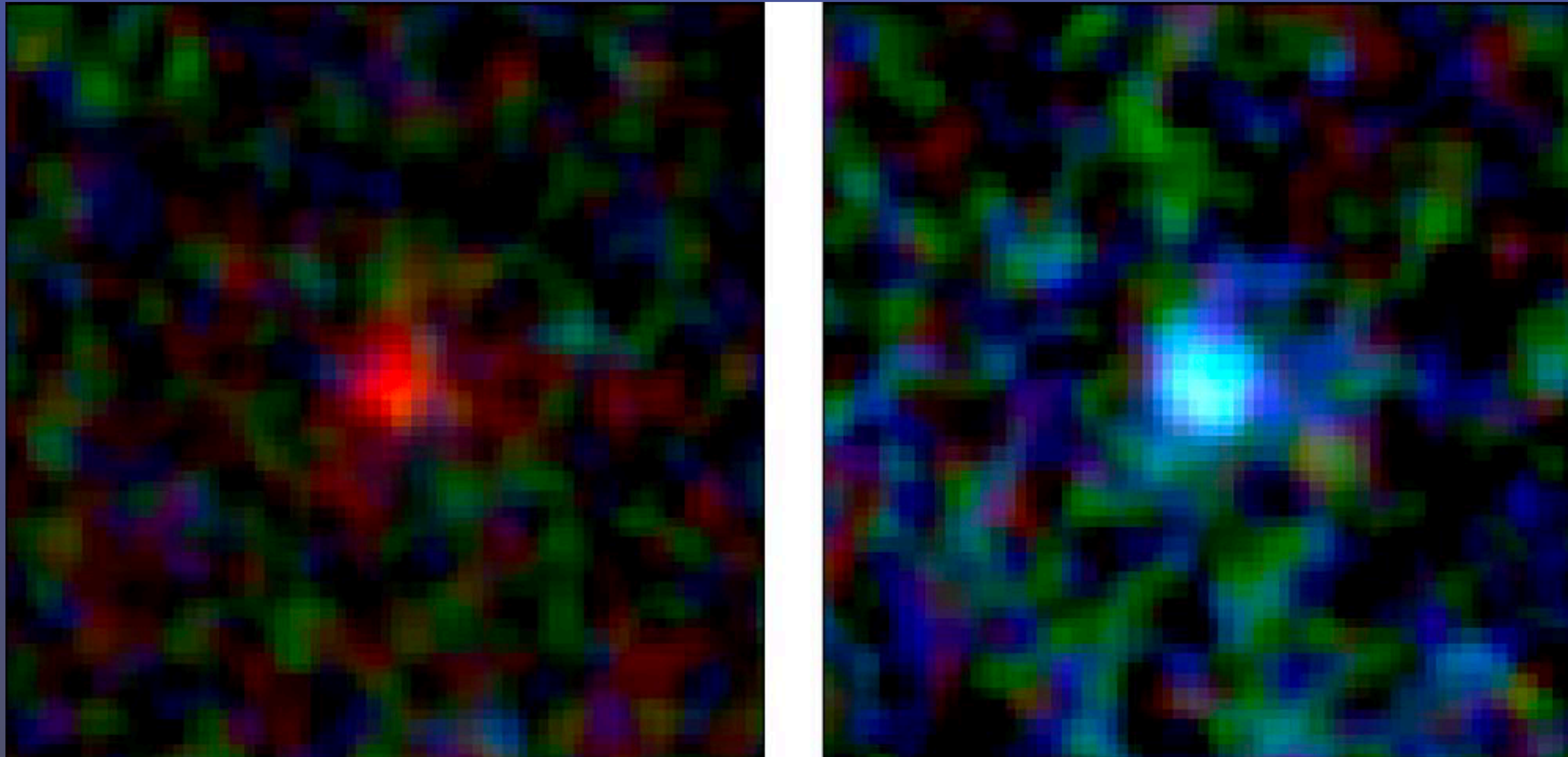


# On-the-fly Calculation of an X-ray Background and Its Impact on the Number Density of Population III Stars

Jongwon Park (Yonsei University/University of Maryland)

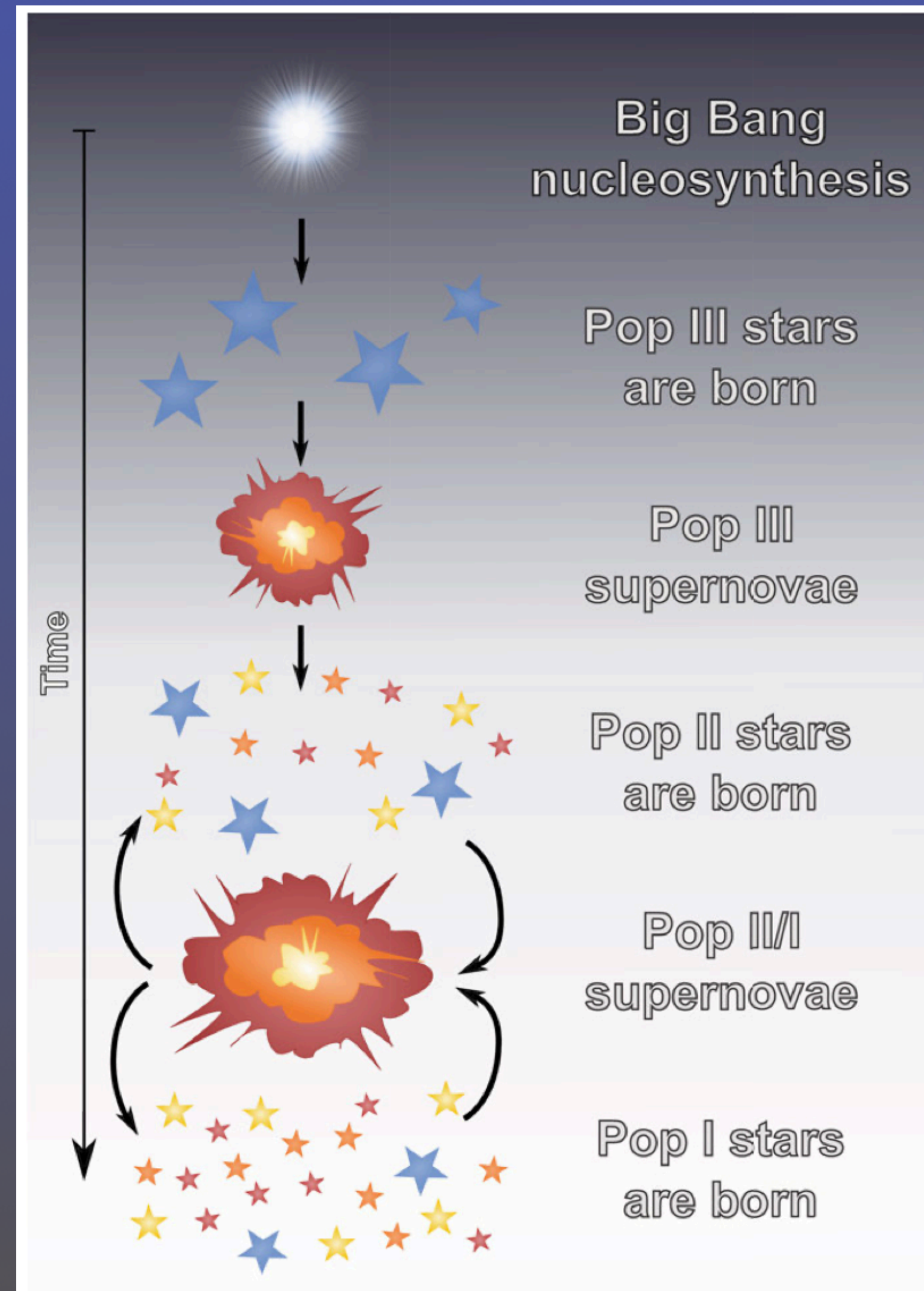
Massimo Ricotti (University of Maryland)

# The First Galaxies



Galaxy at  $z \sim 12$   
Finkelstein+ 2022

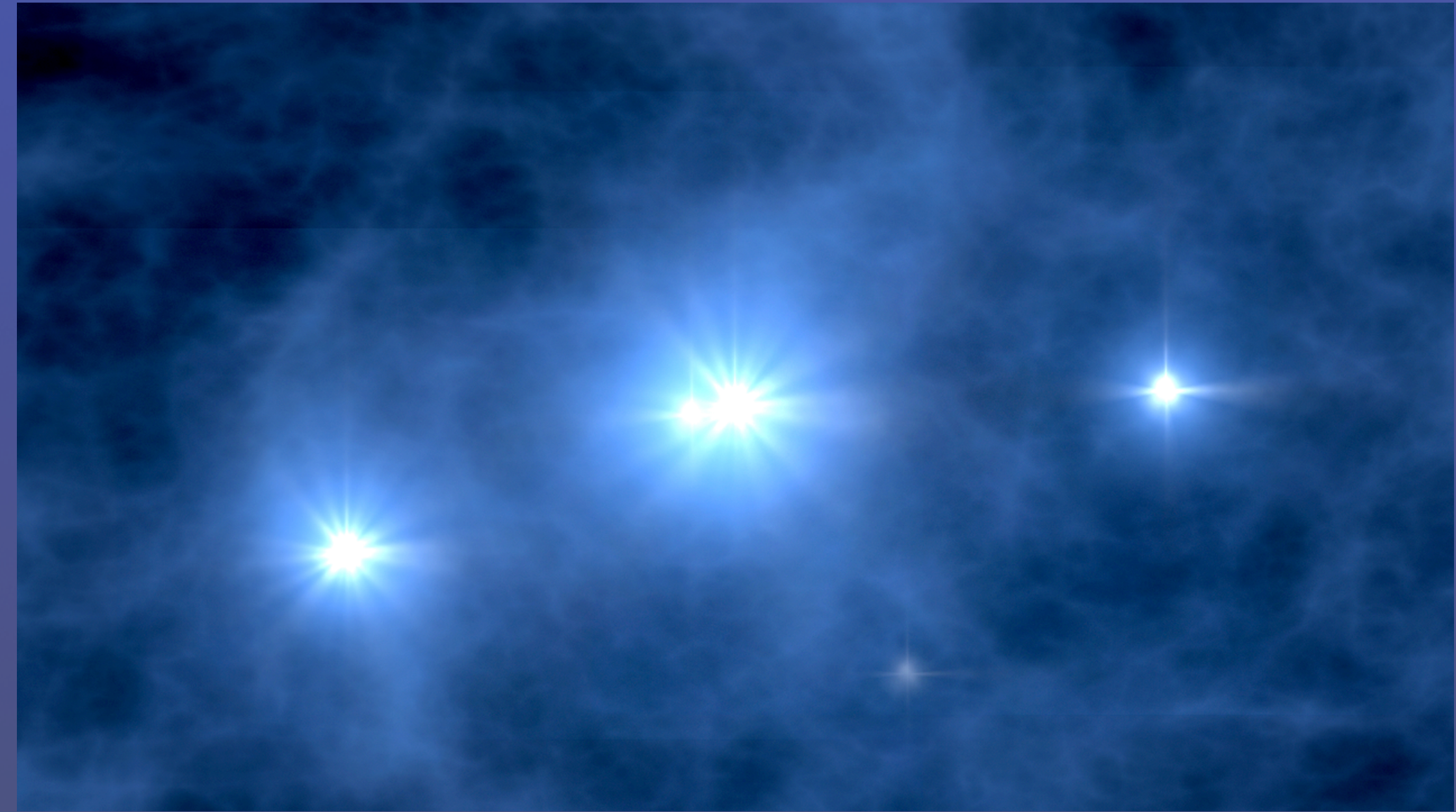
# The First Galaxies



Chemical Enrichment  
(Thomas Nordlander  
PhD Thesis)

# Population III Stars

- present in the early universe
  - $z \sim 30 - 10$
  - 0.1 ~ 0.5 Gyr after the Big Bang
- massive,  $M \sim 100 M_{\odot}$
- Pop III - metal-free



Artist's rendering of Population III star  
Credit: NASA/WMAP Science Team

# Molecular Hydrogen

- The formation of Pop III stars is triggered by molecular hydrogen (H<sub>2</sub>).
- H<sub>2</sub> forms in gas.



# Radiation Background



- Lyman-Werner
  - Photodissociate  $\text{H}_2$
- X-rays
  - Pop III SN, AGN, HMXB...
  - increase the electron fraction
  - promotes Pop III star formation

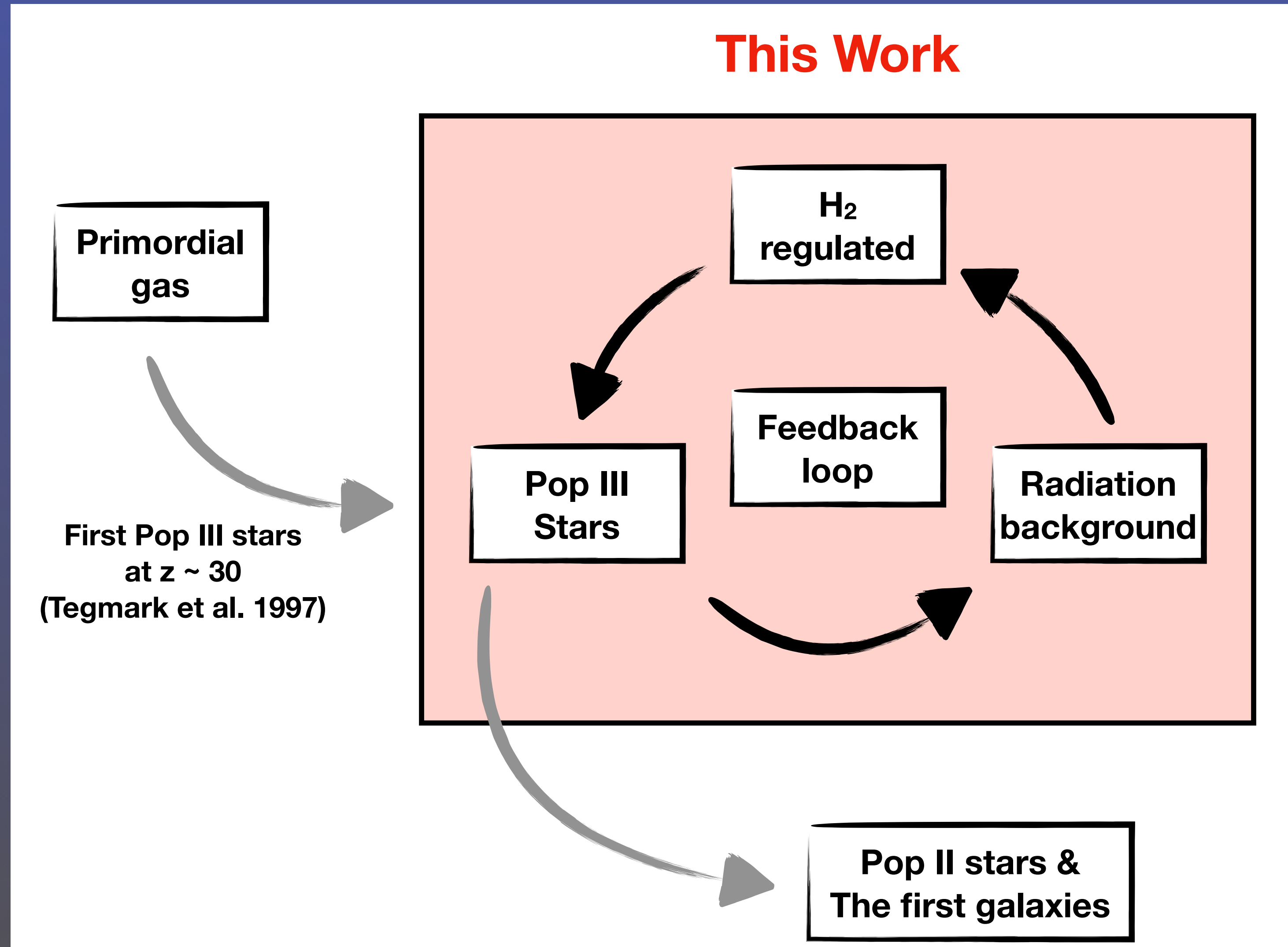
# Radiation Background



- Lyman-Werner
  - Photodissociate  $\text{H}_2$
- X-rays
  - Pop III SN, AGN, HMXB...
  - increase the electron fraction
  - promotes Pop III star formation

- ~~- Ionizing UV ( $E > 13.6 \text{ eV}$ )~~
  - ~~- Absorbed by neutral medium...~~

# X-ray Feedback Loop



# Estimating X-ray Background

## 1. Pop III star

c.f. Haardt & Madau 2012

## 2. Feedback loop - Interplay between Pop III stars and X-rays

c.f. Ahn+ 2015 / Xu+ 2016

## 3. Radiation from distant ( $> 10$ Mpc/h) sources

c.f. Jeon+ 2014

>>> How can we consider feedback loop and distant sources in a high-resolution simulation?

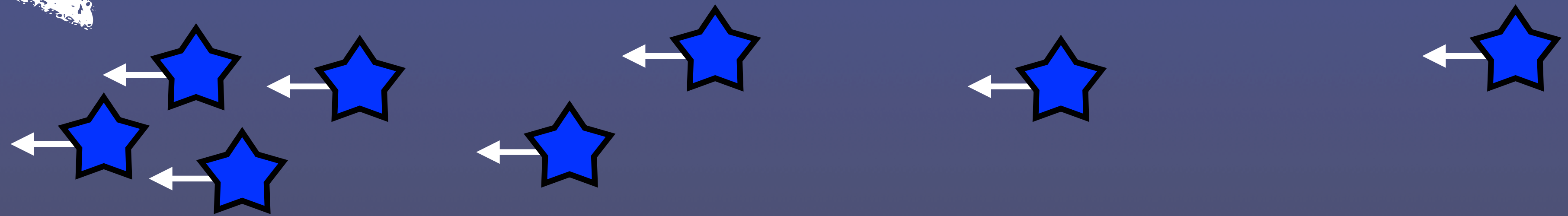
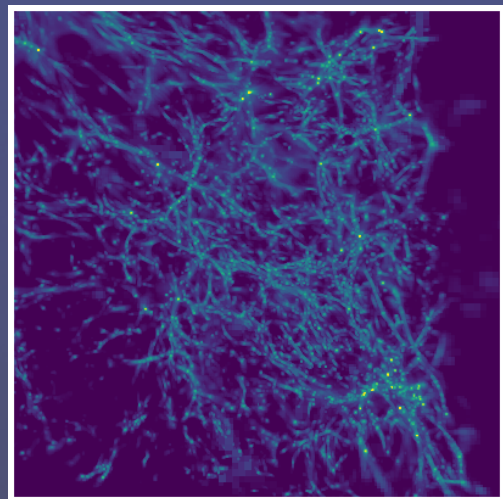
# On-the-fly Calculation of X-rays

$$J_{\nu_0}(z_0) = \frac{c}{4\pi} \int_{z_{\text{box}}}^{z_{\text{start}}} \left| \frac{dt}{dz} \right| dz \frac{(1+z_0)^3}{(1+z)^3} \epsilon_{\nu}(z) e^{-\tau_{\nu}(z)}$$

[erg s<sup>-1</sup> cm<sup>-2</sup> Hz<sup>-1</sup> Sr<sup>-1</sup>]

distant  
high z

current z



SFH in the box ->  
distant sources

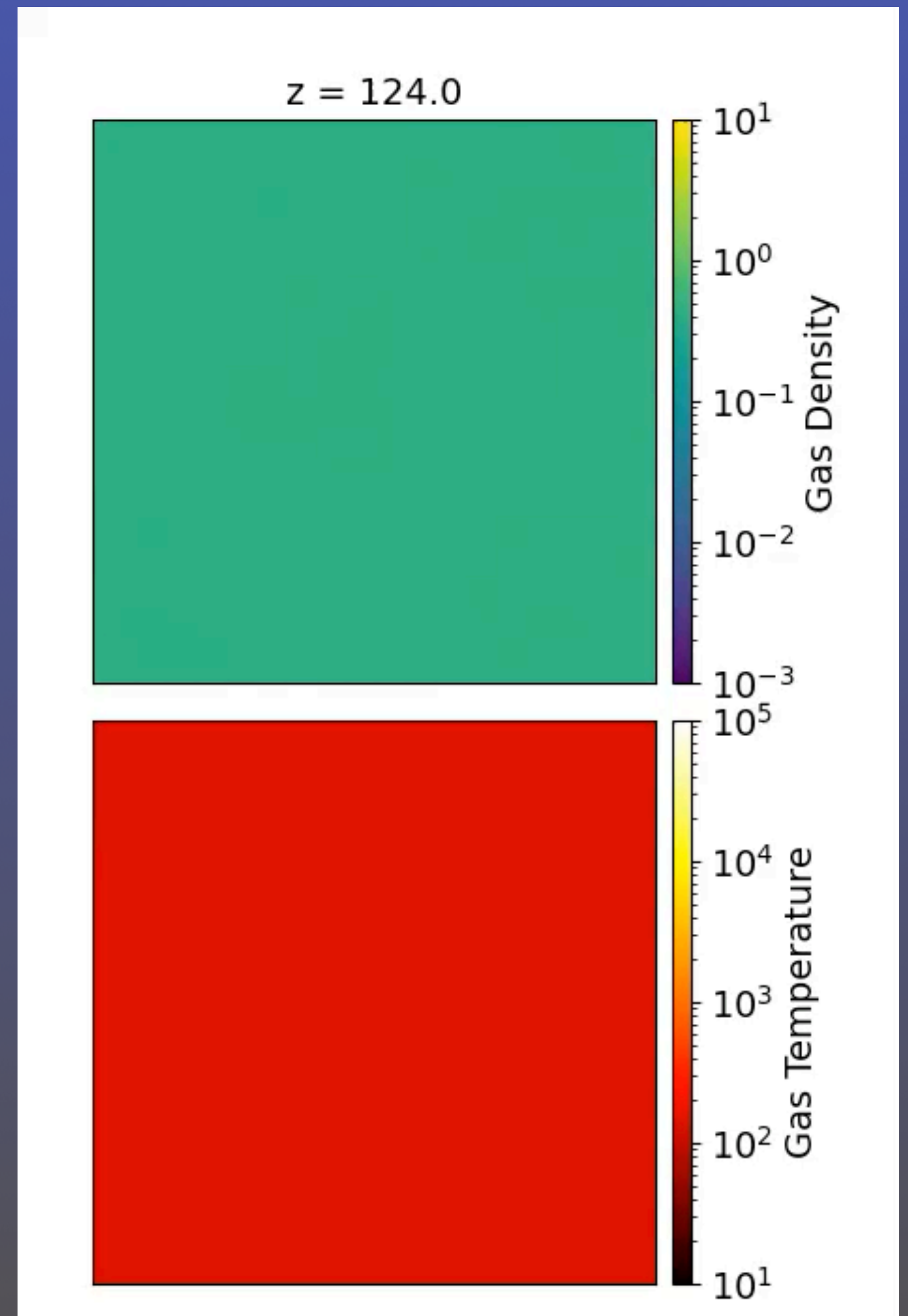
# Simulations

## – RAMSES-RT

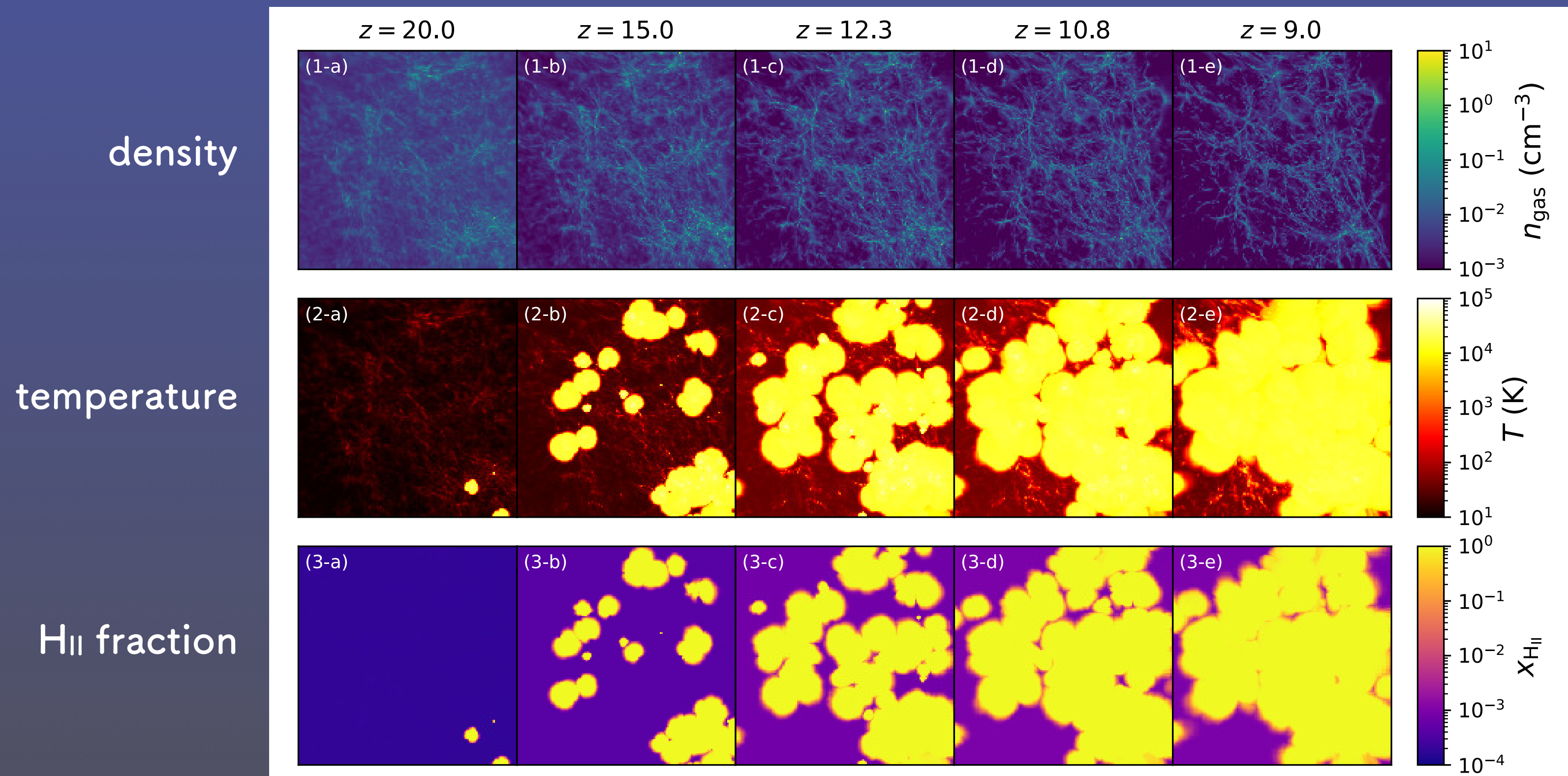
- zoom-in simulations of 1.0 and 0.5 Mpc/h
- 10 volumes
- LW-only / LW + X-ray

## – Physics

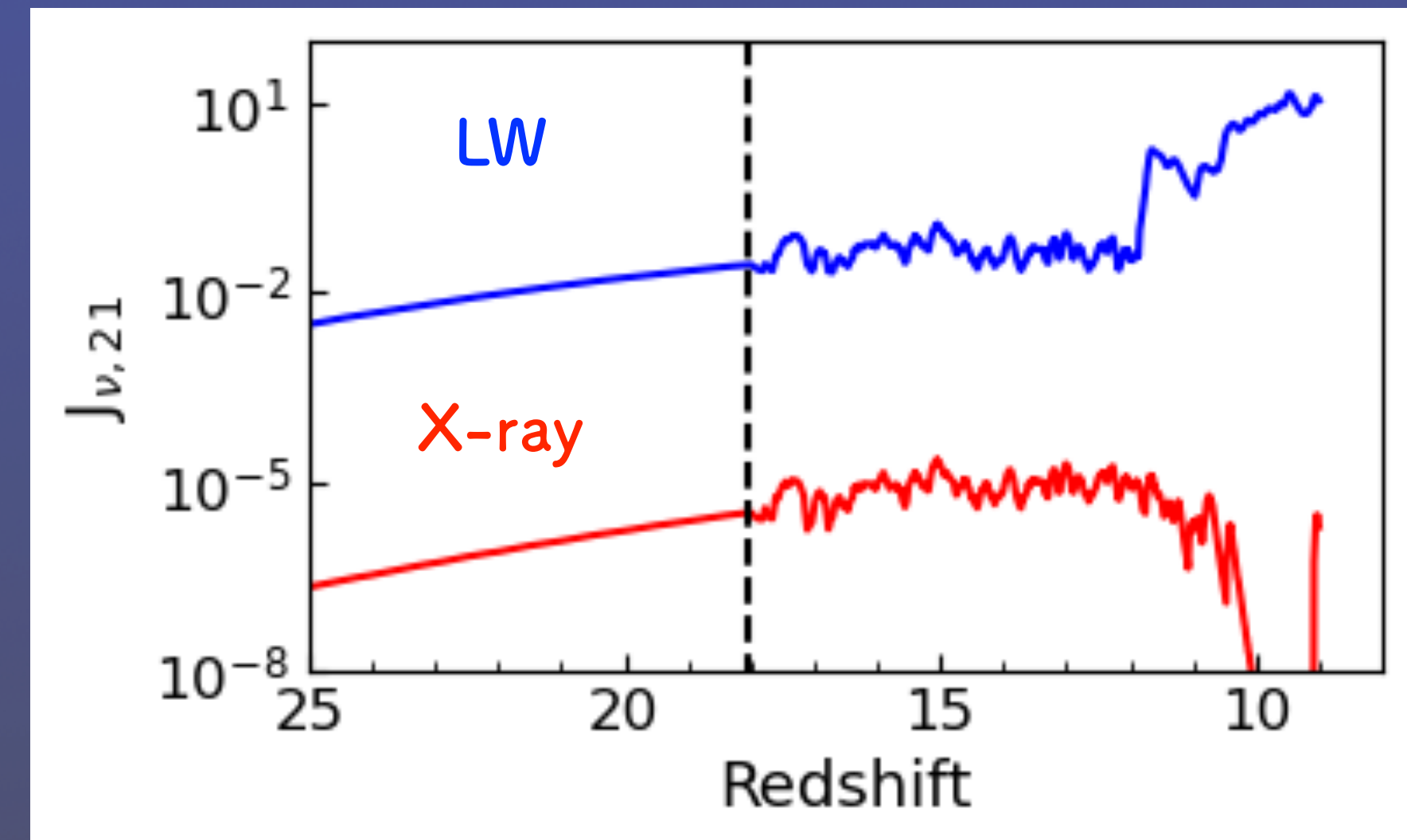
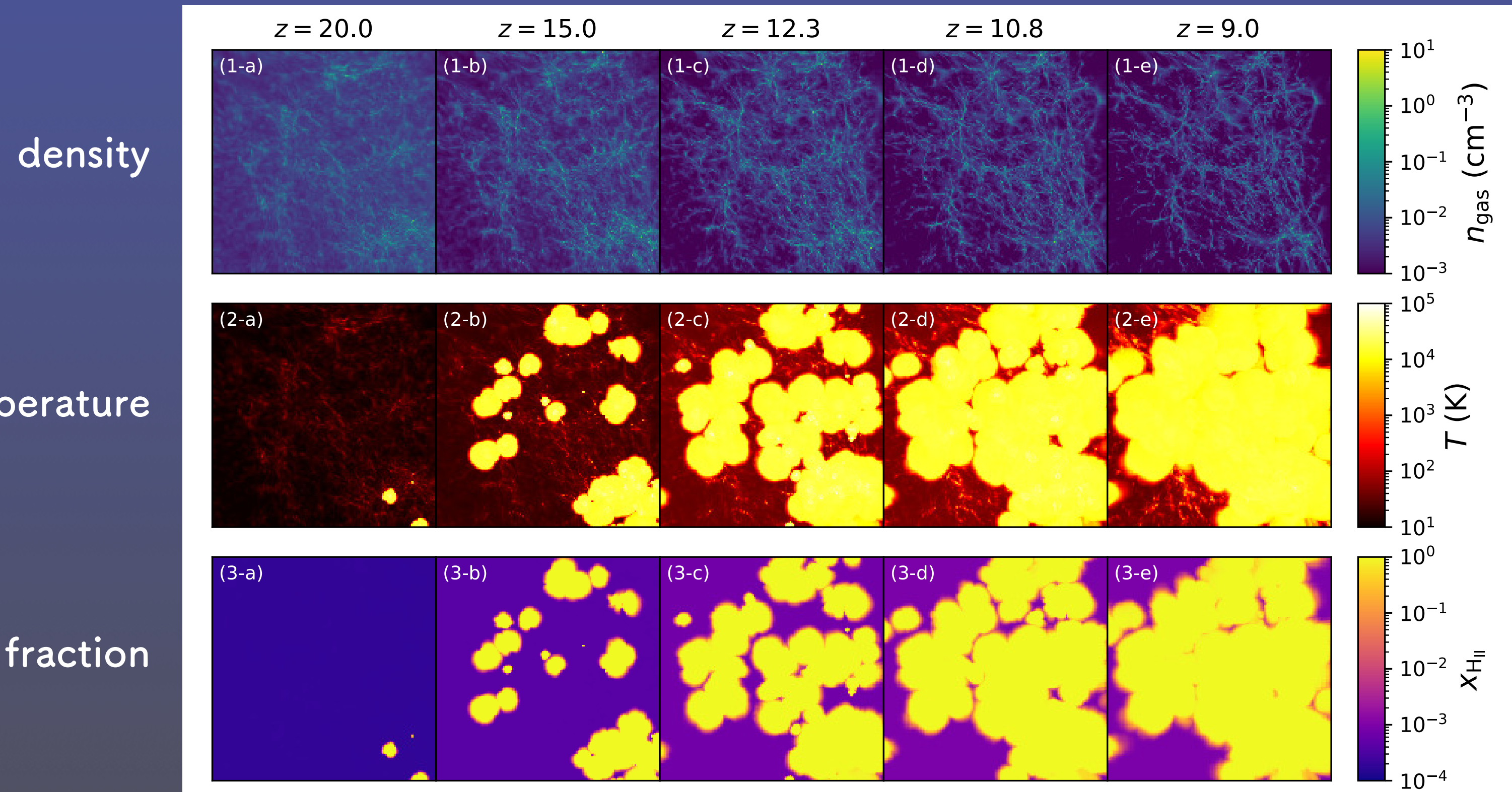
- X-ray/LW radiation background
- secondary ionization
- primordial chemistry



# X-ray Feedback



# X-ray Feedback

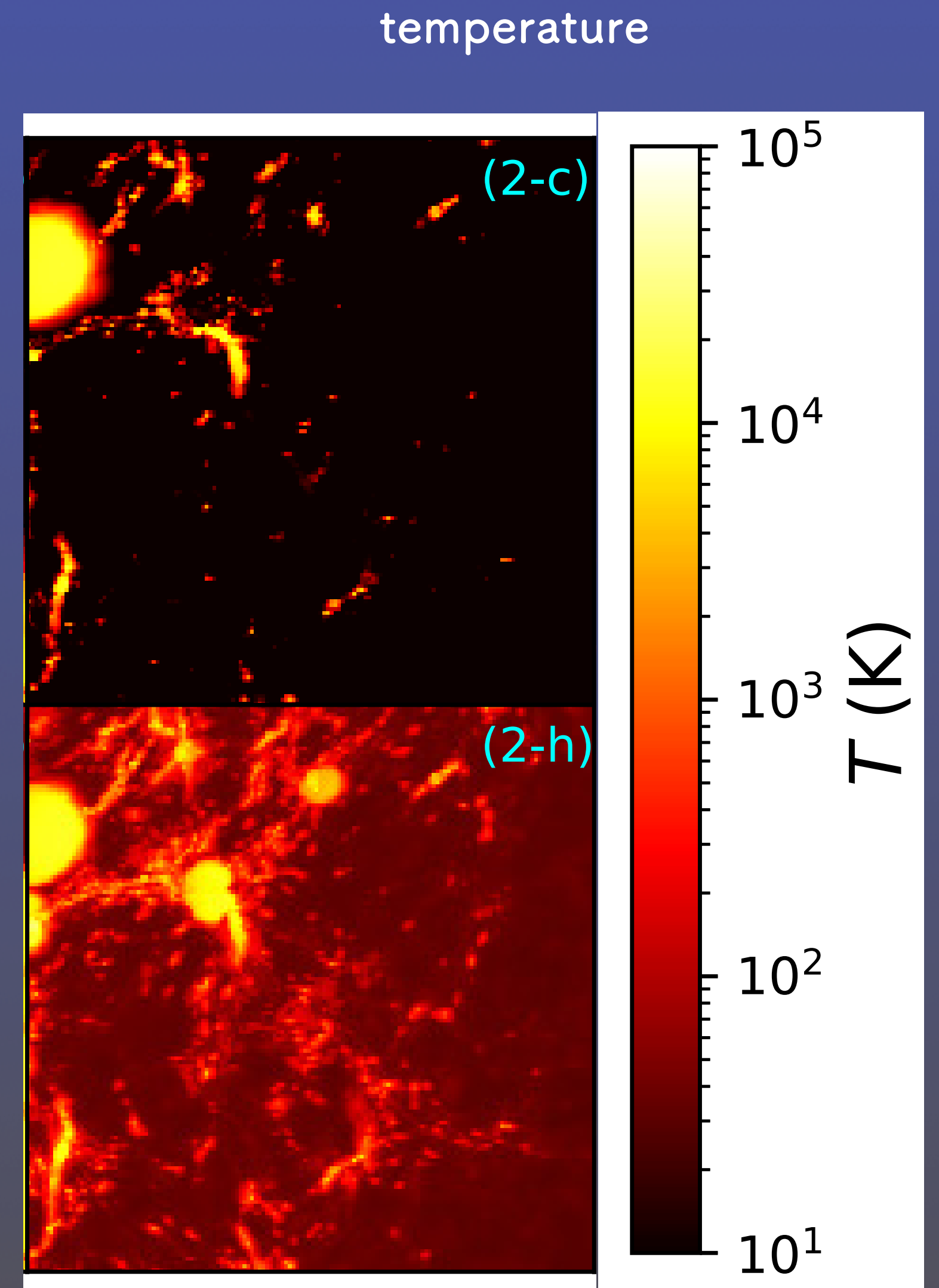


# X-ray Feedback

- The X-ray mildly heats and ionize the IGM
- More Pop III stars form under X-ray feedback

No X-ray

X-ray



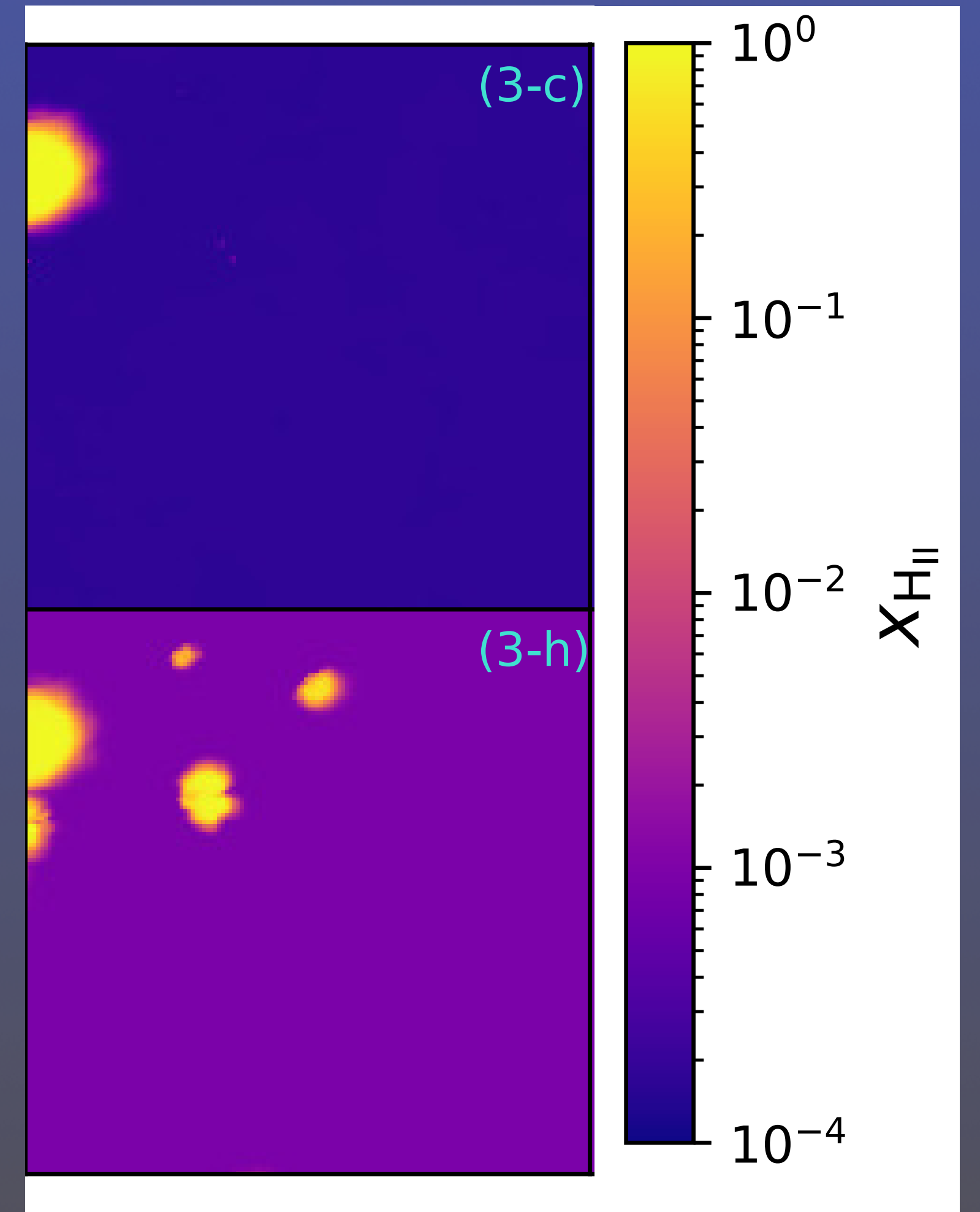
# X-ray Feedback

- The X-ray mildly heats and ionize the IGM
- More Pop III stars form under X-ray feedback

No X-ray

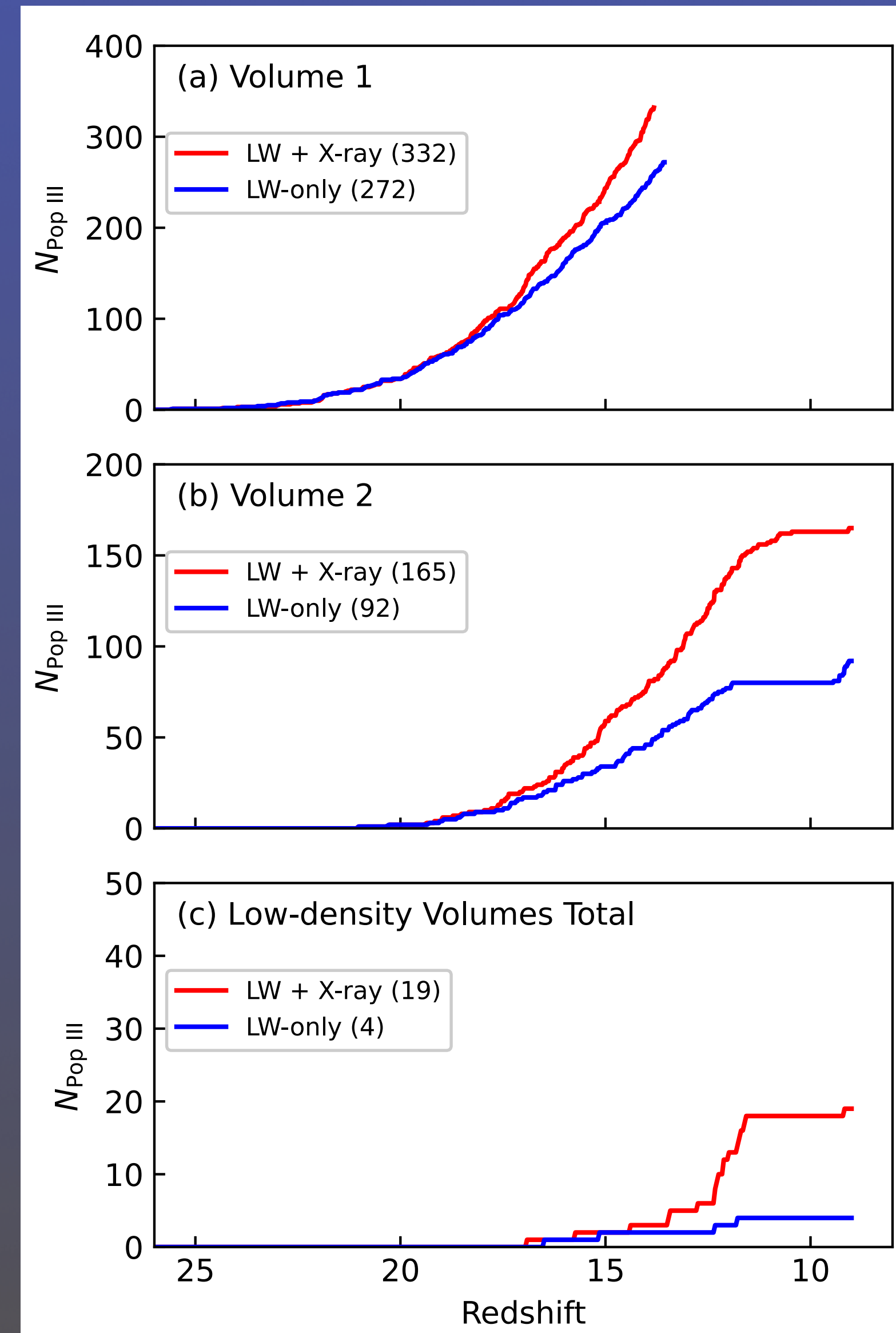
X-ray

H<sub>II</sub> fraction

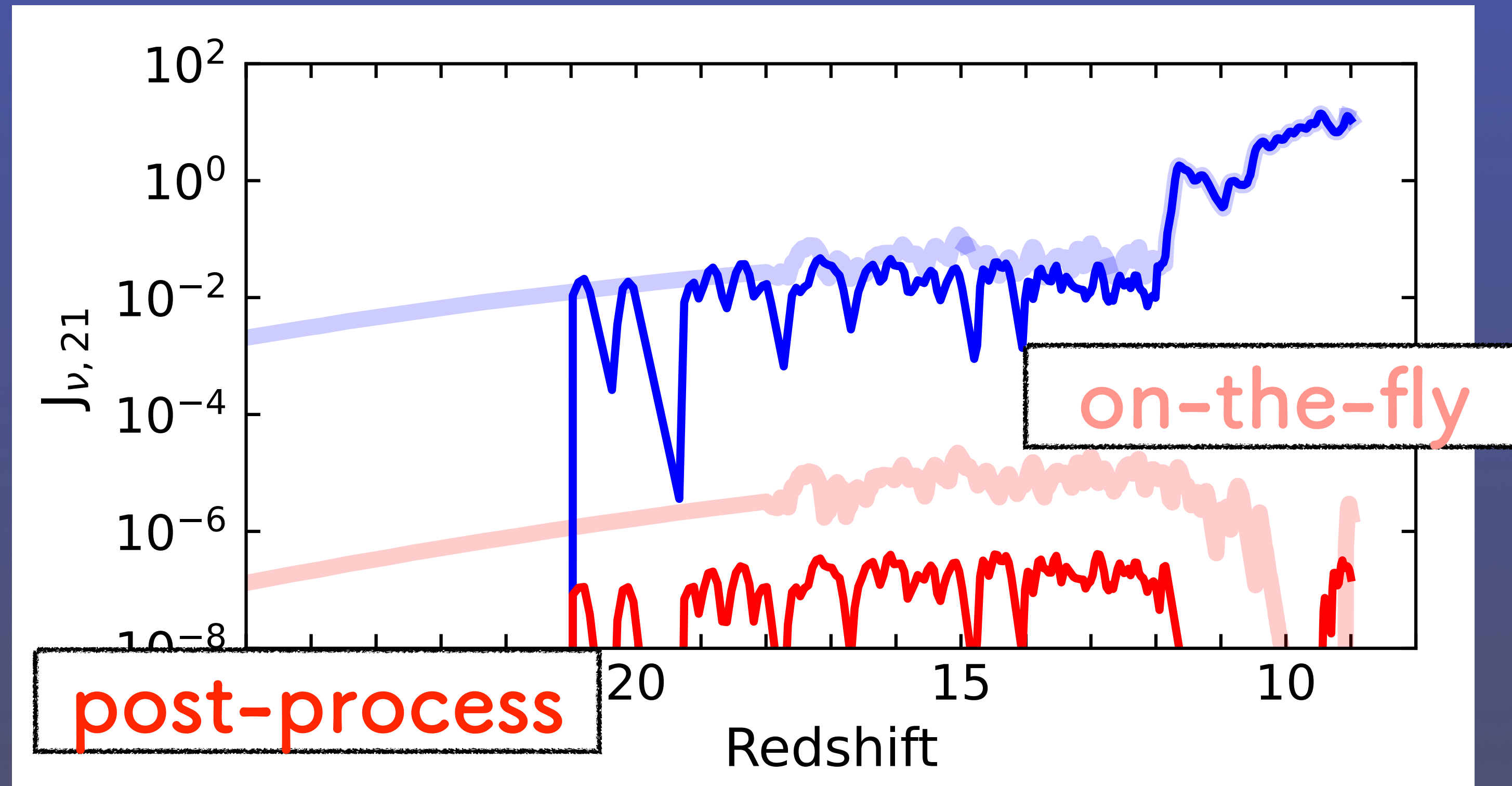


# Promotion of Pop III Star Formation

- The number of halos forming Pop III stars increases with X-rays

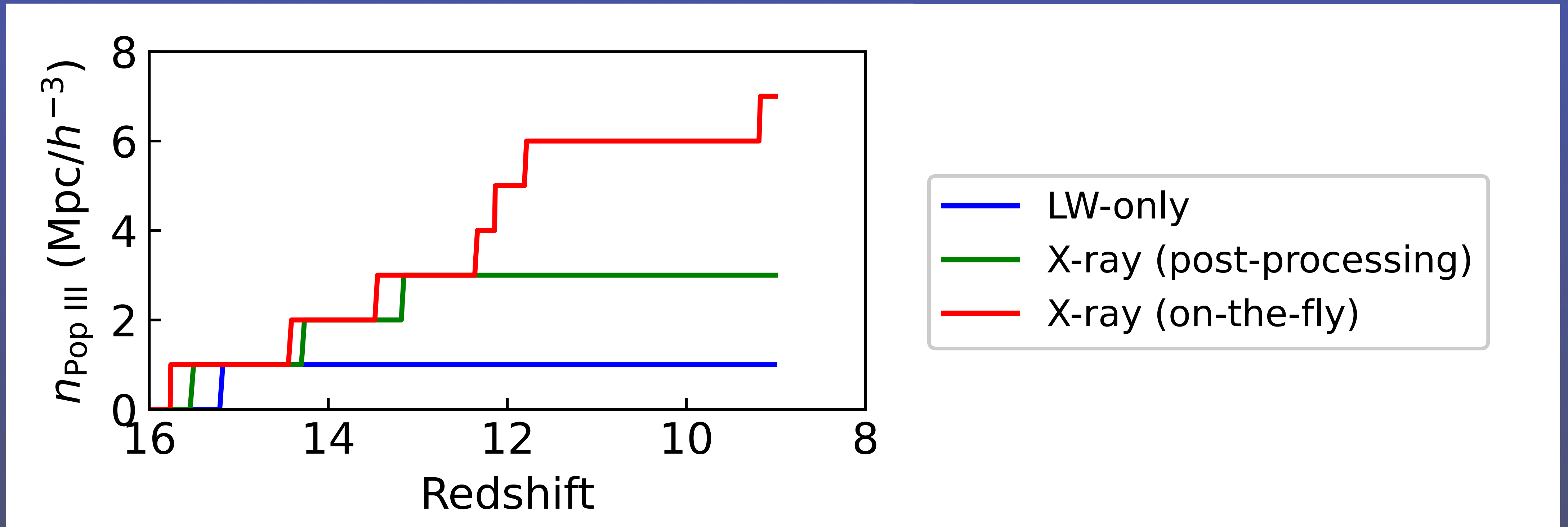


# Effect of On-the-fly Method



- A stronger X-ray background develops with the on-the-fly method.

# Effect of On-the-fly Method



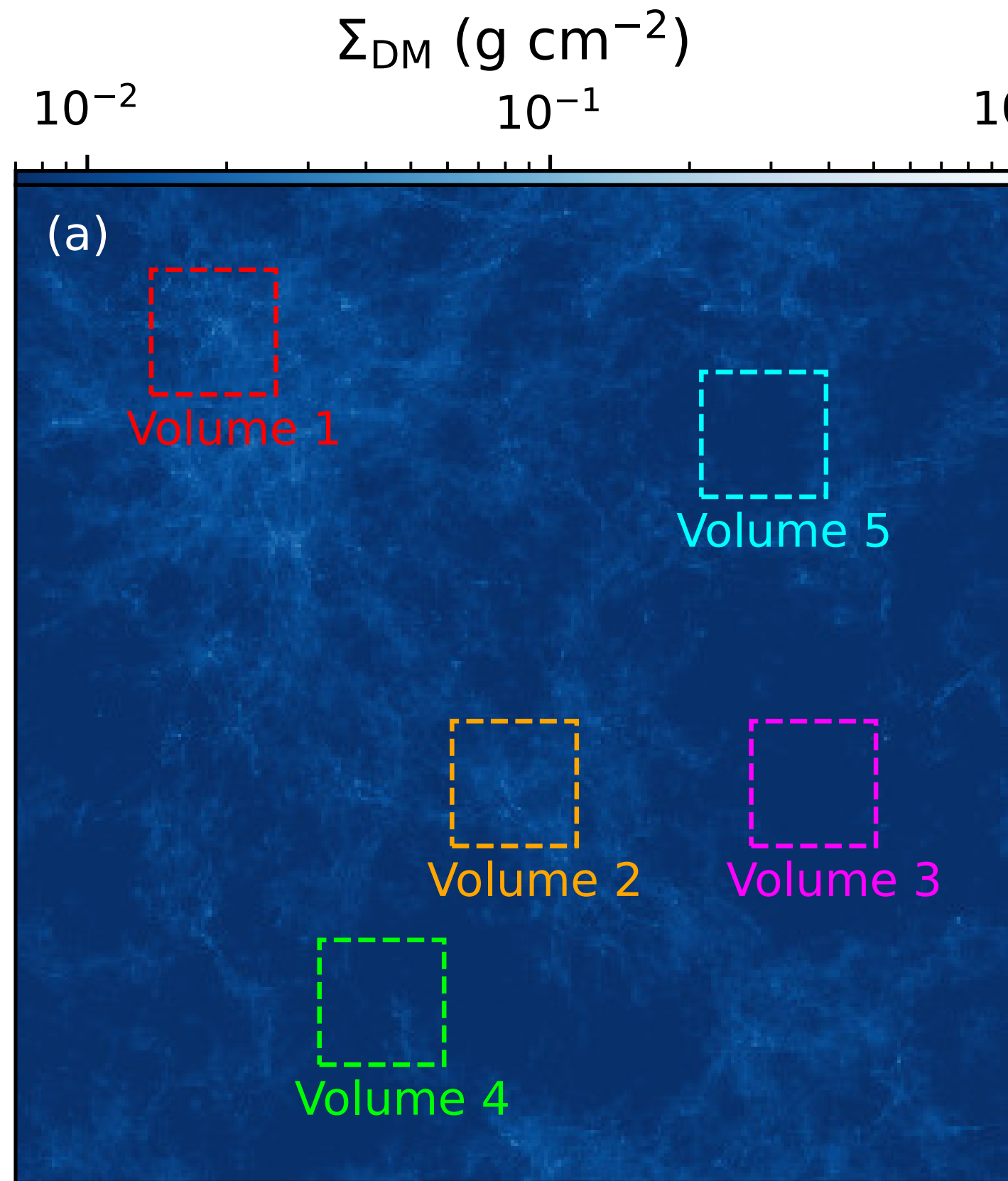
- A stronger X-ray background develops with the on-the-fly method.
- On-the-fly method results in greater number of Pop III stars.

# Summary

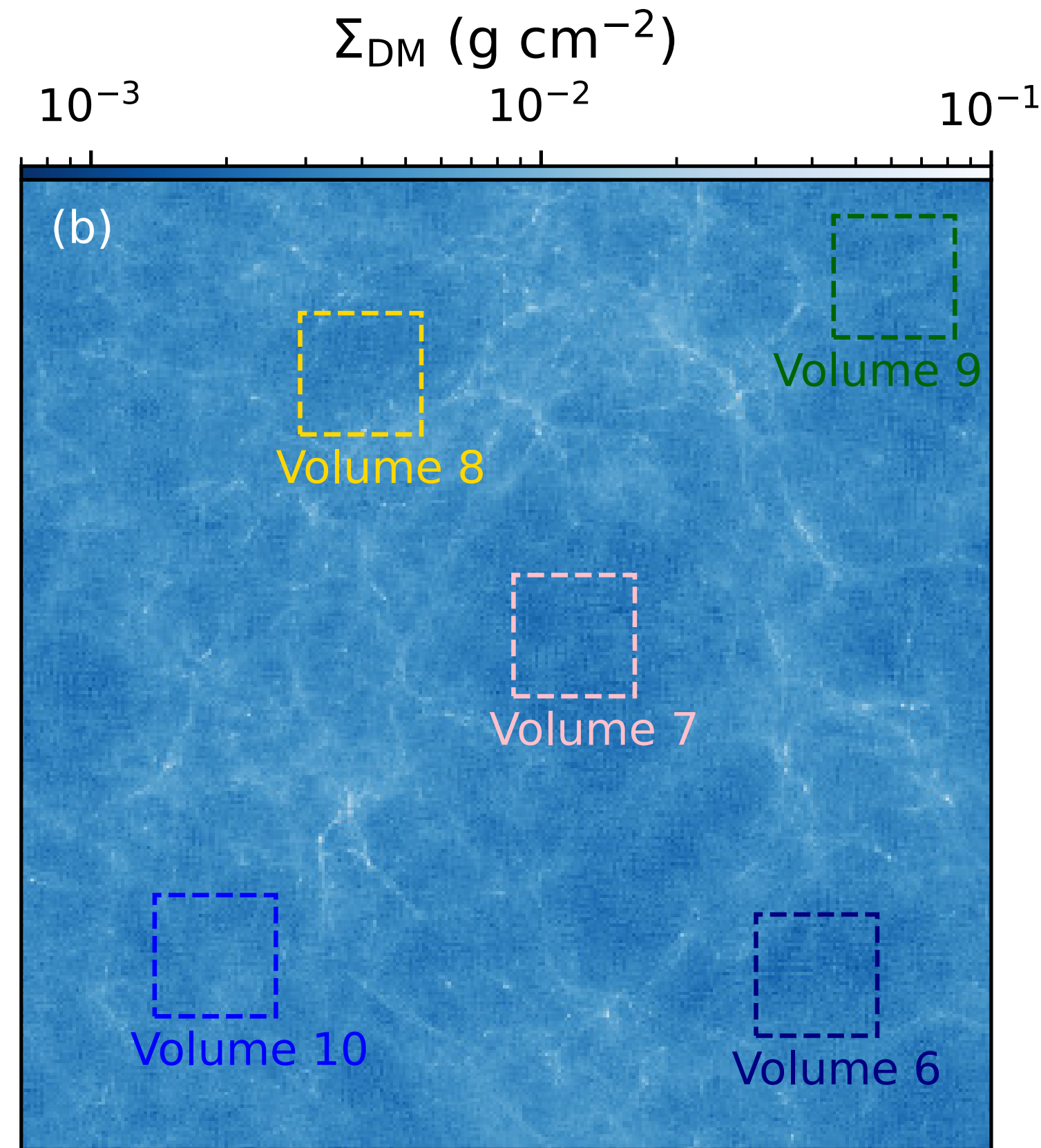
- Using on-the-fly method, we estimated LW and X-ray backgrounds in the early Universe.
- A stronger positive feedback is produced with the on-the-fly method.
- The X-ray background promotes Pop III star formation.
- Two papers will be submitted by the end of this year.



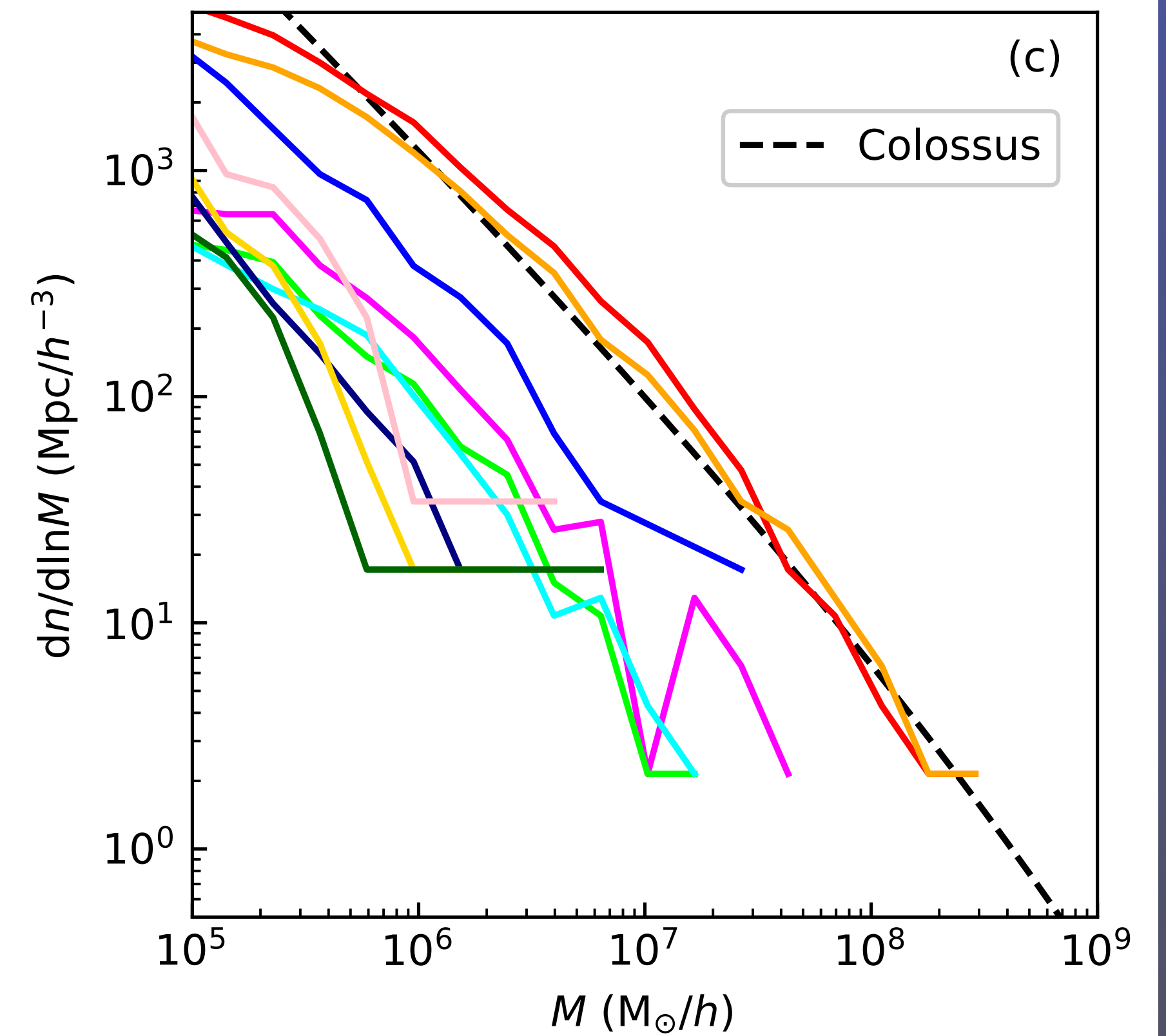
# Different Environments



DM-only ( $L = 8 \text{ Mpc}/h$ )



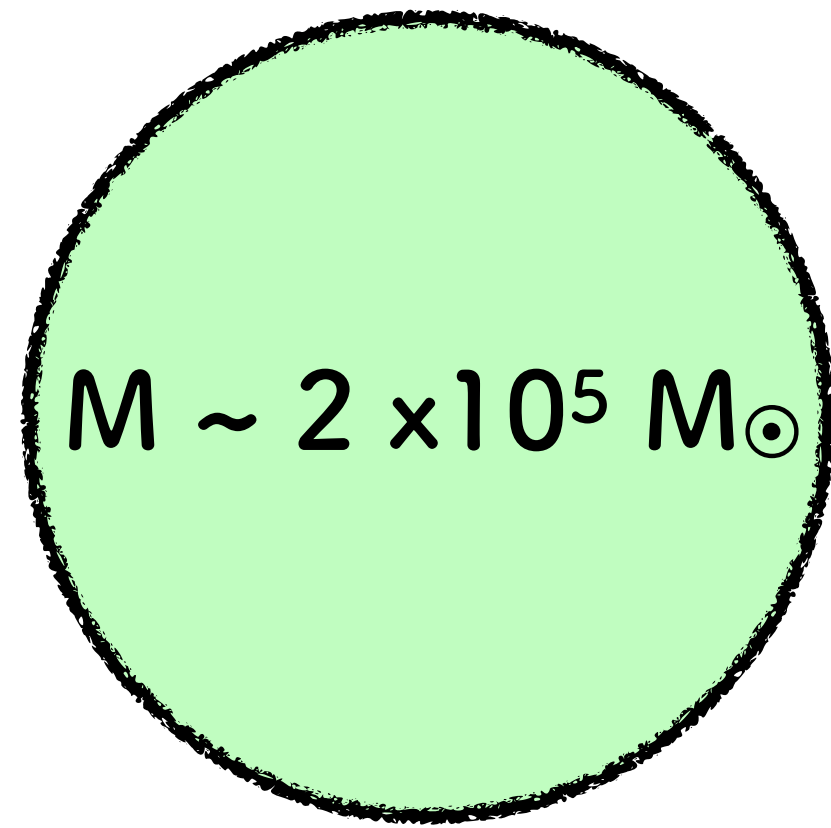
DM-only ( $L = 4 \text{ Mpc}/h$ )



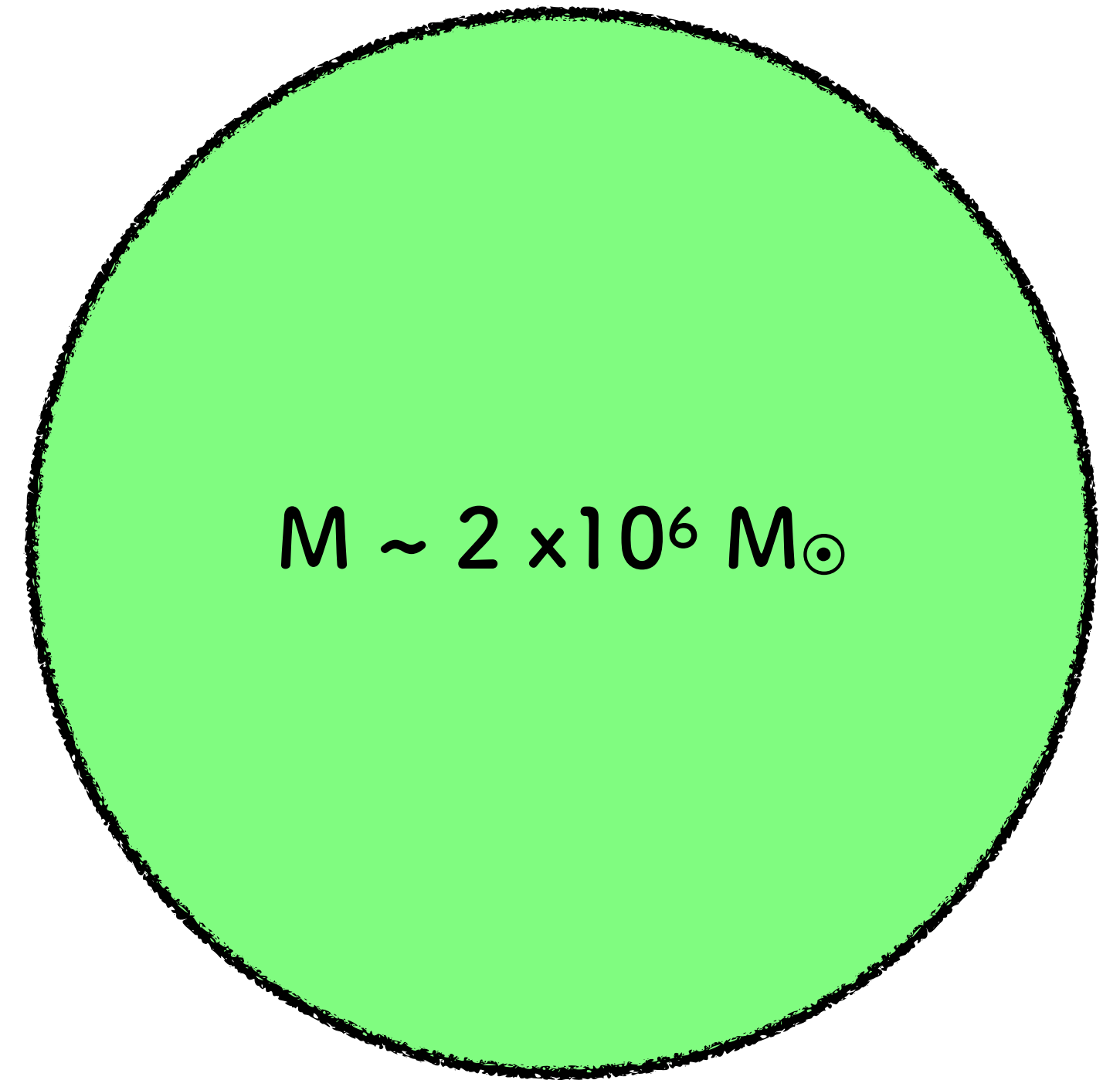
# Host Halo Masses



$$M_{\text{crit}} = 10^6 M_{\odot}$$



Pop III stars X



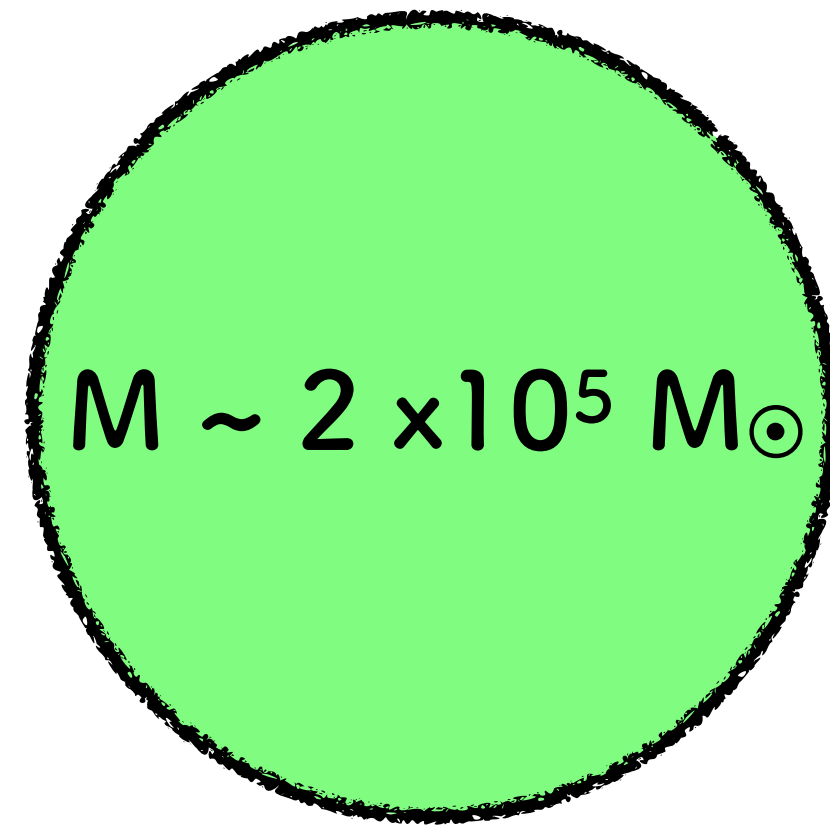
Pop III stars O

# Host Halo Masses



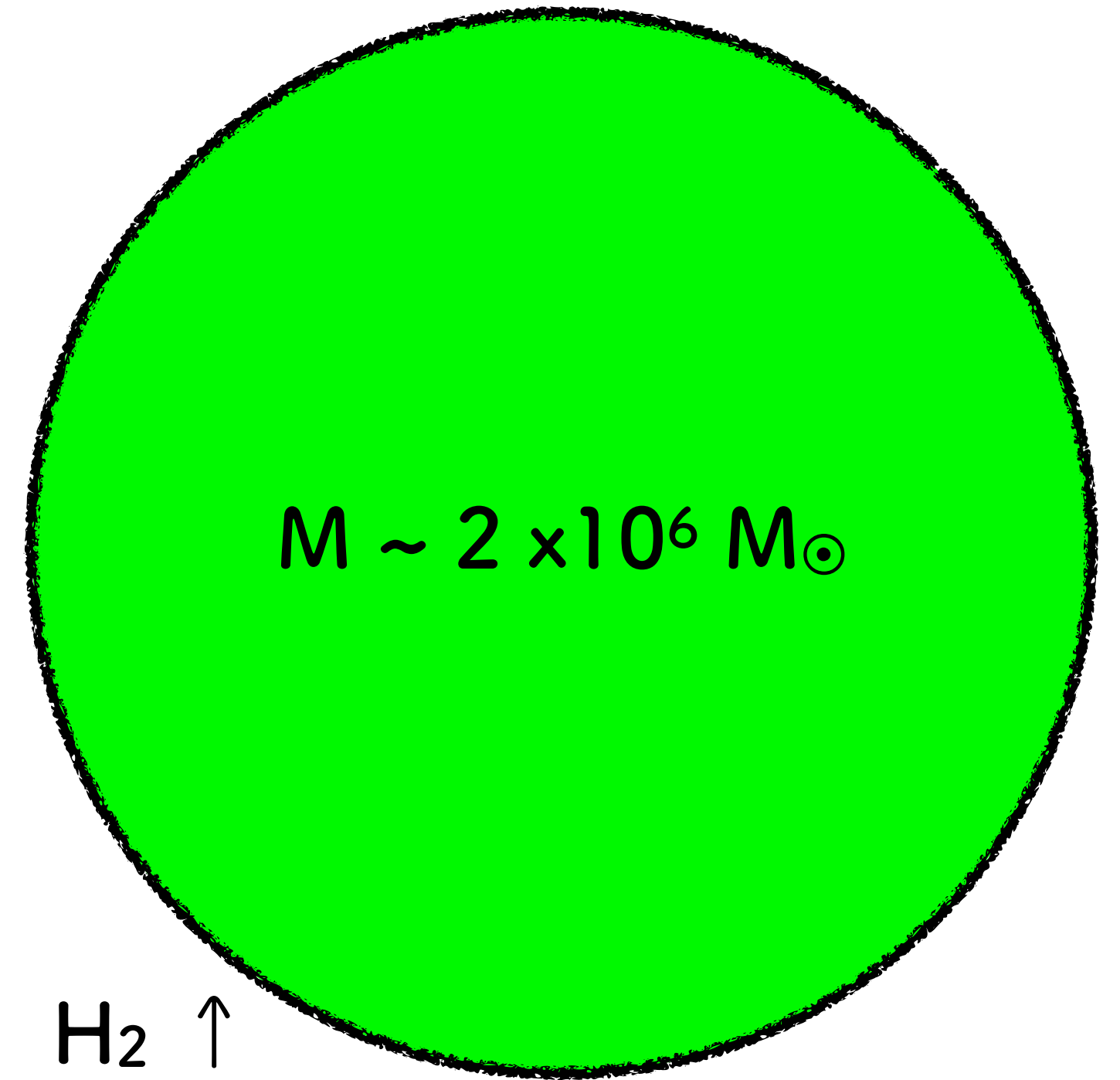
w X-ray,  $M_{\text{crit}} \downarrow$

$M_{\text{crit}} = 10^5 M_{\odot}$



$\text{H}_2 \uparrow$

Pop III stars  $\odot$



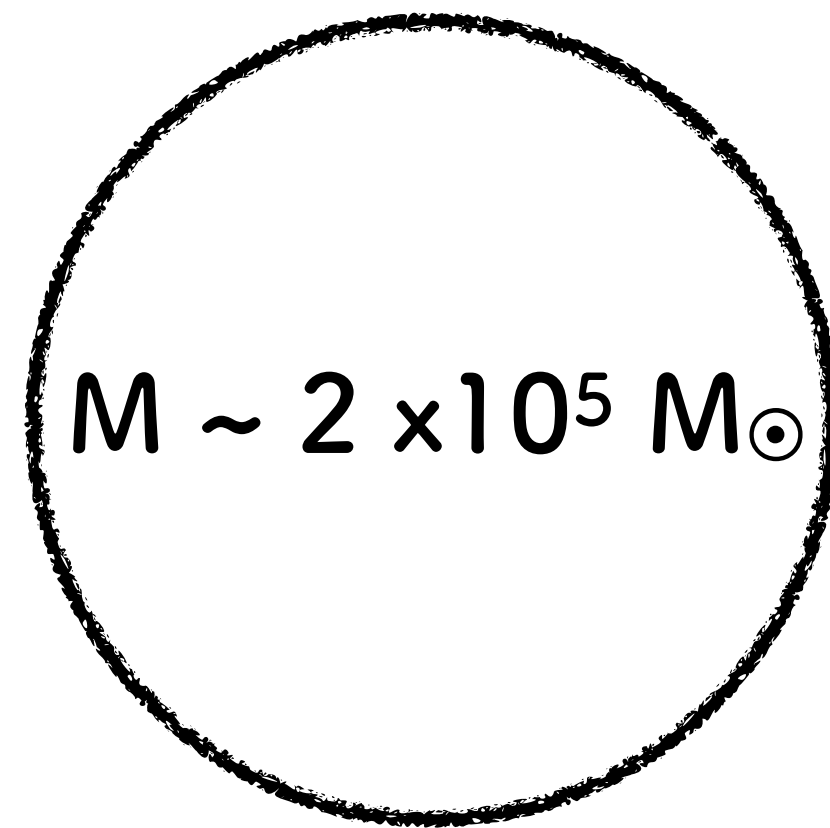
$\text{H}_2 \uparrow$

Pop III stars  $\odot$

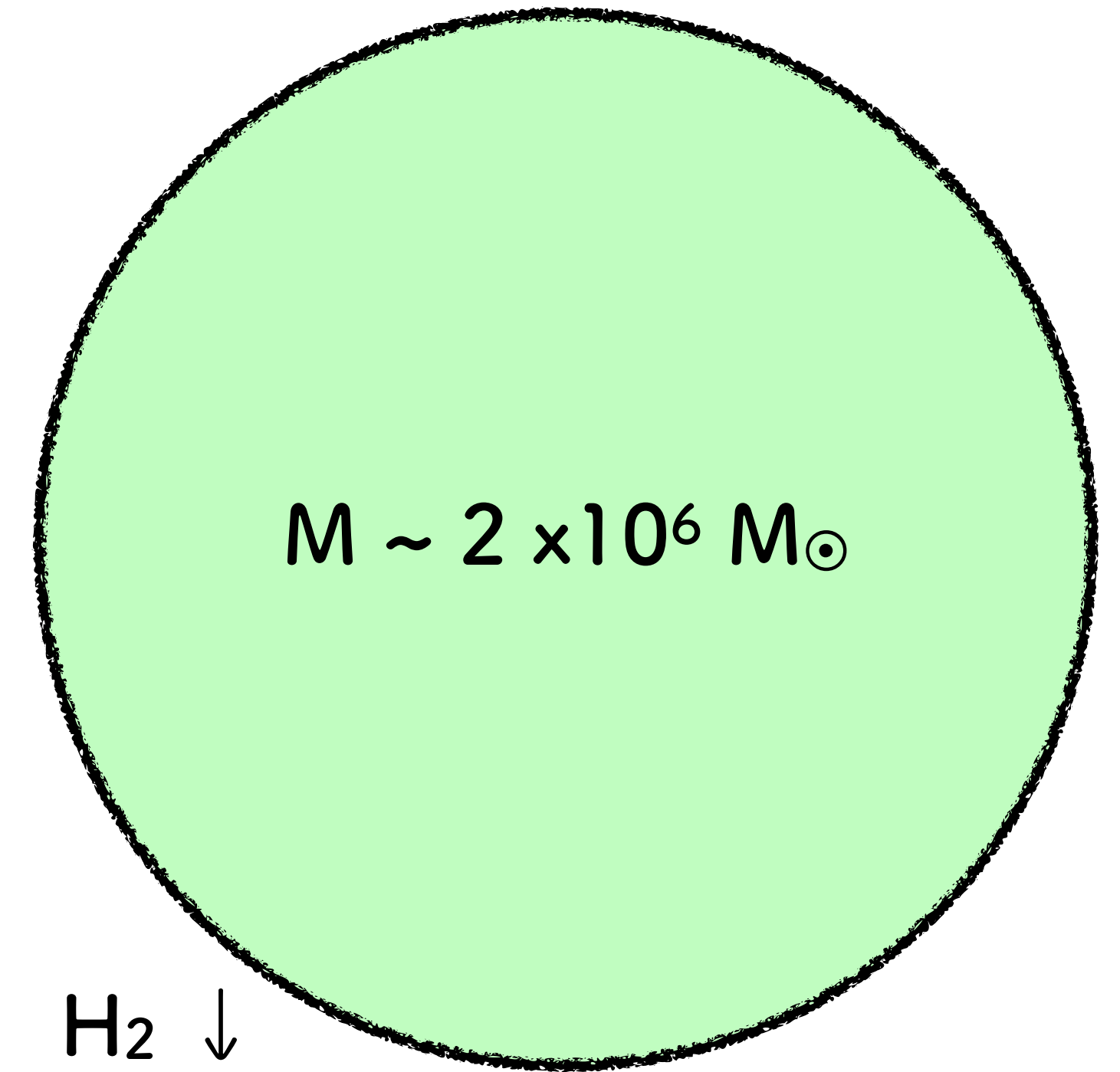
# Host Halo Masses



w LW,  $M_{\text{crit}} \uparrow$   
 $M_{\text{crit}} = 10^7 M_{\odot}$

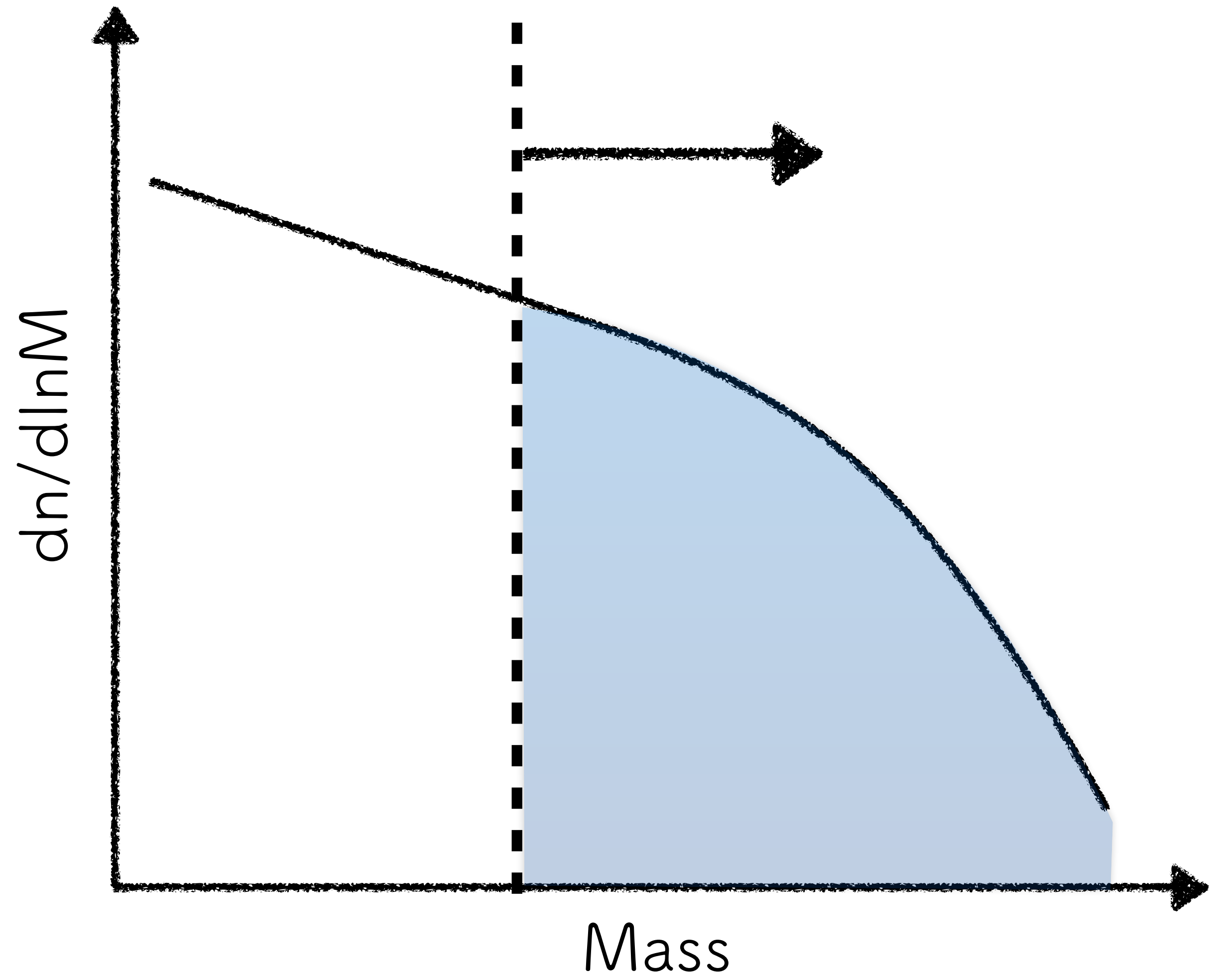
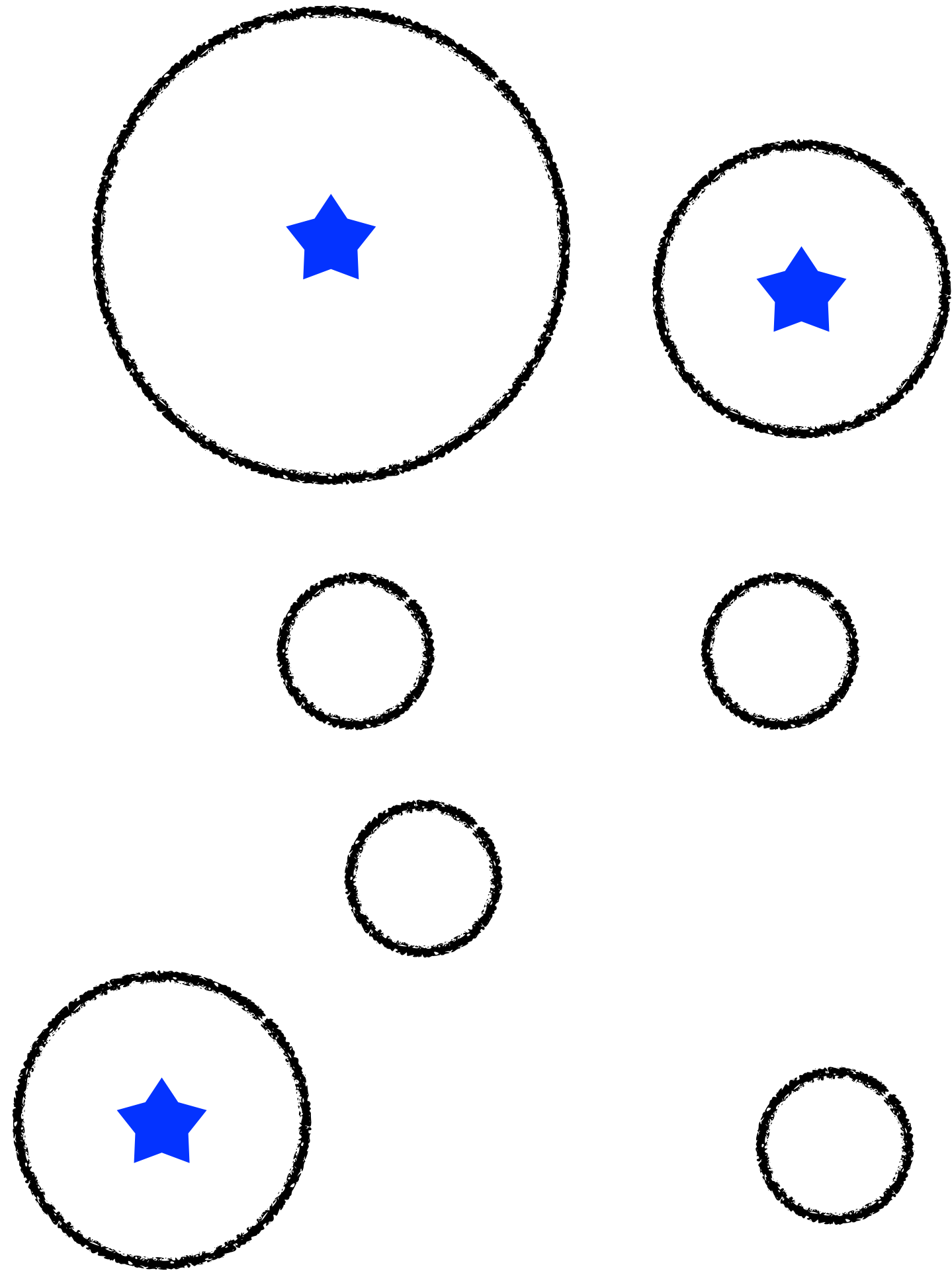


Pop III stars X

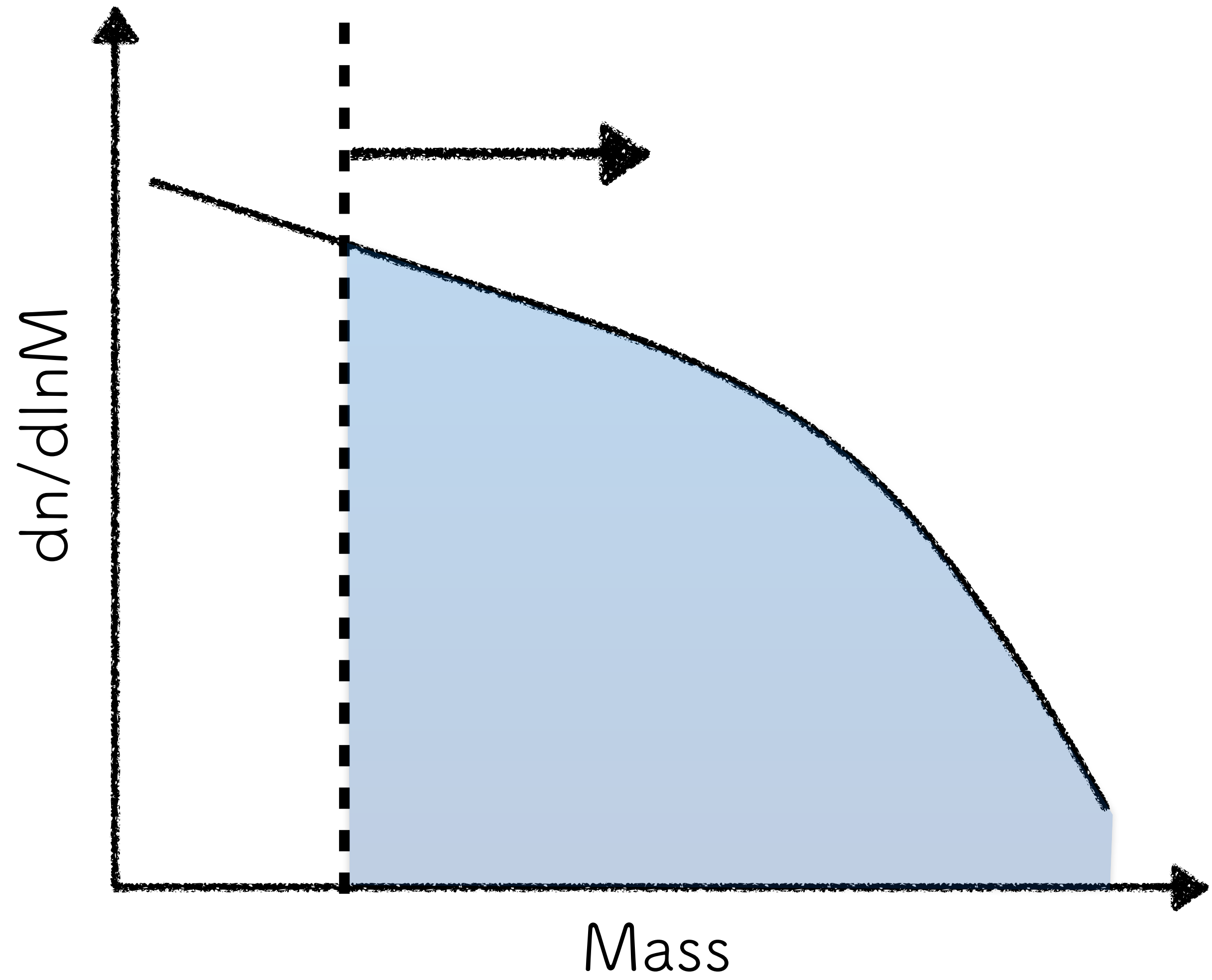
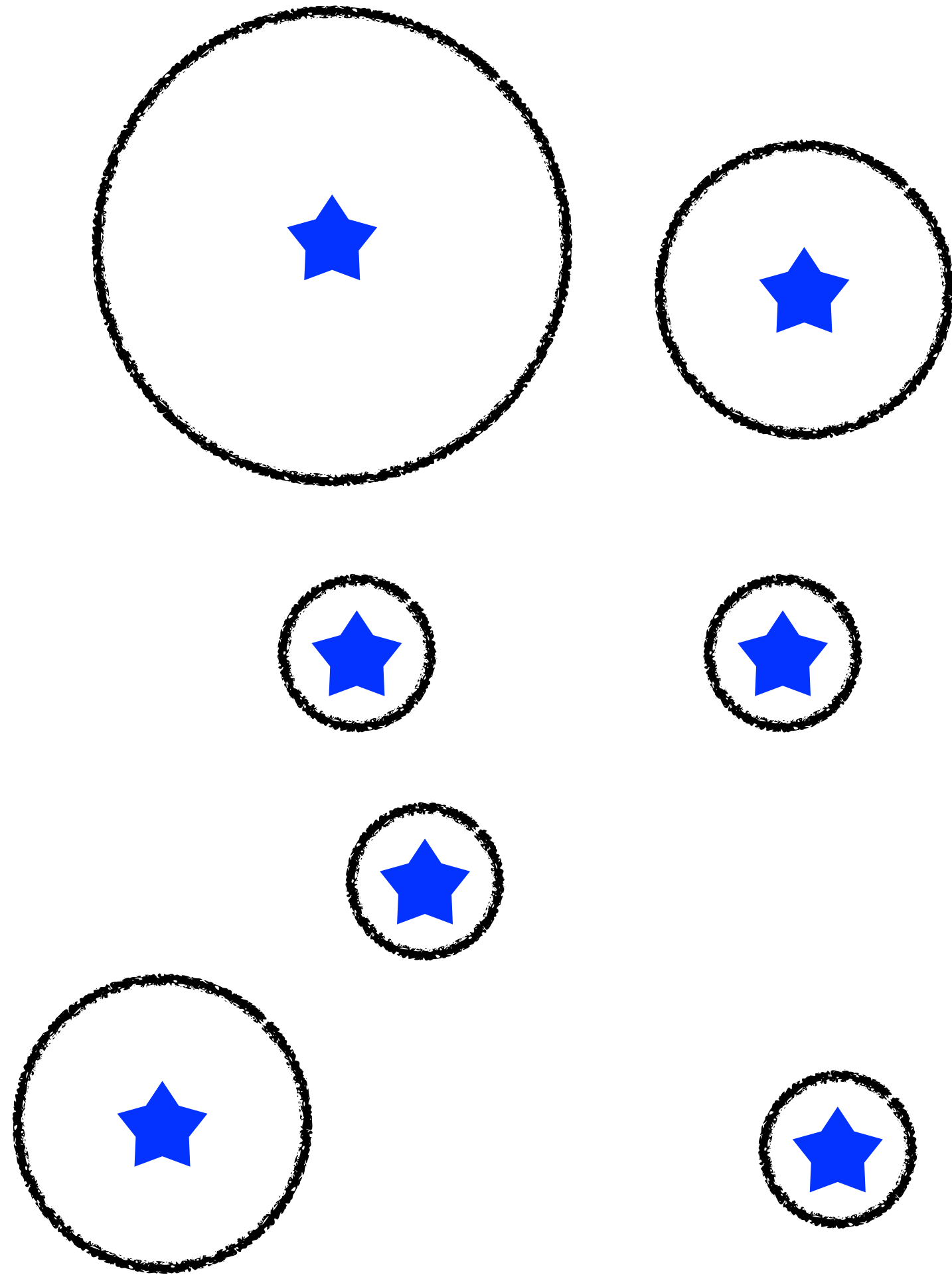


Pop III stars X

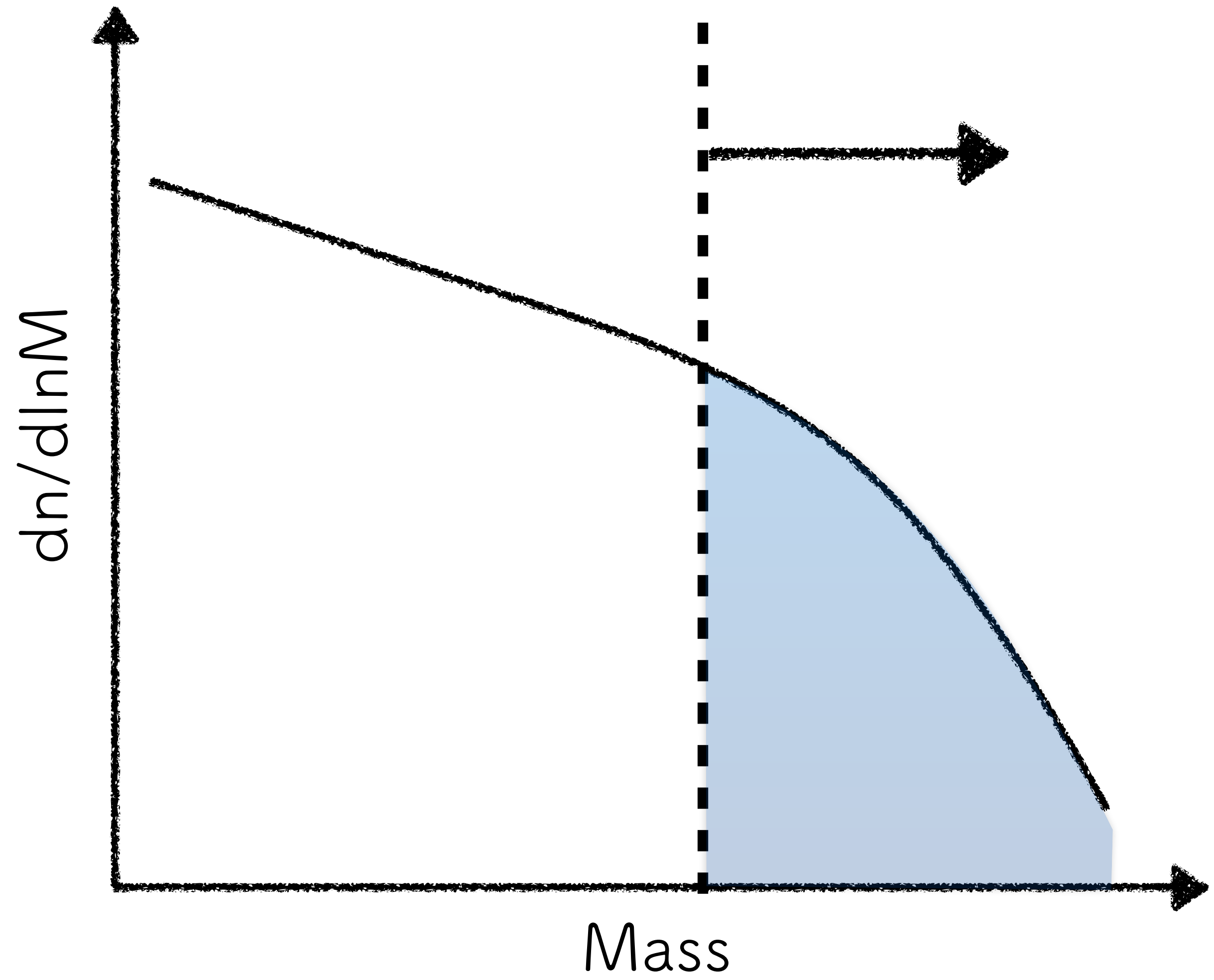
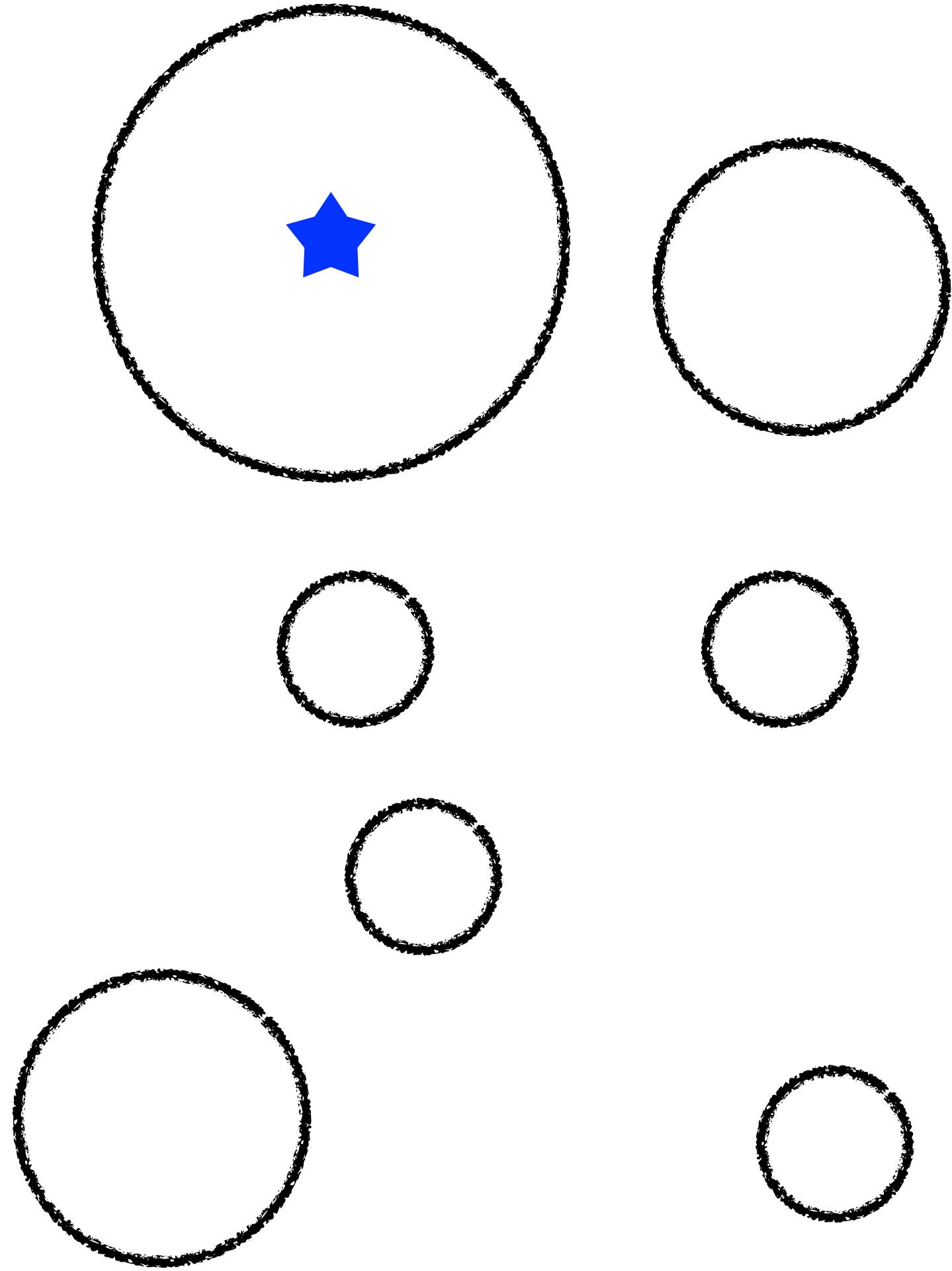
# Host Halo Masses



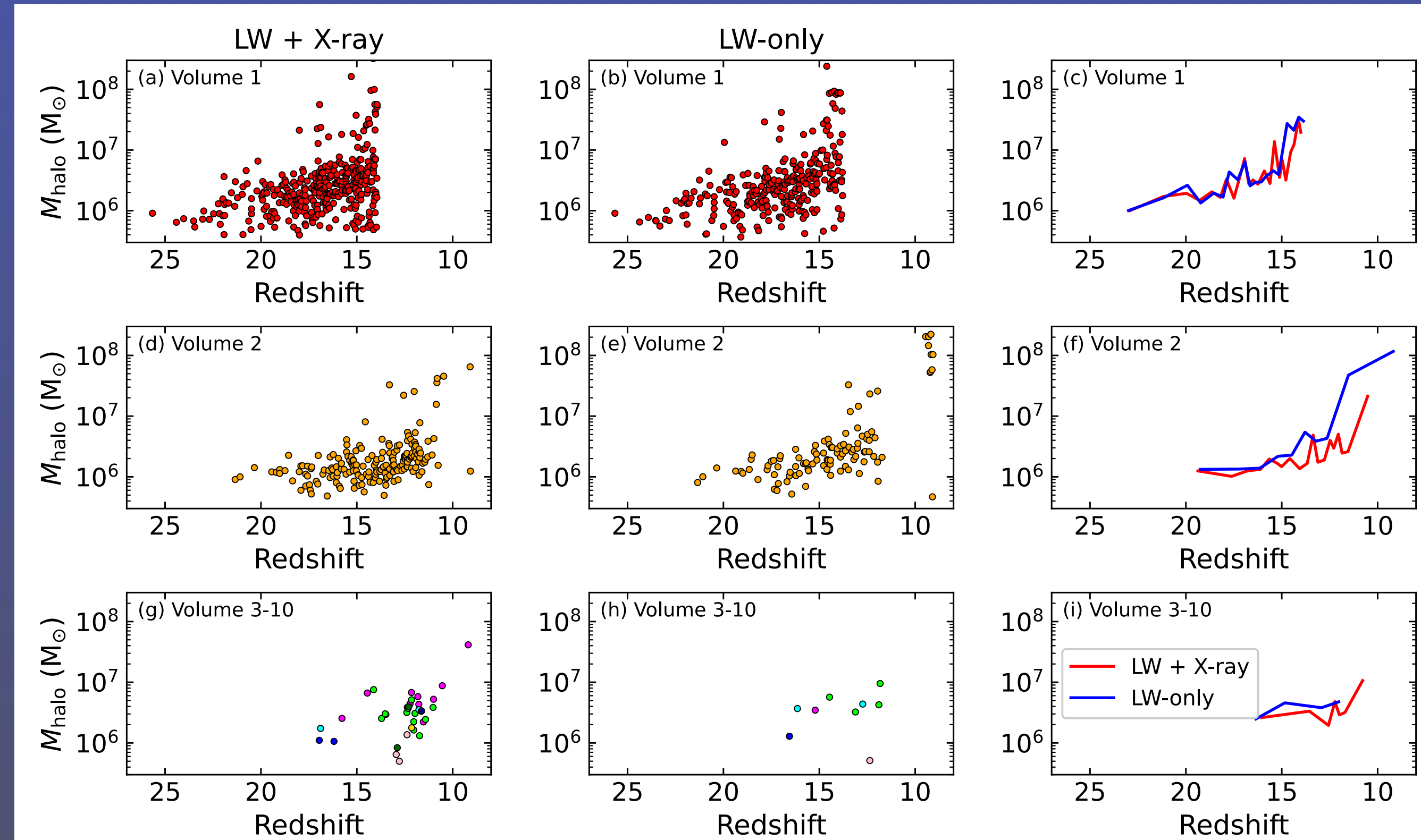
# Host Halo Masses



# Host Halo Masses



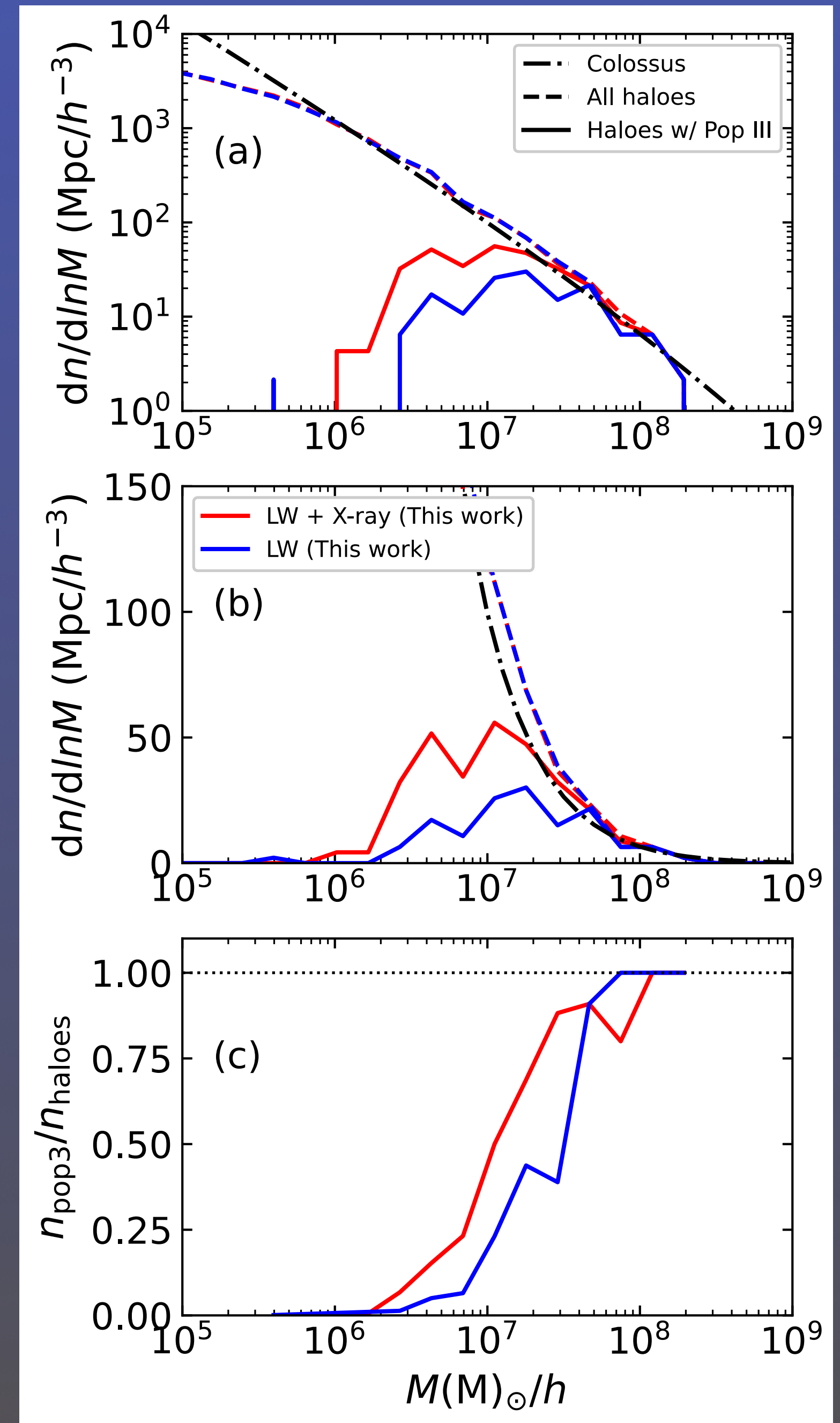
# Promotion of Pop III Star Formation



- The number of halos forming Pop III stars increases

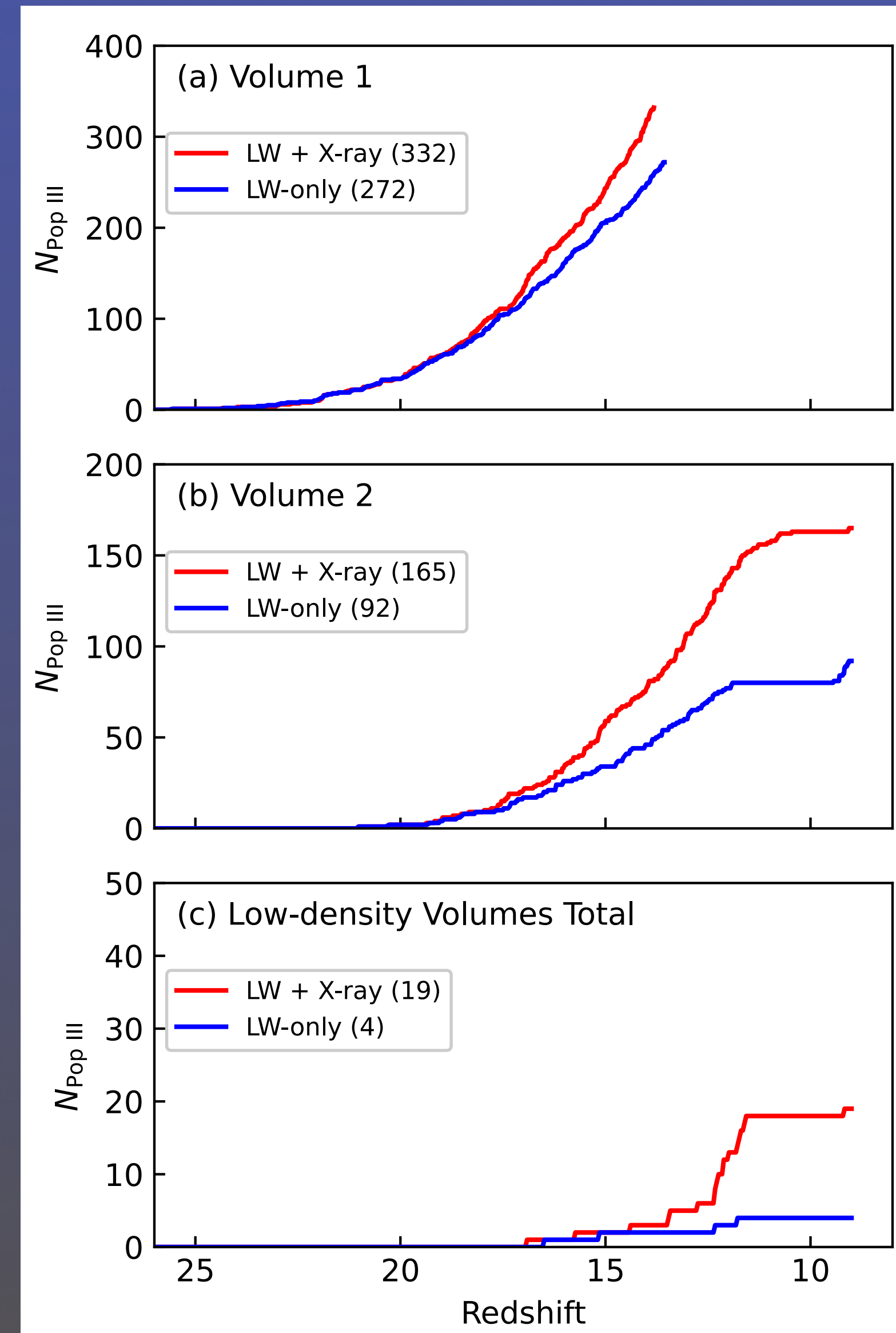
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- The number of halos forming Pop III stars increases

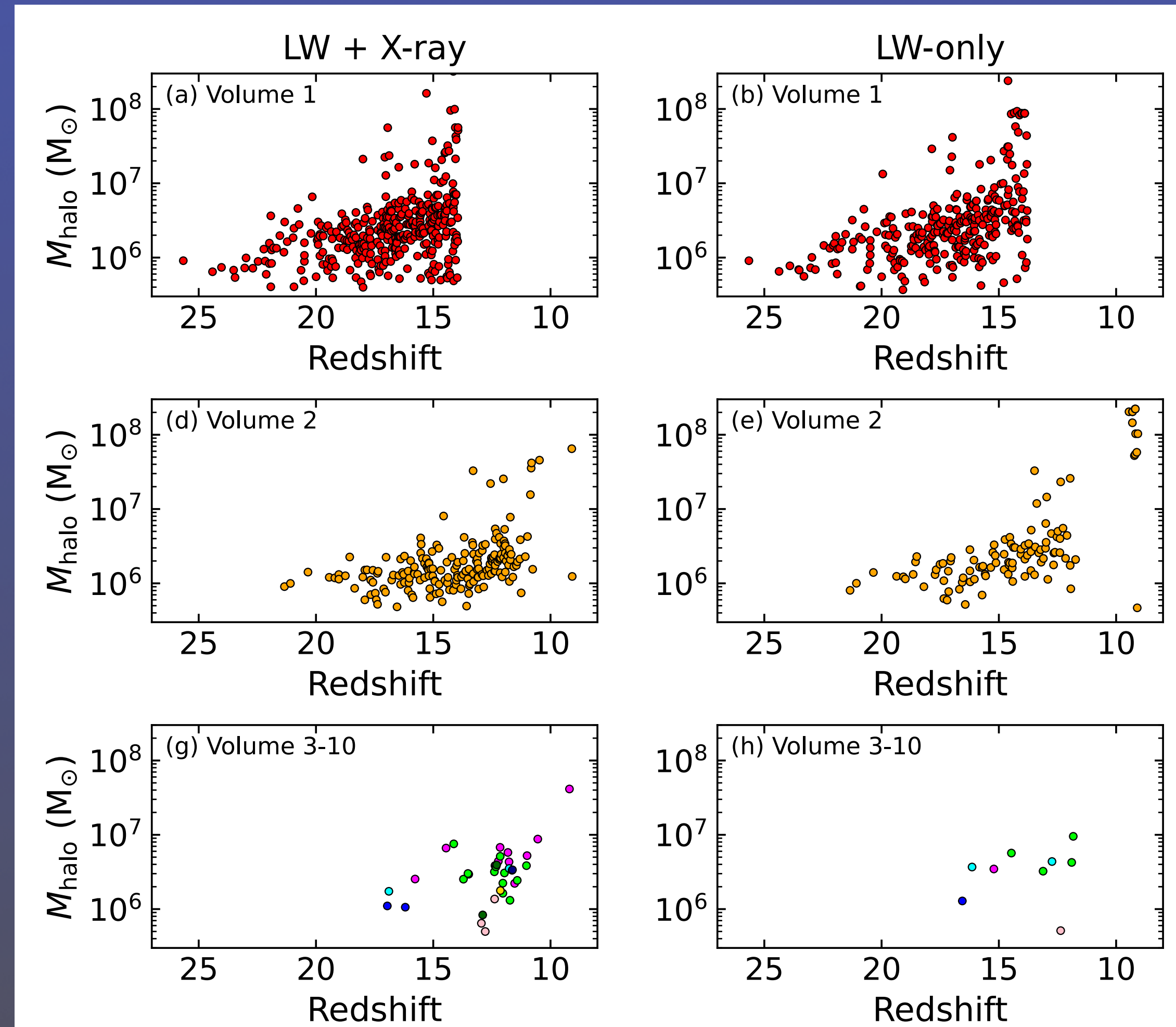


# Promotion of Pop III Star Formation

- The number of halos forming Pop III stars increases



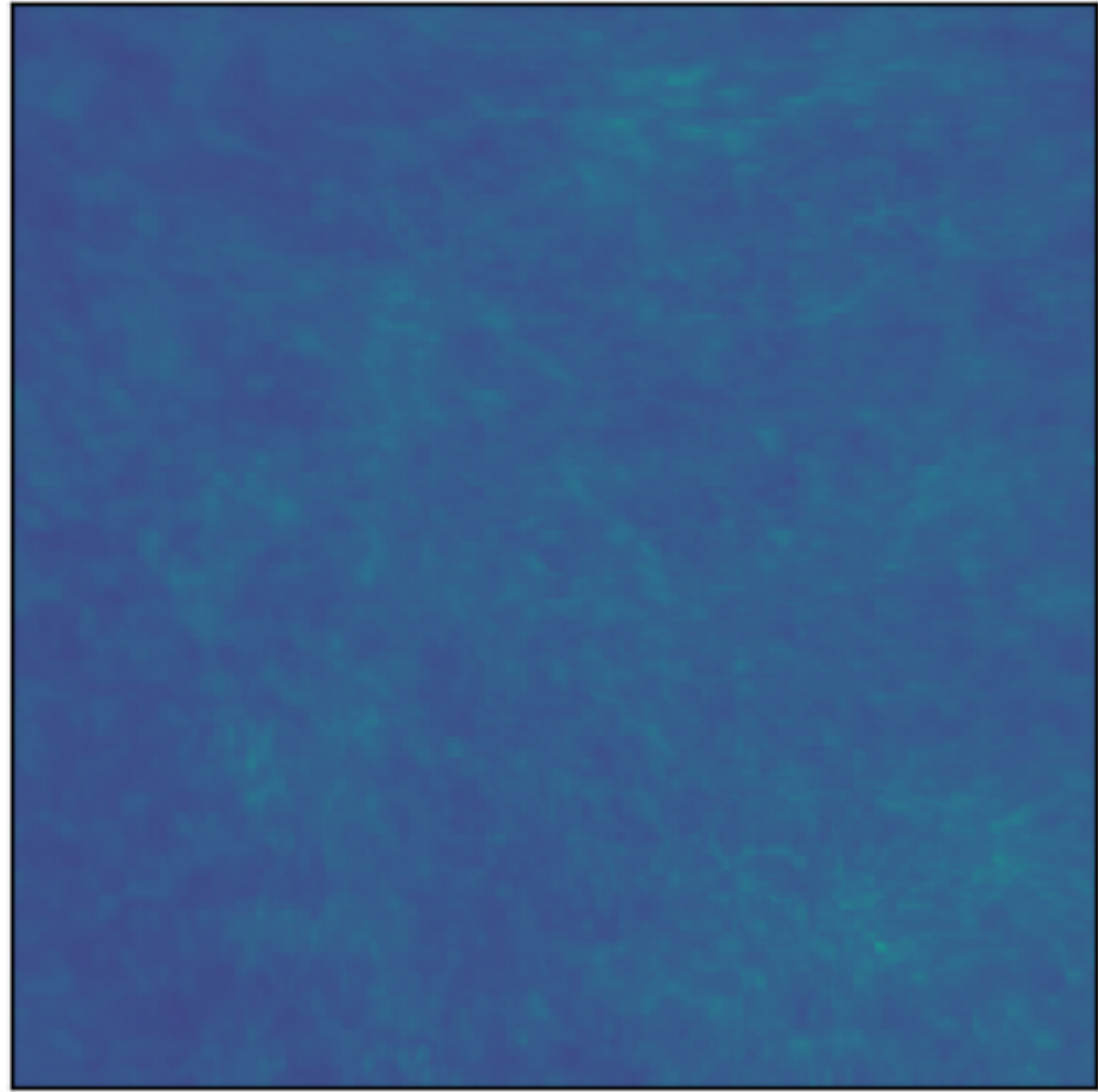
# Promotion of Pop III Star Formation



- The number of halos forming Pop III stars increases with X-rays

# Estimate of an X-ray - Post-process

$z = 32.3$



$SFR_{\text{PopIII}}$



Time

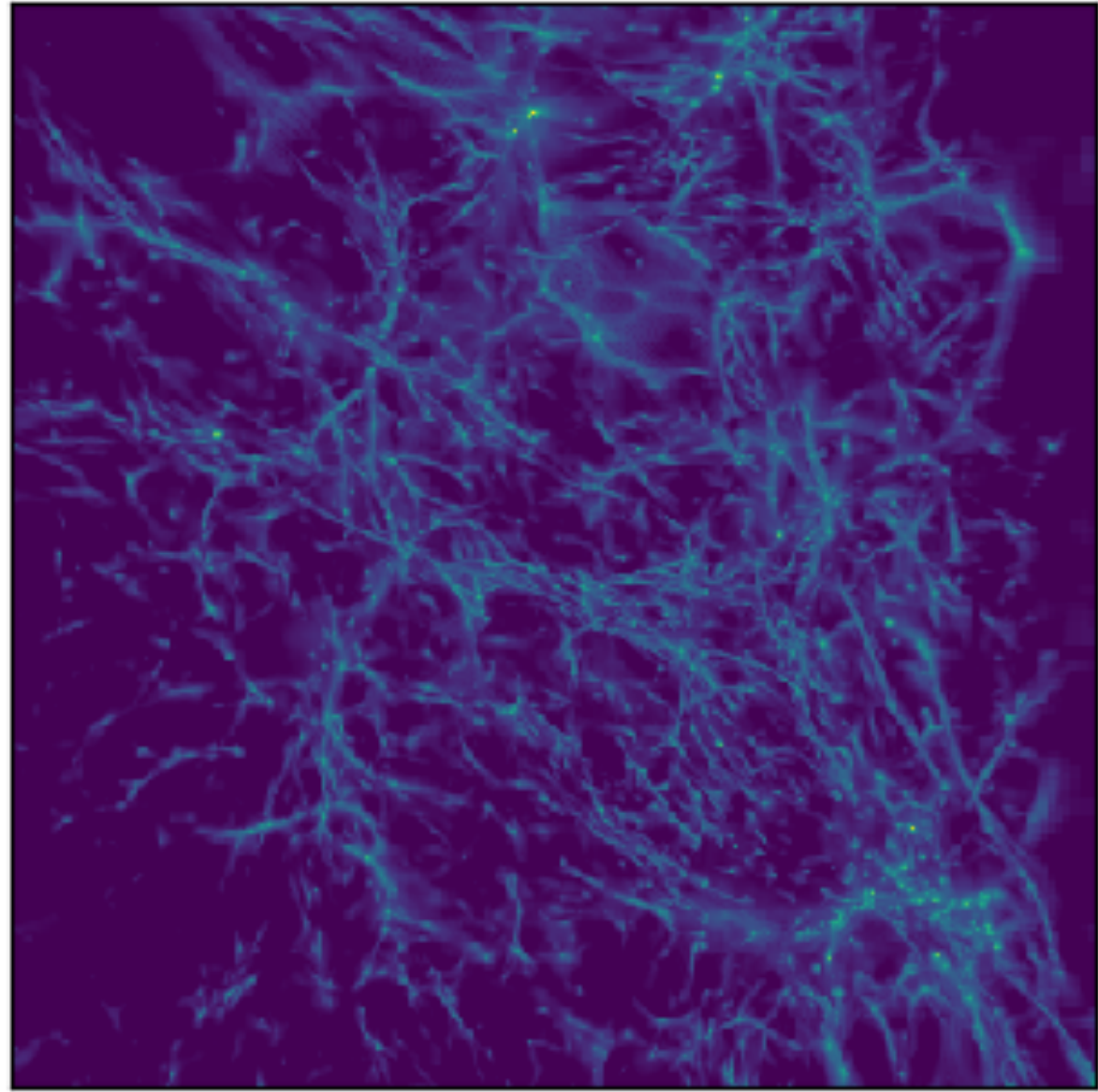
X-ray  
Intensity



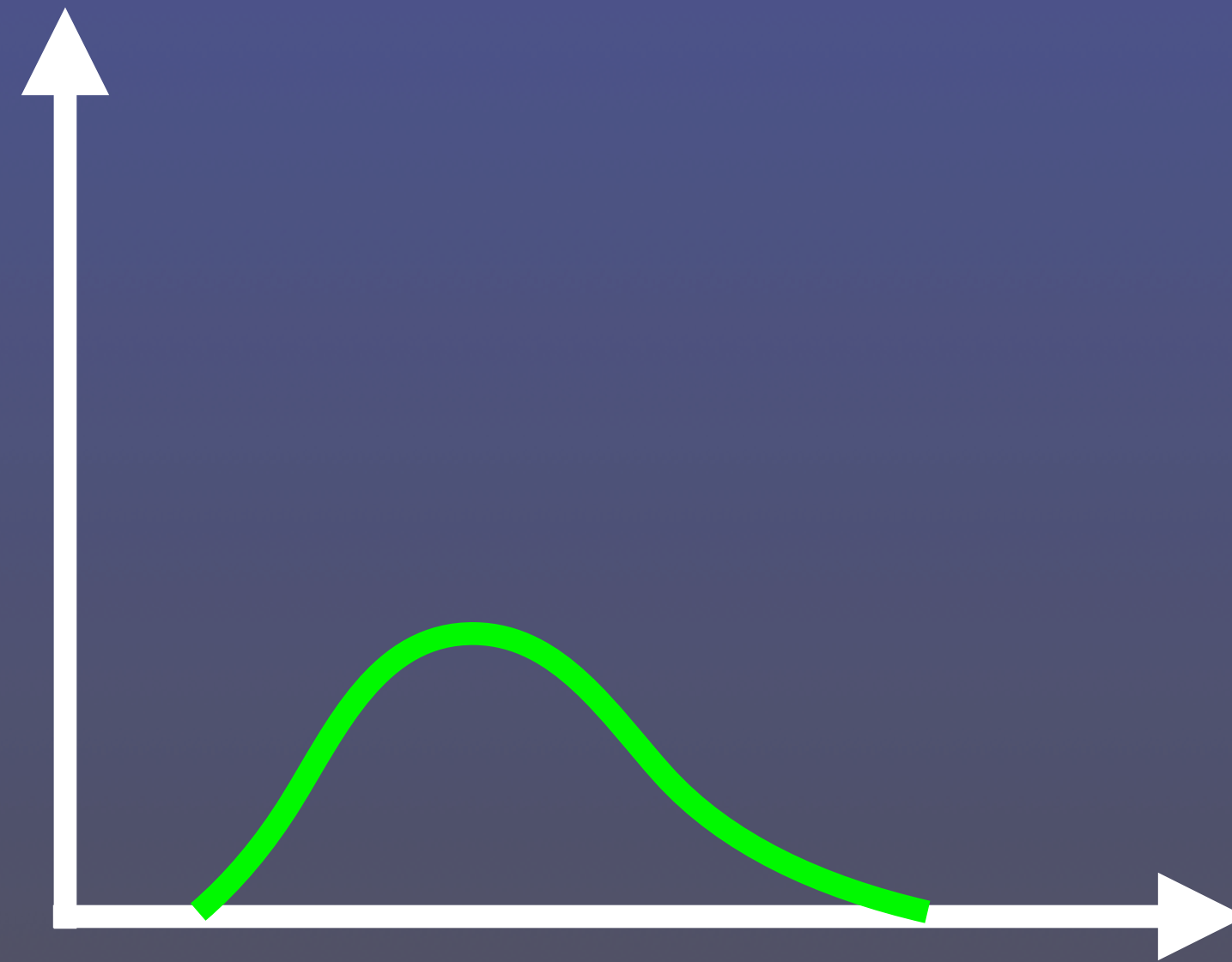
Time

# Estimate of an X-ray - Post-process

$z = 9.0$

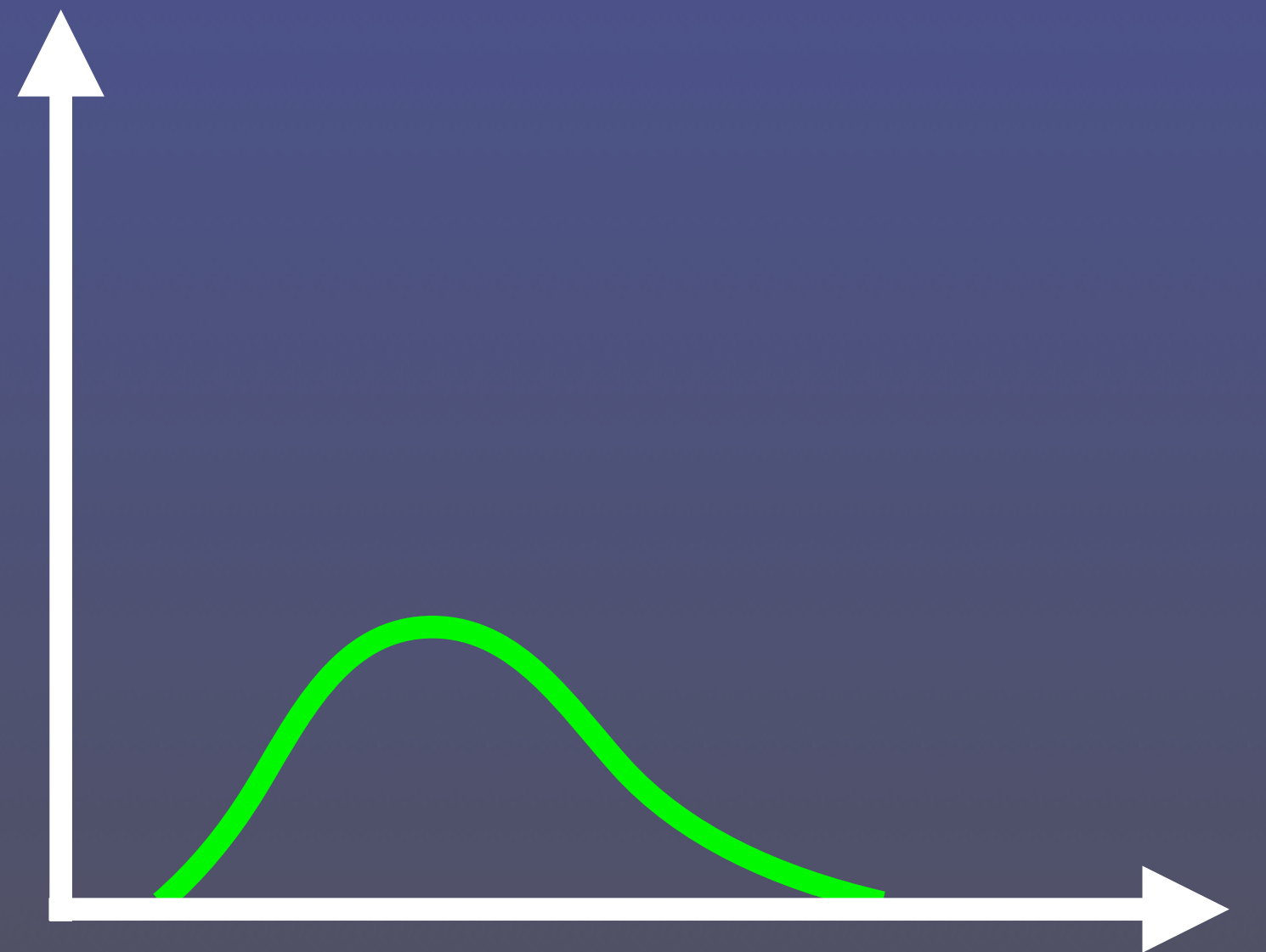


$SFR_{\text{PopIII}}$



Time

X-ray  
Intensity

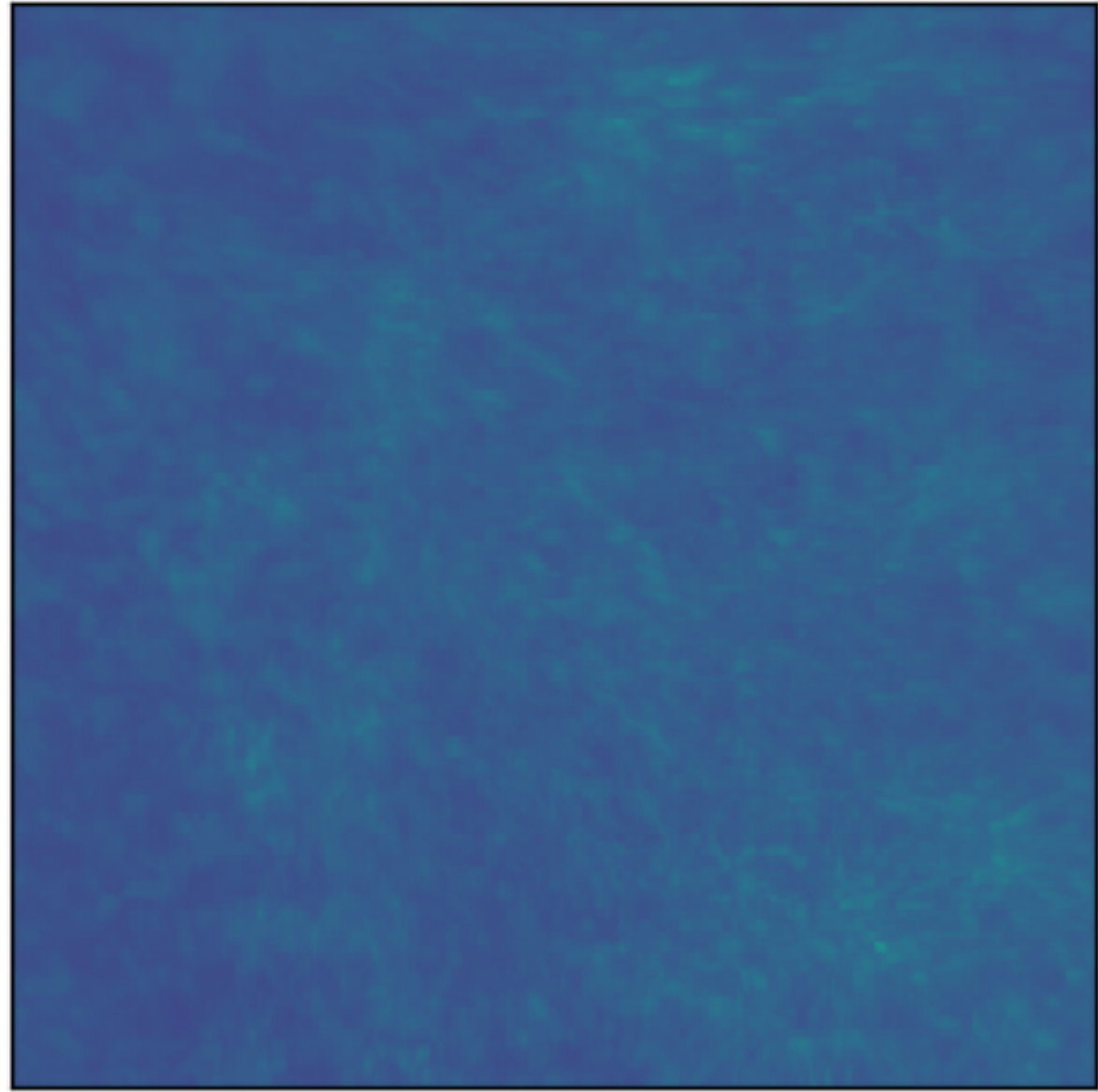


Time

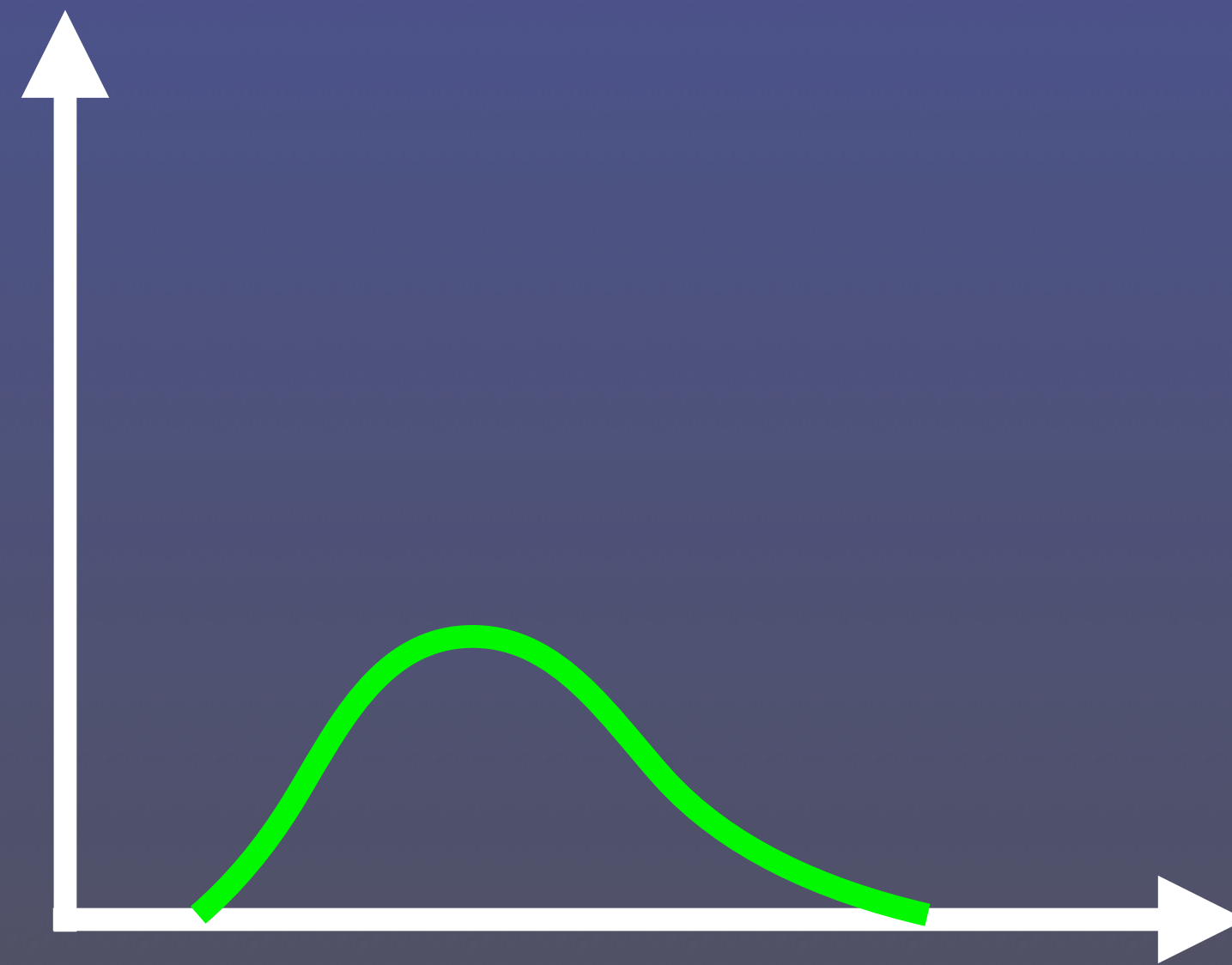


# Estimate of an X-ray - On-the-fly

$z = 32.3$

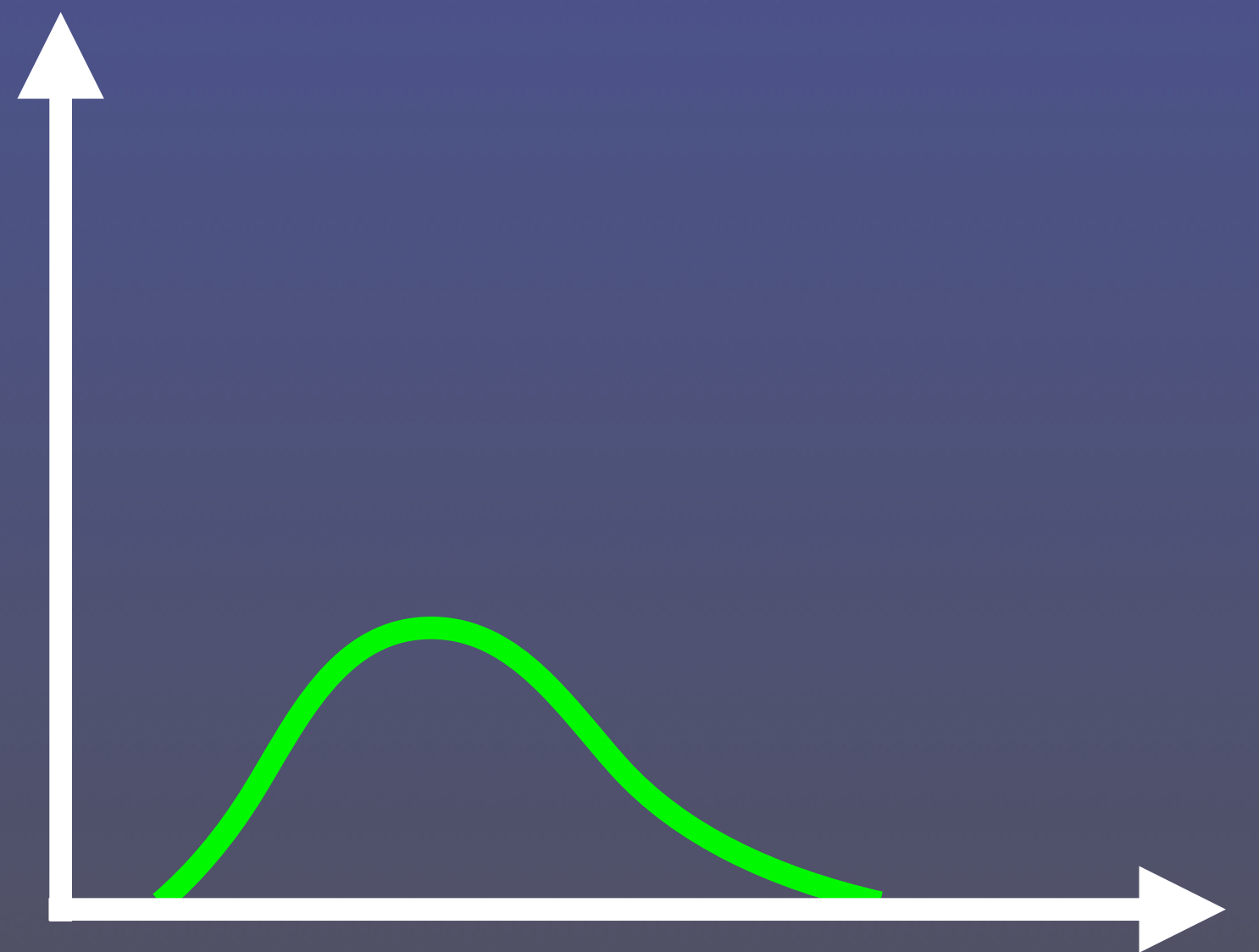


$SFR_{\text{PopIII}}$



Time

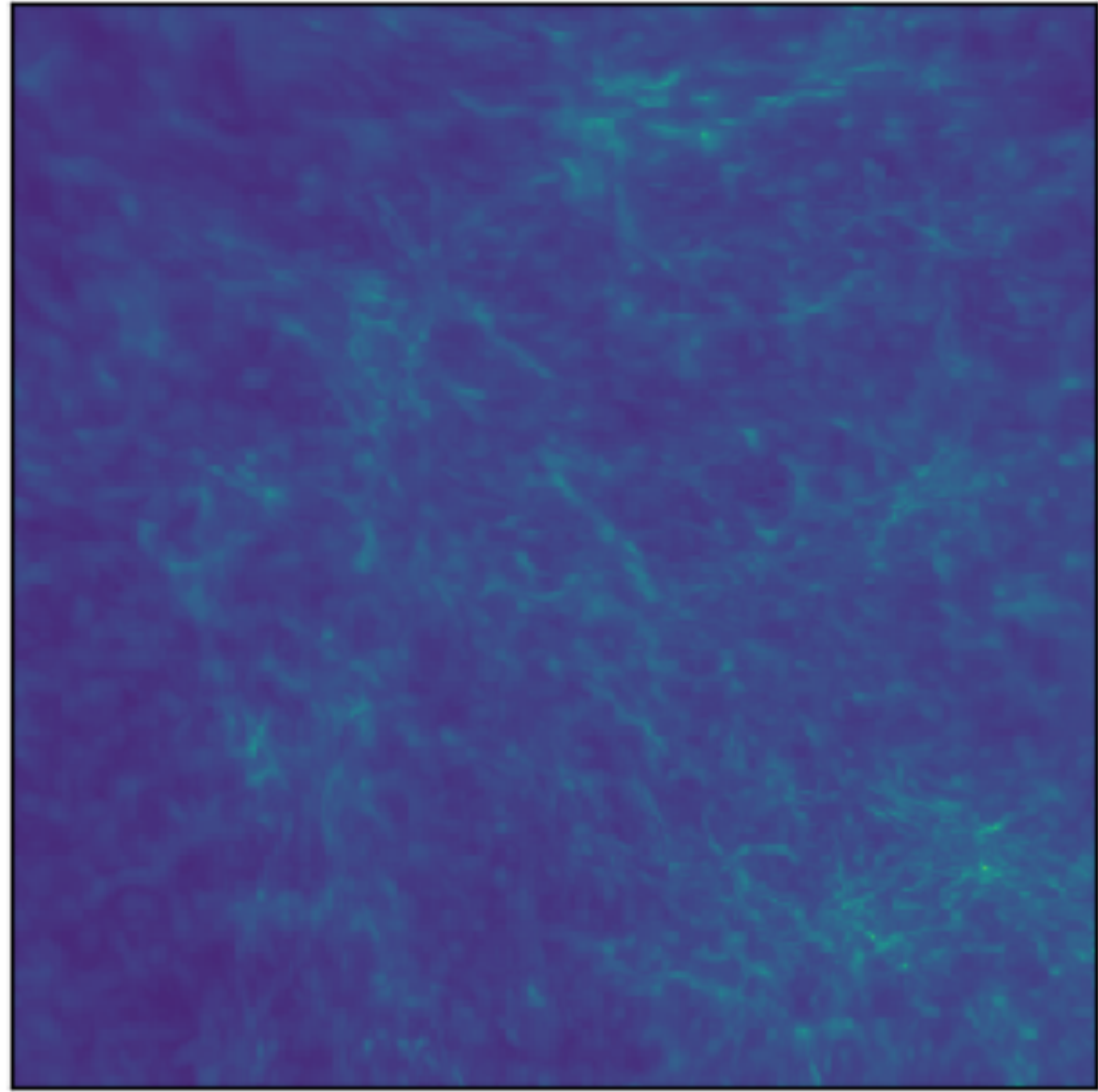
X-ray  
Intensity



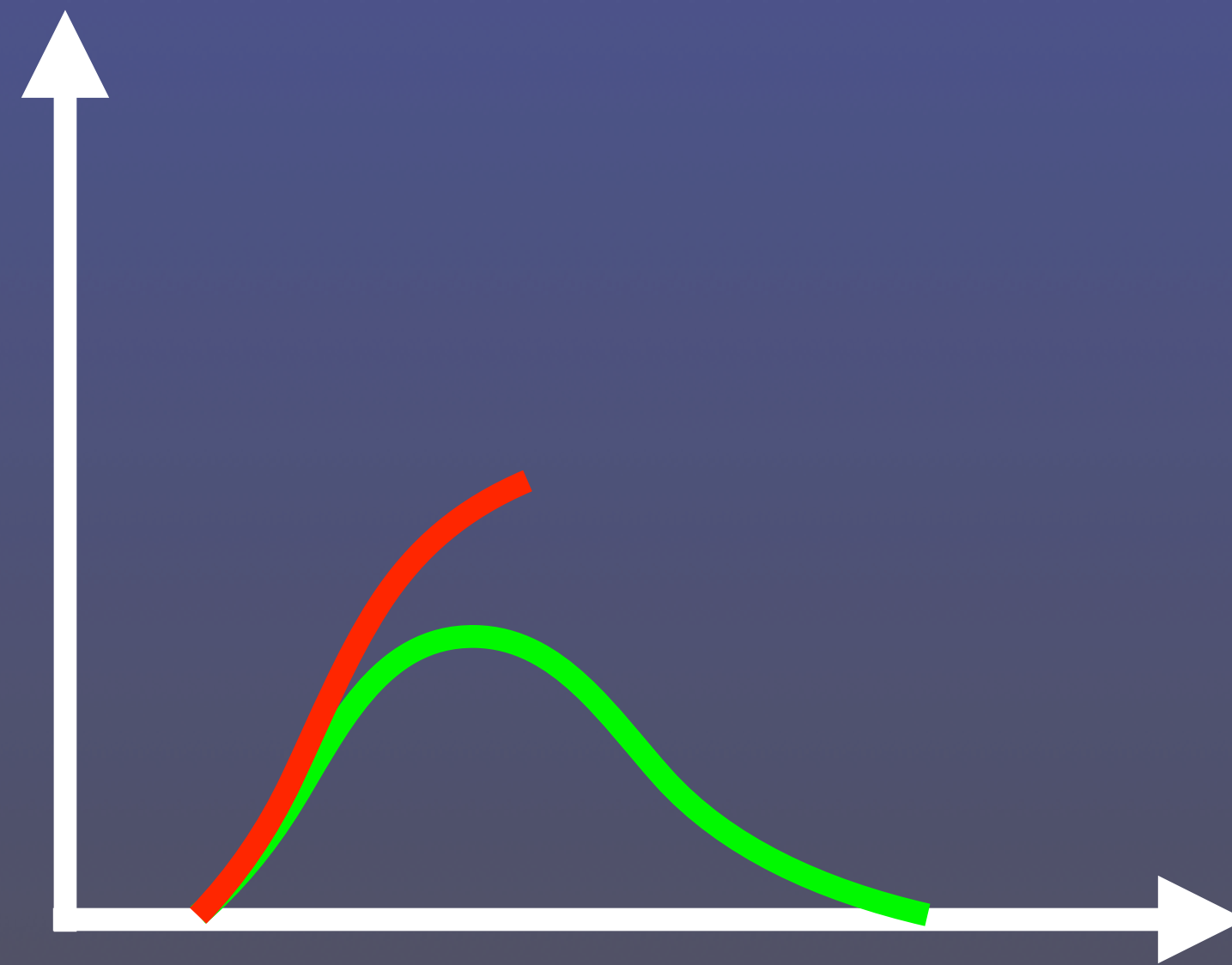
Time

# Estimate of an X-ray - On-the-fly

$z = 22.3$

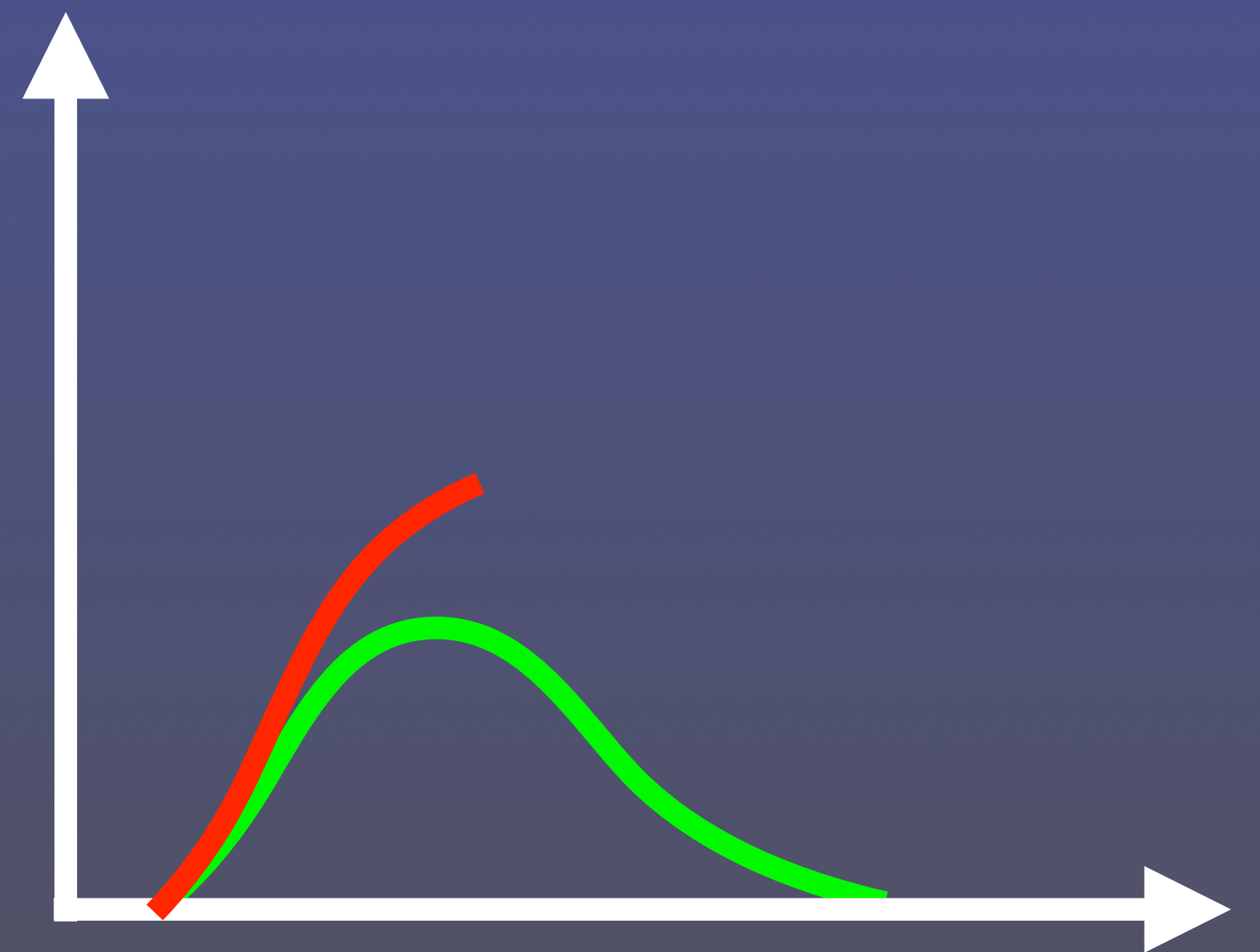


$SFR_{\text{PopIII}}$



Time

X-ray  
Intensity



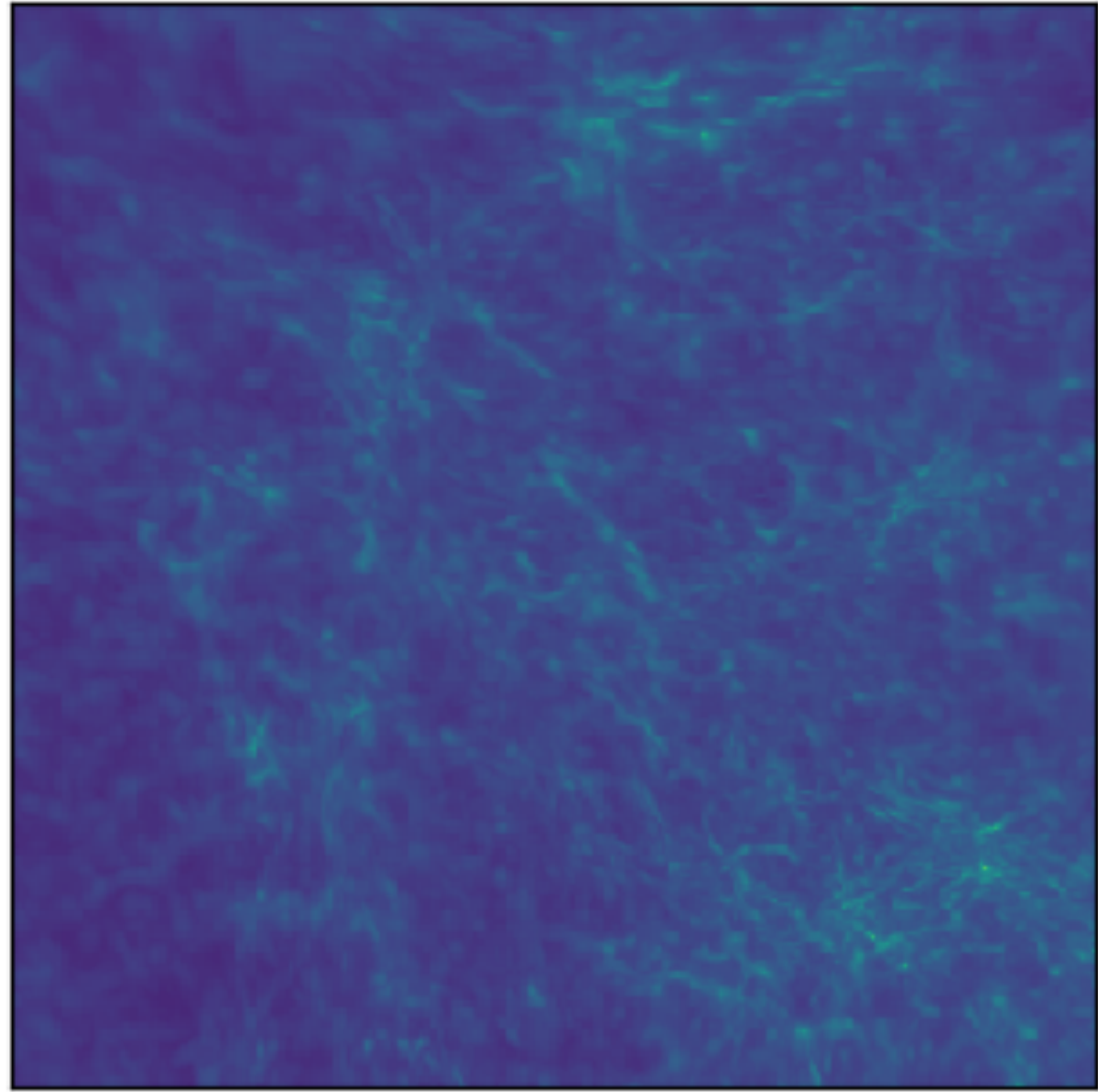
Time



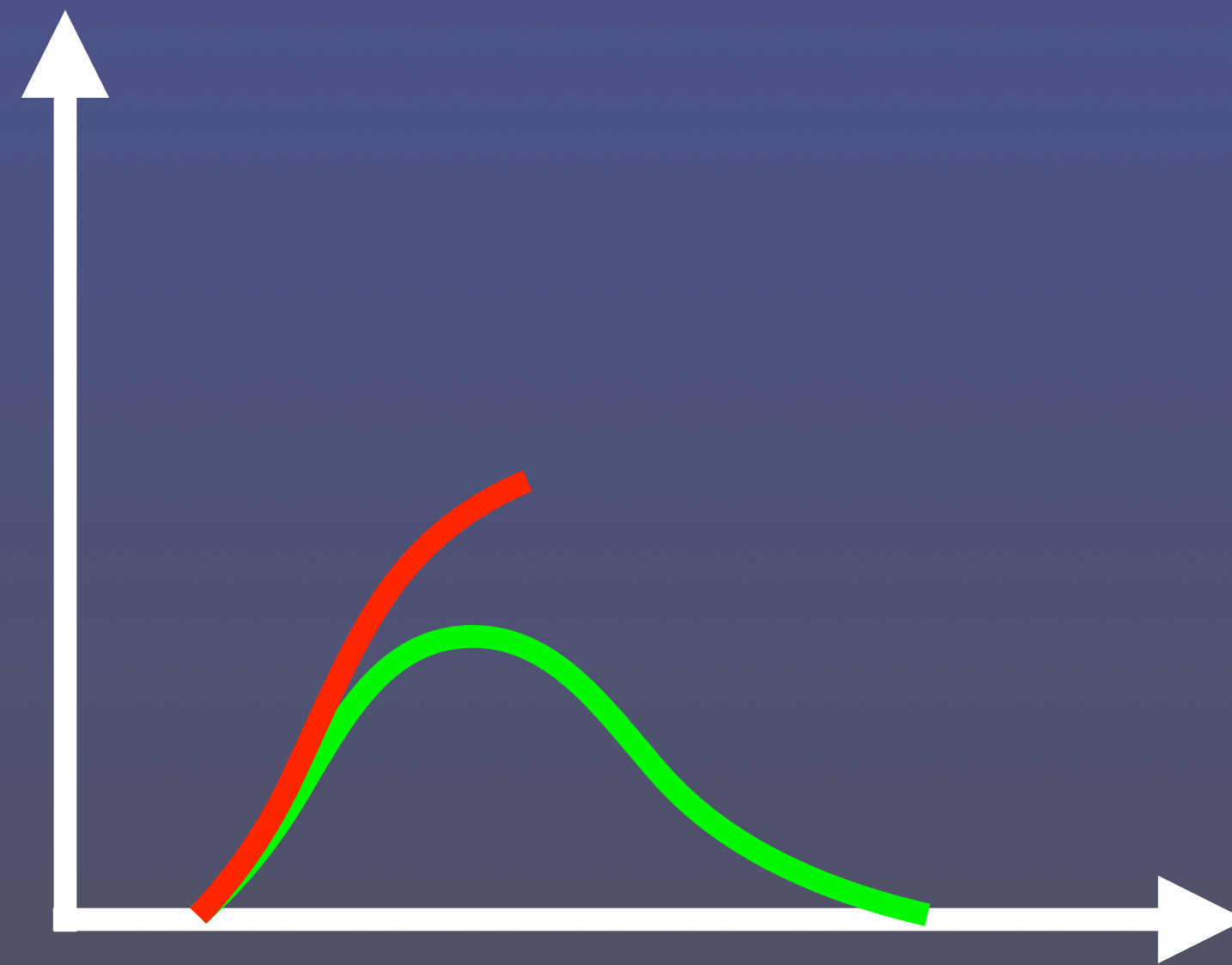
# Estimate of an X-ray - On-the-fly



$z = 22.3$

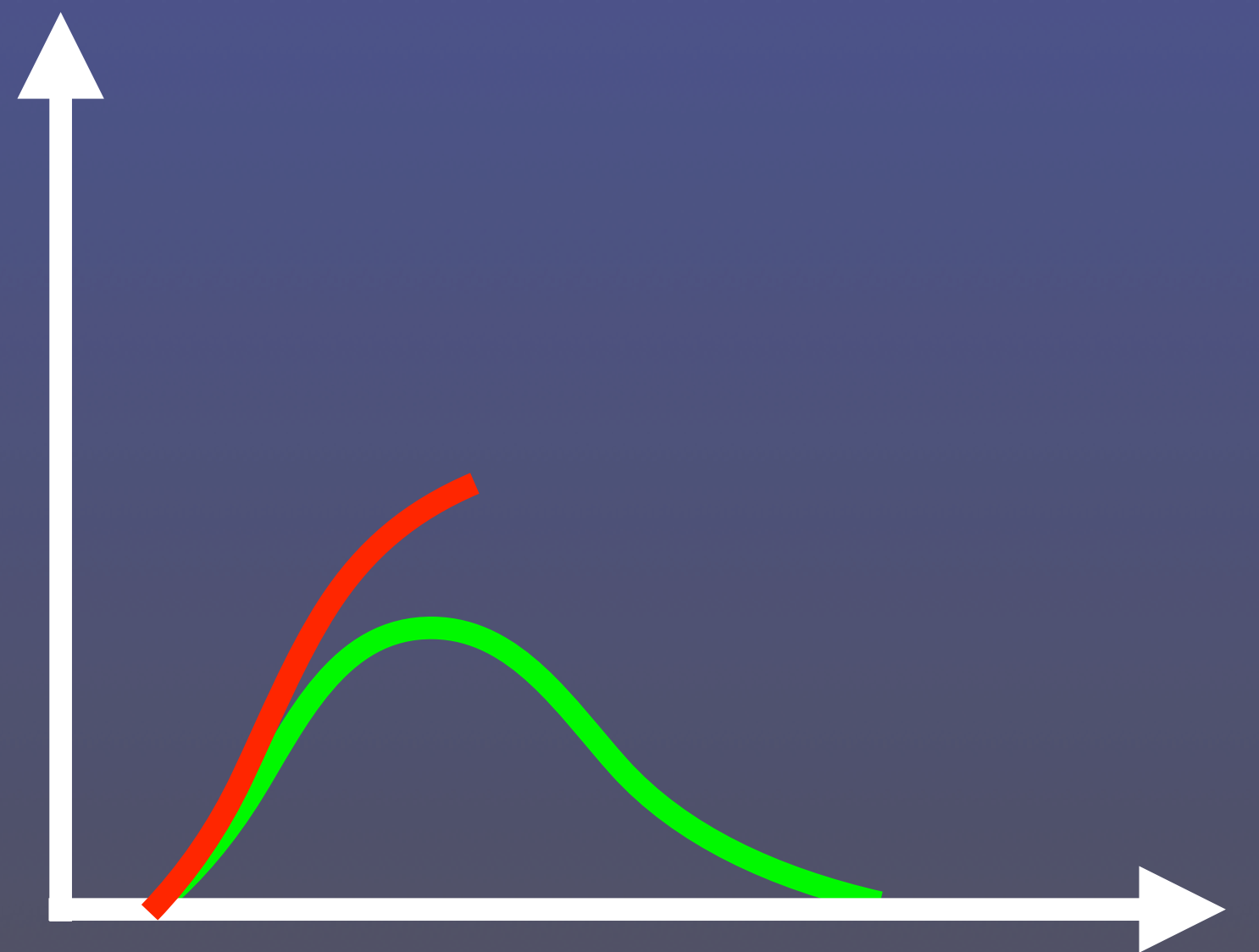


$SFR_{\text{PopIII}}$



Time

X-ray  
Intensity



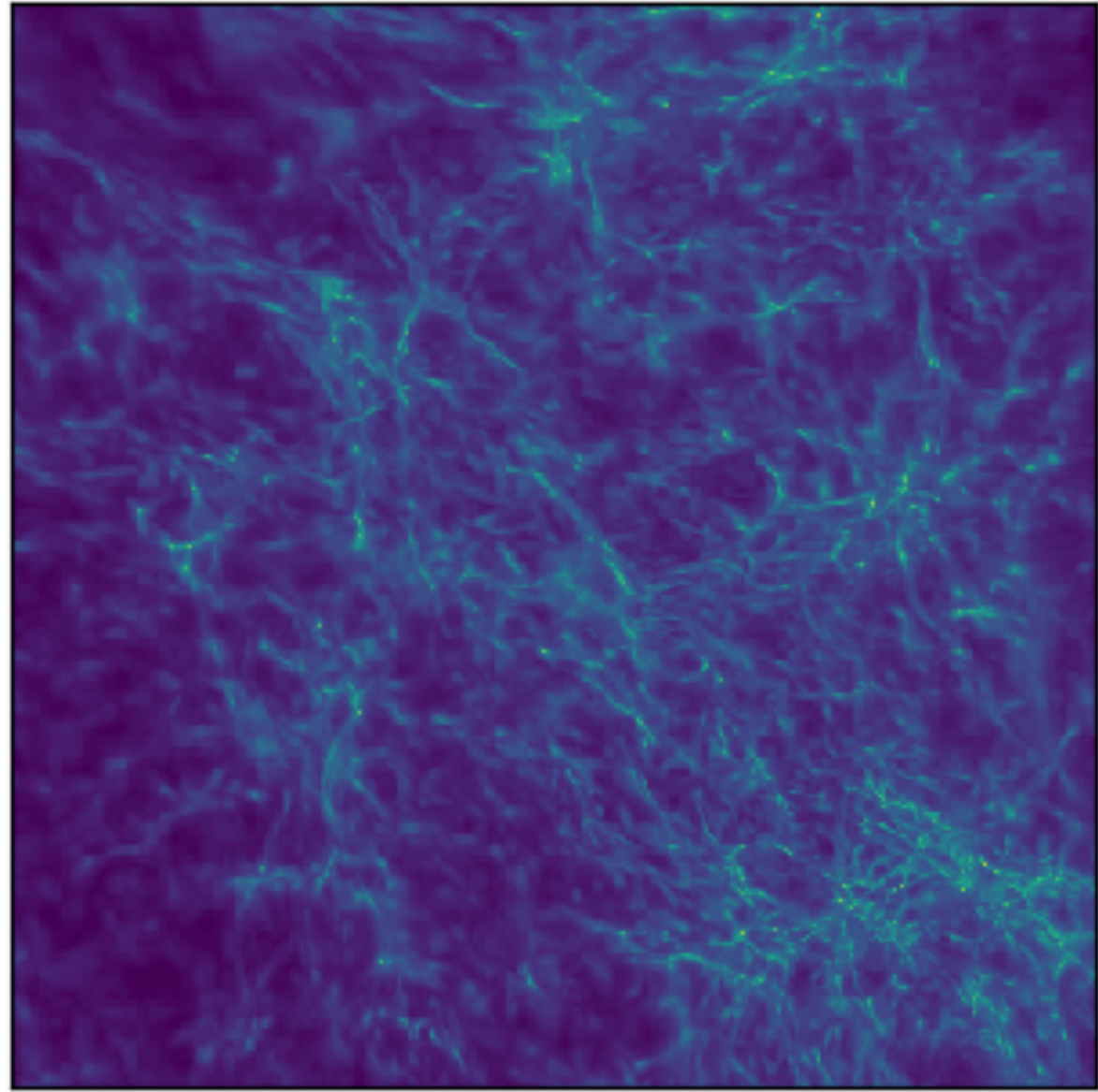
Time



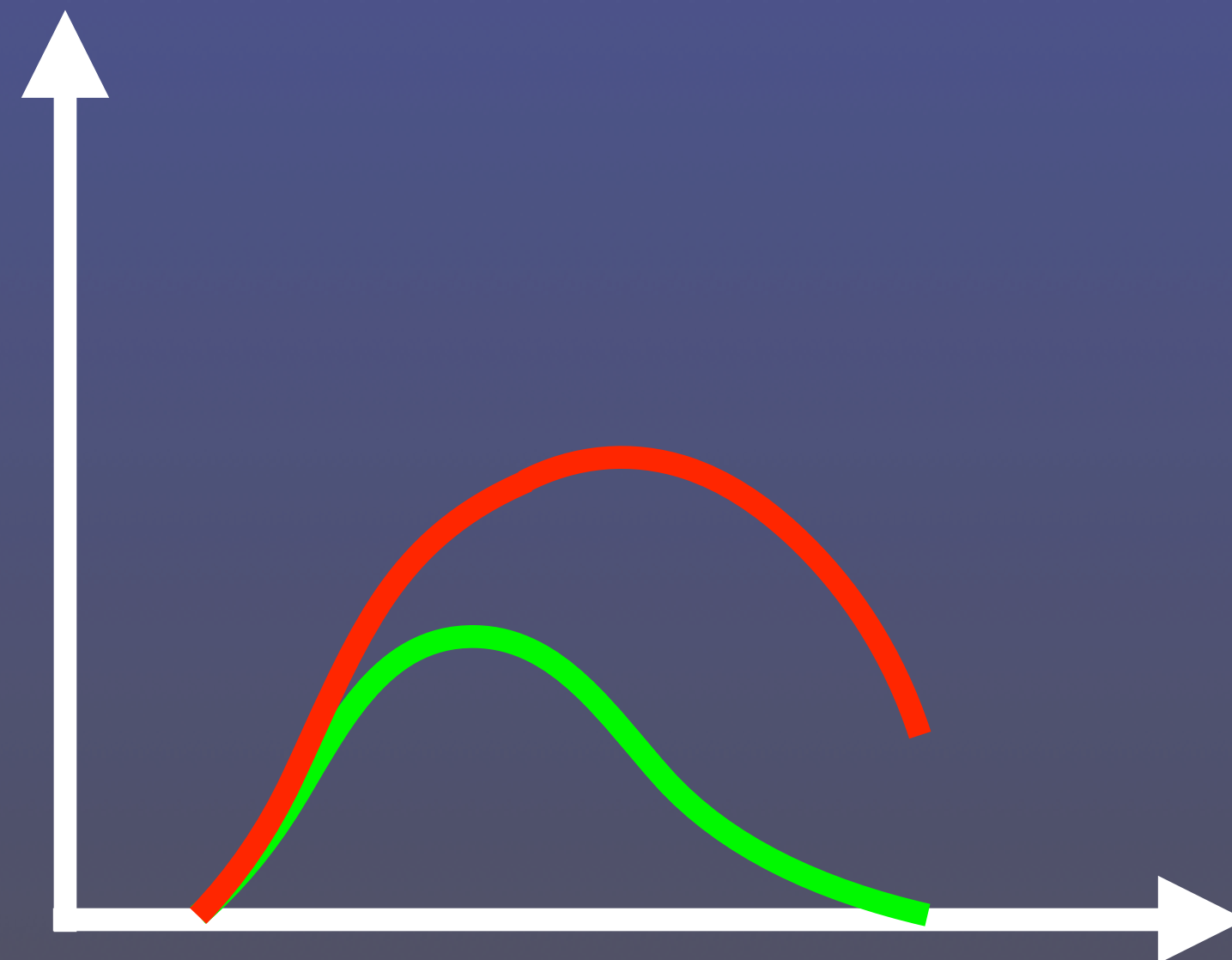
# Estimate of an X-ray - On-the-fly



$z = 14.9$

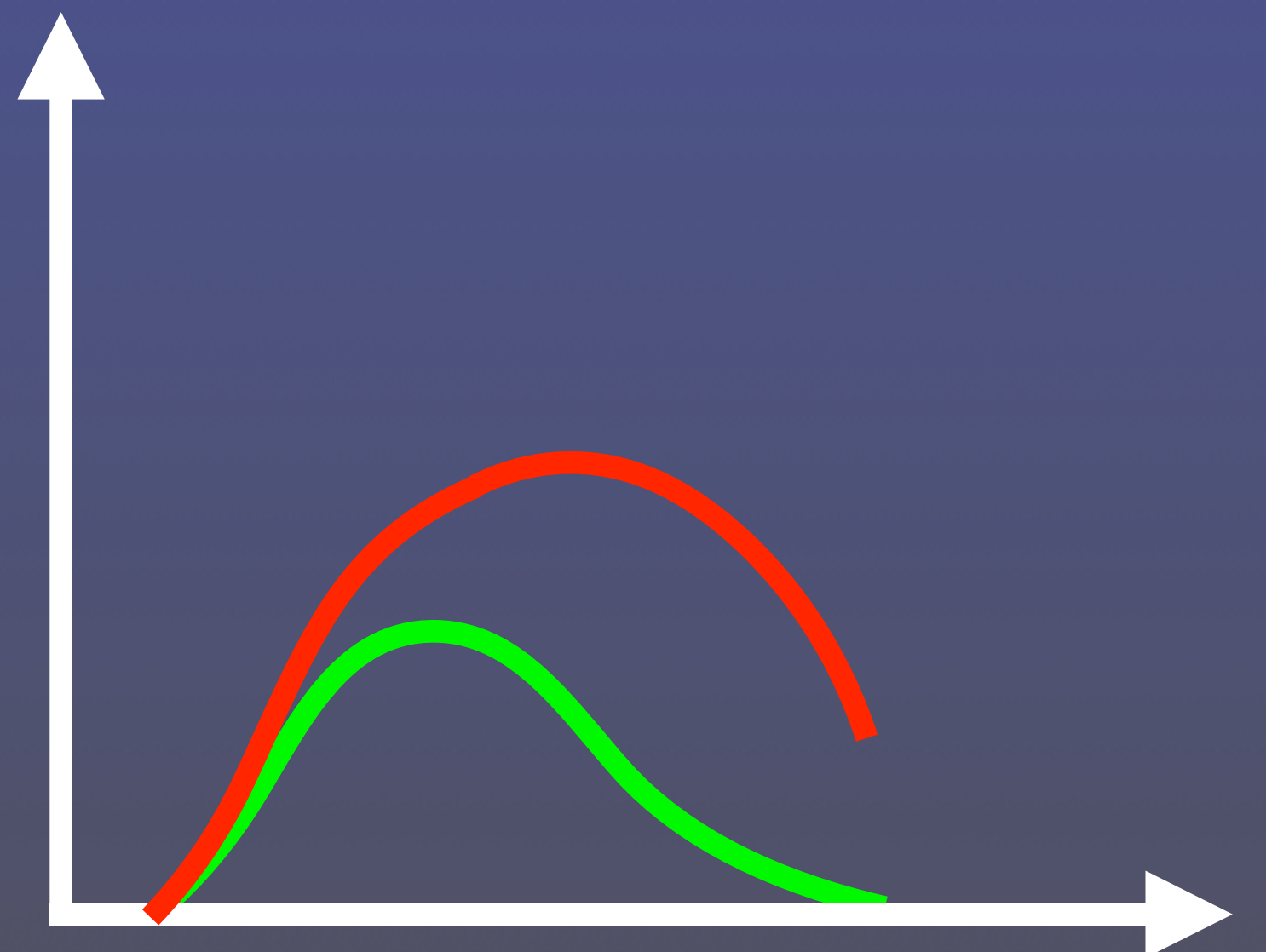


$SFR_{\text{PopIII}}$



Time

X-ray  
Intensity



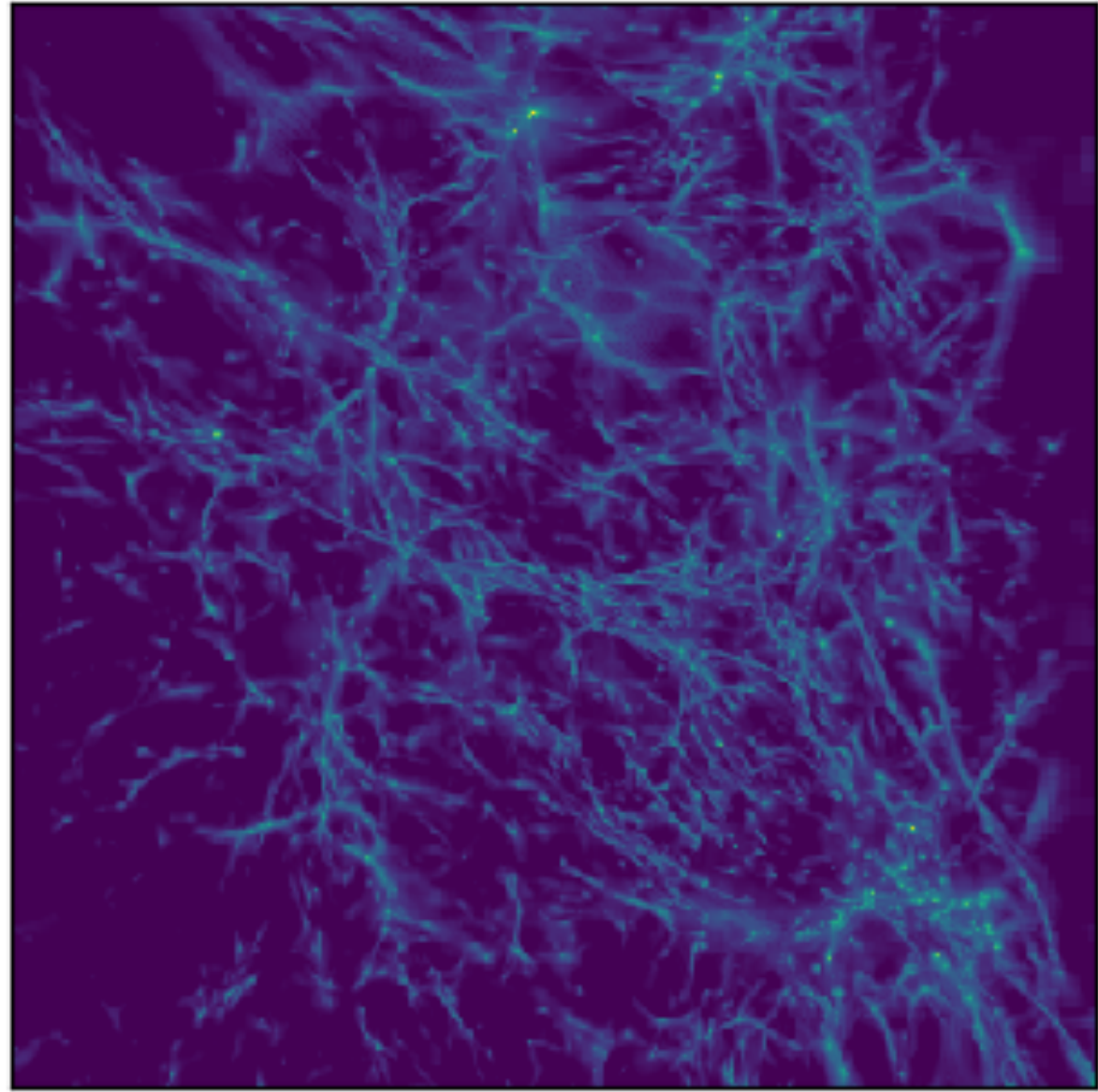
Time



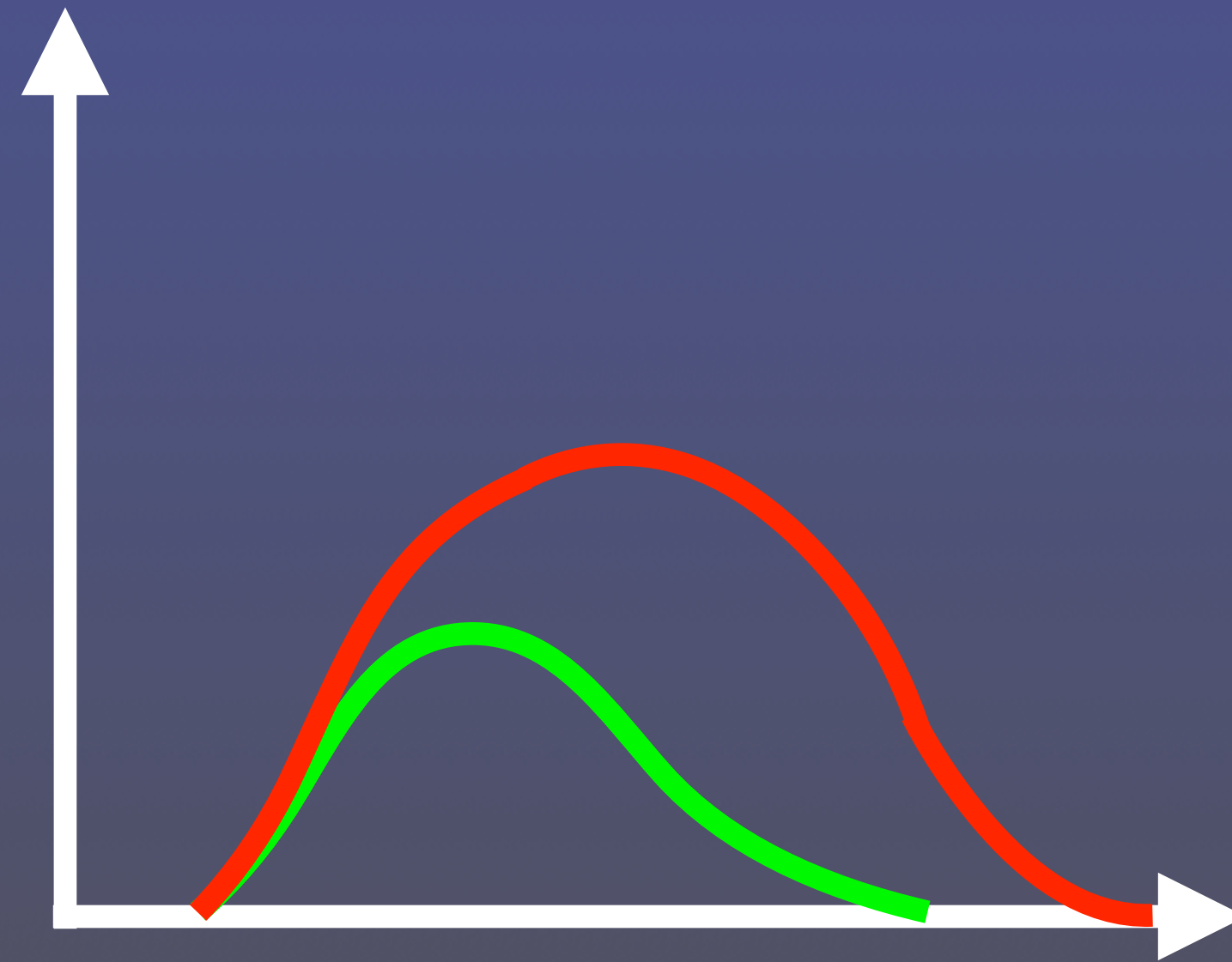
# Estimate of an X-ray - On-the-fly



$z = 9.0$

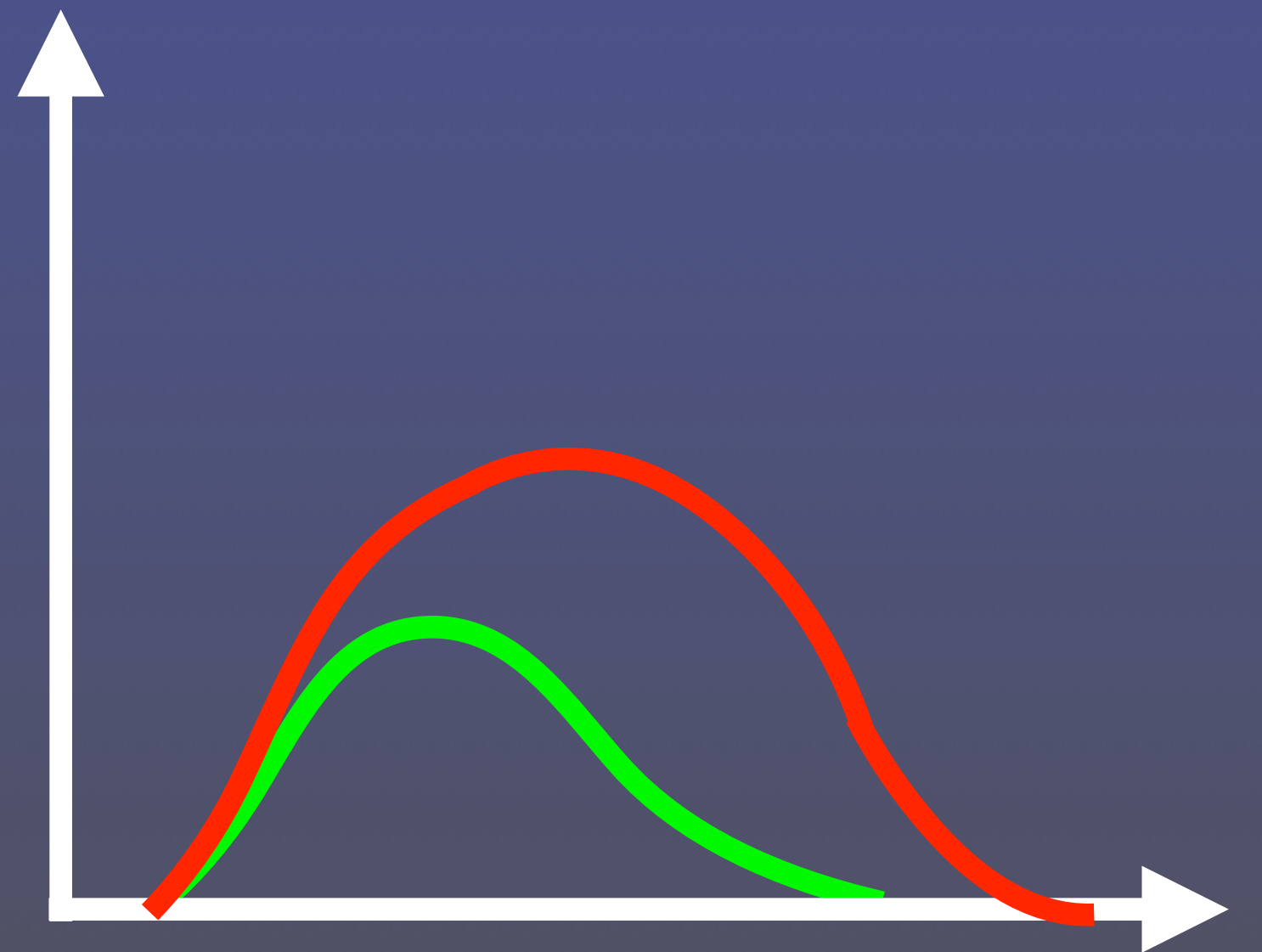


$SFR_{\text{PopIII}}$



Time

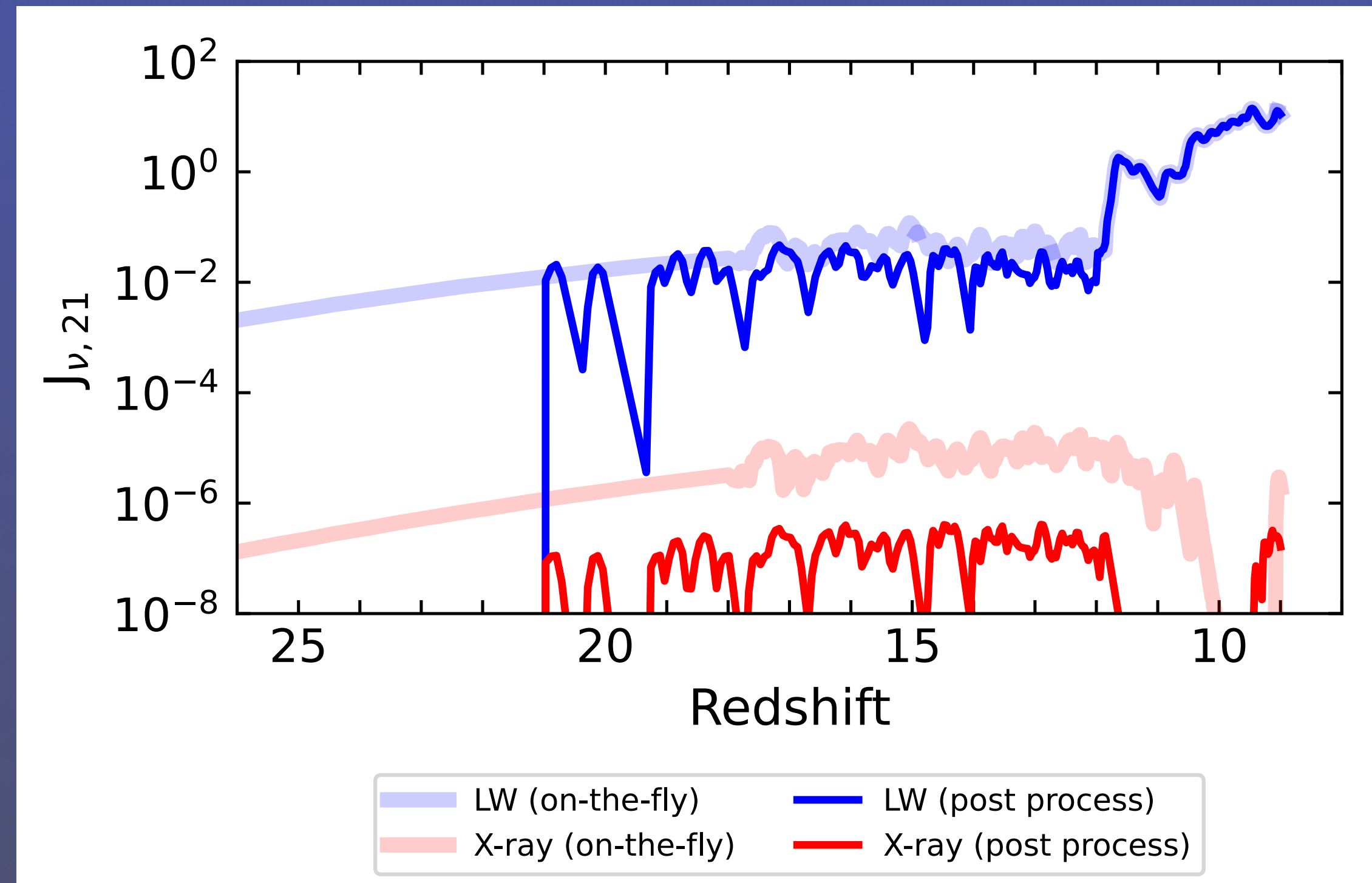
X-ray  
Intensity



Time



# Effect of On-the-fly Method



- A stronger X-ray background develops with the on-the-fly method.