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Populations of binary black holes: open questions and challenges

Main collaborators:

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15 – 20 May 2022, Kathmandu, Nepal

OUTLINE:

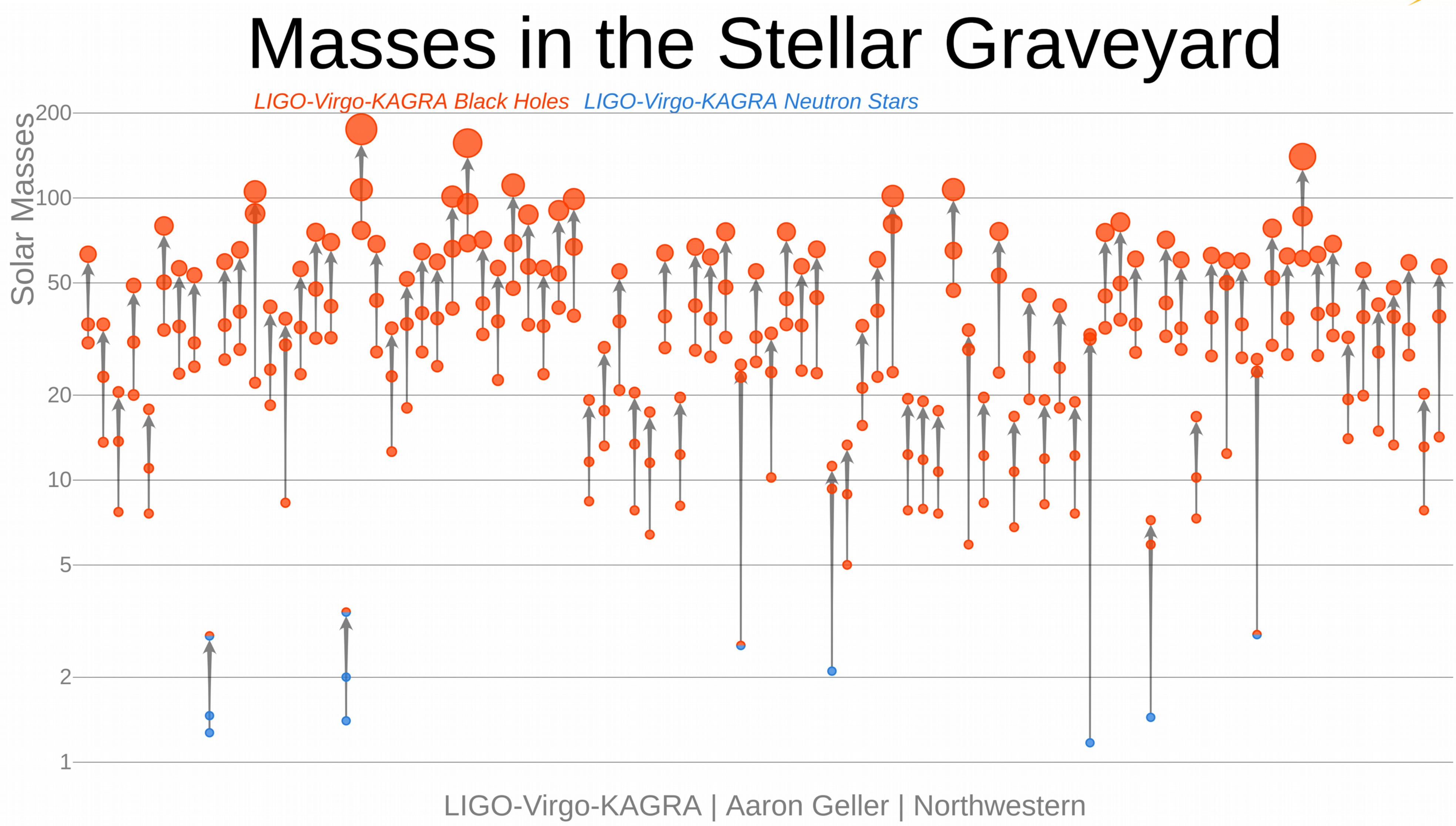
1. Preamble: what have we learned from gravitational waves (GWs)?

2. The mass of black holes

3. Formation of BBHs from binary evolution and dynamics

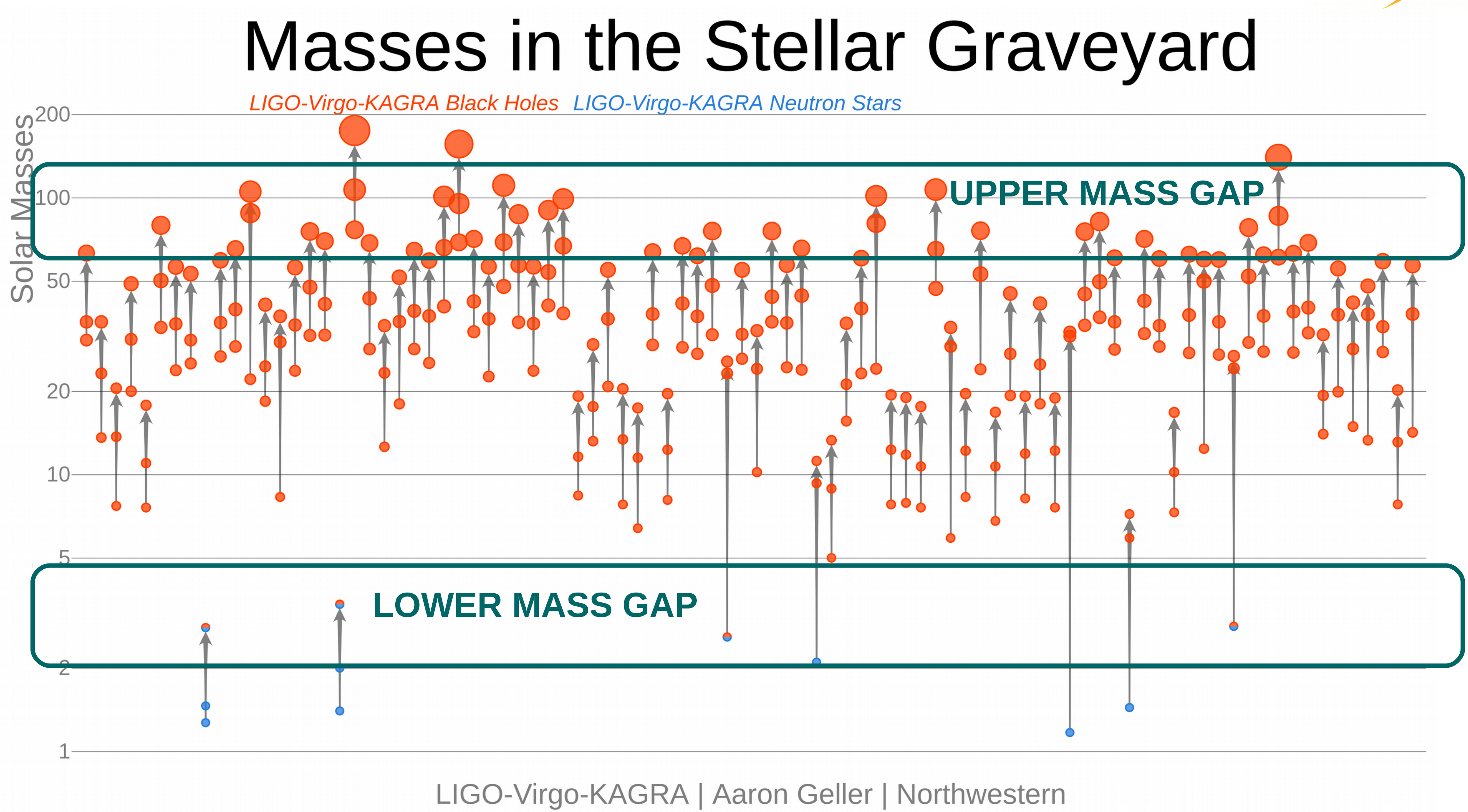
4. Merger rate evolution and future perspectives

1. Lessons learned from GW detections: masses



Abbott et al. 2022, GWTC-3

1. Lessons learned from GW detections: masses



Abbott et al. 2022, GWTC-3

Open questions from GWs

1. What determines BBH MASS and SPIN?
2. Are there any MASS GAPS at all?
3. What are the formation channels of BBHs?

2. The mass of black holes: what determines the mass of black holes?

MASSIVE STARS lose mass by stellar WINDS

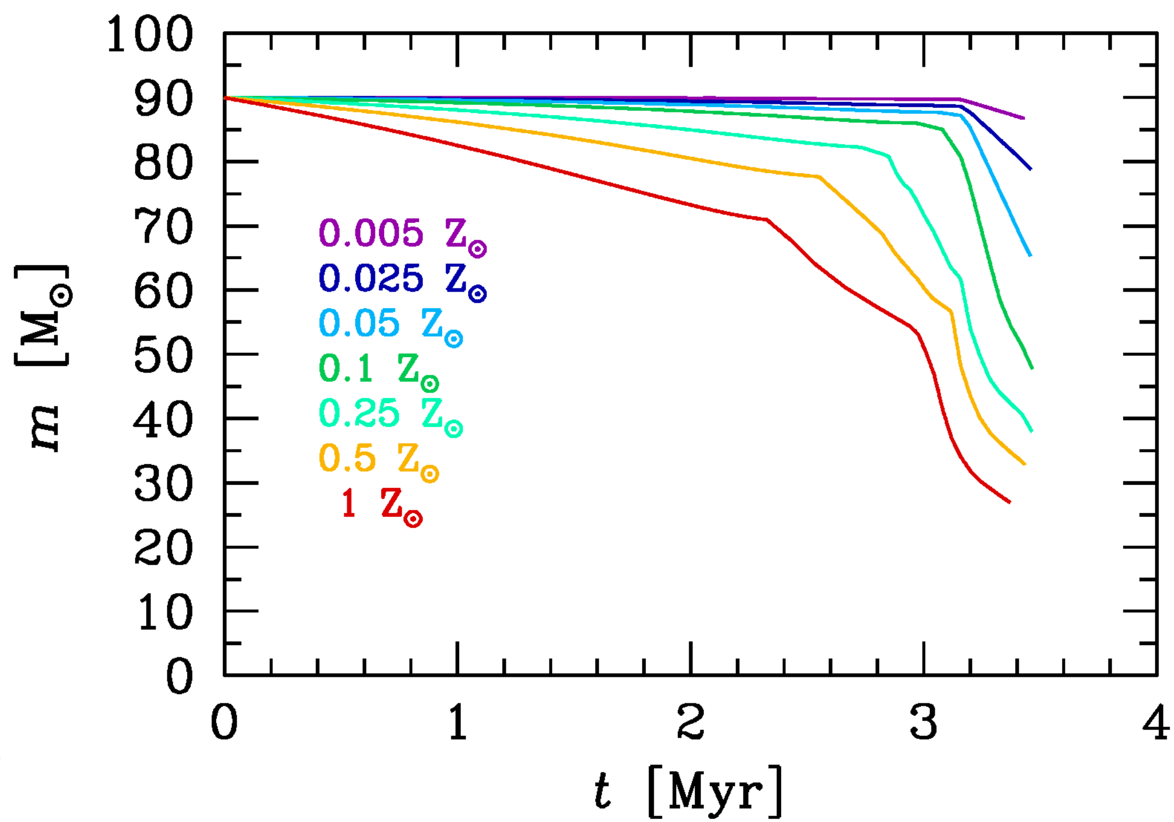
Stellar winds depend on metallicity & stellar luminosity
(e.g. Vink et al. 2001; Graefener & Hamann 2008; Vink et al. 2011)

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

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

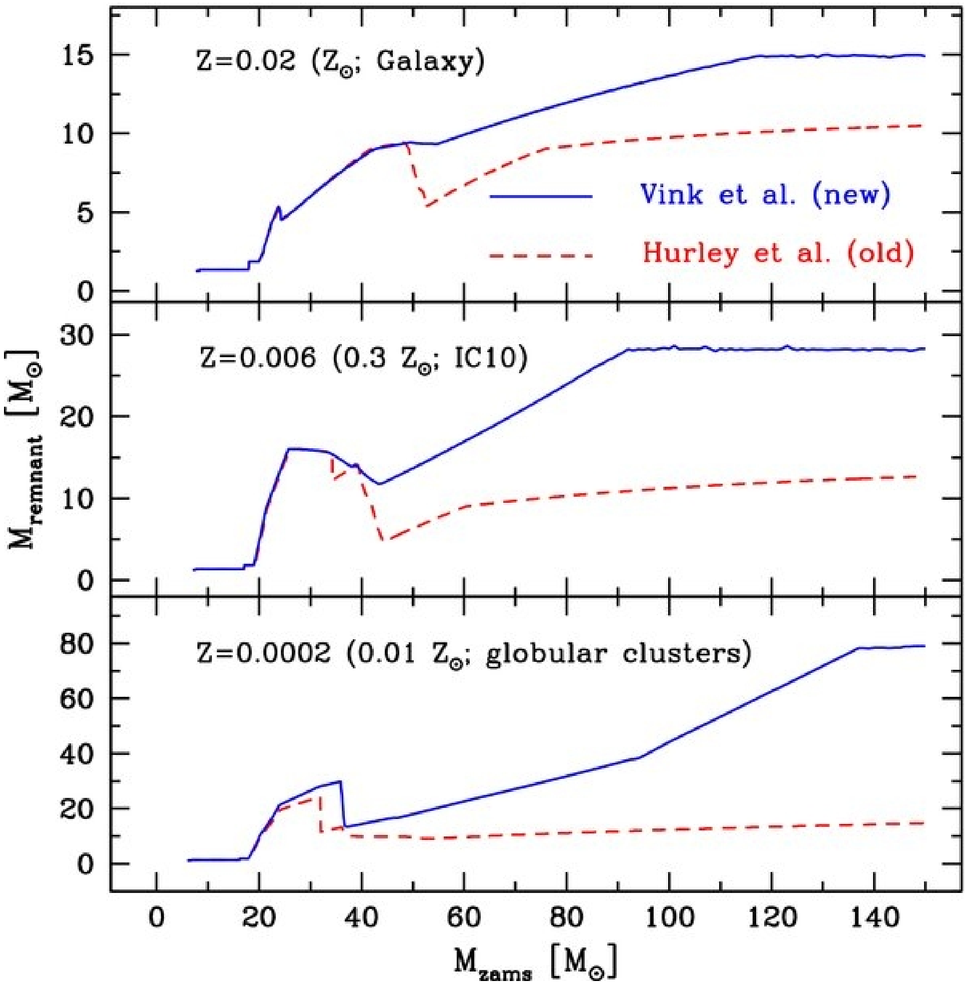
$$\Gamma = \frac{L_*}{L_{\rm Edd}}$$

Chen, Bressan et al. (2015)

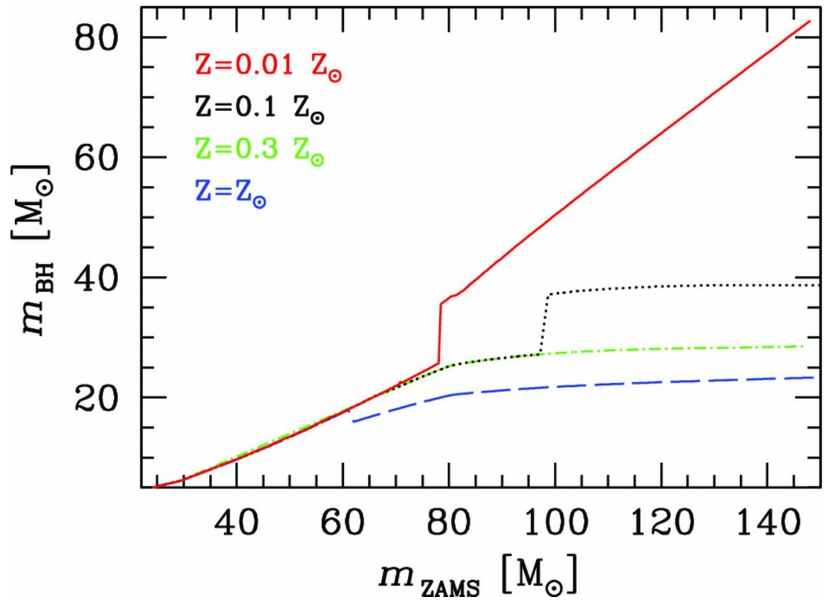


Massive metal-poor stars end their life with higher mass than metal-rich ones

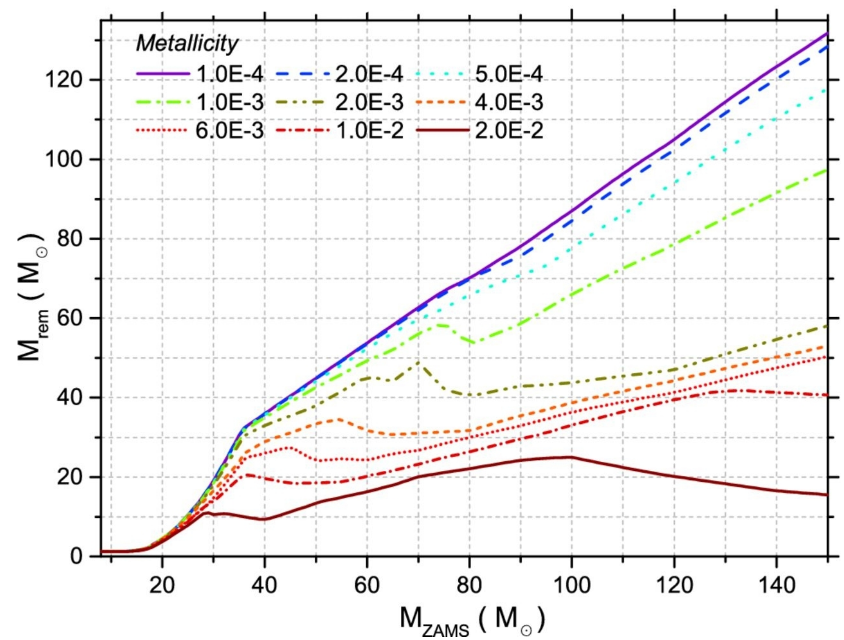
2. The mass of black holes: what determines the mass of black holes?



Belczynski et al. 2010; Fryer et al. 2012



MM et al. 2009, 2010, 2013



Spera, MM & Bressan 2015

LOWER METALLICITY
HIGHER MAXIMUM BLACK HOLE MASS

2. The mass of black holes: pair instability

$$\Gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$

Very massive metal poor stars efficiently produce gamma-ray (~1 MeV) photons
at the end of carbon burning

Leading to formation of **electron-positron pairs**

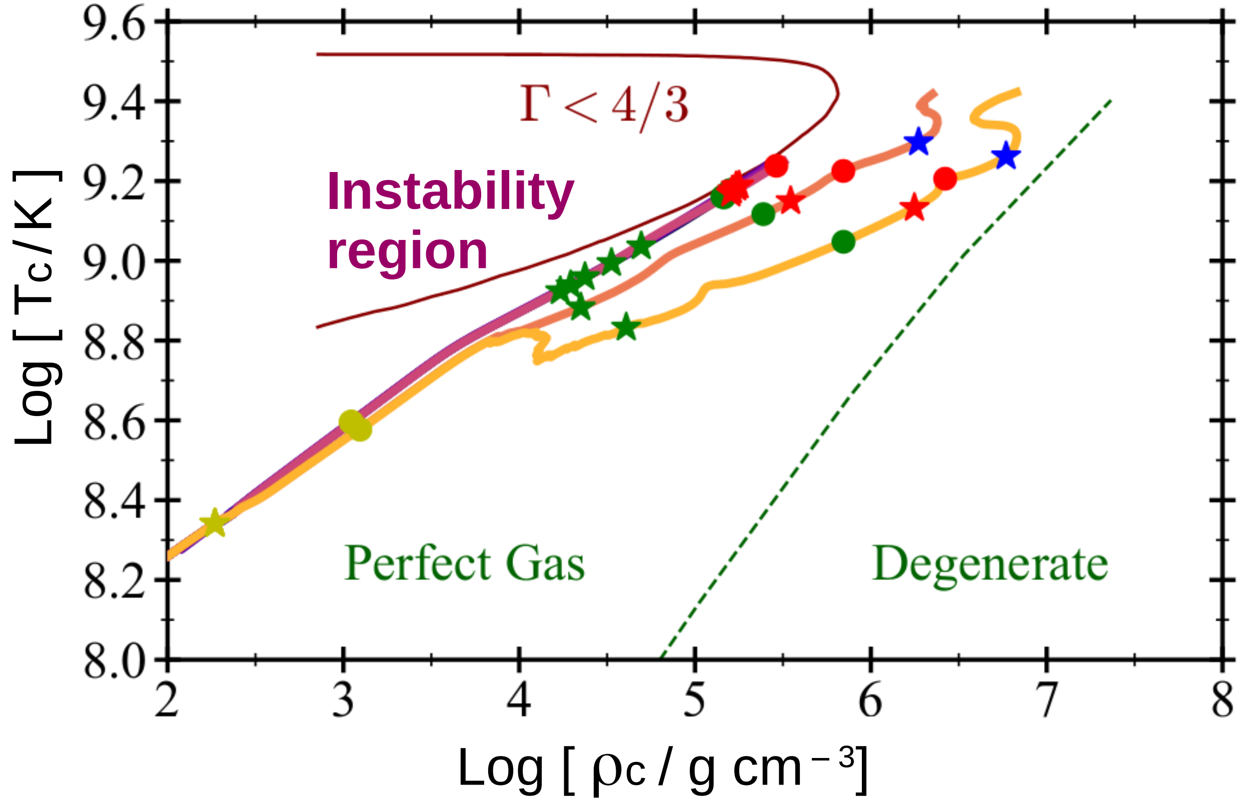
Missing photon pressure triggers instability:

PAIR INSTABILITY

* contraction of stellar core

* premature ignition of neon, oxygen, silicon

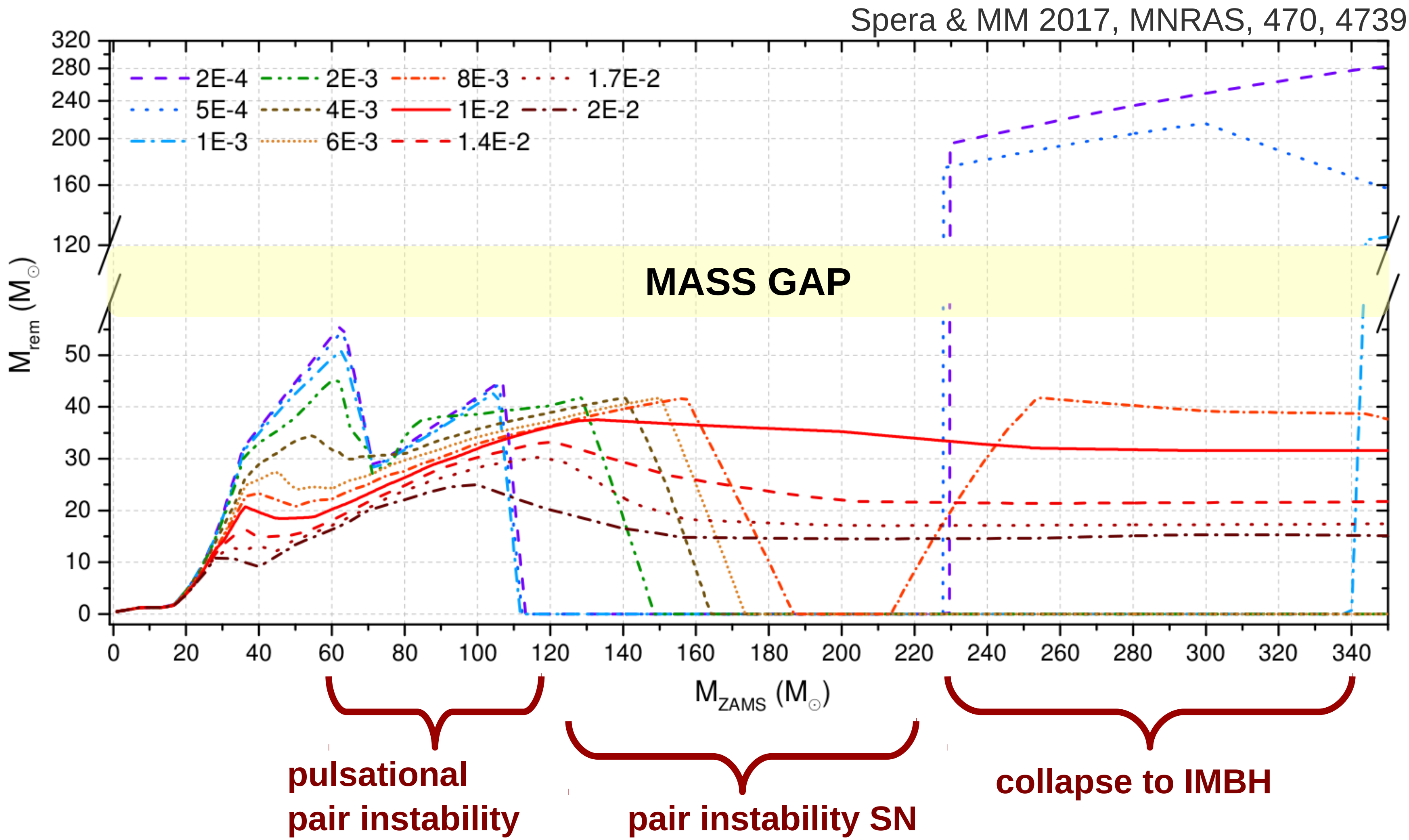
Costa et al. 2021, MNRAS, 501, 4514



Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

Fowler & Hoyle 1964, Barkat et al. 1967, Rakavy & Shaviv 1967, Ober et al. 1983, Bond et al. 1984, Woosley et al. 2002, Heger & Woosley 2002, Woosley et al. 2007, Yoshida et al. 2016, Belczynski et al. 2016, Woosley 2017, 2019, Marchant et al. 2018, 2019, Stevenson et al. 2019

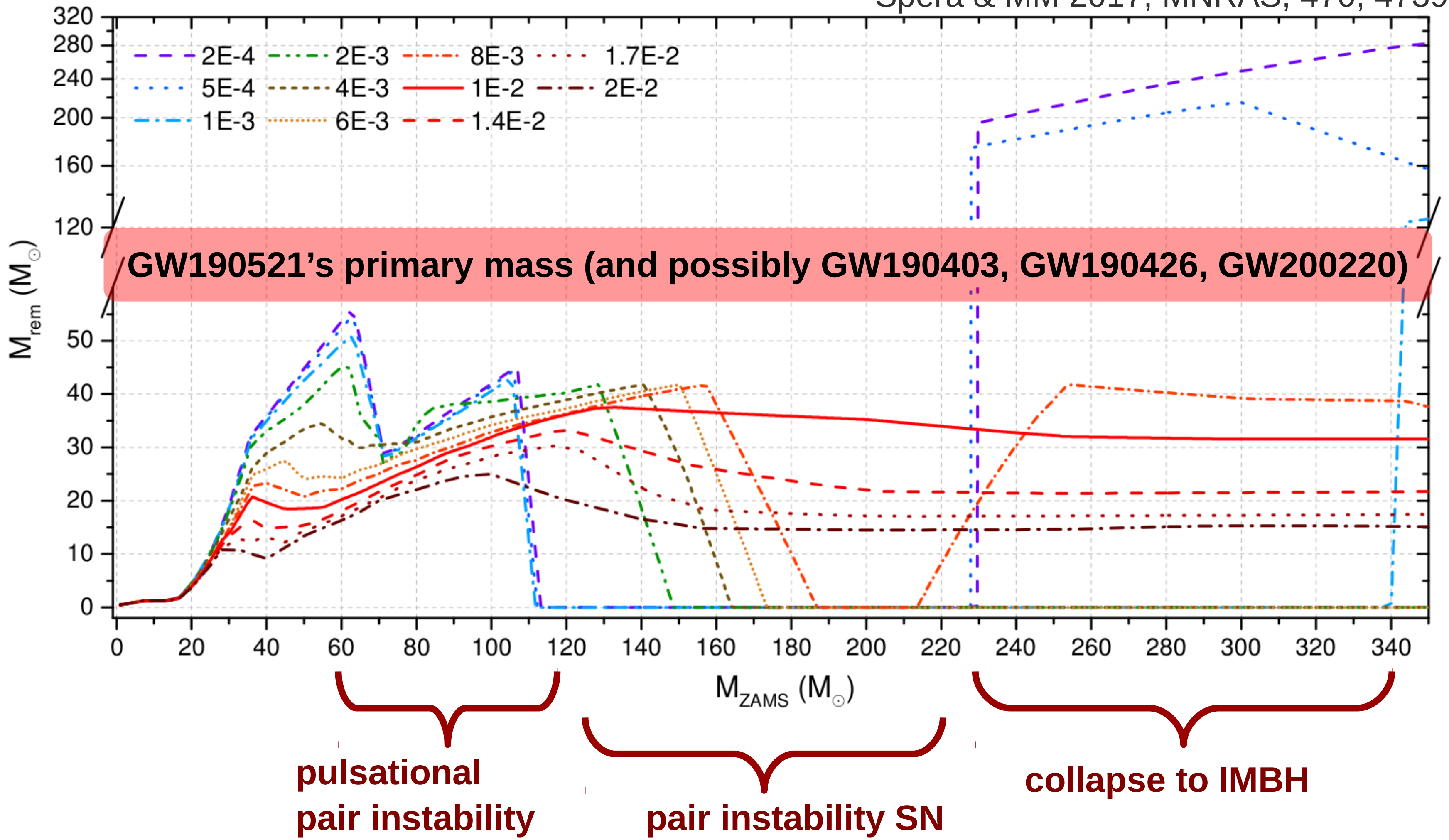
2. The mass of black holes: pair instability



Takahashi 2018; Leung et al. 2018; Farmer et al. 2019, 2020; MM et al. 2020; Marchant et al. 2019, 2020; Tanikawa et al. 2020; Farrell et al. 2020; Renzo et al. 2020; van Son et al. 2020; Liu & Bromm 2020; Safarzadeh & Haiman 2020; Belczynski 2020; Kinugawa et al. 2020; Umeda et al. 2020; Woosley & Heger 2021; Vink et al. 2021; Costa et al. 2021

2. The mass of black holes: pair instability

Spera & MM 2017, MNRAS, 470, 4739



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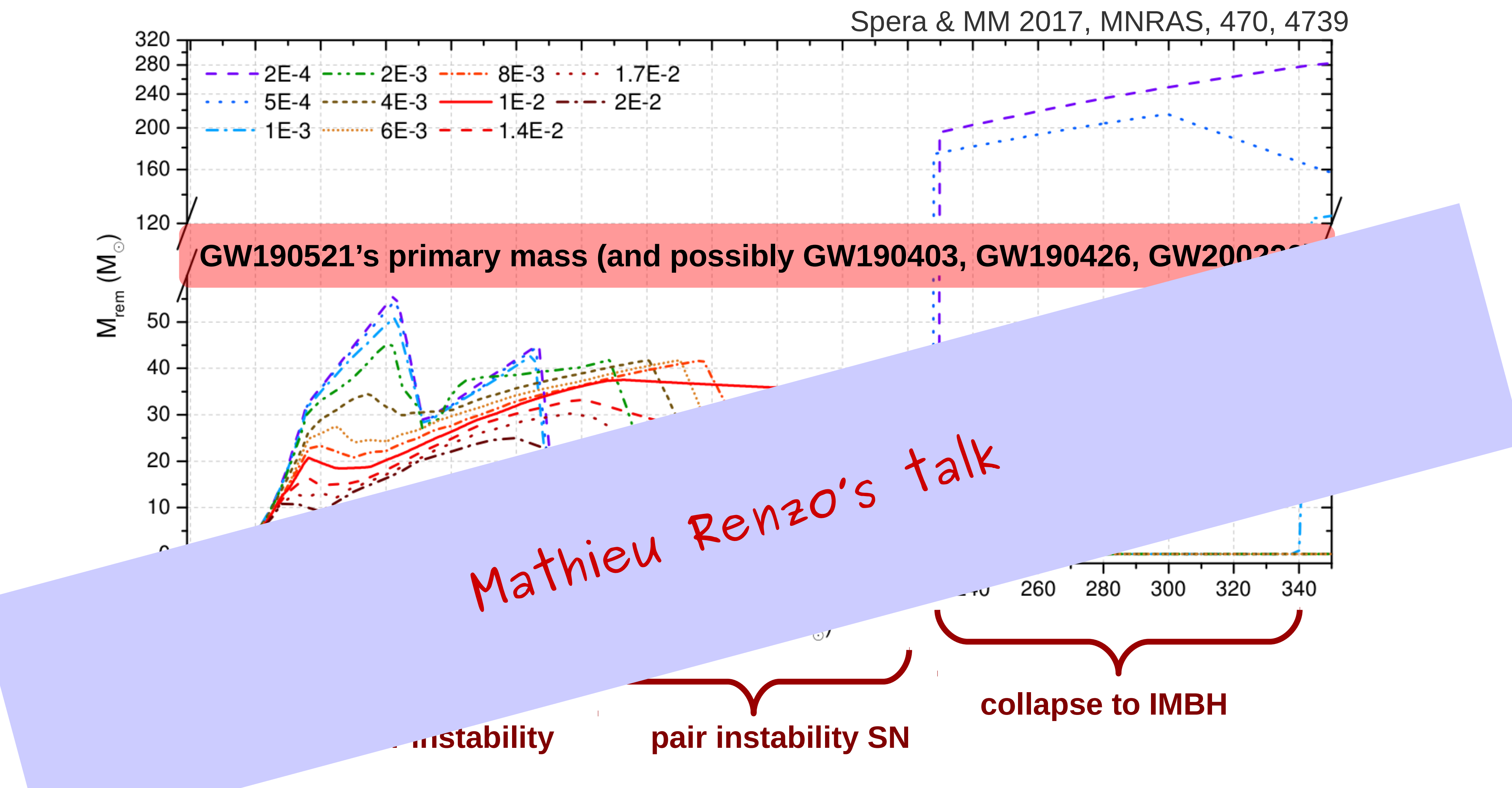

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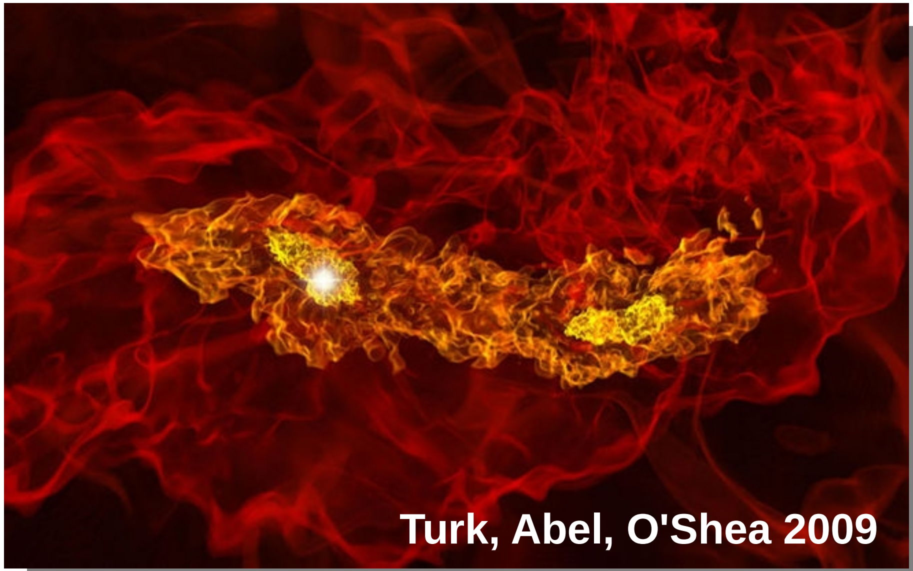
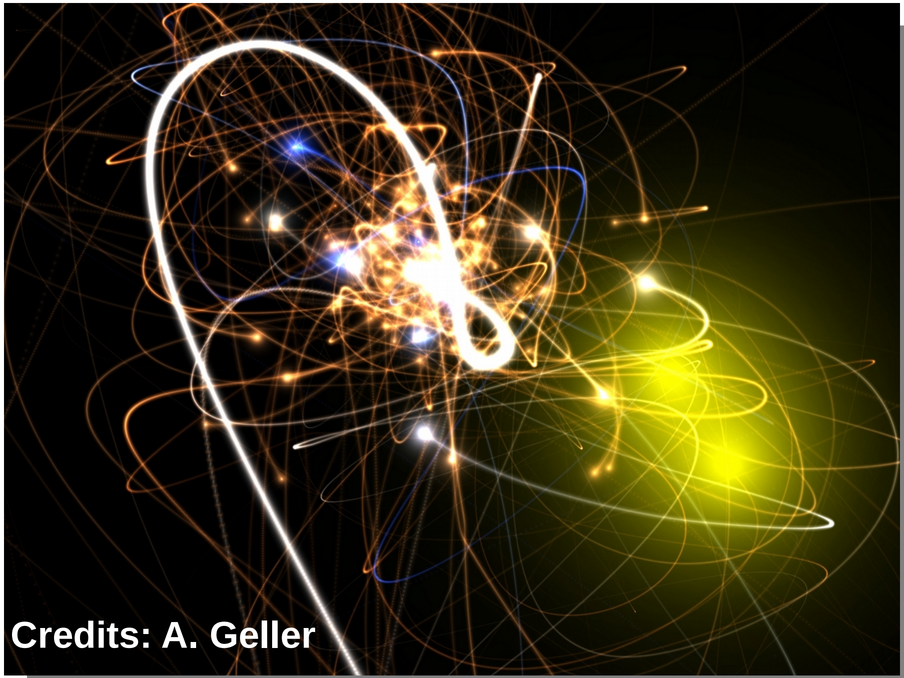
3. Formation channels of BBHs

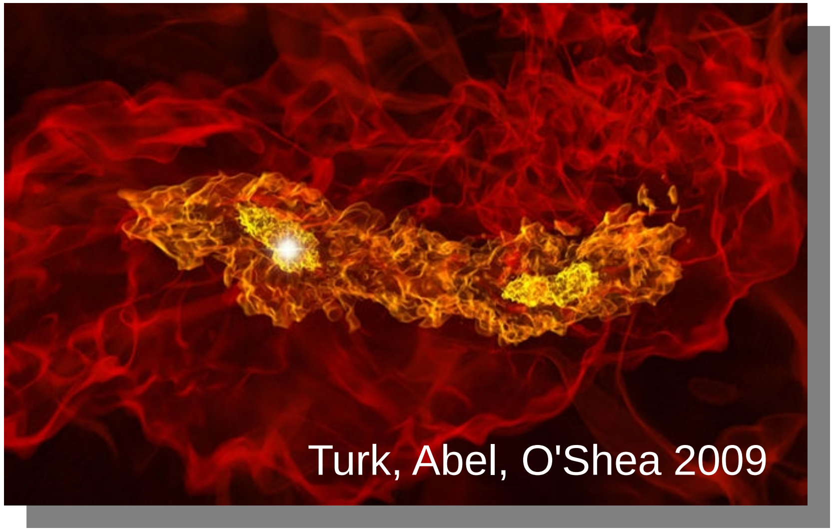
ISOLATED BINARIES:
two stars form from same cloud
and evolve into two black holes
gravitationally bound


Turk, Abel, O'Shea 2009


Credits: A. Geller

DYNAMICAL BINARIES:
Binary black holes
form and/or evolve
by dynamical processes
in star clusters

3. Formation channels of BBHs

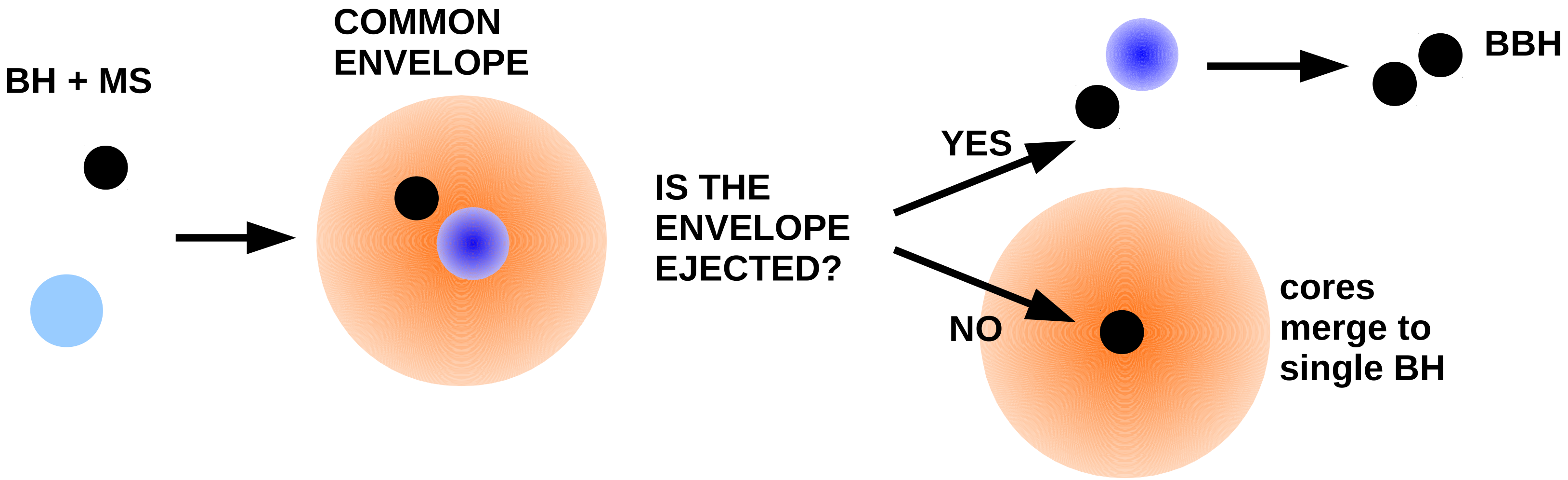


ISOLATED BINARIES:

Two stars form from same cloud and form a BBH

Massive stars form preferentially in binary – multiple systems (Sana et al. 2012; Moe & Di Stefano 2017)

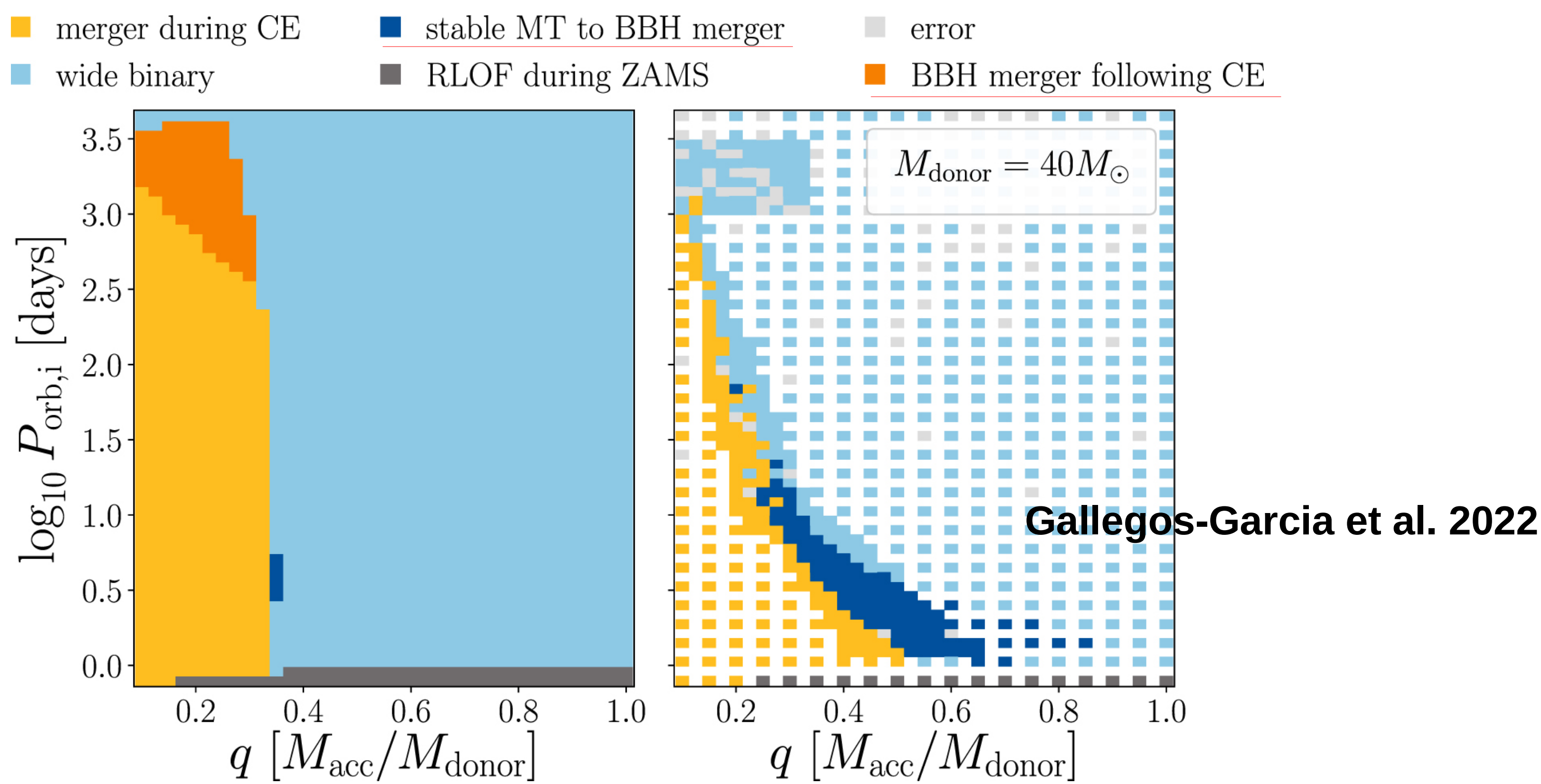
Many evolutionary processes affect a tight binary e.g. stable and unstable mass transfer (common envelope)



REVIEW: IVANOVA ET AL. 2013, A&ARv, 21, 59

3. Formation channels of BBHs: common envelope vs stable MT

Is common envelope really part of the game?



Population synthesis (COSMIC):
most BBHs from common envelope

Stellar structure integration (MESA):
most BBHs from stable mass transfer (no common envelope)

Ge et al. 2015; Giacobbo et al. 2018; Neijssel et al. 2019; Olejak et al. 2021; Marchant et al. 2021; Shao & Li 2021; van Son et al. 2021

3. Formation channels of BBHs: dynamics

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

i.e. only in dense star clusters (Dorota Rosinska's talk)

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

R136, credit: NASA

Young star clusters

47 Tucanae, credit: NASA/ESA/HST

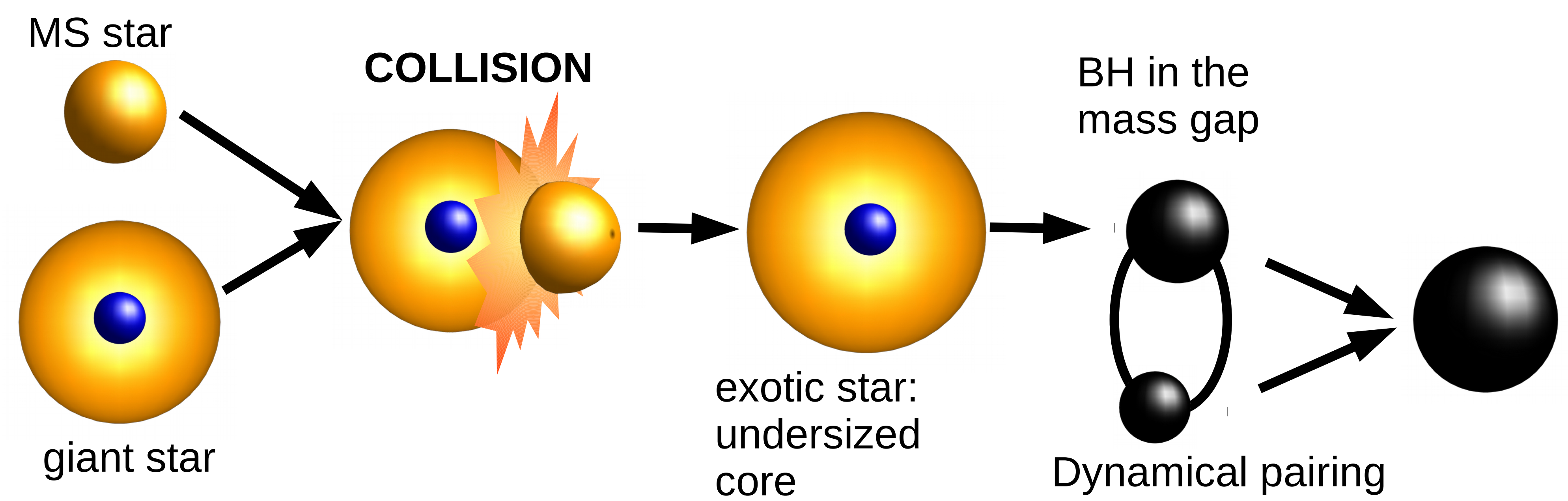
Globular clusters

Nuclear star clusters

Credit: ESO, Gillessen et al.

3. Formation channels of BBHs: star – star collisions

Star – star collision scenario for mass-gap BHs



Core mass determines central T and ρ

The exotic star avoids pair instability if collapses to BH before substantial core growth

Di Carlo et al. 2019, MNRAS 487, 4947
Di Carlo et al. 2020a, MNRAS, 497, 1043

3. Formation channels of BBHs: star – star collisions

Isolated binary black holes (BBHs) only up to total mass $m_1+m_2 \sim 80\ M_\odot$

Dynamical BBHs with total mass $m_1+m_2 > 80\ M_\odot$

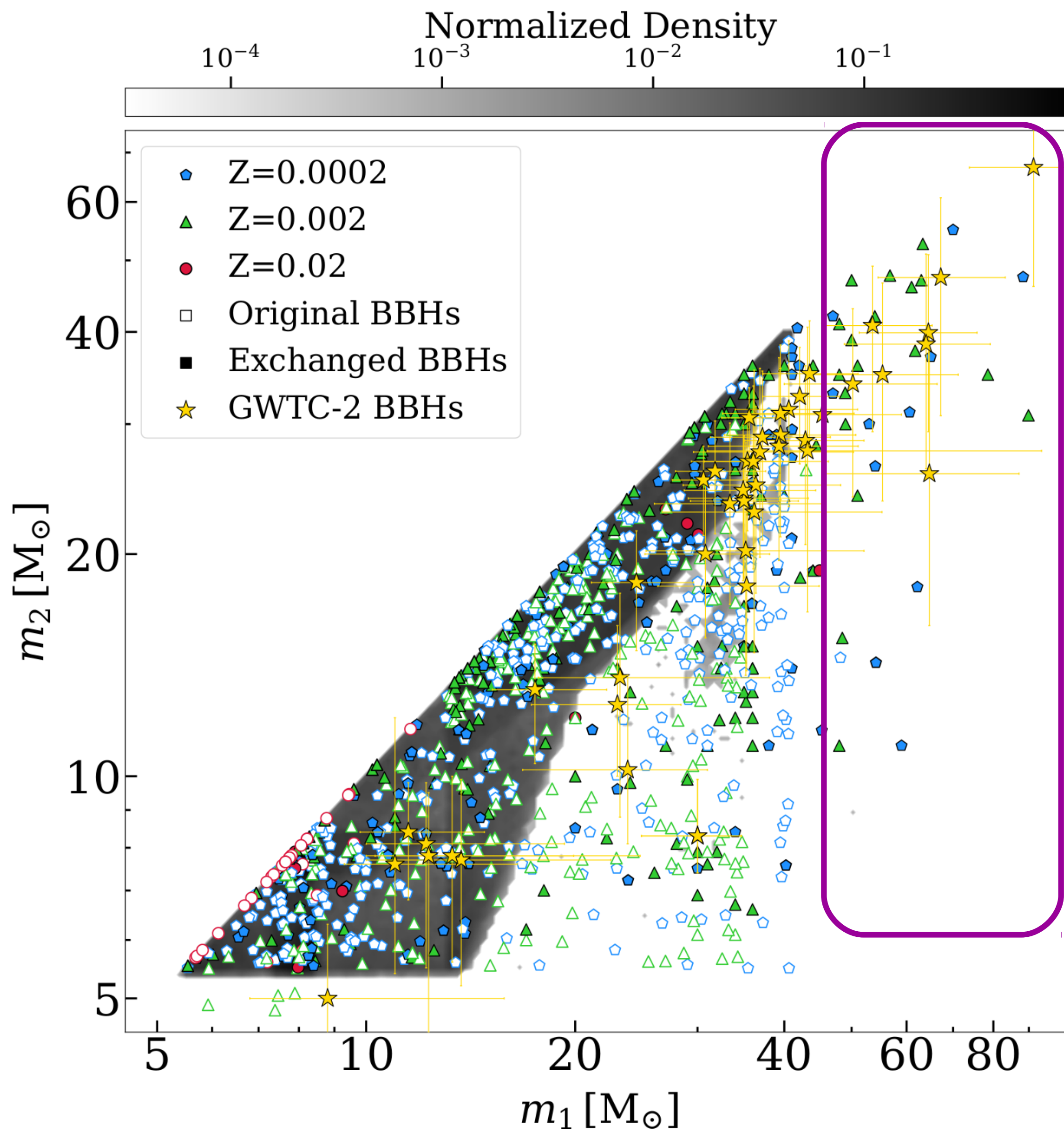
~ 1 % BBH mergers with mass in the pair instability mass gap, corresponding to

~ 5% of detectable events

Direct N-body simulations with population synthesis by

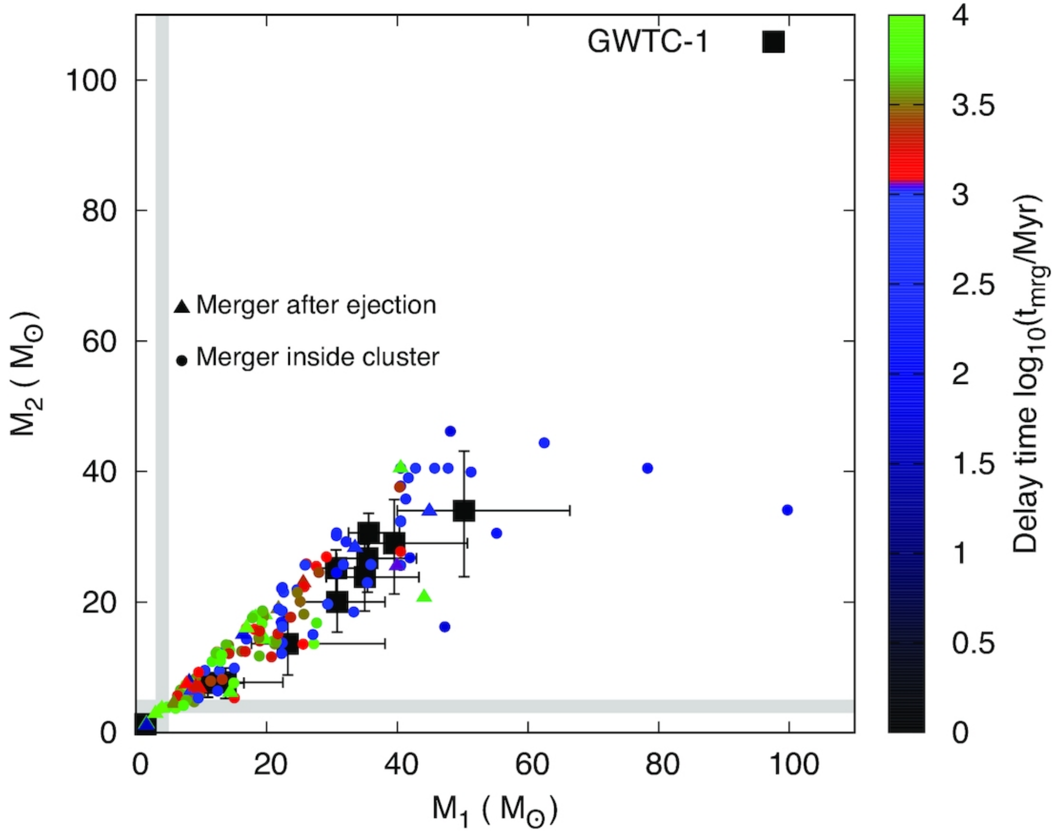
Di Carlo et al. 2019, MNRAS 487, 4947

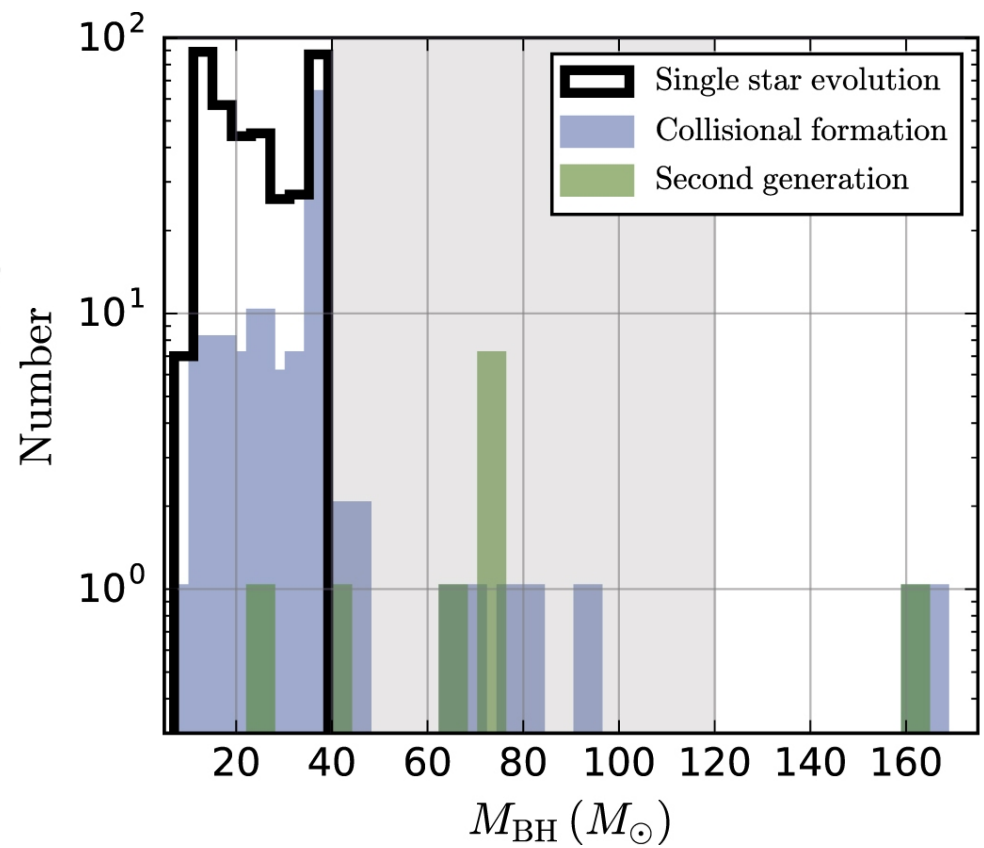
Rastello et al. 2021, MNRAS, 507, 3612



3. Formation channels of BBHs: star – star collisions

More massive YSCs



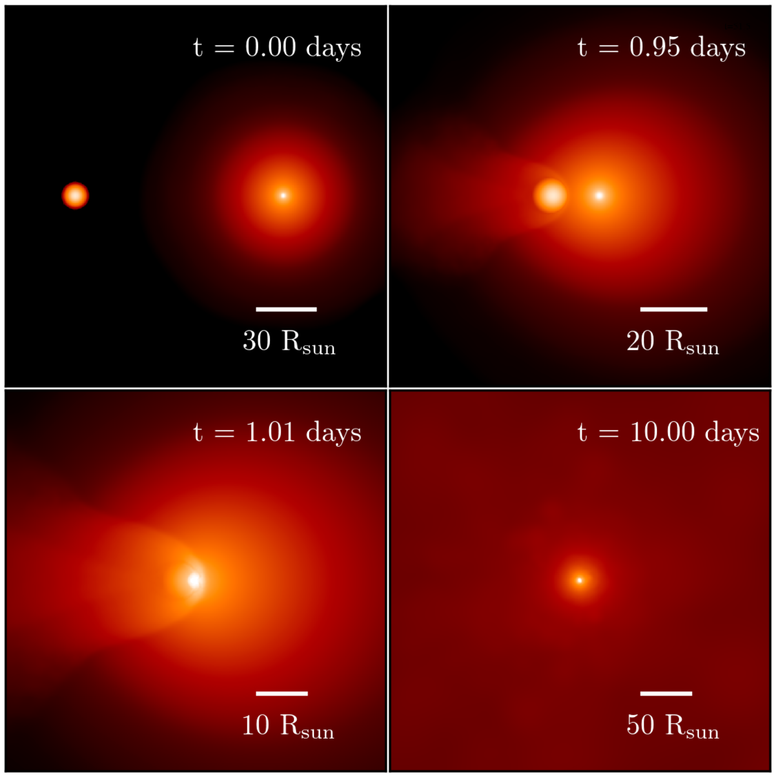


Banerjee, 2021, MNRAS, 500, 3002

Kremer et al. 2020, ApJ, 903

3. Formation channels of BBHs: star – star collisions

Mass loss during collision? → needs hydro-dynamical simulations of the collision

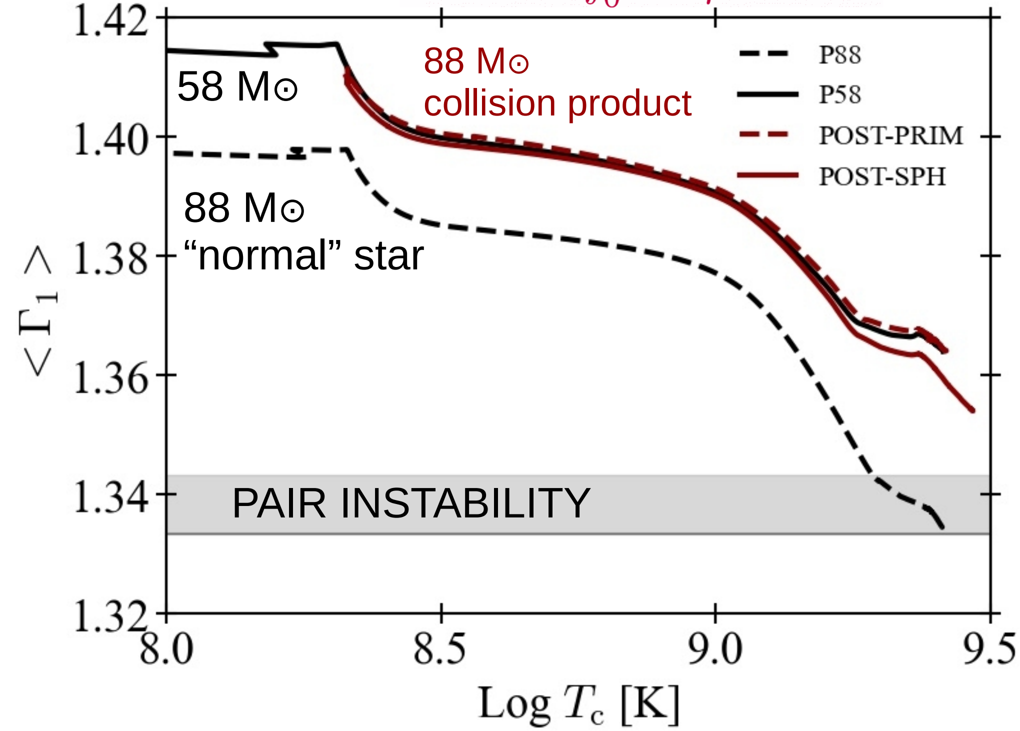


Max 12% mass loss during head-on star – star collision

Chemical composition significantly mixed

Ballone et al. 2022, arXiv:2204.03493

$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{ad} \qquad \langle \Gamma_1 \rangle = \frac{\int_0^M \Gamma_1 \, P \, \rho^{-1} \, dm}{\int_0^M P \, \rho^{-1} \, dm}$$

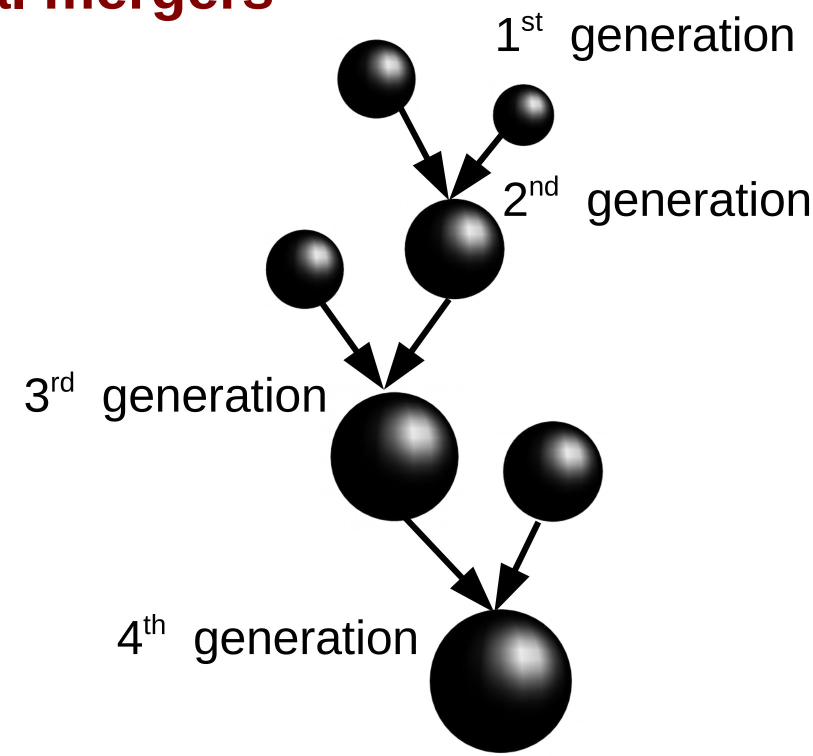


A normal 88 M⊙ star undergoes pair instability

The collision product avoids pair instability (like a 58 M⊙ star)

Costa et al. 2022, arXiv:2204.03492
Renzo et al. 2020, ApJ, 904, L13

3. Formation channels of BBHs: hierarchical mergers



Possible only in star clusters: the merger remnant can pair up by dynamical exchange
(e.g. Miller & Hamilton 2002)

RELATIVISTIC KICK up to few x 1000 km/s
(e.g. Campanelli et al. 2007)
→ the merger product might be ejected

R136, credits: NASA

Young star clusters:
Escape velocity:
few km/s

47 Tucanae, credits: NASA/ESA/HST

Globular clusters:
Escape velocity:
few ten km/s

Credits: ESO, Gillessen et al.

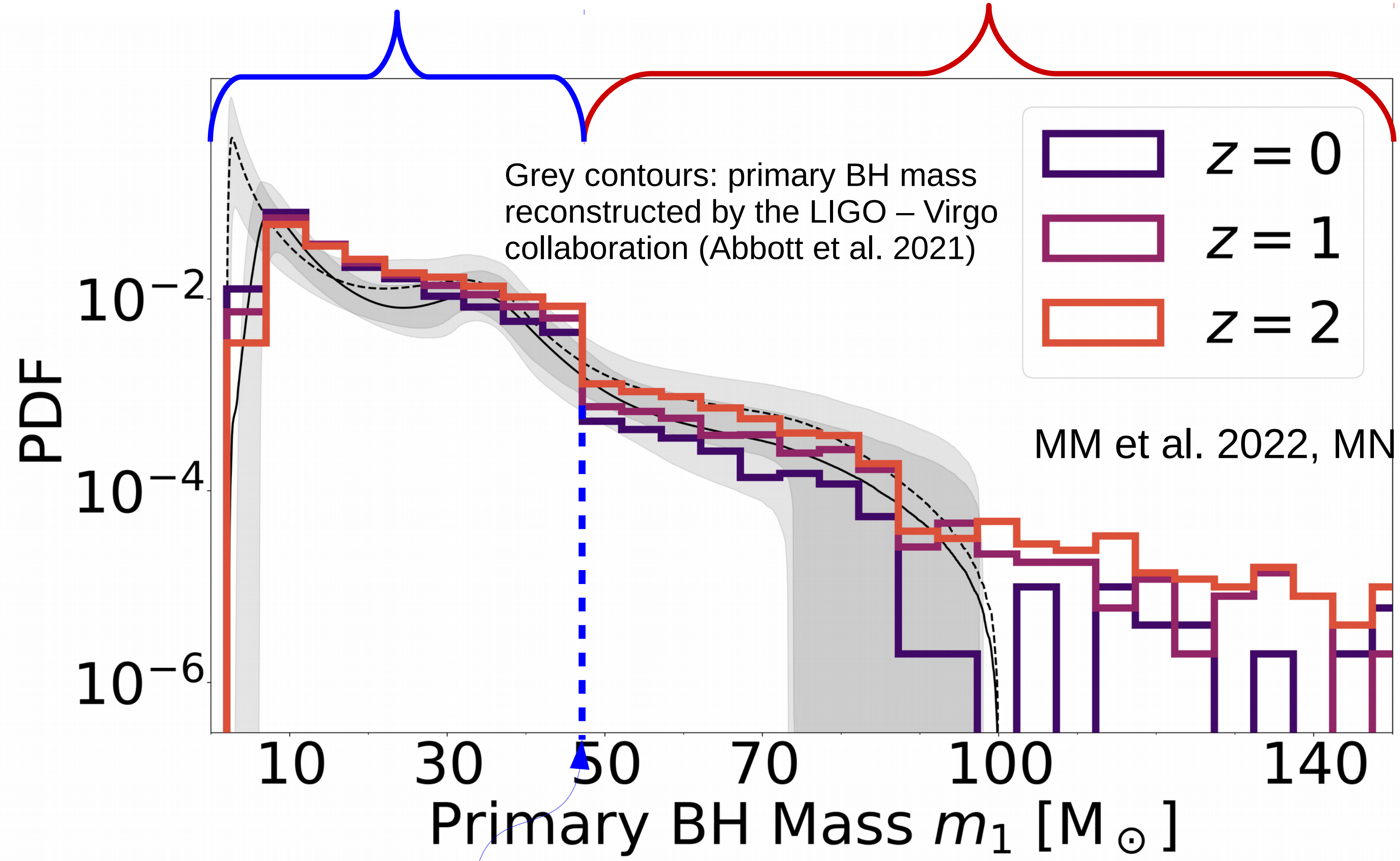
Nuclear clusters:
Escape velocity:
~ hundred km/s

Miller & Hamilton 2002
Gerosa & Berti 2017
Rodriguez et al. 2019
Antonini et al. 2019

What kind of BHs do we expect from hierarchical mergers?

3. Formation channels of BBHs: hierarchical mergers

Isolated binaries + **hierarchical mergers**



MM et al. 2022, MNRAS, 511,5797

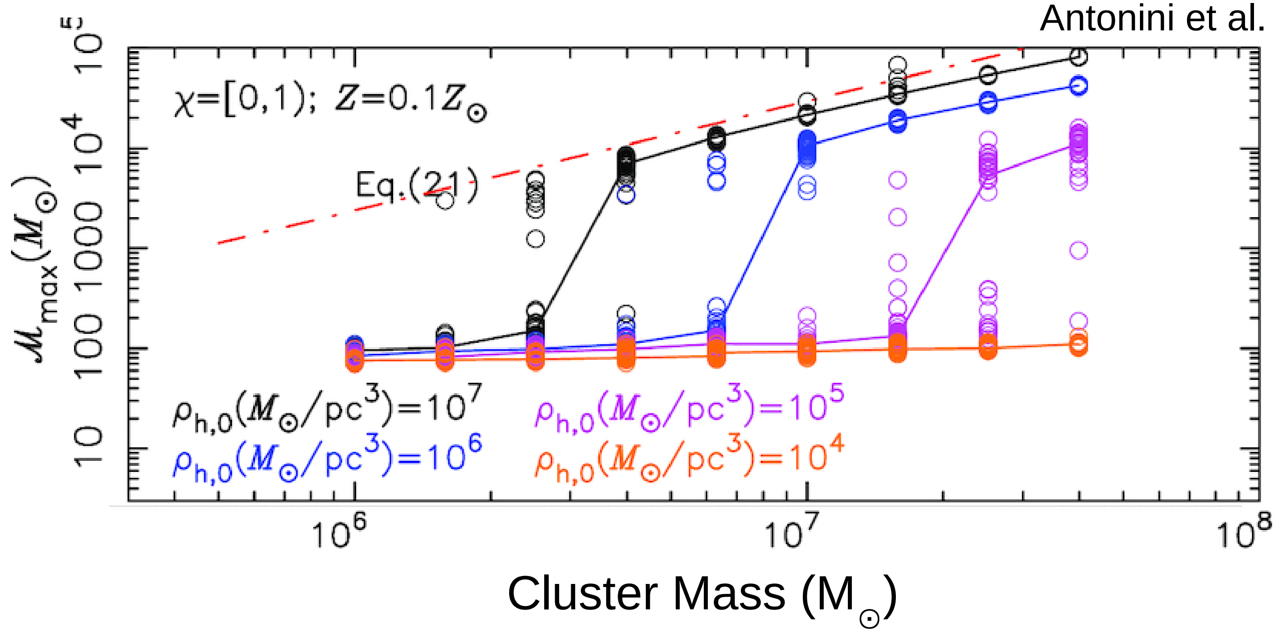
Max mass of first generation BHs in our input model

Hierarchical mergers essential to explain the most massive BHs observed

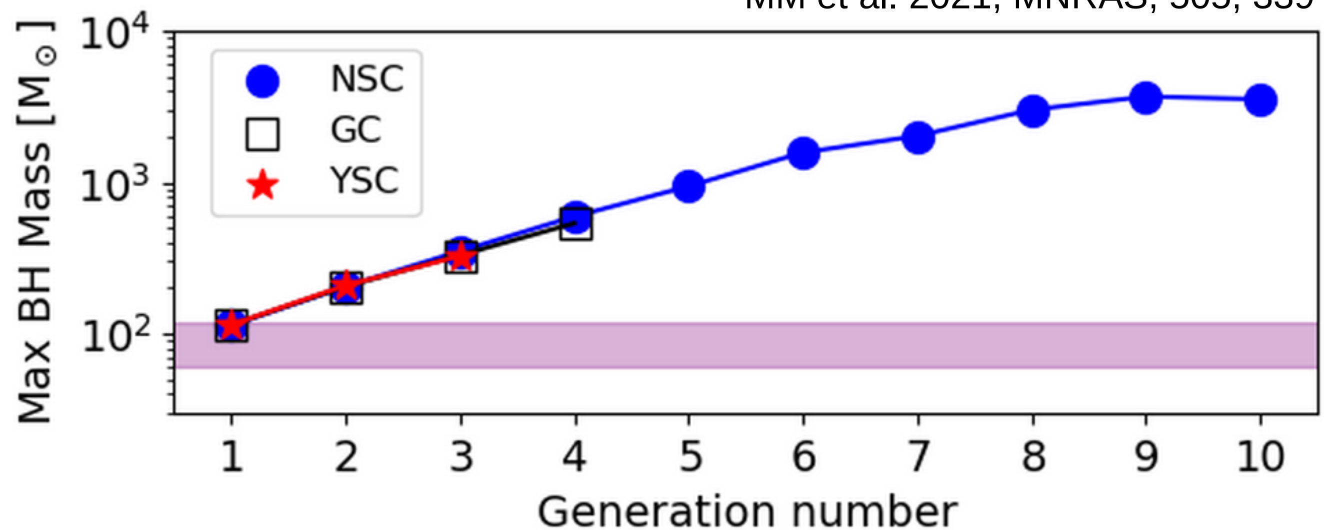
See also: Rodriguez et al. 2019; Arca Sedda et al. 2020; Fragione et al. 2020, 2021; MM et al. 2021; Gerosa et al. 2021; Rizzuto et al. 2021, 2022

3. Formation channels of BBHs: hierarchical mergers

Antonini et al. 2019, MNRAS, 486, 5008



MM et al. 2021, MNRAS, 505, 339

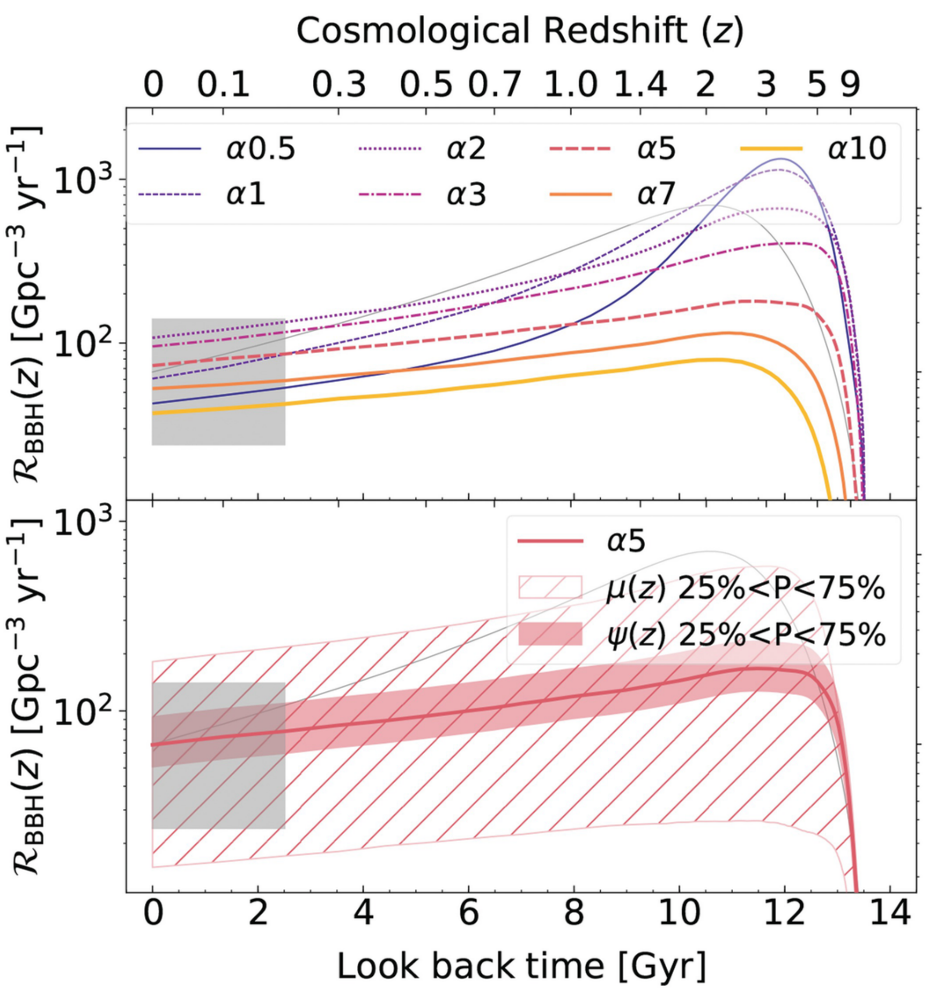


Hierarchical mergers lead to intermediate-mass black holes (IMBHs) in nuclear clusters

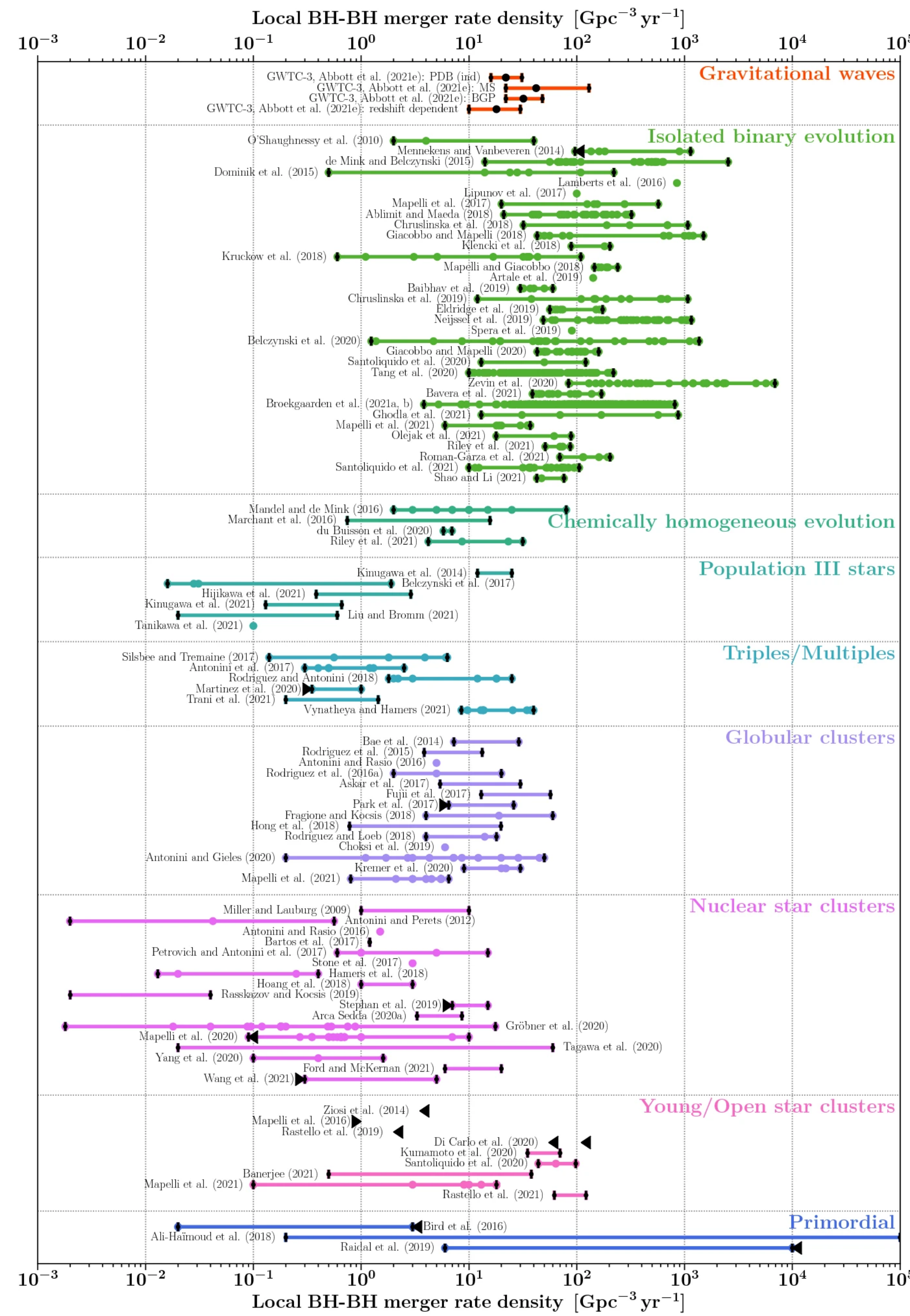
See also: Rodriguez et al. 2019; Arca Sedda et al. 2020; Fragione et al. 2020, 2021; MM et al. 2021; Gerosa et al. 2021; Rizzuto et al. 2021, 2022

4. Merger rate and cosmic evolution

Uncertainties on BBH merger rate evolution in **isolated binaries**



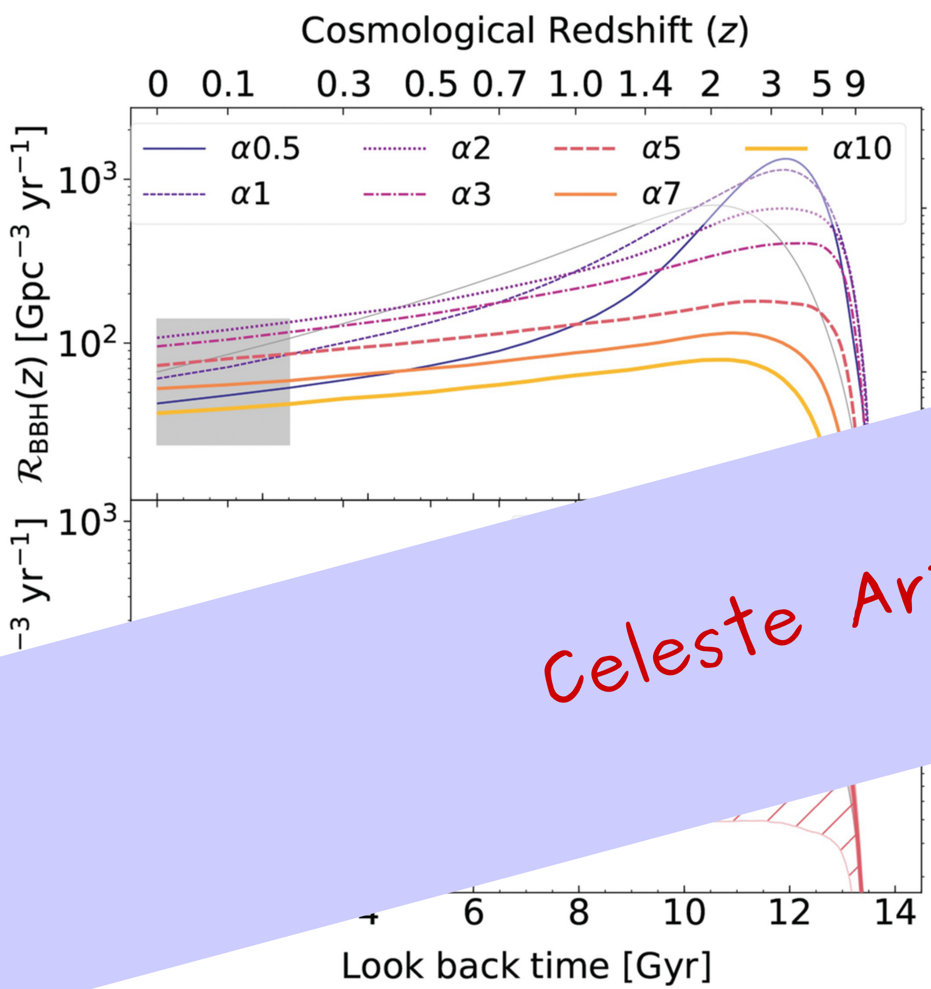
Santoliquido et al. 2021, MNRAS, 502, 4877
see also Broekgaarden et al. arXiv:2112.05763



Mandel & Broekgaarden 2022, LRR, 25, 1

4. Merger rate and cosmic evolution

Uncertainties on BBH merger rate evolution in **isolated binaries**



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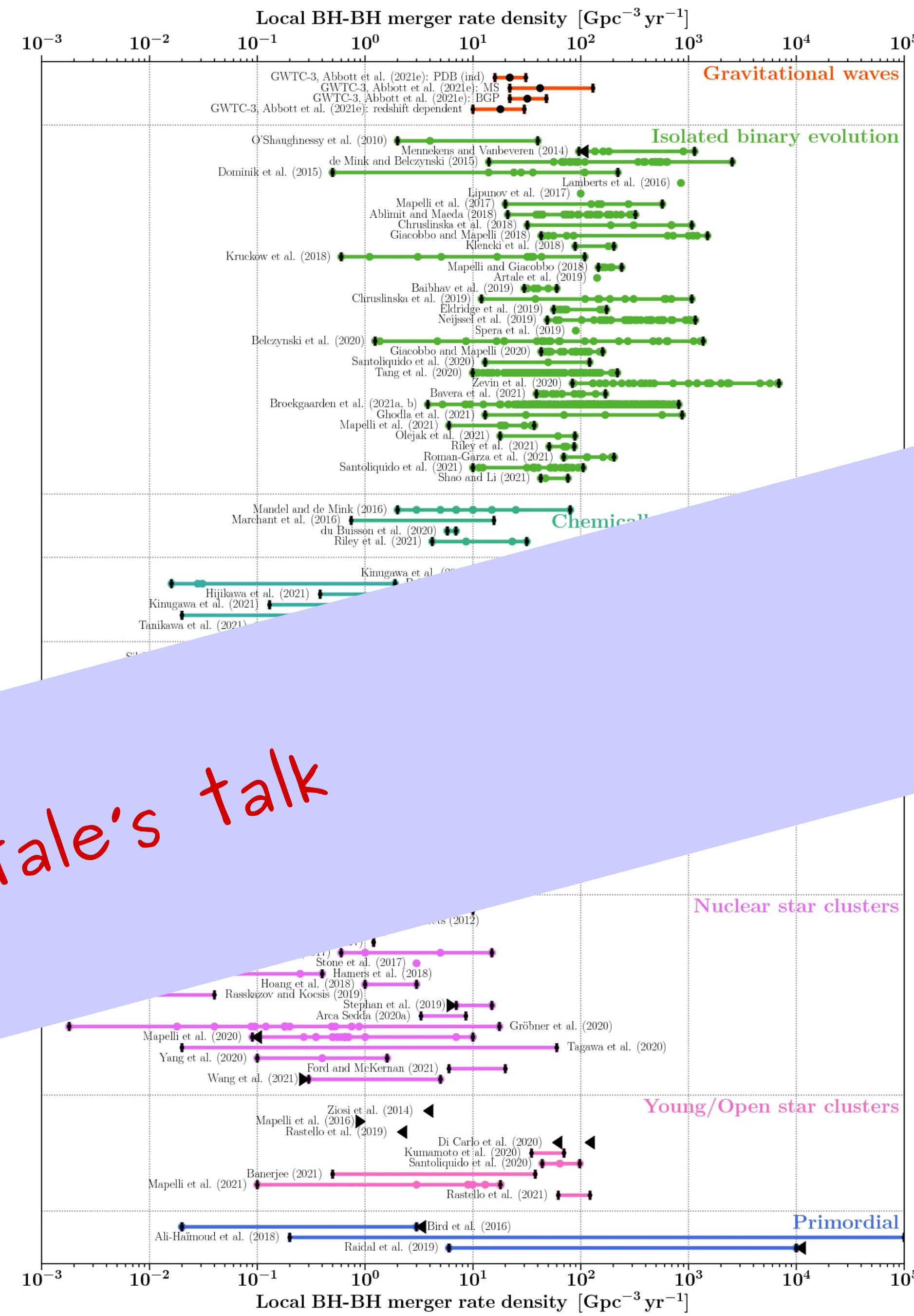
see also Broekgaarden et al. arXiv:2112.05763



Celeste Artale's talk

Mandel & Broekgaarden 2022, LRR, 25, 1

4. Conclusions

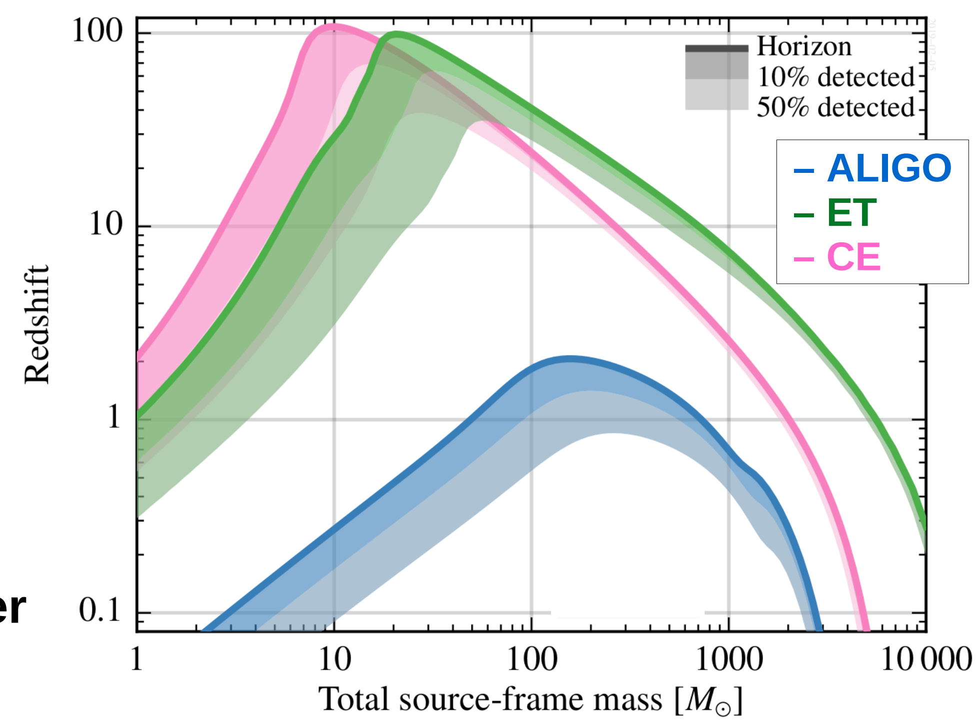
* LIGO and Virgo open new perspectives on the study of binary black holes

* Pair instability opens a mass gap in the BH mass spectrum ~60 – 120 $M_\odot$

* Isolated BBH mergers only up
to total mass ~ 80 $M_\odot$

* Dynamics leads to more massive BBHs
and isotropic spins:
events in the pair-instability gap
from star – star collisions and
hierarchical mergers

*** The future is loud:**
Einstein Telescope and Cosmic Explorer
will observe black hole mergers
up to redshift 20 or more



THANK YOU