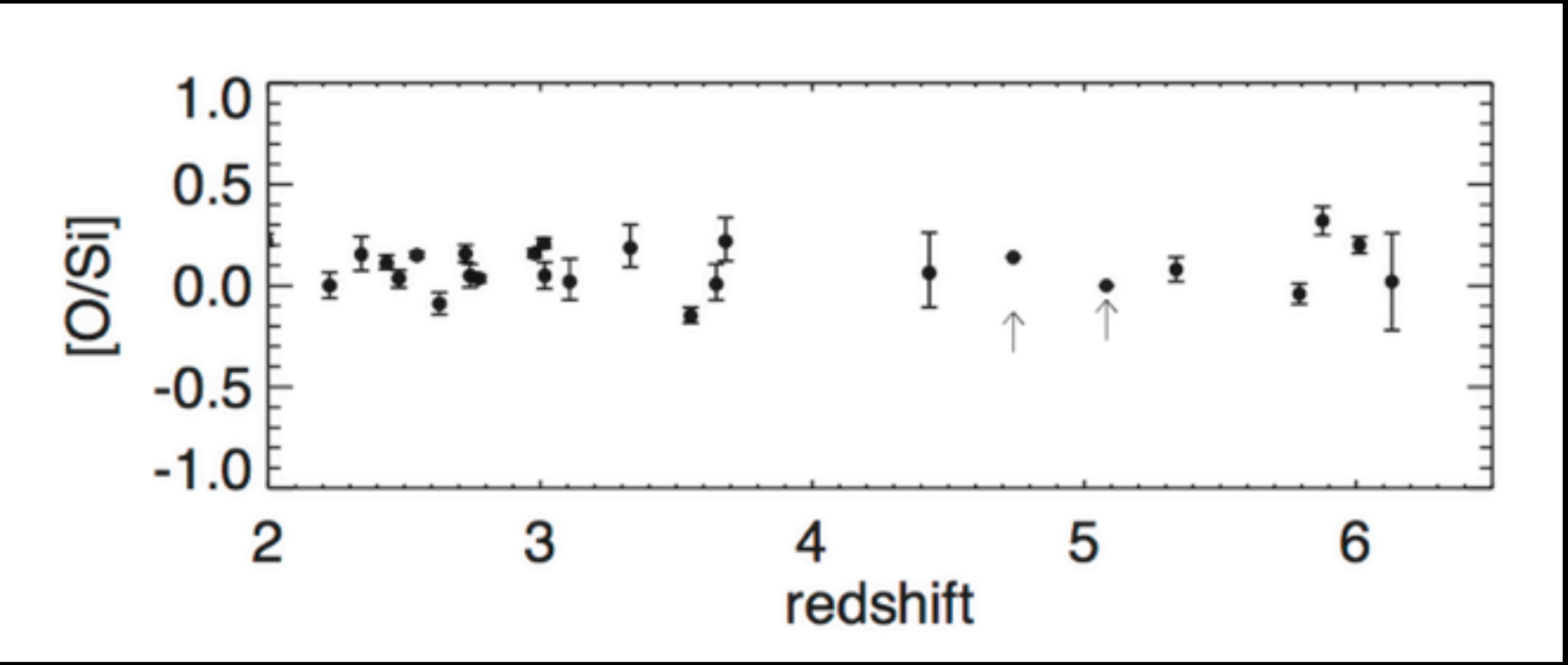
Becker et al. 2012



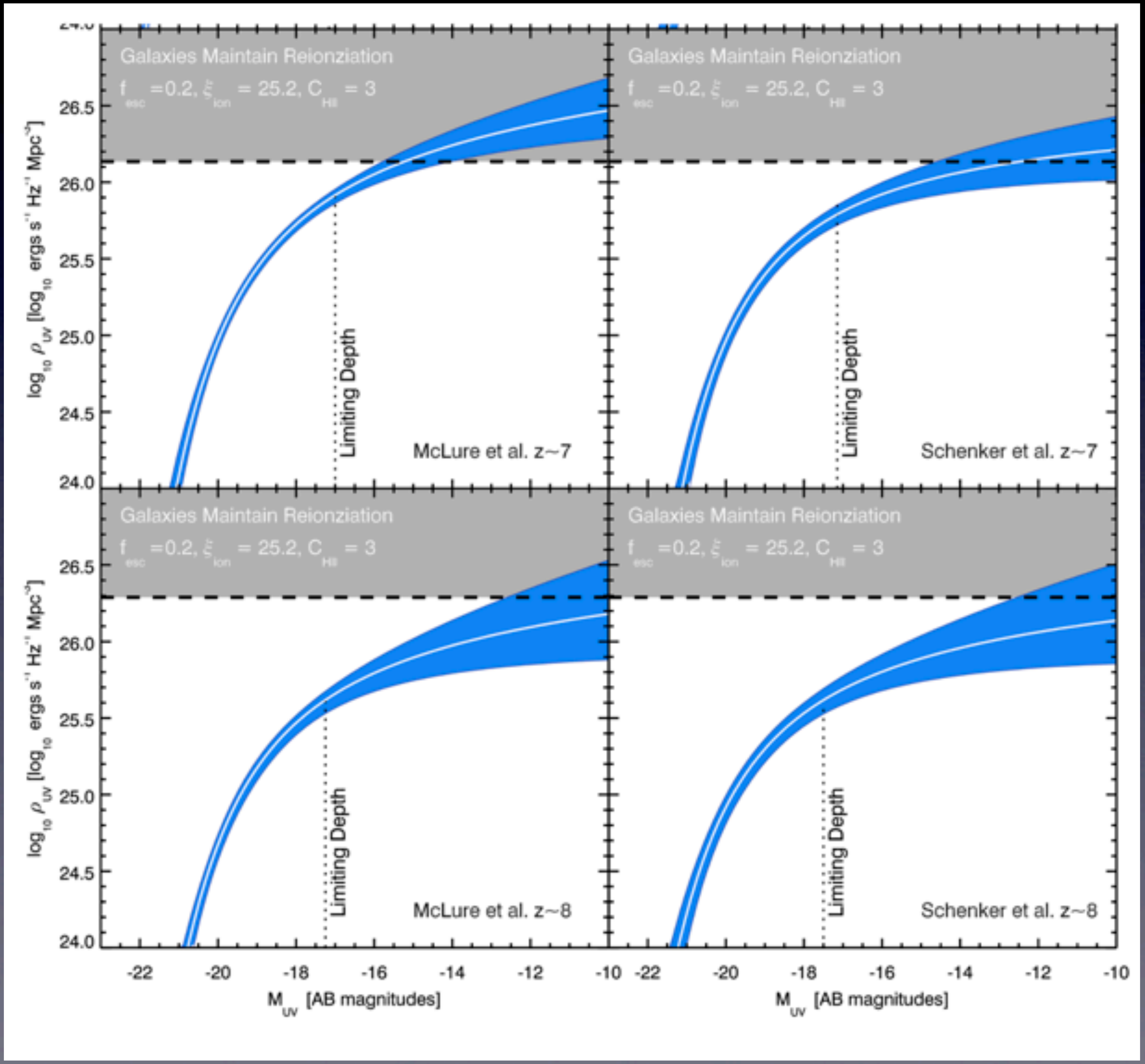
DLA chemical enrichment as a direct constraint on Pop III star formation

Girish Kulkarni – MPIA Heidelberg – July 15, 2013

Emmanuel Rollinde (IAP), Joe Hennawi (MPIA),
Elisabeth Vangioni (IAP)

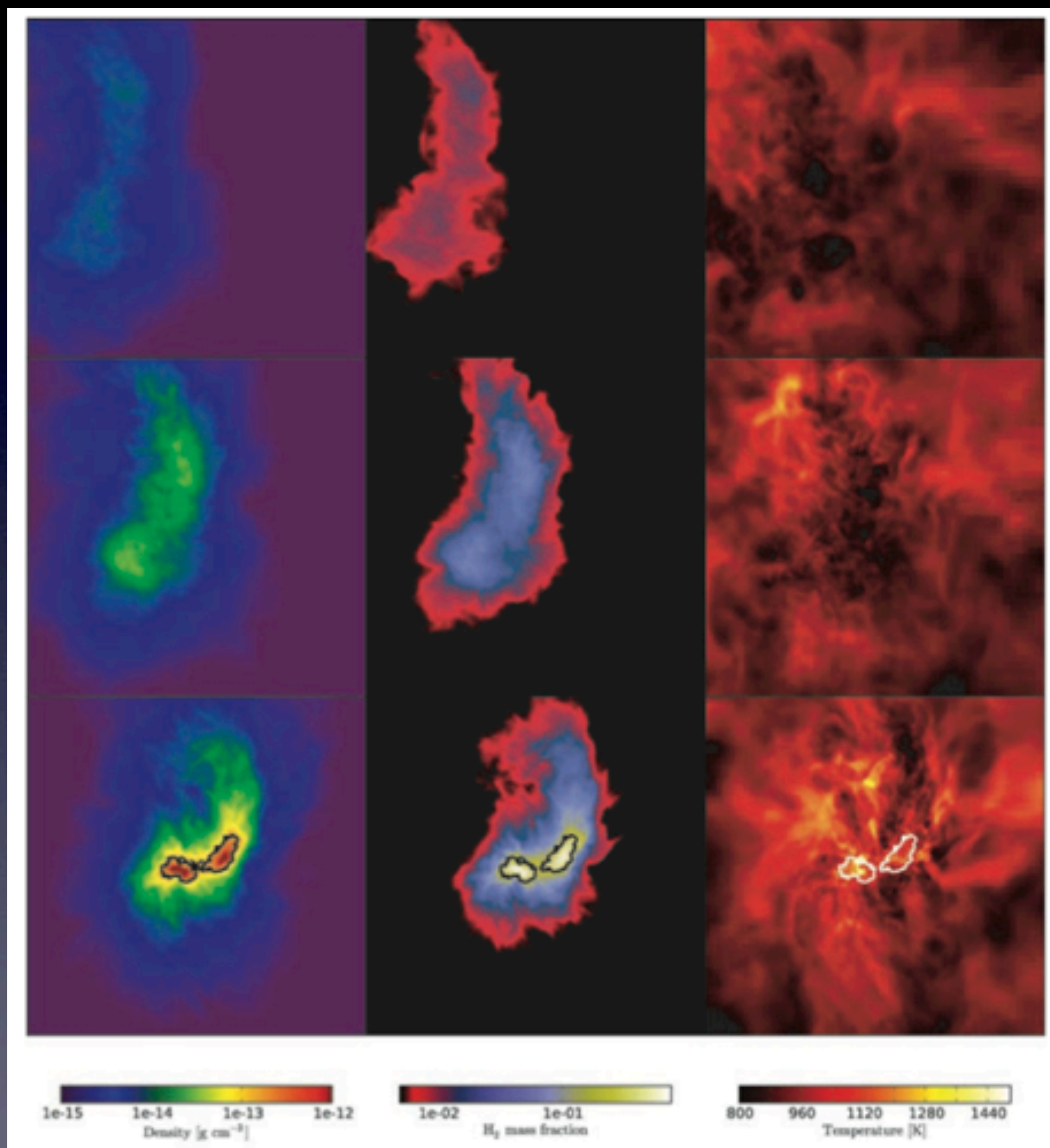
What are the sources of reionization?

Robertson et al. 2013

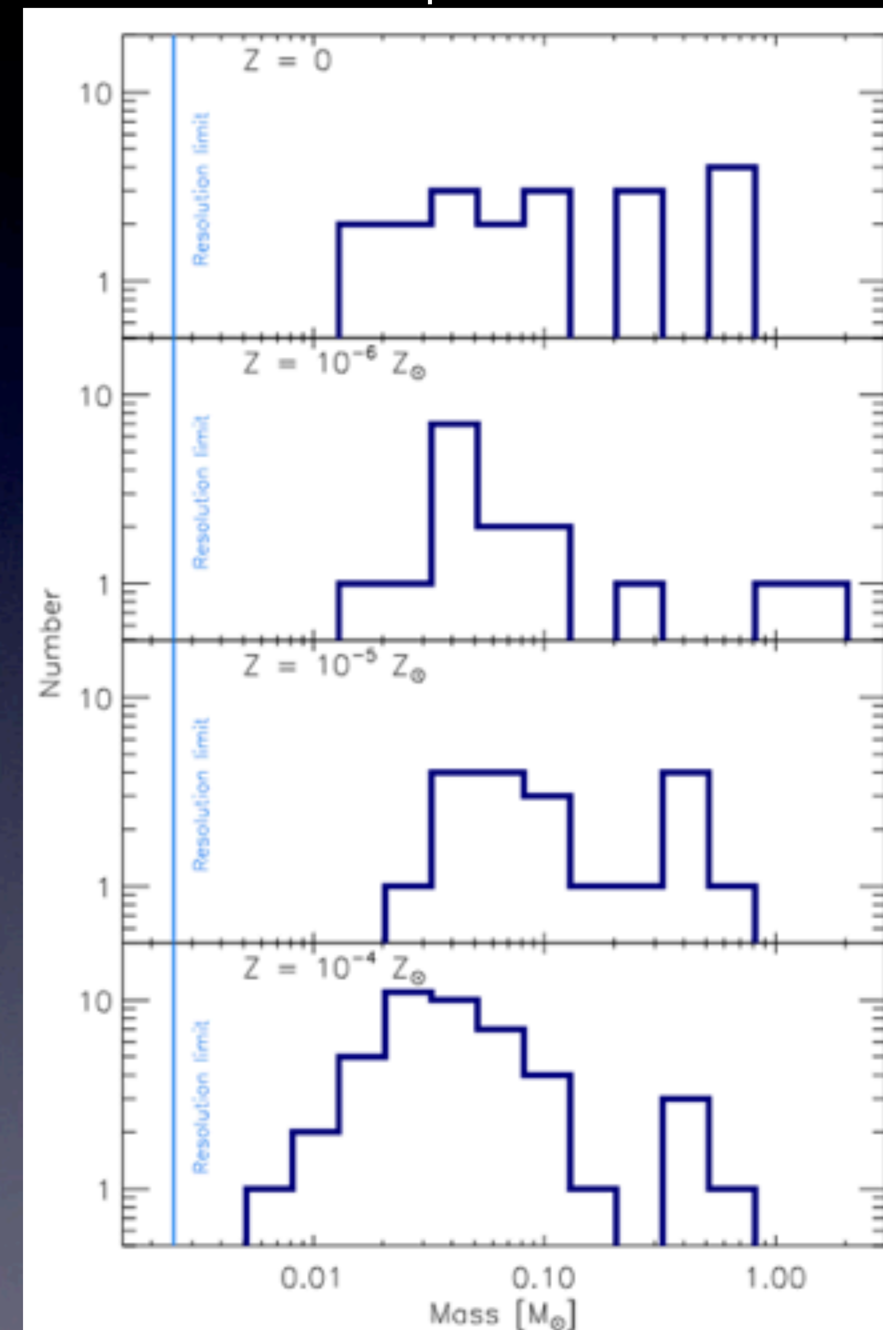


The Population III IMF is unknown

Turk et al. 2009



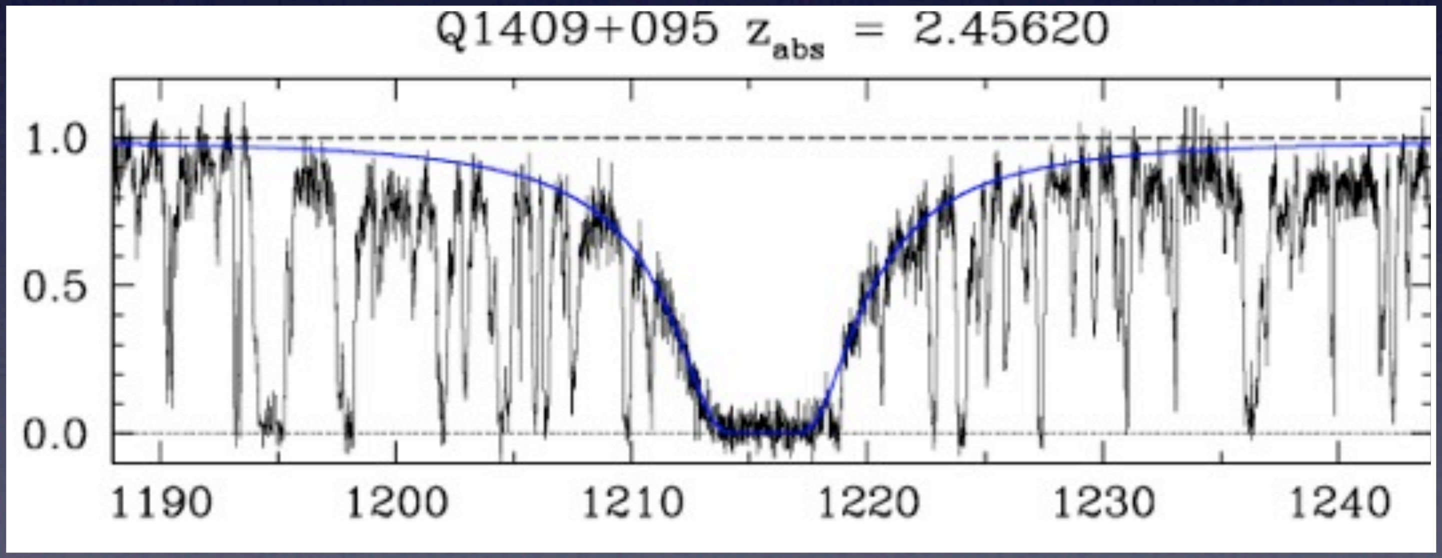
Dopcke et al. 2012



Population III stars *have* to exist but where and how remain unknown.

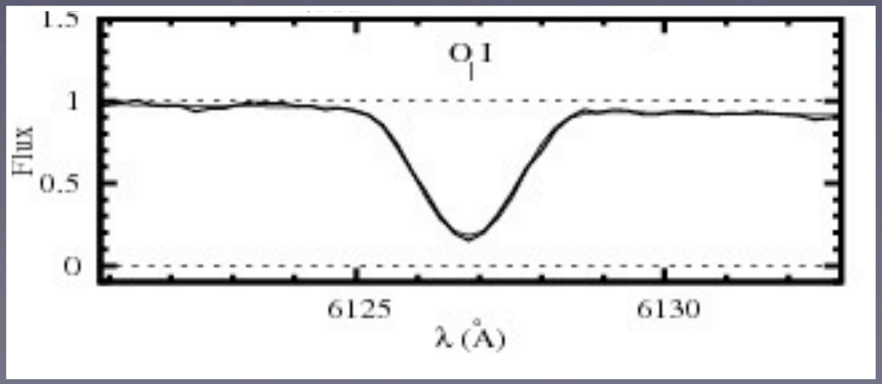
DLAs as probes of high z baryons

Trace cold gas at high redshift



Defined as systems with

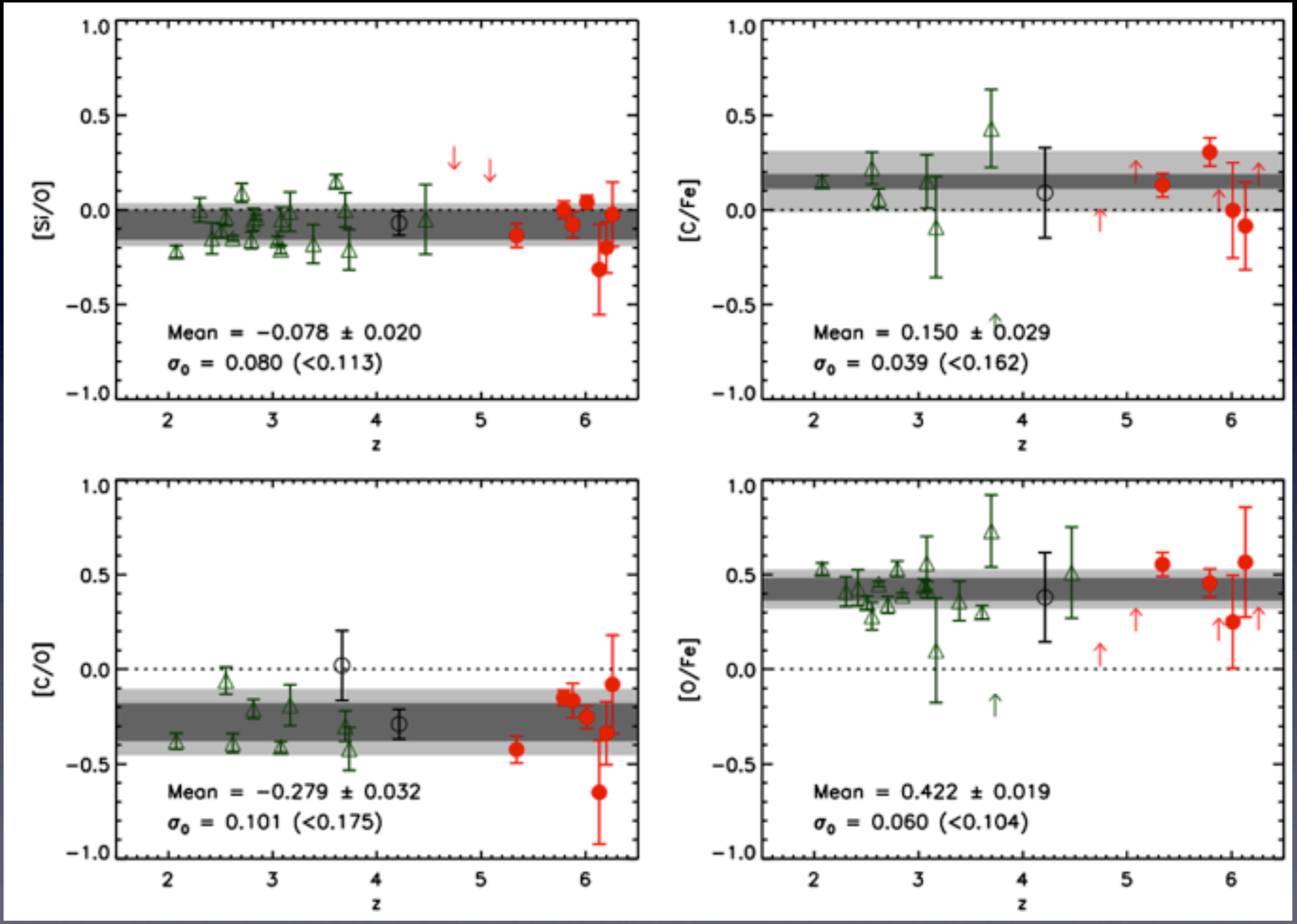
$$N_{\rm HI} > 2 \times 10^{20} {\rm cm}^{-2}$$



Excellent place to look for metals

DLAs as cosmic chemical records

Becker et al. 2012



Chemical measurements in DLAs are highly accurate (error ~ 0.1 dex) and can be done even beyond z ~ 6

Yields are clues to the stellar IMF

Abundance Yield IMF Stellar mass Metal mass

$$\frac{Z_{\rm O}}{Z_{\rm Si}} = \frac{y_{\rm O}}{y_{\rm Si}} = \frac{\int dm \cdot \phi(m) \cdot m \cdot p_{\rm O}(m)}{\int dm \cdot \phi(m) \cdot m \cdot p_{\rm Si}(m)}$$

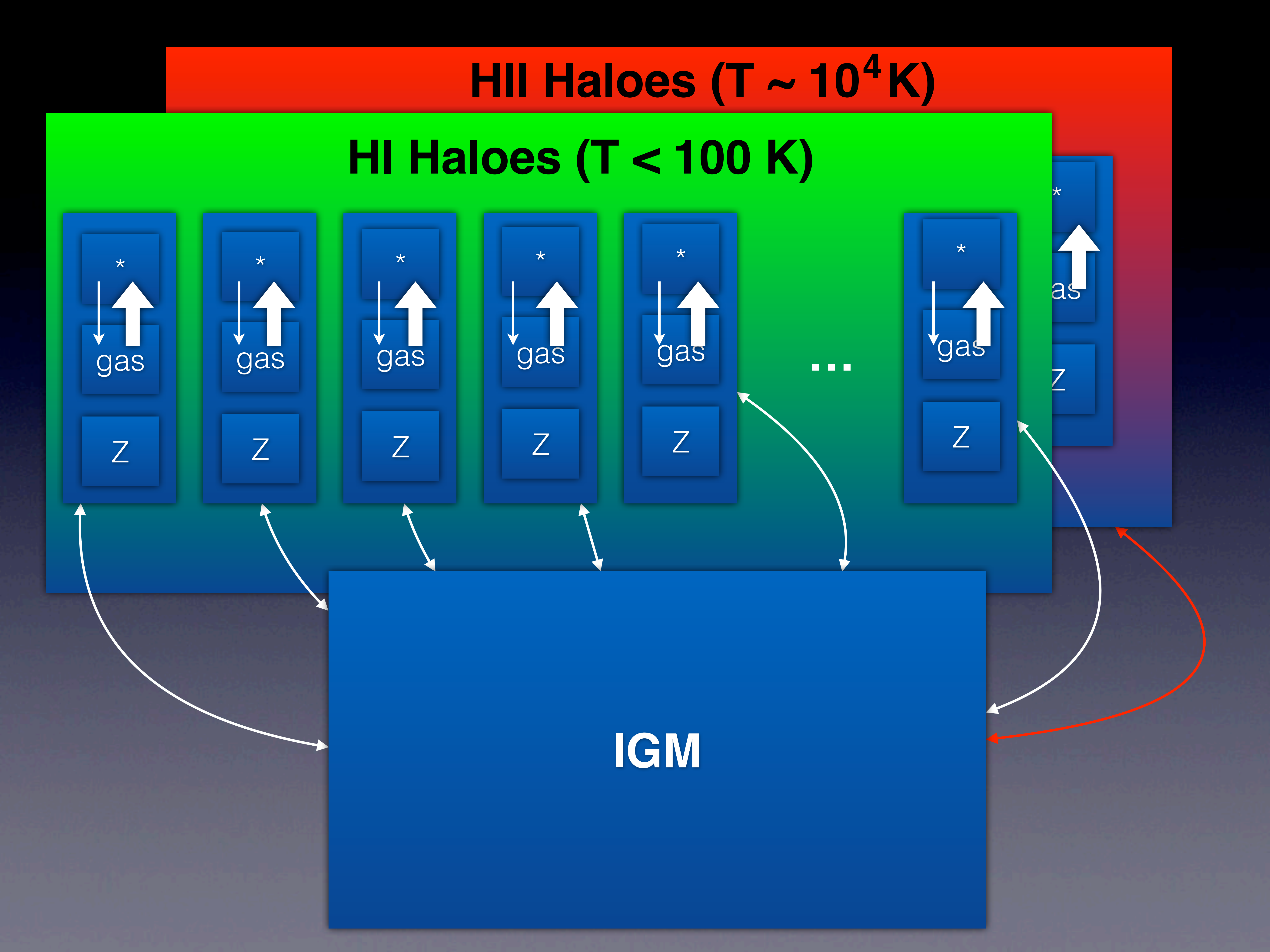
- Abundance ratios are interesting because they have simple dependance on the IMF.
- Therefore, abundance ratios usually change only if there is a change in the IMF.

Need cosmic chemical evolution model

- The model should
  - predict LFs and star formation rates
  - incorporate stellar yields to predict chemistry
  - include stellar lifetimes
  - couple to the IGM for reionization, reheating, and photoheating feedback
- Difference from conventional SAMs: we need a model that treats the IGM as well as galaxy formation.
- IGM $\longleftrightarrow$ Haloes $\longrightarrow$ DLAs

Algorithm

1. Take dark matter **halo assembly history** from simulations
2. Implement the baryon cycle in each halo: **gas, stars, and metals**
3. Model **interaction with the IGM**: outflows, inflows, reionization, reheating
4. Calibrate model using low-redshift observations: SFR density, photoionization rate, CMB optical depth, mas-metallicity relation
5. Implement **Population III** using a critical metallicity argument
6. Change **Pop III IMF** and observe effect on all observables, recalibrating each time


HII Haloes (T ~ 10^4 K)
HI Haloes (T < 100 K)
*
gas
Z
...
IGM

Algorithm

1. Take dark matter **halo assembly history** from simulations
2. Implement the baryon cycle in each halo: **gas, stars, and metals**
3. Model **interaction with the IGM**: outflows, inflows, reionization, reheating
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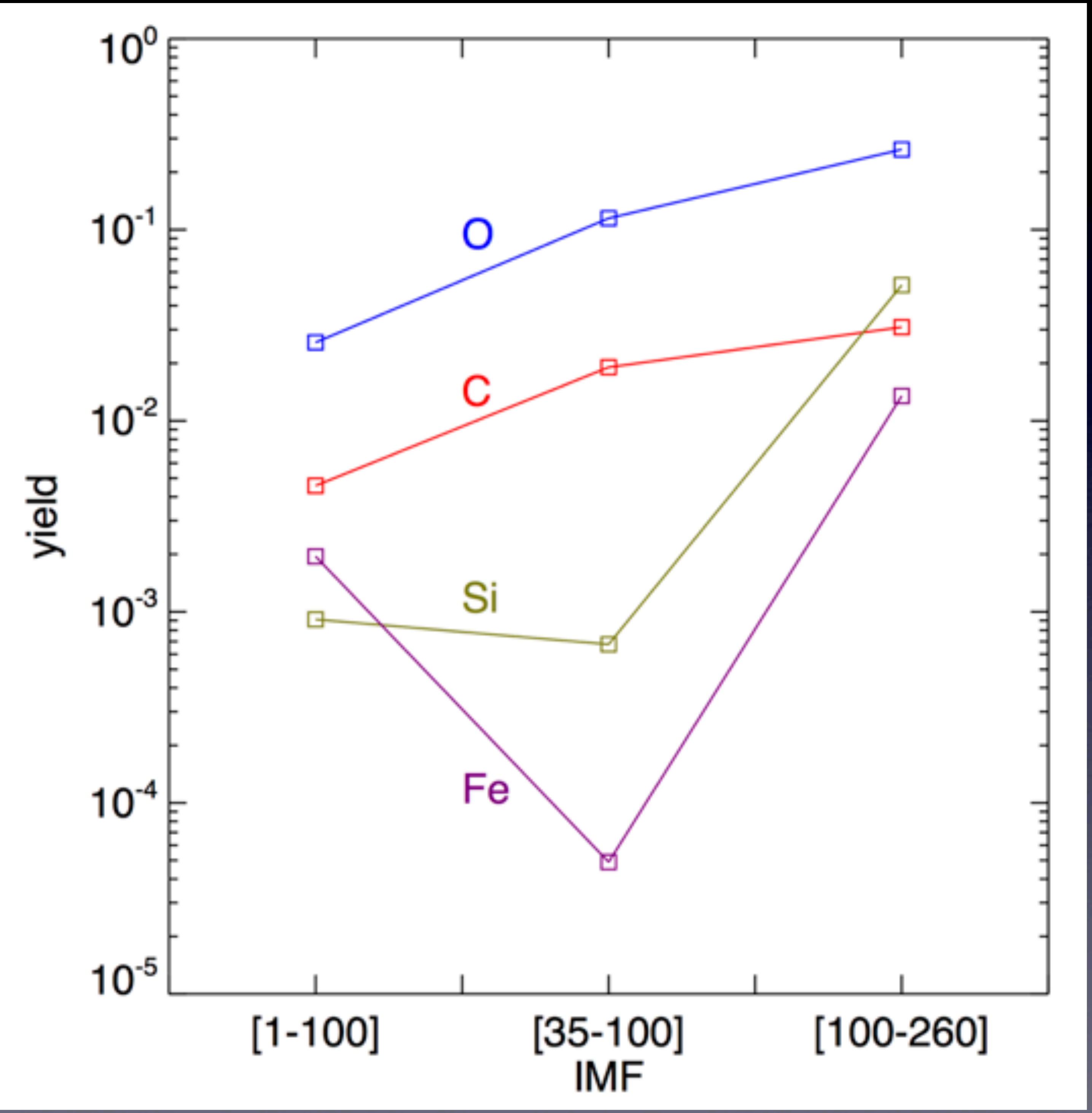
6. Change **Pop III IMF** and observe effect on all observables, recalibrating each time

Implement Pop III via critical metallicity

$$Z_{\rm cr} = 10^{-4} Z_\odot$$

1–100 Msun
35–100 Msun
100–300 Msun

Pop II always
0.1–100 Msun

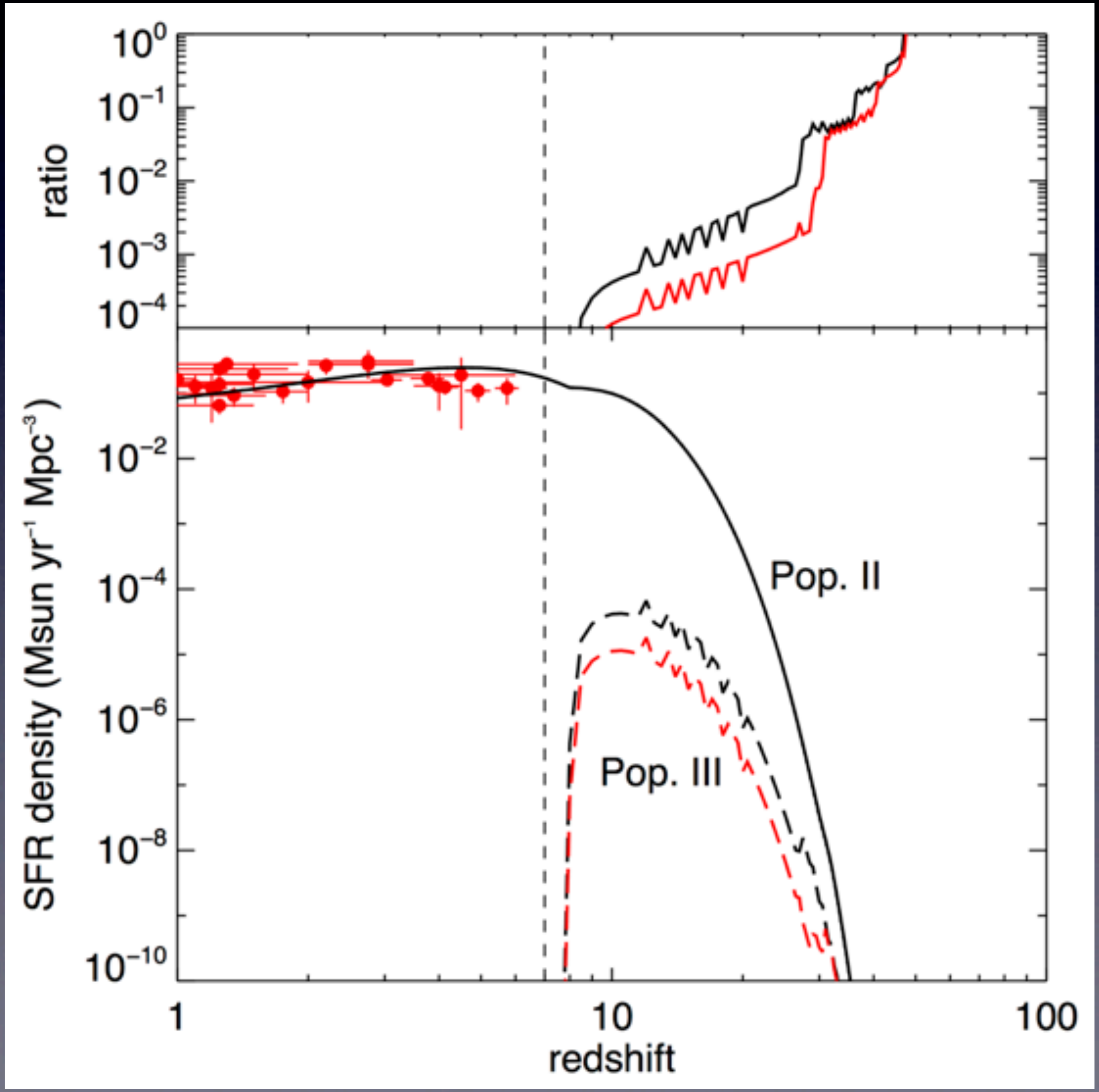


$$\text{yield} = \int dm \cdot \phi(m) \cdot m \cdot p(m)$$

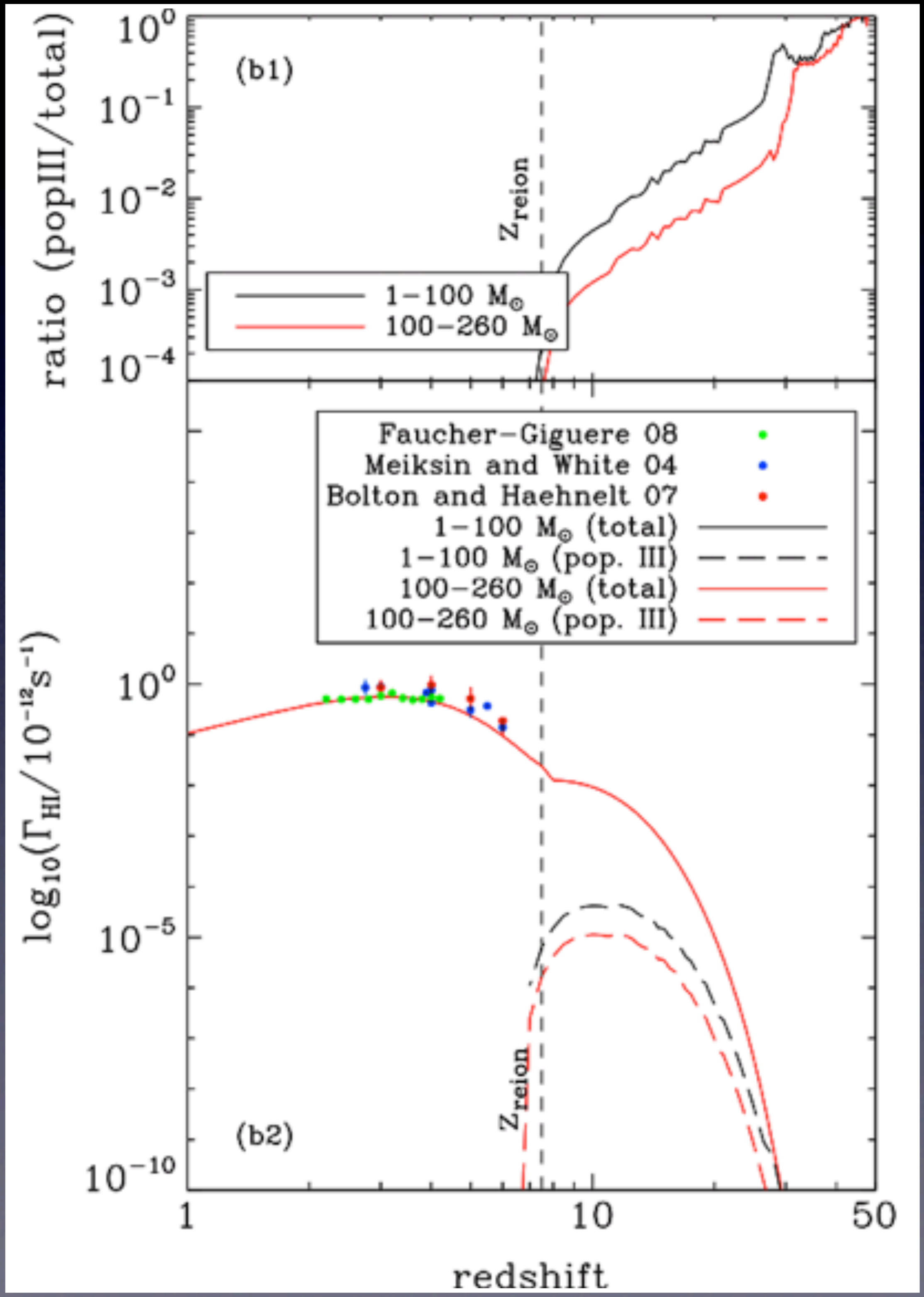
Population III star formation

- No Population III below z ~ 8.
- Little effect on reionization.
- Easily understood as effect depends on halo mass and Mstar haloes move to Population II SF very soon.

GK et al. 2013



Pop III effect on reionization is low



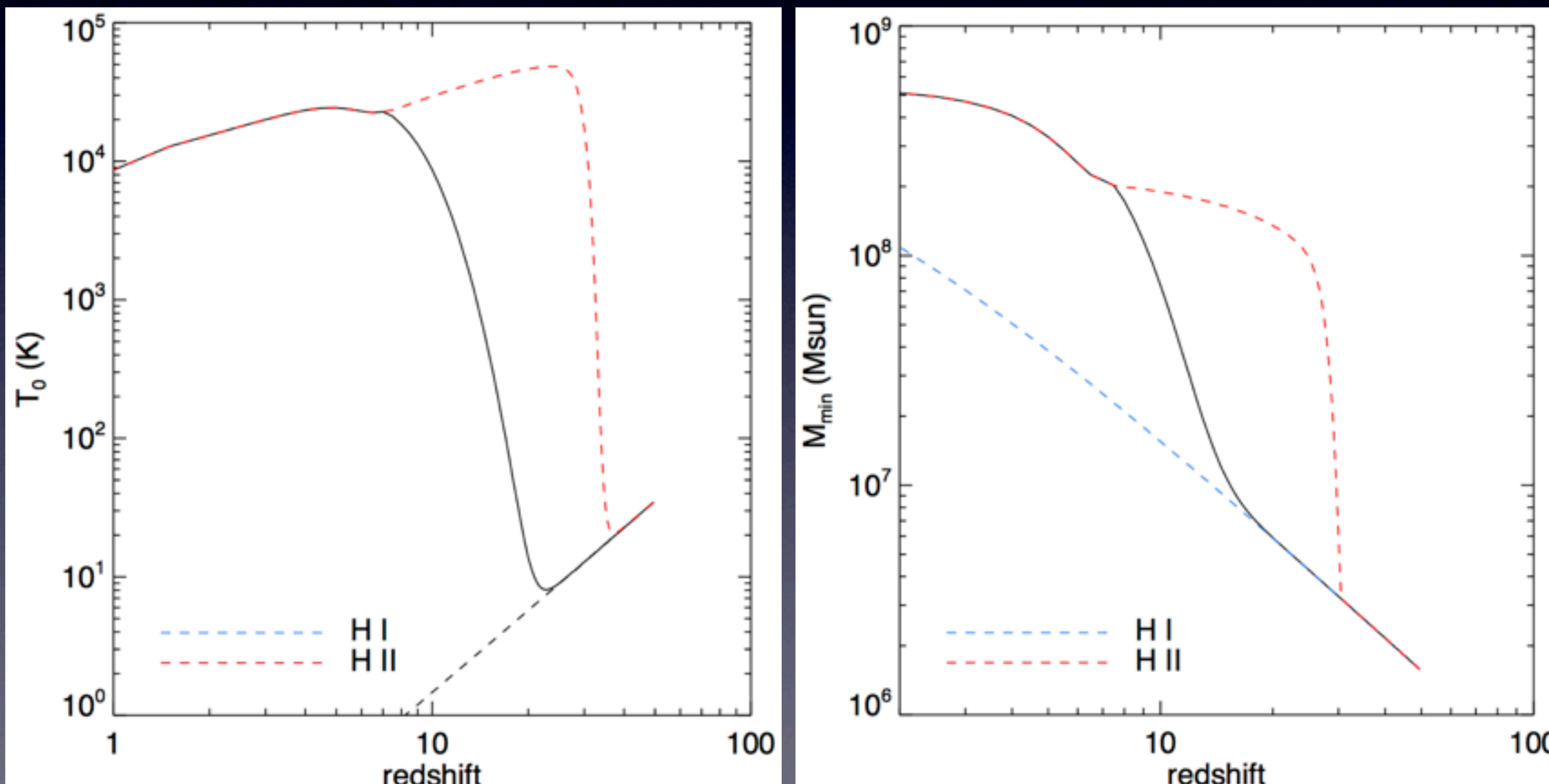
GK et al. 2013

- Less than 0.1% at z~6
- Result of our mixing assumption. Will return to that.
- Match with flat photoionization rate requires cosmic SFR to peak at slightly higher z (Faucher-Giguere et al., 2012)

IGM thermal history = feedback

Photoheating feedback: $M_{\min} \propto \left(\frac{k_B T}{G\rho}\right)^{3/2}$

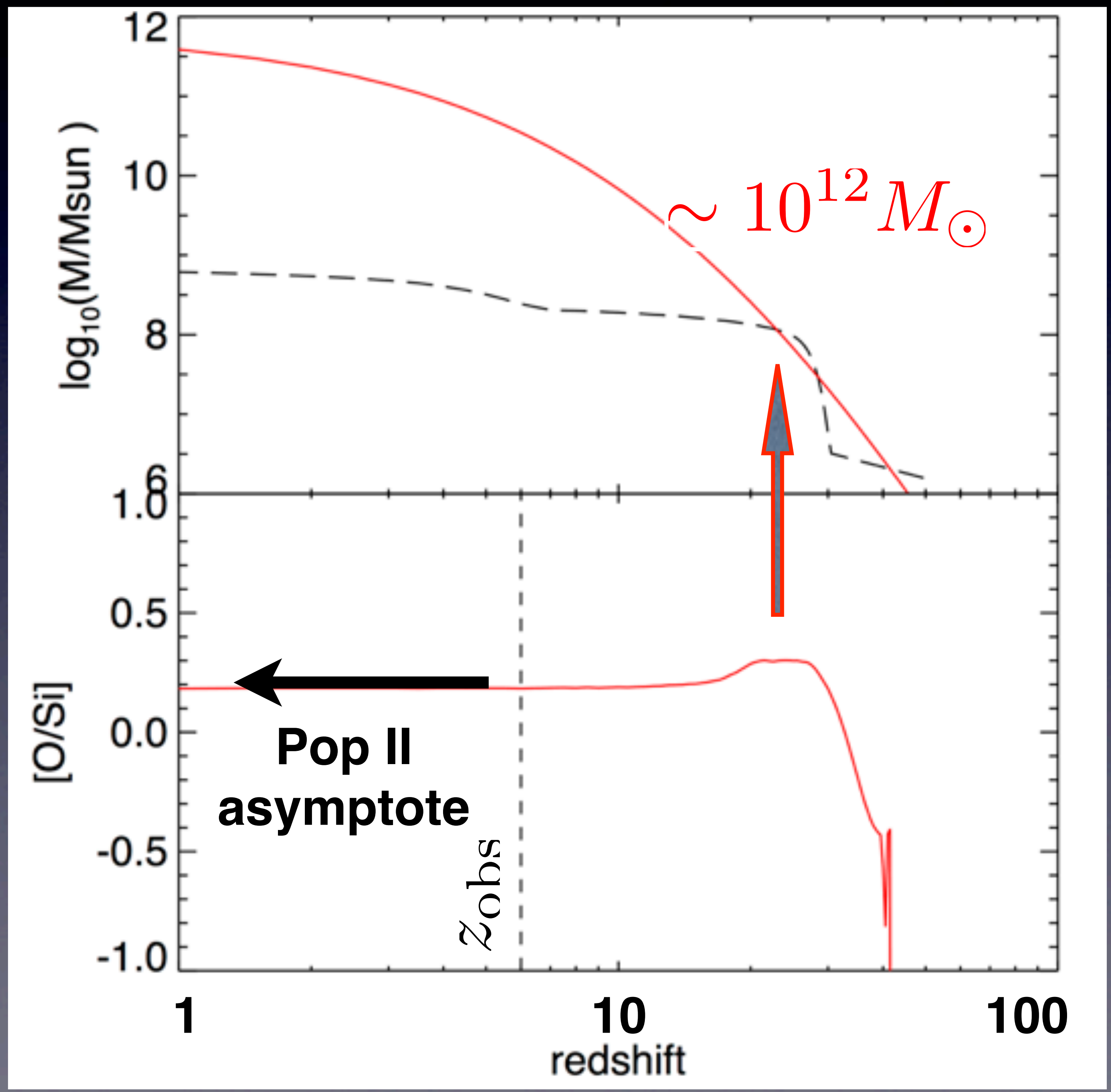
IGM temperature at mean density



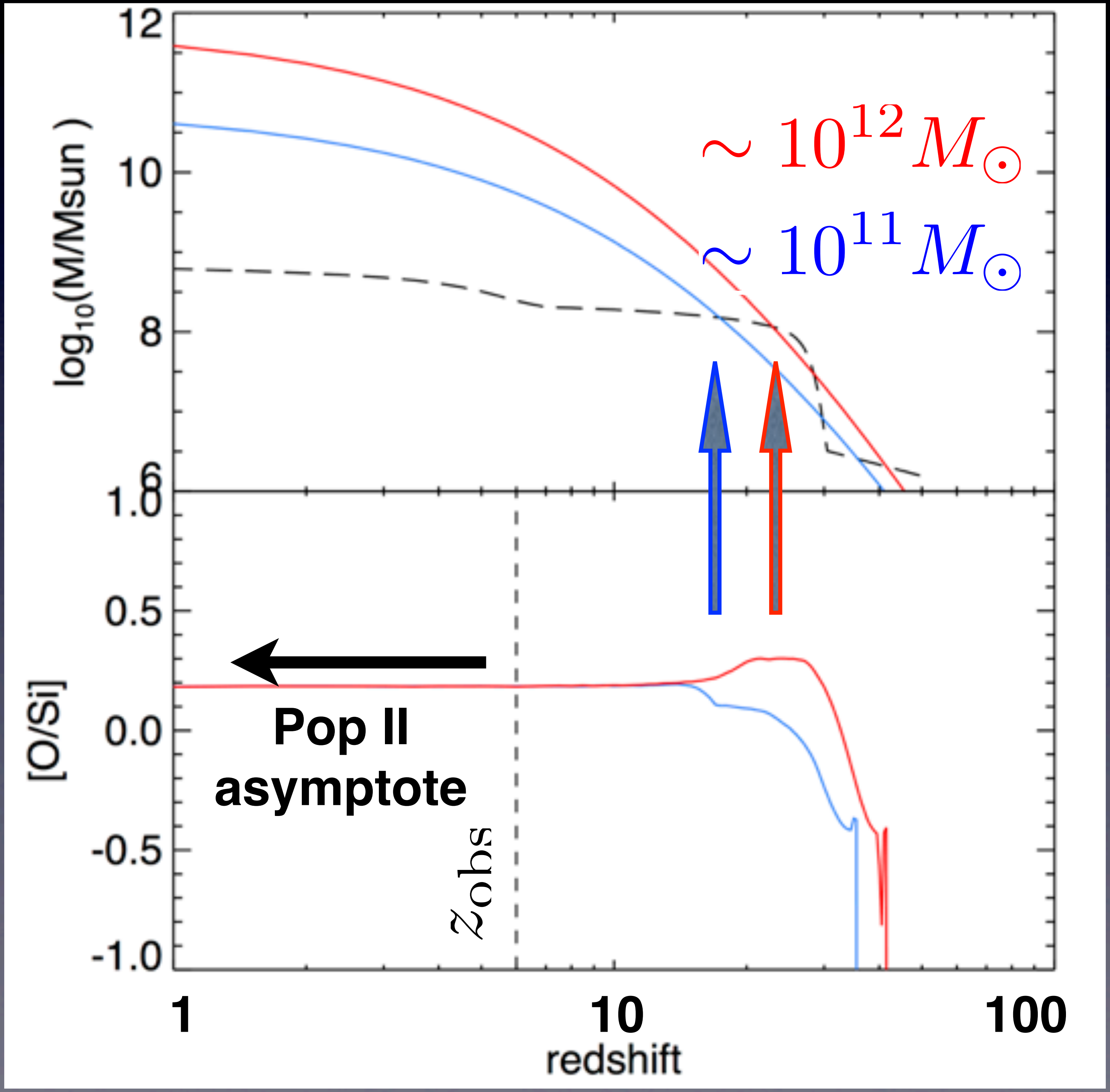
Minimum mass

Thermal history of H I and H II regions is quite different, resulting in different levels of feedback.

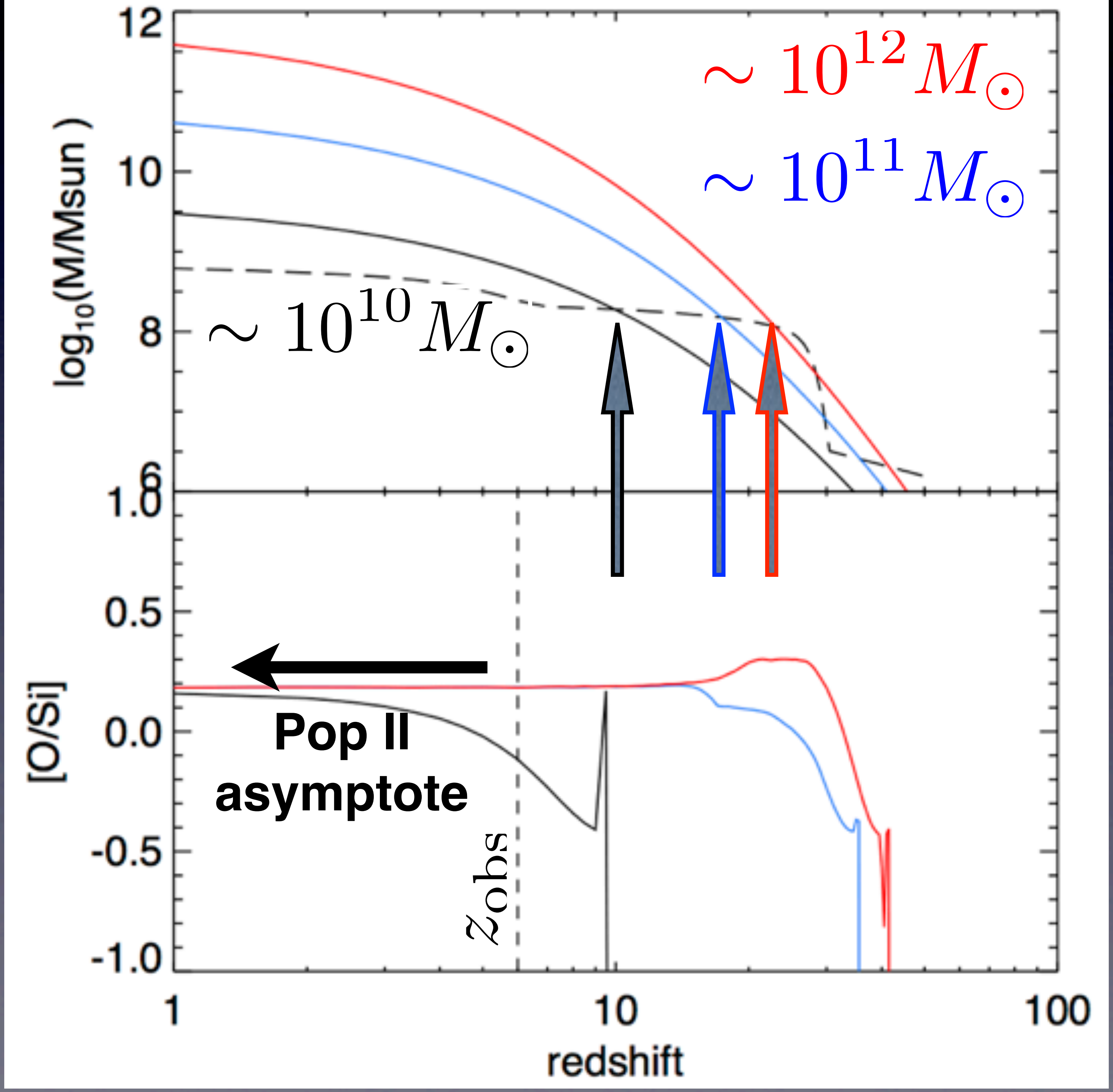
Chemical evolution of a halo depends on its mass!



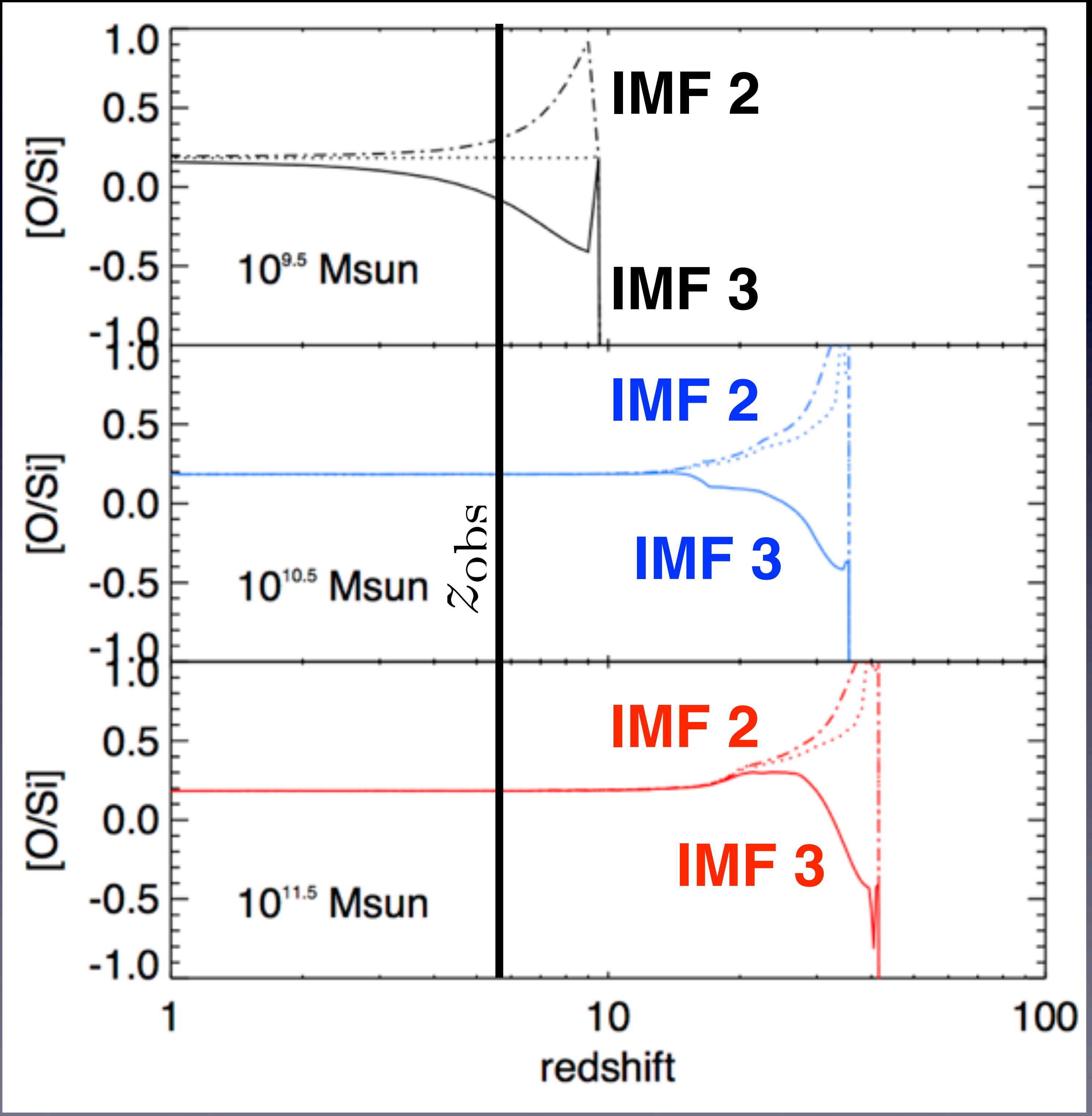
Chemical evolution of a halo depends on its mass!



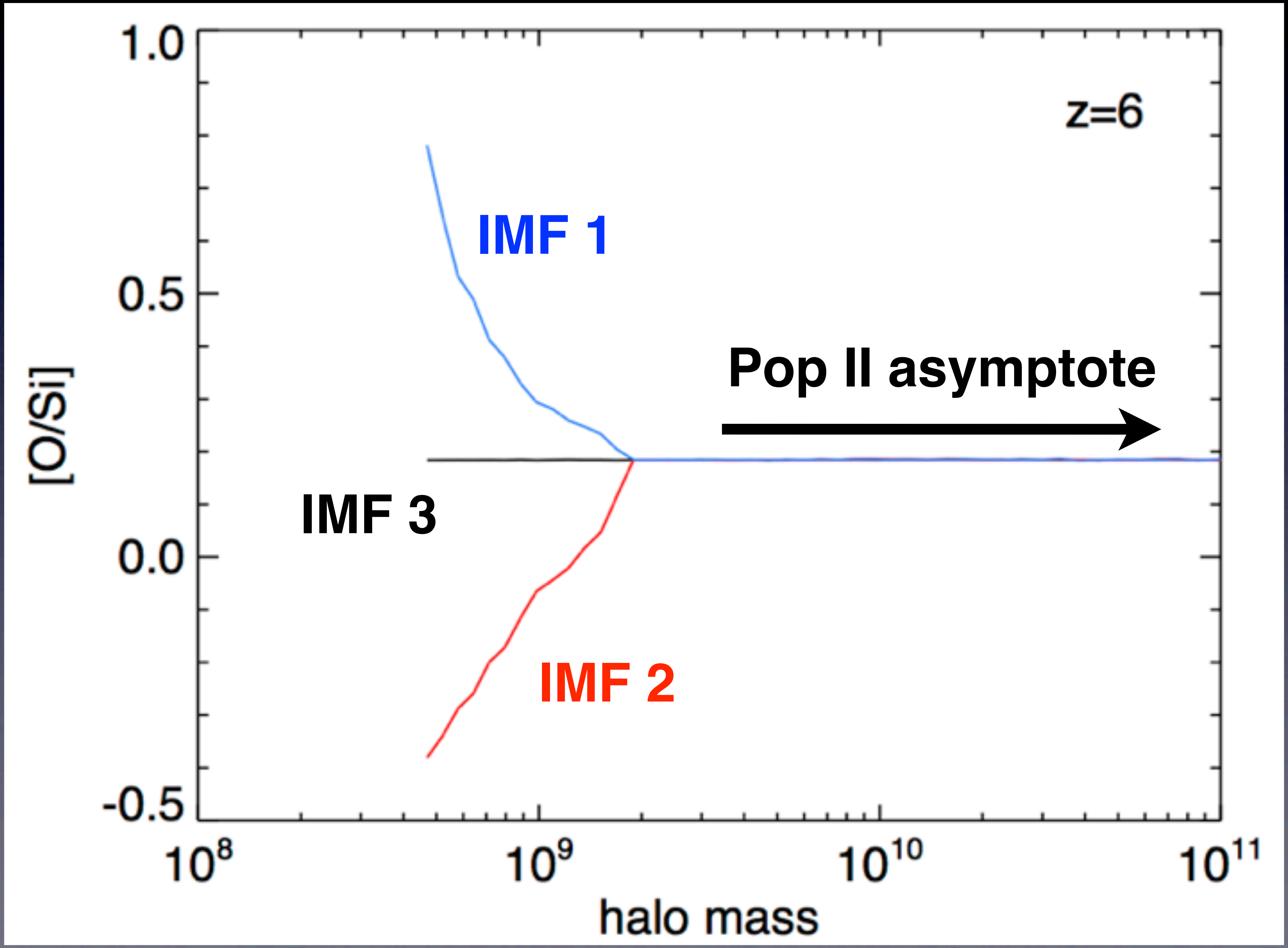
Chemical evolution of a halo depends on its mass!



Effect of Pop III IMF depends on halo mass!

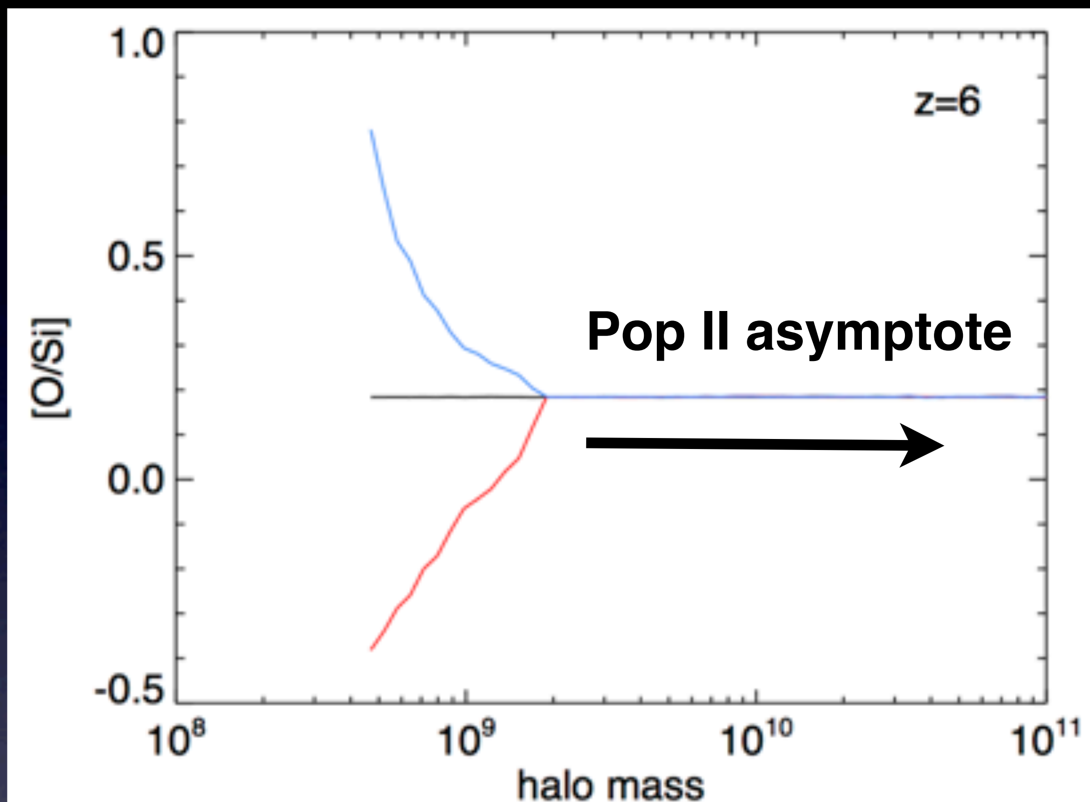


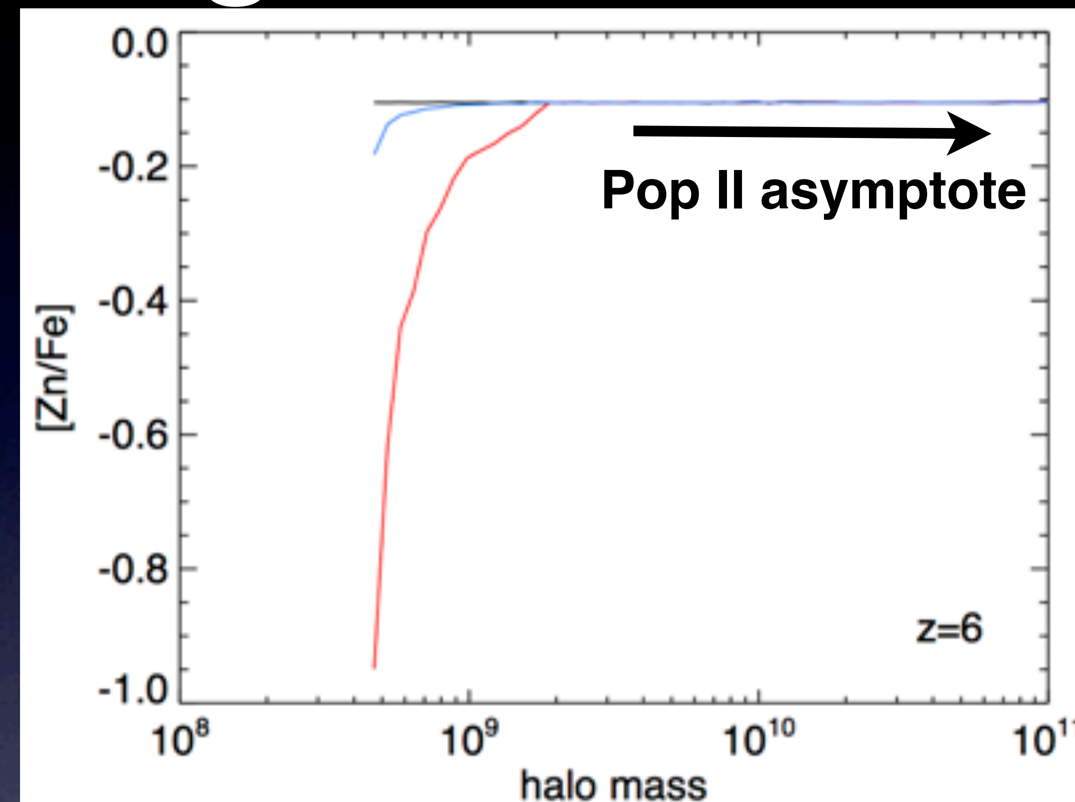
Mass-dependance is reflected in abundance ratios at given redshift

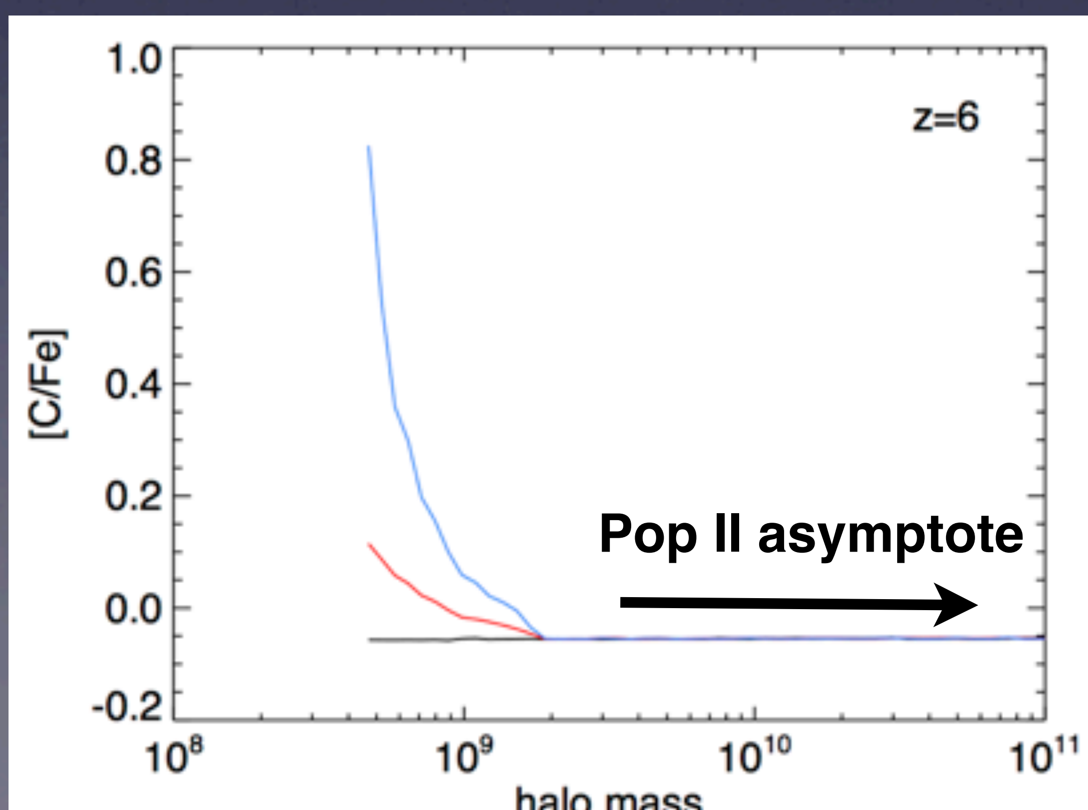


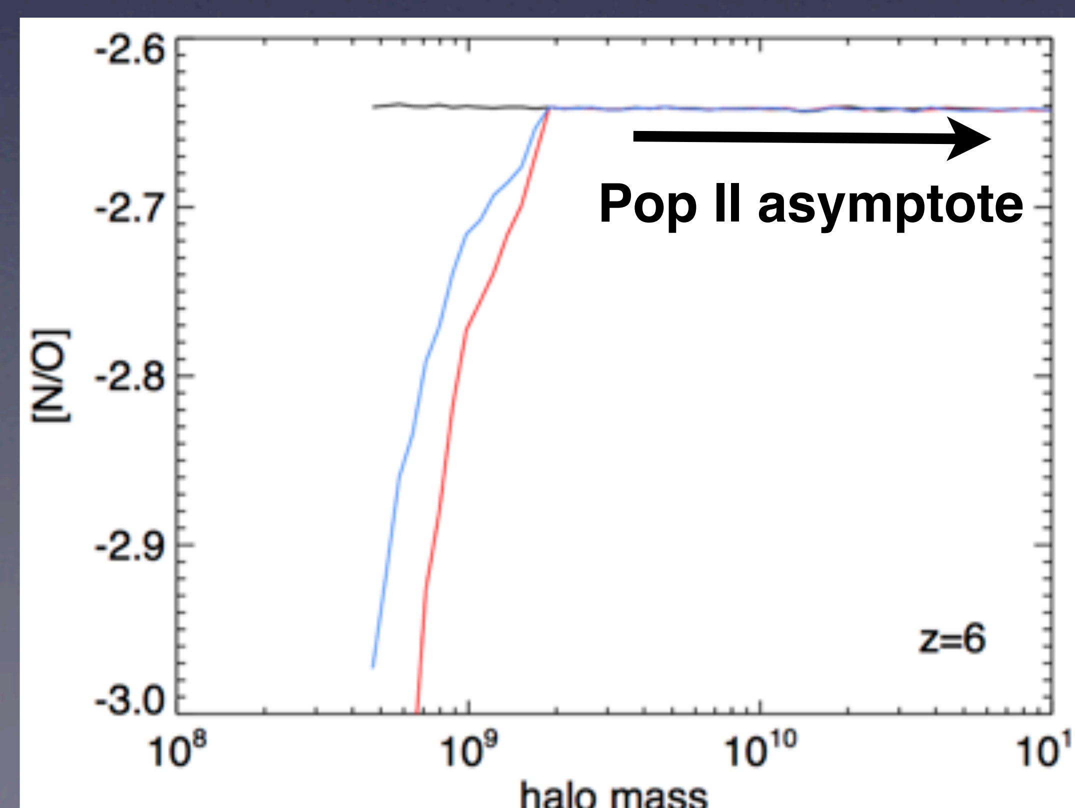
Kulkarni et al. 2013

Mass-dependance is reflected in abundance ratios at given redshift



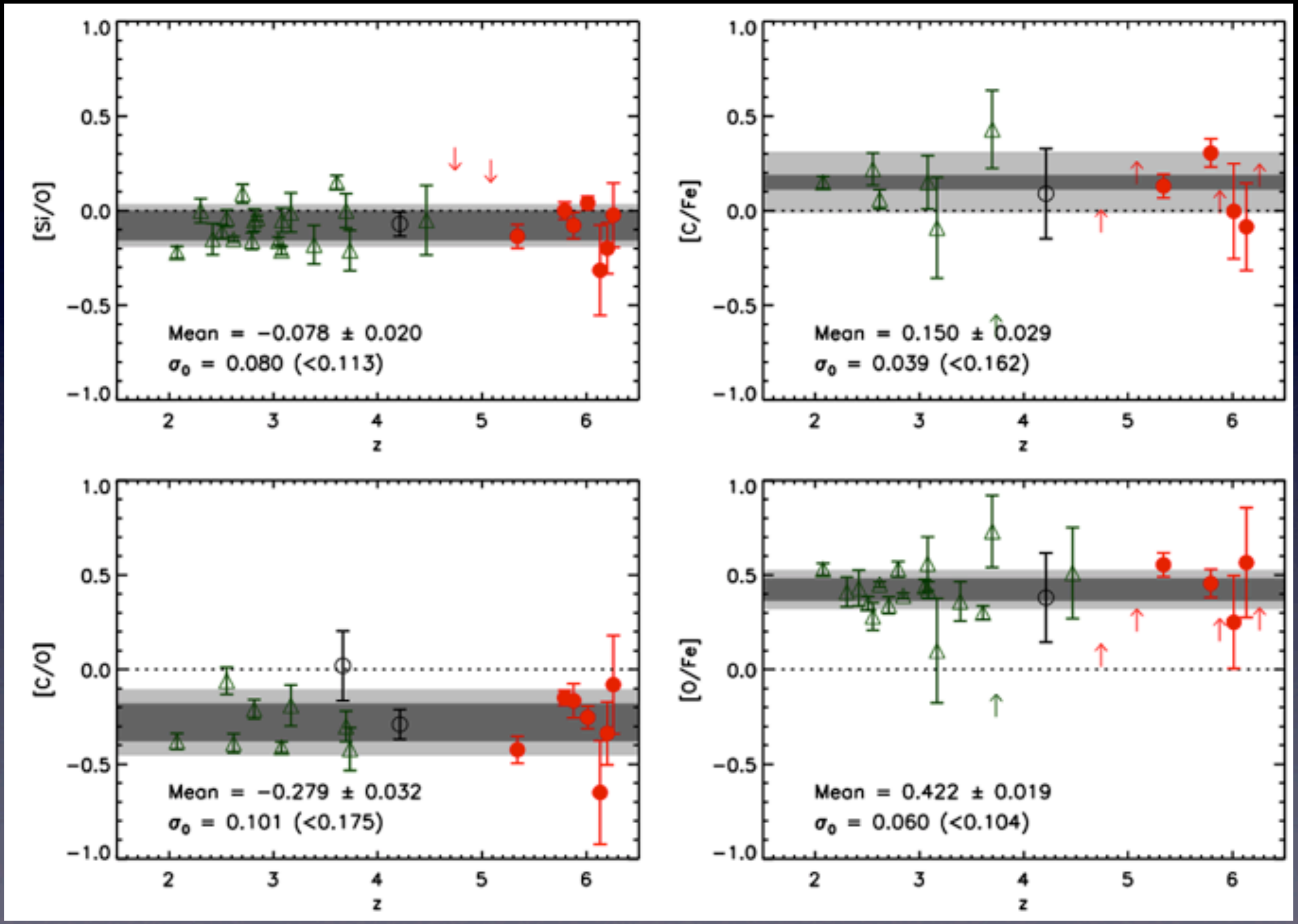






Now look at DLAs

Becker et al. 2012



DLA-Halo connection maps problem to DLAs

- DLAs are cold gas reservoirs in high redshift haloes.
- We assign a mass-dependant "HI size" to each halo

$$\Sigma(M) = \Sigma_0 \left(\frac{M}{M_0}\right)^2 \left(1 + \frac{M}{M_0}\right)^{\alpha-2}$$

- With this assignment, we can translate previous halo results to DLAs
- Can now do statistics:

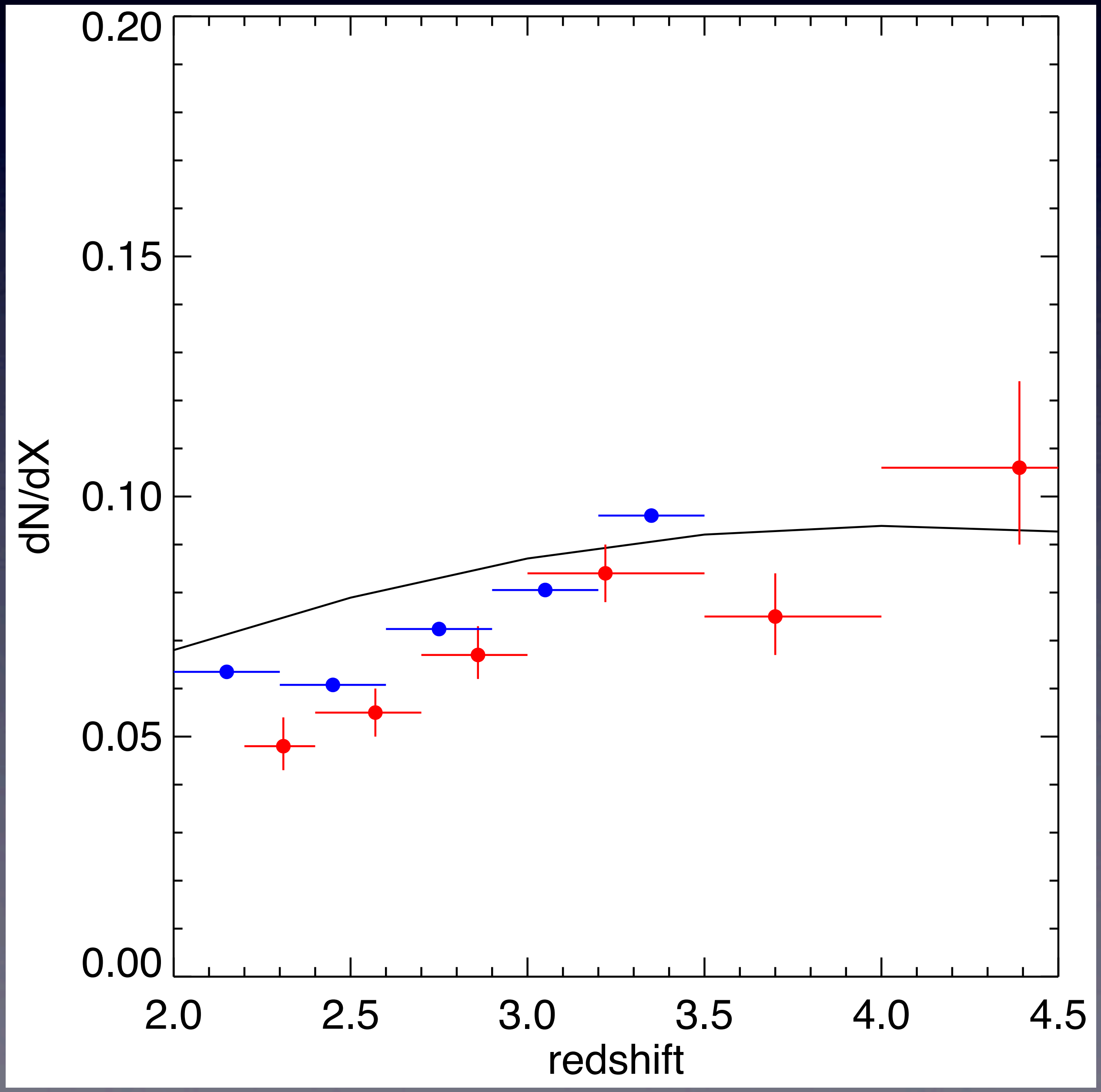
$$\frac{d^2N}{dz\,d[\mathrm{O/Si}]} = N_h(M) \cdot \Sigma(M) \cdot \frac{dl}{dz} \frac{dM}{d[\mathrm{O/Si}]} \cdot (1+z)^3$$

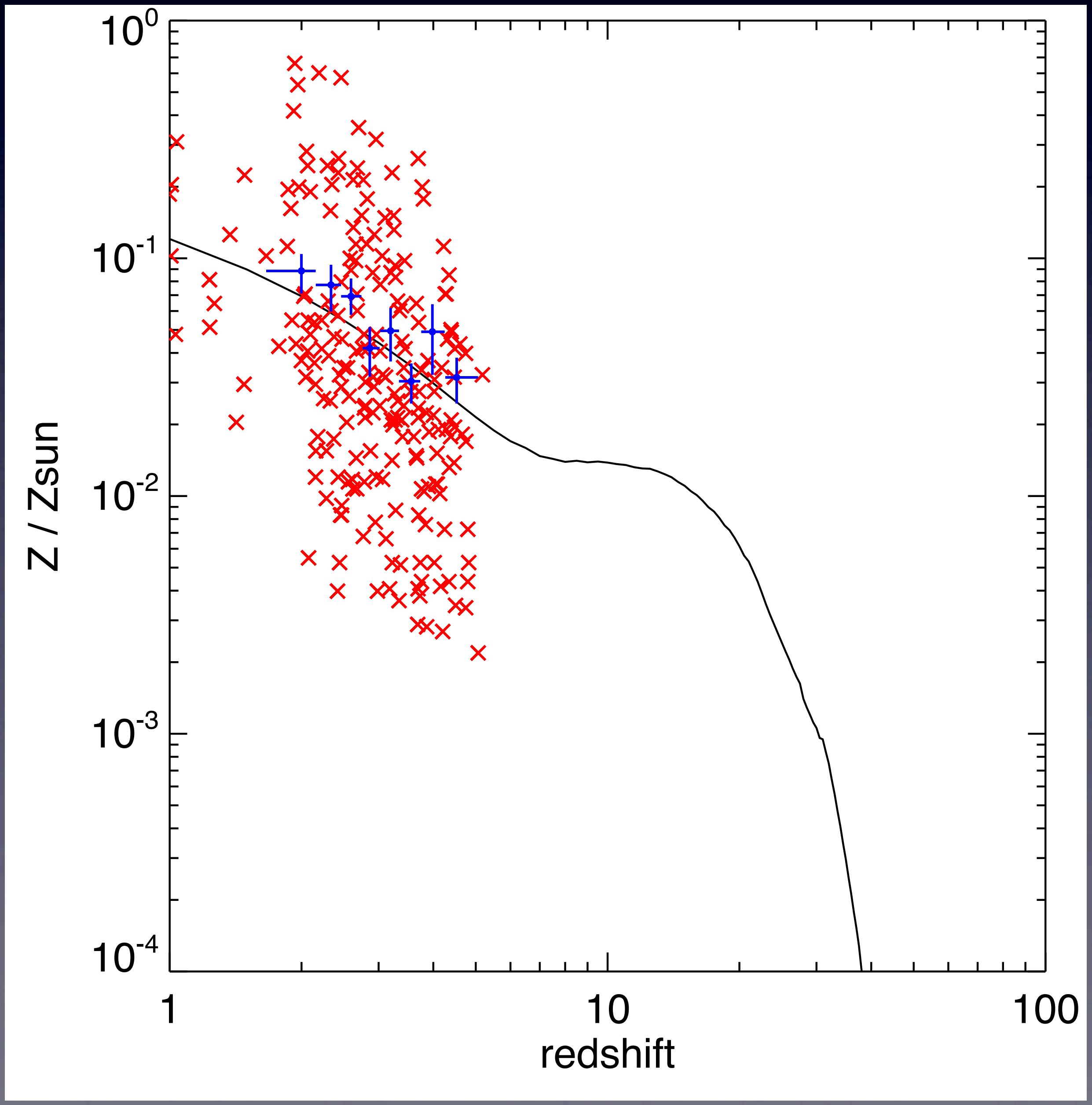
Predicted DLA bulk properties agree with observations

Prochaska et al. 2005,
Noterdaeme et al. 2012

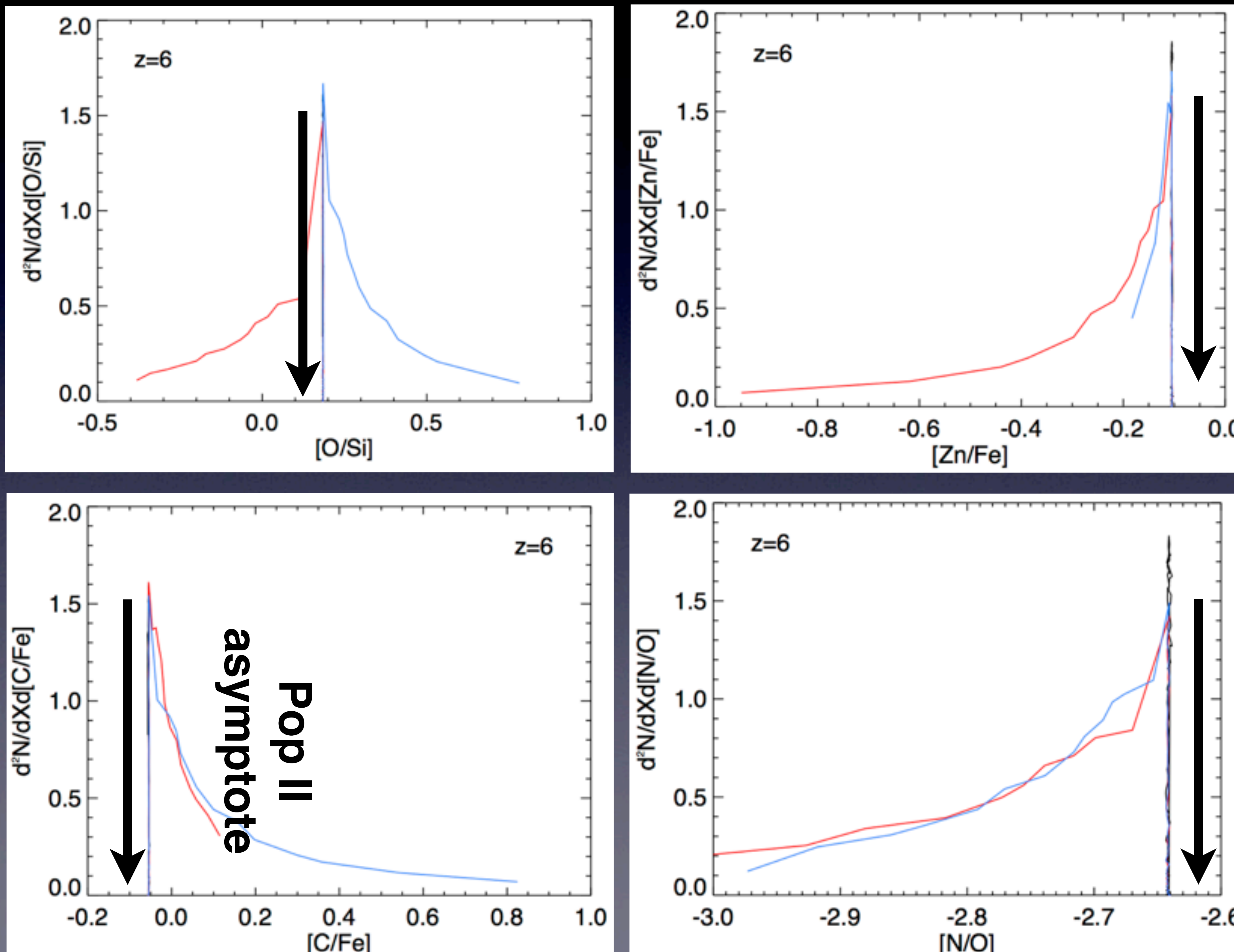
GK et al. 2013

Rafelski et al. 2012

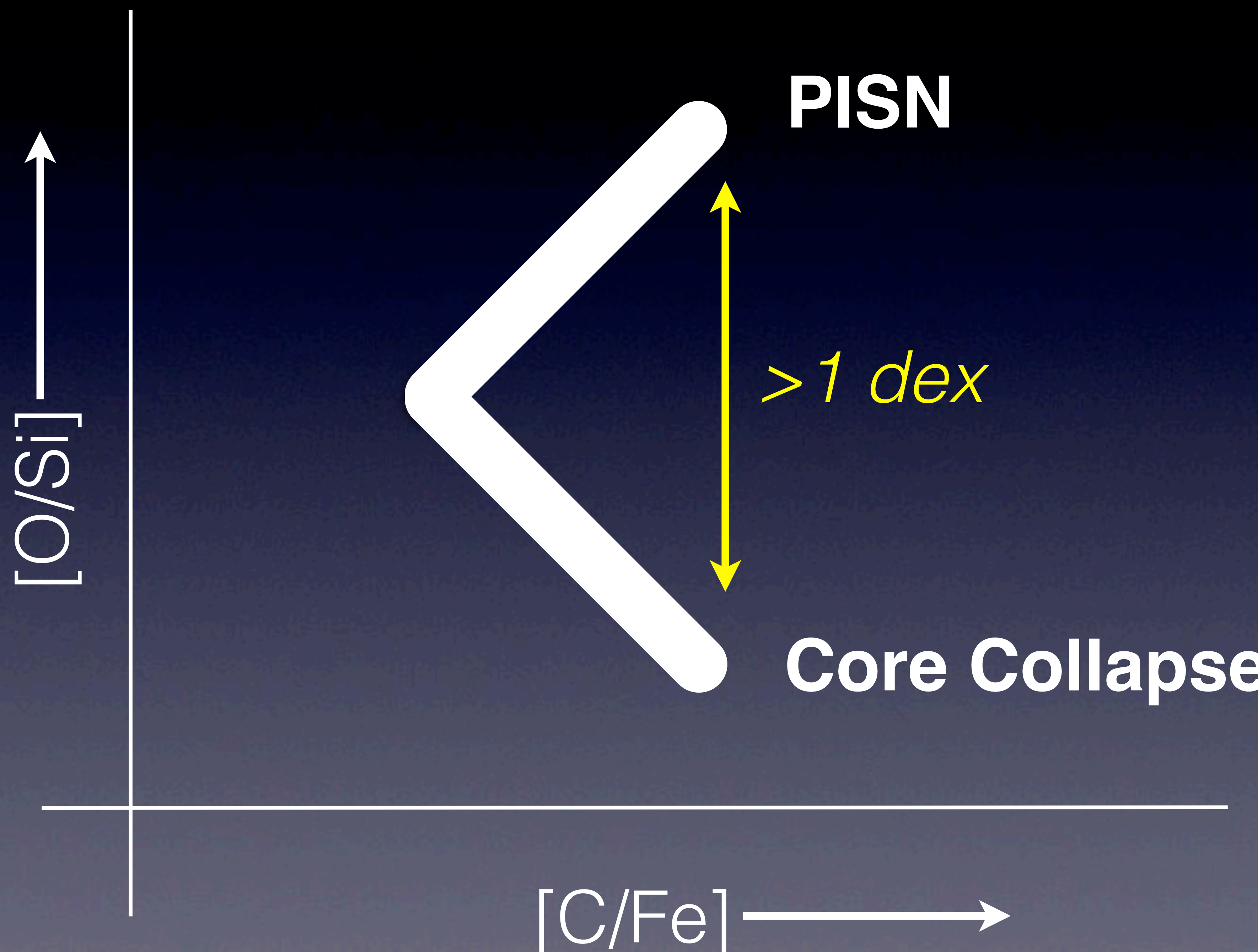




DLA abundance ratio distributions (z = 6)

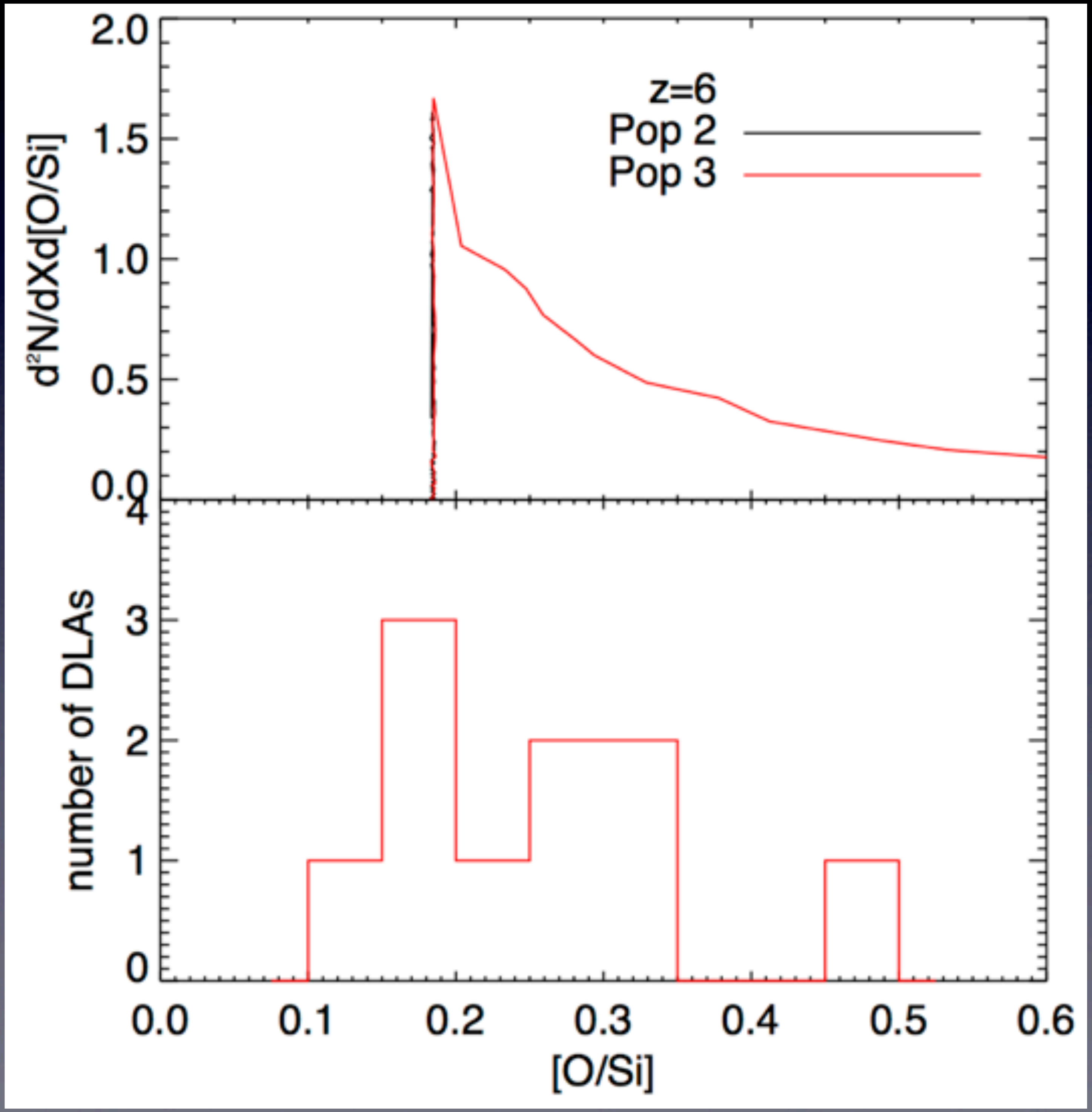


DLA abundance ratio distributions (z = 6)



This effect is easily observable

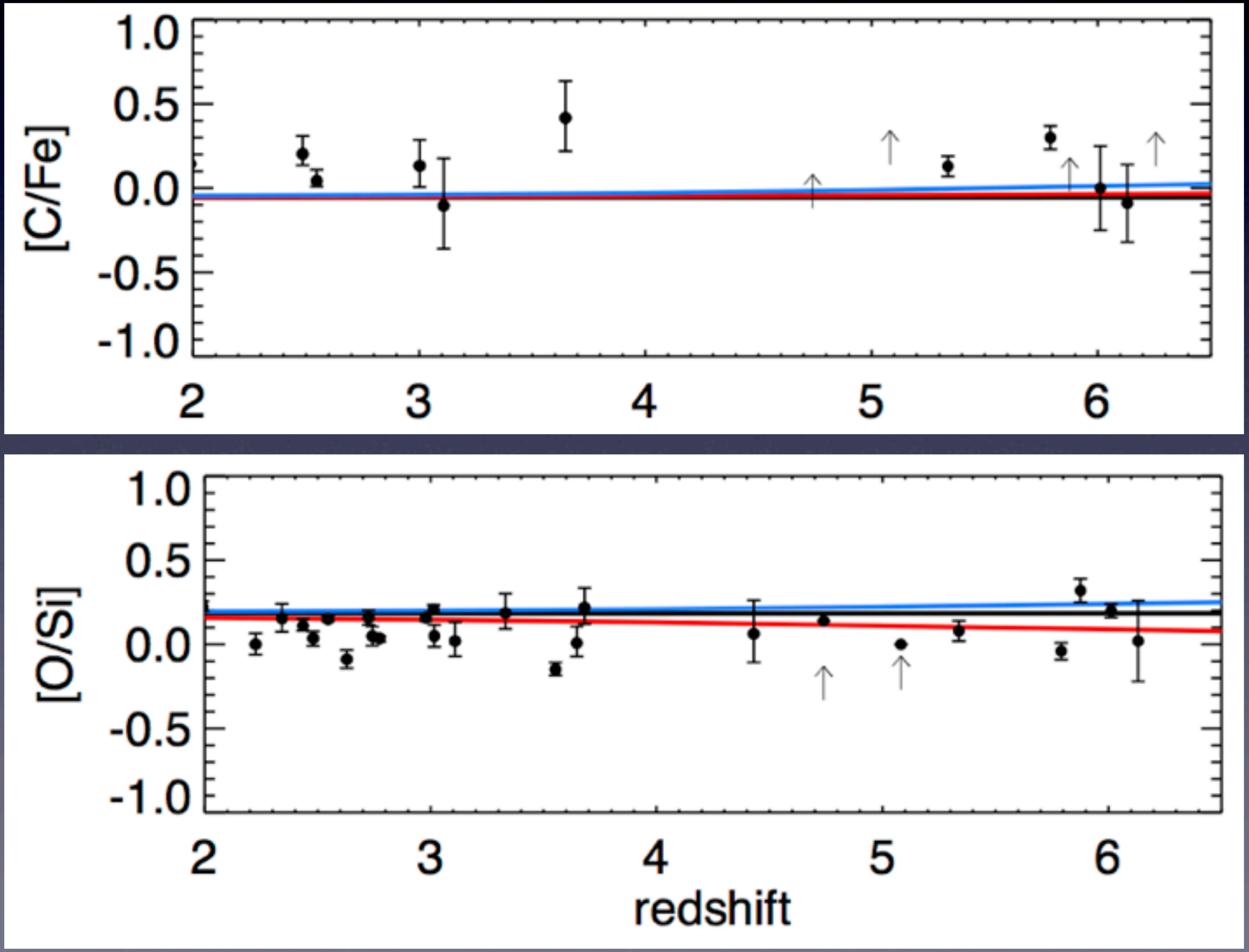
GK et al. 2013



- Create a simulated data set of 10 DLAs with measurement error of 0.1 dex
- KS test rejects Pop II IMF at 4-sigma
- 100 samples gave average significance of 3.8-sigma

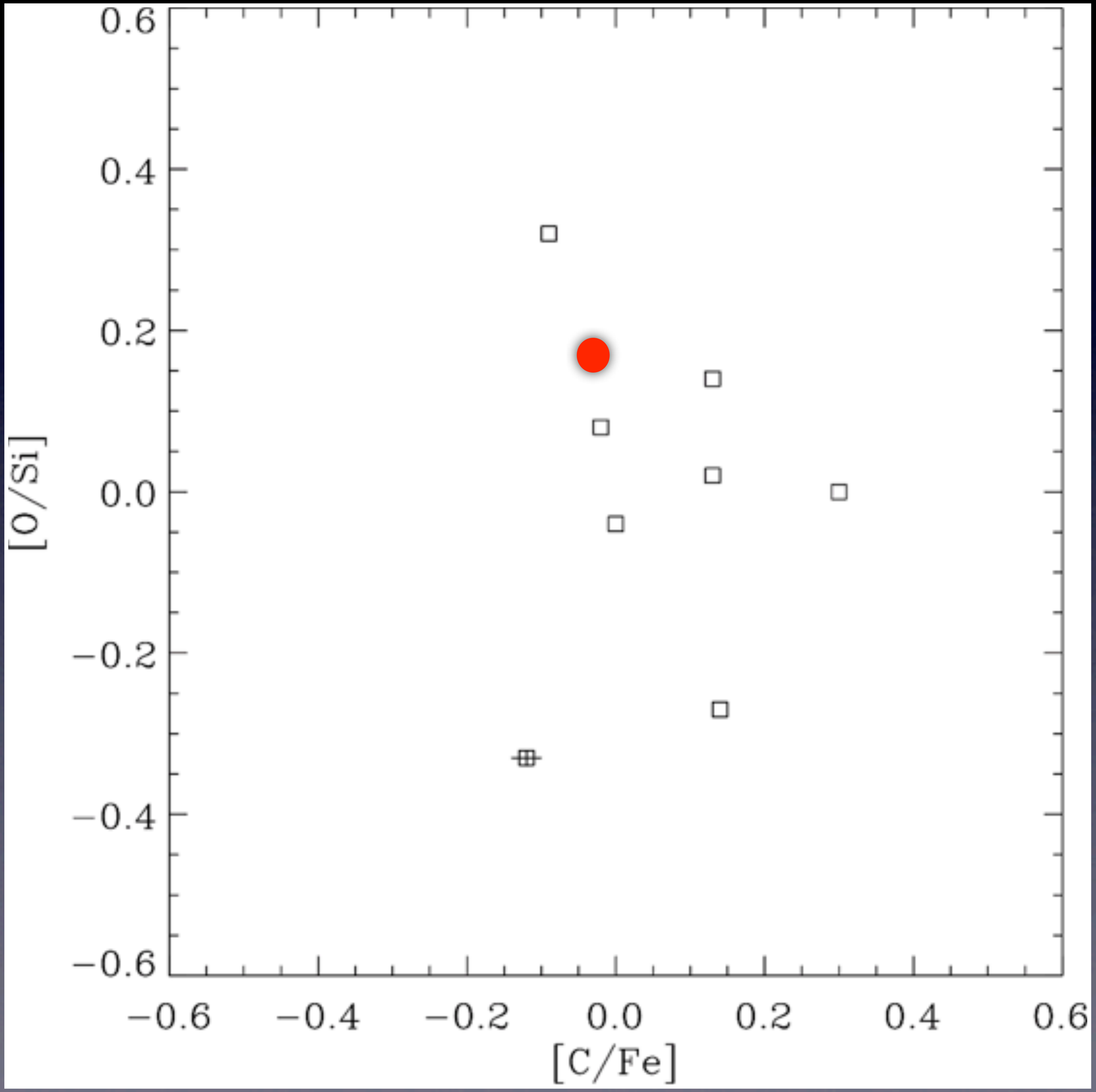
It's the distribution, not the mean

Cooke et al. 2011; Becker et al. 2012



What do the data show?

Becker et al. 2012

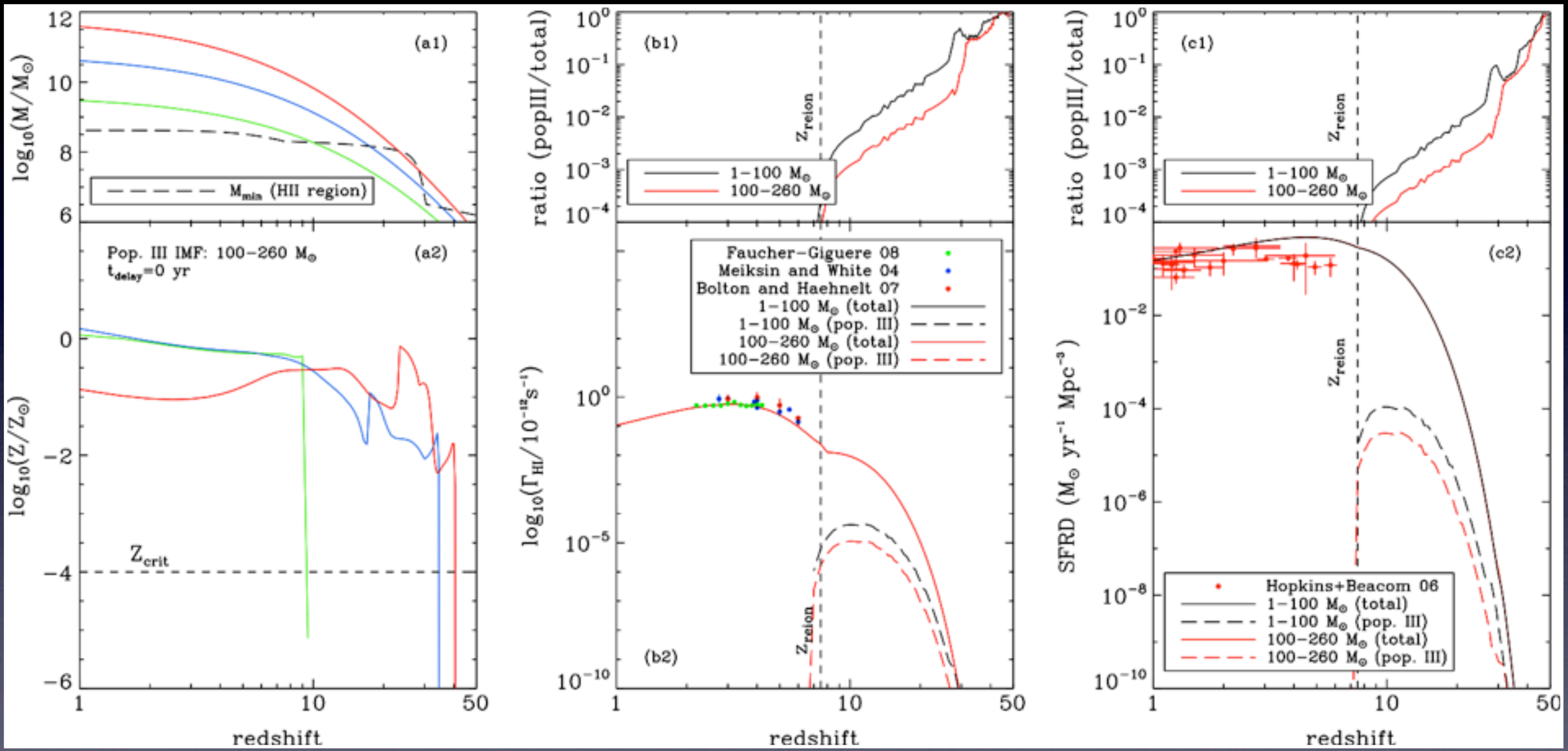


- Data consistent with Pop-II-only SF
- But prefer Core-collapse Pop-III at around 2-sigma
- Inconsistent with PISN yields

How can we constrain Pop III?

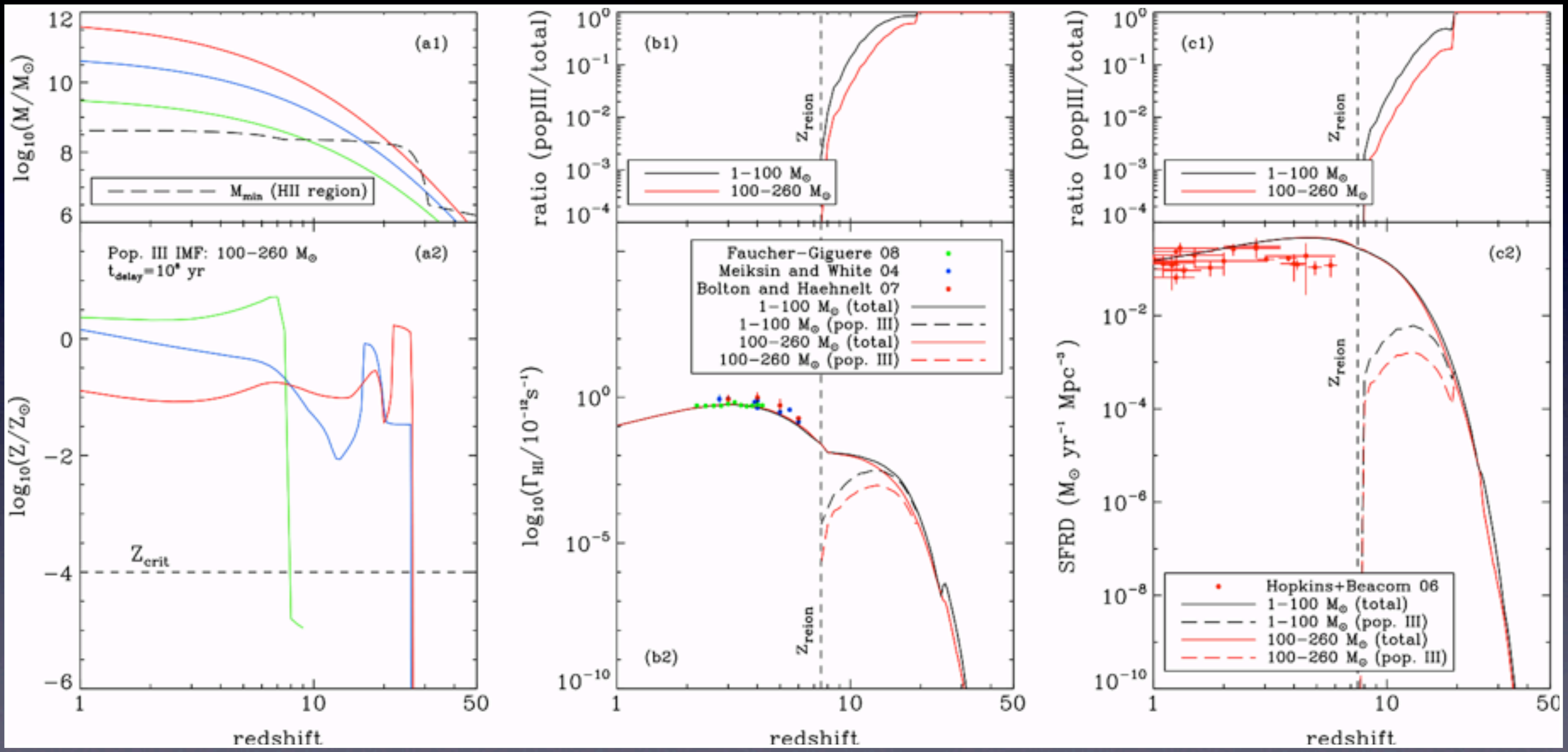
	Z-poor stars	Individual DLAs	DLA Statistics
LTE vs. NLTE	✘	✔	✔
1D vs. 3D	✘	✔	✔
Statistics	✘	✔	✔
Degenere-cies	✘	✘	✔
IMF statistics	✘	✘	✔
Dust	✔	✘	✘
Saturation	✔	✘	✘

Fiducial model does not give much



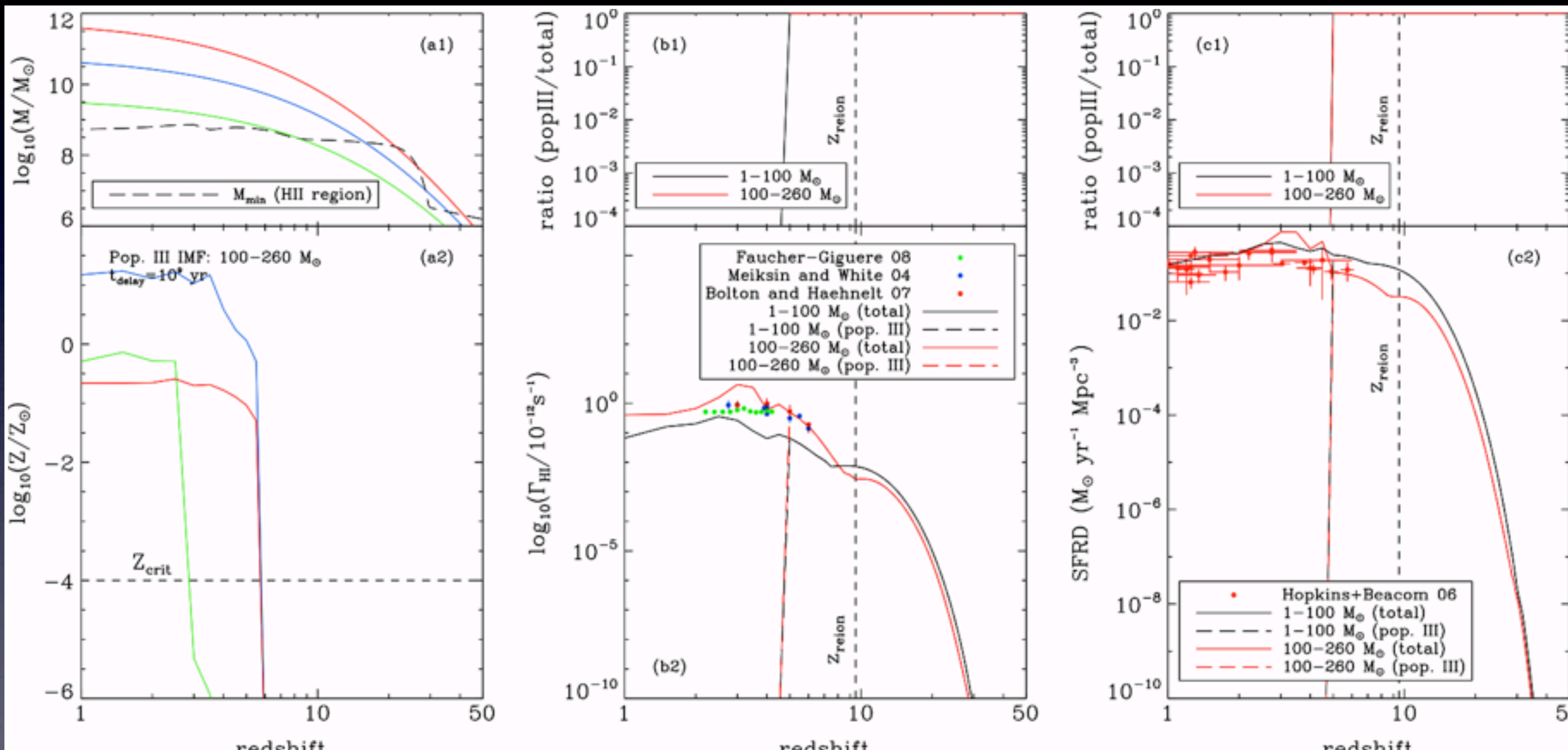
Pop III contribute less than 0.1% at z = 7

Increase mixing time



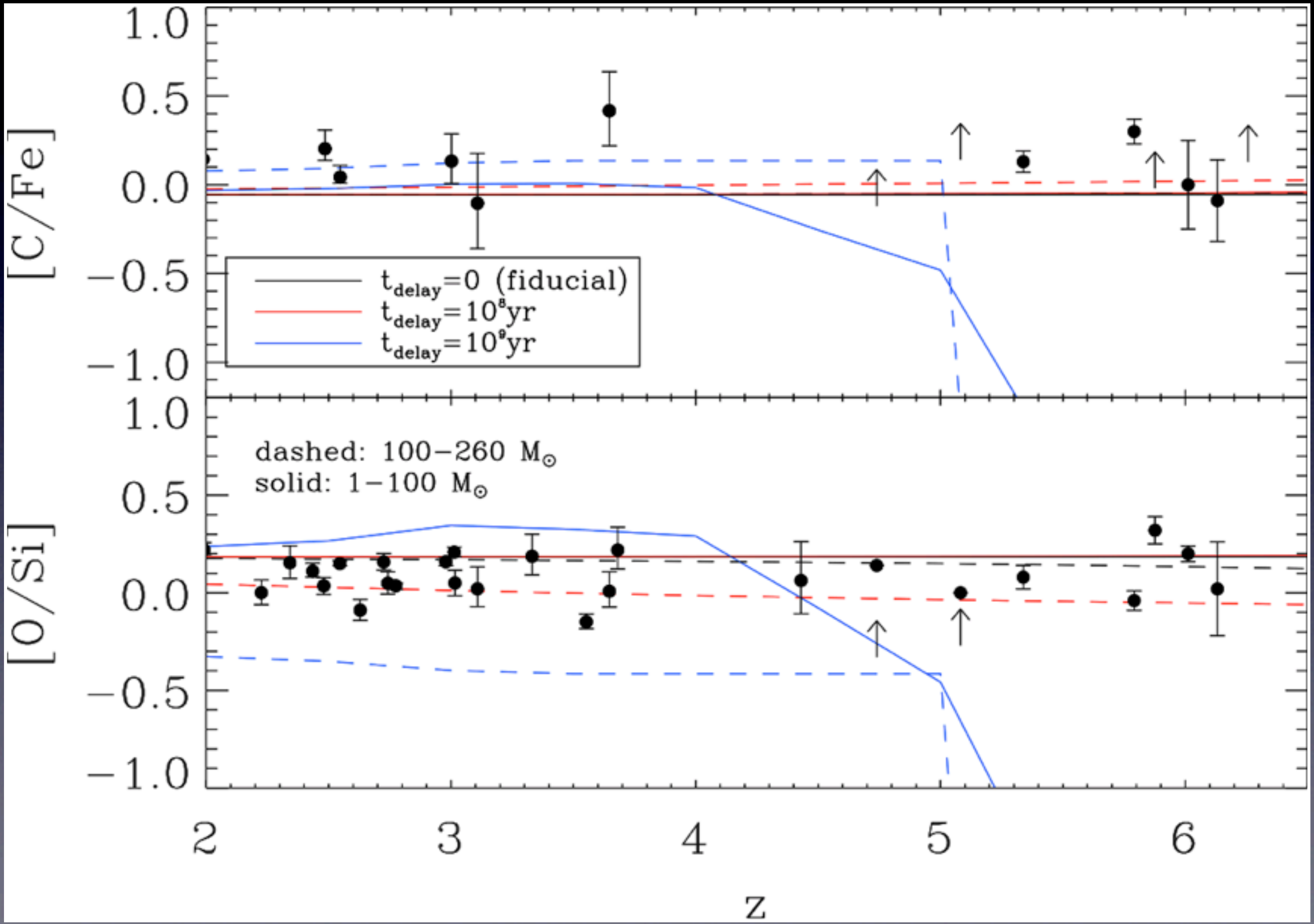
Increasing mixing time scale increases contribution

Increase mixing time further



Increasing mixing time scale increases contribution

Long mixing times ruled out by DLA data



Summary

- Presented a **SAM** that is **fully coupled to IGM thermal history**: reionization, photoheating feedback, evolution of all abundances, IMF evolution.
- Global **Population III SFR** is zero at $z < 8$ in vanilla model
- **DLA sample abundance ratio distributions** have an easily observable dependance on Population III IMF. This is an excellent probe.
- Current data are inconsistent with PISN yields. Weakly prefer Metal-free type-II.
- DLA data put strong constraints on Population III contribution to reionization