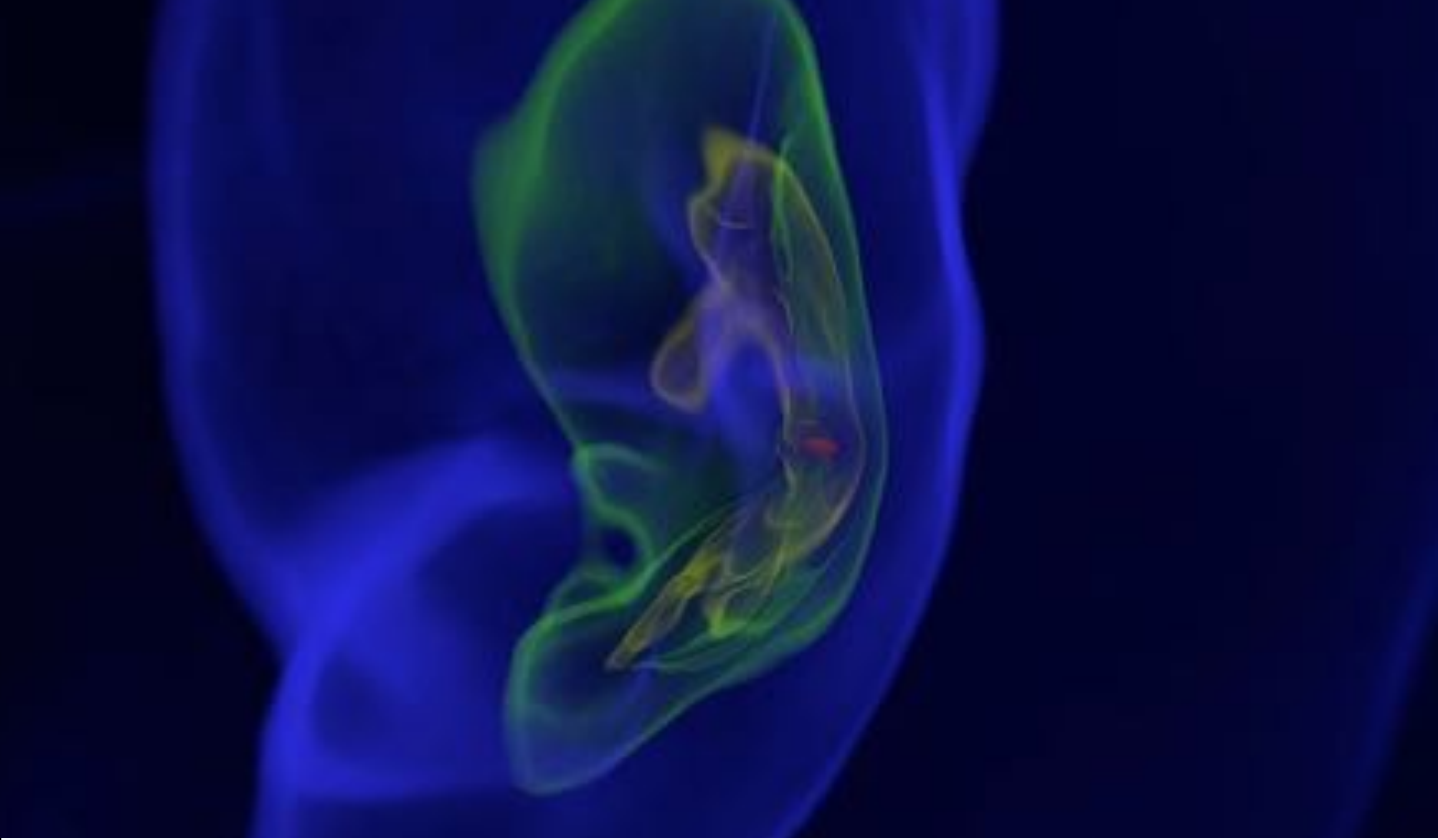


The First Black Holes and their Host Galaxies

John Wise Georgia Tech

Chao Shi (GT), Pengfei Chen (UCSD), Ayçin Aykutalp (GT), Tom Abel (Stanford), Peter Johansson (Helsinki), Michael Norman (UCSD), Brian O'Shea (MSU), John Regan (Helsinki), Britton Smith (Edinburgh), Matthew Turk (NCSA), Hao Xu (UCSD)

Outline

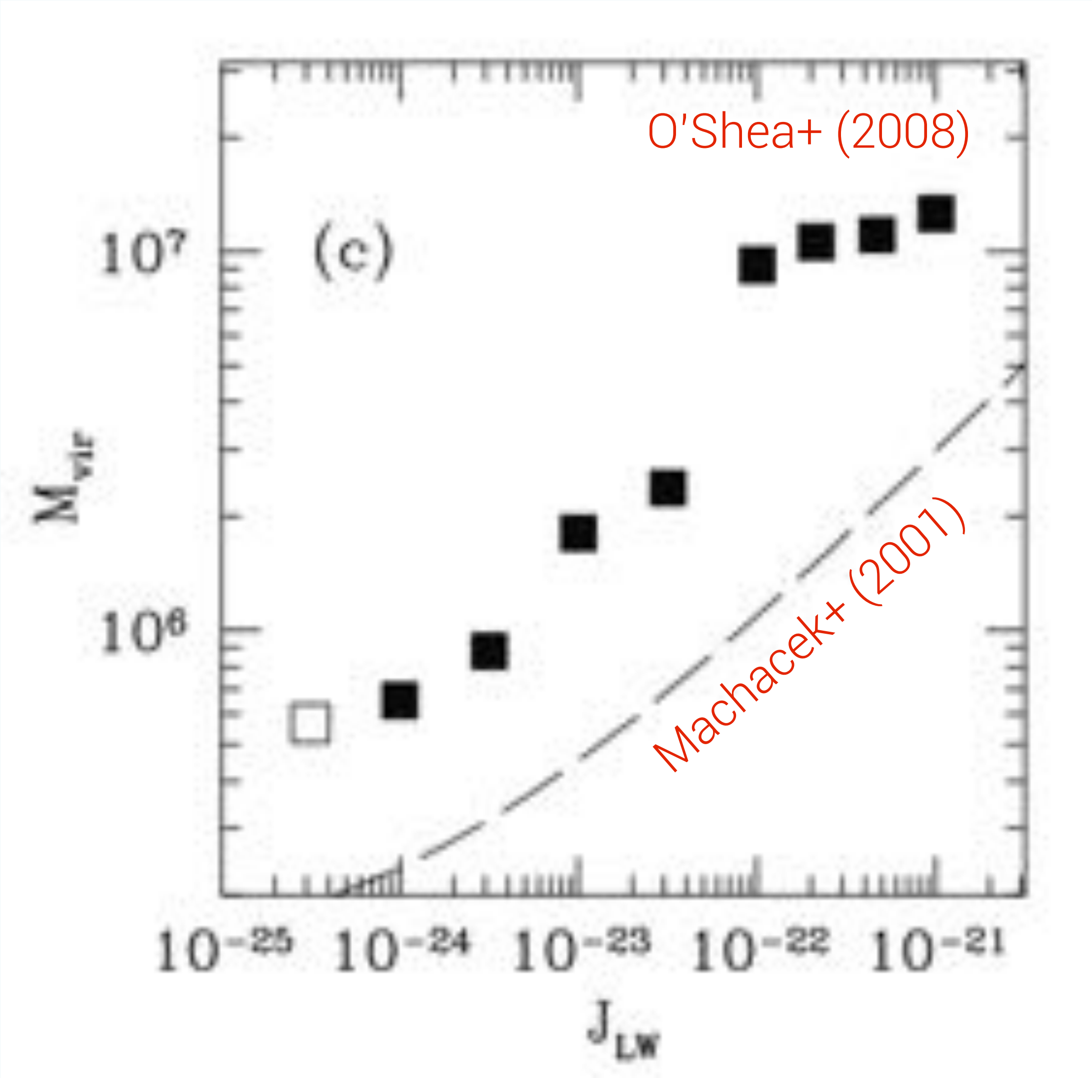
- **Overview of Pop III characteristics**
- **BH seeds from Pop III stars:**
  - A study on the importance of radiative feedback
  - Early mass accretion history in minihalos
- **Massive BH seed formation**
- **BH seeds in the first galaxies:**
  - Spatial distributions (central or dispersed?)
  - Mean multiplicities
- **How common are each case? What type of BH mass function arises? How does star formation occur around central BH seeds?**

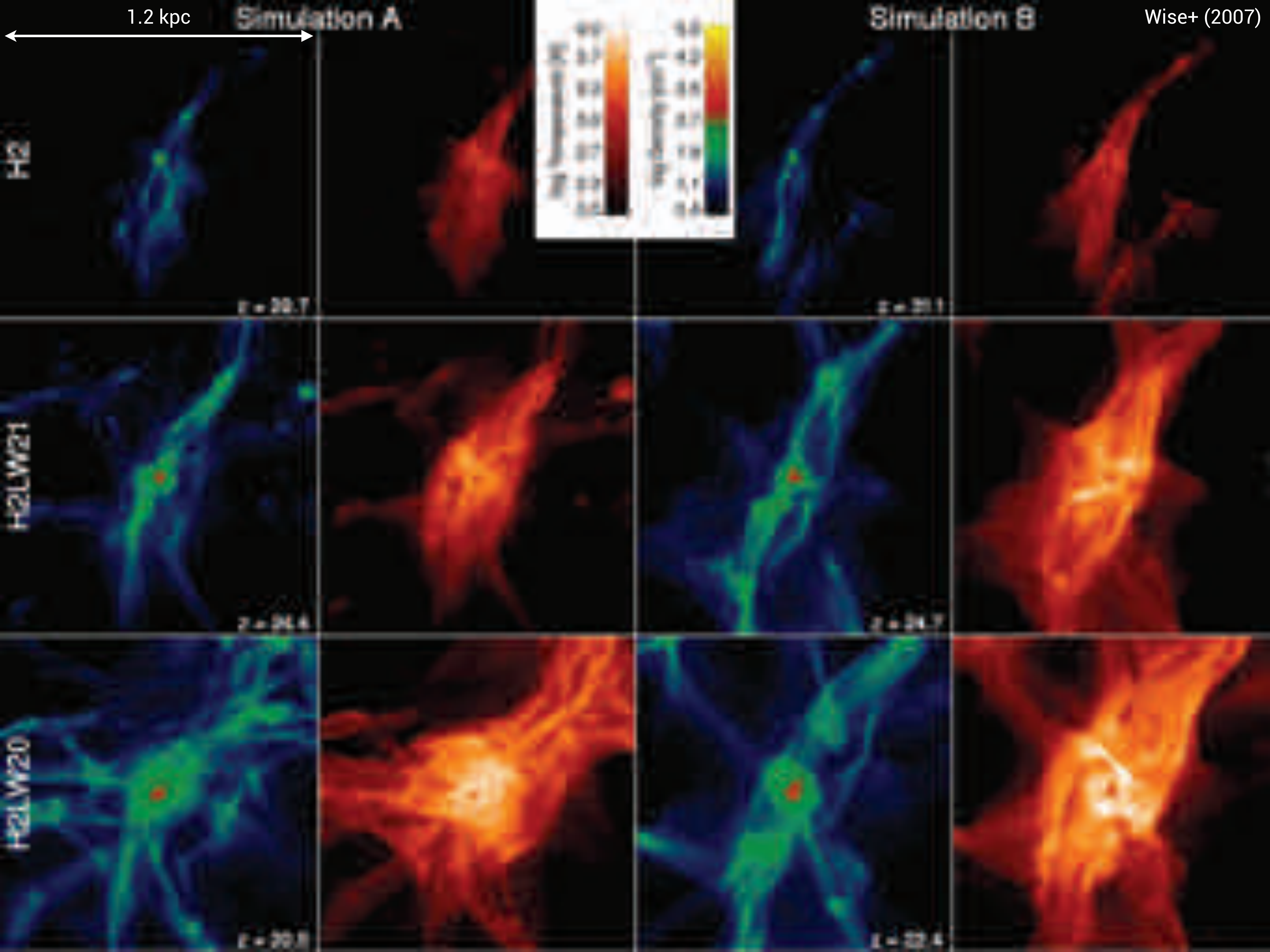
Population III Stars
Formation

- 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.

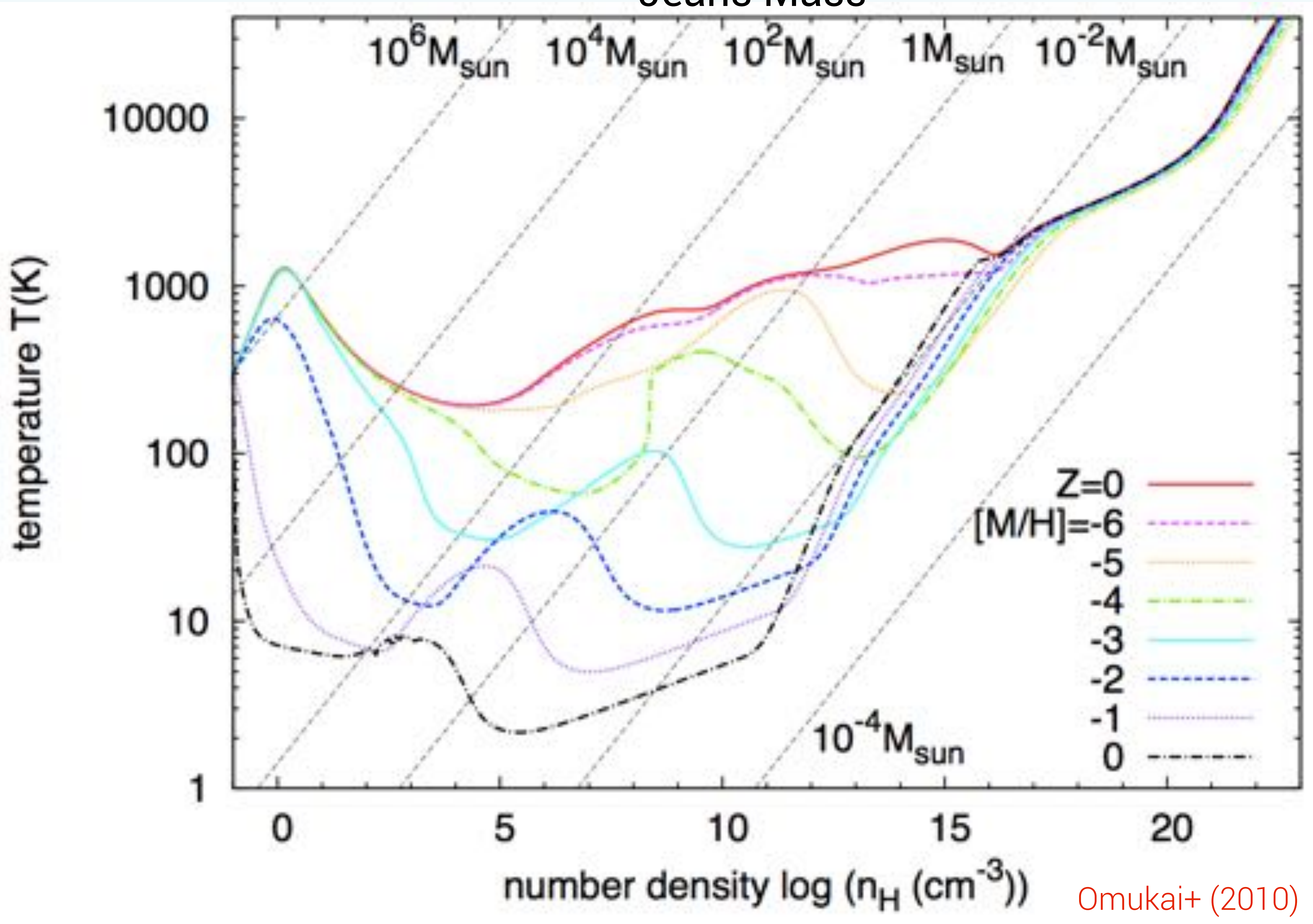



1.2 kpc
Simulation A
Simulation B
Wise+ (2007)
H2
H2LW21
H2LW20

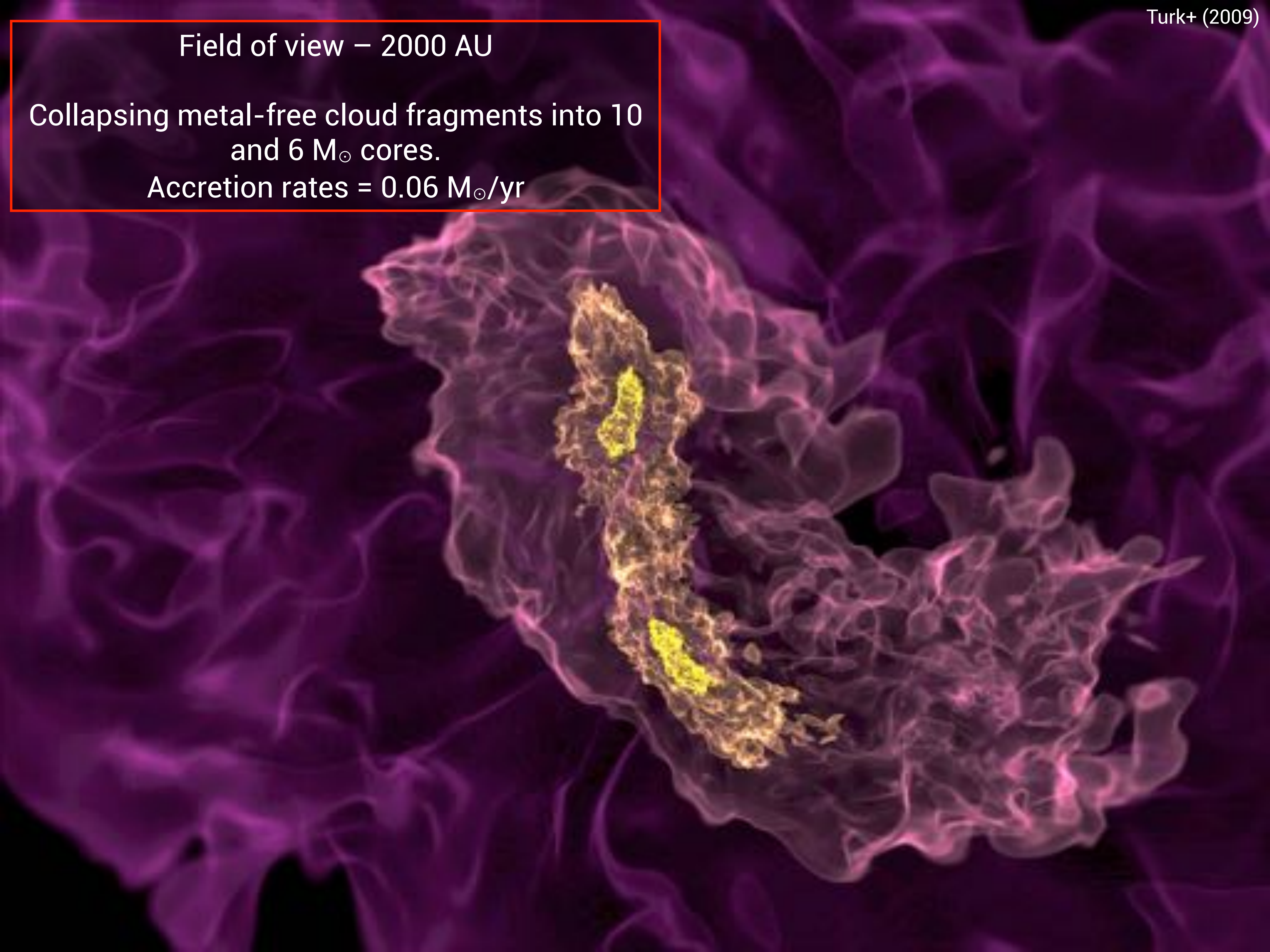
Population III Stars
Formation

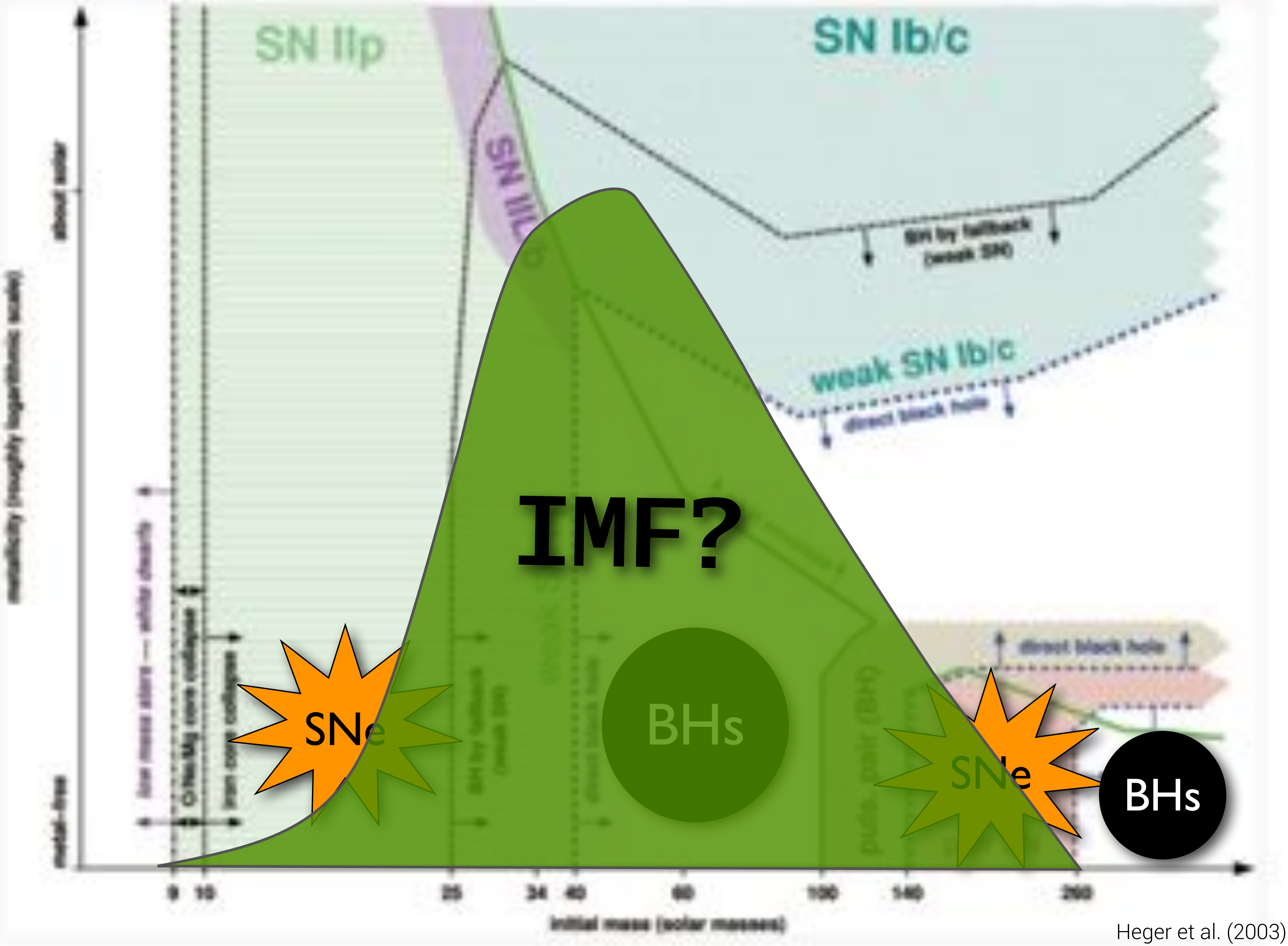
- Cooling efficient only down to ~300 K.
- Sets the Jeans mass of the central molecular cloud → 1000 $M_\odot$
- Some cores may fragment into multiple systems with stellar masses of **tens of $M_\odot$**

Jeans Mass



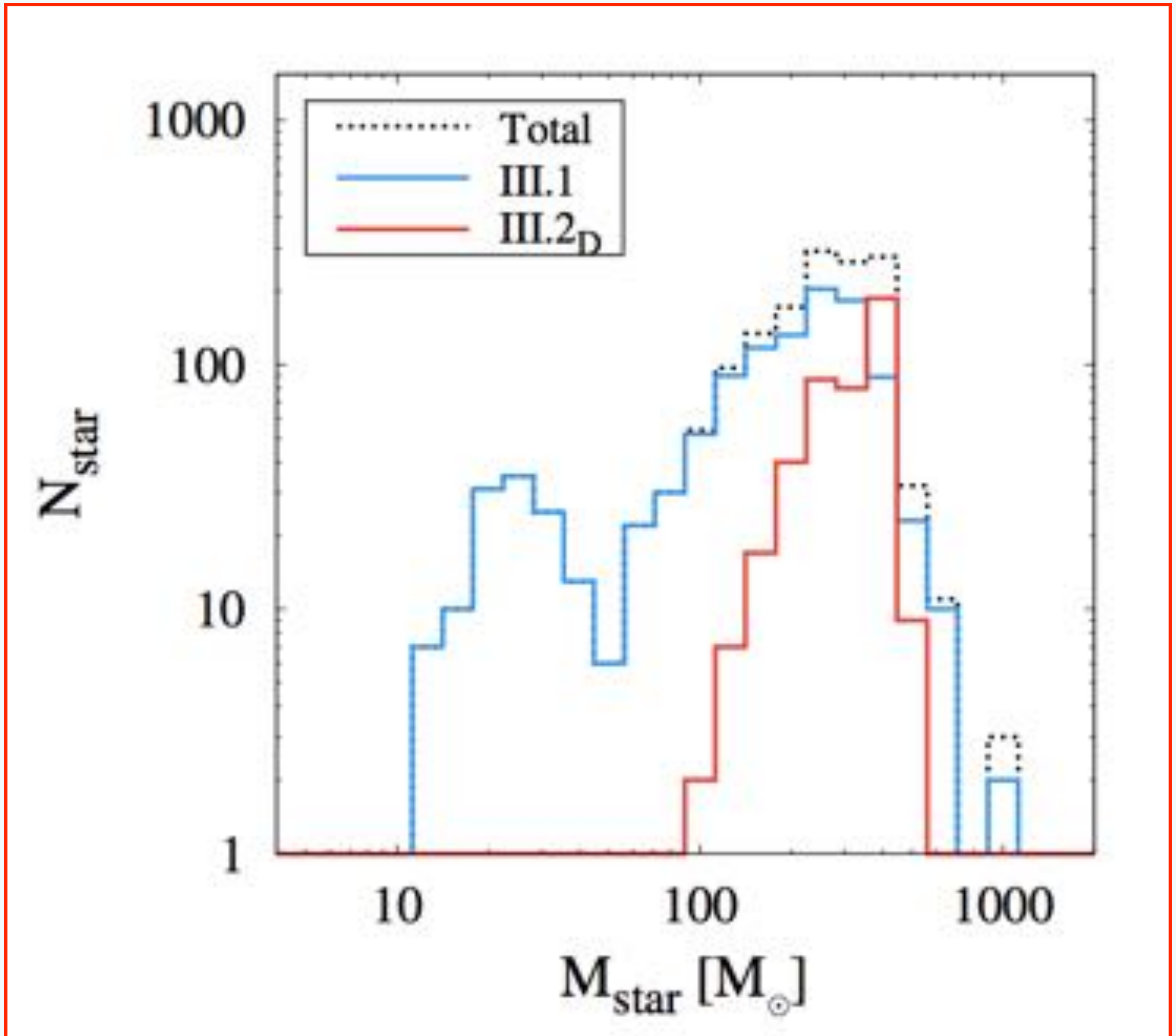
Omukai+ (2010)

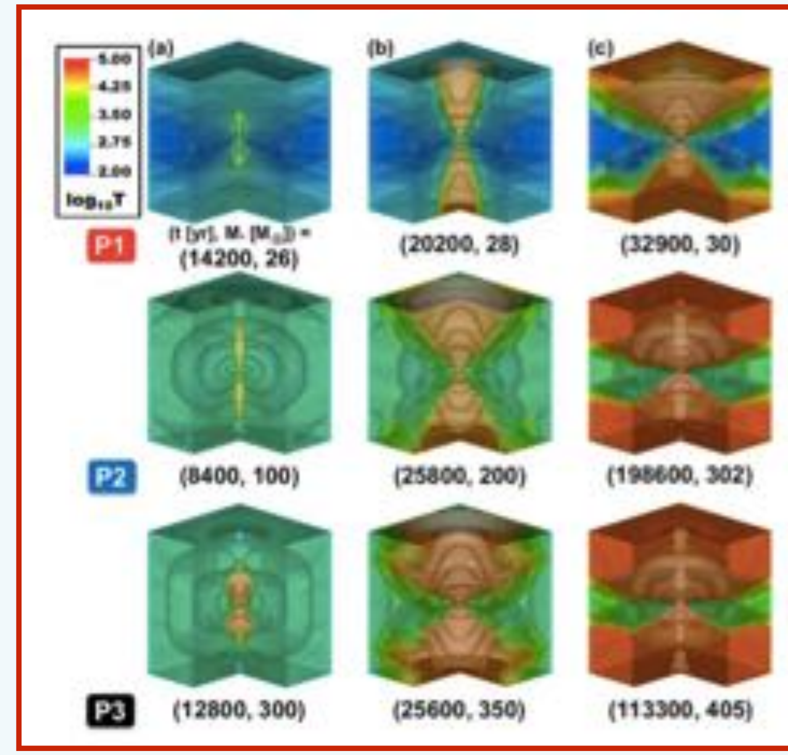

Turk+ (2009)
Field of view – 2000 AU
Collapsing metal-free cloud fragments into 10 and 6 $M_\odot$ cores.
Accretion rates = 0.06 $M_\odot$/yr



Heger et al. (2003)

Population III Stars
Working toward an IMF

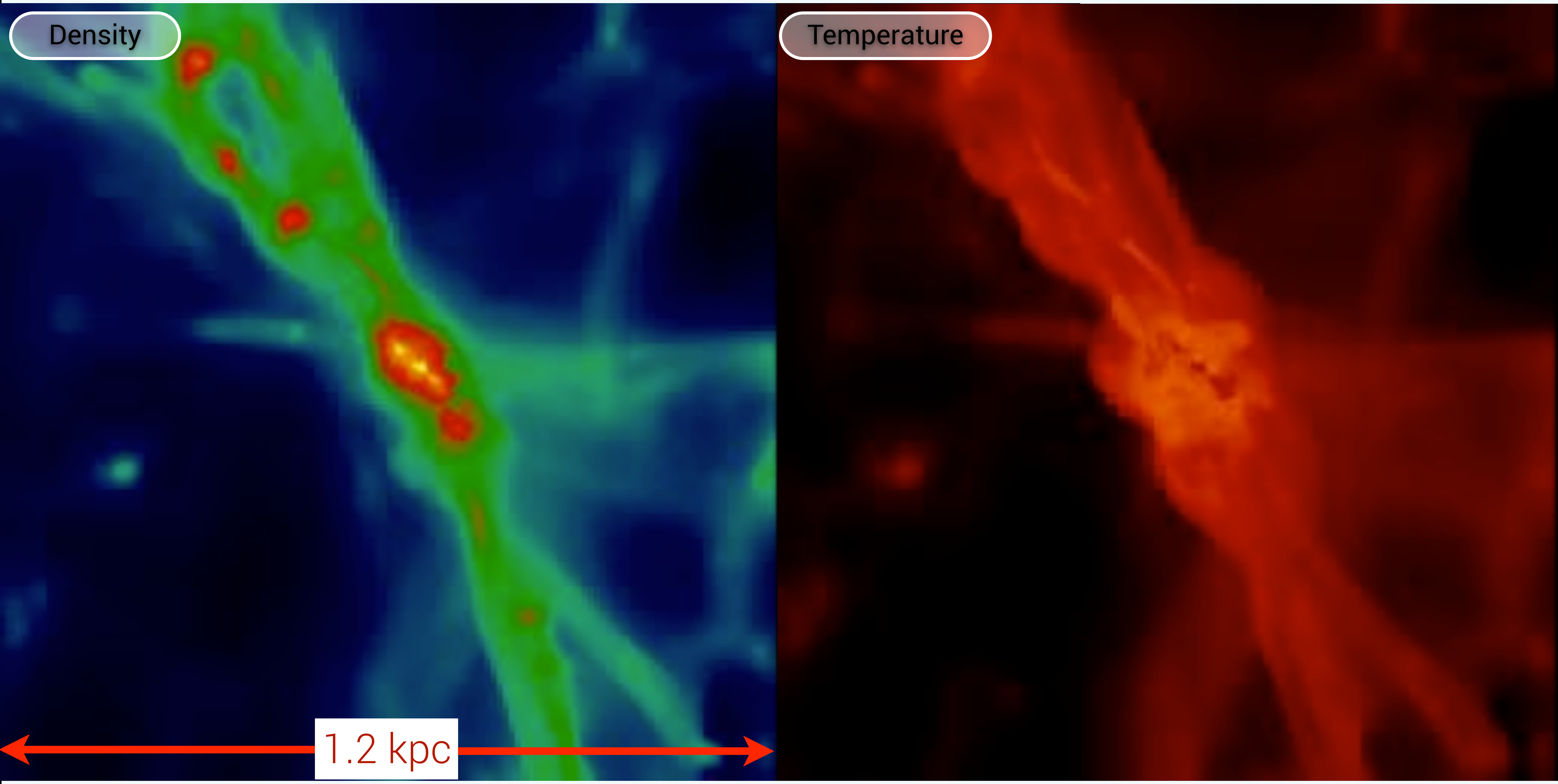




1540 2.5D protostellar radiation-hydro calculations, taken from a cosmological sample

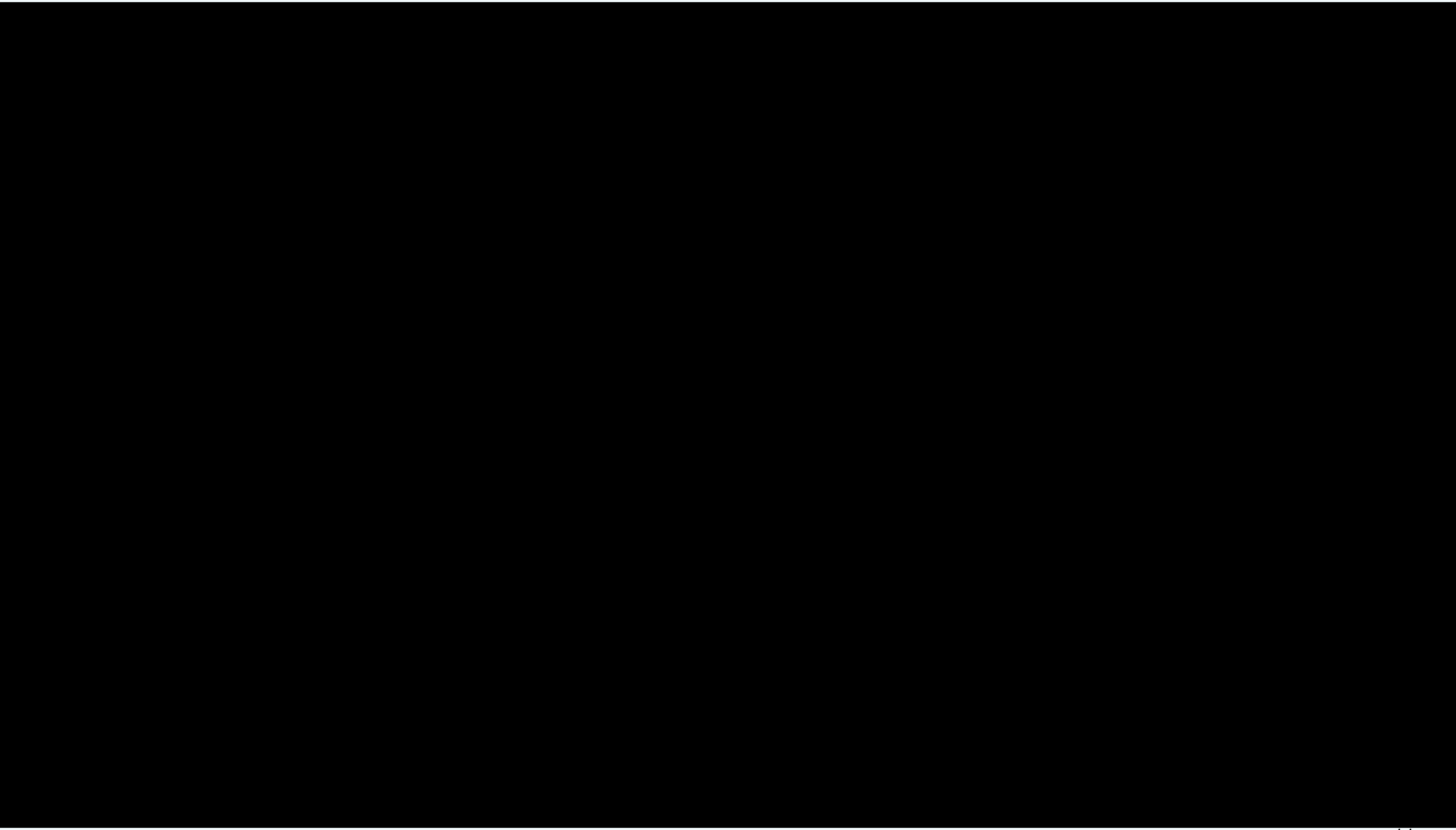
Hirano+ (2015)

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

Early stages of reionization from the first stars and galaxies (1 comoving Mpc^3; $z = 30 - 10$)

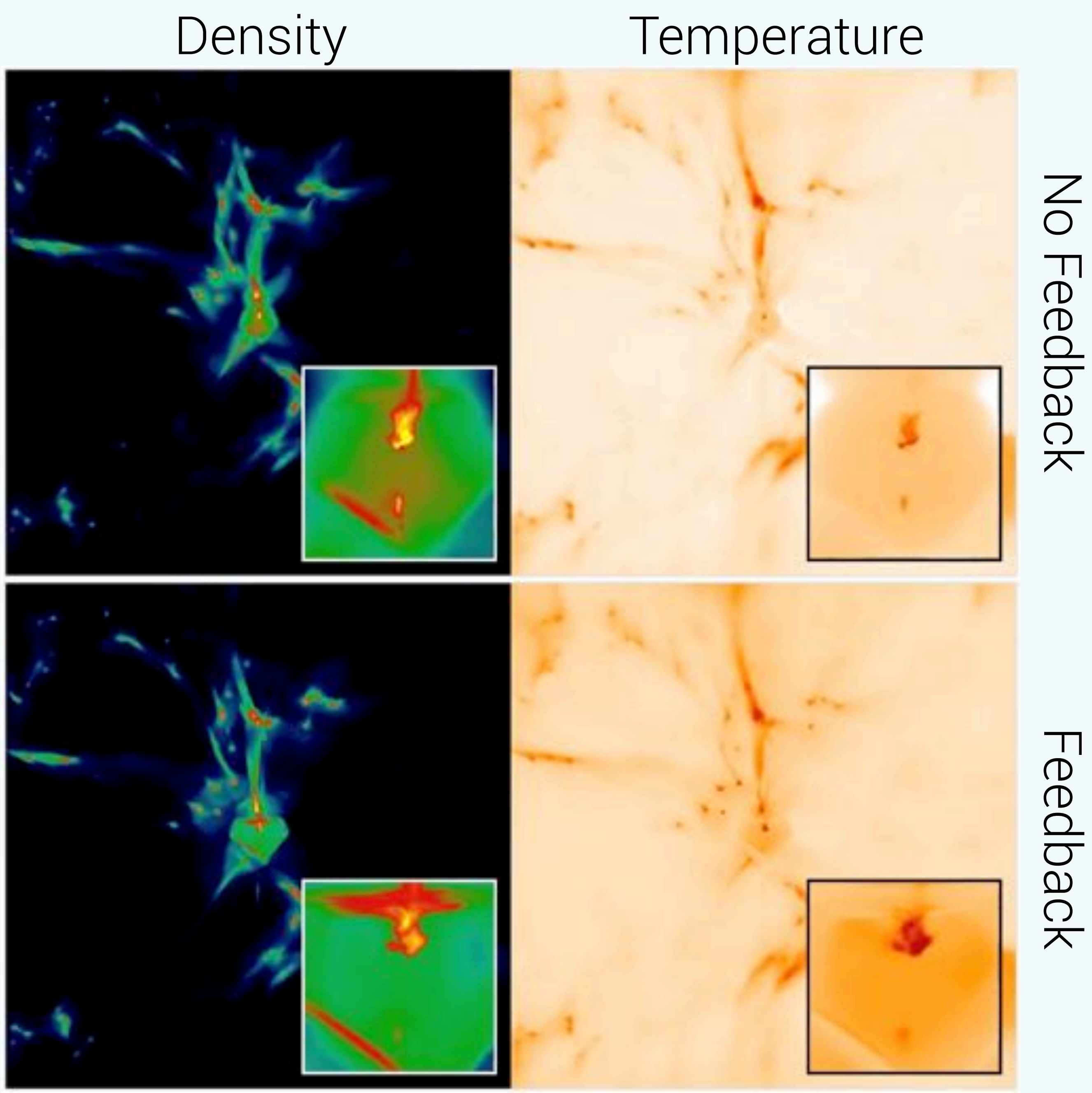


Accretion onto a Single Seed BH

Alvarez+ (2009)

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

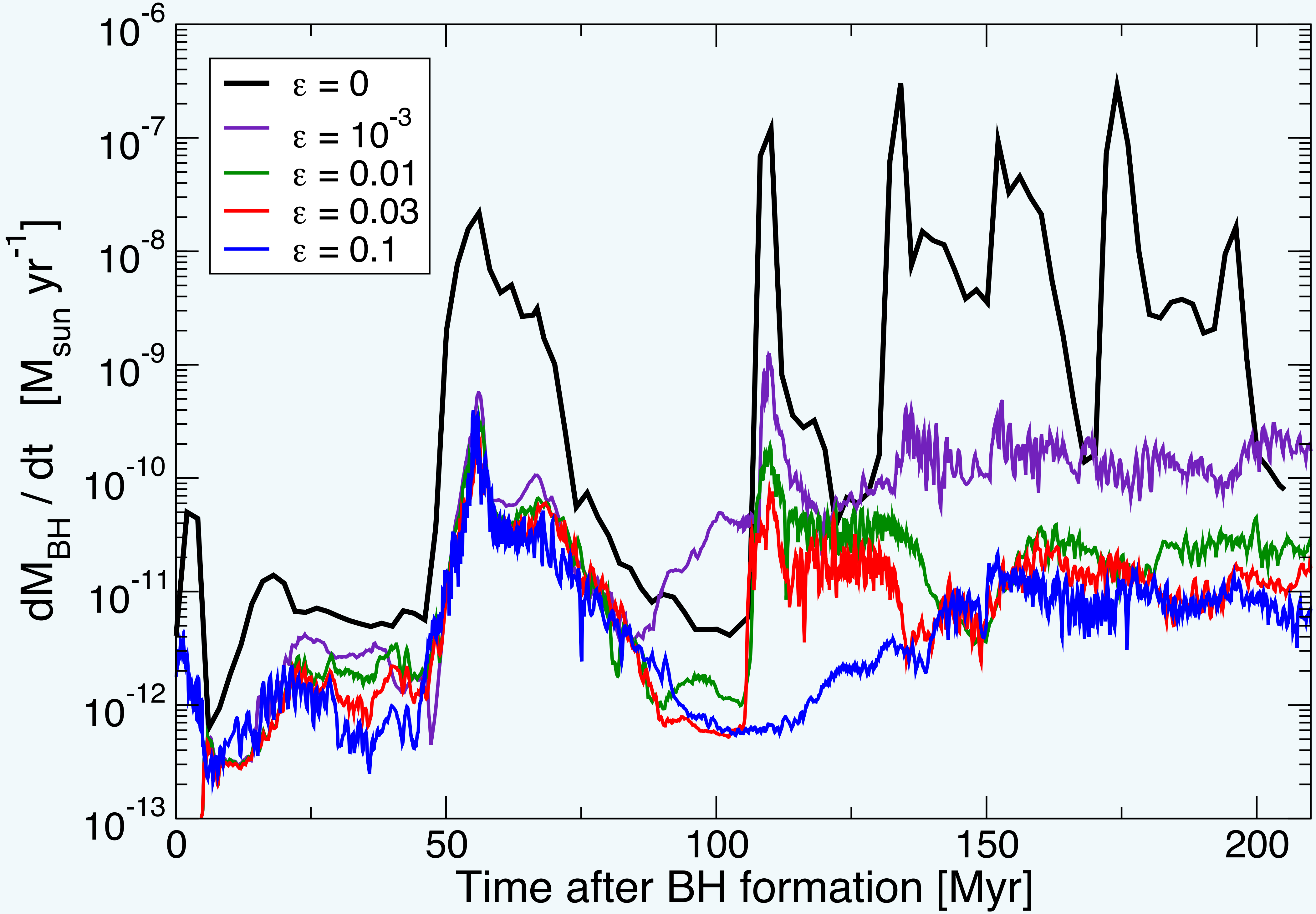
- Focus on BH accretion and radiation after main sequence in a 5 x 10^5 $M_\odot$ halo for 200 Myr.
- Initial BH mass = 100 $M_\odot$
- Assume Bondi-Hoyle accretion. Simulation resolves the Bondi radius.
- <1 $M_\odot$ of accretion as the halo grows by a factor of 10.



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

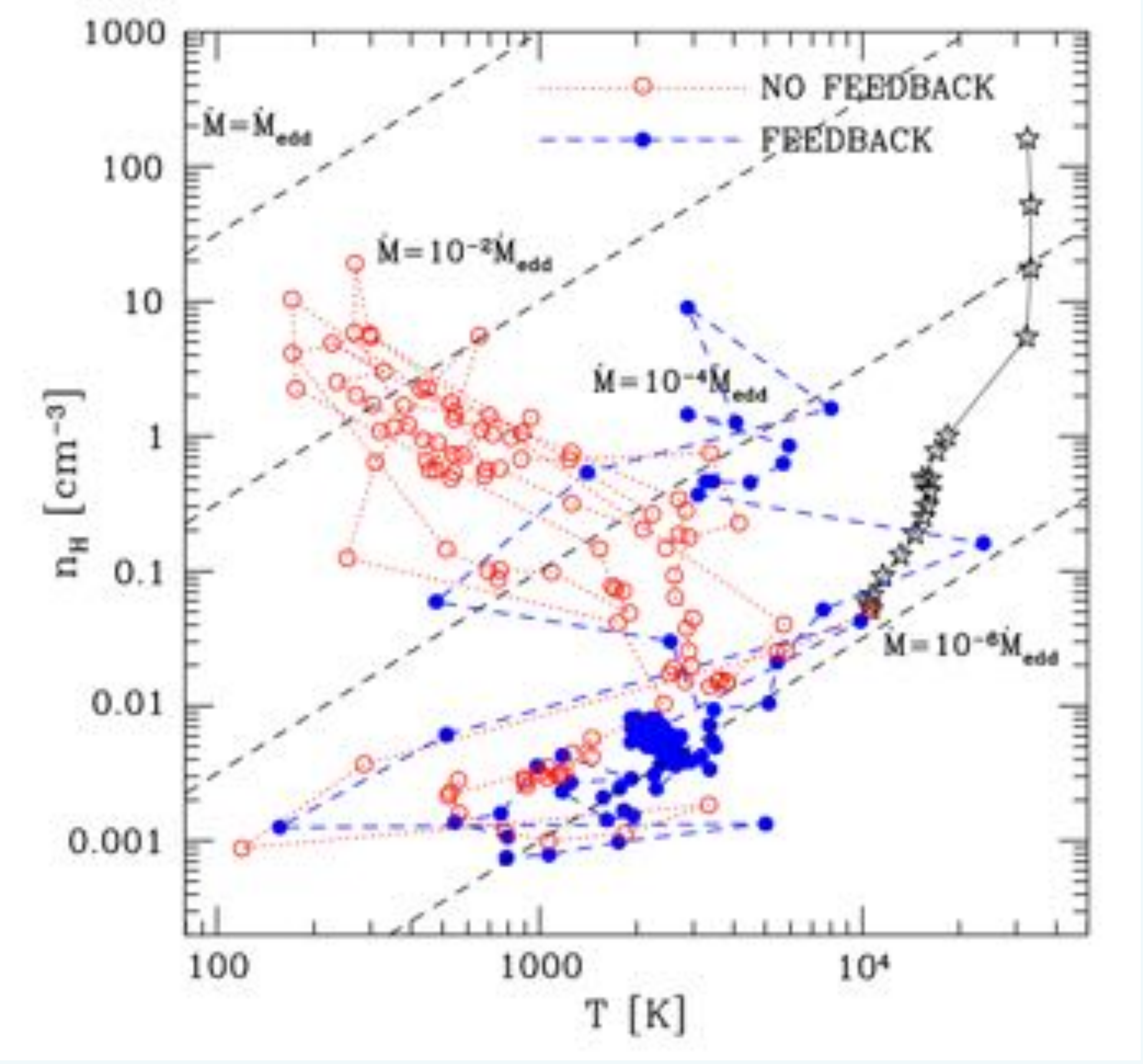
Accretion onto a Single BH

Effects of X-ray Radiative Feedback



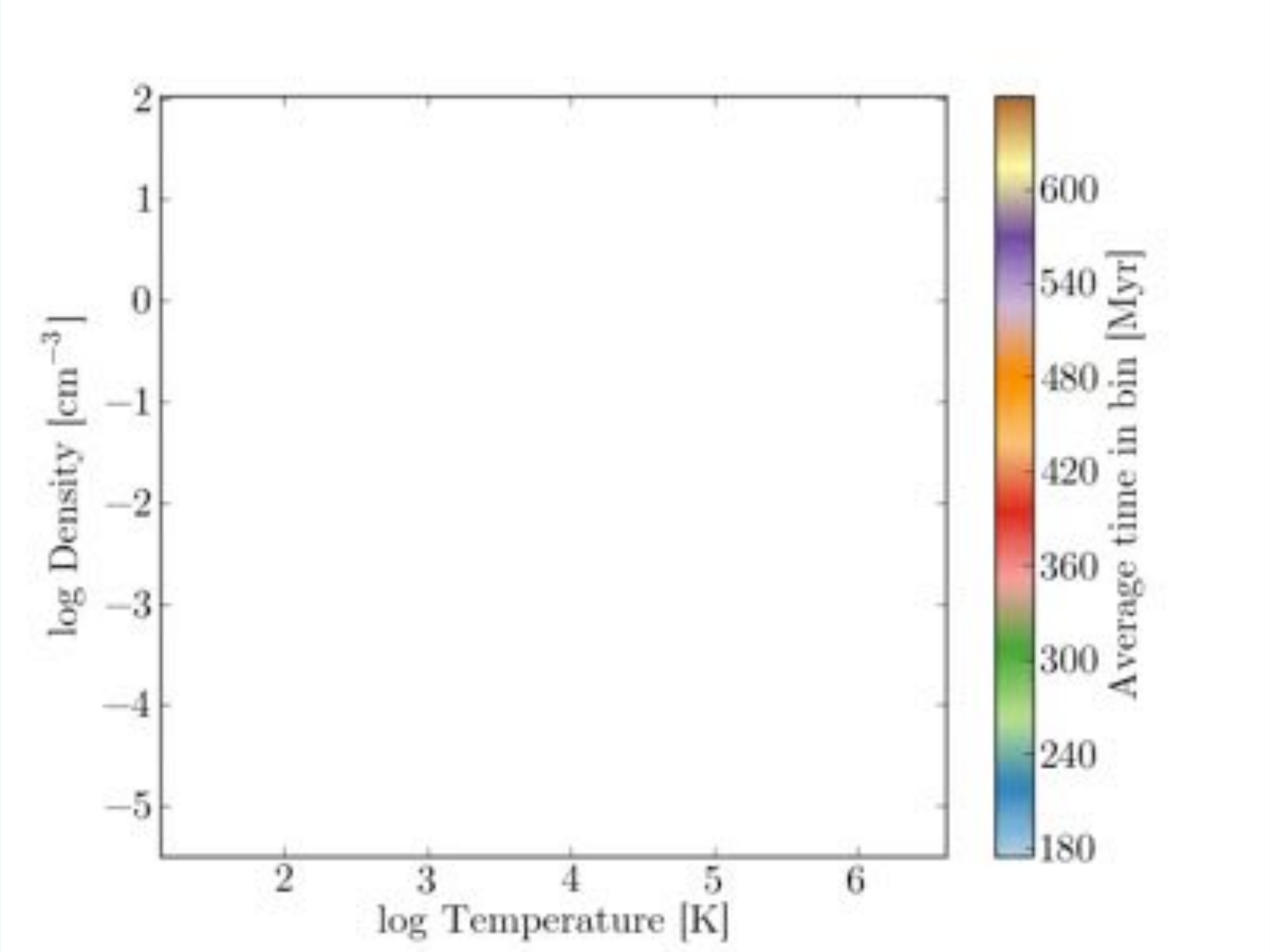
Accretion onto a Single BH
Effects of X-ray Radiative Feedback

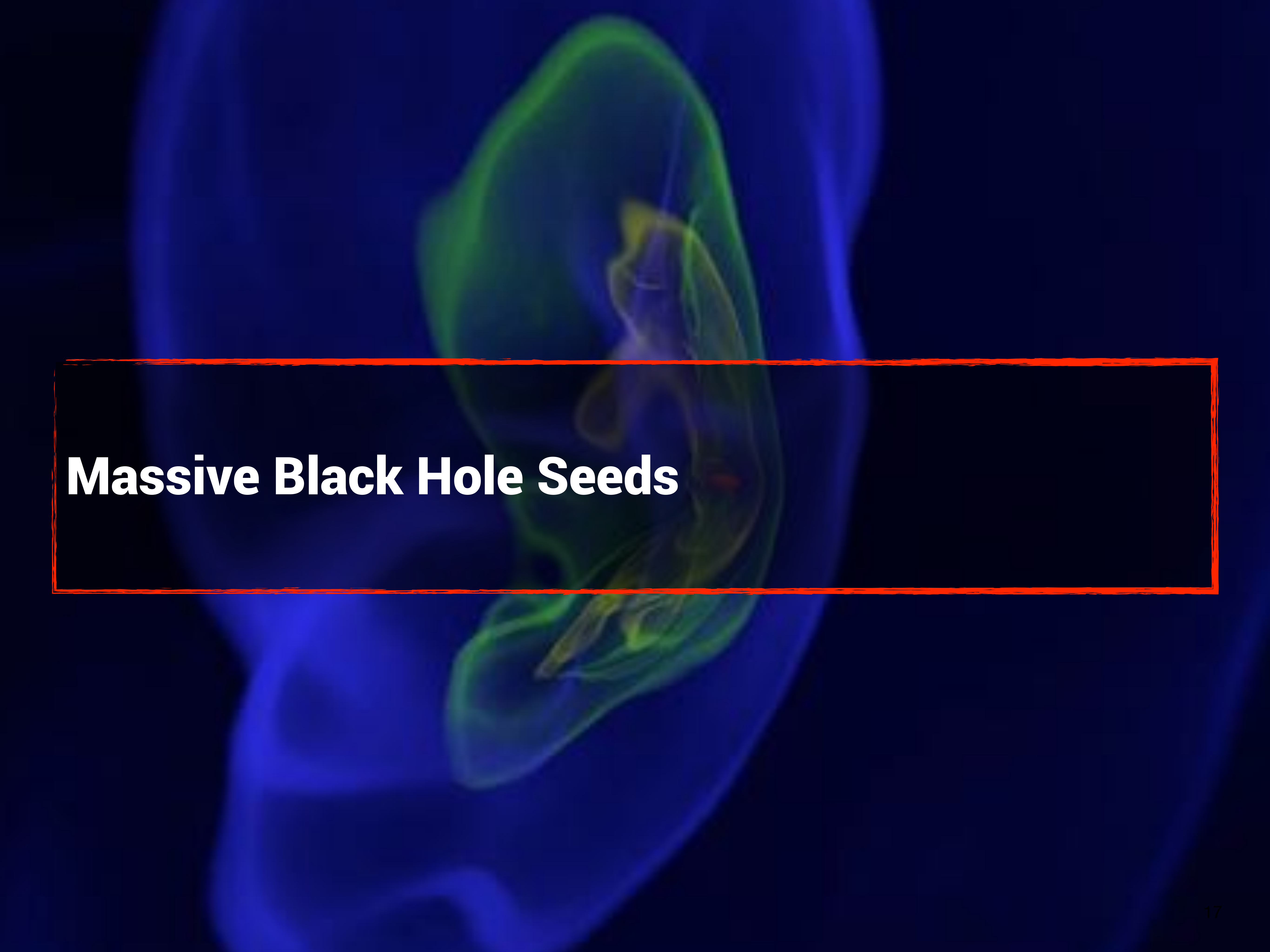
- With radiative feedback, maximum accretion rates reach are reduced by a factor of 100–10^4 to 10^{-4} $(dM/dt)_{edd}$
- Only followed the evolution up to 5 x 10^6 $M_\odot$ halo.
- Is rapid accretion possible in atomic cooling halos?



Accretion onto a Single BH

Effects of X-ray Radiative Feedback



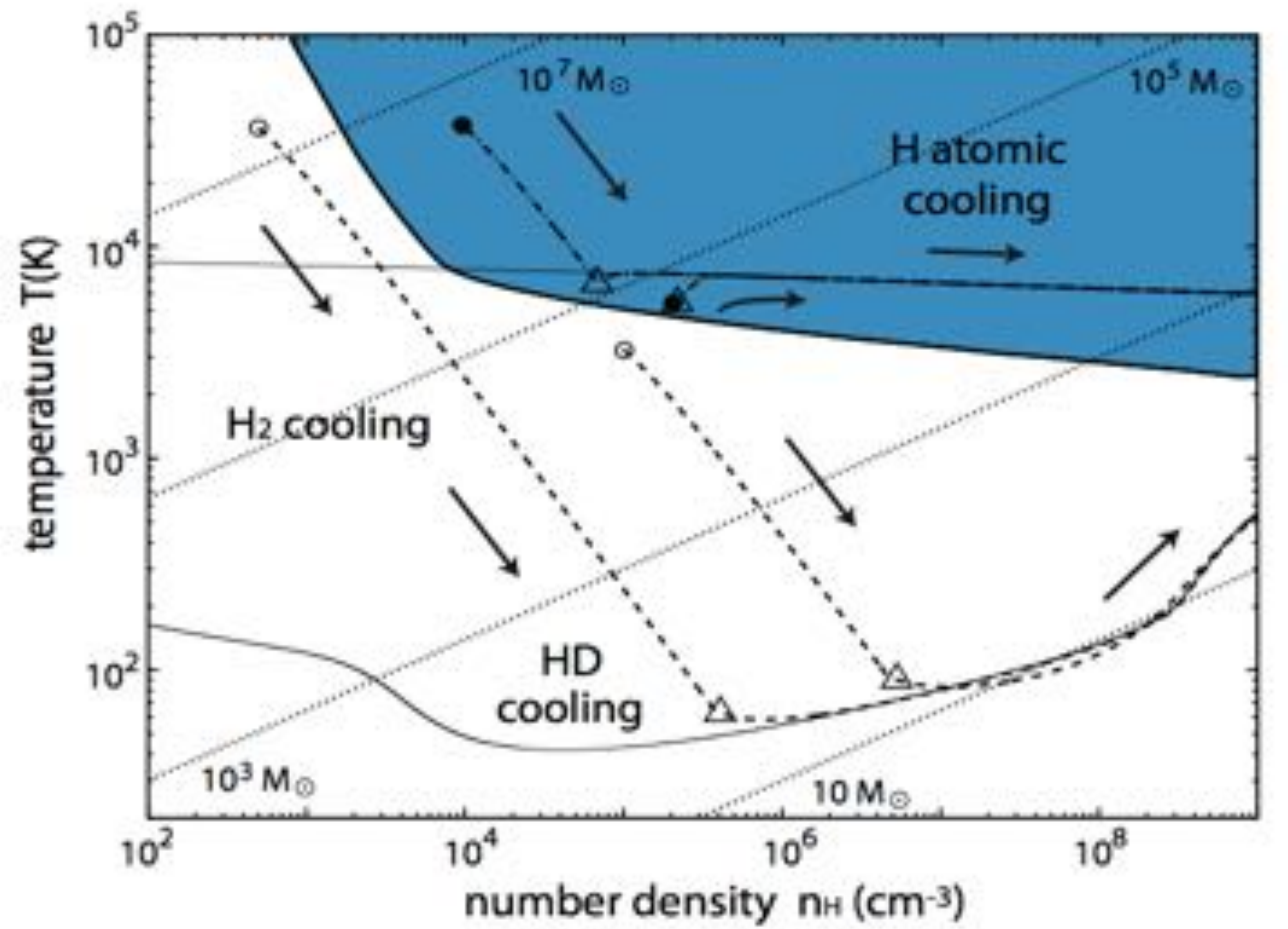


Massive Black Hole Seeds

Direct Collapse Black Hole Formation

- **"Standard" picture of DCBH formation in pre-galactic clouds**
- Isothermal collapse with T ≈ 8000 K. Requires metal-free and H_2-free gas to prevent cooling to lower temperatures.

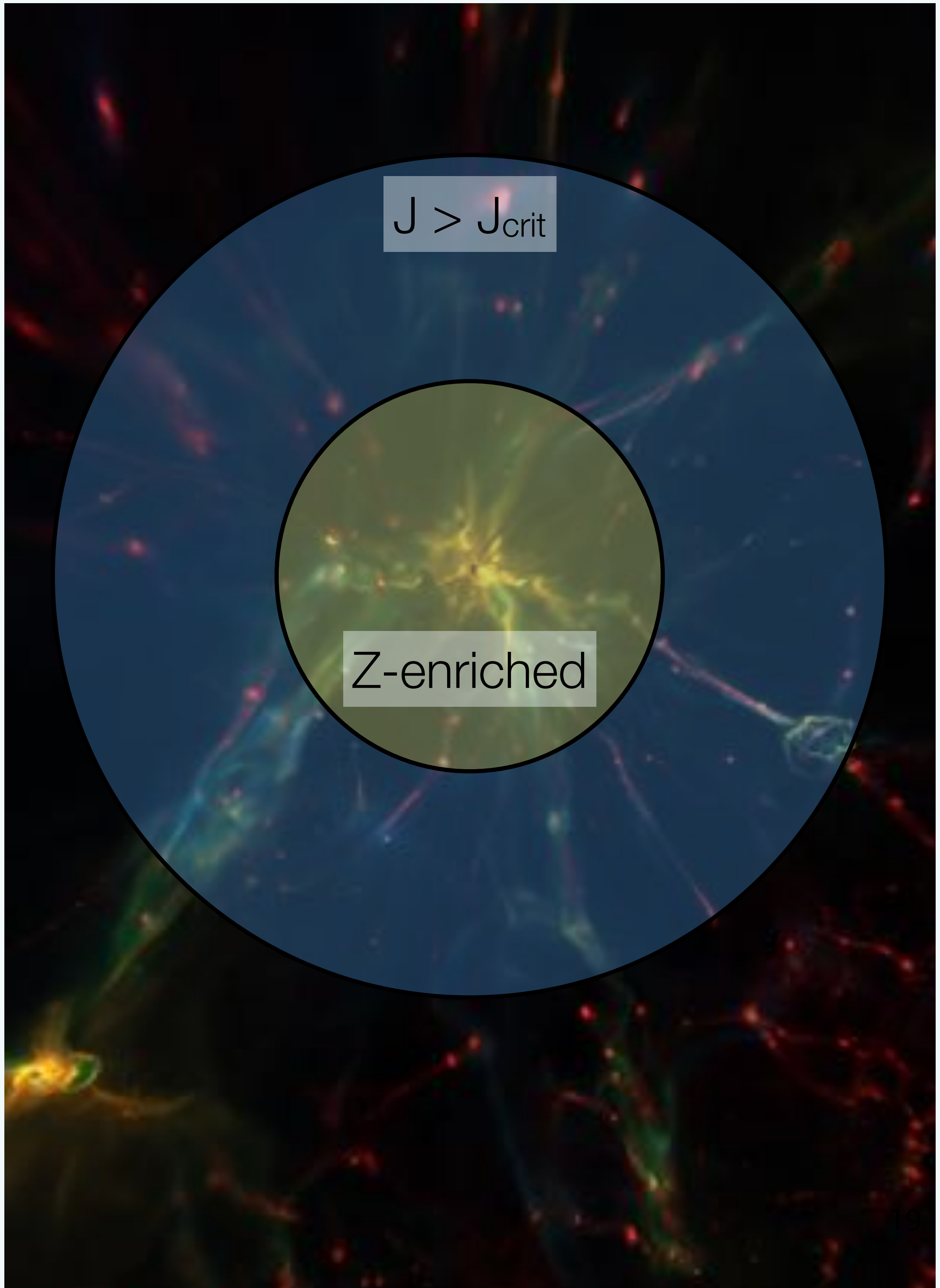
$$H + e^- \rightarrow H^- + \gamma$$
$$H^- + H \rightarrow H_2 + e^-$$



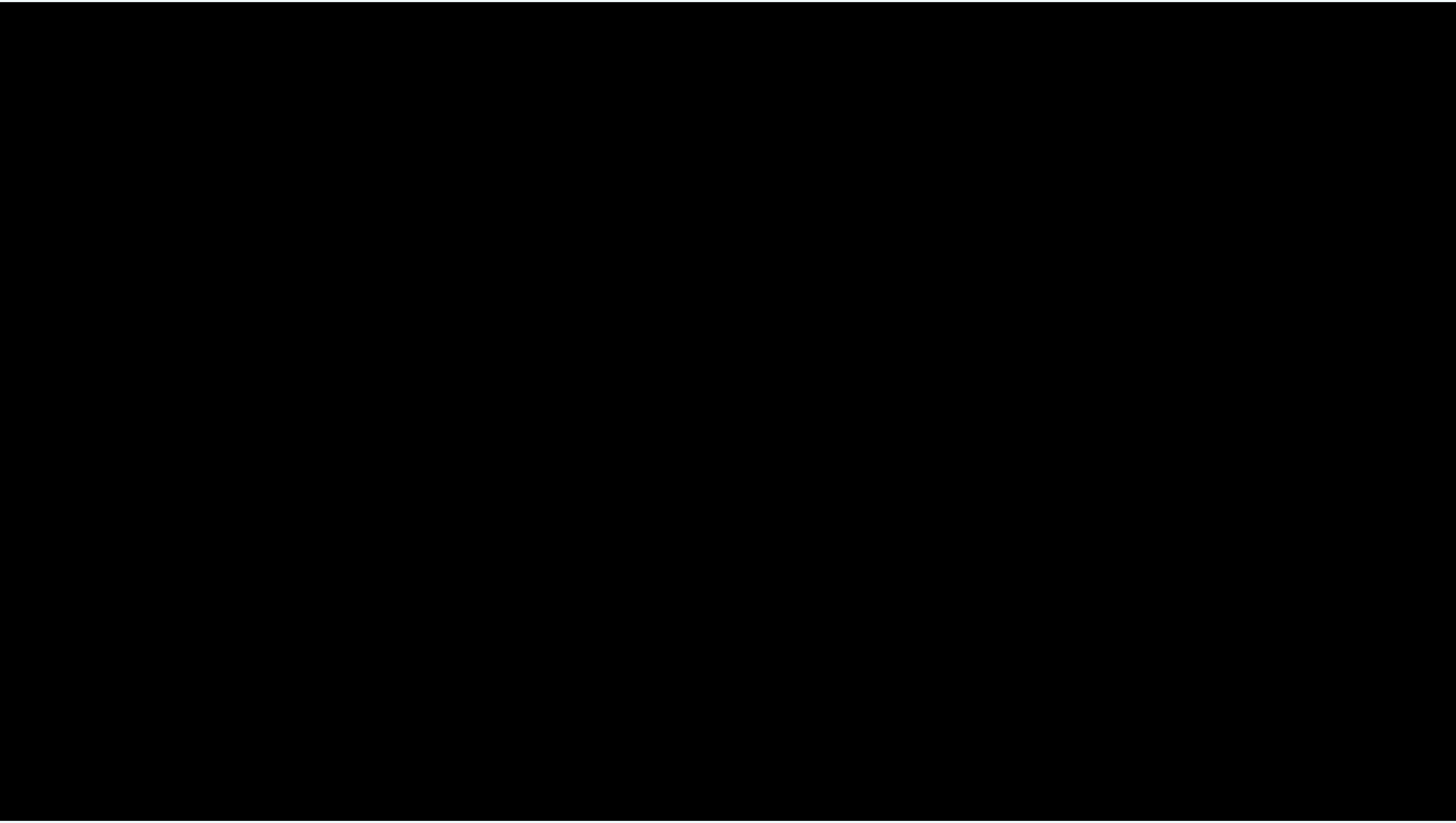
Inayoshi & Omukai (2012)

Ingredients for a DCBH host halo

- How can we have a metal-free and H_2-free halo?
  - Requires a strong UV incident field that dissociates H_2. Nearby radiation source, not a background.
  - BUT be far enough away that the halo is not metal-enriched.
- Need a Goldilocks scenario with a close pair of $T_{vir} \sim 10^4$ K halos forming (Dijkstra+ 2008; Visbal+ 2014).
- Rare but not impossible.



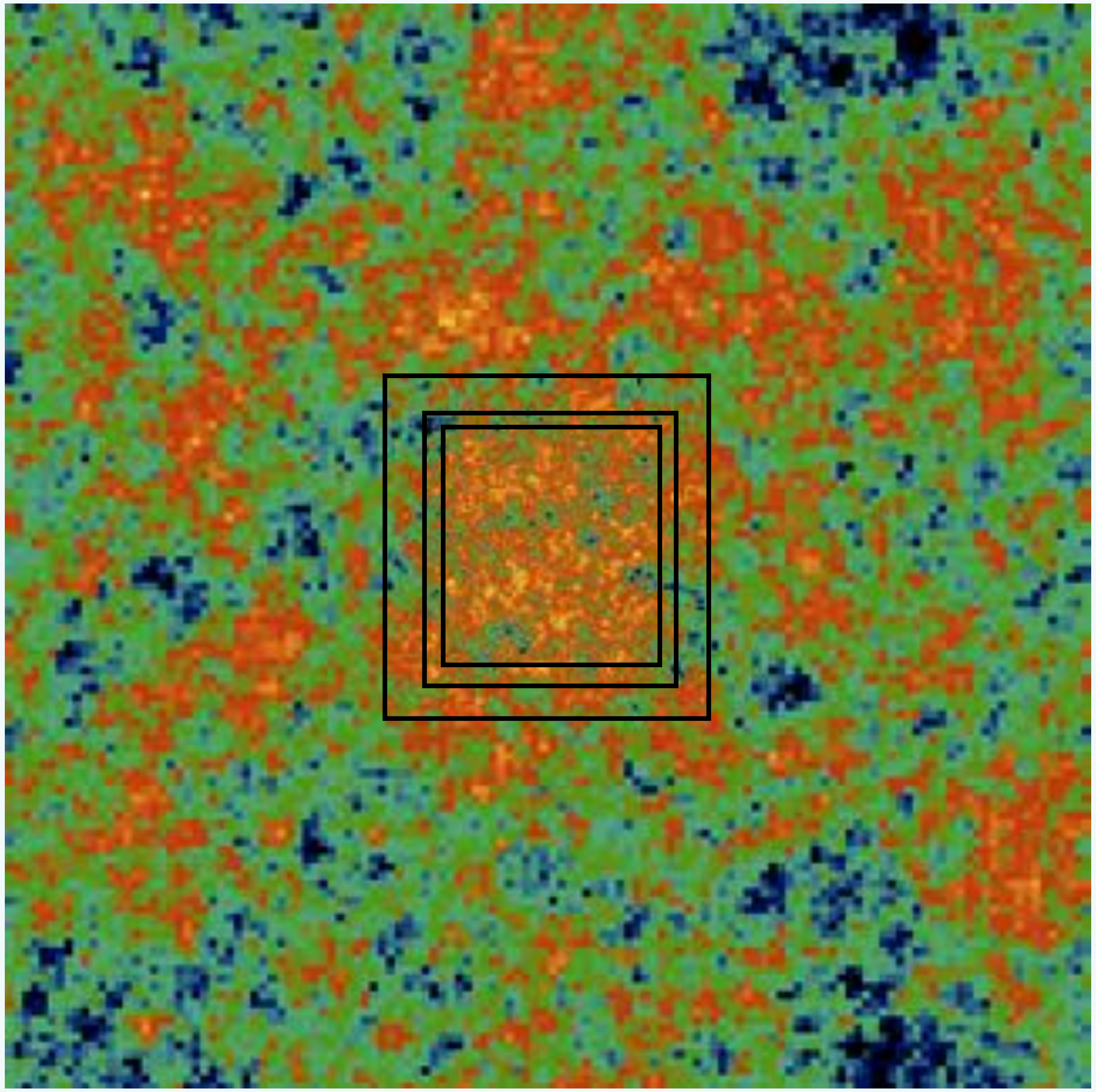
Avoiding metal enrichment?



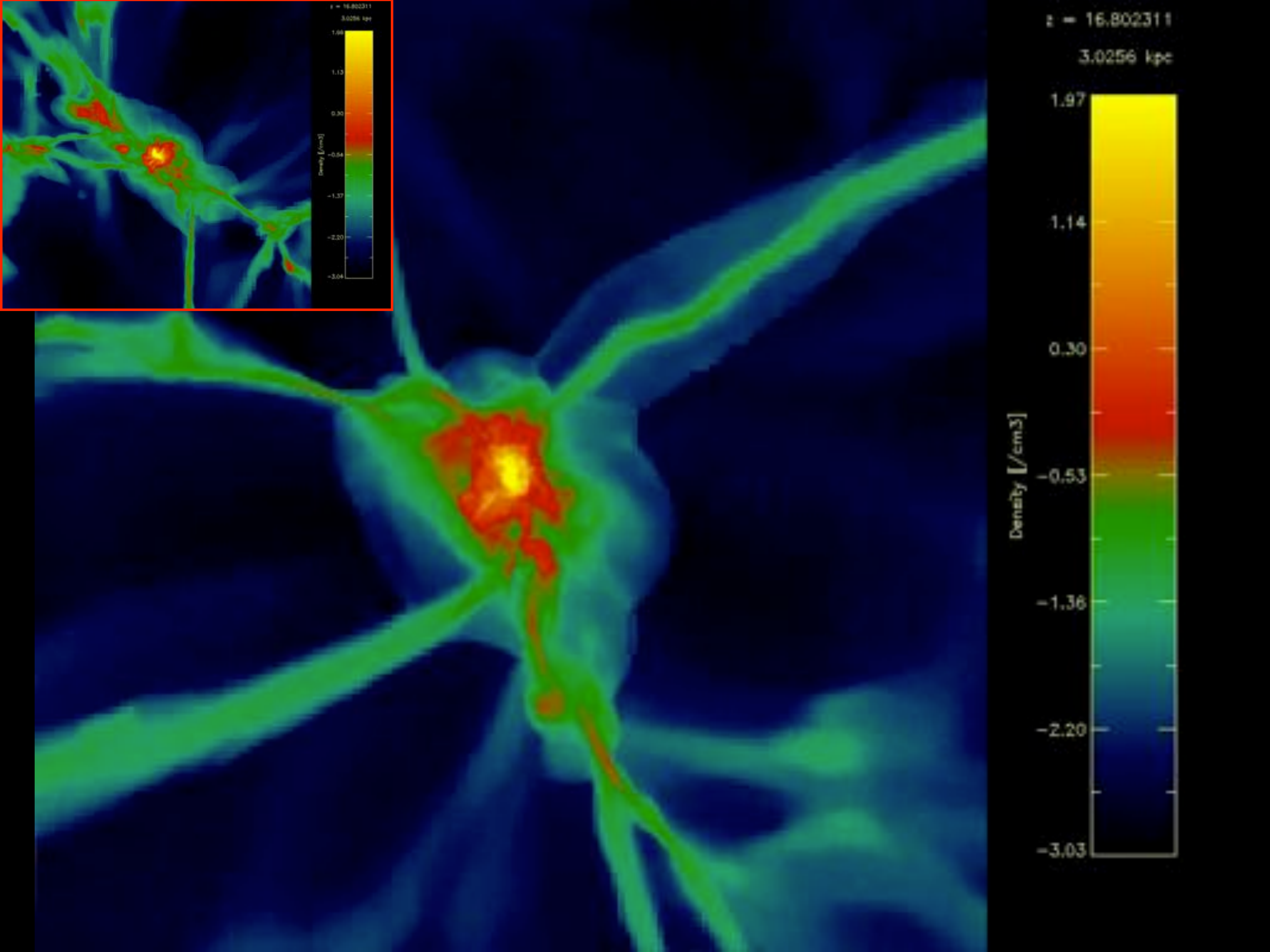
Wise, Turk, & Abel (2008)

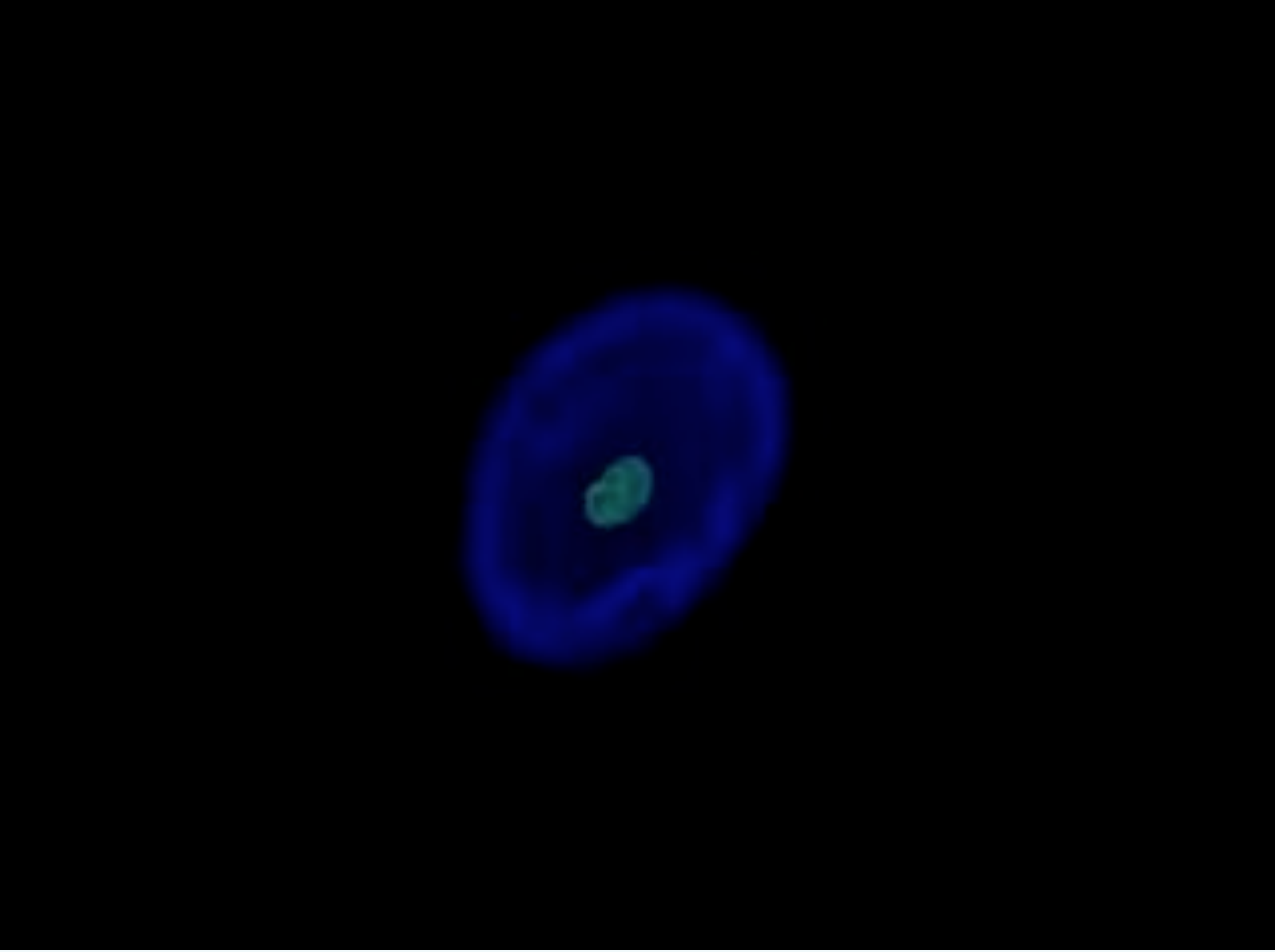
Direct BH Collapse
Simulation Setup

- Zoom-in calculation to focus on the formation of $T_{vir} = 10^4$ K halo.
- Idealized with only atomic H/He cooling (emulates a very strong dissociating UV background)
- $(1.5\ \mathrm{Mpc})^3$ volume
- DM mass resolution: 100 $M_\odot$
- Max AMR level: 41 (dx = 0.01 $R_\odot$)

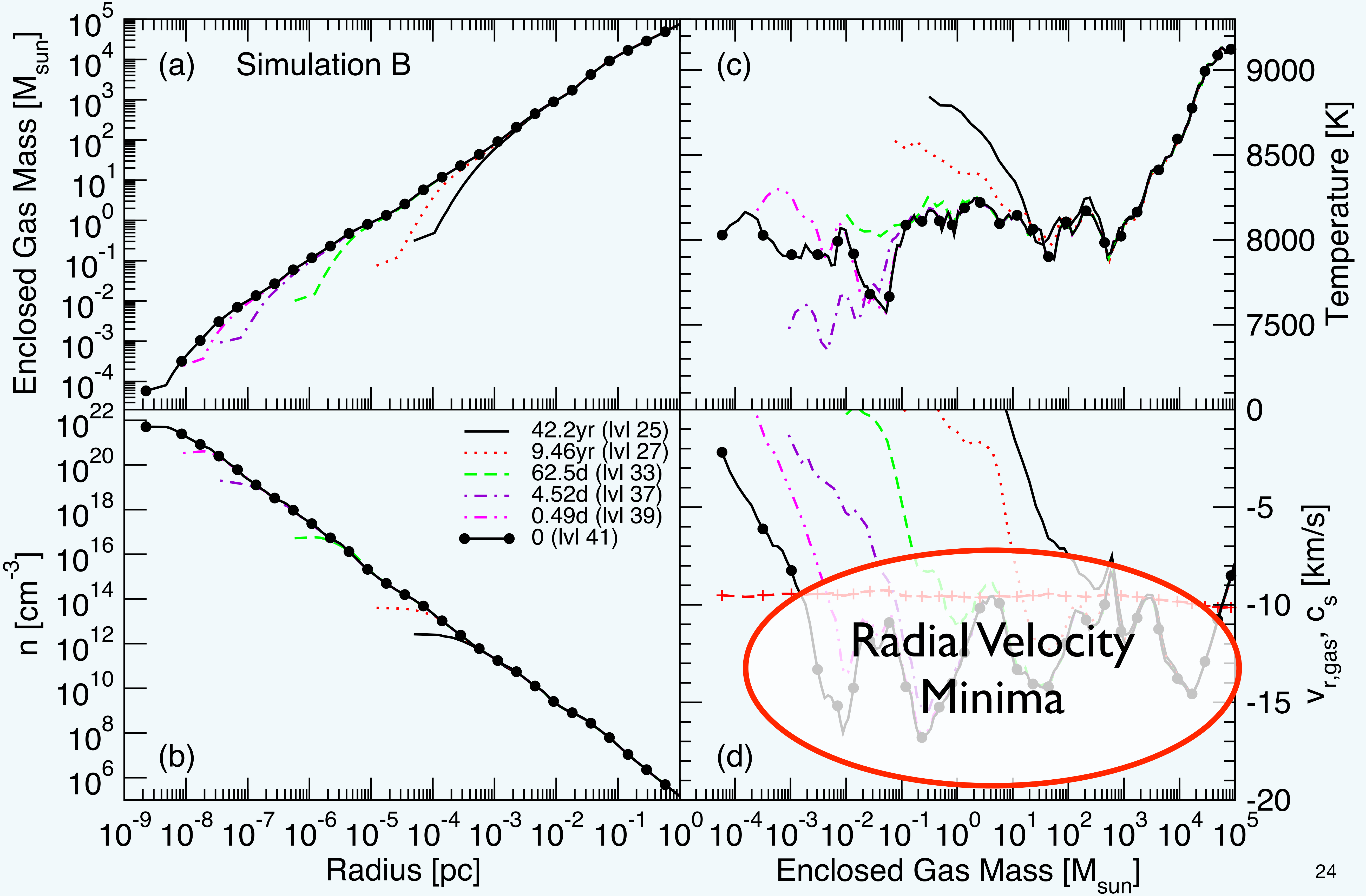


円相 Enzo

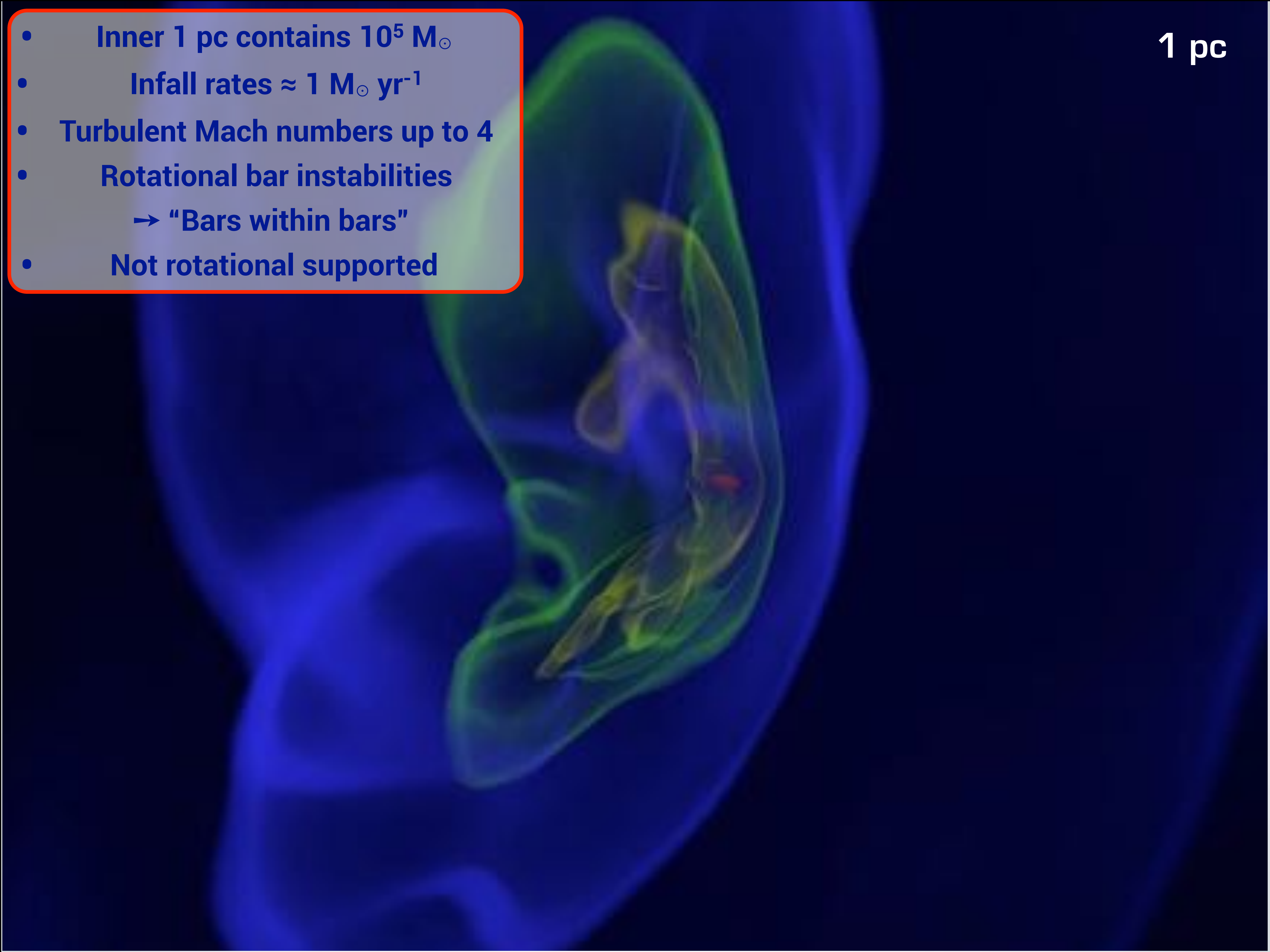

z = 16.802311
3.0256 kpc
1.97
1.14
0.30
−0.53
−1.36
−2.20
−3.03
Density [/cm3]



Turbulent Gravitational Collapse



- Inner 1 pc contains 10^5 $M_\odot$
- Infall rates ≈ 1 $M_\odot$ yr^{-1}
- Turbulent Mach numbers up to 4
- Rotational bar instabilities
  → "Bars within bars"
- Not rotational supported



Massive BH Seed Formation
Working past the ideal case

- **Strong UV background** with self-shielding: H_2 dissociation and H^- photo-detachment (e.g. Shang et al. 2010; Wolcott-Green & Haiman 2012; Regan, Johansson, & Wise 2014).

- **Lyman-α trapping** above $n \sim 10^6$ cm^{-3}. Can be modeled with an effective equation of state (Spaans & Silk 2006; Schleicher et al. 2010). Or can we directly compute the radiative transfer? Graduate student Qi Ge is working on an approximate Lyman-α radiation transport scheme in the optically-thick regime.

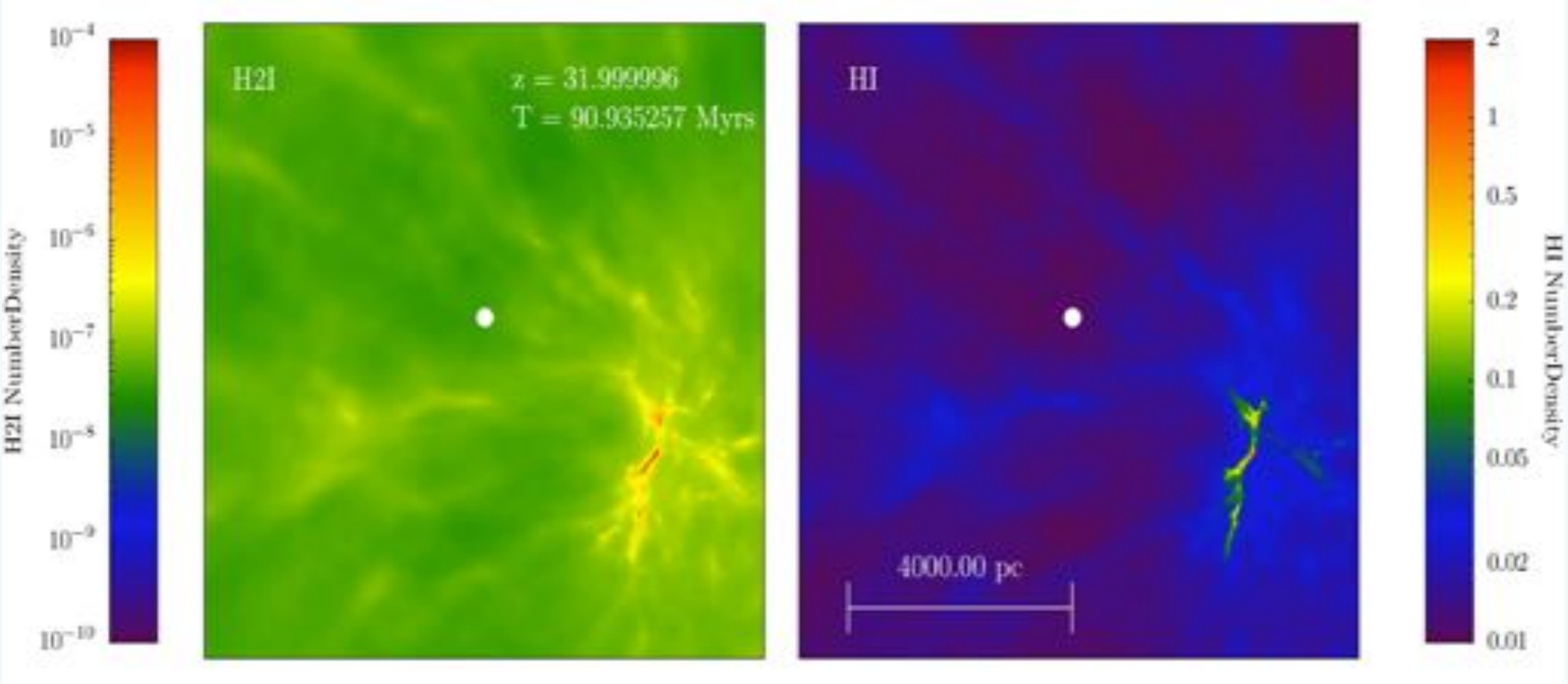
- **Magnetic fields** suppressing fragmentation? (Latif et al. 2013)

- Intermediate stage: **Supermassive (quasi-)star & supernova**? (Begelman et al. 2006; Hosokawa et al. 2013; Heger et al. 2013).

- **Feedback** from the initial seed?

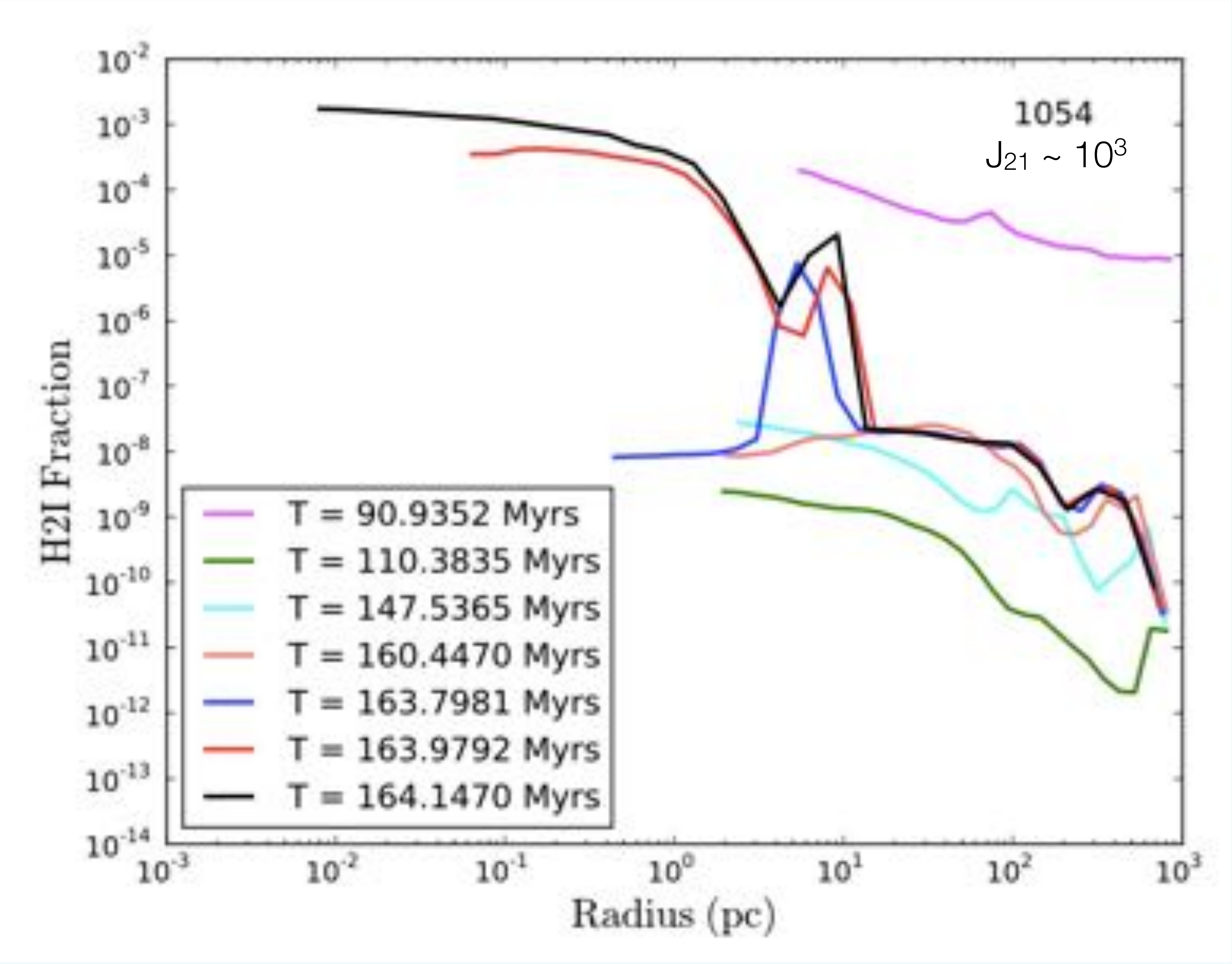
Effects of an anisotropic radiation source

- Simulation setup: 2 Mpc/h box with a 4.2-σ peak (10^6 $M_\odot$ at z=30; 6 x 10^7 $M_\odot$ at z=20).
- Emulate a nearby (3 proper kpc) galaxy with a radiation point source.
- Use radiation transport (adaptive ray tracing) for **only** Lyman-Werner photons, using the Draine & Bertoldi (1996) shielding function, corrected by Wolcott-Green (2012).



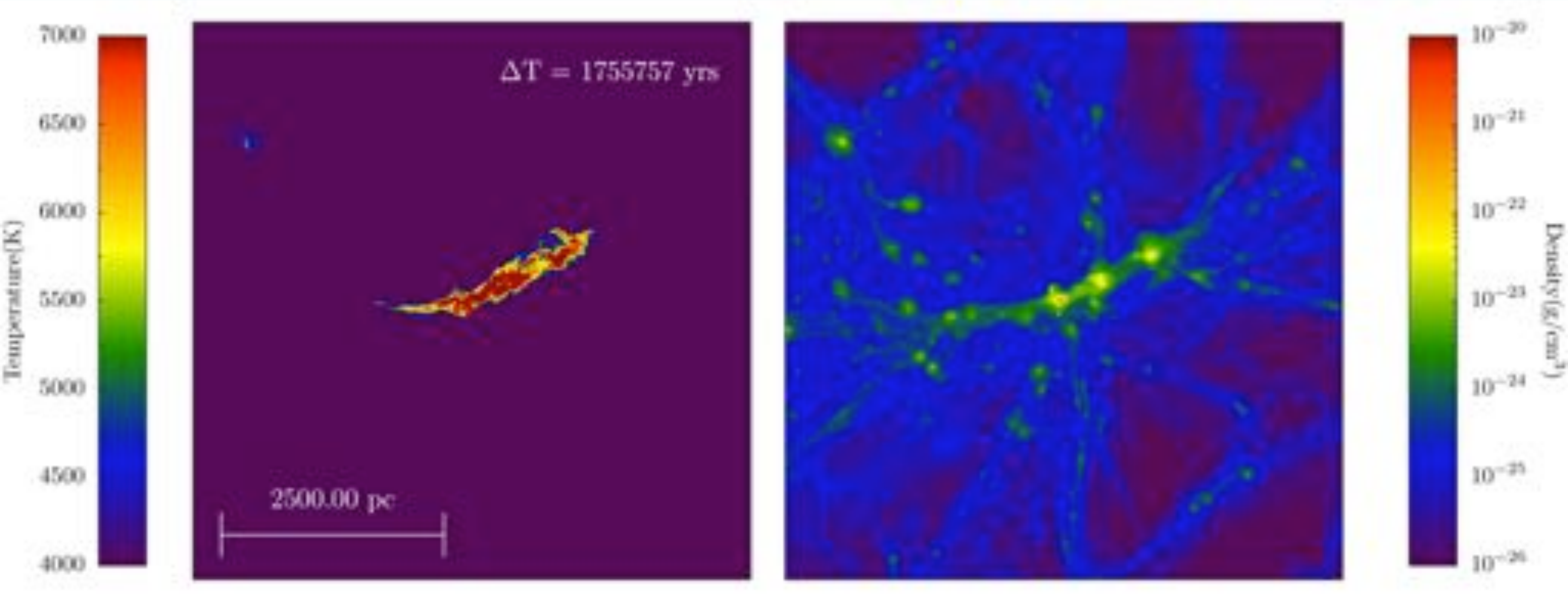
Effects of an anisotropic radiation source

- Requires a UV background intensity of $J_{21} \sim 10^3$ to suppress H_2 formation, allowing a central $10^5\ M_\odot$ Jeans unstable object to form.
- Strong accretion flows of >0.2 $M_\odot$/yr still occur with an anisotropic radiation source.



Regan, Johansson, Wise (2014)

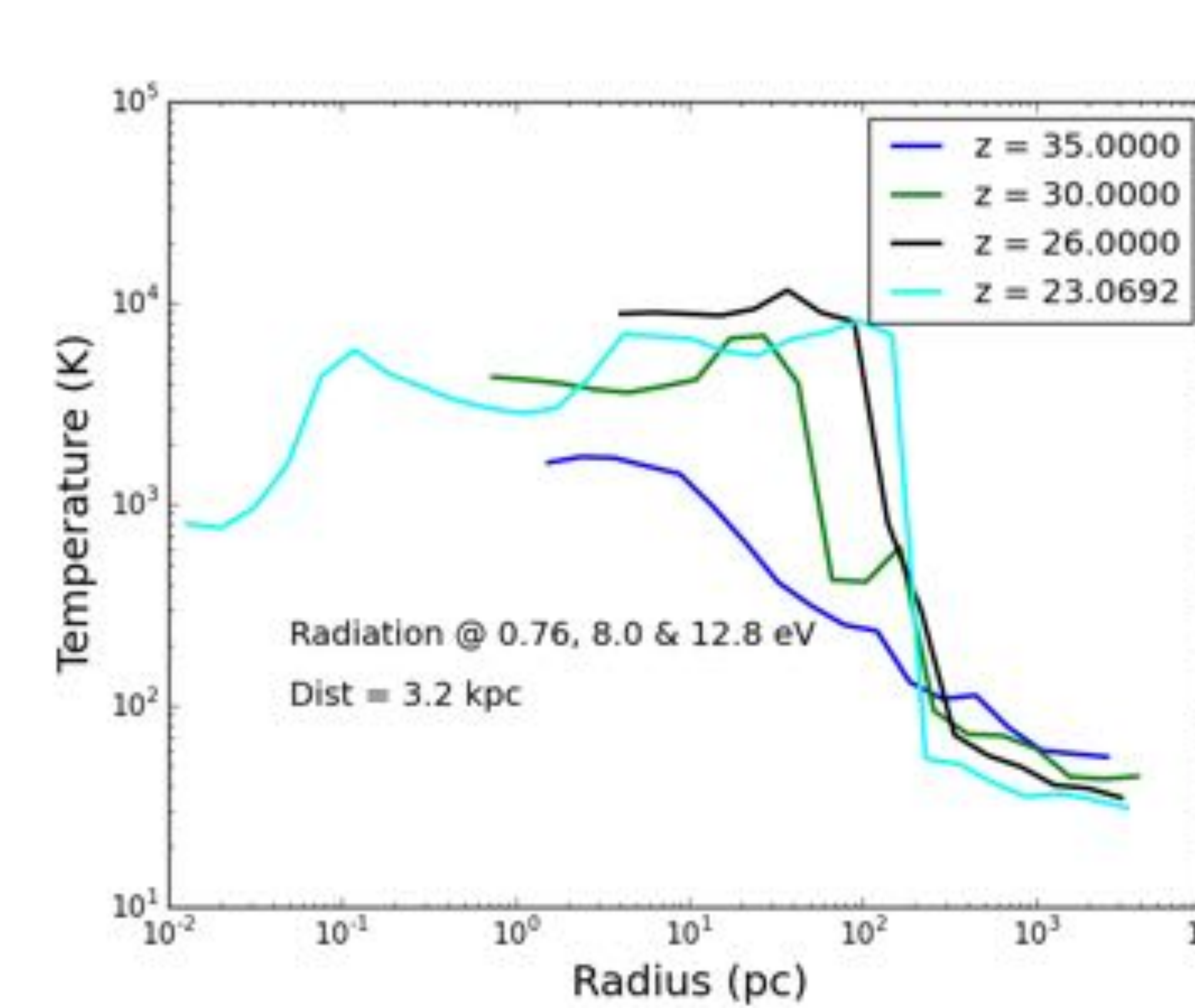
Effects of an anisotropic radiation source



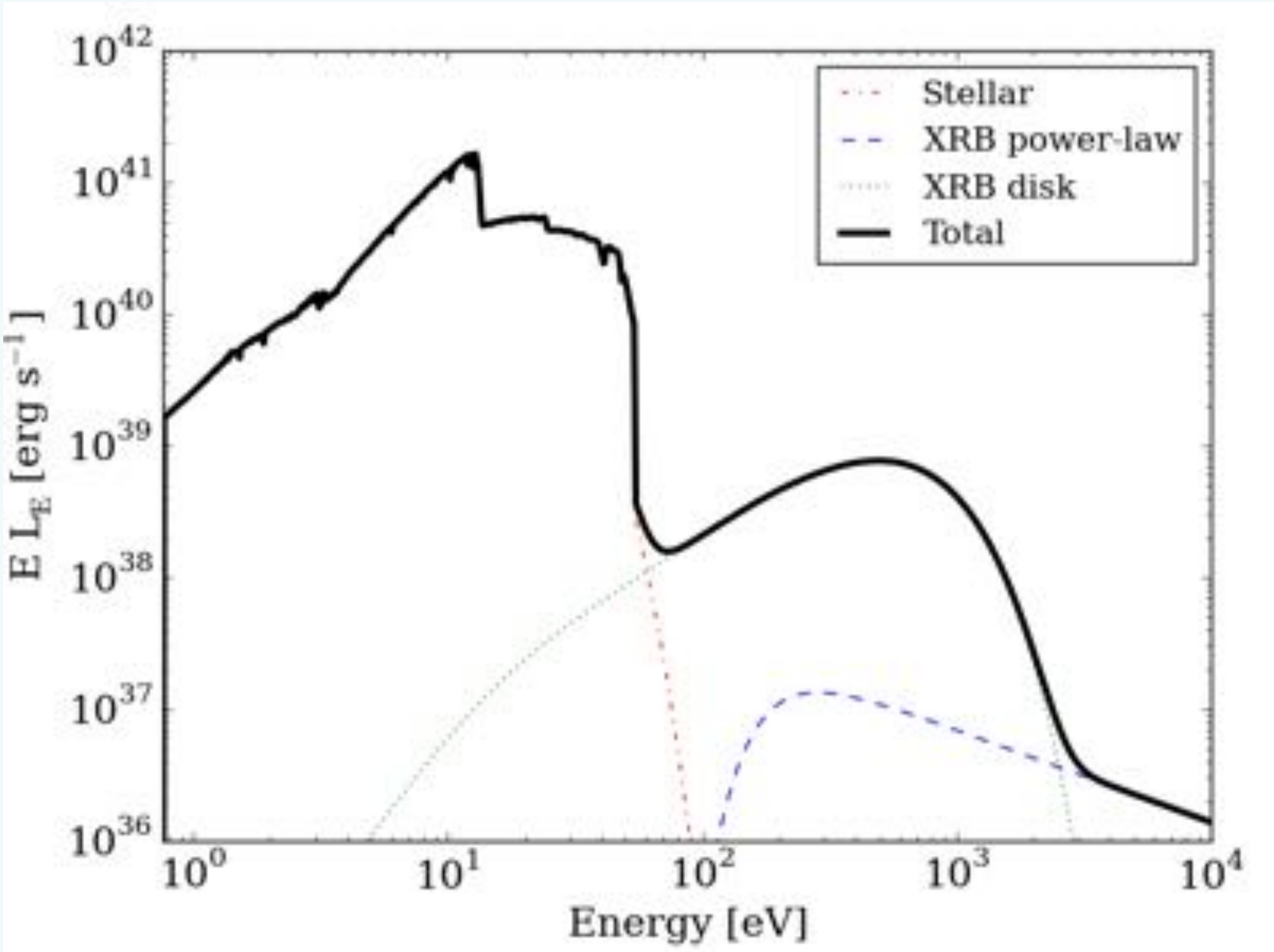
Regan, Johansson, Wise (in prep)

Preliminary results: Effects of an anisotropic radiation source with IR radiation

- Update reaction rates and include HeH^+ (Glover 2015)
- Include radiation transport of
  - H^- photo-detachment
  - H_2^+ ionizing
- Upgrade to 64-bit precision (0.4 mas vs. 26″ for 32-bit) in the adaptive ray tracing.



Next step: Realistic SED with H- and He-ionizing and X-ray radiation



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?

  - See Ayçin Aykutalp's talks on Wednesday and Thursday.

- What happens when a pre-existing BH exists in a pristine, collapsing gas cloud?

The First Galaxies

Numerical Approach
Cosmological Simulations – Enzo

円相 Enzo

enzo-project.org

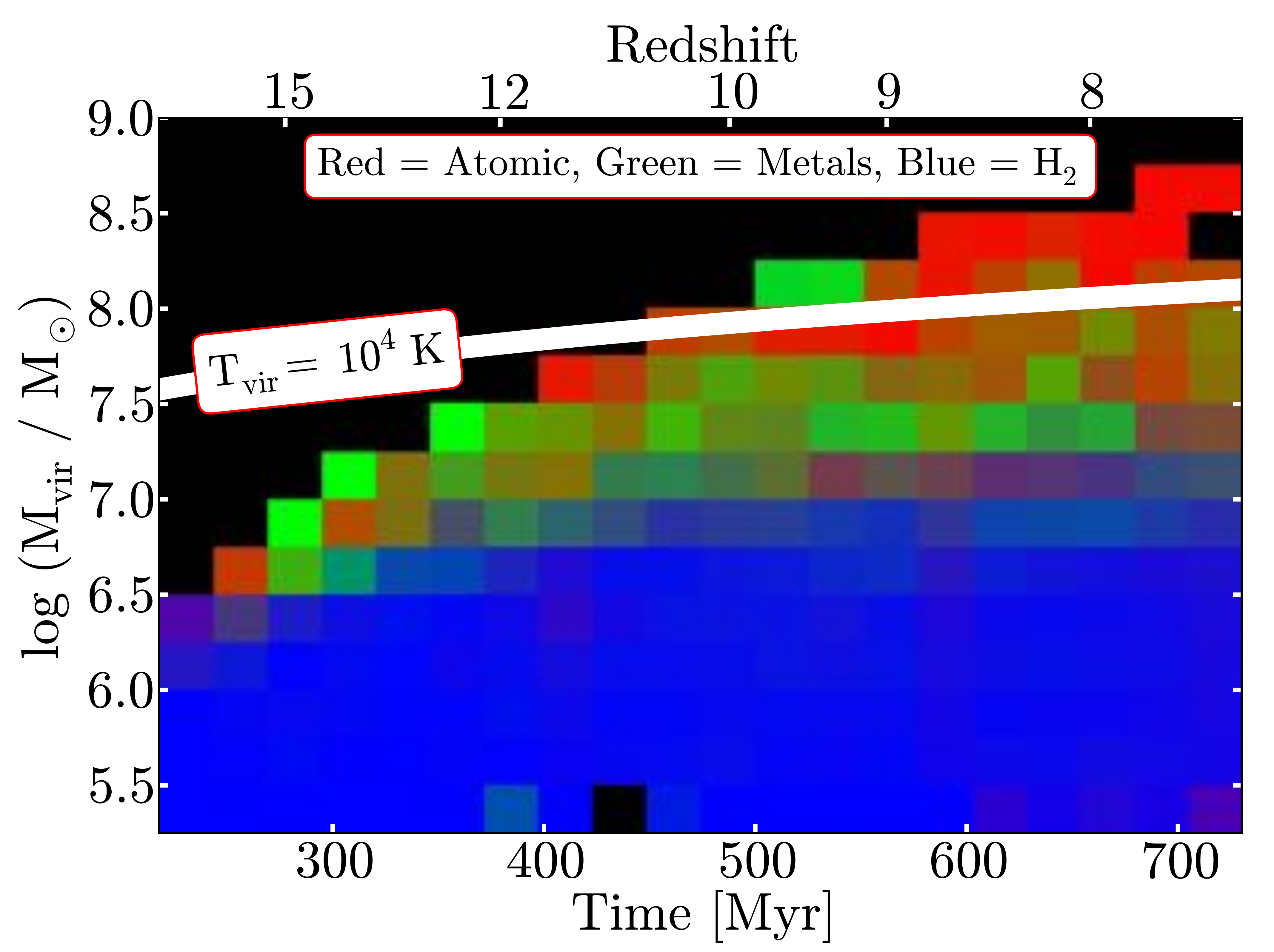
- Requirements:
  - Follows the high-z formation of a ~10^9 $M_\odot$ halo
  - Resolves the smallest (Pop III) star-forming mini-haloes (M ~ 10^5 $M_\odot$)
  - Accurate model of star formation and feedback – smaller halos are more susceptible to feedback effects.
- Approaches:
  - Small-scale boxes (< 3 comoving Mpc^3)
  - Adaptive mesh refinement (AMR)
  - Distinct modes of Population II and III star formation and feedback
  - Radiative and supernovae feedback from both populations

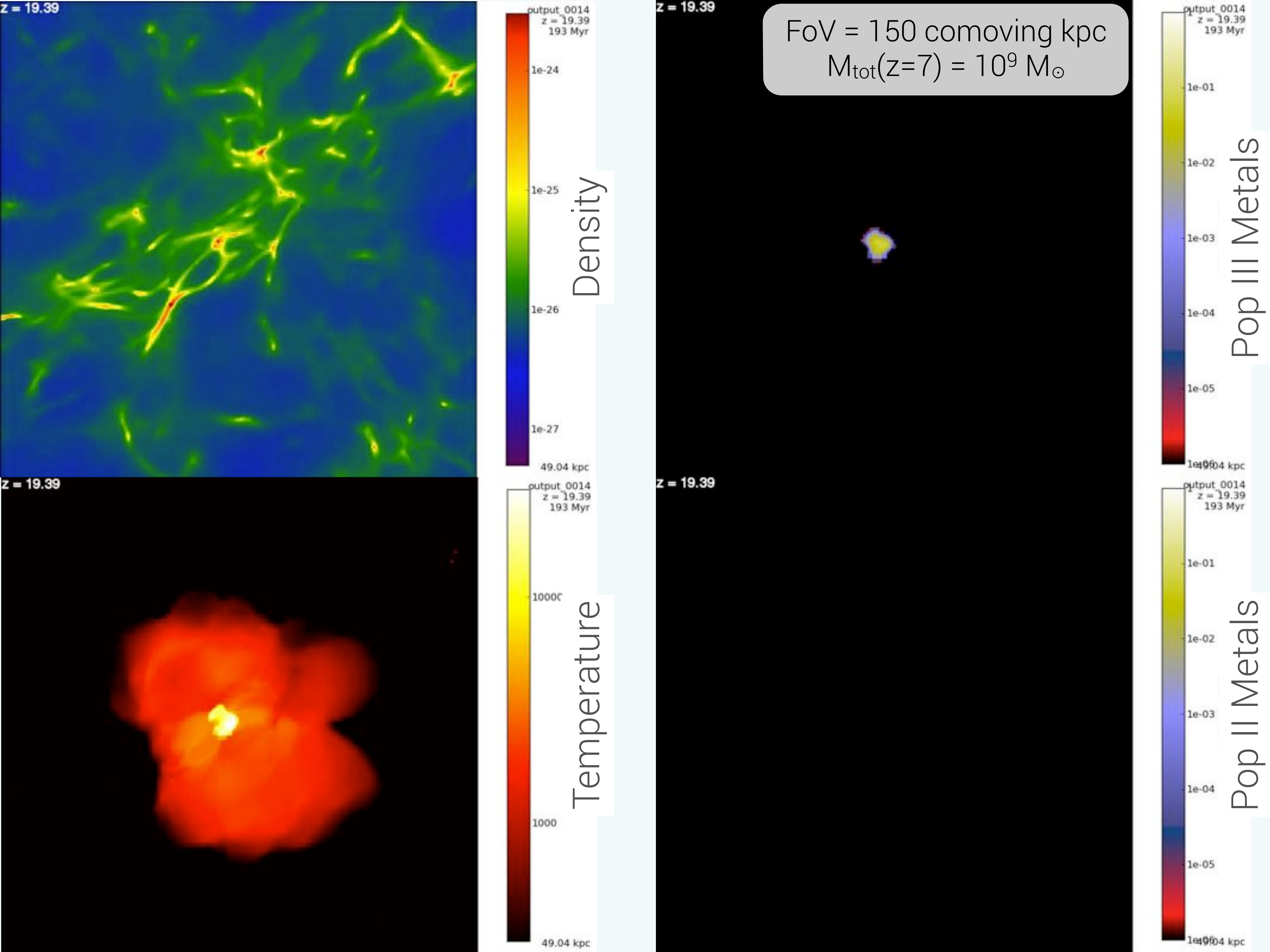
Wise et al. (2012ab, 2014)

Wise et al. (2014)

Pre-reionization dwarf galaxy properties

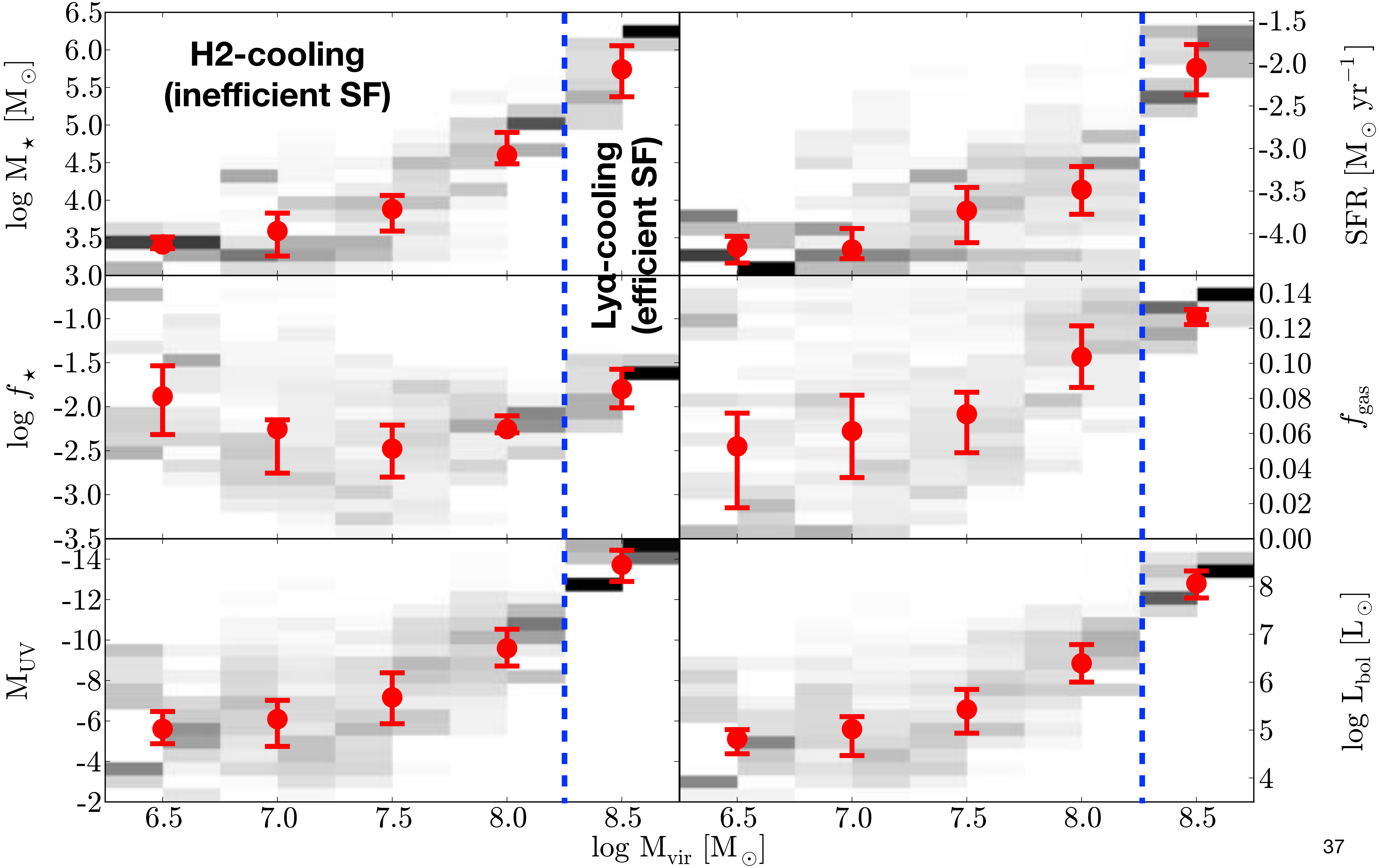
Radiative cooling agents



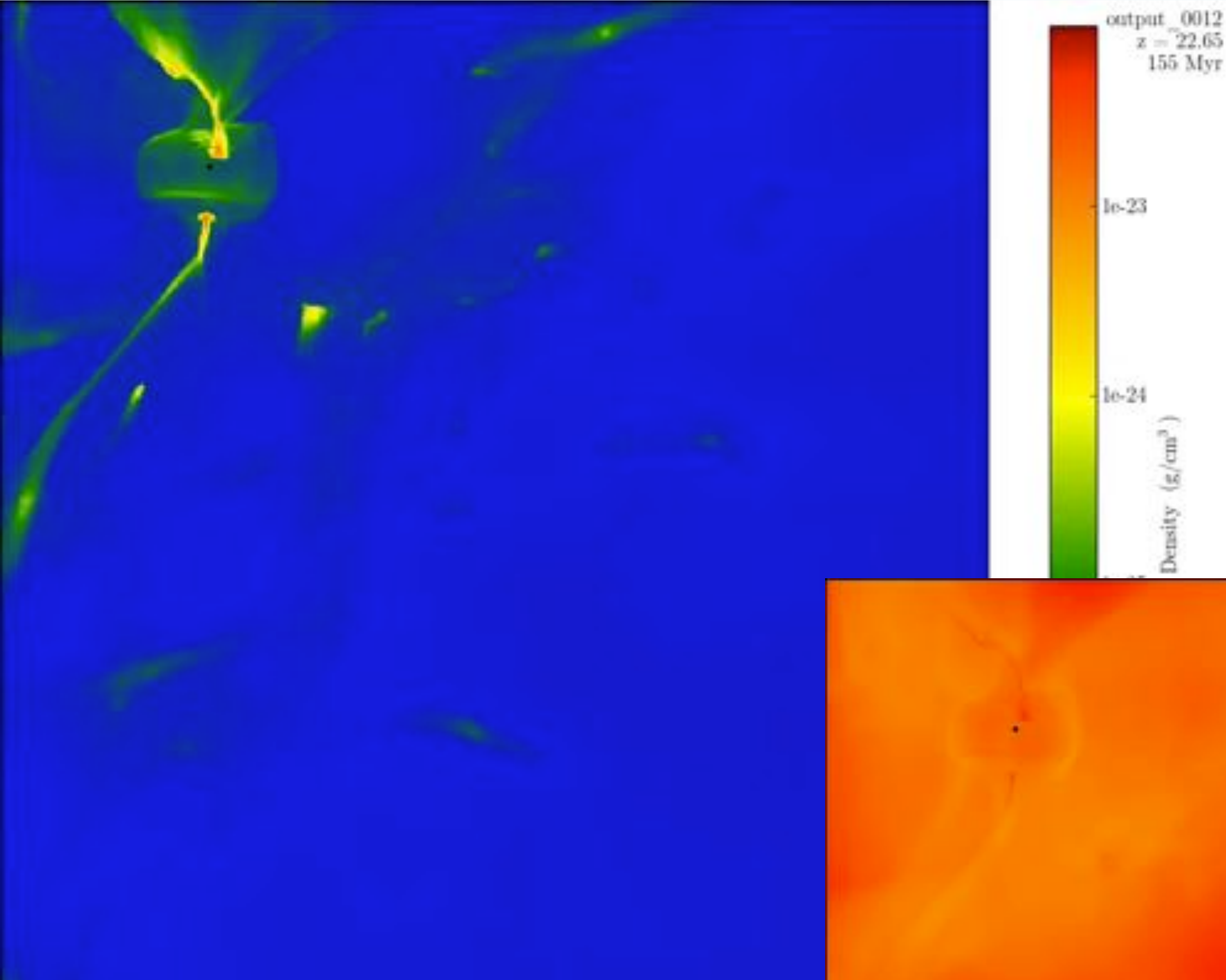


FoV = 150 comoving kpc
Mtot(z=7) = 10^9 M⊙
z = 19.39
output_0014
z = 19.39
193 Myr
1e-24
1e-25
1e-26
1e-27
49.04 kpc
Density
z = 19.39
output_0014
z = 19.39
193 Myr
1e-01
1e-02
1e-03
1e-04
1e-05
49.04 kpc
Pop III Metals
z = 19.39
output_0014
z = 19.39
193 Myr
10000
1000
49.04 kpc
Temperature
z = 19.39
output_0014
z = 19.39
193 Myr
1e-01
1e-02
1e-03
1e-04
1e-05
49.04 kpc
Pop II Metals

First galaxy properties

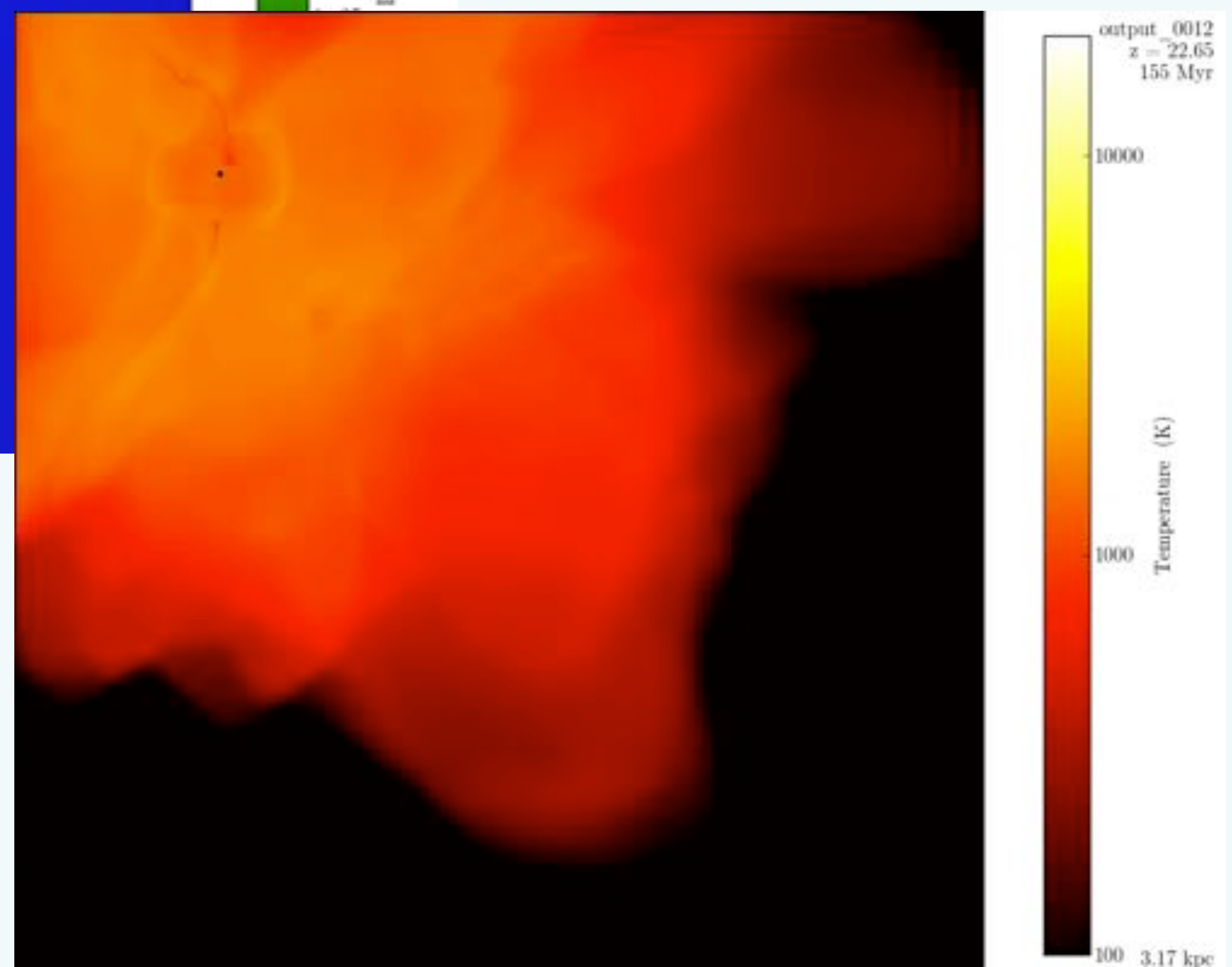


$z = 23 \rightarrow 11$
75 comoving kpc



Projected Density
Black dots = BHs

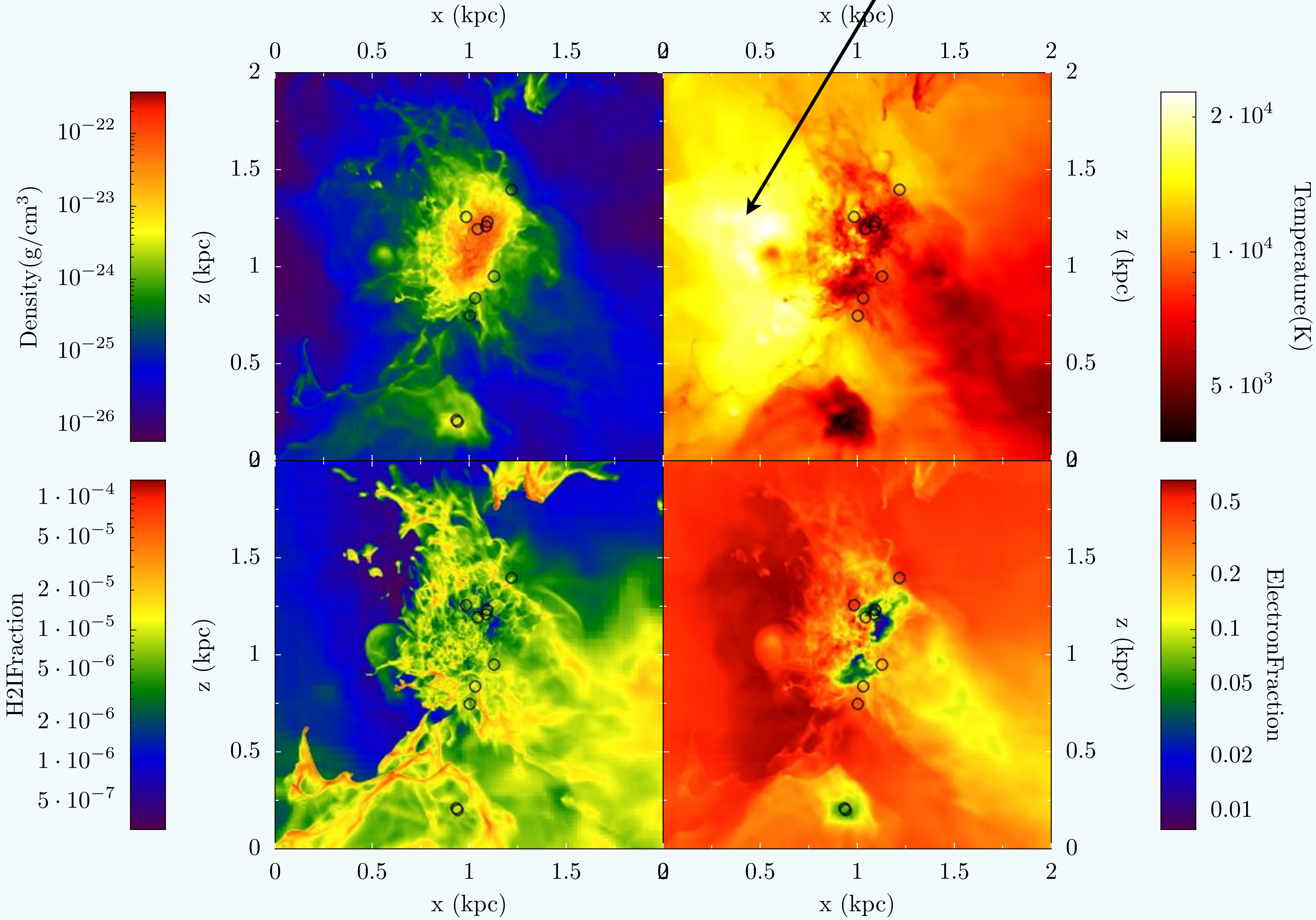
Projected Temp.



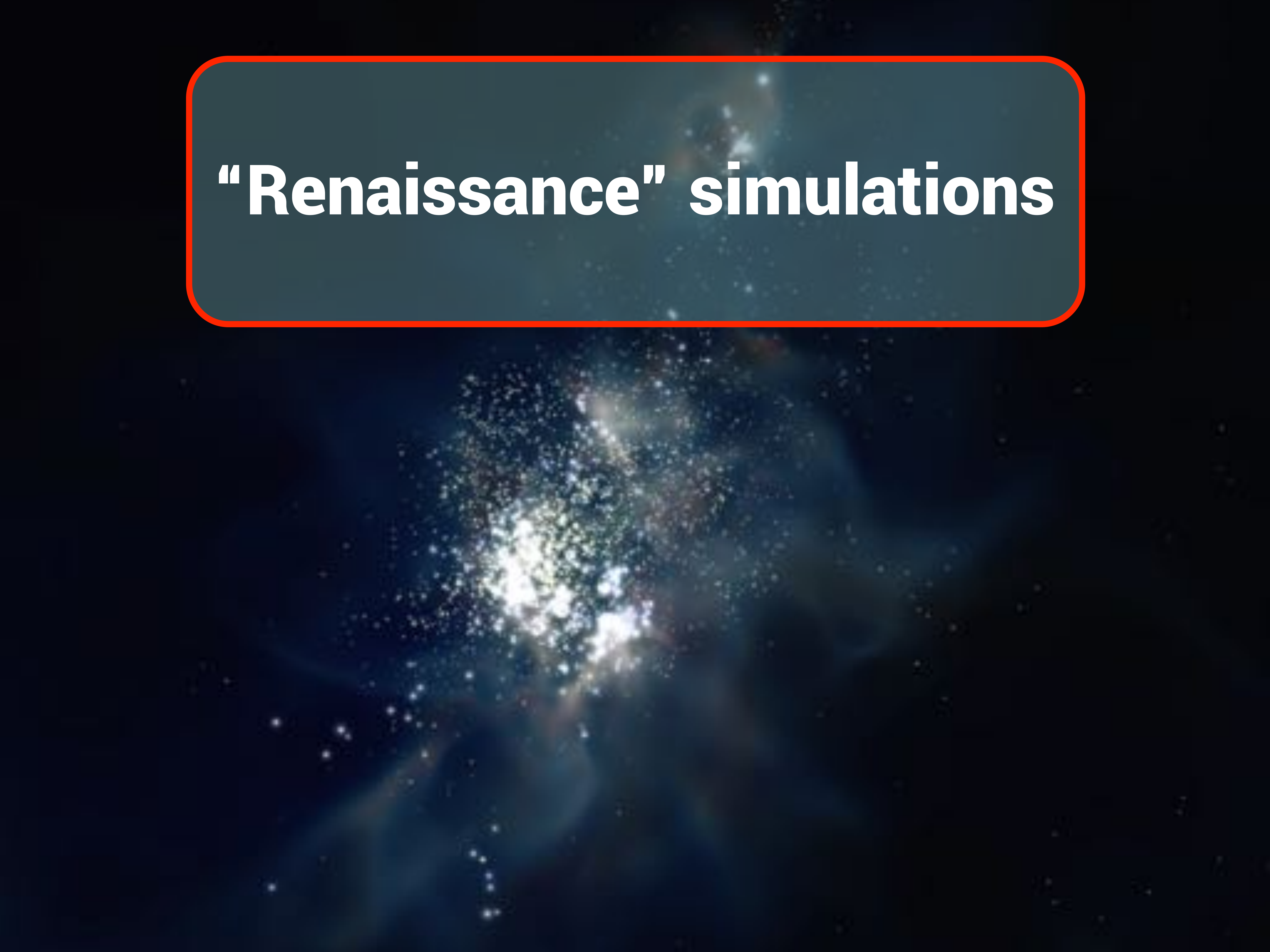
The First Galaxies
BH Populations

Escaping stellar radiation

10^8 M halo; z = 11



“Renaissance” simulations

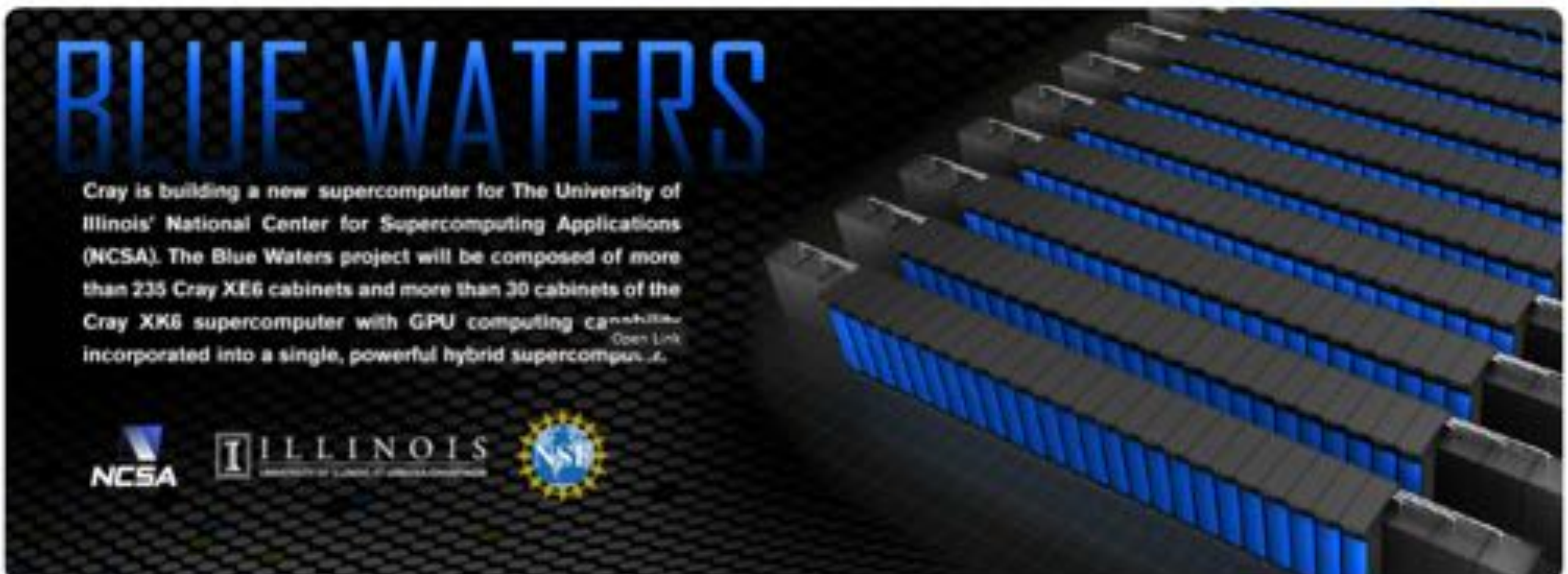


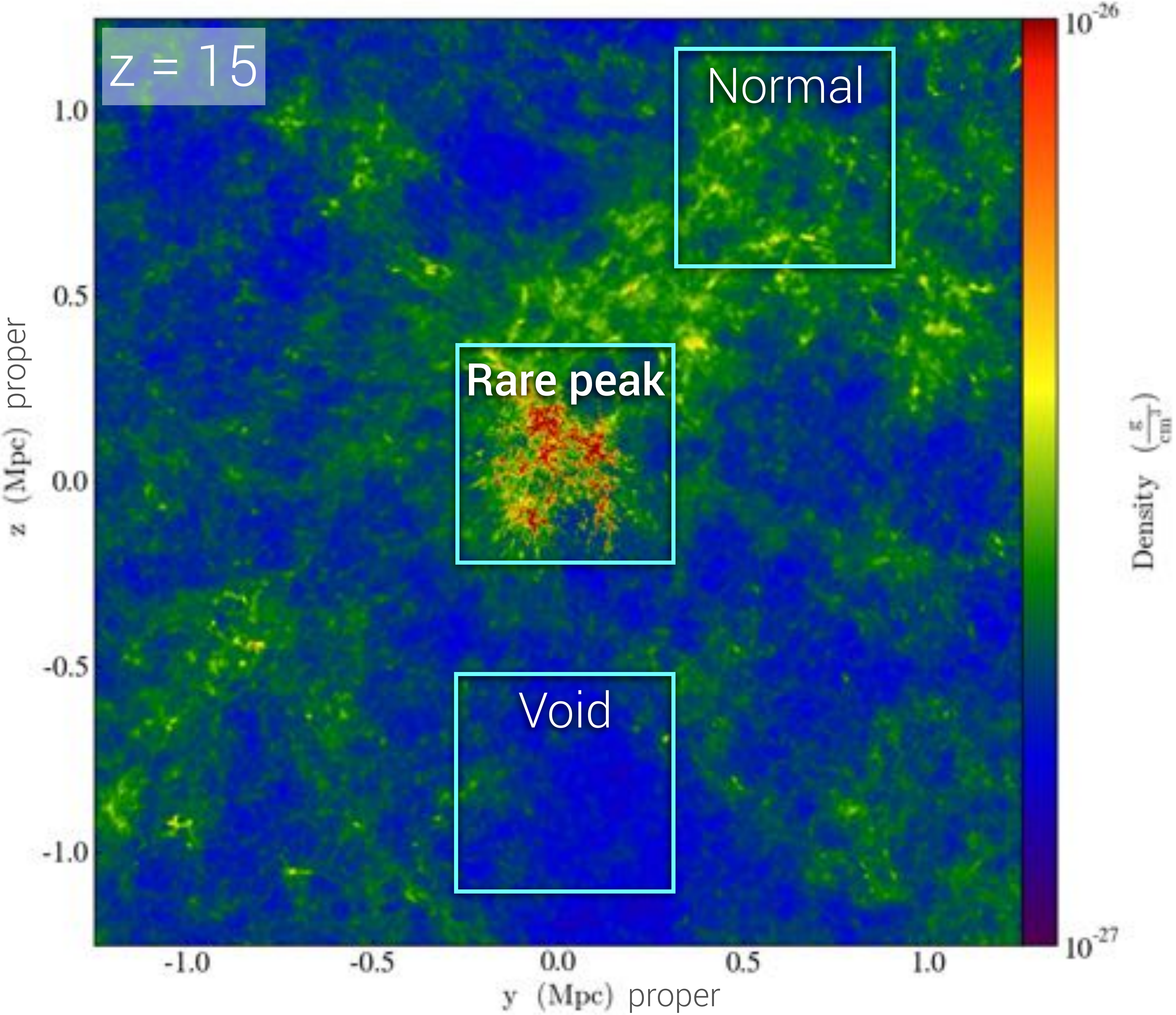
The First Galaxies
Renaissance Simulations

enzo-project.org

- Follow three regions ("rare peak", mean, void) until z ~ 10.
  - 40 comoving Mpc box, 5 comoving Mpc zoom-in region
- At z = 15 in the rare peak region, there are
  - Three >10^9 $M_\odot$ DM halos; >13,000 Pop III stars
  - ~3 x 10^8 $M_\odot$ of Pop II stars in ~1,000 dwarf galaxies

Xu, JW, Norman (2013)
Xu et al. (2014)
Chen, JW, et al. (2014)
Ahn et al. (2015)
O'Shea, JW, et al. (2015)

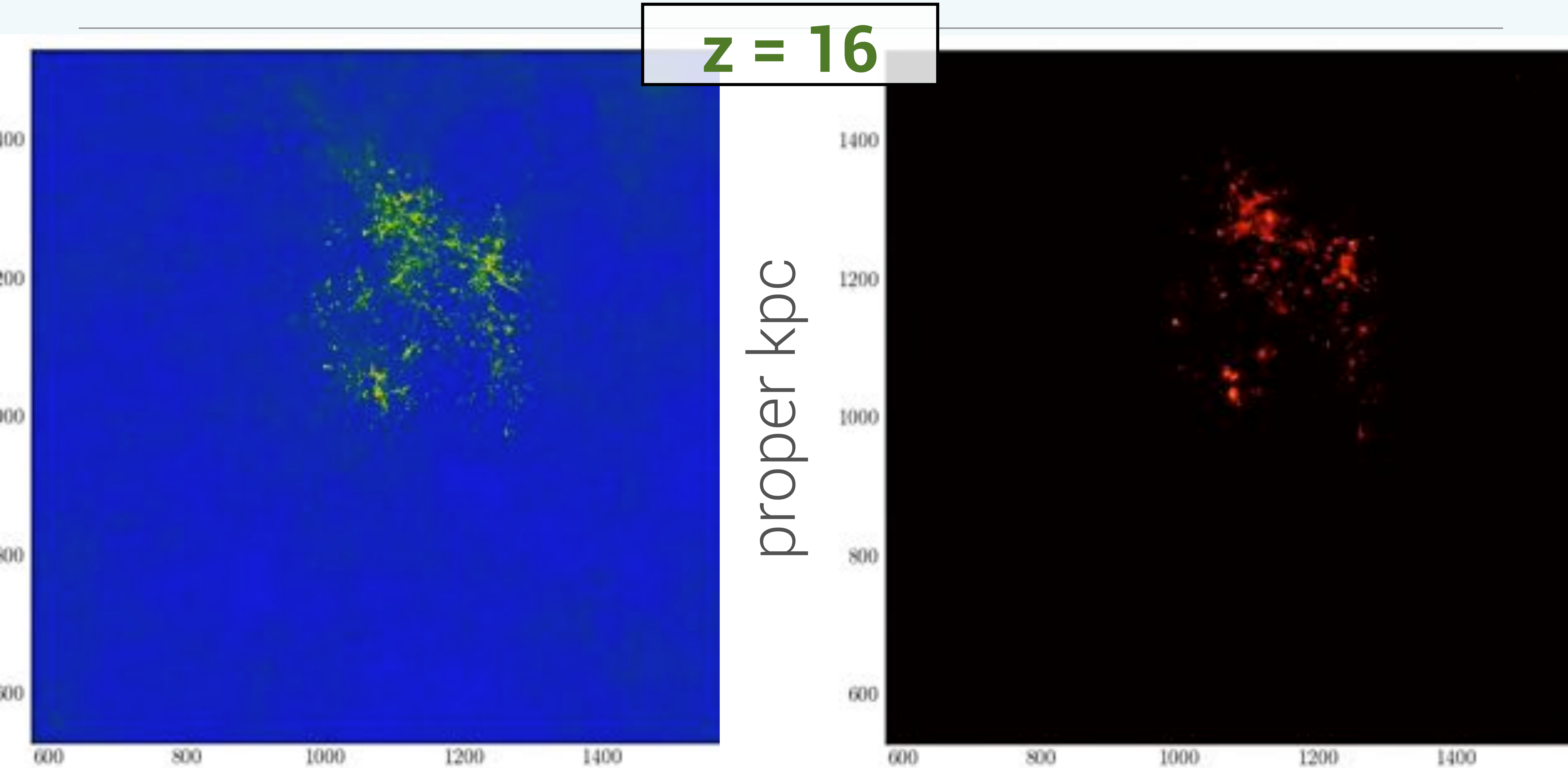




z = 15
Normal
Rare peak
Void
1.0
0.5
0.0
-0.5
-1.0
z (Mpc) proper
y (Mpc) proper
10^{-26}
10^{-27}
Density $\left(\frac{g}{cm^3}\right)$

The First Galaxies
Overdense "Rare Peak" Region

Xu, Wise, Norman (2013)
Xu et al. (2014)
Chen et al. (2014)
Ahn et al. (2015)
O'Shea et al. (2015)

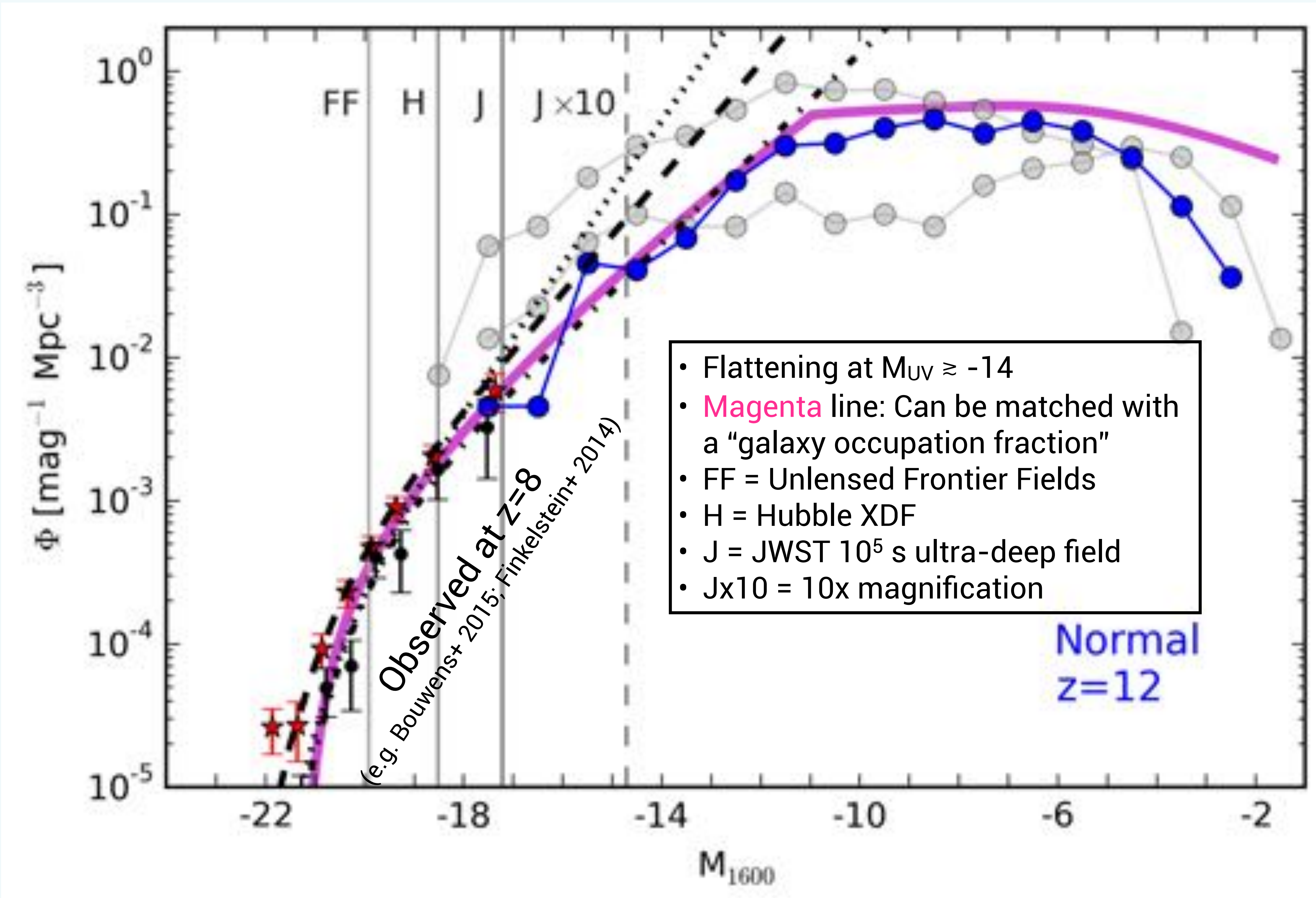


Projected Density
(scale: 3×10^{-28} – 3×10^{-24} g/cm^3)

Projected Temperature
(scale: 10^3 – 3×10^4 K)

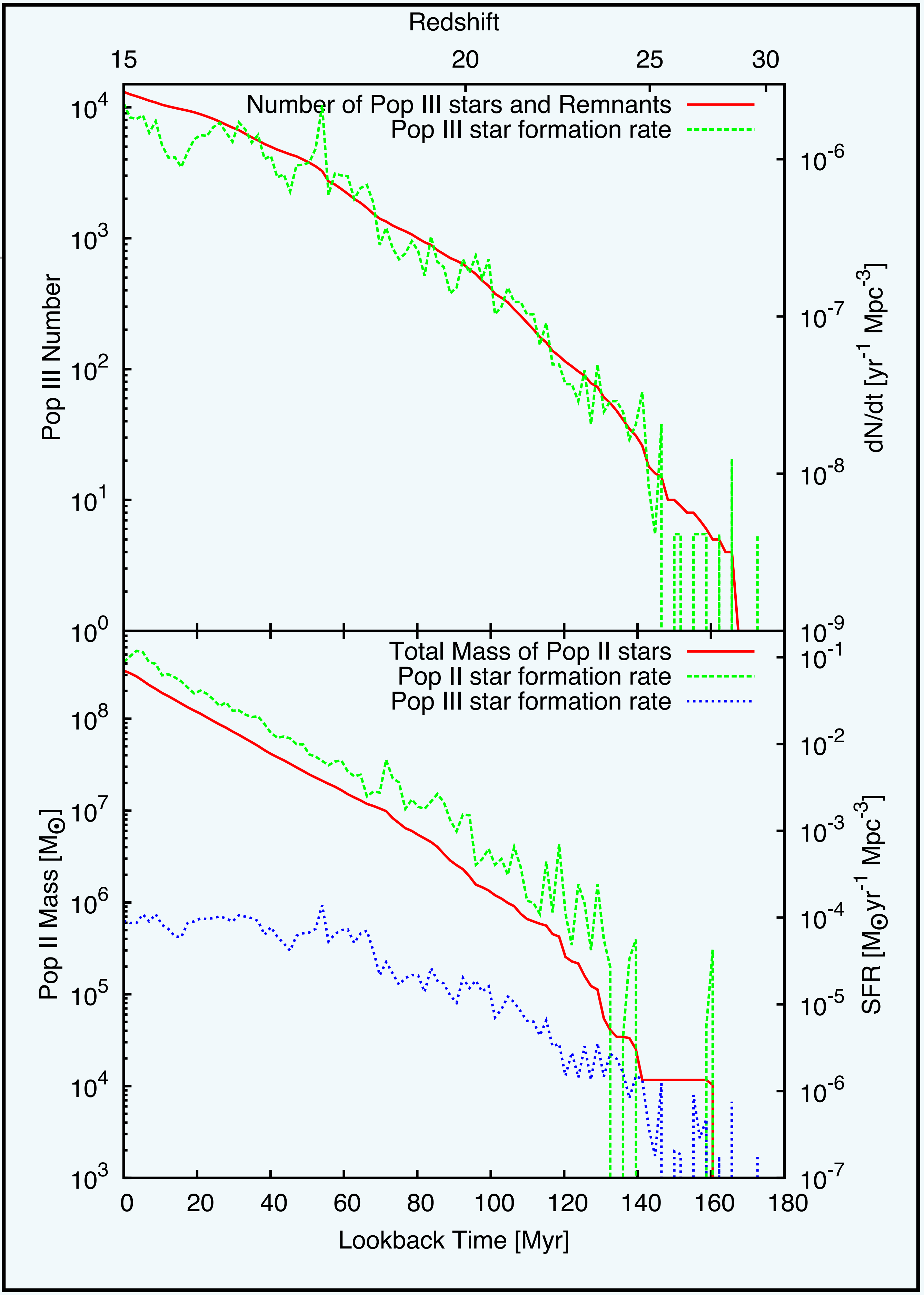
O'Shea, JW, et al. (2015)

The First Galaxies
High-z Galaxy Luminosity Functions



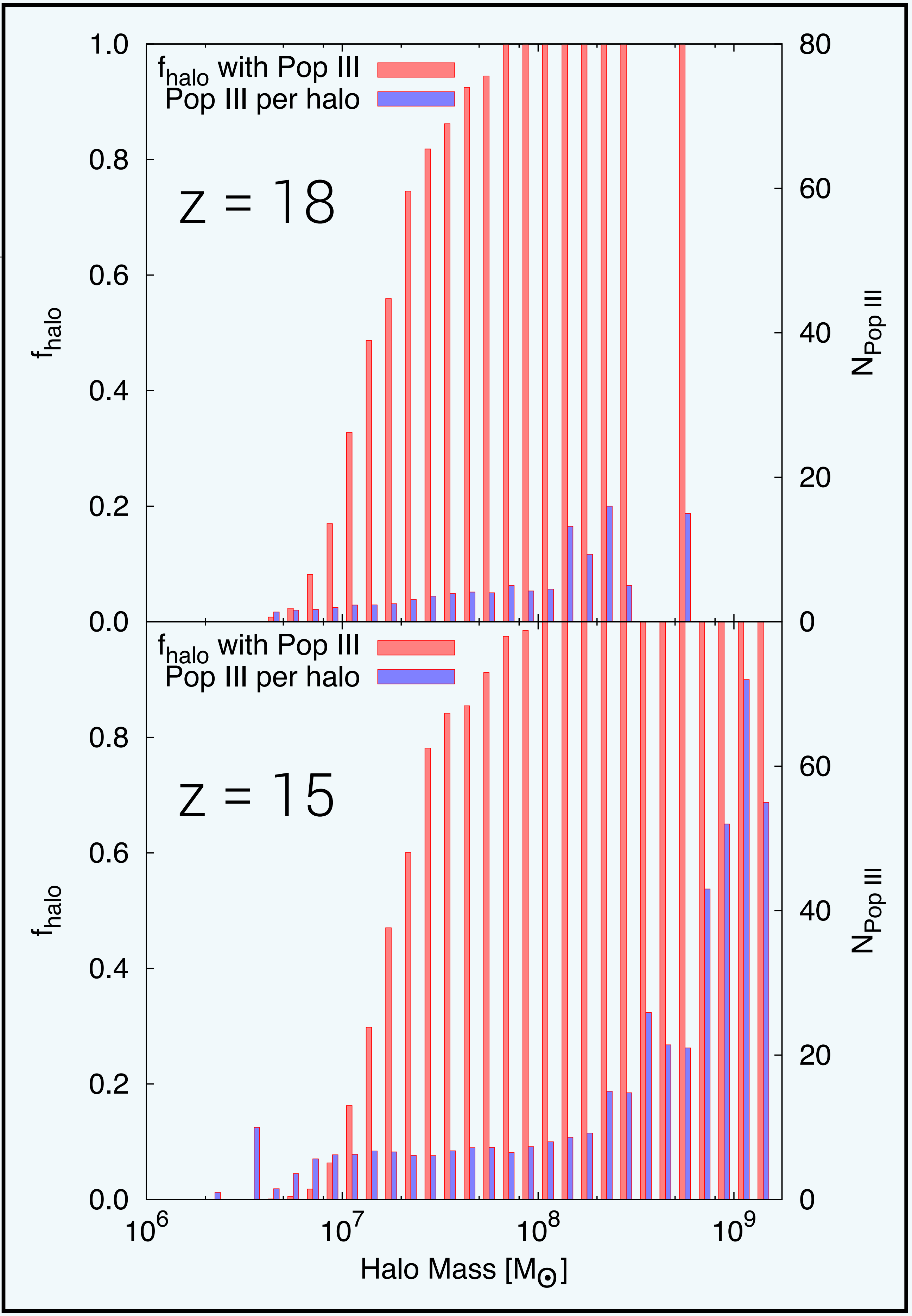
The First Galaxies
Pop III Remnant Multiplicity

- 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



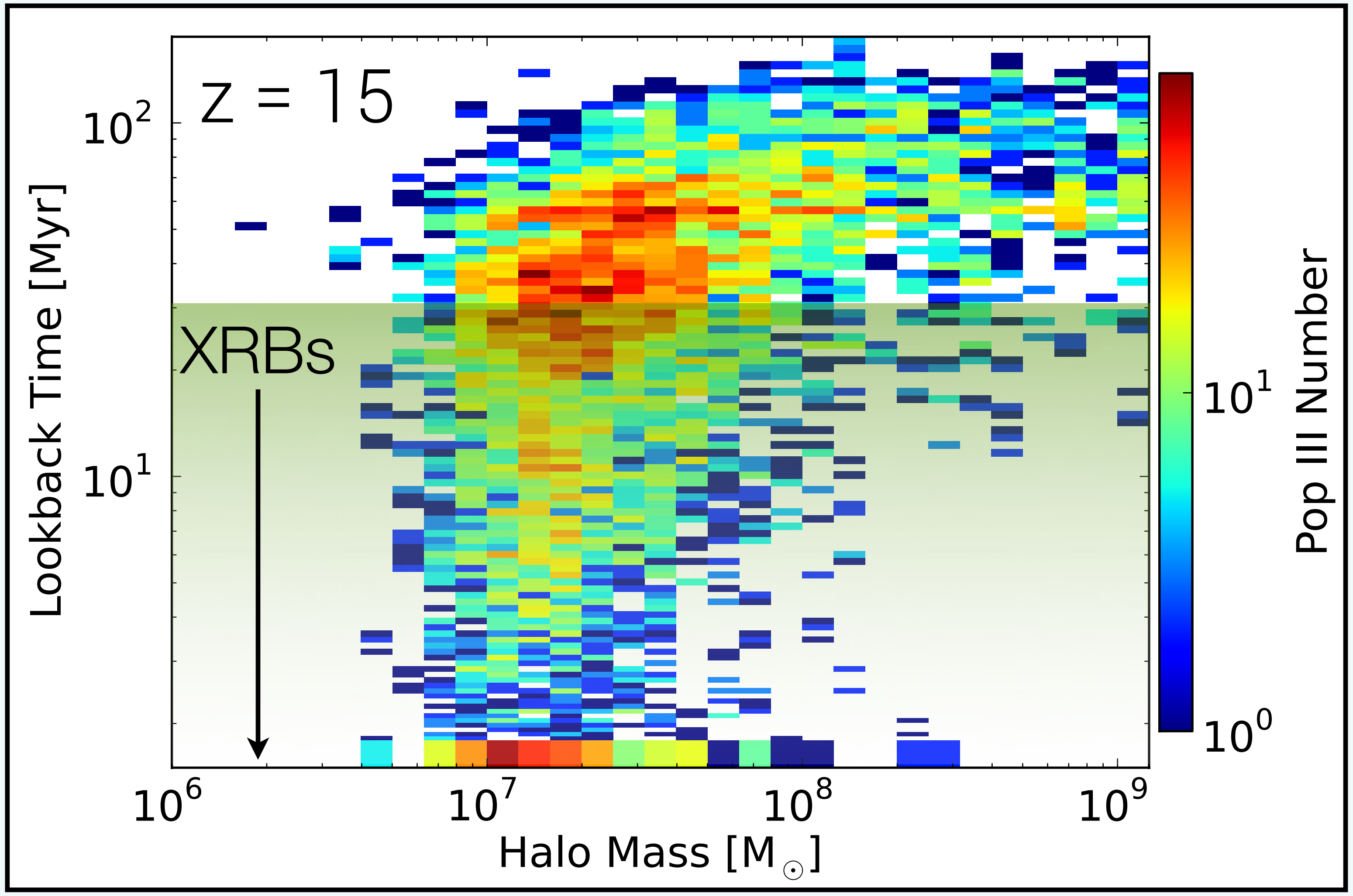
The First Galaxies
Pop III Remnant Multiplicity

- 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.



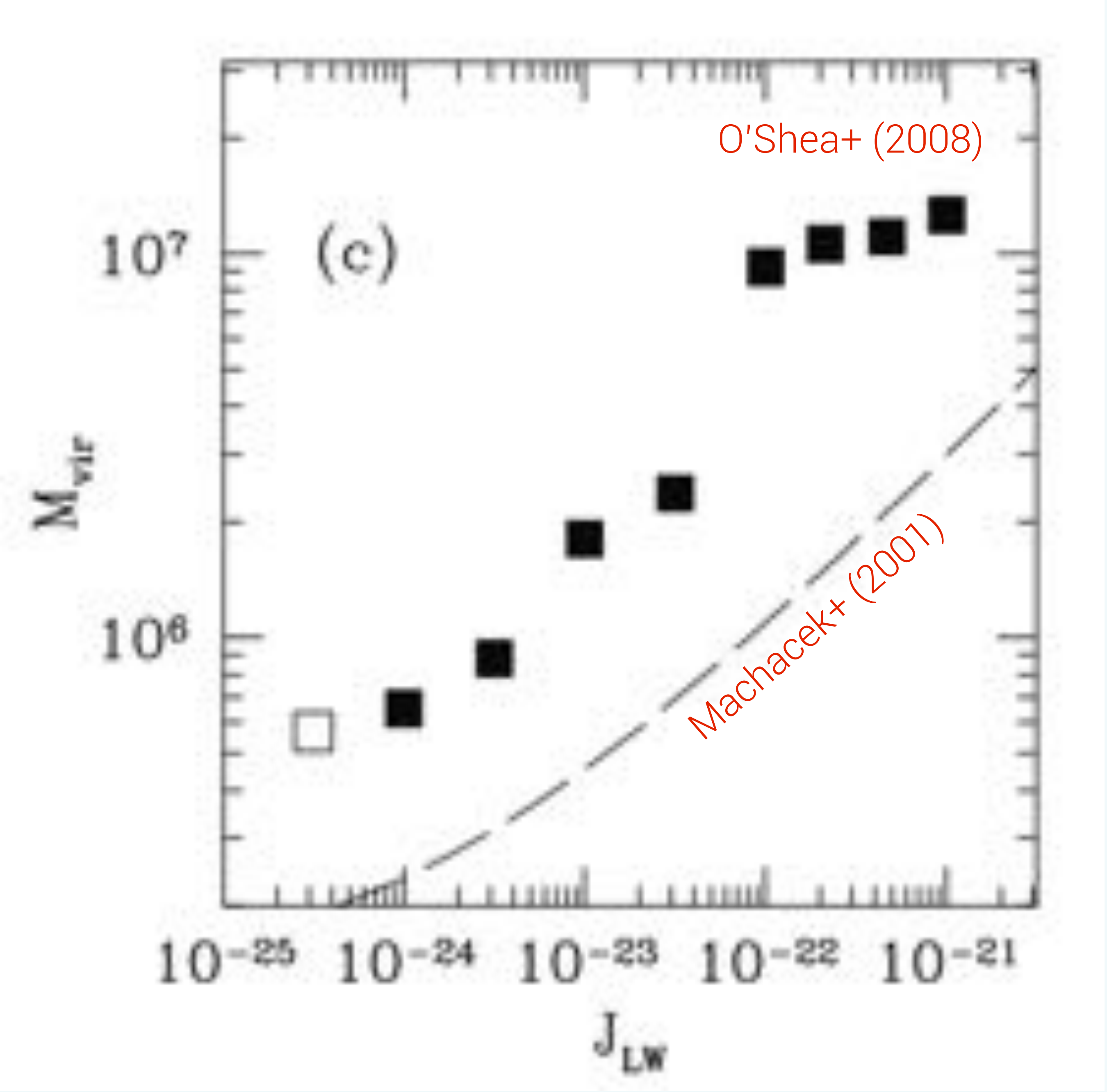
The First Galaxies
Pop III Remnant Multiplicity – X-ray binaries?

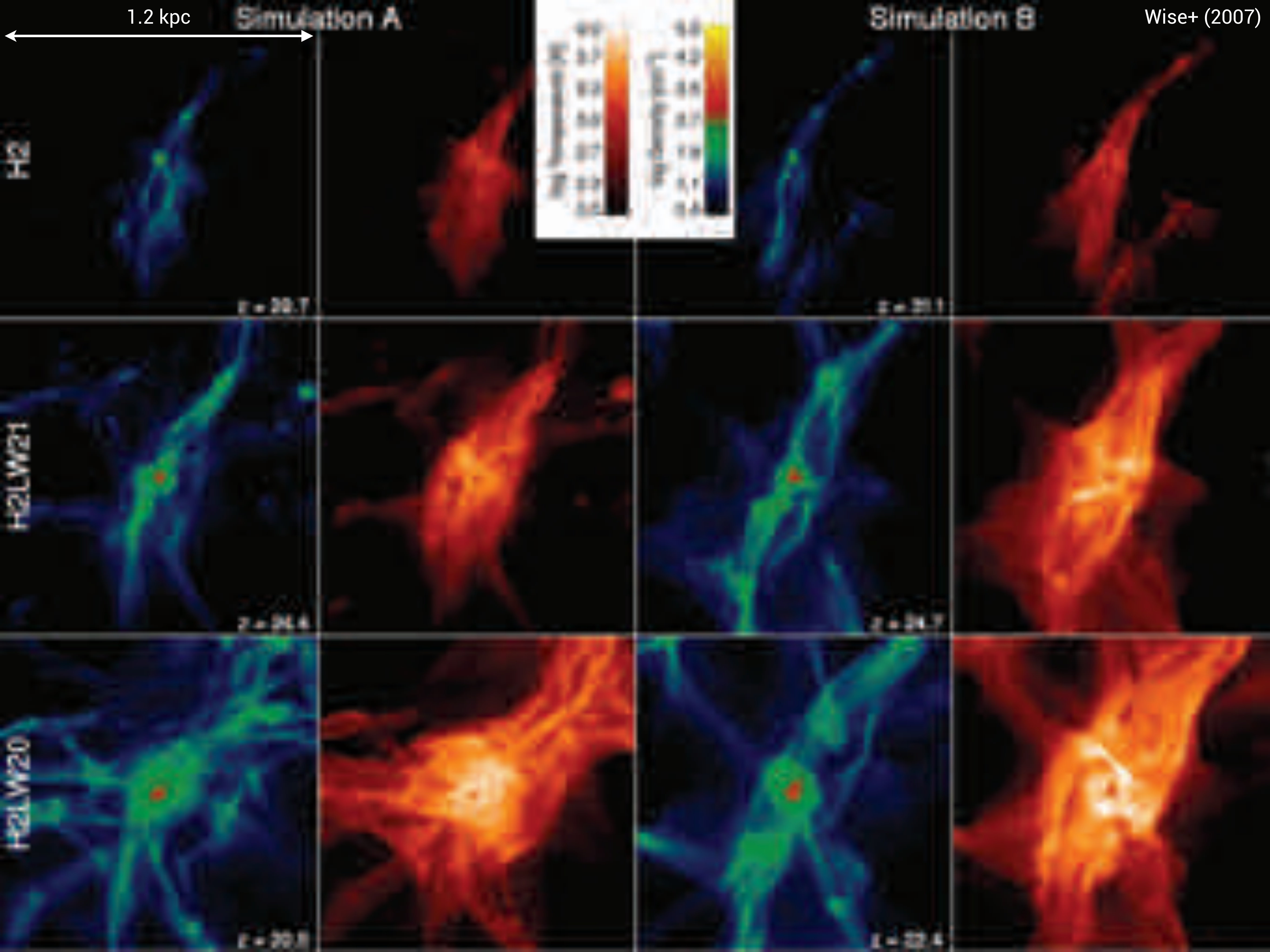
- Recall that recent simulations have suggested that Pop III stars may form in binaries
- High-mass X-ray binaries could exist in dwarf galaxies
- (Xu+ 2014) Partially photo-ionizes and photo-heats the IGM.
- (Ahn+ 2014) Could be detected in 21cm observations with SKA.



Piecing it All Together

- Depending on its neighbors and collapse time, every halo should experience some UV background.
- $J_{21} \rightarrow M_{form} \rightarrow f_{\star} \rightarrow N_{BH}$ or M_{BH}
    - Also determines whether Pop III star formation or DCBH.
- Frequency of all of these events results in an initial BH mass function.




1.2 kpc
Simulation A
Simulation B
Wise+ (2007)
H2
H2LW21
H2LW20

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.
- Massive BH seed formation may occur in some rare metal-free halos in strong UV radiation field.