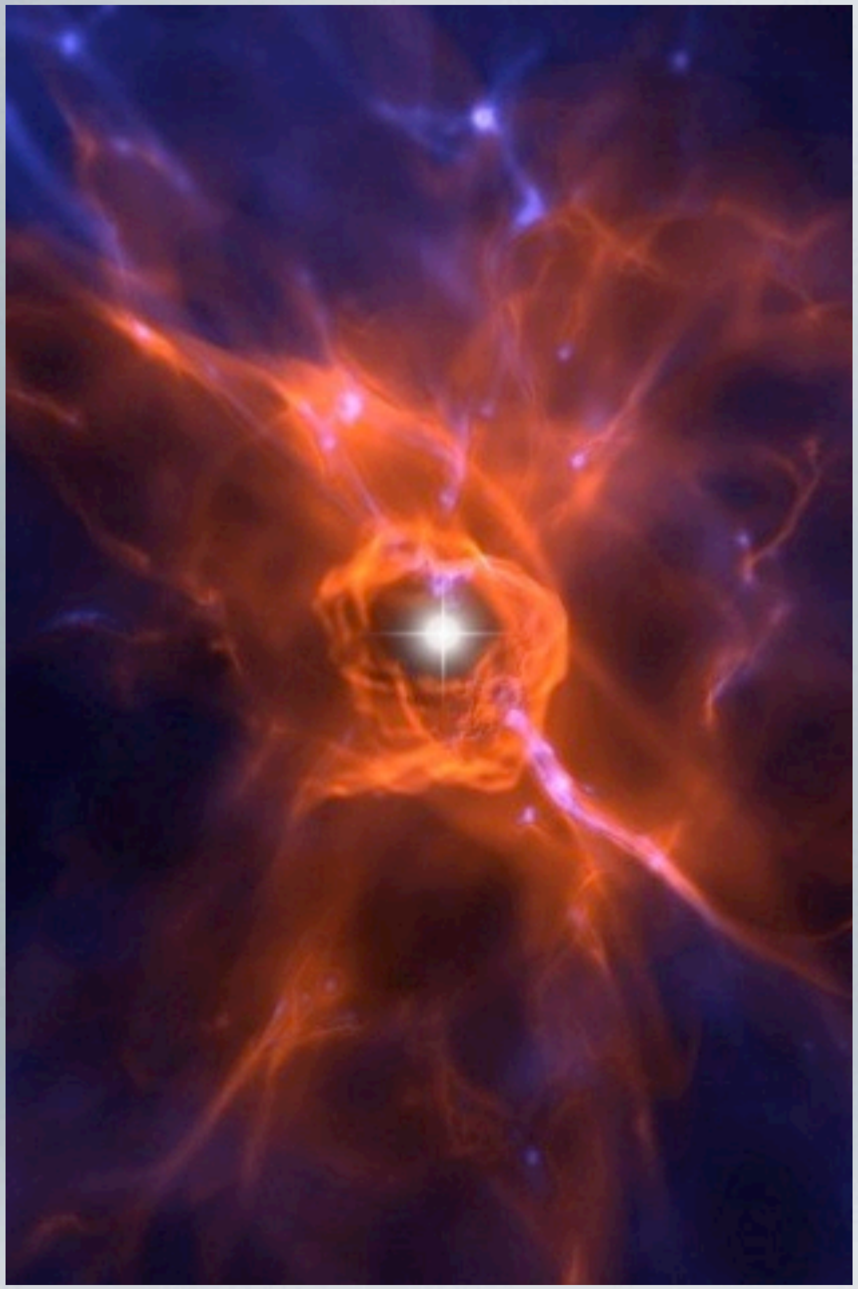
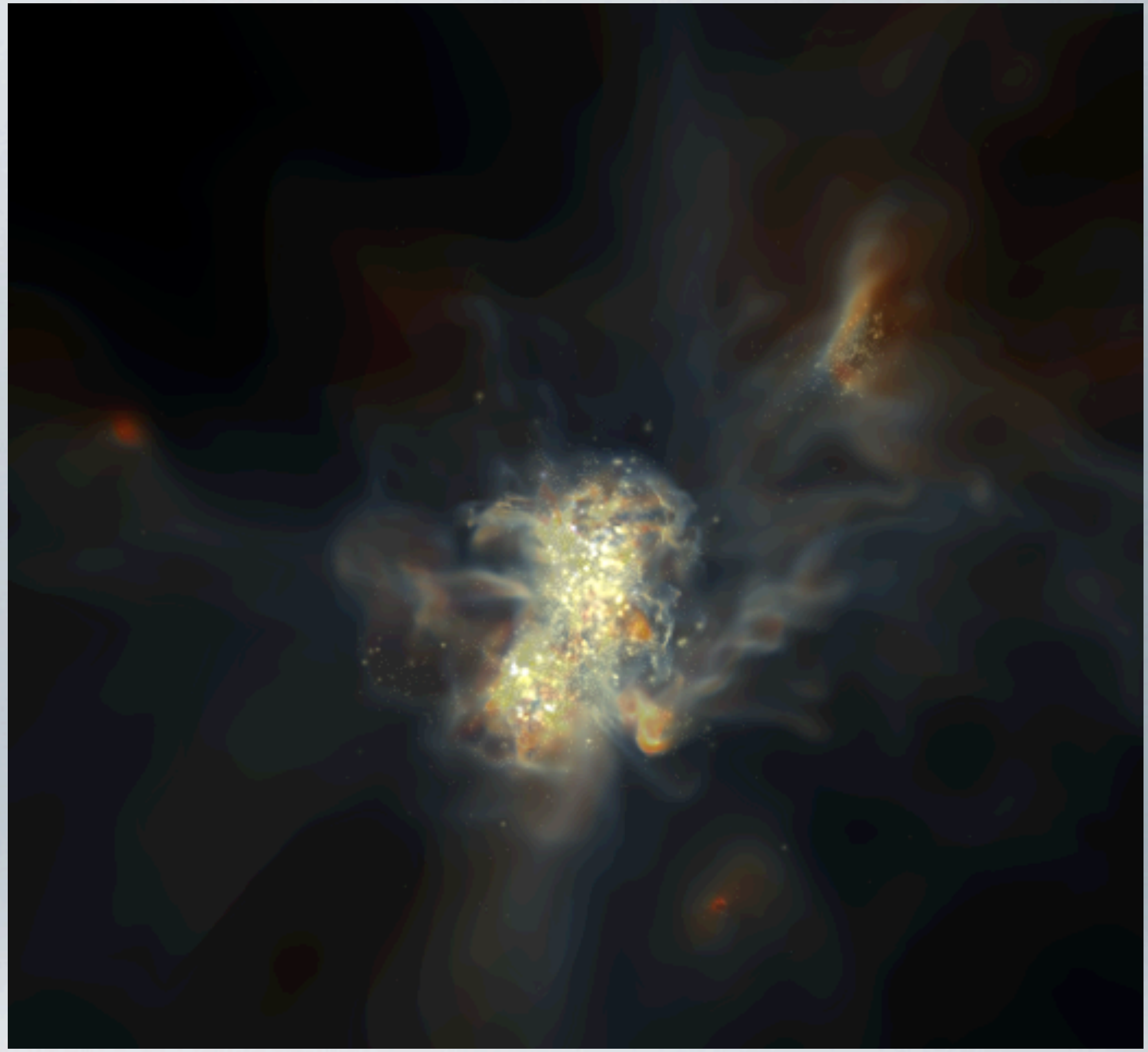




THE ROLE OF RADIATION PRESSURE IN HIGH-Z DWARF GALAXIES

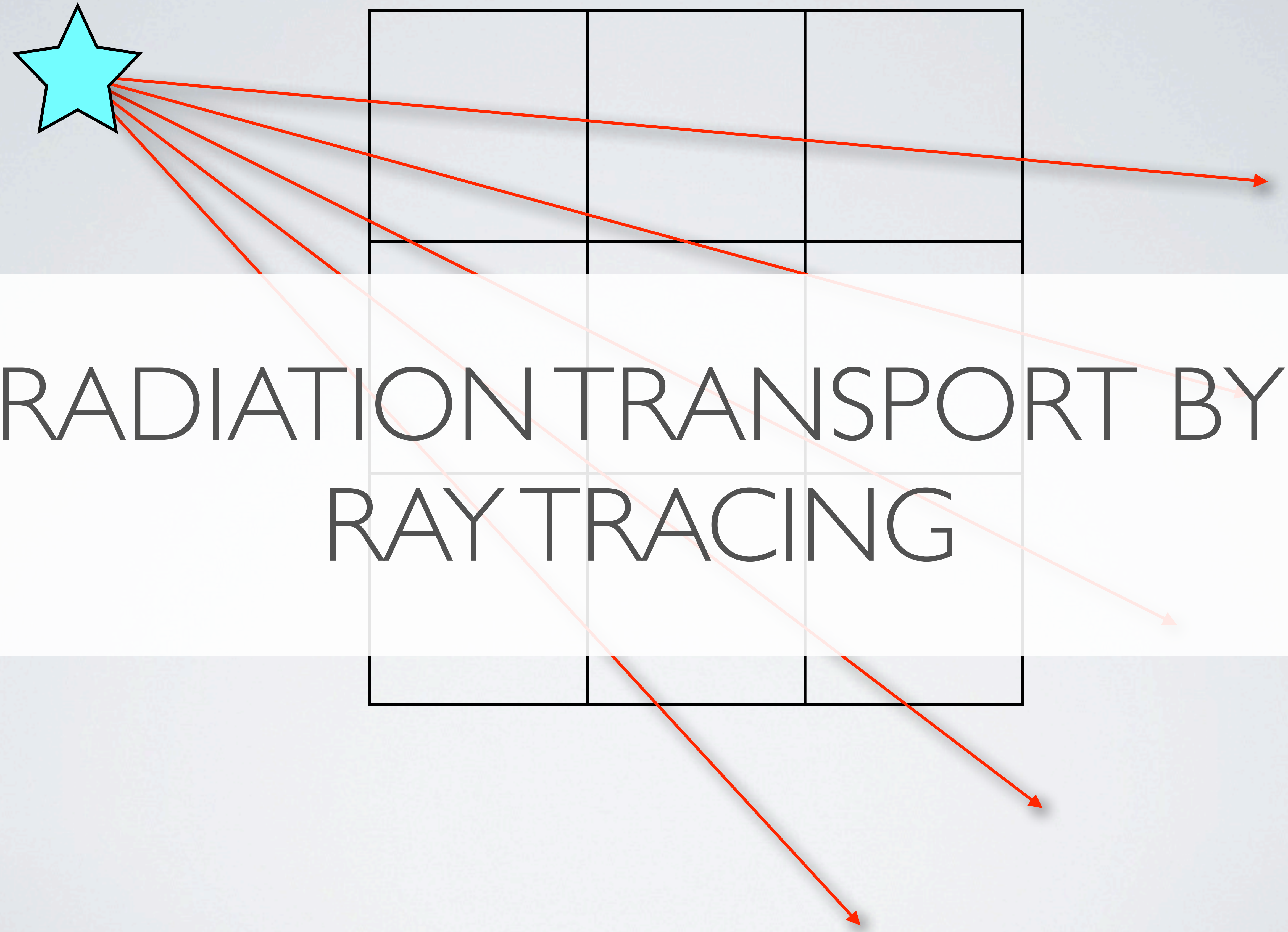
John Wise (Georgia Tech)
Tom Abel (Stanford), Michael Norman (UC San Diego), Britton Smith (Michigan State),
Matthew Turk (Columbia)

14 Dec 2012

CRTW 2012

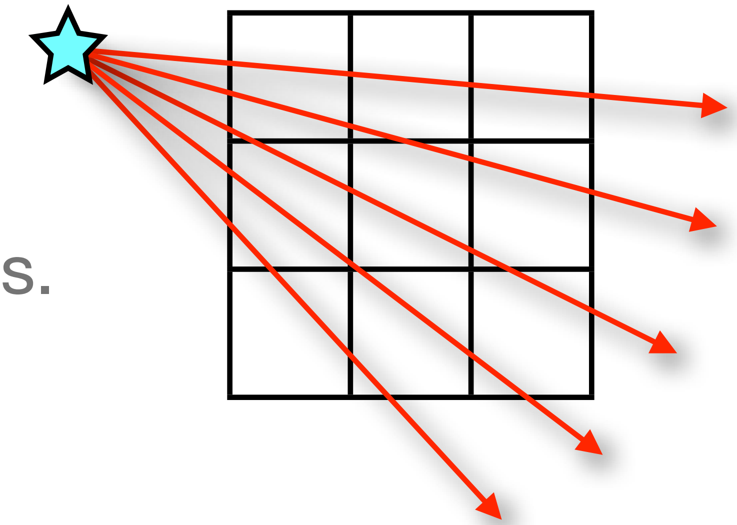
OUTLINE

- Enzo+Moray: Adaptive ray tracing and merging
- Pop III → II transition and dwarf galaxy formation
- The role of radiation pressure in dwarf galaxies



RADIATION TRANSPORT BY RAY TRACING

RT Equation along a Ray



- Consider point sources of radiation

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

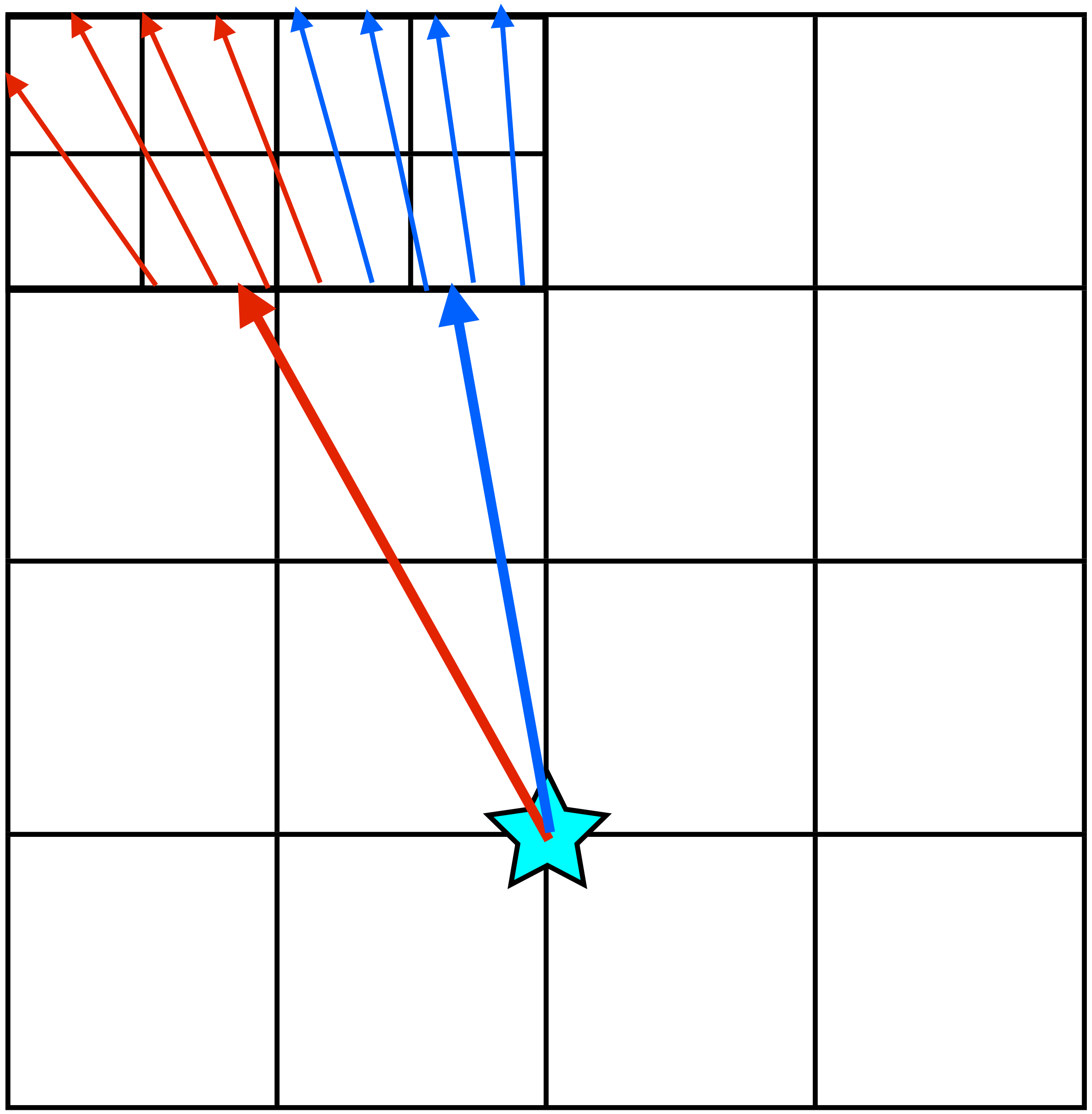
$$\frac{1}{c}\frac{\partial P}{\partial t} + \frac{\partial P}{\partial r} = -\kappa P$$

- P := photon flux in the ray

Adaptive Ray Tracing (Enzo+Moray)

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

- Ray directions and splitting based on HEALPix (Gorski et al. 2005)
- Coupled with (magneto-) hydrodynamics of Enzo
- 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.
- MPI/OpenMP hybrid parallelized.

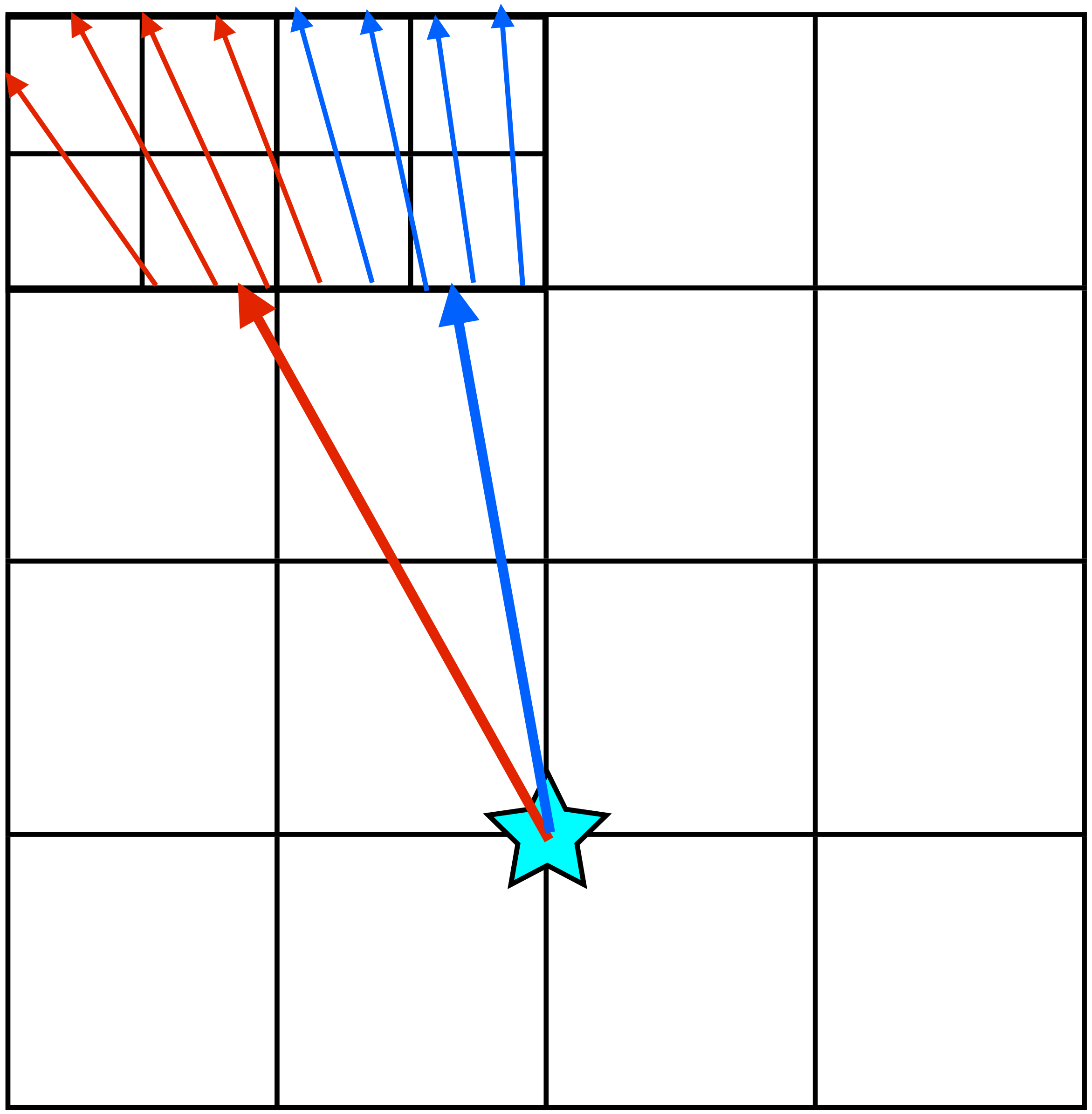


All development in
https://bitbucket.org/enzo

Adaptive Ray Tracing (Enzo+Moray)

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

- H + He ionization (heating)
- X-rays (secondary ionizations)
- Lyman-Werner transfer (based on Draine & Bertoldi shielding function)
- Choice between energy discretization and general spectral shapes (column density lookup tables, see C^2-Ray)
- See Mirocha+ (2012) for optimized choices for energy bins.
- Radiation pressure from continuum
- Choice between c = Ac, ∞
- Can delete a ray when its flux drops below some fraction of the UVB for local UV feedback.



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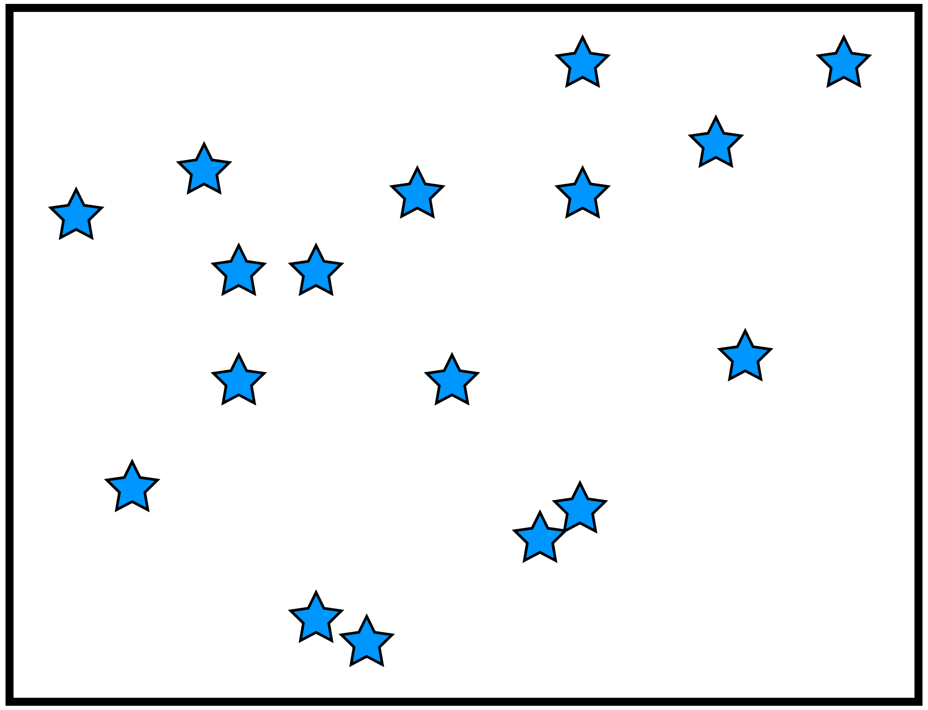
OVERCOMING O(N_{STAR}) :: RAY / SOURCE MERGING

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.
- Have run simulations with 25k point sources.



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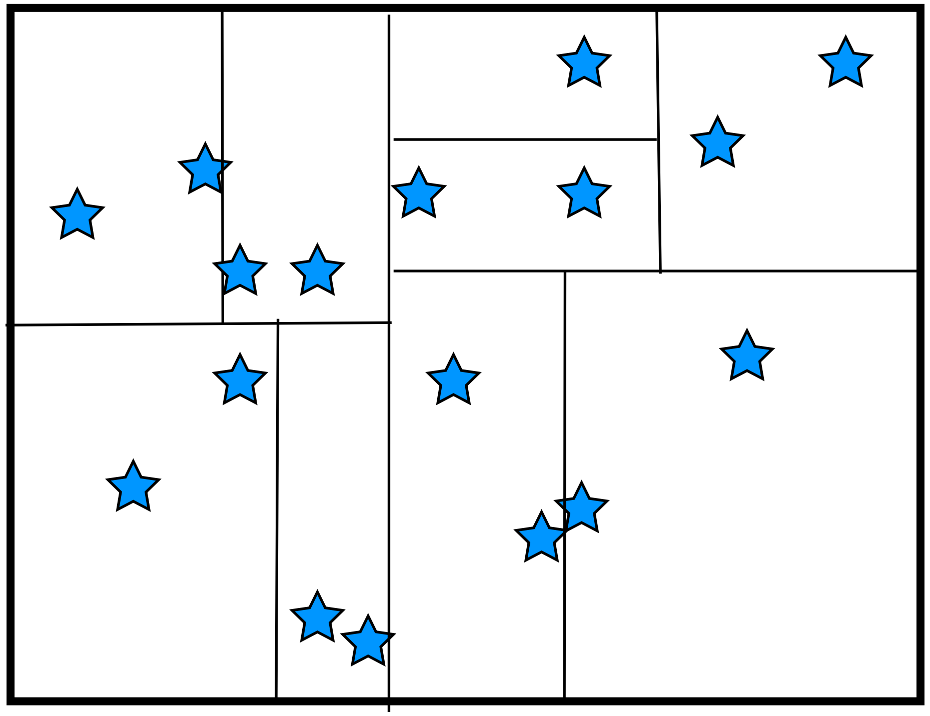

OVERCOMING $O(N_{\mathrm{STAR}})$ :: RAY / SOURCE MERGING

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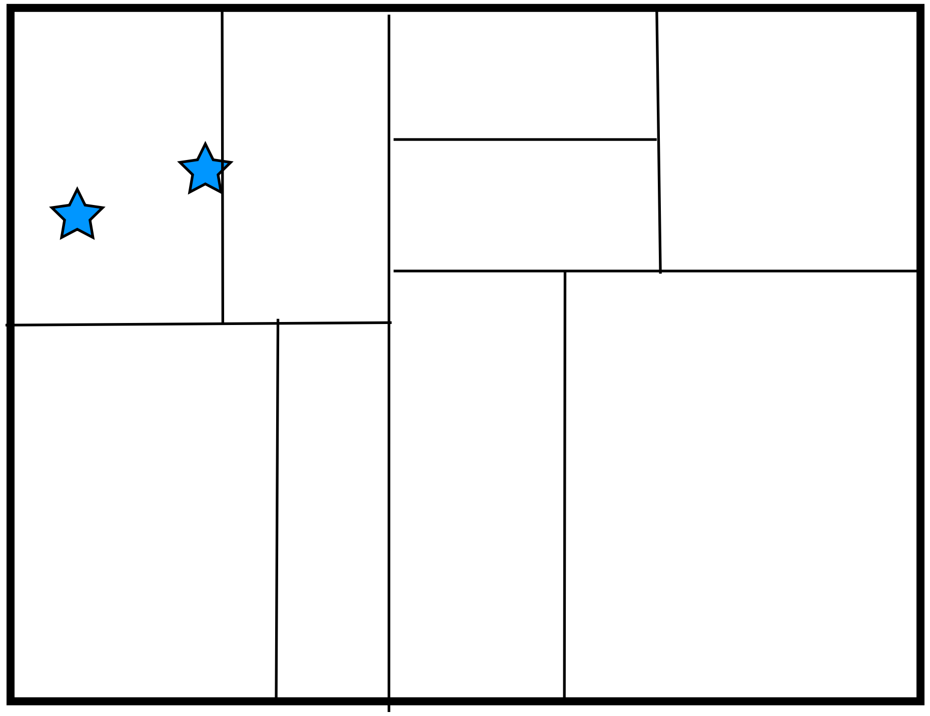

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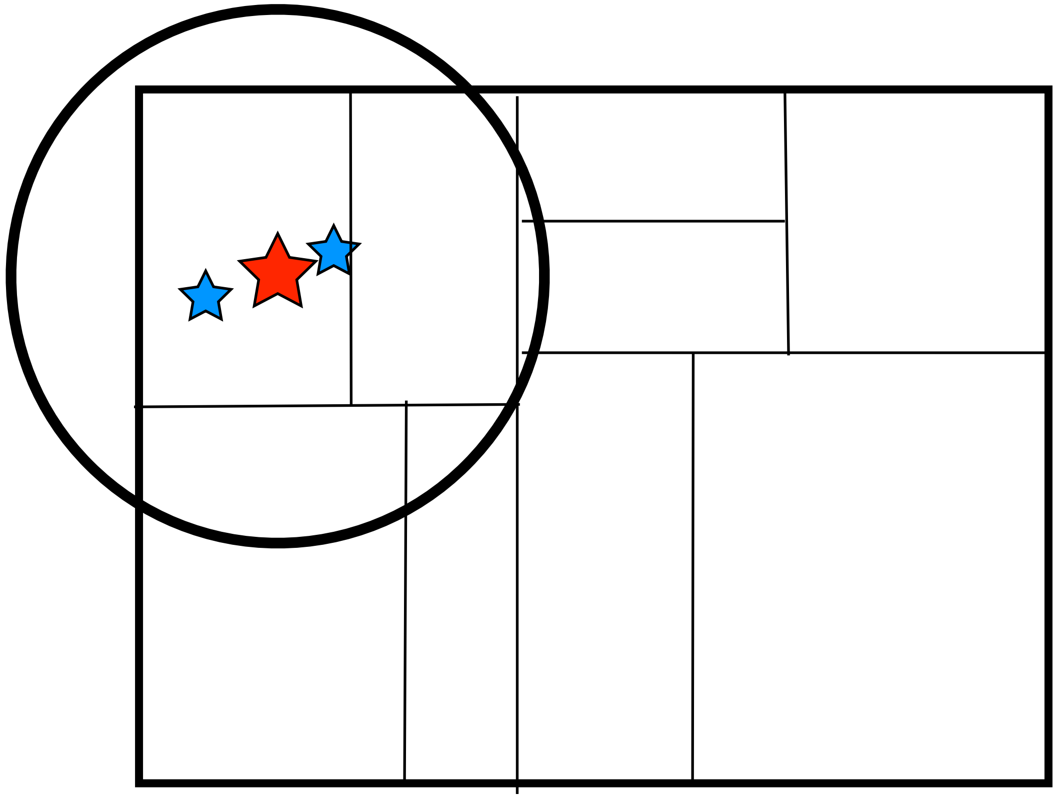

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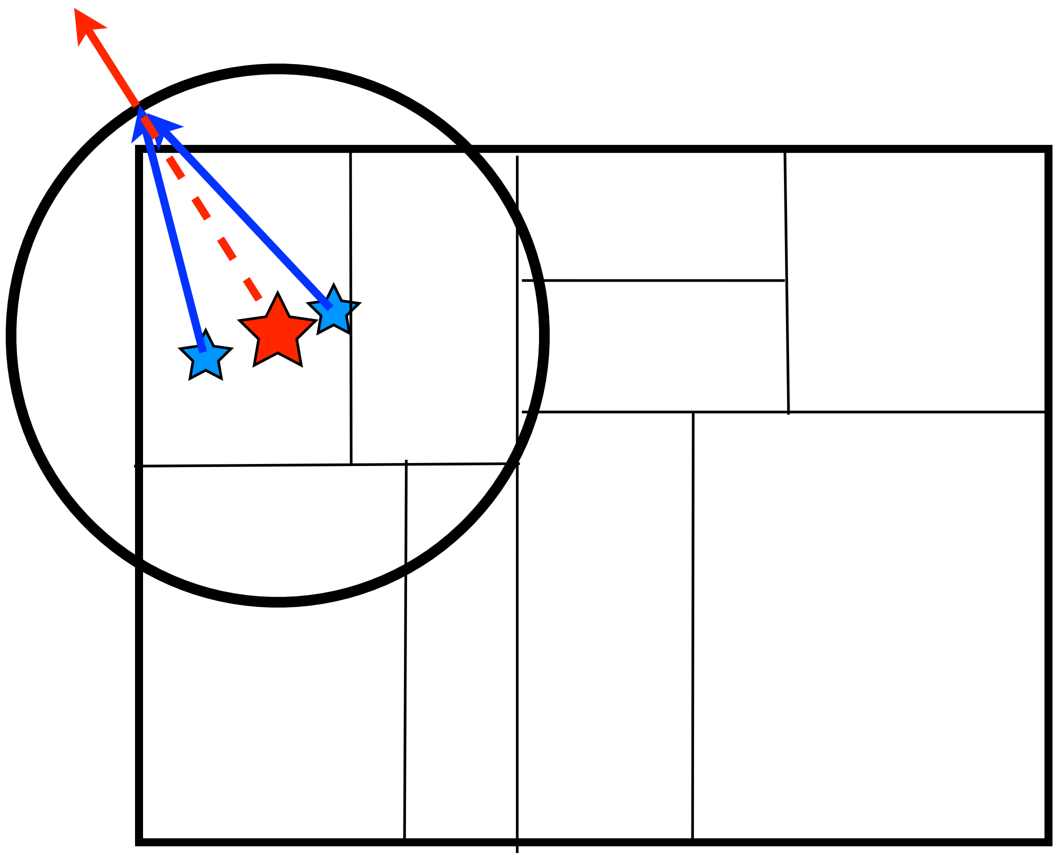

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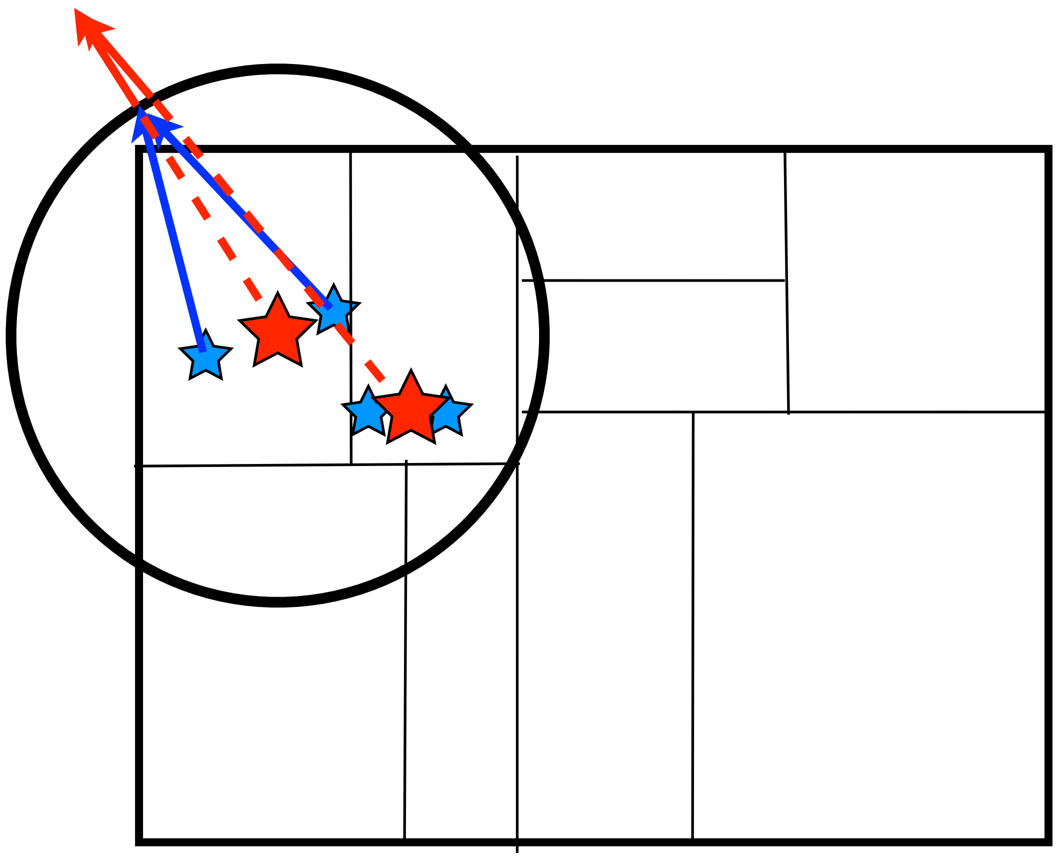

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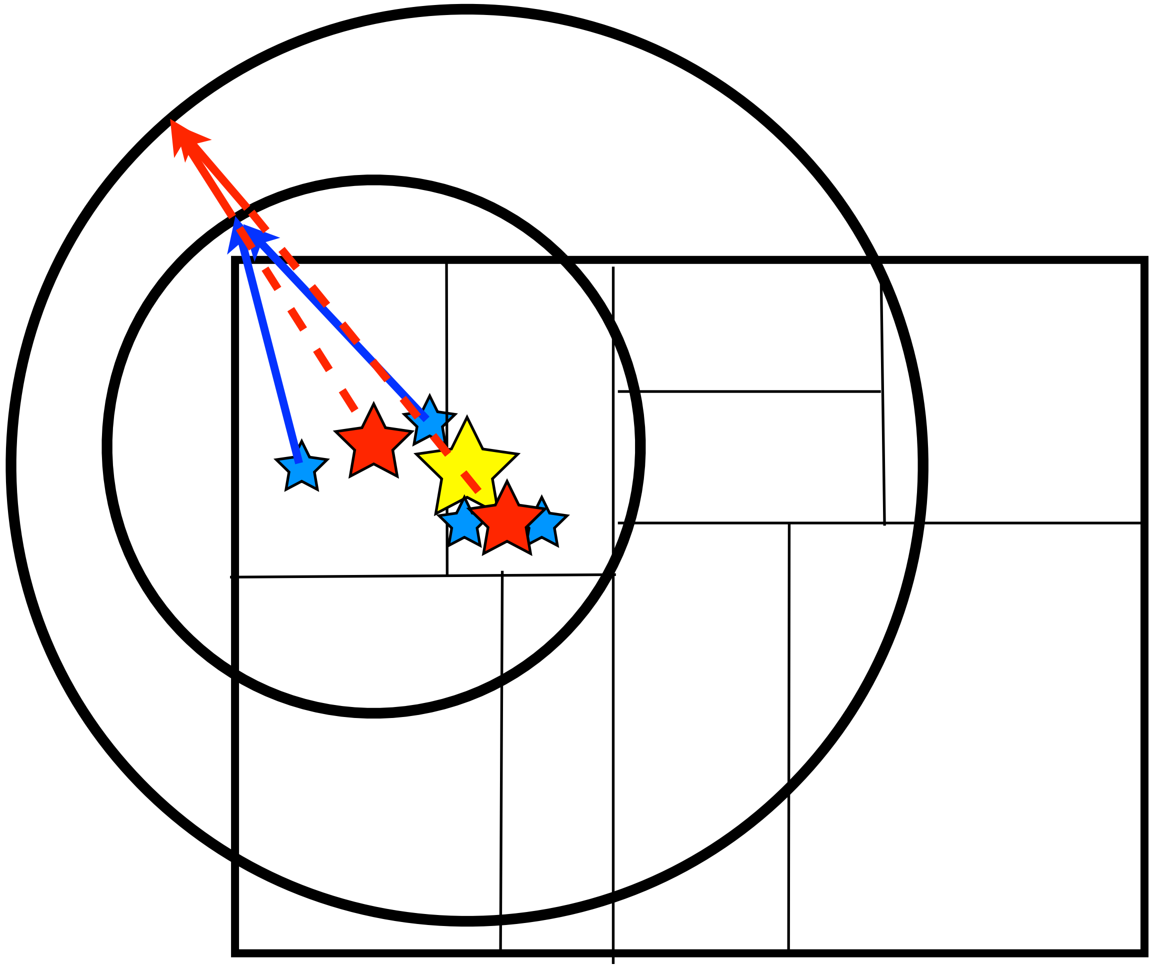

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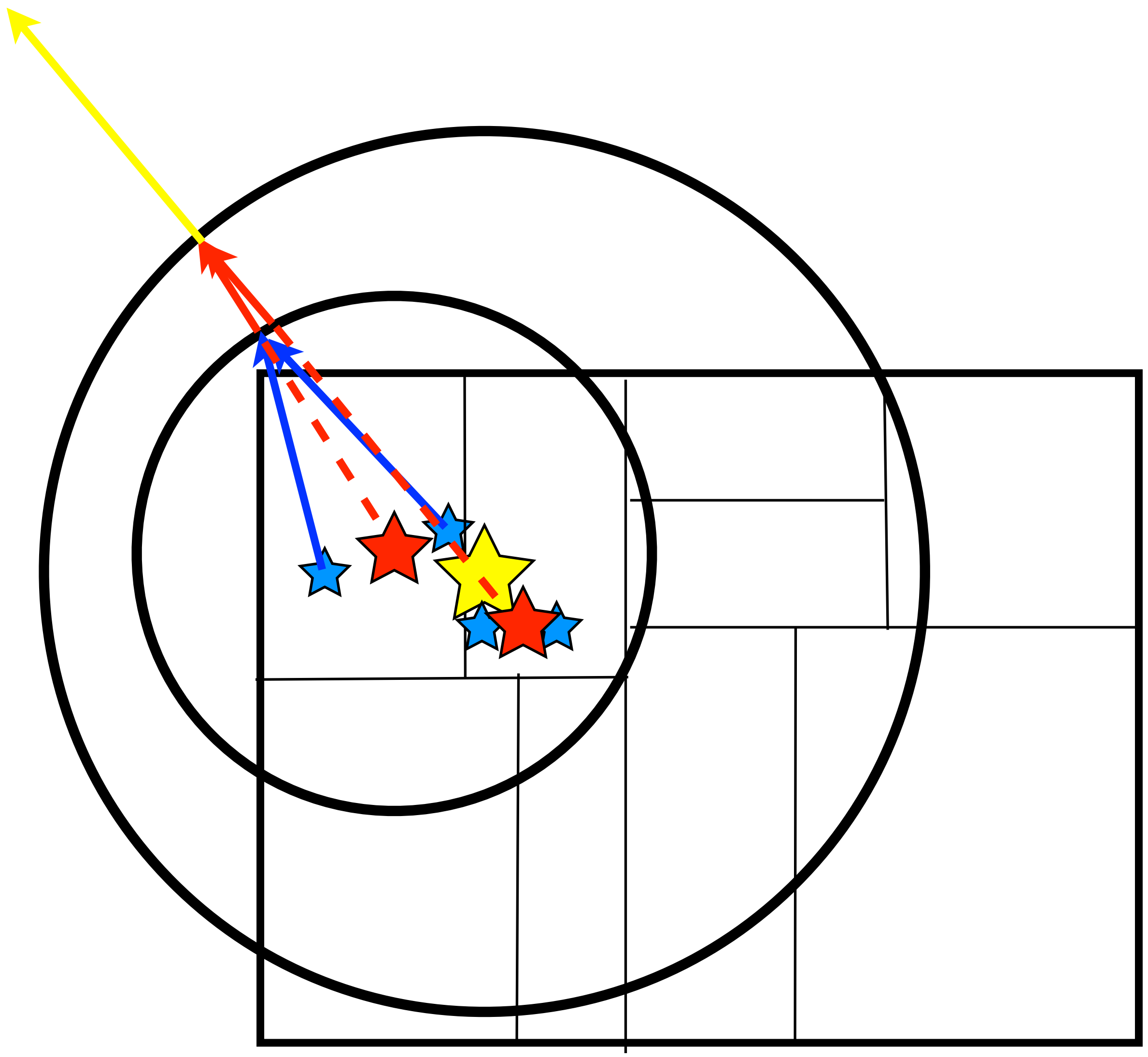
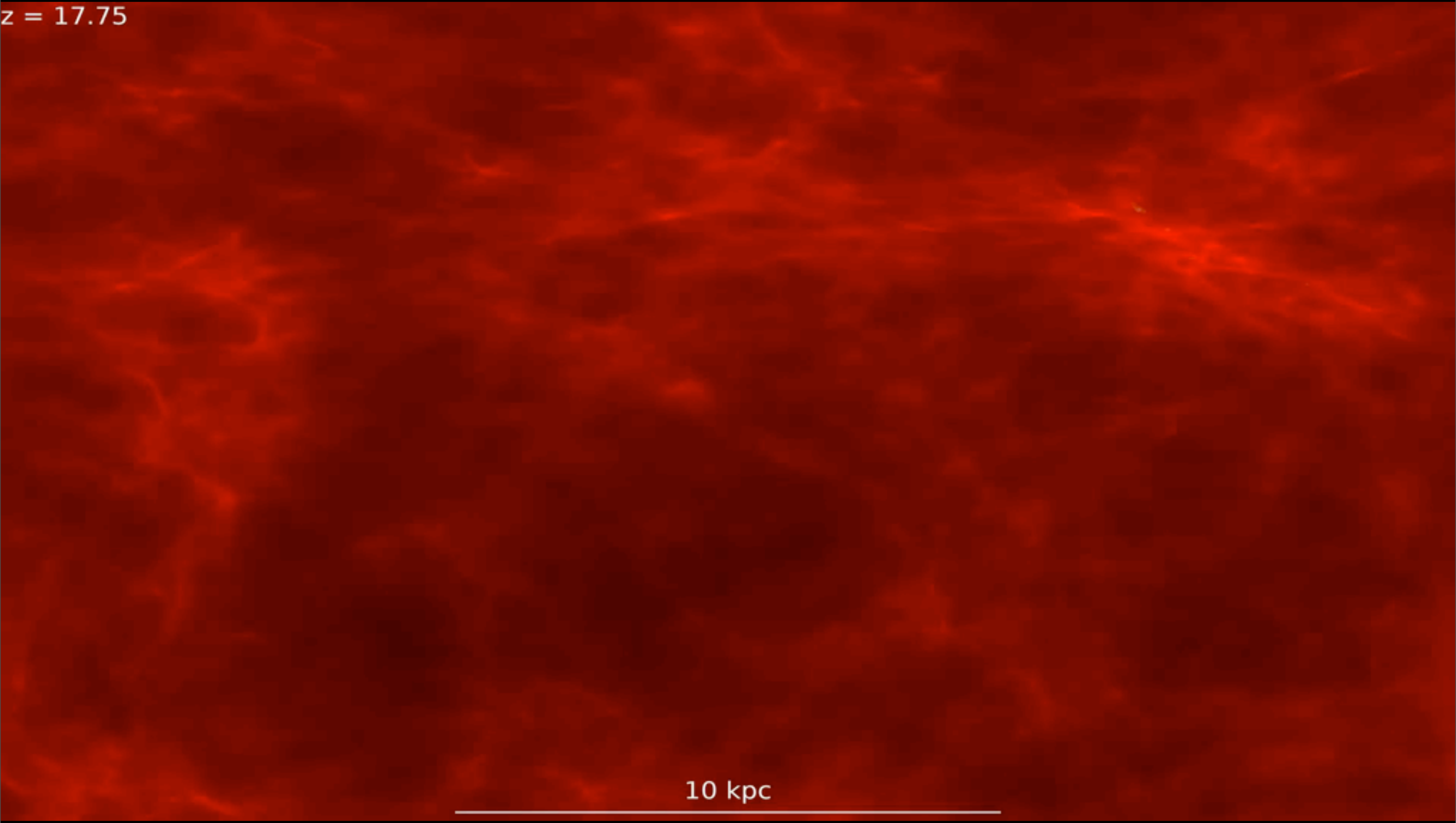


Wise, Turk, Norman, & Abel (2012)

SIMULATION SETUP: POP III → II TRANSITION AND GALAXY FORMATION

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

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


z = 17.75
10 kpc

FoV = 1 c.m. Mpc

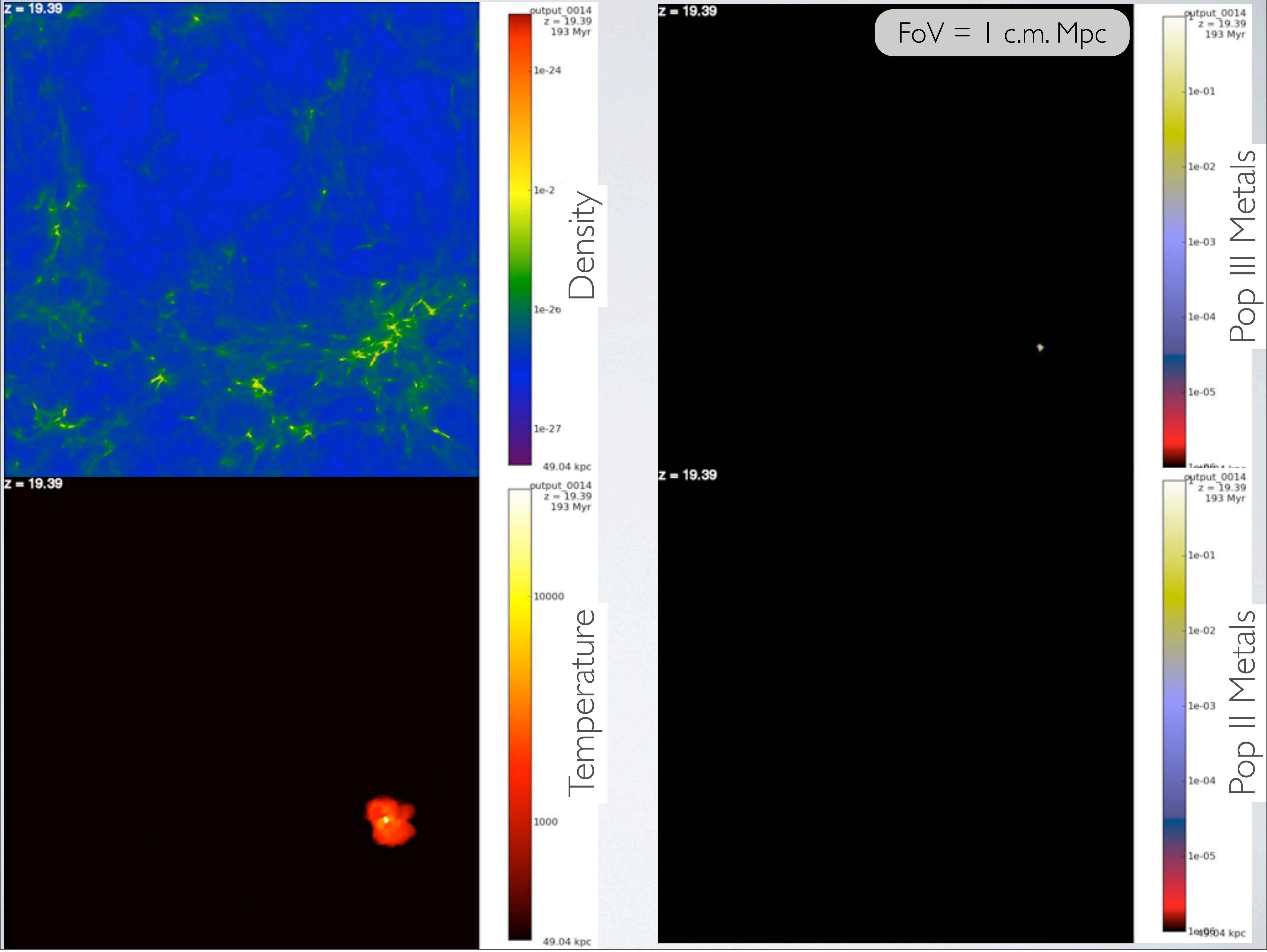
Density

Pop III Metals

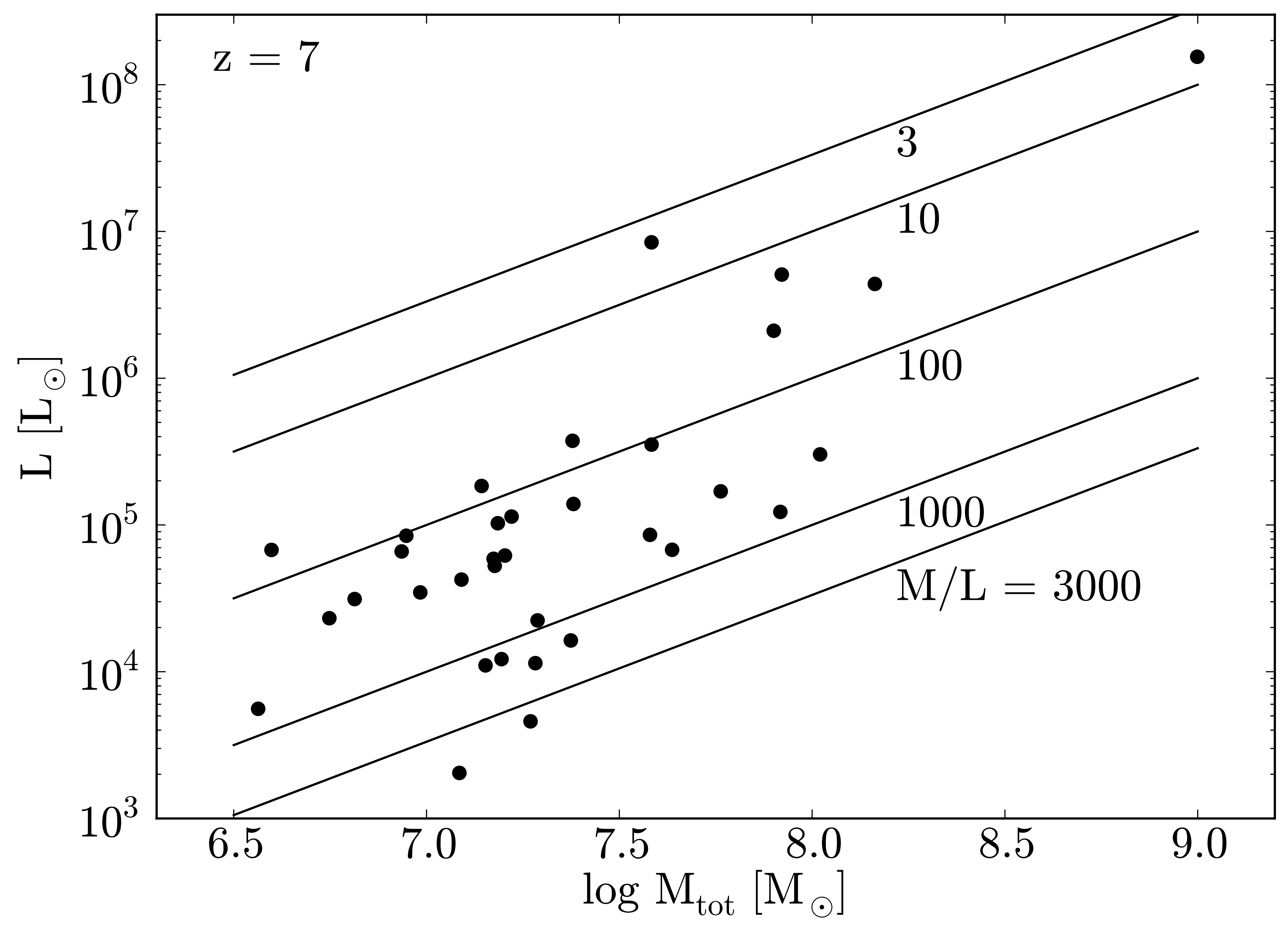
Temperature

Pop II Metals

FoV = 1 c.m. Mpc


z = 19.39
output_0014
z = 19.39
193 Myr
1e-24
1e-2
1e-26
1e-27
49.04 kpc
Density
z = 19.39
output_0014
z = 19.39
193 Myr
10000
1000
49.04 kpc
Temperature
z = 19.39
output_0014
z = 19.39
193 Myr
1
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
z = 19.39
output_0014
z = 19.39
193 Myr
1
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
49.04 kpc
Pop II Metals

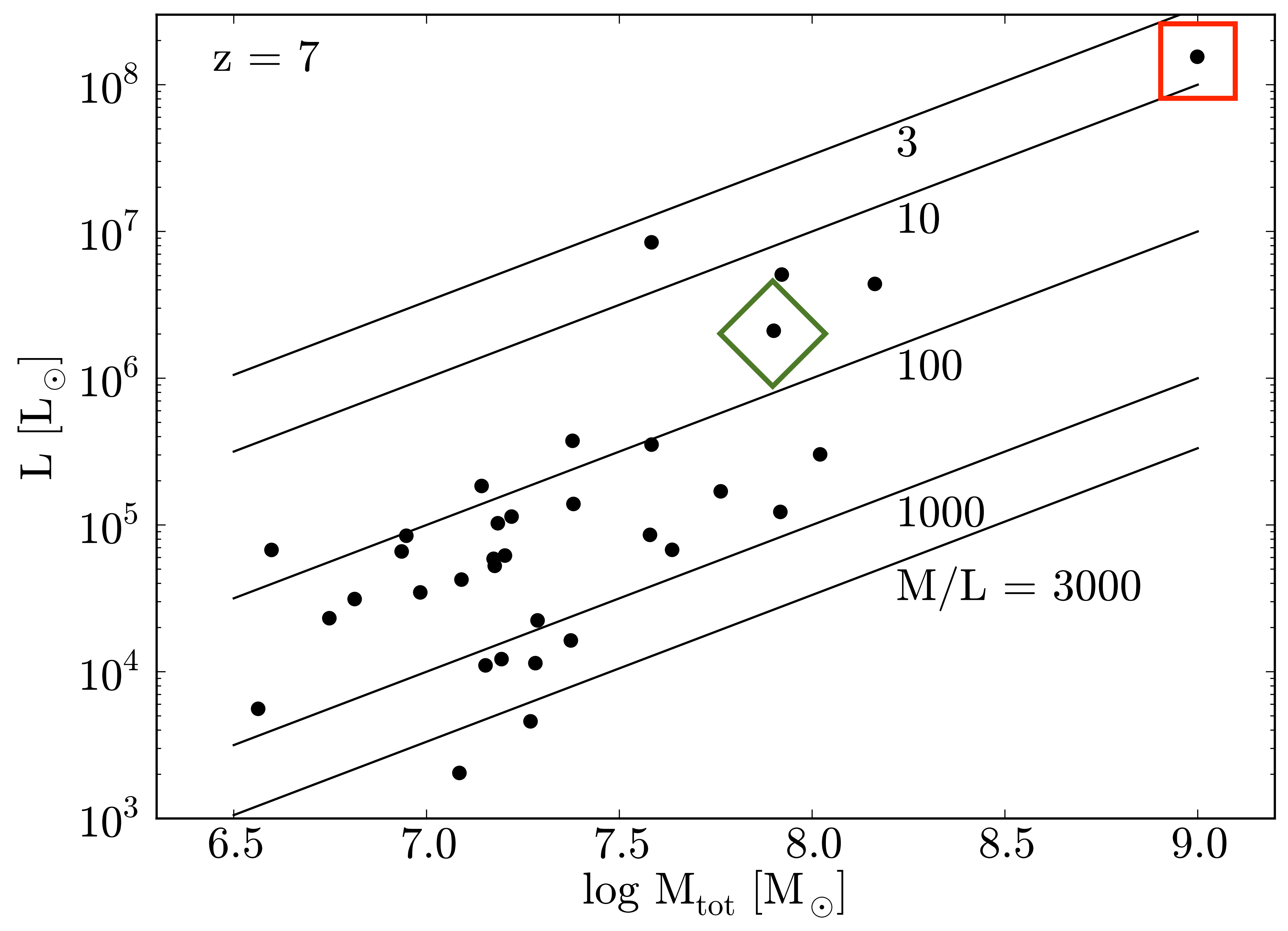
MASS-TO-LIGHT RATIOS



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

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

MASS-TO-LIGHT RATIOS



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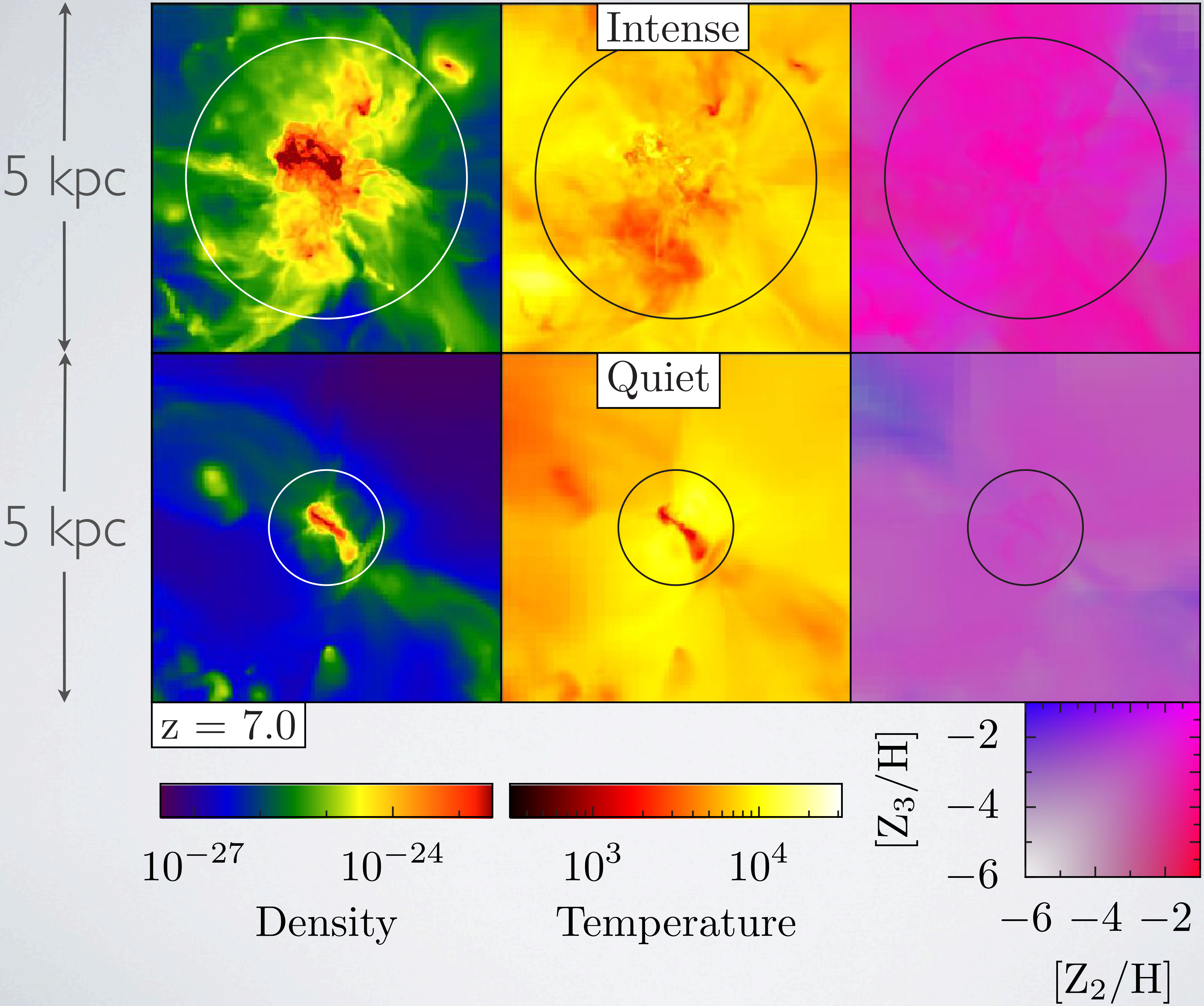
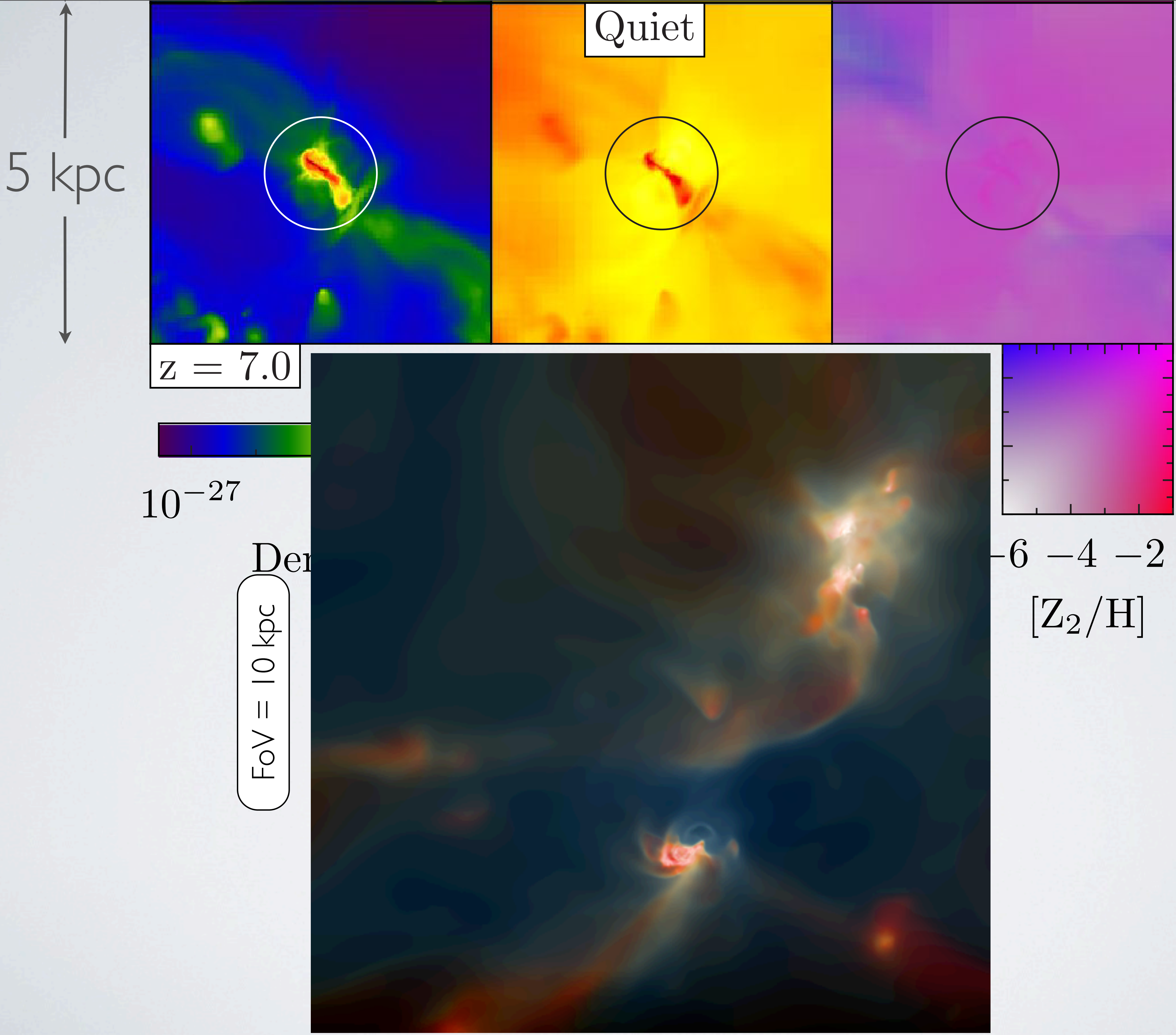
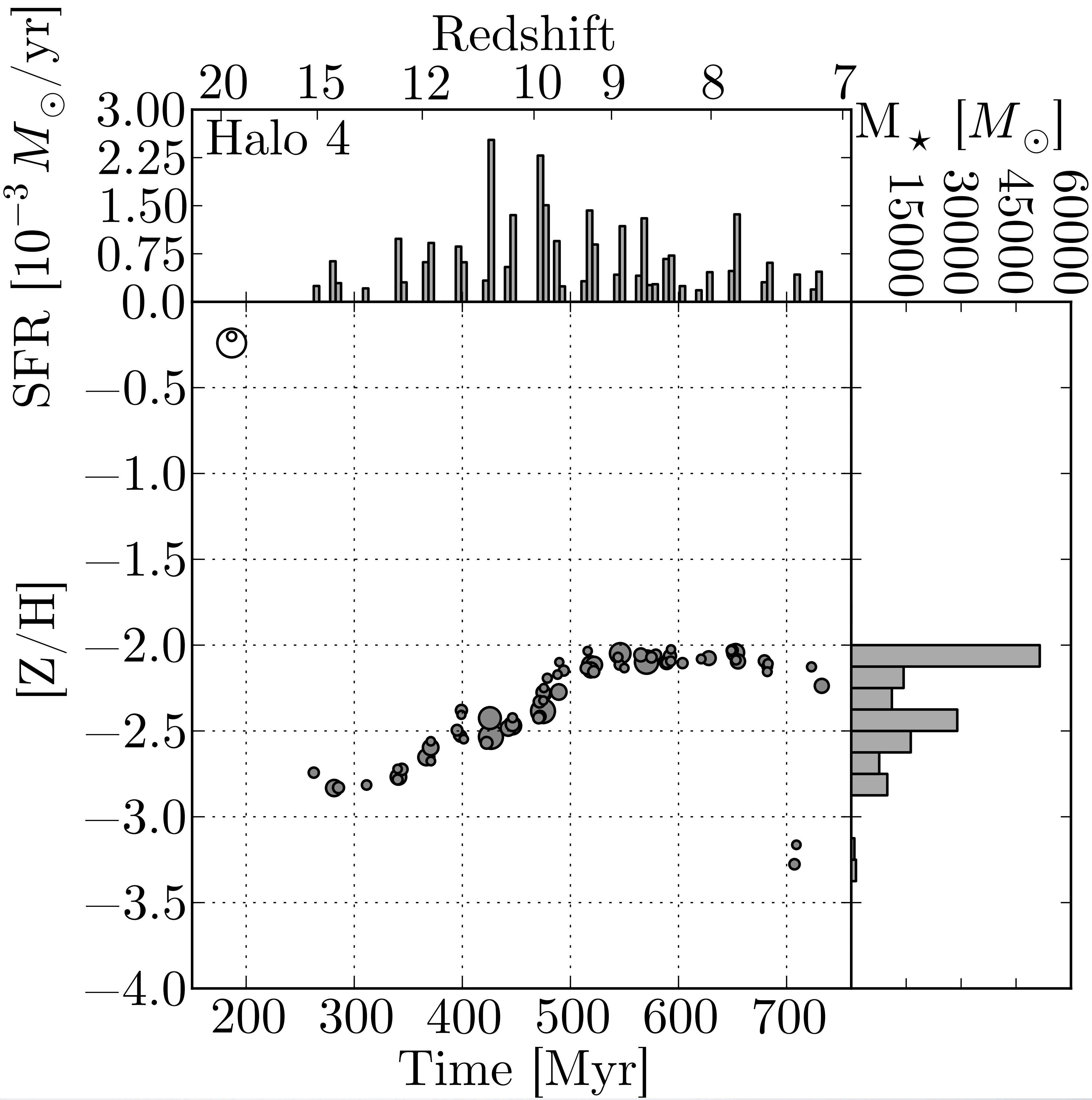
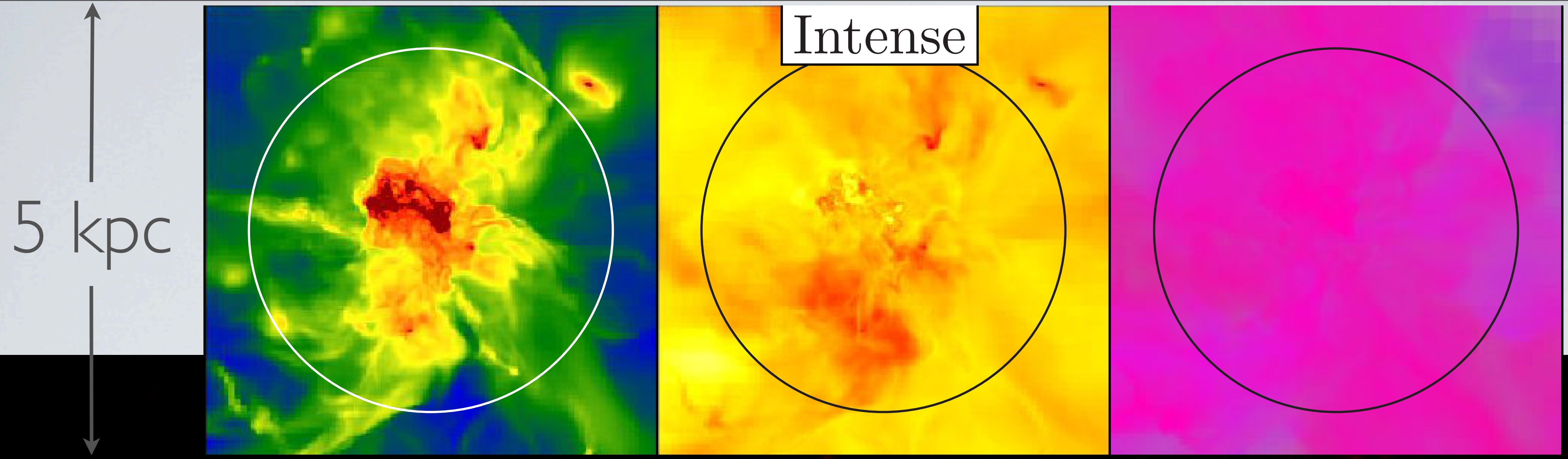
Wise, Turk, Norman, & Abel (2012)

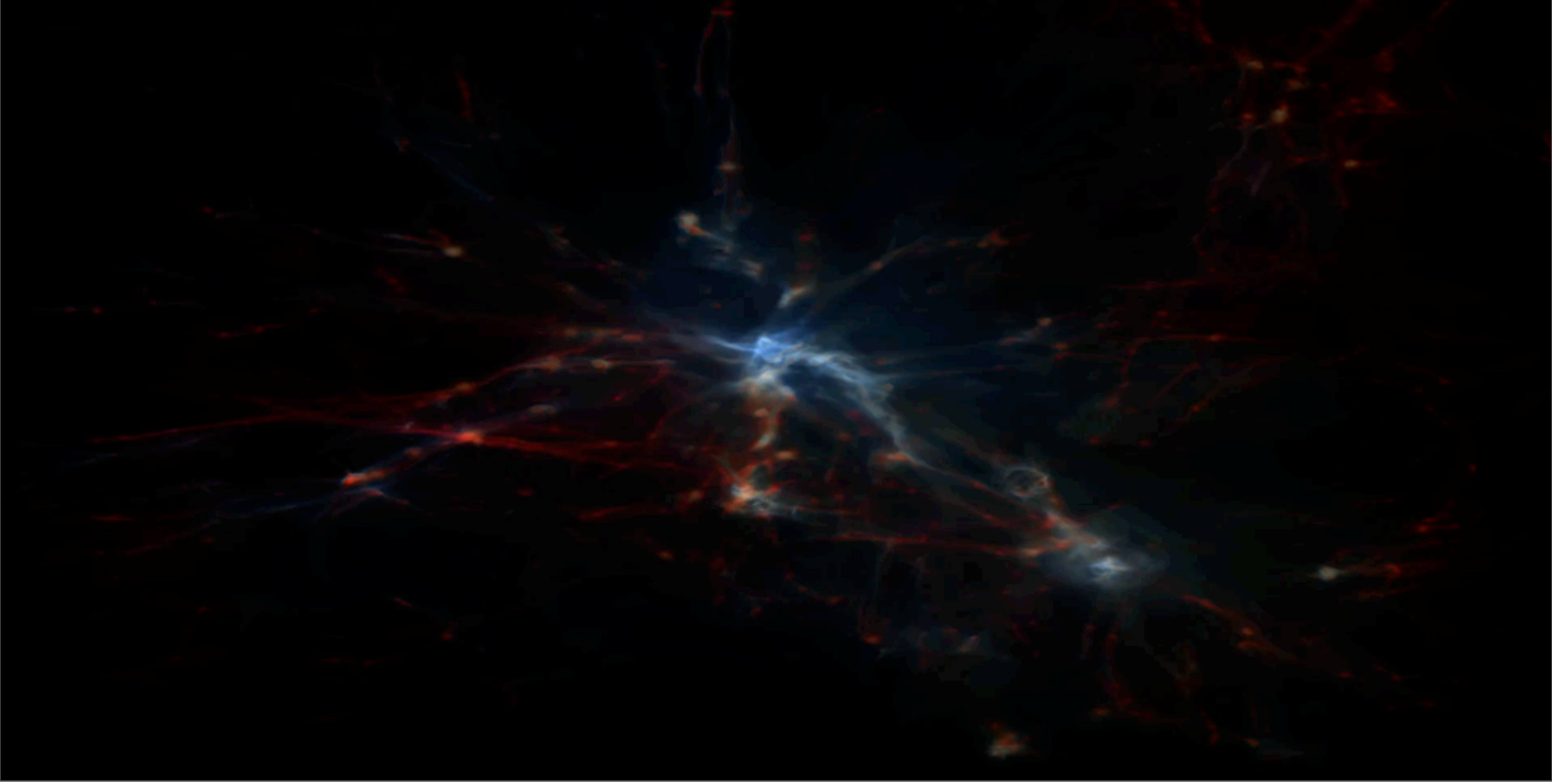


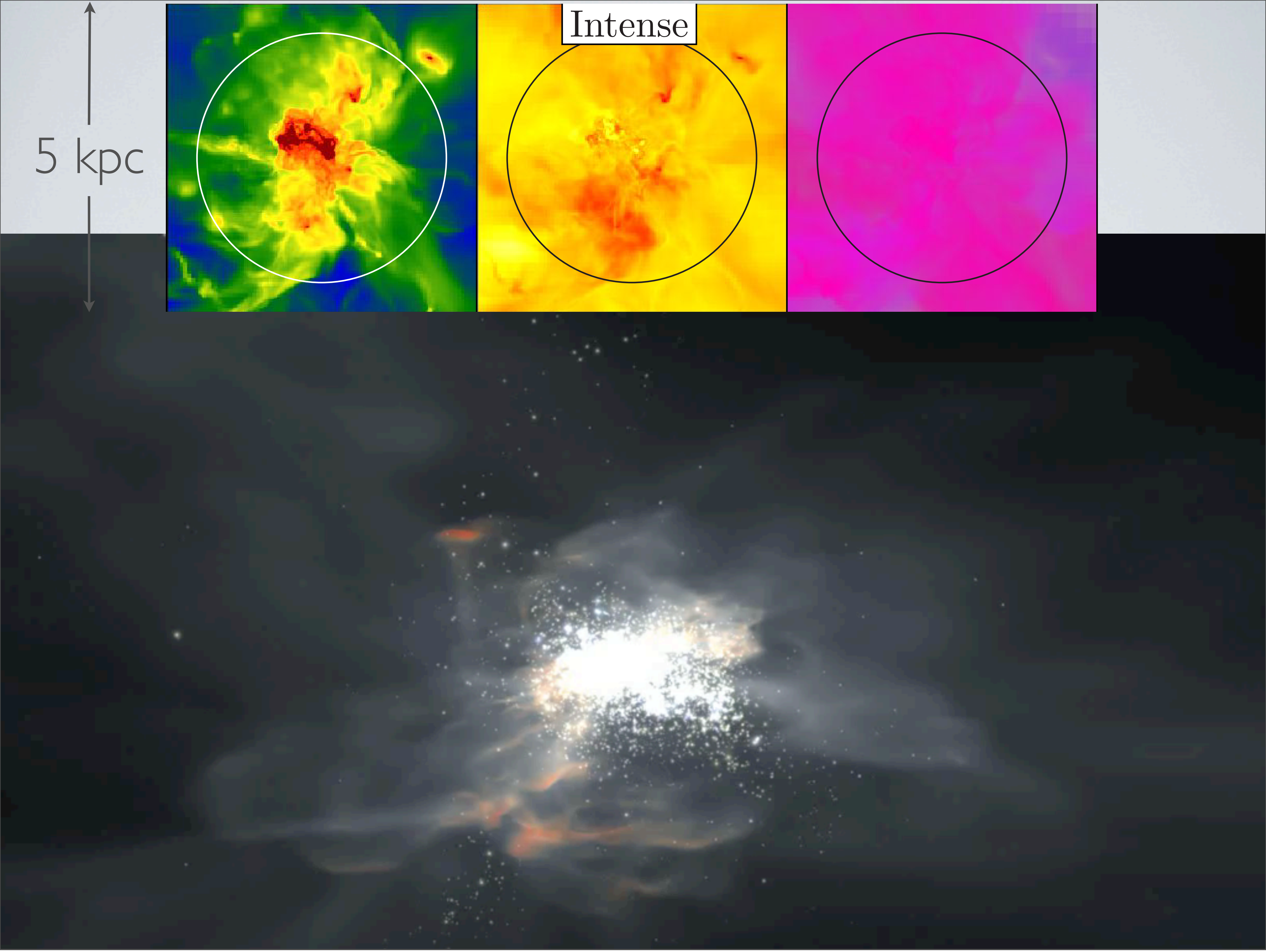

5 kpc
Quiet
$z = 7.0$
10^{-27}
Der
-6 -4 -2
$[Z_2/H]$
FoV = 10 kpc

- 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

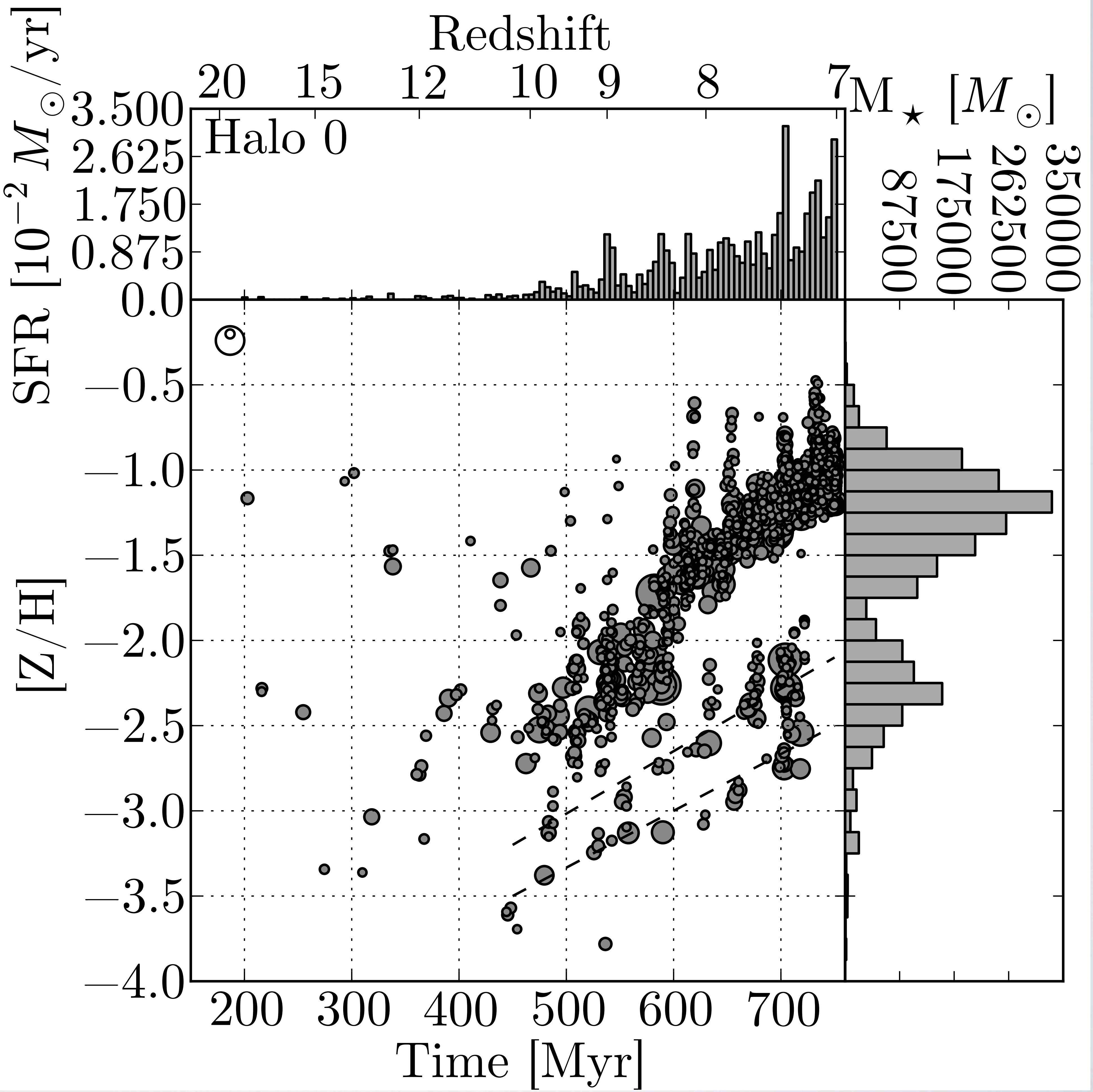



5 kpc
Intense



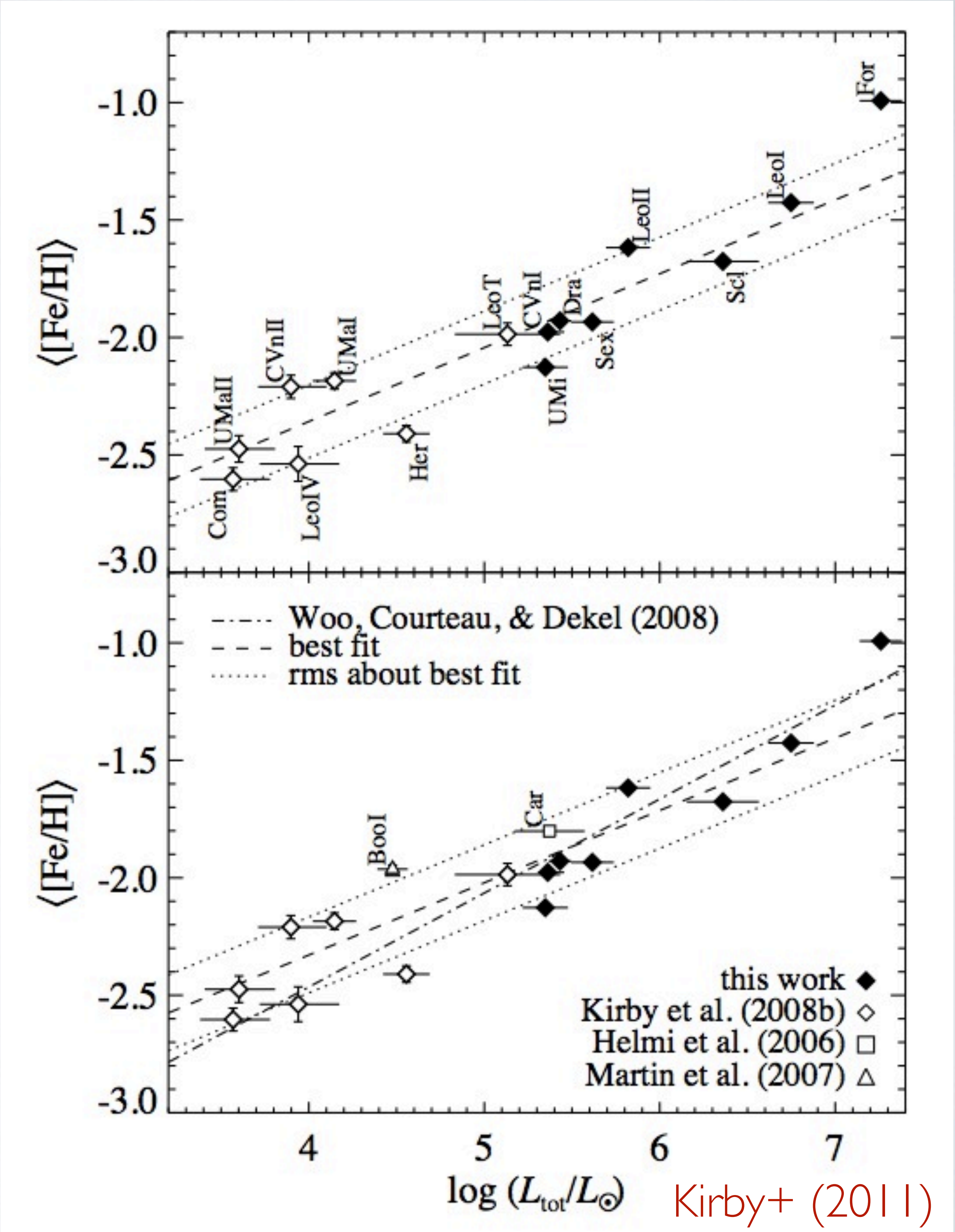

5 kpc
Intense

- 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.

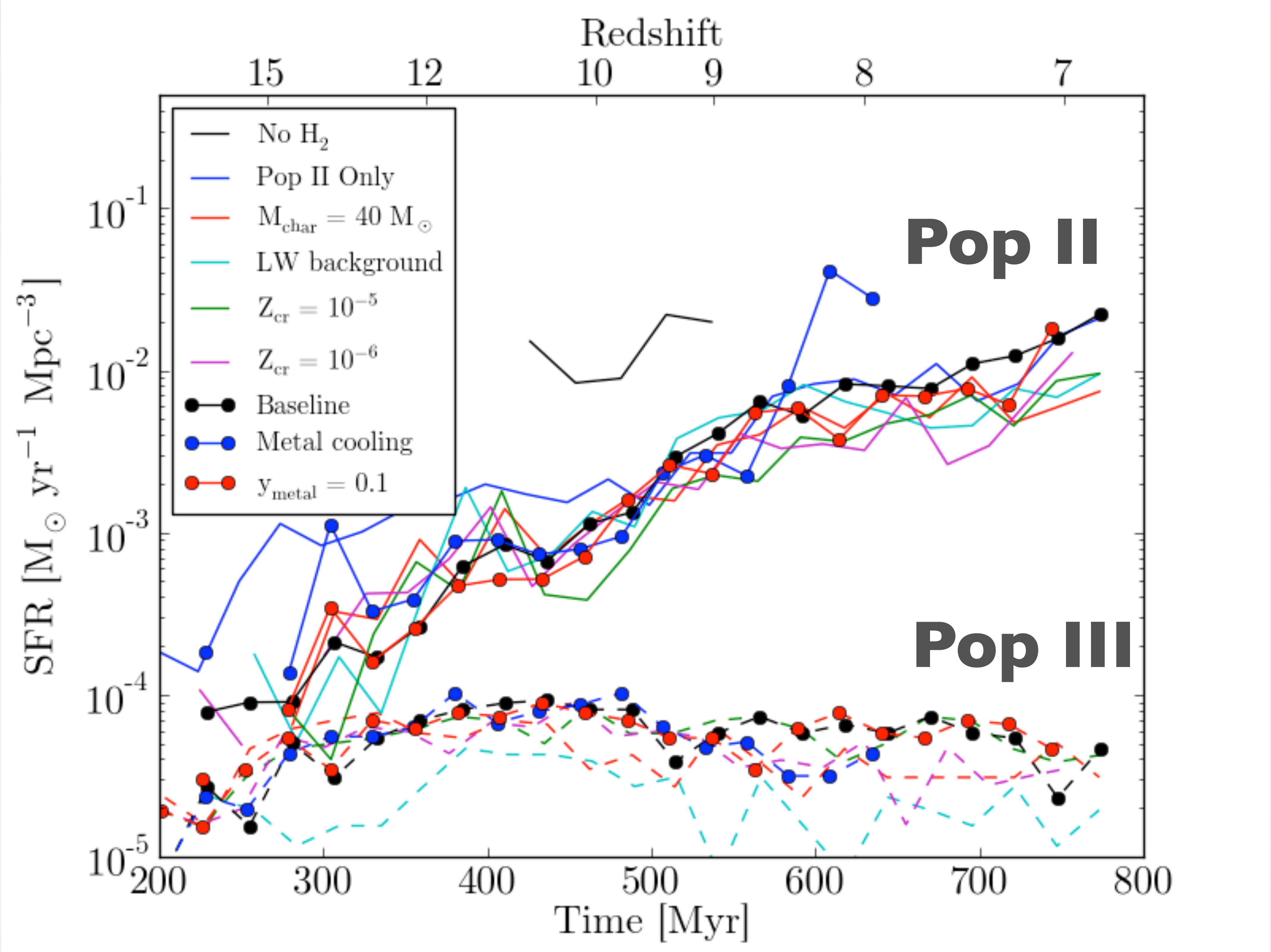


Kirby+ (2011)

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+ (2012 MNRAS v427)

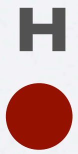
RADIATION PRESSURE FROM CONTINUUM ABSORPTION

- Acceleration is added to the cell from the absorbed radiation (hydrogen- and helium-ionizing and X-rays).

$$\boxed{d\mathbf{p}_{\rm rp} = \frac{dP\,E_\gamma}{c}\,\hat{\mathbf{r}} \qquad\qquad d\mathbf{a}_{\rm rp} = \frac{d\mathbf{p}_{\rm rp}}{dt\,\rho\,V_{\rm cell}}}$$

- where *dP* is the number of photons absorbed in the cell.

- In Enzo+Moray, acceleration from radiation is saved as 3 more grid fields.



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$p_\gamma = E/c$

H

JHW+ (2012 MNRAS v427)

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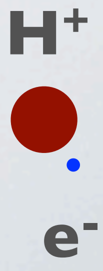

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RADIATION PRESSURE FROM CONTINUUM ABSORPTION

- Radiation pressure on dust grains increases the momentum transfer by the number of absorptions for a single photon, f_{trap}. For many scatterings, $f_{trap} \sim v/c$.

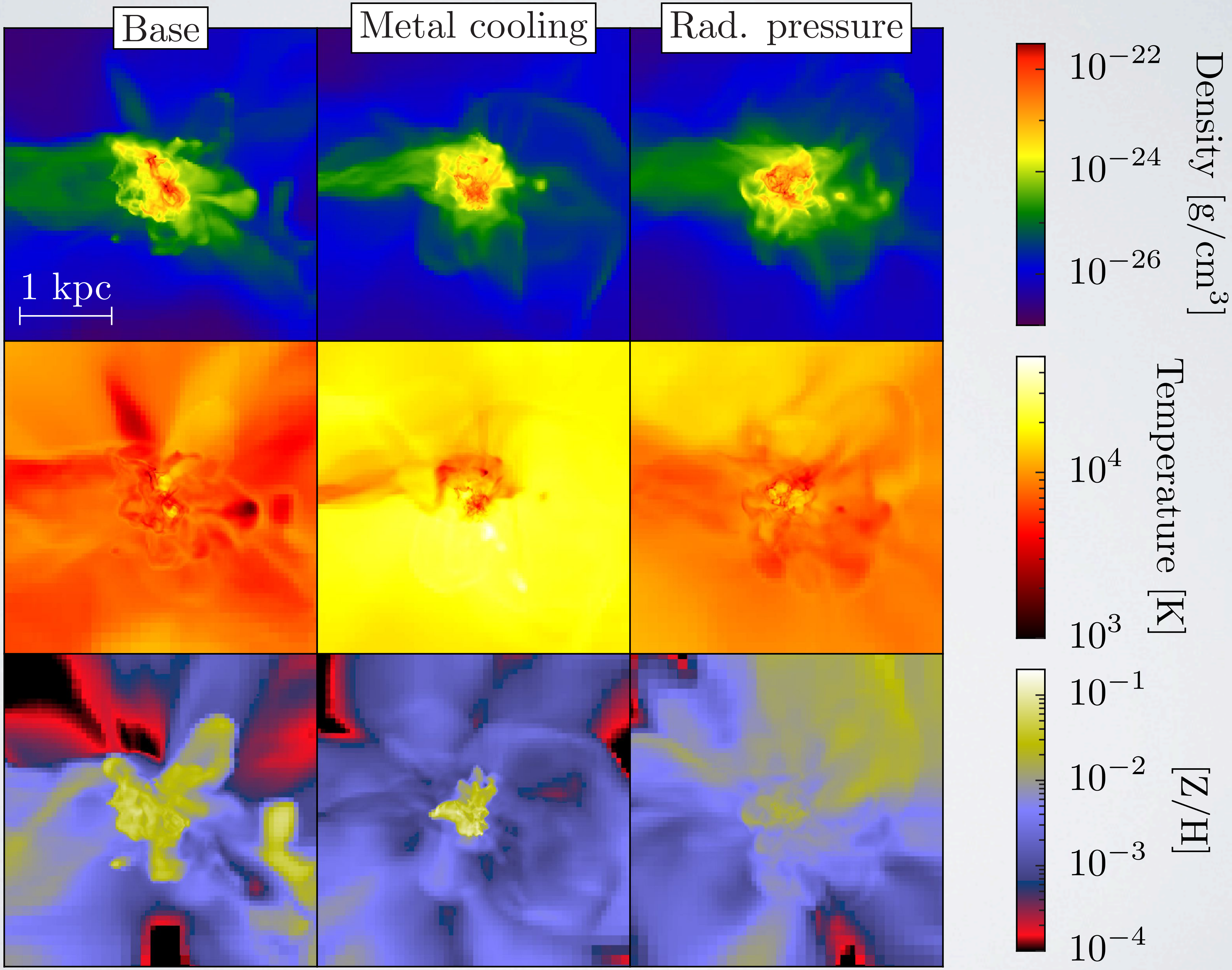
- Krumholz & Thompson (2012) found that $f_{trap} \approx \Sigma a_{grav}/(F_o/c) - 1$ and is lower than the IR optical depth.

- We do not consider dust in this calculation, but $\tau_{IR} \ll 1$ in this simulation.

JHW+ (2012 MNRAS v427)

EFFECTS OF RADIATION PRESSURE

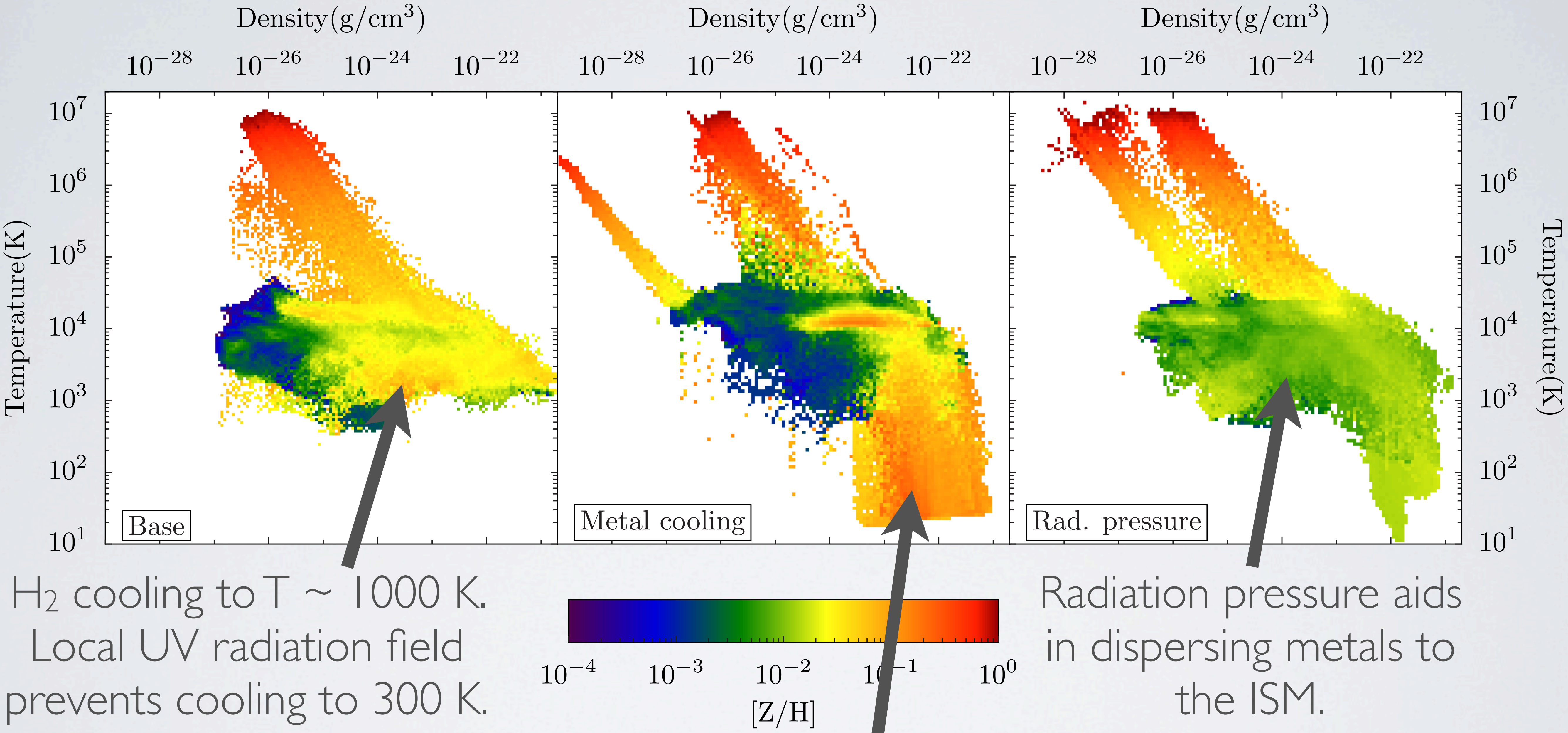
$M_{VIR} = 3 \times 10^8\ M_\odot$ GALAXY AT $z = 8$



JHW+ (2012 MNRAS v427)

EFFECTS OF RADIATION PRESSURE

AVG. METALLICITIES IN DENSITY-TEMPERATURE SPACE



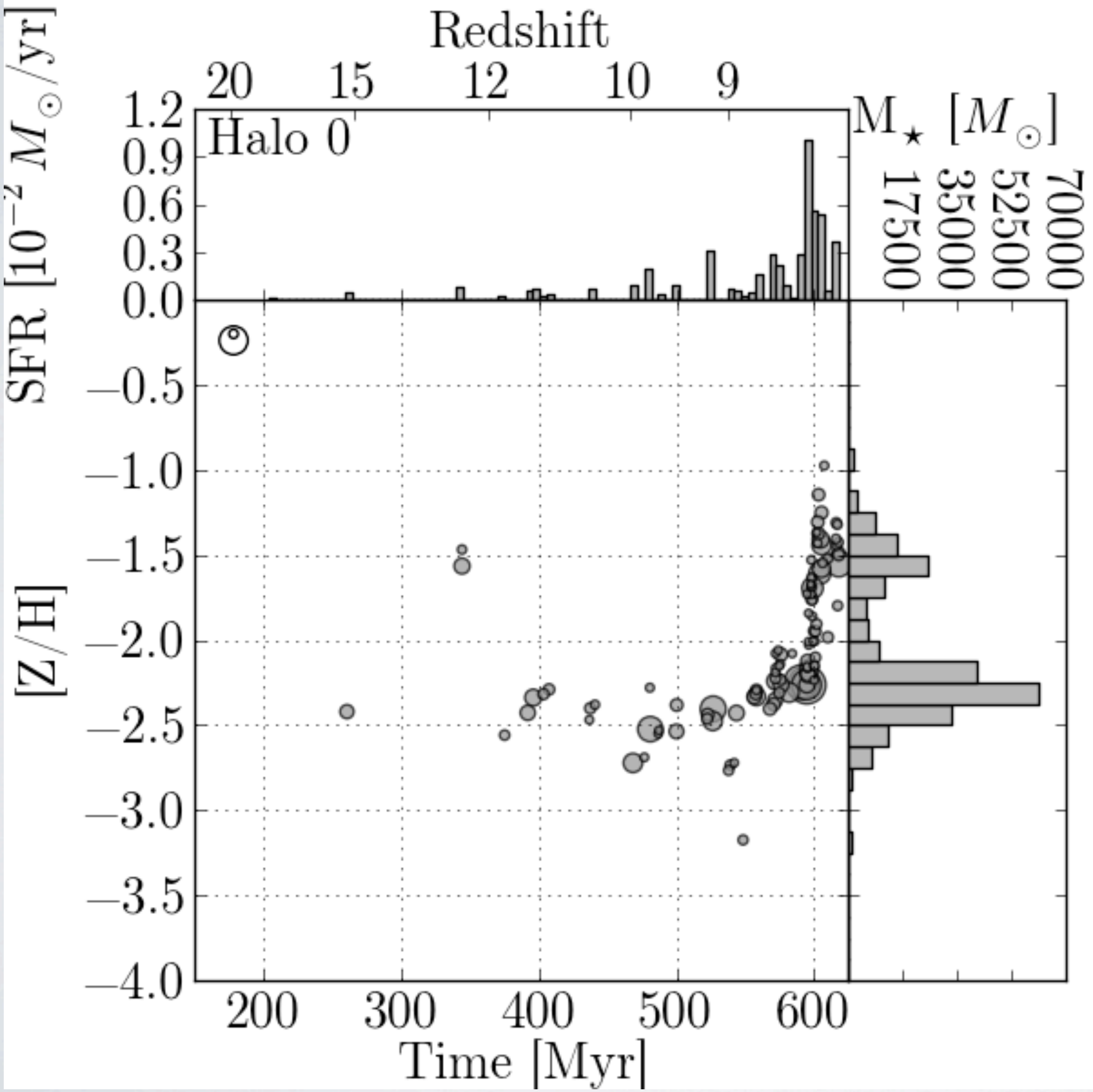
H_2 cooling to T ~ 1000 K. Local UV radiation field prevents cooling to 300 K.

Radiation pressure aids in dispersing metals to the ISM.

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

JHW+ (2012 MNRAS v427)

BASELINE AT $z = 8$



Main Limitation:

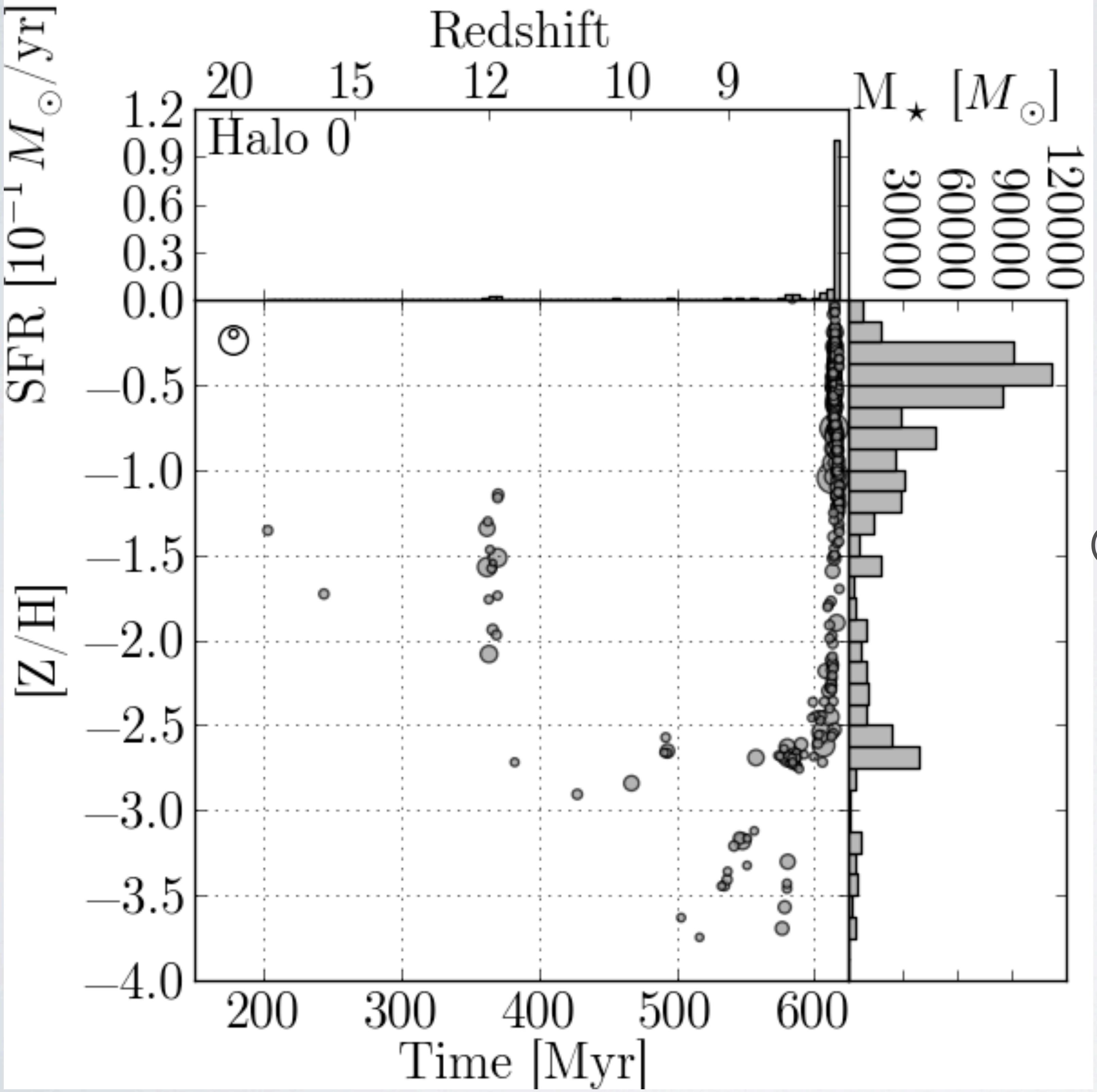
lacking

Metal cooling

Soft UV background

JHW+ (2012 MNRAS v427)

+ METAL COOLING & SOFT UVB



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

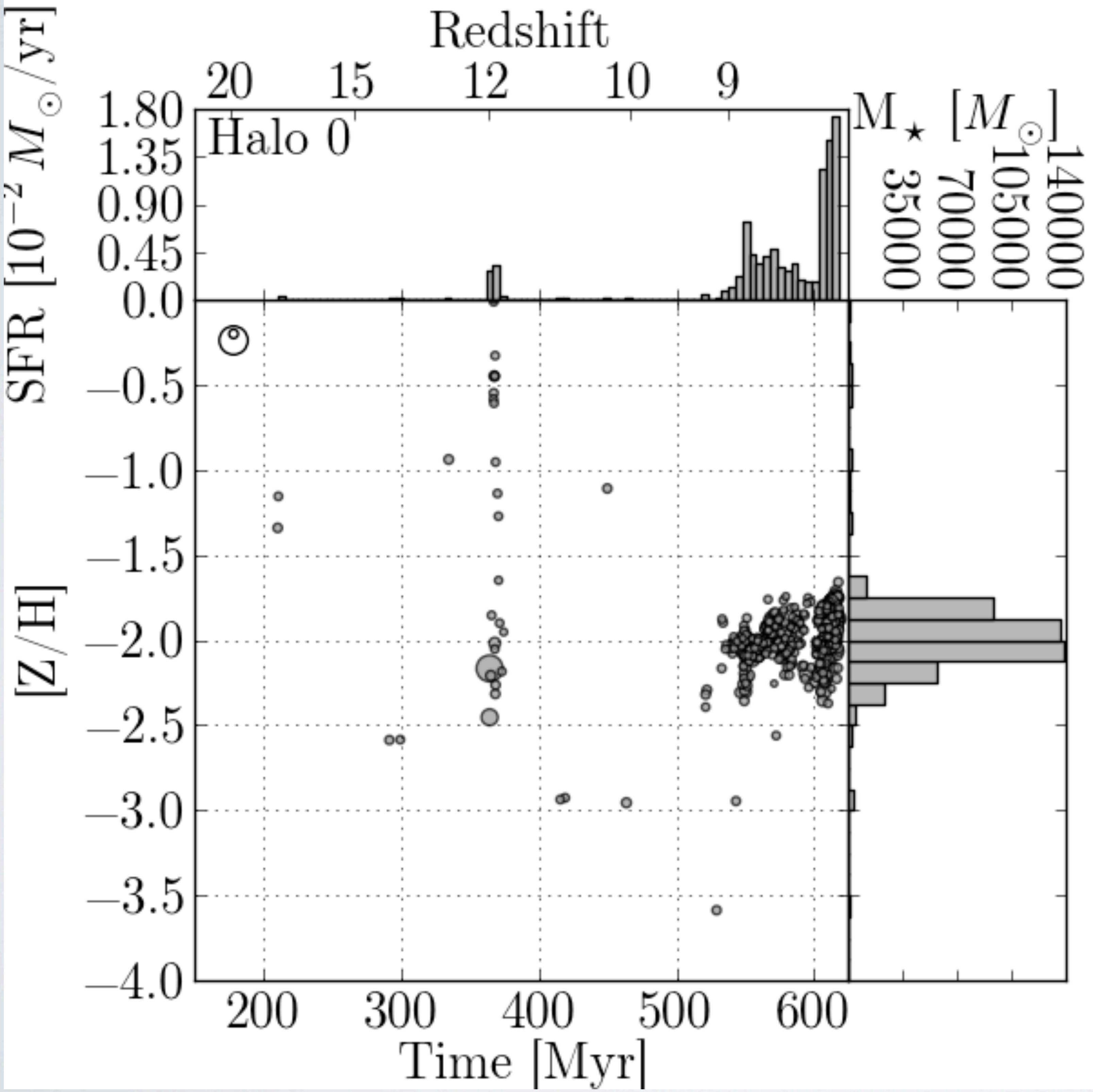
Katz+ (1996) plus many more...

Causes over-enrichment – nearly solar metallicities.

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

JHW+ (2012 MNRAS v427)

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

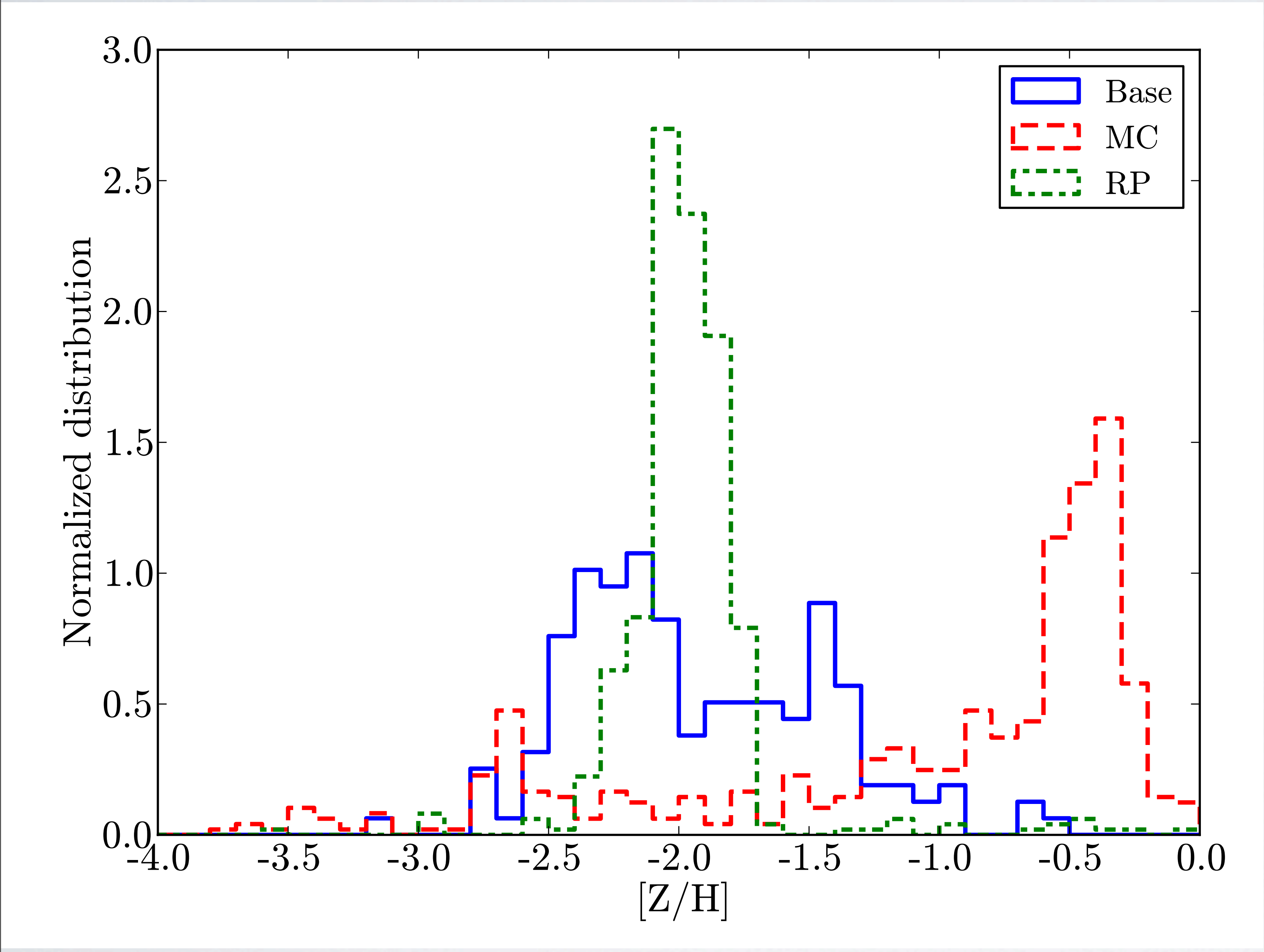
SF decreases because dense gas is further dispersed.

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

JHW+ (2012 MNRAS v427)

EFFECTS OF RADIATION PRESSURE

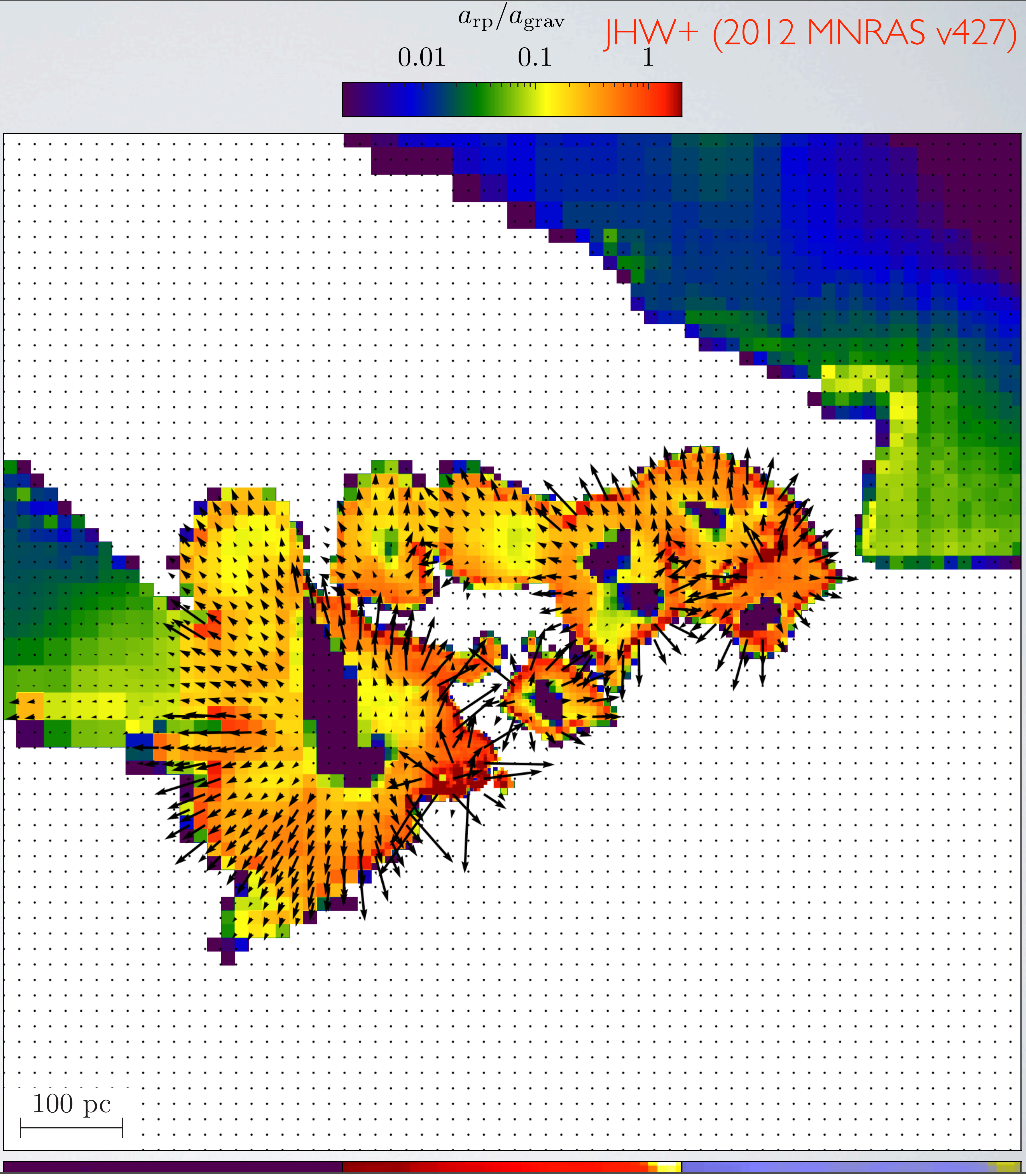
METALLICITY DISTRIBUTION FUNCTIONS



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

JHW+ (2012 MNRAS v427)

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



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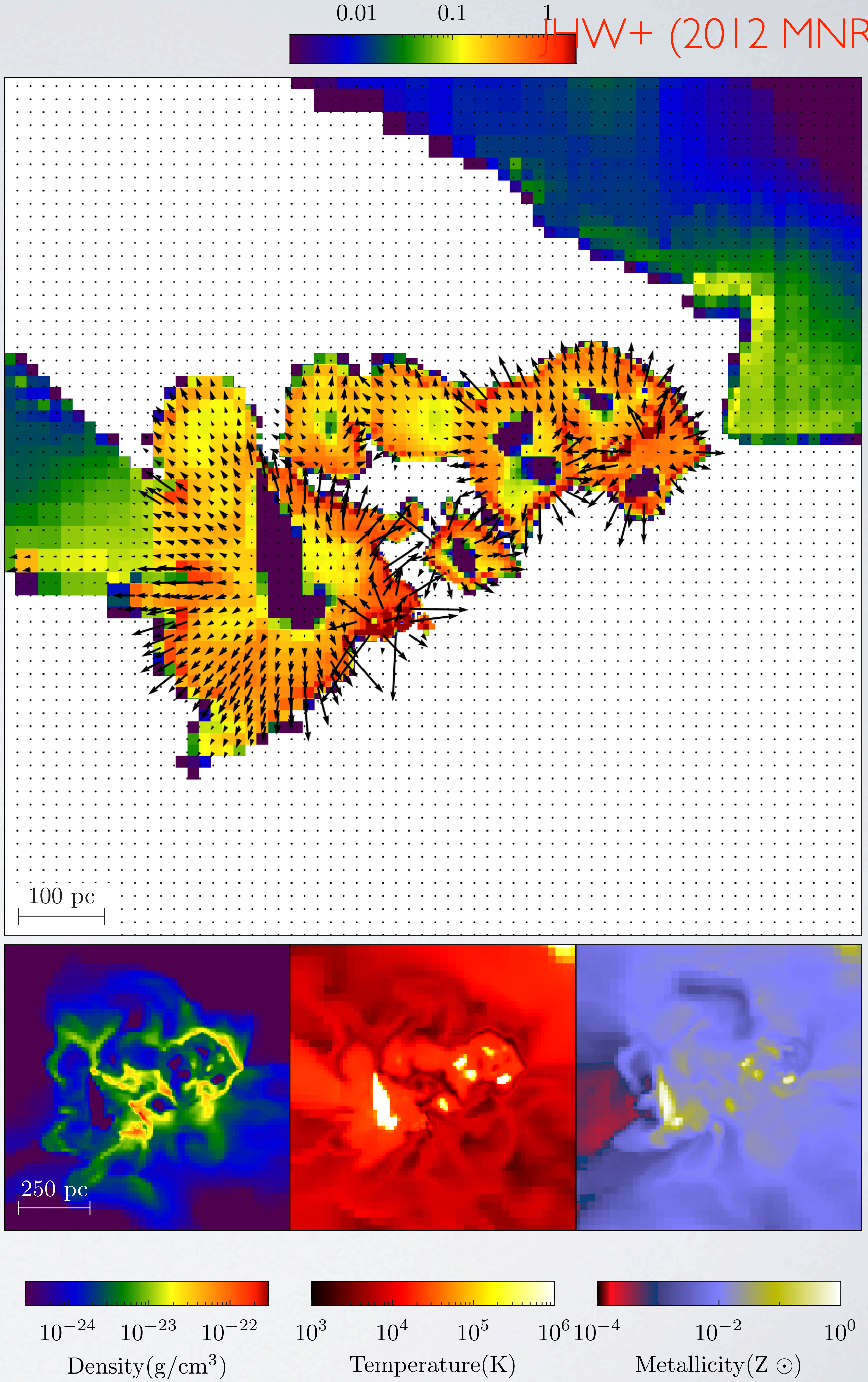
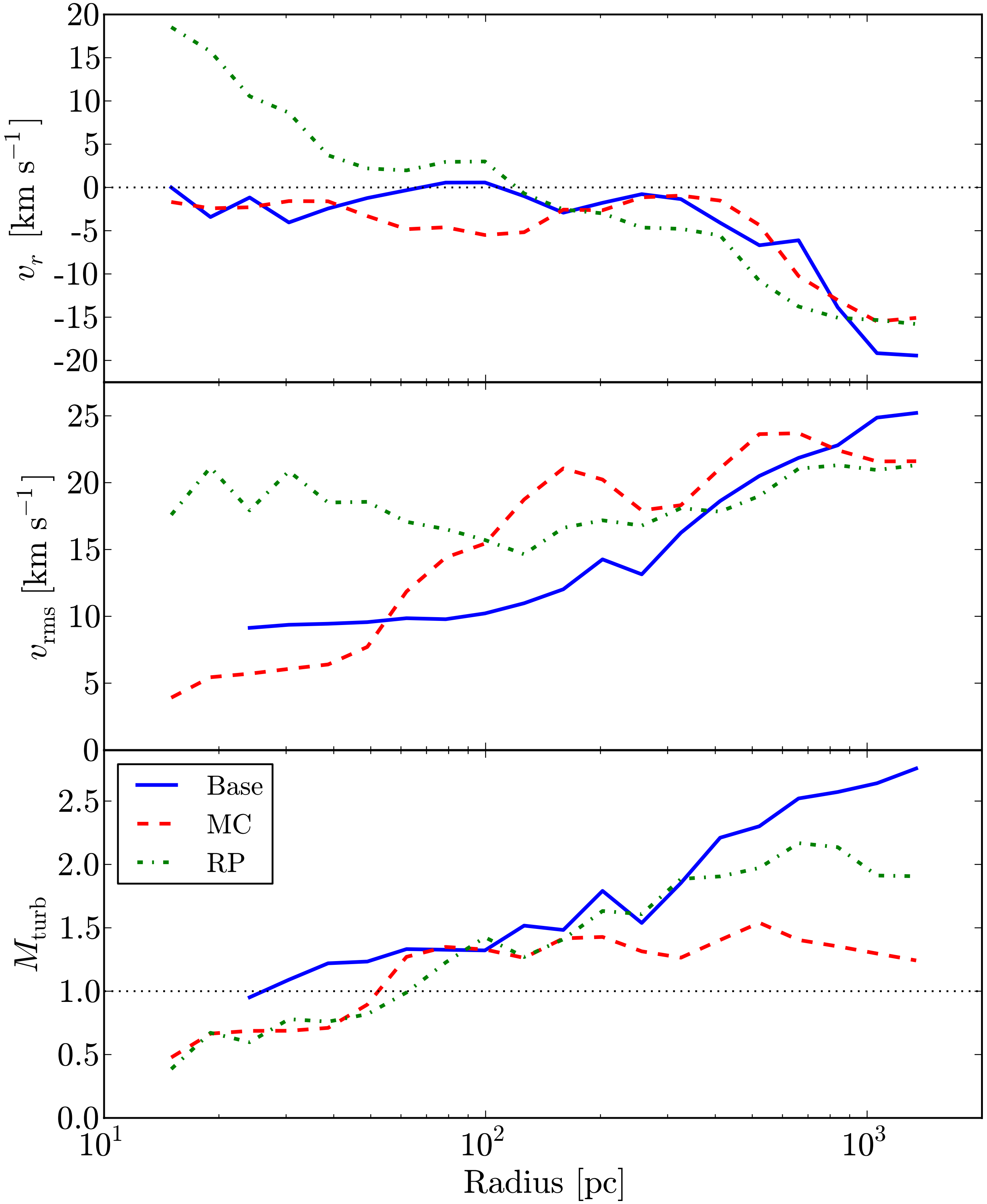


JHW+ (2012 MNRAS v427)

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

- 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.