星一つ一つを再現した
大質量星団形成シミュレーション

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Outline

- Why we want to perform star-by-star massive star cluster formation simulations?
- Our code: ASURA+BRIDGE
- Formation of globular clusters with intermediate-mass black holes
- Summary

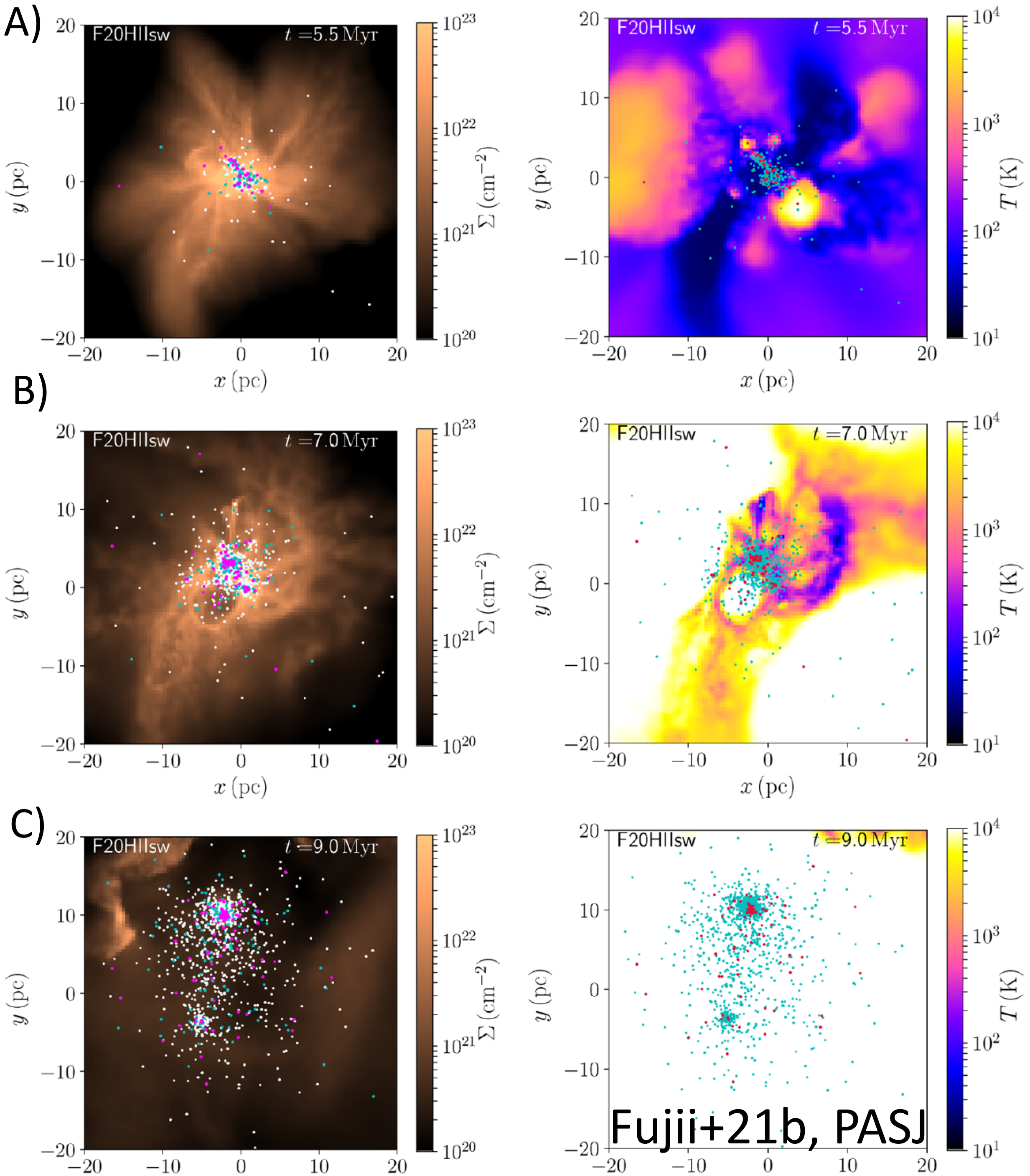
Star-cluster formation

A) Stars form in collapsing molecular clouds

B) Cluster formation in the deepest potential

C) Gas expulsion and dynamical evolution reduce the cluster density

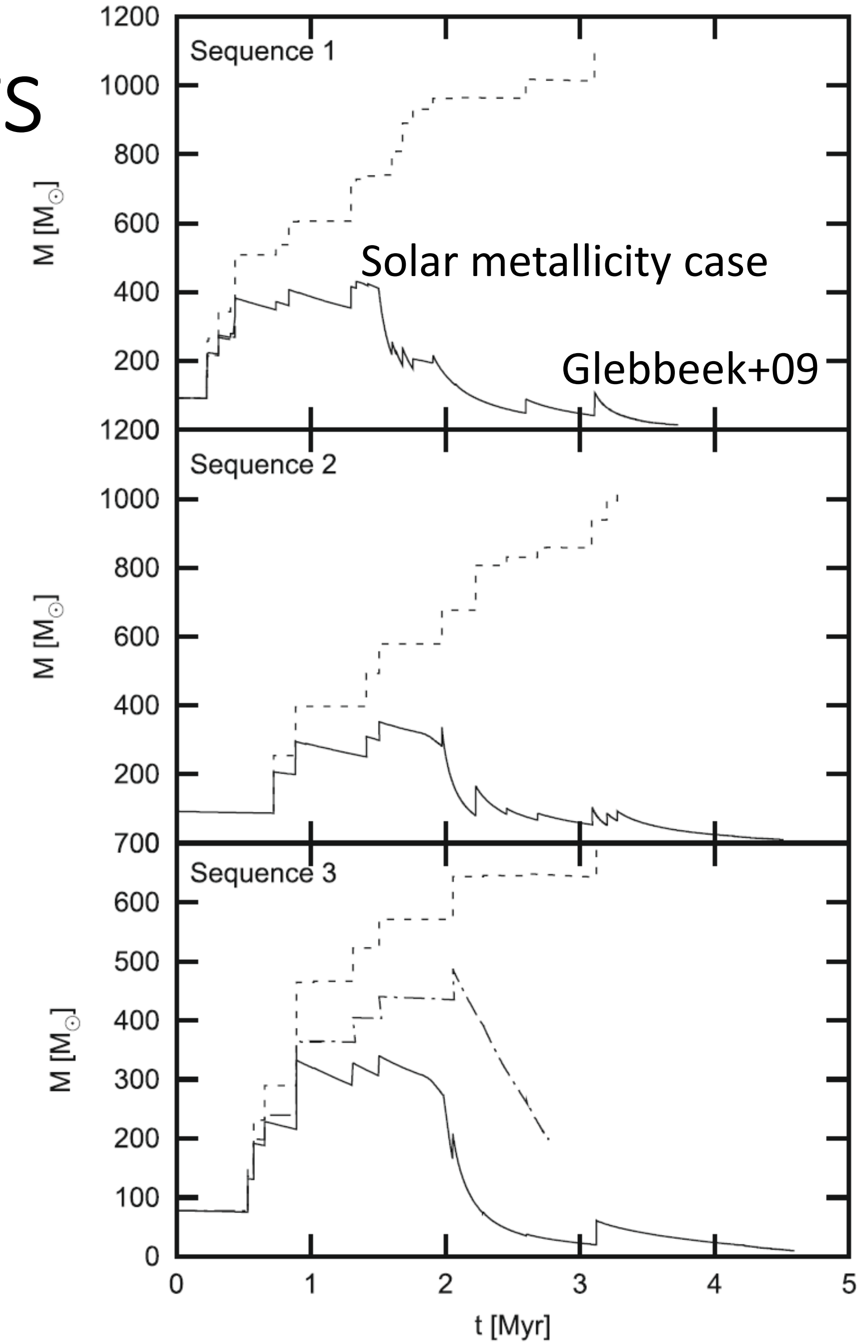
- **The highest cluster density can be achieved during the formation phase -> runaway collisions of stars**
- To follow collisions, we need
  - **Resolving individual stars**
  - **Treat star clusters as a collisional system**



Runaway collisions in star clusters

- Globular cluster centers can reach extremely high densities
- Stars continuously collide and merge (runaway collisions)
- Very massive stars can form and then they may evolve to intermediate-mass black holes (Portegies Zwart & McMillan 2002)
- Mass loss may prevent the formation of IMBHs (Glebeek+09)
- **BUT, These simulations started from a formed cluster** (spherical, in equilibrium, gas free)

Cluster Mass ~$4x10^5$Msun



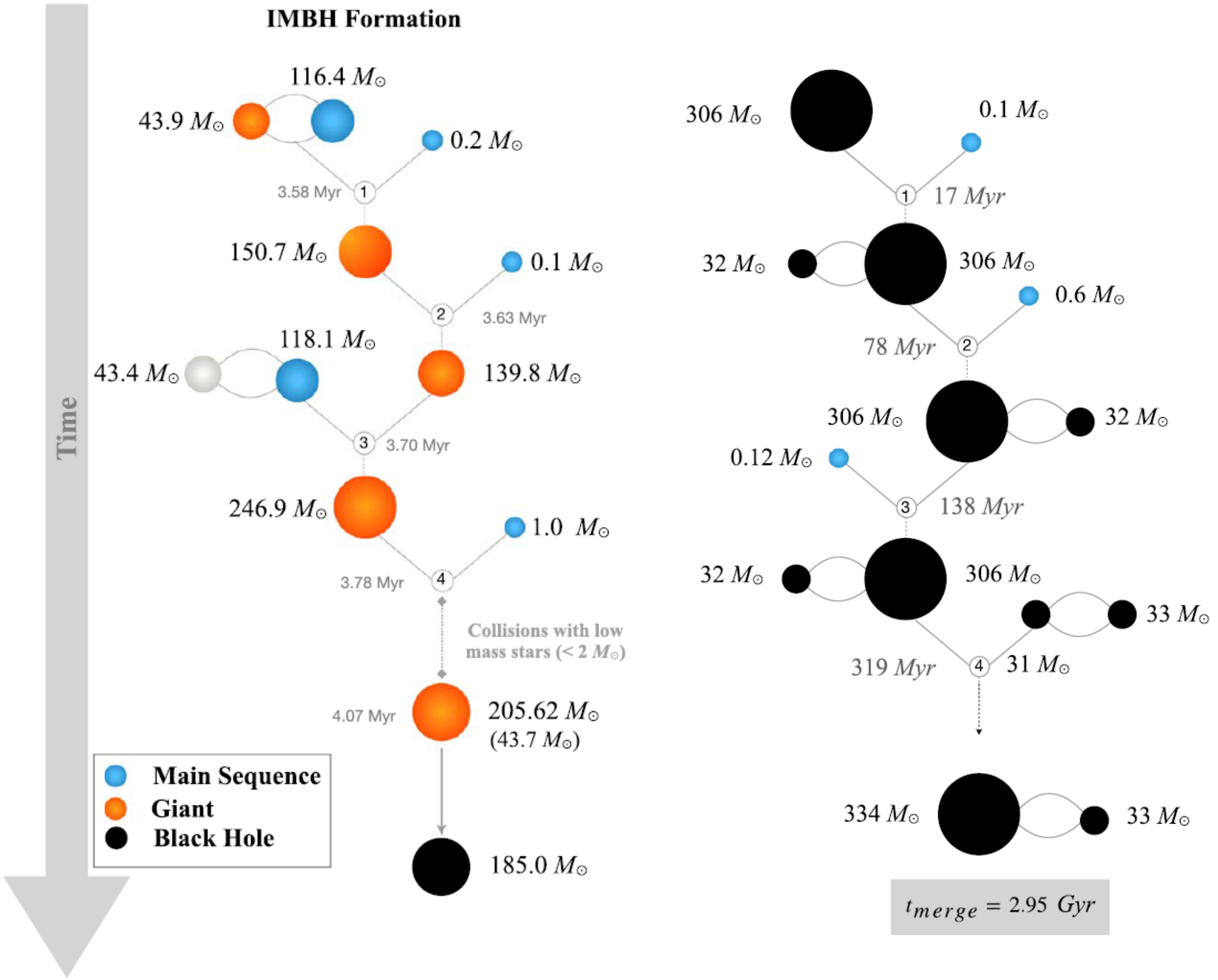
Intermediate-mass black holes (IMBHs)

- Stellar-mass BHs: <~100 Msun
    - BHs formed from normal massive stars
    - The maximum mass (~50 Msun) may depend on stellar evolution models
- Supermassive BHs: >~10^5 Msun
    - Massive BHs located at the center of galaxies
    - MW hosts 4×10^6 Msun SMBH

- Intermediate-mass BHs: between Stellar-mass and supermassive BHs -> ~100 – 10^4 Msun
    - Compared to the others, difficult to observe

Two possible formation scenarios in star clusters

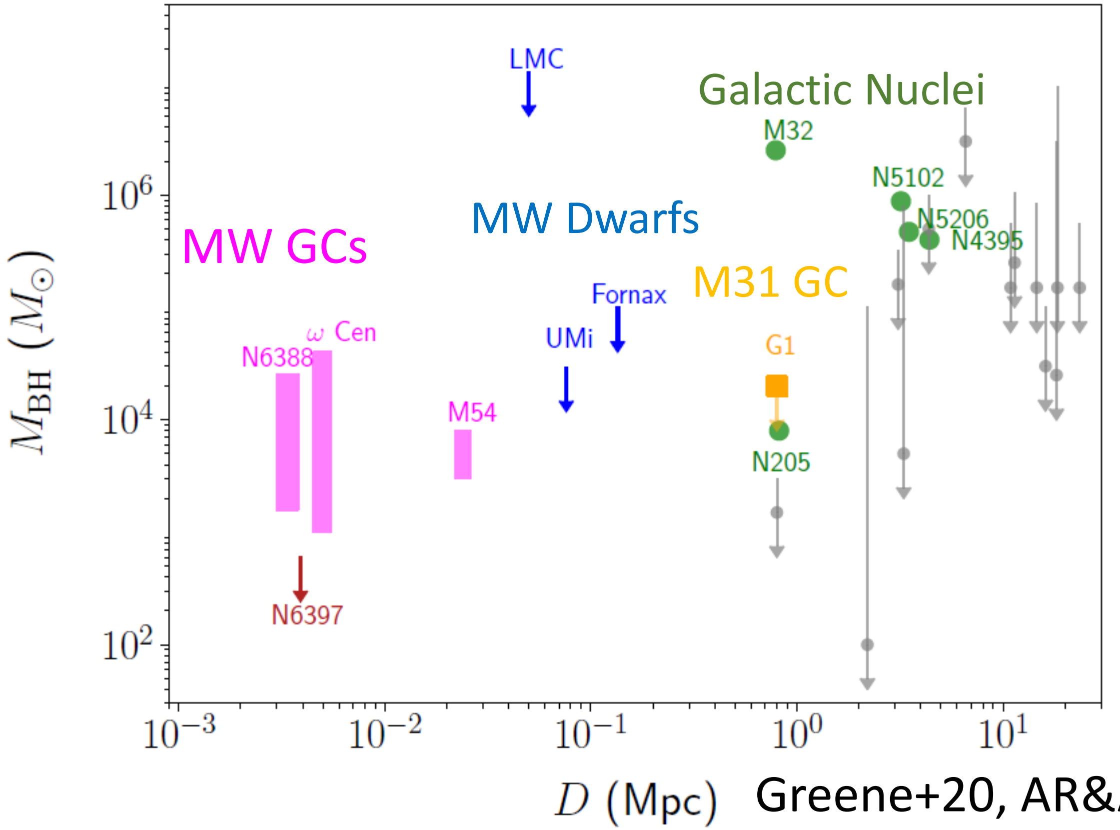
- Runaway collisions of main-sequence stars
  - Globular clusters were initially dense
  - Once massive stars collide and form a more massive star, gravitational focusing accumulate stars and collisions repeat
- Multiple IMBH-BH mergers
  - Studied using N-body simulations of star clusters
  - Gravitational recoil kick ejects IMBHs before they reach 500 Msun (Holley-Bockelmann+2008, González Prieto+2022)



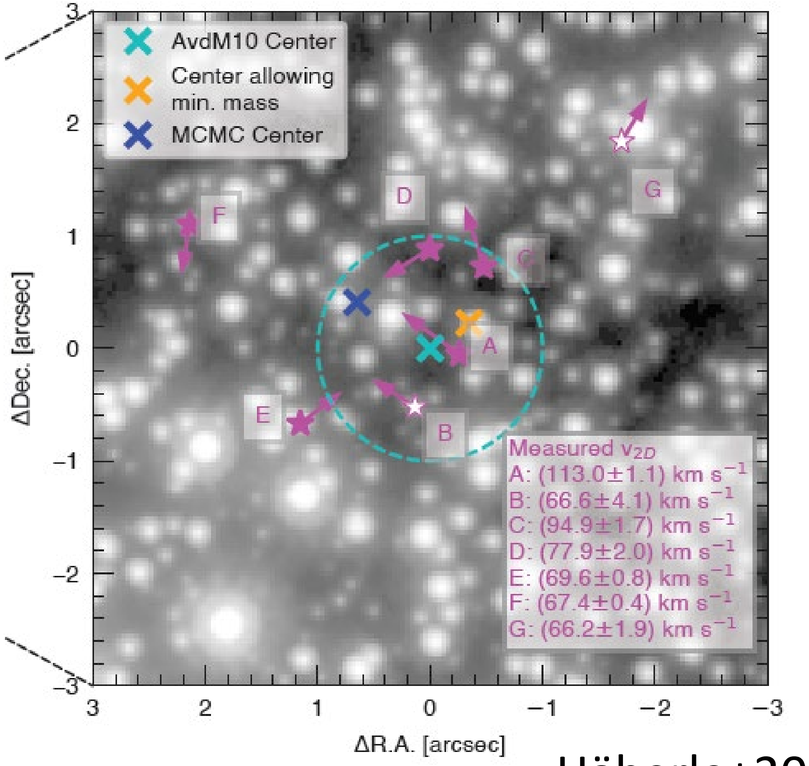
González Prieto+2022

IMBHs in globular cluster?

- Globular clusters: old and compact star clusters in the halo (10^{5-6} Msun)
- Some globular cluster may host 10^3-10^4 Msun IMBHs
  - But, not really convincing yet



Greene+20, AR&A review



Häberle+2024

Difficulties of star-by-star cluster-formation SPH simulations

- Relatively high-resolution for star formation
  - To use sink particles and resolve 0.1 Msun stars, <0.01 Msun mass resolution is required
    -> >10^8 particles for 10^6 Msun molecular cloud
  - Typically, ~100 au (~0.01 pc) sink radius is used
  - We use a probabilistic star-formation recipe like galaxy formation simulations!

- Simulations without gravitational softening length
  - To treat collisions, we cannot use softening length
    -> very small timestep is required (high-order integrator is required)
  - We use a hybrid integrator!

ASURA+BRIDGE code

Fujii+21ab, Hirai+21, PASJ

- Based on ASURA, N-body/SPH code initially developed for galaxy formation
  - SPH and N-body is coupled using BRIDGE scheme, a hybrid integrato (Fujii et al. 2007)

- ASURA+BRIDGE can integrate stellar orbits without gravitational softening
  - We use **PeTar** (tree-based direct N-body code including binary treatments; Wang+2020)
- Probabilistic star formation similar to galaxy simulation
  - Density and temperature thresholds for star formation
  - Draw a stellar mass from a given IMF such as Kroupa IMF
  - No sink particles to reduce calculation cost
- HII region feedback using Strömgren radius
  - Set gas temperature within Strömgren radius to 10,000 K

ASURA+BRIDGE code

Fujii+21ab, Hirai+21, PASJ

- Collisions occur when two stars approach to the sum of their radii
  - We assumed perfect collision
- Stellar evolution using SSE (Tanikawa ver. 2020)
  - SSE give the radius, luminosity, and mass loss
  - Lost mass given to the surrounding gas particles
  - Mass loss rate for VMS (Vink 2018)

$$\log[\dot{m}_{\rm SW}/M_{\odot}\,{\rm yr}^{-1}] = -9.13 + 2.1\log[m/M_{\odot}] + 0.74\log[Z/Z_{\odot}],$$

- SIRIUS Project
  - https://sites.google.com/g.ecc.u-tokyo.ac.jp/sirius-project/
- Simulations were performed using ATERUI-II, NAOJ
  - For the largest one, it took >3 month using 1000 CPU cores

Initial conditions and parameters

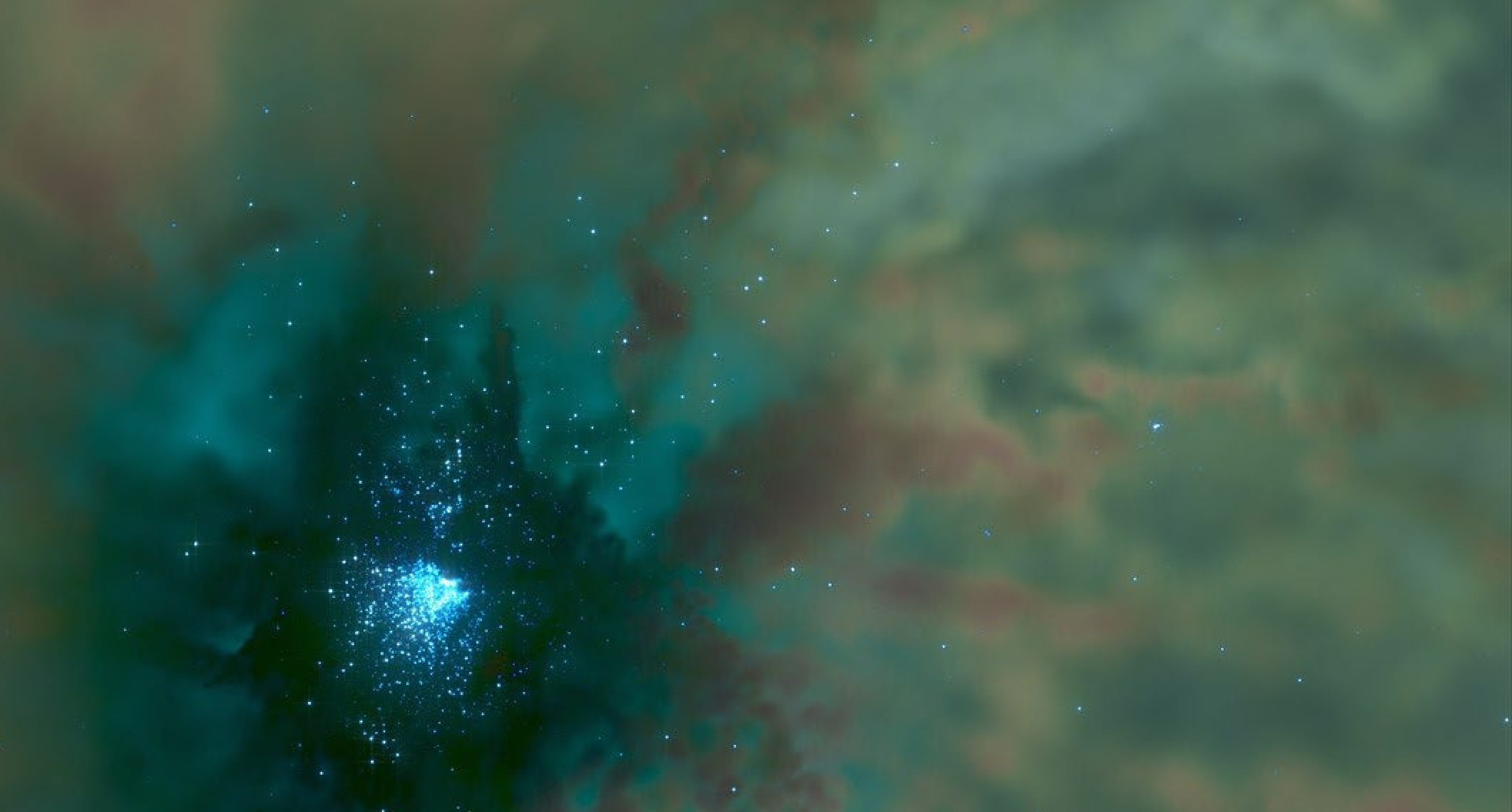
Homogeneous sphere with an initial turbulent velocity field

We picked up models forming a dense cluster from Fukushima+ 2021

We still don't know how such a massive and dense cloud forms

Table S1: **Initial conditions.** From the left: model name, metallicity (Z), initial cloud mass (M_g), radius (R_g), initial density (n_{ini}), initial surface density (Σ_{ini}), initial free-fall time ($t_{ff,ini}$), virial ratio (α_{vir}), and the number of runs (N_{run}).

Name	Z ($Z_\odot$)	M_g ($M_\odot$)	R_g (pc)	n_{ini} (cm^{-3})	Σ_{ini} ($M_\odot$ pc^{-2})	$t_{ff,ini}$ (Myr)	α_{vir}	N_{run}
M1e5R5Z002v01	0.02	10^5	5	5600	1300	0.59	0.1	5
M1e6R10Z002v05	0.02	10^6	10	7000	3200	0.52	0.5	3
M1e6R10Z002v01	0.02	10^6	10	7000	3200	0.52	0.1	2
M1e6R17Z002v01	0.02	10^6	17	1400	1100	1.16	0.1	1
M1e5R5Z01v01	0.1	10^5	5	5600	1300	0.59	0.1	3
M3e5R7Z01v01	0.1	3×10^5	7.5	4500	1700	0.62	0.1	3

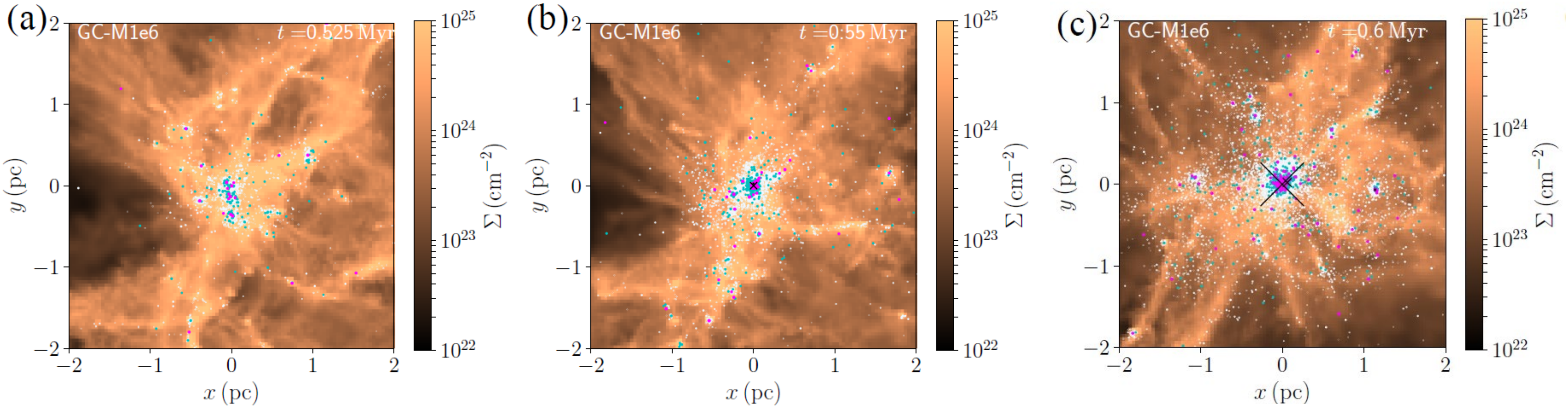


- Visualization based on the simulation result by Takaaki Takeda

Fujii+24, Science, arXiv:2406.06772

Star cluster formation

X: Very massive star

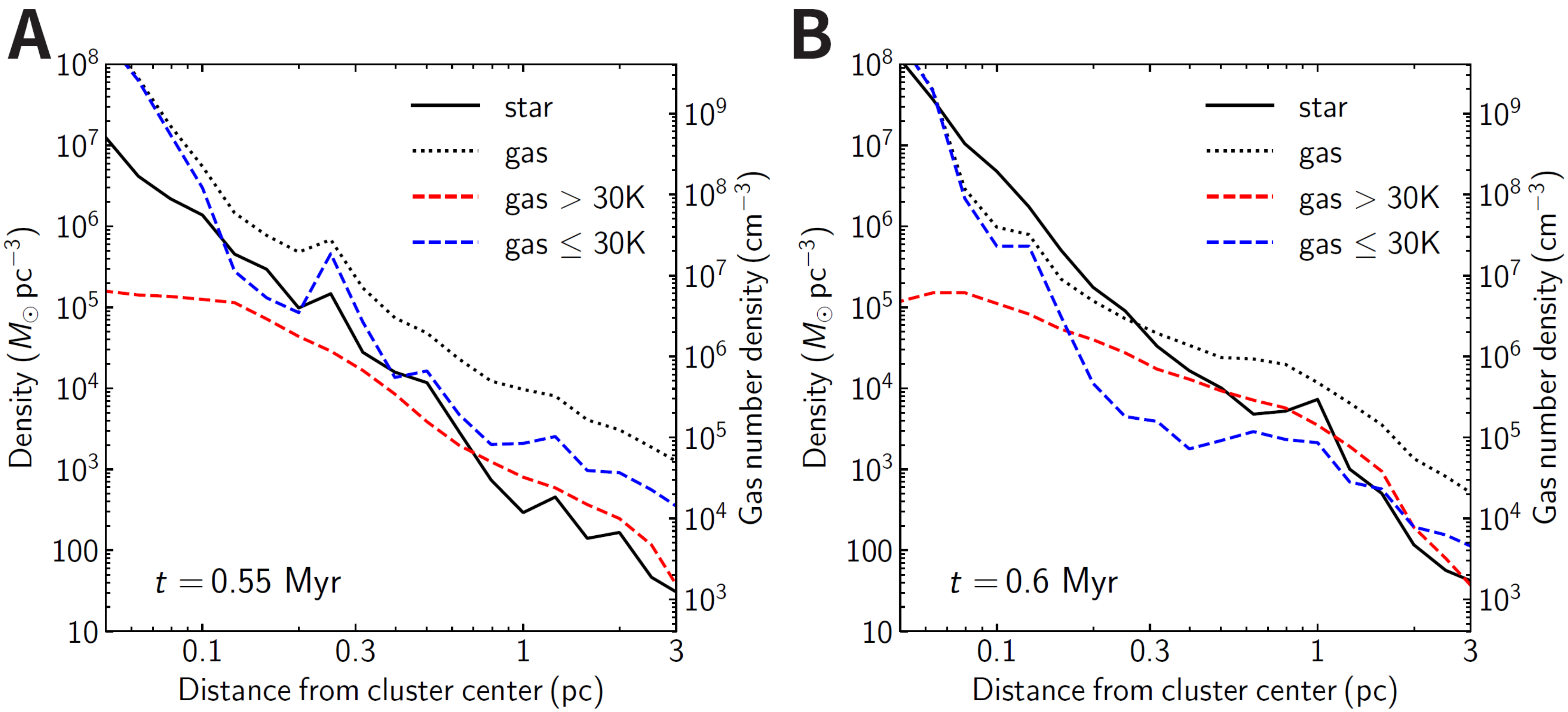


- Star formation starts at around the initial free-fall time
- This cluster mass exceeded 10^5 Msun
  (the most massive star-by-star cluster formation simulation)

Fujii+24, Science, arXiv:2406.06772

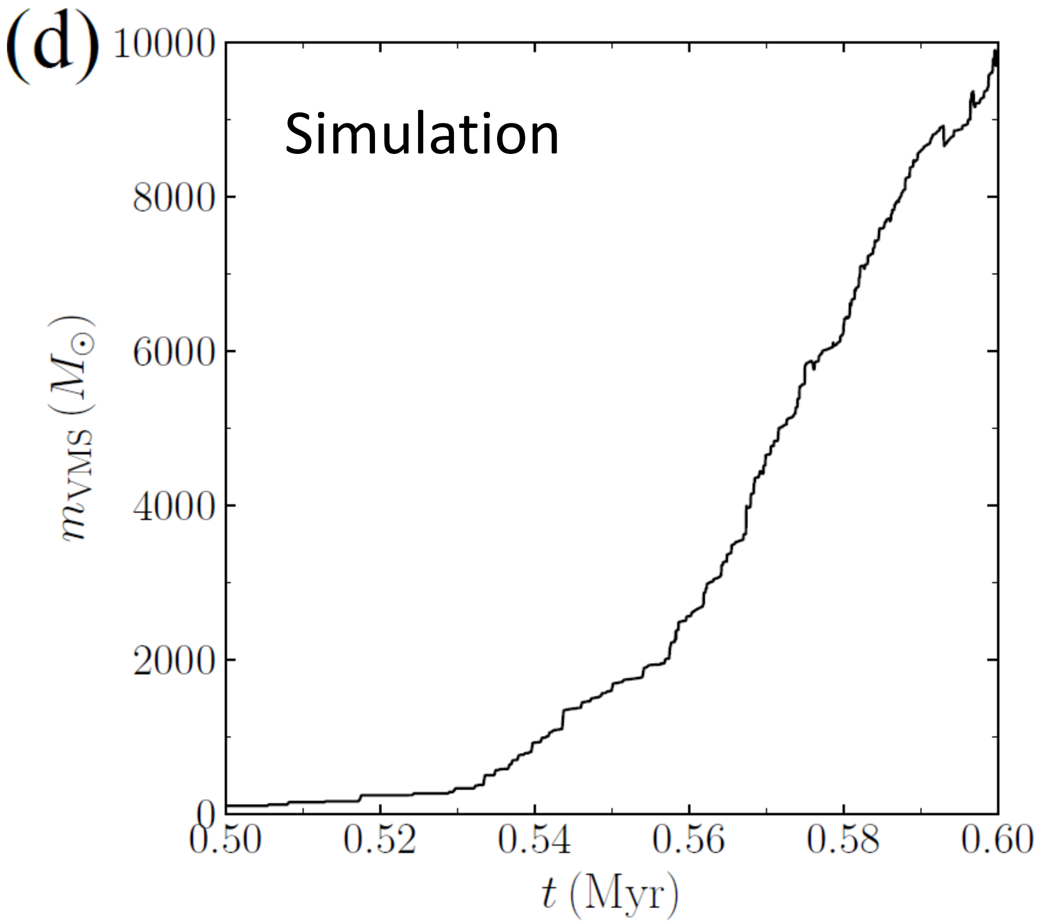
Density distribution

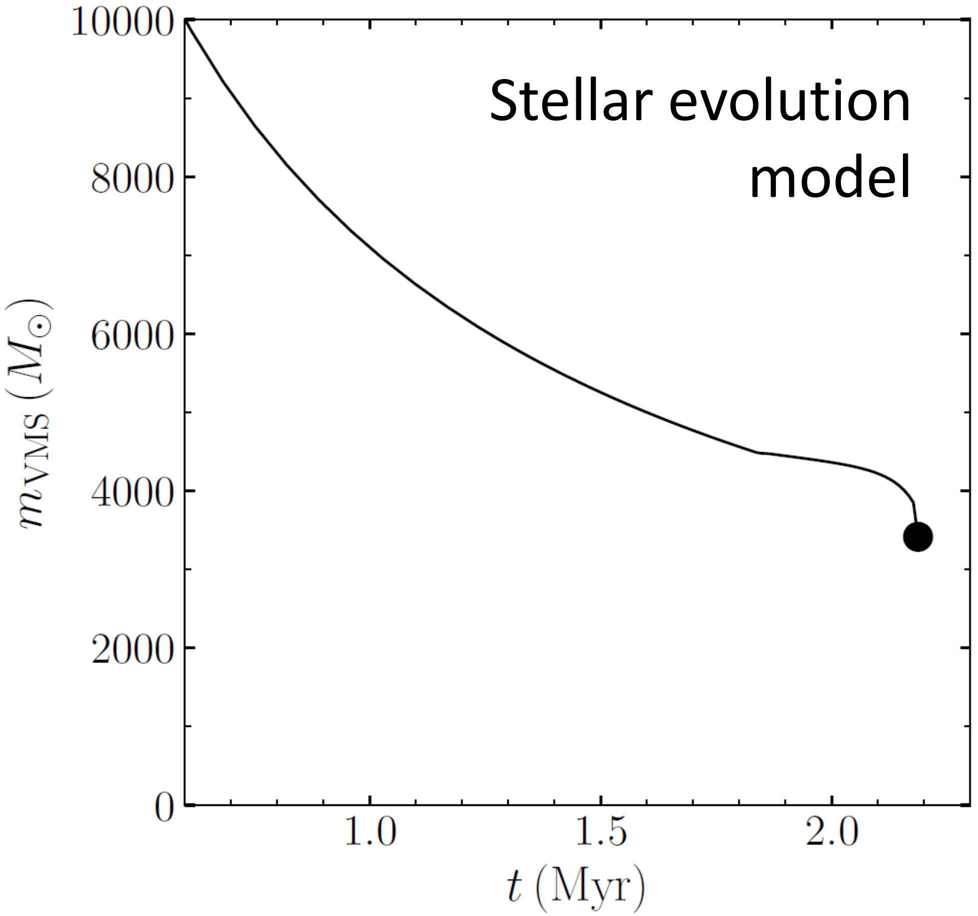
- Extremely high density is realized



Runaway collision and following stellar evolution

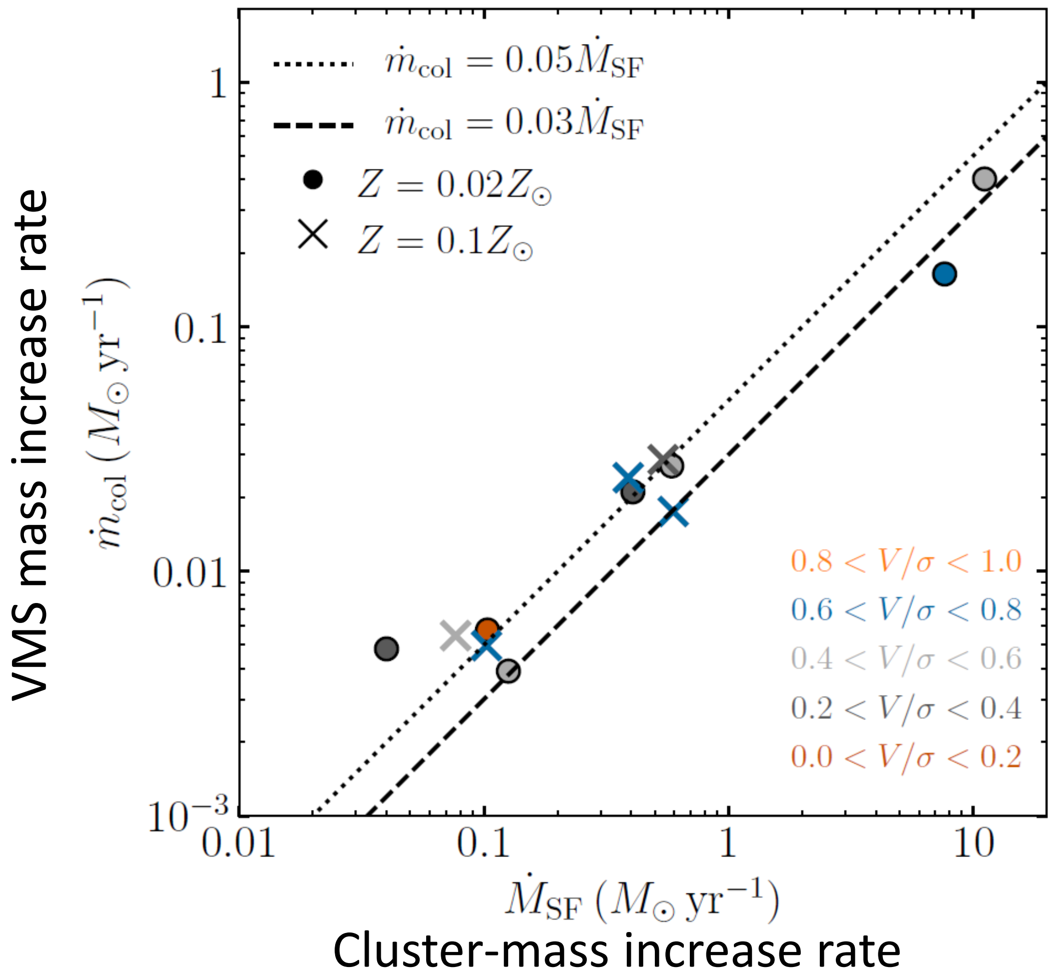
- We stopped the simulation at 0.6 Myr
- The following mass loss is based on a stellar evolution model.

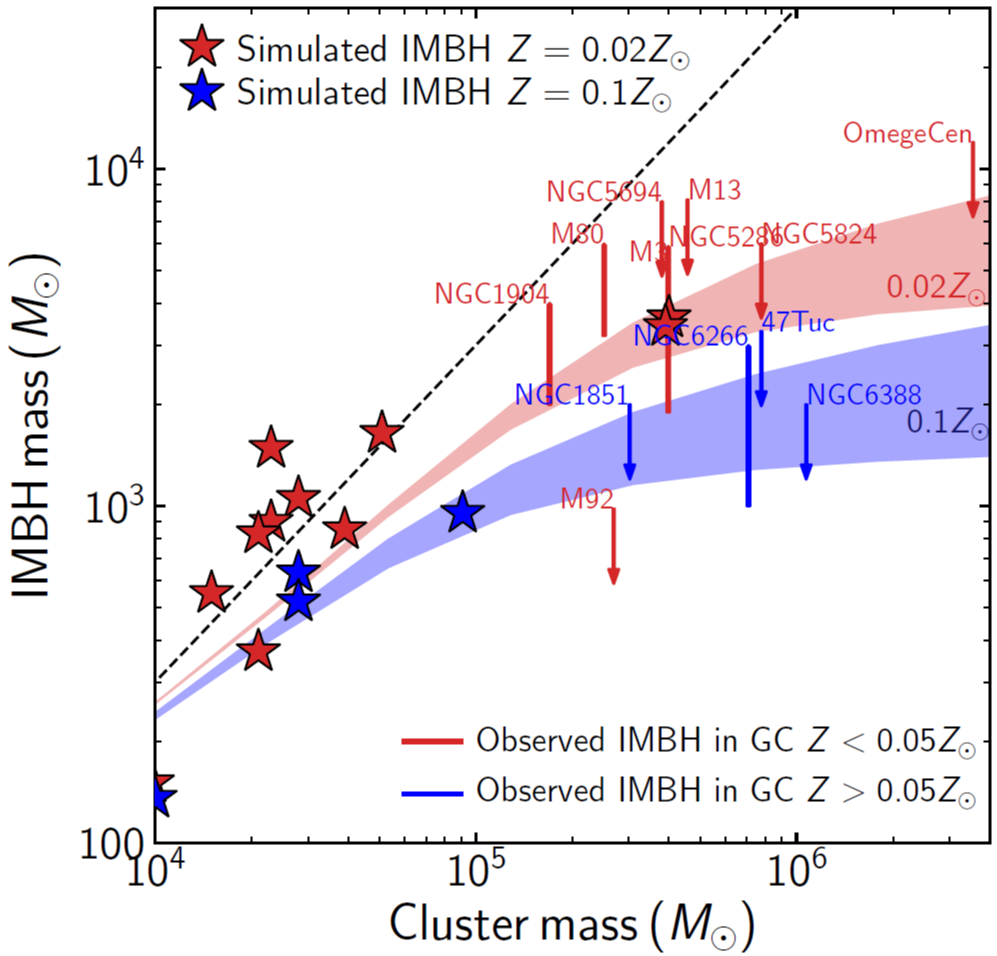




Cluster-IMBH mass

Fujii+24, Science, arXiv:2406.06772



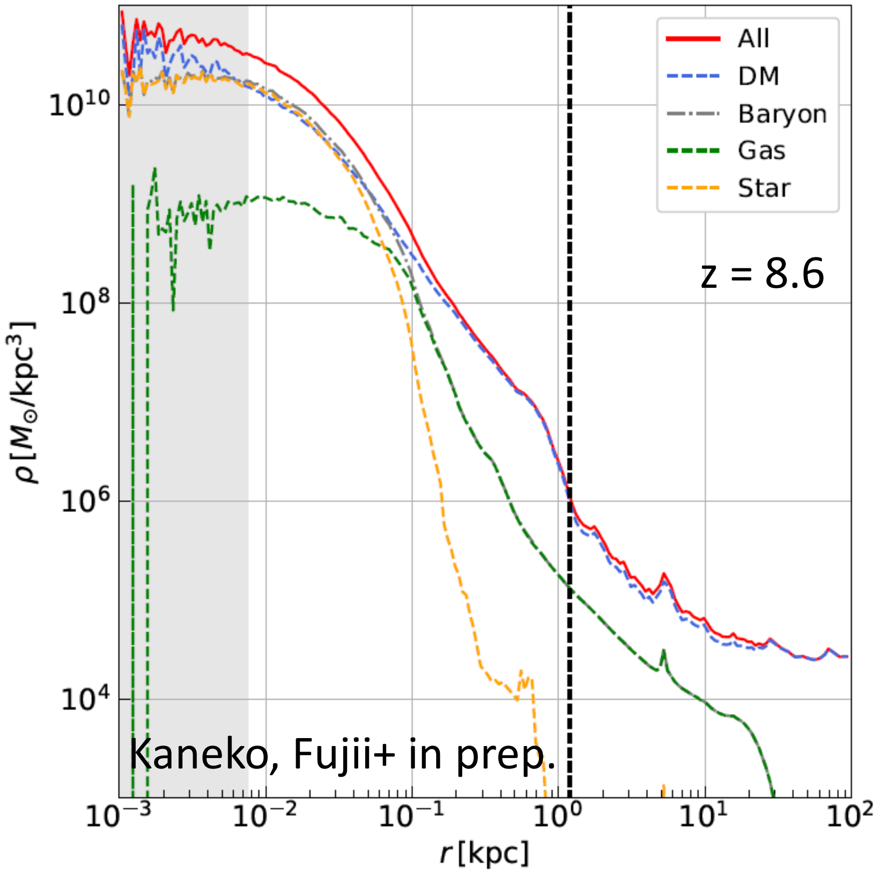


- 3-5% of cluster mass goes to VMS
- ~10^4 Msun IMBH would be the upper limit

What's next?

- Pollution from very massive stars
  - Our code records the pollution fraction -> multiple population of globular clusters?
- Primordial binaries
  - We can put binaries instead of single stars
- Star-by-star galaxy simulations
  - Dwarf size is possible
  - First galaxies? First clusters?

Dwarf galaxy simulation



Summary

- We for the first time performed N-body/SPH simulations of star-by-star globular-cluster formation with runaway collisions
  - Our code, ASURA+BRIDGE, can integrate stars without gravitational softening
- Runaway collision occurs during the formation phase of globular clusters
- ~10^4 Msun VMSs formed via runaway collisions
- VMS-mass increase rate was 3-5 % of cluster-mass increase rate
- These VMSs will collapse to IMBH with >1000 Msun