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THE ONES THAT GOT AWAY

FORMATION AND EVOLUTION OF INTERMEDIATE-MASS BLACK HOLES IN MASSIVE STAR CLUSTERS

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In collaboration with: Michela Mapelli, Manuel Arca Sedda, Marica Branchesi, Sara Rastello, Stefano Torniamenti

MASSIVE STAR CLUSTERS

Westerlund 2 - *NASA, ESA*

ω Centauri - *ESO*

YOUNG MASSIVE CLUSTERS

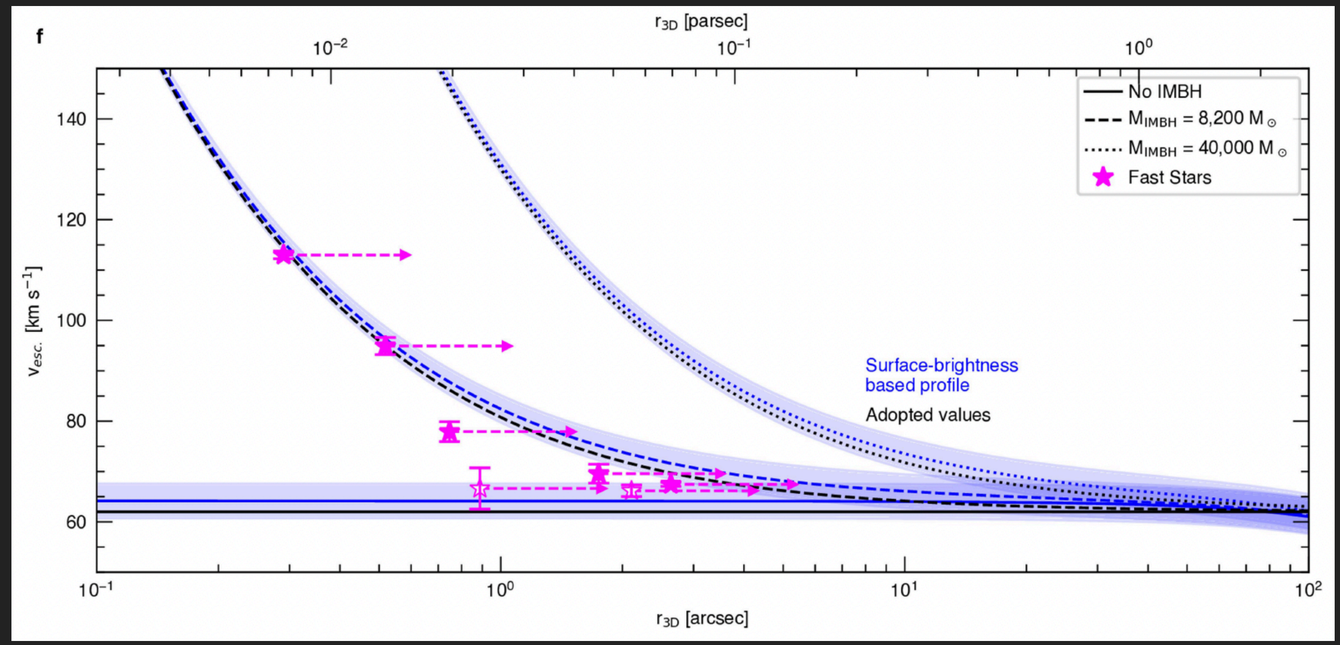
- YOUNG GLOBULAR CLUSTERS
- $M_{\rm tot} \lesssim 10^6\,{\rm M}_\odot$
- AGE $\sim 10^2\,{\rm Myr}$

GLOBULAR CLUSTERS

- $M_{\rm tot} \lesssim 10^6\,{\rm M}_\odot$
- AGE $\sim 10\,{\rm Gyr}$

WHAT HIDES AT THEIR CENTER?

- **Intermediate-mass black hole (IMBH)** with $m_{\mathrm{BH}} \sim 10^3 - 10^4\,\mathrm{M}_\odot$
  - **Recent observation of IMBH in ω Centauri**
  - **GW190521** (?)



ω Cen IMBH - Häberle et al. 2024

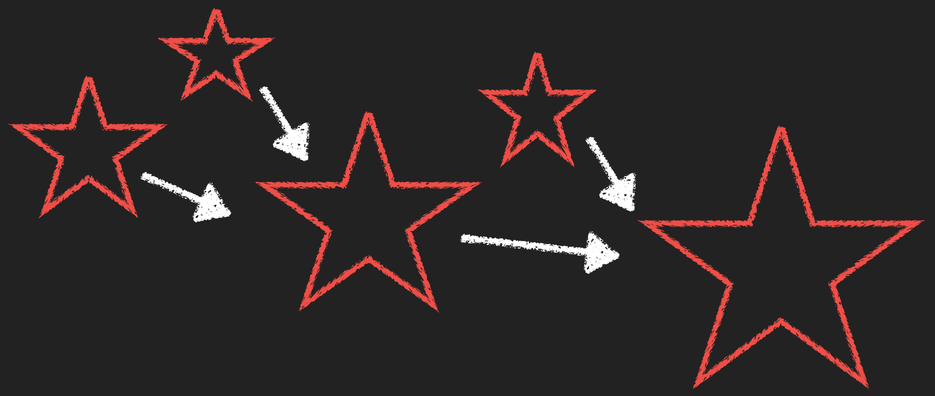
HOW DO WE FORM AN IMBH?

FAST SCENARIO

STELLAR RUNAWAY COLLISIONS

(Portegies Zwart & McMillan 2002)

- $t_{\rm rlx} < 25\,{\rm Myr}$
- Formation of very massive star (VMS)
- Final IMBH with $m_{\rm BH} \sim 0.1\,\%\,M_{\rm tot}$

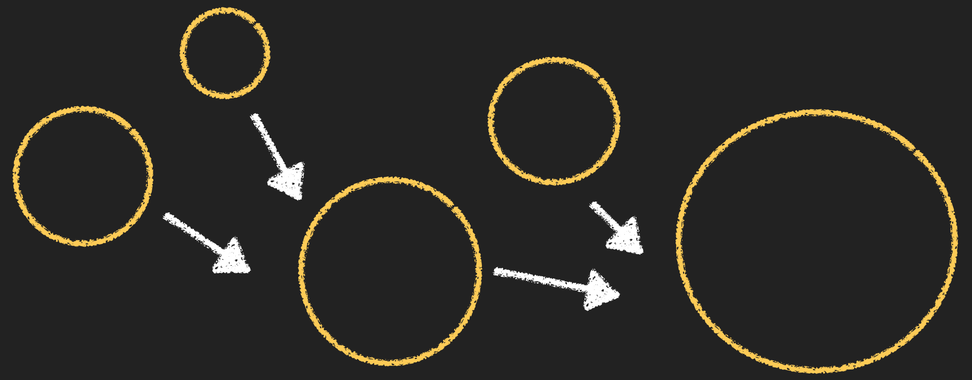


SLOW SCENARIO

HIERARCHICAL MERGERS

(Miller & Hamilton 2002)

- Central BH $\gtrsim 50\,{\rm M}_\odot$
- Mergers with mass-segregated BHs
- IMBH of $\sim 10^3\,{\rm M}_\odot$ in $\sim 10\,\%$ clusters



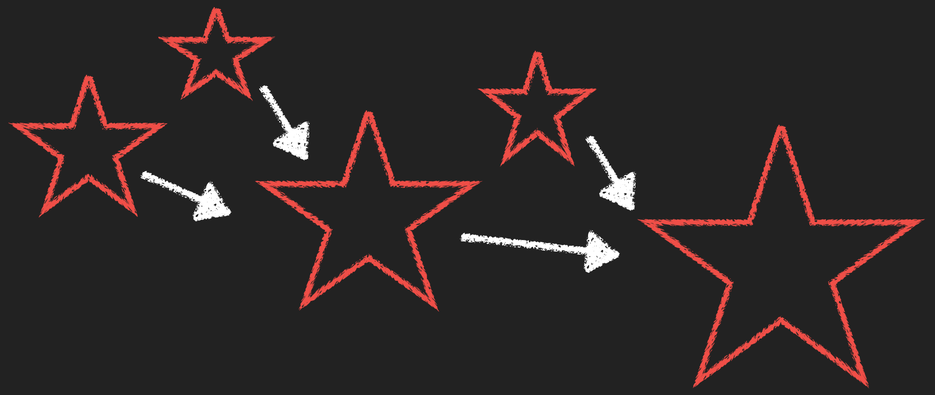
NOT THAT EASY...

FAST SCENARIO

STELLAR RUNAWAY COLLISIONS

(Portegies Zwart & McMillan 2002)

- Massive clusters usually have $t_{\rm rlx} \gtrsim 100\,{\rm Myr}$
- Dependence on density
- Dependence on metallicity

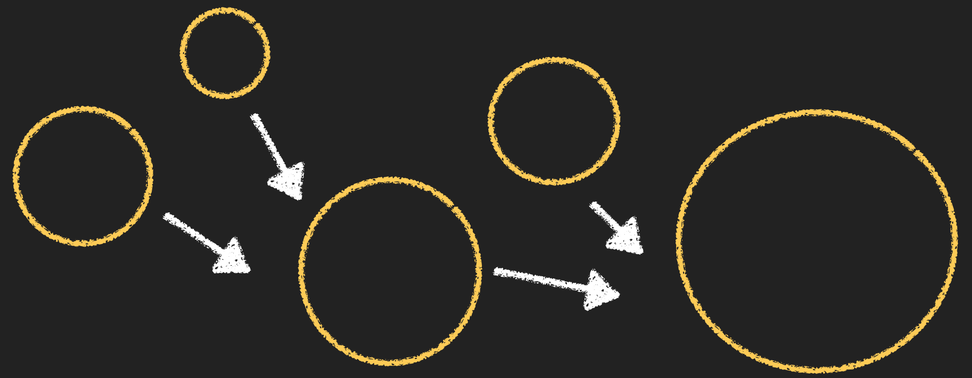


SLOW SCENARIO

HIERARCHICAL MERGERS

(Miller & Hamilton 2002)

- High relativistic kicks ($v_{\rm kick} > v_{\rm esc}$)
- Dependence on cluster mass and density
- Dependence on metallicity



IS IT POSSIBLE TO FORM IMBHs IN MASSIVE STAR CLUSTERS WITH LOW DENSITY?

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WHAT IS THE MAIN FORMATION CHANNEL?
WHAT ARE THEIR PROPERTIES?

METHODS

PETAR + MOBSE

Wang et al. 2020; Mapelli et al. 2017

- N-body code
- Stellar evolution (`MOBSE`)
- Milky Way galactic potential (`galpy`)

Realistic simulations of massive clusters

Download here!

Check out Lavinia's talk!

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

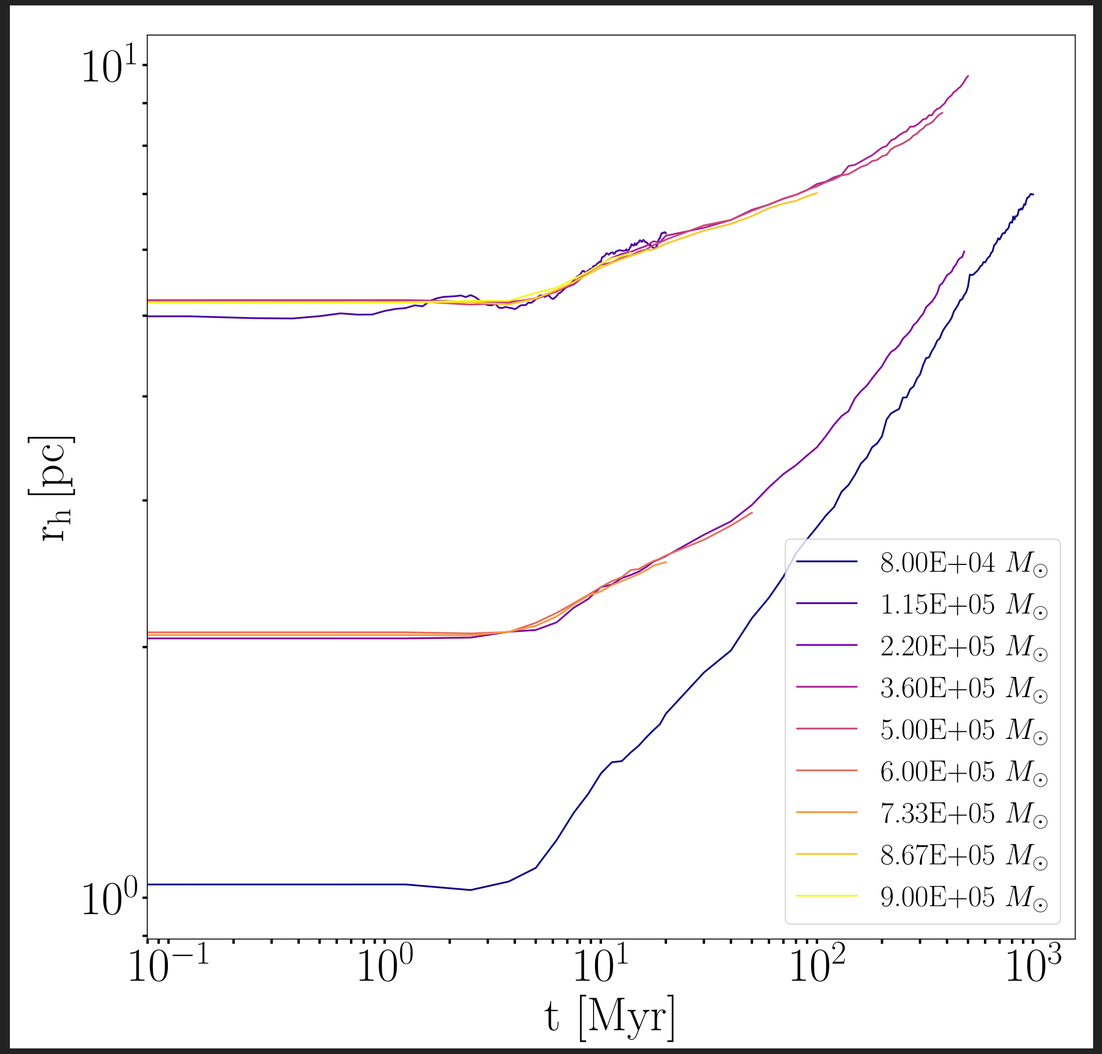
INITIAL CONDITIONS

$$Z = 10^{-2}\,\mathrm{Z}_{\odot}$$

$$10^{5} \lesssim M_{\mathrm{tot}} \lesssim 10^{6}\,\mathrm{M}_{\odot}$$

$$100\,\mathrm{Myr} \lesssim t_{\mathrm{rlx}} \lesssim 3\,\mathrm{Gyr}$$

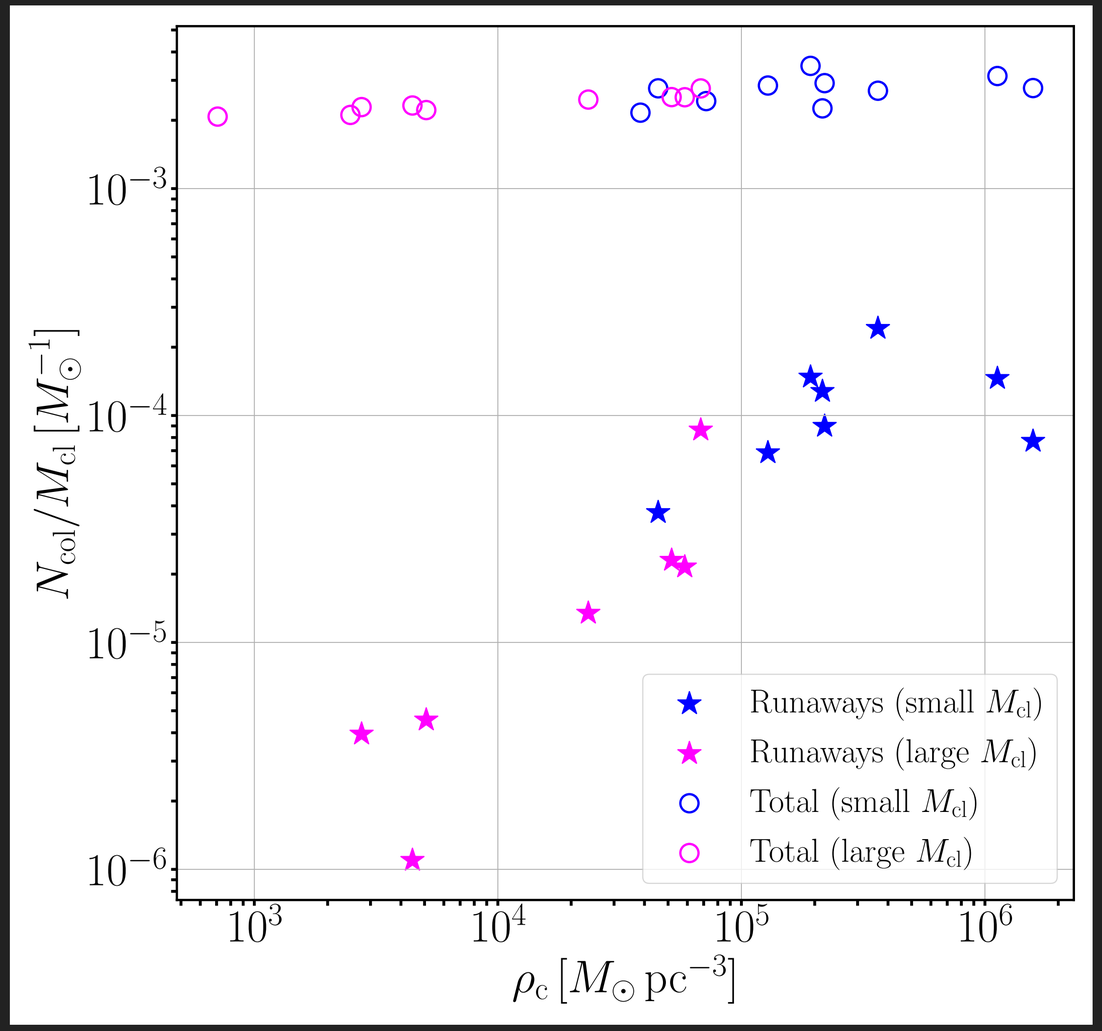
$$10^{3} \lesssim \rho_{\mathrm{c}} \lesssim 10^{5}\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-3}$$



Mestichelli et al. (in prep.)

EFFICIENCY OF REPEATED COLLISIONS

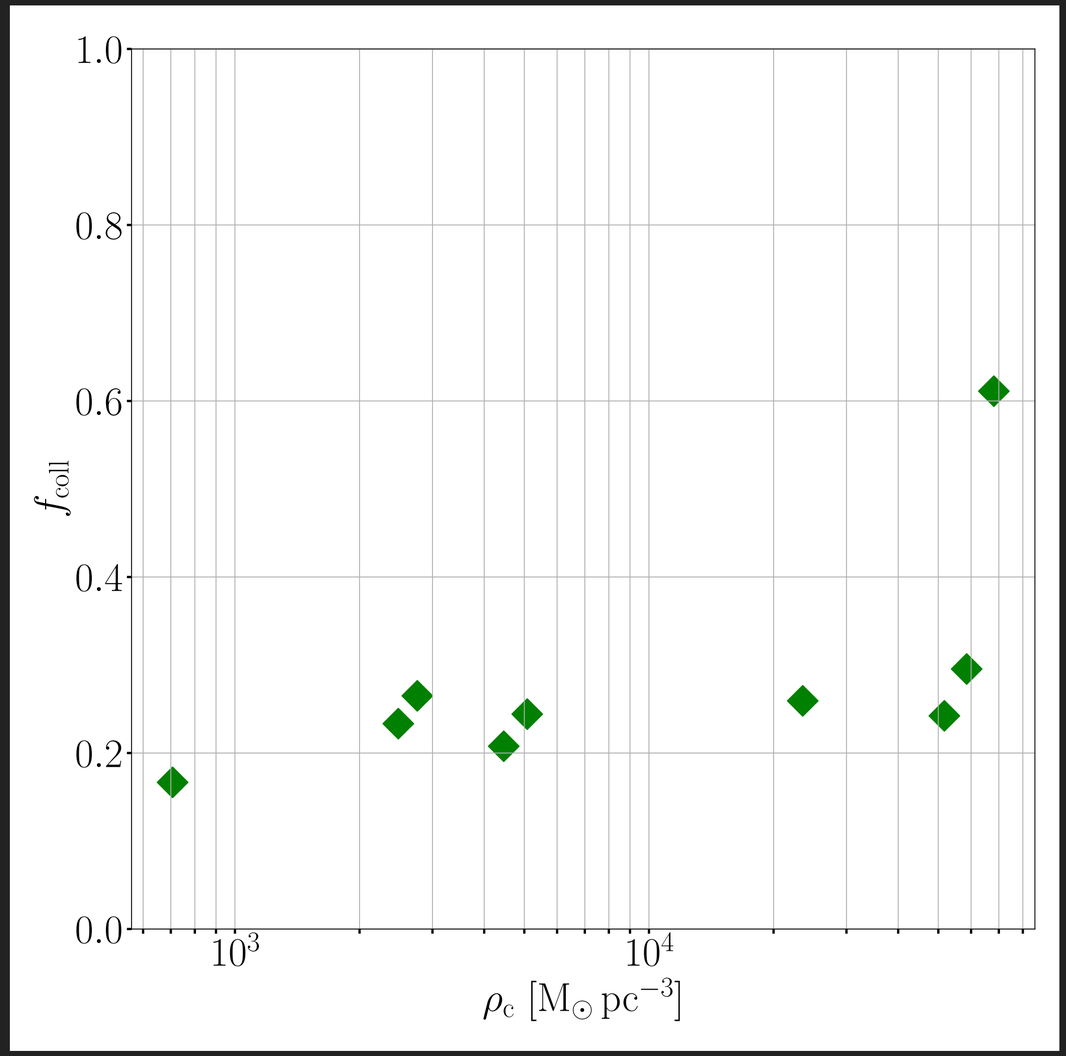
- Efficiency of **collisions** is **constant** with $\rho_{\rm c}$
- Efficiency of **repeated collisions grows** with $\rho_{\rm c}$
  - Dependence on $t_{\rm rlx}$ at high $\rho_{\rm c}$



Mestichelli et al. (in prep.)

FRACTION OF VMSs FROM COLLISIONS

- Fraction of VMS from collisions + repeated collisions **grows sharply** at $\rho_c \sim 10^5\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$
- At **lower** ρ_c most VMS are **born** with high mass



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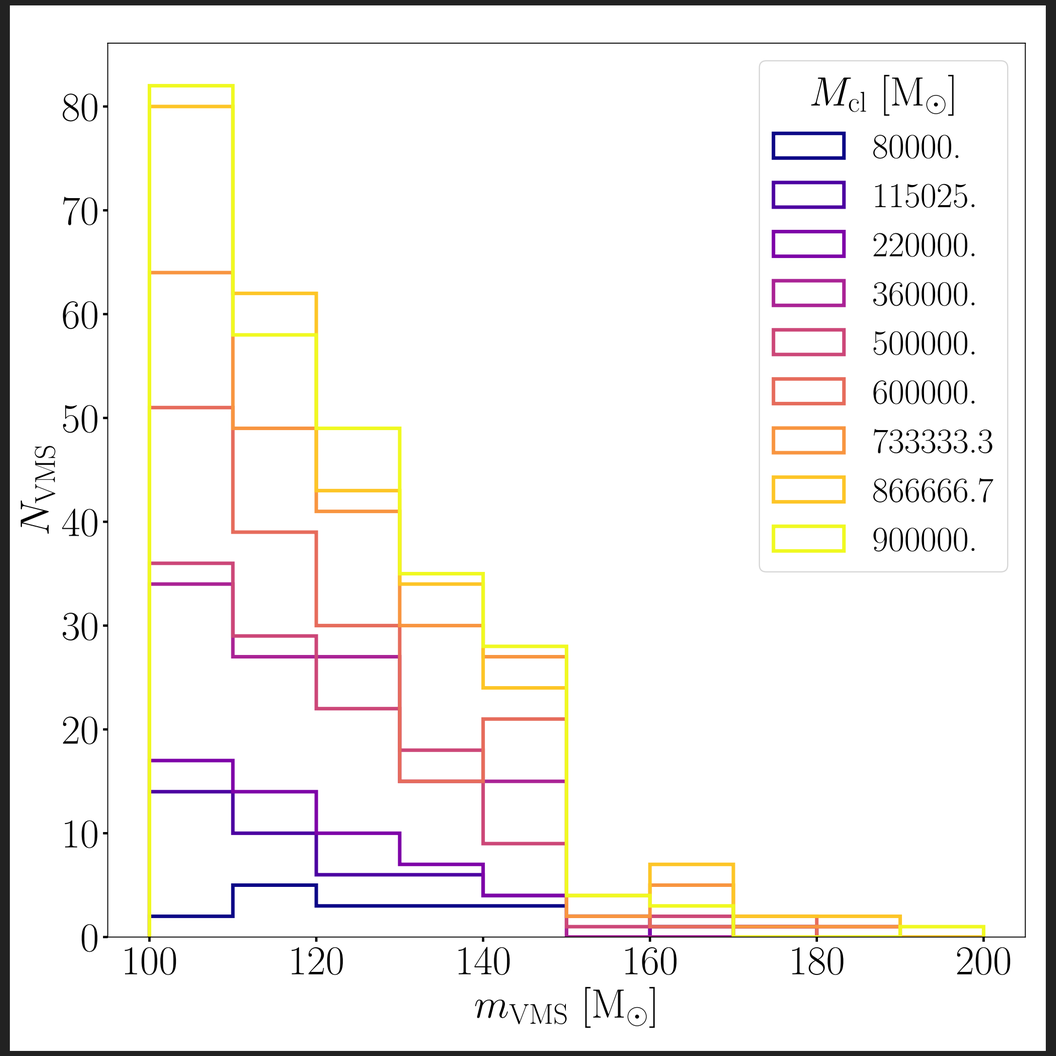
MASS SPECTRUM OF VMSs

- Larger number of VMSs in high-mass clusters
- Maximum mass $\sim 200\,\mathrm{M}_\odot$



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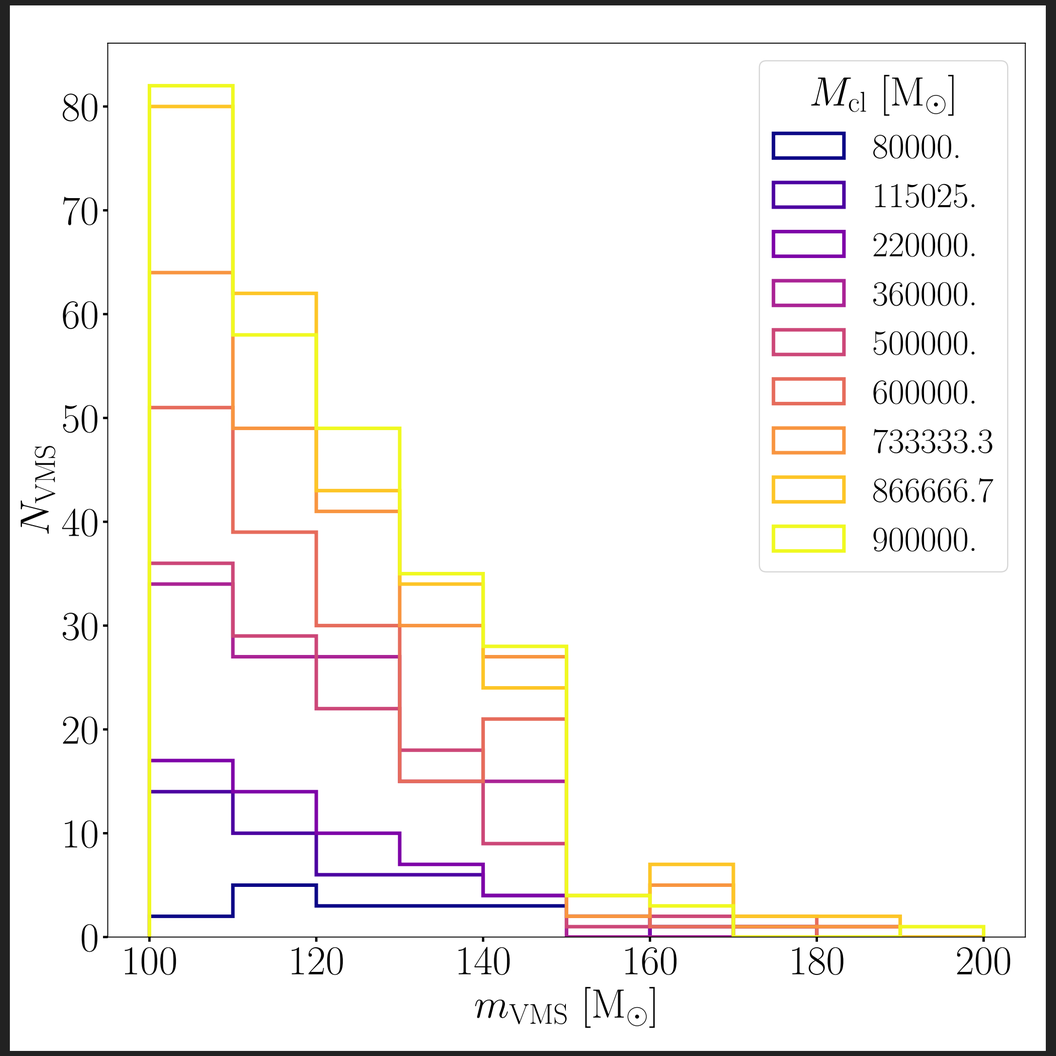
VMSs COLLAPSING INTO IMBHs?



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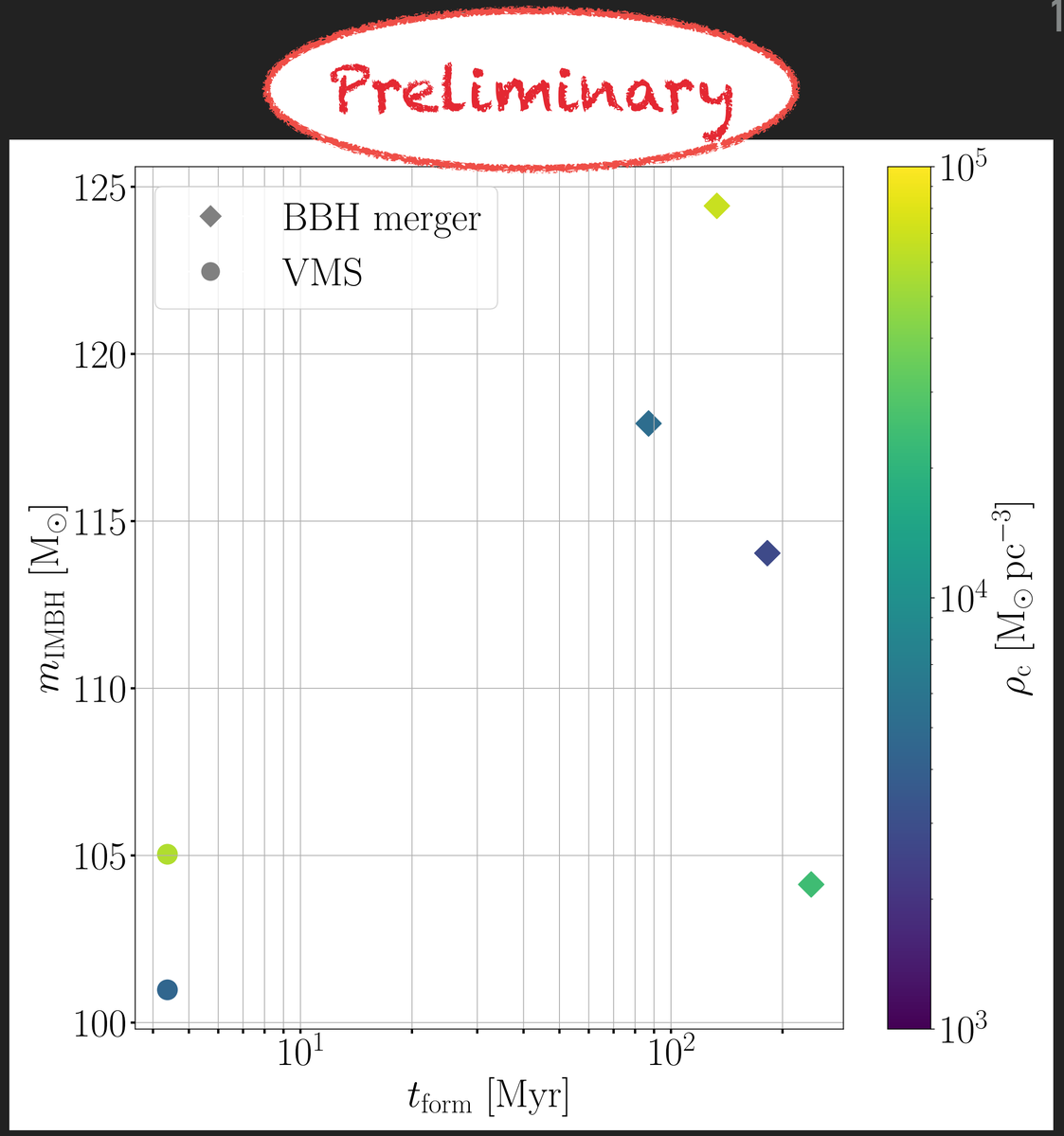
IMBH LANDSCAPE

- Only **two** IMBHs from VMS collapse:
  - Mass loss due to PPISN
  - Mass loss due to common envelope events
- Most IMBH from BBH mergers: **they all leave the cluster!**



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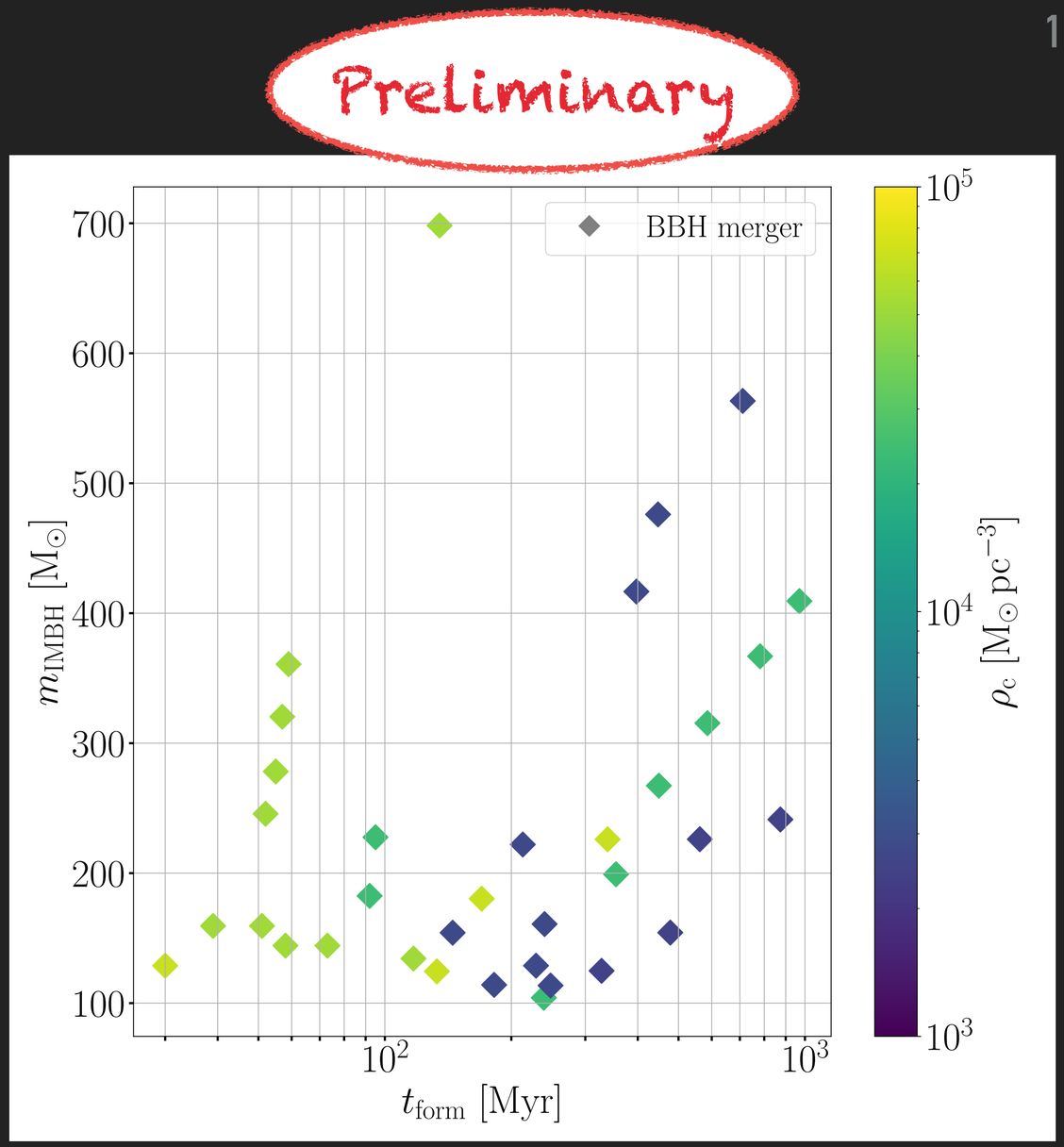

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SUMMARY

- Formation channels of IMBHs in massive clusters: runaway collisions and hierarchical mergers
- In N-body simulations with `PeTar-MOBSE`:
  - VMS fraction from **stellar collisions low** at $\rho_{\rm c} < 10^5\,{\rm M}_\odot\,{\rm pc}^{-3}$
  - Large number of VMS at high $M_{\rm cl}$ but **only two collapsing into IMBH**
  - **Most IMBH from BBH merger (no chain because of relativistic kicks!)**

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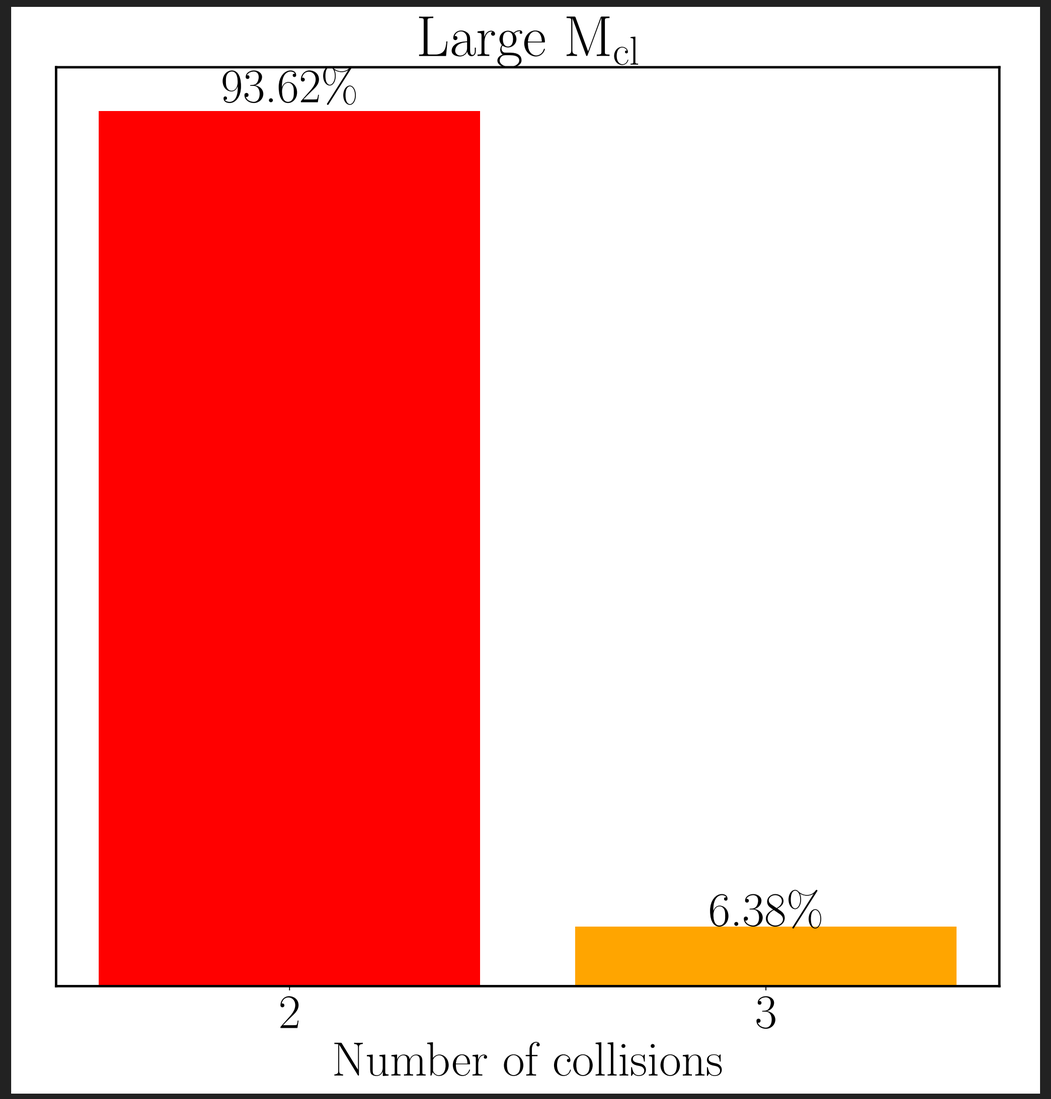
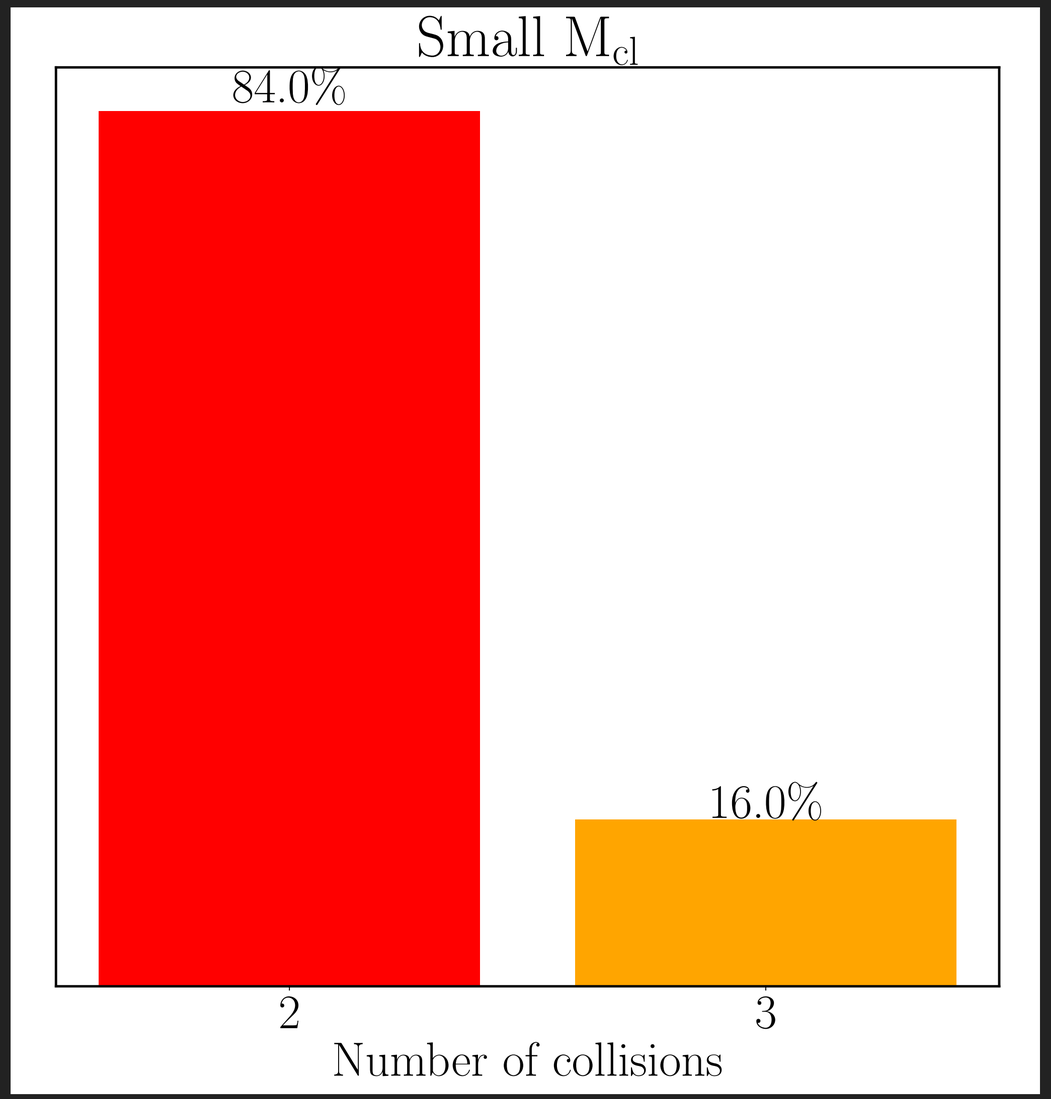
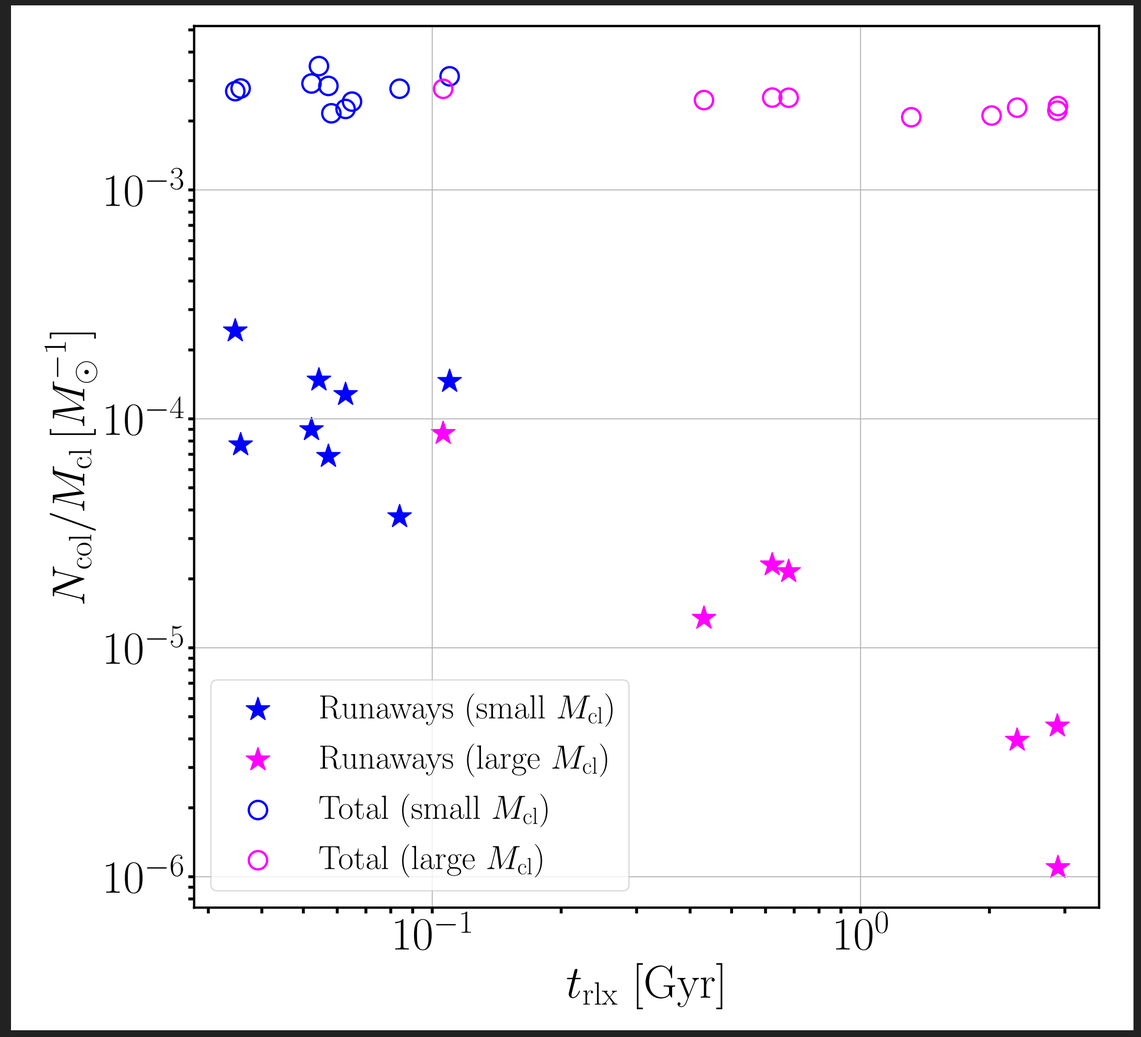
REPEATED COLLISIONS





REPEATED COLLISIONS VS. RELAXATION TIME



VMS NUMBER VS CLUSTER MASS