How Population III Stars Begin Cosmological Reionization

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Population III 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. (2006)

- $L \sim 10^6\ L_\odot$, $\sim 10^{50}$ ionizing photons / sec

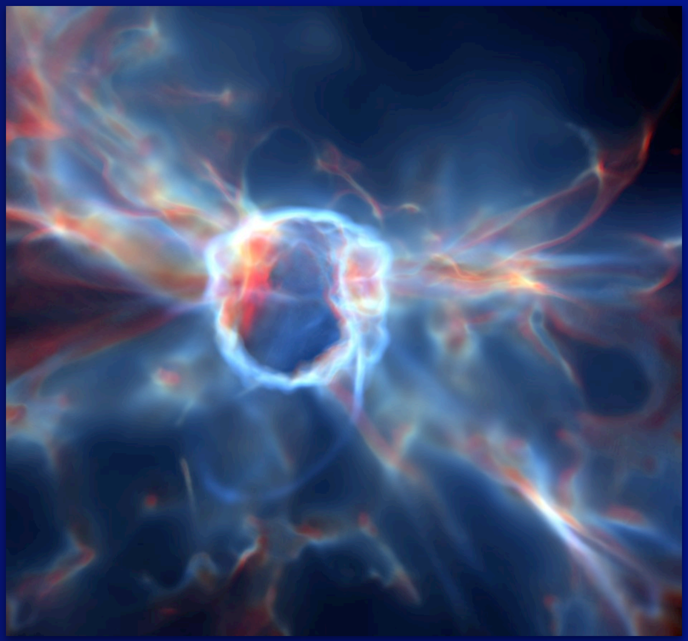
- Lifetime ~ 3 Myr

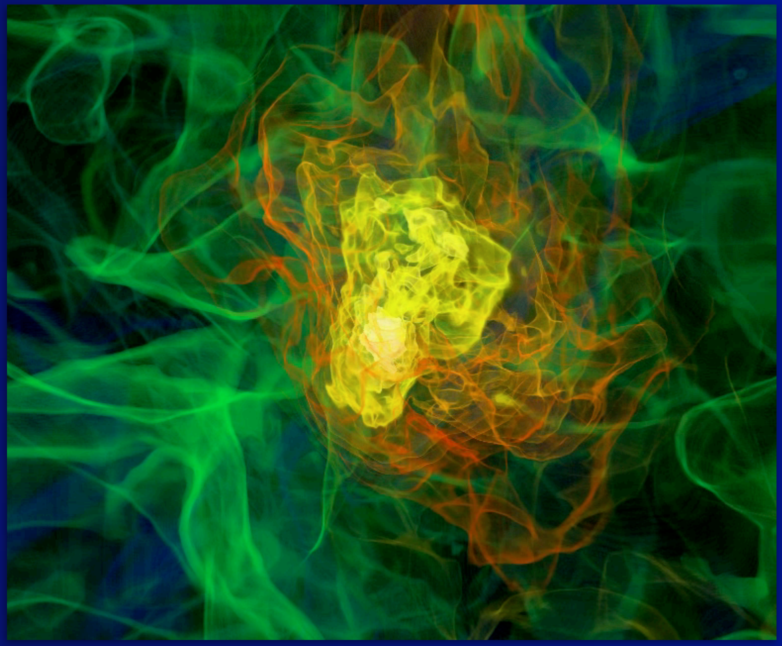
  Schaerer (2002)

- H_2 is the main coolant, which is easily dissociated by distant sources of radiation.

  Dekel & Rees (1987)

- Provide the first ionizing radiation and metals to the universe.

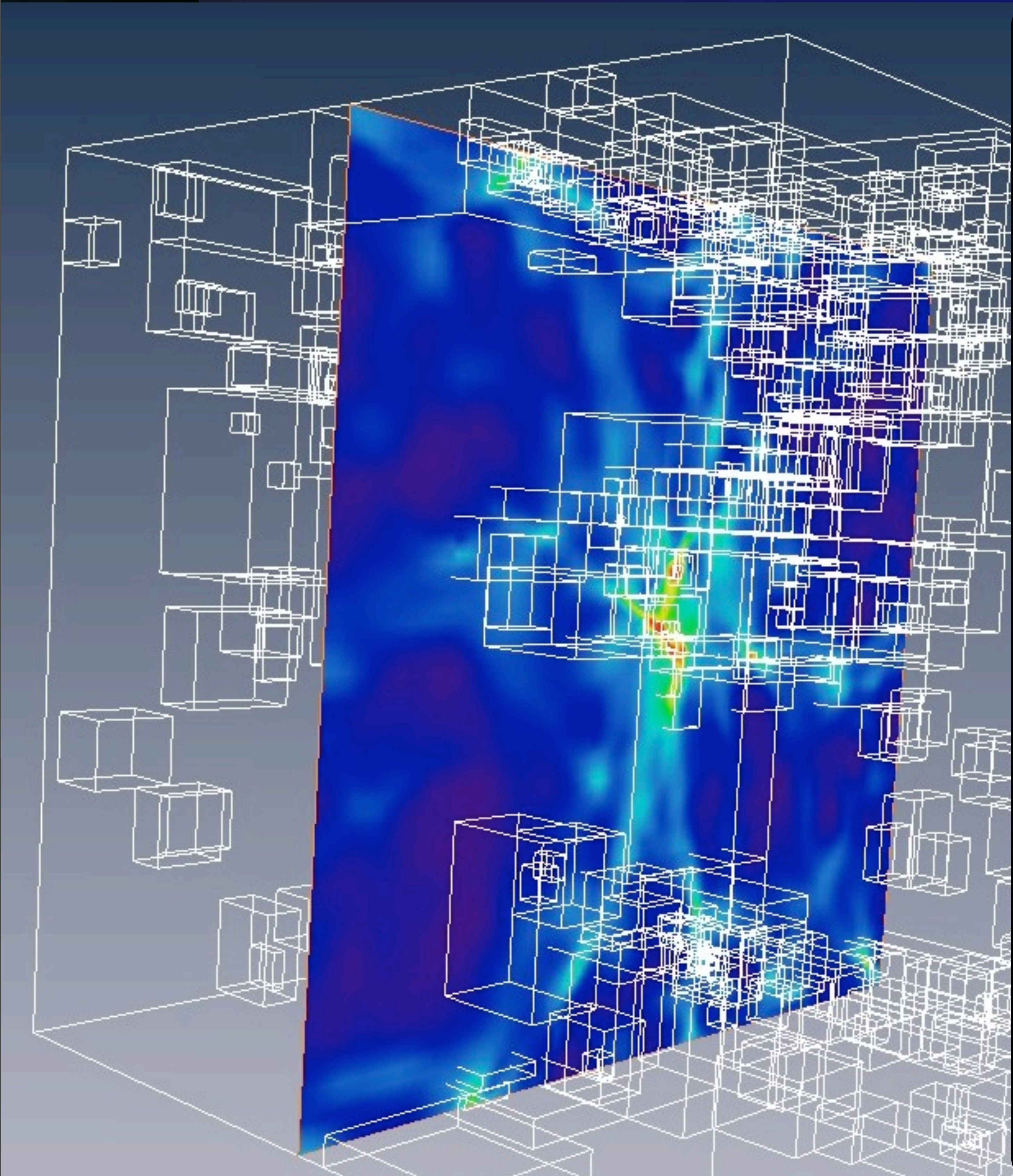




Motivation

- To calculate key quantities that can be used in semi-analytical or large box calculations.
    - Star formation rates, photon escape fractions, clumping factors, photo-evaporation, etc.
- To obtain the characteristics of low mass galaxies: baryon fractions, spin parameters that may affect star formation and photon escape fractions.
- Maybe deconvolve Pop III stellar properties from future observations of low mass z>6 galaxies?

Enzo



Versatile AMR Code

Bryan & Norman (1997, 1999); O'Shea (2005)

Physics:

- Gravity
- Hydrodynamics
- Non-equilibrium chemistry — Abel et al. (1997)
- Radiation transport — Abel & Wandelt (2002)
- MHD

Refinement:

- Baryon overdensity
- Dark matter overdensity
- Jeans length by 16 cells — Truelove et al. (1997)

Stable to 41 levels
(10^{14} dynamical range)

Wise, Turk, & Abel (2008)

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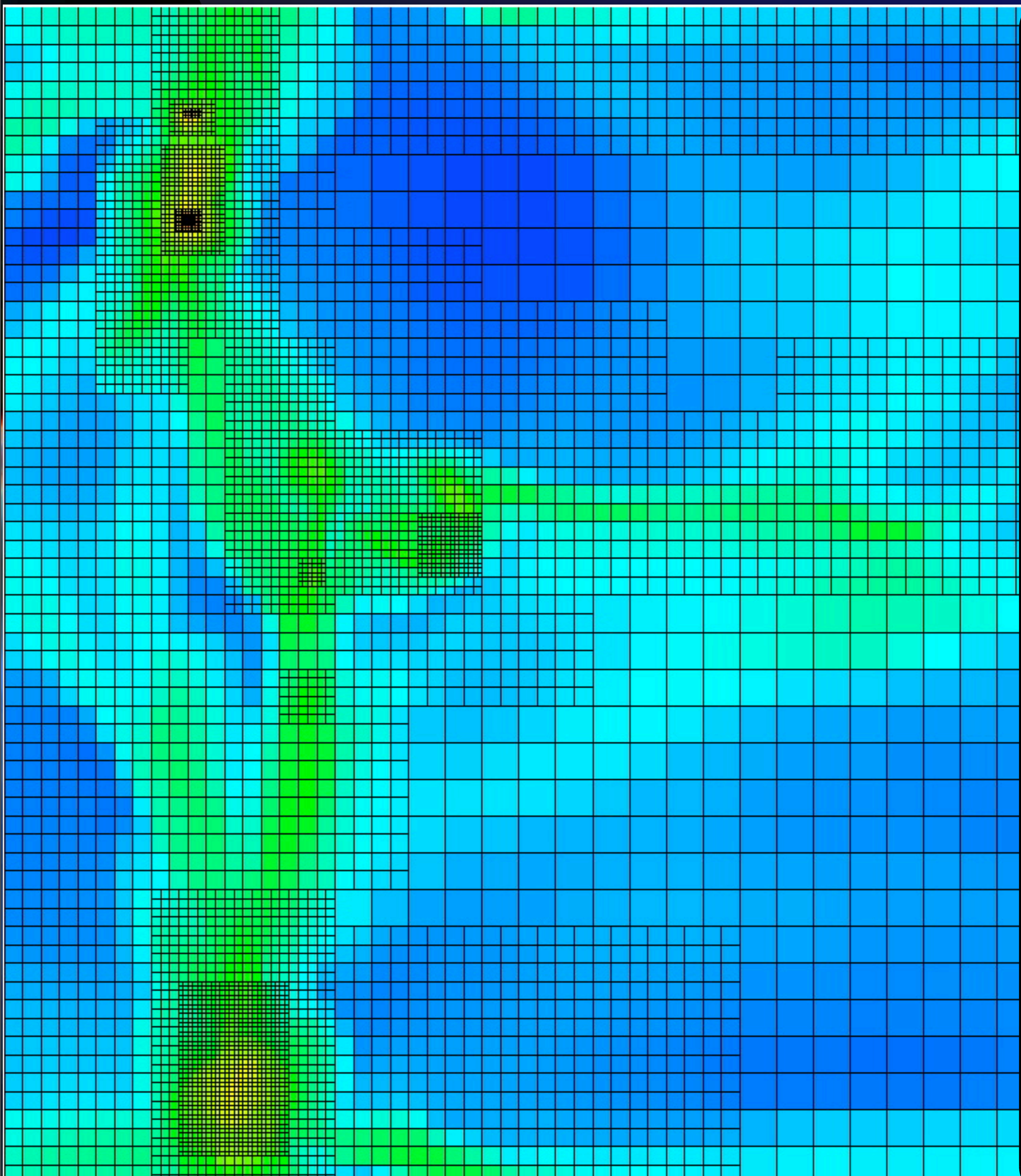

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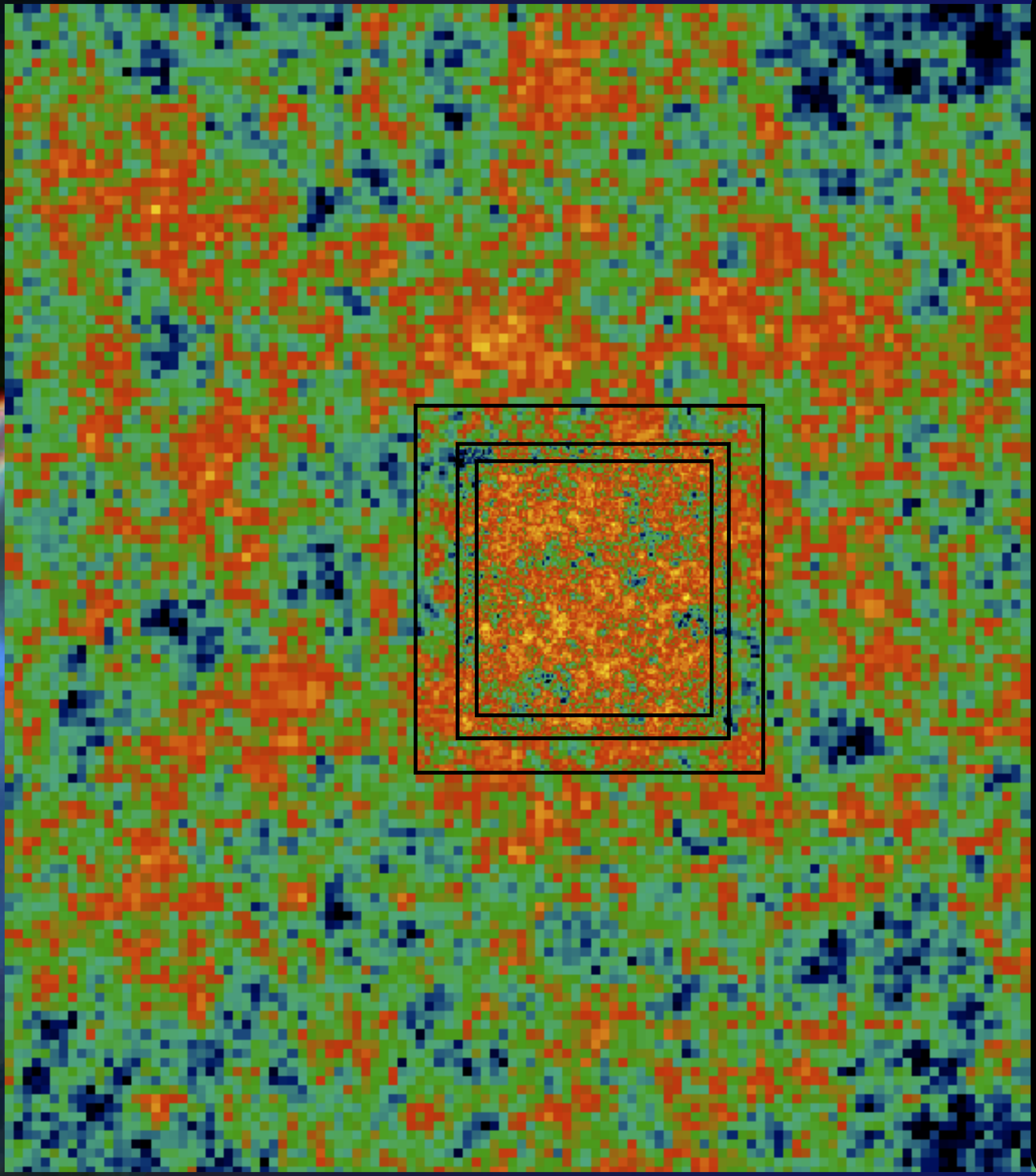
Simulation Setup



- Two random phases:
  - Simulation “A” and “B”
- Atomic H, He, and H_2 cooling
- Population III stellar formation and feedback
- Radiation transport
- Supernova feedback and metal tracer field
- Max AMR level = 12 (0.1 pc at z=20)

	Simulation A	Simulation B
Initial Redshift	130	120
Comoving Box Size	1.0 Mpc	1.5 Mpc
DM Mass Resolution	30 $M_\odot$	100 $M_\odot$
Maximum # of Unique Cells	1.2×10^8 (494^3)	6.5×10^7 (420^3)

Star Formation and Feedback

- Modified Cen & Ostriker (1992) prescription.

Star formation only

- 100 $M_\odot$ stars, 1.2 x 10^{50} ionizing photons / sec, 2.7 Myr lifetime

Plus pair-instability SNe

- 170 $M_\odot$ stars, 2.3 x 10^{50} ionizing photons / sec, 2.3 Myr lifetime

➡ Model radiation with adaptive ray tracing

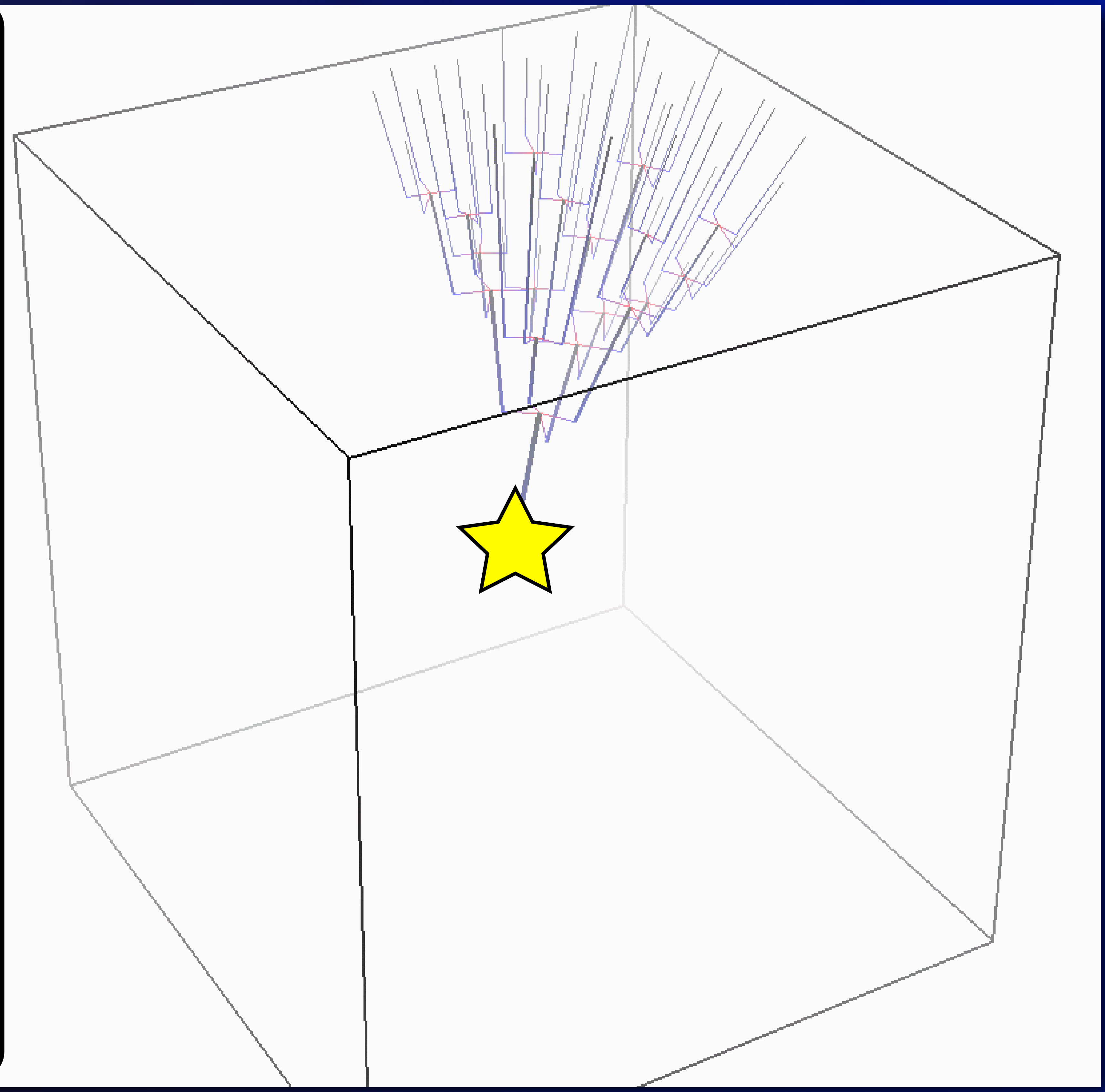
Adaptive Ray Tracing

Abel & Wandelt (2002)

- Radiative transfer is computed using an adaptive ray tracing technique.
- We require at least 5 rays per cell. Rays are split when this criterion is not met.
- Direction of the rays and splitting are determined by HEALPix.

Gorski et al. (2005)

- Fully integrated and coupled with the hydrodynamic, chemistry, and energy solvers in Enzo.
- Parallelized with MPI and dynamically load-balanced.



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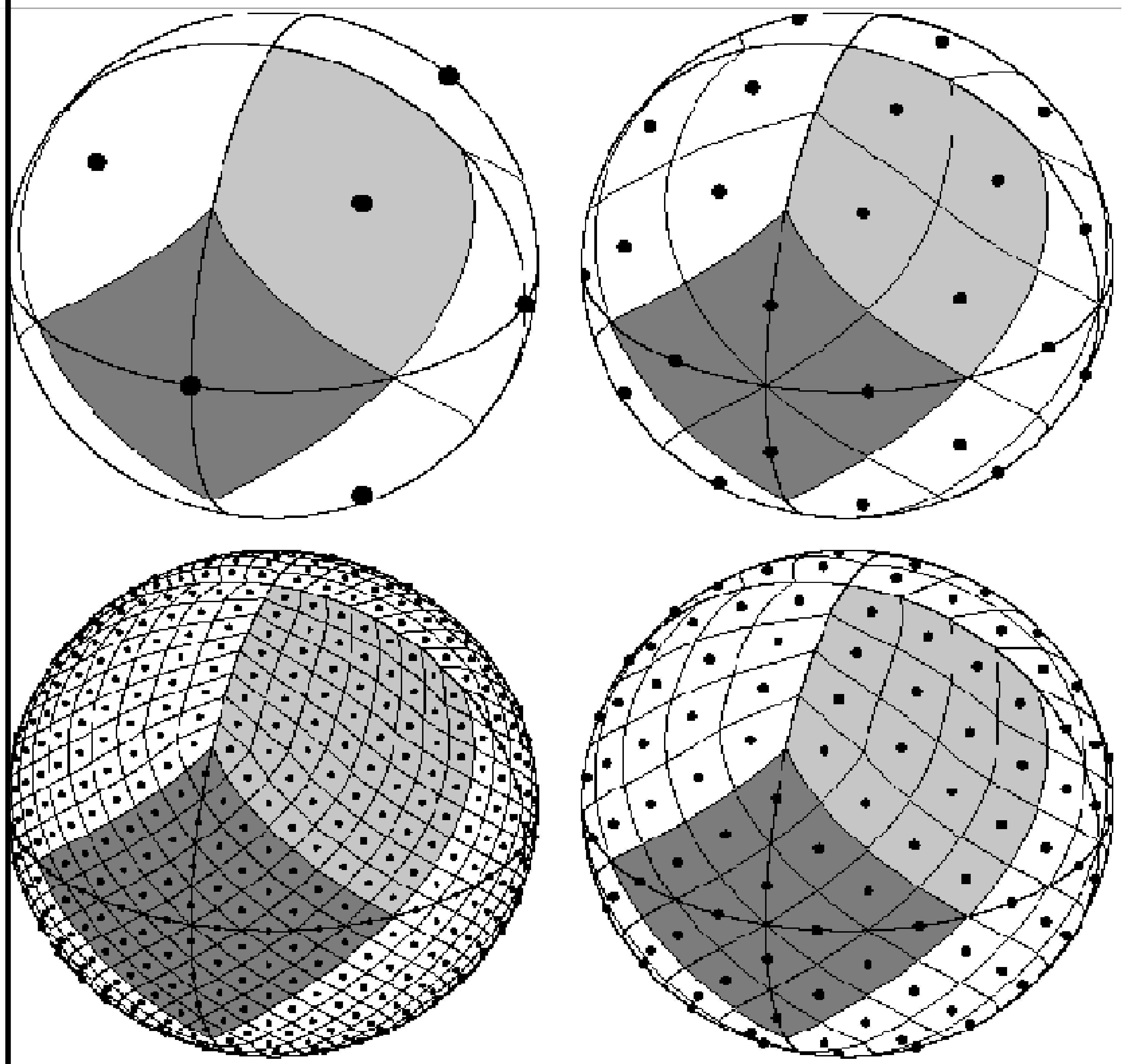


Abel, Wise, & Bryan (2007)

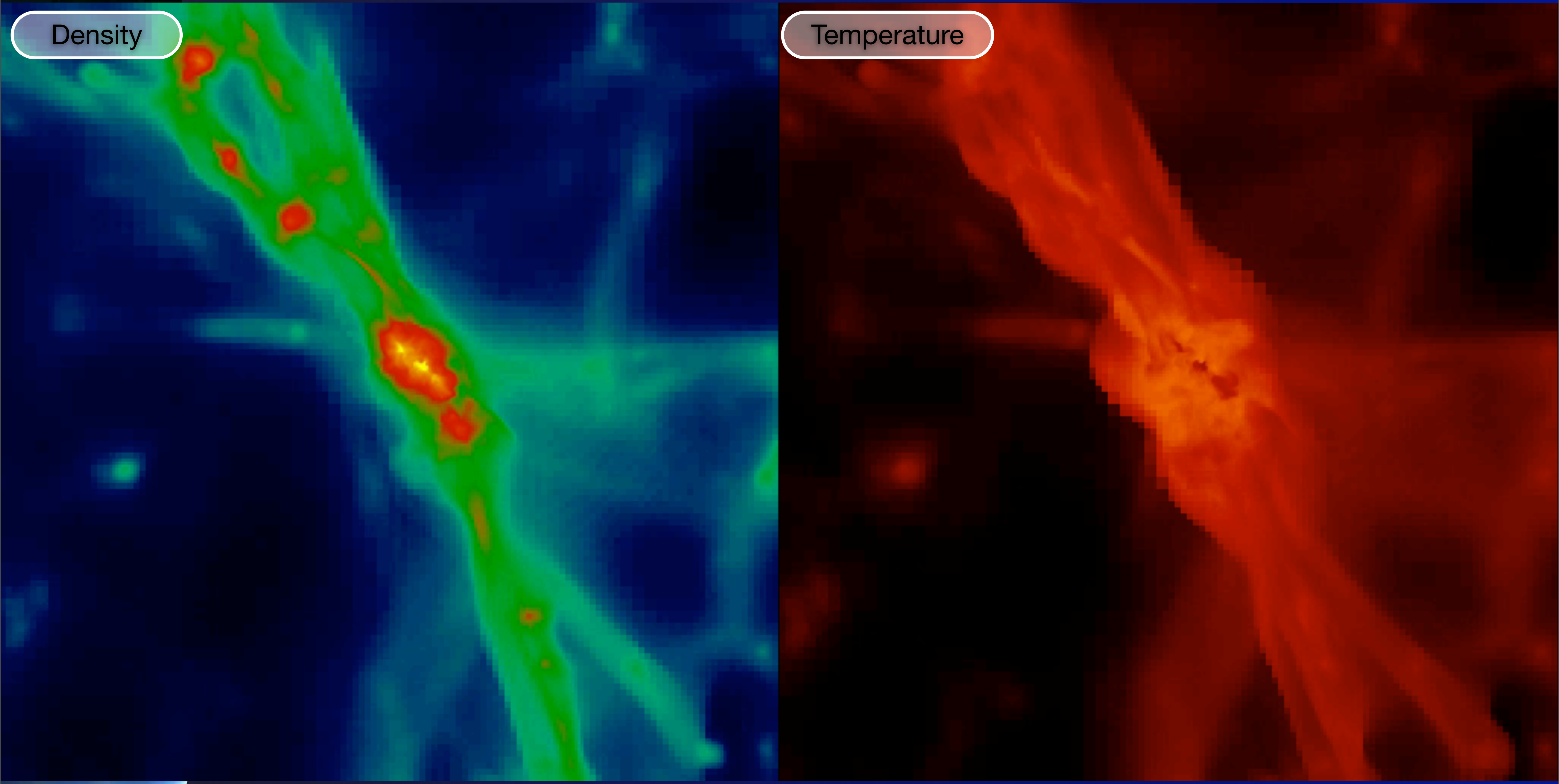
HII Region of a Primordial Star

Density

Temperature

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

HII Region of a Primordial Star



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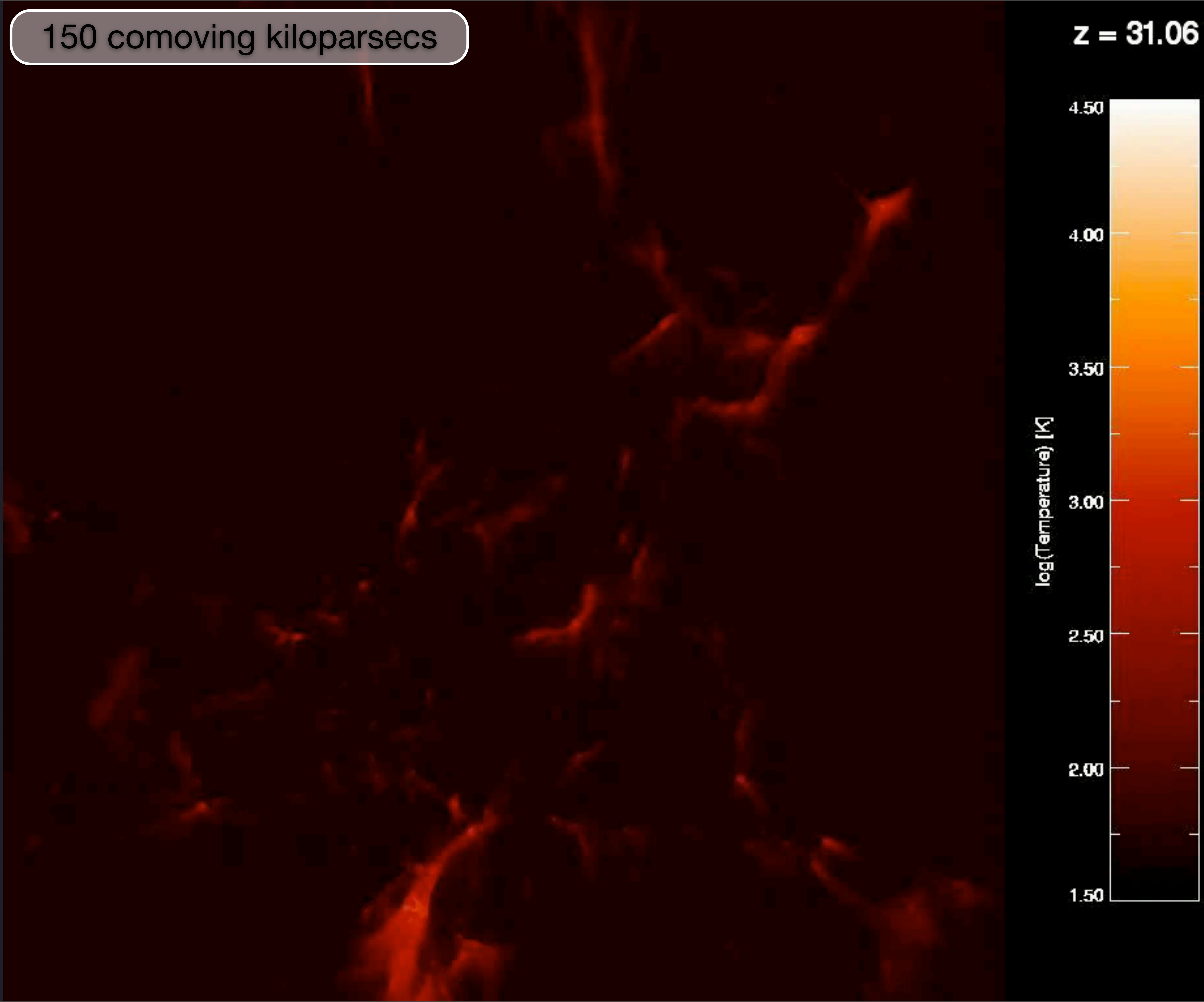
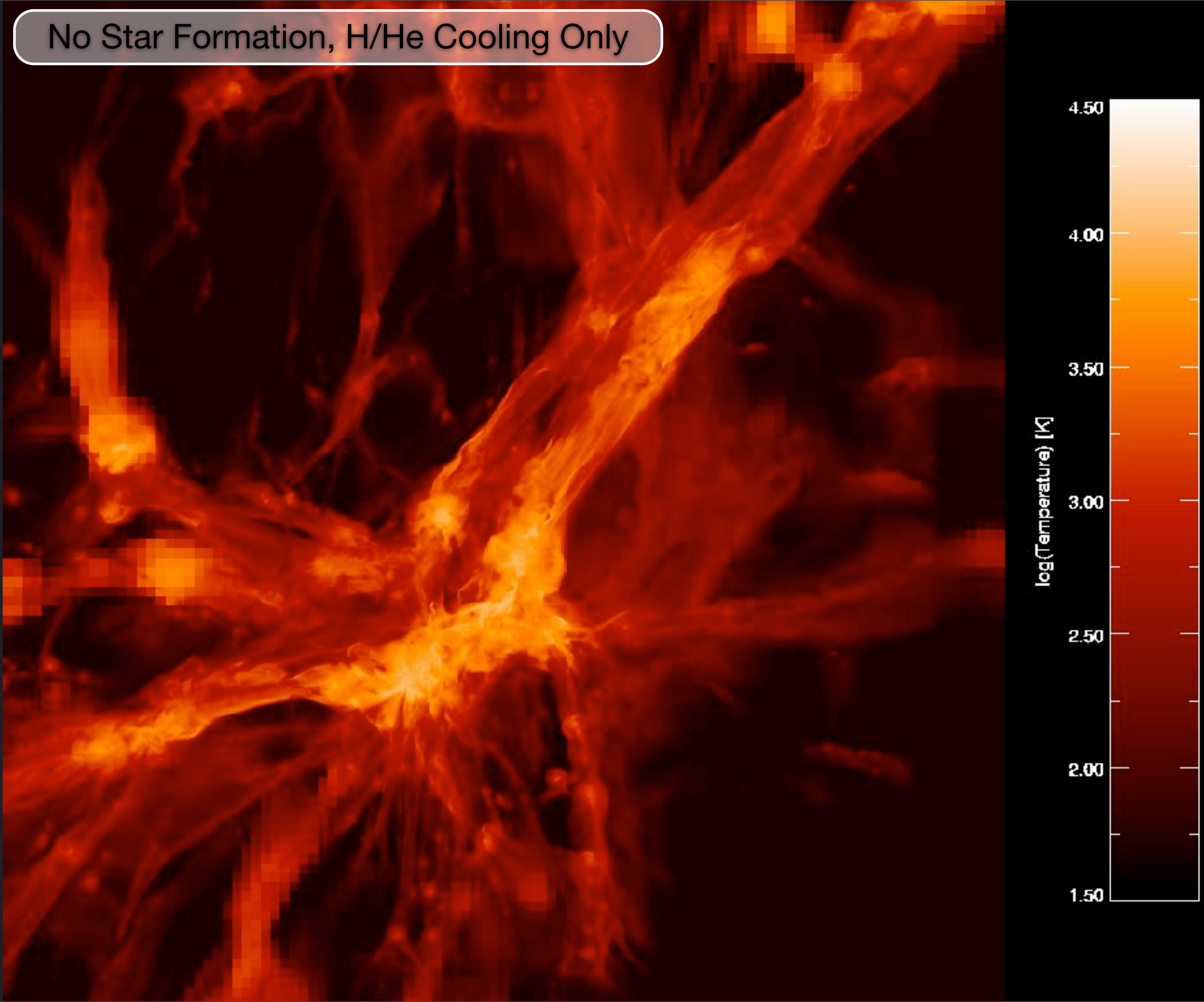
150 comoving kiloparsecs


150 comoving kiloparsecs
z = 31.06
log(Temperature) [K]
4.50
4.00
3.50
3.00
2.50
2.00
1.50

No Star Formation, H/He Cooling Only

9 physical kpc; z = 17



Star Formation

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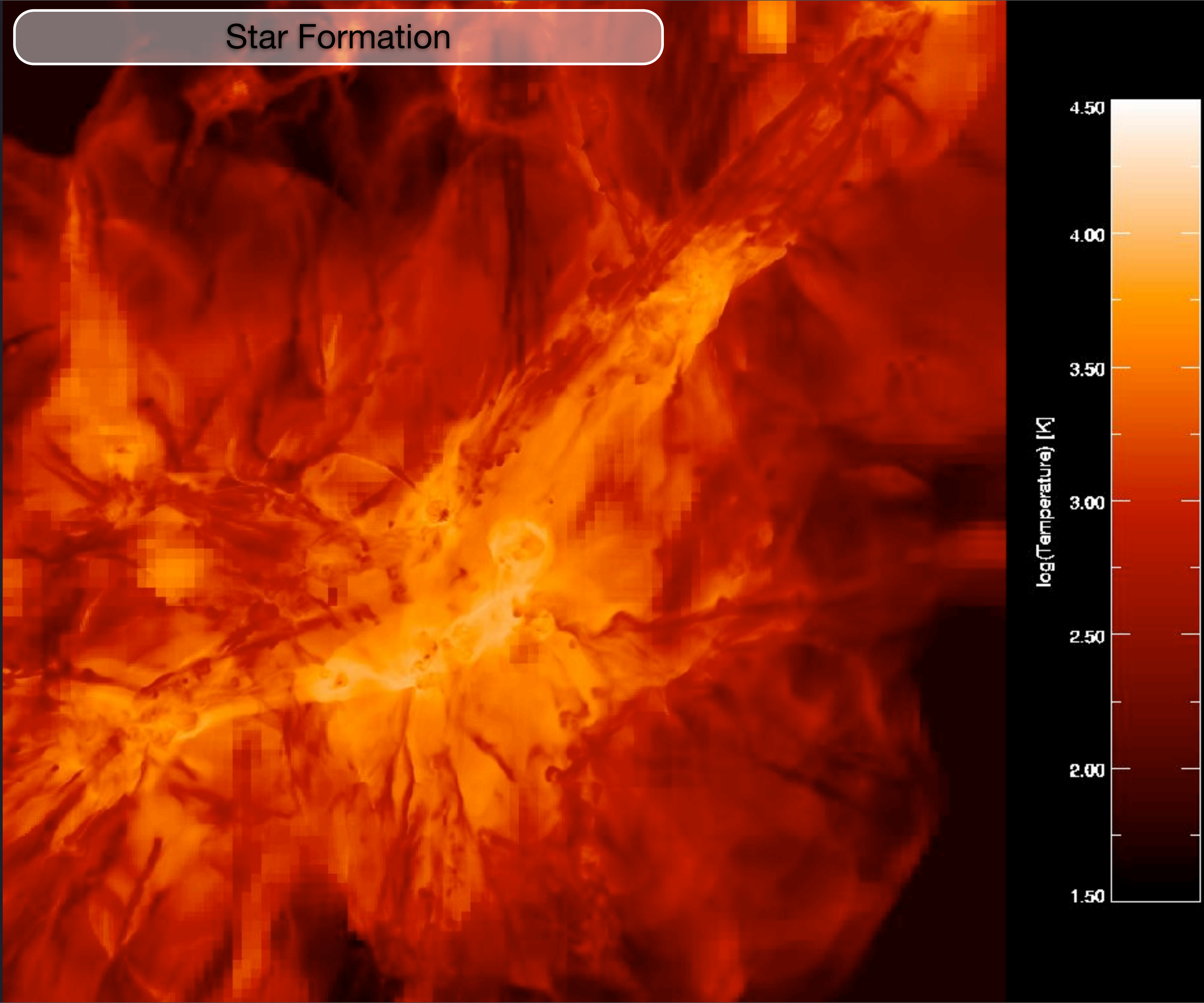

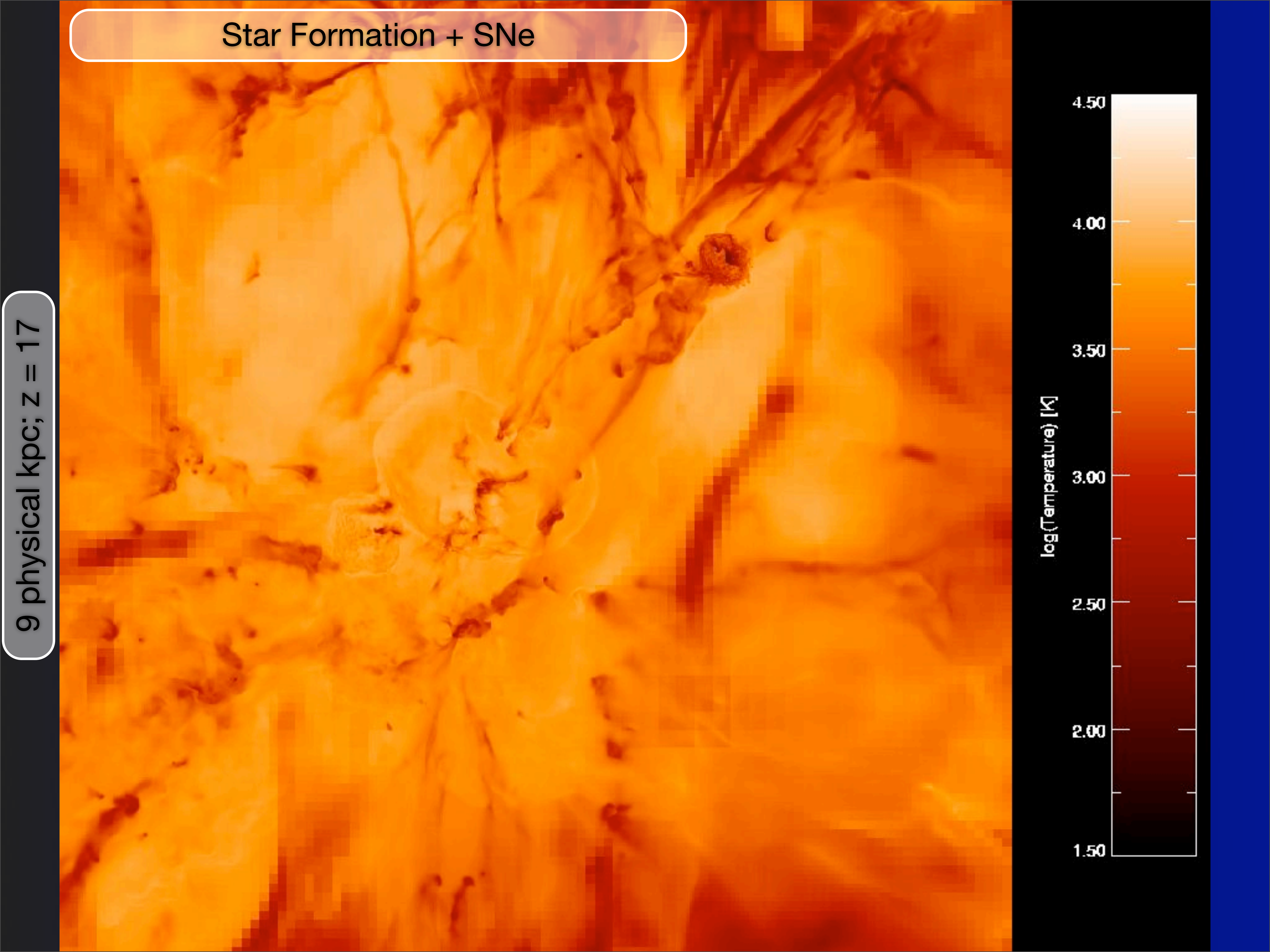
Star Formation + SNe
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4.00
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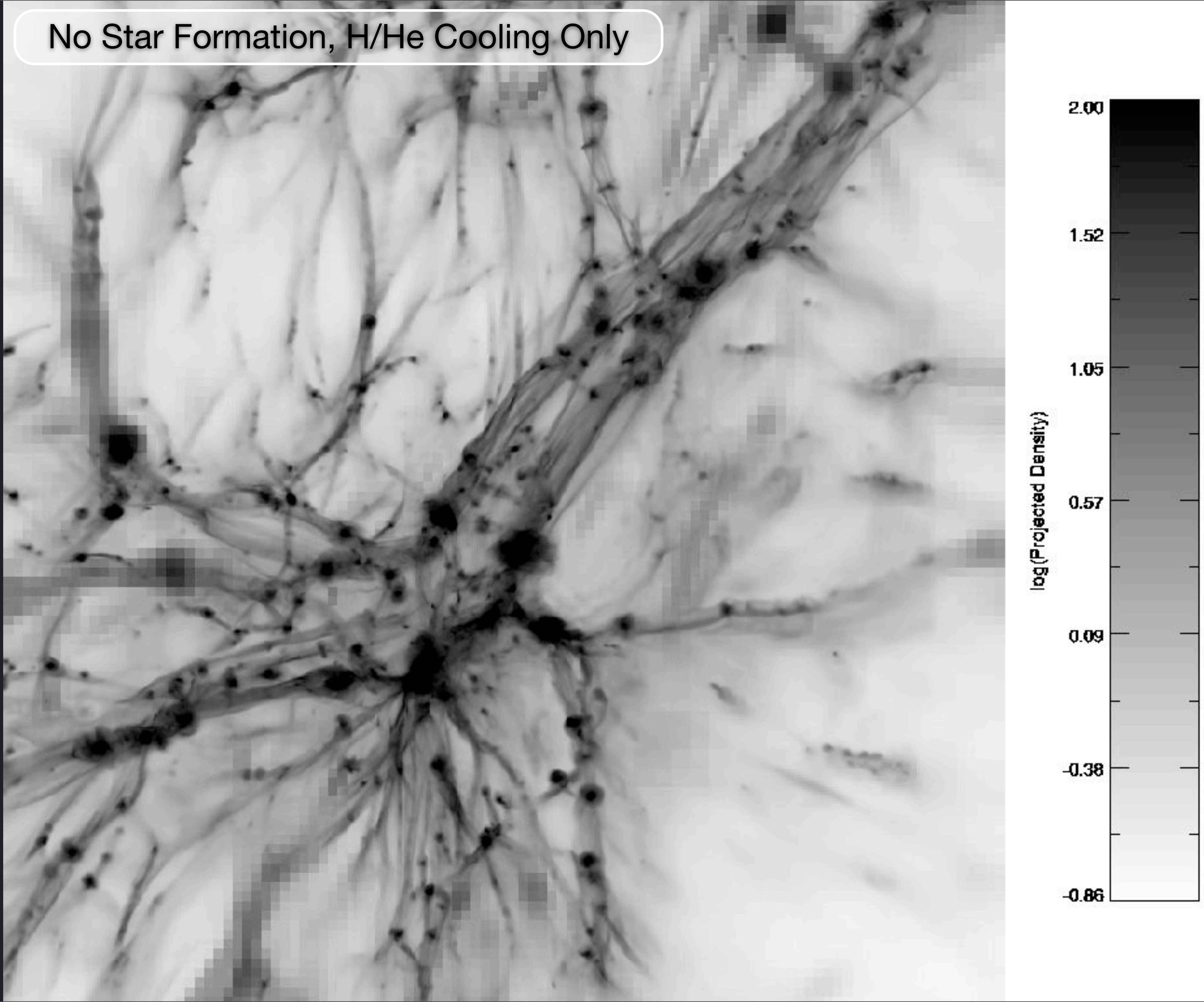
1.50



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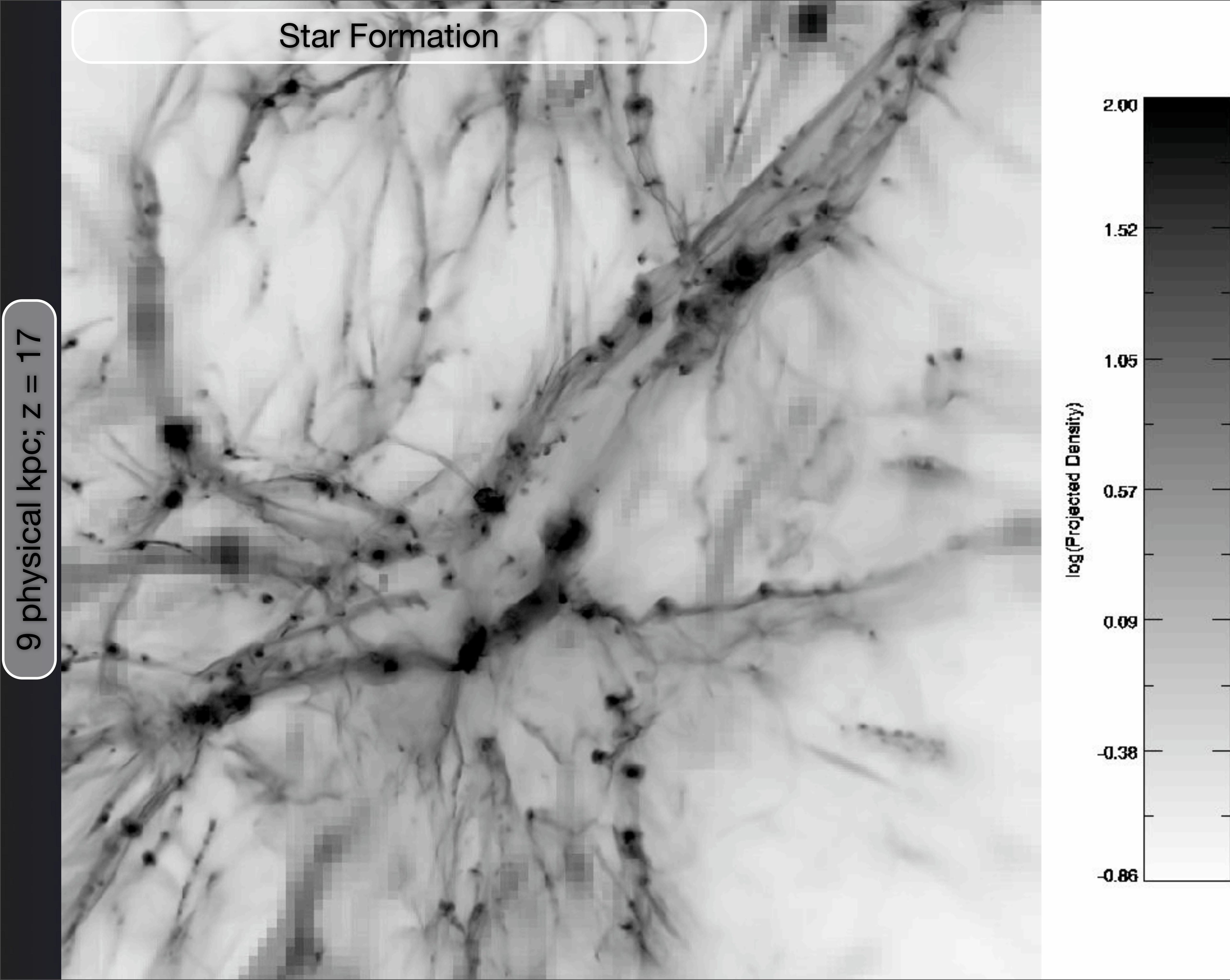
Star Formation



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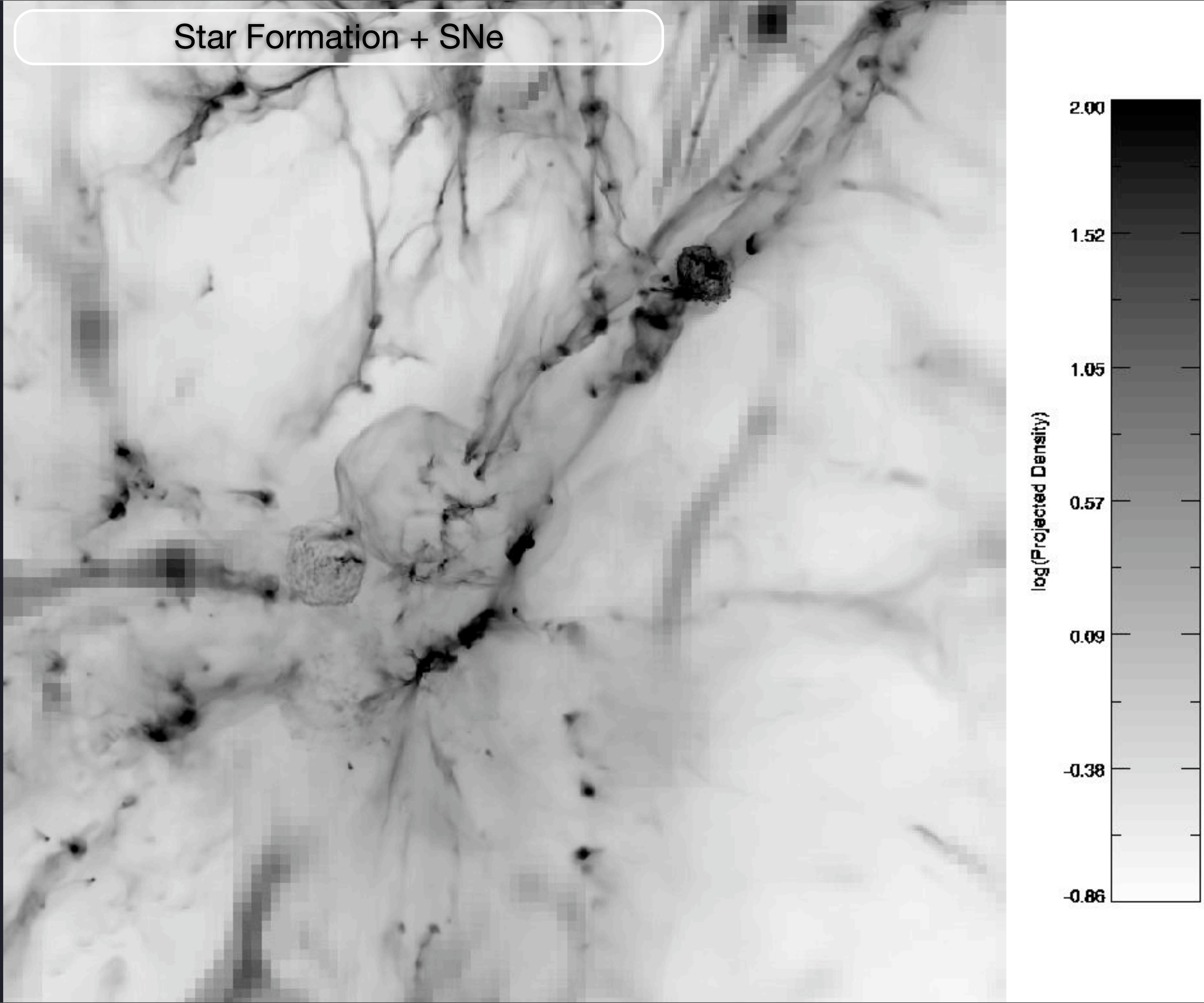

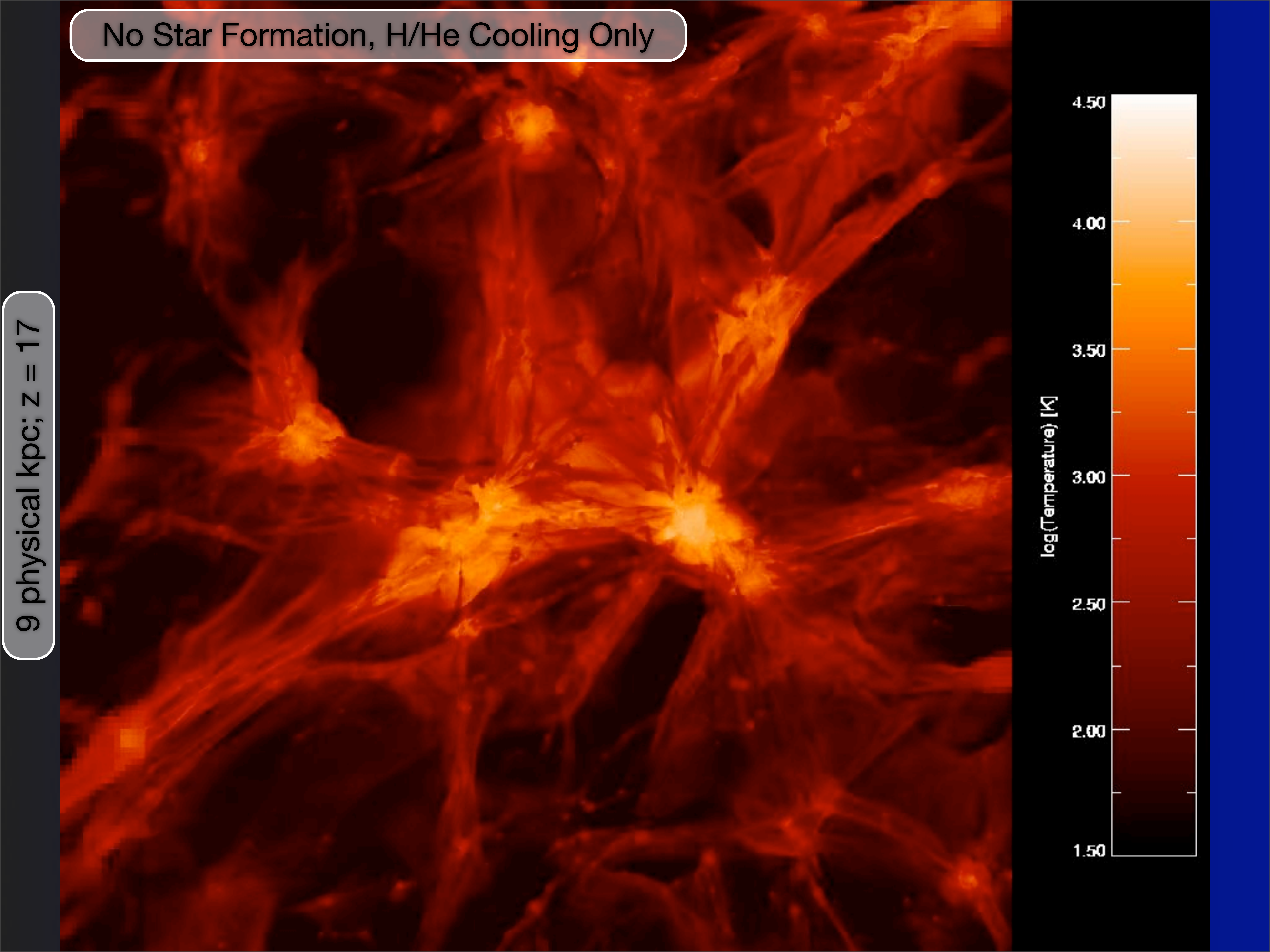
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4.50
4.00
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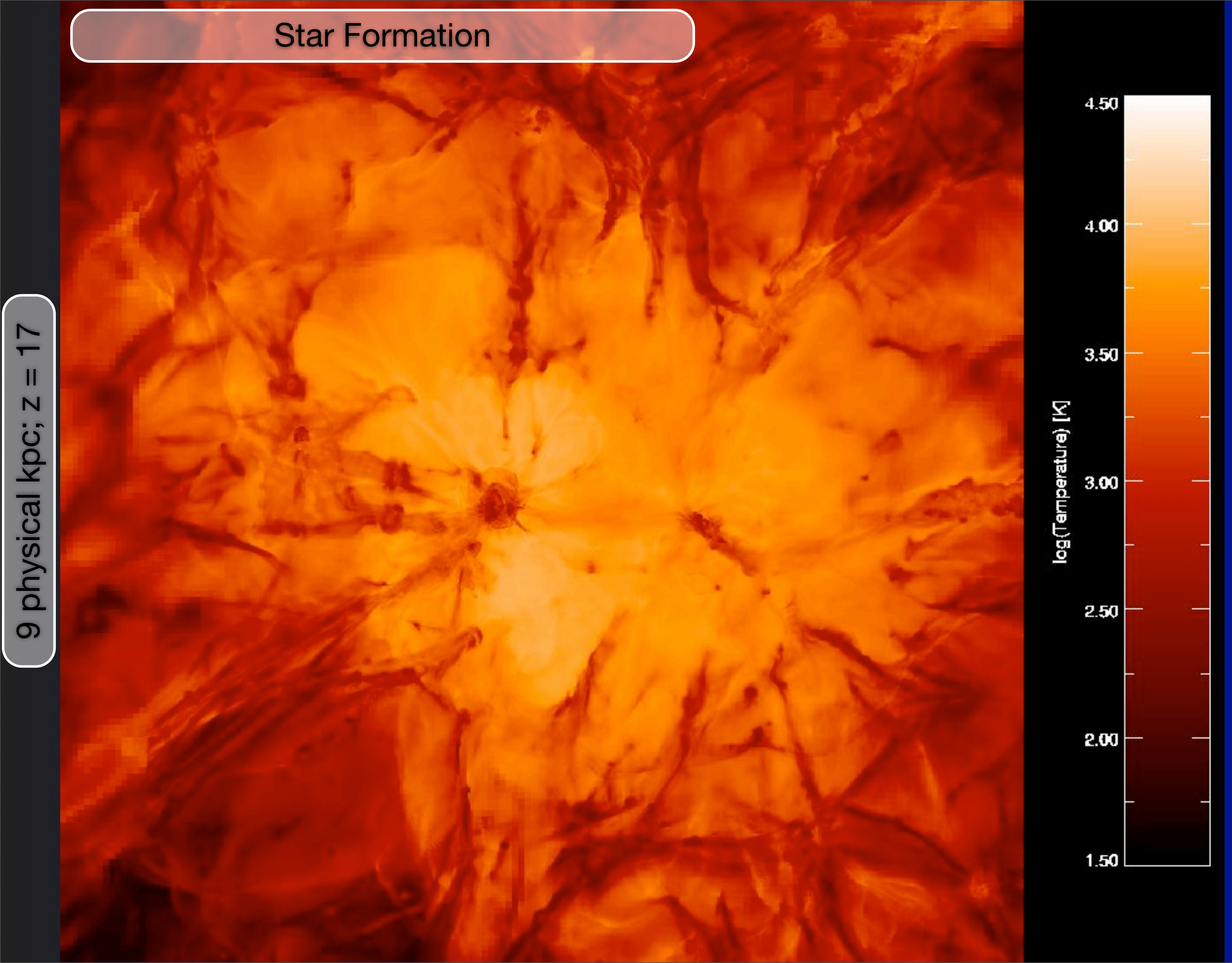
Star Formation



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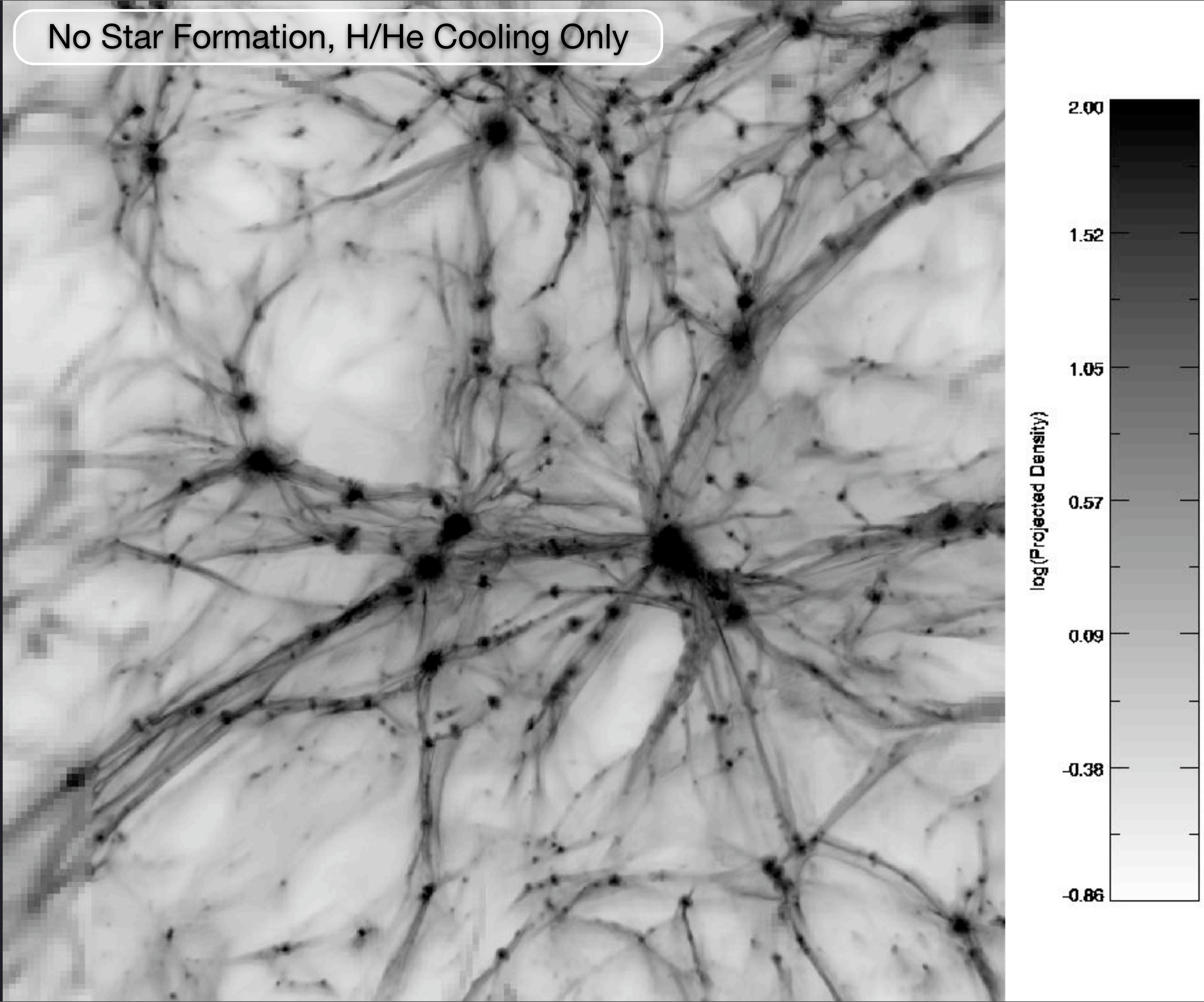

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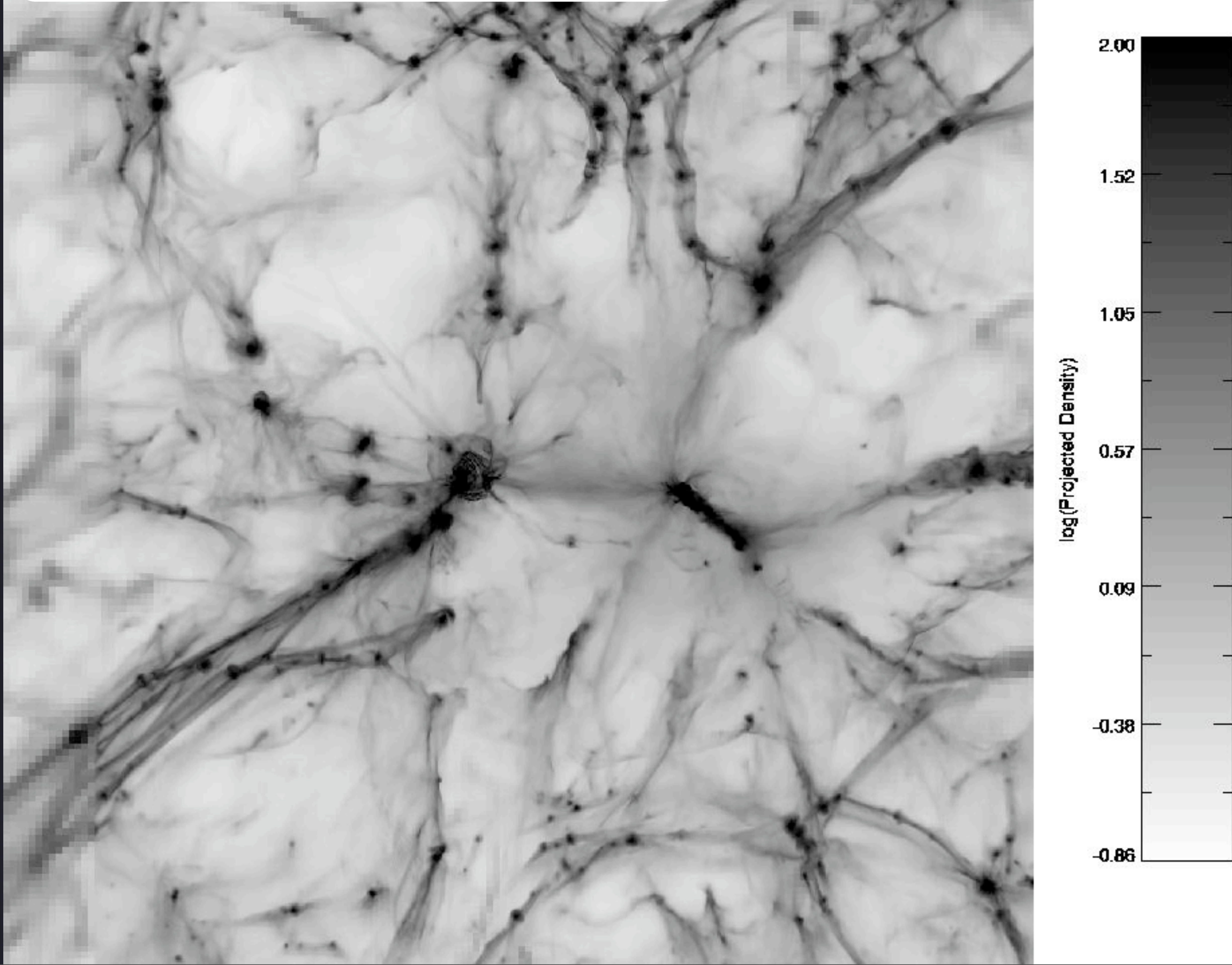
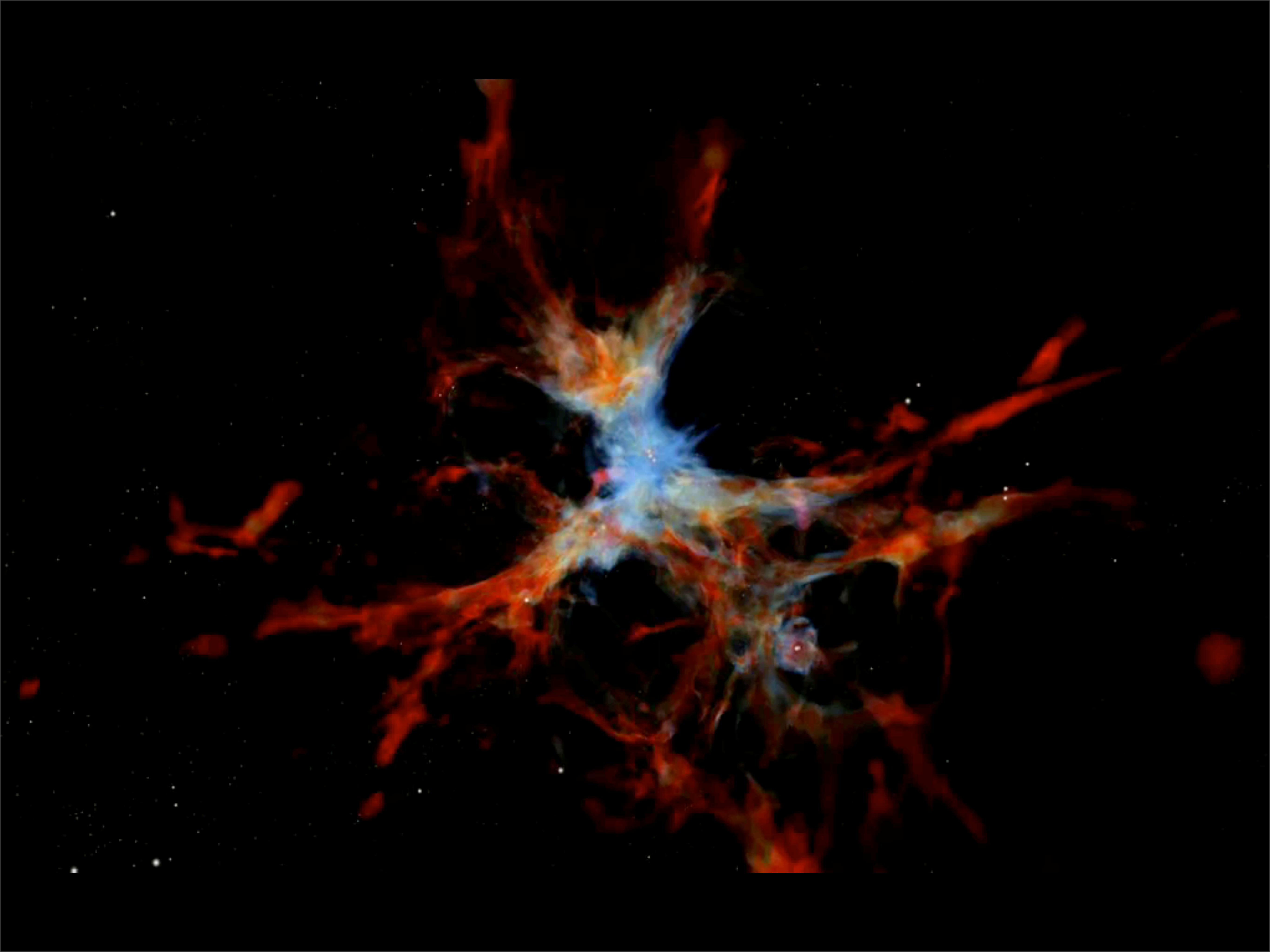
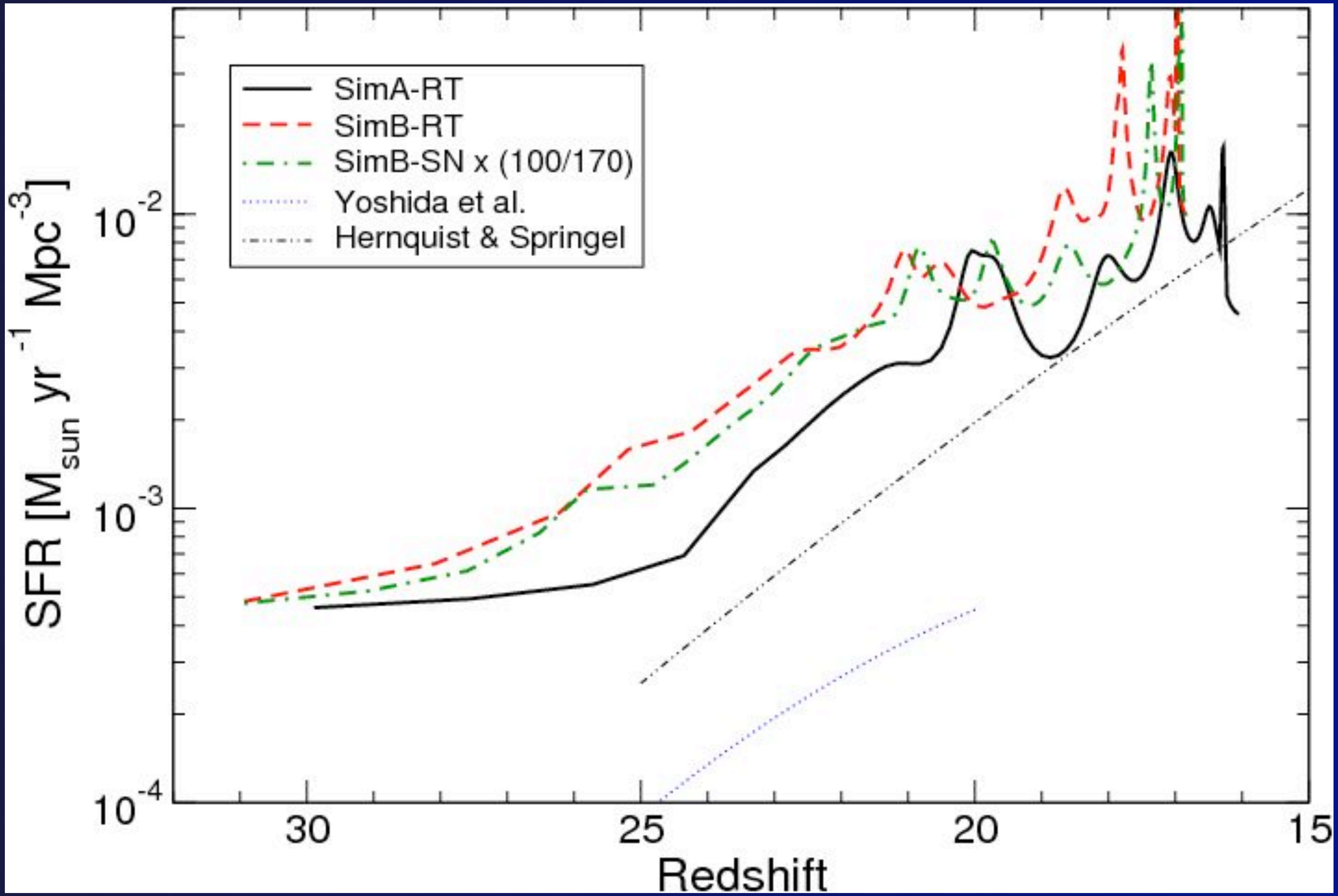




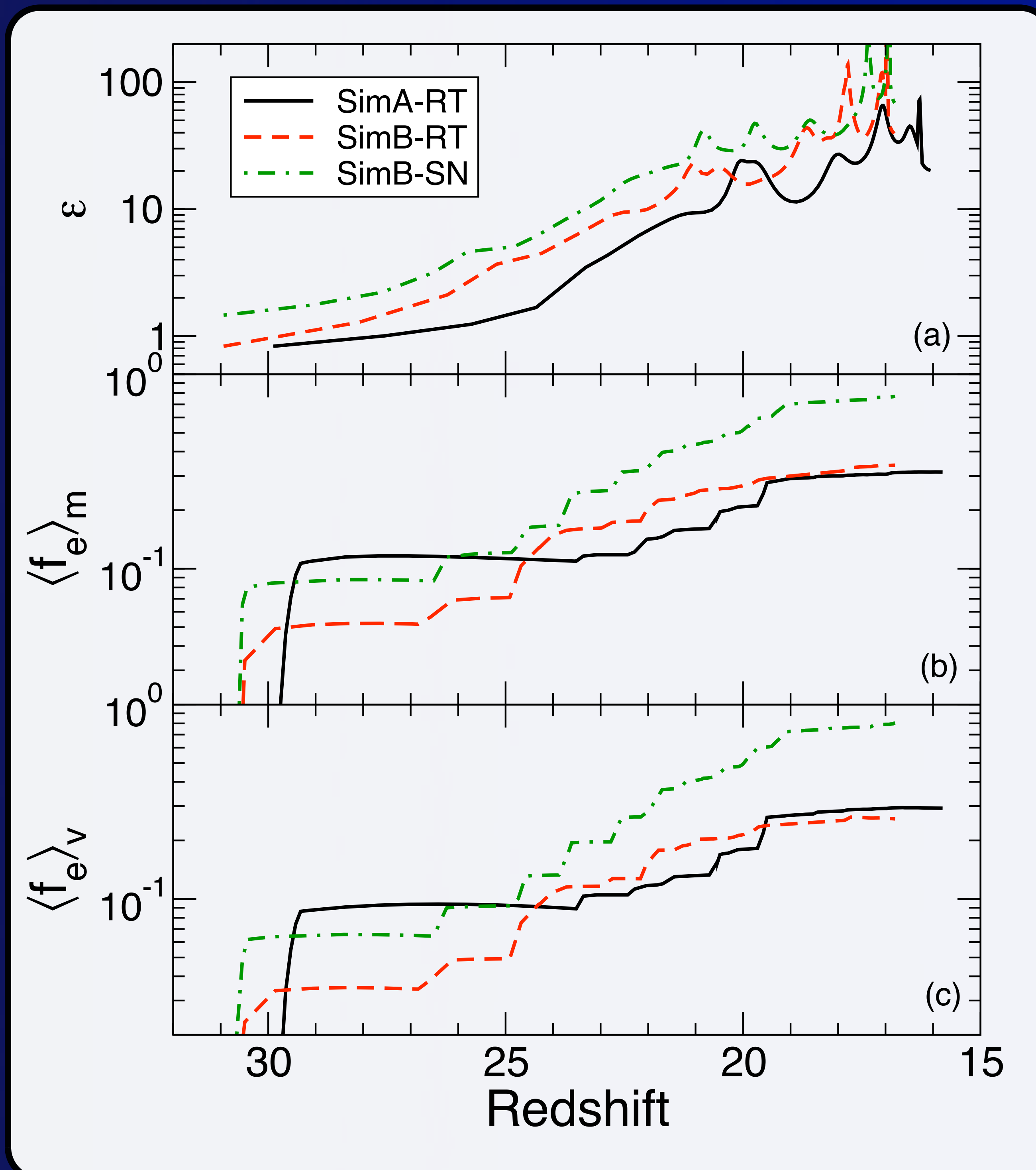
Star Formation Rates



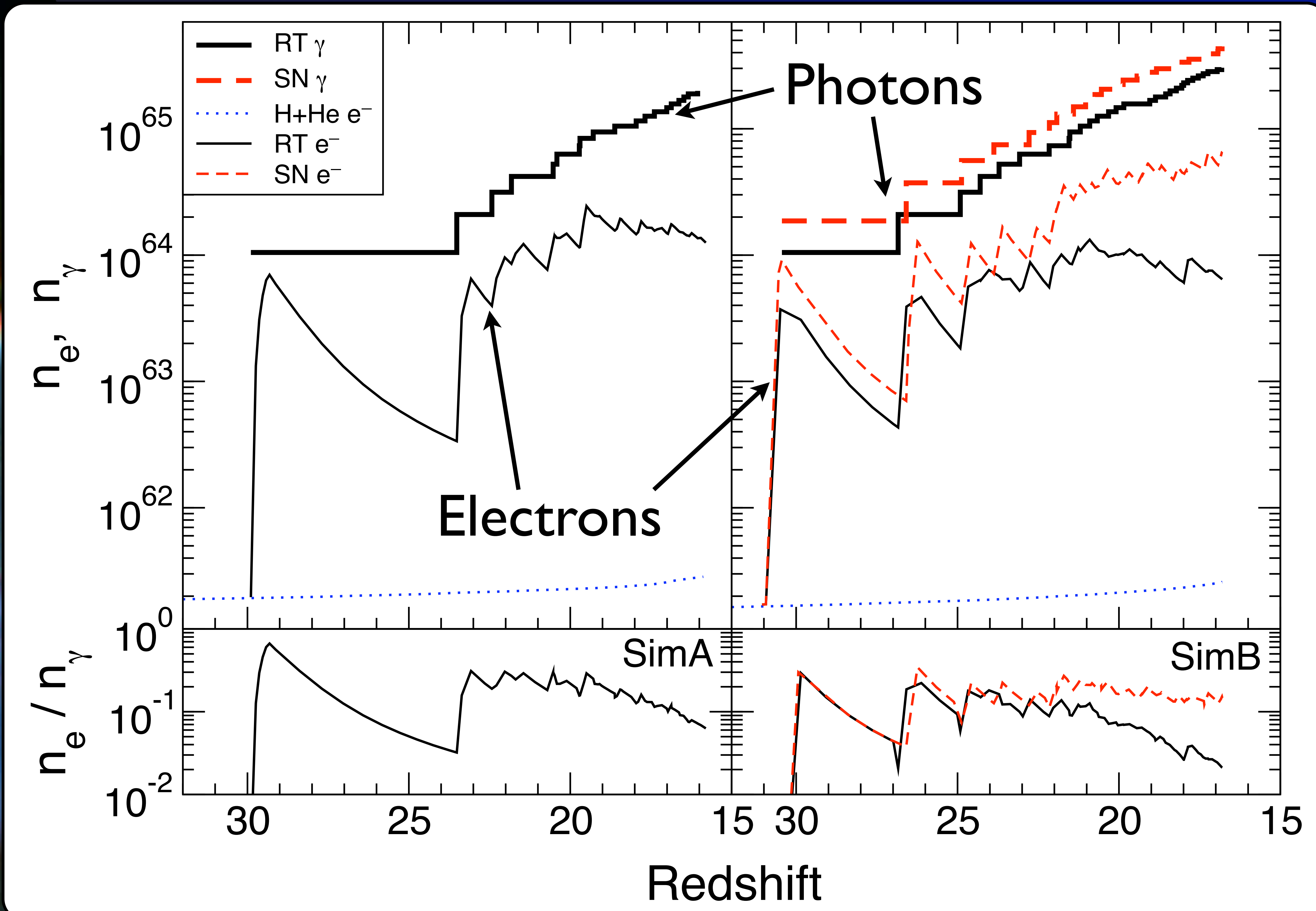
- Bursting star formation in larger halos
- Higher SFR than analytical estimates because our simulations sample cosmologically overdense regions (3-σ)

Ionized Fractions

- Emissivity in units of ionizing photons per baryon per Hubble time
- Ionizes the nearby IGM to 30% - 75%
- Beware: not representative of global ionization fractions – highly biased (i.e. inside out)



Effective Ionizations



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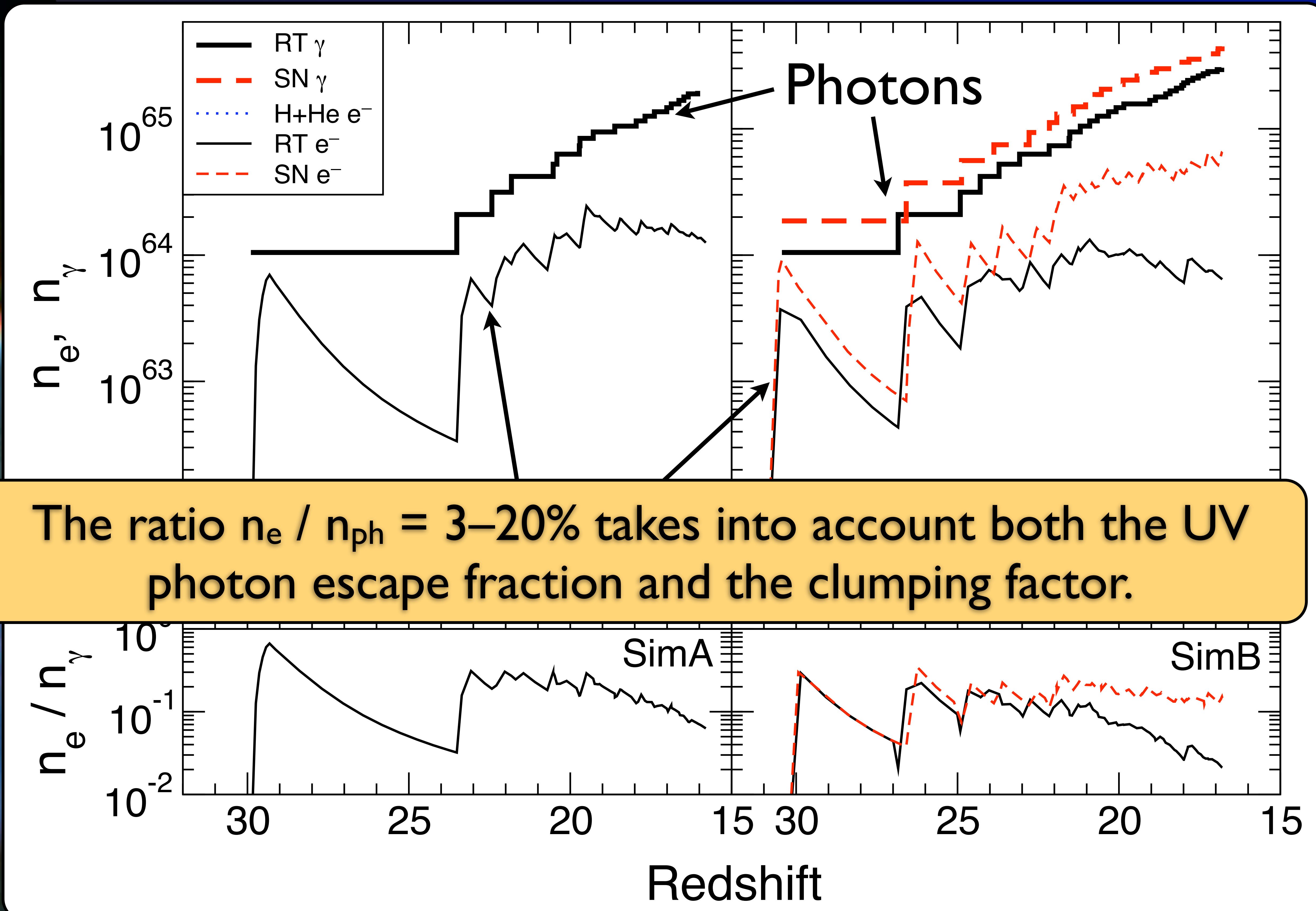
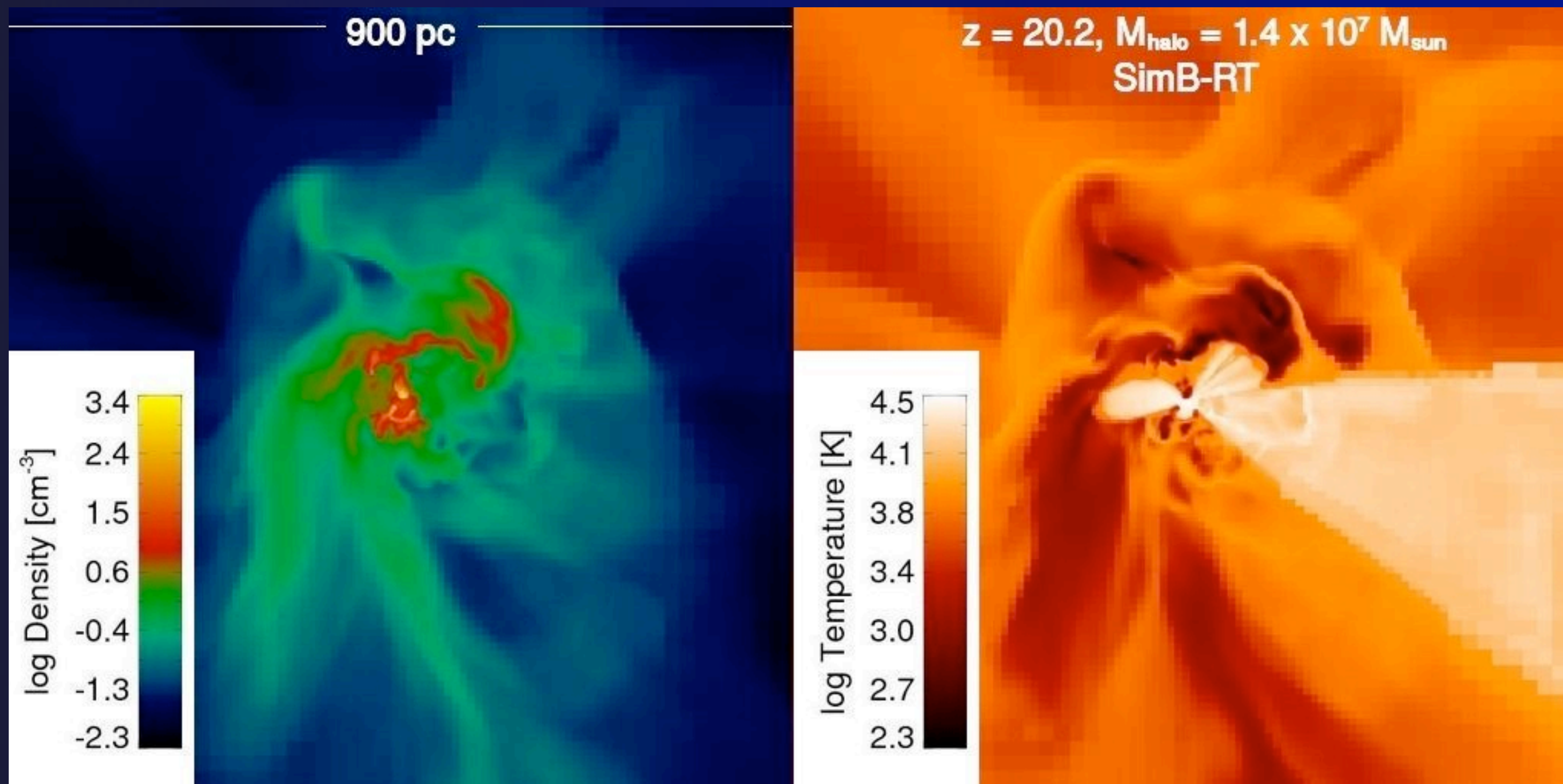


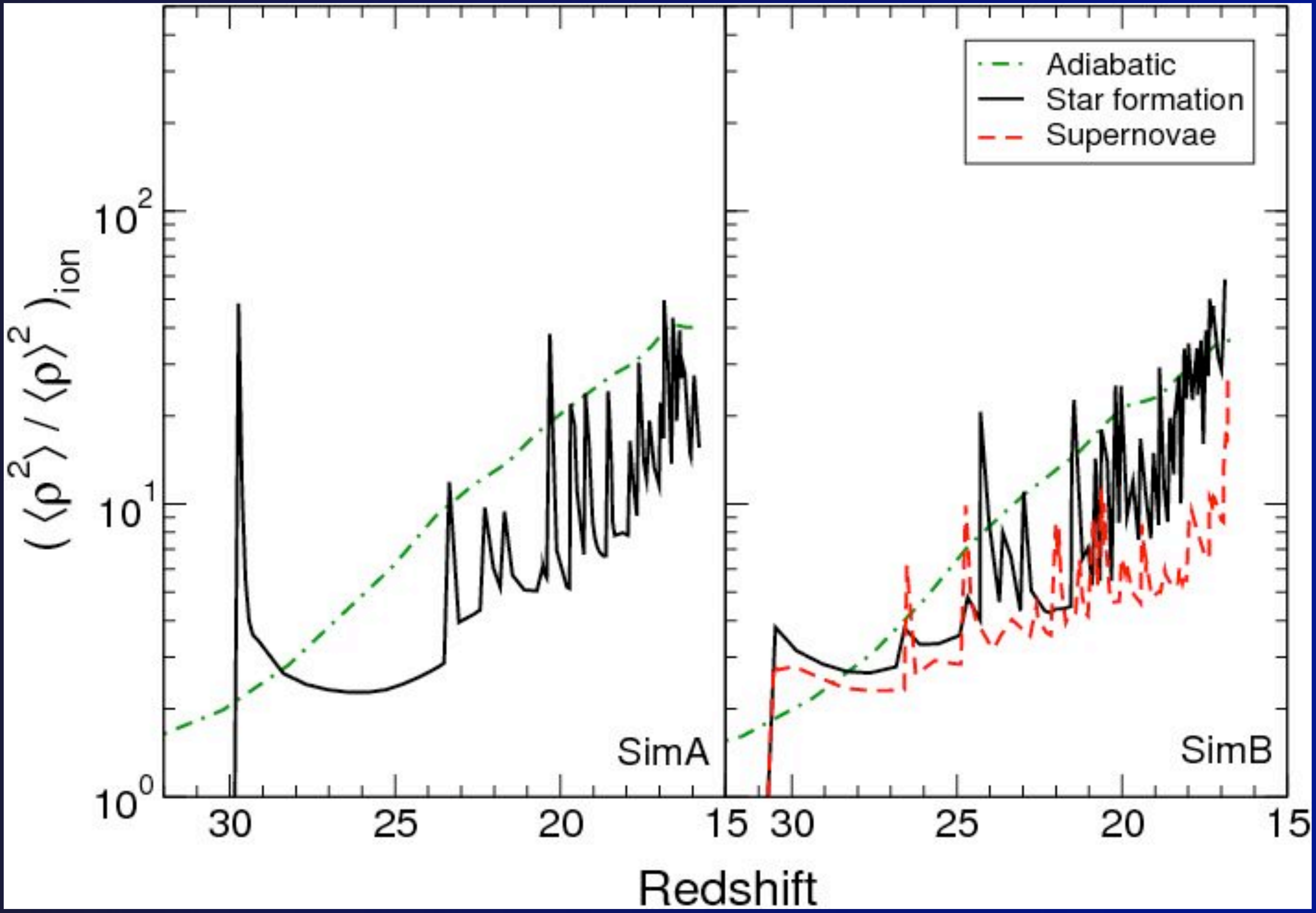
The ratio n_e / n_{ph} = 3–20% takes into account both the UV photon escape fraction and the clumping factor.

Anisotropic H II Regions



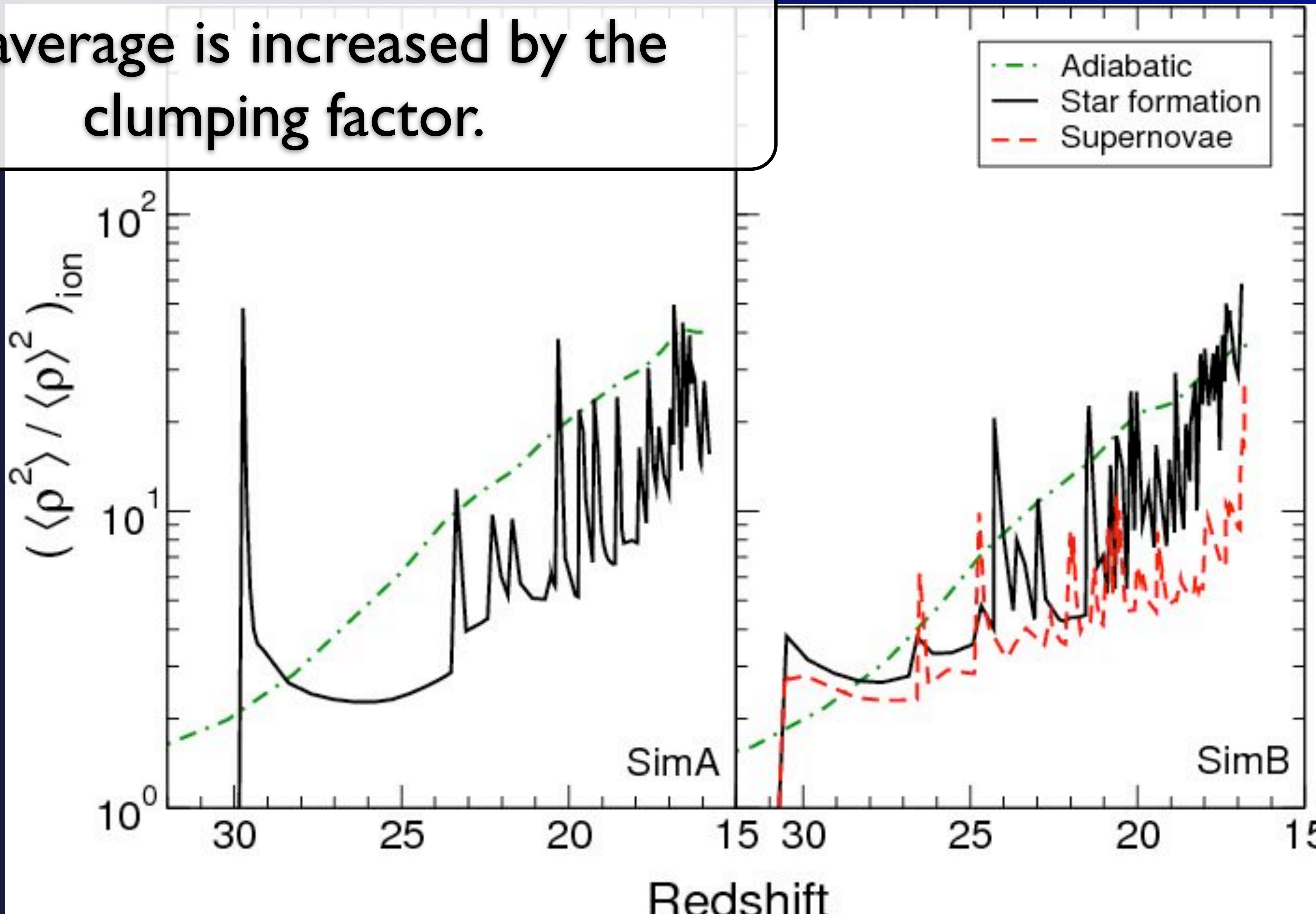
- HII regions become more anisotropic in larger halos
- Photon escape fractions decrease with halo mass

Clumpy IGM


Adiabatic
Star formation
Supernovae
$(\langle\rho^2\rangle / \langle\rho\rangle^2)_{ion}$
10^2
10^1
10^0
SimA
SimB
30
25
20
15
Redshift

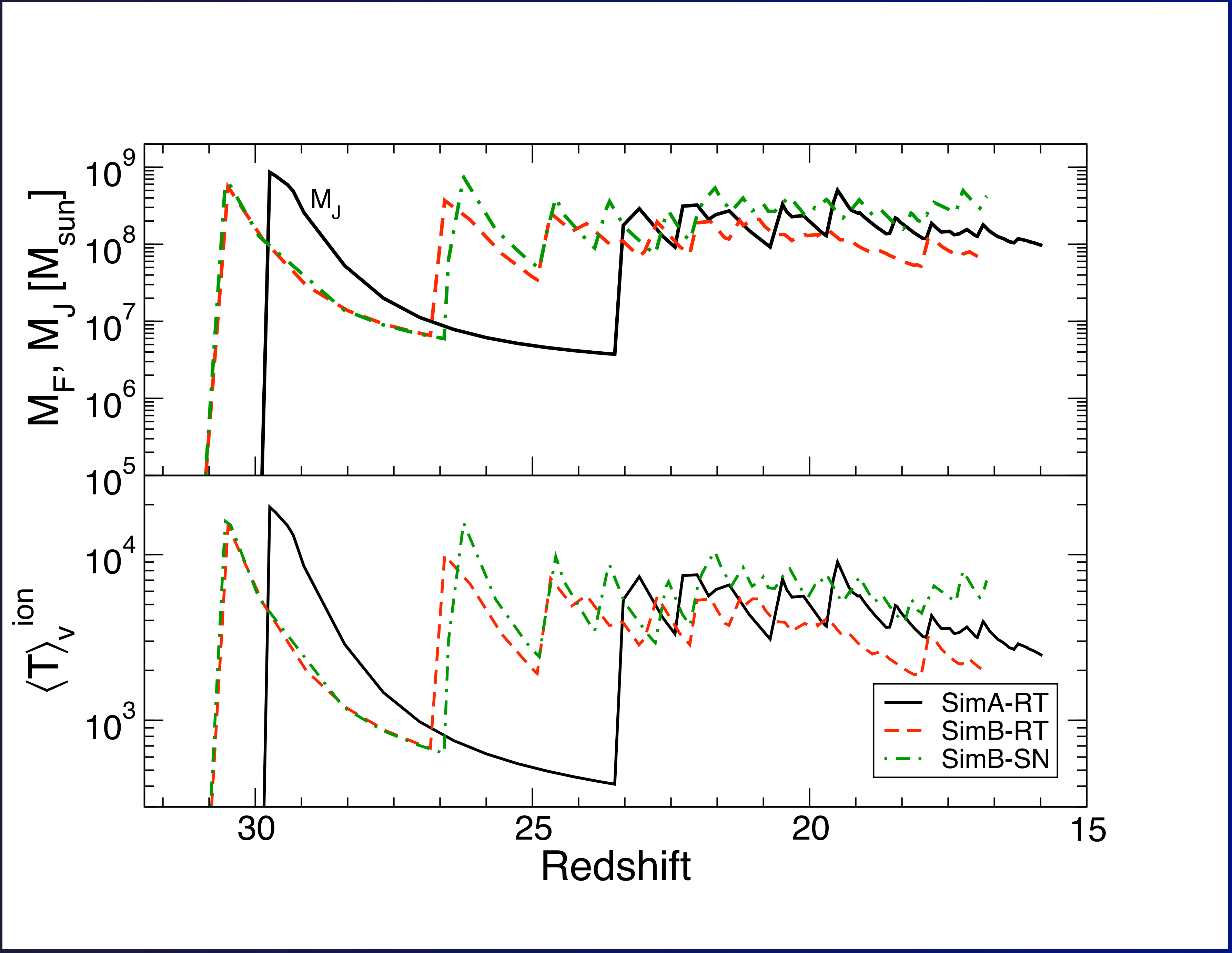
Clumpy IGM

The recombination rate in the IGM on average is increased by the clumping factor.



Minimum Galaxy Mass

(aka Filtering Mass)



Minimum Galaxy Mass

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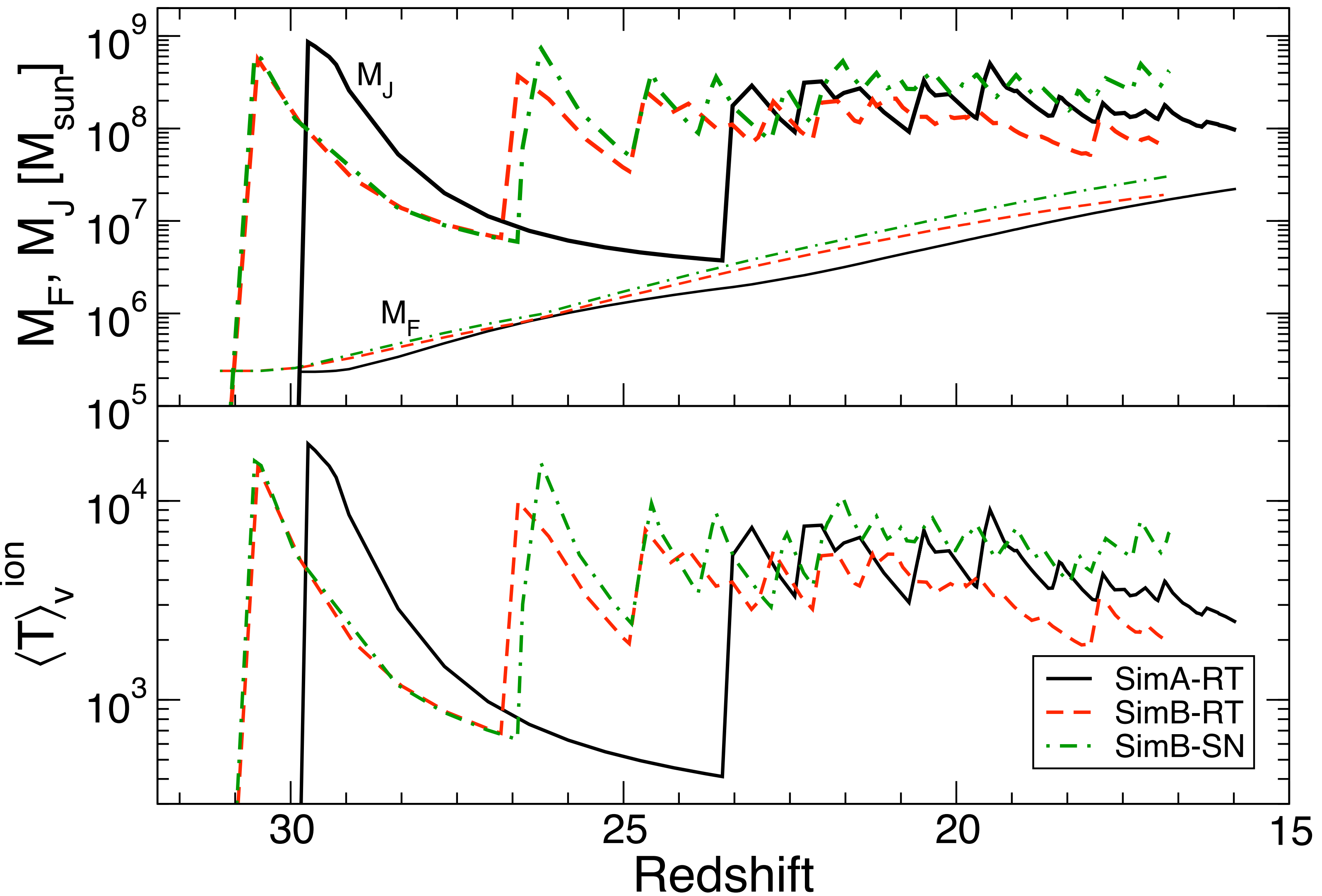
Jeans Filtering Mass $M_F^{2/3} = \frac{3}{a}\int_0^a da'\, M_J^{2/3}(a')\left[1 - \left(\frac{a'}{a}\right)\right]$



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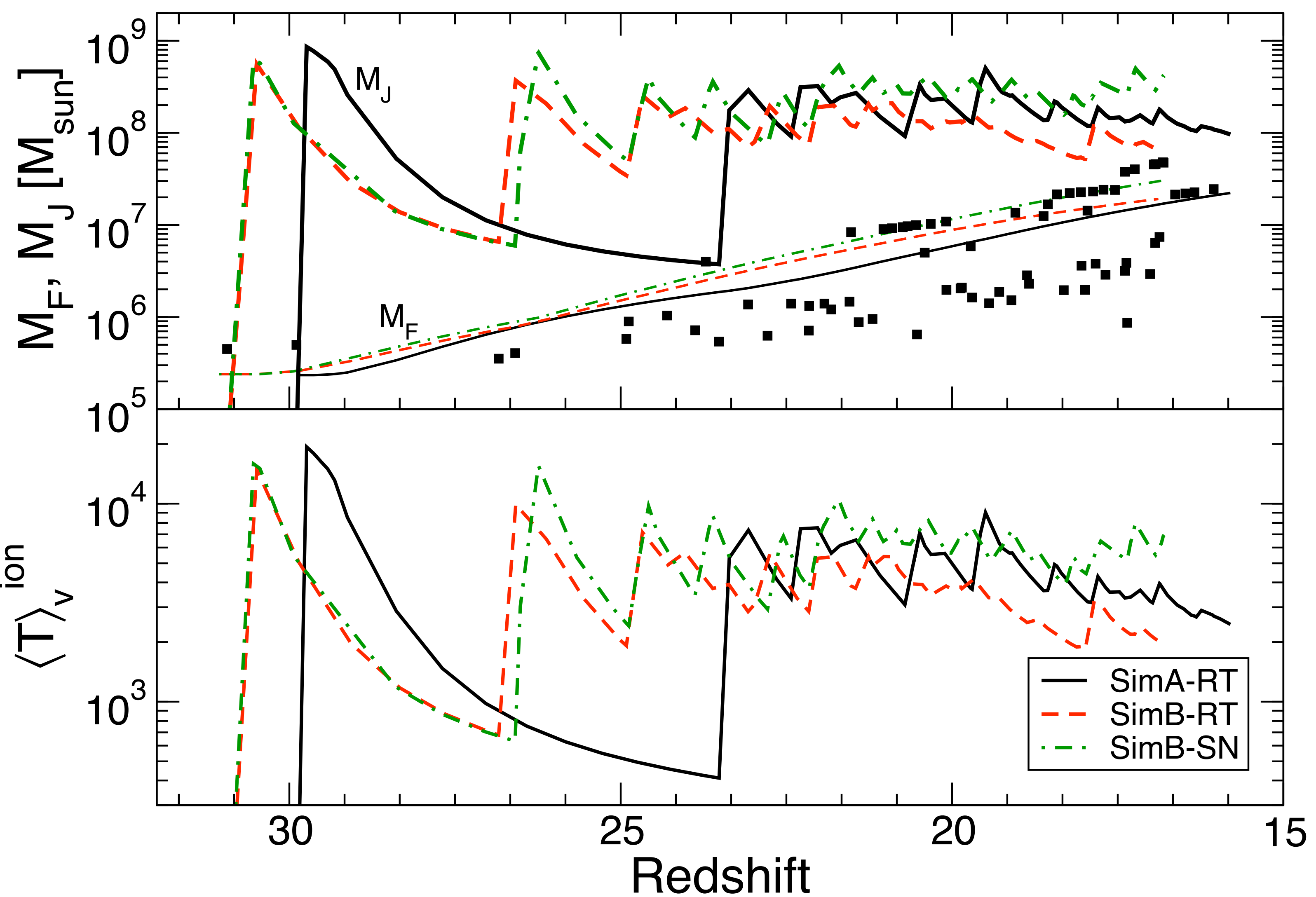

Minimum Galaxy Mass

(aka Filtering Mass)

1st star in halo:

- Minimum mass regulated by an H_2 dissociating background
  Machacek et al. (2001)
- Also regulated by photo-evaporation.
  e.g. Haiman et al. (2000), Iliev et al. (2005), Ciardi et al. (2006)

2nd+ star in halo:

- Halo grows by accreting gas heated from previous stars
- Regulated by the Jeans "filtering" mass
  Gnedin & Hui (1998)

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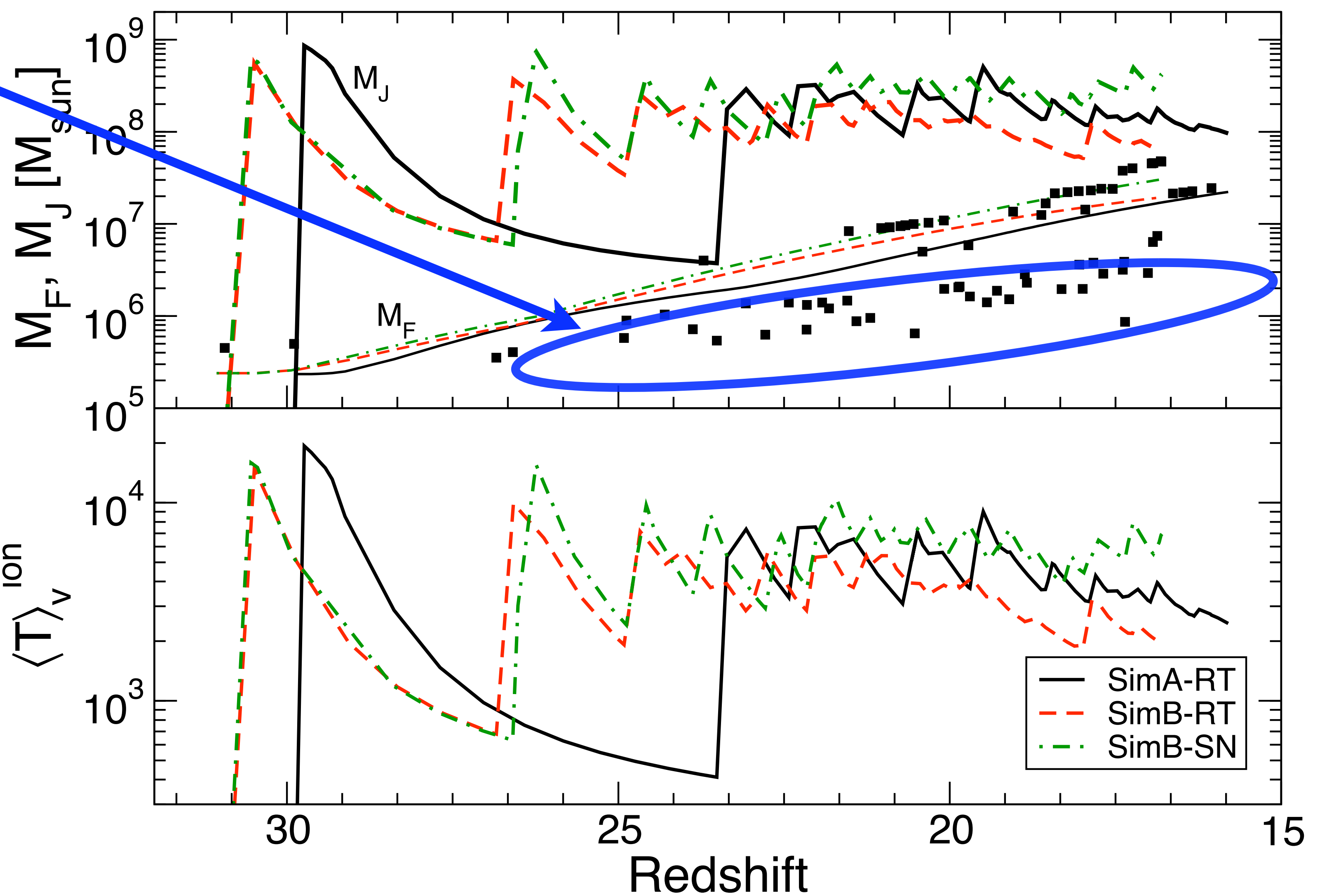

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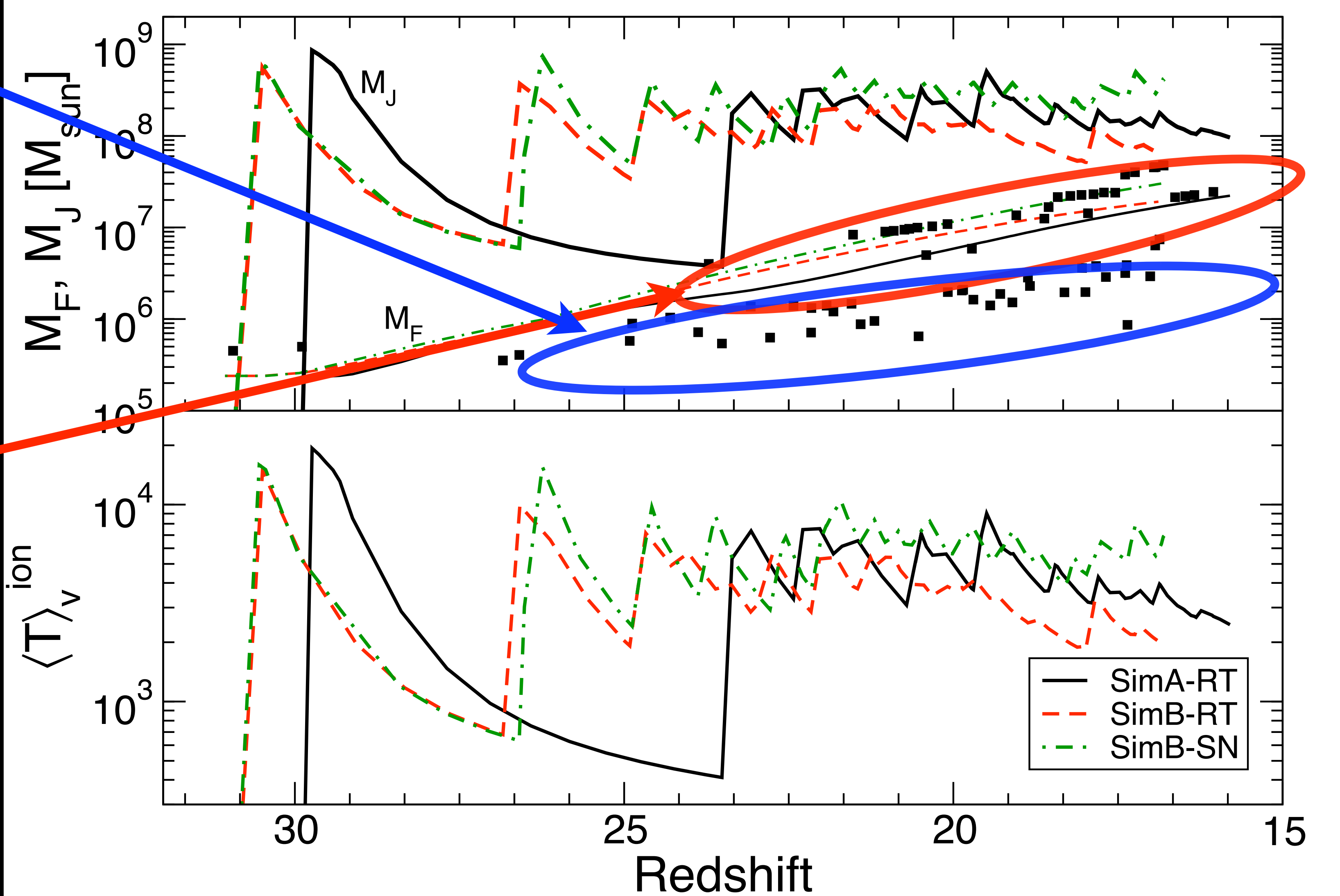

Shortcomings

- Small box simulation – highly biased region
- Neglecting self-shielding of Lyman-Werner radiation
- Fixed stellar mass – no IMF
- Neglecting ~30 $M_\odot$ (“Pop III.2”) stars that may form in halos embedded in relic HII regions with HD cooling
- No metal cooling to study the transition to Pop II star formation

Future Directions?

- Similar simulations for less biased regions
  - External ionizing source from high sigma peaks. Use “semi-numerical” methods to predict ionization epoch based on a coarse grid?

Mesigner & Furlanetto (2007); Zahn et al. (2007)

- Sub-grid models for ~100 Mpc simulations
- Lyman-Werner radiation self-shielding
- Metal line, HD, and dust cooling

e.g. Glover & Jappsen (2007); Smith et al. (2007)

- Pop II star formation
- Larger boxes (3–5 Mpc) + Similar mass resolution → Larger halos (10^9 – 10^{10} $M_\odot$)

Even Low Mass Galaxies are Complex!

- Isolated $M_{vir} = 10^8 M_\odot$ halo – Radiation Hydro – 100 Myr

Density

830 physical pc

Temperature

1660 physical pc

Wise & Cen (in prep.)

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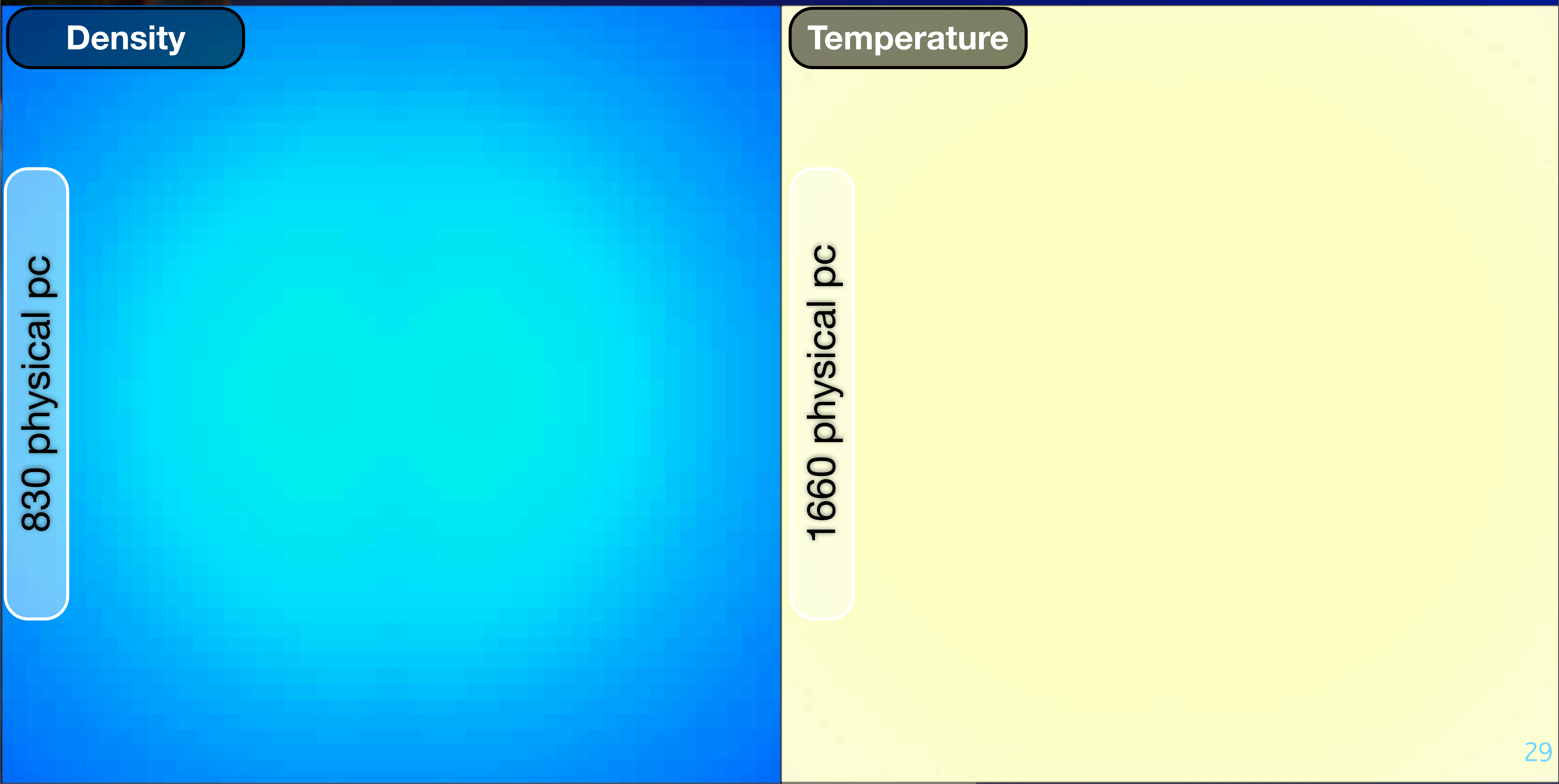

Conclusions

- Star formation is delayed for ~50 Myr after the first star. Once material is reincorporated into the halo, SFR ~ 10^{-2} $M_\odot$/yr/Mpc^{-3}
- Clumping factors are highly variable but are, on average, a factor of 2 lower than in the adiabatic case without star formation
- Roughly 1 in 10 ionizing photons result in a sustained ionization
- Jeans filtering mass is an excellent measure of the minimum halo mass that undergoes its 2nd instance of star formation.
- Only the beginning toward building galaxies one star at a time!