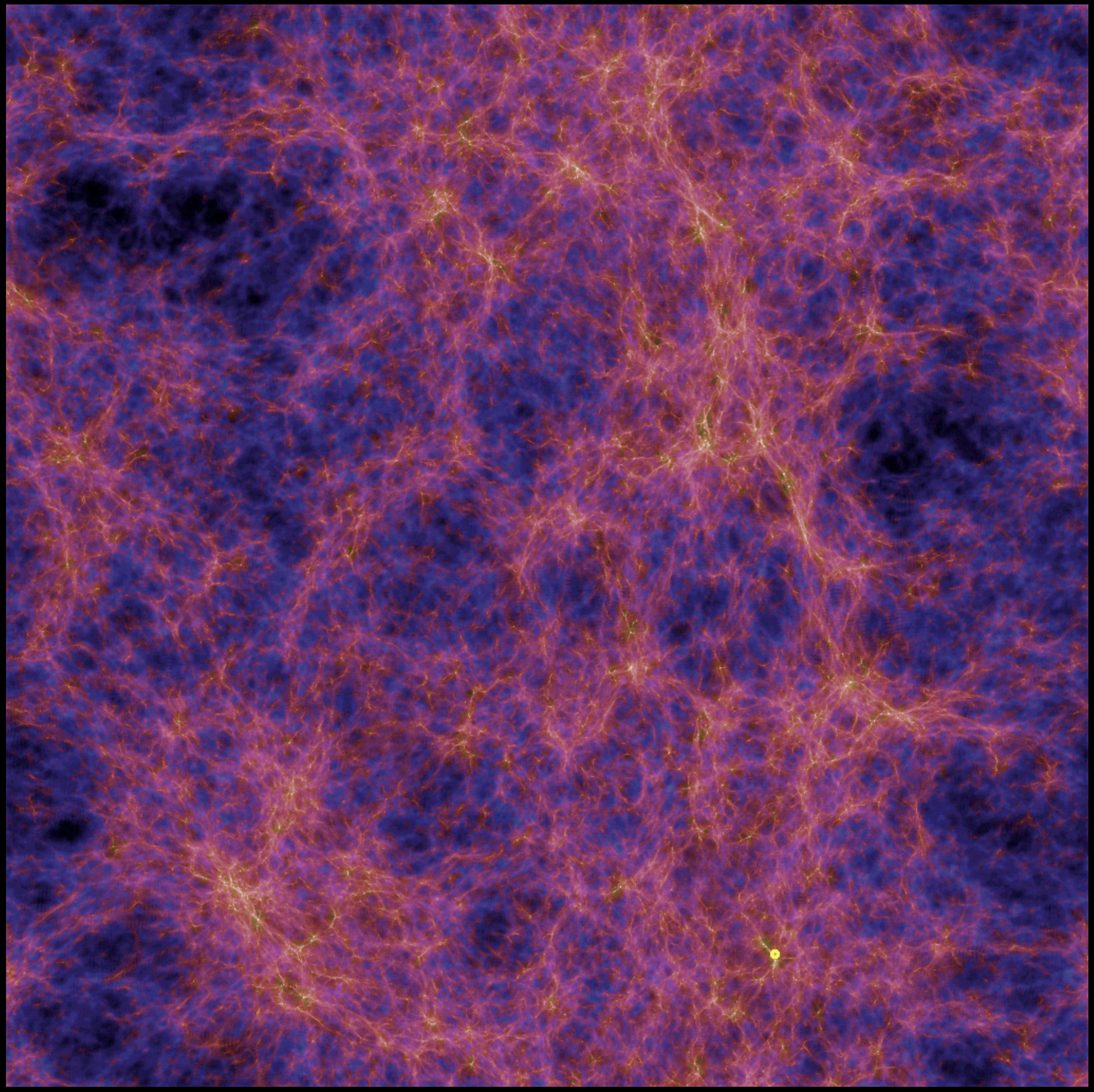
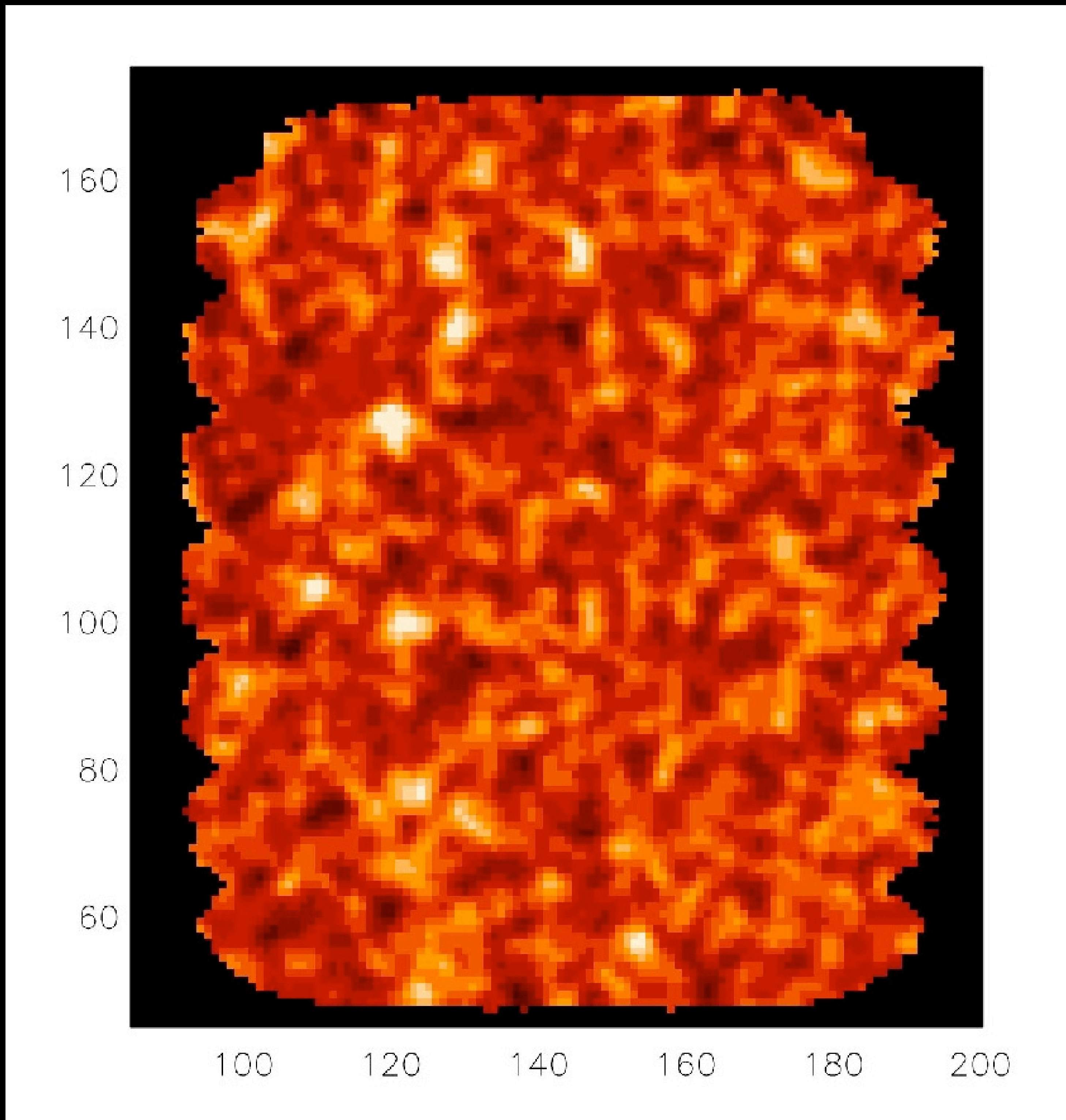
"Critical Metallicity of the Second-Generation Stars"

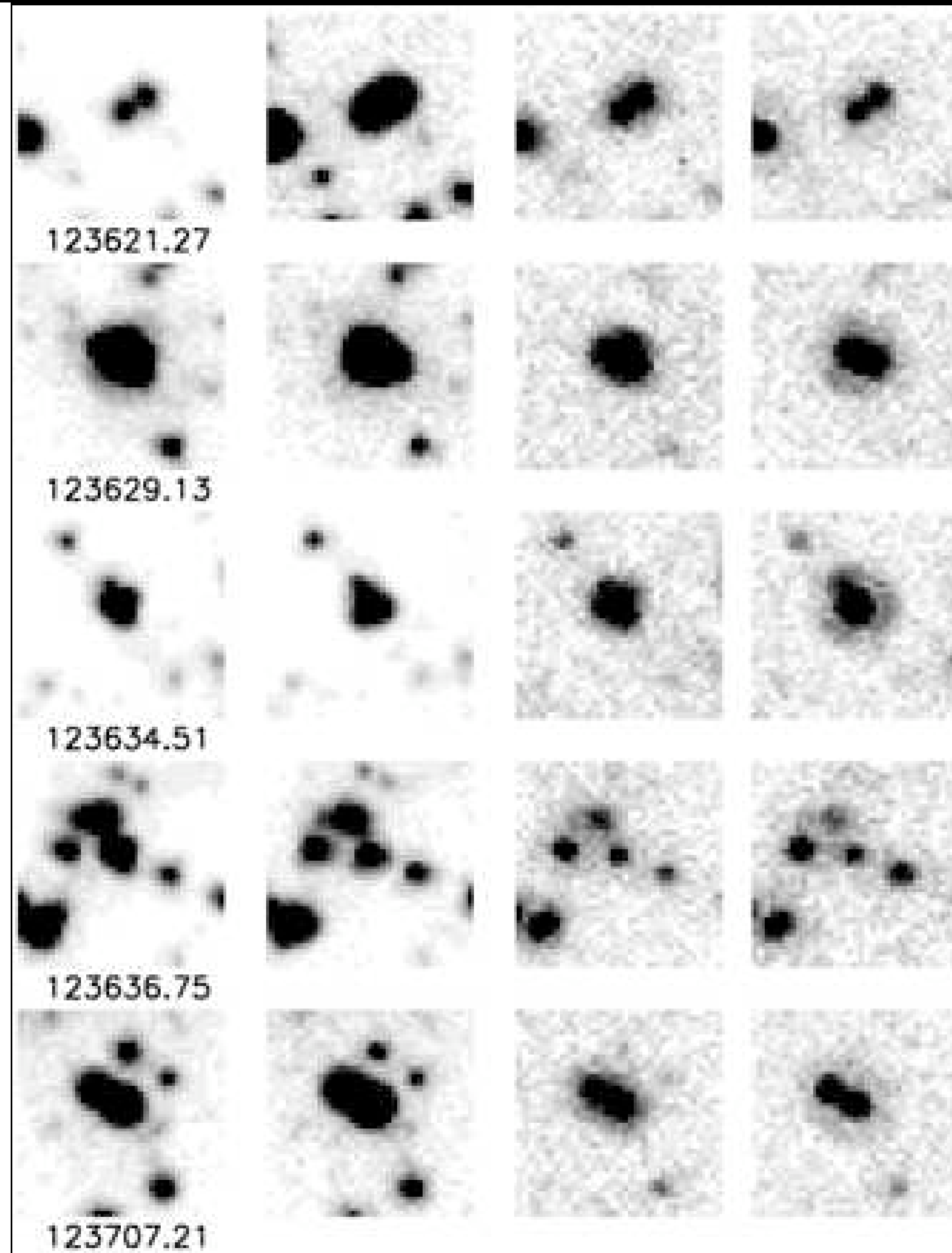
Michael Shull
University of Colorado

CCAT Workshop
(Boulder CO)
May 13, 2008

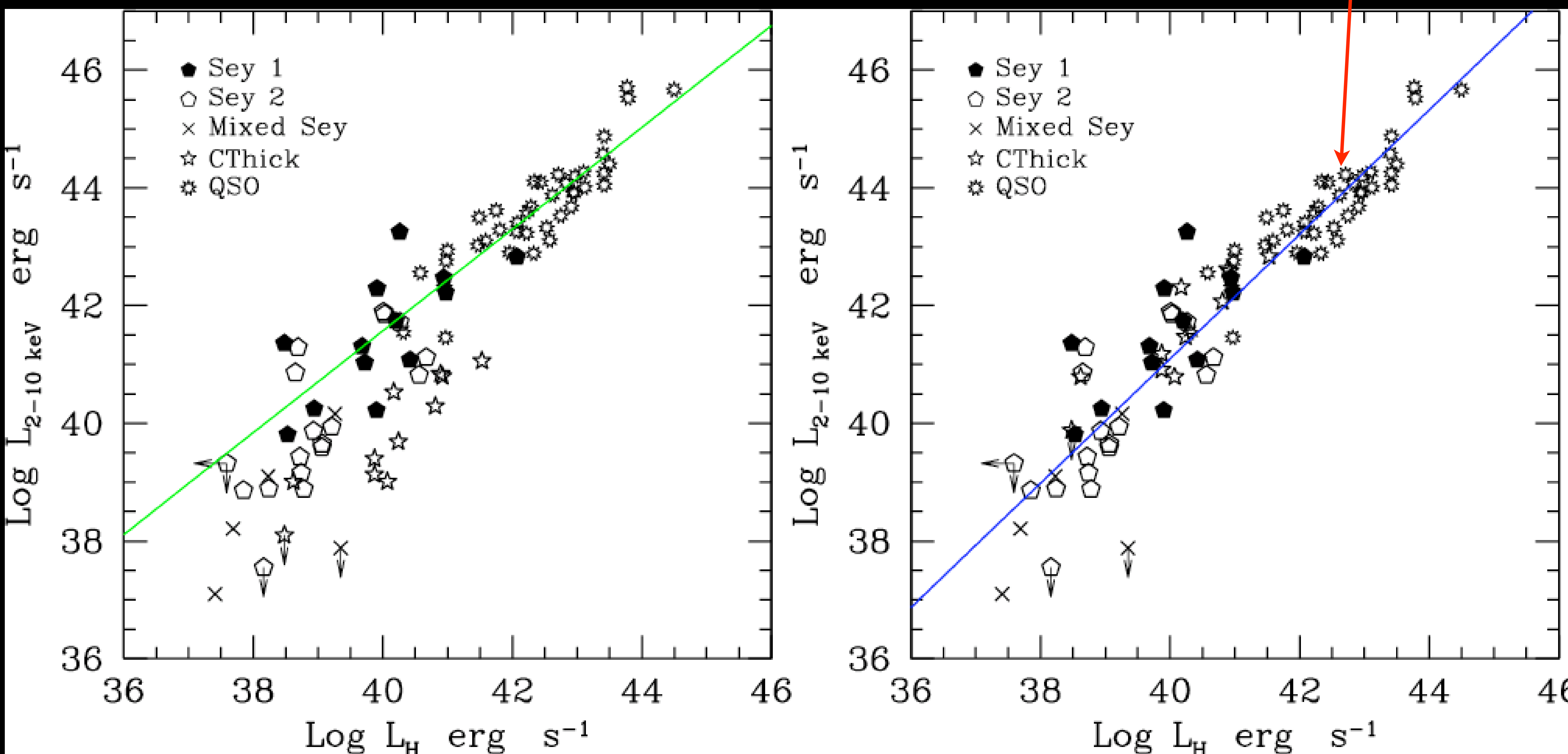


Submillimeter Galaxies





Compton-thick quasars



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?
Are there still pockets of low-metal IGM gas?

- 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 ?

Jeans Mass and Star Formation

$$M_J \approx [c_s^3/G^{3/2}\rho^{1/2}]$$

$(4\ M_{sun})\ (c_s/0.2\ \mathrm{km/s})^3\ (n_H/10^3\ \mathrm{cm}^{-3})^{-1/2}$

Isothermal: $M_J \propto \rho^{-1/2}$ (drops as ρ increases)

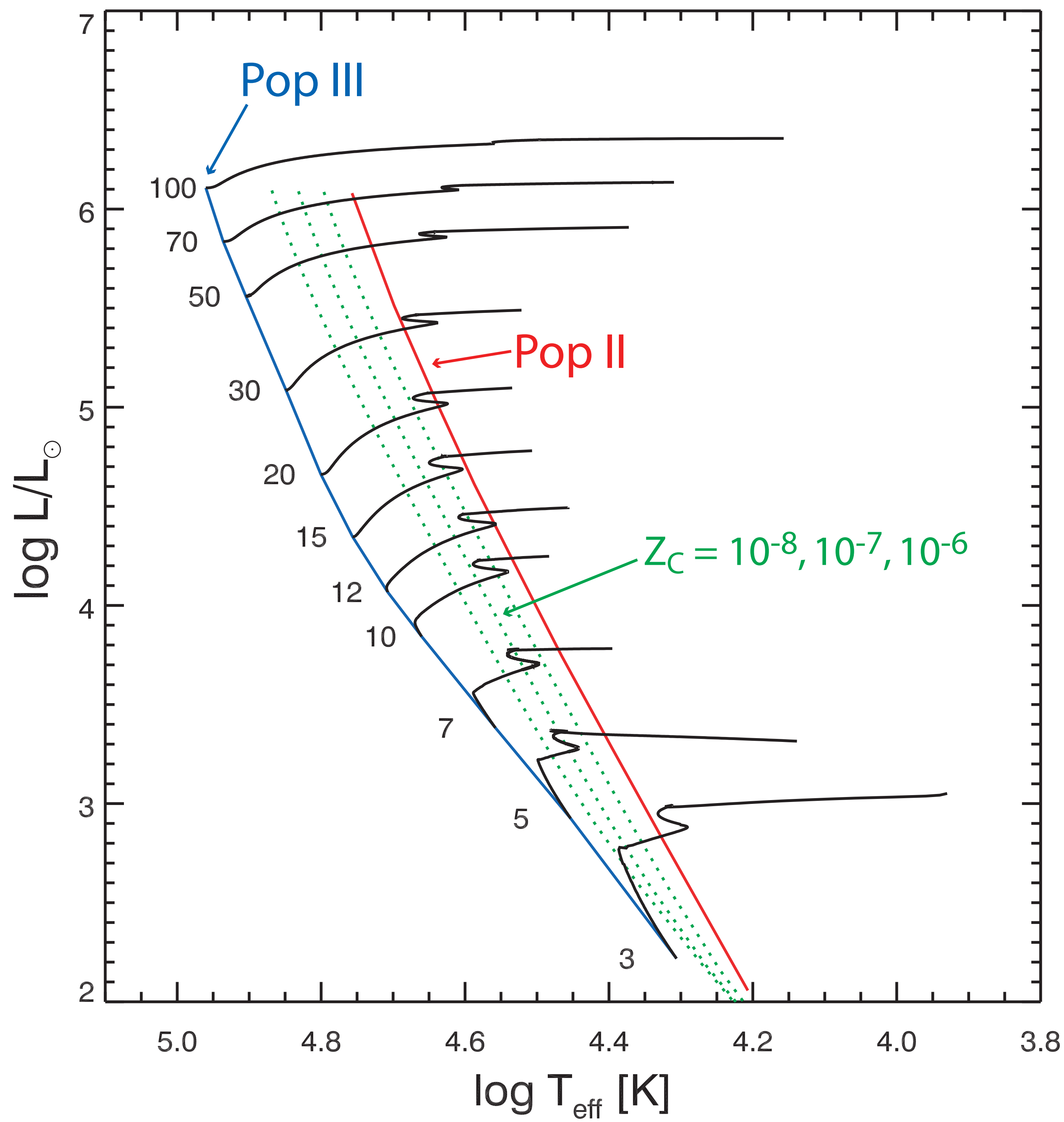
Adiabatic: $M_J \propto \rho^{1/2}$ (rises as $T \propto \rho^{2/3}$)

Radiative cooling is needed to allow star formation to proceed with collapse

Primordial cooling depends on both H_2 abundance and metallicity

Evolution of Low-Metal Stars

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



Why important?

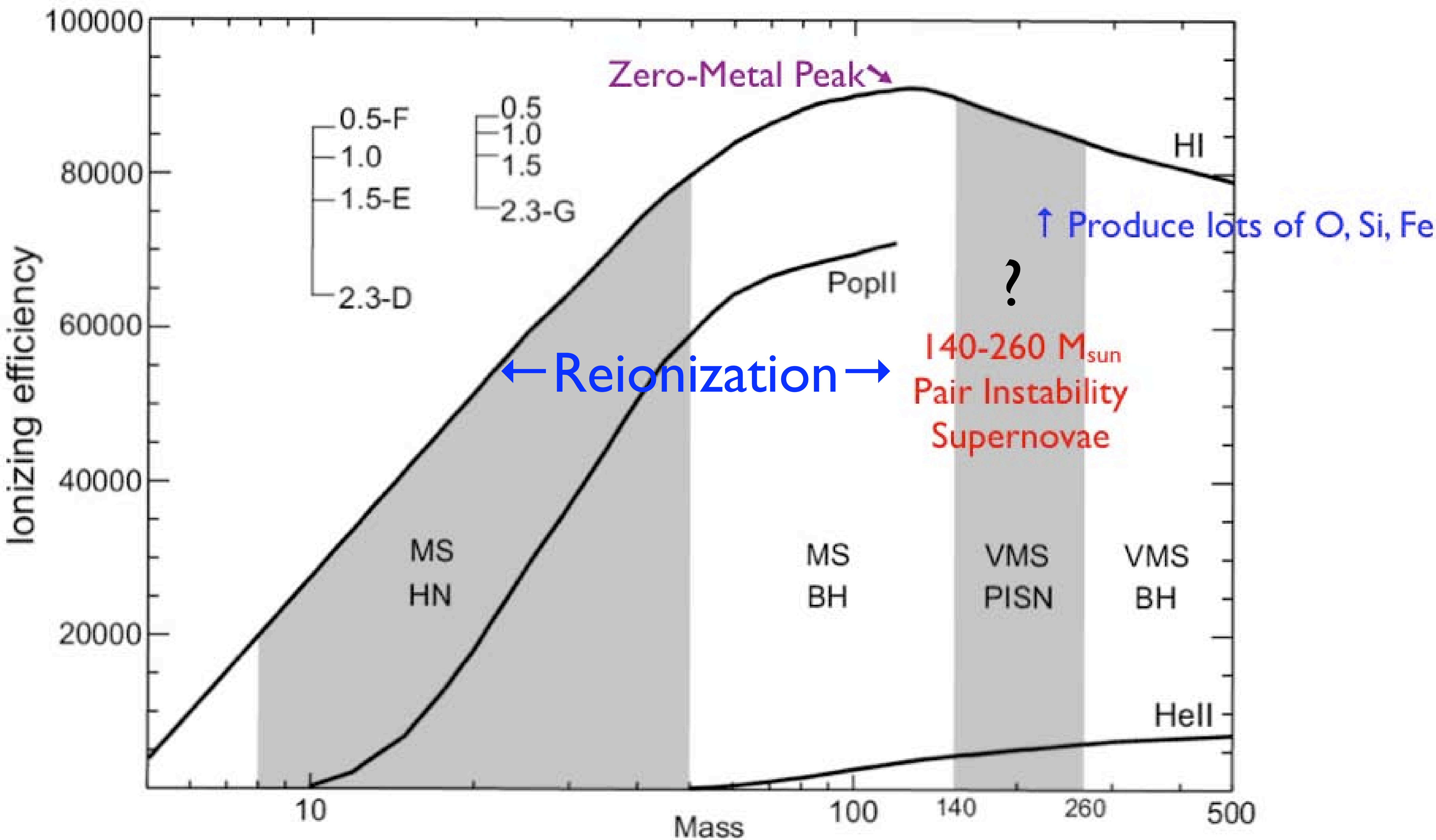
Increased T_{eff} for Pop III stars at low metallicity

10-100 M_{sun} dominate the IGM ionization

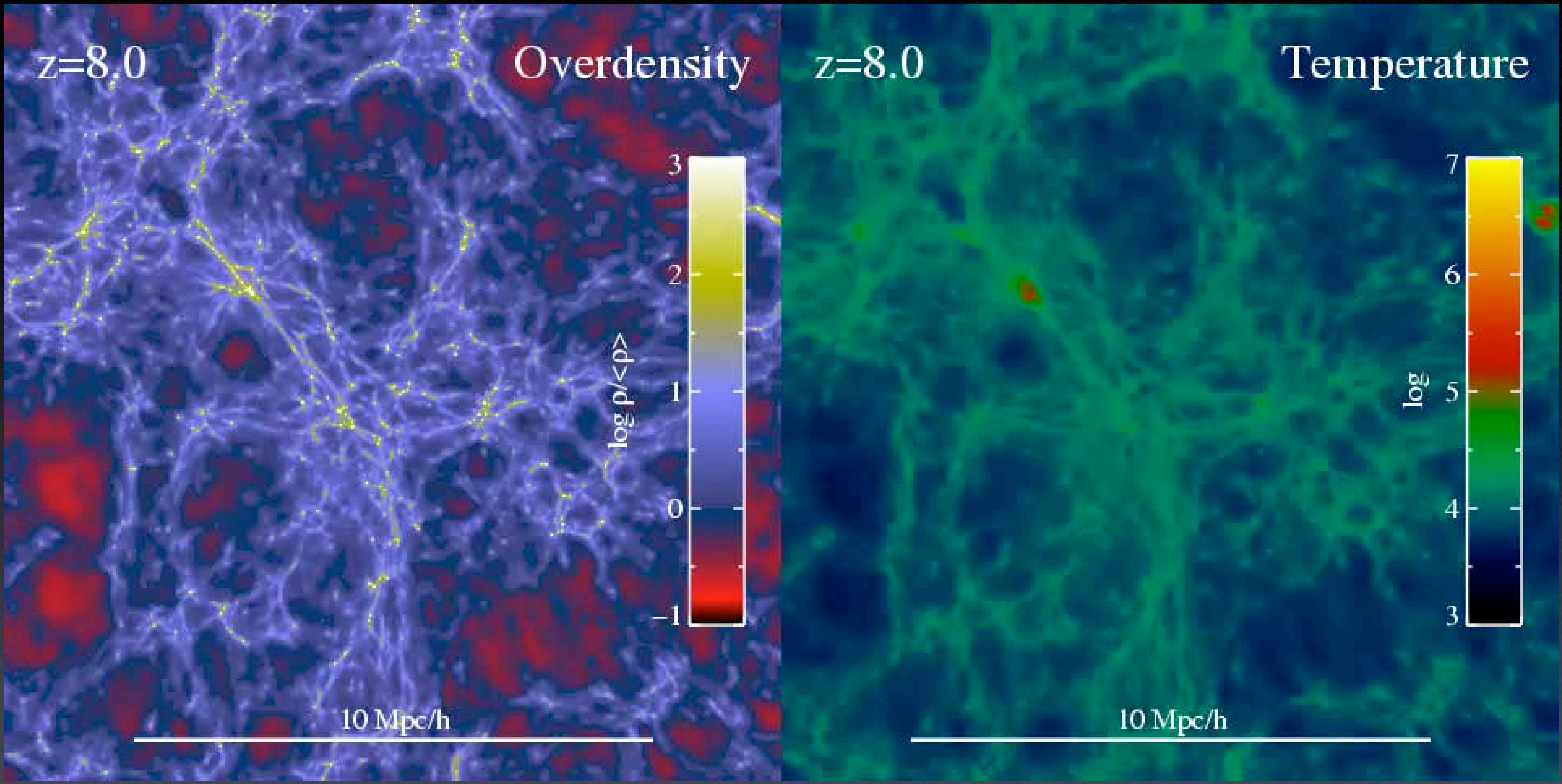
but for how long?

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

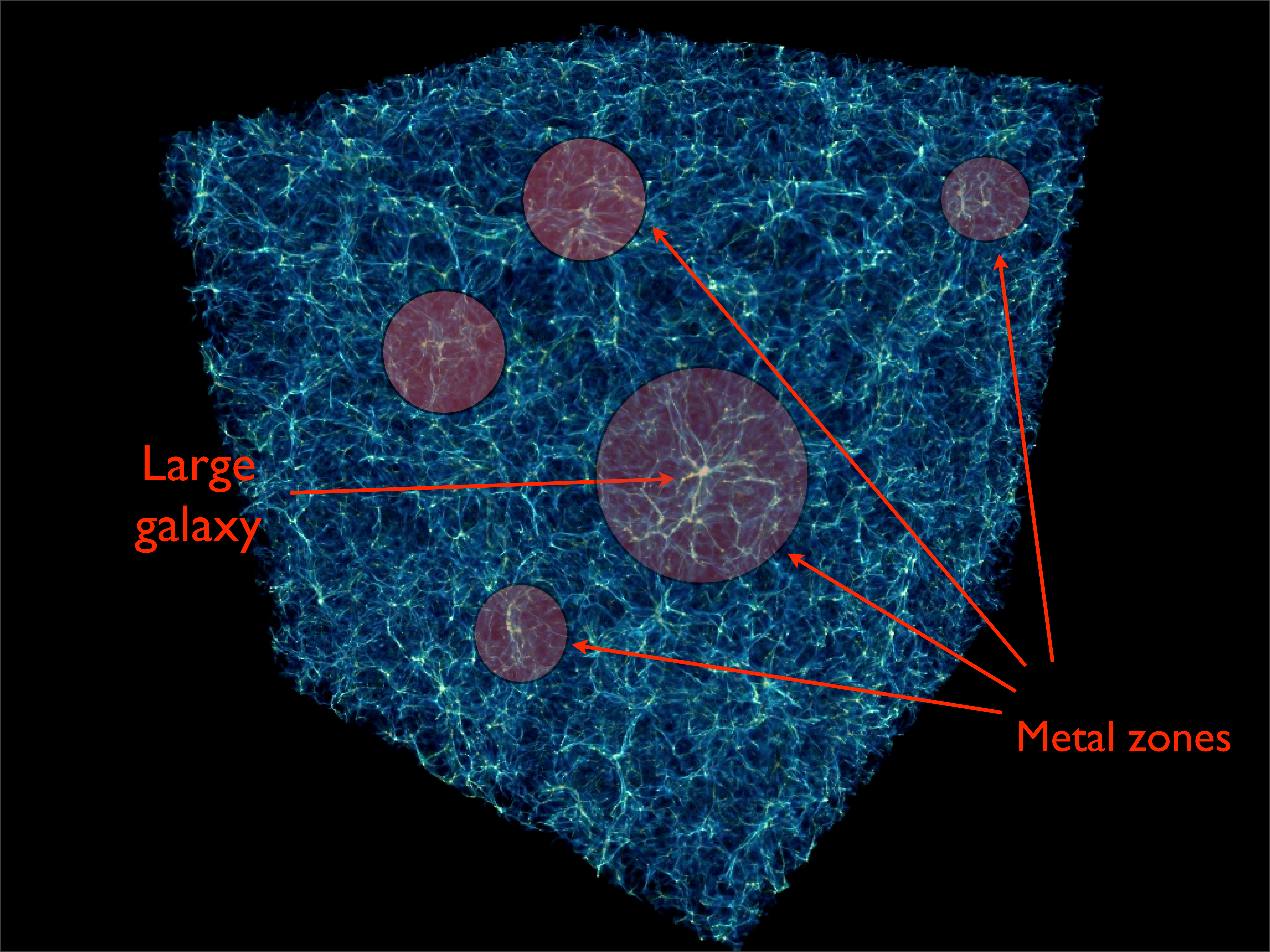
Tumlinson, Venkatesan, & Shull (2004) ApJ, 612, 602



Simulations of Structure Formation



Oppenheimer, Davé, & Finlator (Princeton Univ.)


Large galaxy
Metal zones

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

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

$$= \frac{(0.1\ M_\odot\ \mathrm{yr}^{-1}\mathrm{Mpc}^{-3})(0.024)(10^9\ \mathrm{yr})t_9}{(0.0224)(1.879\times10^{-29}\ \mathrm{g\ cm}^{-3})(0.02)}$$

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

Z→1% solar in ~Gyr

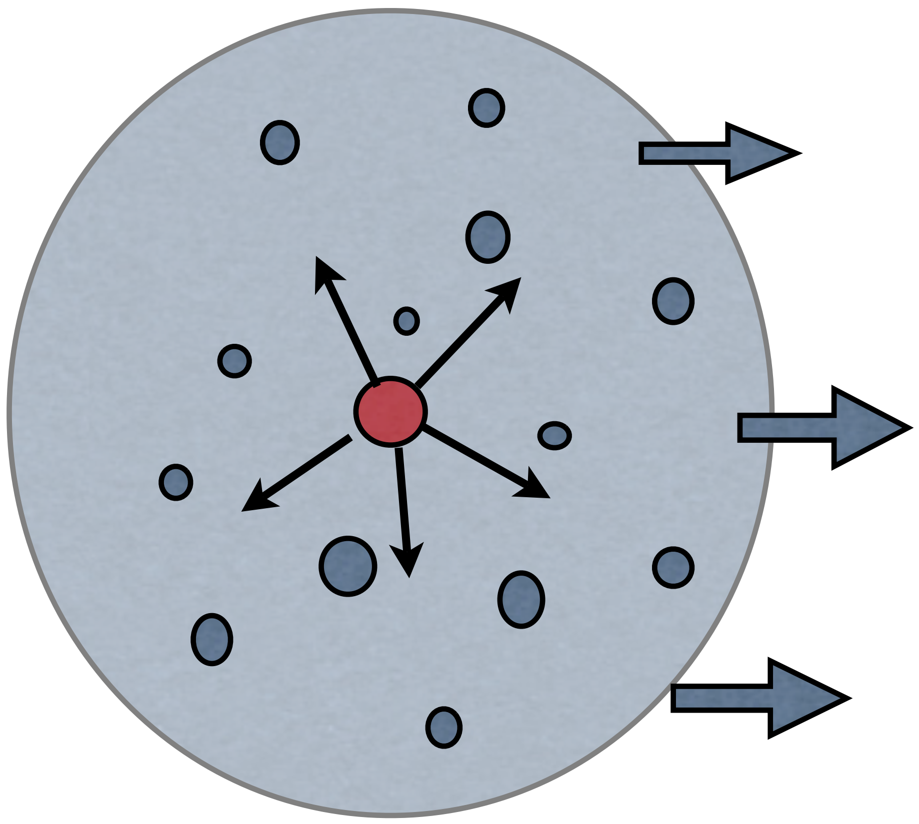
Assumed metal yield y_m = 0.024 (per M_{sun})

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

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

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

Tumlinson, Venkatesan & Shull 2004



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

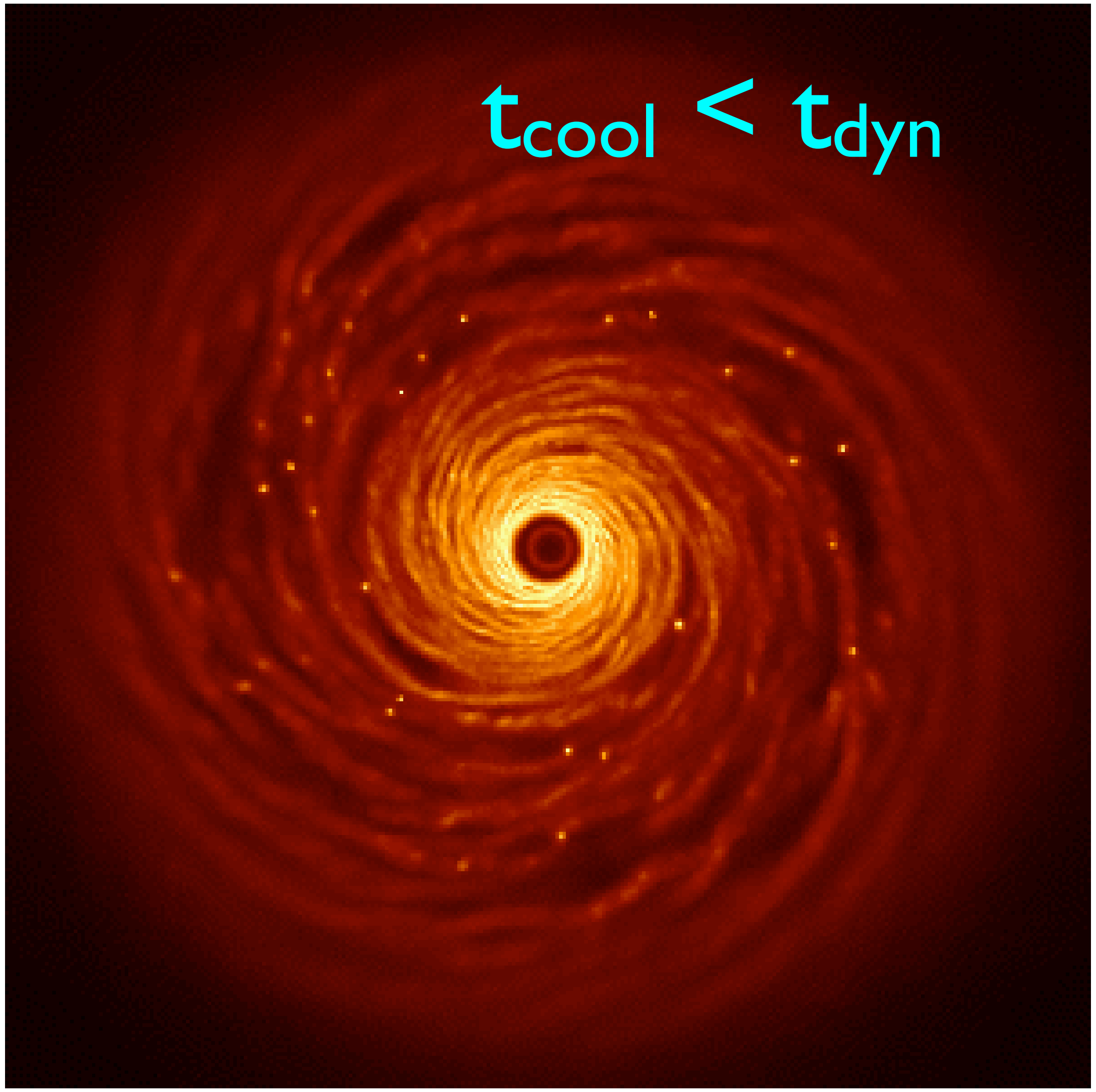
Gas undergoes star formation at halo center, geometric capture fraction of clumps ($\rho_{cl}/\rho_h = 100$) is:

$f_{cap} \approx (0.096) \, (\rho_h/\rho_{cl})^{2/3} \approx 0.0045$

The rest of metals blow out into the IGM

Fragmentation?

(Armitage simulations)



Or, quasi-static collapse of clumps?

Santoro & Shull (2007)

We explore cooling for 5%, 10%, 15% of the local Hubble time between z = 10-30

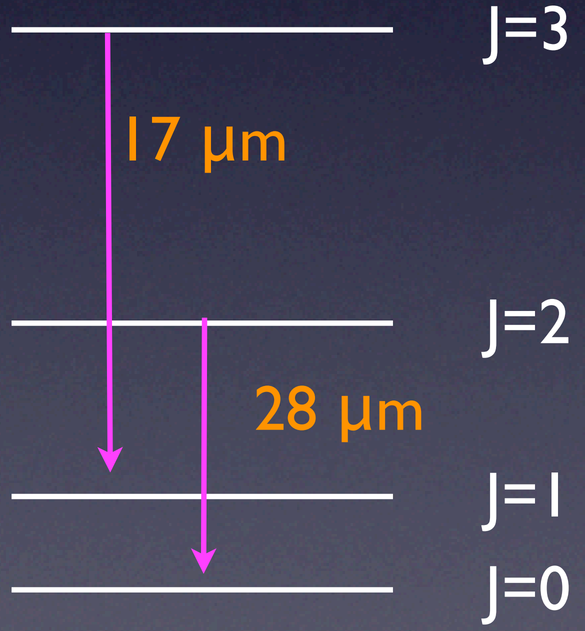
$$t_{cool} \leq t_{Hubble}$$

Molecular Cooling (H_2 rotational lines)
Santoro & Shull (2006) ApJ, 643, 26

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}

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



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)

Radiative Cooling = Adiabatic Heating Rate

$\Gamma_{ad} \propto T\, n^{3/2}$ $(nkT/t_{ff}$ or $-P\, d \ln \rho/dt)$

$L_{rad} \propto n\, Z\, f(T)$ for $n > n_{cr}$ $(L \propto n^2$ for $n < n_{cr})$

Scaling relations:

$Z_{crit} \propto T\, n^{1/2} / f(T)$ -- for $n > n_{cr}$

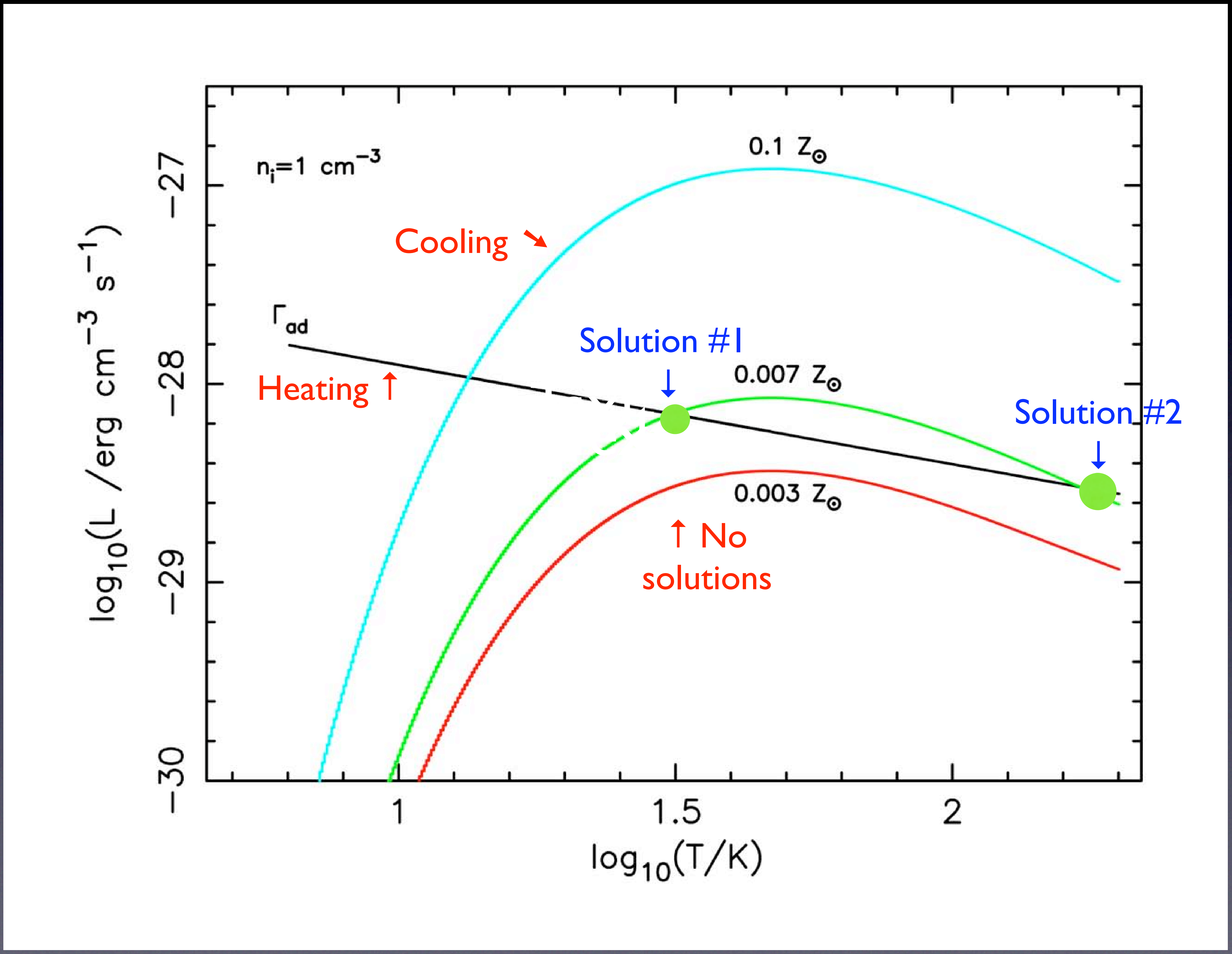
$Z_{crit} \propto T\, n^{-1/2} / f(T)$ -- for $n < n_{cr}$

Result is parabolic behavior, with minimum value of $Z_{crit}\,(n_{cr}) \sim 10^{-3.5}\, Z_{sun}$ (O, Si, Fe)

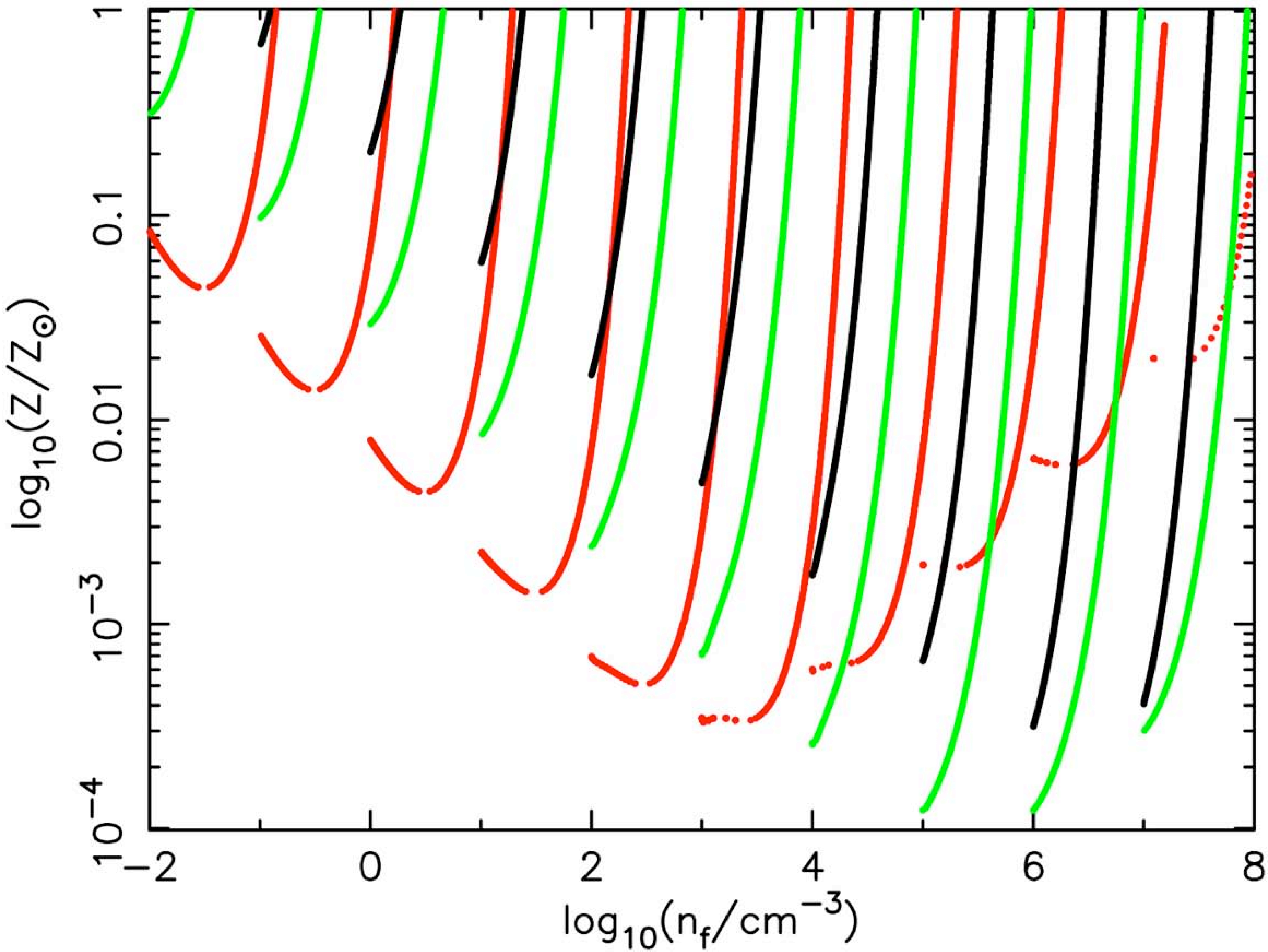
Most efficient cooling occurs when levels reach LTE at $n_H \sim n_{cr} > 10^{5\text{-}6}\ cm^{-3}$ (for O I, Si II, Fe II)

Radiative Cooling = Adiabatic Heating Rate

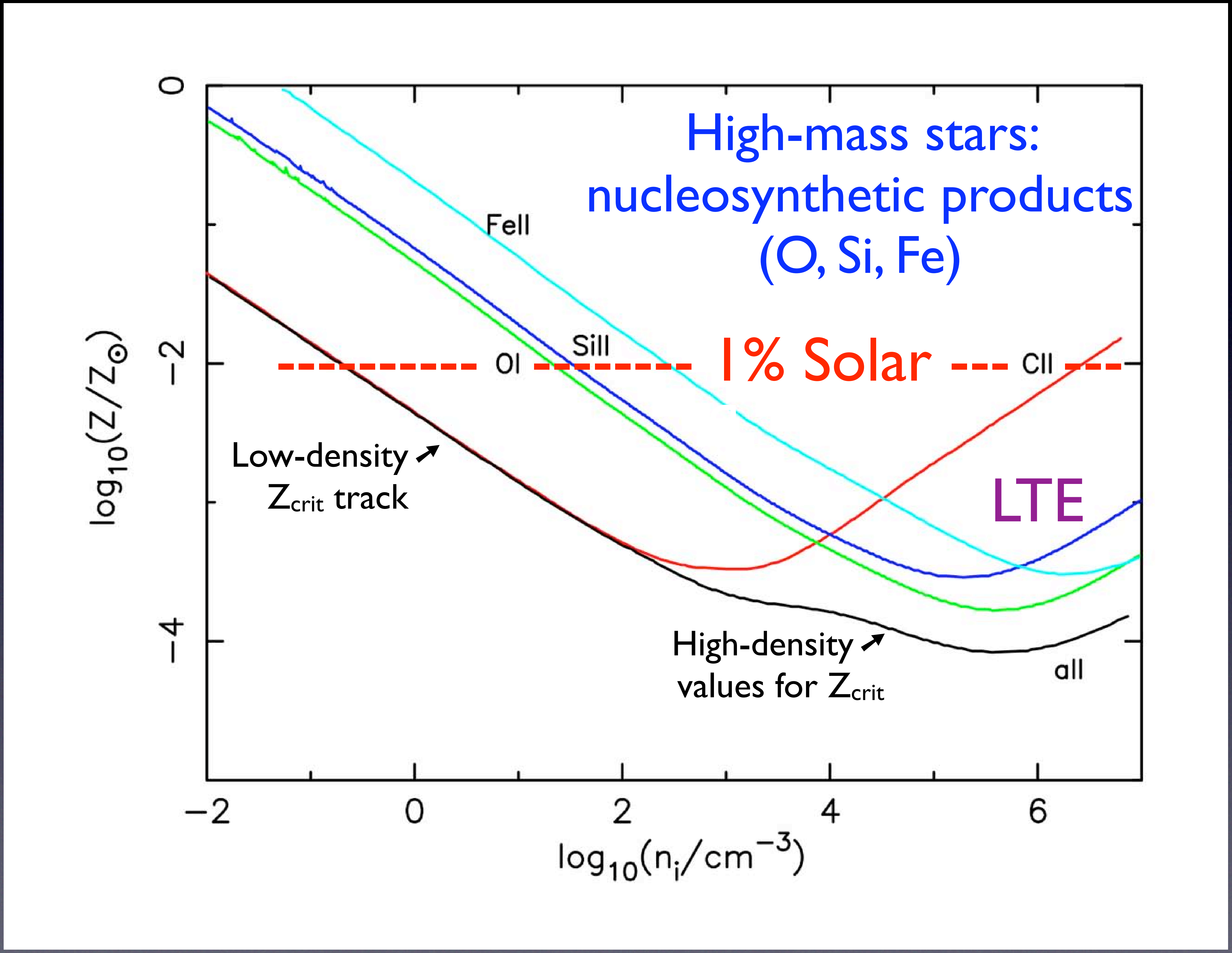
(Defines the Critical Metallicity) (at nT = constant)



Critical Metallicities (various elements)
(C = red; Si/O = green, Fe = black)

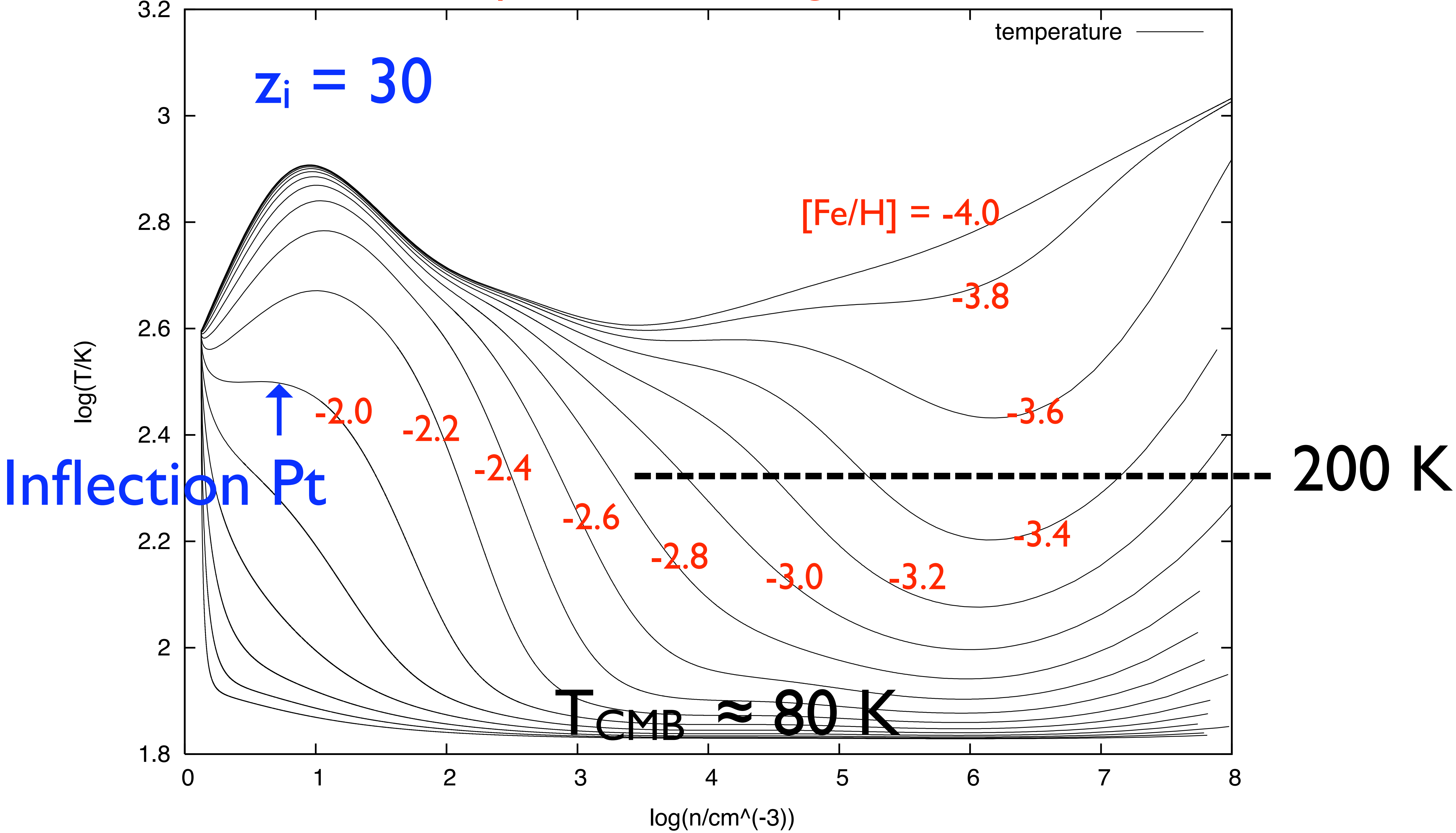


Locus of Minimum Z_{crit} values



Time-dependent Cooling

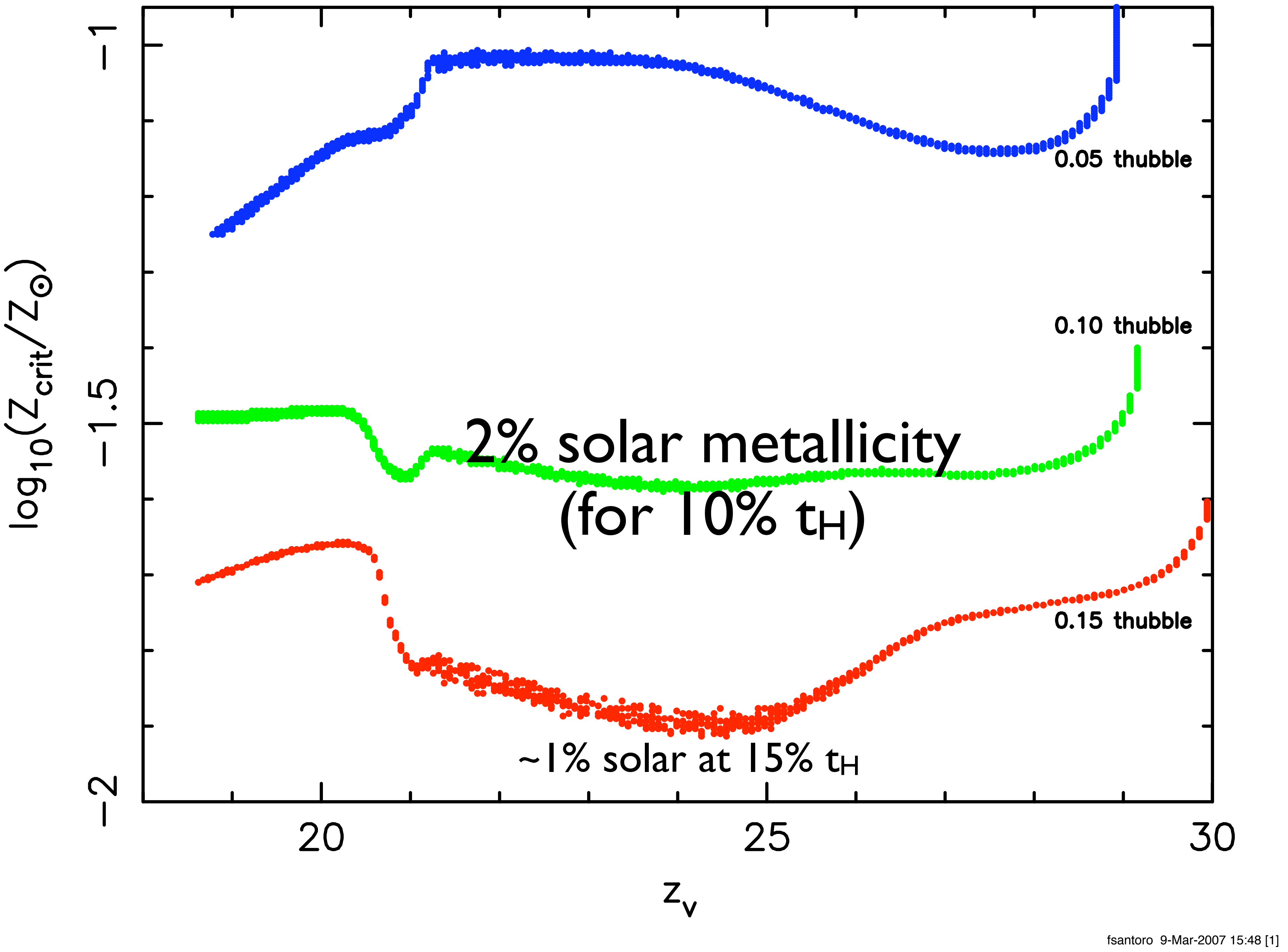
Santoro & Shull 2007



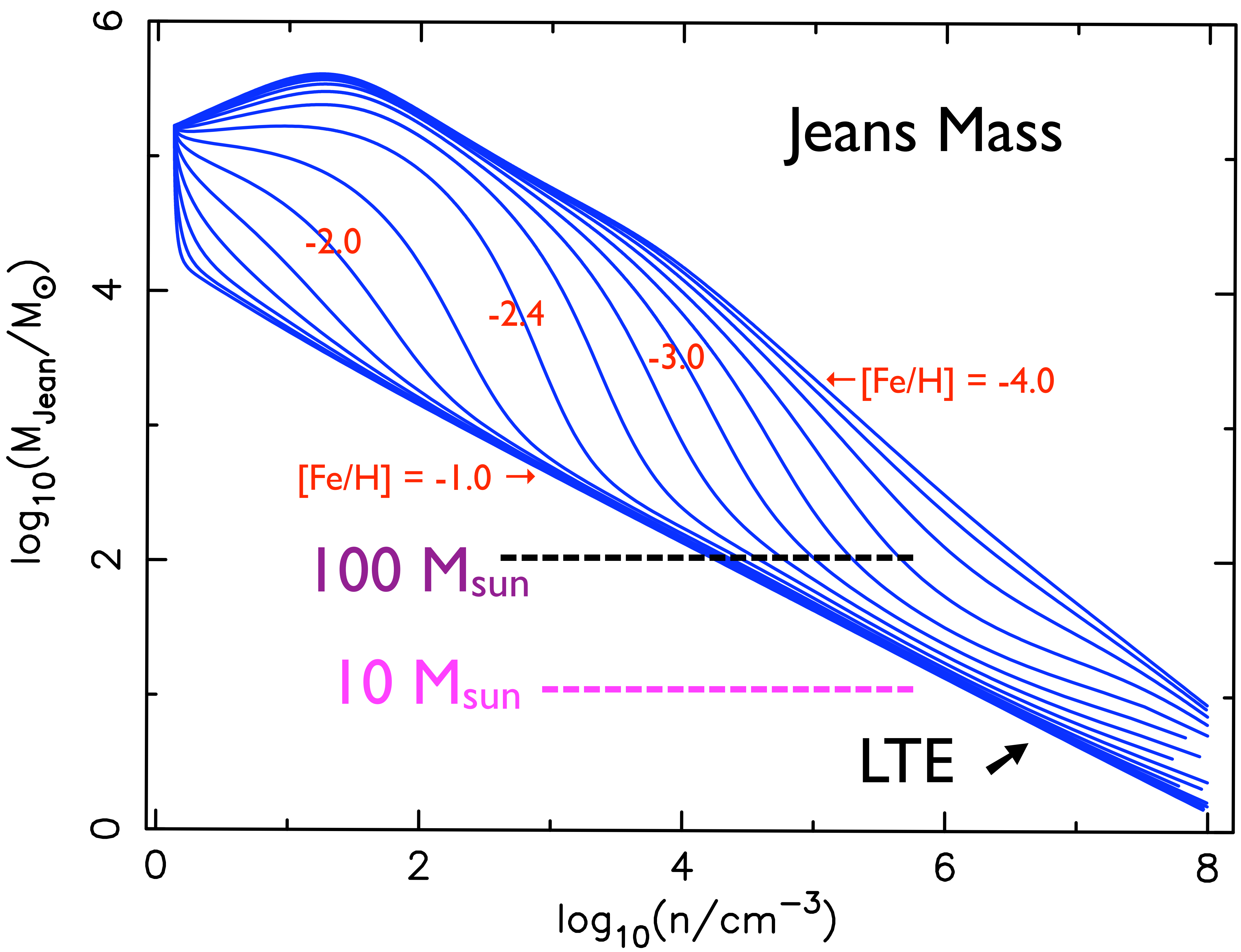
Cooling to $n = 10^4$ cm^{-3} takes some time

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

Critical Metallicity (after time, z = 20-30)

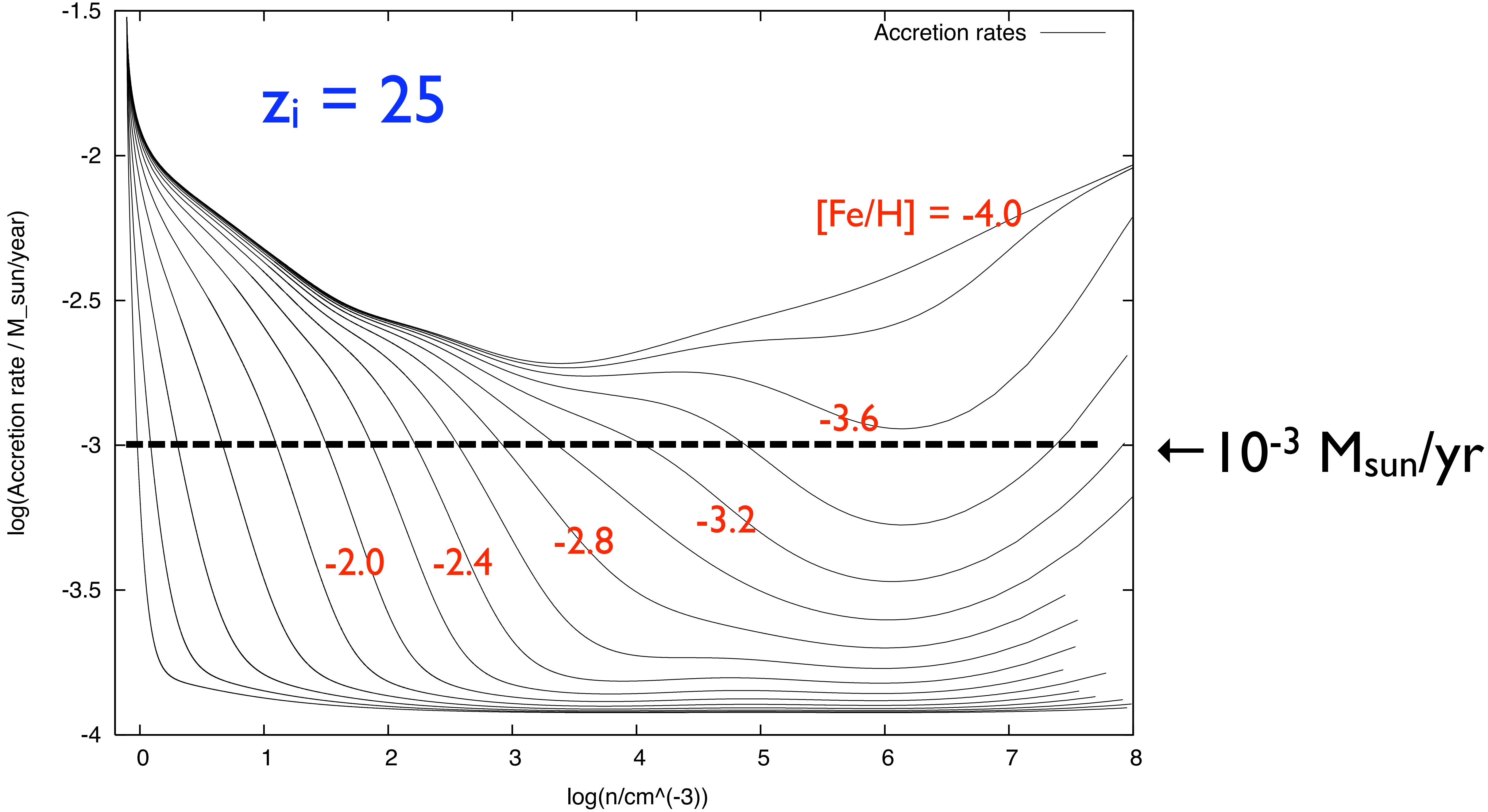


Santoro & Shull
2007



fsantoro 17-Oct-2006 16:57 [1]

Mass Accretion Rate $\approx (c_s)^3 / G$



Thermal Limit on Envelope Accretion

"The Fossil Record"

Gas in the Intergalactic Medium

- Low-Redshift Metals (UV spectra)

FUSE satellite (low-z O VI surveys of IGM)

Cosmic Origins Spectrograph on HST (Aug 2008)

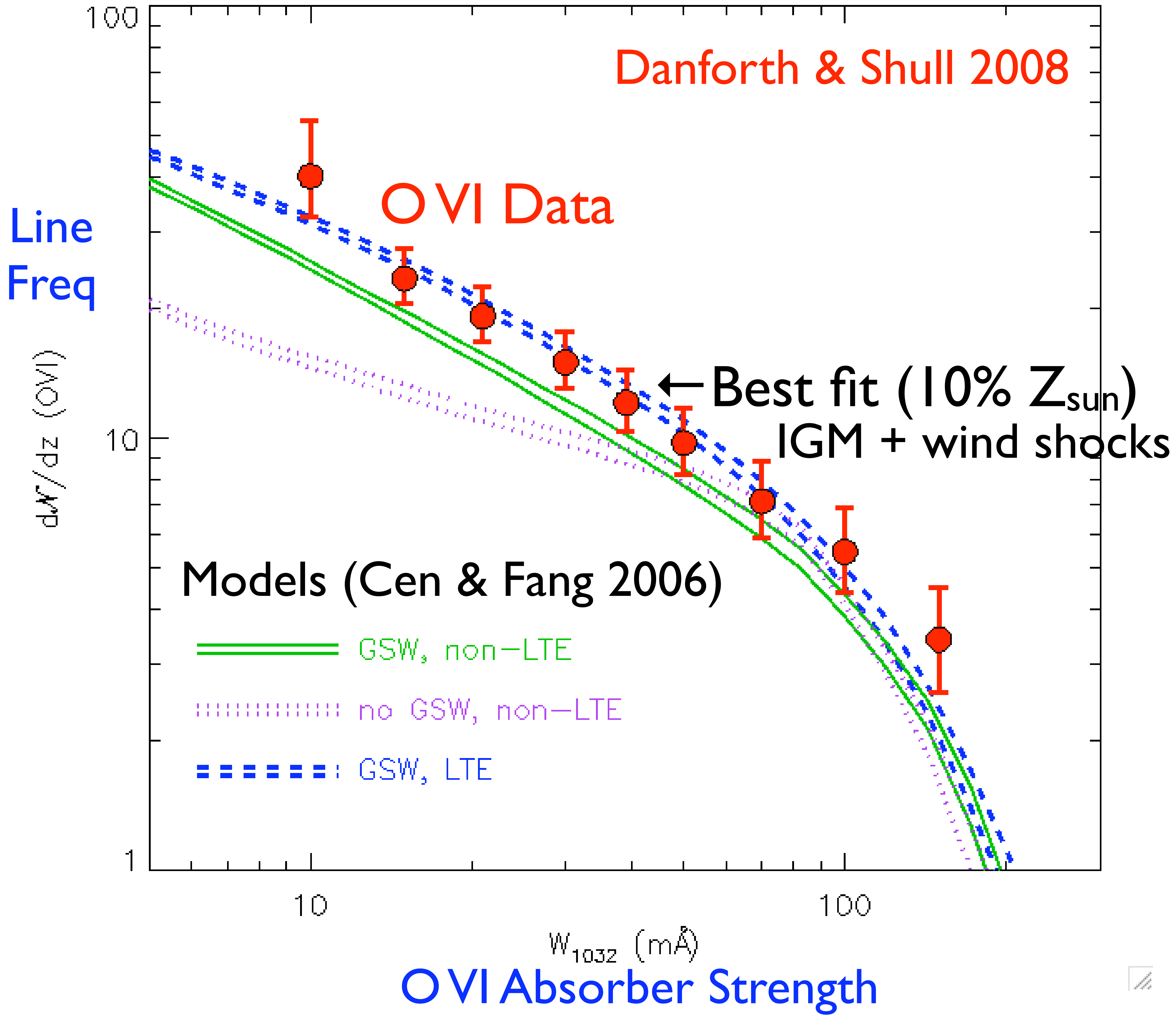
UV spectra of the IGM (1150-3000 A)

- High-Redshift (FIR/Sub-mm) coolants

Future Instruments in Space? H_2 lines 28.2 μm, 17.0 μm

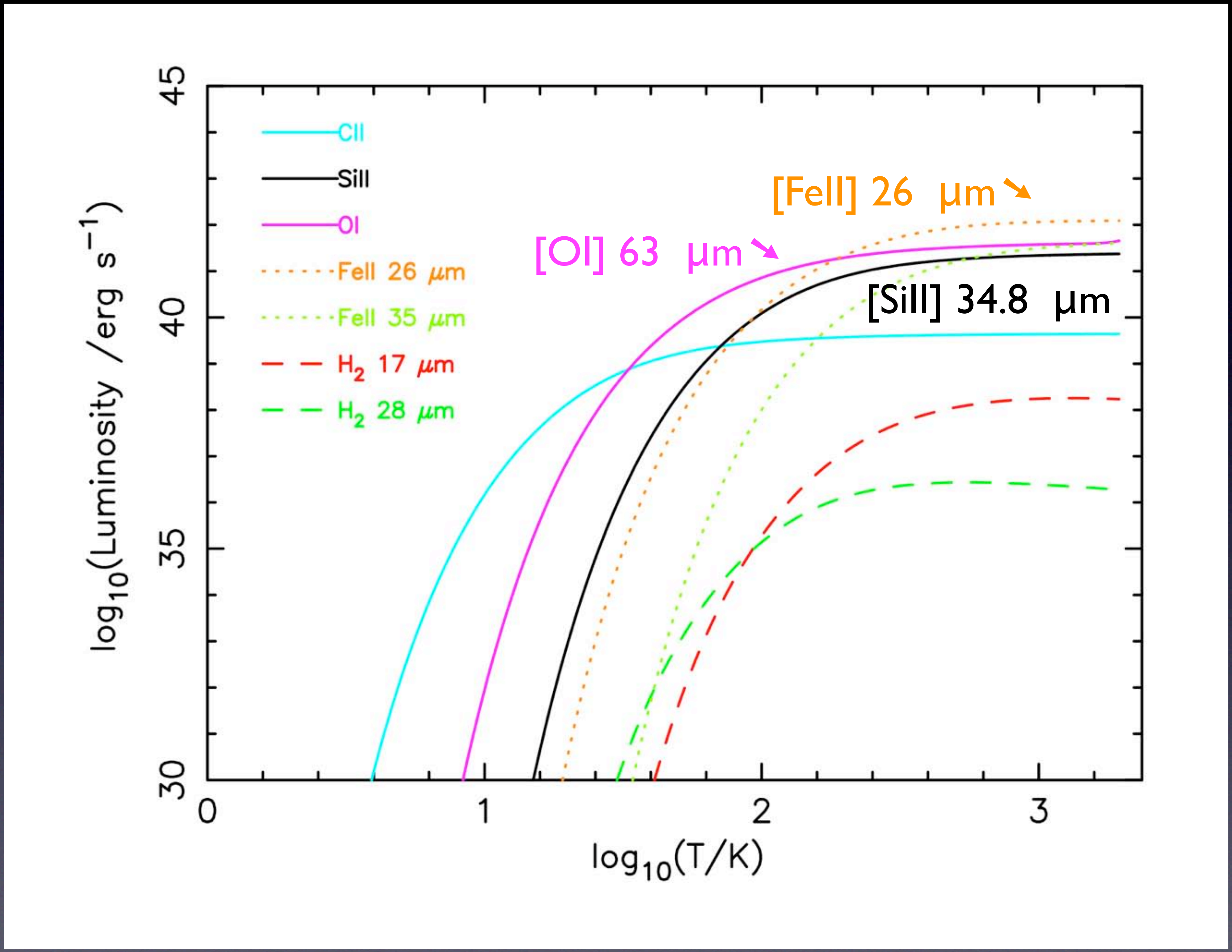
Metal Fine-structure lines [C II], [O I], [Si II], [Fe II]

157.74 μm 63.18 μm 34.8 μm 25.99 μm



Danforth & Shull 2008
O VI Data
Line Freq
dN/dz (OVI)
← Best fit (10% Zsun)
IGM + wind shocks
Models (Cen & Fang 2006)
GSW, non-LTE
no GSW, non-LTE
GSW, LTE
100
10
1
10
100
W1032 (mÅ)
O VI Absorber Strength

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)

$L_i \approx 1\text{-}2 \times 10^{41}$ erg/s

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

Astrophysical Summary

- Low-z IGM has mean metallicity ~10% solar
- High-z: use individual values of Z(C, O, Si, Fe)
- Z_{crit} depends on density -- 1% solar at low-n
- There could be small pockets of low-metal stars
- High-n cores have $Z_{crit} \sim 10^{-3.5} Z_{sun}$
- Cooling FS lines: FIR/sub-mm at 10^{-21} W m^{-2} (hard!)

These observations will require major new (large) telescopes