SIMULATING INTERMEDIATE-MASS BLACK HOLES IN THE FIRST STAR CLUSTERS

BENEDETTA MESTICHELLI

XV ET SYMPOSIUM - 27/05/2025

IN COLLABORATION WITH: MANUEL ARCA SEDDA, MARICA BRANCHESI, MICHELA MAPELLI, STEFANO TORNIAMENTI, GIULIANO IORIO, GUGLIELMO COSTA, FILIPPO SANTOLIQUIDO, ALESSANDRO LUPI, MARTA VOLONTERI

WHAT IS AN INTERMEDIATE-MASS BLACK HOLE?

Stellar-mass BHs

$$m_{\rm BH} \sim 5 - 10^2\,{\rm M}_\odot$$

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Supermassive BHs

$m_{\mathrm{BH}} \gtrsim 10^5\,\mathrm{M}_\odot$

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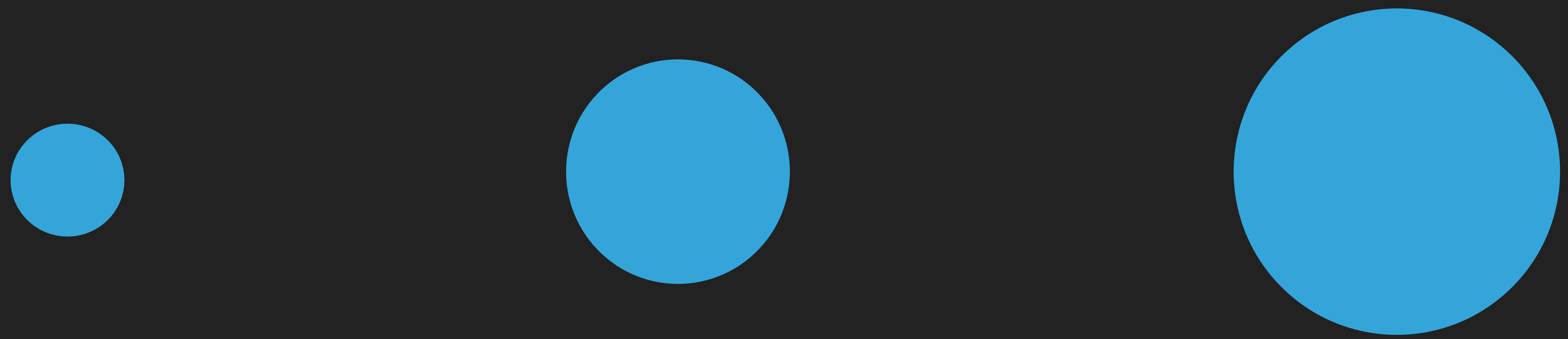


Stellar-mass BHs

$m_{\mathrm{BH}} \sim 5 - 10^2\,\mathrm{M}_\odot$

Intermediate-mass BHs

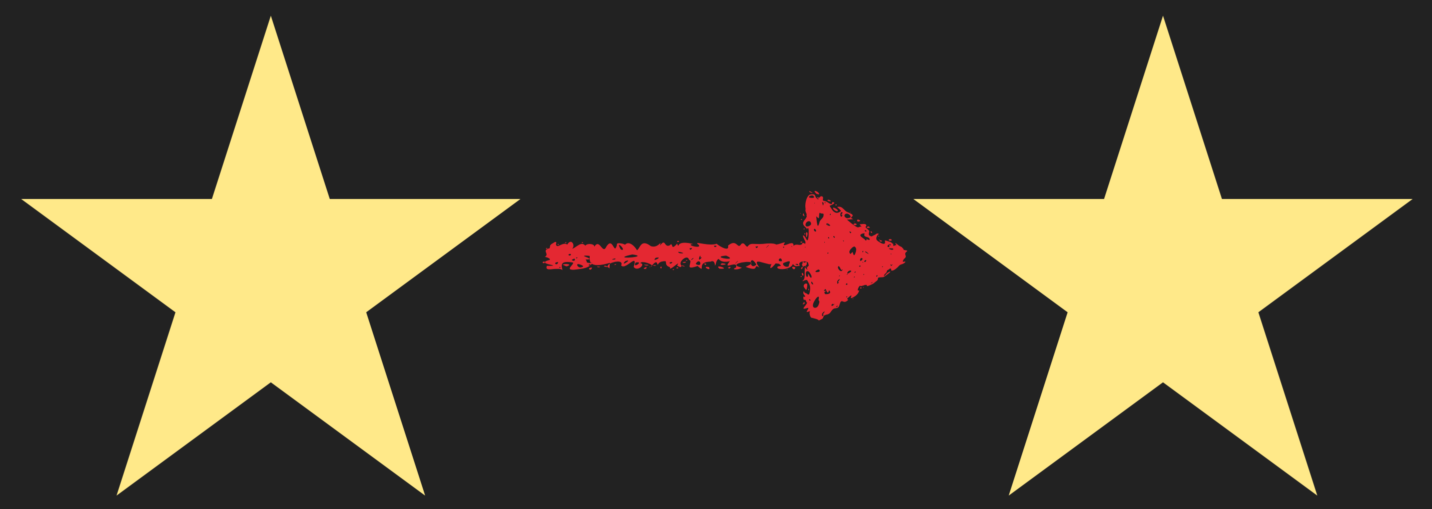
$m_{\mathrm{BH}} \sim 10^2 - 10^5\,\mathrm{M}_\odot$

Supermassive BHs

$m_{\mathrm{BH}} \gtrsim 10^5\,\mathrm{M}_\odot$

POPULATION III STARS

- **Metal-free**
  (Haiman et al. 1996; Yoshida et al. 2003)



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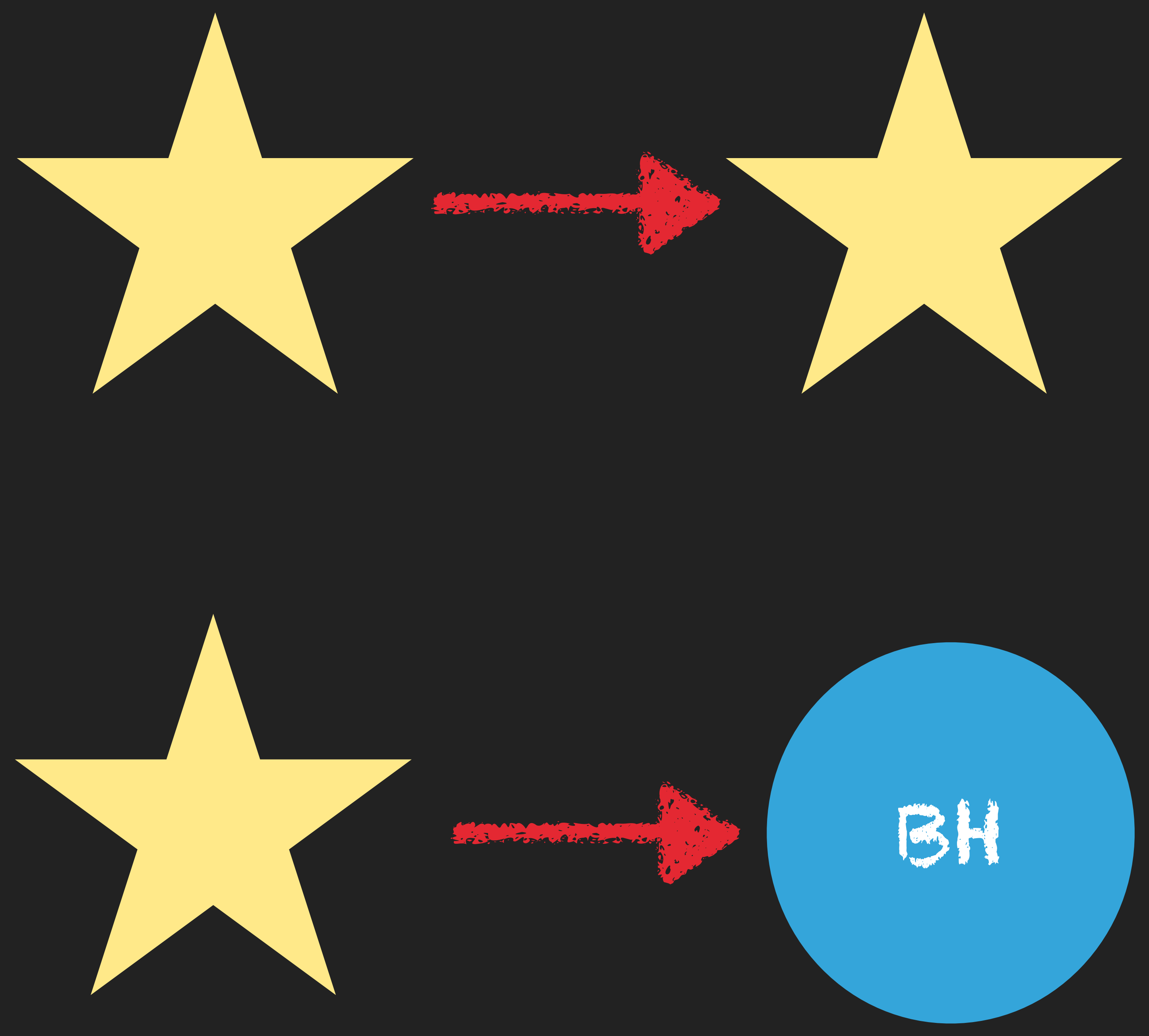

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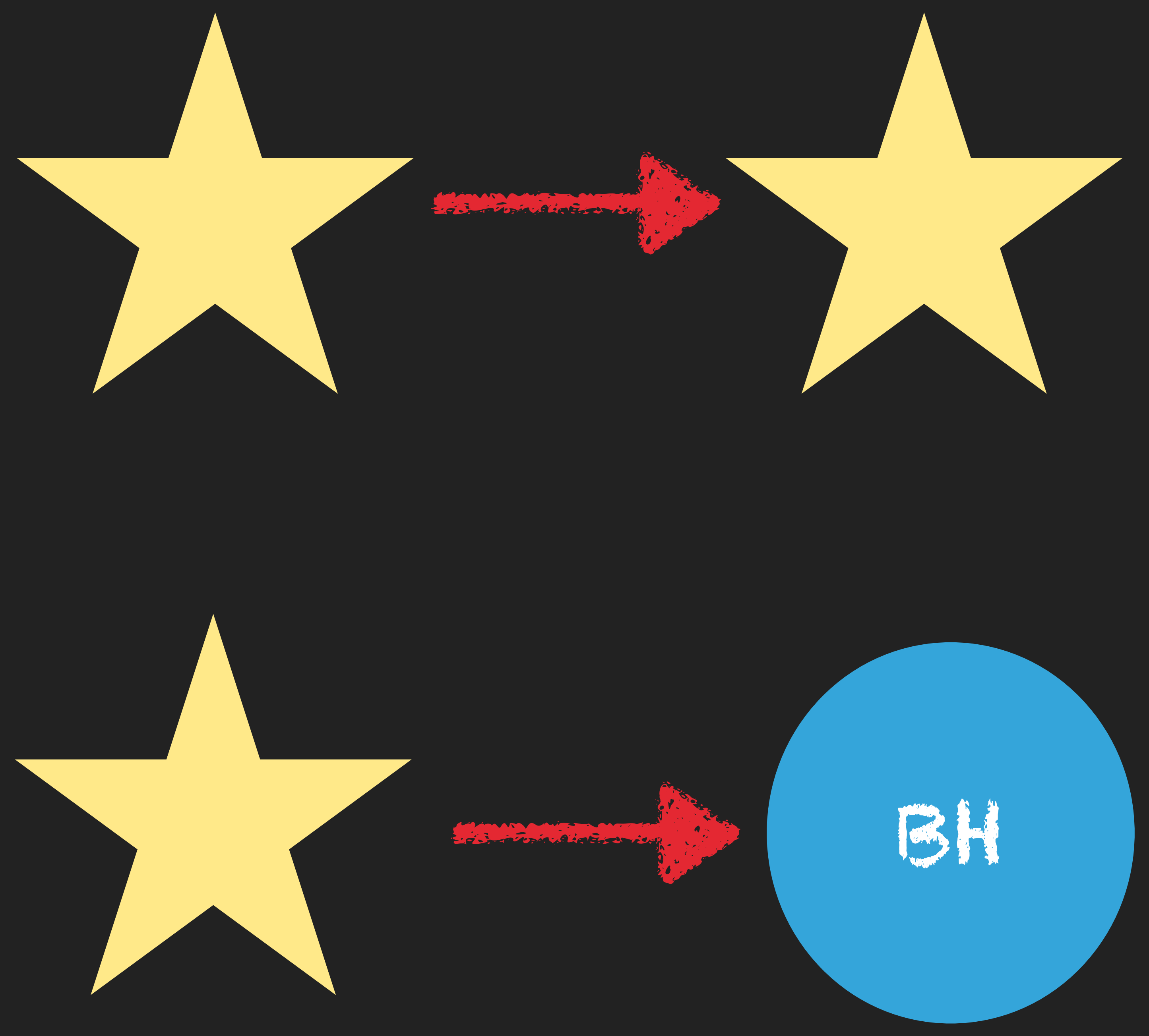
- Form at **high redshift** $z \gtrsim 20$
  (e.g. Hartwig et al. 2022)



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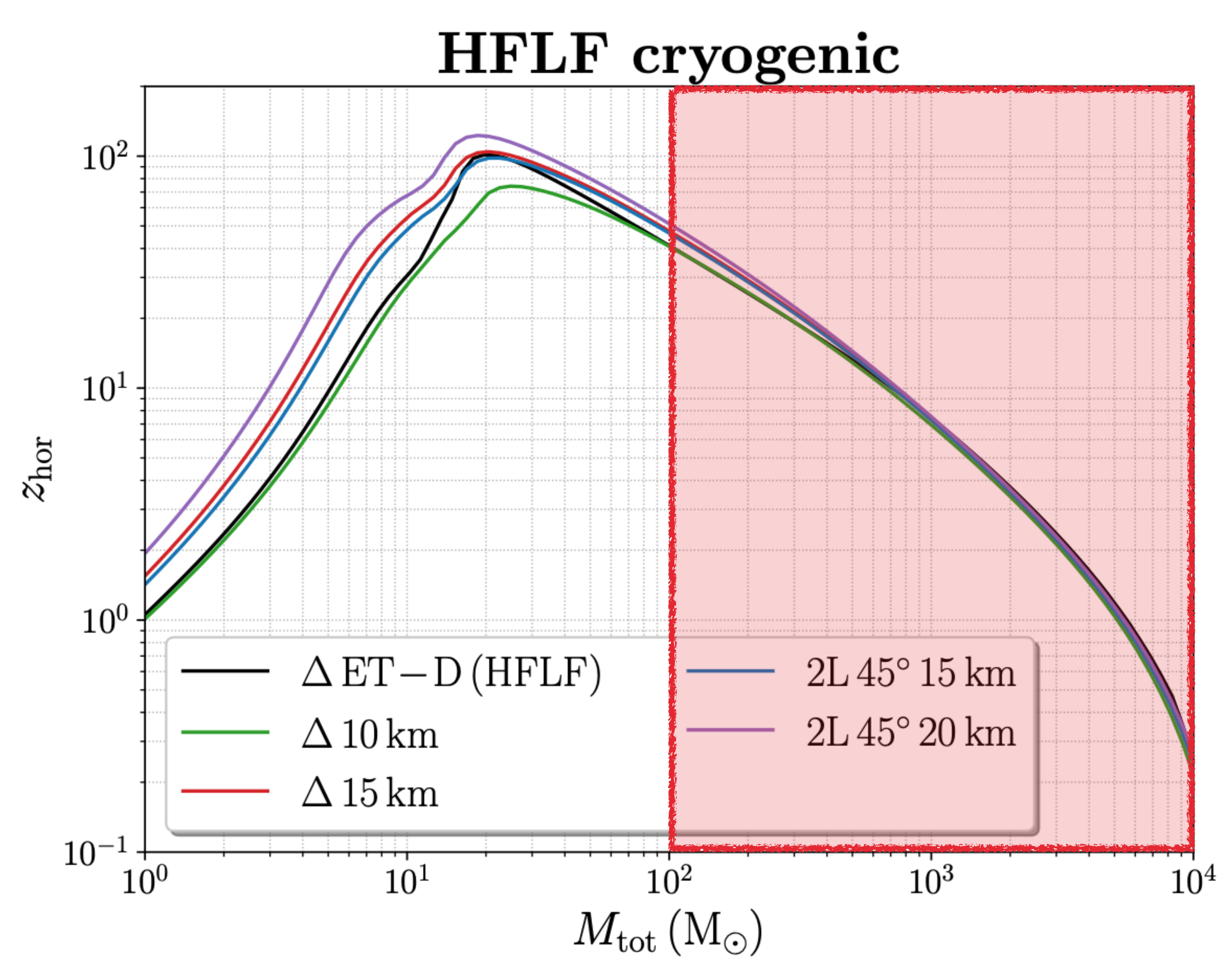
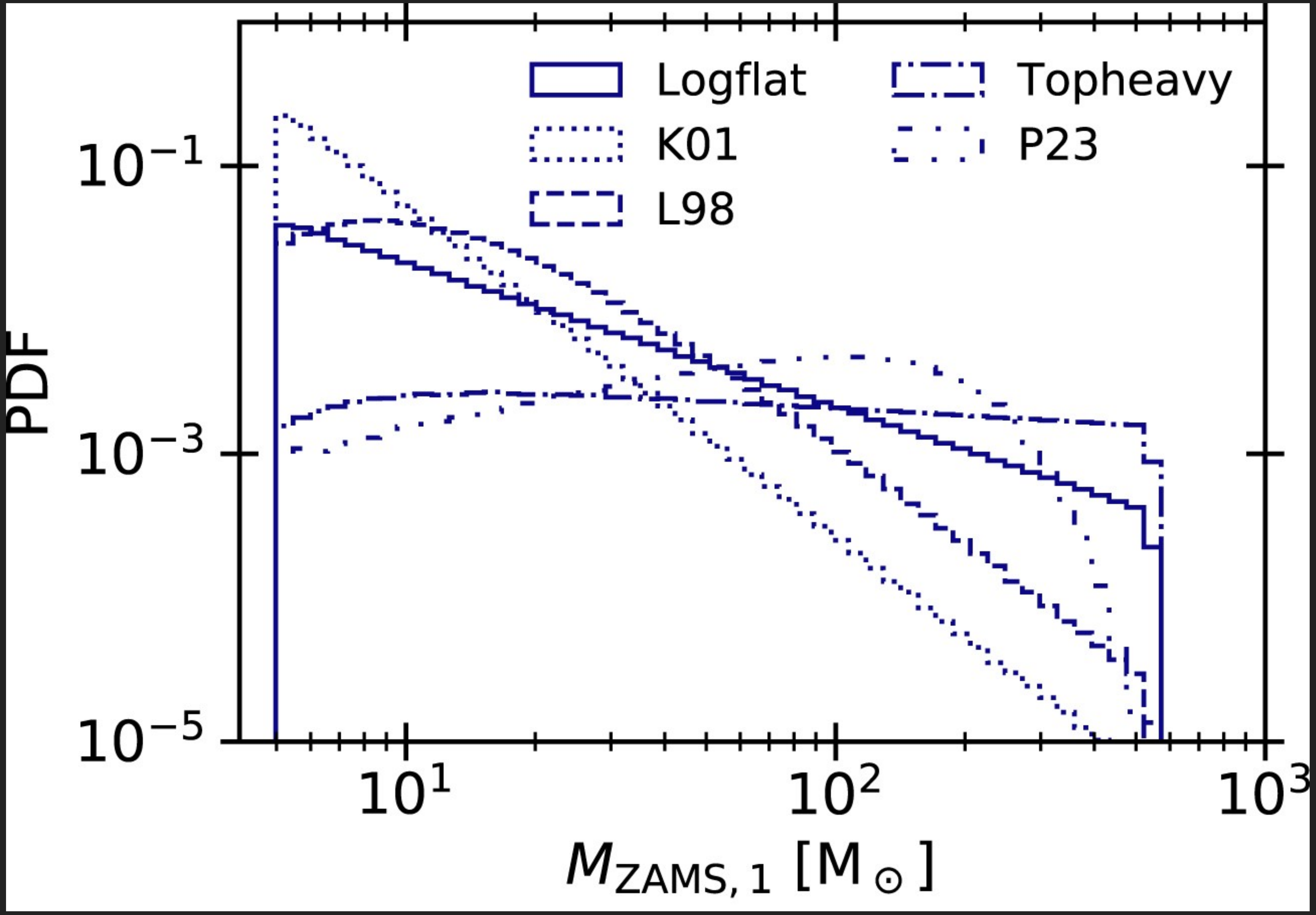
PERFECT SOURCES OF SIGNALS FOR THIRD GENERATION INTERFEROMETERS

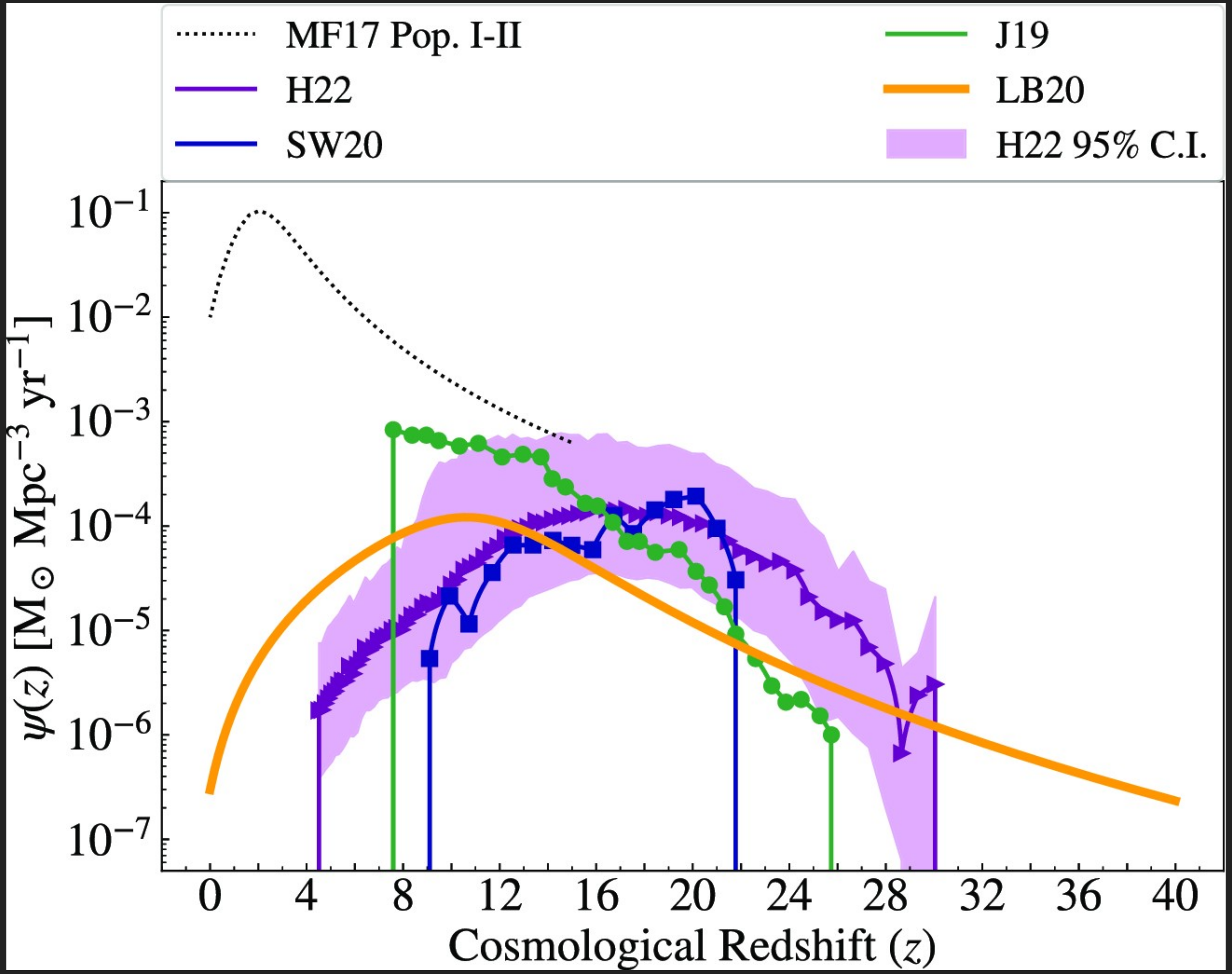


Kalogera et al. 2021; Branchesi et al. 2023

UNCERTAINTIES ON IMF AND SFR



Costa et al. 2023



Santoliquido et al. 2023

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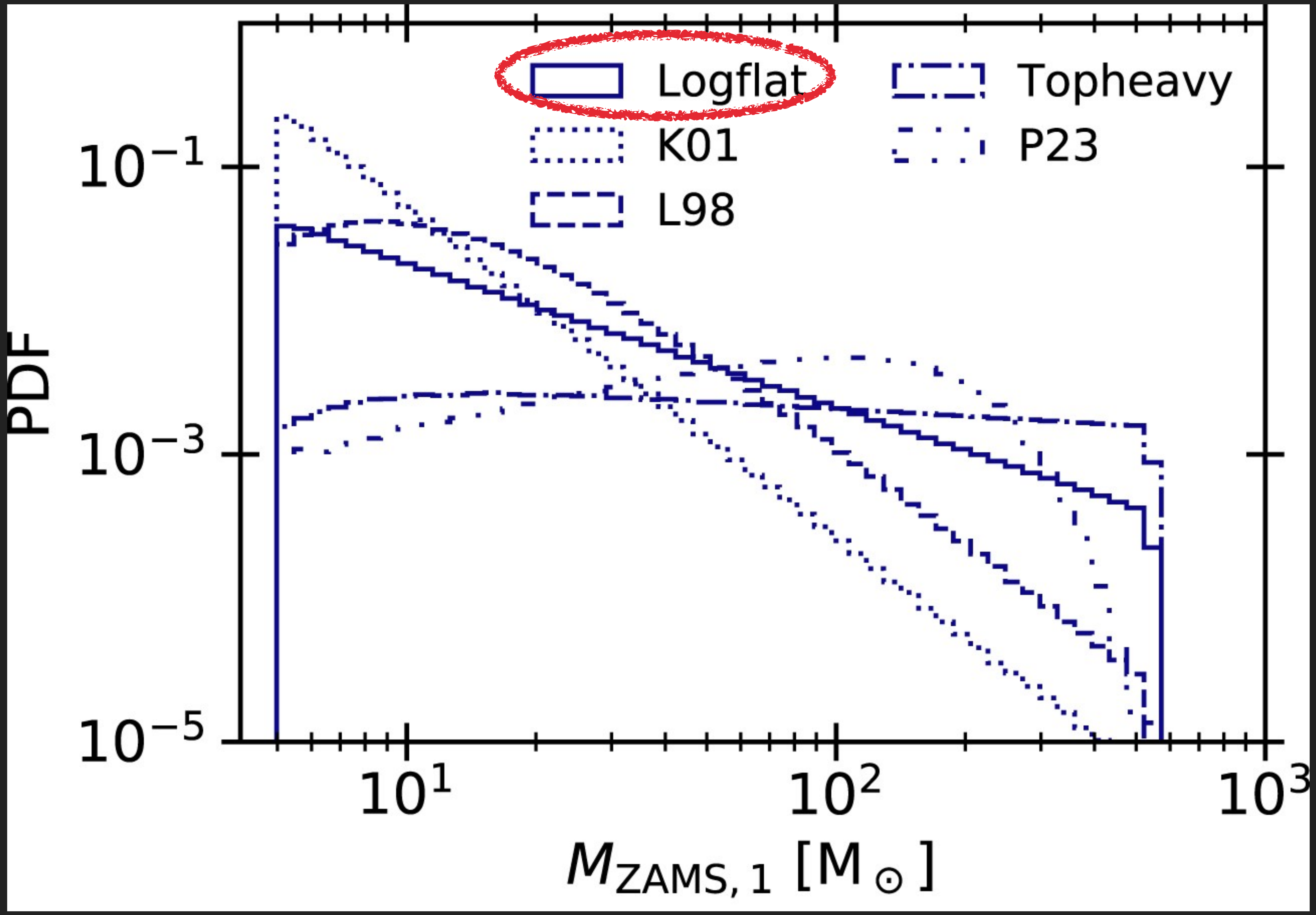

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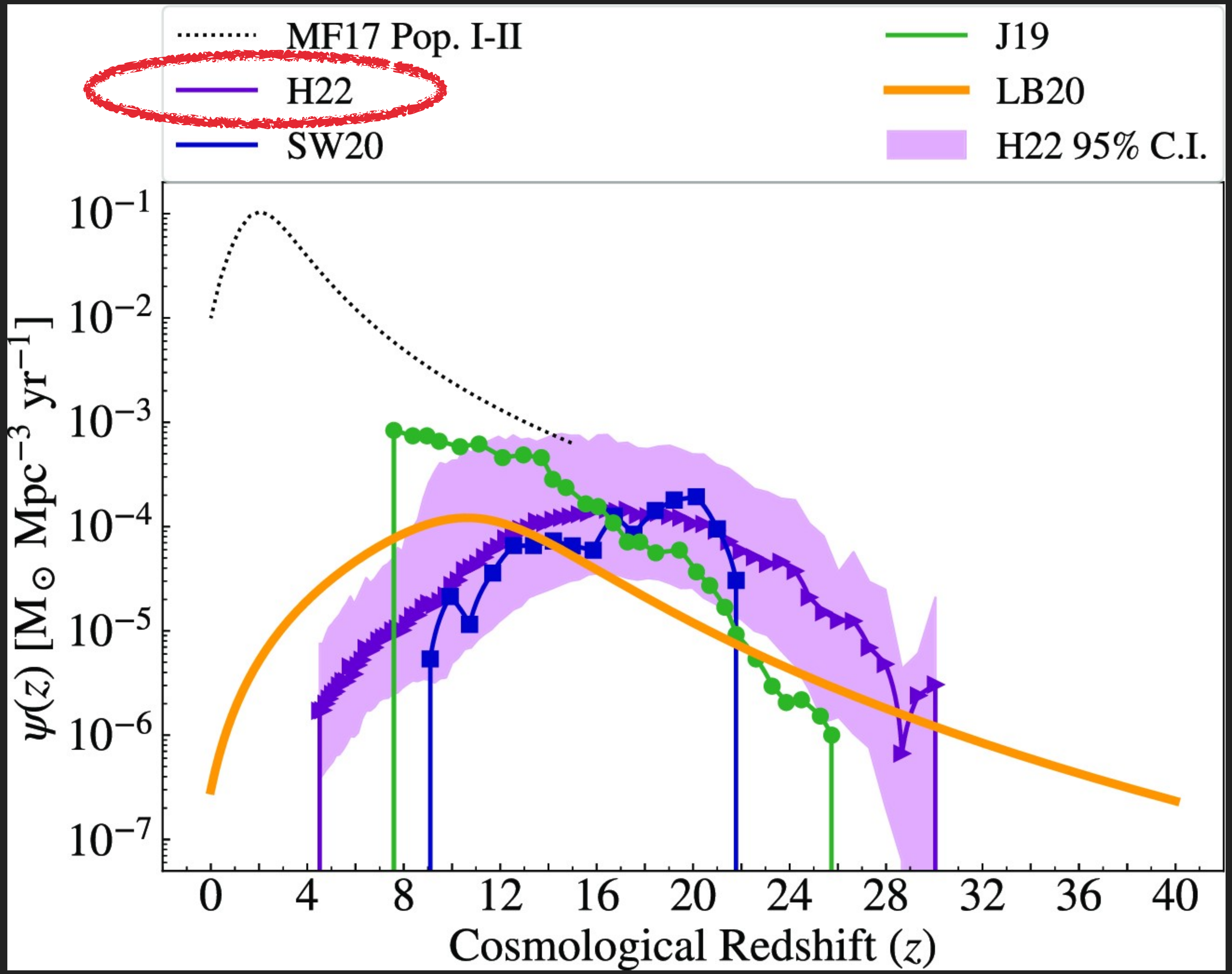
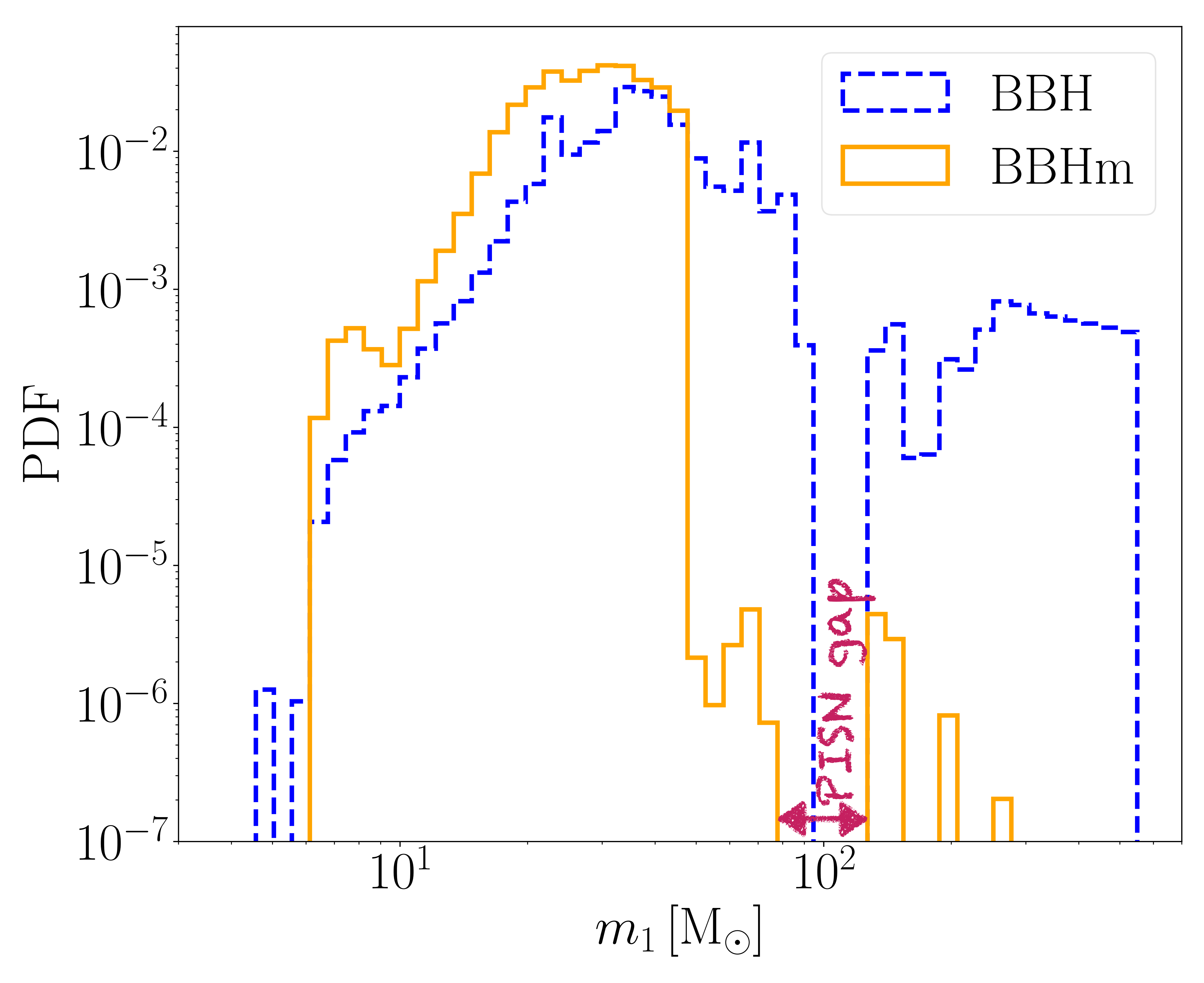


Santoliquido et al. 2023

POP III BINARY BLACK HOLE MERGERS ABOVE THE GAP

- BBHs with IMBH primary form (Tanikawa et al. 2020-2024; Costa et al. 2023; Santoliquido et al. 2023)
- **Almost no mergers above the pair instability mass gap**



Costa et al. 2023; Mestichelli et al. 2024

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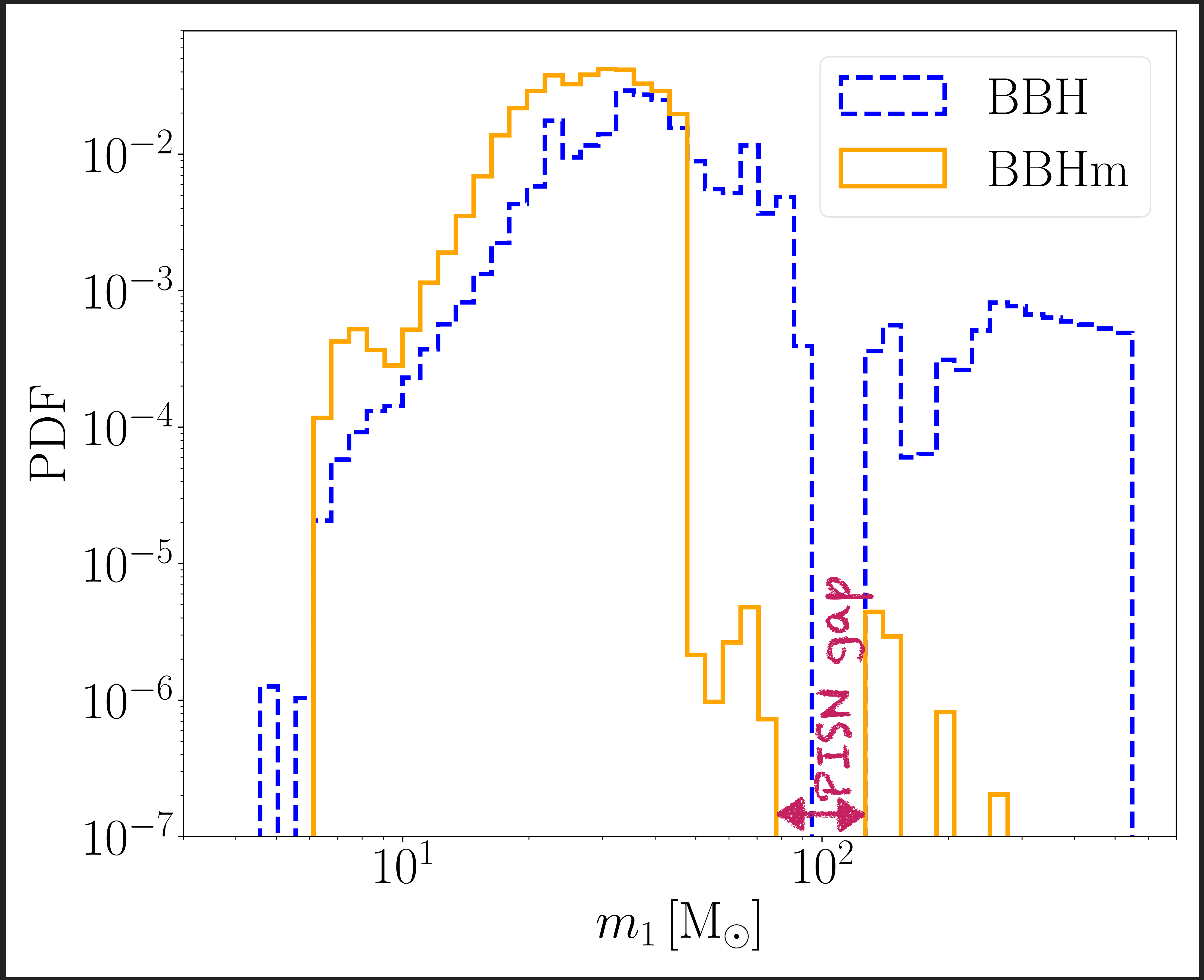
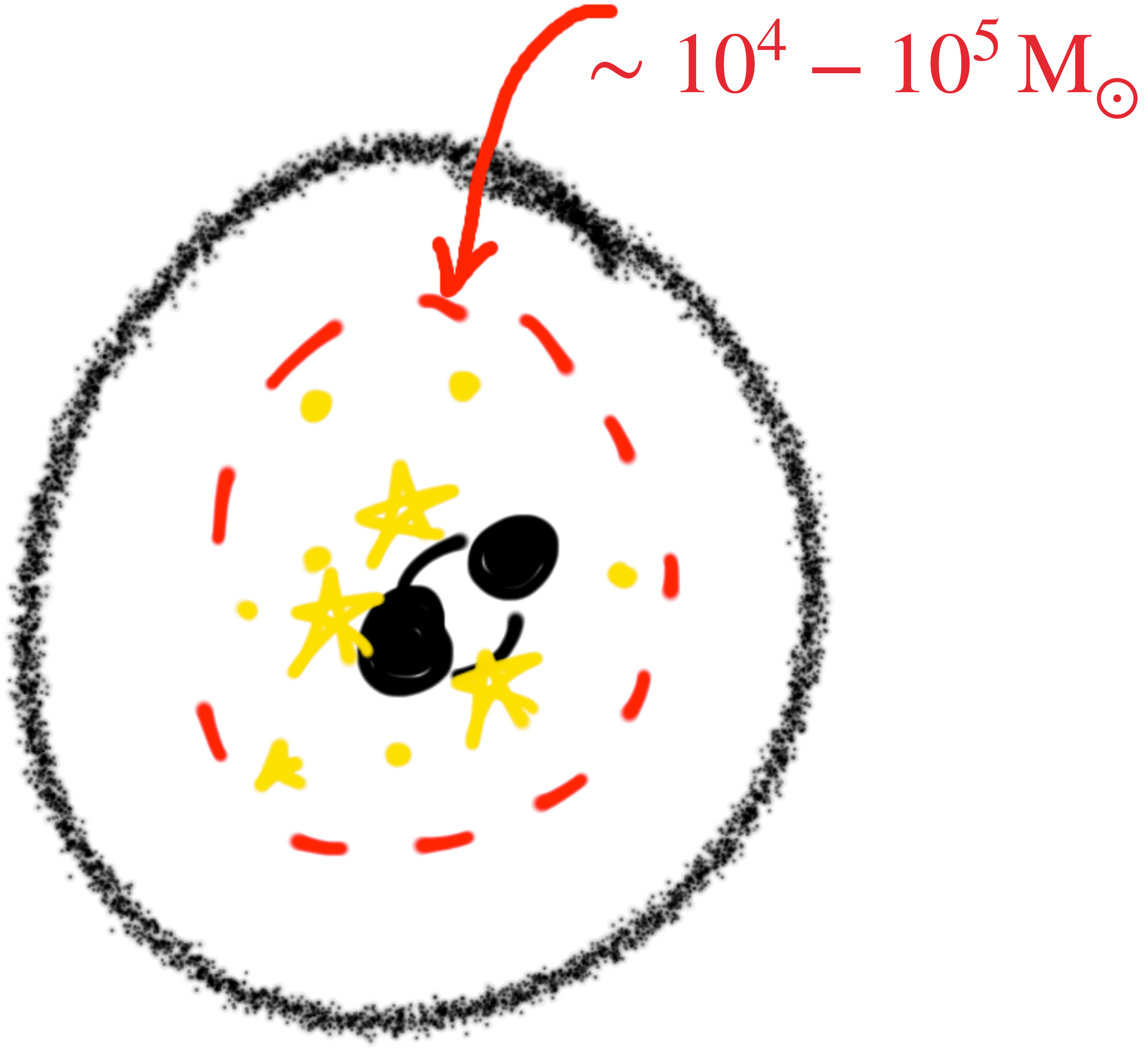


Costa et al. 2023; Mestichelli et al. 2024

WHAT IF THE FIRST STARS WERE BORN IN CLUSTERS?

- Formation of **very massive stars** via **repeated stellar collisions**
- Boost of pair-up, hardening and **merger of BBHs above gap**
    - **Dynamics pairs up massive BHs**
    - **Three-body interactions** contribute to **hardening**
- **Hierarchical mergers**



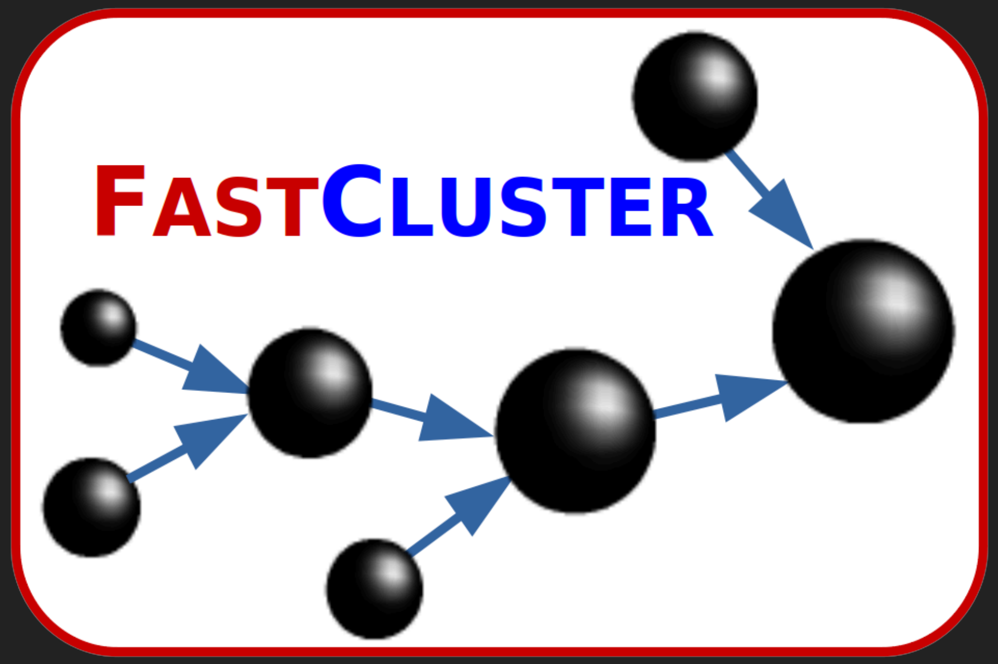
Mini-DM halo

$\sim 10^7\,M_\odot$

Sakurai et al. 2017; Wang et al. 2022;
Mestichelli et al. 2024*; Reinoso et al. 2025*

MASSIVE CLUSTERS

$\sim 10^4 - 10^5\,M_\odot$



Mapelli et al. 2021, 2022;
Torniamenti et al. 2024

- Semi-analytic
- $z = 20 \rightarrow 10$
- Cluster evolution
- No stellar evolution

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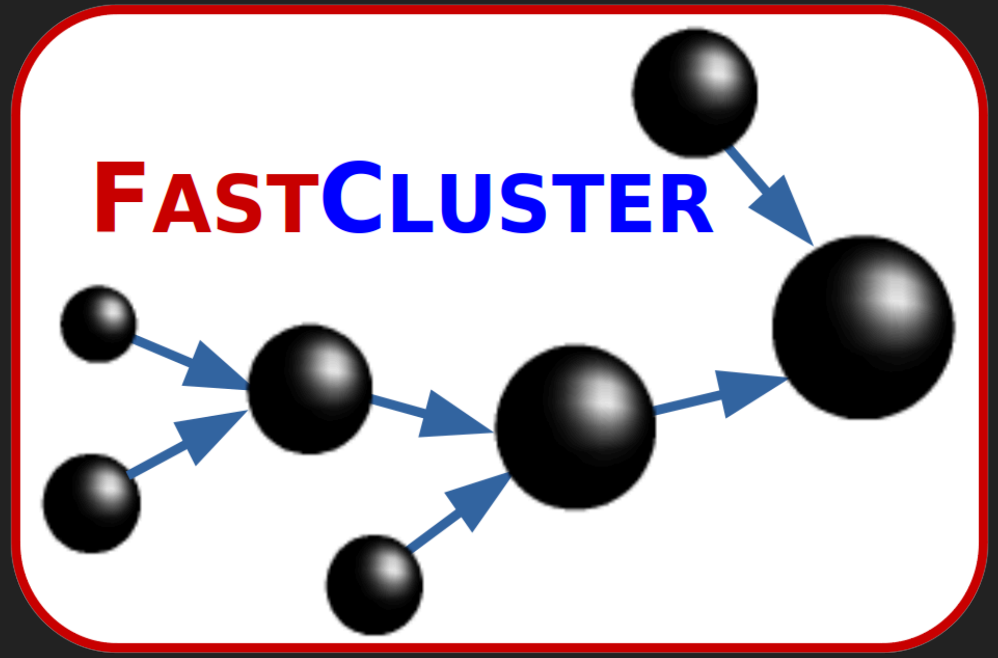
$m_{\rm min} = 2\,\rm M_\odot$
$m_{\rm max} = 600\,\rm M_\odot$

log-flat IMF

MASSIVE CLUSTERS

$\sim 10^4 - 10^5\,\rm M_\odot$



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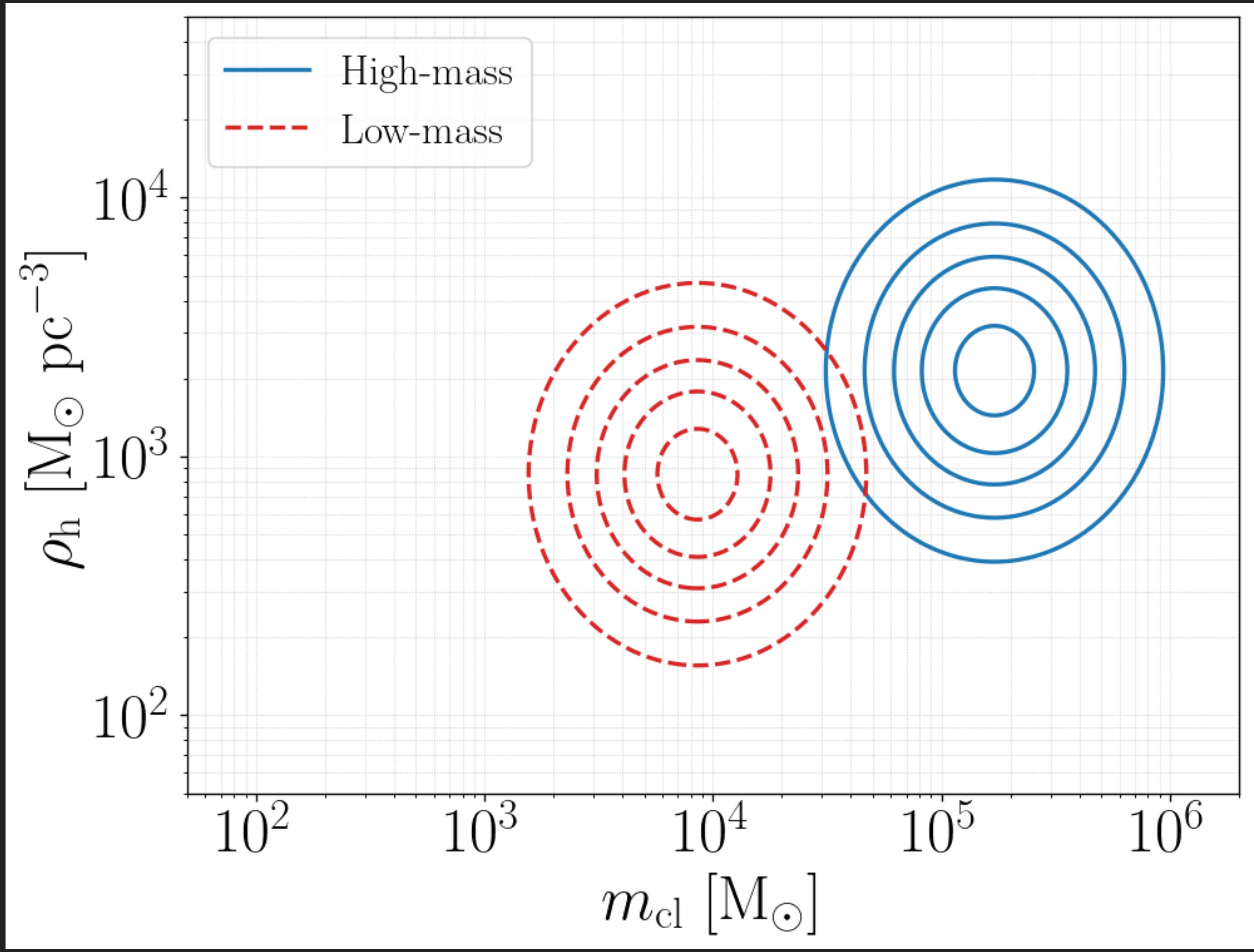
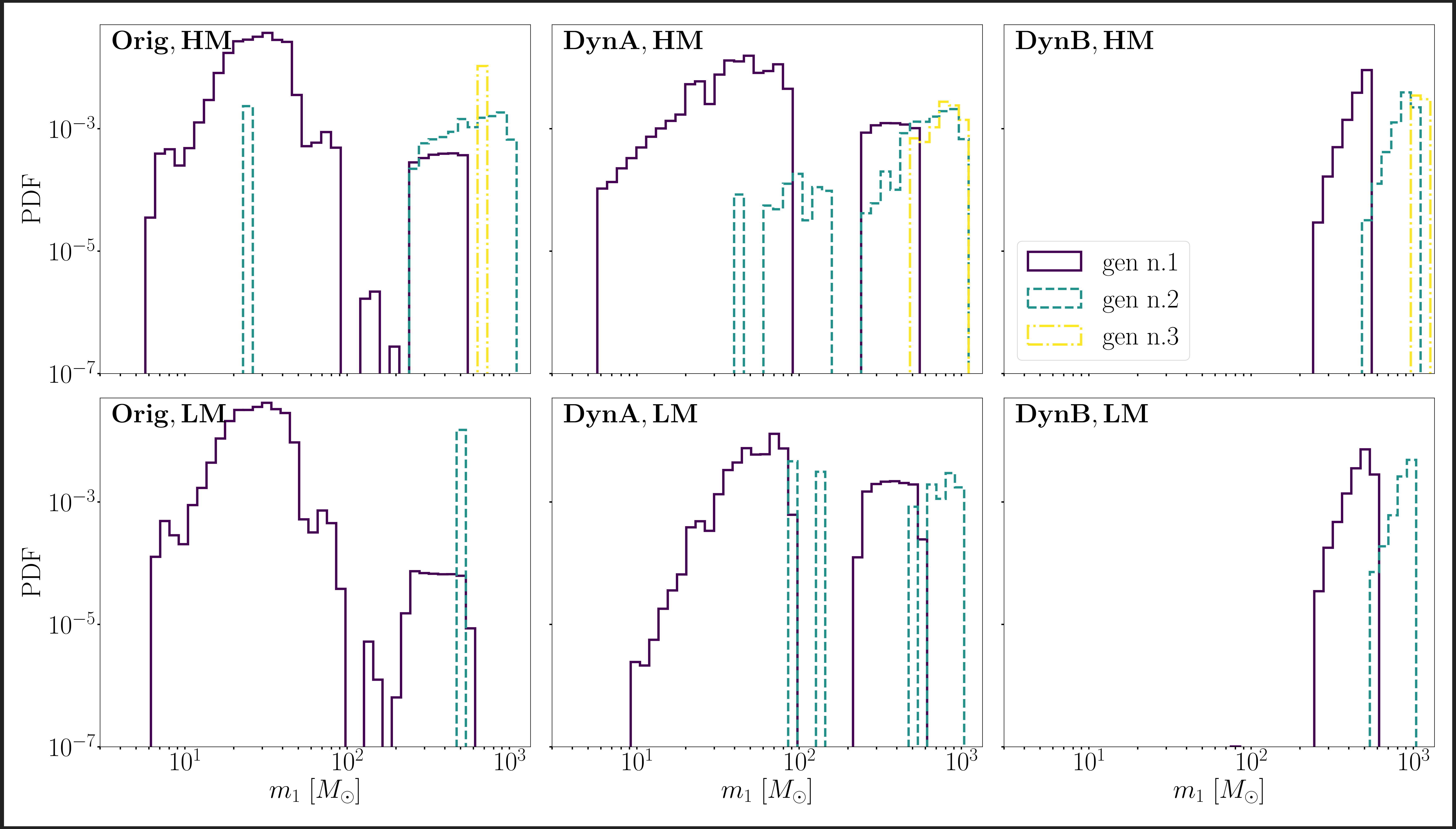


THE BOOST ABOVE THE PAIR INSTABILITY MASS GAP



Mestichelli et al. 2024

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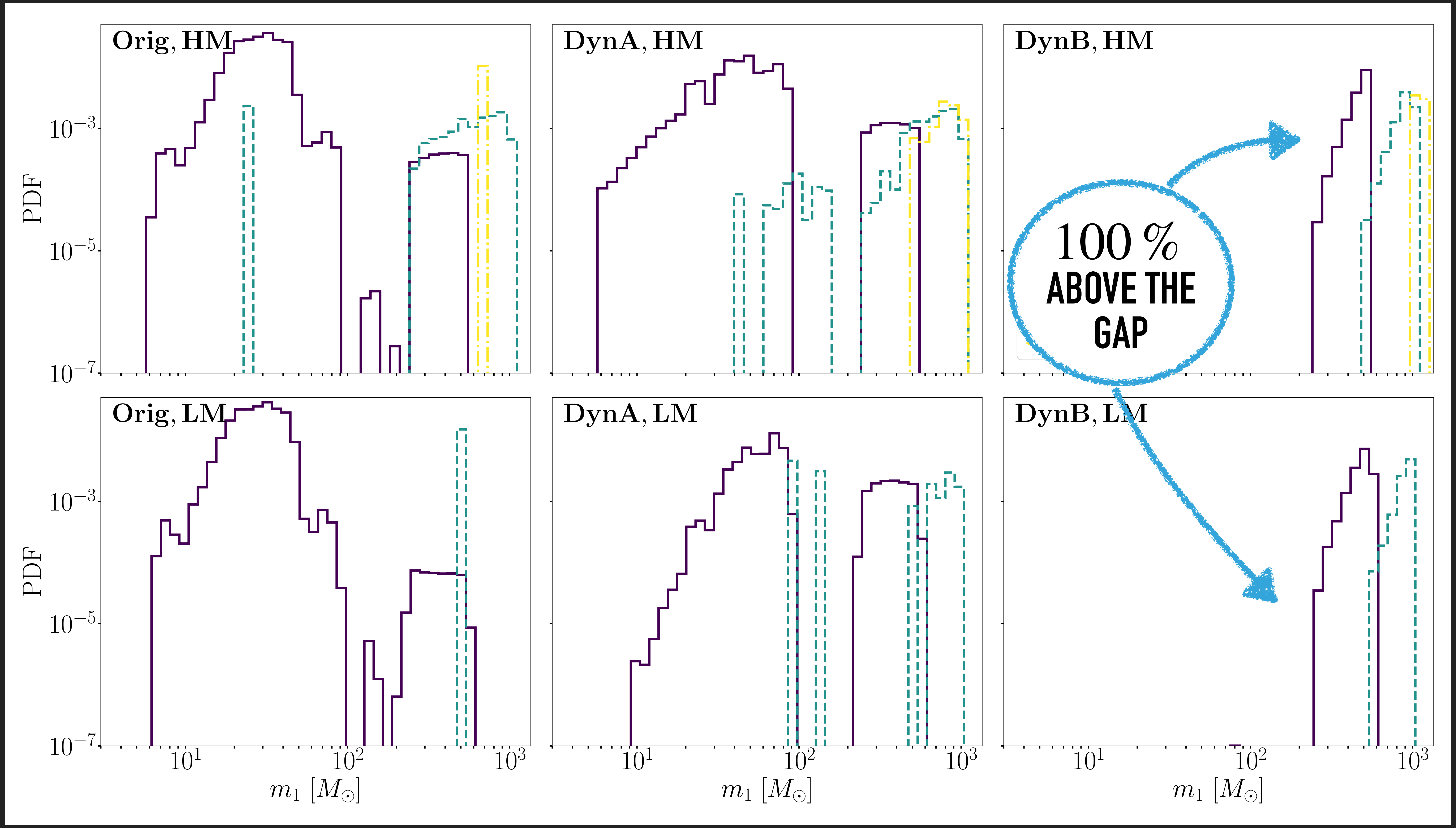
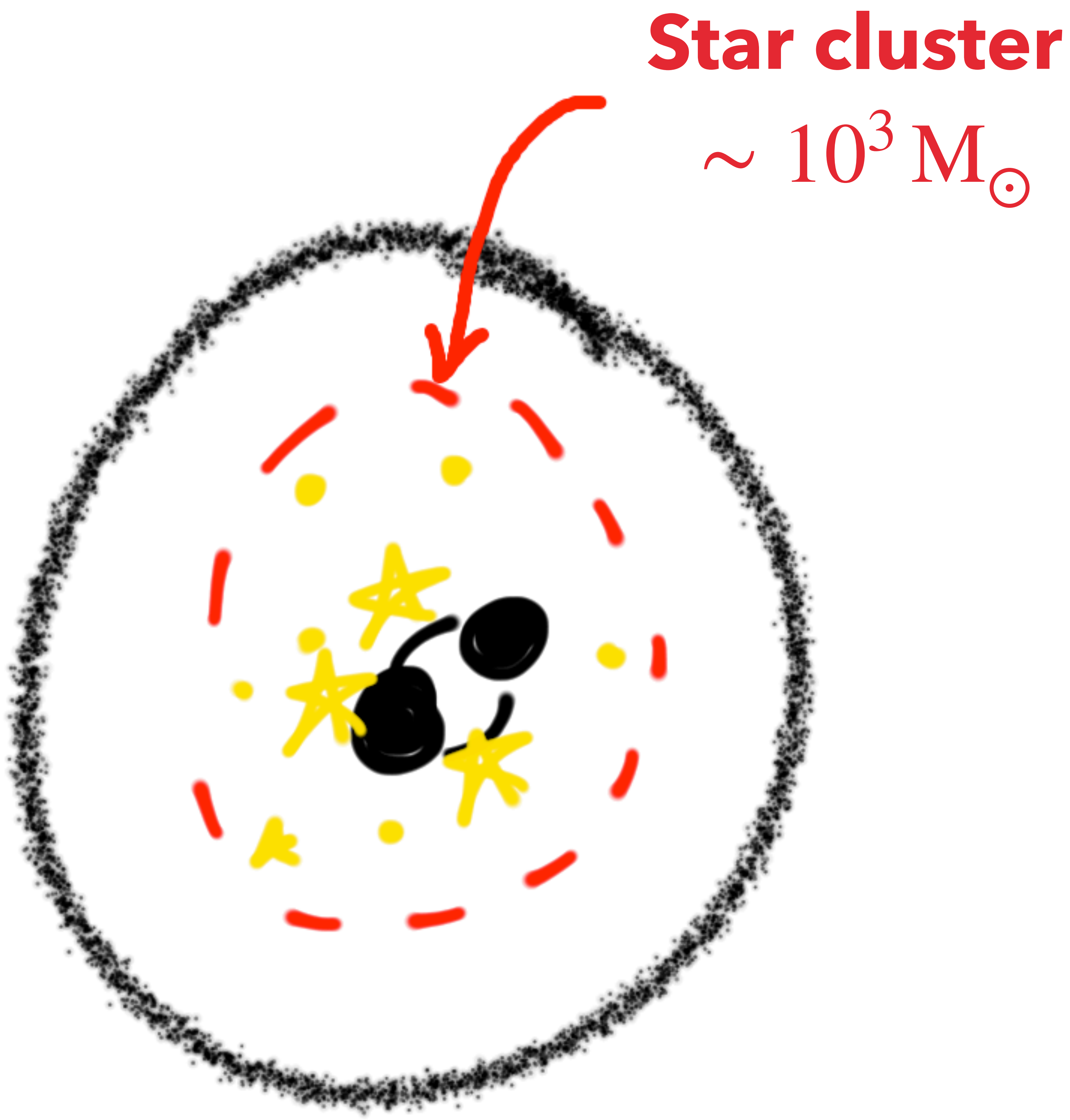


Mestichelli et al. 2024

LOW-MASS CLUSTERS

$\sim 10^3\ M_\odot$



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bseEmp

Wang et al. 2020; Tanikawa et al. 2020

- N-body code
- $z = 20 \rightarrow 10$
- Stellar evolution (bseEmp)
- External potential (galpy)

PRELIMINARY

$m_{min} = 0.8\,M_\odot$
$m_{max} = 300\,M_\odot$

log-flat IMF

LOW-MASS CLUSTERS

$\sim 10^3\,M_\odot$

PETAR

bseEmp

Wang et al. 2020; Tanikawa et al. 2020

- N-body code
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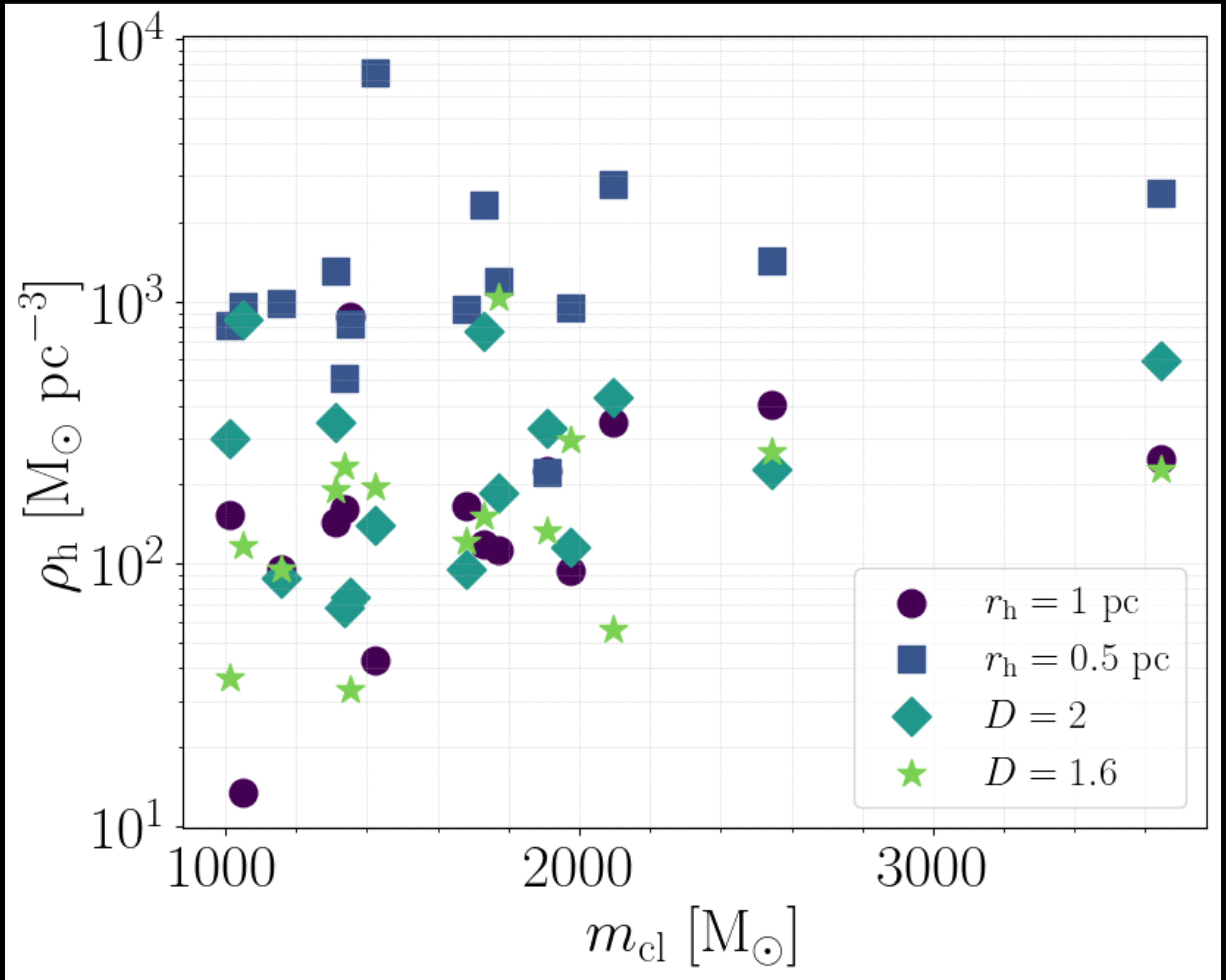
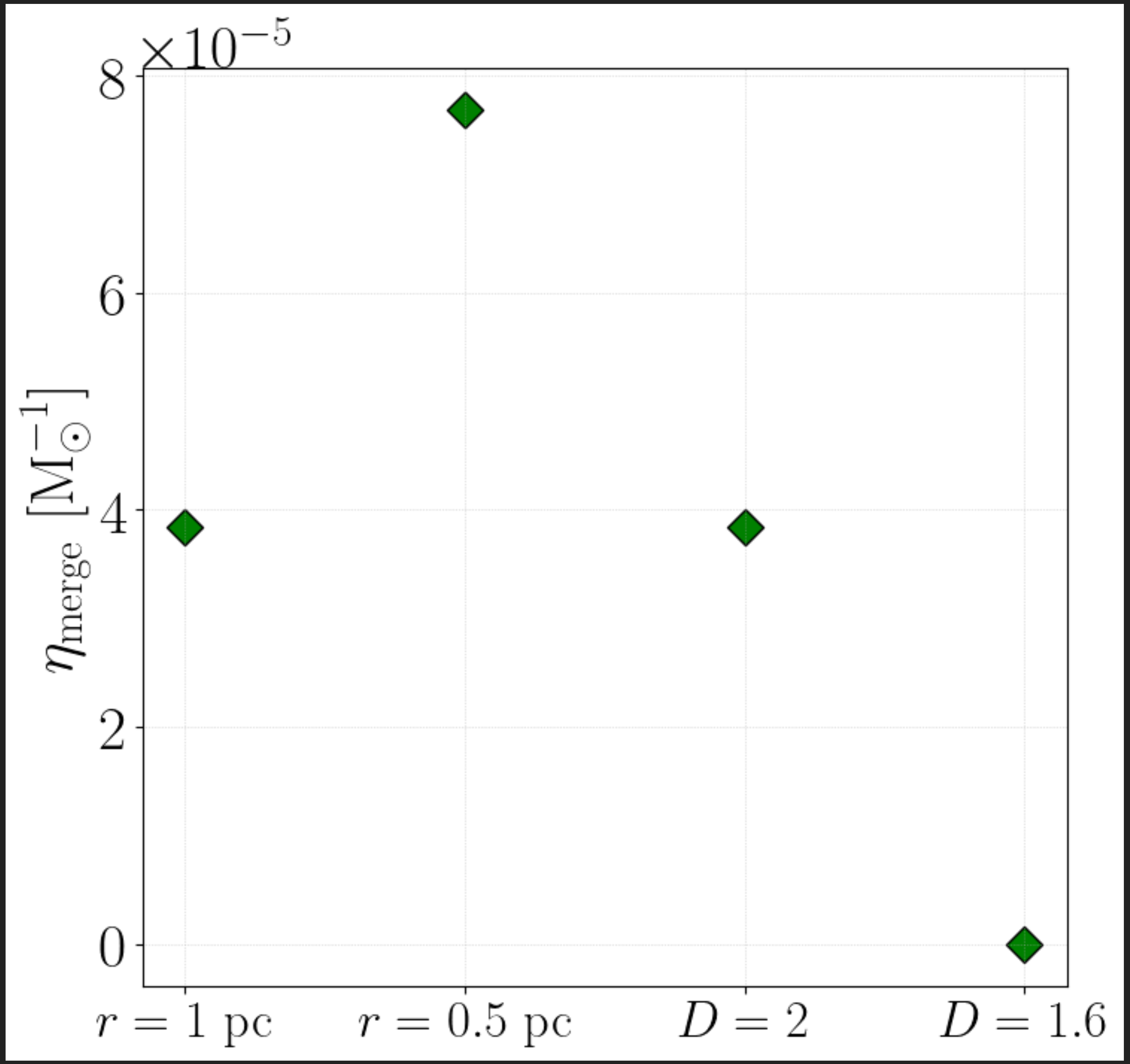


Mestichelli et al., in prep.

MERGER EFFICIENCIES: A COMPARISON



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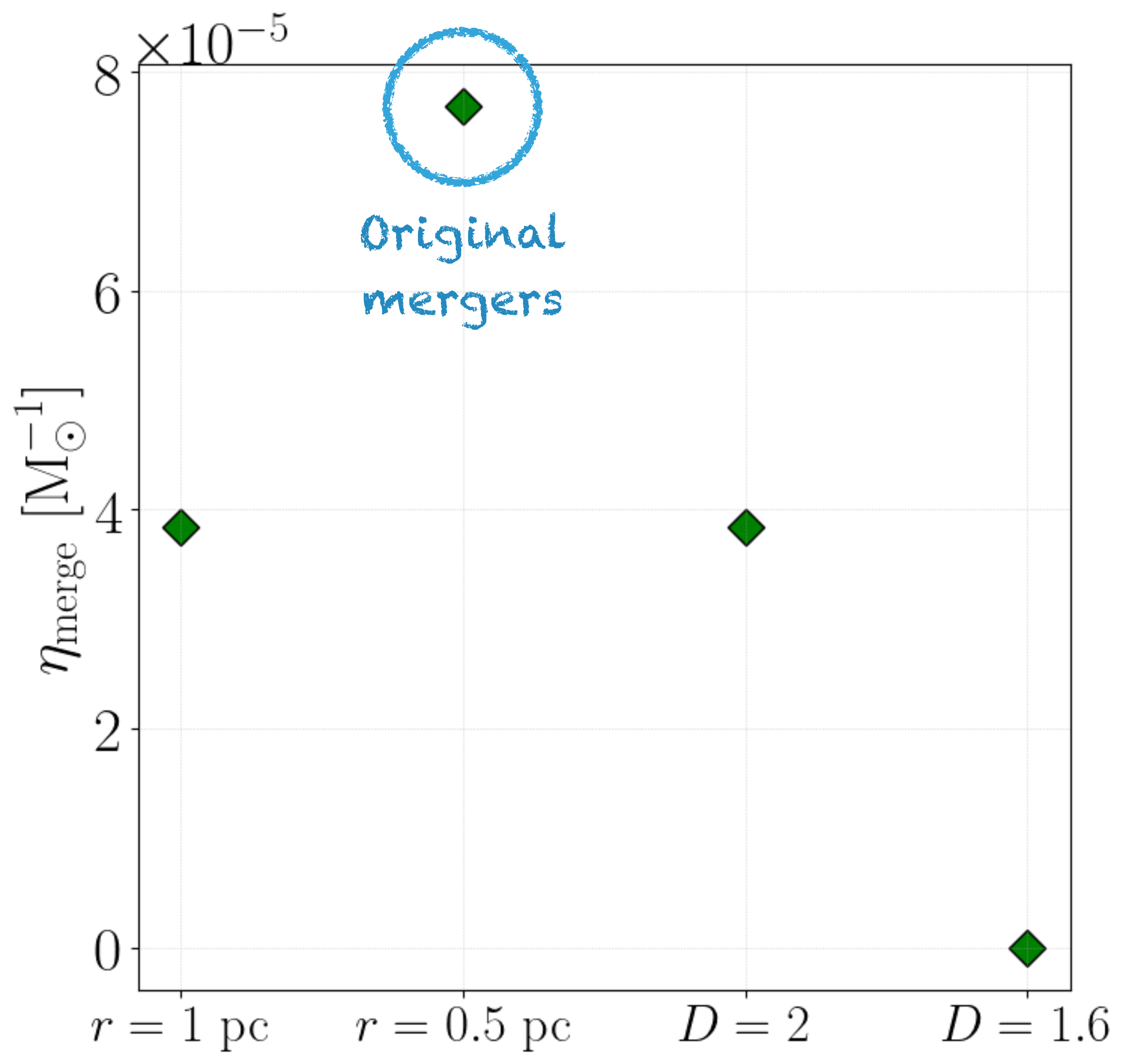

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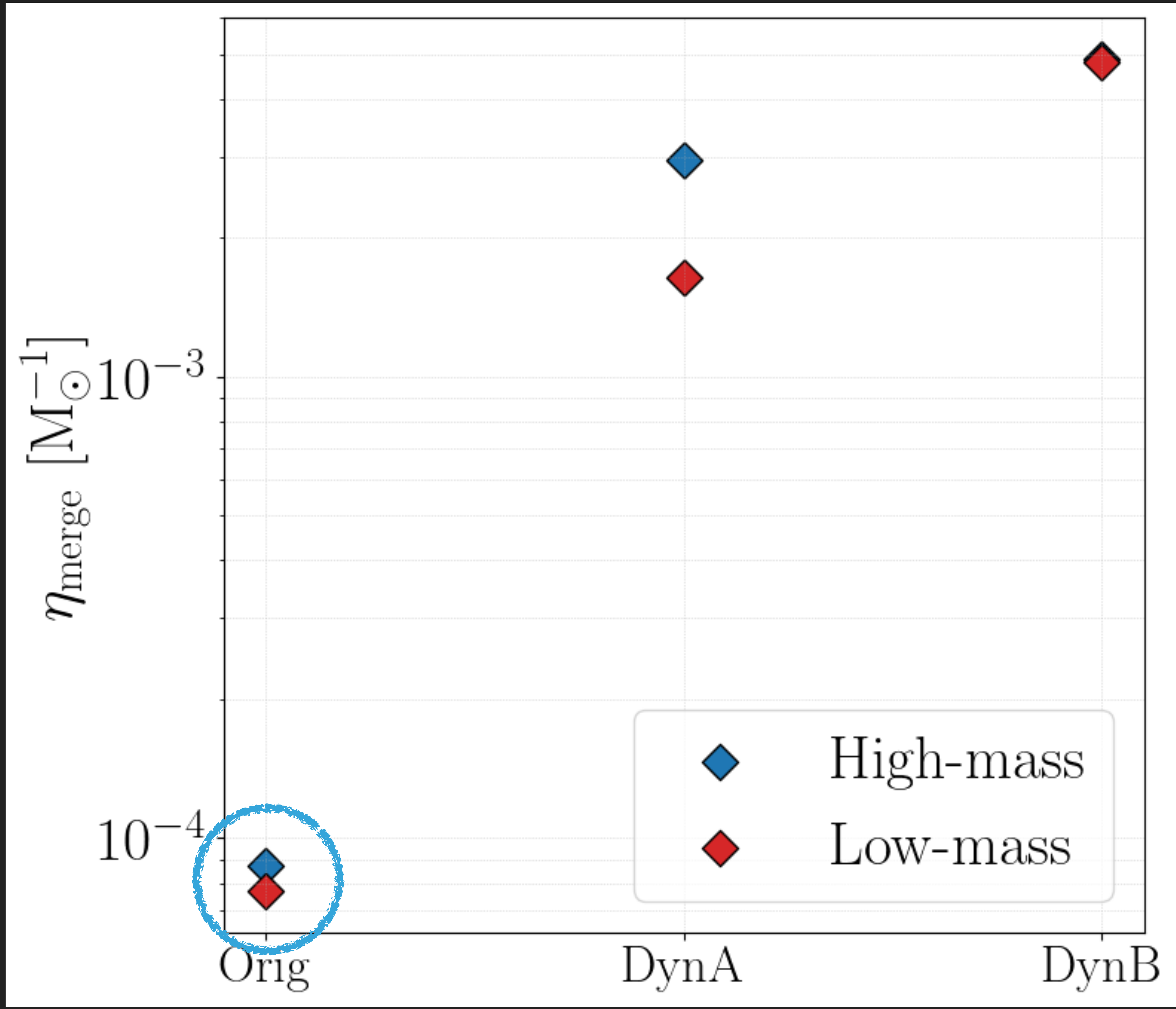

Mestichelli et al. 2024

CONCLUSIONS

- **Pop. III stars** are candidate **progenitors** of **intermediate-mass black holes**
    - *Simulations in field*: binaries with intermediate-mass black hole primaries **form efficiently but don't merge**
- **Stellar dynamics** in the first star clusters can **enhance mergers** above upper-mass gap
    - Massive clusters ($\texttt{fastcluster}$): up to $100\,\%$ of mergers with intermediate-mass black hole primary
    - Low-mass clusters ($\texttt{PeTar+bseEmp}$): only original BBH mergers
    - **Same order of magnitude of merger efficiency**

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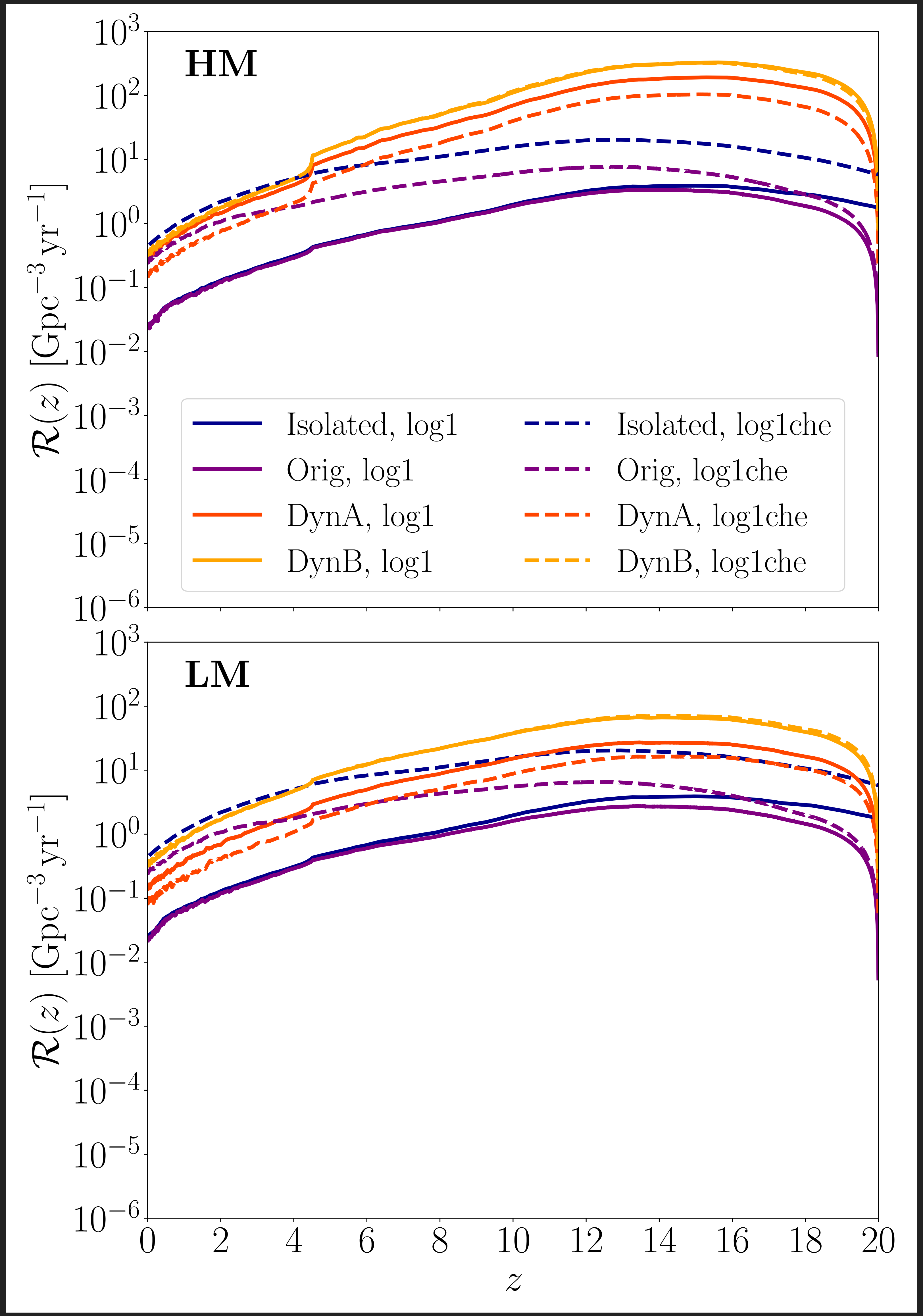
BACK-UP SLIDES

MASSIVE CLUSTERS: MERGER RATE DENSITY

COSMORATE

Santoliquido et al. 2020, 2021

- **MRD** of **dynamical BBHs two orders higher** than **original/isolated MRD**
- **MRD higher** in **HM clusters**
- **MRD** of **CHE BBHs higher**



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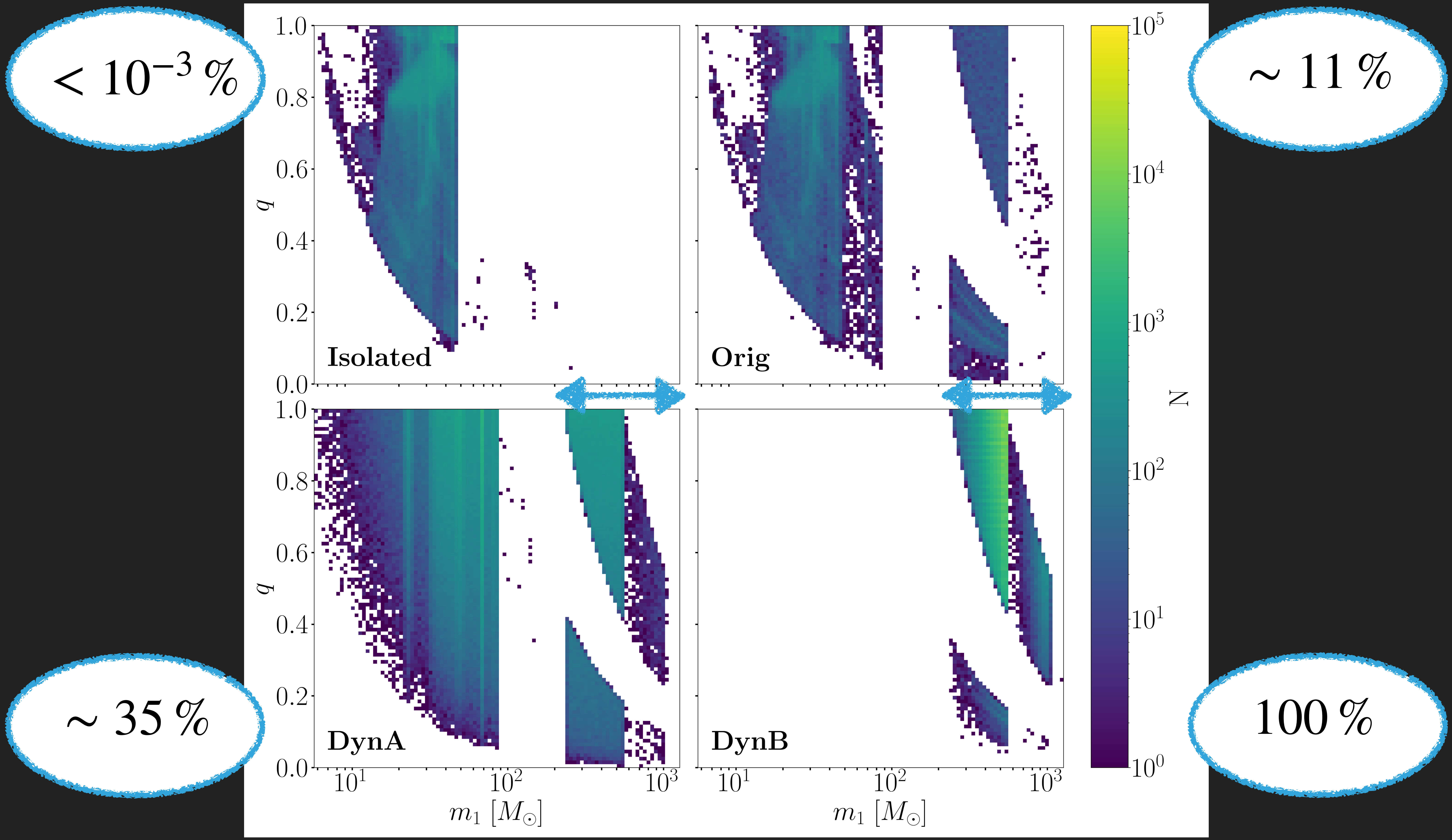


Mestichelli et al. 2024

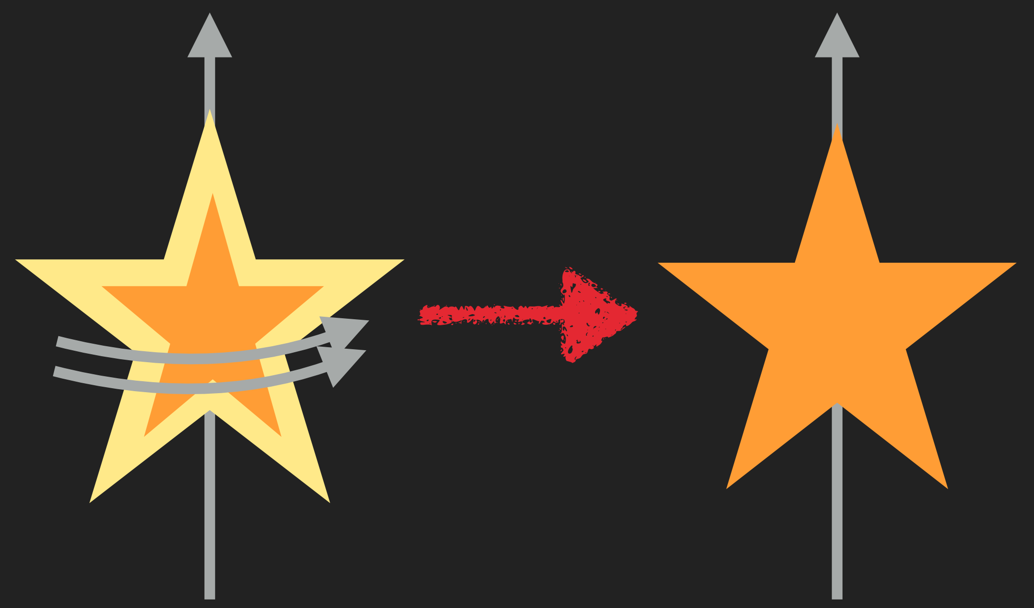
Mestichelli et al. 2024

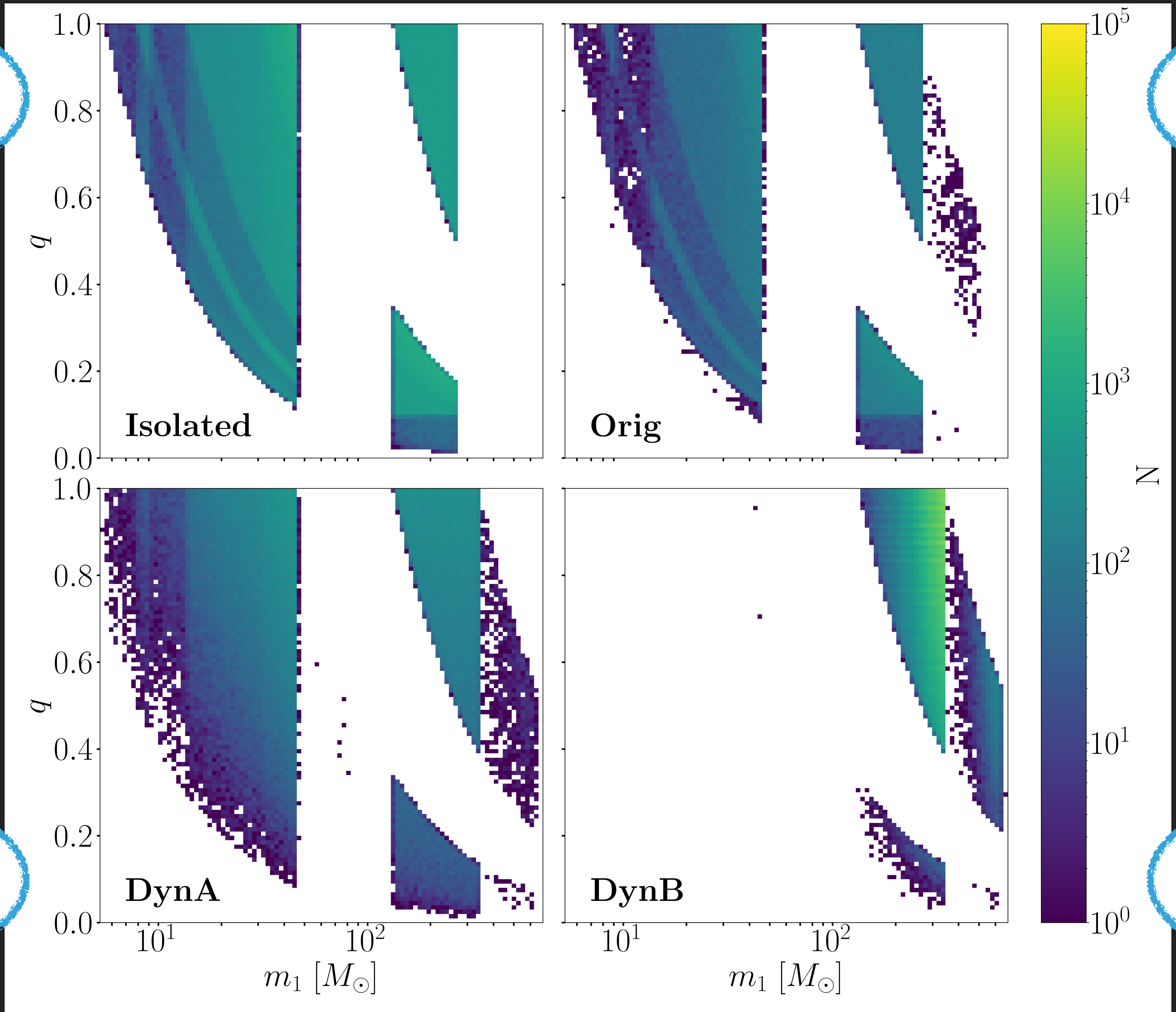
MASSIVE CLUSTERS: CHEMICAL HOMOGENEOUS STARS

~ 39 %

~ 42 %

CHEMICALLY HOMOGENEOUS





~ 46 %

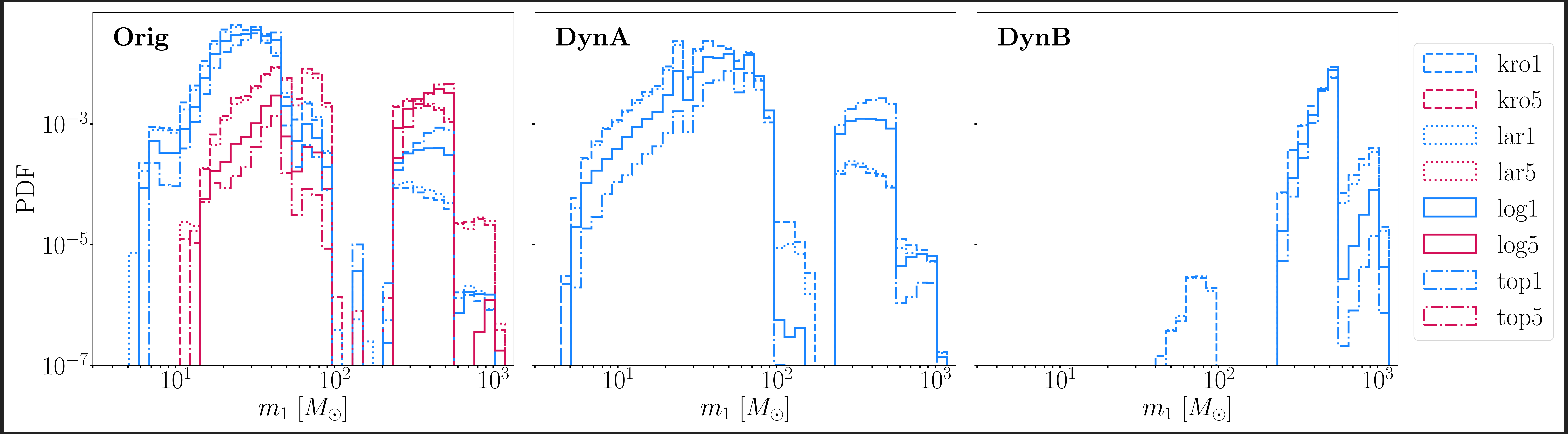
100 %

Mestichelli et al. 2024

MASSIVE CLUSTERS: DEPENDENCE ON INITIAL CONDITIONS

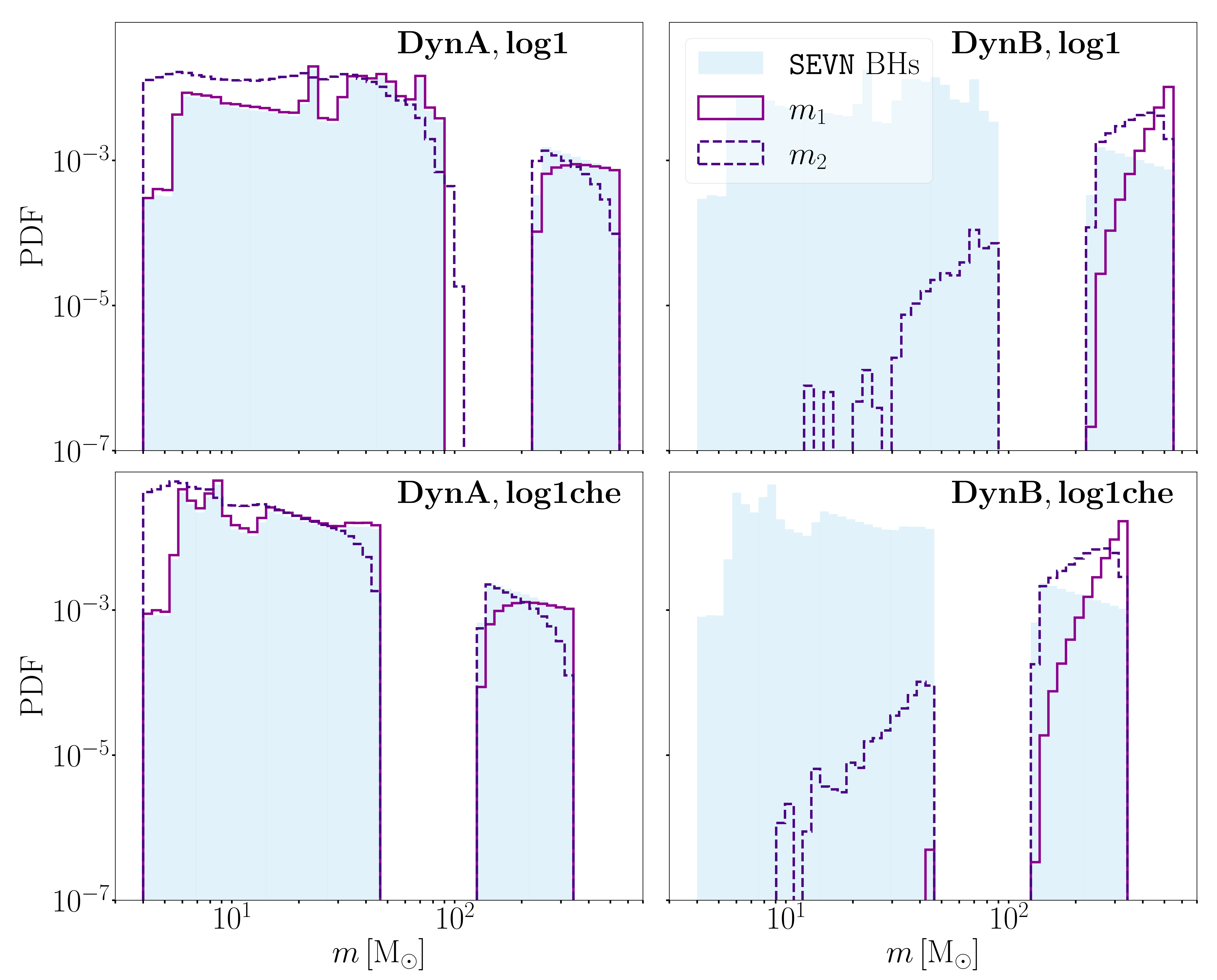
1 = SANA ET AL. 2012

5 = STACY & BROMM 2013



Mestichelli et al. 2024

DYNAMICAL BBHs: MASS SAMPLING FUNCTIONS



Mestichelli et al. 2024

MERGER RATE DENSITY

$$\mathscr{R} = \int_{z_{max}}^{z} \psi(z') \frac{dt(z')}{dz'} \left[\int_{Z_{min}}^{Z_{max}} \eta(Z) \mathscr{F}(z', z, Z)\, dZ \right] dz'$$

SFR density
(Hartwig et al. 2022)

Merger efficiency
(different for orig and dyn)

$$f_{CL}(z', M_{cl}) \frac{\mathscr{N}(z', z, Z)}{\mathscr{N}_{TOT}(Z)}\, p(z', Z)$$

$$\frac{1}{H_0\,(1+z')\,[(1+z')^3\,\Omega_M + \Omega_\Lambda]^{1/2}}$$

COSMORATE

Santoliquido et al. 2020, 2021

FASTCLUSTER: ORBITAL EVOLUTION

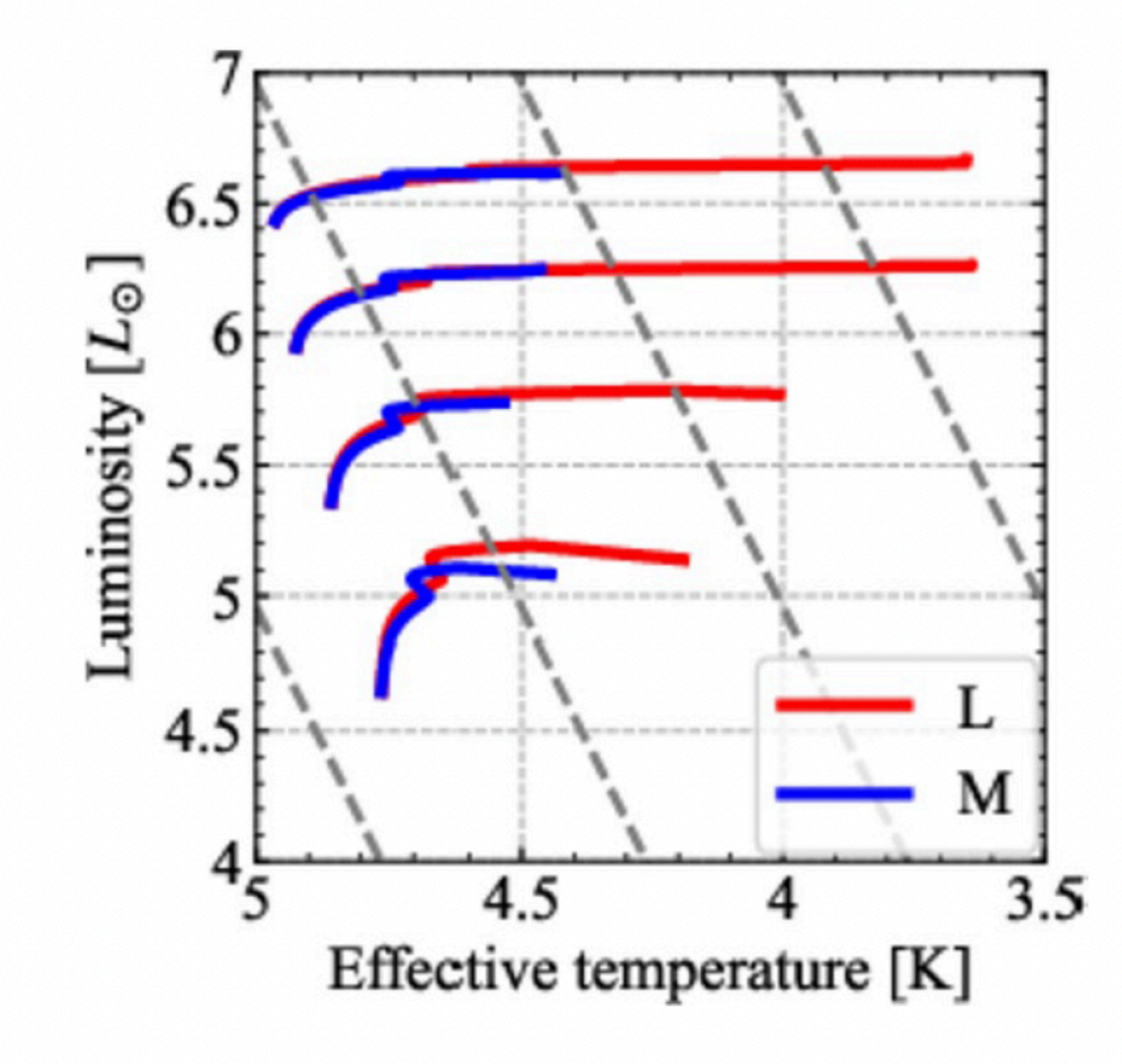
Dynamical hardening (Heggie 1975)

GW emission (Peters 1964)

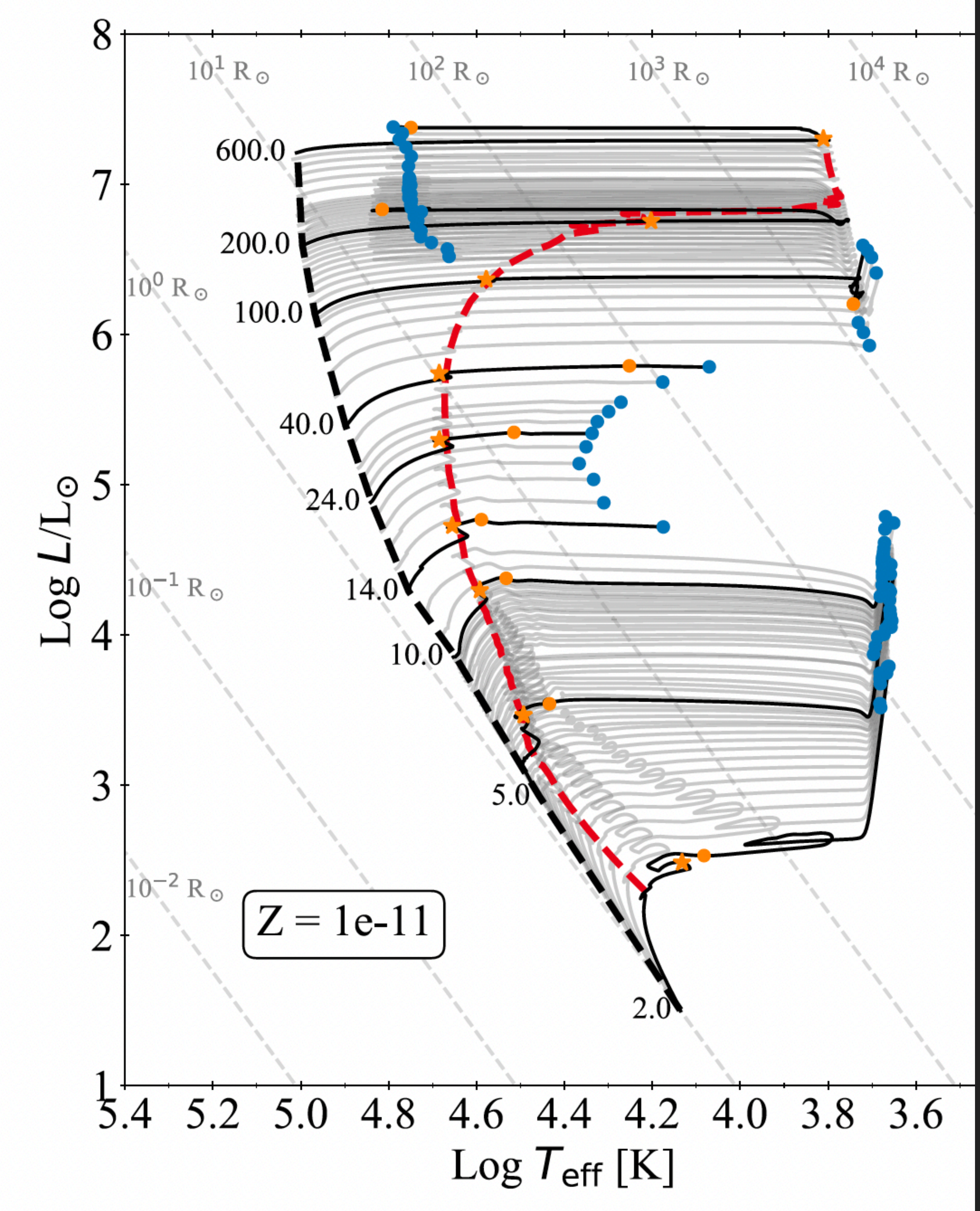
$$\frac{\mathrm{d}a}{\mathrm{d}t} = -2\pi\xi\frac{G\rho_\mathrm{c}}{\sigma}a^2 - \frac{64}{5}\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^3 (1-e^2)^{7/2}} f_1(e)$$

$$\frac{\mathrm{d}e}{\mathrm{d}t} = 2\pi\xi\kappa\frac{G\rho_\mathrm{c}}{\sigma}a - \frac{304}{15}e\frac{G^3 m_1 m_2 (m_1+m_2)}{c^5 a^4 (1-e^2)^{5/2}} f_2(e)$$

STELLAR TRACKS



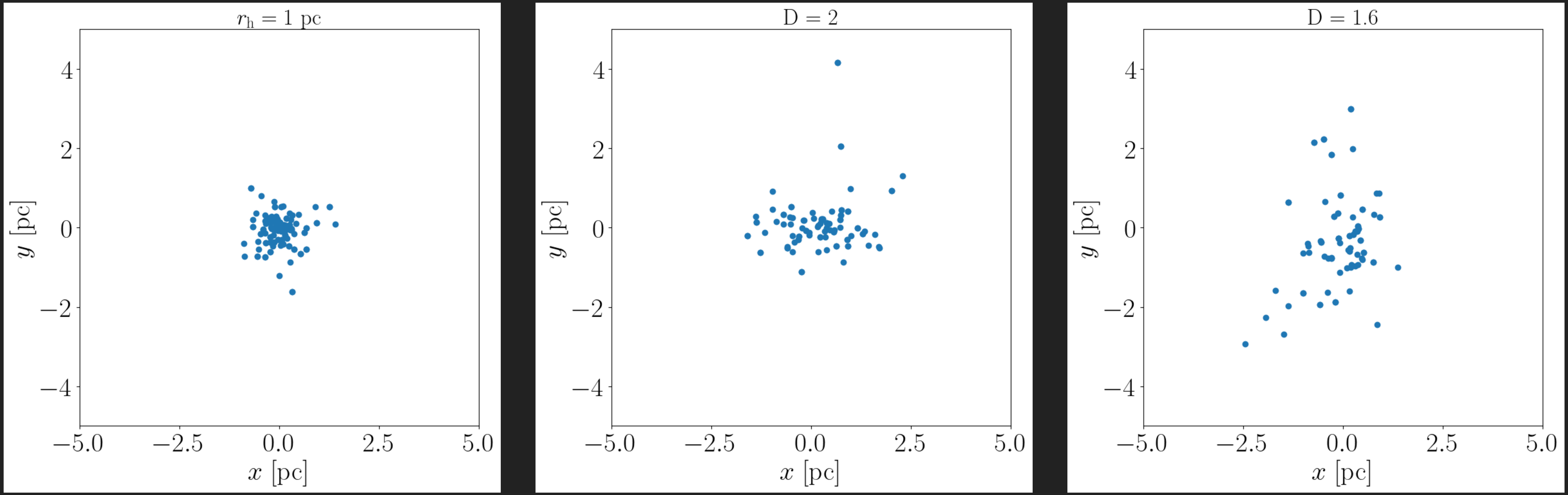
bseEMP; *Tanikawa et al. 2020-2024*



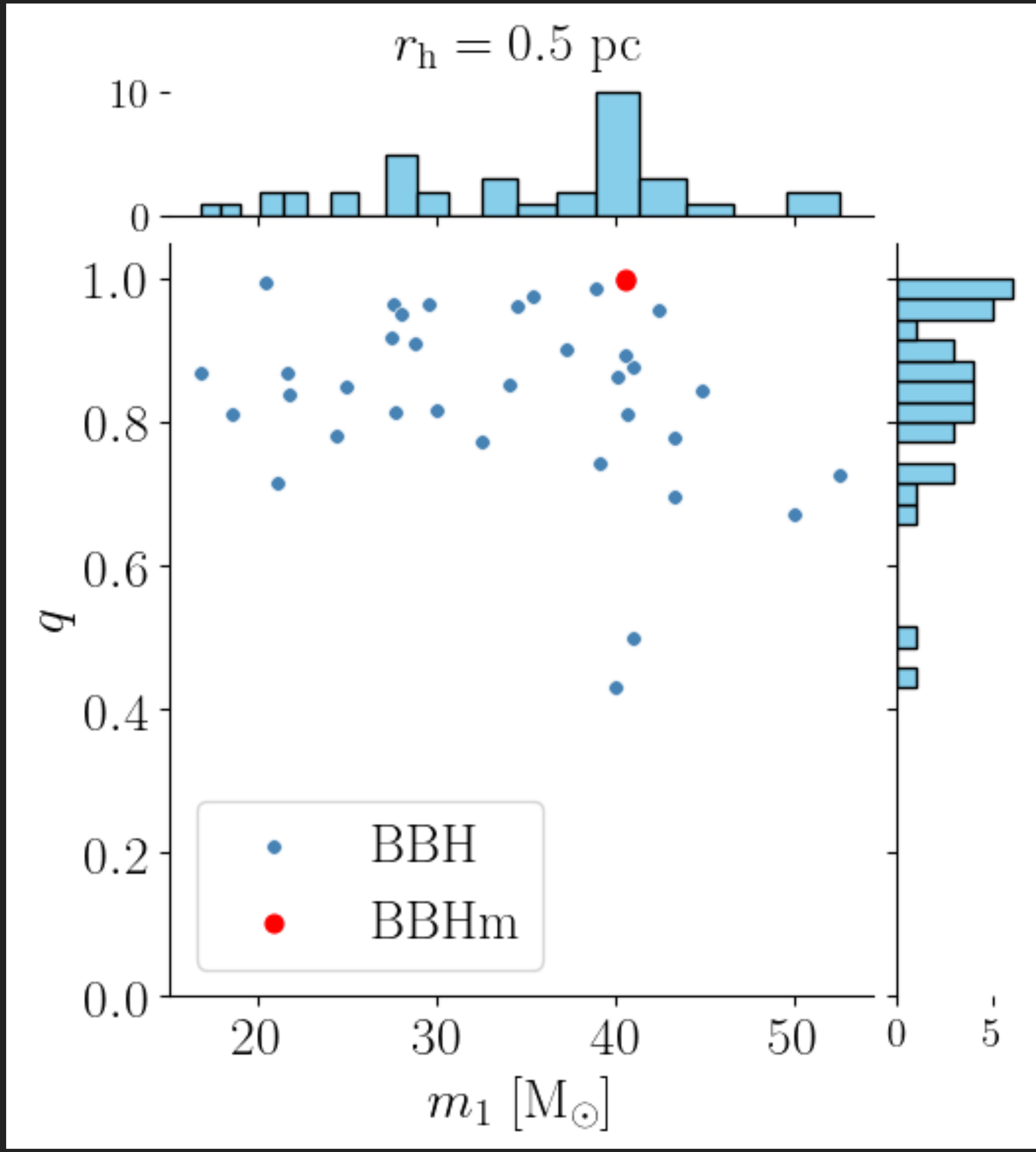
SEVN; *Costa et al. 2023*

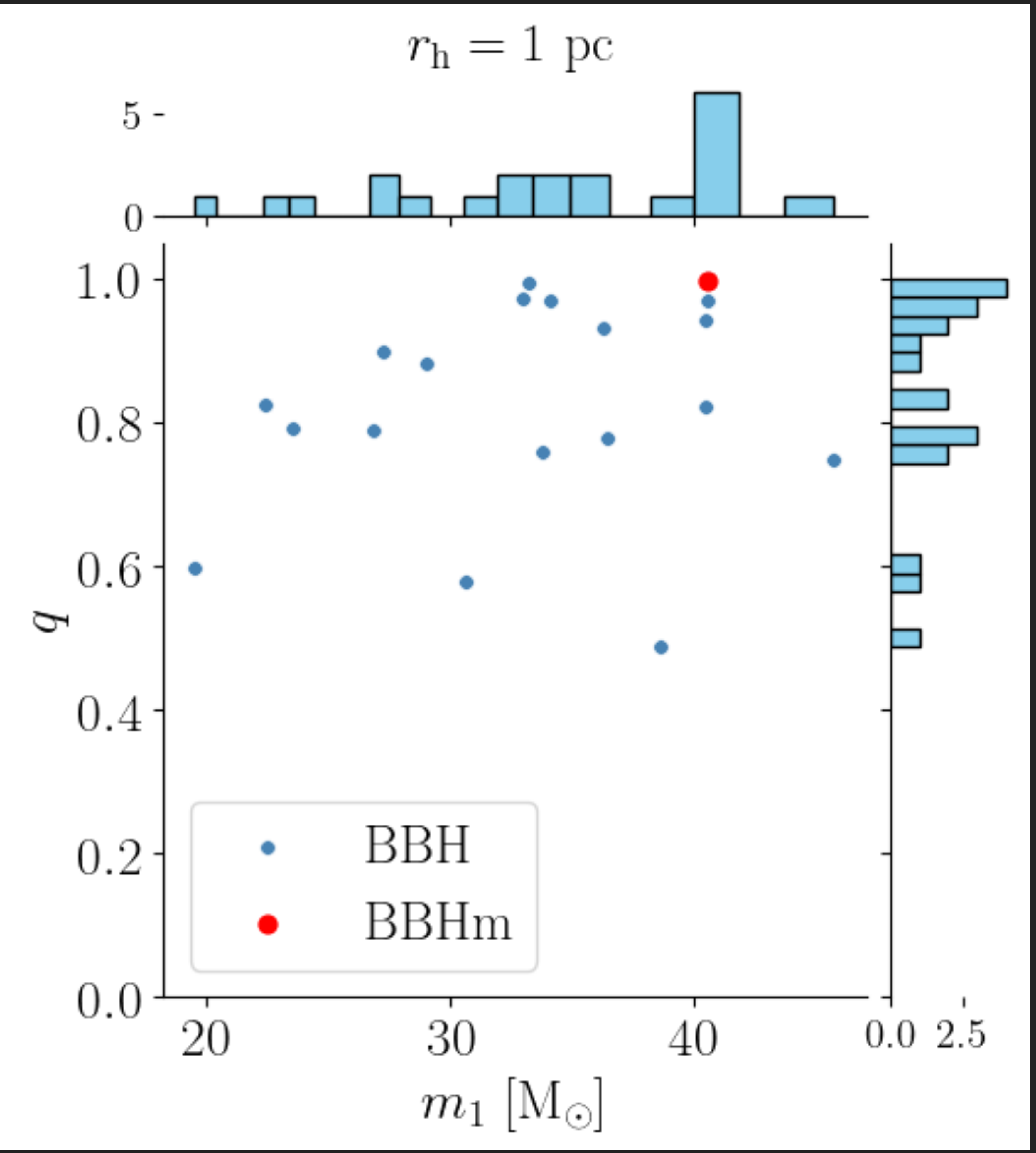
INITIAL POSITIONS

PRELIMINARY



BBH MASS SPECTRUM IN SMALL CLUSTERS





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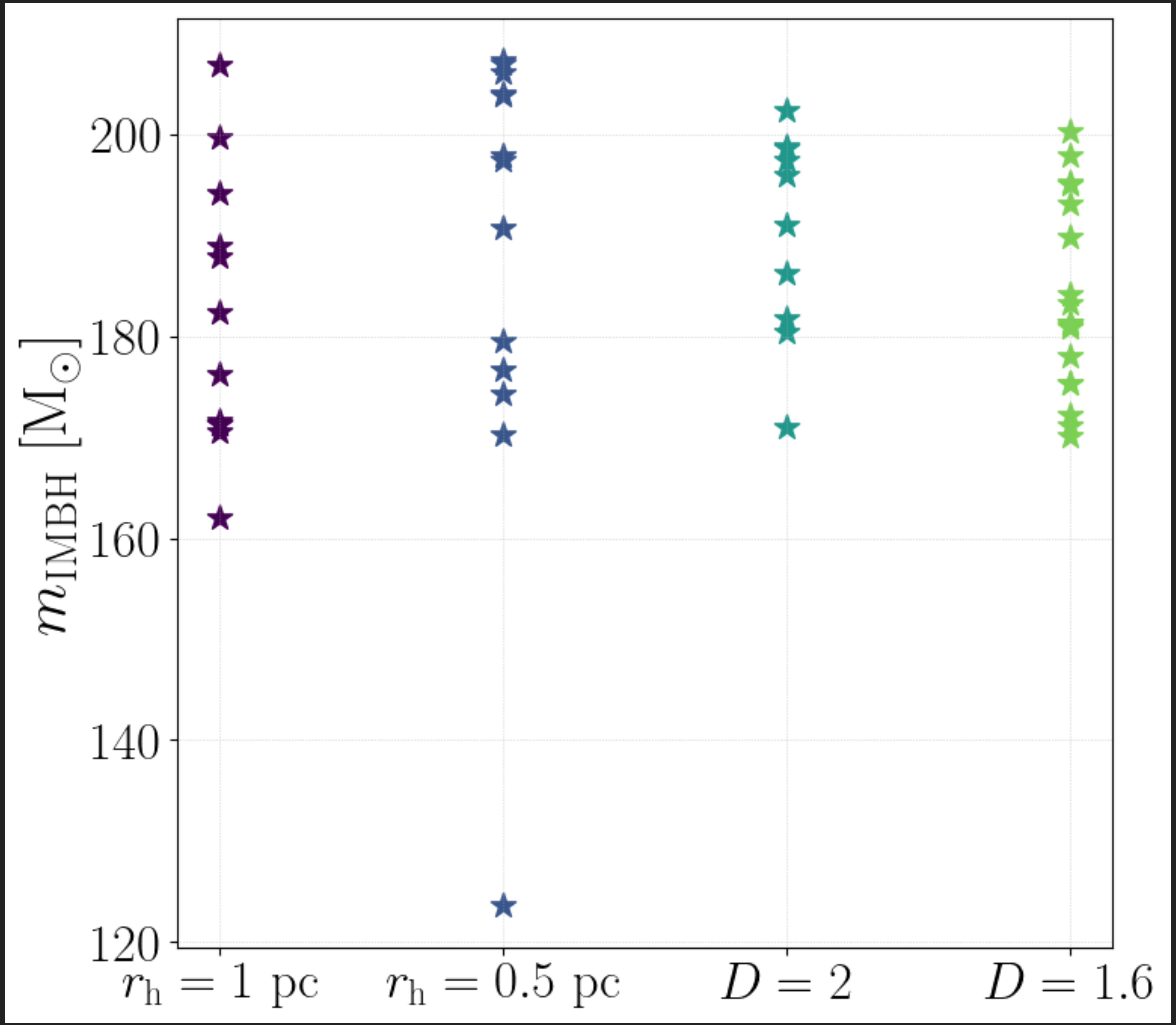
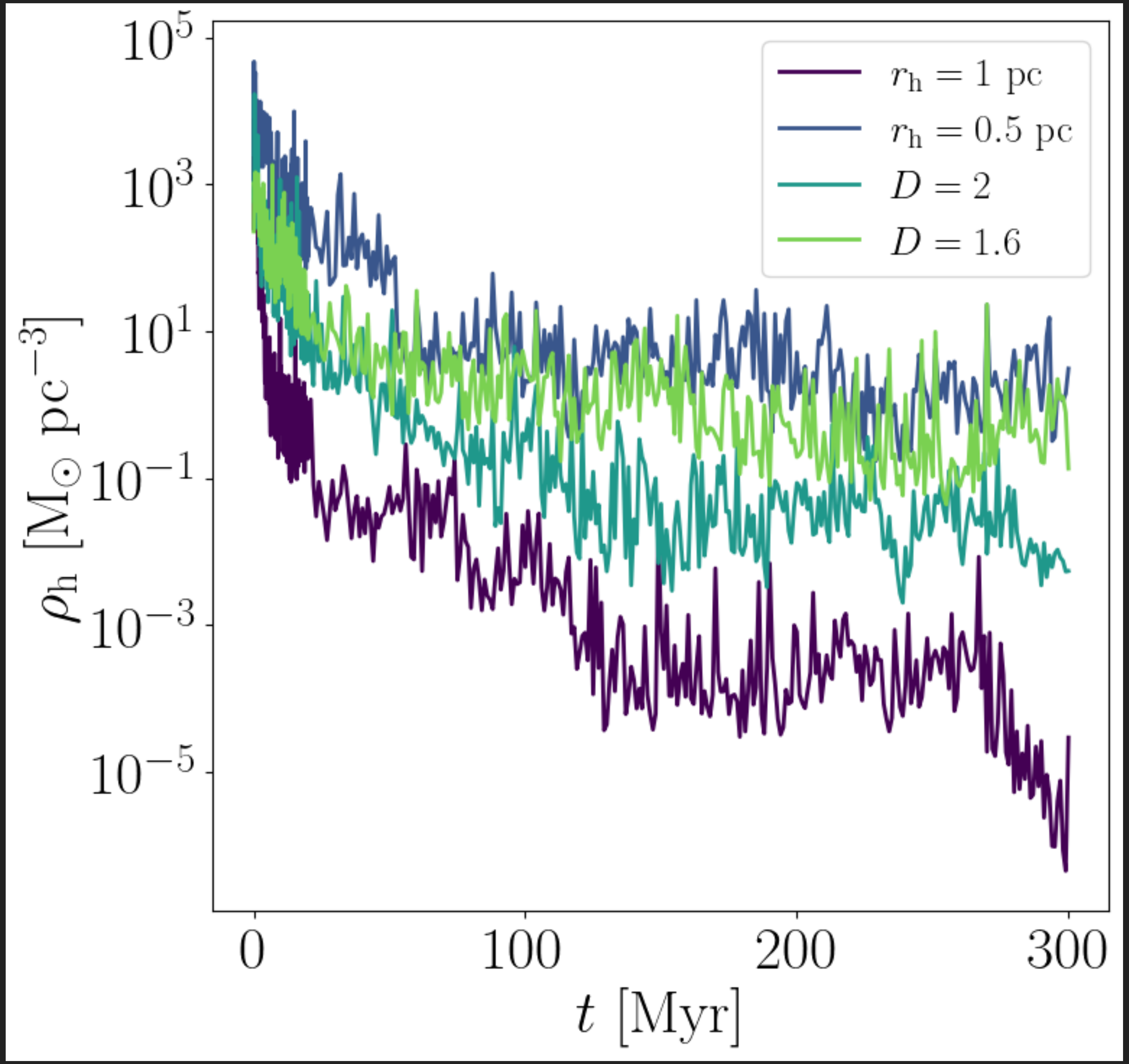
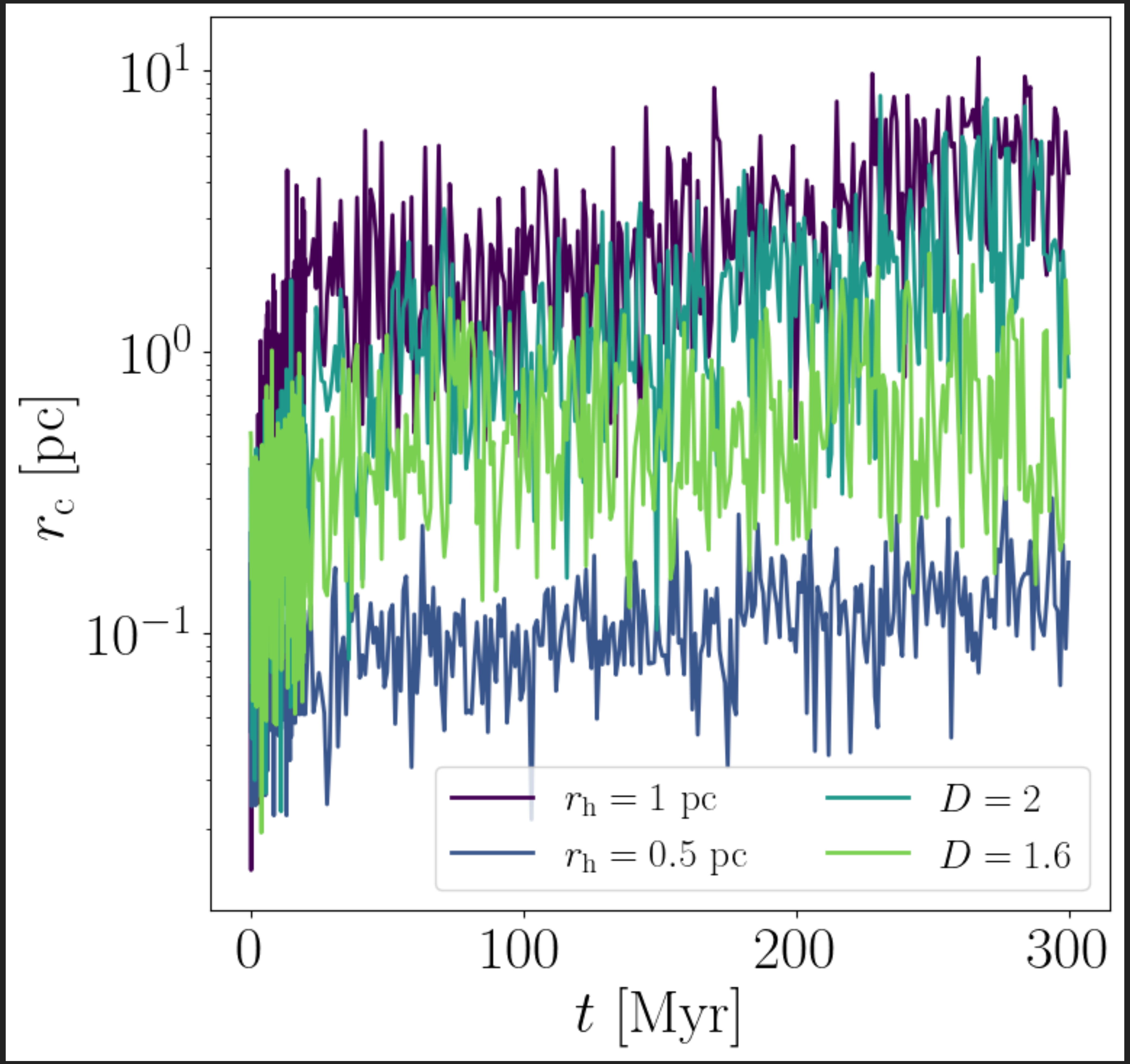
PRELIMINARY



CLUSTER EVOLUTION





WHAT'S NEXT: CLUSTER MERGERS

PRELIMINARY

- **Up to 7 clusters** distributed according to **Plummer density profile** in **free fall**
- Which configuration leads to **higher merger efficiency**?
- Which configuration leads to **IMBH mergers**?