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Stellar-born black holes
across the cosmic time

Main collaborators:

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NEHOP, Napoli, June 20th 2023

OUTLINE:

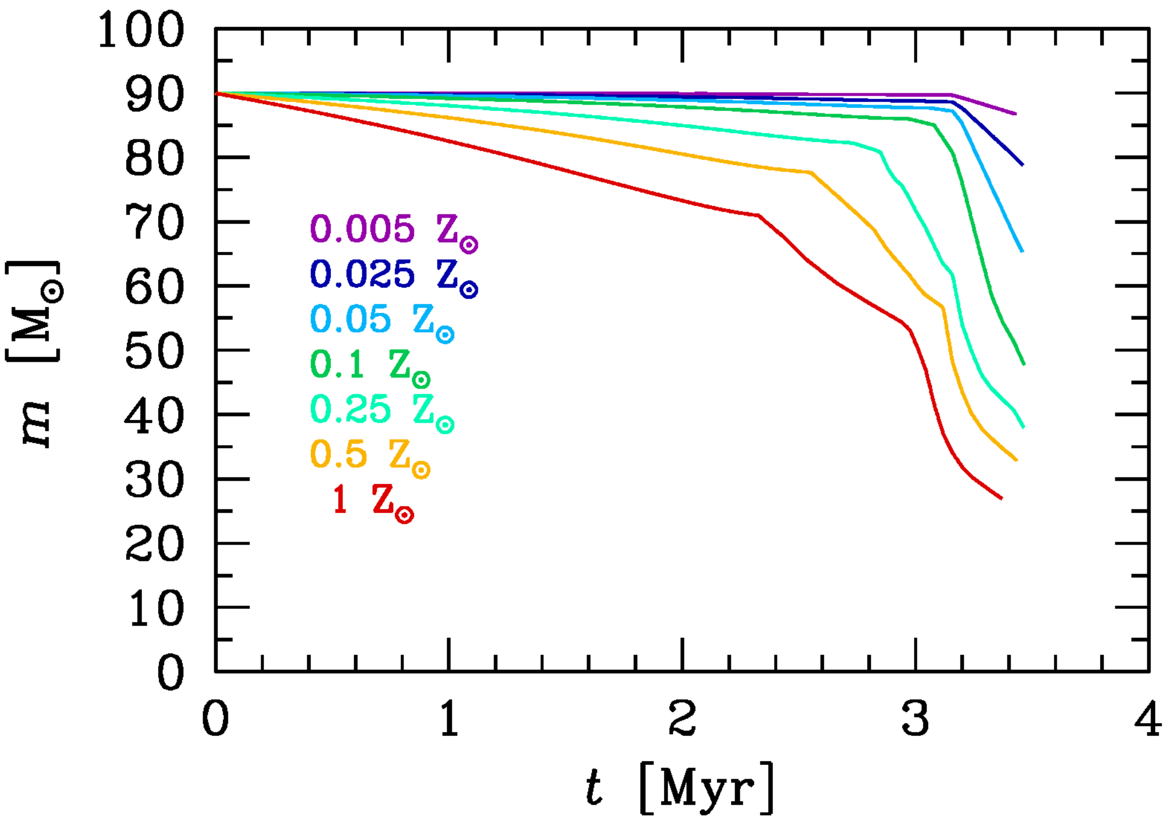
1. Binary black holes from stellar evolution
2. Binary black holes from dynamics
3. Binary black holes from Pop III stars & the Einstein Telescope
4. Conclusions

1. Binary black holes (BBHs) from stellar evolution

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)



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

1. Binary black holes (BBHs) from stellar evolution

CORE – COLLAPSE SUPERNOVA (CC SN) / DIRECT COLLAPSE:

**Fundamental question:
does the star explode as
CC SN?**

YES:
Neutron star (NS) or
low-mass black hole (BH)

NO:
Direct collapse to
black hole (BH)
BH can be MASSIVE

**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)

1. Binary black holes (BBHs) from stellar evolution

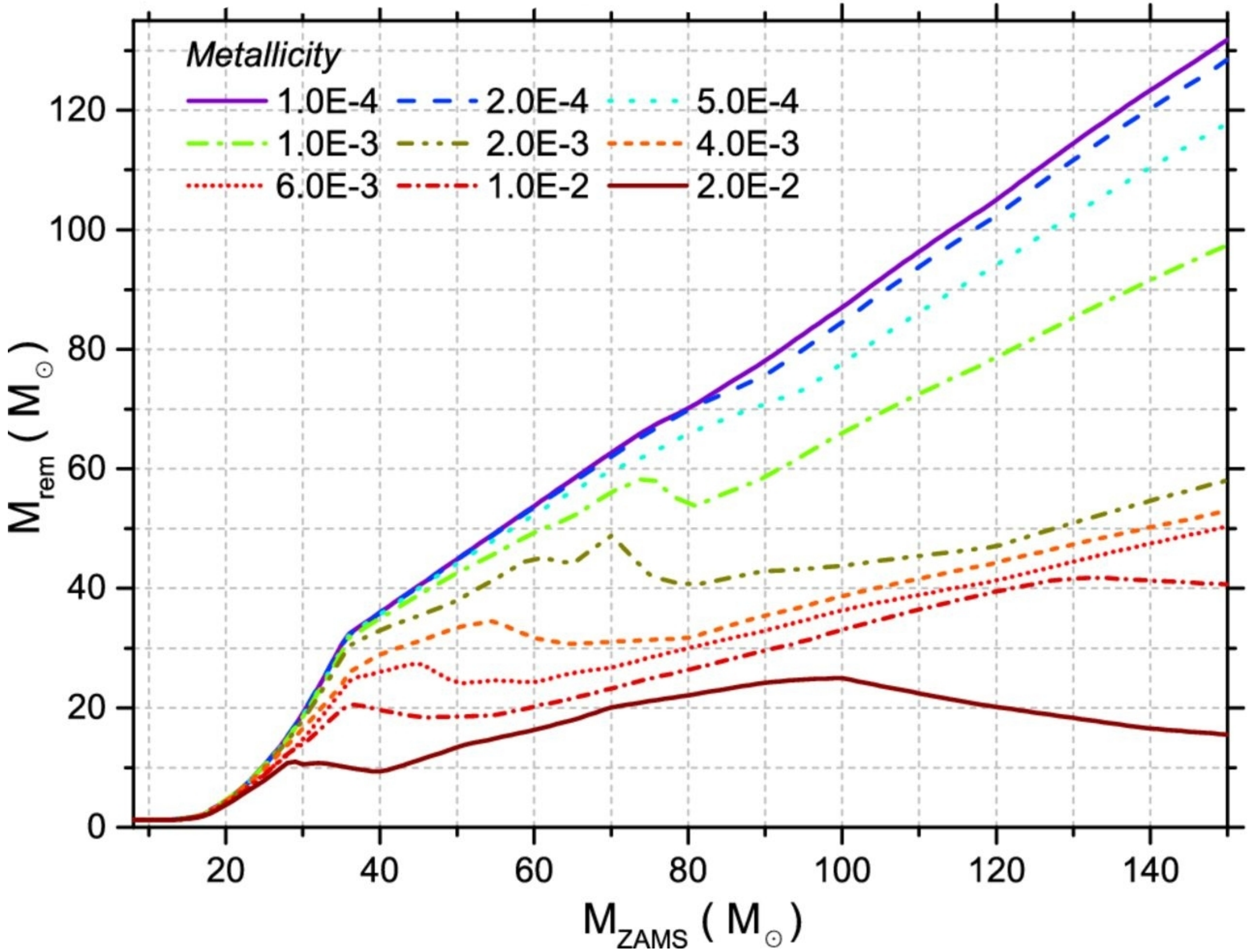


Figure from Spera, MM & Bressan 2015
see also Heger et al. 2003;
MM et al. 2009, 2010, 2013;
Belczynski et al. 2010; Fryer et al. 2012

version by Abbott et al. 2016, ApJ, 818, L22

1. Binary black holes (BBHs) from stellar evolution

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

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

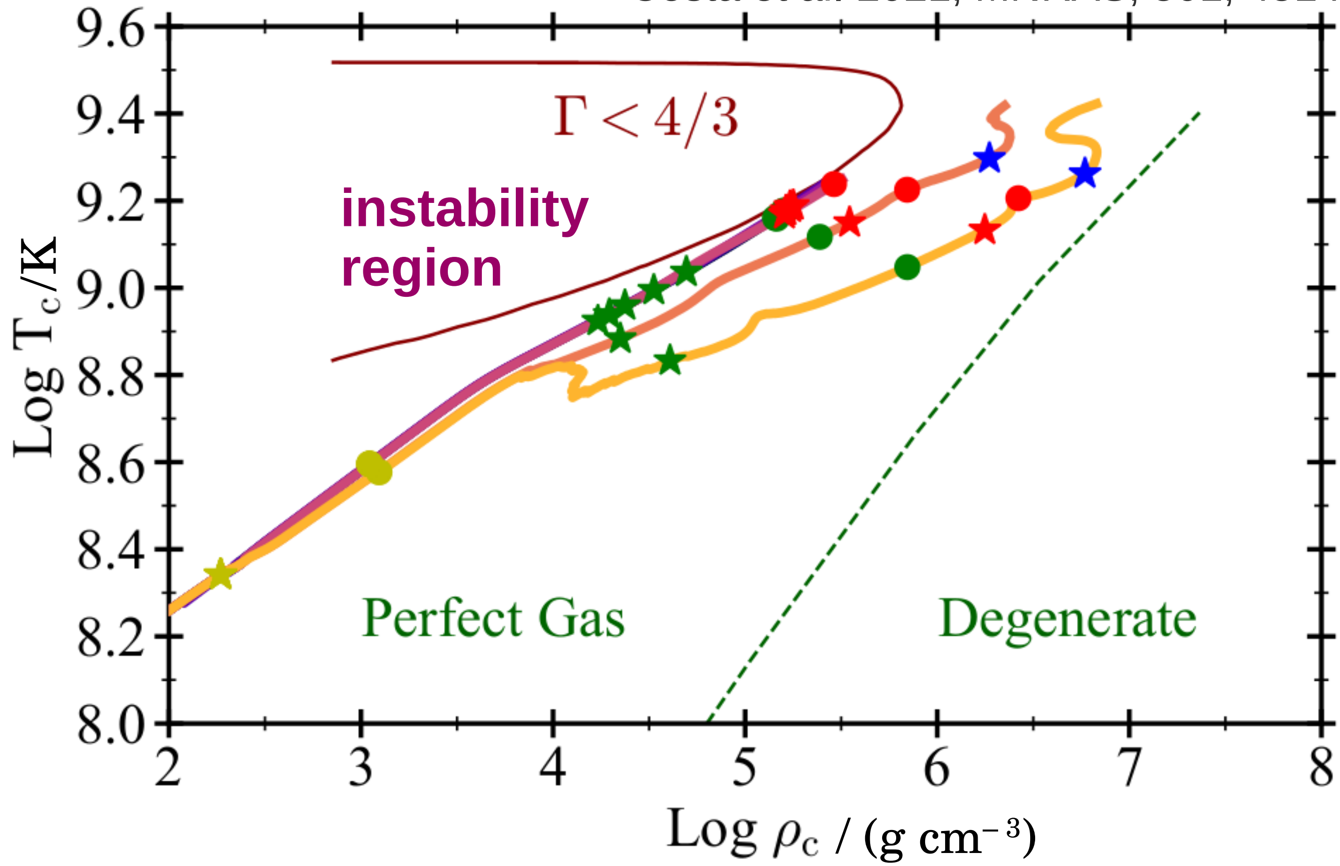
Missing photon pressure
triggers instability:

PAIR INSTABILITY

* contraction of
stellar core

* premature ignition of
neon, oxygen, silicon

Costa et al. 2021, MNRAS, 501, 4514

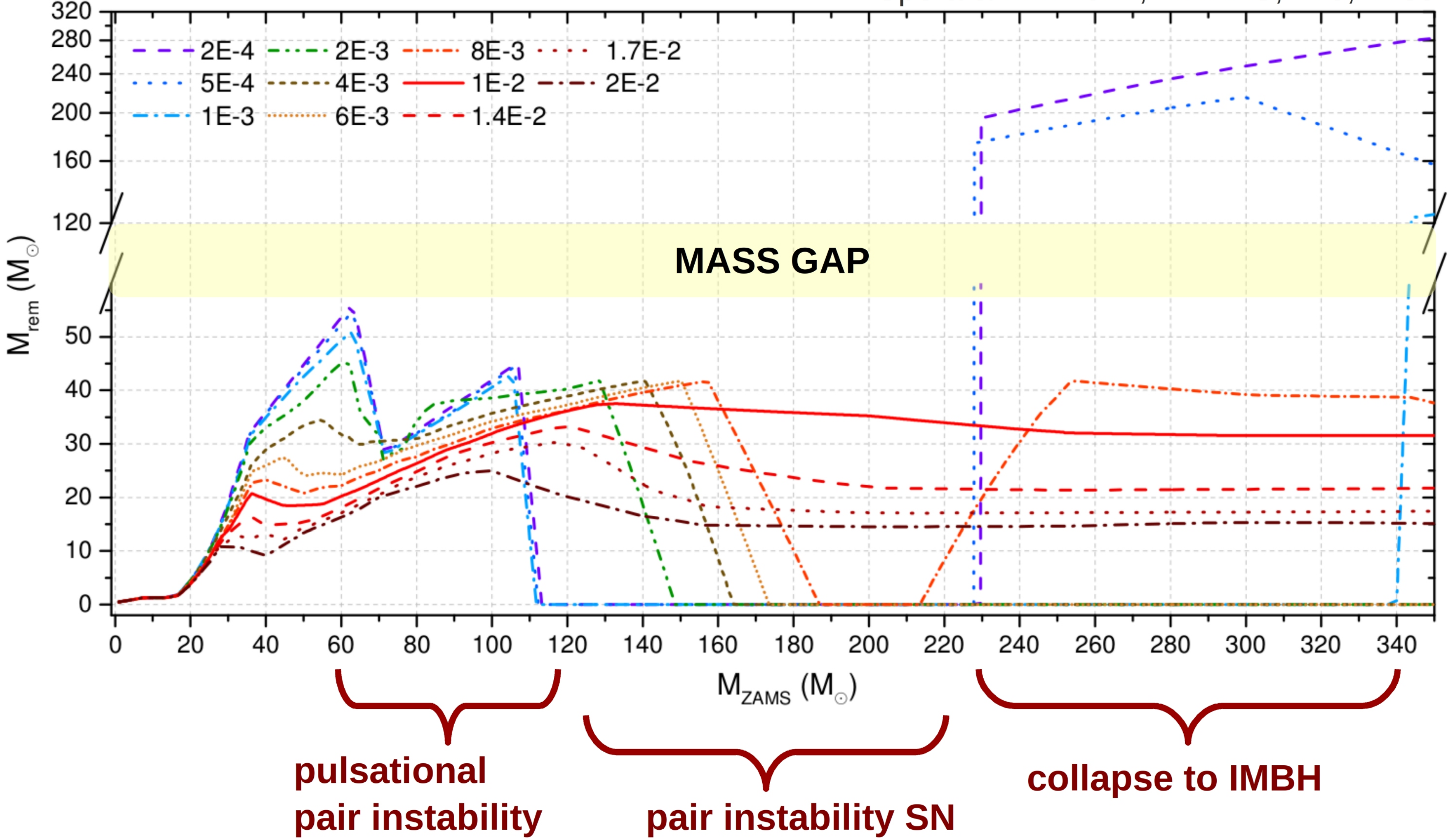


Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

1. Binary black holes (BBHs) from stellar evolution

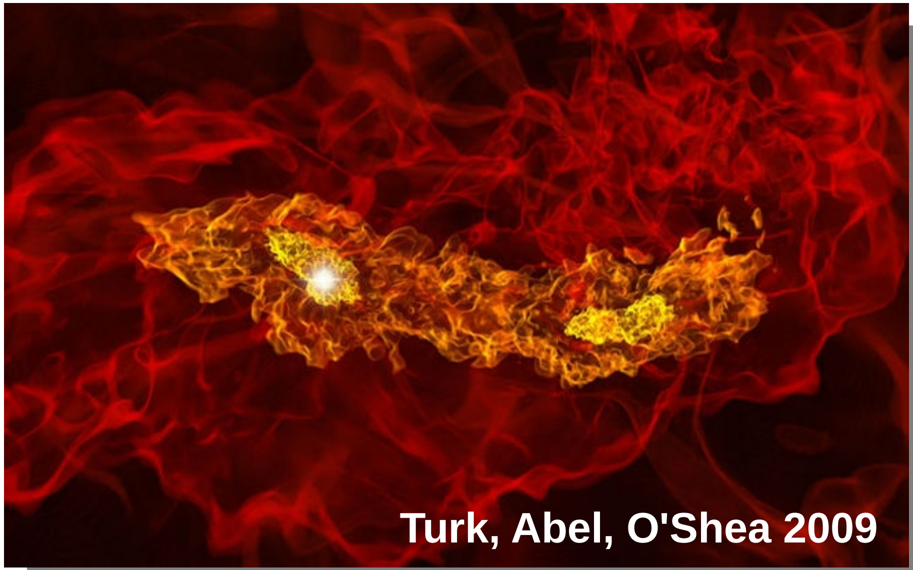
Impact of pulsational pair instability (if $32 < m_{He} / M_\odot < 64$) and pair instability supernovae (if $64 < m_{He} / M_\odot < 135$)

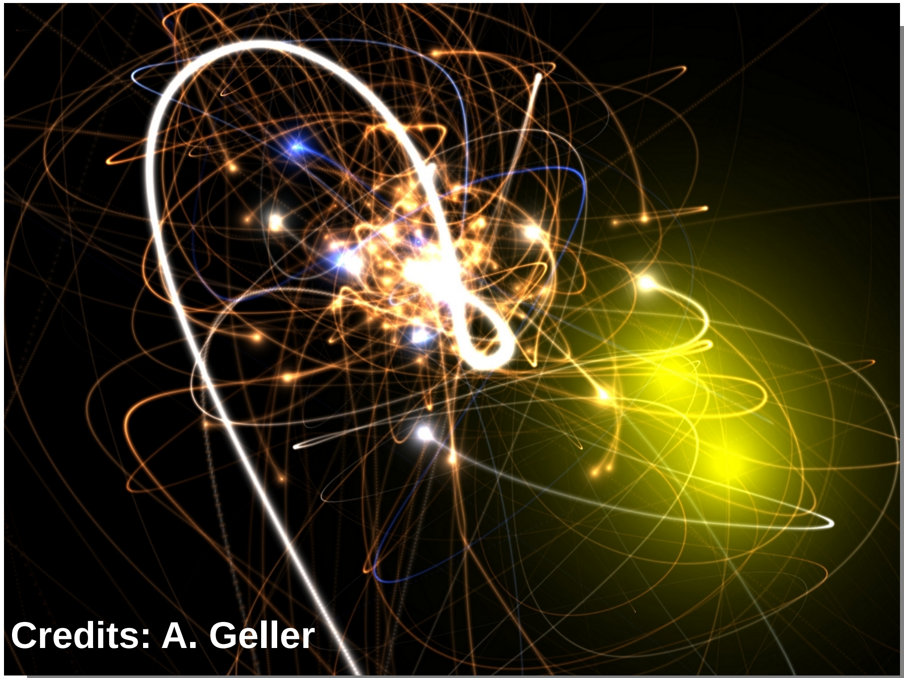
Spera & MM 2017, MNRAS, 470, 4739



1. Binary black holes (BBHs) from stellar evolution

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





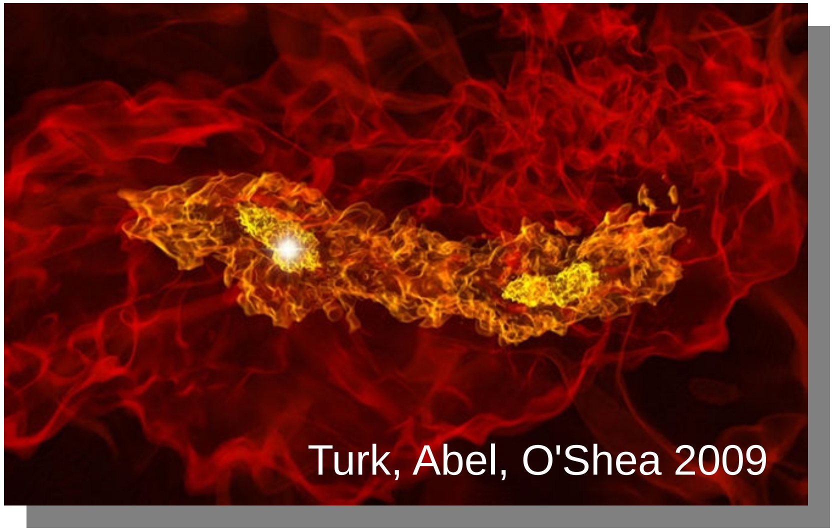
DYNAMICAL BINARIES:
Binary compact objects
(especially BBHs and BHNSs)
form and/or evolve
by dynamical processes
in star clusters

1. Binary black holes (BBHs) from stellar evolution

ISOLATED BINARIES:

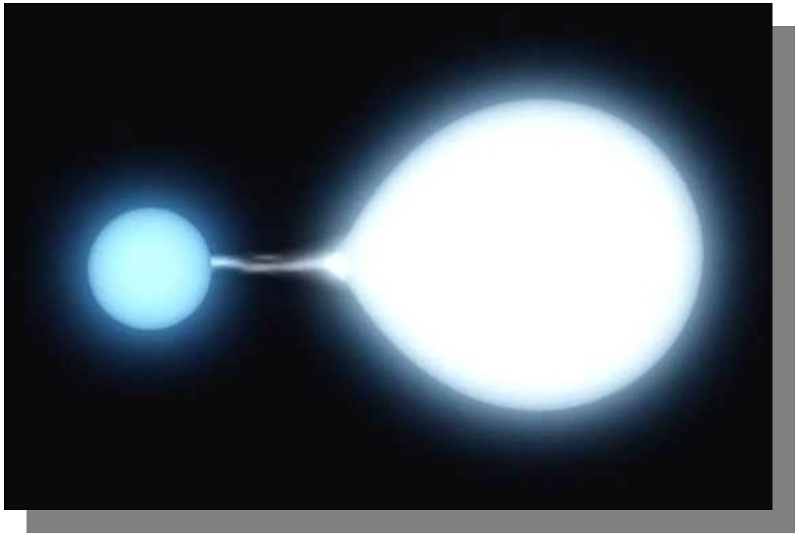
Two stars form from same cloud and form a BBH

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



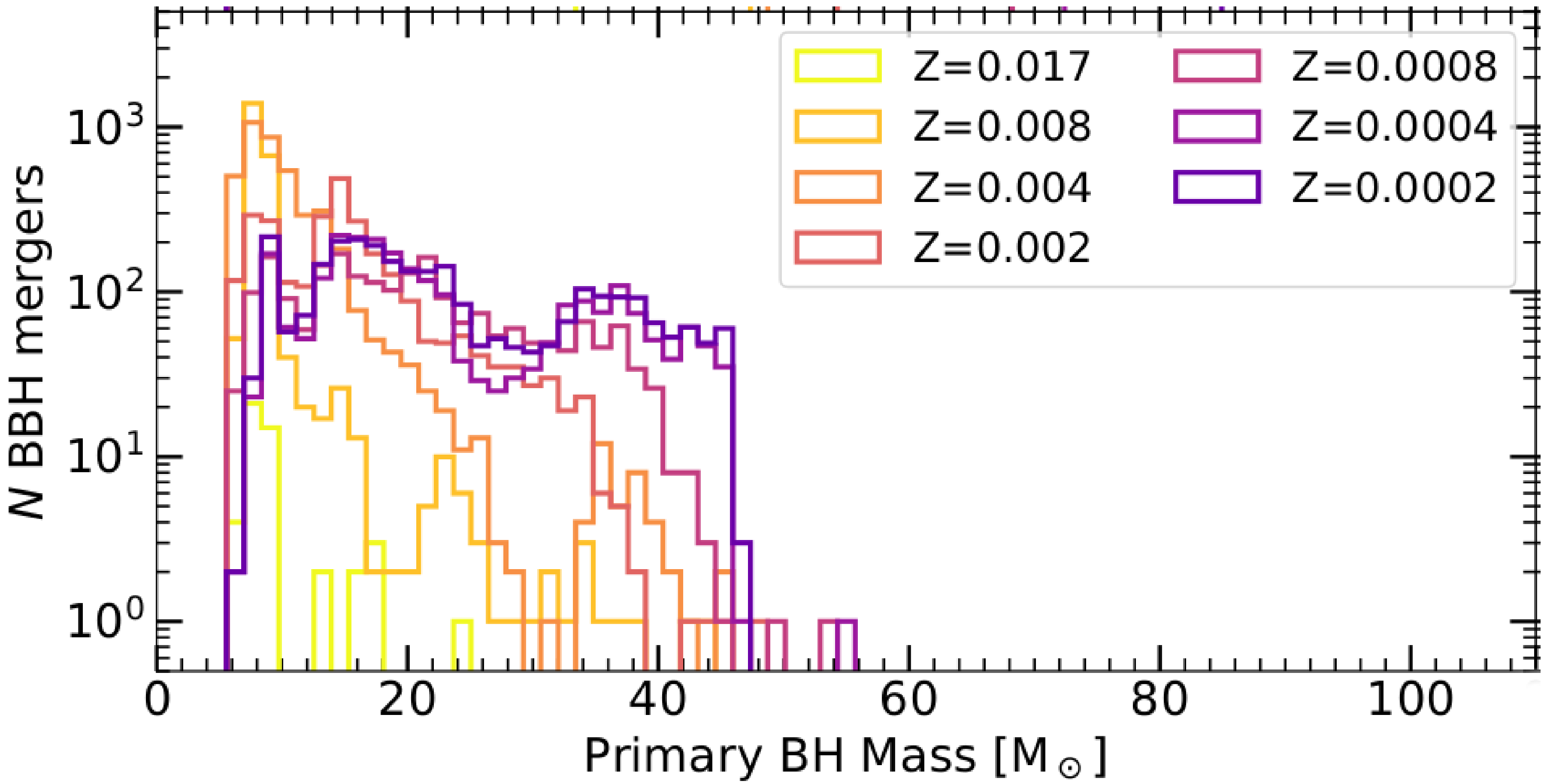
Many evolutionary processes affect a close binary

Credits: ESO



- Wind mass transfer
- Roche lobe overflow
- Common envelope
- Tidal evolution
- SN kick
- Gravitational wave decay

1. Binary black holes (BBHs) from stellar evolution



Iorio, MM, et al. 2023

* Mass and number of BBHs depend on metallicity (Z)
* BHs with mass ≤ 50 $M_\odot$ merge in isolation (wait for dynamics..)

2. Binary black holes (BBHs) from dynamics

DYNAMICS is IMPORTANT ONLY IF

$\boxed{\text{density} > 10^3 \text{ stars pc}^{-3}}$

i.e. only in **dense star clusters**

R136, credit: NASA

Young star clusters

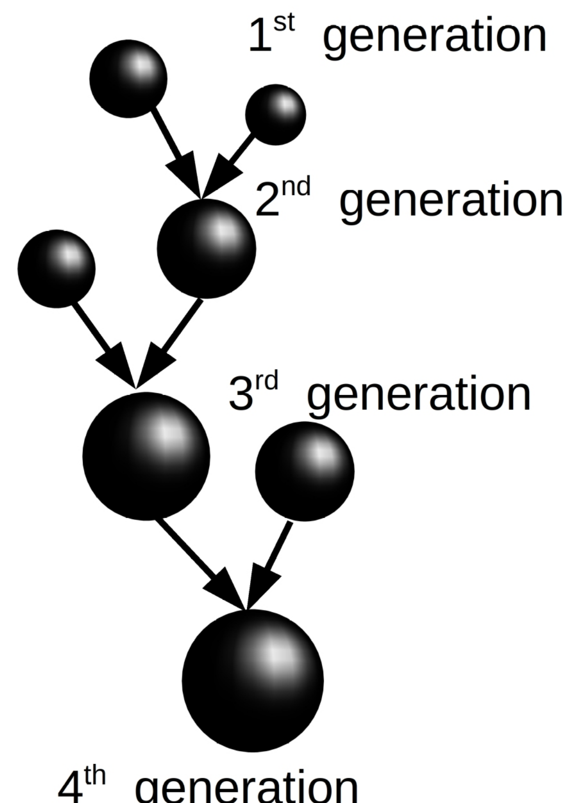
47 Tucanae, credit: NASA/ESA/HST

Globular clusters

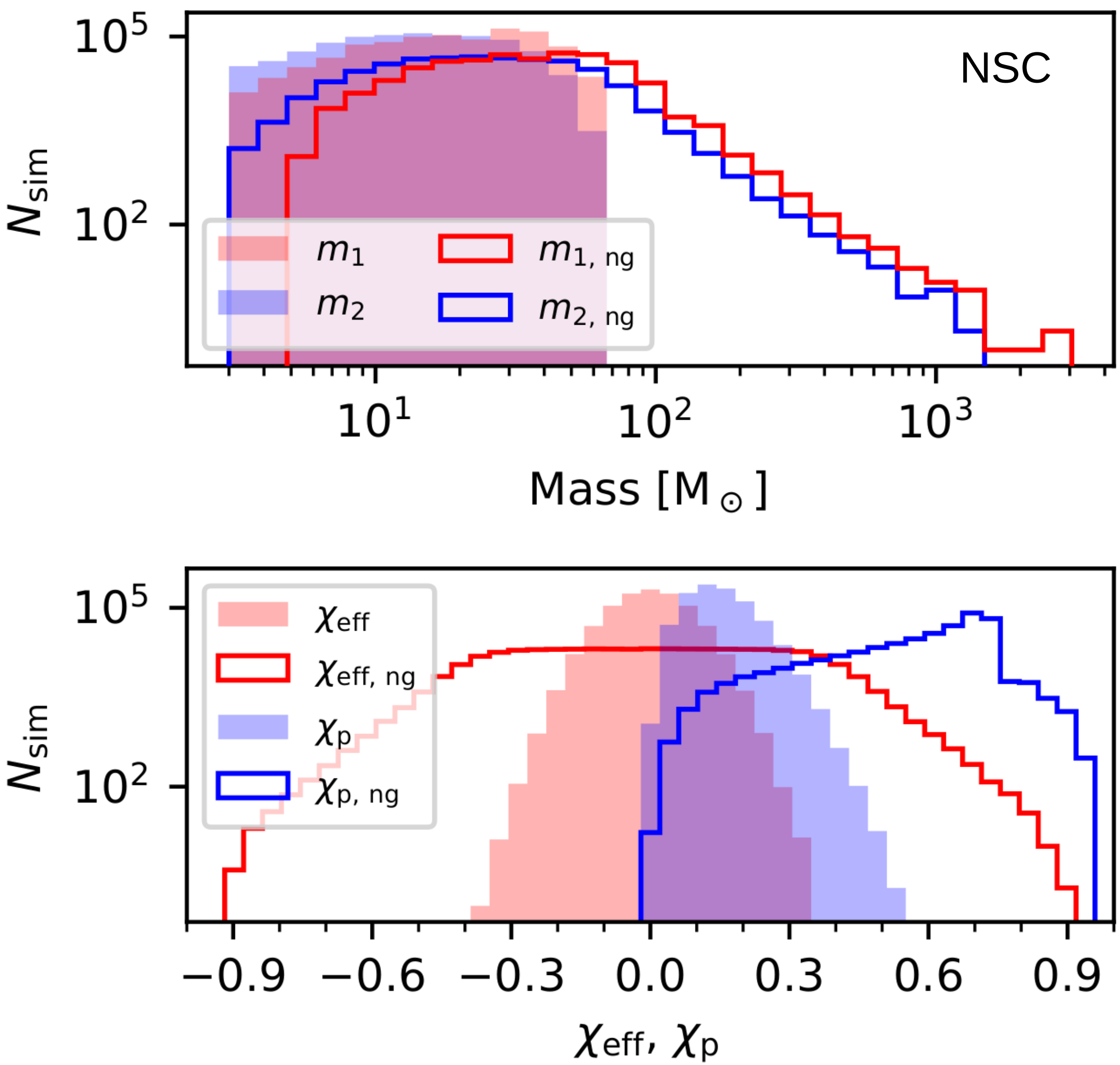
Credit: ESO, Gillessen et al.

Nuclear star clusters

HIERARCHICAL MERGERS:

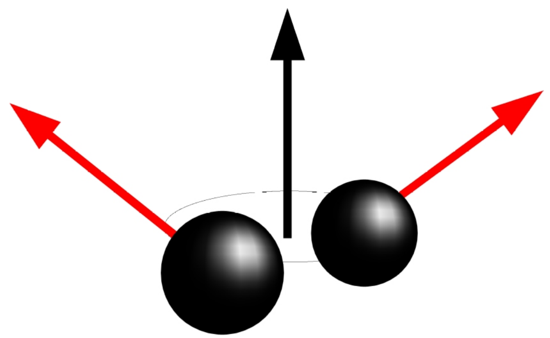


2. Binary black holes (BBHs) from dynamics



Filled histograms: first generation BBH mergers

Unfilled histograms: $2^{\rm nd}$ or higher generation BBH mergers



χeff : = parameter measuring the BBH spin components **aligned with the orbital angular momentum**

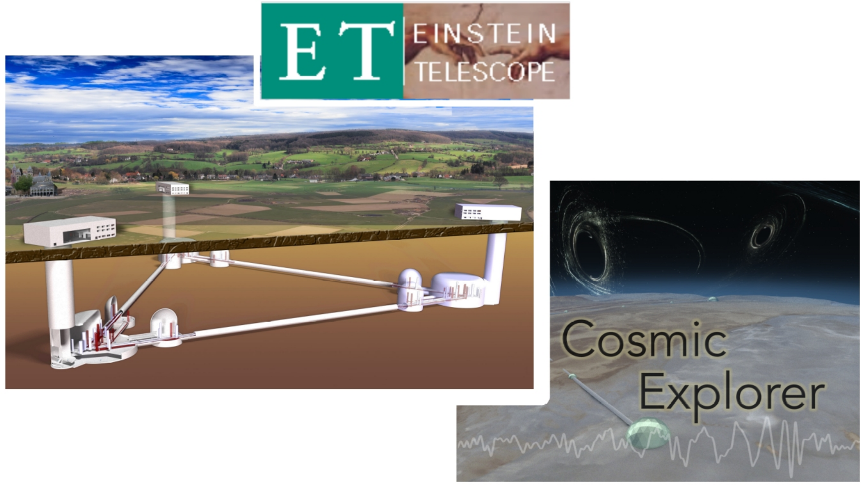
χp : = parameter measuring the BBH spin components lying in the orbital plane

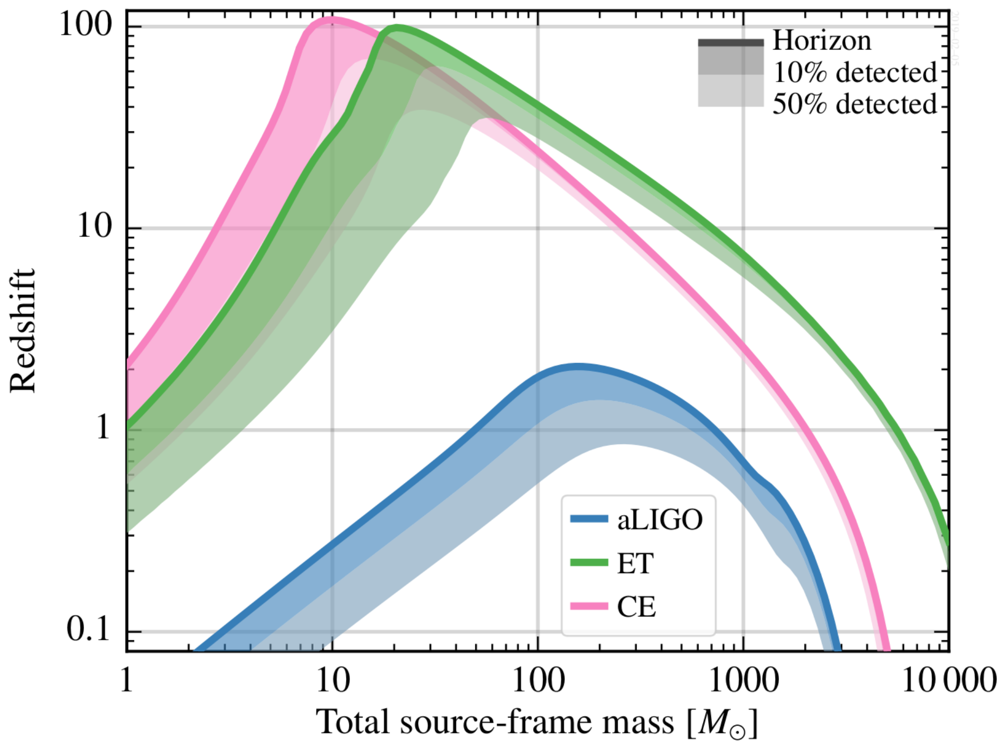
MM et al. 2021, MNRAS, 505, 339

3. BBHs from the first stars (Pop III stars) & the Einstein Telescope

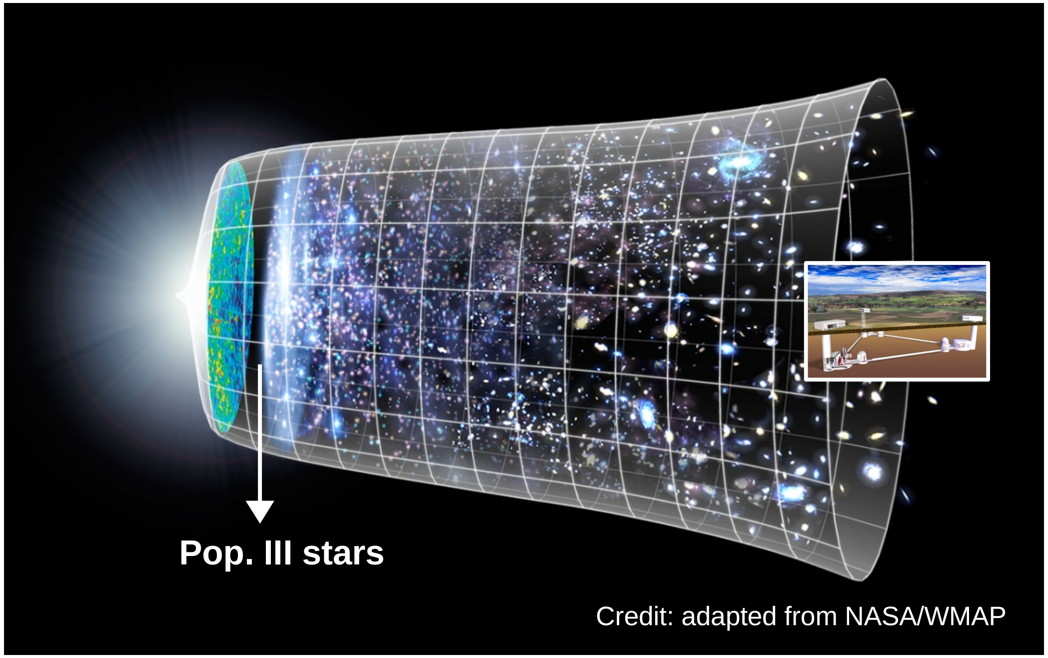
Einstein Telescope (ET) and Cosmic Explorer will observe BBH mergers up to z ~ 30 (~100 Myr after Big Bang)

ET first “light”: 2035 (expected)



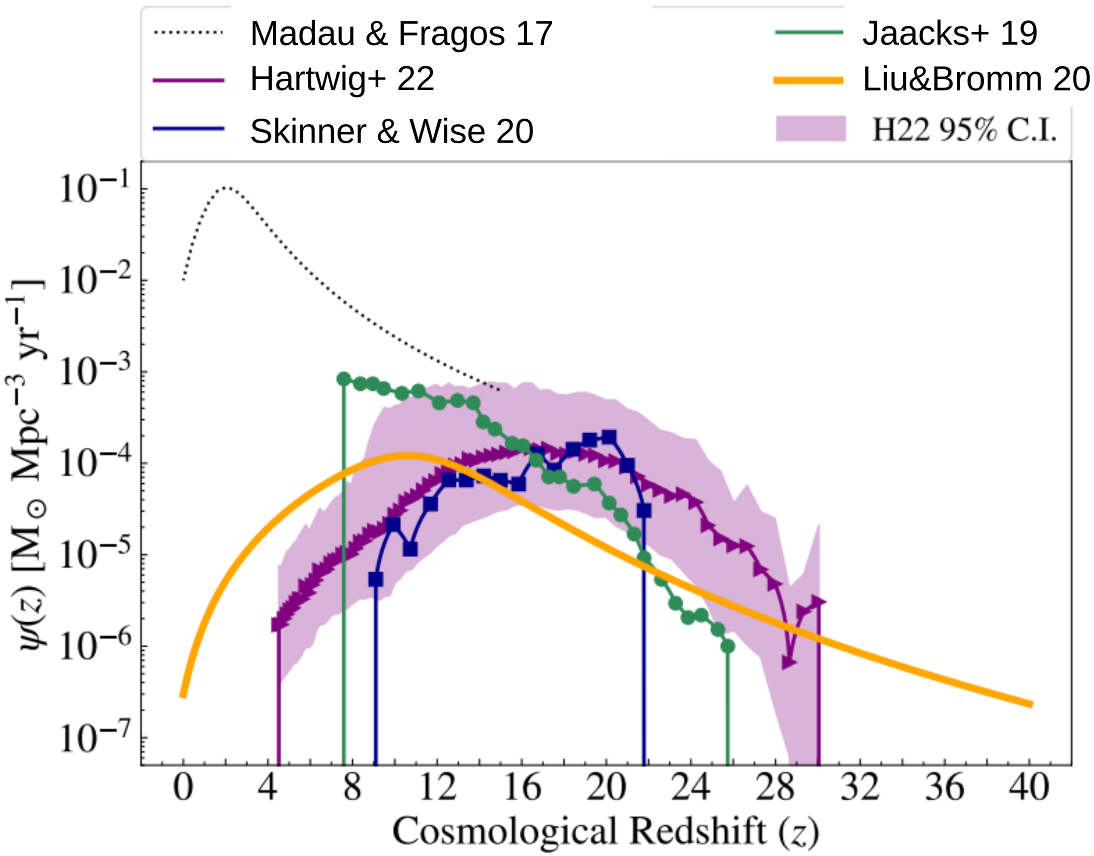


Branchesi et al. 2023



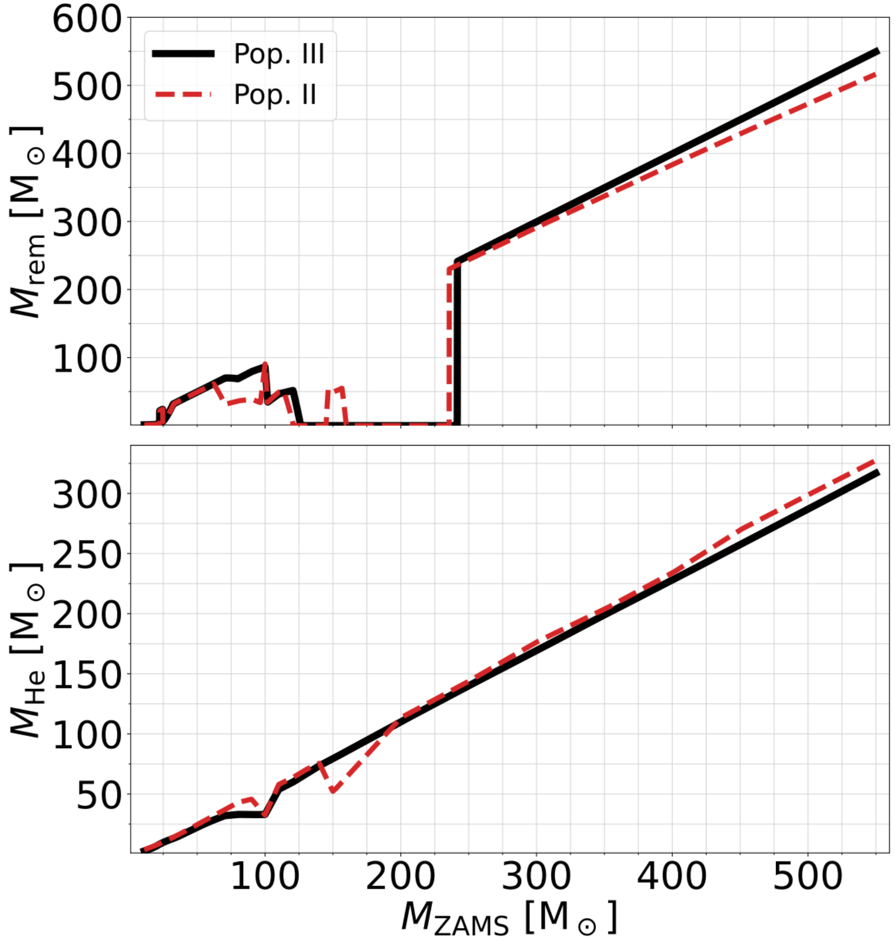
3. BBHs from the first stars (Pop III stars) & the Einstein Telescope

SFR Pop. III stars versus I – II



Santoliquido, MM et al. 2023

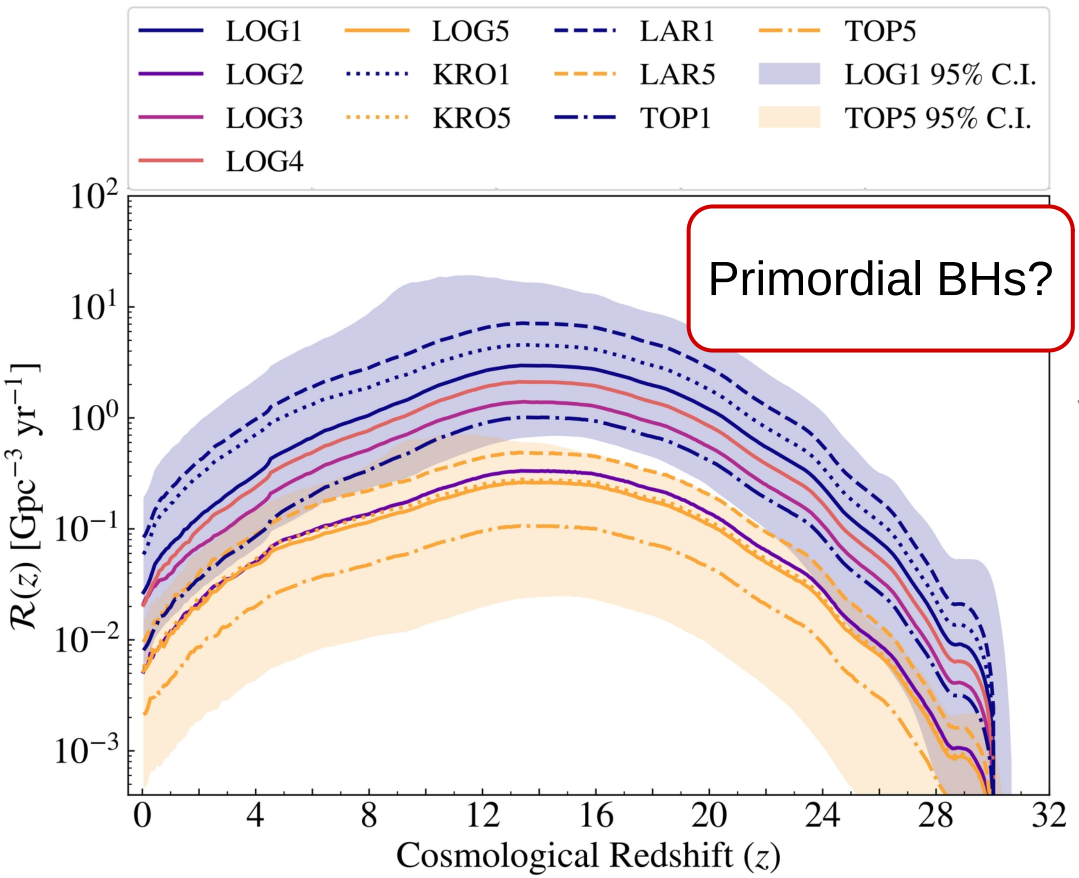
BH mass: Pop. III and Pop. II



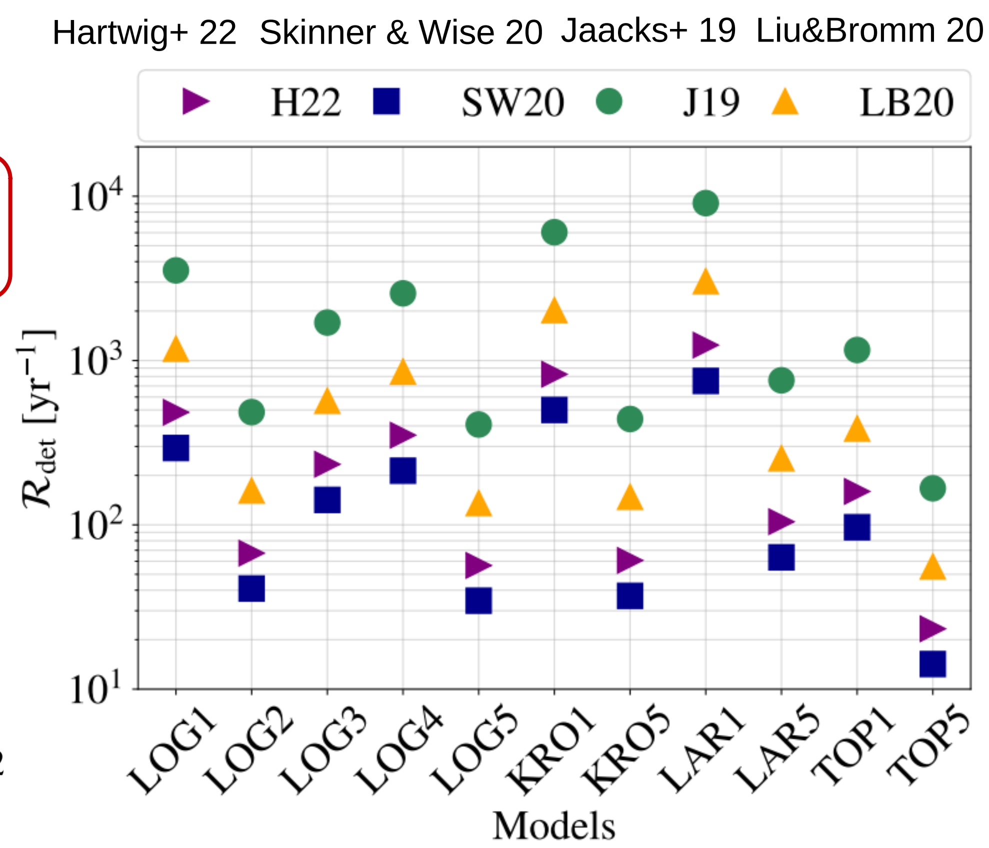
Costa, MM, et al. 2023

3. BBHs from the first stars (Pop III stars) & the Einstein Telescope

Pop III BBHs merger rate density



Detections from ET



Santoliquido, MM et al. 2023

moving soon to

University of Heidelberg

www.demoblack.com

New positions / fellowships available: contact me

4. Conclusions

* Stellar-born black holes form mainly from the interplay of stellar winds, core-collapse, and pair-instability supernovae

* Pair instability opens a mass gap in the BH mass spectrum ~ 60 – 120 $M_\odot$
(Spera & MM 2017; MM et al. 2020; Costa et al. 2021)

* The binary evolution channel forms BBH mergers up to ~ 50 + 50 $M_\odot$
(Iorio et al. 2023)

* Dynamics could fill the pair-instability gap with hierarchical mergers
(MM et al. 2021, 2022)

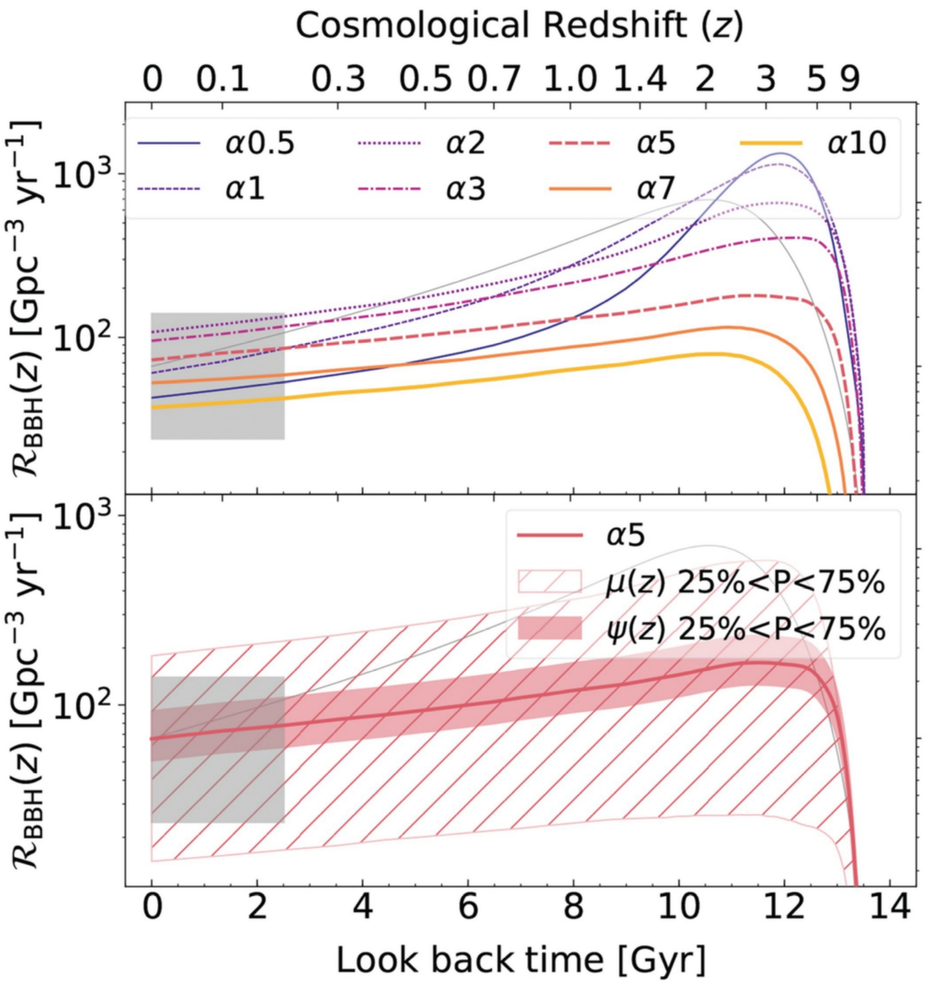
* Next-generation detectors will probe BBH mergers out to z ~ 30 (or higher)
(Branchesi et al. 2023)

* Possibility to observe Pop. III stars via their compact remnants
(Costa et al. 2023; Santoliquido et al. 2023)

THANK YOU

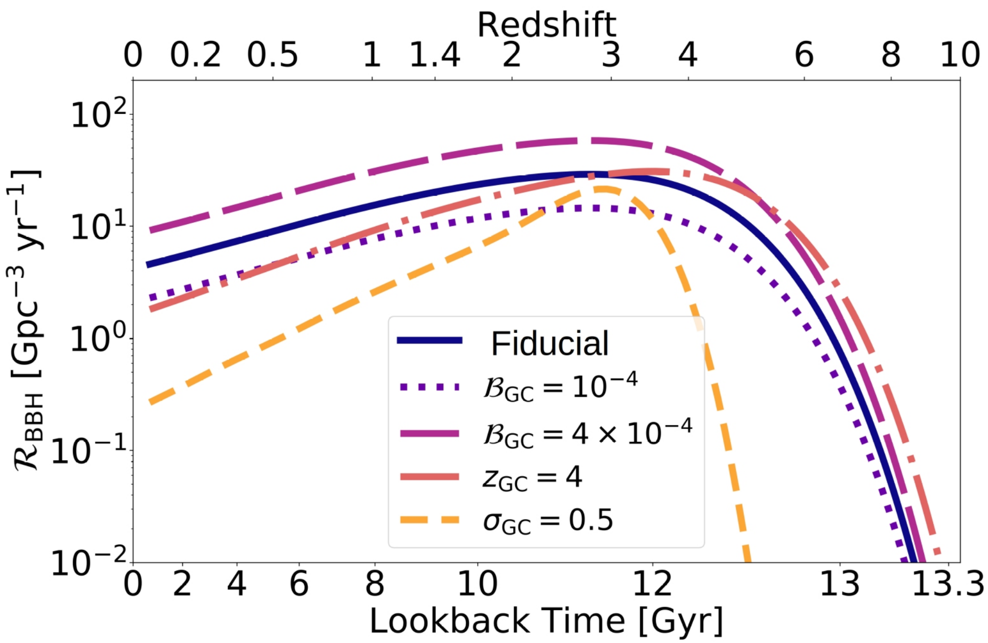
3. BHs from metal-poor and metal-free stars

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



Santoliquido et al. 2021, MNRAS, 502, 4877

Uncertainties on BBH merger rate evolution in **globular clusters**



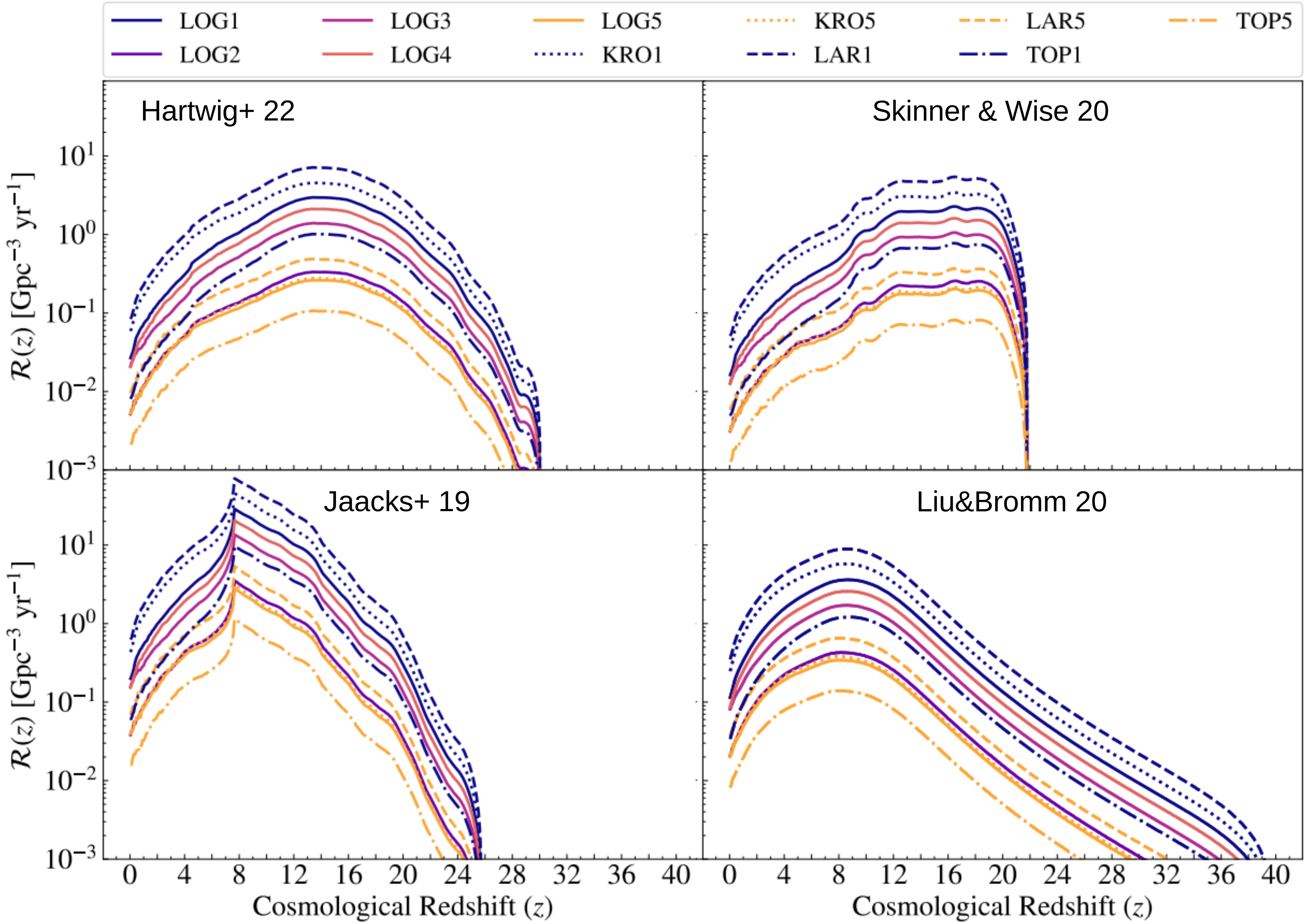
MM et al. 2022, MNRAS, in press

Formation rate of globular clusters:

$$\psi_{\rm GC}(z) = \mathcal{B}_{\rm GC}\,\exp\left[-(z - z_{\rm GC})^2/(2\,\sigma_{\rm GC}^2)\right]$$

3. BHs from metal-poor and metal-free stars

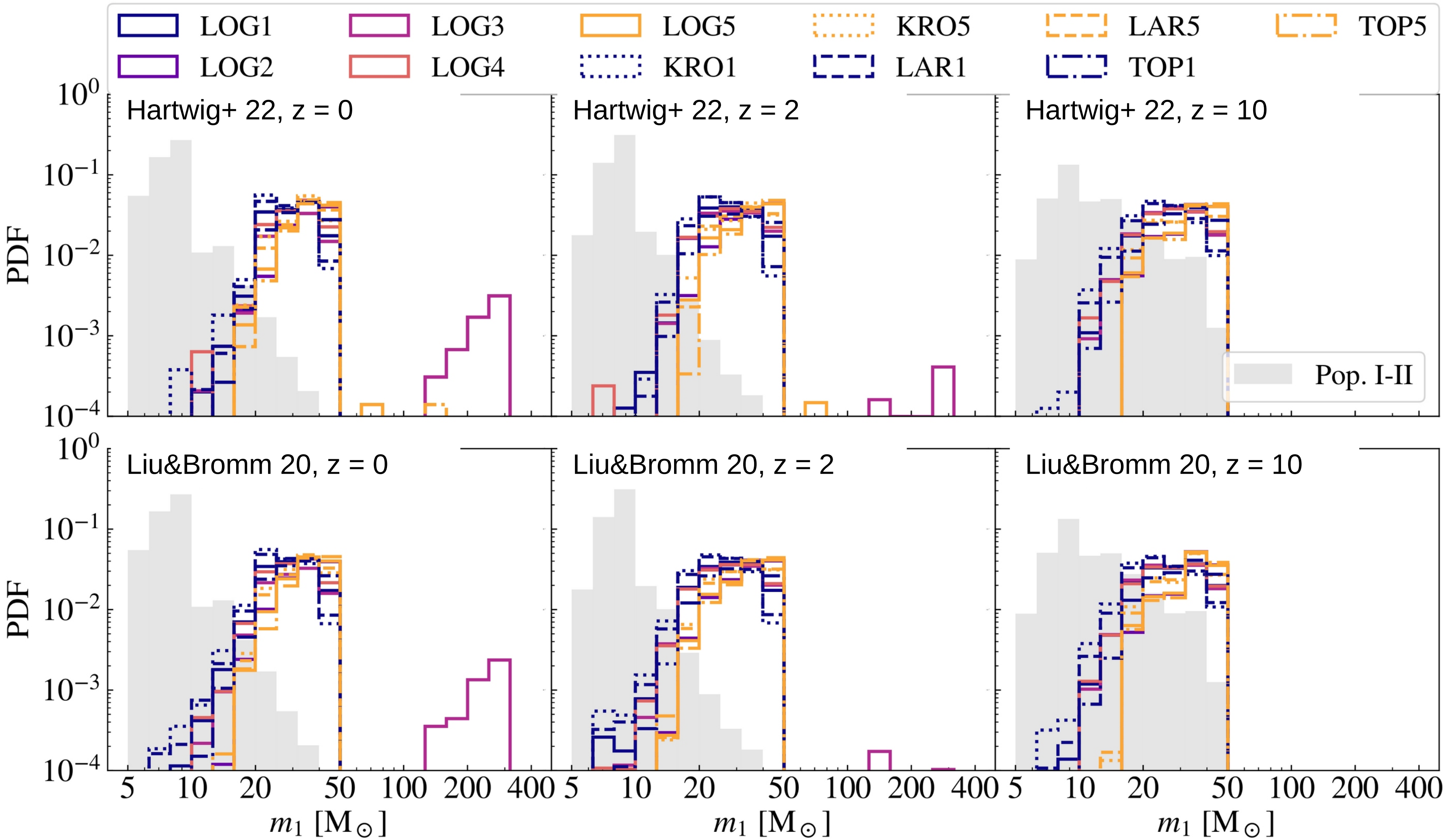
Merger rate density of BBHs from Pop. III stars: uncertainty



Santoliquido, MM et al. 2023, subm.

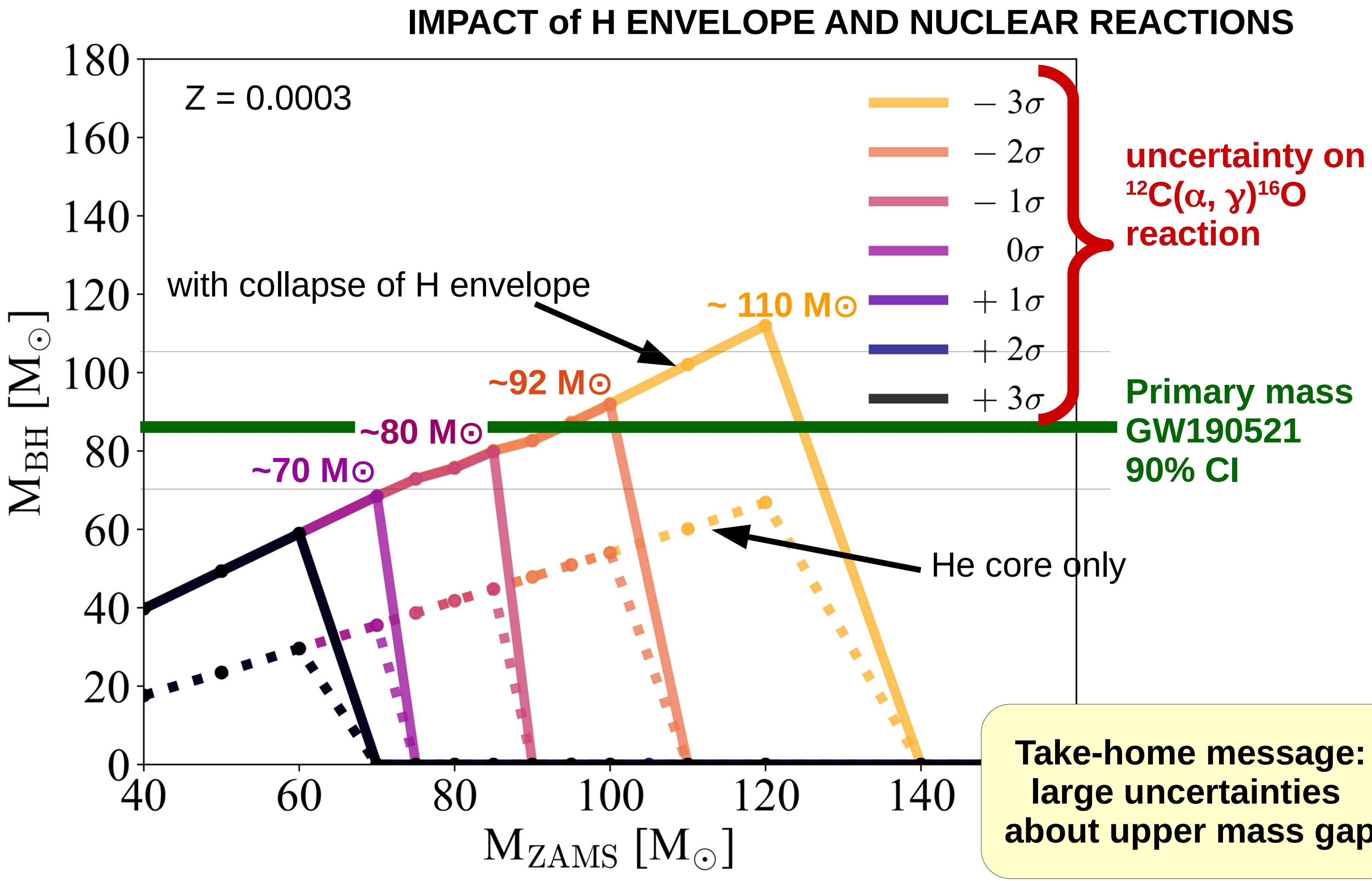
3. BHs from metal-poor and metal-free stars

Mass of Pop. III vs Pop. I BBHs: peak at 30 – 40 M☉ and 8 – 10 M☉ → **large evolution**



Santoliquido, MM et al. 2023, subm.

2. Black holes (BHs) in the pair-instability mass gap



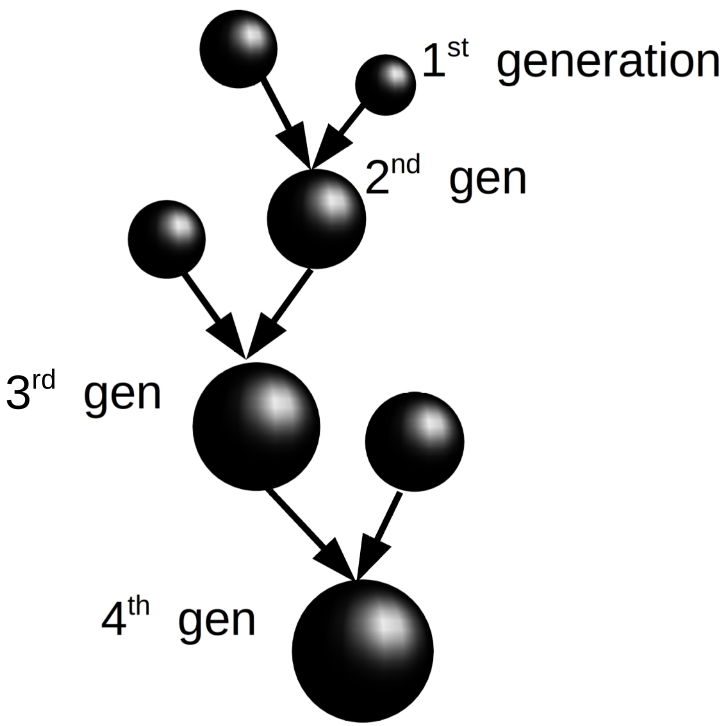
Take-home message: large uncertainties about upper mass gap

Costa et al. 2021, MNRAS, 501, 4514

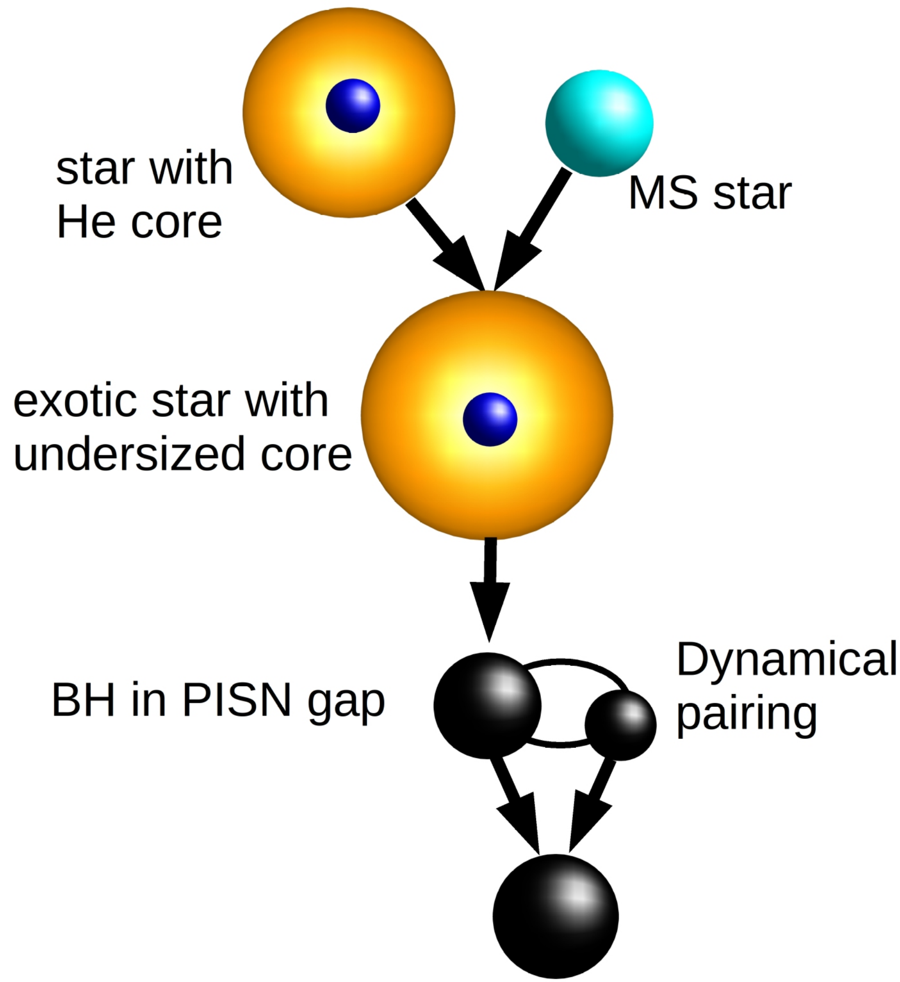
2. Black holes (BHs) in the pair-instability mass gap

HIERARCHICAL MERGERS

Miller & Hamilton 2002



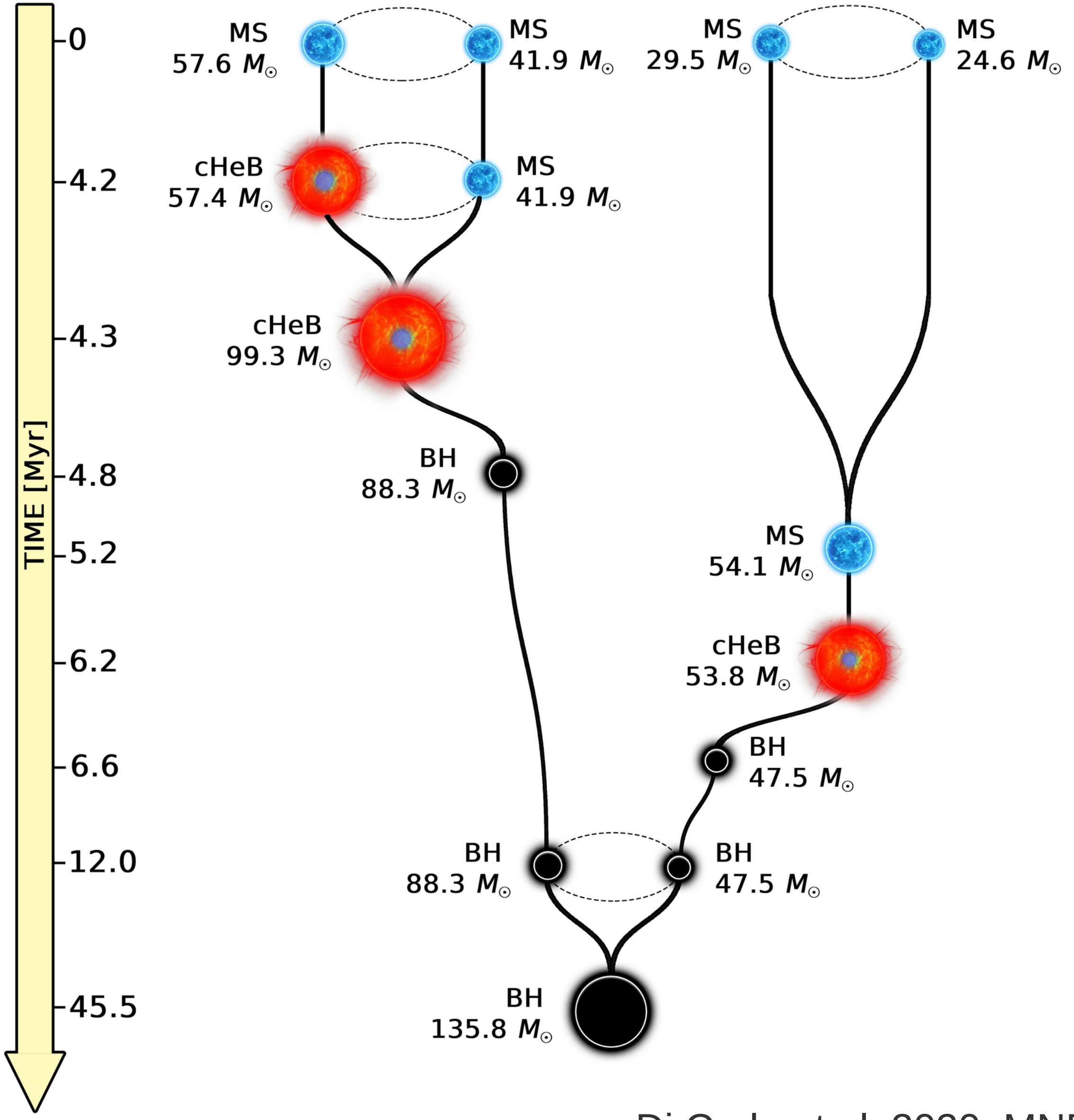
STAR – STAR COLLISIONS



Di Carlo et al. 2019
Di Carlo et al. 2020

2. Black holes (BHs) in the pair-instability mass gap: star collisions

A GW190521-like binary system



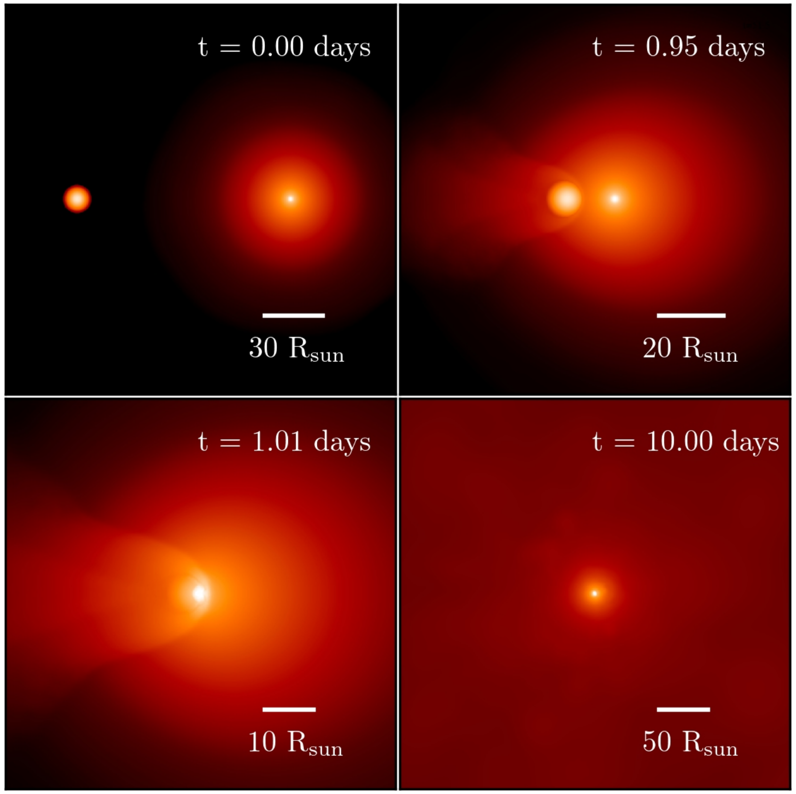
Di Carlo et al. 2020, MNRAS, 498, 495

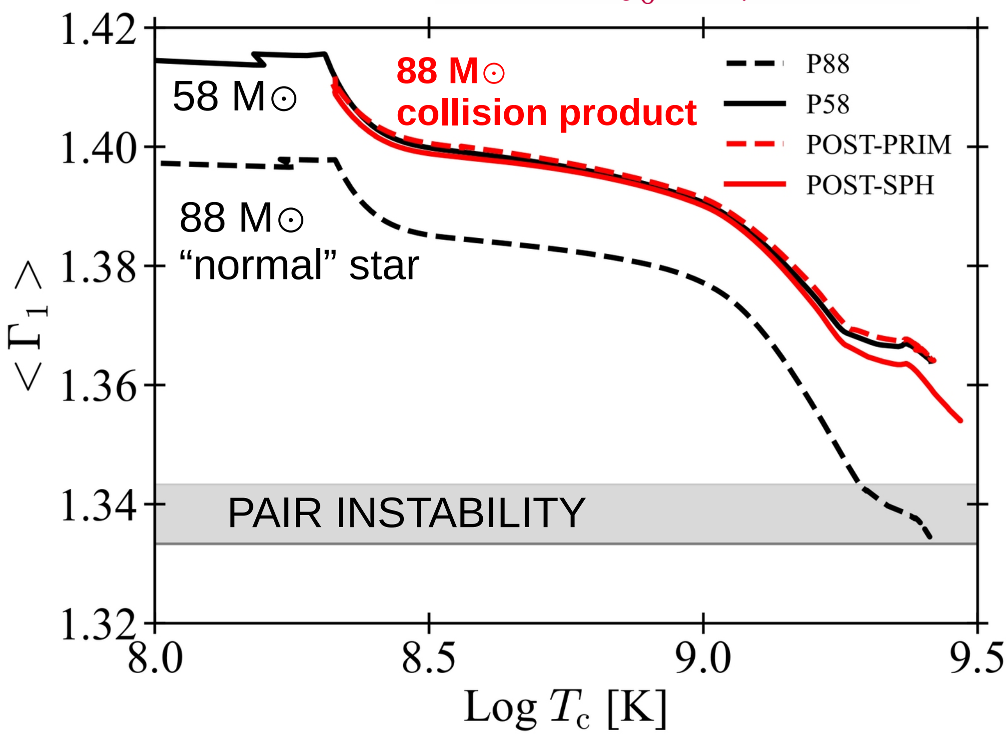
2. Black holes (BHs) in the pair-instability mass gap: star collisions

$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$

Mass loss during collision and further evolution?
→ needs hydro-dynamical simulations of the collision
→ needs accurate stellar evolution model

$$\langle \Gamma_1 \rangle = \frac{\int_0^M \Gamma_1 \, P \, \rho^{-1} \, dm}{\int_0^M P \, \rho^{-1} \, dm}$$





Max 12% mass loss during head-on star – star collision
(Ballone et al. 2022, arXiv:2204.03493)

A normal 88 M⊙ star undergoes pair instability

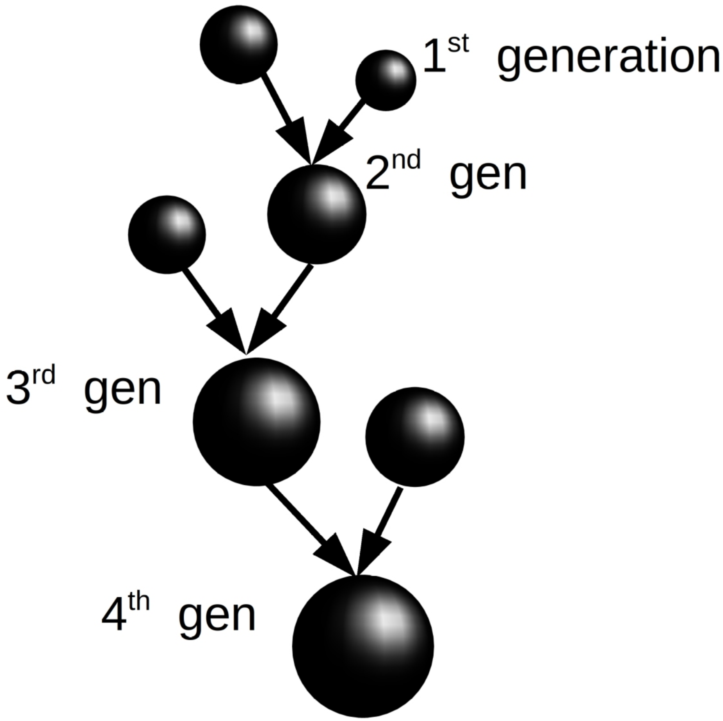
The collision product avoids pair instability (like a 58 M⊙ star)
→ **final BH mass ~ 87 M⊙**

Costa et al. 2022, arXiv:2204.03492

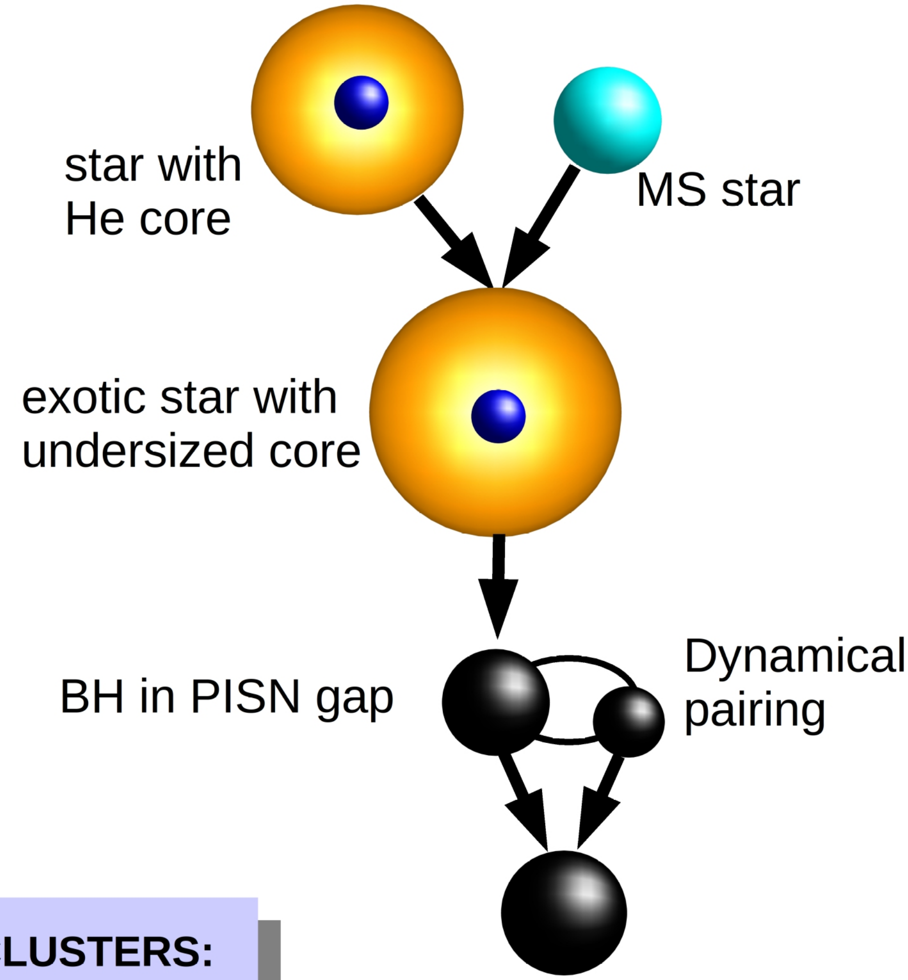
2. Black holes (BHs) in the pair-instability mass gap

HIERARCHICAL MERGERS

Miller & Hamilton 2002



STAR – STAR COLLISIONS



Di Carlo et al. 2019
Di Carlo et al. 2020

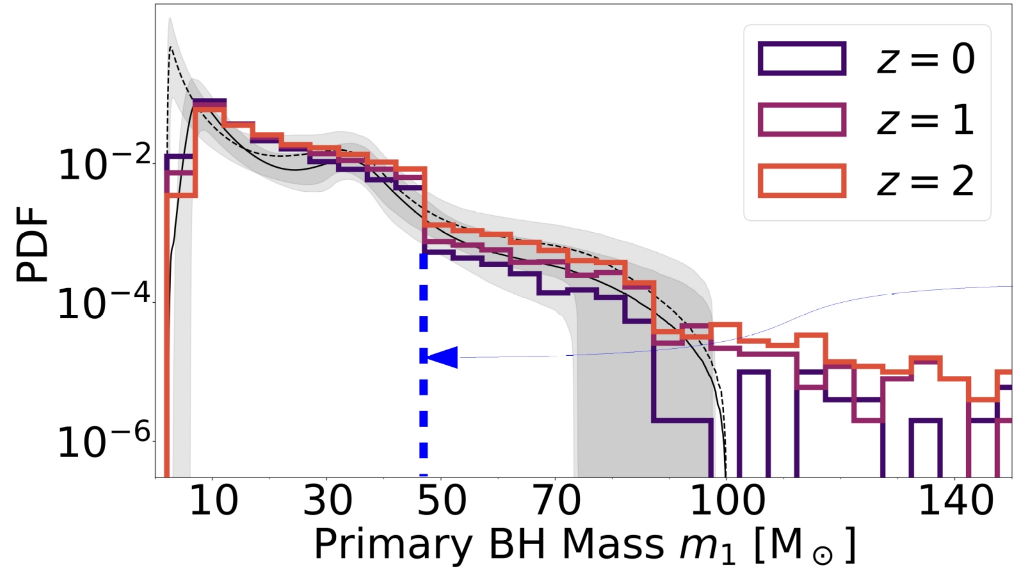
LARGE PARAMETER SPACE & VERY MASSIVE CLUSTERS:

IMPOSSIBLE TO PROBE WITH N-BODY SIMULATIONS

→ **FAST SEMI-ANALYTICAL MODEL WITH DYNAMICS**

2. Black holes (BHs) in the pair-instability mass gap: hierarchical

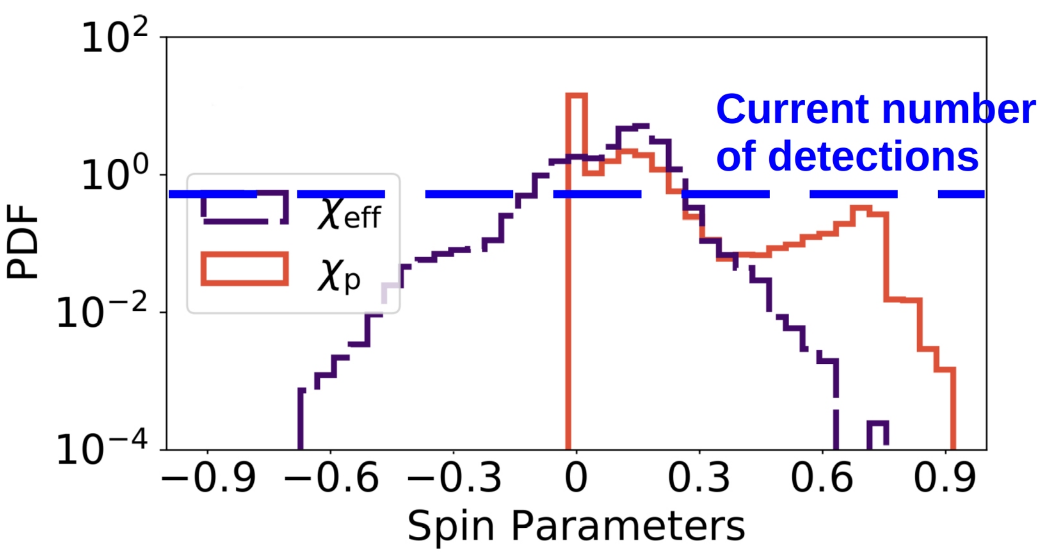
Isolated + dynamical mergers are a reasonable match to LVC masses and spins

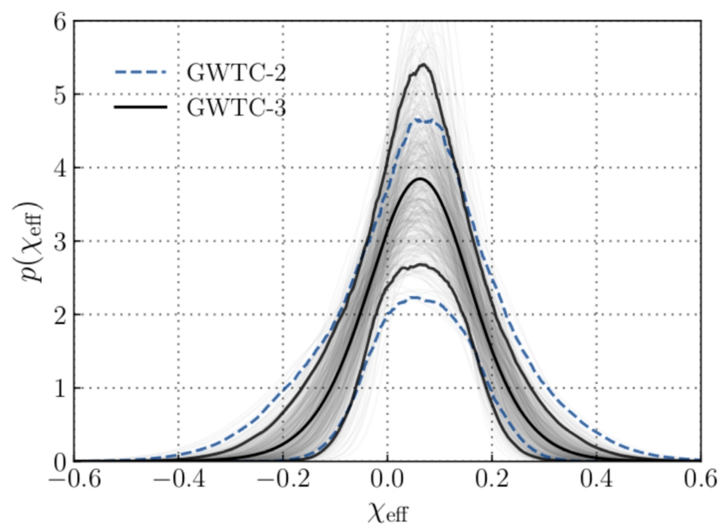


Hierarchical mergers essential to explain the most massive BHs observed

Max mass of 1g BHs in our input model

Grey contours: primary BH mass reconstructed by the LIGO – Virgo collaboration (Abbott et al. 2021)

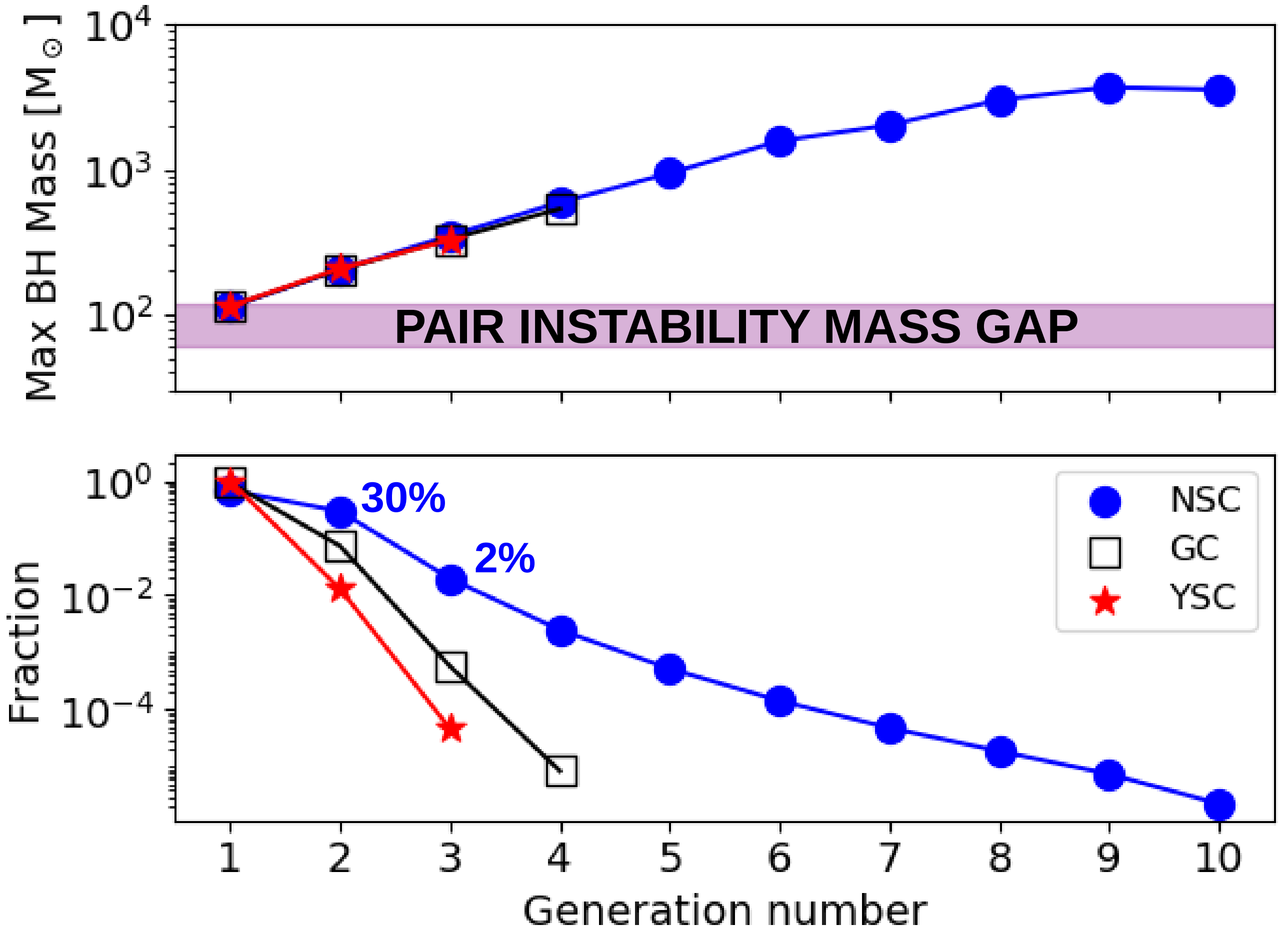




MM et al. 2022, MNRAS

Abbott et al. 2022, population

2. Black holes (BHs) in the pair-instability mass gap: hierarchical



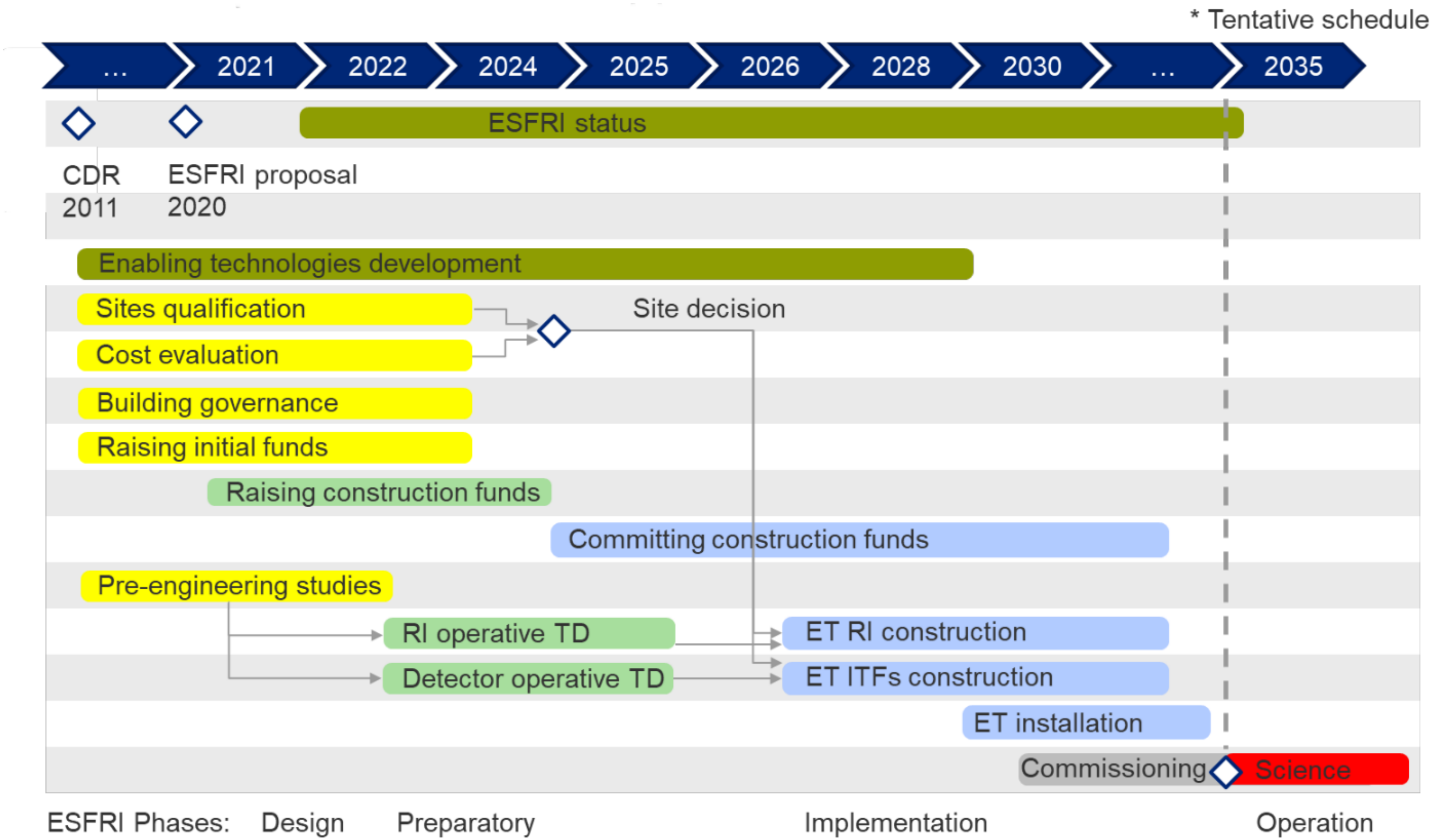
MM et al. 2021, MNRAS, 505, 339

* Up to 10 generations in nuclear star clusters

* Intermediate-mass black holes (IMBHs) form efficiently in nuclear star clusters

* Most hierarchical mergers are 2nd generation

4. Future challenges: getting ready for Einstein Telescope



Courtesy: M. Punturo