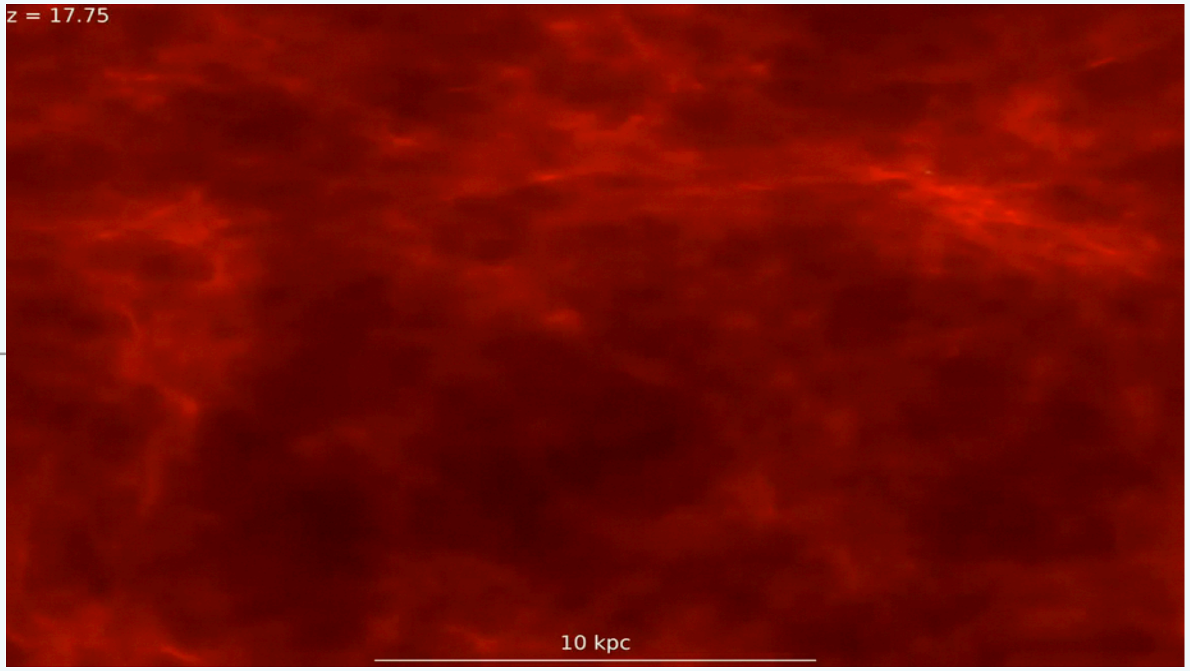
The First Stars and Galaxies in the Universe

John Wise

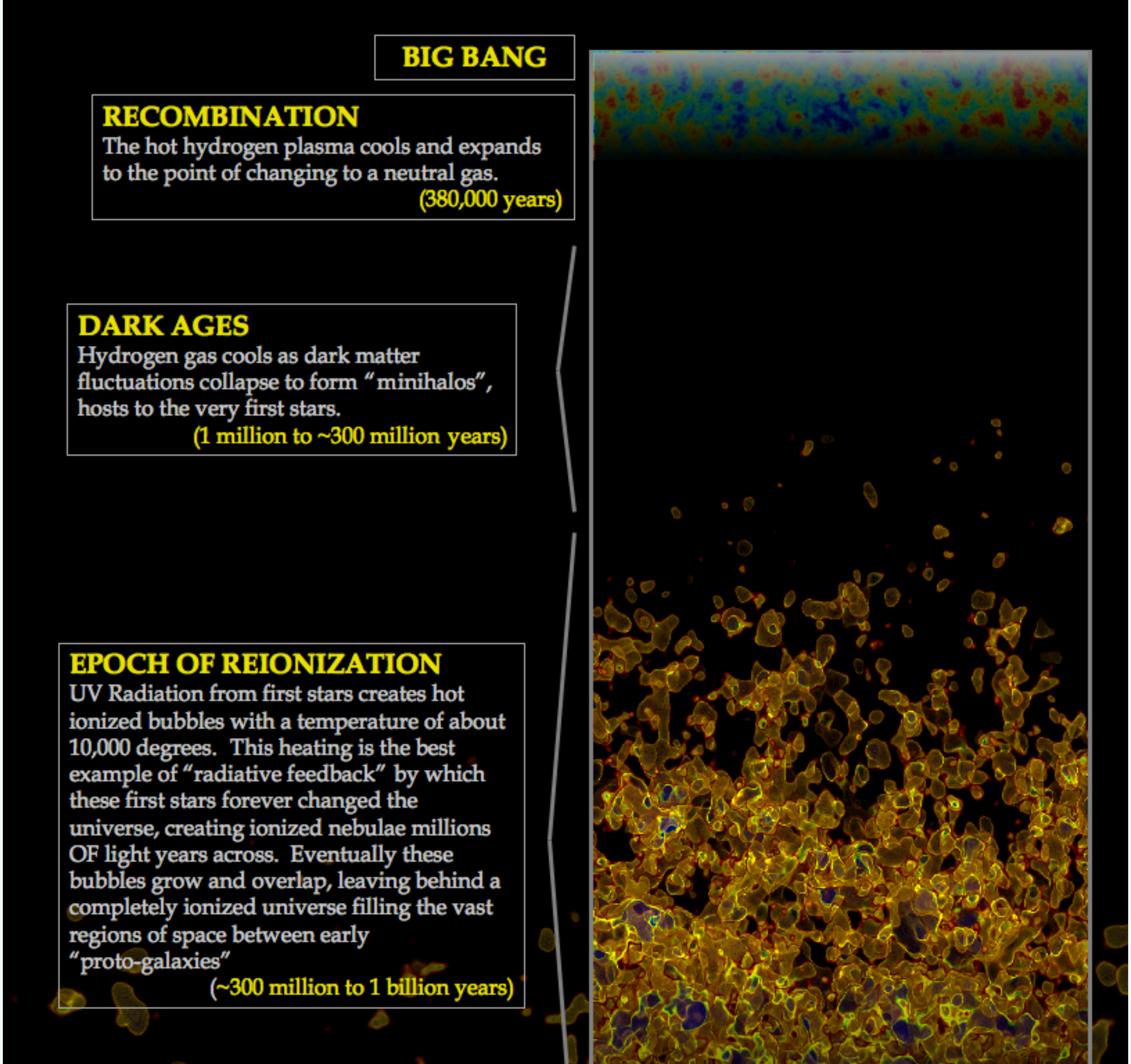
Georgia Tech

SMU Seminar — 09 Nov 2015

Outline



- **The First Stars: Formation and Feedback**
  - A History Lesson
  - A Quest toward the Initial Mass Function
- **The First Galaxies**
  - Constraints from observations of local dwarf galaxies
  - Metal pre-enrichment from the first stars
- **“Birth of a Galaxy” simulation**
  - Star formation histories of two example dwarf galaxies
  - Global properties of dwarf galaxies prior to reionization
  - UV escape fractions and luminosity functions



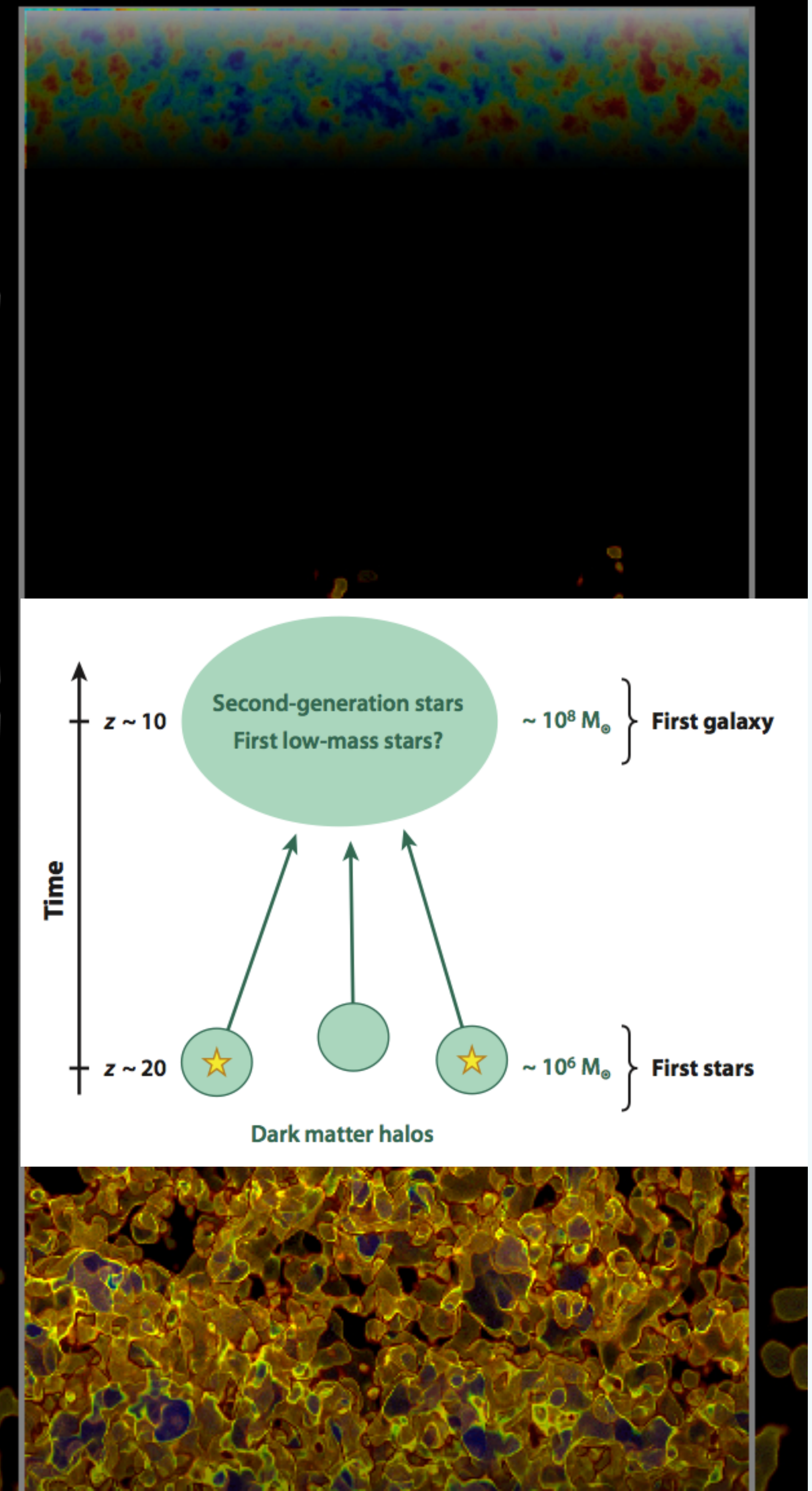
Credit: Marcelo Alvarez & Tom Abel

BIG BANG

RECOMBINATION
The hot hydrogen plasma cools and expands to the point of changing to a neutral gas.
(380,000 years)

DARK AGES
Hydrogen gas cools as dark matter fluctuations collapse to form “minihalos”, hosts to the very first stars.
(1 million to ~300 million years)

EPOCH OF REIONIZATION
UV Radiation from first stars creates hot ionized bubbles with a temperature of about 10,000 degrees. This heating is the best example of “radiative feedback” by which these first stars forever changed the universe, creating ionized nebulae millions OF light years across. Eventually these bubbles grow and overlap, leaving behind a completely ionized universe filling the vast regions of space between early “proto-galaxies”
(~300 million to 1 billion years)



Bromm & Yoshida (2011)

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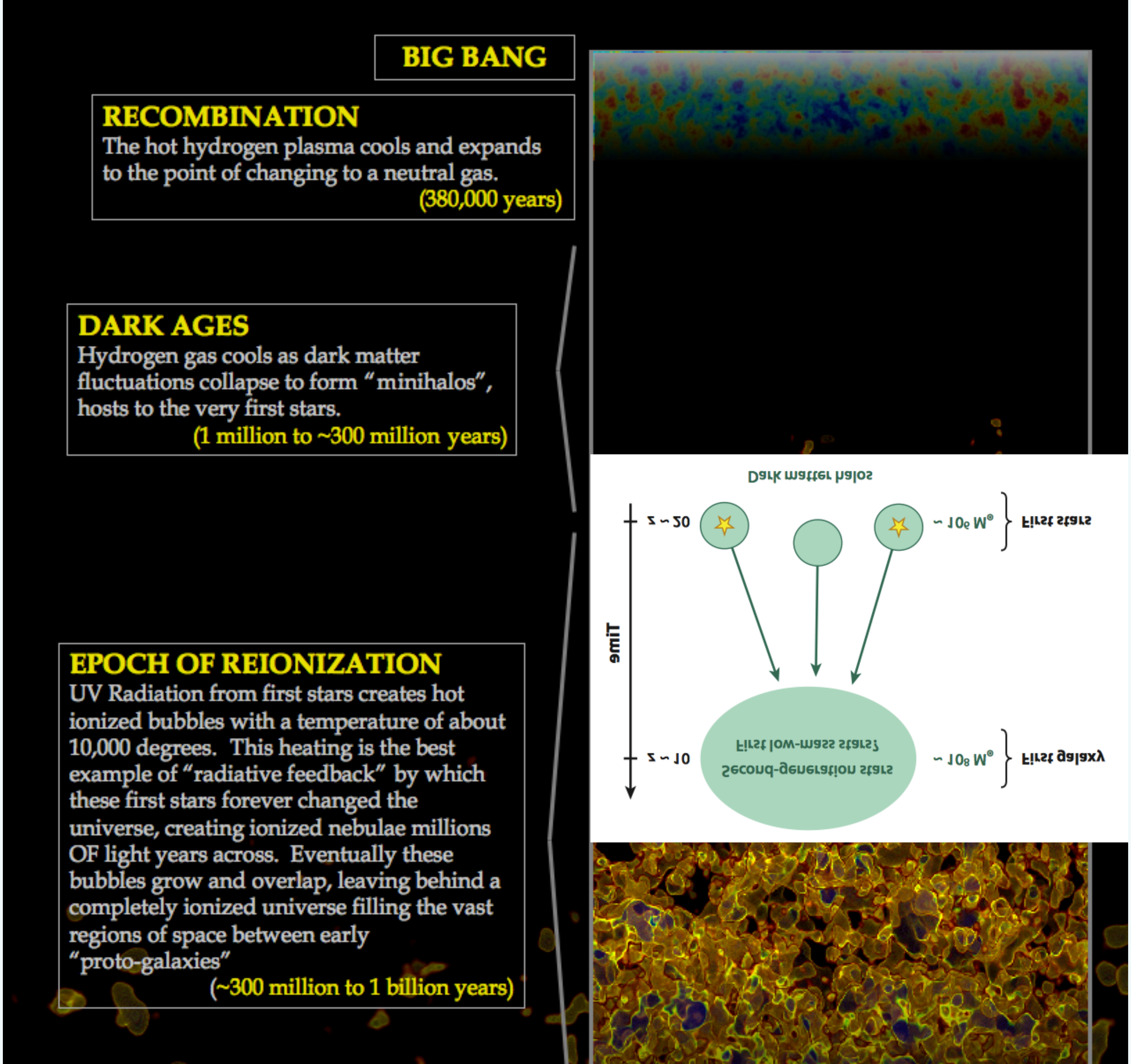

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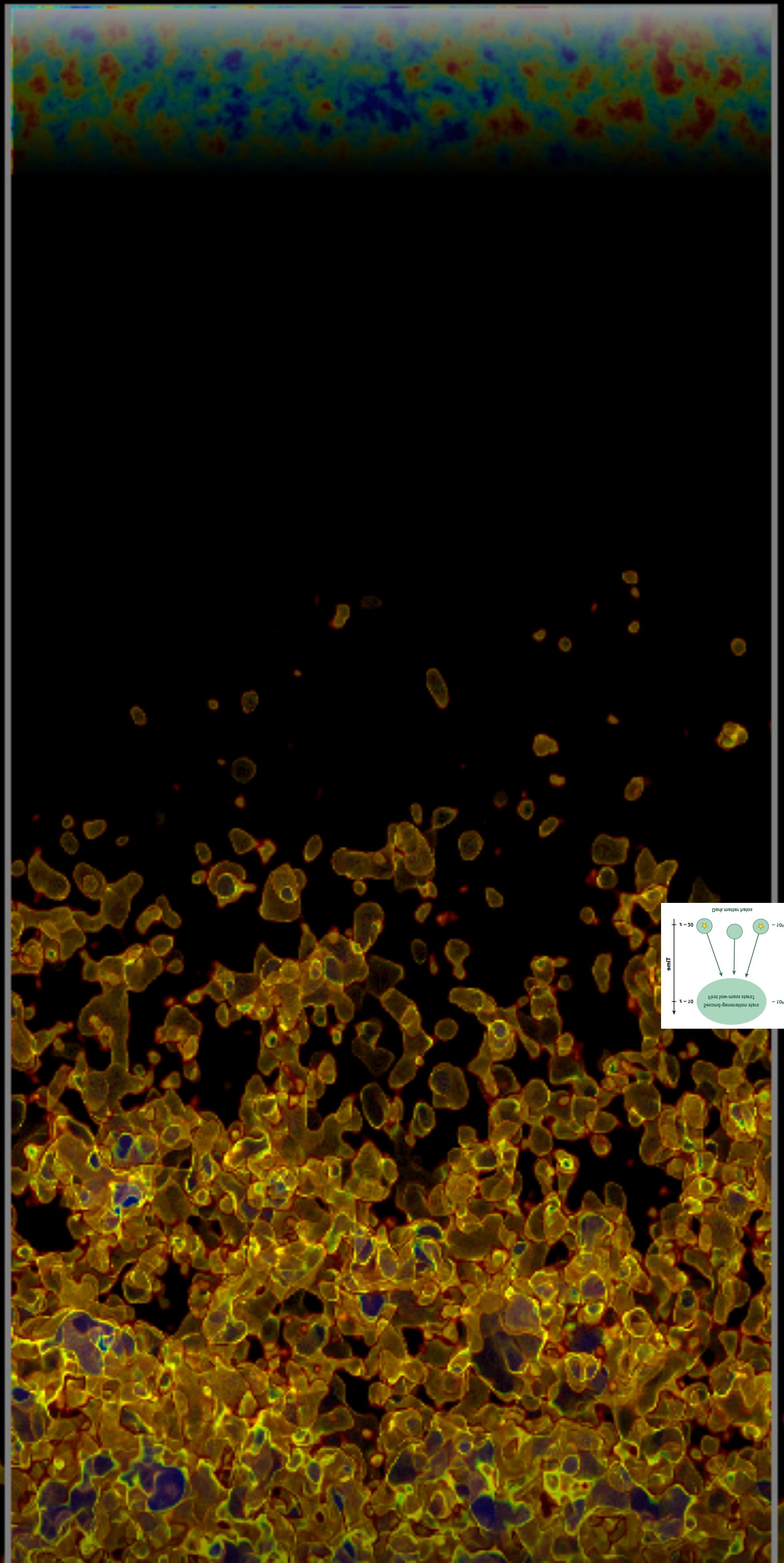

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A History Lesson

- Why do all observed stars contain metals?

A History Lesson

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ON THE EVOLUTION OF STARS AND CHEMICAL ELEMENTS IN THE EARLY PHASES OF A GALAXY

By Martin Schwarzschild and Lyman Spitzer, Jr.

Recent observations have brought together three items all of which hint toward violent evolutionary processes during the early phases of a galaxy. The three items are: (*a*) The very low abundance of the metals in the earliest Population II stars; (*b*) the high frequency of the white dwarfs; (*c*) the red excess of distant elliptical galaxies discovered by Stebbins and Whitford. It appears to us that the interpretation of these three items is furthered by the assumption that the original stellar Population II contained a large number of relatively massive stars and that correspondingly the frequency of star deaths was much higher early in the life of a galaxy than it is now. This suggestion is based on the following arguments.

A History Lesson

- In nearby star forming regions, H_2 forms on dust grains.
- With no metals, how does the gas cool to form stars?
    - H_2 (slowly) forms in the gas-phase through

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

McDowell (1961)

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

NATURE. VOL. 216. DECEMBER 9. 1967

Molecular Hydrogen in Pre-galactic Gas Clouds

by
WILLIAM C. SASLAW
DAVID ZIPOY
Department of Applied Mathematics
and Theoretical Physics,
University of Cambridge

During the collapse of pre-galactic gas clouds through a density of about 10^4 particles/cm^3, hydrogen molecules are produced and dominate the subsequent cooling.

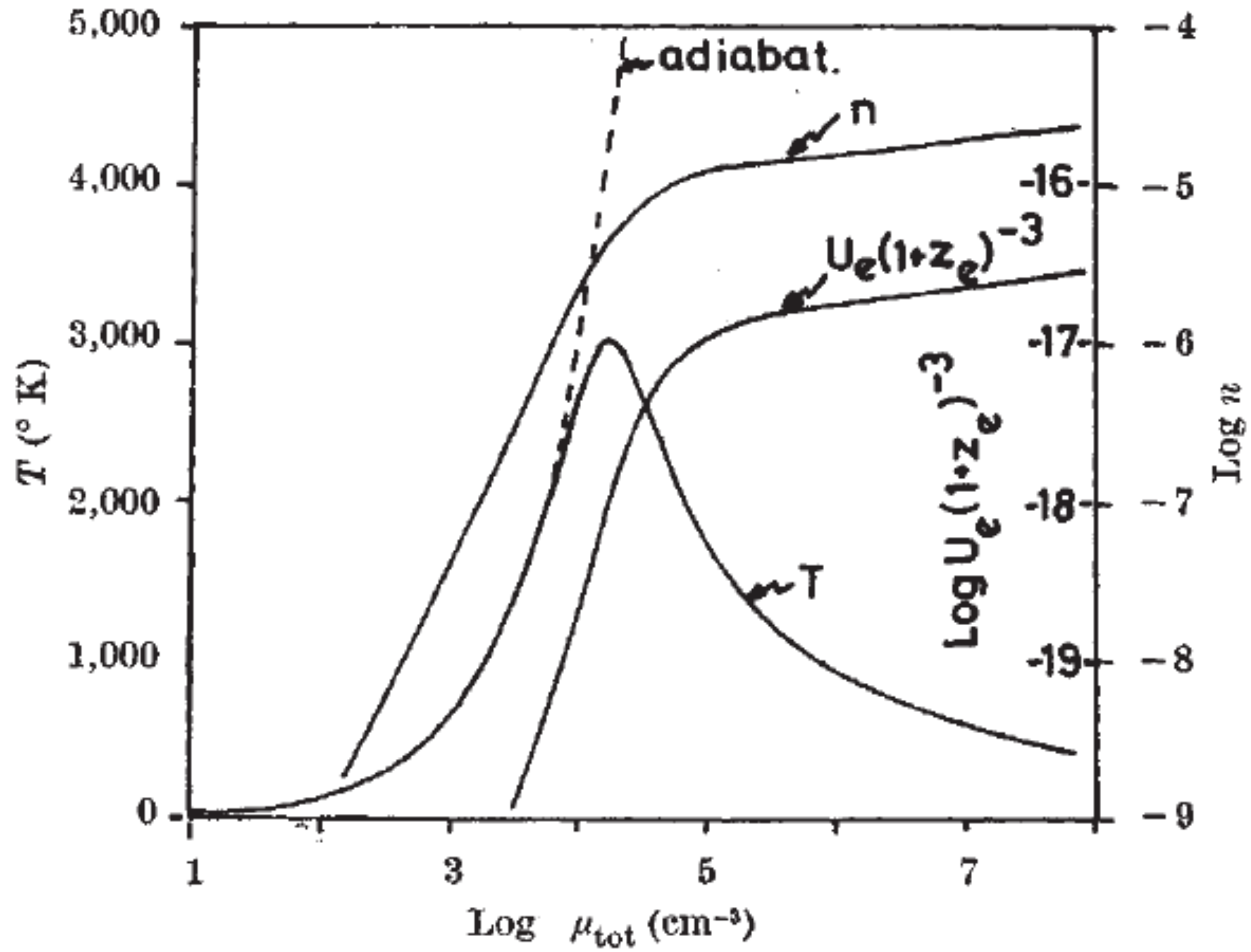
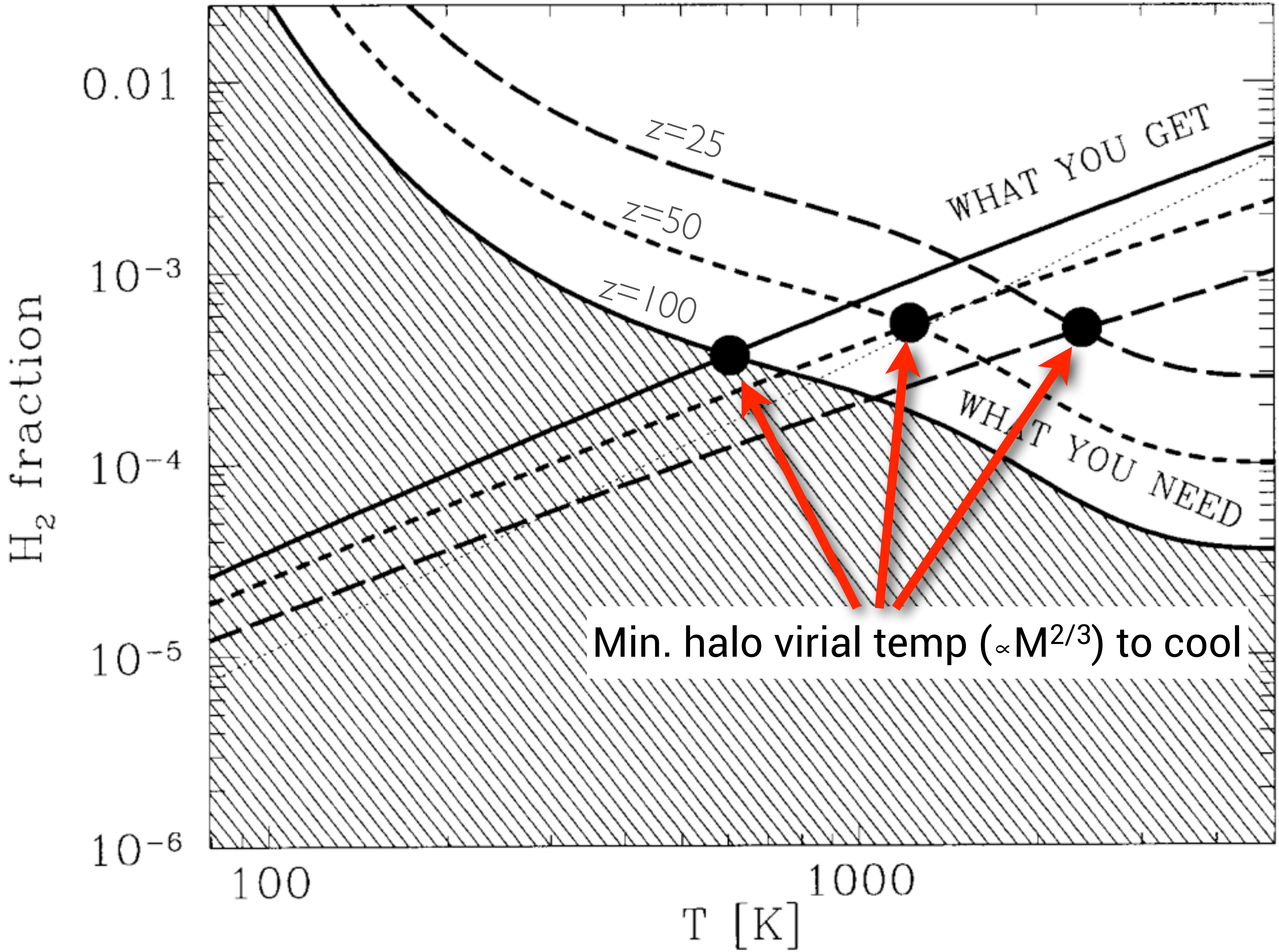


Fig. 1. The temperature, T, fraction of hydrogen, n, and the "invariant" energy density, $U_e(1+Z_e)^{-3}$, are plotted as a function of the instantaneous total density, μ_{tot}, of the collapsing cloud. The dashed extension of T gives the temperature if the cloud does not radiate. The initial conditions are $z_0 = 5$, $m_0 = 10^{-5}$, $\varrho_{\text{universe now}} = 2 \times 10^{-29}$ g/cm^3. A similar plot with $z_0 = 20$ differs from these curves by less than 10 per cent.

Population III Star Formation

- When and where do the first stars form?
- (Couchman & Rees 1986) In rare cosmological peaks in $\sim 10^5\ M_\odot$ DM halos at $z = 20\text{–}30$.
- (Tegmark et al. 1997) Determined a redshift-dependent minimum halo mass for Pop III SF.



0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
H_2 fraction
100
1000
T [K]
z=25
z=50
z=100
WHAT YOU GET
WHAT YOU NEED
Min. halo virial temp ($\propto M^{2/3}$) to cool

Population III Stars
Formation Simulations

- 3D simulations of Pop III star formation (late 1990's and early 2000's)
- Two independent groups: Bromm+ and Abel+
- Gas cools to T ~ few x 100 K
- Characterizes the Jeans mass of the molecular cloud, $M_J \sim 1000\ M_\odot$
- No fragmentation into low-mass objects
- Pointed toward very massive stars → 30–300 $M_\odot$

- (Yoshida et al. 2007) Pushes a simulation to Pop III protostar formation!

- More simulations (e.g. O'Shea+ 2007) gave more samples for an IMF, but always showed a bias toward high masses and no fragmentation.

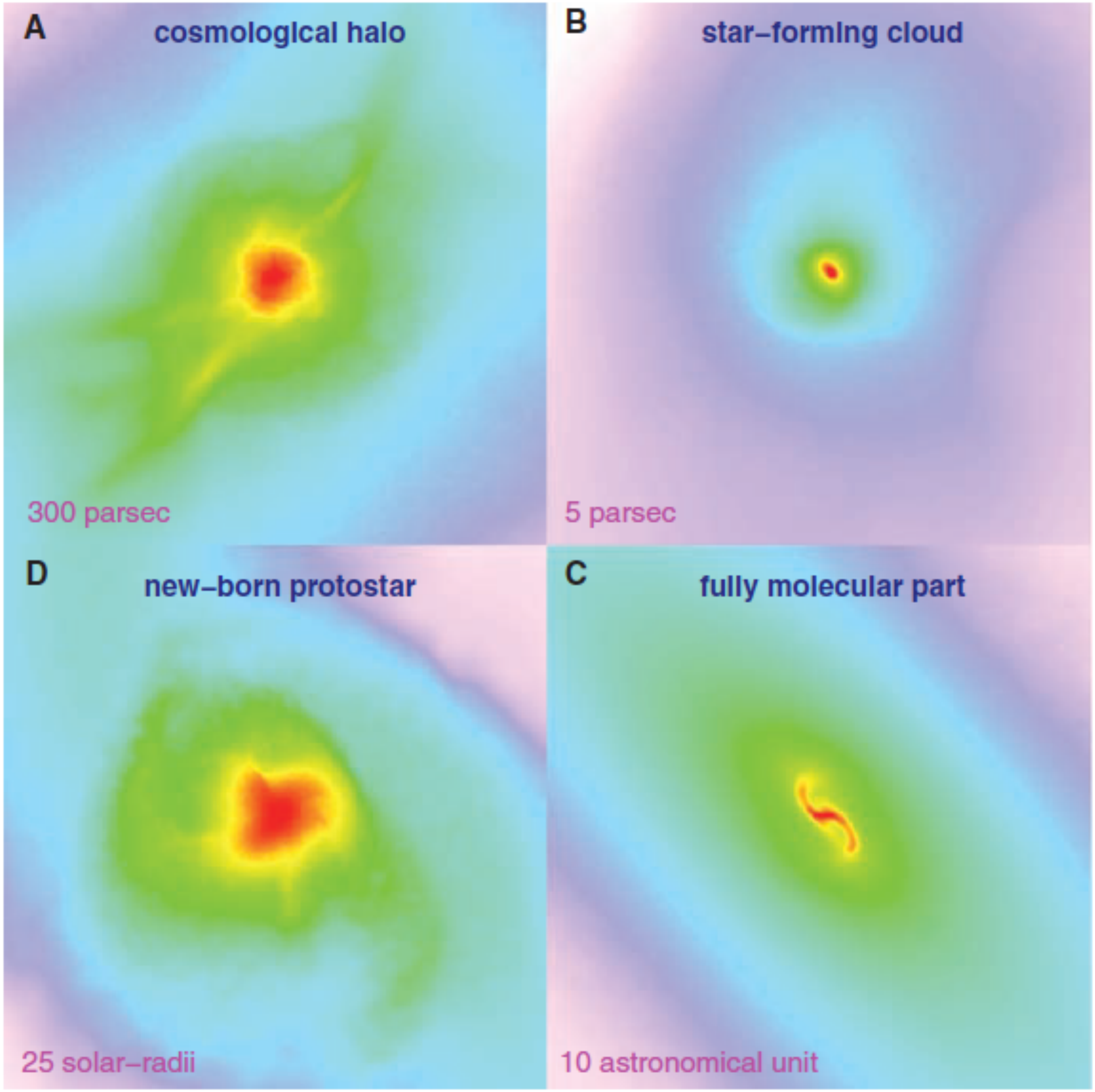
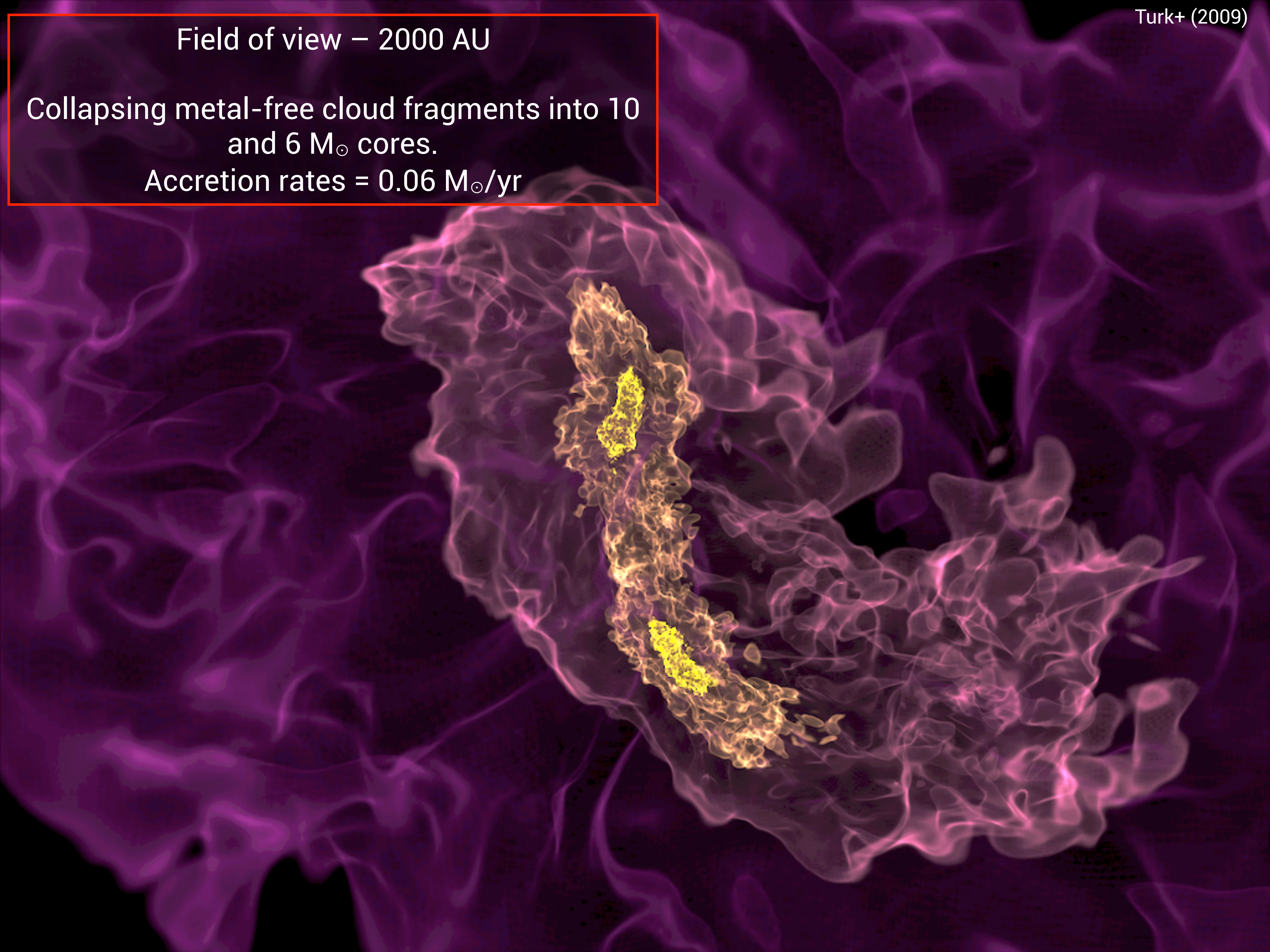


Fig. 1. Projected gas distribution around the protostar. (**A**) The large-scale gas distribution around the cosmological halo (300 pc on a side). (**B**) A self-gravitating, star-forming cloud (5 pc on a side). (**C**) The central part of the fully molecular core (10 astronomical units on a side). (**D**) 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.

Population III Stars
Fragmentation!

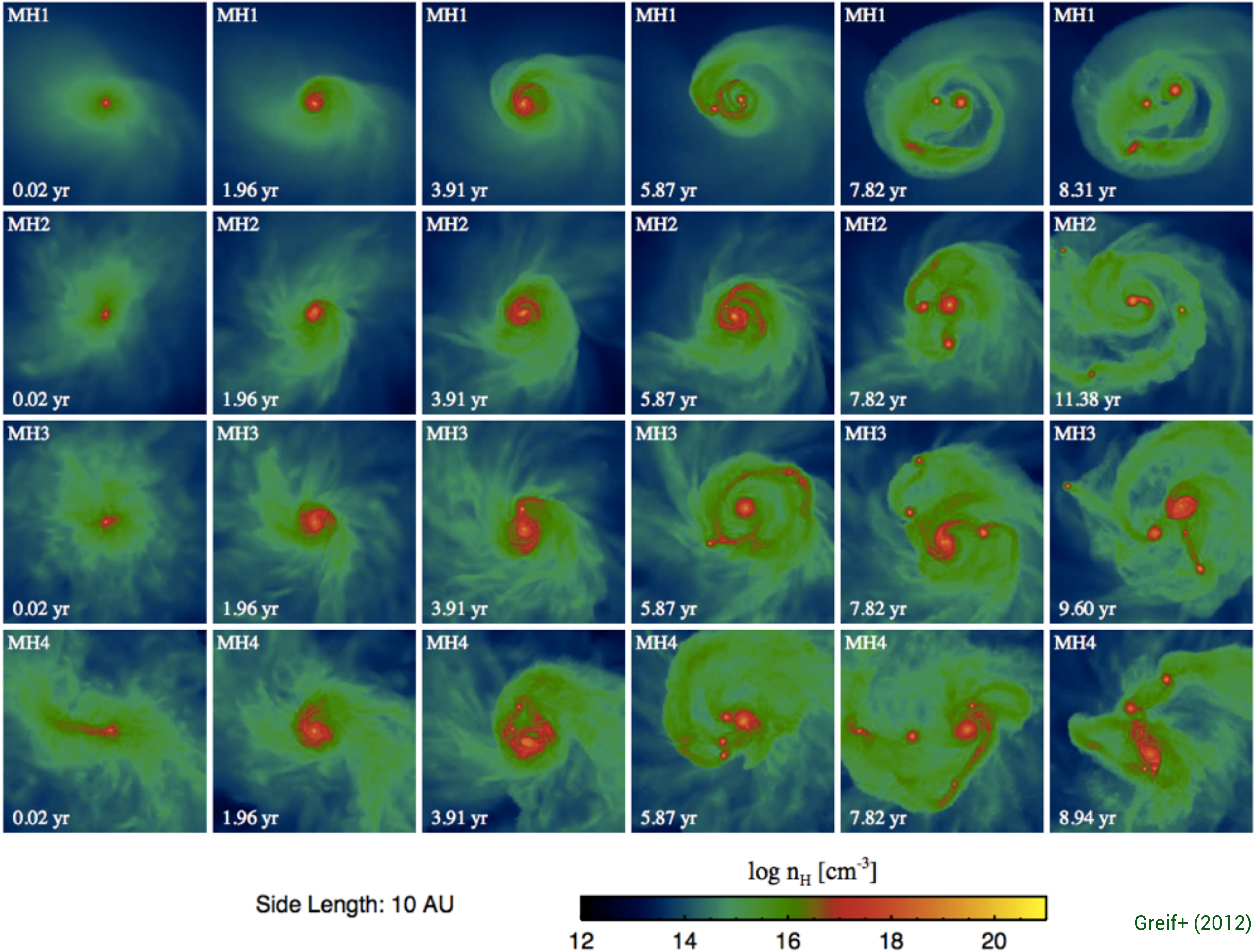
- Improved chemistry models and sink particle implementations allows simulations to progress further than the first collapsing object.

- (Turk+ 2009) Found 1 of 5 realizations fragmented. 50 $M_\odot$ clump fragments into two, separated by 800 AU.


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

Population III Stars
Fragmentation!

- Improved chemistry models and sink particle implementations allows simulations to progress further than the first collapsing object.
- (Turk+ 2009) Found 1 of 5 realizations fragmented. 50 $M_\odot$ clump fragments into two, separated by 800 AU.
- (Stacy+ 2009) Disk instabilities cause fragmentation, forming a 40 $M_\odot$ and 10 $M_\odot$ binary.
- (Greif+ 2011, 2012) Finds fragmentation in five halos, evolving the systems for ~100 dynamical times. Flat protostellar mass function from 0.1–10 $M_\odot$.


MH1
0.02 yr
1.96 yr
3.91 yr
5.87 yr
7.82 yr
8.31 yr
MH2
0.02 yr
1.96 yr
3.91 yr
5.87 yr
7.82 yr
11.38 yr
MH3
0.02 yr
1.96 yr
3.91 yr
5.87 yr
7.82 yr
9.60 yr
MH4
0.02 yr
1.96 yr
3.91 yr
5.87 yr
7.82 yr
8.94 yr
Side Length: 10 AU
log n_H [cm^{-3}]
12
14
16
18
20
Greif+ (2012)

Pop III Final Masses

- When do Pop III stars stop accreting?
- (Hosokawa+ 2011) Modeled protostellar radiative feedback from an accreting Pop III star.
- Found that the star is limited to ~43 $M_\odot$

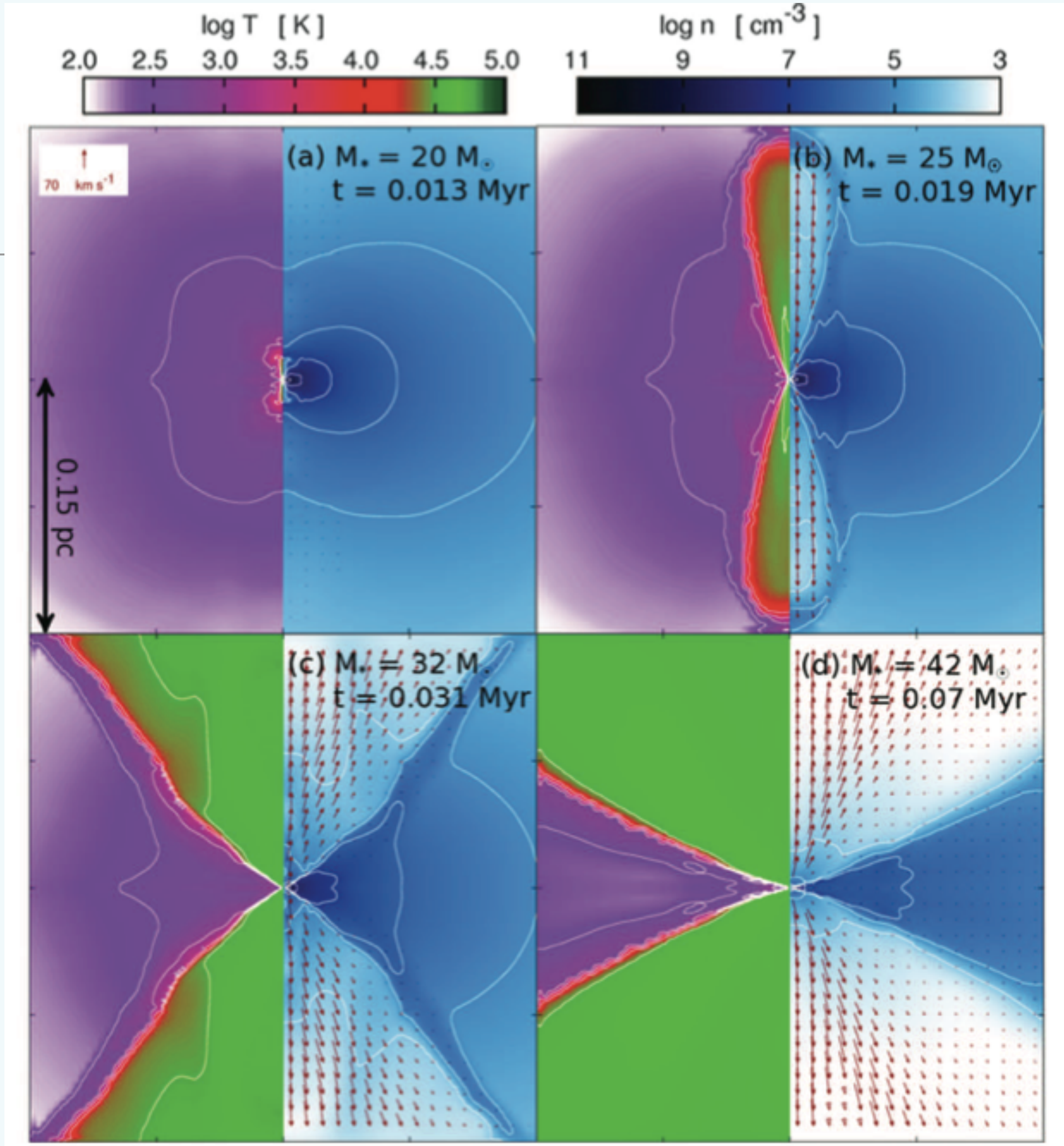
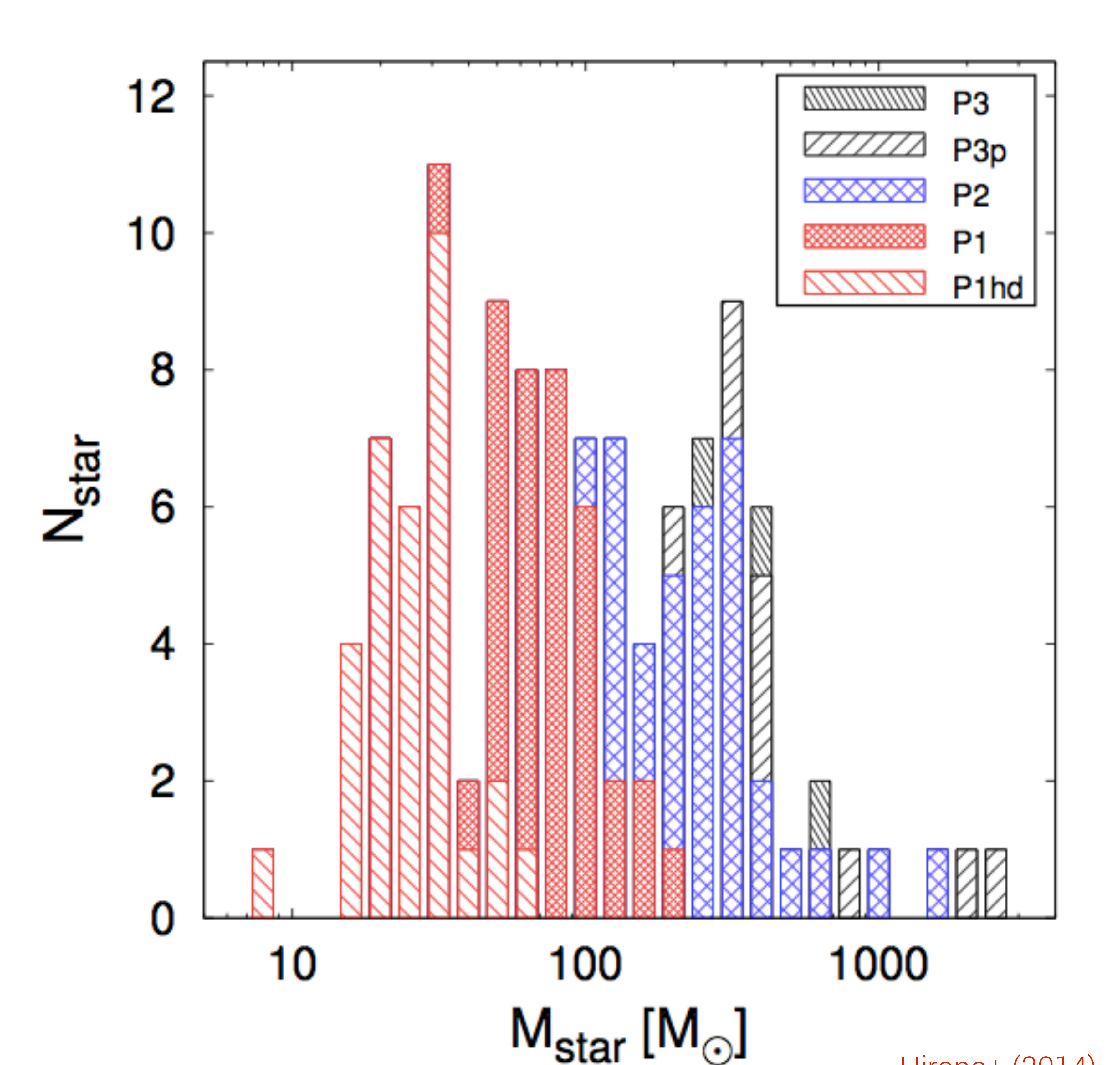
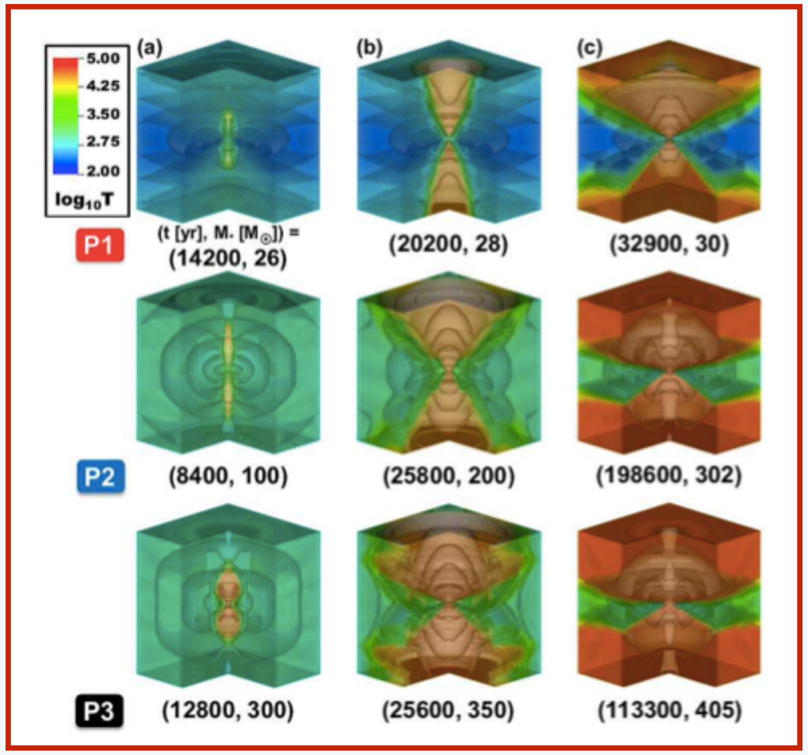


Fig. 2. UV radiative feedback from the primordial protostar. The spatial distributions of gas temperature (left), number density (right), and velocity (right, arrows) are presented in each panel for the central regions of the computational domain. The four panels show snapshots at times when the stellar mass is $M_* = 20\ M_\odot$ (**A**), $25\ M_\odot$ (**B**), $35\ M_\odot$ (**C**), and $42\ M_\odot$ (**D**). The elapsed time since the birth of the primordial protostar is labeled in each panel.

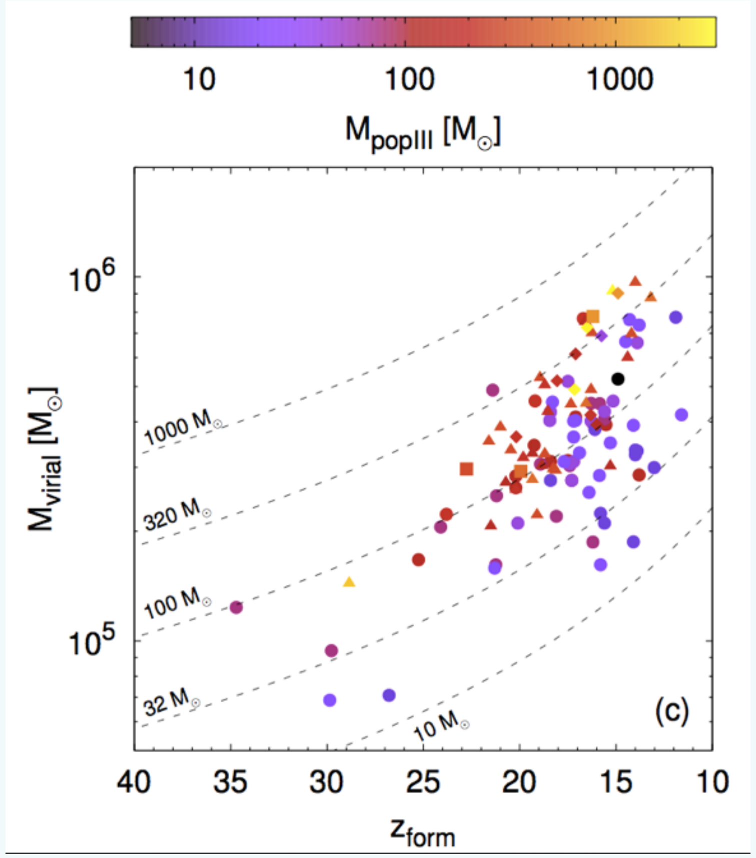
Population III Stars
Working toward an Initial Mass Function (IMF)



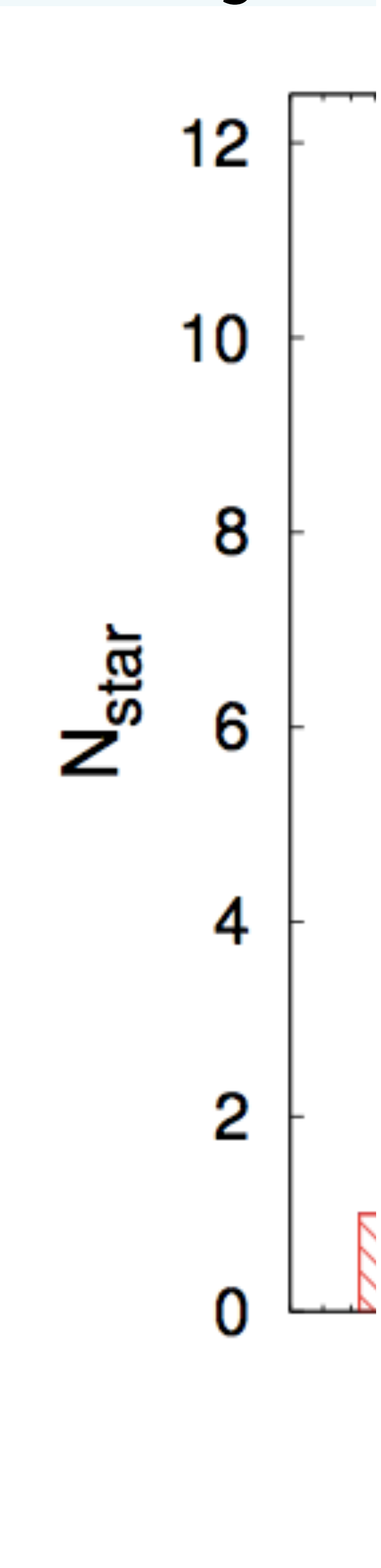
Hirano+ (2014)

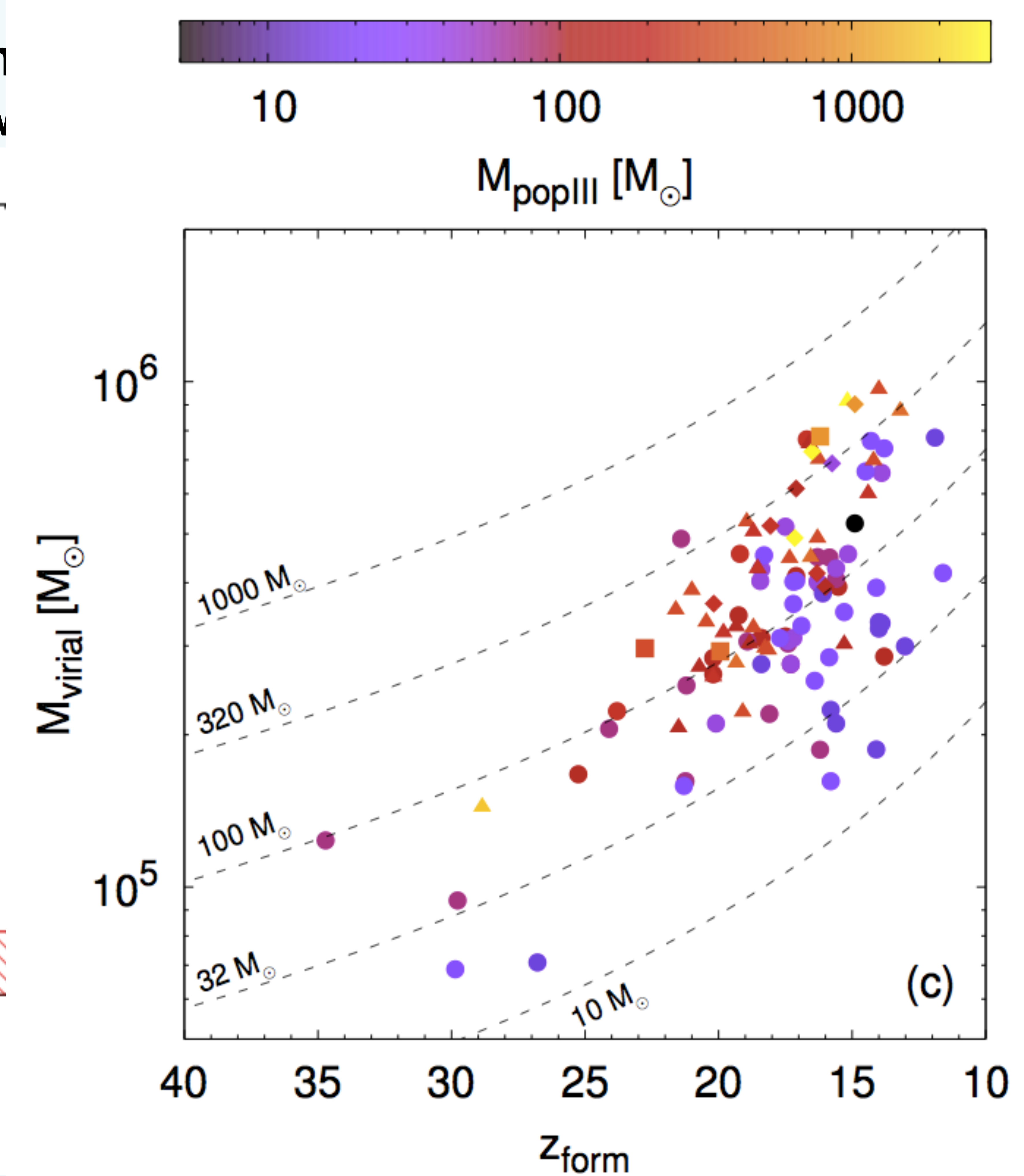


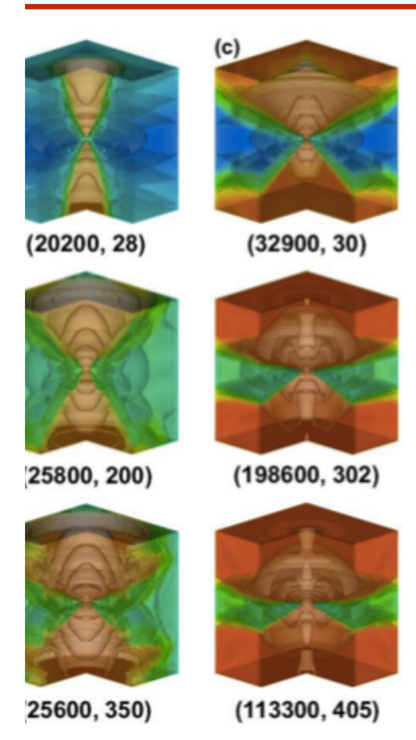
100 2.5D protostellar radiation-hydro calculations, taken from a cosmological sample



Population
Working tow

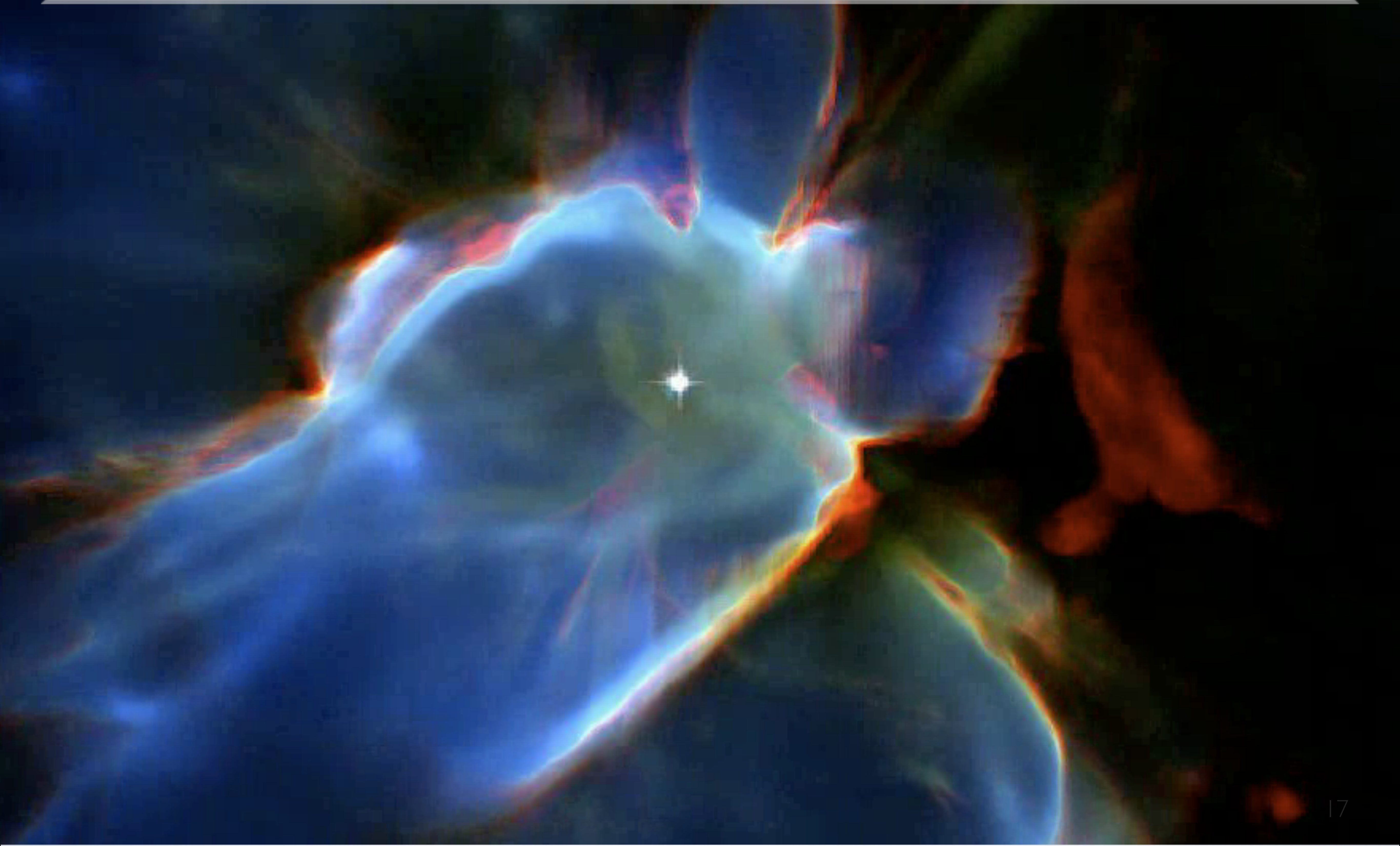






protostellar
on-hydro
taken from a
ical sample

Pop III Radiative Feedback



Population III Stars
Main Sequence – Radiative Feedback

- Pop III Luminosities and Surface Temperatures (Tumlinson & Shull 2000) – Nearly mass-independent $T_{eff} \sim 10^5$ K.

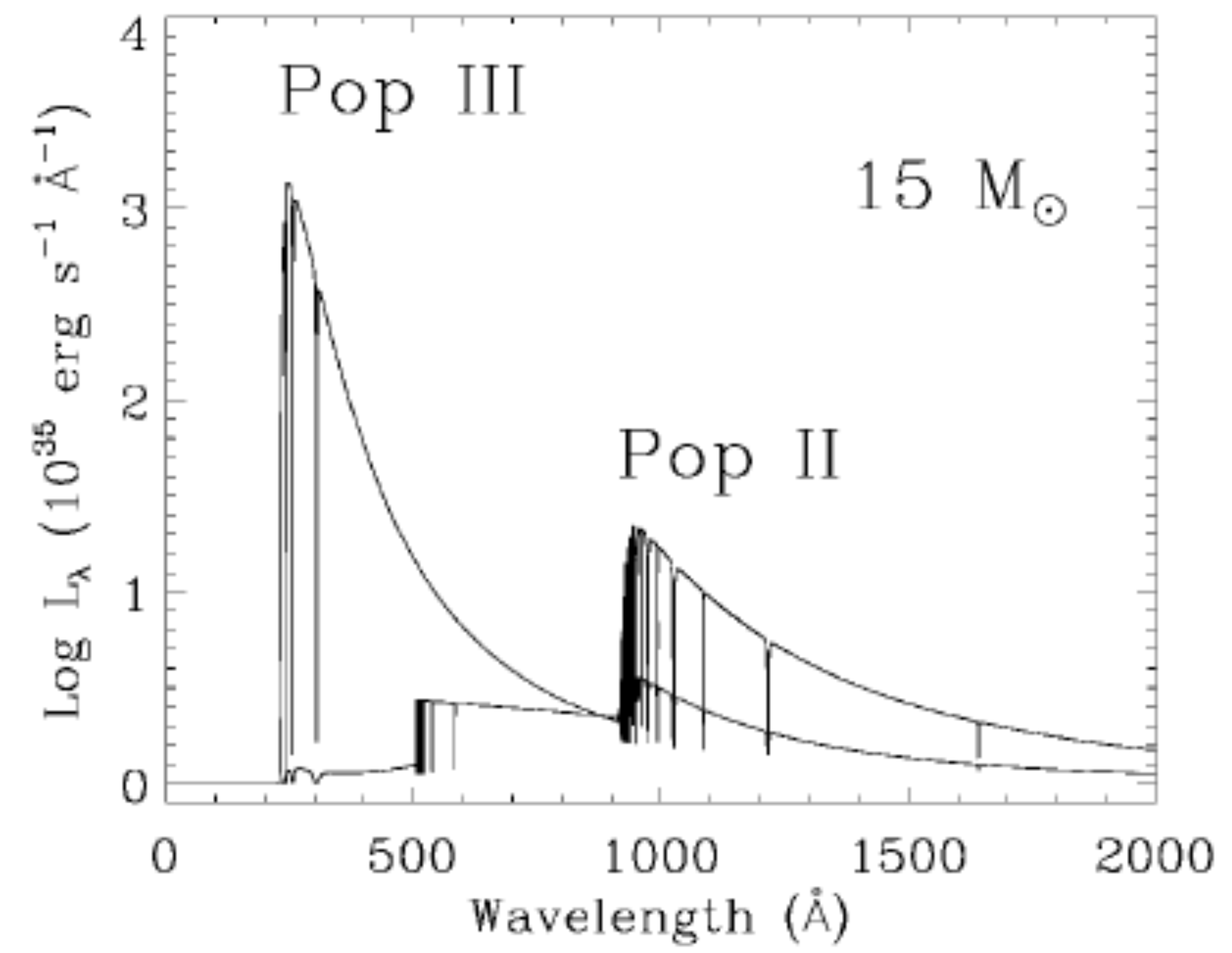


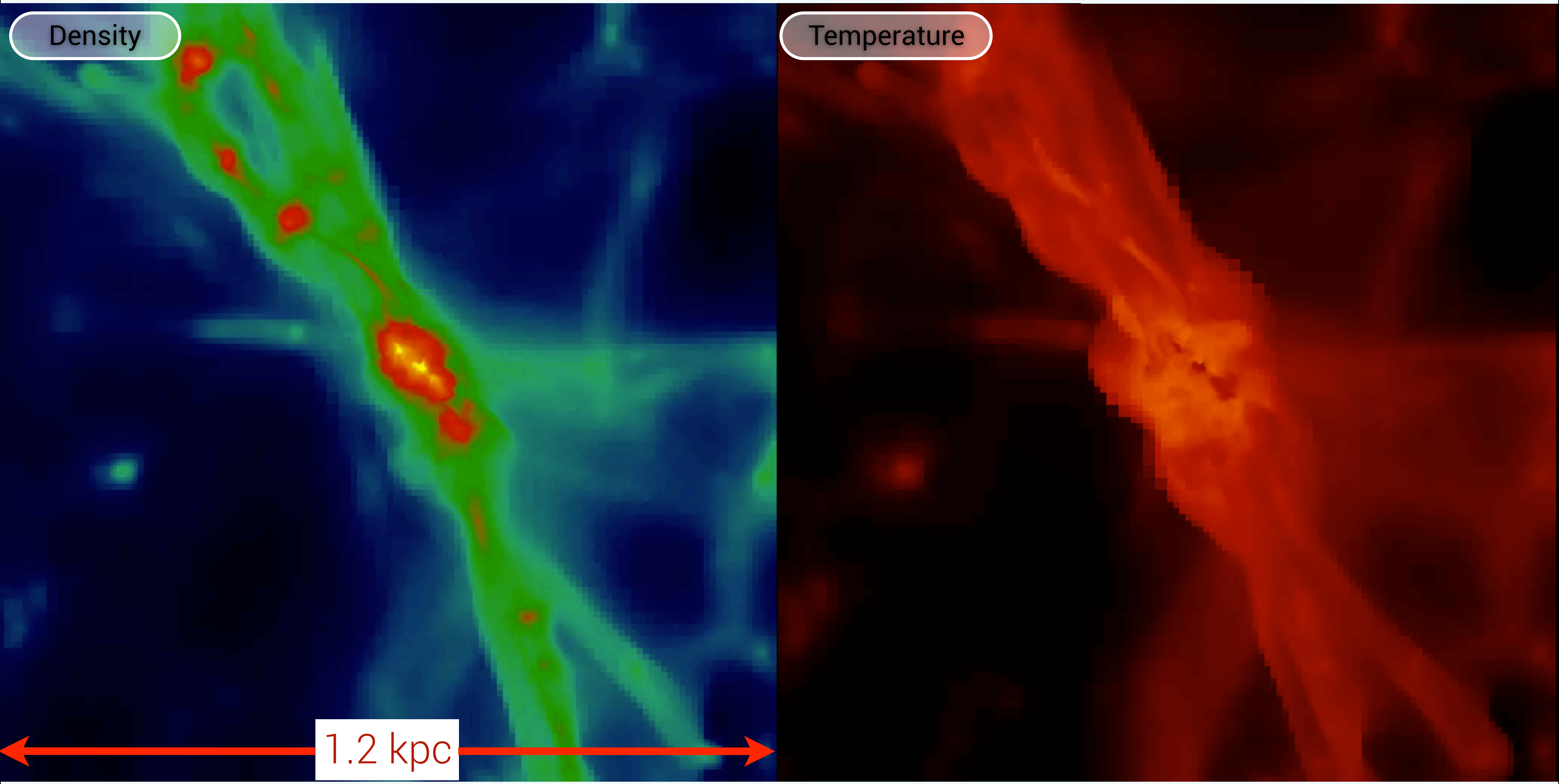
FIG. 2.—Comparison of spectra calculated from atmosphere models of Population II ($Z = 0.001$) and Population III ($Z = 0$) stars of 15 $M_\odot$. The Population II star has $T_{eff} = 36{,}000$ K, and the Population III star has $T_{eff} = 63{,}000$ K. Only H I, He I, and He II lines are included.

Population III Stars
Main Sequence – Radiative Feedback

- **(Kitayama+ 04; Whalen+ 04) First 1-D radiation hydrodynamics calculations.**
  - Starting with the final radially averaged profiles from cosmological halos.
  - They find that most gas is expelled from the halo, driven out by a **30 km/s** shock wave that is created by the ionization front.
- **(Alvarez+ 2006, Abel+ 2007) First 3-D radiative transfer calculations.**
  - Using cosmological initial conditions, found that the star leaves a warm (10^4 K) and diffuse ($0.1\ cm^{-3}$) medium behind.
  - Creates shadows and butterfly shaped HII regions.

Abel, Wise, & Bryan (2007)

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

Abel, Wise, & Bryan (2007)

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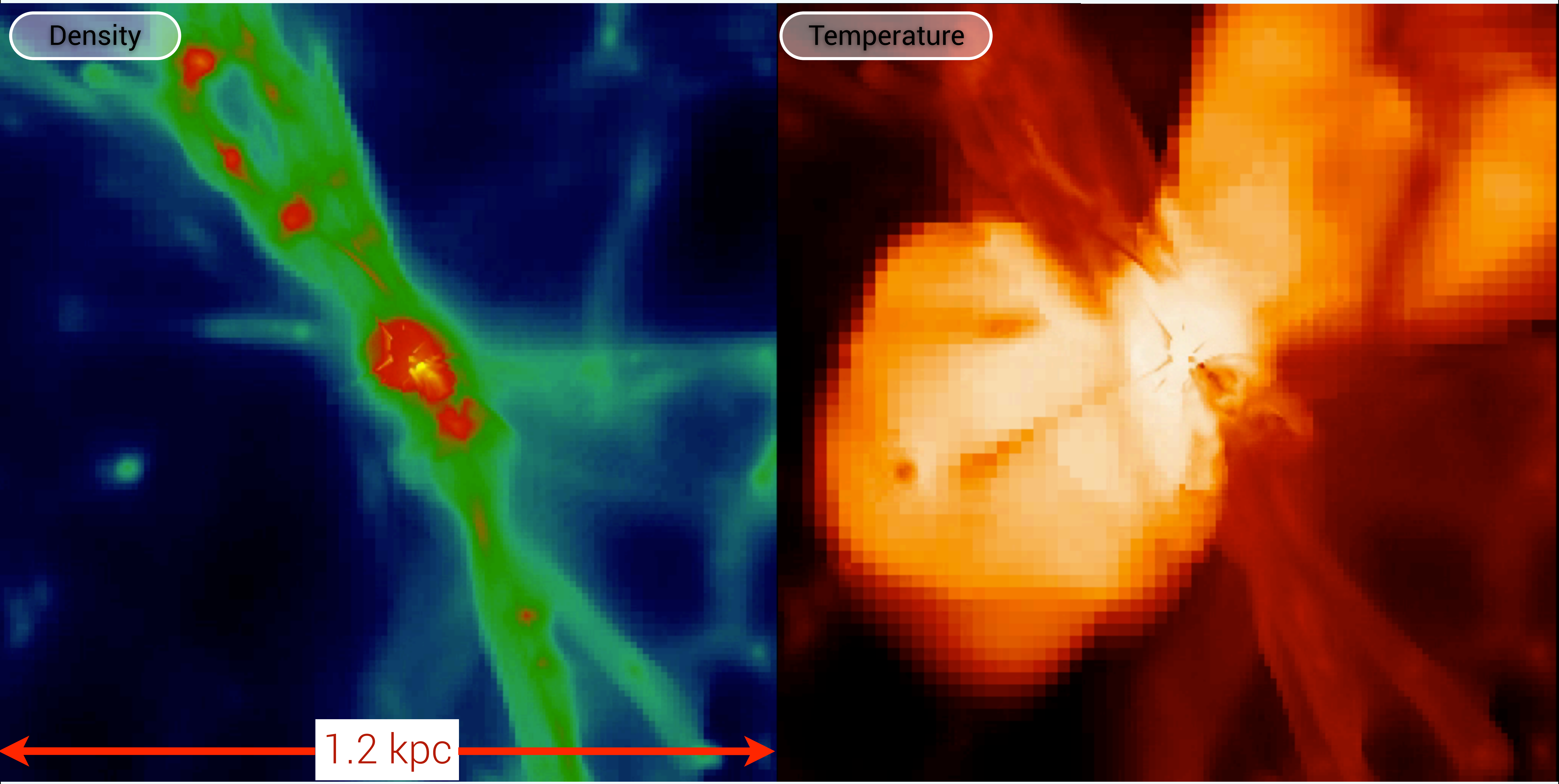

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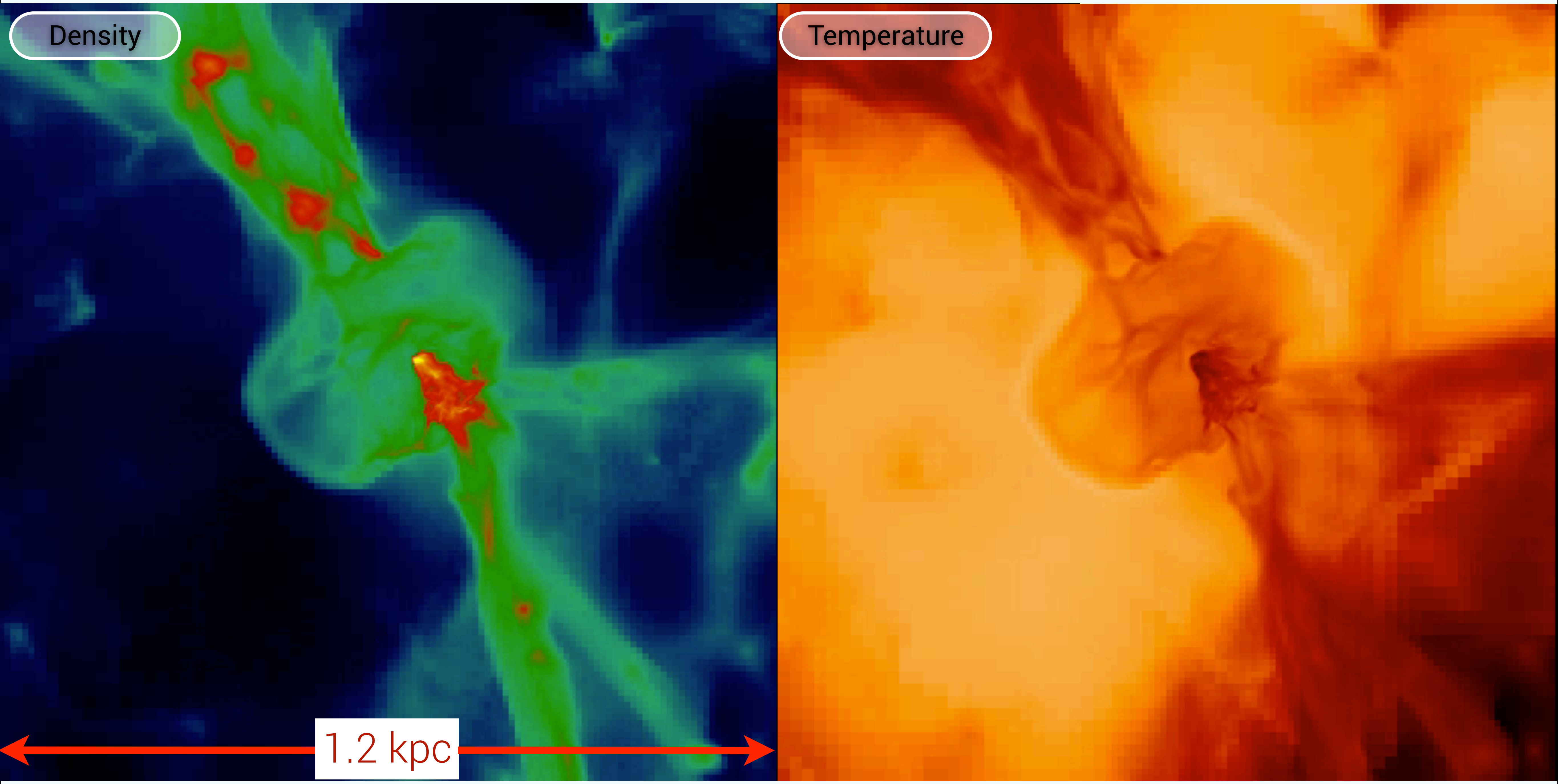

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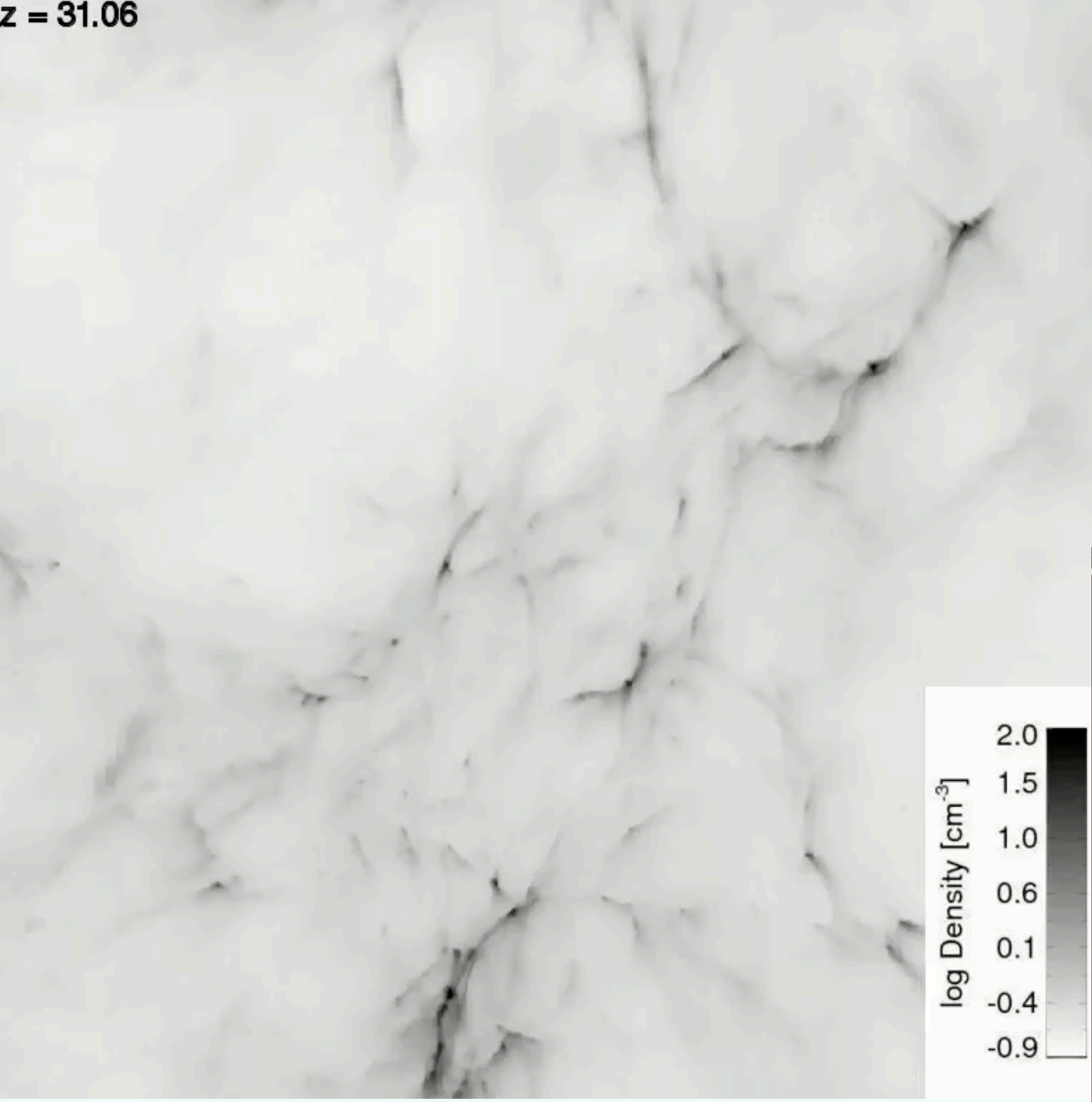
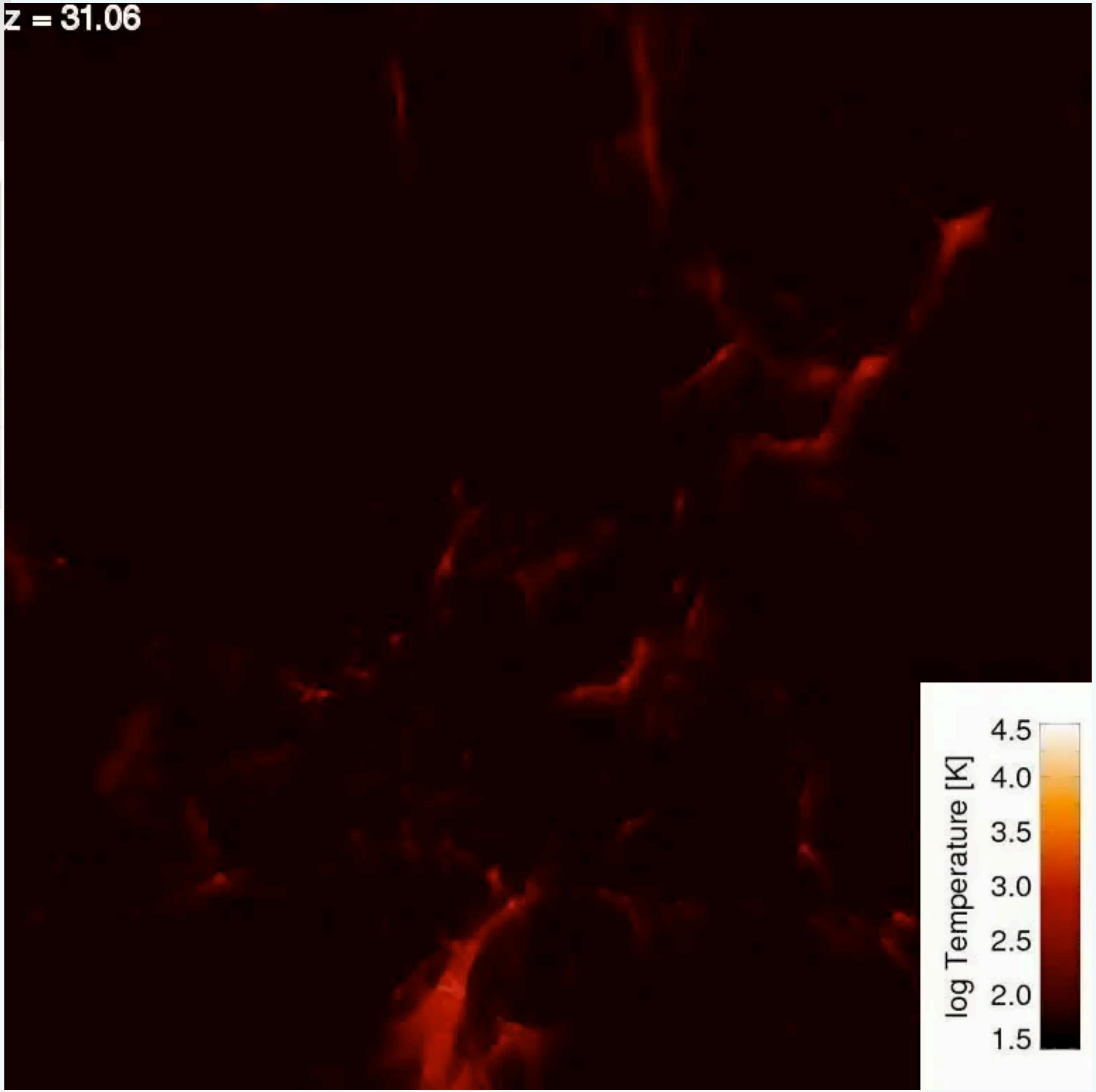
150 comoving kpc
~30 Pop III stars simulated
z = 30 → 16





Wise & Abel (2008)

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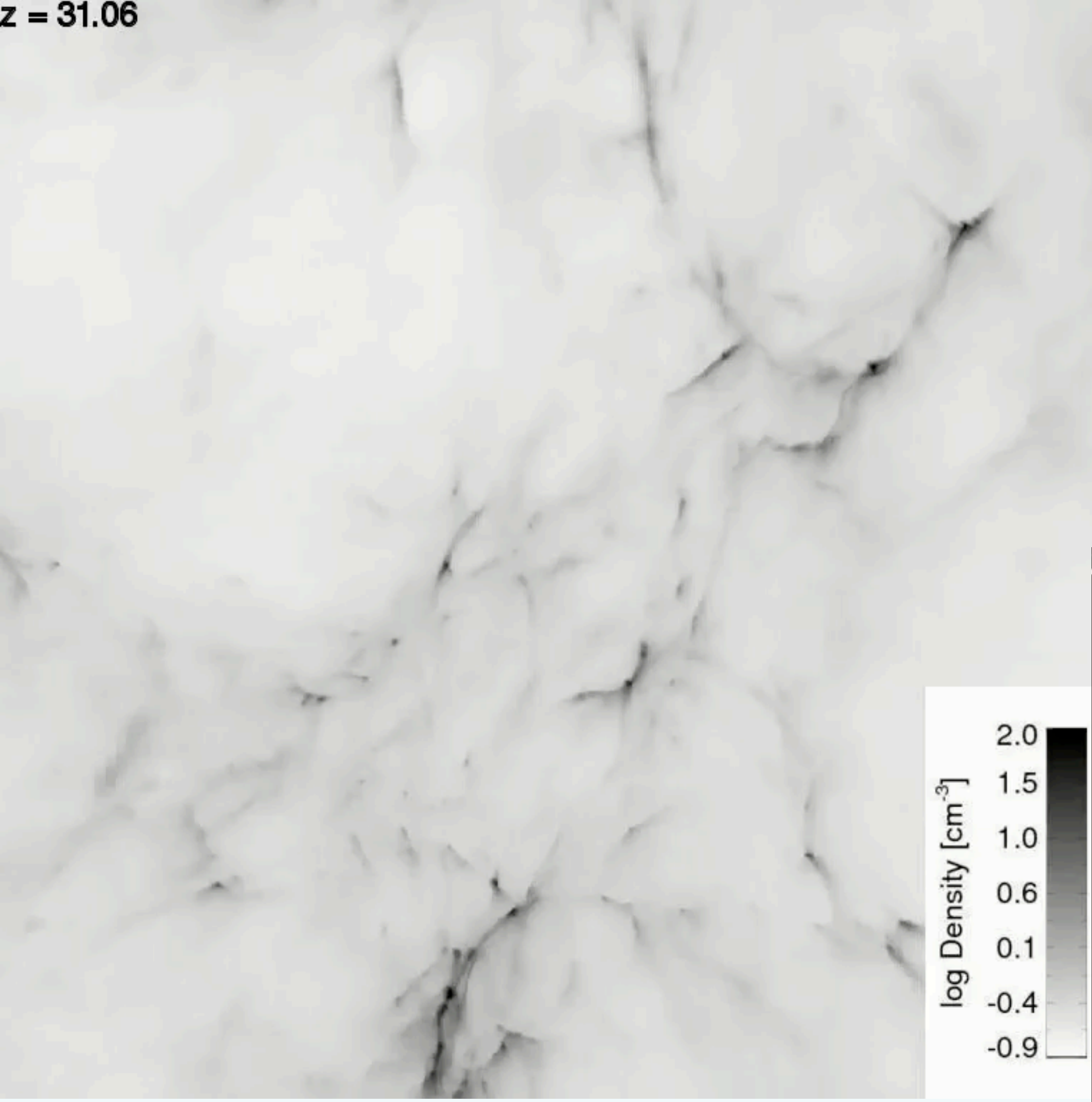

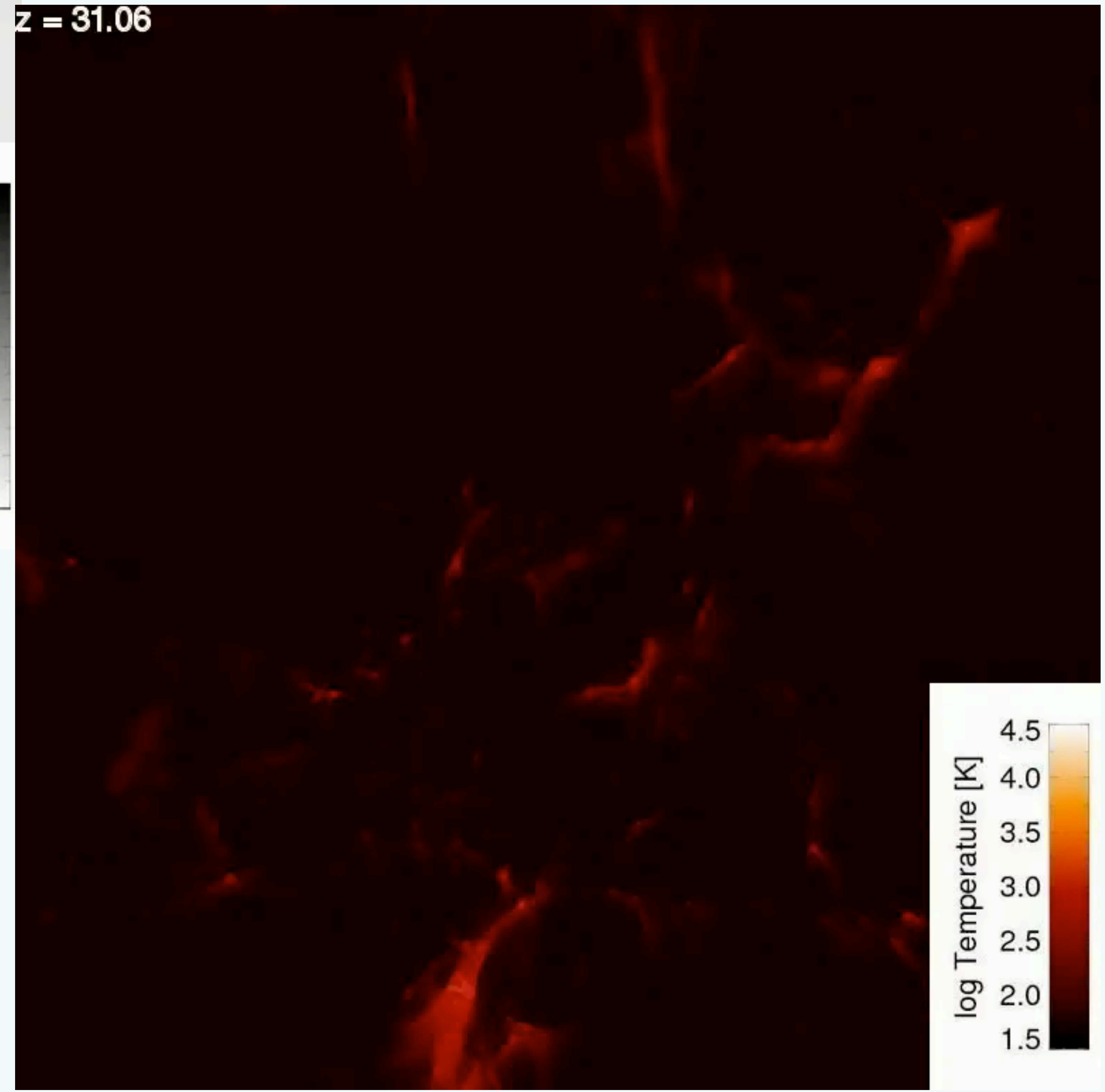

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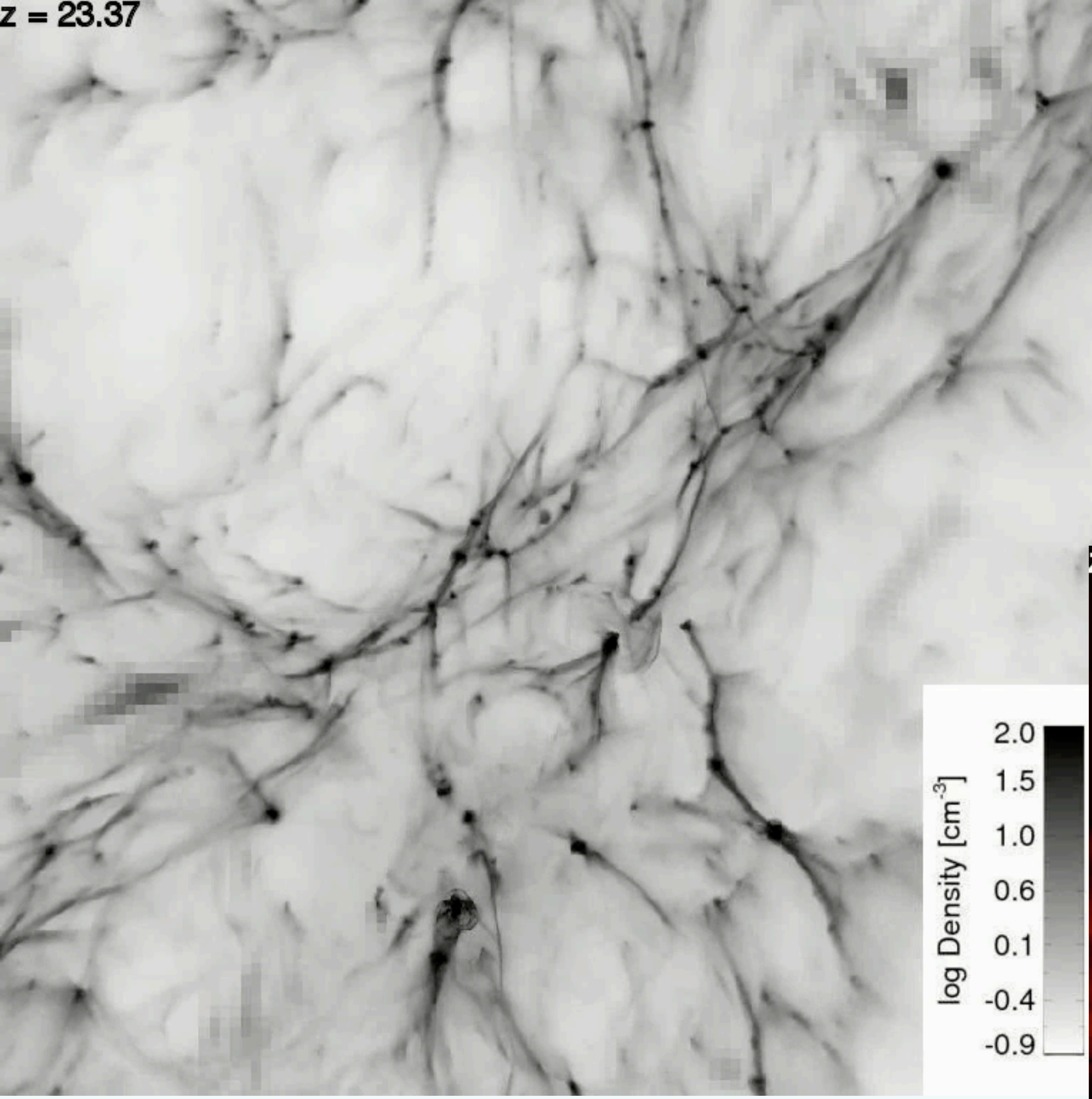

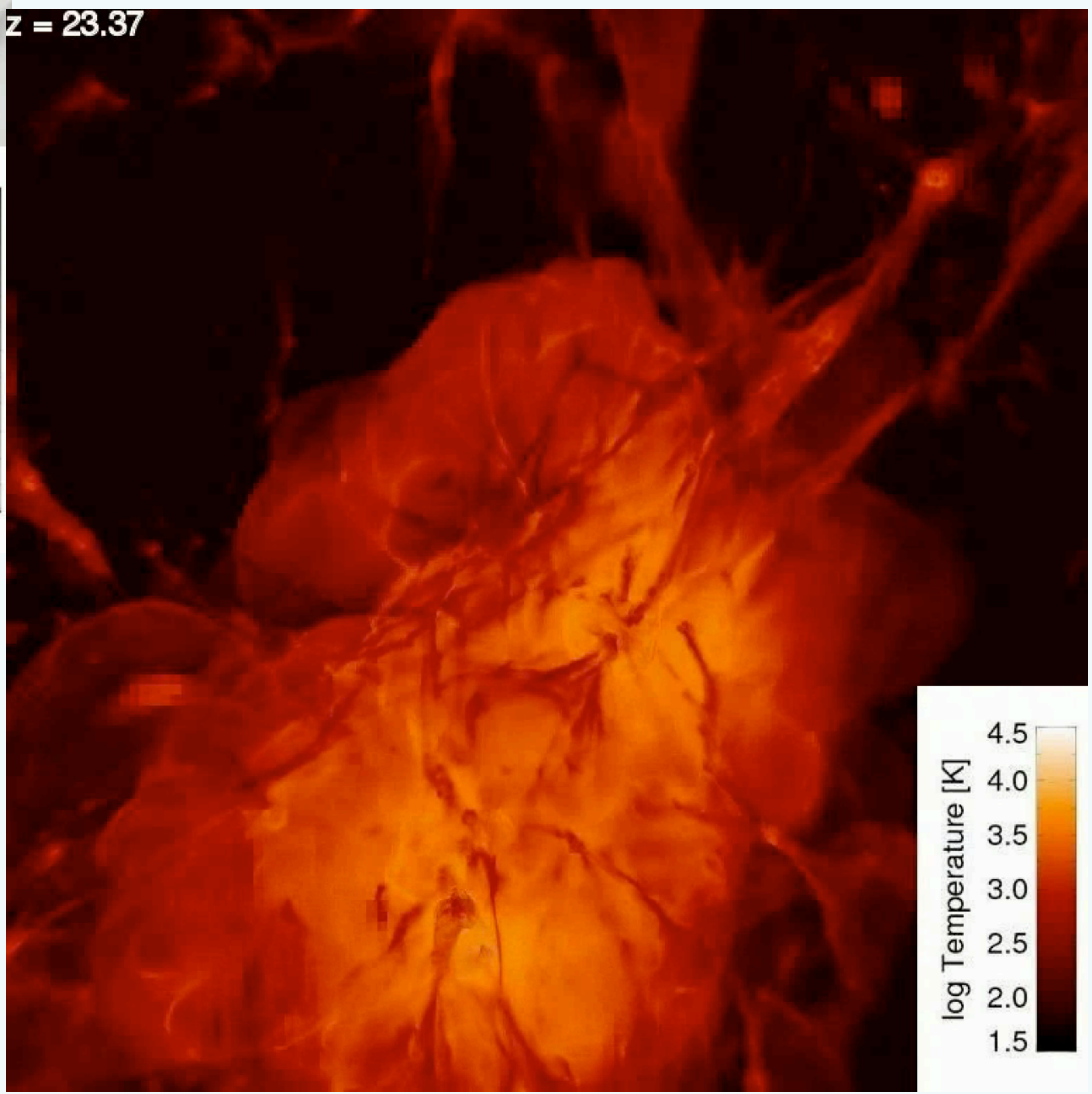

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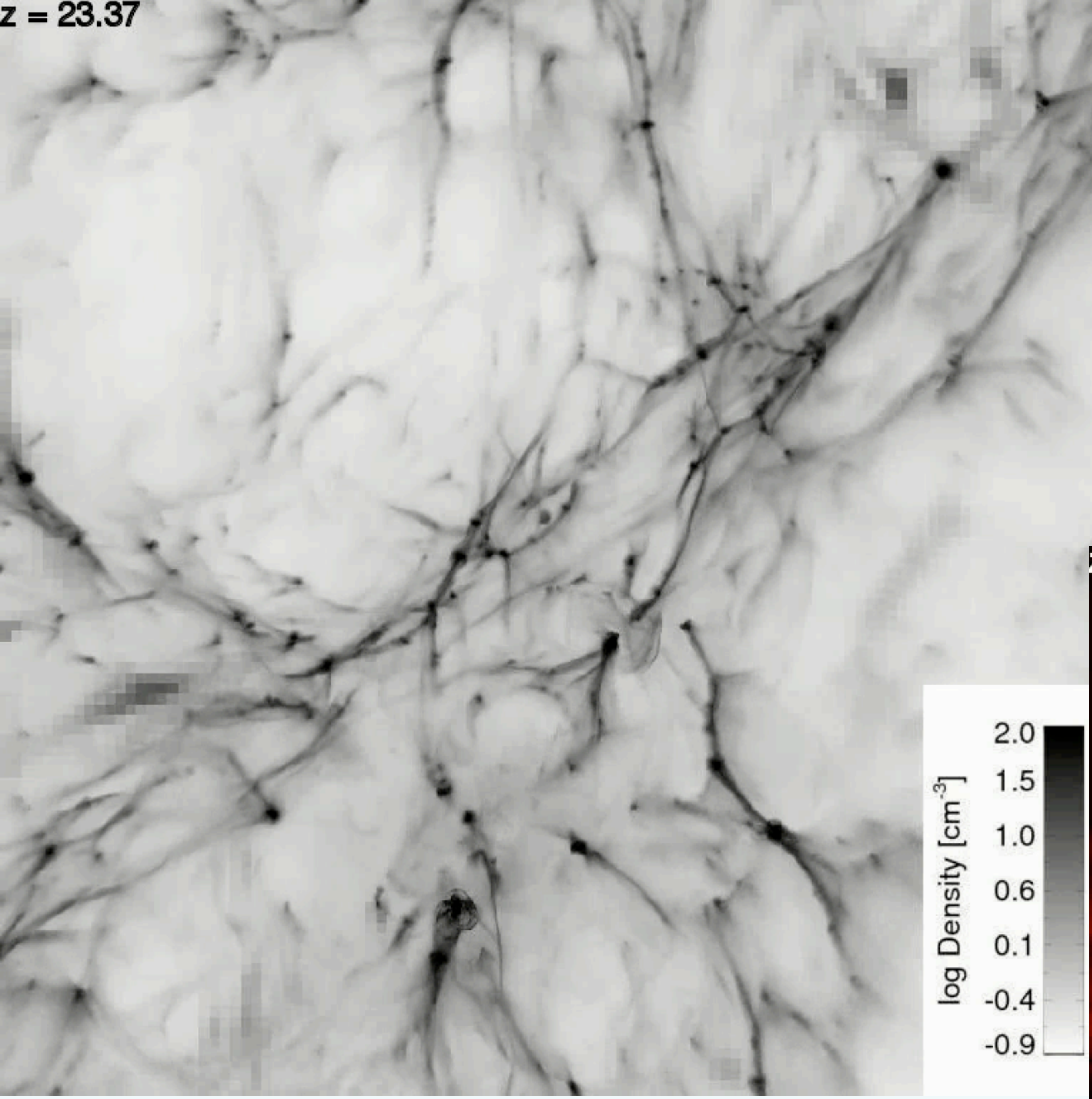

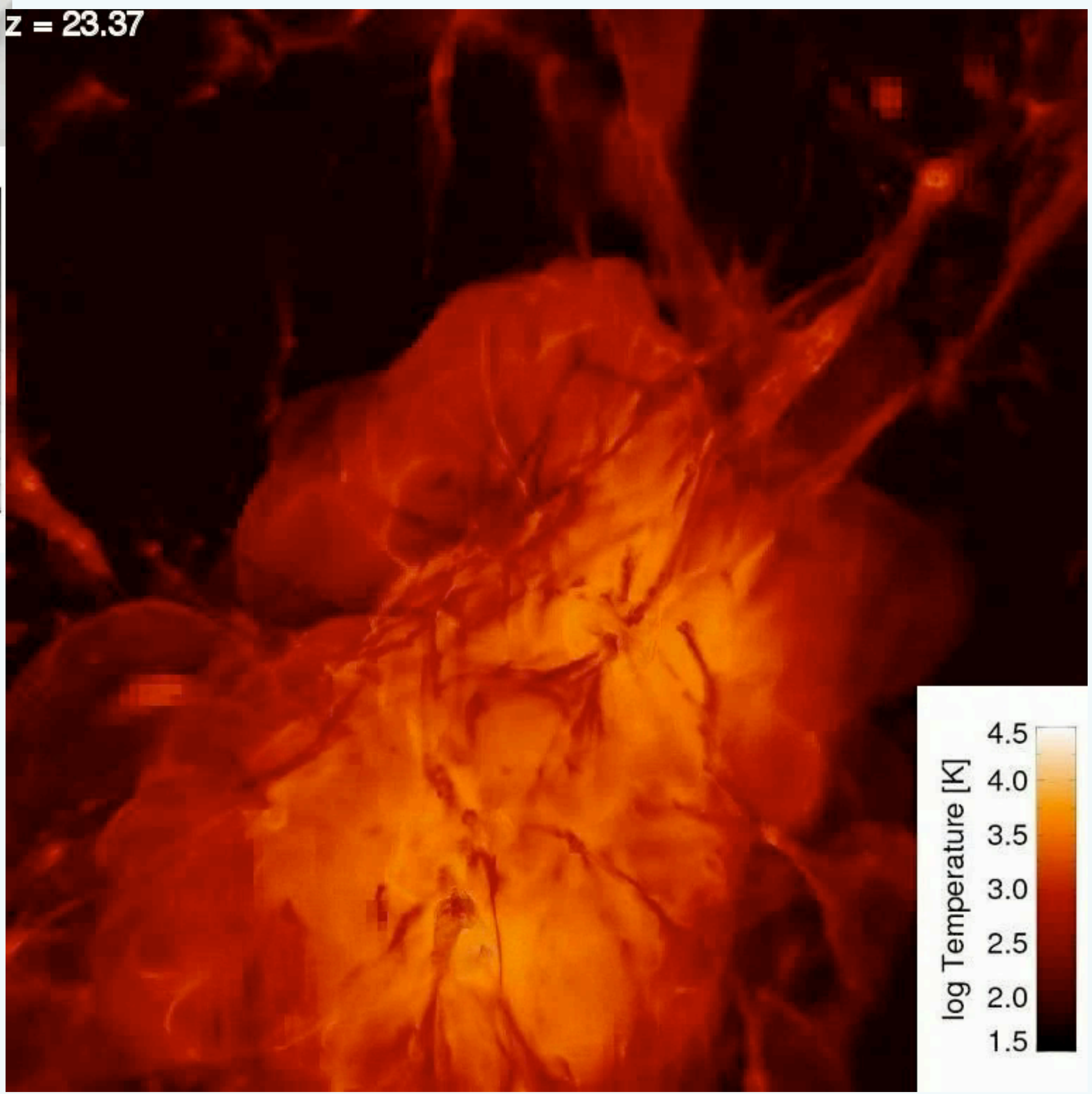

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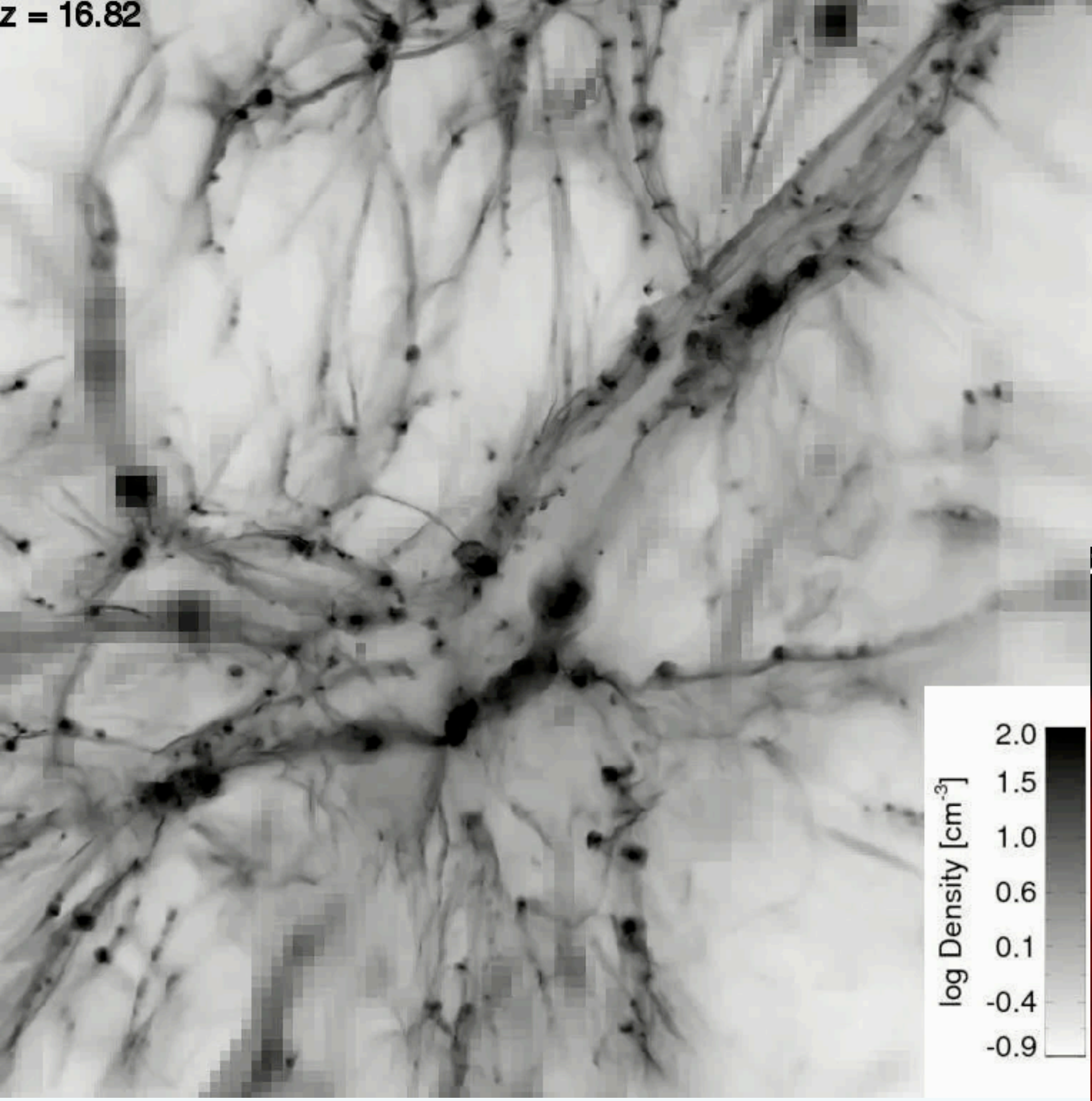
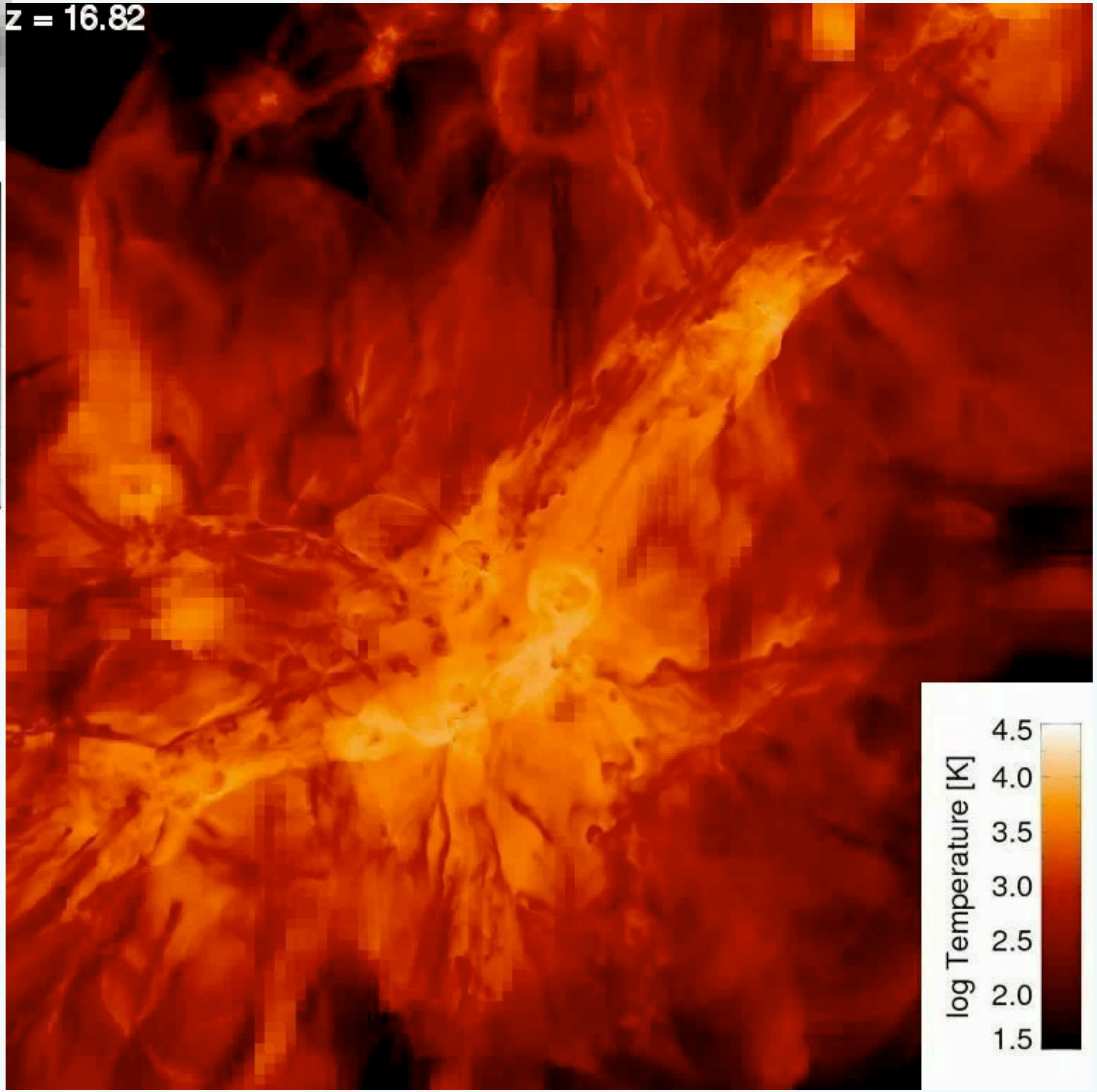
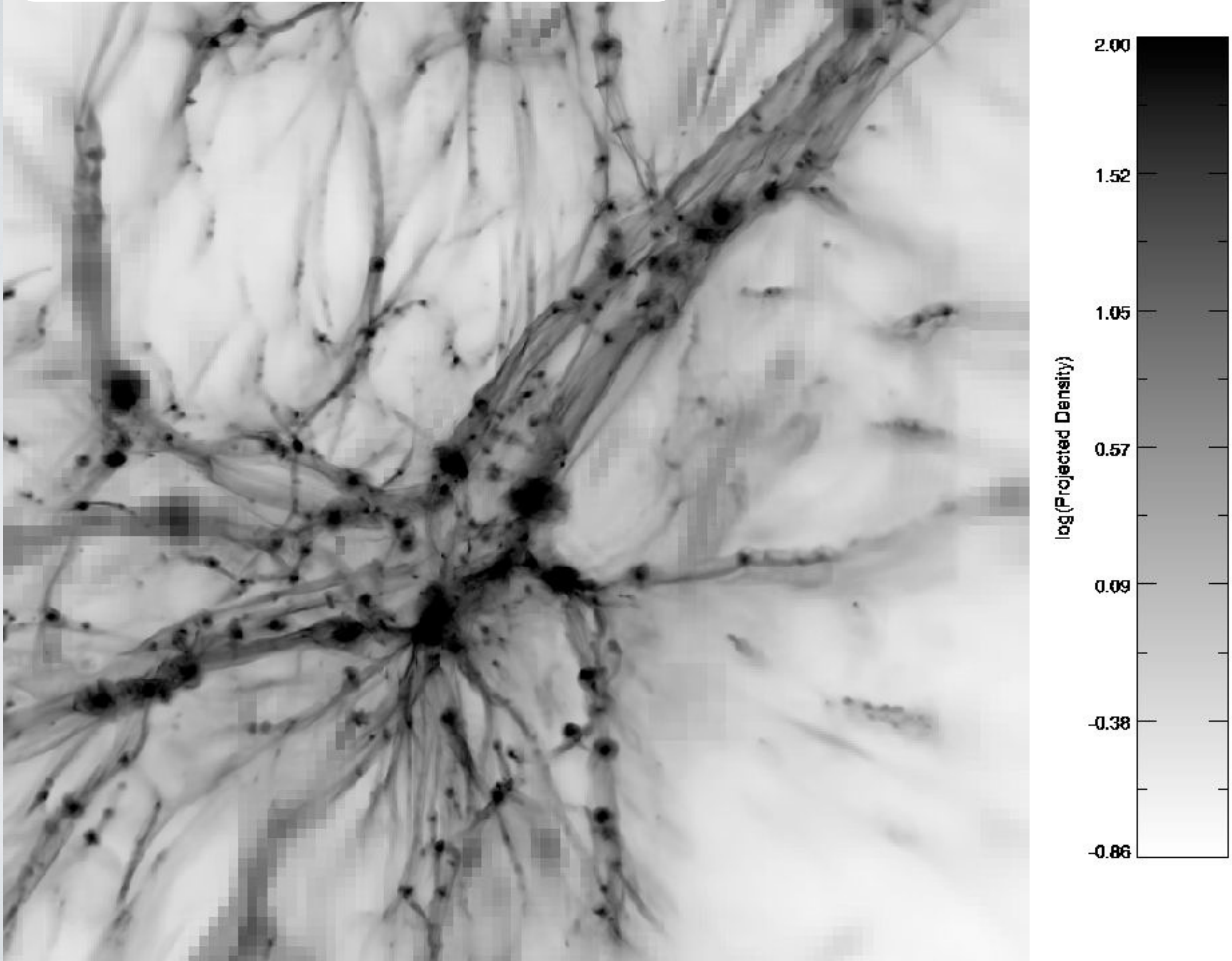




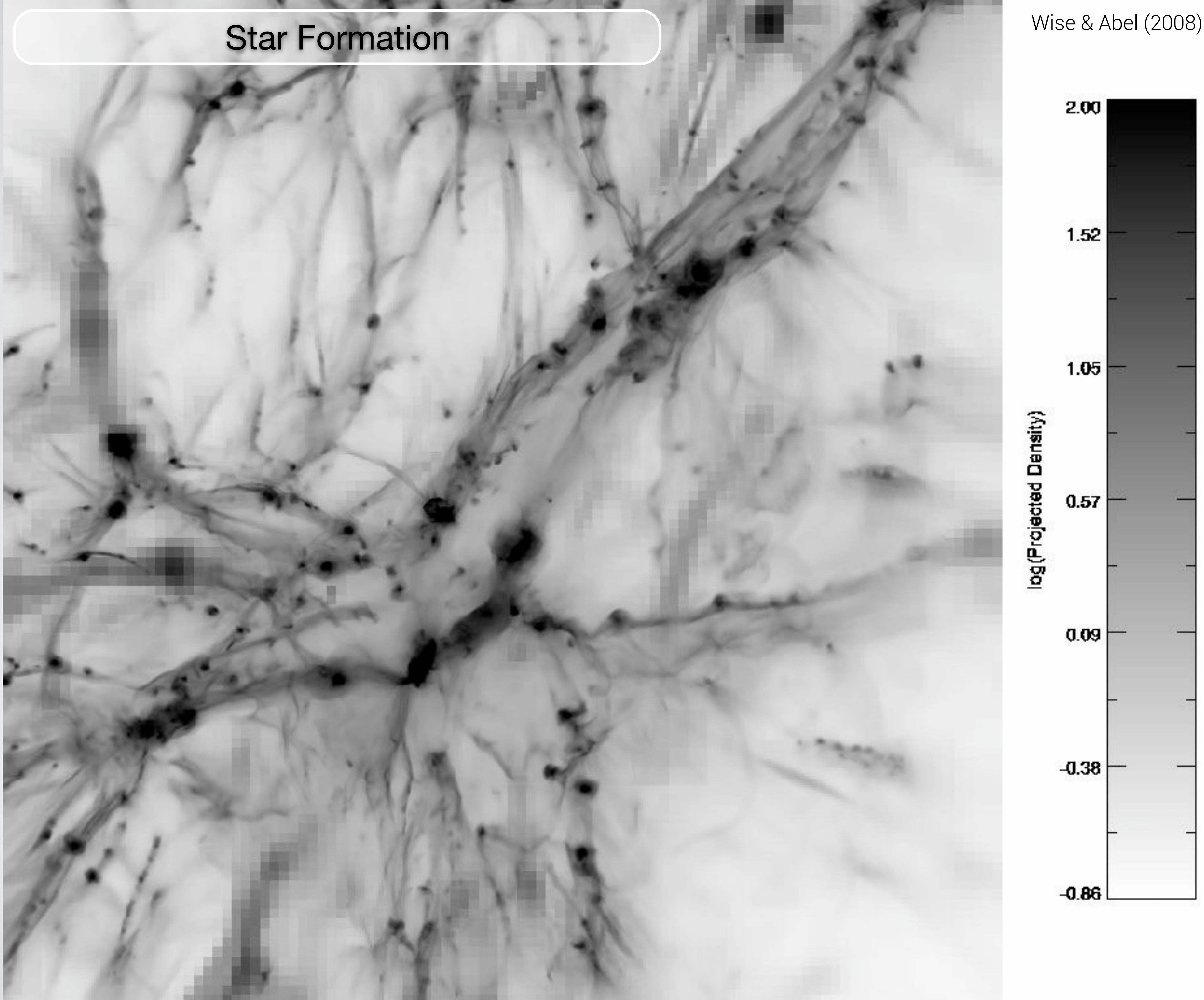
No Star Formation, H/He Cooling Only

9 physical kpc; z = 17

Wise & Abel (2008)



Star Formation



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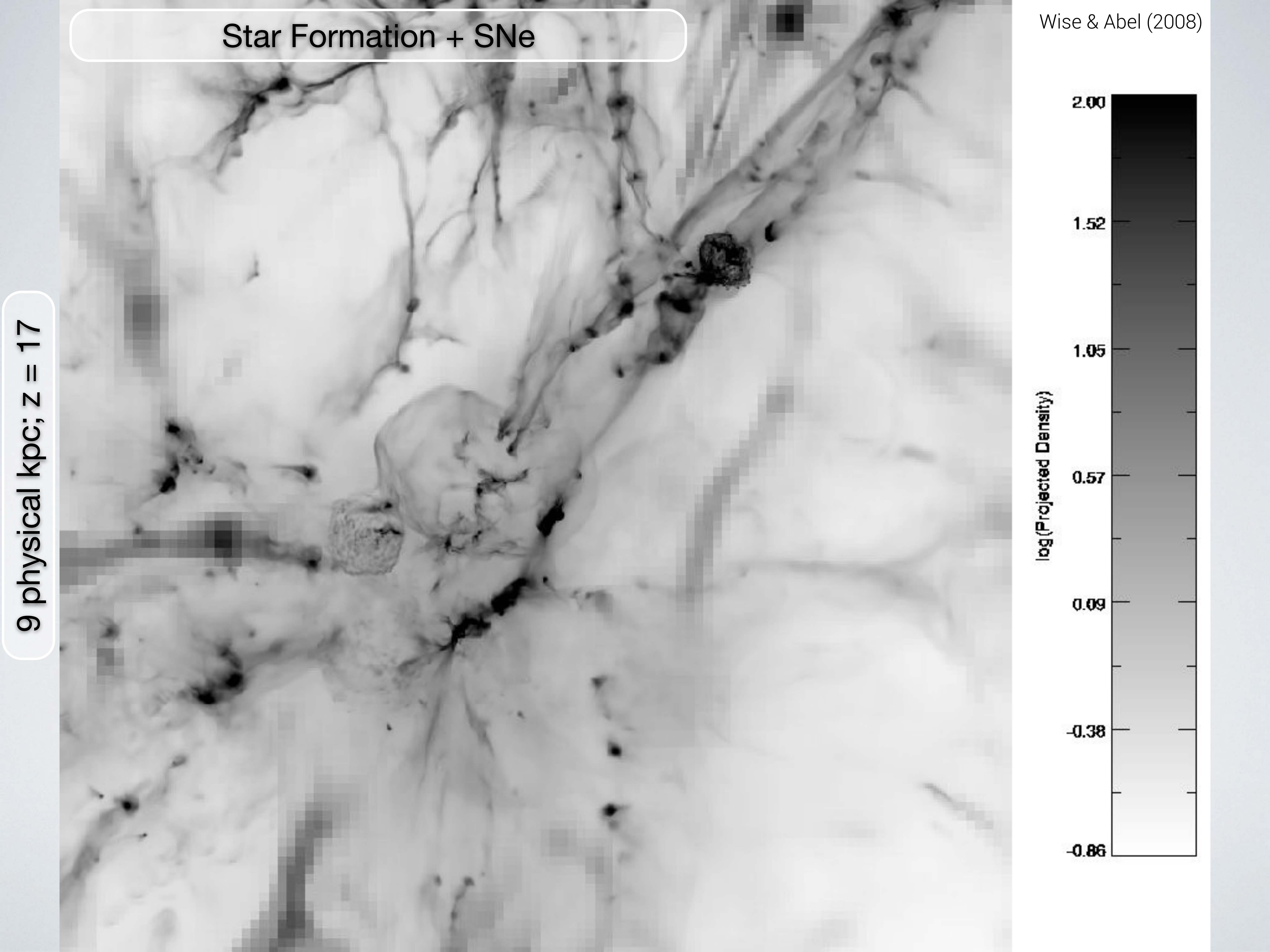
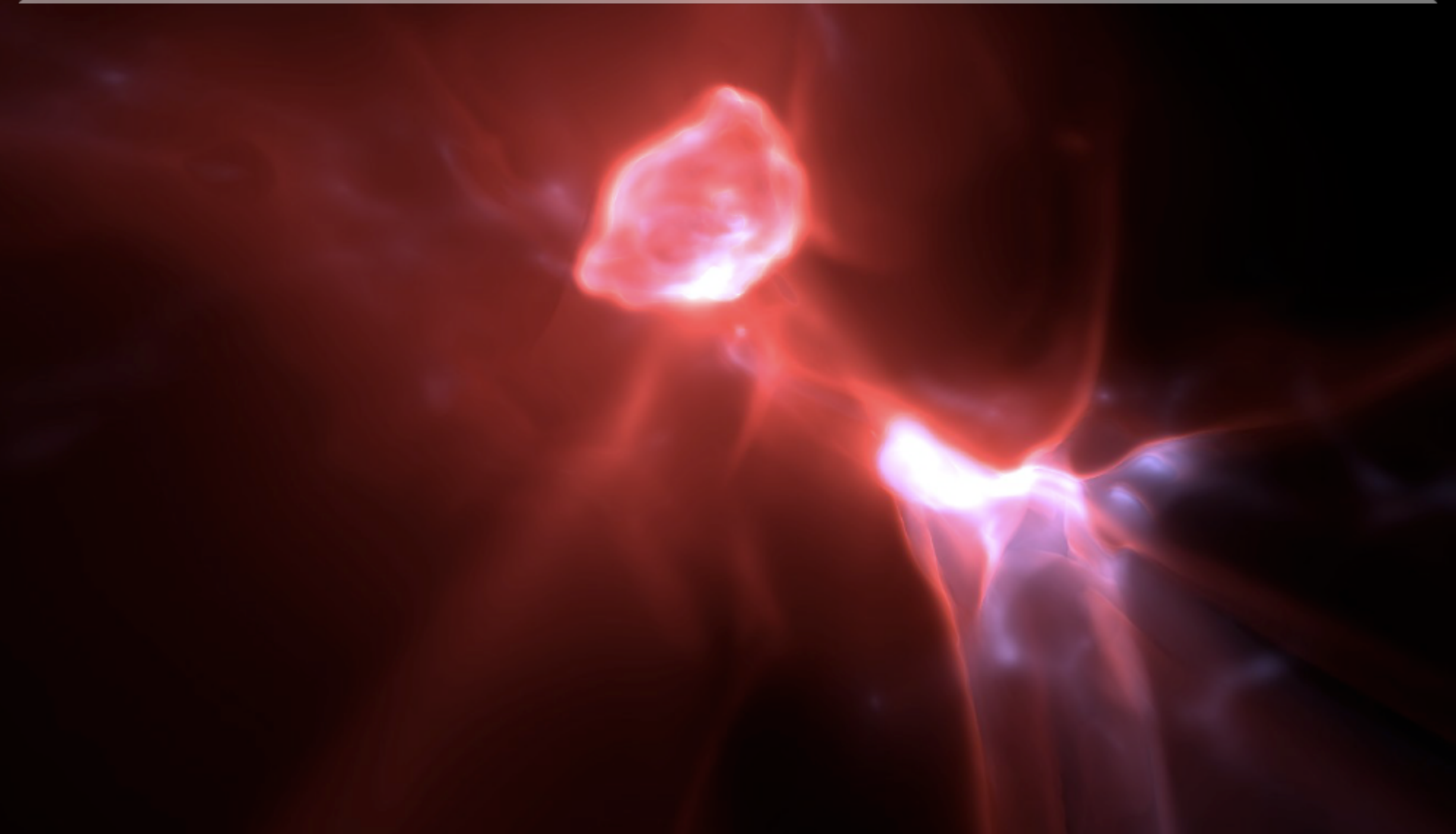
Wise & Abel (2008)



Star Formation + SNe
9 physical kpc; z = 17
Wise & Abel (2008)
2.00
1.52
1.05
0.57
0.09
-0.38
-0.86
log(Projected Density)

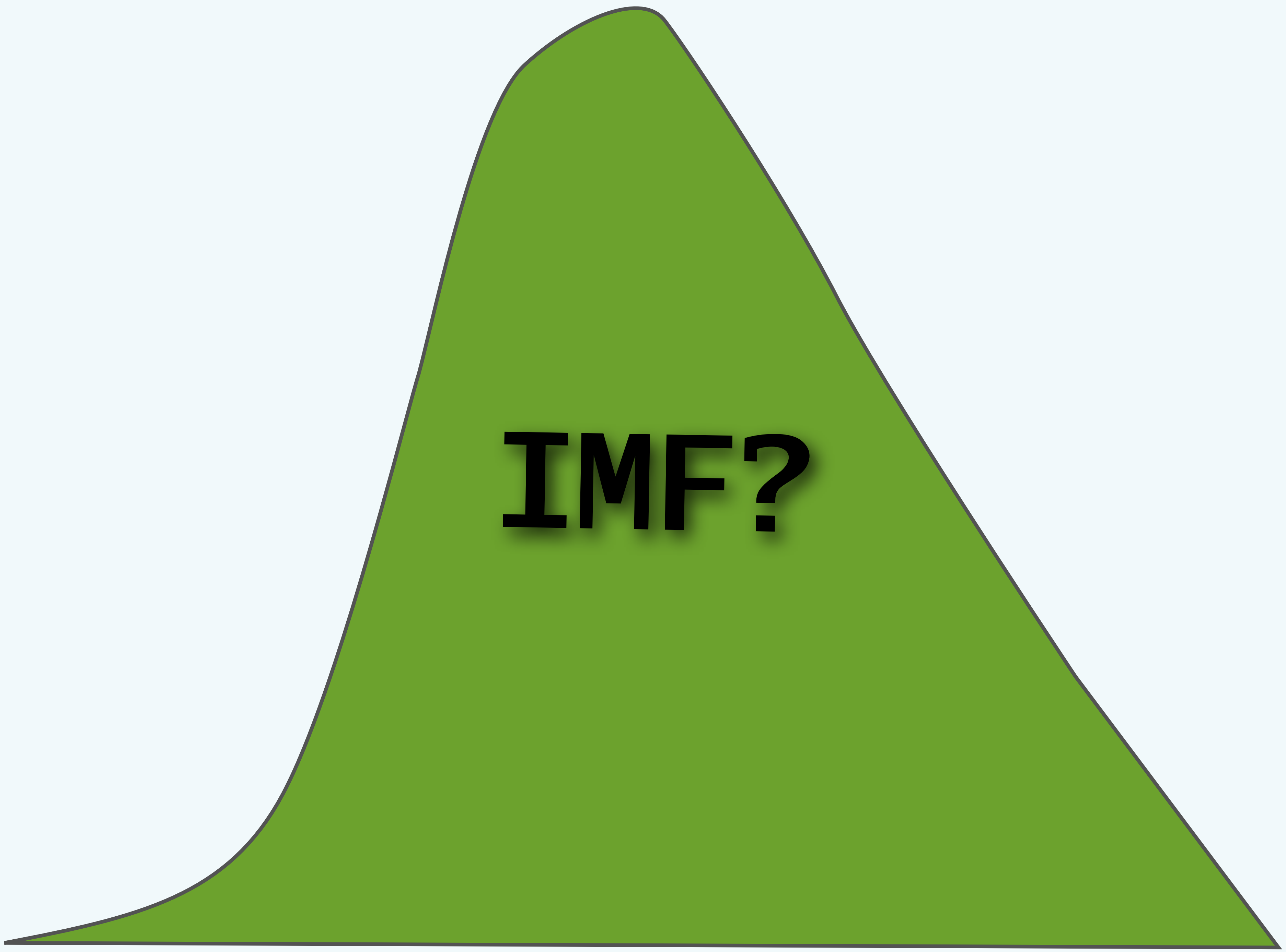
Pop III Supernovae



Barkat (1967); Bond+ (1984); Fryer+ (2001); Heger & Woosley (2002); Heger+ (2003)

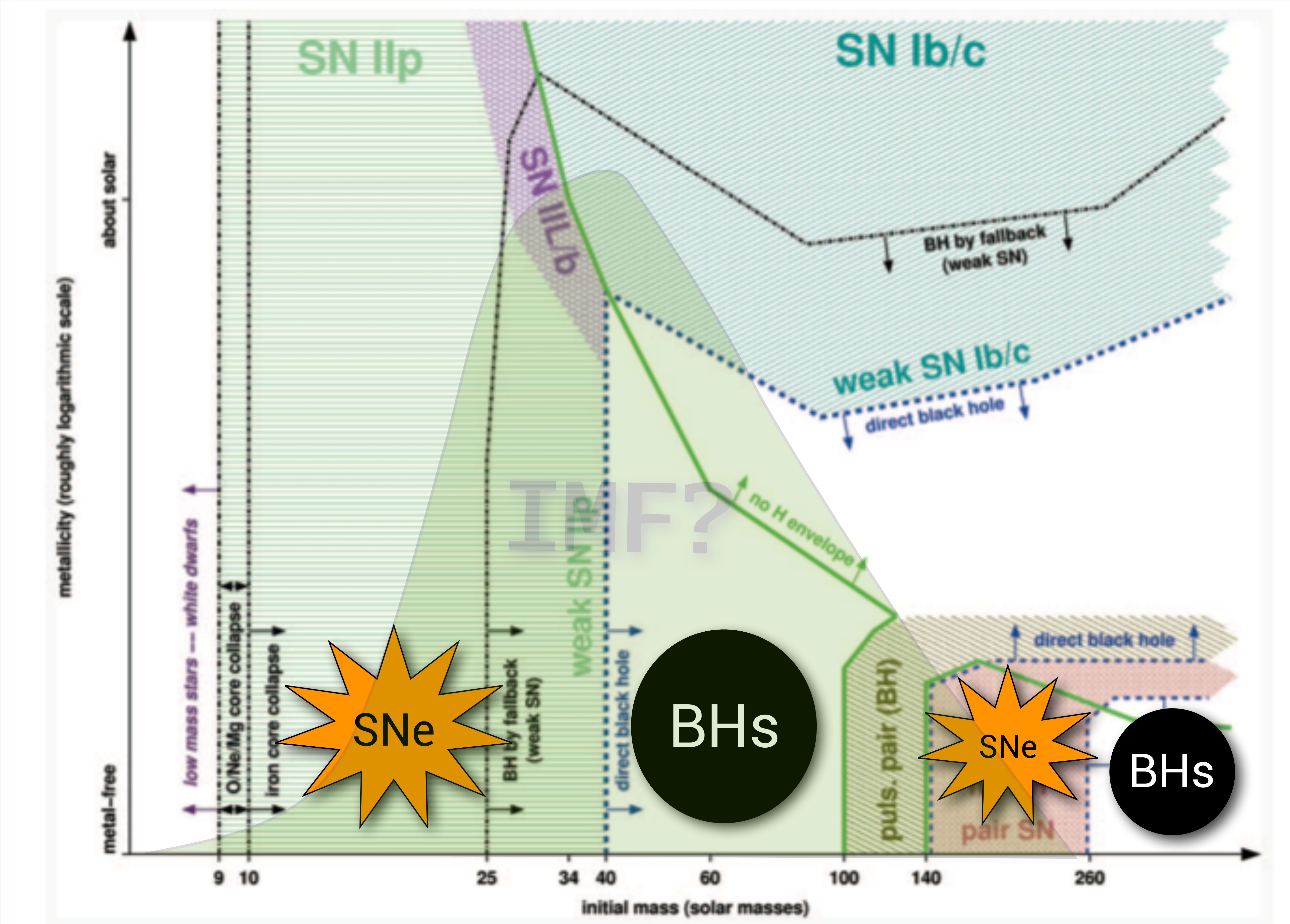
Population III Stars
Supernova Feedback

- Metal-free stars can end its life in a unique type of supernova, a pair-instability SN, between 140–260 $M_\odot$.
- Nearly all of the helium core is converted into metals (~80 $M_\odot$!)
- Chemical abundance patterns are much different than Type II SNe (C, Ca, Mg production independent of mass)


IMF?

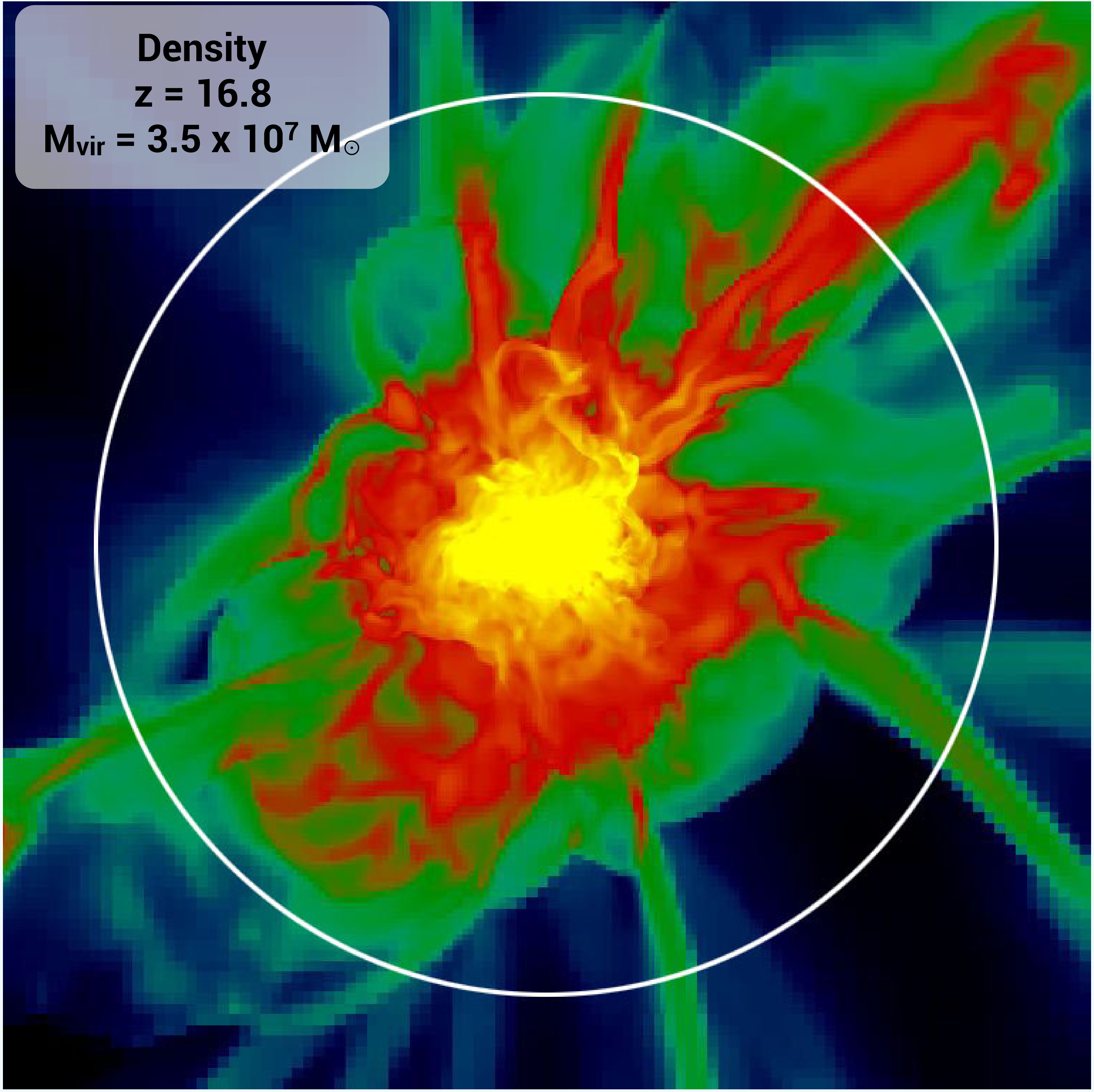
Population III stellar endpoints

Heger et al. (2003)

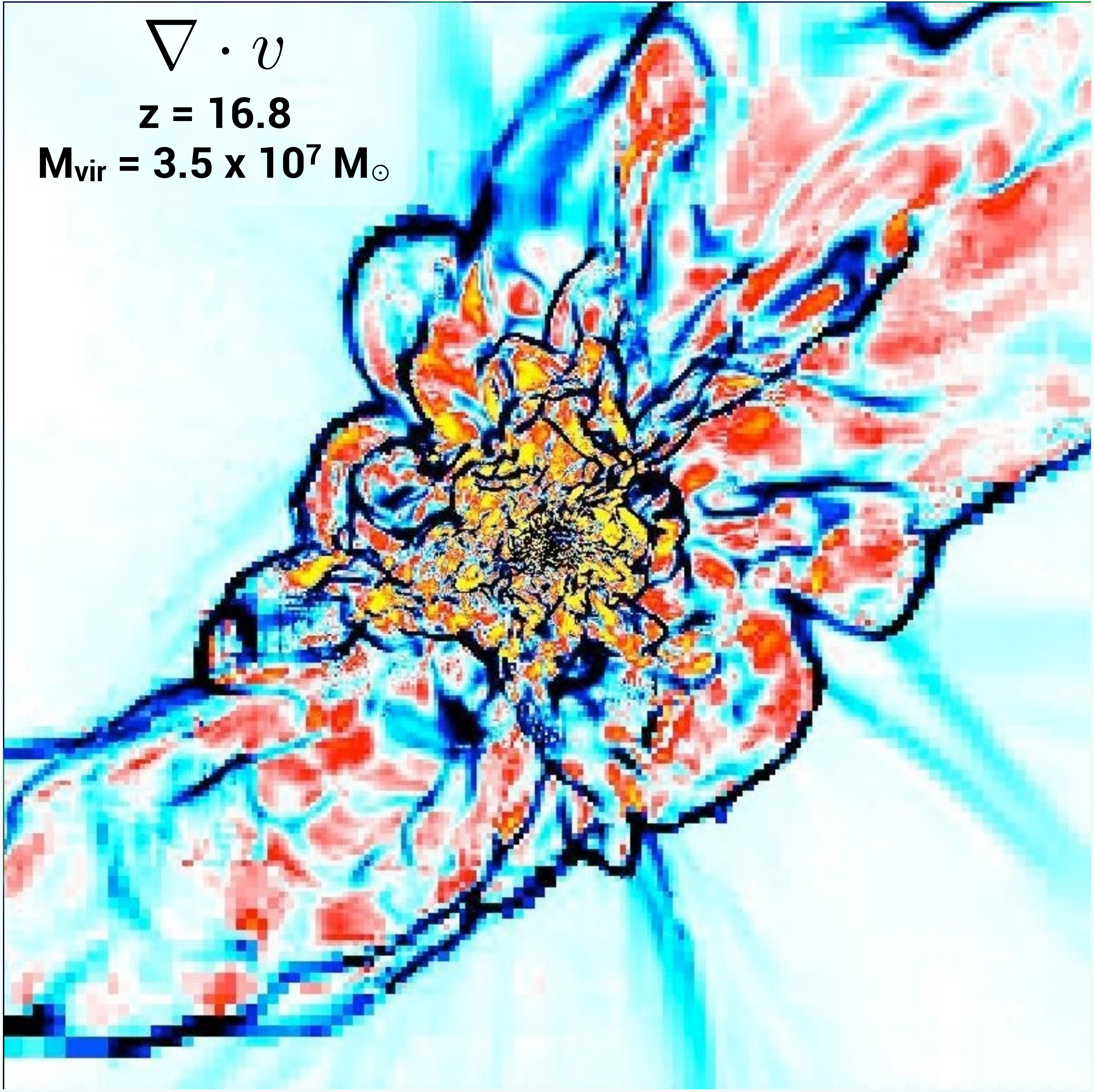


Population III Stars
Supernova Feedback – Chemical Enrichment

- (Bromm+ 2003) PISN in a cosmological setting. Removes 90% of the gas (even without radiative feedback!), pre-enriches the IGM to ≥10-4 $Z_\odot$
- (Wise+ 2008; Greif+ 2010) Nearly uniform enrichment to 10^{-3} $Z_\odot$ from Pop III supernovae in dwarf galaxies.
- Metal mixing in galaxies are driven by virial turbulence (Wise+ 2007; Greif+ 2008).
- About 60% of metals fallback into the galaxy.

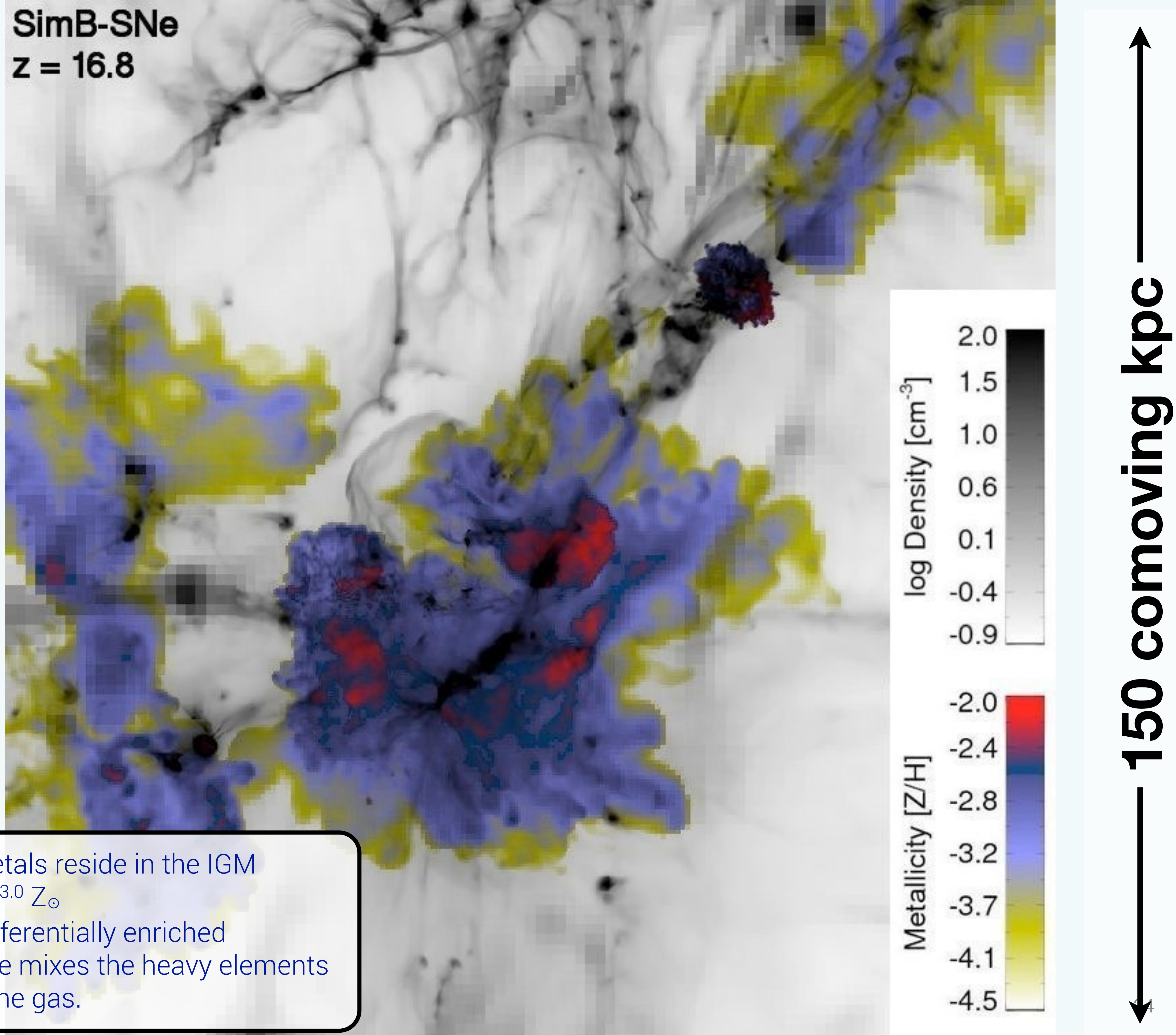


Wise & Abel (2007)



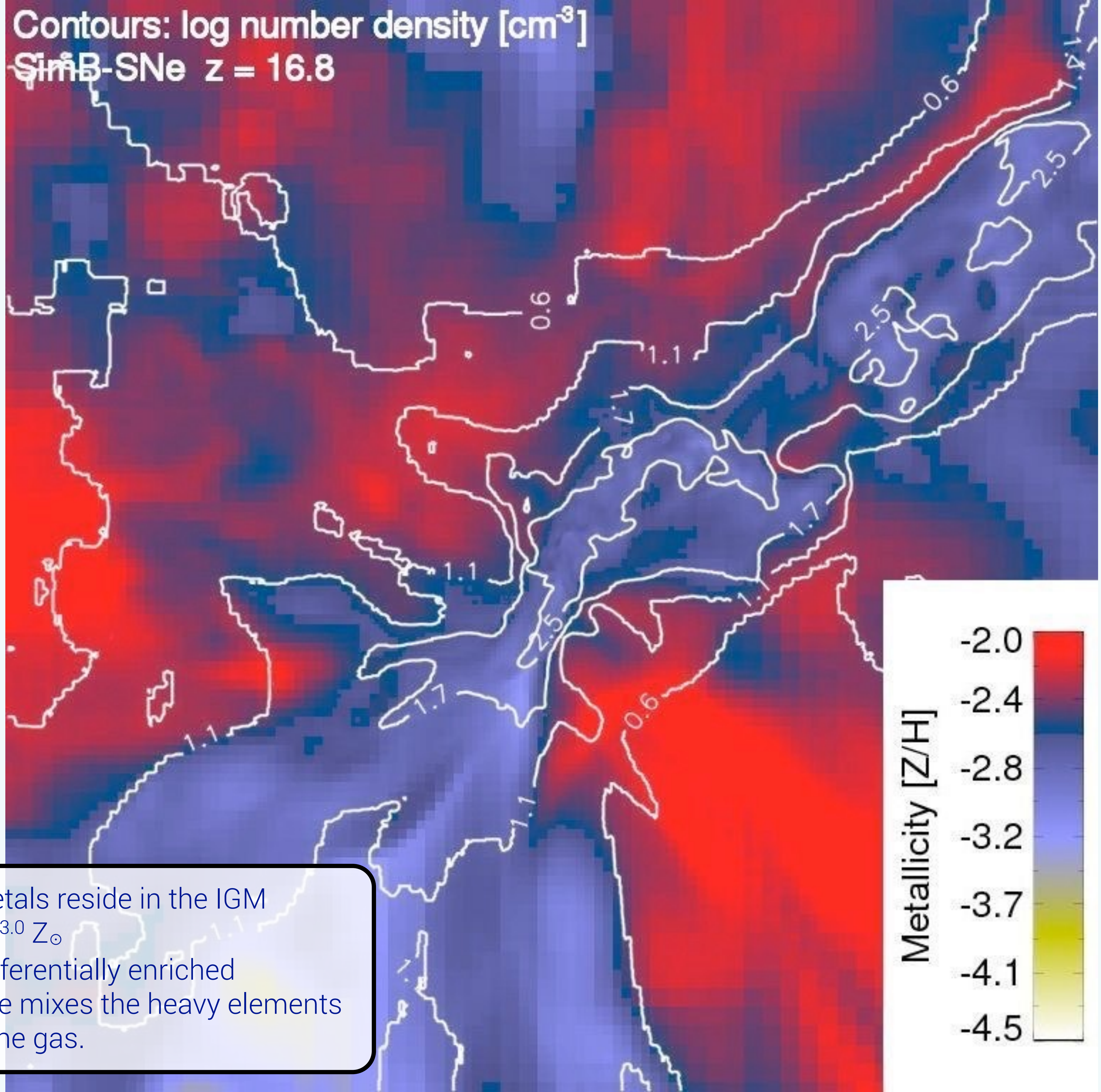
Wise & Abel (2007)

Metal Enrichment



- 40% of metals reside in the IGM
- $Z_{IGM} = 10^{-3.0}\ Z_{\odot}$
- IGM is preferentially enriched
- Turbulence mixes the heavy elements with pristine gas.

Metal Enrichment



20 comoving kpc

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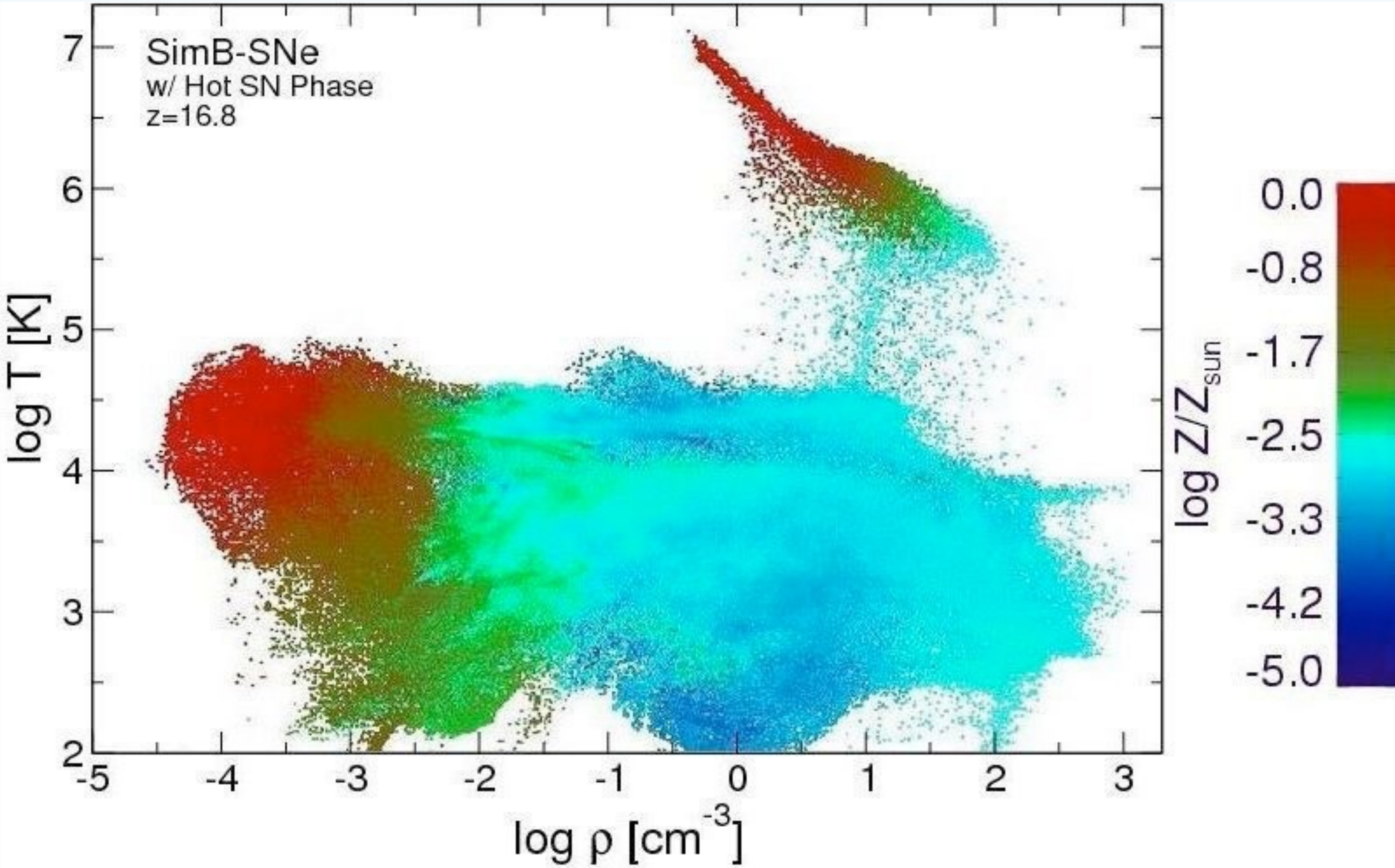
Metal Enrichment

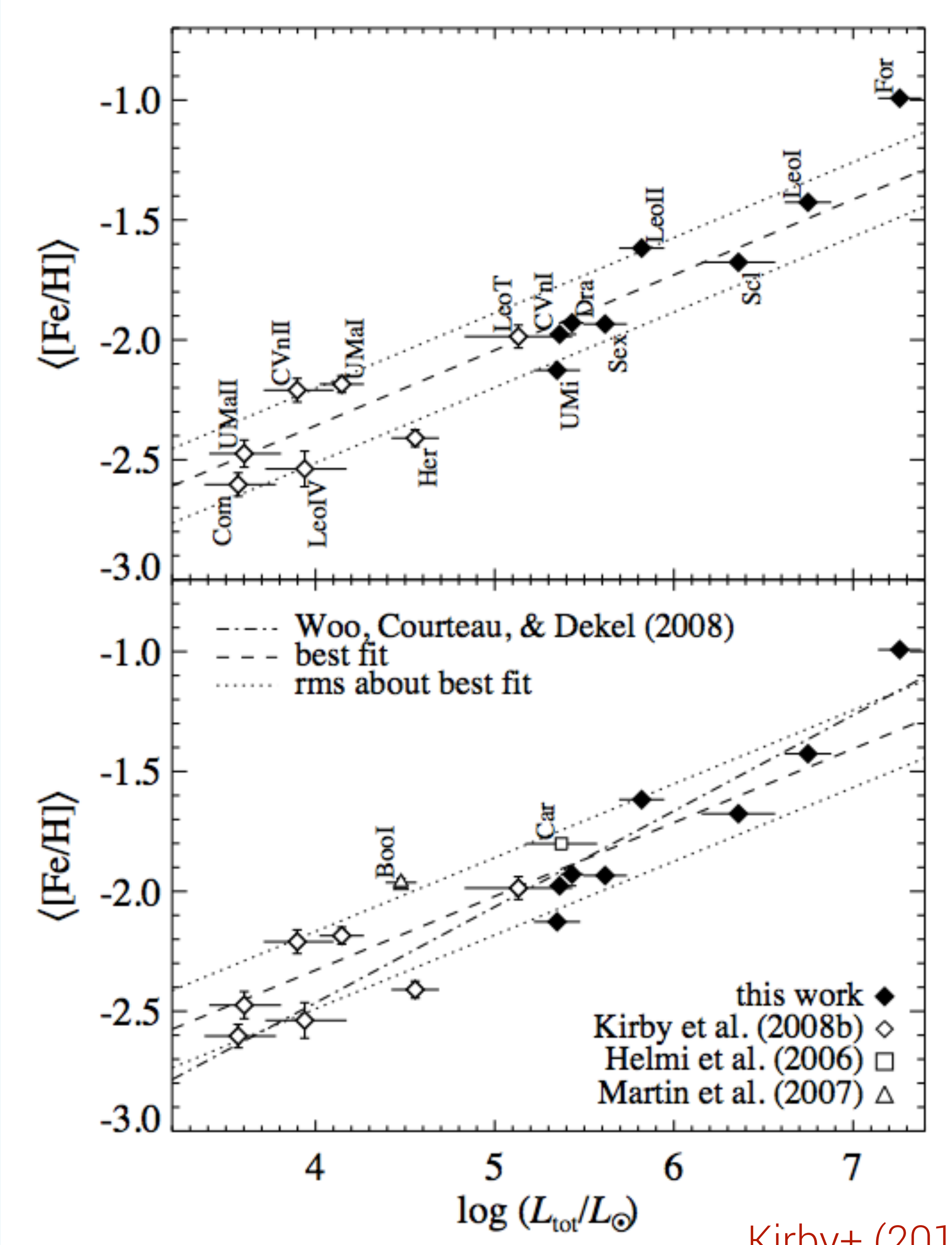


- 40% of metals reside in the IGM
- $Z_{IGM} = 10^{-3.0}\, Z_\odot$
- IGM is preferentially enriched
- Turbulence mixes the heavy elements with pristine gas.

The First Galaxies

Observations in Local Dwarfs
Z-L Relation & Metallicity Distribution Functions

- In the least luminous galaxies, there exists some enrichment.
  - *Where do these metals originate?*
  - *Were the protogalactic clouds pre-enriched by Population III stars?*
  - *What fraction of metals originate from internal star formation?*
- Can we use these observations to constrain theories and simulations of dwarf galaxy formation at high-z?



Kirby+ (2011)

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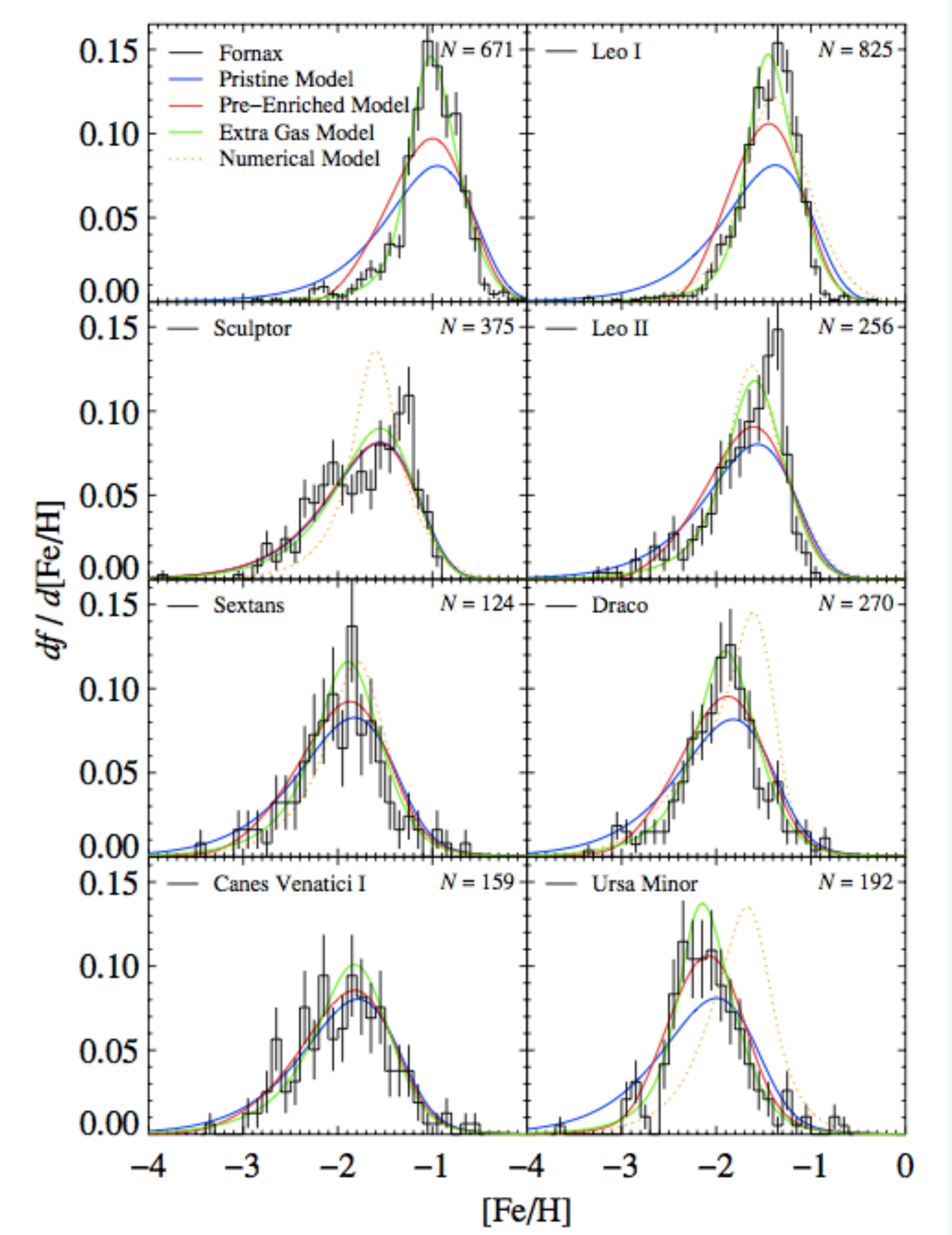


Kirby+ (2011)

Numerical Approach
Cosmological Simulations – 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 ($M \sim 10^5 M_\odot$)
  - Accurate model of star formation and feedback – smaller halos are more susceptible to feedback effects.

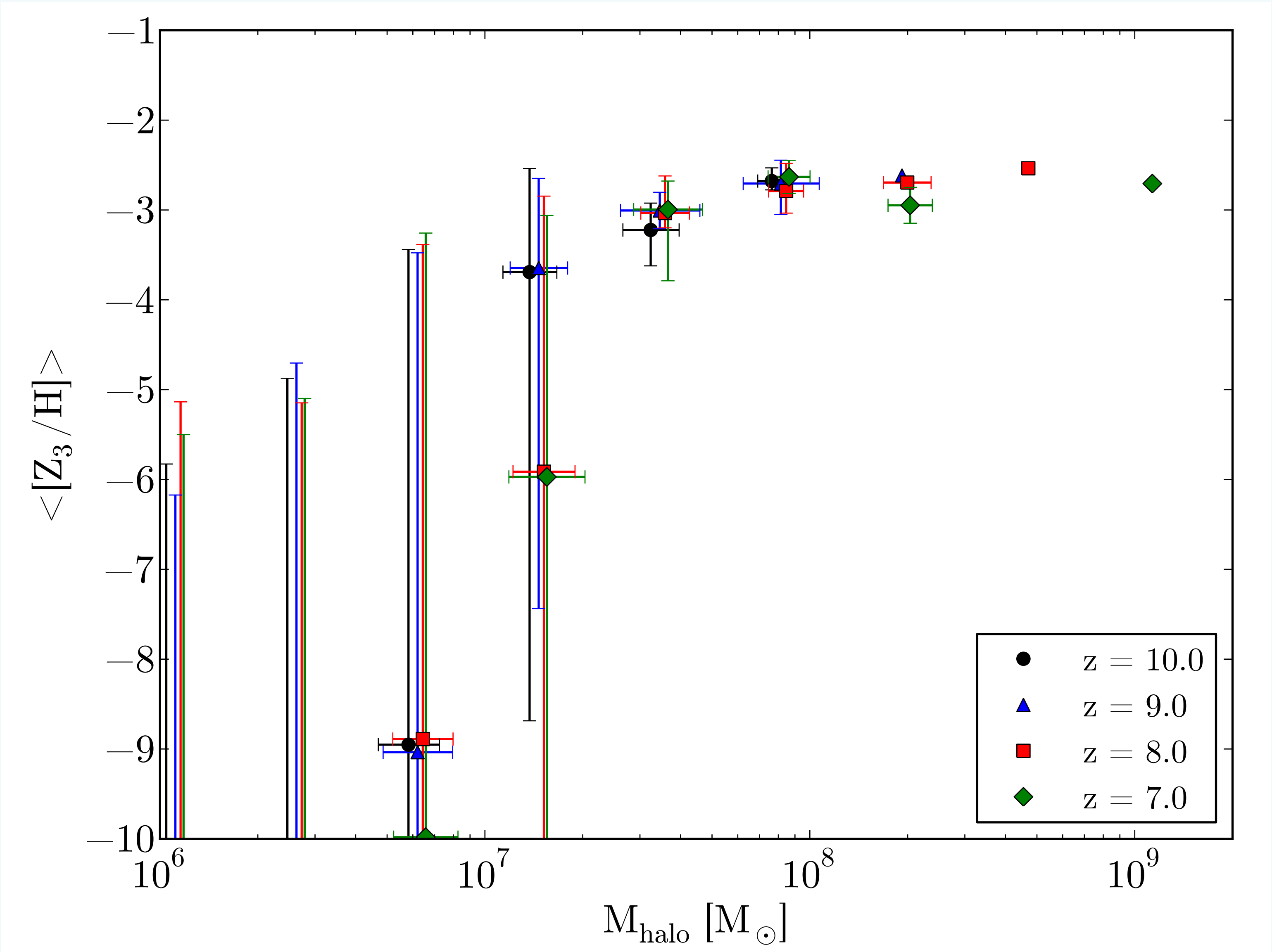
- Approaches:
  - Small-scale boxes (< 3 comoving Mpc^3)
  - Adaptive mesh refinement (AMR)
  - Distinct modes of Population II and III star formation and feedback
  - Radiative and supernovae feedback from both populations

Wise et al. (2012ab)

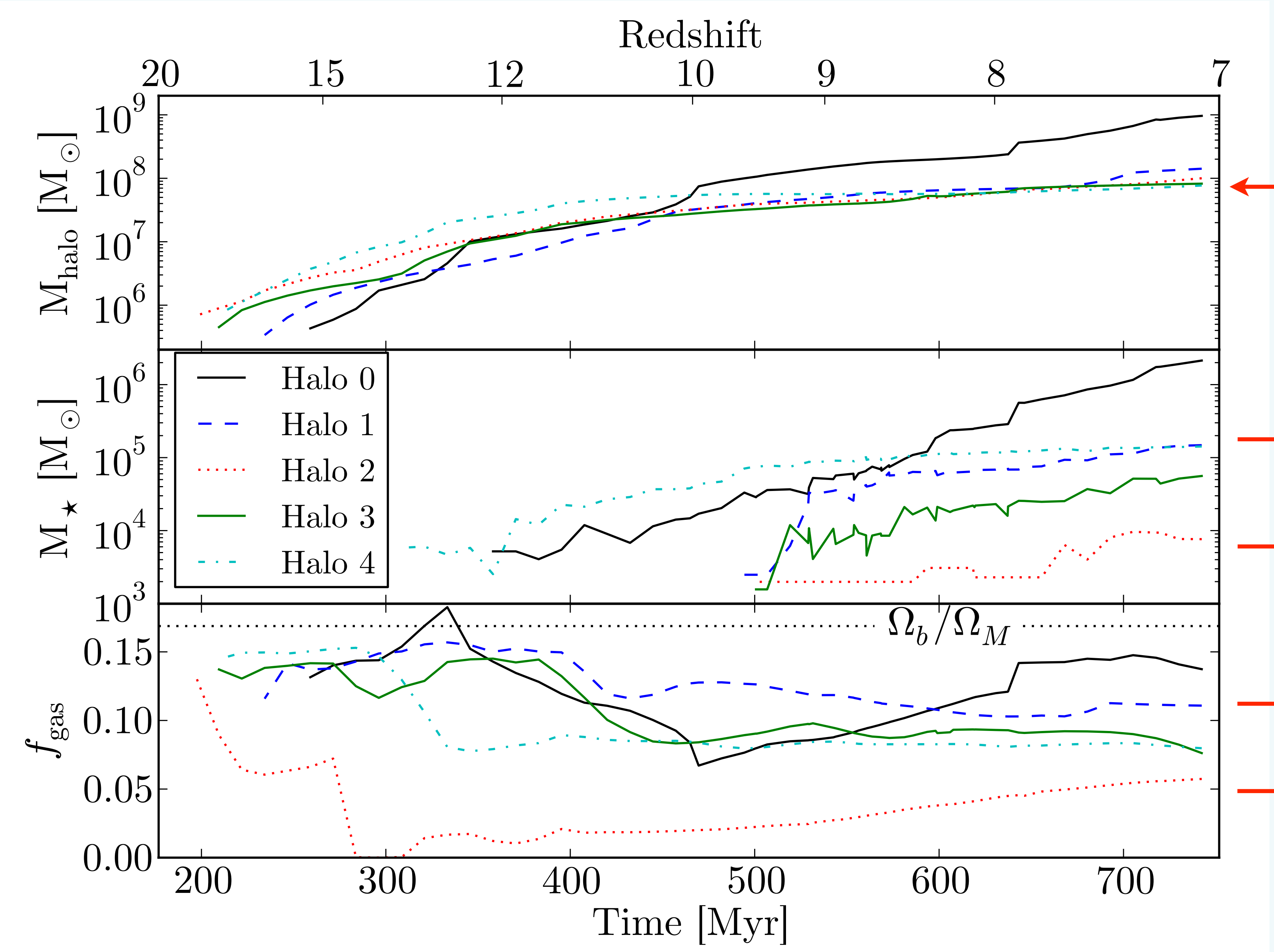
Wise et al. (2012ab)

High-Redshift Dwarf Galaxies
Primordial Enrichment

- Minihaloes: Varied stellar endpoints, creating BHs and SNe, result in a mix of pristine and enriched halos.
- Atomic cooling halos ($T_{vir} \geq 10^4$ K → $M_{vir} \geq 10^8\ M_\odot$): All have been enriched by Pop III SNe to a metallicity floor of [Z/H] ~ −3.
- How sensitive is the metallicity floor on the Pop III IMF?



High-Redshift Dwarf Galaxies
Mass Accretion History



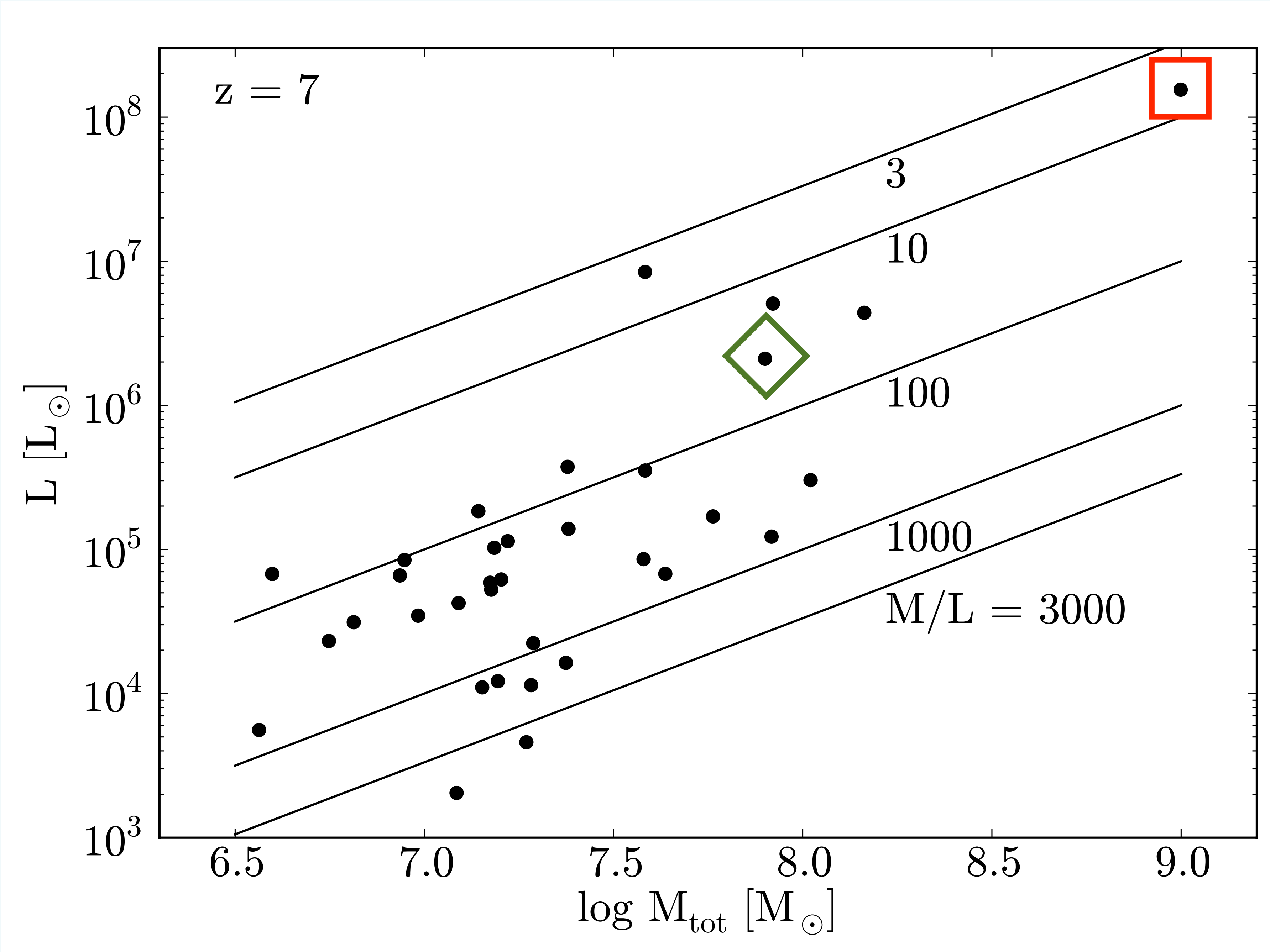
Galaxies with similar halo masses can differ in stellar mass by an order of magnitude!

$M_\star/M_{gas}$ = 0.01–0.05

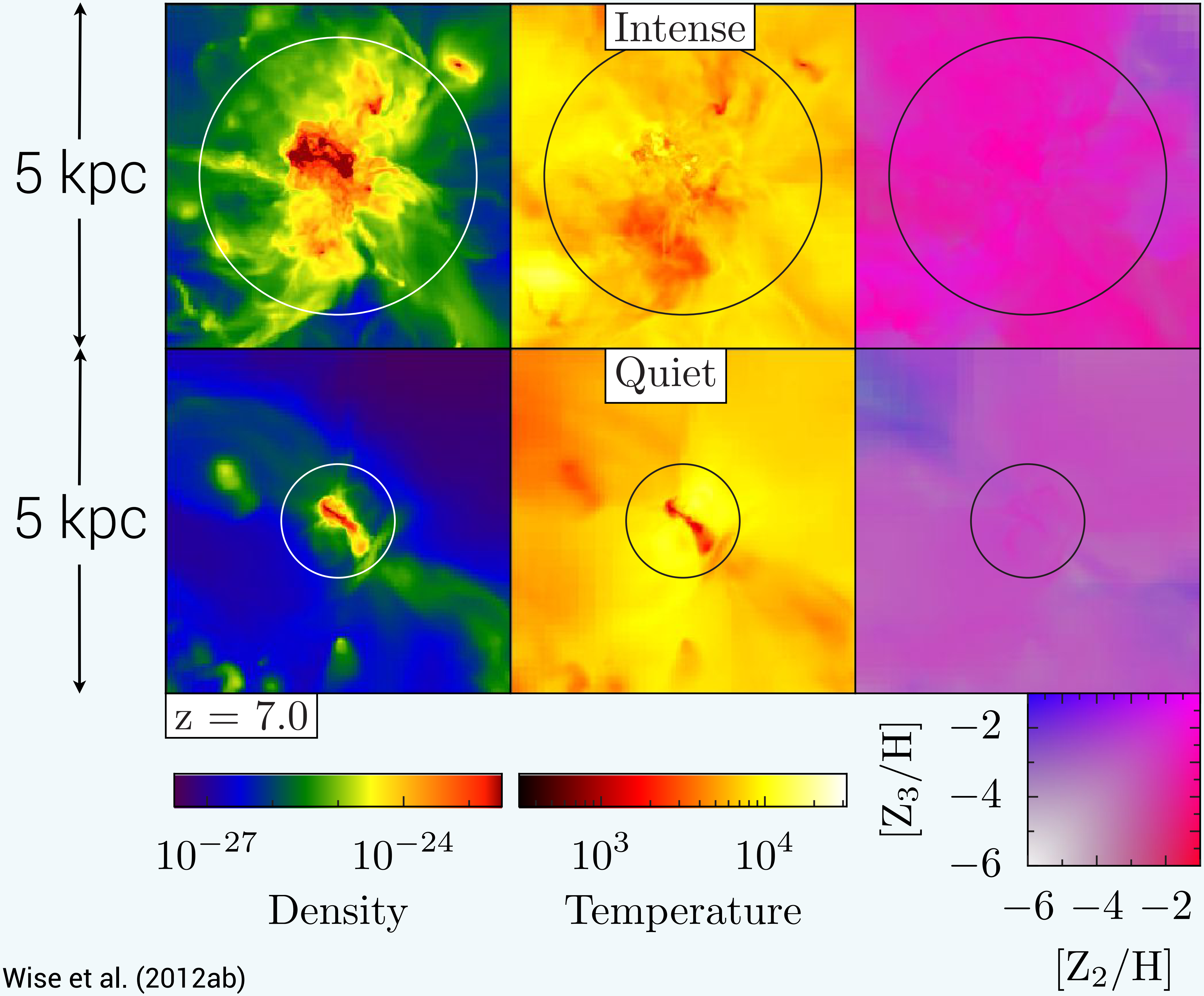
- The initial buildup of the dwarfs are regulated by prior Pop III feedback and radiative feedback from nearby galaxies.

High-Redshift Dwarf Galaxies

Mass-to-Light Ratios

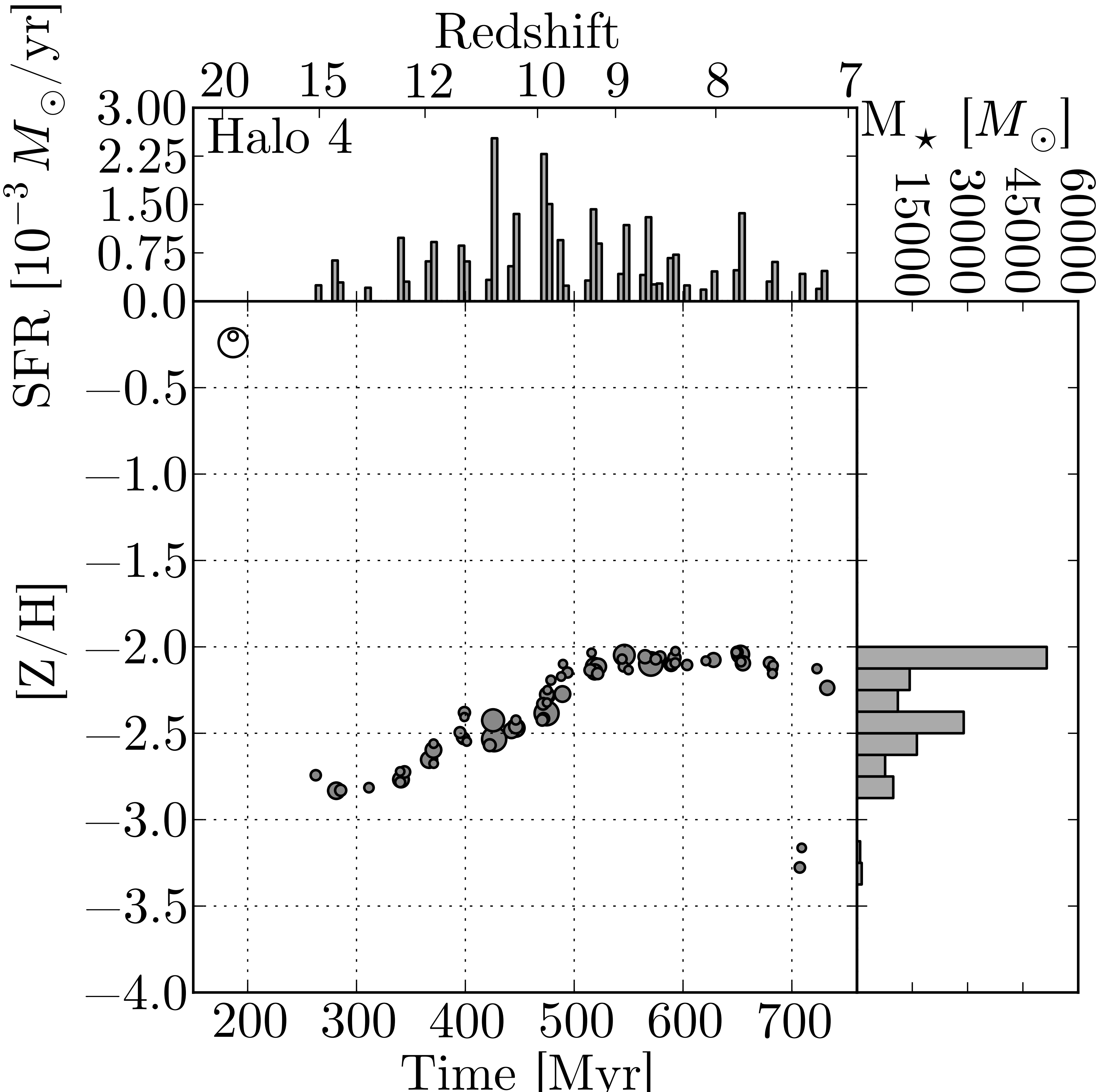


- Scatter at low-mass ($M < 10^8\ M_\odot$) caused by environment and different Pop III endpoints.

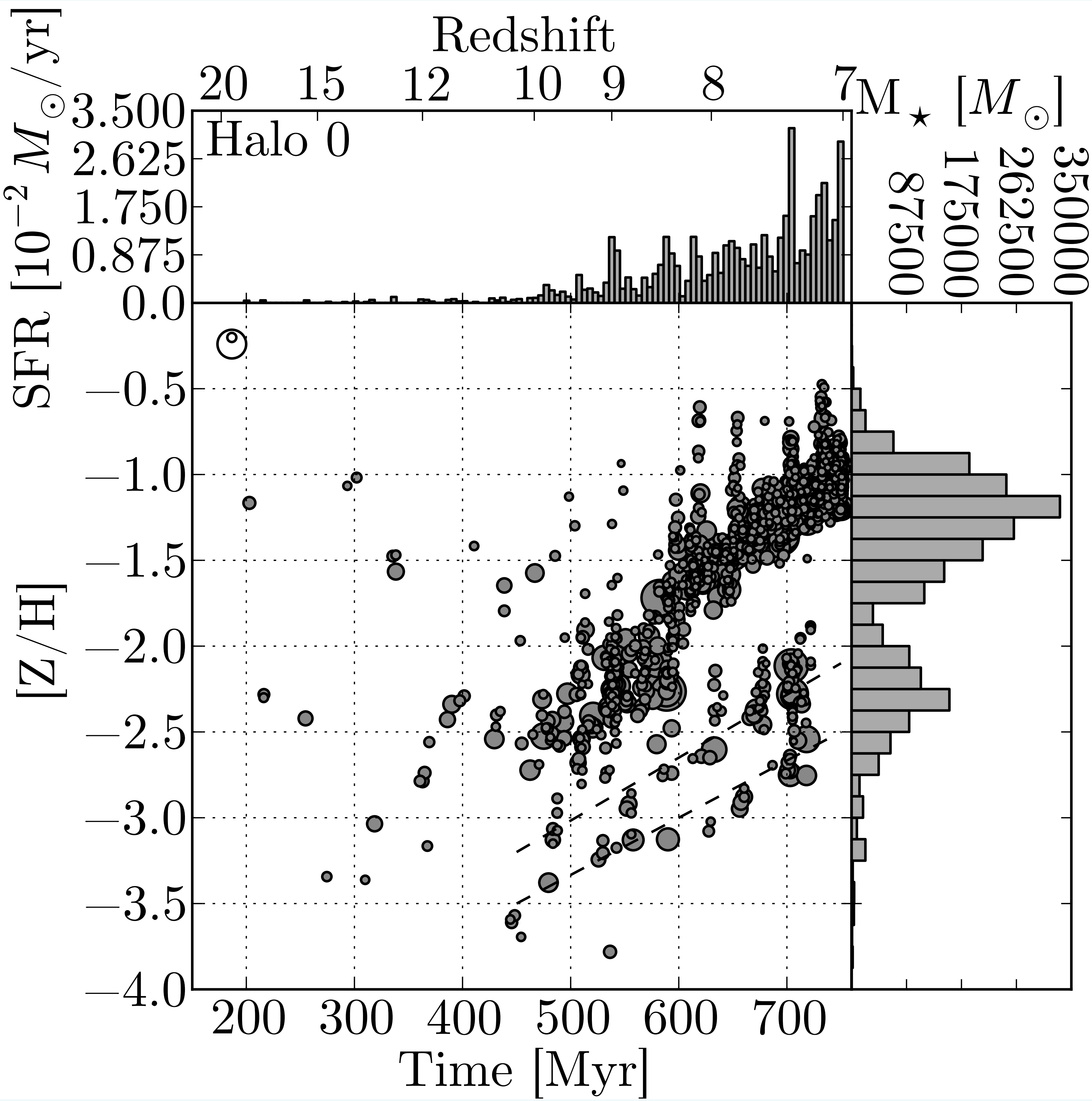


Wise et al. (2012ab)

- Isolated halo (8e7 $M_\odot$) at $z = 7$
- Quiet recent merger history
- Disky, not irregular
- Steady increase in [Z/H] then plateau
- No stars with [Z/H] < −3 from Pop III metal enrichment



- Most massive halo (10^9 $M_\odot$) at $z = 7$
- Undergoing a major merger
- Bi-modal metallicity distribution function
- 2% of stars with [Z/H] < −3
- Induced SF makes less metal-poor stars formed near SN blastwaves

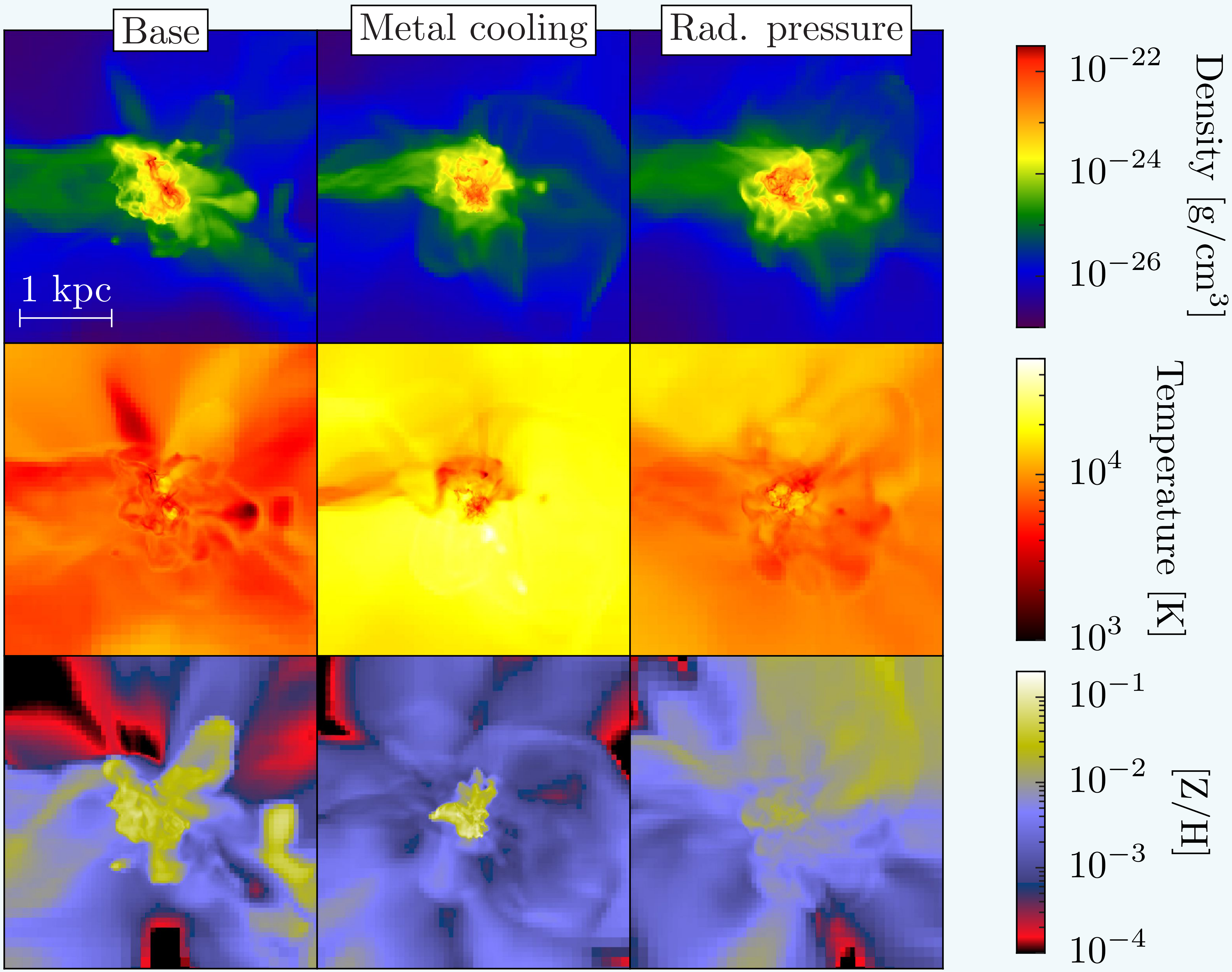


Varying the subgrid models

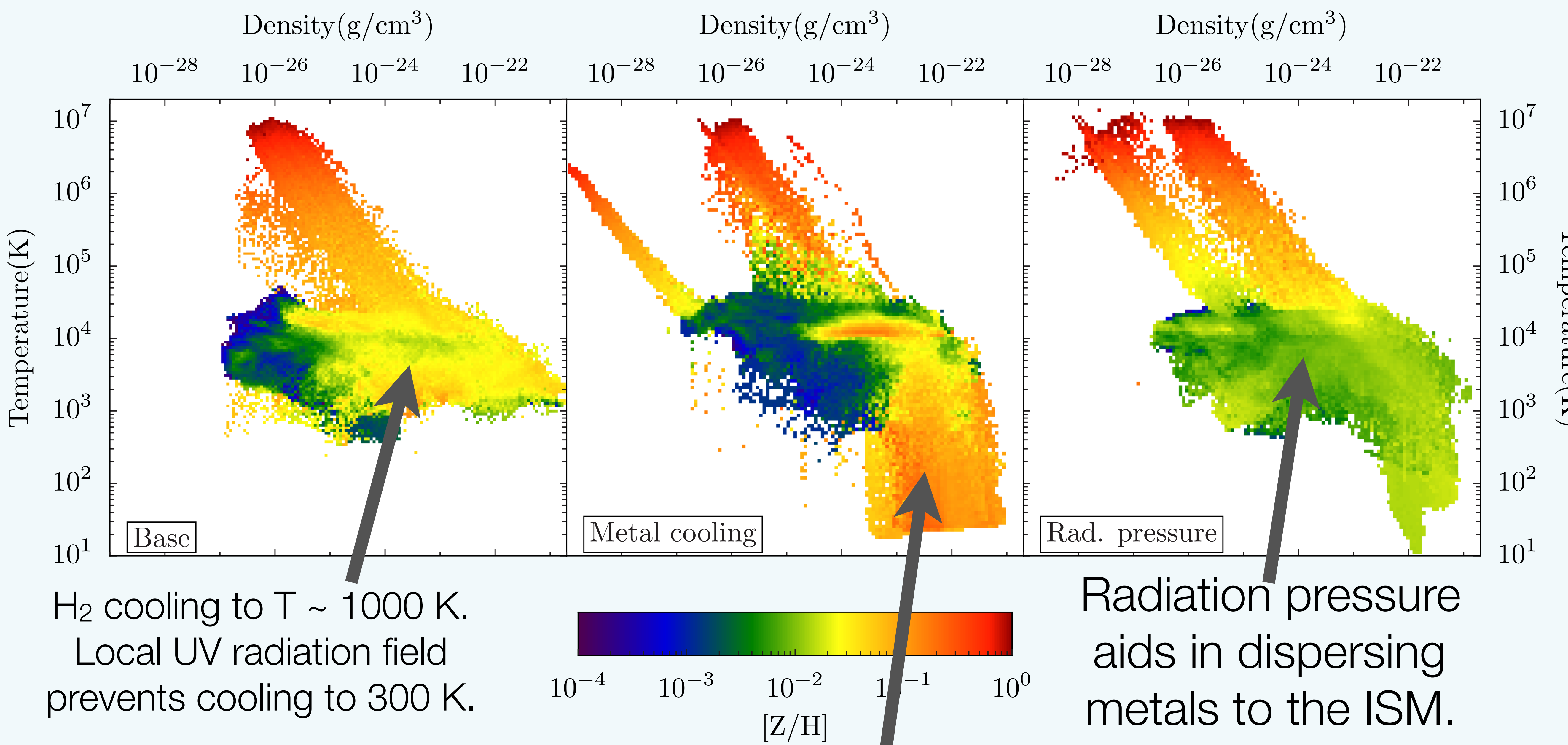
$M_{char} = 40\ M_\odot$	No H_2 cooling (i.e. minihalos)
$Z_{crit} = 10^{-5}$ and $10^{-6}\ Z_\odot$	No Pop III SF
Redshift dependent Lyman-Werner background (LWB)	Supersonic streaming velocities
LWB + Metal cooling	LWB + Metal cooling + enhanced metal ejecta (y=0.025)
LWB + Metal cooling + radiation pressure	

Effects of radiation pressure

M_{vir} = 3 x 10^8 $M_\odot$ galaxy at z = 8



Effects of radiation pressure
Avg. metallicities in density-temperature space

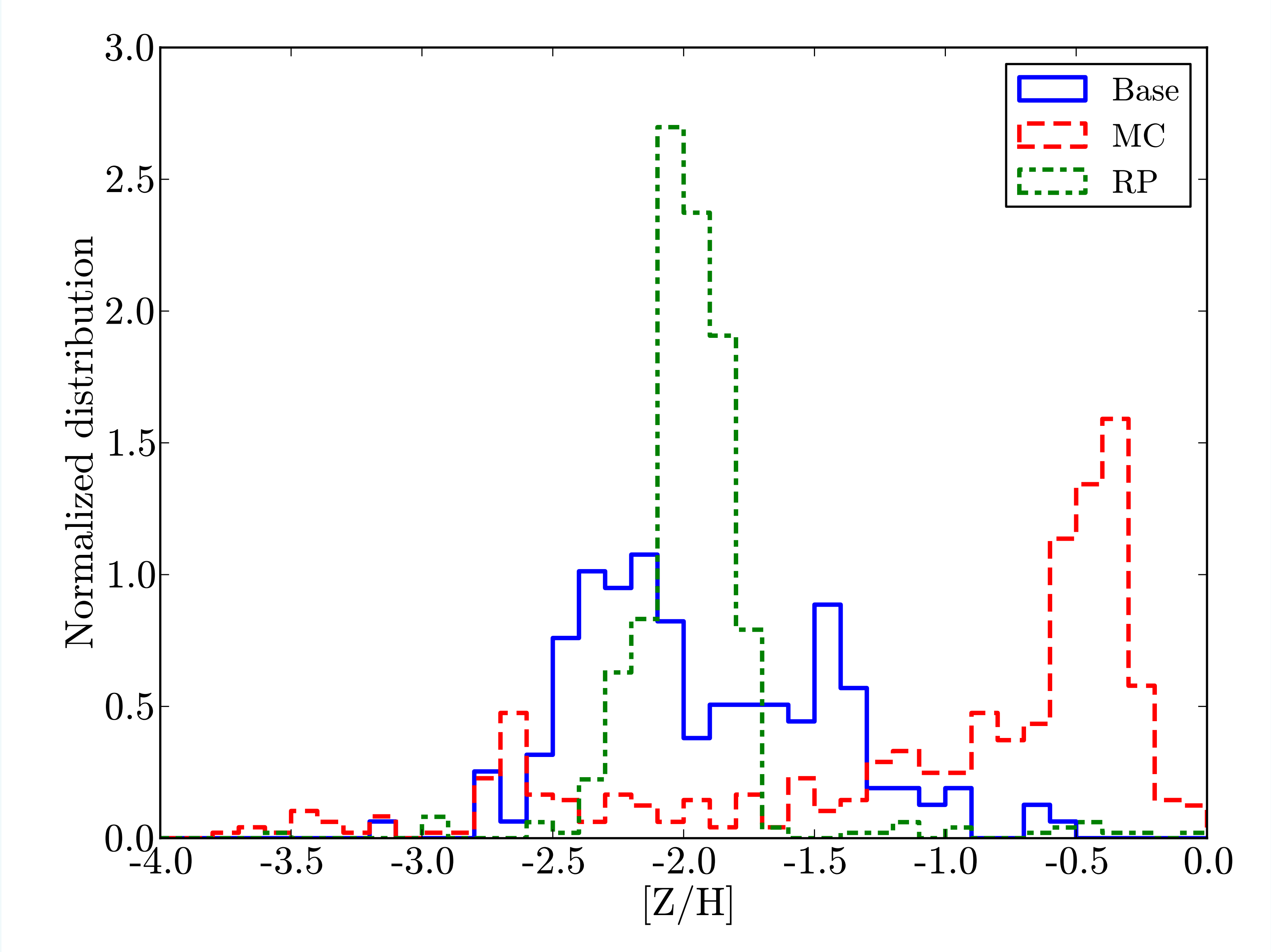


H_2 cooling to T ~ 1000 K. Local UV radiation field prevents cooling to 300 K.

Radiation pressure aids in dispersing metals to the ISM.

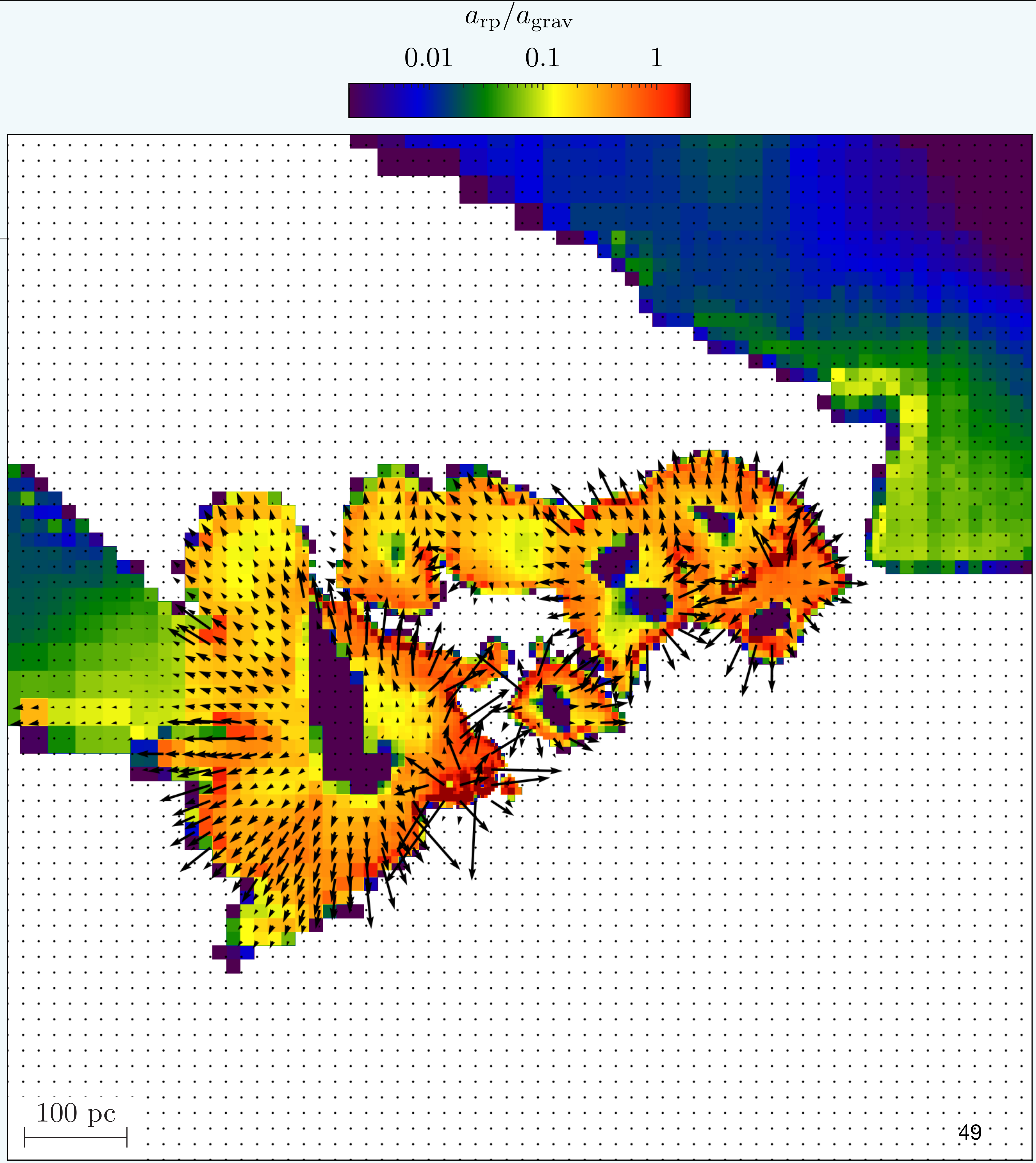
Metal-rich ejecta “trapped” in cold, dense gas. Little mixing.

Effects of radiation pressure
Metallicity distribution functions

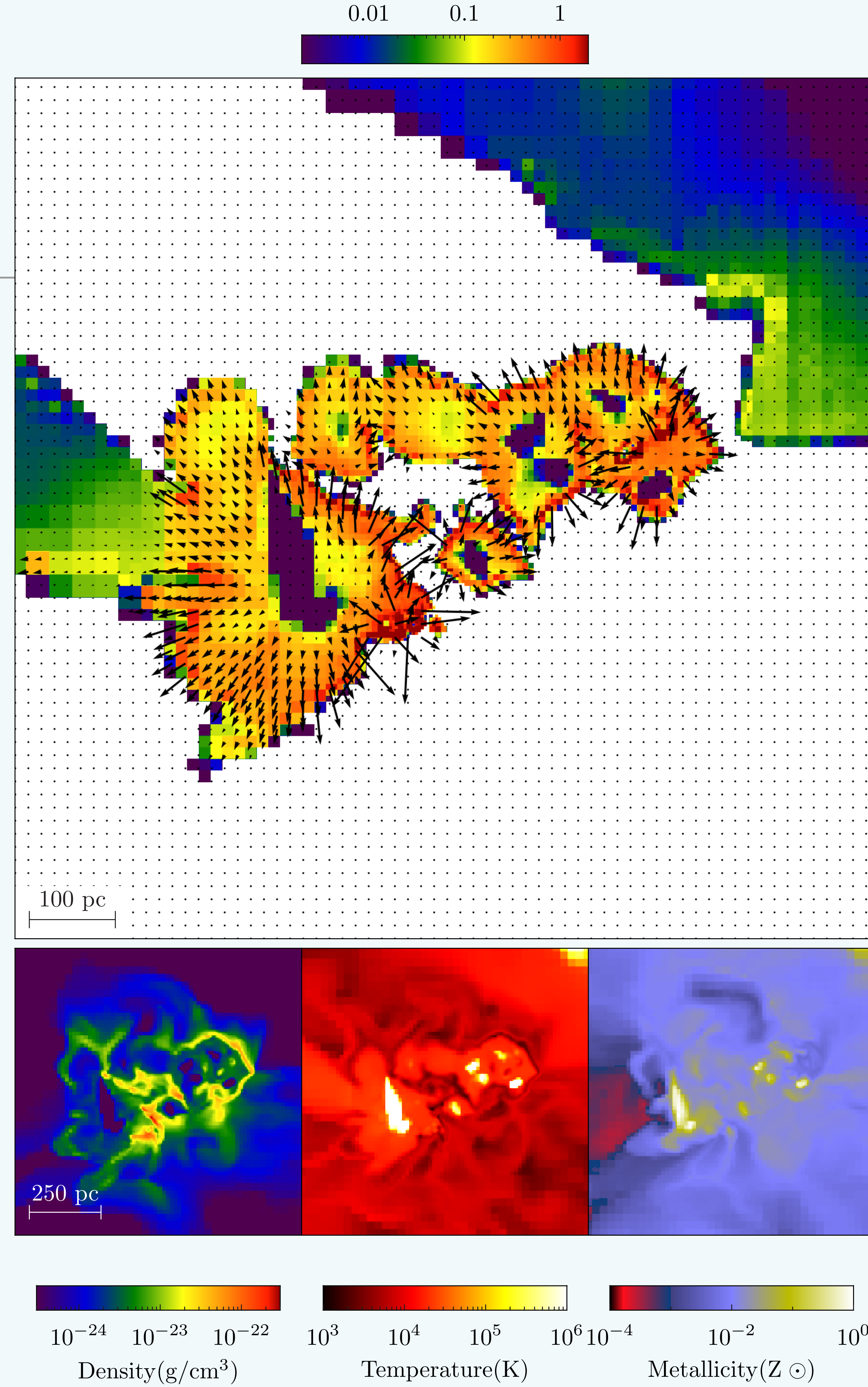


Feedback from radiation pressure more effectively disperses metal-rich ejecta and produces a galaxy on the mass-metallicity relation

Slice of acceleration due to momentum transfer from ionizing photons only, i.e. not including dust opacity

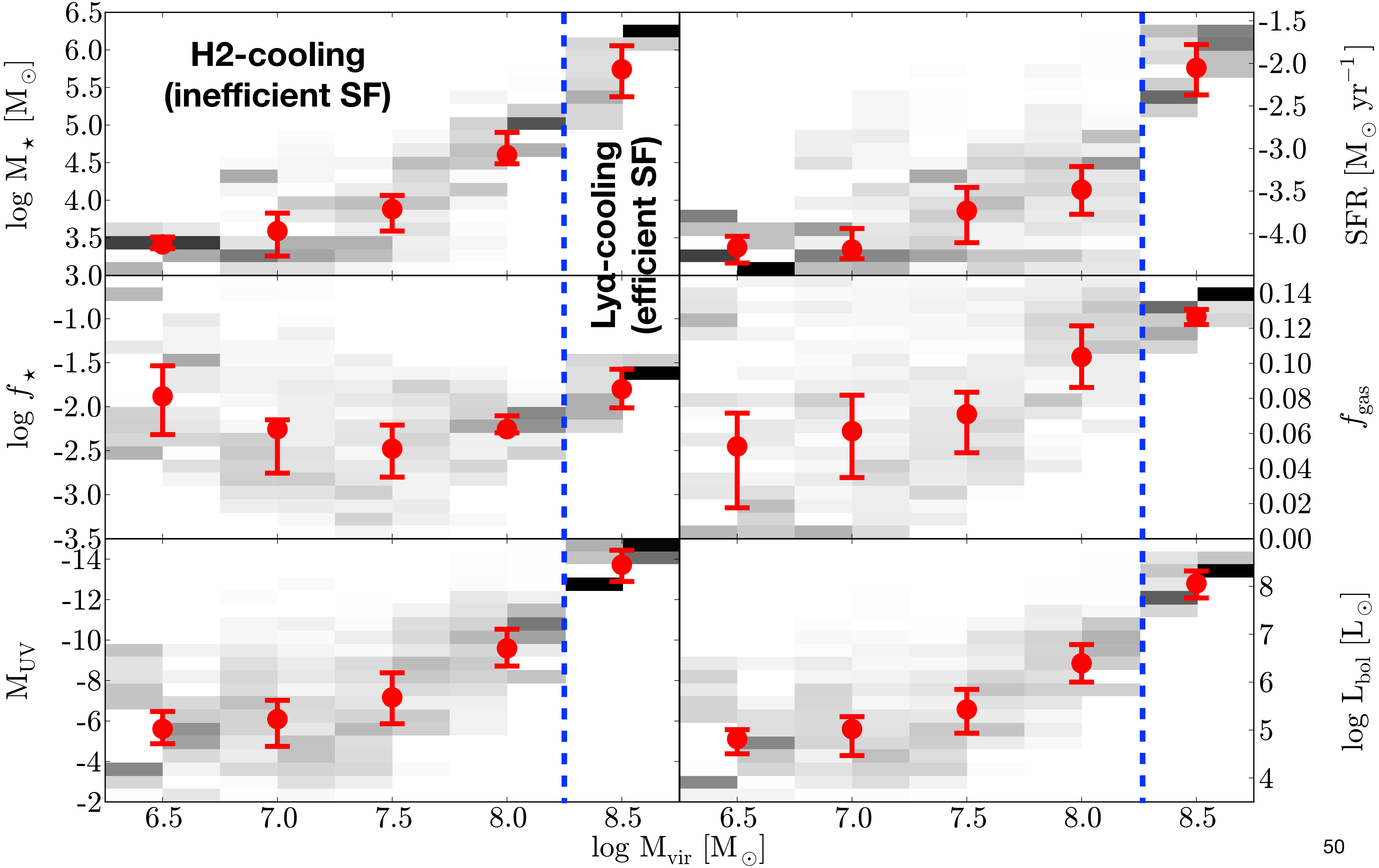


Slice of acceleration due to momentum transfer from ionizing photons only, i.e. not including dust opacity



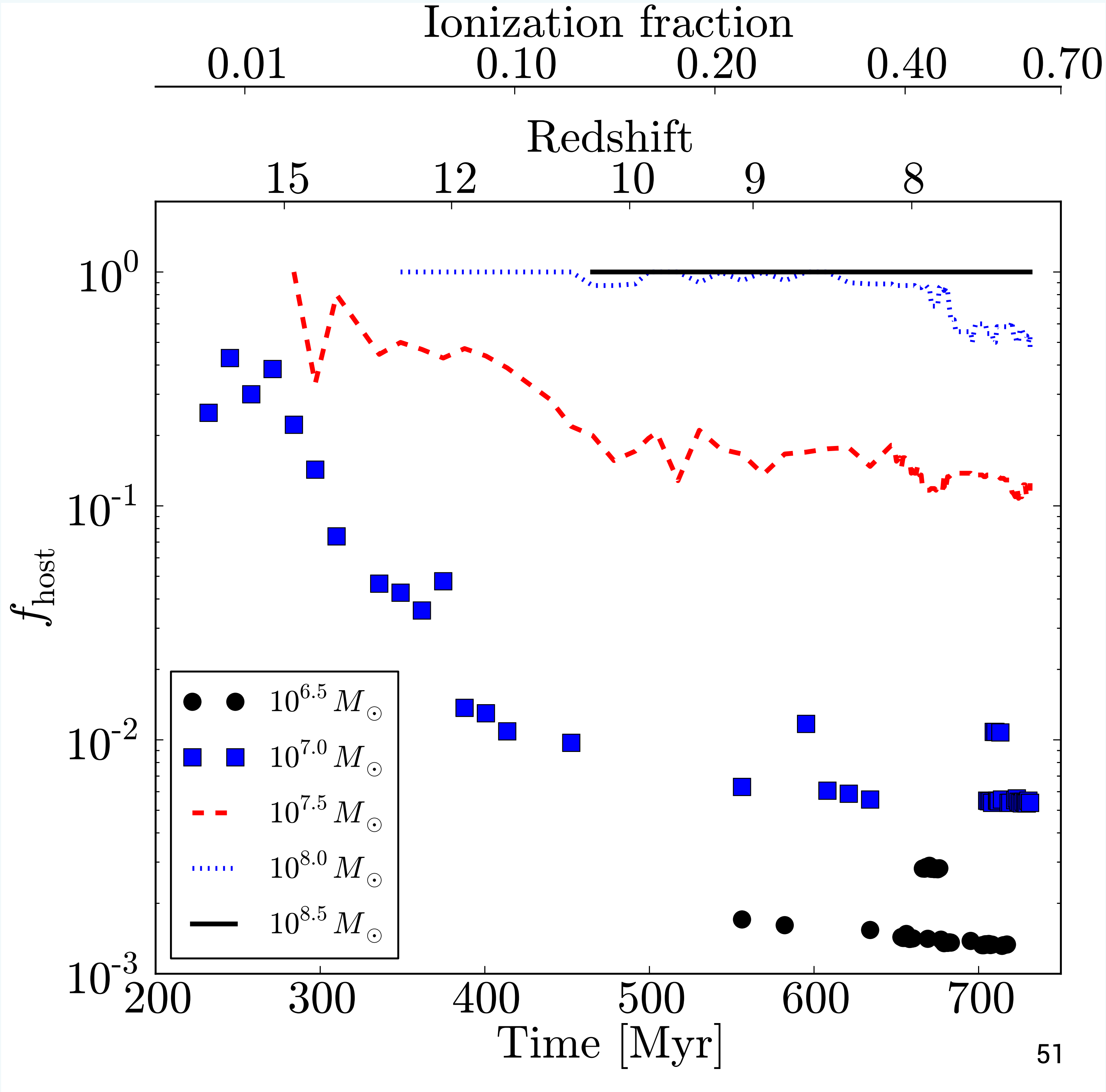
Wise et al. (2014)

Dwarf galaxy properties



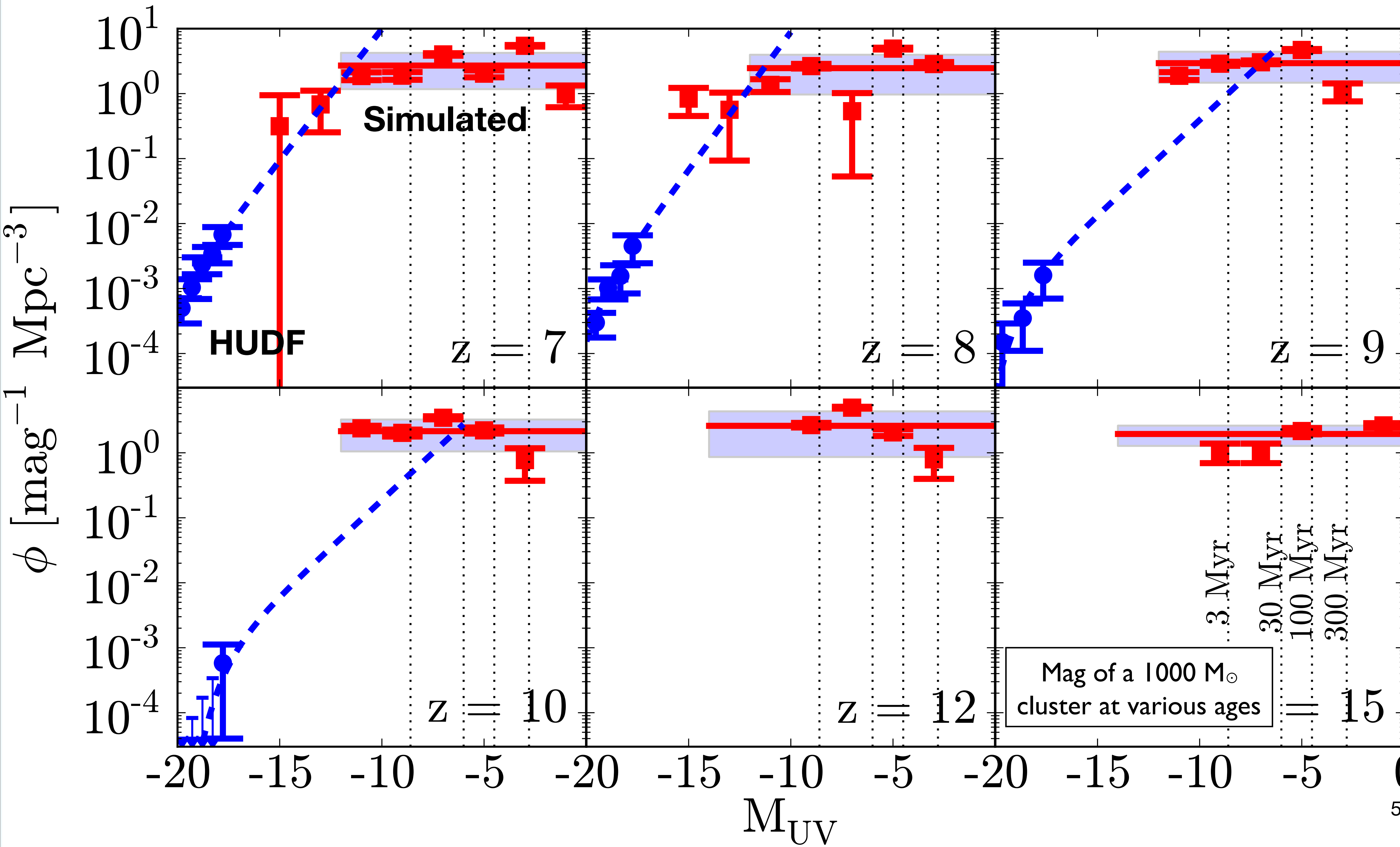
Halo-galaxy occupation fraction

- Molecular-cooling halos can form dwarf galaxies only during the early stages of reionization
- As the filtering mass (related to the IGM Jeans mass) grows, lower mass galaxies are suppressed.



Wise et al. (2014)

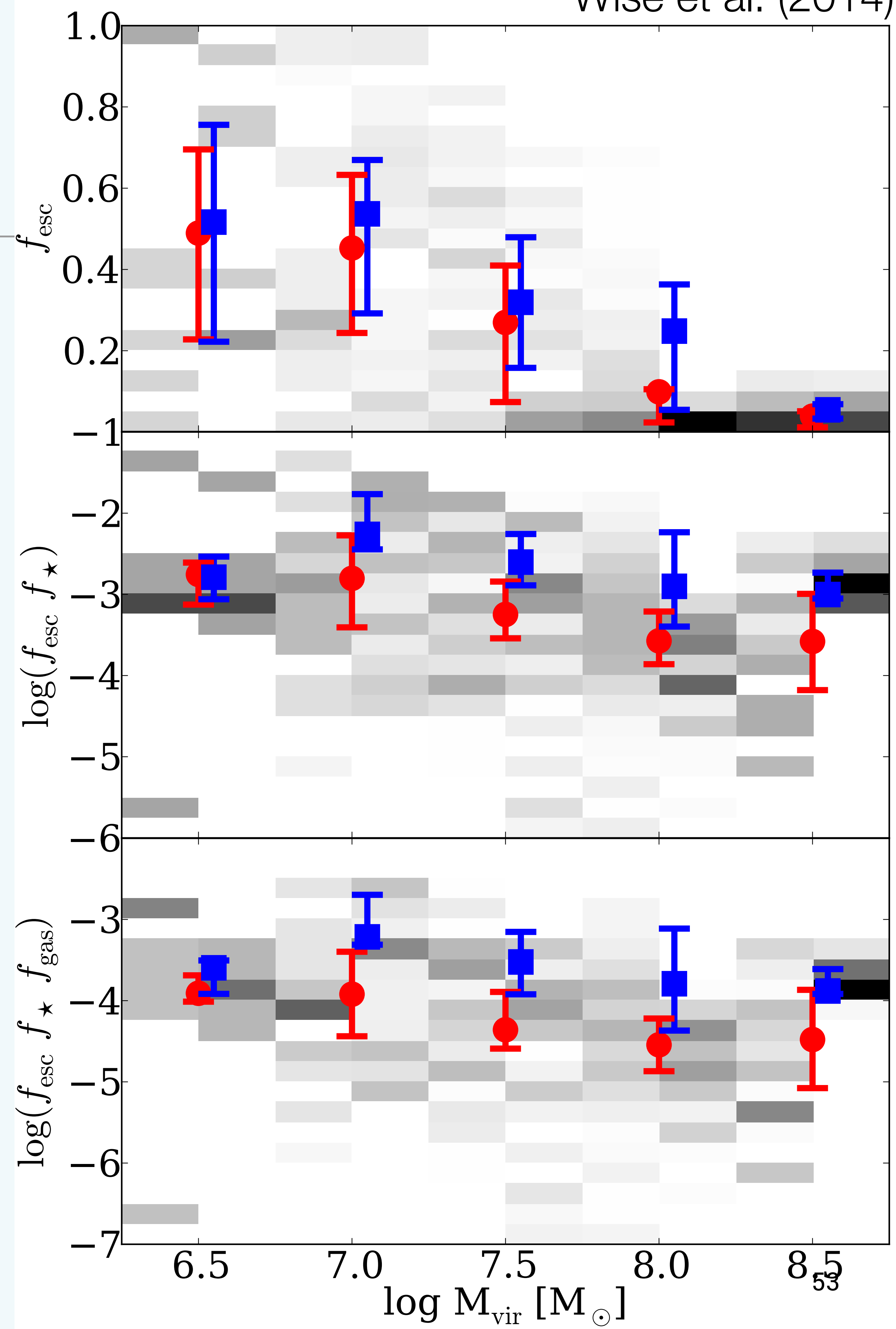
Galaxy luminosity functions

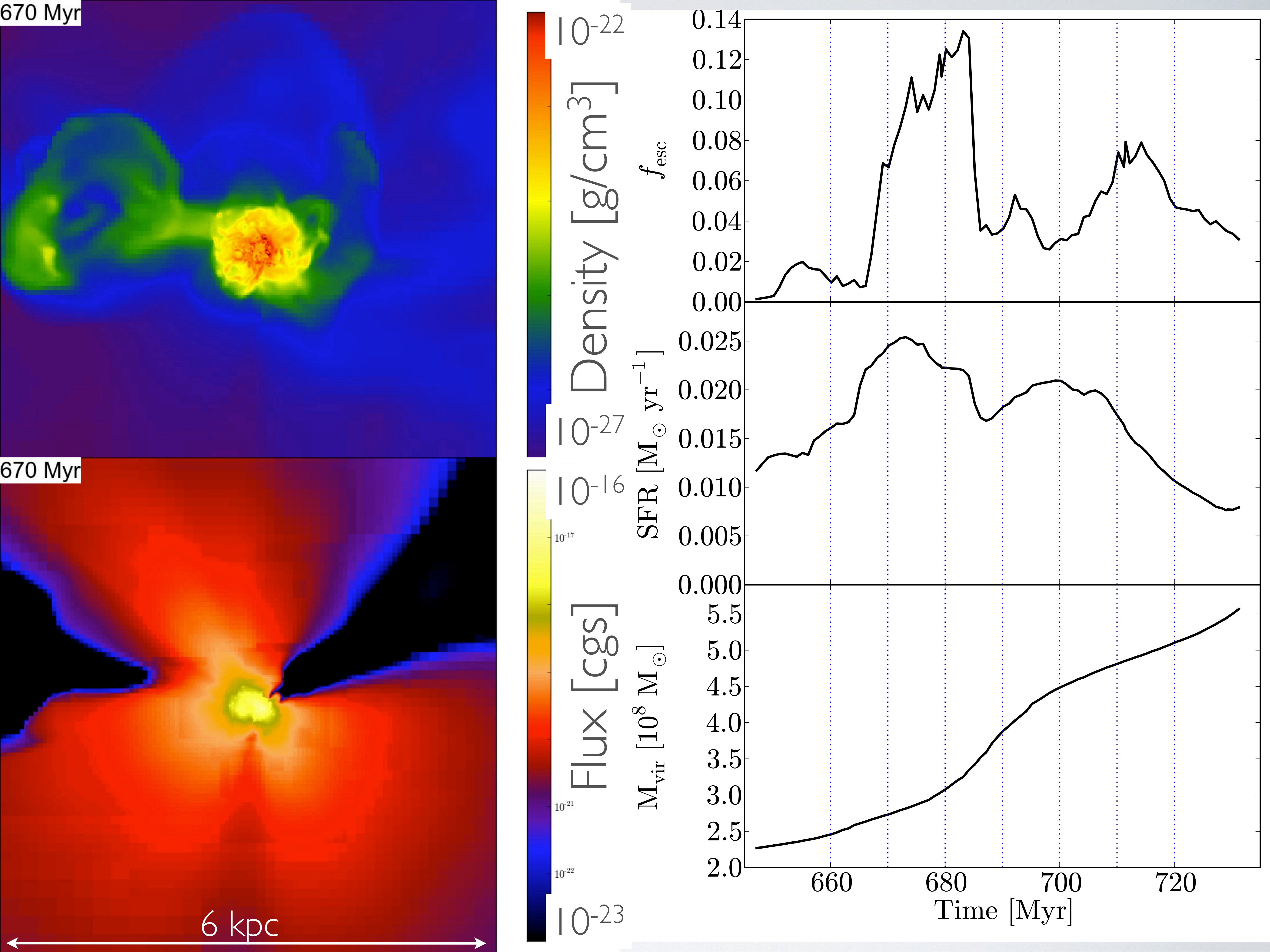


UV escape fractions

- Red: non-weighted mean
- Blue: luminosity-weighted mean
- Halos with M ≤ 10^8 M⊙ contribute the most to the ionizing photon budget at high-redshifts.
  - High escape fractions
  - Able to form stars even without atomic cooling, i.e. T < 10^4 K.
- Escape fractions are highly variable.

Wise et al. (2014)



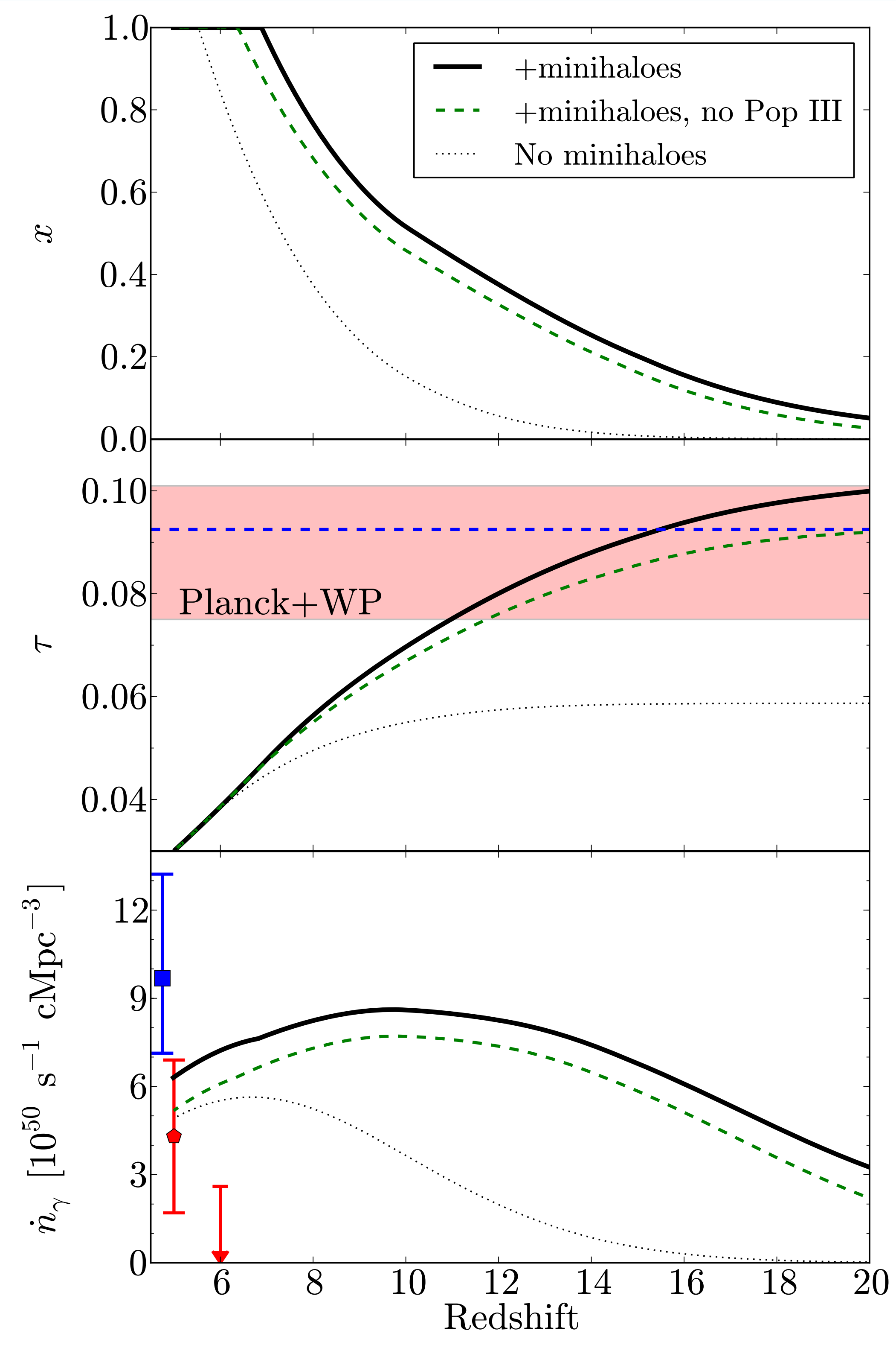


670 Myr
670 Myr
10^{-22}
Density [g/cm^3]
10^{-27}
10^{-16}
10^{-17}
Flux [cgs]
10^{-21}
10^{-22}
10^{-23}
6 kpc
f_{esc}
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
SFR [$M_\odot$ yr^{-1}]
0.025
0.020
0.015
0.010
0.005
0.000
M_{vir} [10^8 $M_\odot$]
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
660
680
700
720
Time [Myr]

Wise et al. (2014)

Semi-analytic reionization model
Including low-luminosity galaxies

- Low-luminosity galaxies are abundant at z > 10 and have high escape fractions.
- Provides the majority of the ionizing radiation at early epochs.
- Extended ionization history from z = 15 to z = 6.
- Matches the Planck + WMAP measurement of the optical depth to Thomson scattering.



Summary

- In minihaloes, there is a mix of pristine and enriched halos, depending on the Pop III stars that were hosted by the halo progenitors.
- Supernovae from Population III stars pre-enrich the protogalactic gas to a metallicity floor of $[Z/H] \sim -3$
  - However, stars with metallicity below the floor are not prevented but are rare in regions with incomplete mixing.
- Afterwards, internal enrichment steadily increases the average stellar metallicities. High-z dwarfs lie below the local Z-L relation.
- Gas depletion, IGM pre-heating, and chemical enrichment all have impacts on the properties of the first galaxies and their stellar populations.
- Low-luminosity galaxies have high UV escape fractions and are the dominant source of ionizing radiation during reionization.