Probing Cosmological Reionization with the High-redshift Lyman-α Forest:

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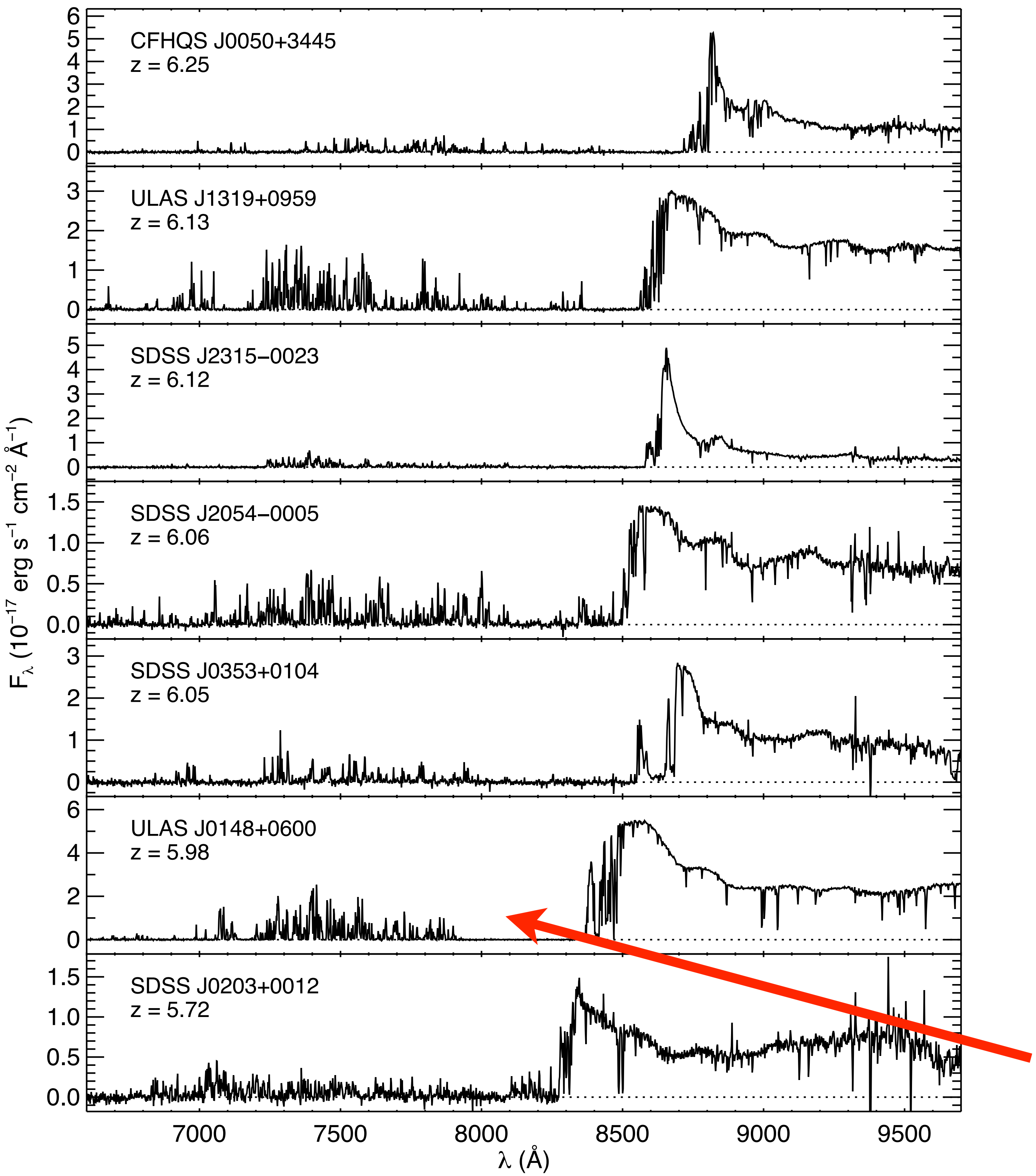
Aspen Center for Physics, 3/10/16

The High-Redshift Lyα Forest



From Becker et al. 2015

- Most z~6 segments of the forest show some transmission

⇒ Reionization largely complete

(McGreer et al. 2015)

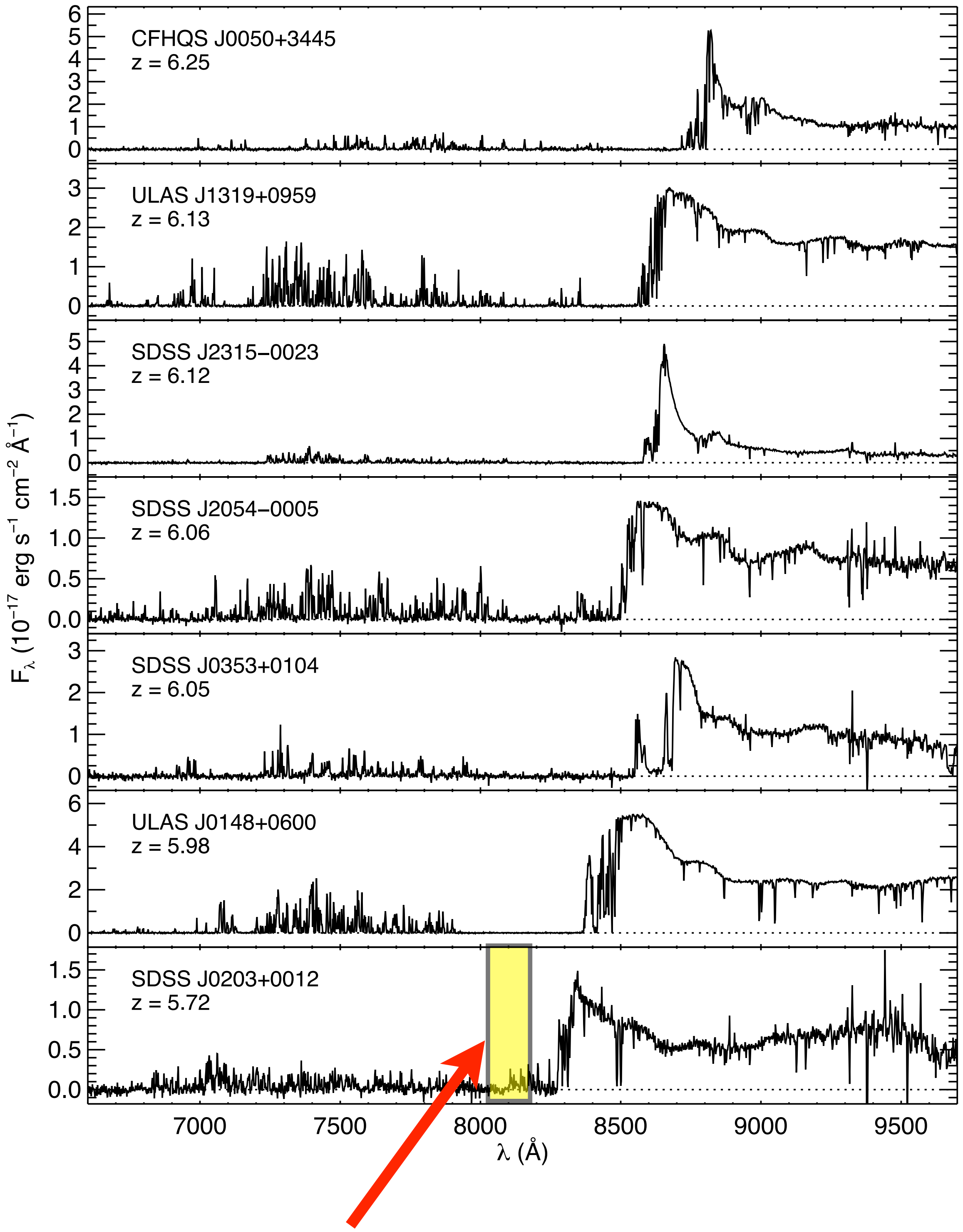
- Measured transmission also constrains UV background after reionization.

(Bolton & Haehnelt 2007;
Becker & Bolton 2013)

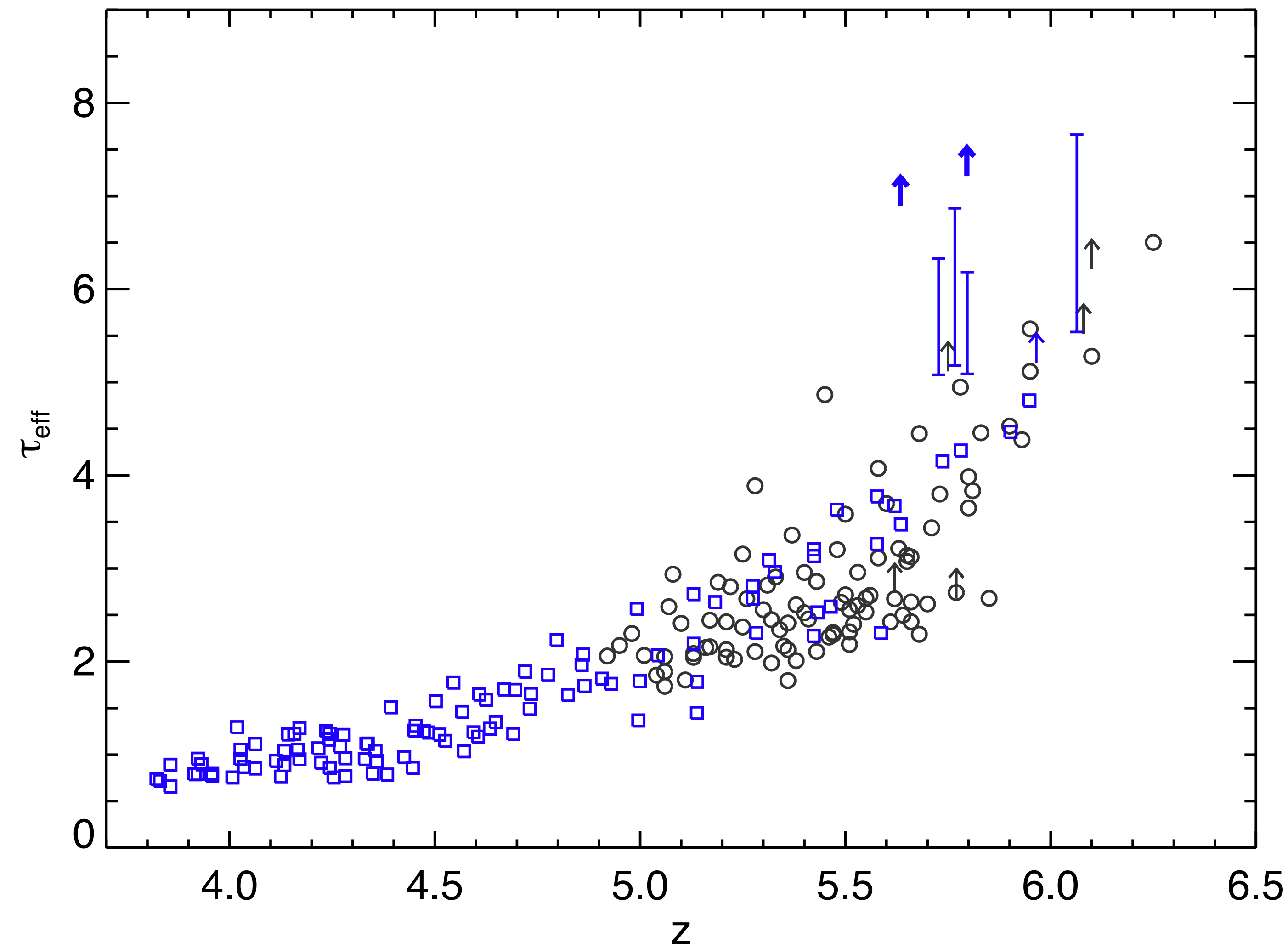
- **Note: large sightline to sightline variations!**

150 Mpc trough!

Quantifying Lyα Forest Opacity



$L = 50h^{-1}$ Mpc



$$\langle F \rangle_L \equiv \exp(-\tau_{\rm eff})$$

(F is continuum normalized)

From Becker et al. (2015) and Fan et al. (2006)

Dispersion in $\tau_{\rm eff}$

- Note evolution in both mean *and* dispersion

$$\tau_{{\rm Ly}\alpha} \propto n_{\rm HI} \propto \frac{\alpha_A n_e n_{\rm HII}}{\Gamma}$$

$$\tau_{{\rm Ly}\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

Density fluctuations

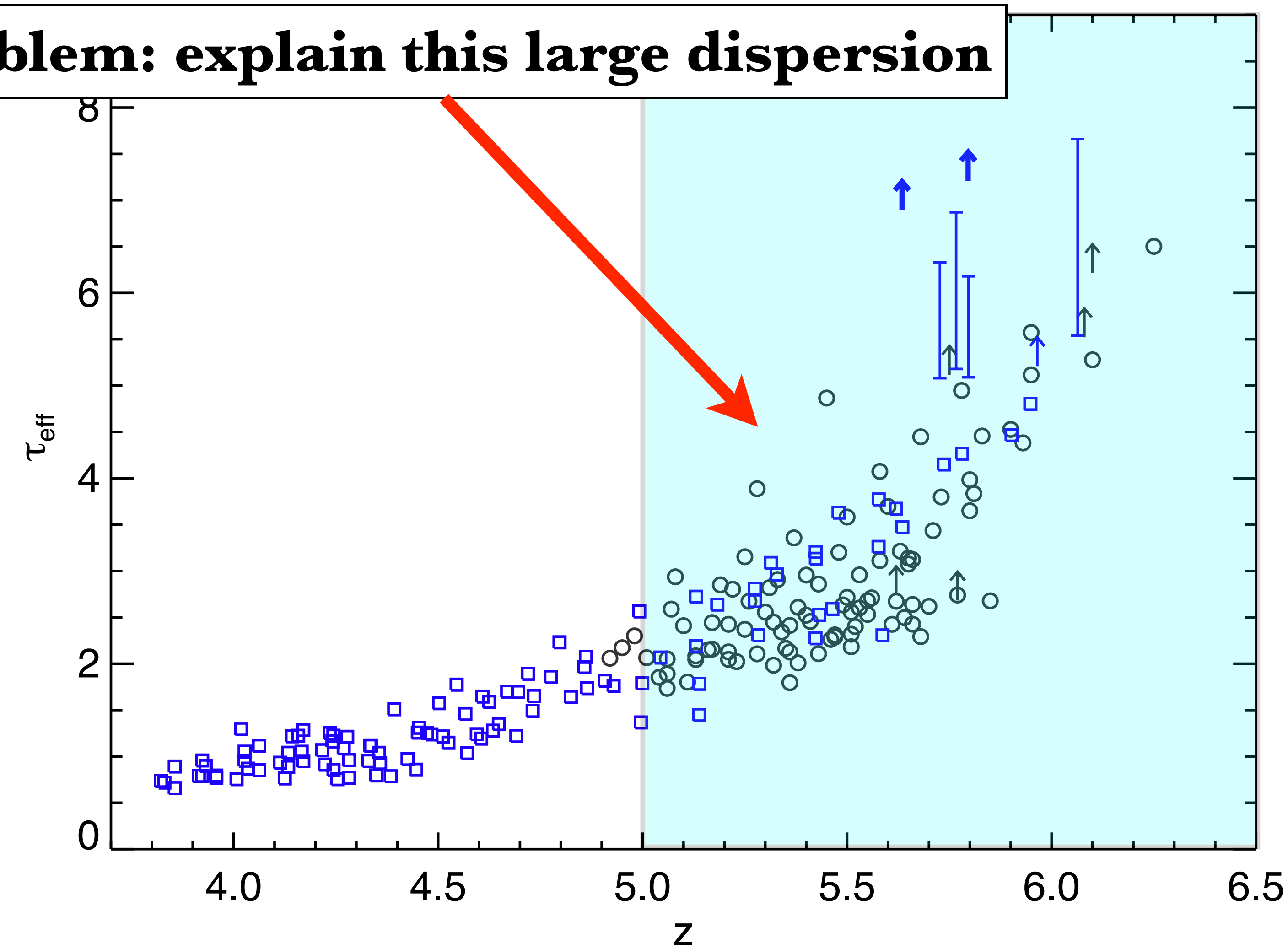
$$\Gamma \propto \int_{13.6{\rm eV}}^{\infty} \frac{{\rm d}\nu}{\nu}\; J_\nu(\nu)\; \sigma_H(\nu)$$

Temperature fluctuations

Ionizing background fluctuations

$$\tau_{{\rm Ly}\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

Problem: explain this large dispersion



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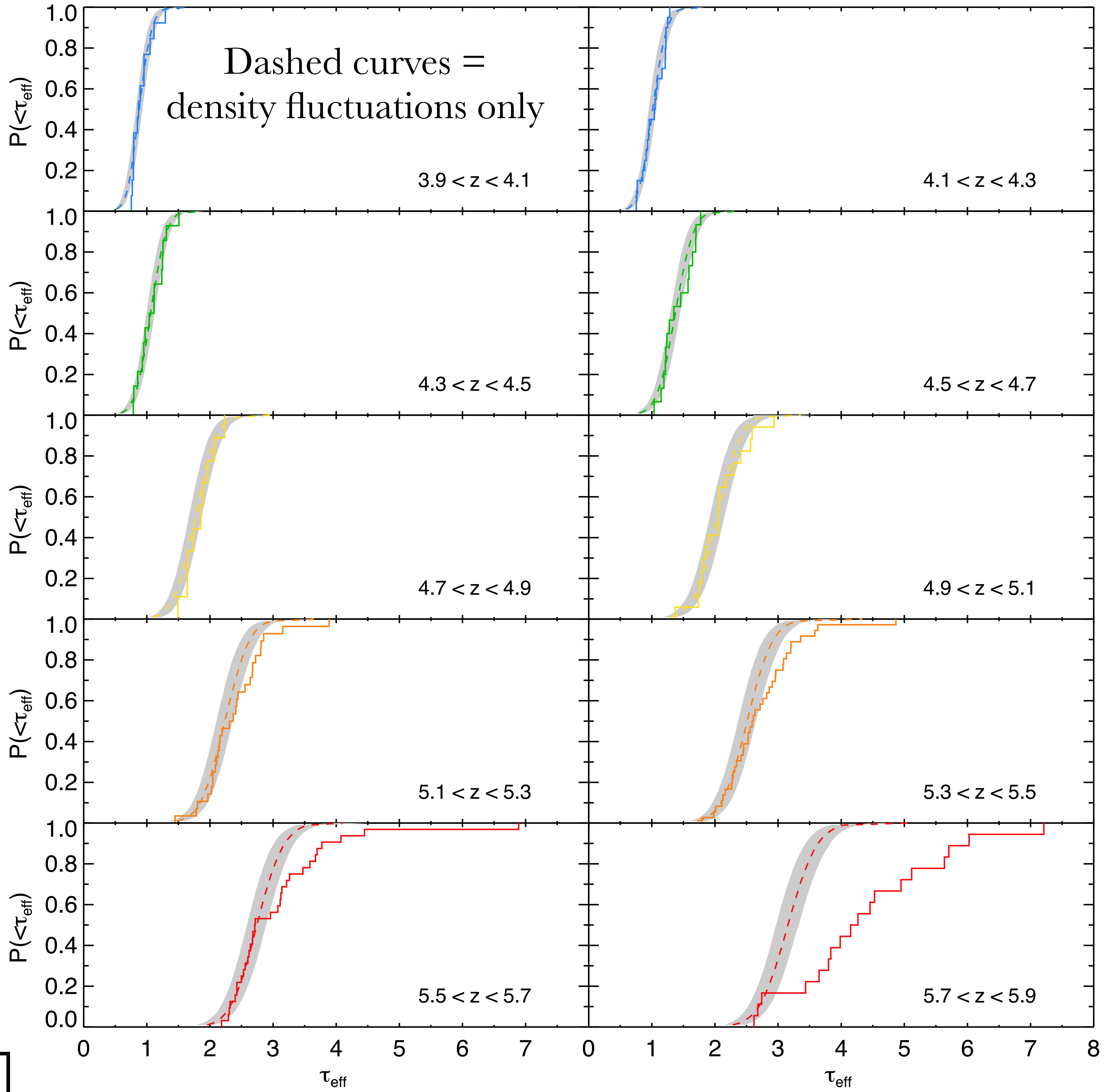
IGM Density Fluctuations are not Enough



$$\tau_{\mathrm{Ly}\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

From Becker et al. (2015)

Ionizing Background Fluctuations (galaxies)

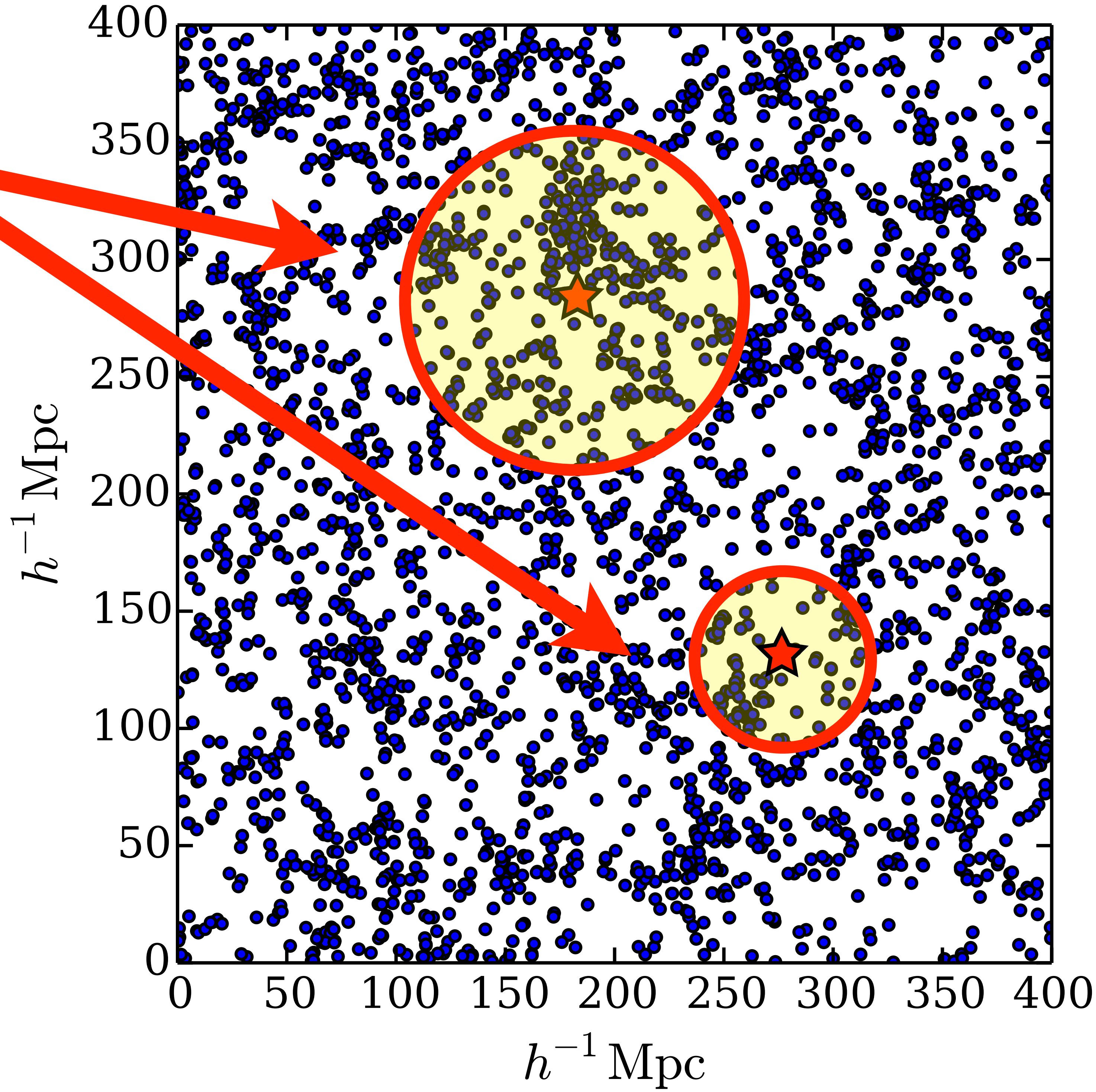
- Mean free path varies over large scales (Davies & Furlanetto 2015)

- Under-dense voids must become the most opaque (largest τ_{eff}).

- Requires <MFP> < 20 Mpc at z =5.6

- MFP = 65 ± 10 Mpc at z=5.2 Worseck et al. (2014)

(Cartoon)



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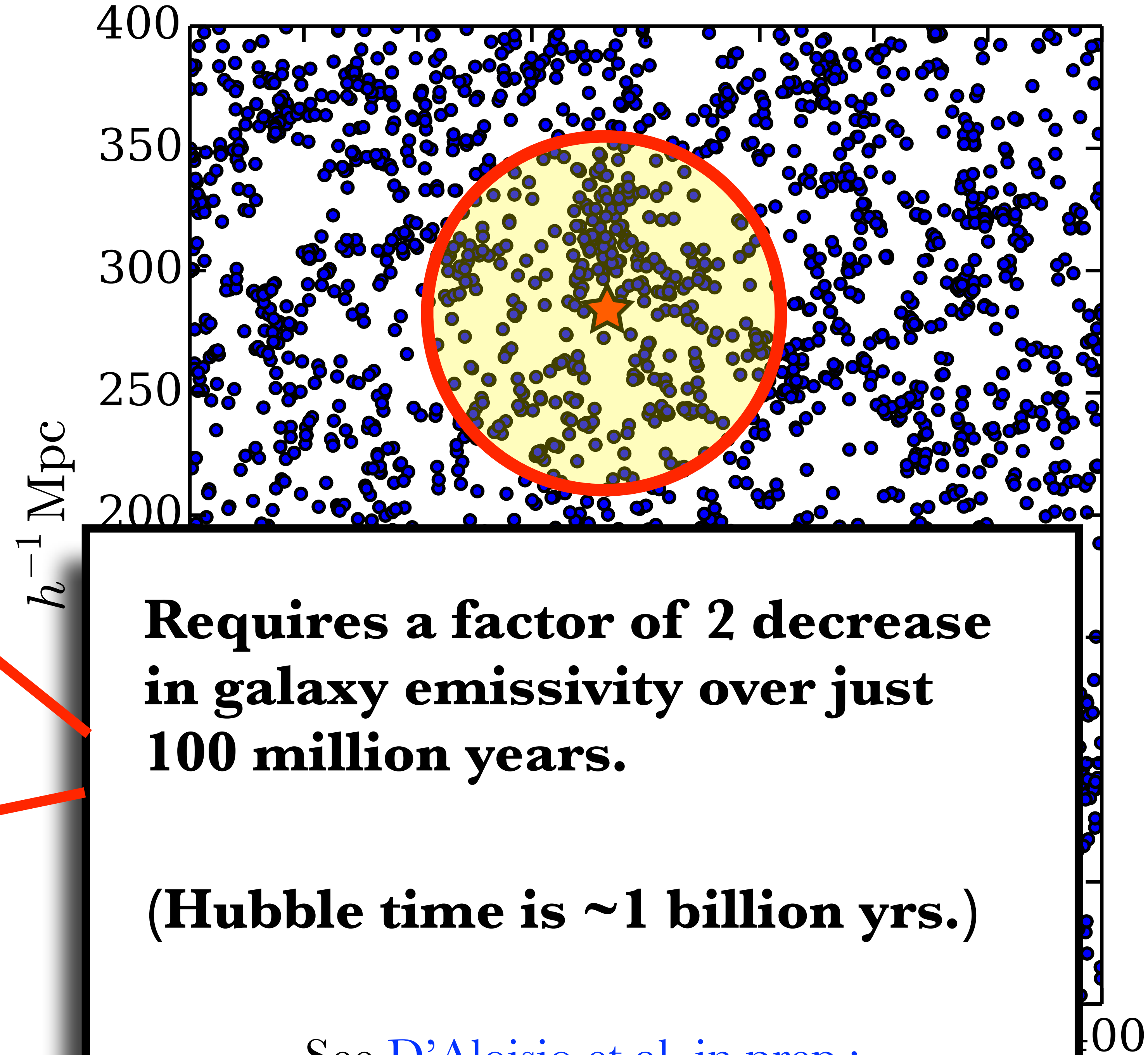


Requires a factor of 2 decrease in galaxy emissivity over just 100 million years.

(Hubble time is ~1 billion yrs.)

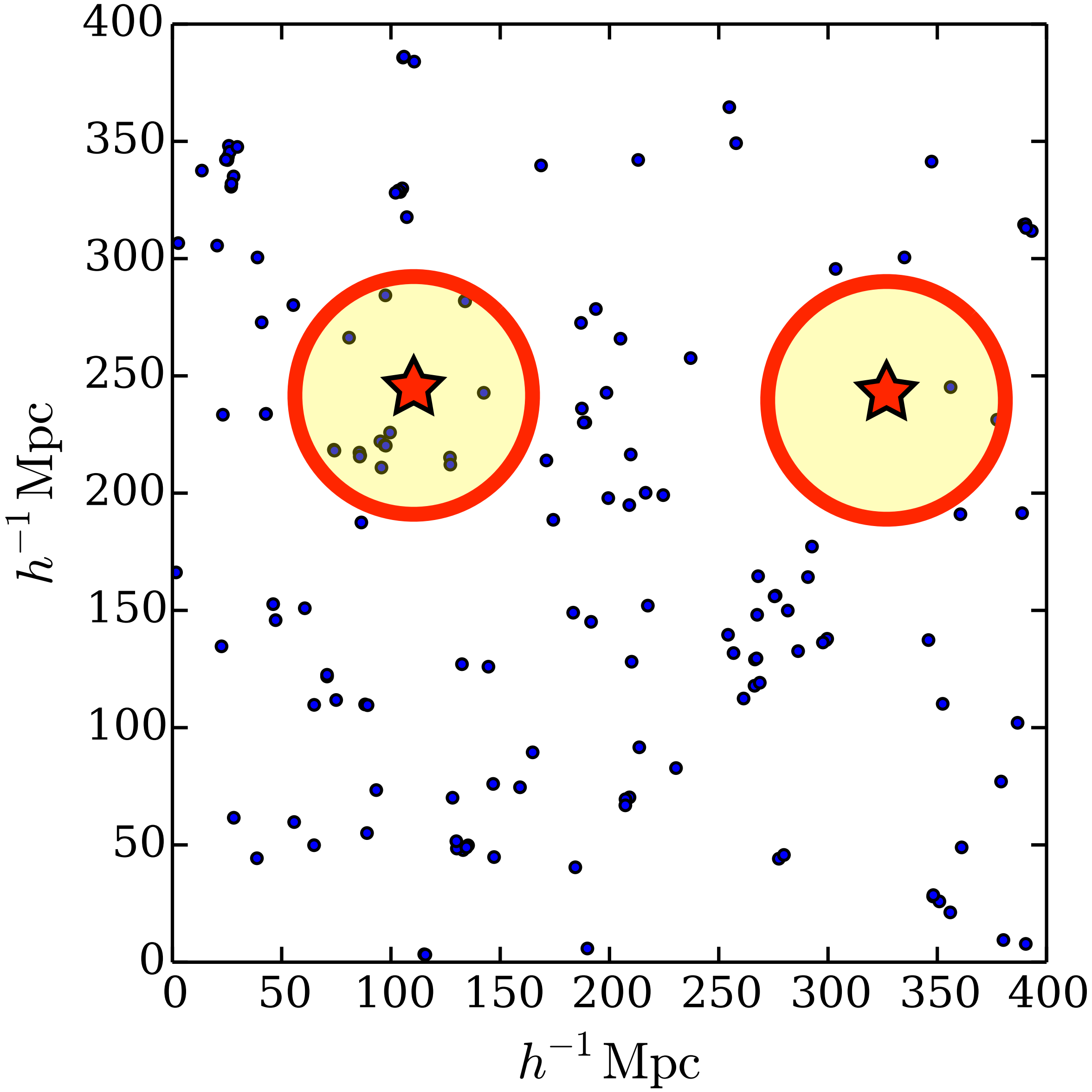
See D'Aloisio et al. in prep.;

$$\tau_{\mathrm{Ly}\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

Rare Sources (Quasars/AGN)

See Chardin et al. 2015

Rarer, brighter sources

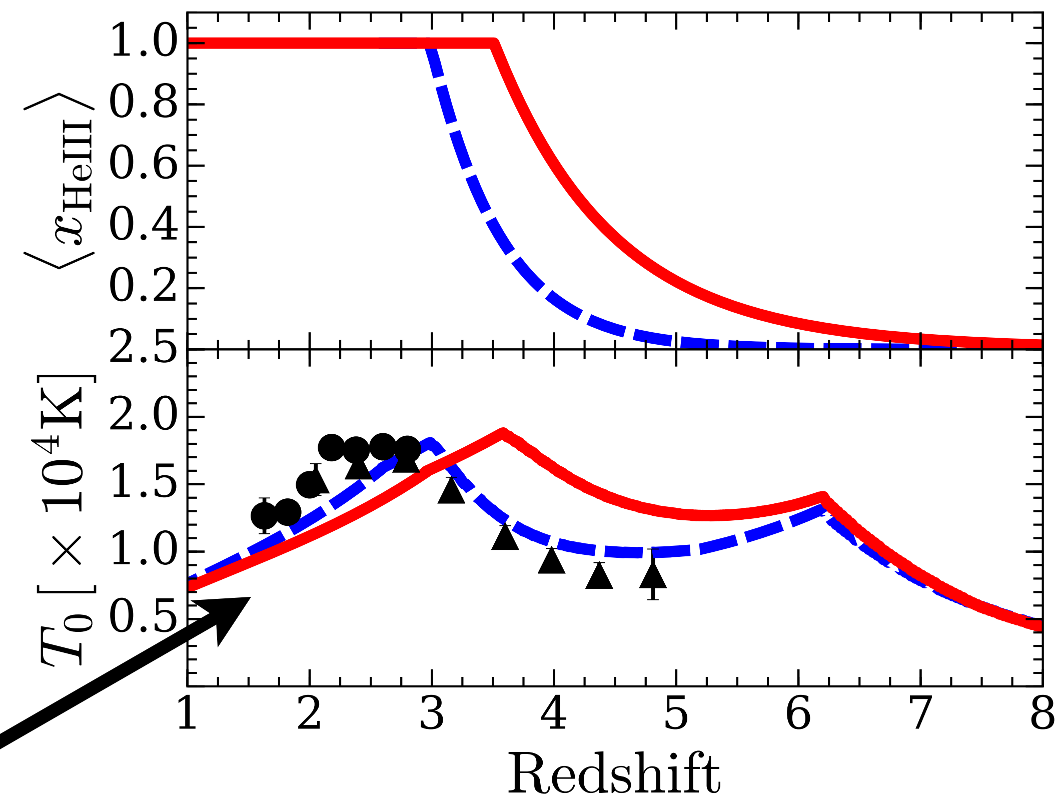


Caveats:

(1) Most previous surveys ⇒ Not enough AGN at $z > 5$.

(see however Giallongo et al. 2015)

(2) For larger AGN contribution, must block > 4 Ry radiation

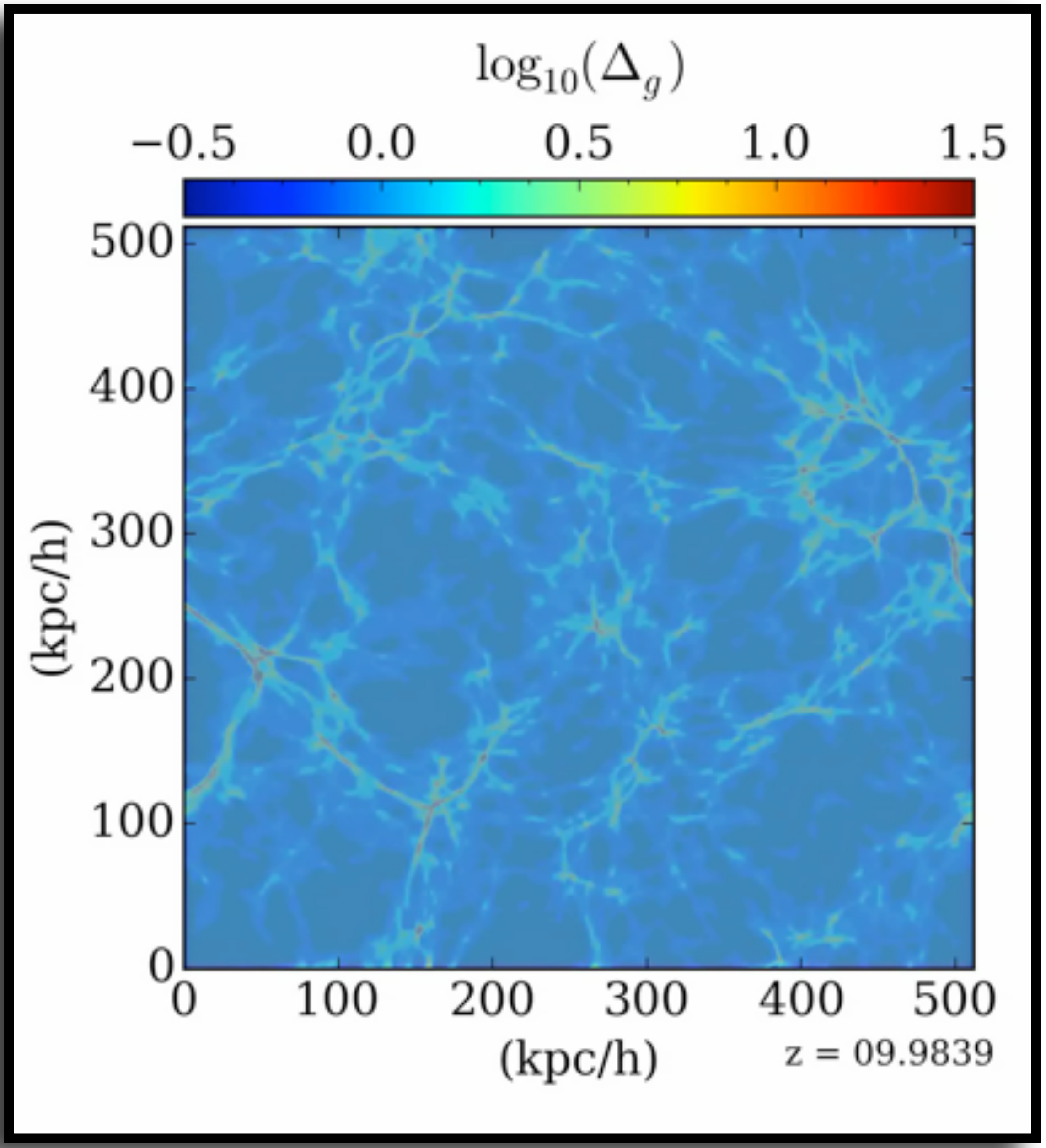


T Measurements by Becker et al. 2011; Boera et al. 2014

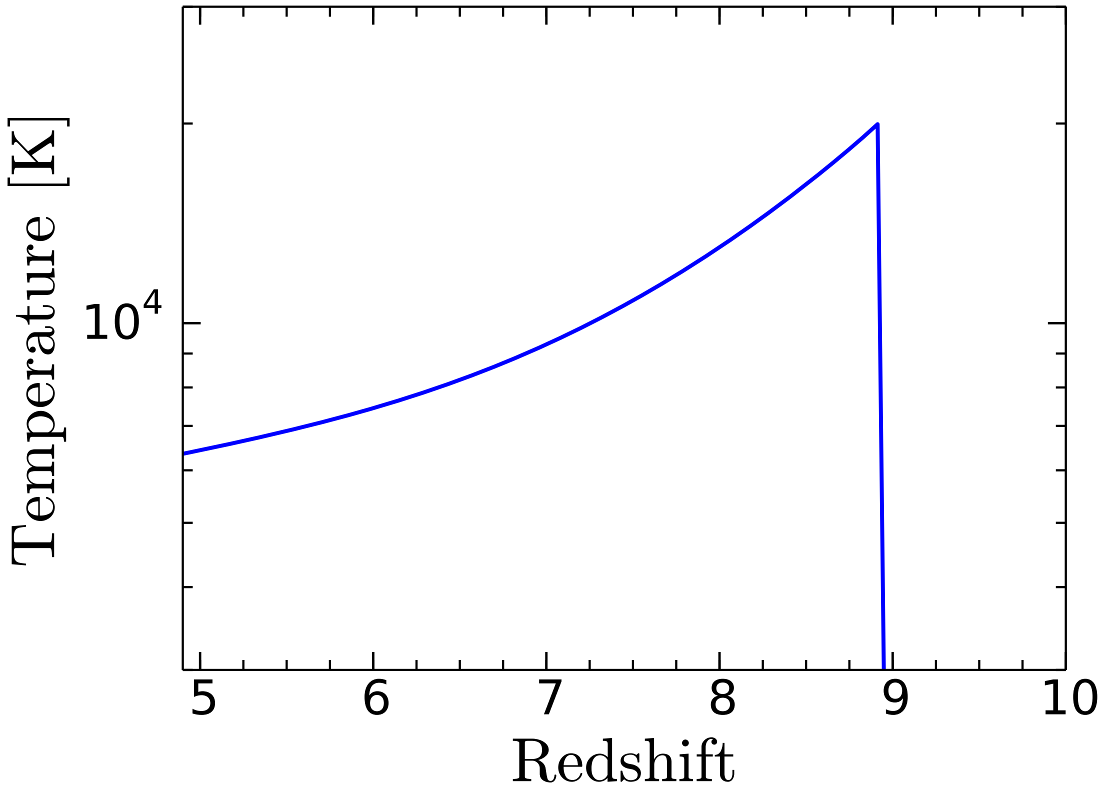
D'Aloisio et al. in prep.; see also Upton Sanderbeck et al. 2016

$$\tau_{\mathrm{Ly}\alpha} \propto \frac{T^{-0.7} \Delta_b^2}{\Gamma}$$

Relic Temperature Fluctuations from Reionization



- Reionization heats IGM to T_{reion} = 20,000 - 30,000 K
- Heating processes: photoheating
- Cooling processes: adiabatic expansion, Compton, recombination, free-free



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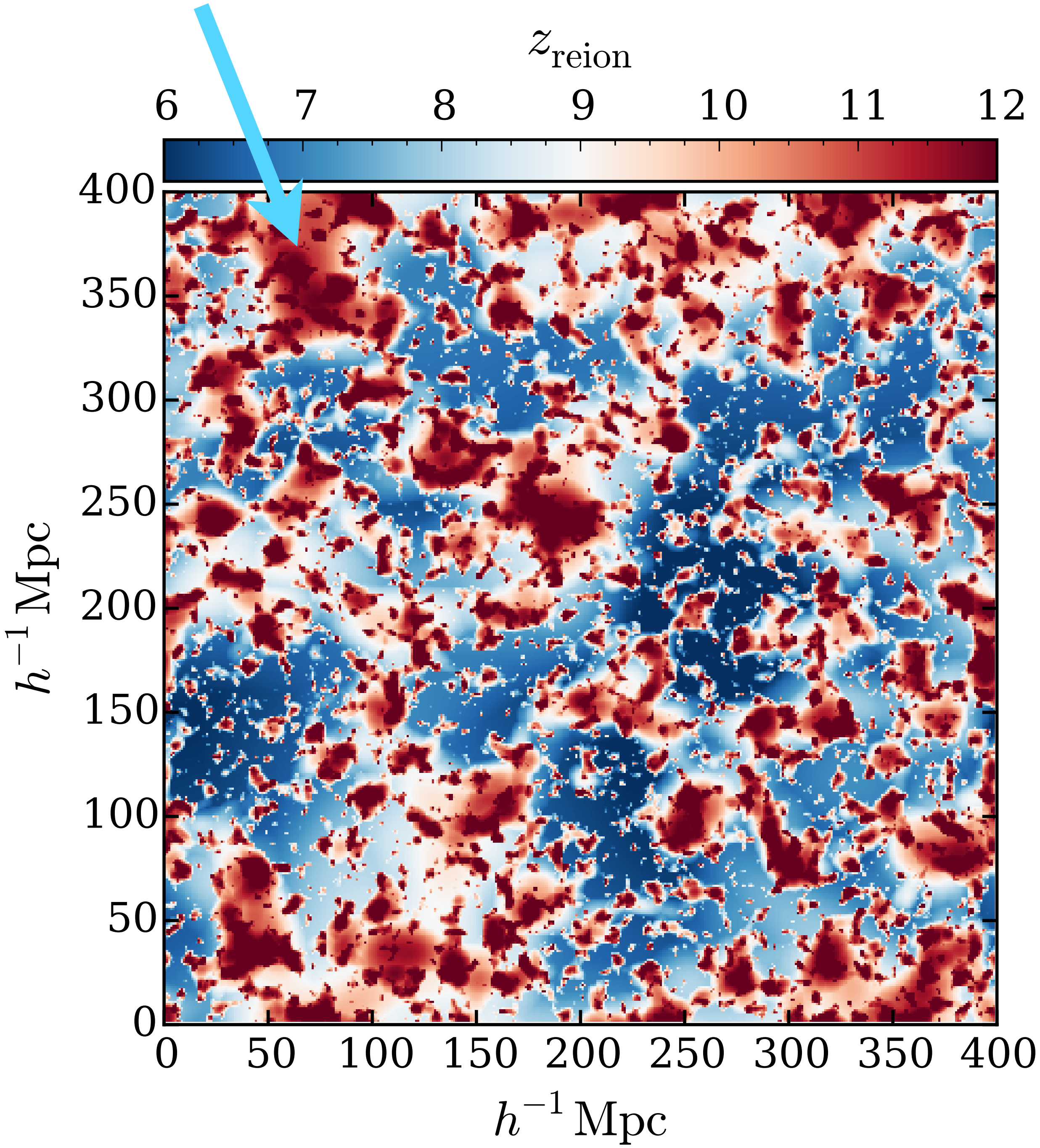
D'Aloisio, McQuinn & Trac 2015
arXiv:1509.02523

Relic Temperature Fluctuations from Reionization

Reionization redshifts



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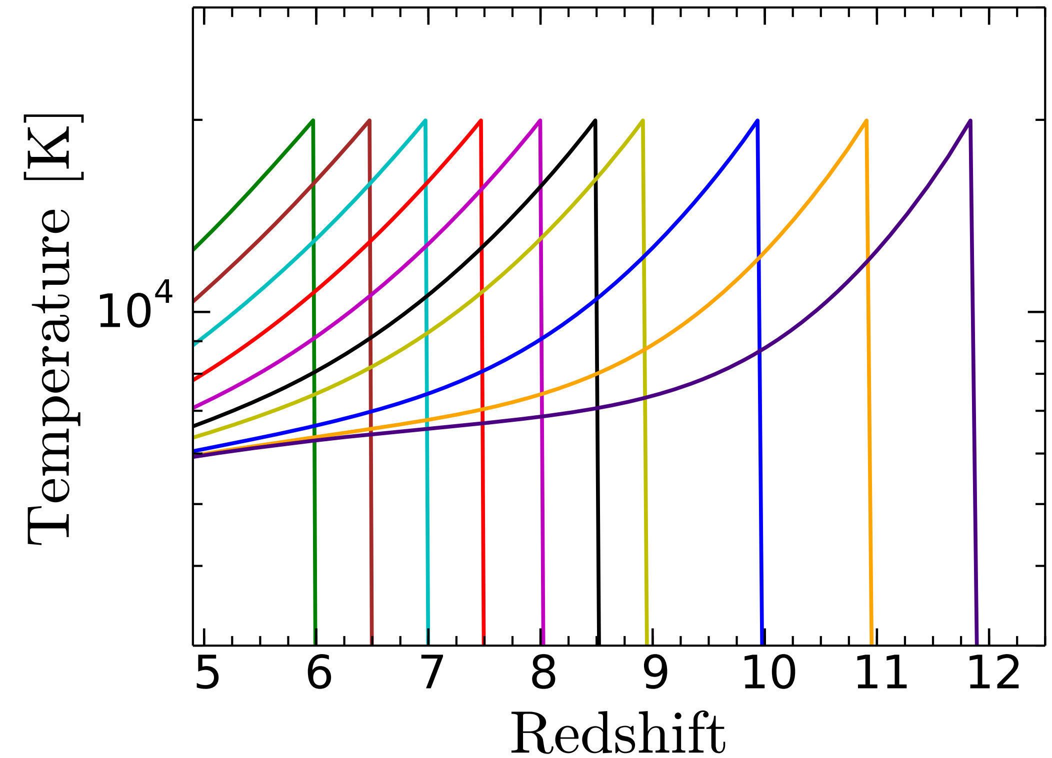

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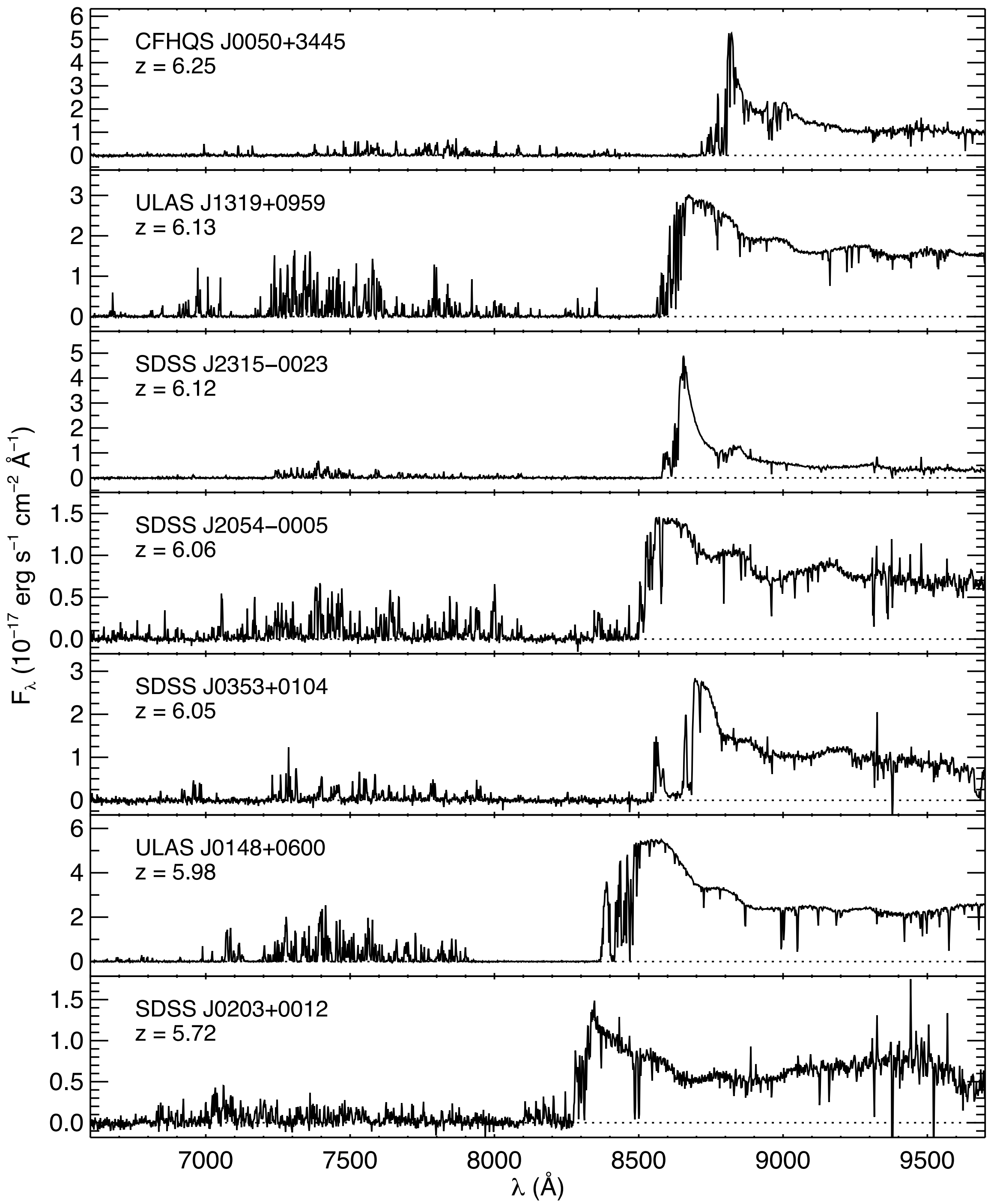
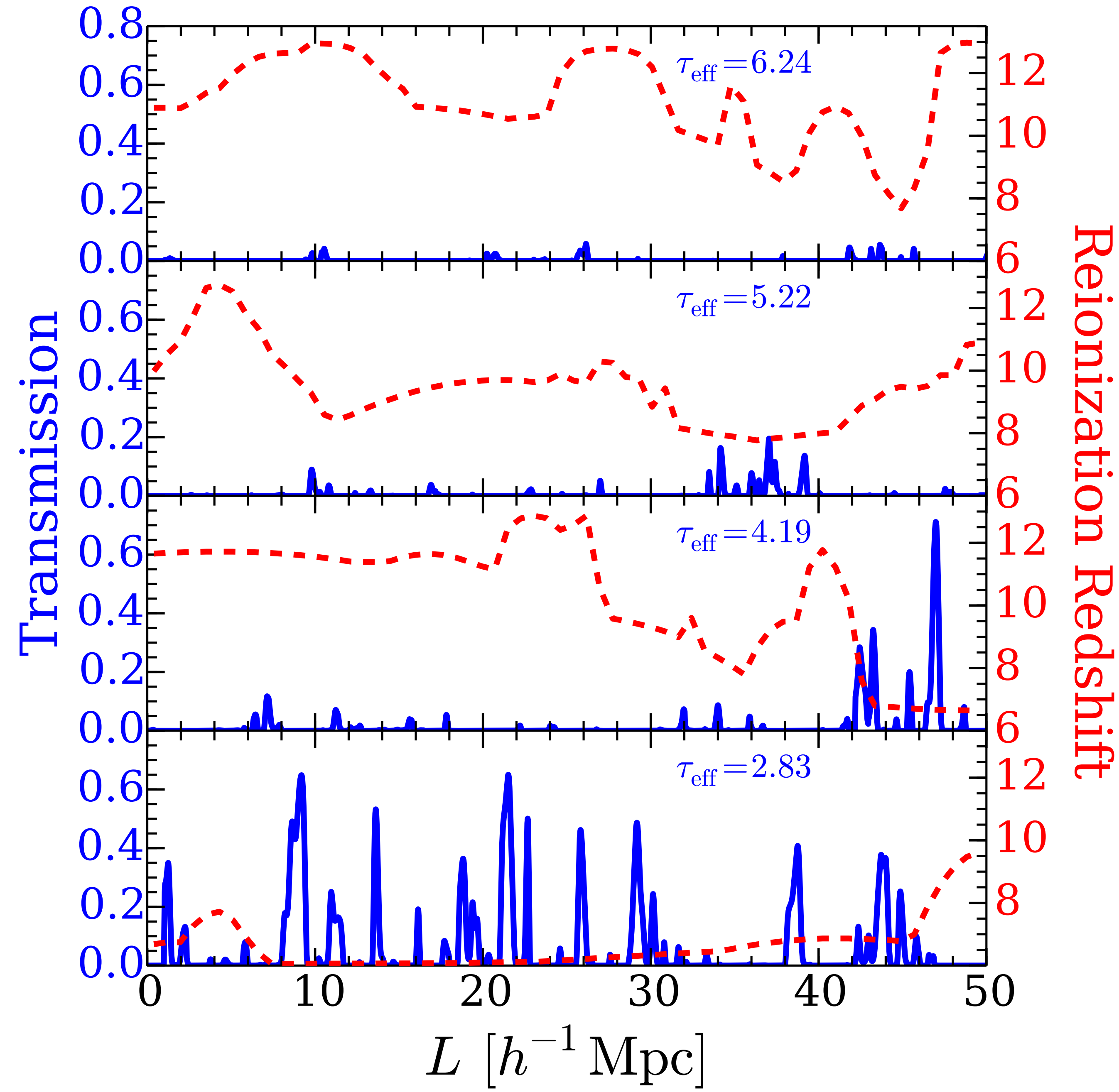
Large Variations in the High-z Forest

(Observed, from Becker et al. 2015)



(Simulated, z = 5.8)

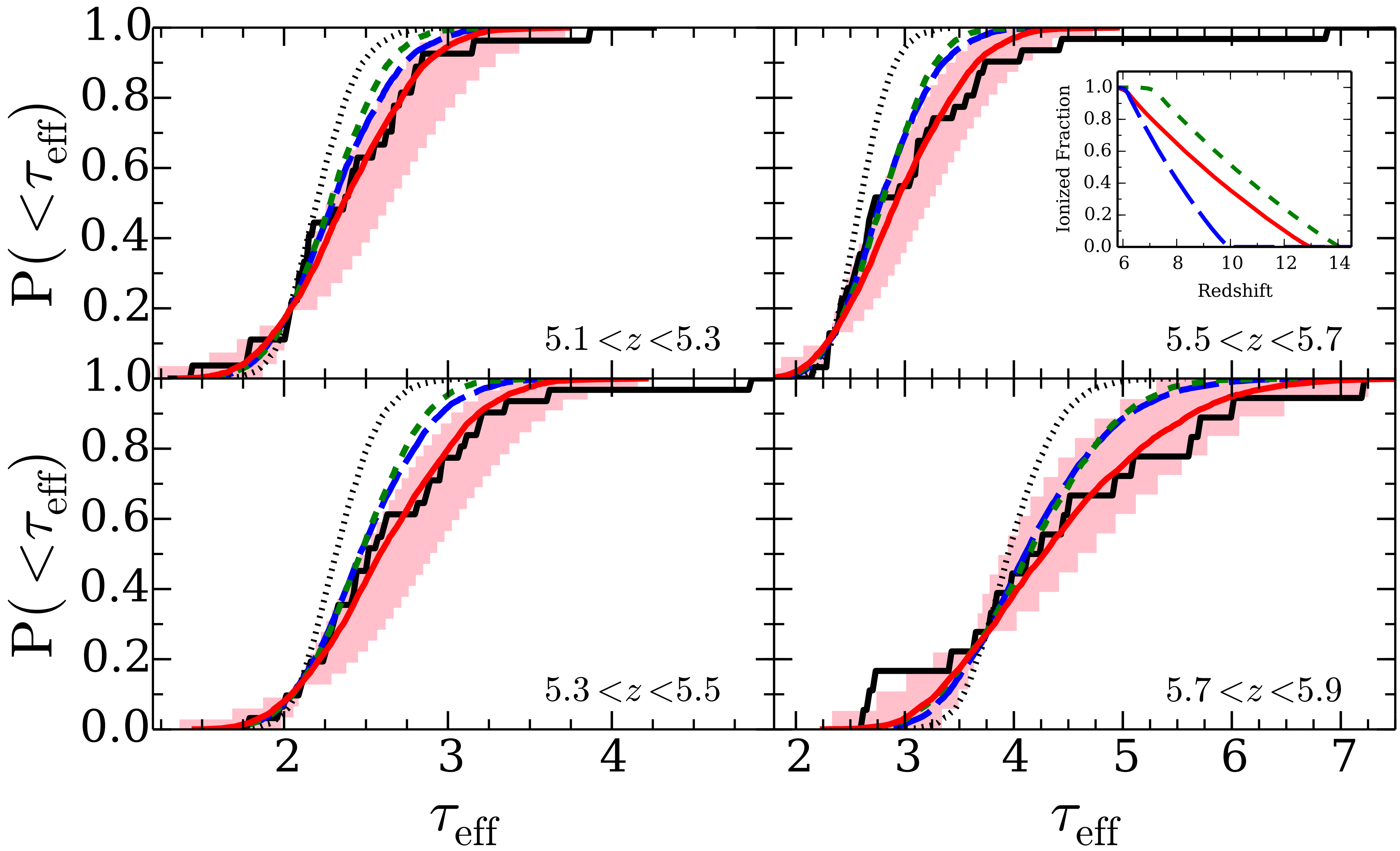


$$\tau_{{\rm Ly}\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

Darkest segments were reionized earliest!

New window into spatial structure of cosmic reionization?

Relic Temperature Fluctuations from Reionization



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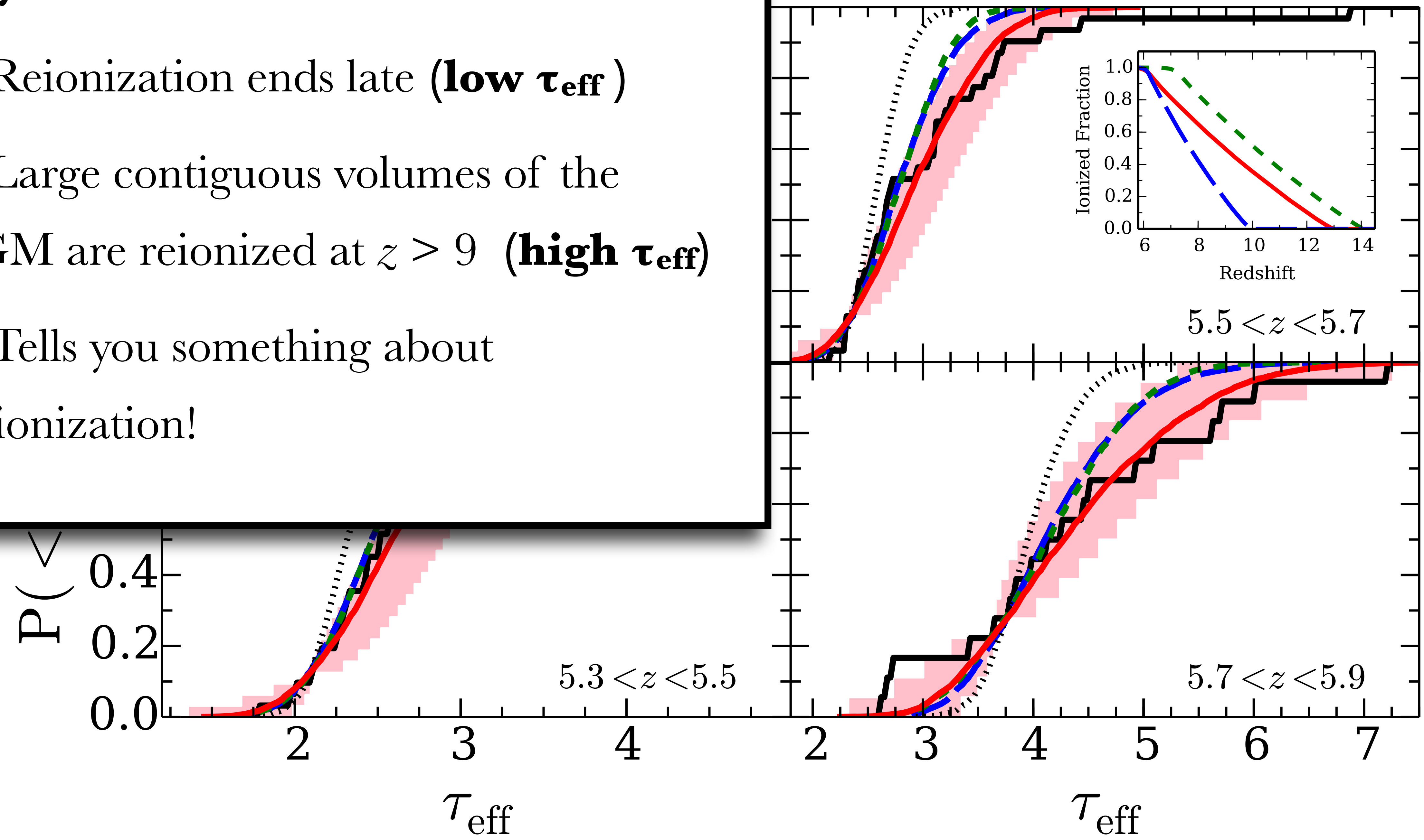
Relic Temperature Fluctuations from Reionization

Key features of successful model:

- Reionization ends late **(low τ_{eff})**
- Large contiguous volumes of the IGM are reionized at $z > 9$ **(high τ_{eff})**
- Tells you something about reionization!



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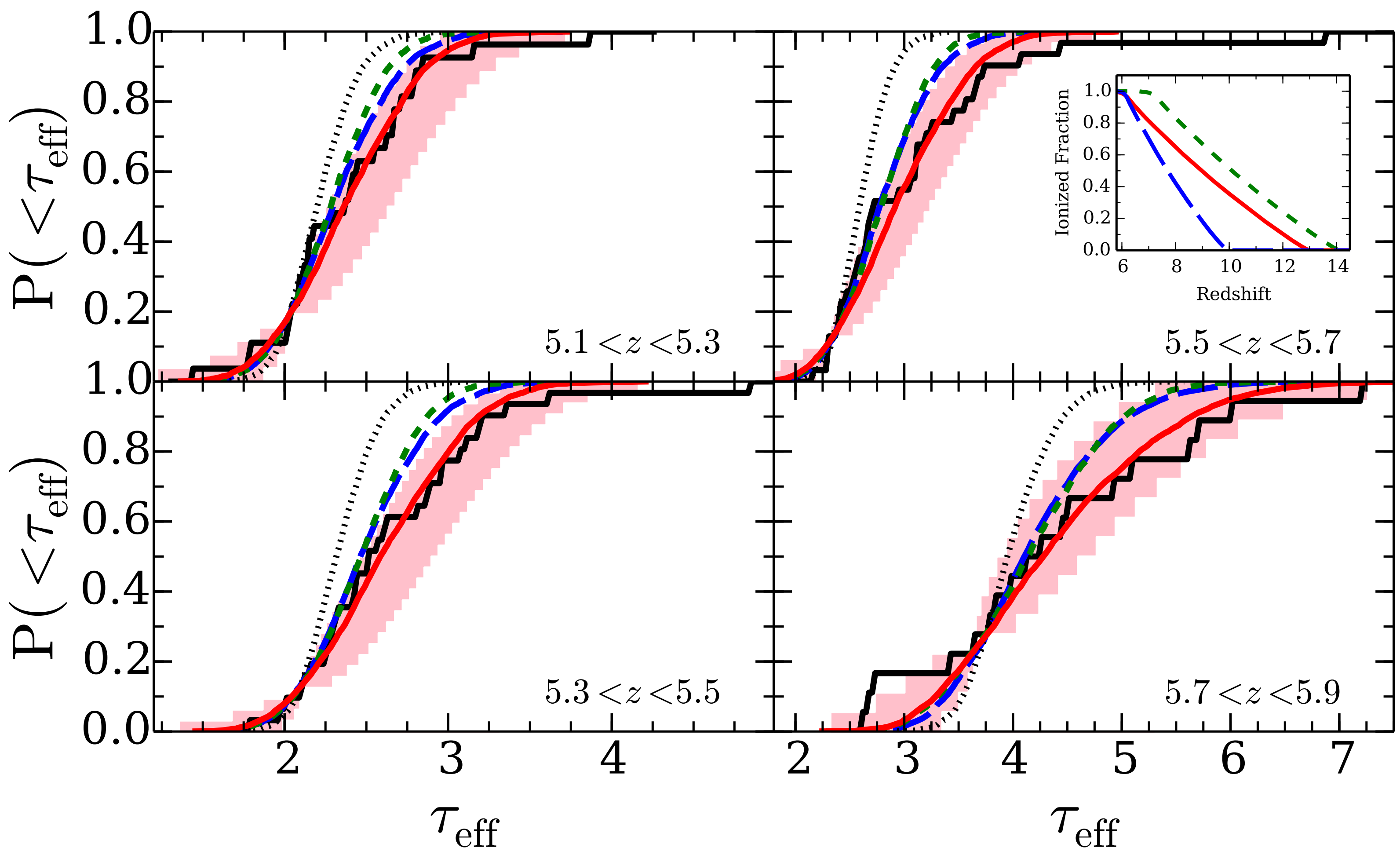
Selling Points



- Red Curve: $\tau_{\rm es} = 0.068$ Planck meas.: $\tau_{\rm es} = 0.066 \pm 0.016$
- Matches observed evolution well; works at lower z too!
- Bonus: may open new window into reionization!

$$\tau_{\rm Ly\alpha} \propto \frac{T^{-0.7}\Delta_b^2}{\Gamma}$$

Where do we stand?

(1) Ionizing Background Fluctuations (Spatially Varying Mean Free Path)

Voids have less sources
They see much lower ionizing background
Absorbers are less ionized there, smaller MFP
Voids are the most opaque

(2) Rare Sources (Quasars/AGN)

Opacity fluctuations driven by rarity and brightness of AGN
AGN near most transmissive regions

(3) Relic Temperature Fluctuations from Reionization

Overdense regions are reionized first
At $z \sim 5.5$, they are colder
They have higher residual neutral H densities
Overdensities are the most opaque