School of Physics

Black Hole Seed Formation in Dense Globular Cluster

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SMBHs

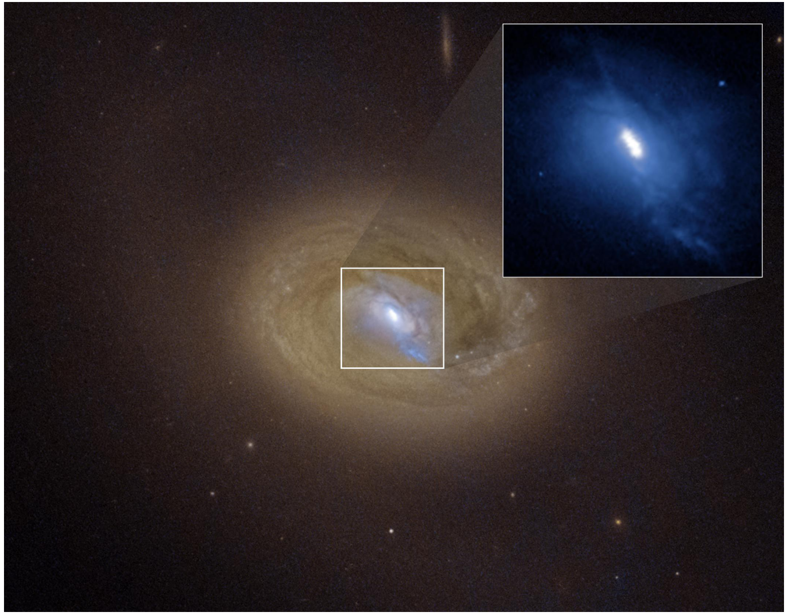
ZHEJIANG UNIVERSITY

Where the super massive black hole(SMBH, $10^{8\sim10}$ M_{sun}) come from at z>6?

A plausible hypothesis is that an initial heavy black hole seed (>10^4 $M_\odot$) forms first, which then grows over time to evolve into a supermassive black hole (SMBH).

The formation of the seed can occur through several mechanisms:

- remnants of massive stars
- runaway collisions in dense cluster
- direct gas collapse



NASA

Globular cluster

Globular clusters (GCs) are considered one of the potential sources for seeding supermassive black holes (SMBHs), primarily due to their unique properties.

High density, especially in the central area

High collision rate between stars

Low metallicity

Frequent dynamic friction

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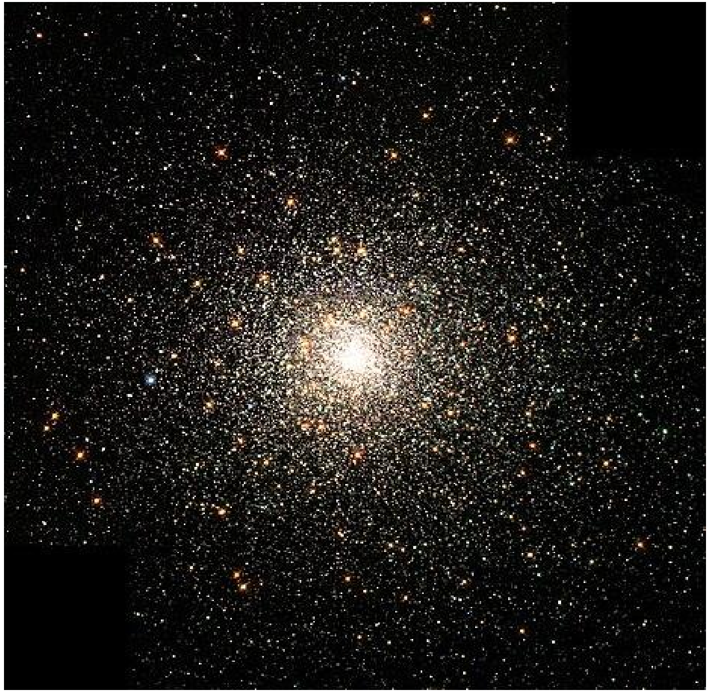


Messier 80
Wikipedia

Simulations

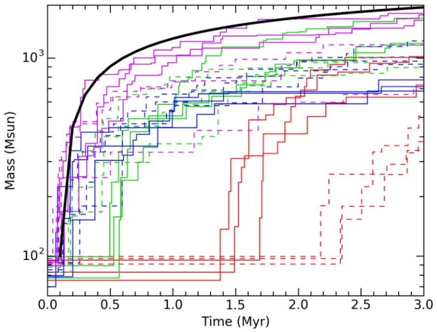


Figure 3. Mass evolution of the stars that undergo runaway collision at the cluster centre. The analytical expression of equation (5) is also plotted (black thick line) for the model G with $m_{\rm seed} = 100\,M_\odot$, $M_{\rm cl} = 1.25 \times 10^5\,M_\odot$, $t_{\rm cc} = 0.1$ Myr and $f_{\rm c} \ln \Lambda = 1$. The line types and colours are the same as in Fig. 2.

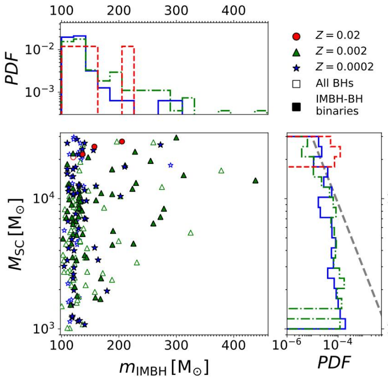
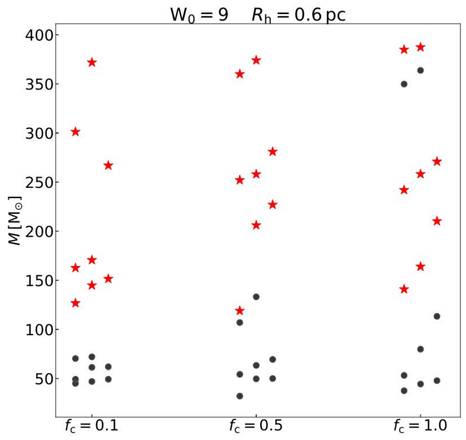


Figure 12. Mass of the host SC ($M_{\rm SC}$) versus the mass of the IMBH ($m_{\rm IMBH}$). The marginal histograms show the distribution of $M_{\rm SC}$ (y-axis) and $m_{\rm IMBH}$ (x-axis). The filled symbols refer to IMBHs in IMBH–BH binaries, while the open symbols are single BHs. The solid blue, dot–dashed green, and dashed red colours refer to $Z = 0.0002$, 0.002, and 0.02, respectively. The grey dashed line shows the initial mass function of SCs ($dN/dM_{\rm SC} \propto M_{\rm SC}^{-2}$).



Y. Sakurai et al. 2017

U. N. Di Carlo et al. 2021

Rizzuto et al. 2021

How to form a seed with mass = $10^4 \sim 10^5\,M_{sun}$?

more massive and denser cluster($10^7 \sim 10^8\,M_{sun}$) !

Mass Redistribution

Kroupa IMF:

$$\xi(m) = \begin{cases} k_1 m^{-0.3}, & m < 0.08\,M_\odot \\ k_2 m^{-1.3}, & 0.08 \le m < 0.5\,M_\odot \\ k_3 m^{-2.3}, & 0.5 \le m < 1.0\,M_\odot \\ k_4 m^{-2.7}, & m \ge 1.0\,M_\odot \end{cases}$$

A cluster with mass = **10^7** M_{sun} —Kroupa mass function→ **$3*10^7$** stars !

It will extremely consume computing resources. It may take several months to operate with thousands of CPU cores.

Mass Redistribution: We clean small mass stars(<3Msun) and regenerate larger stars (>3Msun) at the IC according the situation of low-quality stars. Thus reducing the number of stars.

Initial Condition generation

High-performance N -body code **PeTar**

- particle-tree particleparticle method and slow-down algorithmic regularisation method
- SSE and BSEemp (including SN feedback, Star Wind feedback)
- Parallel computing capabilitiy

Initial condition generator **Mcluster**

- Cluster parameters
- Binary parameters
- IMF: Kroupa (2001), Maschberger(2012)...
- density profile: King Model (1966), Plummer...

Initial Condition generation

Parameter	Value
Cluster Mass	10^5~10^7 Msun
Half-mass radius	3pc
IMF	Kroupa(2001)
Star evolution	SSE/BSEEmp
Density profile	King model(1966)/Plummer
Metallicity	0.01~0.0001
Binary fraction	6%~7%
Binary semi-major axis	0.0001~0.01pc

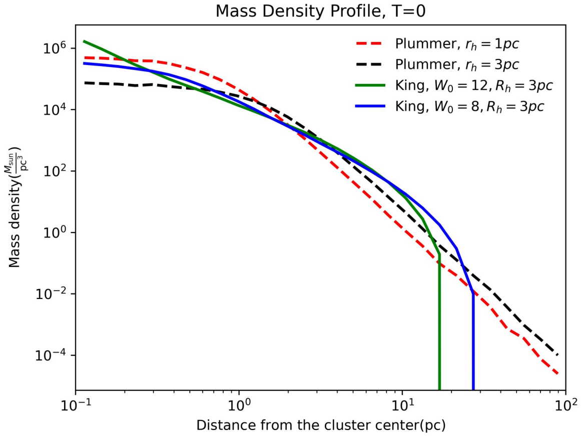
Dense cluster → Runaway merger → A massive star

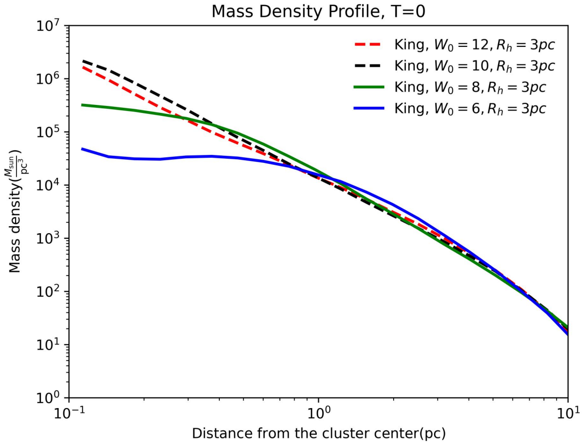
Density Profile

The first goal is to obtain a high-density core that facilitates runaway mergers to occur here.

It is better to adopt the King Model.

W_0 is a parameter in the King model, representing the depth of the potential well of the star cluster. A larger W_0 indicates a deeper potential well.





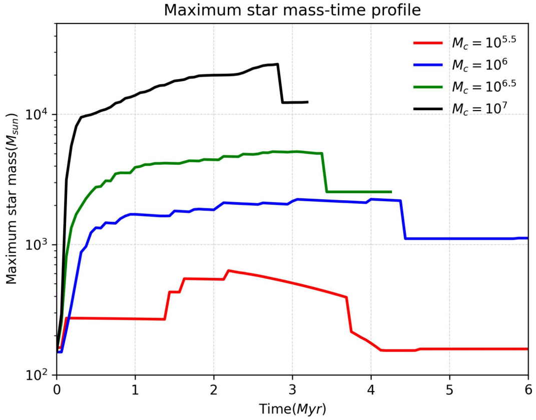
Massive Star Mass

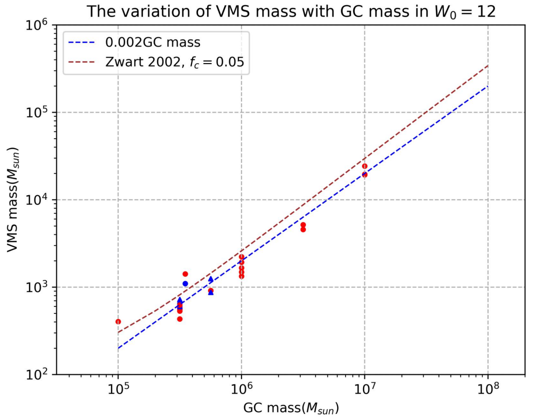
W_0 = 12, r_h = 3pc

Runaway mergers occur in the early stages of simulation, with the entire merger process lasting only a few million years.

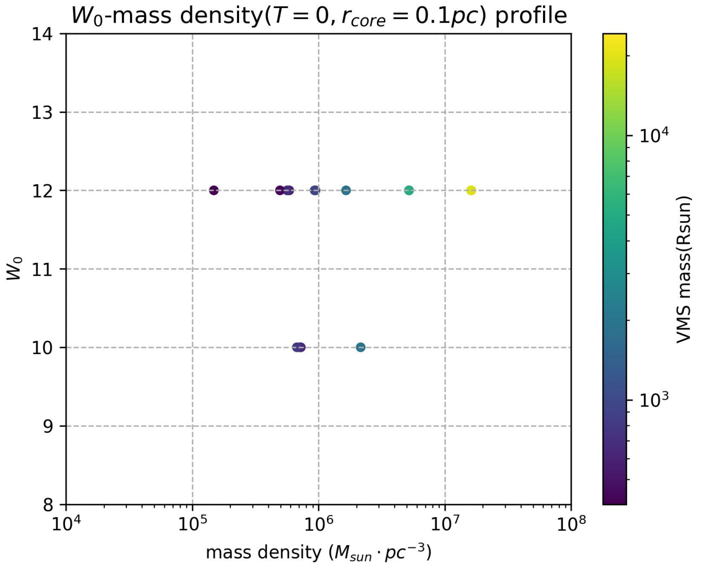
Approximate mass relationship:

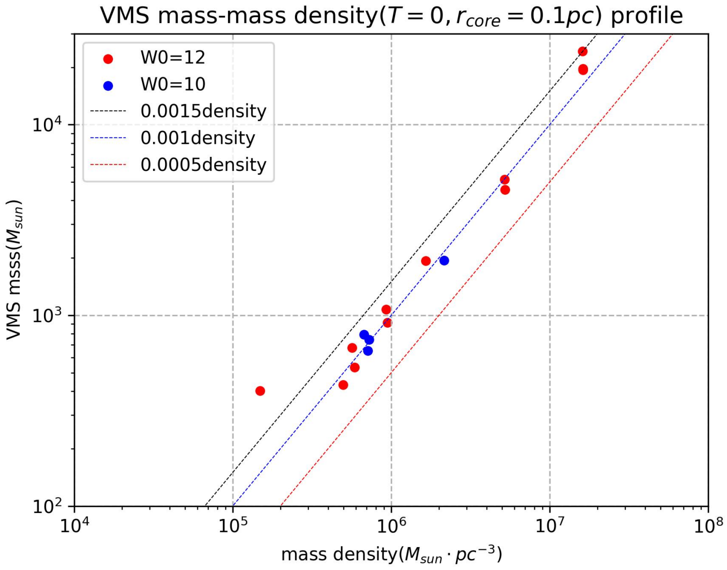
$$M_{VMS} \approx 0.002 M_{GC}$$





Massive Star Mass





Relationship between IC and VMS's Mass

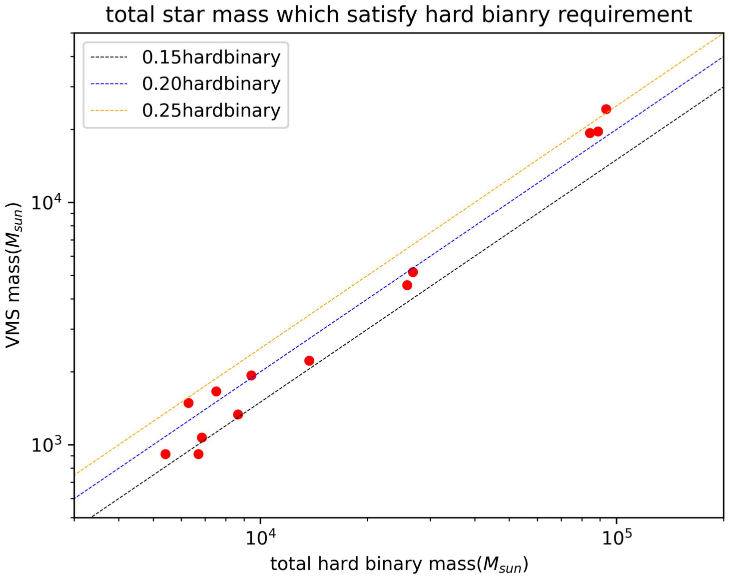
Our goal is to produce a massive star. However, a critical challenge lies in **establishing a relationship** between the massive star mass and the initial condition (IC) of the cluster from physical aspect, and further extending this relationship to a broader context.

There are two feasible approaches:

Angular momentum: It represents the distance between stars and involves the merger of two stars.

Hard binary: **A close binary system**. Its orbital energy is typically greater than the average kinetic energy of the star cluster.It repesents the binding energy between binary stars.

Hard Binary



$$E_{binary} = \frac{1}{2}\frac{M_1 M_2}{M_1 + M_2} V_R^2 - \frac{G M_1 M_2}{r_R}$$

$$E_k = \frac{1}{2}\langle M \rangle \sigma^2$$

Total hard bianry mass: the total mass of all stars capable of forming a binary system with the most massive star.

The ratio of maximum mass over the hard binary mass is ~ **0.2.** This is partly similar to other work(Portegies Zwart et al. 2002, B.Devecchi et al. 2010).

Conclusion

1: Merger process will only last several million years. The very massive star and cluster generally follow the relationship under the above parameter settings: $M_{VMS} \approx 0.002 M_{GC}$

2: We investigated the behavior of the maximum stellar mass within the parameter space of W_0 - GC mass. Runaway mergers leading to the formation of massive stars are only likely to occur when **W_0 >10**.

3: The formation of hard binaries is a physical process that significantly promotes the formation of massive stars. We obtained the merger rate of approximately **0.2**, which is consistent with the results reported in some papers(Portegies Zwart et al. 2002, B.Devecchi et al. 2010).