Seeds to success: growing heavy black holes in dense star clusters

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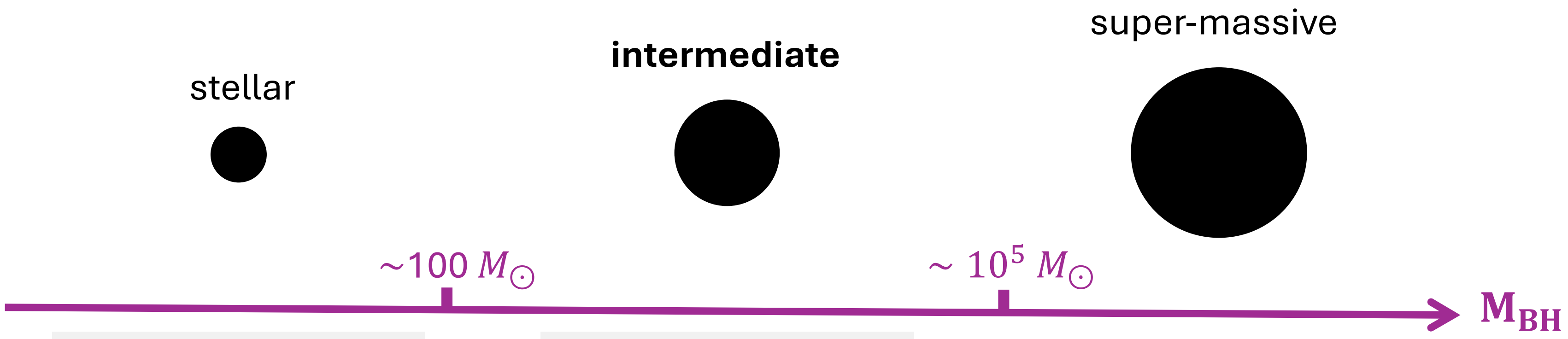
MODEST 24

Black hole weight categories



- gravitational waves
- X-ray binaries

No concrete evidence, few canditates from different observation channels

- Active Galactive Nuclei (AGNs)
- stellar dynamics
- Horizon-scale images

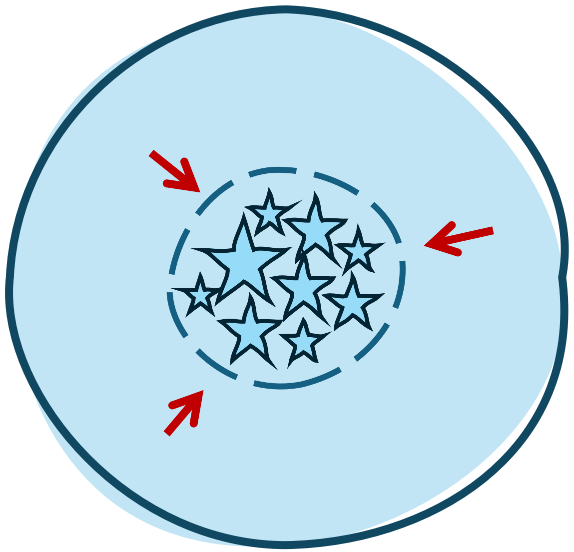
Which are the formation channels of intermediate mass black holes (**IMBHs**)?
(e.g. **formation of IMBHs in star clusters**)

Do they represent a unique class of black holes?

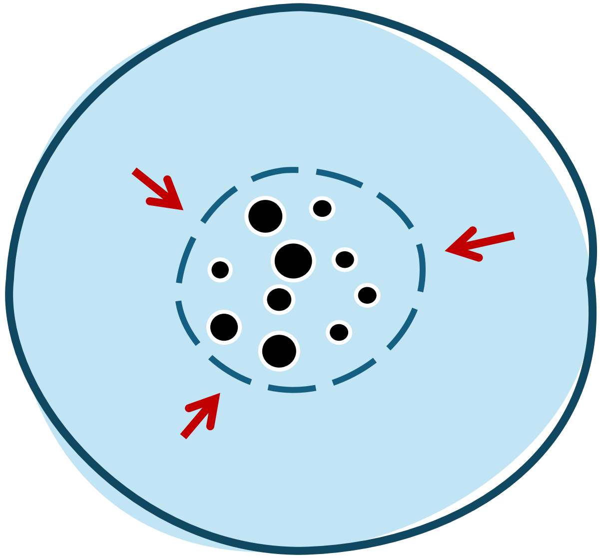
Can they serve as seeds to the formation of super-massive black holes?

Seeding a heavy black hole

seeding → formation of an IMBH *very early* in the evolution of a star cluster



The cluster core collapses before massive stars die



The cluster core collapses when all massive stars already died to black holes

3-5 Myrs

core collapse time [Myrs]

Runaway stellar collisions
Portegies-Zwart & Mc Millan (2002)

Hierarchical black hole mergers
Miller & Hamilton (2002)

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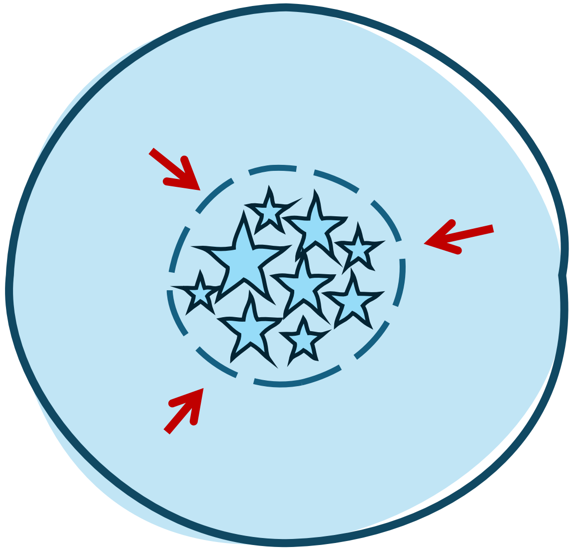

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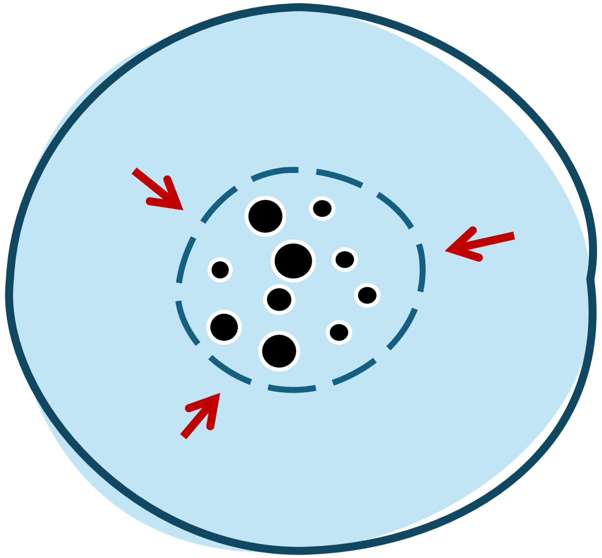


The cluster core collapses when all massive stars already died to black holes

3-5 Myrs

core collapse time [Myrs]

Runaway stellar collisions

Portegies-Zwart & Mc Millan (2002)

$$\mathbf{m_{VMS} \sim m_0 + 4 \cdot 10^{-3}\, f_c\, M_{cl,0} \ln \Lambda_c}$$

Hierarchical black hole mergers

Miller & Hamilton (2002)

Black hole **POP**ulation synthesis **(B-POP)** code

Arca Sedda et al. (2023)

- Semi-analytic code to simulate BH dynamics in stellar clusters and in isolated binaries
- Every instance in the code corresponds to the growth of a single BH (cluster or field)
- Optimized to simulate a *synthetic universe* of BHs (BHs distributed across redshift and metallicity accordingly to phisically motivated distributions)

- Only dynamical BHs
- Only globular clusters(GCs) and nuclear star clusters (NSCs)
- **Runaway stellar collisions seeding for $t_{cc} < 5$ Myrs and $Z < 0.001$**

$2 \cdot 10^6$ BHs

(50 % GCs, 50% NSCs)

An IMBH final fate

Expelled

Ejected → The BBH is ejected out of the cluster by close dynamical encounters with other BHs.

Recoiled → The remnant BH is recoiled out of the cluster because of its natal kick.

Retained

Inside → The BH stays inside the cluster because there are no more BHs to grow from.

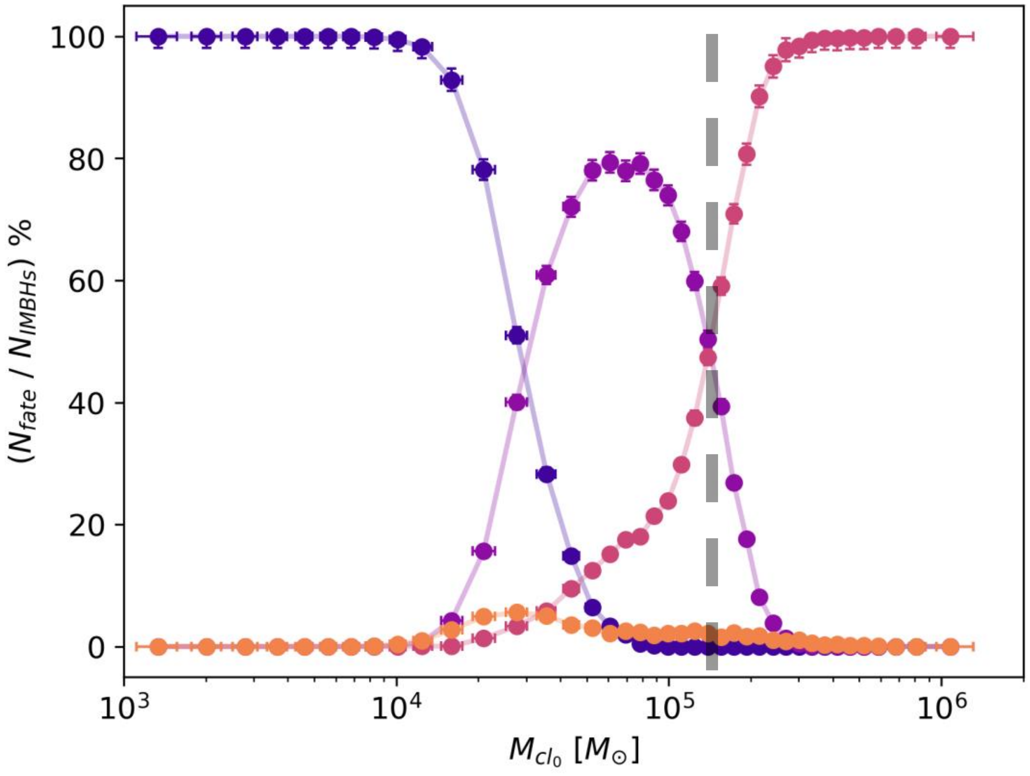
Highlander → The BH is part of a binary which will merge at a time > t_{Hubble}.

↪ How is the final fate of an IMBH linked to the seeding scenario?

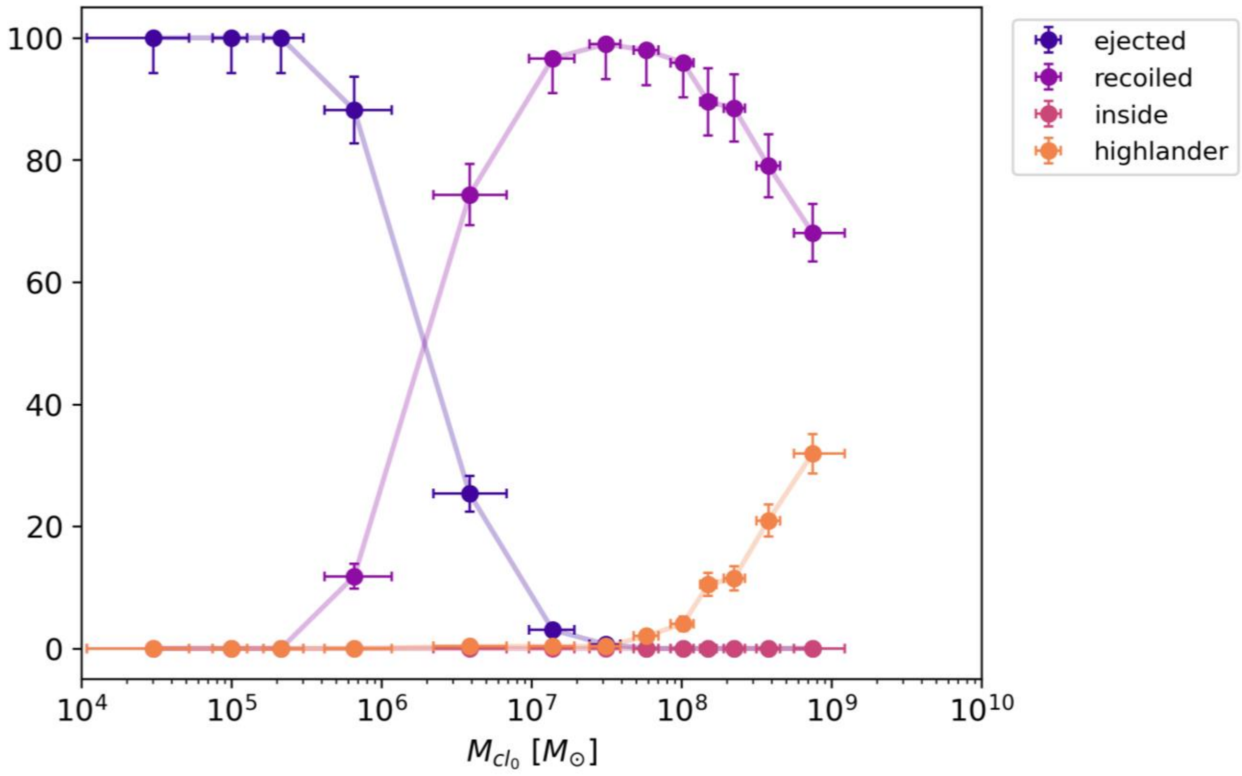
How is it connected to properties of the cluster itself?

- **The final fate of an IMBH strongly depends on the initial mass of the cluster**. The more massive the cluster the higher the percentage of retained IMBHs.

- The **transition** from expelled IMBHs to retained IMBHs happens on smaller cluster masses ($10^5\ M_\odot$ vs. $> 10^9\ M_\odot$) for the runaway seeding scenario thanks to the larger initial mass of the growing (IM)BH.



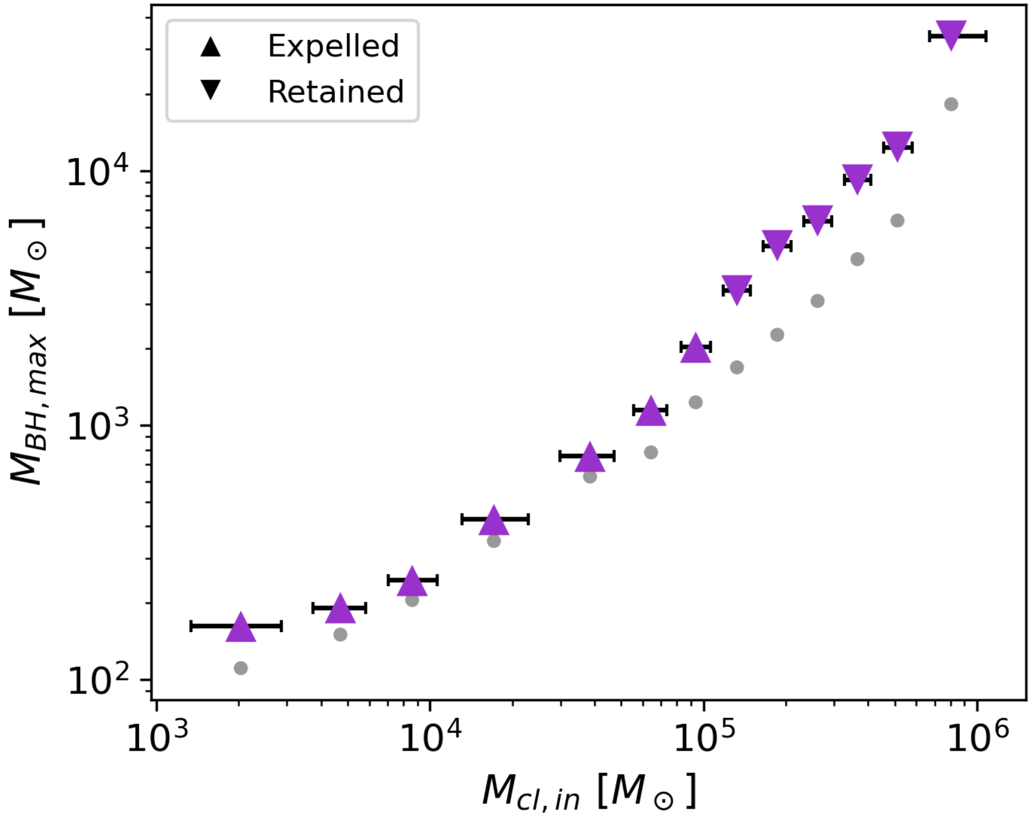
(runaway stellar collisions)



(hierarchical BBH mergers)

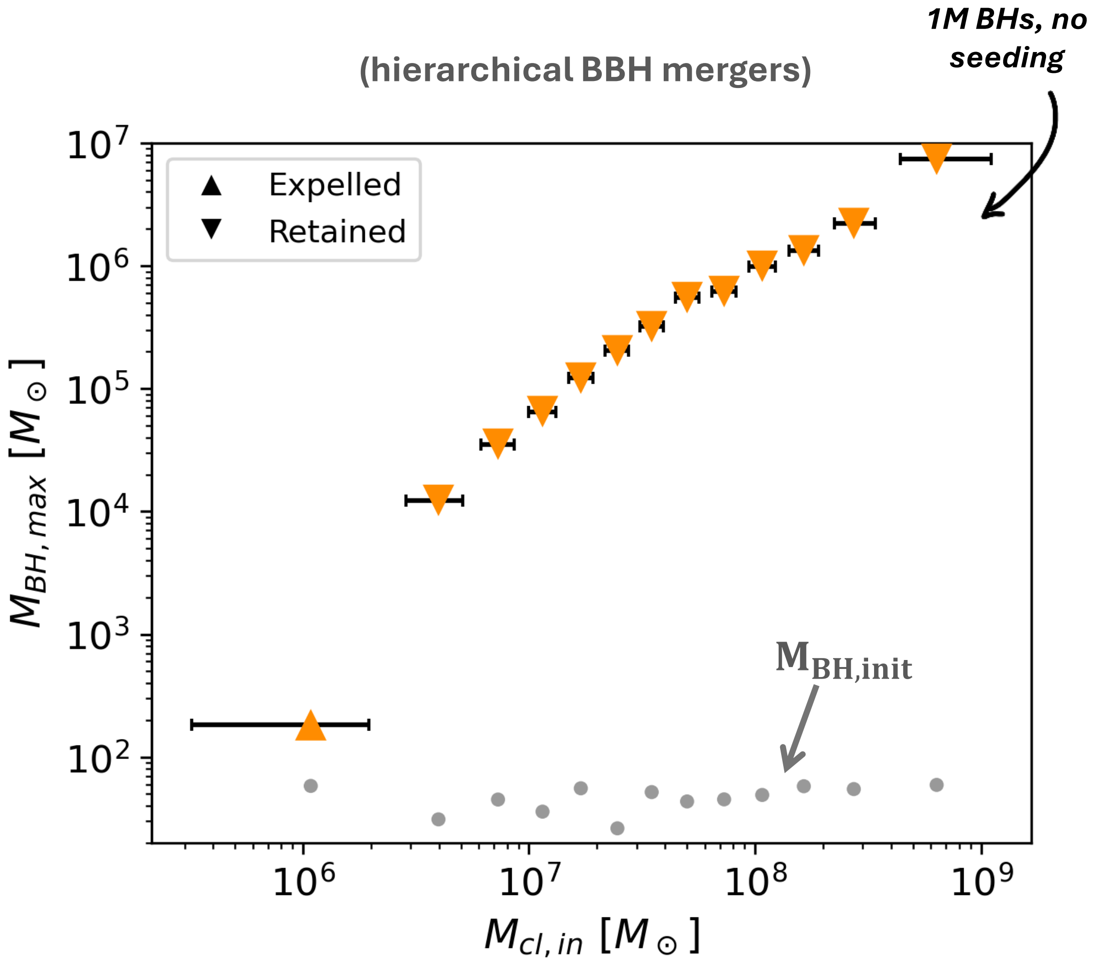
Maximum black hole mass

(runaway stellar collisions)



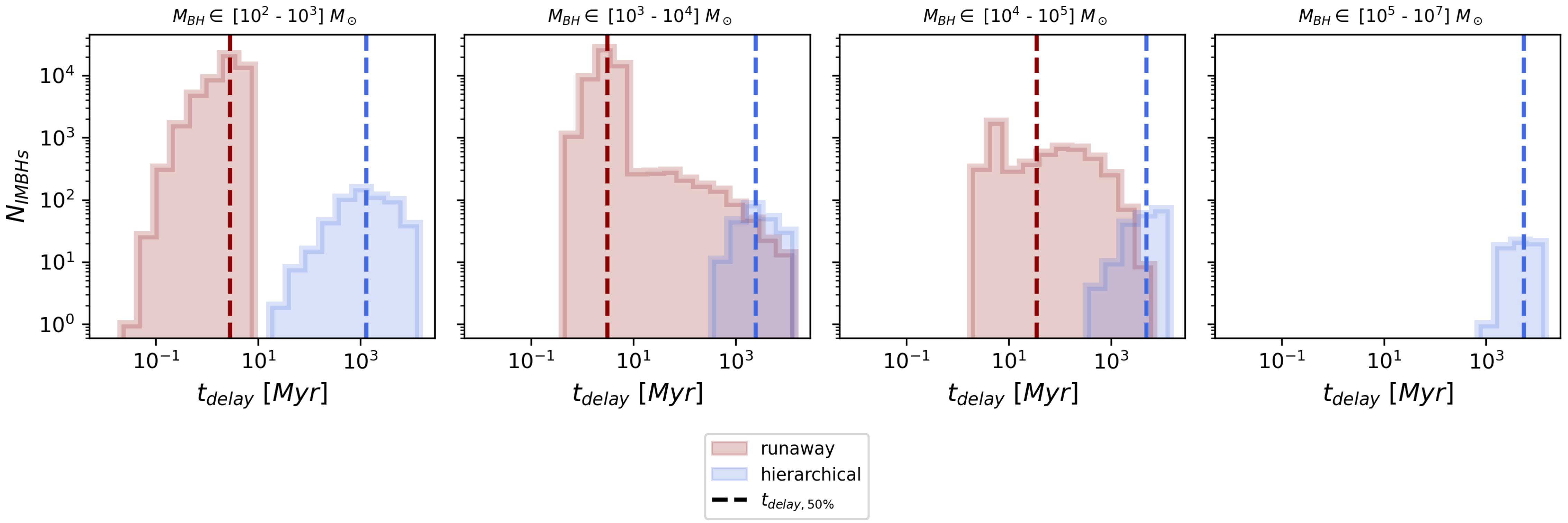
In small but compact (**nuclear**) clusters an IMBH of up to 10^4 $M_\odot$ can be seeded but its further growth via BBH mergers **is quenched by the depletion of massive stars in the clusters**.

(hierarchical BBH mergers)



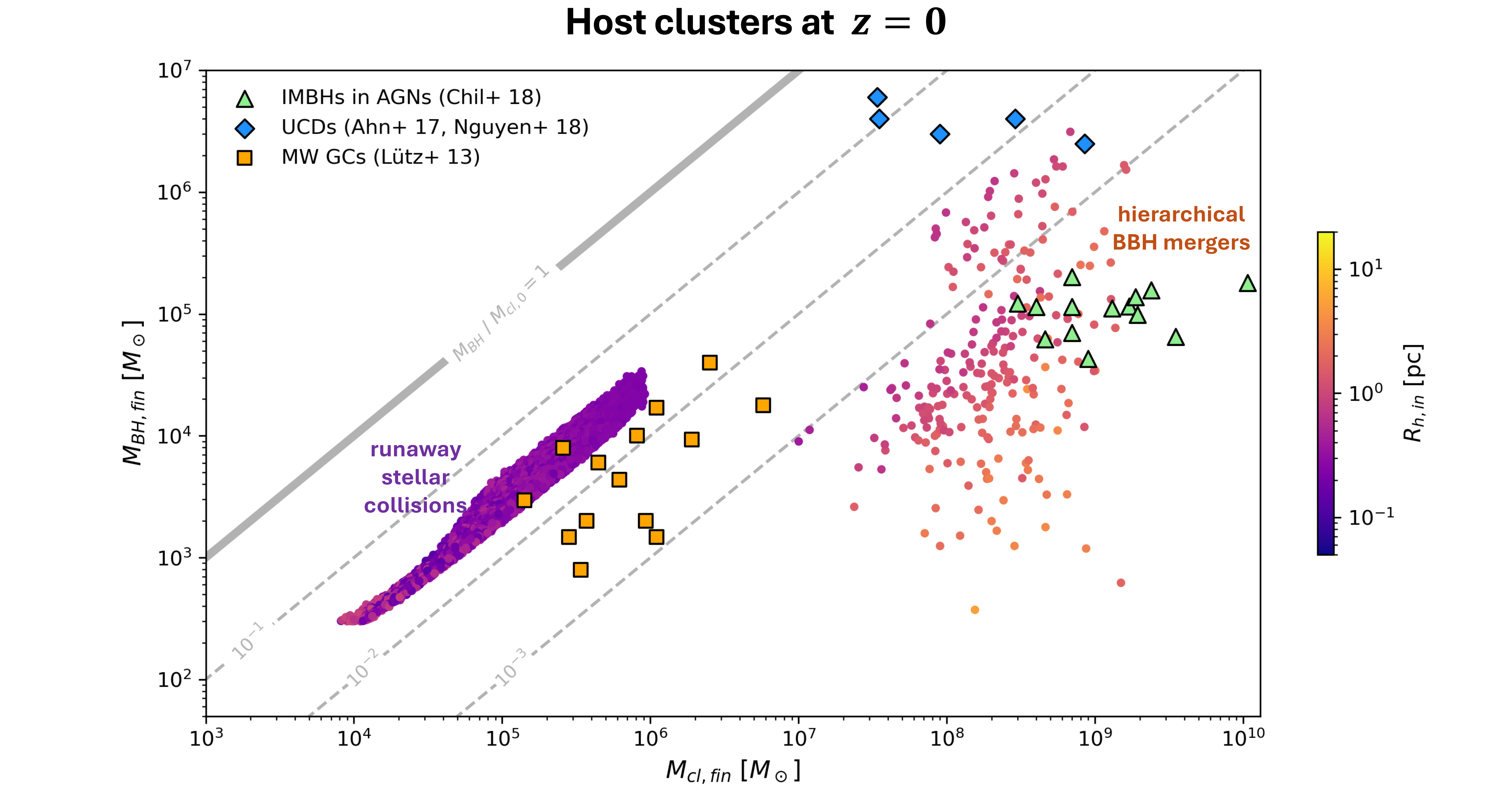
In very massive (**nuclear**) clusters a BH can **grow up to 10^5-10^6 times its initial mass.** We observe a **transition between light and heavy IMBHs** at a cluster mass of $\sim 10^7$ $M_\odot$.

The fastest route to an IMBH



The **runaway seeding process is the fastest at producing IMBHs (seeds) of up to** $\sim \mathbf{10^4}$ but:

- it is **not able to produce IMBHs** $> \mathbf{few\ 10^4\ M_\odot}$
- the further growth of the IMBHs happens on timescales comparable to the ones of hierarchical BBH mergers



Host clusters at $z = 0$
IMBHs in AGNs (Chil+ 18)
UCDs (Ahn+ 17, Nguyen+ 18)
MW GCs (Lütz+ 13)
runaway stellar collisions
hierarchical BBH mergers
$M_{BH} / M_{cl,0} = 1$
10^{-1}
10^{-2}
10^{-3}
$M_{BH,fin}$ [$M_\odot$]
$M_{cl,fin}$ [$M_\odot$]
$R_{h,in}$ [pc]

Conclusions

- We have simulated 2M BHs in globular and nuclear clusters and **assessed the combined role of runaway stellar mergers and hierarchical BH mergers in the build up of heavy IMBHs**.

- **The final fate of an IMBH strongly depends on the initial mass of the host cluster** with more massive clusters better able to retain their IMBHs.

- We observe a **threshold cluster mass around** $\sim \mathbf{10^7\ M_\odot}$ above which IMBHs heavier than 1000 solar masses are produced efficiently (through hierarchical BH mergers) → *physical effect? statistical effect?*

- In the hierarchical BH merger scenario it is possible to produce **very heavy IMBHs** $(> \mathbf{10^4 - 10^5\ M_\odot})$ **but only for extremely massive nuclear clusters** ($> \mathbf{10^8\ M_\odot}$)

- We observe a mild superposition between GCs in the Milky Way and GCs undergoing runaway stellar mergers in our set, as well as between NCs harboring a heavy IMBH and candidate IMBHs in AGN disks and UCD

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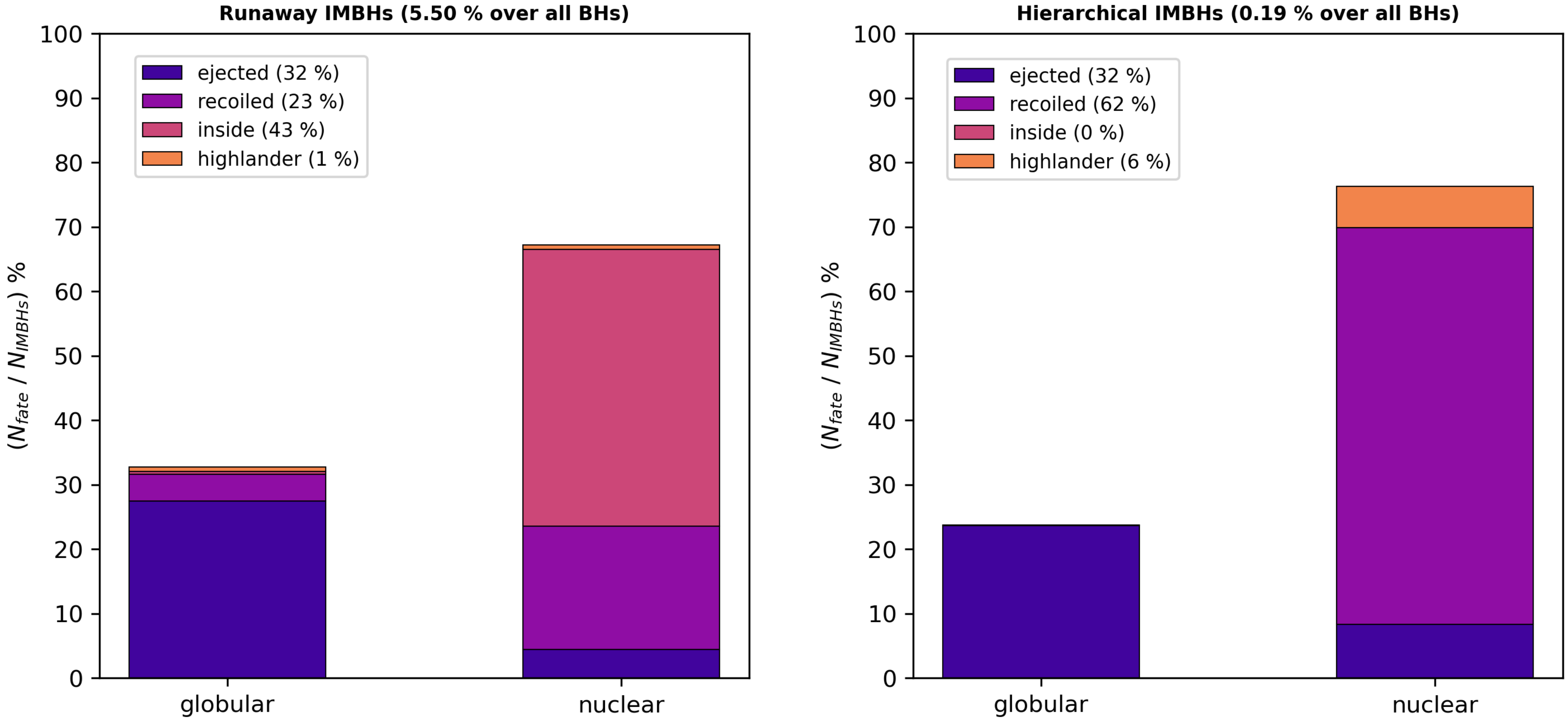
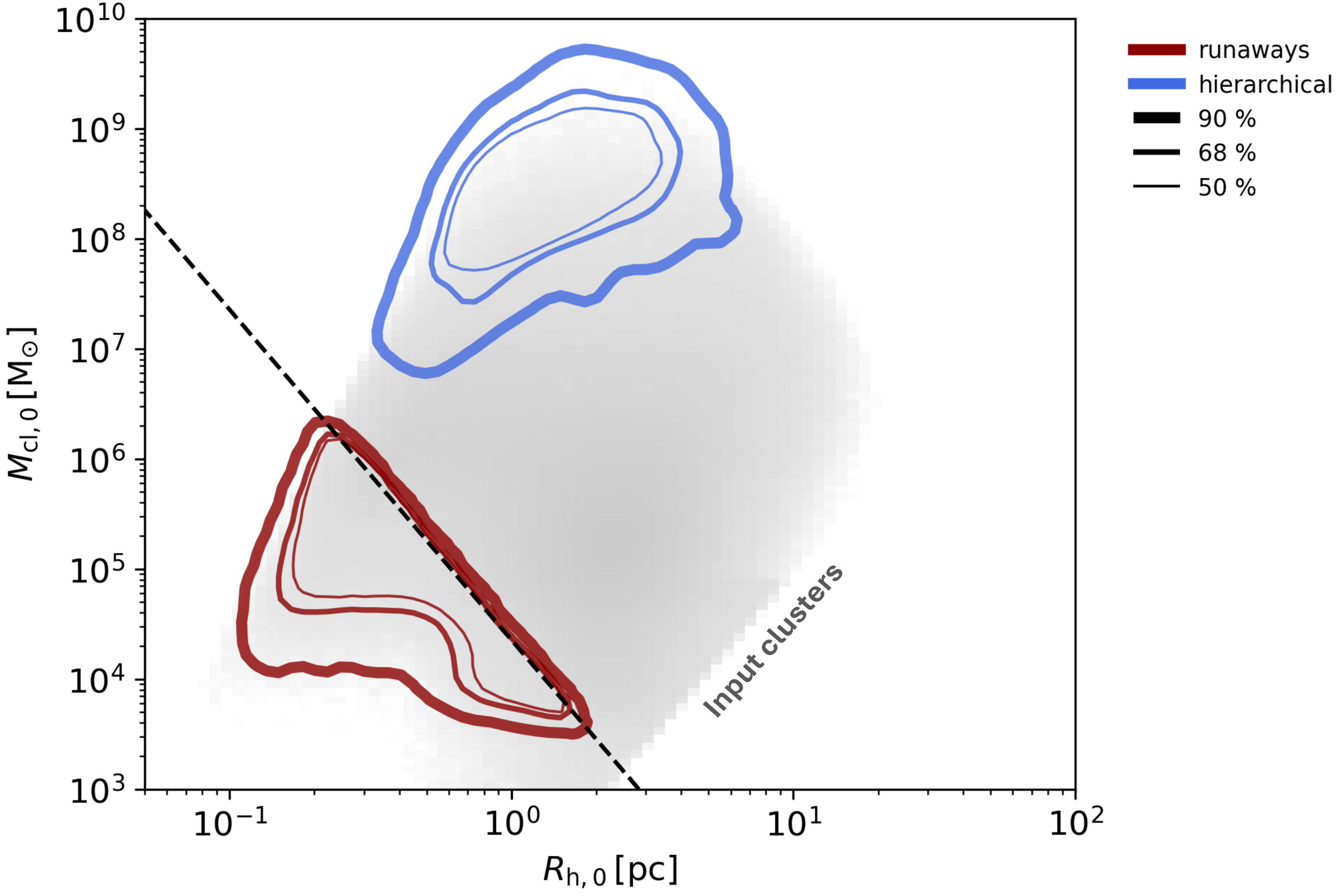
Backup slides



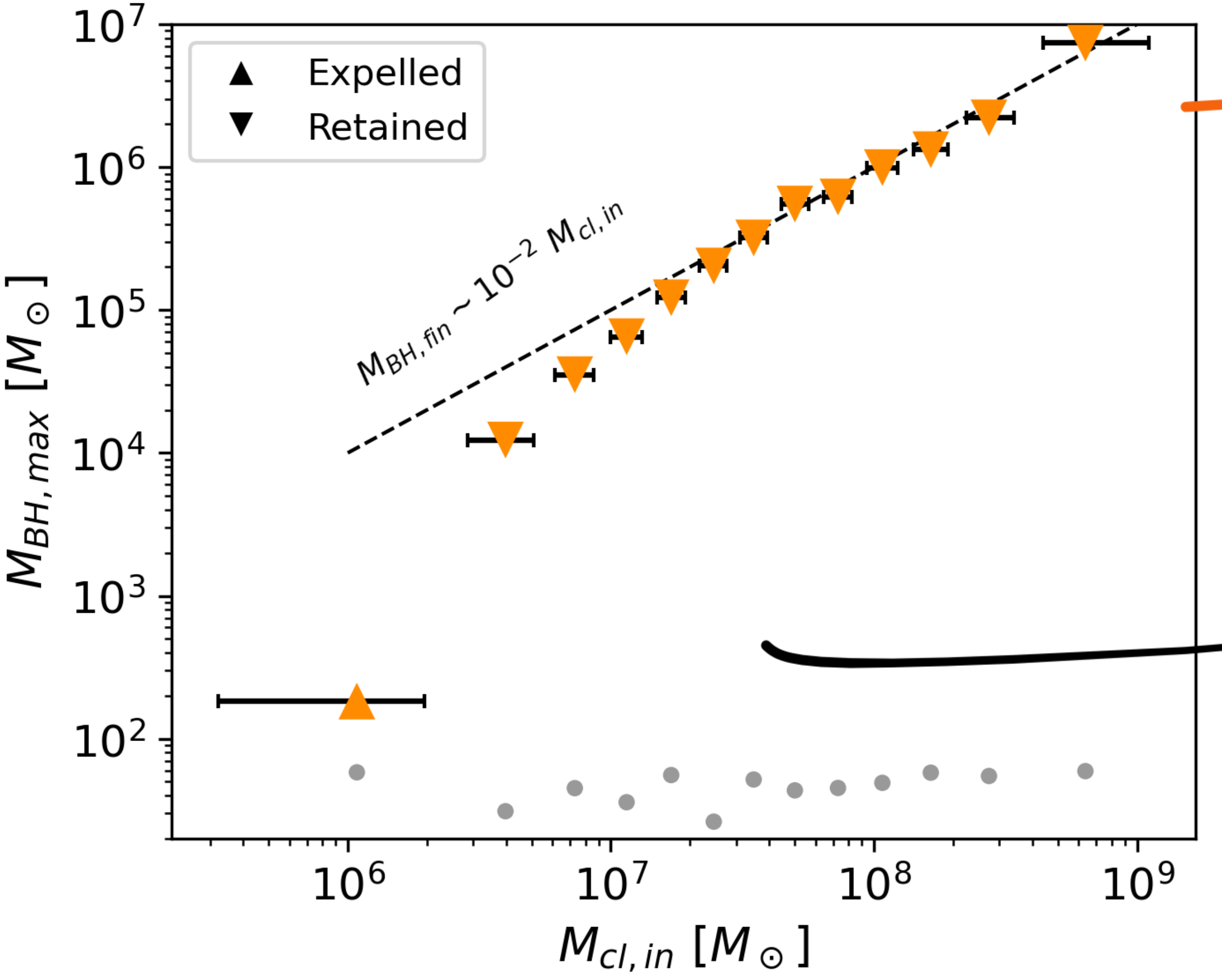
Runaway IMBHs (5.50 % over all BHs)
Hierarchical IMBHs (0.19 % over all BHs)
ejected (32 %)
recoiled (23 %)
inside (43 %)
highlander (1 %)
ejected (32 %)
recoiled (62 %)
inside (0 %)
highlander (6 %)
(N_{fate} / N_{IMBHs}) %
globular
nuclear

M-R diagram and host clusters



Maximum black hole mass

Is there a transition? How does the maximum mass scale?

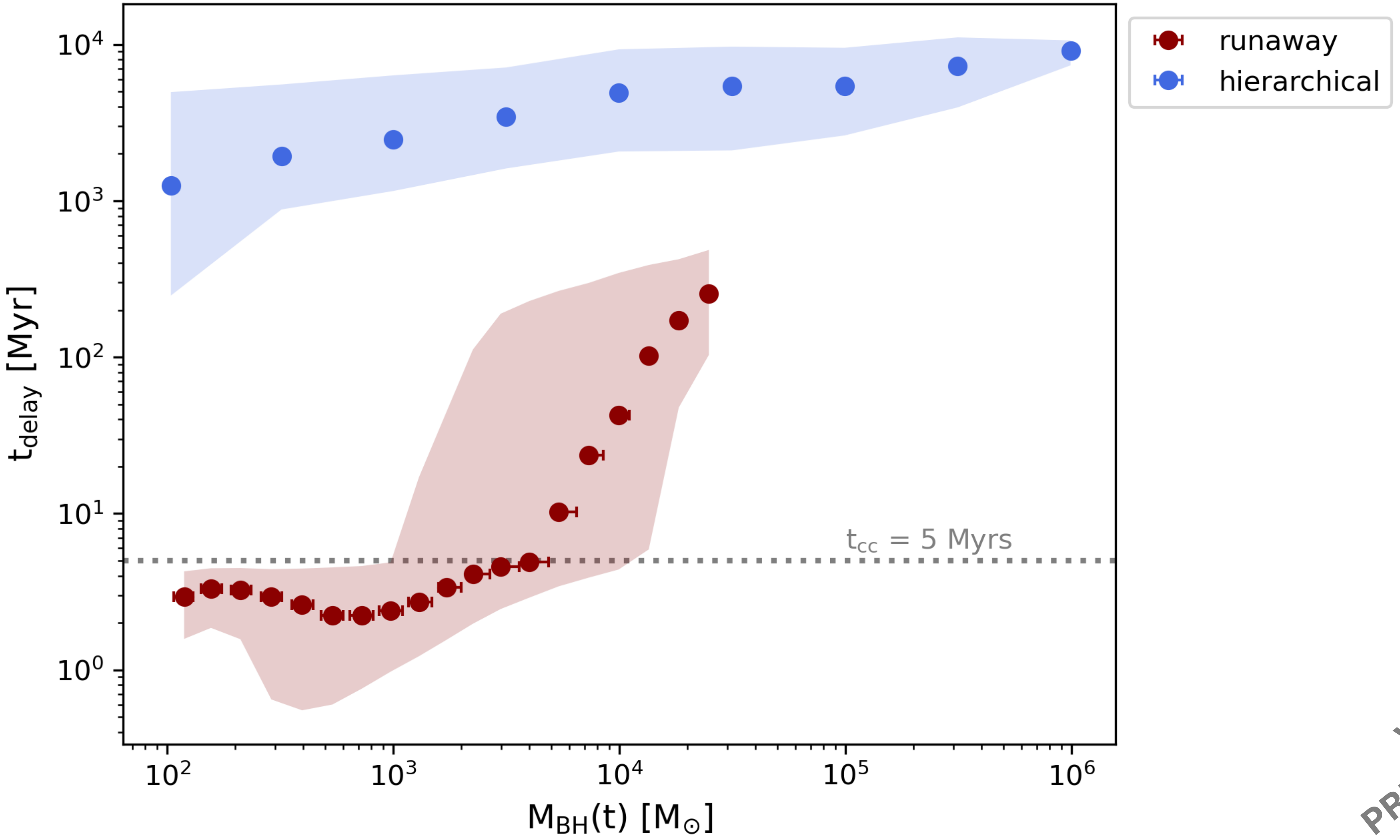


The maximum mass roughly converges around 1/100 of the initial cluster mass.

Is the statistic too low to recover the true maximum mass? (~ 1000 BHs per bin)

VERY PRELIMINARY!

The fastest route to an IMBH



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