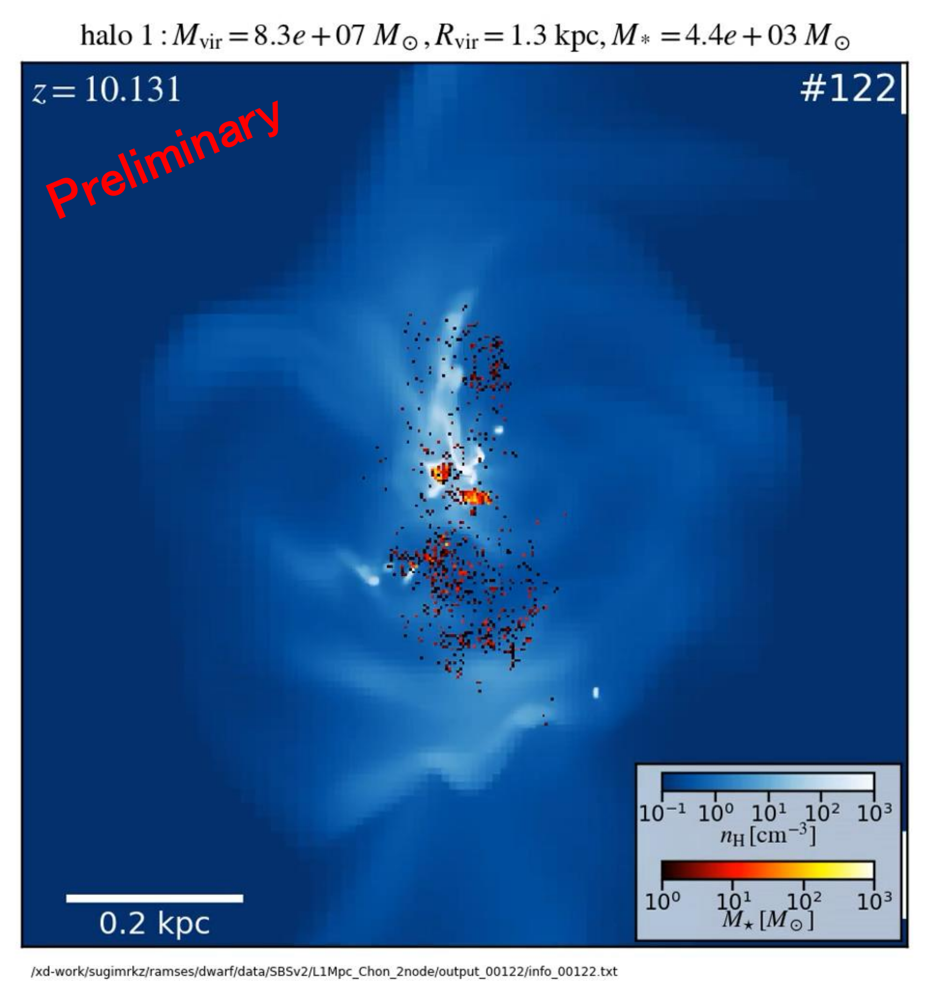
初代銀河形成シミュレーション：金属度依存Pop II IMFモデルの実装

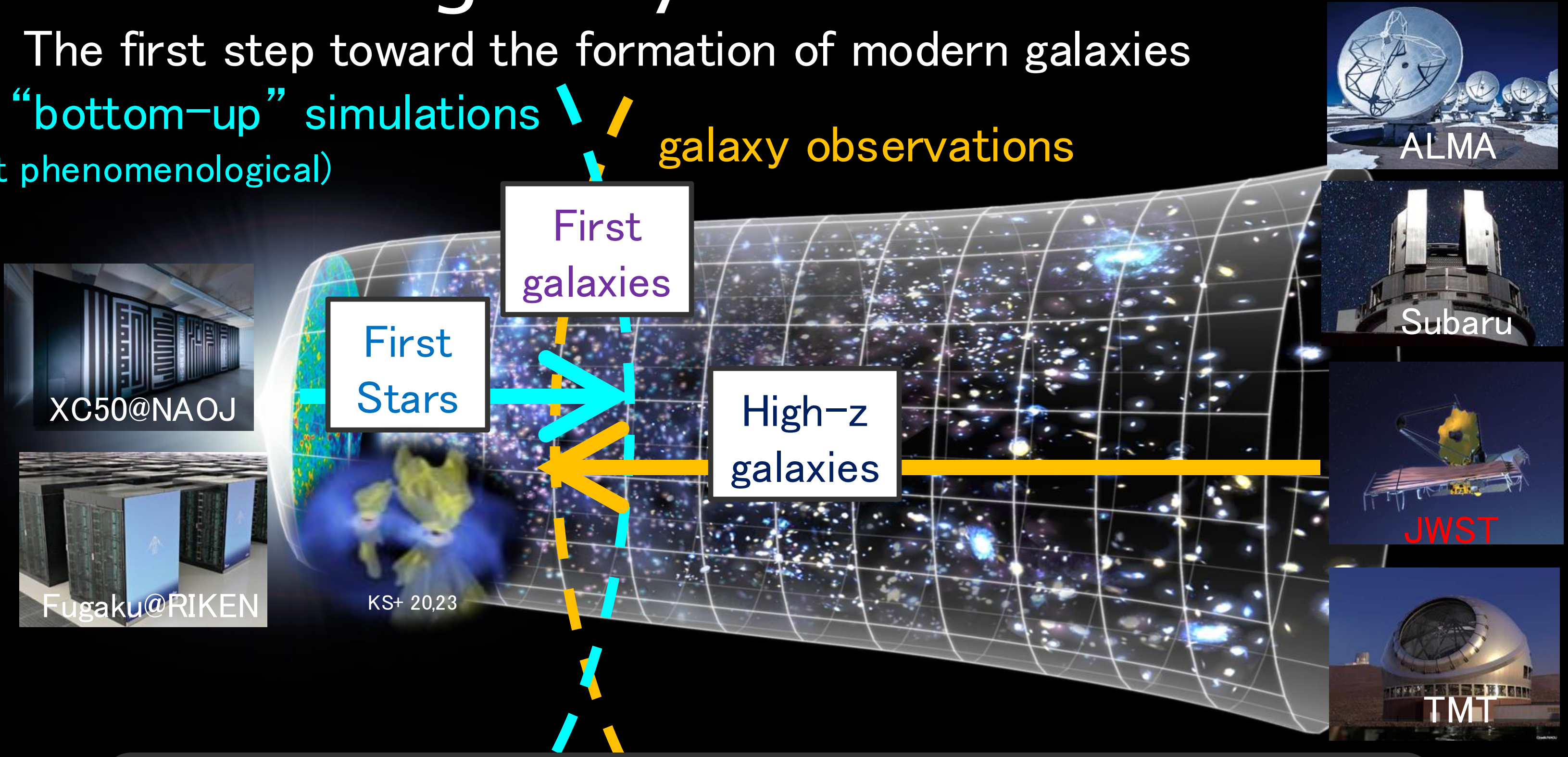
杉村 和幸（北大）



INTRODUCTION

The first galaxy formation

The first step toward the formation of modern galaxies

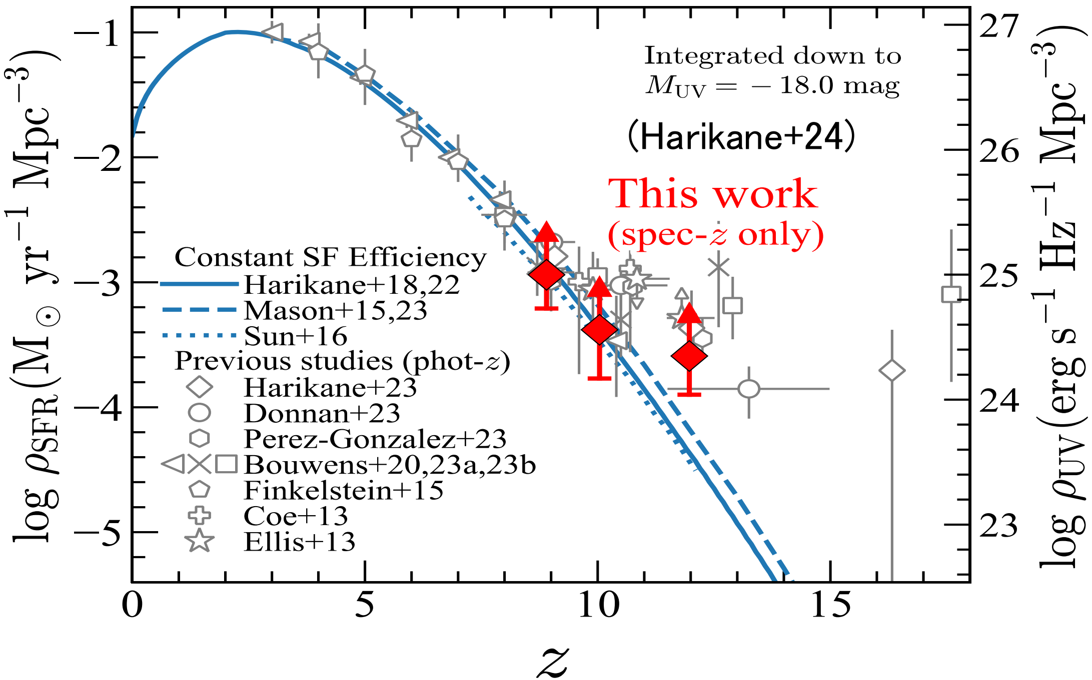


"Bottom-up" simulations of first galaxy formation can be directly tested by observations in the JWST era

JWST is revealing the nature of high-redshift galaxies

More luminous galaxies are found than expected in the pre-JWST time

(Robertson+23, Harikane+23a,24, Hainline+24, and more)



Better theoretical understanding is needed to maximize the merit of observations

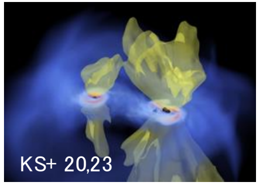
“Bottom-up” simulations of first galaxies

<pc-scale

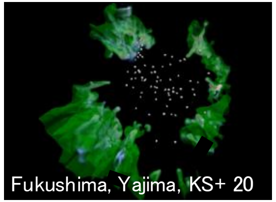
kpc-scale

>Mpc-scale

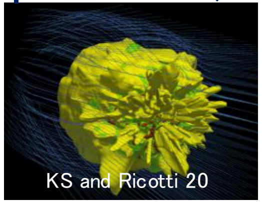
First stars



Pop II clusters

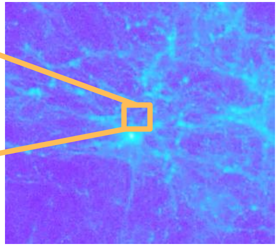


(Supermassive) BHs



First galaxy

Large-scale structures



knowledge on small-scale processes
(not phenomenological models)

well-established ICs and evolution Eqs
(galaxy formation simulations)

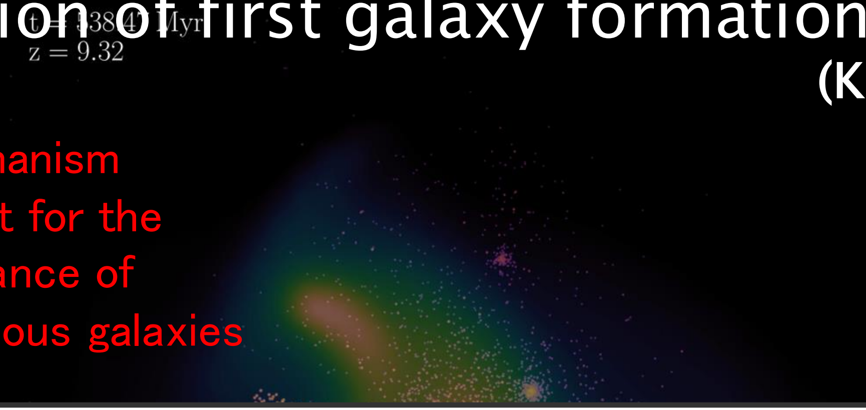
Reveal the first galaxy formation by integrating simulations that solve the large-scale physical law and knowledge on small-scale processes

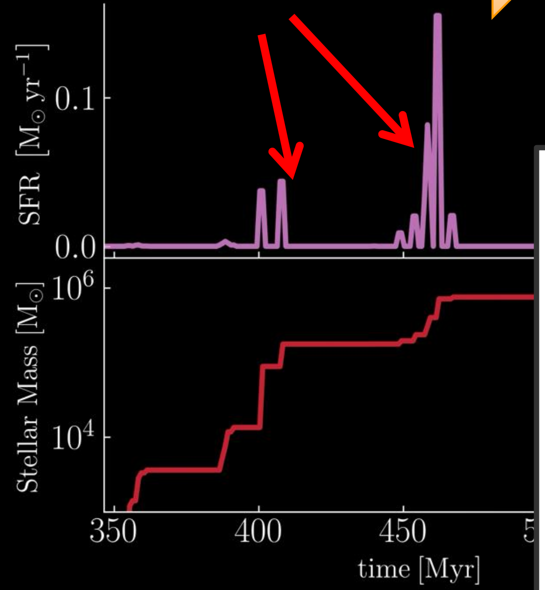
Our previous simulation of first galaxy formation

(KS+24)

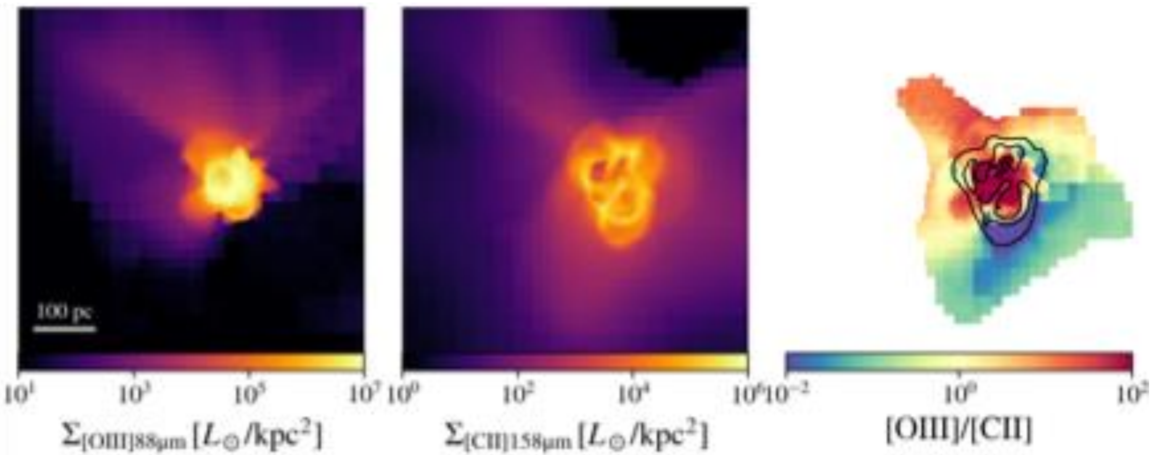
FUV-driven
star formation
bursts

similar mechanism
may account for the
large abundance of
high-z luminous galaxies





and for the high [OIII]/[CII] ratios

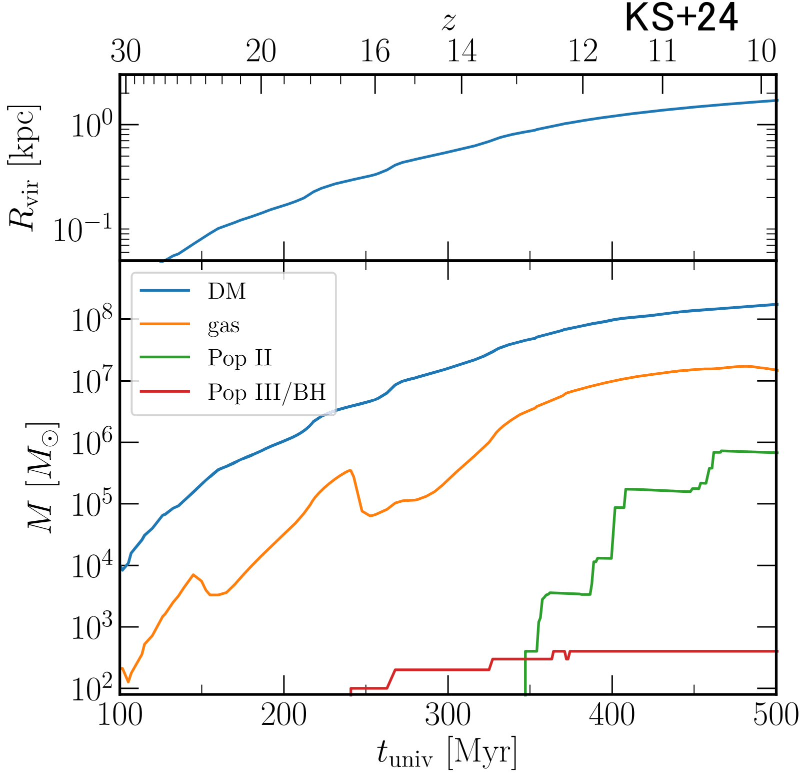


Nakazato, KS, Inoue (2025)

Model of Pop II formation and feedback

- Pop II stars are the main stellar component of first galaxies
- Their feedback (radiation and SNe) determine the evolution of first galaxies
- However, models of Pop II star formation and feedback in previous simulations are insufficient
- Their better modeling is essential for realistic first galaxy simulations

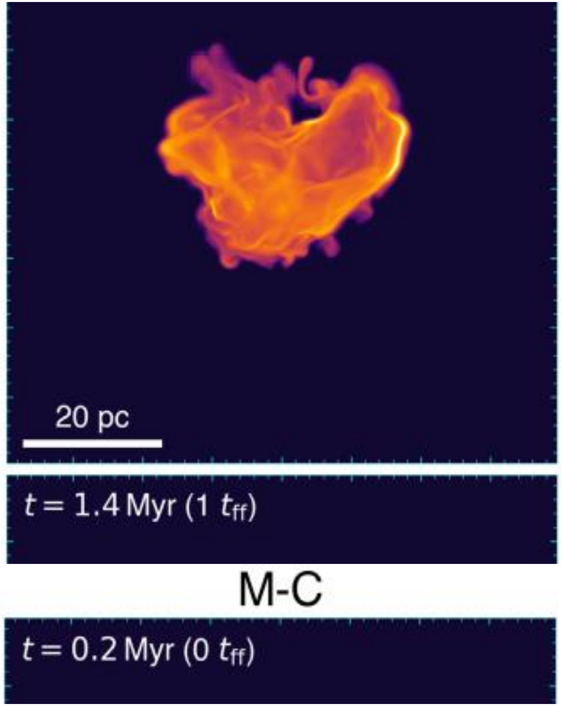
KS+24



Pop II cluster formation

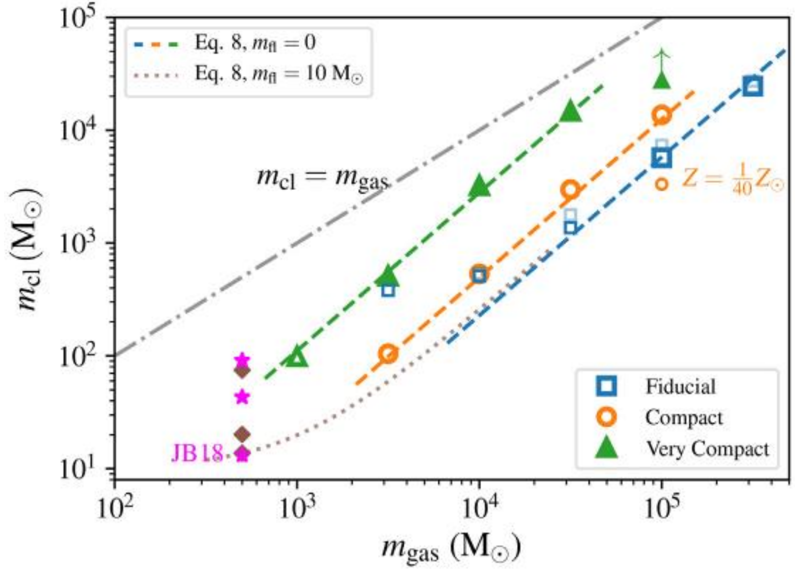
He+19,
See also Fukushima+20,23,
Chon+23,24, Grudic+21, Kim+20, etc.

Radiation (M)HD Simulations of stellar cluster formation from gas clouds



$$m_{\rm cl} = 200\ {\rm M_\odot} \times \left(\frac{m_{\rm gas}}{10^4\ {\rm M_\odot}}\right)^{1.4} \left(1 + \frac{\bar{n}_{\rm gas}}{n_{\rm cri}}\right)^{0.91} + m_{\rm fl}$$

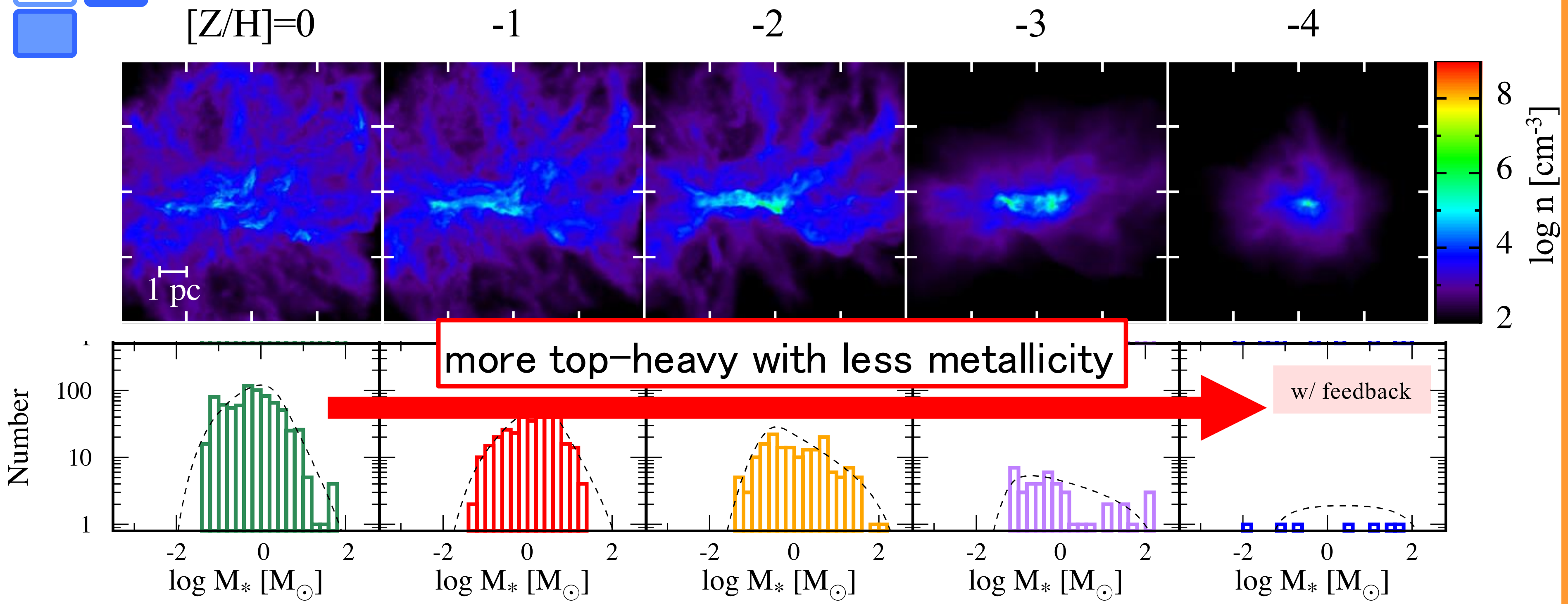
$\bar{n}_{gas}$: average density of cloud $\quad n_{cr} = 10^3 cm^{-3}$



We have implemented this knowledge of star formation efficiency (KS+24)

Metallicity dependence of IMF

Chon+24



more top-heavy with less metallicity

$$\phi(M_*) = \phi_0 M_*^{-\alpha} \left[1 - \exp\left(-\left(\frac{M_*}{m_0}\right)^c\right)\right] \exp\left(-\frac{m_{\min}}{M_*} - \frac{M_*}{m_{\max}}\right)$$

m_{min}, m_{max}, m_0, α, c:
metallicity dependent parameter

This knowledge of Z-dependent IMF must be included in first-galaxy simulations!!

Aim of this work

For more realistic first-galaxy simulations, we will implement

<u>a star-by-star Pop II model with Z-dependent IMF</u>

- star-by-star = each star particle representing an individual star (not a group of stars following an assumed IMF)
- varying IMF can be straightforwardly considered
- computationally feasible for $\sim 10^6$ stars in dwarf galaxies

(see Hirai+21, Deng+24, Calura+24, Lahen+25, and so on)

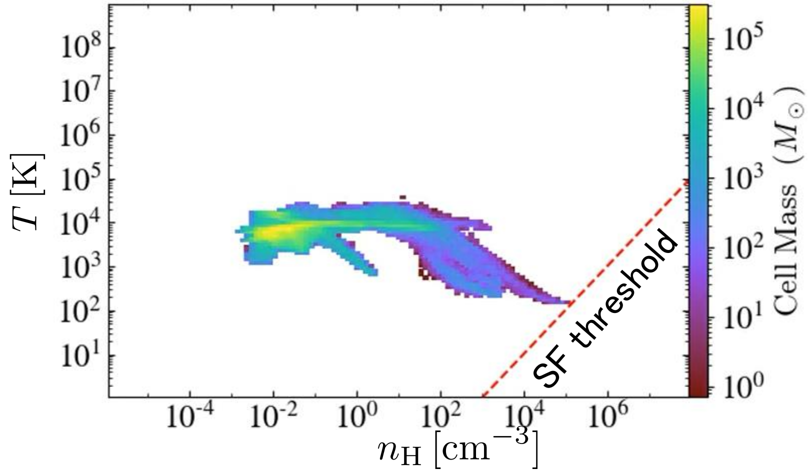
METHODS

Pop II cluster formation I: detecting star-forming gas clouds

1. Detecting a collapsing gas cloud
   - search for a cell with $n_H > n_{SF}$ and $Z > Z_{cr}$

     $n_{SF} = 5 \times 10^4\ \mathrm{cm}^{-3} * ((1+z)/10)^2 * (T/100\ \mathrm{K})$

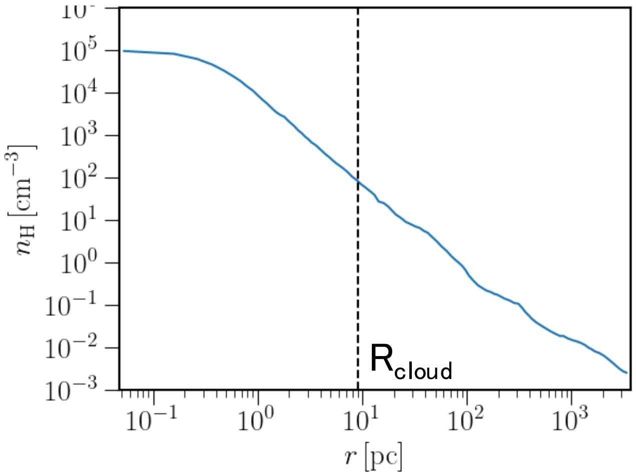
     $Z_{cr} = 10^{-5}\ Z_{sun}$

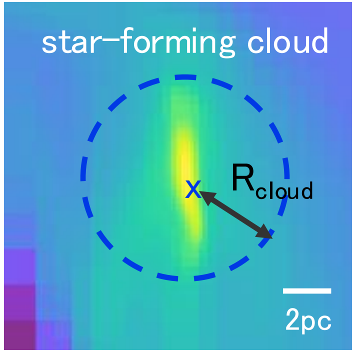


2. Determining the cloud size
   - define the cloud boundary (R_{cloud}) using spherically-averaged profile

     $$n_{1D}(R_{cloud}) = 1/1000 * n_{SF}$$

   - arbitrariness of the boundary may be absorbed by star formation prescription
   - To-do: consideration of non-sphericity





Pop II cluster formation II: converting gas clouds into star clusters

3. Determining stellar mass

$$n_{\rm cloud} = \frac{M_{\rm cloud}}{\frac{4\pi}{3} R_{\rm cloud}^3}$$

- use star formation efficiency f_* depending on M_{cloud}, R_{cloud}, and Z_{cloud} based on cloud-scale simulations (e.g., He+19)

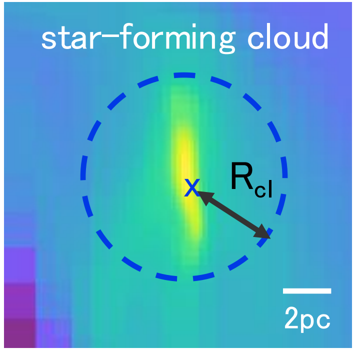
$$f_* = \min\left[0.8,\ 0.004\left(\frac{Z_{\rm cloud}}{10^{-3}\ Z_\odot}\right)^{0.25}\left(\frac{M_{\rm cloud}}{10^4\ M_\odot}\right)^{0.4}\left(1 + \frac{n_{\rm cloud}}{10^2\ {\rm cm}^{-3}}\right)^{0.91}\right]$$

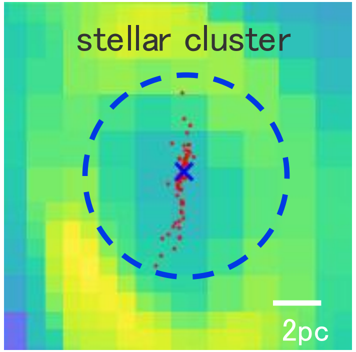
- total stellar mass of cluster

$$M_{\rm cluster} = f_*\, M_{\rm cloud}$$

4. Distributing stellar particles

- mass-weighted random distribution within $r < R_{cloud}$
- In previous simulations (e..g, KS+24), each Pop II particle (100 M_{sun}) represents a group of stars following unresolved Chabrier IMF

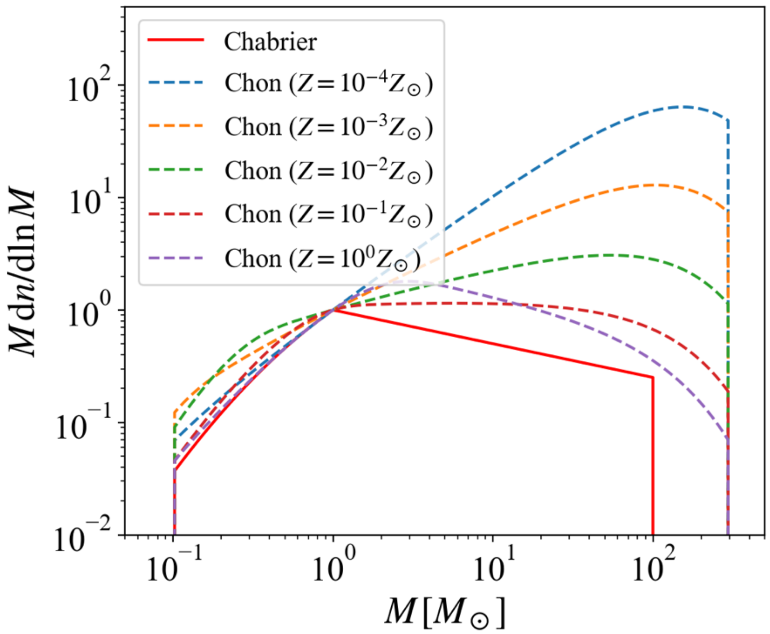




→ Form individual stars following Z-dependent IMF (star-by-star treatment)

Pop II cluster formation III: forming individual stars following a given IMF

see also, e.g., Hirai+21



We adopt two IMF models:

- Chon IMF (Z−dependent)
- Chabrier IMF (Z−independent)

Procedures

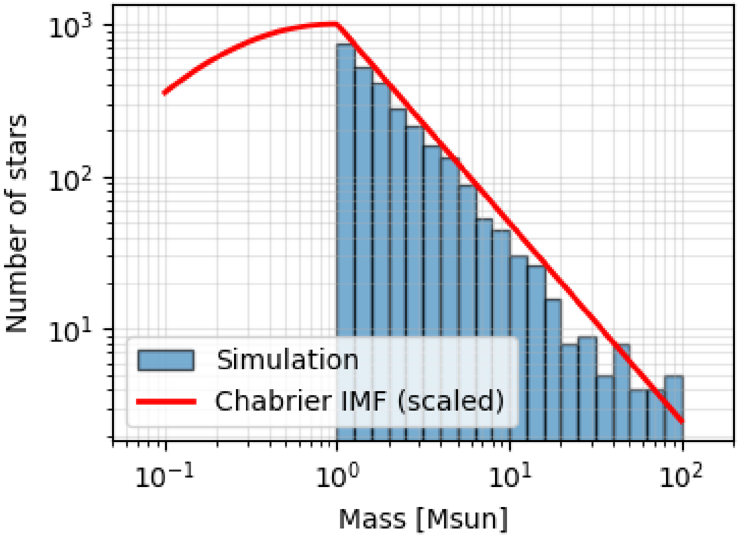
1. Estimate the total mass of resolved stars $M_{res,tot}$ (minimum mass $M_{res,min}$ = 1 M_{sun})
2. Create stars with random stellar masses following the cumulative mass function until the total mass reaches $M_{res,tot}$
3. Create minimum mass star particles for unresolved components

Pop II cluster formation III: forming individual stars following a given IMF

see also, e.g., Hirai+21

Example: $M_{cluster} = 1.2\times10^4\ M_{sun}$

Chabrier IMF ($M_{res,min} = 1\ M_{sun}$)



$M_{res,tot}/M_{cluster} = 0.76$

We adopt two IMF models:

- Chon IMF (Z−dependent)
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Procedures

1. Estimate the total mass of resolved stars $M_{res,tot}$ (minimum mass $M_{res,min} = 1\ M_{sun}$)
2. Create stars with random stellar masses following the cumulative mass function until the total mass reaches $M_{res,tot}$
3. Create minimum mass star particles for unresolved components

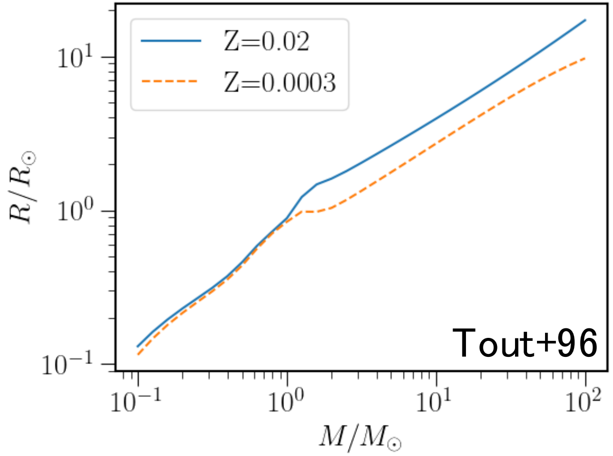
Following STARFORGE simulations (Grudic+21)

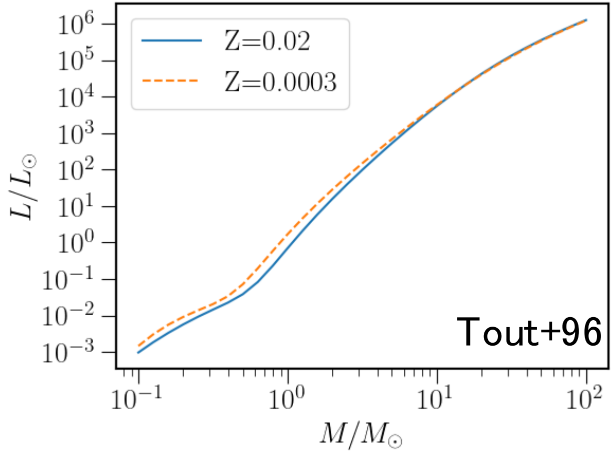
Radiation from individual stars

- Assume zero-age main sequence (ZAMS) luminosity and radius for their entire lifetime (see next slide)
- Inject radiation into the cell that contain the star
- photons are distributed into four frequency bins assuming black body spectrum with T_{rad} obtained from $L = 4\pi R^2 \sigma_{\rm SB} T_{\rm rad}^4$

Bin	Freq range	Description
FUV	11.2–13.6 eV	H_2 dissociation, PEH
EUV1	13.6–24.6 eV	H ionization
EUV2	24.5–54.4 eV	H, He ionization
EUV3	54.4–200 eV	H, He, He^+ ionization

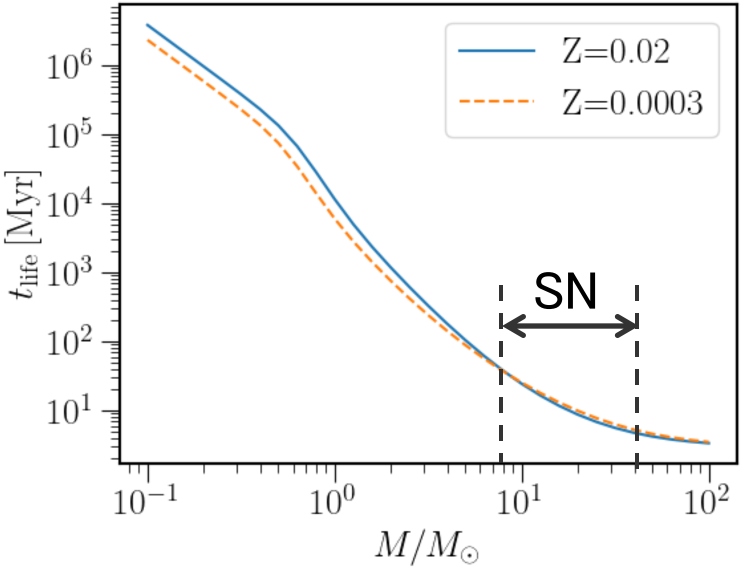
Todo: introducing lower energy UV bin or X-ray bins



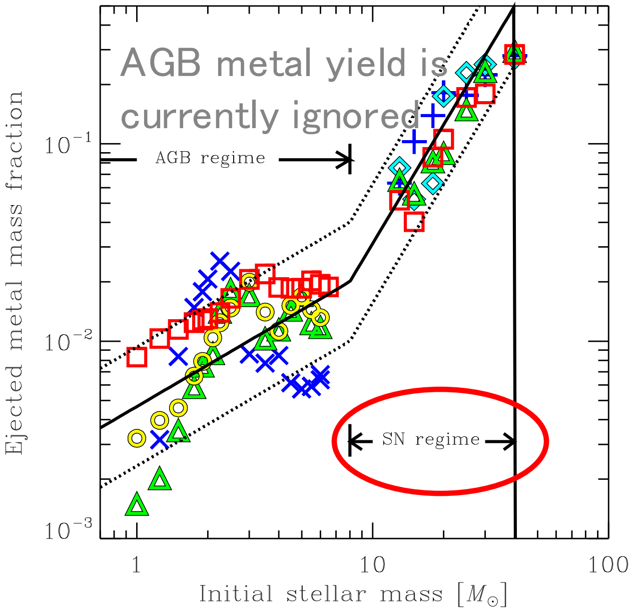


Supernovae from individual stars

- Lifetime (Hurley+00)



- Metal yield (Inoue11)



Thermal energy ($E_{SN} = 10^{51}$ erg) and ejecta (including metal yield) are injected when a massive star ($8 < M_*/M_{sun} < 40$) reaches its lifetime

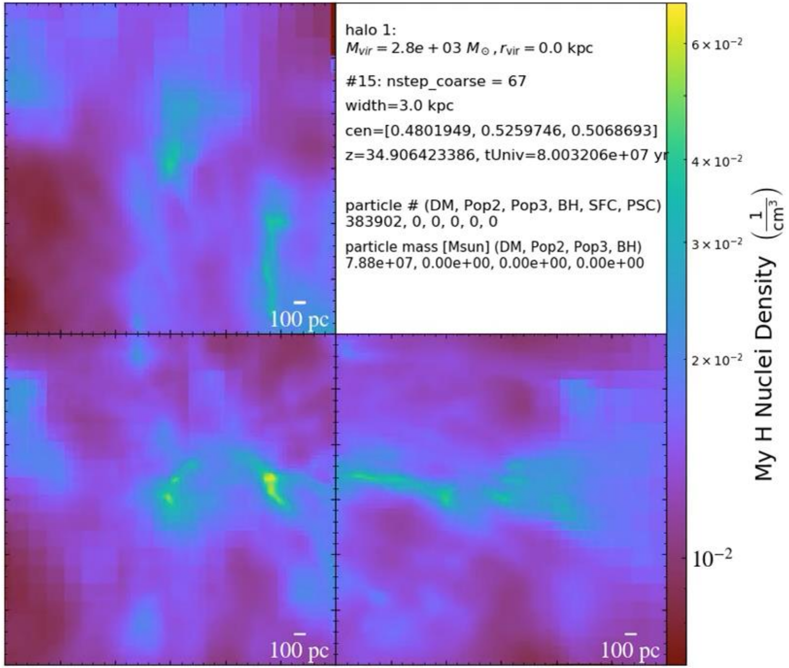
$$\frac{m_Z(m)}{m} = \begin{cases} 0 & (m > 40\,M_\odot) \\ f_Z \left(\frac{m}{8\,M_\odot}\right)^2 & (8\,M_\odot \le m \le 40\,M_\odot) \\ f_Z \left(\frac{m}{8\,M_\odot}\right)^{0.7} & (m < 8\,M_\odot) \end{cases}$$

Summary of simulation set-up (similar to KS+24)

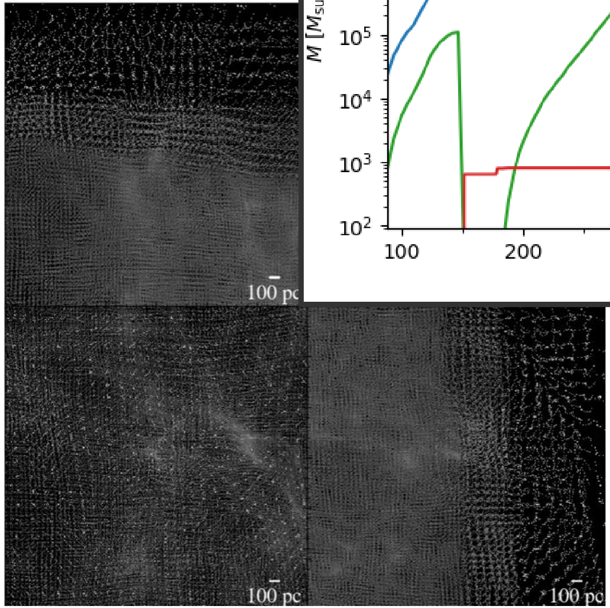
Code	RAMSES-RT (Teyssier 2002, Rosdahl et al. 2013)	Cosmological AMR (M)HD, Moment method RT (M1 closure), DM particle, sink (BH) particle, stellar radiation, SN feedback, non-equil. chemistry/cooling/heating
Initial Cond.	MUSIC (Hahn & Abel 2011)	Zoom-in initial condition at $z = 100$
Final Time	500 Myr after Big Bang	same as $z \sim 10$
Box Size	0.1 h^{-1} cMpc (zoom-region)	1 h^{-1}cMpc (base-box)
DM Mass	100 $M_\odot$ resolution (zoom-region)	10^6 $M_\odot$ (base-box)
Star Mass	Star-by-star treatment above 1Msun	IMF: Chon (Z-dependent) or Chabrier
Refinement	$N_J = 8$ ($\Delta x > 1$ pc), 4 ($\Delta x < 1$ pc)	at least N_J cells per Jeans length
Resolution	$\Delta x_{min} = 0.14\ \mathrm{pc} * [(1 + z)/10]^{-1}$	AMR level = 20
Star Formation	$n_{SF,th} = 6 \times 10^4\ \mathrm{cm}^{-3}\ [(1+z)/10]^{2}\ (T/100\ \mathrm{K})$	Resolving gravitational collapse of clouds

PRELIMINARY RESULTS FROM TEST RUNS

First galaxy formation in Chon-IMF model

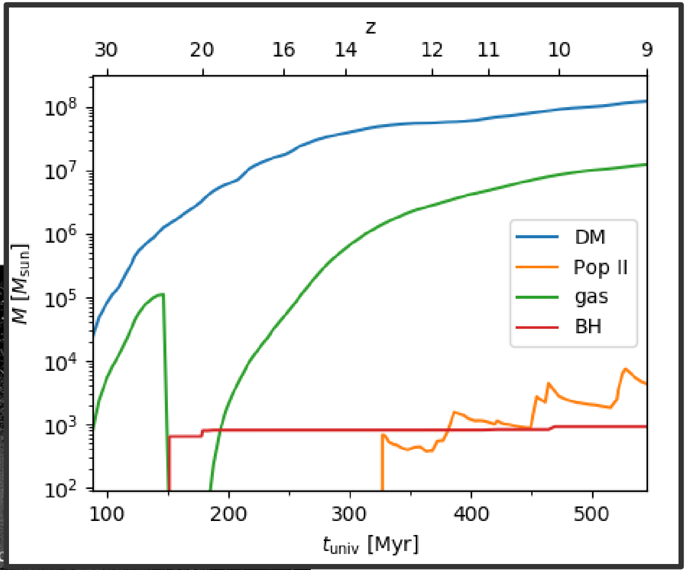


projected density



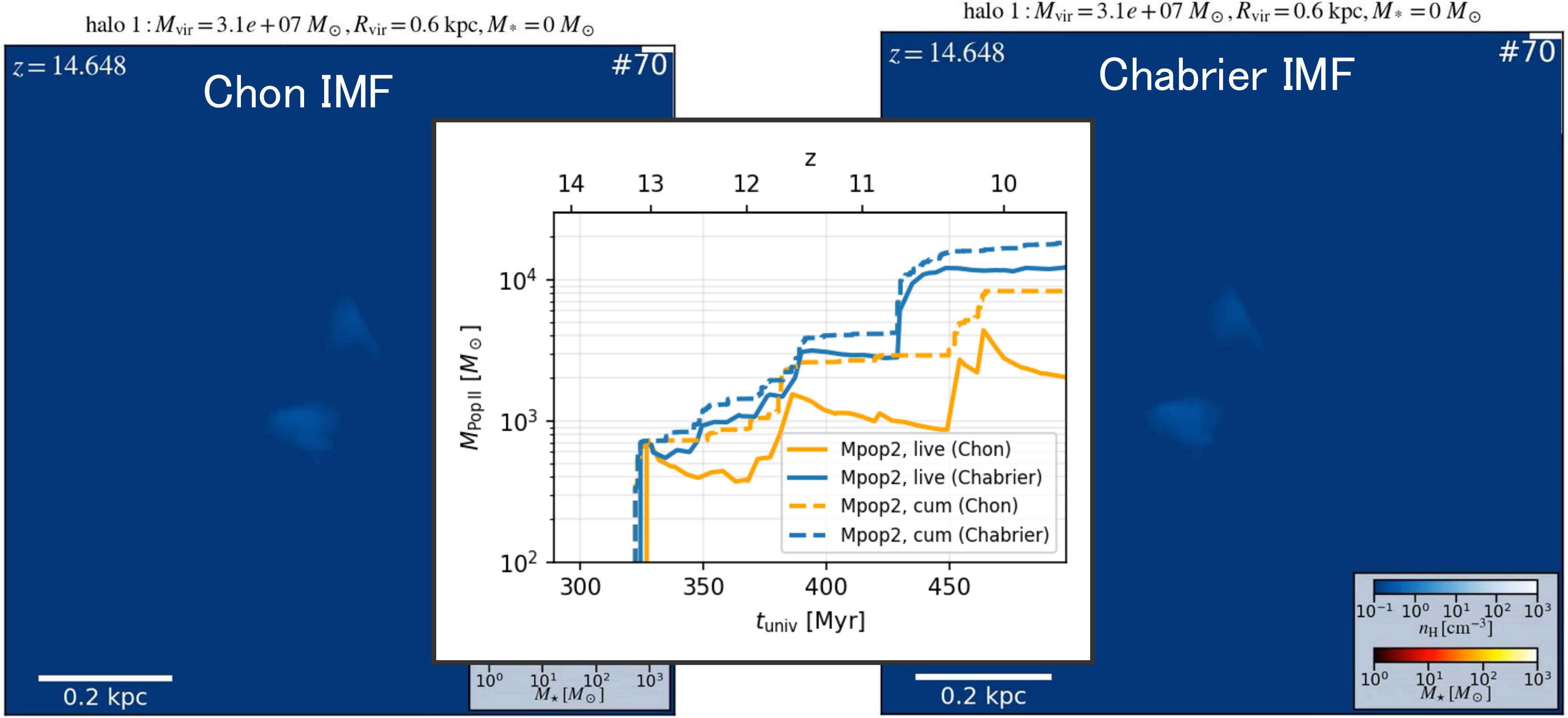
DM distribution

Mass evolution of the main halo



star-formation proceeds inefficiently

Effect of different Pop II models

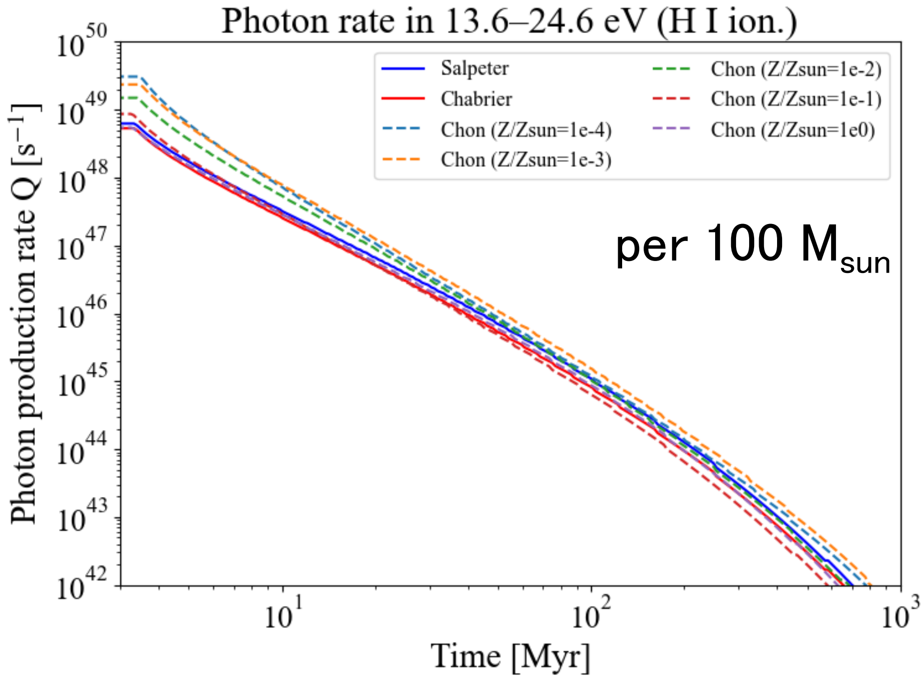


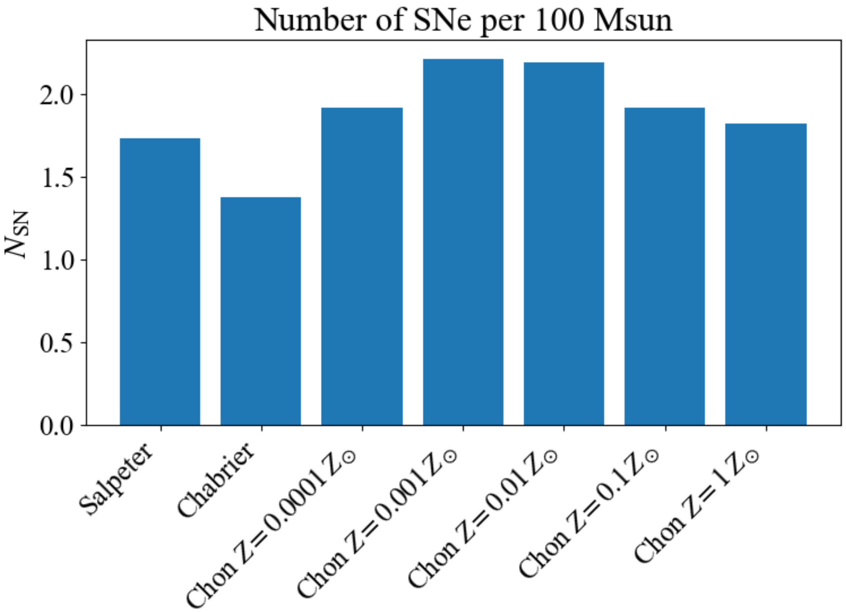
/xd-work/sugimrkz/ramses/dwarf/data/SBSv2/L1Mpc_Chon_2node/output_00070/info_00070.txt

/xd-work/sugimrkz/ramses/dwarf/data/SBSv2/L1Mpc_Chon_2node/output_00070/info_00070.txt

Pop II mass is lower in Chon IMF model than in Chabrier IMF model

Dependence of Feedback on IMF



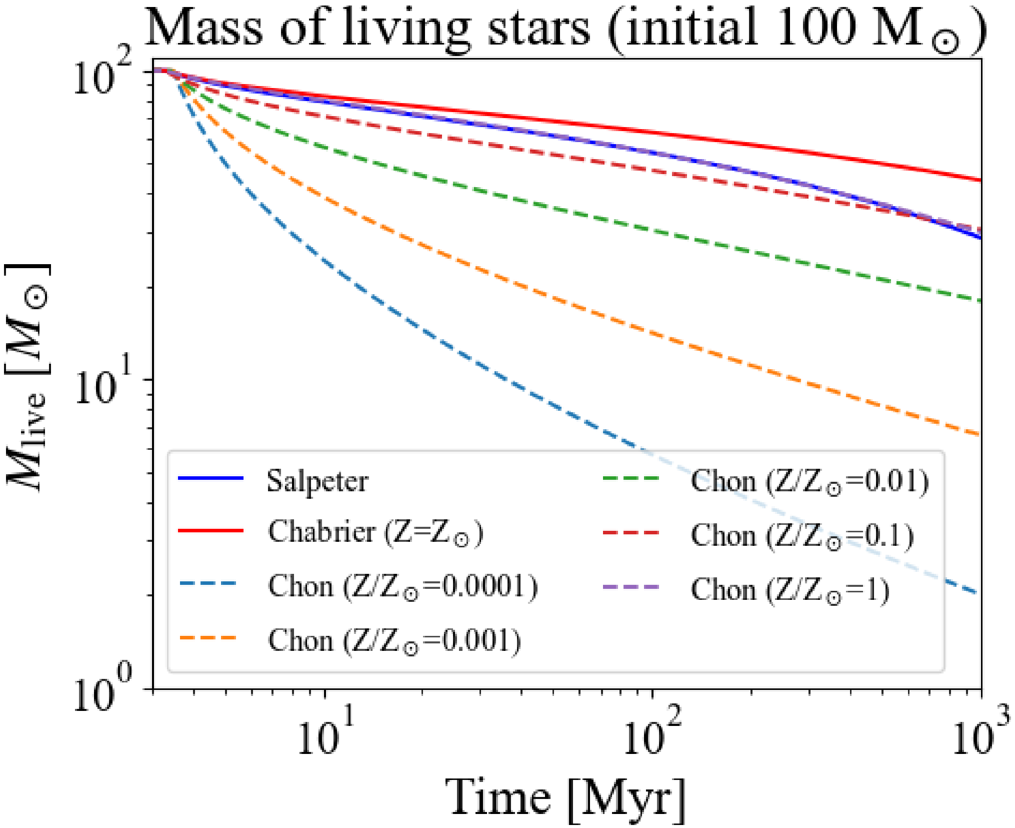


Ionizing photon emissivity per mass is about double for Chon IMF ($Z \sim 10^{-3}\ Z_{sun}$) compared with Chabrier IMF

Number of SNe is also double for Chon IMF ($Z \sim 10^{-3}\ Z_{sun}$) compared with Chabrier IMF

Feedback is stronger for Chon IMF for the same initial mass

Mass of living stars significantly decreases with time



In top-heavy IMF case, the stellar mass decreases significantly with time
→ only ～10% remains after 100 Myr for Chon IMF ($Z \sim 10^{-3}\, Z_{sun}$)

Mass reduction of living stars is efficient for Chon IMF

Stronger Feedback and more efficient mass reduction cause lower Pop II mass in Chon IMF model

CONCLUSION

Conclusion

- To reveal first galaxy formation from the principles of physics, we are working on galaxy formation simulations based on physical knowledge of small-scale processes
- We have implemented a Pop II star formation model considering Z-dependent IMF (Chon+ 2024) with the star-by-star treatment
- (preliminary) Pop II star formation during first galaxy formation is less efficient in Chon-IMF model compared with the baseline Chabrier-IMF model
- This can be understood from the strong feedback and efficient mass reduction in Chon-IMF model
- We are also working on a new Pop III model and investigating the role of Pop III stars in first galaxy formation (see Chiku-kun's and Matsuda-kun's talks).