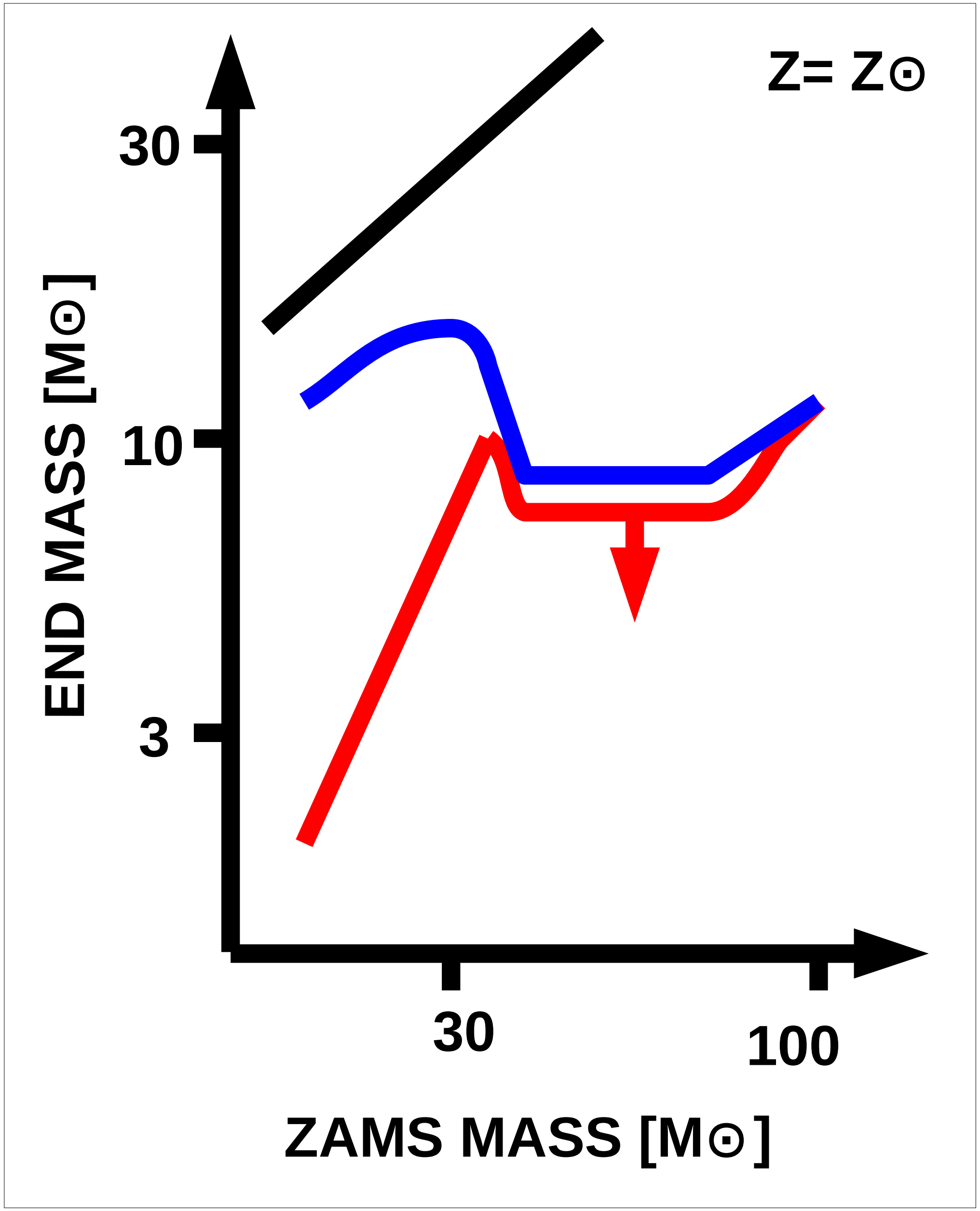
1. + 2. = METAL-POOR STARS PRODUCE MORE MASSIVE BH

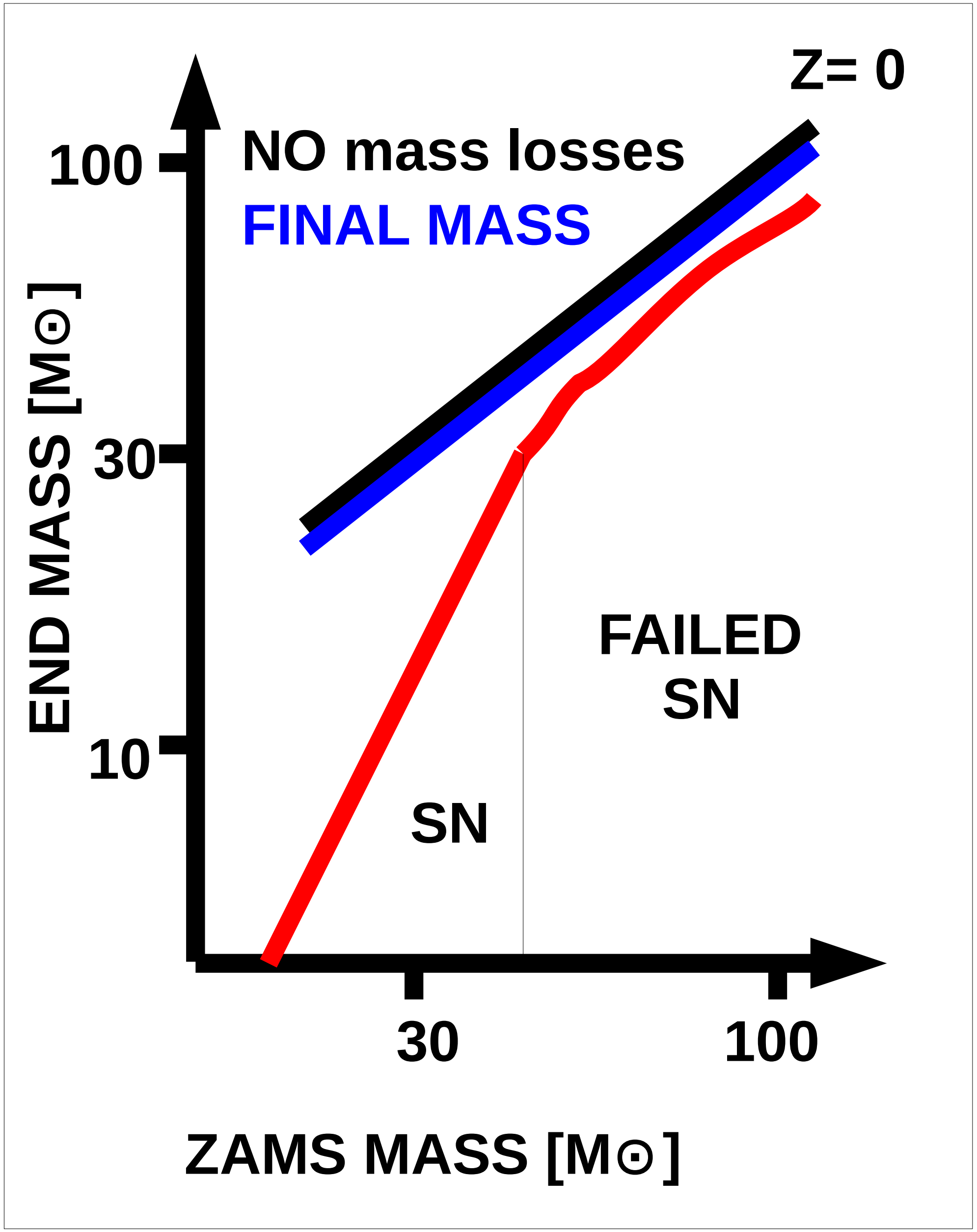
2. the main ingredients: stellar winds and direct collapse



Heger et al. (2003)

2. the main ingredients: stellar winds and direct collapse





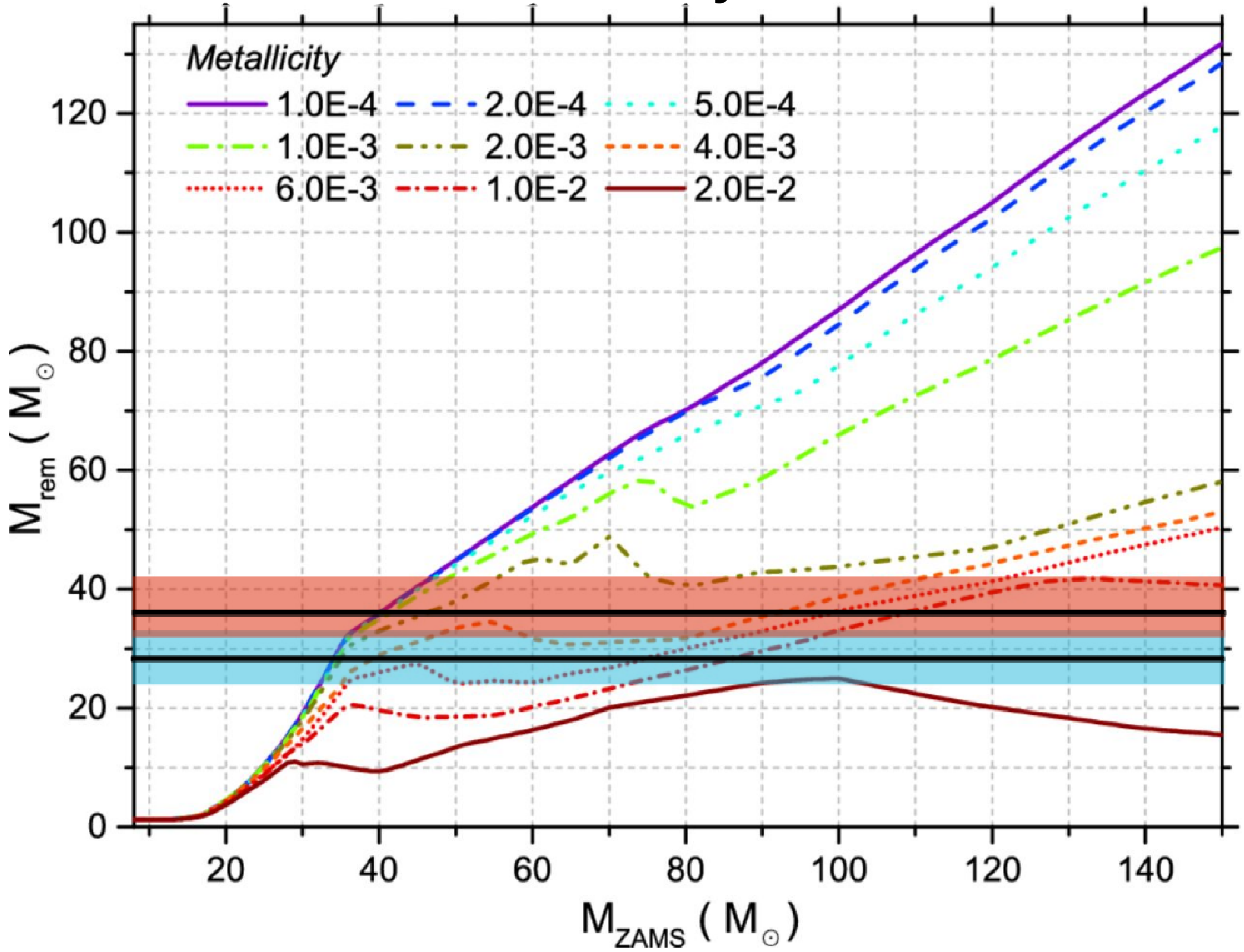
My cartoon from
Heger et al. (2003)

2. the main ingredients: stellar winds and direct collapse

What about intermediate metallicity between zero and solar?

Model	Stellar Evolution	Supernova Model	Max. BH mass at Z~0.01 Zsun
MM+ 2009	Maeder+ 1992	Fryer+ 1999	~50 Msun
MM+ 2010	Portinari+ 1998	Fryer+ 1999	~80 Msun
Belczynski+ 2010	Hurley+ 2000 and Vink+ 2001	Fryer+ 1999	~80 Msun
Fryer+ 2012	Hurley+ 2000 and Vink+ 2001	Fryer+ 2012	~80 Msun
MM+ 2013,2014	SeBa (Portegies Zwart+ 2001) and Vink+ 2001		~85 Msun
Spera, MM & Bressan 2015	PARSEC (Bressan+ 2012; Tang, Bressan+ 2014; Chen, Bressan+ 2015)	O'Connor+2011 Fryer+ 2012 Ertl+ 2015 (6 different SN models compared)	~130 Msun

What about intermediate metallicity between zero and solar?



PARSEC stellar evolution
(Tang, Bressan+ 2014; Chen, Bressan+ 2015)
+
delayed SN model
(Fryer+ 2012)

Spera, MM & Bressan 2015 – used as fig.1 by Abbott+ 2016 paper on Astrophysical implications of LIGO detection

3. dynamics plays `gooseberry'

LIGO observed a BH-BH BINARY

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

1) PRIMORDIAL BINARY

2) DYNAMICALLY FORMED BINARY

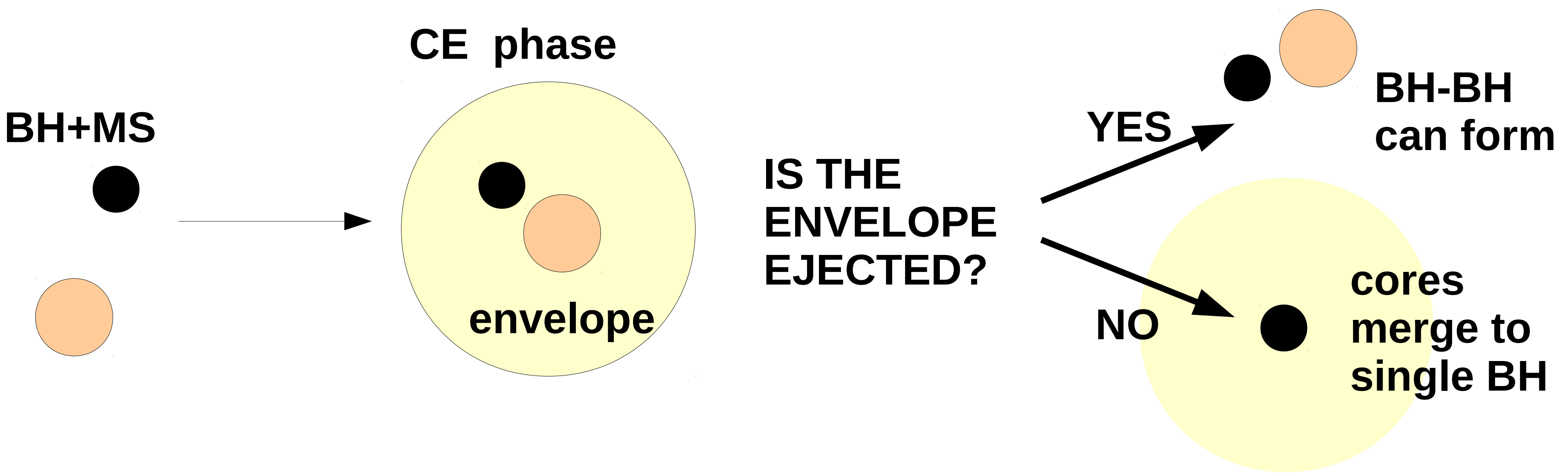
3. dynamics plays `gooseberry'

LIGO observed a BH-BH BINARY
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

NOT SO EASY: 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)

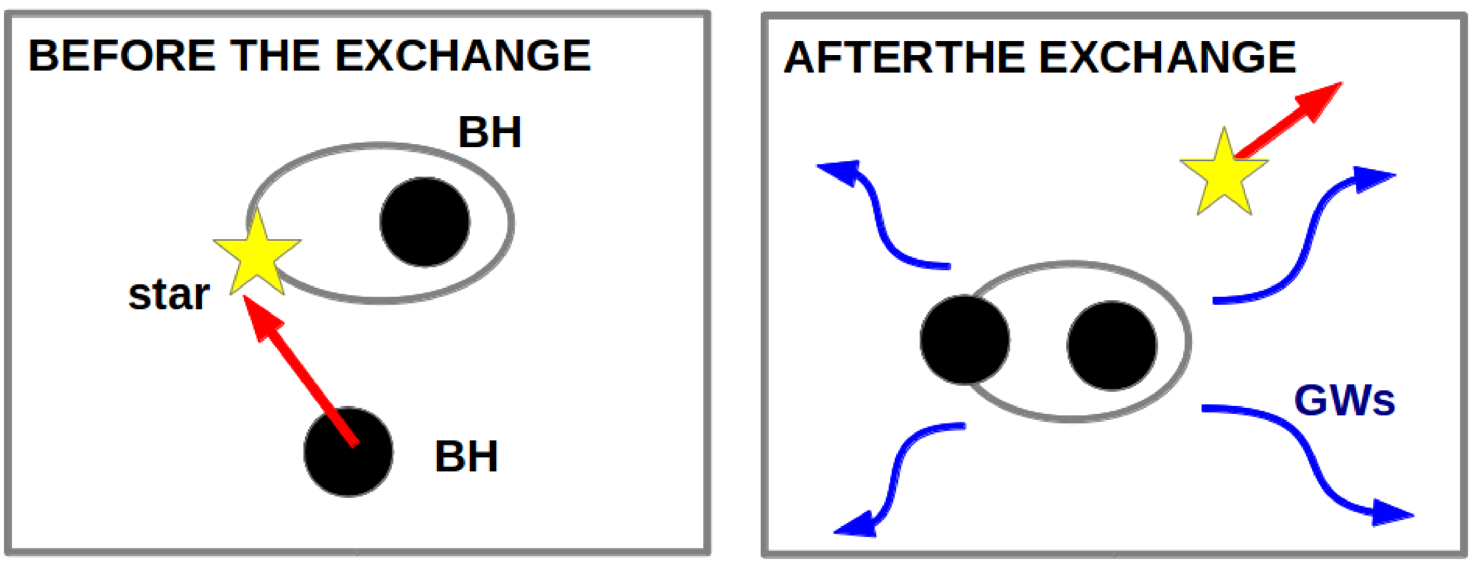
3. dynamics plays `gooseberry'

LIGO observed a BH-BH BINARY

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

2) DYNAMICALLY FORMED BINARY:

2 BHs enter a binary dynamically
only in dense clusters, but stars form in dense clusters



>90% BH-BH binaries form dynamically in star clusters

Exchanges favour formation of massive BH-BH binaries
(Ziosi, MM+ 2014)

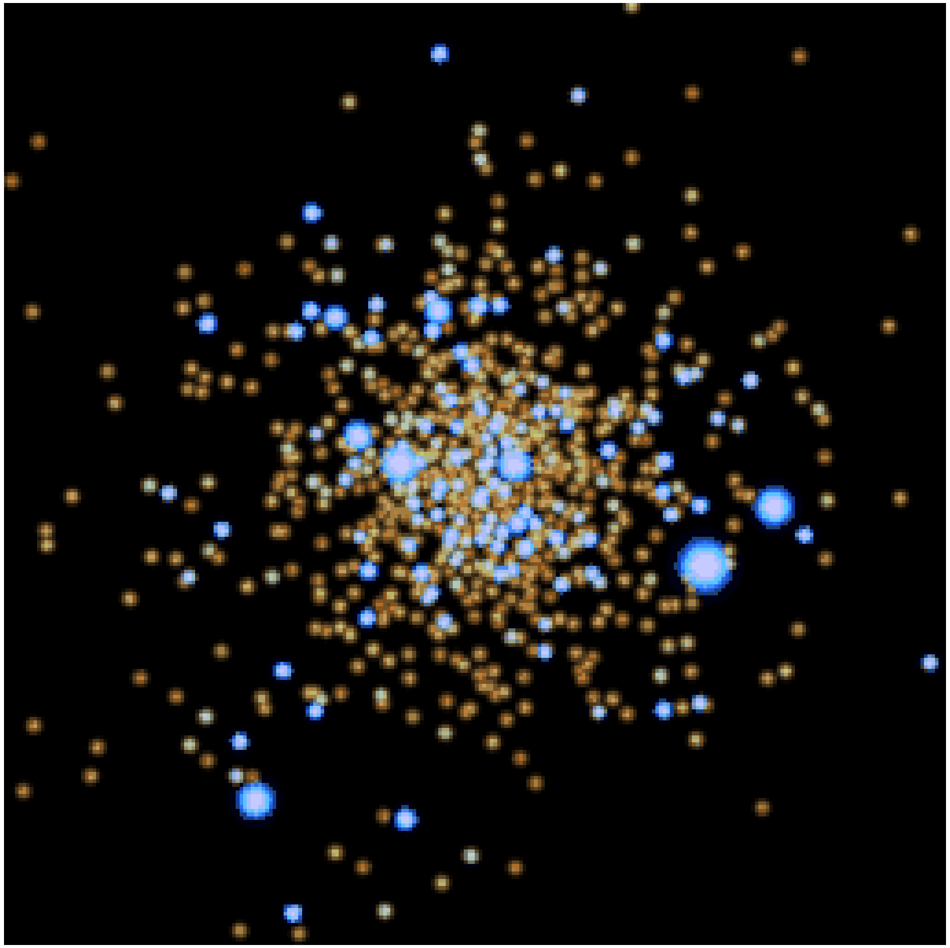
3. dynamics plays `gooseberry'

LIGO observed a BH-BH BINARY

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

2) DYNAMICALLY FORMED BINARY:

Requires N-body simulations of star clusters coupled with stellar evolution



GPU simulations

MM+ 2013, 2014,
Ziosi, MM+ 2014,
MM 2016,
Kimpson+ 2016

3. dynamics plays `gooseberry'

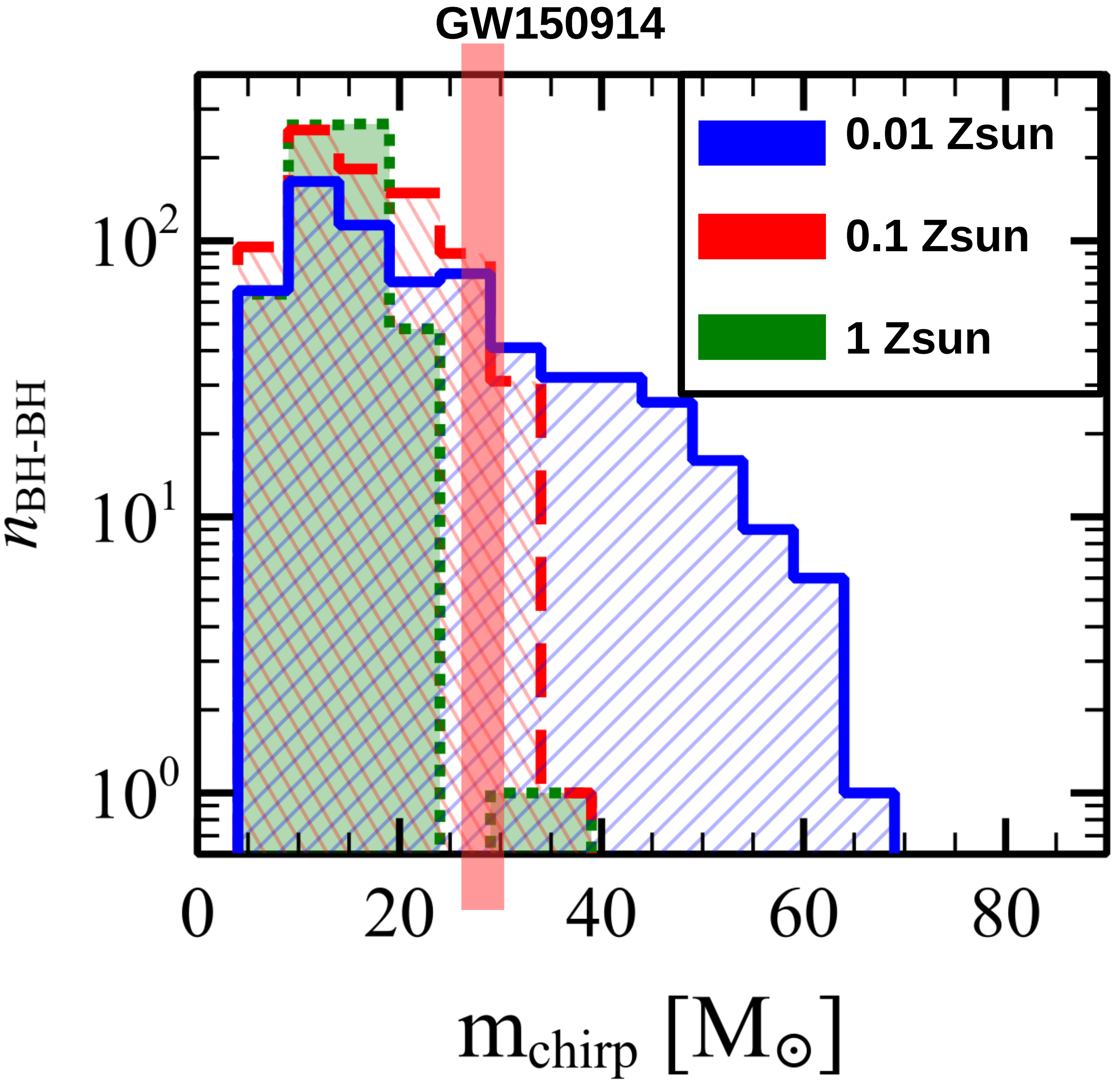
LIGO observed a BH-BH BINARY

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

2) DYNAMICALLY FORMED BINARY:

Chirp masses of BH-BH systems accounting for both primordial and dynamical binaries

$$m_{\rm chirp} = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



From Ziosi, MM+ 2014

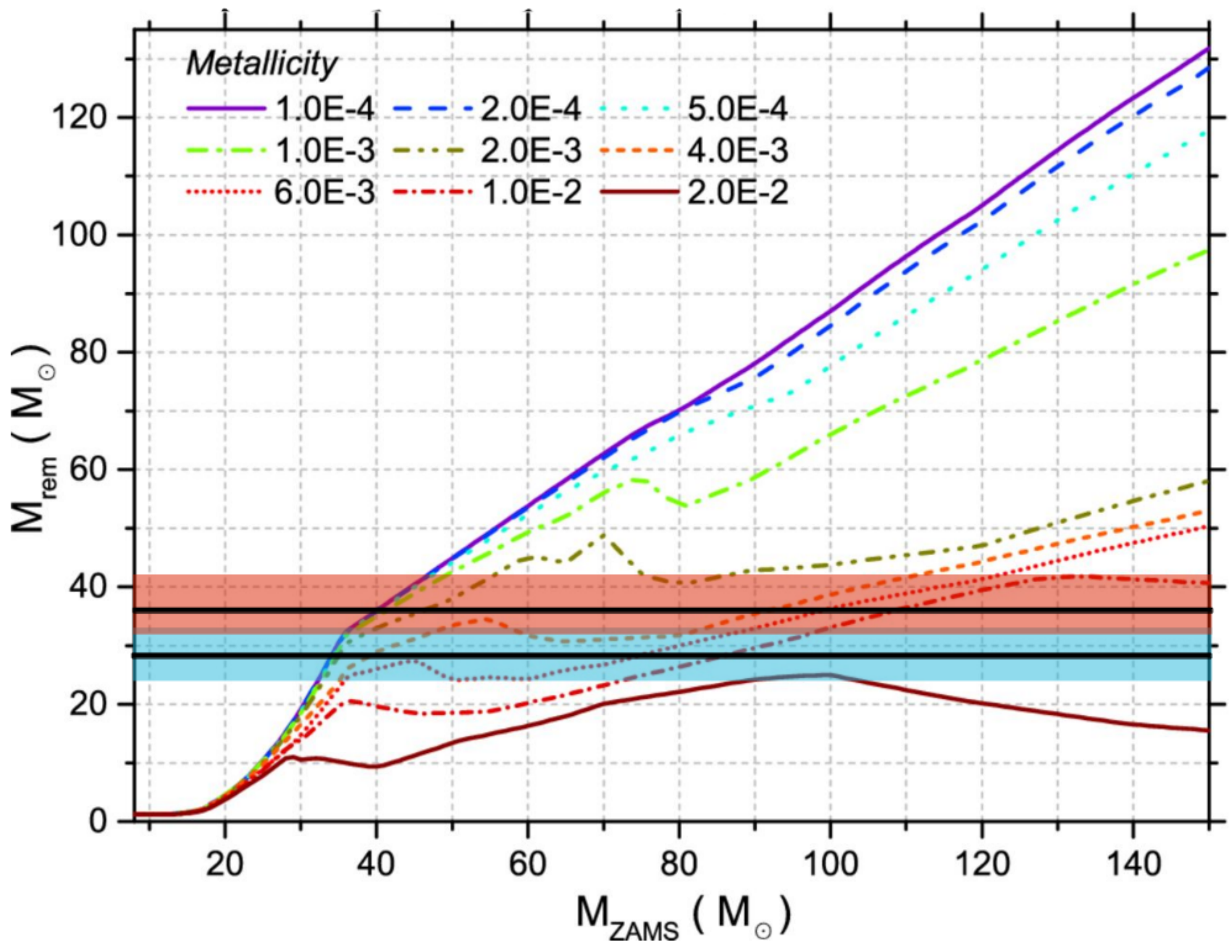
4. what has been done?

OUR TEAM @ INAF: http://web.pd.astro.it/mapelli/group.html

funded ONLY by COMPETITIVE GRANTS (FIRB, PRIN, MERAC)

1. most up-to-date model for the mass of BHs, used by the LIGO collaboration to constrain Z:

WE PREDICTED MASSIVE BHs before LIGO detection



2. we investigate the dynamical processes:

We found that 90% BH-BHs form DYNAMICALLY

MM+ 2009, 2010, 2013; MM & Zampieri 2014; Ziosi, MM, Branchesi, Tormen 2014; Spera, MM & Bressan 2015

4. what has still to be done (for discussion)?

EVERYTHING SOLVED?

NO: we can just reject models with BH mass < 20 Msun

OPEN QUESTIONS for THEORISTS @ INAF:

STELLAR EVOLUTION:

- uncertainties in supernova model
- binary evolution contains free parameters (COMMON ENVELOPE is the black beast)

DYNAMICS:

- initial conditions might be wrong (NO GAS, few primordial binaries!!!)
- role of mergers between stars (runaway collision scenario)
- processes as Spitzer's instability and Kozai not investigated
  → can change the merger rate by orders of magnitude

ELECTROMAGNETIC COUNTERPARTS:

- our study focussed on BHs, still low statistics for NSs
  → how many EM counterparts do we expect and what are they?

5. technical issues (for discussion)

Dynamical simulations are computationally expensive:

1 BH-BH merger every ~ 100 simulated star clusters

Each simulation requests ~ 100 GPU hours

→ **10 000 GPU hours for a single MERGER!!!**

RESOURCES:

– We have a 64 core machine @ OAPD (FIRB2012 project)

– We obtain more time @ CINECA via competitive proposals, but CINECA decides what clusters to buy (these are often non-suitable x astro people)

WE NEED MORE COMPUTATIONAL FACILITIES TO REMAIN COMPETITIVE !!!!

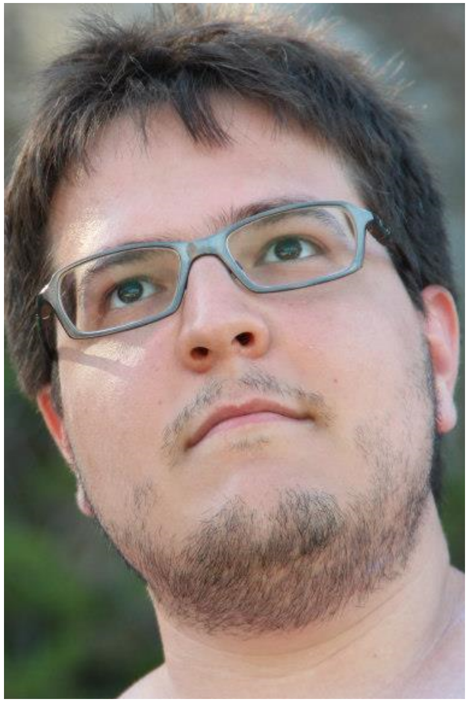
Tier 1 machine @ INAF : a crazy thing?

Can be used by theorists and observers x data- analysis

Our team:

http://web.pd.astro.it/mapelli/group.html

Mario Spera



Brunetto Ziosi

Elisa Bortolas

Alessandro Trani

MAN POWER: we are a small group @ INAF-Padova funded ONLY by COMPETITIVE GRANTS (FIRB, PRIN, MERAC)

(1 staff member, 1 postdoc, 2 PhD students, 1 ex-PhD student + several collaborators @ INAF and other institutes)

Conclusions

- **After LIGO, we know that BH-BH exist, merge in a Hubble time, and that MASSIVE BHs (>25 Msun) exist**

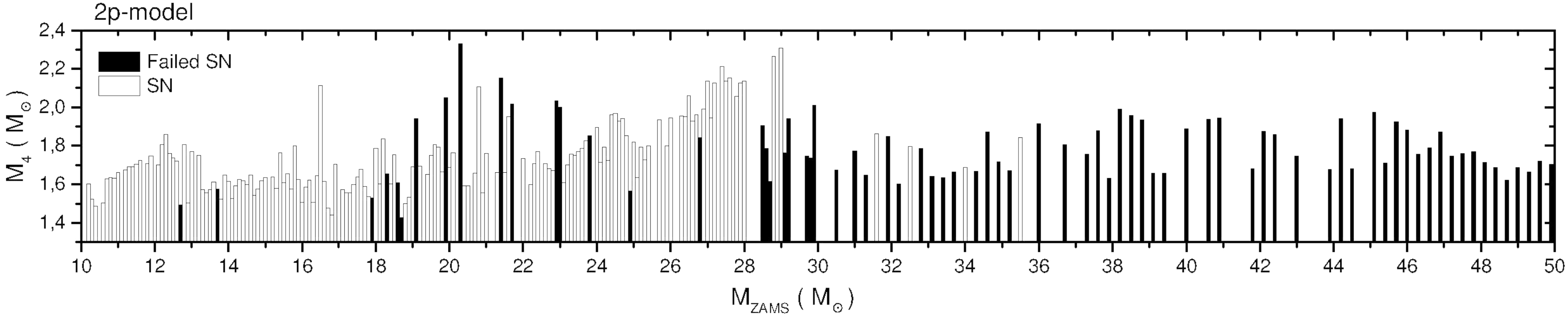
- **Massive BHs have been successfully predicted by a INAF team: we have the expertise @ INAF**
  We are not alone @ INAF: see next talk by Marco Limongi

- **Understanding massive BHs requires models of stellar evolution, binary evolution and DYNAMICS of stellar objects: INTERDISCIPLINARY AND COMPLEX**

- **Future challenges include: full description of dynamics, understanding common envelope, formation of NS-NS**

- **For the discussion: models of double compact-object binaries require COMPUTING TIME with GPUs**

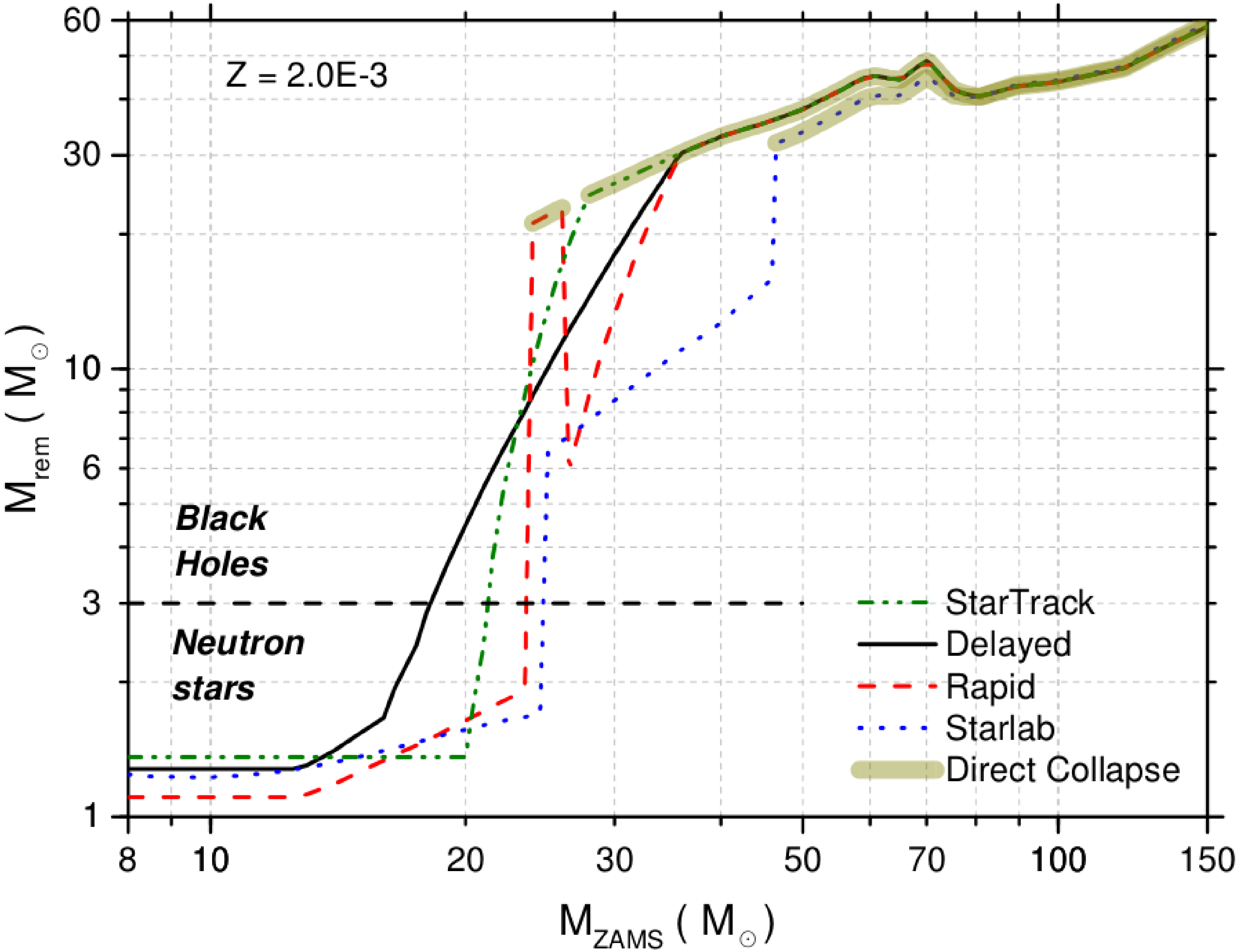
THANK YOU!!!



From Spera et al. 2015

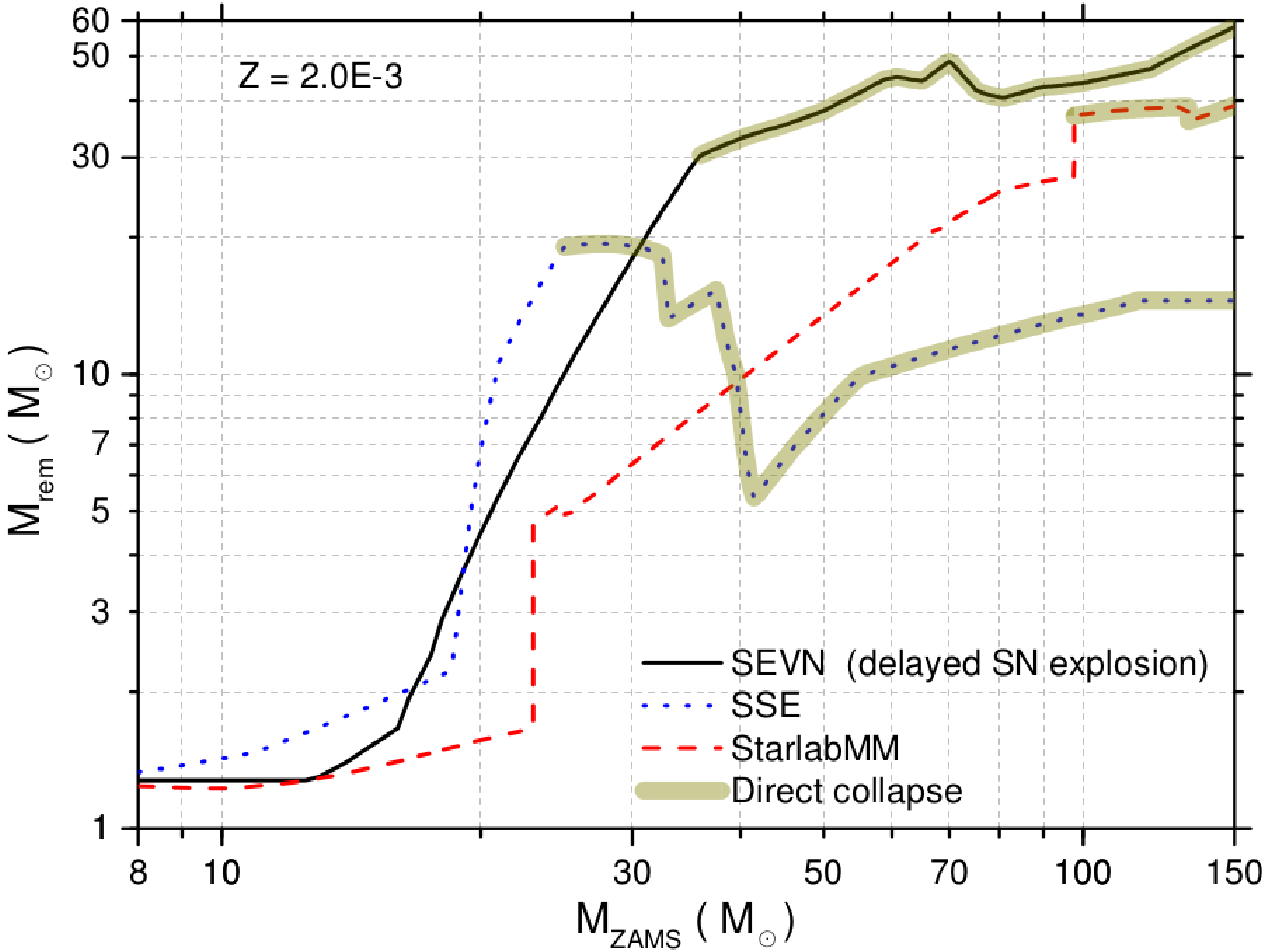
based on SN model by Ertl et al. 2015

M4 is the mass enclosed within radius where dimensionless entropy per baryon is 4
2 parameters: M4 and the compactness of Fe core



From Fig. 10 Spera et al. 2015

Comparison of 5 SN models at Z=0.002=0.1 Zsun (consistent with GW150914)



From Fig. 13 Spera et al. 2015

Comparison of 3 stellar evolution models at Z=0.002=0.1 Zsun
(consistent with GW150914)

5. technical issues!

Dynamical simulations are computationally expensive
1 BH-BH merger every ~ 100 simulated star clusters
→ parameter space investigation is missing

Each simulation requests > 2 weeks on CPUs
~ 1 – 100 hr on GPUs

We have a 64 core machine @ OAPD
(18k euro from FIRB2012 project)

CINECA: high success rate of proposals but CINECA decides what clusters to buy (not suitable to astro people)

WE NEED MORE COMPUTATIONAL FACILITIES TO BE COMPETITIVE !!!!

Tier 1 machine @ INAF : a crazy thing?

~1-2 M EUR first investment (obsolescence ~ 5 yr)
~100k EUR maintenance /yr
Can be used by theorists and observers x data- analysis