"Early Galaxies, Stars, Metals, and the Epoch of Reionization"

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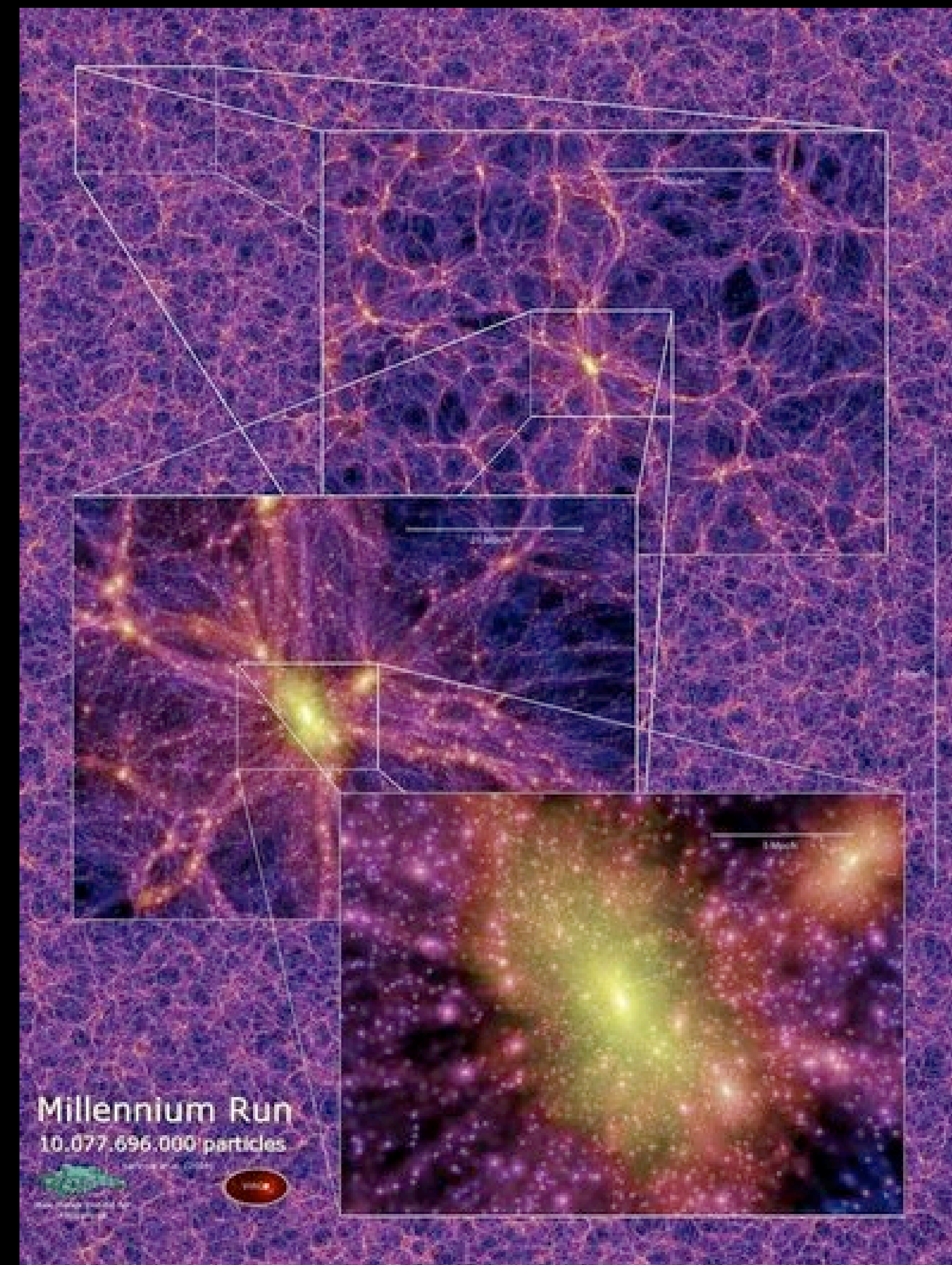
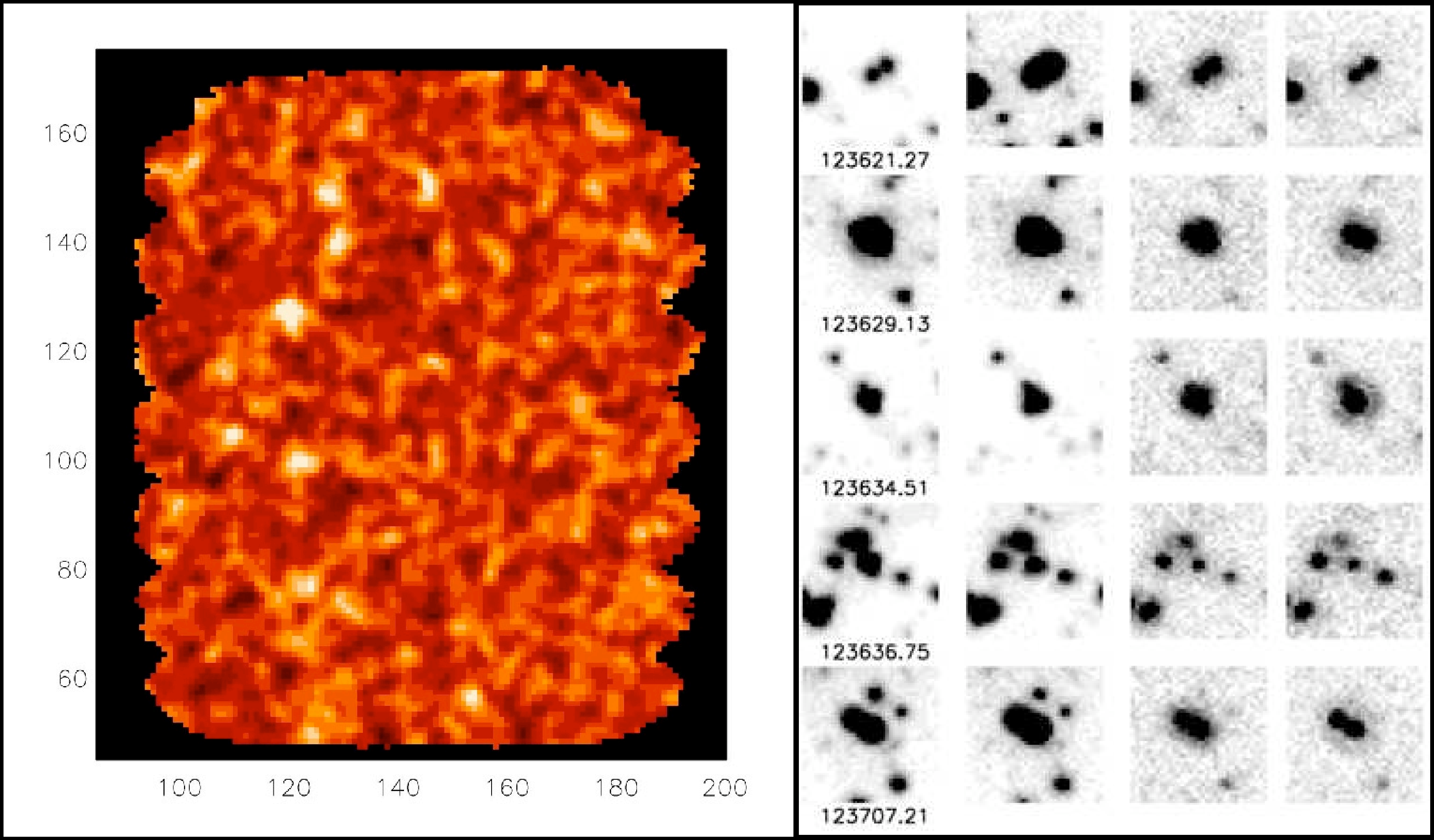
Far-IR Workshop
(Pasadena, CA)   May 29, 2008



Submillimeter Galaxies: only the brightest?

How long? [dust forming? de-shrouding]



Some "Big Picture" Questions

(1) When and how did the first galaxies form?

Was the IMF different? (M_{max}, M_{min}, slope)

Where did the first metals & dust come from?

Which galaxies reionized the IGM?

Star-formation, ionization efficiency?

Primordial coolants? (H_2, metals, dust)

(2) How did later stars/galaxies assemble?

Mergers, cold accretion, rise of metallicity

Black Hole Co-Evolution and "deshrouding"

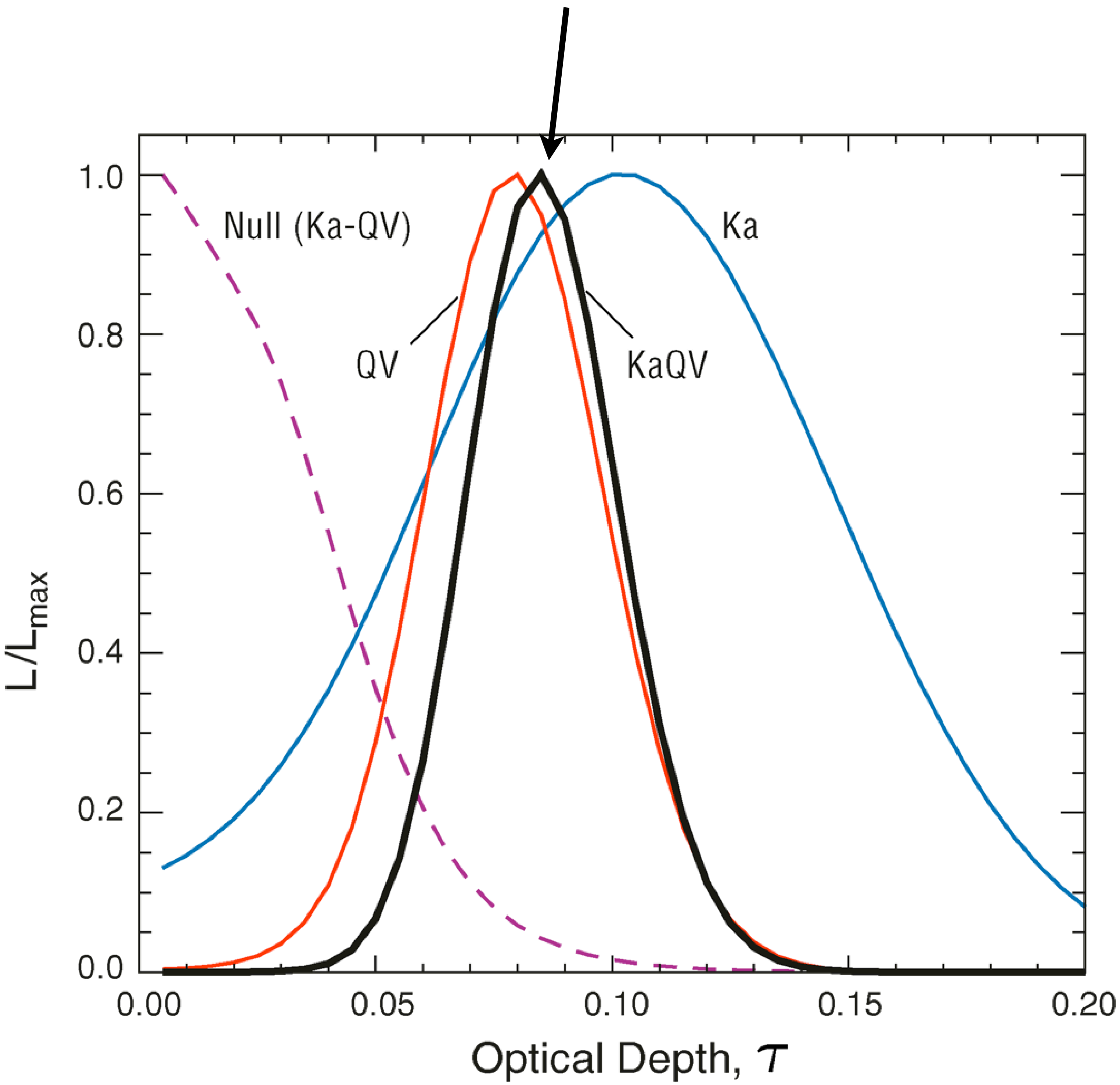
Duration of rapid-accretion, dusty phase?

CMB Optical Depth

(5-year data: Hinshaw etal 2008)

$\tau_e = 0.084 \pm 0.016$

$z_{rei} \approx 10.8 \pm 1.4$



This optical depth can be produced by a fully ionized IGM (at $z \leq z_r \approx 7$)

$\Rightarrow$ $\tau_e = 0.05$

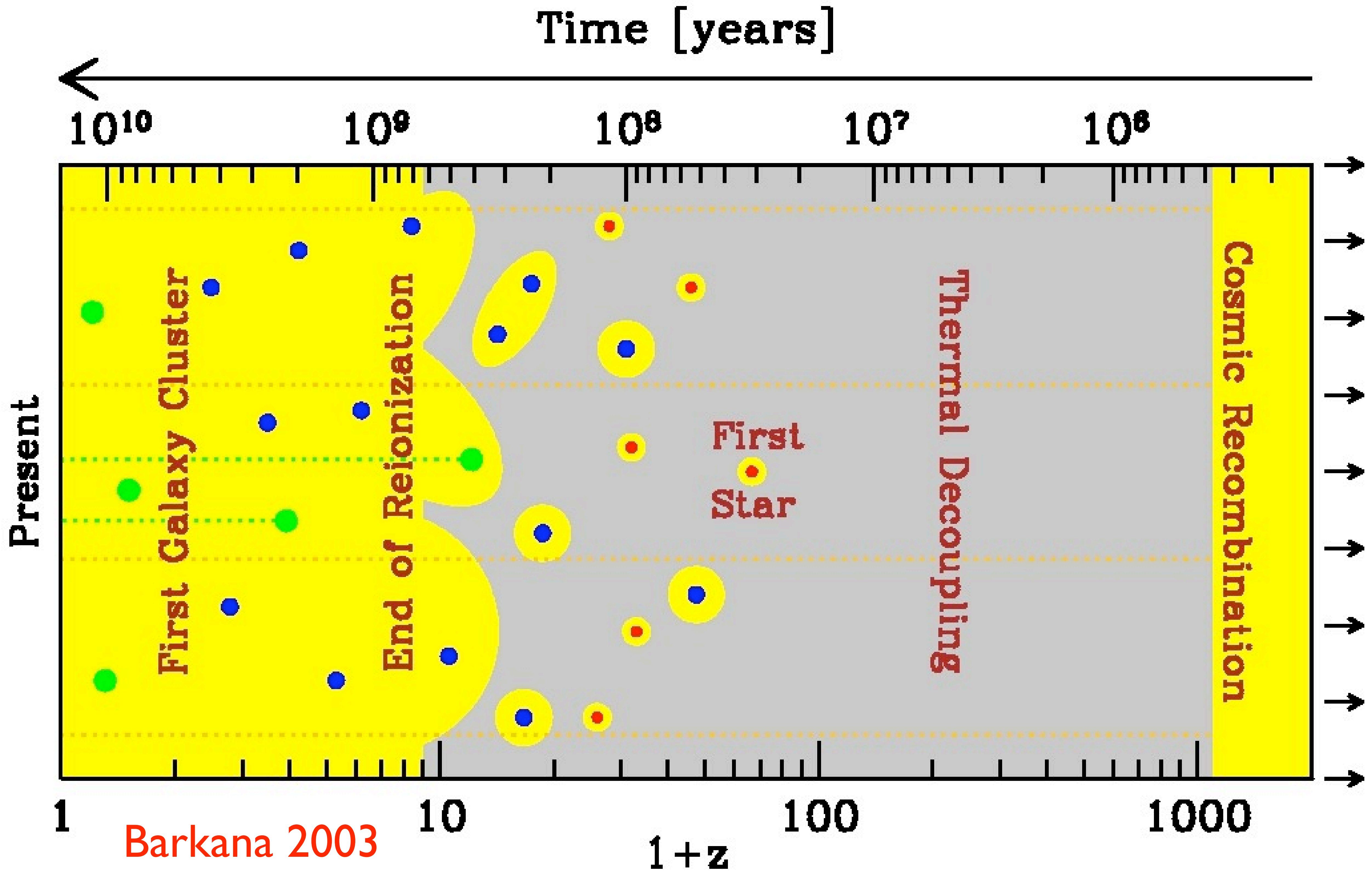
Plus additional optical depth

$\Delta\tau_e \approx 0.03$ at $z > 7$

CMB Opt Depth: $\tau_e \approx (0.05)[(1+z_r)/8]^{3/2}$

Shull & Venkatesan 2008

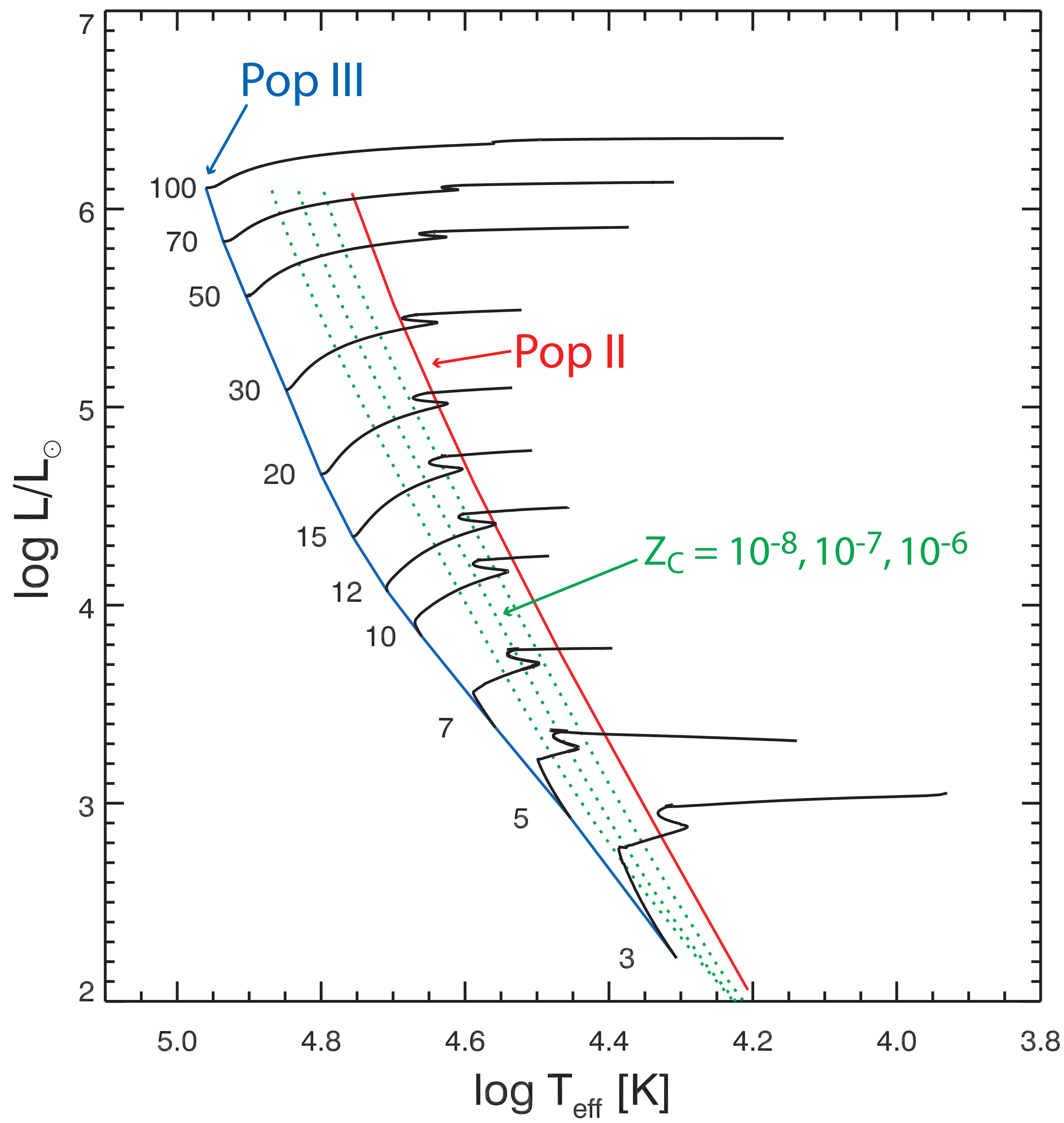
ioniz by stars/AGN ($z \leq 7$)



Barkana 2003

Evolution of Low-Metal Stars

Tumlinson, Shull, & Venkatesan (2003, ApJ, 584, 608)



Why important?

Increased T_{eff} for Pop III stars at low metallicity

10-100 M_{sun} dominate the IGM ionization

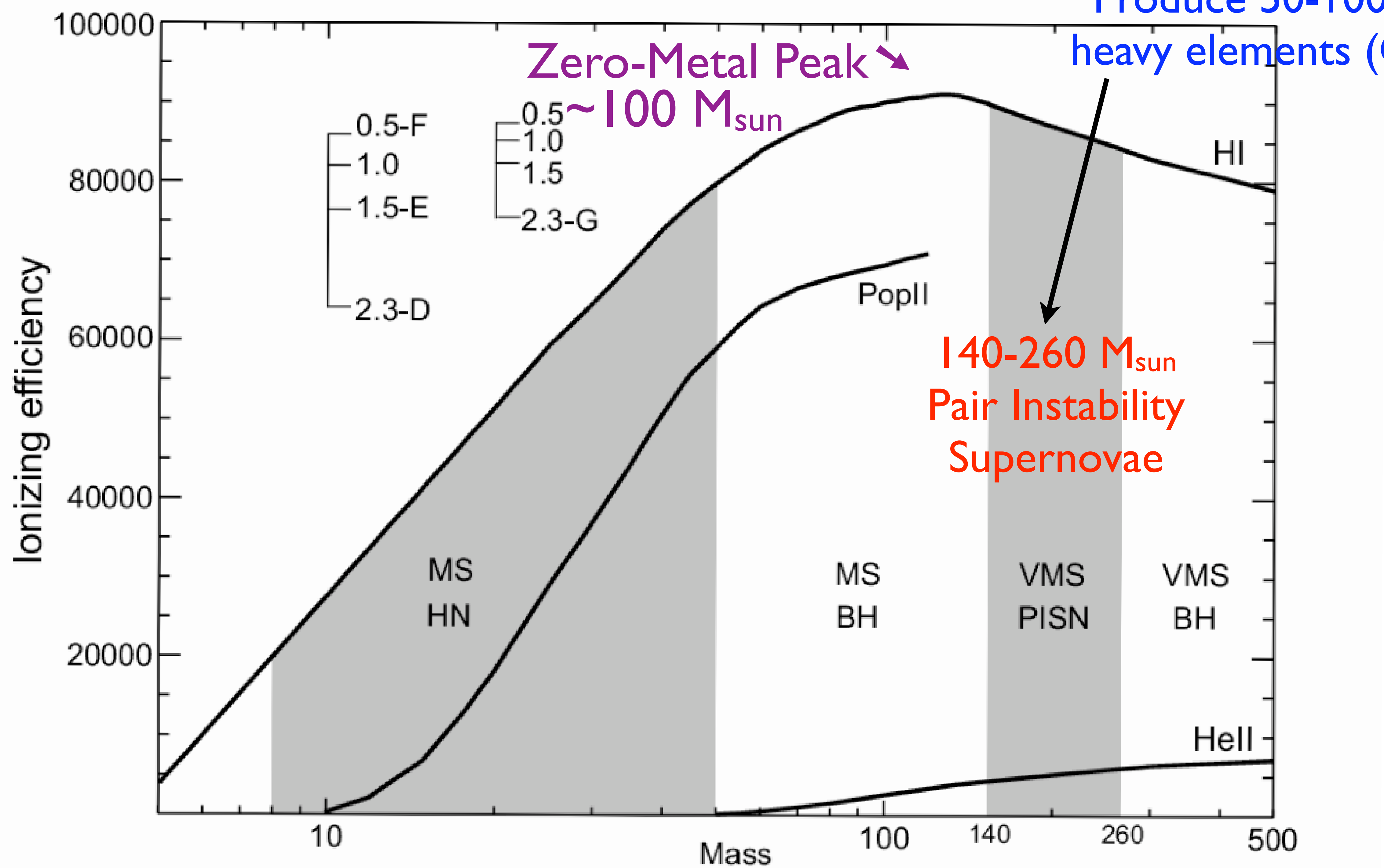
but for how long?

10^7 to 10^8 yrs

When is the transition (Zero-metal to Pop II stars?)

Tumlinson, Venkatesan, & Shull (2004) ApJ, 612, 602

Produce 50-100 M_{sun} of heavy elements (O, Si, Fe)



Cosmology: Halo Mass Distribution and Baryon fraction

$f_b(z)$ = baryon fraction in halos

$f_*(z)$ = fraction of stars formed

"efficiency of ionization"

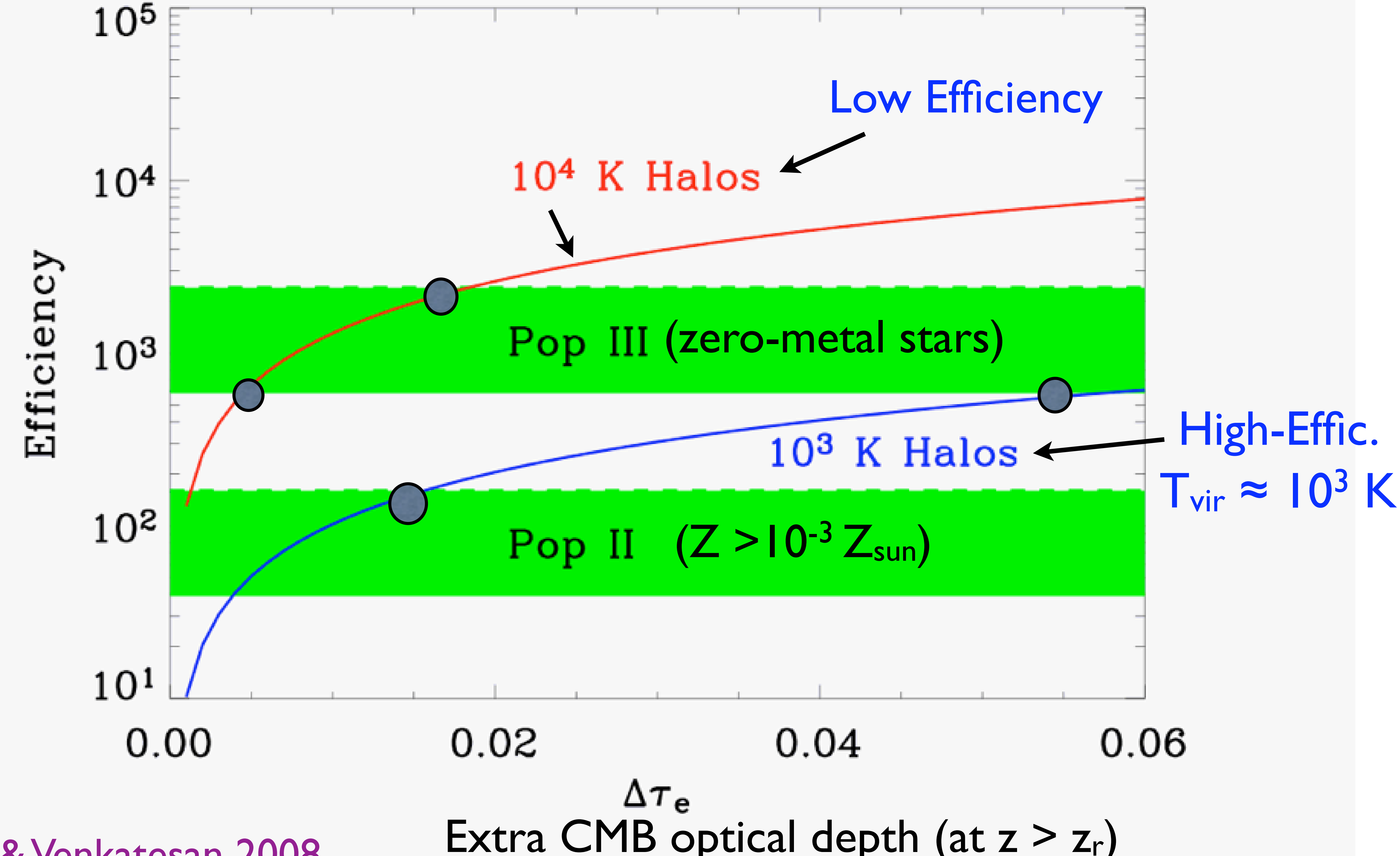
(Ioniz Frac) = $f_b(z)$ $[f_*(z)\ N_\gamma\ f_{esc}(z)]$ / (clumping)

Star formation and stellar astrophysics

Interstellar physics and radiative transfer

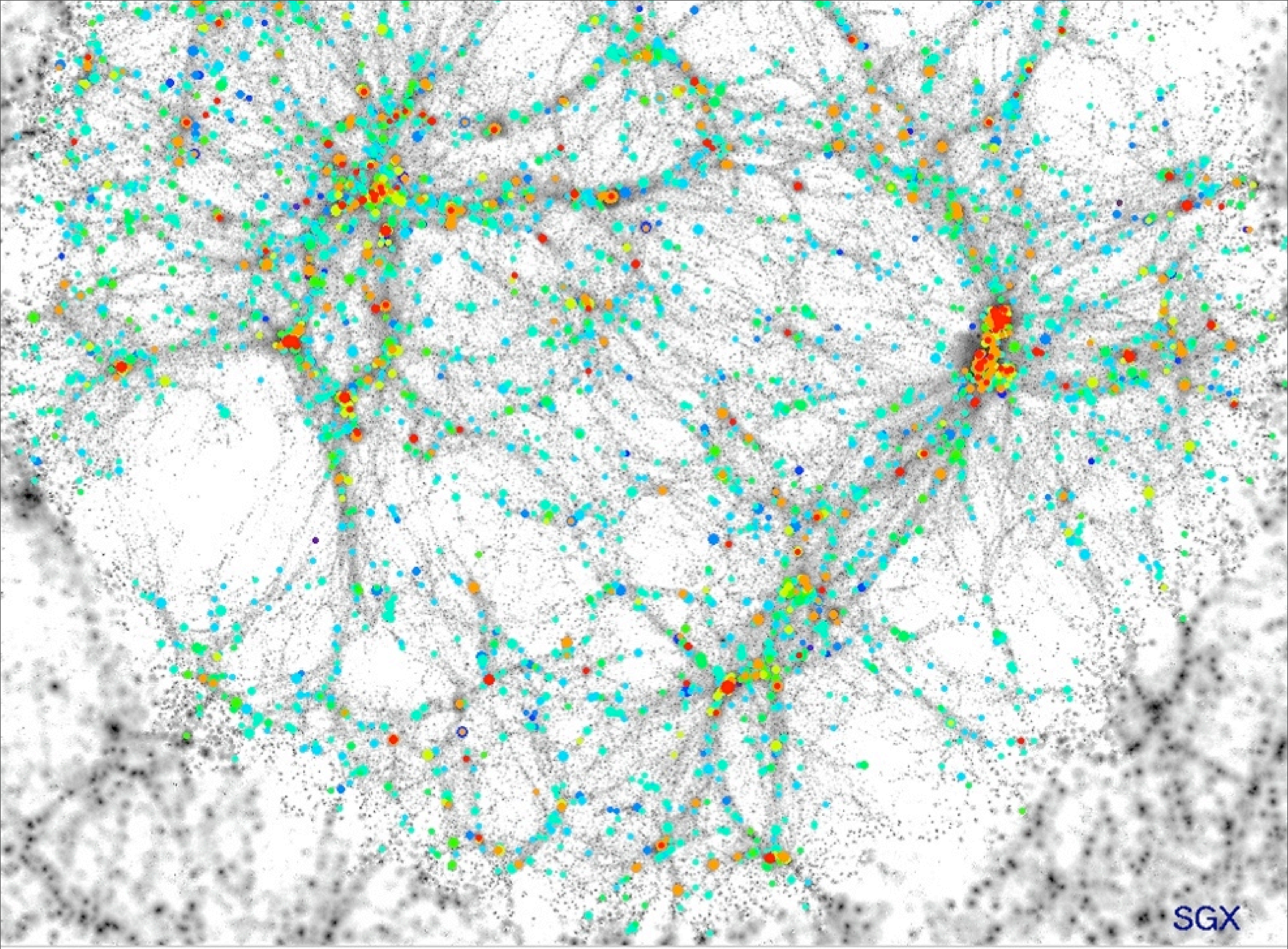
Ionization Efficiency = [$f_* N_\gamma f_{esc}$]

(type of halos and stars needed at $z_r > 7$)

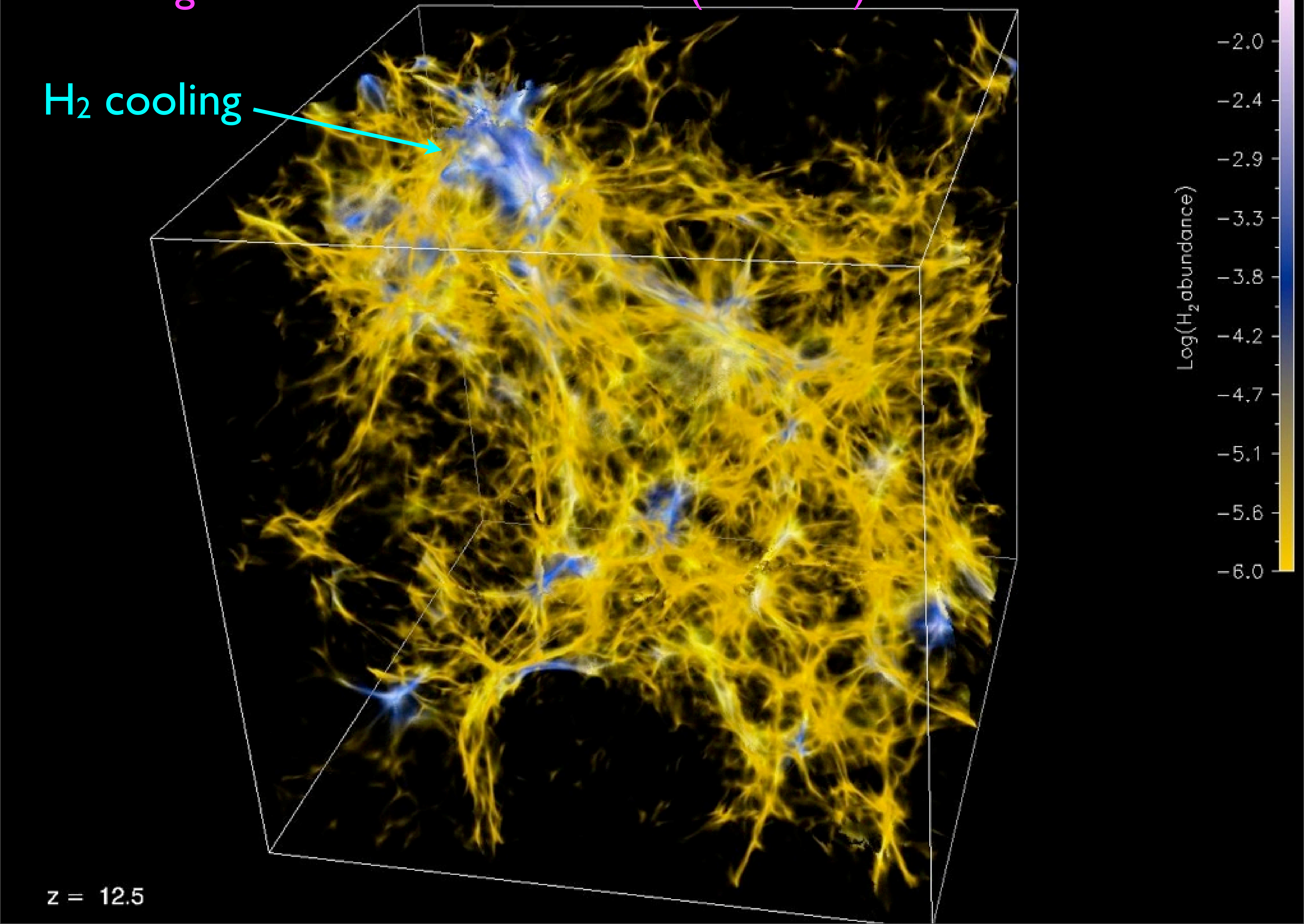


Shull & Venkatesan 2008

Pop III mini-halos, stars transition to Pop II


SGX

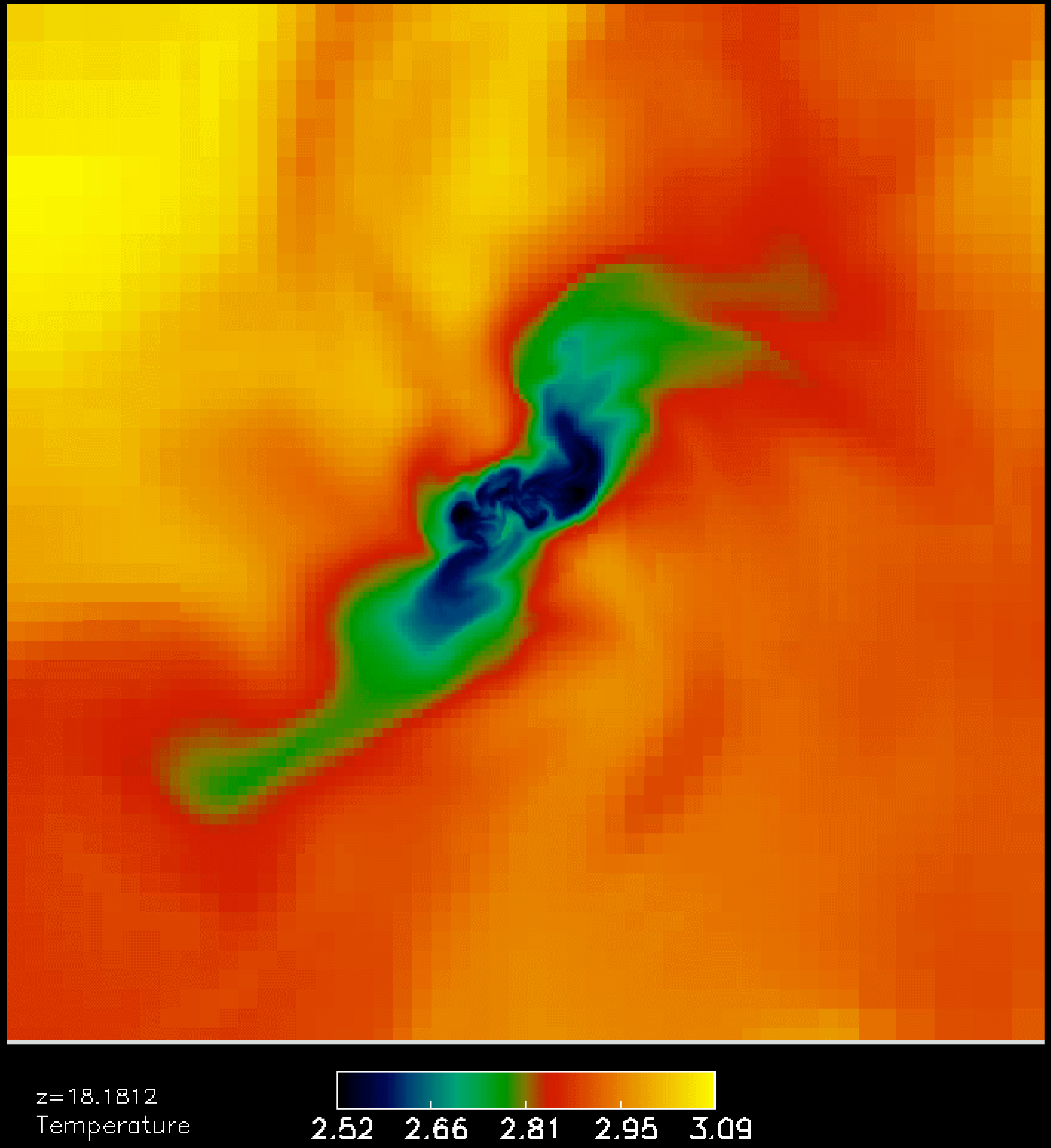
High-Redshift Star Formation (z = 12.5) -- “Cosmic Web”

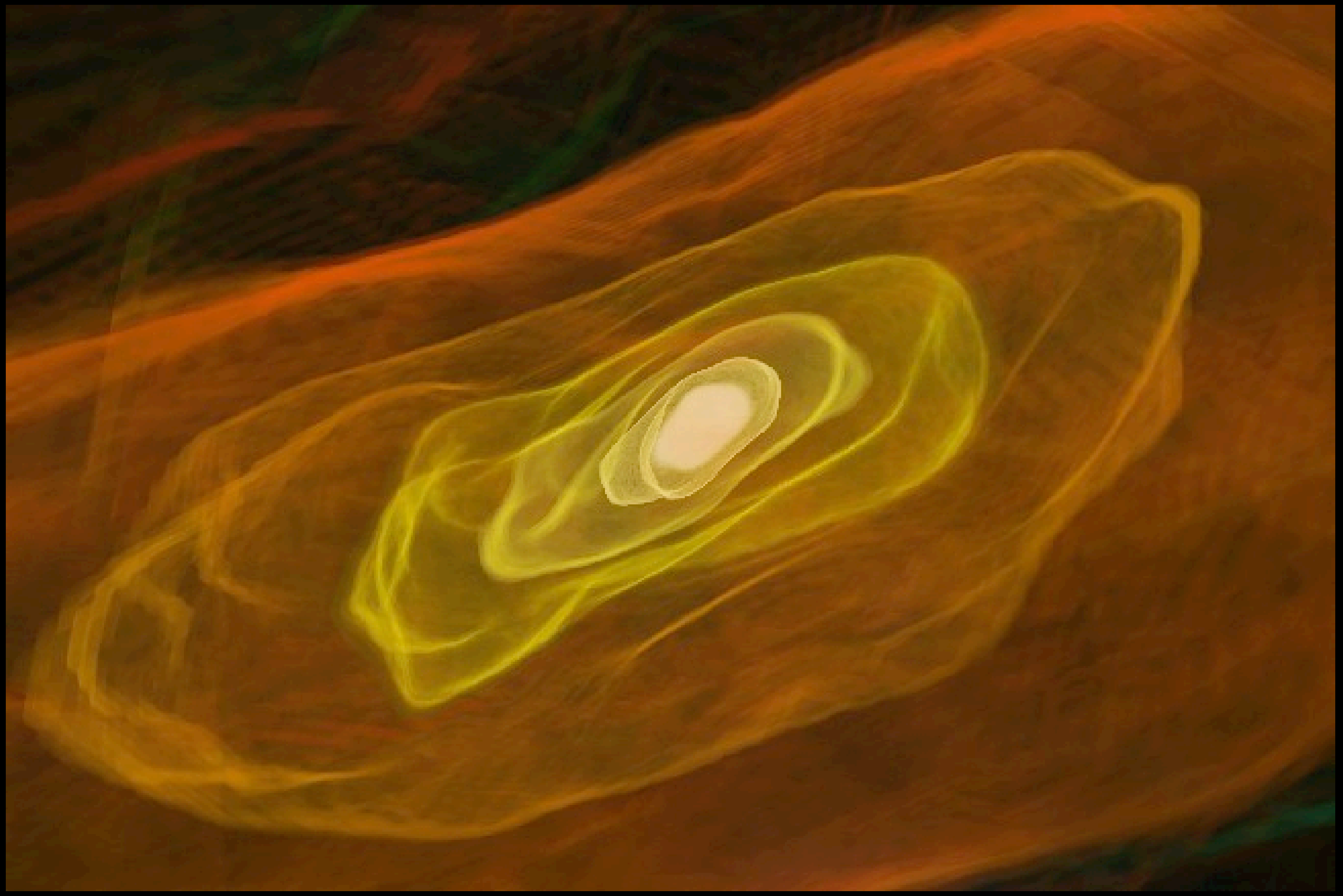


What might the First Stars look like?

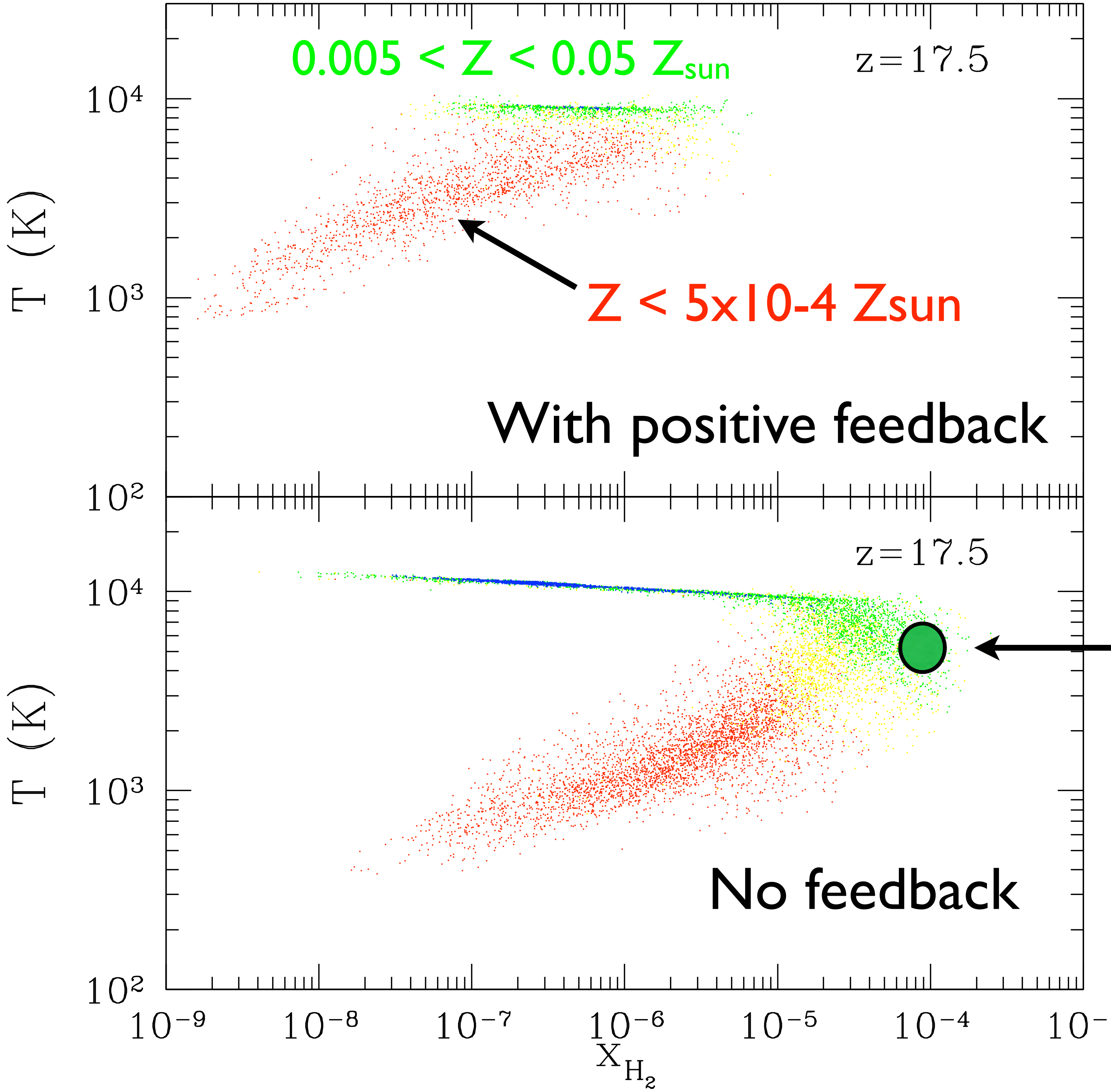
Slow cooling and gravitational collapse of proto-galactic clouds

(Abel 2007)





Ricotti, Gnedin, & Shull 2008 (ApJ, arxiv:0802.2715)

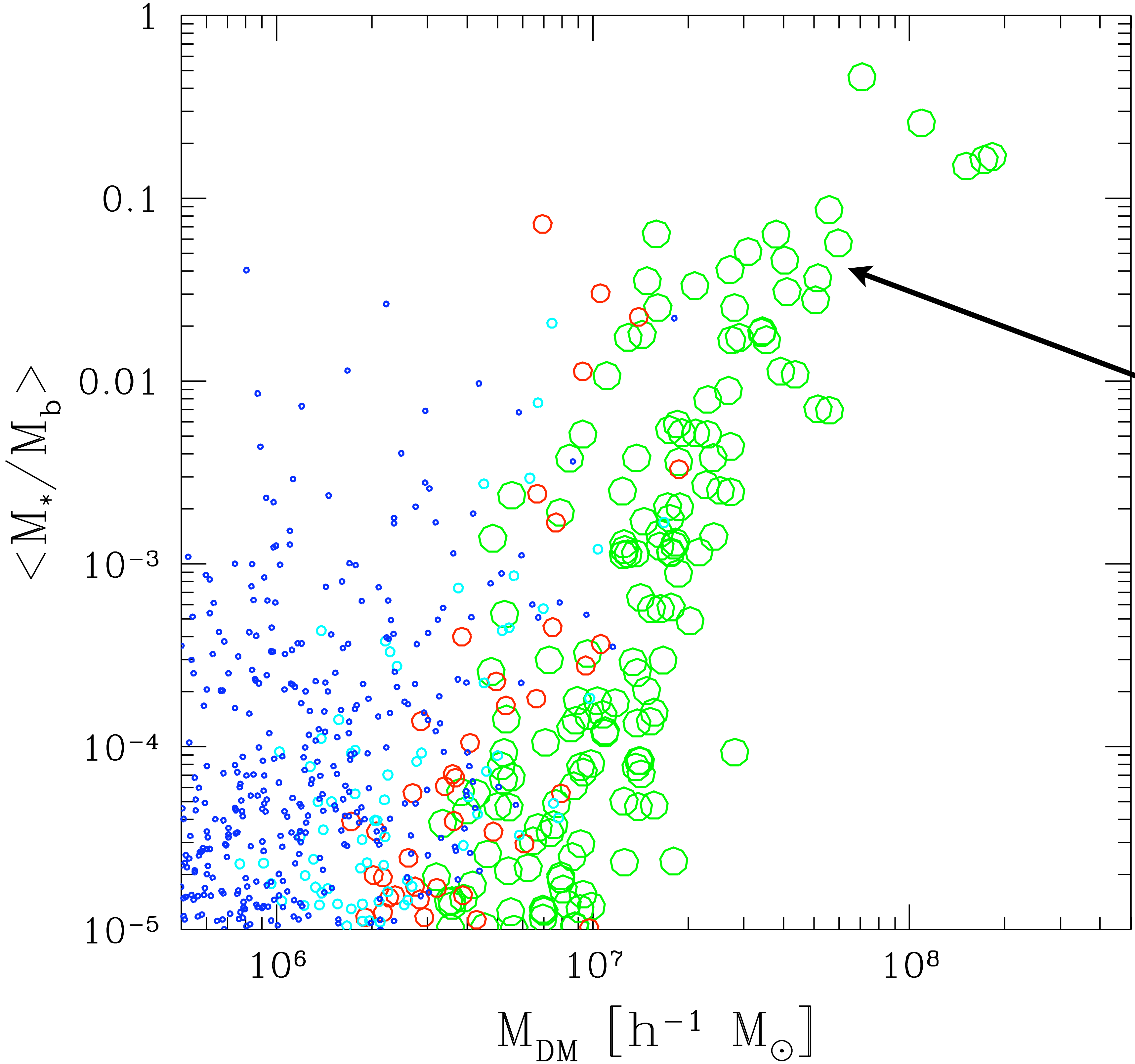


Molecular Hydrogen in the Dark Ages

$x_{H2} \approx 10^{-4}$

$T \approx 5000$ K

Early Star Formation (Mini-halos)

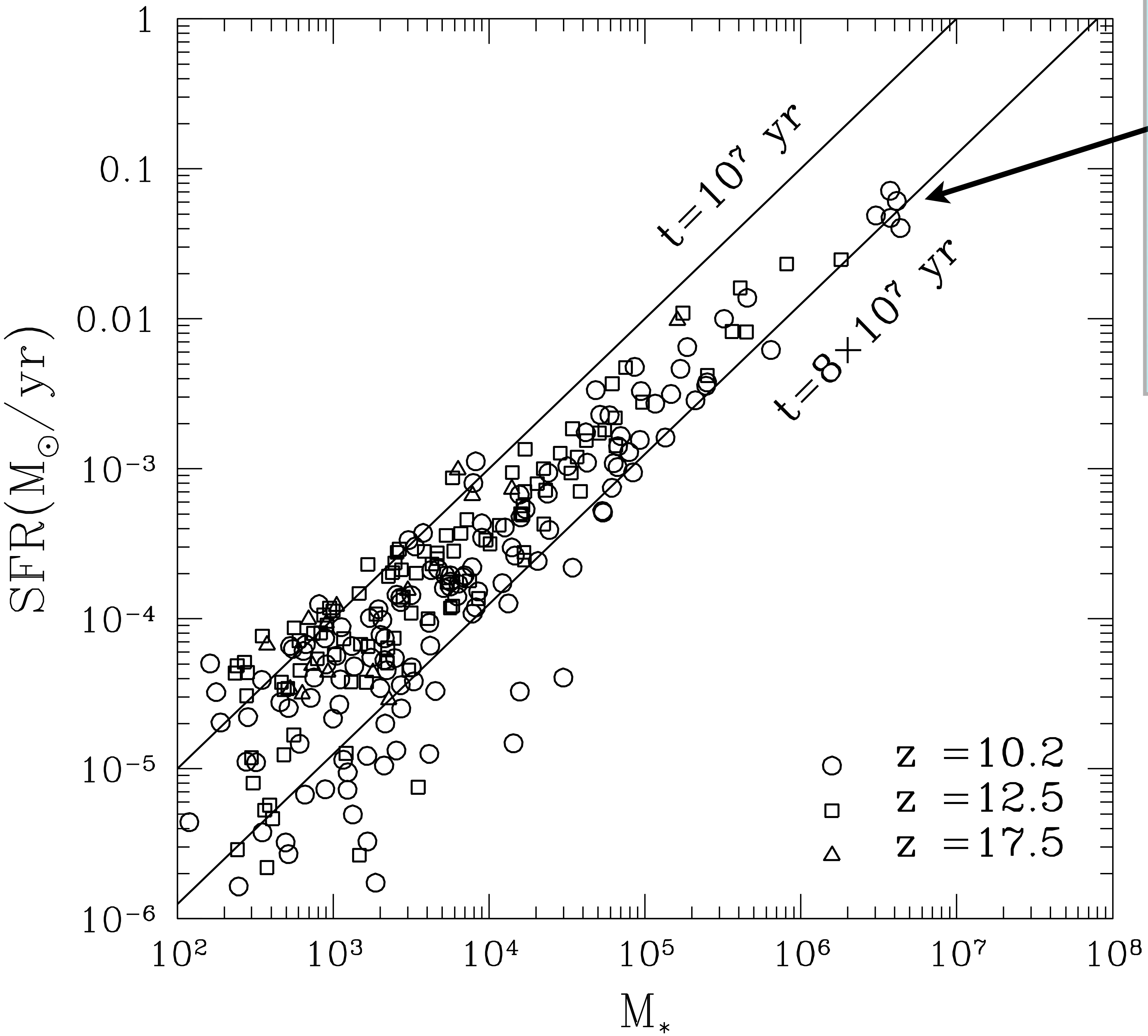


DM Halos:

$f_* = 0.05$

$5\times10^7\ M_{sun}$

Star-Formation Rates



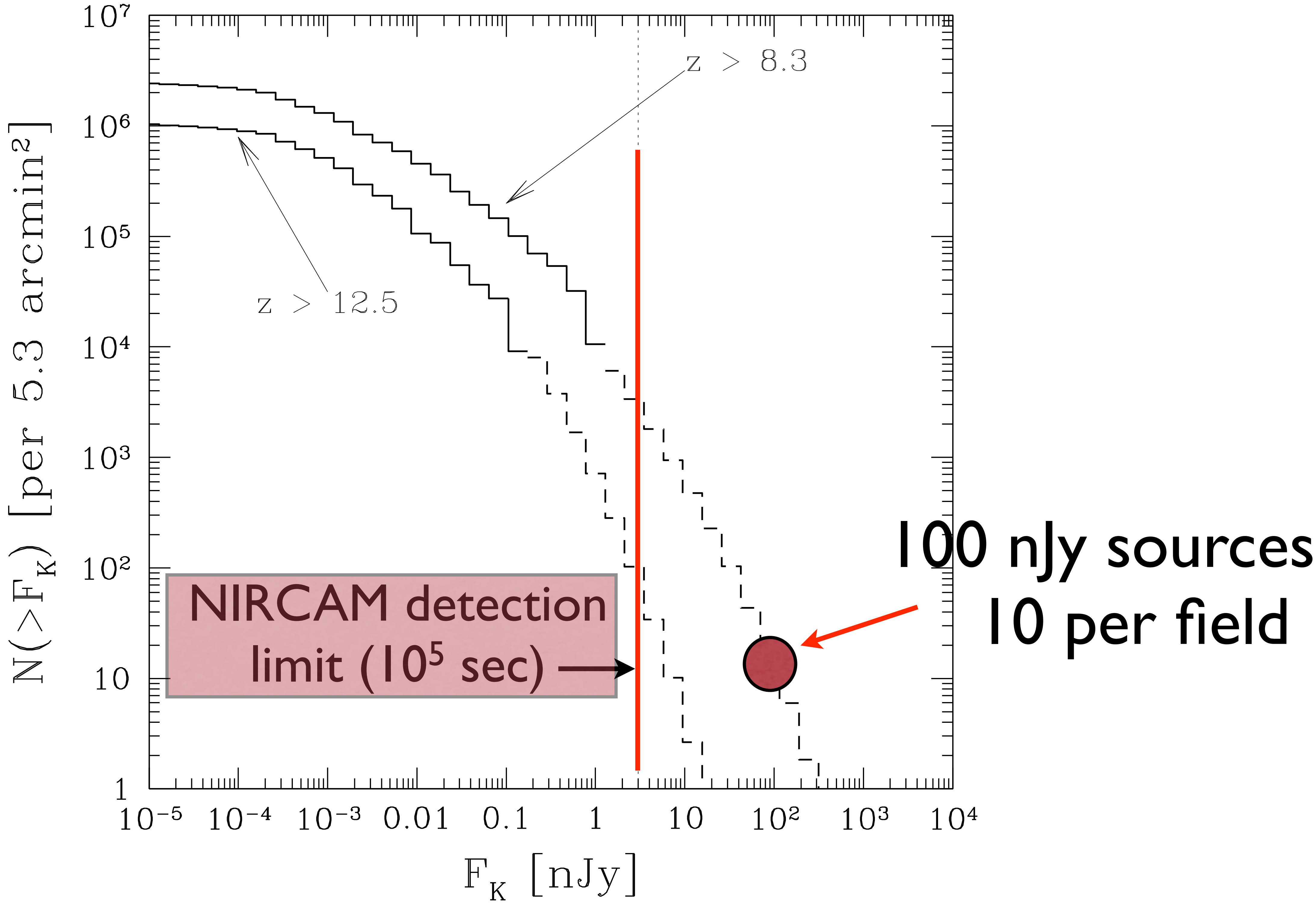
SFR ≈ 0.05 M_{sun}/yr

M_* ≈ 5x10^6 M_{sun}

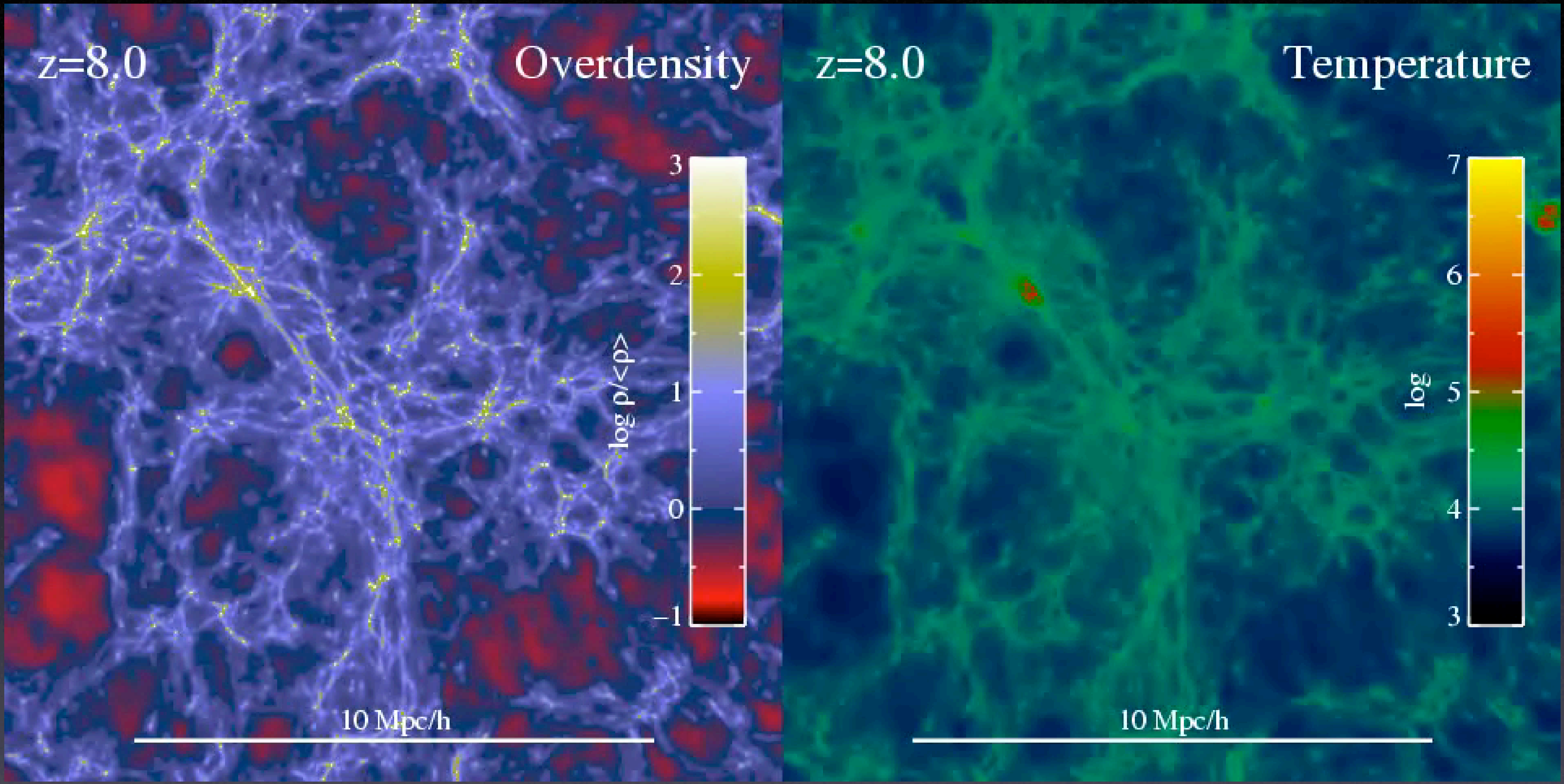
M_{DM} ≈ 10^8 M_{sun}

Predictions for JWST (K-band)

[dwarf primordial galaxies at z > 8]



Structure Formation & Metal Transport



Oppenheimer, Davé, & Finlator (Princeton Univ.)

Growth rate of IGM metallicity (for SFR density over 1 Gyr)

$$\frac{Z}{Z_\odot} = \frac{\rho(\mathrm{SFR}) y_m t}{\Omega_b h^2 \rho_{\mathrm{cr}} (0.02)}$$

$$= \frac{(0.1\ M_\odot\ \mathrm{yr}^{-1} \mathrm{Mpc}^{-3})(0.024)(10^9\ \mathrm{yr}) t_9}{(0.0224)(1.879 \times 10^{-29}\ \mathrm{g\ cm}^{-3})(0.02)}$$

$$= (0.019) \left[\frac{\rho(\mathrm{SFR})}{0.1\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}} \right] t_9 .$$

Z→1% solar in ~Gyr

Assumed metal yield y_m = 0.024 (per M_{sun})

SFR density scaled to peak value (z = 2-6)

SFR ≈ 0.1 M_{sun} yr^{-1} Mpc^{-3}

The first stars, galaxies, and quasars enrich the surrounding gas

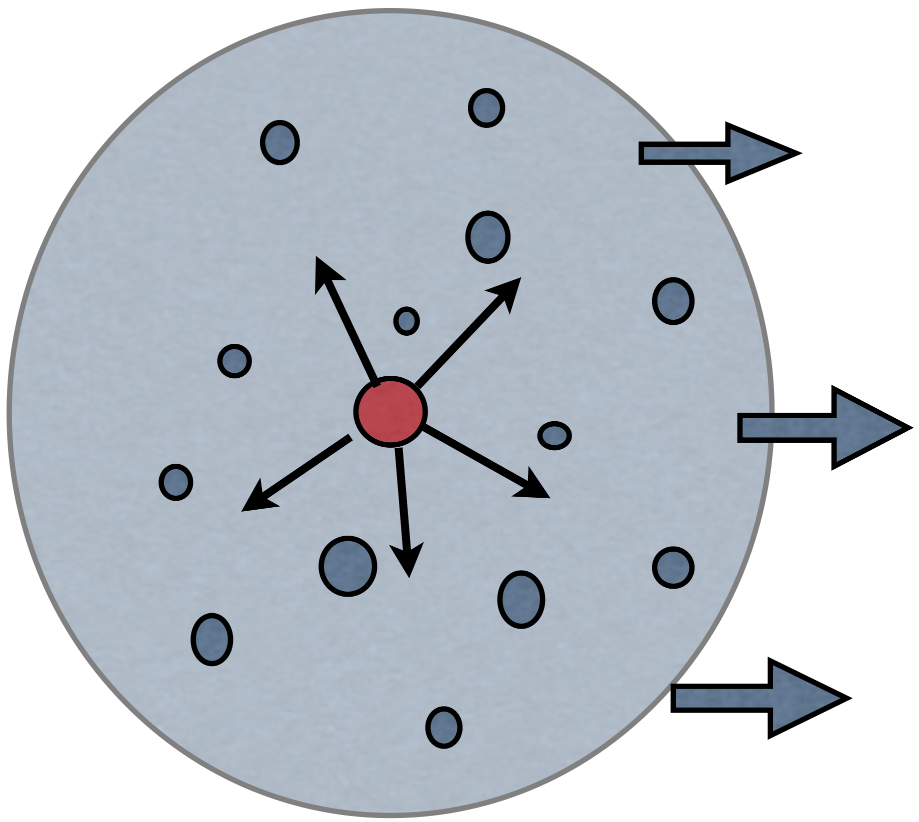
High-mass stars make O, Si, Fe (and some C)
They are prodigious LyC emitters (reionization)

What happens next?

- When does gas cooling exceed adiabatic heating?
- At what Z_{crit} does F-S cooling exceed H_2 cooling?
- Transition from (zero-metal) to Pop II stars?
- Dependence on stellar mass range (O, Si, Fe) ?
- Time-dependent cooling, coupling to CMB ?

Duration of Metal-Free Phase?
(Self-polluting 10^6 M_{sun} halos at $z = 10\text{-}20$)

$t \approx 10^7$ to 10^8 yr



- $R_{vir} = (160 \text{ pc}) \; M_6^{1/3} \; [20/(1+z)]$
- $T_{vir} = (1060 \text{ K}) \; M_6^{2/3} \; [(1+z)/20]$
- $n_{vir,H} = (0.27 \text{ cm}^{-3}) \; [(1+z)/20]^3$

The rest of metals blow out into the IGM

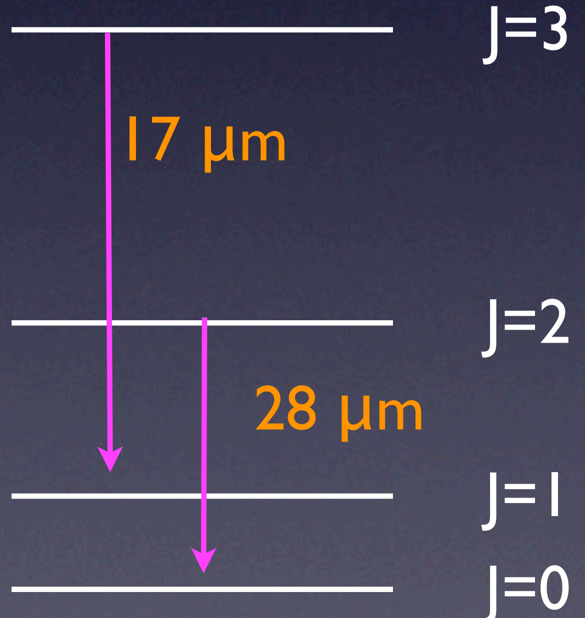
Molecular Cooling (H_2 rotational lines)

Strongest transitions are from ortho-H_2 (J = 3-1) and from para (J = 2-0) rotational states, excited in neutral clouds primarily by H^o - H_2 collisions

Strongest transitions have critical densities
$n_{cr} \approx 10^3$ to 10^4 cm^{-3}

- J = 2 → 0 (28.22 microns) T_{exc} = 510 K
- J = 3 → 1 (17.03 microns) T_{exc} = 1015 K

Santoro & Shull (2006, 2008)



Abundant Heavy Elements

(with ground-state fine structure lines*)

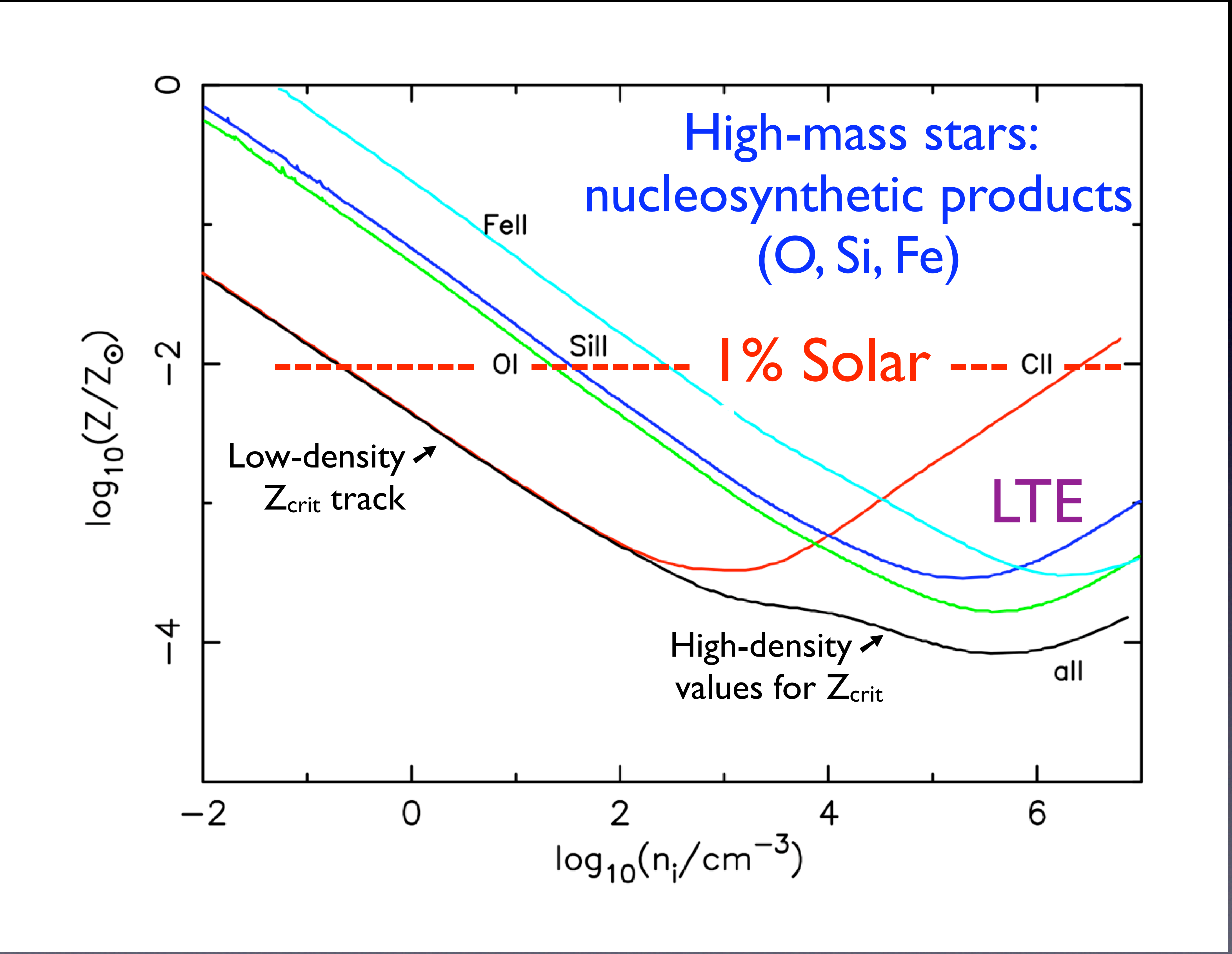
No fine structure in S II, Mg II, Ca II, Ar I

- C II (2p) $^2P_{1/2,3/2}$ 157.74 microns
- O I ($2p^4$) $^3P_{2,1,0}$ 63.18 & 145.5 microns
- Si II (3p) $^2P_{1/2,3/2}$ 34.8 microns
- Fe II (4s $3d^6$) $^6D_{9/2,7/2}$ 25.99 microns

*Assume ionization state set by FUV photons ($E < 13.6$ eV)

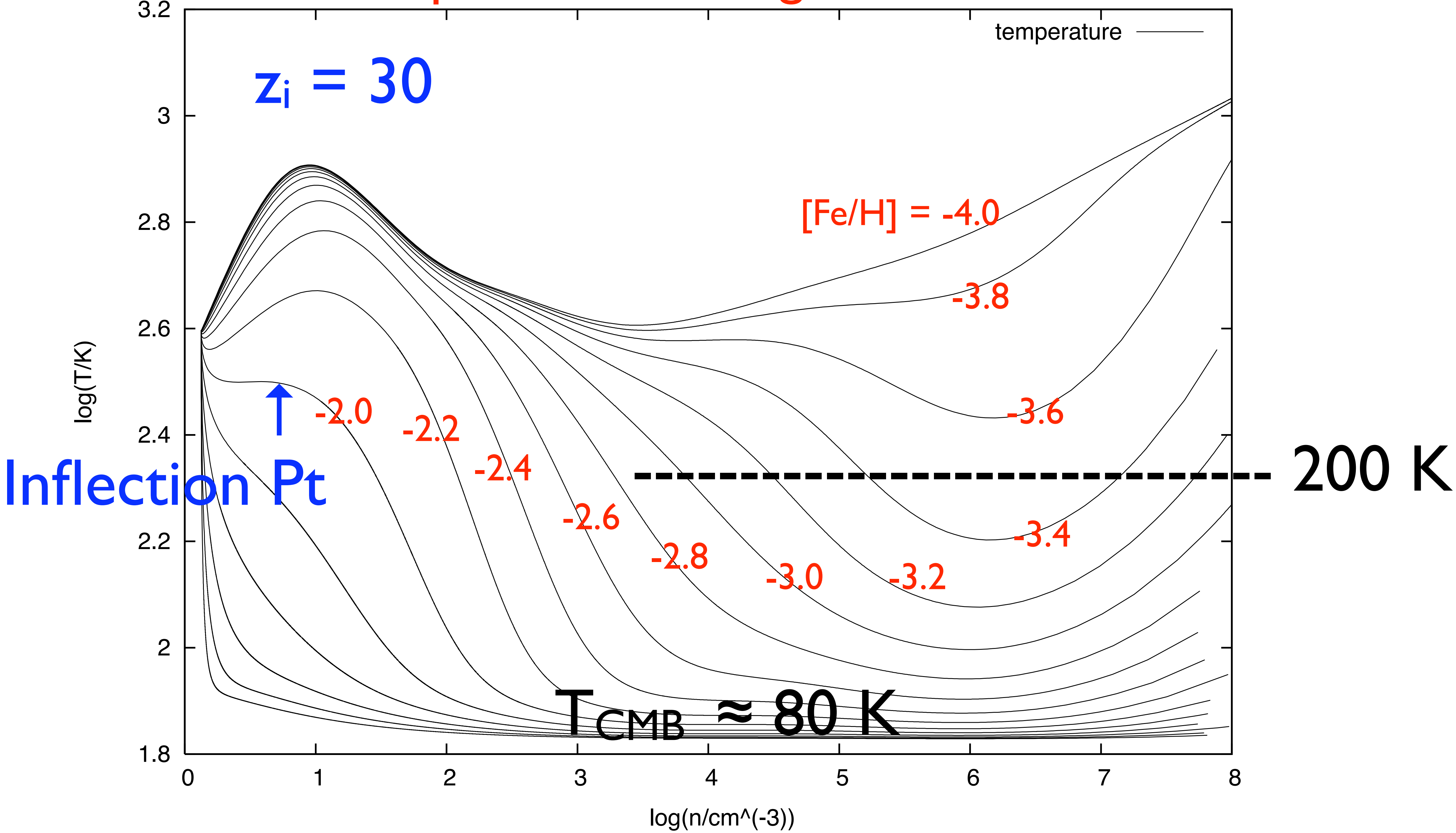
Thus, dominant ions are C II, Si II, Fe II

Locus of Minimum Z_{crit} values



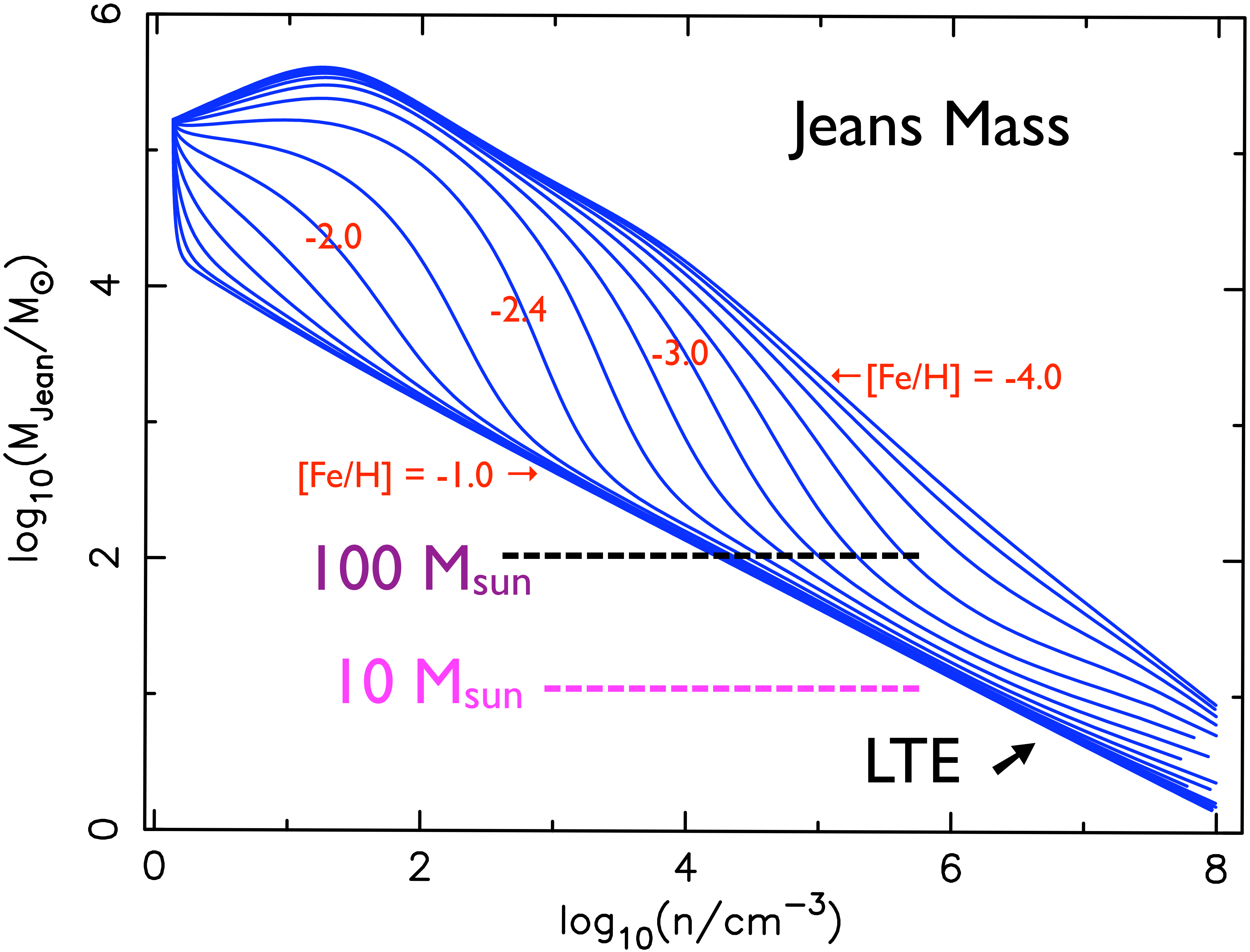
Time-dependent Cooling

Santoro & Shull 2008



Cooling to $n = 10^4$ cm^{-3} requires

$Z_{crit} \approx 10^{-2} Z_{sun}$ at $n = 100$ cm^{-3}



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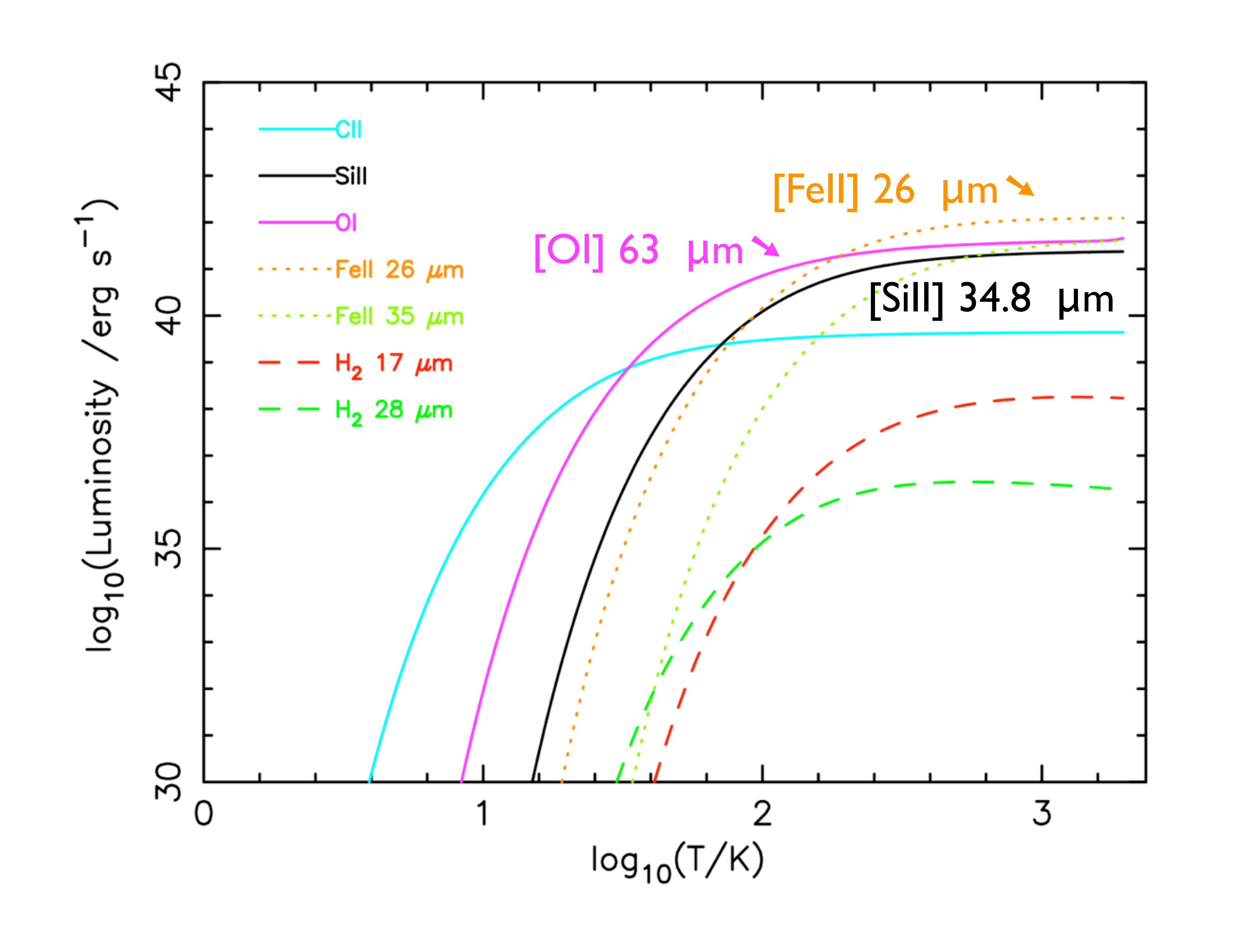
Fine-Structure Line Luminosities (LTE)
(10^8 M_{sun} cooling at 200 K and 0.01 Z_{sun})



Strongest lines:
Fe II 26 μm, O I 63 μm
and Si II 35 μm

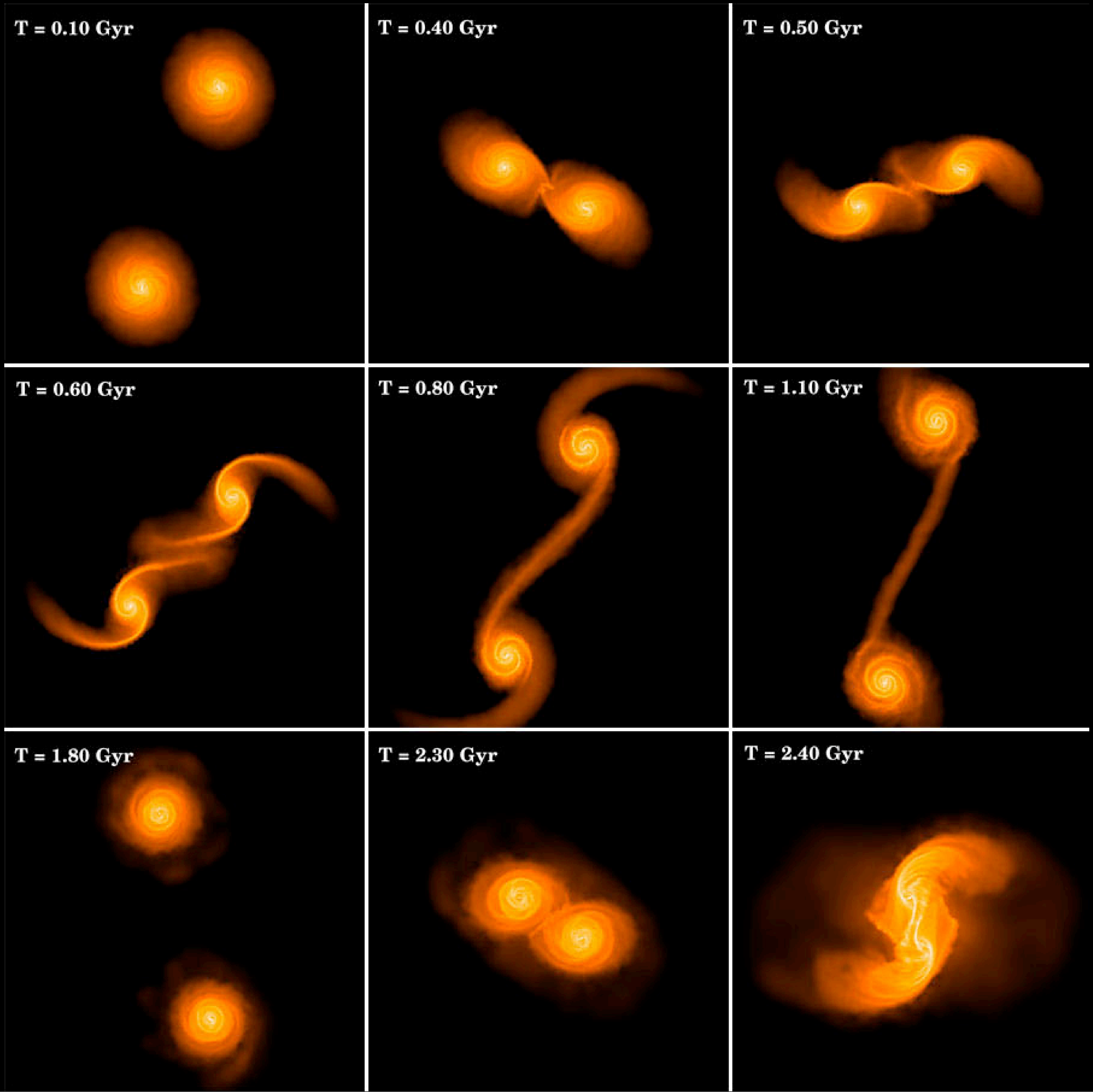
[O I] 63 μm redshifted into the FIR/sub-mm (e.g., 350 μm window)

$L_i = 10^{41-42}$ erg/s

Fluxes (z=4)
10^{-21} to 10^{-20} W m^{-2}

H_2 emission will be much stronger in merging systems

More gas (10^{9-10} M_{sun}) and hotter (shocks)



Astrophysical Summary

- Primordial Dwarf galaxies (10^{6-7} M_{sun}) - 100 nJy sources (K-band)
- Reionization ($z \approx 8$-10) by early massive stars and BHs (X-rays)
- High-z: individual values of Z(C, O, Si, Fe) - enhanced O,Si,Fe)
- Primordial cooling H_2 and FS lines: FIR at 10^{-21} to 10^{-20} W m^{-2}
  (easier to detect H_2 in shocked/merging systems)

These observations will require major (large) telescopes