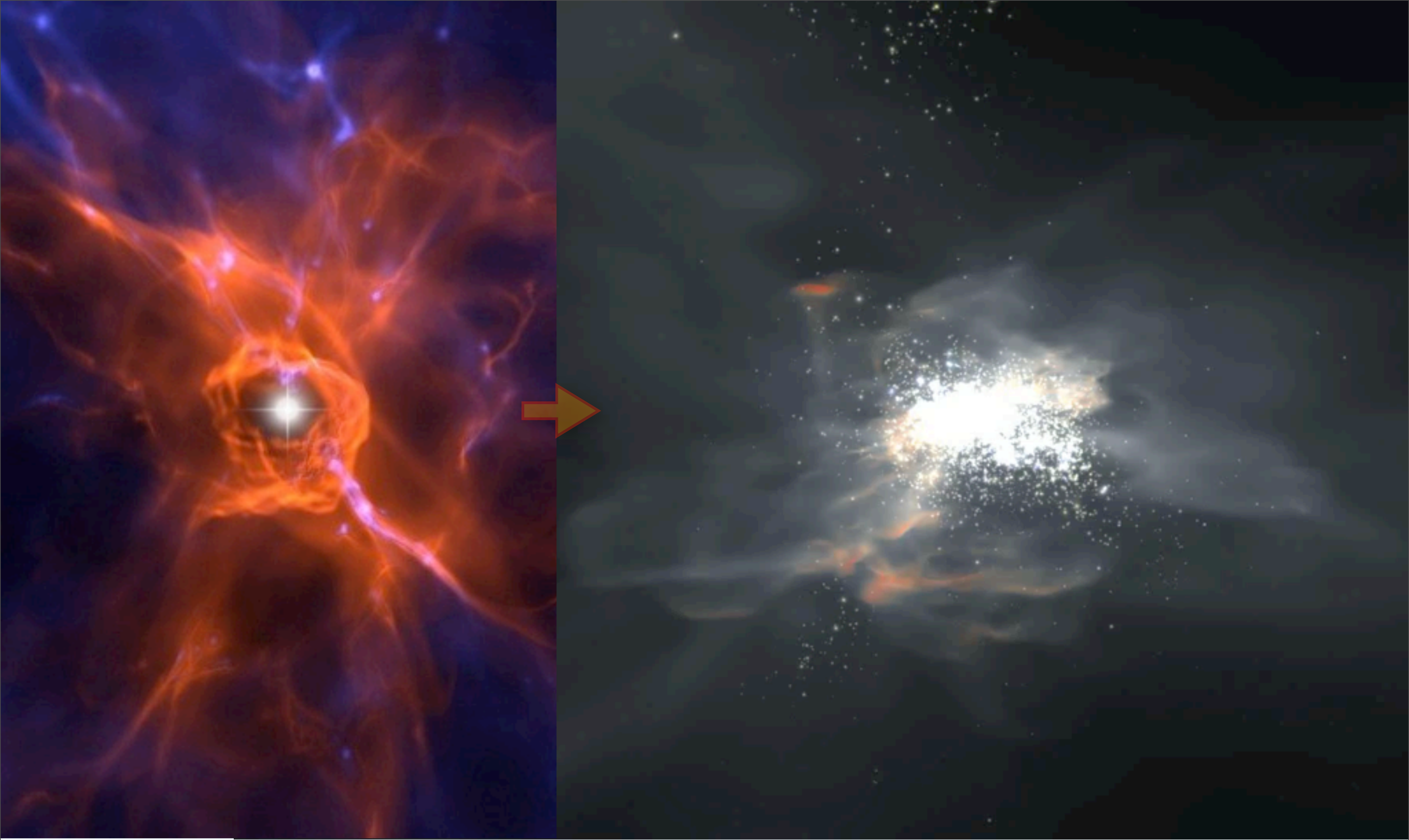
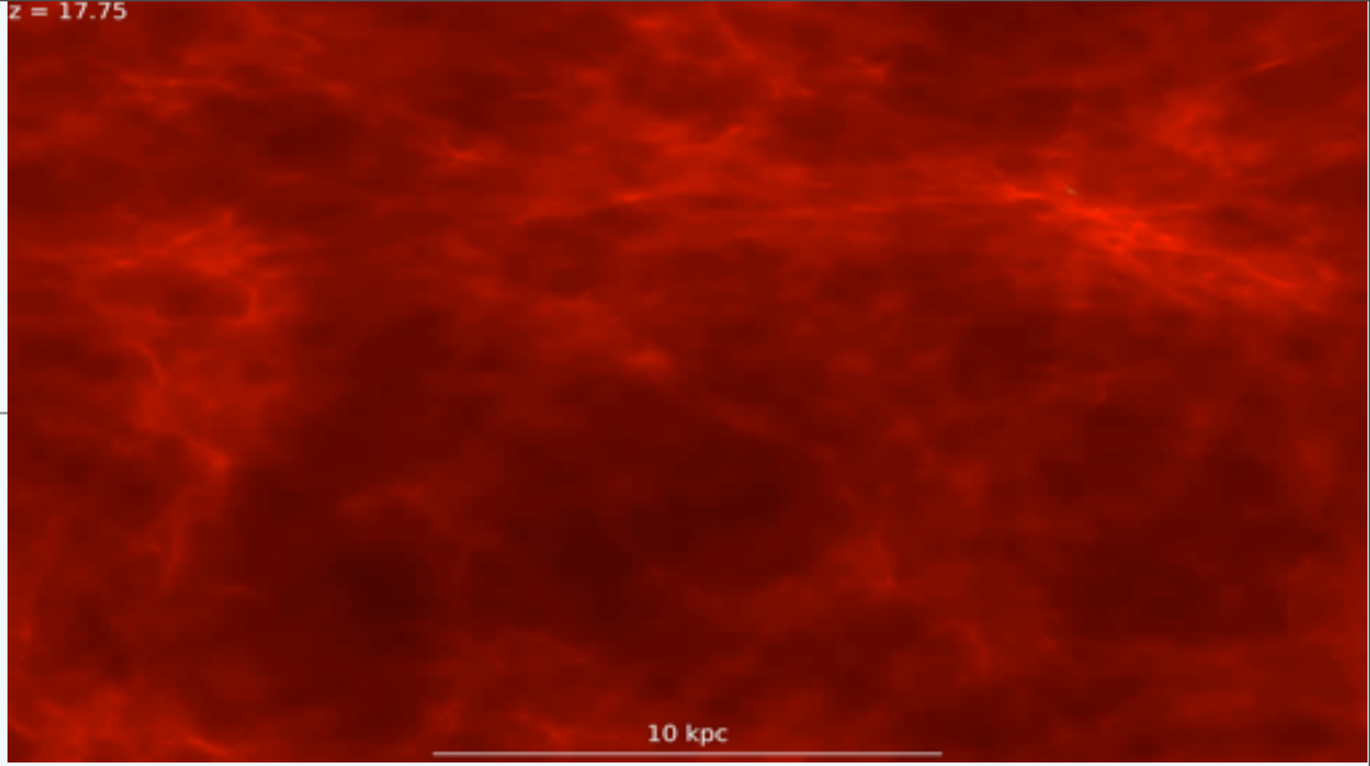


The First Stars
Black Hole Seeds

John Wise
Georgia Tech

Tom Abel (Stanford), Marcelo Alvarez (CITA), Michael Norman (UCSD), Chao Shi (GT), Matthew Turk (Columbia), Hao Xu (UCSD)

Outline



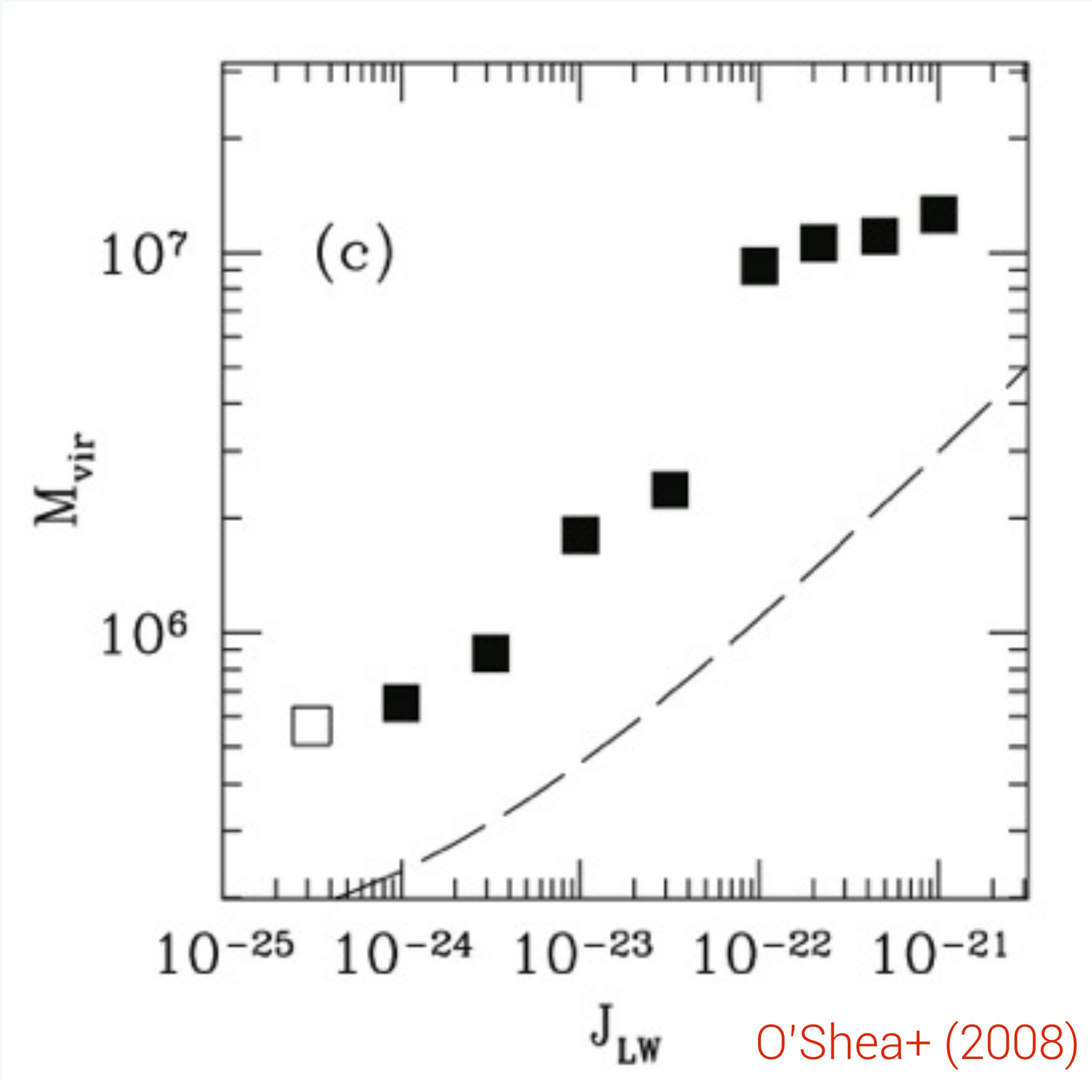
- **Overview of Pop III characteristics**
- **A single BH seed:**
    - A study on the importance of radiative feedback
    - Early mass accretion history in minihalos
- **BH seeds in the first galaxies:**
    - Spatial distributions (central or dispersed?)
    - Mean multiplicities

Population III Stars
Formation

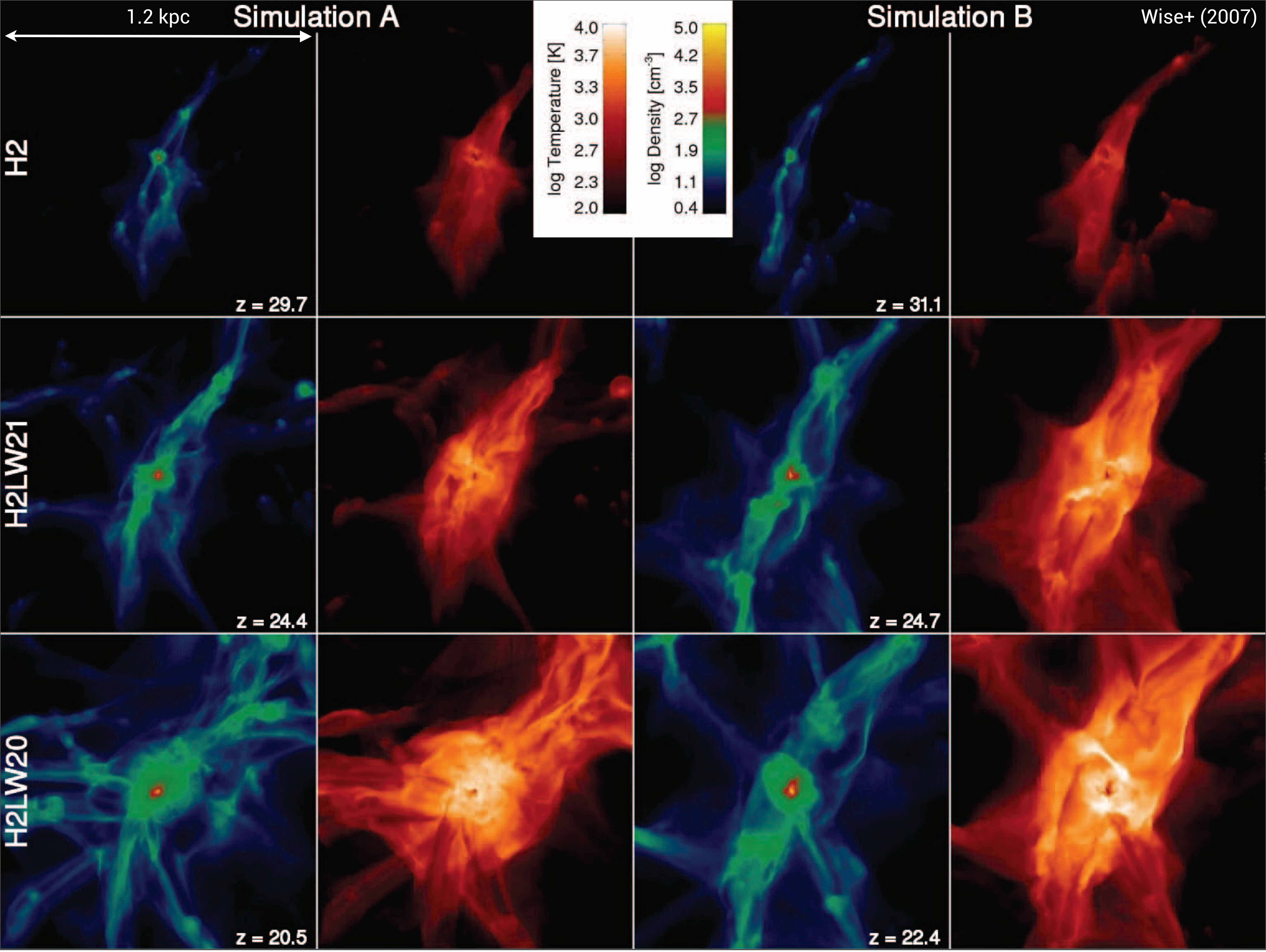
- Metal-free star formation primarily rely on H_2 cooling in the gas phase.

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma$$
$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^-$$

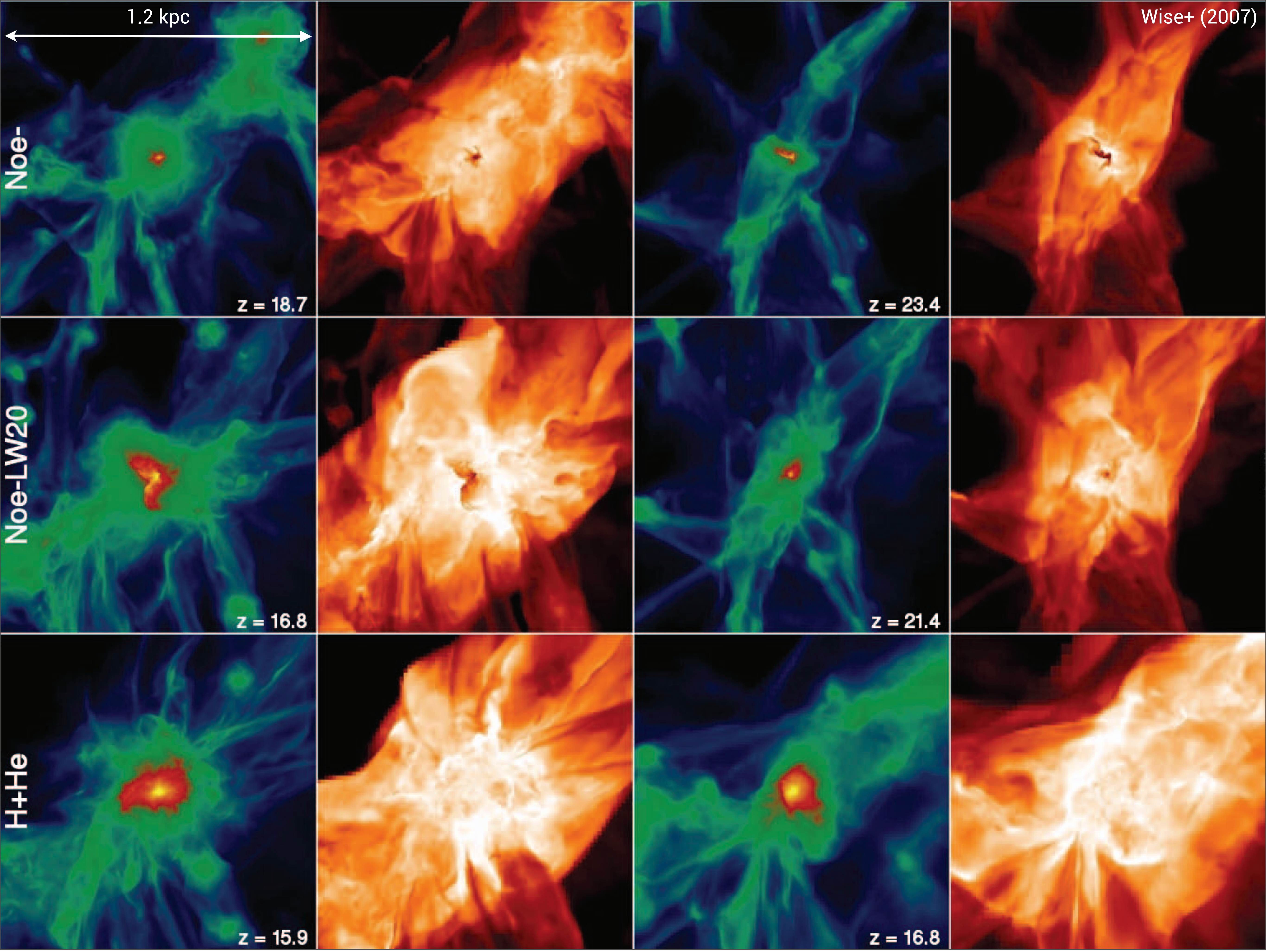
- Form in DM halos with masses $10^{5\text{-}7}\ M_\odot$ at $z \geq 5$, depending on H_2 dissociating radiation background.



O'Shea+ (2008)



1.2 kpc
Simulation A
Simulation B
Wise+ (2007)
log Temperature [K]
4.0
3.7
3.3
3.0
2.7
2.3
2.0
log Density [cm^{-3}]
5.0
4.2
3.5
2.7
1.9
1.1
0.4
H2
H2LW21
H2LW20
z = 29.7
z = 31.1
z = 24.4
z = 24.7
z = 20.5
z = 22.4

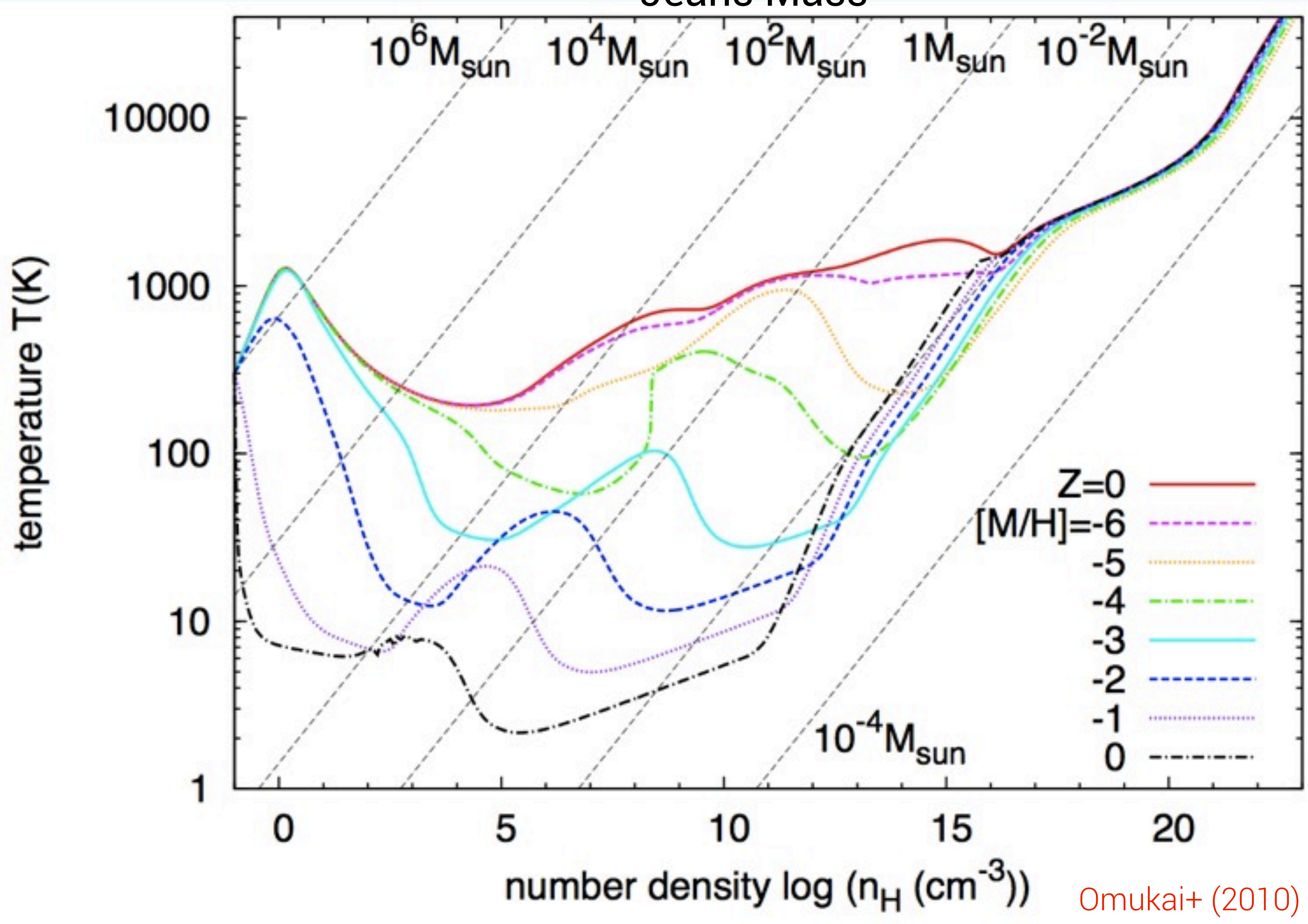


1.2 kpc
Wise+ (2007)
Noe-
Noe-LW20
H+He
z = 18.7
z = 23.4
z = 16.8
z = 21.4
z = 15.9
z = 16.8

Population III Stars
Formation

- Cooling efficient only down to ~300 K.
- Sets the Jeans mass of the central molecular cloud → 1000 $M_\odot$
- Some cores may fragment into multiple systems with stellar masses of **tens of $M_\odot$**

Jeans Mass

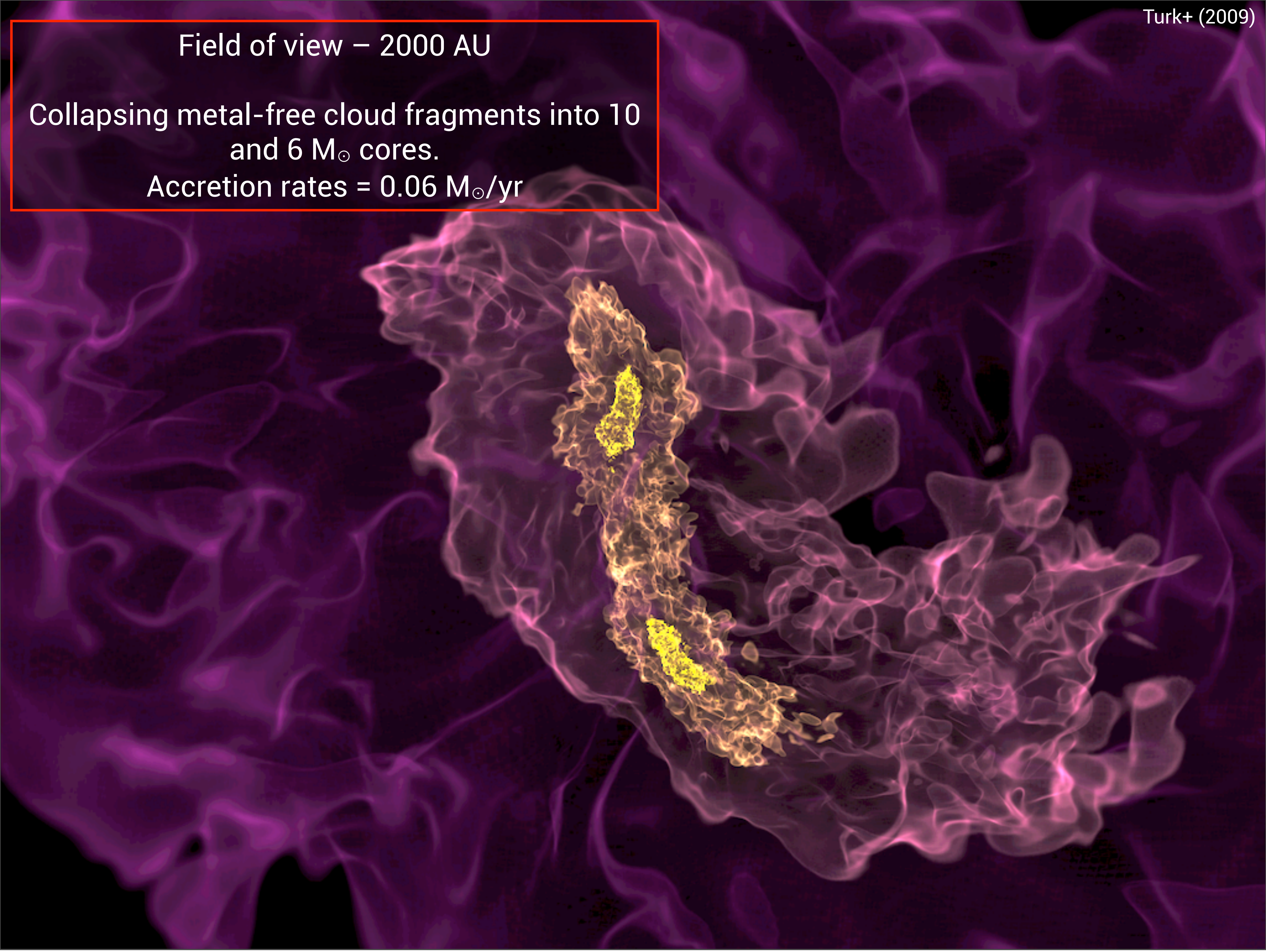


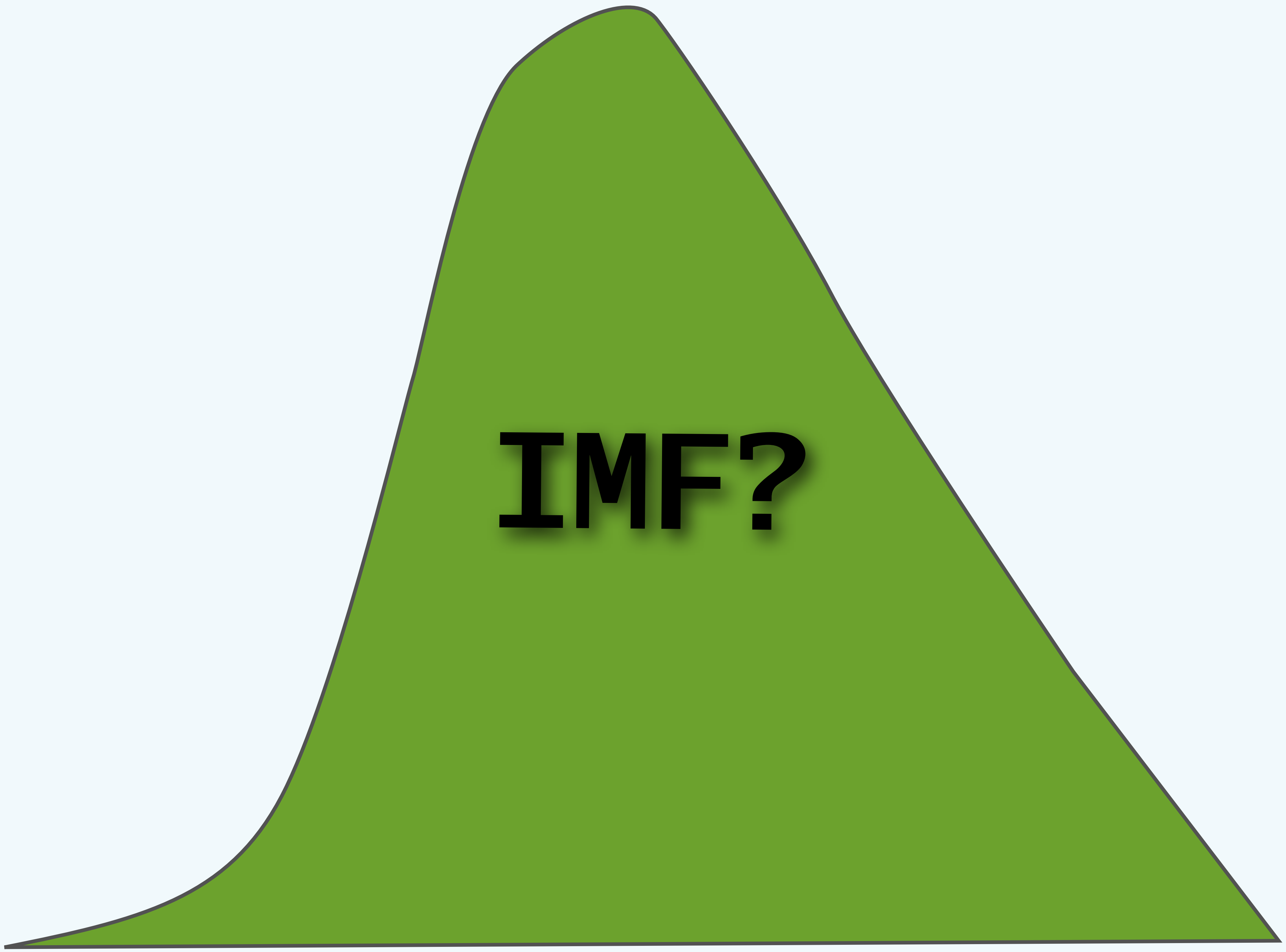
Omukai+ (2010)

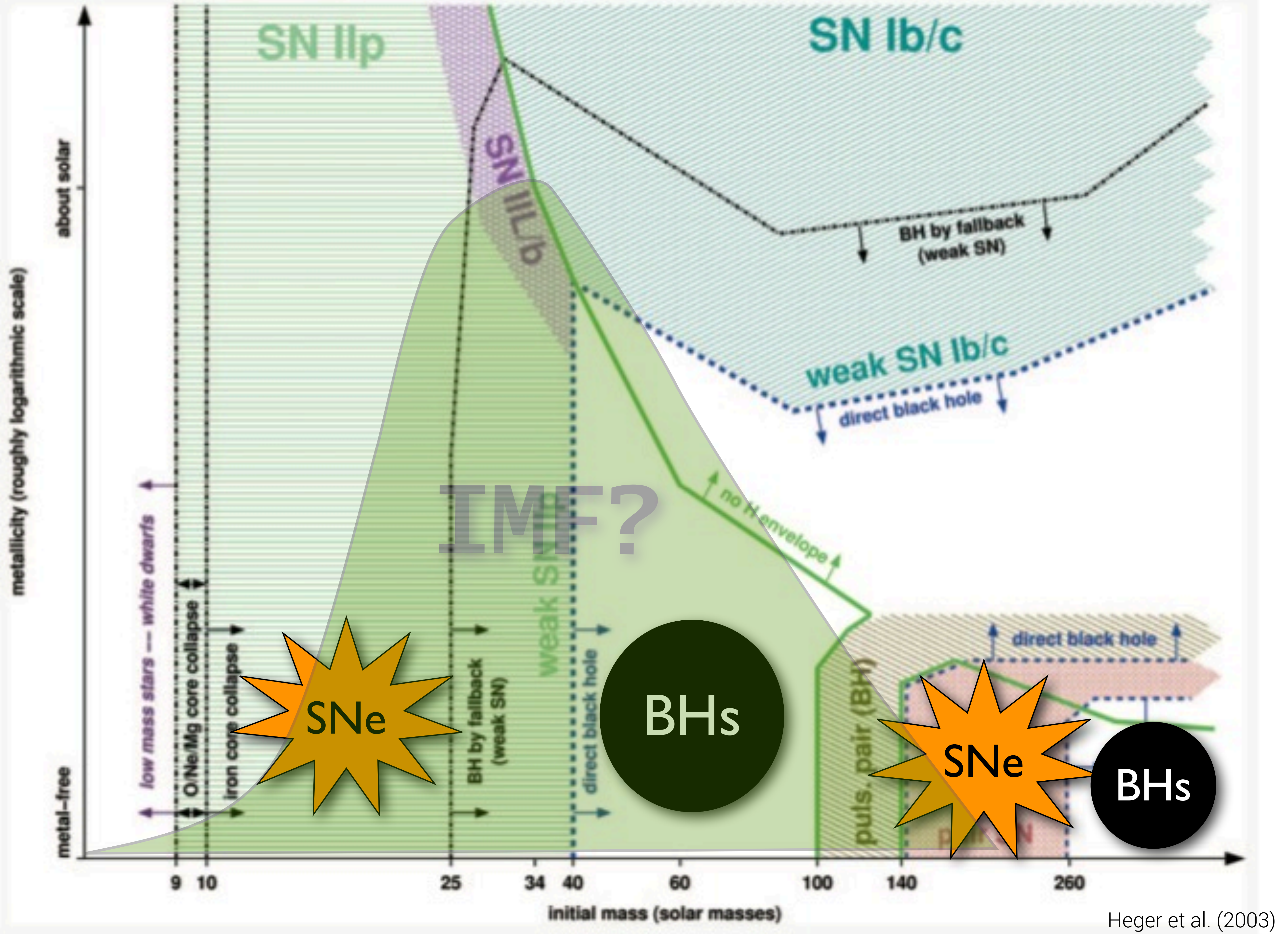
Field of view – 2000 AU

Collapsing metal-free cloud fragments into 10 and 6 $M_\odot$ cores.

Accretion rates = 0.06 $M_\odot$/yr




IMF?



Heger et al. (2003)

Abel+ (2007)

Population III Stars
Main Sequence – Radiative Feedback

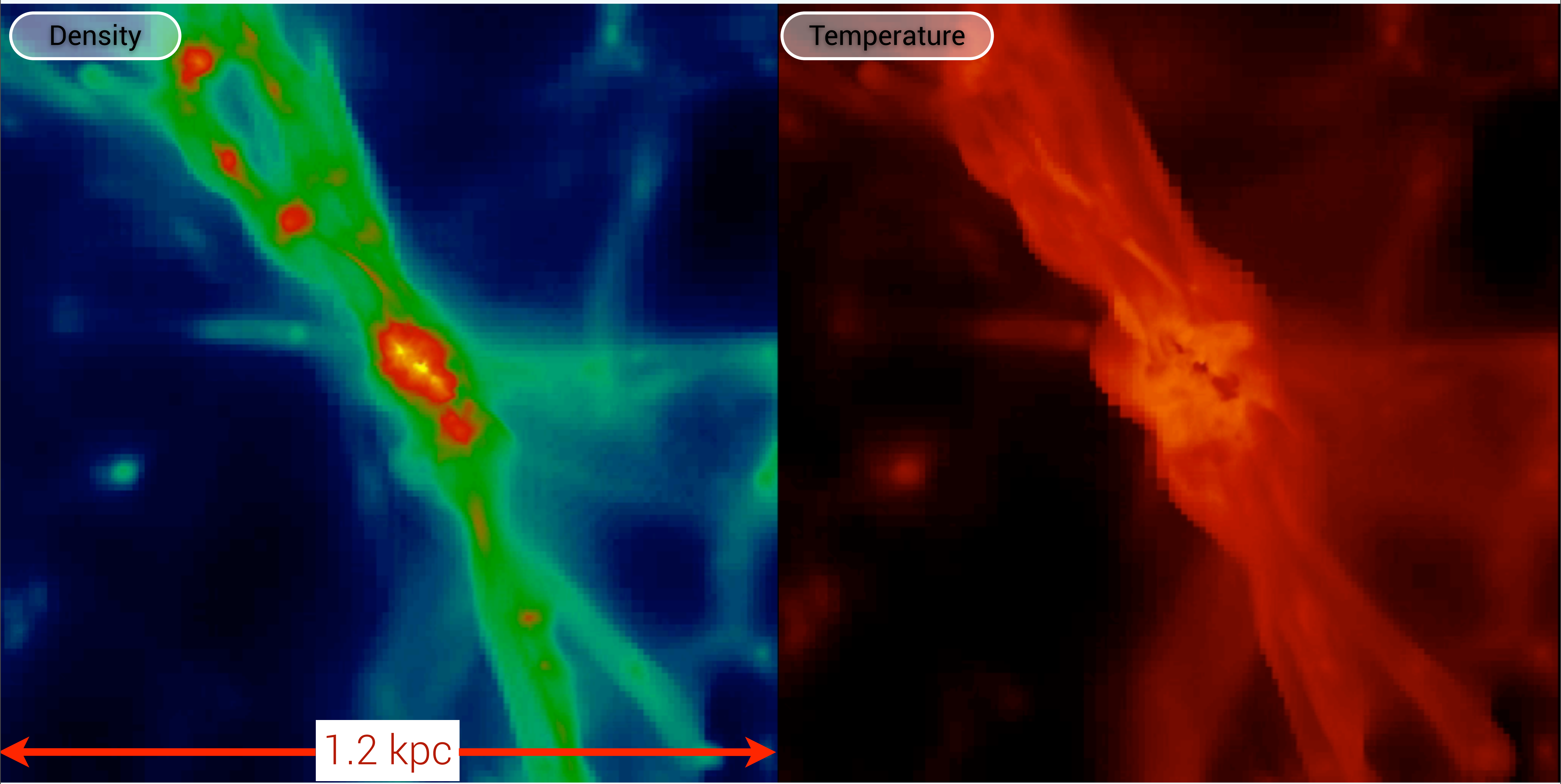
Density

Temperature

1.2 kpc

- 10^6 $M_\odot$ DM halo; z = 17; single 100 $M_\odot$ star (no SN)
- Drives a 30 km/s shock wave, expelling most of the gas

Population III Stars
Main Sequence – Radiative Feedback



- 10^6 $M_\odot$ DM halo; z = 17; single 100 $M_\odot$ star (no SN)
- Drives a 30 km/s shock wave, expelling most of the gas

Accretion onto a Single Seed BH

Alvarez+ (2009)

Accretion onto a Single BH
Effects of X-ray Radiative Feedback

Density | Temperature

- Focus on BH accretion and radiation after main sequence in a 5×10^5 $M_\odot$ halo for 200 Myr.
- Initial BH mass = 100 $M_\odot$
- Assume Bondi-Hoyle accretion. Simulation resolves the Bondi radius.
- <1 $M_\odot$ of accretion as the halo grows by a factor of 10.

No Feedback

Feedback

Field of view = 7 kpc (inset: 300 pc)
$z = 17 \rightarrow 11$

Accretion onto a Single BH
Effects of X-ray Radiative Feedback

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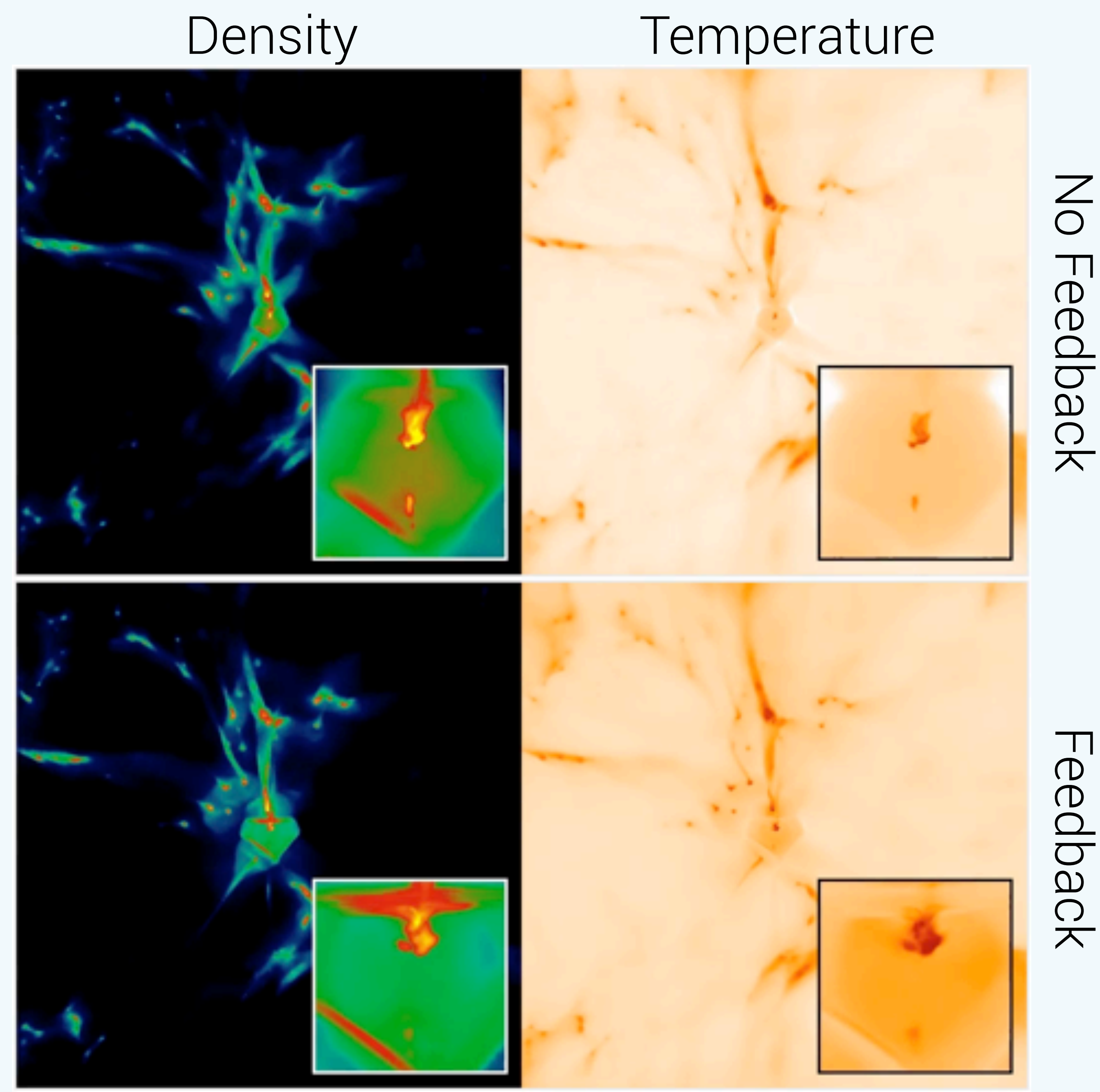
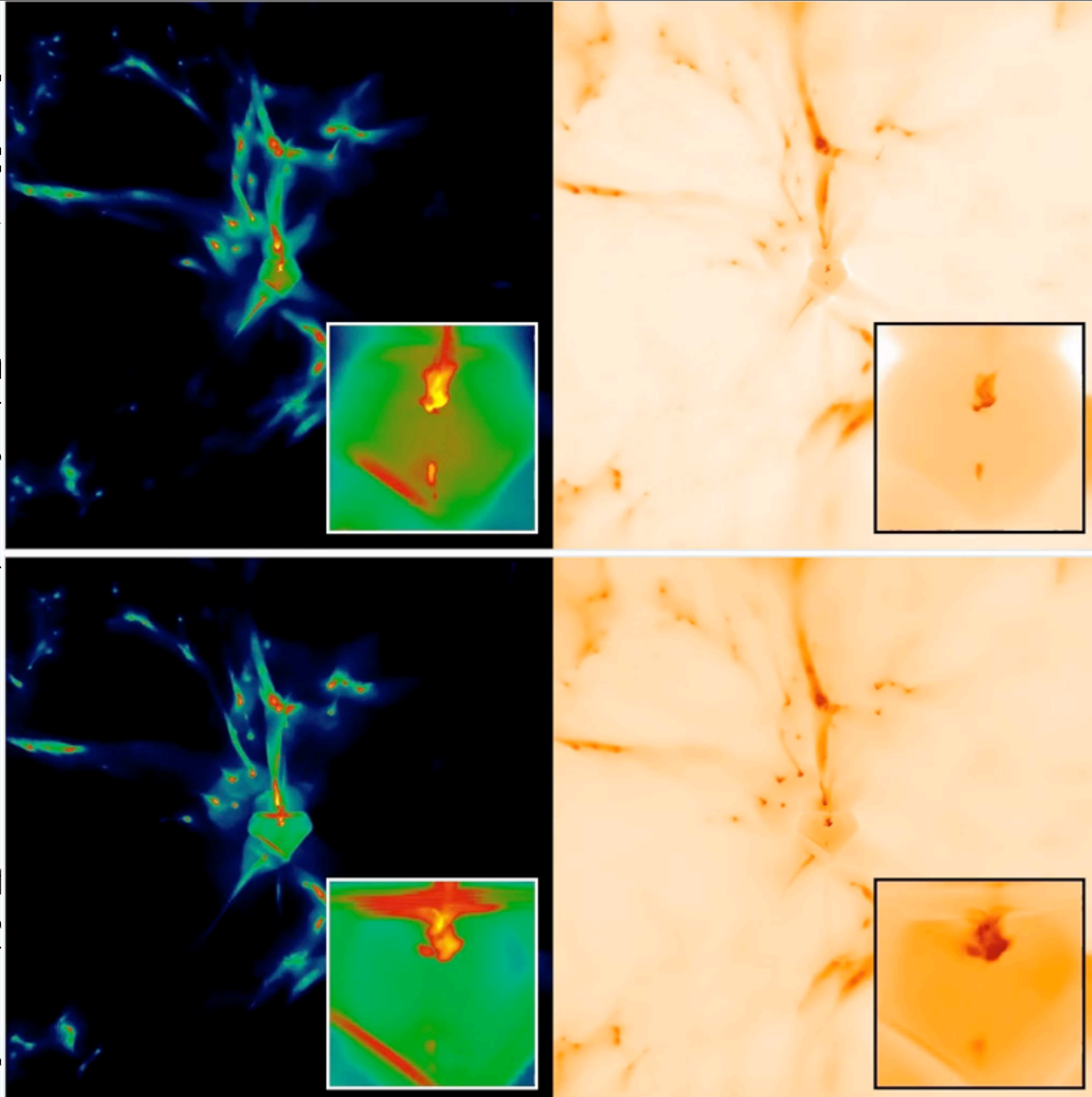


Field of view = 7 kpc (inset: 300 pc)
z = 17 → 11

Alvarez+ (2009)

Accr
Effec

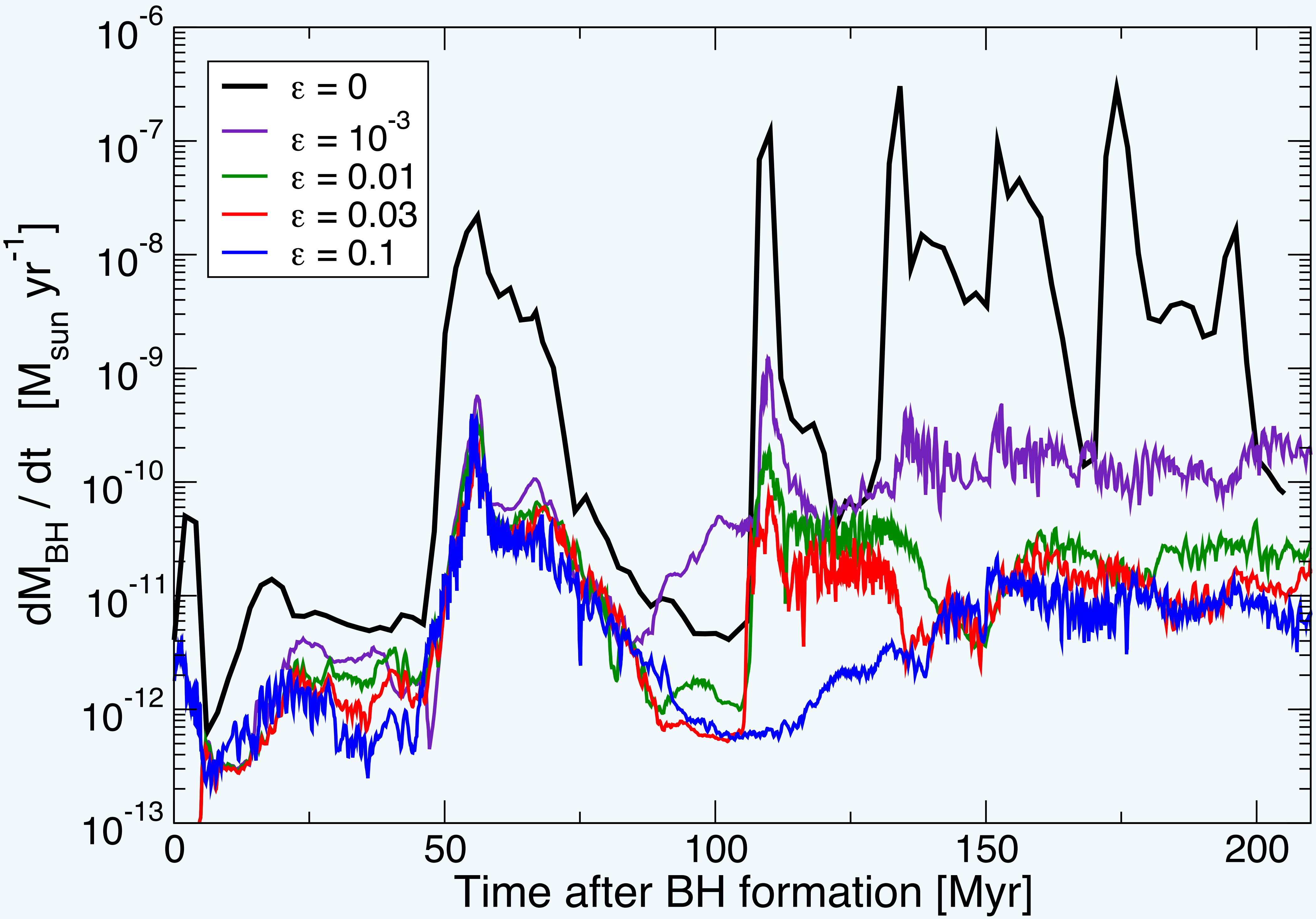


e

- Focus o
radiation
5 x 10^5 M
- Initial BH
- Assume
Simulati
radius.
- <1 M$_\odot$ of
grows by

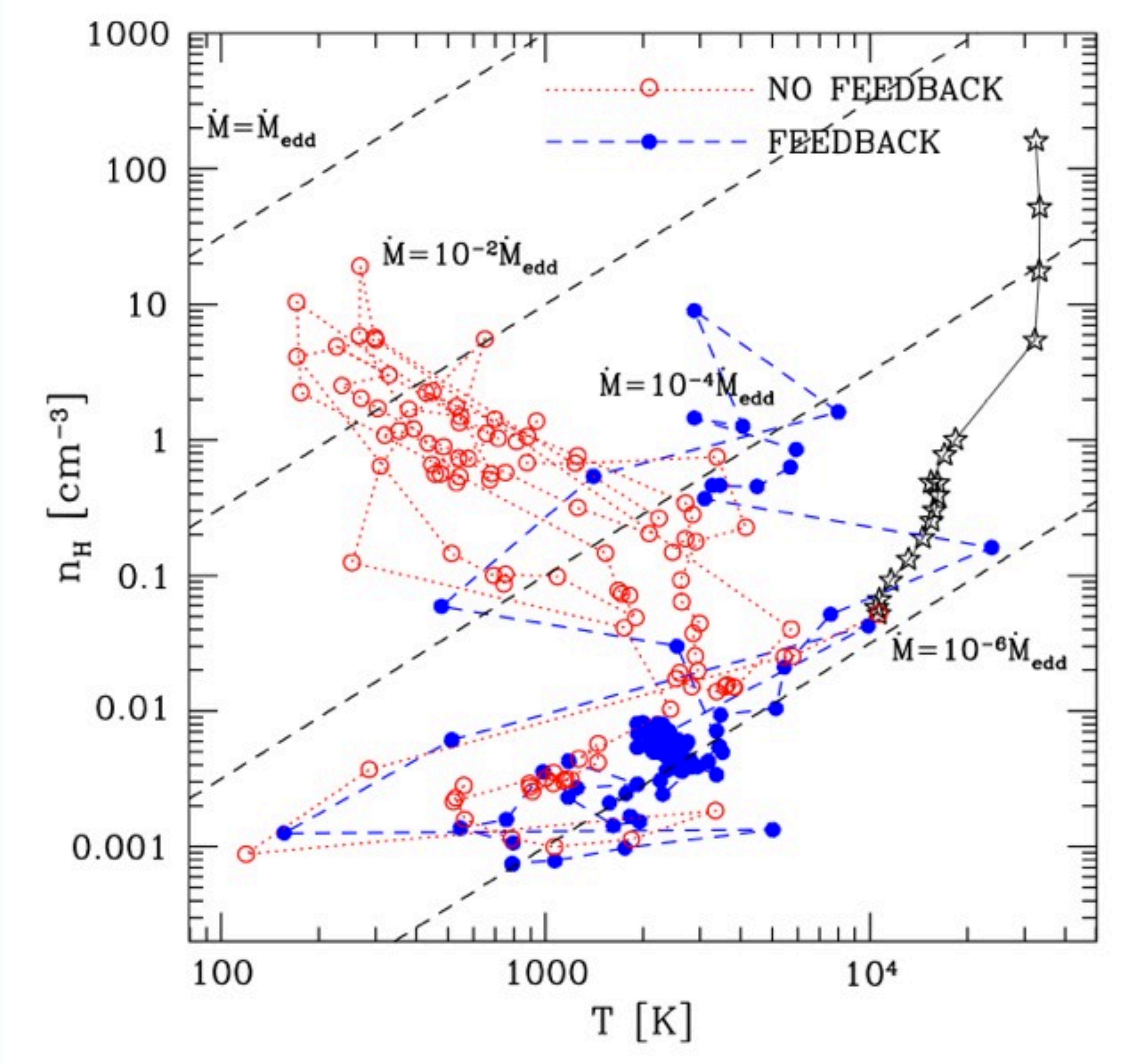
pc)

Accretion onto a Single BH
Effects of X-ray Radiative Feedback

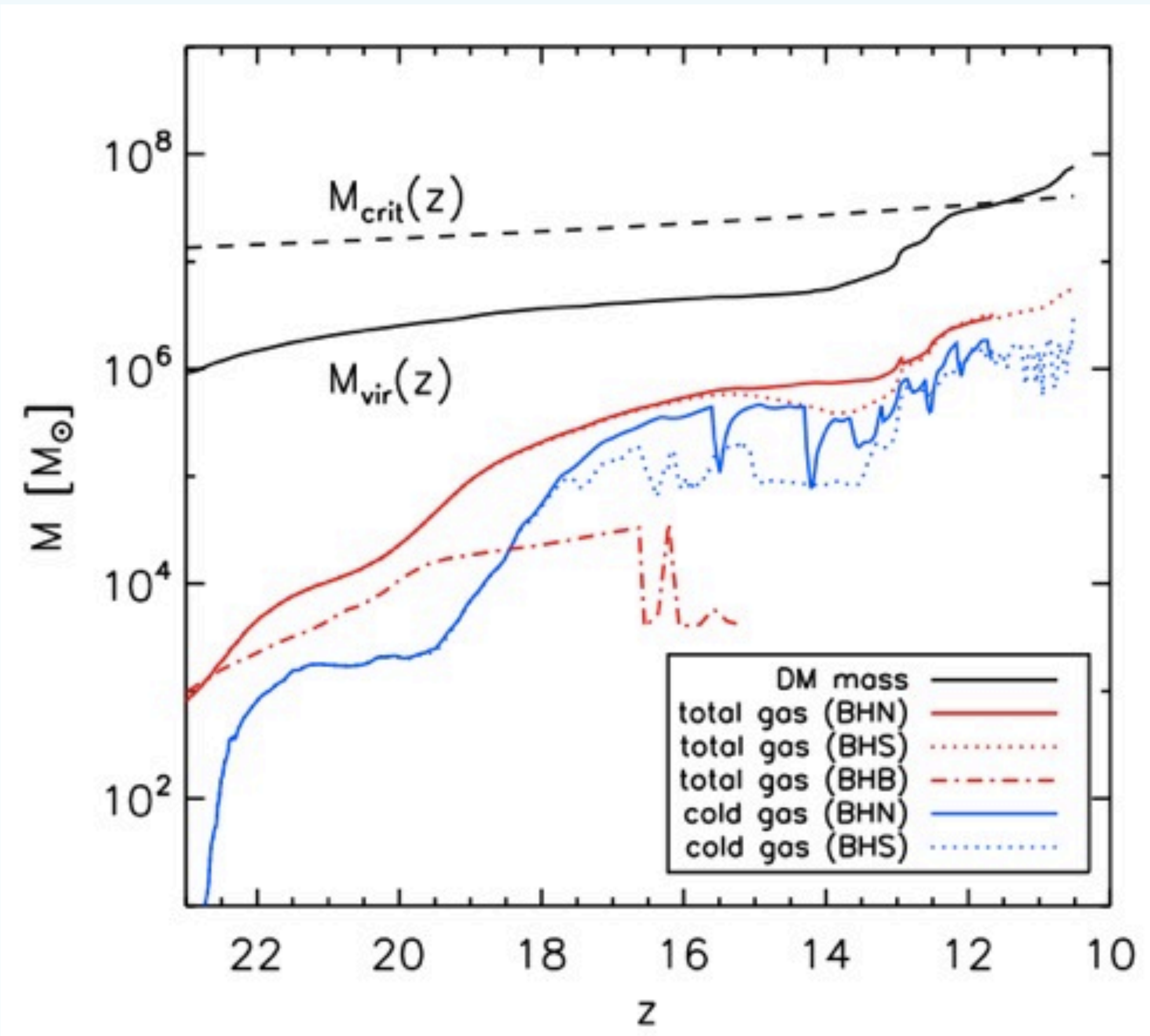


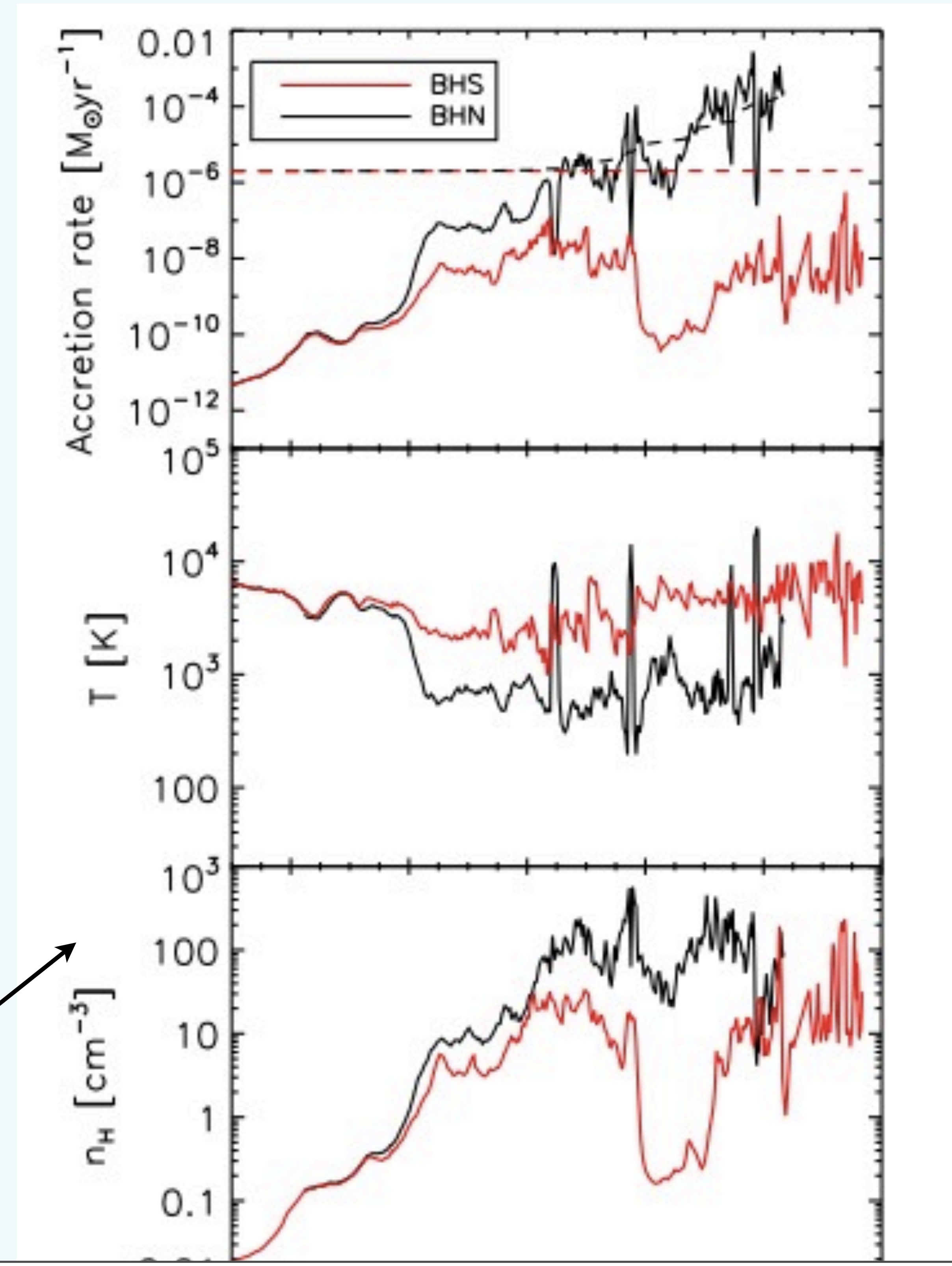
Accretion onto a Single BH
Effects of X-ray Radiative Feedback

- With radiative feedback, maximum accretion rates reach are reduced by a factor of 100–10^4 to 10^{-4} $(dM/dt)_{edd}$
- Only followed the evolution up to 5 x 10^6 $M_\odot$ halo.
- Is rapid accretion possible in atomic cooling halos?



Accretion onto a Single BH
Effects of X-ray Radiative Feedback

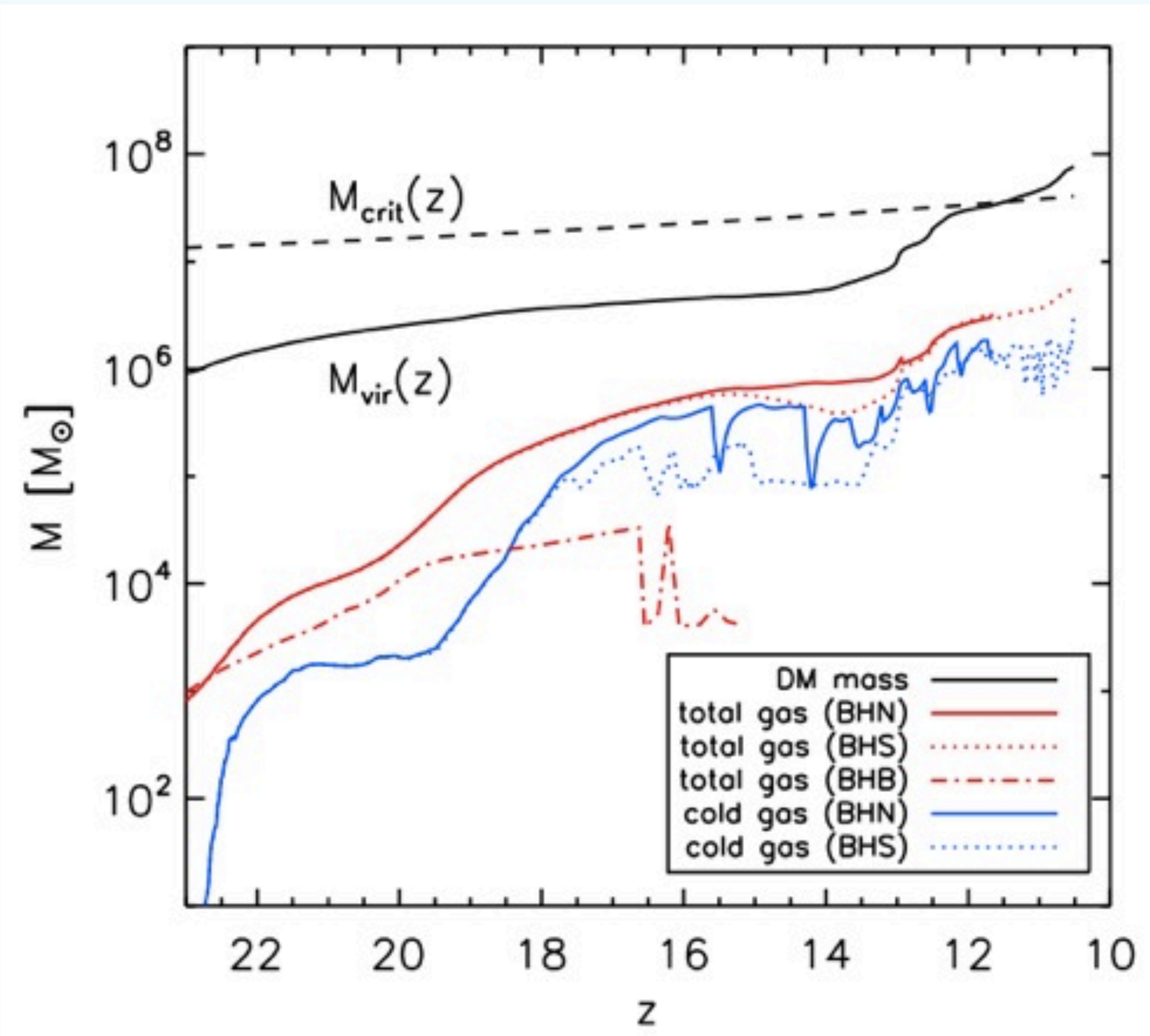


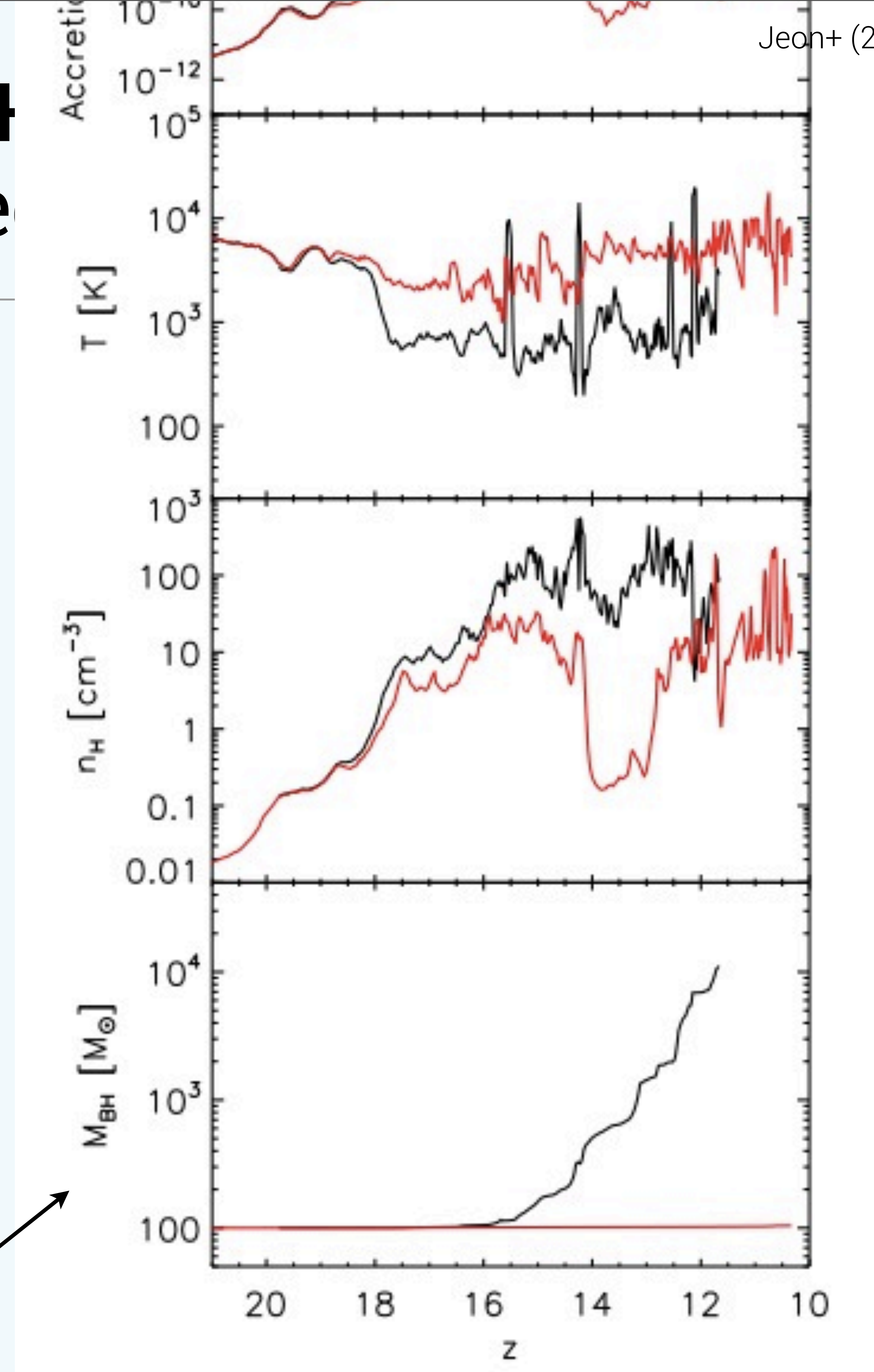


Black: No feedback
Red: Feedback

Accretion onto a Single BH
Effects of X-ray Radiative Fee

Jeon+ (2012)





Black: No feedback
Red: Feedback

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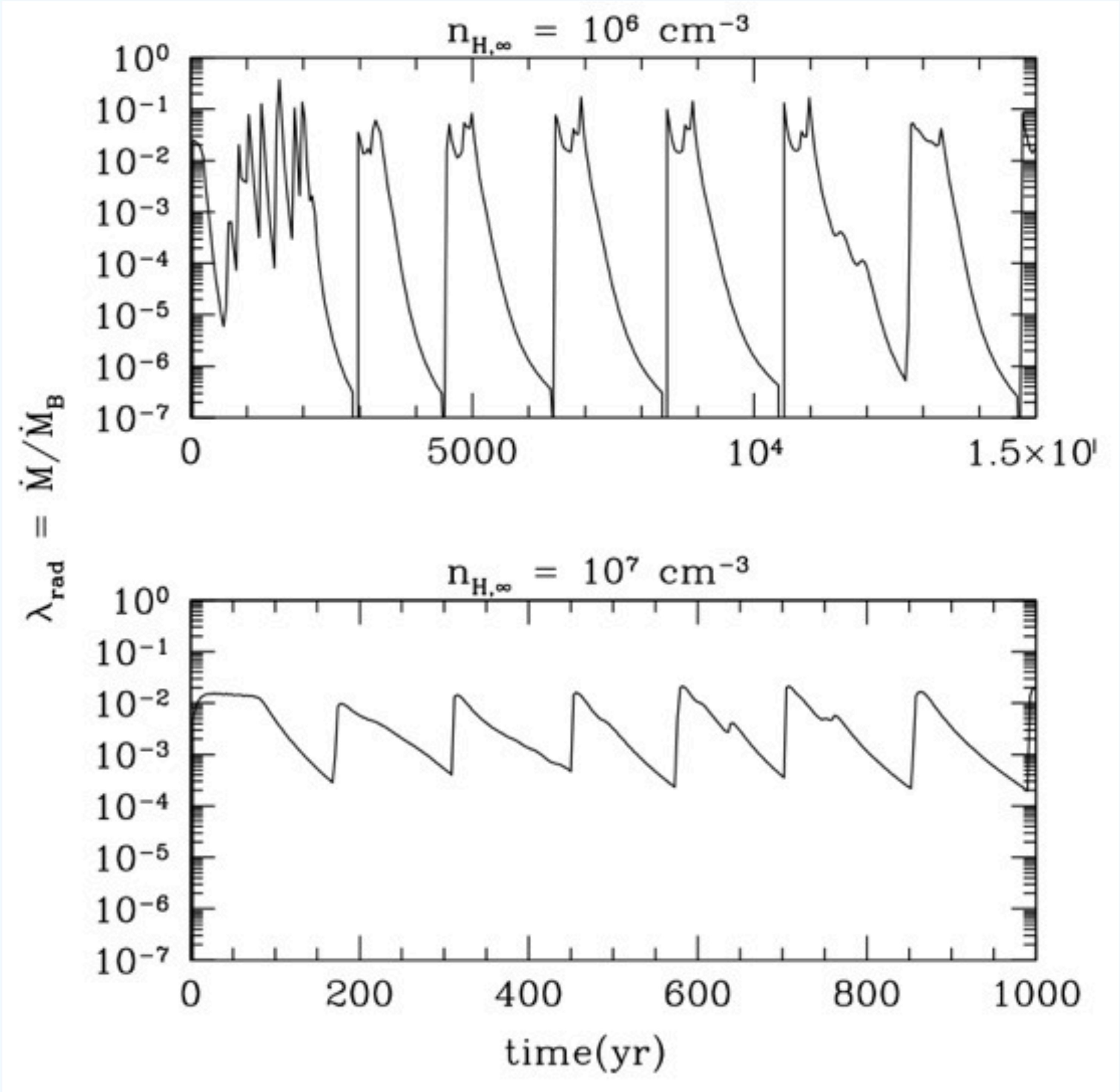
Accretion onto a Single BH
Effects of X-ray Radiative Feedback

- Is the Bondi accretion rate accurate when radiative feedback affects the flows interior to the Bondi radius?
- Two modes of accretion
  - Rapid (~50%) duty cycles in dense (>5 x 10^6 cm^{-3}) gas, caused by a collapse of the ionization front.
  - Slow (~6%) duty cycles otherwise



BH Populations in the First Galaxies

The First Galaxies
BH Populations

enzo-project.org

- **Simulation setup:**
  - 1.5 comoving Mpc box, 100 $M_\odot$ DM particles, 1 comoving pc (maximal) resolution
  - Pop II & III star formation and feedback (transition at 10^{-4} $Z_\odot$)
  - Randomly sample Pop III stars from a top-heavy IMF with a characteristic mass of 40 $M_\odot$.
  - Only stars in the proper mass range create stellar-mass BHs.

Wise+ (in prep)

The First Galaxies
BH Populations

enzo-project.org

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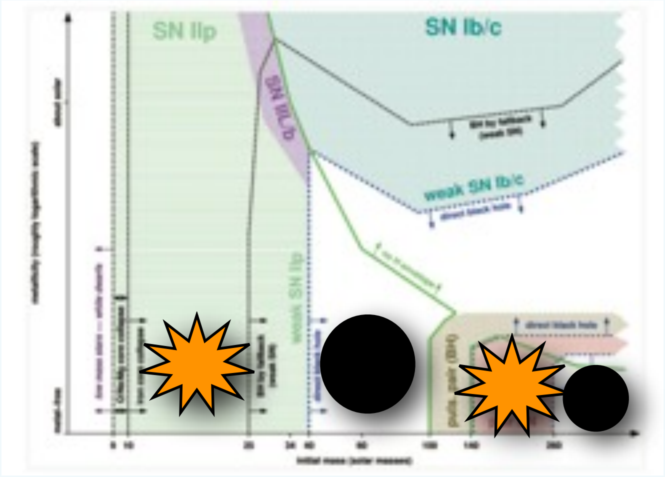
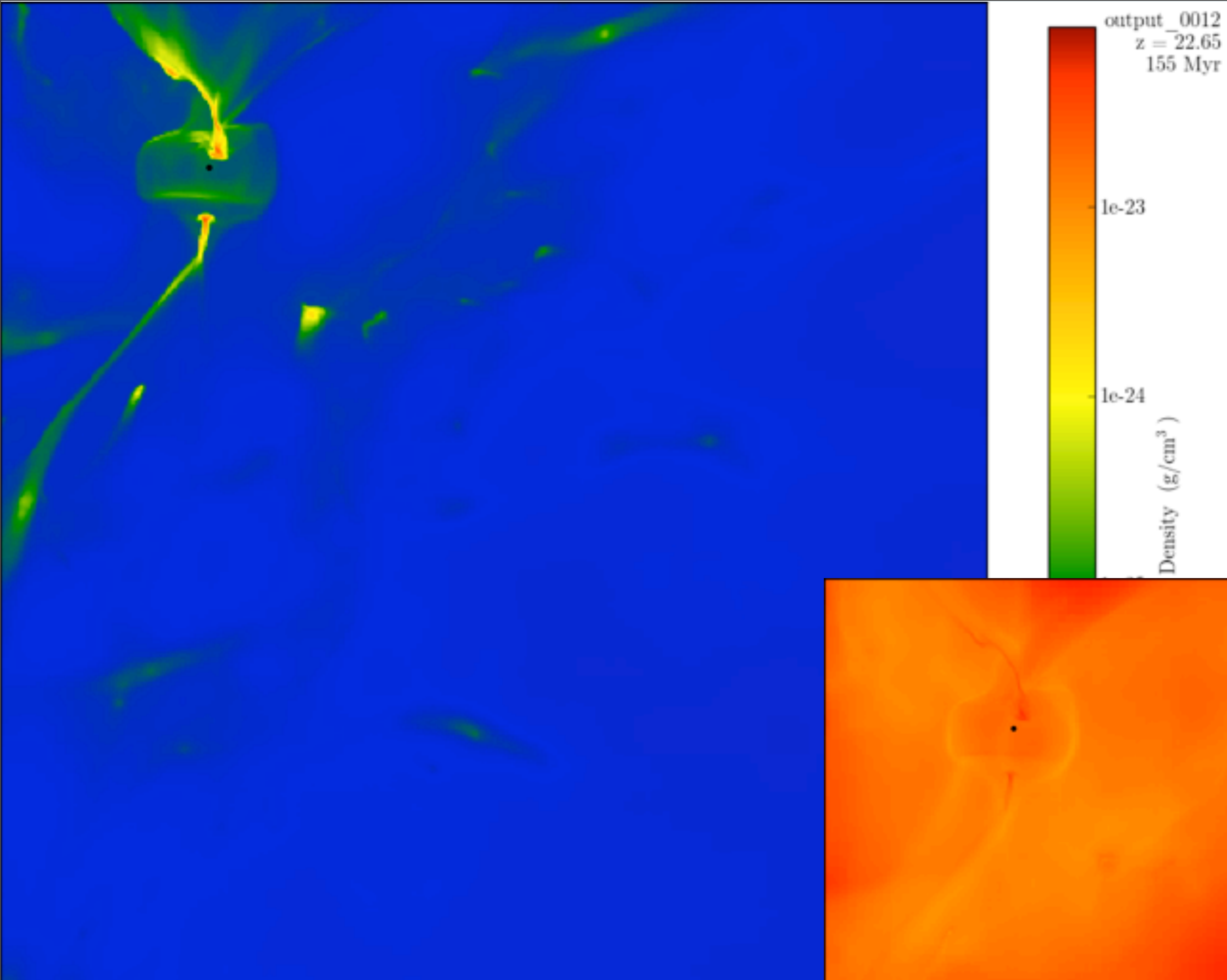
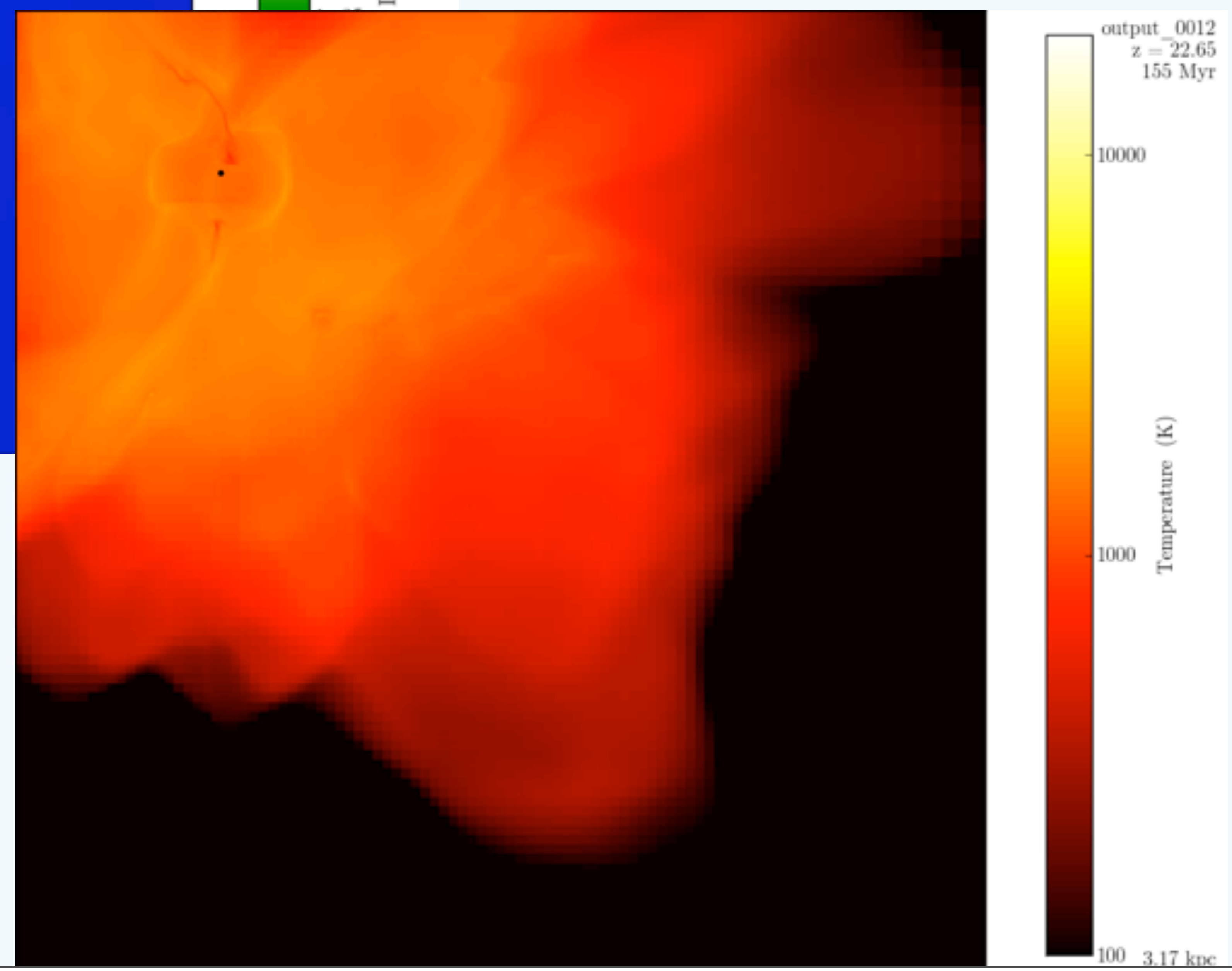




z = 23 → 11
75 comoving kpc

Projected Temp.

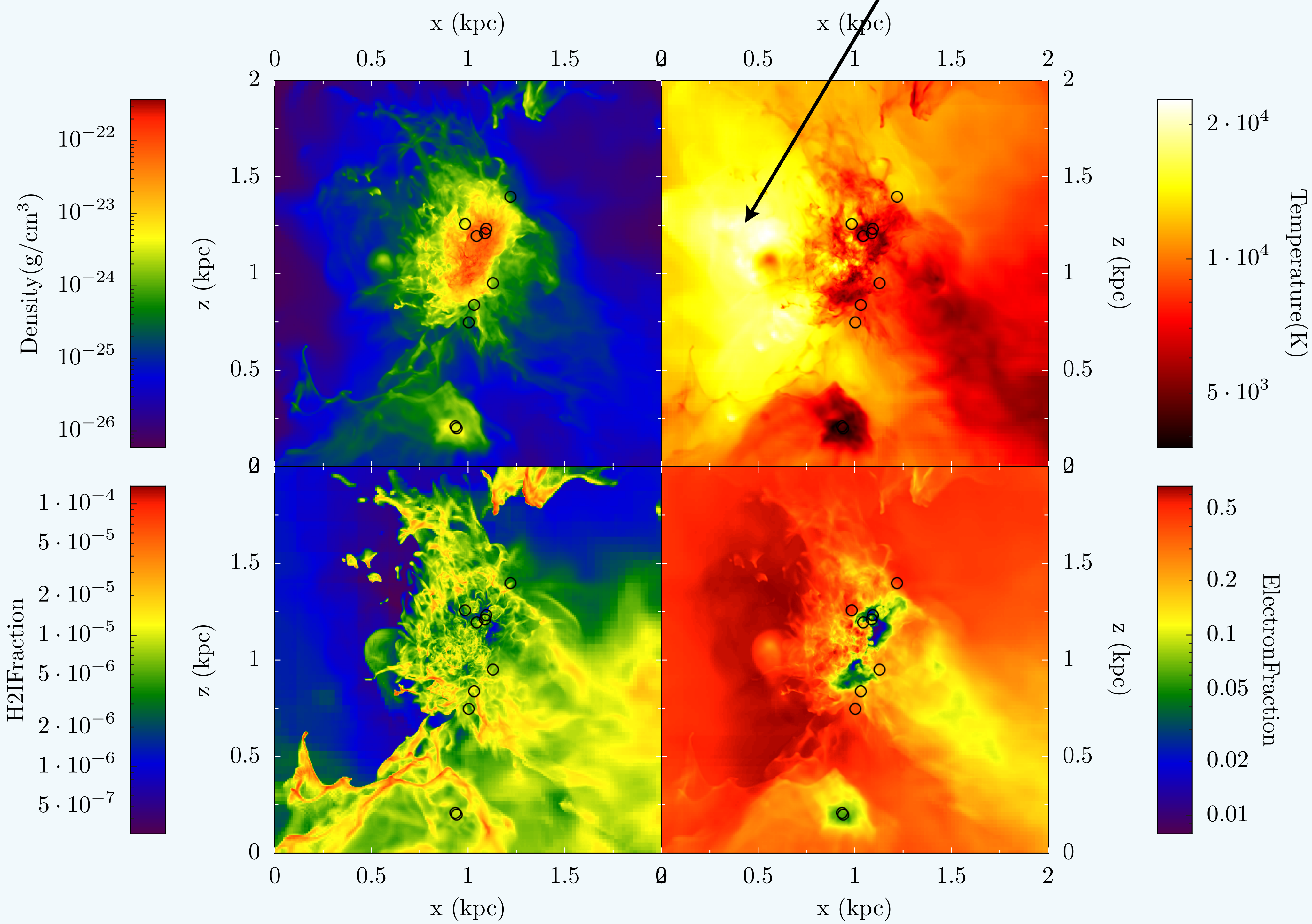


Projected Density
Black dots = BHs

The First Galaxies
BH Populations

Escaping stellar radiation

10^8 M halo; z = 11



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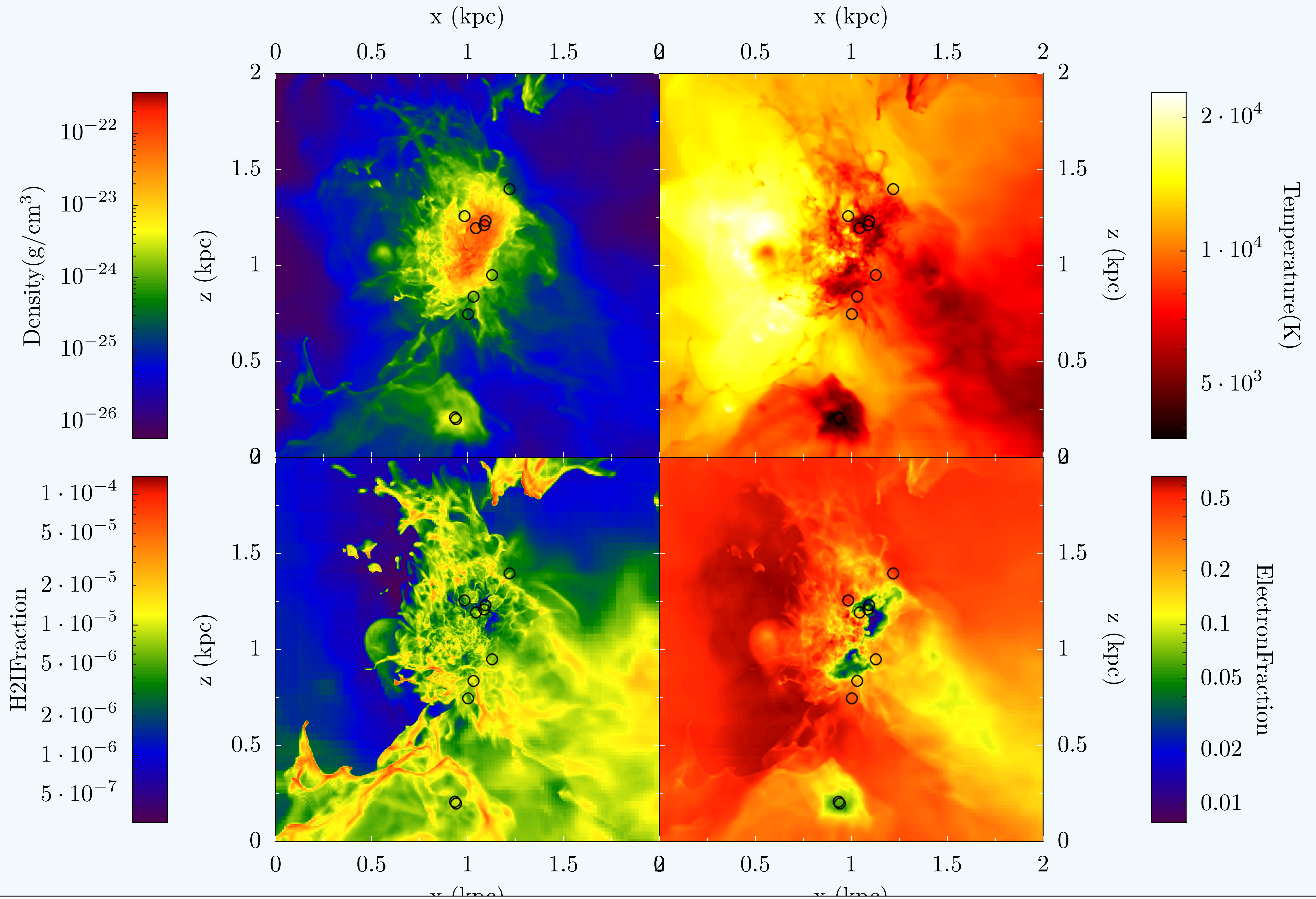
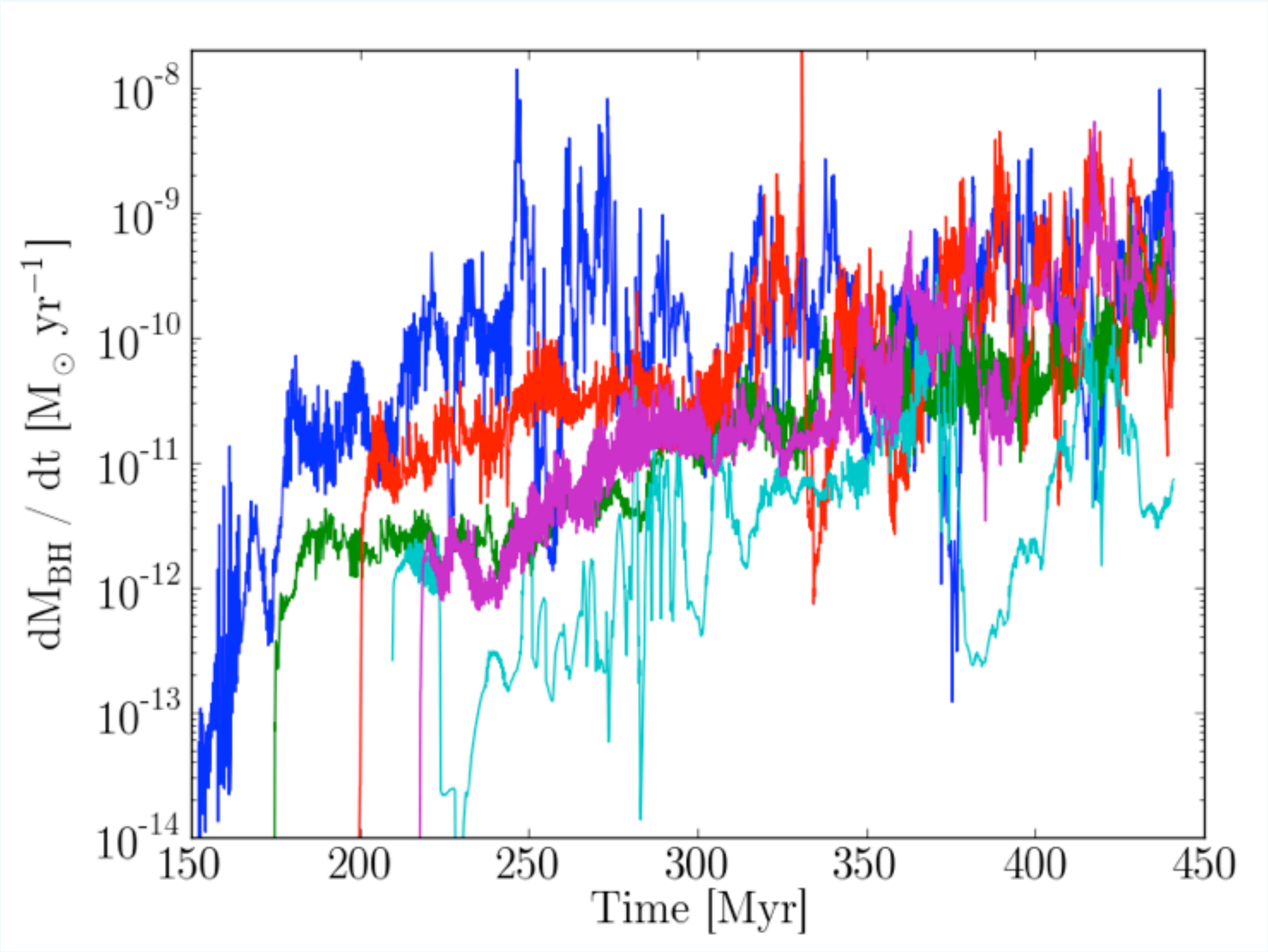
Wise+ (in prep)

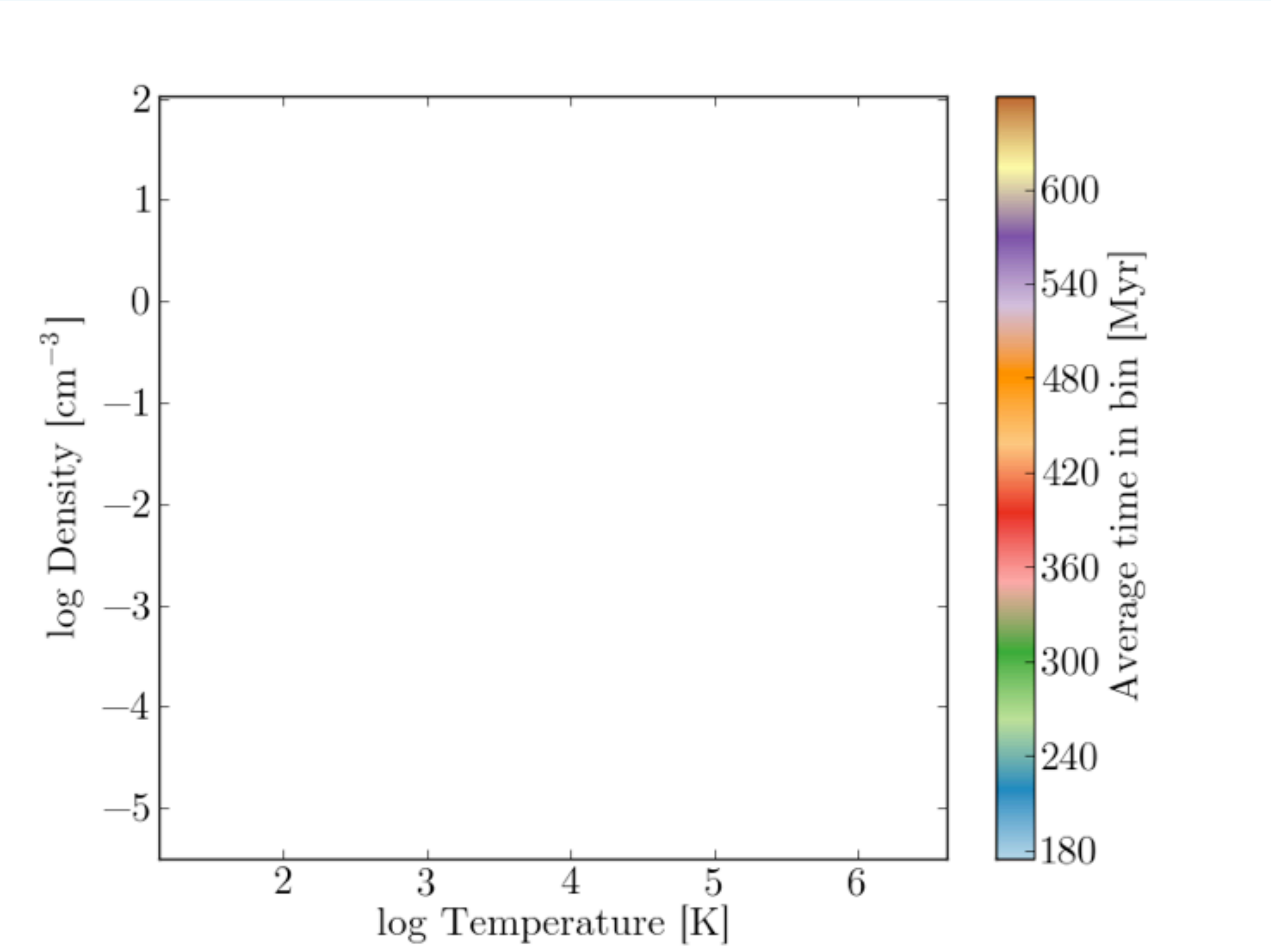
The First Galaxies



The First Galaxies
BH Accretion Rates (5 Highest)



The First Galaxies
BH Accretion Rates



Xu, Wise, Norman (2013)

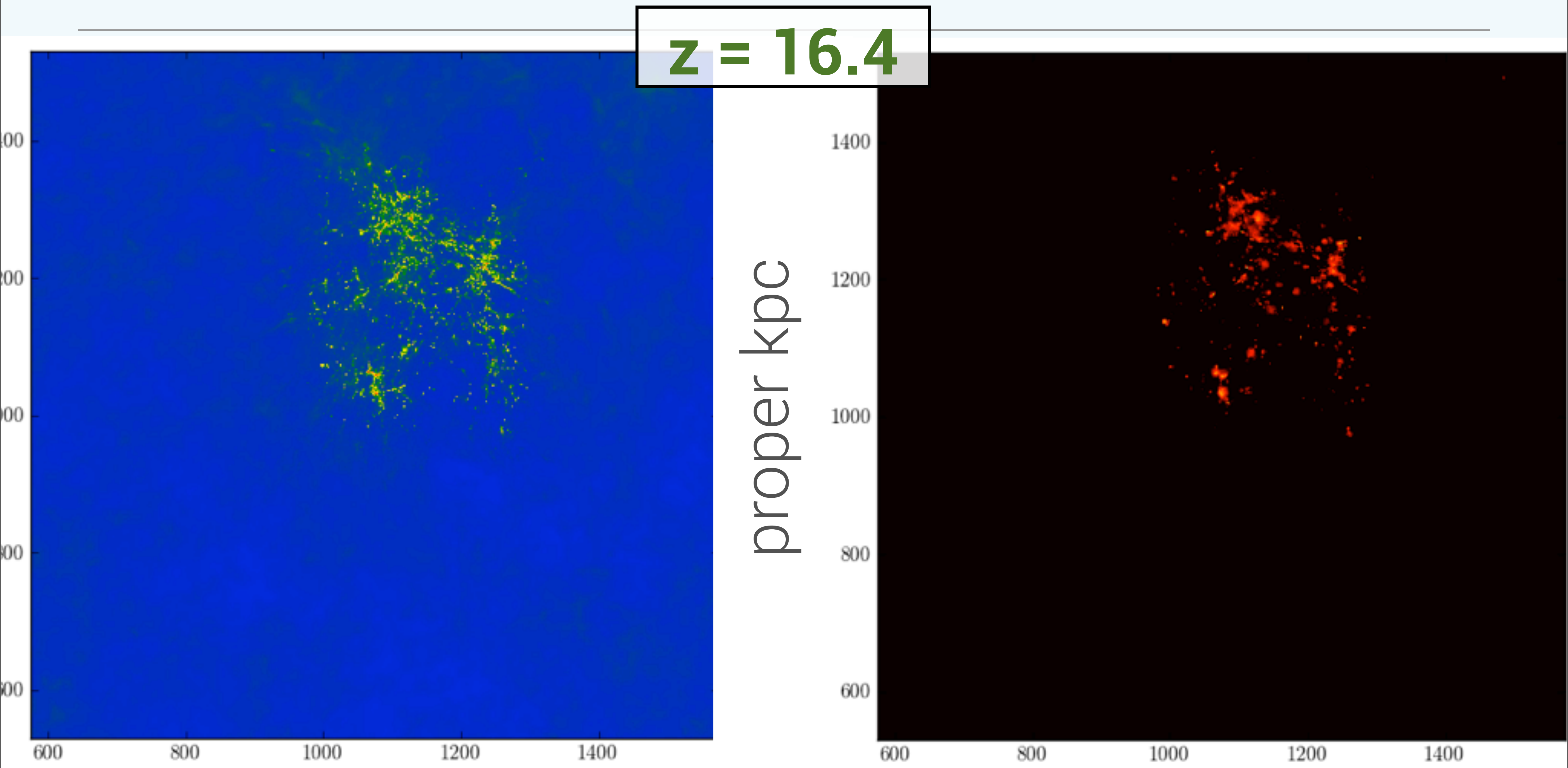
The First Galaxies
Pop III Remnant Multiplicity

enzo-project.org

- Follow a “rare peak” forming galaxies until z = 15.
  - 40 comoving Mpc box, 5 comoving Mpc zoom-in region
  - 34,000 $M_\odot$ DM particles, 19 comoving pc (maximal) resolution
  - Same physics and phenomenology as previous simulation, but no BH radiative feedback or accretion (yet).
- At z = 15, there are
  - Three $>10^9$ $M_\odot$ DM halos
  - 13,123 Pop III stars
  - $\sim 3 \times 10^8$ $M_\odot$ of Pop II stars in ~3000 dwarf galaxies

Xu, Wise, Norman (2013)

The First Galaxies
Pop III Remnant Multiplicity

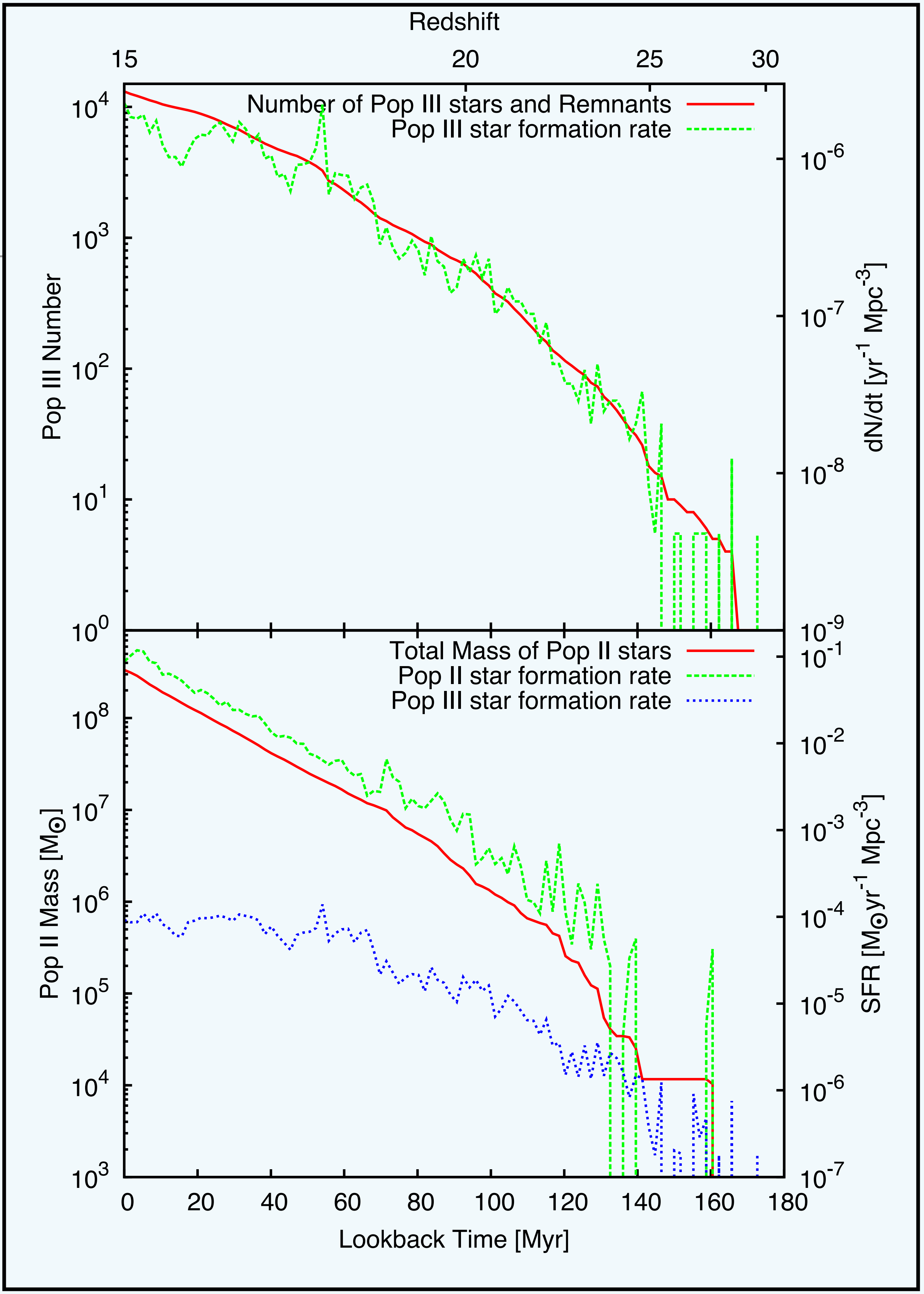


Projected Density
(scale: $3 \times 10^{-28} - 3 \times 10^{-24}$ g/cm^3)

Projected Temperature
(scale: $10^3 - 3 \times 10^4$ K)

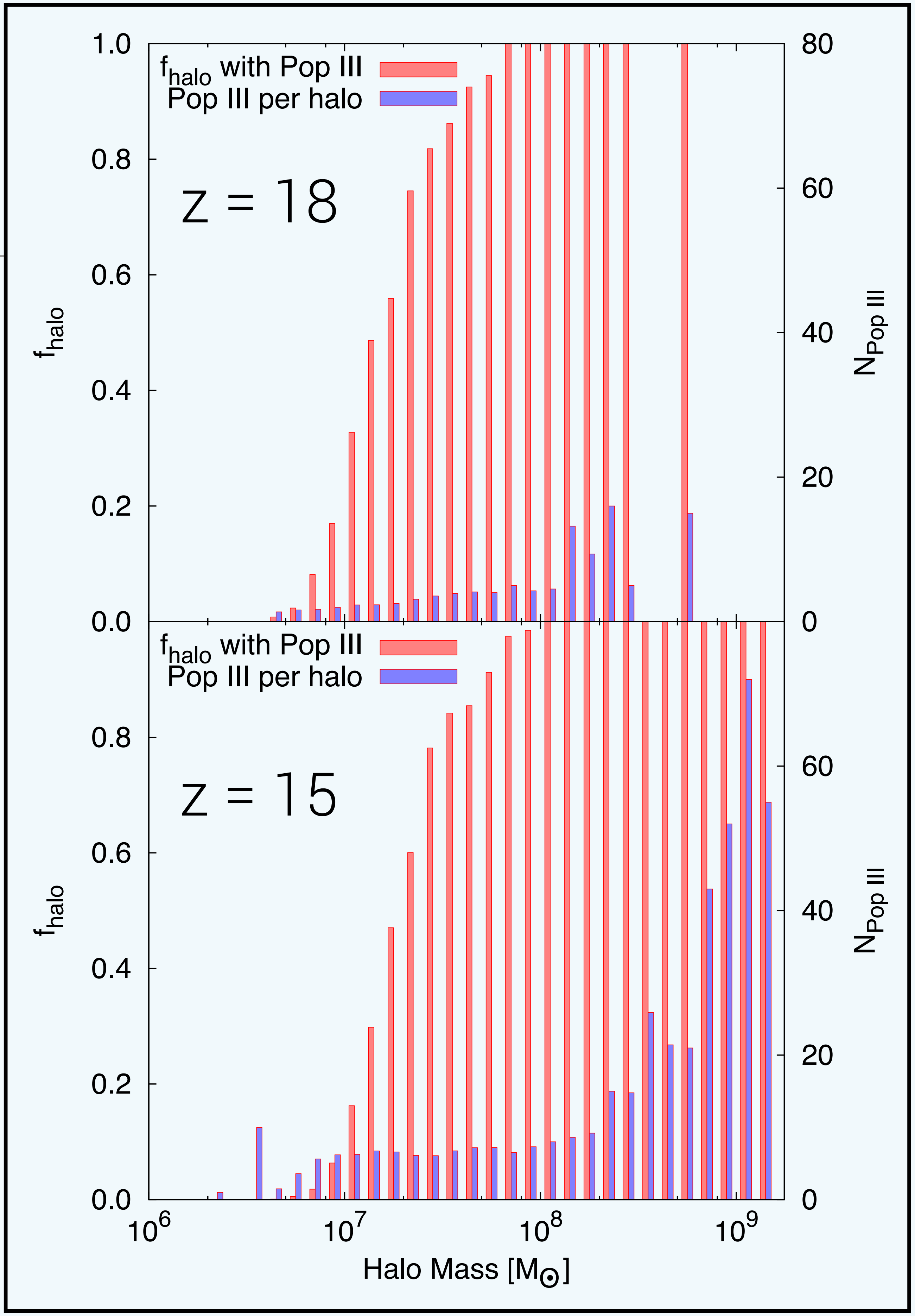
The First Galaxies
Pop III Remnant Multiplicity

- Zoom-in region hosts a few 10^9 $M_\odot$ (4-σ) halos by z=15.
- Halo mass function has 5x the abundances as a mean region.
- Similar to a mean density region at z = 10.
- Pop III SFR suppressed but constant for the last 60 Myr at 10^{-6} yr^{-1} $cMpc^{-1}$
    - Mainly caused by Lyman-Werner feedback



The First Galaxies
Pop III Remnant Multiplicity

- In this “rare peak”, strong local Lyman-Werner feedback suppresses Pop III star formation below 10^7 $M_\odot$.
- Most Pop III stars form in 1-2 x 10^7 $M_\odot$ halos.
- Afterward through mergers, halos between 10^7 and 10^8 $M_\odot$ host 10 Pop III remnants on average at z = 15.
- 10^9 $M_\odot$ host about 50 Pop III remnants.
- Interesting note: There are several atomic cooling halos that haven't hosted Pop III stars.



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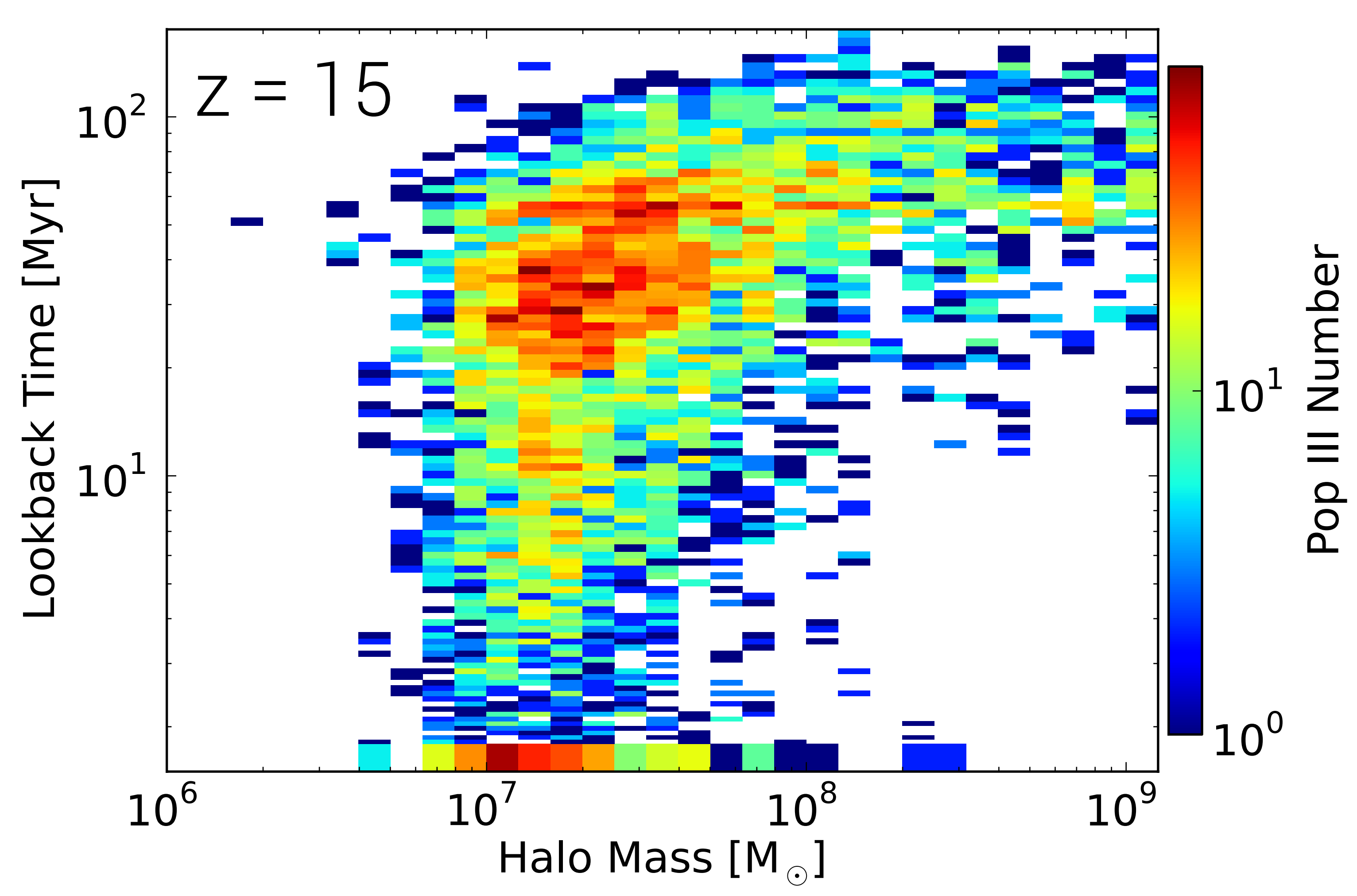
The First Galaxies
Pop III Remnant Multiplicity – X-ray binaries?

- Recall that recent simulations have suggested that Pop III stars may form in binaries
- High-mass X-ray binaries could exist in dwarf galaxies
- Could contribute to reionization by partially ionizing the IGM (long mean free paths).



The First Galaxies
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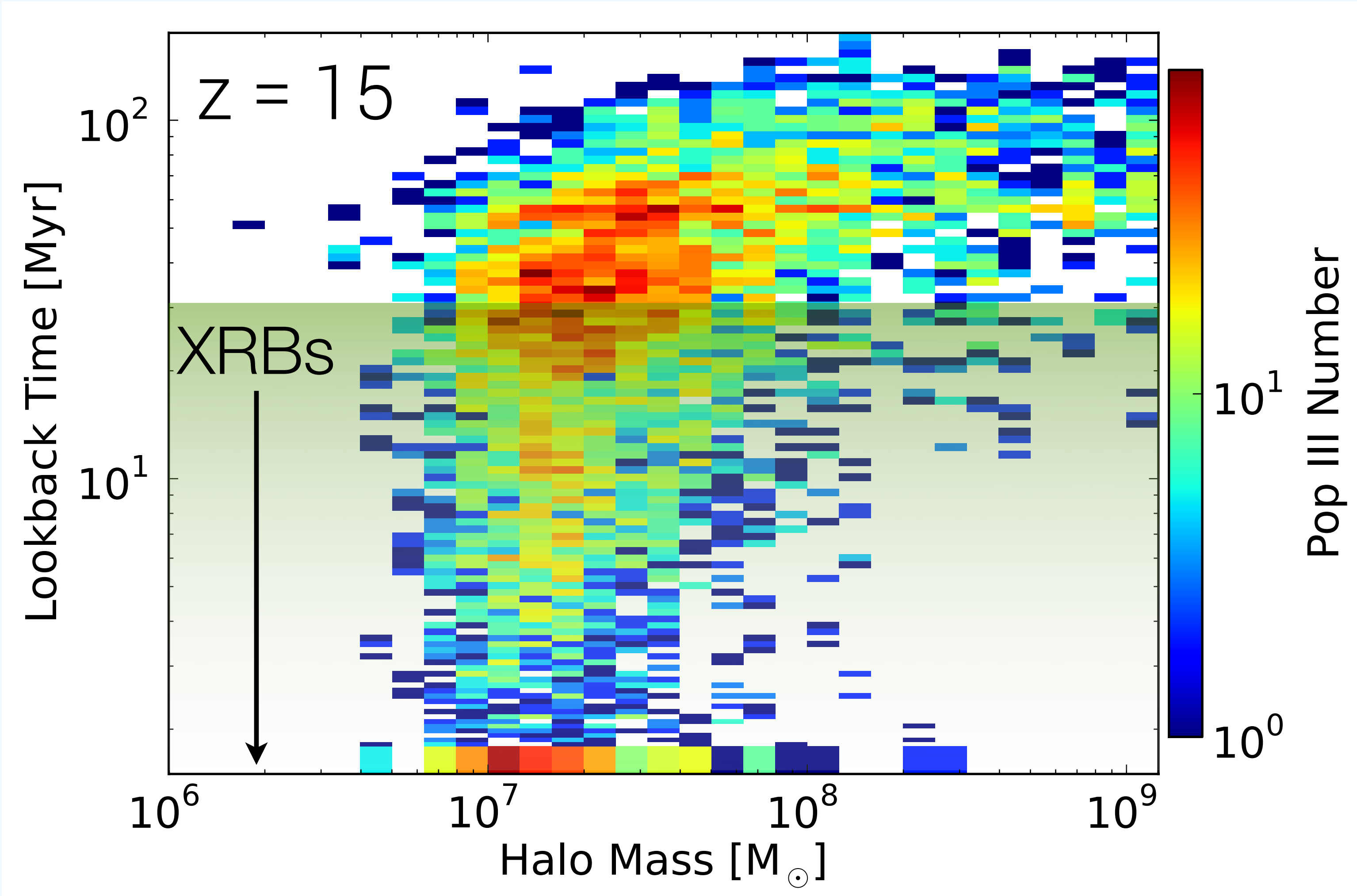


Open Questions
Fragmentation in Isothermal Collapses

Are we missing later fragmentation in the massive seed scenario?
Analogous to the progress in Pop III star formation simulations?

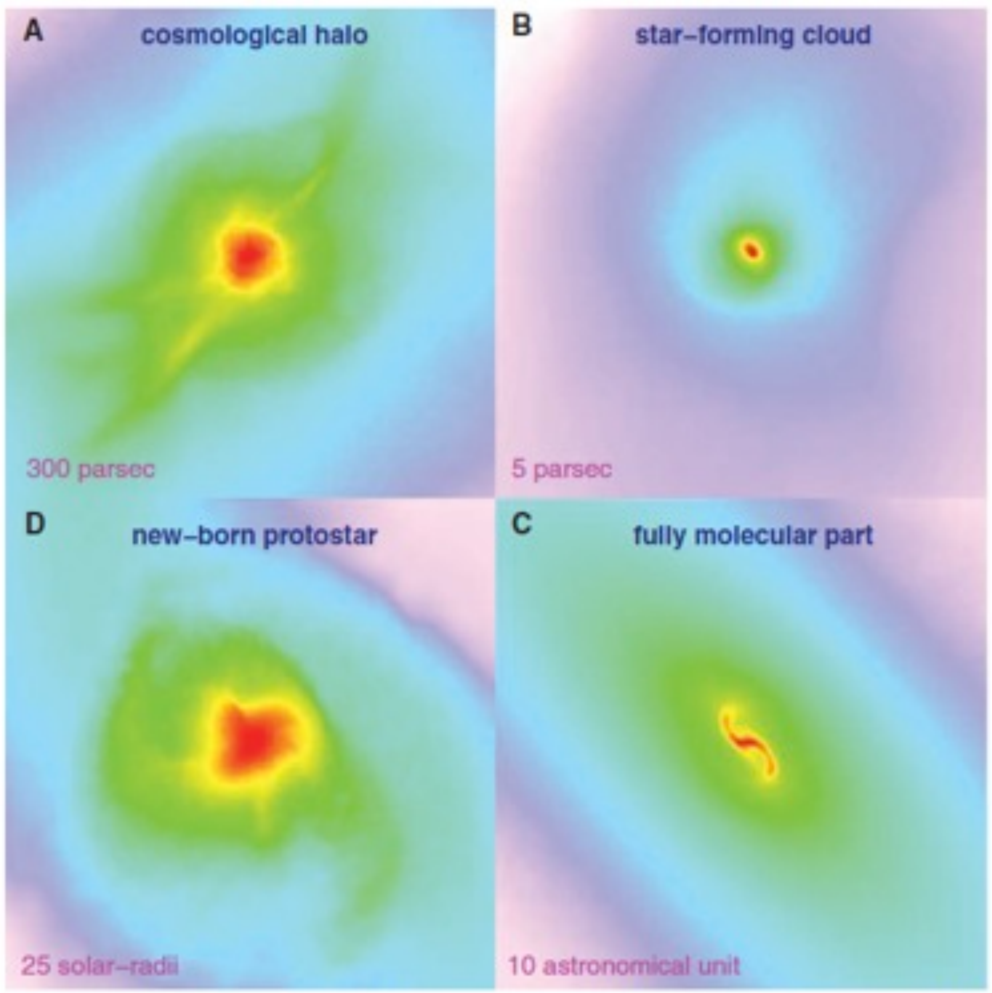
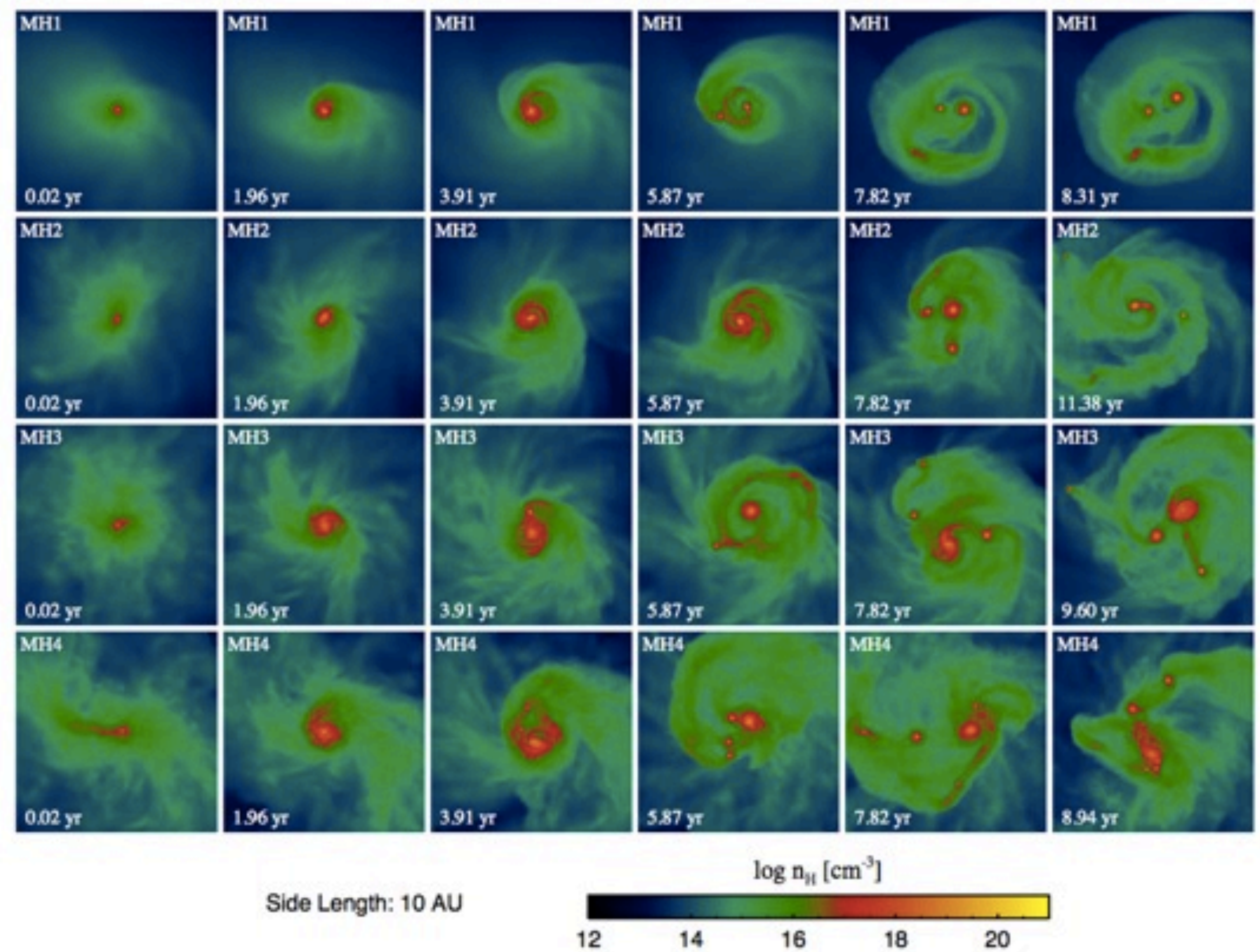


Fig. 1. Projected gas distribution around the protostar. **(A)** The large-scale gas distribution around the cosmological halo (300 pc on a side). **(B)** A self-gravitating, star-forming cloud (5 pc on a side). **(C)** The central part of the fully molecular core (10 astronomical units on a side). **(D)** The final protostar (25 solar radii on a side). The color scale from light purple to dark red corresponds to logarithmically scaled hydrogen number densities from 0.01 to 10^3 cm^{-3} (A), from 10 to 10^6 cm^{-3} (B), and from 10^{14} to 10^{19} cm^{-3} (C). The color scale for (D) shows the density-weighted mean temperature, which scales from 3000 to 12,000 K.

Yoshida+ (2007) – no fragmentation



Greif+ (2012) – disk fragmentation

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Open Questions
Feedback in the Massive BH Seed Formation

- What fraction of gas goes into the BH, stars, and outflows?
- What are the effects of radiative feedback on the inflows in the direct collapse scenario?
  - Decreasing accretion rates?
  - Triggered / suppressed star formation?
- What happens when a pre-existing BH exists in a pristine, collapsing gas cloud?

Summary

- Radiative feedback from Pop III seed BHs has little dynamical effect on large-scales but heats and rarefies the local surrounding medium, limiting accretion rates to $\sim 10^{-10}\ M_\odot/yr$.
- BH accretion is limited in most minihalos, and points to growth in halos with $M > 10^8\ M_\odot$.
- In high-redshift galaxies, there are tens of BH seeds from Pop III stars roaming around the ISM, weakly accreting material.