Astro Theory Group
理論宇宙物理学研究室

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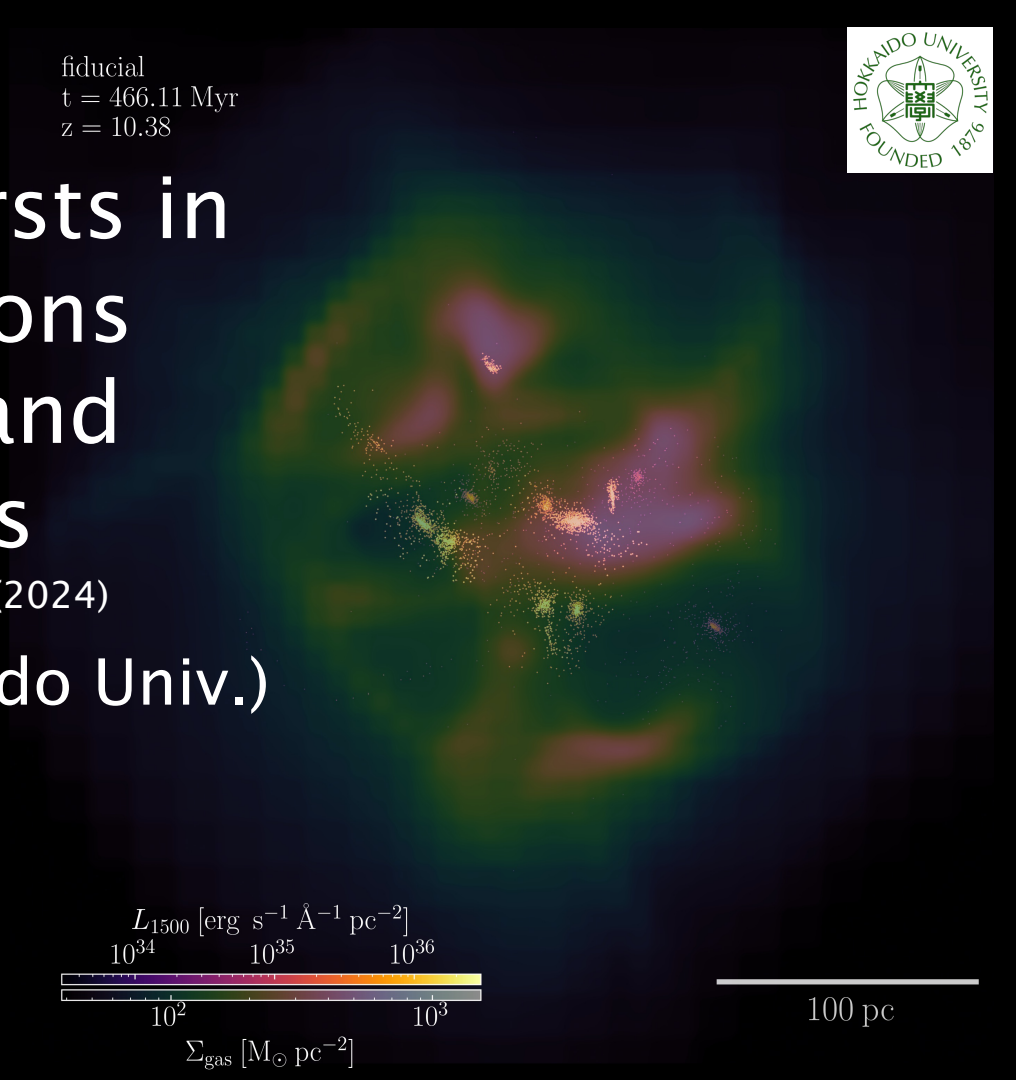

FUV-induced starbursts in first-galaxy simulations connecting galactic and star-formation scales

ApJ, 970, 14 (2024)

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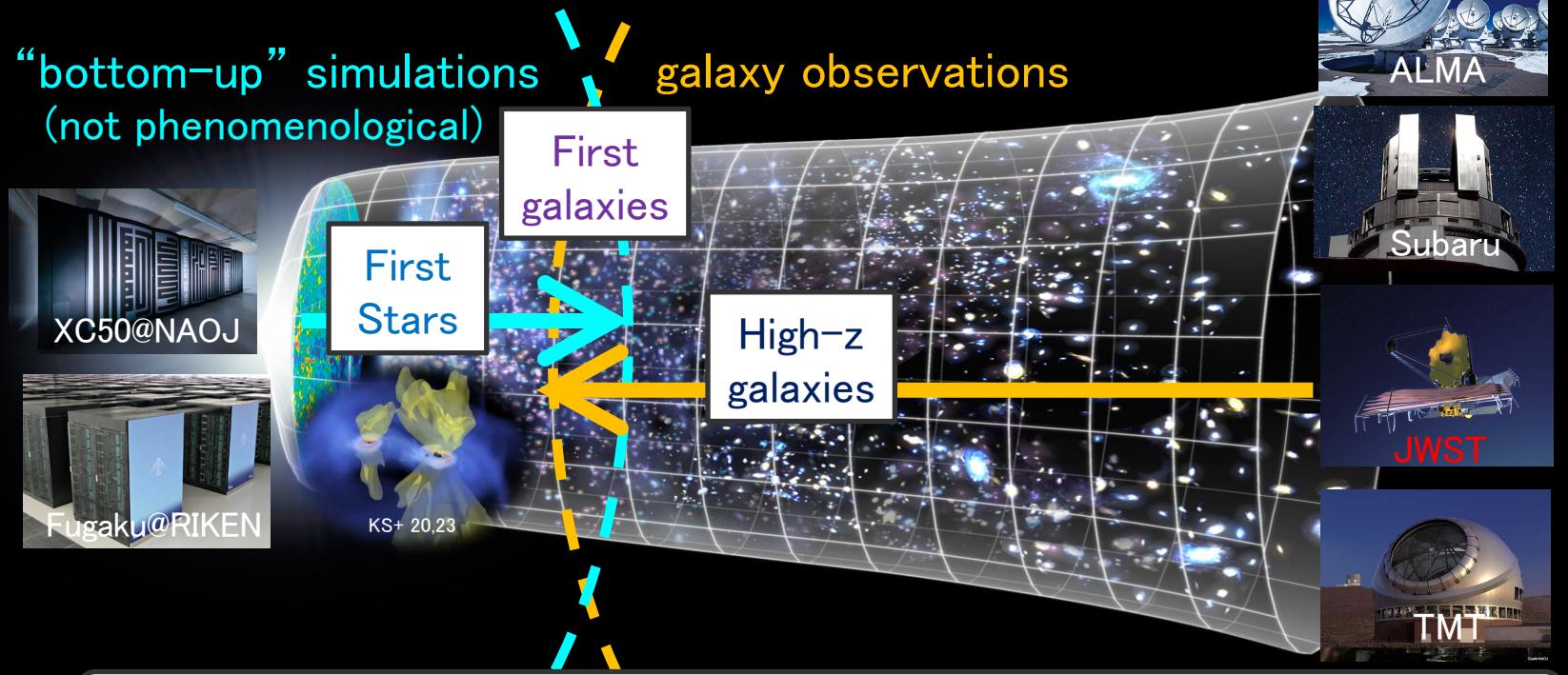
INTRODUCTION

The first galaxy formation

The first step toward the formation of modern galaxies

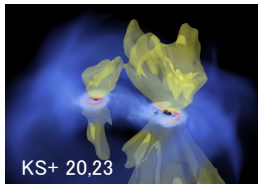


Simulations of first galaxies can be directly tested by observations!

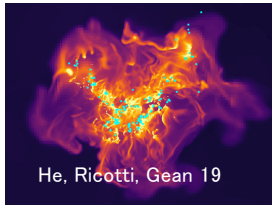
Multi-scale nature of first galaxy formation

<pc-scale

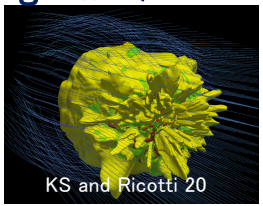
First stars



Pop II clusters



BH growth/feedback



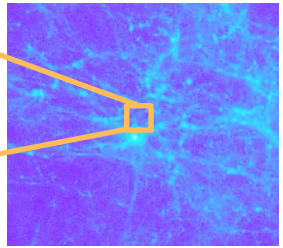
knowledge of small-scale objects

kpc-scale

First galaxy

>Mpc-scale

Large-scale structures

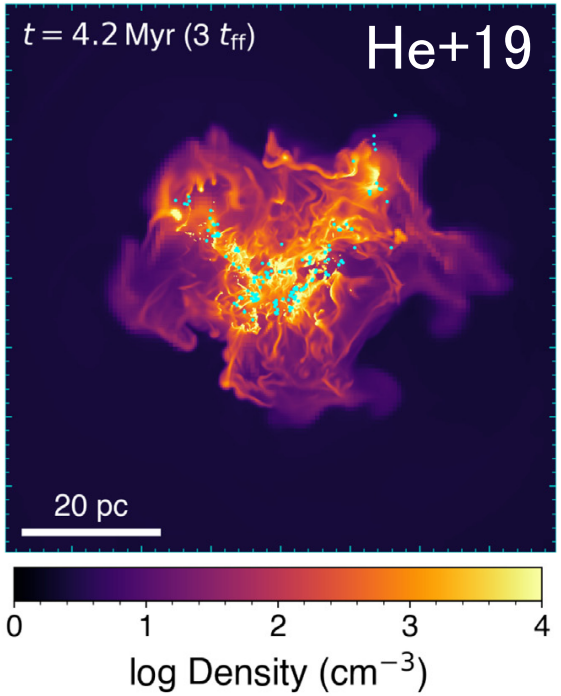


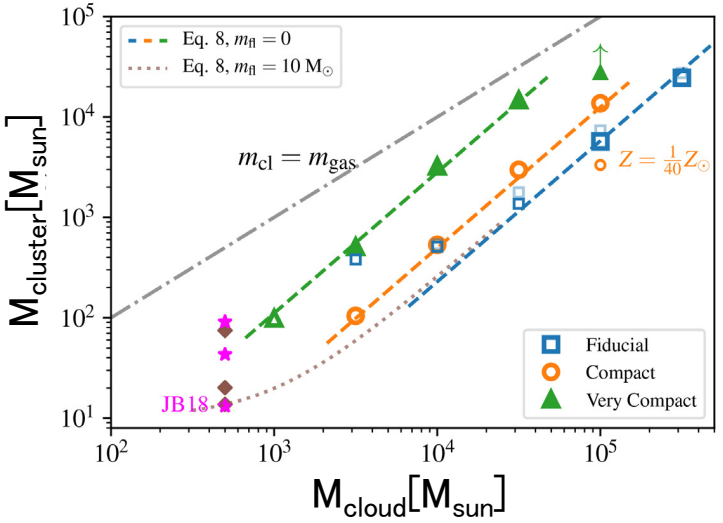
cosmological simulations

We aim to study first galaxies by high (~0.1pc)-resolution cosmological simulations integrating the latest knowledge of small-scale objects

Knowledge of Pop II cluster formation from cloud-scale simulations

He+19, see also Fukushima+20,23, Chon+23,24, Grudic+21, Kim+20, etc.





He+19

star formation efficiency (SFE)

$$f_{*,\rm He19} = \frac{M_{\rm cluster}}{M_{\rm cloud}} = 0.004 \left(\frac{M_{\rm cloud}}{10^4\ M_\odot}\right)^{0.4} \left(\frac{Z_{\rm cloud}}{10^{-3}\ Z_\odot}\right)^{0.25} \left(1 + \frac{n_{\rm cloud}}{10^2\ \rm cm^{-3}}\right)^{0.91}$$

(He+19,KS+24)

Cloud-to-cluster SFE depends on cloud mass, density, and metallicity

We integrate this knowledge into galaxy formation simulations

METHODS

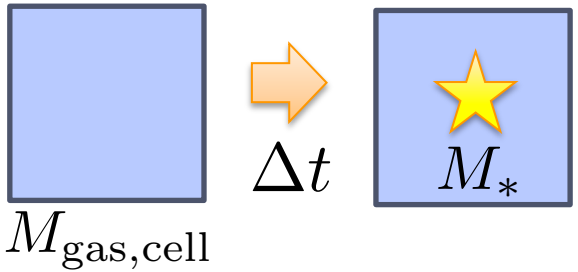
Star-formation models in galaxy simulations

probability: $P = \epsilon_{\rm ff} \dfrac{\Delta t\, M_{\rm gas,cell}}{t_{\rm ff}\, M_*}$

1. Free-fall-time-based models (standard)

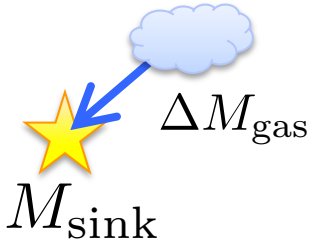
$$\dot{\rho}_* = \epsilon_{\rm ff} \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

(some variants in $\varepsilon_{\rm ff}$)



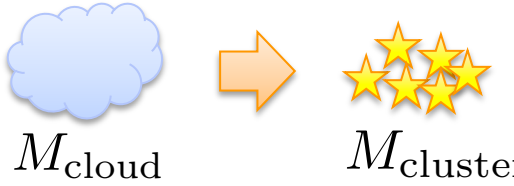
2. Sink-particle models (see Thomspon and Kang's talk)

$$M_{\rm sink}(t+\Delta t) = M_{\rm sink}(t) + \Delta M_{\rm gas}$$



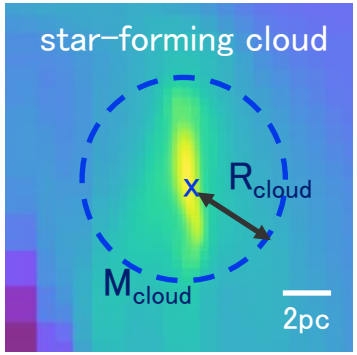
3. Cloud-to-cluster model (This work)

can include the cloud-to-cluster SFE



KS, Ricotti, Park, Garcia, Yajima (2024)

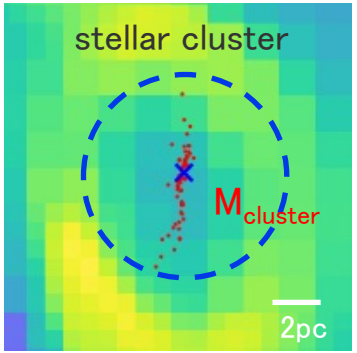
Cloud-to-cluster Pop II formation model for first galaxy simulations



1. Detect a collapsing gas cloud by searching for a cell with
   - ✓ $n_H > n_{SF} = 5 \times 10^4\ cm^{-3} * ((1+z)/10)^2 * (T/100\ K)$
   - ✓ $Z > Z_{cr} = 10^{-5}\ Z_{sun}$ (Pop III formation for lower-metallicity case)
2. Obtain cloud properties using on-the-fly spherically-averaged profile
   - ✓ determine cloud size R_{cloud} by $n_{1D}(R_{cloud}) = 1/1000 * n_{SF}$
   - → ✓ other cloud properties M_{cloud}, n_{cloud}, Z_{cloud}, etc.
3. Estimate the total stellar mass of Pop II cluster

$$M_{\rm cluster} = f_{*,\rm He19}(M_{\rm cloud}, n_{\rm cloud}, Z_{\rm cloud})\, M_{\rm cloud}$$

cloud-to-cluster SFE from He+19



4. Distribute Pop II particles
   - ✓ each star particle ($M_* = 100\ M_{sun}$) represents a group of stars obeying Salpeter IMF (1–100 M_{sun})

Zoom-in simulations of a single galaxy ($M_{halo} = 10^8 M_{sun}$ at z = 10)

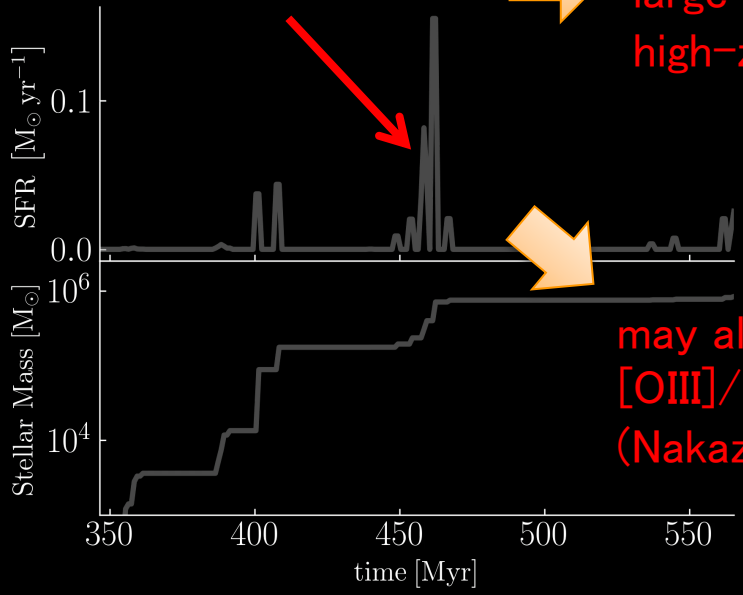
Code	RAMSES-RT (Teyssier 2002, Rosdahl+ 2013)	We added our star-formation model to a modified version of RAMSES-RT (Kimm+17, Katz+17)
Initial Cond.	MUSIC (Hahn & Abel 2011)	Zoom-in initial condition at z = 127
Final Time	500 Myr after Big Bang	same as z ~ 10
Box Size	0.3 h^{-1} cMpc (zoom-region)	35 h^{-1}cMpc (base-box)
DM Mass	800 $M_\odot$ resolution (zoom-region)	10^{11} $M_\odot$ (base-box)
Star Mass	100 $M_\odot$ resolution	Salpeter IMF
Refinement	$N_J = 8$ ($\Delta x > 1$ pc), 4 ($\Delta x < 1$ pc)	at least N_J cells per Jeans length
Resolution	$\Delta x_{min} = 0.15$ pc * $[(1 + z) / 10]^{-1}$	AMR level = 25
Star Formation	$n_{SF} = 5 \times 10^4$ cm^{-3} $[(1+z)/10]^2$ (T/100 K)	To resolve gravitational collapse of clouds Pop II/III formation depending on metallicity

RESULTS

First galaxy formation in the fiducial run

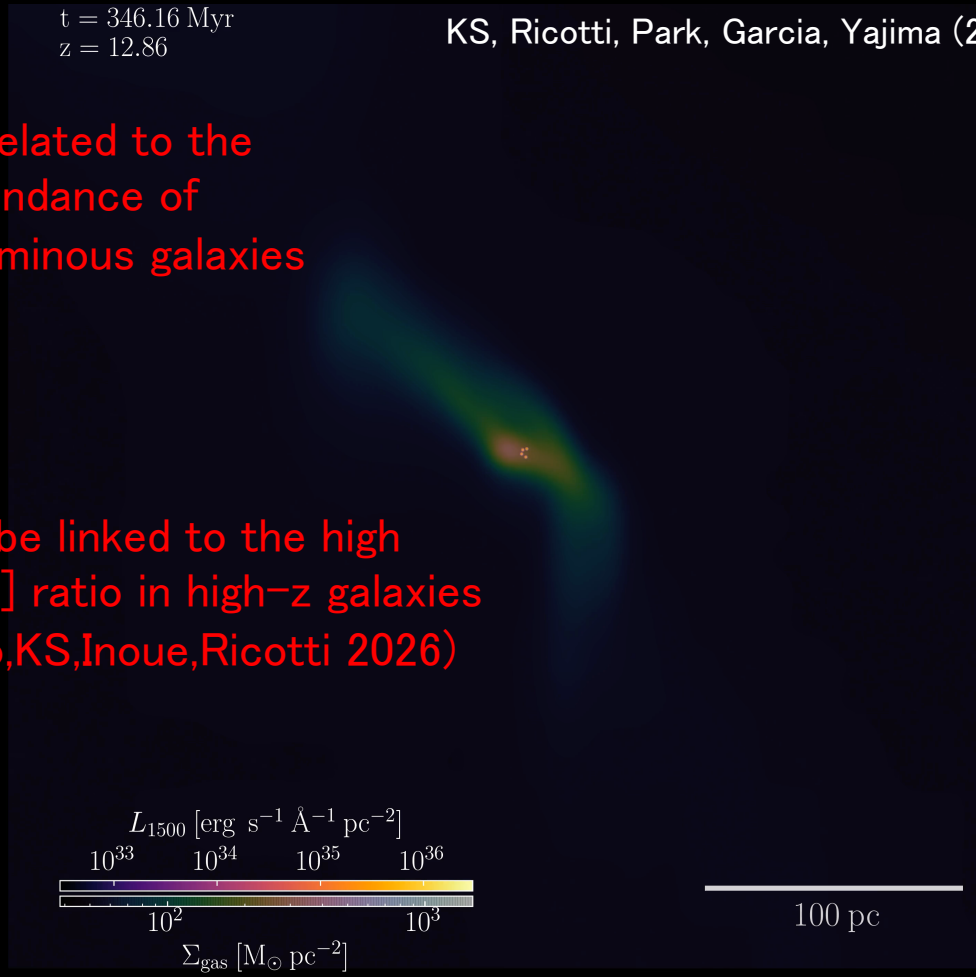
KS, Ricotti, Park, Garcia, Yajima (2024)

Steep starburst

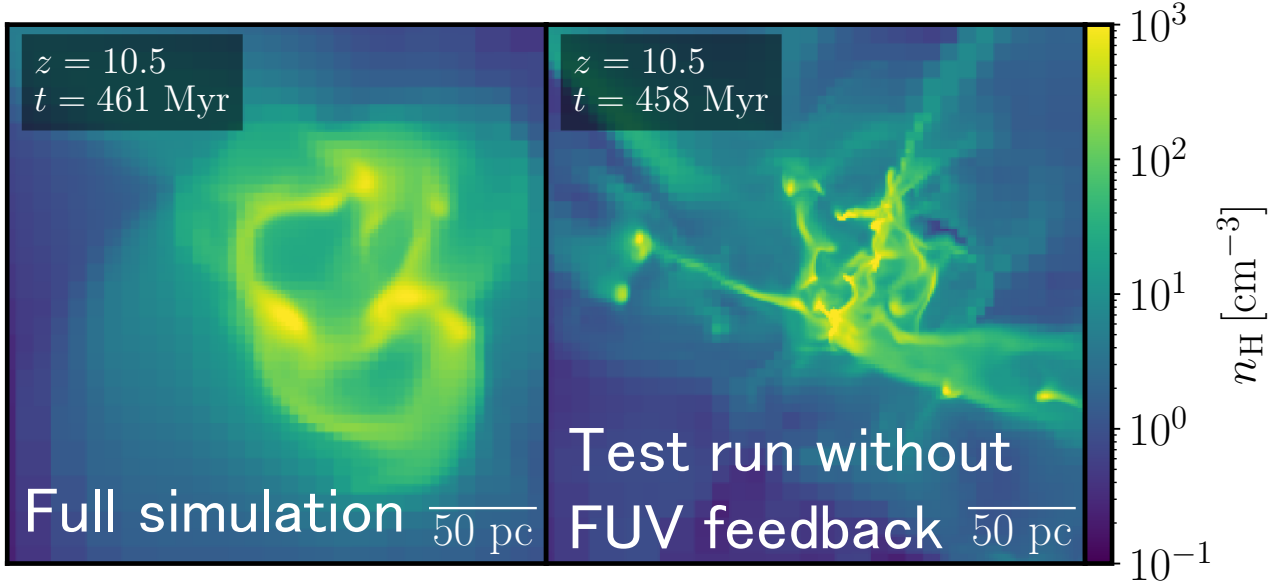


may be related to the large abundance of high-z luminous galaxies

may also be linked to the high [OIII]/[CII] ratio in high-z galaxies (Nakazato,KS,Inoue,Ricotti 2026)



Examining the burst mechanism: gas distribution with and without FUV feedback



- entire star-forming cloud collapses with weak fragmentation

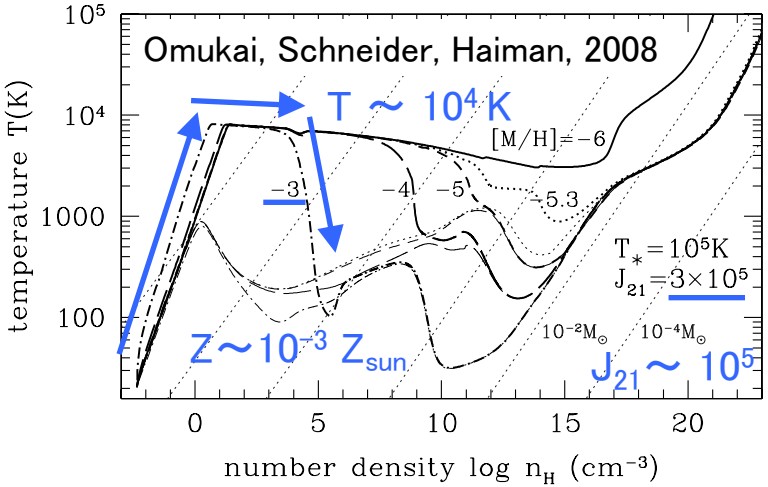
  ⇨ bursty star formation

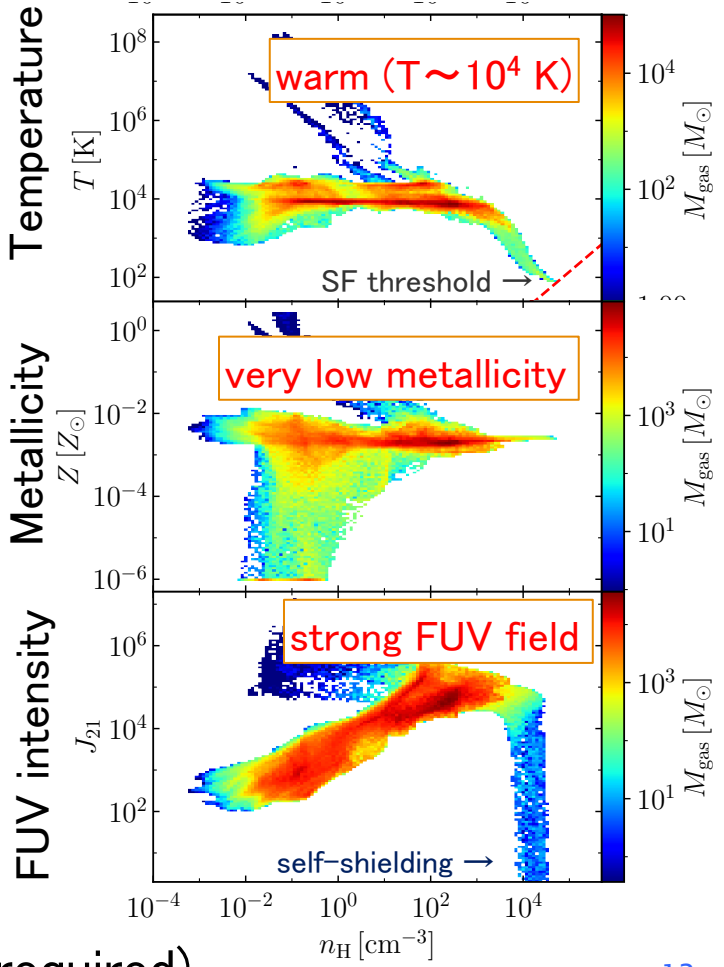
- entire cloud is fragmented into small star-forming clumps

  ⇨ continuous star formation mode

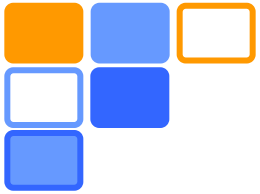
Anatomy of FUV-induced starburst

- metal-poor gas irradiated by strong FUV is heated to T～10^4 K





- entire cloud collapses after they become massive enough → FUV-induced starburst!!
- it is essential to resolve grav. col. （Δx～0.1pc required）



CONCLUSION

Summary and Discussion

- We have performed sub-pc resolution simulations of first galaxy formation integrating the latest knowledge of small-scale physics
- We have developed a model of star-cluster formation that incorporates the star-formation efficiency from cluster-scale simulations
- We have found FUV-induced starburst caused by the following mechanism
    1. metal-poor gas under strong FUV field is heated to $T \sim 10^4$ K
    2. entire clouds collapse after they become massive enough
    3. FUV-induced starburst!!
- We are currently working on star-by-star simulations with Z-dependent IMF