初代銀河形成における EUV/FUVフィードバックの役割

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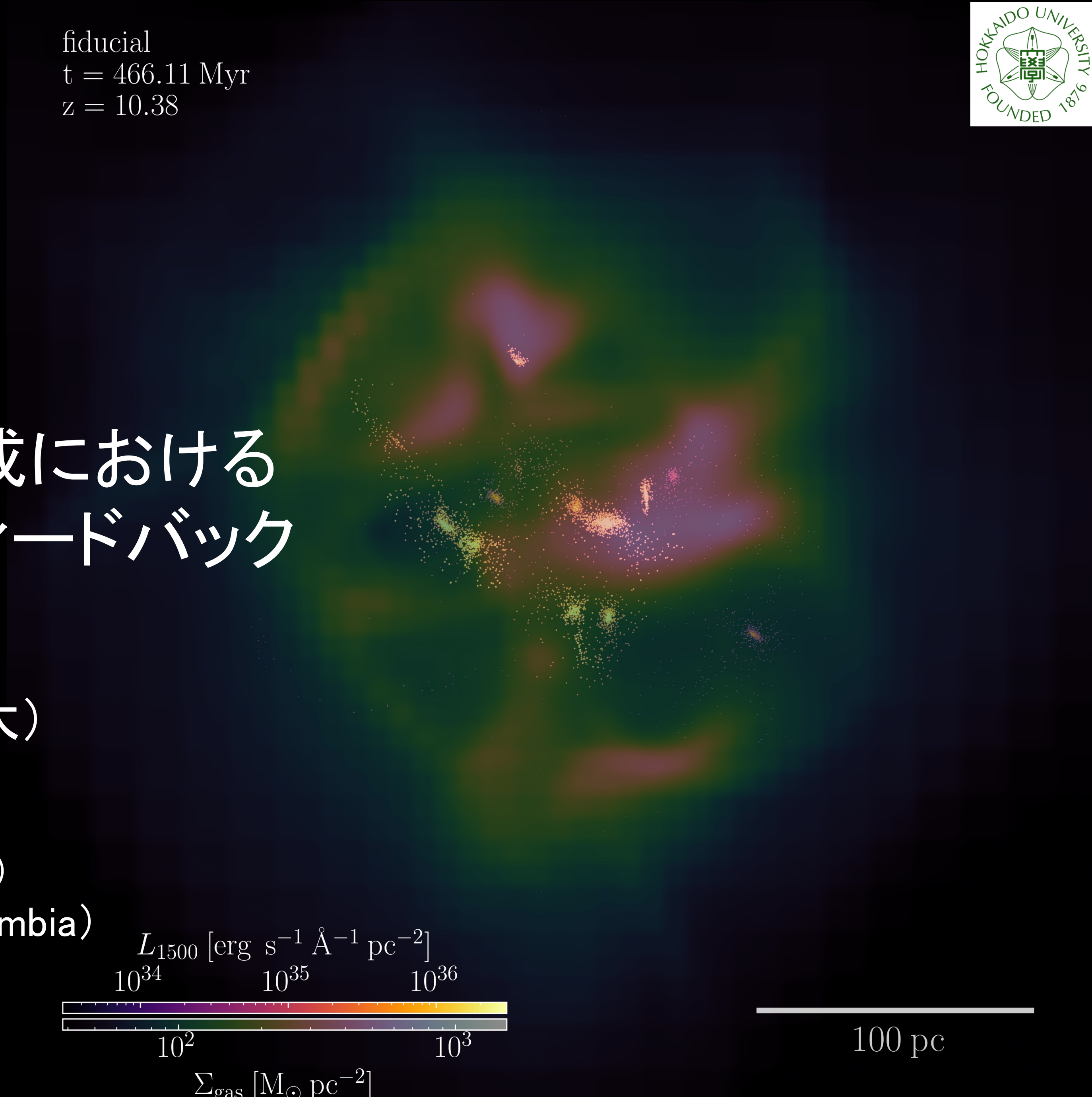

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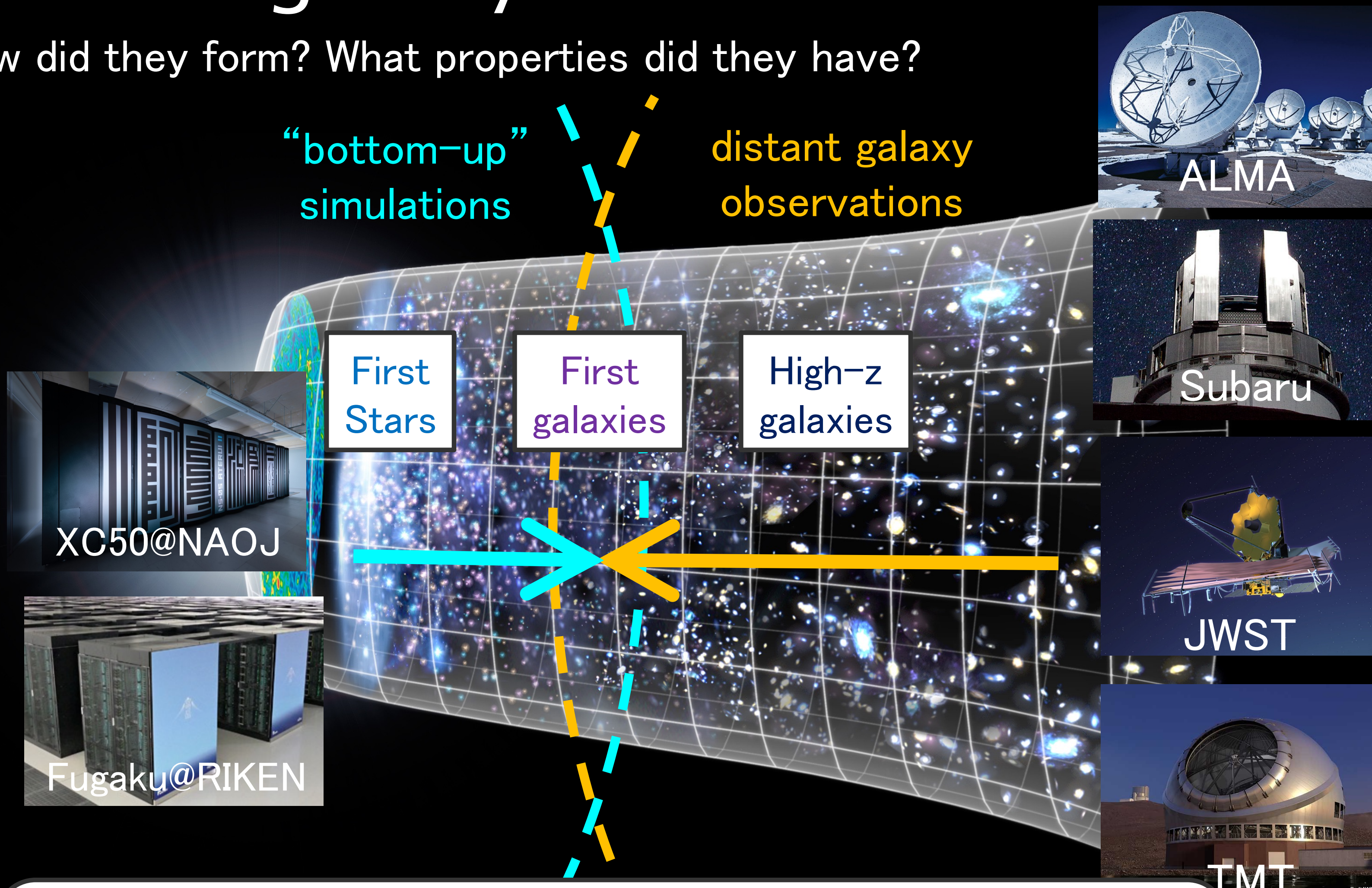
INTRODUCTION

The first galaxy formation

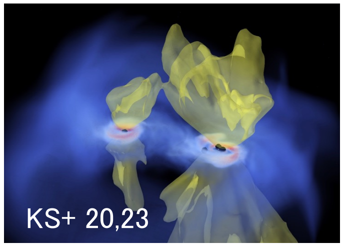
How did they form? What properties did they have?



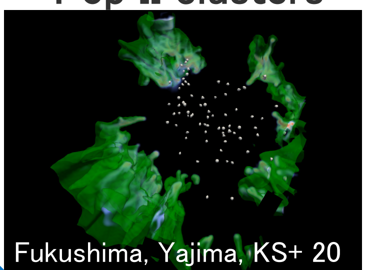
宇宙初期の矮小銀河に限定することで、高い解像度・詳細な物理モデルのシミュレーションを実現
→ しかも観測と比較可能な時代

“bottom-up” simulations of first galaxies

First stars



Pop II clusters

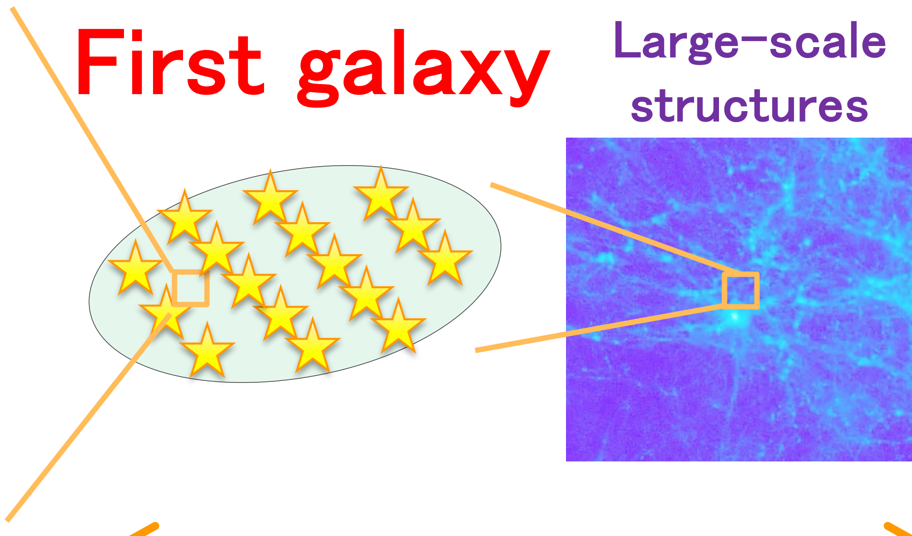


BH growth/feedback

growing knowledge about small-scale processes

First galaxy

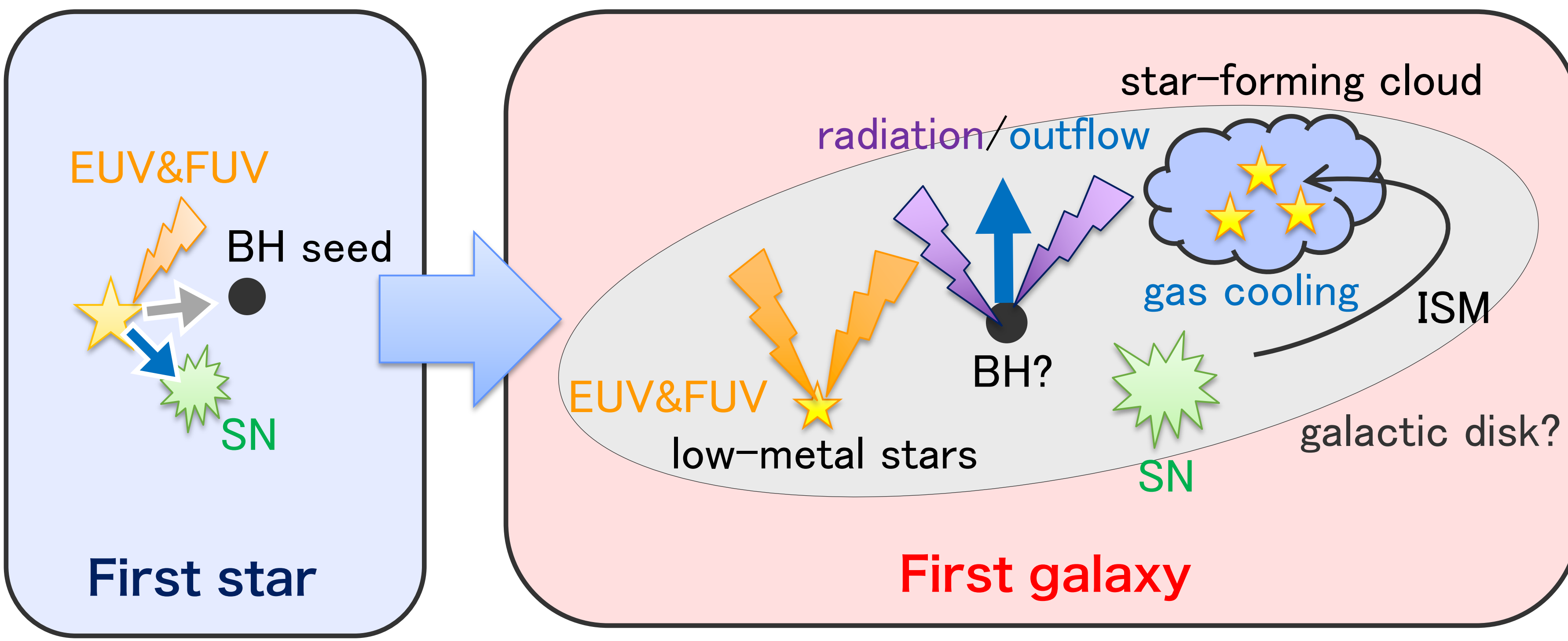
Large-scale structures



well-established ICs and evolution Eqs

Our goal is to reveal the formation of first galaxies from a theoretical side by combining simulations that follow the large-scale physical law and knowledge of small-scale processes

Various physical processes that affect the formation of the first galaxies

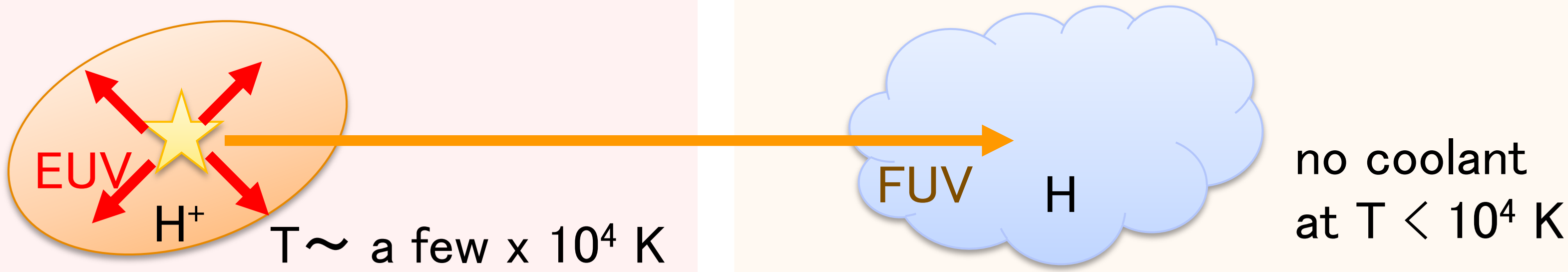


To understand first galaxy formation is to understand how the gas in a halo is converted to stars through various physical processes

EUV/FUV feedback

EUV feedback: H + EUV → H^+ + e^-

FUV feedback: H_2 + FUV -> 2H



Ionization bubble

Photodissociation region

- blows away surrounding gas by pressure of hot ionization bubble

- suppress star formation by dissociation of coolant (H_2)
- sometimes leads to supermassive star formation

Purpose of this work

To understand the role of FUV/EUV feedback in the first galaxy formation using cosmological radiation hydrodynamics simulations

METHODS

see also Garcia, Ricotti, Sugimura, Park (2023)

Simulation methods

Zoom-in simulations of a single galaxy ($M_{halo} = 10^8\ M_{sun}$ at z = 10)		
Code	RAMSES-RT (Teyssier 2002, Rosdahl & Teyssier 2015)	Cosmological AMR (M)HD, Moment method RT (M1 closure), DM particle, sink (BH) particle, stellar radiation, SN feedback, non-equil. chemistry/cooling/heating
Initial Conditions	MUSIC (Hahn & Abel 2011)	Generate initial condition at z = 127 w/ zoom technique
Last cosmic time	500 Myr	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	Internal Salpeter-like IMF
Refinement	1) $N_J = 8$ ($\Delta x > 1$ pc), 4 ($\Delta x < 1$ pc) 2) Lagrangian for DM and stars	1) at least N_J cells per Jeans length 2) to keep star clusters bound
Spatial Resolution	Δx_{min} = 0.15 pc * [(1 + z) / 10]	AMR level = 25
Star Formation	$n_{SF} = 5\times10^4\ cm^{-3}$ * $[(1+z)/10]^2$ * (T/100 K)	Binary Pop III (M_{tot}=120M_{sun}) for Z < $10^{-5}\ Z_{sun}$ Pop II cluster ($M_{cl} \sim 10^{2-5}\ M_{sun}$) for Z > $10^{-5}\ Z_{sun}$

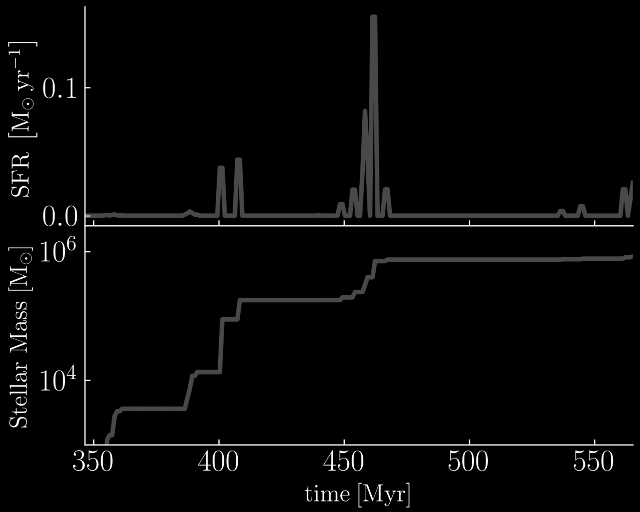
Feedback models

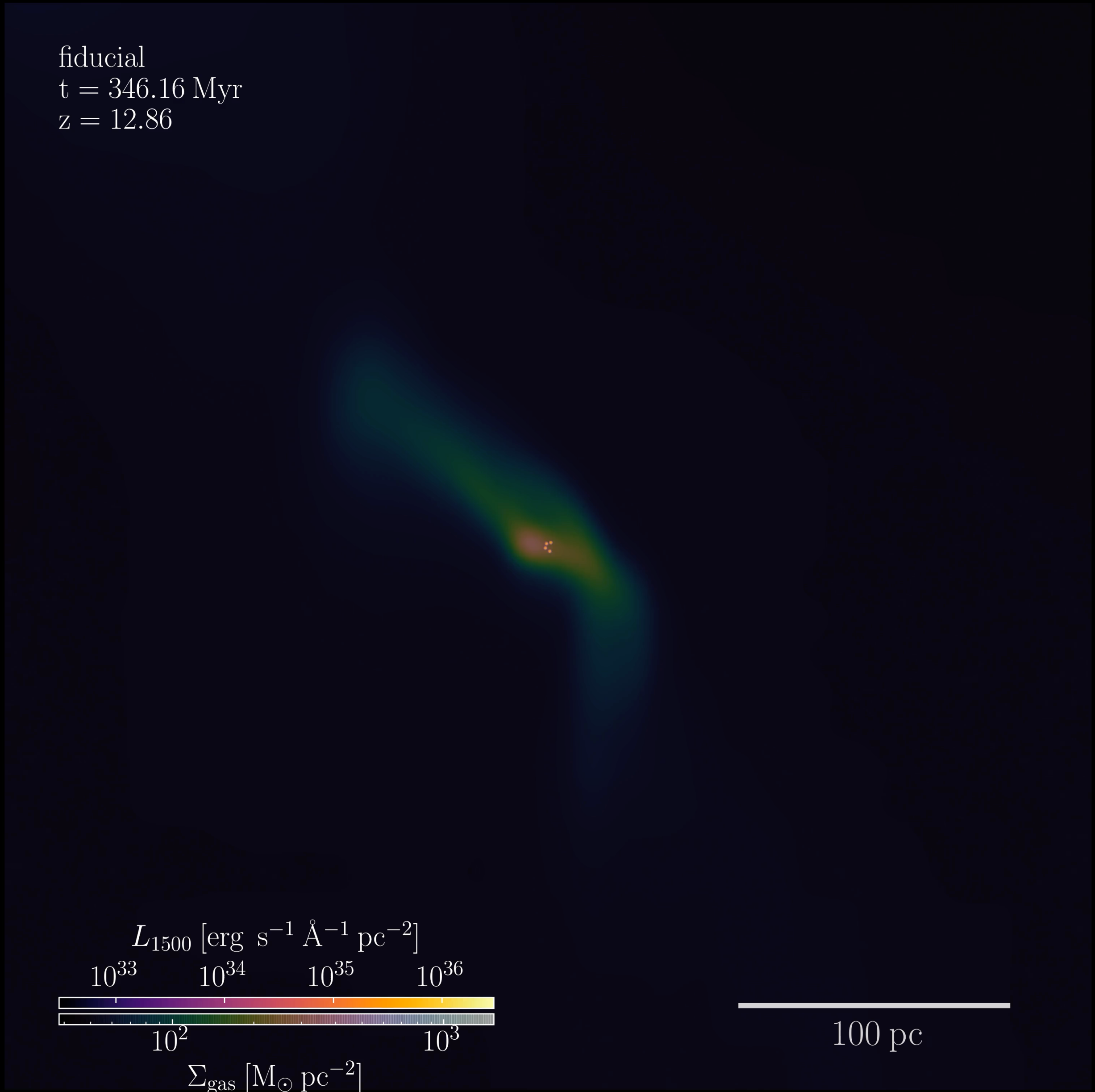
We perform runs with different feedback models to clarify the role of EUV/FUV radiative feedback separately

Run	Pop III		Pop II	
	FUV	EUV	FUV	EUV
fiducial	○	○	○	○
p2noFUV	○	○	–	○
p2noEUV	○	○	○	–
noFUV	–	○	–	○
noEUV	○	–	○	–

RESULTS

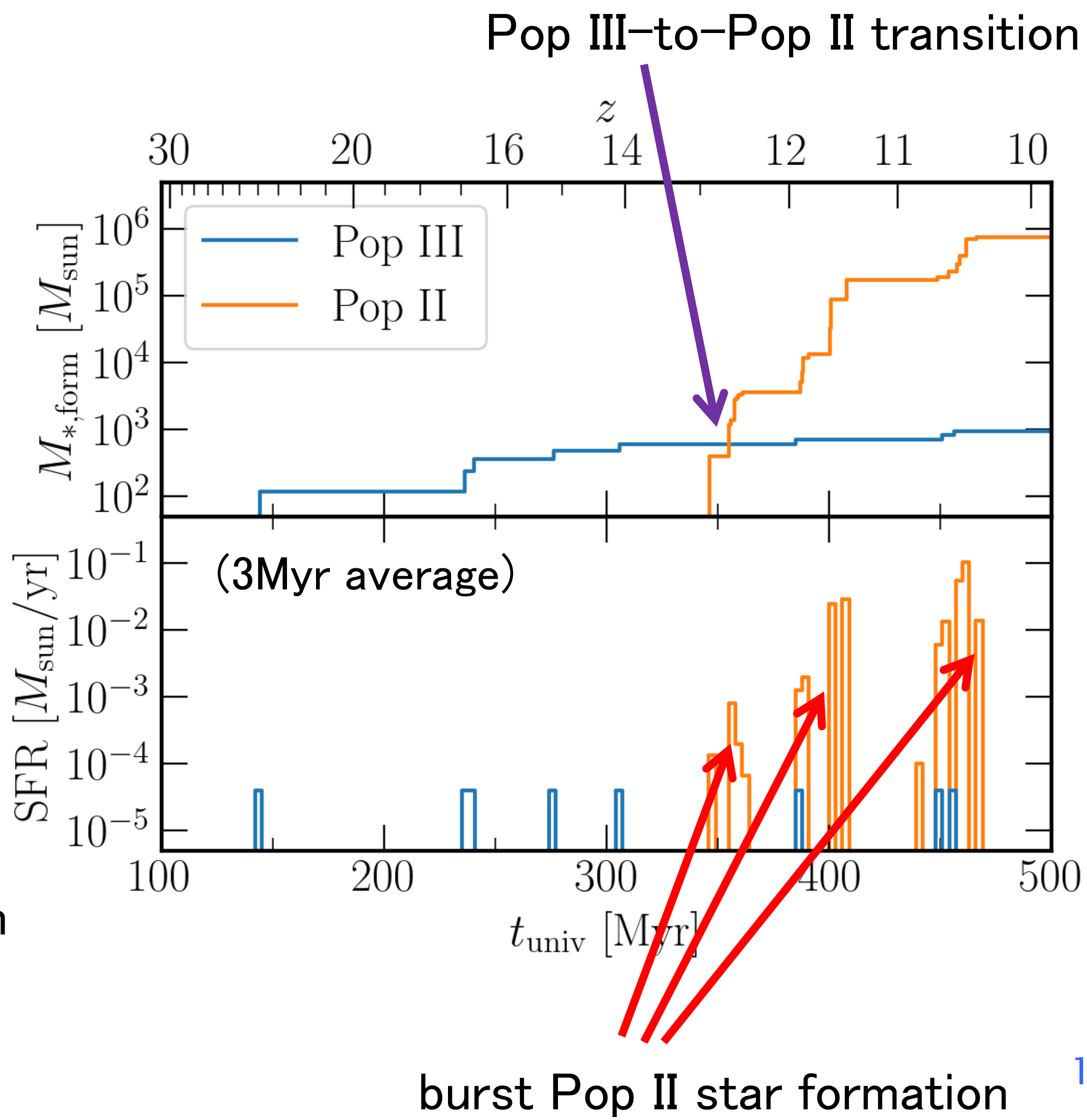
First galaxy formation in fiducial run





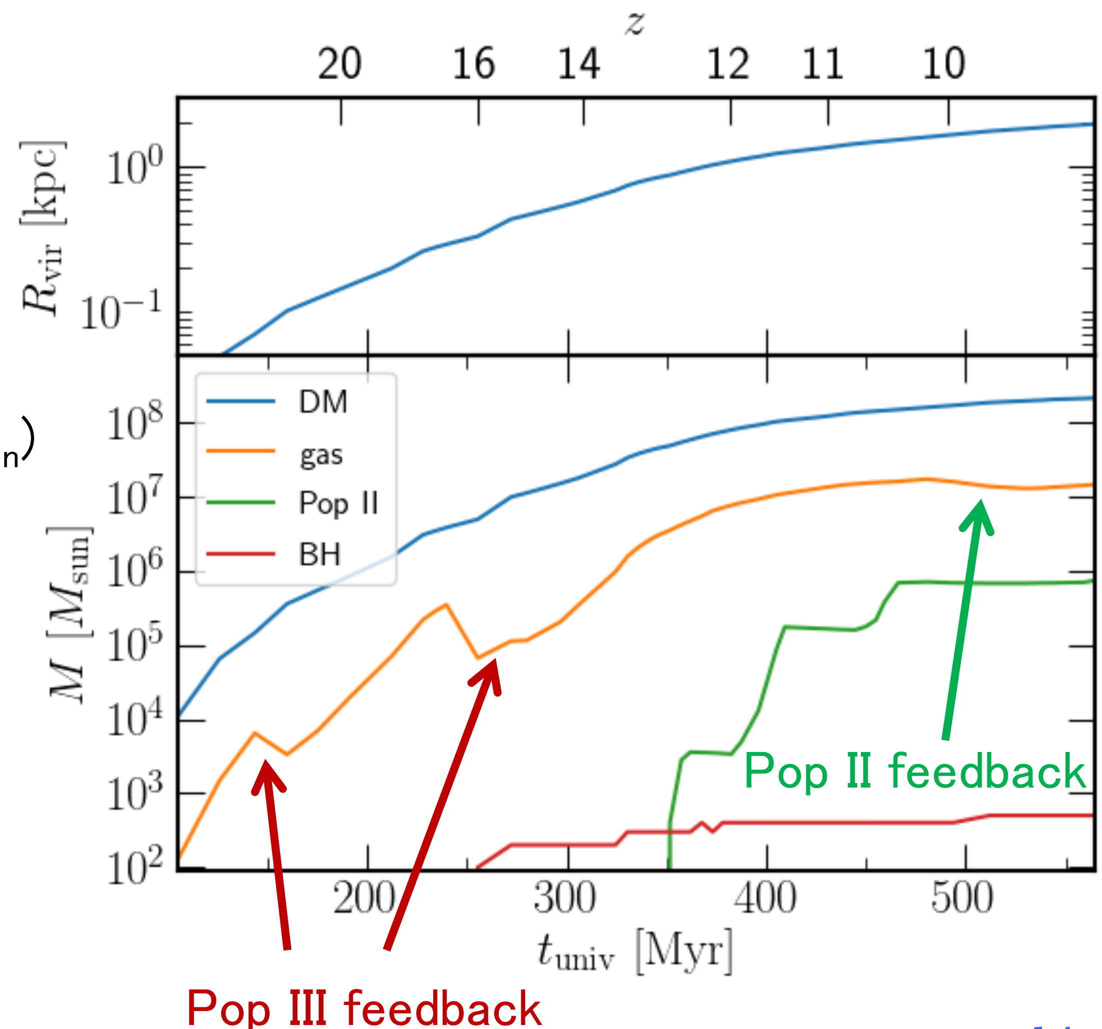
Star-formation history in the zoom-in region of fiducial run

- star-formation history in the 300 ckpc zoom-in region
- first Pop III star appears at z=26
- Pop III-to-Pop II transition occurs at z=13
- Pop II stars form through several burst events
- Pop III stars continue to form until z～10

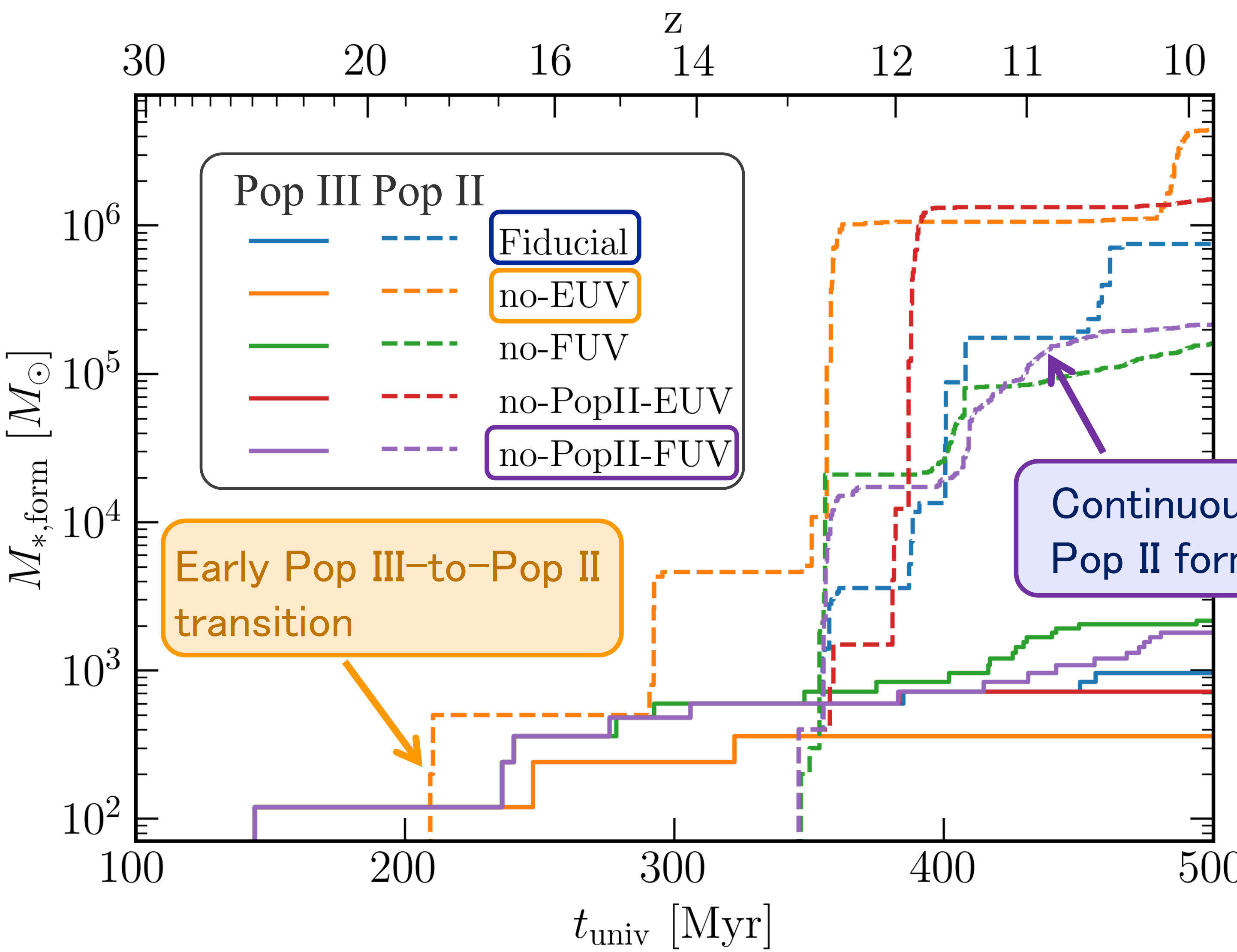


Internal state of the galaxy during its formation

- star-formation history in the virial radius of main merger tree (using Rockstar halo finder; Berhoozi+ 2013)
- Pop III-remnant BHs (∼100 M_{sun}) hardly grow by gas accretion (BHL accretion assumed)
- feedback sometimes evacuates gas from the halo



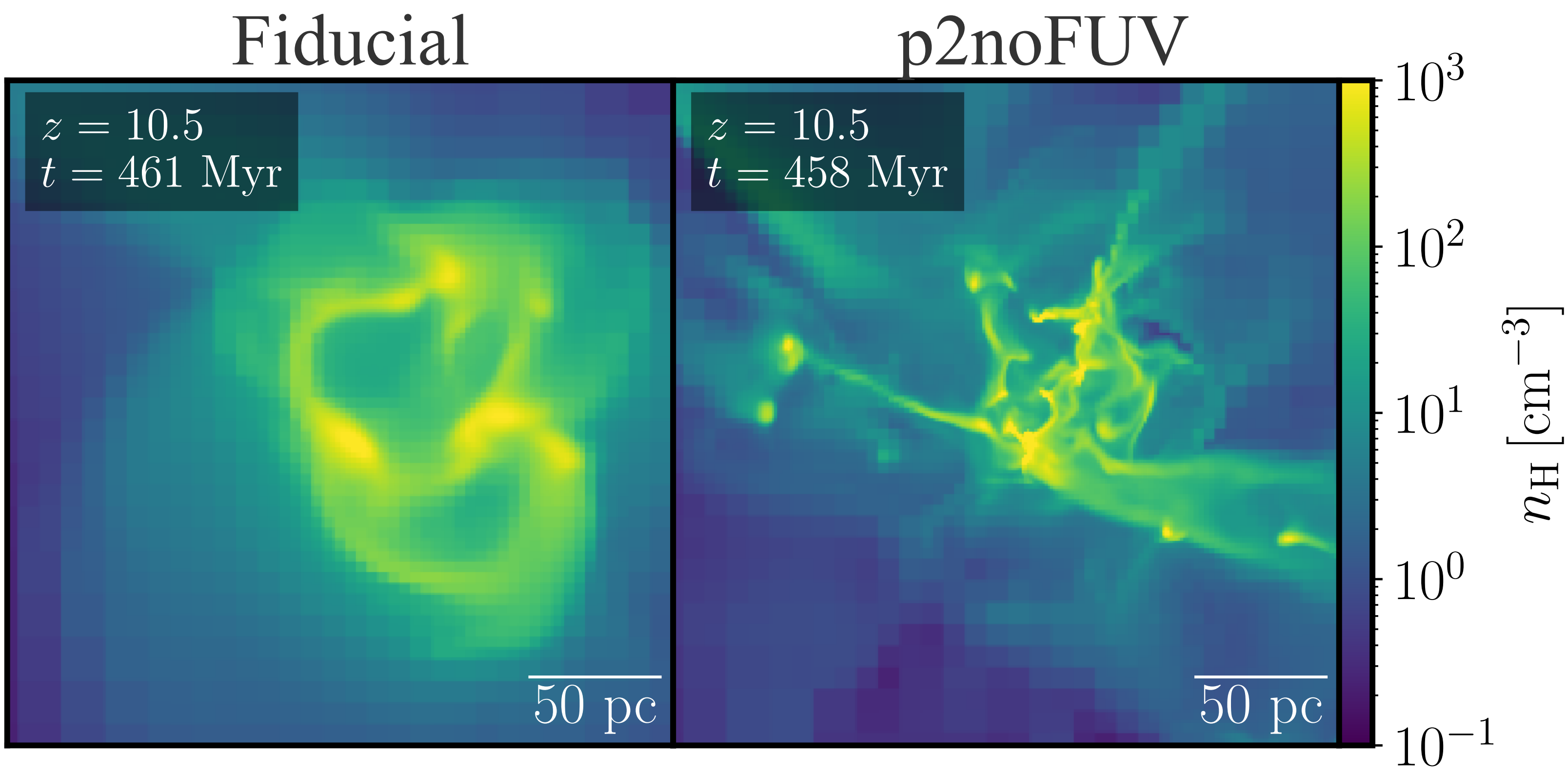
Model dependence of SFH



Early Pop III–to–Pop II transition

Continuous Pop II formation

Gas distribution during star formation with and without FUV feedback



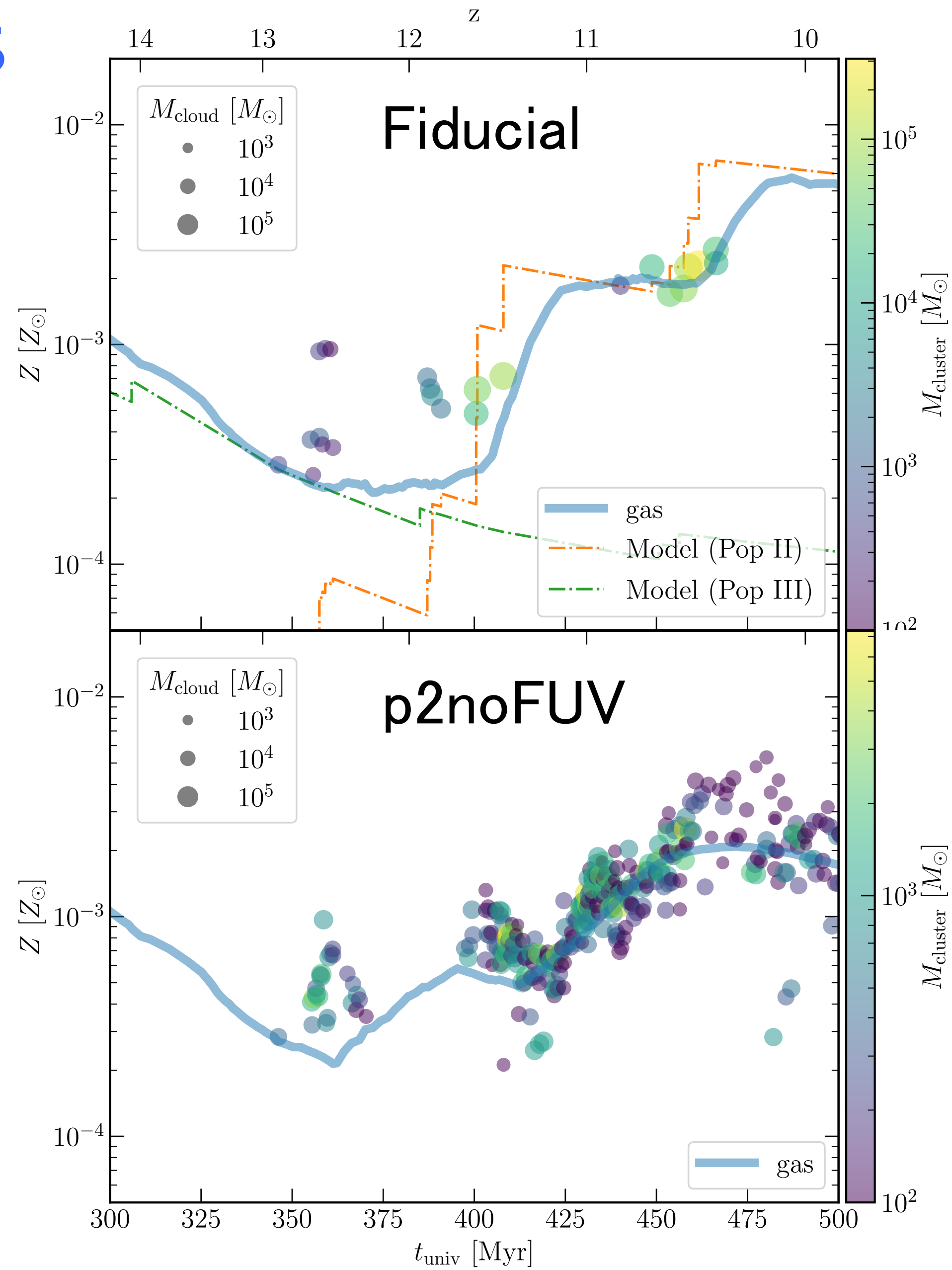
- large star-forming cloud collapses as a whole with weak fragmentation (similar to SMS formation site)
- star formation proceeds in small fragmented star-forming clouds

Stellar clusters w/ and w/o FUV feedback

- Fewer but bigger clusters formed in the run w/ FUV
- Metallicity generally follow the average gas metallicity inside virial radius with ～0.5 dex scatter
- Metallicity evolution can be reproduced by a simple model based on $M_{*,\mathrm{form}}$ and M_{halo}

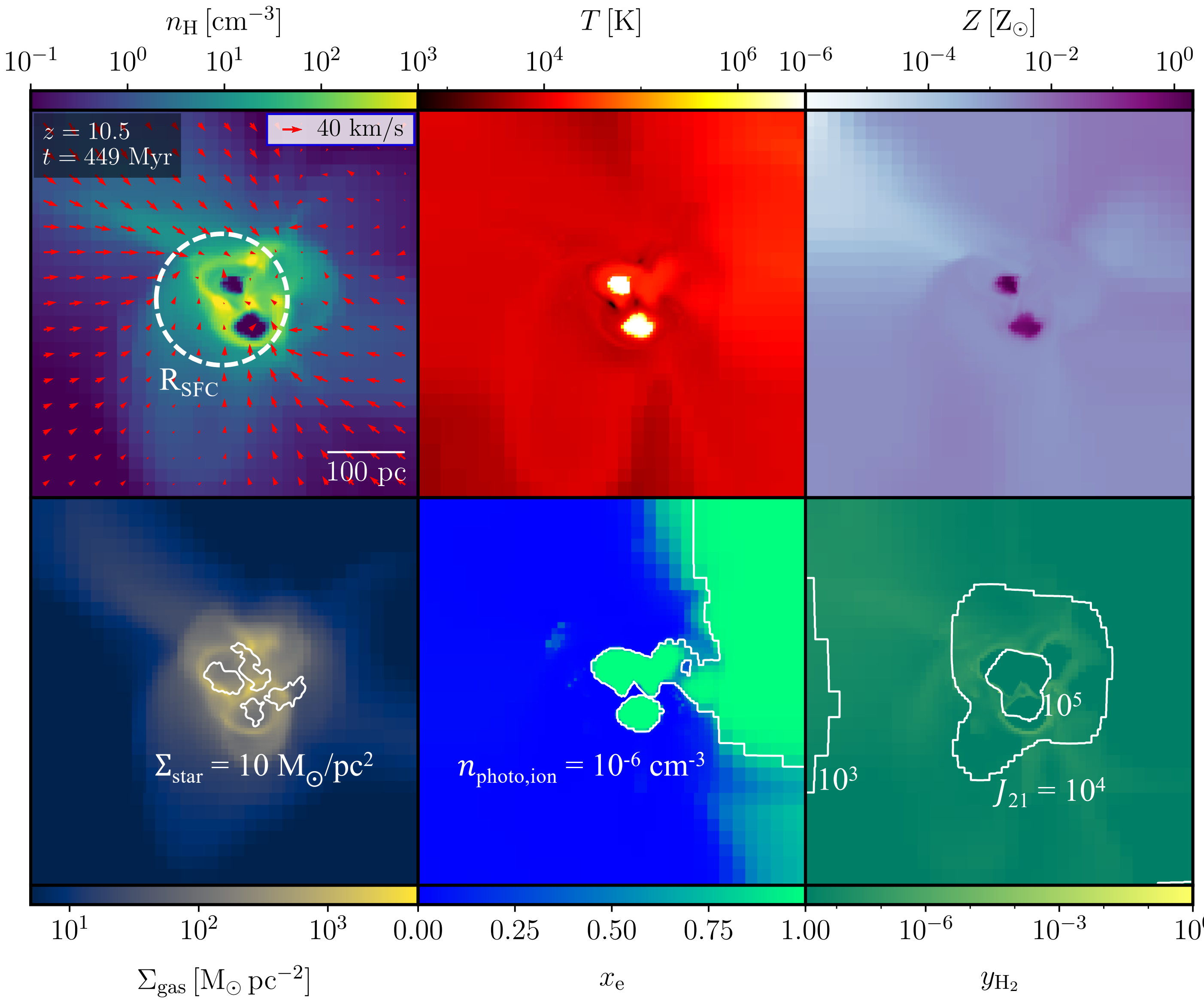
$$Z_{\mathrm{PopII}}\,[Z_\odot] = 0.47 \times \left(\frac{M_{\mathrm{PopII,form}}}{M_{\mathrm{vir}}}\right)$$

$$Z_{\mathrm{PopIII}}\,[Z_\odot] = 7.0 \times \left(\frac{M_{\mathrm{PopIII,form}}}{M_{\mathrm{vir}}}\right)$$

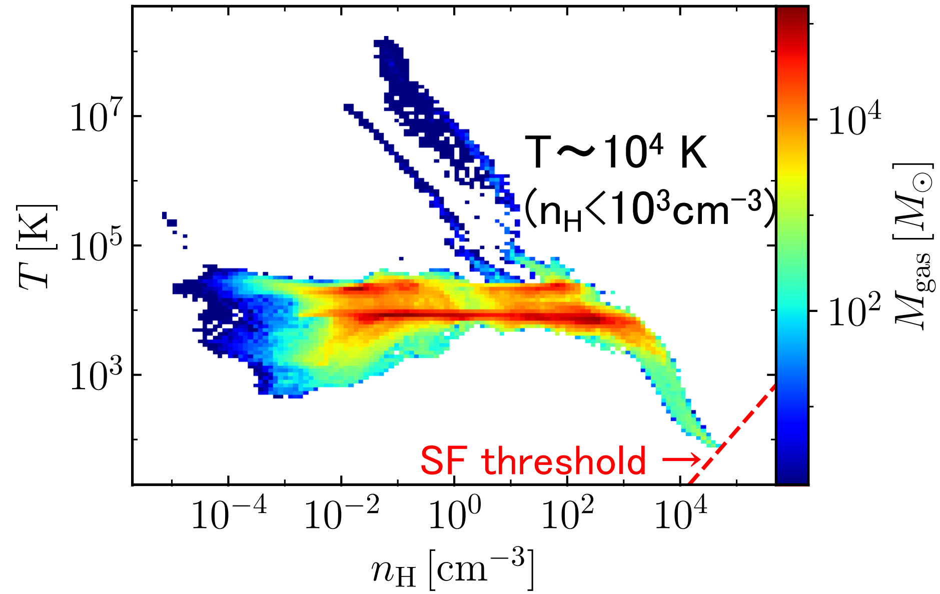


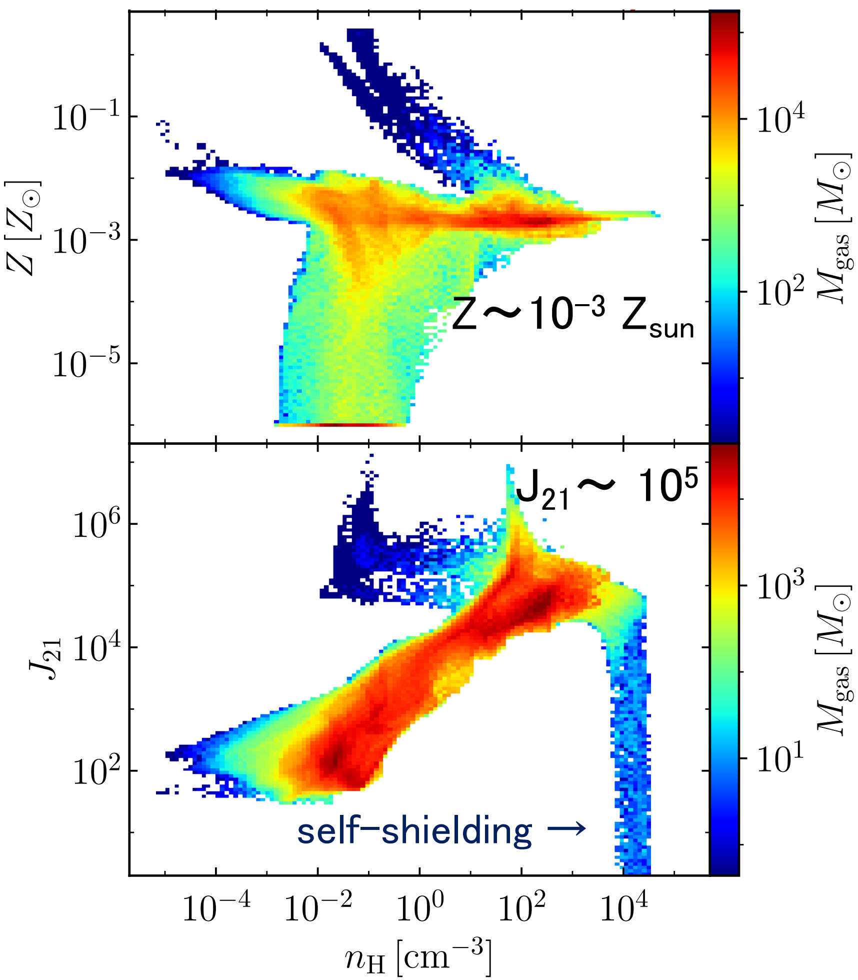
(depends on underlying IMF, metal escape fraction and gas mass fraction)

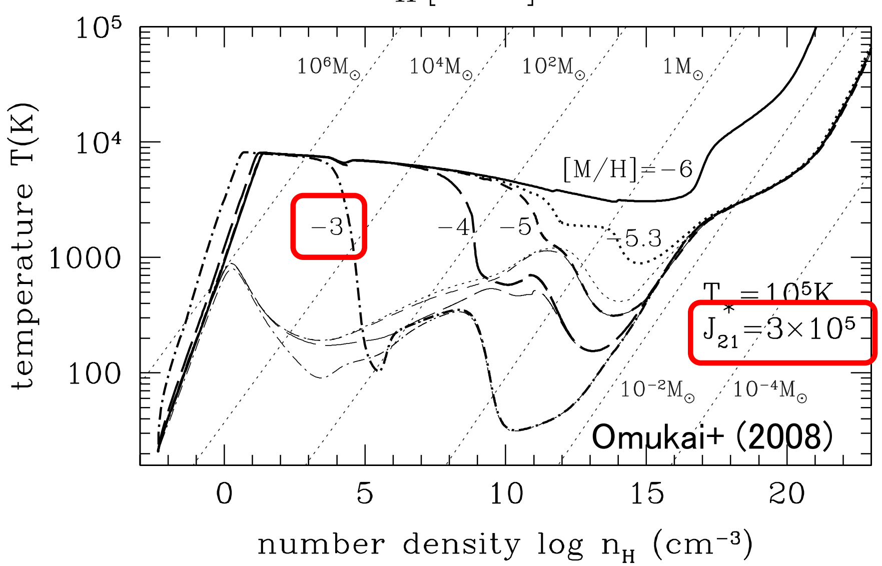
Snapshot of a star forming cloud in the run with FUV



Phase diagram of a star forming cloud in the run with FUV

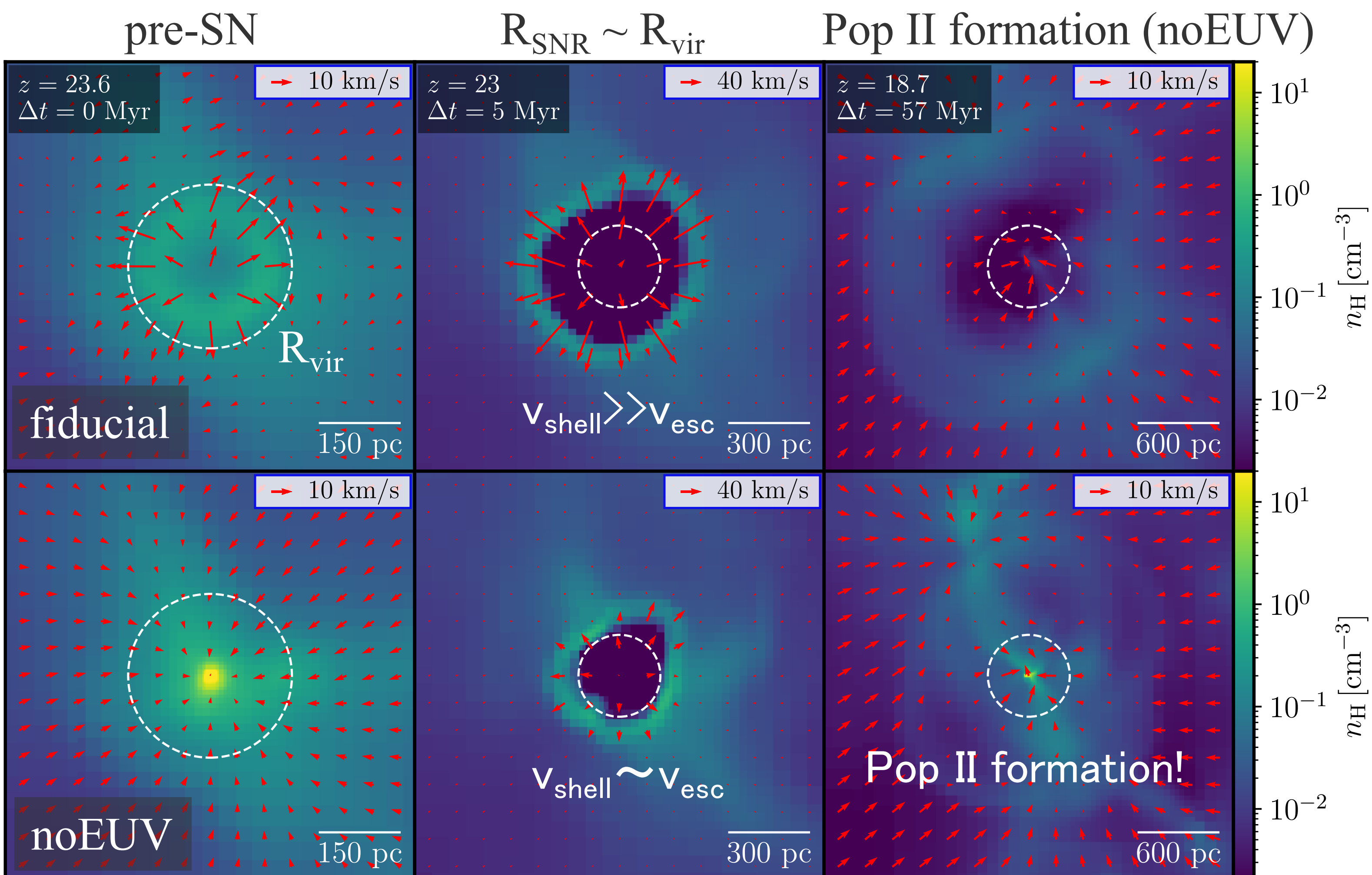






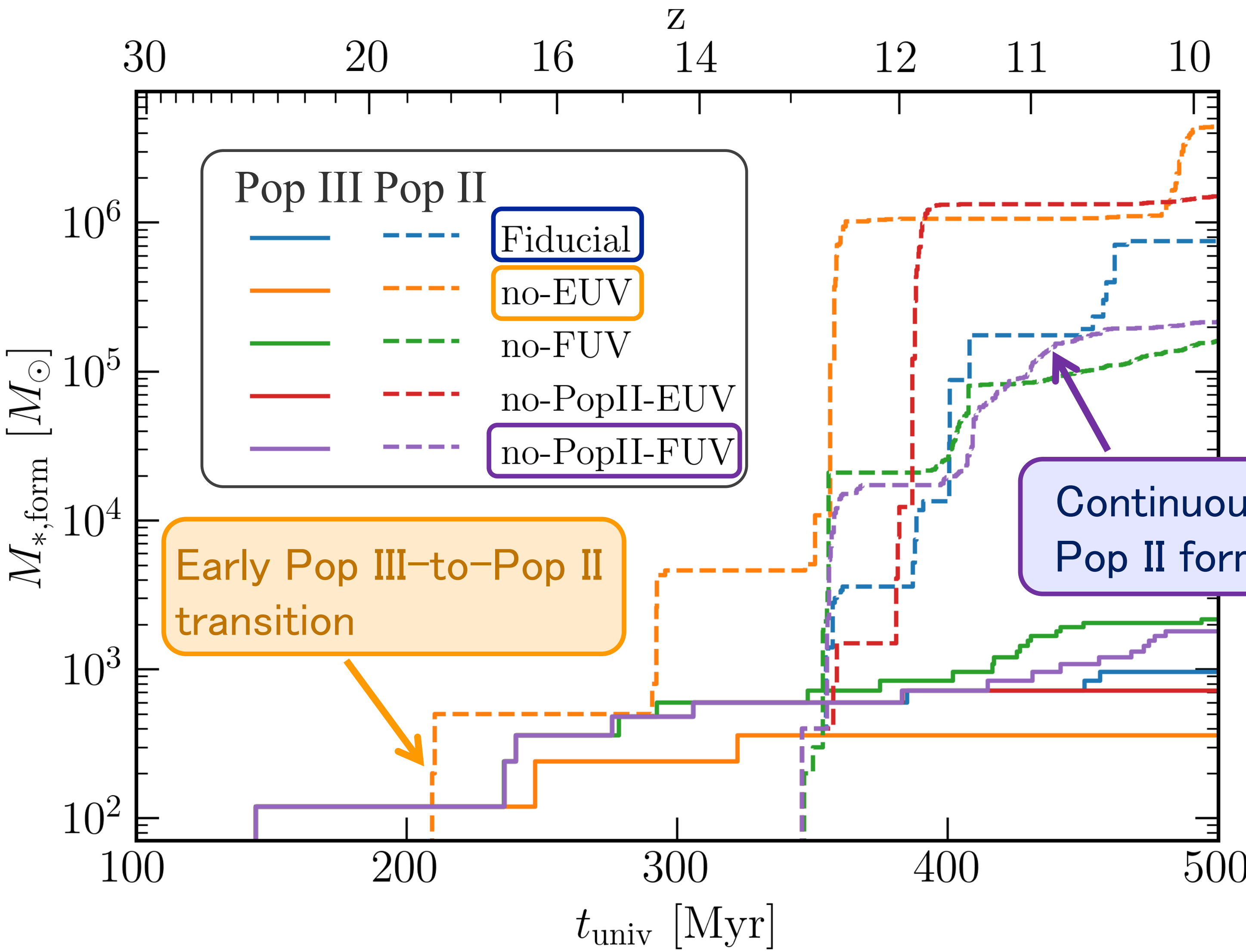
← Similar condition realized during the formation of first galaxy

EUV pre-SN feedback changes the fate of the first SN bubble



EUV also enhances the efficiency of Pop II SN feedback → higher SFE

Model dependence of SFH (again)



CONCLUSION

結論

- 現象論的なサブグリッドモデルを用いない、ボトムアップ的な初代銀河形成シミュレーションに取り組んでいる

- 本研究では初代銀河形成においてEUV/FUVのそれぞれのフィードバックがどのような役割を果たすかを調べた

- FUVフィードバックはガス分裂を抑制しPop II形成を間欠的にする
  - 星形成効率（最終的な星質量）はむしろ上昇（ポジティブフィードバック）

- EUVフィードバックは超新星の前に周囲の密度を下げ、超新星フィードバックの影響を増加させる
  - Pop III超新星の後、すぐにガスがフォールバックしてPop IIを作るのを抑制
  - Pop II超新星の影響を強めて星形成効率を低下させる

- 今後は、Pop III形成モデルの改良（平野くんformula x 連星）、star-by-star Pop II形成モデルの実装、BHフィードバック入り計算などを進める予定