Filling the gaps with intermediate-mass black holes

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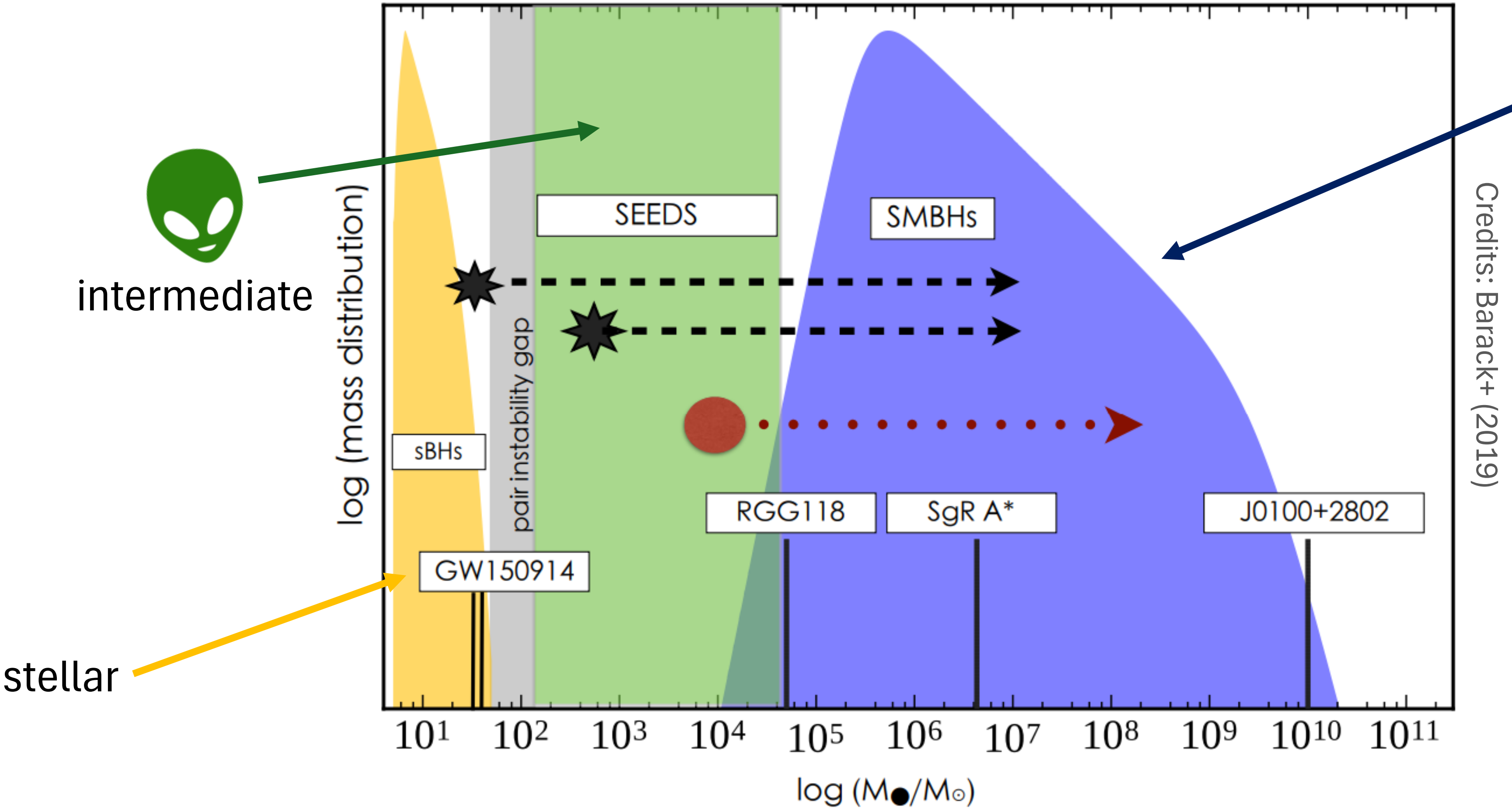
GS
SI

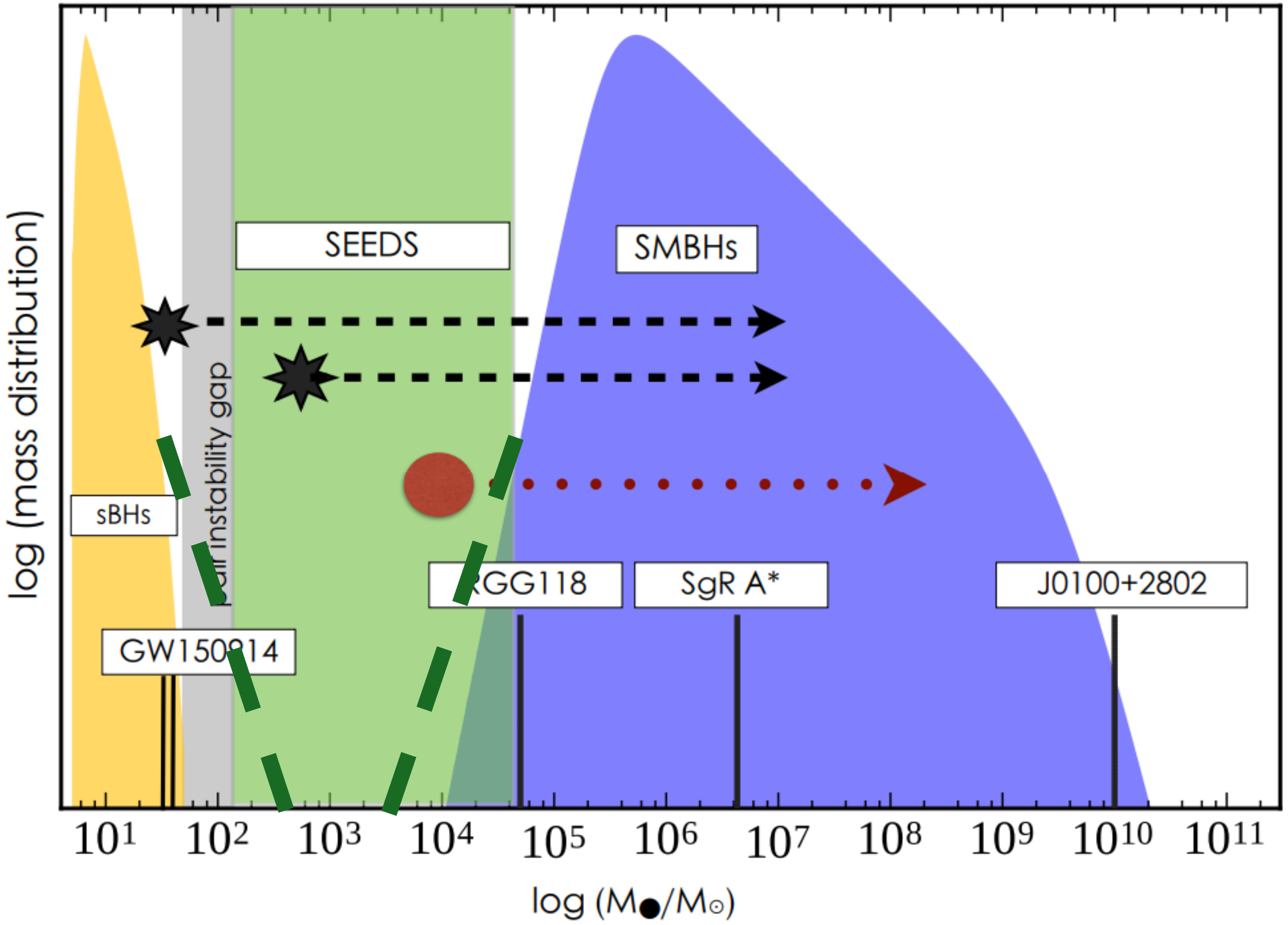
Intermediate-mass black holes: *where is everybody?*

- We are fairly certain about what intermediate-mass black holes (IMBHs) are not, and we believe they must exist to explain the presence of supermassive black holes (SMBHs).



Intermediate-mass black holes: *where is everybody?*

- We do not yet know whether they bridge the gap between stellar-mass black holes (BHs) and SMBHs and if they just represent the extremes of these two classes or a class of their own.



Credits: Barack+ (2019)

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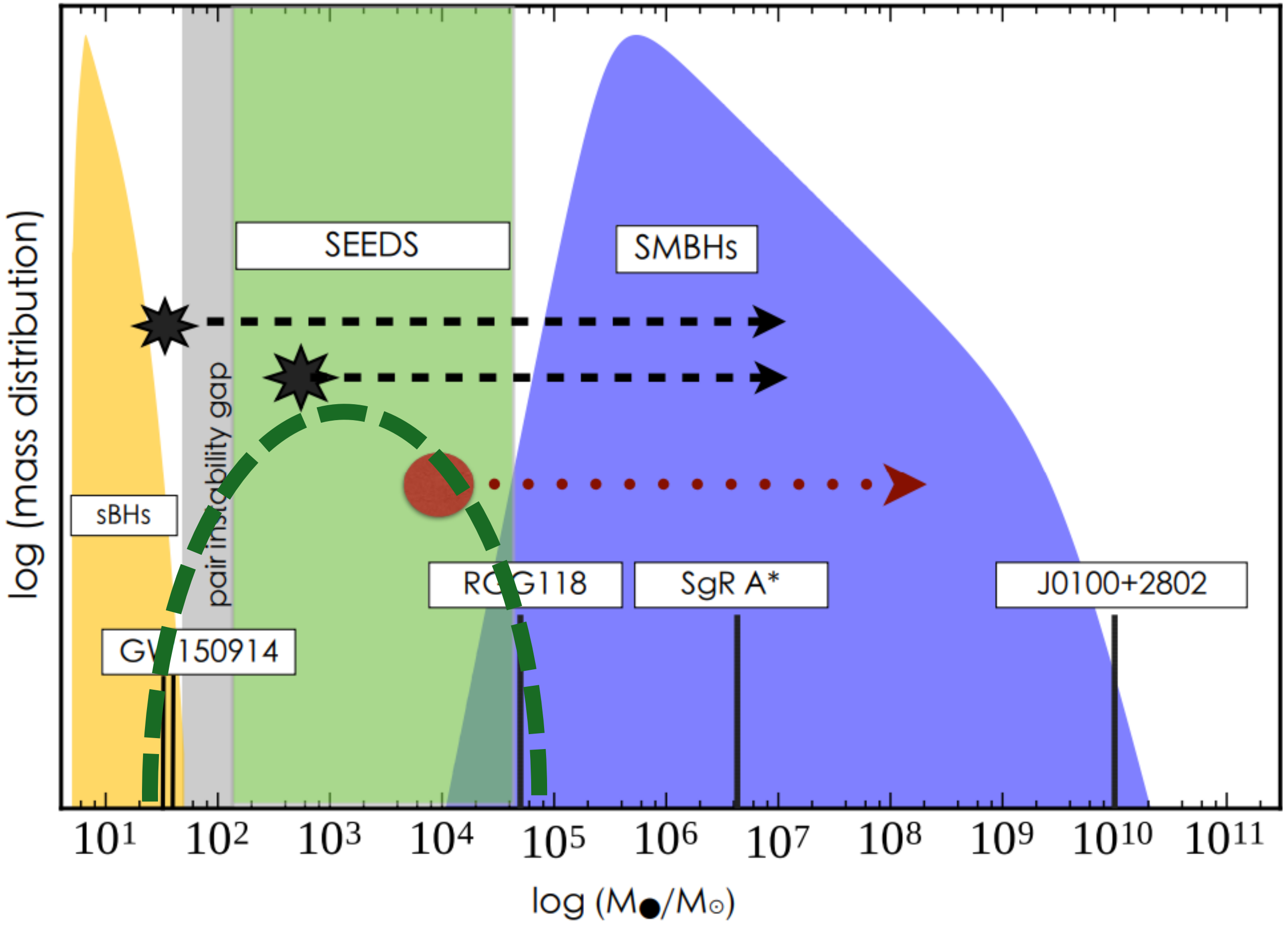
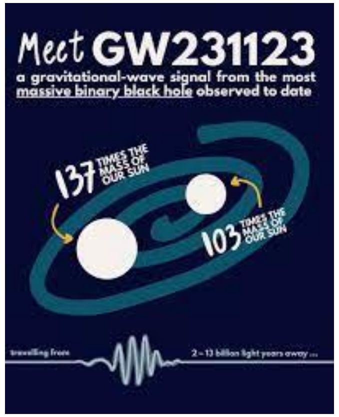
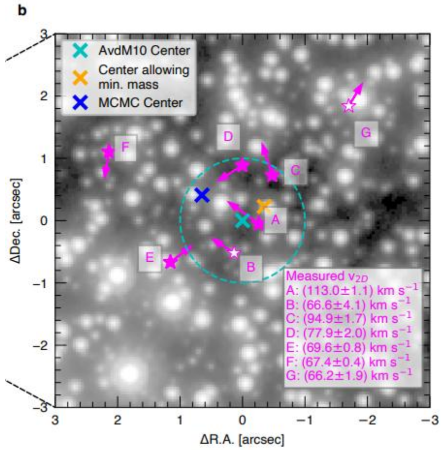


Credits: Barack+ (2019)

New interesting observations

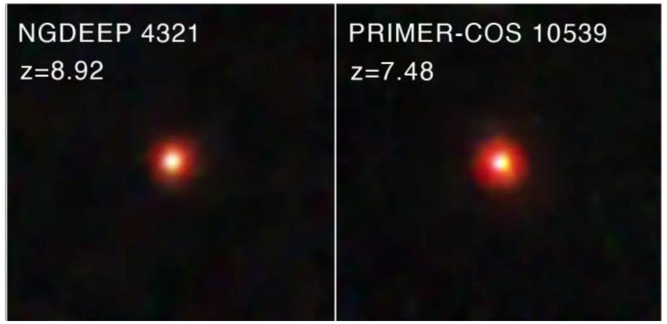
Credits: LVK collab.





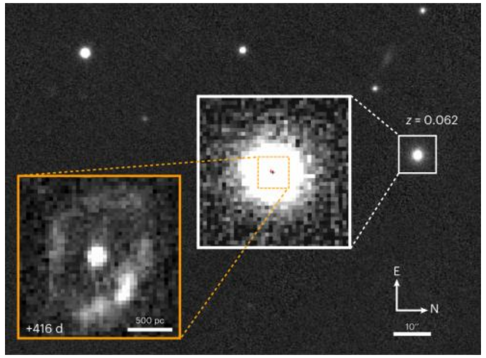
Credit: Haberle+ (2024)

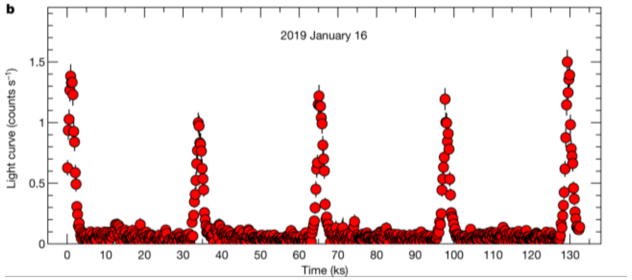
Credit: NASA, ESA, CSA, STScI, D. Kocevski (Colby College)



hundreds **thousands** **millions** [solar masses]

Credit: Angus+ (2022)

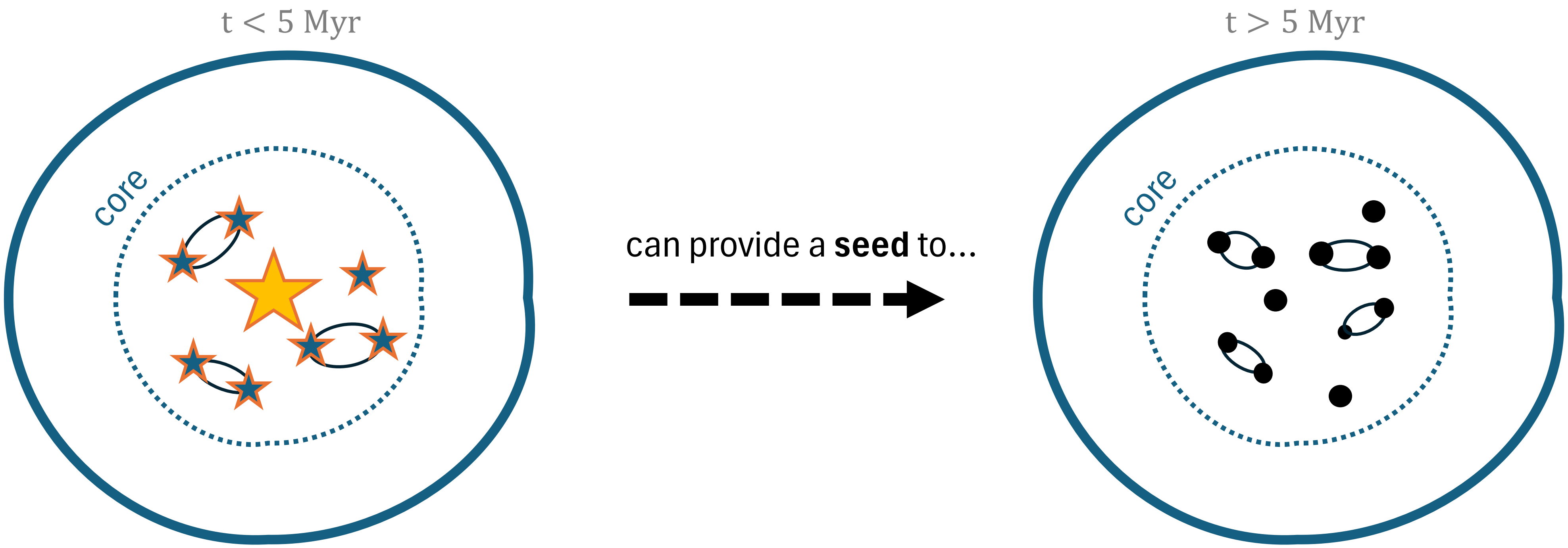




Credit: Miniutti+ (2019)

First project: Studying *where* and *how* IMBHs form

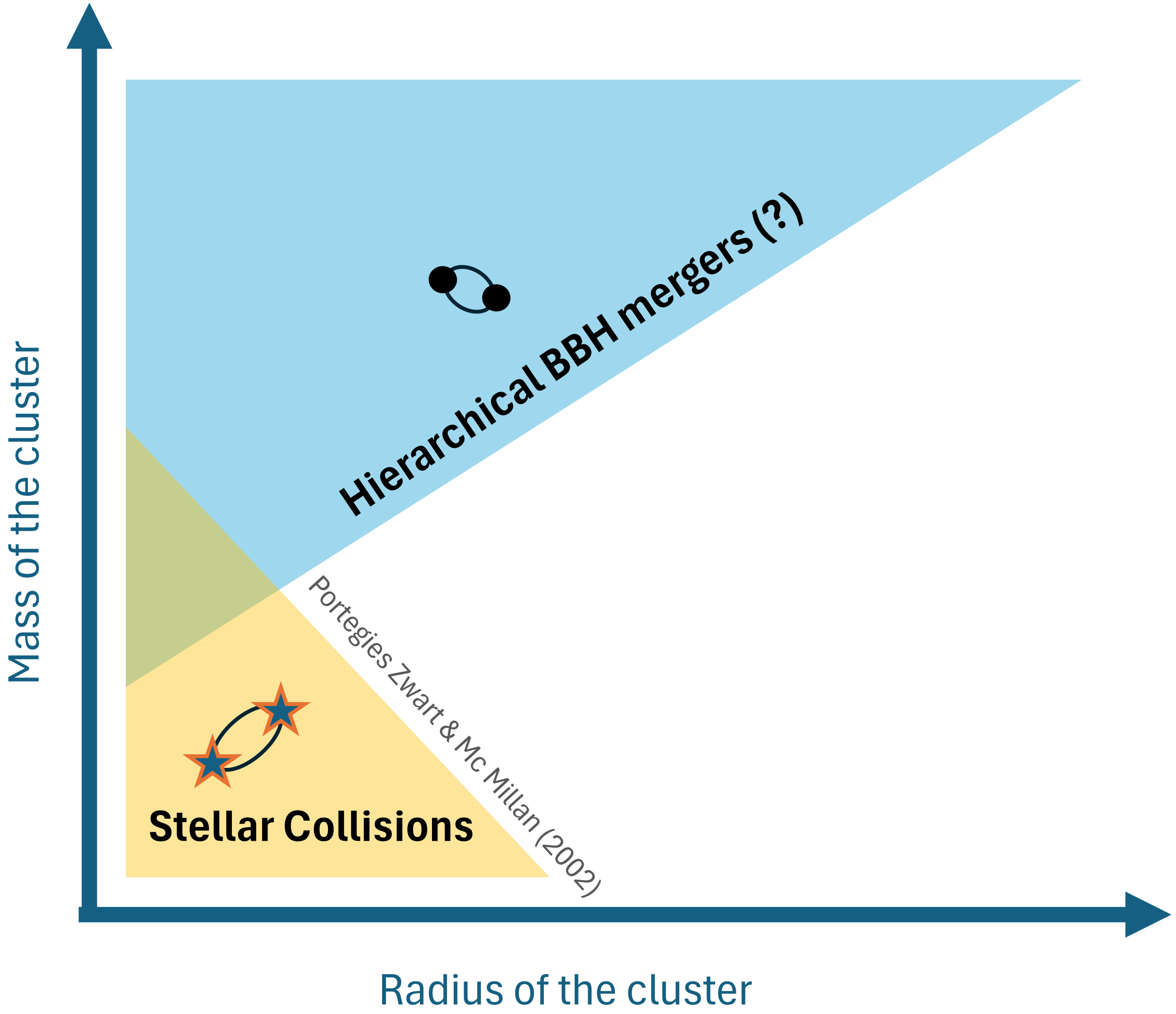
Two main (*not mutually exclusive*) mechanisms to build IMBHs in star clusters:



Stellar Collisions
can produce a very
massive star which
collapses to an IMBH

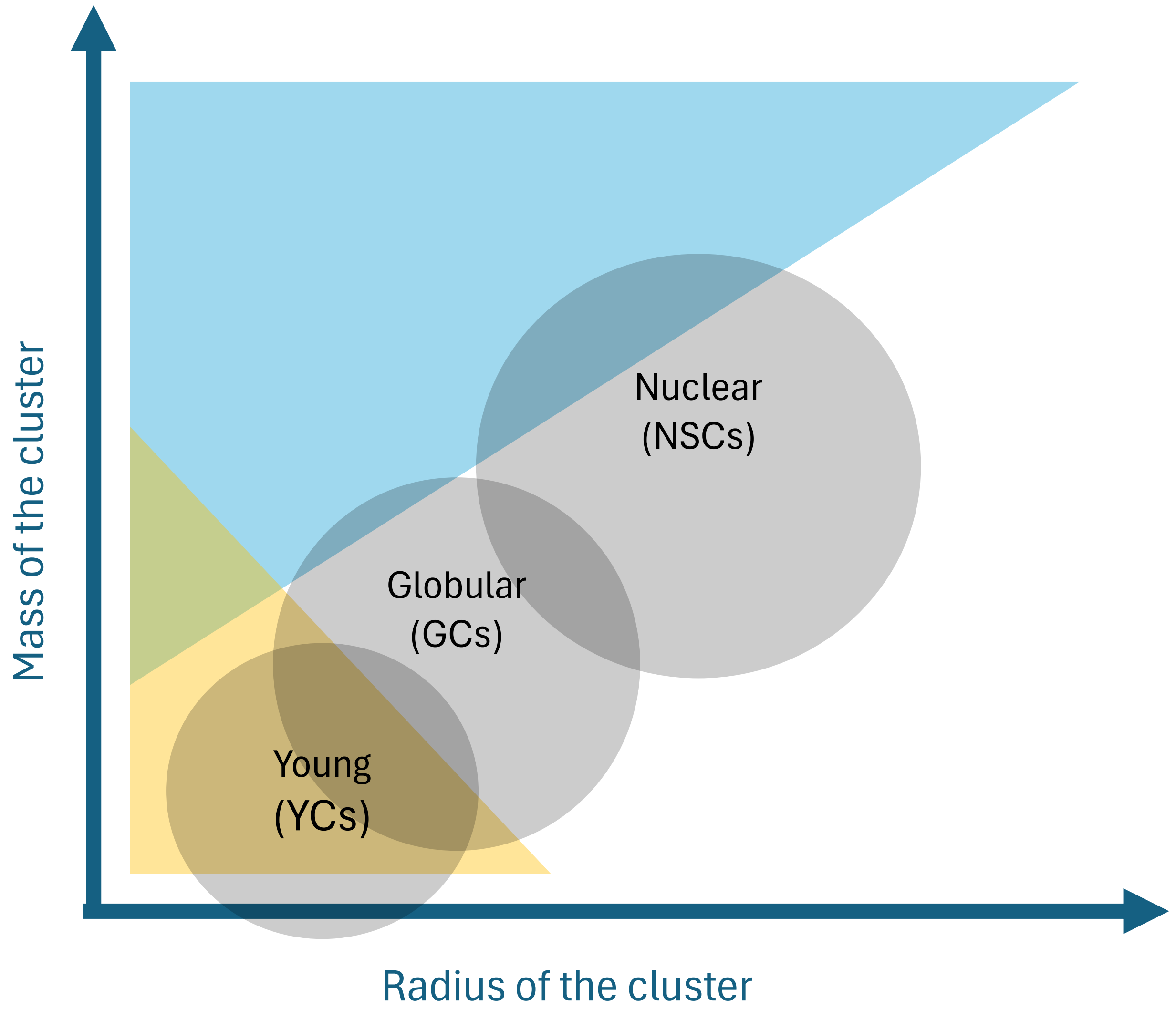
Hierarchical binary BH (BBH) mergers
can assemble an IMBH

First project: Studying *where* and *how* IMBHs form



- The efficiency of these two processes can vary significantly depending on the environment!
- *Typically*, stellar collisions are expected in light but compact clusters
- Hierarchical BBH mergers are expected in massive and dense clusters (high escape velocities)

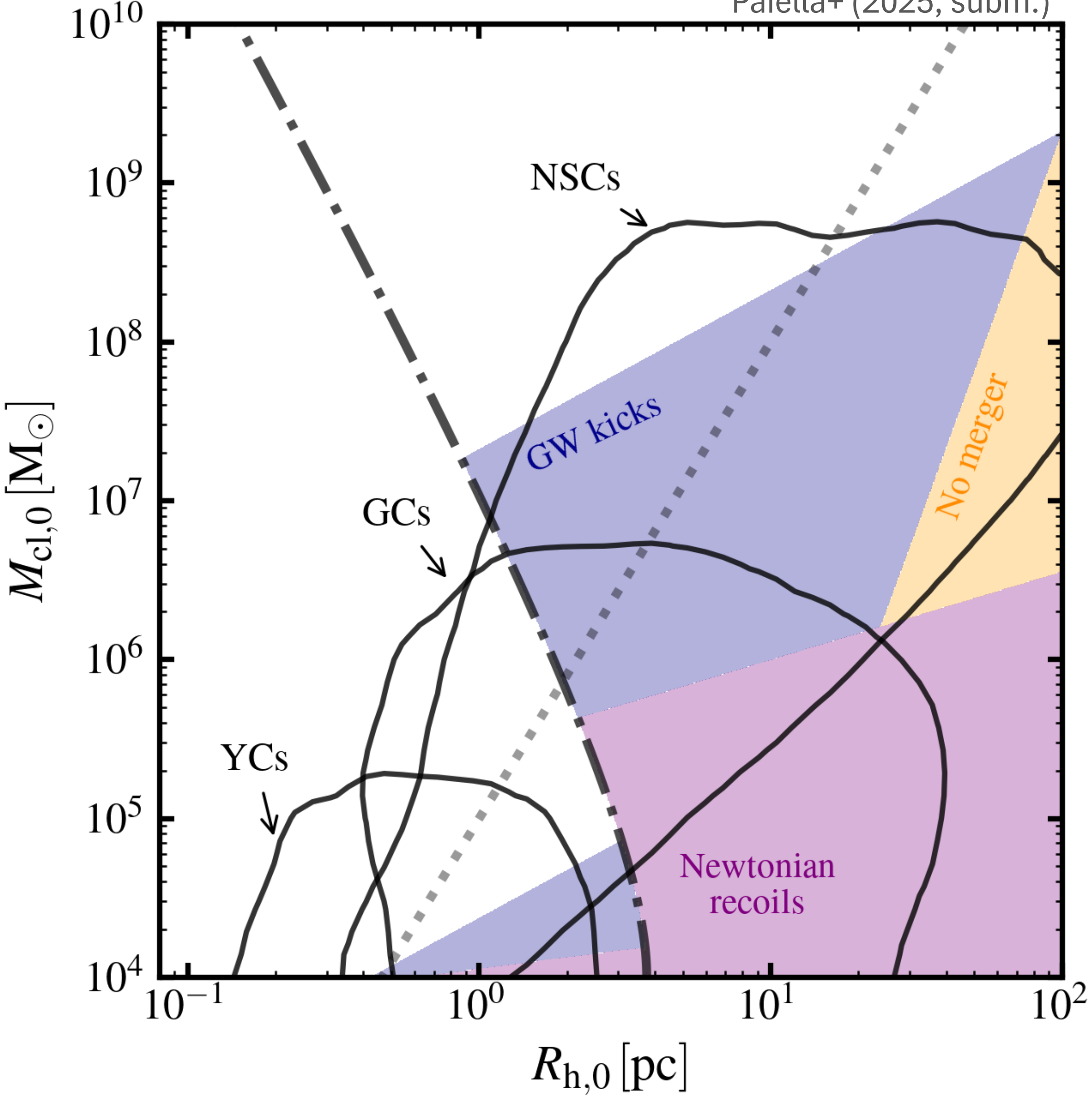
First project: Studying *where* and *how* IMBHs form



- The efficiency of these two processes can vary significantly depending on the environment!
- Young and (light) globular clusters can host stellar collisions
- Nuclear clusters are more efficient at sustaining hierarchical mergers

First project: Studying *where* and *how* IMBHs form

Paiella+ (2025, subm.)



Predicting IMBH formation efficiency is actually far more complicated:

1. Depends on other clusters properties (e.g. metallicity / formation redshift)
2. Depends on the stellar collision model assumed
3. Depends on the dynamical evolution of the cluster (which is coupled to the one of the growing BH)
4. Simulations are computationally prohibitive with N-body / Monte Carlo codes for very massive clusters (> 1-10 million particles)

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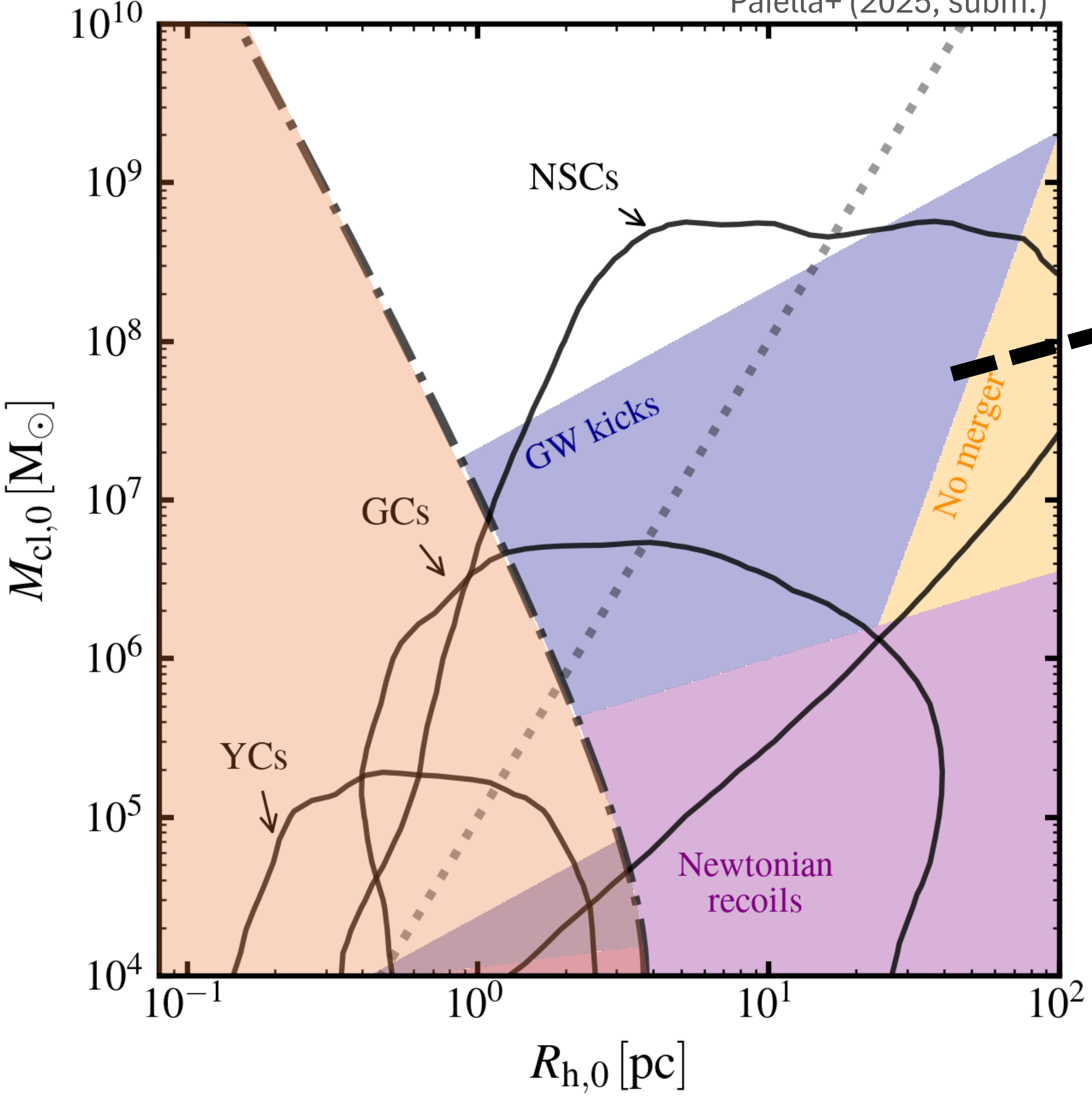

Arca Sedda+ (2023), Arca Sedda+ (in prep.)

We investigate different **stellar collisions / seeding models** and formation histories for the clusters:

- **Runaway** stellar collisions ($t_{cc} < 5$ Myr)
- **Mild** stellar collisions ($\rho_{cl} > 3 \cdot 10^5\ M_\odot/pc^{-3}$)

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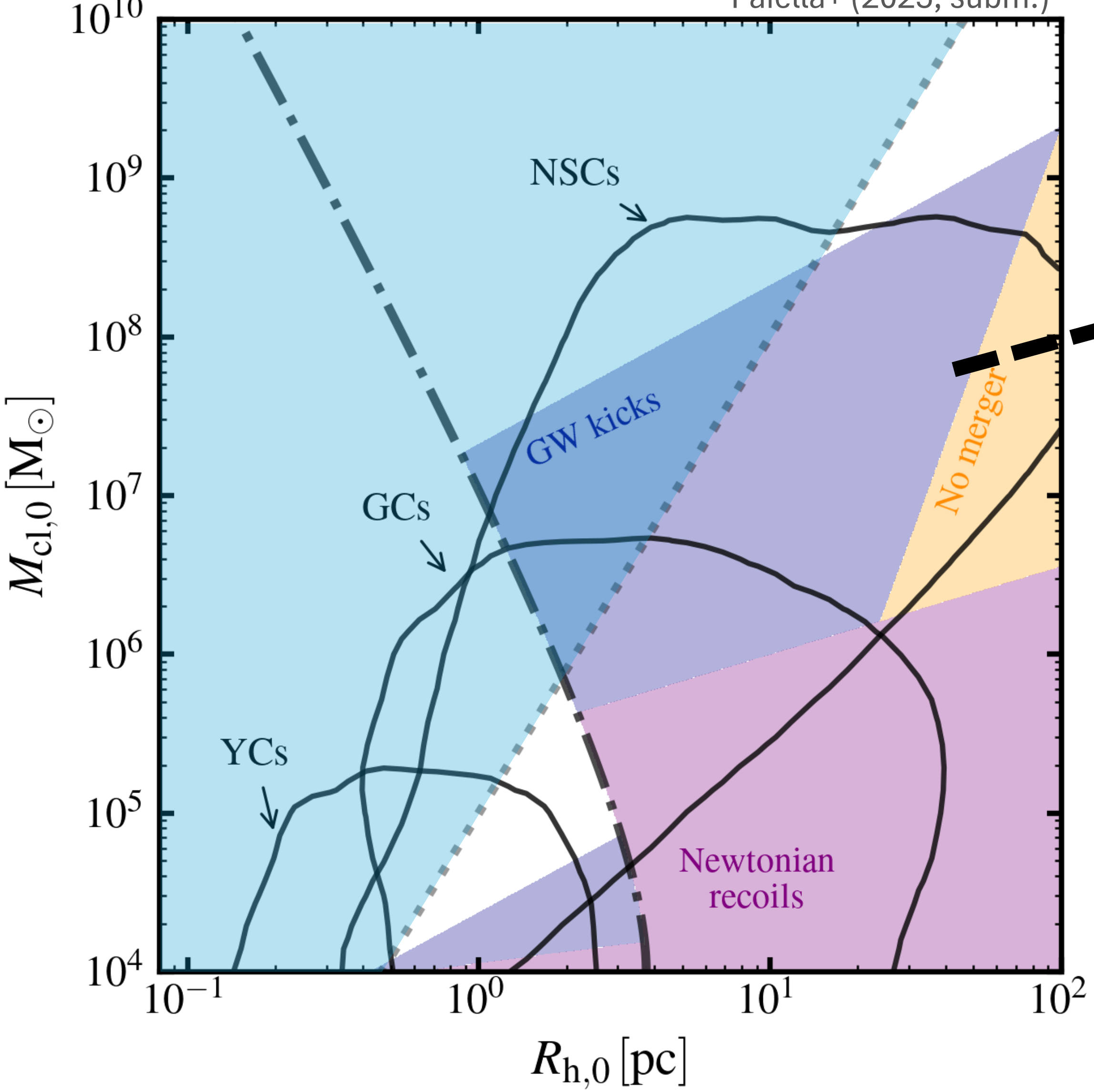

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Results: IMBHs retained in their clusters at redshift z = 0

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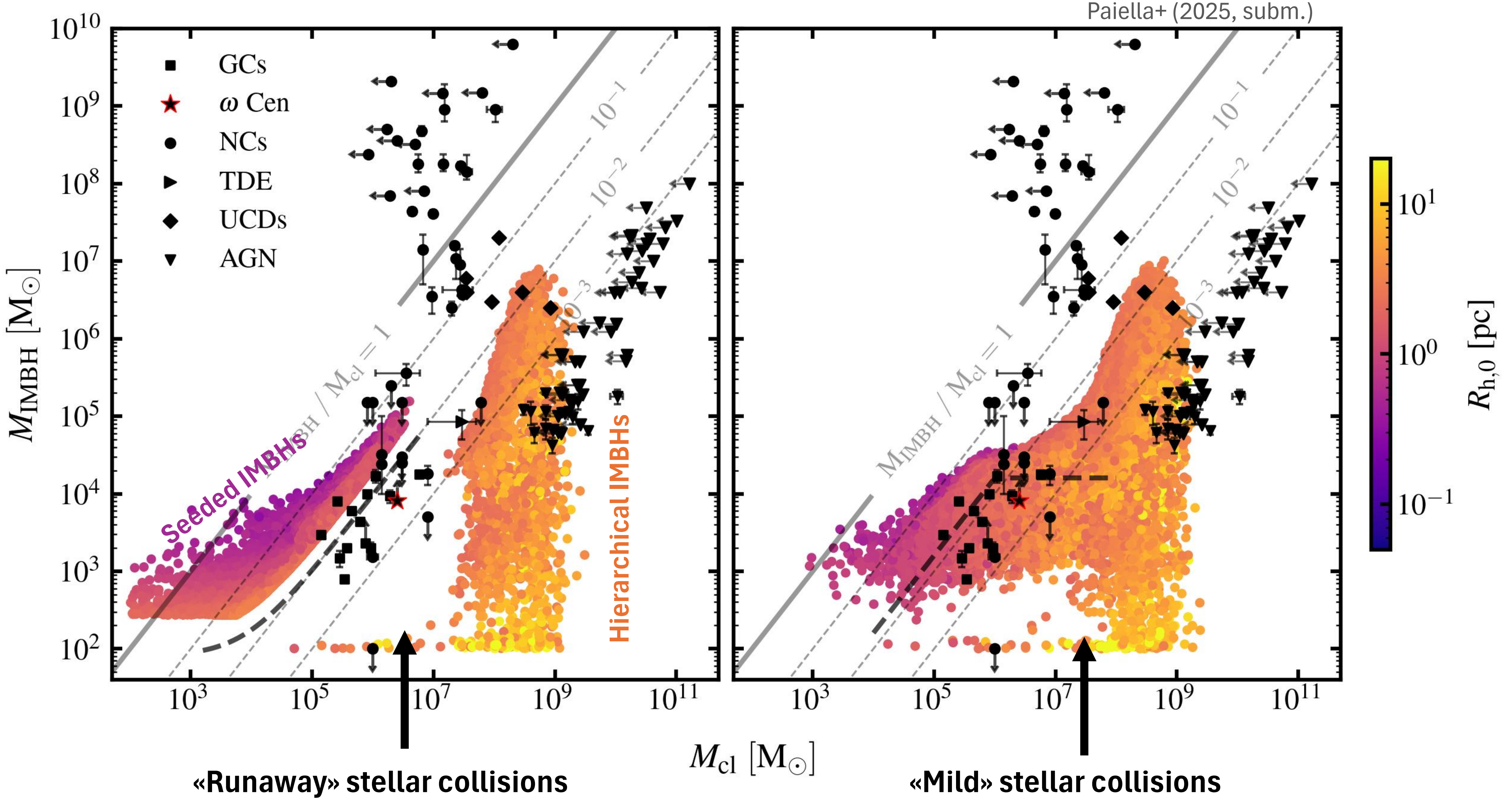

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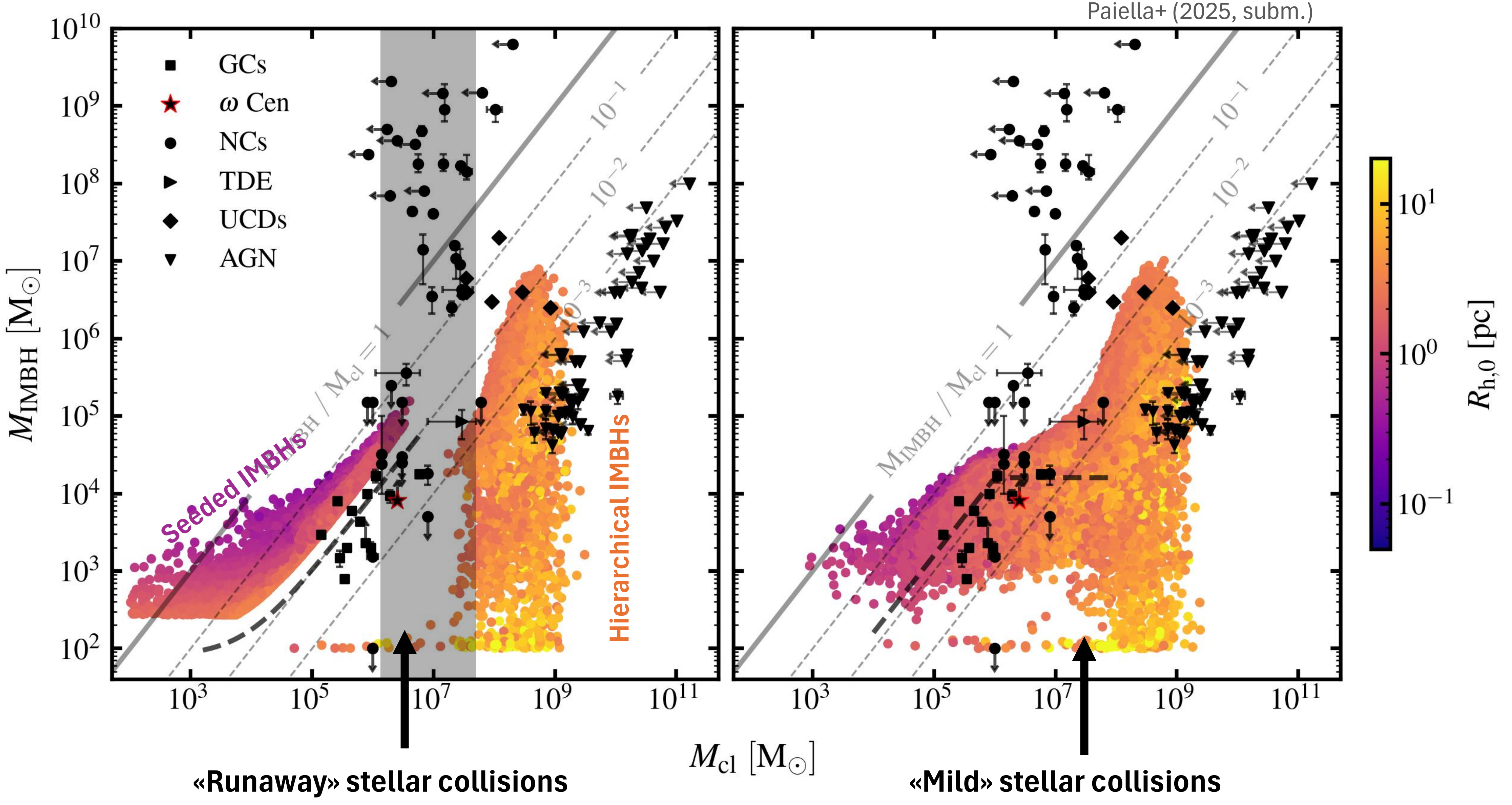

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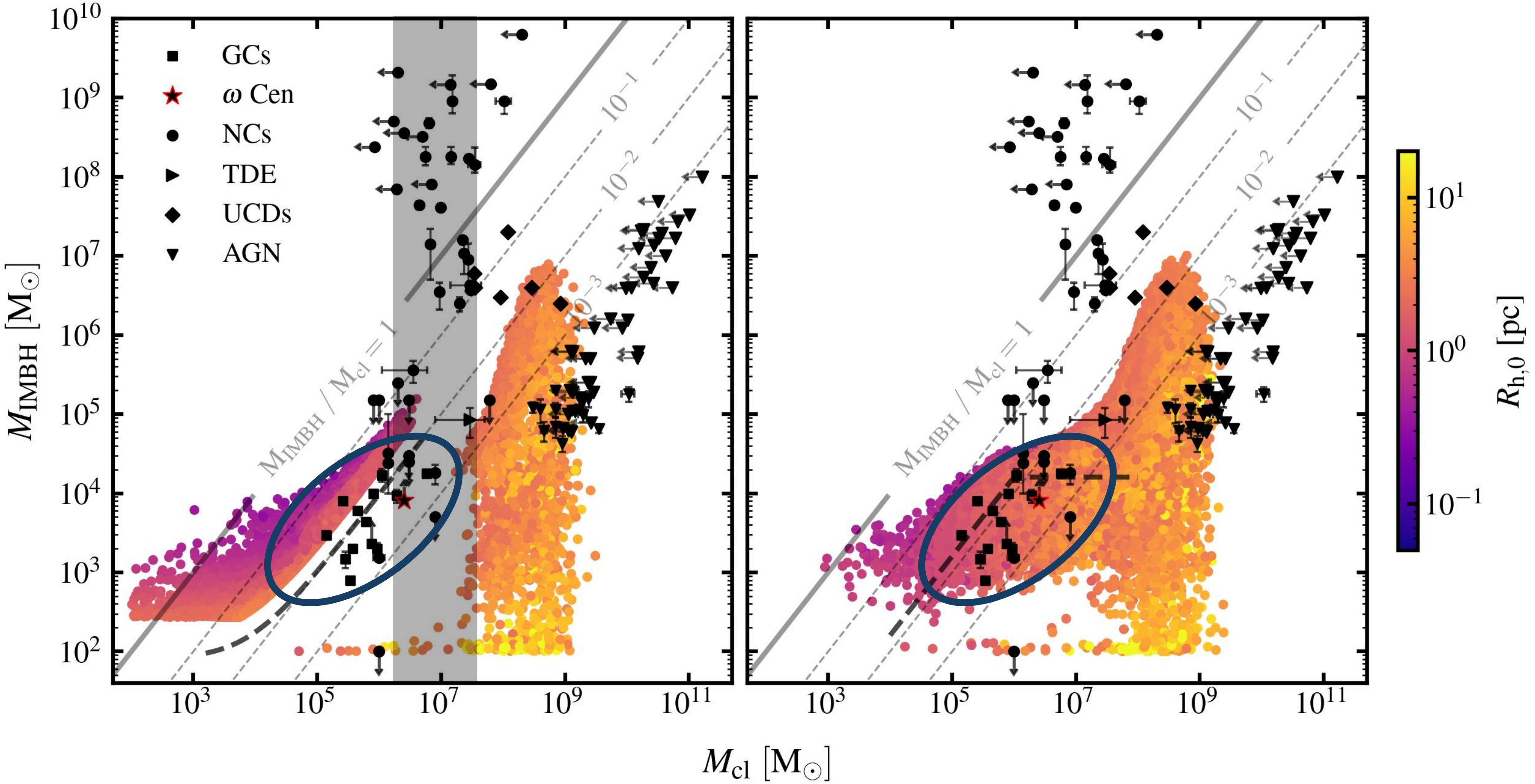
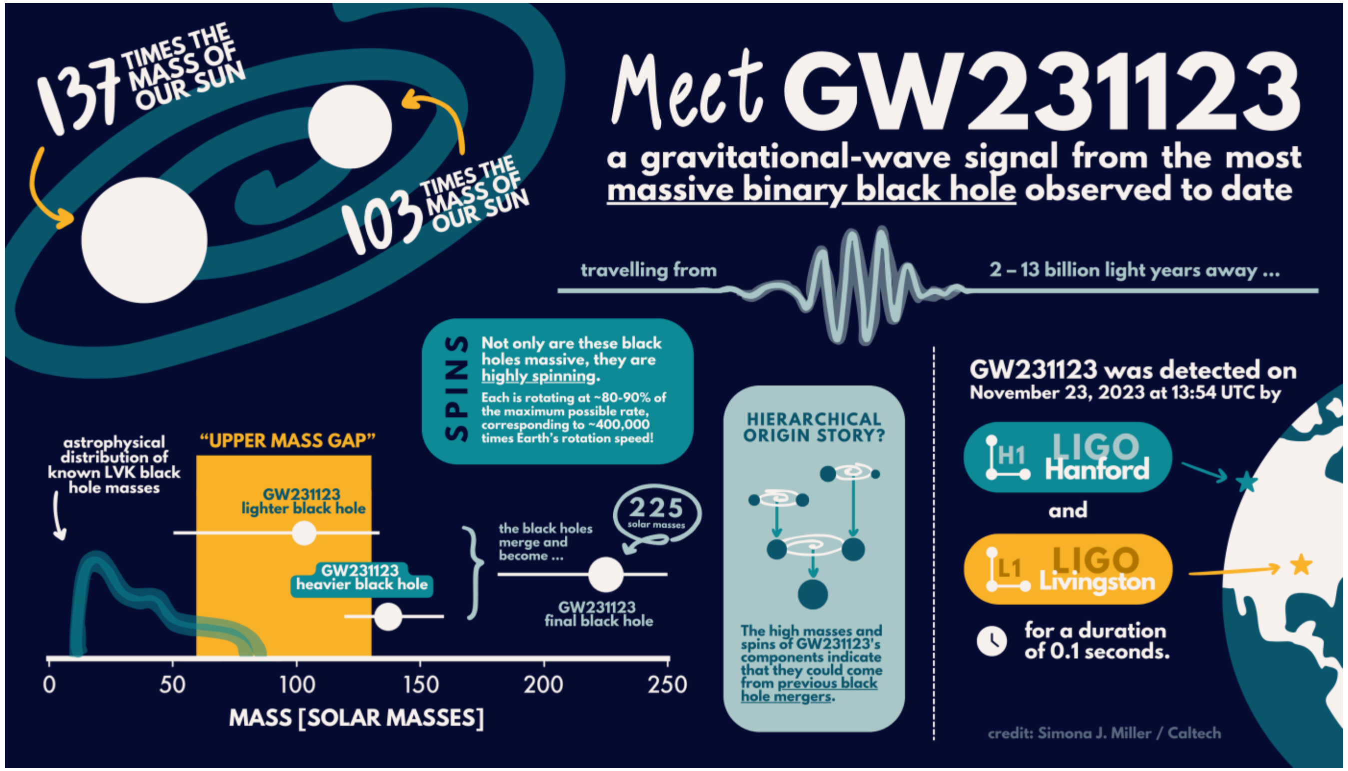


Potential IMBH **observations in Milky Way globular clusters** are well reproduced in our models only in a «mild» stellar collision scenario

Intermezzo: GW231123



Primary mass $m_1/M_\odot$	137^{+22}_{-17}	Primary spin magnitude χ_1	$0.90^{+0.10}_{-0.19}$
Secondary mass $m_2/M_\odot$	103^{+20}_{-52}	Secondary spin magnitude χ_2	$0.80^{+0.20}_{-0.51}$

1. The most massive event detected so far by the LIGO-Virgo-Kagra (LVK) collaboration

2. At least one of the two BHs falls in the **upper-mass gap** (*more on this later*)

3. Both BHs show evidence for **high spins**

Intermezzo: GW231123

Many possible formation channels (*each one with its pros and cons*):

- **hierarchical BBH mergers and / or stellar mergers in star clusters;**
- isolated evolution chemically homogeneous stars;
- dynamical formation in active galactive nuclei (AGN);

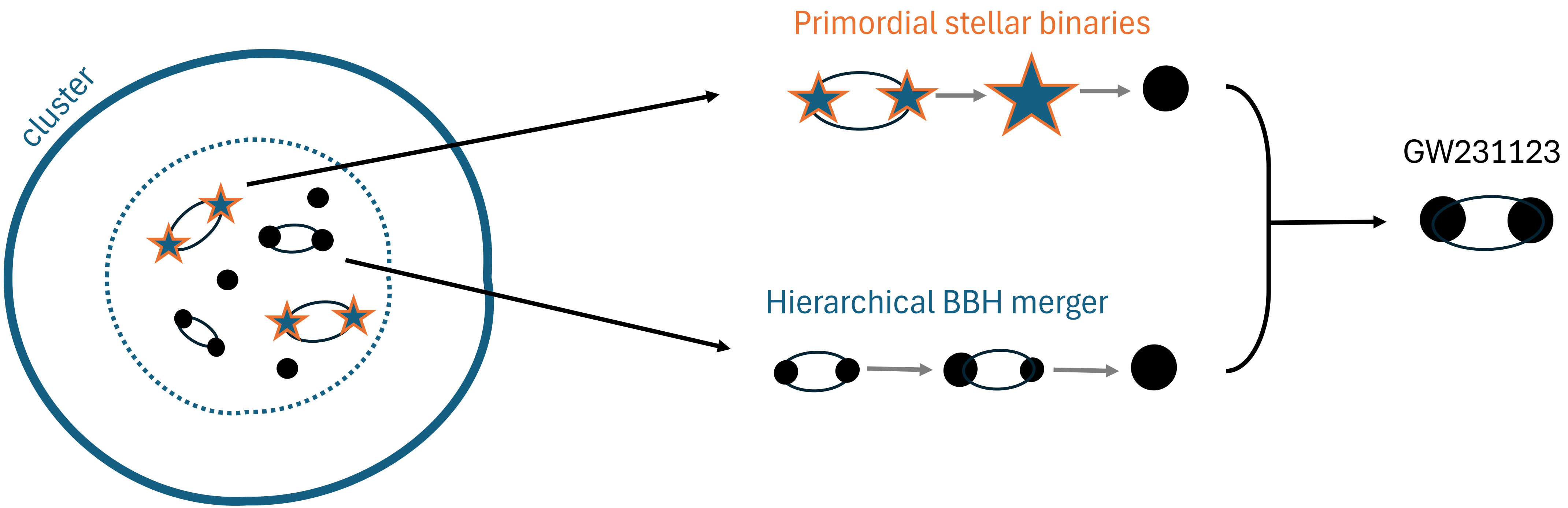
And more!

(see e.g. G.-P. Li, X.-L. Fan 2025; Y.-J. Li et al. 2025,D. Croon et al. 2025, S. A. Popa & S. E. de Mink 2025, J. Stegmann et al. 2025; F. Kıroglu et al. 2025, S. Liu et al. 2025)

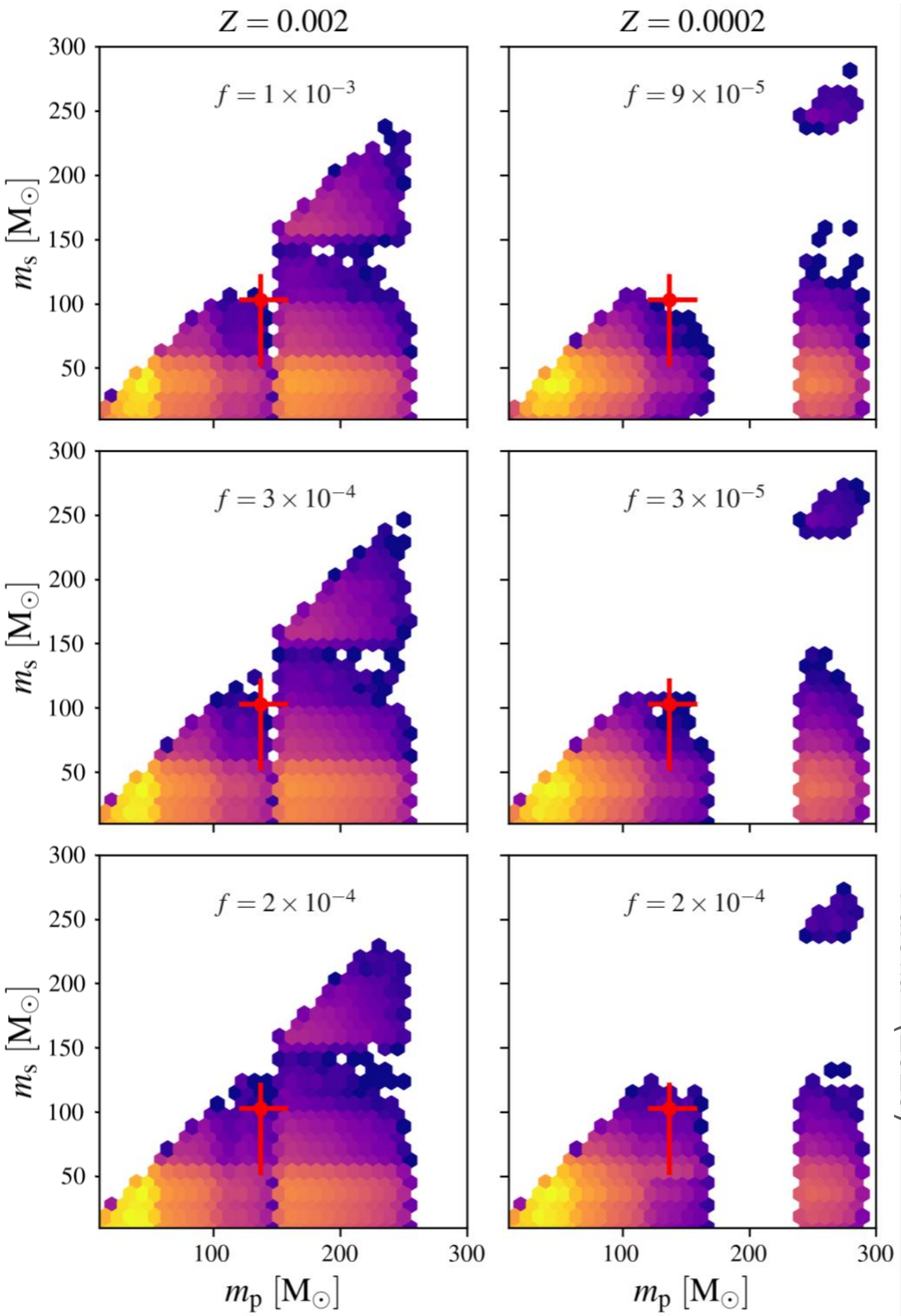
Accepted on ApJL!

Paiella, Ugolini, Spera, Branchesi and Arca Sedda (2025)

Second project:
Assembling GW231123 in star clusters



Note that in our simulations only the primary BH can undergo previous mergers!
(see **Ugolini+, in prep**. for multiple generation secondaries)



Paiella+ (2025)

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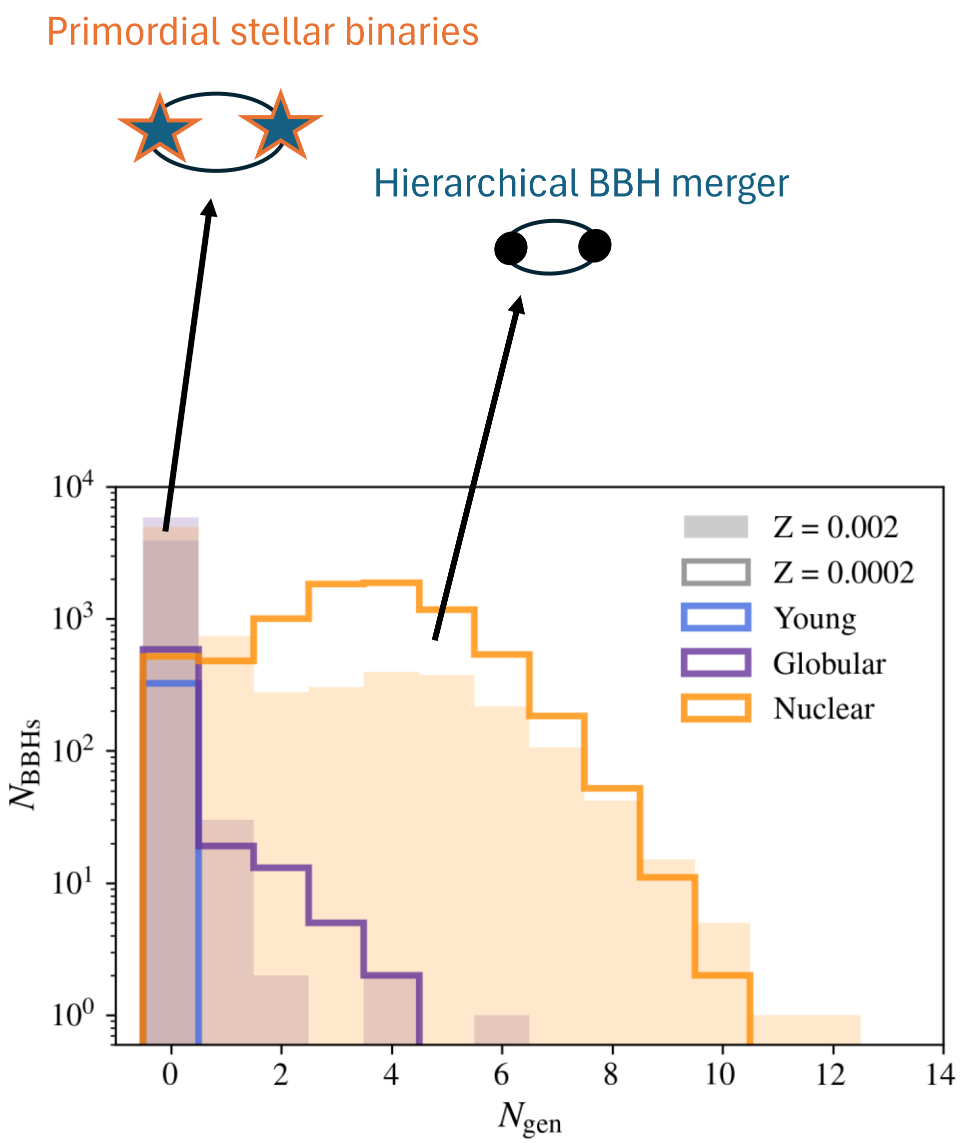

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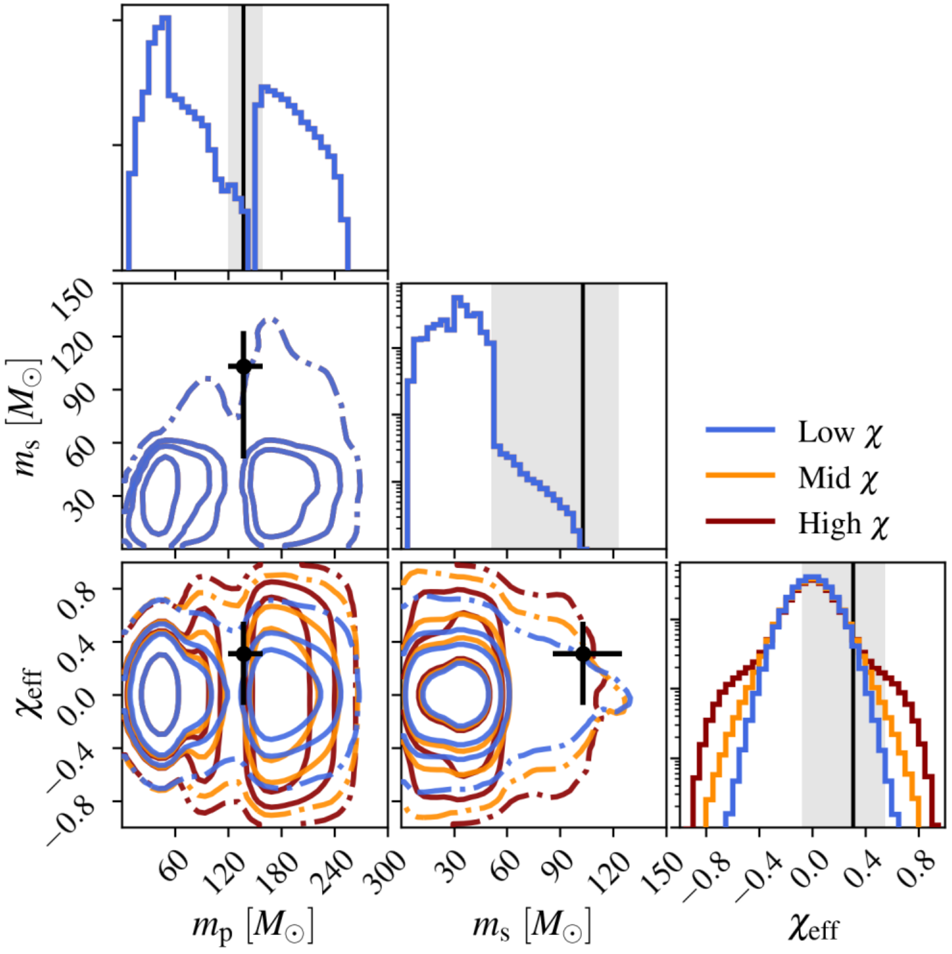

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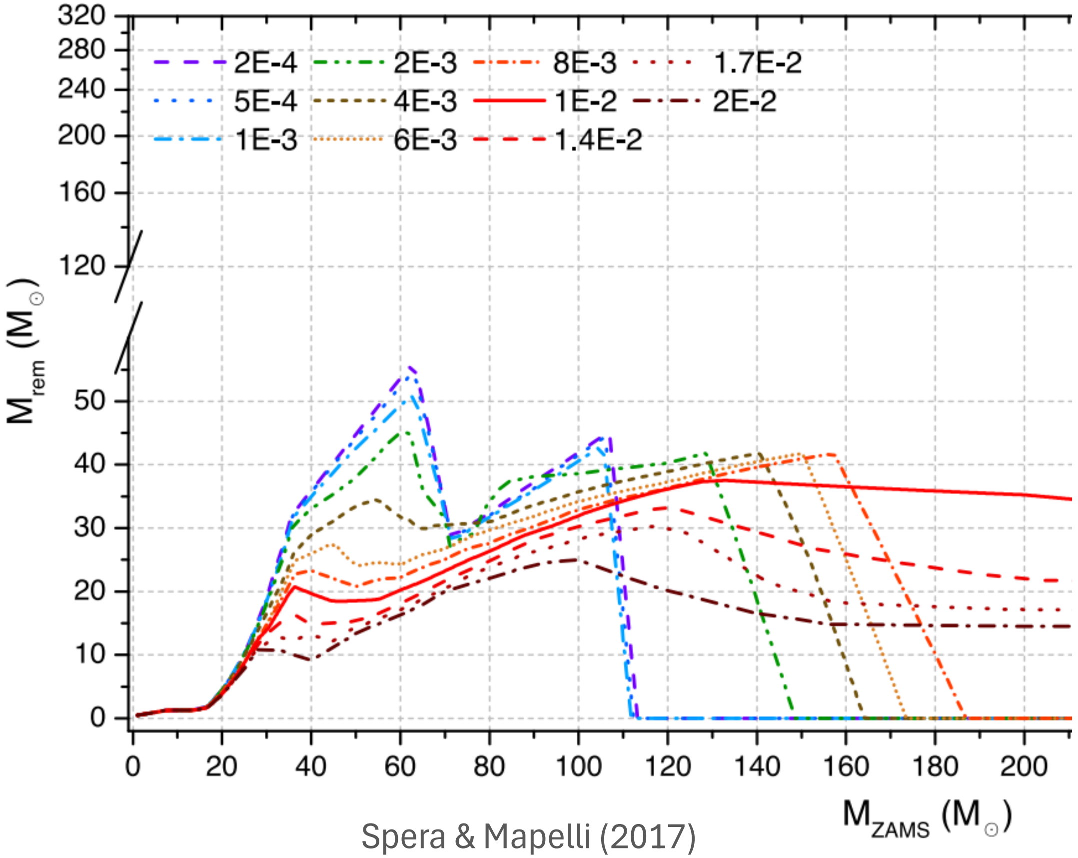
- In young and globular clusters («light clusters») GW231123 analogs are typically made of BHs processed in primordial stellar binaries
- In nuclear clusters («heavy clusters») they are systems in which the primary BH already underwent previous mergers
- We investigate three spin scenarios from BHs formed in or above the gap and find that increasing natal spins can increase GW231123 by 2-3 orders of magnitude

Ongoing project: Connecting IMBHs to *supernovae**

Collaborators: Francesco Gabrielli, Mario Spera, Cristiano Ugolini, Benedetta Mestichelli, Manuel Arca Sedda

The emergence of pair instability supernovae (PISNe) prevents the formation of light IMBHs from stars with masses around 100 – 200 solar masses (*helium core of 60 – 130 solar masses, depends on the metallicity*).



Spera & Mapelli (2017)

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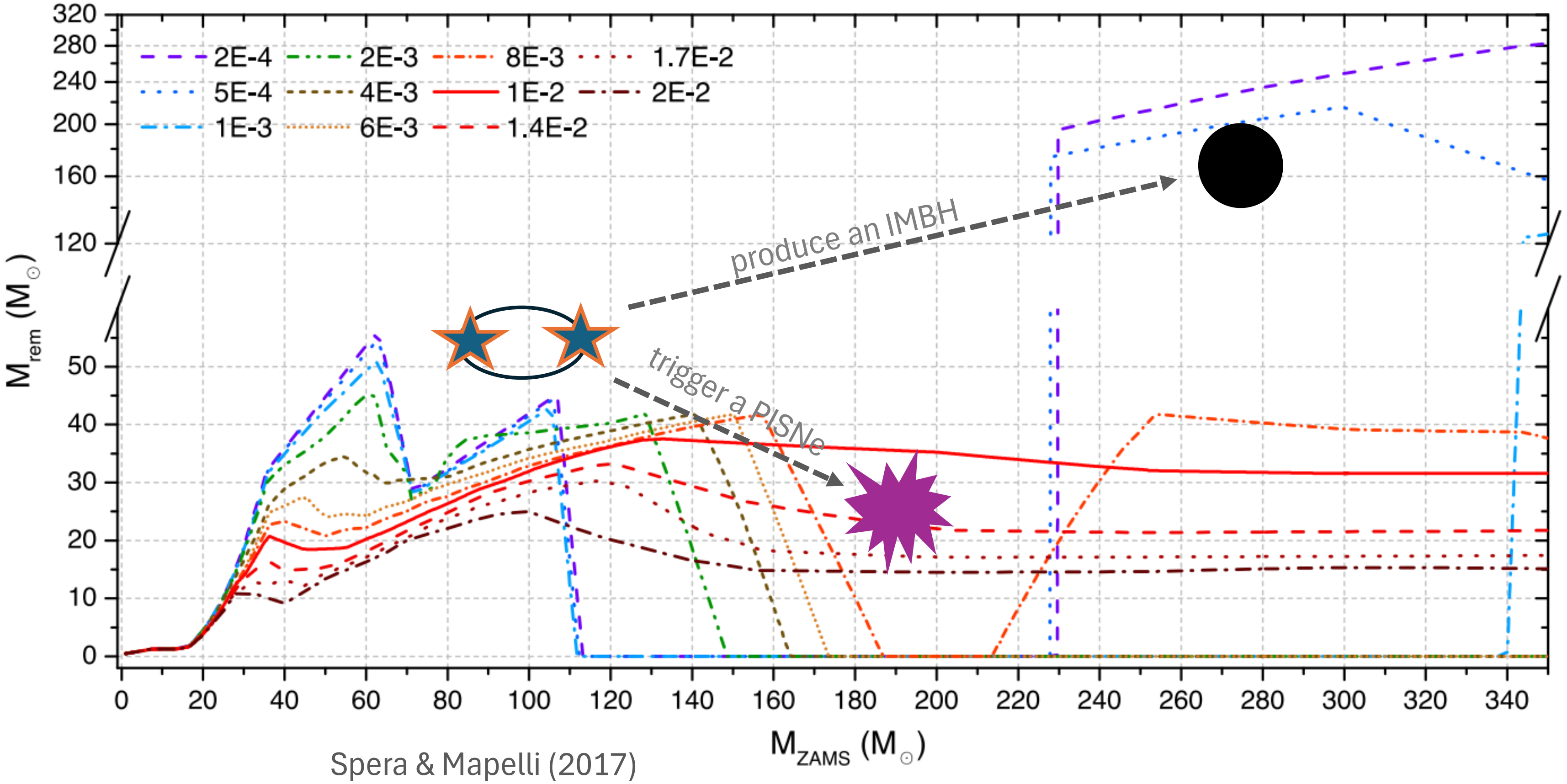
Stellar mergers in star clusters can potentially produce stars in and beyond the PISN regime, i.e. having a significant effect the production of PISNe and IMBHs.



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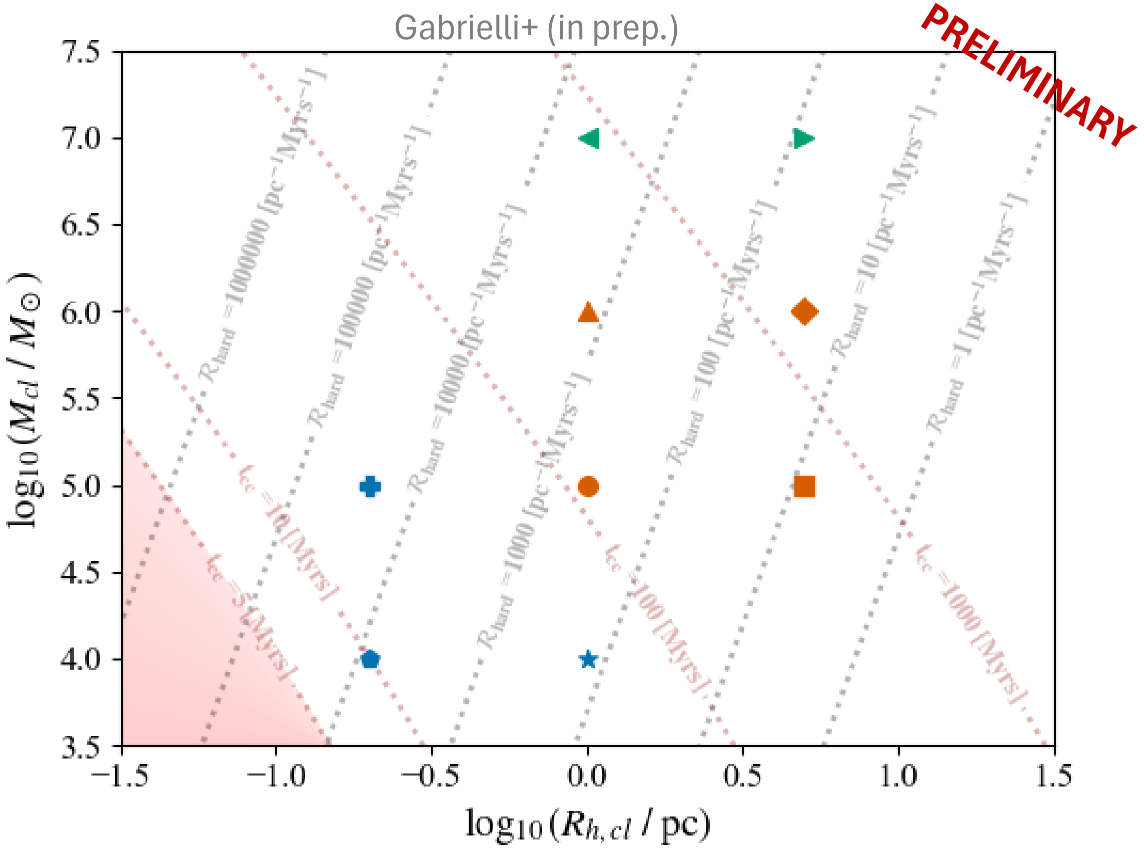
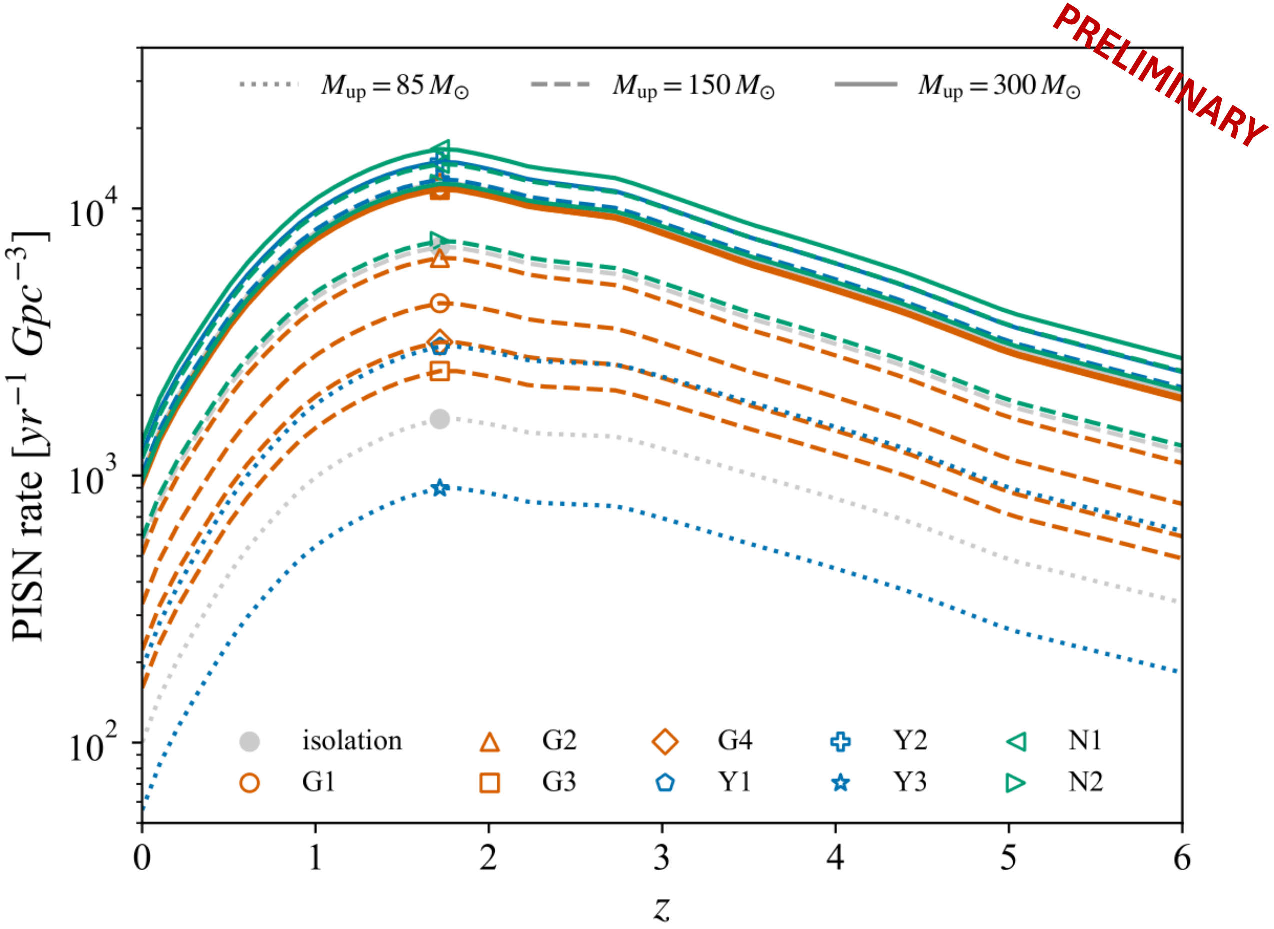


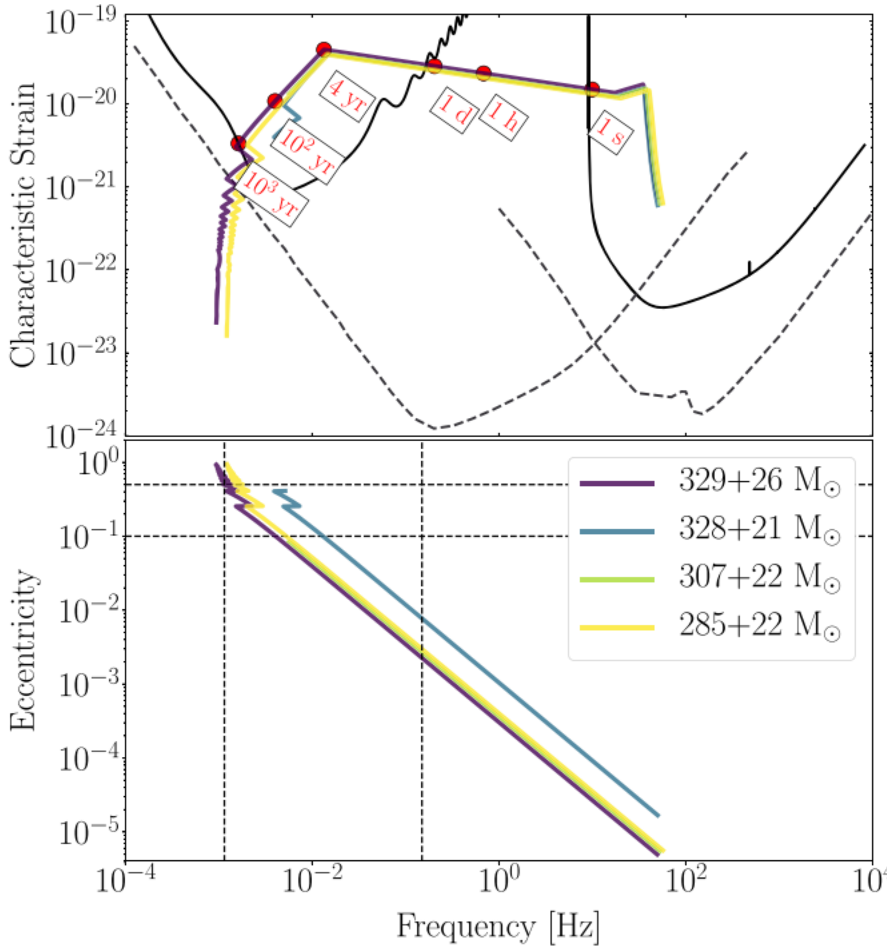


How are different clusters affecting the PISNe rate?

(Iorio et al., 2022, Spera et al., 2019)

Next project(s)? IMBHs in the deci- and milli-Hz

IMBH-BH mergers and IMBH-IMBH mergers represent interesting targets for future detectors in the deci- and milli-Hz, like LISA.



Arca Sedda+ (2021)

Extend / interface B-POP with a code simulating the **merger of star clusters in the galactic disk and triggering an IMBH-IMBH merger**

Conclusions

- **Motivation:**
  We expect IMBHs to exist and we have growing evidence of them but we are still unsure on how / where they form and if they can bridge stellar mass BHs and supermassive BHs

- **Our work so far:**

  Project 1 **(concluded) -** We studied IMBH formation in star clusters via stellar collisions and / or hierarchical BBH mergers and assessed the impact of different seeding conditions;

  Project 2 **(concluded) -** We explored the feasibility of a dynamical origin for GW231123, an exceptional event found in the O4 run by the LVK collaboration;

  Project 3 **(ongoing, / SISSA) -** We are currently investigating the possible connections between PISNe and IMBH formation in star clusters via the SEVN code.

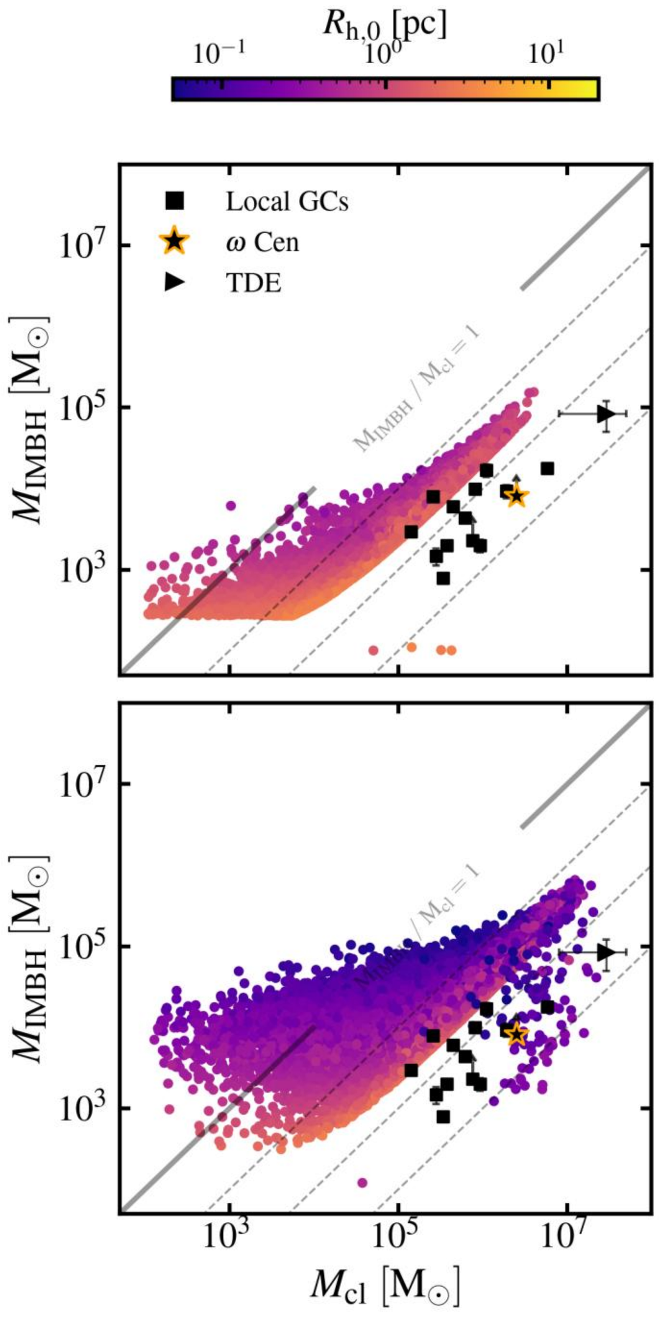
- **Next steps:**

  Understanding the capability of next-gen. interferometers (deci- and milli- Hz) to detect and constrain the properties of IMBH-IMBH mergers and IMBH-BH mergers.

Thank you for the attention!

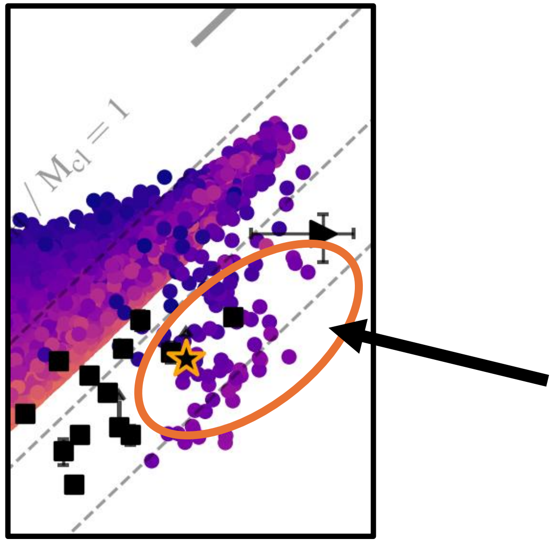
Back-up

Gap and clusters initial properties



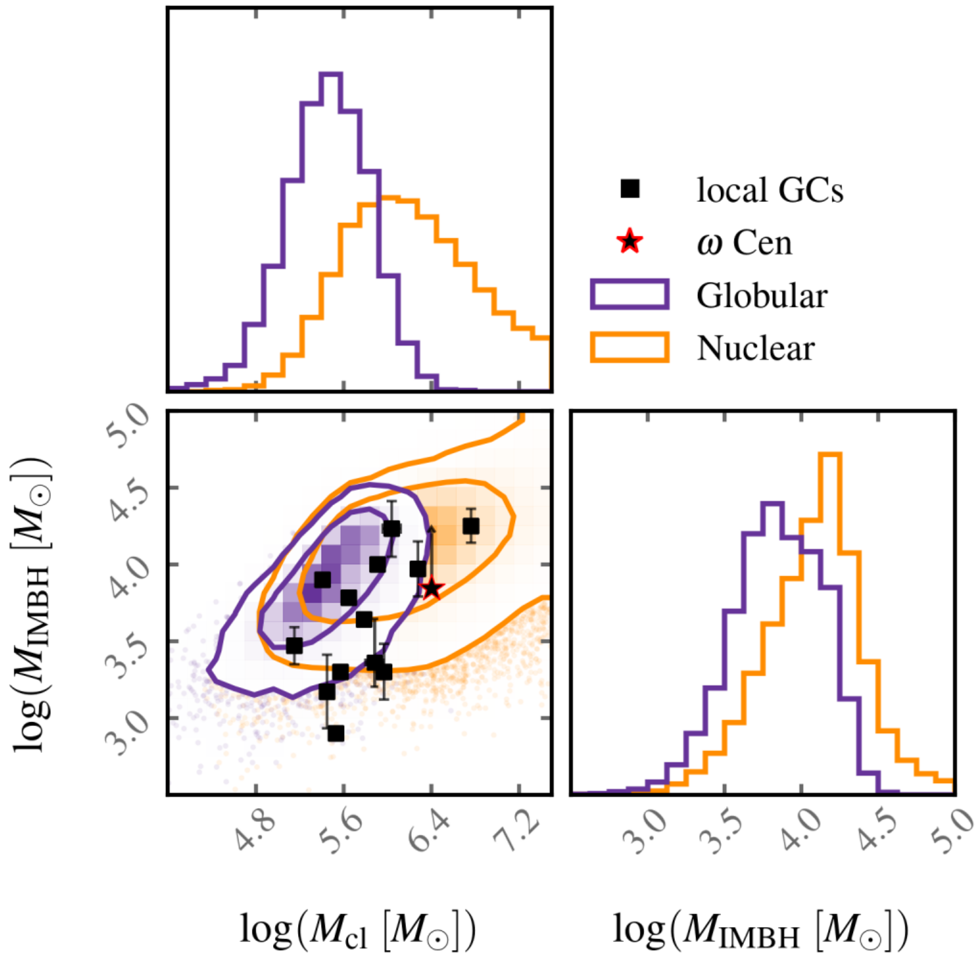
Paiella+ (2025, subm.)

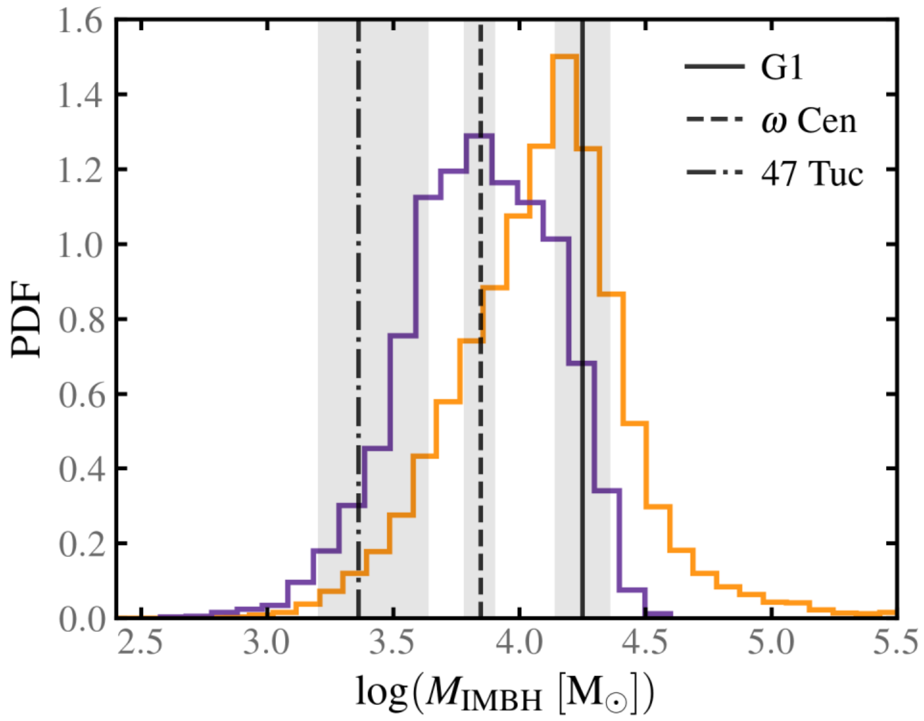
- We try a more compact and massive initial configuration for globular clusters (0.5 dex heavier, 1 dex more compact)
- Still unable to fully reproduce galactic globular clusters through the runaway stellar collisions scenario
- More IMBHs compatible with the observations coming from hierarchical BBH mergers



Clusters (mis)classification

Paiella+ (2025, subm.)





The fundamental impact of spins

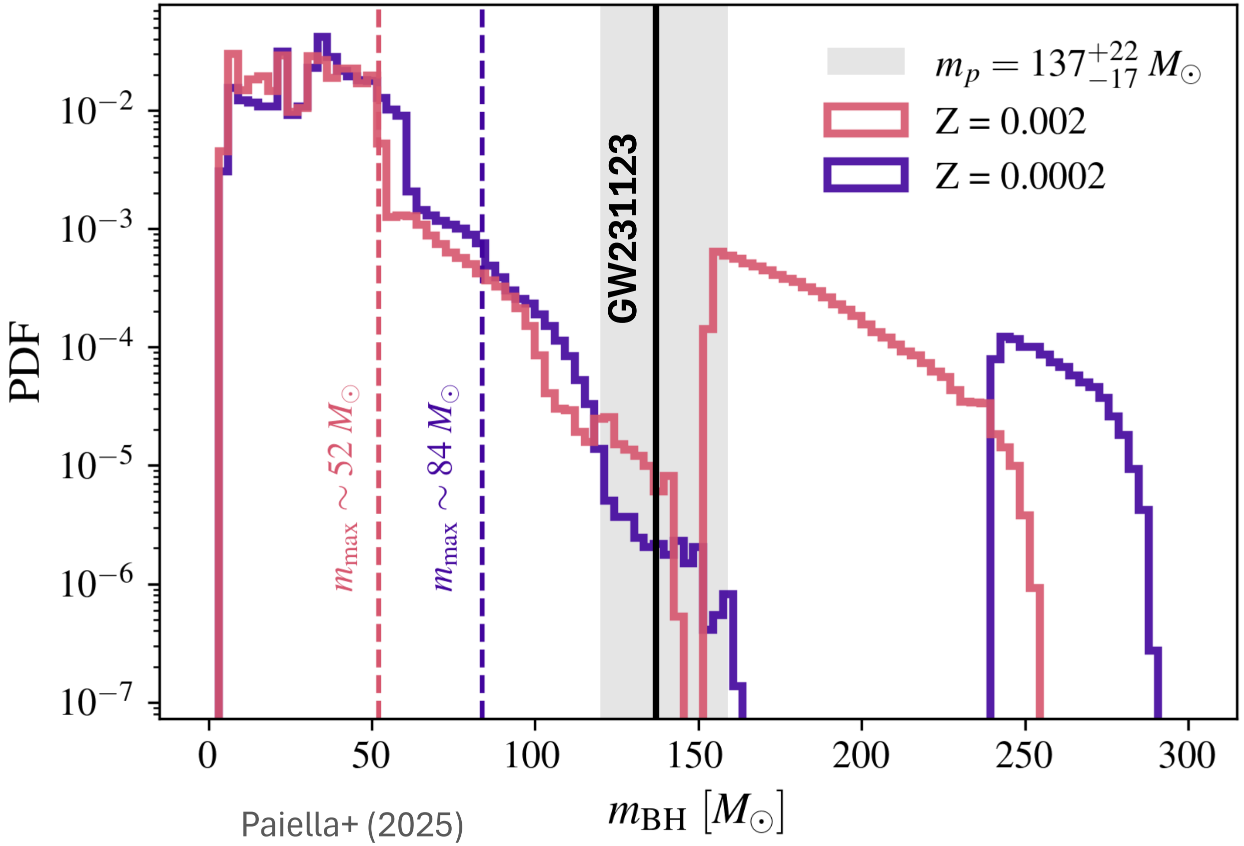
Clu.	Z	f_{mer}	$f_{mer,\chi}$	BSE			H			MC		
		low	low	low	mid	high	low	mid	high	low	mid	high
YCs	0.002	1×10^{-3}	3×10^{-6}	10	435	2250	–	–	–	–	–	–
	0.0002	9×10^{-5}	3×10^{-7}	1	24	145	–	–	–	–	–	–
GCs	0.002	3×10^{-4}	2×10^{-6}	21	572	3368	1	–	–	4	4	4
	0.0002	3×10^{-5}	3×10^{-7}	2	54	274	–	–	–	4	4	4
NCs	0.002	2×10^{-4}	8×10^{-6}	21	478	2787	57	30	28	182	182	182
	0.0002	2×10^{-4}	2×10^{-4}	3	48	208	37	16	15	845	845	845

«binary stellar evolution»

«hybrid»

«merger chain»

GW231123 and the upper-mass gap



Paiella+ (2025)

- GW231123 primary mass falls close to upper-mass gap for $Z = 0.002$ and $Z = 0.0002$
- We expect the **PISNe model** and the **modelling of the primary mass uncertainties** to have a significant impact on the abundance of GW231123 analogs