Formation of globular clusters with intermediate-mass black holes

Michiko Fujii (UTokyo)

Collaboration with **Long Wang** (Sun Yat-sen Univ.),
Ataru Tanikawa (Fukui Pref. Univ.), **Yutaka Hirai**
(Tohoku Univ.), **Takayuki Saitoh** (Kobe Univ.)

Abstract

- We have developed a new N-body/SPH code, ASURA+BRIDGE
- We can integrate stars without gravitational softening and follow binary evolution with gas
- We performed a globular-cluster formation simulation
  - **First star-by-star globular-cluster formation simulation**
  - **We were curious about the collisional evolution in forming star clusters**
- Runaway collision occurred in the forming cluster
- The maximum stellar mass reached 10,000Msun
- Such a VMS can collapse to an IMBH

IMBHs in globular cluster?

- Intermediate-mass black hole: 100—10^5 Msun BH

- Some globular cluster may host 10^3-10^4 Msun IMBHs


Greene+20, AR&A review
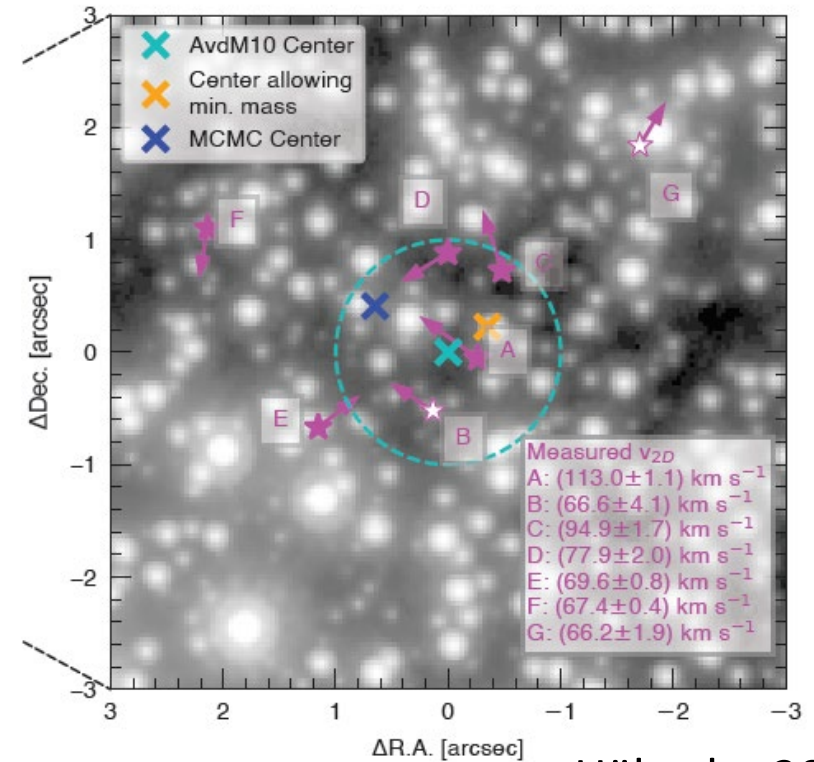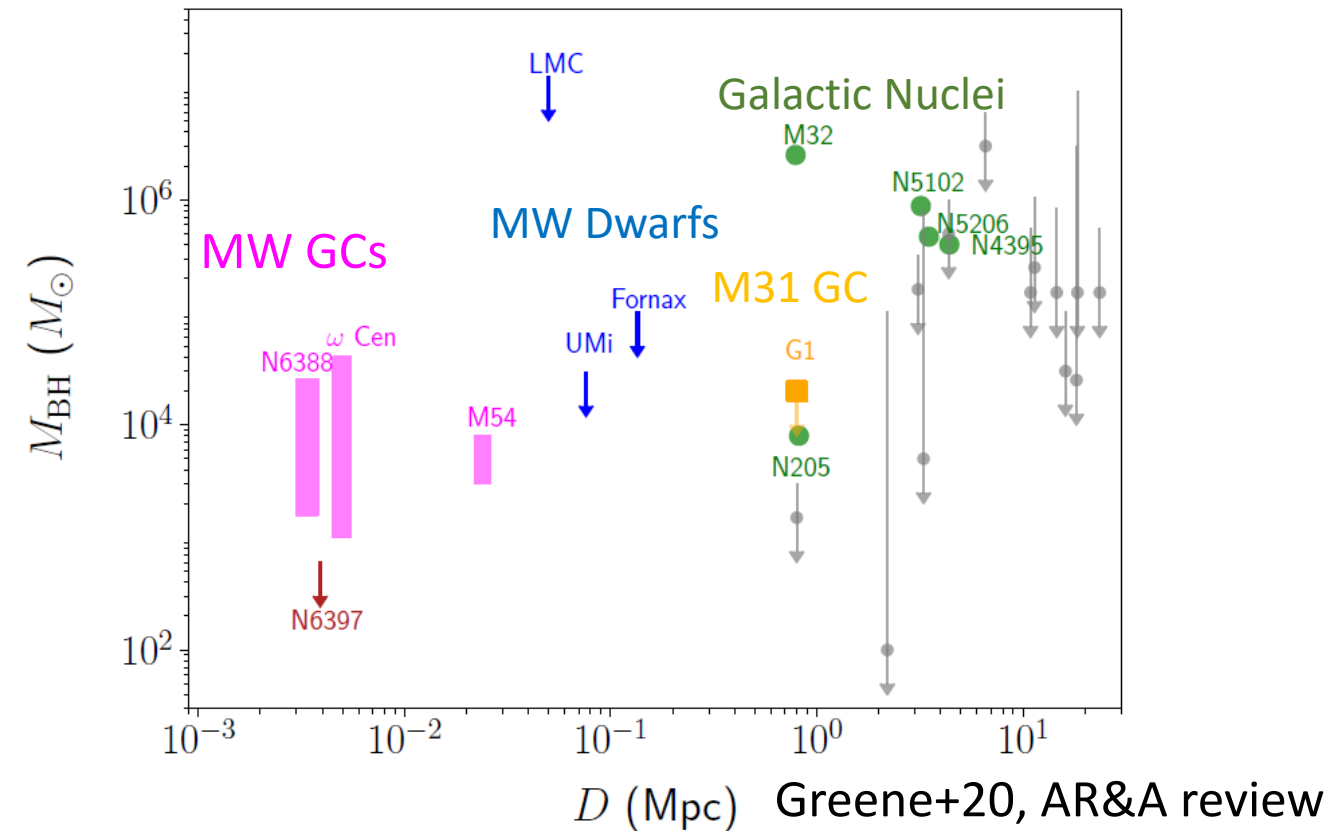
Häberle+2024

Runaway collisions in GCs

- GC centers can reach extremely high densities

- Stars continuously collide and merge (runaway collisions)

- Very massive stars can form (Portegies Zwart & McMillan 2002)
  - But, Mass loss may prevent the formation of IMBHs Glebeek+09

- These simulations started from a formed cluster (spherical, in equilibrium, gas free)

Cluster Mass ~4×10^5Msun

Sequence 1

Solar metallicity case

Glebbeek+09

Sequence 2

Sequence 3
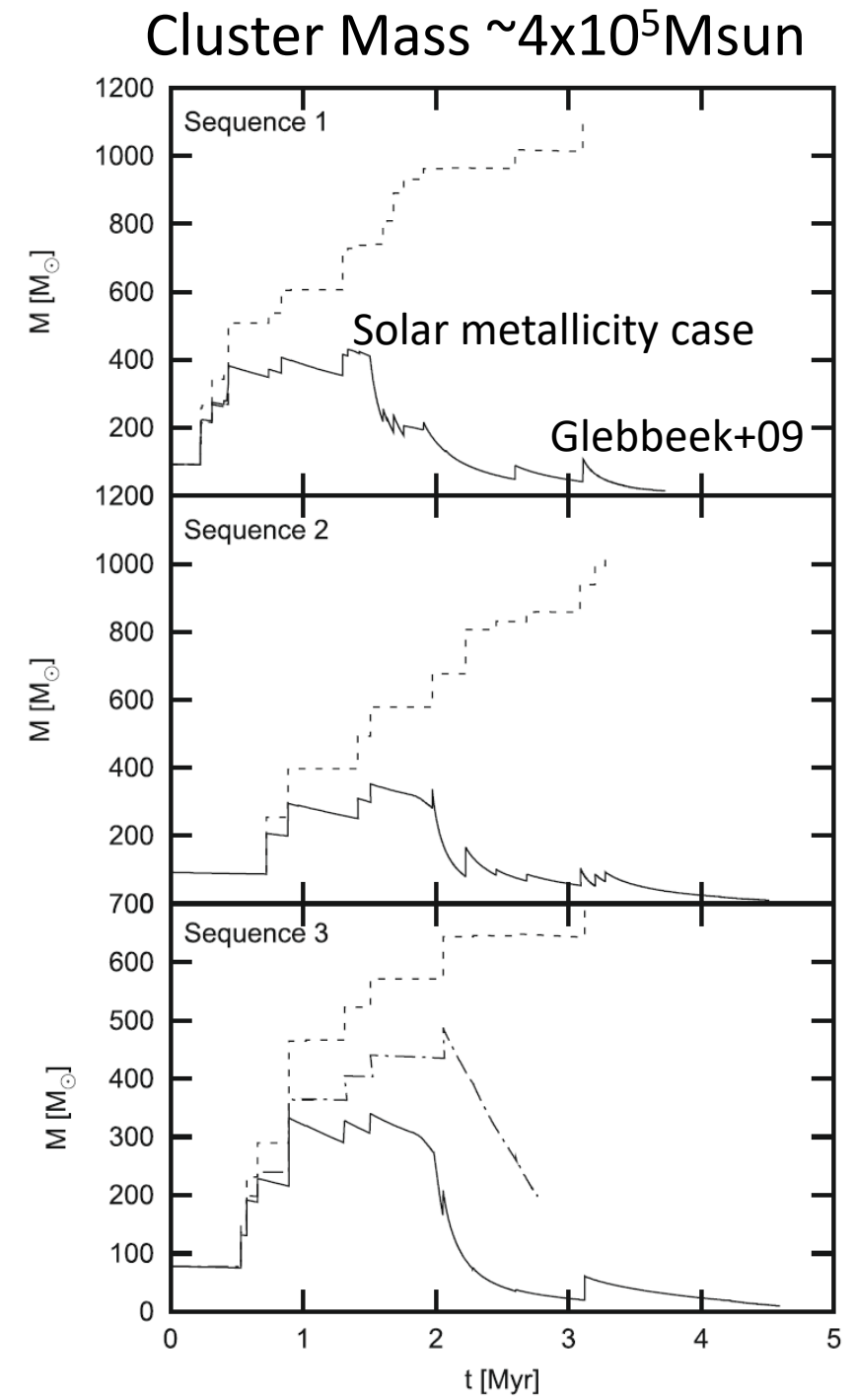
Star-cluster formation

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**

- To follow collisions, we need
  - **Resolving individual stars**
  - **Treat star clusters as a collisional system**

Fujii+21b, PASJ
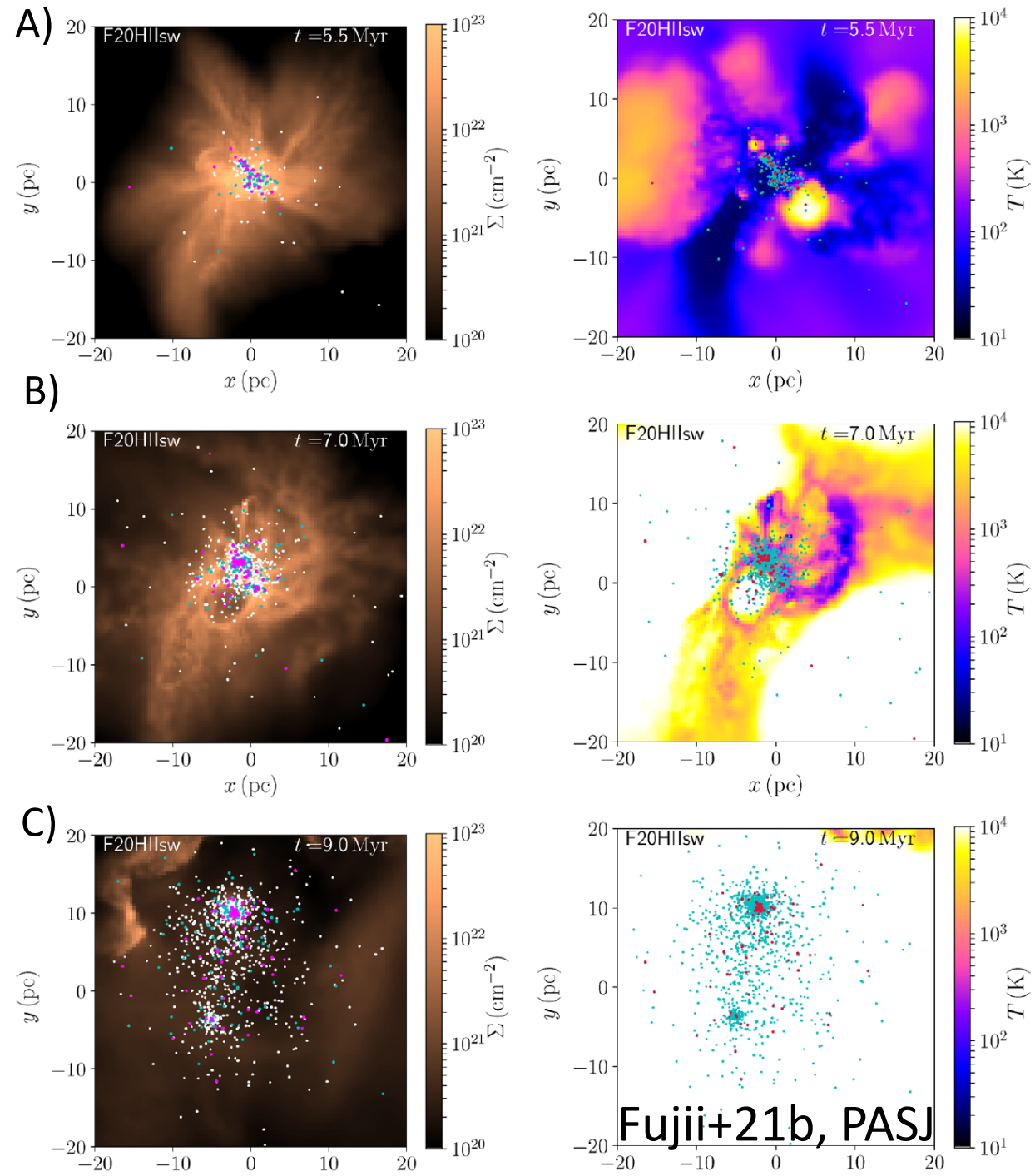
ASURA+BRIDGE code

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 (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

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Movie:
https://www.youtube.com/watch?v=bvKDx8t
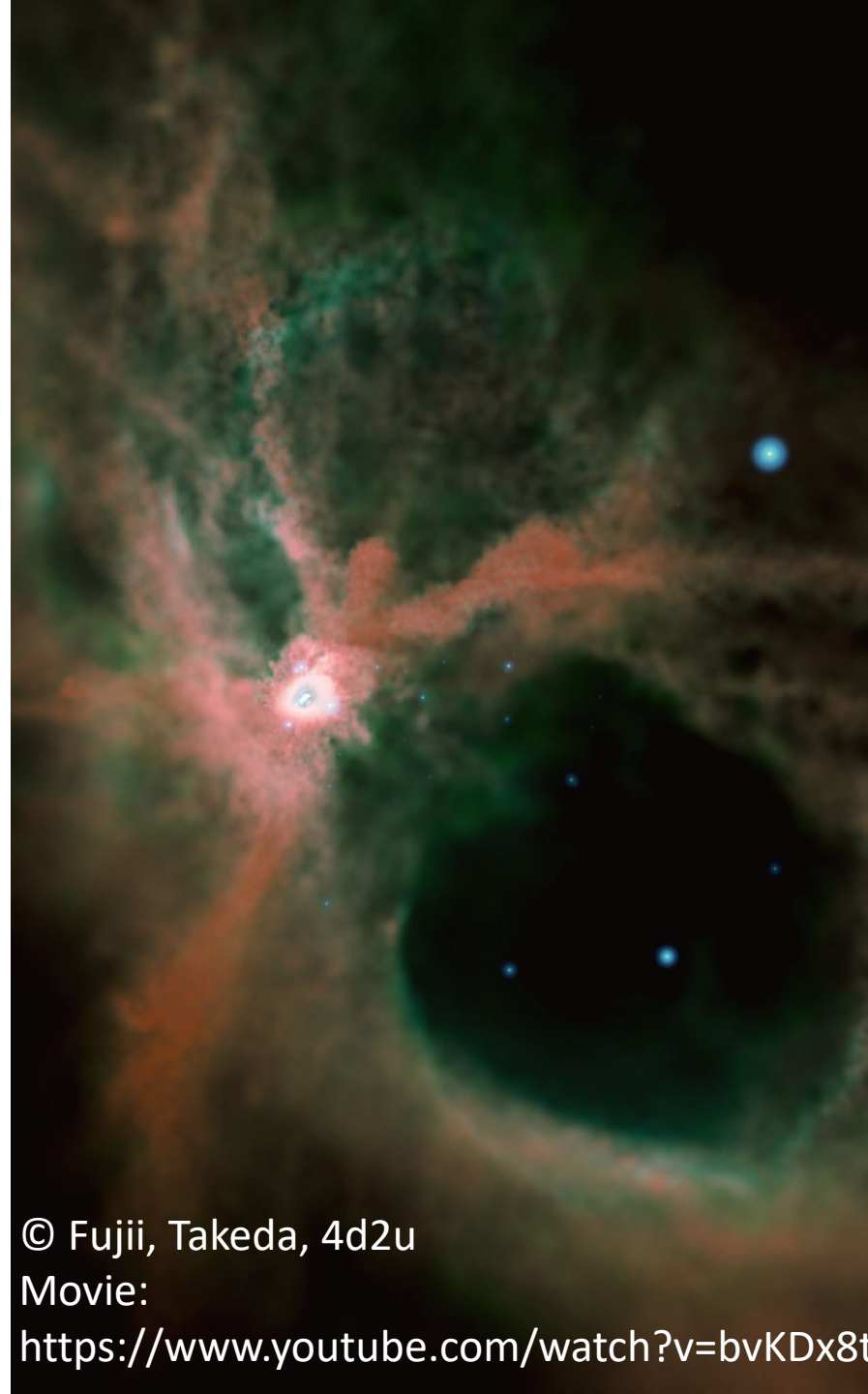
ASURA+BRIDGE code

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)

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

- 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

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Movie:
https://www.youtube.com/watch?v=bvKDx8t
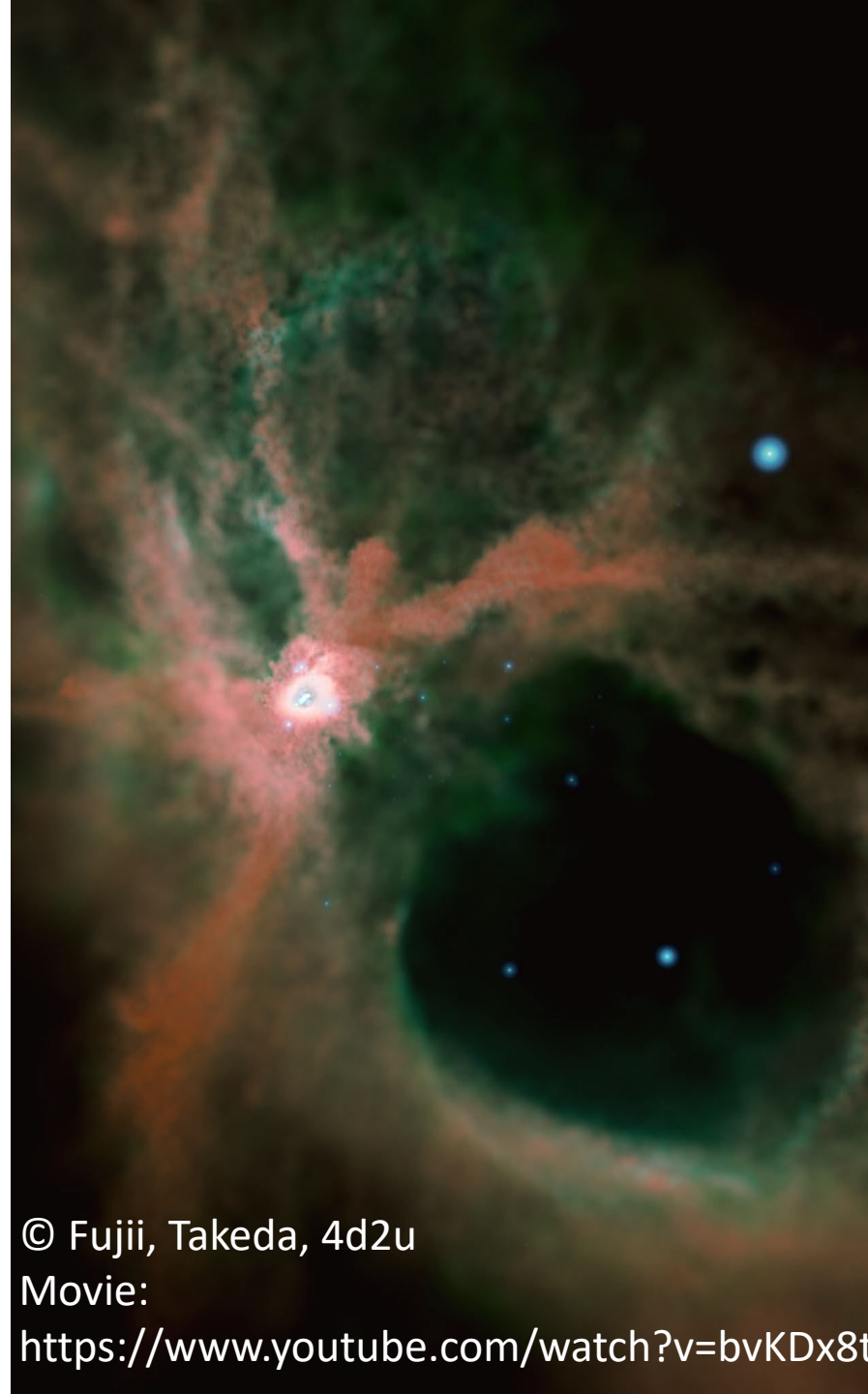
Initial conditions and parameters

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

Star cluster formation

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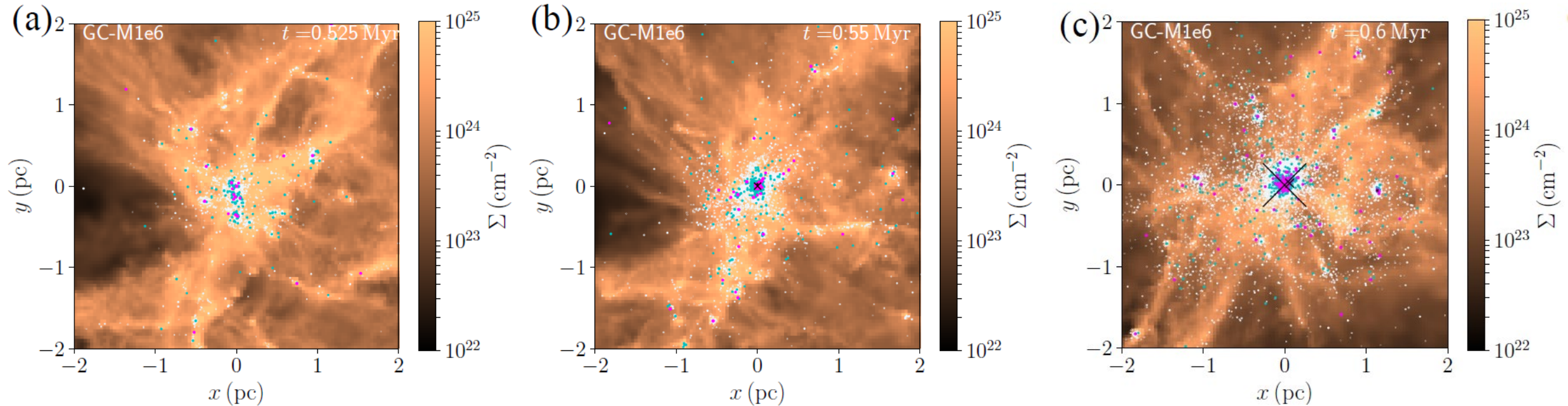
- Star formation starts at around the initial free-fall time
- This cluster mass exceeded 10^5 Msun
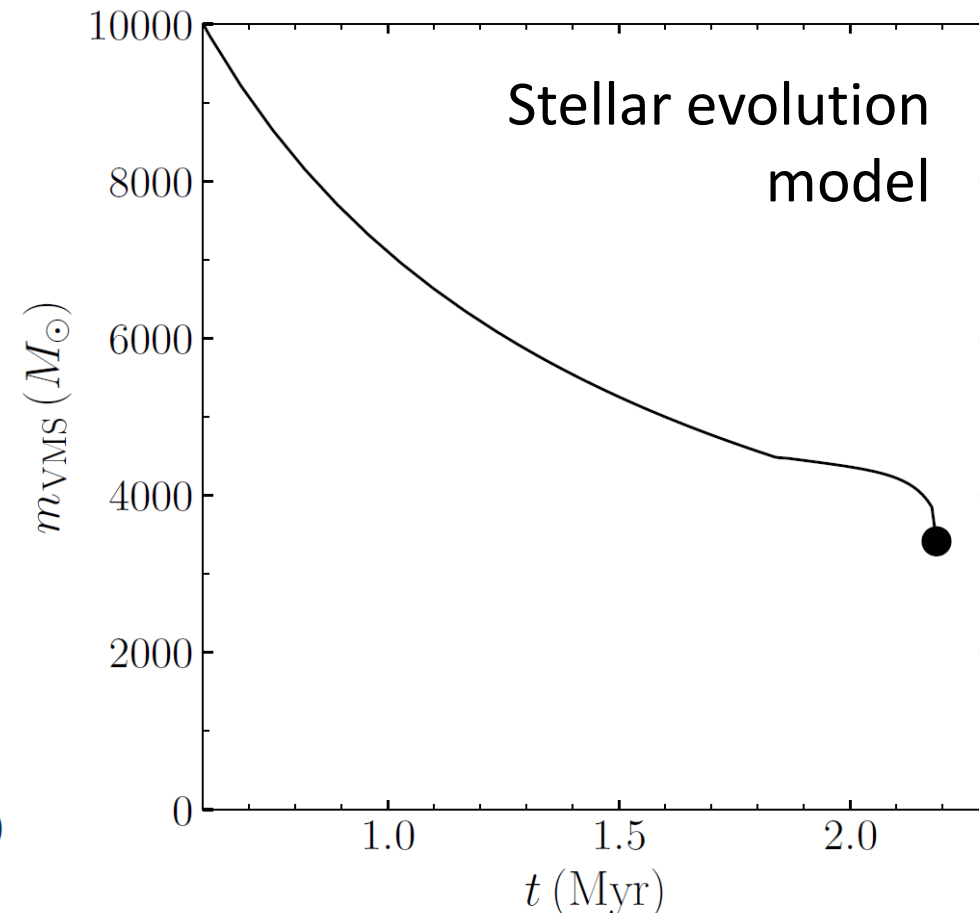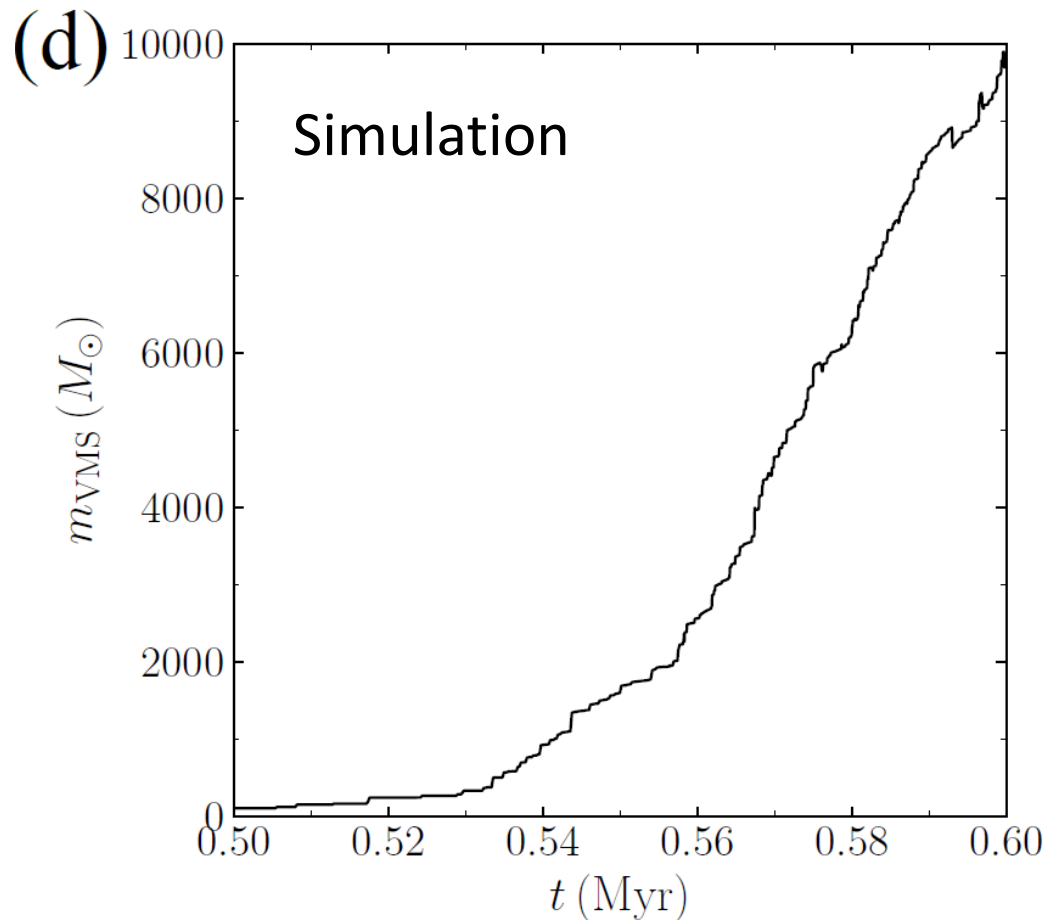 (the most massive star-by-star cluster formation simulation)

Density distribution
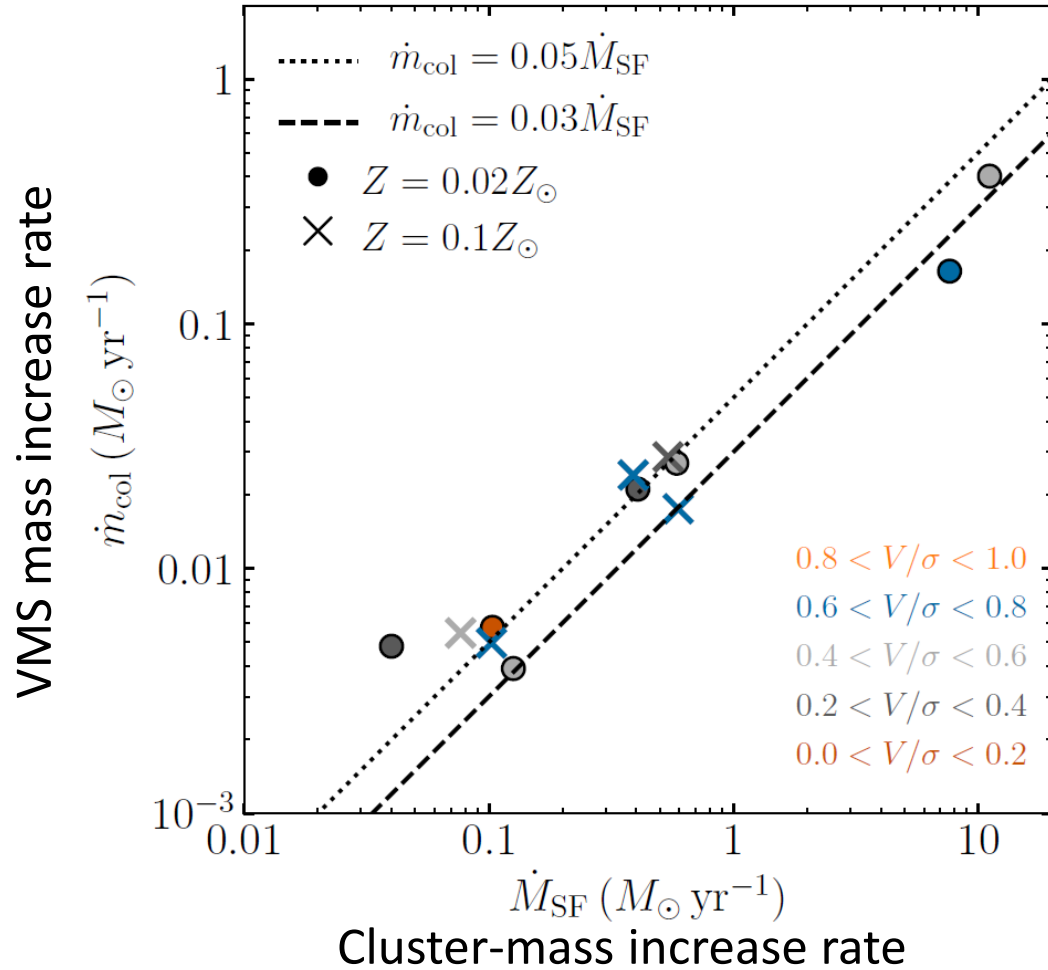
- Extremely high density is realized
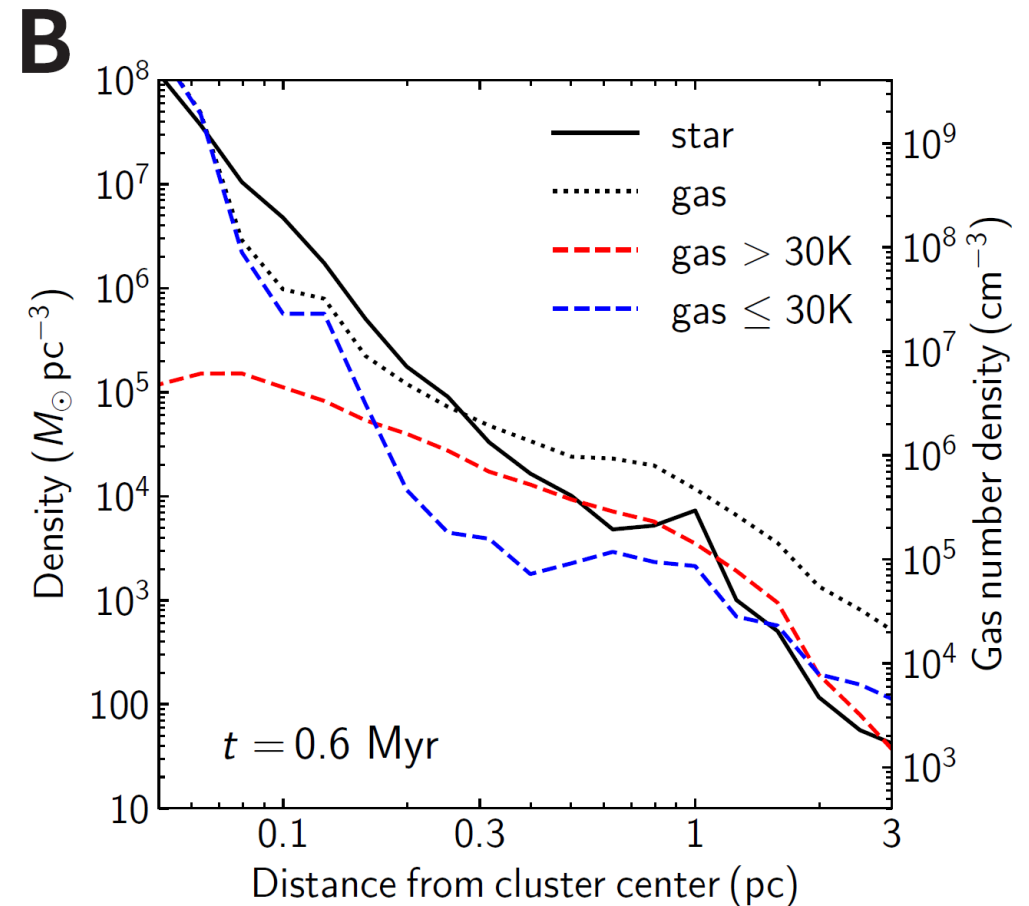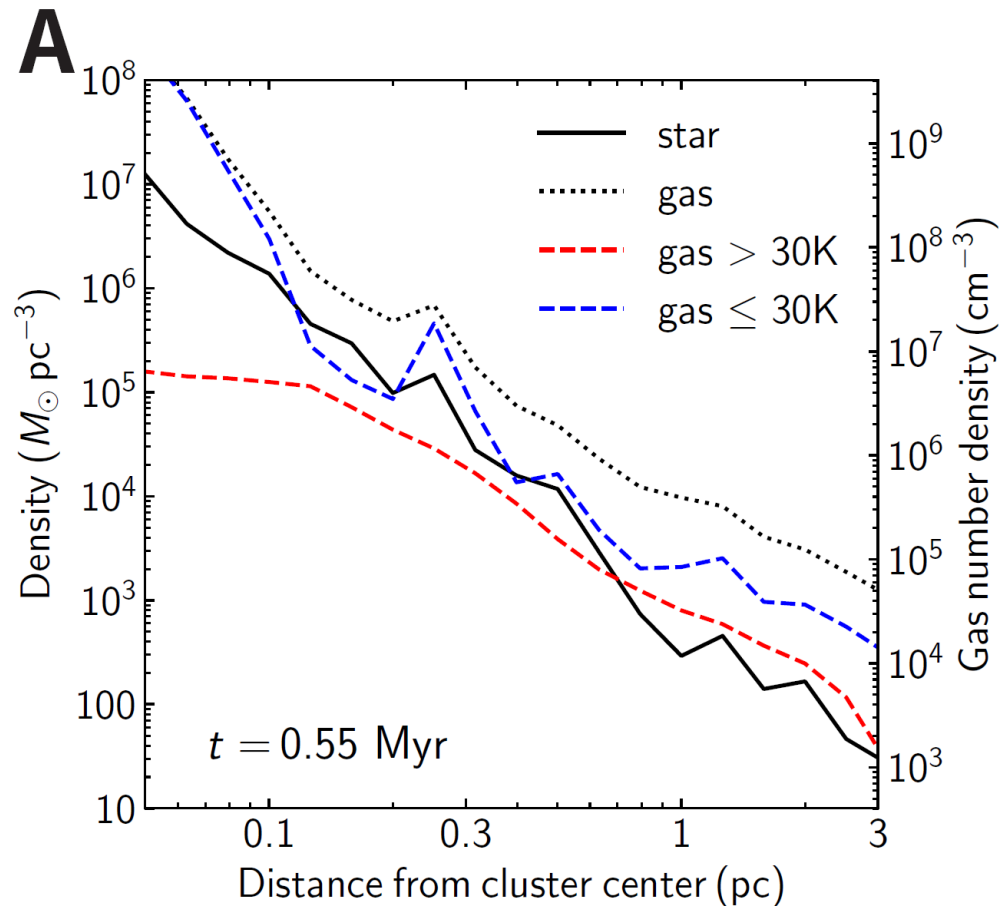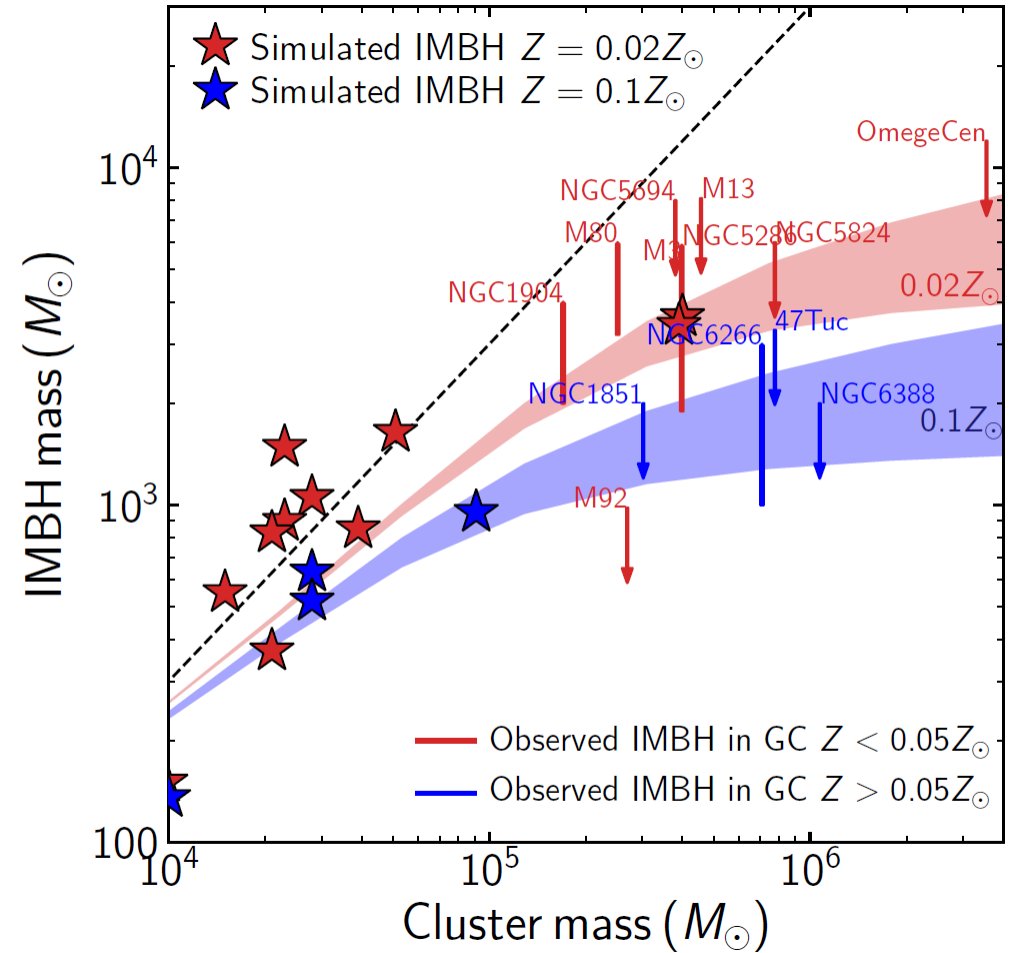
Runaway collision

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

Cluster-IMBH mass

- 3-5% of cluster mass goes to VMS

- ~10^4 Msun IMBH would be the upper limit

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 is 3-5 % of cluster-mass increase rate
- These VMSs will collapse to IMBH with >1000 Msun