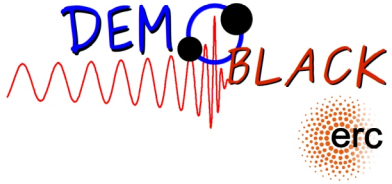
SIGRAV, Trieste, September 8th 2023

The black hole mass function and merger rate across cosmic time

Michela Mapelli

Heidelberg University



Main collaborators:

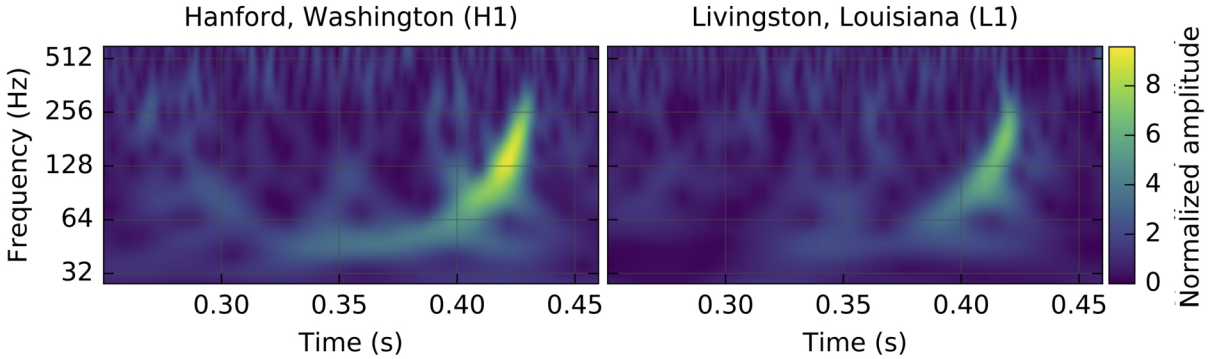
M. Celeste Artale, Guglielmo Costa, Marco Dall'Amico, Ugo Di Carlo, Gaston Escobar, Giuliano Iorio, Erika Korb, Benedetta Mestichelli, Carole Périgois, Sara Rastello, Filippo Santoliquido, Cecilia Sgalletta, Mario Spera, Stefano Torniamenti, Paola Vaccaro, & the DEMOBLACK team

OUTLINE:

1. Lessons learned from gravitational waves (GWs)
2. Binary black holes (BBHs) from star evolution
3. BBHs from dynamics
4. BHs from metal-free and metal-poor stars
5. Conclusions

1. Lessons learned from GW detections

GW150914: the first binary black hole (BBH)



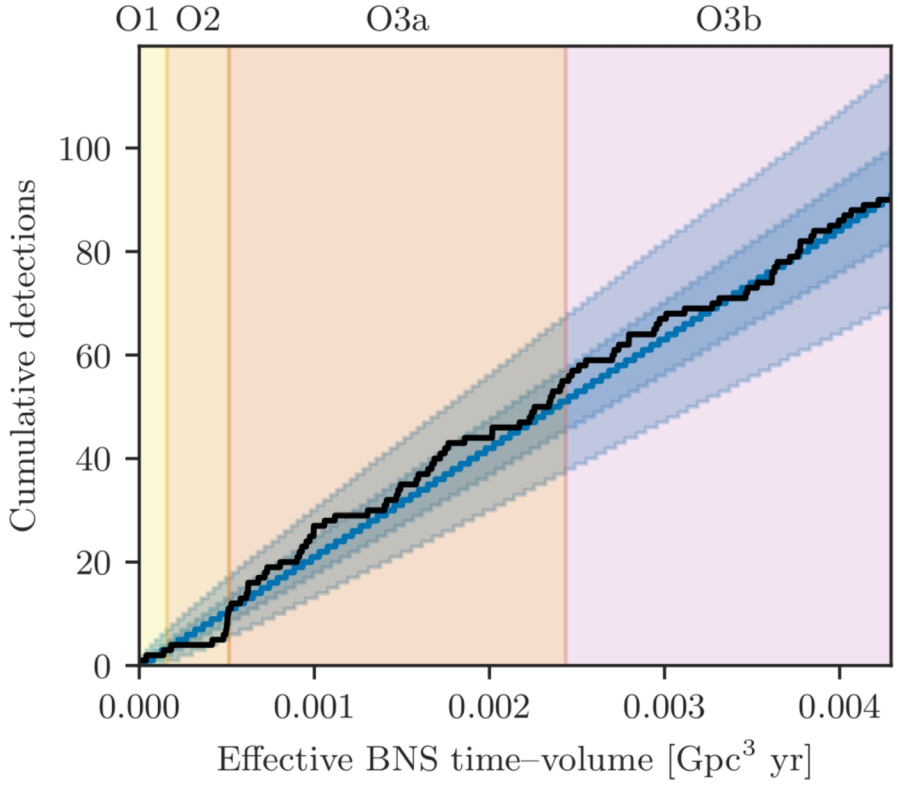
Abbott et al. 2016, PhRvL, 116, 1102

O1 + O2 + O3:

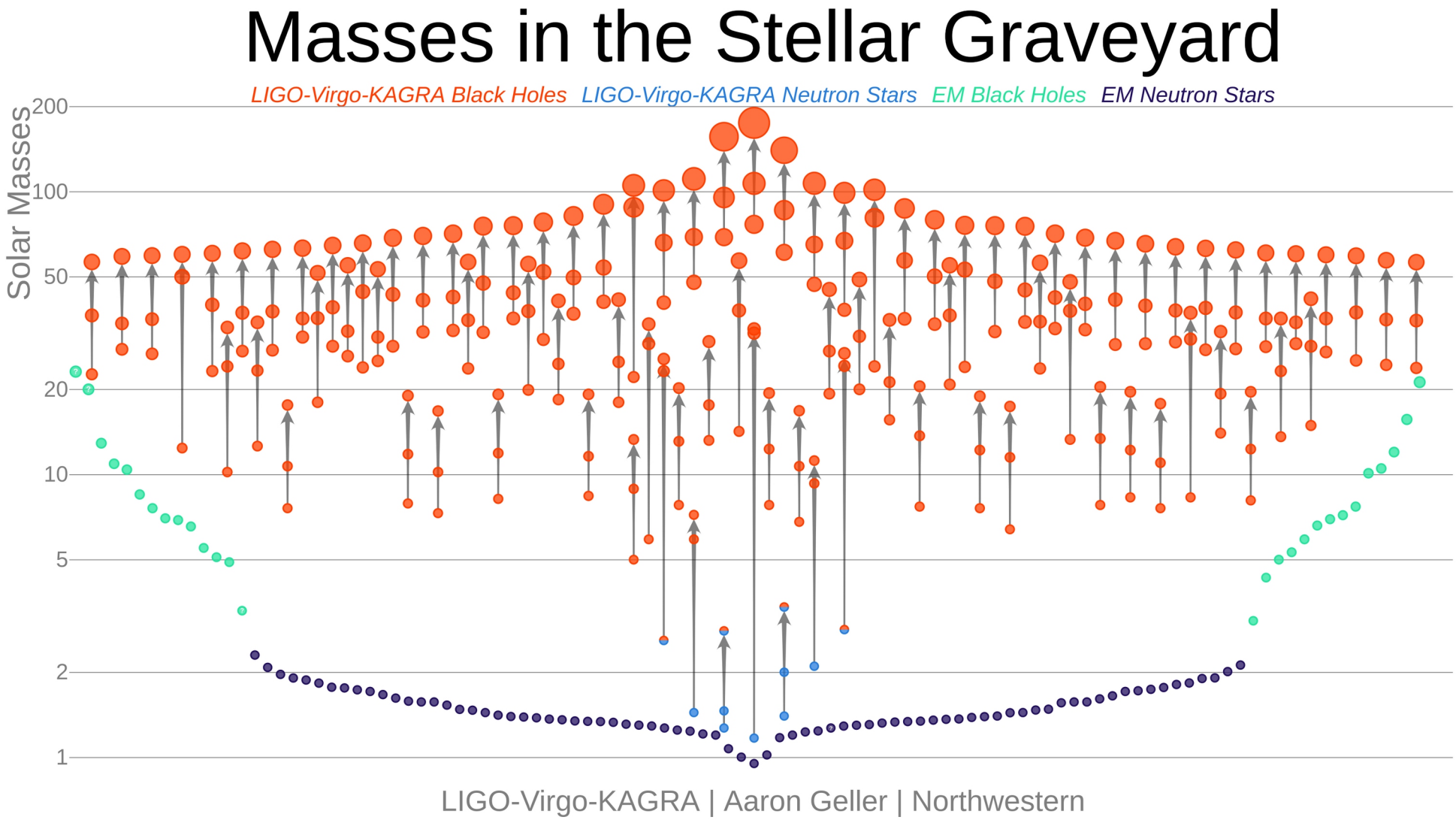
90 GW event candidates
most of them BBHs

(Abbott et al. 2021, GWTC-2;
Abbott et al. 2022, GWTC-2.1;
Abbott et al. 2022, GWTC-3)

O4 ongoing: stay tuned



1. Lessons learned from GW detections: masses



Abbott et al. 2022, GWTC-3

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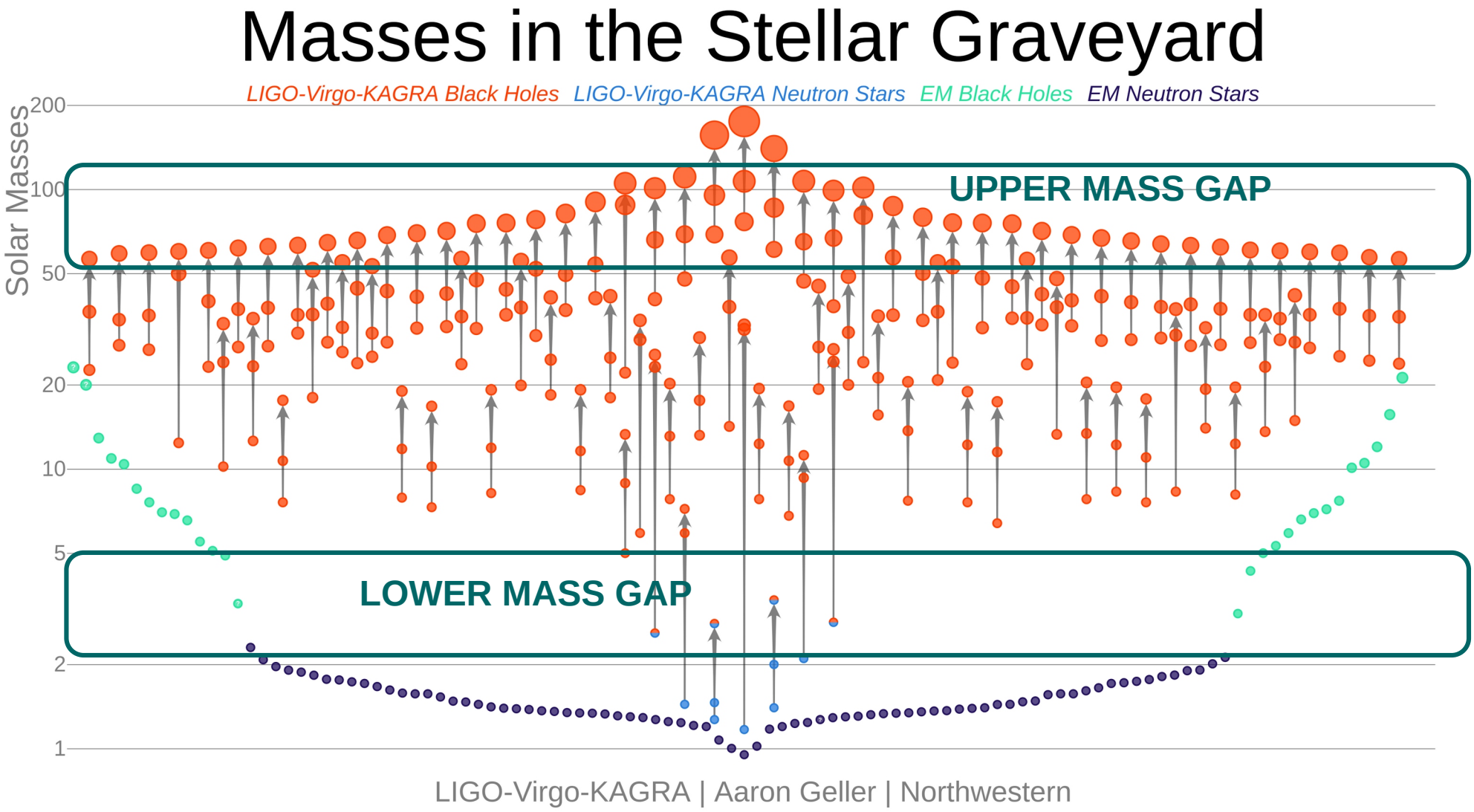

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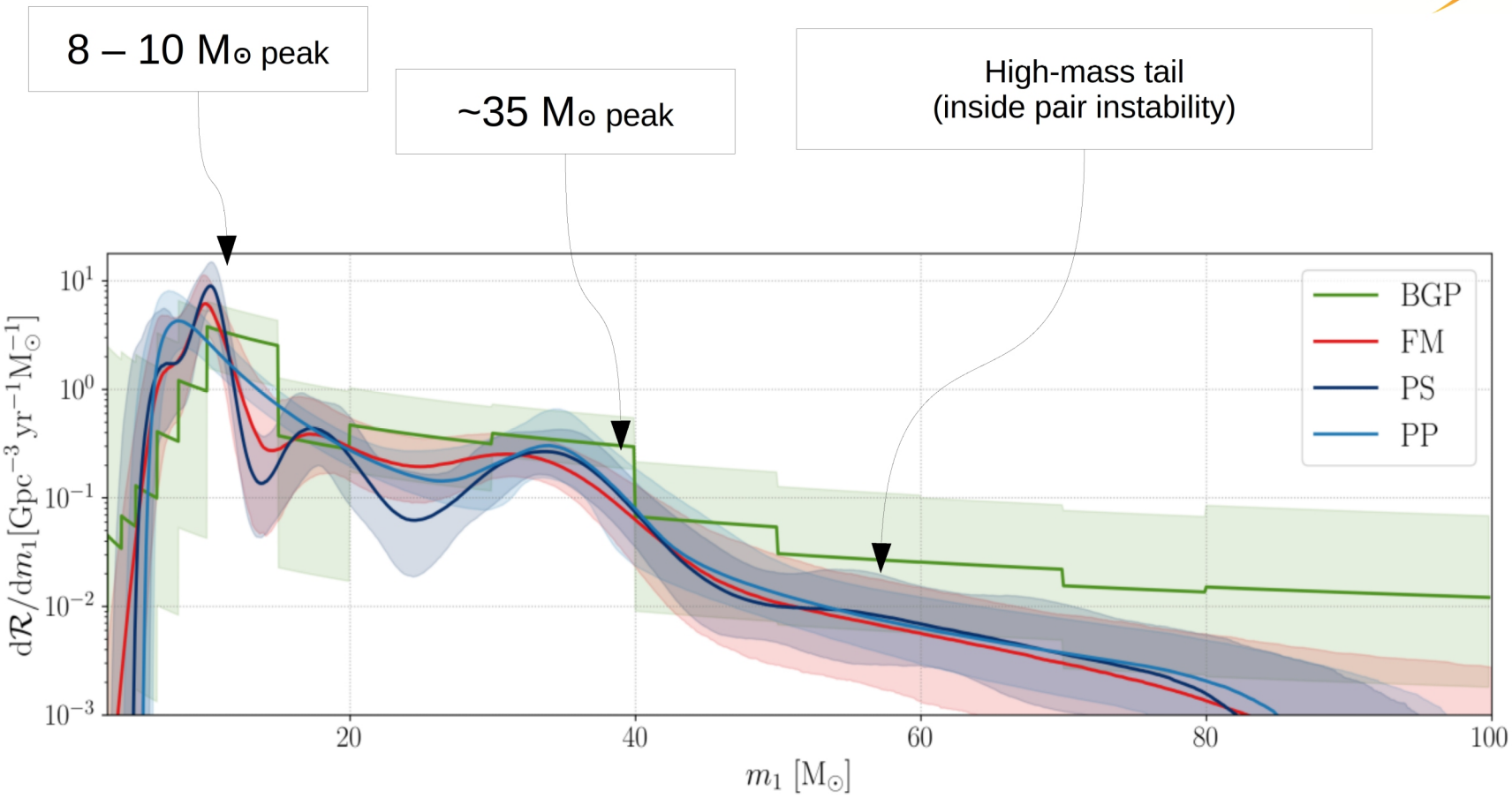


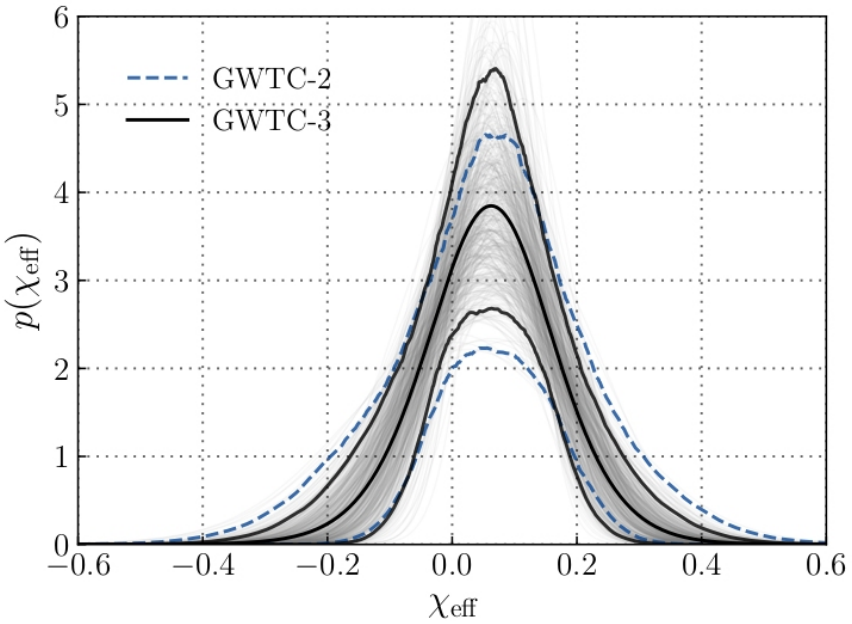
Reconstructed
primary mass function:

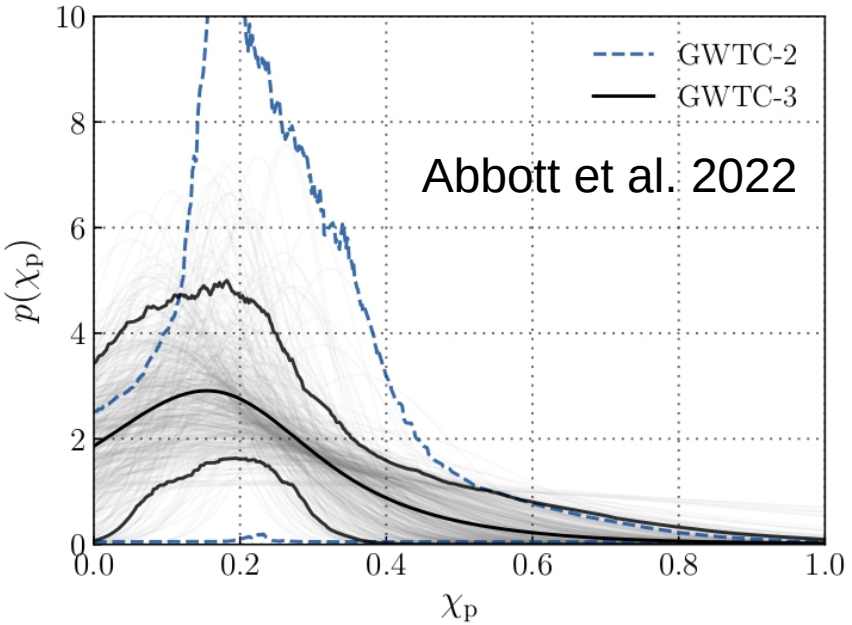
possible peaks at ~ 10 and 35 M⊙
tail up to ~ 80 M⊙

What causes this mass spectrum?

Abbott et al. 2023, population paper

1. Lessons learned from GW detections: spins

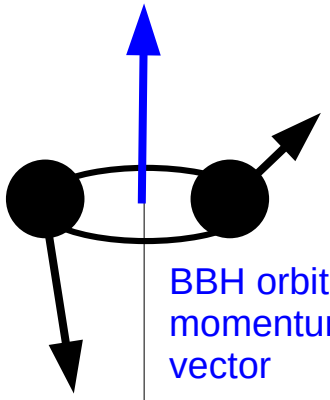




Effective spin: mass weighted component of spins along angular momentum vector

$$\chi_{\rm eff} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2)}{(m_1 + m_2)} \cdot \frac{\vec{L}}{L}$$

$$-1 \leq \chi_{\rm eff} \leq 1$$



Precession spin: parameter measuring dominant spin component in the orbital plane

$$\chi_p = \frac{1}{B_1\, m_1^2} \max(B_1\, S_{1,\perp},\ B_2\, S_{2,\perp}) > 0$$

$$B_1 = 2 + 3\,\frac{q}{2} \qquad B_2 = 2 + \frac{3}{2\,q}$$

Open questions from GWs

1. What determines the MASS of BHs?
2. Are there any MASS GAPS at all?
3. What can we learn from the SPINS?
4. Do BBH populations evolve across the cosmic time?

2. Binary black holes (BBHs) from star 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)

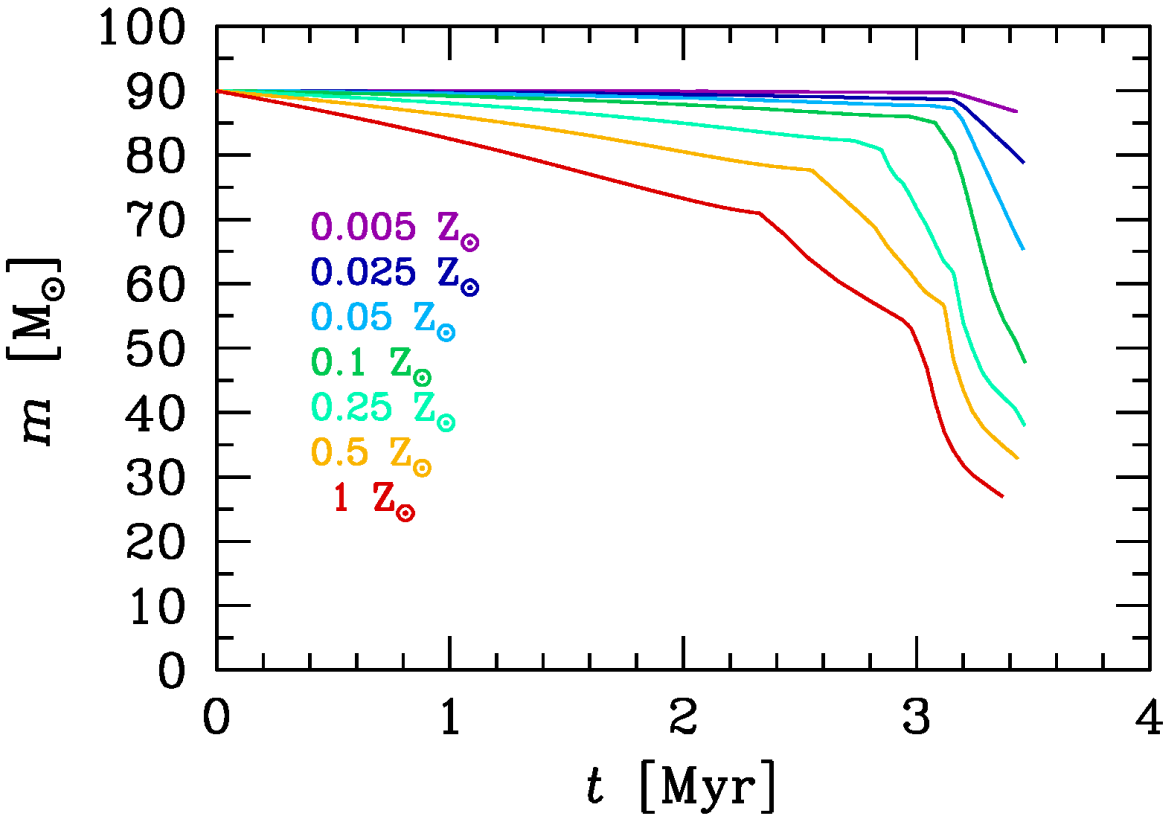
$$\dot{M} \propto Z^{\alpha}$$

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

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

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

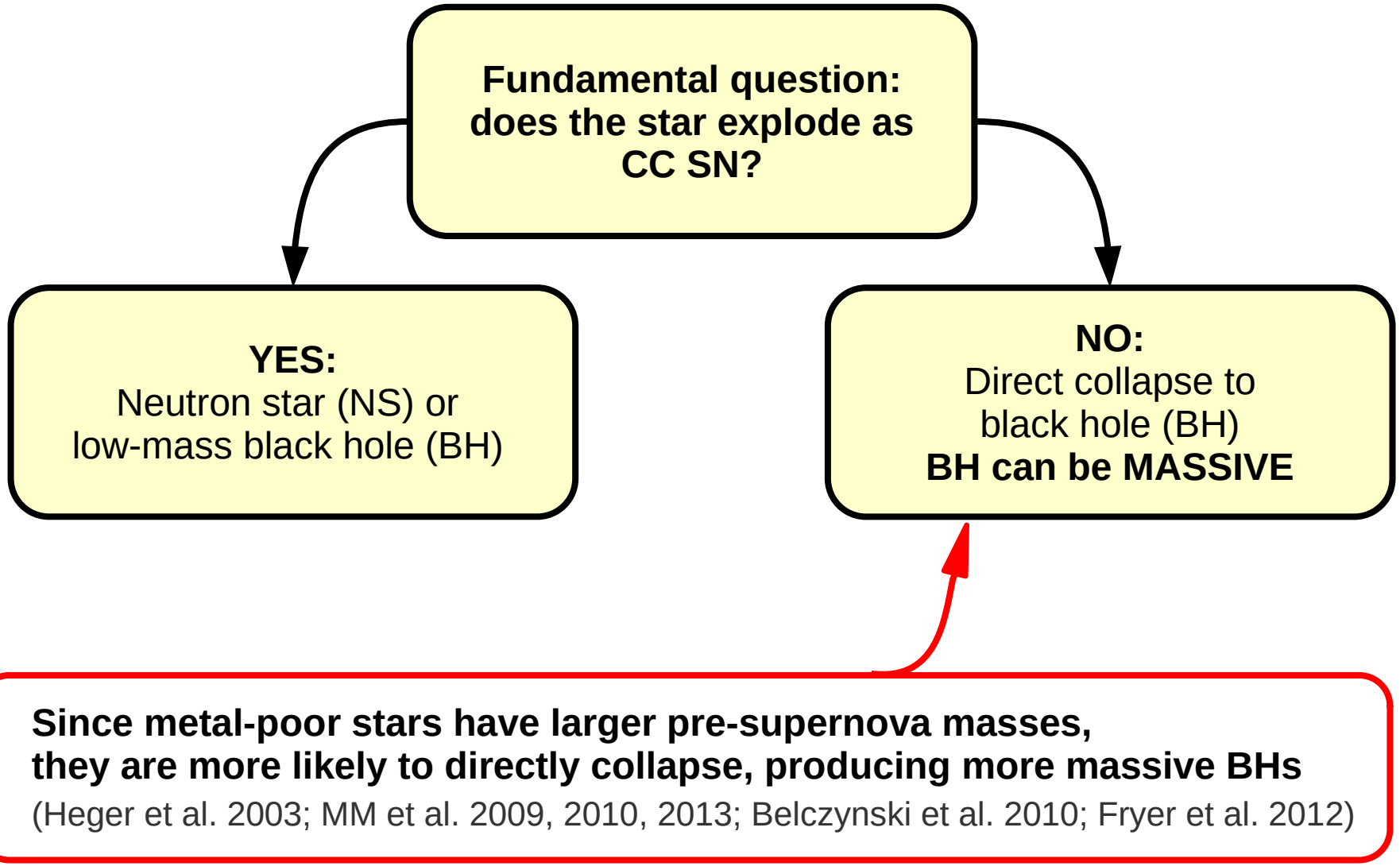
Chen, Bressan et al. (2015)



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

2. Binary black holes (BBHs) from star evolution

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



2. Binary black holes (BBHs) from star evolution

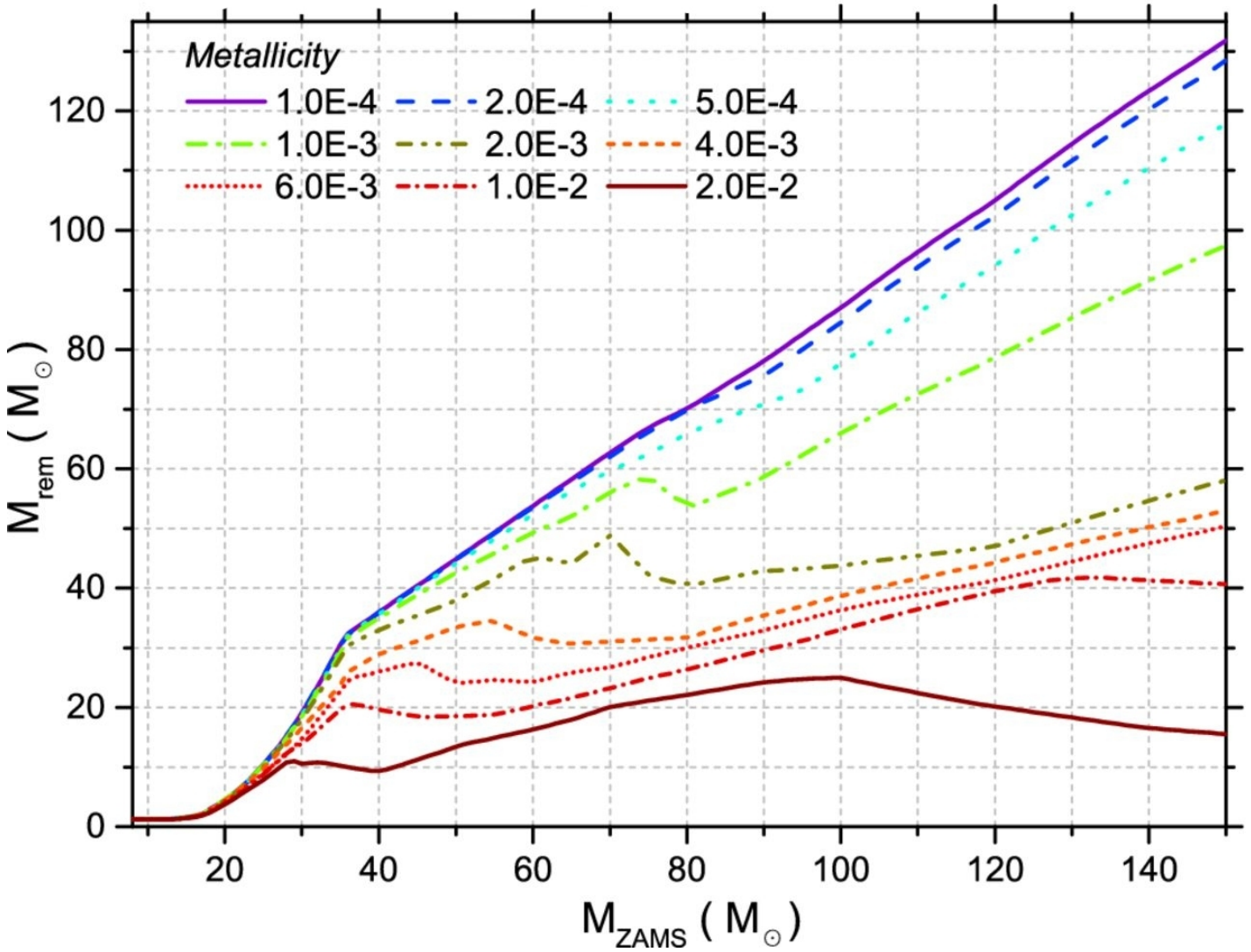


Figure from Spera, MM & Bressan 2015
see also Heger et al. 2003;
MM et al. 2009, 2010, 2013;
Belczynski et al. 2010; Fryer et al. 2012

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

2. Binary black holes (BBHs) from star 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

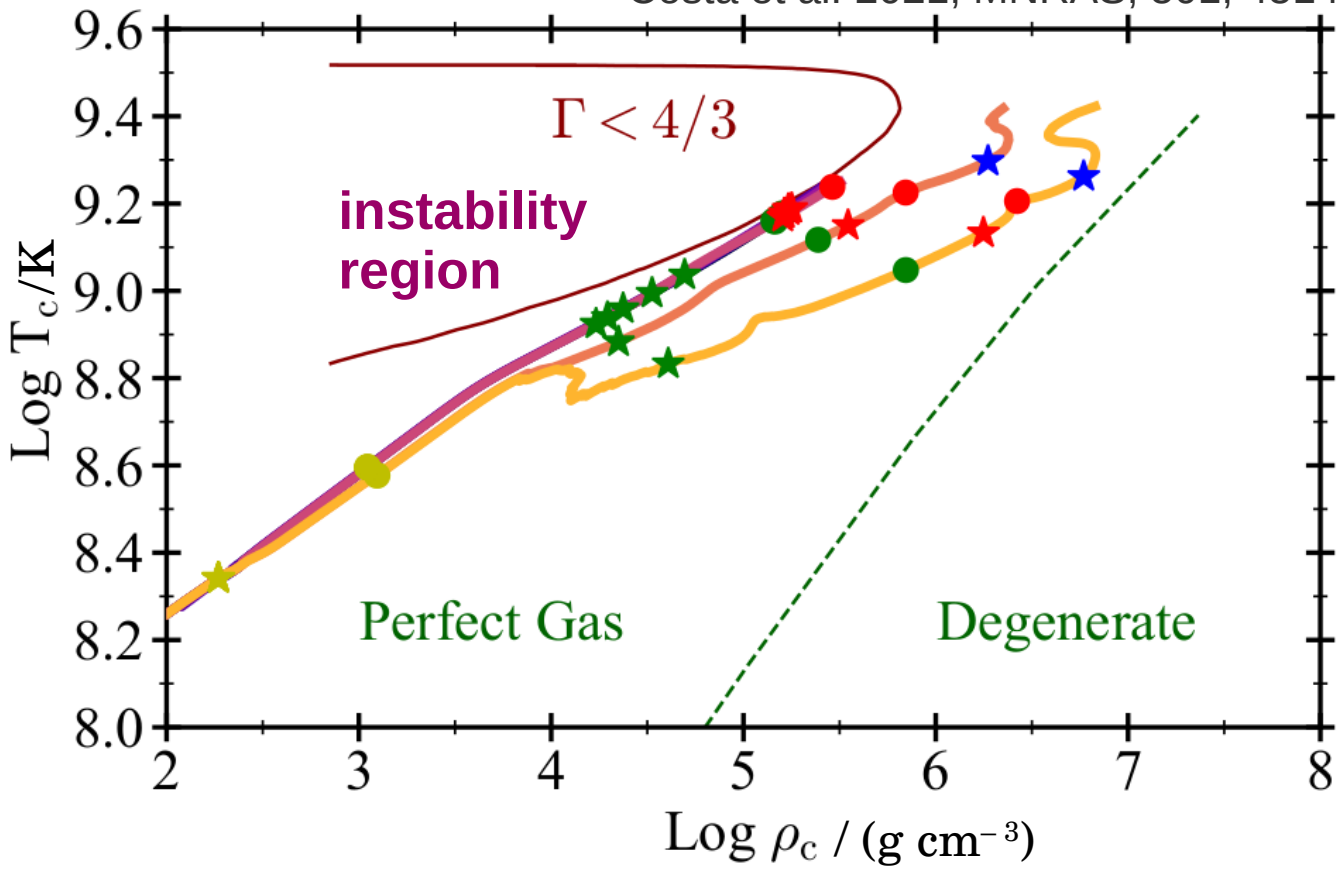
Missing photon pressure
triggers instability:

PAIR INSTABILITY

* contraction of
  stellar core

* premature ignition of
  neon, oxygen, silicon

Costa et al. 2021, MNRAS, 501, 4514

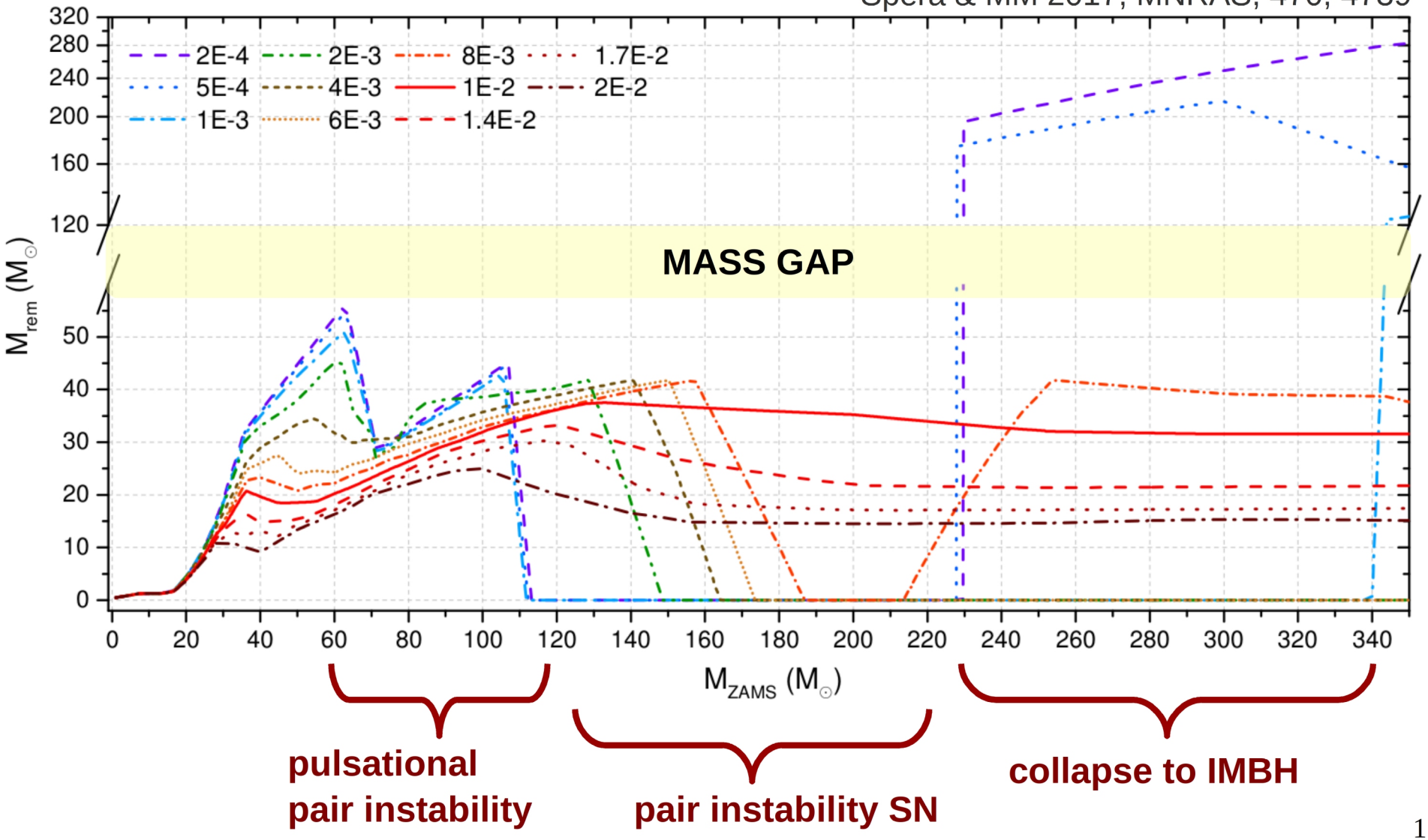


Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

2. Binary black holes (BBHs) from star 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



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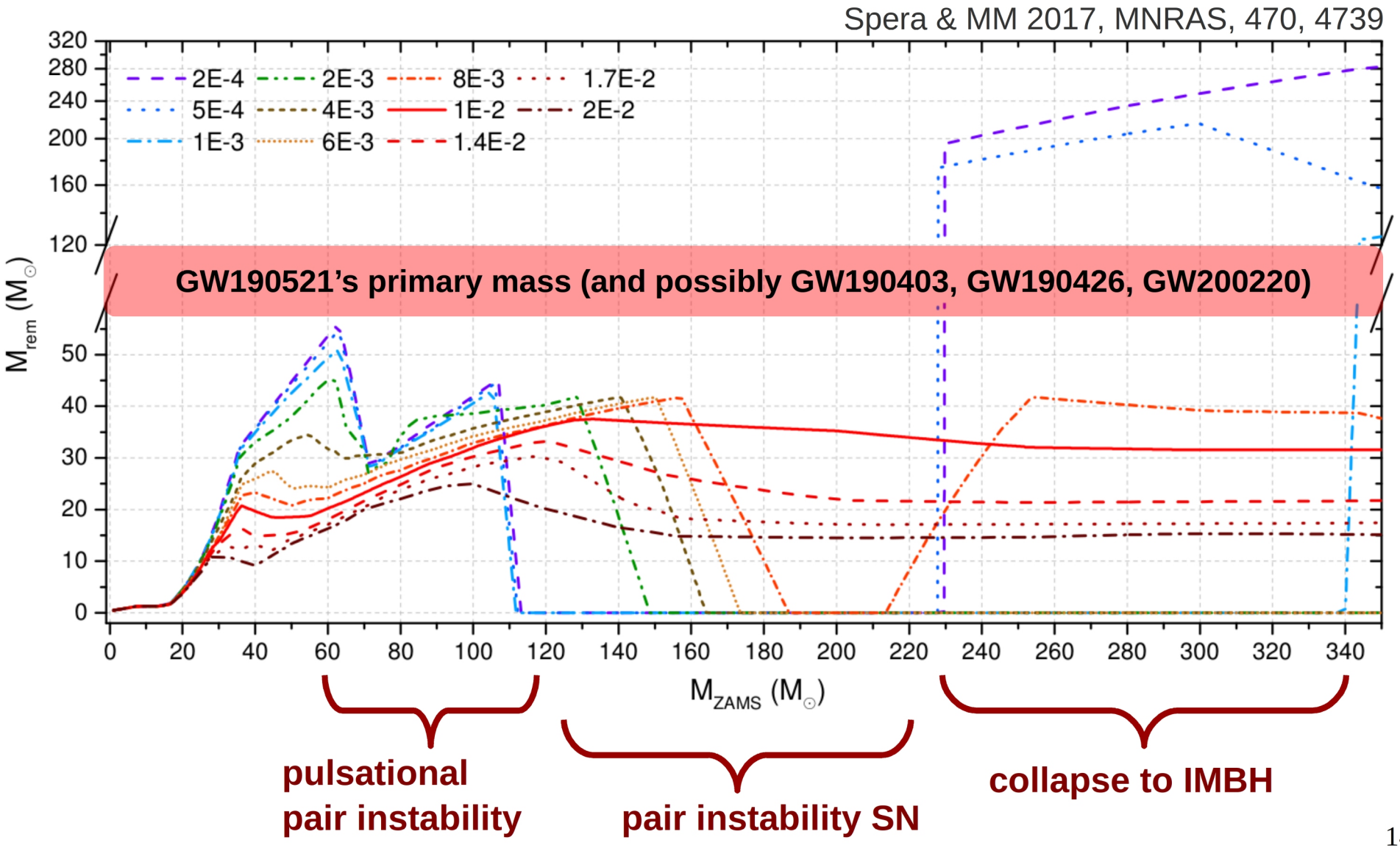
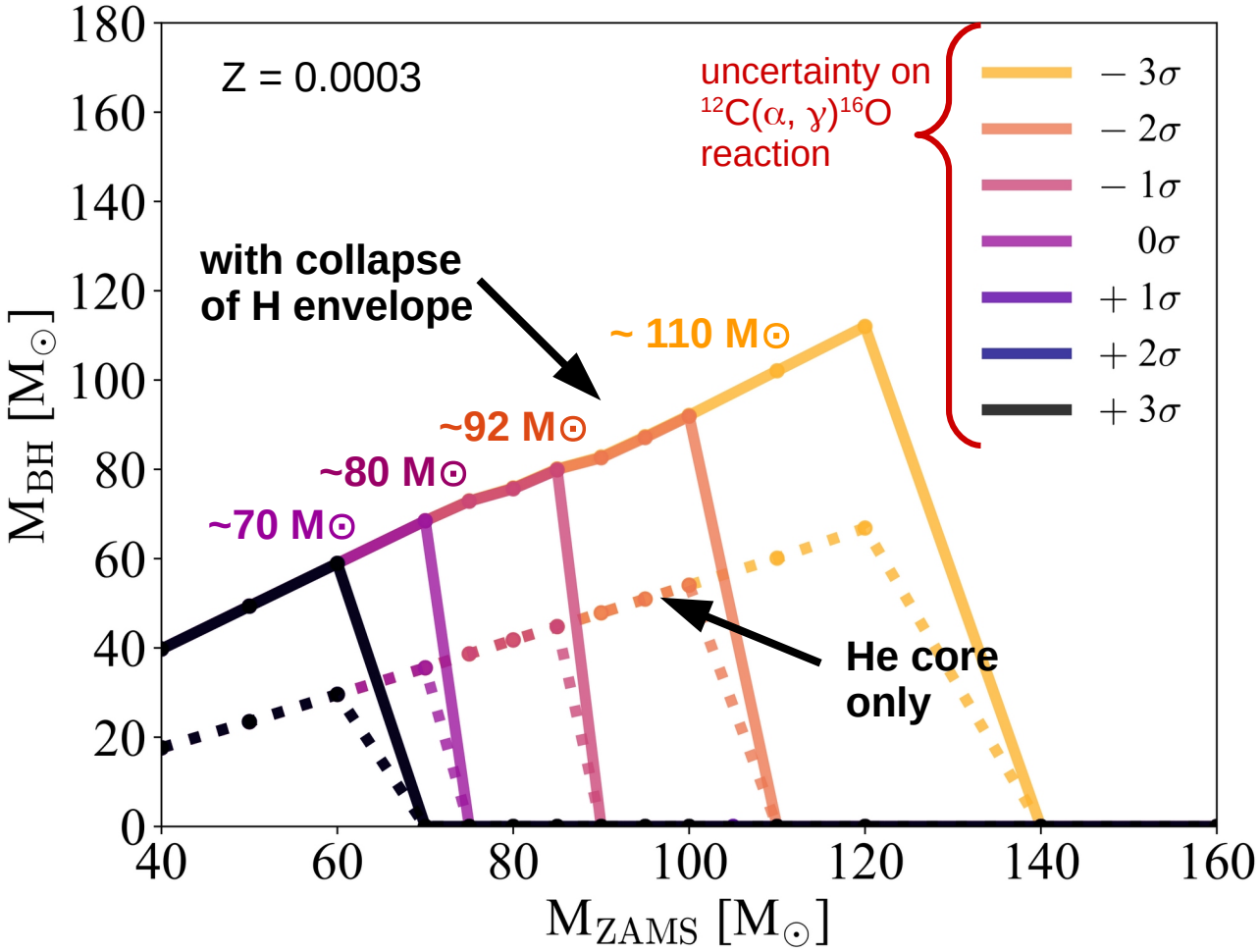


2. Binary black holes (BBHs) from star evolution

IMPACT of H-rich ENVELOPE and nuclear reactions



Costa et al. 2021, MNRAS, 501, 4514

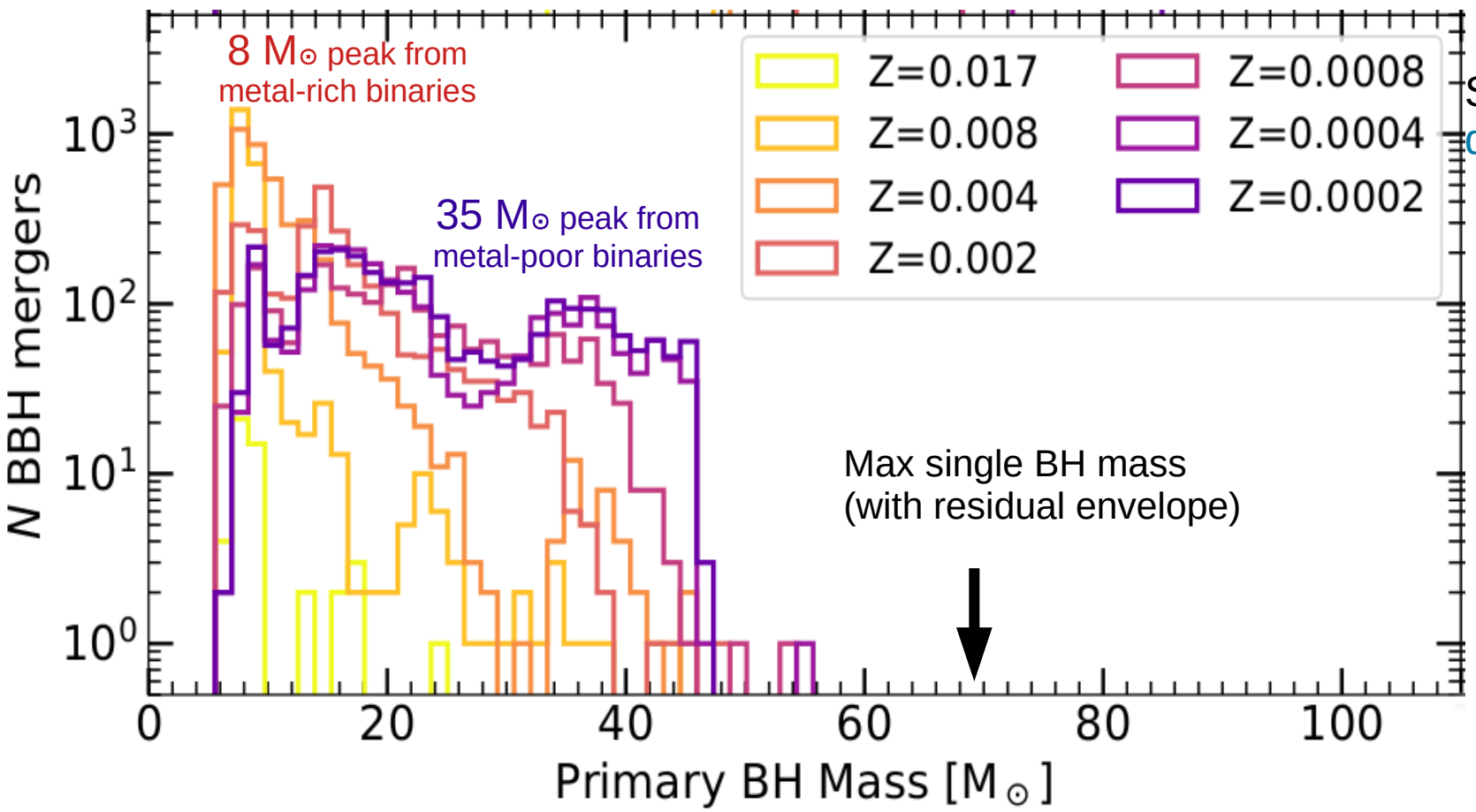
Take-home messages:

1. large uncertainties about upper mass gap boundaries

2. **envelope collapse results in large BH mass**

   BUT stars in tight binary systems **shed their envelope by stripping**

2. Binary black holes (BBHs) from star evolution



SEVN code
download link

Iorio, MM, et al. 2023

* High-Z peak at 8 – 10 $M_\odot$ and low-Z peak at ~35 $M_\odot$

* BHs with mass ≤ 50 $M_\odot$ merge in isolation (even if max BH mass ~ 65 $M_\odot$)
  because of envelope stripping in binary evolution

2. Binary black holes (BBHs) from dynamics

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

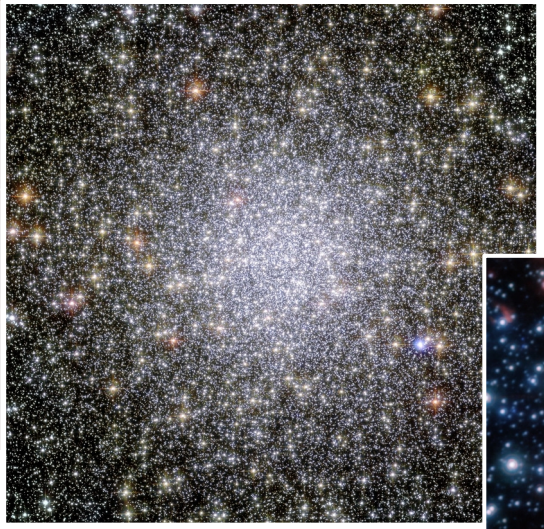
i.e. only in dense star clusters

but massive stars (BH progenitors) form in star clusters

(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; Portegies Zwart et al. 2010)

R136, credit: NASA

Young star clusters



47 Tucanae, credit: NASA/ESA/HST

Nuclear star clusters

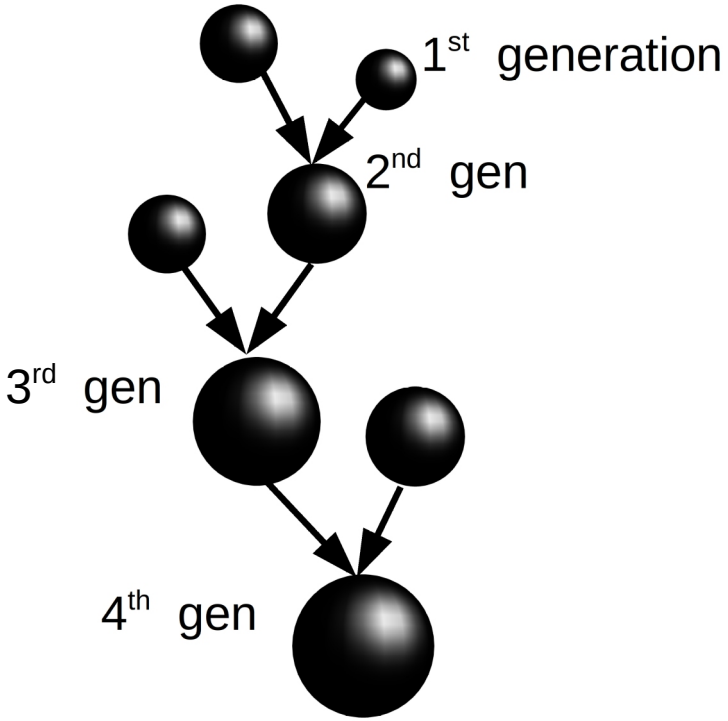
Globular clusters

Credit: ESO, Gillessen et al.

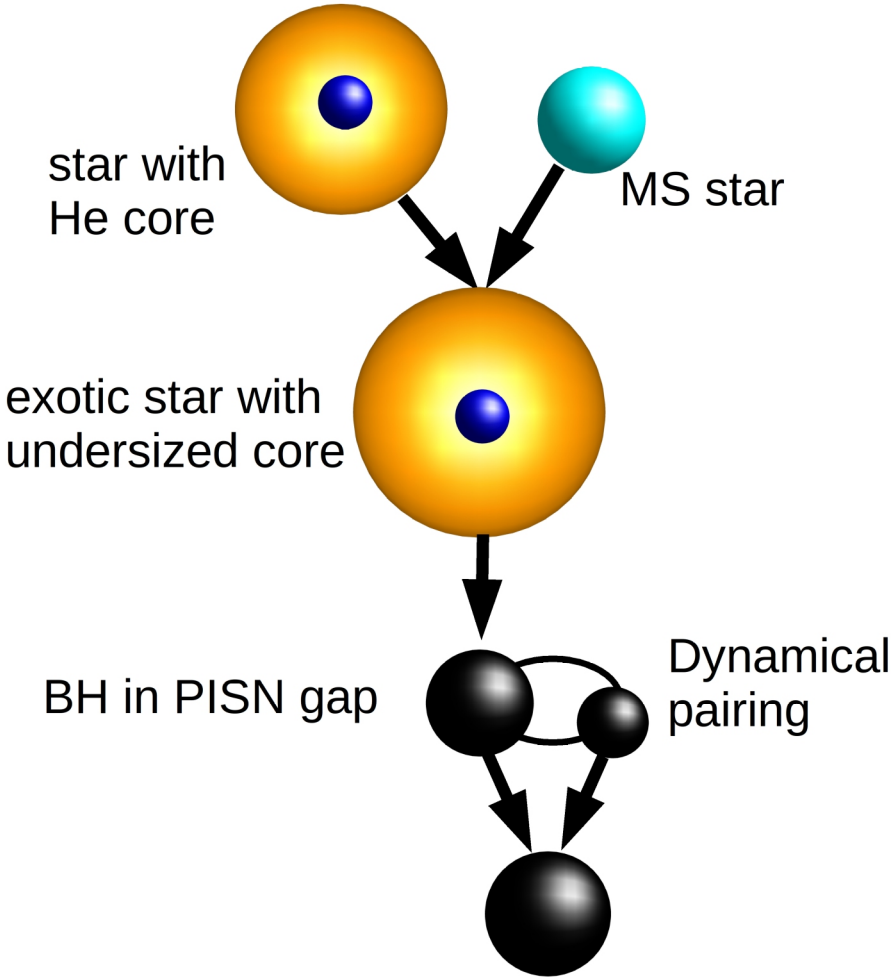
2. Binary black holes (BBHs) from dynamics

HIERARCHICAL MERGERS

Miller & Hamilton 2002



STAR – STAR COLLISIONS



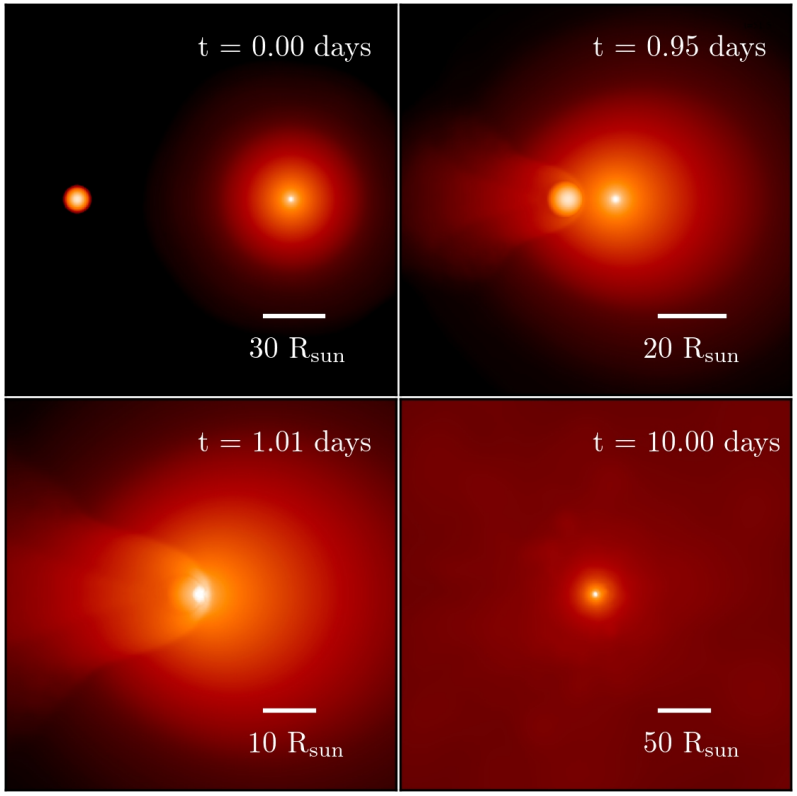
Di Carlo et al. 2019
Di Carlo et al. 2020

2. Binary black holes (BBHs) from dynamics: star – star collisions

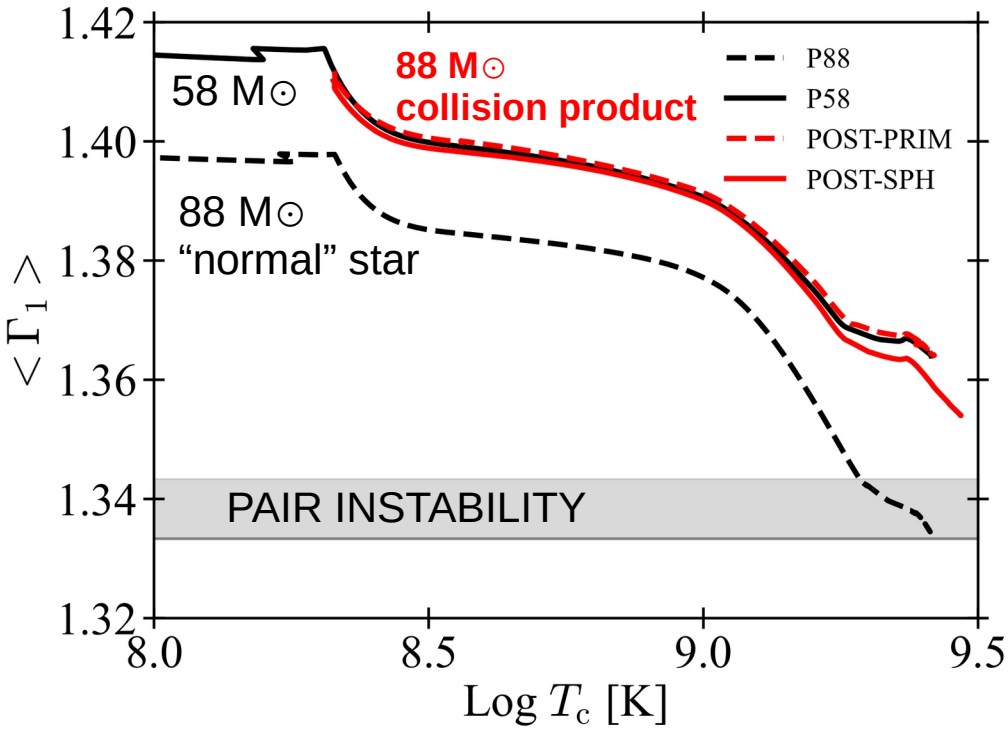
Mass loss during collision and further evolution?
→ needs hydro-dynamical simulations of the collision
→ needs accurate stellar evolution model

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

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



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

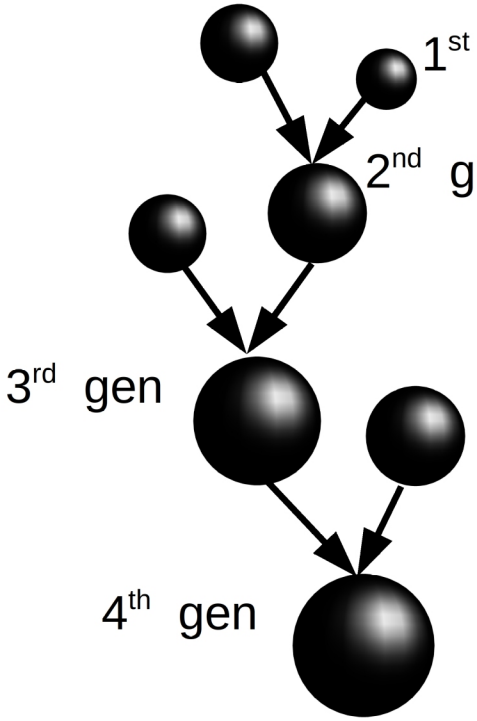
The collision product avoids pair instability (like a 58 M⊙ star)
→ final BH mass ~ 87 M⊙

Costa et al. 2022, arXiv:2204.03492

2. Binary black holes (BBHs) from dynamics: star – star collisions

HIERARCHICAL MERGERS

Miller & Hamilton 2002



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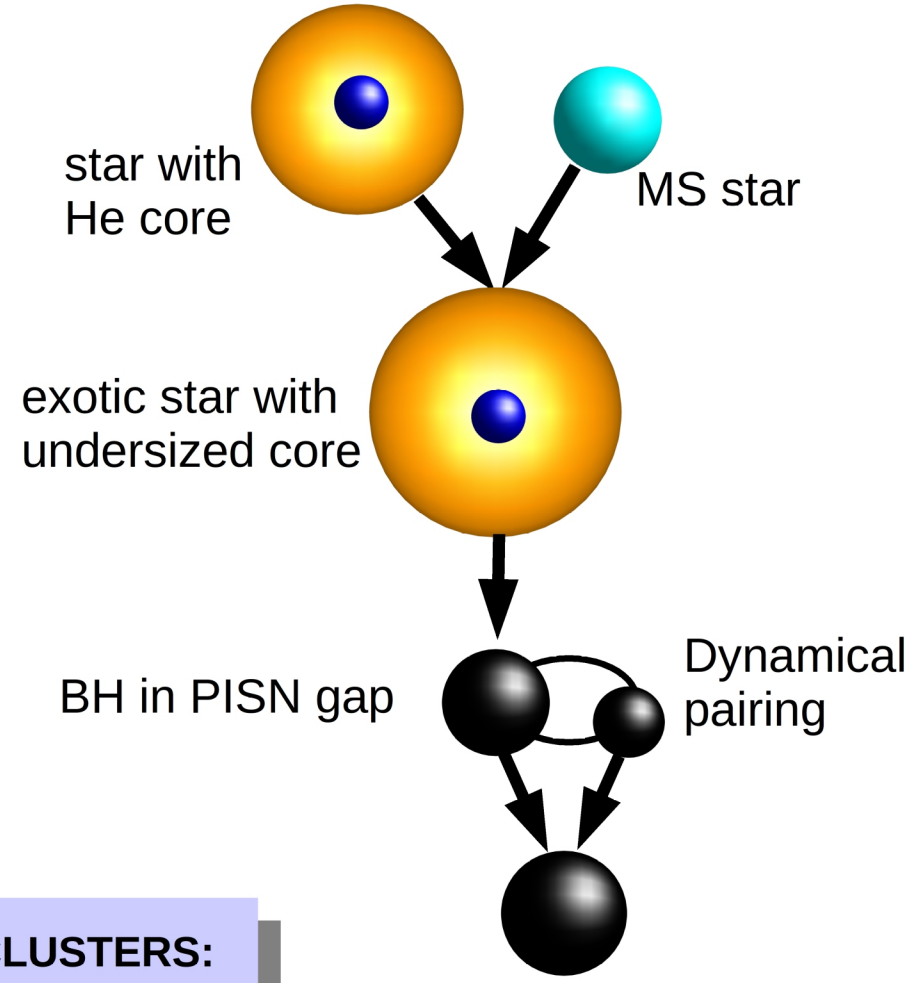


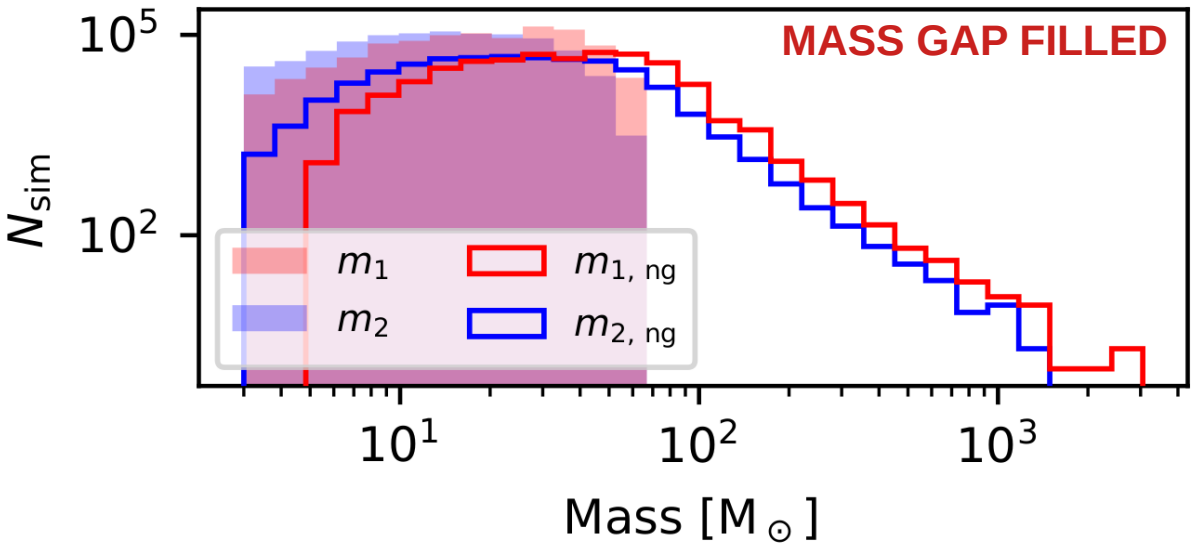
Di Carlo et al. 2019
Di Carlo et al. 2020

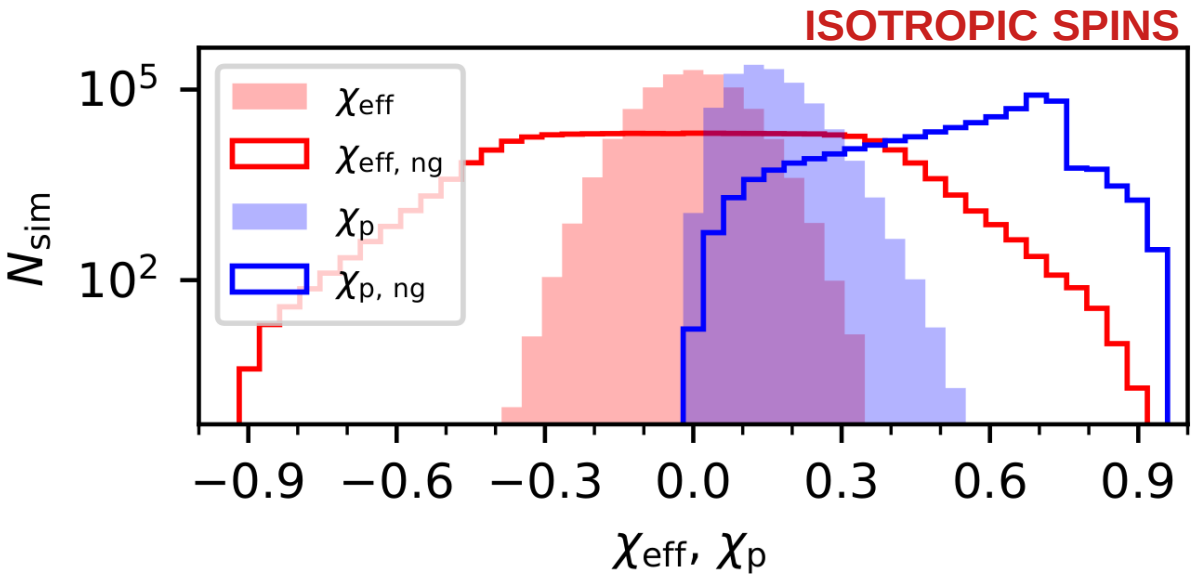
LARGE PARAMETER SPACE & VERY MASSIVE CLUSTERS:

IMPOSSIBLE TO PROBE WITH N-BODY SIMULATIONS

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

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





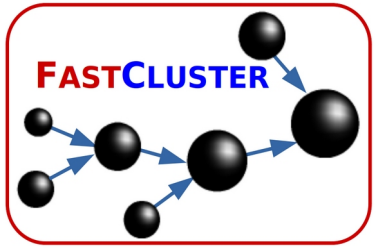
MM et al. 2021
MM et al. 2022

Filled histograms: first generation BBH mergers

Unfilled histograms: 2nd or Nth generation BBH mergers

χ_{eff} → measuring spin components **aligned with orbital angular momentum**

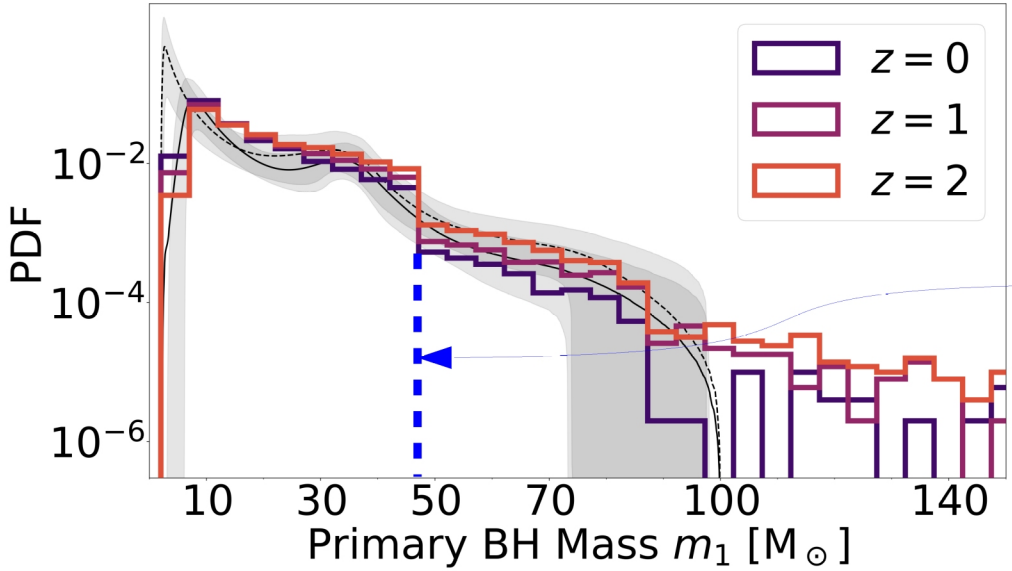
χ_p → measuring spin components **in the orbital plane**



dynamics population code FASTCLUSTER: open-source version available at this link

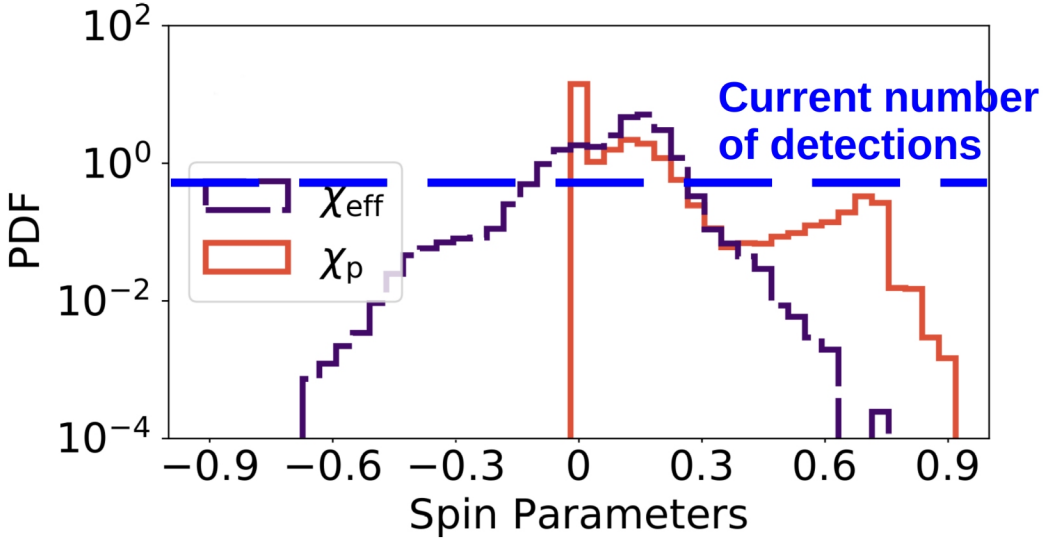
2. Black holes (BHs) in the pair-instability mass gap: hierarchical

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



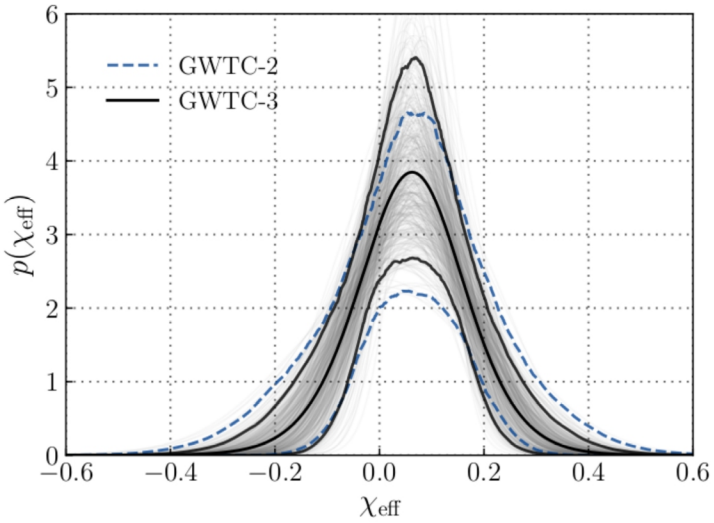
Hierarchical mergers essential to explain the most massive LVK BHs

Max mass of 1g BHs in our input model



MM et al. 2022

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



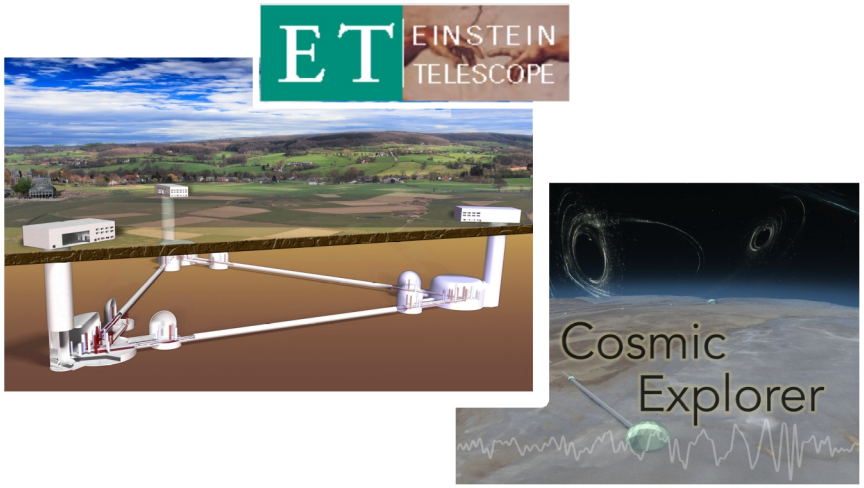
Abbott et al. 2022, population

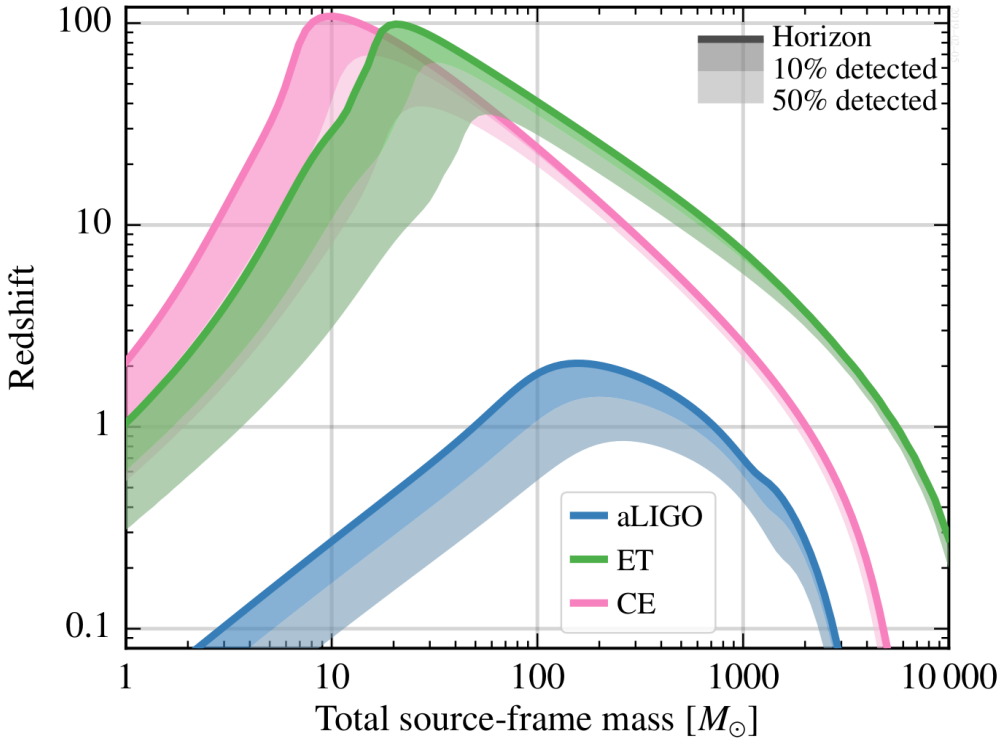
3. BHs from metal-poor and metal-free stars

Einstein Telescope (ET) and Cosmic Explorer will observe BBH mergers at Cosmic Dawn

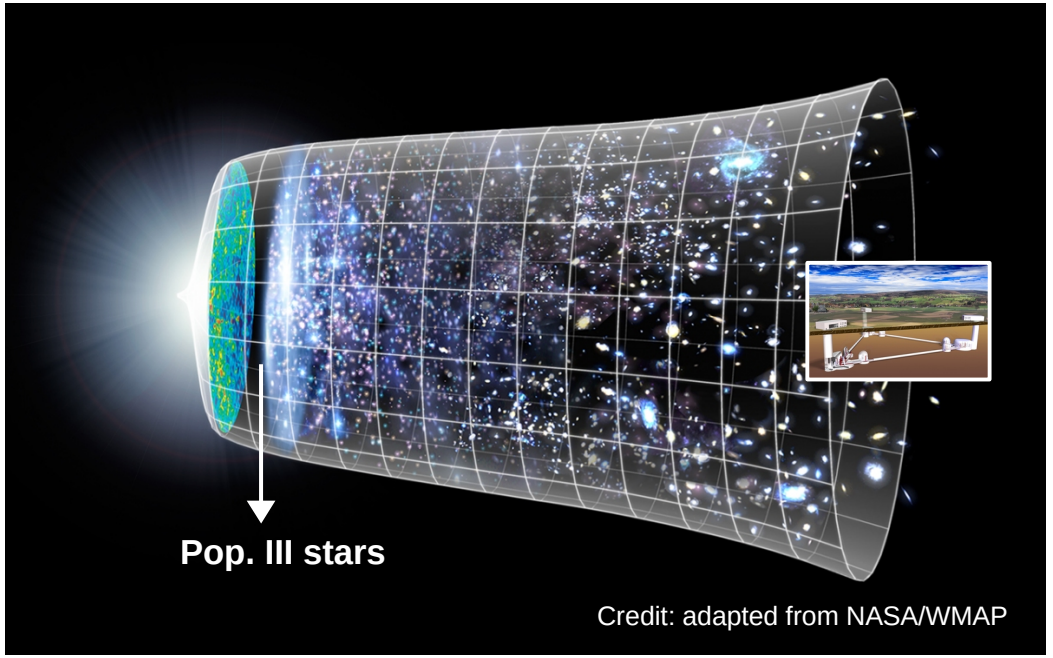
ET first light: 2035 (expected)

Join ET observation science board now



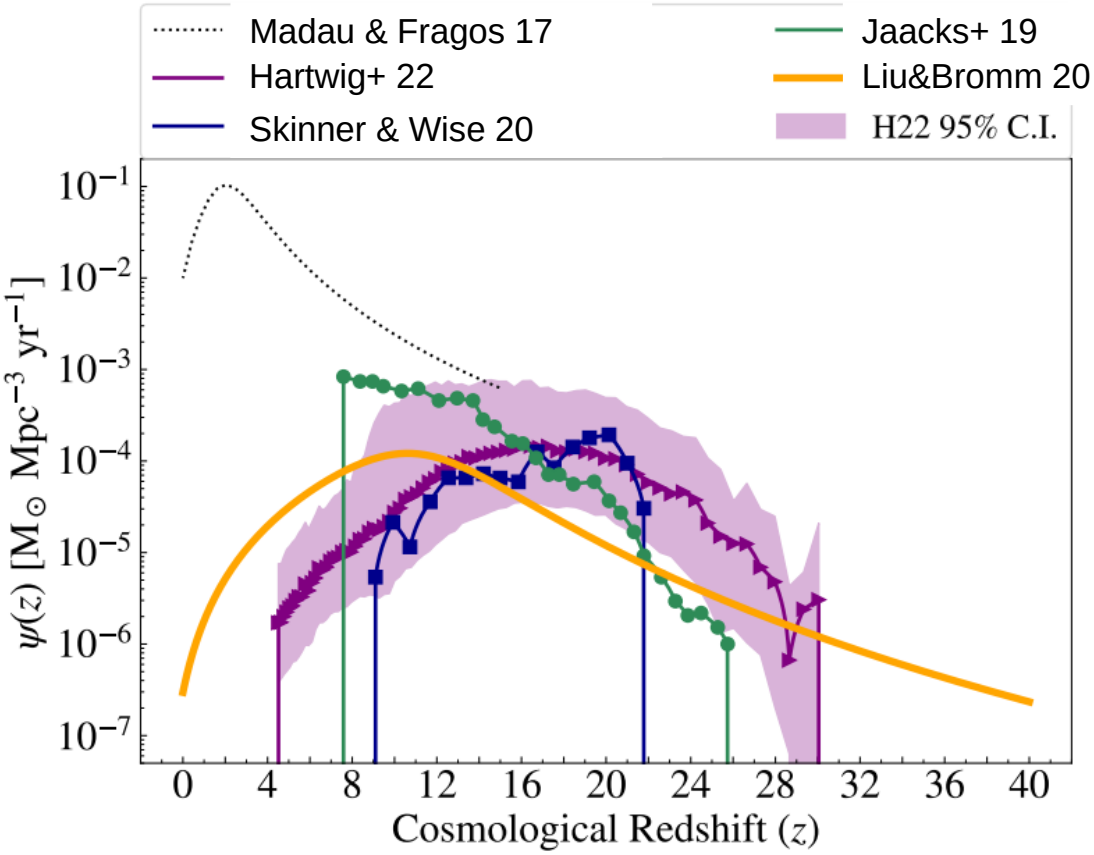


Branchesi et al. 2023



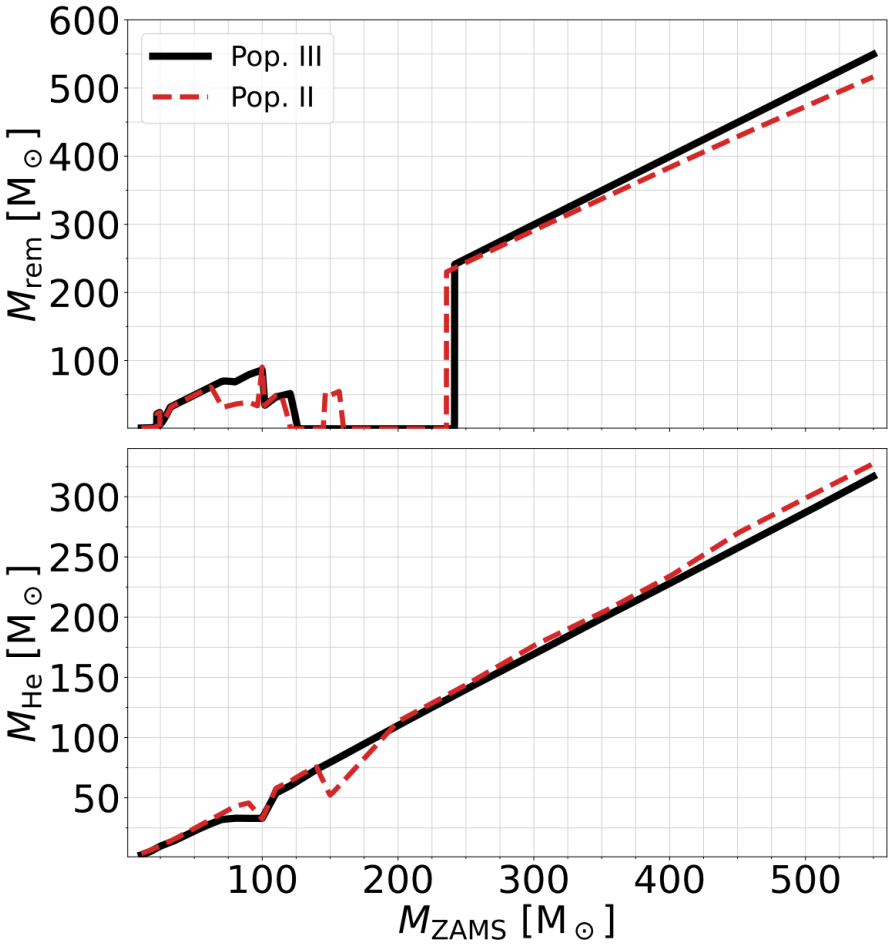
3. BHs from metal-poor and metal-free stars

SFR Pop. III stars versus I – II



Santoliquido, MM et al. 2023

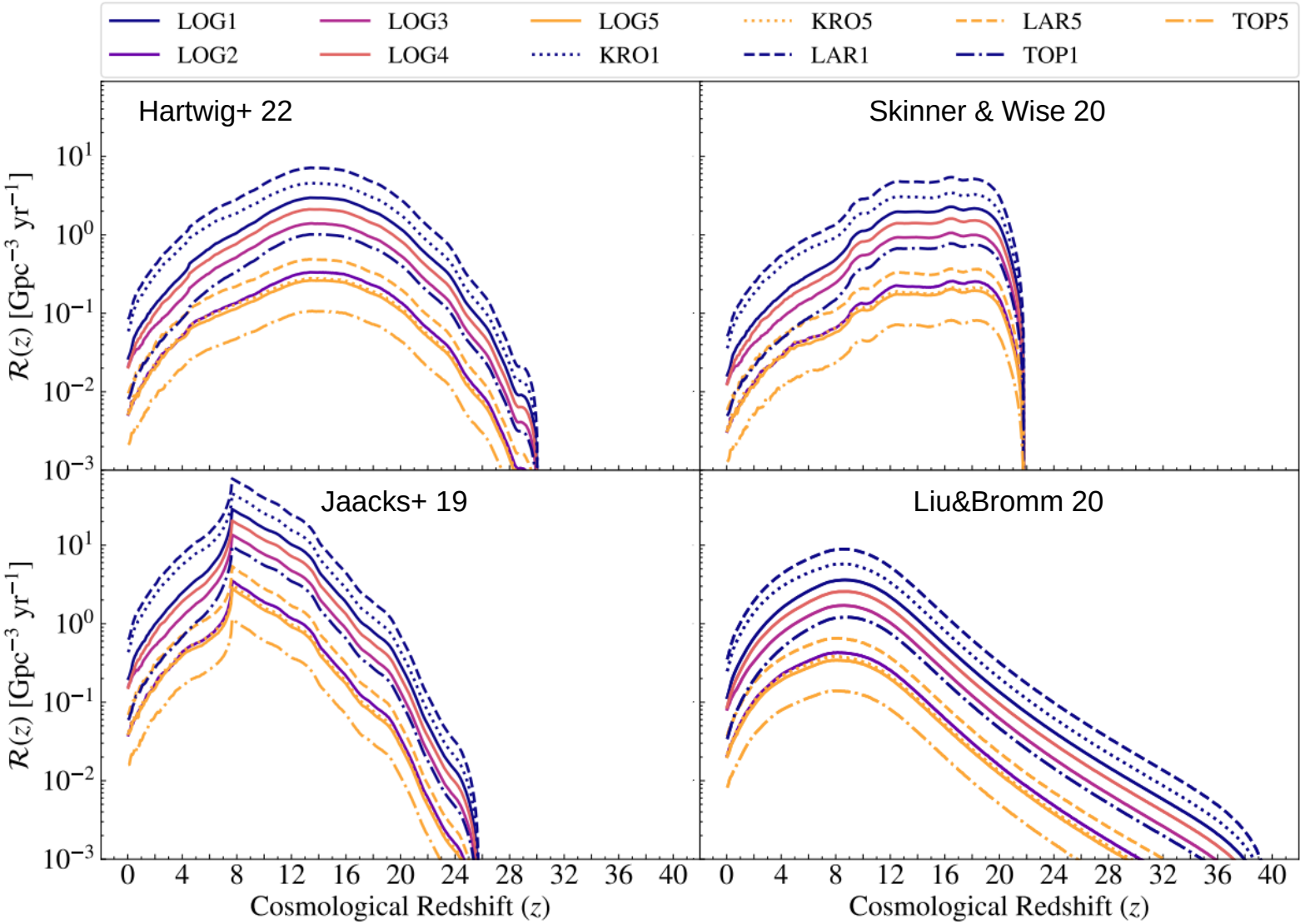
BH mass: Pop. III and Pop. II



Costa, MM, et al. 2023

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

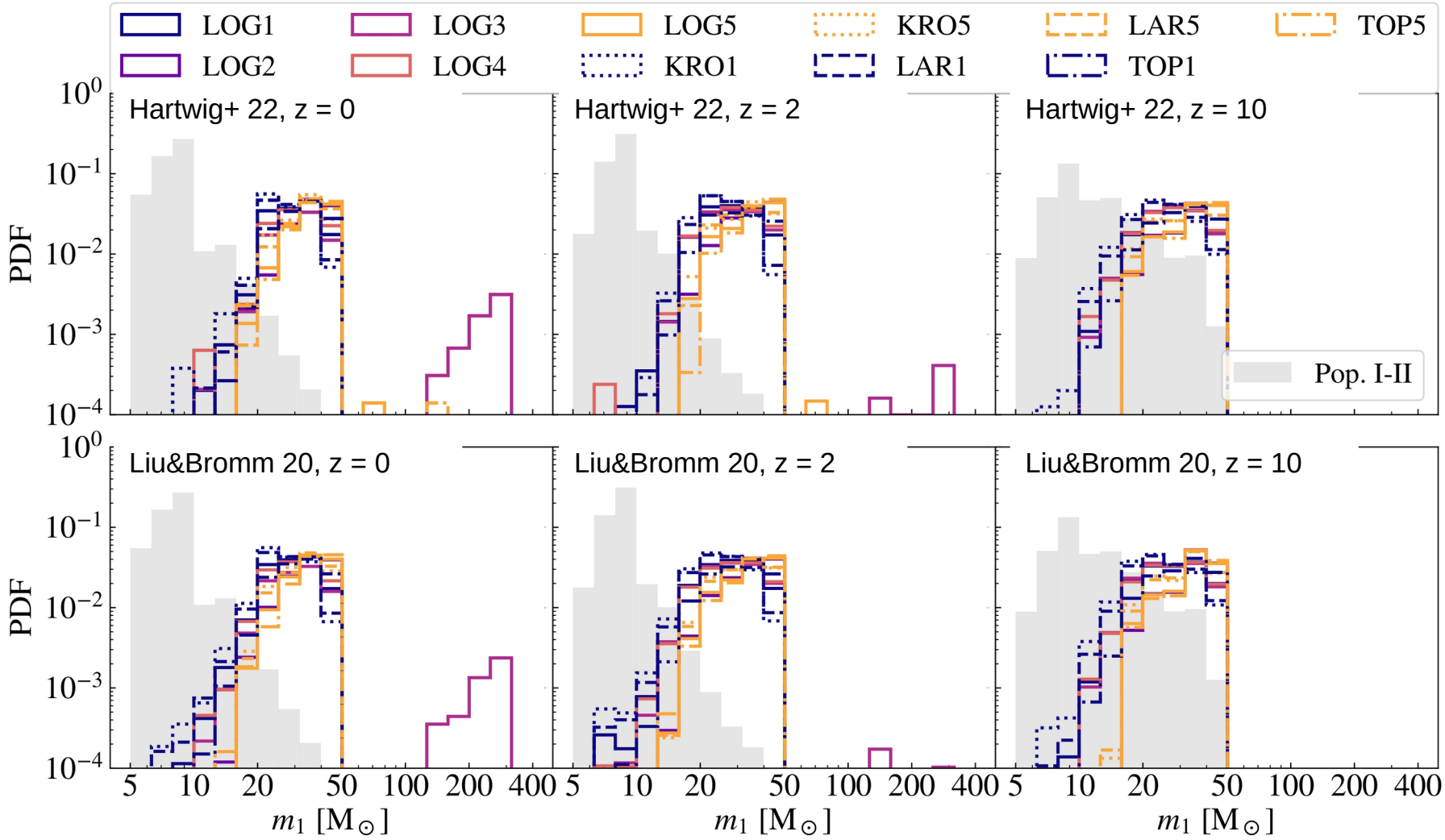
Merger rate density of BBHs from Pop. III stars: uncertainty



Santoliquido, MM et al. 2023

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**

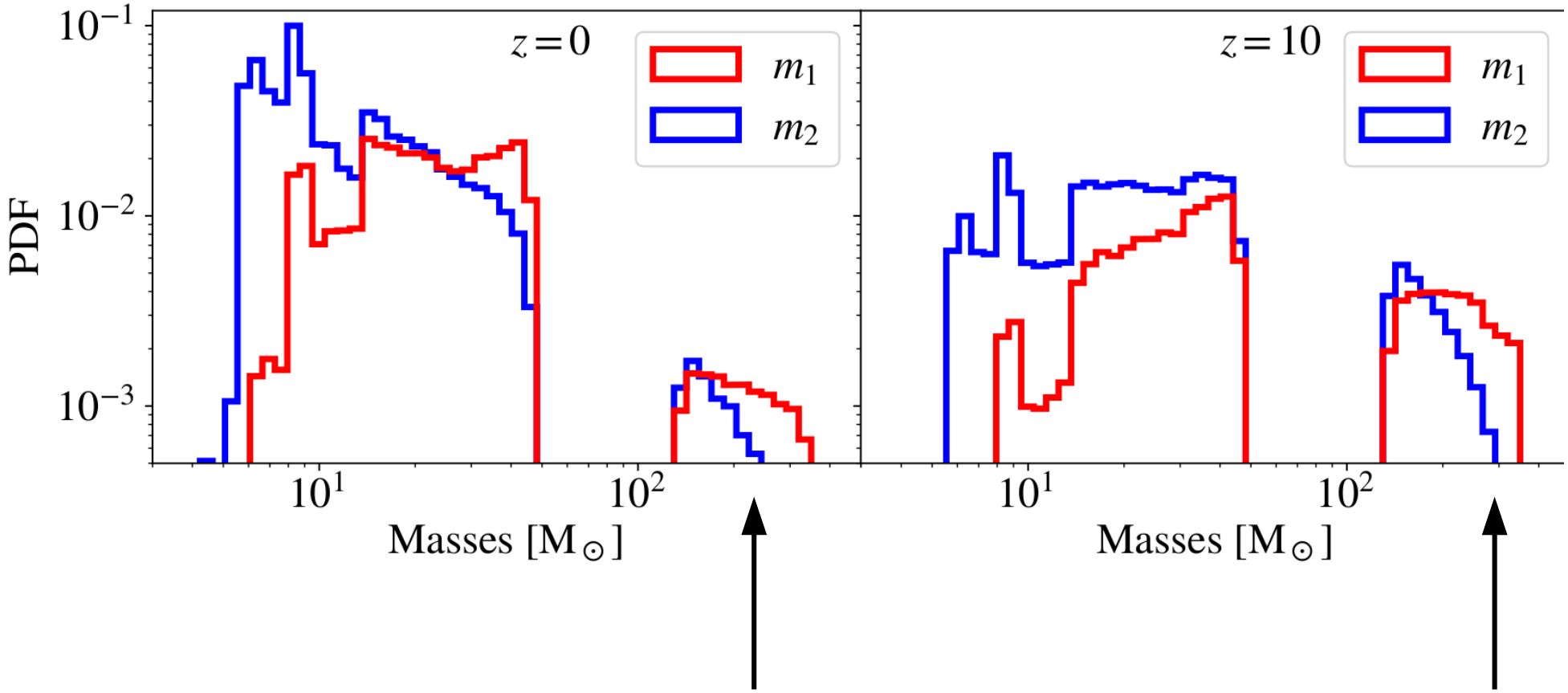


Santoliquido, MM et al. 2023

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

What about intermediate-mass black holes from Pop III stars?

We need star cluster dynamics and/or chemically homogeneous evolution



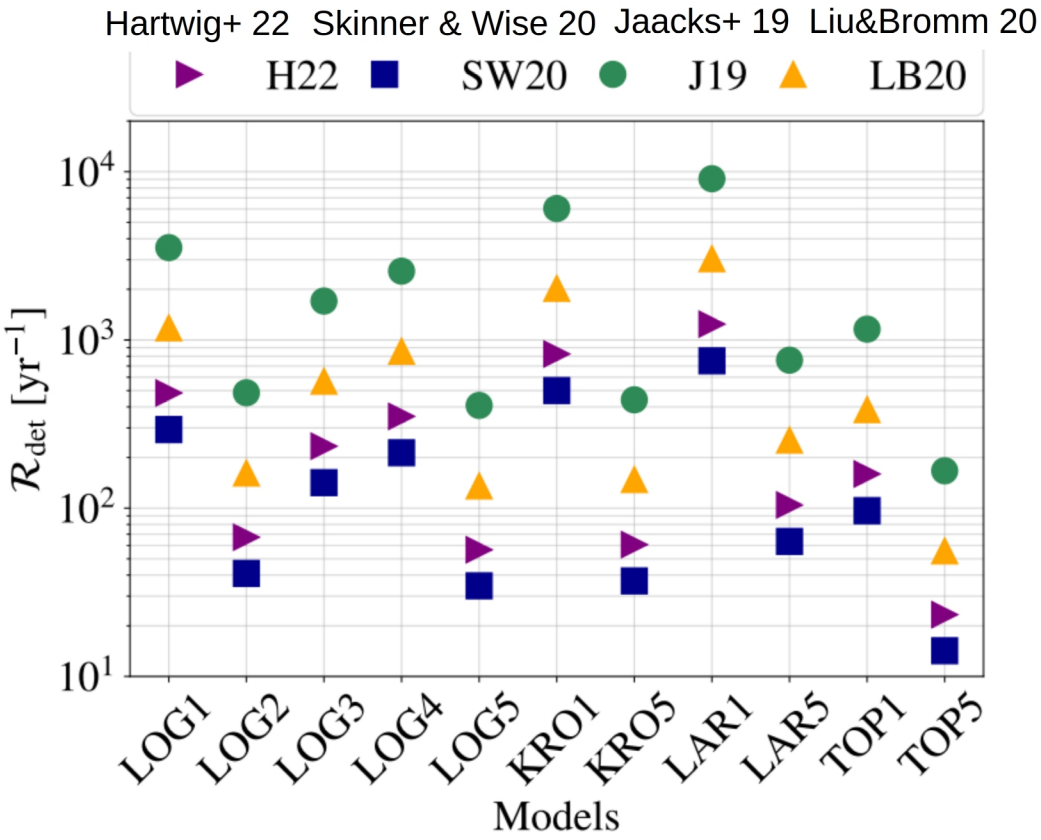
IMBHs from chemically homogeneous Pop III stars

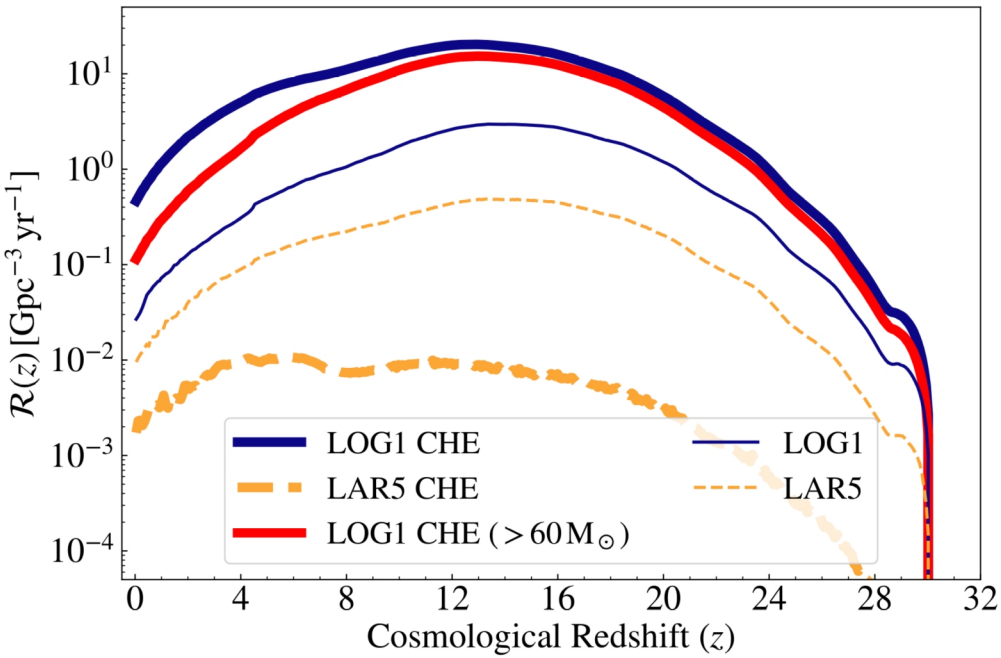
Santoliquido, MM et al. 2023

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

Detections from ET

Mass-gap BHs are rare without dynamics





Santoliquido, MM et al. 2023

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4. Conclusions

* LVK data start probing the mass function and spin of BBHs

* Pair instability opens a mass gap in the BH mass spectrum ~ 60 – 120 $M_\odot$
(Spera & MM 2017)

  but uncertainties on H envelope collapse, rotation and nuclear reaction rates still allow for narrower mass gap range
(MM et al. 2020; Costa et al. 2021)

* Dynamics could fill the pair-instability gap with star – star collisions and hierarchical mergers
(MM 2016; Di Carlo et al. 2019, 2020; Bouffanais et al. 2022; MM et al. 2021, 2022; Ballone et al. 2023; Costa et al. 2023)

* Next-generation detectors will probe BBH mergers out to z ~ 30 (or higher)
  – large uncertainties on rate from different models
  – possibility to observe Pop. III stars via their compact remnants
  – primary BH mass of Pop. III and II peaks at ~30 – 40 $M_\odot$
(Costa et al. 2023; Santoliquido et al. 2023)

THANK YOU