The High-Resolution Case Against Late Reionization

(and for Radiative Transfer)

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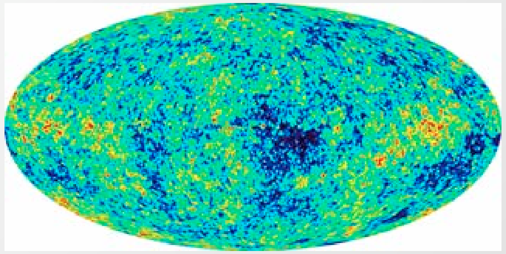
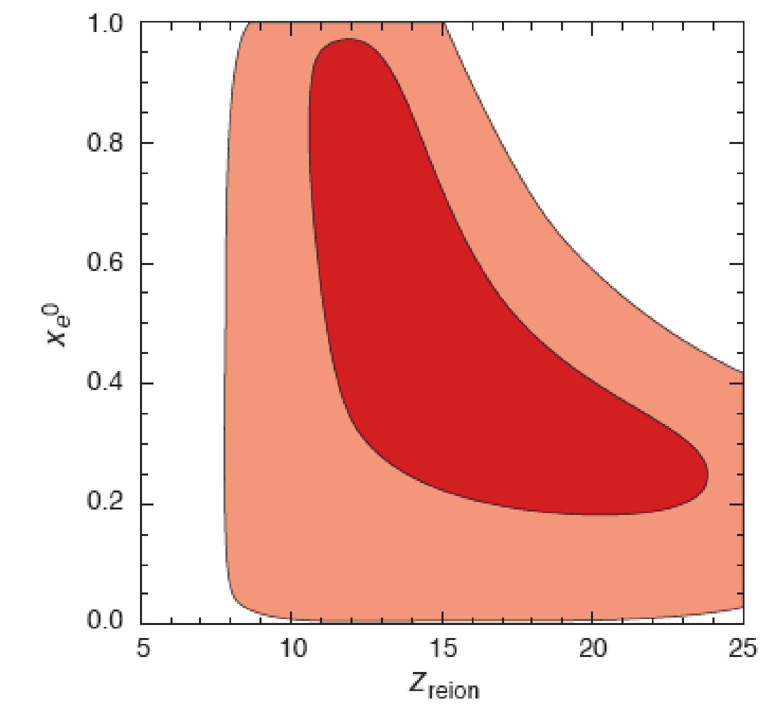
H I Survival
June 11, 2007

Reionization - Two limits



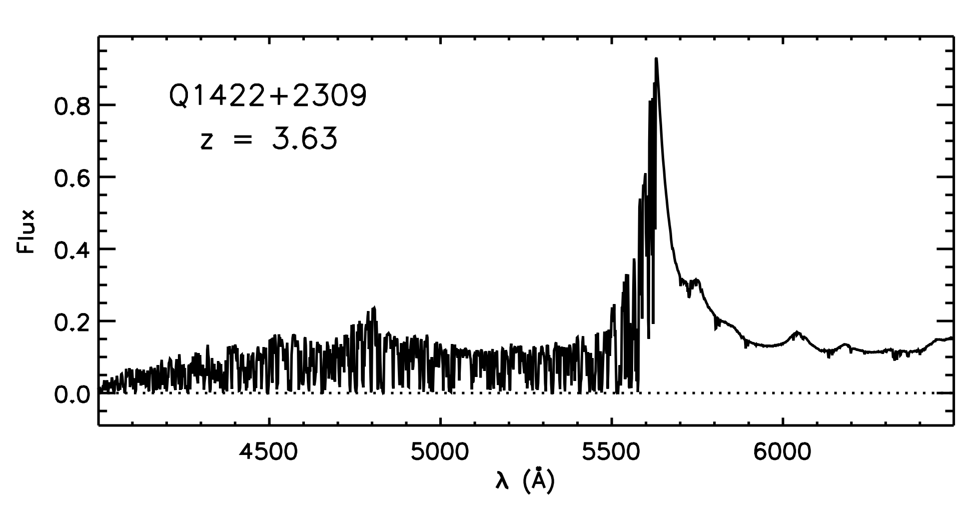
Early
CMB

$$\tau_e = 0.09 \pm 0.03$$



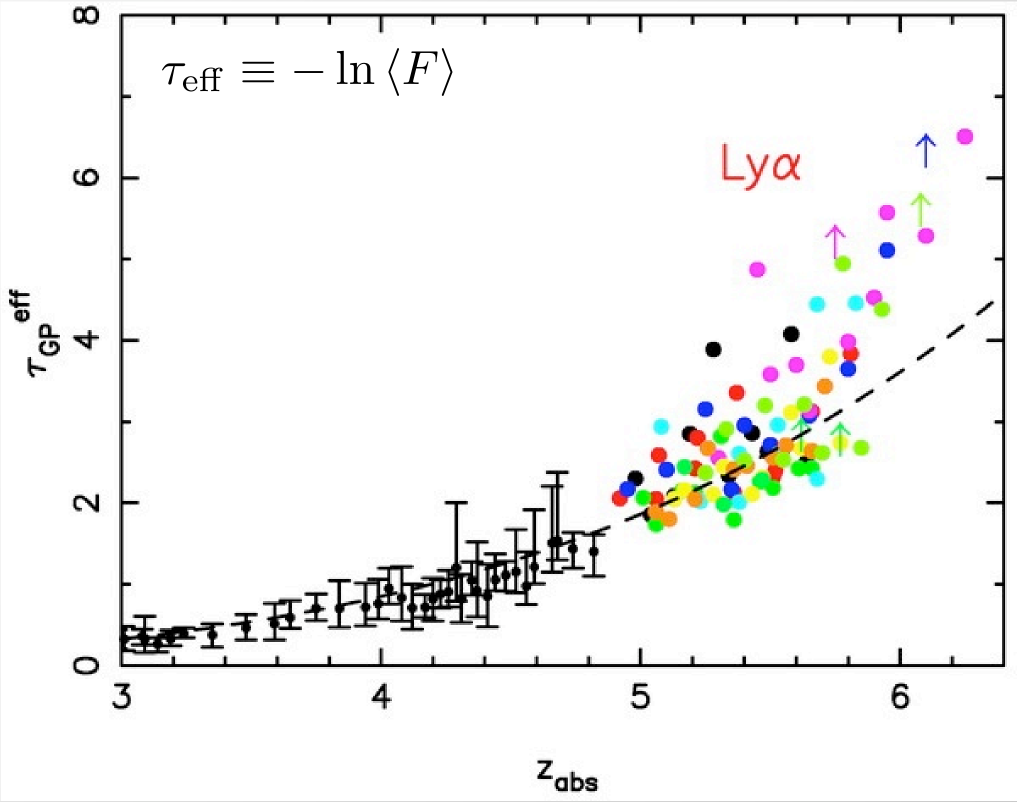
Spergel et al. (2006)

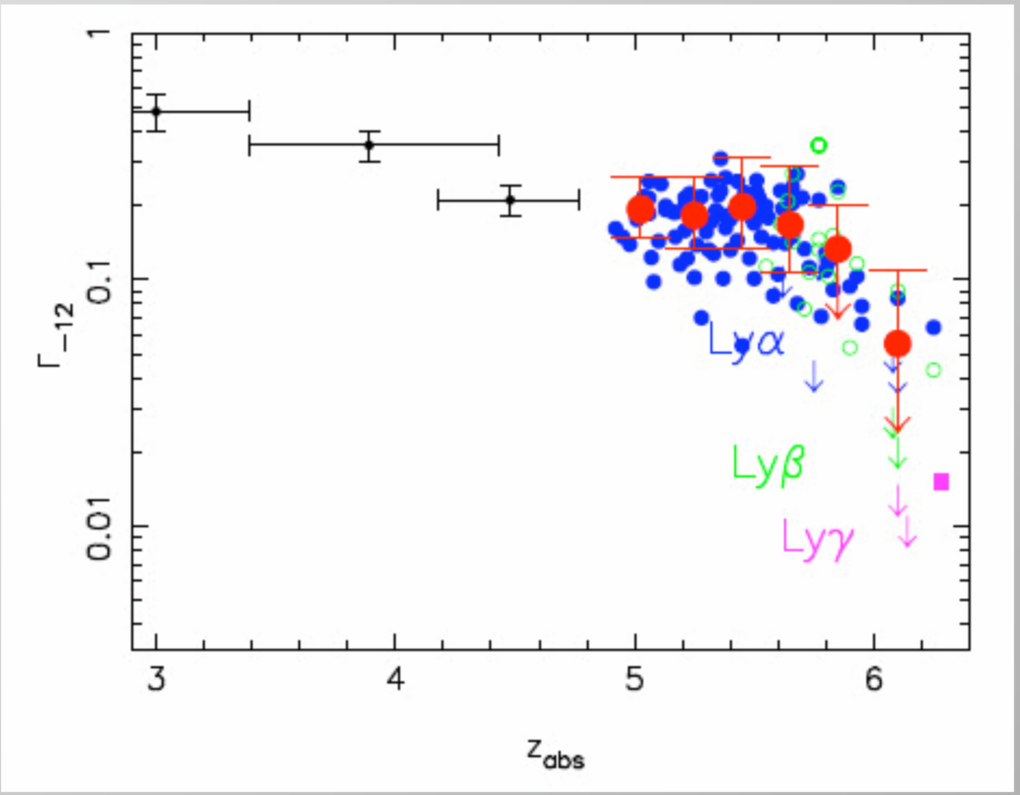
Late
Transmission in Lyα forest



IGM must be highly ionized at z < 6

Best evidence for late reionization

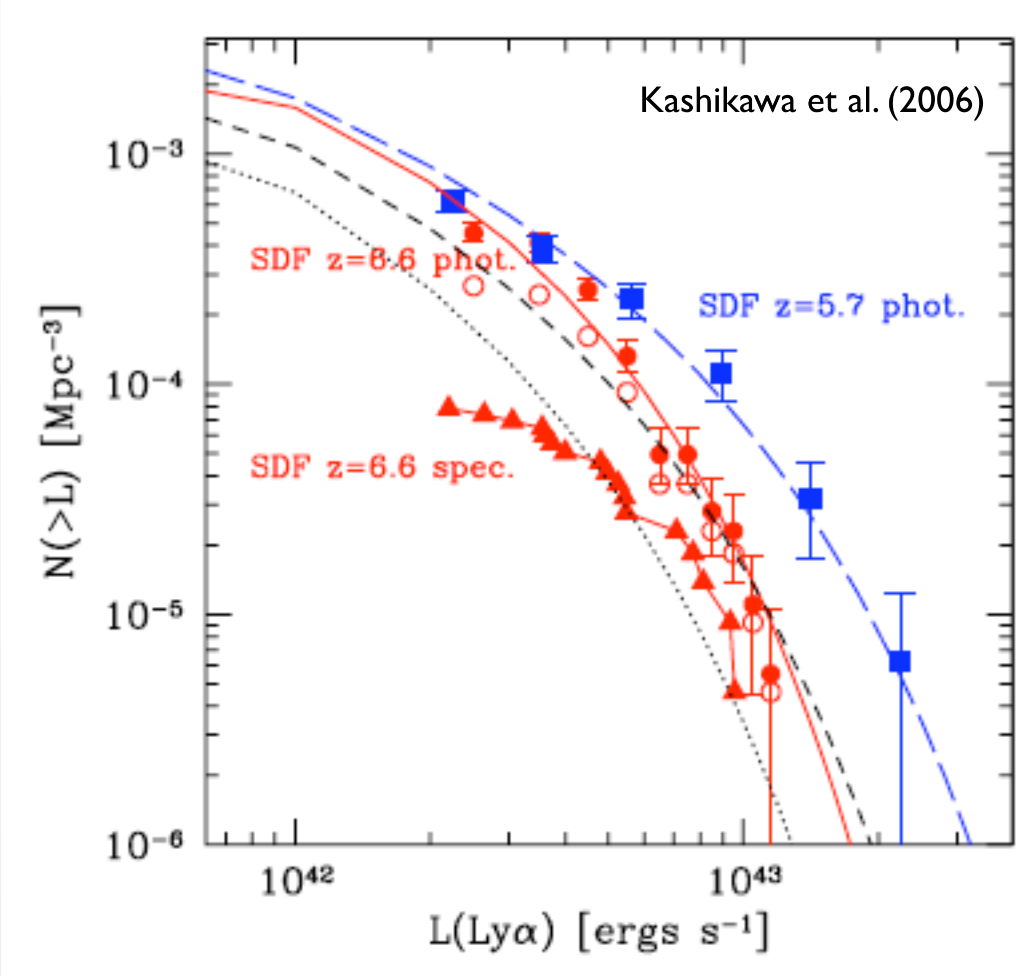


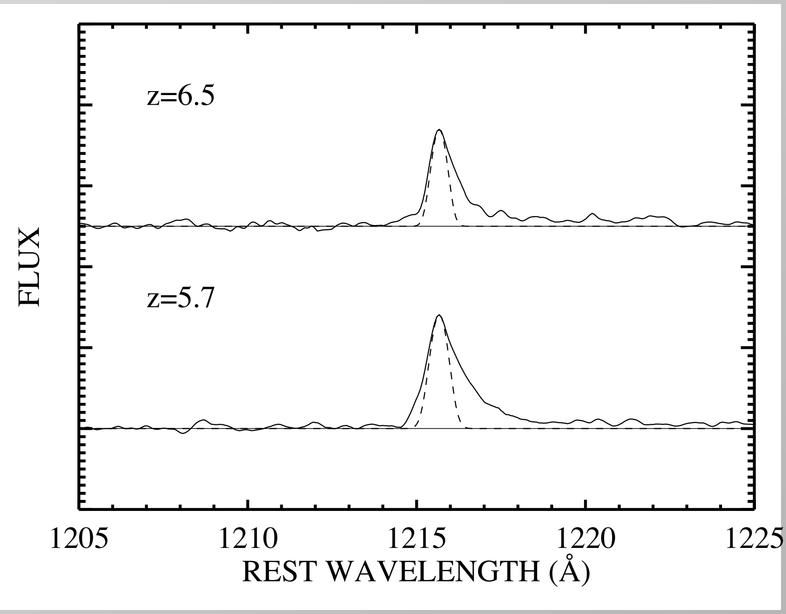


Fan et al. (2006)

Mean flux measurements

Lyα-emitting galaxies

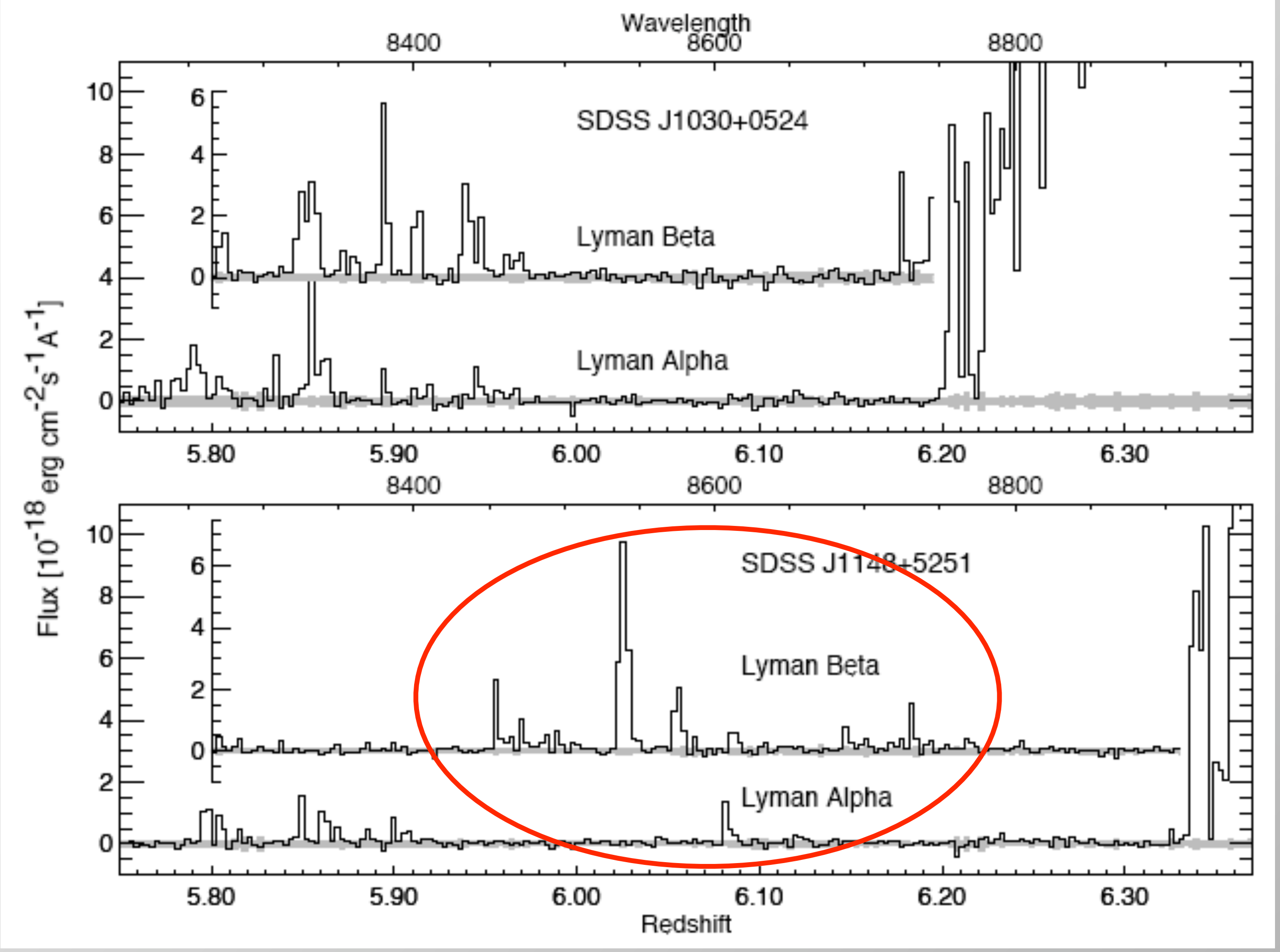




Hu & Cowie (2006)

Dijkstra et al. (2006): Evolution in LF can be entirely attributed to evolution in DM halo mass function and cosmic expansion.

Transmitted flux at z > 6



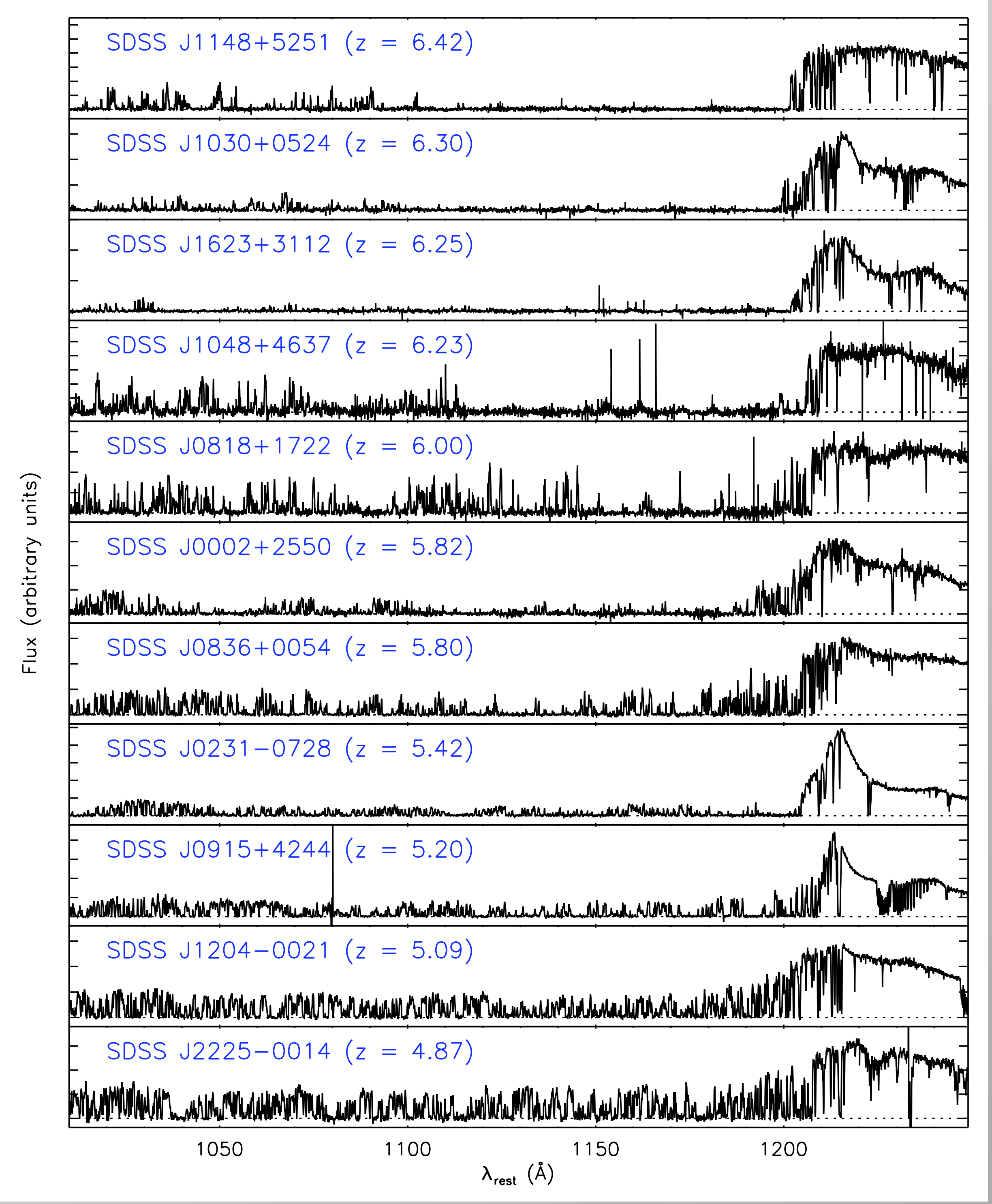
White et al. (2003)

Patchy reionization?

The High-res, High-z sample

11 QSOs at $4.9 < z < 6.4$

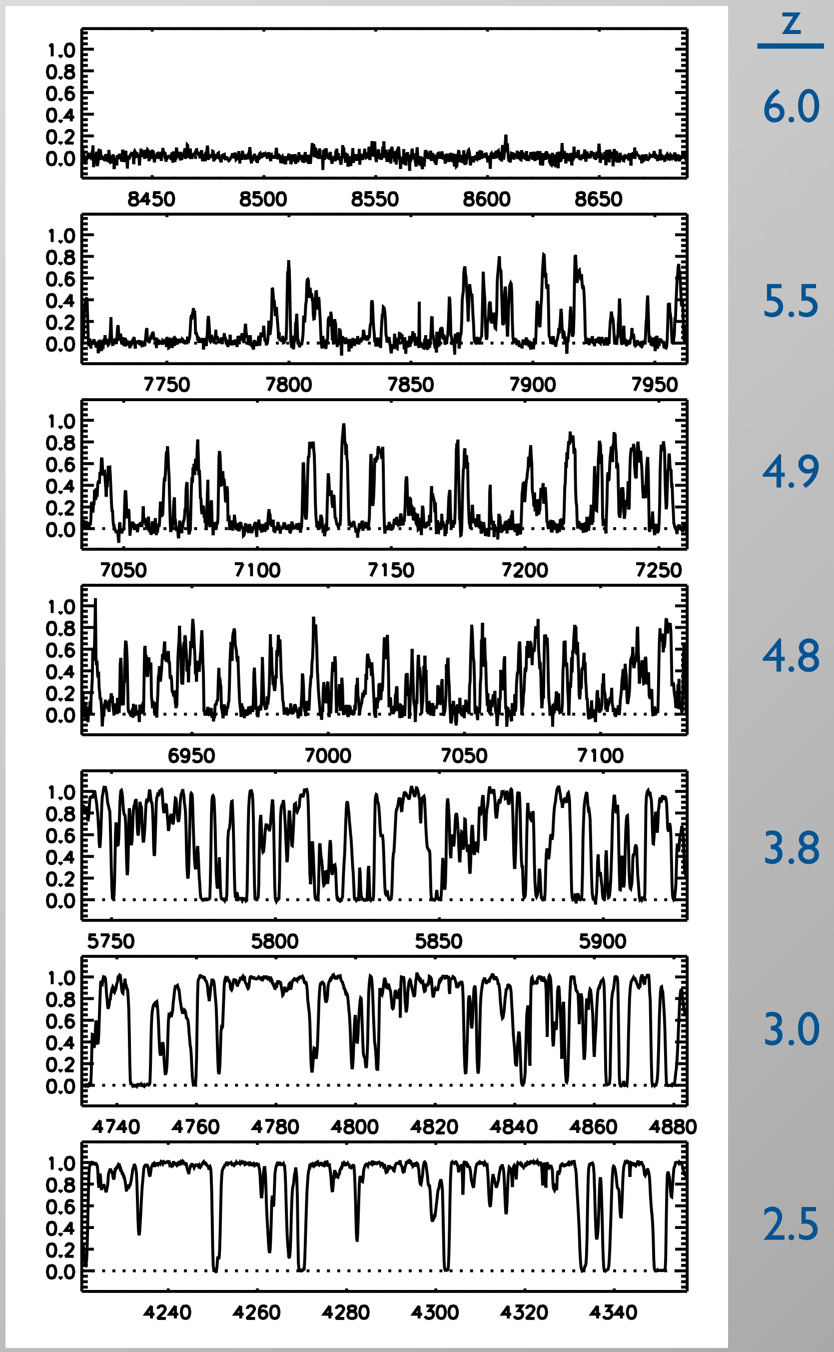
Full sample:
58 QSOs at $2 < z < 6.4$



Flux distributions

- Models give you $P_\tau(\tau) \longrightarrow P_F(F)$
- Test two theoretical τ distributions
  1. Numerical simulation with simple assumptions
     - Miralda-Escudé et al. 2000 (MHR00)
     - Used to infer late reionization
     - uniform UVBG + isothernal IGM
  2. Lognormal
     - Could arise from either a lognormal *density* distribution OR from non-uniform temperatures and/or ionization rates

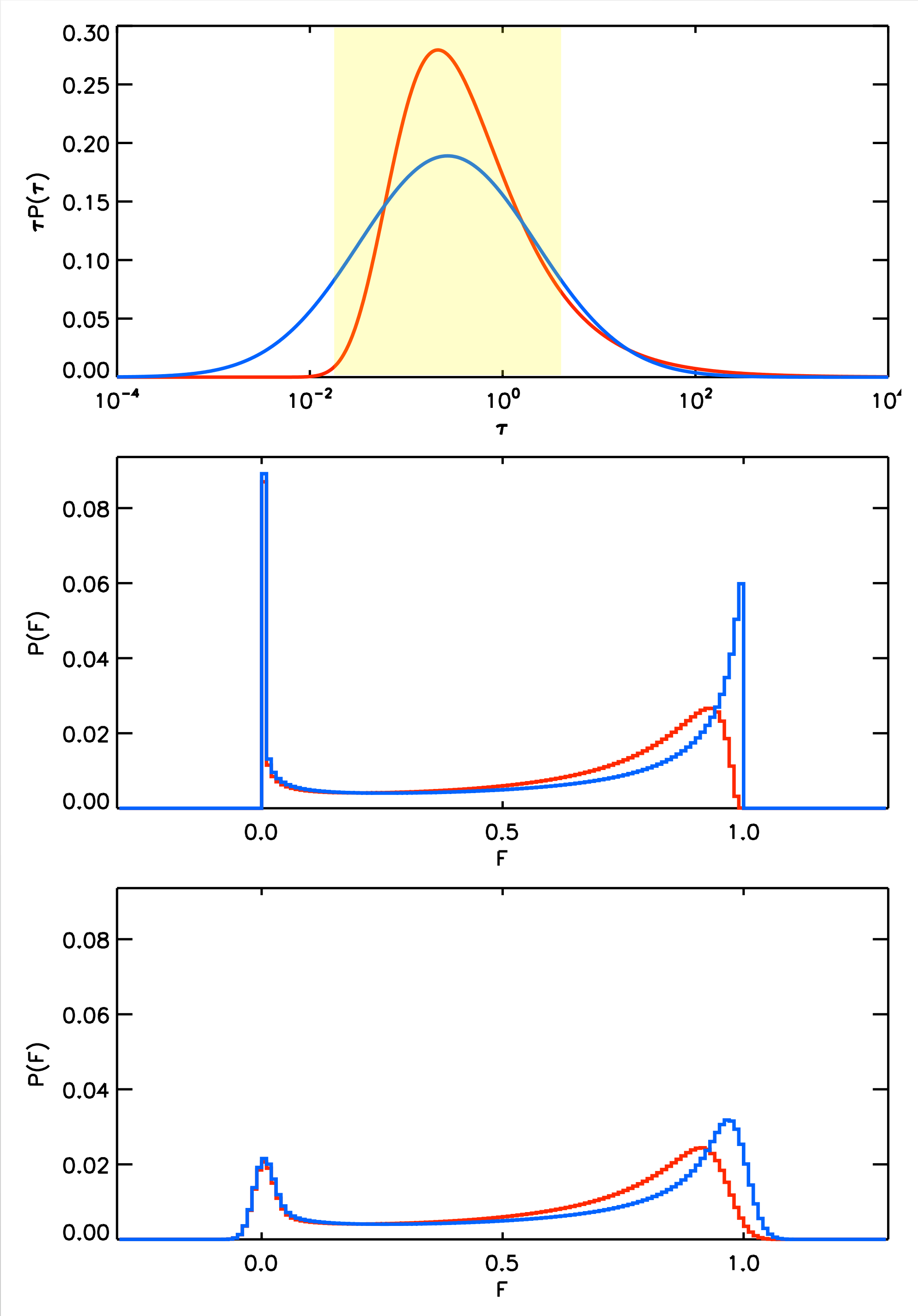
✳ Must use high-resolution data



Optical depth

Flux

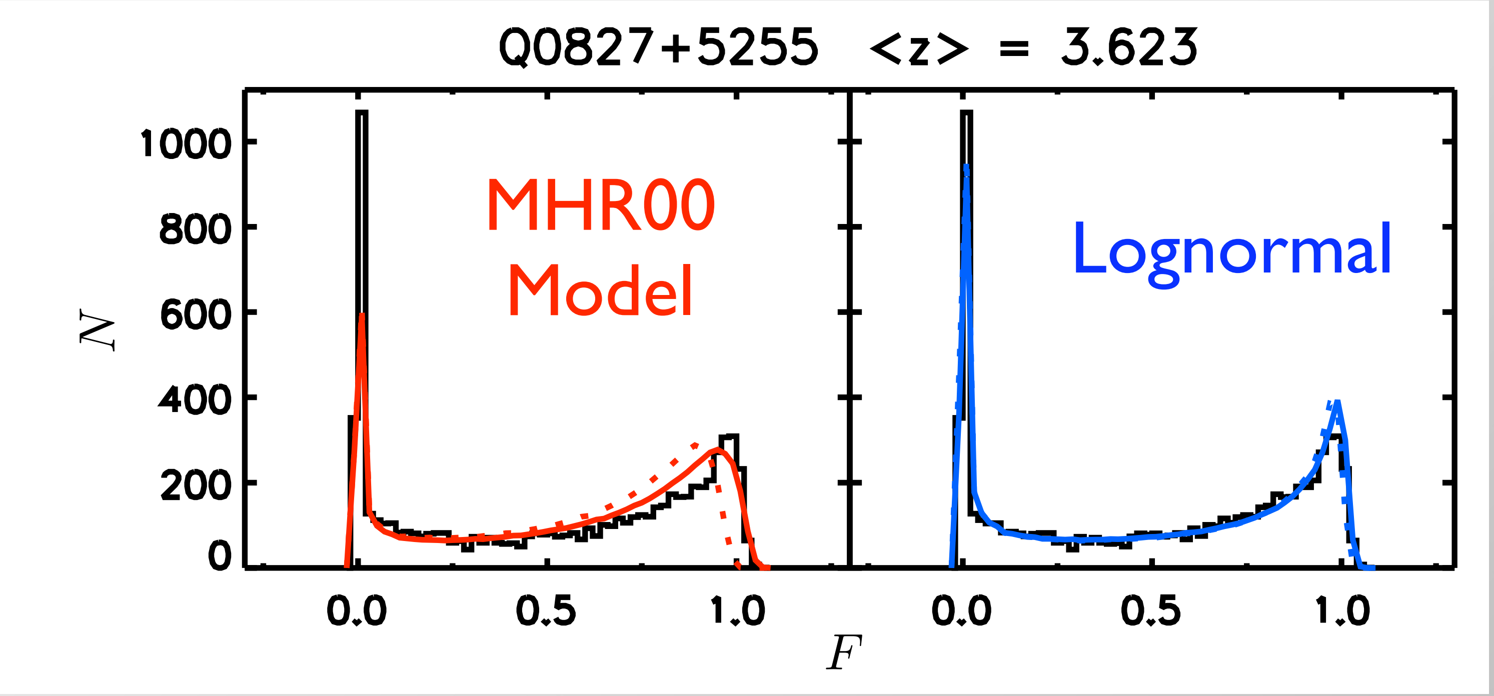
Flux with noise



MHR00 Model

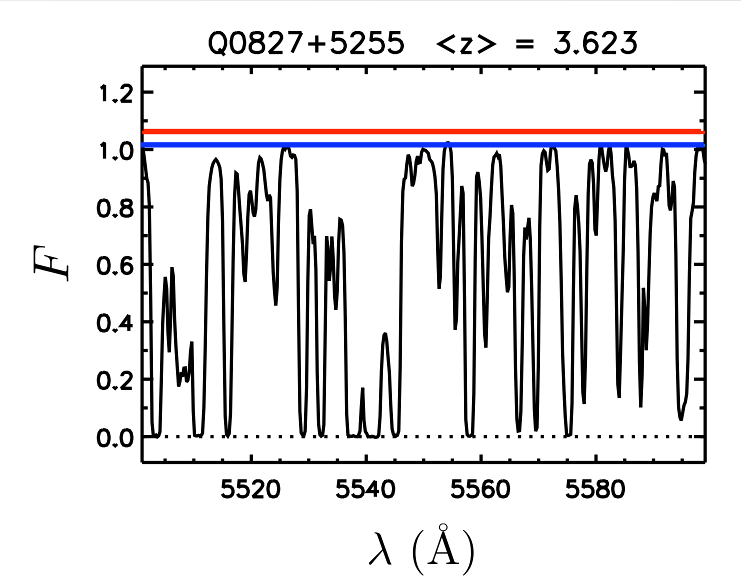
Lognormal

Example Flux PDF fit



Continuum fixed

Continuum variable



"Best fit" continua

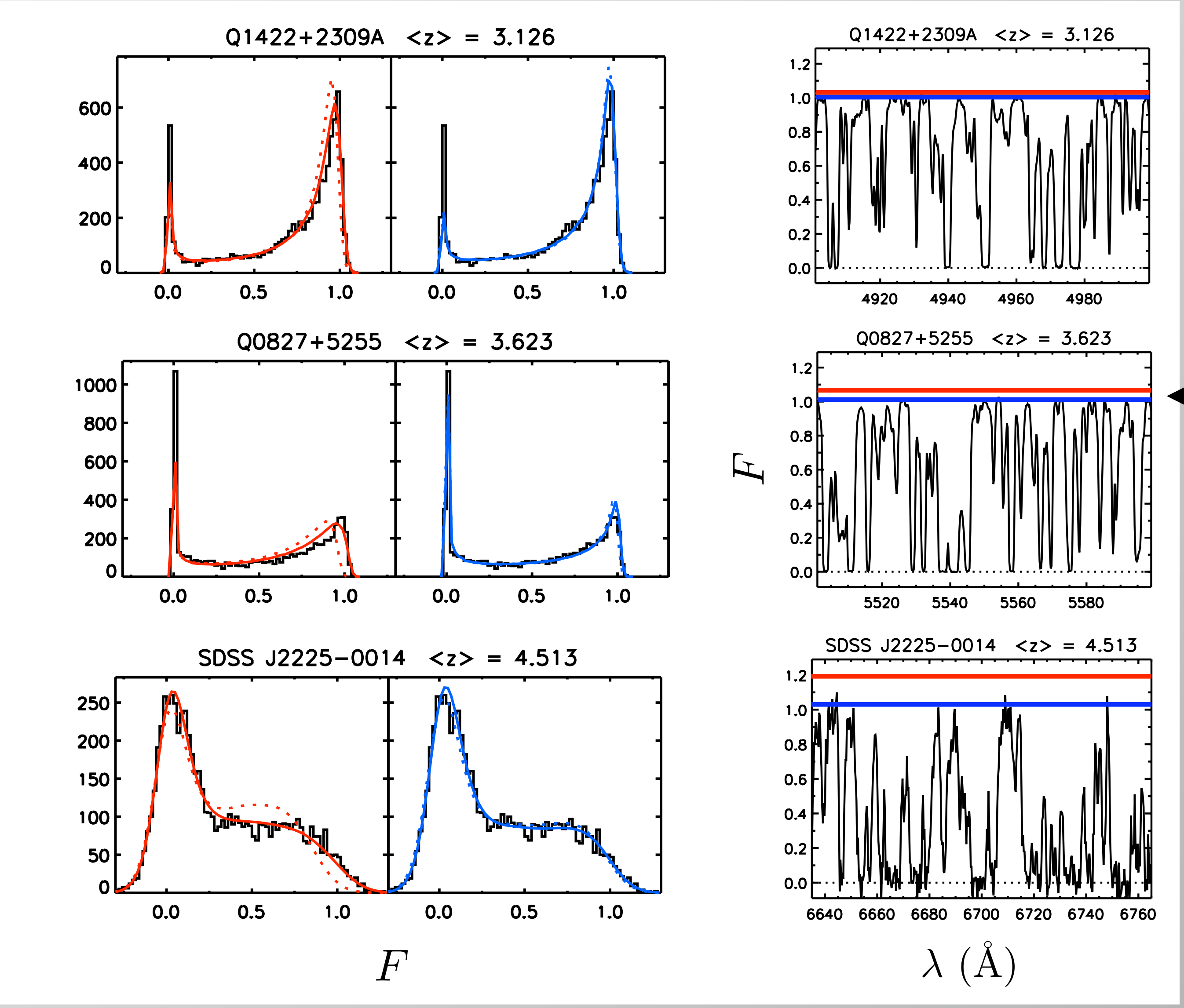
More Flux PDF fits

MHR00 Model

Lognormal

Continuum fixed

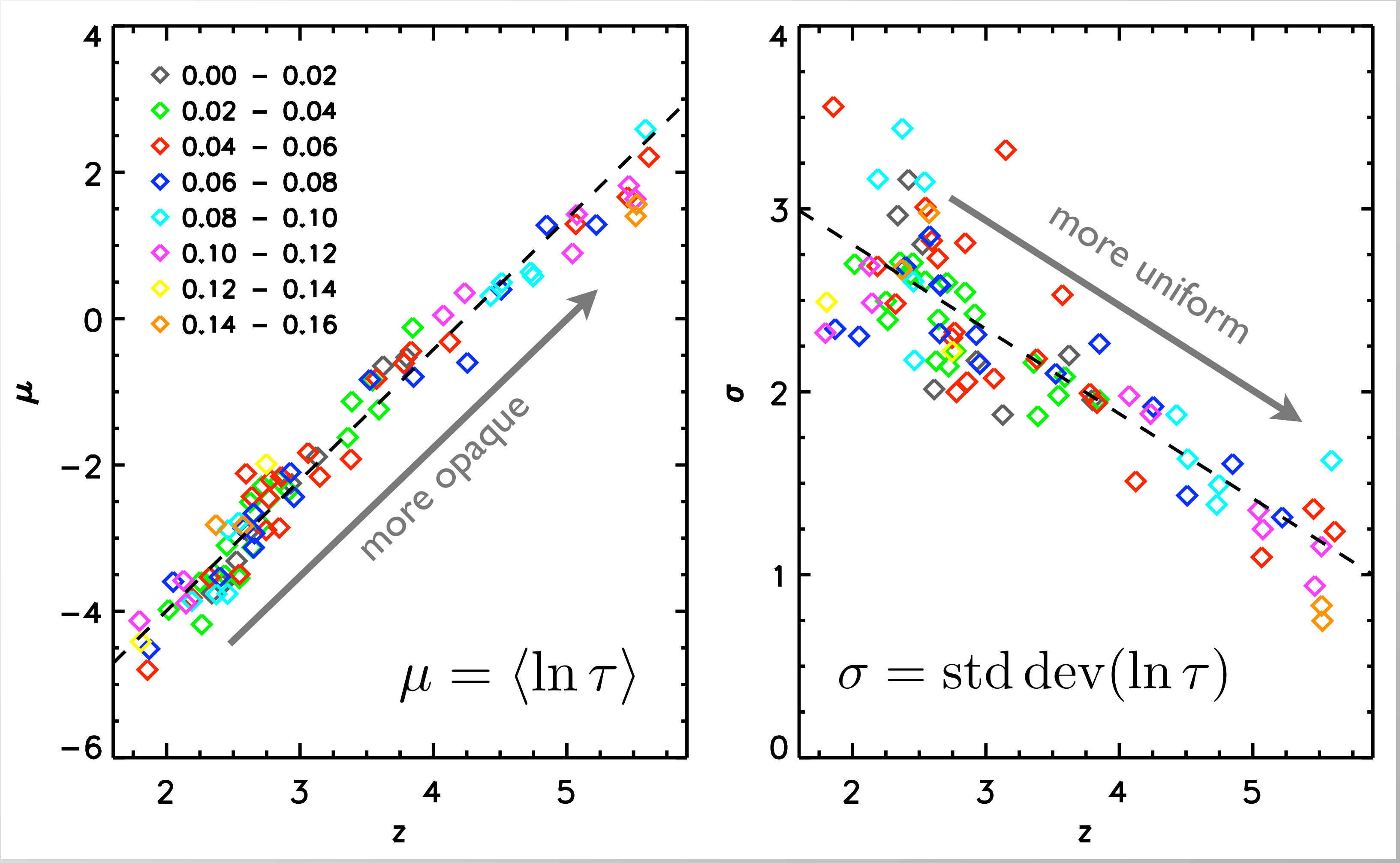
Continuum variable



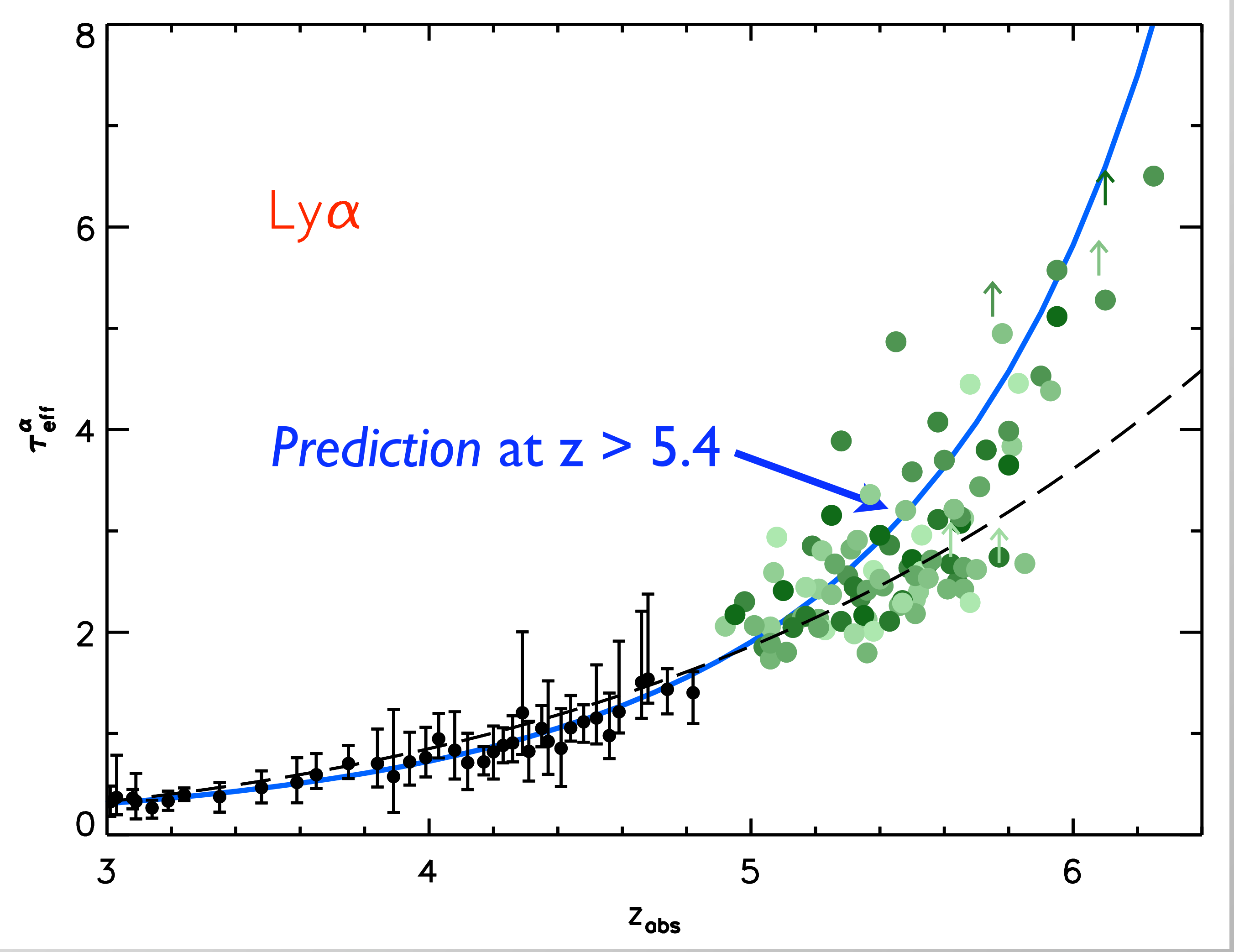
"Best fit" continua

MHR00 model fits require a QSO continuum adjustment.

Evolution of Lognormal Parameters



Mean transmitted flux (I)

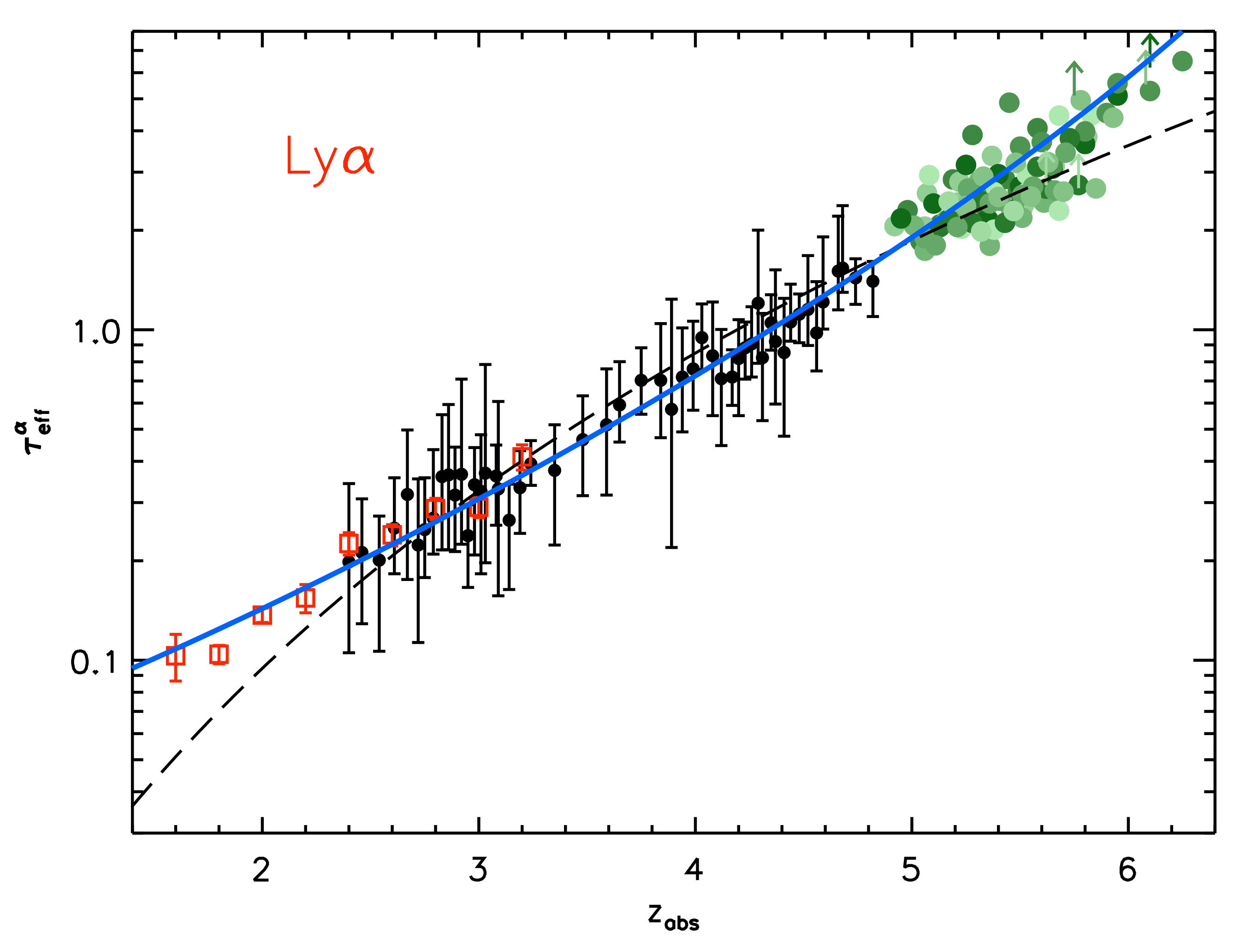


Data
z > 4.9 Fan et al. (2006)
z < 4.9 Songaila (2004)

PDF Fit to z < 5.4

power law fit to z < 5.7

Mean transmitted flux (2)



Data

z > 4.9 Fan et al. (2006)

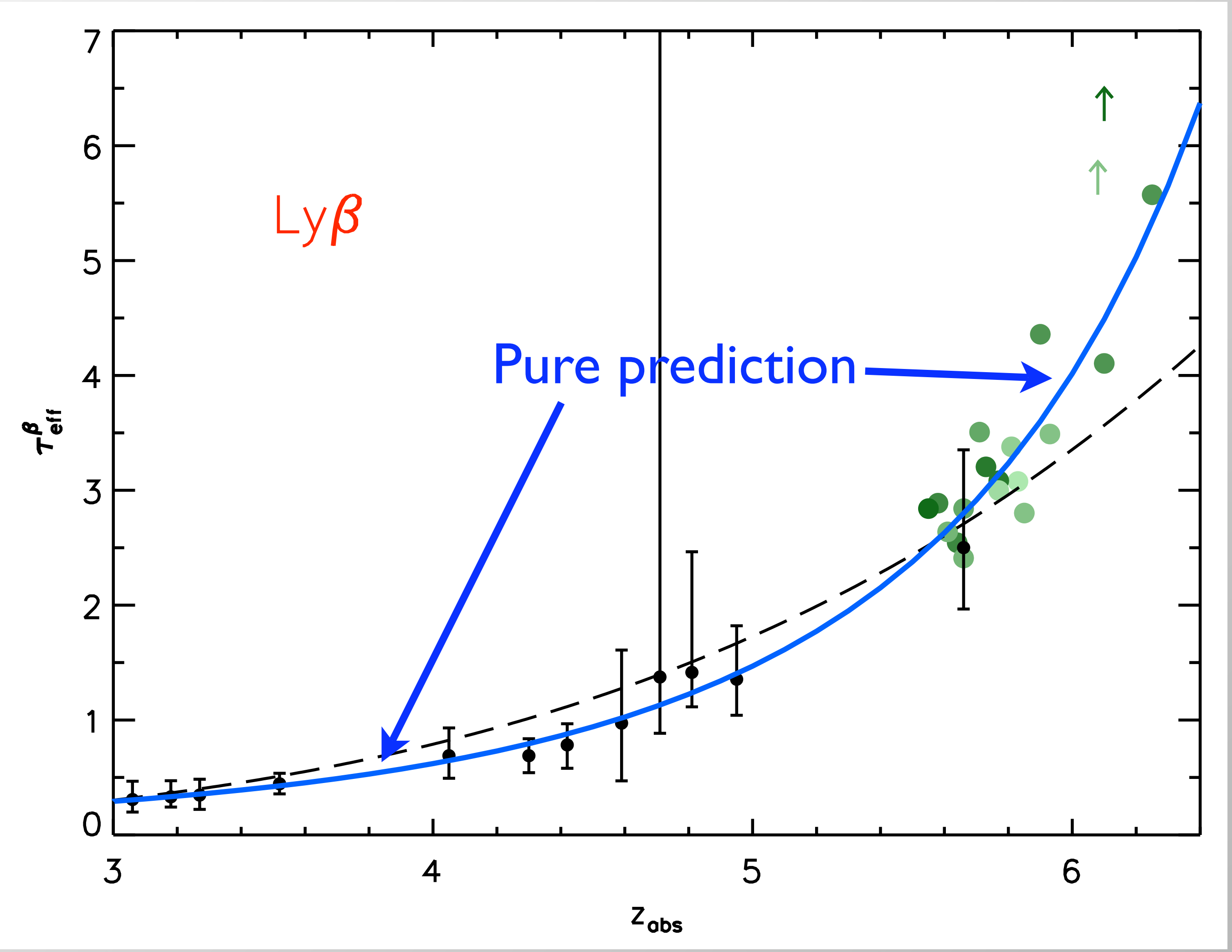
2.4 < z < 4.9 Songaila (2004)

1.6 < z < 3.2 Kirkman et al. (2005)

PDF Fit to z < 5.4

power law fit to z < 5.7

Mean transmitted flux (3)



Data

z > 5.5 Fan et al. (2006)

z < 5.7 Songaila (2004)

PDF Fit to z < 5.4

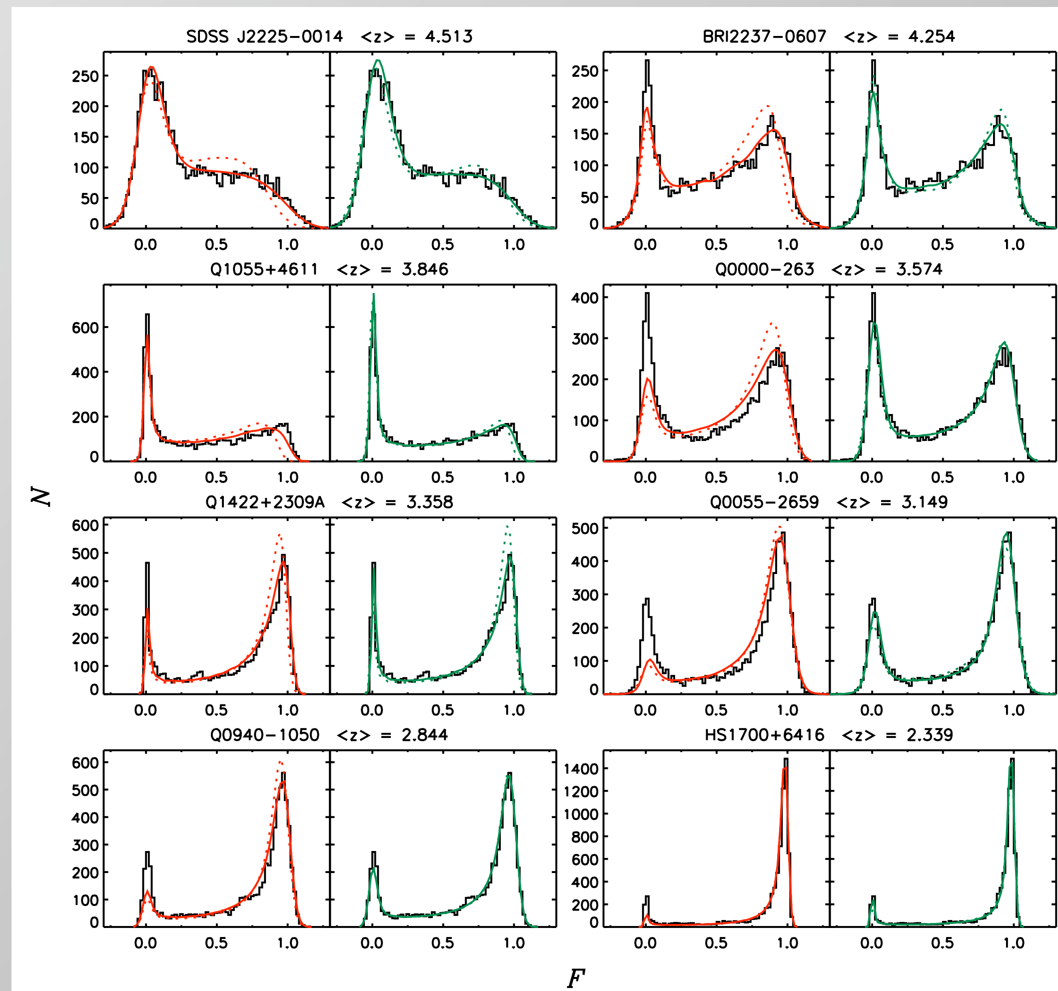
power law fit to z < 5.7

An inverse T-ρ relation?

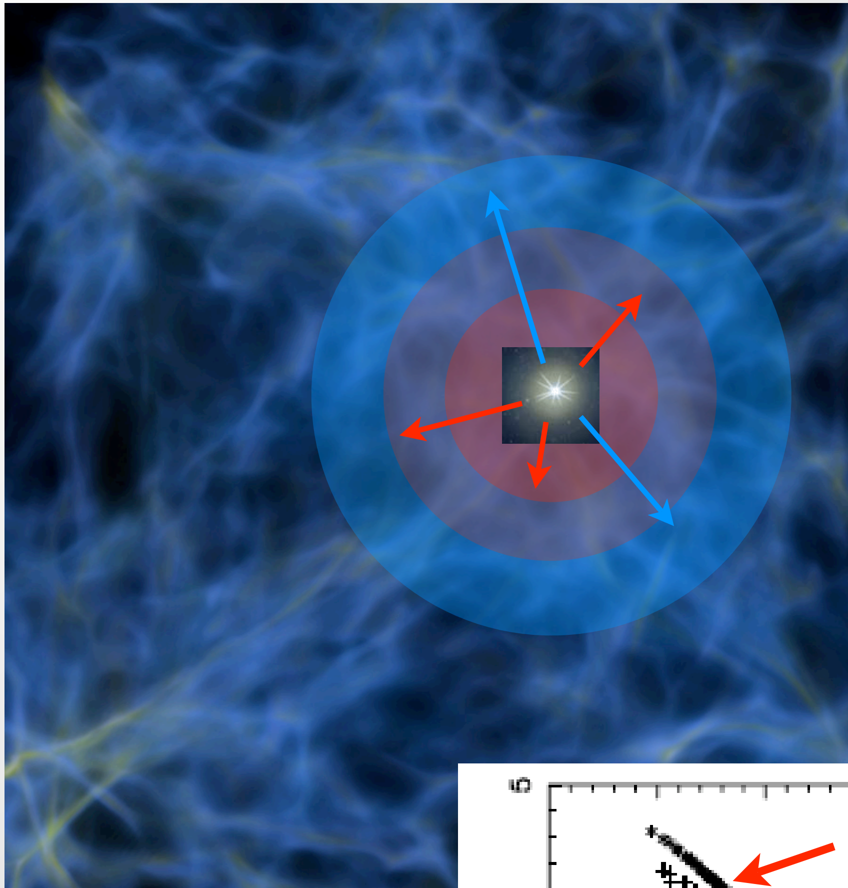
- The *density* distribution from simulations is probably correct.
- Optical depths depend on T, Γ

$$\tau(\Delta) \propto \frac{(1+z)^{4.5}(\Omega_{\rm b}h^2)^2\alpha[T(\Delta)]}{h\Gamma(\Delta,z)\Omega_{\rm m}^{0.5}}\Delta^2$$

- "Equation of state" $T(\Delta) \propto \Delta^{\gamma-1}$
  - *Expect* $1 \leq \gamma \leq 1.6$
- Get very good fits with $\gamma \sim 0.5$
- Radiative transfer effects (e.g., Bolton et al 2004)? He II heating?



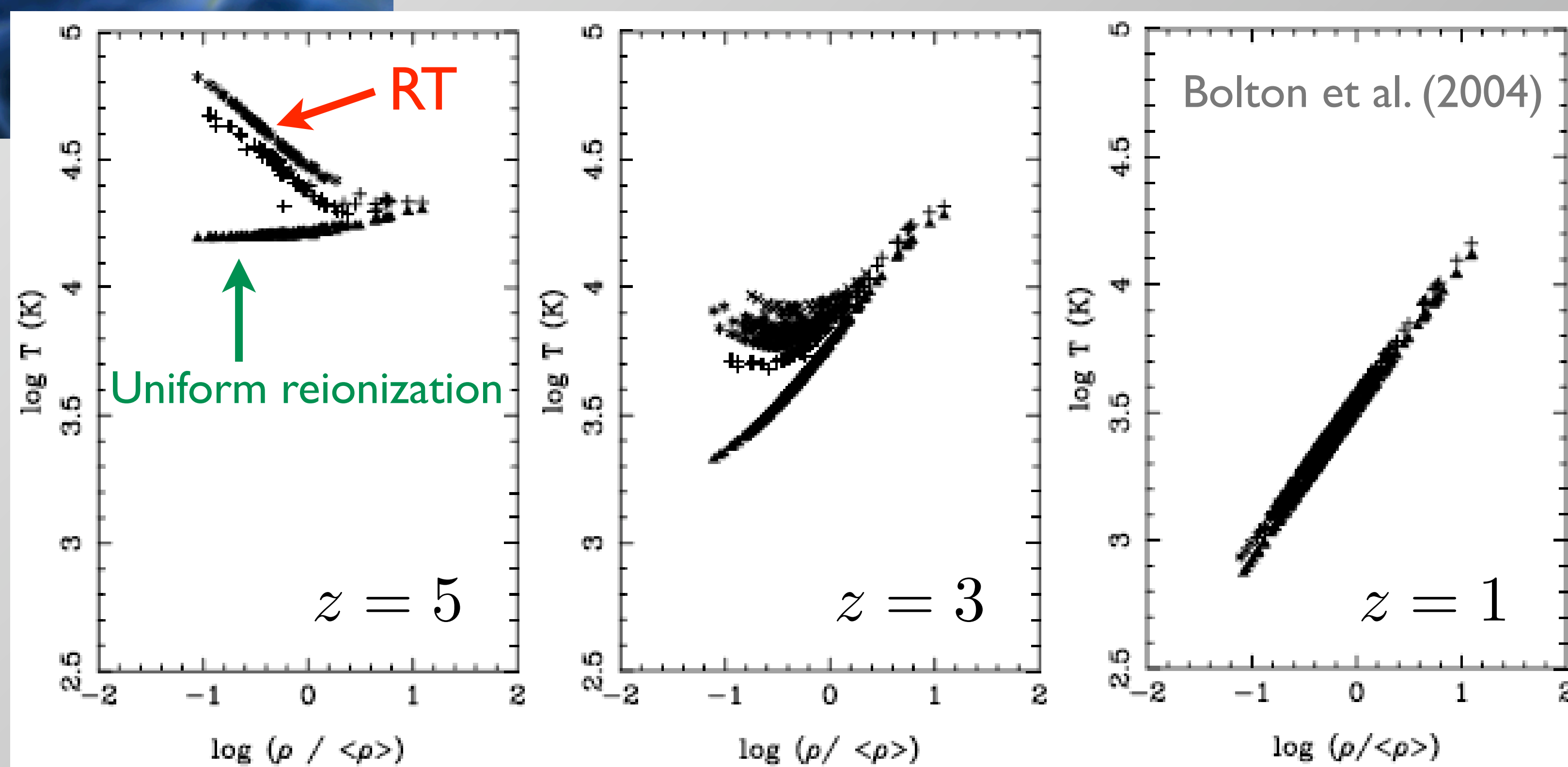
MHR00 model: Isothermal
Non-isothermal



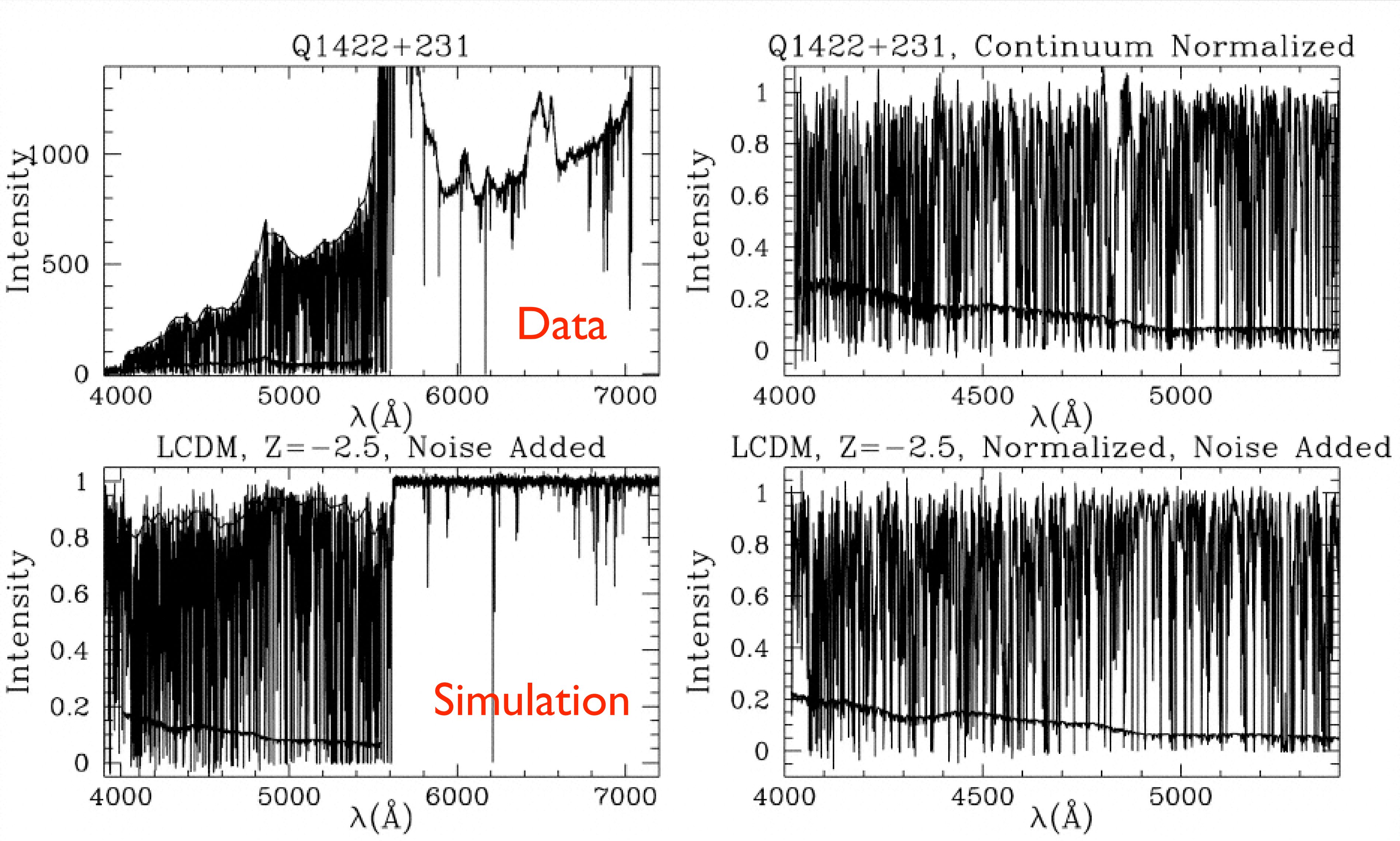
Radiative Transfer Effects

Higher-energy photons have longer mean free path.

Increased photoionization heating vs. uniform radiation field.



The “Problem” with Quasars

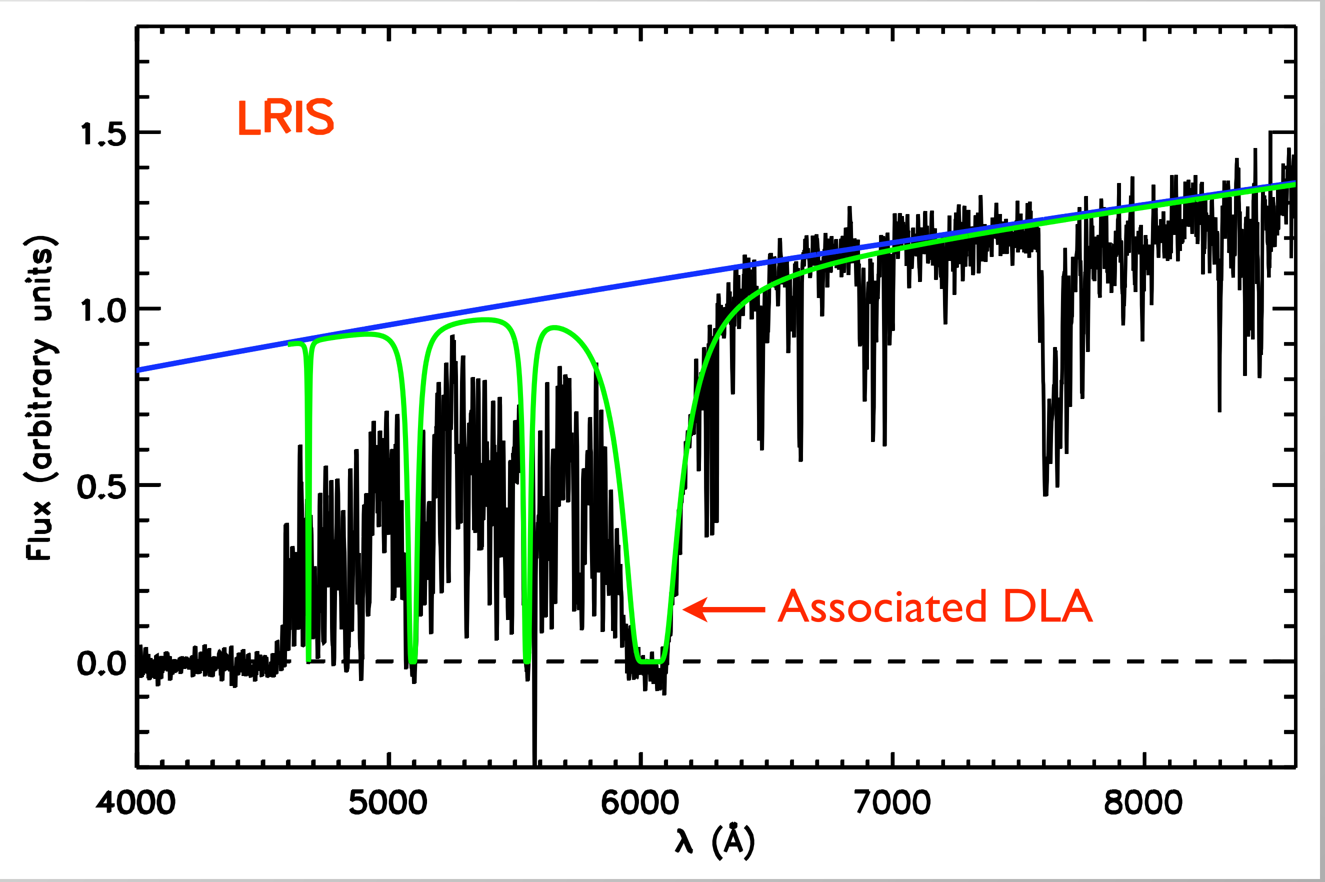


Davé et al. (1998)

GRBs as IGM probes

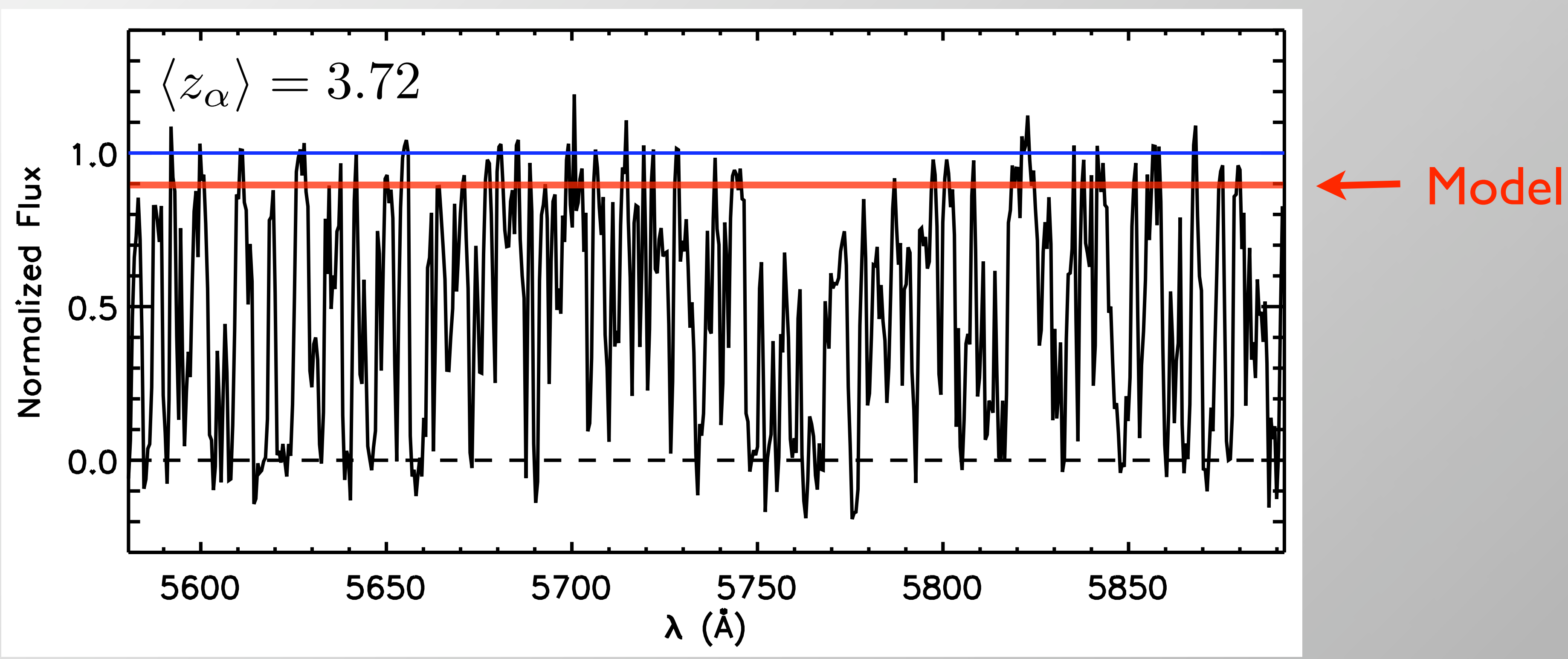
- GRBs have power-law continua
- "Objectively" measure low-density IGM
- Must be able to flux-calibrate high-resolution spectra
- Divide out associated absorption

GRB050730 (z = 3.96)



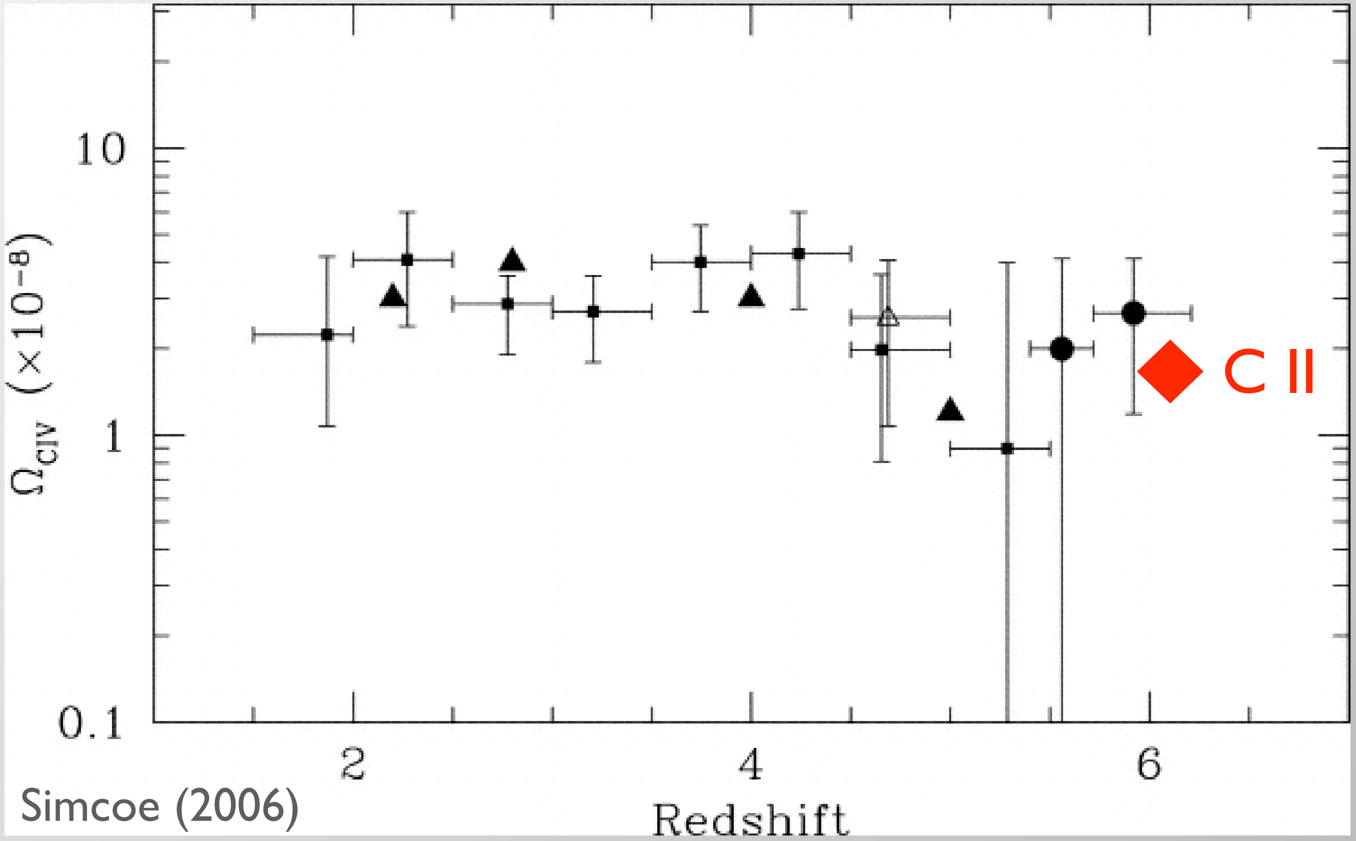
Use low-resolution spectrum to flux-calibrate the high-resolution spectrum...

GRB050730 MIKE Spectrum



- Calibrate MIKE data with LRIS data
- GRB spectrum looks like quasar spectra (QSO continua OK?)
- Voids at z~4 *do* appear more transparent than numerical simulations predict. Heating from radiate transfer effects?

Enough Ionizing Photons to Reionize by z~6?



$$Z^{C}_{z=6} \geq 10^{-3.4}\ Z_{\odot}$$

→ Massive stars produced ≥ 2-20 ionizing photons/baryon by z = 6

(Venkatesan & Truran 2003)

Conclusions

- The simple model for the Lyα forest that has been used to make claims of late reionization does not match high-resolution data, especially at low optical depths (voids).
  - Better simulation and/or better data calibration may be needed.
- Empirically, the Lyα forest evolves smoothly over $1.6 < z < 6.2$.

  ➡ A sudden change due to late reionization is not required.
- If the density distribution from simulations is correct, then fluctuations in the UV background and/or IGM temperature may be required to produce the correct flux PDF.
  - Inverse temperature-density relation at low densities?