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Formation of the First Galaxy via the Formation and Merger of Pop II Star Clusters

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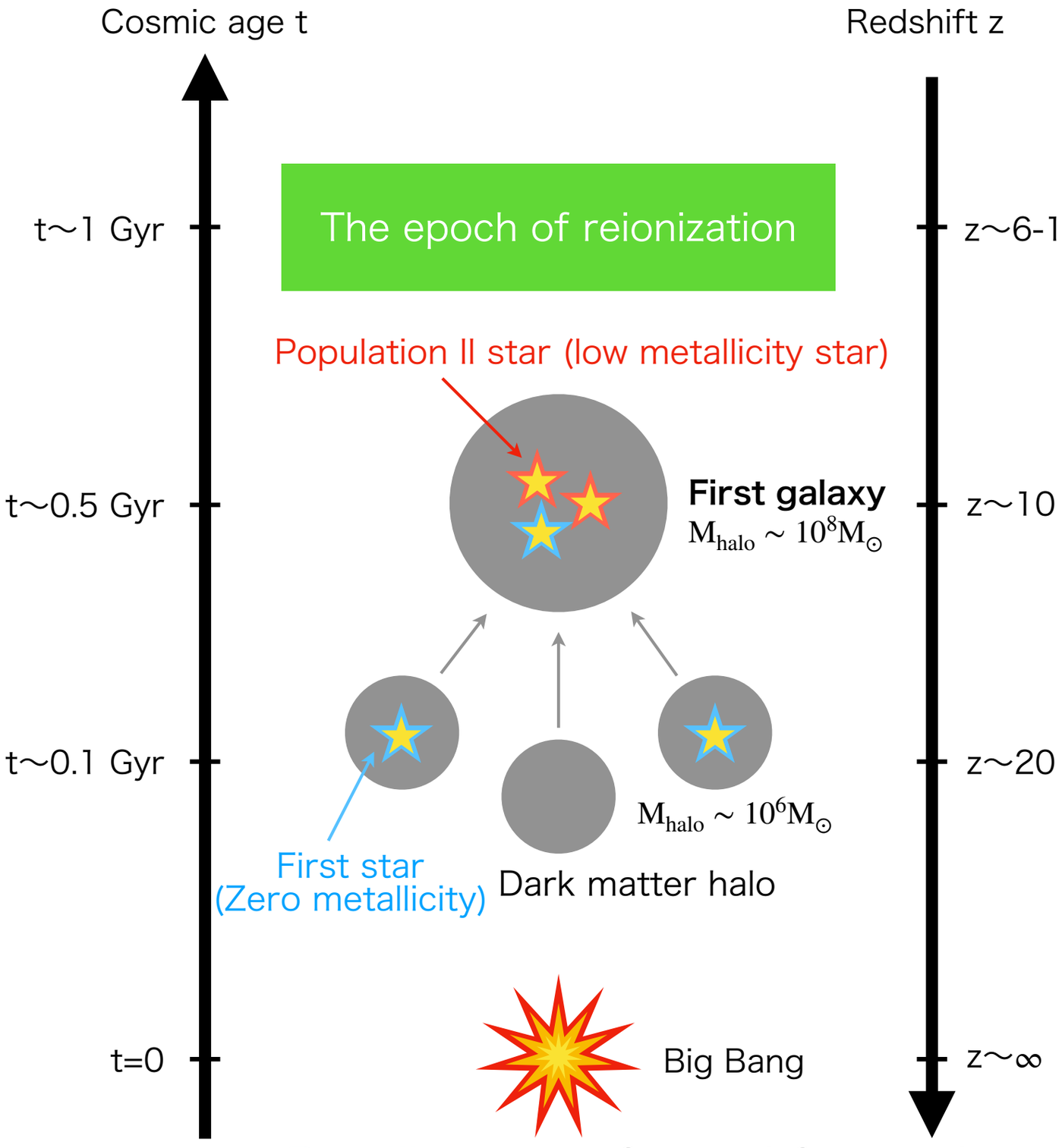
What is First Galaxy

✓Theoretical picture of first galaxy formation



Dark matter(DM) assembles in dense regions and forms DM halos.

Baryons accumulate at the centers of DM halos due to the gravitational potential of the DM and line-emission cooling.

First stars form, when $M_{\rm h} \sim 10^6 M_\odot$.

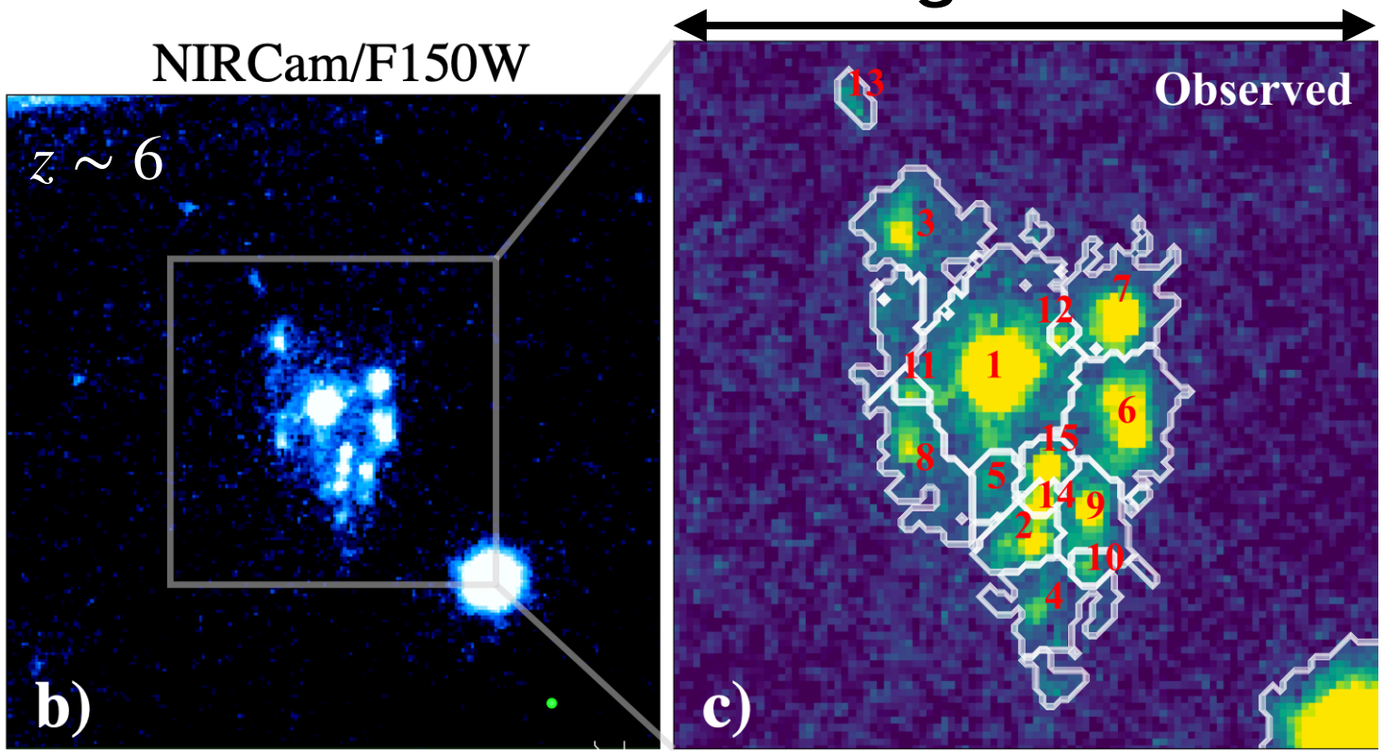
First galaxies form, when $M_{\rm h} \sim 10^8 M_\odot$.

First galaxy is the first stellar system to form at the center of a DM halo.

- Pop III stars ⋯ formed from primordial gas
- Pop II stars ⋯ formed from metal-polluted gas

Morphological properties of high-redshift galaxies

✓ JWST Observations Through Gravitational Lensing effect



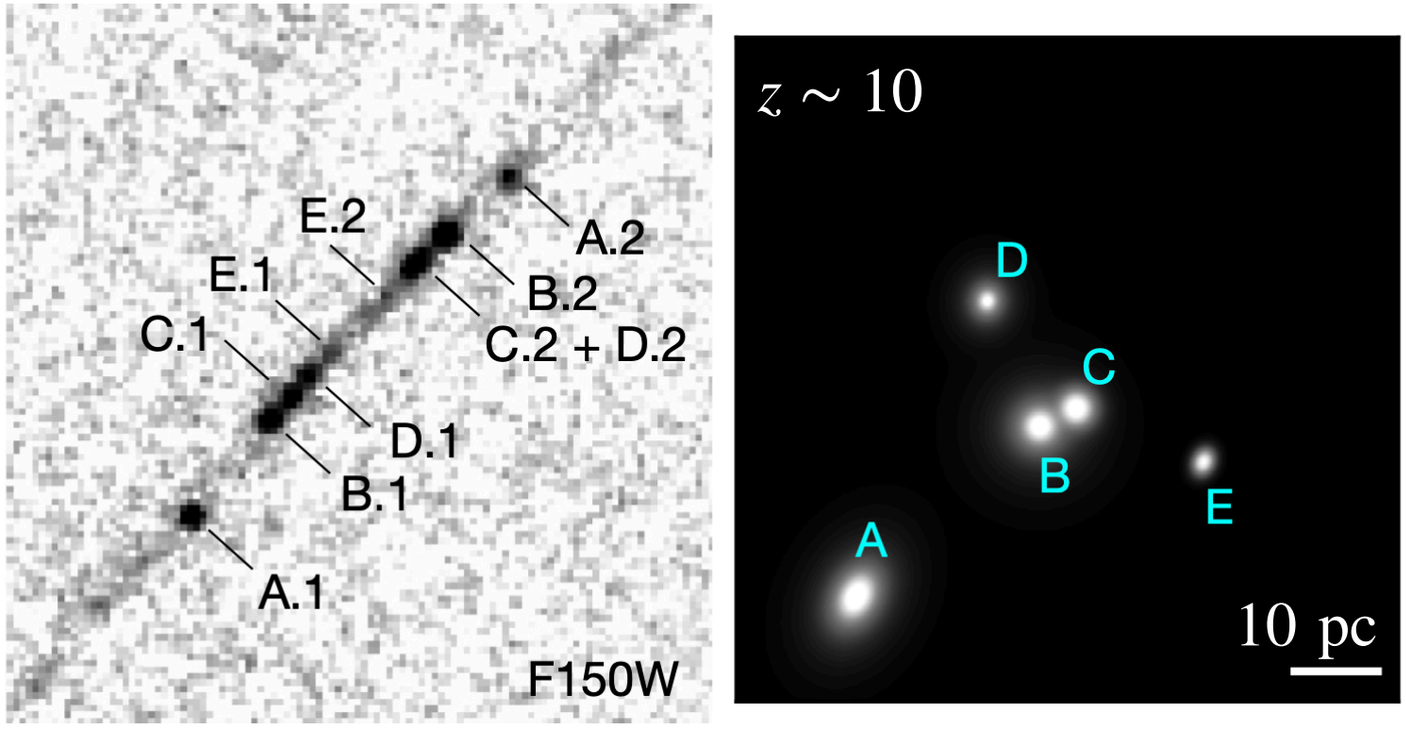
The Cosmic Grapes
(Fujimoto et al. 2024)

- Clumpy structure
- High surface density

$\Sigma_{gas} \simeq 10^{3-5}$ [$M_\odot$/pc^2]

$\Sigma_* \sim 10^5$ [$M_\odot$/pc^2]

However, the formation mechanism of such structures is still not well understood.



The Cosmic Gems arc (Adamo+24, Messa+25)

Molecular hydrogen(H_2) as a dominant coolant

One of the most difference from nearby universe and early universe is the cooling process of gas.

H_2 is the dominant coolant in early universe.

But it is destructed by radiation from stars.

✓ Radiative feedback on the abundance of molecular hydrogen

- photo-dissociation of H_2 via Lyman-Werner radiation $H_2 + h\nu \rightarrow 2H$

  $(11.2 - 13.6\ \mathrm{eV})$
- photo-detachment of H^- via photons ($h\nu > 0.75\ \mathrm{eV}$) $H^- + h\nu \rightarrow H + e^-$

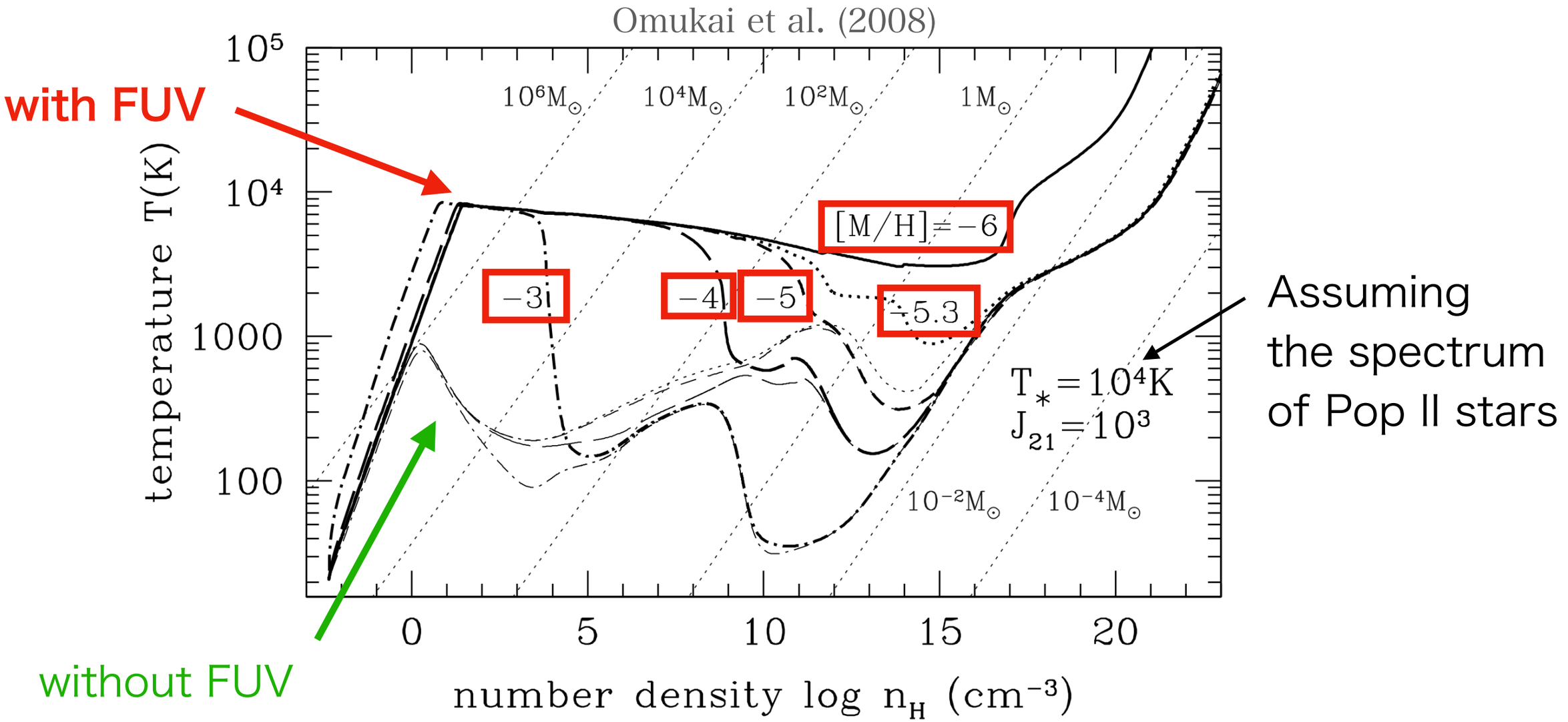
If the abundance of H_2 is low,

atomic cooling or metal-line cooling becomes important.

Because these three cooling processes compete with each other,

the situation becomes complicated.

Thermal evolution of isothermal gas sphere



- the difference of thermal evolution is significant in high density regime.
- Due to the Lyman-Werner (FUV) radiation, the fragmentation via self-gravity of star forming gas is suppressed until gas density becomes high.
  →A dense star cluster will be formed in such gas.

Aim

We conduct high resolution cosmological hydrodynamical simulations to study the formation of compact star cluster and morphology of first galaxy.

Cosmological Zoom-in Simulation

Code : GADGET-3 (Springel et al. 2001; Springel 2005)

- SPH + N-body (DM and star particles) simulation
- Non-equilibrium chemistry of primordial gas ($e^-, H, H^+, He, He^{++}, H_2, H_2^+, H^-, D, D^+, HD, HeH^+$) (Maio et al. 2007)

Zoom-in Simulation

- Simulation time : redshift 100 → 9 (~ 0.5 Gyr)
- Halo mass (at redshift 9) : $\sim 5\times10^8 M_\odot$, $\sim 1\times10^9 M_\odot$, $\sim 2\times10^9 M_\odot$, $\sim 5\times10^9 M_\odot$
- SPH mass $\sim 130\ M_\odot$(smoothing $h \sim 1\left(\frac{10}{1+z}\right)$ pc)、Softening $\epsilon = 9.83\left(\frac{10}{1+z}\right)$ pc

Star Formation Parameters

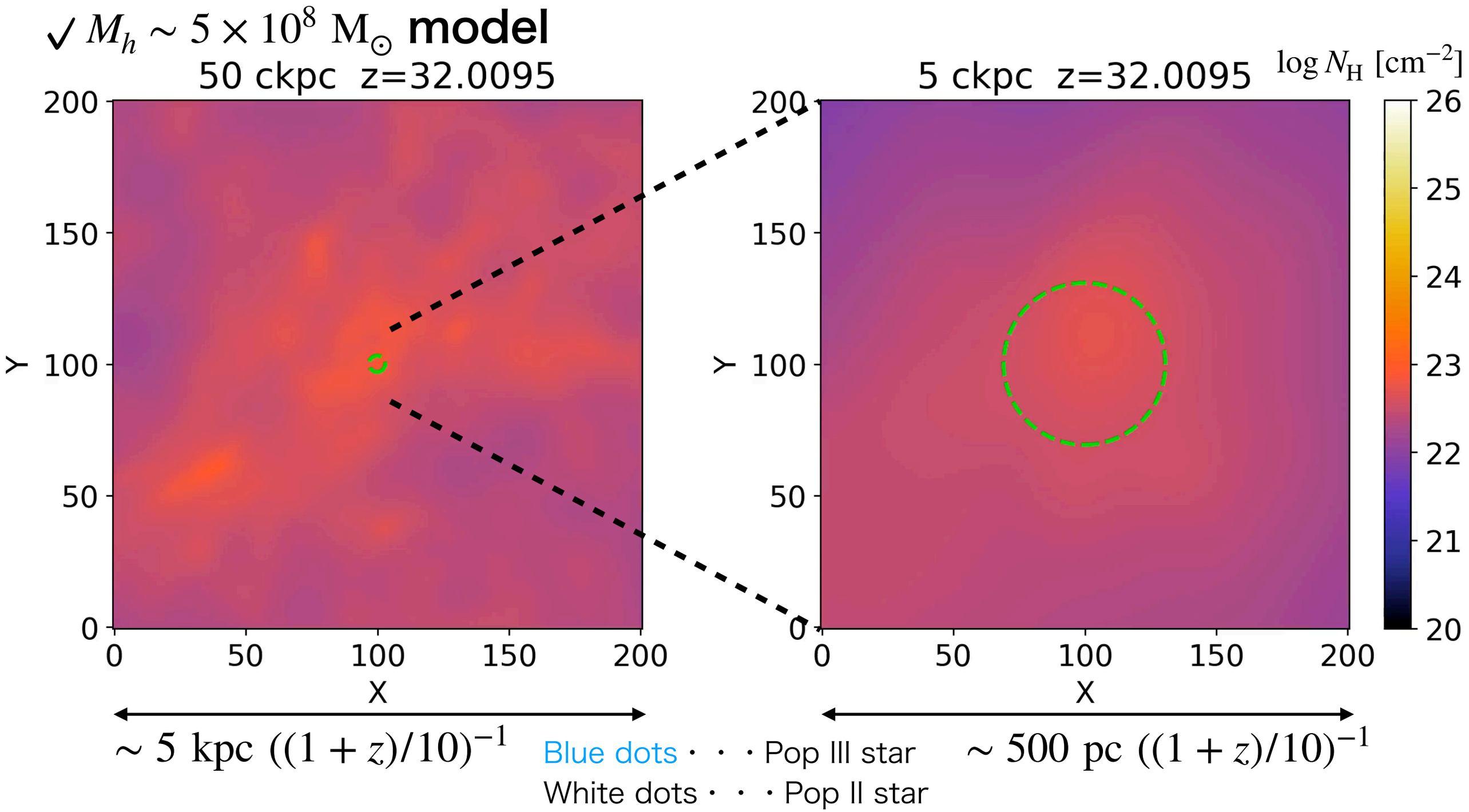
- Star formation rate (density) : $\frac{d\rho_*}{dt} = c_* \frac{\rho_{\rm gas}}{t_{\rm ff}}$ $(c_* = 0.05)$ (Federrath & Klessen 2012)
- Star formation criteria : $10^2\ {\rm cm}^{-3} < n_{\rm H} < 10^5\ {\rm cm}^{-3}$ and $T < 2000$ K
- Pop III → Pop II transition metallicity : $Z > 1.5\times10^{-4}\ Z_\odot$ (Omukai et al. 2005)
- Initial mass function (IMF) :
  Pop III : log-flat IMF $[10M_\odot < M < 500M_\odot]$ (Hirano et al. 2014)
  Pop II : Chabrier IMF $[0.1M_\odot < M < 100M_\odot]$

Stellar Feedback

- Average lifetime of massive stars : $t_{\rm fb} = 14$ Myr
- Type II SNe (Dalla Vecchia & Schaye 2012) , Ionizing and FUV radiation (Abe et al. 2021)

Column density map of gas

✓ $M_h \sim 5 \times 10^8\ \mathrm{M}_\odot$ model



Blue dots ・・・Pop III star

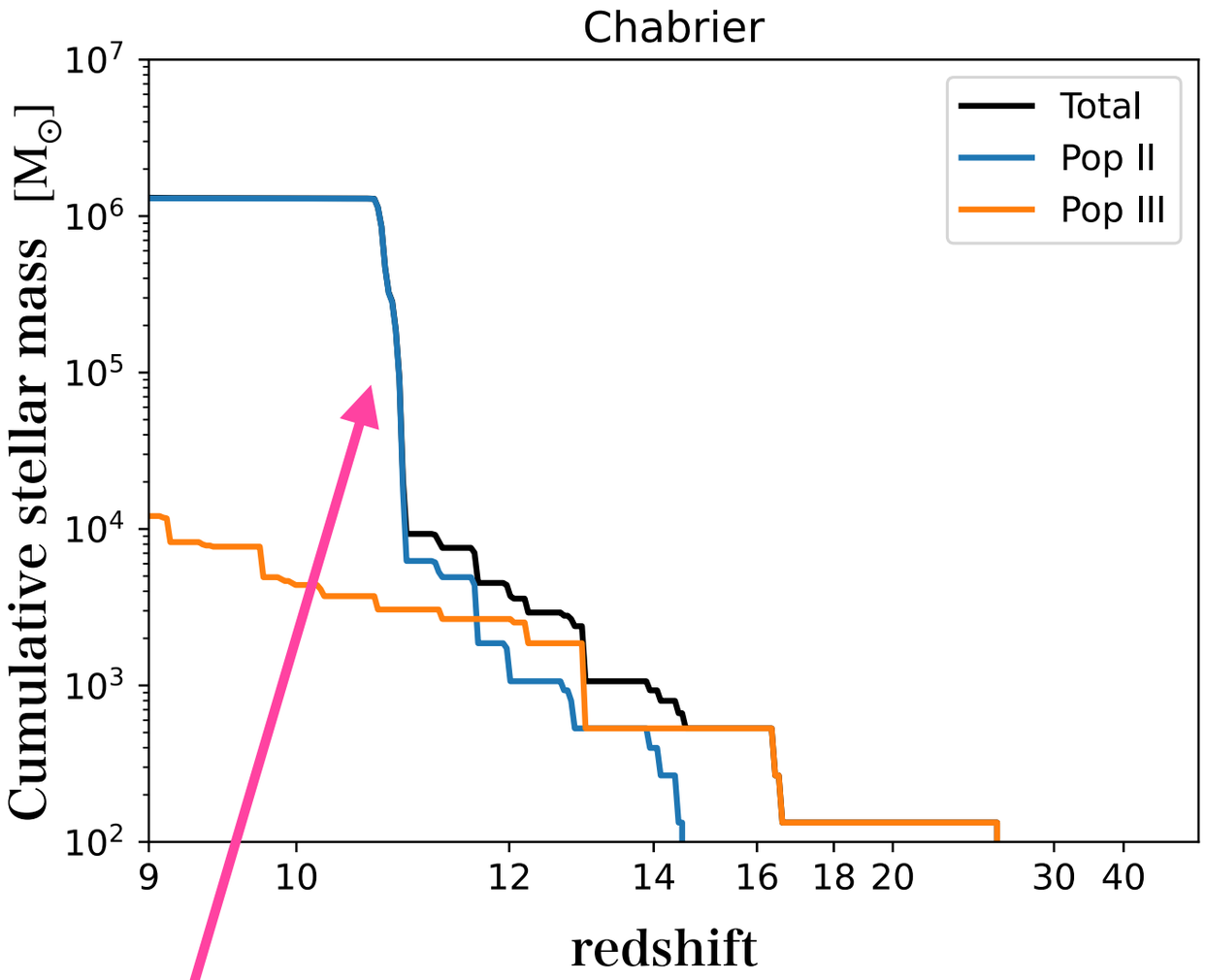
White dots ・・・Pop II star

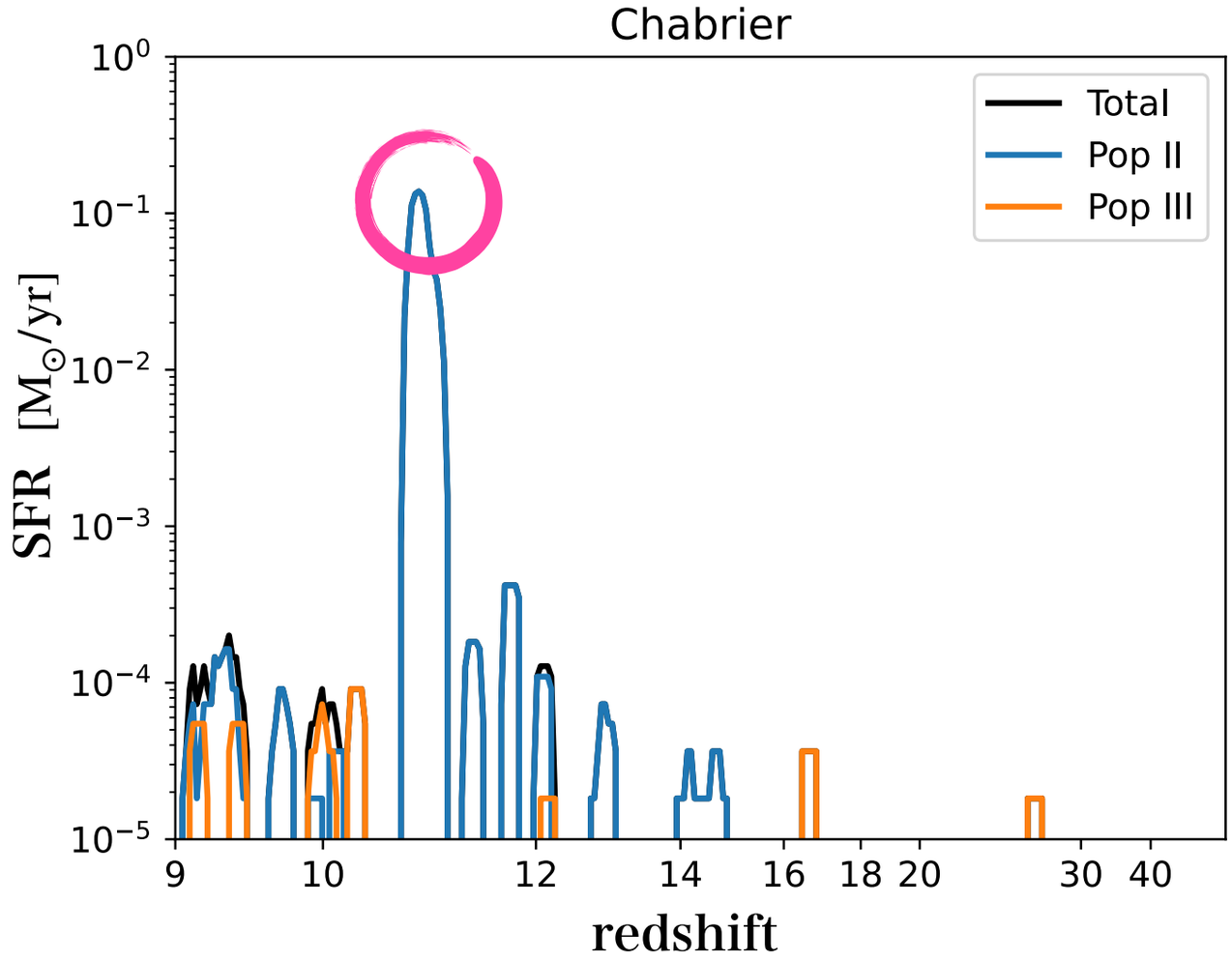
A compact gas clump ($R_{\mathrm{gas,half}} \simeq 8.4$ pc) was formed at the center of DM halo.

A compact star cluster ($R_{*,\mathrm{half}} \simeq 3.8$ pc) was formed from it.

Surface density is $\Sigma_* \simeq 1.4 \times 10^4\ \mathrm{M}_\odot/\mathrm{pc}^2$.

The time evolution of the stellar mass and SFR





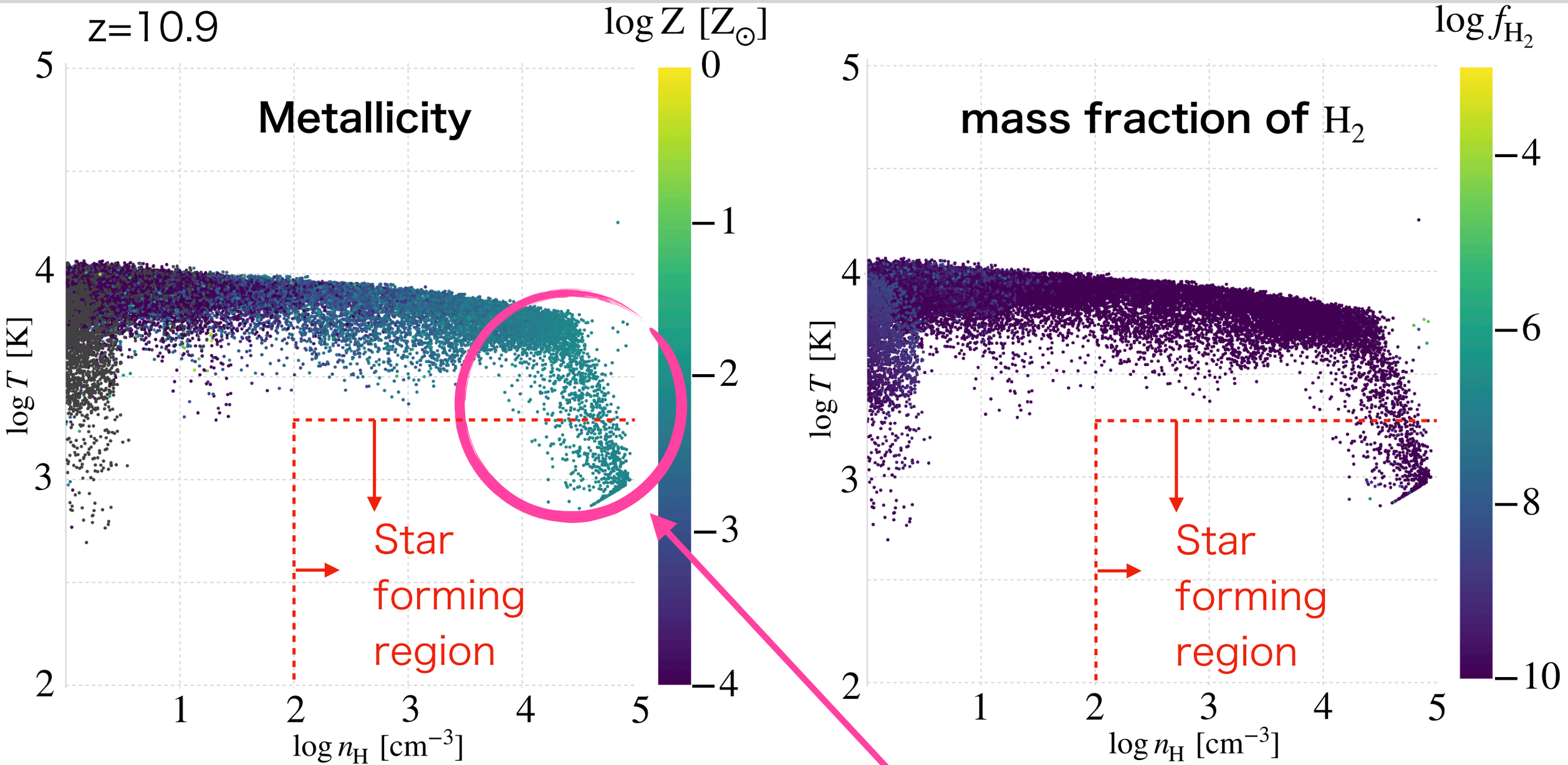
A rapid increase in both the stellar mass and the SFR.

A Pop II starburst occurs at redshift ~ 11. (Sugimura et al. 2024)

Stellar masses $\sim 10^6\ \mathrm{M}_\odot$, SFR $\sim 0.1 - 0.2\ \mathrm{M}_\odot/\mathrm{yr}$

This determines the final stellar mass of the galaxy.

Cause of Compact Gas Clump Formation



- The metallicity at the center of the gas clump is relatively high ($Z \sim 10^{-2} Z_\odot$), while the metallicity outside the center is low ($Z \sim 10^{-3} Z_\odot$).
- Most of the molecular hydrogen in the gas clump is dissociated by strong LW radiation ($f_{H_2} < 10^{-10}$).
- We found that the Pop II starburst also occurs via metal-line cooling.

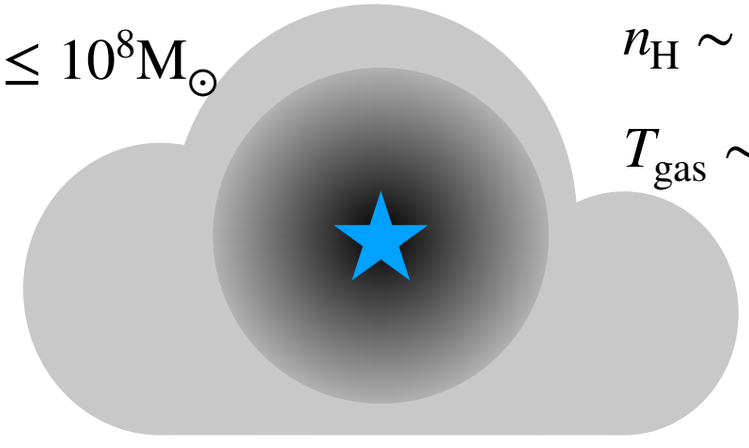
Mechanism of Pop II Starbursts: A Schematic View

(Ishida et al. in prep.)

$M_{\rm h} \leq 10^8 {\rm M}_\odot$

$n_{\rm H} \sim 10^{0-2}$ [cm^{-3}]

$T_{\rm gas} \sim 10^4$ [K]

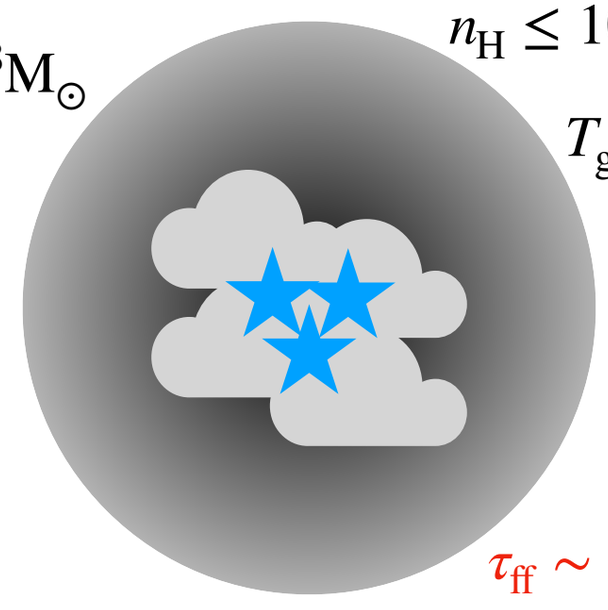


Star formation is suppressed by internal strong LW radiation.

$M_{\rm h} \geq 10^8 {\rm M}_\odot$

$n_{\rm H} \leq 10^5$ [cm^{-3}]

$T_{\rm gas} \sim 10^4$ [K]



$\tau_{\rm ff} \sim 100$ [Myr]

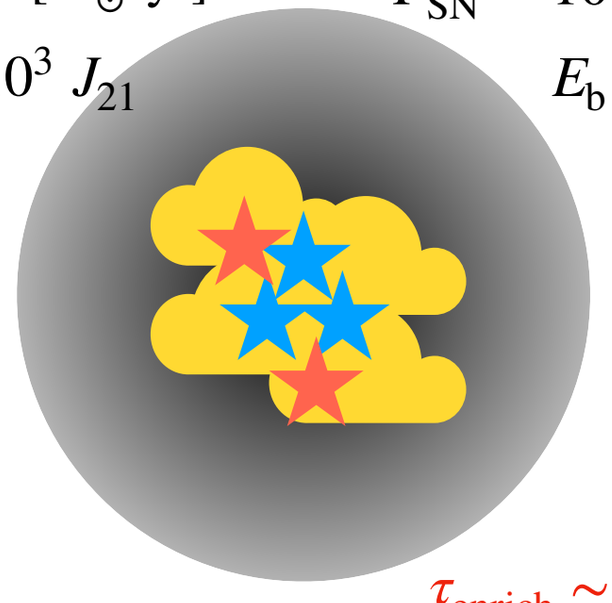
Compact dense gas clump is formed at the center of DM halo.

SFR $\sim 10^{-3}$ [M$_\odot$/yr]

$J_{\rm LW,crit} \sim 10^3\ J_{21}$

$\Gamma_{\rm SN} \sim 10^{52}$ [erg/Myr]

$E_{\rm b} \sim 10^{54}$ [erg]

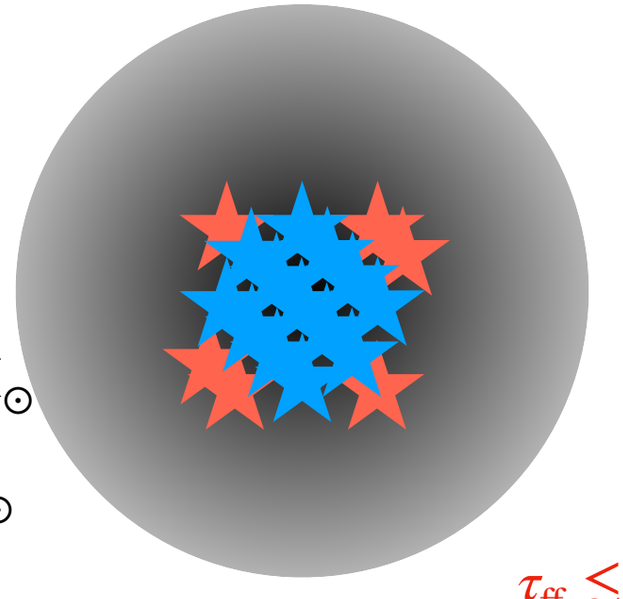


$\tau_{\rm enrich} \sim 10$ [Myr]

Since $E_{\rm b} > E_{\rm SN,10Myr} \sim 1 \times 10^{53}$ [erg], only metal enrichment is going on inside the gas clump.

$M_* \sim 10^6 {\rm M}_\odot$

$Z \sim 10^{-2} {\rm Z}_\odot$



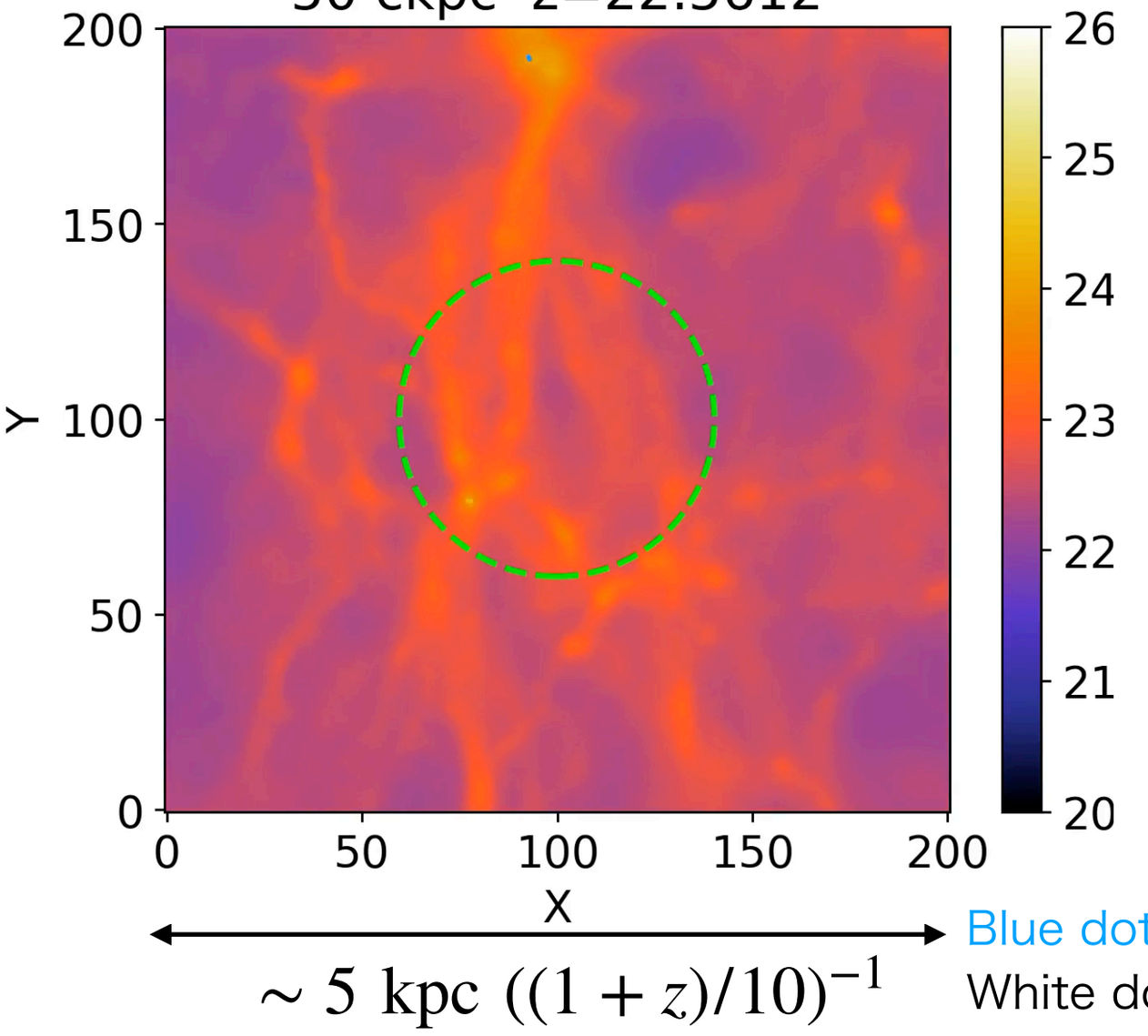
$\tau_{\rm ff} \lesssim 1$ [Myr]

Metal-cooling become efficient in high dense region ($\sim 10^{4-5}$ [cm^{-3}]) and then, starburst occurs.

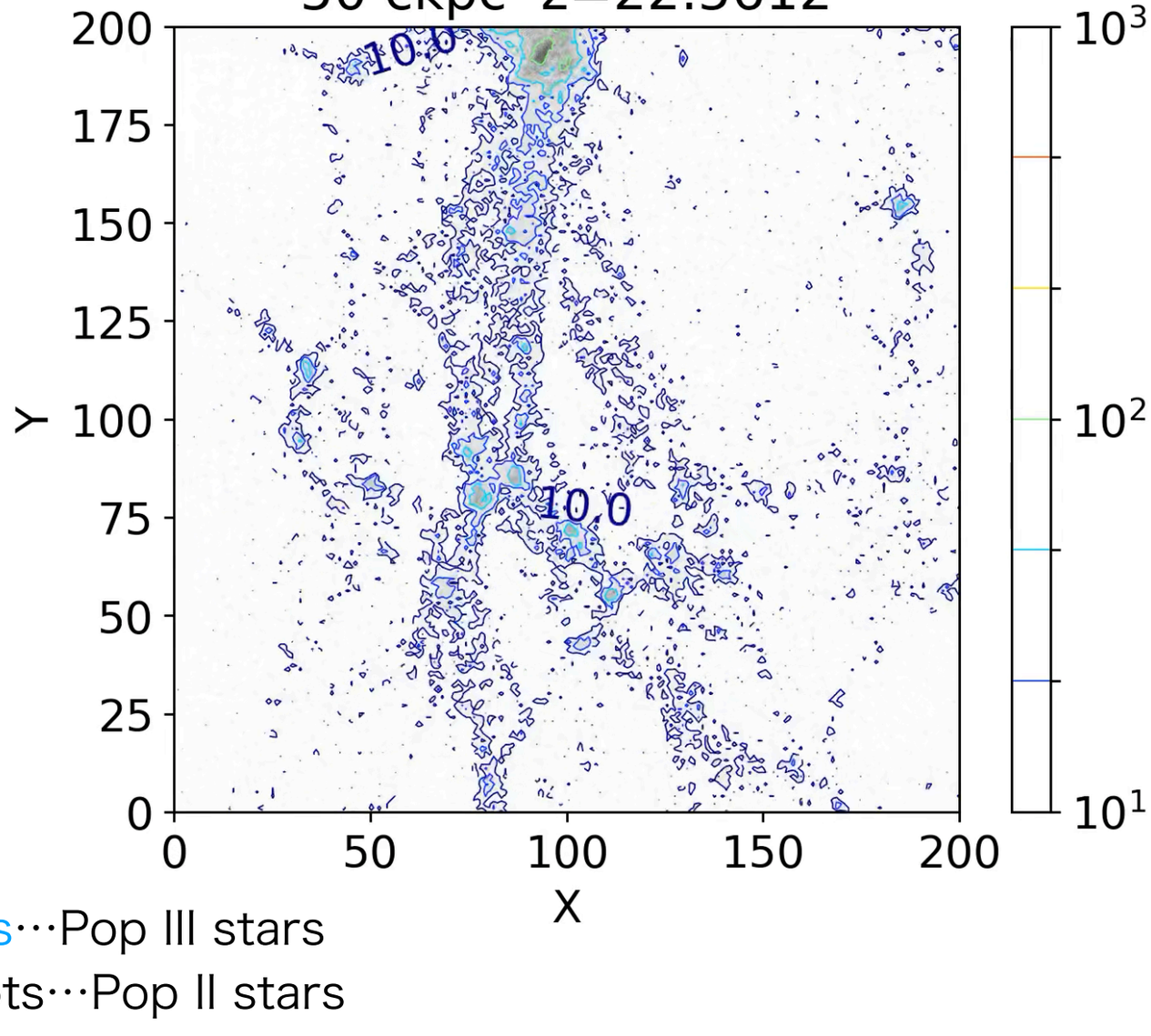
Results：surface density of gas and DM

✓ $M_h \sim 2 \times 10^9\ \mathrm{M}_\odot$ model

column density of gas



DM surface density



$\sim 5\ \mathrm{kpc}\ ((1+z)/10)^{-1}$

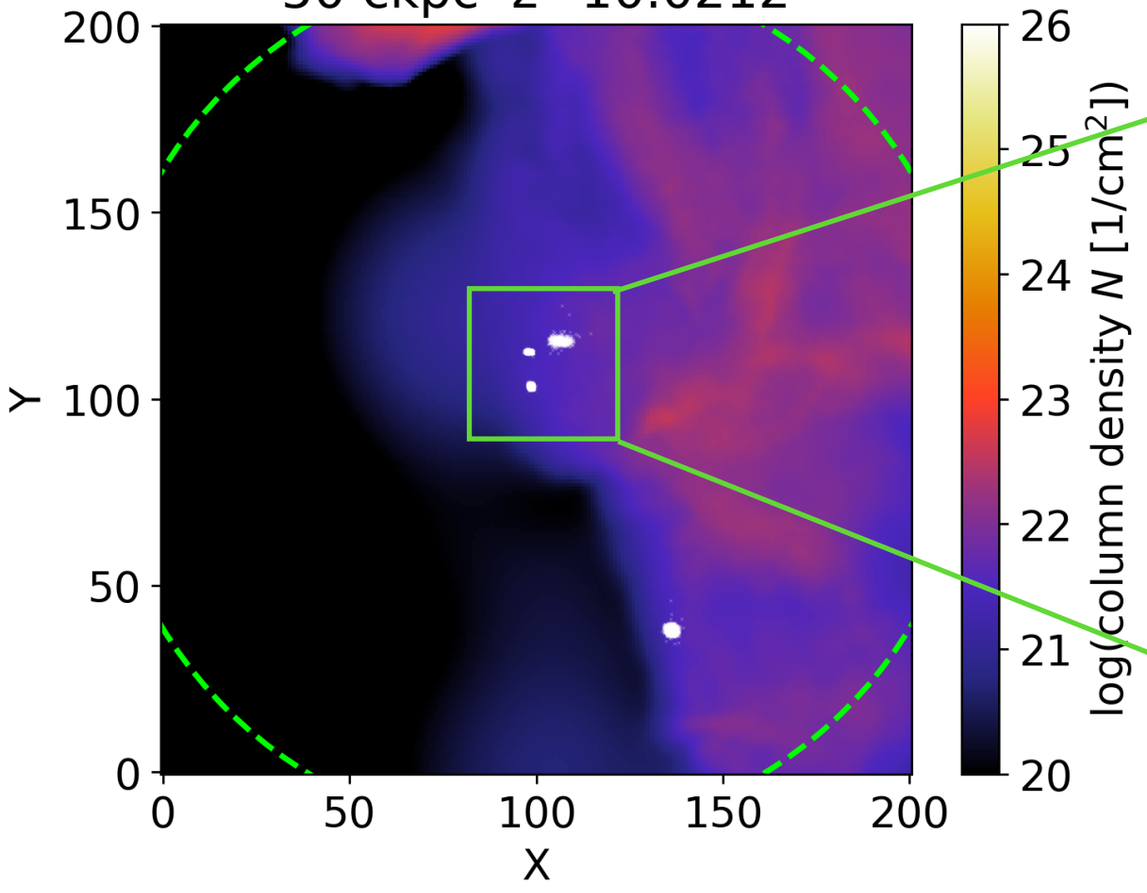
Blue dots…Pop III stars

White dots…Pop II stars

- 3 compact gas clumps and star clusters(SC) are formed at the centers of their respective dark matter halos.
- Kind of 3-body interaction occurred, then 2 of them became a “SC binary”.
- We found that massive first galaxy evolve through multiple SC mergers.

Discussion：Morphology of first galaxies

(Ishida et al. in prep.)



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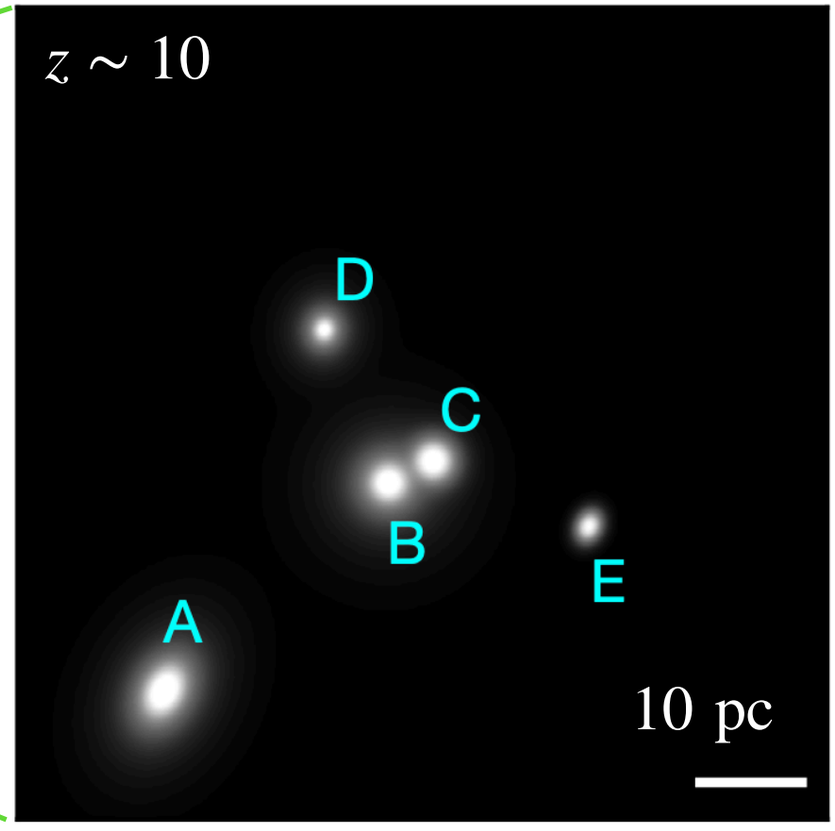
(Adamo et al. 2024)



- The observed system which resides GC-like star clusters can be explained by multiple star cluster mergers.
- But will the central region be observed like this universally?
- this multiple GC-like system will eventually become a single, larger stellar system (or precursor of bulge).
- What is the timescale for this process?
- Is the timescale long enough for such a system to be observed?

Summary

We performed high-resolution cosmological zoom-in simulations of massive first galaxies that are comparable to observations.

- A compact dense gas clump forms at the center of DM halo via Lyman-Werner radiation from Pop II stars and Lyα cooling.

- A compact star cluster forms via Pop II starburst at the center of DM halo.

- We confirmed that the Pop II starburst occurs not only via H_2 self-shielding but also via metal line cooling.

- Massive first galaxies are formed through the mergers of individual star clusters.

- Massive first galaxies can host multiple star clusters.

- The surface density of the formed stars is similar to that of Globular Clusters, suggesting that Pop II starbursts may be the origin of them.