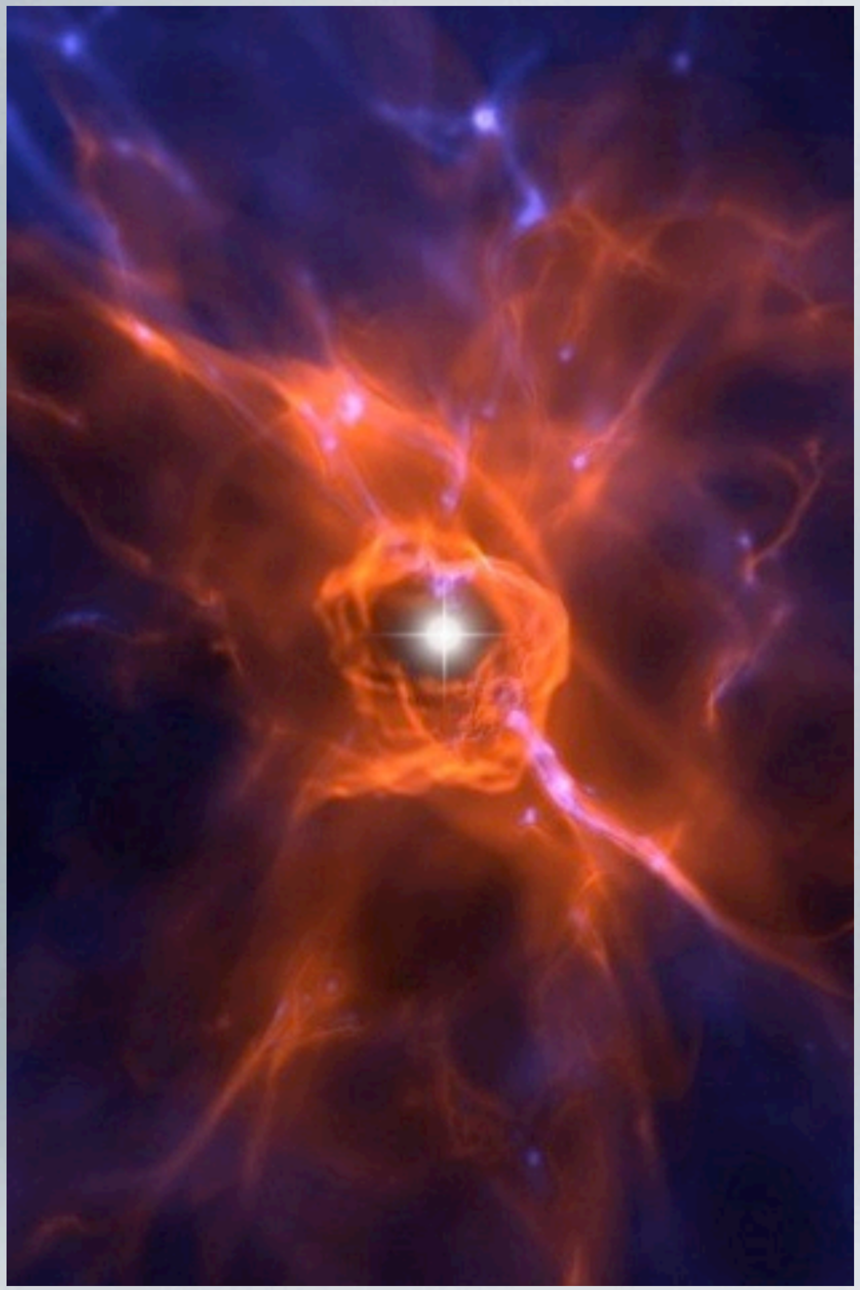
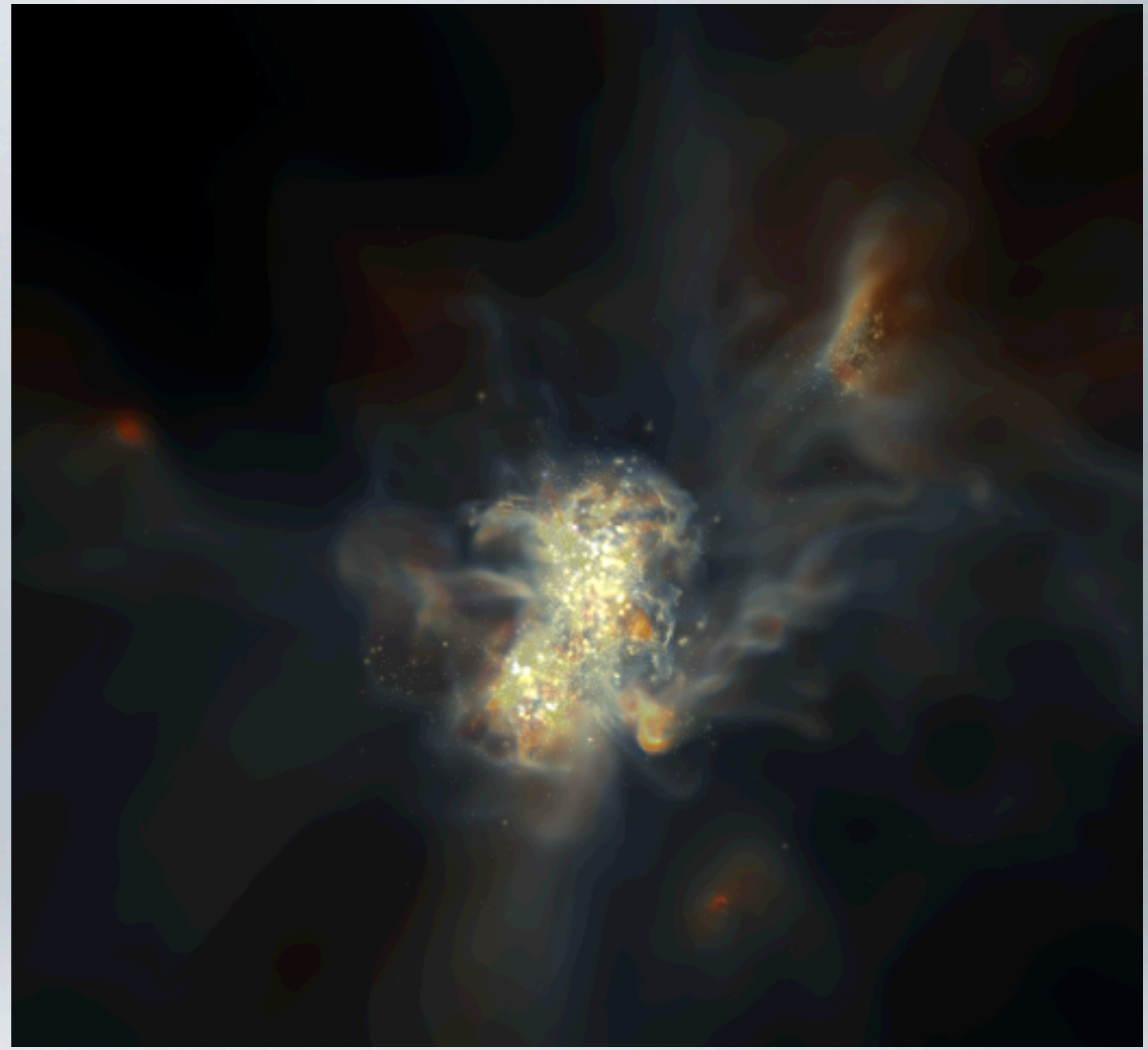
 

THE FIRST STARS AND GALAXIES

John Wise (Georgia Tech)

Tom Abel (Stanford), Marcelo Alvarez (CITA), Michael Norman (UC San Diego), Britton Smith (Michigan State), Matthew Turk (Columbia)

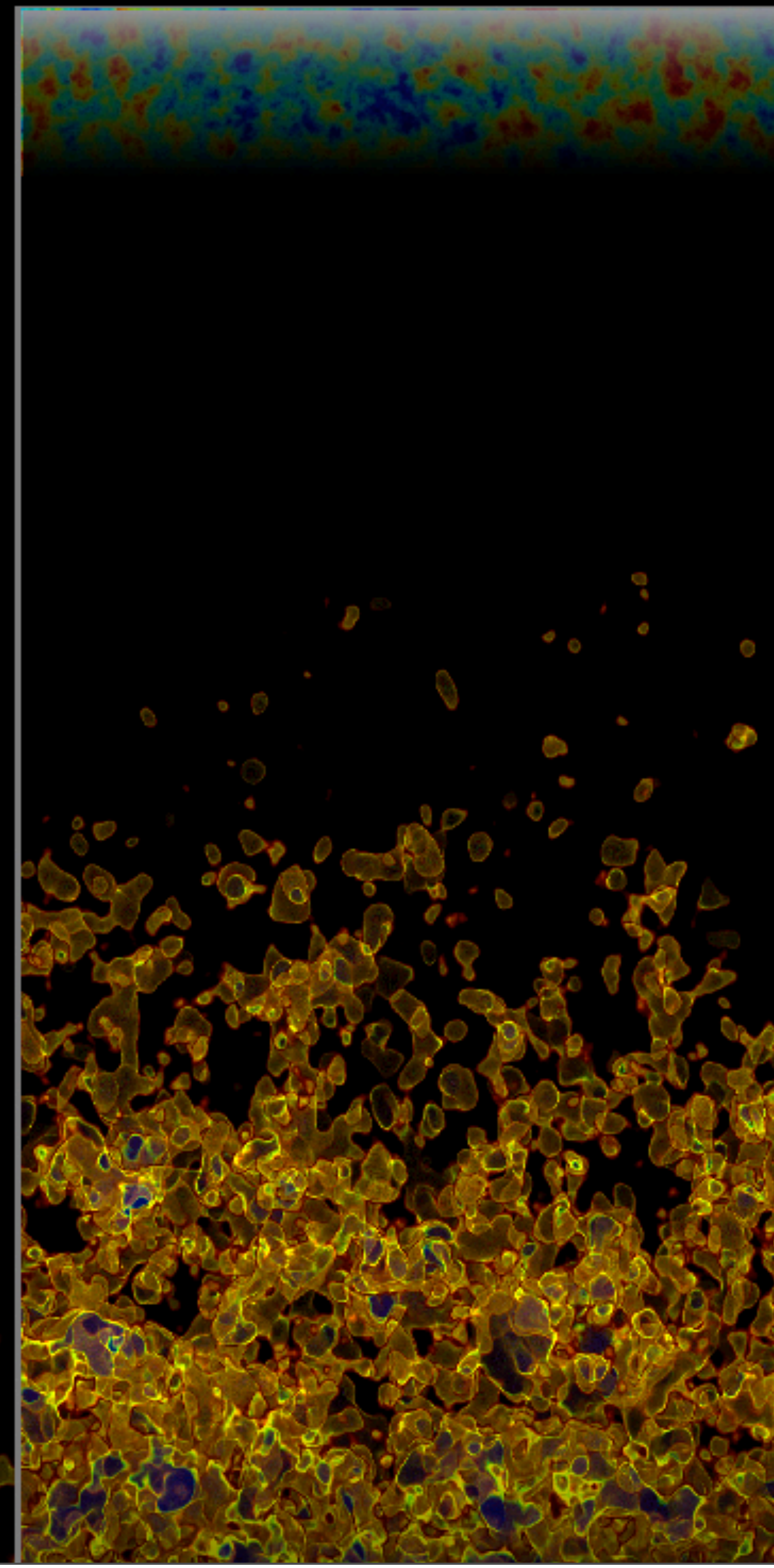
Credit: Marcelo Alvarez & Tom Abel

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)



Credit: Marcelo Alvarez & Tom Abel

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)

EPOCH OF GALAXY FORMATION

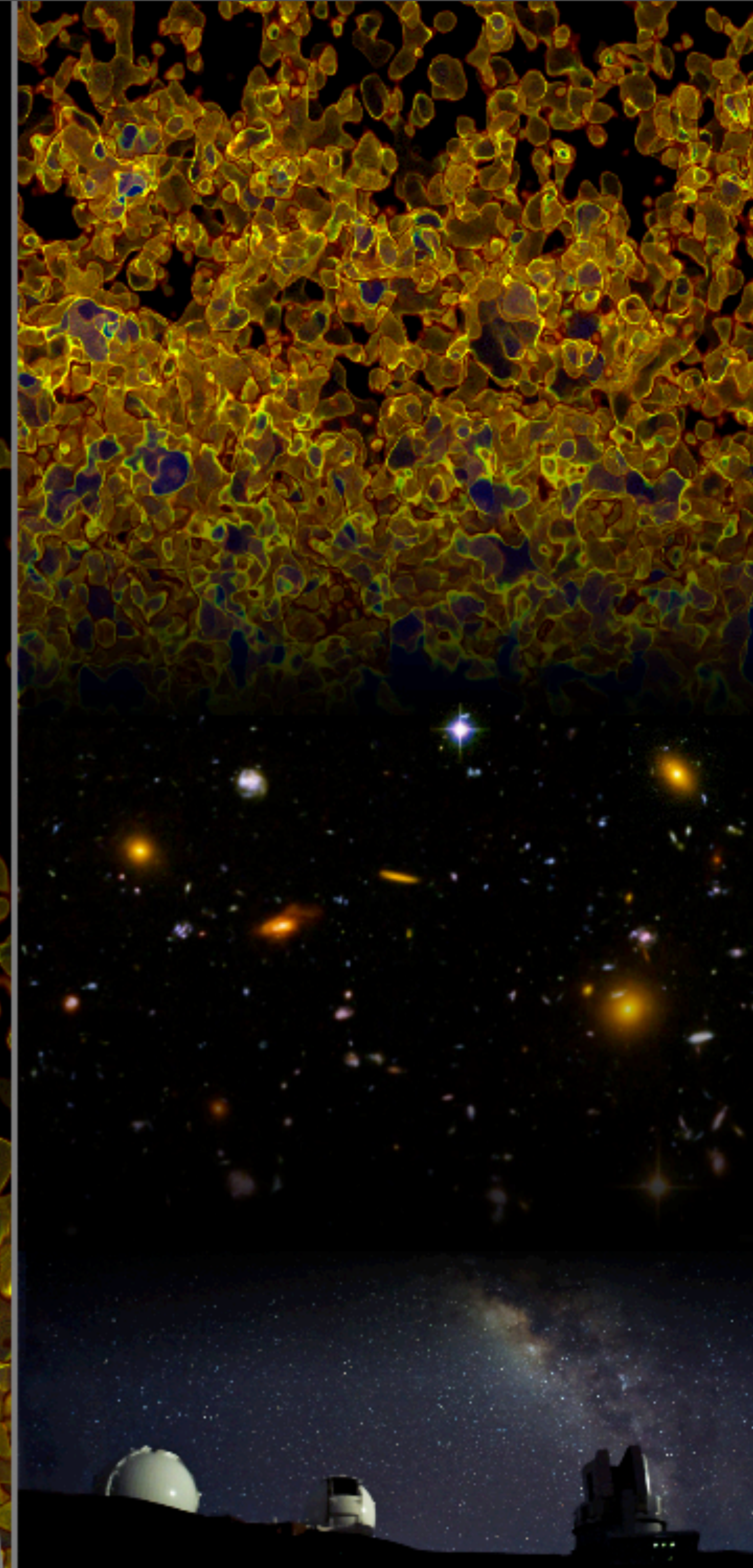
Larger and larger halos of dark matter collapse, leading to vigorous star formation within the first galaxies. Accretion onto supermassive black holes in some galaxies powers the most luminous objects in the universe -- qusars.

(~1 billion to 9 billion years)

PRESENT DAY UNIVERSE

Solar system forms, and galaxies like our own Milky Way continue to evolve. Large clusters of thousands of galaxies, bound by the gravity of the largest halos of dark matter in the universe, are beginning to form.

(~9 billion to 13.6 billion years)



OUTLINE

- Population III star formation
- Radiative transfer calculations (ray tracing)
- Population III stellar feedback
  - Radiative feedback
  - Mechanical & chemical feedback
- Impacts on the early galaxy formation
  - Stellar populations – metallicities and star formation rates
  - The role of radiation pressure

POP III STAR FORMATION

- 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.

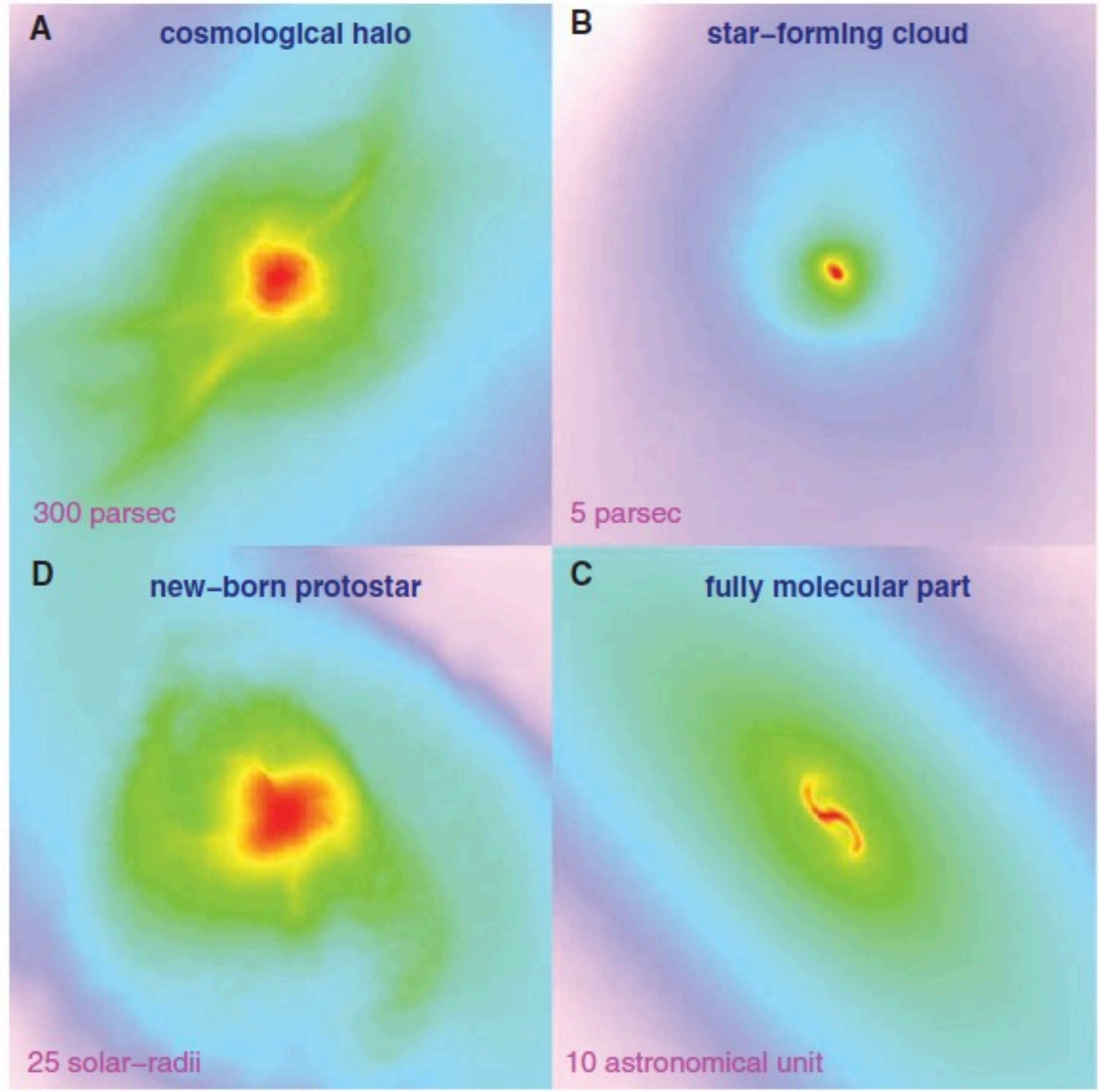
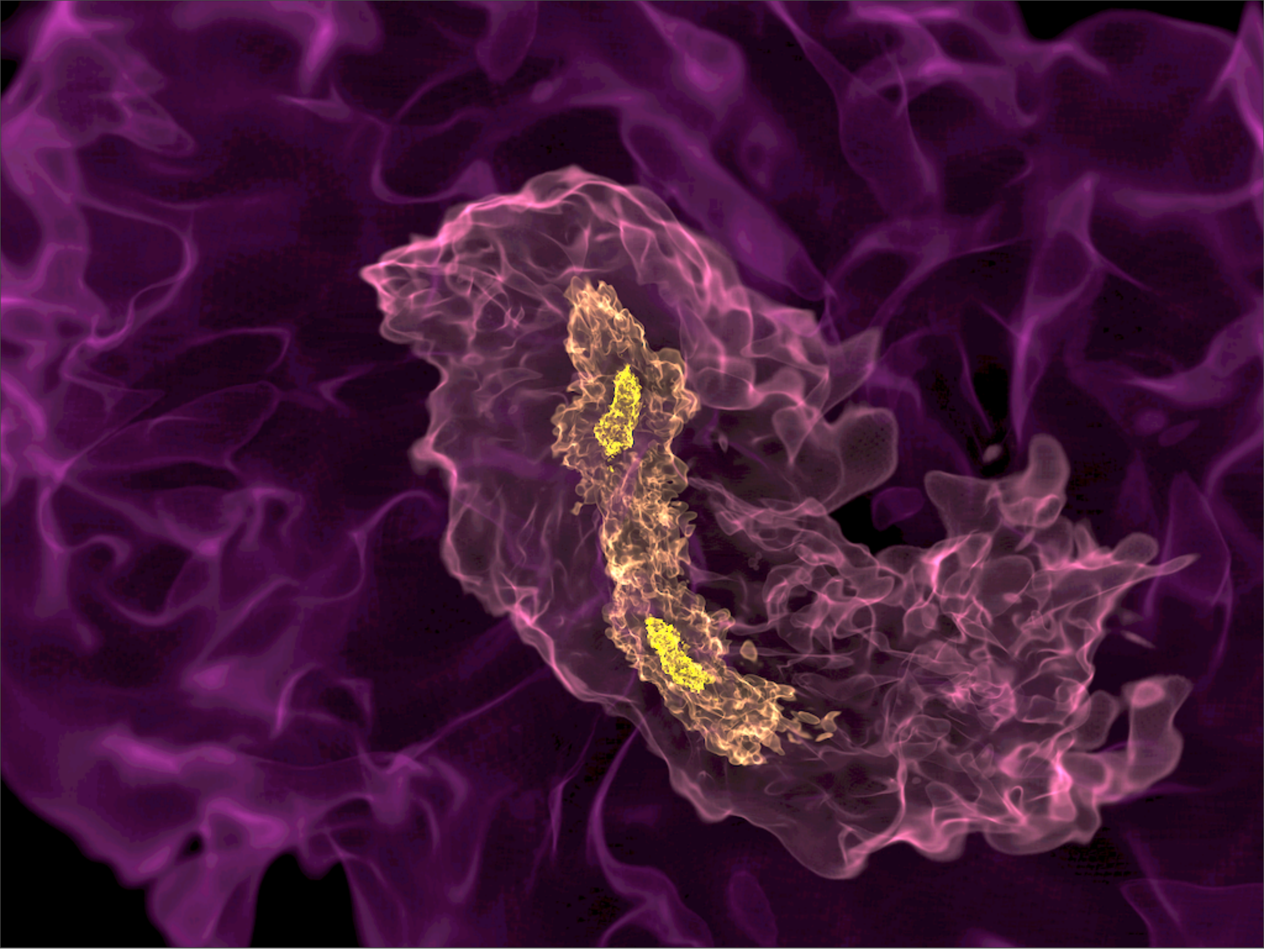


Fig. 1. Projected gas distribution around the protostar. (**A**) The large-scale gas distribution around the cosmological halo (300 pc on a side). (**B**) A self-gravitating, star-forming cloud (5 pc on a side). (**C**) The central part of the fully molecular core (10 astronomical units on a side). (**D**)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

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.



FRAGMENTATION!

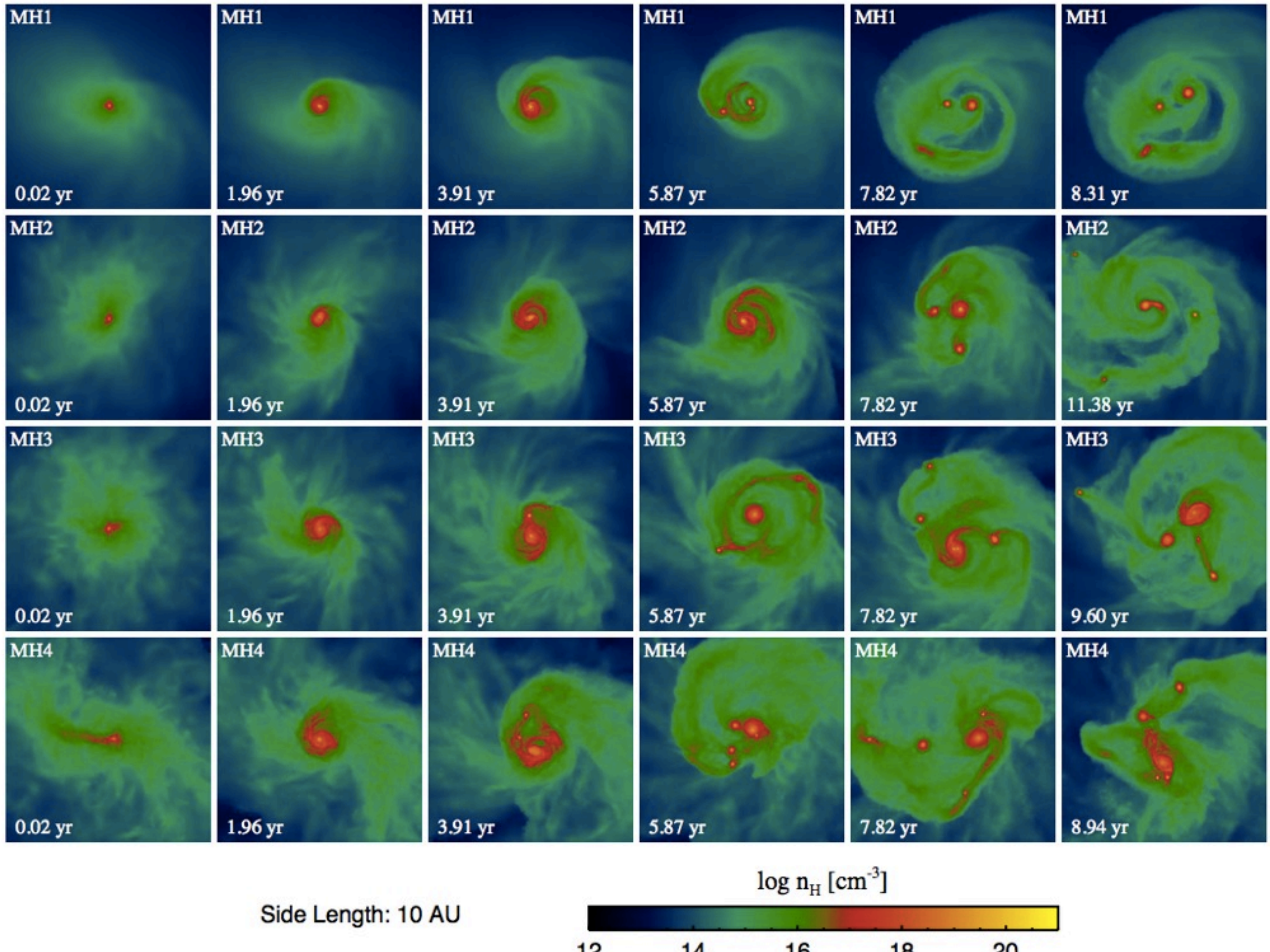
- Improved chemistry models and sink particle implementations allows simulations to progress further than the first collapsing object.

  - (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.

FRAGMENTATION!

- (Clark+ 2011) Disk fragmentation to form tight (sometimes < AU) multiple systems
- (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

POP III FINAL MASSES

- When do Pop III stars stop accreting?
  - (Stacy+ 2011, Hosokawa+ 2011) Modeled protostellar radiative feedback from an accreting Pop III star.
    - Stacy+: Found that the star grows to ~30 $M_{\odot}$ in a binary system.
    - Hosokawa+: Found that the star is limited to ~43 $M_{\odot}$

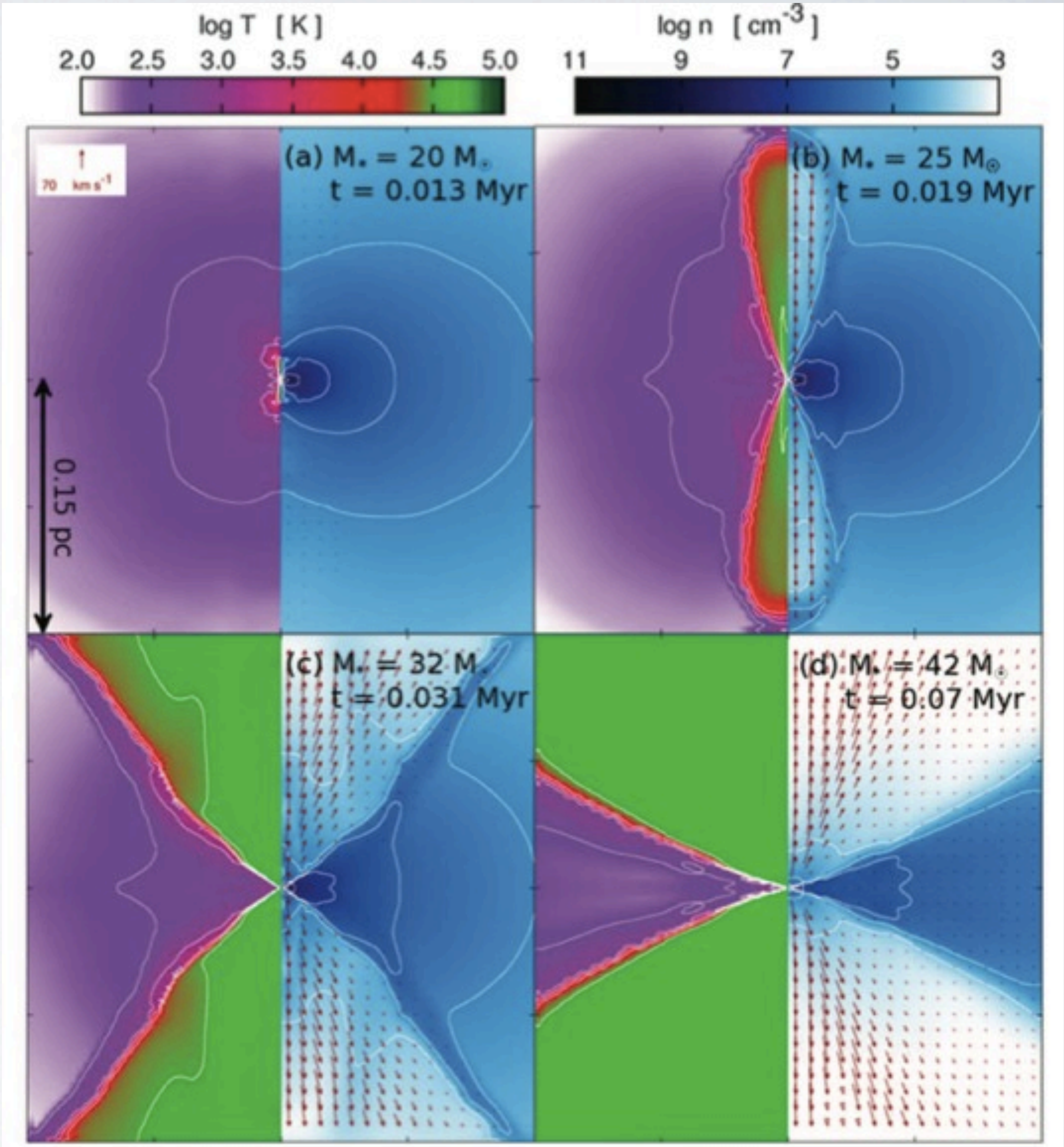
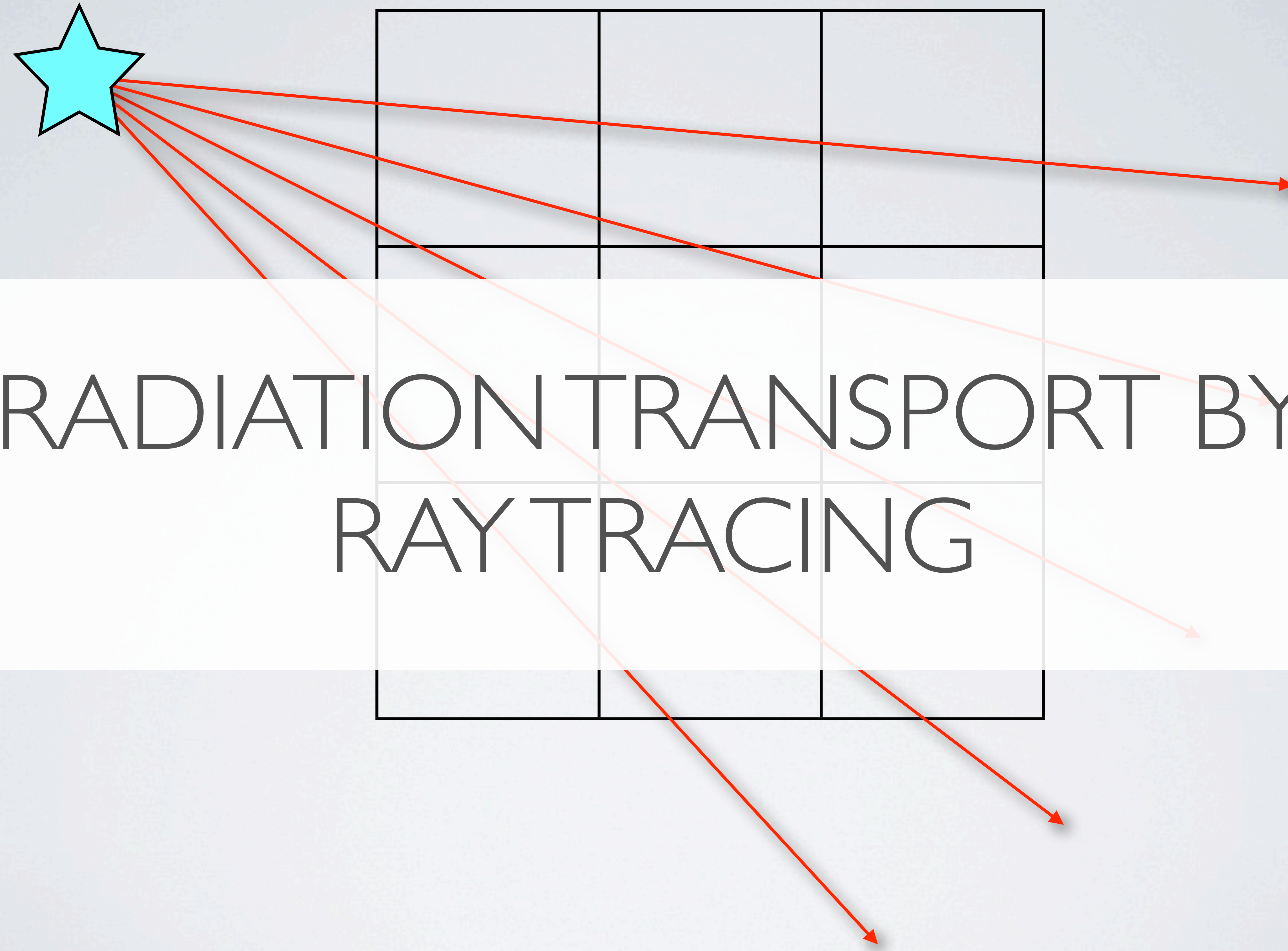


Fig. 2. UV radiative feedback from the primordial protostar. The spatial distributions of gas temperature (left), number density (right), and velocity (right, arrows) are presented in each panel for the central

RADIATION TRANSPORT BY RAY TRACING



Cosmological Radiative Transfer Equation

$$I_\nu \equiv I(\nu, \mathbf{x}, \Omega, t)$$

n := normal vector
a := scale factor
ā := a/a$_{em}$
H := Hubble factor
ν := frequency

$$\frac{1}{c}\,\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{\bar{a}} - \frac{H}{c}\,\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + j_\nu$$

Cosmological Radiative Transfer Equation

$$I_\nu \equiv I(\nu, \mathbf{x}, \Omega, t)$$

n := normal vector
a := scale factor
ā := a/a$_{em}$
H := Hubble factor
ν := frequency

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{\bar{a}} - \frac{H}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + j_\nu$$

Propagation & Cosmic Expansion

Redshifting

Cosmological Dilution

Absorption

Emission

Simplifications – “Local” Approximation

1. Short timesteps (ā = 1)
2. Ignore cosmological redshift and dilution (may become important >50 Mpc)

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{\bar{a}} - \frac{H}{c}\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + j_\nu$$

Propagation & Cosmic Expansion

Redshifting

Cosmological Dilution

Absorption

Emission

Simplifications – “Local” Approximation

1. Short timesteps (ā = 1)
2. Ignore cosmological redshift and dilution (may become important >50 Mpc)

$$\frac{1}{c}\,\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{} - \frac{H}{c}\,\left(\nu\frac{\partial I_\nu}{\partial \nu} - 3I_\nu\right) = -\kappa_\nu I_\nu + j_\nu$$

Propagation & Cosmic Expansion

Redshifting

Cosmological Dilution

Absorption

Emission

Simplifications – "Local" Approximation

1. Short timesteps (ā = 1)
2. Ignore cosmological redshift and dilution (may become important >50 Mpc)

$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \frac{\hat{n}\cdot\nabla I_\nu}{} - \qquad\qquad\qquad) = -\kappa_\nu I_\nu + j_\nu$$

Propagation & Cosmic Expansion

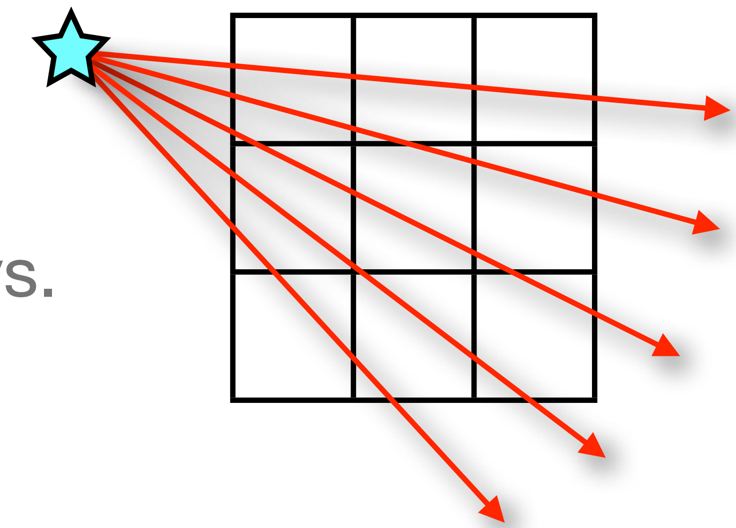
Redshifting

Cosmological Dilution

Absorption

Emission

RT Equation along a Ray



- Consider point sources of radiation

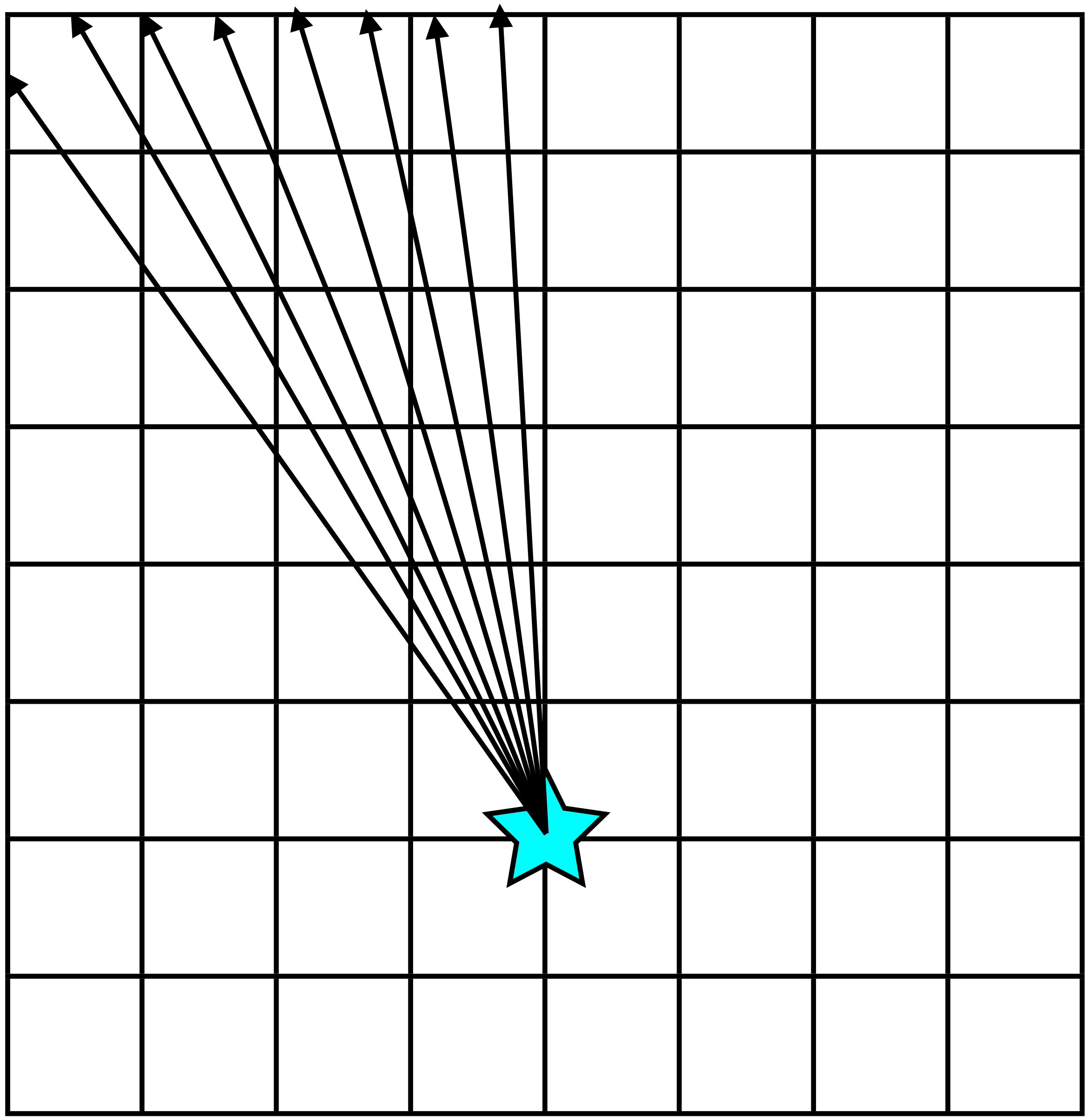
- Initially, the radiation flux is split equally among all rays.

$$\frac{1}{c}\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r} = -\kappa P$$

- P := photon flux in the ray

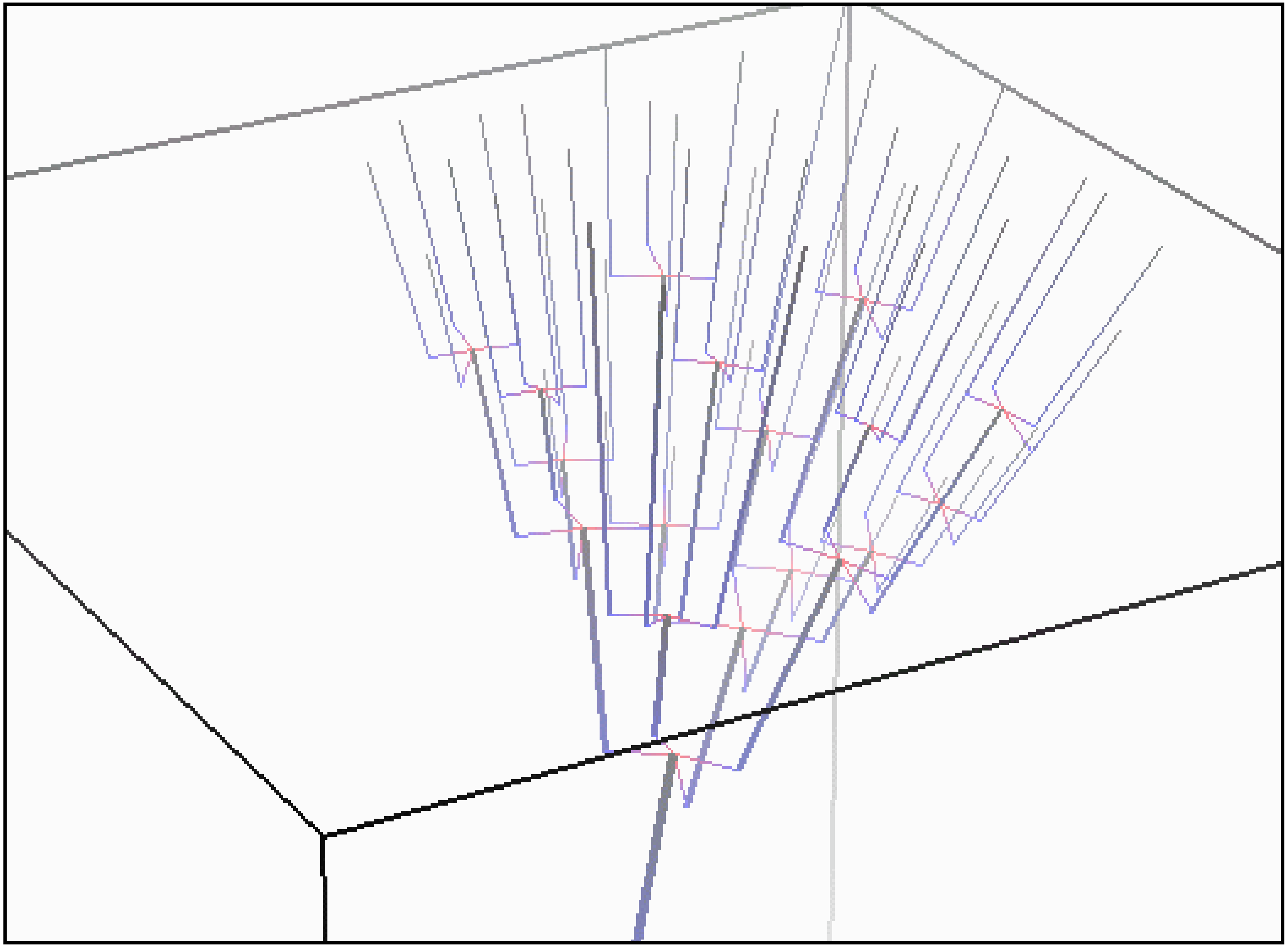
Adaptive Ray Tracing

Abel & Wandelt (2002)



Adaptive Ray Tracing

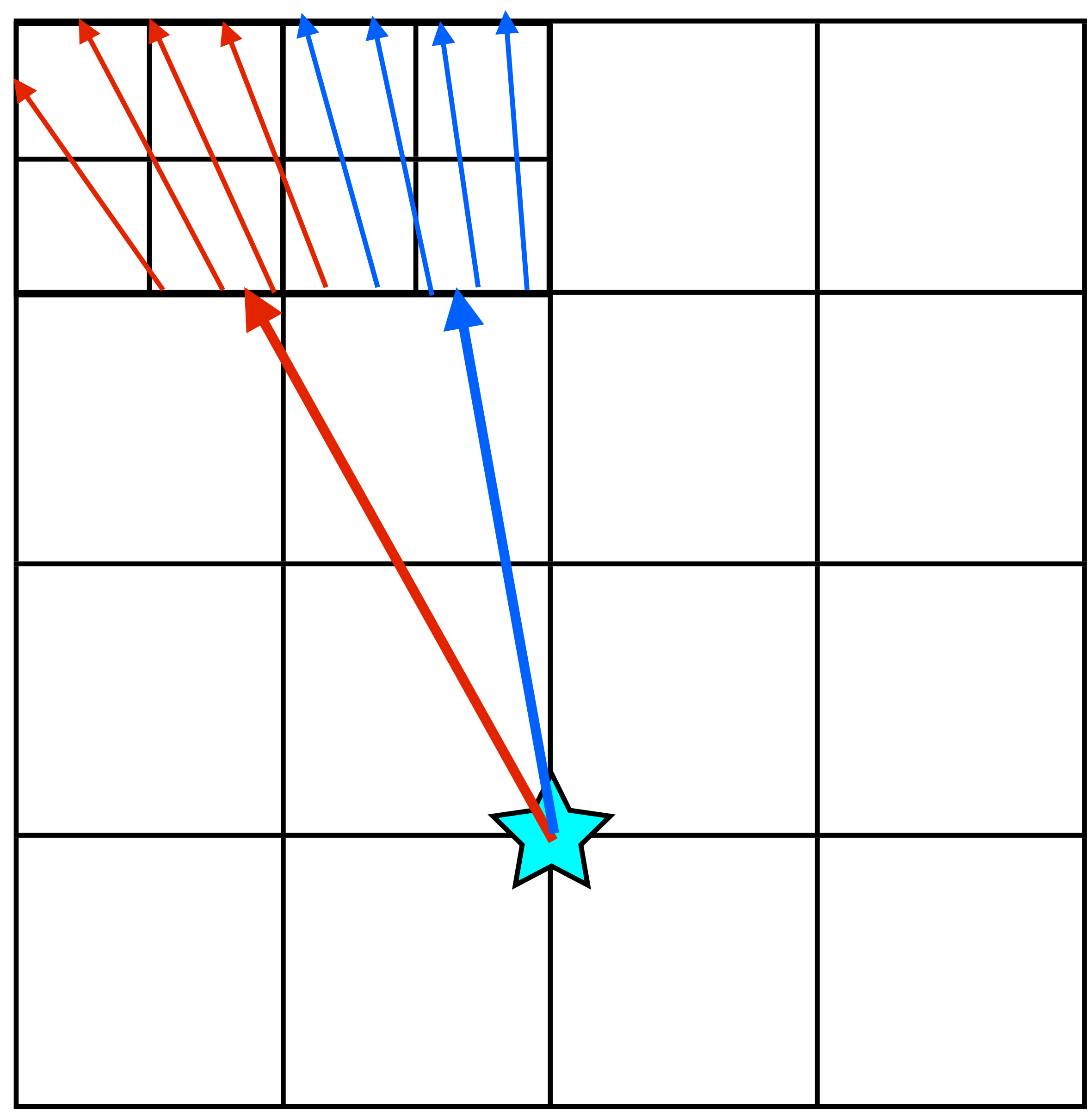
Abel & Wandelt (2002)



Adaptive Ray Tracing

Abel & Wandelt (2002)
Wise & Abel (2011)

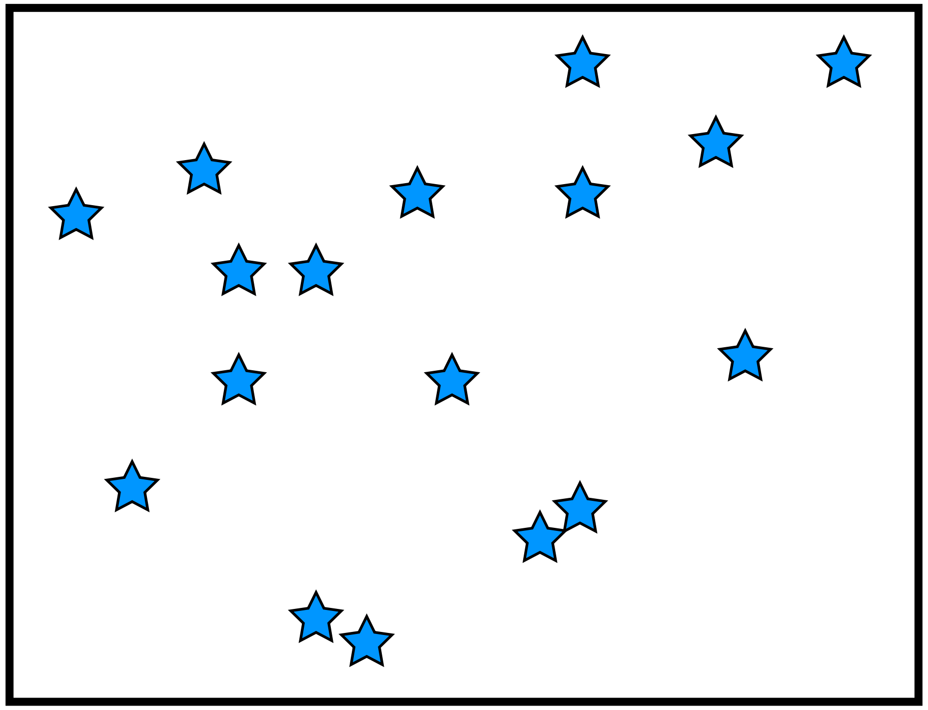
- Ray directions and splitting based on HEALPix (Gorski et al. 2005)
- Rays are split into 4 child rays when the solid angle is large compared to the cell face area
- Well-suited for AMR
- Can calculate the photo-ionization rates so that the method is photon conserving.



Overcoming O(N_{STAR}) :: Ray / Source Merging

Okamoto et al. (2011)
Wise & Abel (in prep)

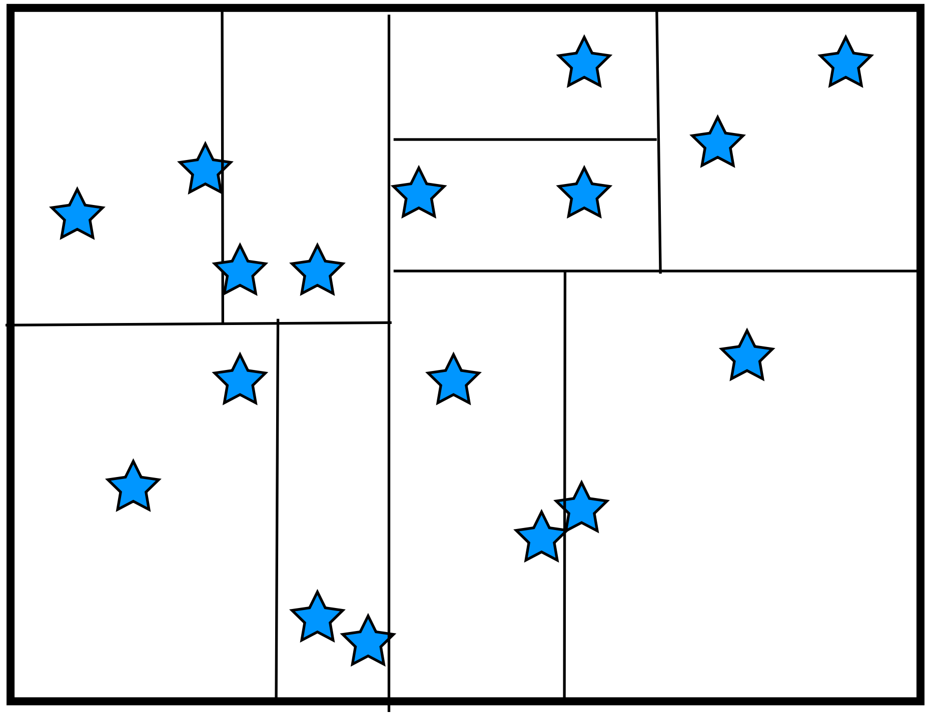
- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

Okamoto et al. (2011)
Wise & Abel (in prep)

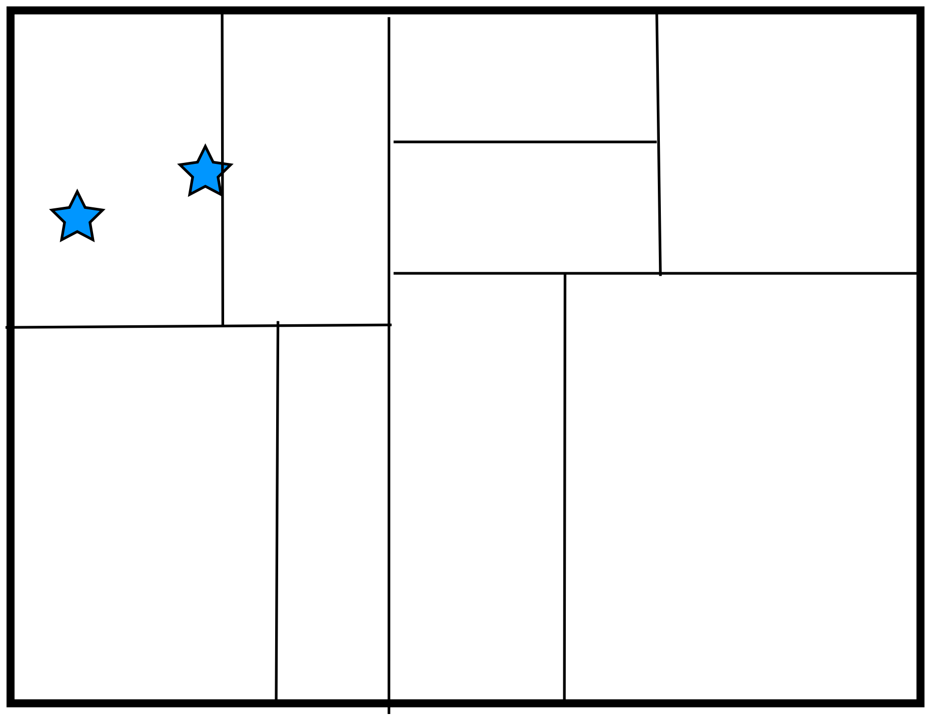
- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

Okamoto et al. (2011)
Wise & Abel (in prep)

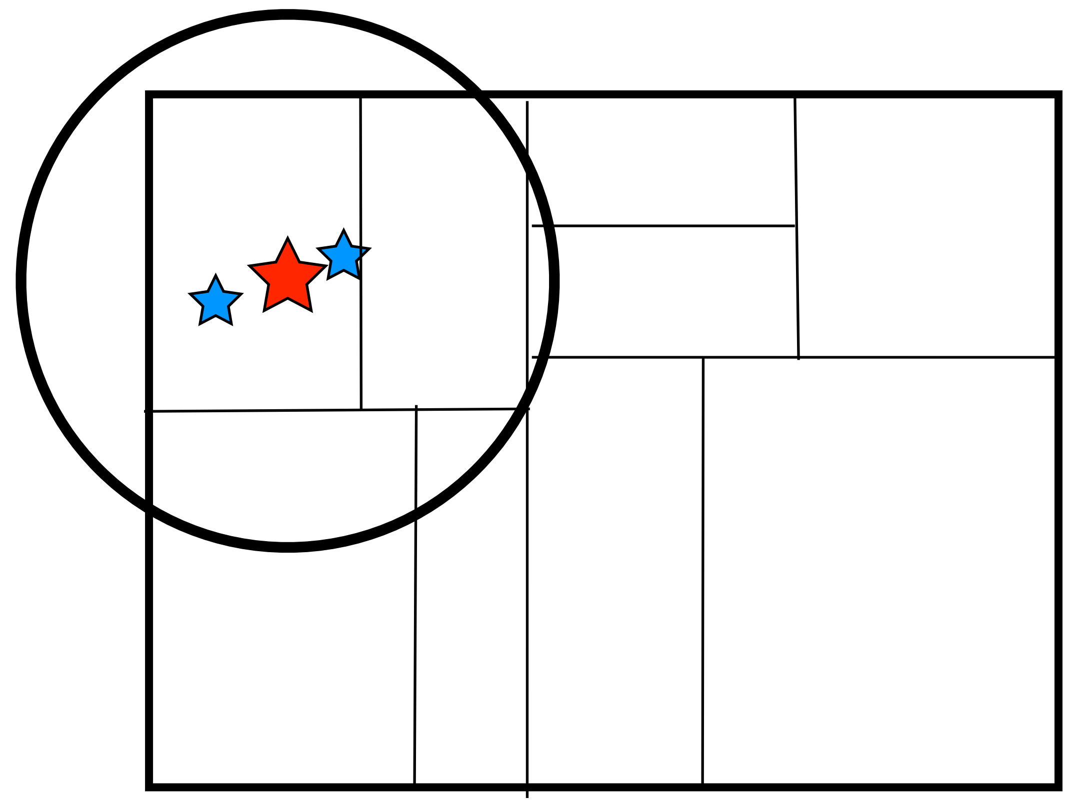
- Sources are grouped on a binary tree.
- On each leaf, a “super-source” is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

Okamoto et al. (2011)
Wise & Abel (in prep)

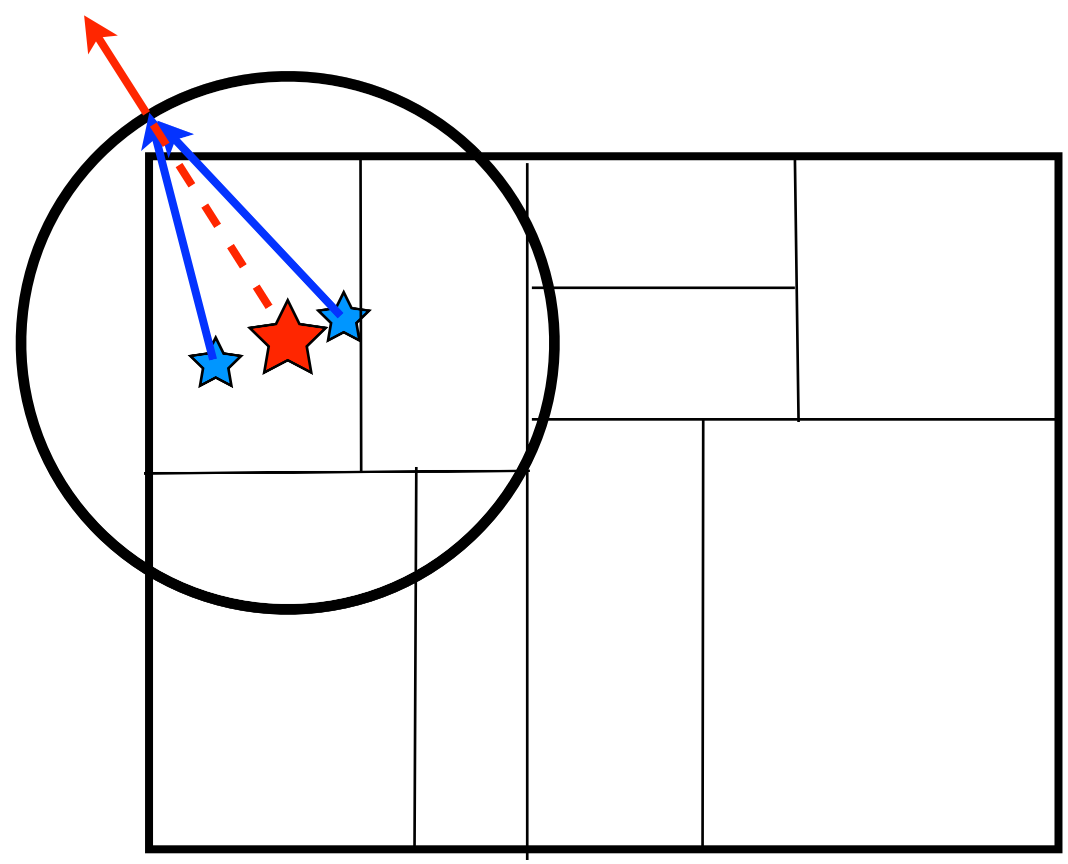
- Sources are grouped on a binary tree.
- On each leaf, a “super-source” is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

Okamoto et al. (2011)
Wise & Abel (in prep)

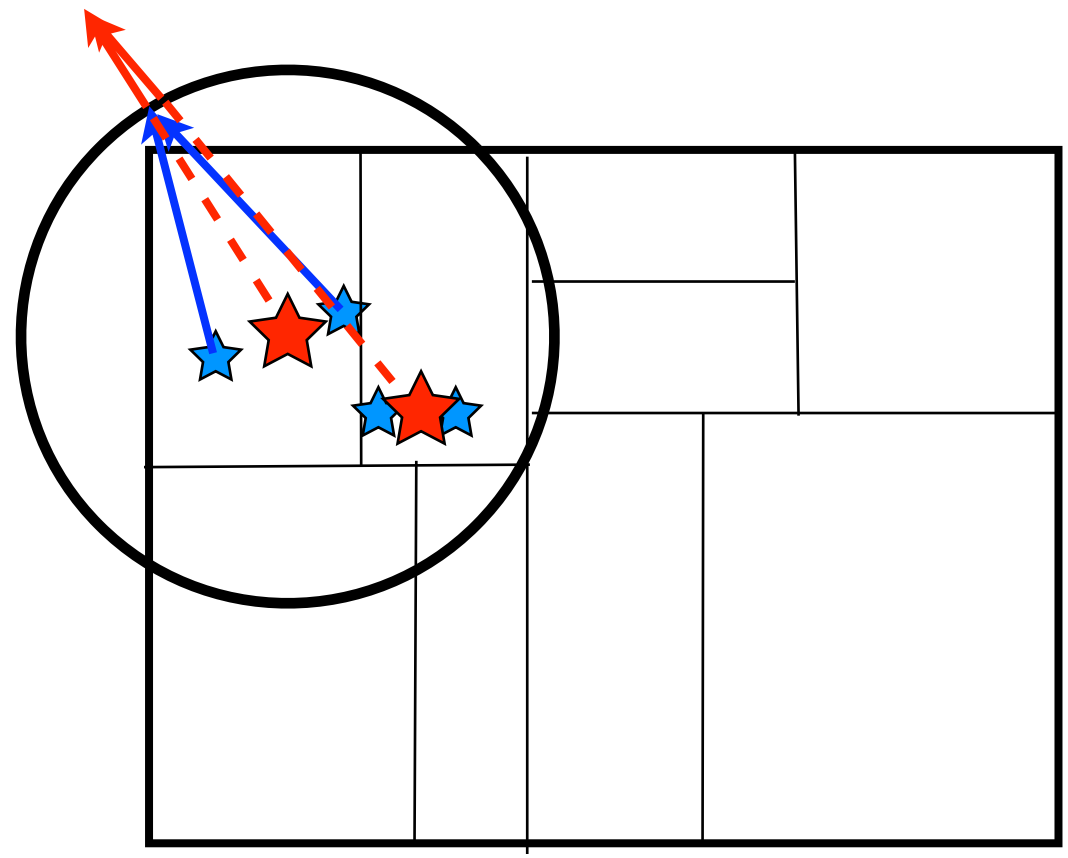
- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

Okamoto et al. (2011)
Wise & Abel (in prep)

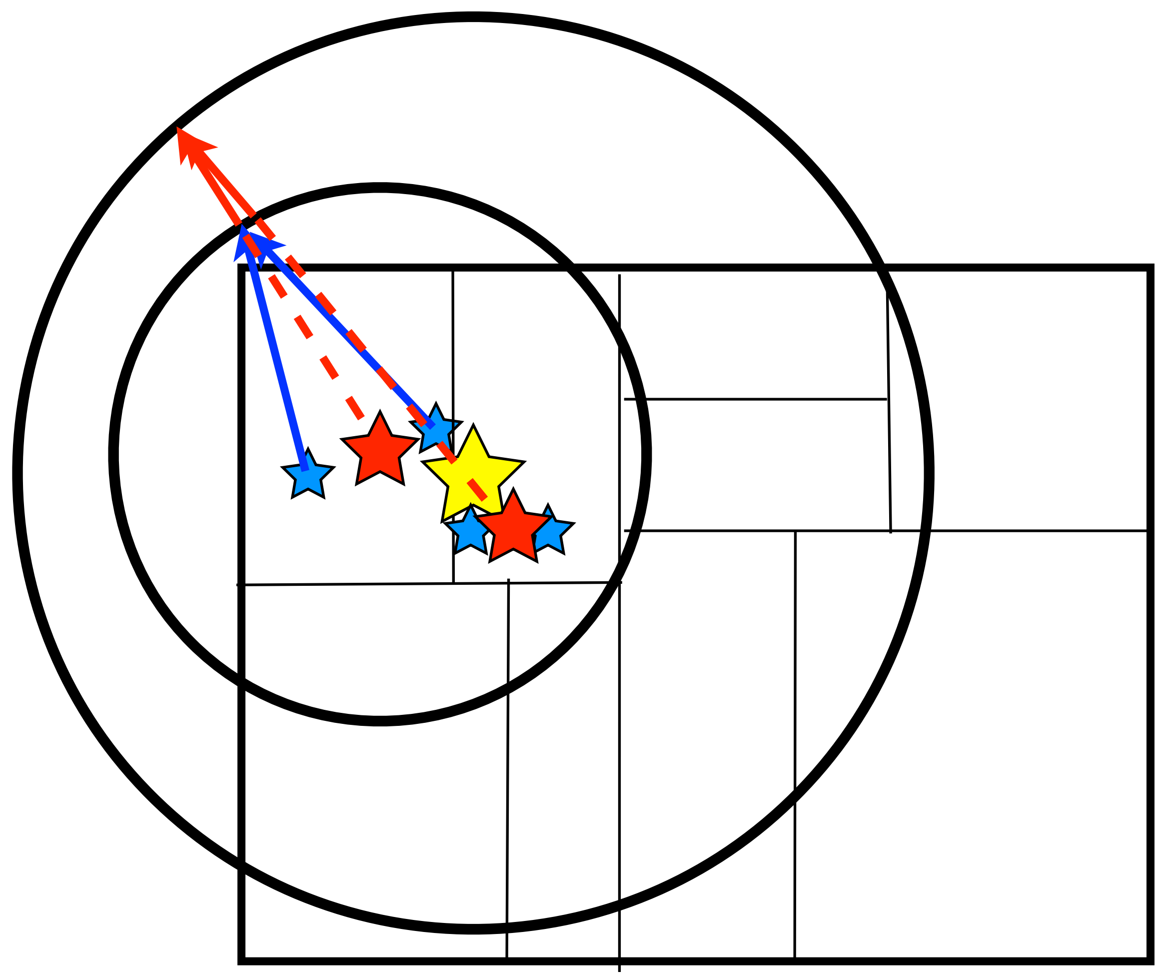
- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



Overcoming O(N_{STAR}) :: Ray / Source Merging

Okamoto et al. (2011)
Wise & Abel (in prep)

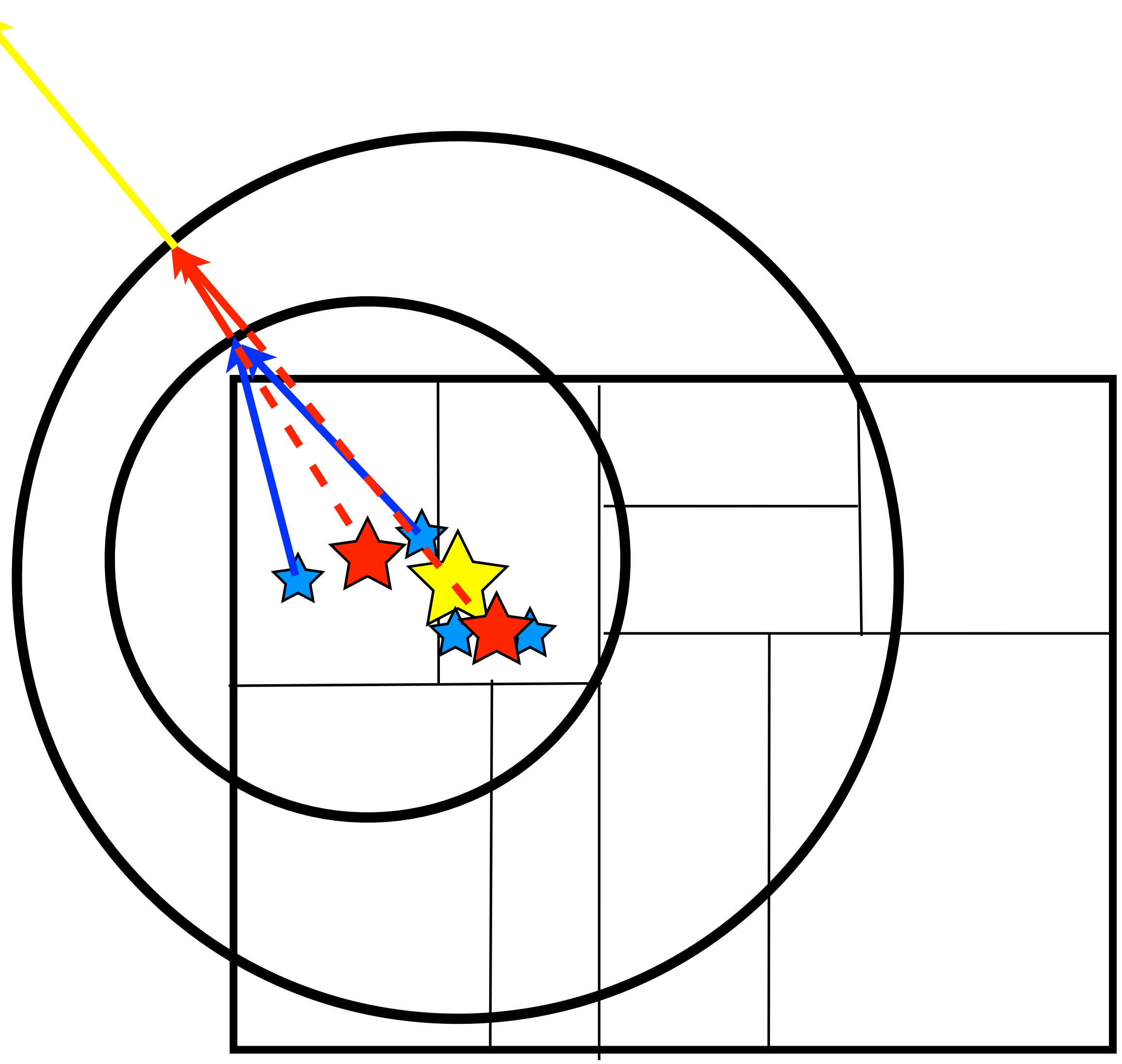
- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



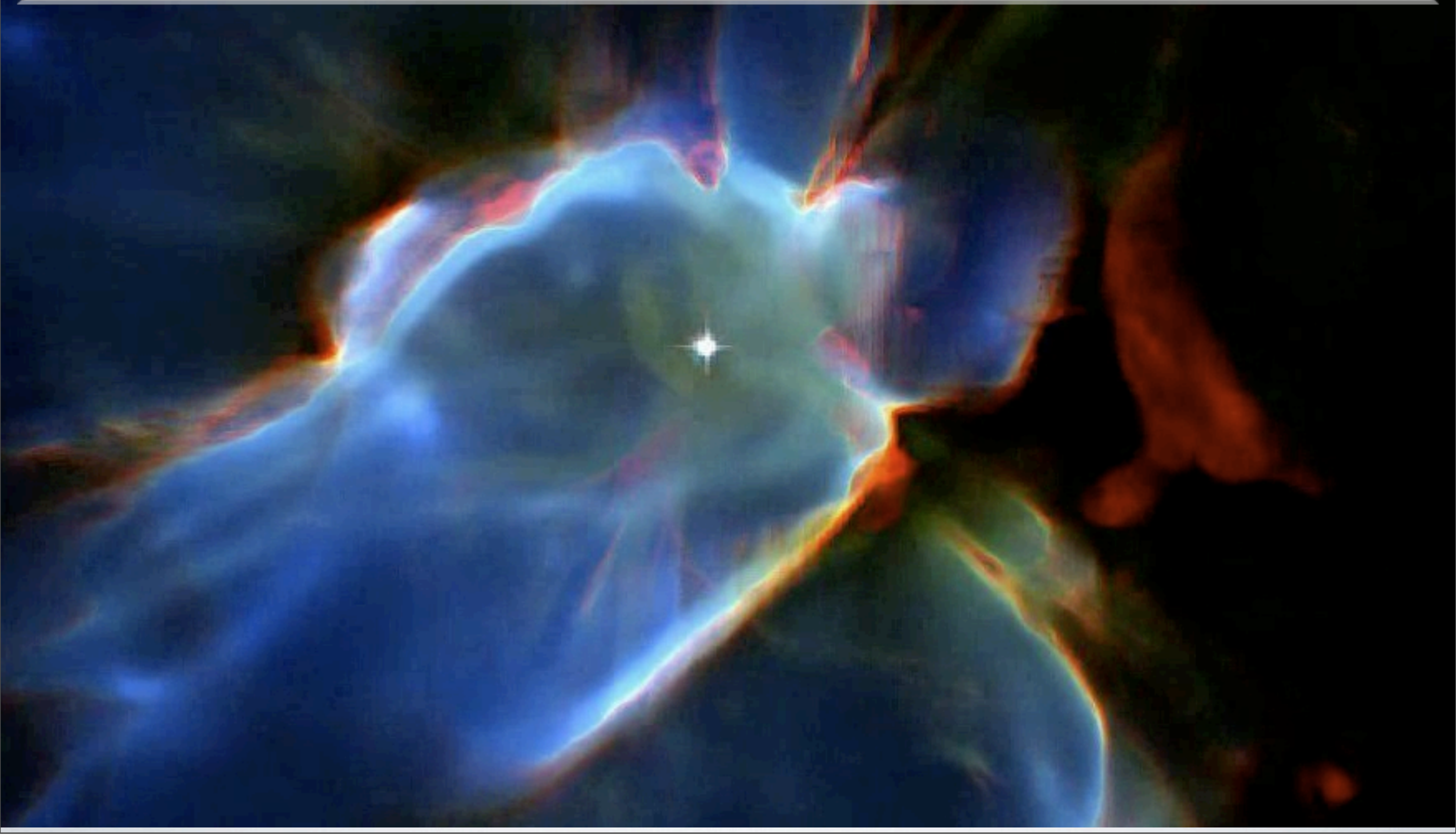
Overcoming $O(N_{STAR})$ :: Ray / Source Merging

Okamoto et al. (2011)
Wise & Abel (in prep)

- Sources are grouped on a binary tree.
- On each leaf, a "super-source" is created that has the center of luminosity.
- After the ray travel ~3-5 times the source separation, the rays merge.
- Recursive.



POP III RADIATIVE FEEDBACK



POP III 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.

POP III RADIATIVE FEEDBACK

- (Shapiro+ 2004) 2-D calculations of photo-evaporation of nearby halos

- (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)

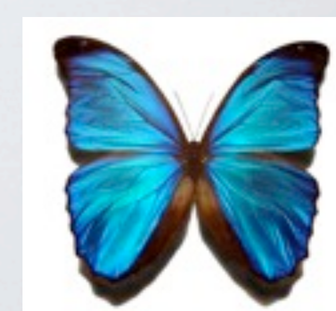
H II REGION OF A PRIMORDIAL STAR

Density

Temperature

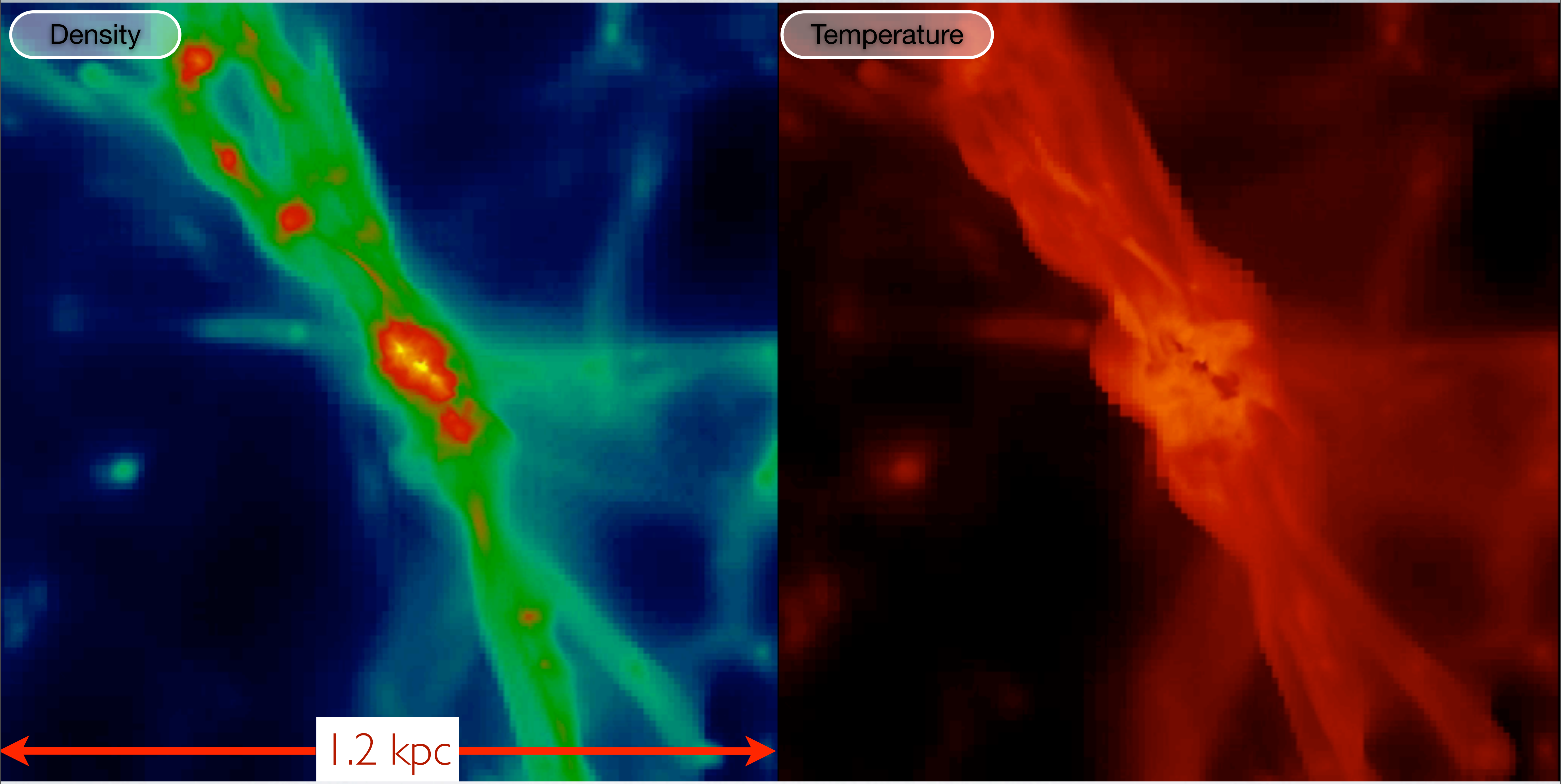
1.2 kpc

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



Abel, Wise, & Bryan (2007)

H II REGION OF A PRIMORDIAL STAR

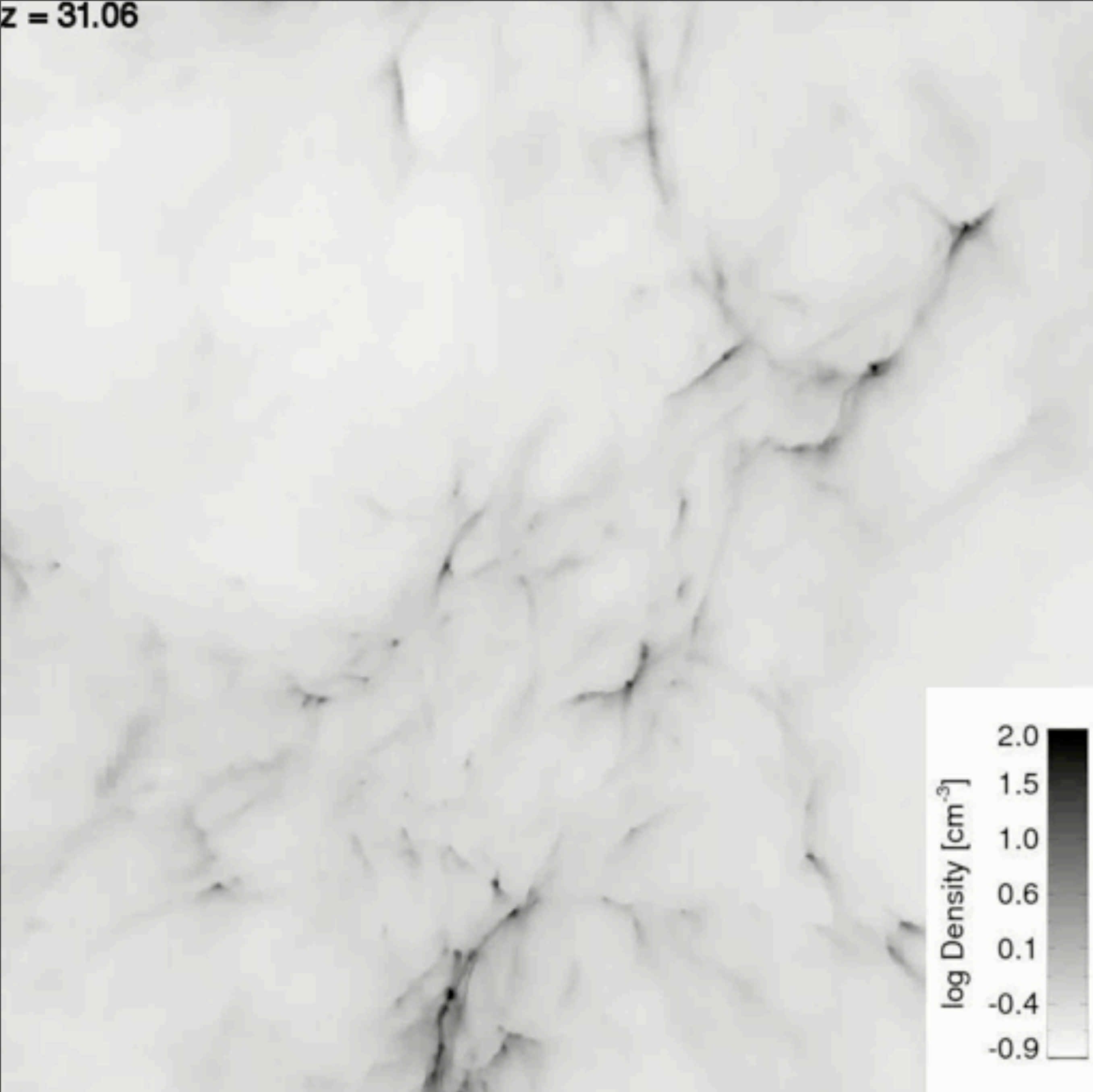


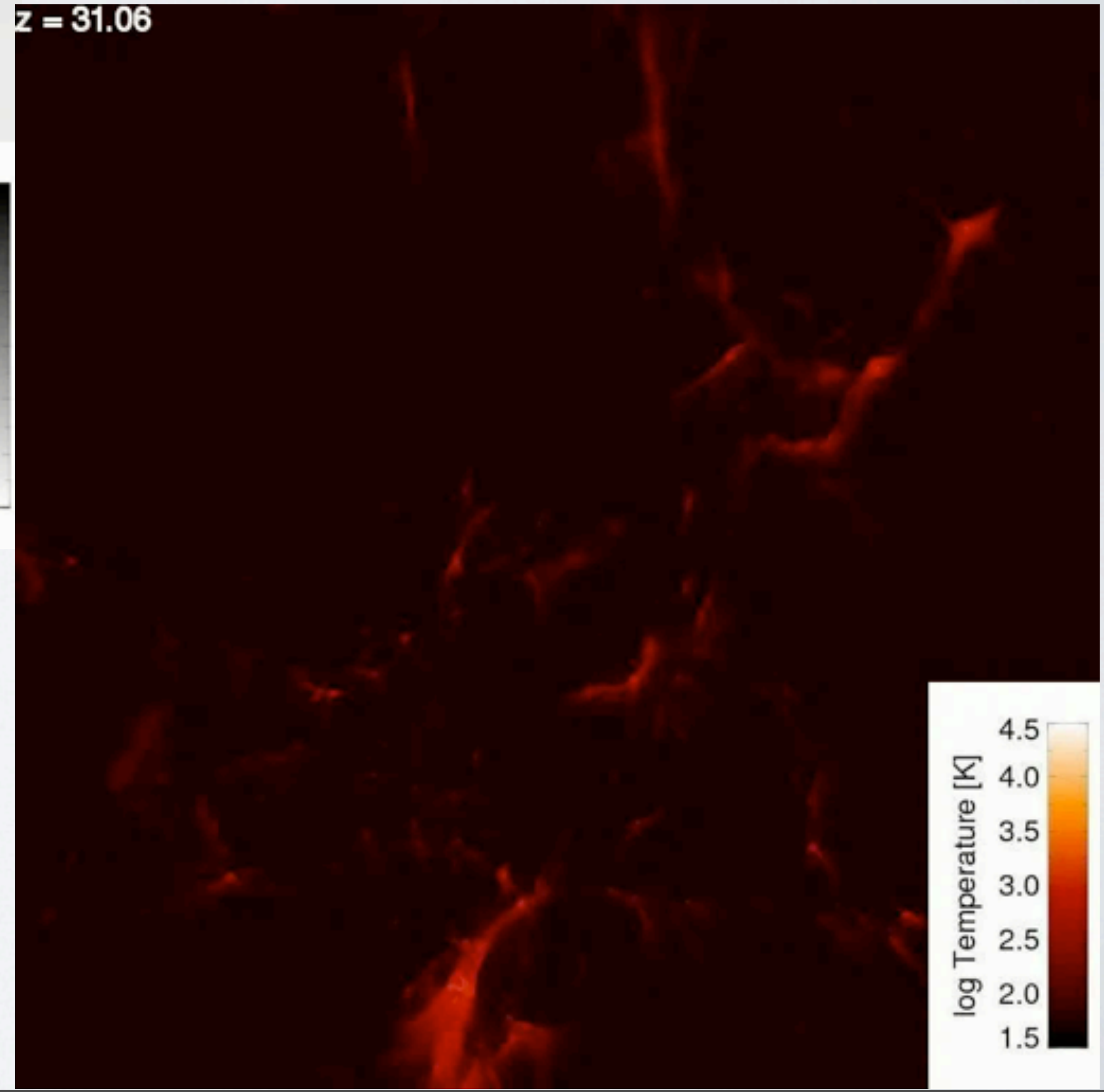
- $10^6\ M_\odot$ DM halo; $z = 17$; single $100\ M_\odot$ star (no SN)
- Drives a 30 km/s shock wave, expelling most of the gas

CONTRIBUTION TO REIONIZATION?

- By 2007-2008, several Pop III stars were being simulated in cosmological simulations that had radiative transfer (Johnson+ 2007; Wise & Abel 2008)

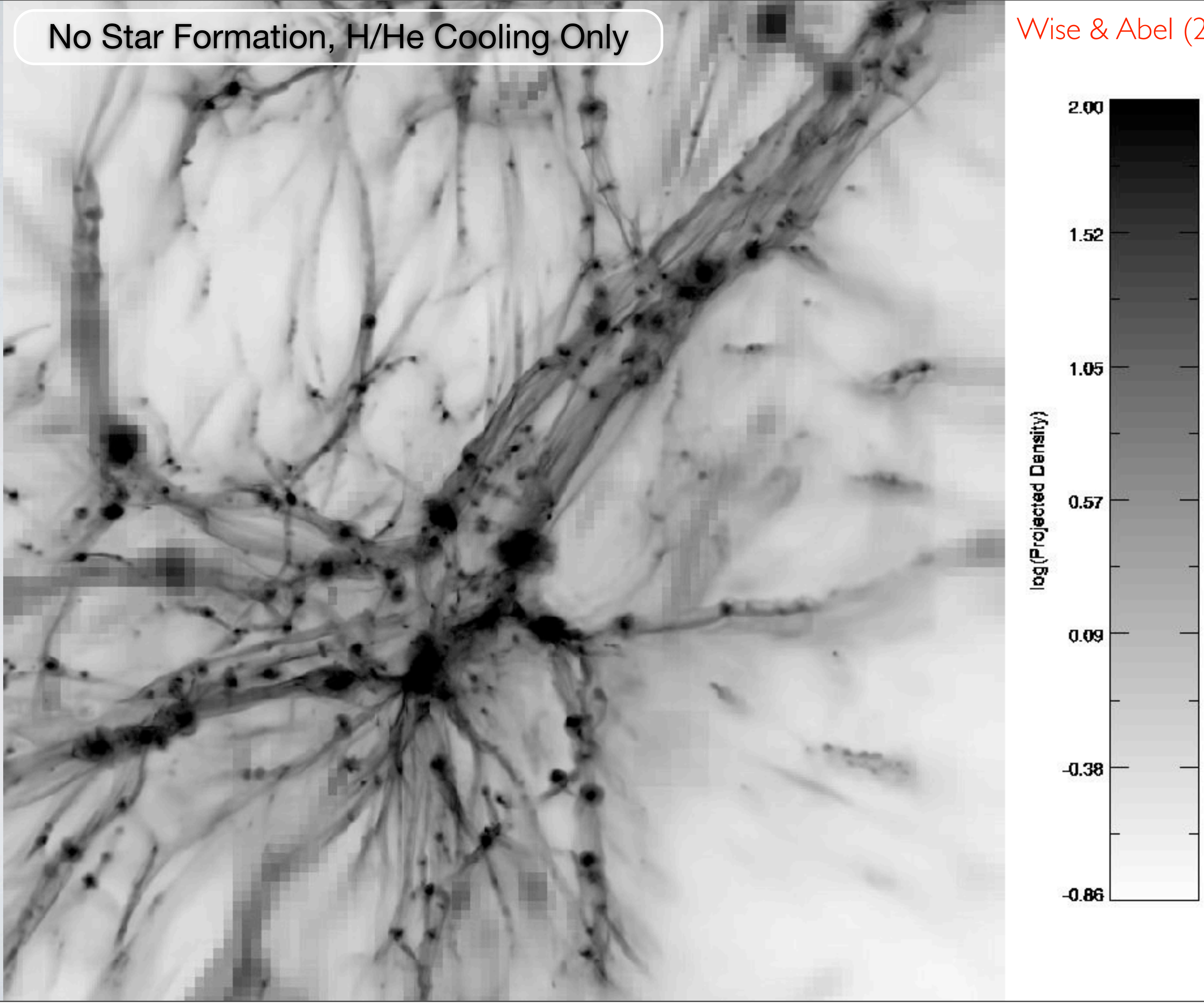
150 comoving kpc
~30 Pop III stars simulated
$z = 30 \rightarrow 16$





No Star Formation, H/He Cooling Only

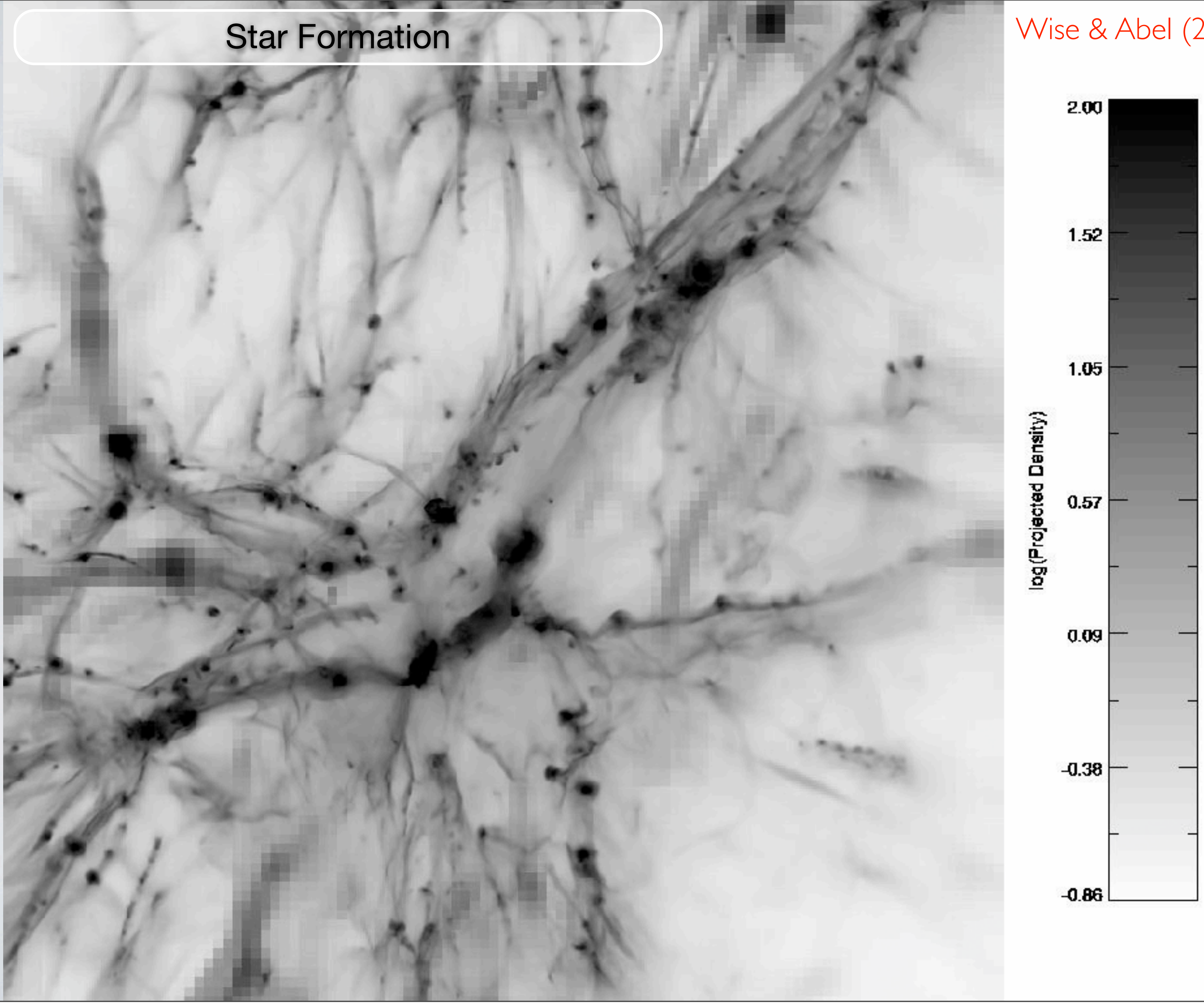
Wise & Abel (2008)



9 physical kpc; z = 17

Star Formation

Wise & Abel (2008)

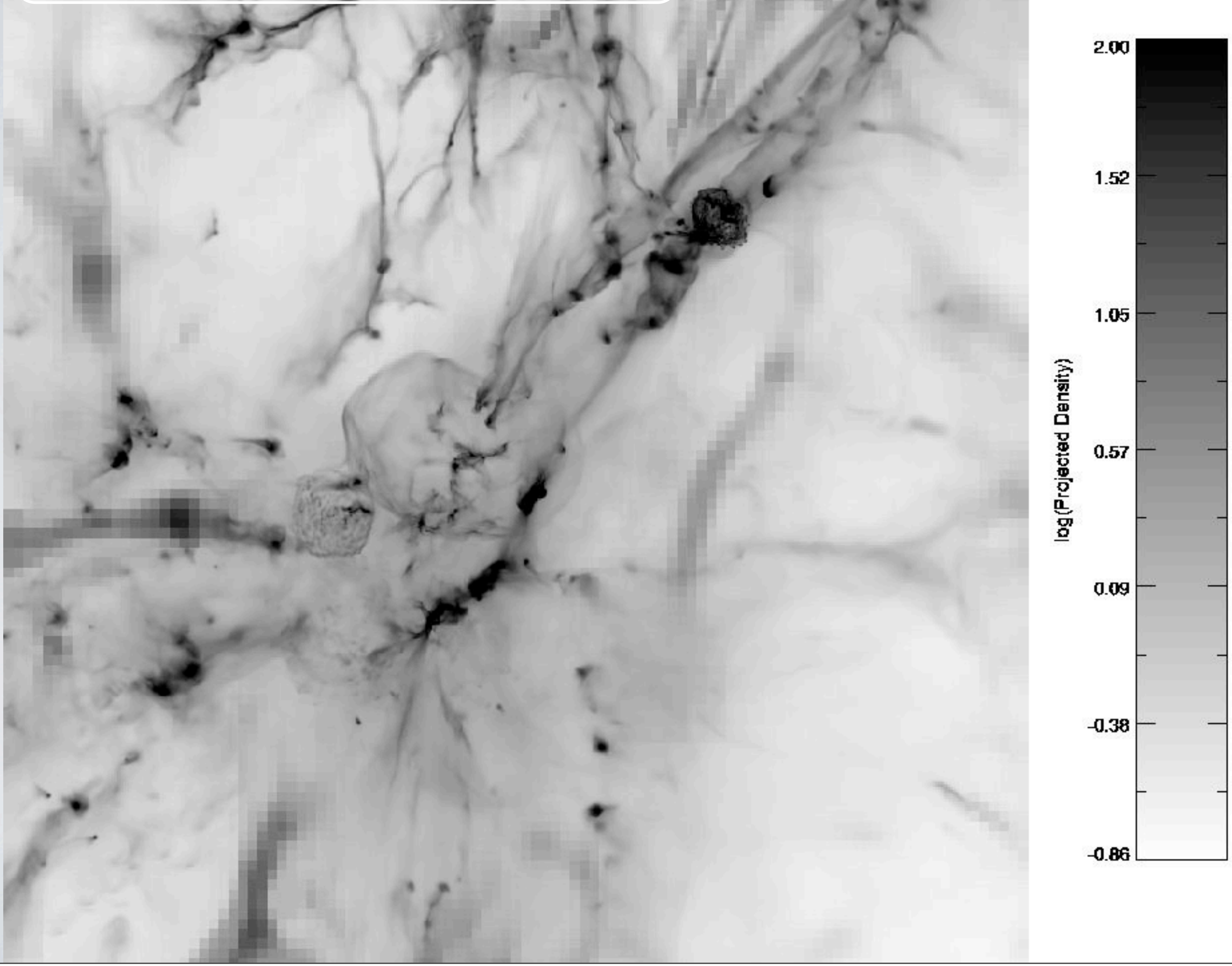


9 physical kpc; z = 17

Star Formation + SNe

Wise & Abel (2008)

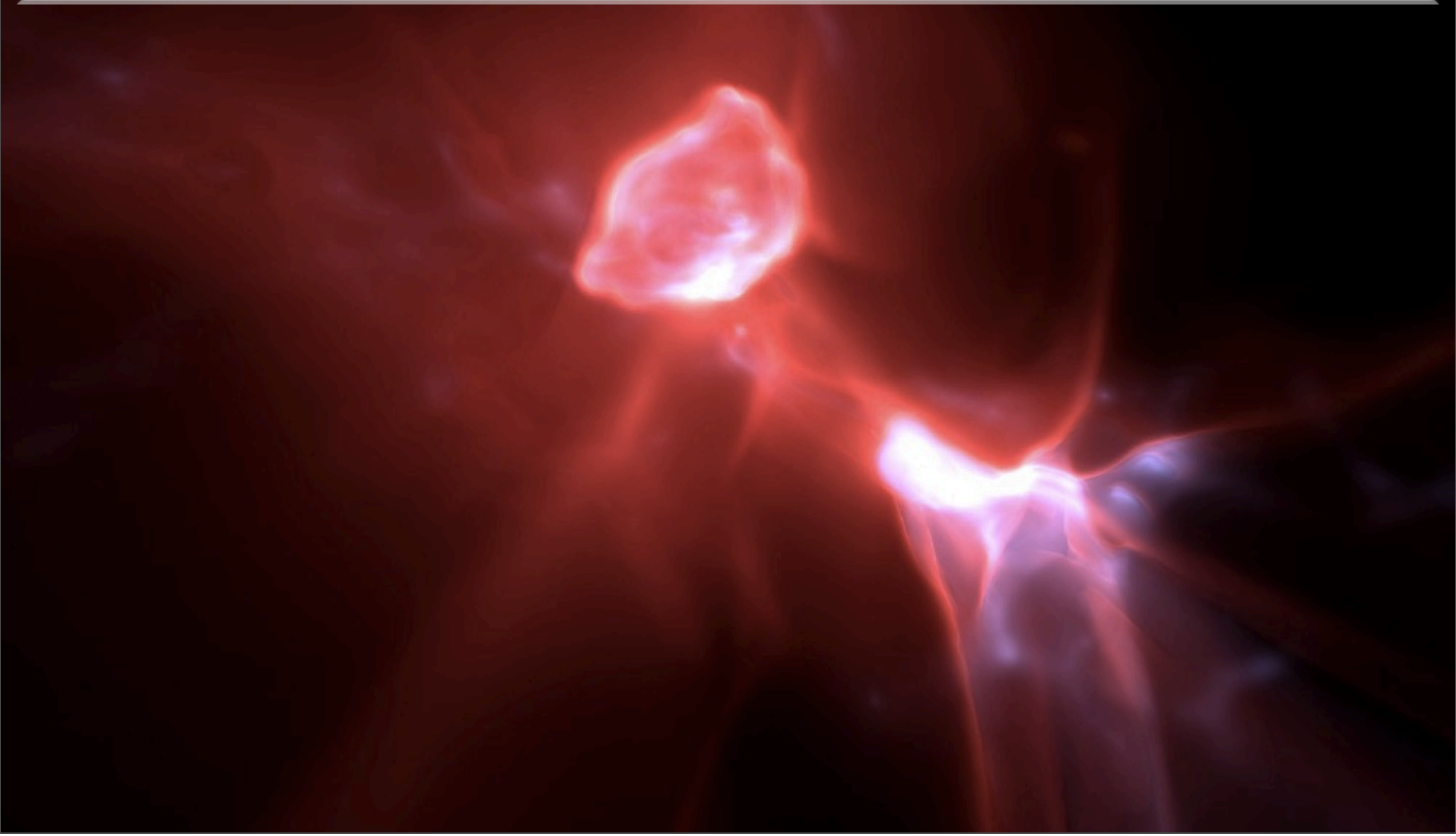
9 physical kpc; z = 17



CONTRIBUTION TO REIONIZATION?

- By 2007-2008, several Pop III stars were being simulated in cosmological simulations that had radiative transfer (Johnson+ 2007; Wise & Abel 2008)
  - Showed that ~25% of biased regions can be ionized before a galaxy forms.
  - Increases the minimum mass of a star-forming halo by pre-heating the IGM.
  - 1 in 10 ionizing photons results in a sustained ionization
  - Photo-evaporates neighboring minihalos.

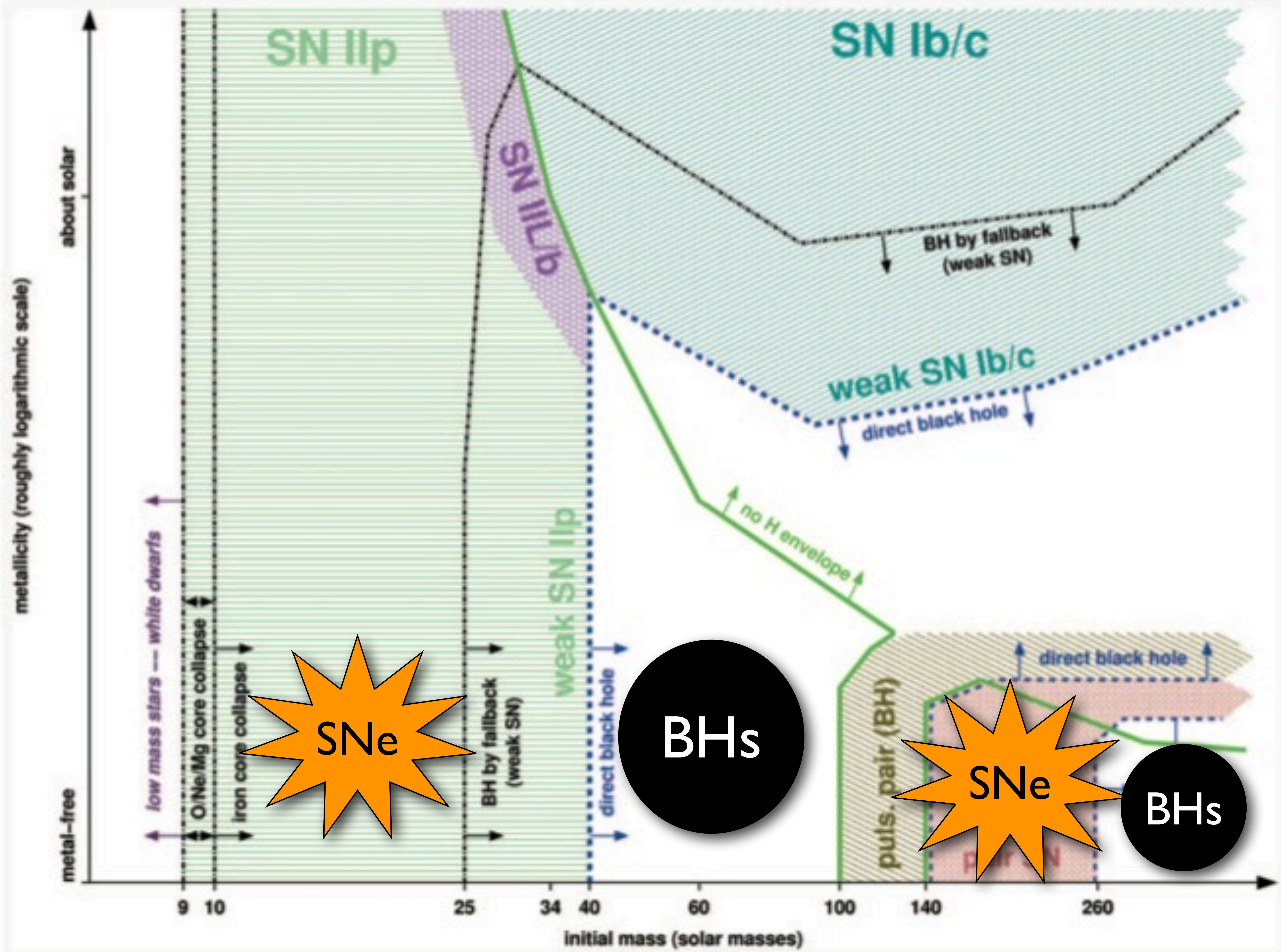
POP III SUPERNOVAE



POP III CHEMICAL FEEDBACK

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

- 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)



Heger et al. (2003)

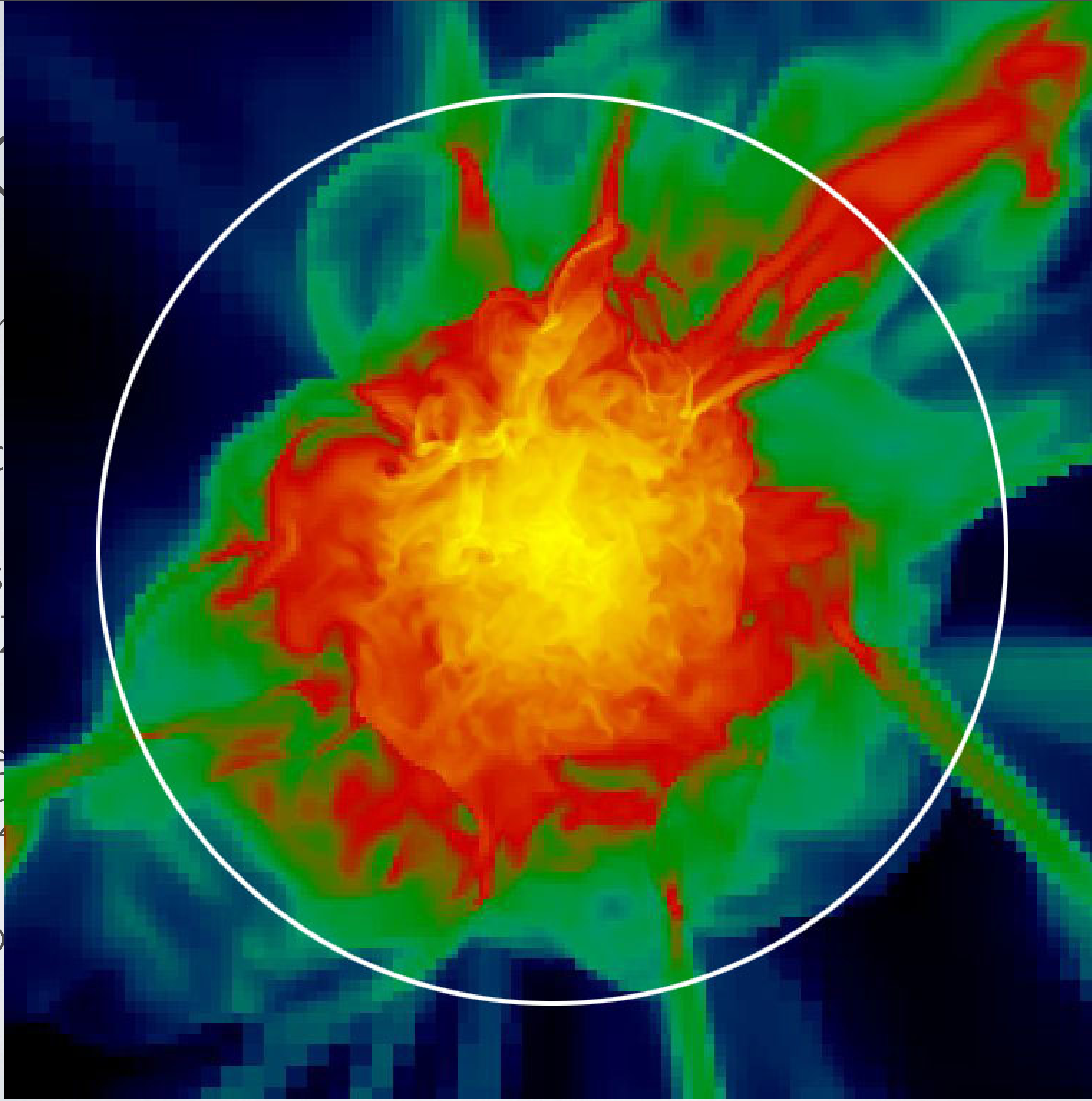
CHEMICAL ENRICHMENT

- (Bromm+ 2003) PISN in a cosmological setting. Removes 90% of the gas (even without radiative feedback!), pre-enriches the IGM to $\geq 10^{-4}\ Z_{\odot}$

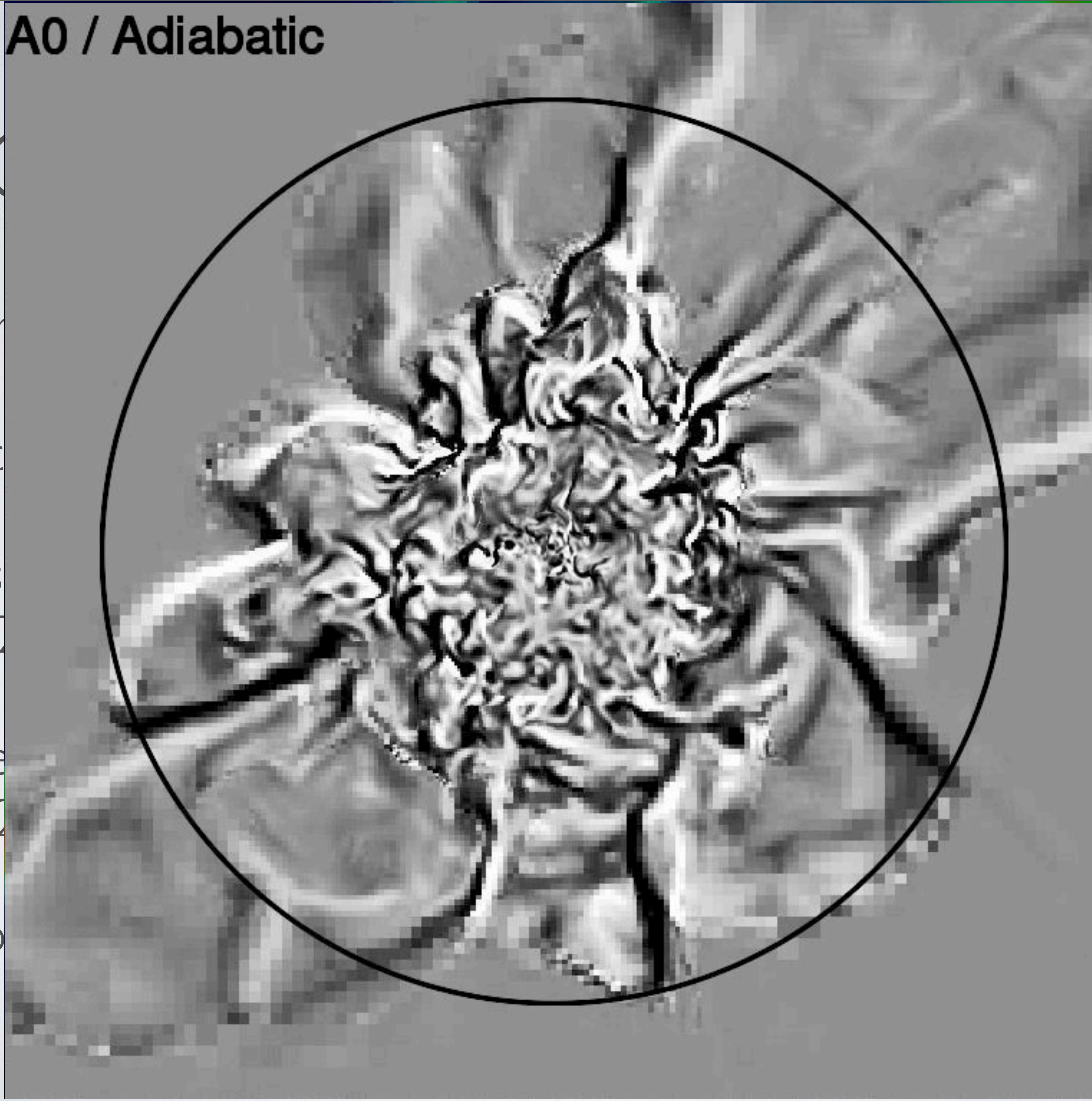
- (Wise+ 2008; Greif+ 2010) Nearly uniform enrichment to $10^{-3}\ Z_{\odot}$ from Pop III supernovae in dwarf galaxies.

  - Metal mixing in galaxies are driven by virial turbulence (Wise + 2007; Greif+ 2008).

  - About 60% of metals fallback into the galaxy.

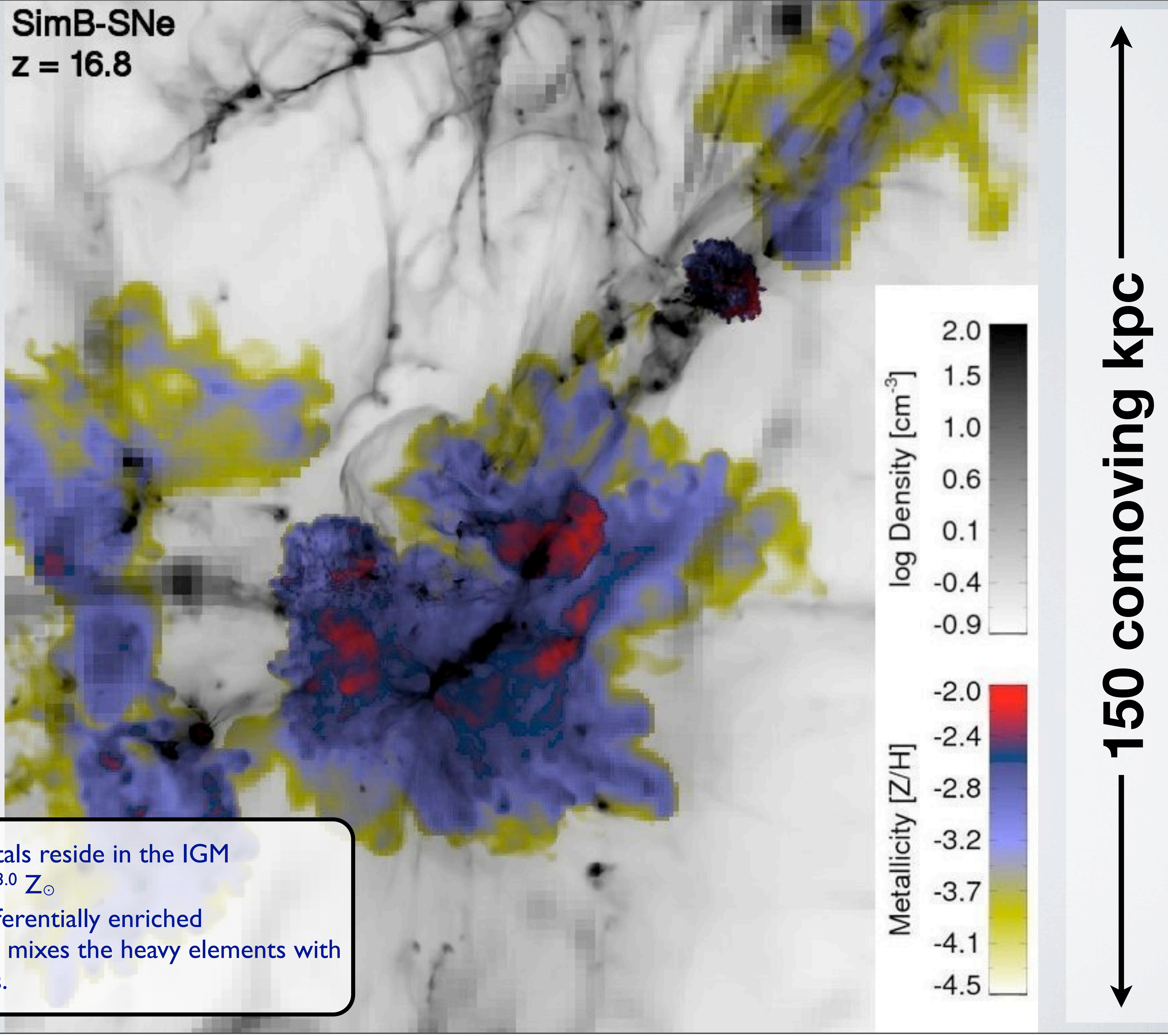


- (Bror es
  90%
  enric
- (Wis to
  10^{-3} Z
  - Me (Wise
    + 2
  - Ab



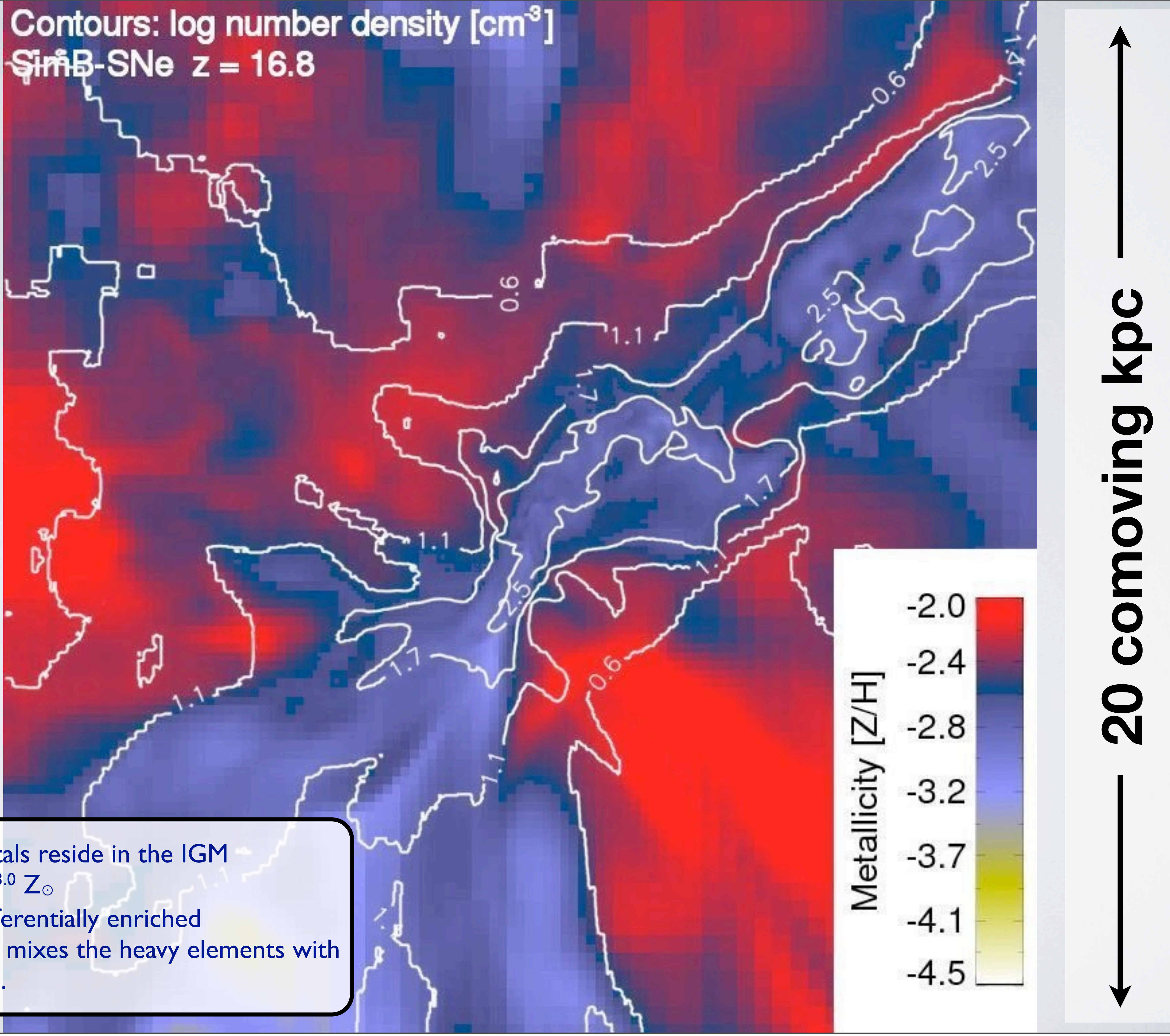
- (Bron … es
  90%
  enric
- (Wis … to
  10^{-3} 2
  - Me … (Wise
    + 2
  - Ab

Metal Enrichment



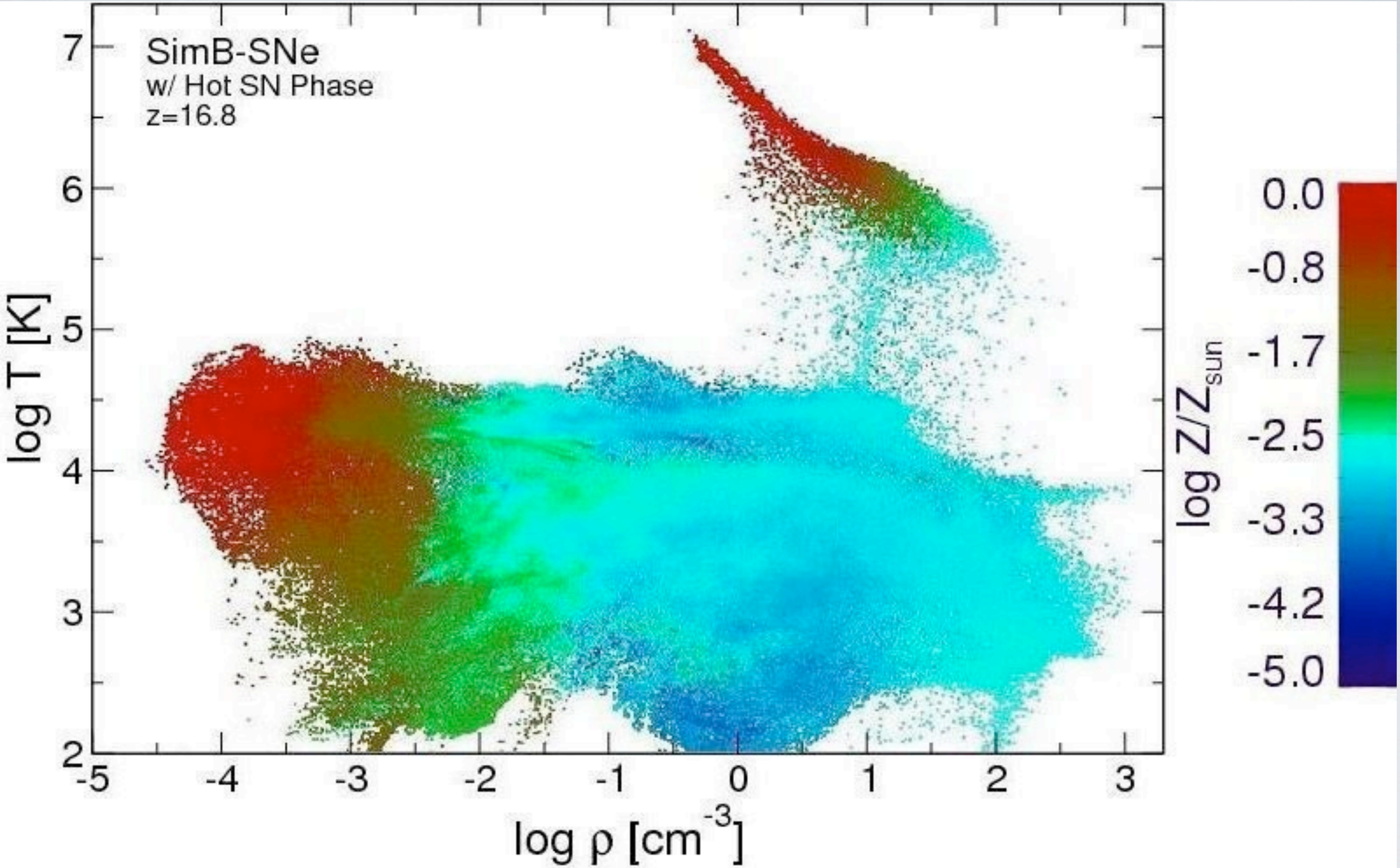
- 40% of metals reside in the IGM
- $Z_{IGM} = 10^{-3.0}\ Z_{\odot}$
- IGM is preferentially enriched
- Turbulence mixes the heavy elements with pristine gas.

Metal Enrichment



- 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



- 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.

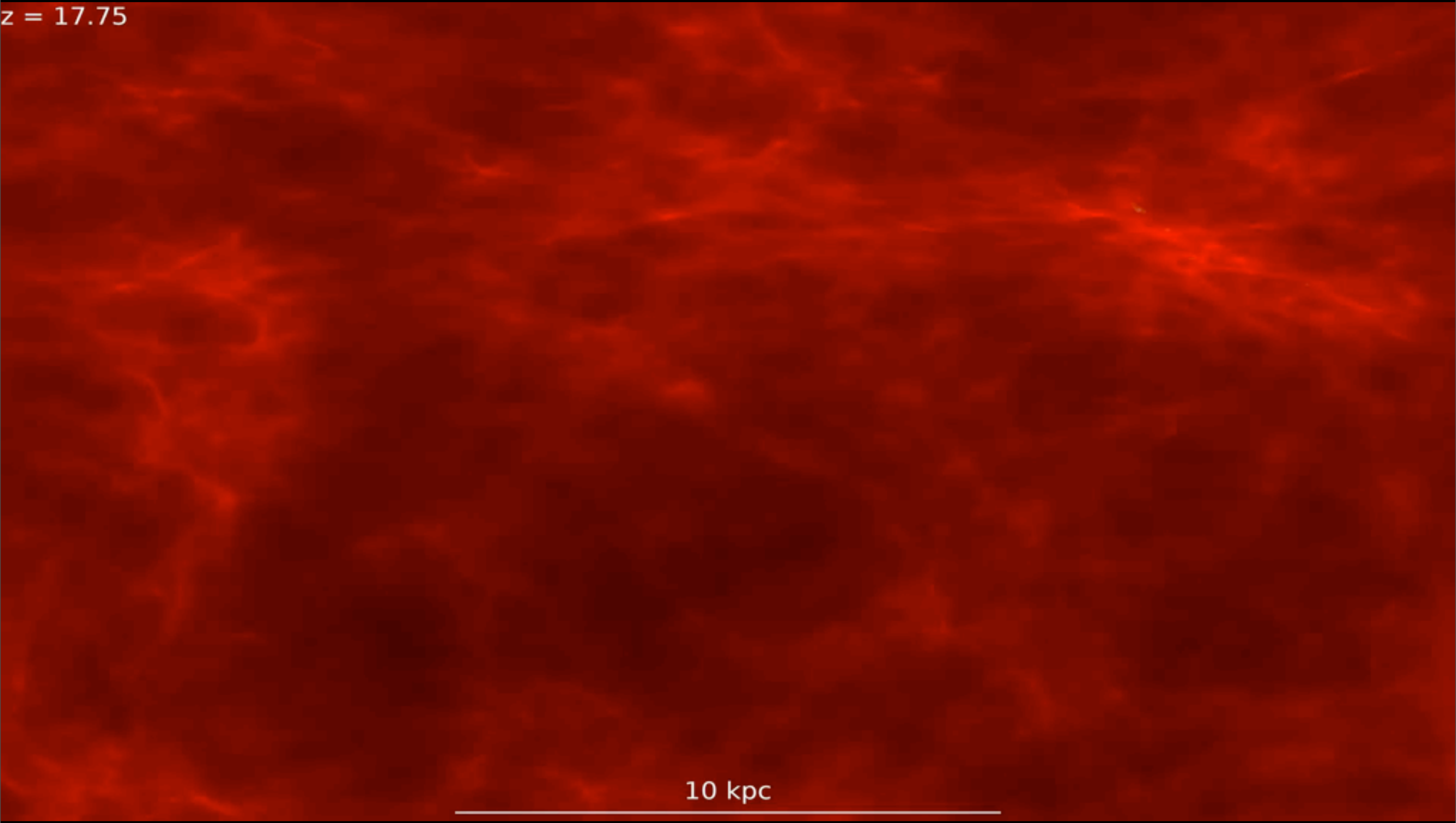
HIGH-Z DWARF GALAXIES

Wise, Turk, Norman, & Abel (2012)

TRANSITION TO GALAXIES

- Small-scale (1 comoving Mpc^3) AMR radiation hydro simulation with Pop II+III star formation and feedback (1000 cm^{-3} threshold)
- Coupled radiative transfer (ray tracing: optically thin and thick regimes)
- 1800 $M_\odot$ mass resolution, 0.1 pc maximal spatial resolution
- Self-consistent Population III to II transition at 10^{-4} $Z_\odot$
- Assume a Kroupa-like IMF for Pop III stars with mass-dependent luminosities, lifetimes, and endpoints.

$$f(\log M) = M^{-1.3} \exp\left[-\left(\frac{M_{\rm char}}{M}\right)^{1.6}\right], \quad M_{\rm char} = 100 M_\odot$$



z = 17.75
10 kpc

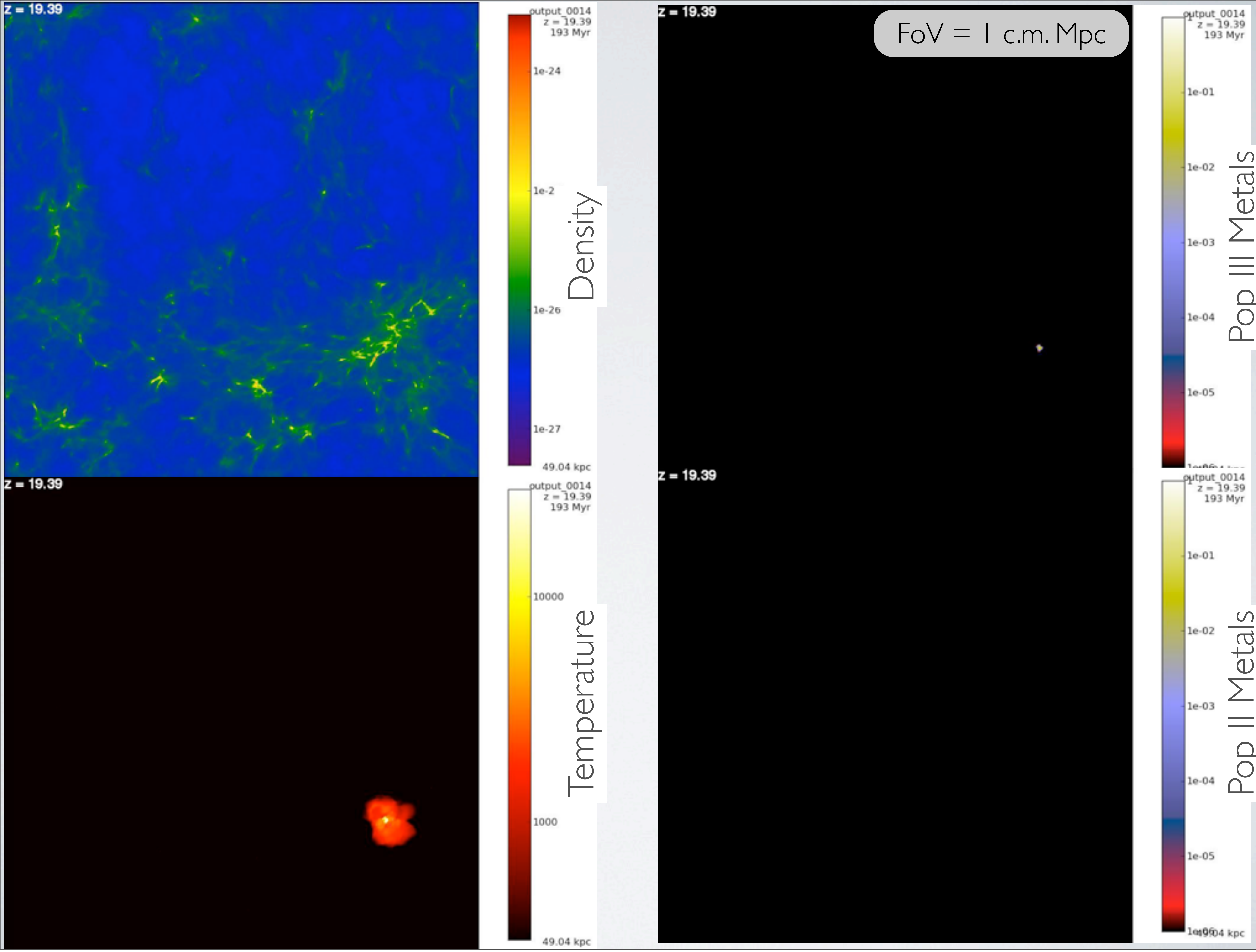
FoV = 1 c.m. Mpc

Density

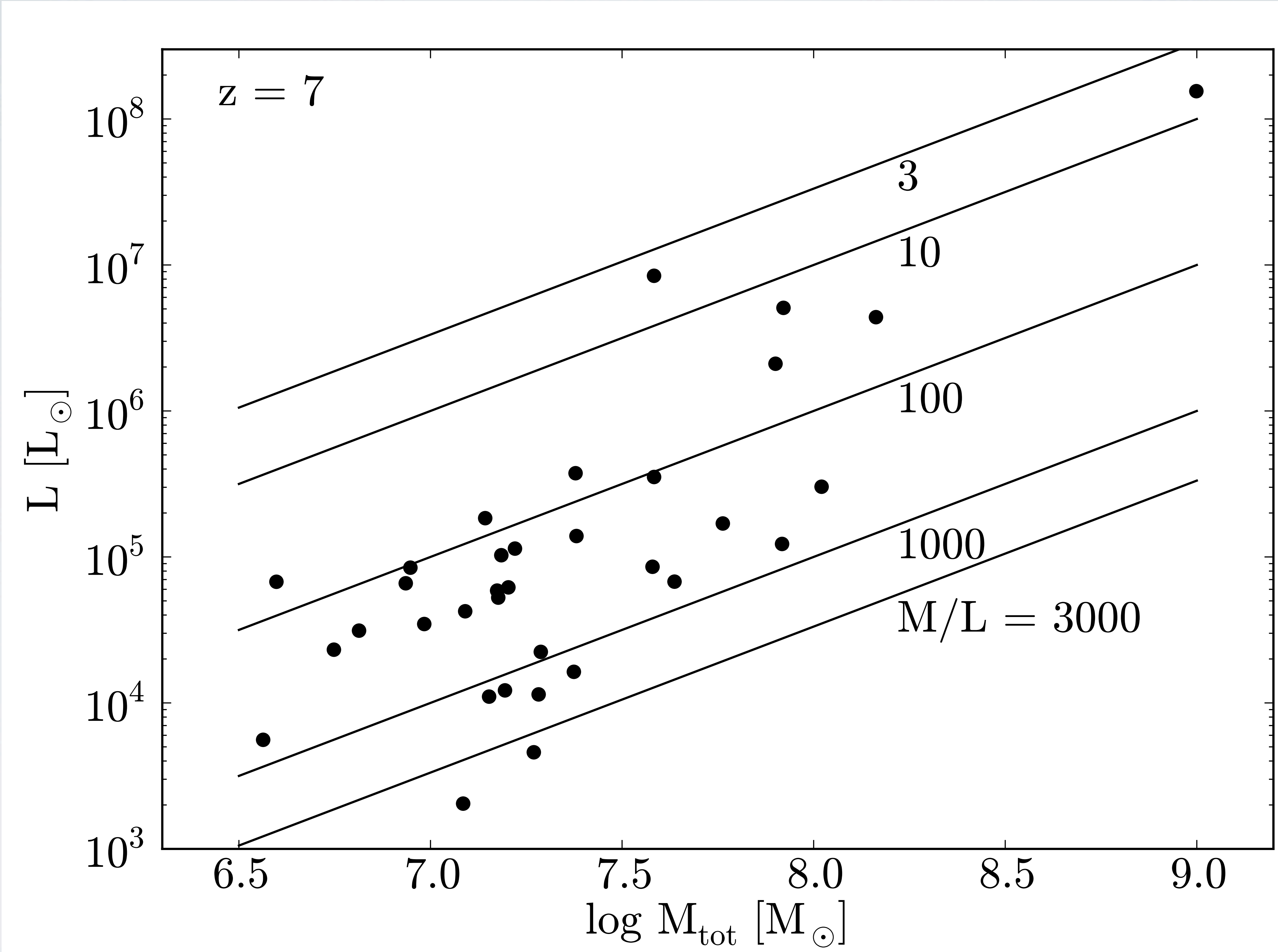
Pop III Metals

Temperature

Pop II Metals


z = 19.39
output_0014
z = 19.39
193 Myr
1e-24
1e-2
1e-26
1e-27
49.04 kpc
Density
FoV = 1 c.m. Mpc
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
10000
1000
Temperature
Pop II Metals

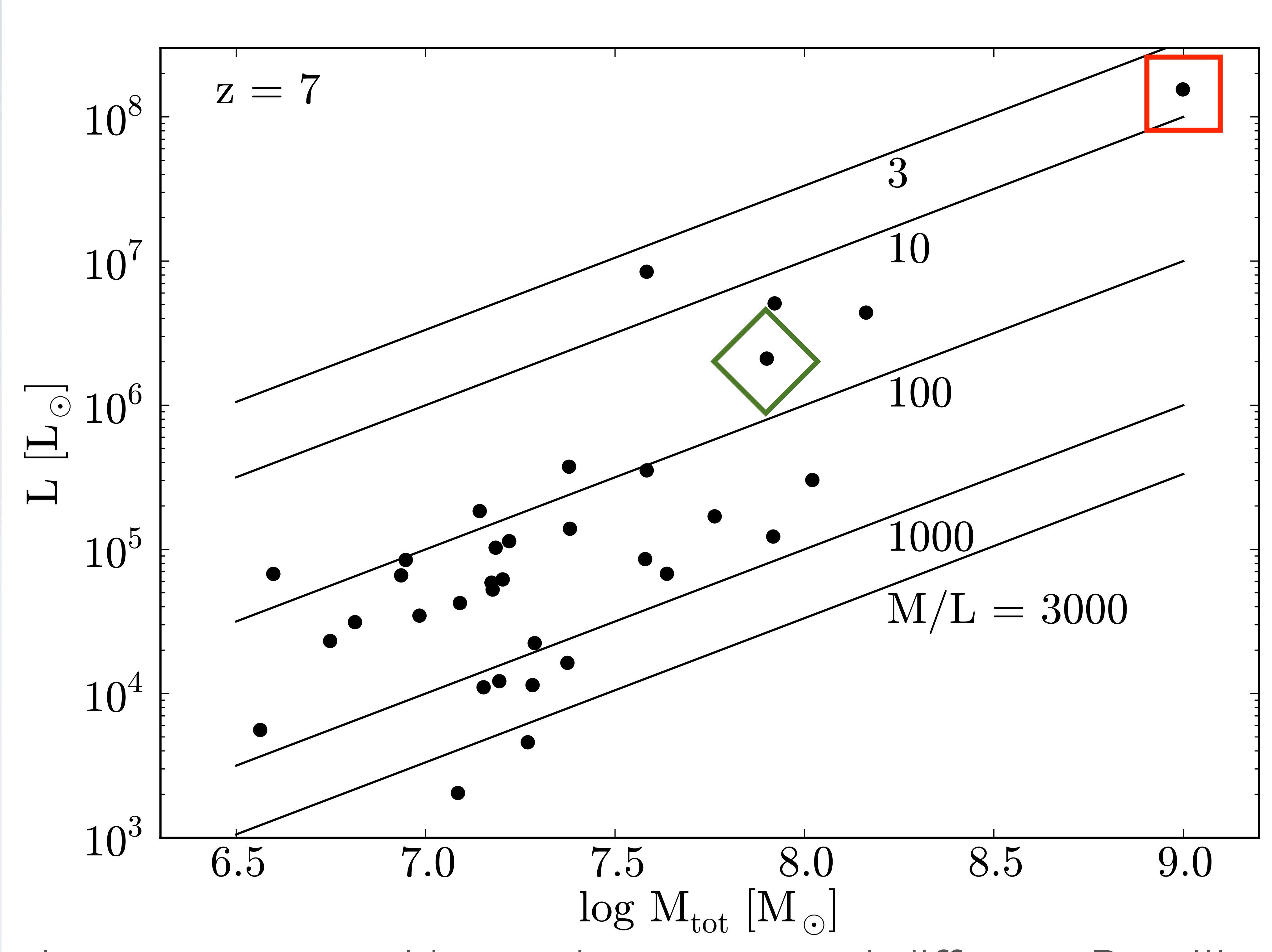
MASS-TO-LIGHT RATIOS



Scatter at low-mass caused by environment and different Pop III endpoints

$M < 10^8\ M_\odot$ halos

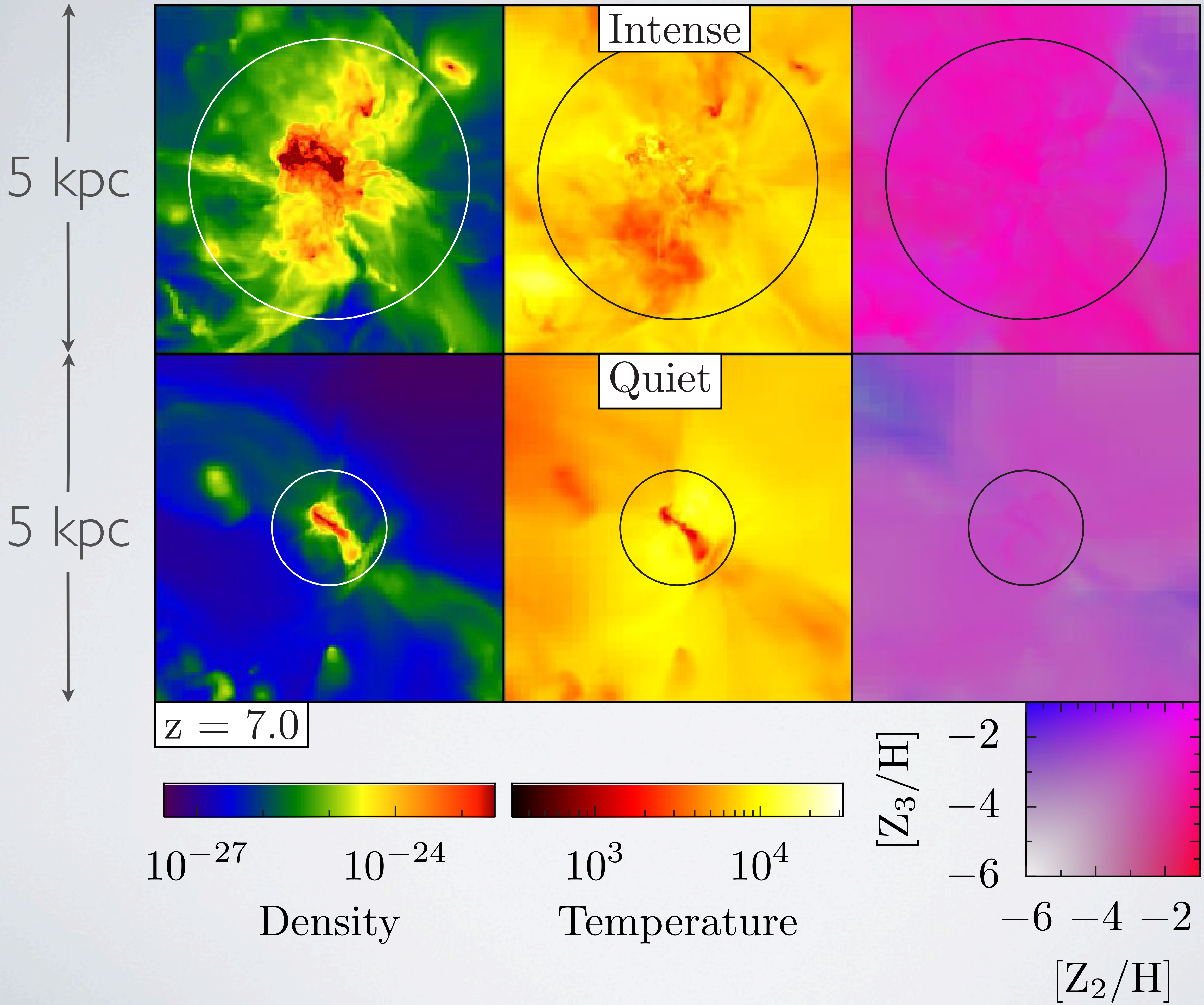
MASS-TO-LIGHT RATIOS

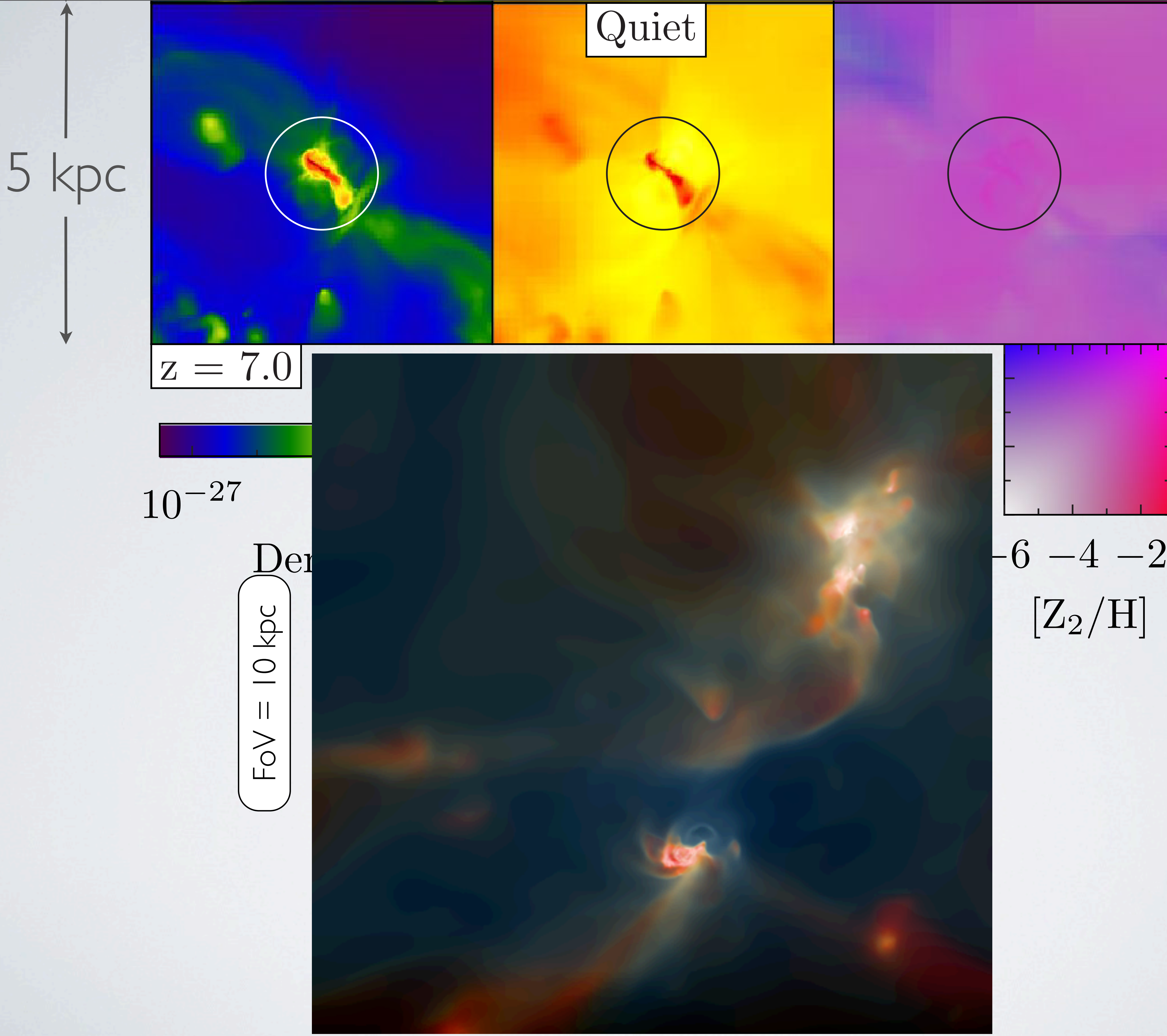


Scatter at low-mass caused by environment and different Pop III endpoints

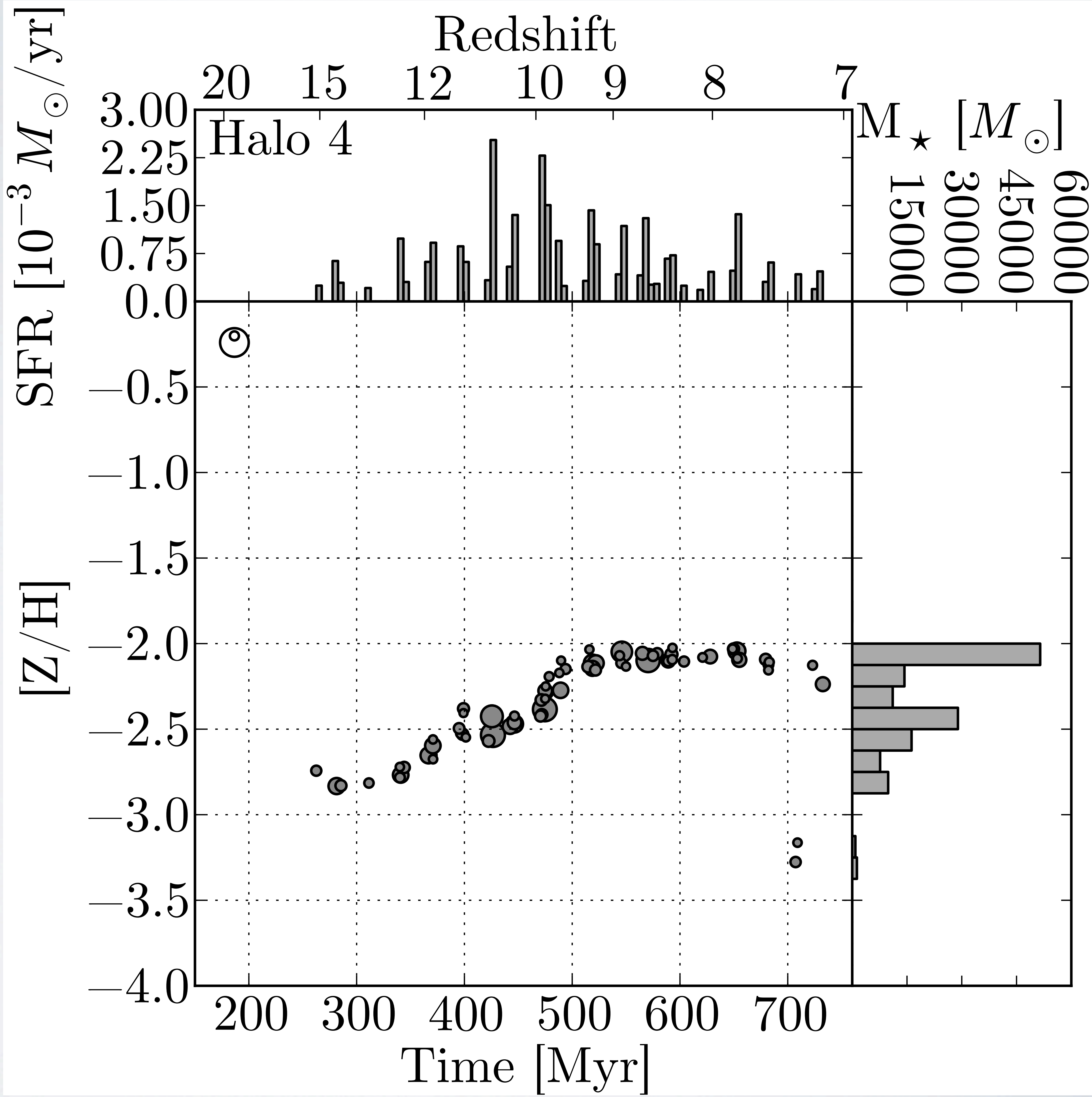
$M < 10^8 M_\odot$ halos

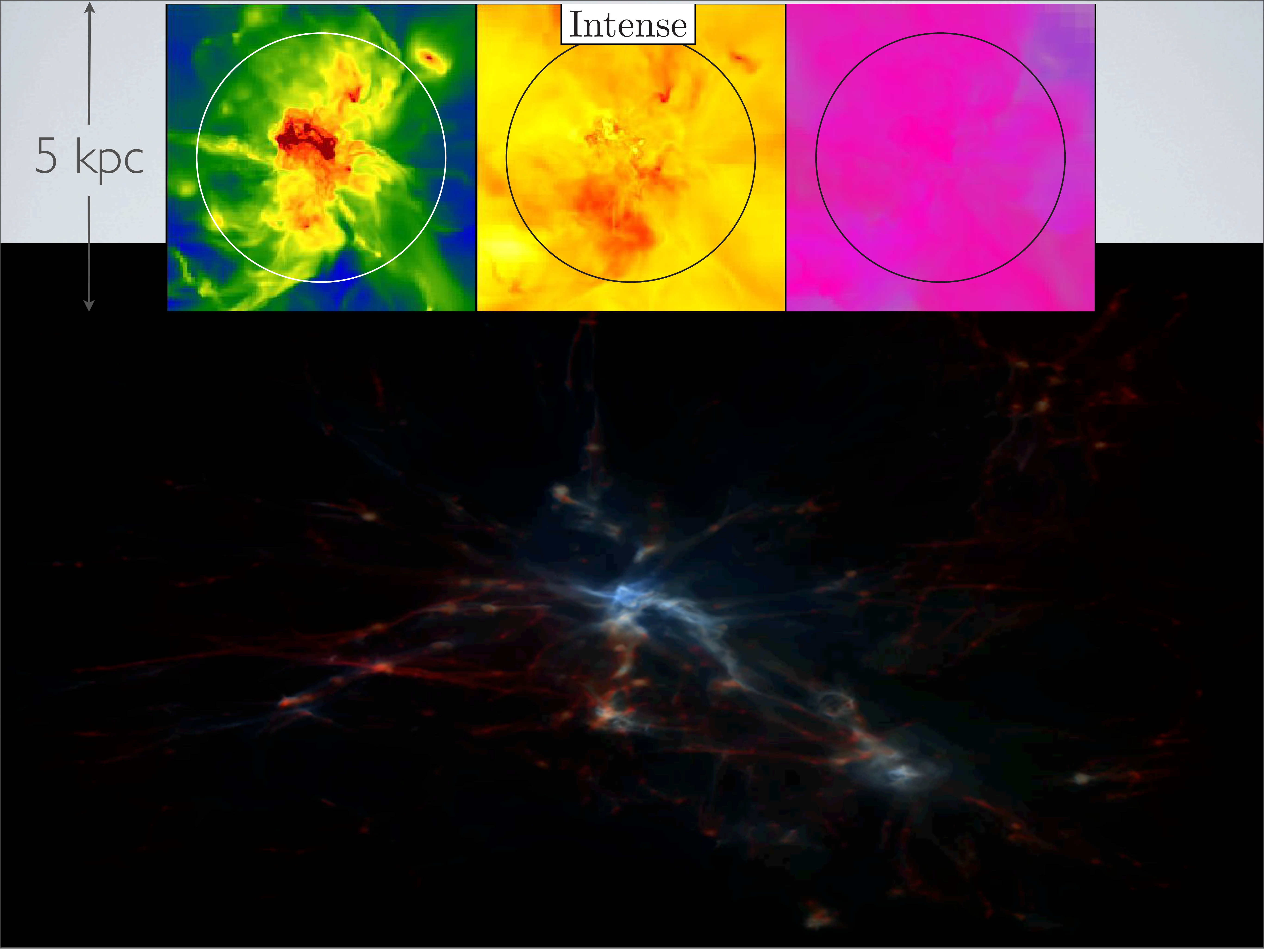
Wise, Turk, Norman, & Abel (2012)



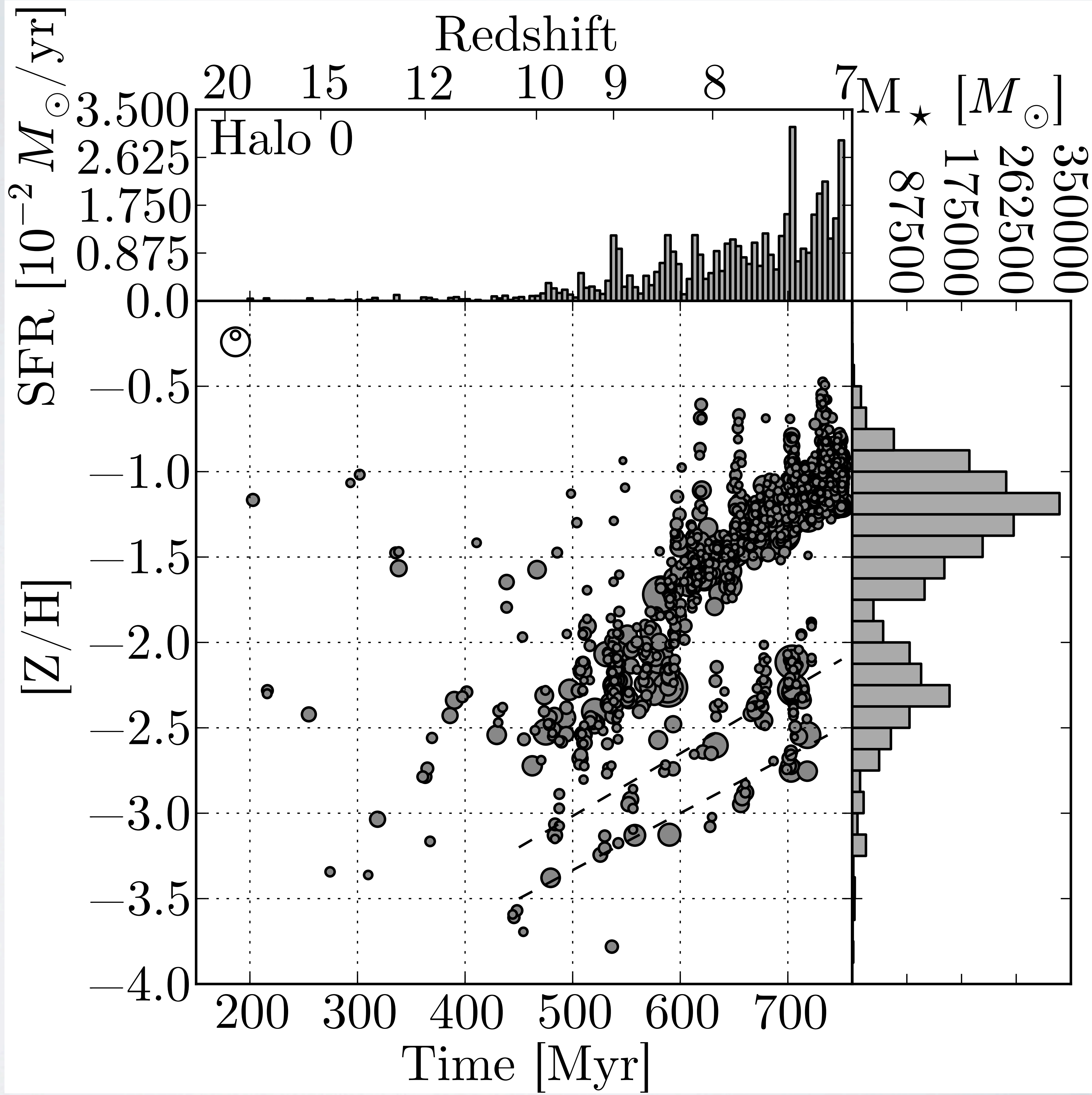

5 kpc
Quiet
z = 7.0
10^{-27}
De
-6 -4 -2
$[Z_2/H]$
FoV = 10 kpc

- Isolated halo (8e7 M☉) 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



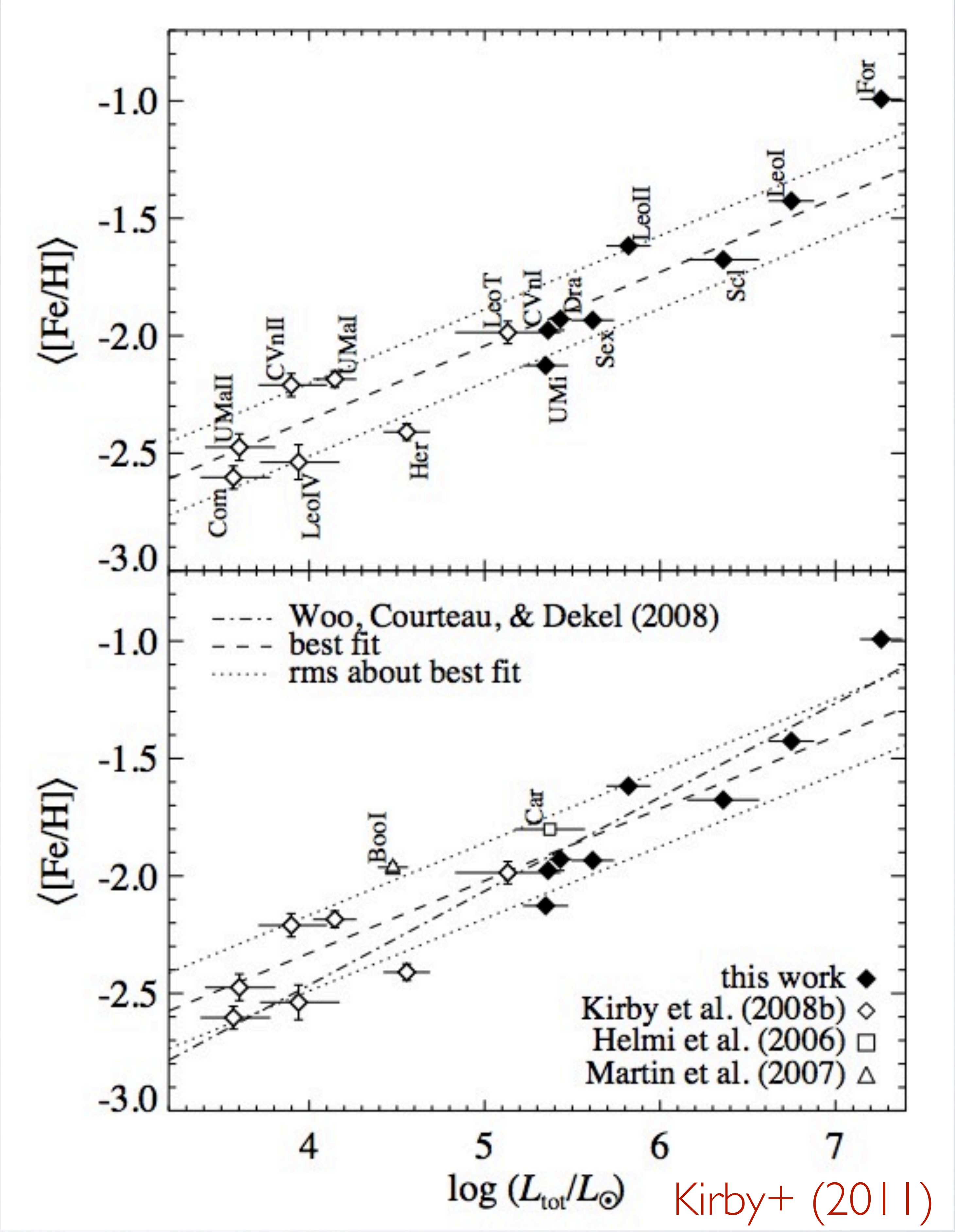

5 kpc
Intense

- 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



Z-L RELATION IN LOCAL DWARF GALAXIES

- Average metallicity in a 10^6 $L_\odot$ galaxy is [Fe/H] ~ –2
- Useful constraint of high-redshift galaxies, if we assume that this metal-poor population was formed during reionization.

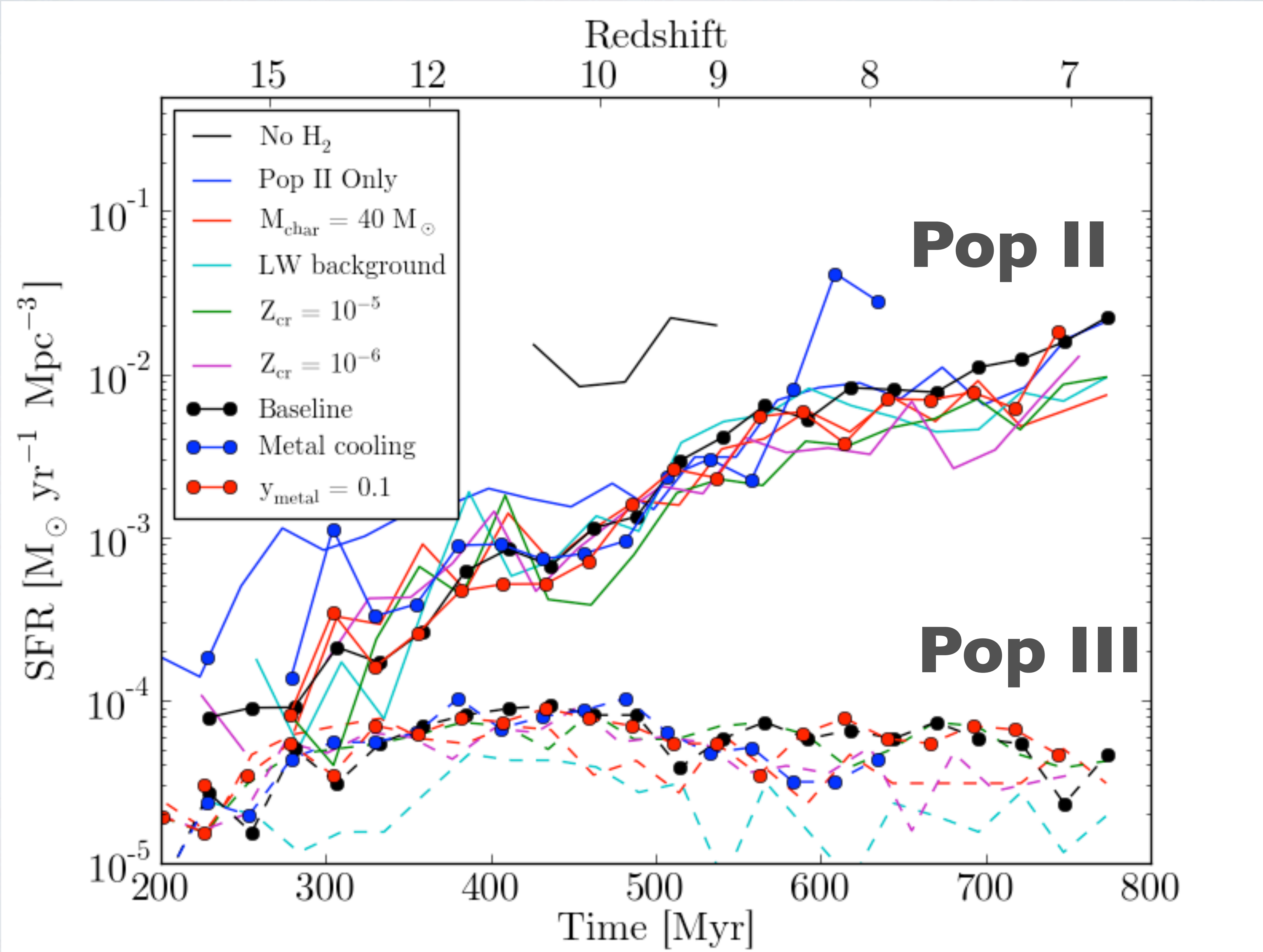


Kirby+ (2011)

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	

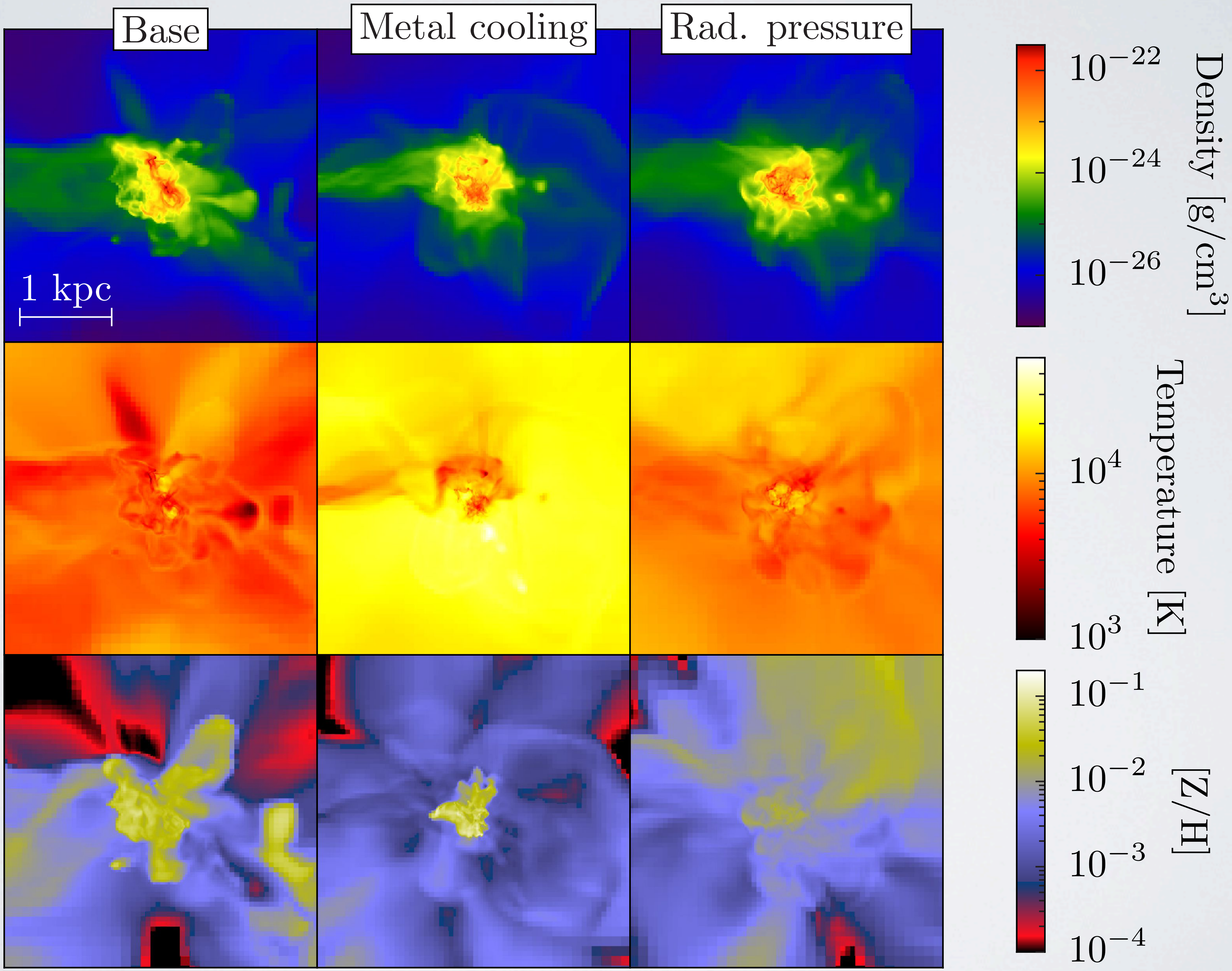
STAR FORMATION RATES



JHW+ (arXiv:1206.1043)

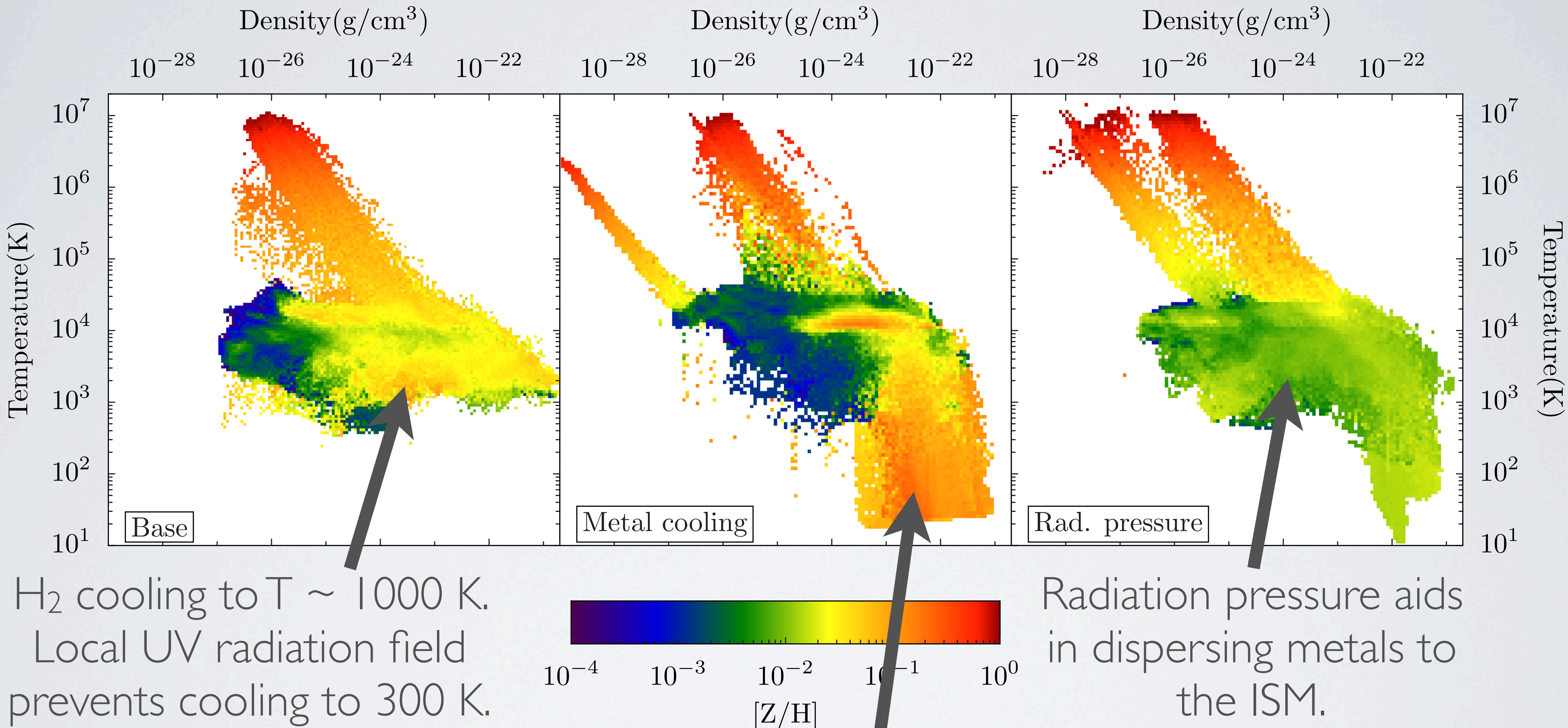
EFFECTS OF RADIATION PRESSURE

$M_{VIR} = 3 \times 10^8\ M_\odot$ GALAXY AT $z = 8$



EFFECTS OF RADIATION PRESSURE

AVG. METALLICITIES IN DENSITY-TEMPERATURE SPACE



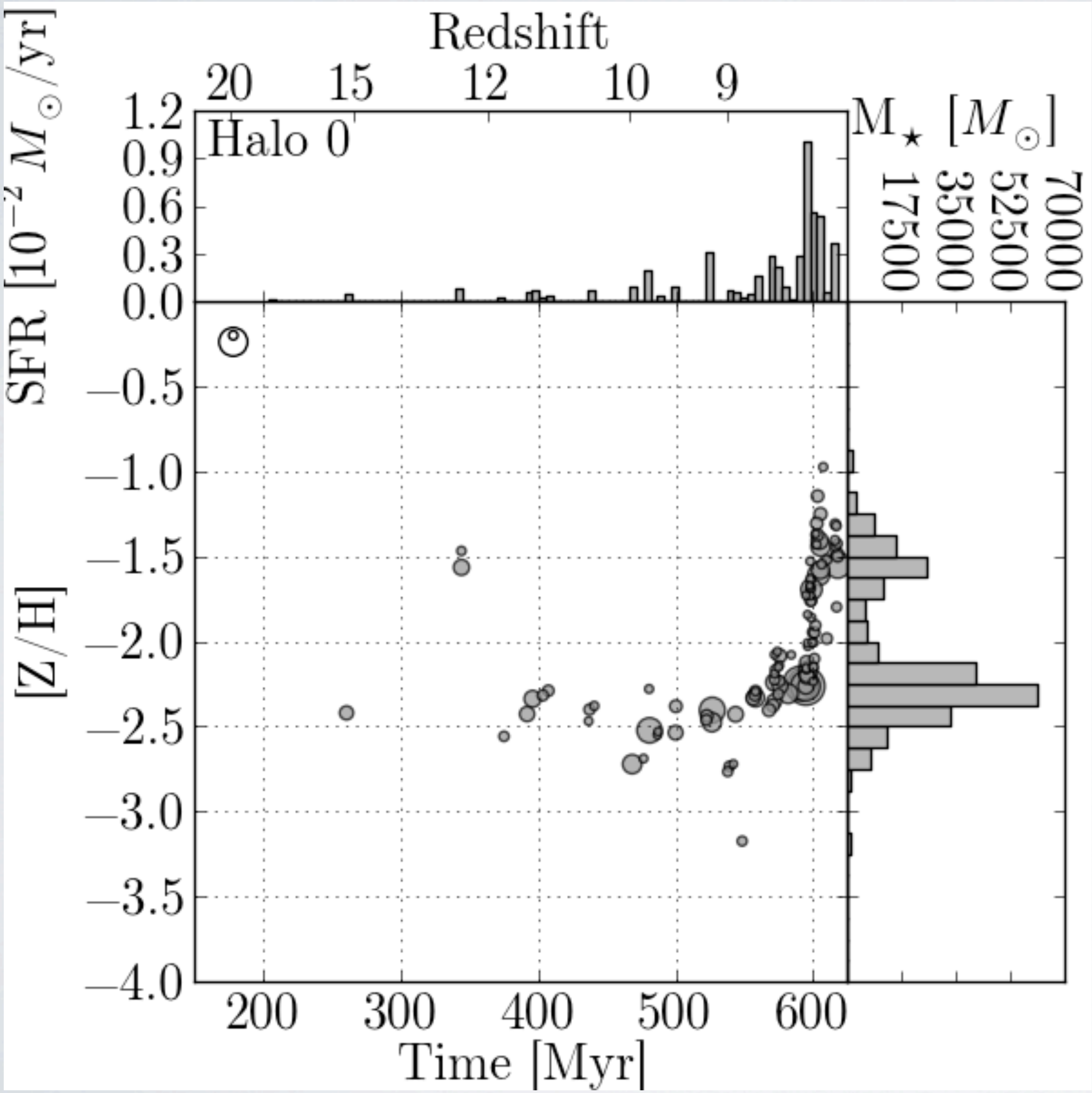
H_2 cooling to T ~ 1000 K. Local UV radiation field prevents cooling to 300 K.

Radiation pressure aids in dispersing metals to the ISM.

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

JHW+ (arXiv:1206.1043)

BASELINE AT $z = 8$



Main Limitation:

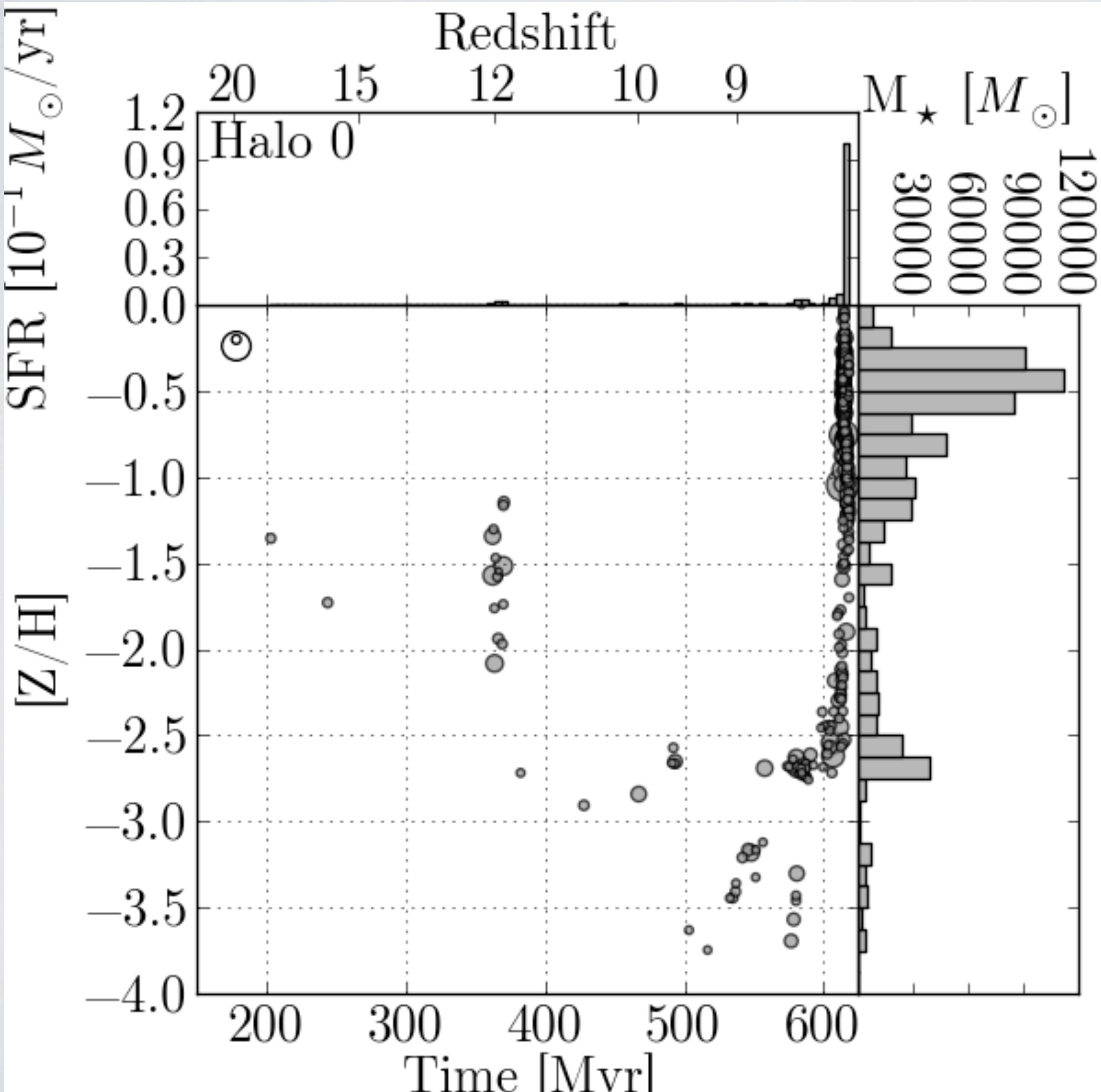
lacking

Metal cooling

Soft UV background

JHW+ (arXiv:1206.1043)

+ METAL COOLING & SOFT UVB



(Re-)introducing typical overcooling problem during initial star formation at $M \sim 10^8 M_\odot$

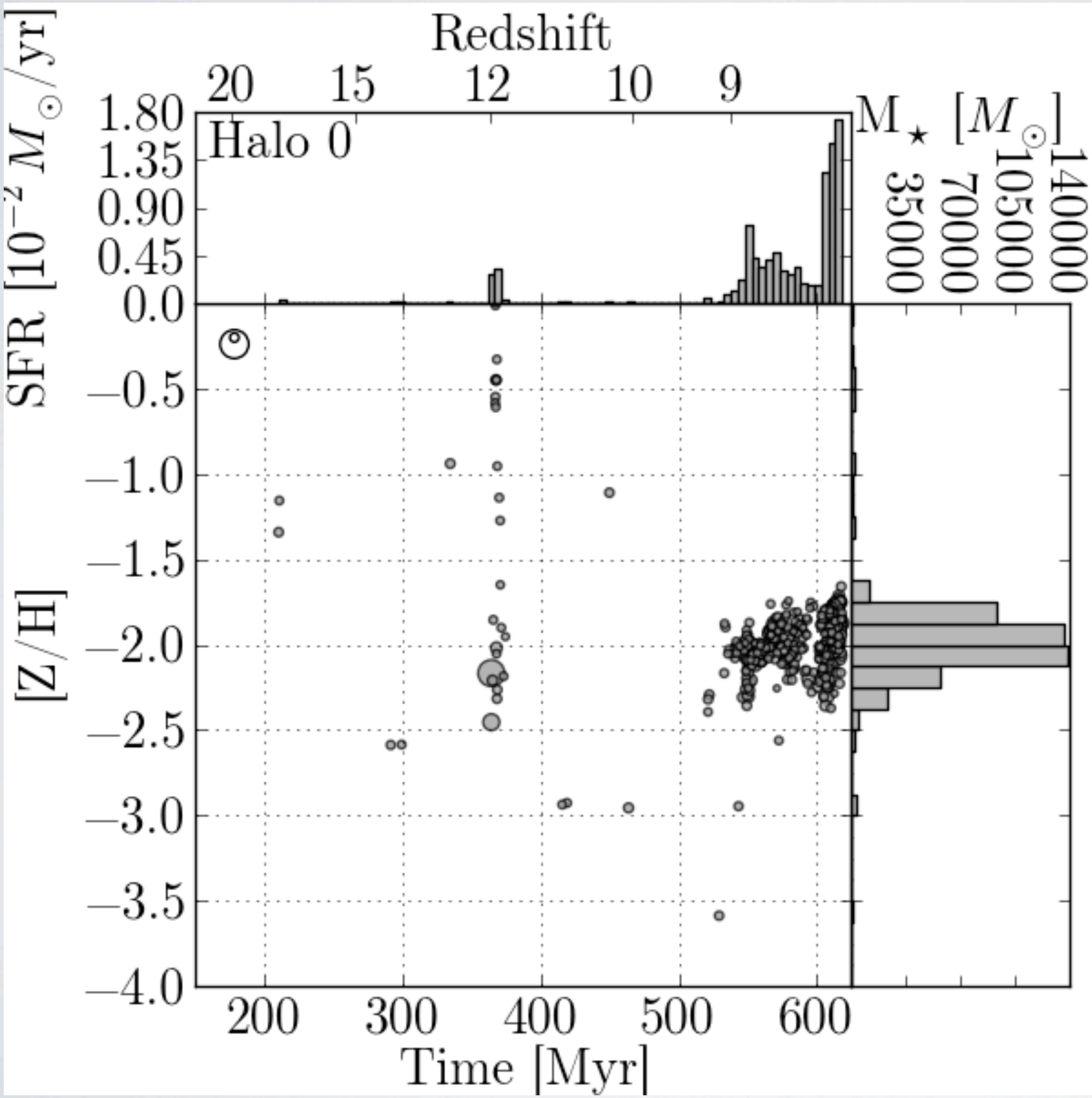
Katz+ (1996) plus many more...

Causes over-enrichment – nearly solar metallicities.

Doesn't match with $z = 0$ dwarfs, *but* this could be incorporated into a bulge

JHW+ (arXiv:1206.1043)

SOFT UVB + METAL COOLING + RAD. PRESSURE



Momentum transfer from ionizing radiation

Haehnelt (1995)
Murray, Quataert, & Thompson + TQM (2005)

No treatment of radiation pressure on dust → lower limit on its effects

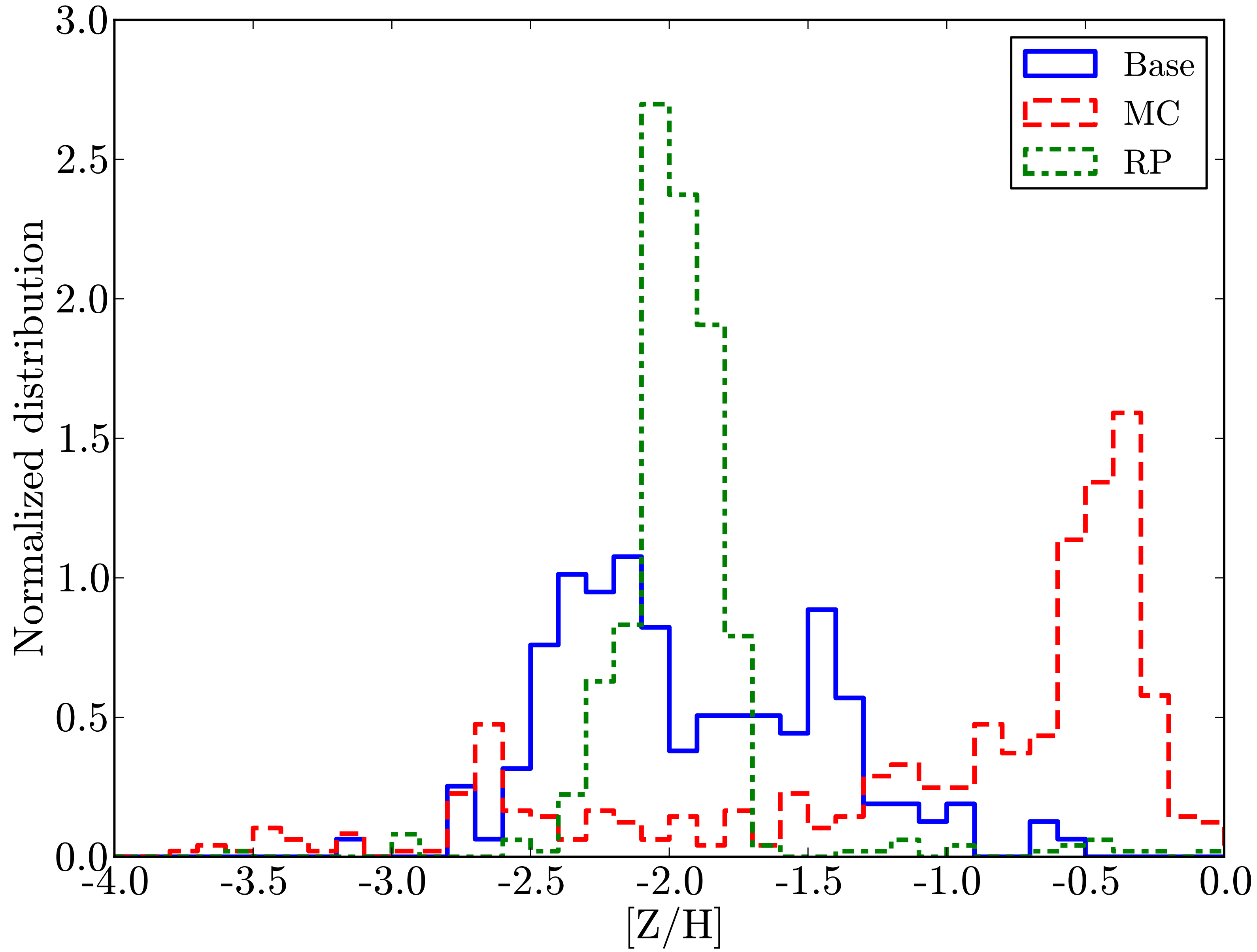
SF decreases because dense gas is further dispersed.

Enhanced metal mixing, resulting in an average metallicity of 10^{-2} $Z_\odot$

JHW+ (arXiv:1206.1043)

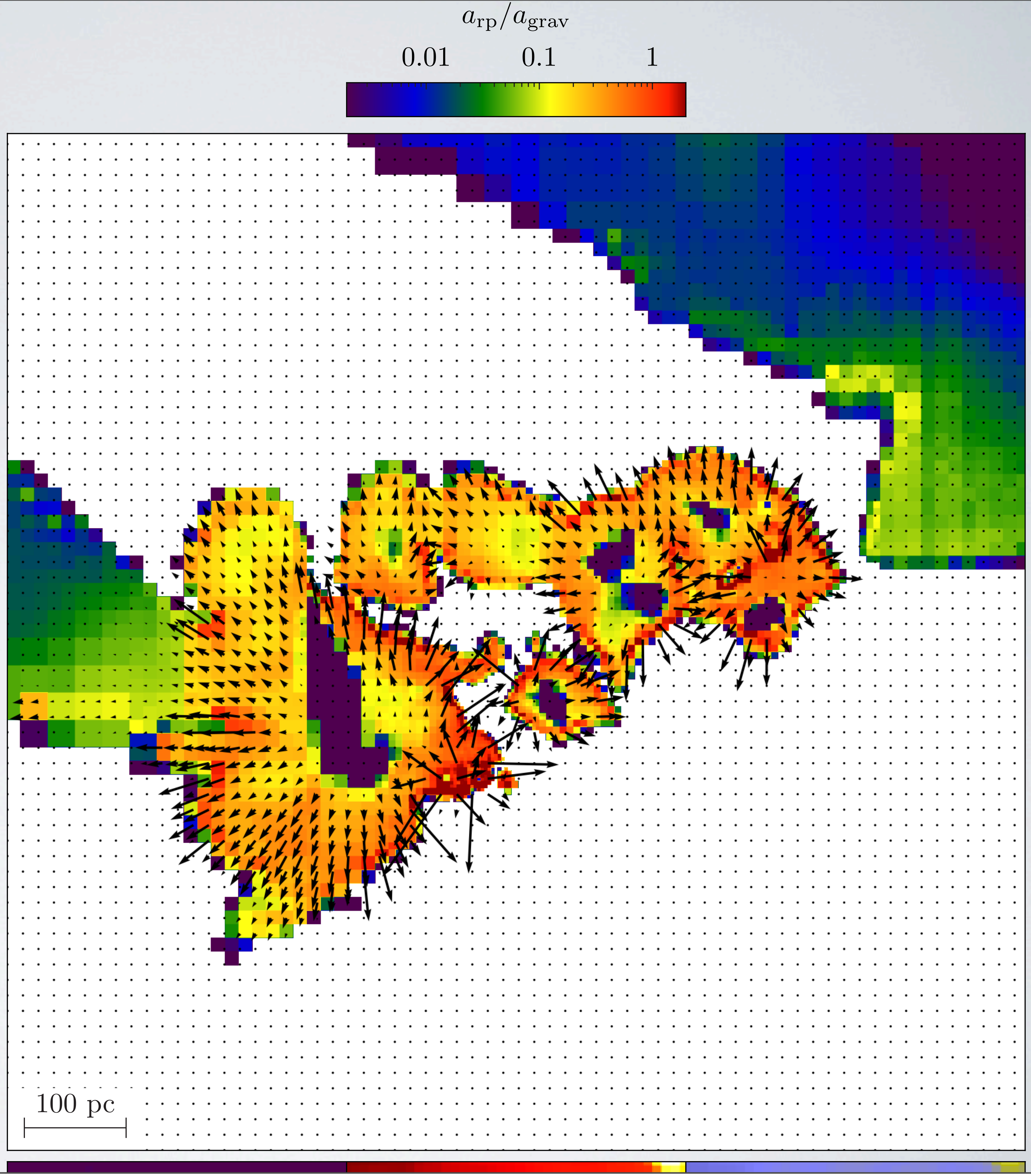
EFFECTS OF RADIATION PRESSURE

METALLICITY DISTRIBUTION FUNCTIONS

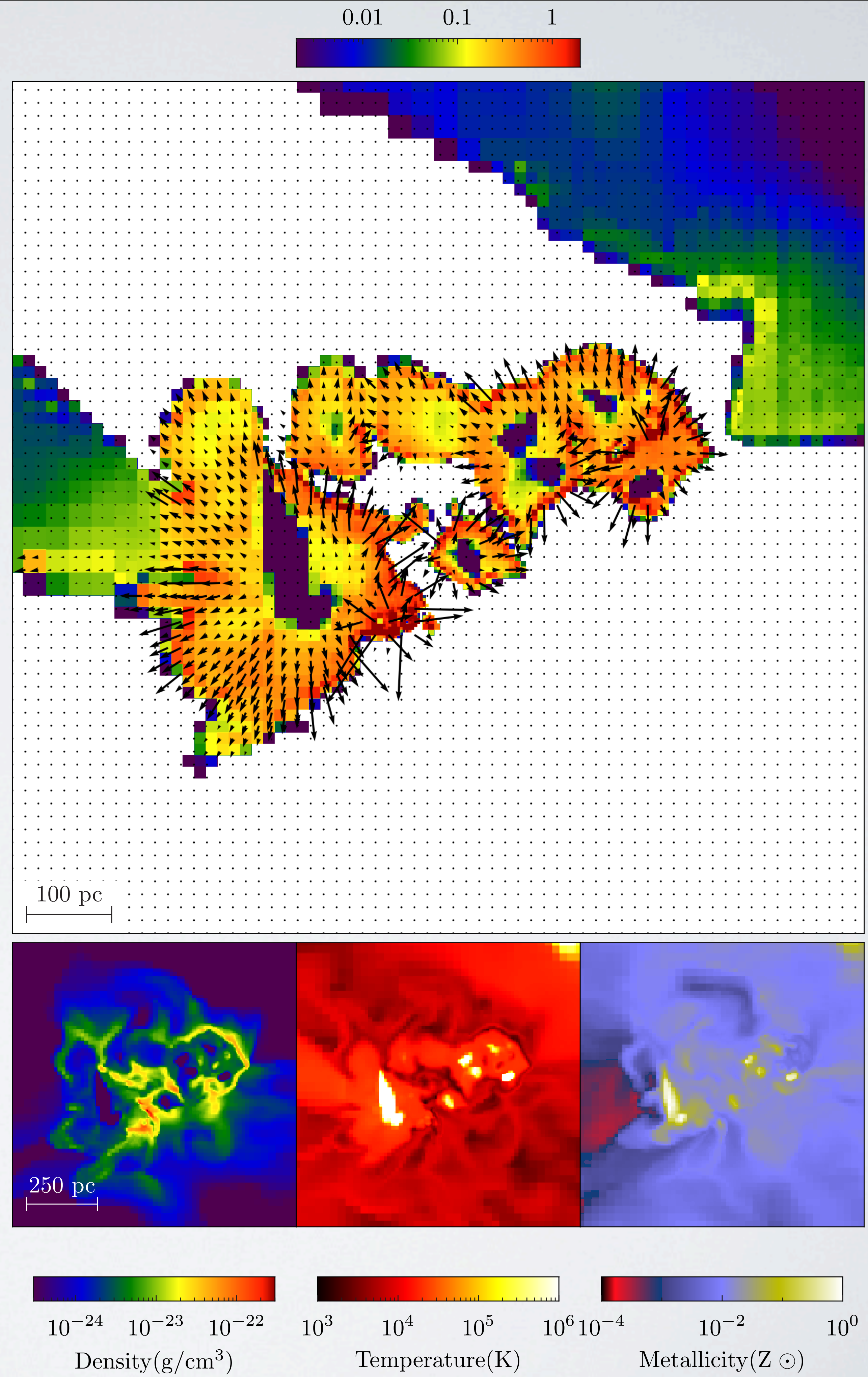


Feedback from radiation pressure more effectively disperses metal-rich ejecta and produces a galaxy on the mass-metallicity relation

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



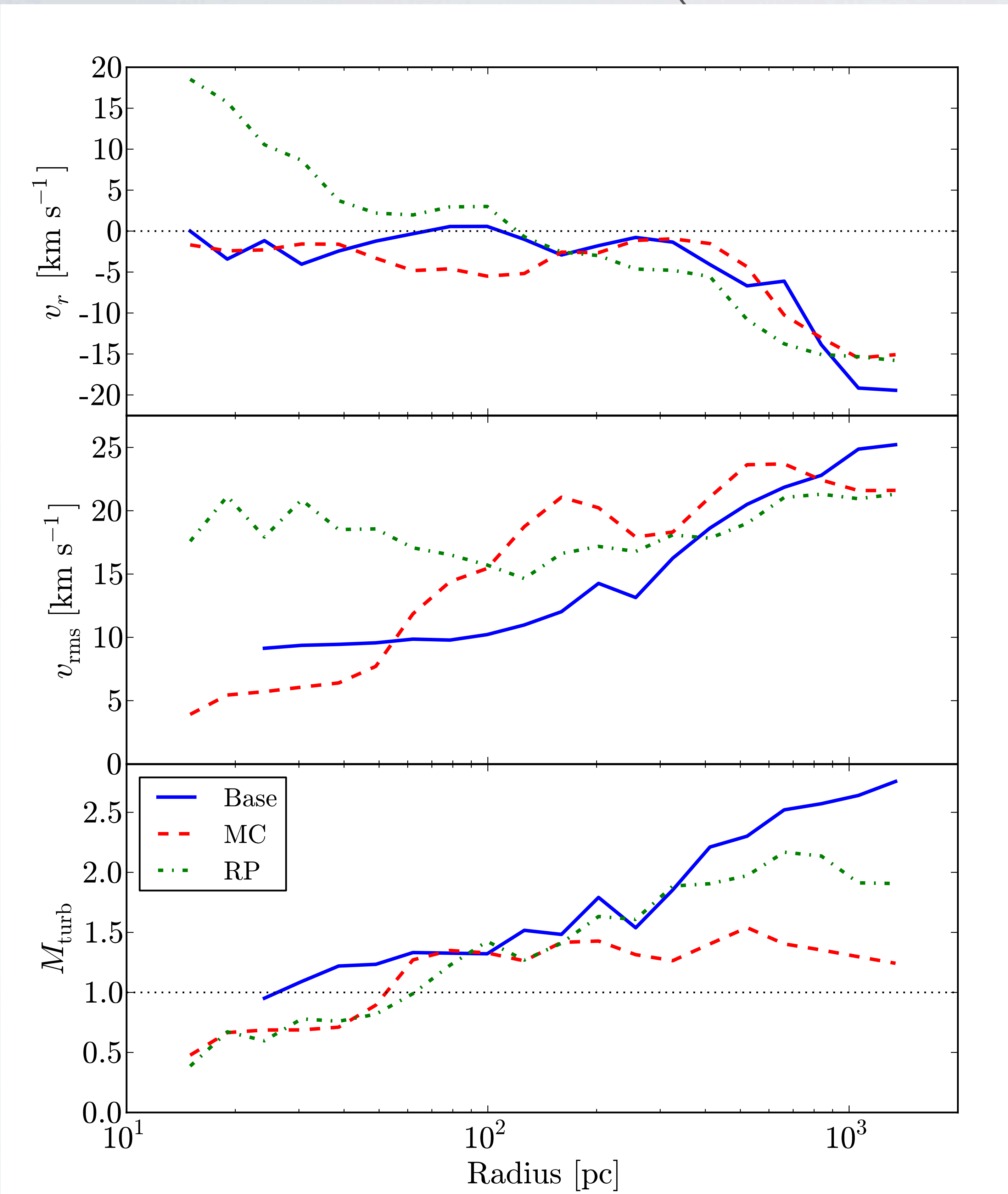
Slice of acceleration due to momentum transfer from ionizing photons only, i.e. not including dust opacity



JHW+ (arXiv:1206.1043)

EFFECTS OF RADIATION PRESSURE

RADIAL VELOCITIES (OVERCOOLING → DECREASED SF)



- Reverses infall, increases turbulent motions, and decreases SF in the inner 100 pc.
- In rad. pressure simulations,

$$v_{\rm rms} \sim V_c$$

compared to 25% without it.

SUMMARY

- Over the past decade, numerical work have begun to refine the formation scenario for the first stars.
  - Stellar masses ~ tens of solar masses
  - Binaries possible (X-ray pre-ionization?)
- Pop III radiative feedback creates gas-poor halos and delays star formation for 10–50 Myr.
- Pop III supernova feedback enriches the first galaxies to a nearly uniform 10^{-3} $Z_\odot$ but is the demise of Pop III stars.
- The gas depletion, IGM pre-heating, and chemical enrichment all have impacts on the properties of the first galaxies.
- Radiation pressure plays an important role in regulating star formation in the first galaxies through driving turbulence and allowing SN feedback drive outflows more efficiently.