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Radiation hydrodynamics simulations of star cluster formation in high-z galaxies

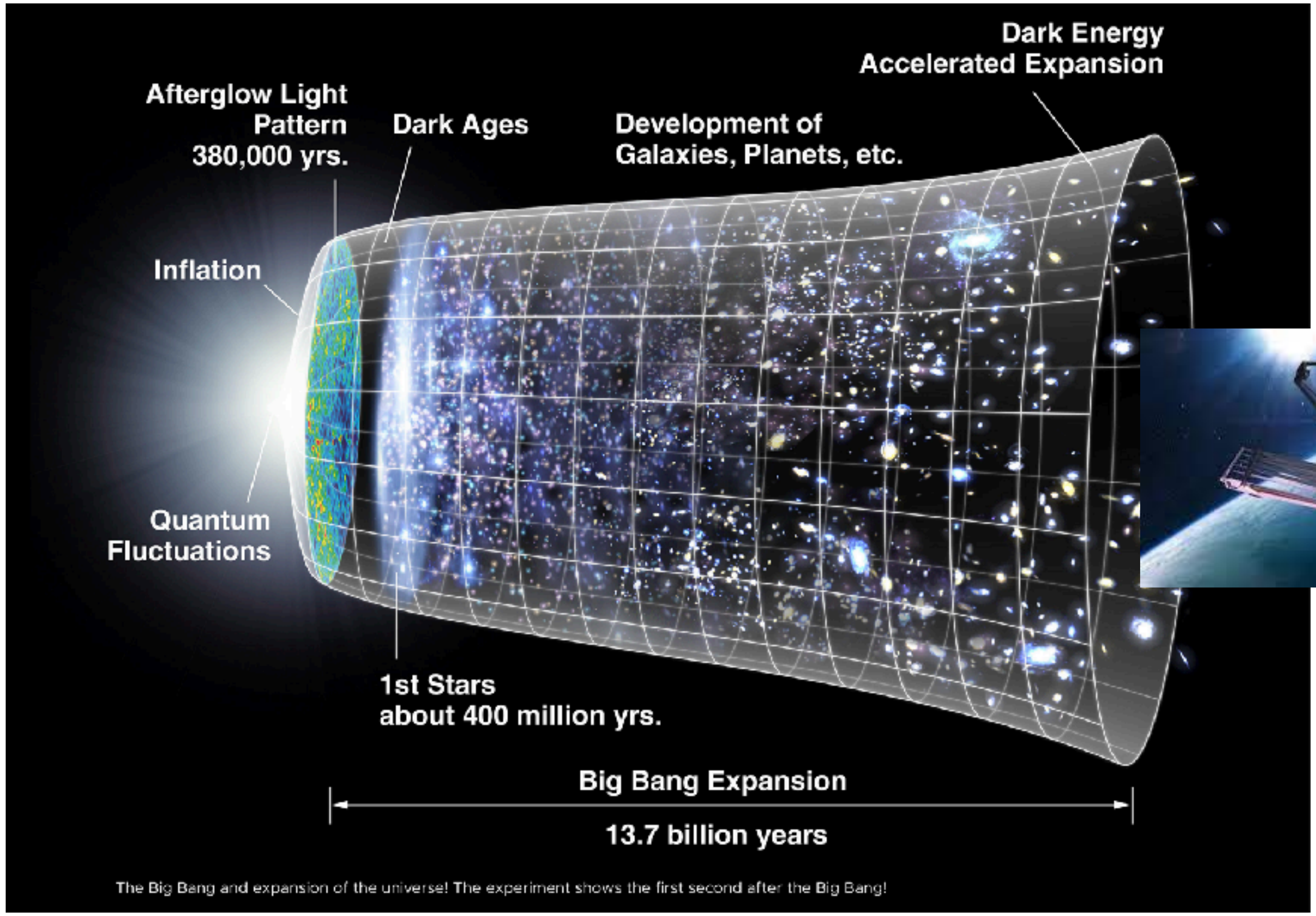
Hajime Fukushima

筑波大学
University of Tsukuba

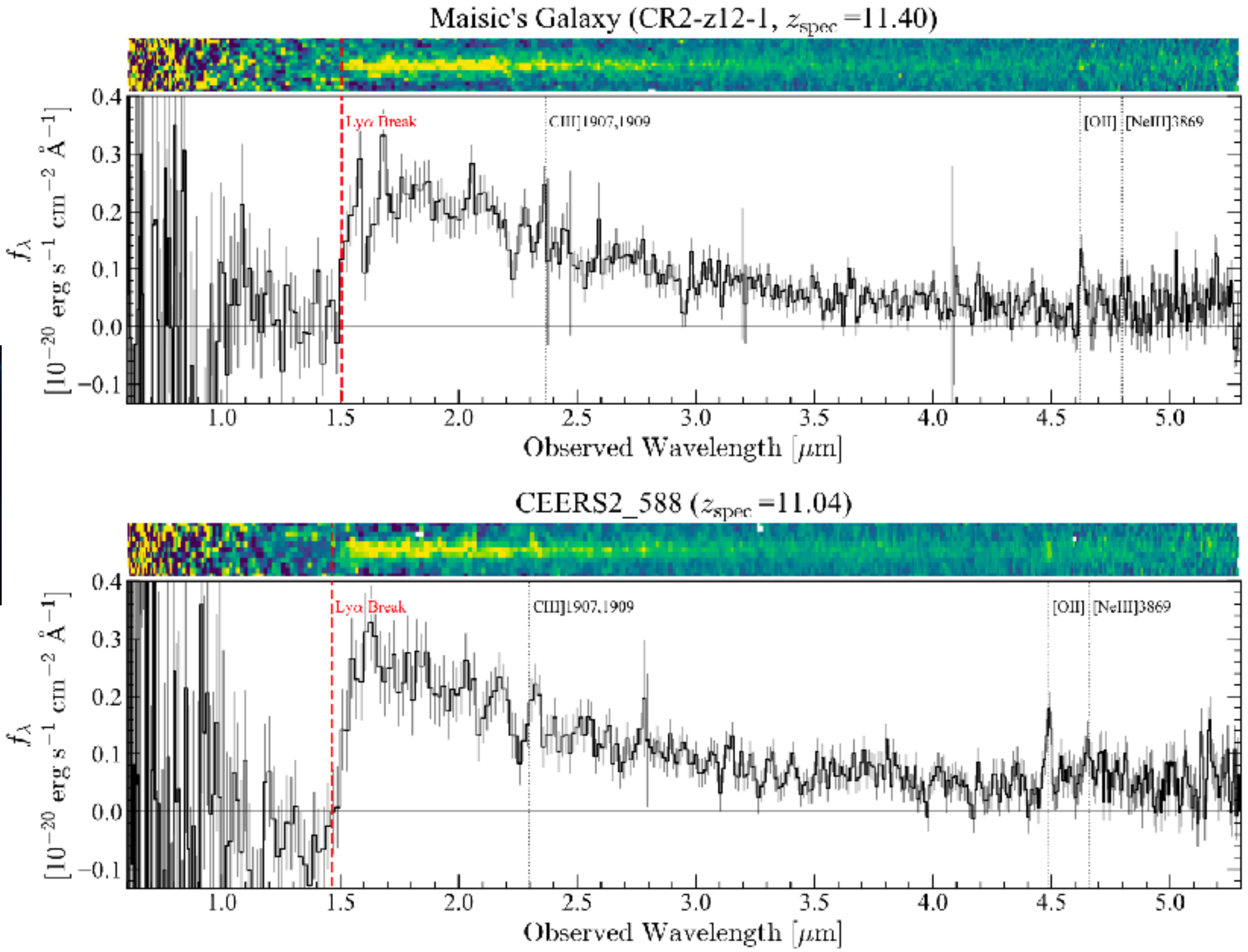
筑波大学
計算科学研究センター
Center for Computational Sciences

Collaborators:
Hidenobu Yajima, Makito Abe

JWST: high-z galaxy observations



(https://www.jpl.nasa.gov/infographics/the-big-bang-and-expansion-of-the-universe)

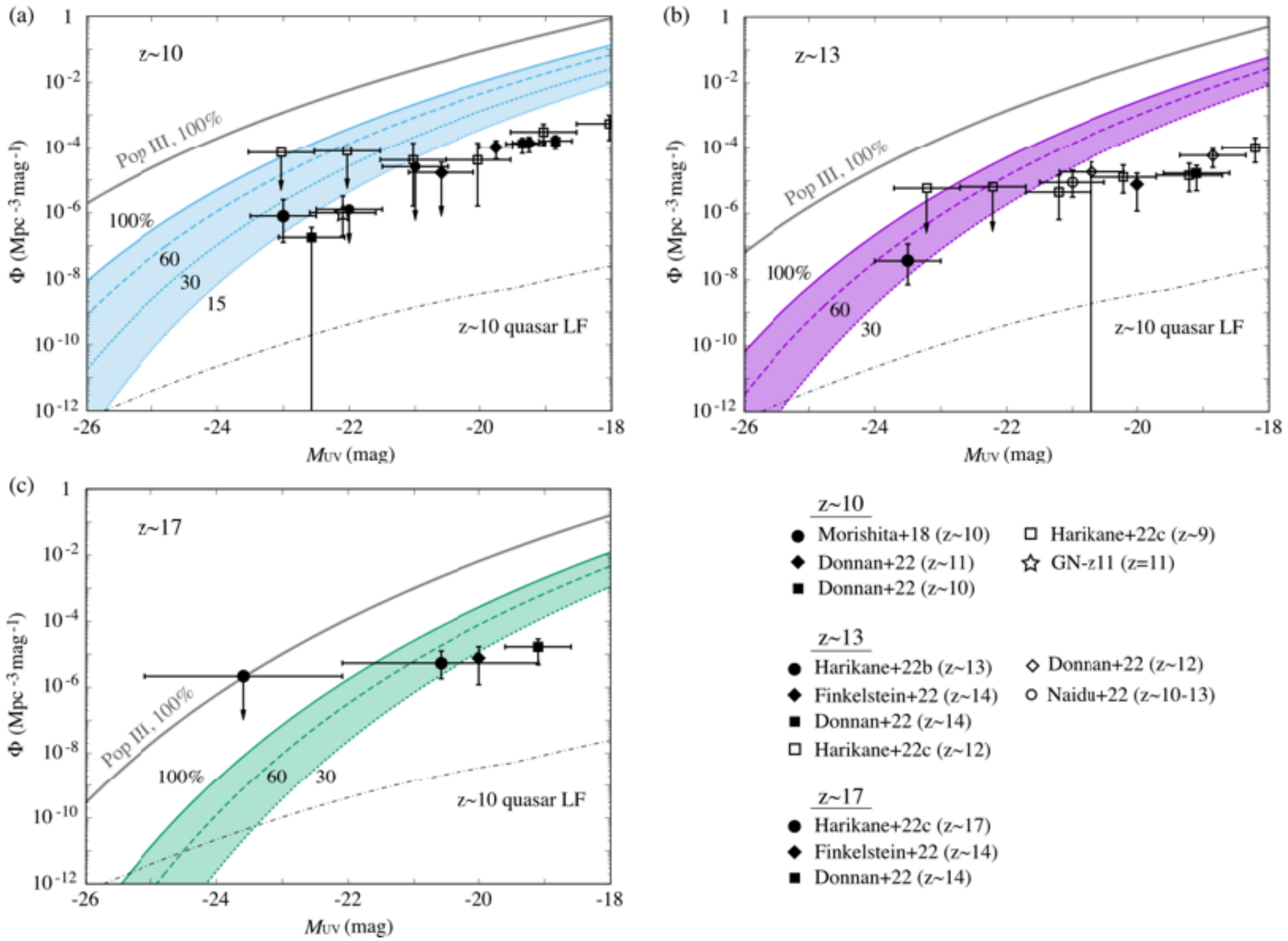


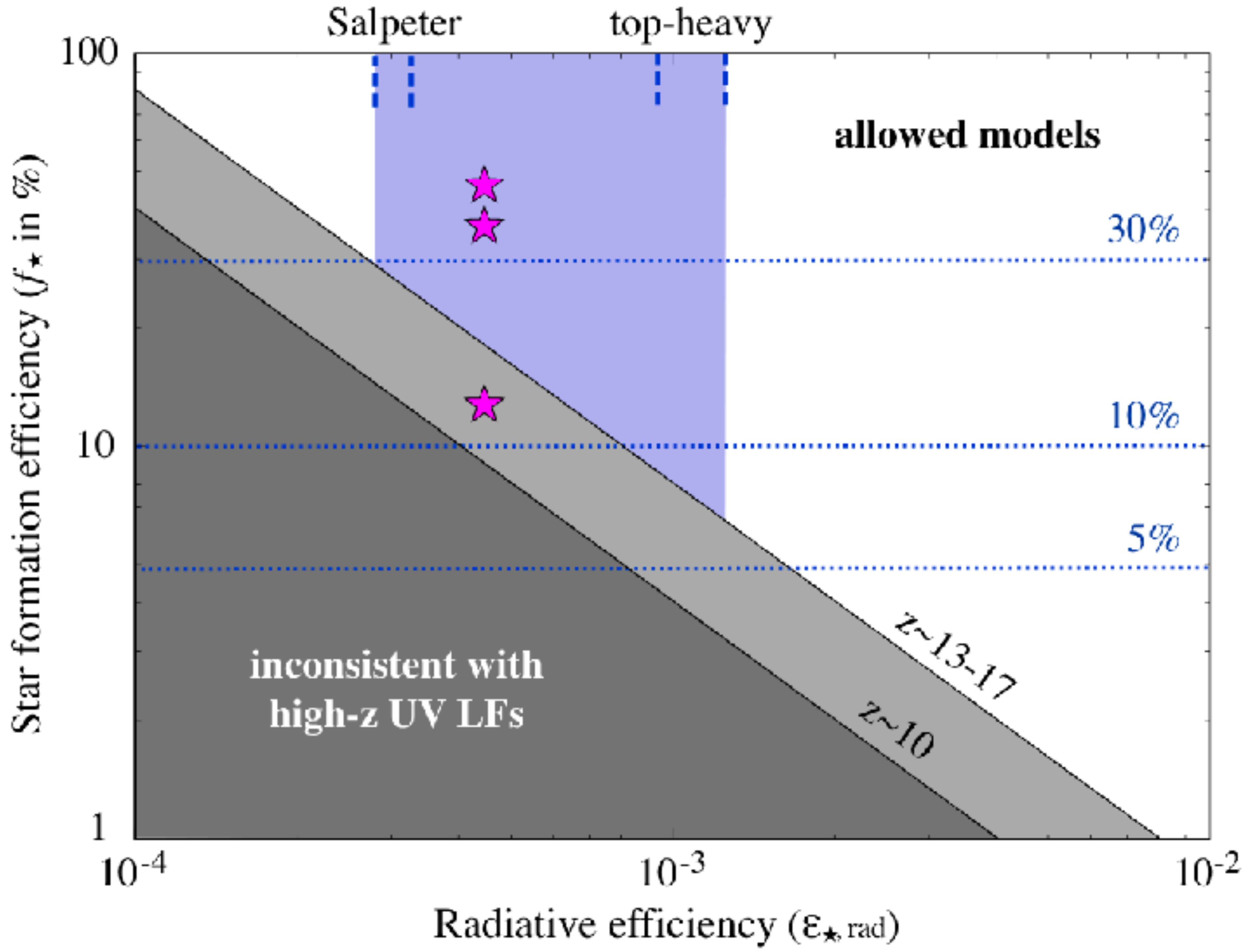
(e.g., Harikane+23)

- Galaxies with z>10 are discovered, and star formation properties are investigated

Star formation properties in high-z galaxies

- Luminosity functions & star formation efficiencies



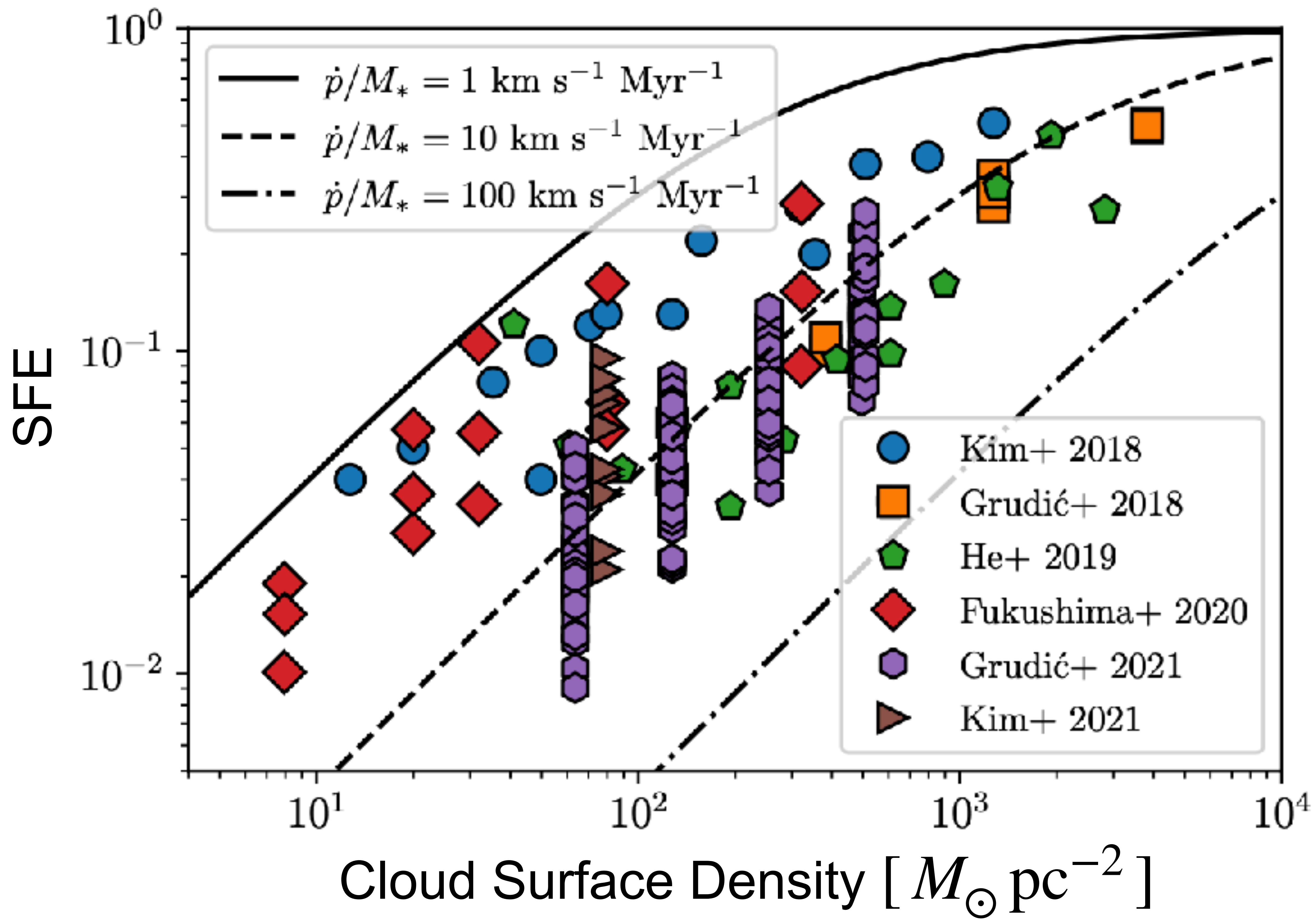


(Inayoshi+22, updated by Harikane+23)

- The lower bound of radiative efficiency and star formation efficinecies are derived with the UV luminosity funcitons.
- High-star formation efficiencies (>5%) or top-heavy IMF is realized (at $z \gtrsim 12$).

(Harikane+23)

High SFE in star cluster formation

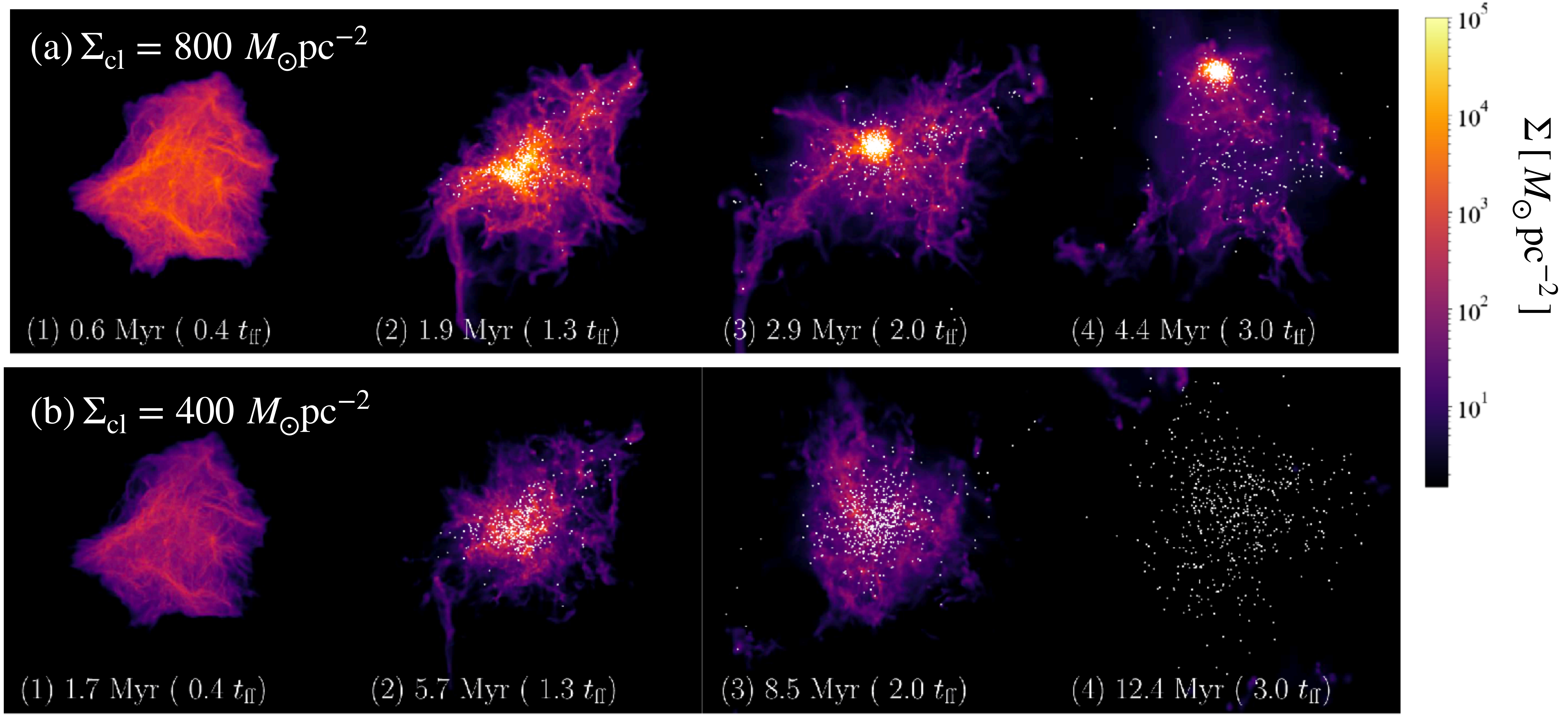


(Chevance+22)

- In more compact clouds, feedback from massive cannot supress star formation, and thus SFEs increase. (Bressert+12, Dale+12)
- SFEs increase in more compact star forming clouds.
- Properties of star clusters born in compact clouds?

Yound massive star cluster (YMC) formation

- Cloud mass: $M_{\rm cl} = 10^6\ M_\odot$



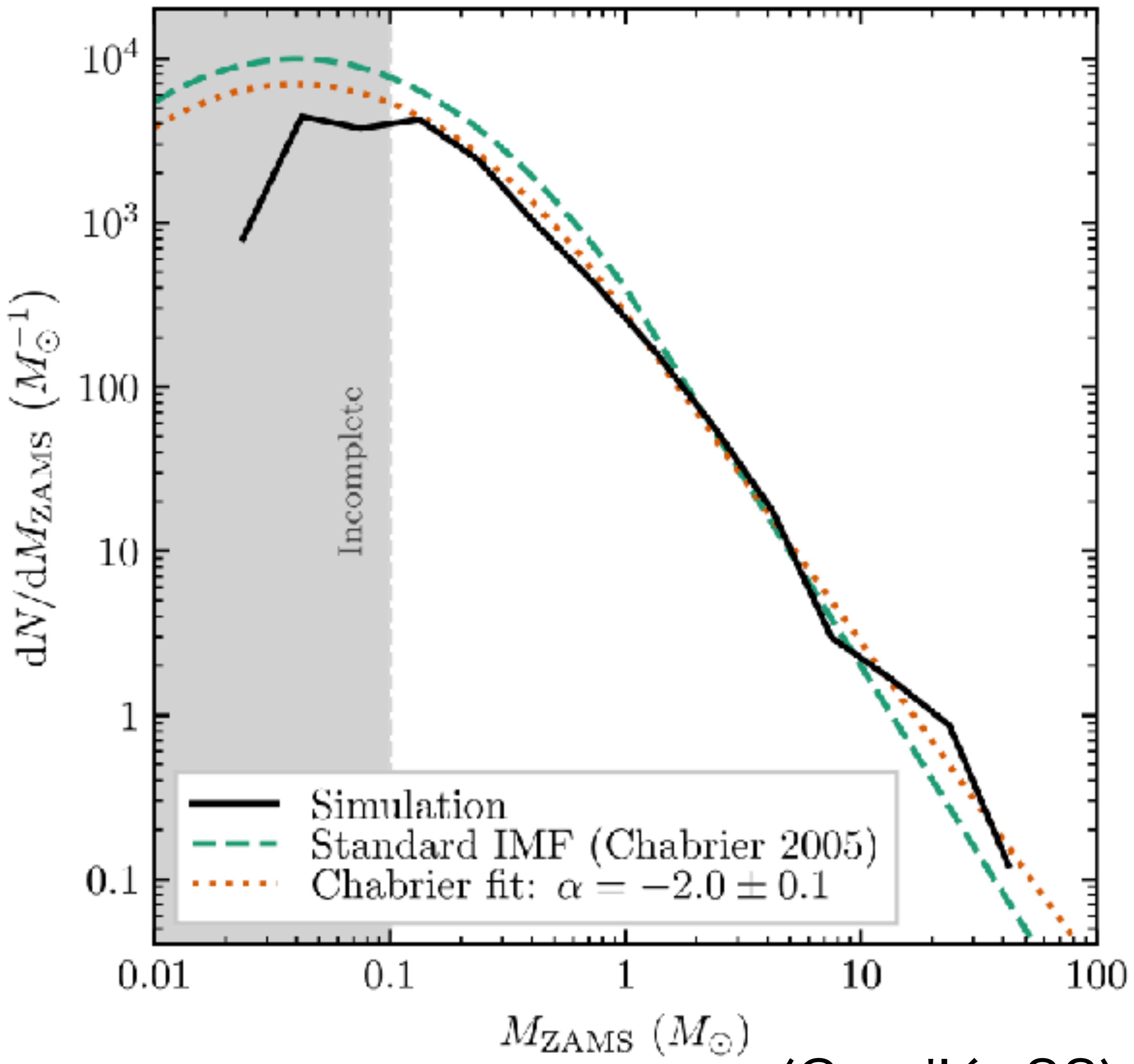
(HF&Yajima 2021)

- In compact clouds, high-density star clusters are formed (YMCs).
- In high-z galaxies, star clusters are mainly born as young massive clusters?

(e.g., Vanzella+2023)

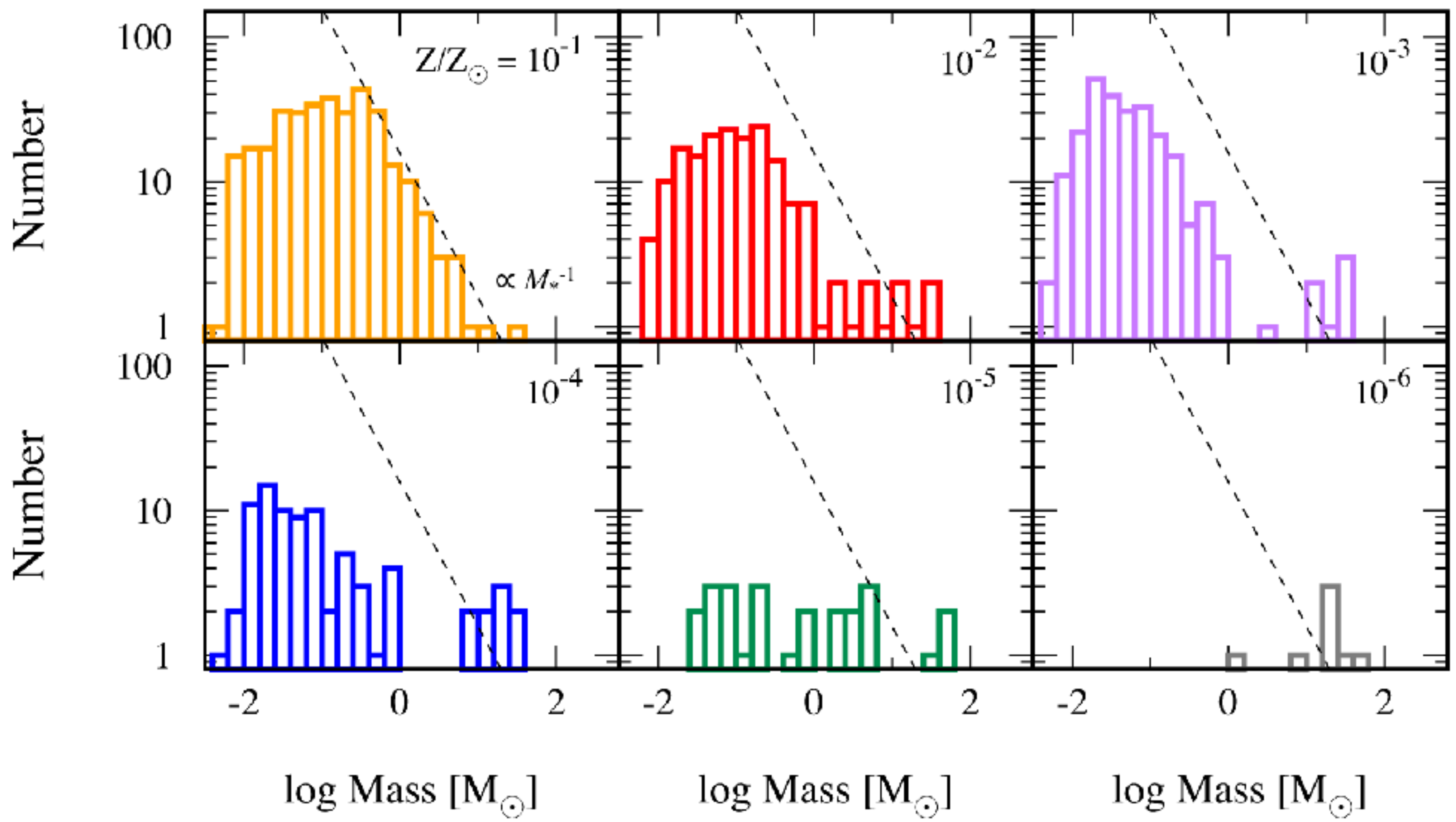
IMF in star cluster formation

Present days($Z = Z_\odot$)



(Grudić+22)

Early galaxies ($Z < 10^{-1} Z_\odot$)



(Chon+21, related to Protostellr mass function session)

- Emissivity of ionizing photon increases with top-heavy IMFs.

How compact clouds is needed to form YMCs with top-heavy IMFs?

Simulation Method

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

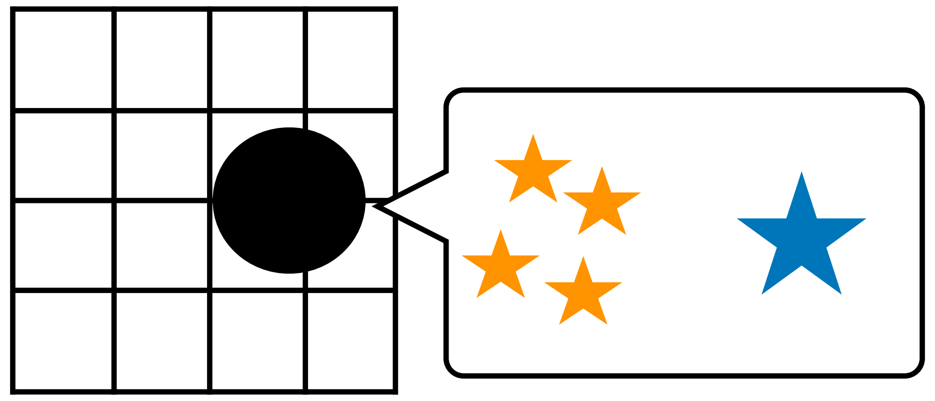
(Rosdahl+13, HF&Yajima 21)

Initial conditions

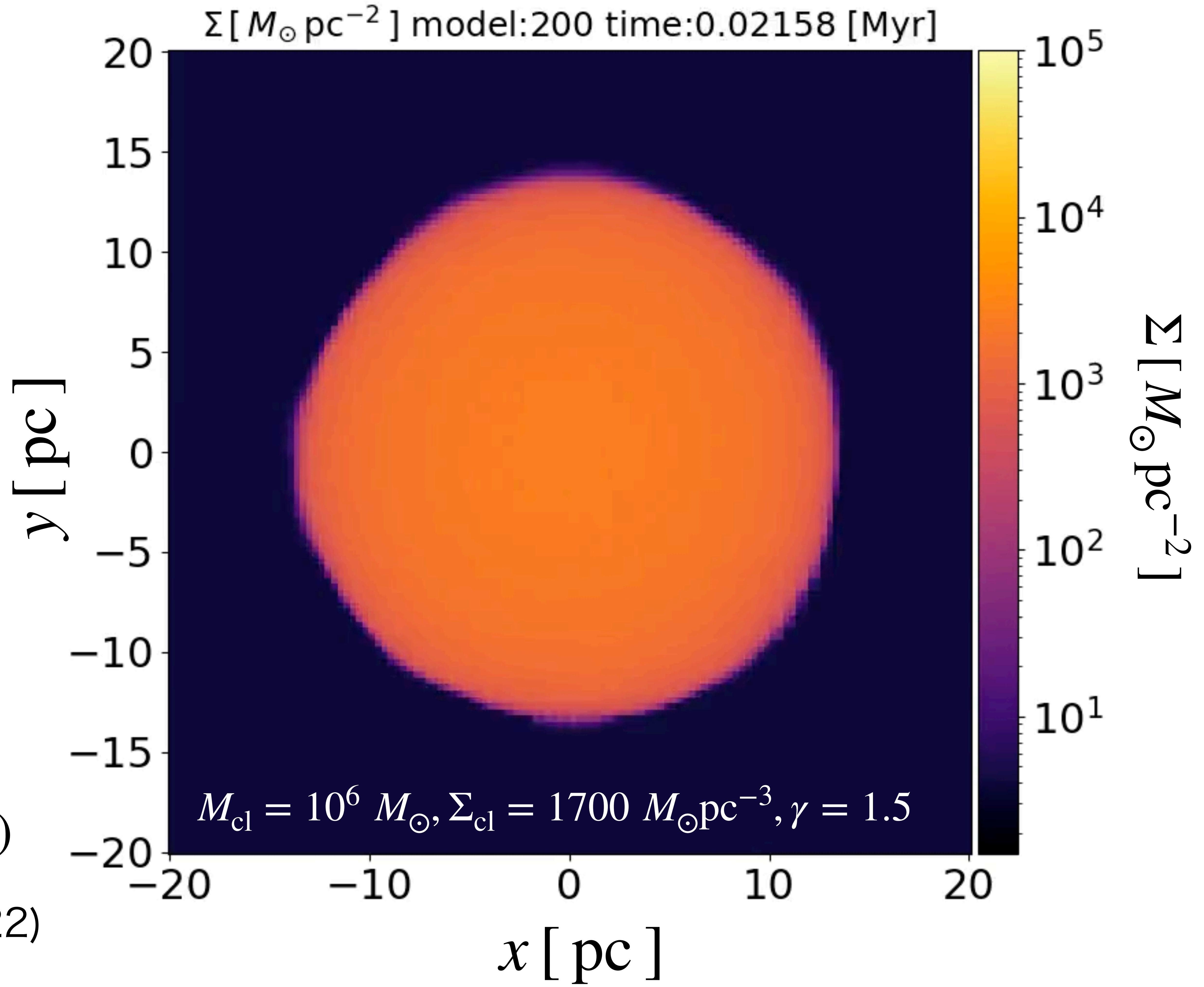
- Uniform density sphere with turbulent motions.
- Cloud mass: $M_{\rm cl} = 10^6, 10^7\ M_\odot$
- Surface density: $\Sigma_{\rm cl} = 400 - 2000\ M_\odot {\rm pc}^{-2}$
- Metallicity: $Z = 10^{-3}\ Z_\odot$

Sink models

- Sink particles contain several stars
- We stochastically distribute stars with probability from the IMF.
- We vary the slope of IMFs $(dn \propto m^\gamma, \gamma = 1 - 2.35)$

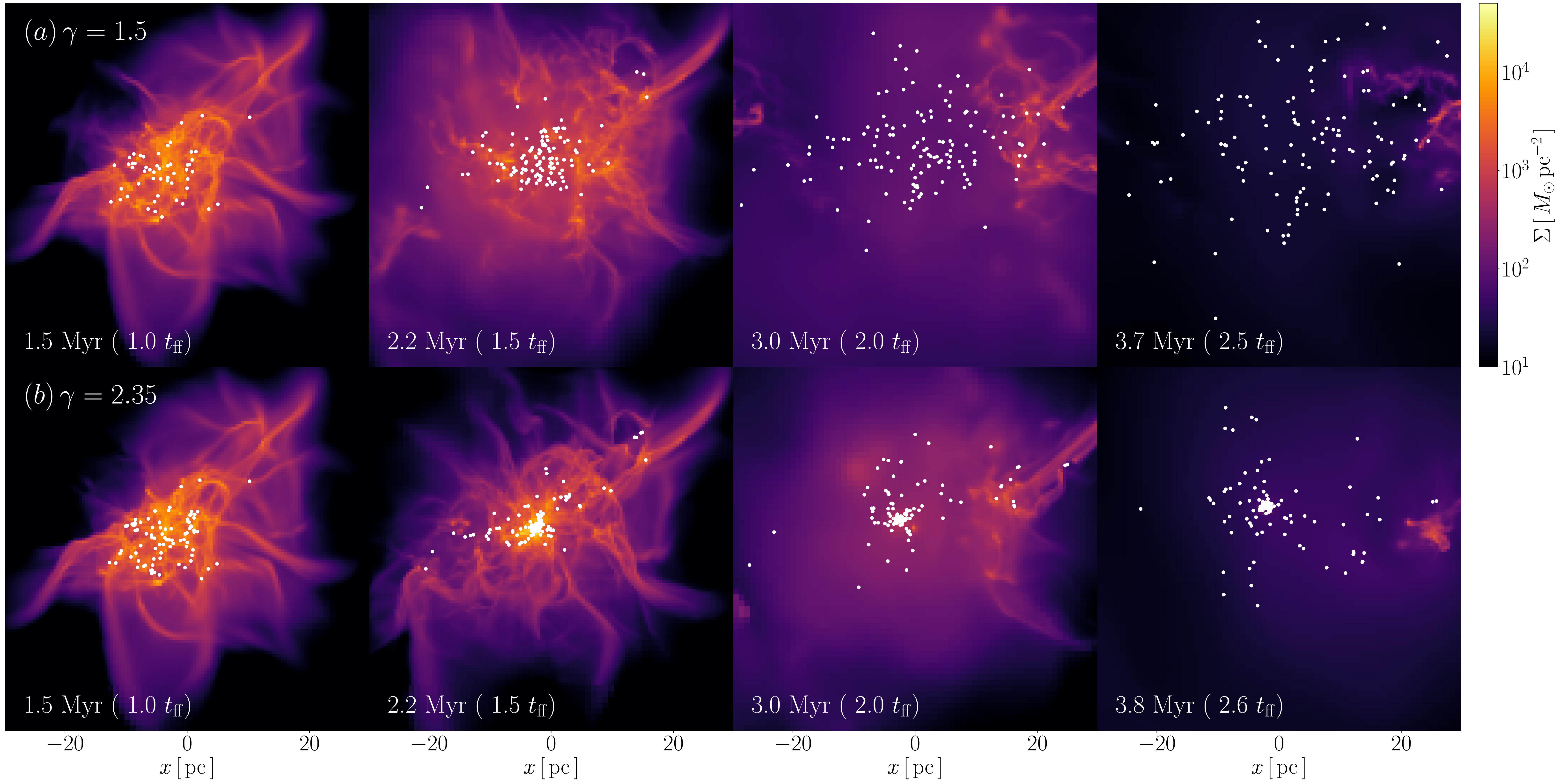


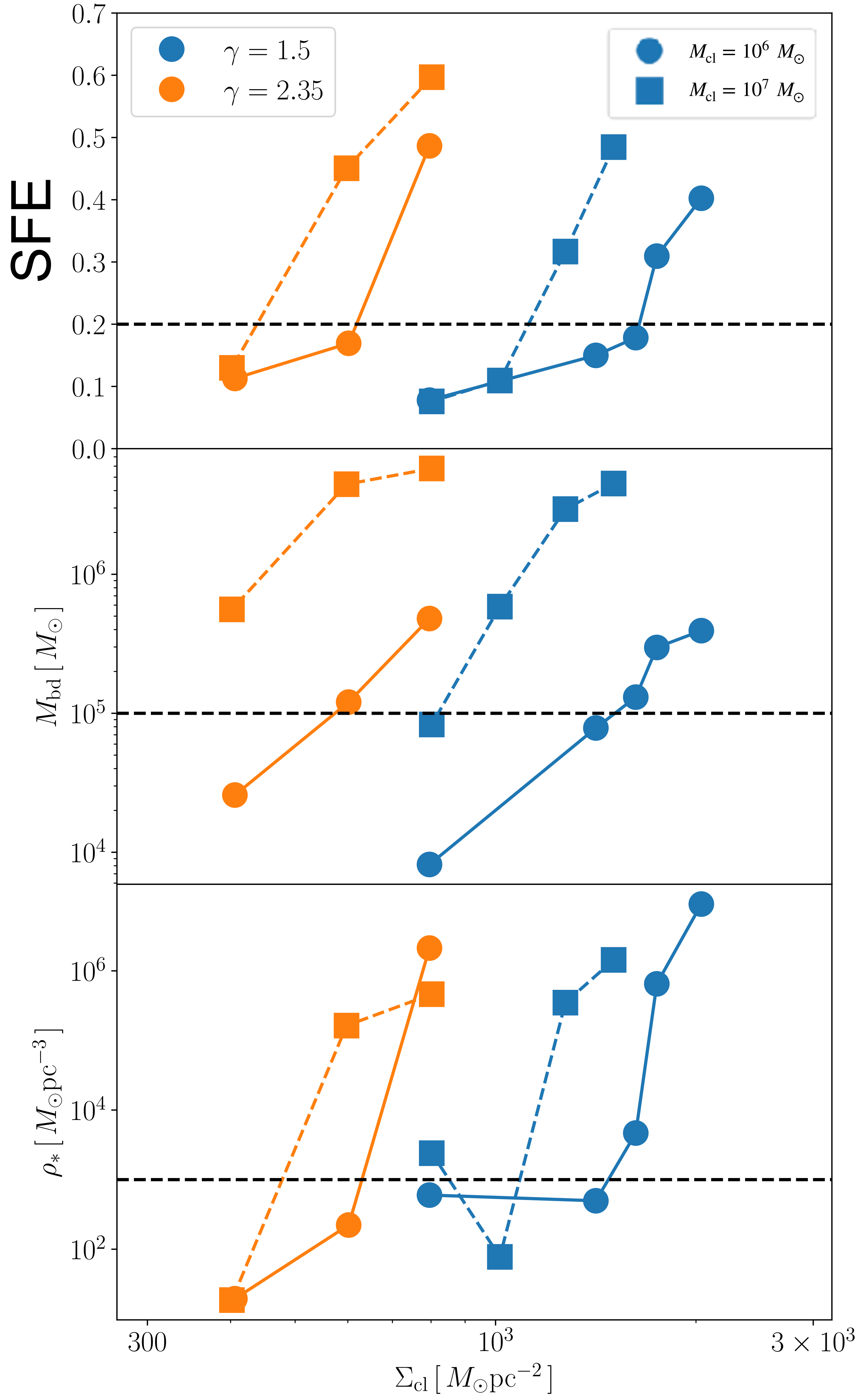
(HF&Yajima 22)



Results

- $M_{\rm cl} = 10^6\ M_\odot, \Sigma_{\rm cl} = 800\ M_\odot \mathrm{pc}^{-2}$



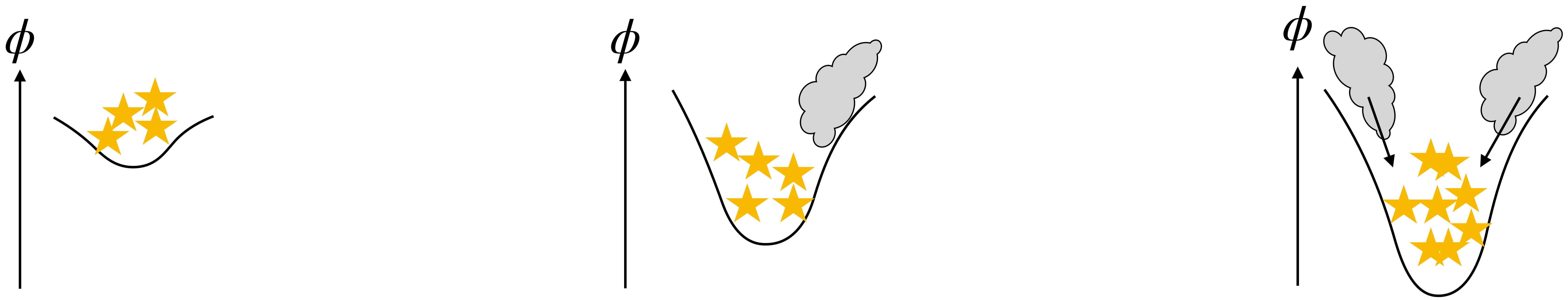


- Photoionization feedback is more effective in dispersing clouds.

YMC formation mechanism

(a) Cloud evolution

(b) Gravitational potential



(1) Start of star formation

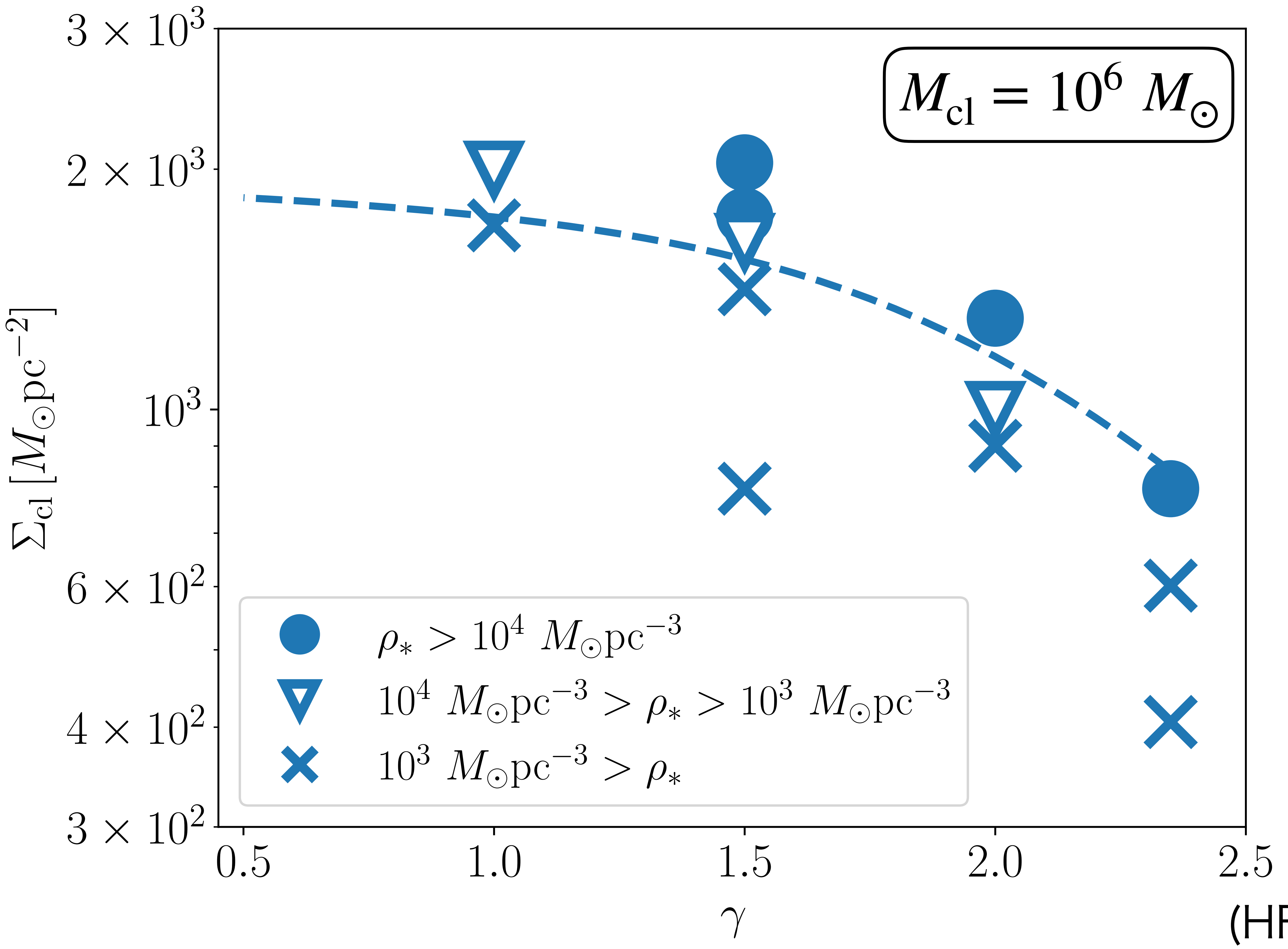
(2) Stars begin to gravitationally bind each other.

(3) Thermal pressure cannot push ambient gas.

Condition of stellar core formation :

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

Conditions for YMC formation



γ: power-law index of IMF

(HF&Yajima 23)

- We also construct the analytical model of YMC formation.

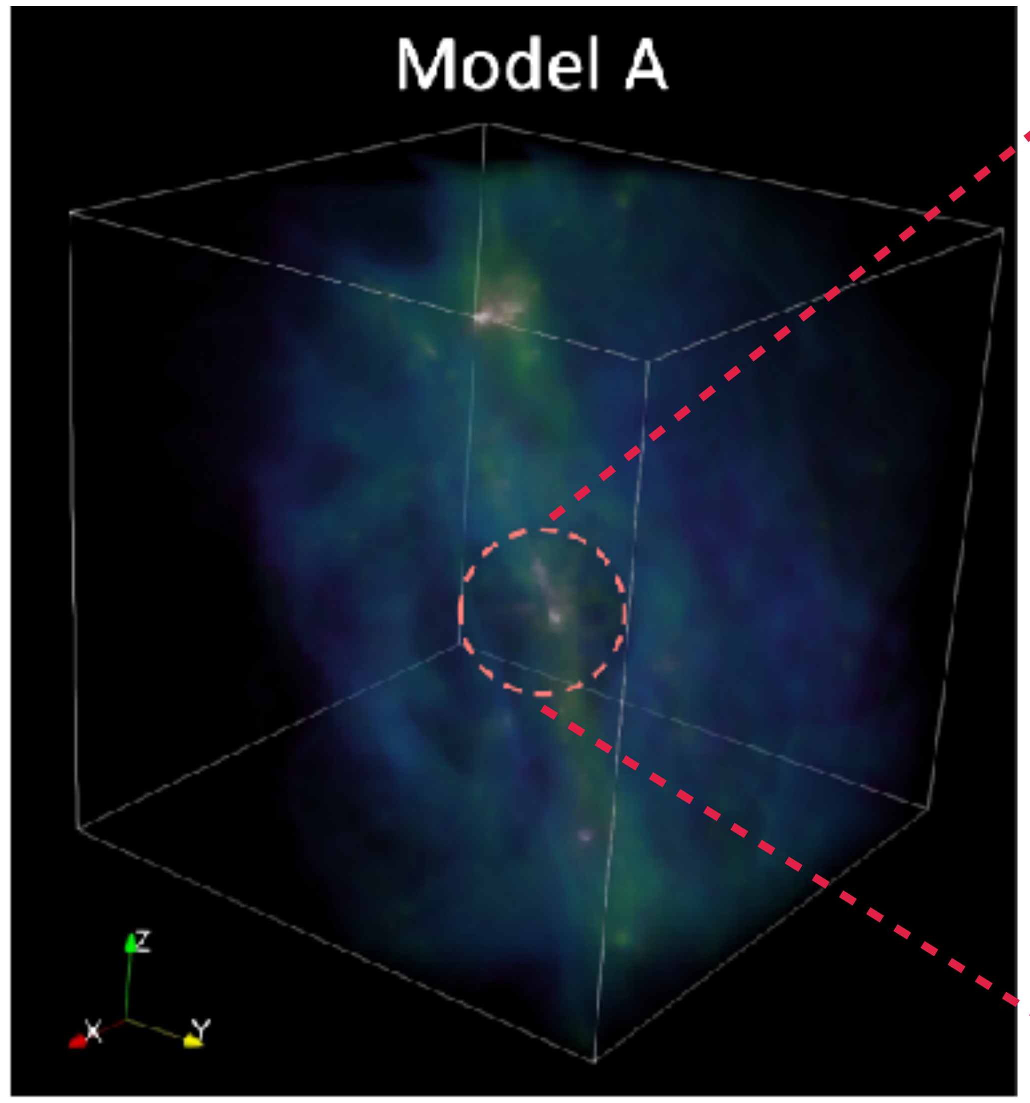
$$\Sigma_{\rm cl} > \Sigma_{\rm thr} = 670\ M_\odot {\rm pc}^{-2} \left(\frac{M_{\rm cl}}{10^6\ M_\odot}\right)^{-1/5} \left(\frac{s_*}{10^{47}\ M_\odot^{-1} s^{-1}}\right)^{2/5} \left(\frac{T_{\rm HII}}{2.5 \times 10^4\ {\rm K}}\right)^{28/25}$$

s_*: emissivity of ionizing photons per stellar mass, $M_{\rm cl}$: cloud mass, $T_{\rm HII}$: temperature of ionizing gas

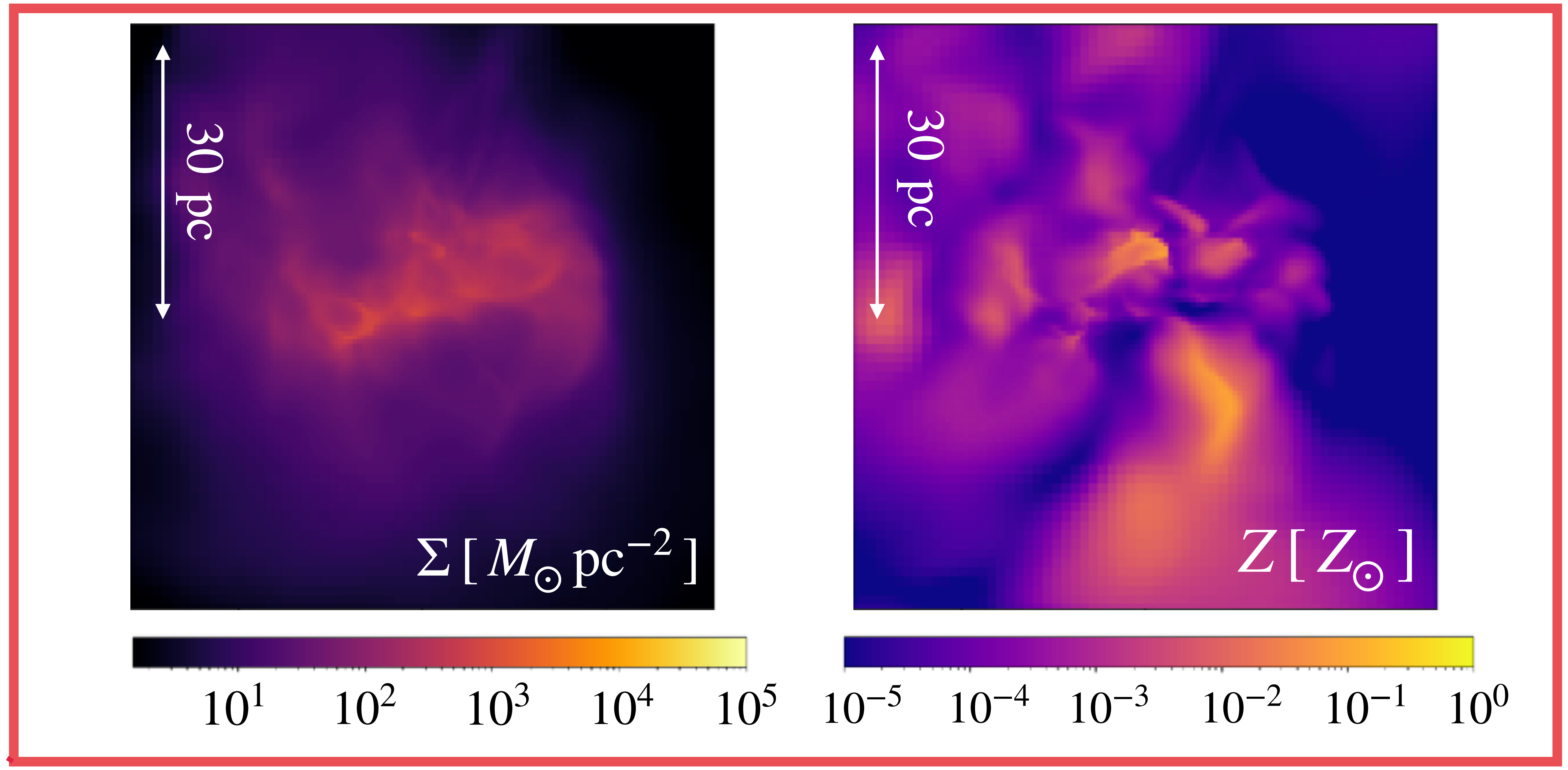
IMF in early galaxies: high resolution simulation

- We also simulate mass growth of individual stars
  - Higher resolutions (sink radius is less 10^{-2} pc)
  - Anisotropic radiation model (Ogata+ in prep)
  - Stellar evolution (Hosokawa & Omukai 09, HF+18)
  - Outflow (Matzner & McKee2000, Cunningham+2011, Grudić+21)

- Initial conditions: star forming clouds in cosmological simulations

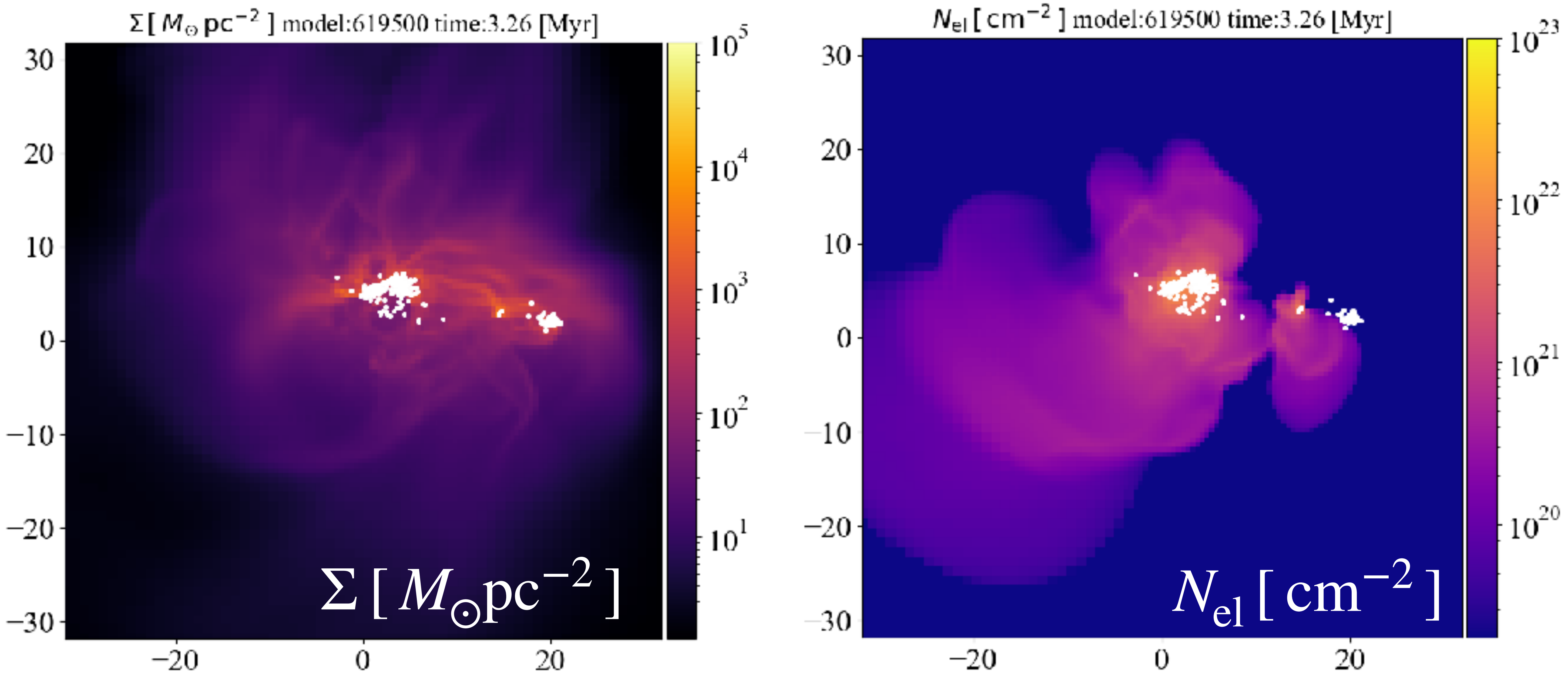


(Abe et al. 2021)

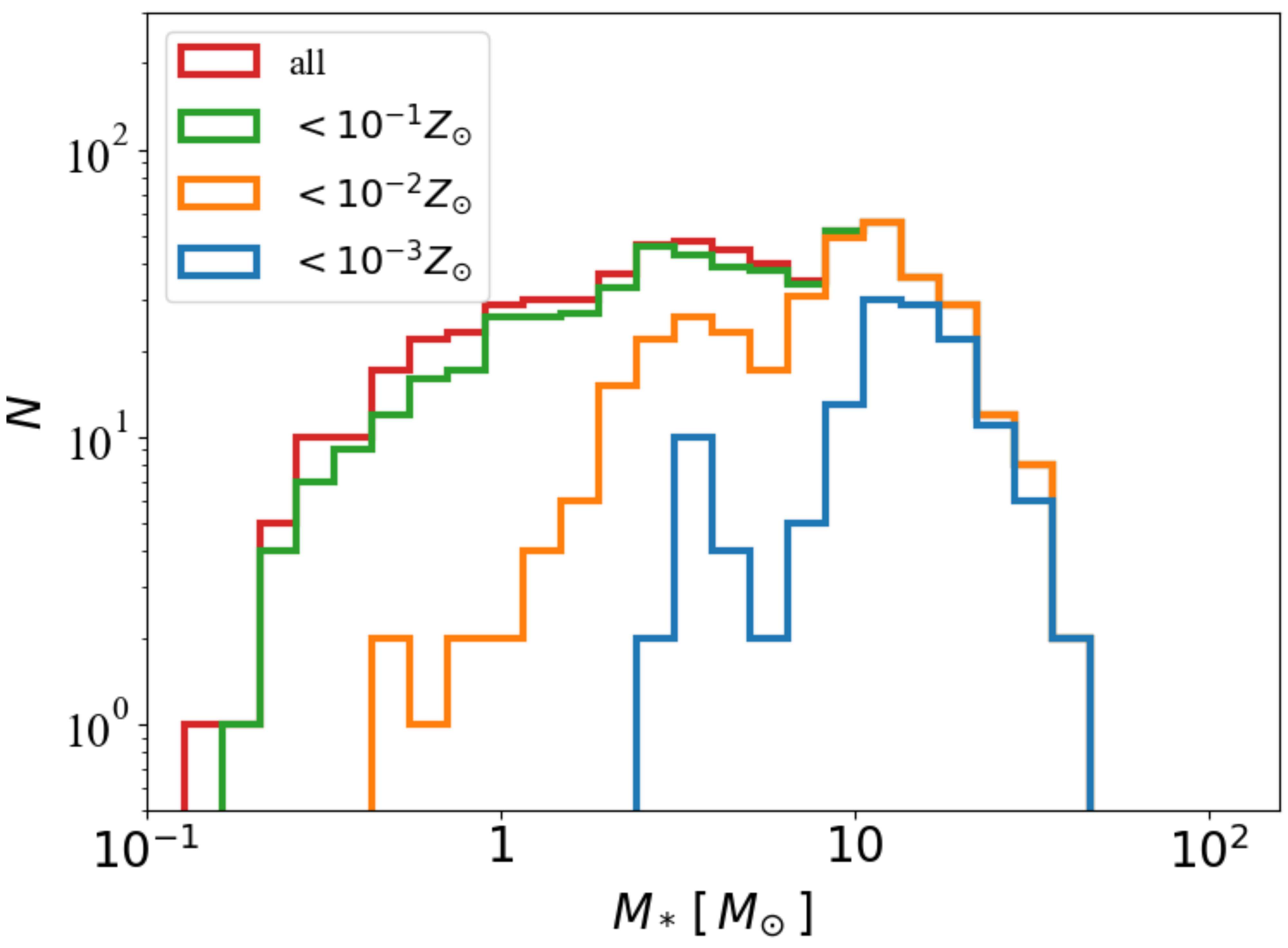


Redshift: 11.52, halo mass: $1.1 \times 10^8 M_\odot$, cloud mass: $1.3 \times 10^5\ M_\odot$, Surface density: $31\ M_\odot \mathrm{pc}^{-2}$

IMF in early galaxies: high resolution simulation



Stellar mass distributions:



Total stellar mass: $\sim 4 \times 10^3\ M_\odot$

- Flat stellar mass functions
- Stellar metallicity is widely distributed ($10^{-4} Z_\odot < Z < Z_\odot$)
- Massive stars are born as low-metallicity stars ($Z < 10^{-2}\ Z_\odot$)

Summary

We perform radiative hydrodynamics simulations of star cluster formation.

We obtain the threshold values of YMC formation as

$$\Sigma_{\rm cl} > \Sigma_{\rm thr} = 670\ M_\odot {\rm pc}^{-2} \left(\frac{M_{\rm cl}}{10^6\ M_\odot}\right)^{-1/5} \left(\frac{s_*}{10^{47}\ M_\odot^{-1} s^{-1}}\right)^{2/5} \left(\frac{T_{\rm HII}}{2.5\times 10^4\ {\rm K}}\right)^{28/25}$$

The high-star formation efficiency in high-z galaxies is attributed to the formation of young massive star clusters.

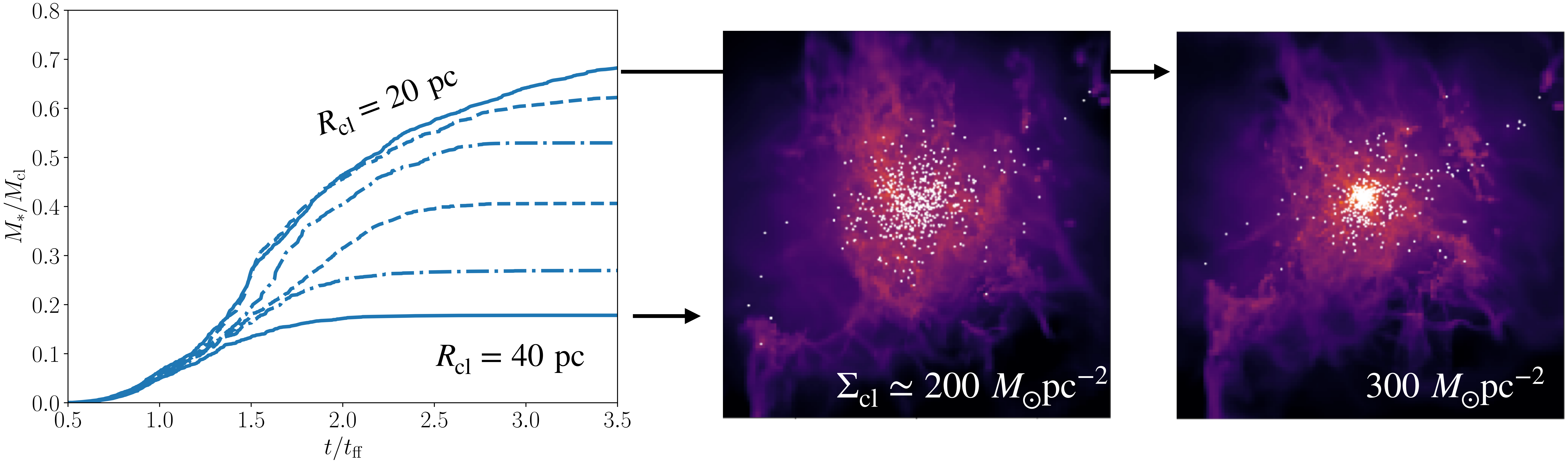
We also obtain the stellar IMF with the high resolution simulation.

Massive stars are born as low-metallicity stars.

SFEs vs Surface density

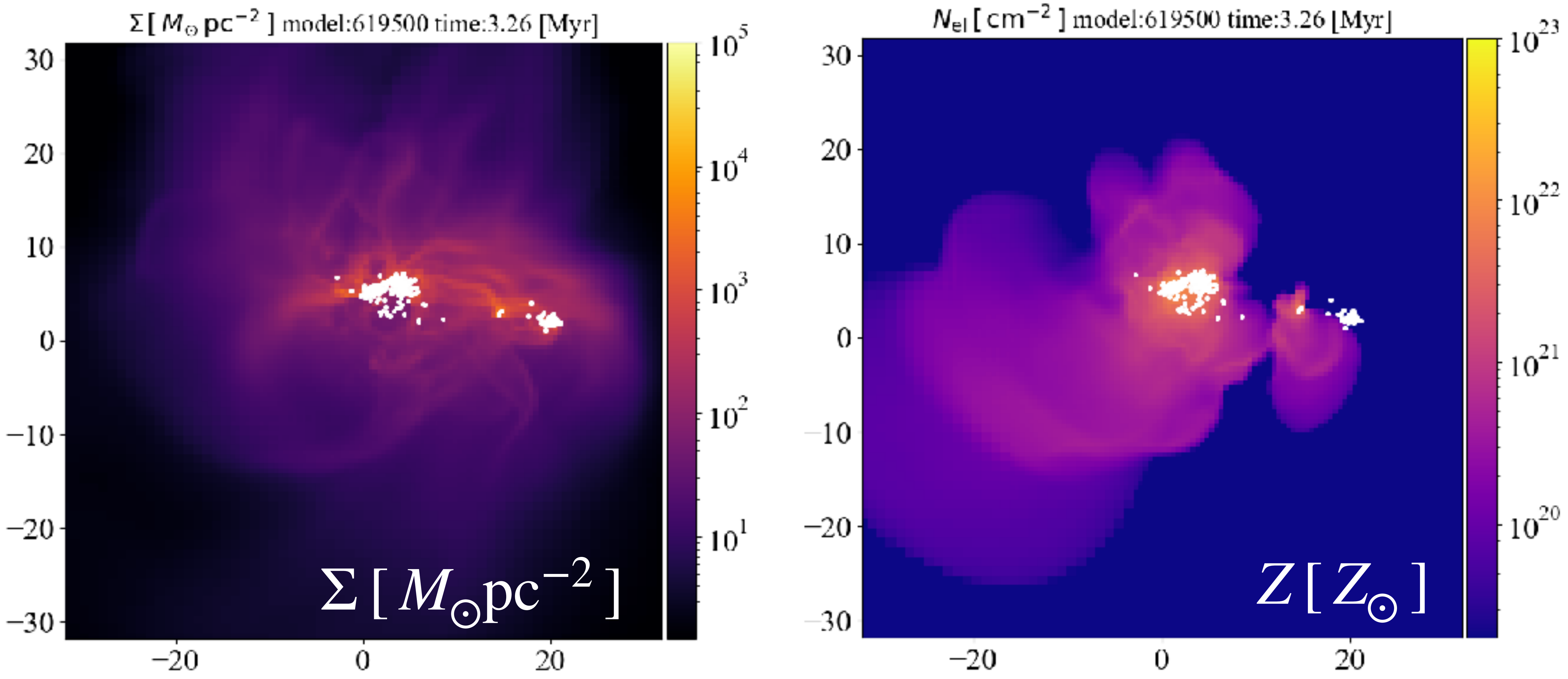
Time evolution of total stellar mass

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



- 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 $\sim 1.3\ t_{\rm ff}$.

W/o outflow



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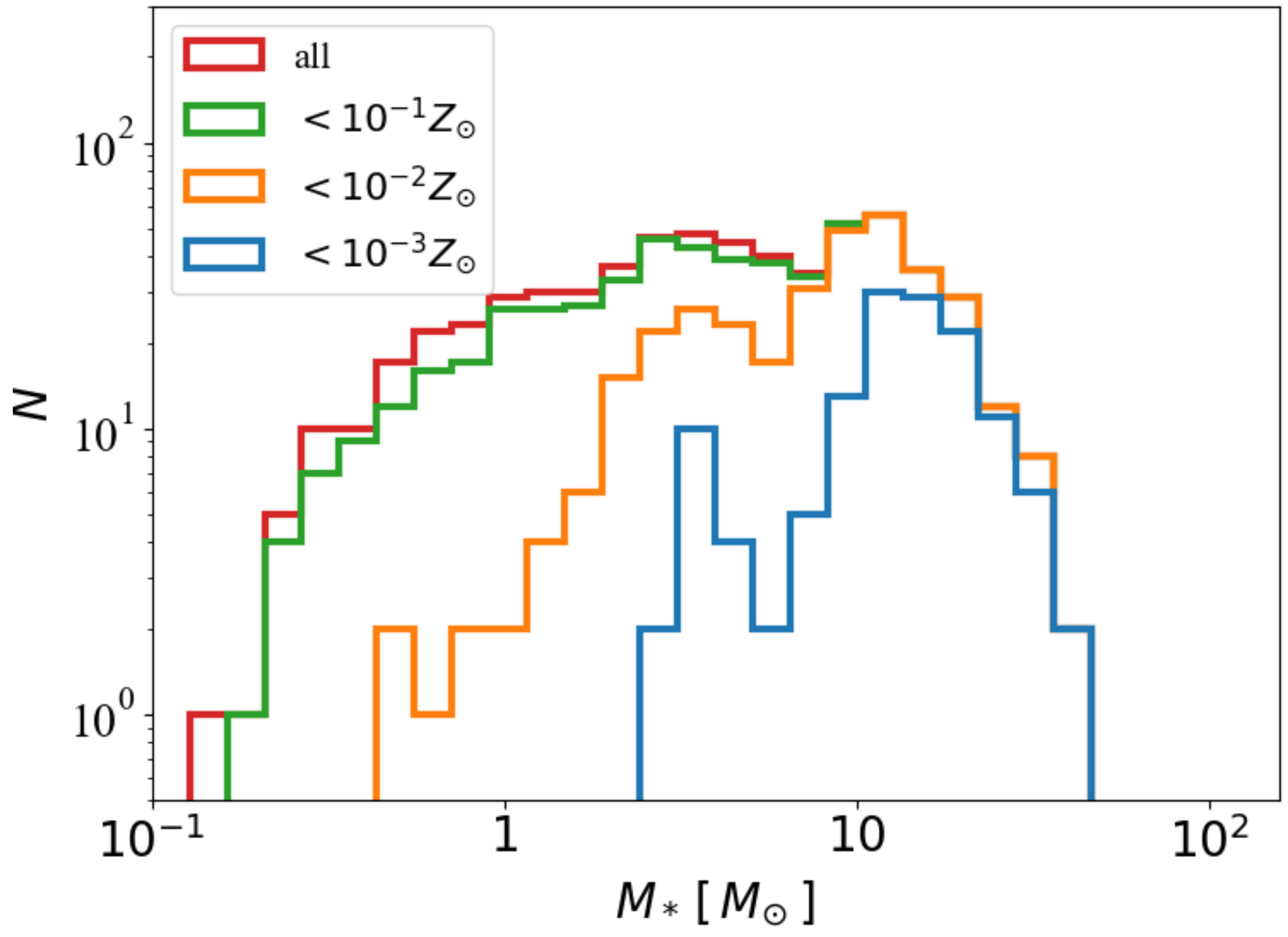

Total stellar mass: $\sim 4 \times 10^3\ M_\odot$

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