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Demography of binary compact objects: from theory to data

Main collaborators: M. Celeste Artale, Alessandro Ballone, Yann Bouffanais, Guglielmo Costa, Ugo N. Di Carlo, Nicola Giacobbo, Giuliano Iorio, Mario Pasquato, Sara Rastello, Filippo Santoliquido, Nadeen Sabha, Mario Spera, Stefano Torniamenti

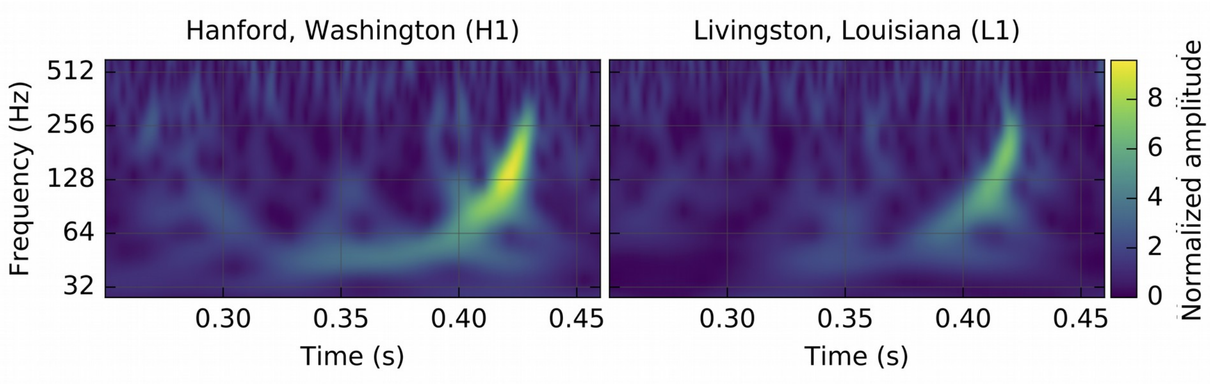
Virtual Iberian GW Meeting, October 19th – 20th 2020

OUTLINE:

1. Lesson learned from gravitational wave (GW) detections
2. The mass of black holes (BHs)
3. The formation channels of binary compact objects
4. The cosmological context
5. Conclusions

1. Lesson-learned from GW detections

GW150914: the first binary black hole (BBH)



Abbott et al. 2016, PhRvL, 116, 1102

O1 + O2: 10 BBHs and 1 binary neutron star

(Abbott et al. 2019, PhRvX...9c1040A)

O3:GW190412 (Abbott et al. 2020, PhRvD, 102, 3015)

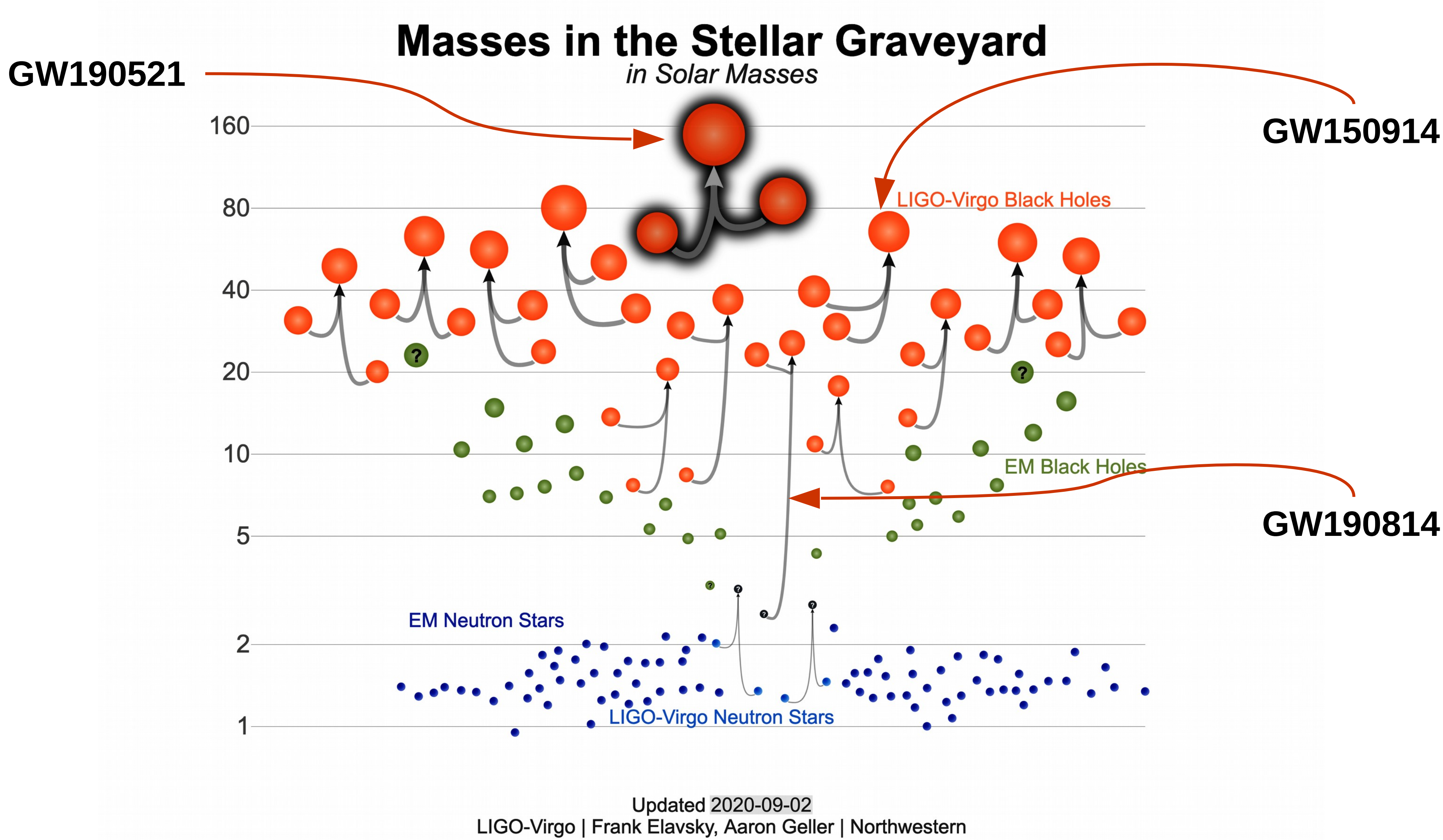
GW190425 (Abbott et al. 2020, ApJ, 892, L3)

GW190521 (Abbott et al. 2020, PhRvL, 125, 1102; 2020, ApJ, 900, L13)

GW190814 (Abbott et al. 2020, ApJ, 896, L44)

56 public detection candidates (https://gracedb.ligo.org/)

1. Lesson-learned from GW detections



Abbott et al. 2019, GWTC1, https://ui.adsabs.harvard.edu/abs/2019PhRvX...9c1040A/

2. The mass of black holes

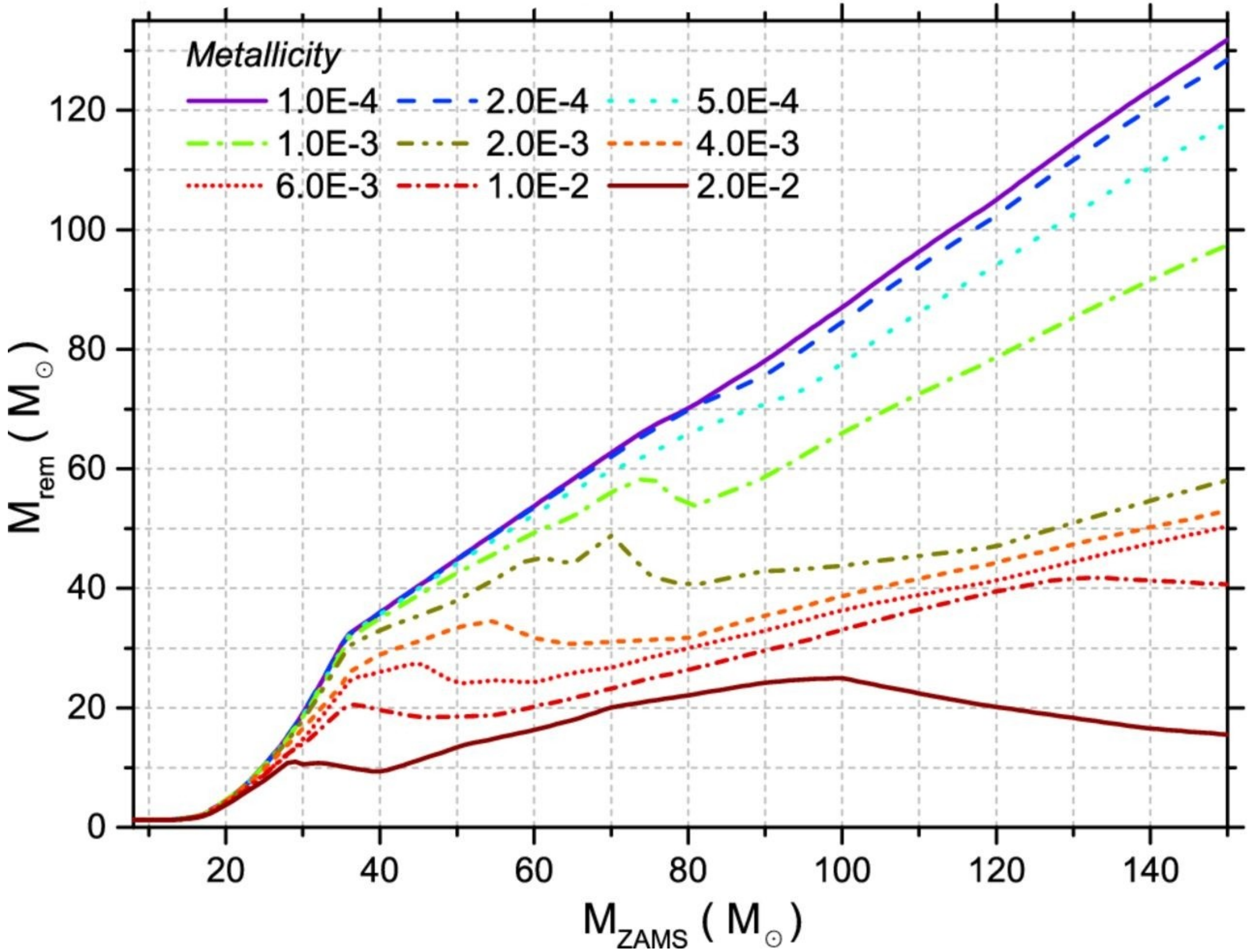
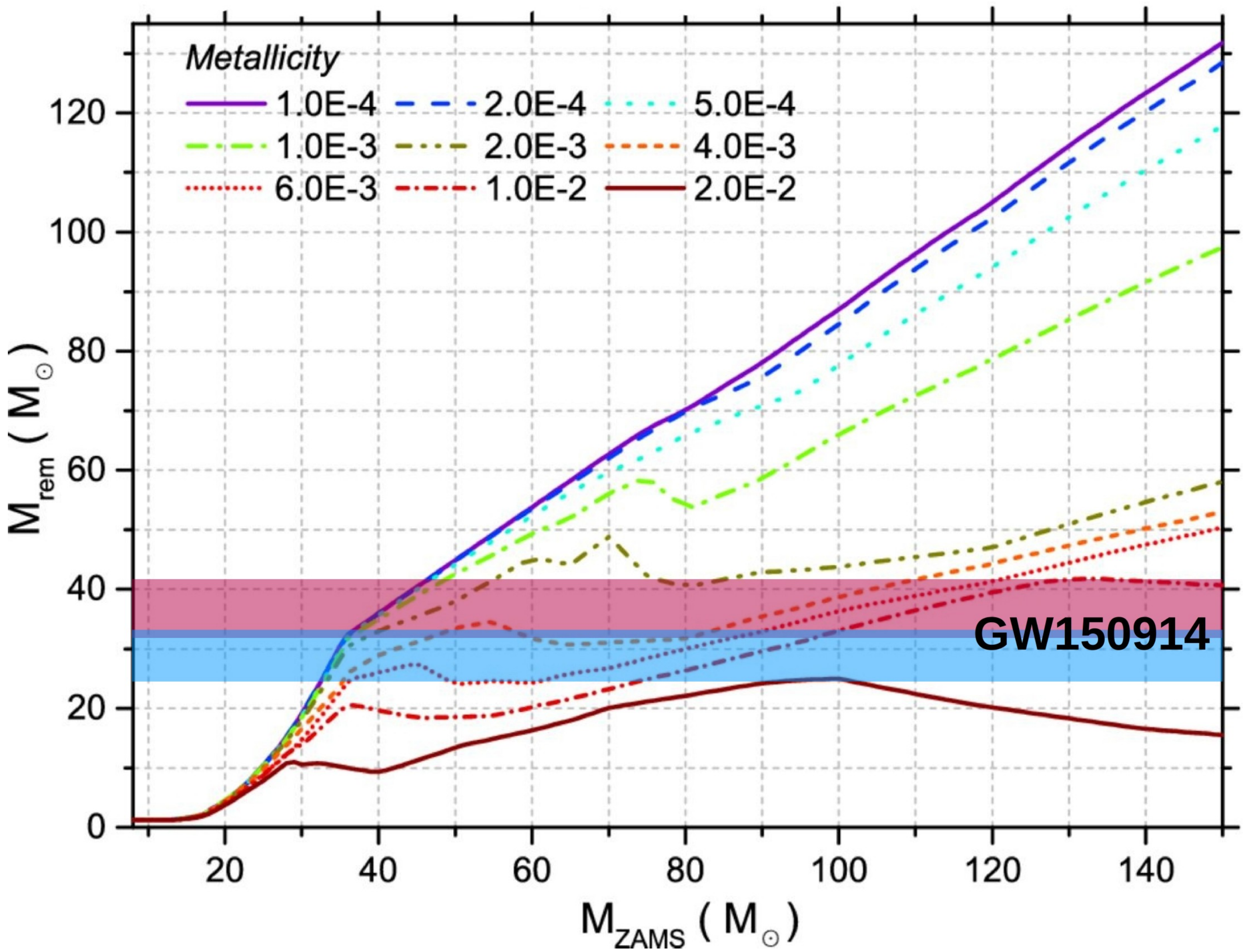


Figure from Spera, MM & Bressan 2015
see also Woosley & Heger 2002;
Heger et al. 2002; MM et al. 2009, 2010, 2013;
Belczynski et al. 2010; Fryer et al. 2012

2. The mass of black holes



Used by Abbott et al. 2016, ApJ, 818, L22 to interpret GW150914 (Fig. 1)

Figure from Spera, MM & Bressan 2015 see also Woosley & Heger 2002; Heger et al. 2002; MM et al. 2009, 2010, 2013; Belczynski et al. 2010; Fryer et al. 2012

2. The mass of black holes: stellar winds and direct collapse

MASSIVE STARS lose mass by stellar WINDS

*** Winds depend on metallicity & Eddington ratio**
(e.g. Vink et al. 2001; Graefener & Hamann 2008; Vink et al. 2011)

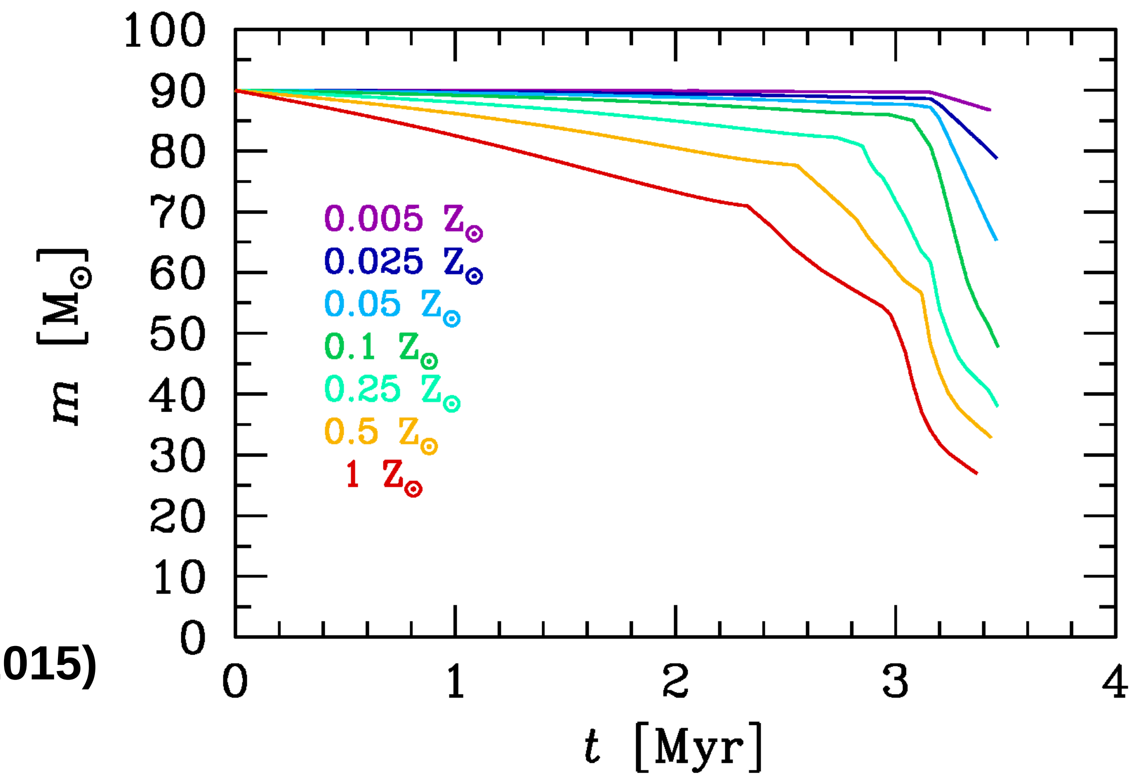
$$\dot{M} \propto Z^{\alpha}$$

$$\alpha = 0.85 \quad [\text{if } \Gamma < 2/3]$$

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

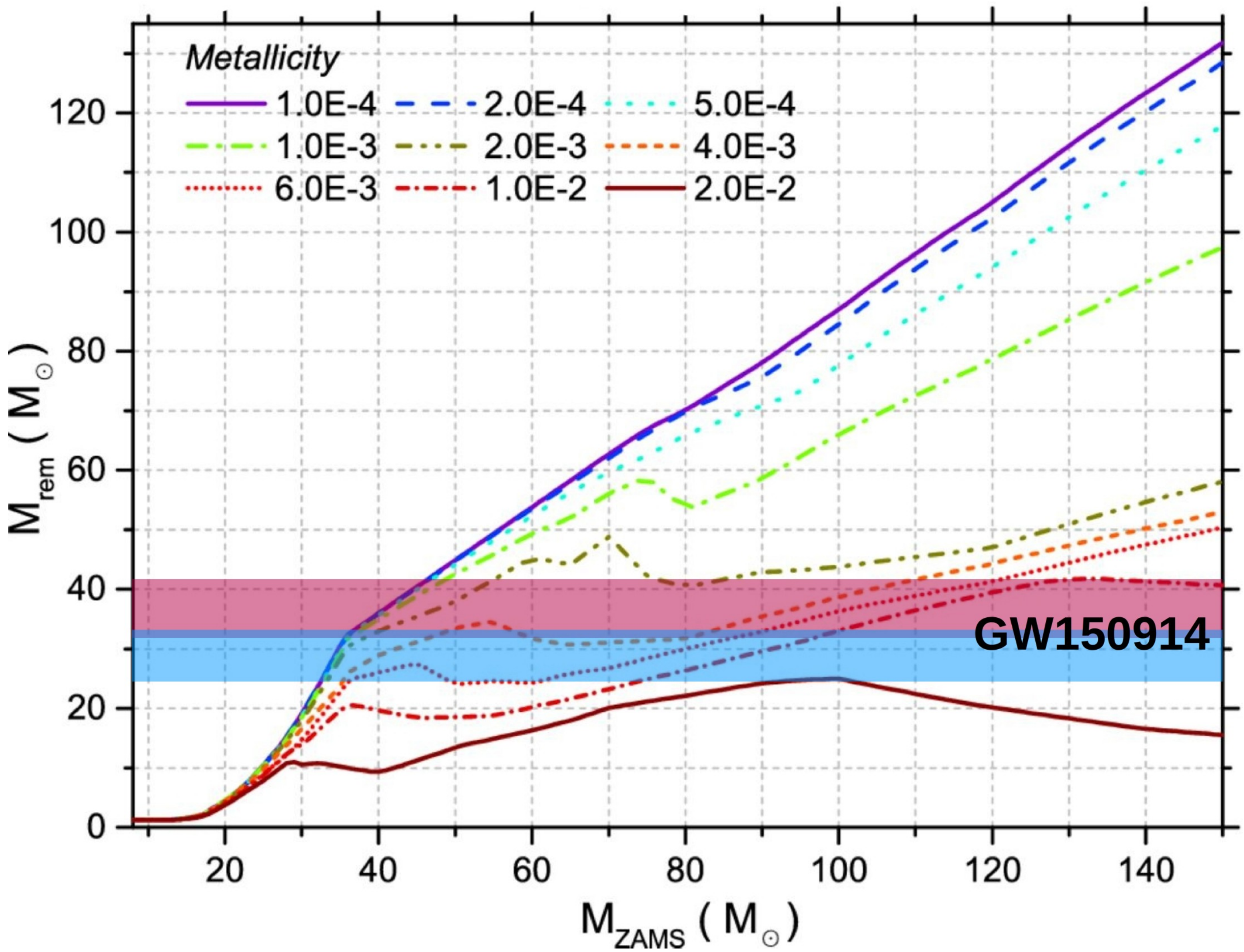
$$\Gamma = \frac{L_*}{L_{\rm Edd}}$$

PARSEC (Chen, Bressan et al. 2015)



*** Since metal-poor stars have larger pre-supernova masses, they are more likely to directly collapse, producing more massive BHs**
(Heger et al. 2003; MM et al. 2009, 2010, 2013; Belczynski et al. 2010; Fryer et al. 2012)

2. The mass of black holes: stellar winds and direct collapse



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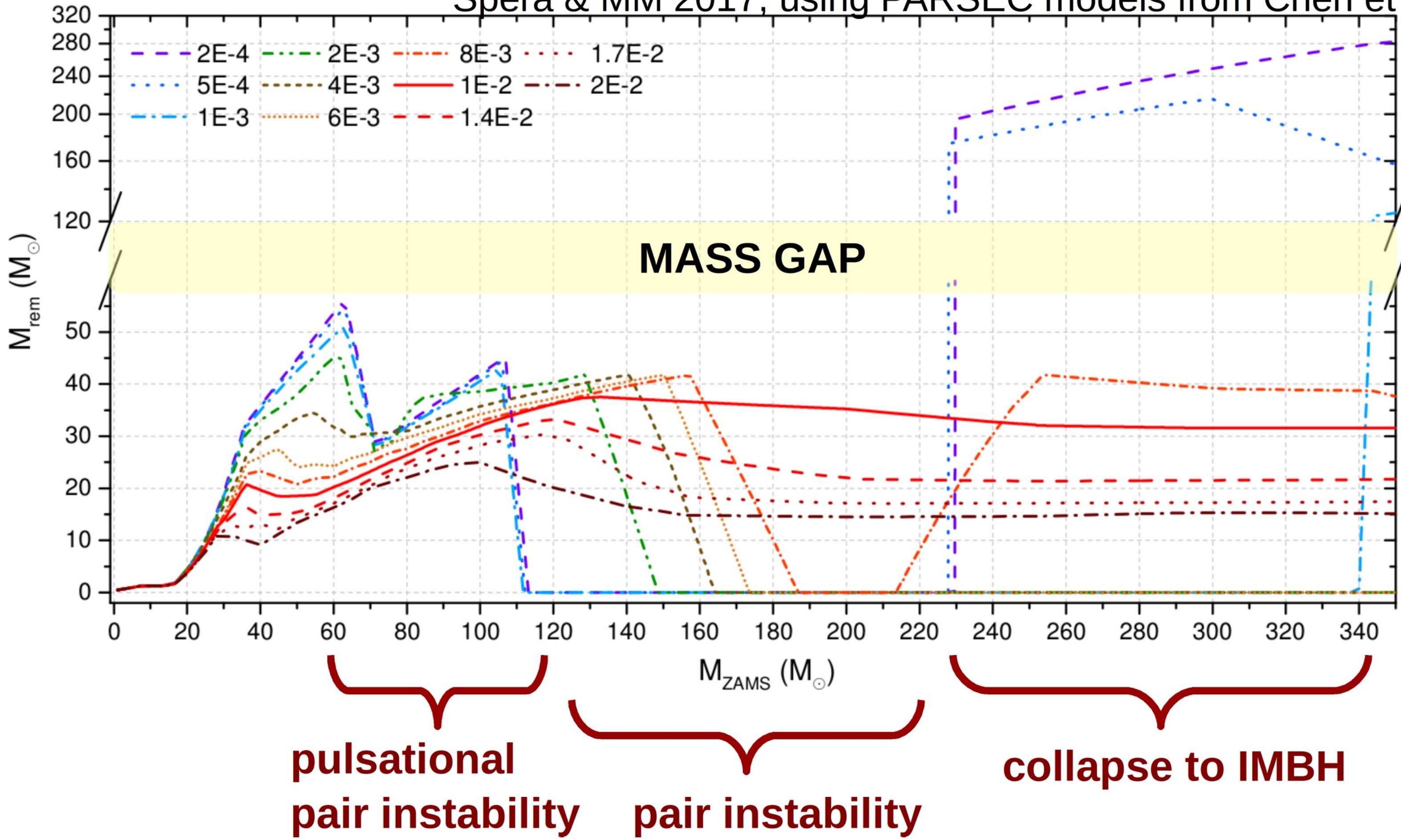
2. The mass of black holes: pair instability

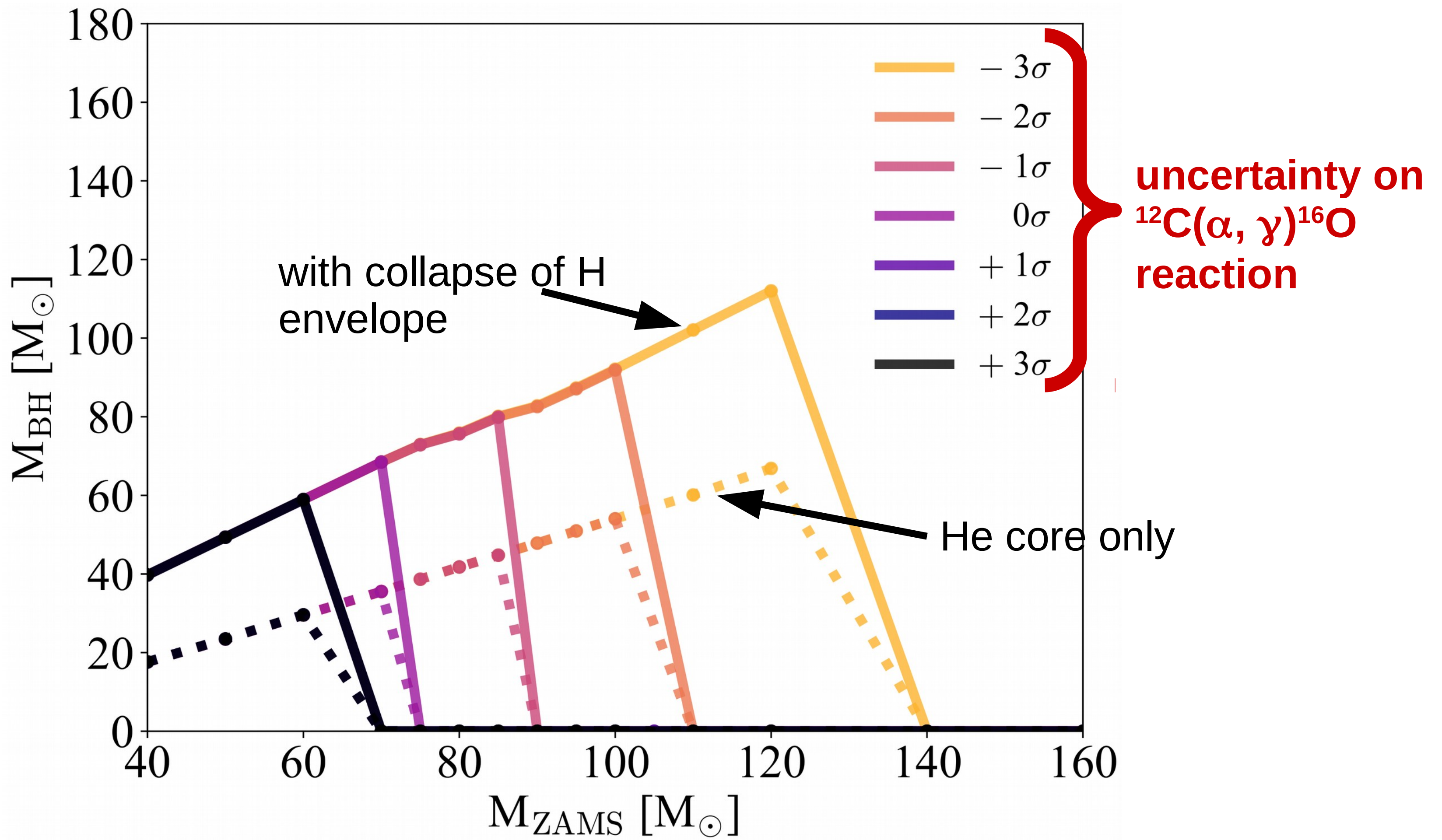
Impact of pulsational pair instability (if $32 < m_{He} / M_\odot < 64$) and pair instability supernovae (if $64 < m_{He} / M_\odot < 135$)

Spera & MM 2017, using PARSEC models from Chen et al. 2015



Woosley 2017, 2019; Belczynski et al. 2016; Marchant et al. 2018, 2019
Stevenson et al. 2019; Renzo et al. 2019; MM et al. 2020

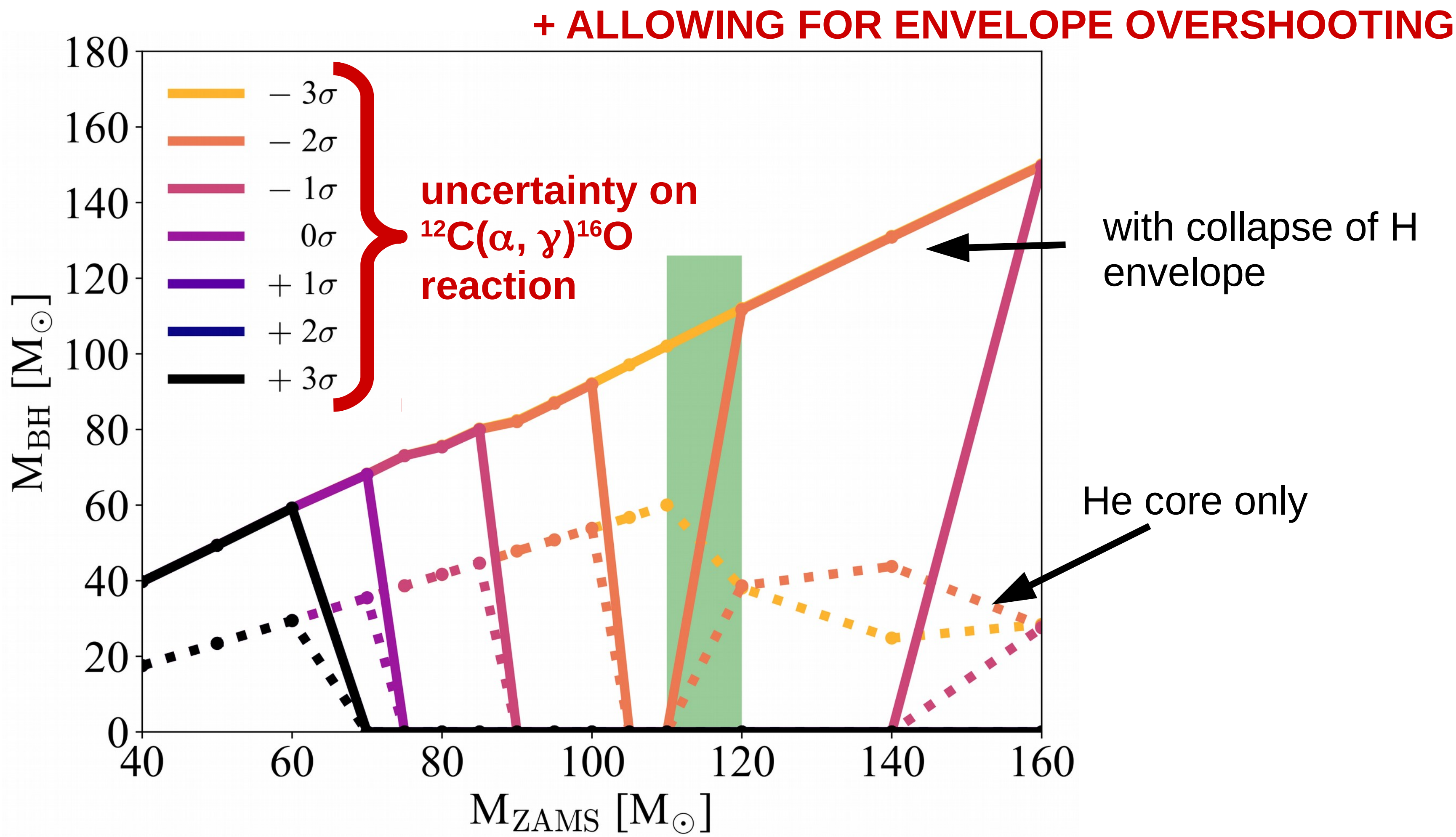
2. The mass of black holes: is GW190521 impossible?



Costa et al. 2020, https://arxiv.org/abs/2010.02242

See also Farmer et al. 2019, 2020; van Son et al. 2020; Marchant et al. 2020; Belczynski et al. 2020; Farrell et al. 2020

2. The mass of black holes: is GW190521 impossible?



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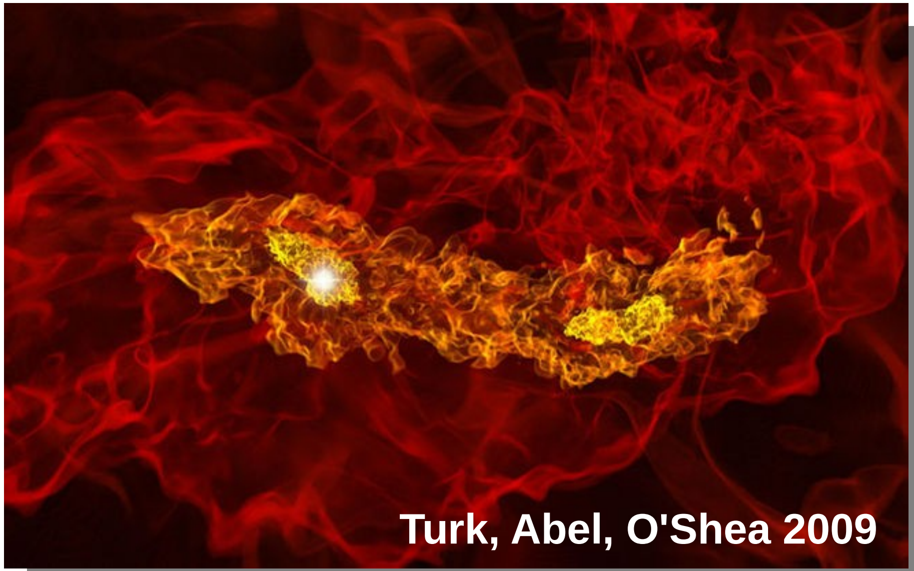
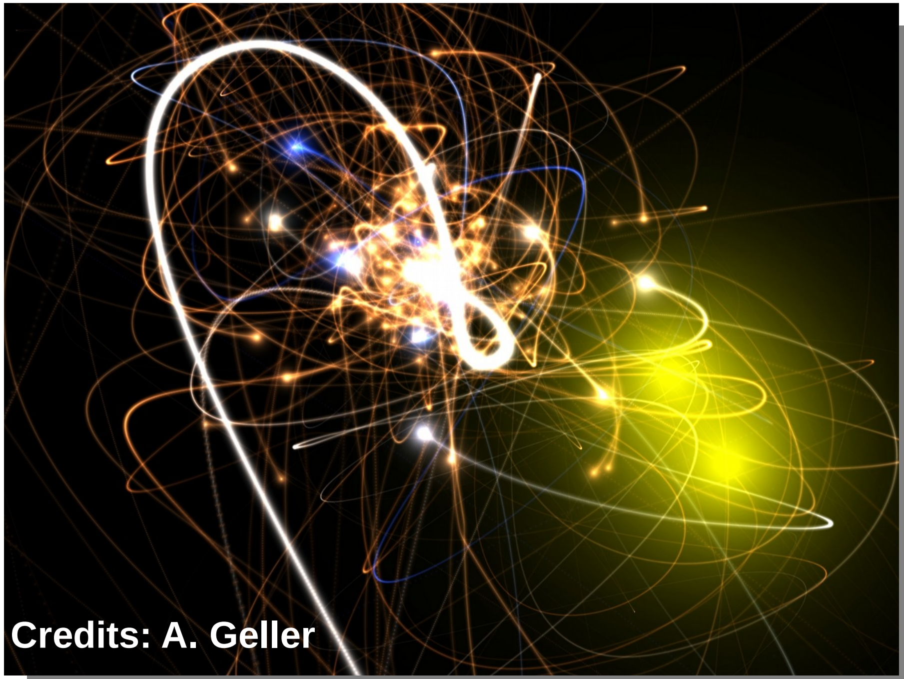
See also Farmer et al. 2019, 2020; van Son et al. 2020; Marchant et al. 2020; Belczynski et al. 2020; Farrell et al. 2020

3. What are the formation channels of binary compact objects?

ISOLATED BINARIES:
two stars form from same cloud
and evolve into two compact objects
gravitationally bound





DYNAMICAL BINARIES:
Binary compact objects
(especially binary BHs and BH – NS)
form and/or evolve
by dynamical processes
in star clusters

3. Formation channels of binary compact objects: isolated

Binary evolution via POPULATION SYNTHESIS:

- **stellar evolution (fitting formulas or look-up tables)**
- **prescriptions for SNe**
- **formalism for binary evolution processes**

Examples of binary population-synthesis codes:

B – Pass	(Eldridge+ 2016, 2017, 2018)
BSE/MOBSE	(Hurley+ 2002; Giacobbo, MM+ 2018)
ComBinE	(Kruckow+ 2018)
COMPAS	(Stevenson et al. 2017; Barrett et al. 2017)
Seba	(Portegies Zwart+ 2001; Toonen+ 2012; MM+ 2013)
SEVN	(Spera+ 2015; Spera & MM 2017; Spera+ 2019)
StarTrack	(Belczynski+ 2008, 2010)

3. Formation channels of binary compact objects: isolated

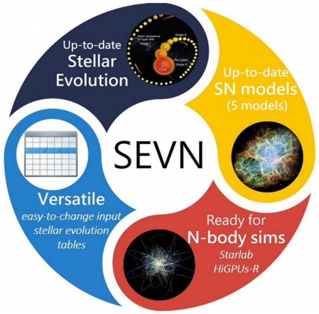
Binary evolution via POPULATION SYNTHESIS:

- **stellar evolution (fitting formulas or look-up tables)**
- **prescriptions for SNe**
- **formalism for binary evolution processes**

Our population-synthesis codes:

MOBSE

(MM et al. 2017, 2018;
Giacobbo et al. 2018;
Giacobbo & MM 2018, 2019)



SEVN

(Spera, MM & Bressan 2015;
Spera, MM et al. 2019)

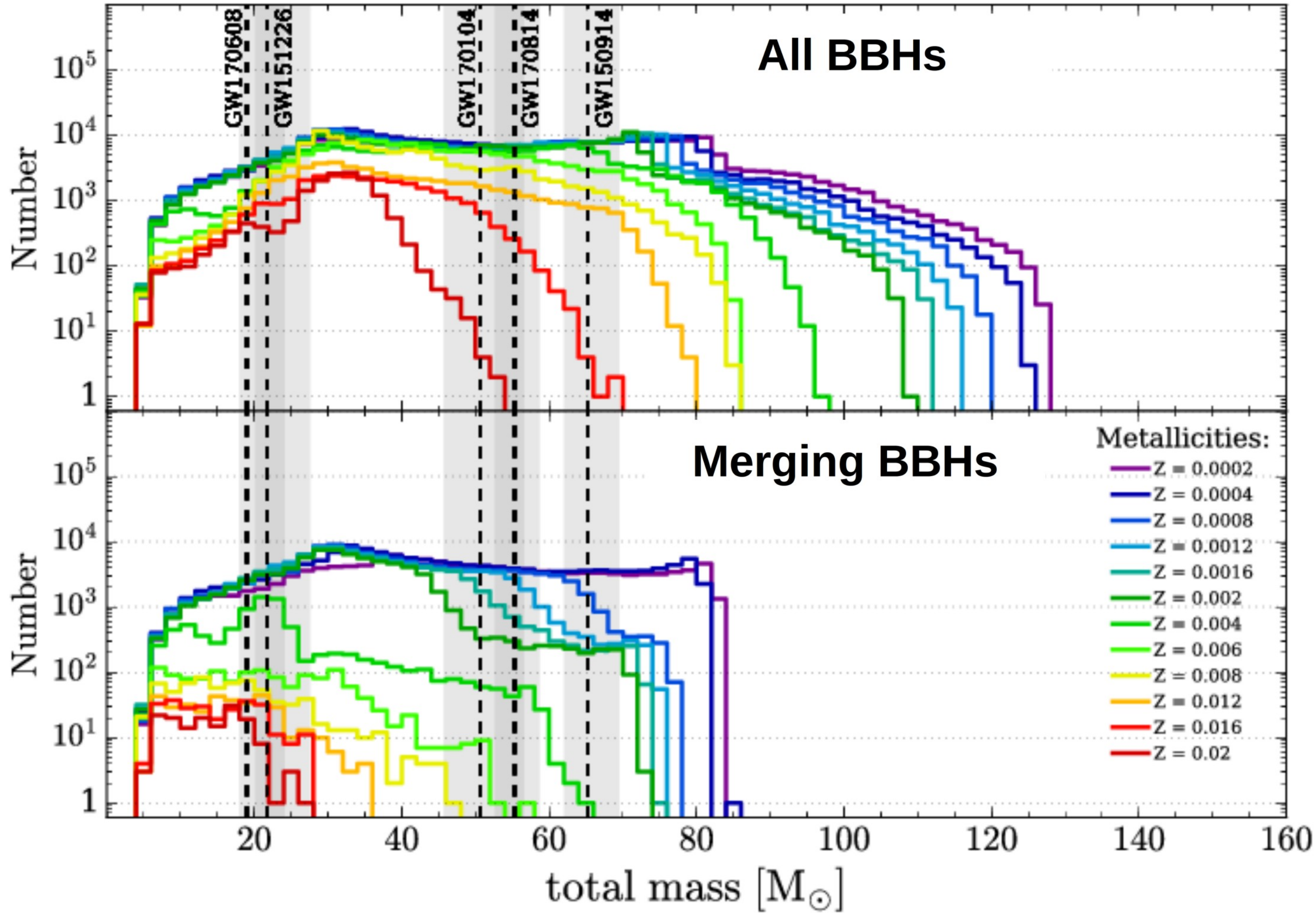
Nicola Giacobbo
postdoc

Mario Spera
MSCA fellow

Giuliano Iorio
postdoc

Download MOBSE and SEVN from http://demoblack.com/

3. Formation channels of binary compact objects: isolated



Giacobbo & MM 2018; Spera et al. 2019

* Mass and number of BBHs depend on metallicity (Z)

* BHs with mass ≤ 65 $M_\odot$ form, but only BHs with mass ≤ 40 $M_\odot$ merge in isolation (wait for dynamics..)

3. Formation channels of binary compact objects: dynamical

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

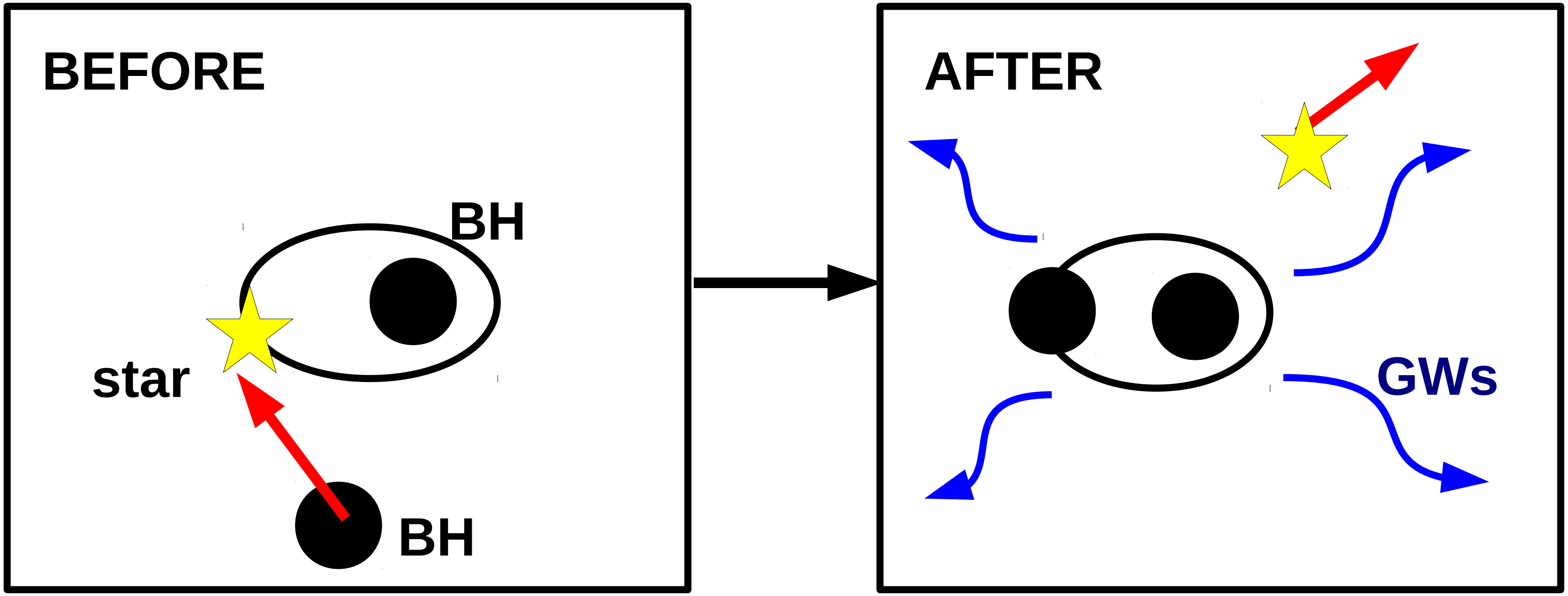
i.e. only in dense star clusters

but massive stars (BH progenitors) form in star clusters
***(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; see Portegies Zwart et al. 2010 for a review*)**

R136
in the LMC

HST – NASA

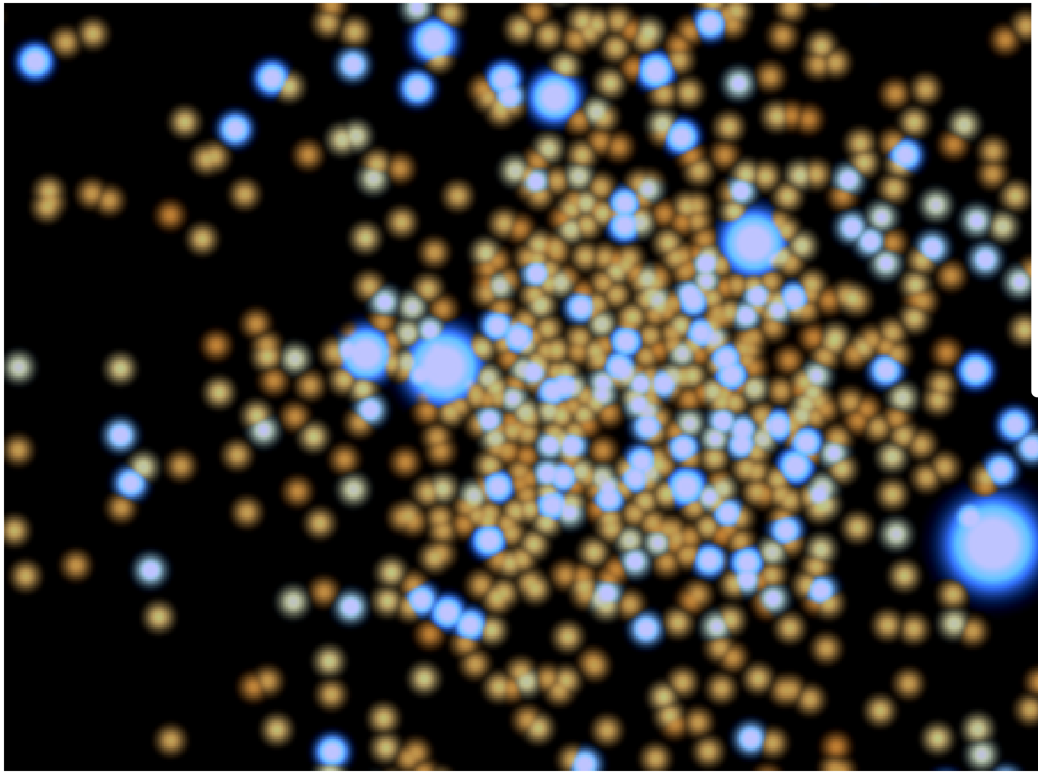
Exchanges bring BHs in binaries



see e.g. Portegies Zwart & McMillan 2000; Colpi et al. 2003; Banerjee et al. 2010; Downing et al. 2011; Tanikawa et al. 2013; Ziosi et al. 2014; Rodriguez et al. 2015, 2016, 2018; MM 2016; Hurley et al. 2016; Askar et al. 2017; Banerjee 2017, 2018, 2019; Fujii et al. 2017; Kumamoto et al. 2019, 2020; Rastello et al. 2019; Di Carlo et al. 2019 and many others

3. Formation channels of binary compact objects: dynamical

MOBSE (MM et al. 2017) & Nbody6++GPU (Wang et al. 2015, 2016)



Ugo Di Carlo
PhD student

Sara Rastello
postdoc

> 100’000 YOUNG STAR CLUSTERS (300 – 30’000 M⊙)
with fractal initial conditions
& initial binary fraction ~ 100% (for massive stars)

MM 2016
Di Carlo et al. 2019, 2020a, 2020b
Rastello et al. 2020

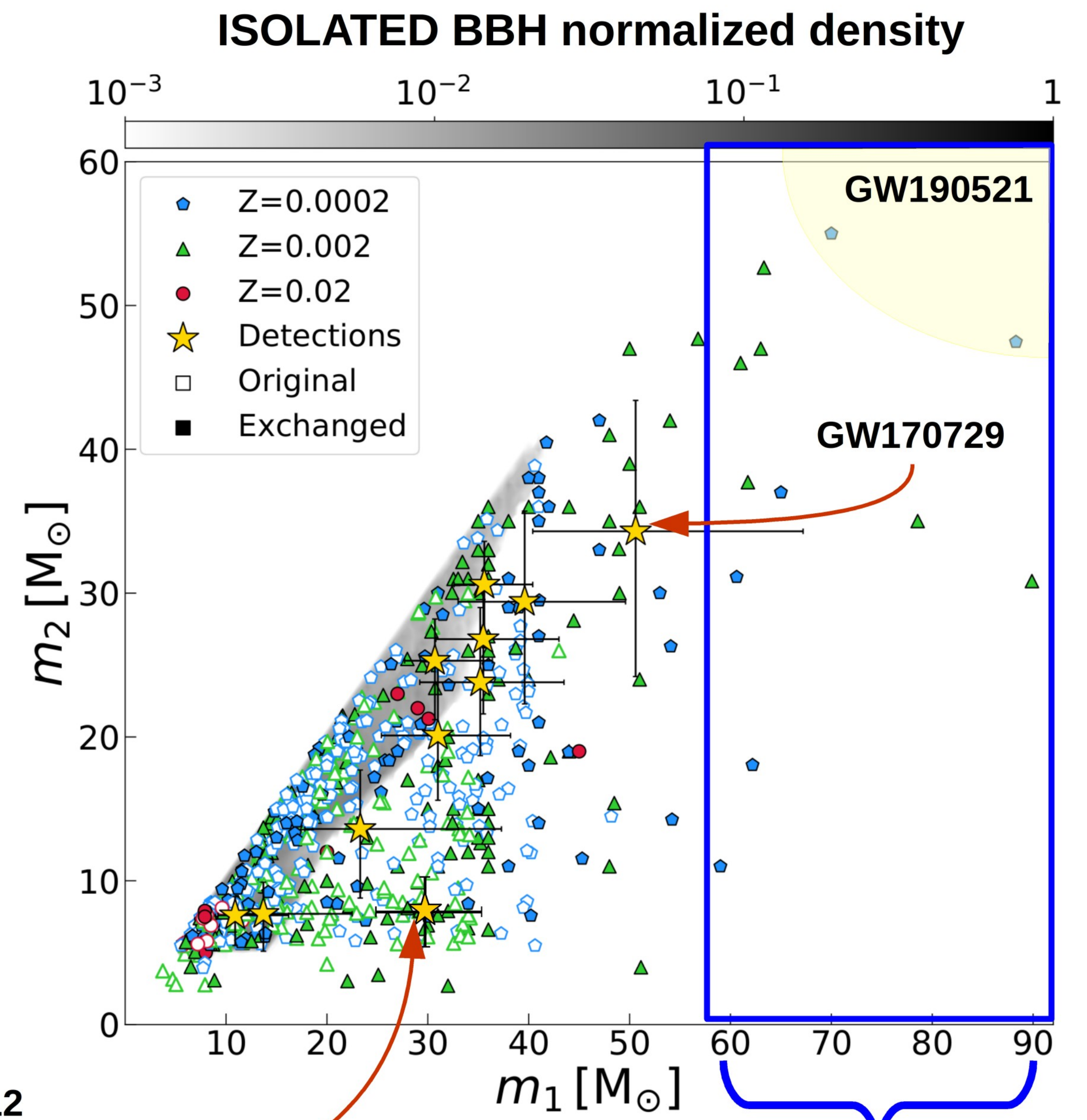
3. Formation channels of binary compact objects: BBHs

Dynamical systems with total mass >> 80 M⊙

GW170729 explained only with exchanges

~2% BBH mergers with mass > 60 M⊙ (in the pair instability gap)

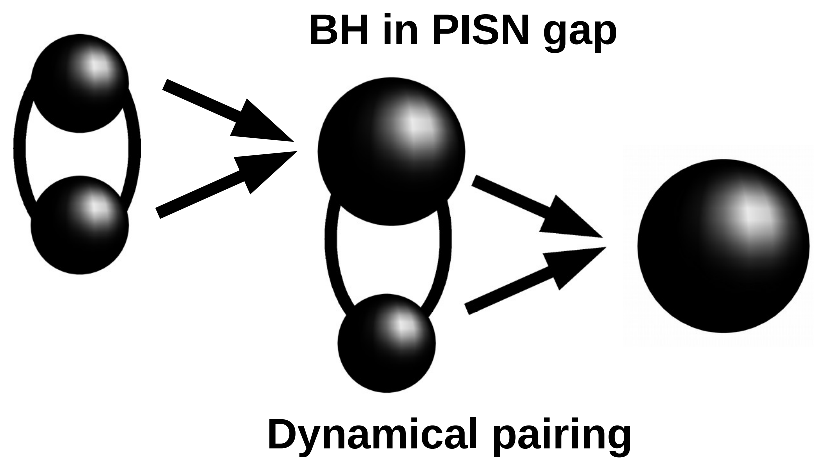
Di Carlo et al. 2019, 2020a, 2020b



3. Formation channels of binary compact objects: BHs in the mass gap

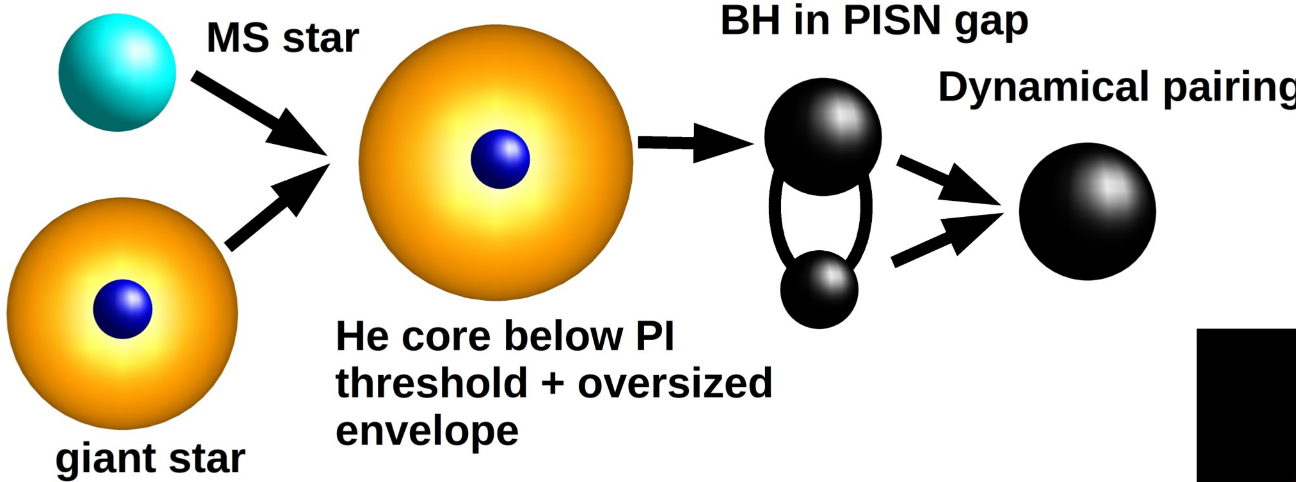
1. Second-generation black holes

(e.g. Miller & Hamilton 2002; Fishbach et al. 2017; Gerosa & Berti 2017; Gerosa et al. 2019; Kimball et al. 2019; Rodriguez et al. 2019; Fragione et al. 2020)



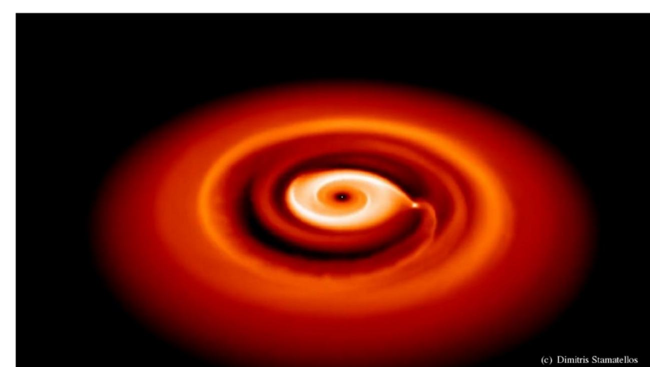
2. BHs born from stellar mergers

(Di Carlo et al. 2019, 2020a, 2020b; Kremer et al. 2020)

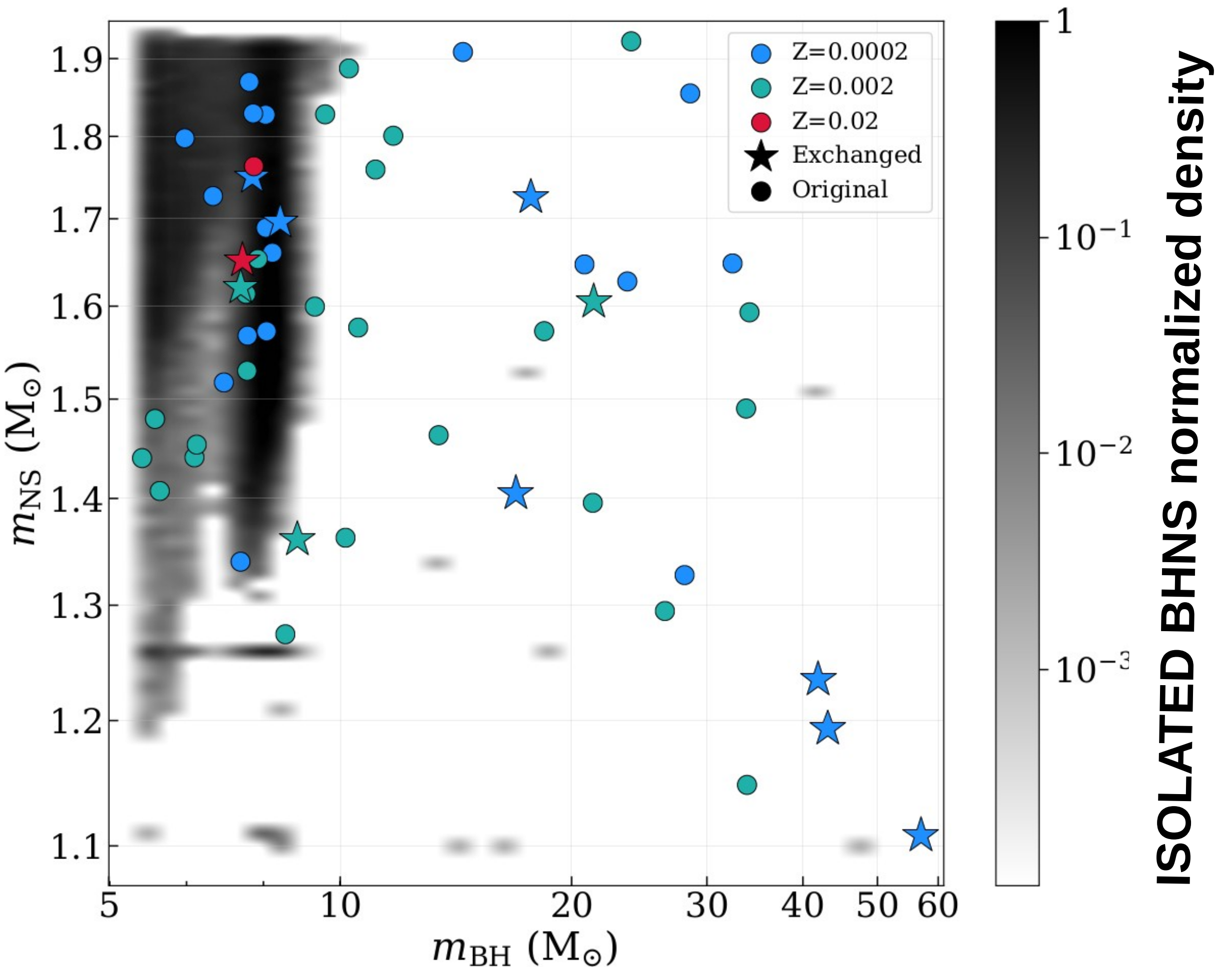


3. Hierarchical mergers in AGN discs

(e.g. McKernan et al. 2012, 2018, 2019; Bartos et al. 2017; Fragione & Antonini 2019; Yang, Bartos et al.2019; Gayathri et al. 2020)



3. Formation channels of binary compact objects: BHNs



Rastello et al. 2020

* BHNSs in star clusters more massive than in the field
* Extreme mass ratios like GW190814 possible in star clusters

4. The cosmological context: importance and challenge

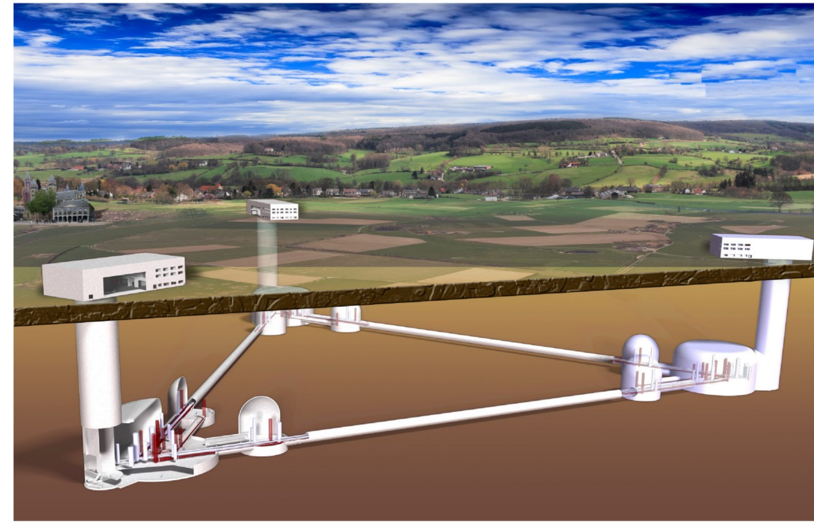
IMPORTANCE:

binary merging at $z \sim 0.1$
might have formed at $z \gg 0.1$

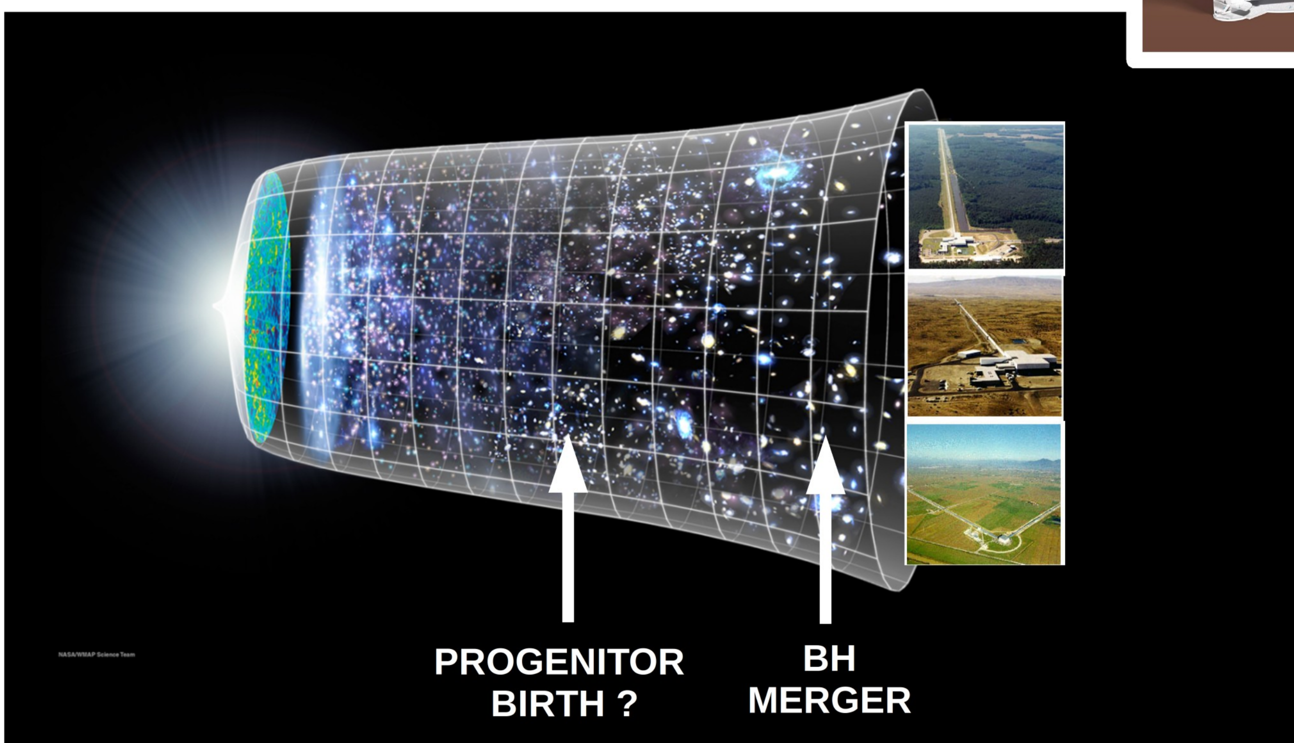
+ 3G detectors will detect
BBH mergers at $z \sim 10$

CHALLENGE:

humongous physical range



EINSTEIN TELESCOPE



4. The cosmological context: Monte Carlo method

Cosmological simulations

(e.g. Lamberts+ 2016; O'Shaughnessy+ 2017; MM+ 2017, 2018, 2019; Schneider+ 2017)

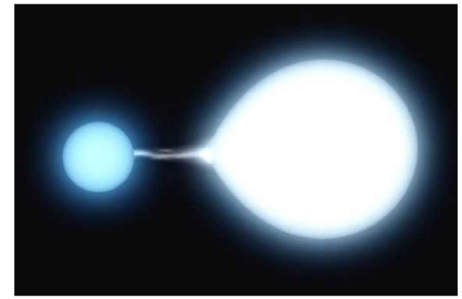
or data – driven approach

(e.g. Dominik+ 2013, 2015; Dvorkin+ 2016, 2018; Neijssel+ 2019; Santoliquido+ 2020)

Pop. synthesis of isolated binaries and dynamical simulations

EAGLE cosmo. simulation (Schaye et al. 2015)

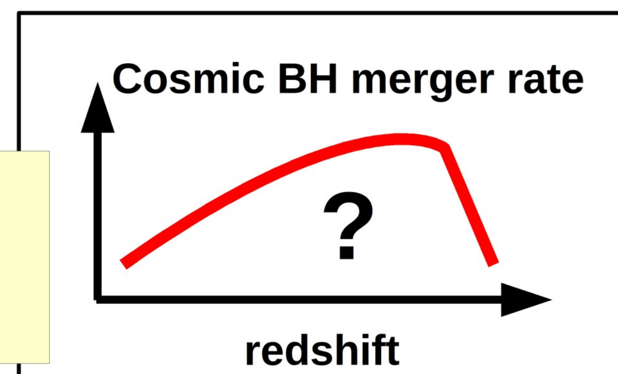
star formation and metallicity in galaxies



BBH, BNS, BHNS catalogues

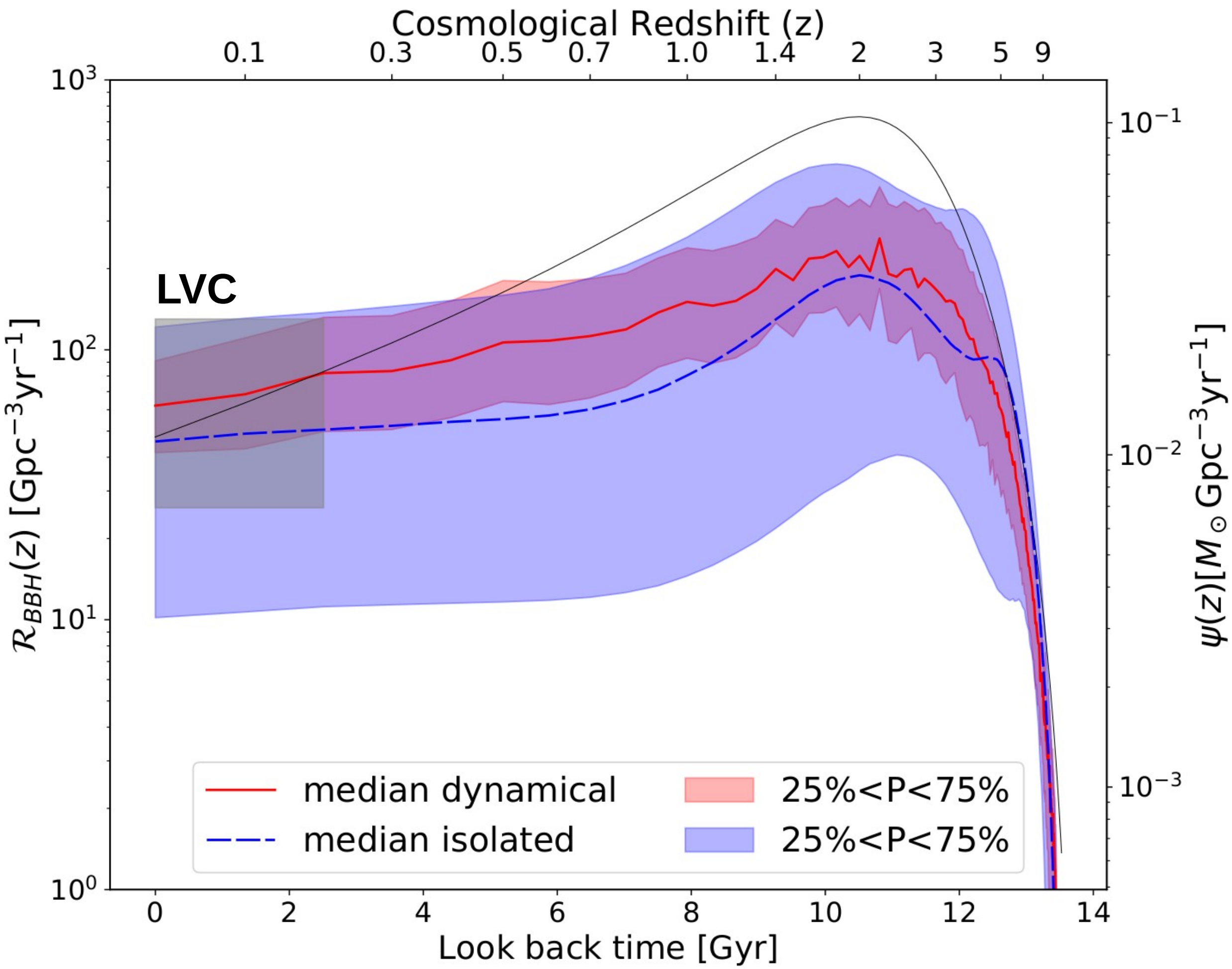
semi-analytic model
to seed BBHs in galaxies

Cosmic BH merger rate & host galaxy properties



4. The cosmological context: BBH merger rate

Filippo Santoliquido
PhD student

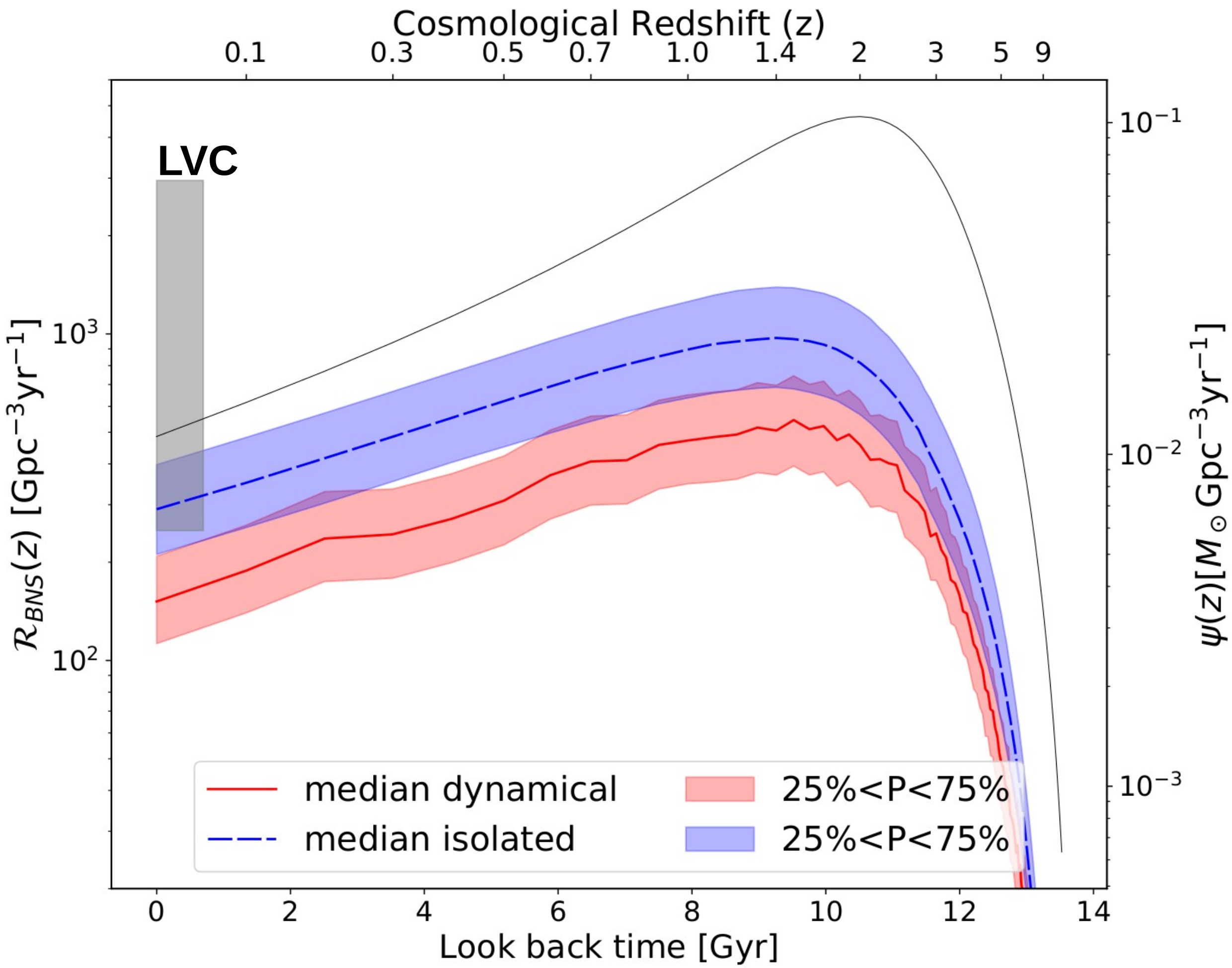


MM et al. 2017, 2018
Santoliquido et al. 2020

* SFR from Madau & Fragos (2017), metallicity from De Cia et al. (2018)
* Both dynamical and isolated BBH mergers scale with SFR, modulated by metallicity and delay time
* large uncertainty (mostly from metallicity)

4. The cosmological context: BNS merger rate

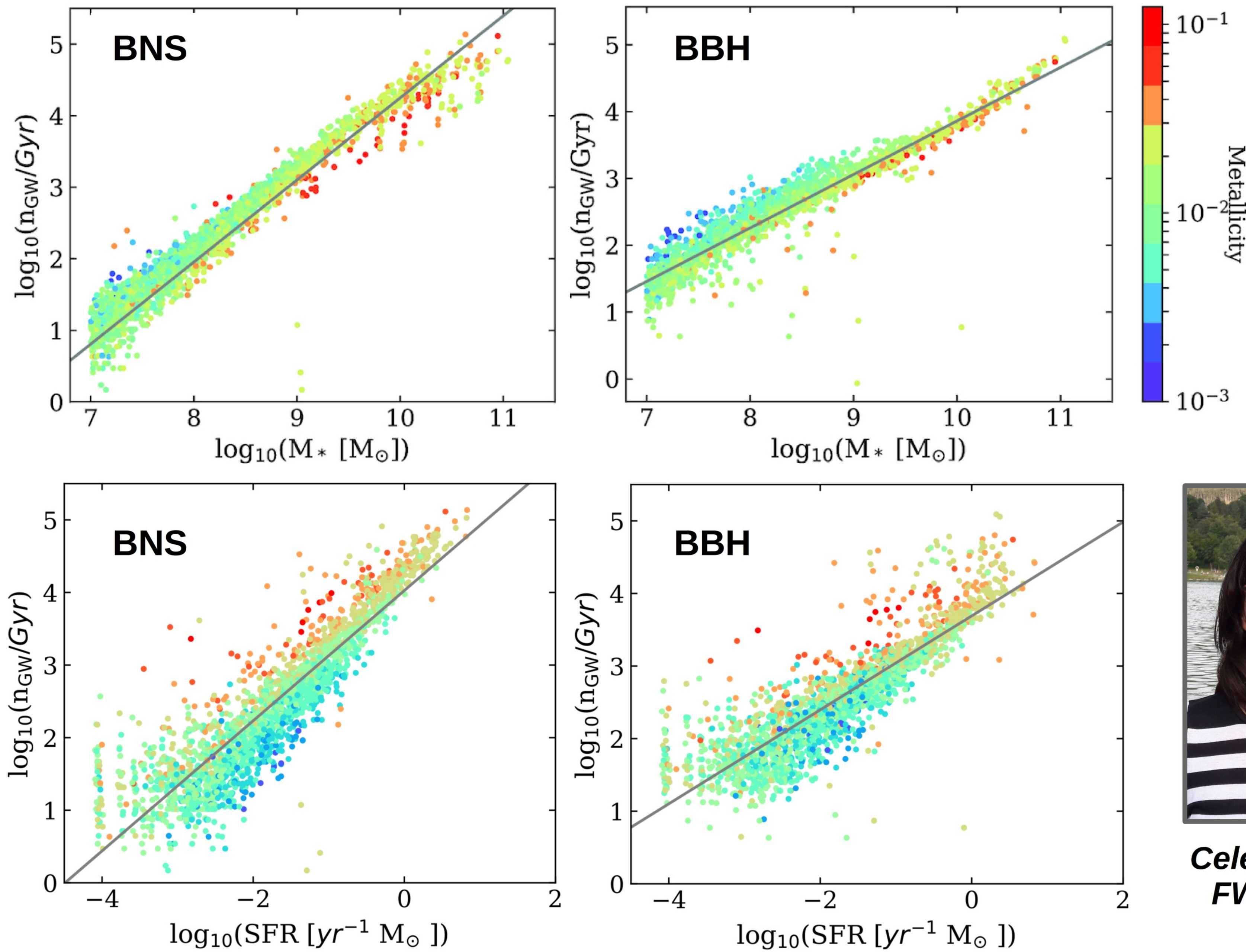
Filippo Santoliquido
PhD student



MM et al. 2017, 2018
Santoliquido et al. 2020

* SFR from Madau & Fragos (2017), metallicity from De Cia et al. (2018)
* BNS merger rate from star clusters lower than field
* main uncertainty is SFR

4. The cosmological context: host galaxies of compact objects



Celeste Artale FWF fellow

MM et al. 2018; Artale, MM et al. 2019, 2020; Toffano, MM et al. 2019

www.demoblack.com

Work with us: https://jobregister.aas.org/ad/a2d1edad

contact me: michela.mapelli@unipd.it

5. Conclusions

* Dependence of BH mass on metallicity necessary to account for BHs with mass > 30 $M_\odot$

* Pair instability opens a mass gap ~ 60 – 120 $M_\odot$

* but uncertainties on H envelope collapse, nuclear reaction rates and core overshooting still allow for GW190521-like objects

* Dynamics leads to more massive BBHs: some rare (~ 2 – 10 %) events in the pair-instability gap (60 – 120 $M_\odot$)

* Redshift distribution of compact binary mergers traces cosmic SFR, modulated by metallicity and delay time

* Mergers more likely in massive galaxies with high SFR

THANK YOU