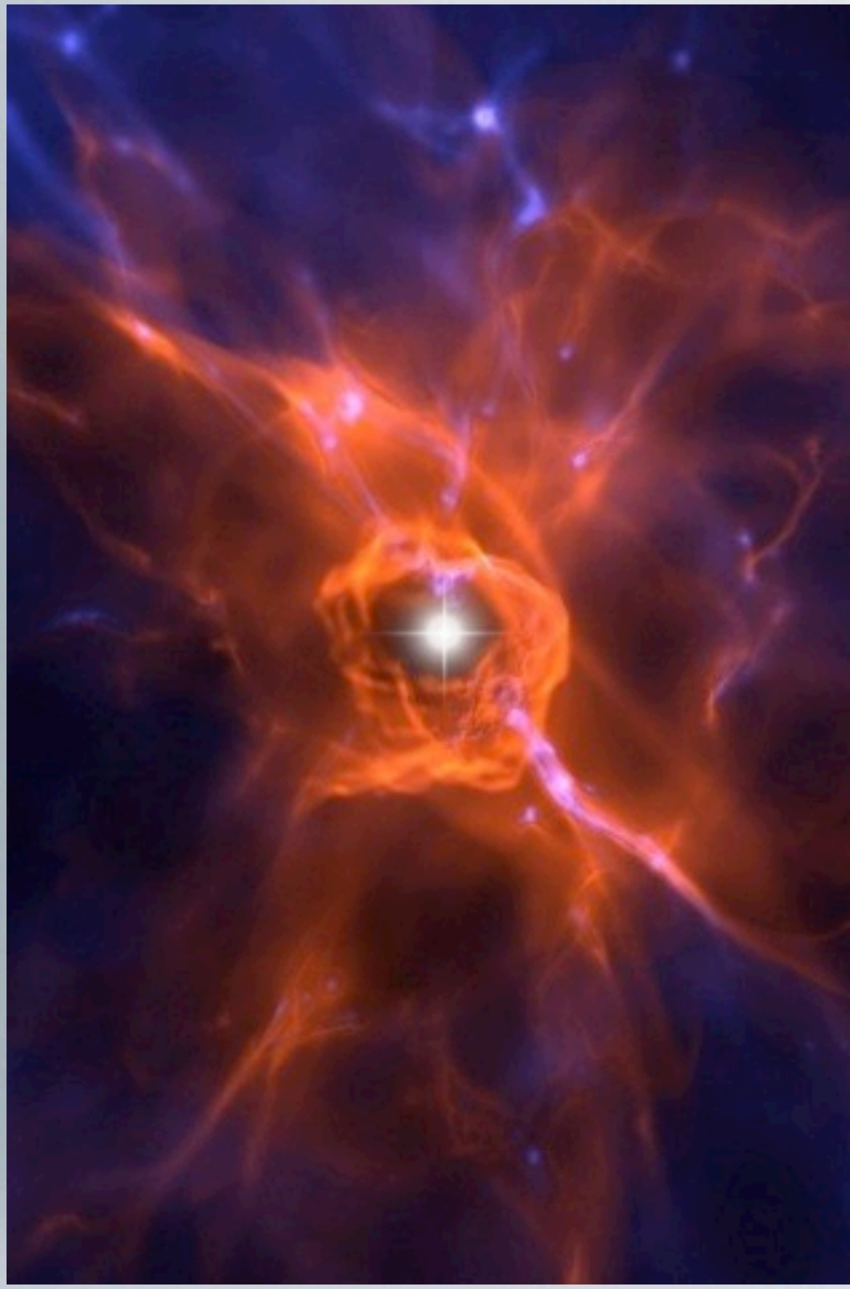
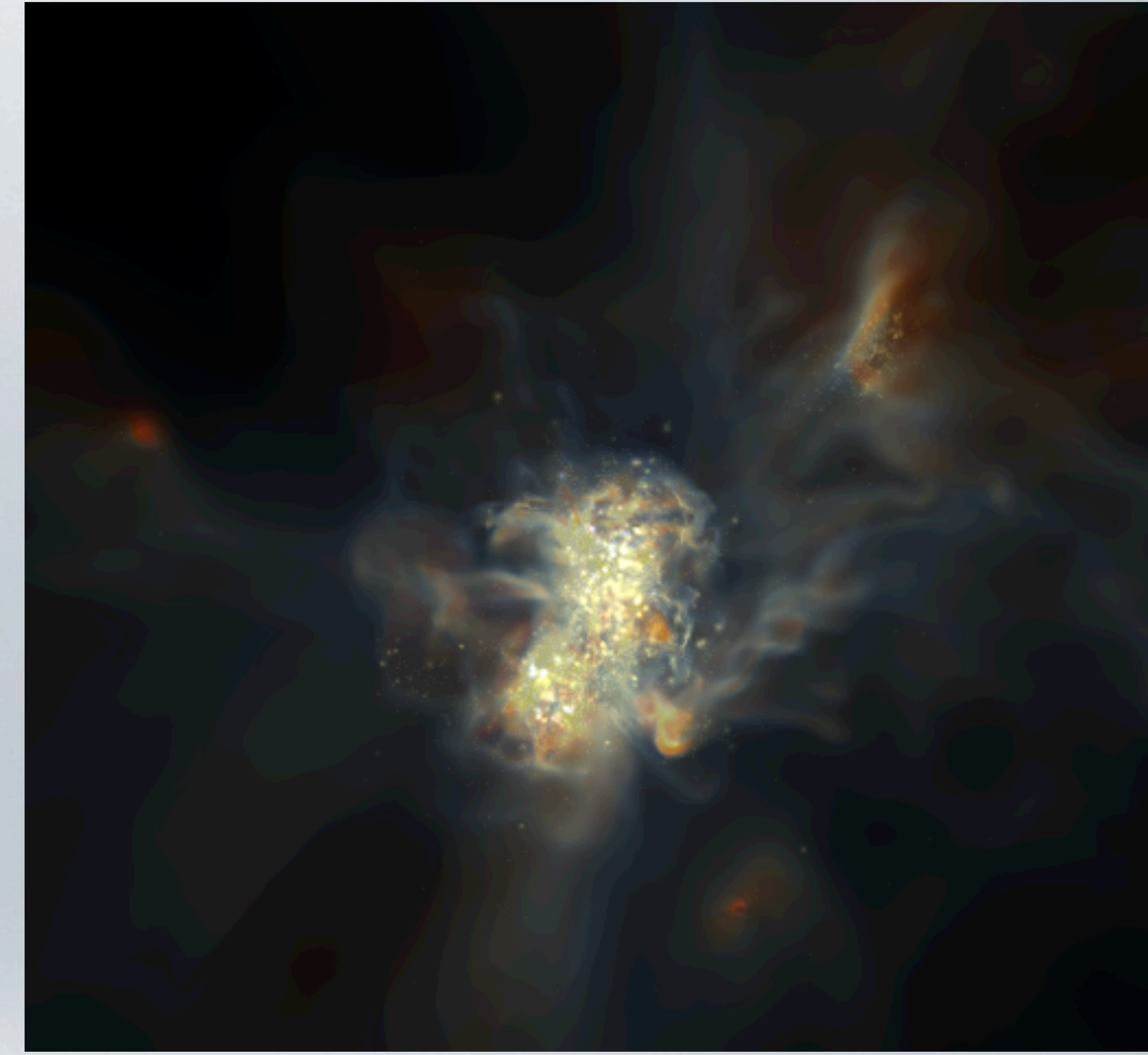
 

FROM THE FIRST STARS TO DWARF GALAXIES

John Wise (Princeton → Georgia Tech)
Collaborators: Tom Abel (Stanford), Michael Norman (UCSD), Britton Smith (MSU), & Matthew Turk (Columbia)

OPEN QUESTIONS:

POP III STARS AND GALAXIES BEFORE REIONIZATION

- How did metal-free (Pop III) stars affect high-z structure formation?
  - Metal enrichment
  - Reionization
  - Galaxy properties
- Why do current models overpredict SF in low-mass galaxies at high redshift?
- How do these dwarf galaxies depend on environment?
- Do Pop III stars leave any physical (e.g. metallicity gradients, M/L ratios, metallicity distributions) imprint on dwarf galaxies?

OUR APPROACH:

SIMULATIONS

- Small-scale AMR radiation hydro simulations
- Include as much physics as possible
- Coupled radiative transfer (ray tracing in the optically thin and thick regimes)

enzo.googlecode.com

Thursday, 21 July 2011

POPULATION III STARS

- Various computational techniques (AMR, SPH, Arepo) have calculated that the first stars are massive (10–300 $M_\odot$) and could be a mix of isolated and binary systems.

  Abel+ 2002, Bromm+ 2002, Yoshida+ 2006, Turk+ 2009, Greif+ 2011

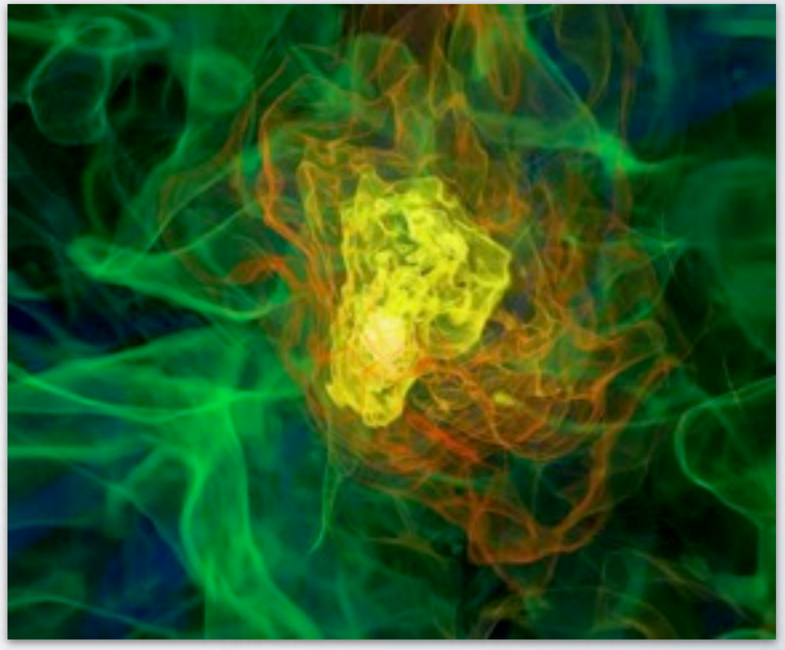
- $L \sim 10^6\ L_\odot$, $\sim 10^{50}$ ionizing photons / sec

  Schaerer (2002)

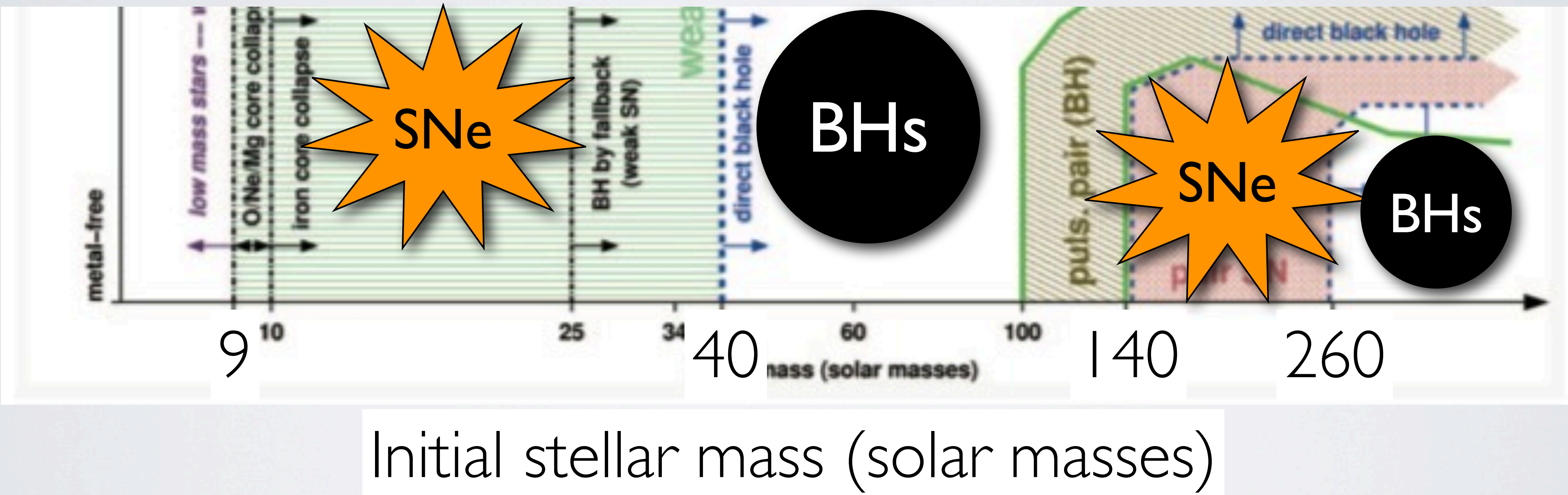
- Lifetime ~ 3 Myr

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

  Dekel & Rees (1987)



STELLAR ENDPOINTS OF METAL-FREE STARS



Heger et al. (2003)

Abel, Wise, & Bryan (2007)

H II REGION OF A PRIMORDIAL STAR

Density

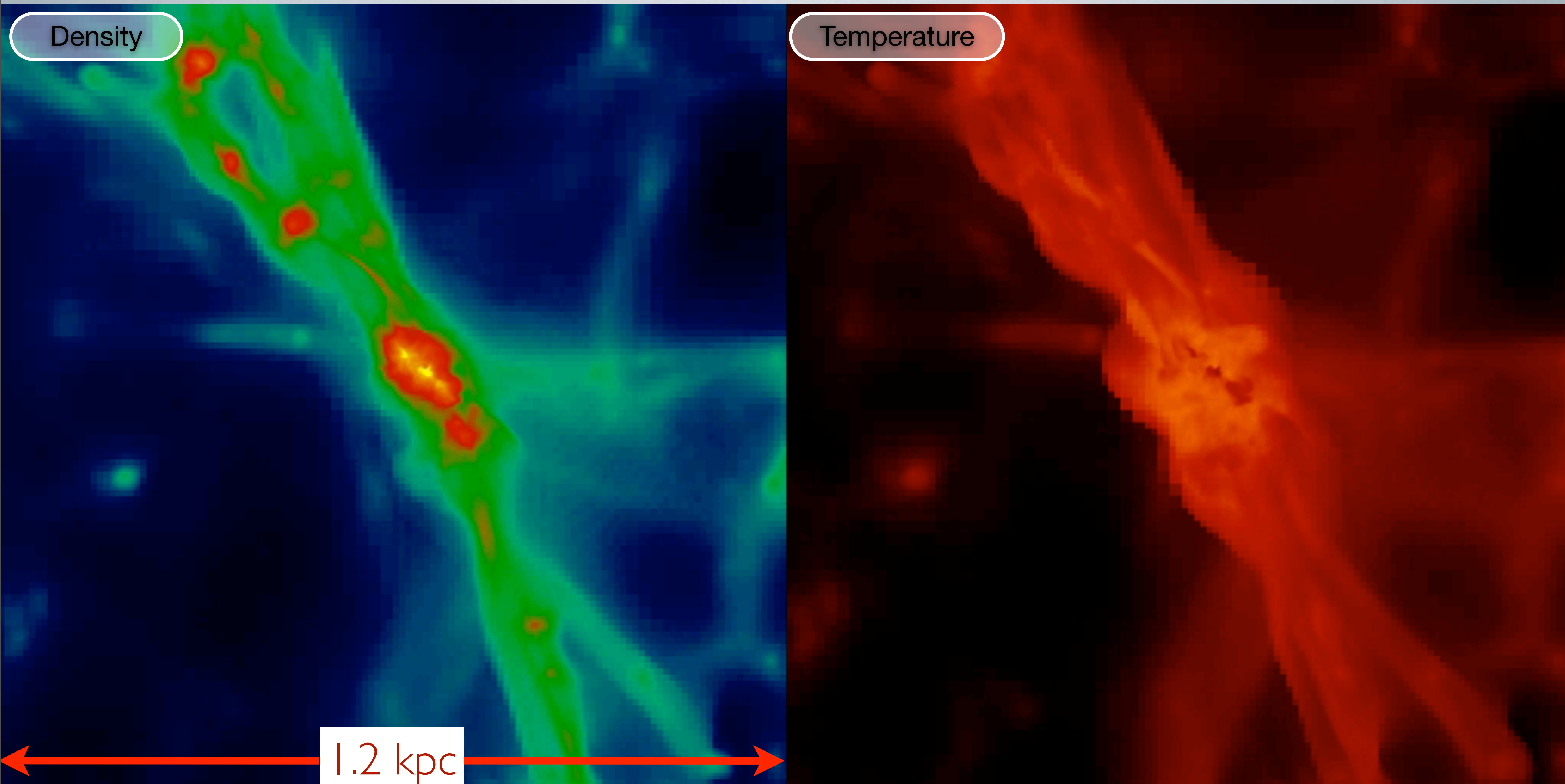
Temperature

← 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
- DM cusp → core (Wise & Abel 2008)

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
- DM cusp → core (Wise & Abel 2008)

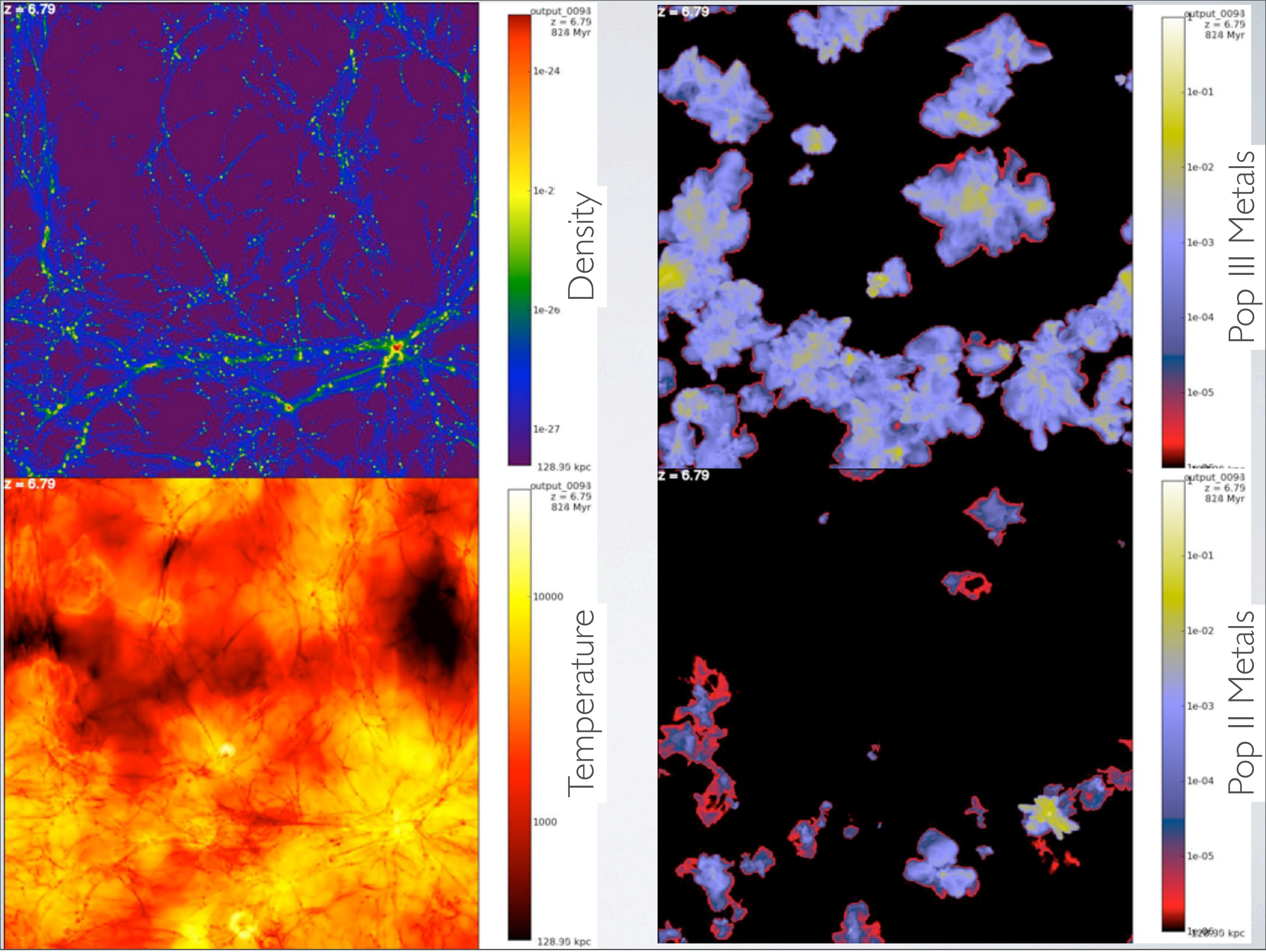
Wise, Turk, Norman, & Abel, arXiv:1011.2632

OUR APPROACH:

AMR RAD-HYDRO SIMULATIONS

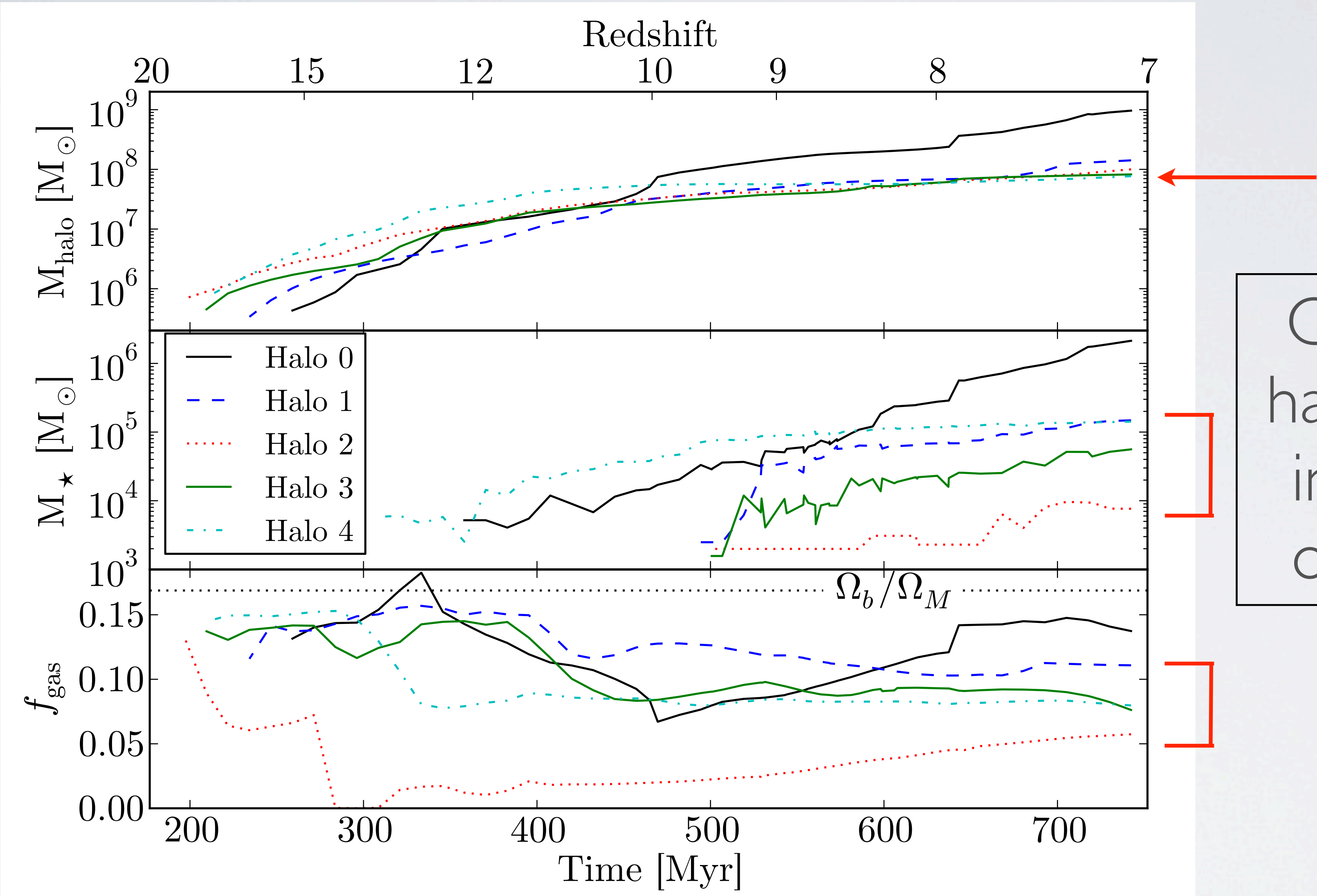
- Small-scale (1 comoving Mpc^3) AMR radiation hydro simulation with Pop II+III star formation and feedback (1000 cm^{-3} threshold)
- Coupled radiative transfer (ray tracing: optically thin and thick regimes)
- 1800 $M_\odot$ mass resolution, 0.1 pc maximal spatial resolution
- Self-consistent Population 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 = 6.79
1e-24
1e-26
1e-27
Density
z = 6.79
10000
1000
Temperature
z = 6.79
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
z = 6.79
1e-01
1e-02
1e-03
1e-04
1e-05
Pop II Metals

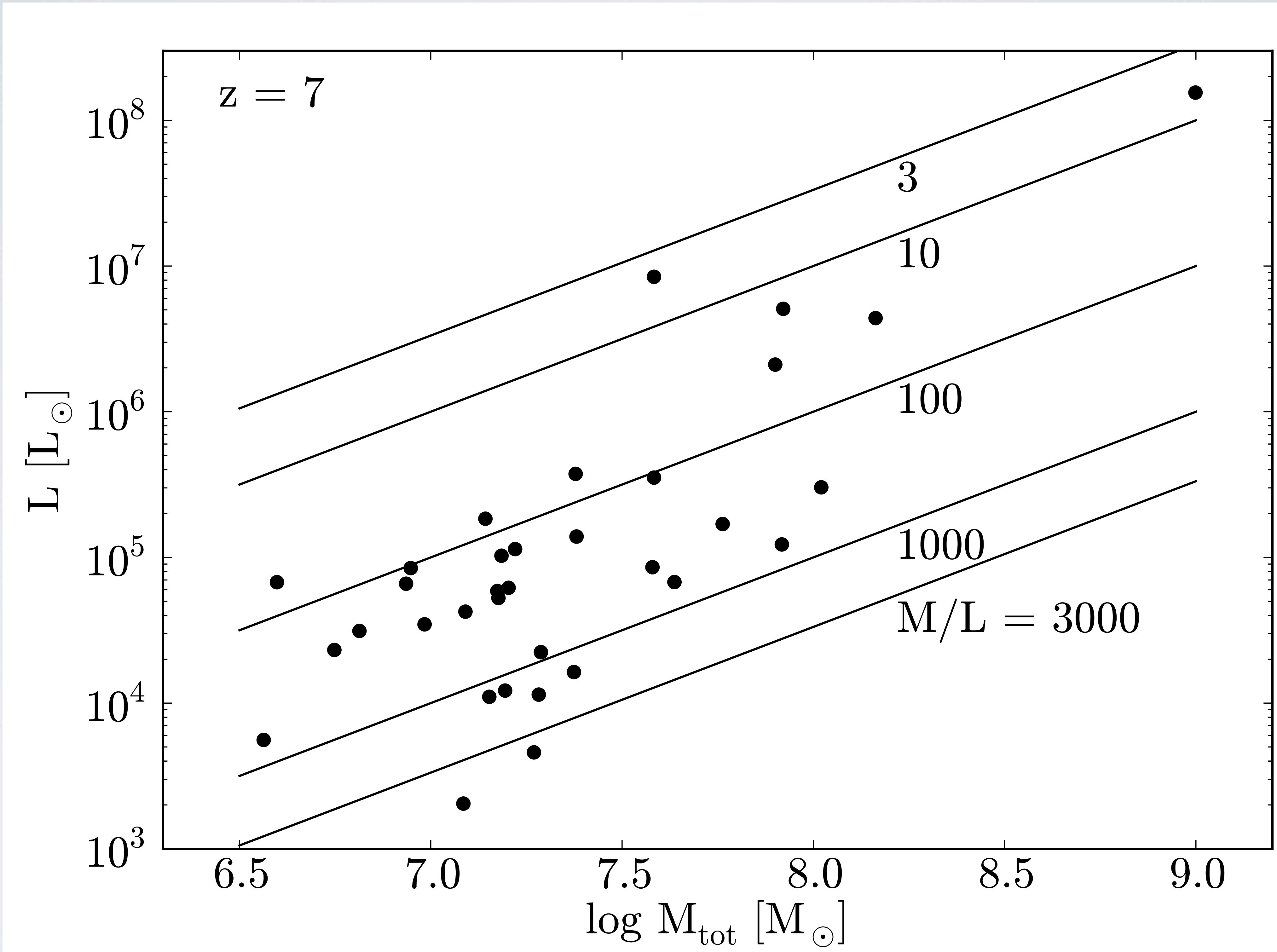
DWARF GALAXY BUILDUP



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

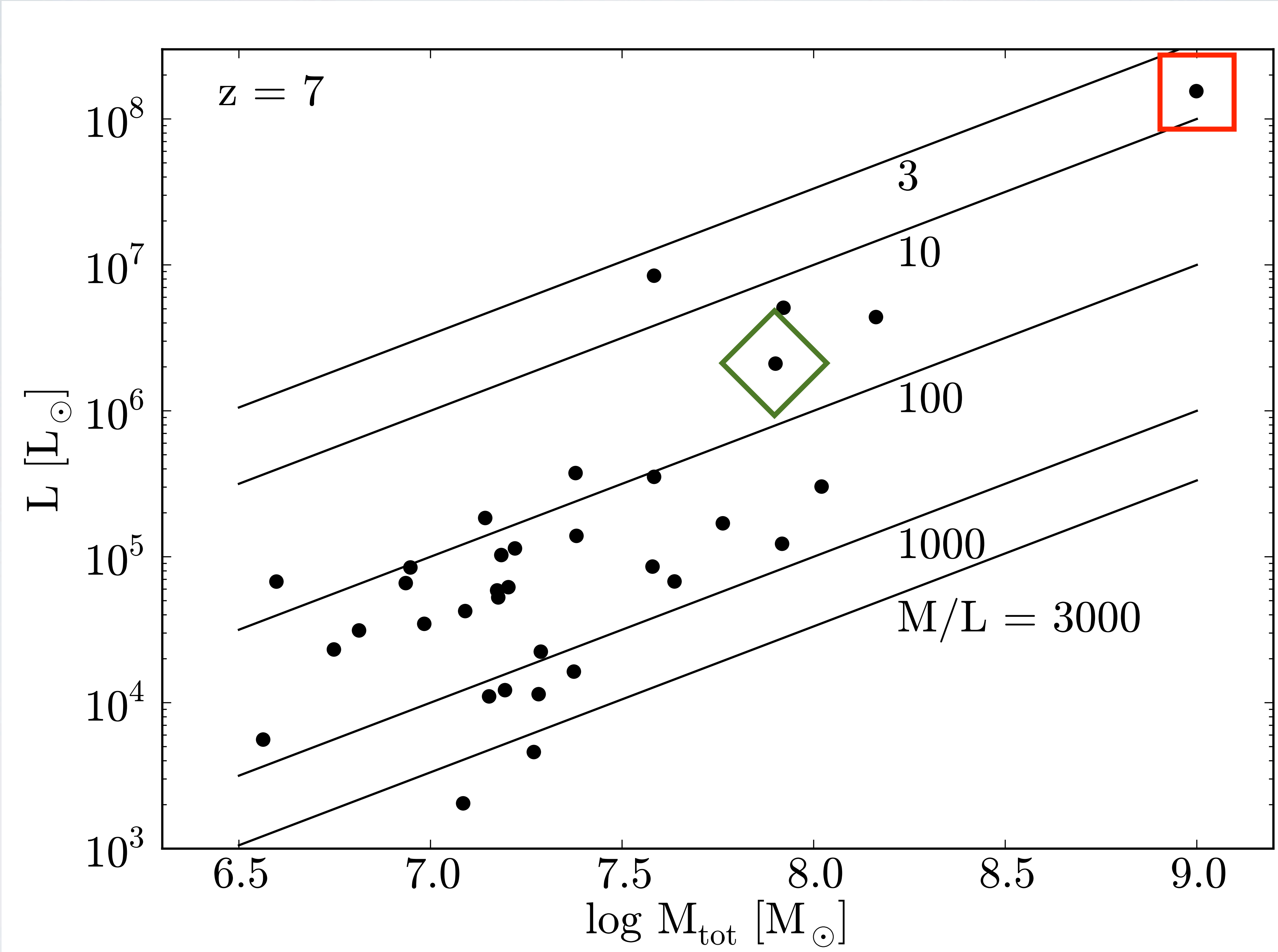
- The initial buildup of the dwarfs are regulated by prior Pop III stellar feedback and radiative feedback from nearby galaxies.

MASS-TO-LIGHT RATIOS

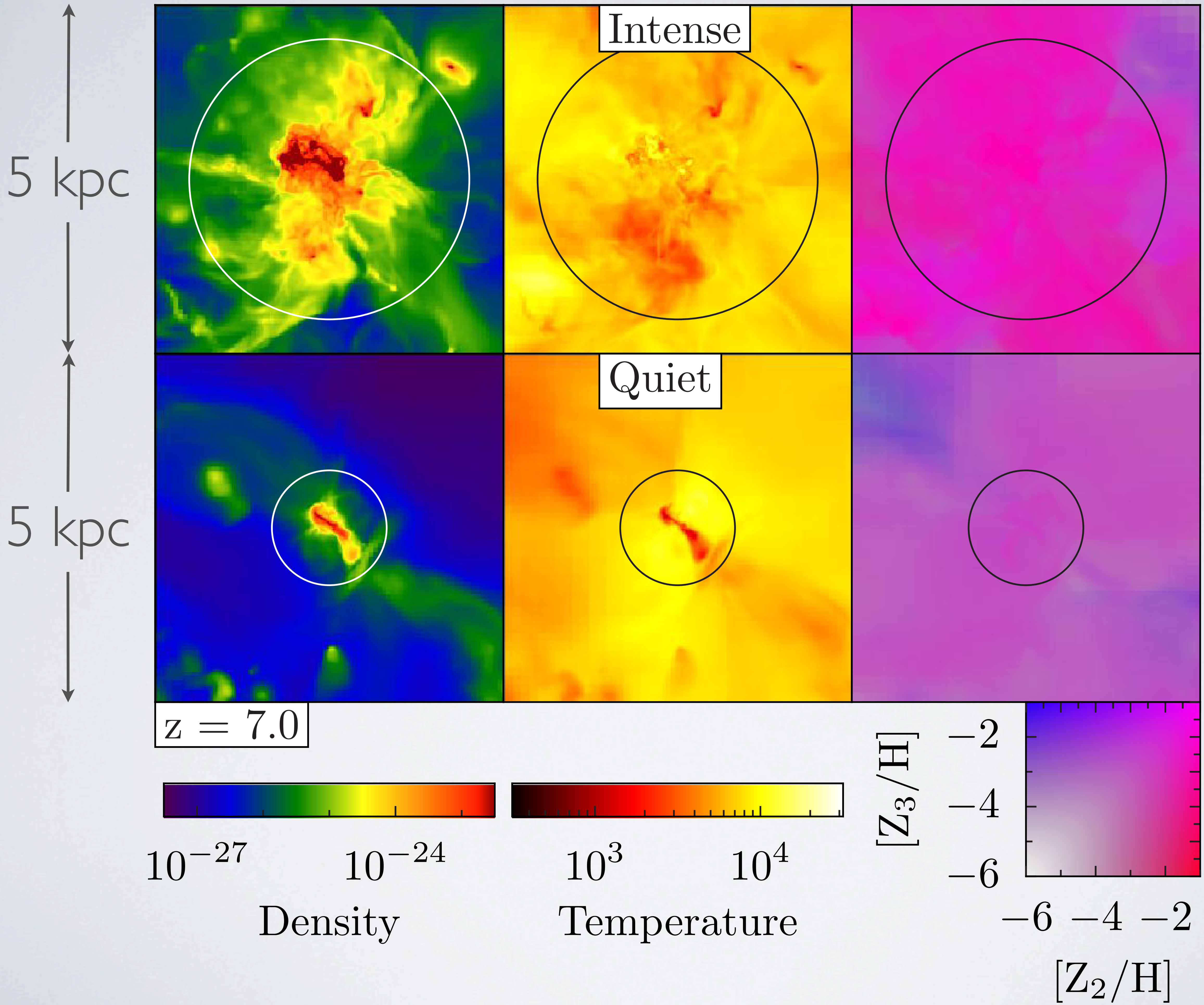


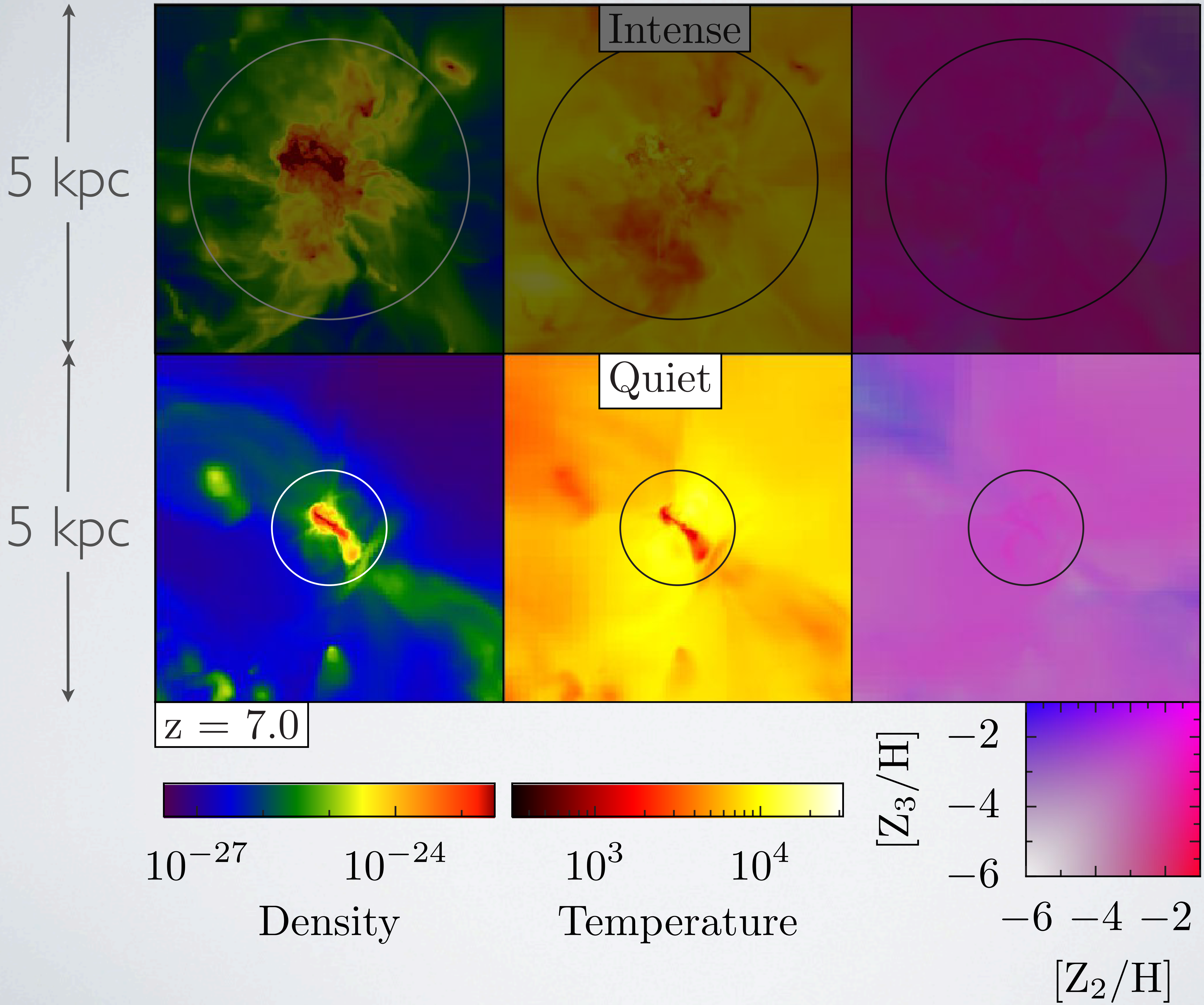
Scatter at low-mass caused by environment and different Pop III endpoints

MASS-TO-LIGHT RATIOS

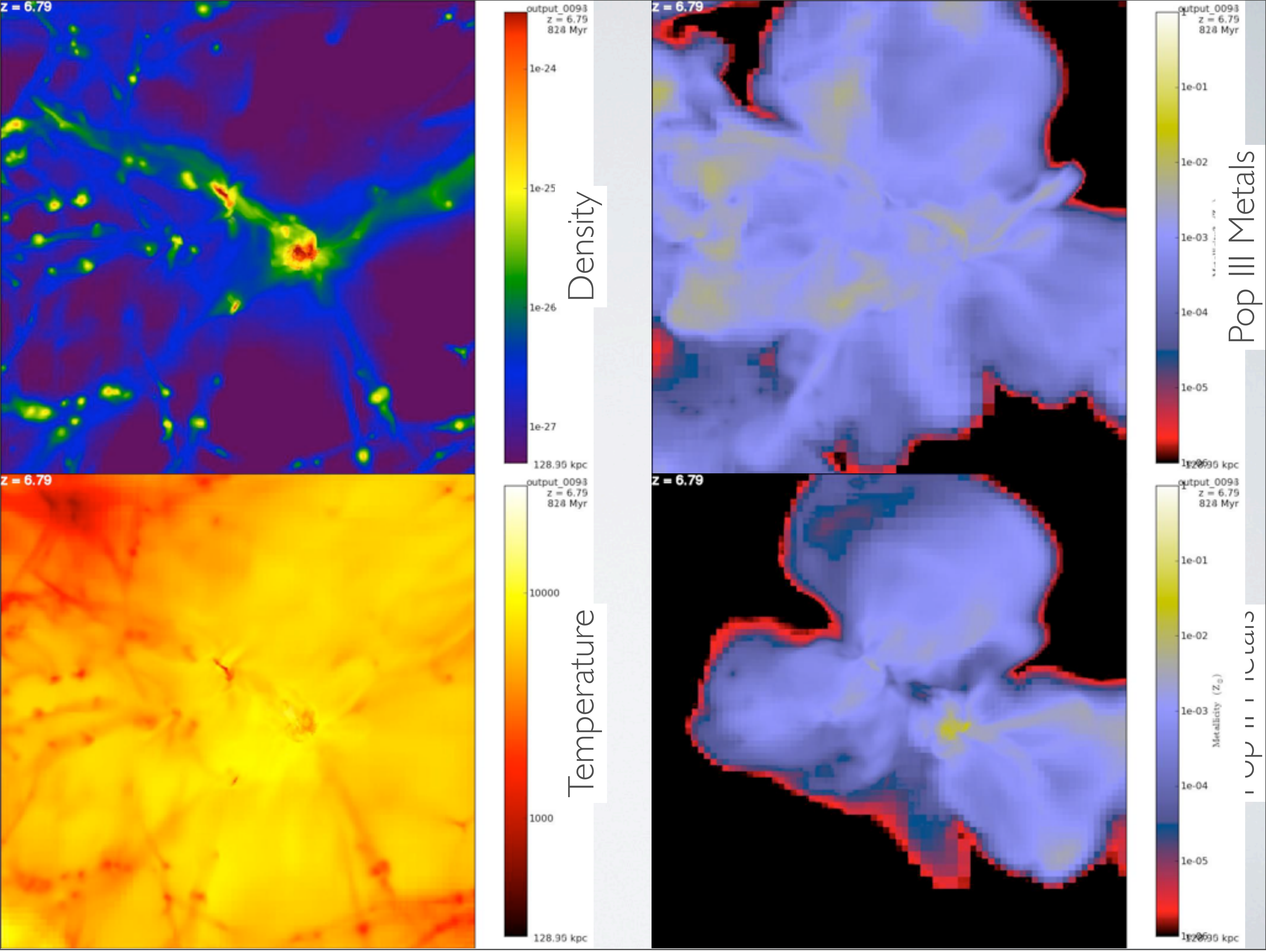


Scatter at low-mass caused by environment and different Pop III endpoints

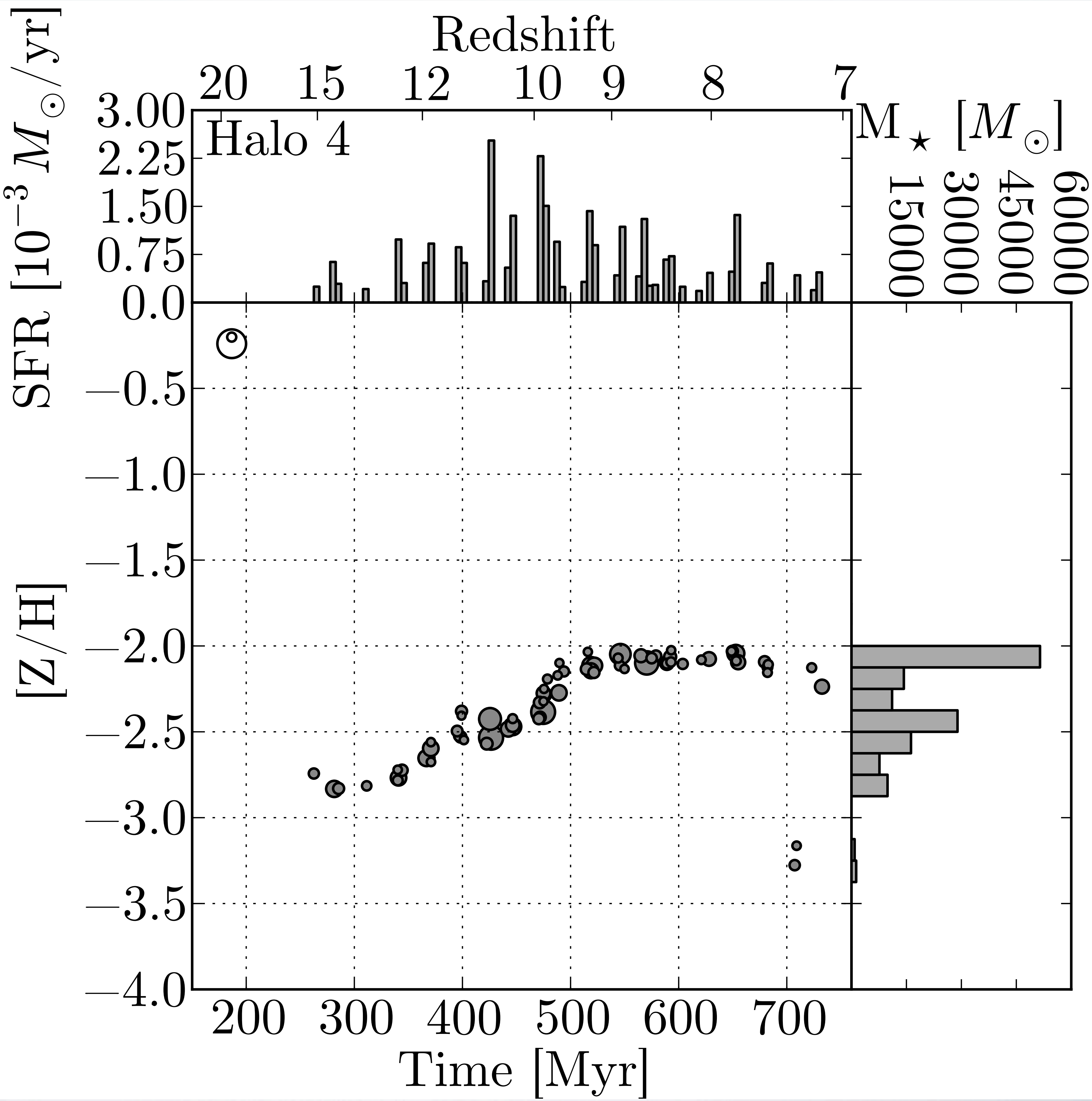

5 kpc
5 kpc
Intense
Quiet
z = 7.0
10^{-27}
10^{-24}
Density
10^3
10^4
Temperature
$[Z_3/H]$
−2
−4
−6
−6 −4 −2
$[Z_2/H]$

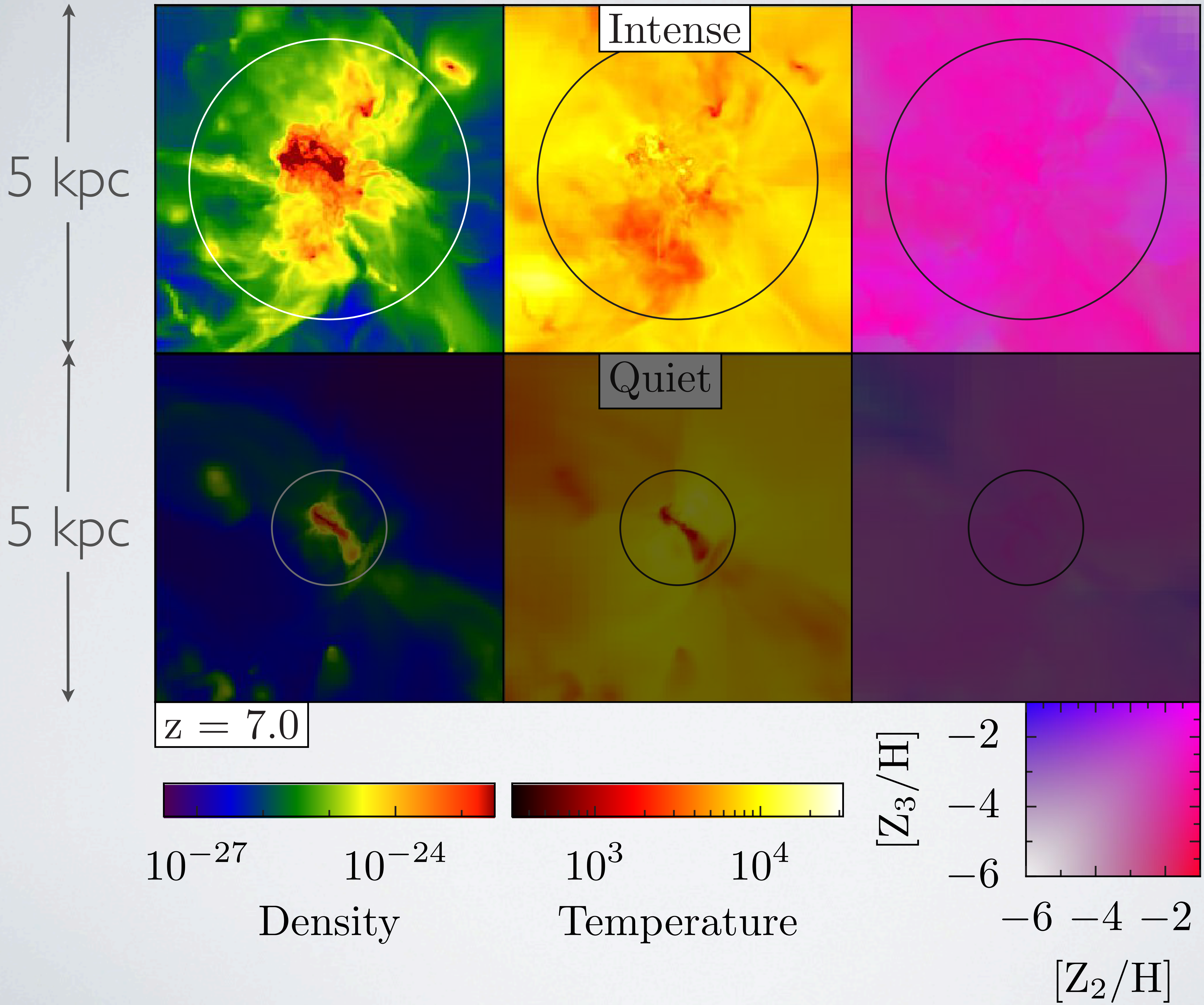


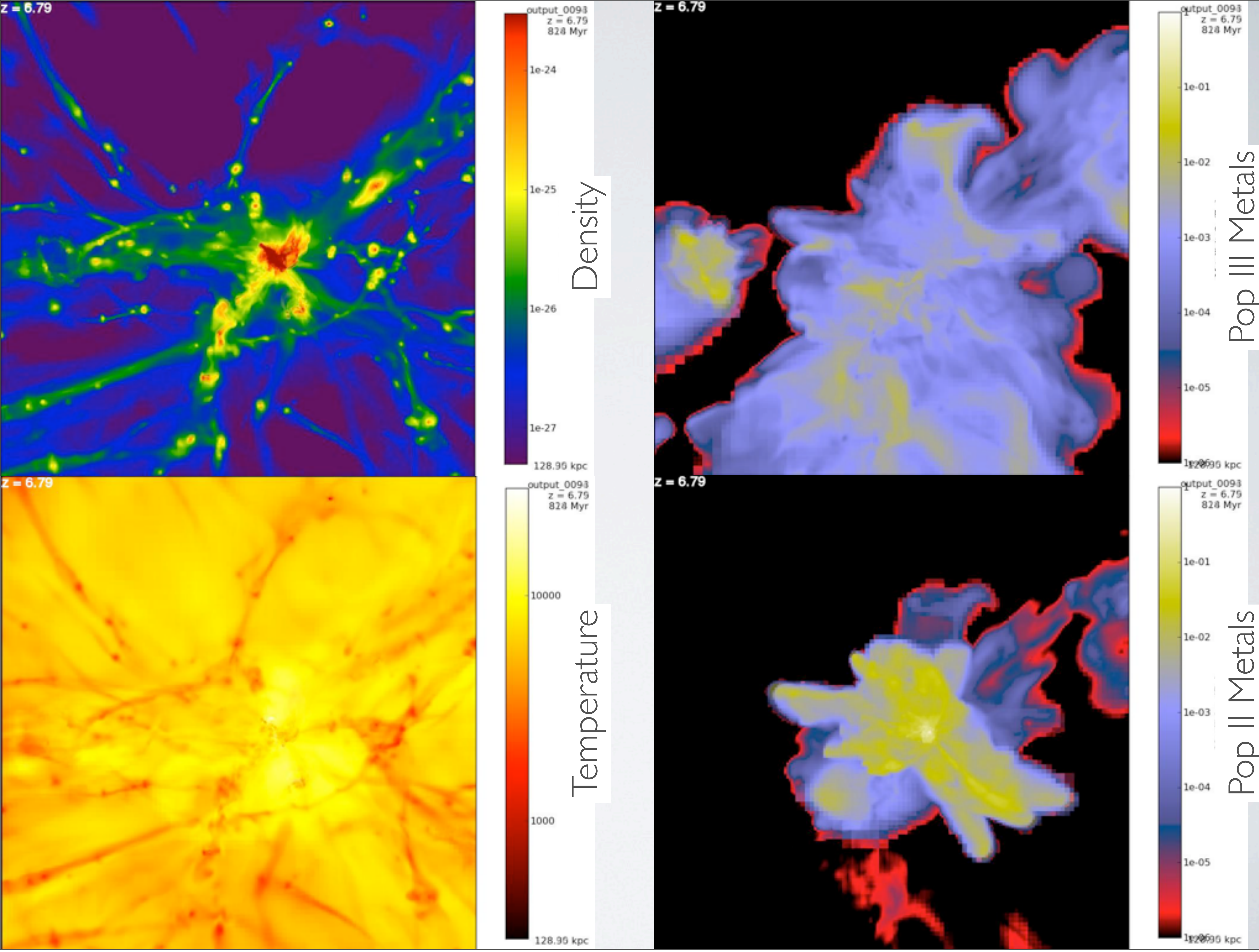
5 kpc
5 kpc
Intense
Quiet
z = 7.0
10^{-27}
10^{-24}
Density
10^{3}
10^{4}
Temperature
$[Z_3/H]$
−2
−4
−6
−6 −4 −2
$[Z_2/H]$


z = 6.79
output_0093
z = 6.79
828 Myr
1e-24
1e-25
1e-26
1e-27
Density
z = 6.79
Pop III Metals
1e-01
1e-02
1e-03
1e-04
1e-05
z = 6.79
10000
1000
Temperature
z = 6.79
1e-01
1e-02
1e-03
1e-04
1e-05

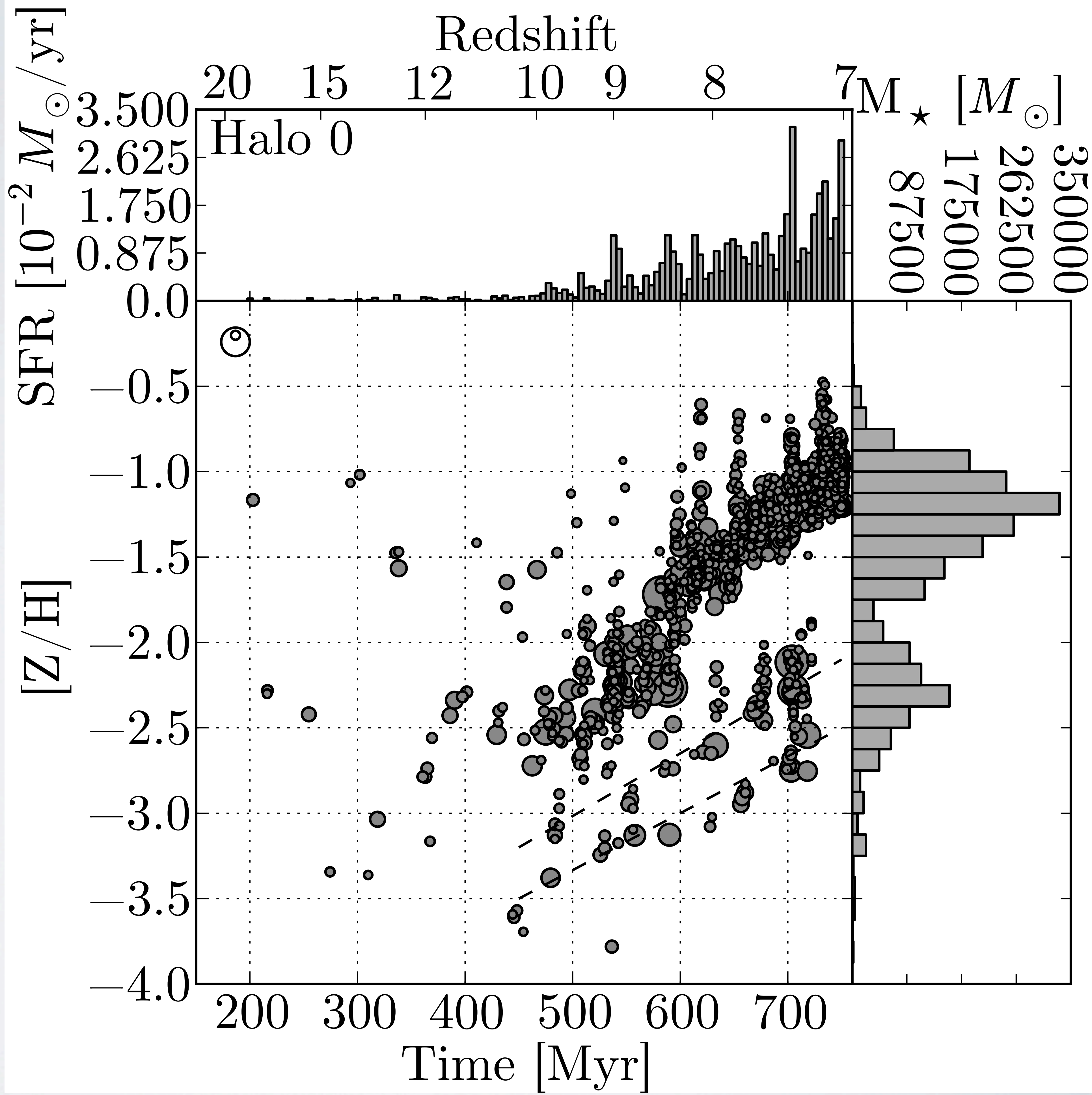
- Isolated halo (8e7 $M_\odot$) at z=7
- Quiet recent merger history
- Disky, not irregular
- Steady increase in [Z/H] then plateau
- No stars with [Z/H] < -3 from Pop III metal enrichment

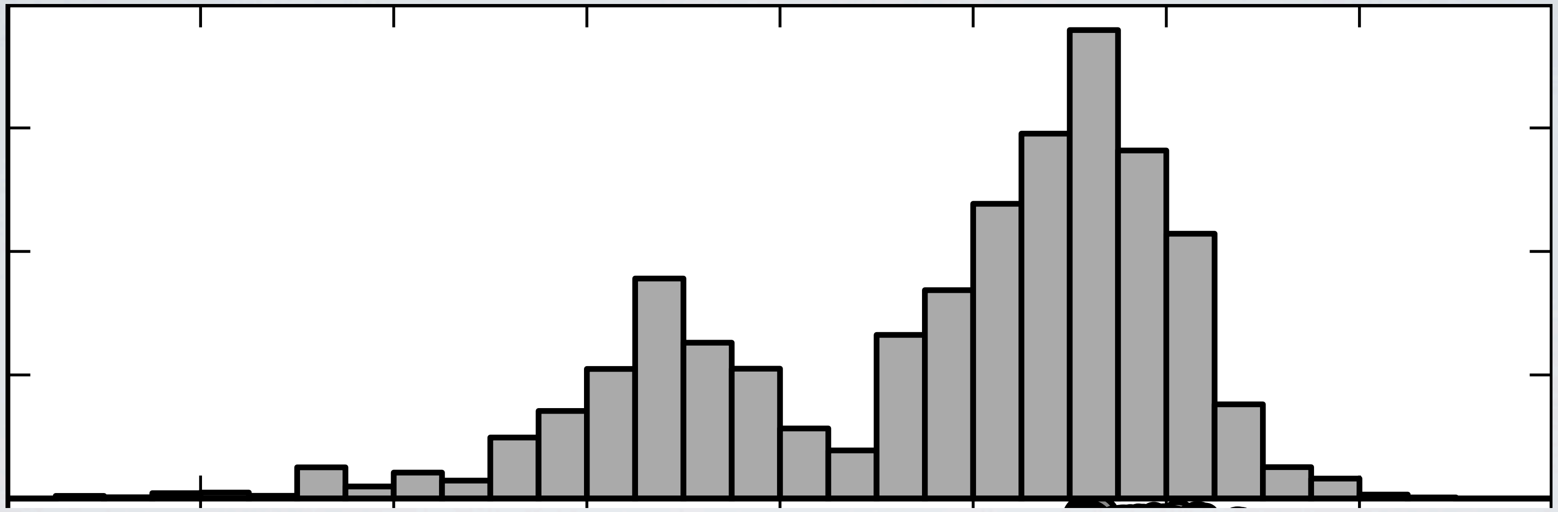



5 kpc
5 kpc
Intense
Quiet
z = 7.0
10^{-27}
10^{-24}
Density
10^{3}
10^{4}
Temperature
$[Z_3/H]$
−2
−4
−6
−6 −4 −2
$[Z_2/H]$


z = 6.79
output_0093
z = 6.79
828 Myr
1e-24
1e-25
1e-26
1e-27
128.95 kpc
Density
z = 6.79
output_0093
z = 6.79
828 Myr
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
z = 6.79
output_0093
z = 6.79
828 Myr
10000
1000
128.95 kpc
Temperature
z = 6.79
output_0093
z = 6.79
828 Myr
1e-01
1e-02
1e-03
1e-04
1e-05
Pop II Metals

- Most massive halo (10^9 M☉) 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





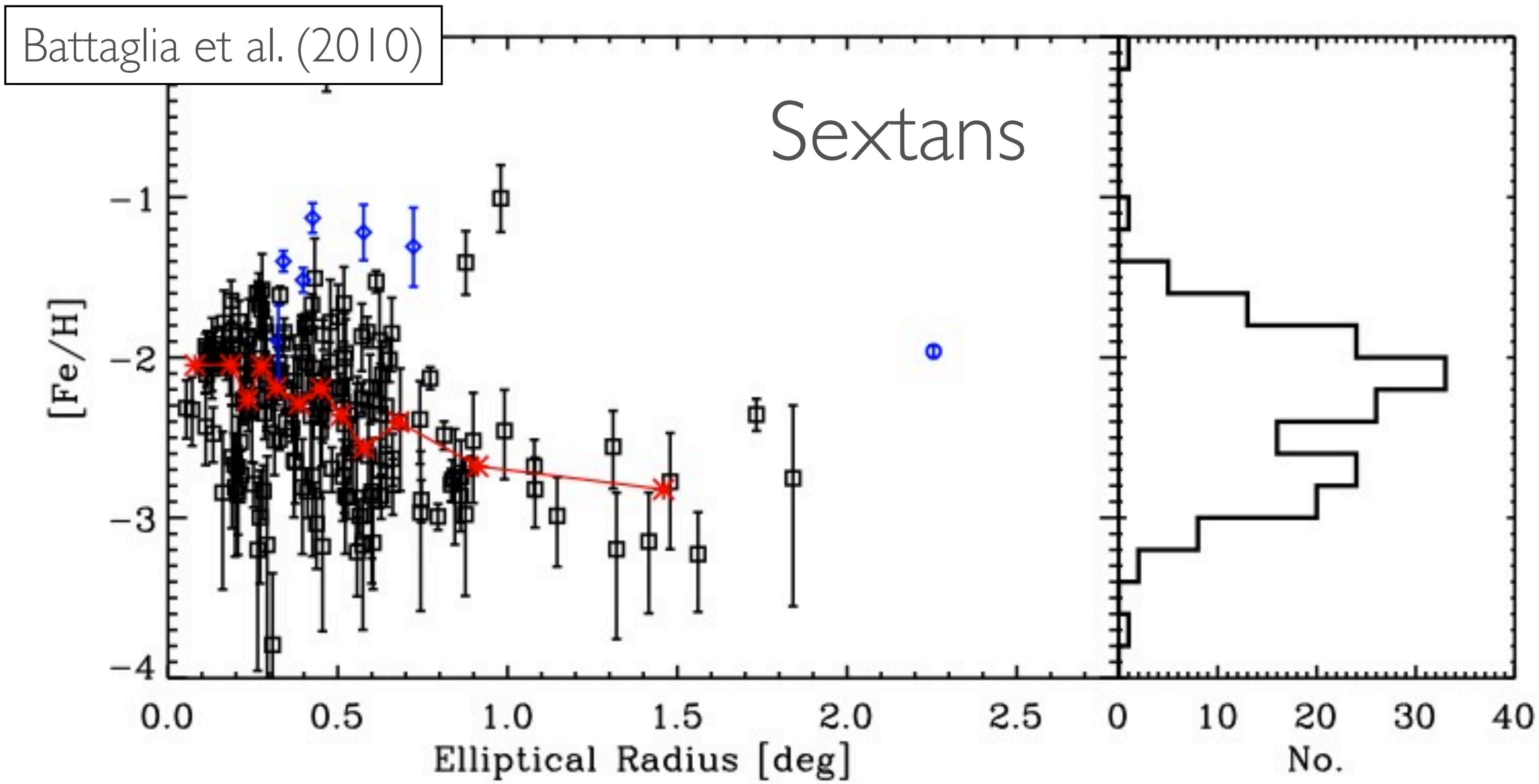
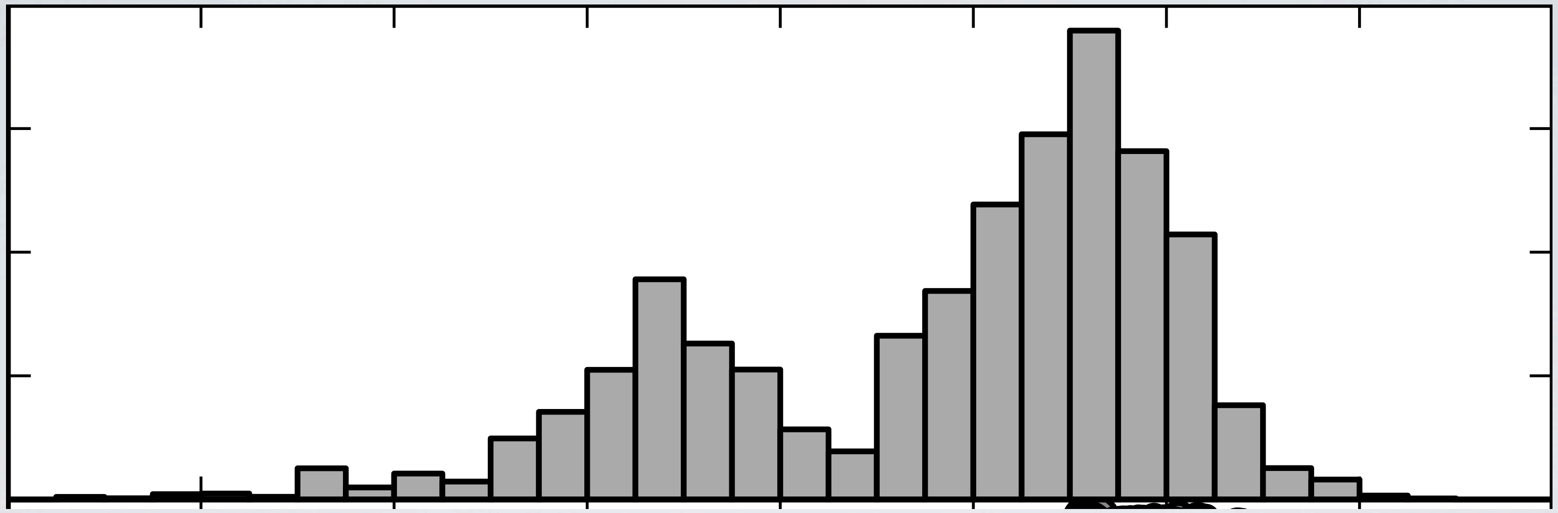
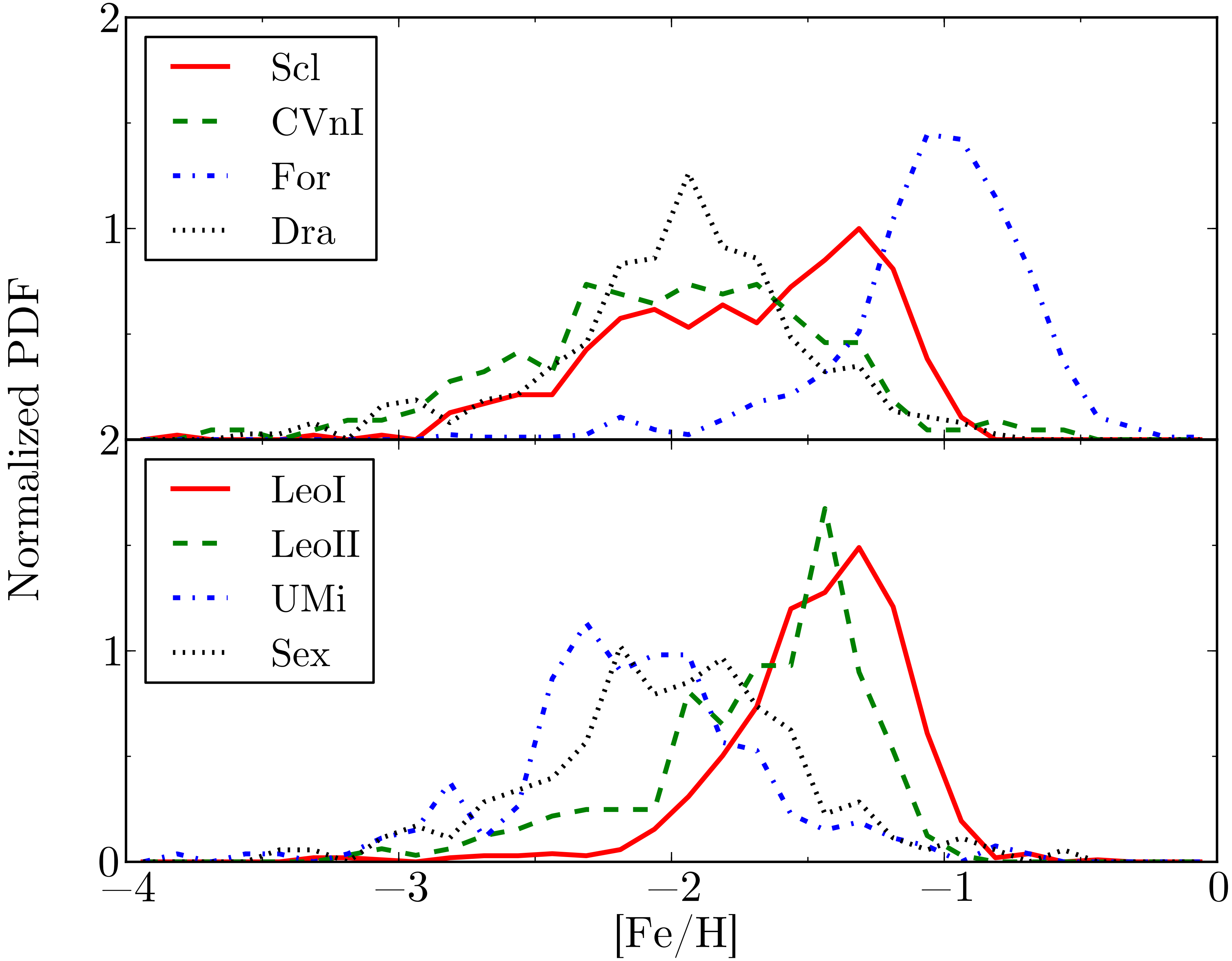


Figure 8. Left: Metallicity distribution as function of elliptical radius for the probable members of Sextans (squares with error-bars). The diamonds with error-bars show those stars whose velocities fall within the 3σ range of membership, but that are likely non-members based on their large Mg I EW (> 0.5 Å). The small blue circle indicate the star with peculiar location on the CMD. Since the stars represented with the diamonds and the blue circle are likely non-members they will not be considered when deriving properties relative to Sextans. The red asterisks connected by a solid line represent a running median over 15 stars (except for the last point, which is over 9 stars. Right: Metallicity distribution for Sextans members (from the squares in right-handside panel).



data from Kirby et al. (2010)

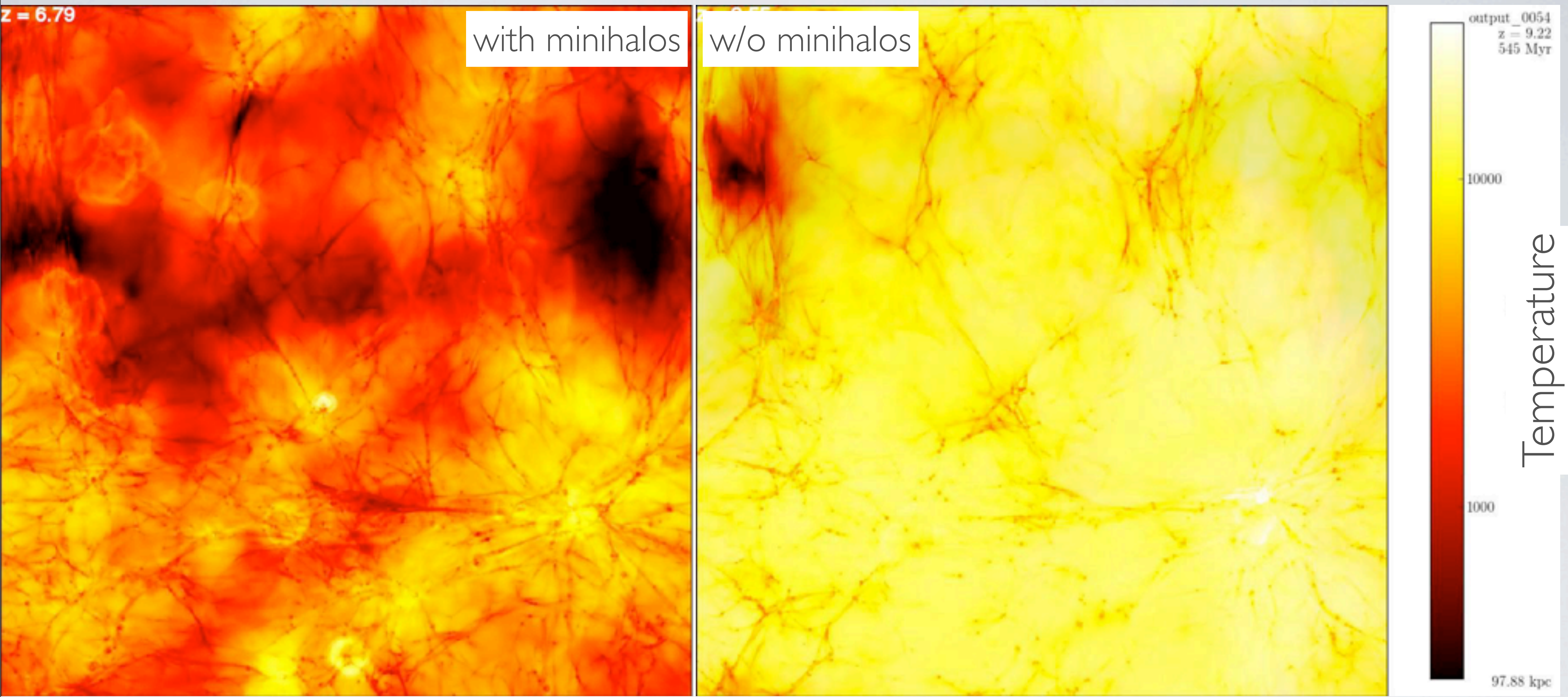


JHW+ (in prep.)

VARYING THE SUBGRID MODELS

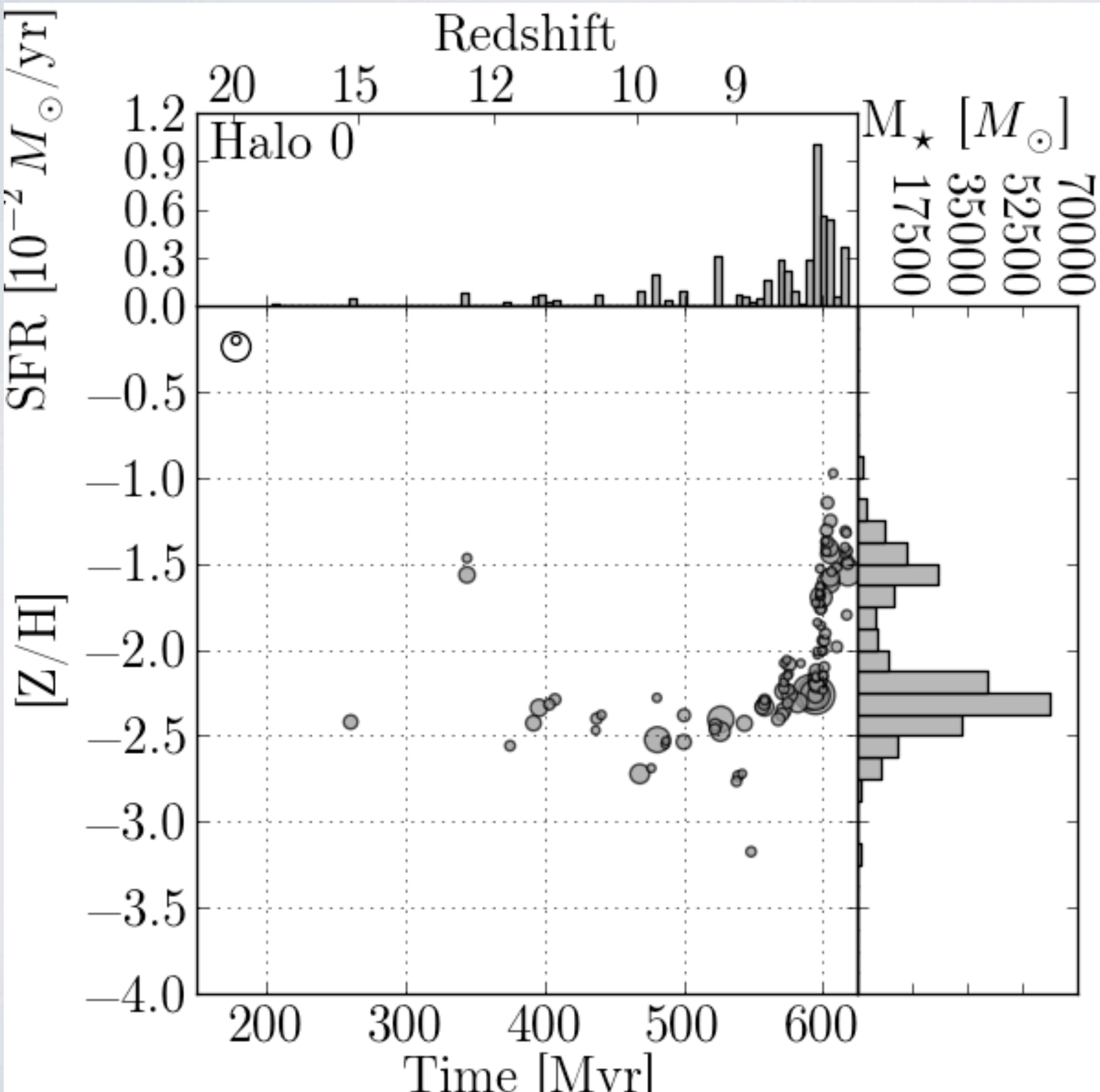
$M_{char} = 40\ M_{\odot}$	No H_2 cooling
$Z_{crit} = 10^{-5}$ and $10^{-6}\ Z_{\odot}$	No Pop III SF
Redshift dependent Lyman-Werner background (LWB)	Supersonic streaming velocities
LWB + Metal cooling	LWB + Metal cooling + enhanced metal ejecta (y=0.025)
LWB + Metal cooling + radiation pressure	

NEGLECTING $M < 10^8 M_\odot$ HALOS



- No stellar feedback in $M < 10^8 M_\odot$ halos → $f_{gas} = \Omega_b / \Omega_m$
- High-z halos are too gas-rich, leading to an overproduction of stellar mass and SFR in low-mass, high-z galaxies.

BASELINE AT Z = 8.1



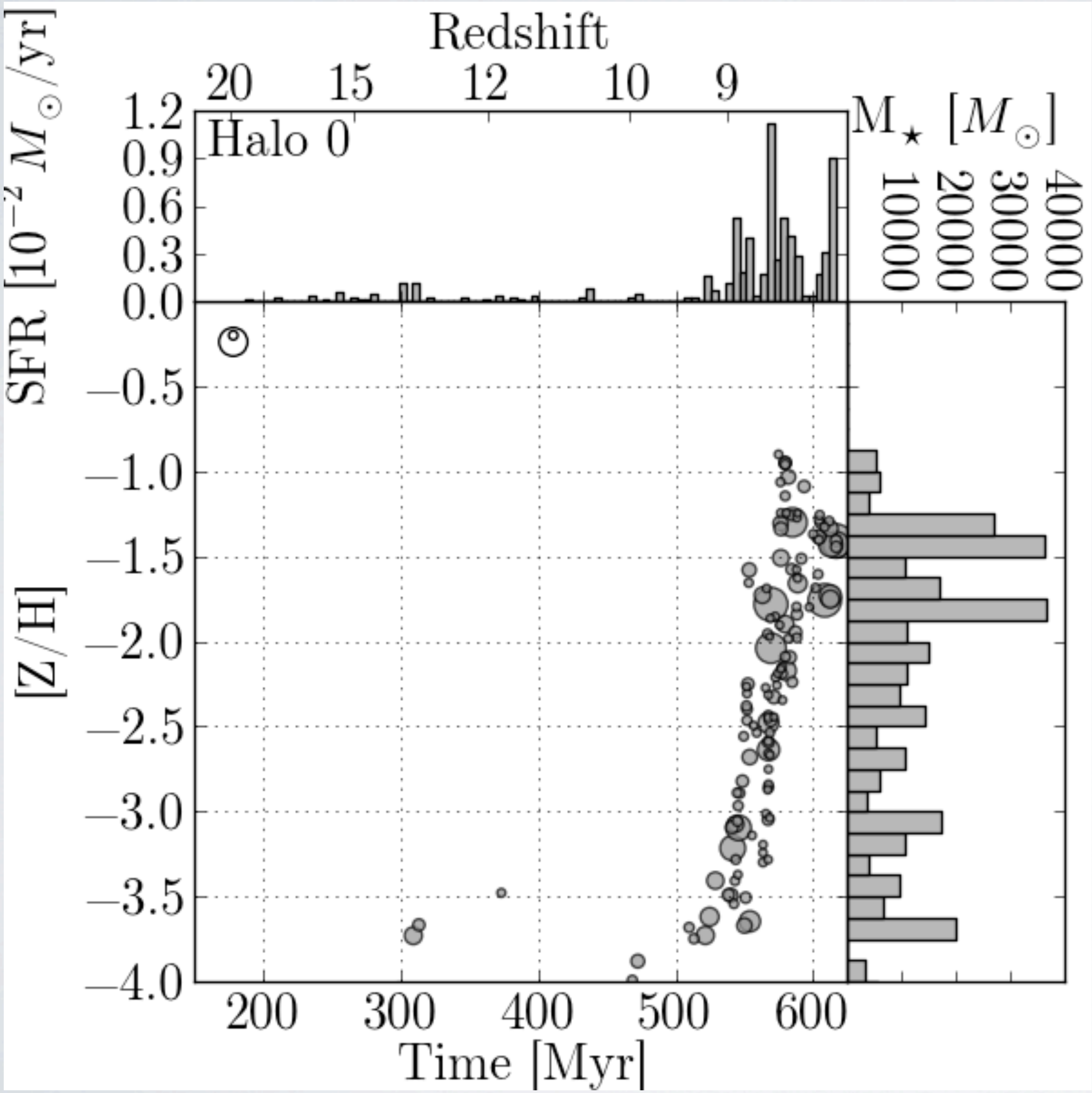
Main Limitation:
Lacking physics

mainly

Metal cooling
Soft UV background

JHW+ (in prep.)

H_2 COOLING BUT NO POP III

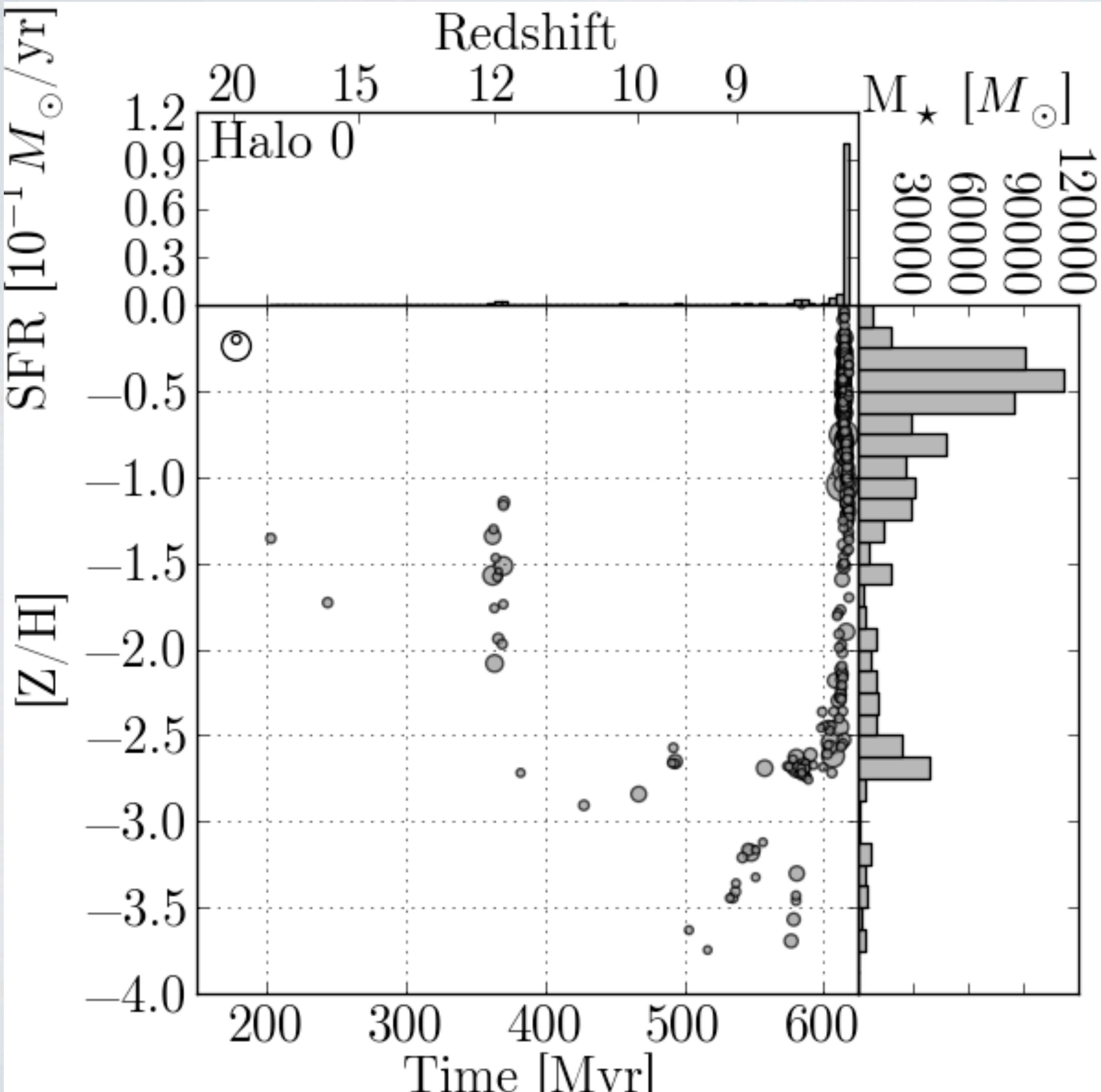


Similar subgrid model as typical galaxy formation simulations

Flat metallicity distribution function, arising from self-enrichment.

Doesn't match z = 0 dwarfs

+ METAL COOLING & SOFT UVB

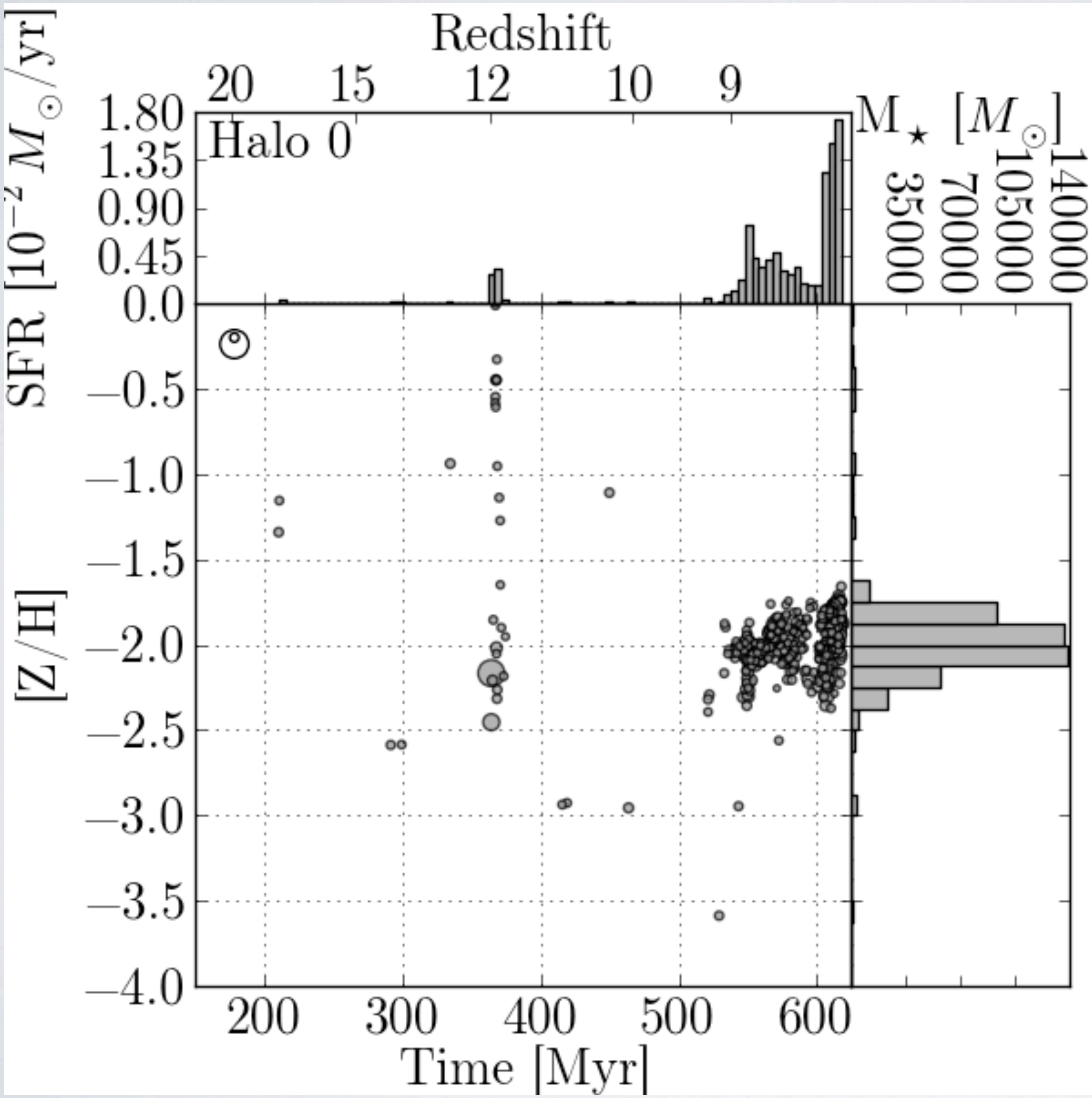


Typical overcooling problem during the initial starburst at M ~ 10^8 $M_\odot$

Causing over-enrichment – nearly solar metallicities. Doesn't match with z = 0 dwarfs

JHW+ (in prep.)

SOFT UVB + METAL COOLING + RAD. PRESSURE



Momentum transfer from ionizing radiation

Haehnelt (1995), Thompson et al. (2005)

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

Self-regulation of internal SF through dispersing dense gas

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

CONCLUSIONS

- Radiative and chemical feedback plays an important role in the formation of the first galaxies and starting reionization

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- Population III stars enrich the IGM and dwarf galaxies up to $10^{-3} Z_\odot$, providing a metallicity floor for halo and dSph stars and DLAs.
- Differing Population III stellar feedback can cause a scatter in M/L up to a factor of 30 at a fixed DM mass.
- Radiation pressure (in addition to photo-heating) may regulate star formation as well as drive galactic outflows.

- Even the smallest galaxies are complex with star formation and feedback, and these sophisticated galaxy models will aid in the interpretation of future observations.