宇宙史研究センター　成果報告&交流会

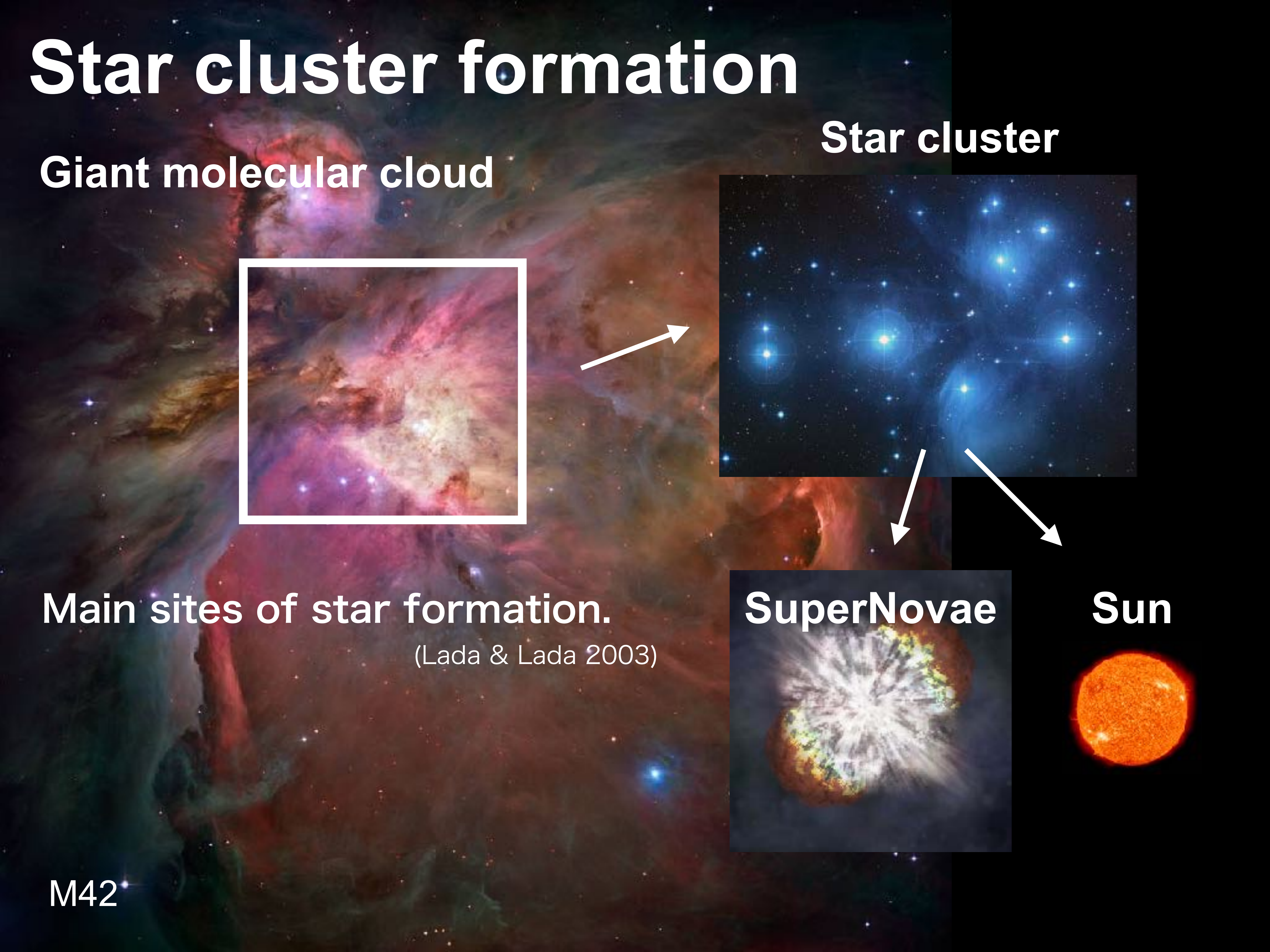
星団形成の輻射流体シミュレーション

福島　肇

(Hajime Fukushima)

筑波大学
University of Tsukuba

筑波大学
計算科学研究センター
Center for Computational Sciences


Star cluster formation
Giant molecular cloud
Star cluster
Main sites of star formation.
(Lada & Lada 2003)
SuperNovae
Sun
M42

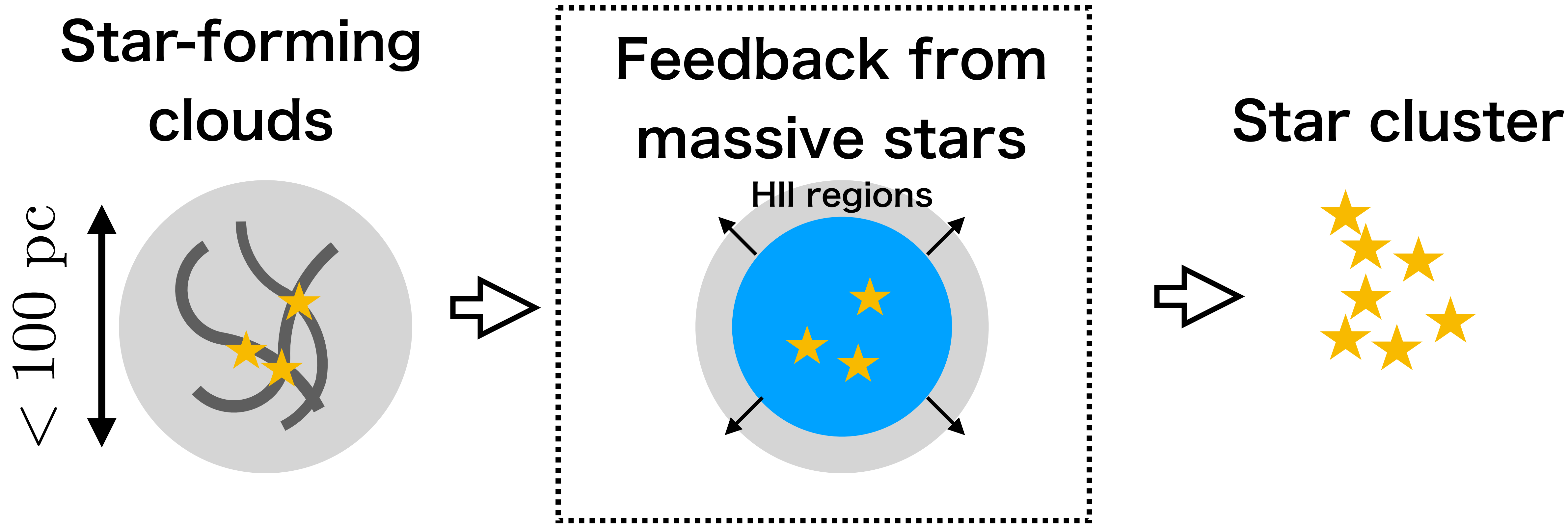
Globular clusters

- Low mass ($\lesssim 10^3\ M_\odot$)
- Young ($\lesssim 0.3$ Gyr)
- Low-density ($\lesssim 10^3\ M_\odot \mathrm{pc}^{-3}$)

- Massive ($\gtrsim 10^5\ M_\odot$)
- Old ($\gtrsim 10$ Gyr)
- High-density ($\gtrsim 10^3\ M_\odot \mathrm{pc}^{-3}$)

Globular clusters (GCs) are more massive and compact than open clusters.

Star Cluster Formation

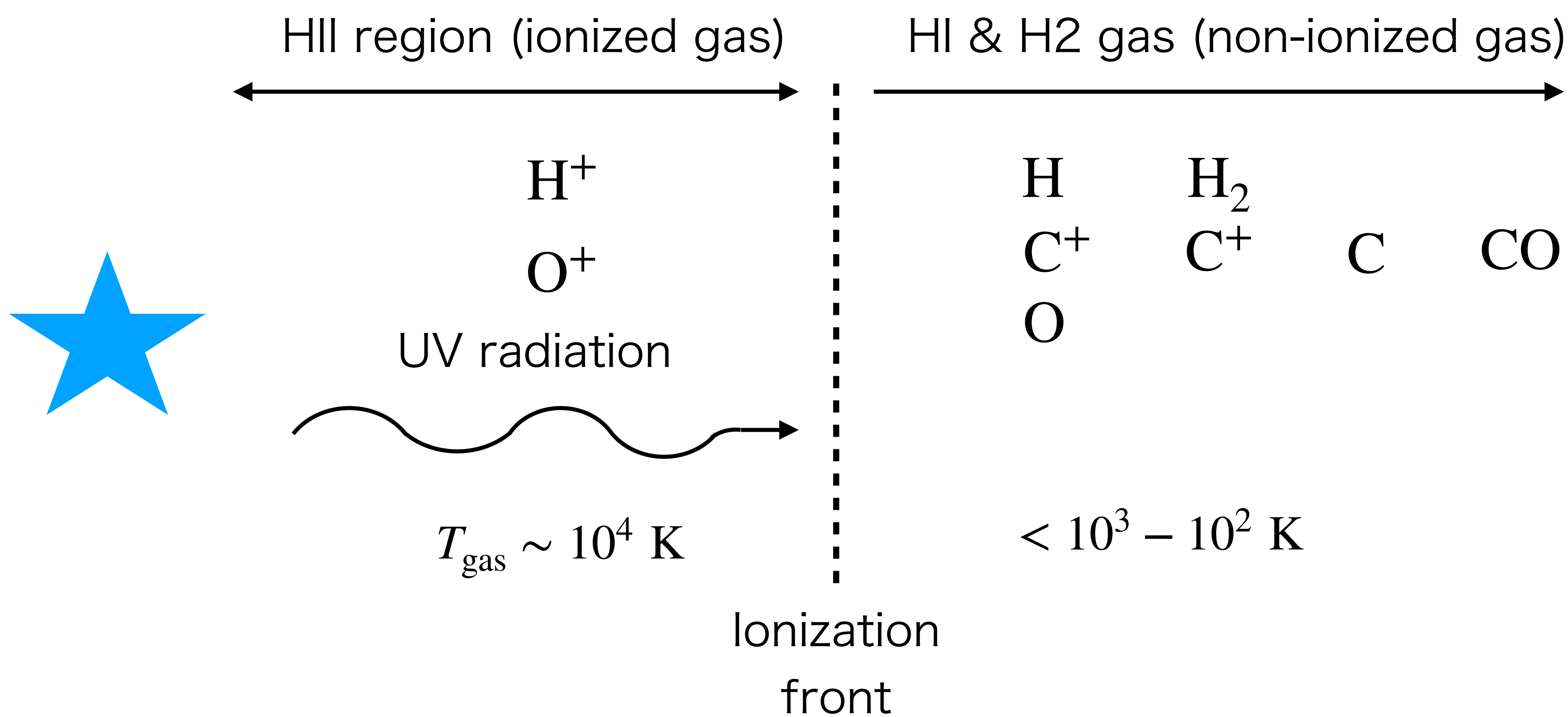


- **Properties of star cluster formation in nearby galaxies:**
  - Duration time of the star formation: 1-5 Myr.
  - Star formation efficiencies: 1-10%

(e.g., Fukui & Kawamura 2010, Kruijssen et al. 2019, Chevance et al. 2020)

Pre-supernova feedback suppresses the star formation.

Radiative feedback



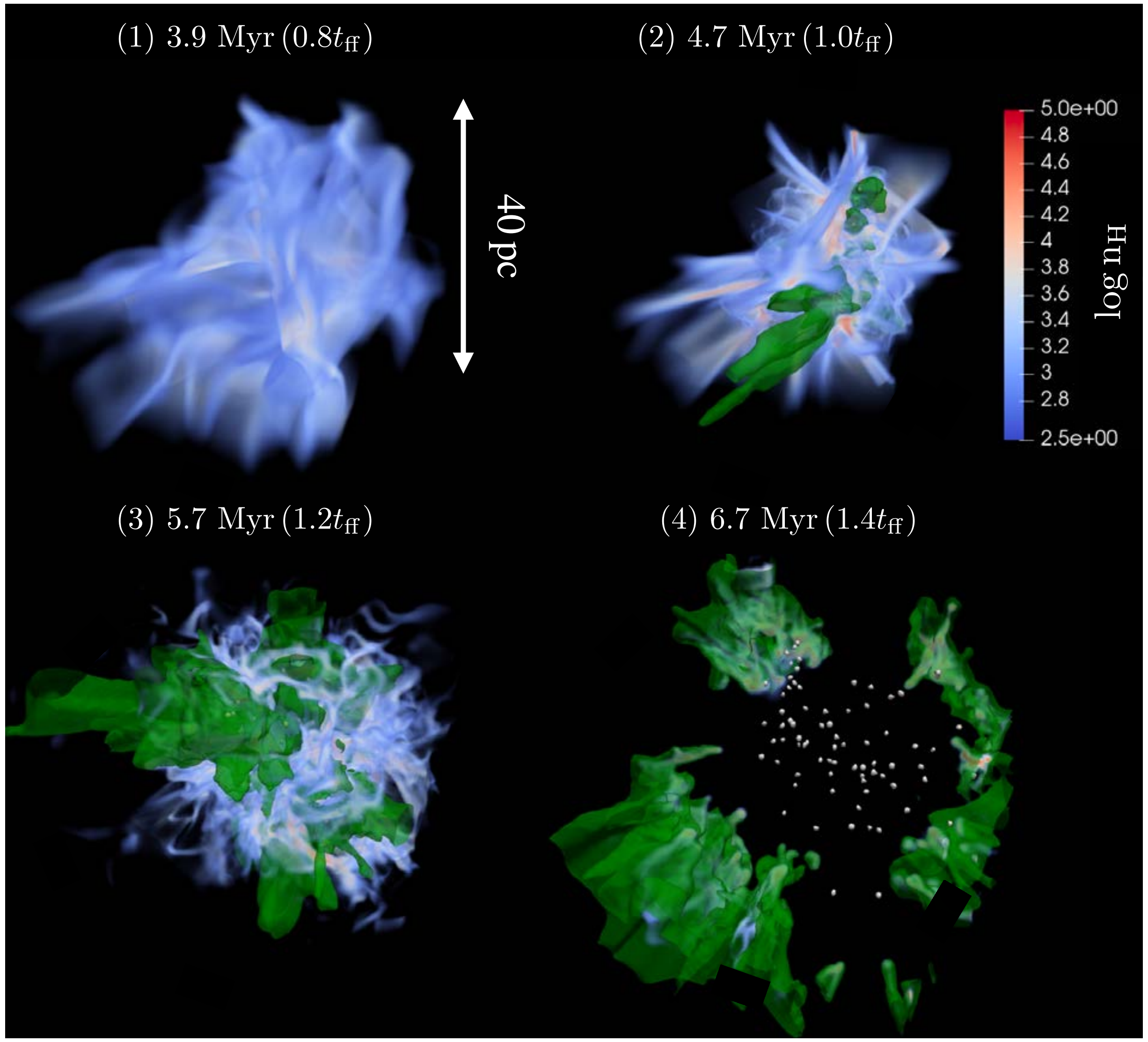
Photoionization feedback (EUV feedback):

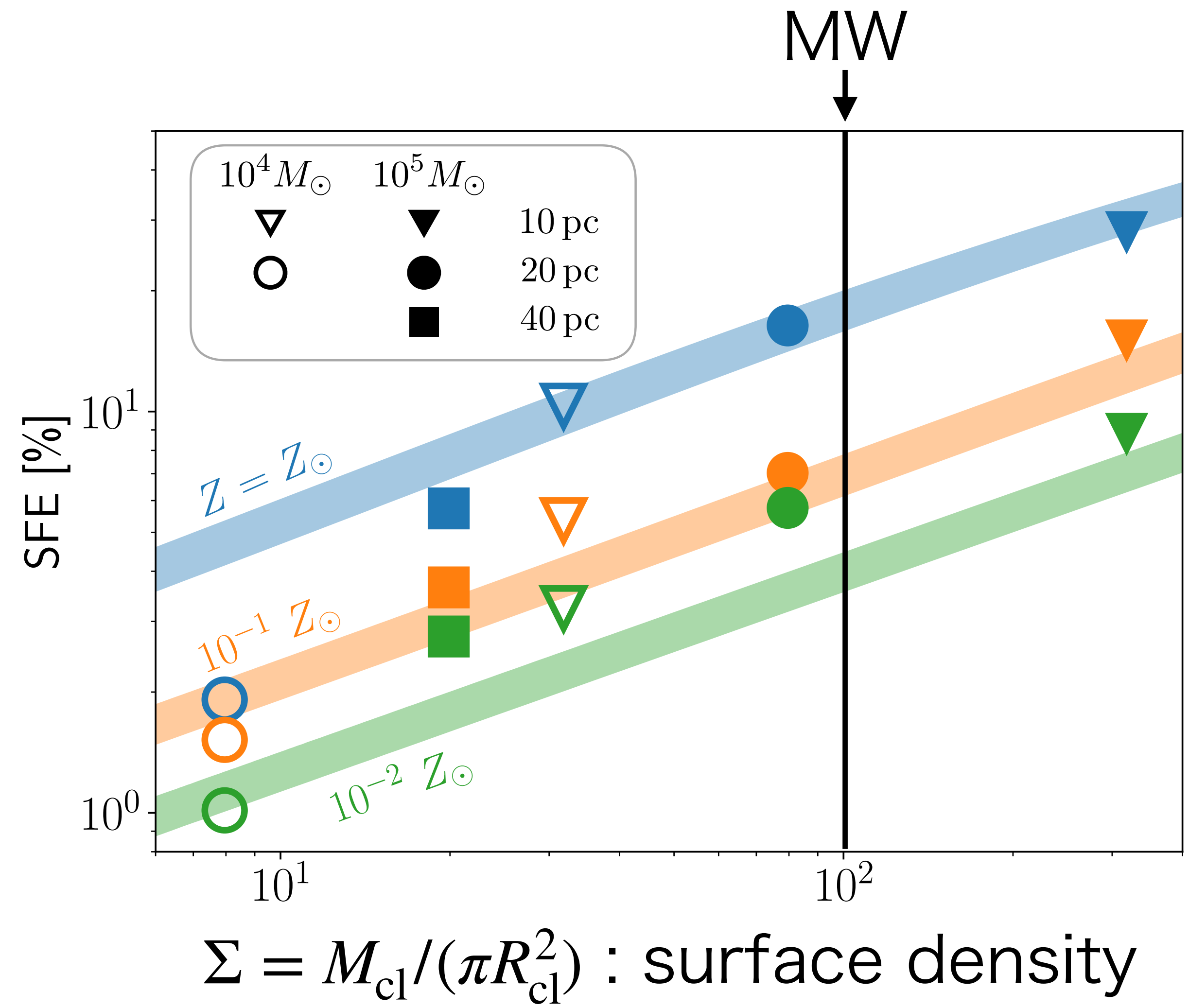
Thermal pressure of ionized gas ($\sim 10^4$ K) pushes ambient gas.

(e.g., Dale et al. 2012, Geen et al. 2015, Kim et al. 2018, 2020, Ali et al. 2018)

To investigate the star cluster formation, we need to perform **radiation hydrodynamics (RHD)** simulations.

RHD simulations of star cluster



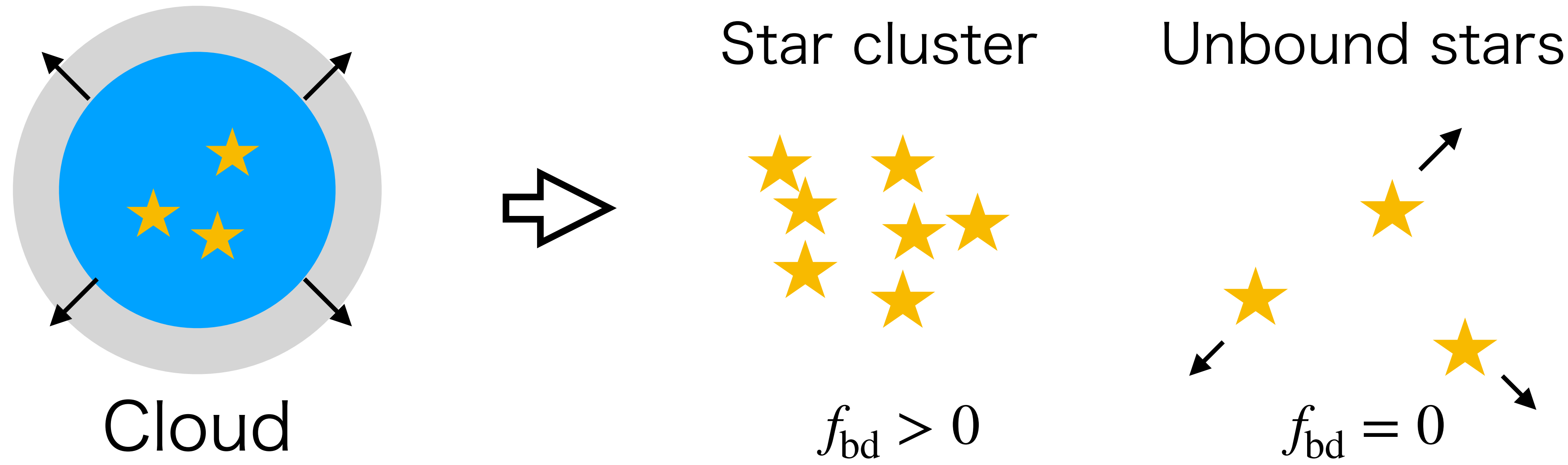


(HF et al. 2020)

In the previous studies, we performed the simulation of open cluster formation, and their star formation efficiencies (SFEs) are consistent with that of the Milky Way.

The condition for massive star cluster formation is still unclear.

Bound fractions



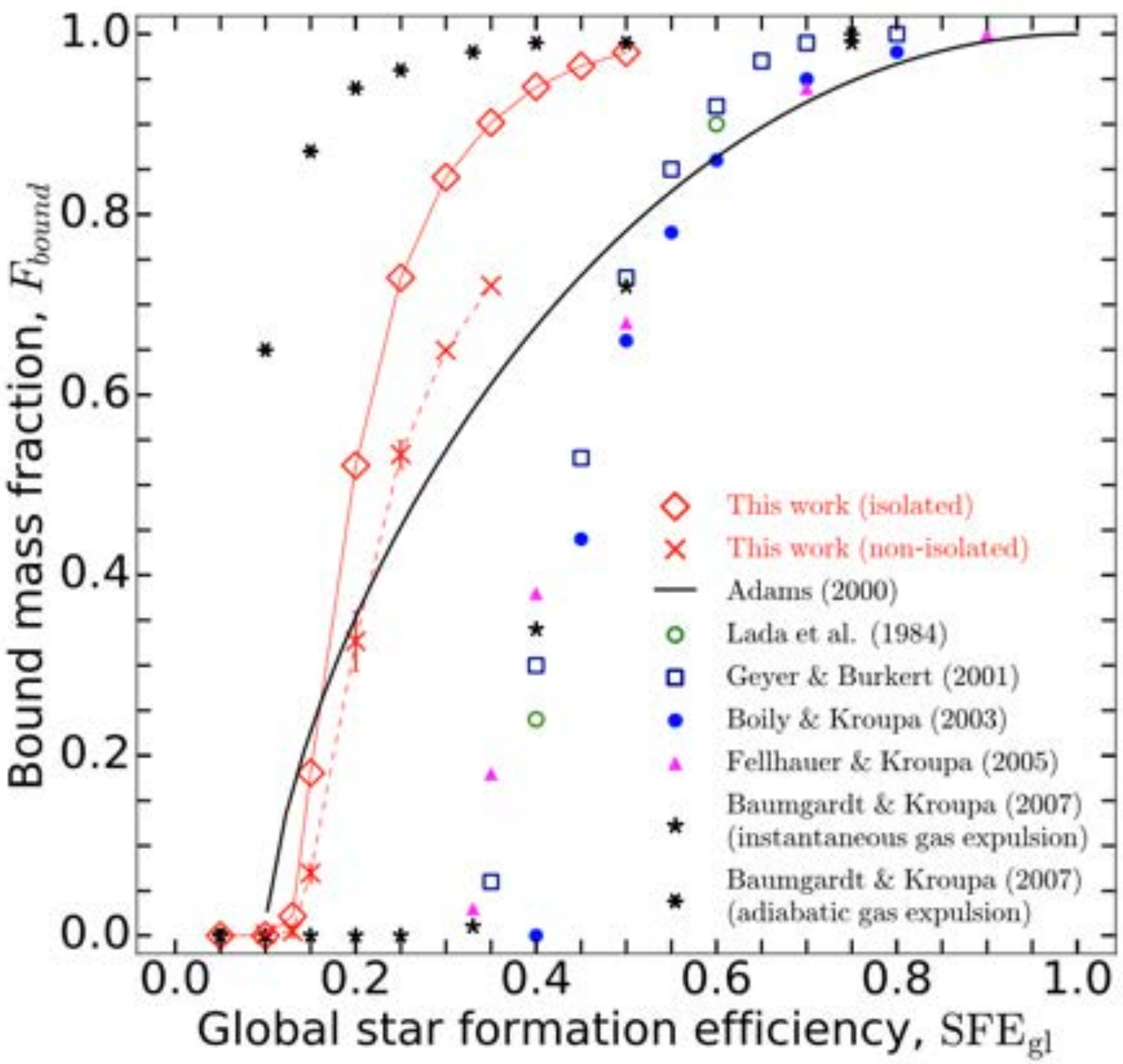
Bound fraction:

$$f_{\rm bd} = \text{(Bound stellar mass)/(Total stellar mass)}$$

The bound fraction is determined with the timescale of gas expulsion and the star formation efficiencies.

(e.g, Adams 2000, Baumgardt & Kroupa 2007, Shukirgaliyev 2019)

Bound fractions & SFE



(shukirgaliyev et al. 2019)

Star formation efficiencies (SFEs) is need to be larger than 30% to form bound star cluster. (e.g, Adams 2000, Baumgardt & Kroupa 2007, Shukirgaliyev 2019)

To form bound star cluster, the mechanism which enhances the SFEs.

Method: Radiation hydrodynamic simulation

- **Self-gravitational AMR (M)HD + Sink particles**

(Matsumoto 2007, 2015)

- **Non-Equilibrium chemistry**
  - H, H_2, H^+, H^-, H_2^+, e, CII, OI, OII, OIII, CO
- **Heating & Cooling**
  - Photoionization & photodissociation heating
  - Line cooling (CII, CO, OI, OII, OIII), dust cooling
  - Chemical heating & cooling

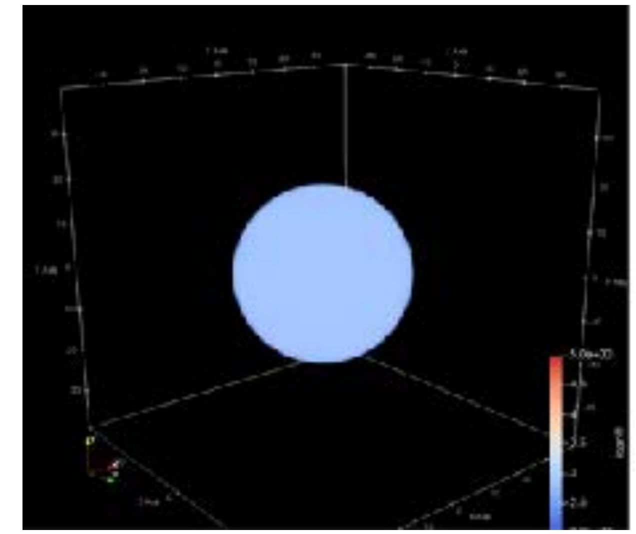
(Sugimura et al. 2020, CO network:Nelson & Langer 1997)

- **Radiation transfer with moment method (M1-closure, reduced speed of light)**
  - EUV photons
  - FUV photons (H_2, CO photodissociation)
  - Dust thermal emission

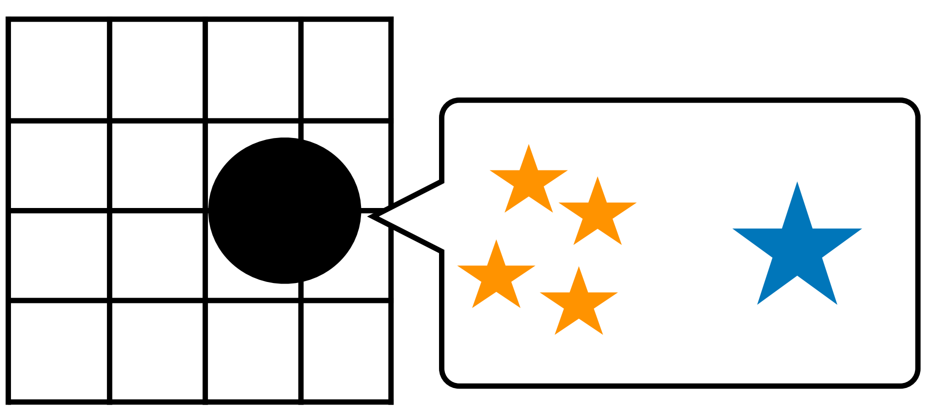
(HF & Yajima 2021)

Initial conditions

- **Uniform density sphere with the turbulent motions**
  - Cloud masses: $M_{\rm cl} = 10^5, 10^6\ M_\odot$
  - Radius: $5 - 60$ pc
  - Surface density: $\Sigma_{\rm cl} = M_{\rm cl}/(\pi R_{\rm cl}^2) = 80 - 3200\ M_\odot {\rm pc}^{-2}$
  - Virial parameter: $\alpha_0 = 2K/U_{\rm g} = 1,\ \sigma_{\rm v}(\lambda) \propto \lambda^{1/2}$



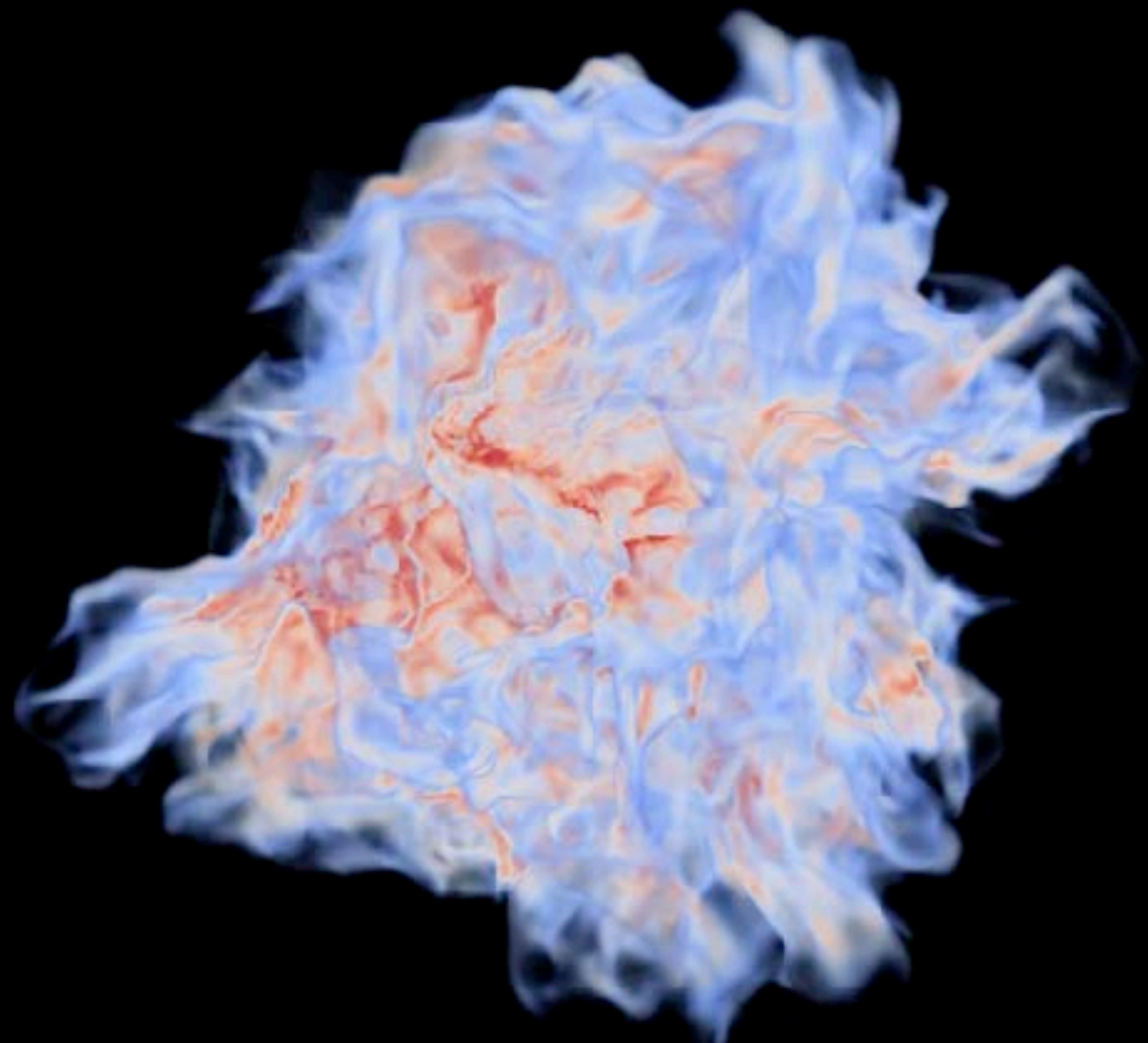
- **Sink Particles**:
  - Sink radius: $R_{\rm sink} = 0.59\ {\rm pc}\ (R_{\rm cl}/20{\rm pc})$ (Matsumoto et al. 2015, Gong & Ostriker 2013)
  - Light-to-mass ratios are constant (Chabrier IMF)



Sink particles represents the mini star clusters.

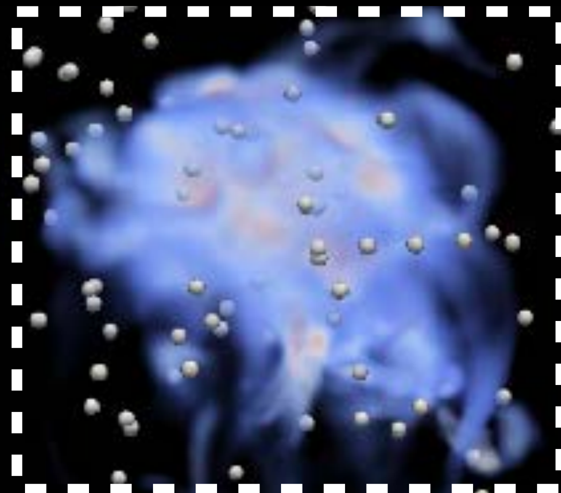
Massive star cluster formation

(Fukushima & Yajima 2021, MNRAS, vol506, 5512)



Massive star cluster formation

(Fukushima & Yajima 2021, MNRAS, vol506, 5512)

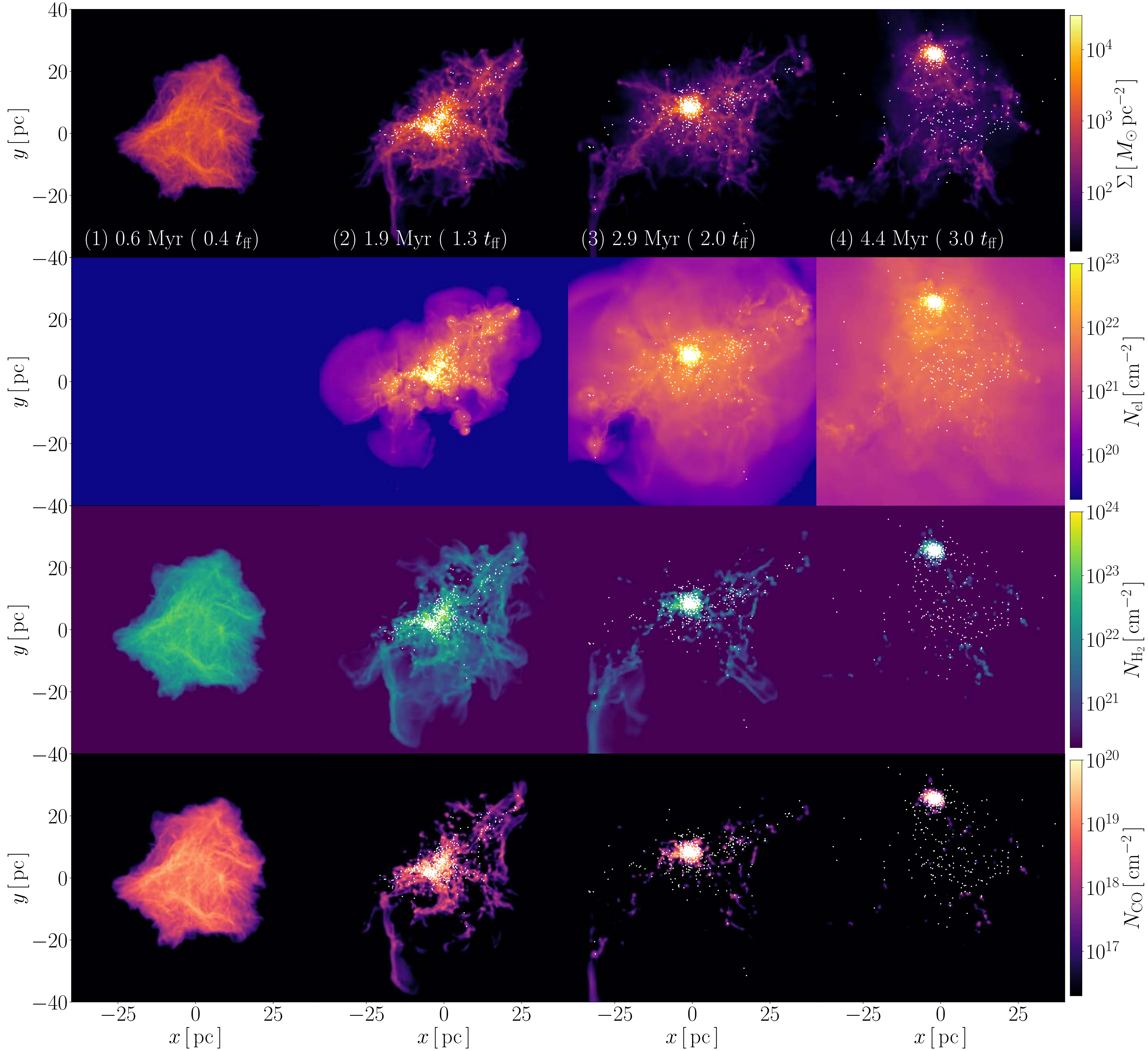


Stars are embedded

Globular clusters

Stellar density is smilar to GCs.

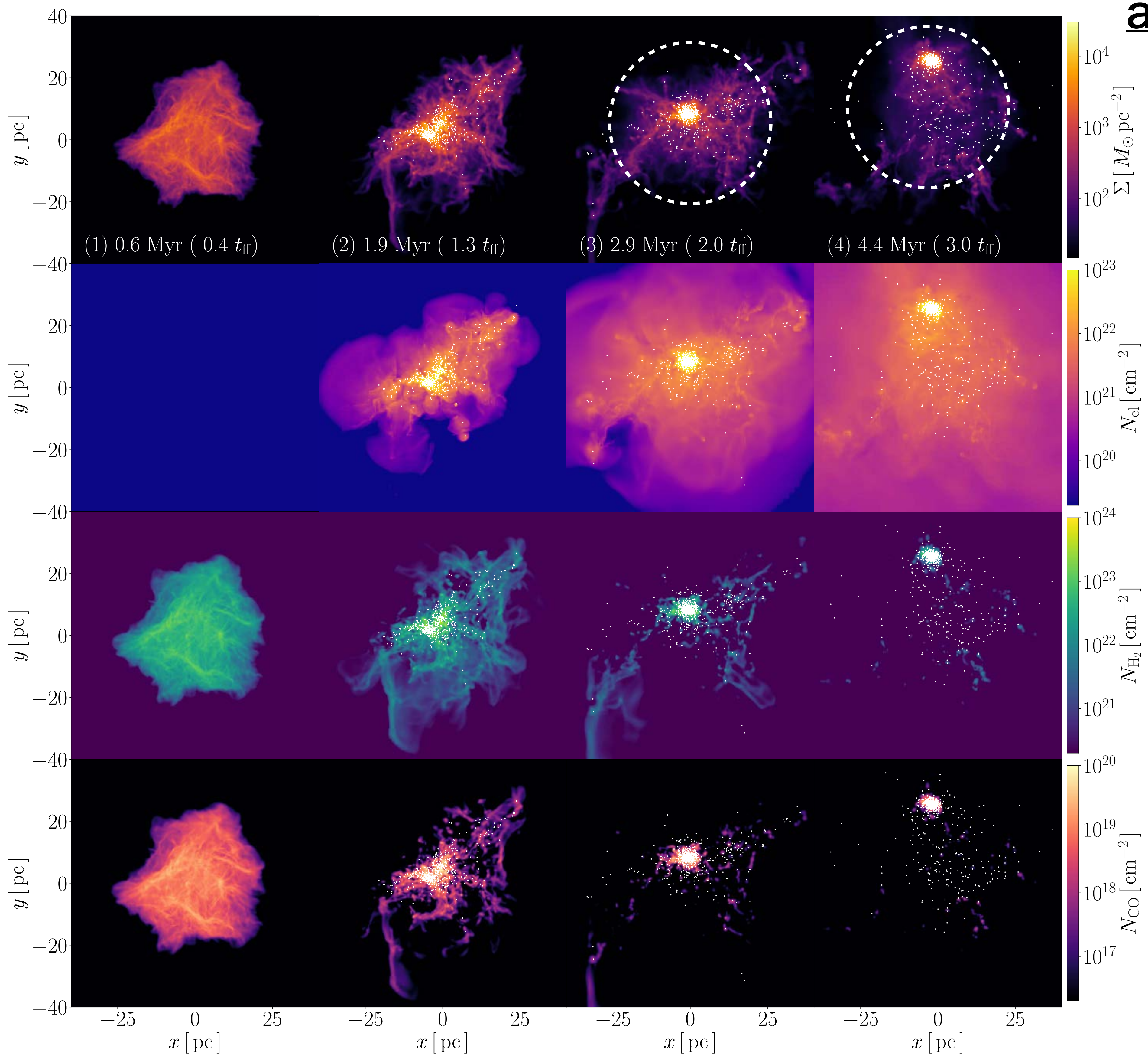
(1) $(M_{\rm cl}, R_{\rm cl}, Z) = (10^6 M_\odot, 20{\rm pc}, Z_\odot)$



Σ: Surface densities, $N_{\rm el}$: Column density of electron, $N_{\rm H_2}$: H_2, $N_{\rm CO}$: CO

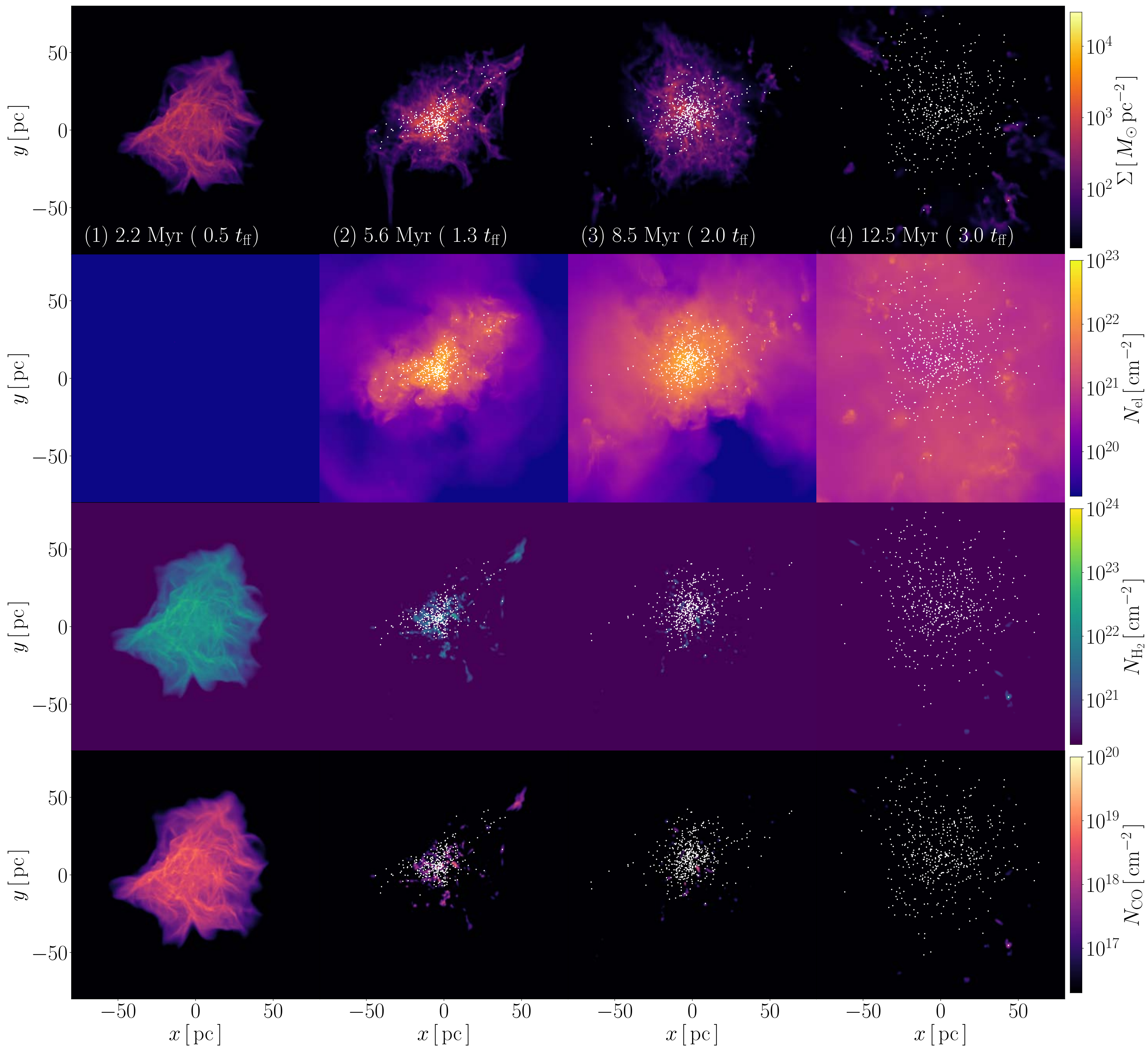
(1) $(M_{\rm cl}, R_{\rm cl}, Z) = (10^6 M_\odot, 20{\rm pc}, Z_\odot)$

Core structure appears



Σ: Surface densities, $N_{\rm el}$: Column density of electron, $N_{\rm H_2}$: H_2, $N_{\rm CO}$: CO

(2) $(M_{\rm cl}, R_{\rm cl}, Z) = (10^6 M_\odot, 40{\rm pc}, Z_\odot)$

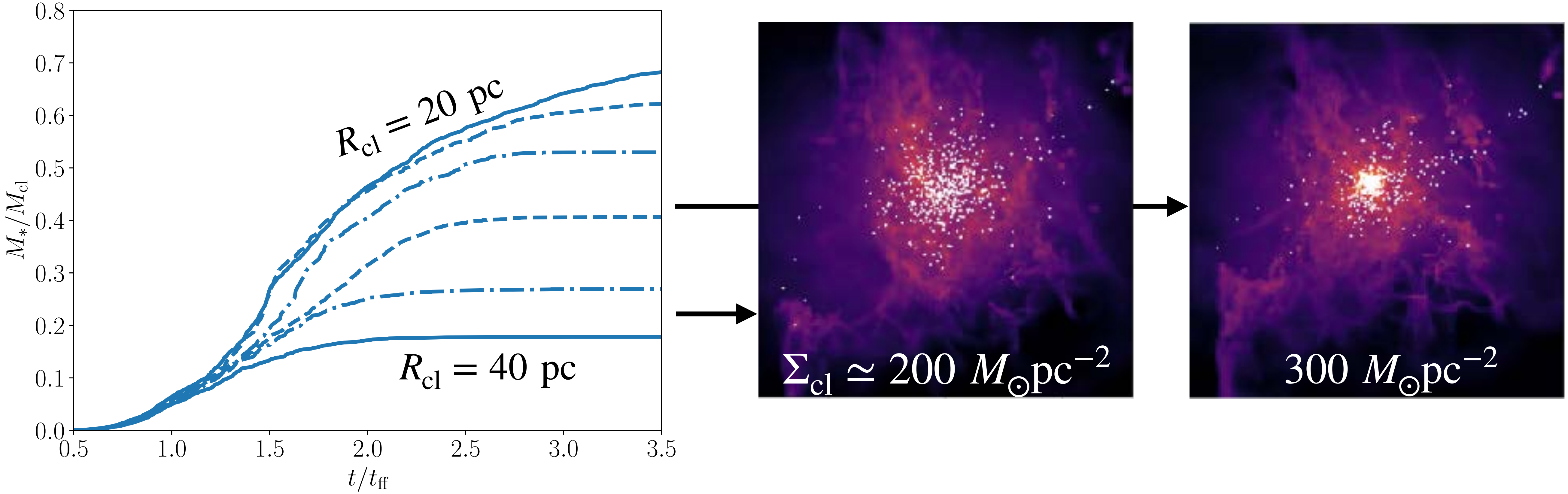


Σ: Surface densities, $N_{\rm el}$: Column density of electron, $N_{\rm H_2}$: H_2, $N_{\rm CO}$: CO

SFEs vs Surface density

Time evolution of total stellar mass

$M_{\rm cl} = 10^6\ M_\odot, R_{\rm cl} = 20, 25, 30, 32.5, 35, 40\,{\rm pc}$

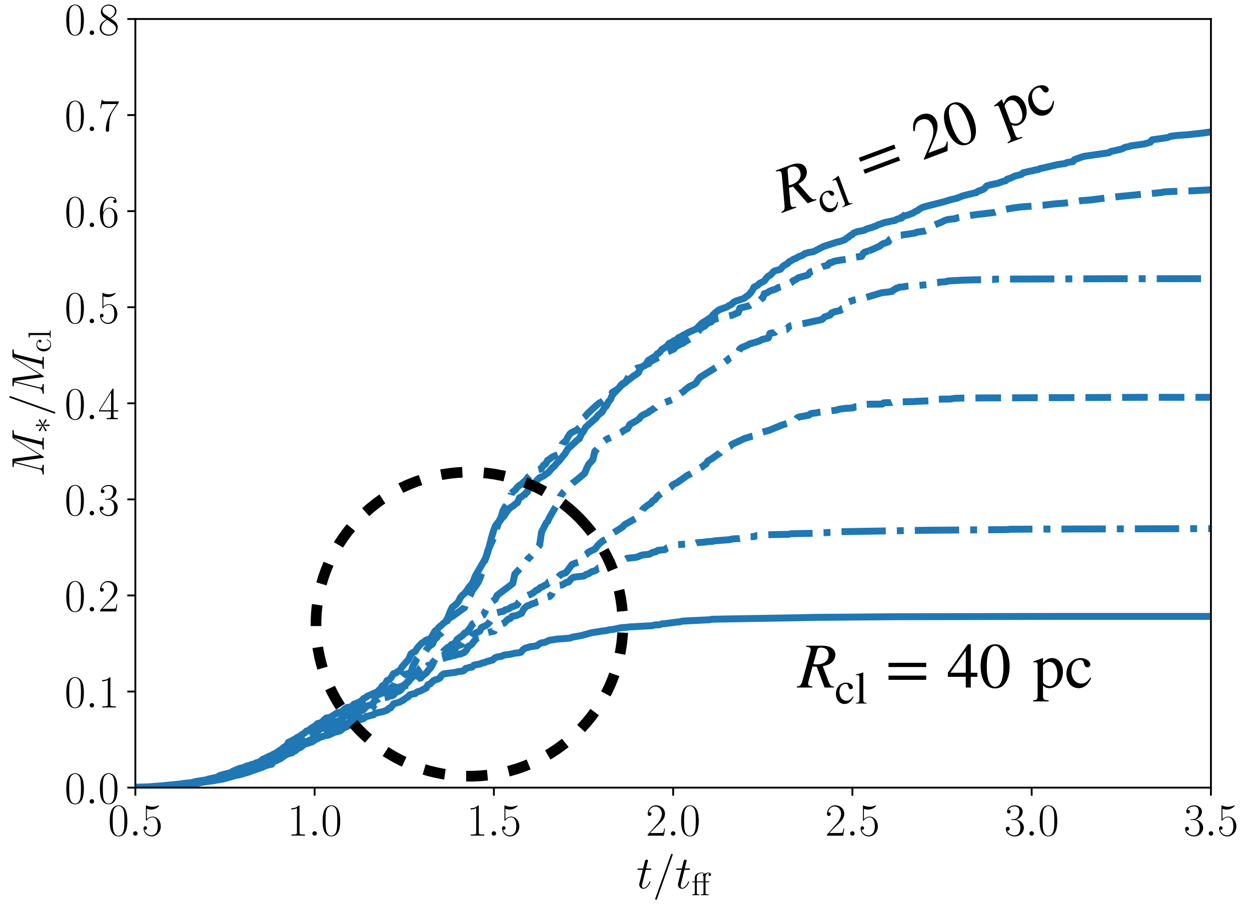


- Rapid increase of SFEs occurs at $\Sigma_{\rm cl} \sim 300\ M_\odot{\rm pc}^{-2}$.
- The histories of star formation are almost the same until $\sim 1.3\ t_{\rm ff}$.

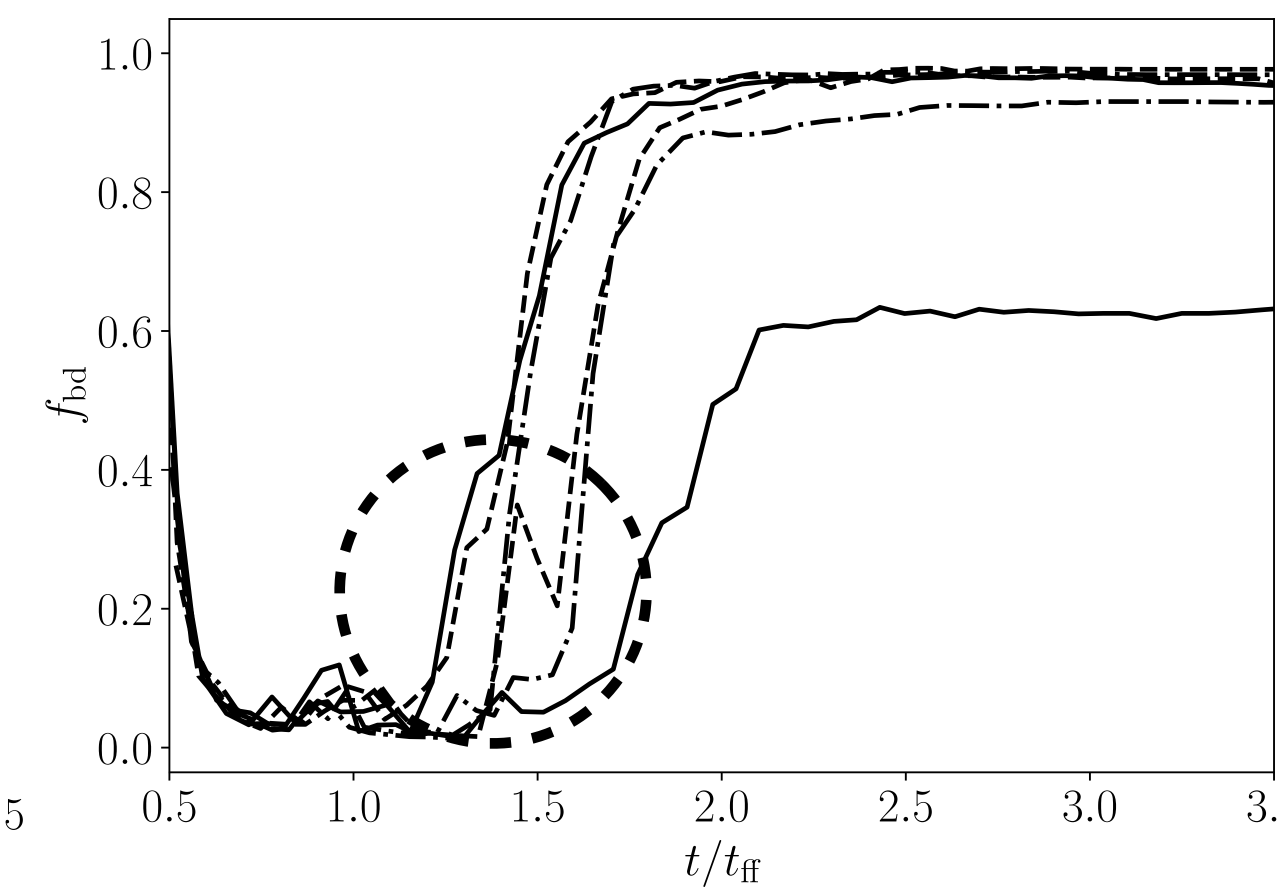
Relations between SFEs and bound fractions

Time evolution of total stellar mass

$M_{cl} = 10^6\ M_\odot, R_{cl} = 20, 25, 30, 32.5, 35, 40$ pc



Time evolution of bound fraction (f_{bd})



- Bound fraction:
  f_{bd} = (gravitationally bound stellar mass)/(total stellar mass)
- When the bifurcation occurs, the bound fraction of stars rapidly increases.

➡ The epoch of the bifurcation corresponds to that of the stellar core formation ($t \sim 1.3\ t_{ff}$).

Stellar core formation

(a) Cloud evolution

(b) Gravitational potential

(1) Start of star formation

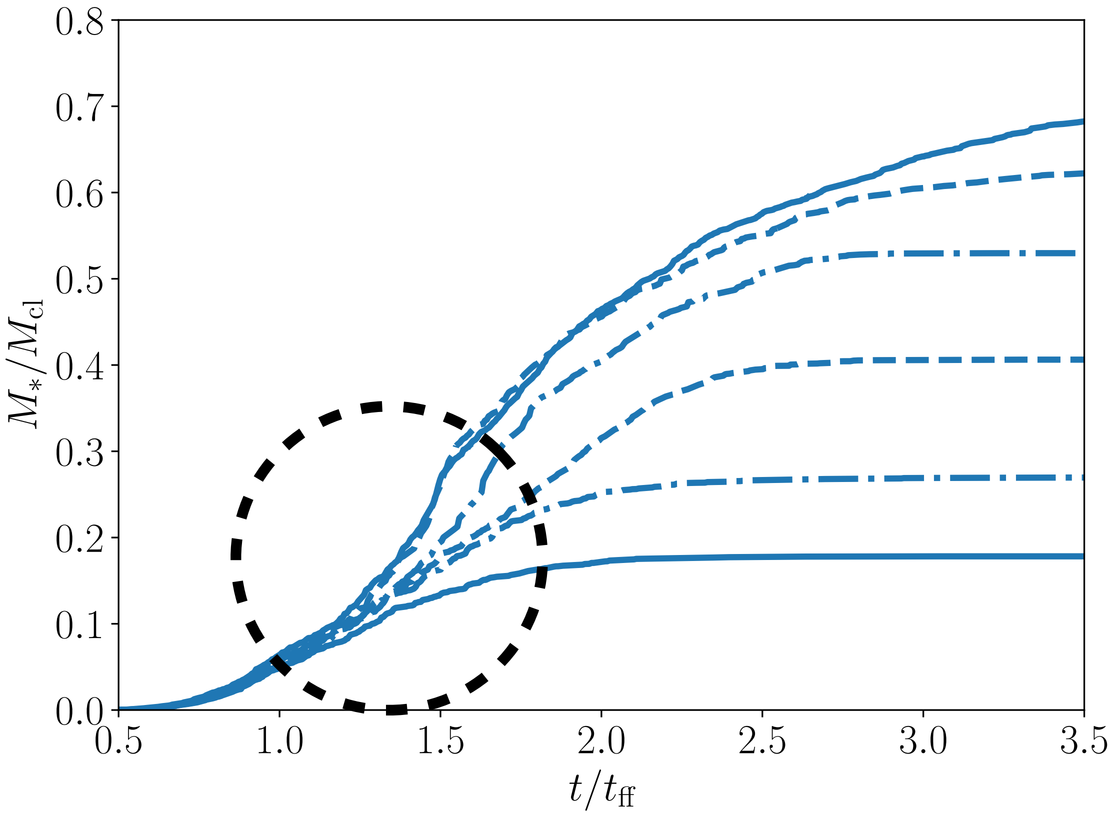
(2) Stars begin to gravitationally bind each other.

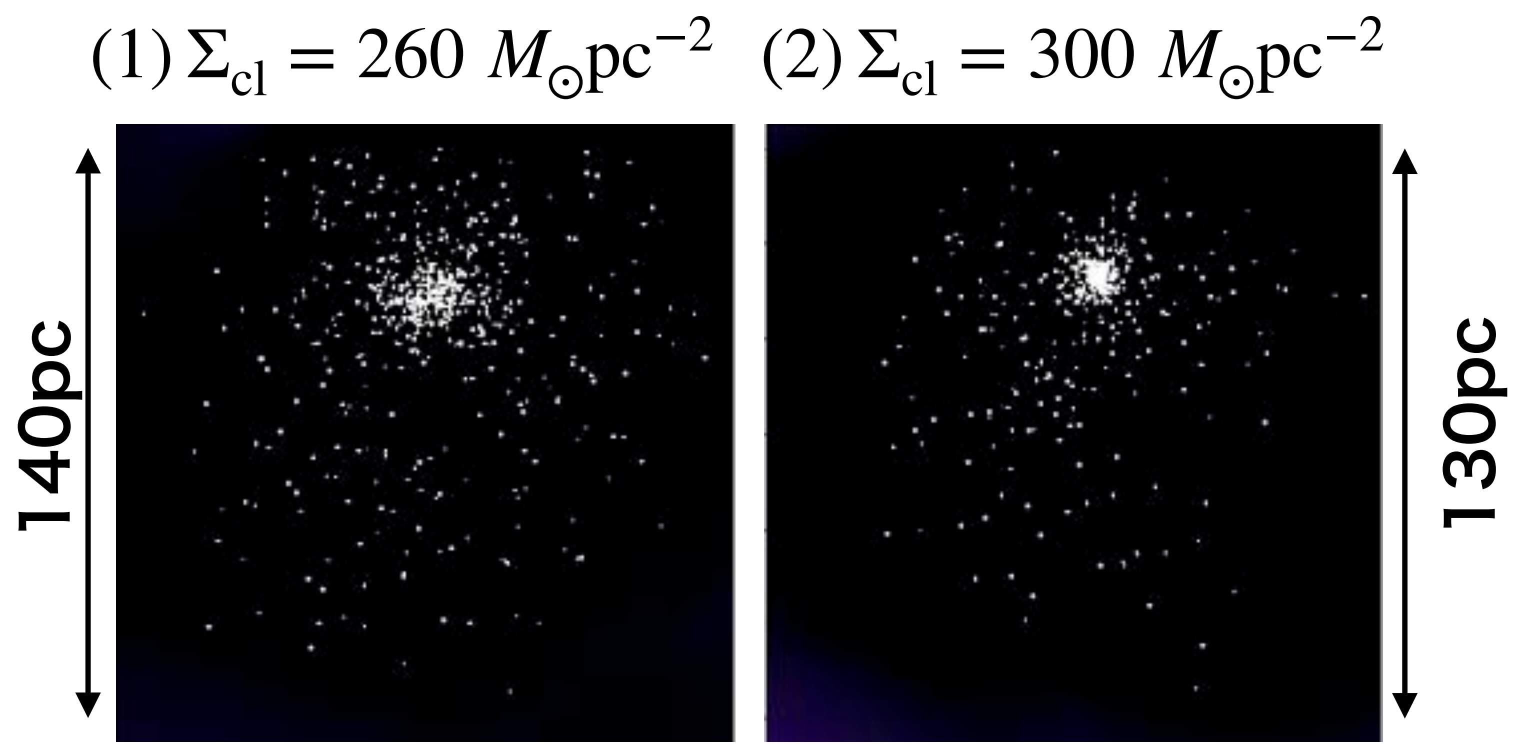
(3) Thermal pressure cannot pushes ambient gas. Runaway star formation occurs.

Condition of stellar core formation :

Velocity of expanding shell (v_{sh}) < escape velocity from the core v_{esc}

Condition of stellar core formation





Condition of stellar core formation :

Velocity of expanding shell (v_{sh}) **< escape velocity from the core** v_{esc}

$$v_{sh} < v_{esc} = \sqrt{\frac{2GM_{core}}{R_{core}}}$$

Mass: $M_{core} \sim 0.1 \times 0.1 M_{cl}$ Radius: $R_{core} \sim 0.1 R_{cl}$

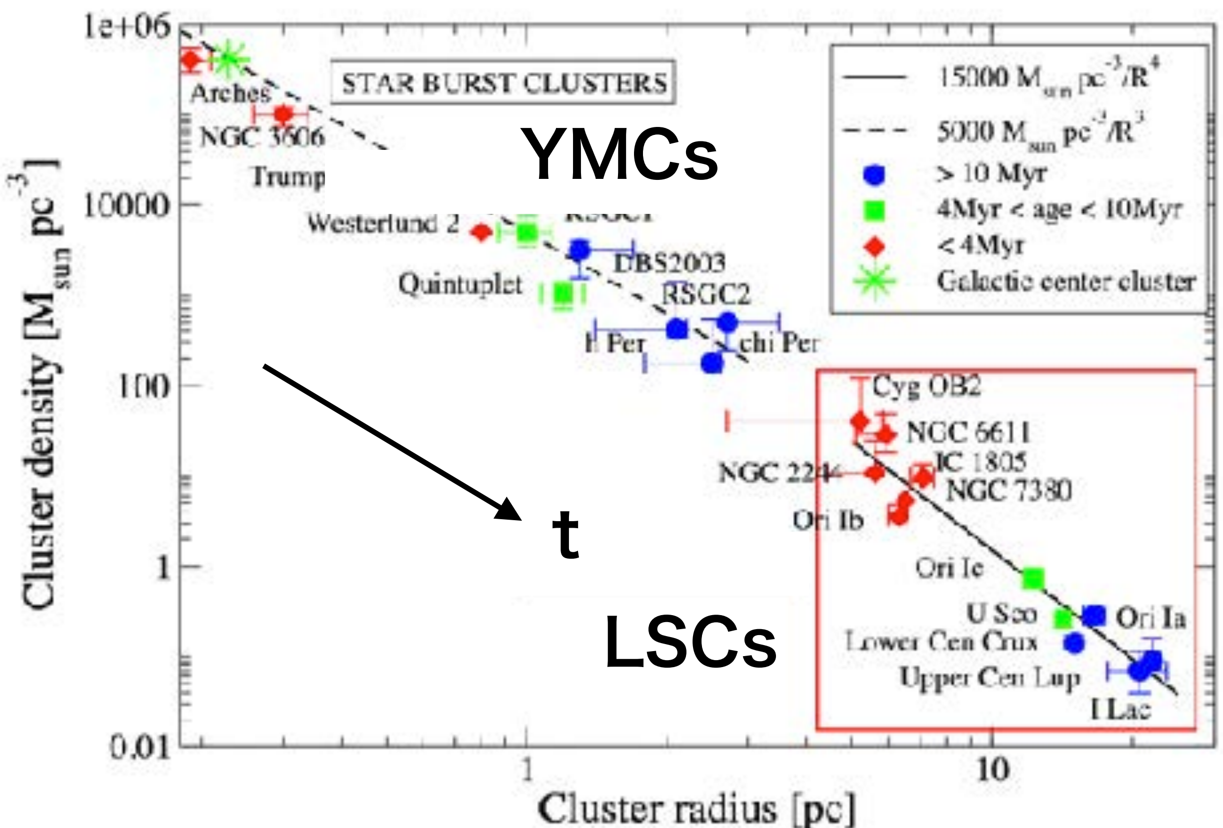
Shell velocity: $v_{sh,th} \simeq 4.9\ \mathrm{km/s}$

$$\Sigma_{cl} > \Sigma_{th} \simeq 280\ M_{\odot}pc^{-2} \left(\frac{M_{cl}}{10^6 M_{\odot}}\right)^{-1/5} \left(\frac{T_i}{8000\ \mathrm{K}}\right)^{28/25}$$

The stellar density rapidly increases with the surface density of clouds.

Young massive star clusters

There are two population of young massive star cluster.



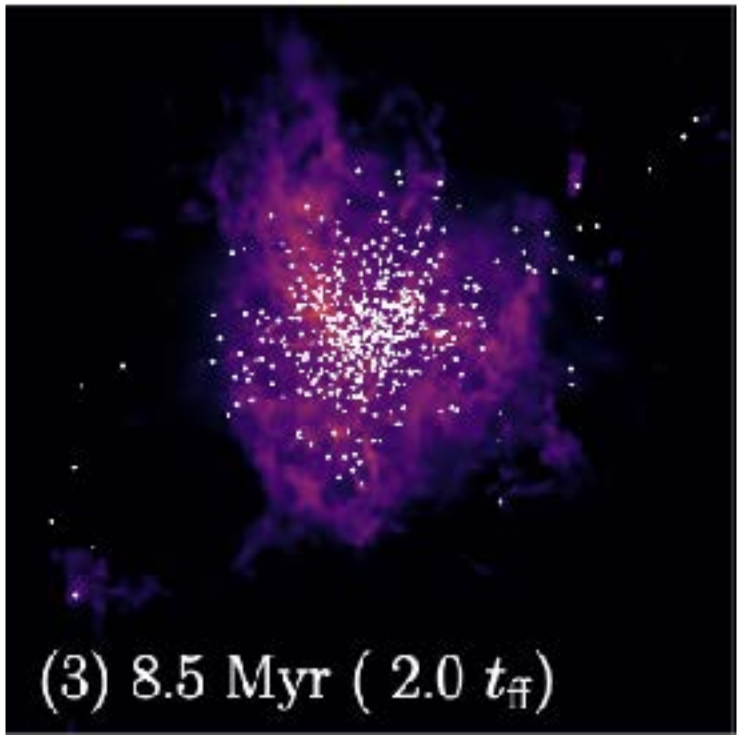
(Pfalzner 2009)

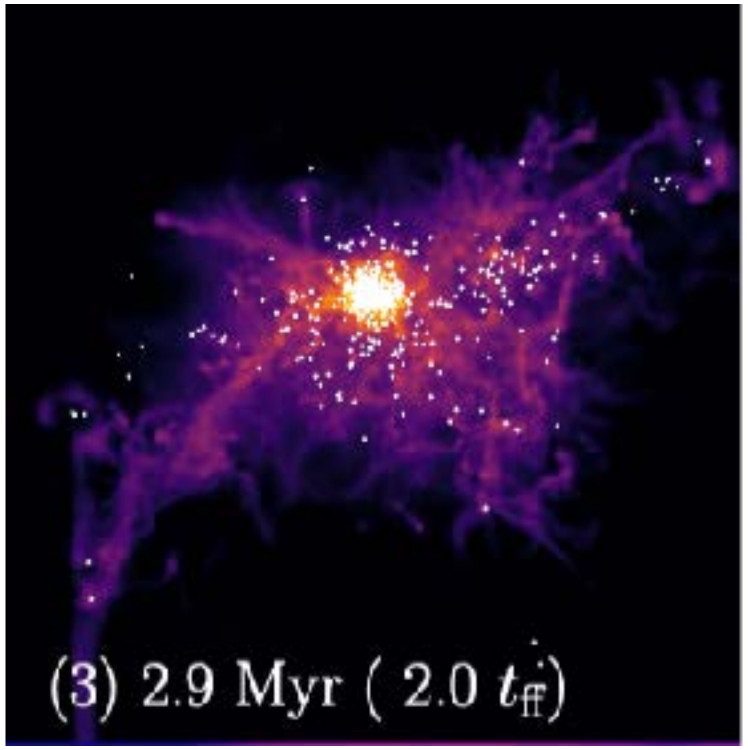
- **Young massive star cluster (YMCs)**
  - Mass: $M_{\rm cl} > 10^4 M_\odot$
  - Stellar density: $\rho_{\rm c} \gtrsim 10^3\, M_\odot\, {\rm pc}^{-3}$
- **Leaky Star Clusters (LSCs)**
  - Mass: $M_{\rm cl} > 10^4 M_\odot$
  - Stellar density: $\rho_{\rm c} < 10^3\, M_\odot\, {\rm pc}^{-3}$

(Portegies Zwart et al. 2010)

In addition, we suggest that globular clusters are relics of the more compact clouds than that of typical one in the Galaxy.

Summary





We perform radiative hydrodynamics simulations of star cluster formation.

We estimate the condition of the dense stellar core formation:

$$\Sigma_{\rm cl} > \Sigma_{\rm th} \simeq 280\ M_\odot {\rm pc}^{-2} \left(\frac{M_{\rm cl}}{10^6 M_\odot}\right)^{-1/5} \left(\frac{T_{\rm i}}{8000\ {\rm K}}\right)^{28/25} \quad @\ Z = Z_\odot$$

We will consider the observational signatures of YMC formation.