“Critical Metallicity”

Fine-Structure Emission Lines and Primordial Cloud Cooling

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[work with Fernando Santoro]
(see astro-ph/0509101)

The first stars enrich the surrounding gas

[High-mass stars make lots of O, Si, S, Fe]

What happens next?

Schneider et al. 2002; Bromm & Loeb 2003 (single-Z)
Santoro & Shull 2005 - multiple metallicities

- When does total cooling exceed adiabatic heating in collapse?
- At what metallicity (Zcrit) does metal cooling exceed H_2 cooling?
- Transition from Pop III (zero-metal, high-mass) to Pop II stars?
- Cooling time, gas temperature, fragment Jeans mass?
- Dependence on stellar mass range (O, Si, Fe enhancements)?

Molecular Cooling (H_2 rotational lines)

Strongest transitions are from ortho-H_2 (J = 3-1) and from para-H_2 (J = 2-0) rotational states, excited primarily by HI - H_2 collisions

Critical densities (for LTE) are $n_H \sim 10^{3\text{-}4}$ cm^{-3}

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

Abundant Heavy Elements
(with ground-state fine structure lines*)

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

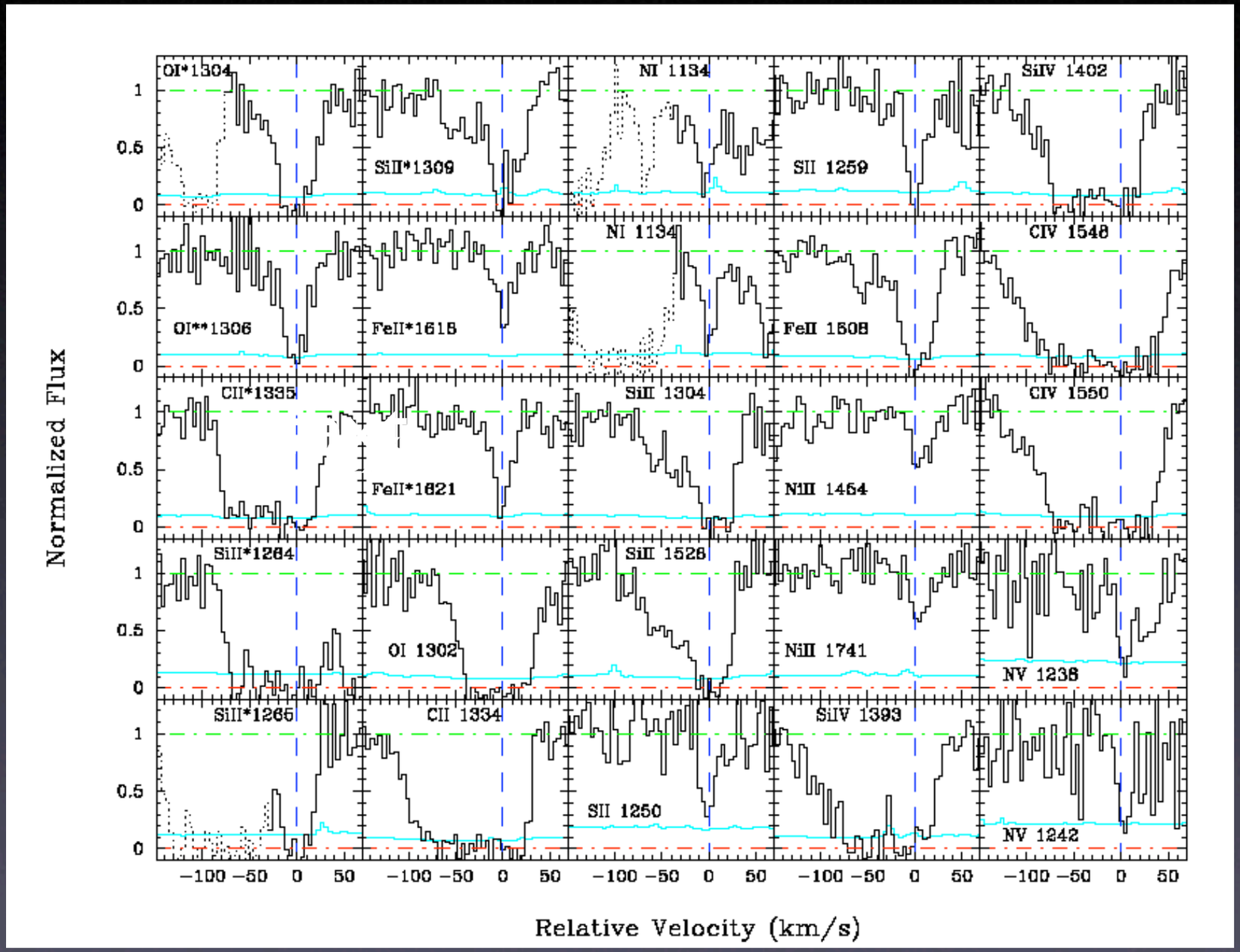
*Assume an ionization state set by FUV photons (E < 13.6 eV)

Fine Structure Excitation in GRB Afterglow

UV absorption lines of FeII*, CII*, SiII*, OI*, OI**

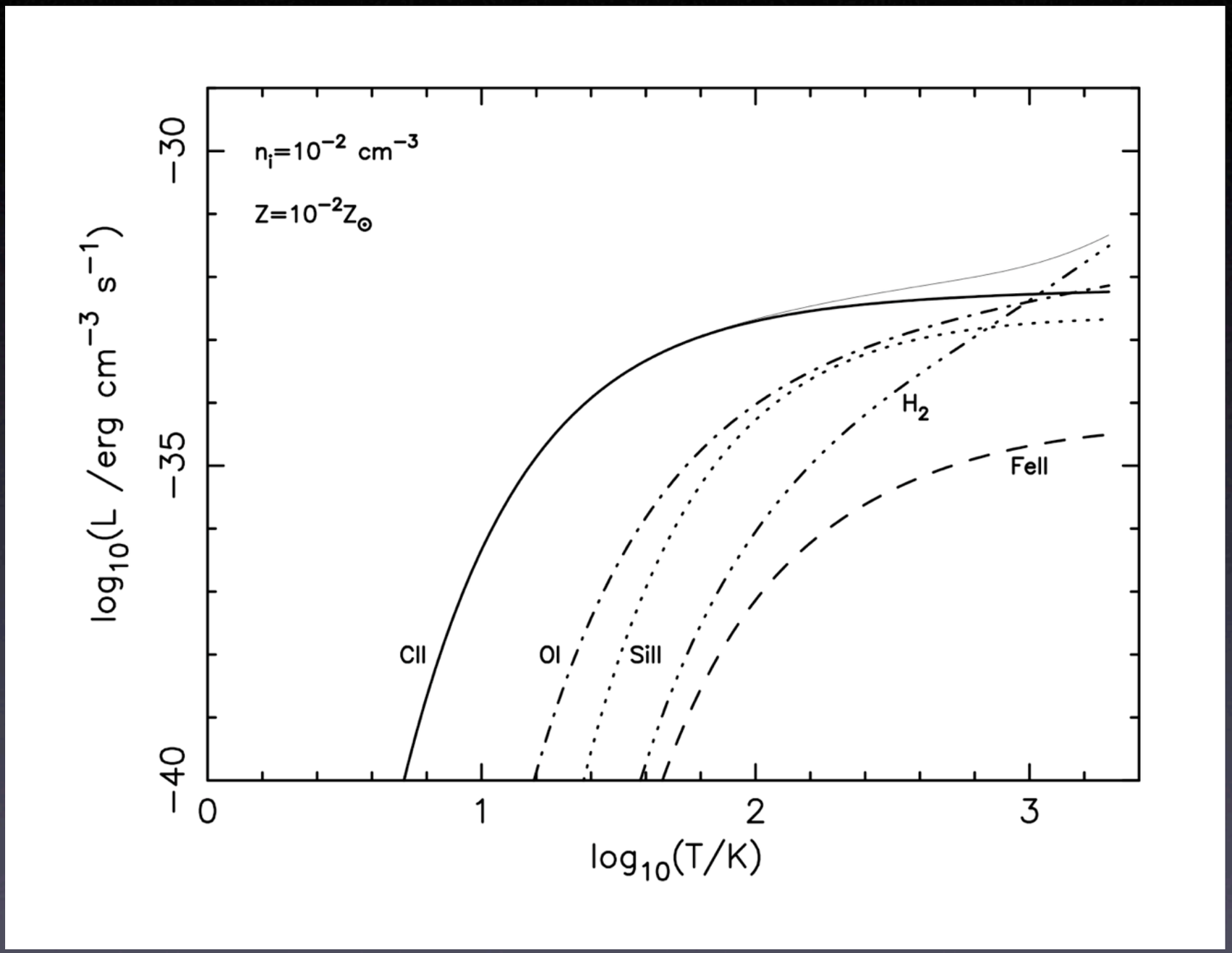
Chen et al. (2005) astro-ph/0508270

UV fine-str lines:
OI* 1304, 1306
SiII* 1264,1309
FeII* 1618,1621
CII* 1335



Radiative Cooling Rates (low-n)

[dominated by CII*, OI*, SiII*, H2]



Radiative Cooling = Adiabatic Heating Rate
(Analytic formulae valid for $n_H > n_{crit}$)

$$\Gamma_{\rm ad} = (24\pi)^{1/2}\,[1 - R/R_0]^{1/2}(n_{\rm t}kT)\sqrt{G\rho}\,.$$

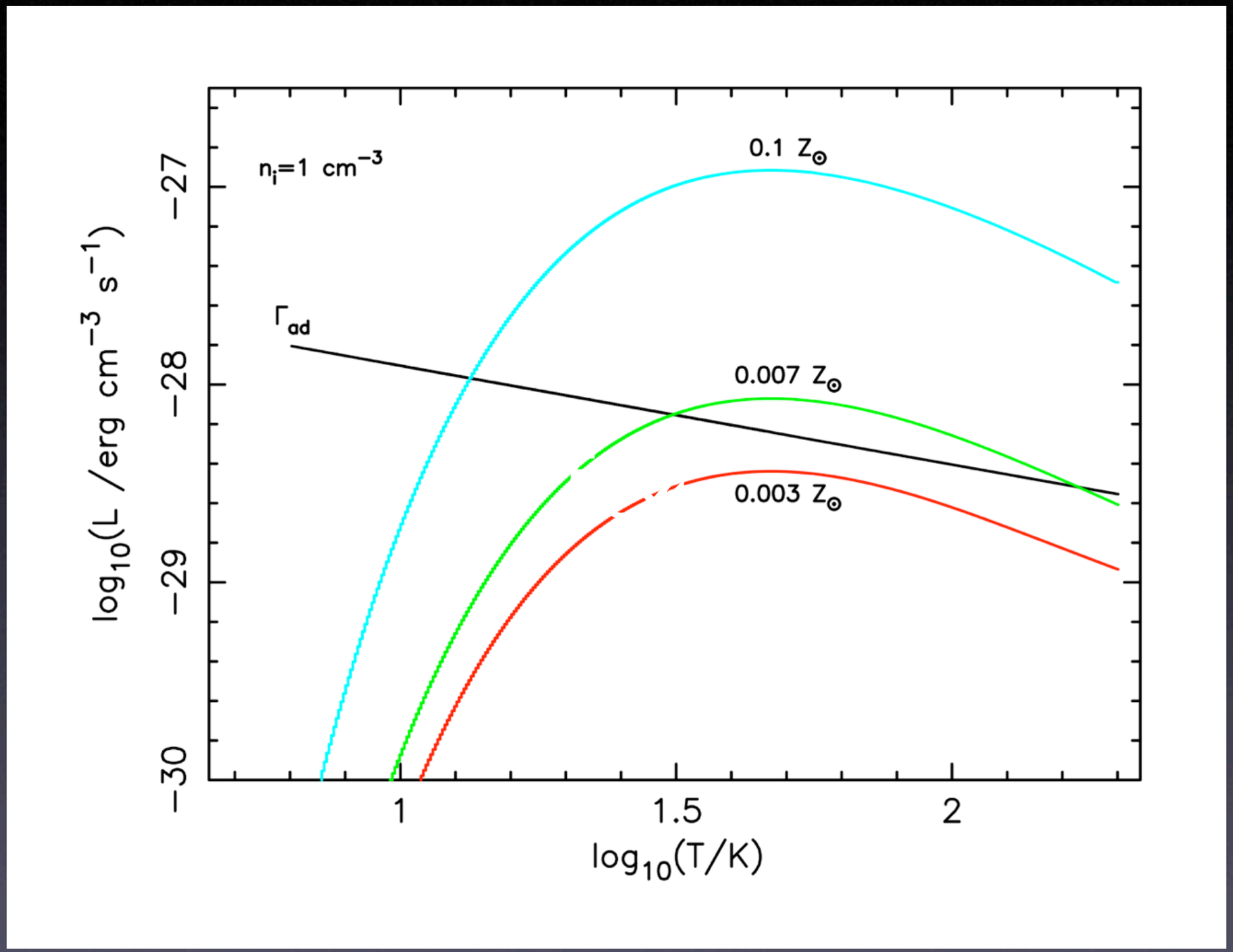
$$Z_{\rm crit}/Z_\odot = \left[\frac{a\,T}{f(T)}\right] n^{1/2}$$

$$f(T) = \frac{A_i\,A_{21}^{(i)}\,E_{21}^{(i)}}{[1 + (g_1/g_2)\exp(E_{21}^{(i)}/kT)]}\,;$$

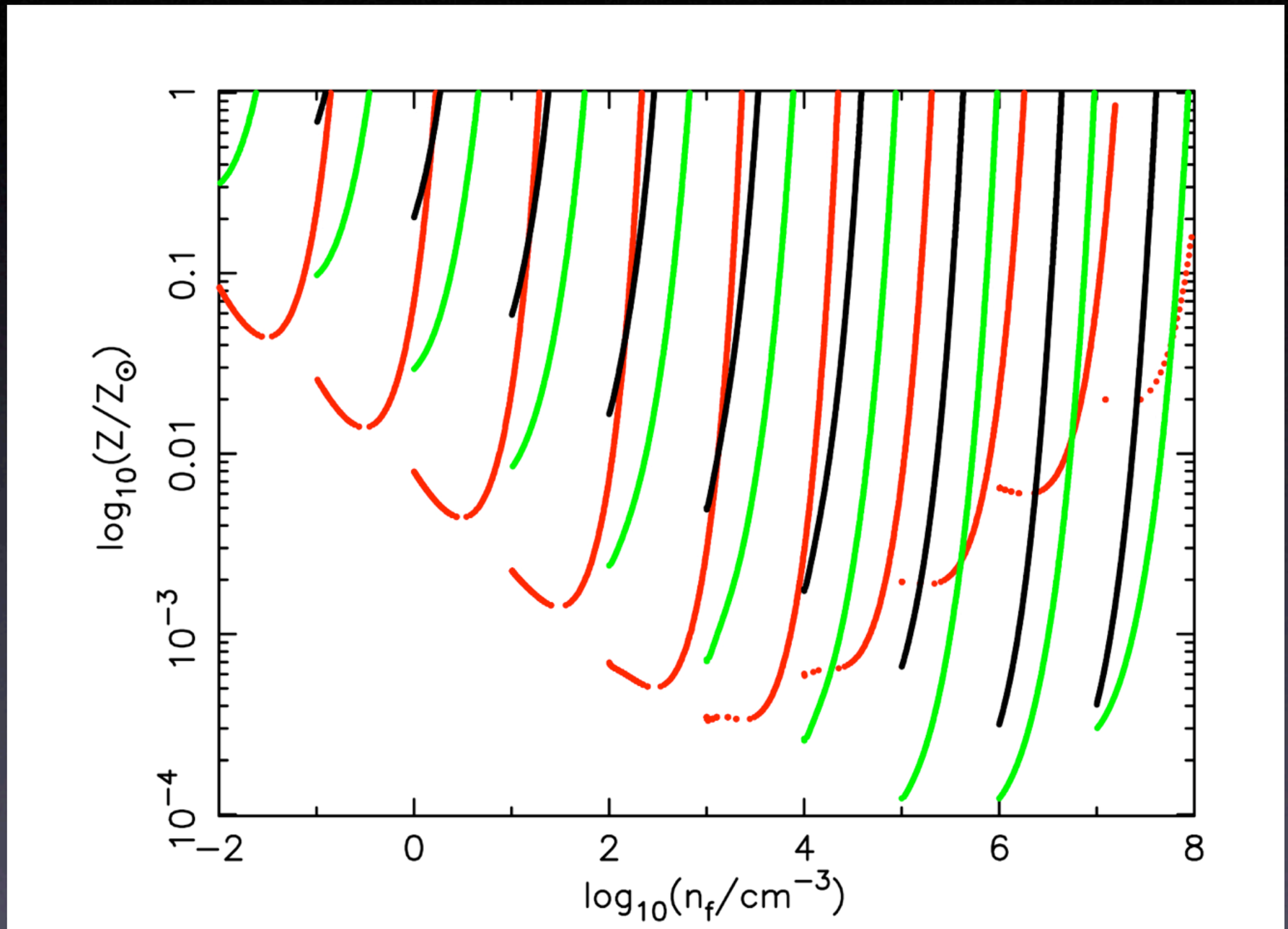
$$Z_{\rm crit}/Z_\odot = \left[\frac{2.74k(G\mu)^{1/2}}{A_i A_{21}^{(i)} E_{21}^{i}}\right]\left[1 + \frac{g_1}{g_2}\exp(E_{21}^{(i)}/kT)\right] n^{1/2}T$$

These formulae all give $Z_{crit} \sim 10^{-3.5}\,Z_{sun}$
(LTE minimum at densities $n_H \sim n_{crit}$)

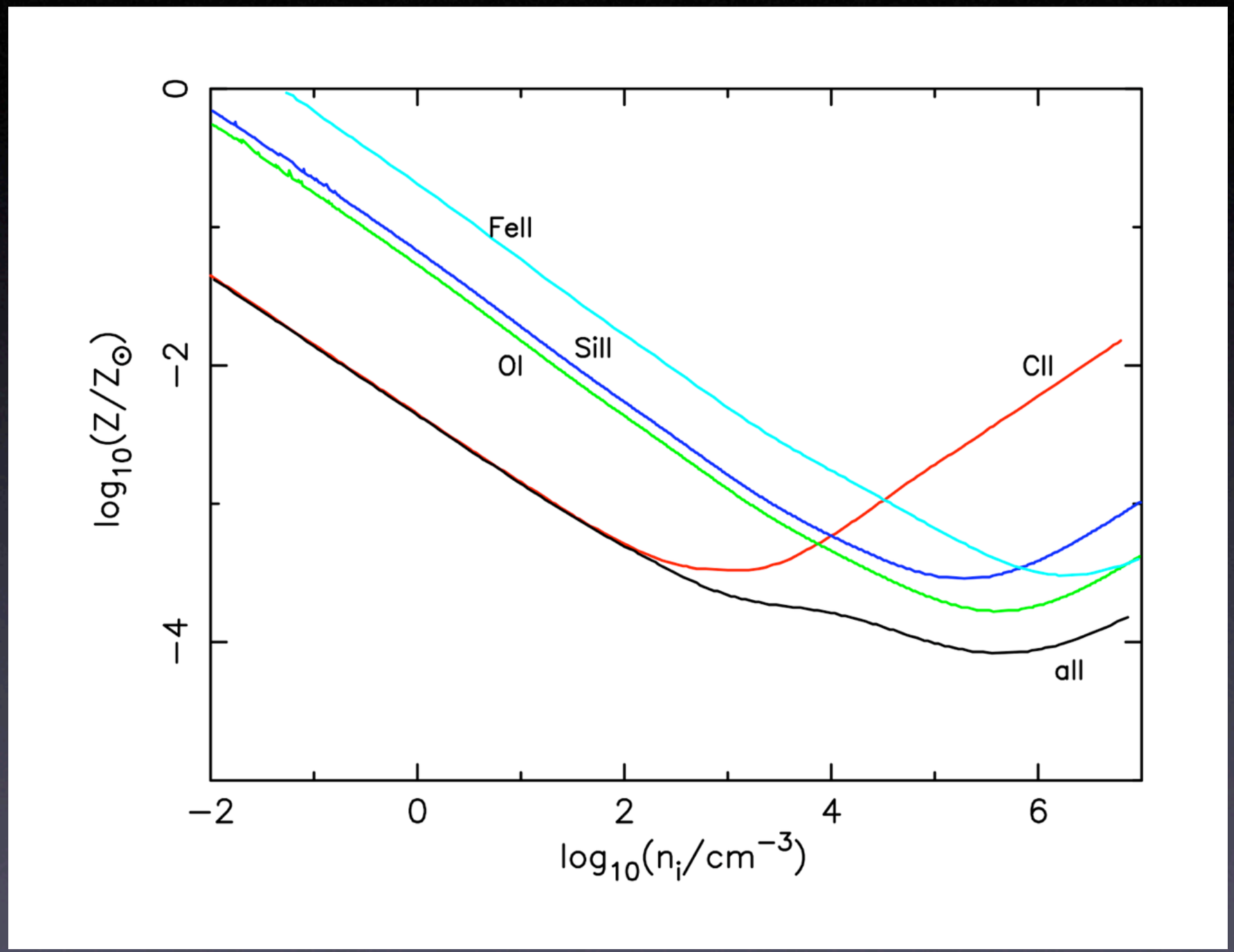
Radiative Cooling = Adiabatic Heating Rate



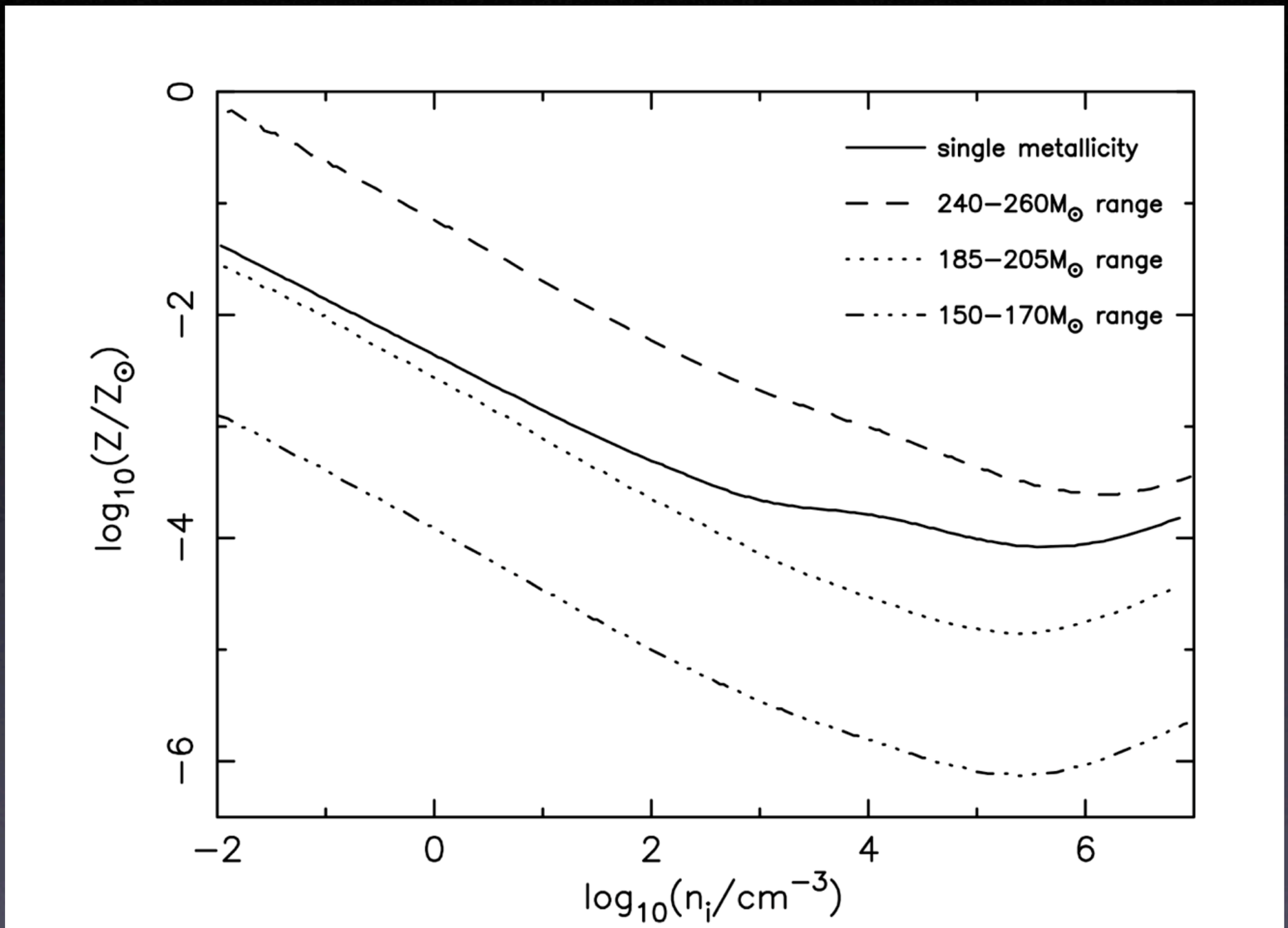
Critical Metallicities (various elements)
(C = red; Si/O = green, Fe = black)



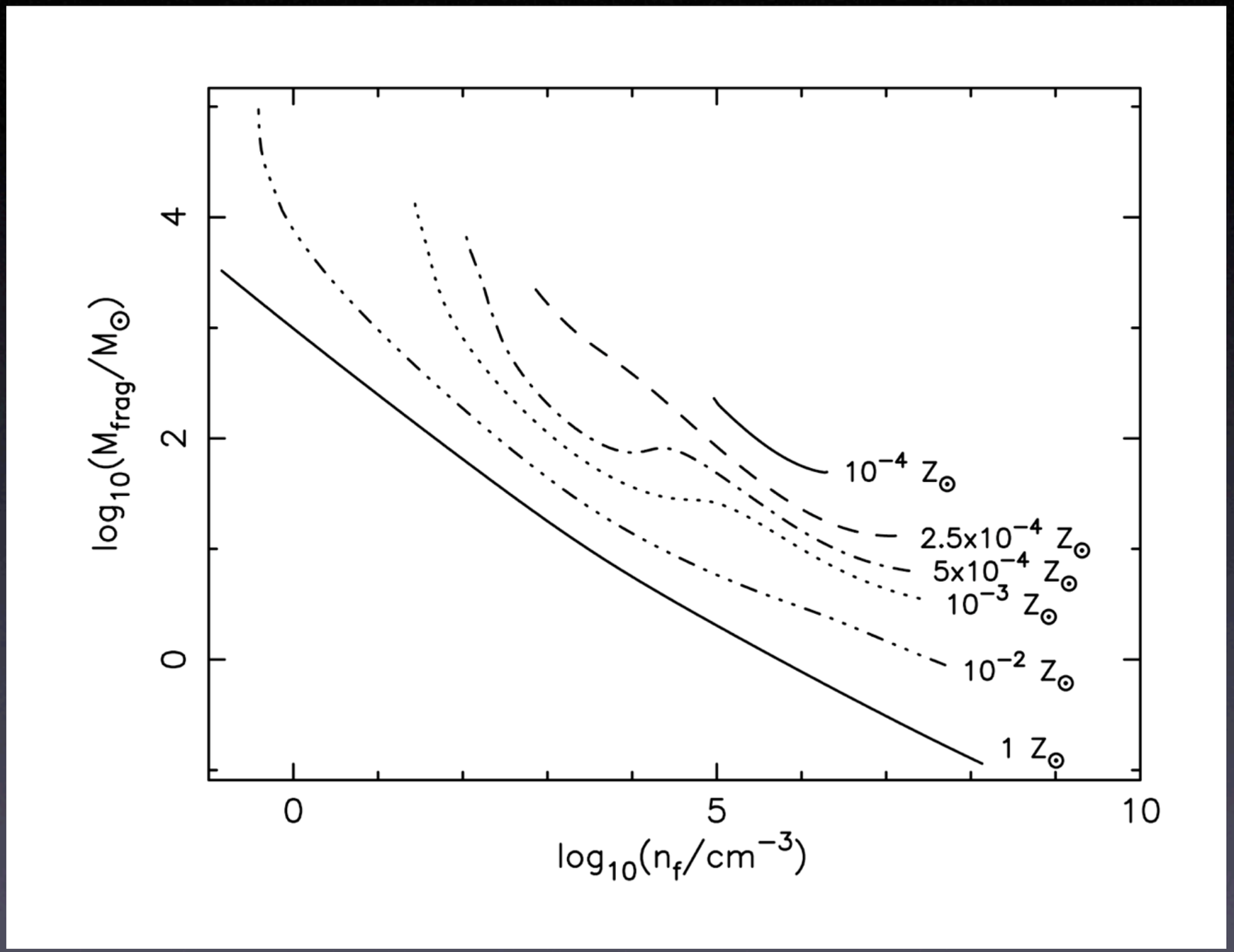
Locus of Minimum Z_{crit} values



Z_{crit} for different high-mass ranges

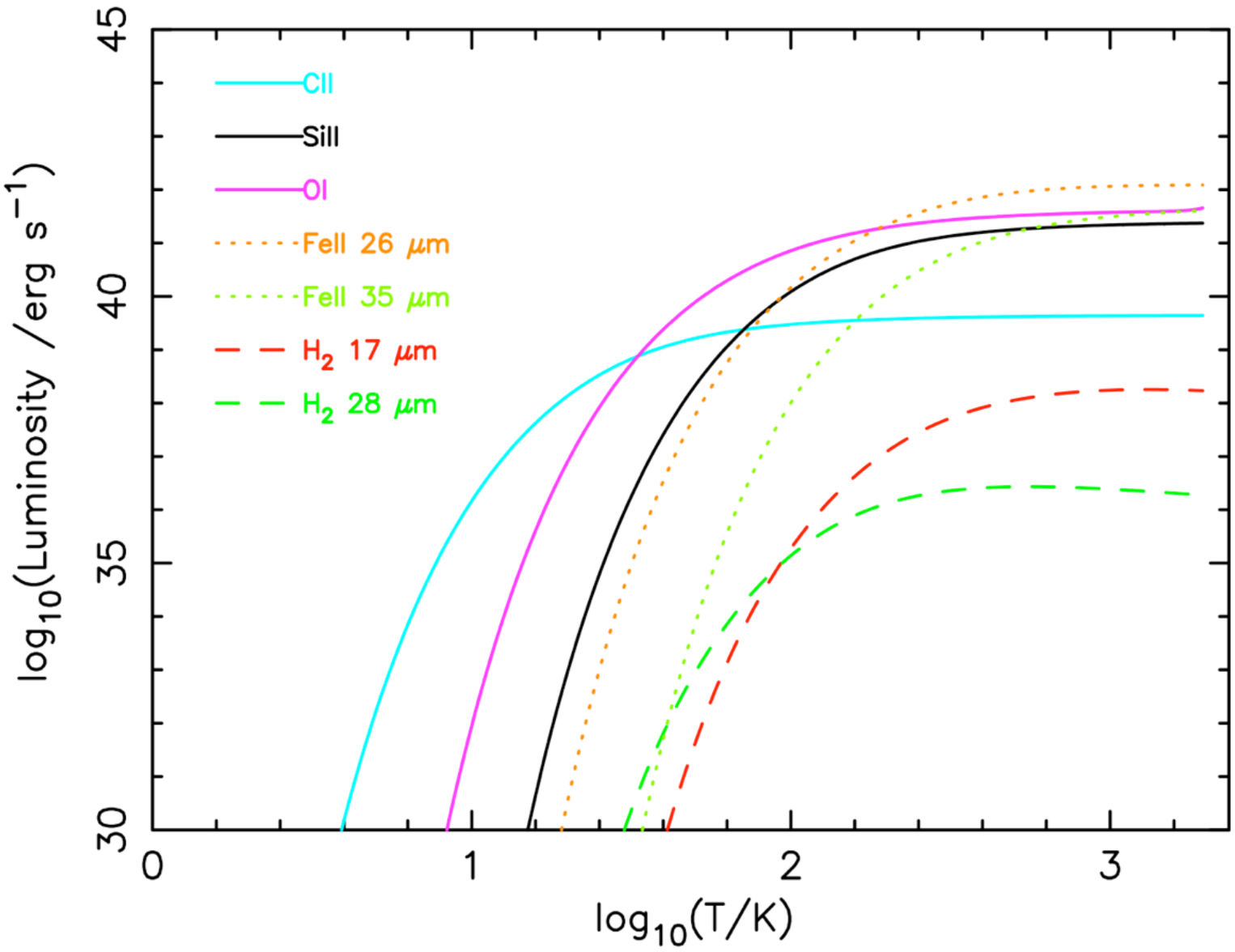


Jeans Masses vs Final Density (and Z_{crit})



Fine-Structure Line Luminosities (LTE)

(10^8 M_{sun} at 200 K and 0.01 Z_{sun})



Strongest lines:

FeII*, OI*, SiII*

[for dense clumps of cooling gas]

Astrophysical Summary

- Single metallicity no good (O, Si, Fe dominant)
- At low n the Z_{crit} may be as high as 1% solar
- At high n the minimum $Z_{crit} \sim 10^{-3.5}\ Z_{sun}$
- *Enrichment transition may occur on low-n track (mass-dependent)*
- FIR/sub-mm detections need 10^{-21} W m^{-2} *(hard!)*