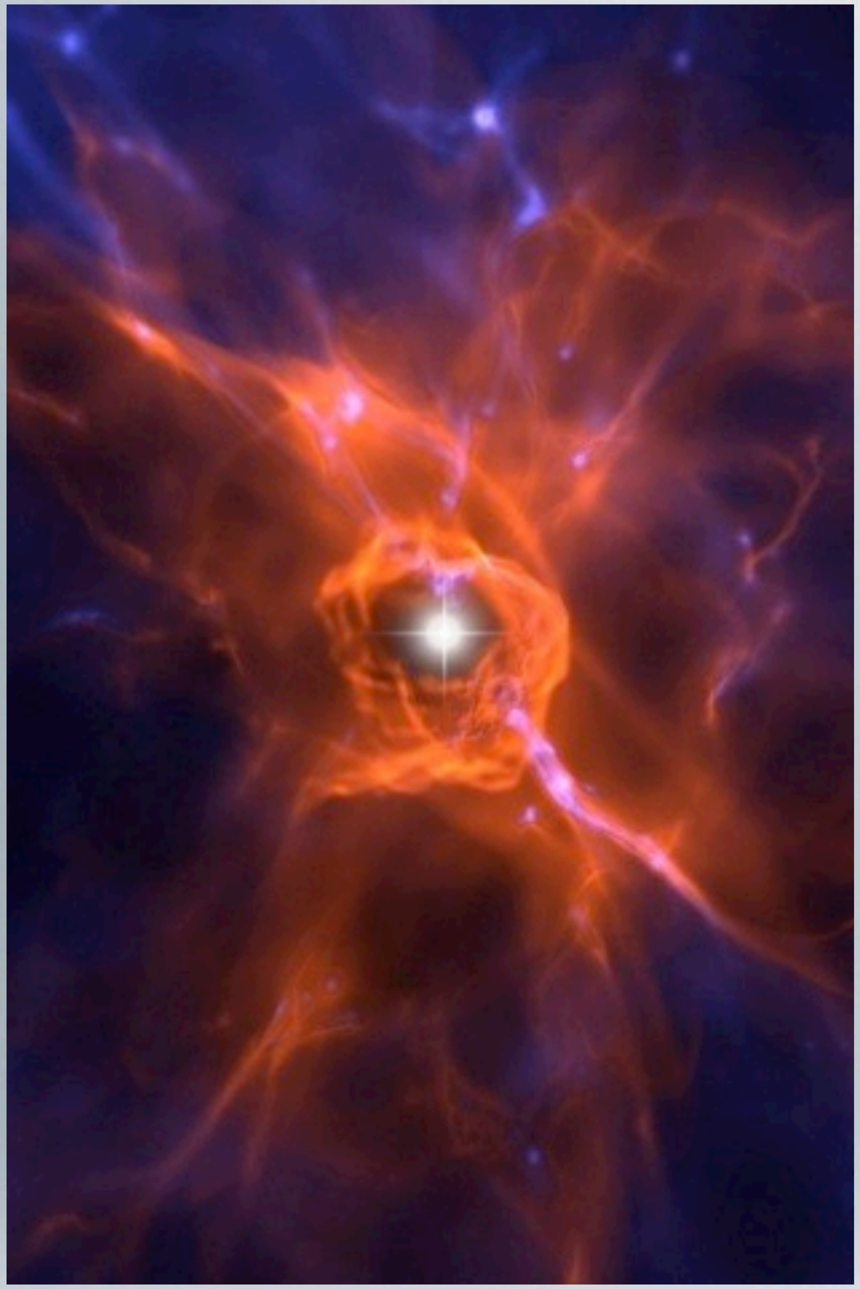
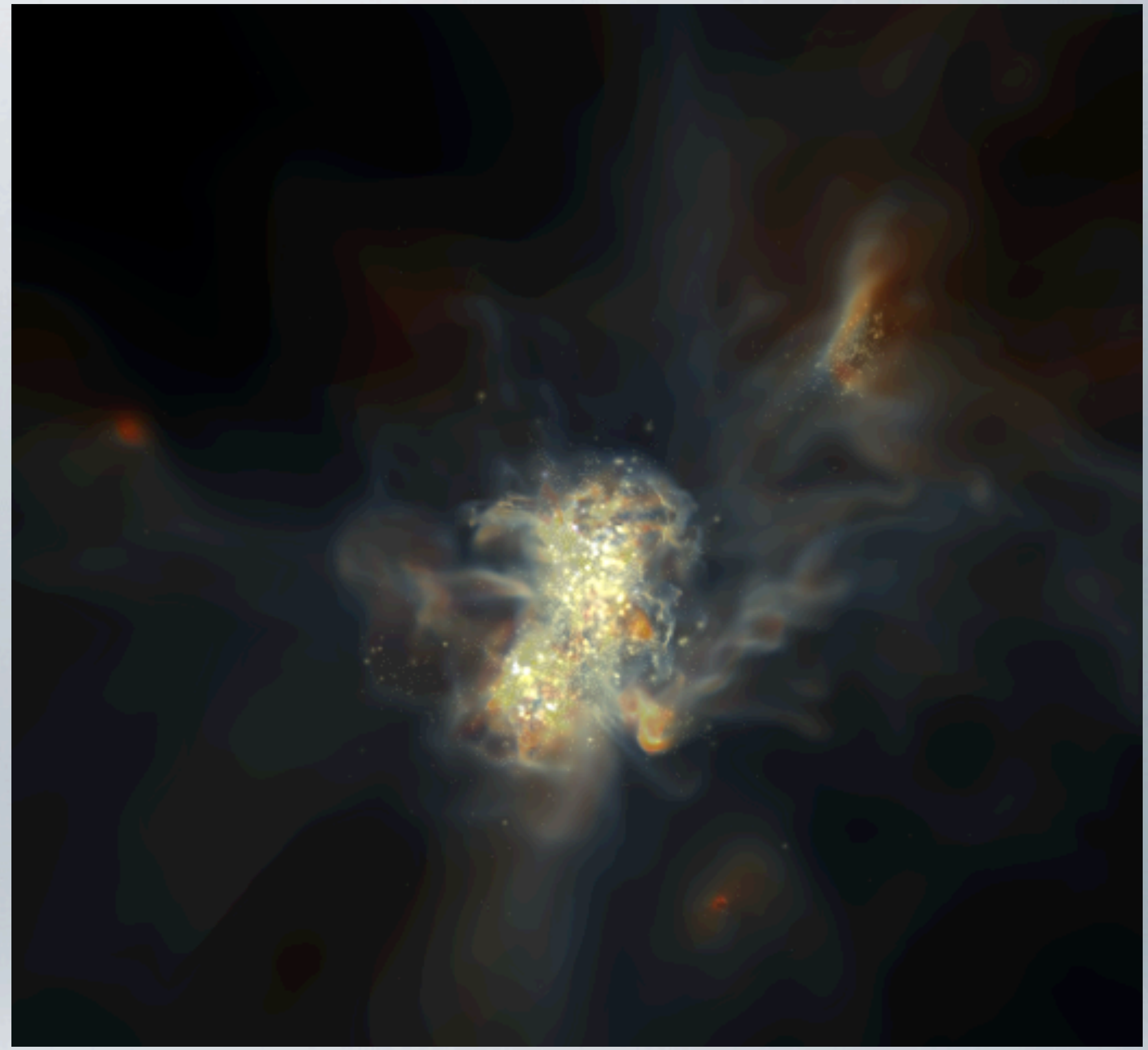
 

THE TRANSITION FROM THE FIRST STARS TO THE FIRST GALAXIES

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

OPEN QUESTIONS:

POP III STARS AND GALAXIES DURING REIONIZATION

- How did metal-free (Pop III) stars affect high-z structure formation?
  - Metal enrichment
  - Reionization
  - Dwarf 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 (<3 Mpc^3) AMR radiation hydro simulations
- Coupled radiative transfer (ray tracing in the optically thin and thick regimes)

enzo-project.org

Abel, Wise, & Bryan (2007)

H II REGION OF A PRIMORDIAL STAR

Density

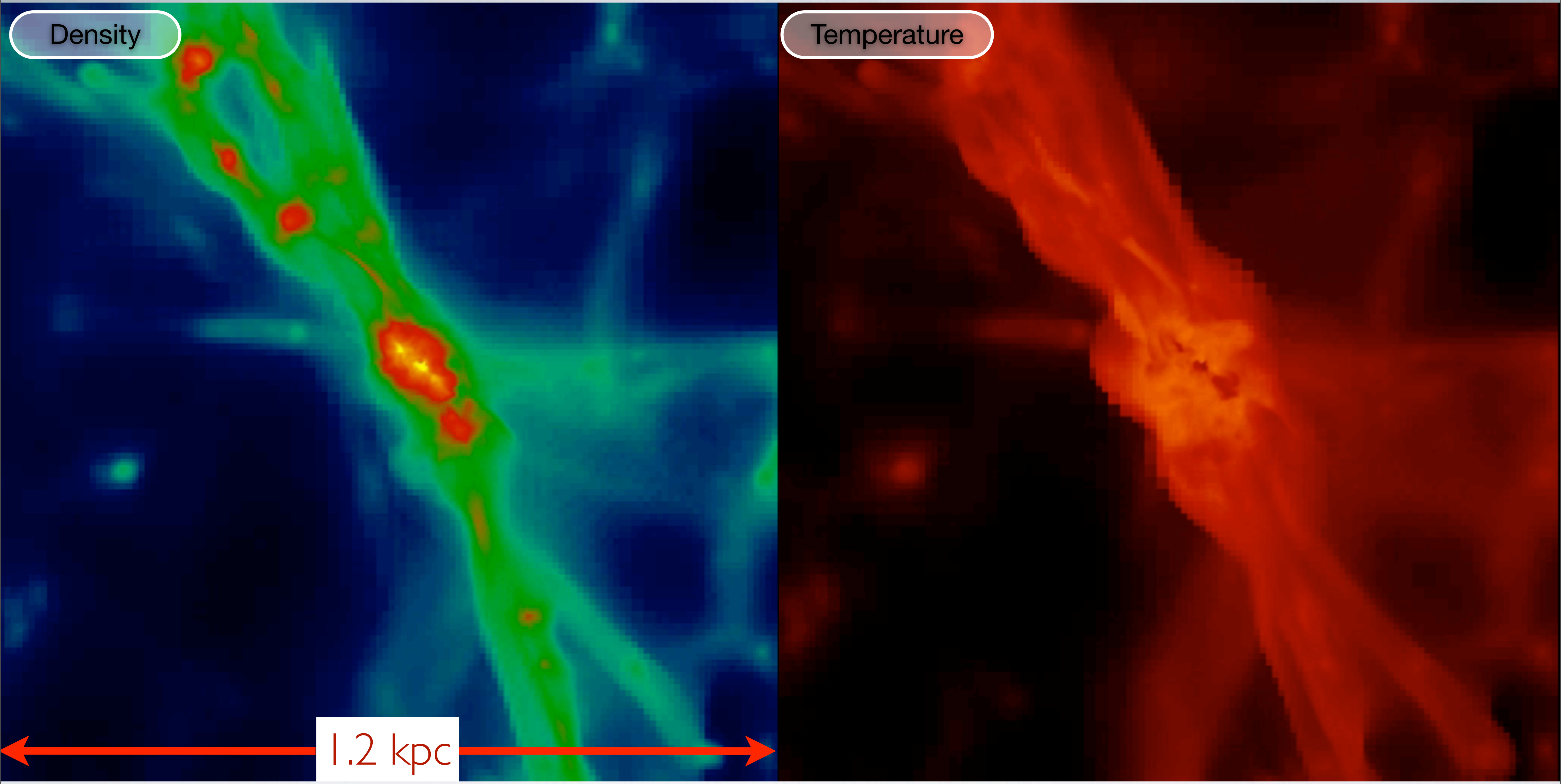
Temperature

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

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

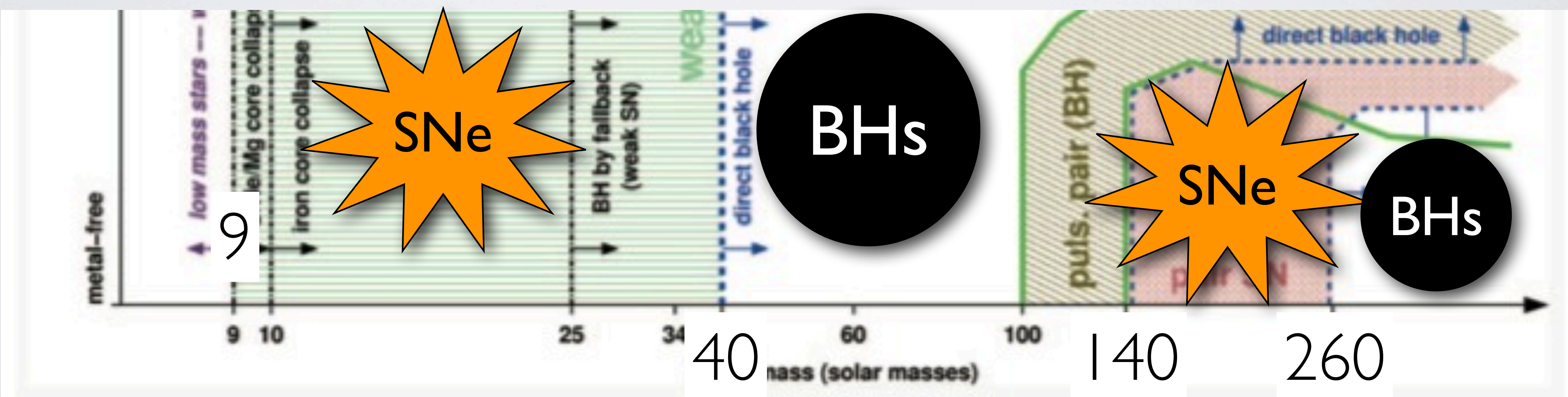
OUR APPROACH:

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. Schaerer (2002), Heger+ (2003)

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

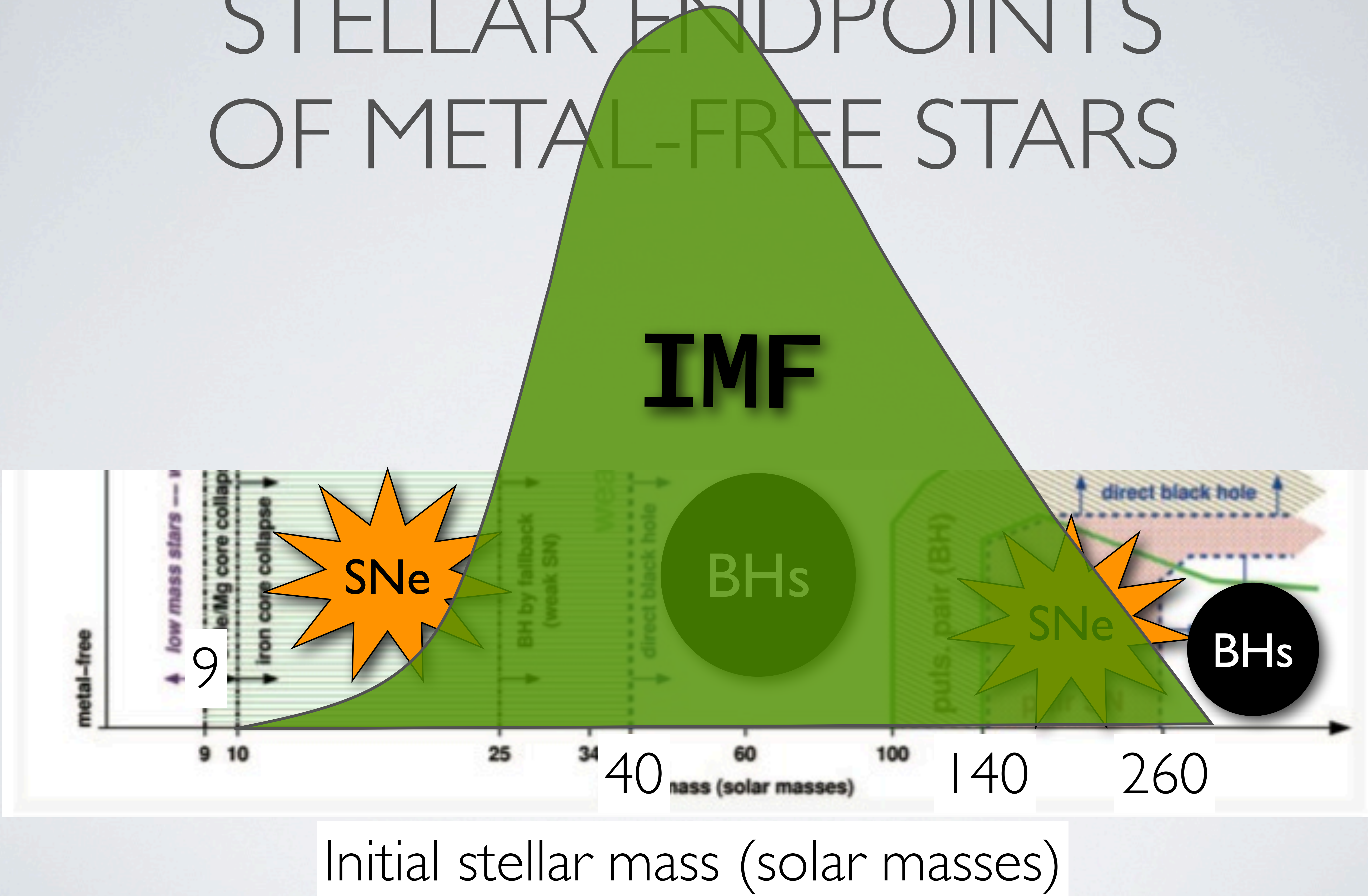
STELLAR ENDPOINTS OF METAL-FREE STARS



Initial stellar mass (solar masses)

Heger et al. (2003)

STELLAR ENDPOINTS OF METAL-FREE STARS



Heger et al. (2003)

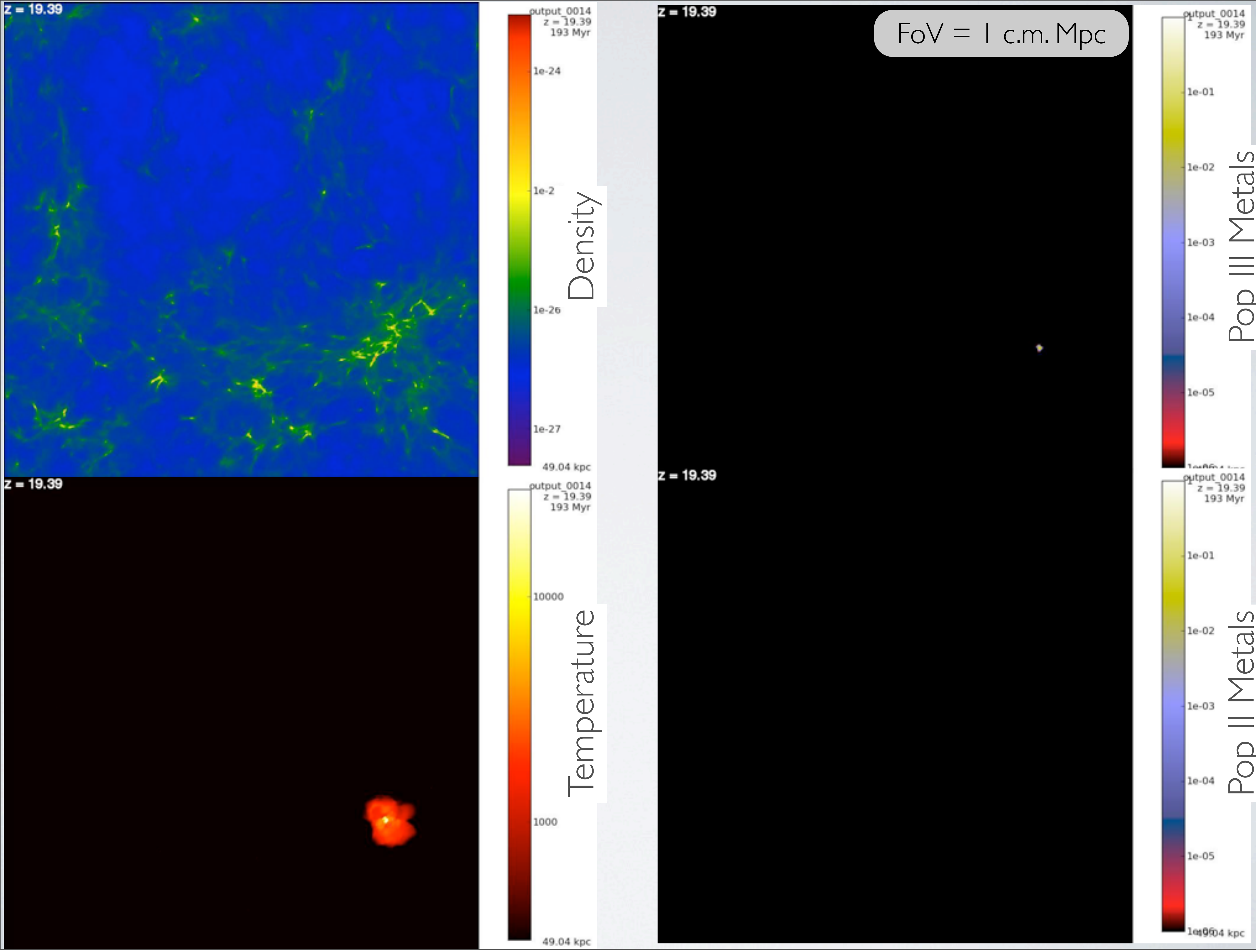
FoV = 1 c.m. Mpc

Density

Pop III Metals

Temperature

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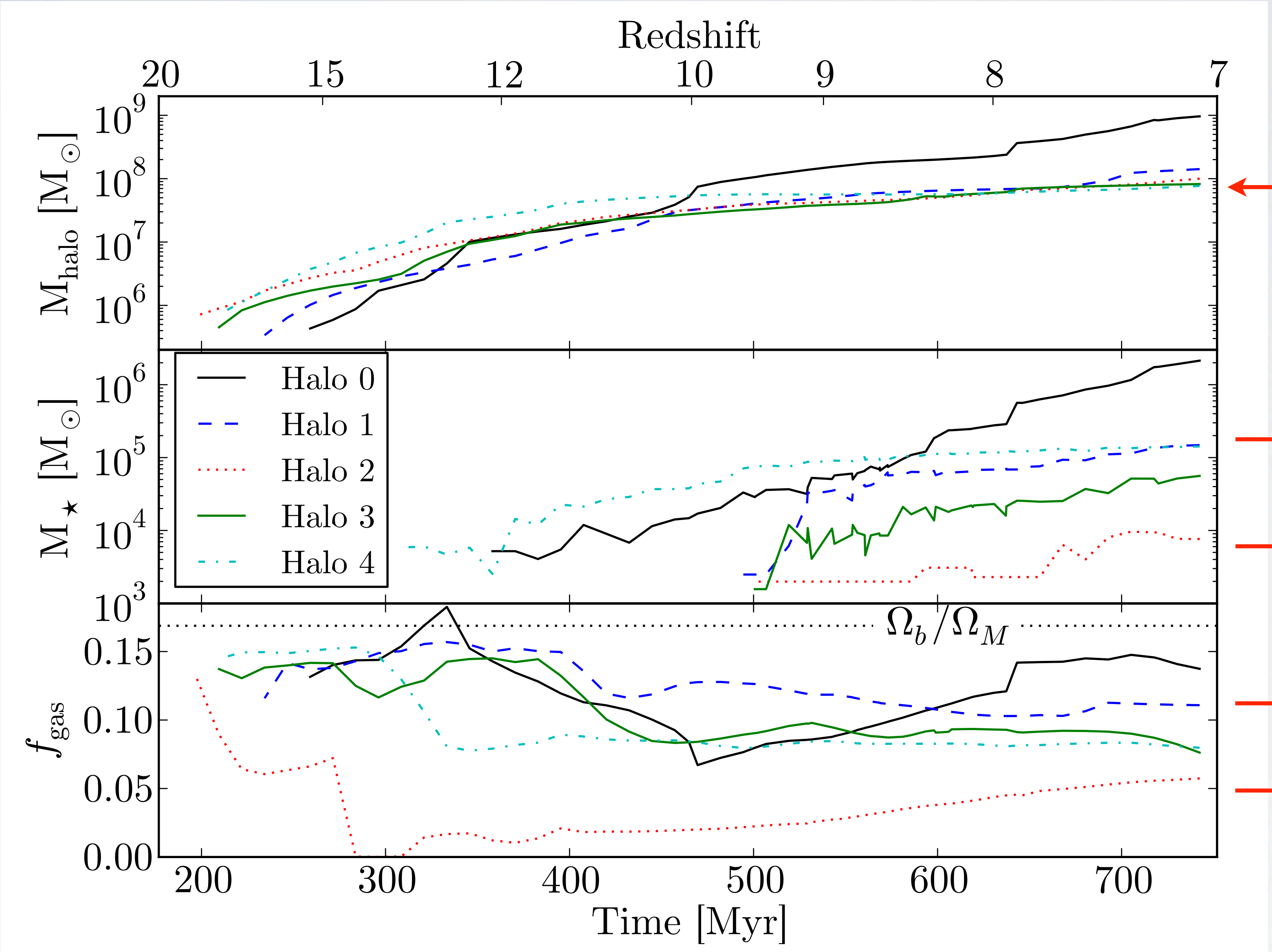
output_0014
z = 19.39
193 Myr
1e-24
1e-2
1e-26
1e-27
49.04 kpc
Density
z = 19.39
FoV = 1 c.m. Mpc
output_0014
z = 19.39
193 Myr
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
z = 19.39
output_0014
z = 19.39
193 Myr
10000
1000
49.04 kpc
Temperature
z = 19.39
output_0014
z = 19.39
193 Myr
1e-01
1e-02
1e-03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

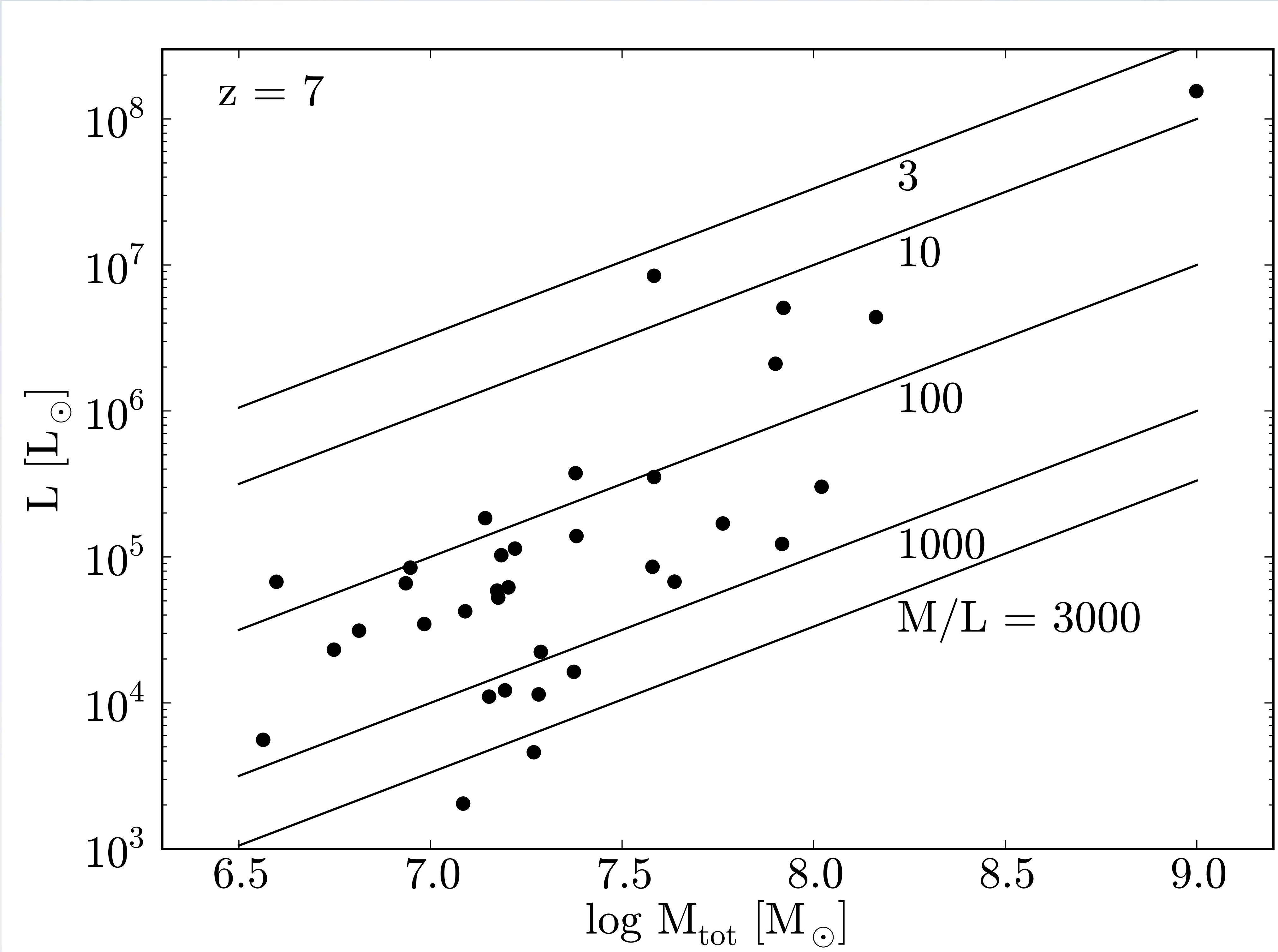
DWARF GALAXY BUILDUP



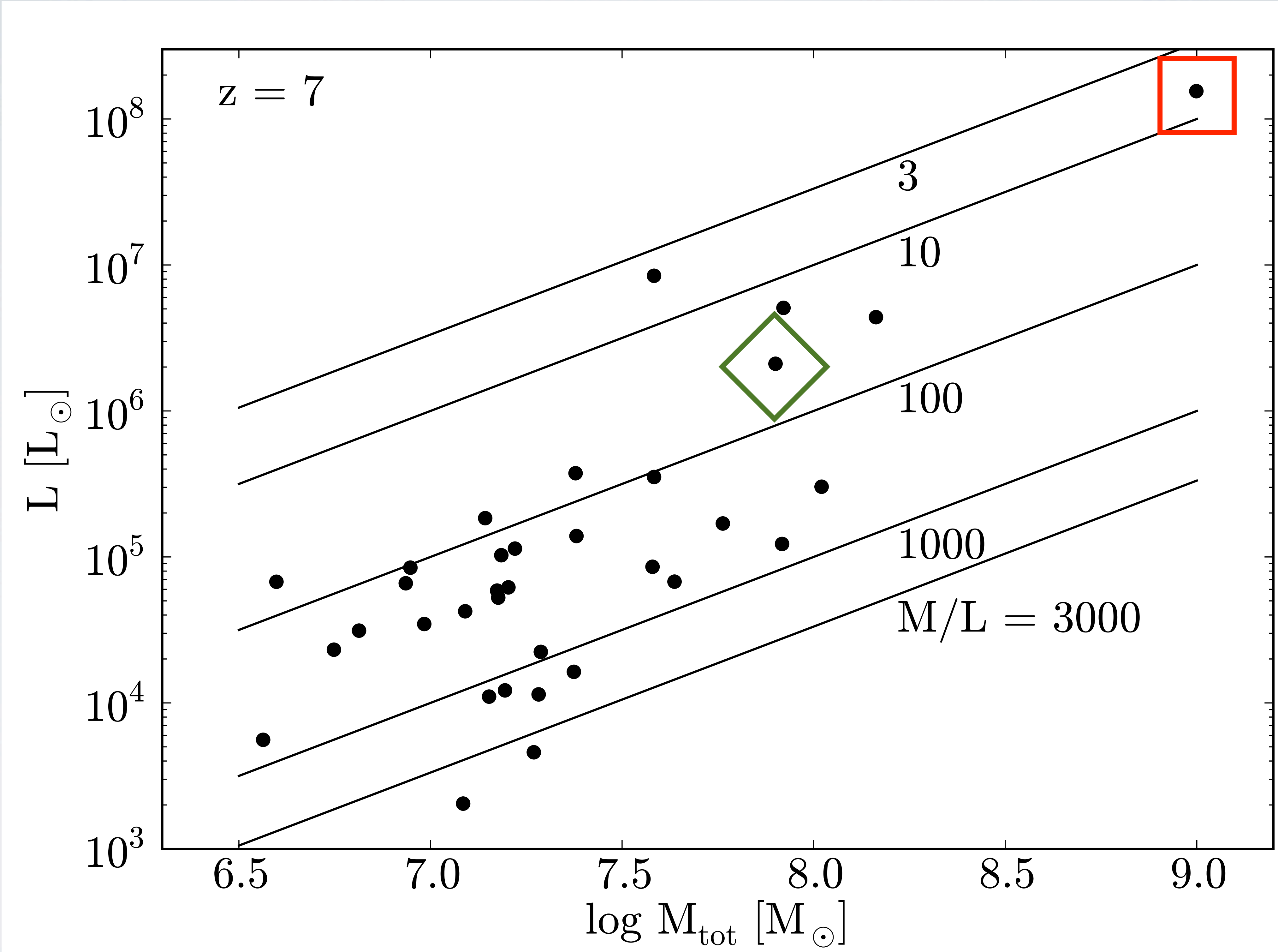
Galaxies with similar halo masses can differ in stellar mass by an order of magnitude!

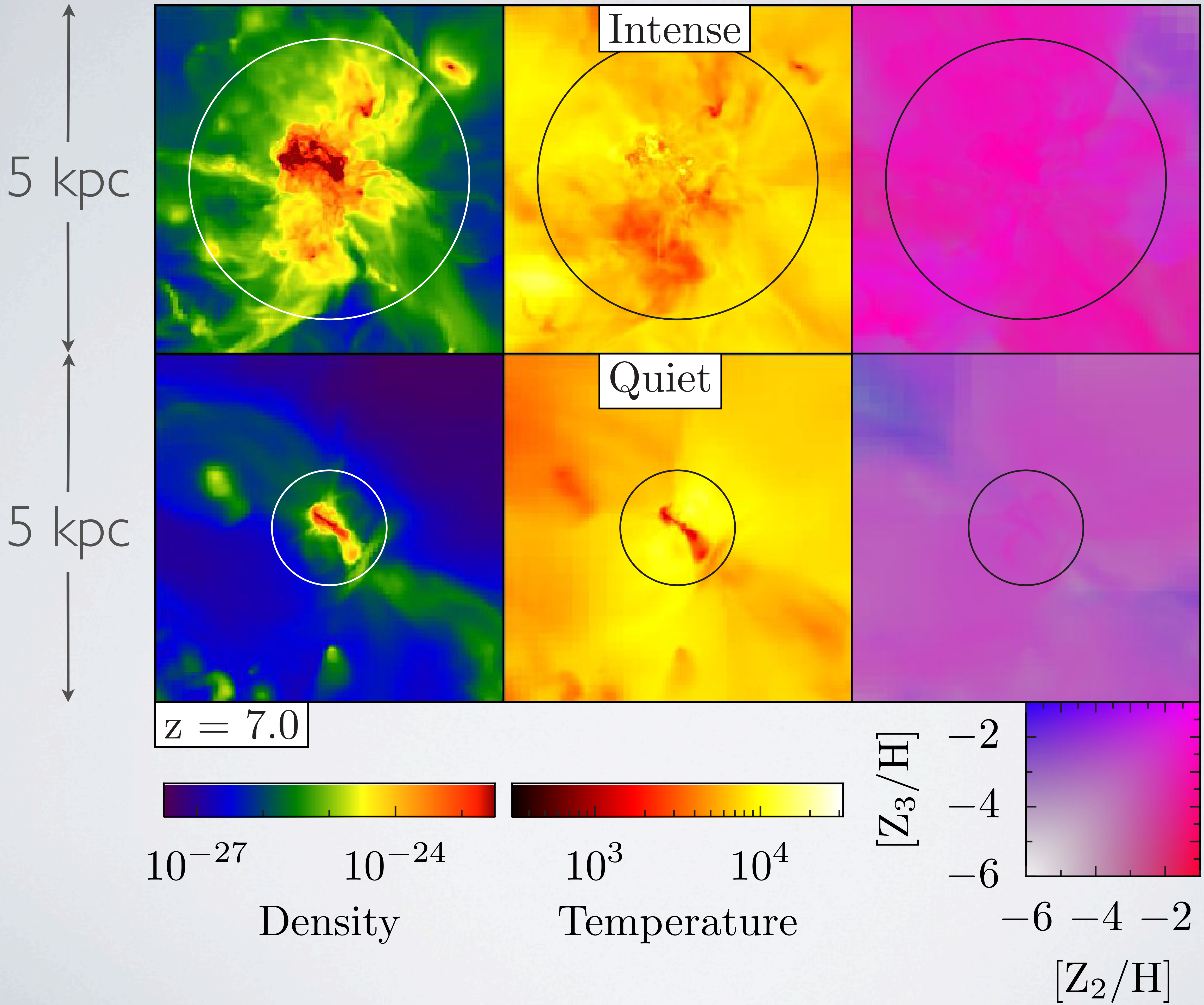
- The initial buildup of the dwarfs are regulated by prior Pop III feedback and radiative feedback from nearby galaxies.

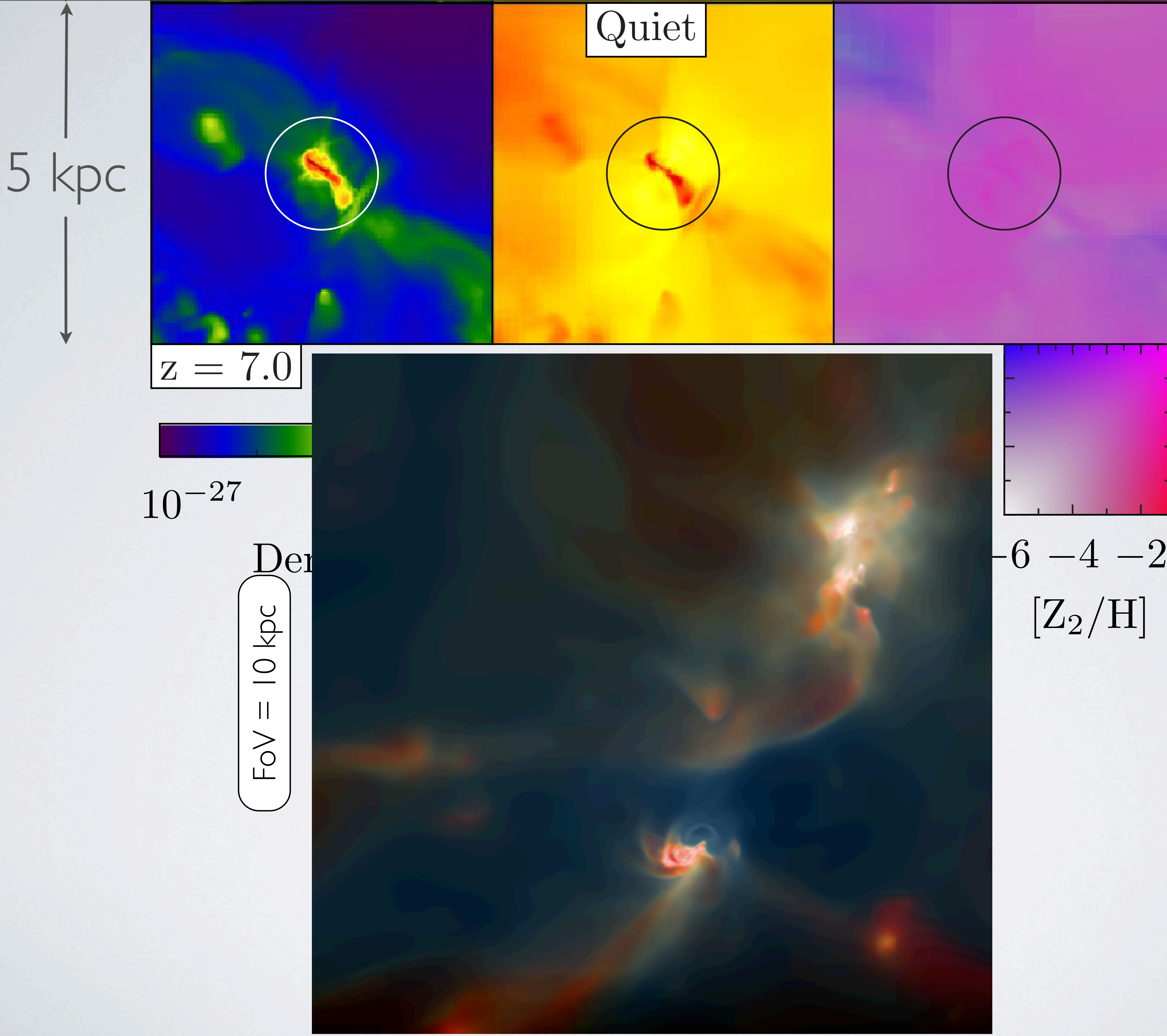
MASS-TO-LIGHT RATIOS

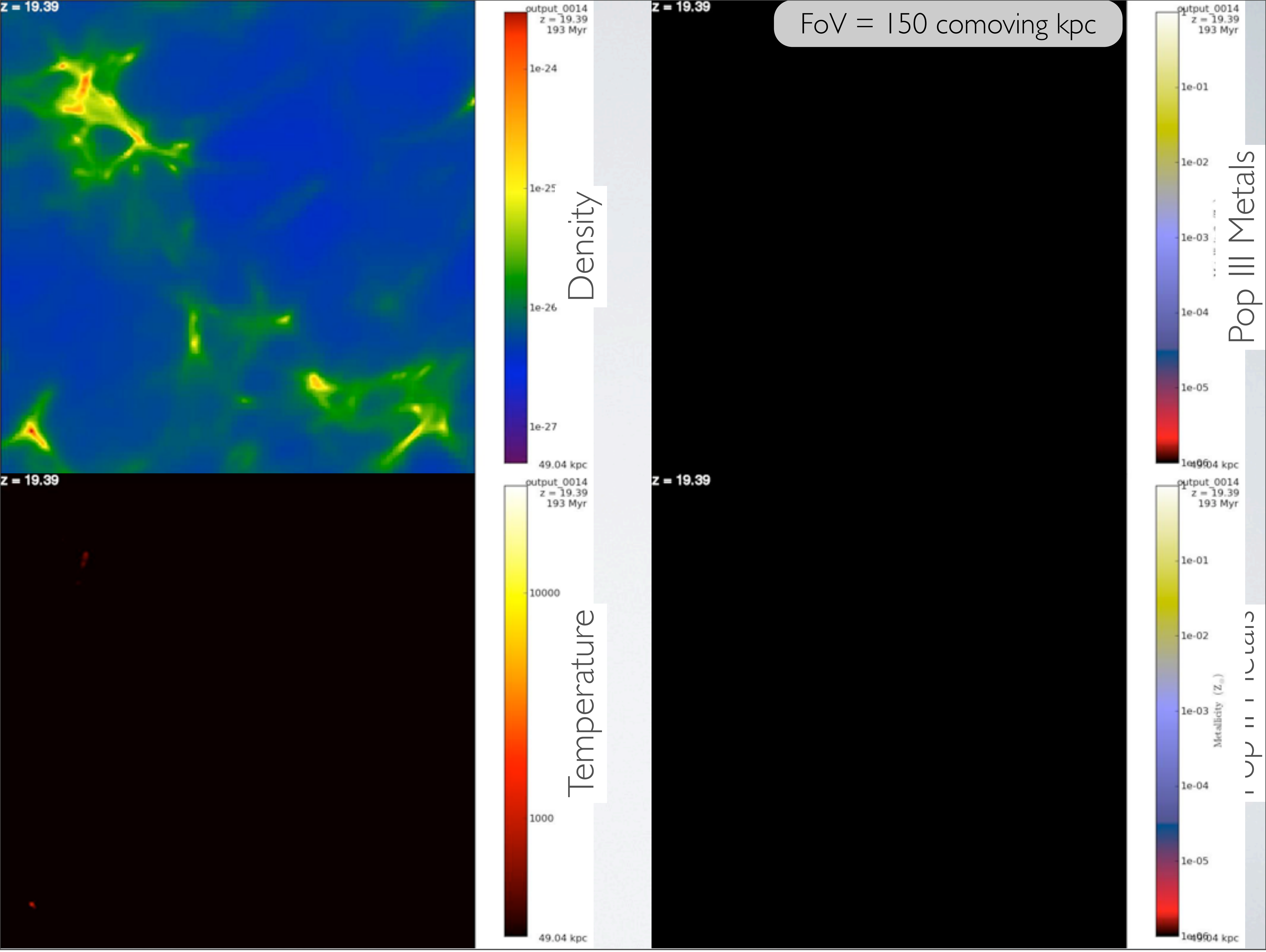


MASS-TO-LIGHT RATIOS



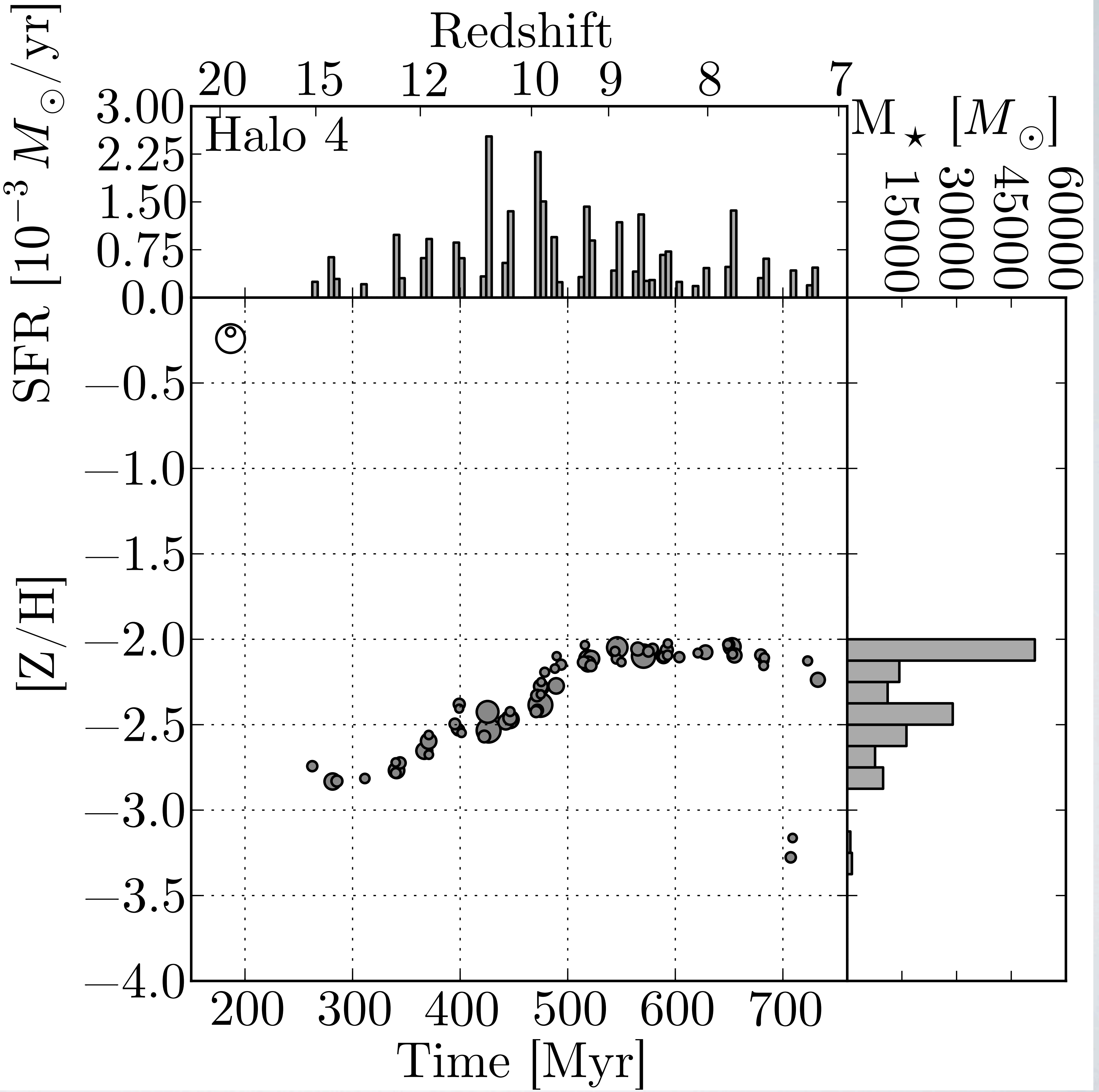

5 kpc
5 kpc
Intense
Quiet
z = 7.0
10−27
10−24
Density
10³
10⁴
Temperature
[Z3/H]
−2
−4
−6
−6 −4 −2
[Z2/H]


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

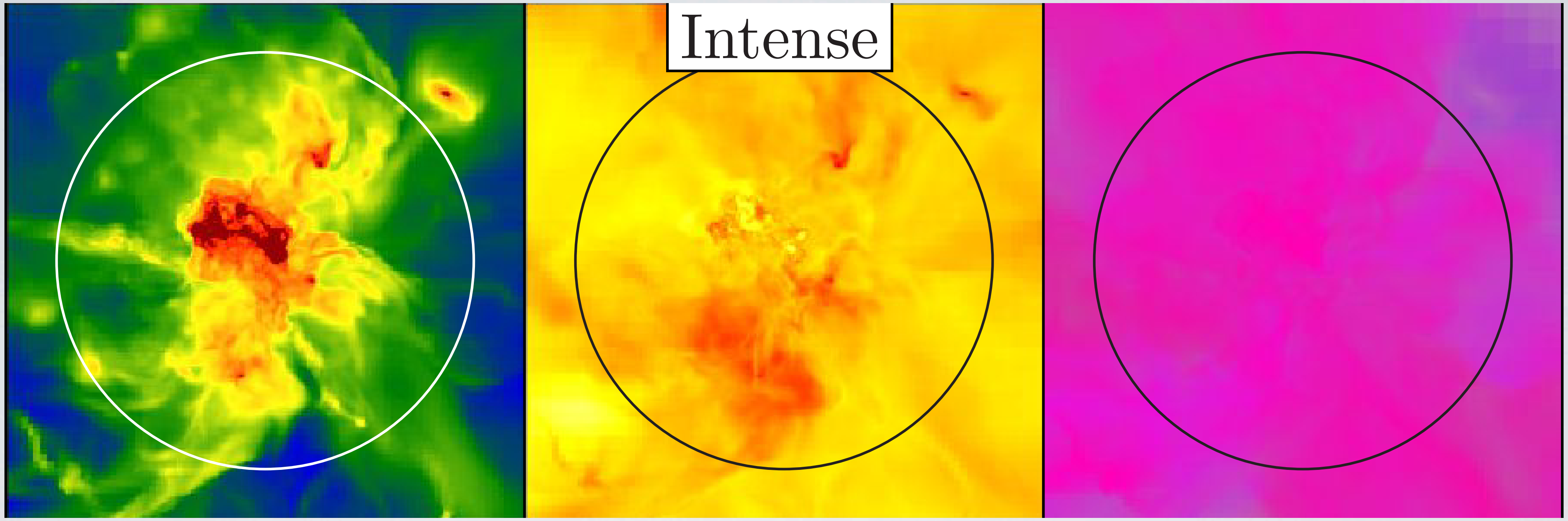


z = 19.39
output_0014
z = 19.39
193 Myr
1e-24
1e-25
1e-26
1e-27
49.04 kpc
Density
FoV = 150 comoving kpc
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
10000
1000
Temperature
Metallicity (Z☉)

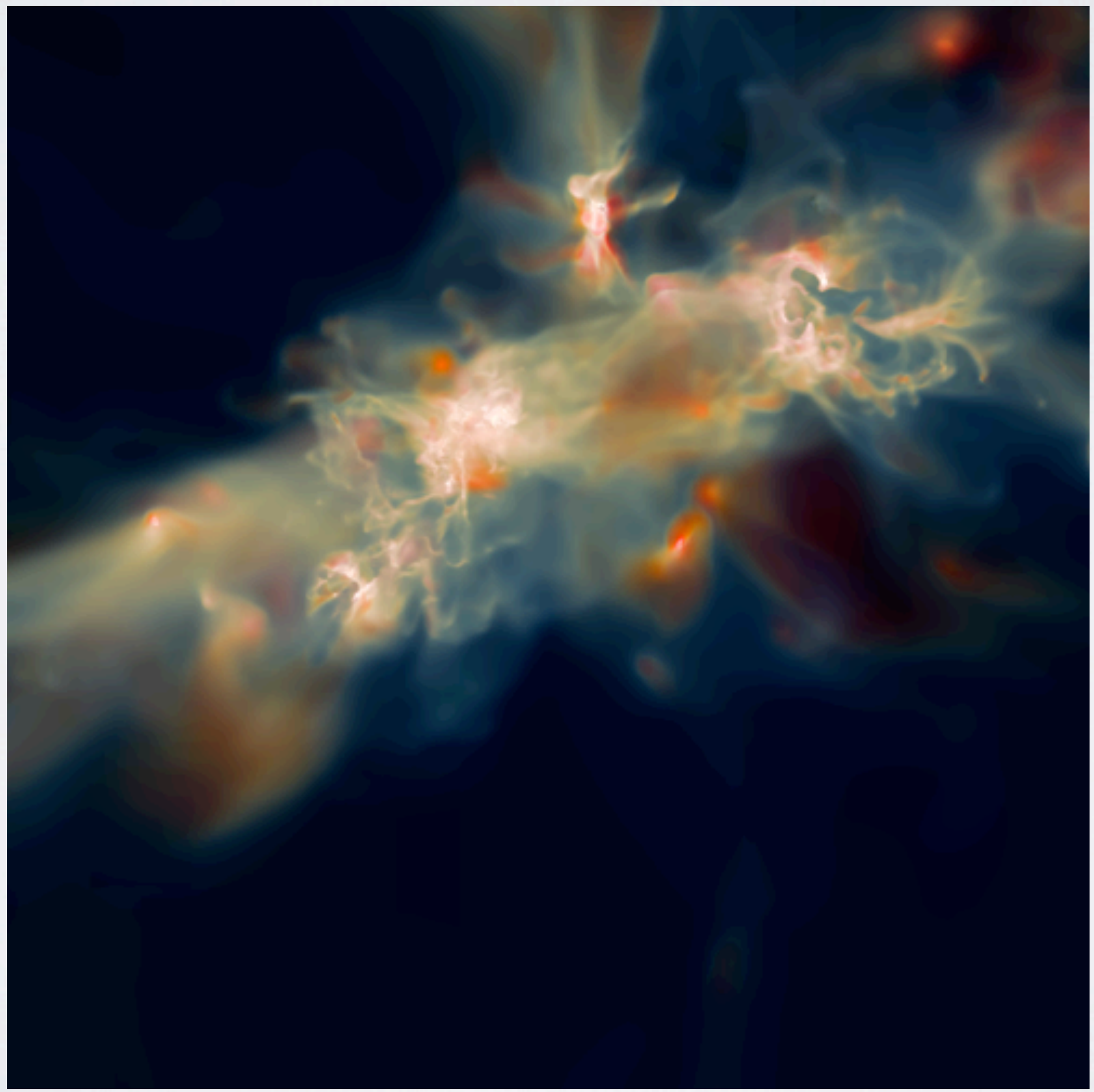
- Isolated halo (8e7 M☉) at z=7
- Quiet recent merger history
- Disky, not irregular
- Steady increase in [Z/H] then plateau
- No stars with [Z/H] < -3 from Pop III metal enrichment

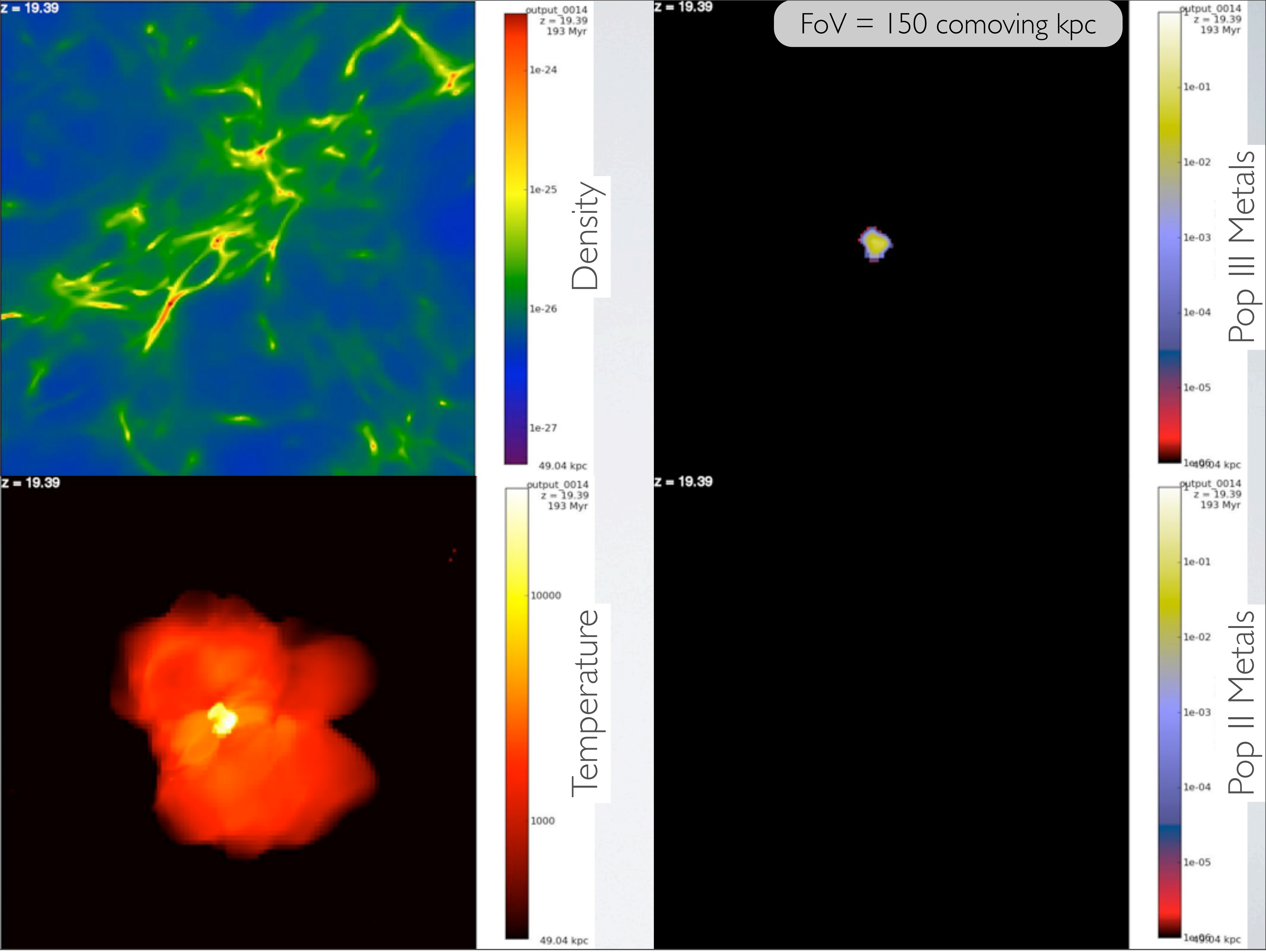


5 kpc



FoV = 10 kpc




FoV = 150 comoving kpc
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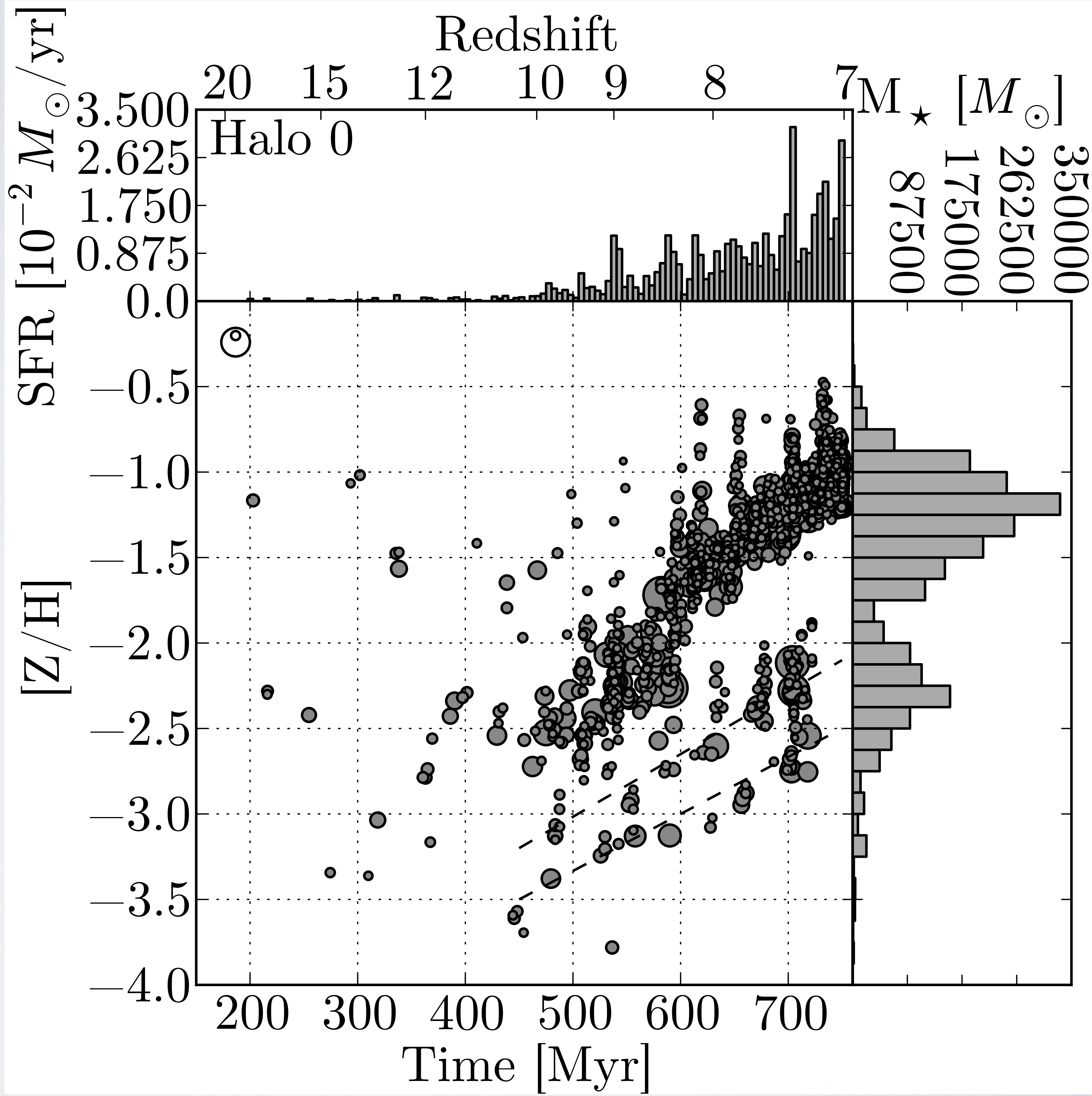
1e-27
49.04 kpc
Density
Temperature
10000
1000
Pop III Metals
Pop II Metals
1e-01
1e-02
1e-03
1e-04
1e-05

- 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



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	

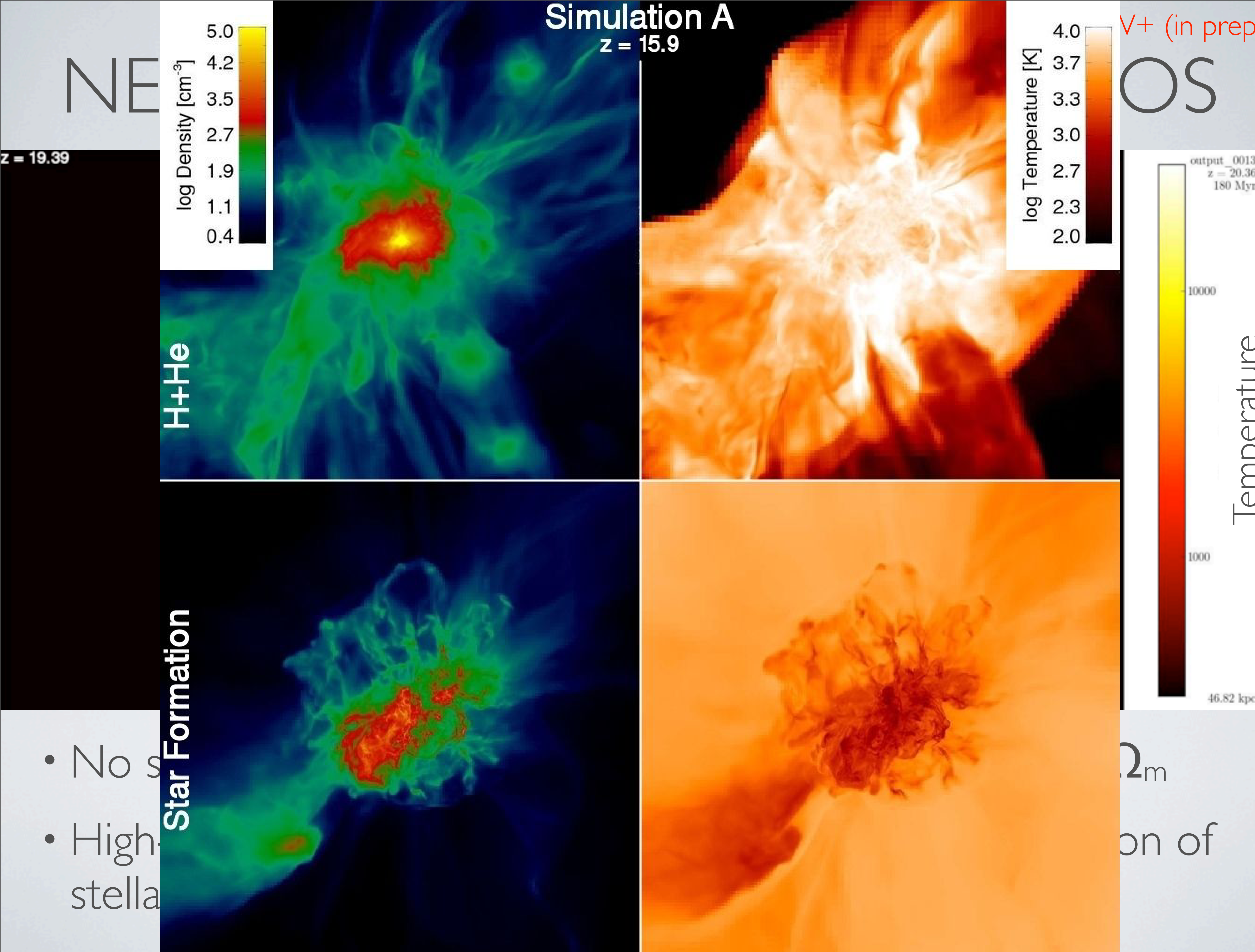
Wise & Abel (2008); JHW+ (in prep.)

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.

V+ (in prep.)

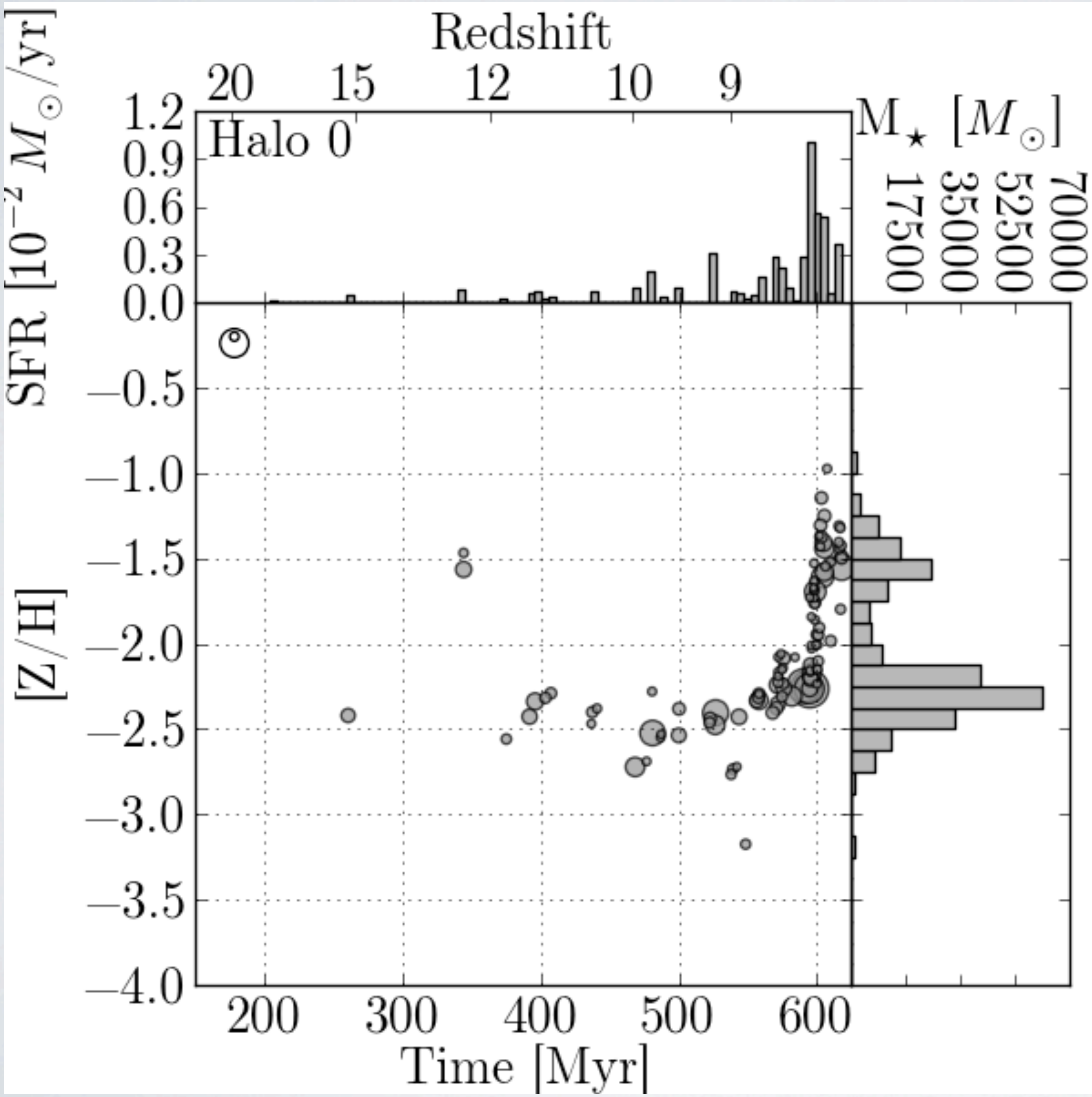
NE OS



- No s Ω_m
- High- on of stella

JHW+ (in prep.)

BASELINE AT $z = 8$



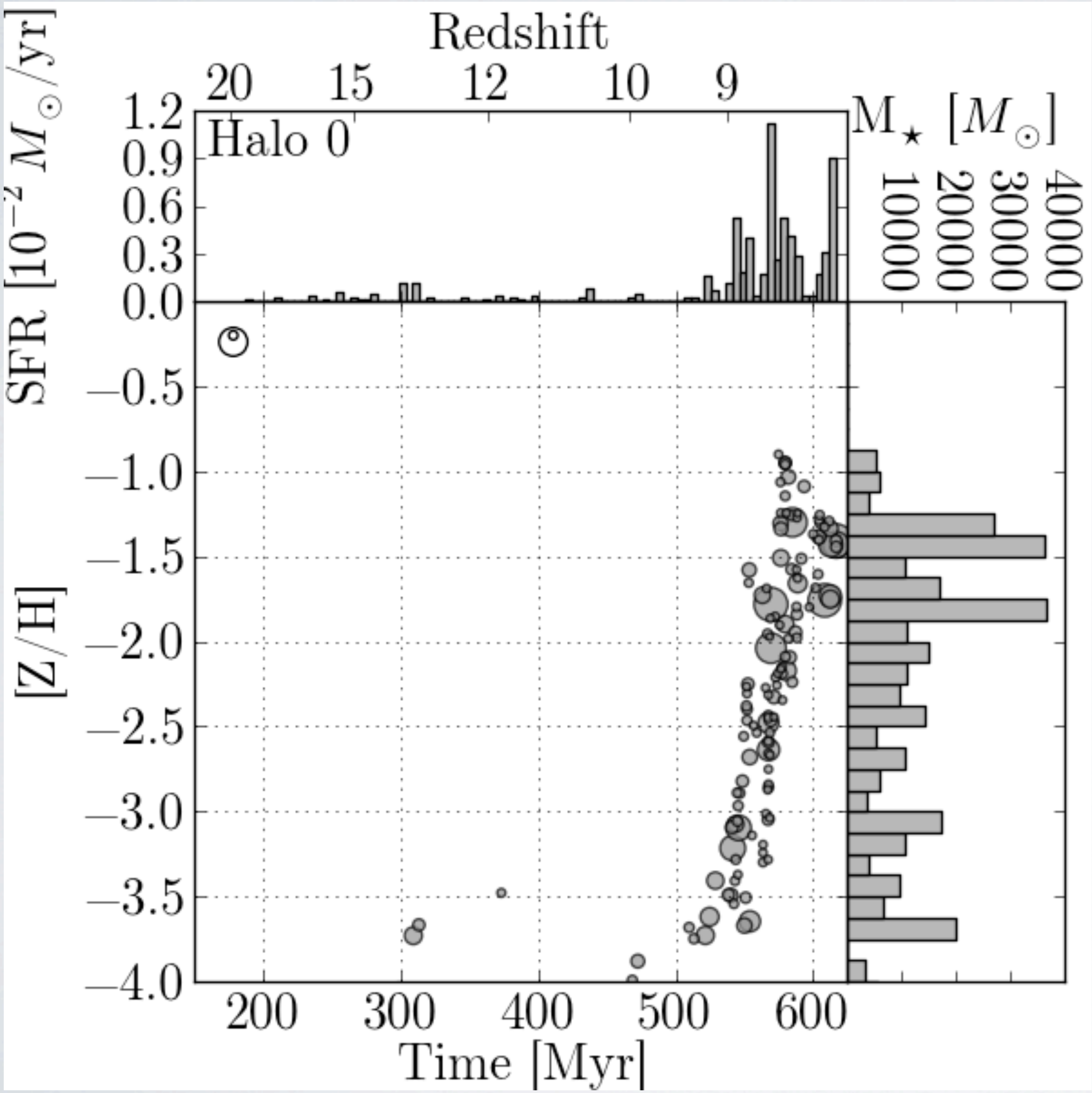
Main Limitation:

lacking

Metal cooling

Soft UV background

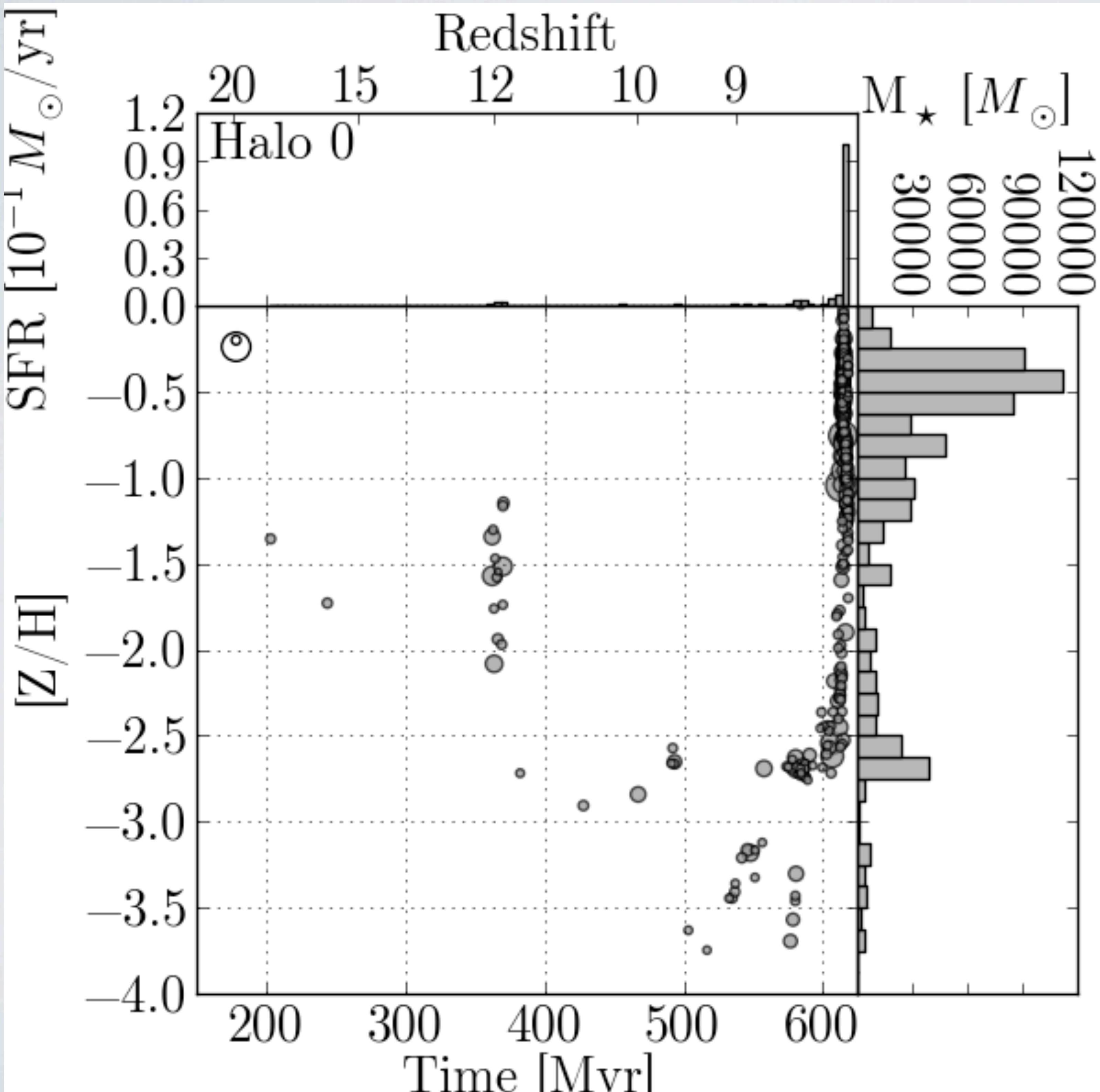
H_2 COOLING BUT NO POP III



Similar subgrid model as typical galaxy formation simulations

Flat metallicity distribution function, arising from self-enrichment.

+ METAL COOLING & SOFT UVB



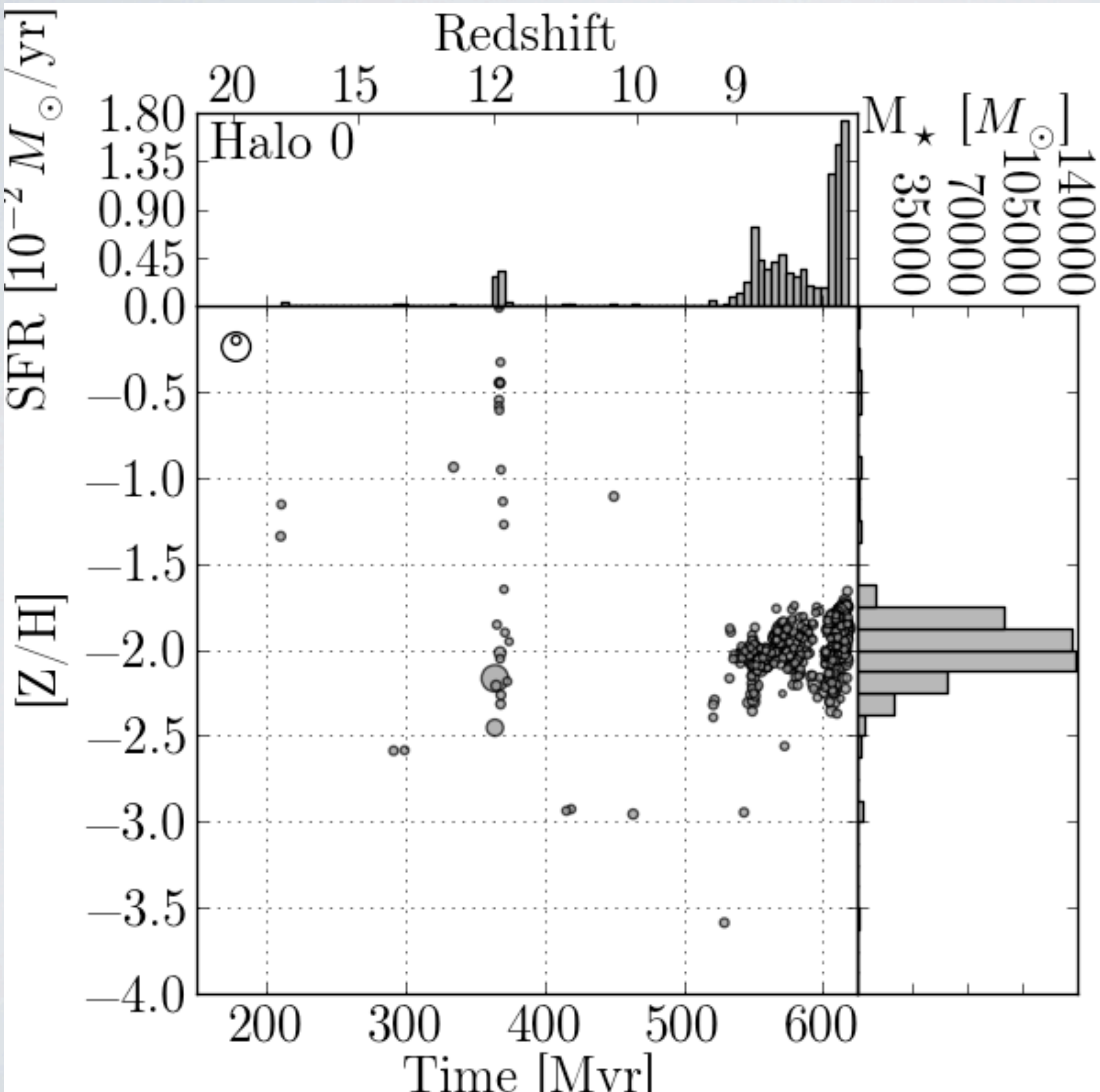
(Re-)introducing typical overcooling problem during initial star formation at $M \sim 10^8 M_\odot$

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

SOFT UVB + METAL COOLING + RAD. PRESSURE



Momentum transfer from ionizing radiation

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

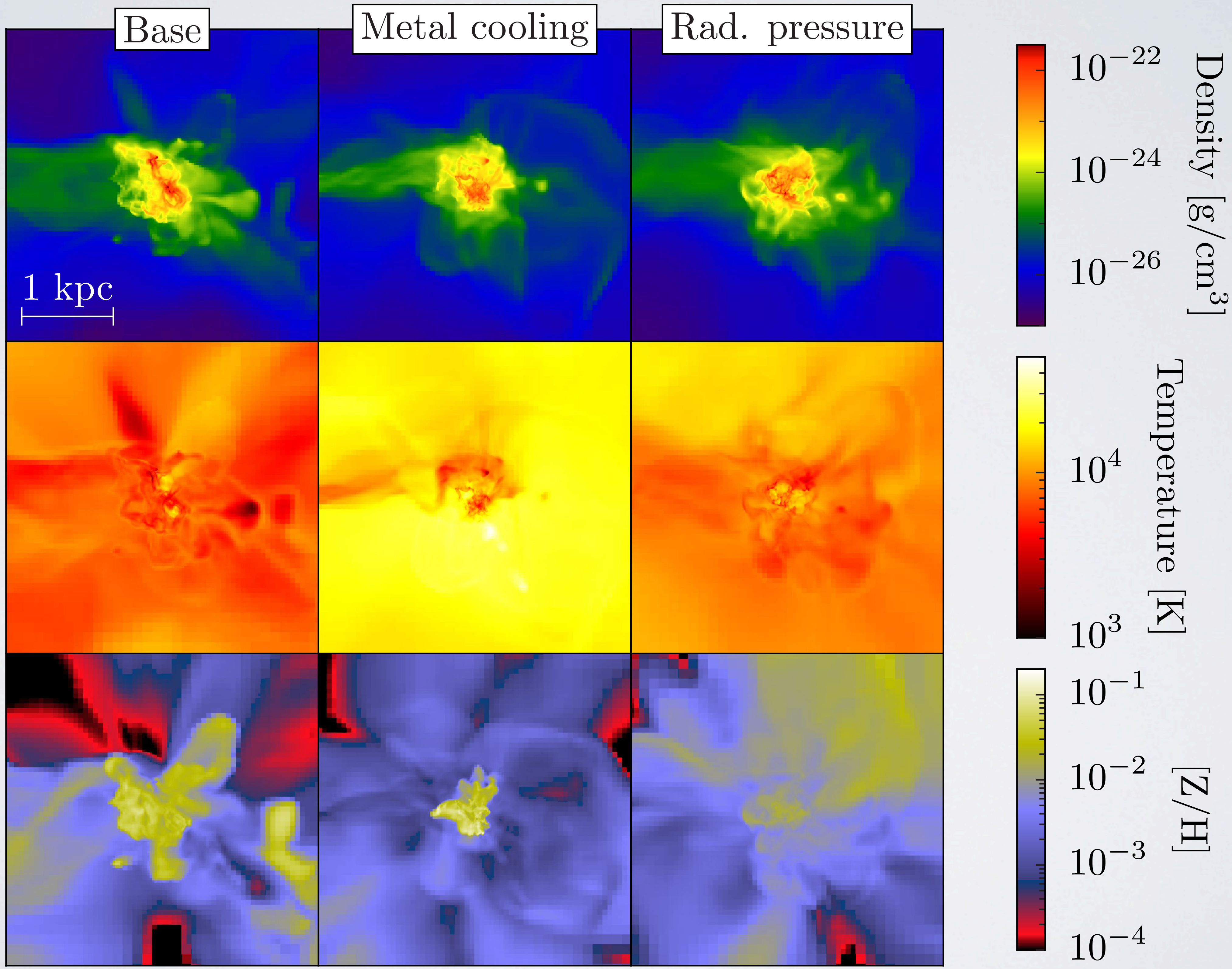
No treatment of radiation pressure on dust → lower limit on its effects

Self-regulation of internal SF through further dispersing dense gas

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

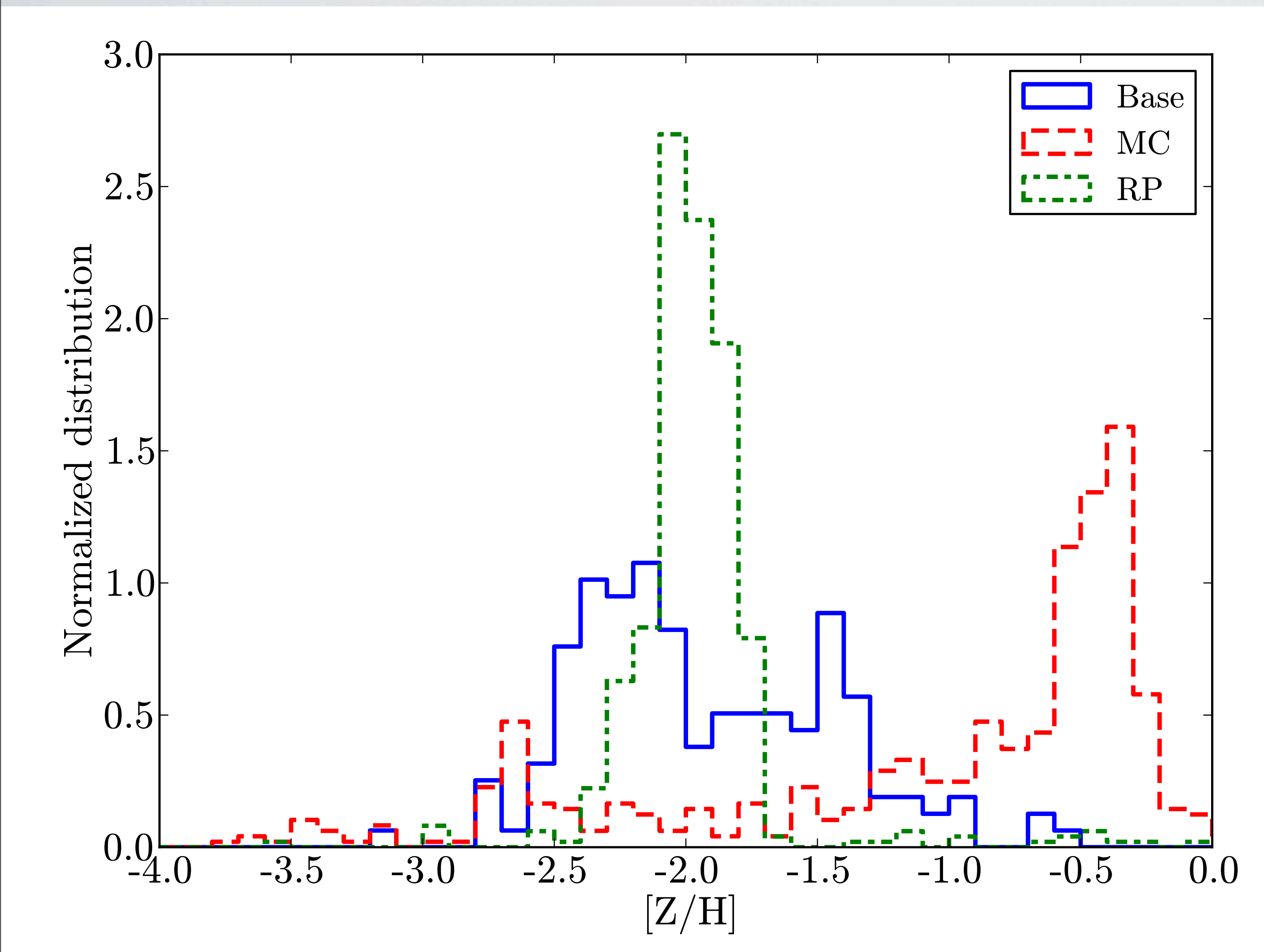
EFFECTS OF RADIATION PRESSURE

10^8 $M_\odot$ GALAXY AT Z=8



EFFECTS OF RADIATION PRESSURE

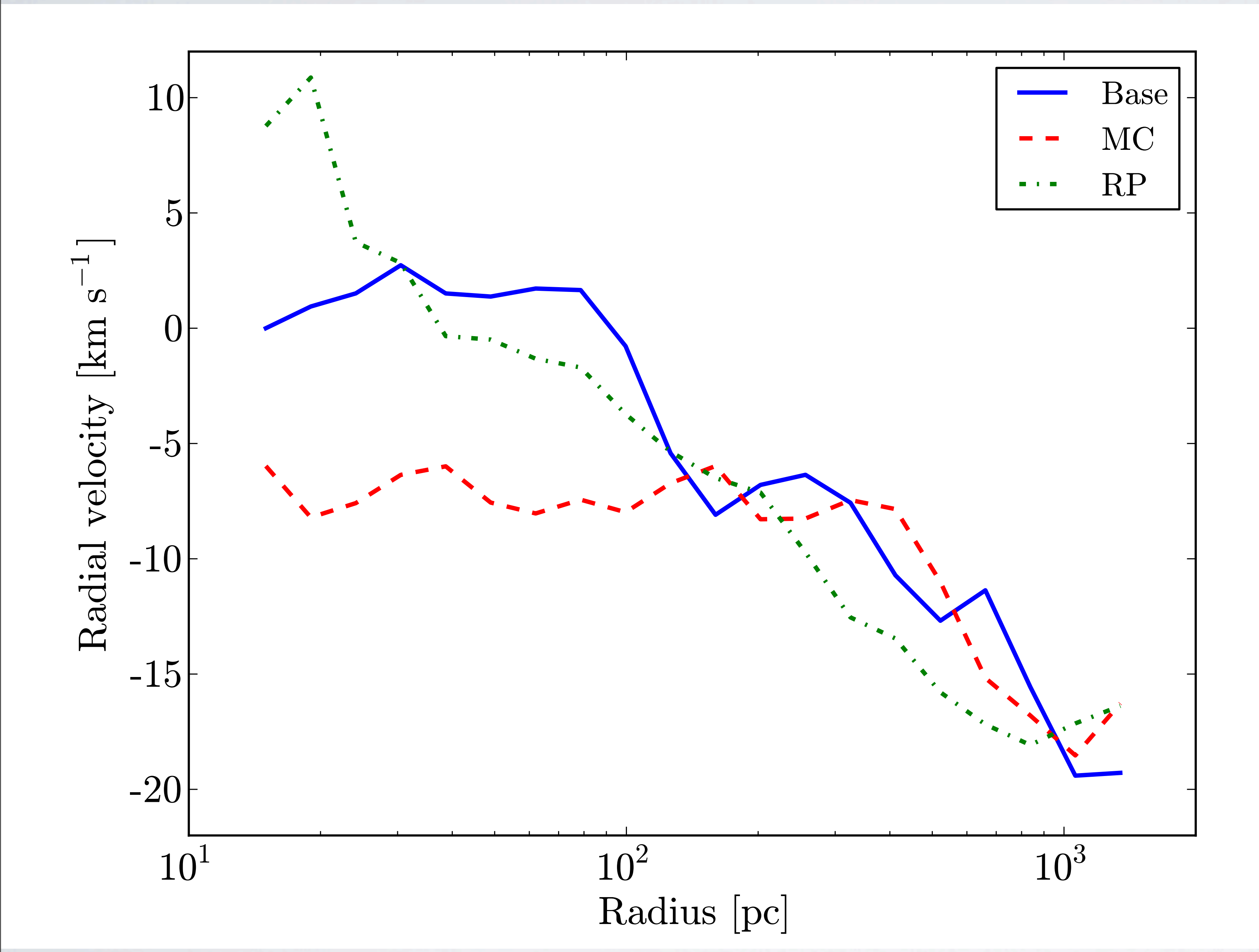
METALLICITY DISTRIBUTION FUNCTIONS



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

EFFECTS OF RADIATION PRESSURE

RADIAL VELOCITIES (OVERCOOLING → SELF-REGULATION)



Reverses infall and locally self-regulates star formation in the inner 100 pc.

CONCLUSIONS

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

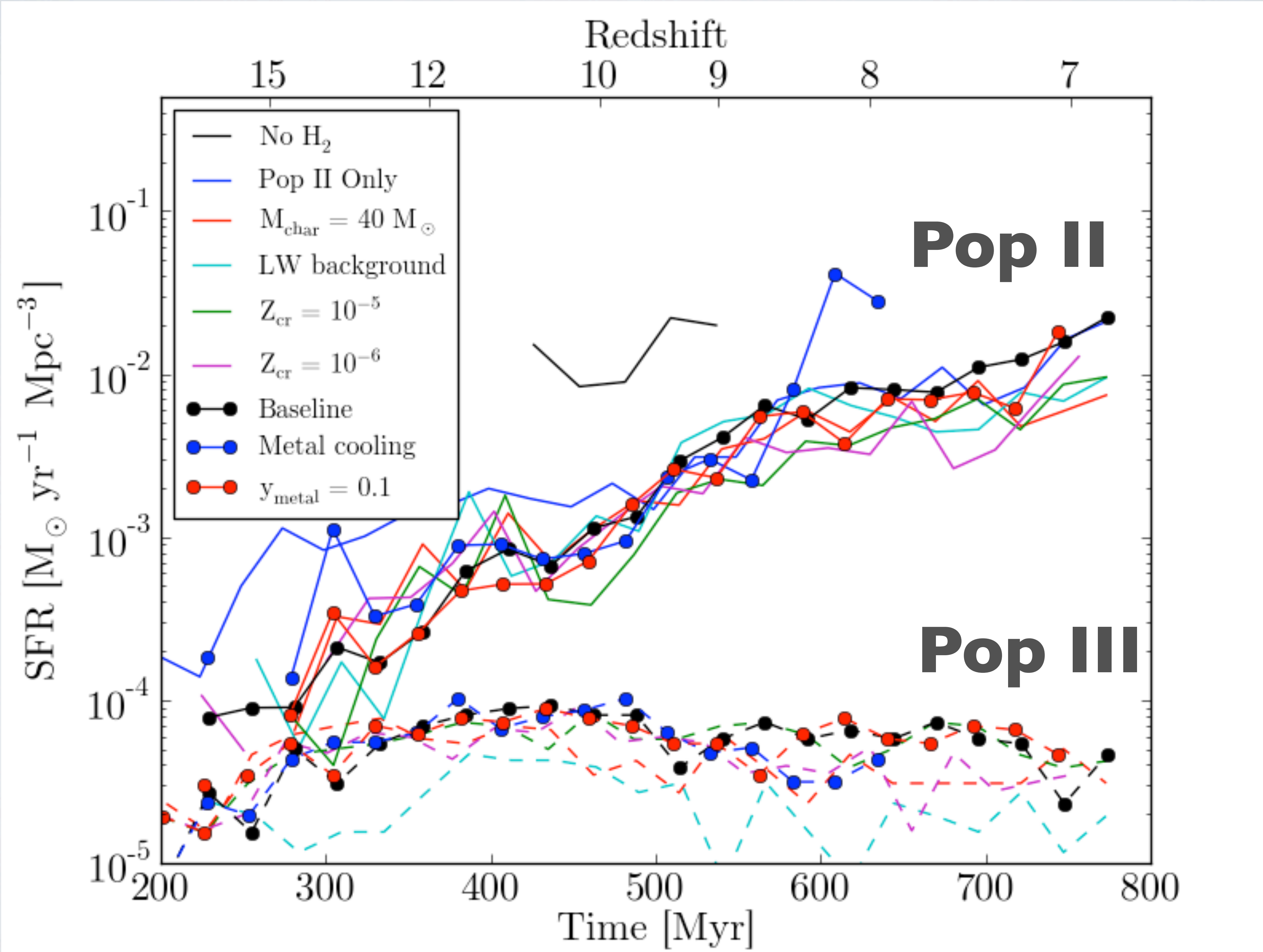
- Population III stars enrich the IGM and dwarf galaxies up to $10^{-3} Z_{\odot}$, possibly providing a metallicity floor for halo/dSph stars and DLAs.

- 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.

STAR FORMATION RATES



IONIZATION HISTORY