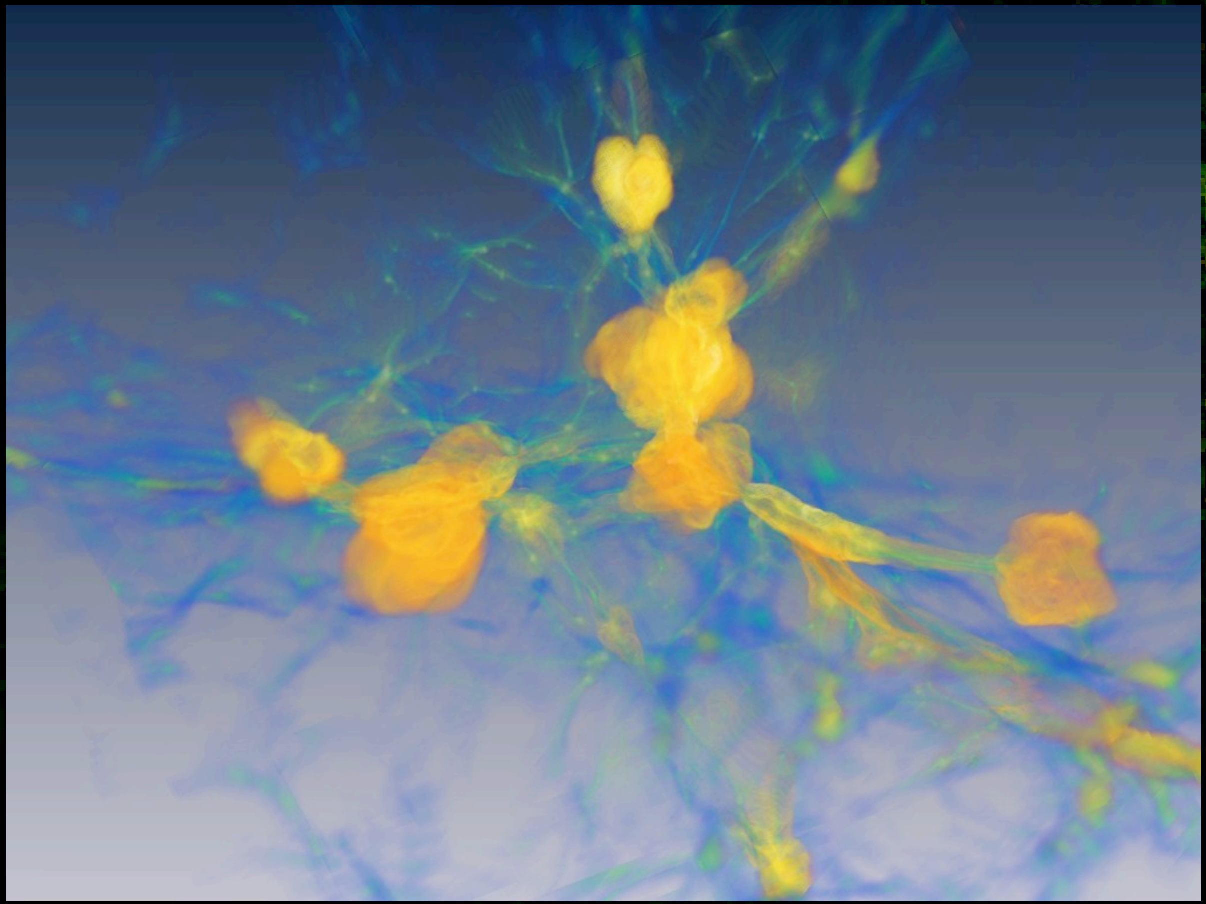
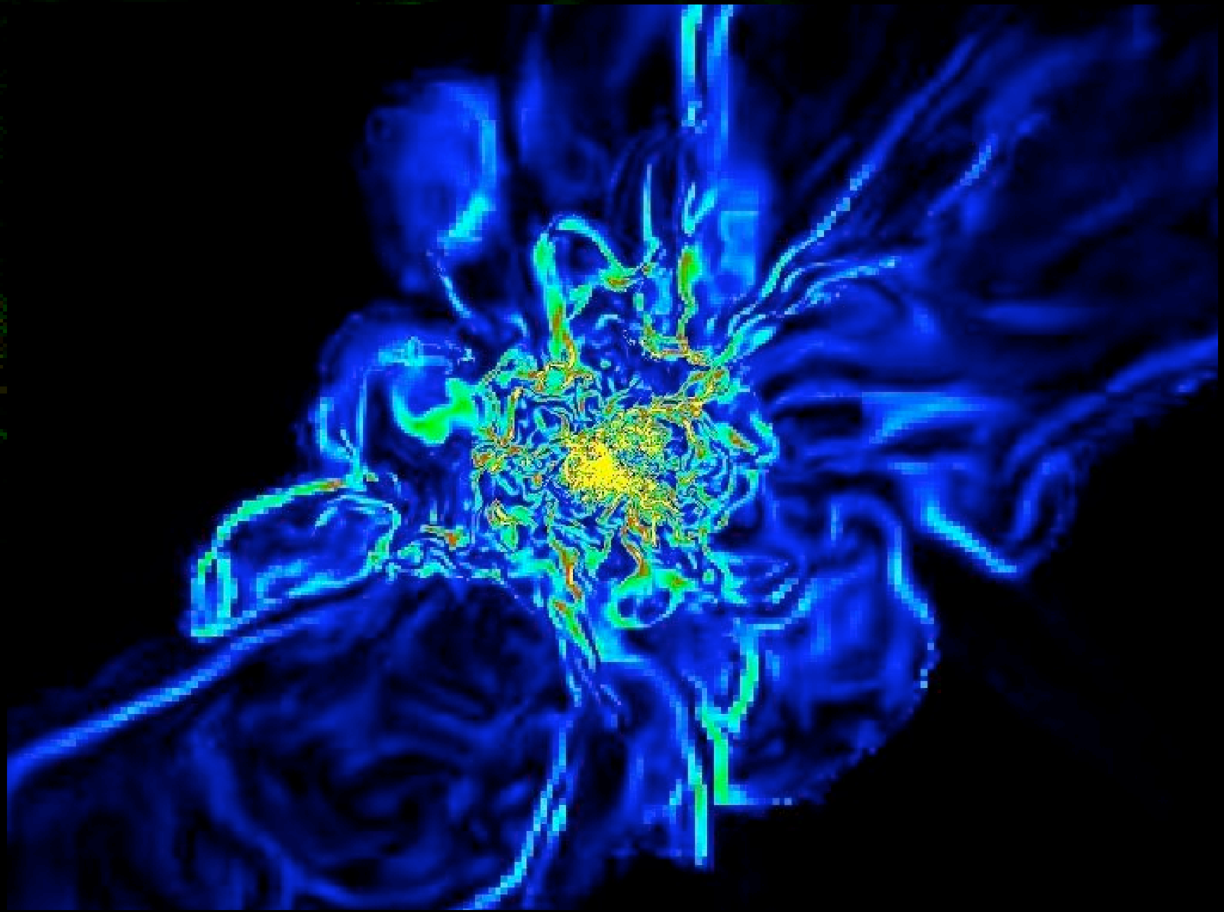
Resolving the Formation of Protogalaxies

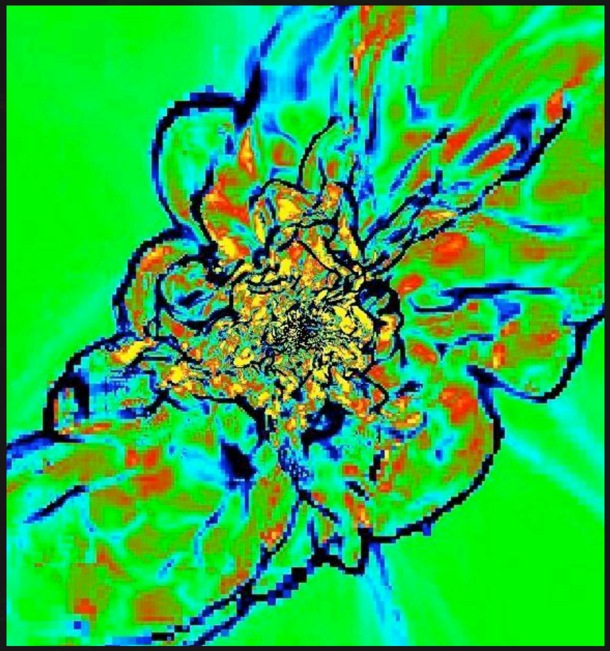




John H. Wise (KIPAC / Stanford)
Thesis Advisor: Tom Abel
Collaborators: Matt Turk (KIPAC), Greg Bryan (Columbia)

Outline

- Introduction to The Dark Ages, First Stars, and First Galaxies
- Observational and Theoretical Motivations
- Standard Galaxy Formation Models
- Molecular Hydrogen Cooling
- Primordial Star Formation and Feedback
- Effects on Protogalaxy Formation
- Physical and Computational Models



Early Structure Formation

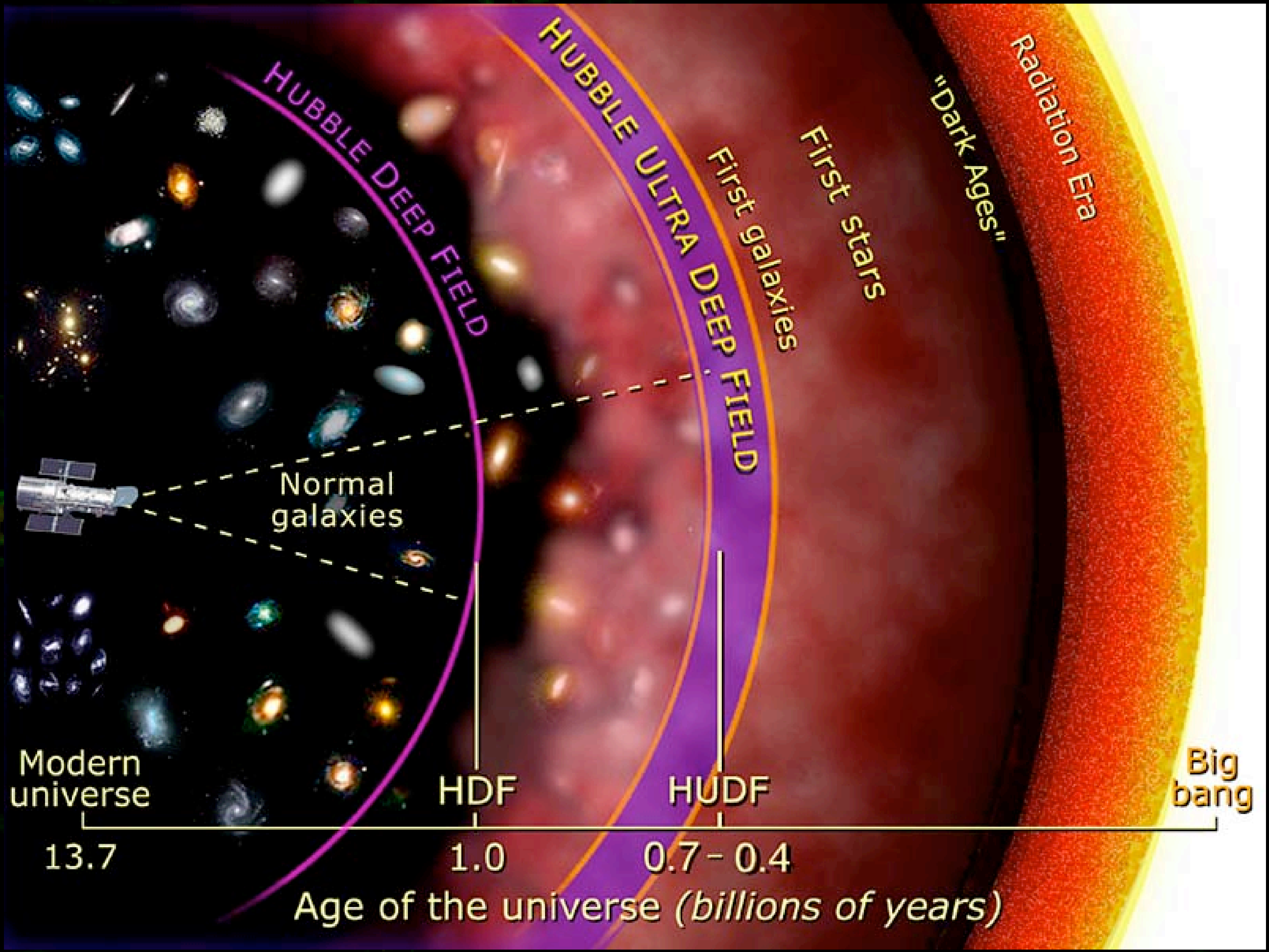
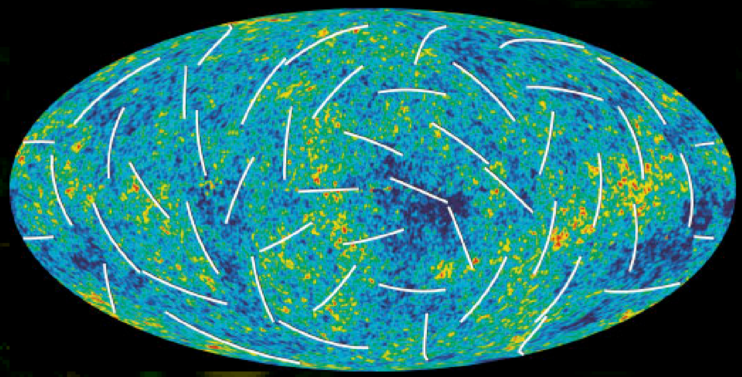


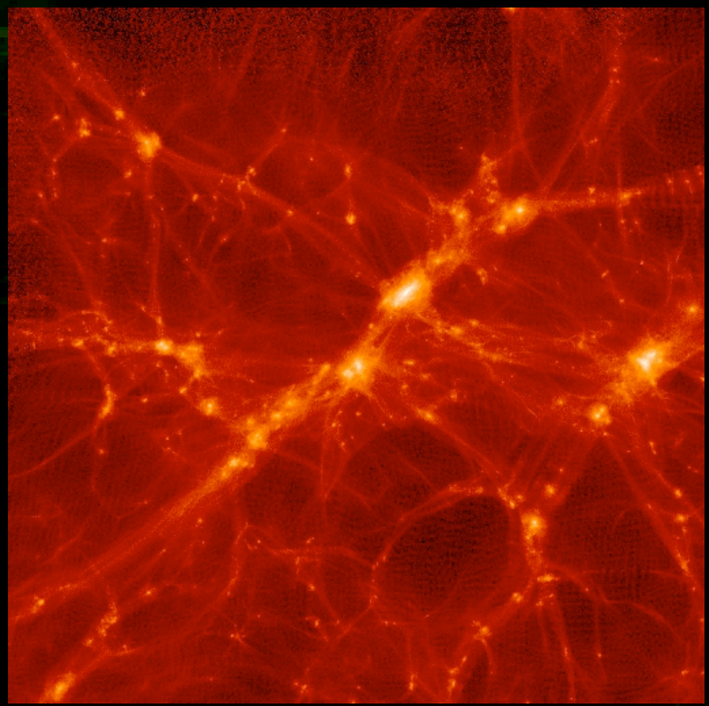
Illustration Credit: NASA and A. Feild (STScI)

CMB and The Dark Ages

- With the WMAP results, the conditions at this epoch are very well calibrated.
  Spergel et al. (2003, 2006)
- In CDM models, DM can clump on the free-streaming scale.
- However, baryons experience pressure forces and must overcome the cosmological Jeans mass before collapsing.
- Residual free electrons that exist after recombination aid the formation of molecular hydrogen.
  Saslaw & Zipoy (1967), Peebles & Dicke (1968), Tegmark et al. (1997)

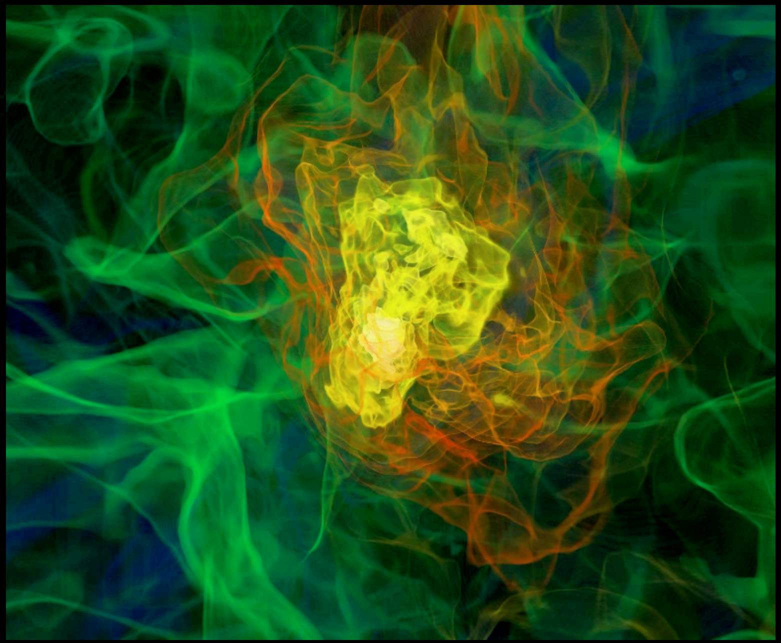


Credit: NASA/WMAP Science Team



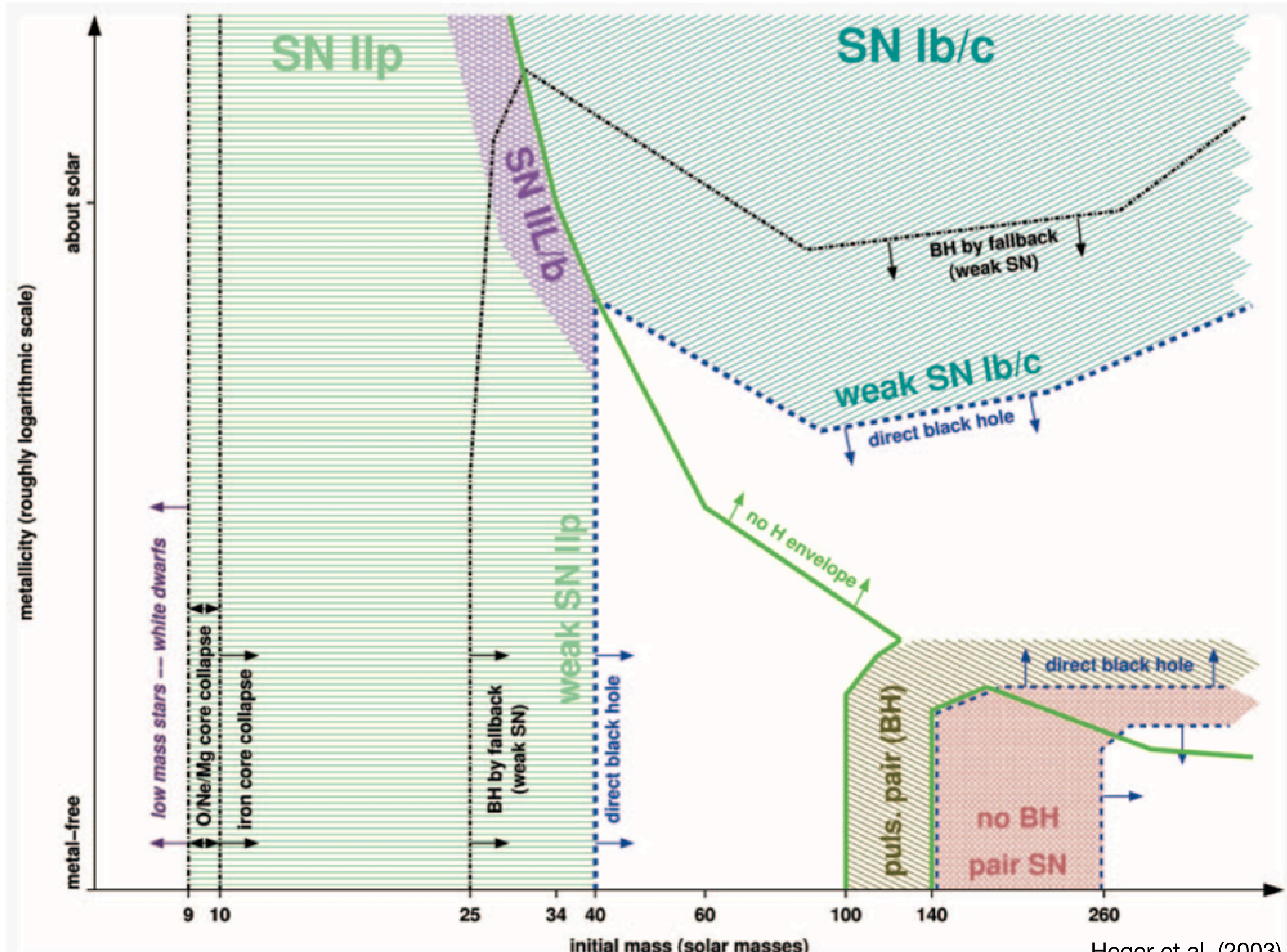
The First Stars

- Various computational techniques have calculated and verified that the first stars are massive (30 - 300 $M_\odot$) and isolated.
  Abel et al. (2002), Bromm et al. (2002), Yoshida et al. (2003)
- $L \sim 10^6 L_\odot$, $\sim 10^{50}$ ionizing photons / sec
- Lifetime ~ 3 Myr
  Schaerer (2002)
- H_2 is the main coolant, which is easily dissociated by distant sources of radiation.
  Dekel & Rees (1987)
- Provide the first ionizing radiation and first metals to the Universe.



Viz: Kähler, Wise, & Abel

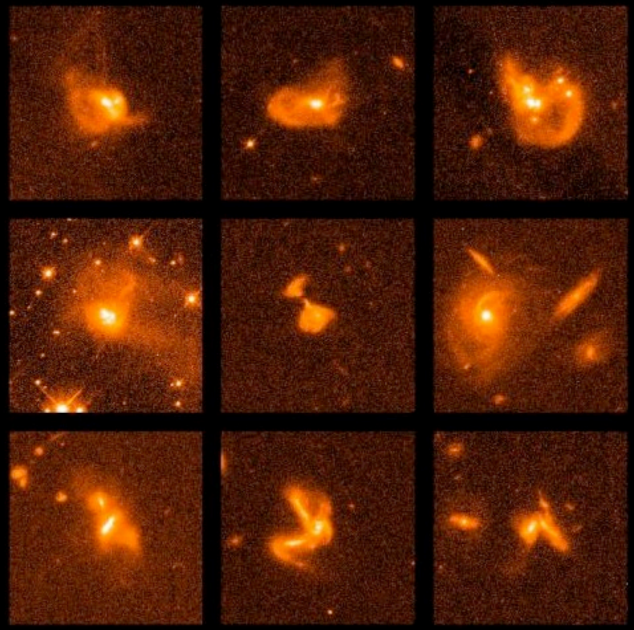
The First Stars



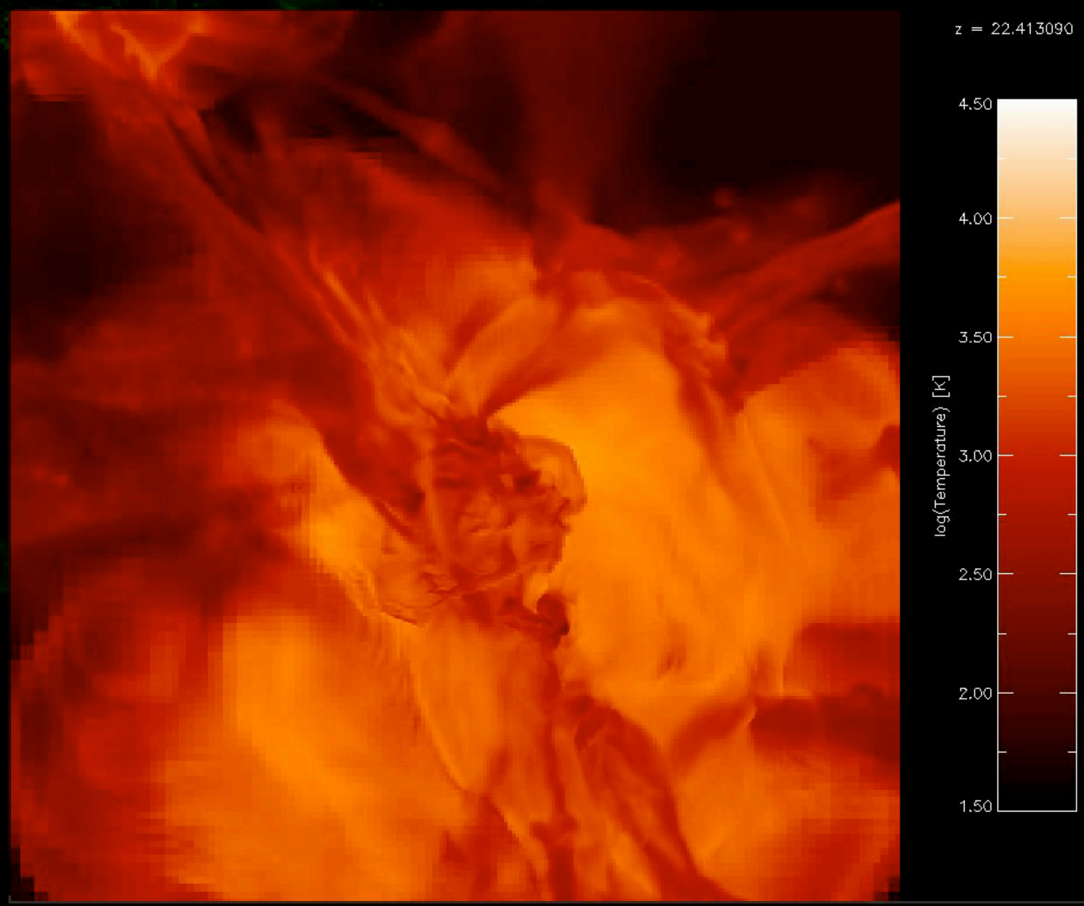
Heger et al. (2003)

The First Galaxies

- The transition from primordial stars to “normal” star formation is determined by the nature of the stellar population.
- Clustered and metal-enriched (Salpeter IMF) stellar population
- Traditionally halos with $T_{vir} > 10^4$ K are considered (proto)galaxies, where gas can cool and collapse through hydrogen lines.
  Rees & Ostriker (1977), White & Rees (1978)
  Spitzer (1978)
- H_2 cooling is enhanced by the free electrons created from this ionization in the first stars and galaxies.
  O’Shea et al. (2005)

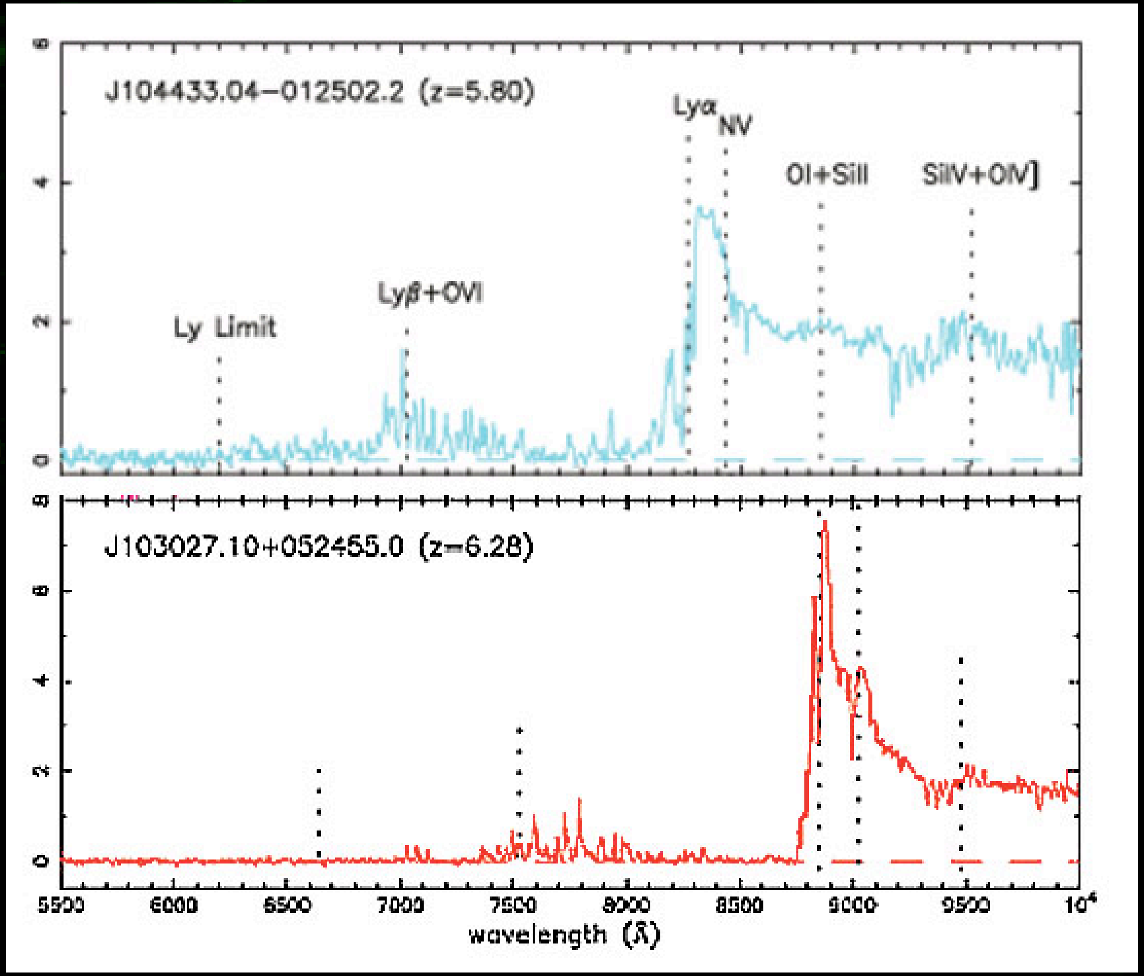


Borne et al. (2001)



Observational Motivations

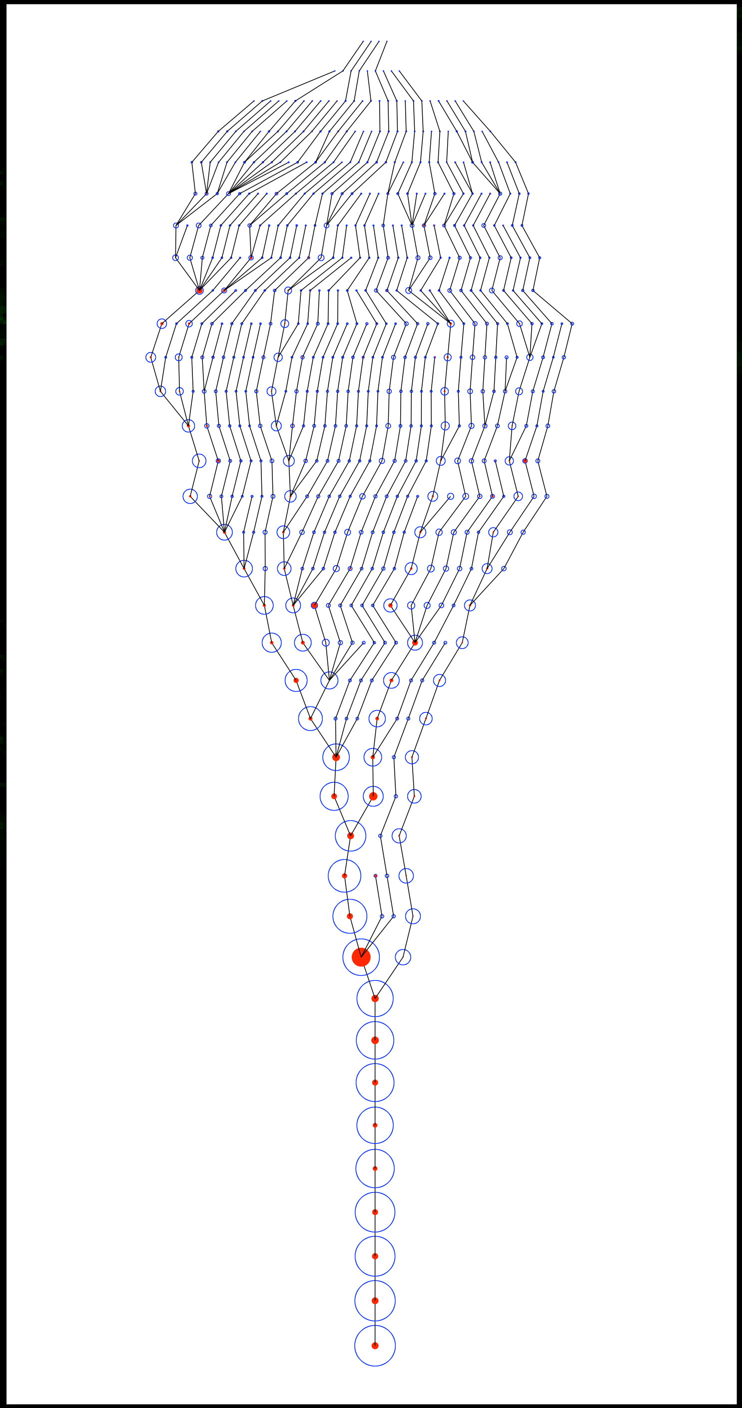
- z ~ 6 SMBHs have up to 10^9 $M_\odot$
- Gunn-Peterson troughs observed in z > 6 QSOs
  Becker et al. (2001), Fan et al. (2002)
- WMAP electron scattering optical depth indicates a reionization of z ~ 10 if a sudden reionization is assumed.
  Page et al. (2006)
- Halo and dwarf galaxy stellar metallicities
  Tolstoy et al. (2004), Qian & Wasserburg (2005)
- Lyman alpha metallicities
  Songaila & Cowie (1995), Songaila (2001)



Credit: SDSS

Theoretical Motivations

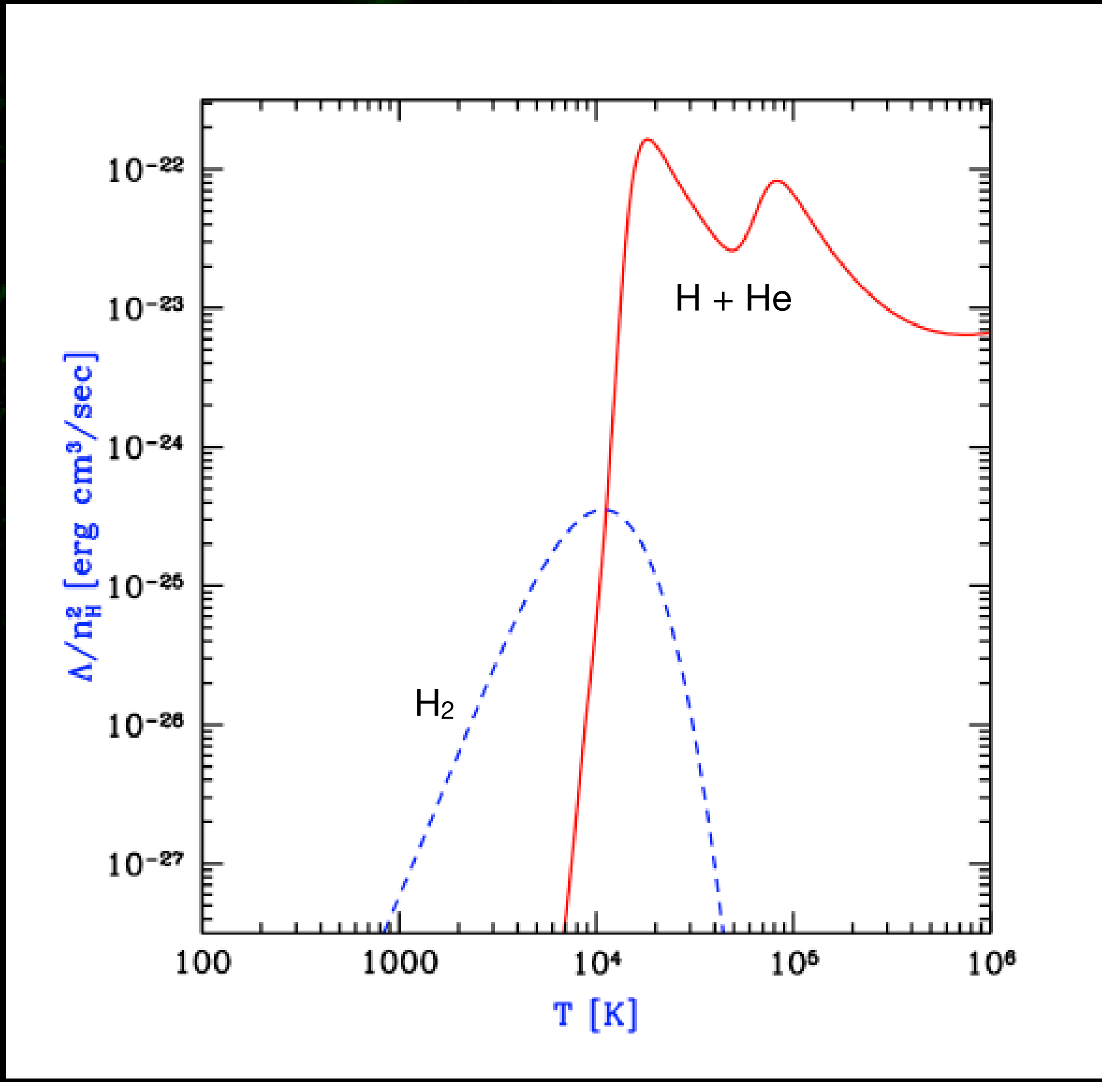
- Hierarchical structure formation – the dynamics and history of smaller galaxies influences all later objects.
  Peebles & Dicke (1968), White & Rees (1978)
- Currently, observations only probe the most massive objects at $z > 6$.
- Protogalaxies are responsible for most of reionization in many semi-analytic models.
  Cen (2003), Ciardi et al. (2003), Ricotti & Ostriker (2003)
- How does the transition from primordial to "normal" star formation occur? Metal mixing may play a large role in this determination.



Wechsler et al. (2002)

Standard Galaxy Formation Model

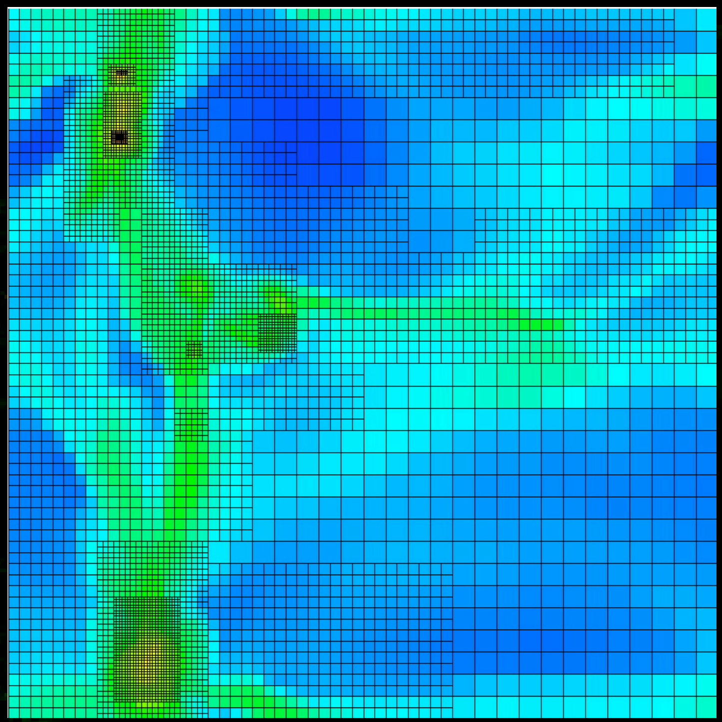
- White & Rees (1978) set the stage for standard galaxy formation models by embedding galaxy formation within hierarchical structure formation.
- Expanded by White & Frenk (1991) to include better calibrated star formation models and metallicity effects.
- DM and baryons are treated as solid body rotators.
  e.g. Loeb & Rasio (1994), Mo et al. (1998)
- Star formation in a rotationally supported disk.

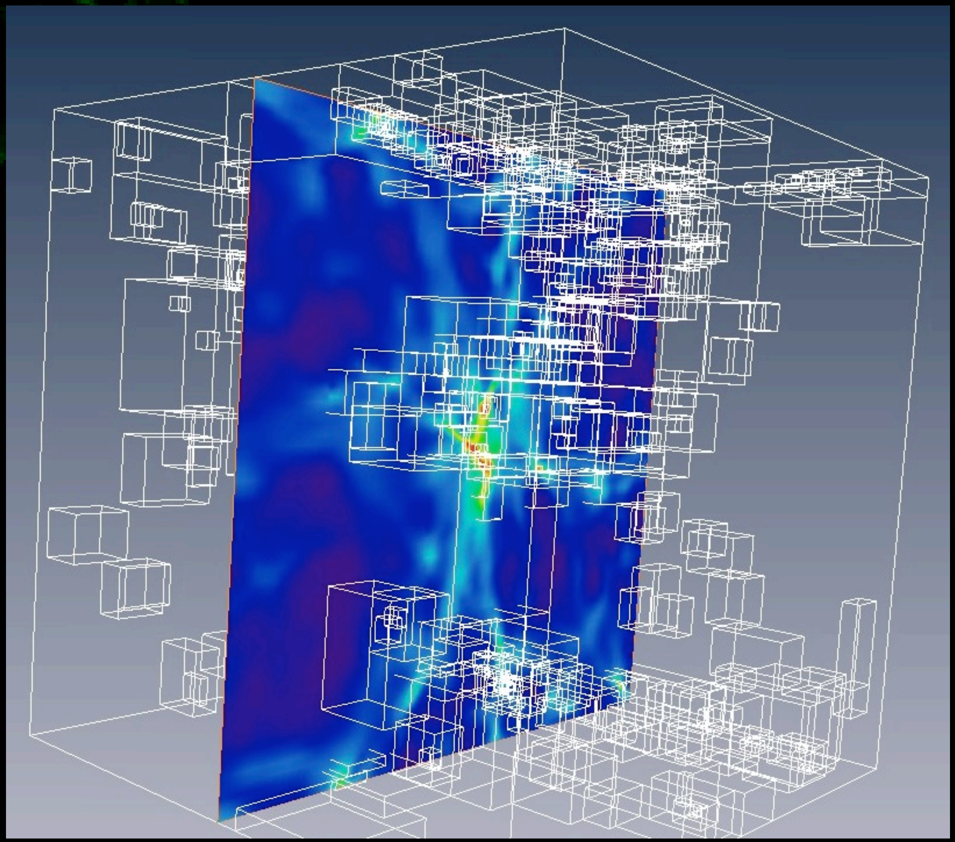


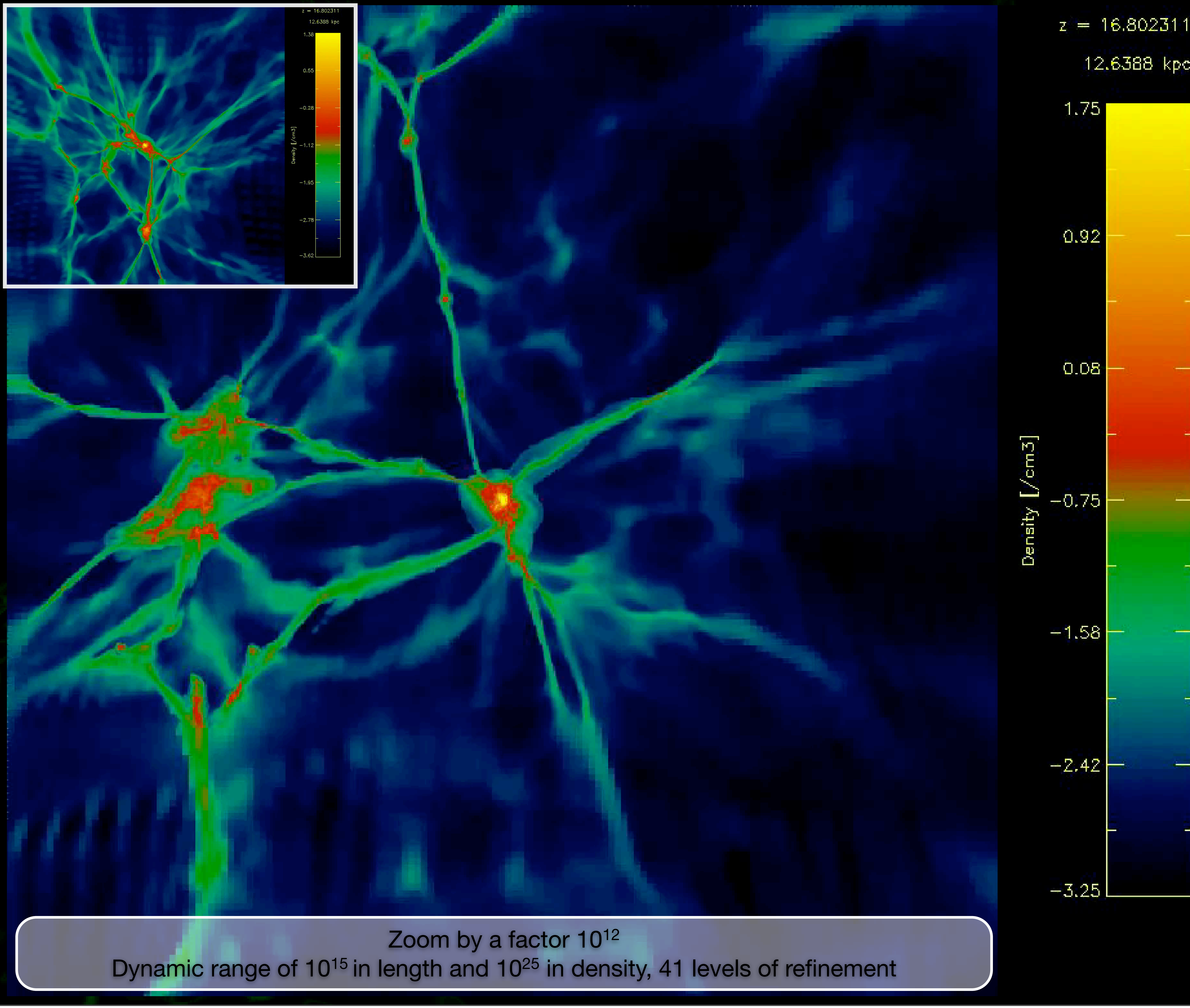
Barkana & Loeb (2001)

Simulation Setup

- *enzo* – Adaptive Mesh Refinement
- Refine on dark matter and gas densities and resolve the Jeans length by at least 16 cells.
- 22 179 grids
- 74 000 000 (420^3) unique cells
- Hydrogen and helium cooling only
- 1.5 comoving Mpc box
- Initial redshift = 120





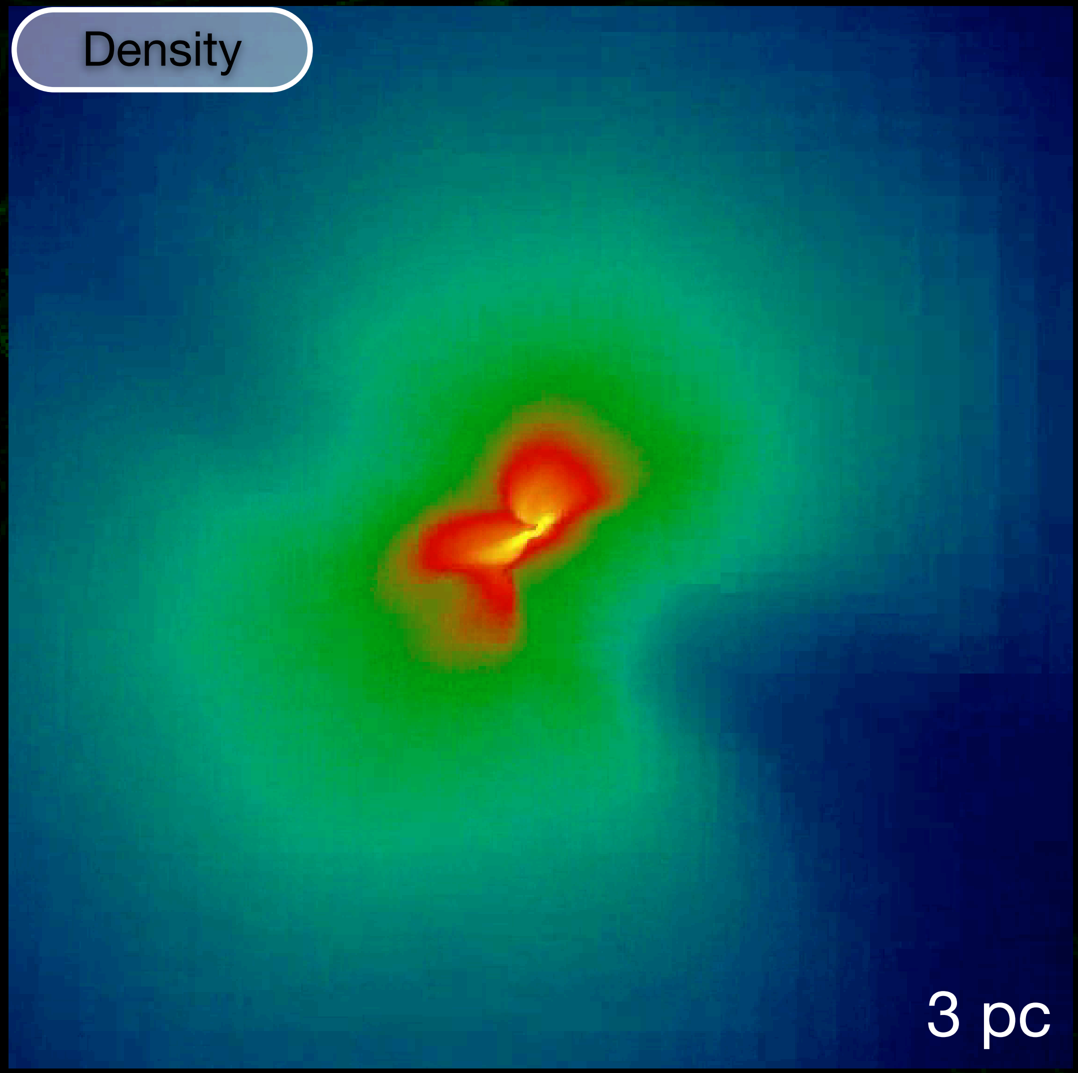


Zoom by a factor 10^{12}
Dynamic range of 10^{15} in length and 10^{25} in density, 41 levels of refinement

Turbulent Collapse within the Standard Galaxy Formation Model

- Mass = 3.6 x 10^7 $M_\odot$, T_{vir} = 9900 K, z = 16.8
- There is no rotationally supported disk, but a thick, pressure supported disk with a radius of ~50 pc.
- 10^5 $M_\odot$ in the central parsec becomes gravitationally unstable and has a Mach number of 2-3. We expect a SMBH to form in this case.

  Loeb & Rasio (1994), Bromm & Loeb (2003), Spaans & Silk (2006) Begelman et al. (2006), Lodato & Natarajan (2006)
- No fragmentation down to sub-solar scales.
- Central collapse occurs before any fragmentation in the disk.



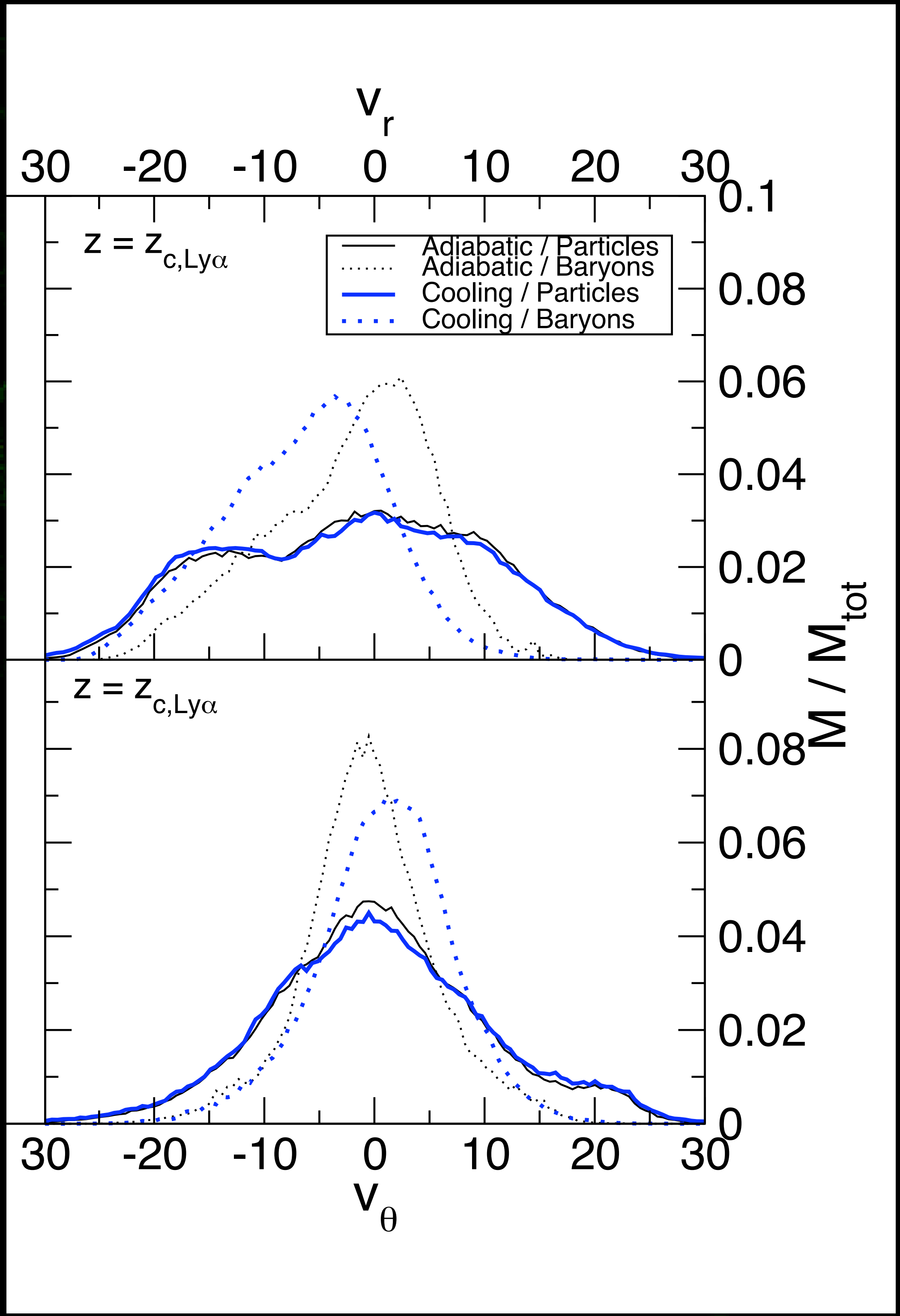
Turbulent Collapse within the Standard Galaxy Formation Model

- Baryons undergo violent relaxation similar to DM.
- Maxwellian (not a solid body rotator!) velocity distribution
- Angular momentum segregation. Due to Rayleigh's inviscid rotational stability argument:

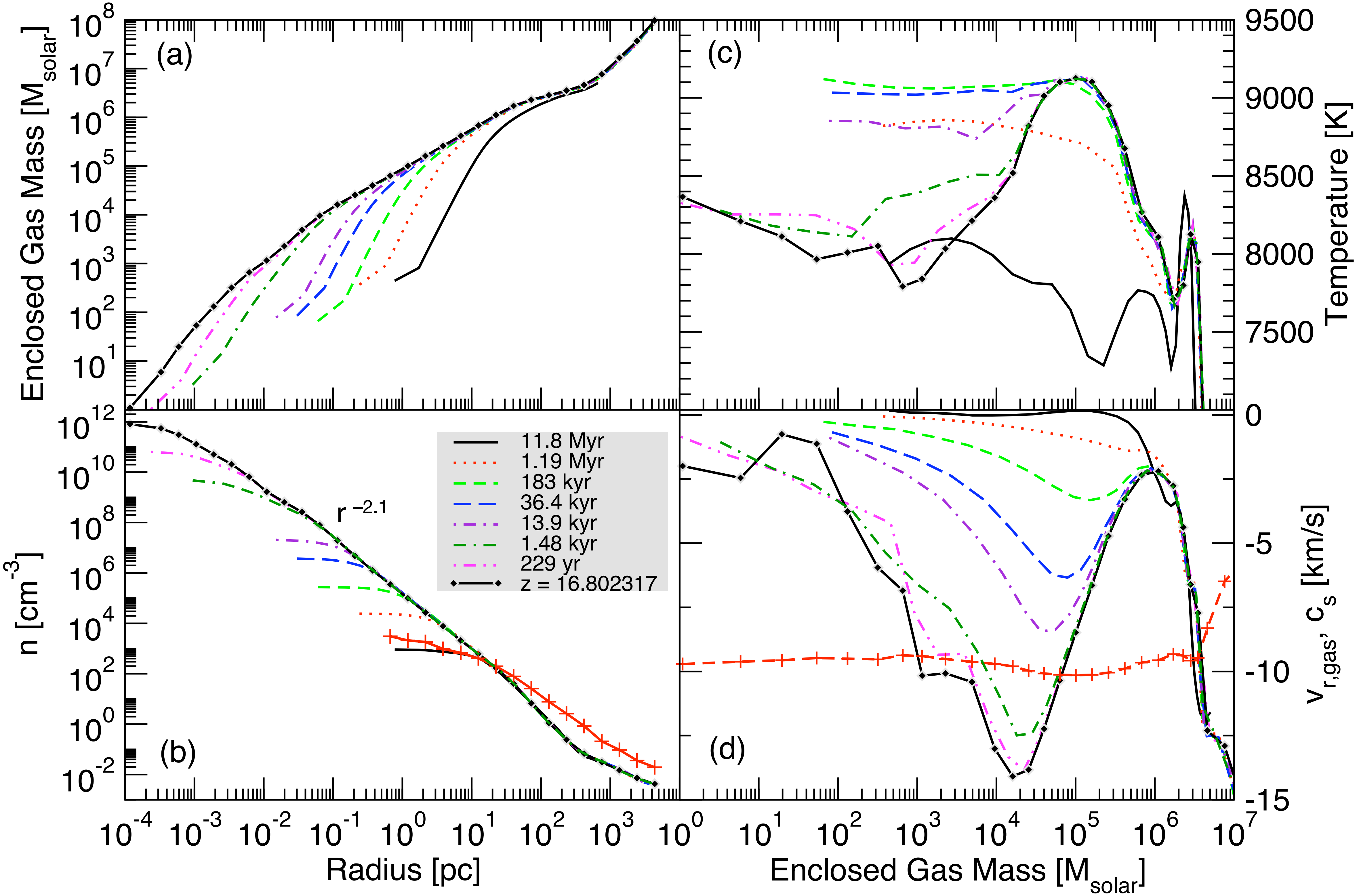
$$\frac{dj^2}{dr} > 0$$

- Only the lowest AM gas filters to the central parsec.
- Afterwards, gravitational bar instabilities.

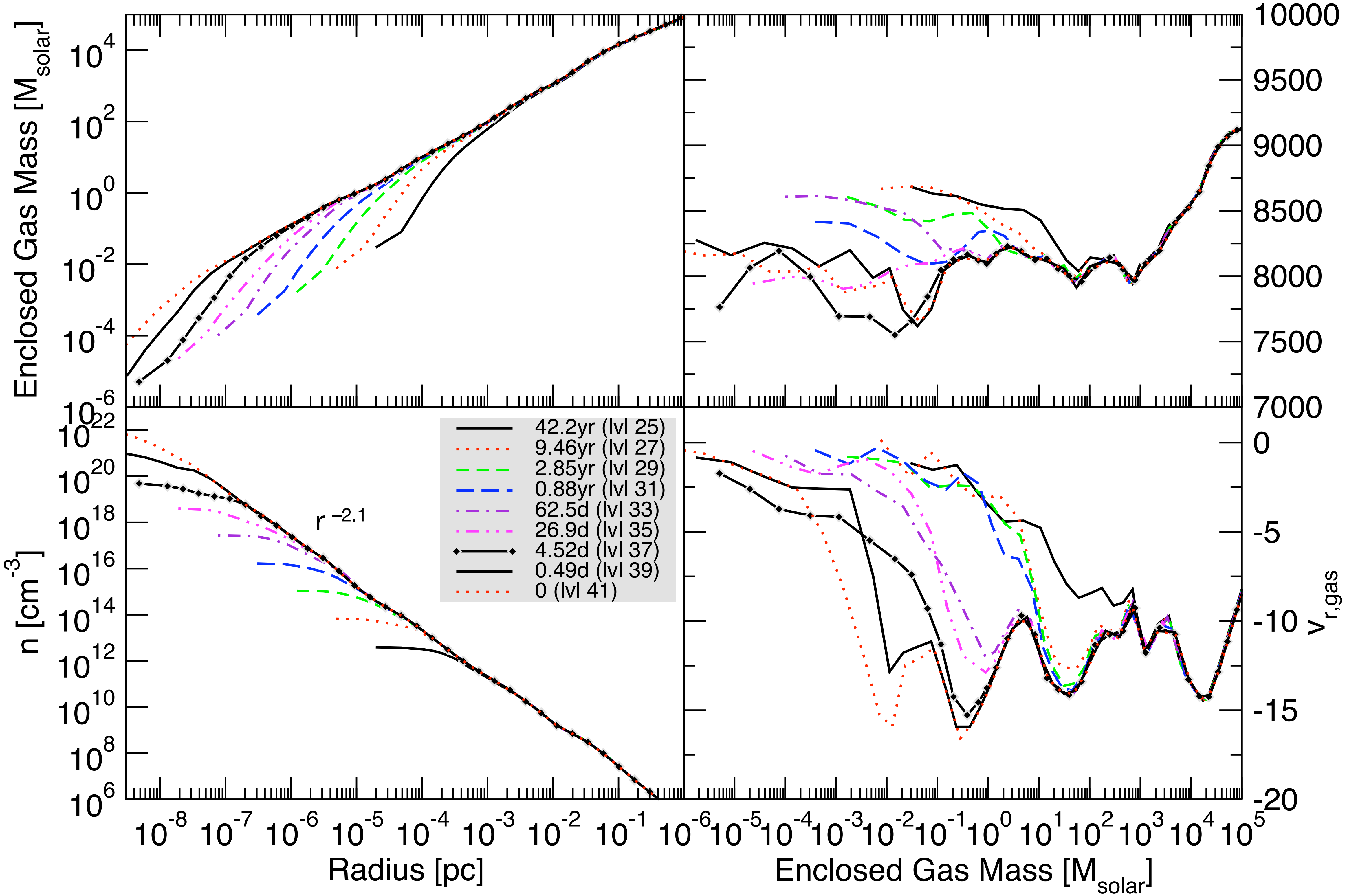
Shlosman et al. (1989, 1990), Begelman et al. (2006)



Radial profiles of the halo

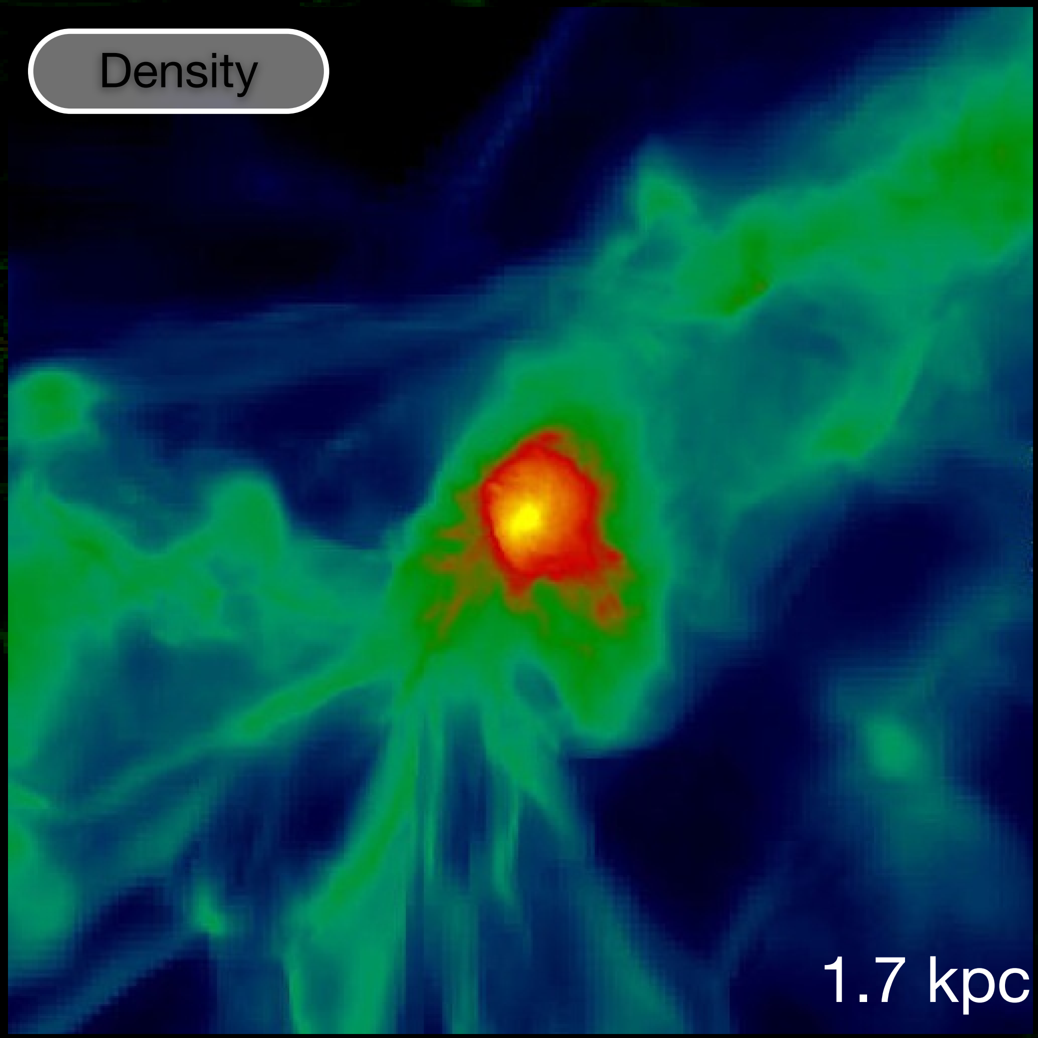


Radial profiles of the inner parsec



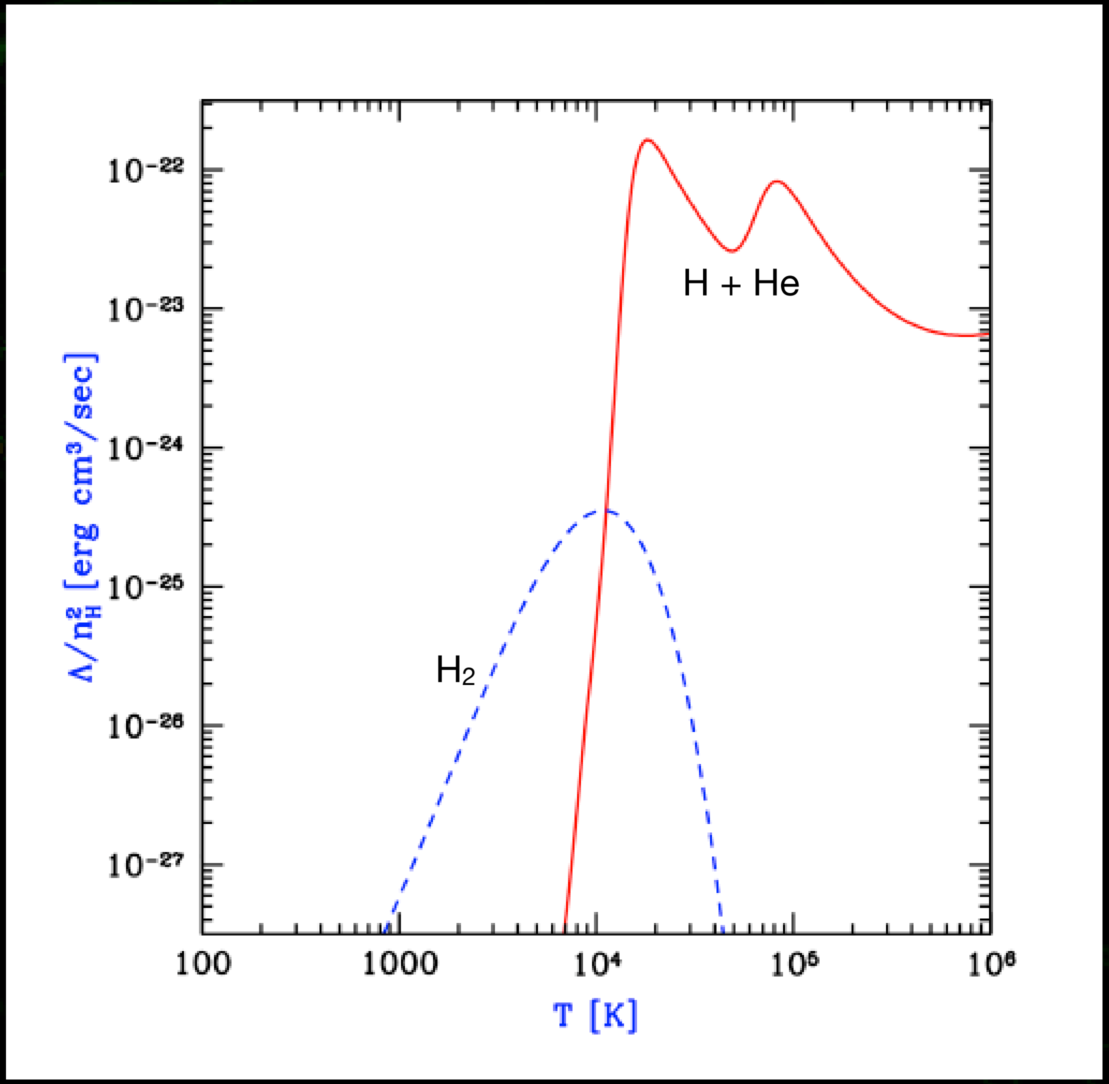
Turbulent Collapse within the Standard Galaxy Formation Model

- Whether the central object be a starburst or SMBH, its feedback will have grand consequences on later star formation within the halo / disk.
- Ignoring H_2 chemistry and primordial star formation made this simulation possible.
- This may *never* happen in nature, but it provides a good testbed for turbulent collapses and what the standard simulations of galaxy formation should find.
- **What have we learned in this stage?** The halo is *turbulent* and not rigidly rotating. It centrally collapses without fragmentation *before* disk formation.



Molecular Hydrogen Cooling

- H_2 cooling is efficient to 300K at high densities.
- Easily dissociated by (Lyman-Werner) radiation between 11.2 – 13.6 eV.
  Field et al. (1966), Stecher & Williams (1967)
- Soft UV backgrounds and nearby sources are important to quantify.
- Primordial star formation is not halted by this radiation but only delayed.
- The halo mass required to cool and collapse increases with the background intensity.
  Machacek et al. (2001), Wise & Abel (2005)



Barkana & Loeb (2001)

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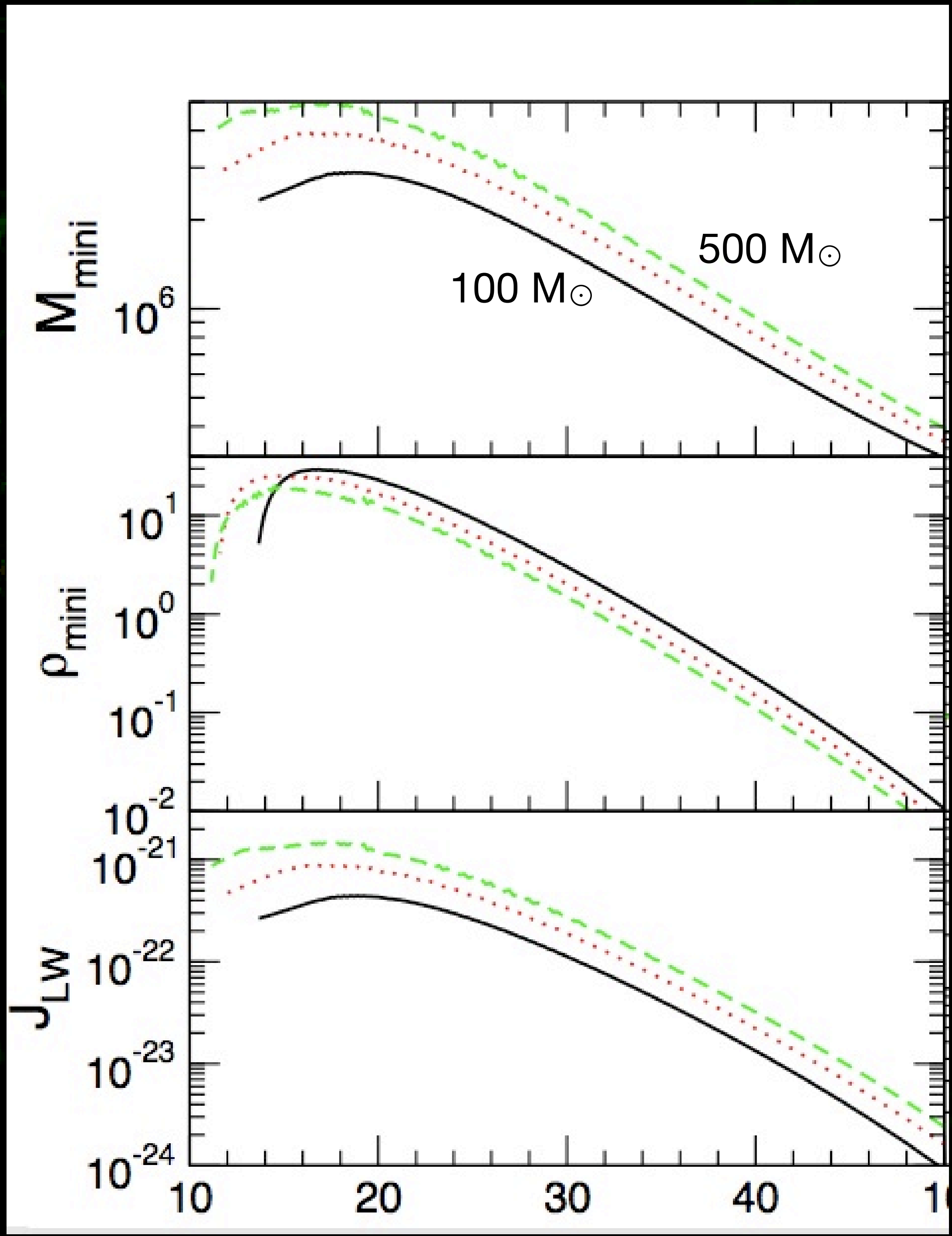


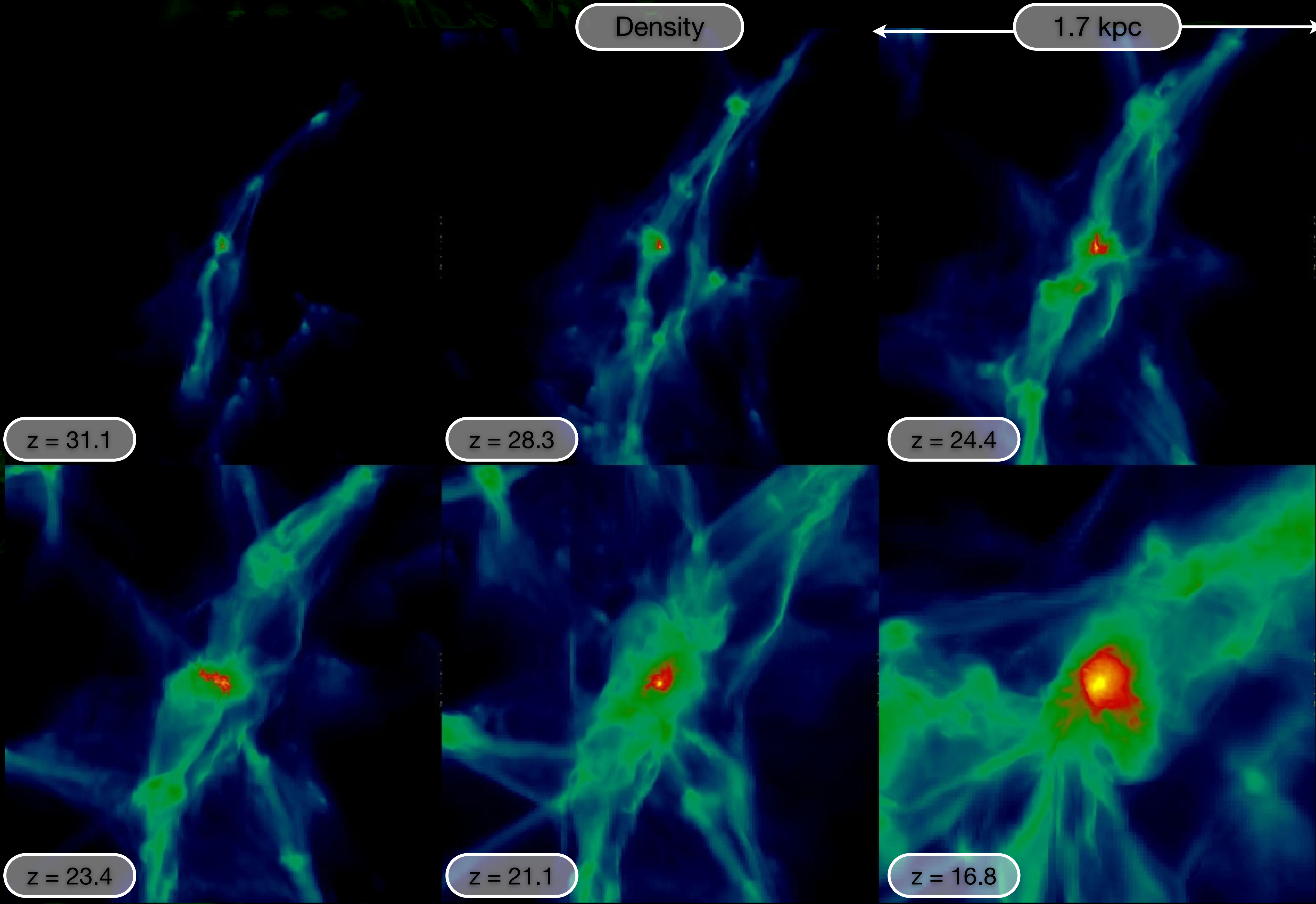
Redshift

Wise & Abel (2005)

H_2 Cooling Simulations

No UV Background	$J = 10^{-22}$ UV Background	$J = 10^{-21}$ UV Background
No residual e^- No UV Background	No residual e^- $J = 10^{-20}$ UV Background	Hydrogen & Helium Only

H_2 Cooling Simulations



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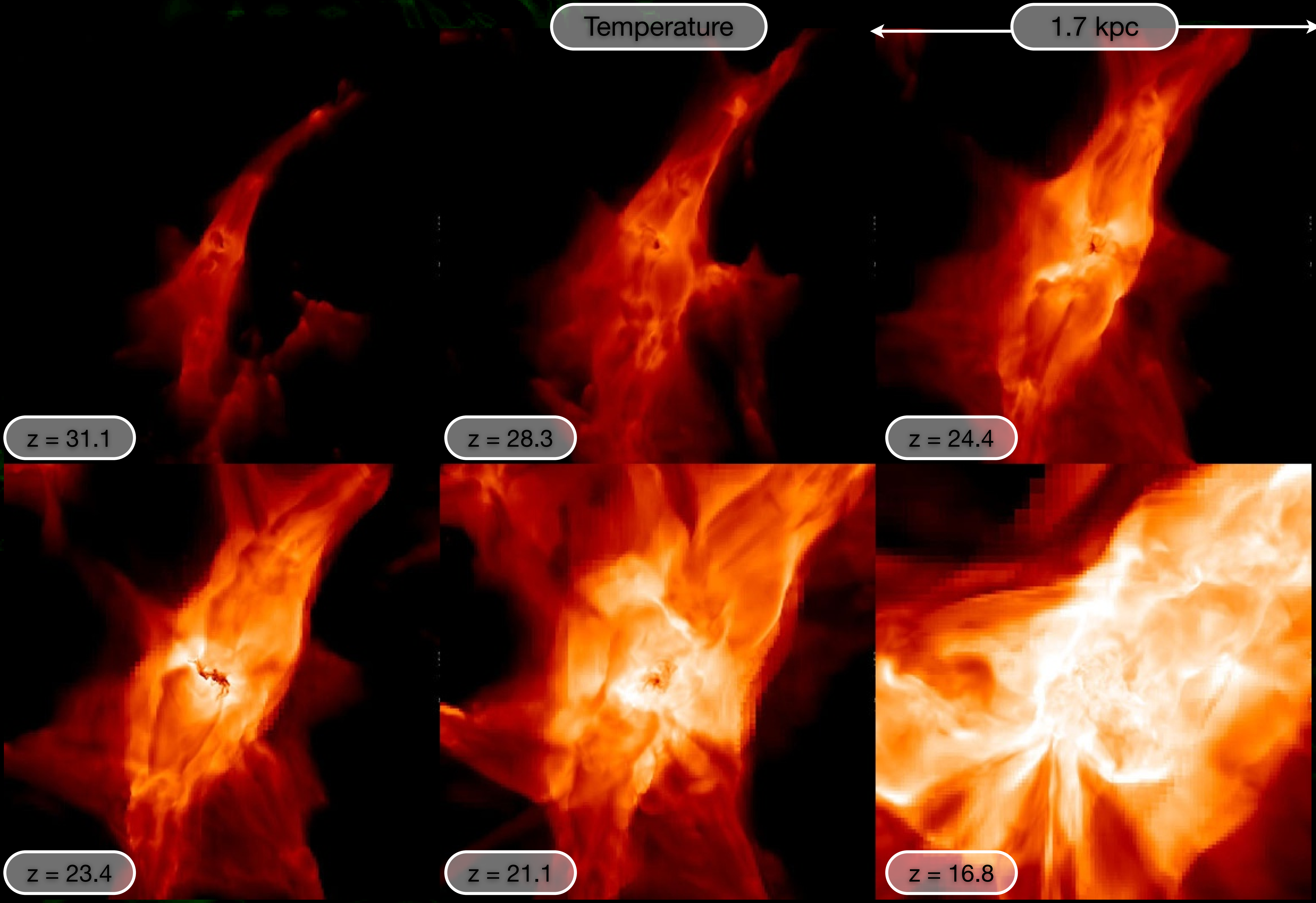

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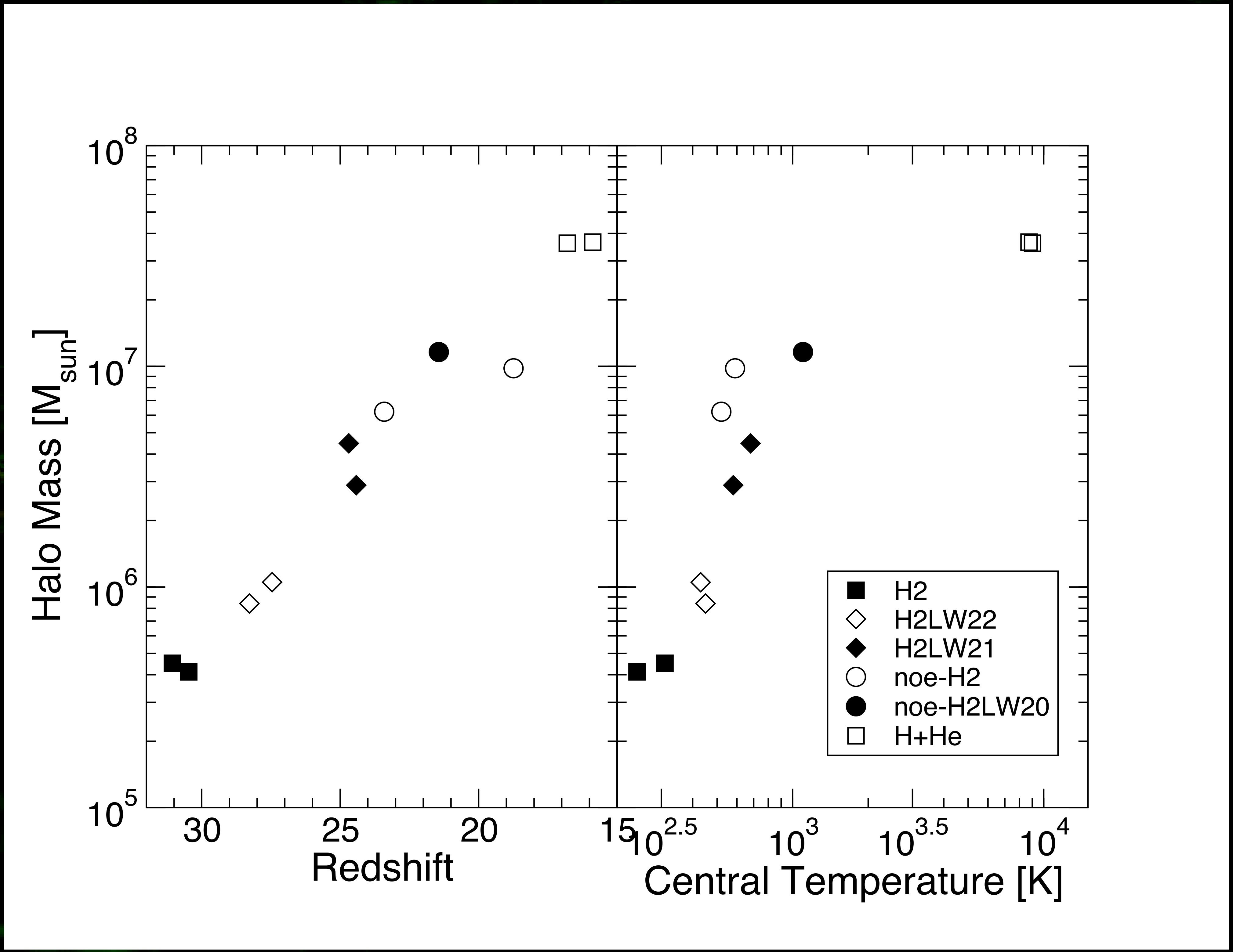
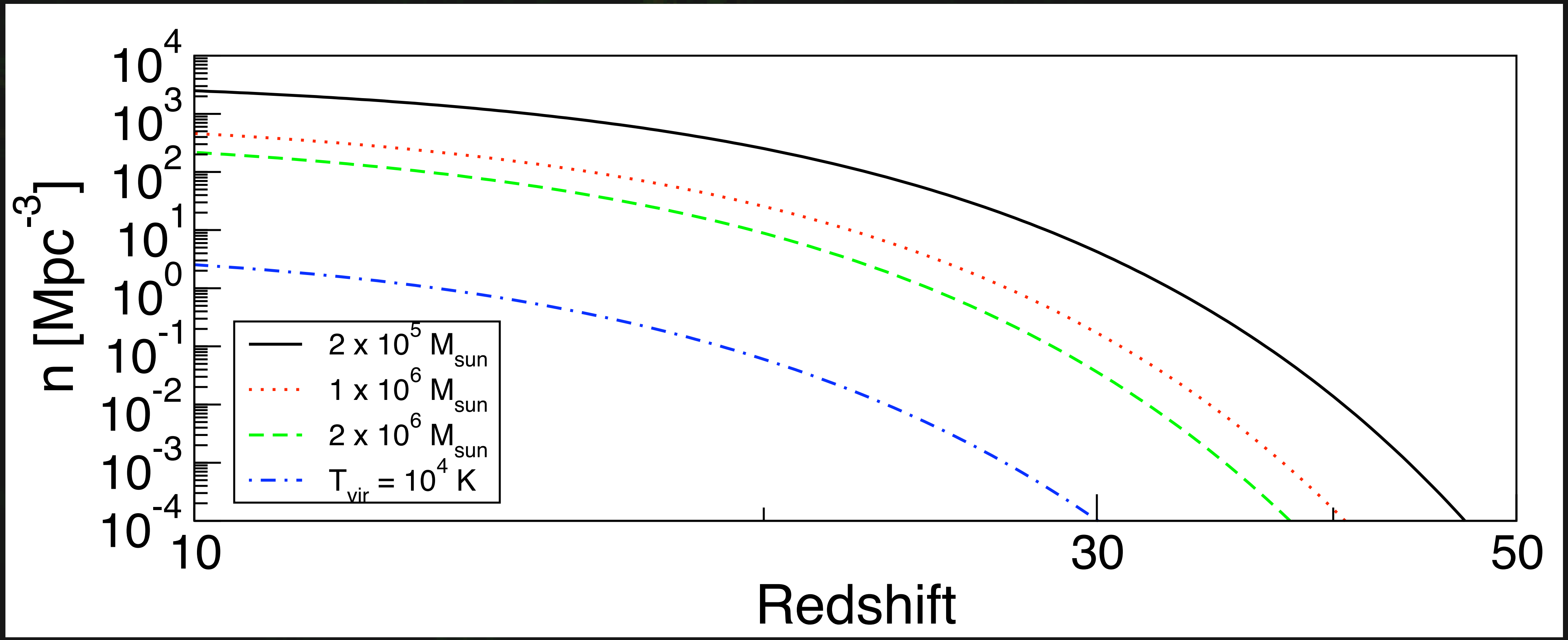


H_2 Cooling Simulations

- Even in the *worst case scenario* with no residual electrons and a soft UV background of J = 10^{-20}, we see halos cooling and collapsing before virial temperatures reach 10^4 K.
- Critical minimum masses are ~3x (~5x with no UV background and no residual electrons) smaller than previously thought.
- Due to the exponential nature of Press-Schechter formalism, this results in an order of magnitude increase of protogalaxies.

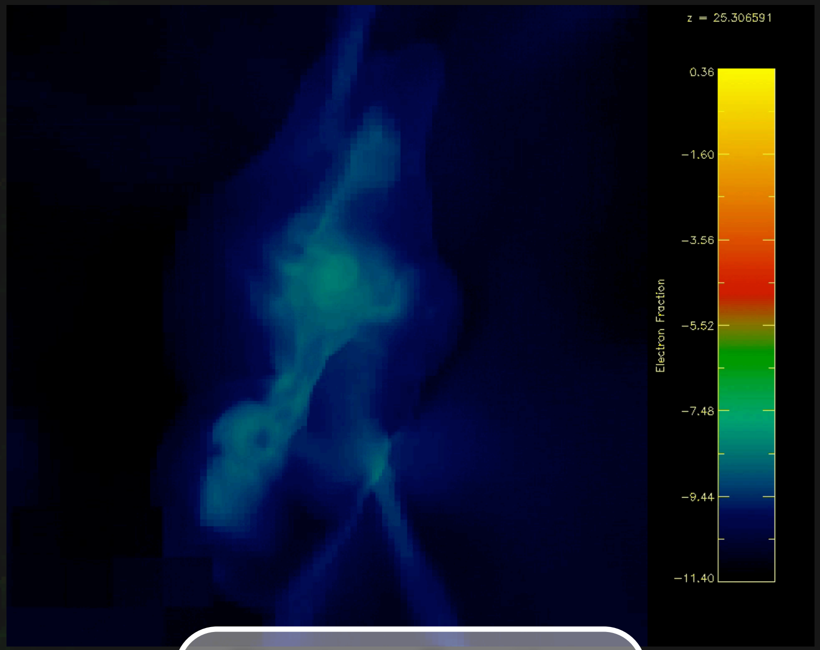


H_2 Cooling Simulations

- These halos can cool by H_2 in such extreme conditions due to the excess electrons created by collisional ionization.

$$T_{vir} = \frac{\mu m_p V_c^2}{2k}$$

- In this mass range, a halo with μ = 1.22 and T_{vir} = 7000K only needs 20% of the mass to virially heat gas to 10^4 K.



Electron Fraction

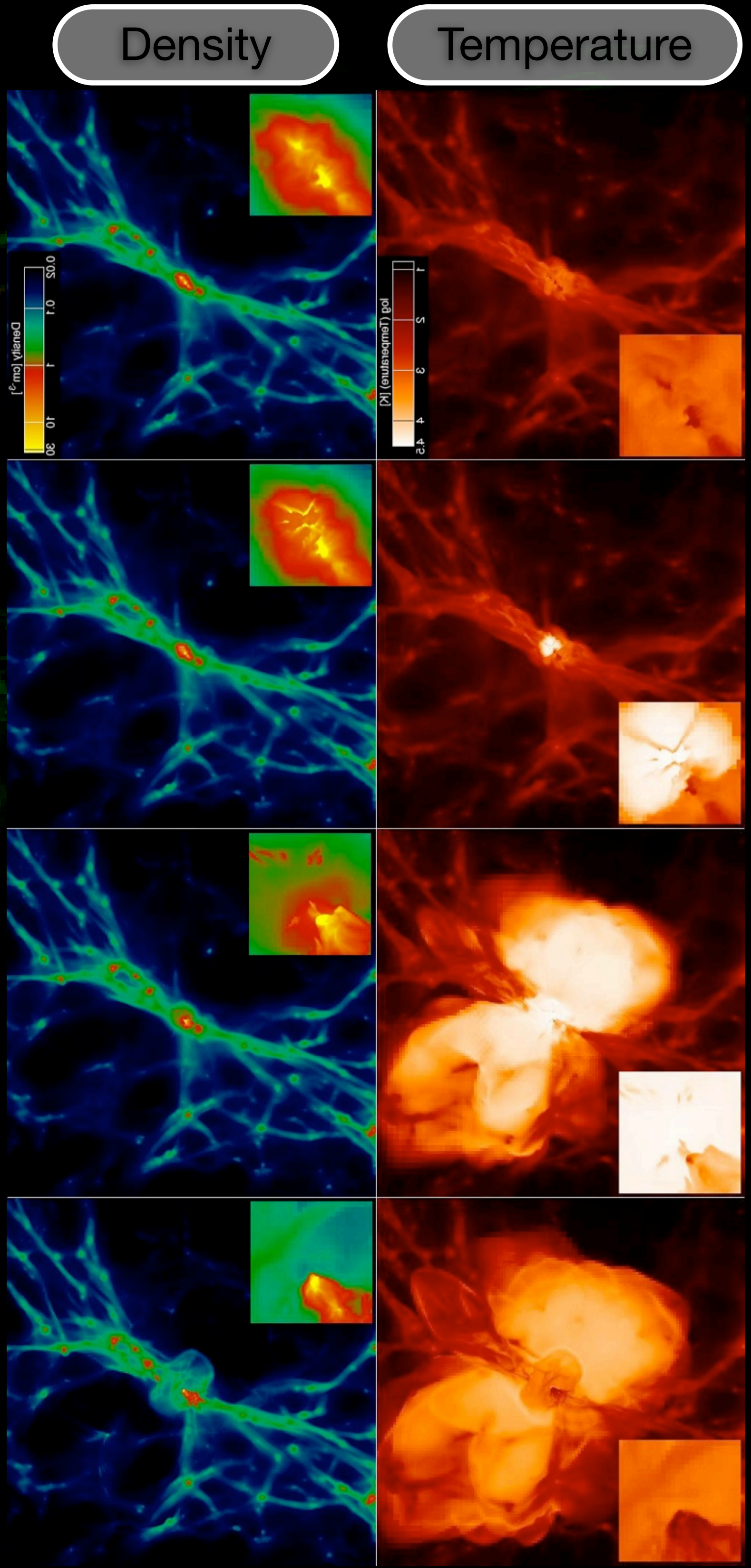
- This could result in earlier and more abundant galaxy formation.
- Semi-analytic models of reionization usually use minimum mass of different populations of stars. The gap between protogalaxies and primordial stars is only a factor of ~3-5.
- Perhaps a smooth transition occurs from H_2 to Lya cooling. However, *metallicity* should govern the transition from isolated to clustered star formation.

Primordial Star Formation and Feedback

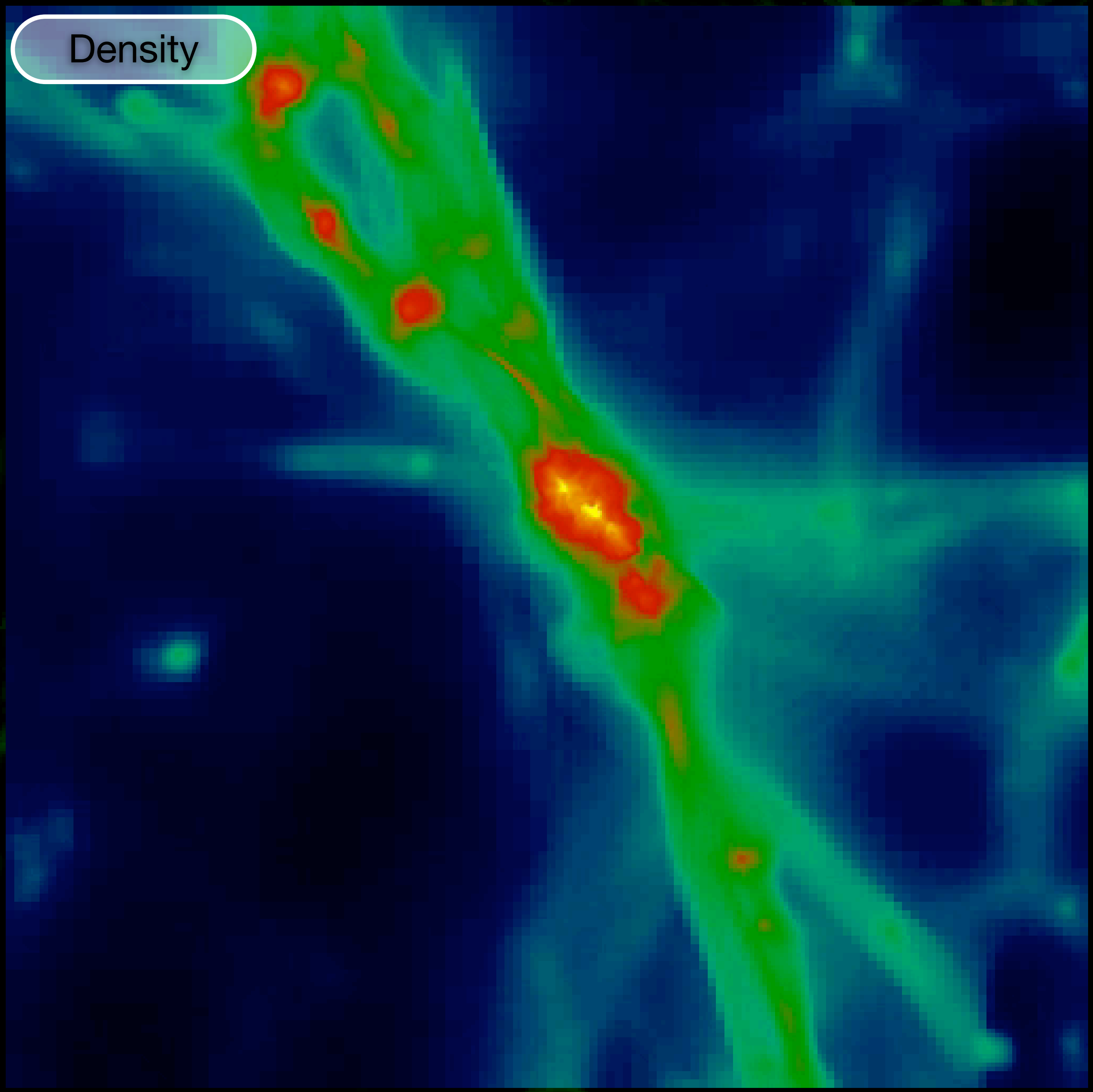
- With adaptive ray tracing and an optically thin, $1/r^2$ Lyman-Werner radiation field, we studied the radiative transfer from a single primordial star.

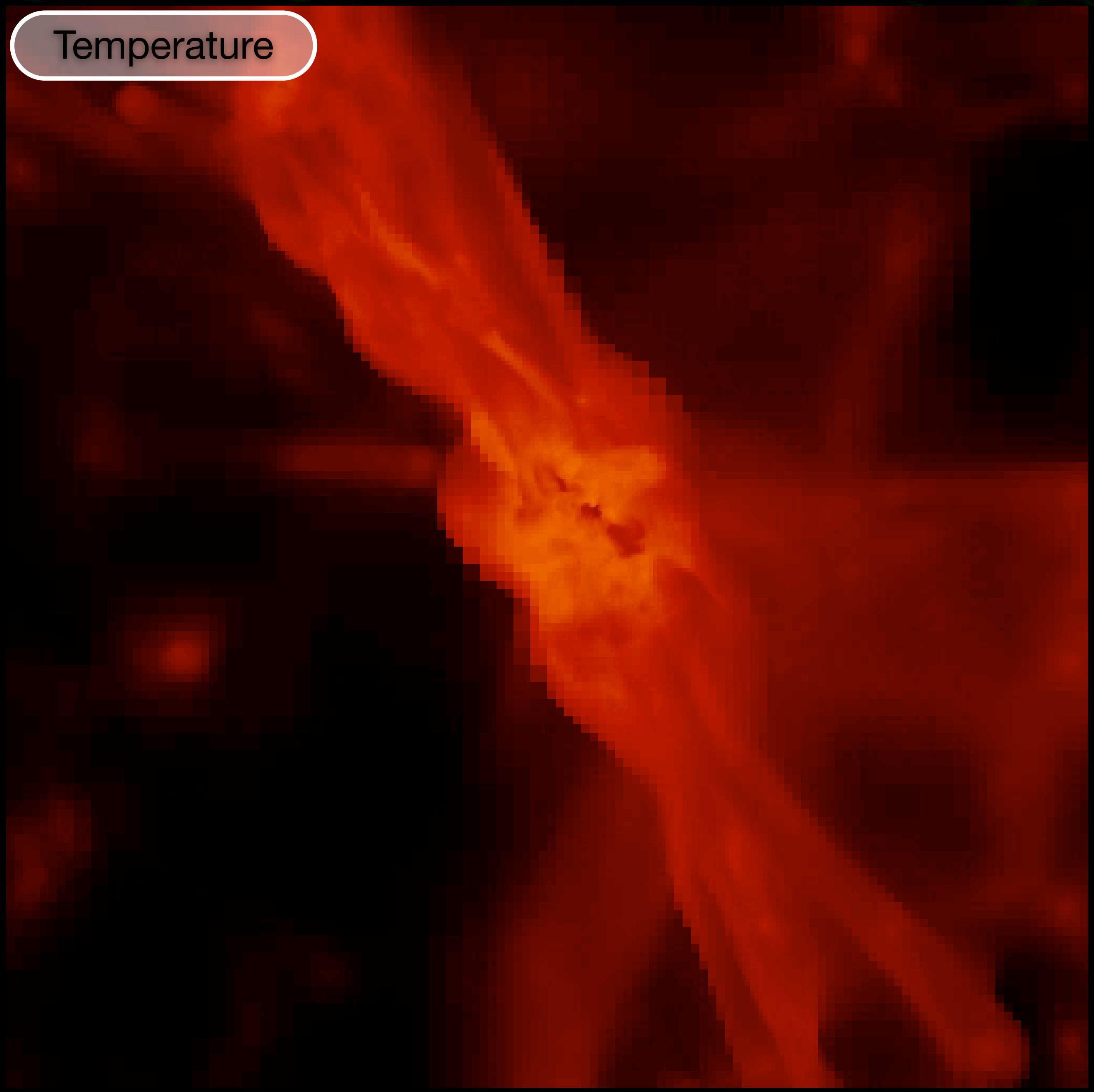
Abel et al. (2006)

- Our radiative transfer is coupled to the hydrodynamics, chemistry, and energy solvers. MPI Parallelized.
- When the results are radially averaged, they agree with previous 1D calculations very well.
- We see cometary structures and shadowing in our 3D simulation, similar to Galactic star forming regions.



Primordial Star Formation and Feedback

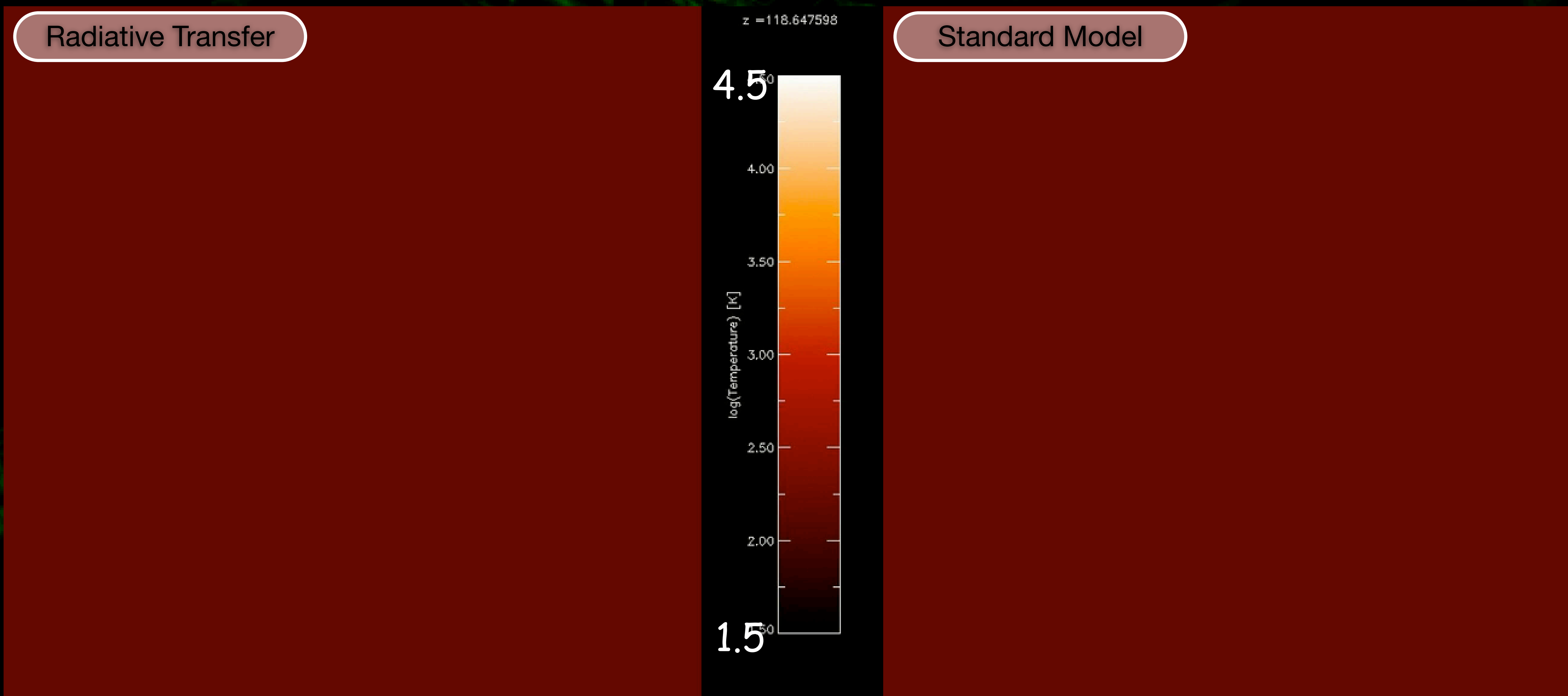




Photorealistic volume rendering of a primordial stellar lifetime and SN
Colors correspond to the gas’ blackbody spectrum
Hardware accelerated rendering at 10 fps

Primordial Star Formation and Feedback

Primordial Star Formation and Feedback



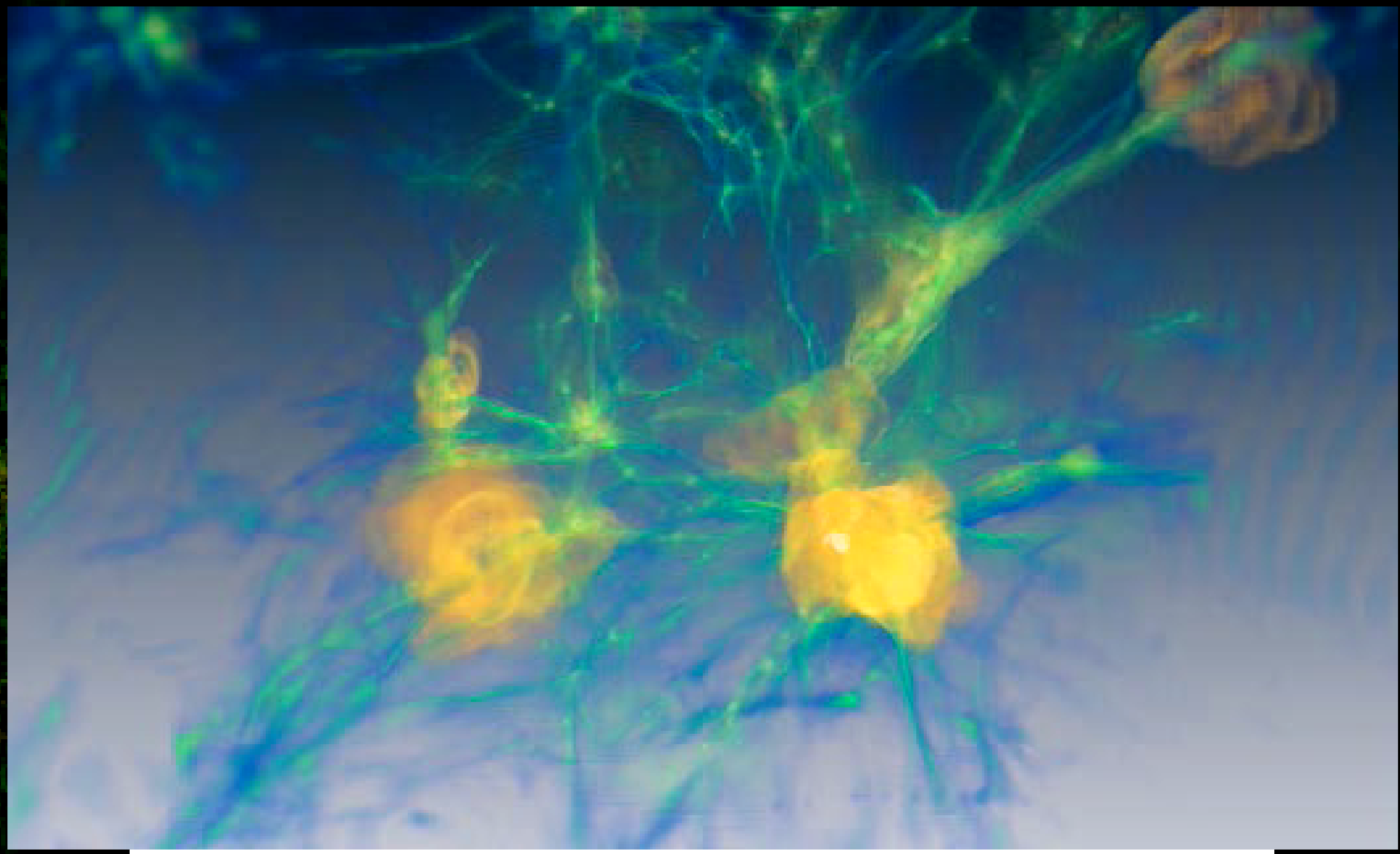
Temperature

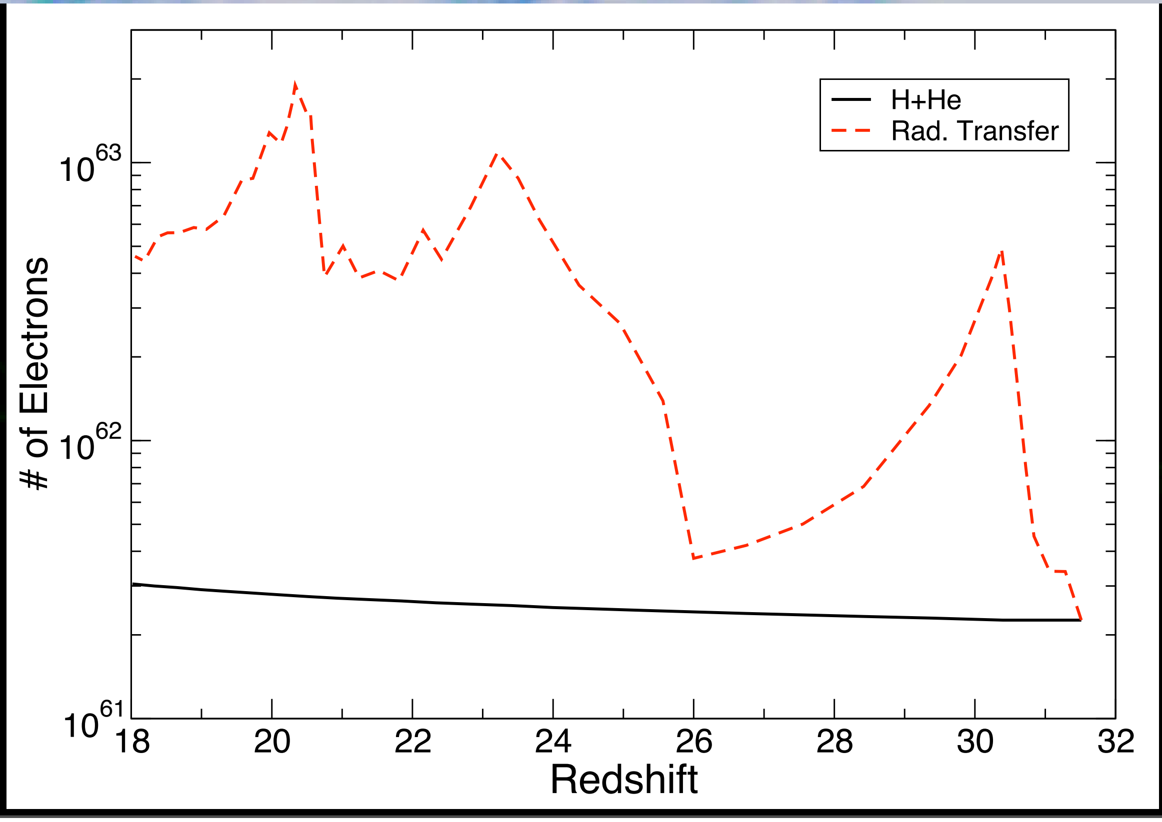
Primordial Star Formation and Feedback

- Only 1 in 200 photons contribute to reionization due to high recombination rates at high-z.
- As stars form in larger mass halos, the effective escape fraction decreases and the radiation becomes more anisotropic.
- Excess electrons in relic HII regions result in positive feedback.

O'Shea et al. (2005)

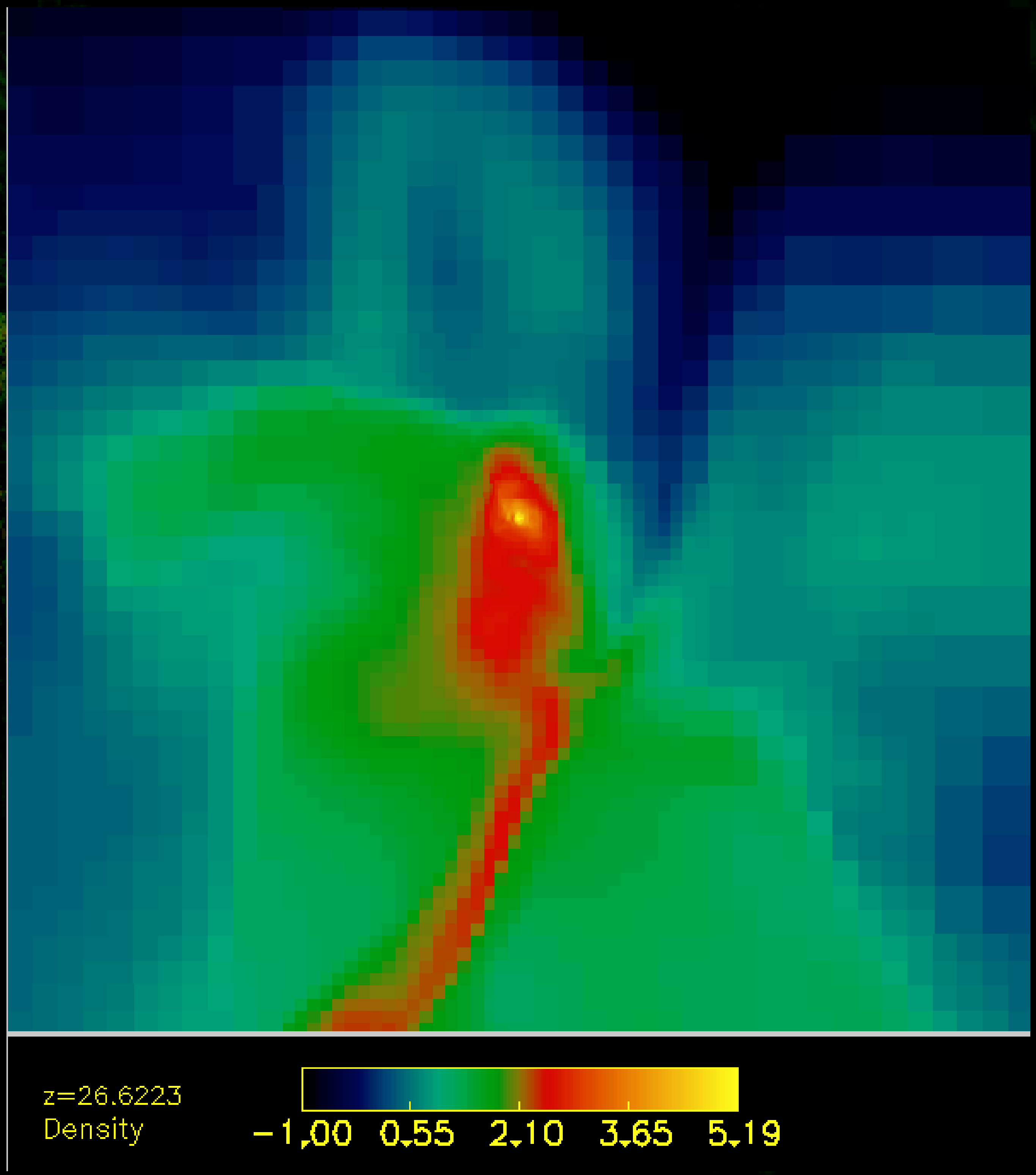
- With merger trees in the standard model, we only expect 8 primordial stars forming. However, we see twice as many in the full radiative transfer case.





Primordial Star Formation and Feedback

- Pair instability supernovae case – $M = 170\ M_\odot$, $M_{ej} = 81\ M_\odot$
- The metals from these SNe enrich both the IGM and nearby halos.
- Enrichment of dense structures require longer times since metals must mix, whereas in the voids, they freely expand.
- The 2nd star forms on the SN shell and is metal enriched to $\sim 10^{-6}$ solar metallicity.



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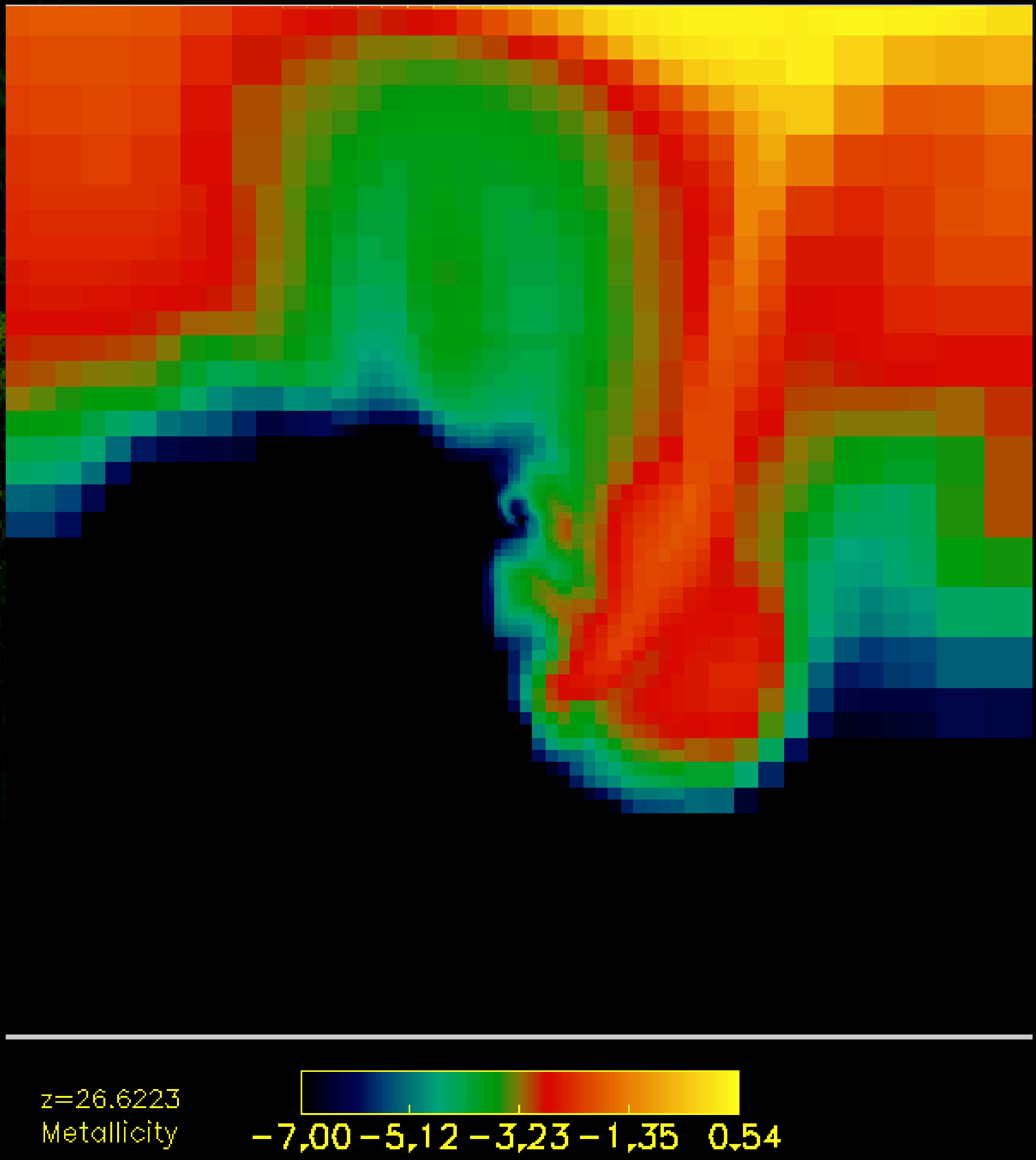

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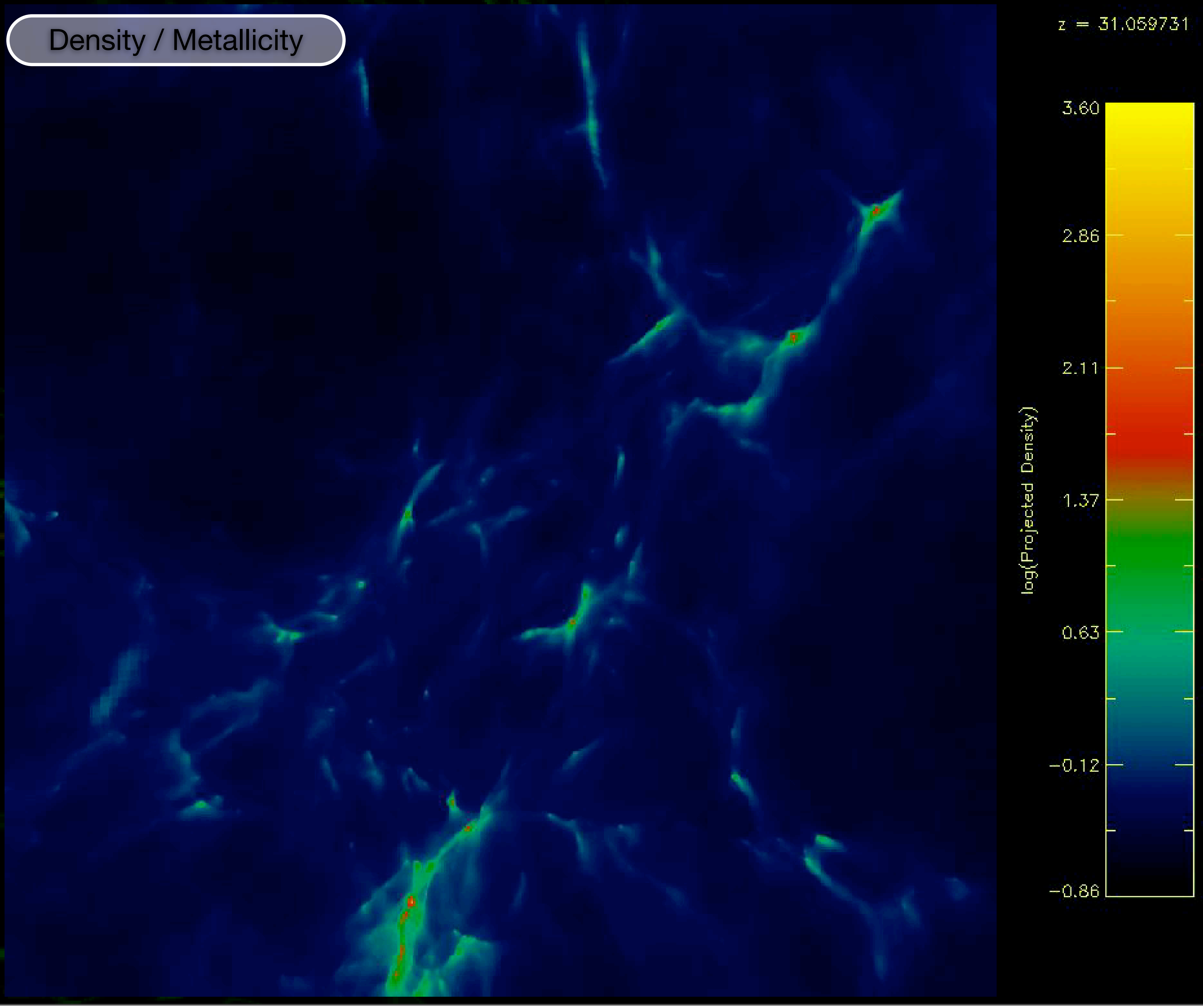


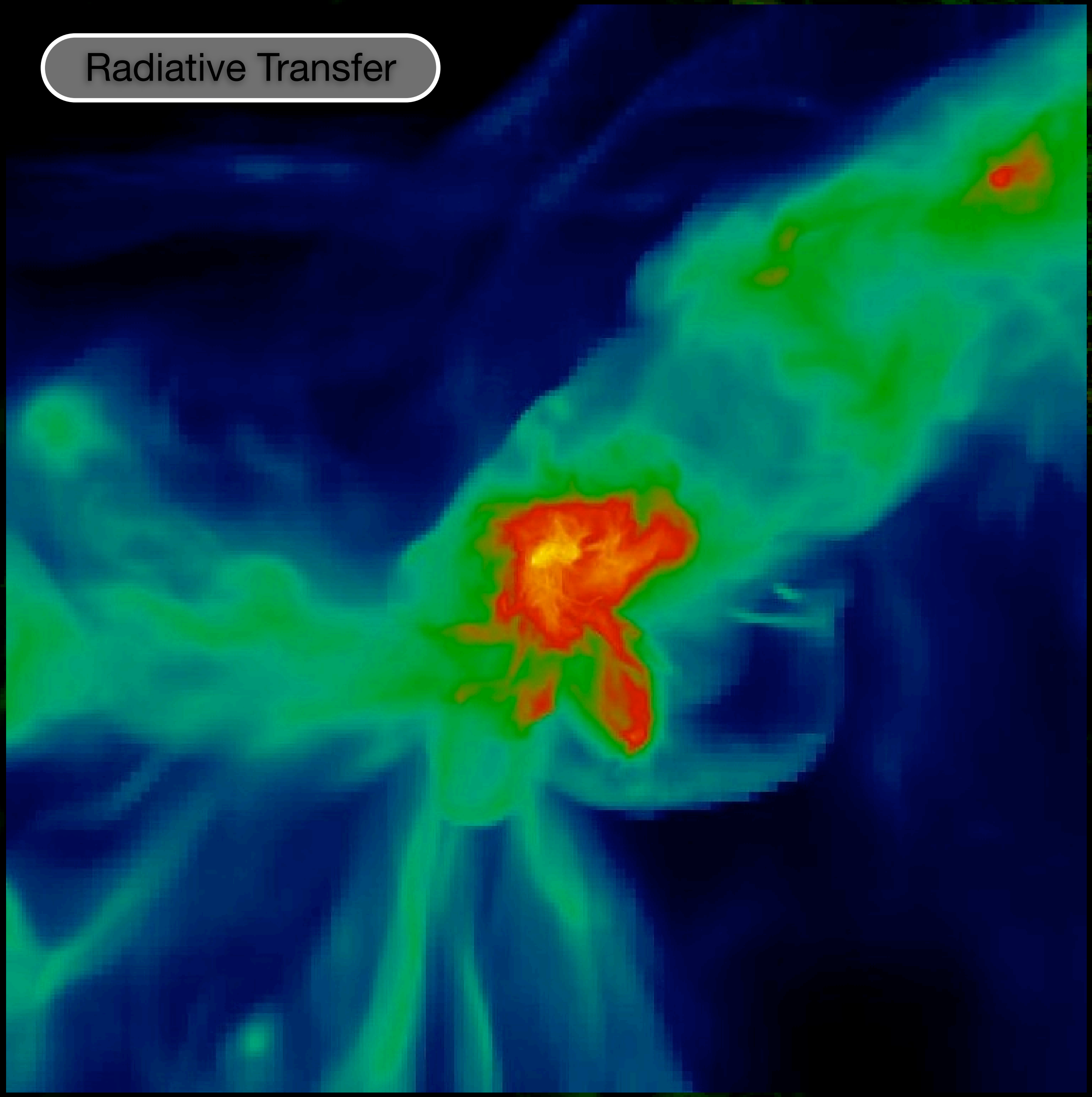
Effects on the Protogalaxy

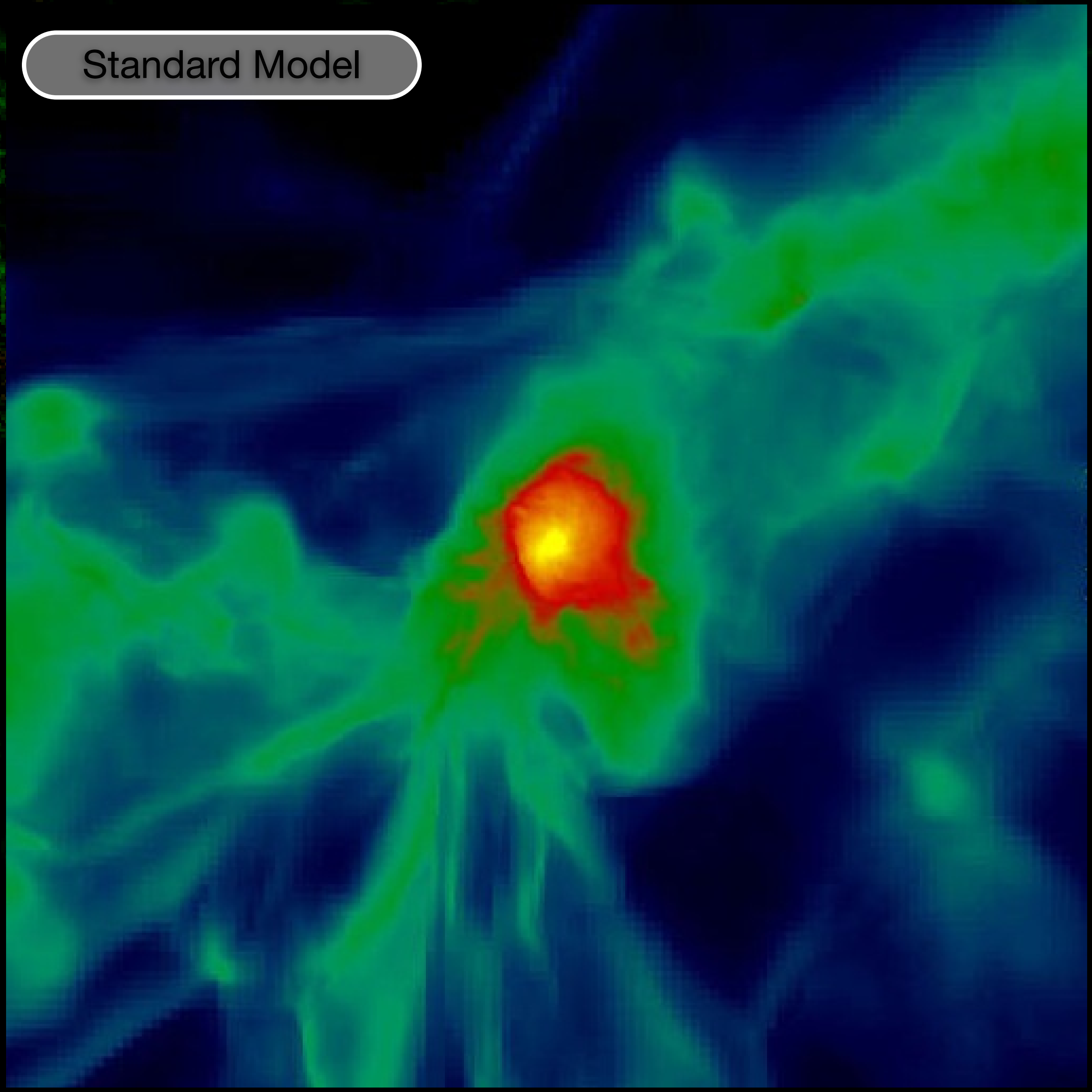
- Decreased baryon fraction
- Increased spin parameter – altered angular momentum distribution
- Metal Enrichment
- Accretion of pre-heated gas

Values given at z = 16.8 (19.7)

	Baryon Fraction	Spin Parameter	Metallicity
Standard	13.5% (12.6%)	0.010 (0.047)	N/A
Radiation Only	10.6% (6.3%)	0.022 (0.094)	N/A
+ SNe	(6.9%)	(0.099)	(–2.5)

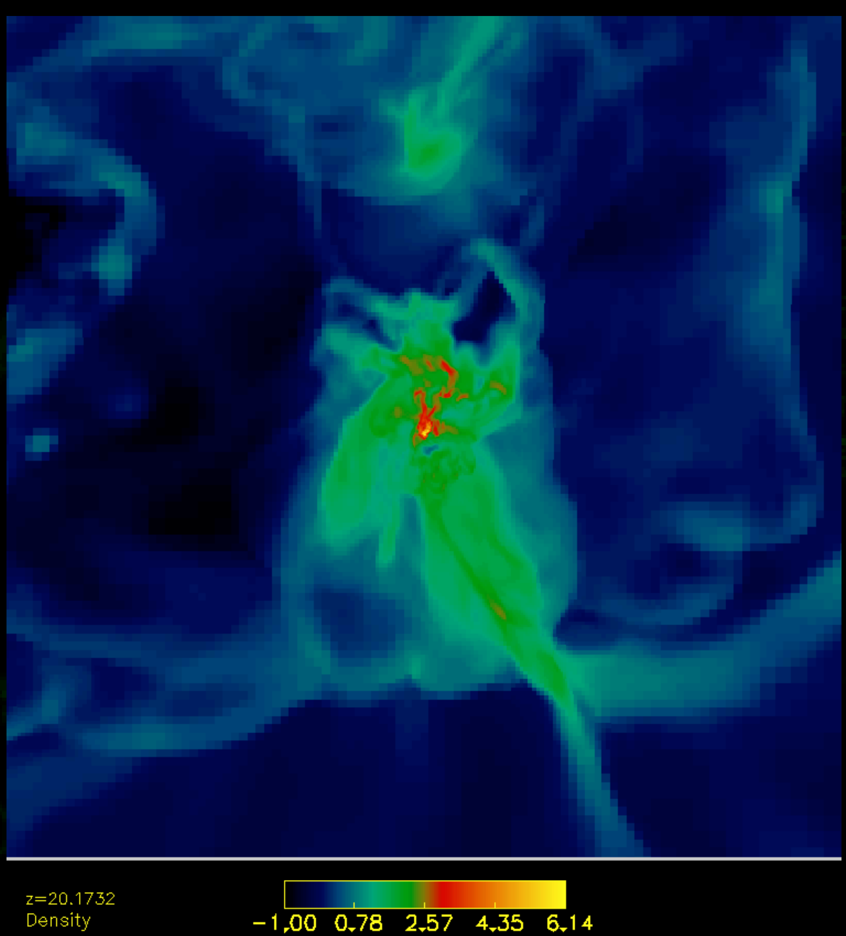
Effects on the Protogalaxy



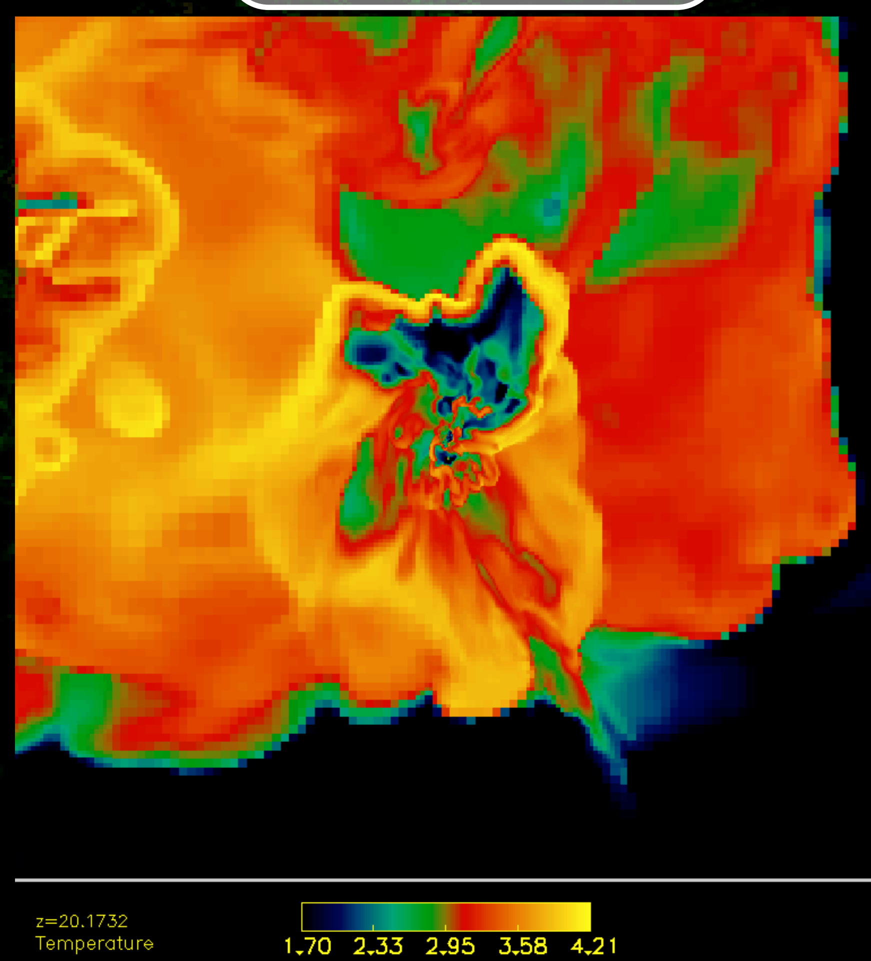


Effects on the Protogalaxy

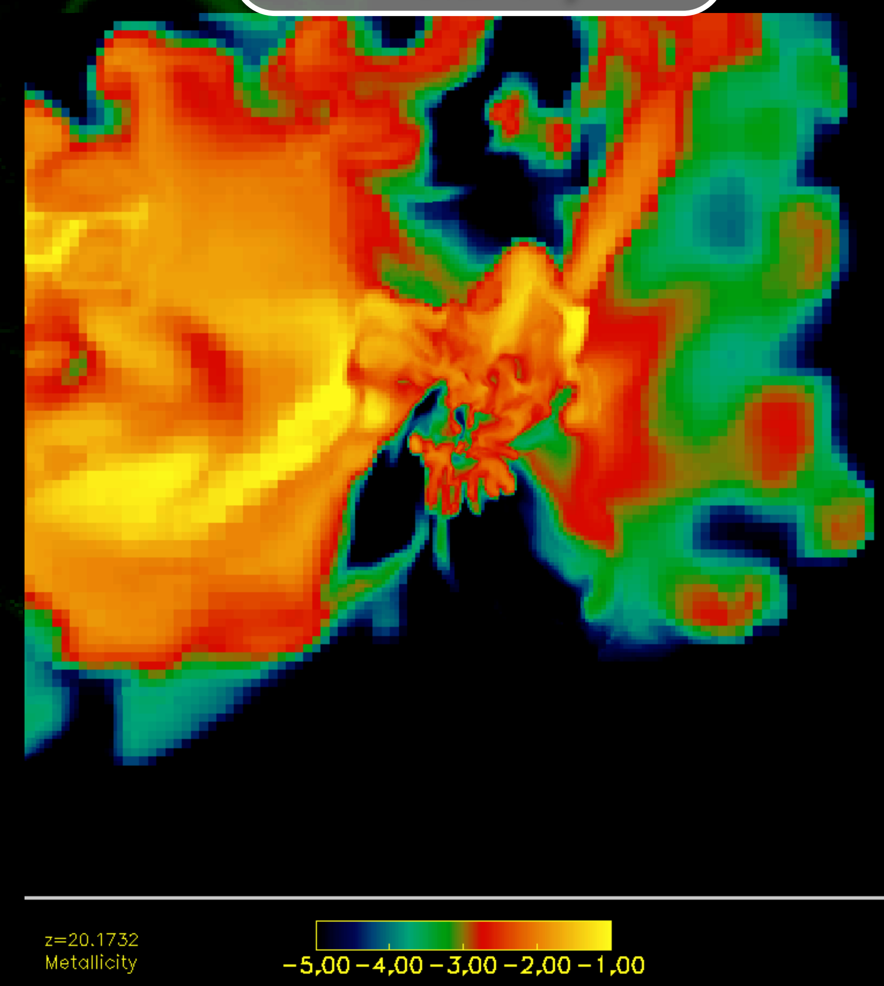
Density



Temperature



Metallicity



Physical Models

Primordial Star Formation

- Formation criteria are an extended version of Cen & Ostriker (1992)
  - *Original:* Converging velocity, Jeans unstable, overdense, cooling rapidly
  - *Added:* H_2 fraction must exceed 0.1%, metallicity must not exceed 10^{-3} solar. *Removed:* Jeans unstable
- When a cell reaches these criteria, a particle is formed and mass is removed from the grid in a sphere that has twice the mass of the star.
- Fully automatic – no manual star insertion required.
- As of now, all stars have equal mass and is user-defined.

Physical Models

Pair Instability Supernovae

- When the primordial star is between 140 and 260 M$_\odot$, the star completely destroys itself and explodes with 10^{51} – 10^{53} ergs.
- Nearly the entire helium core is converted into metals (e.g. 50 M$_\odot$ of ^{56}Ni for a 260 M$_\odot$ star!).

$$M_{metals} \approx \frac{13}{24}(M_\star - 20M_\odot)$$

Heger et al. (2002)

- Energy and metals are injected into a sphere of radius 1 pc that is centered where the star exists.

$$E = \rho_0\epsilon_0 V_{cell} + \rho_{SN}\epsilon_{SN} V_{cell} \qquad \epsilon' = \frac{E}{\rho_{tot}V_{cell}} = \frac{\rho_0\epsilon_0}{\rho_0 + \rho_{SN}} + \frac{\rho_{SN}\epsilon_{SN}}{\rho_0 + \rho_{SN}}$$

- Baryons are returned to the computational grid in this sphere.

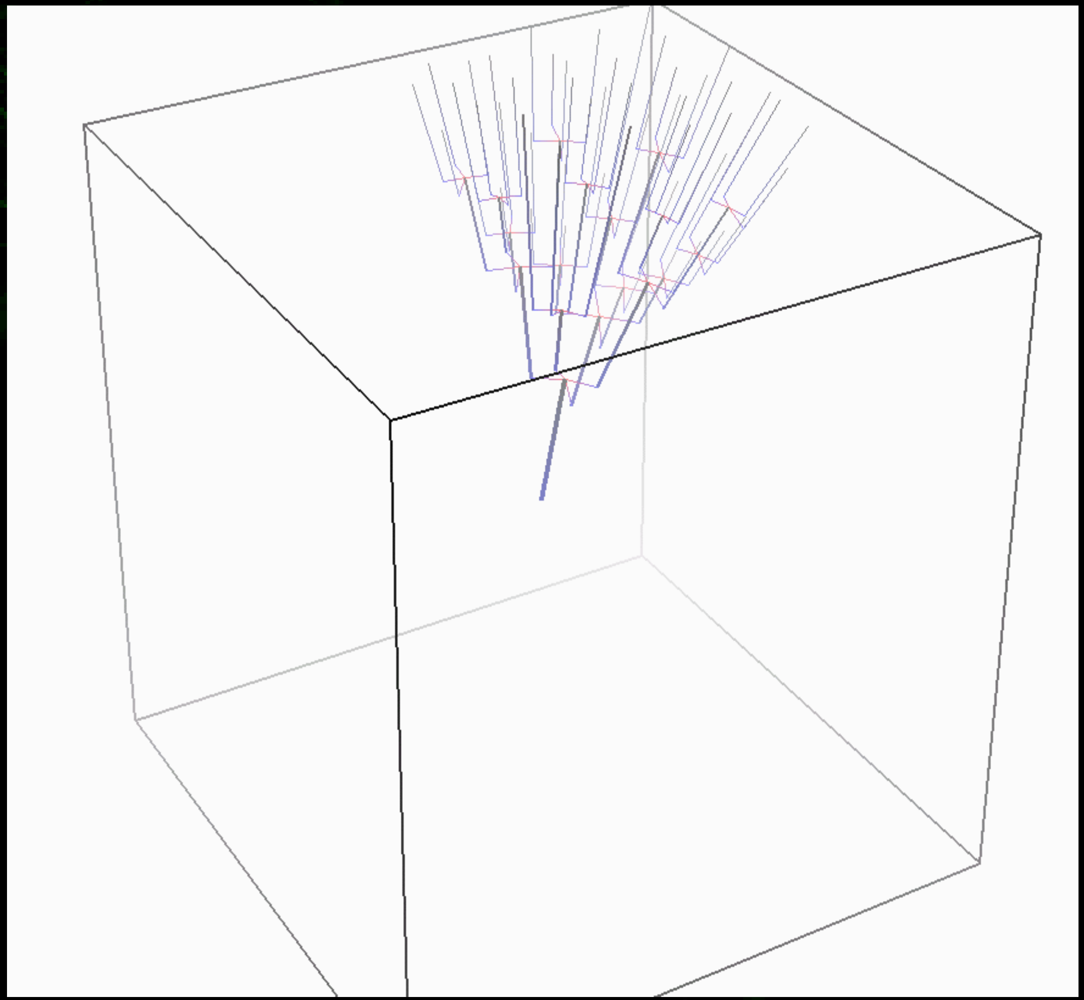
Physical Models

Adaptive Ray Tracing

- Radiative transfer is computed using a novel ray tracing technique.
- We require at least 5 rays per cells. Rays are split when this criterion is not met.
- Direction of the rays and splitting are determined by HEALPix.
- Fully integrated and coupled with the hydrodynamic, chemistry, and energy solvers in *enzo*.
- Parallelized with MPI and dynamically load balanced. Computational time is comparable with the hydrodynamic calculations.

$$\frac{dn_H}{dt} = k_{rec} n_p n_e - n_H n_e - n_H k_{ph}$$

$$k_{ph} = \sum_{rays} \frac{I_r [1 - \exp(-\delta\tau)]}{V_{cell}}$$



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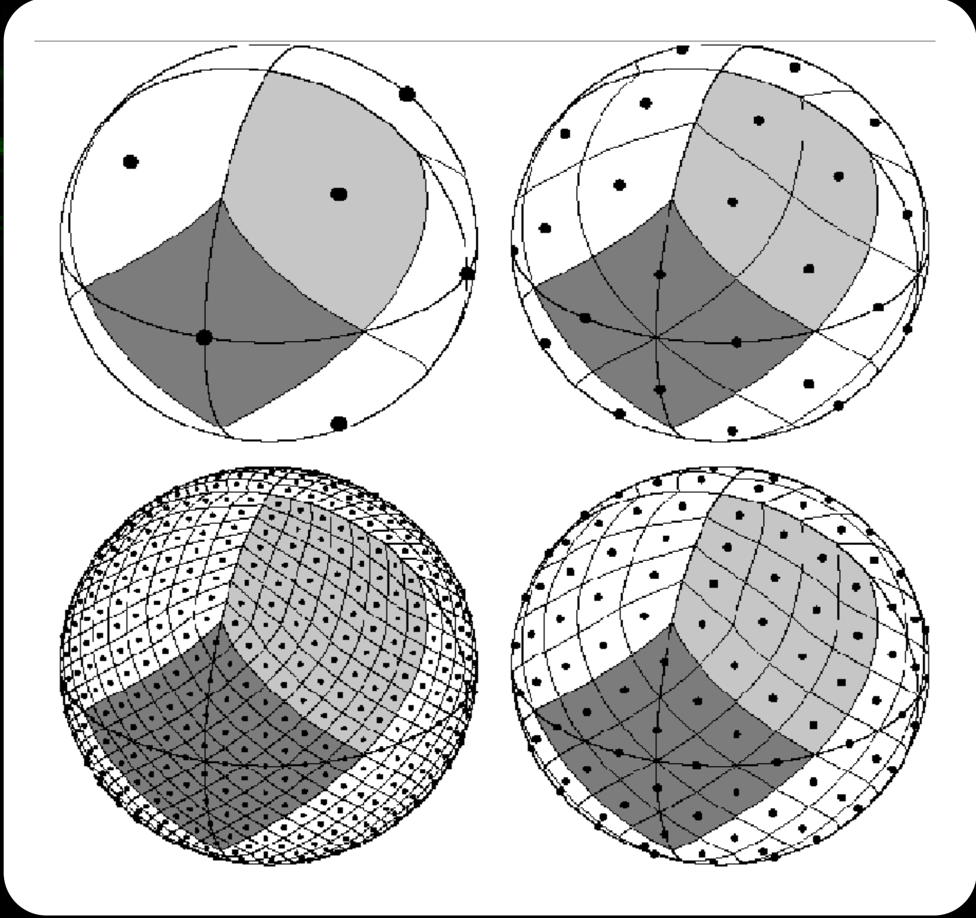
- Fully integrated and coupled with the hydrodynamic, chemistry, and energy solvers in *enzo*.
- Parallelized with MPI and dynamically load balanced. Computational time is comparable with the hydrodynamic calculations.

$$\frac{dn_H}{dt} = k_{rec} n_p n_e - n_H n_e - n_H k_{ph}$$

$$k_{ph} = \sum_{rays} \frac{I_r [1 - \exp(-\delta\tau)]}{V_{cell}}$$



Summary

- **Standard galaxy formation model – hydrogen and helium cooling**
  - Turbulent collapse to a central object with a mass of 10^5 $M_\odot$ without a rotationally supported disk.
  - No fragmentation down to sub-solar scales.
  - This full scenario may never occur in nature.
- **Molecular hydrogen cooling and radiation backgrounds**
  - Halos can cool and collapse with $T_{vir} < 10^4$ K even in extreme cases.
  - Protogalaxy formation could begin earlier and more frequently than previously thought.
- **Primordial Star Formation and Feedback**
  - In minihalos, baryons are expelled, leaving a 1 cm^{-3} ambient medium.
  - 1 in 200 photons contribute to reionization
  - Positive feedback in relic HII results in twice the number of primordial stars.
  - Metal mixing is dependent on the structure.
- **Effects on the Protogalaxy**
  - Lowers baryon fractions
  - Increases angular momentum ~2x
  - Metal enrichment
  - Accretion of pre-heated gas

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Still many outstanding questions about galaxy formation.

Magnetic fields? Dust? Transition to “normal” star formation? BH accretion and merging? Starburst or SMBH or both?

Questions?