Stellar Archaeology as a Time Machine to the First Stars
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Growth of intermediate mass black holes in the first star clusters

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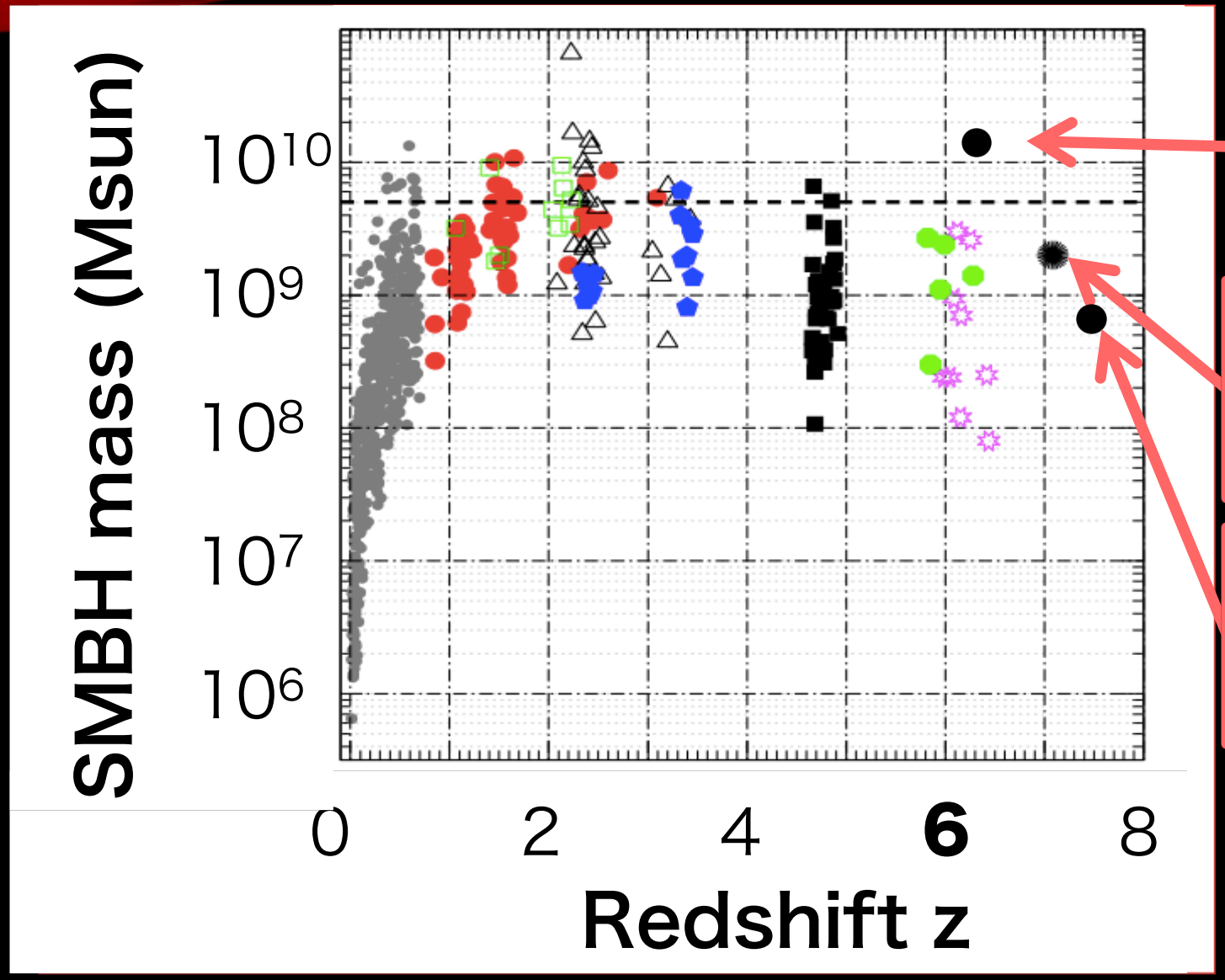
N. Yoshida (U. Tokyo), M. S. Fujii (U. Tokyo)

arXiv: 1810.01985

Observations of SMBHs in the early universe



~1.2×10^{10} Msun
Wu et al. (2015)

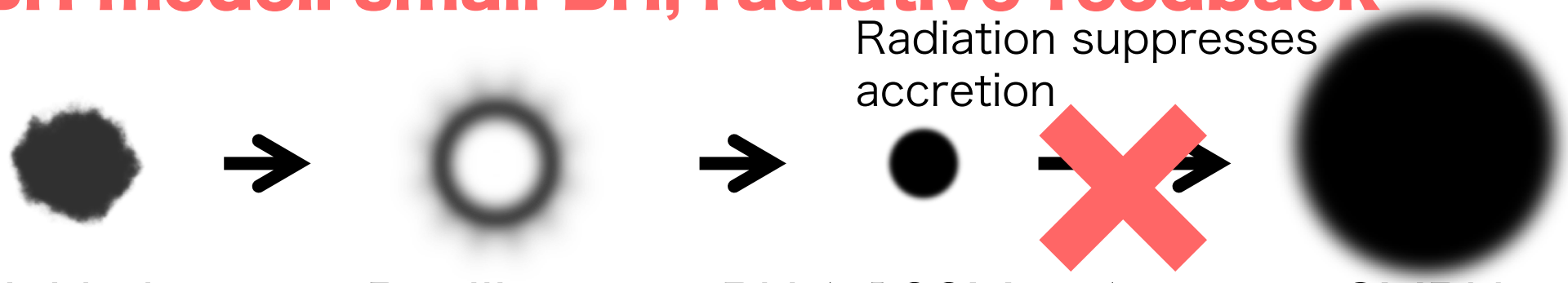
~2×10^{9} Msun
Mortlock et al. (2011)

~8×10^{8} Msun
Bañados et al. (2017)

Marziani & Sulentic (2012)

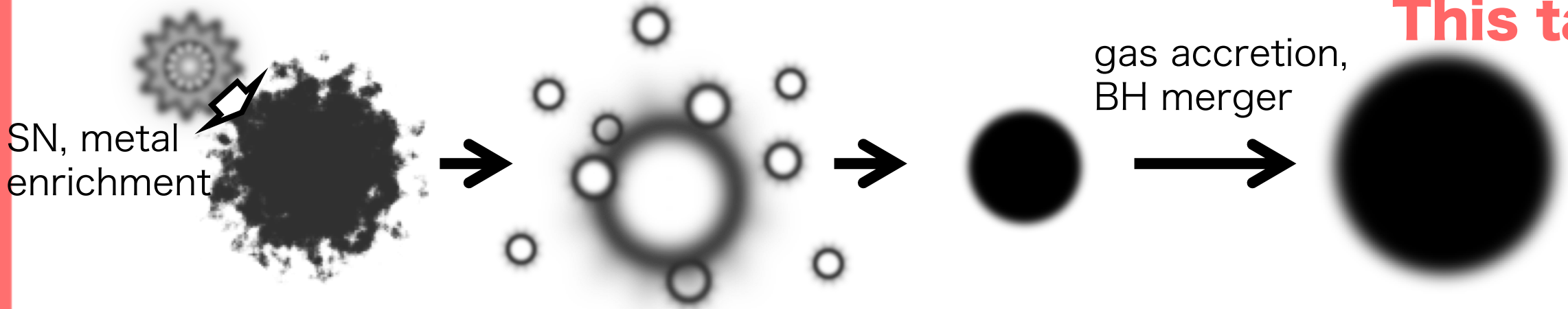
Runaway stellar collision model

Pop III BH model: small BH, radiative feedback

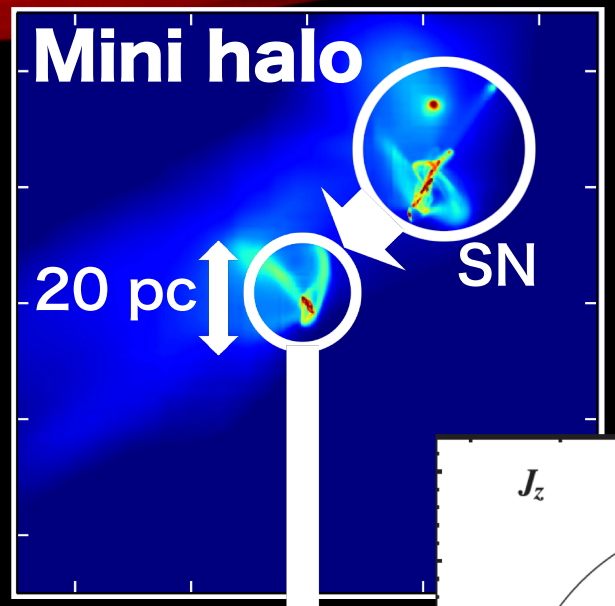


Runaway stellar collision (RC) model: large BH

This talk

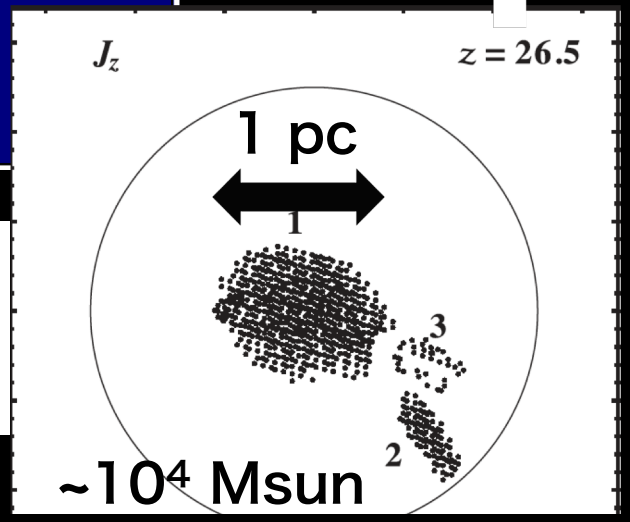


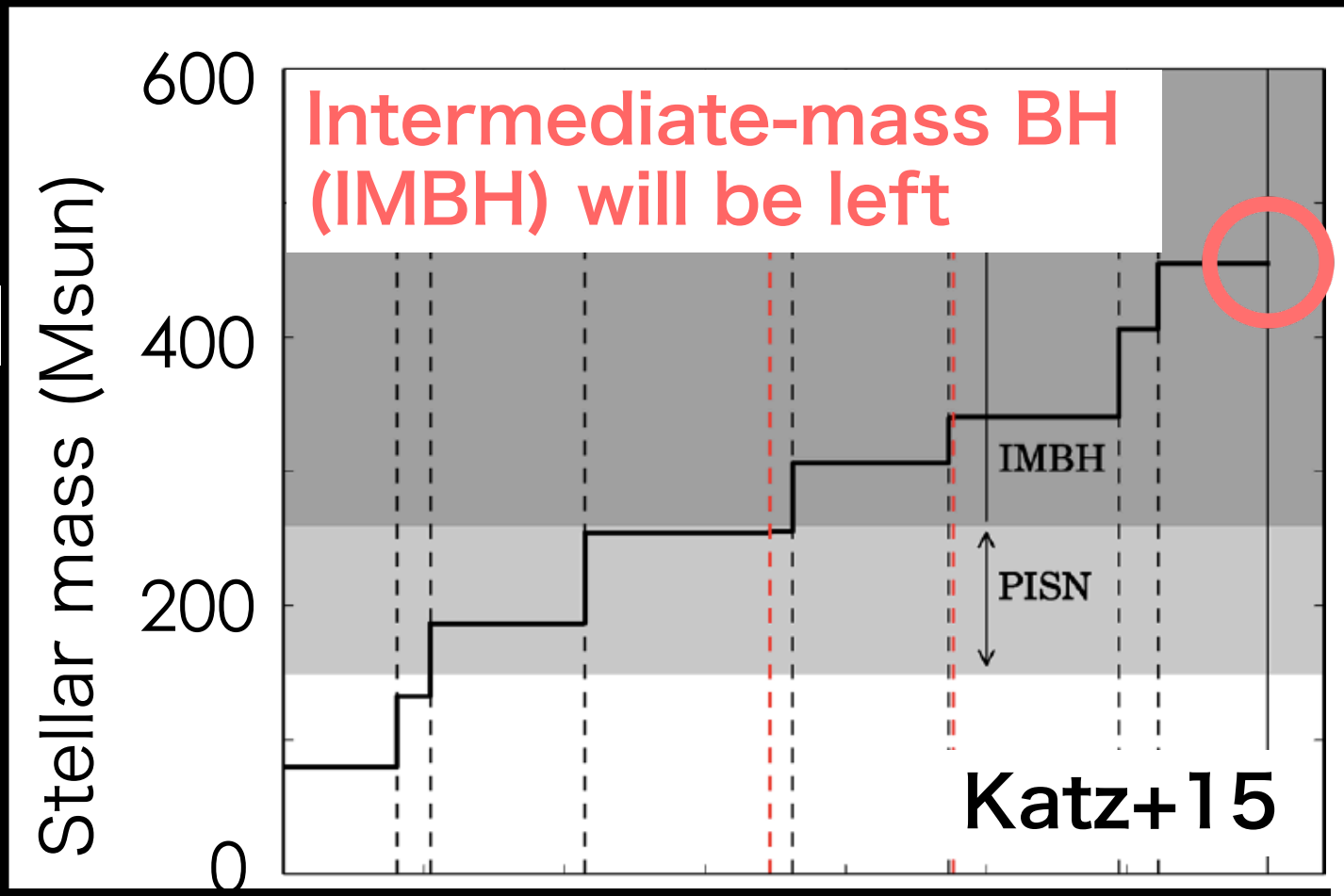
Runaway collision in primordial star clusters



star cluster (SC) formation (assumption)

N-body sim.



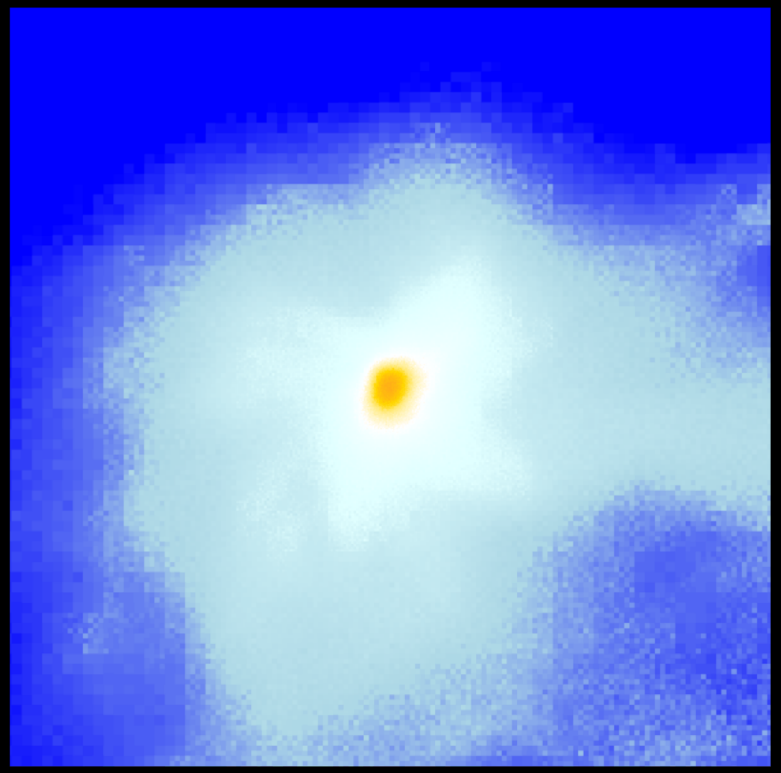


Motivation: Does RC also occur in atomic-cooling (AC) halos to form IMBH?

Previous work (Sakurai et al. 2017)

Cosmological sim.
(AC halo identification)

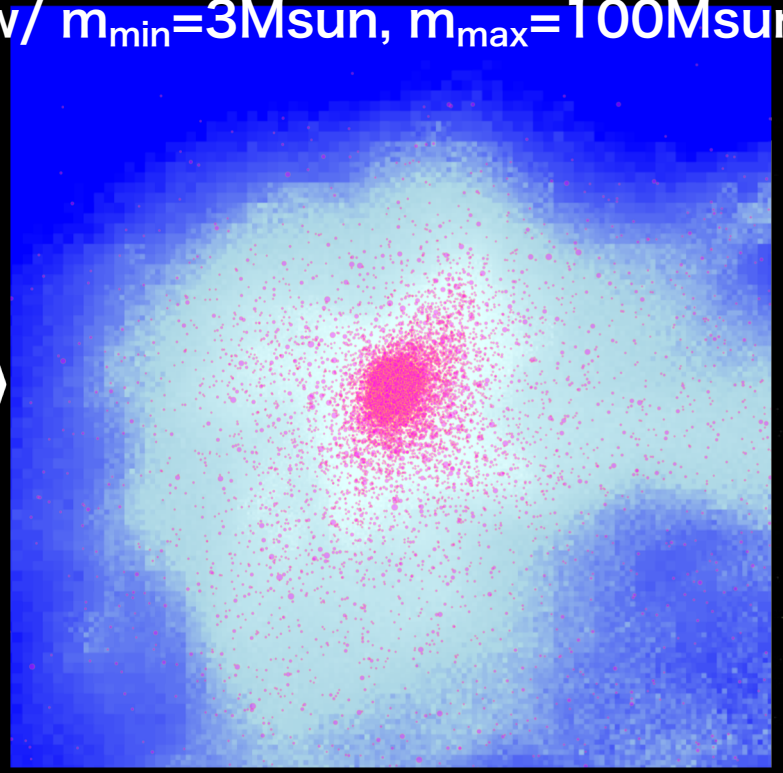
Gadget-2, 8AC halos



20 pc

Generation of SCs

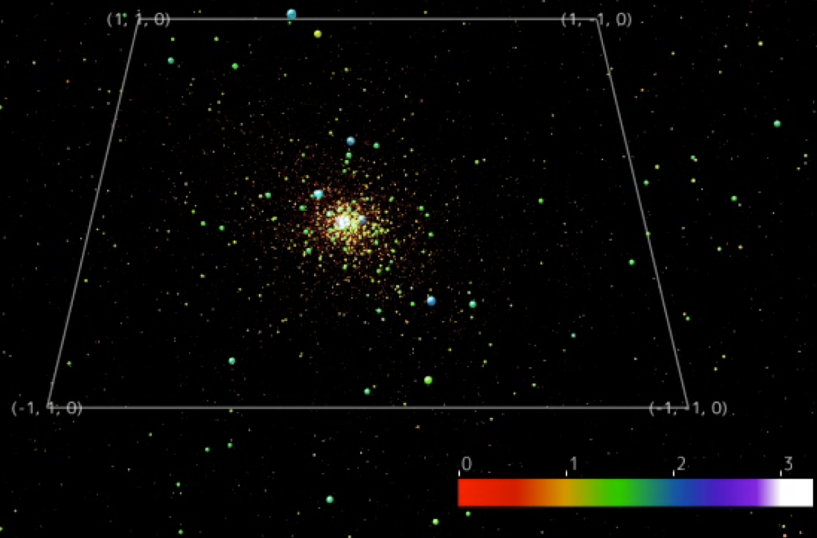
Salpeter IMF
w/ m_{min}=3Msun, m_{max}=100Msun



N-body sim.

BRIDGE code, 3 Myr

Star + DM



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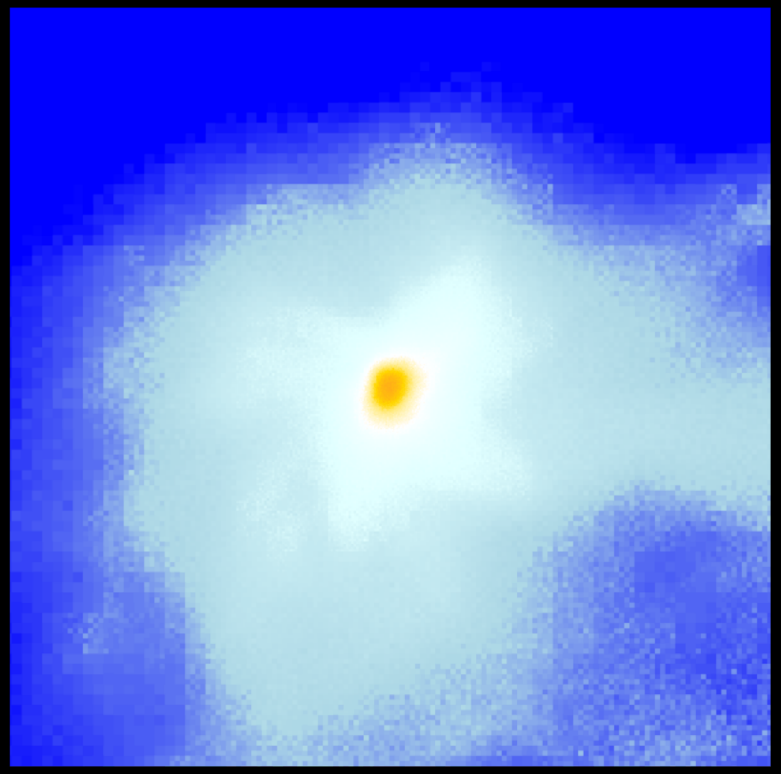


20 pc

Generation of SCs

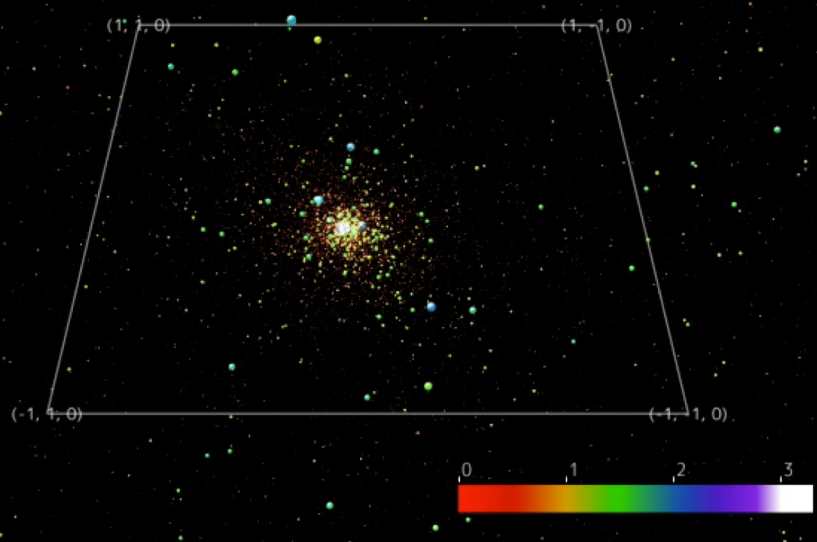
Salpeter IMF
w/ m_{min}=3Msun, m_{max}=100Msun

	$\overline{M}_{cl}$ (10^4 $M_\odot$)	$\overline{N}$ (10^3)
A	16.4	19.9
B	13.0	15.7
C	12.1	14.7
D	11.7	14.1
E	4.76	5.76
F	9.00	10.8
G	12.5	15.0
H	7.70	9.32

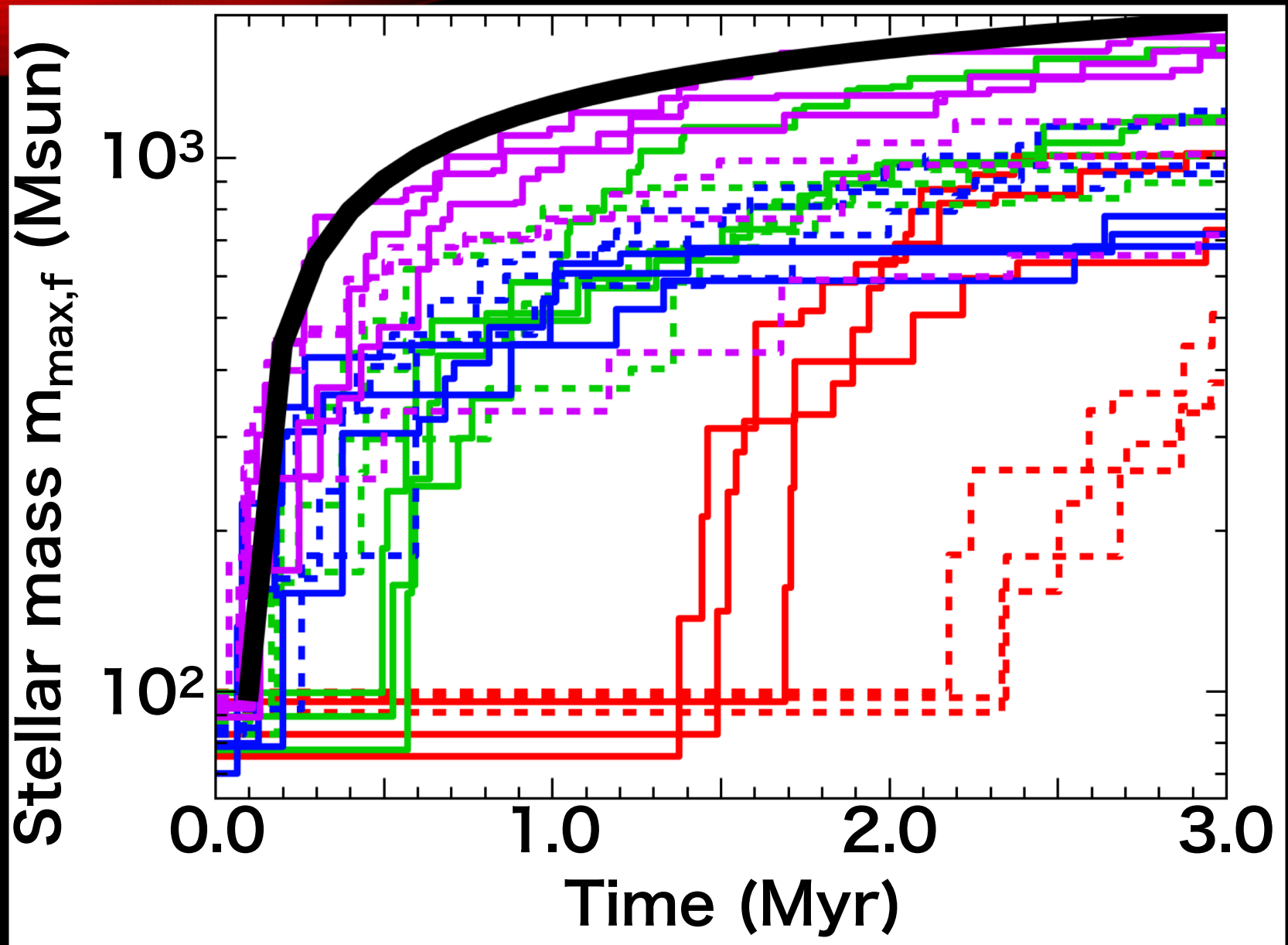
N-body sim.

BRIDGE code, 3 Myr

Star + DM



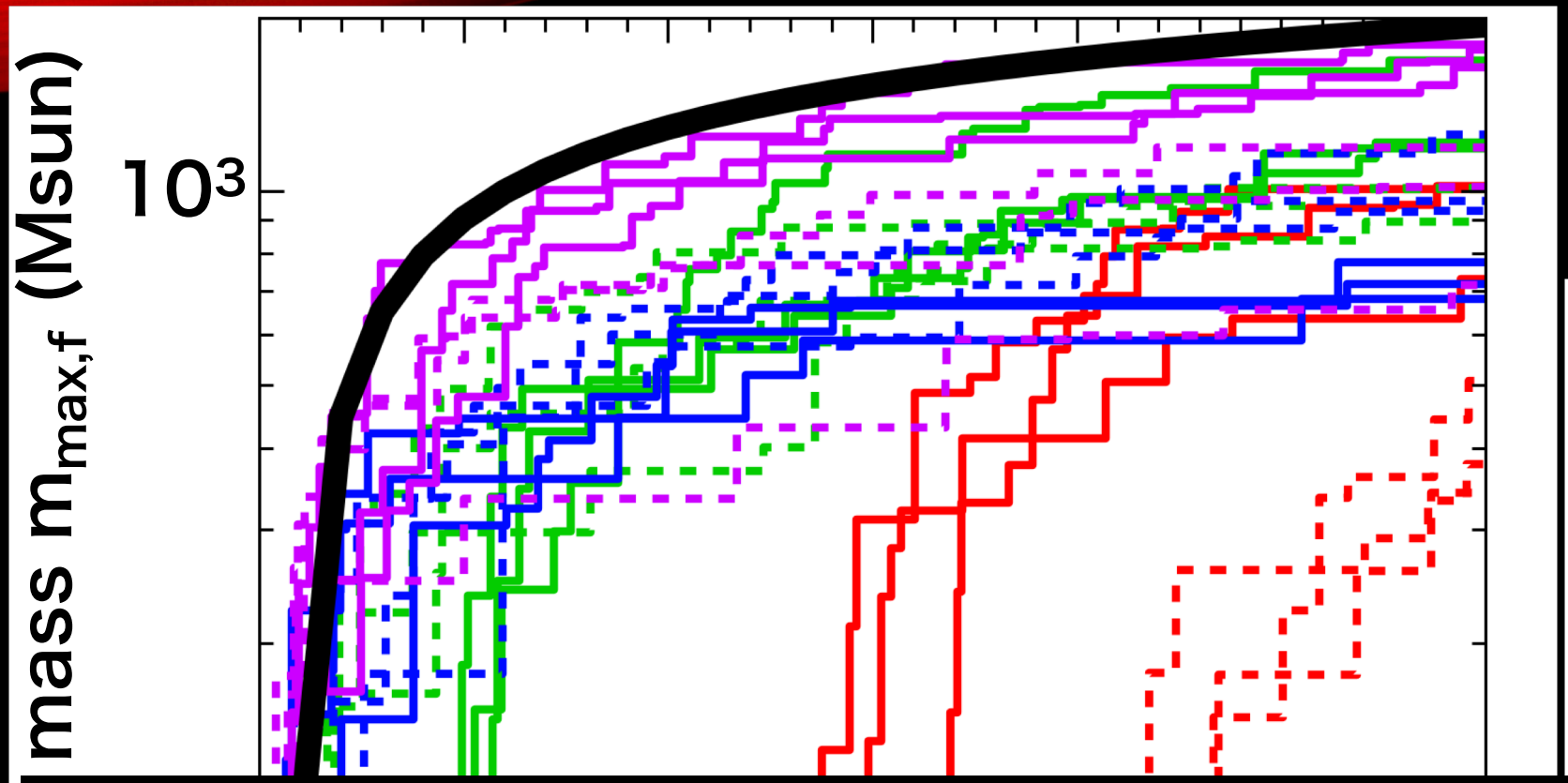
RC and IMBH formation occur (Sakurai+17)



RC in all SCs
~ 400-1900 Msun
→collapse to IMBH

	$\overline{m}_{\rm max,f}$ ($M_\odot$)	$\overline{N}_{\rm coll}$
A	929	11.7
B	409	4.67
C	1330	18.3
D	971	13.7
E	773	9.67
F	1100	14.0
G	1660	25.0
H	964	15.0

RC and IMBH formation occur (Sakurai+17)



RC in all SCs
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	$\overline{m}_{\rm max,f}$ ($M_\odot$)	$\overline{N}_{\rm coll}$
A	929	11.7
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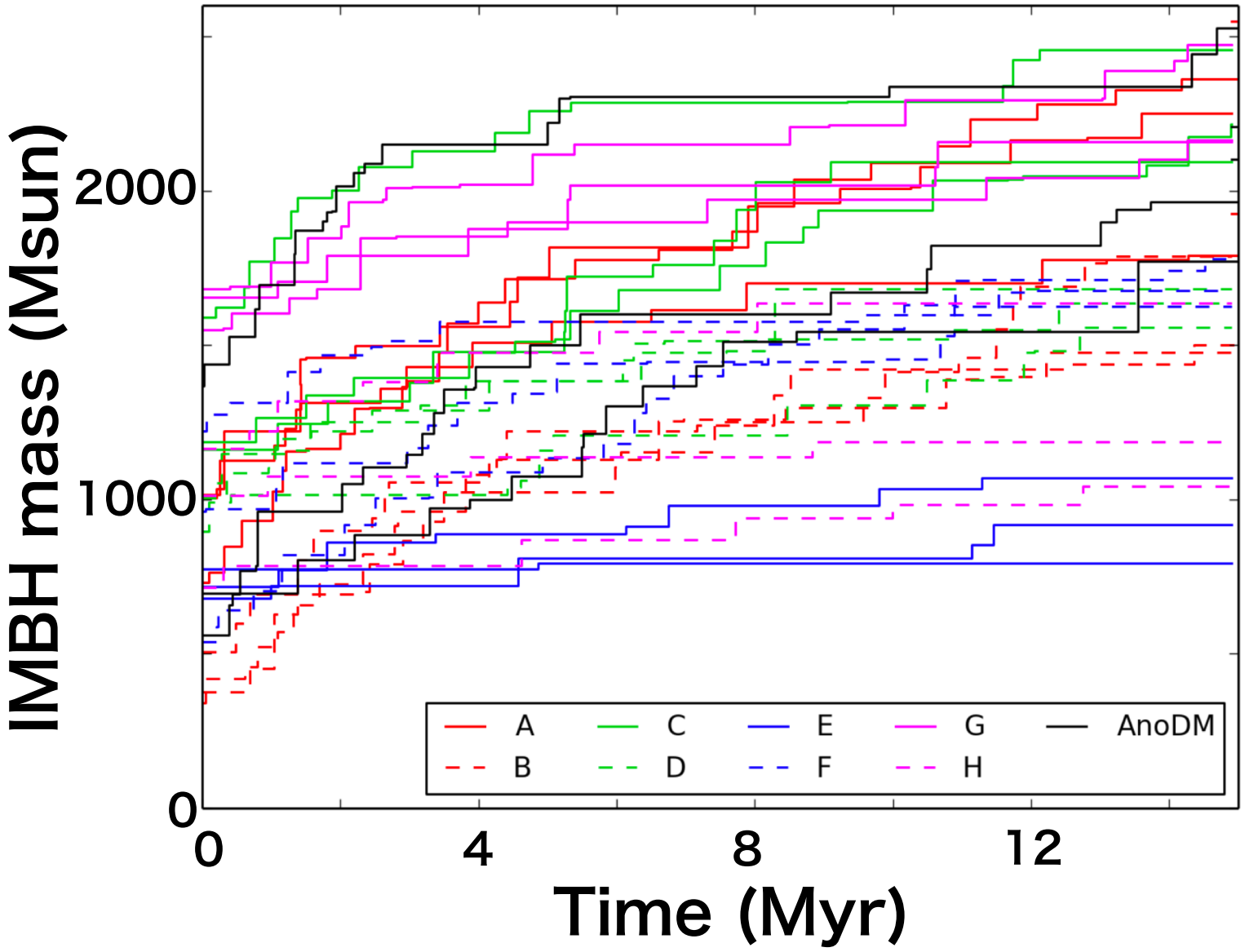
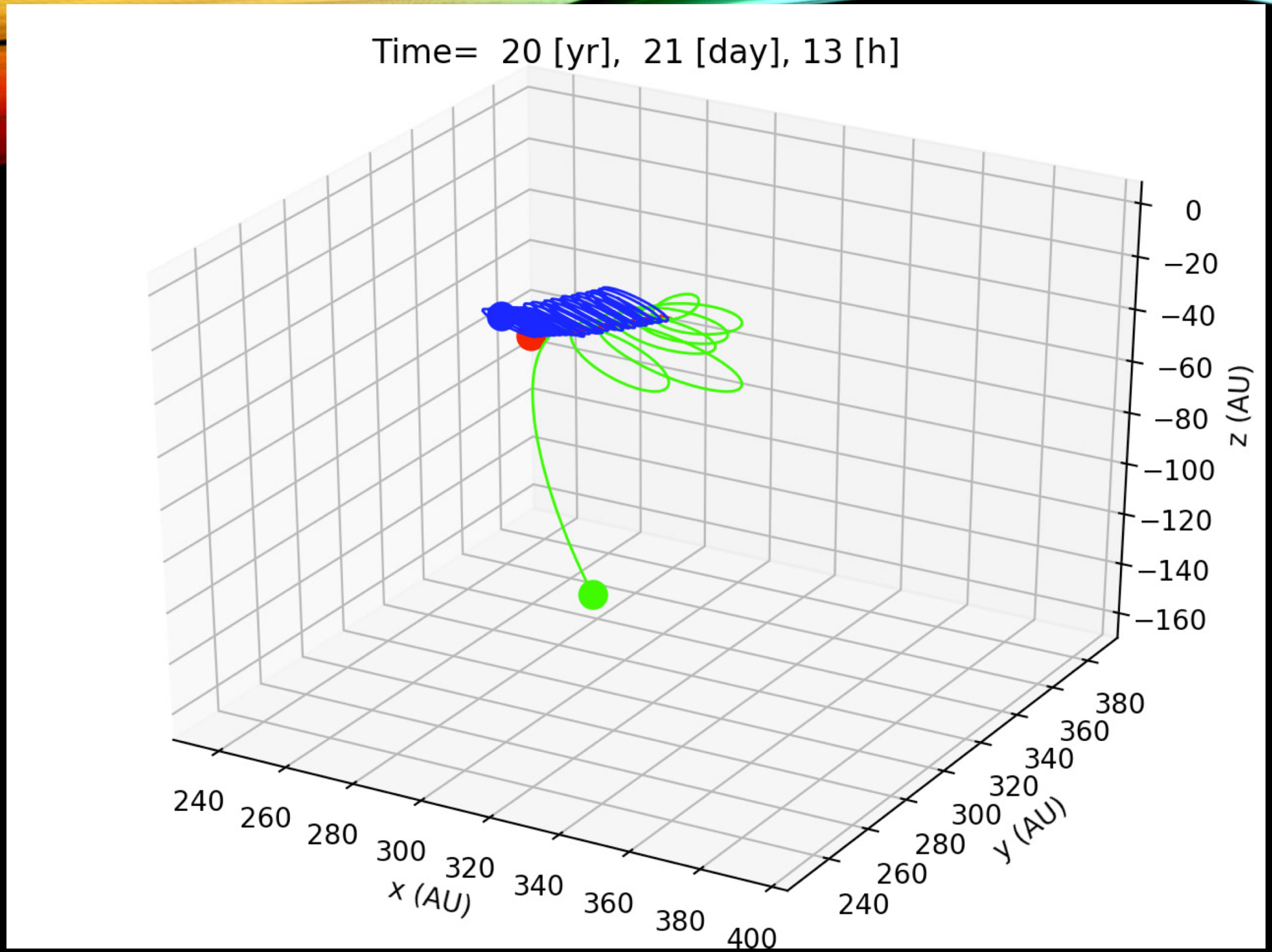
C	1330	18.3
D	971	13.7

- We further follow the later evolutions for 15 Myr after IMBH formation
- IMBH growth would proceed by tidal disruption events (TDEs) of infalling stars

BH growth is moderate (as expected)

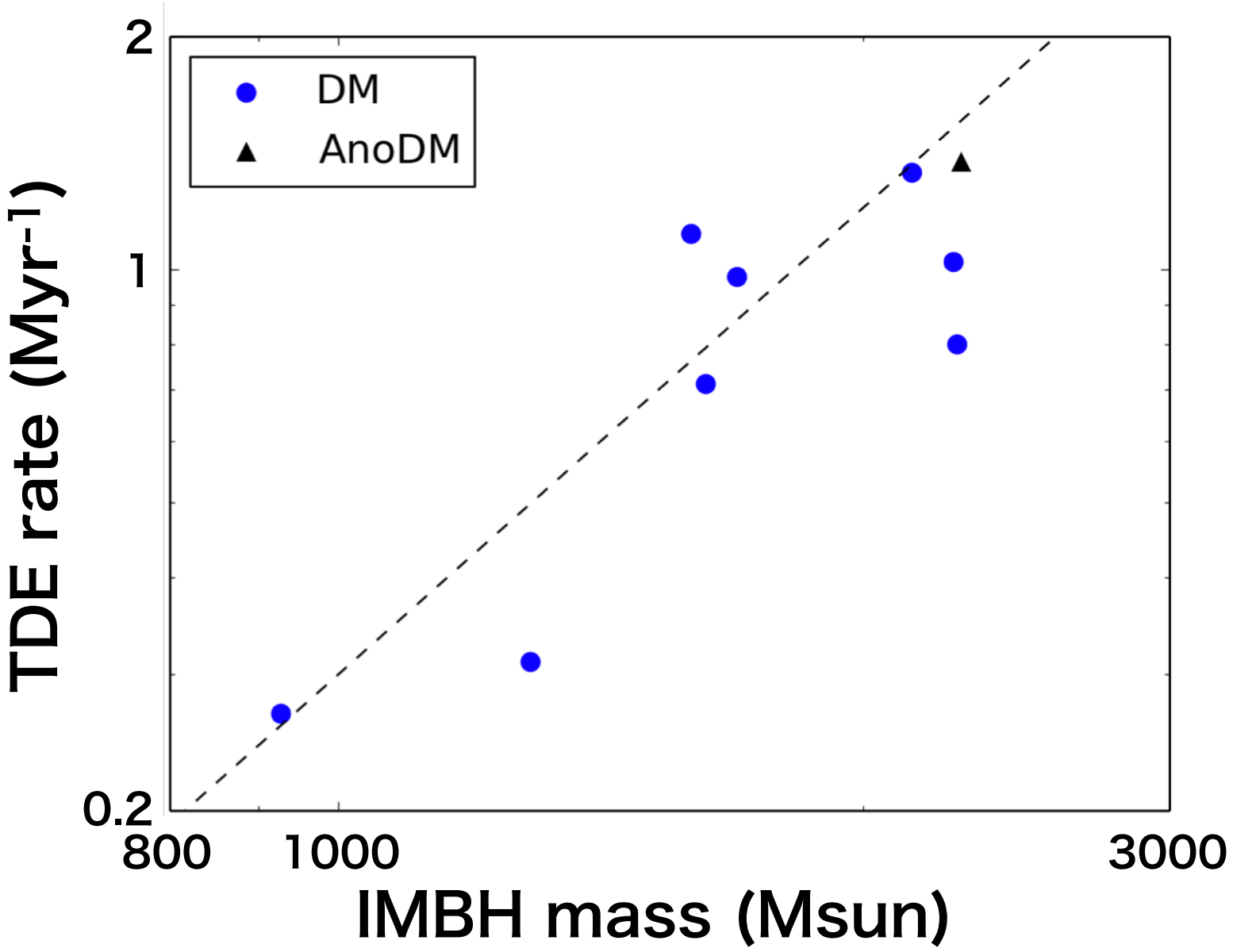


Model	$M_{\mathrm{IMBH,f}}$ ($\mathrm{M}_\odot$)
A	2134
B	1594
C	2255
D	1625
E	927
F	1694
G	2266
H	1289
AnoDM	2087


Time= 20 [yr], 21 [day], 13 [h]
0
−20
−40
−60
−80
−100
−120
−140
−160
z (AU)
240
260
280
300
320
340
360
380
400
x (AU)
240
260
280
300
320
340
360
380
y (AU)

TDE rate

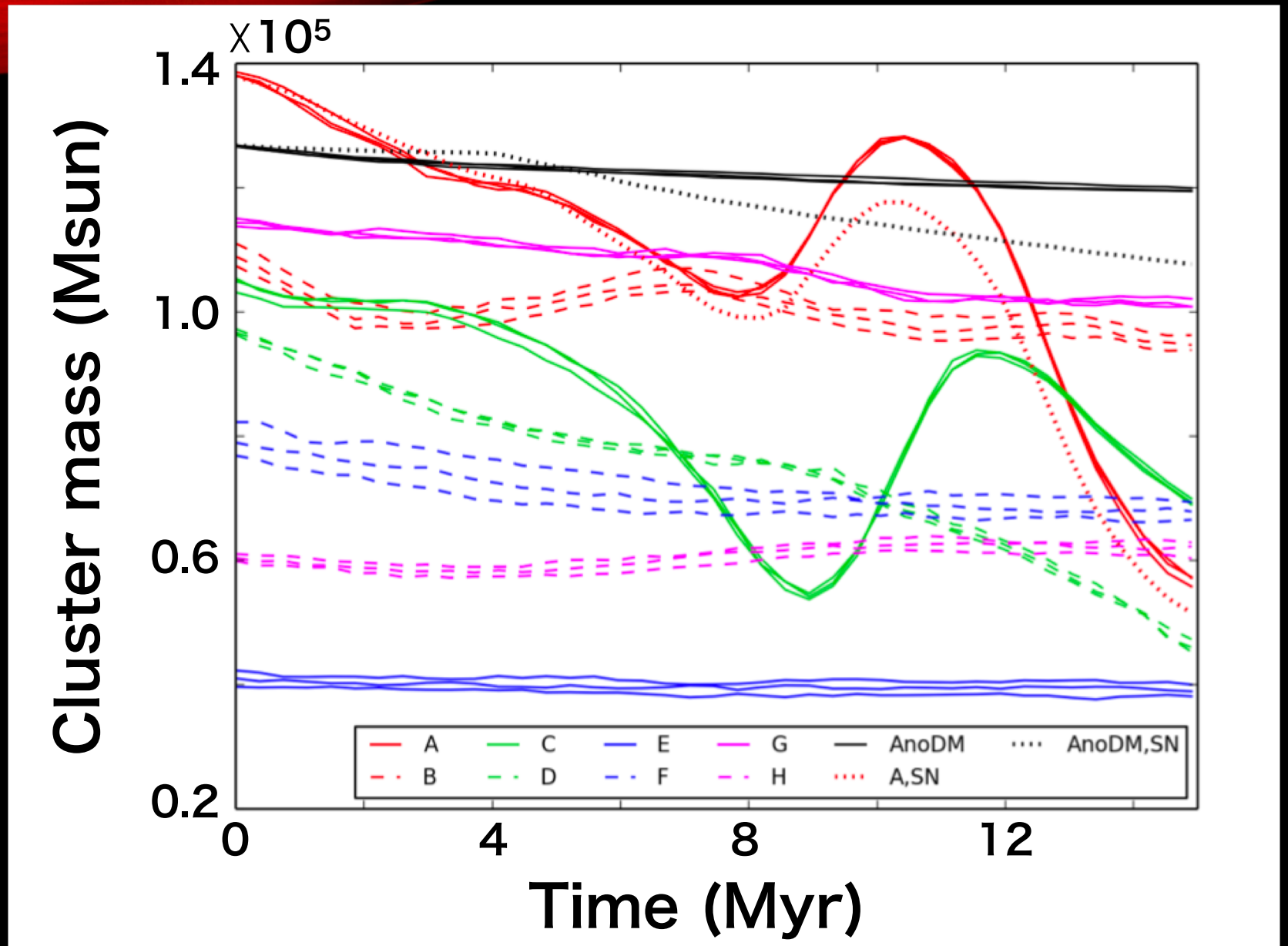
$$\dot{N}_{\rm TDE} \sim 0.3\,{\rm Myr}^{-1} \left(\frac{M_{\rm IMBH,f}}{1000\,{\rm M}_\odot} \right)^2$$



Baumgardt, Makino & Ebisuzaki (2004)

Model	$\dot{N}_{\rm TDE}$ ($\rm Myr^{-1}$)
A	1.33
B	1.11
C	1.02
D	0.711
E	0.267
F	0.978
G	0.800
H	0.311
AnoDM	1.18

DM motion enhances cluster evaporation

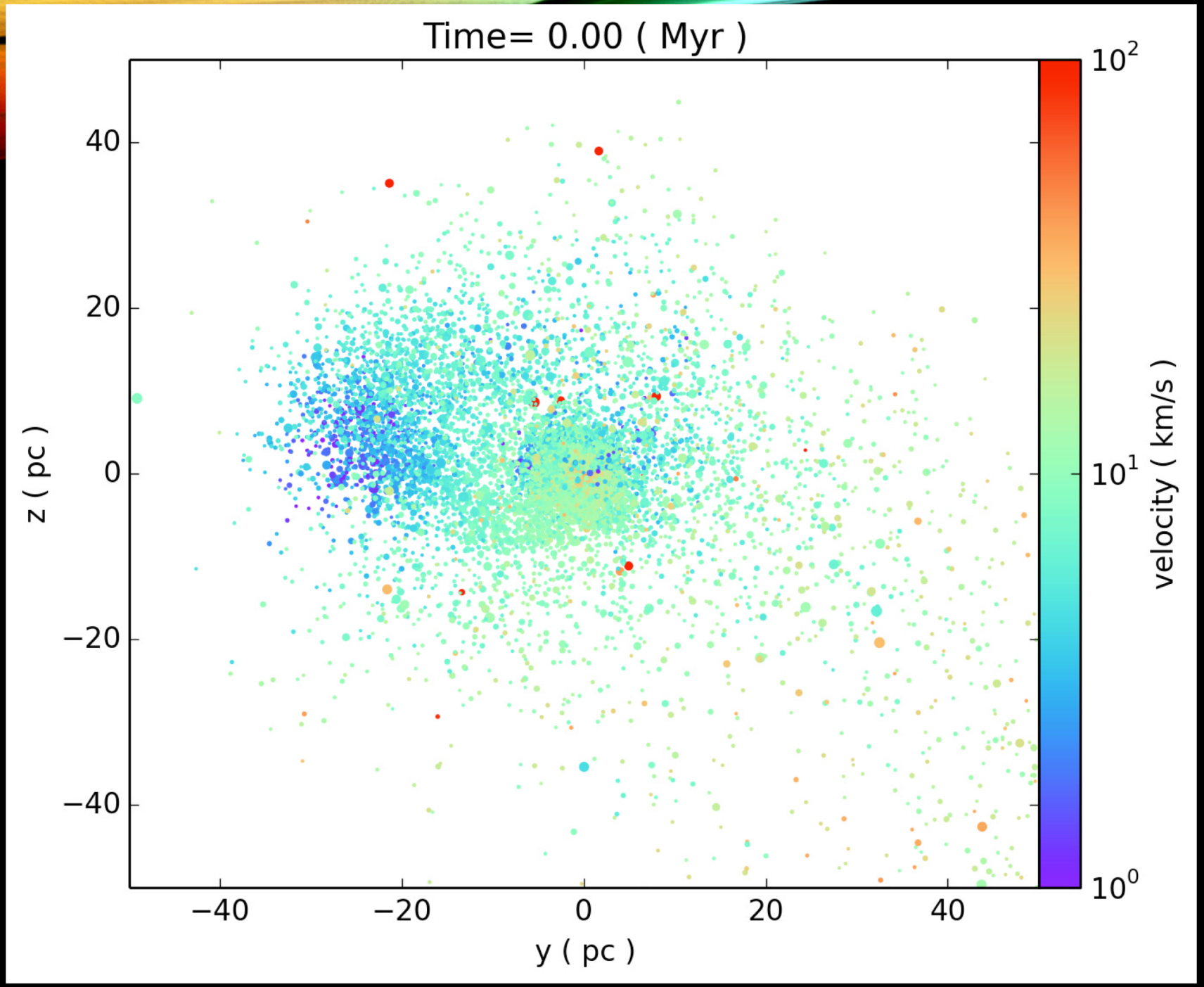


When cluster mass decreases...

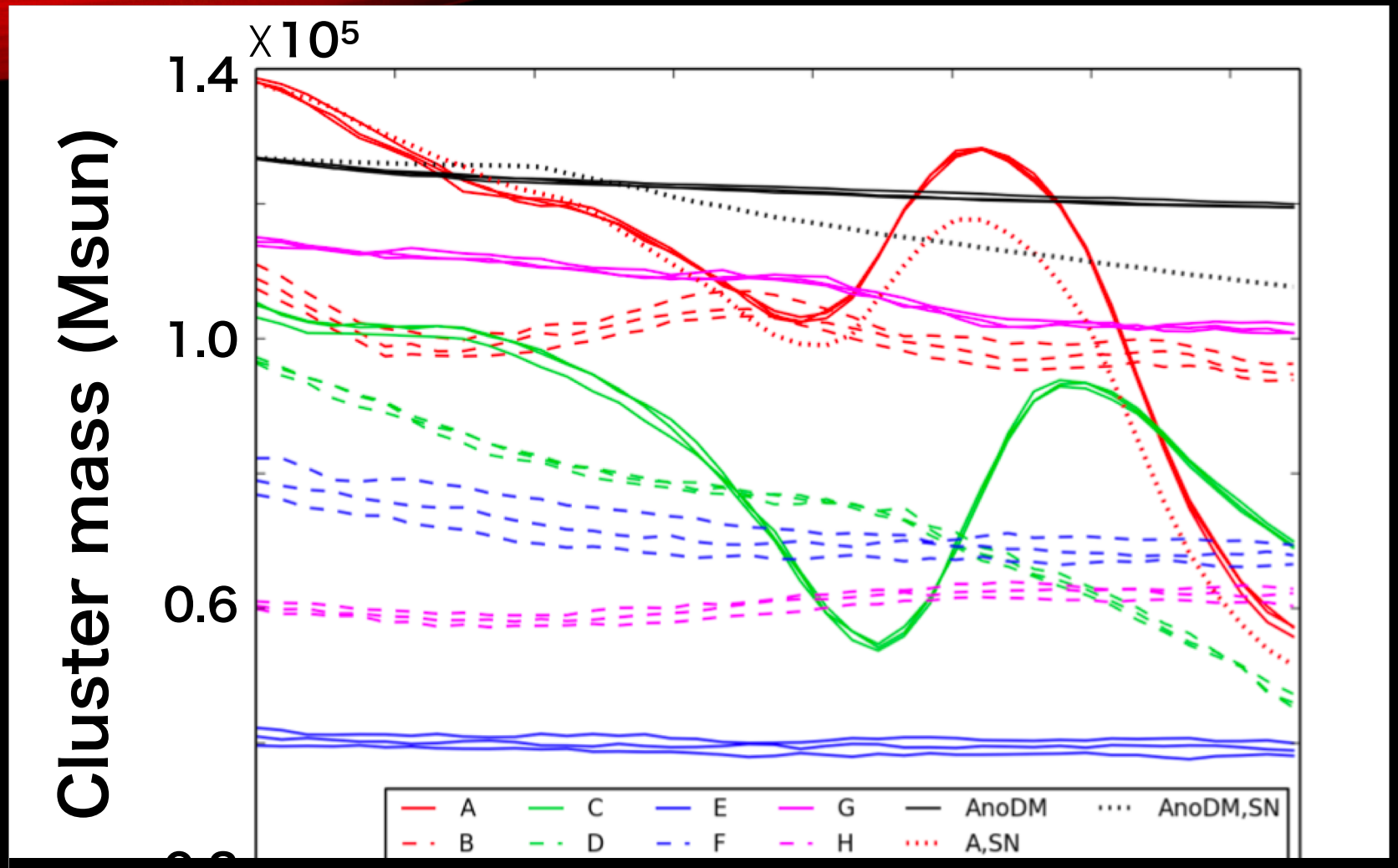
DM mass increases in central regions

Stars in outer regions of clusters are accelerated

Stars become unbound from the clusters


Time= 0.00 (Myr)
40
20
0
−20
−40
z (pc)
−40
−20
0
20
40
y (pc)
10^2
10^1
10^0
velocity (km/s)

DM motion enhances cluster evaporation



When cluster mass decreases...

DM mass increases in central regions

Stars in outer regions of clusters are accelerated

Stars become unbound from the

When the clusters evaporate, the IMBHs can no longer increase their mass by TDEs

Conclusion

- We follow star cluster evolutions after IMBH formation

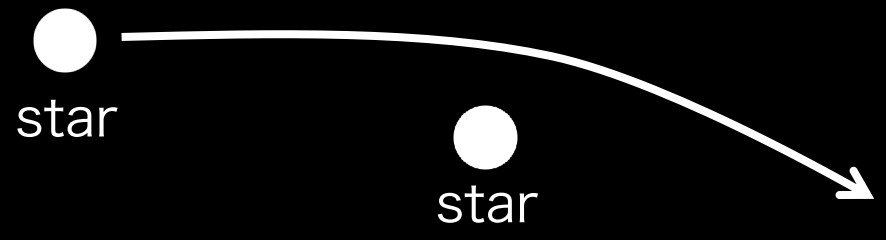
- **IMBHs grow moderately to ~700-2500 Msun**
- **TDE rate ~ 0.3 Myr^{-1} $(M_{IMBH}/1000\ Msun)^2$**
- **DM motion enhances star cluster evaporation**

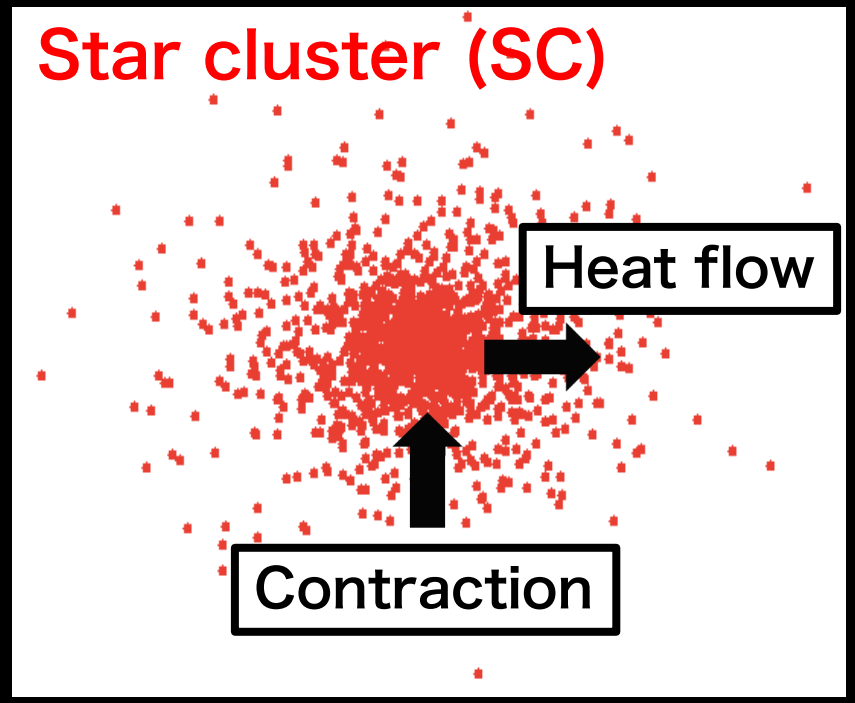
- Possible fates of the IMBHs
  - IMBHs may grow if a large amount of gas is supplied through, e.g, galaxy mergers or large gas accretion
  - IMBHs may remain in the present-day universe

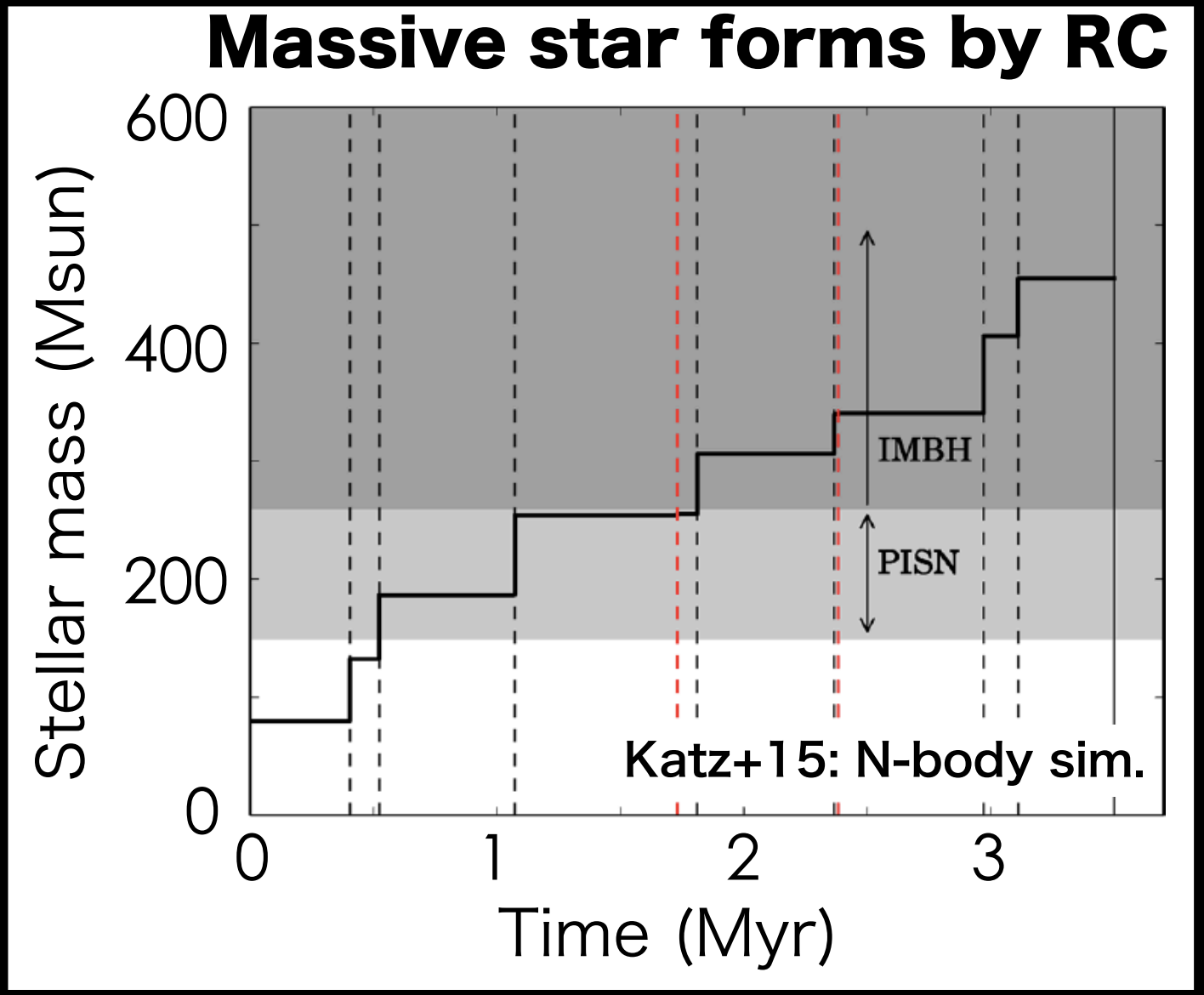
Two-body relaxation and runaway collision (RC)

Two-body relaxation:

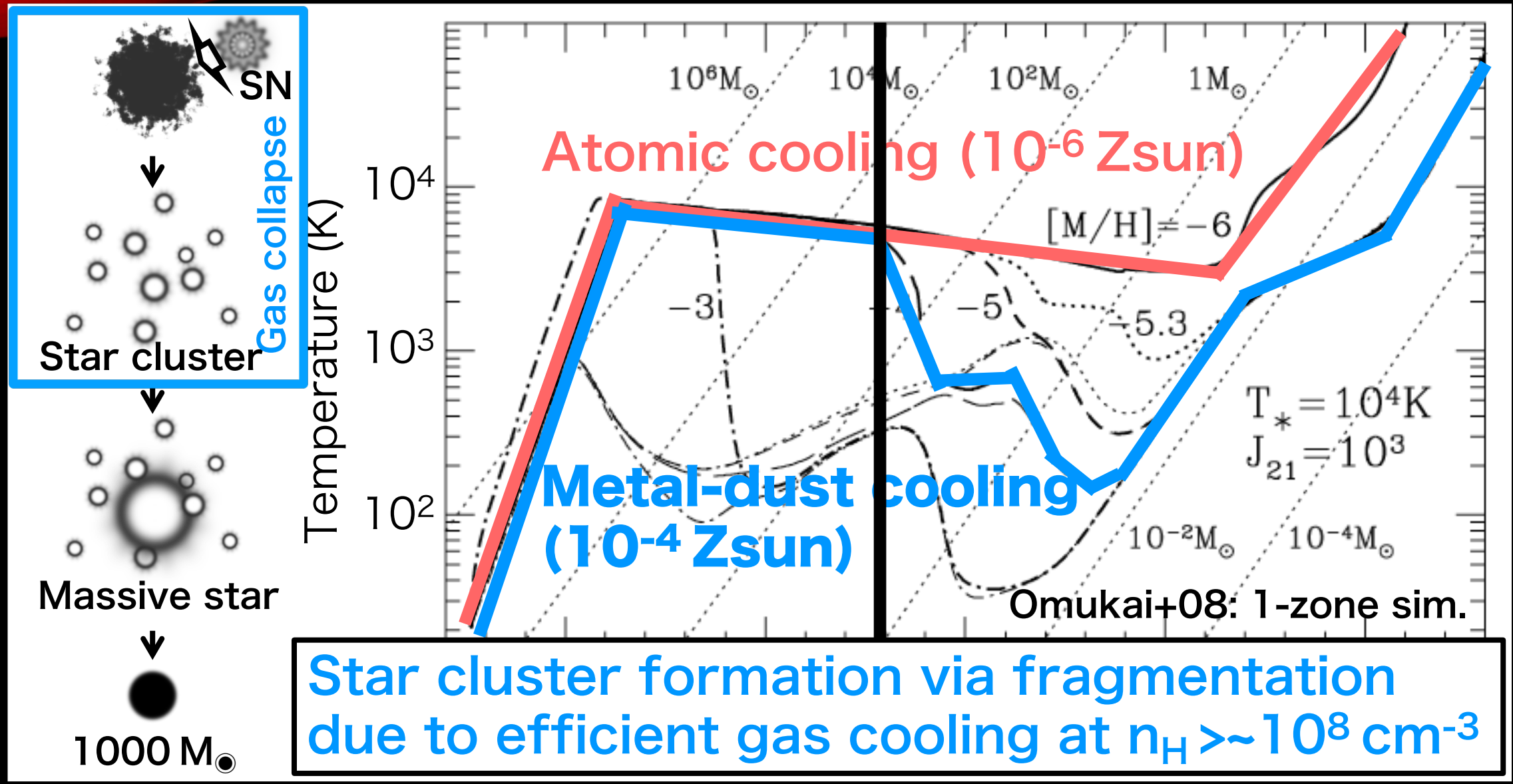
Kinetic energy (heat) transport







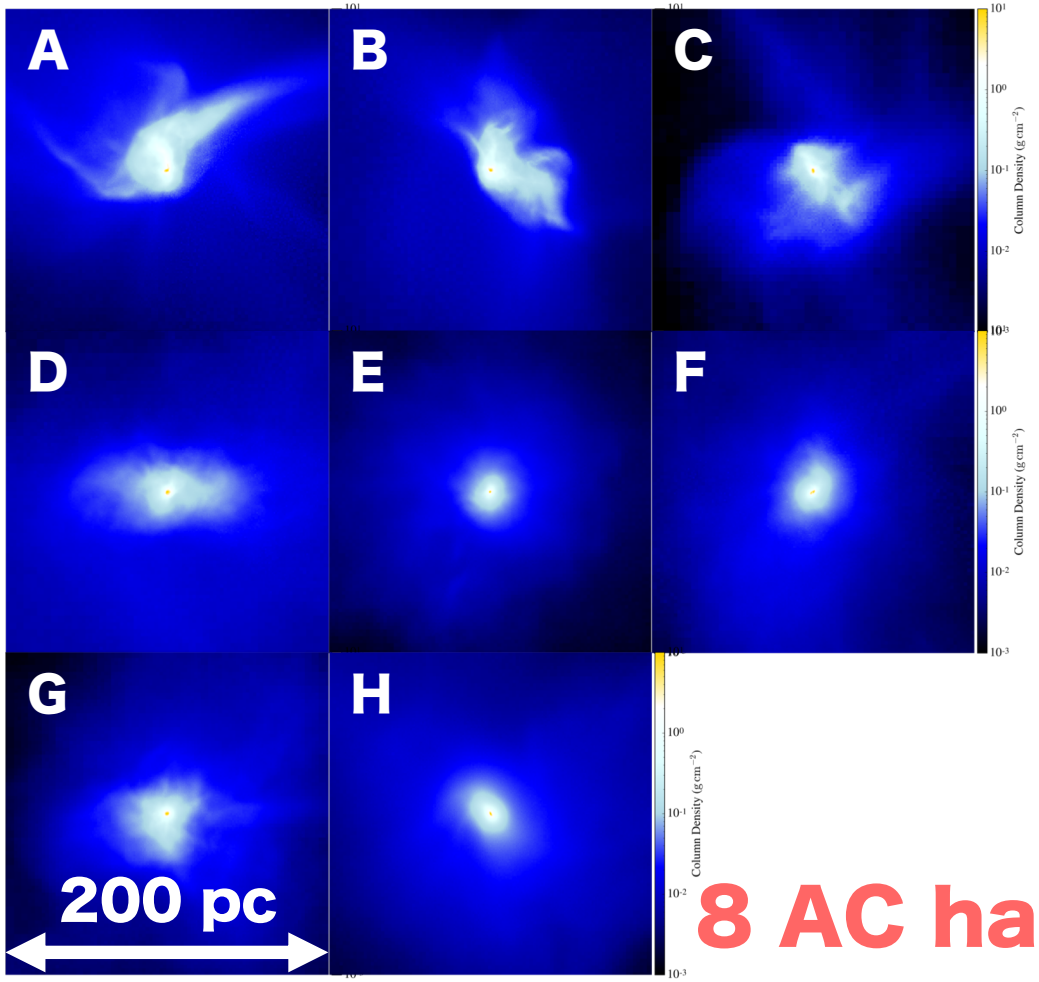
Primordial star cluster formation



Star cluster formation via fragmentation due to efficient gas cooling at $n_H >\sim 10^8\ cm^{-3}$

Cosmological SPH simulations (by S. Hirano)

- Code: Gadget-2 (Springel 2005, version in Hirano et al. 2014)
- IC: MUSIC software (Hahn & Abel11), z=99, box size=$10h^{-1}$ Mpc



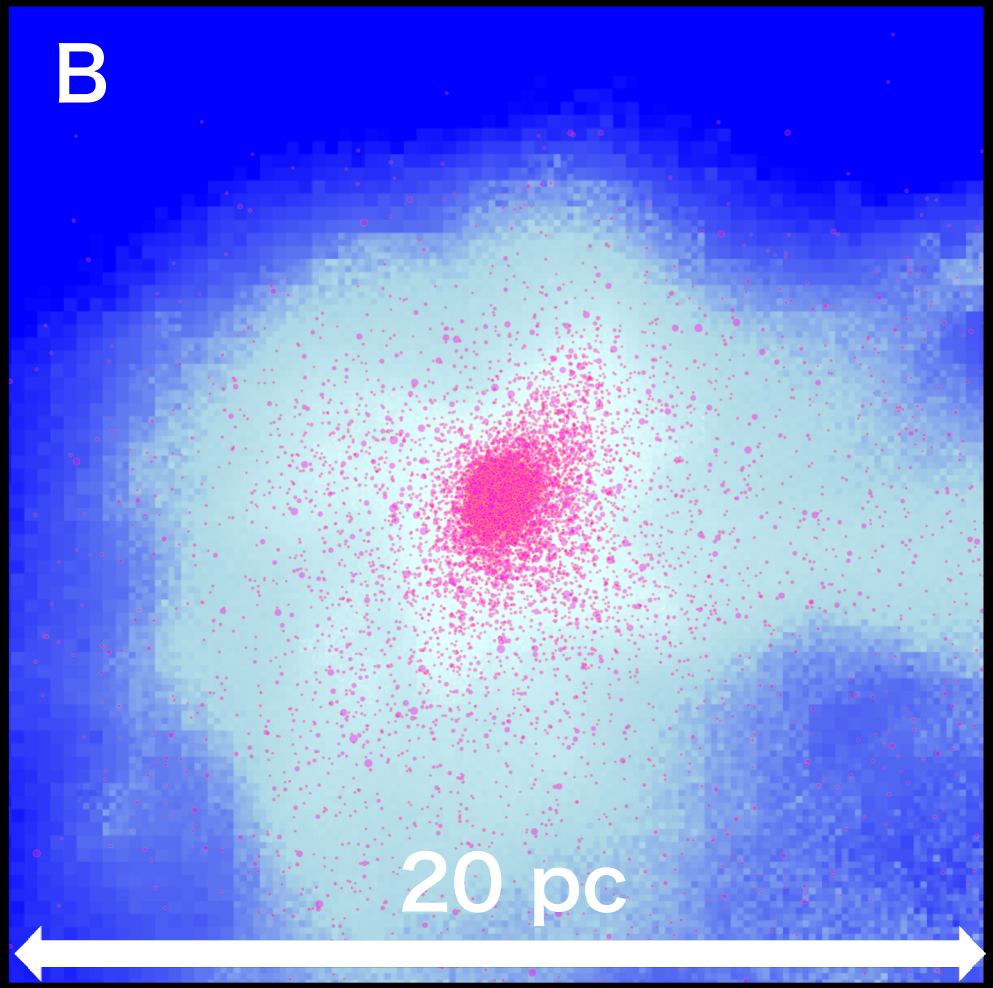
Model	Redshift	$R_{\rm vir}$ (10^2 pc)	$M_{\rm vir}$ (10^7 $M_\odot$)
A	19.72	2.81	4.03
B	19.57	2.76	2.97
C	19.73	2.08	2.03
D	14.89	3.21	2.60
E	17.06	2.64	1.47
F	16.53	3.12	2.01
G	16.91	2.42	1.99
H	11.67	5.41	4.22

8 AC halos are identified at n_H~10^7 cm^{-3}

Generation of star clusters

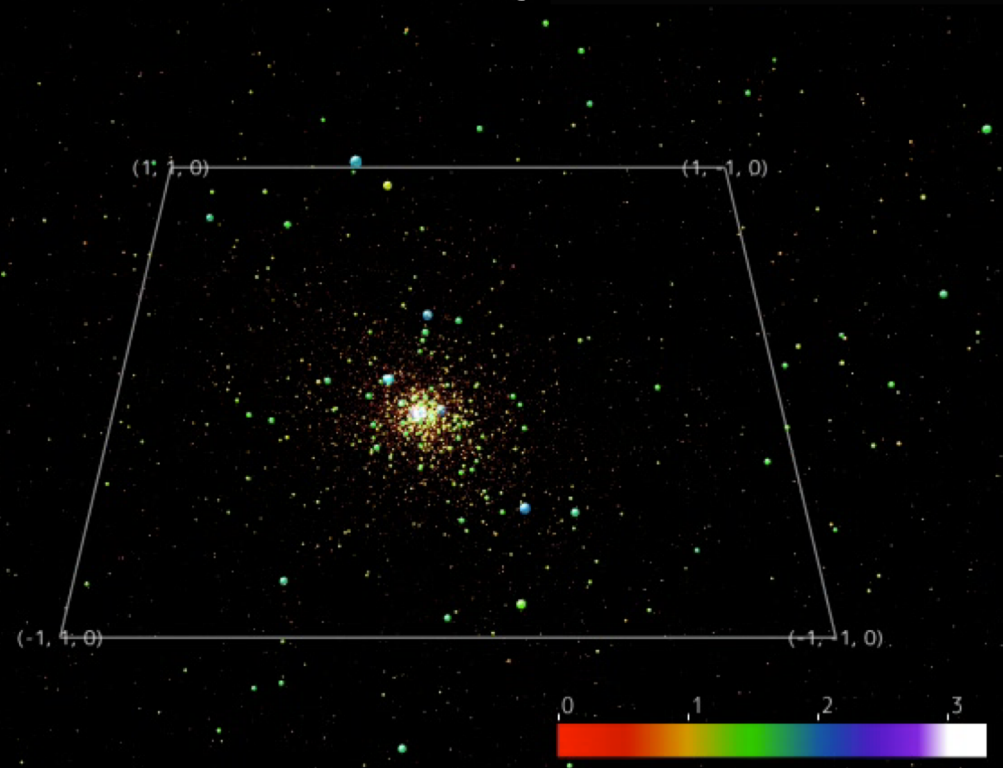
- A part of SPH particles is replaced; DM particles are all retained
- Params: a local SFE; Salpeter IMF w/ m_{min}=3Msun, m_{max}=100Msun

	$\overline{M}_{cl}$ (10^4 $M_\odot$)	$\overline{N}$ (10^3)	$\overline{\epsilon}_{sfe}$ (per cent)
A	16.4	19.9	5.91
B	13.0	15.7	6.12
C	12.1	14.7	10.1
D	11.7	14.1	7.16
E	4.76	5.76	8.15
F	9.00	10.8	8.67
G	12.5	15.0	9.48
H	7.70	9.32	5.55



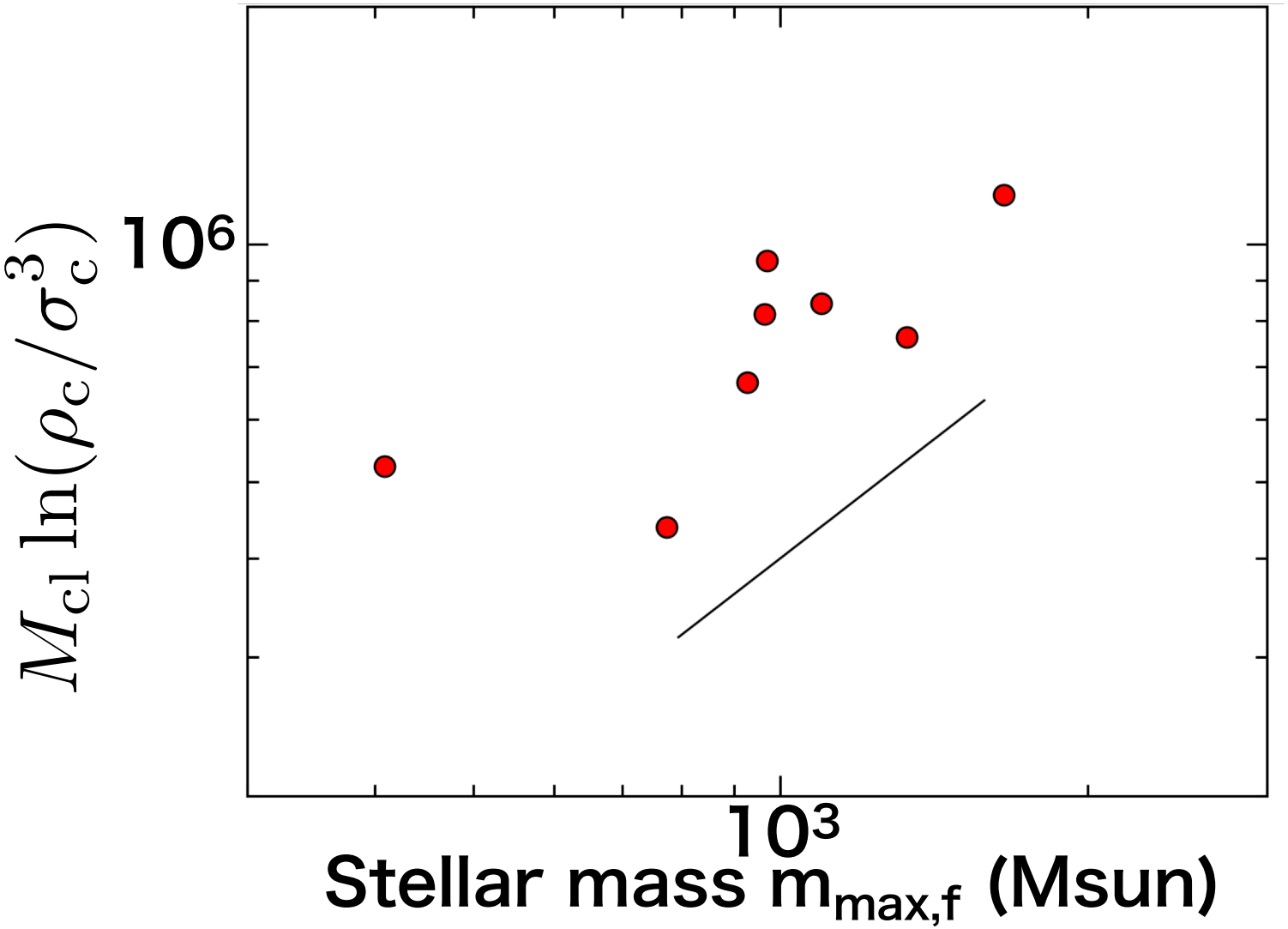
Hybrid N-body simulations

- Code: BRIDGE (Fujii et al. 2007)
  - Grav. computation: Stars-direct; DM-tree method
  - Collision cond. : stellar separation < R_1+R_2 (Tout+96)
  - End of computation ~ 3 Myr (massive star lifetime)



$m_{max,f}$ larger w/ larger M_{vir} & $\rho_{c,gas}$, smaller $\sigma_{c,gas}$

$$m_{\rm max,f} \propto M_{\rm vir} \ln(\text{const.} \times \overline{\rho}_{\rm c,gas}/\sigma^3_{\rm c,gas})$$



BH mass-cluster mass relation

IMBH mass~0.01×cluster mass
Consistent w/ observations