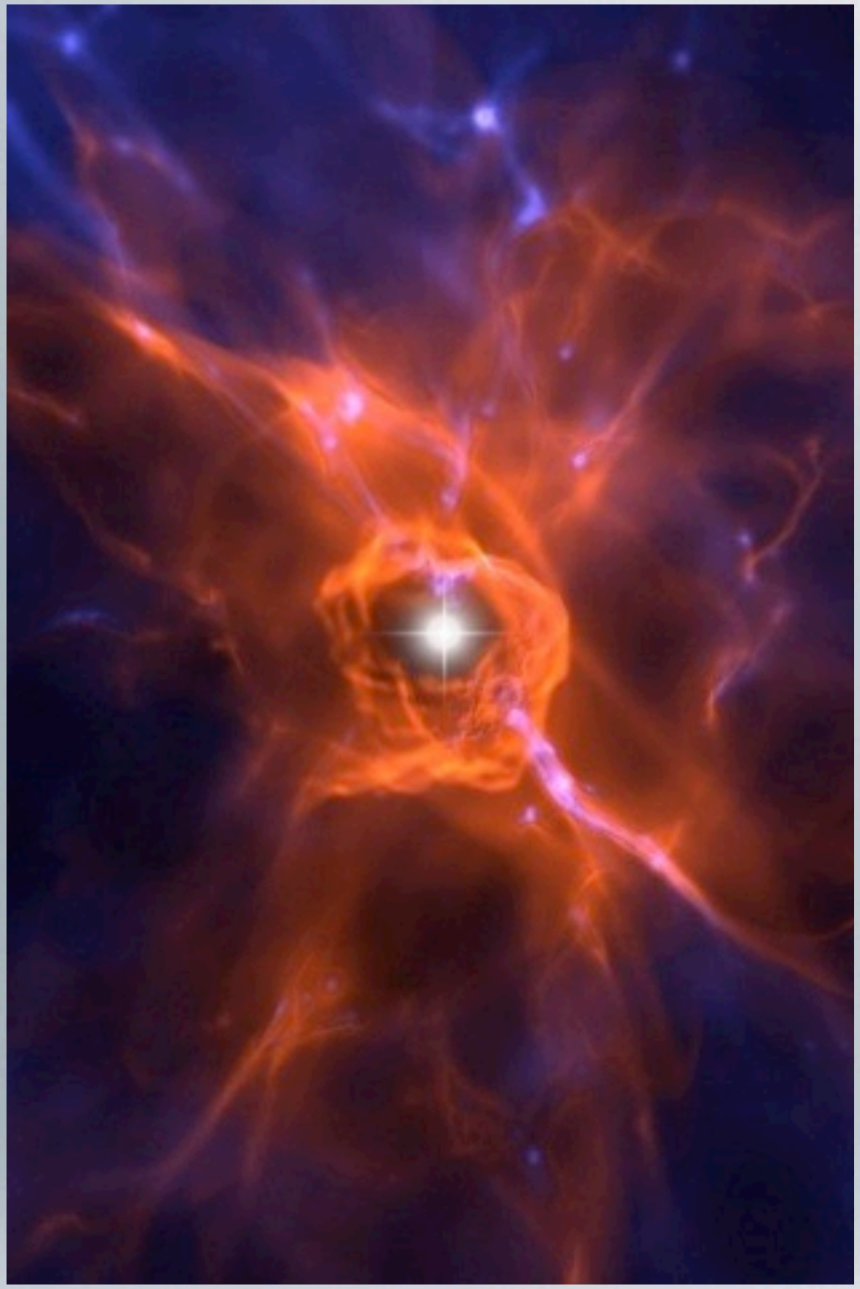
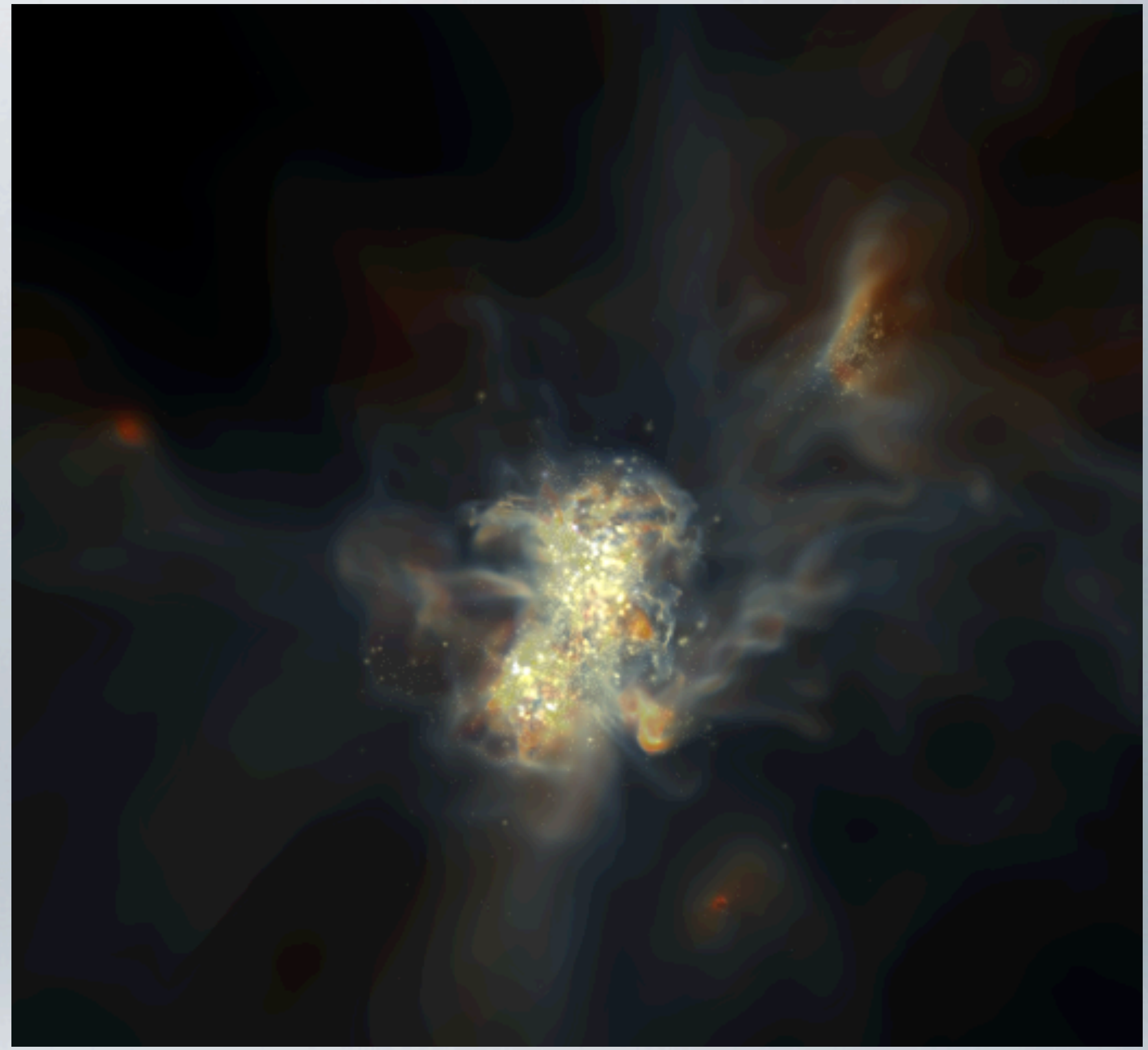




THE REIONIZERS: HIGH-Z DWARF GALAXIES

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? aka "forming-too-many-stars-at-high-z problem"
- 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)

円相 Enzo

enzo-project.org

Abel, Wise, & Bryan (2007)

H II REGION OF A PRIMORDIAL STAR

Density

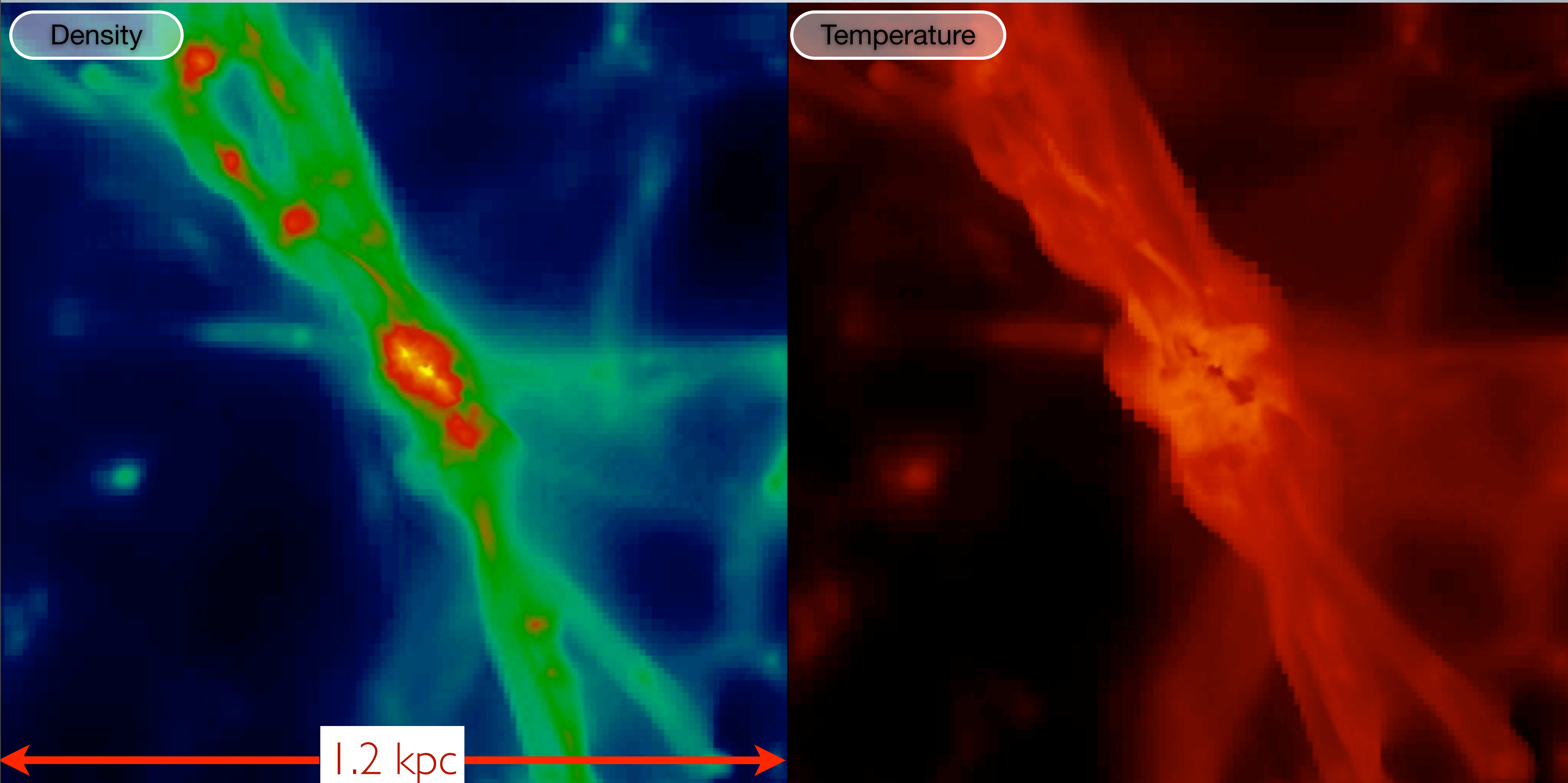
Temperature

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 (2012)

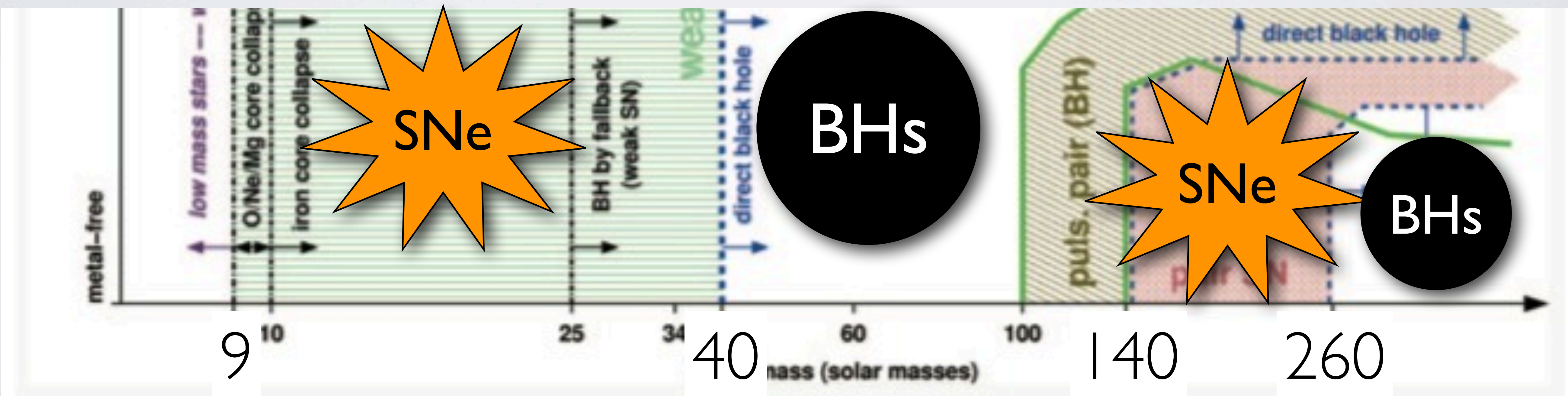
OUR APPROACH:

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)

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

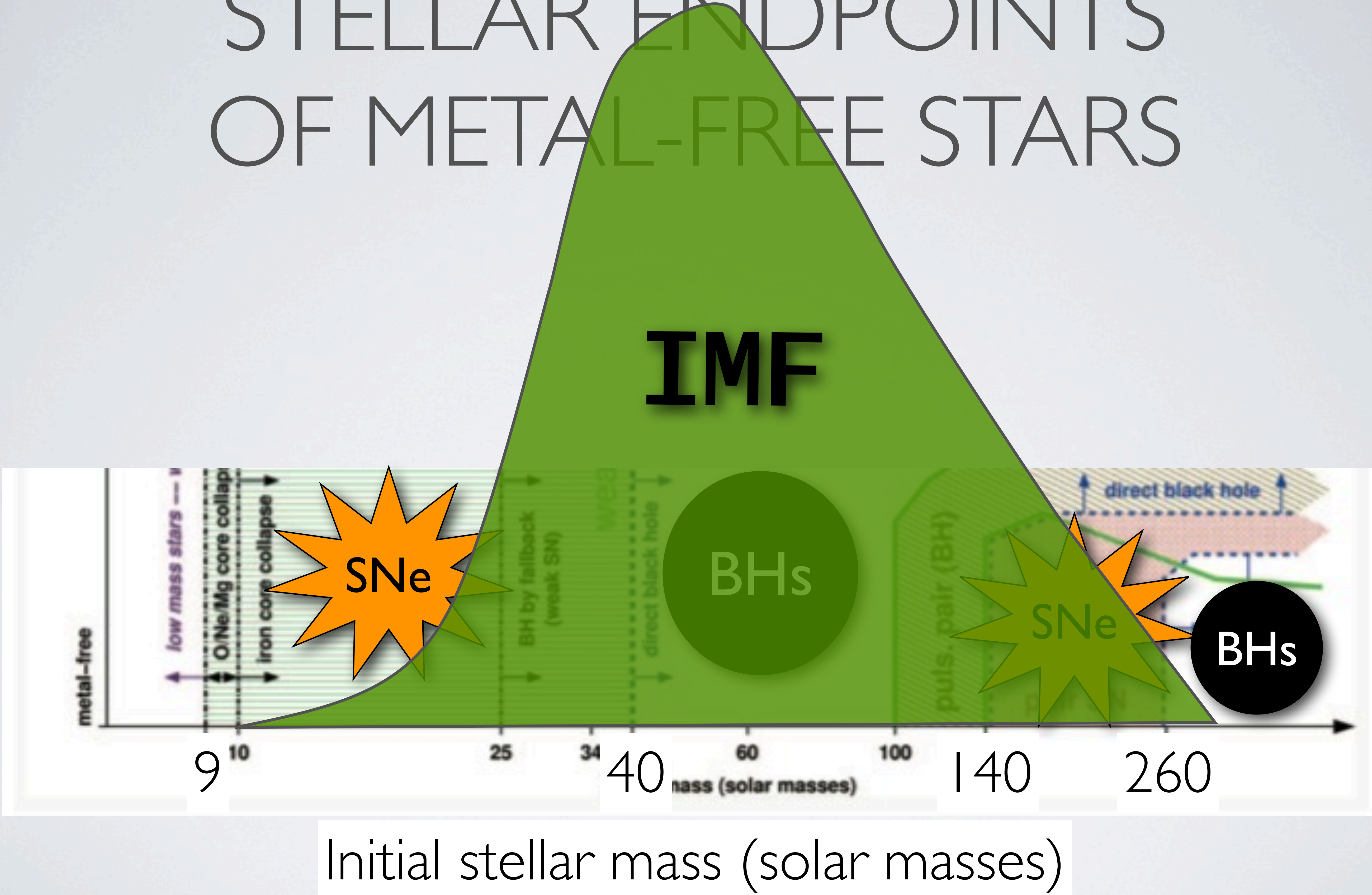
STELLAR ENDPOINTS OF METAL-FREE STARS



Initial stellar mass (solar masses)

Heger et al. (2003)

STELLAR ENDPOINTS OF METAL-FREE STARS



Heger et al. (2003)

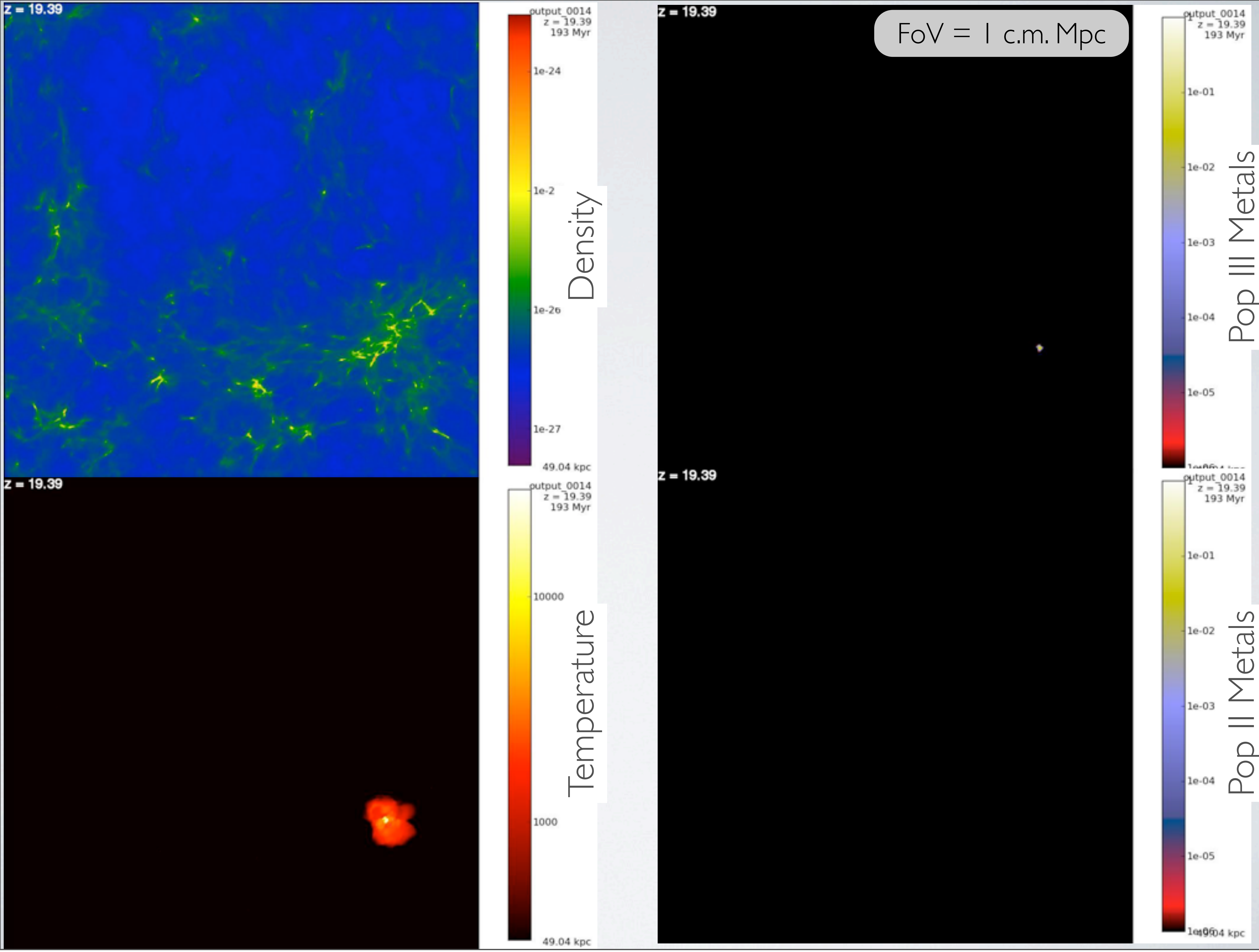
FoV = 1 c.m. Mpc

Density

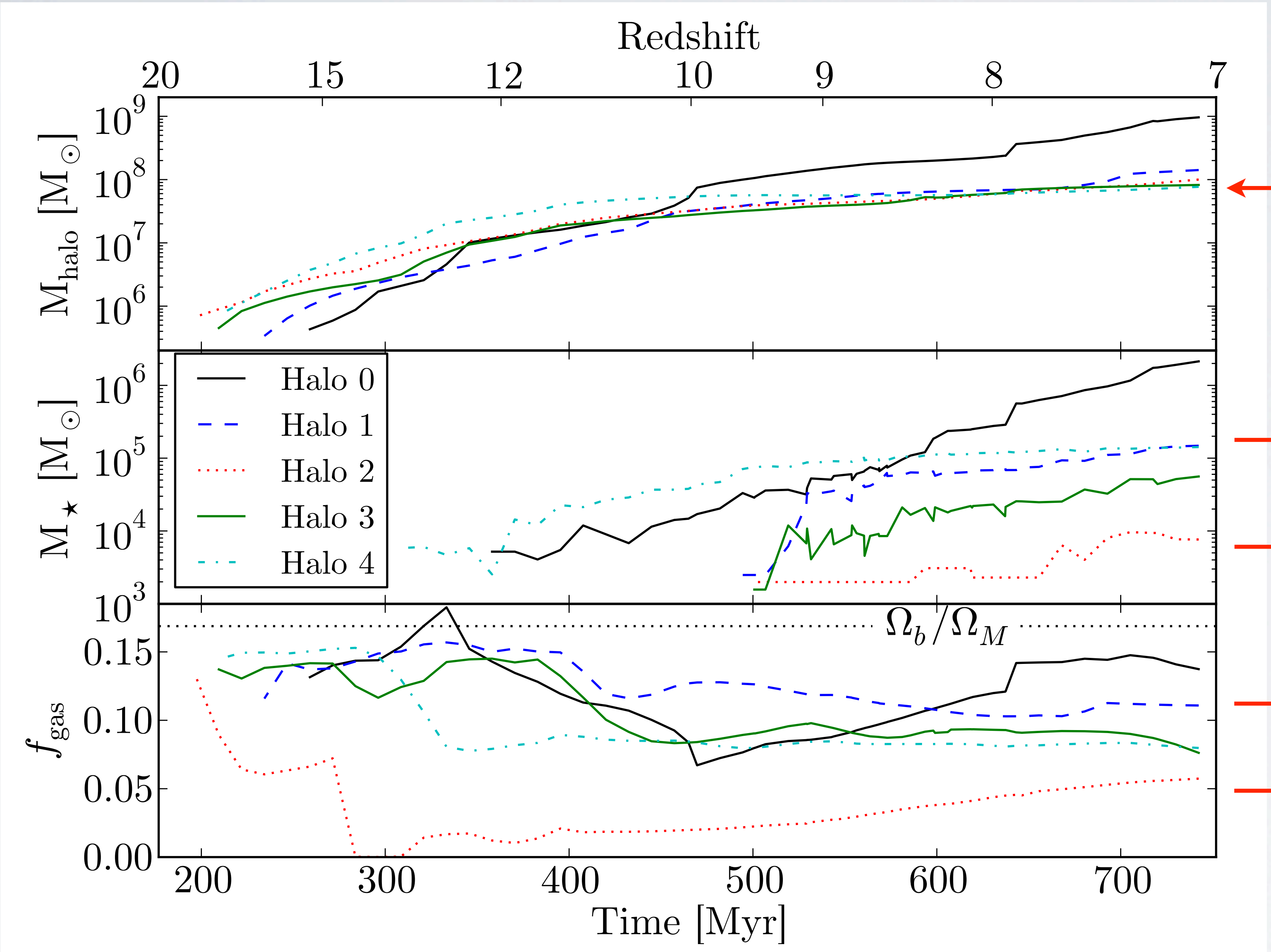
Pop III Metals

Temperature

Pop II Metals


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

DWARF GALAXY BUILDUP

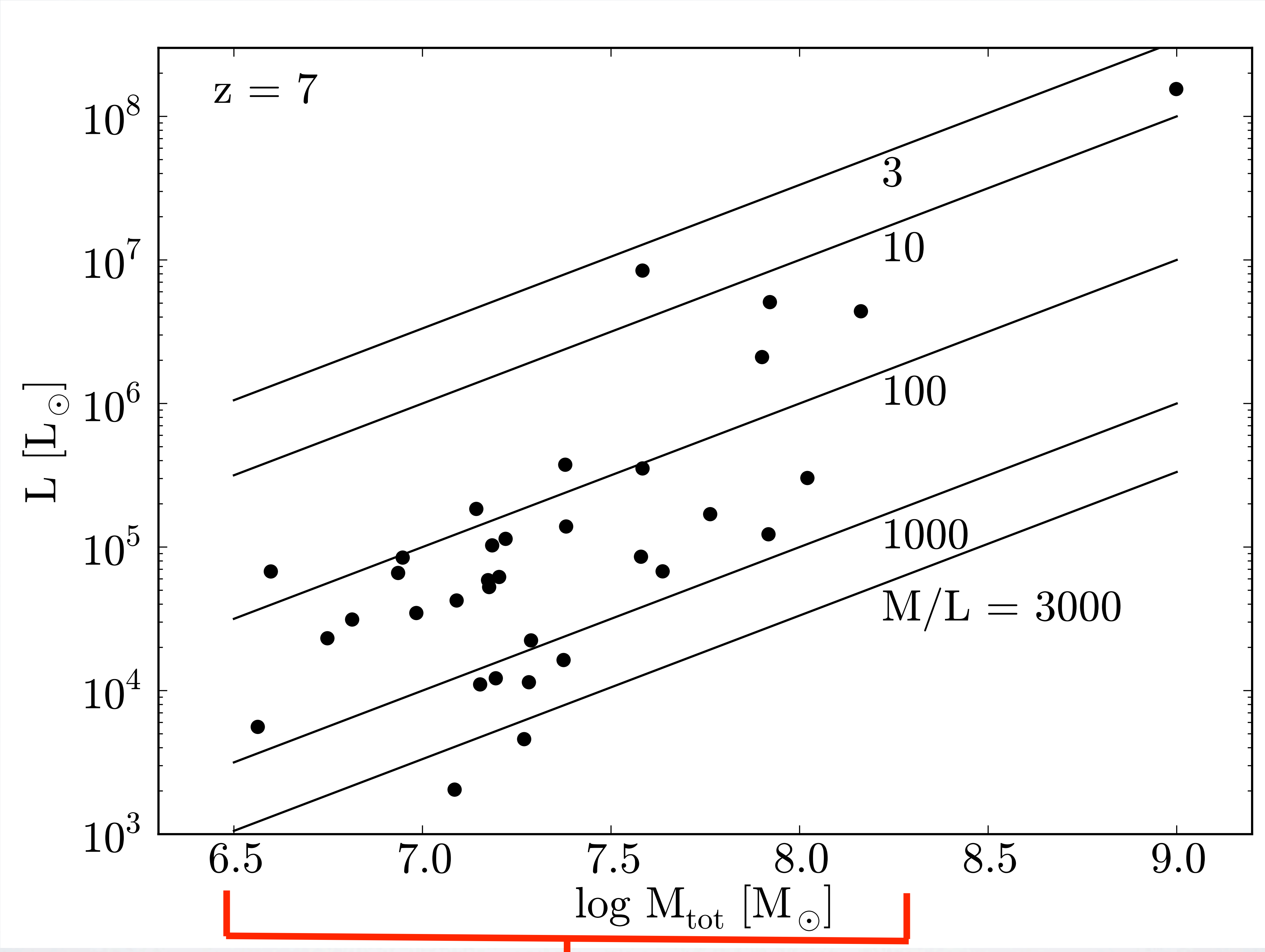


Galaxies with similar halo masses can differ in stellar mass by an order of magnitude!

$M_\star/M_{gas}$ = 0.01–0.05

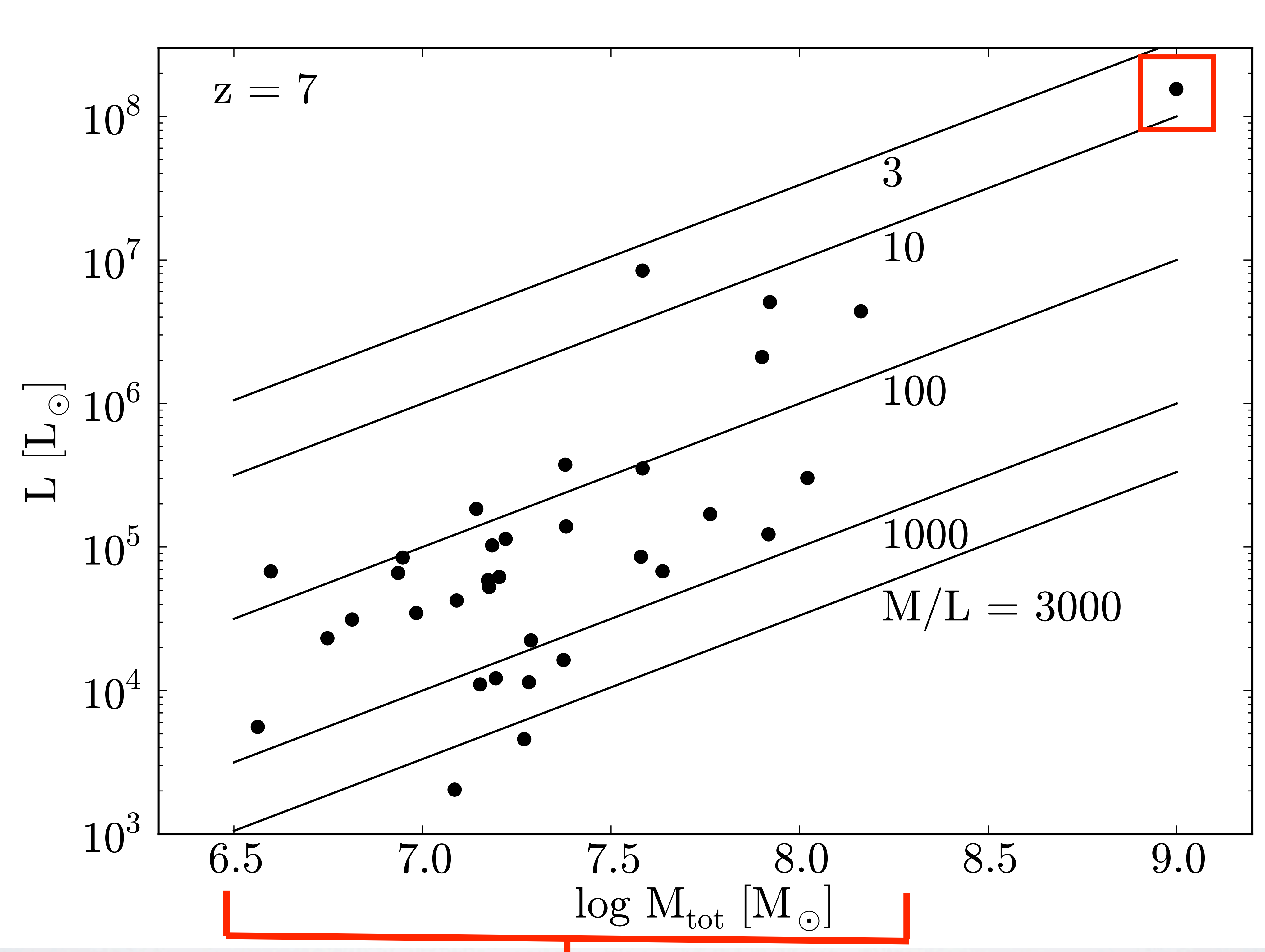
- The initial buildup of the dwarfs are regulated by prior Pop III feedback and radiative feedback from nearby galaxies.

MASS-TO-LIGHT RATIOS

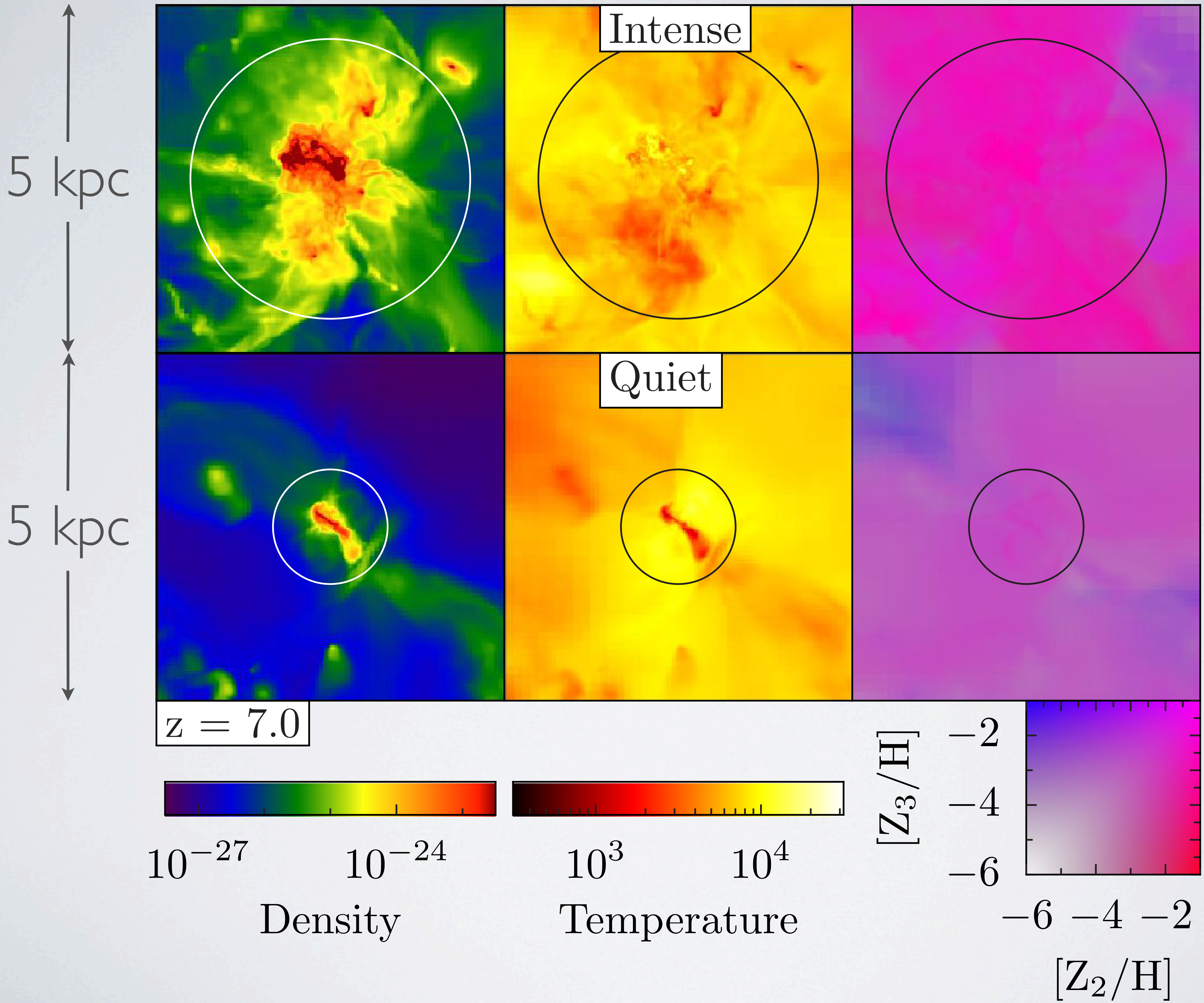


Scatter created by different environments and Pop III progenitor masses

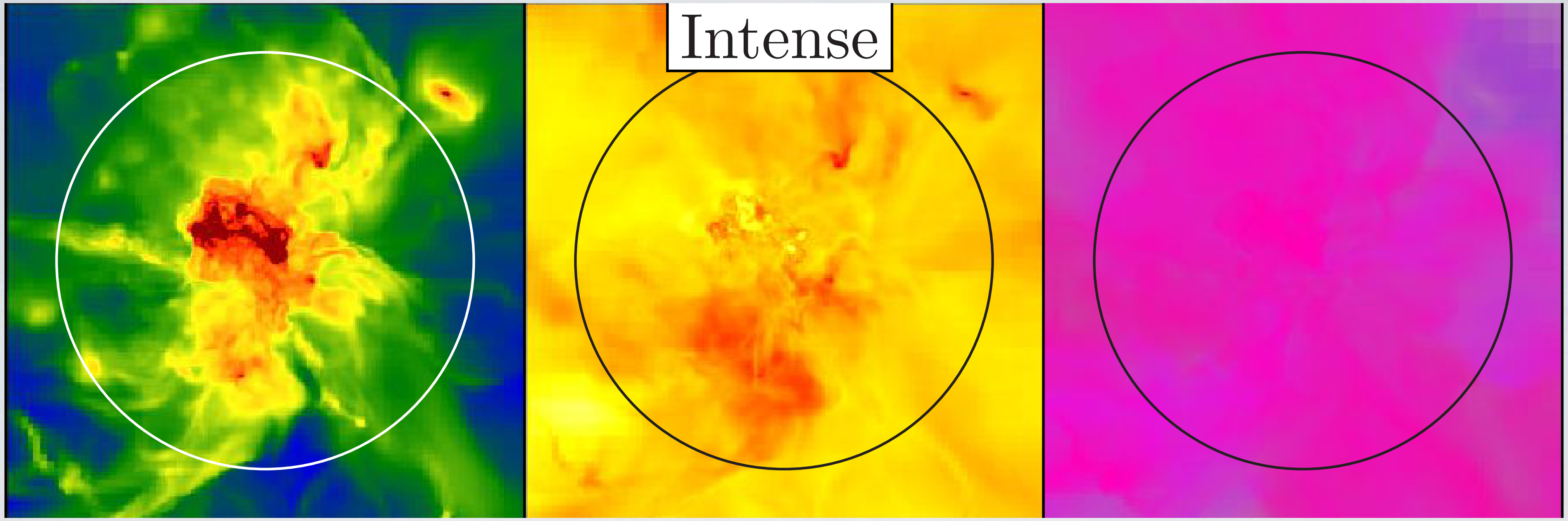
MASS-TO-LIGHT RATIOS



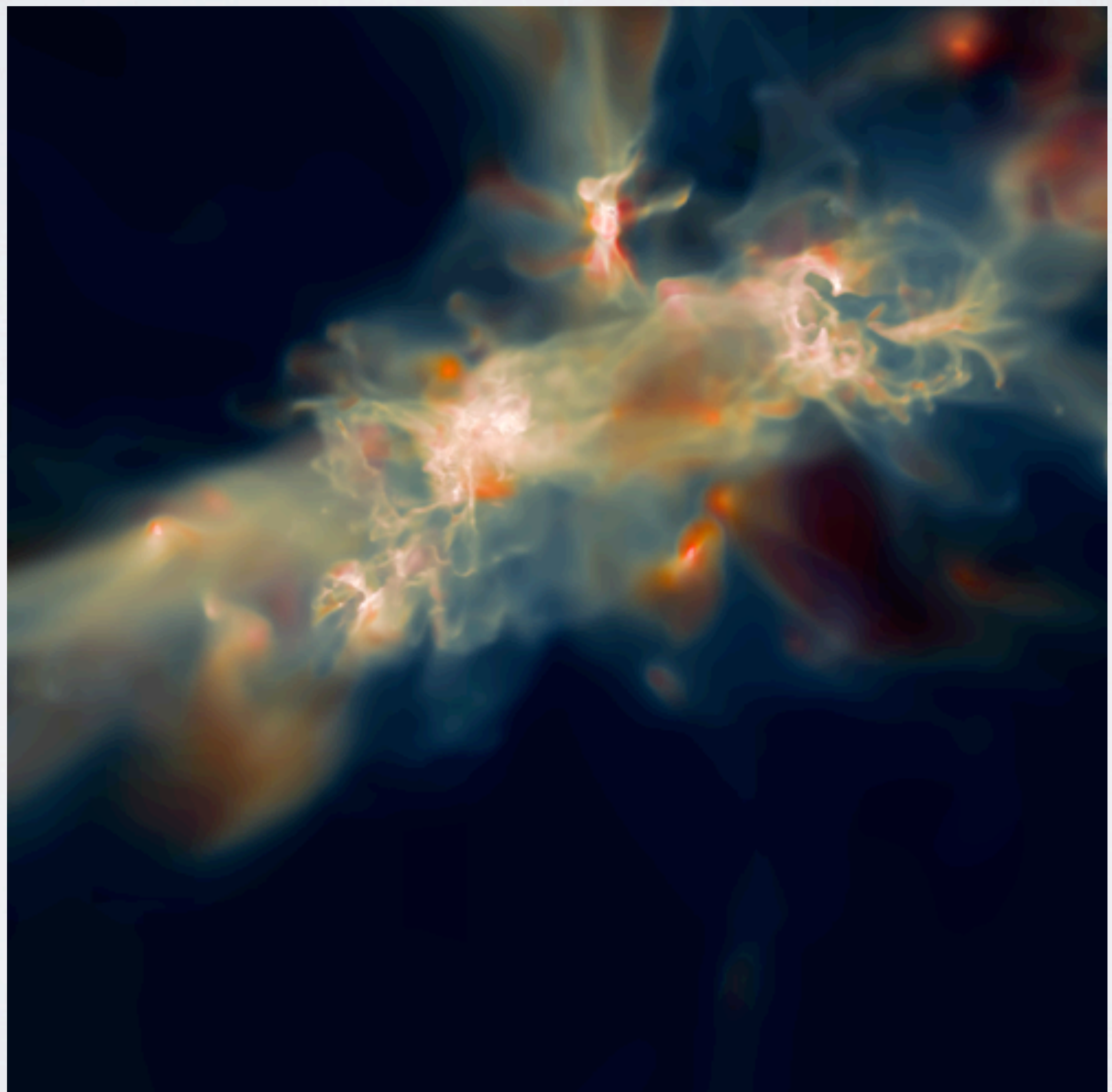
Scatter created by different environments and Pop III progenitor masses

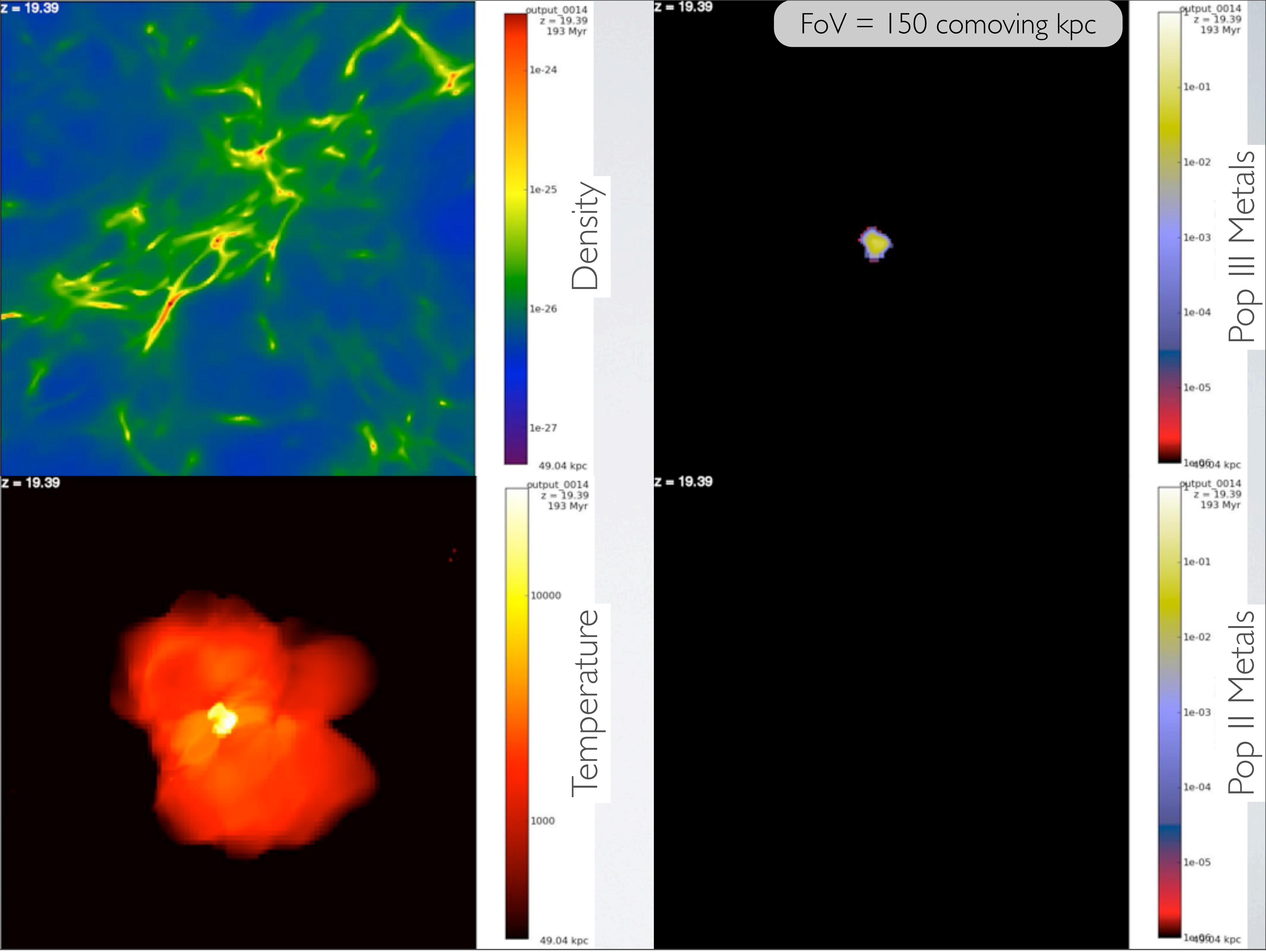

5 kpc
5 kpc
Intense
Quiet
z = 7.0
10^{-27}
10^{-24}
Density
10^3
10^4
Temperature
$[Z_3/H]$
−2
−4
−6
−6 −4 −2
$[Z_2/H]$

5 kpc

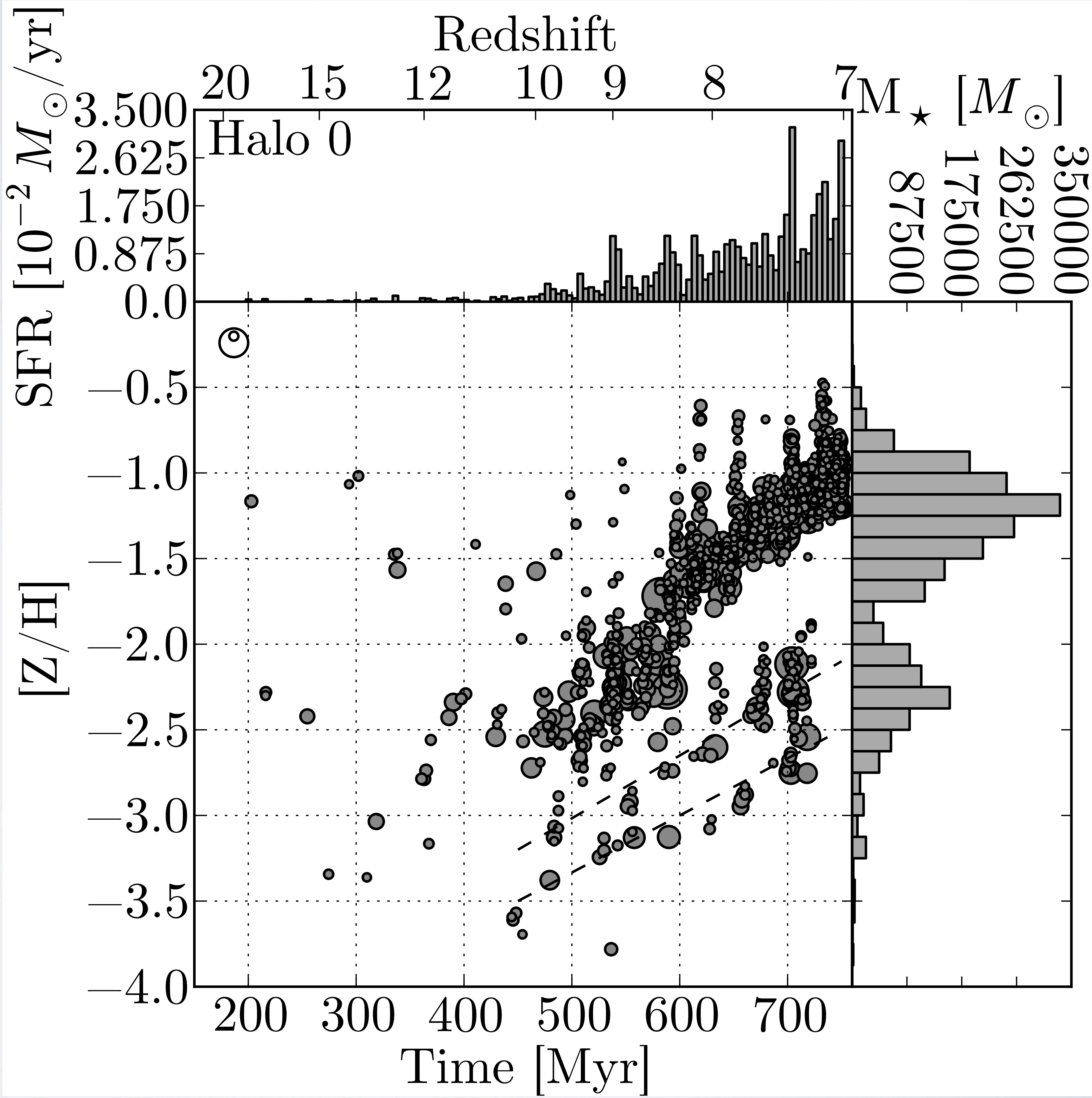


FoV = 10 kpc



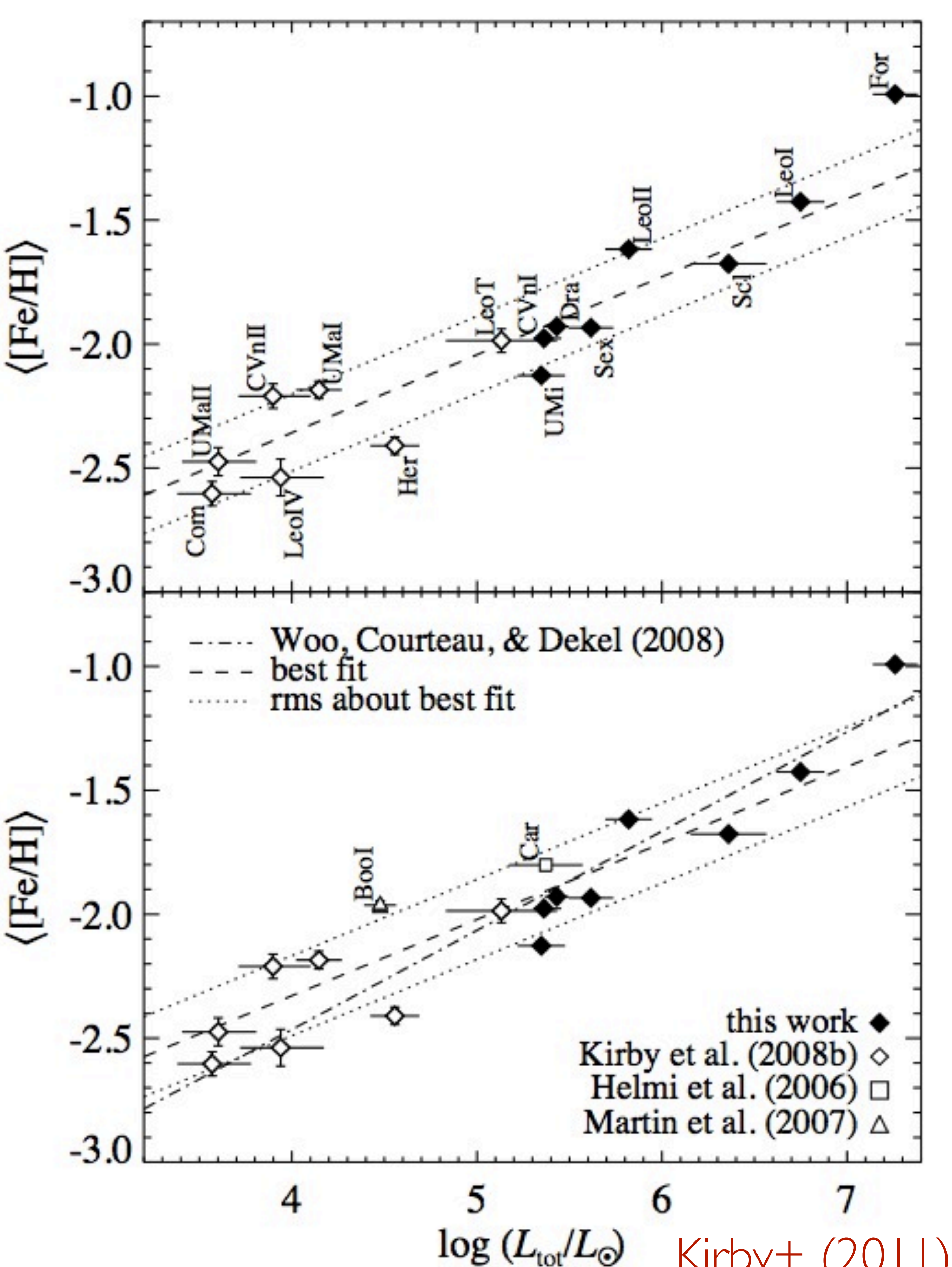

z = 19.39
output_0014
z = 19.39
193 Myr
1e-24
1e-25
1e-26
1e-27
49.04 kpc
Density
FoV = 150 comoving kpc
1e-01
1e-02
1e-03
1e-04
1e-05
Pop III Metals
Temperature
10000
1000
Pop II Metals

- 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



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.

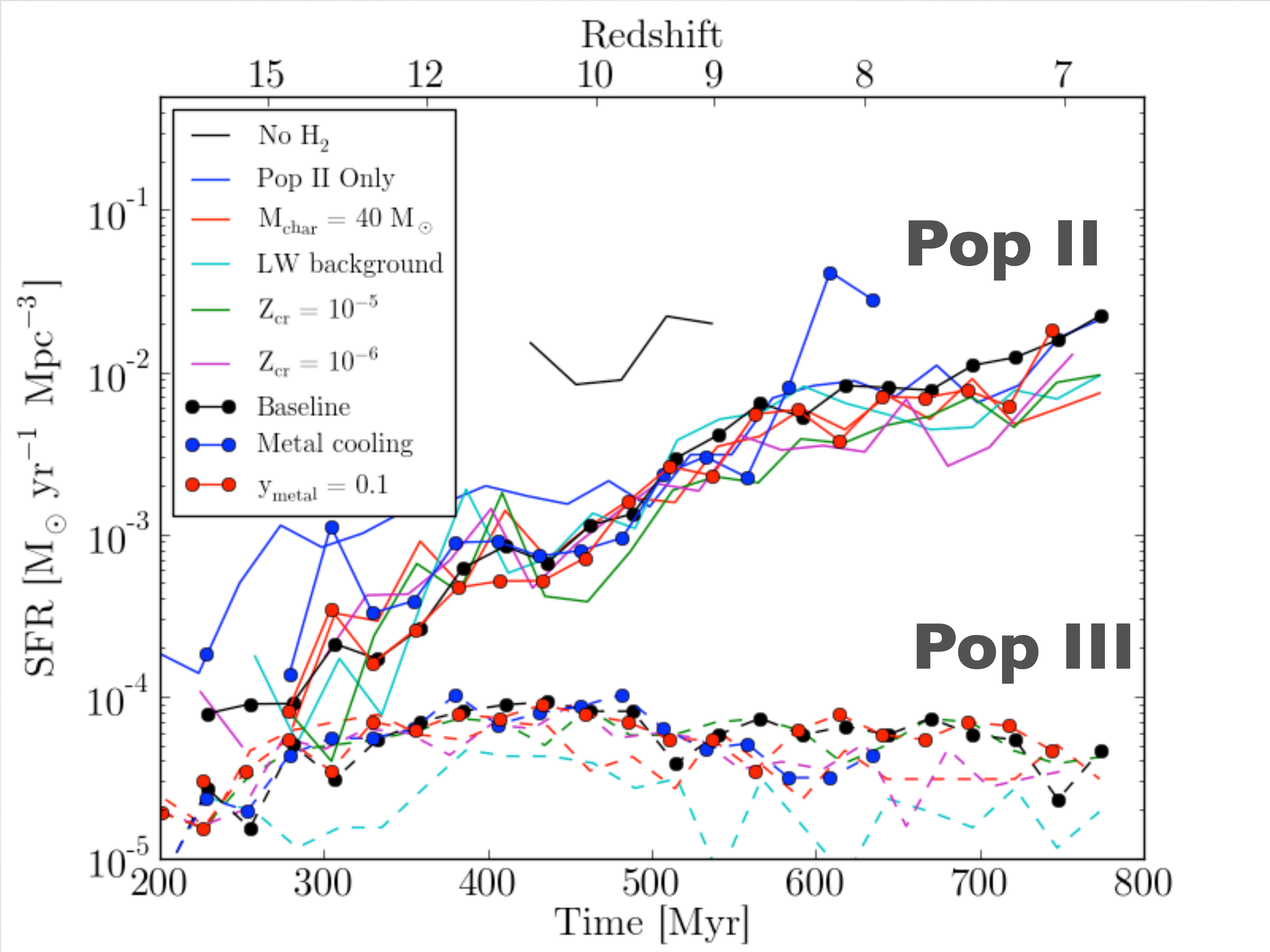


Kirby+ (2011)

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



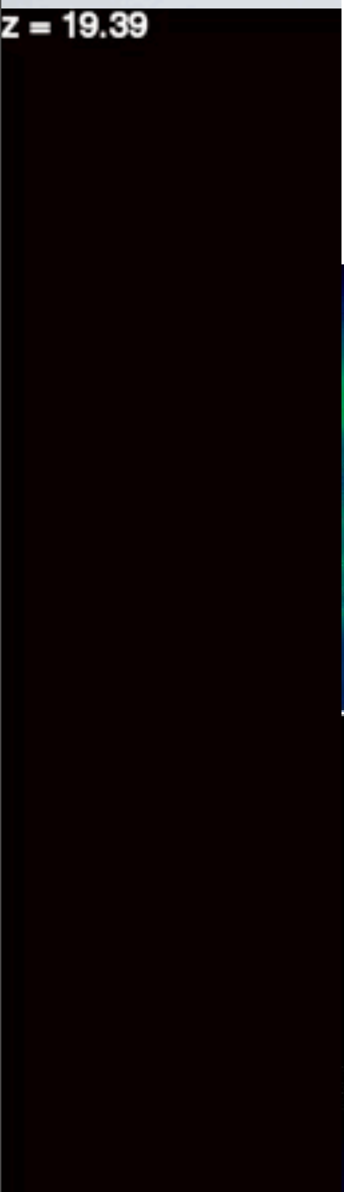
Wise & Abel (2008); JHW+ (in prep.)

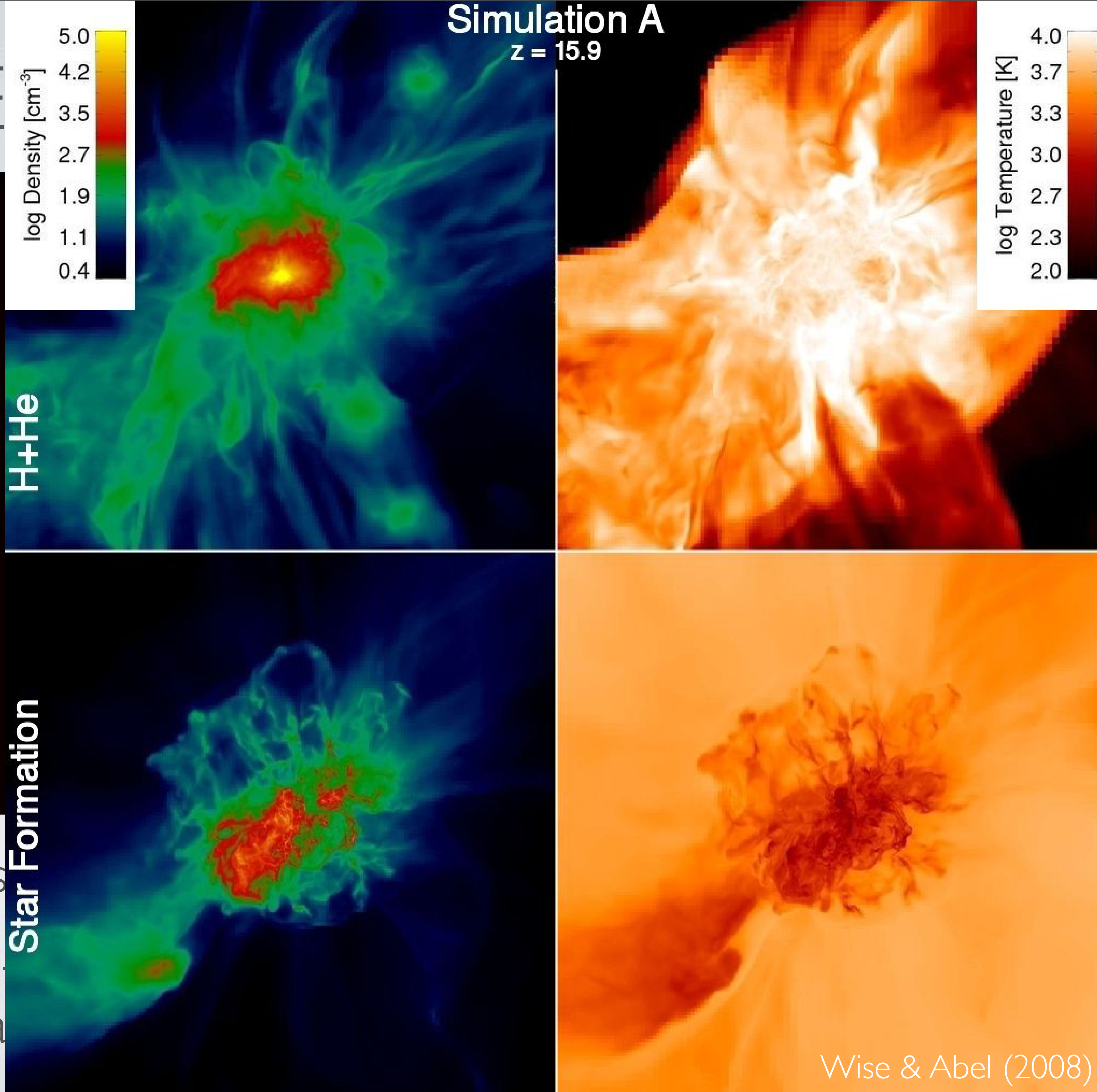
NEGLECTING M < 10^8 M$_\odot$ HALOS

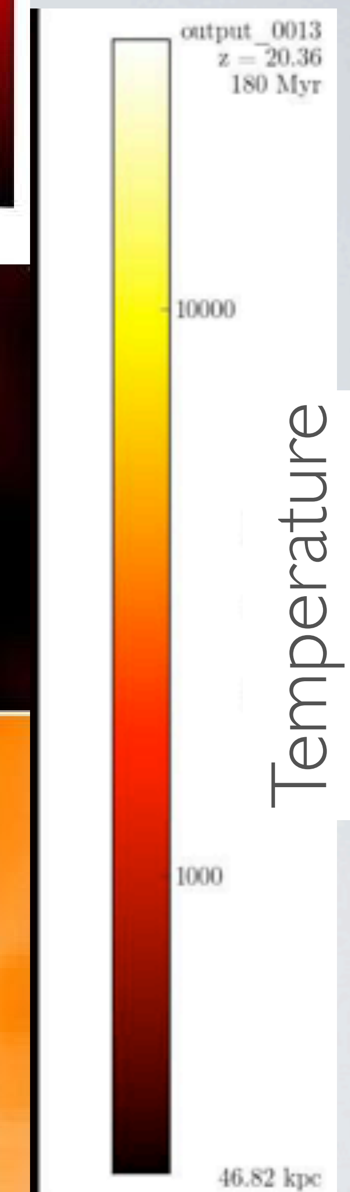
- No stellar feedback in M < 10^8 M$_\odot$ halos → $f_{gas} = \Omega_b / \Omega_m$
- High-z halos are too gas-rich, leading to an overproduction of stellar mass and SFR in low-mass, high-z galaxies.

V+ (in prep.)

NE OS





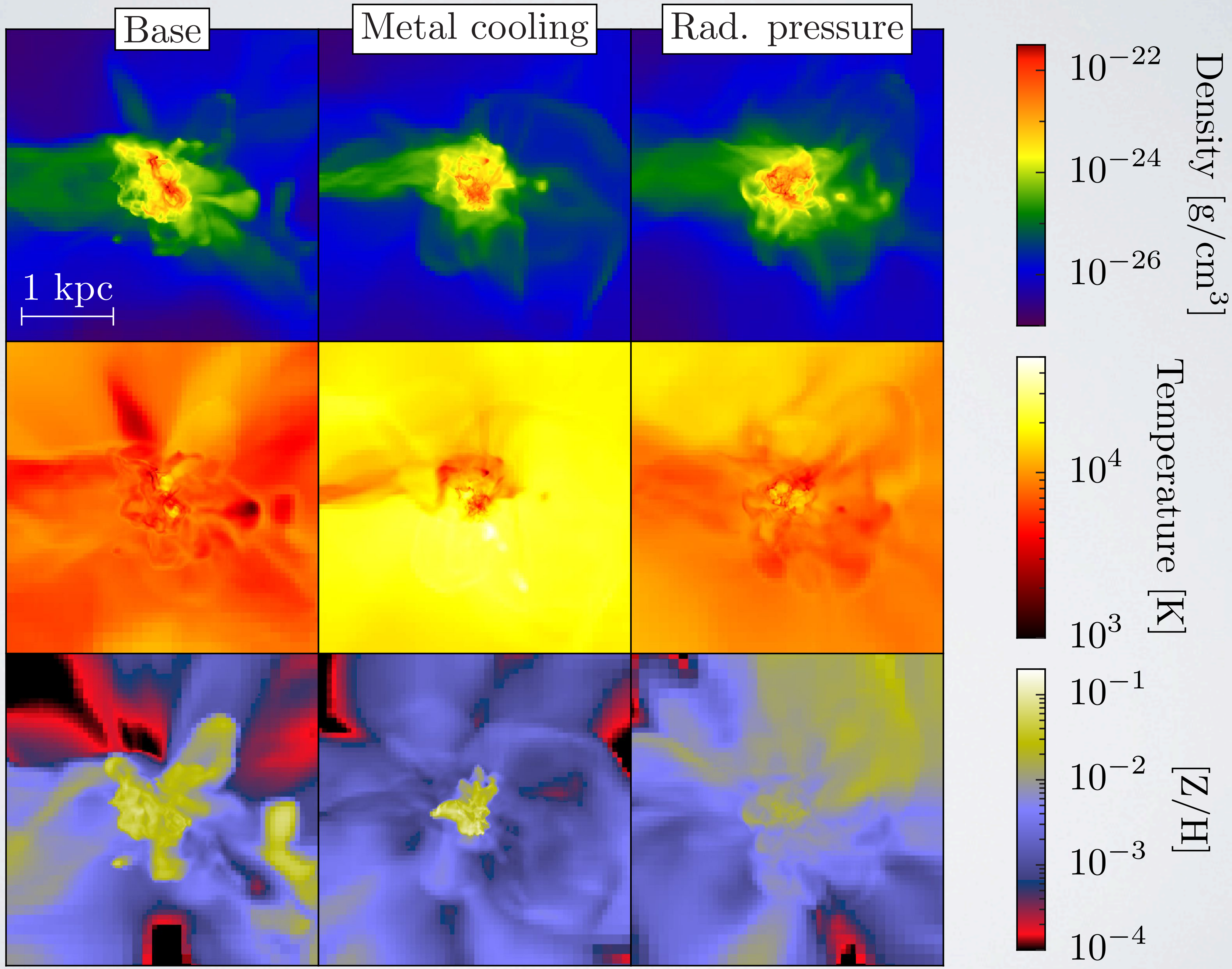


- No s Ω_m
- High- on of stella

JHW+ (arXiv:1206.1043)

EFFECTS OF RADIATION PRESSURE

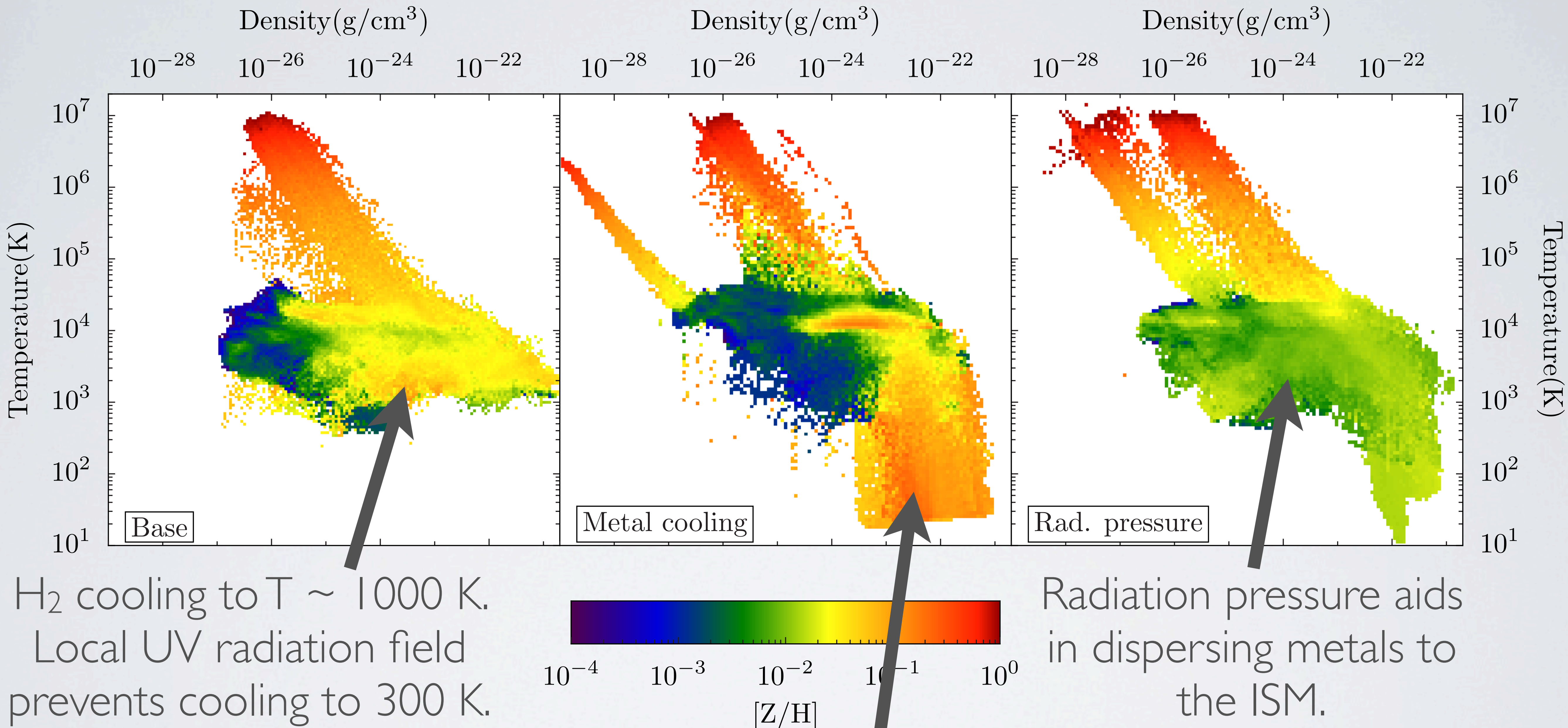
$M_{VIR} = 3 \times 10^8 M_\odot$ GALAXY AT $z = 8$



JHW+ (arXiv:1206.1043)

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.

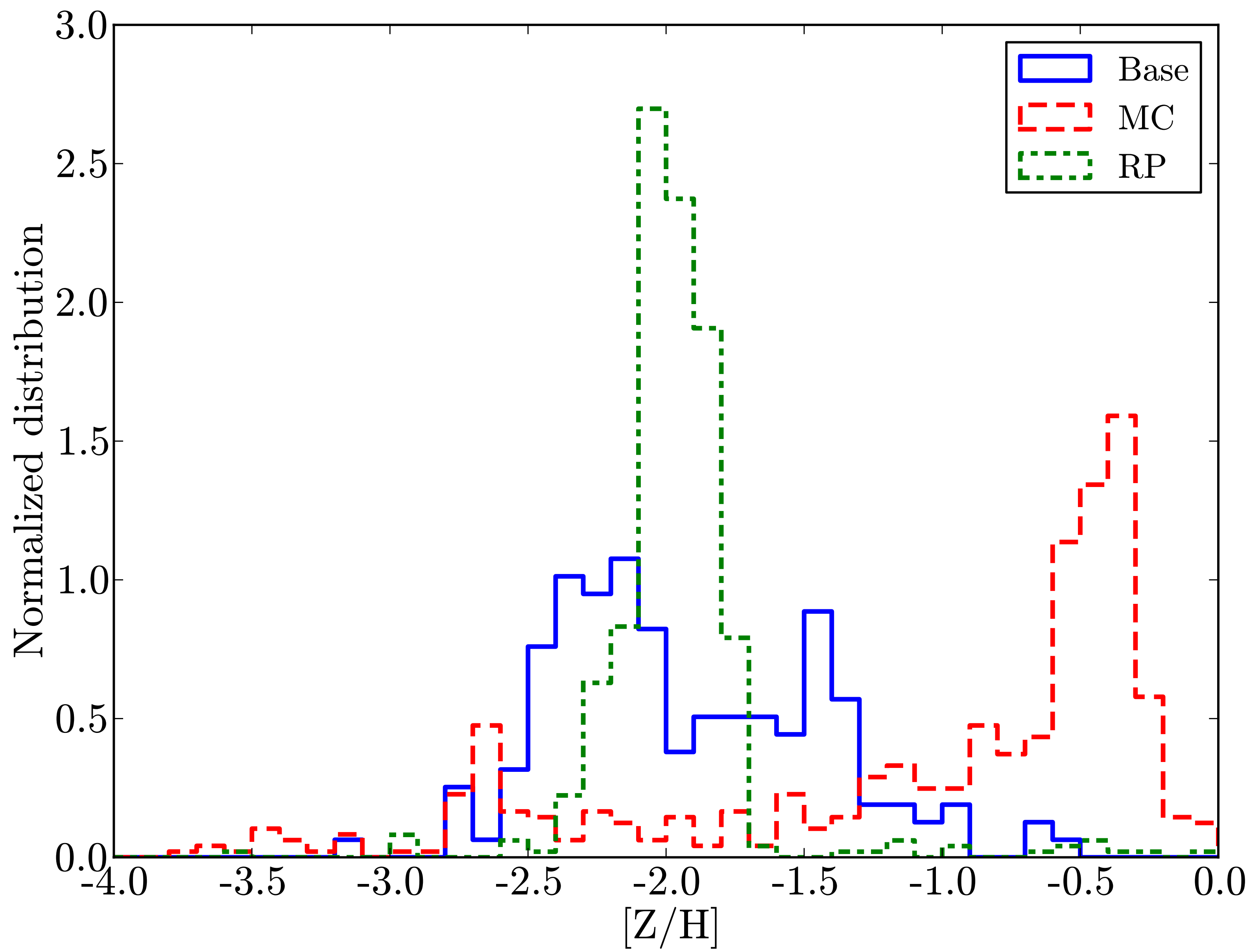
Radiation pressure aids in dispersing metals to the ISM.

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

JHW+ (arXiv:1206.1043)

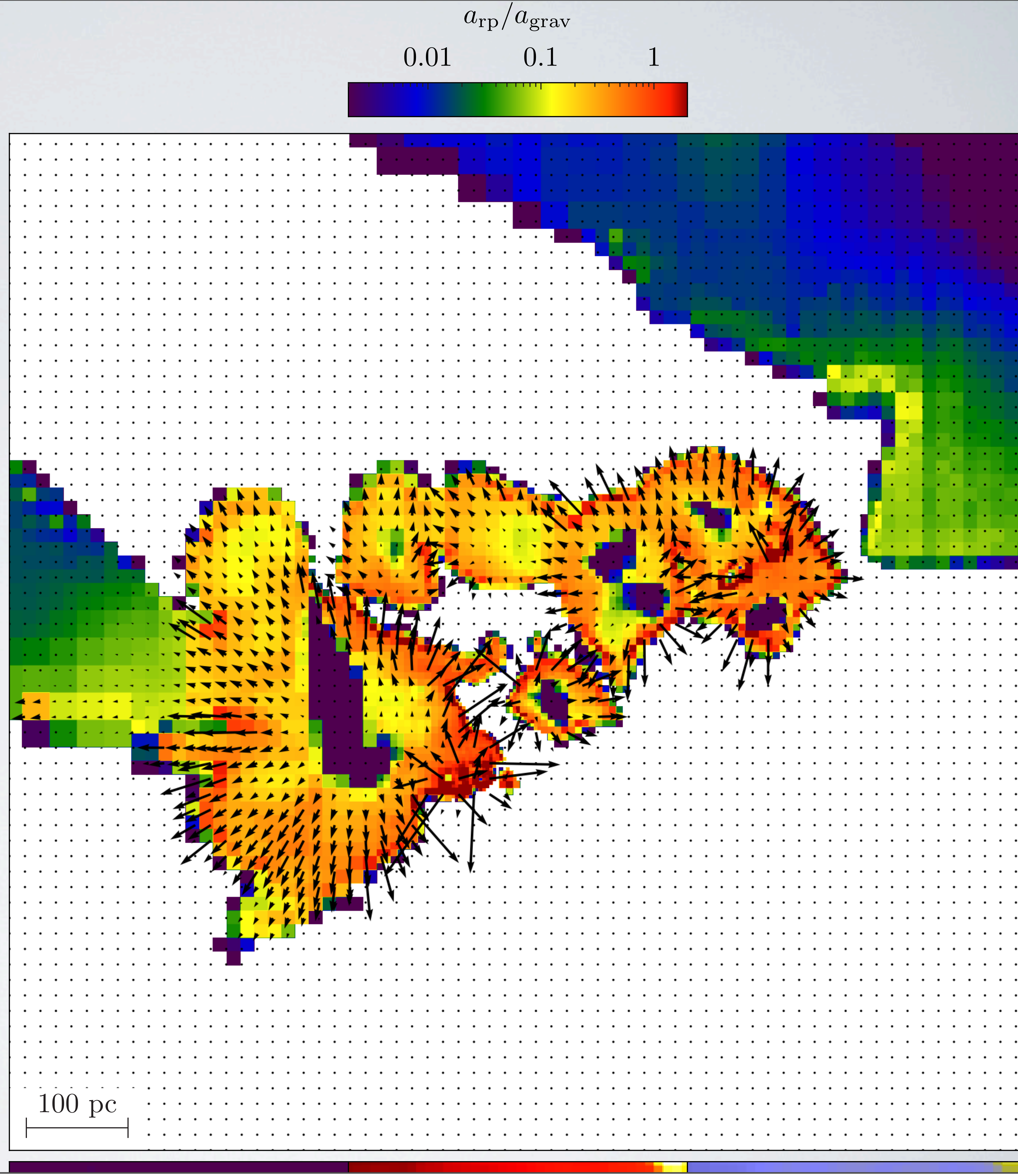
EFFECTS OF RADIATION PRESSURE

METALLICITY DISTRIBUTION FUNCTIONS

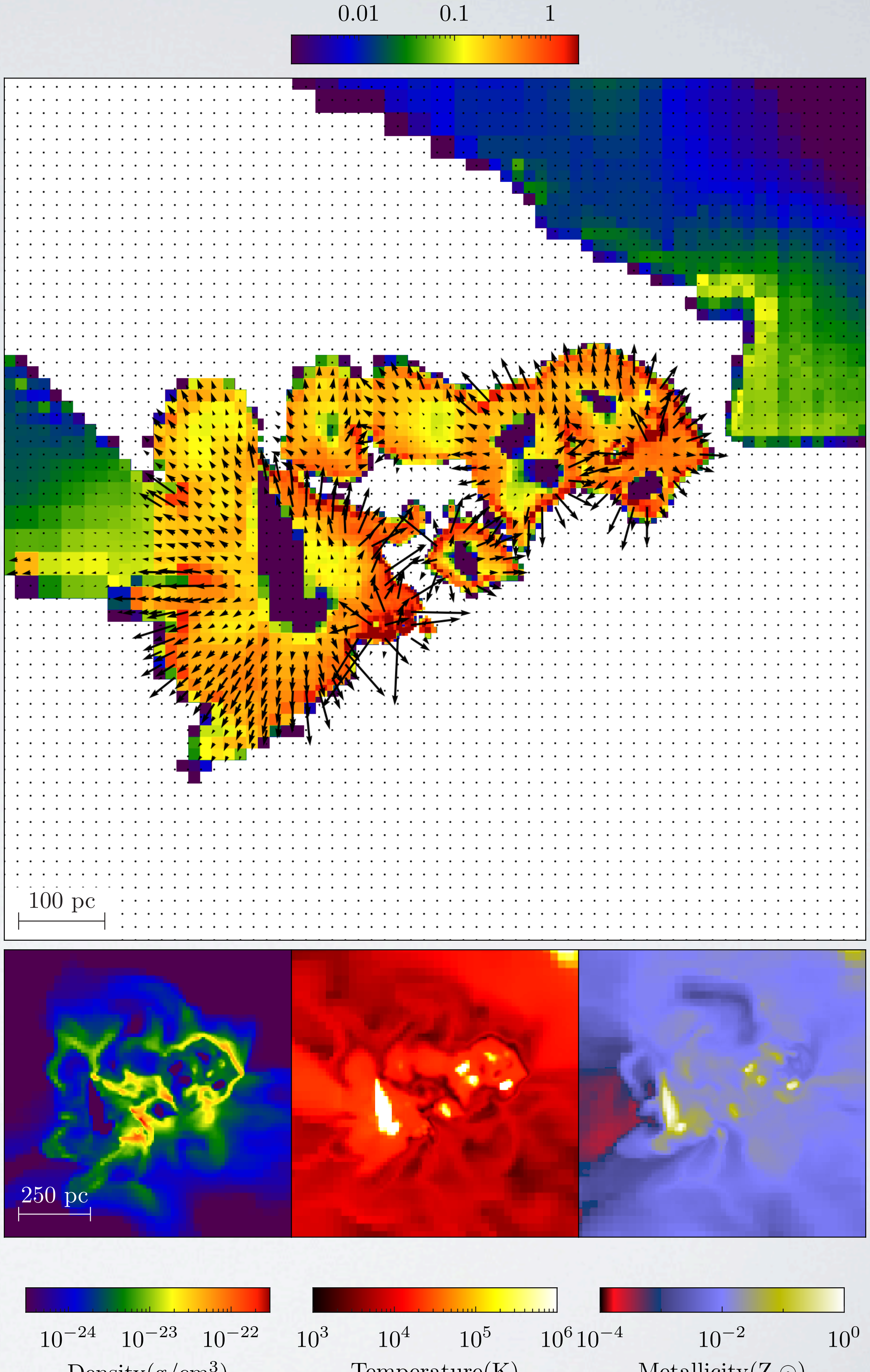


Feedback from radiation pressure more effectively disperses metal-rich ejecta and produces a galaxy on the mass-metallicity relation

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

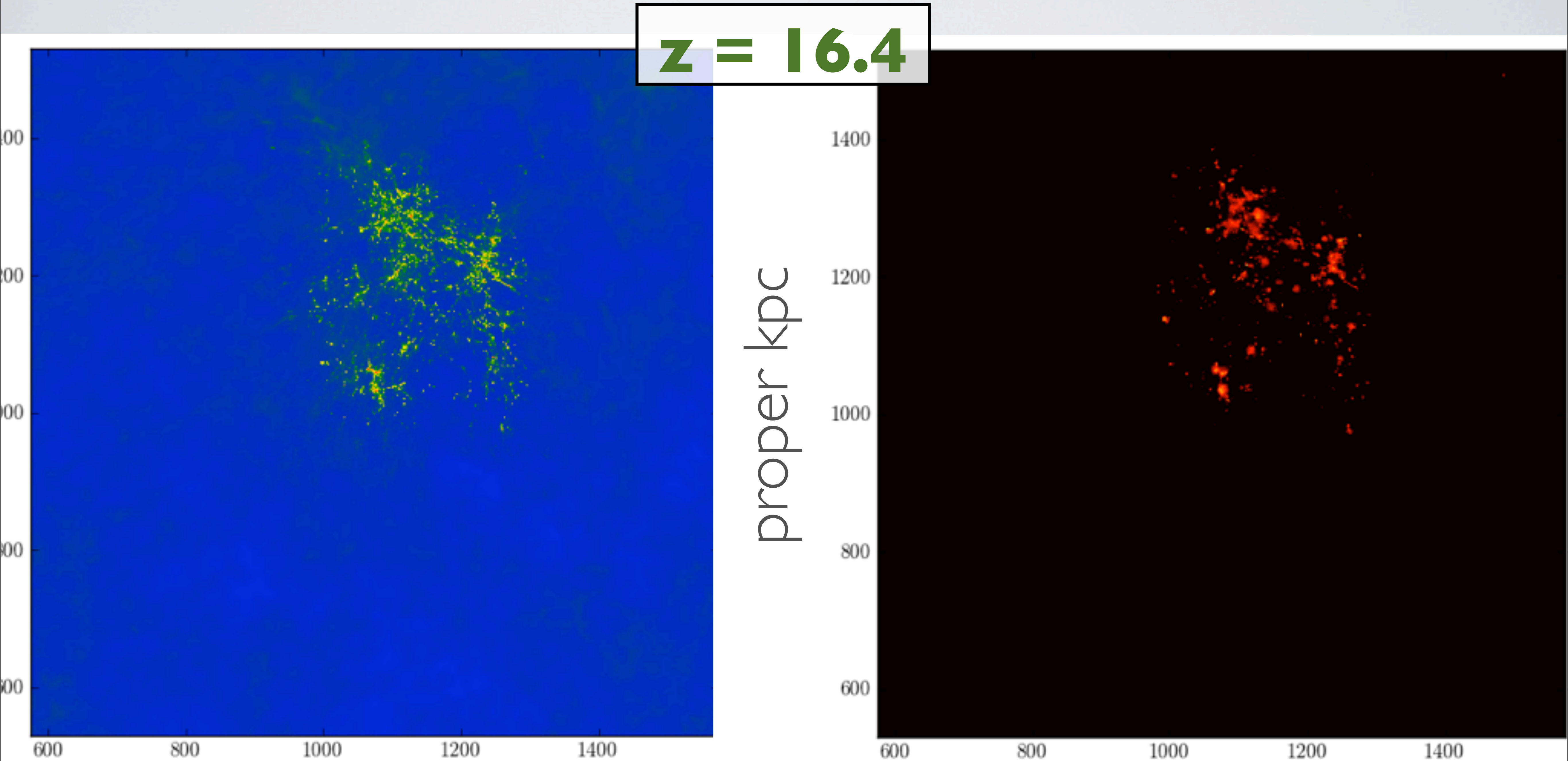


Slice of acceleration due to momentum transfer from ionizing photons only, i.e. not including dust opacity



FUTURE WORK

- Same physics (M_{char} = 40 $M_\odot$)
- 40 cMpc box
- Zoom-in region of 5 cMpc
- 10^4 M_{sun} DM particles



Projected Density
(scale: 3×10^{-28} – 3×10^{-24} g/cm^3)

Projected Temperature
(scale: 10^3 – 3×10^4 K)

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 and SNe) may play an important role in high-z dwarf galaxy formation.

- Even the smallest galaxies are complex with star formation and feedback.

IONIZATION HISTORY