On-the-fly Calculation of an X-ray Background and Its Impact on Population III Star Formation

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Park & Ricotti 2026, arXiv:2603.26352
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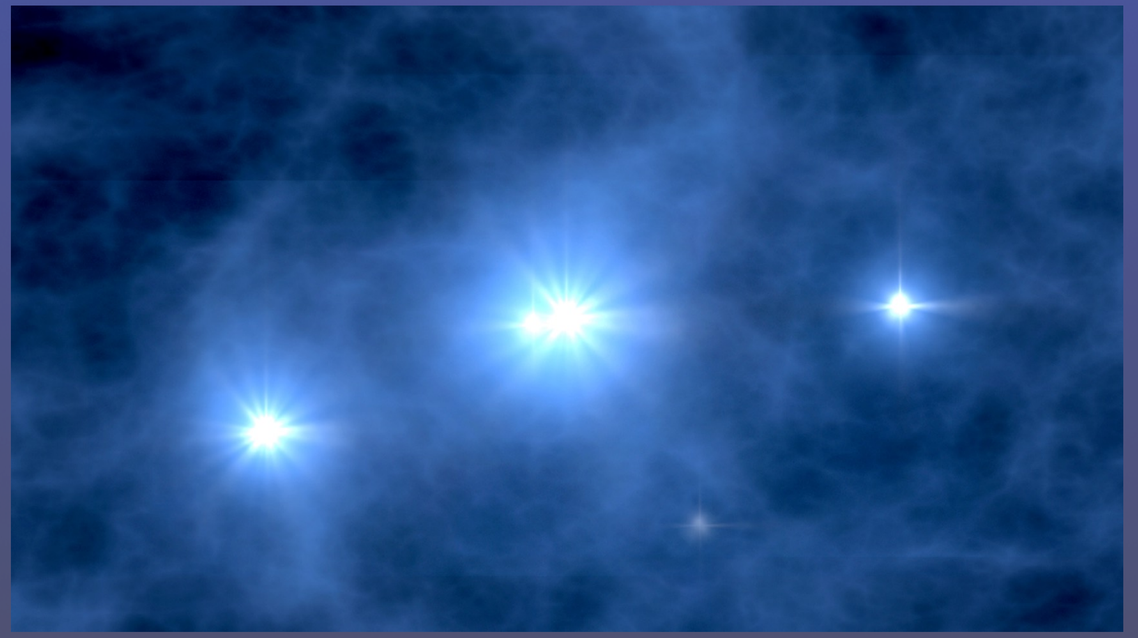
Population III Stars

- metal-free
- M ~ 100 $M_\odot$
- Forming in minihalos (M_{vir} ~ 10^6 $M_\odot$) in the early Universe (z ~ 30 - 10)
- Regulate the formation of Pop II stars through radiative & supernova feedback
- Produce first heavy elements



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

Role of Radiation Background

$$H + e^- \rightarrow H^- + \gamma$$

$$H + H^- \rightarrow H_2 + e^-$$

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- Lyman-Werner ($11.2\ eV \leqq E \leqq 13.6\ eV$)
  - Photodissociate H_2

Role of Radiation Background

- ~~Ionizing UV (E > 13.6 eV)~~
  - ~~Absorbed by neutral medium…~~

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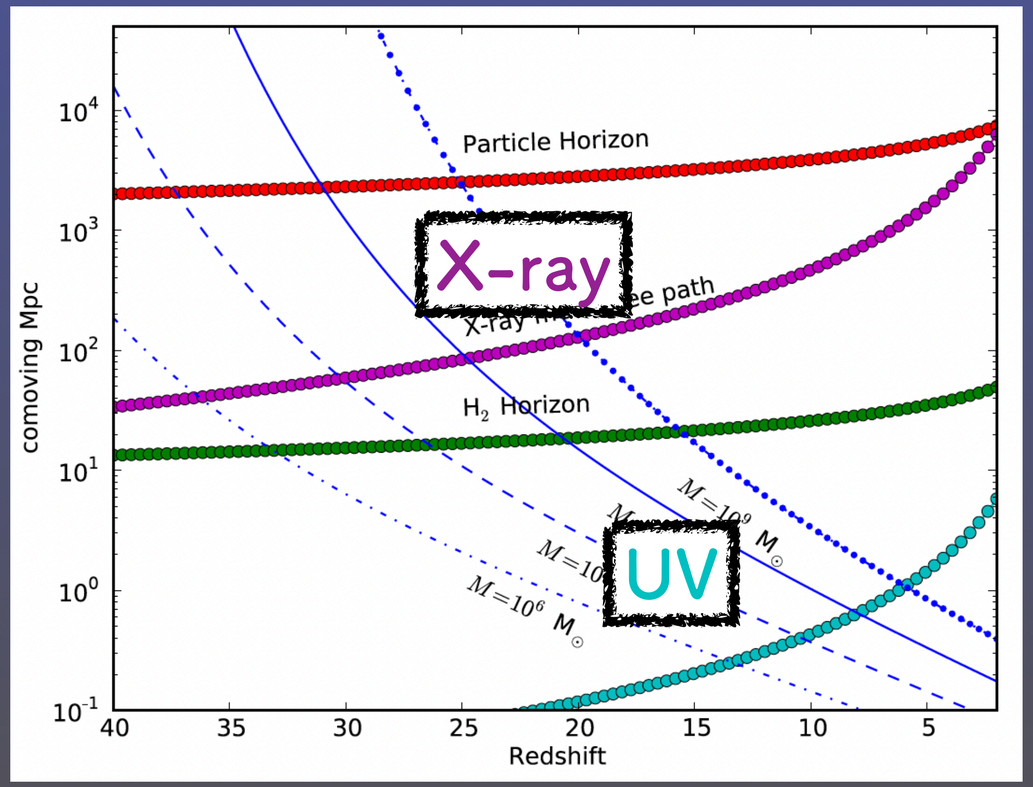
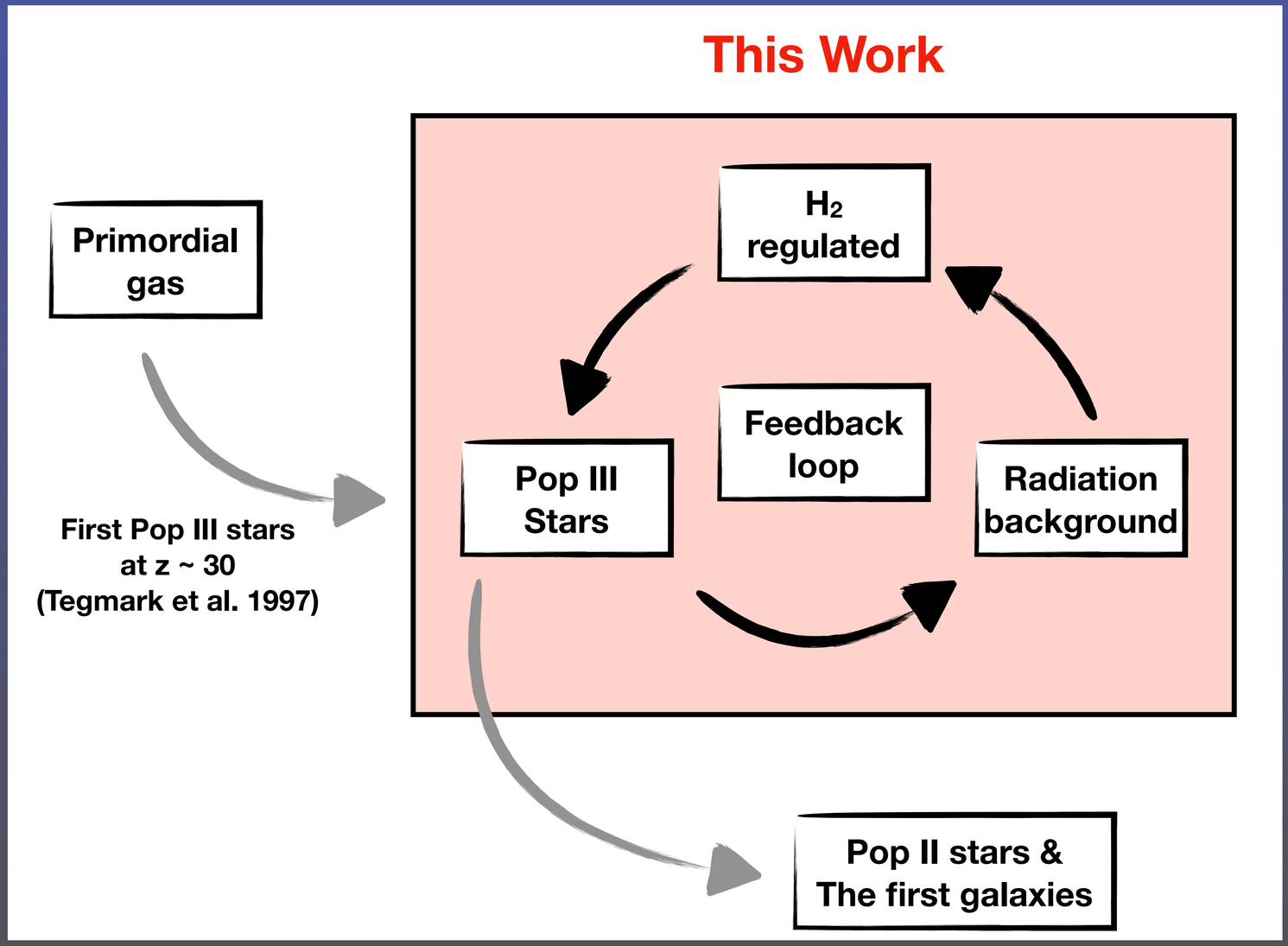
- X-rays (E ≳ 0.2 keV)
  - Pop III SN, AGN, HMXB…
  - increase the electron fraction

Mean Free Paths



Ricotti 2016

X-ray Feedback Loop



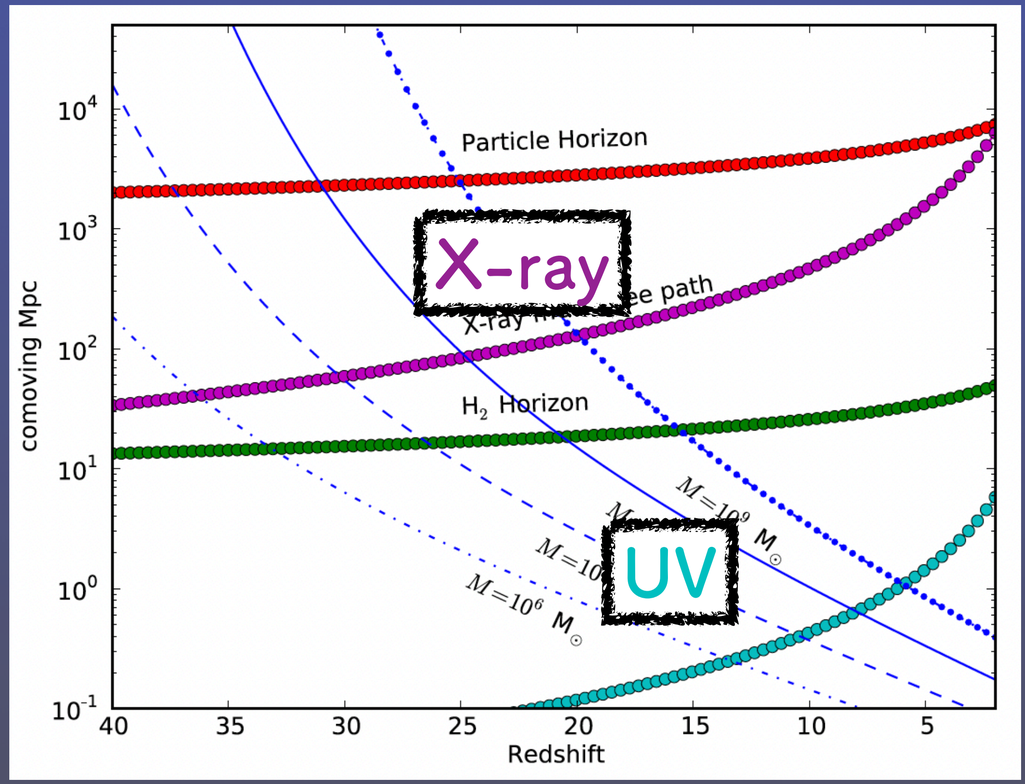
X-ray Feedback Loop

- X-rays have large mean free paths
  - $\lambda \approx 100$ Mpc/h
  - large cosmological volume

- Pop III stars form in minihalos
  - $M_{halo} \sim 10^6\ M_\odot$
  - $M_{DM} \sim 10^3\ M_\odot$
  - high-resolution
    - 2048^3 base grids for 8 Mpc/h^3
    - 32768^3 base grids for 128 Mpc/h^3

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

Mean Free Paths



Ricotti 2016

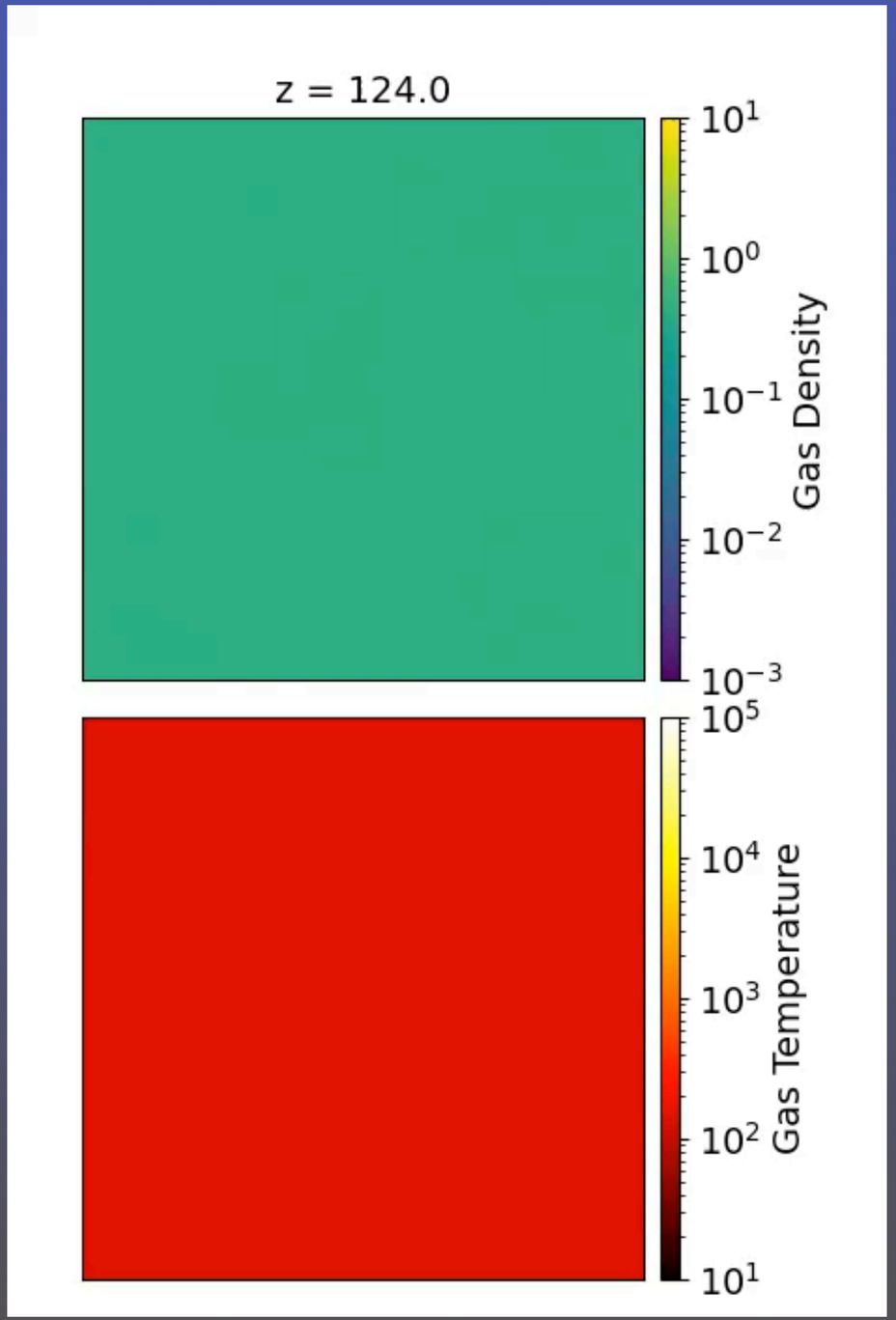
Scientific Goal

1. Run high resolution simulations with a small box
2. Replace a large box with radiative transfer calculation
3. Consider the interplay between Pop III stars and radiation background
4. Estimate an X-ray background produced by Pop III supernovae
5. Impact on the number density of Pop III stars

Simulations

- RAMSES-RT
  - zoom-in simulations
  - 1.0 Mpc/h box inside 8 Mpc/h box
  - 0.5 Mpc/h box inside 4 Mpc/h box
  - 10 volumes
  - LW-only / LW + X-ray

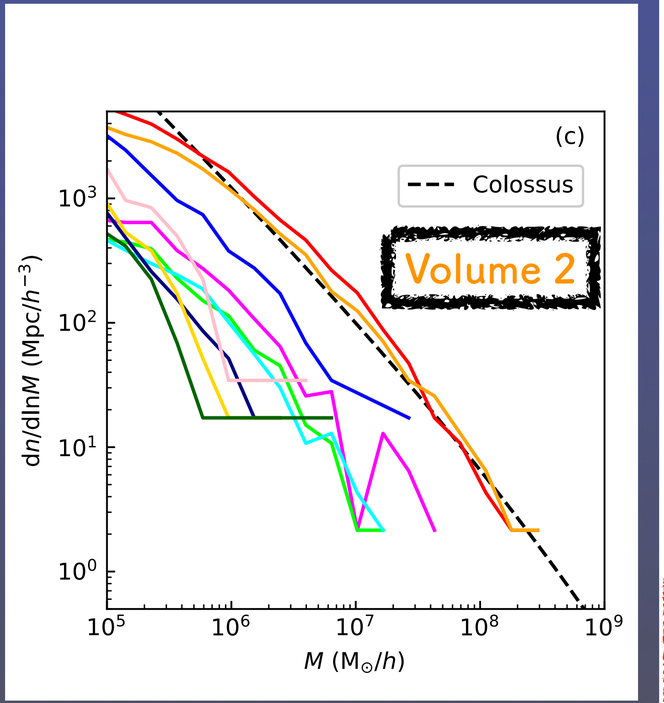
- Physics (Park, Ricotti & Sugimura 2021)
  - star formation, radiative feedback, supernova feedback
  - X-ray/LW radiation background
  - secondary ionization
  - primordial chemistry

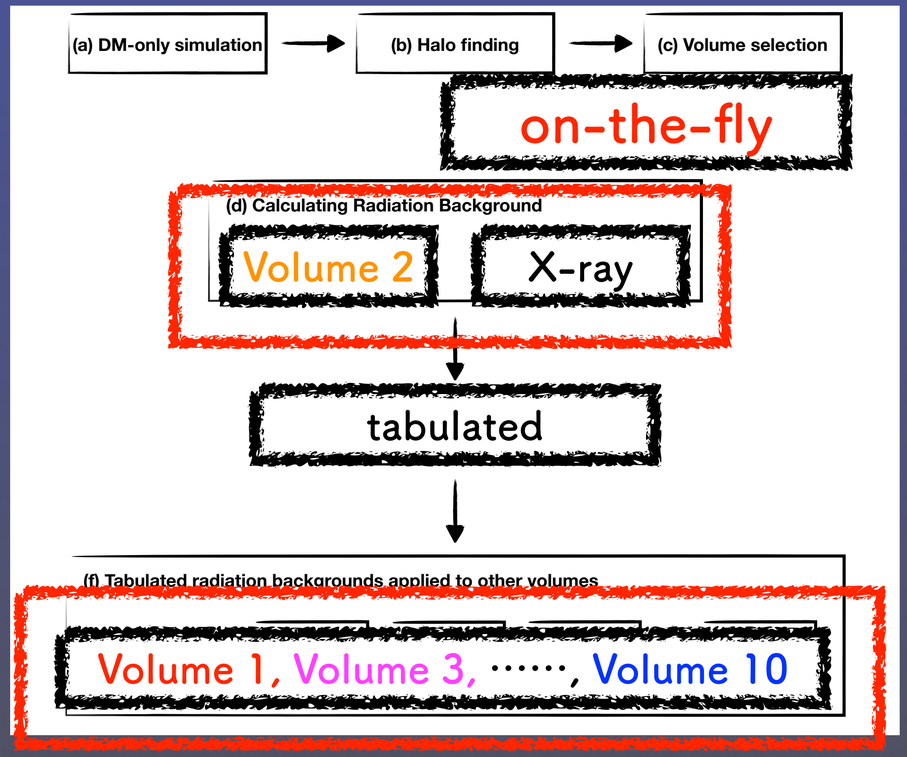


On-the-fly Calculation of X-rays

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

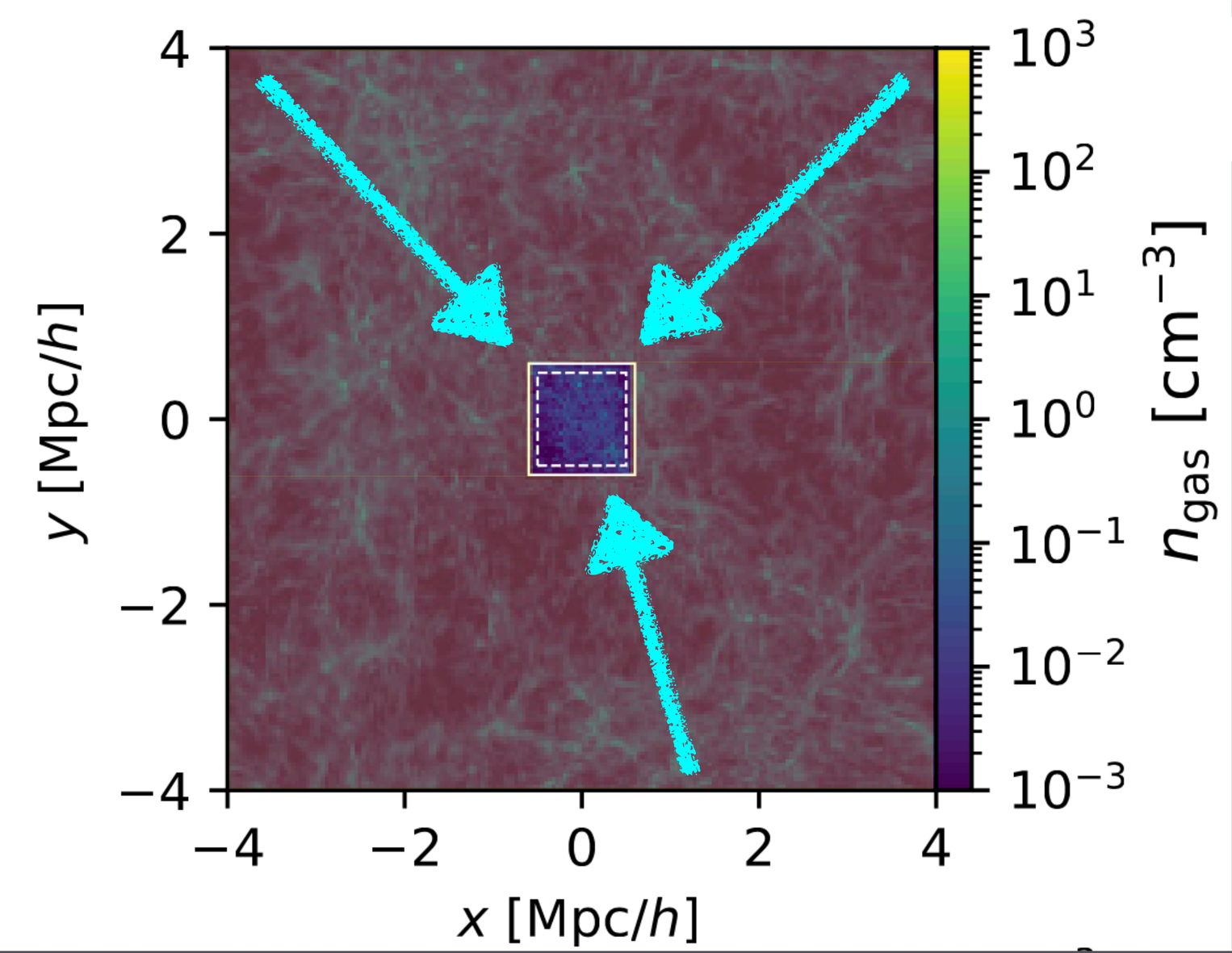
$$[\text{erg s}^{-1}\ \text{cm}^{-2}\ \text{Hz}^{-1}\ \text{Sr}^{-1}]$$





- Star Formation History
  - Should reflect the star formation history of the entire Universe
  - J and ϵ affect each other (feedback loop)

On-the-fly Calculation of X-rays



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Post-processing

Simulation

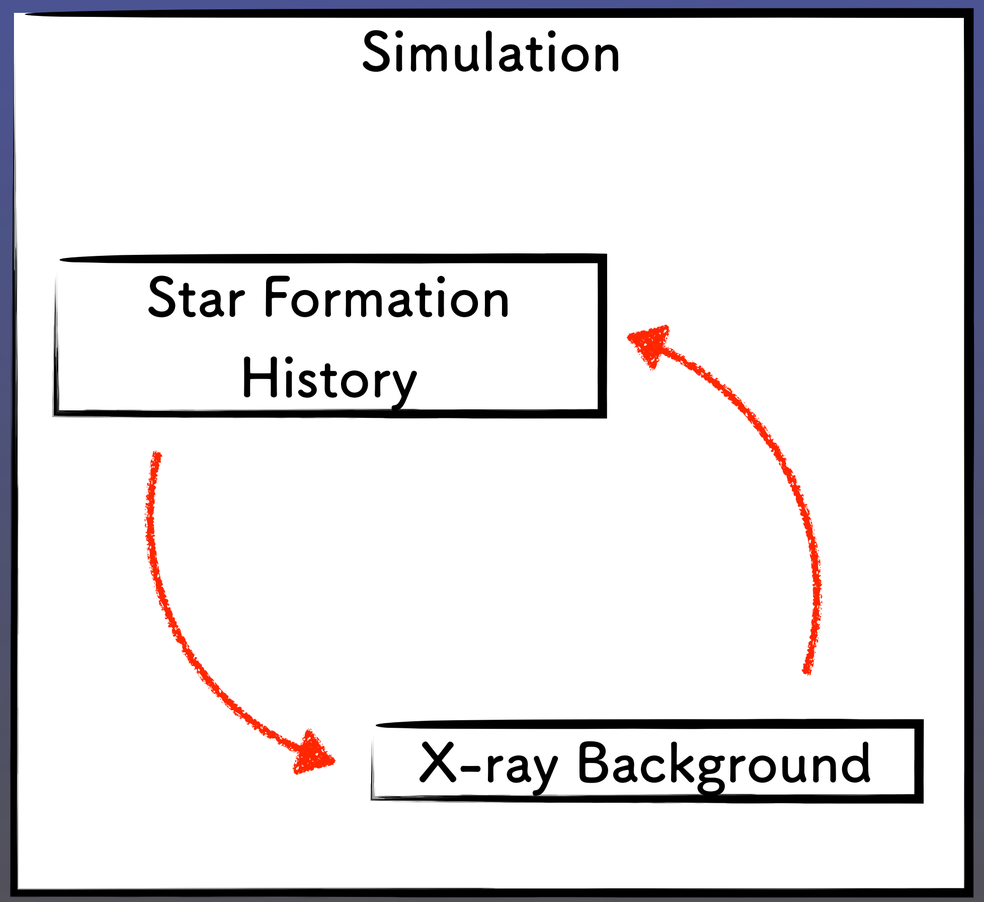
↓

Star Formation History

↓

X-ray Background

On-the-fly



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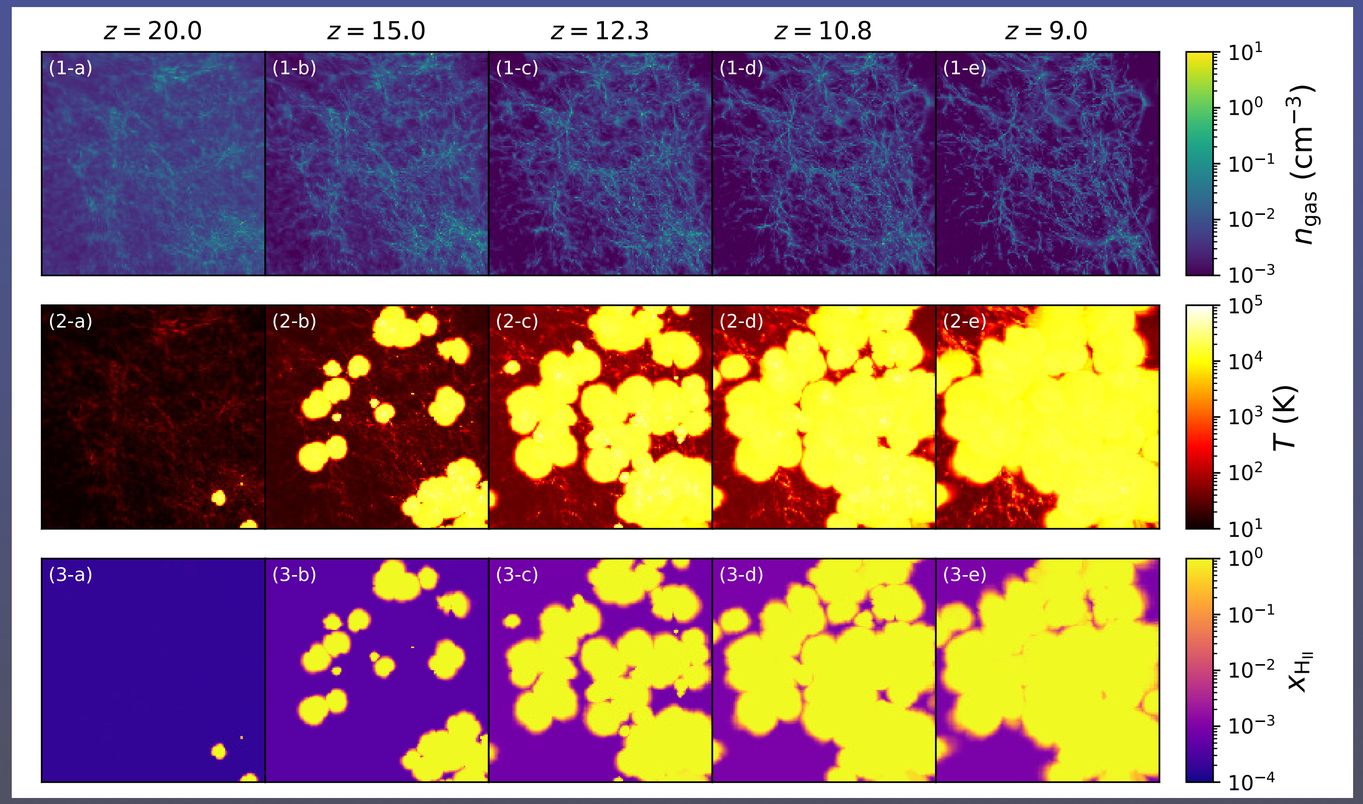
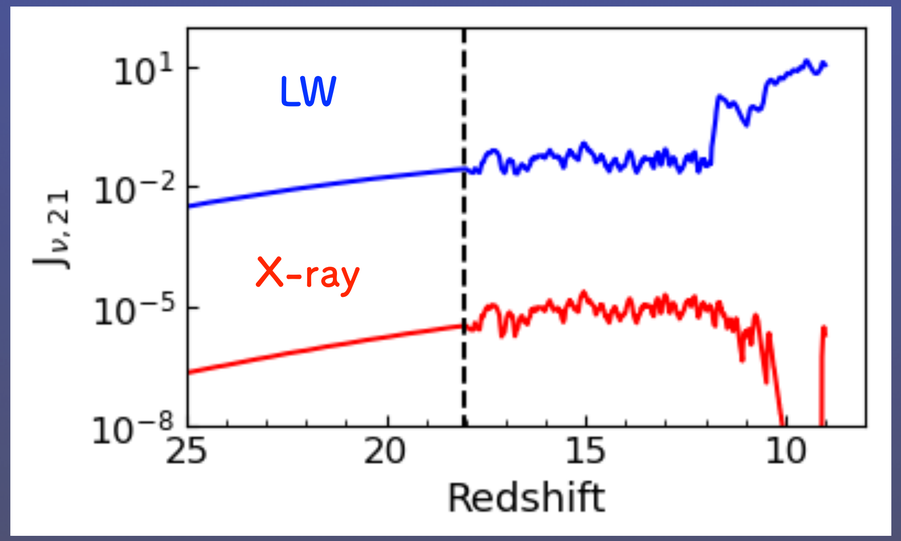
X-ray Feedback

density

temperature

H_{II} fraction

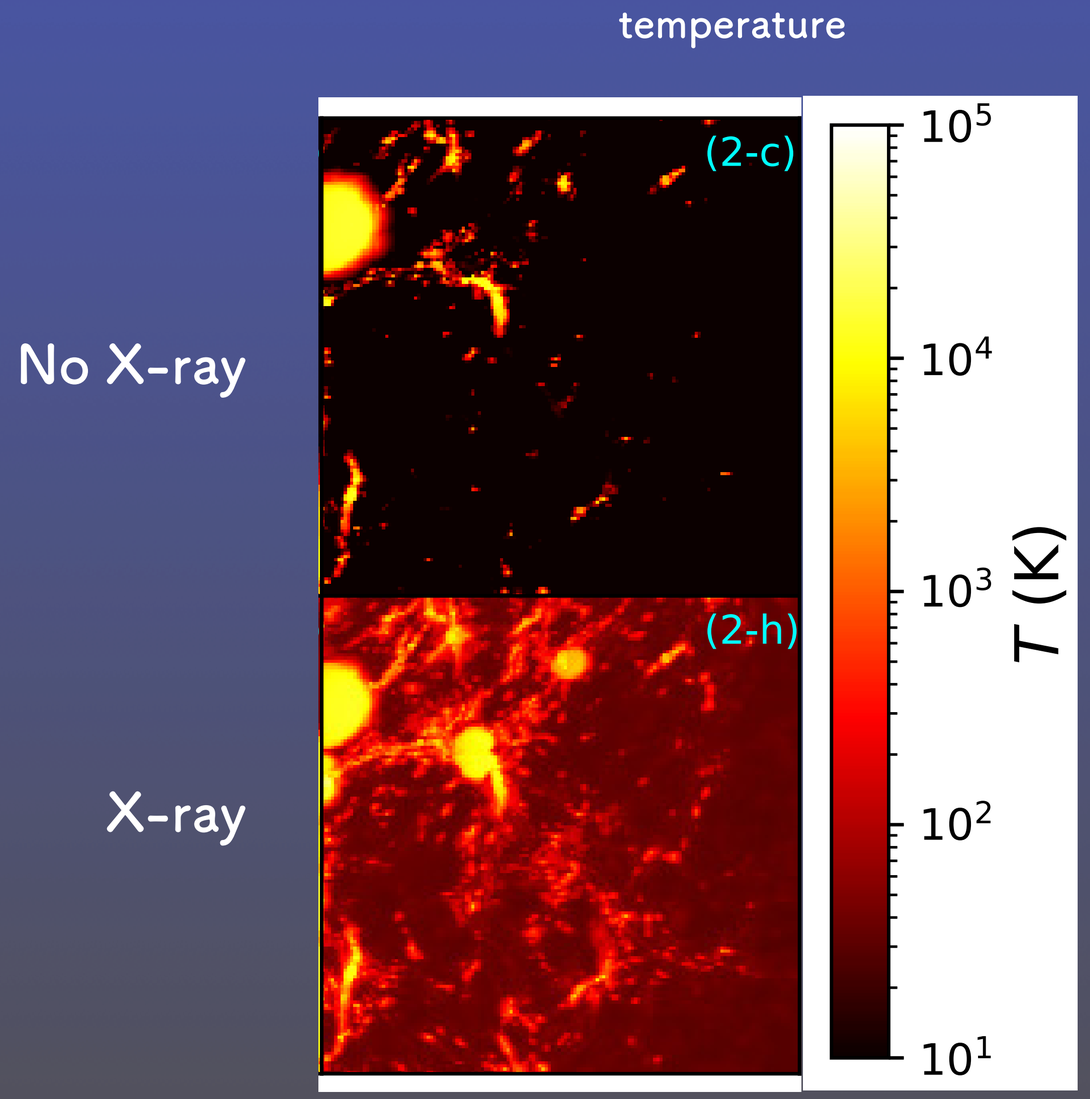




X-ray Feedback

- The X-ray mildly heats and ionises the IGM

- More Pop III stars form under X-ray feedback



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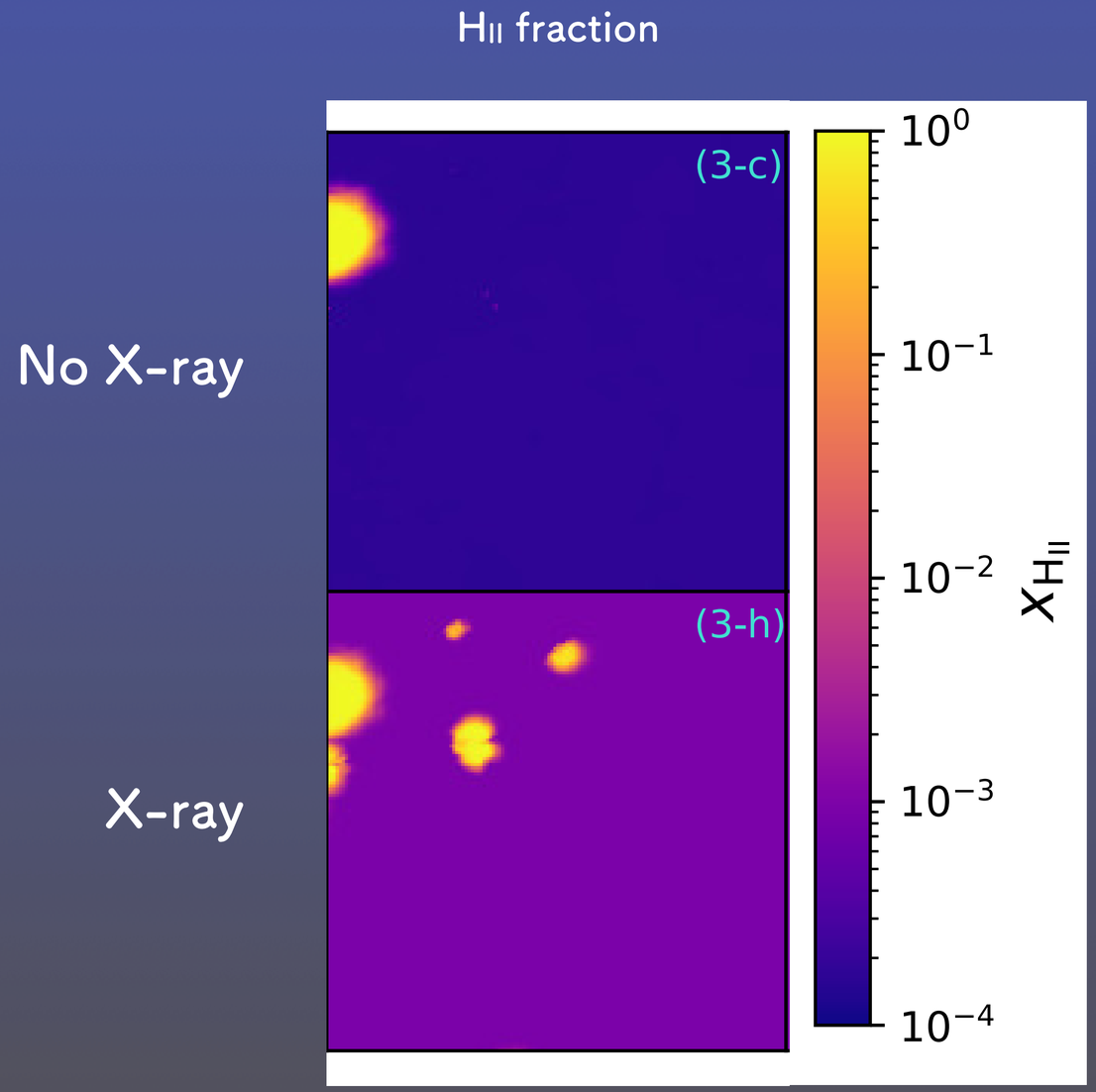
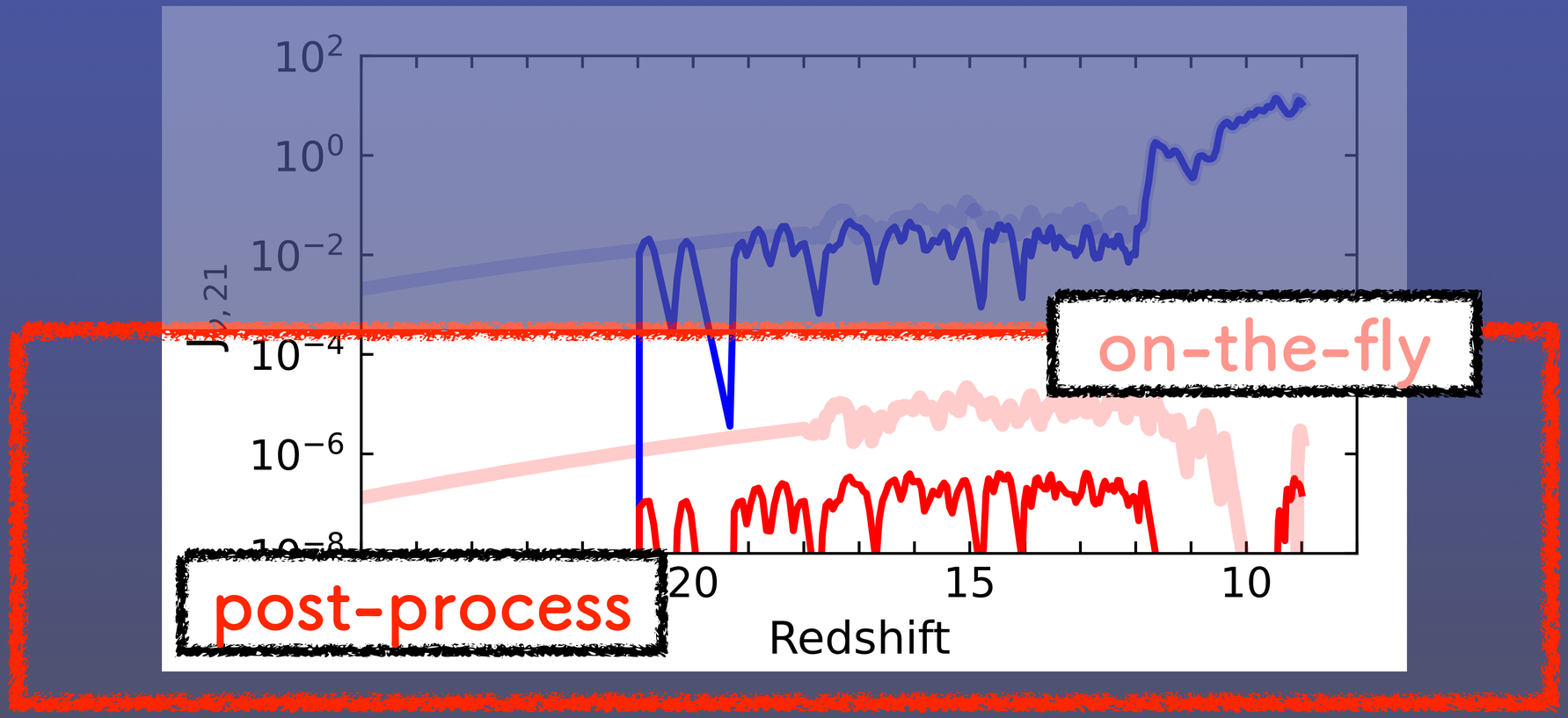


Result I: Post-process vs On-the-fly



- A more intense X-ray background is produced with the on-the-fly method

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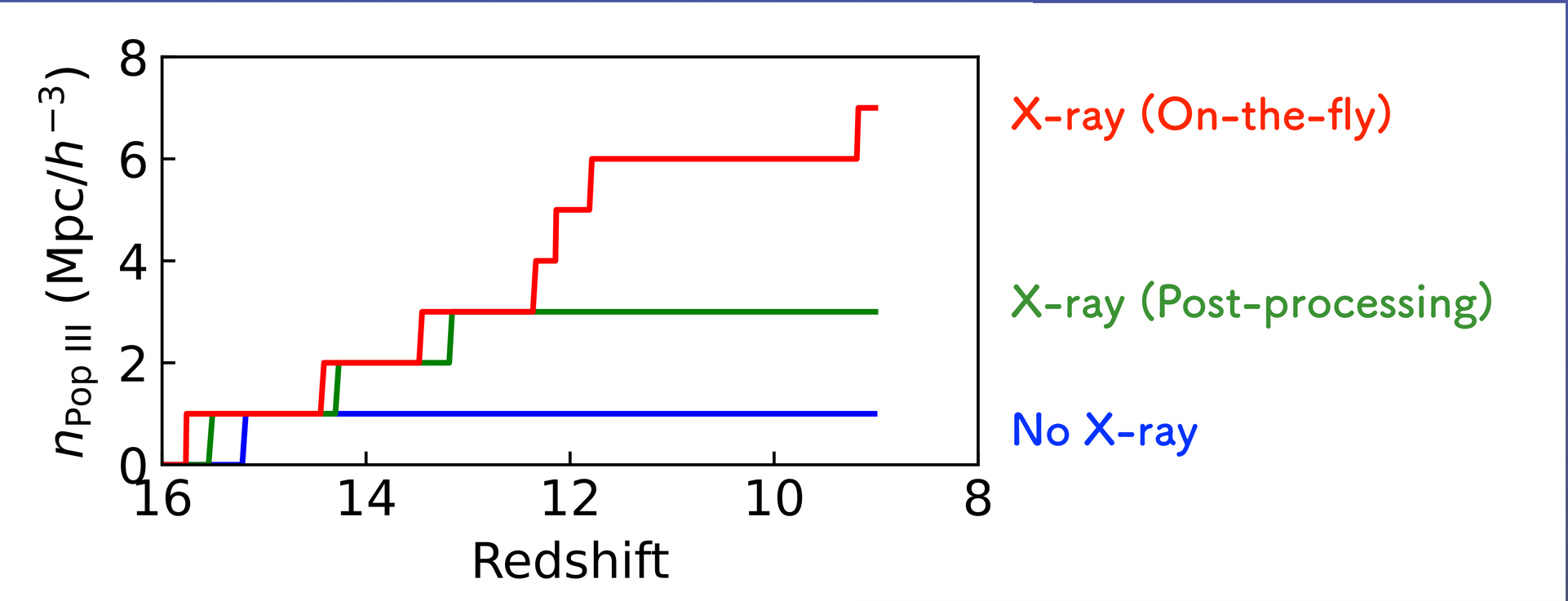
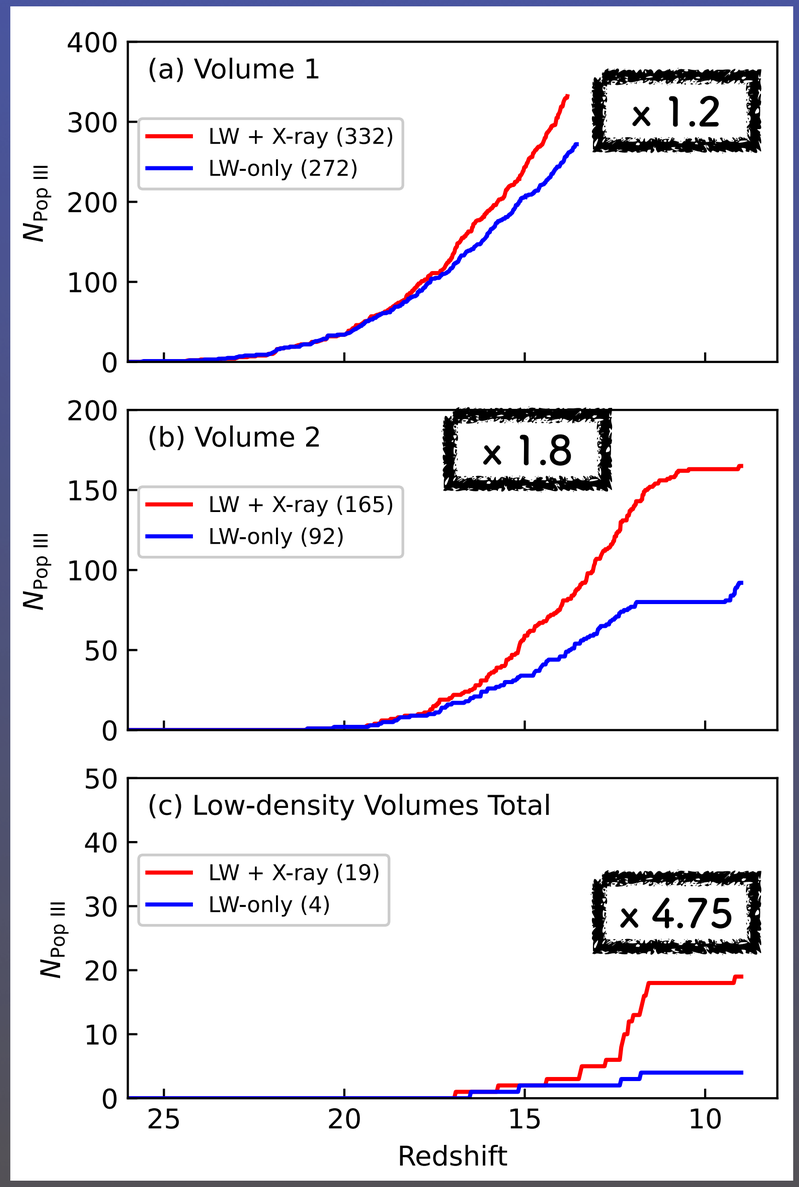


- A more intense X-ray background is produced with the on-the-fly method
- Positive X-ray feedback is more effective with the on-the-fly method

Result II: Environmental Effects

- X-rays enhance Pop III star formation

- Pop III formation enhancement varies across environment
  - over-density region: ~1.2
  - mean-density region: ~1.8
  - under-dense regions: ~ 4

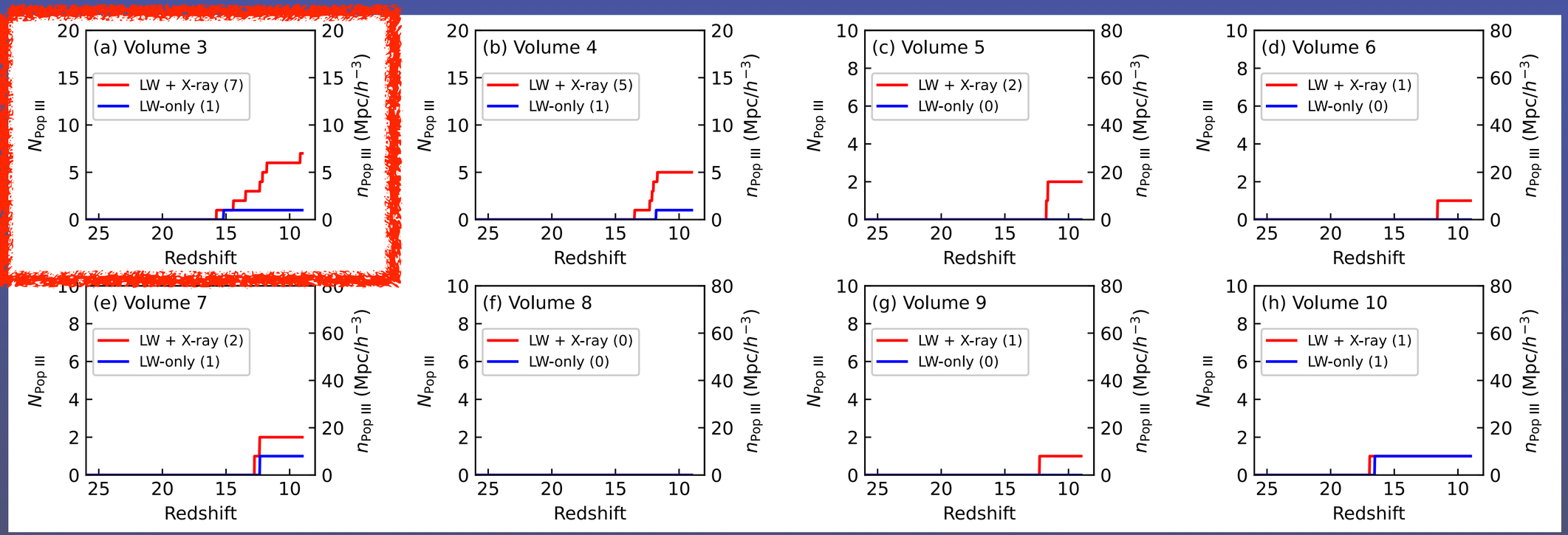


over-dense region

mean-density region

under-dense regions

Result II: Environmental Effects



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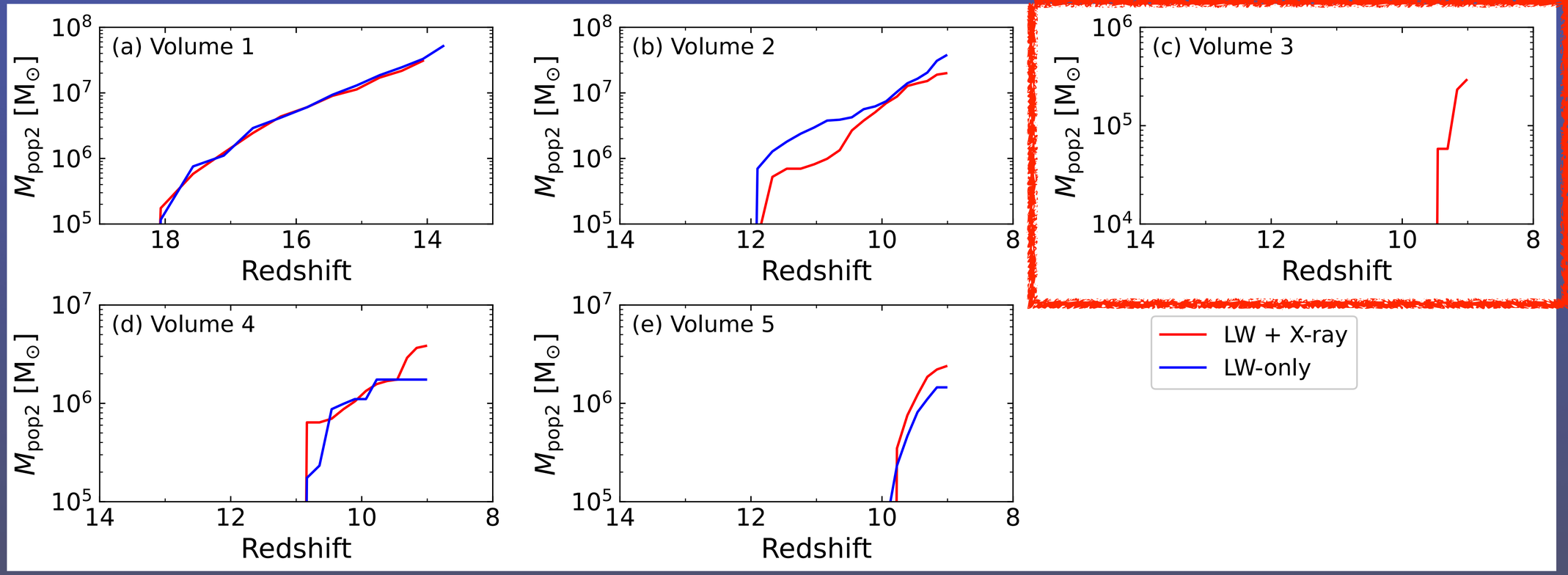

- Enhanced Pop III star formation
  - increases Pop II stellar masses
  - increases gas-phase metallicity

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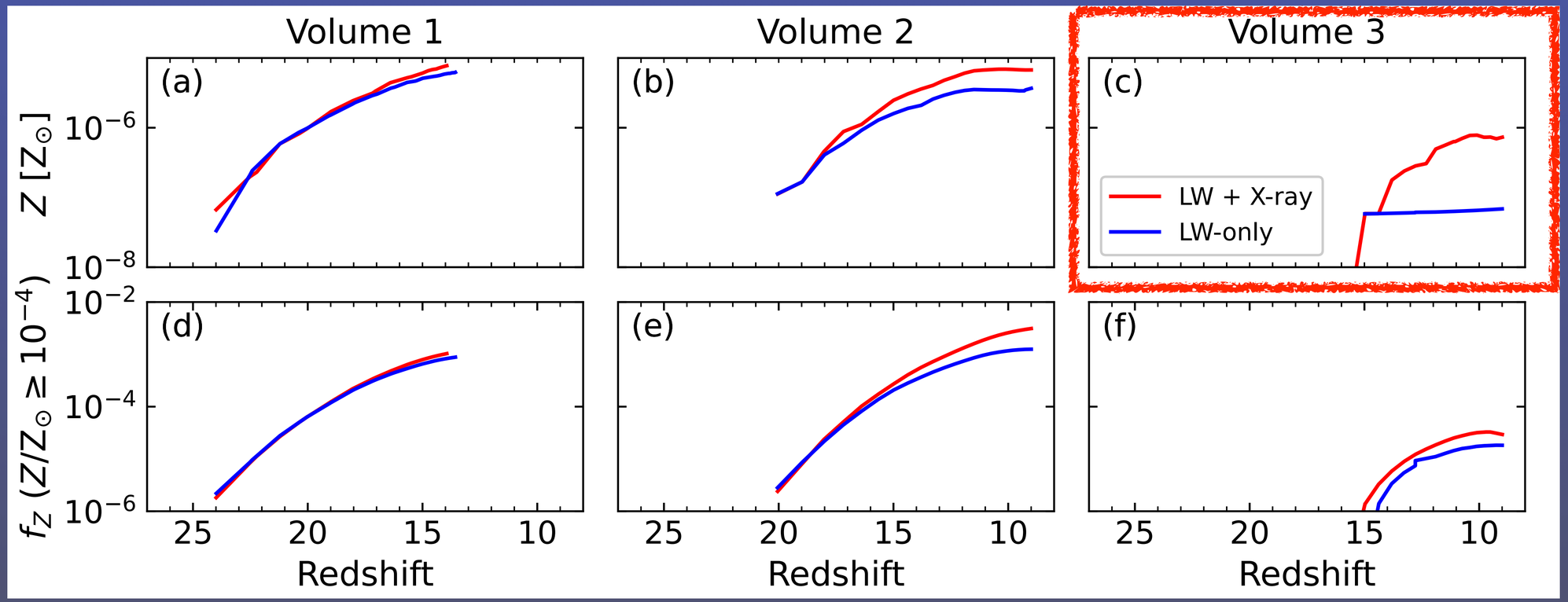

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Implication: Galaxy Formation

- Pop III formation enhancement varies across environment
  - over-density region: ~1.2
  - mean-density region: ~1.8
  - under-dense regions: ~3-4

- X-rays may affect the stellar mass and chemical properties of dwarf galaxies

Future Works

- X-rays from various sources
  - Pop III supernovae
  - AGN, HMXB……

- Formation of low-metallicity stars in X-rays
  - Carbon, Oxygen, Iron

- Indirect impacts of X-rays on galaxy formation
  - mechanical feedback - Kimm+ 2015
  - bursty star formation - Sugimura+ 2024, Kang+ 2025

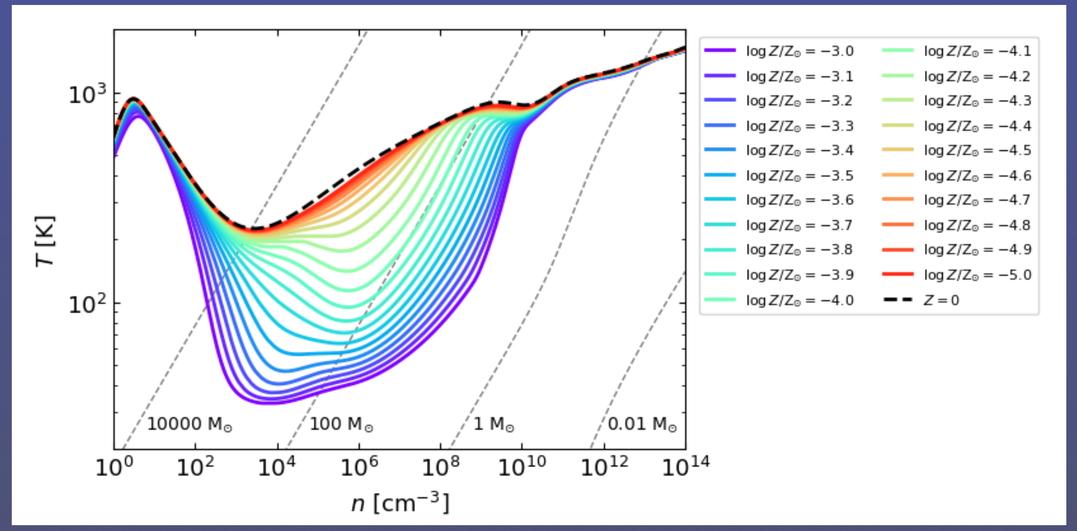
Summary

- We develop a method to approximate an X-ray radiation background considering feedback loop

- Pop III star formation is promoted by an X-ray background
  - stronger X-ray feedback w/ on-the-fly
  - X-ray feedback effective in low-density environments
  - Enhanced Pop III star formation increases Pop II stellar masses and gas-phase metallicity in low-density environment

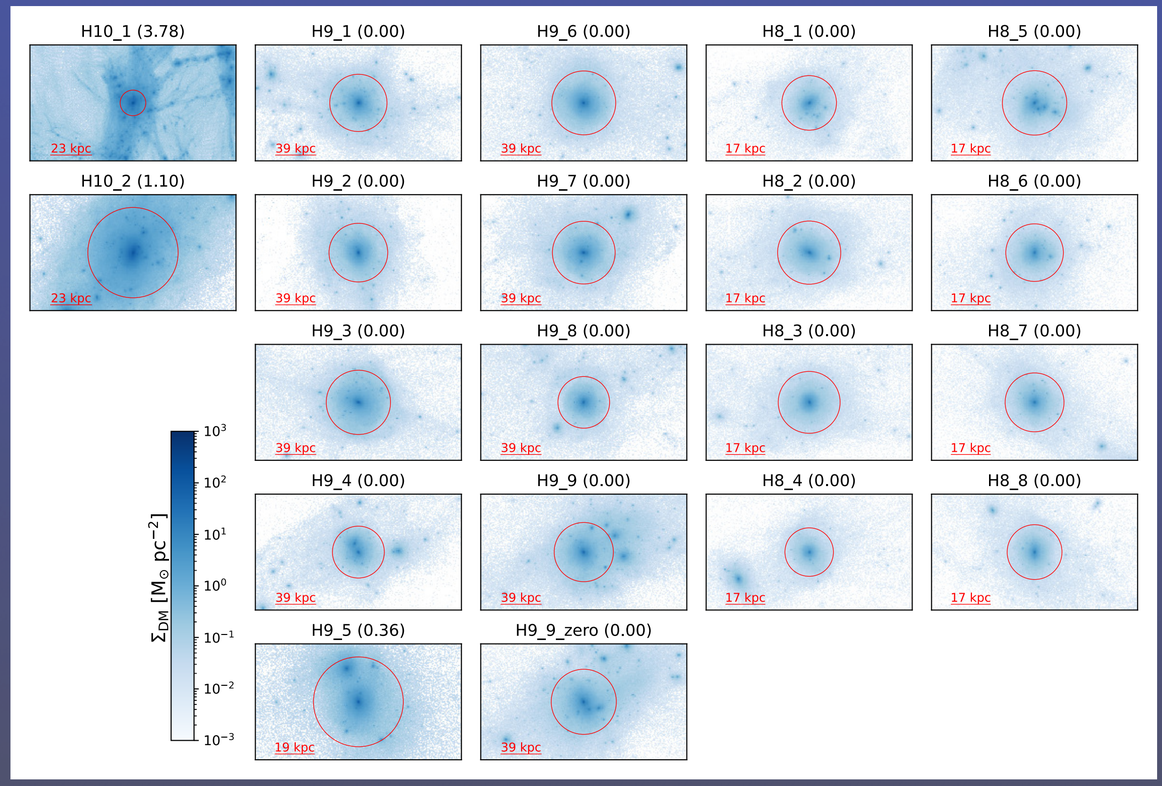
Other Projects w Ramses

PRISM+



- H_2O and OH
- escape probability of fine-structure line emissions
- primordial chemistry (Park, Ricotti & Sugimura 2021)
- higher density physics (n ~ 10^{18} cm^{-3})

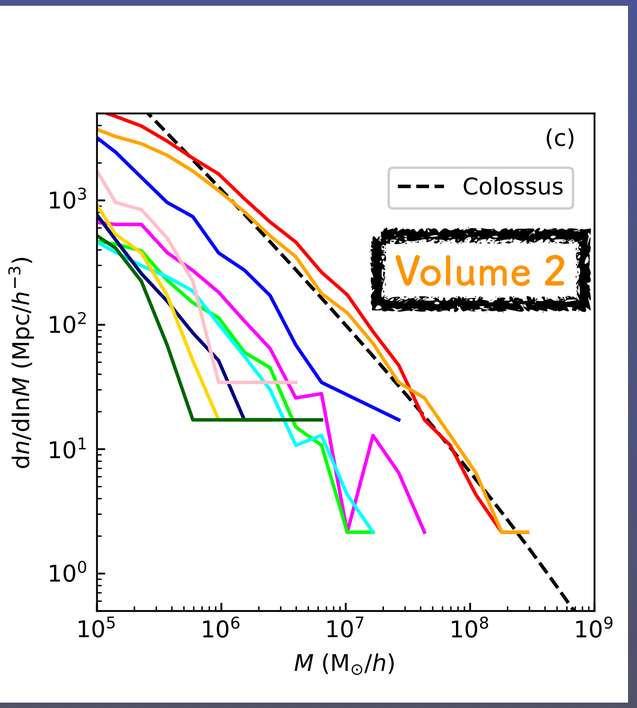
Darwin-3

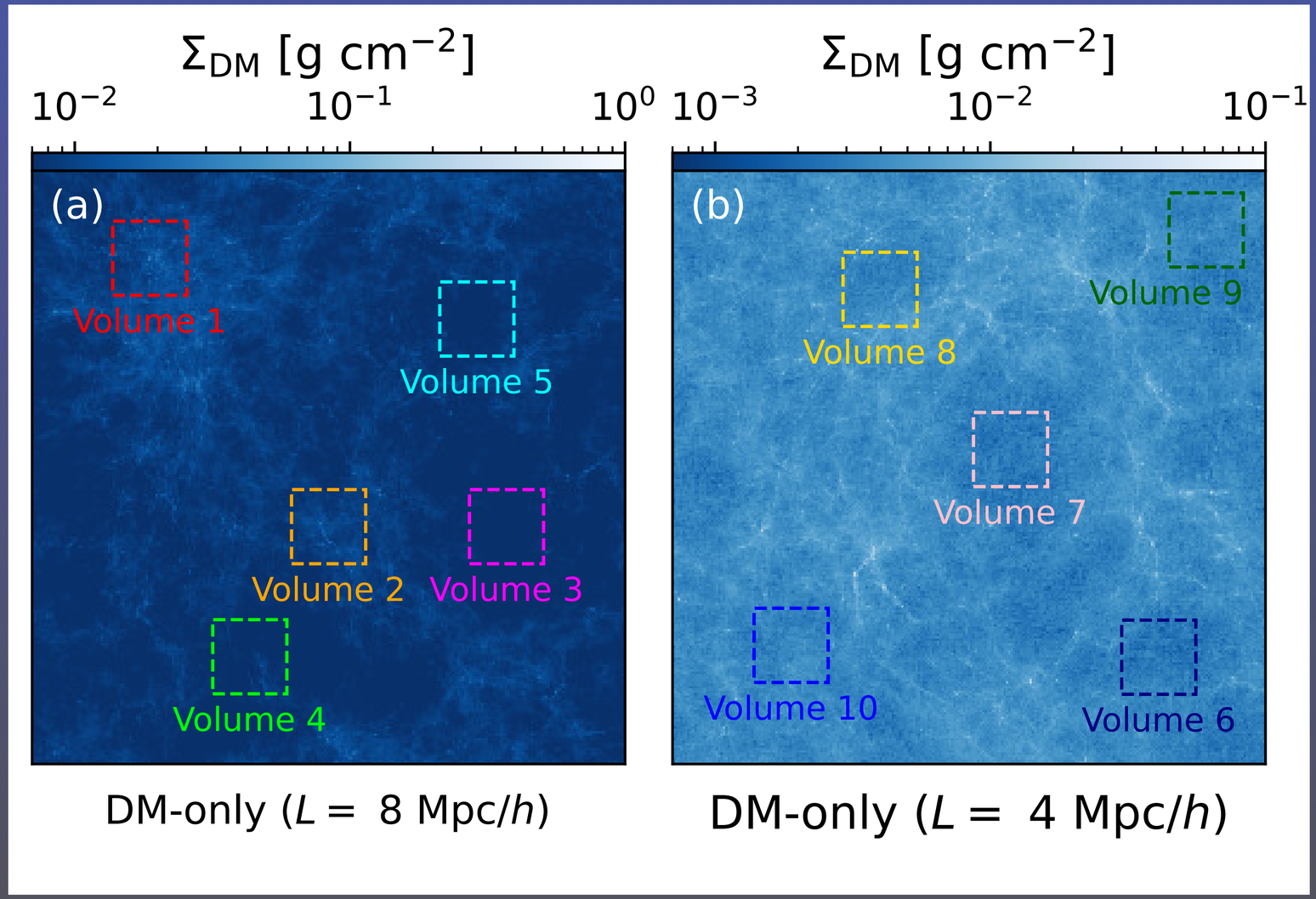


- ~20 simulations of dwarf galaxies
- physics-rich + high-resolution (~ 4 pc) RHD
- Darwin-1 and Darwin-2
- Kyungwon's talk

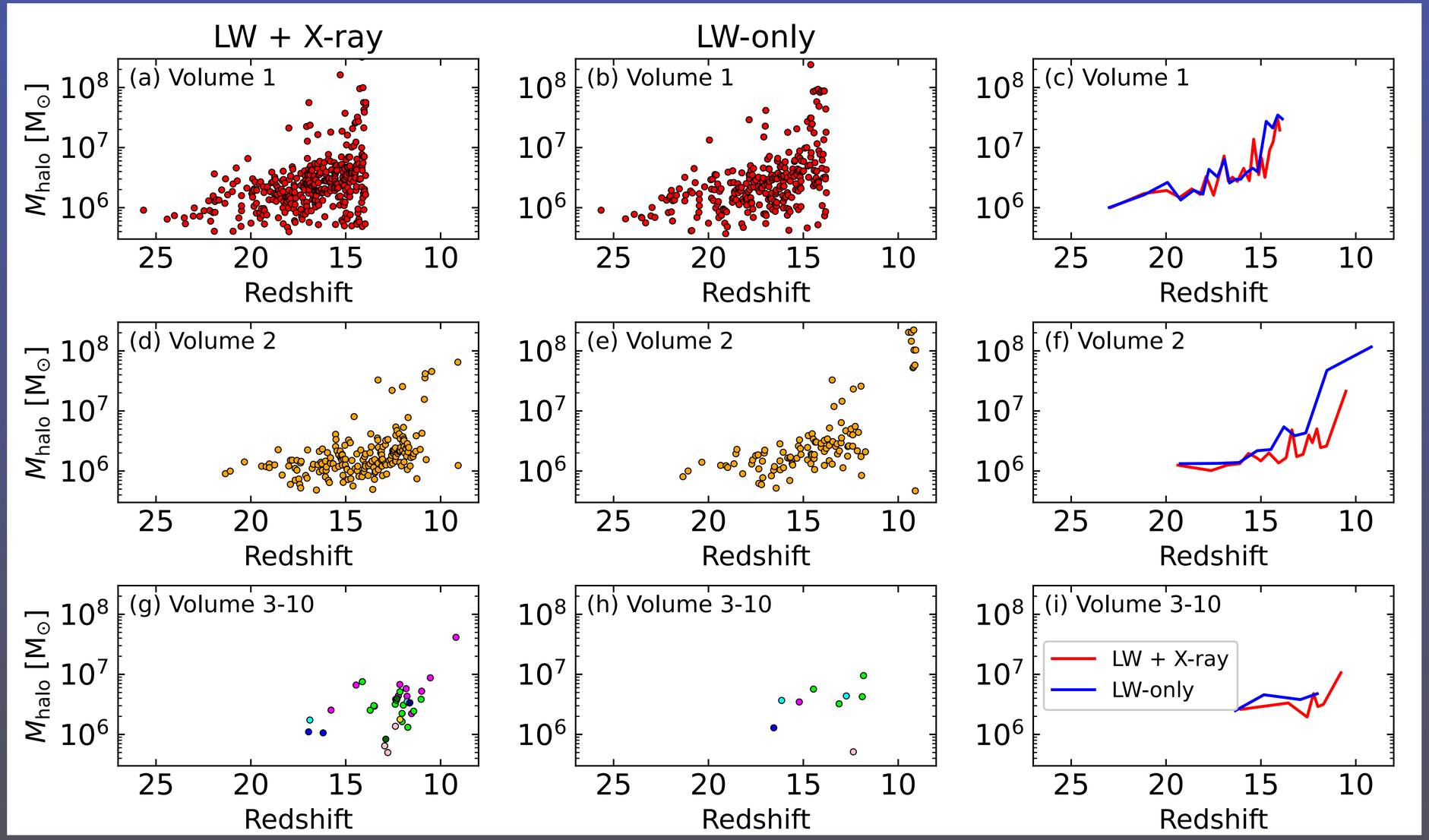
Backup Slides

On-the-fly Calculation of X-rays

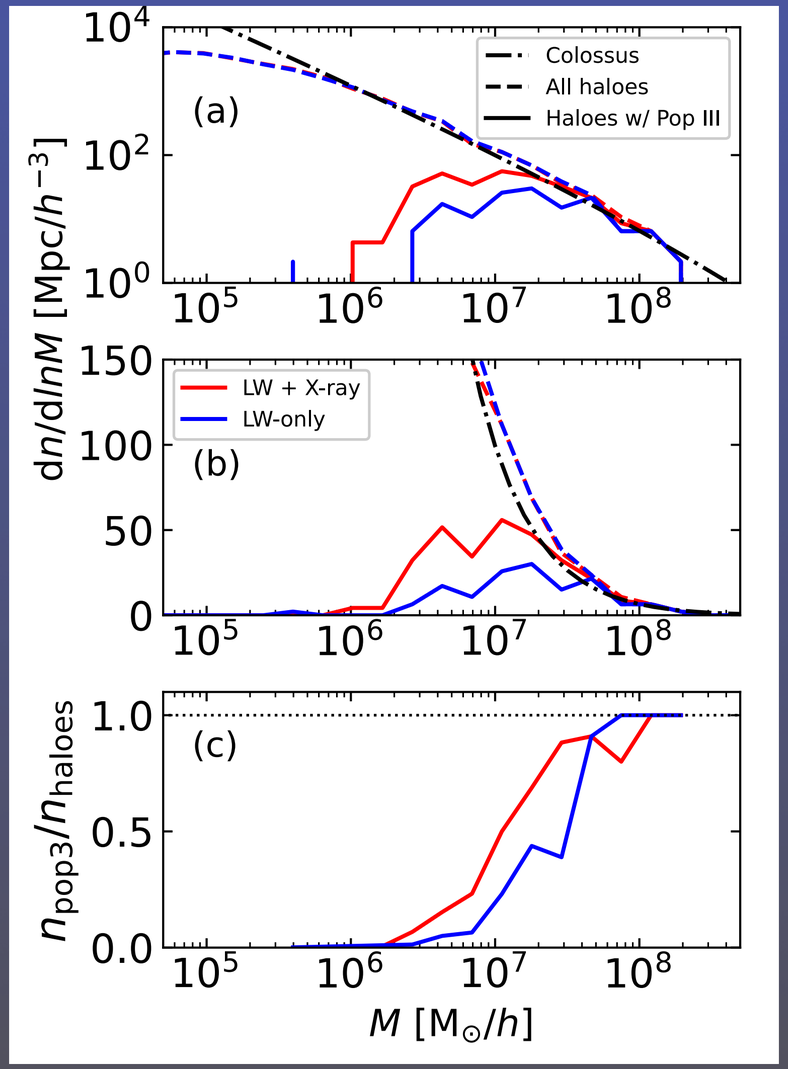




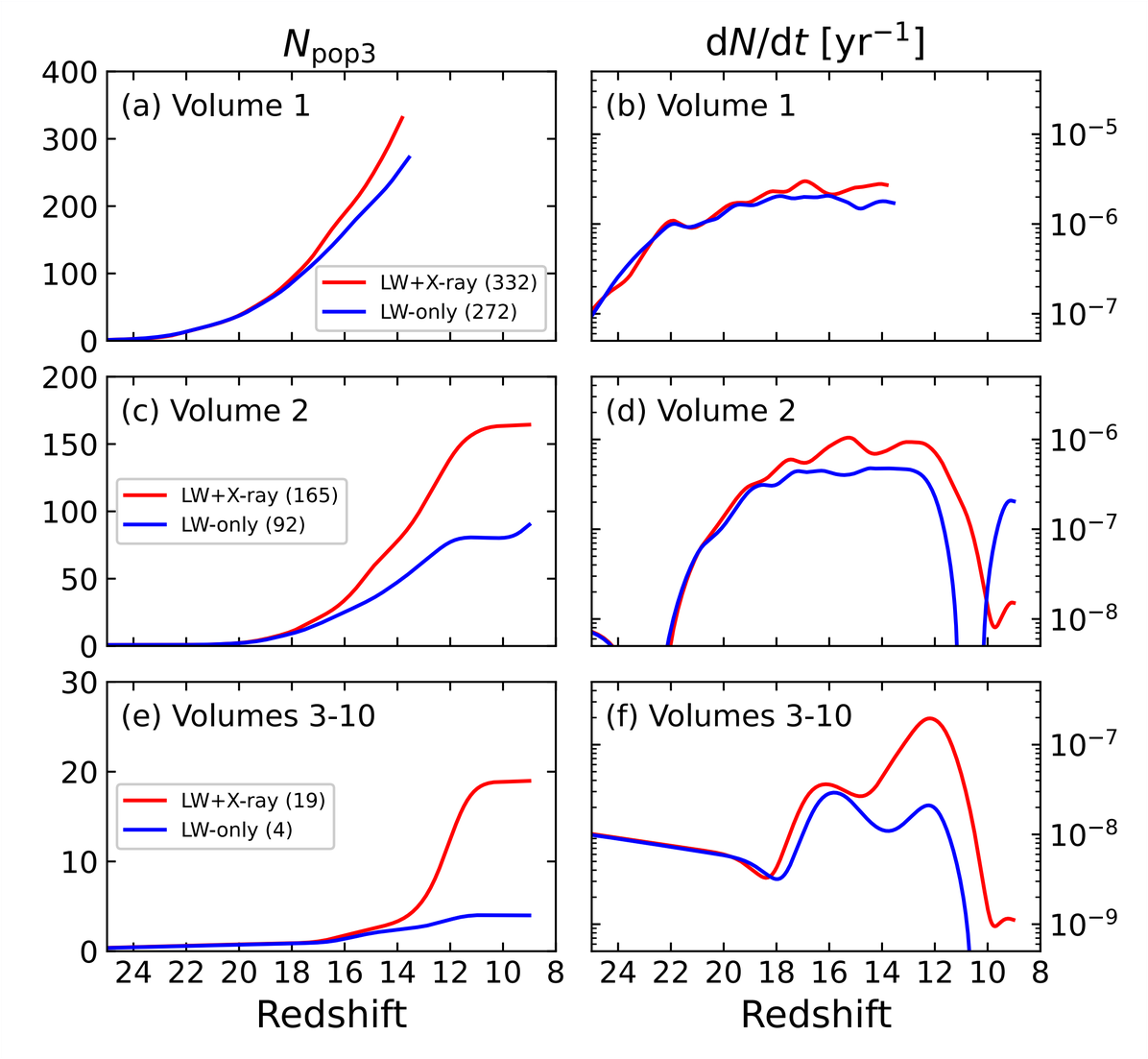
Halo Mass of Pop III Star Formation



Mass Functions of Pop III-Forming Halos



X-ray Positive Feedback



Effect of Local UV Feedback