New Measurements of the UV Background in the Post-Reionization Epoch

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6.26.2013

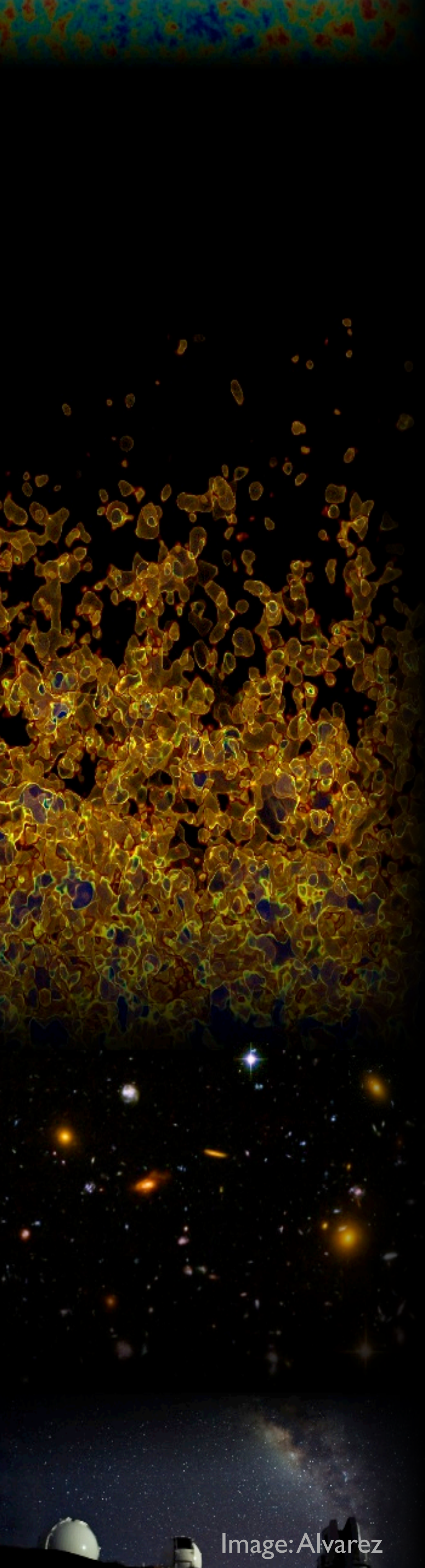
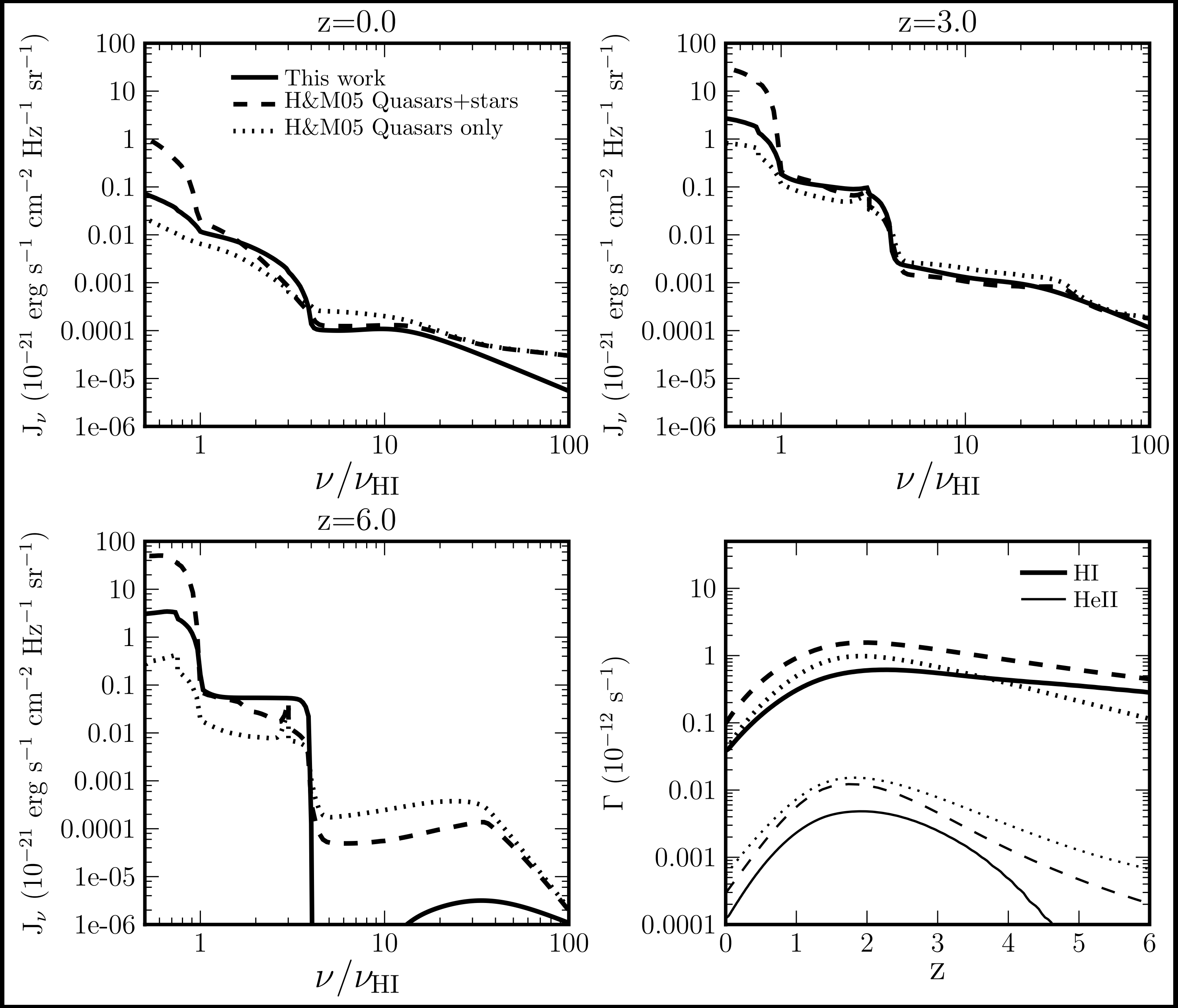


Image: Alvarez

Outline

- Motivation
- New measurements of IGM Temperature & Lyα Opacity
- UVB Results
- Implications for Reionization & High-z Galaxies

The UV Background



Faucher-Giguere+

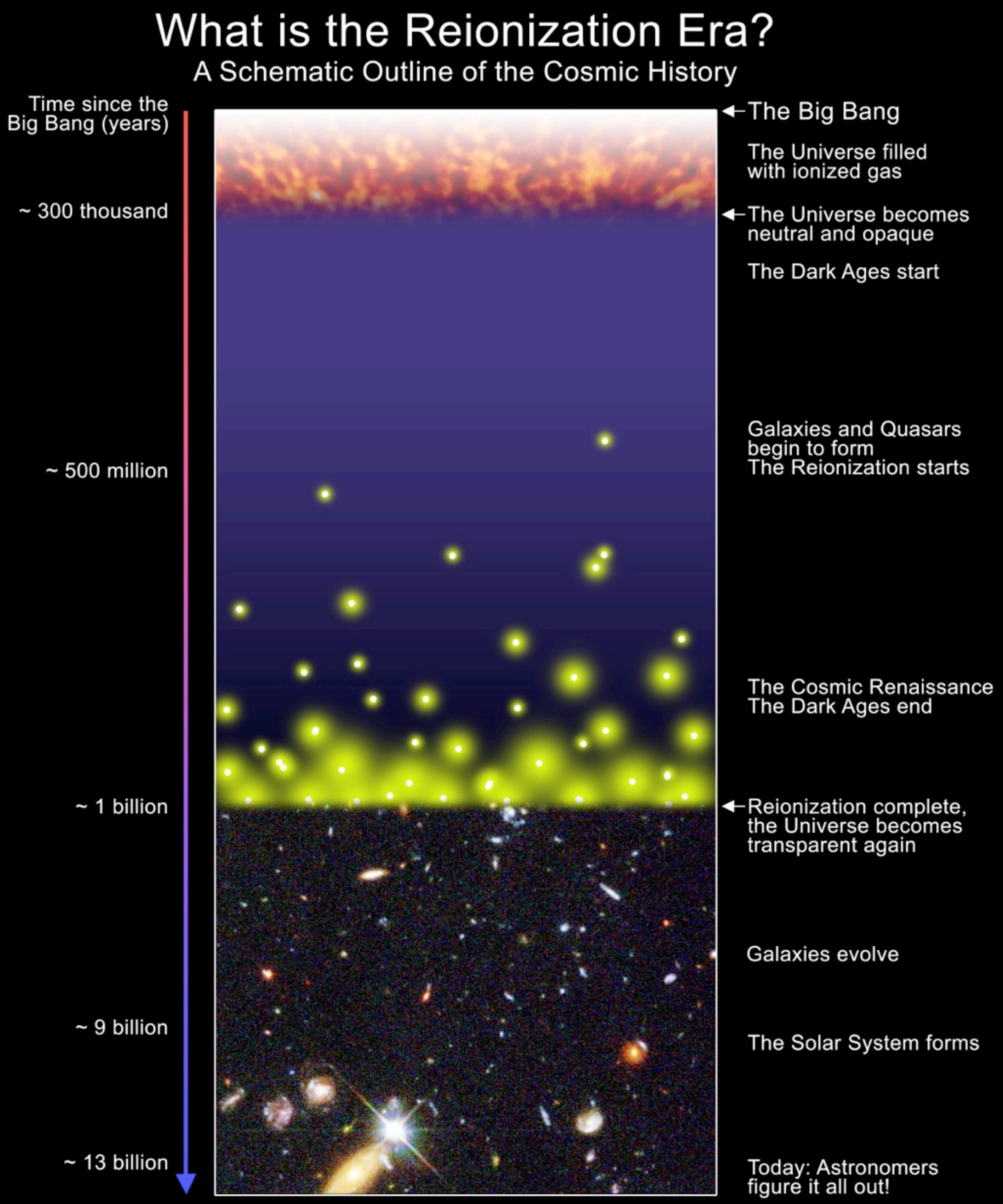
1. Modeling absorbers

2. Understanding sources
   - Faint and/or high-z
   - Ionizing spectra

Cosmic Reionization

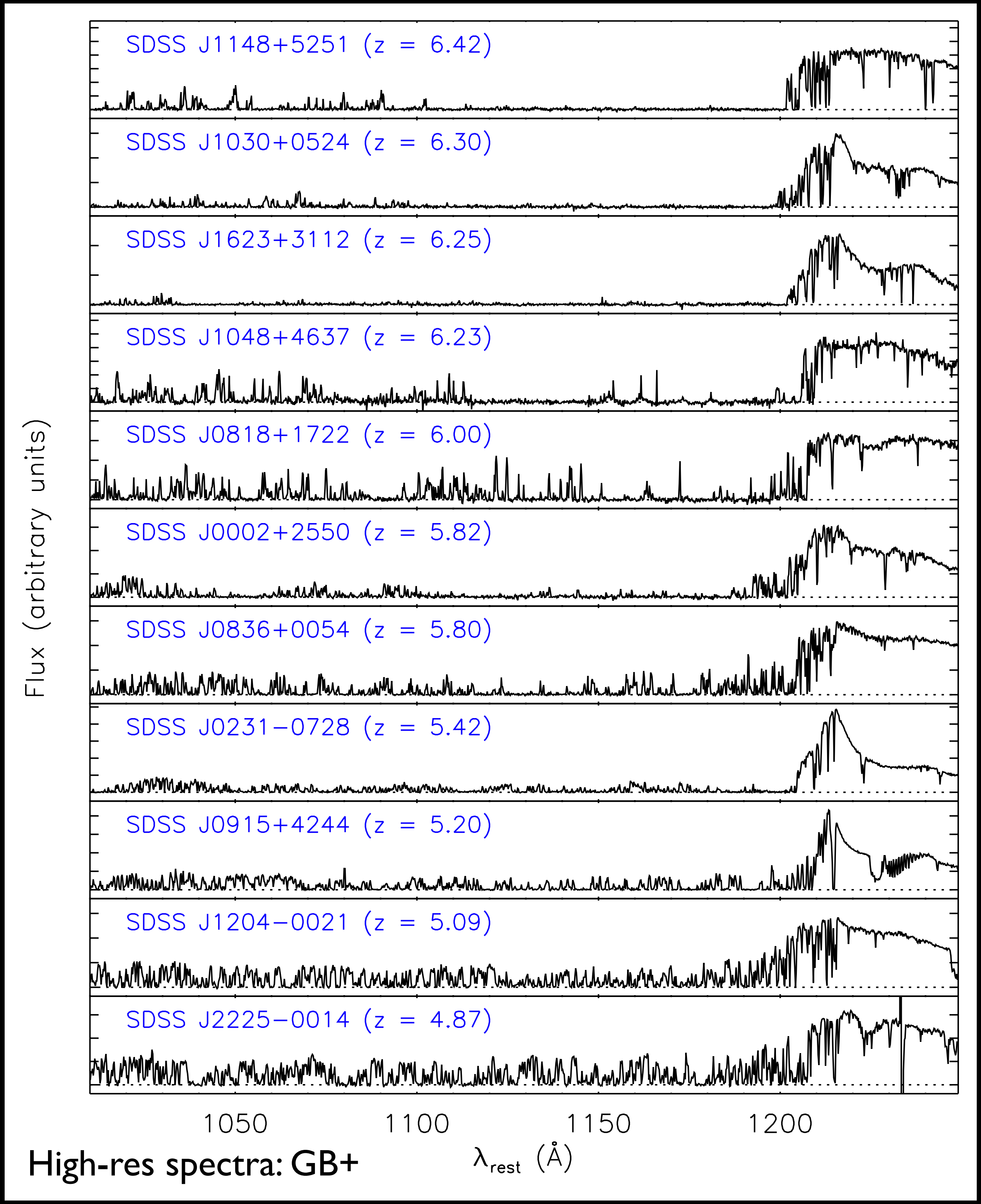
1. Hydrogen Reionization
   z > 6, galaxies?

2. Helium Reionization
   z > 3, AGN

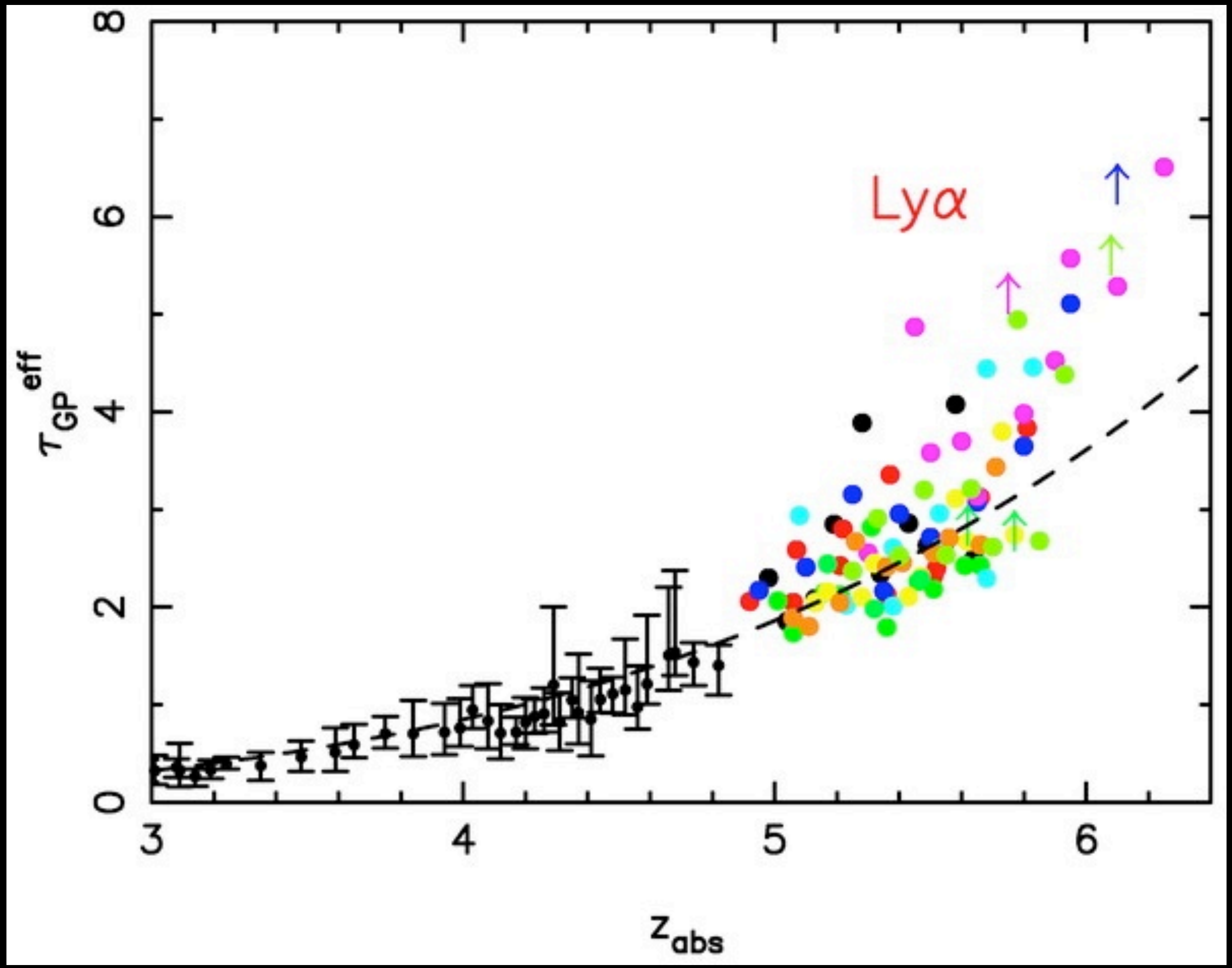


S.G. Djorgovski et al. & Digital Media Center, Caltech

Hydrogen Reionized at z > 6



High-res spectra: GB+

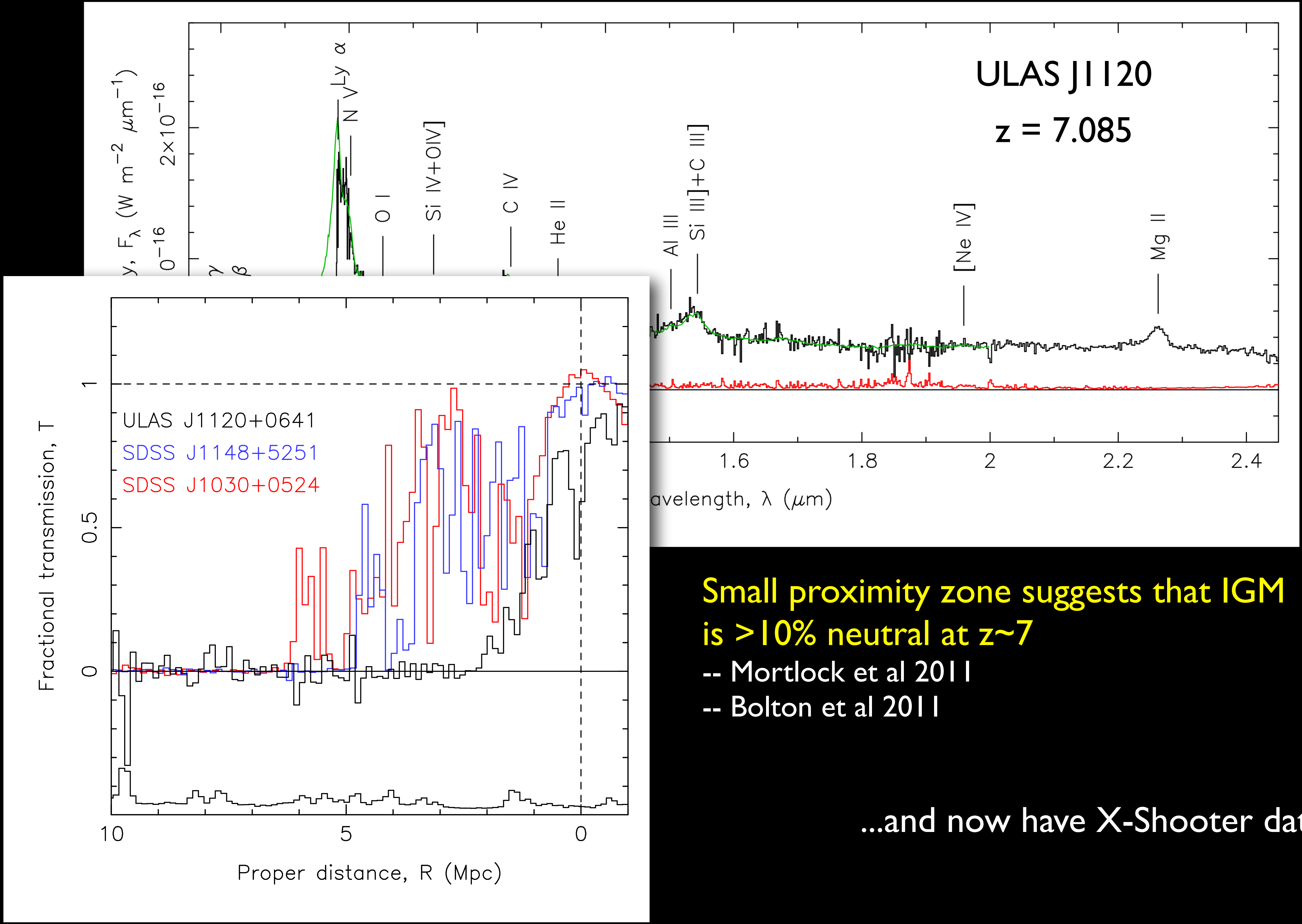


However, $$\tau_{\rm GP} \approx 4 \times 10^5 f_{\rm H\,I} \Delta \left(\frac{1+z}{7} \right)^{3/2}$$

IGM must be highly ionized at z < 6

Fan+ 2006, Becker+ 2007

The first z=7 QSO!



Small proximity zone suggests that IGM is >10% neutral at z~7

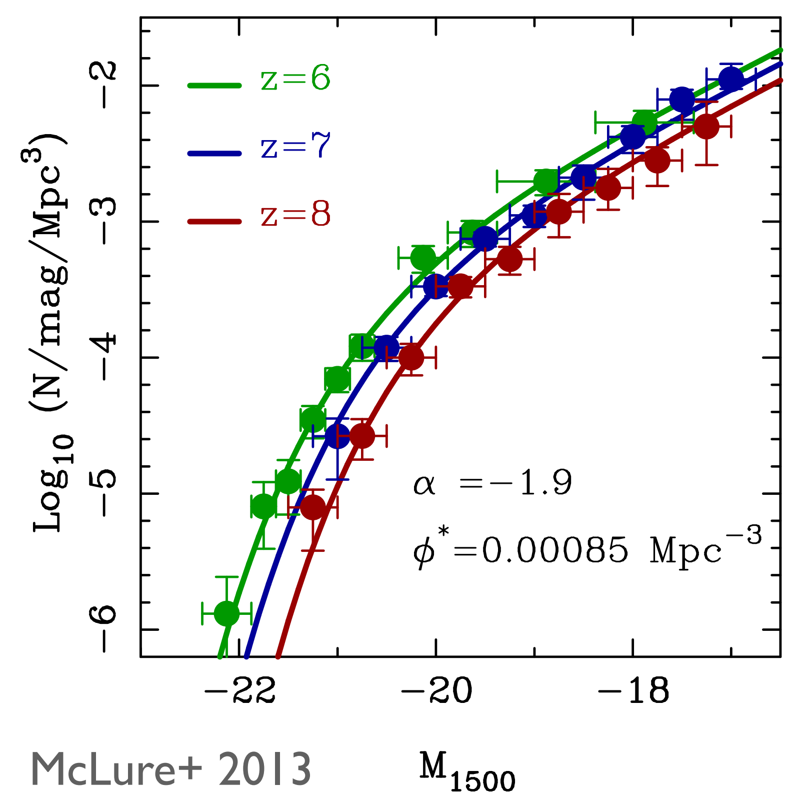
-- Mortlock et al 2011

-- Bolton et al 2011

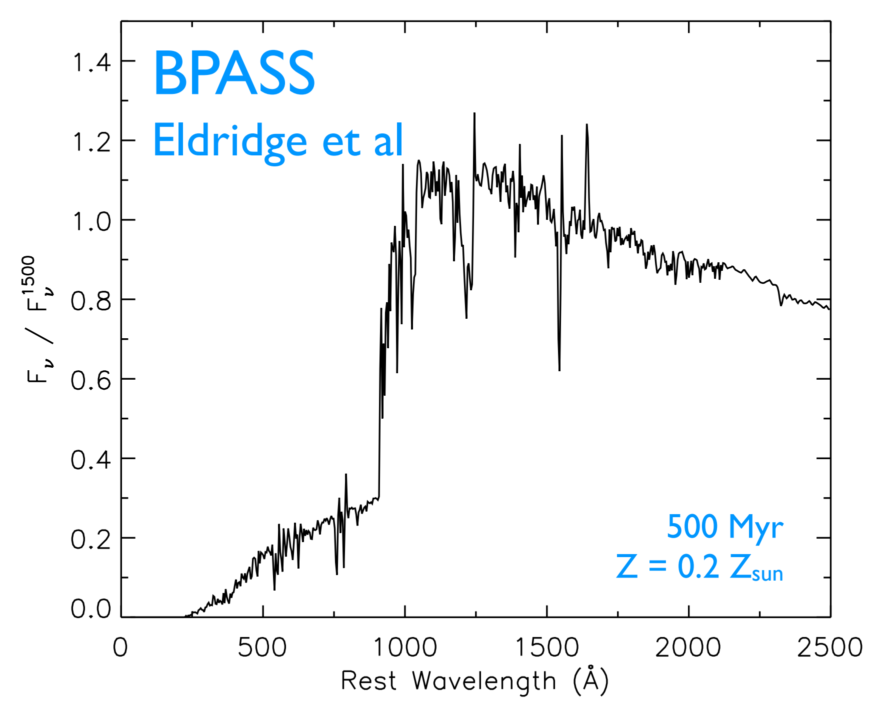
...and now have X-Shooter data!

George Becker - IoA & KICC

The photon problem



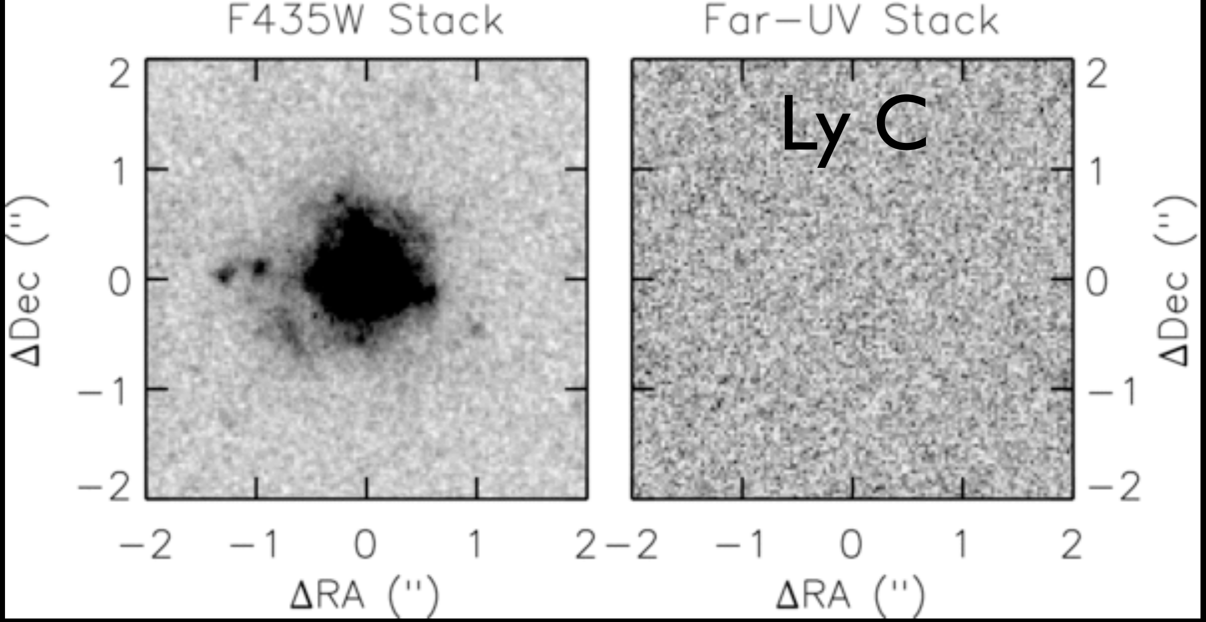
McLure+ 2013



To reionize hydrogen, need to emit at least a few ionizing photons/atom into the IGM by z=6

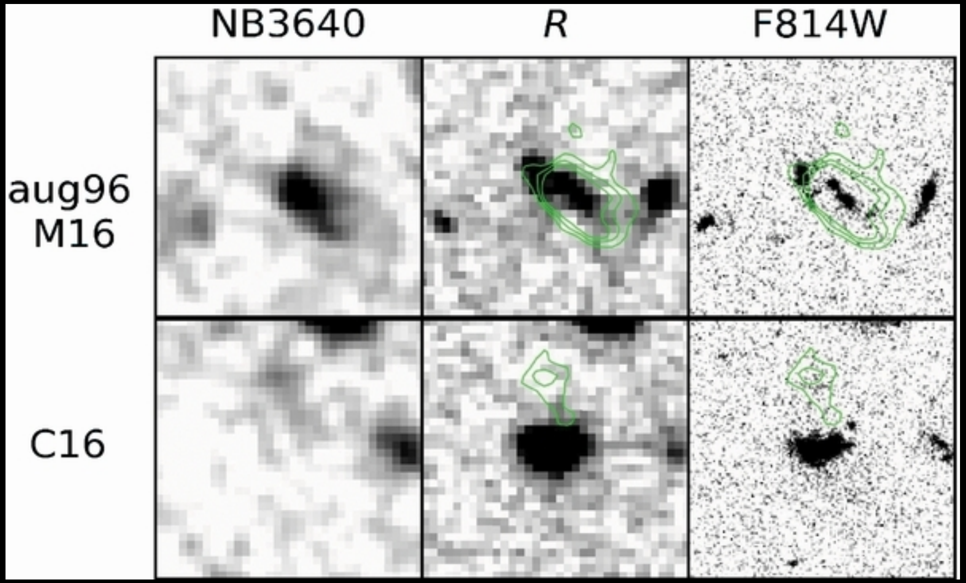
For standard SEDs and 10% escape fraction, z=6 galaxies emit ~1-3 ionizing photon/atom/Gyr -- but global SFR drops rapidly at z > 6!

Evolving? escape fraction



Siana+ 2010

At z~1, f_{esc} ~ 0



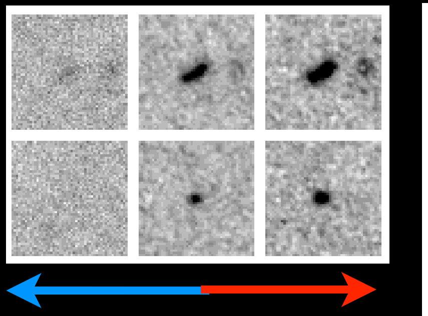
Nestor+ 2011, 2012
Vanzella+ 2012

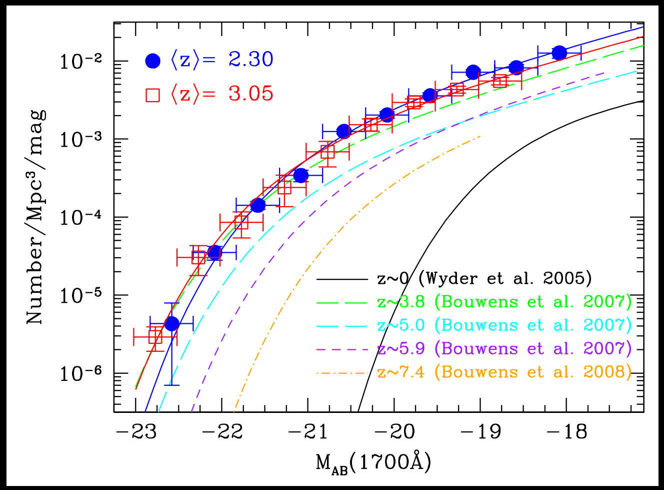
Possibly higher at z~3,
but difficult to measure
(faintness & contamination)

Extremely difficult to measure at z ≥ 4

Ionizing Emissivity

Galaxy UV Luminosity Fn





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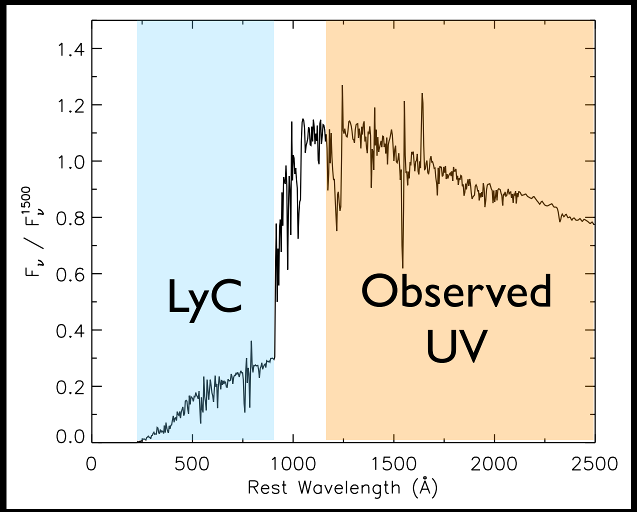
SED



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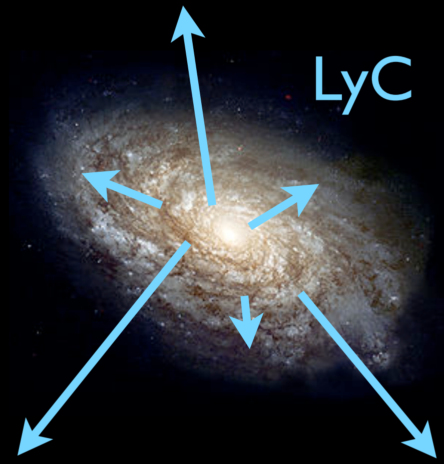
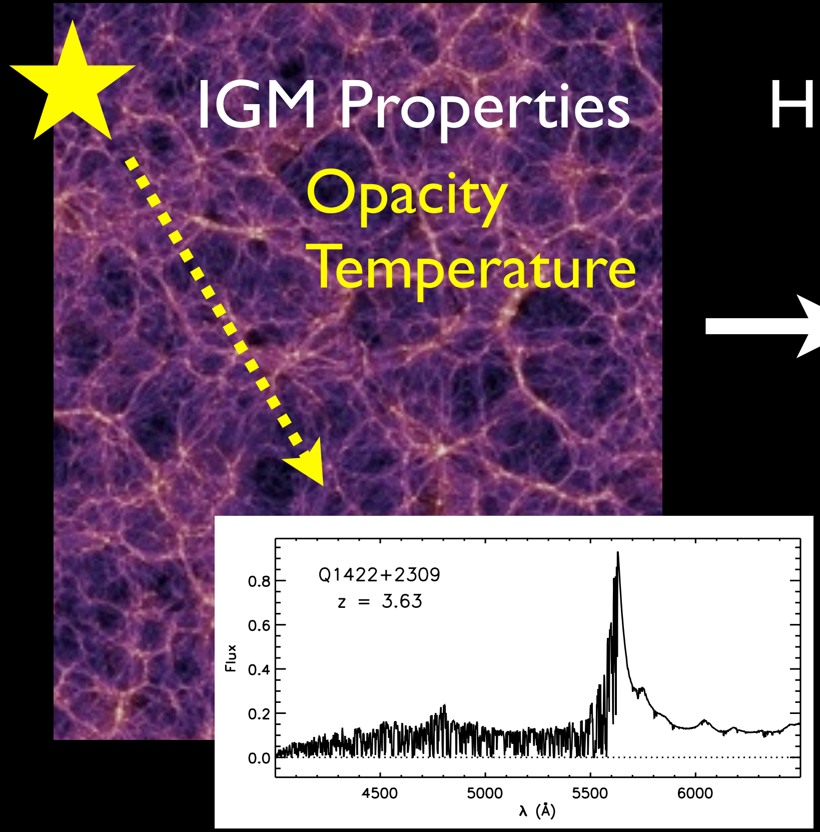
Escape fraction





IGM Properties

Opacity

Temperature

→

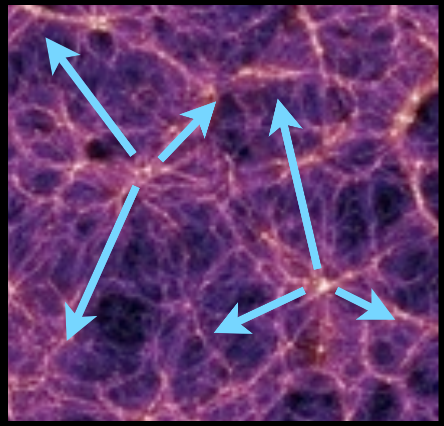
H I Ionization rate

Γ

s-1

+

IGM opacity



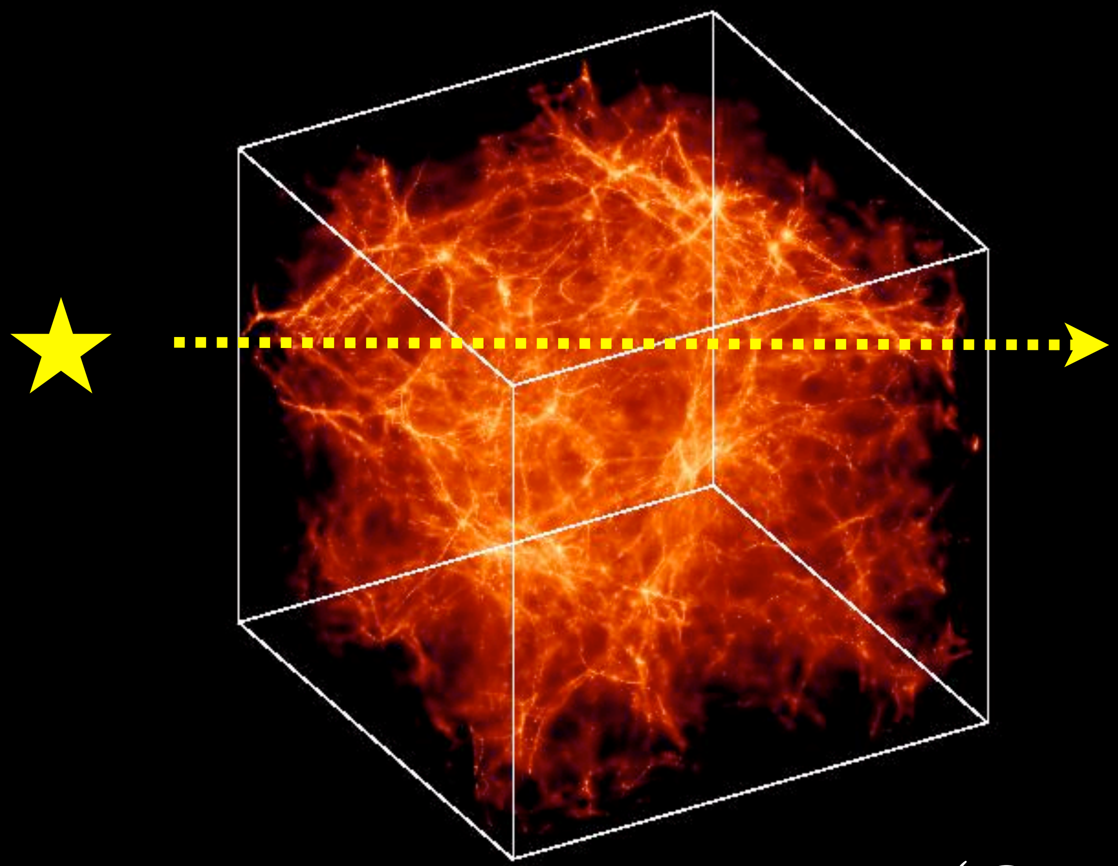
→

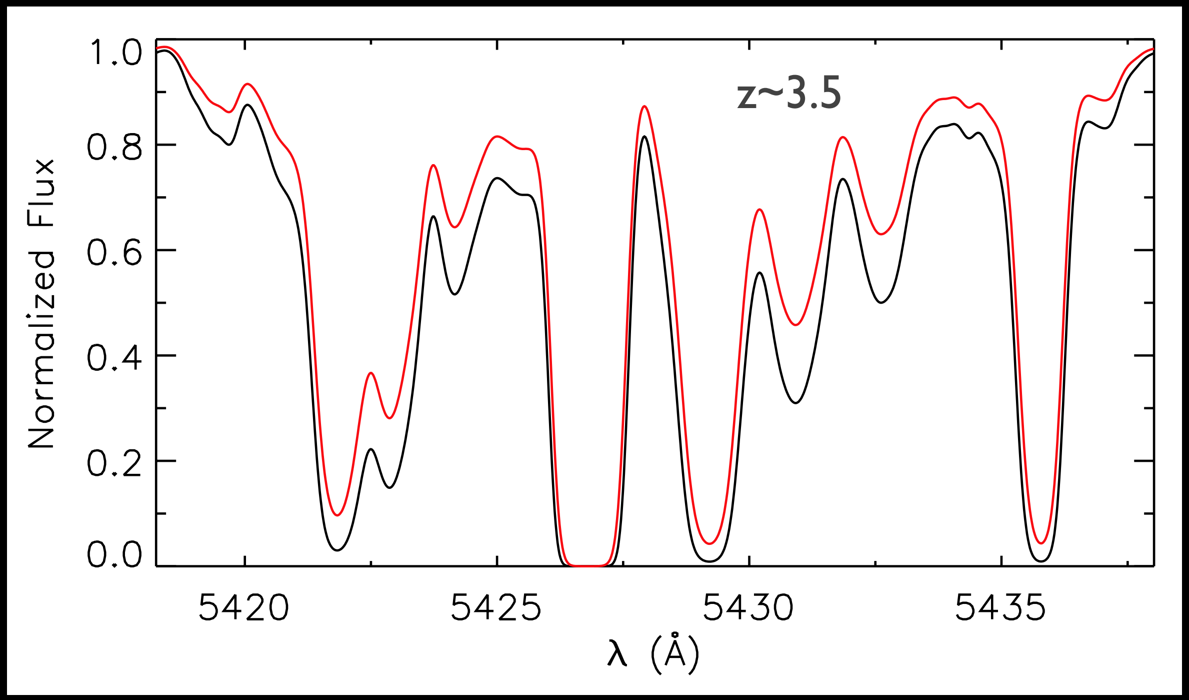
Emissivity

$\dot{N}_{\mathrm{ion}}$

photons s^{-1} Mpc^{-3}

Counting photons in the IGM





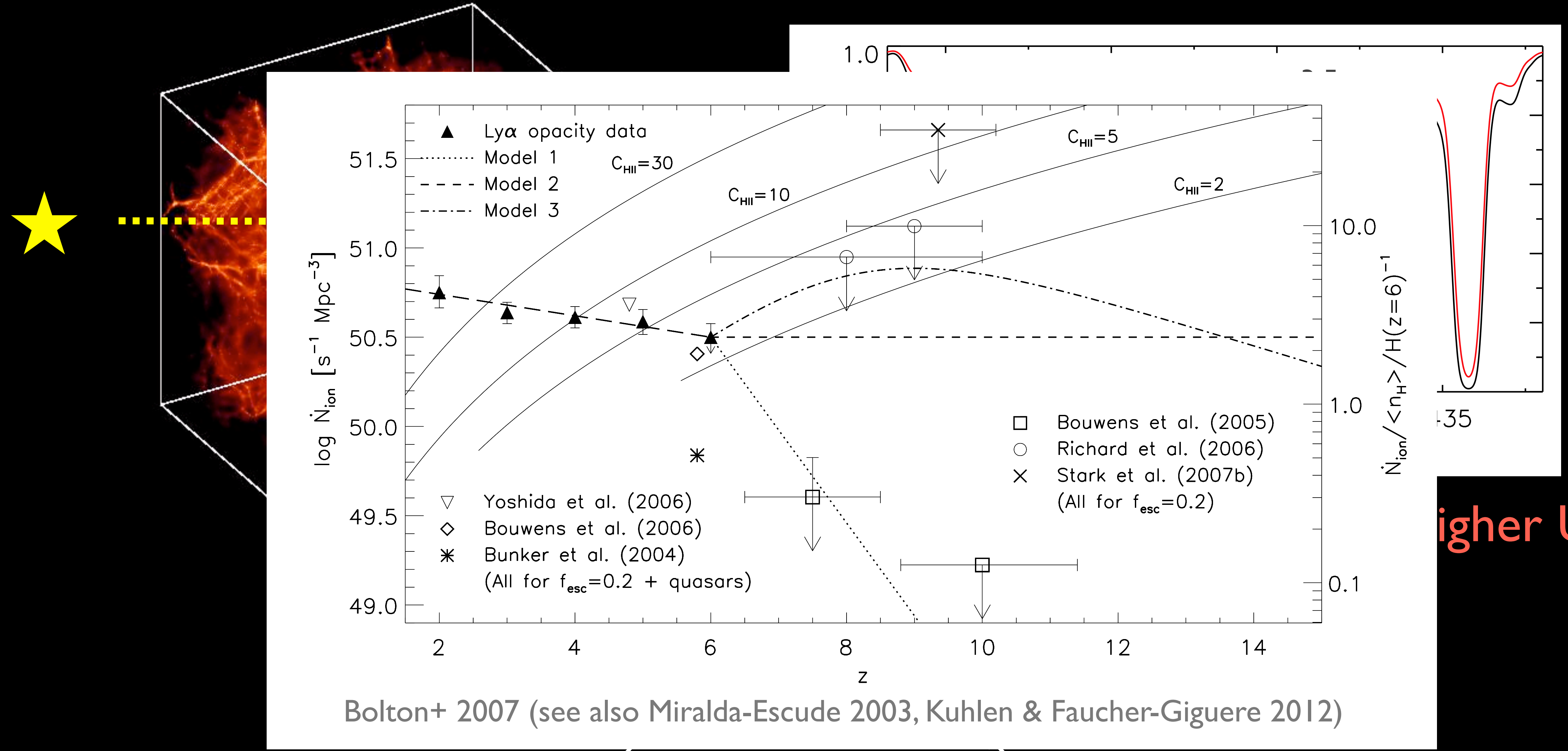
— 50% higher UVB

$$\tau \propto \frac{(\Omega_b h^2)^2\,(1+z)^6}{T^{0.7}\,H(z)\,\Gamma(z)}$$

Recombination rate: $\alpha_{\rm B} \propto T^{-0.7}$

H I ionization rate s^{-1}

Counting photons in the IGM



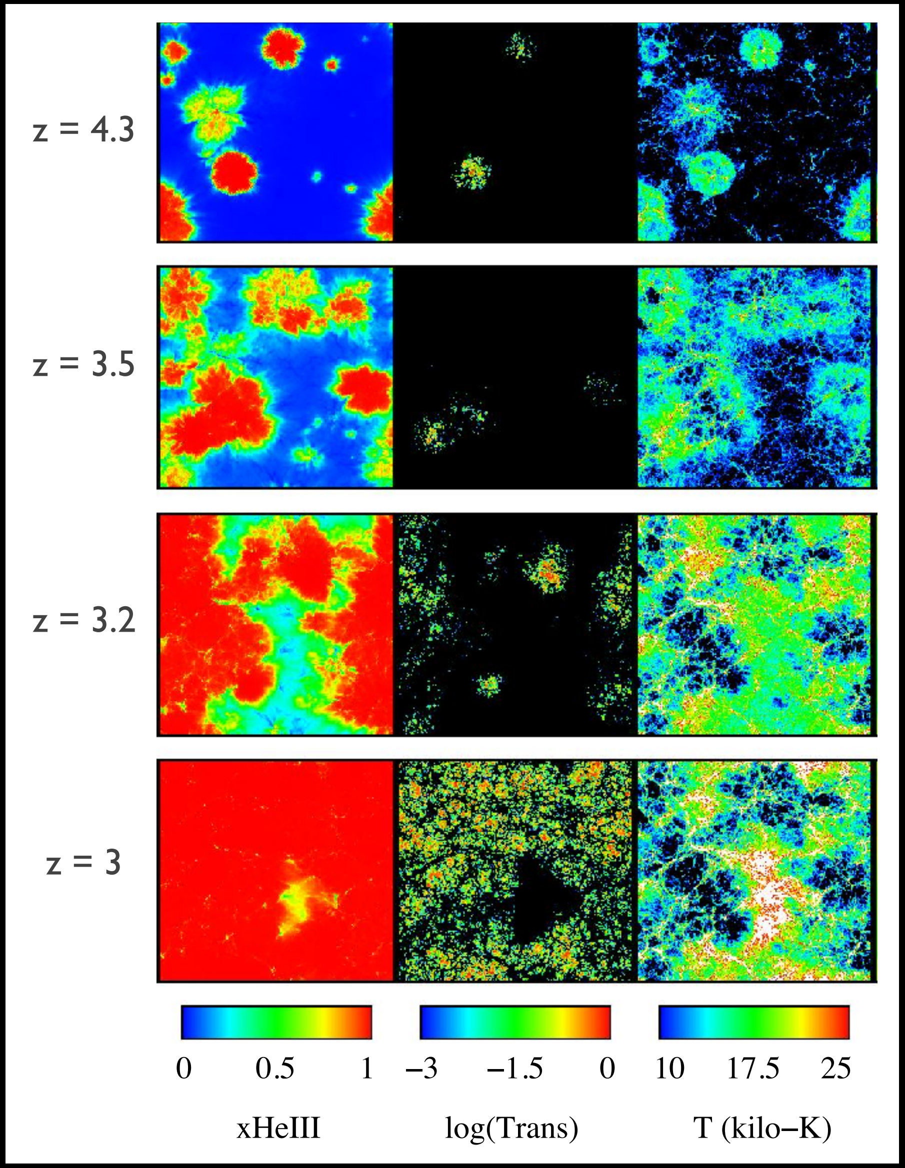
Bolton+ 2007 (see also Miralda-Escude 2003, Kuhlen & Faucher-Giguere 2012)

igher UVB

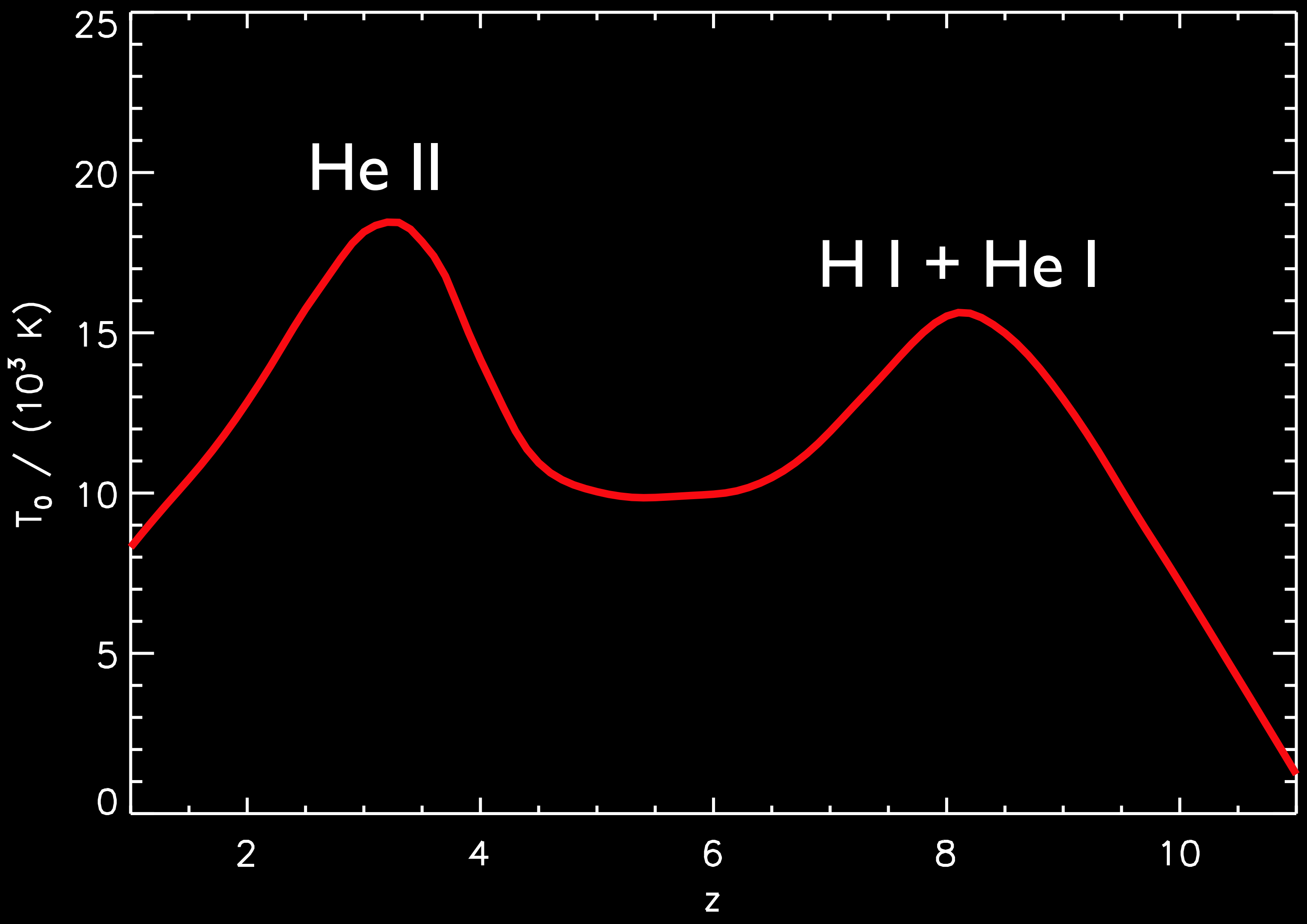
Recombination rate: $\alpha_{\rm B} \propto T^{-0.7}$

H I ionization rate s^{-1}

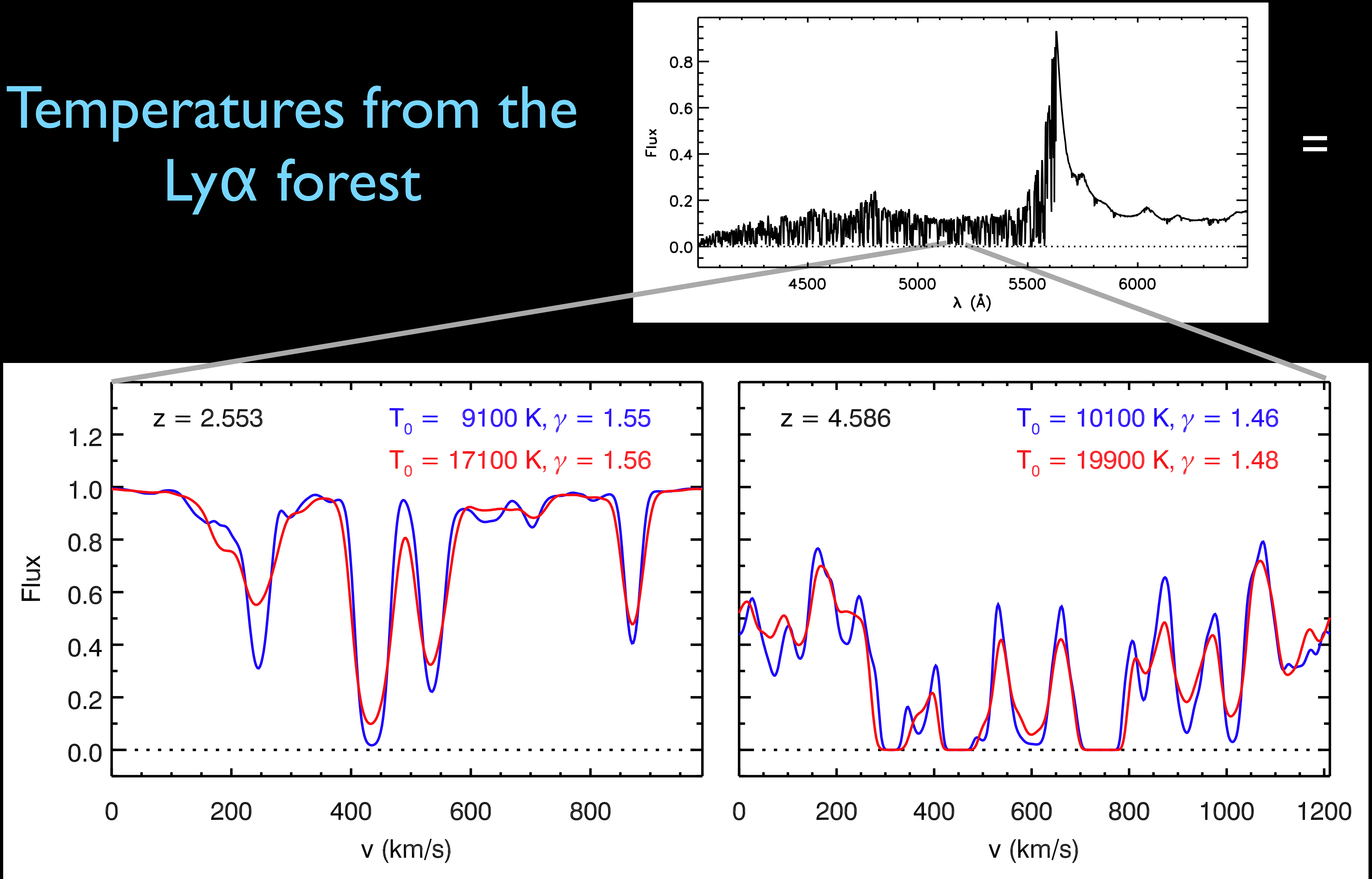
IGM Temperatures



McQuinn+ 2011

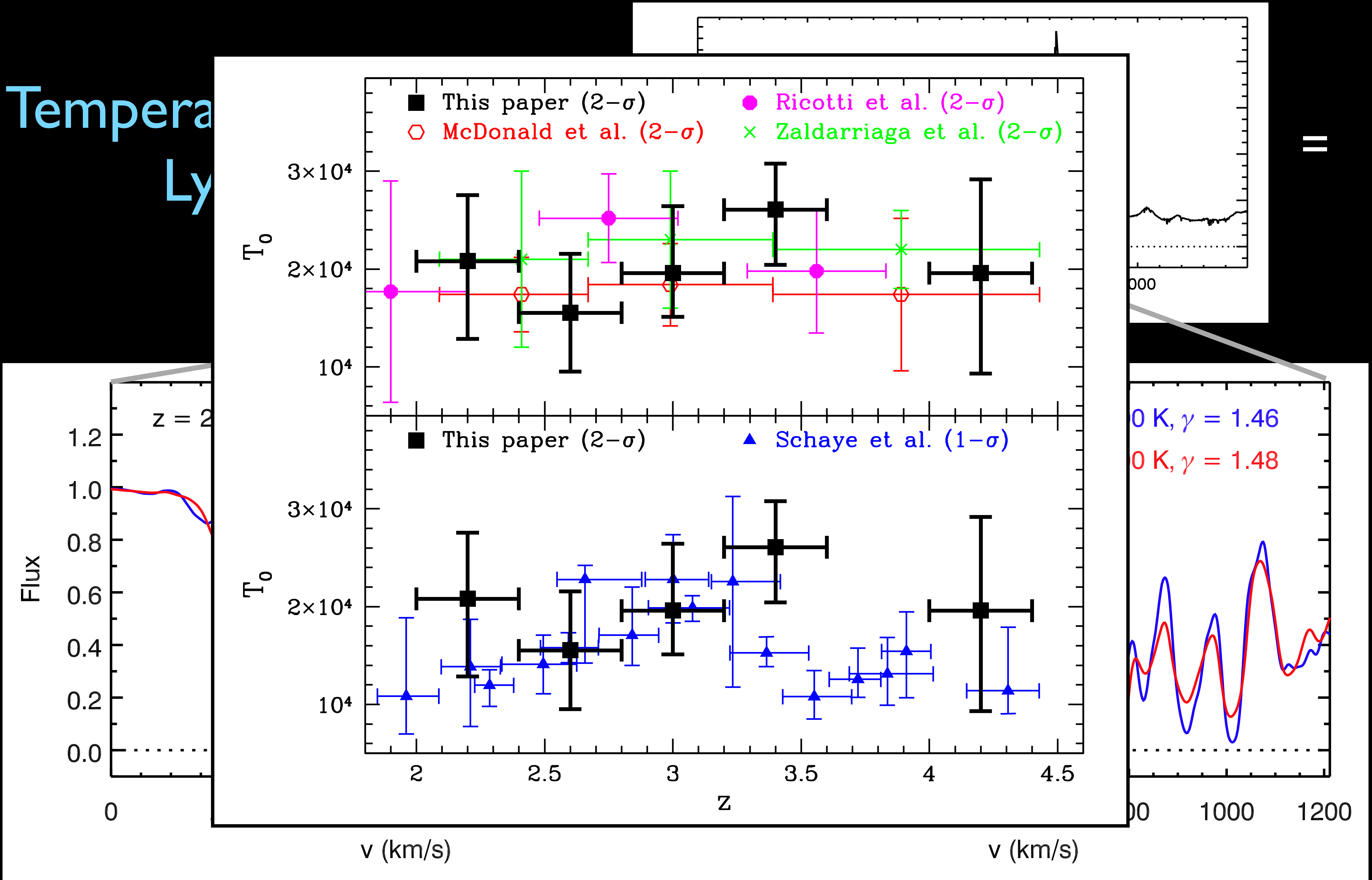


Temperatures from the Lyα forest



=

Tempera
Ly



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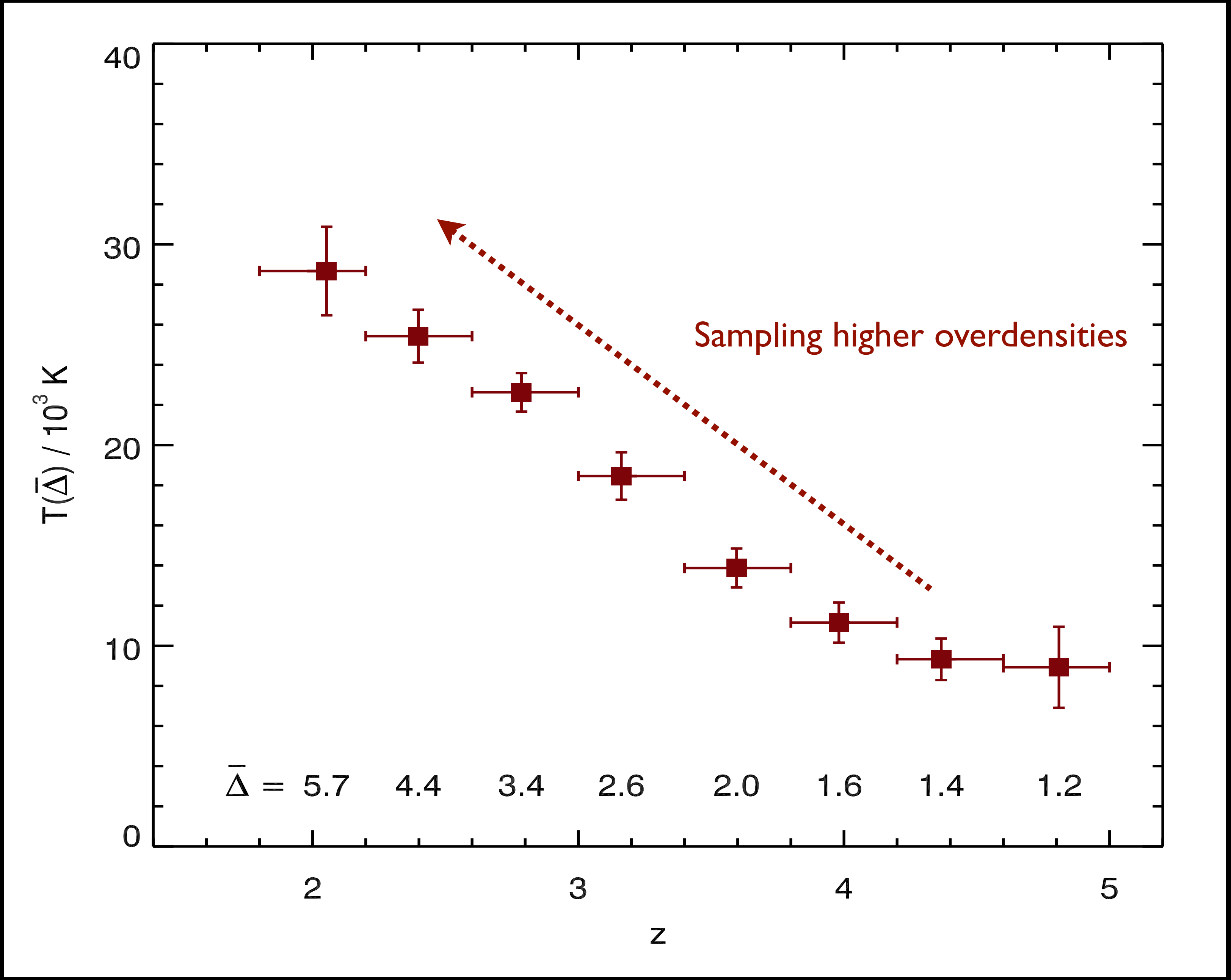
Compilation from Lidz et al 2010
see also Theuns et al

Temperatures from the Curvature

T(Δ) at Lyα forest densities

Temperature-density relation:

$$T(\Delta) = T_0 \Delta^{\gamma-1}$$

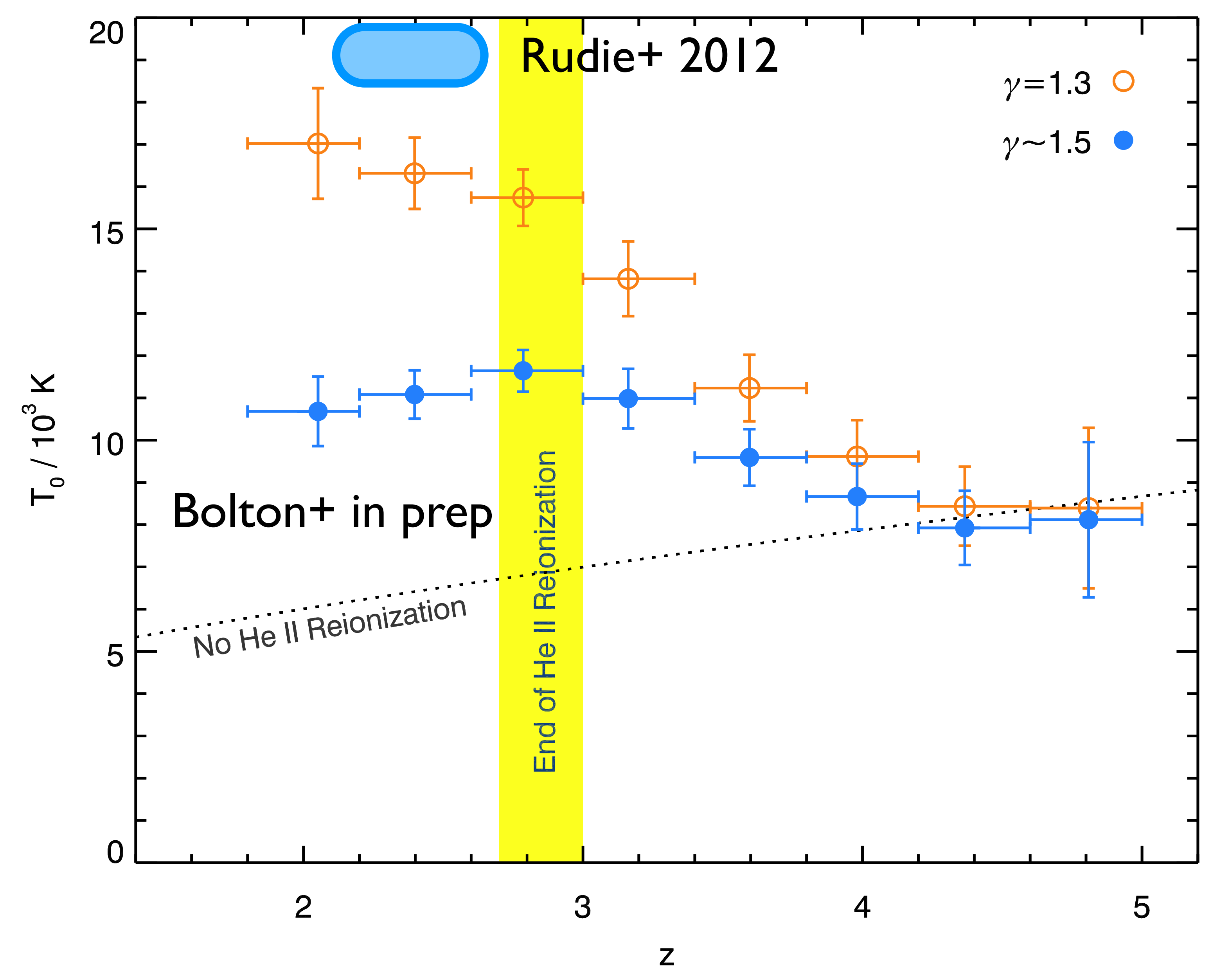


Becker+ 2011

Temperatures from the Curvature

Temperature-density relation:

$$T(\Delta) = T_0 \left(\frac{\rho}{\langle \rho \rangle} \right)^{\gamma - 1}$$



Becker+ 2011

* Extended He II Reionization *

Temperatures from the Curvature

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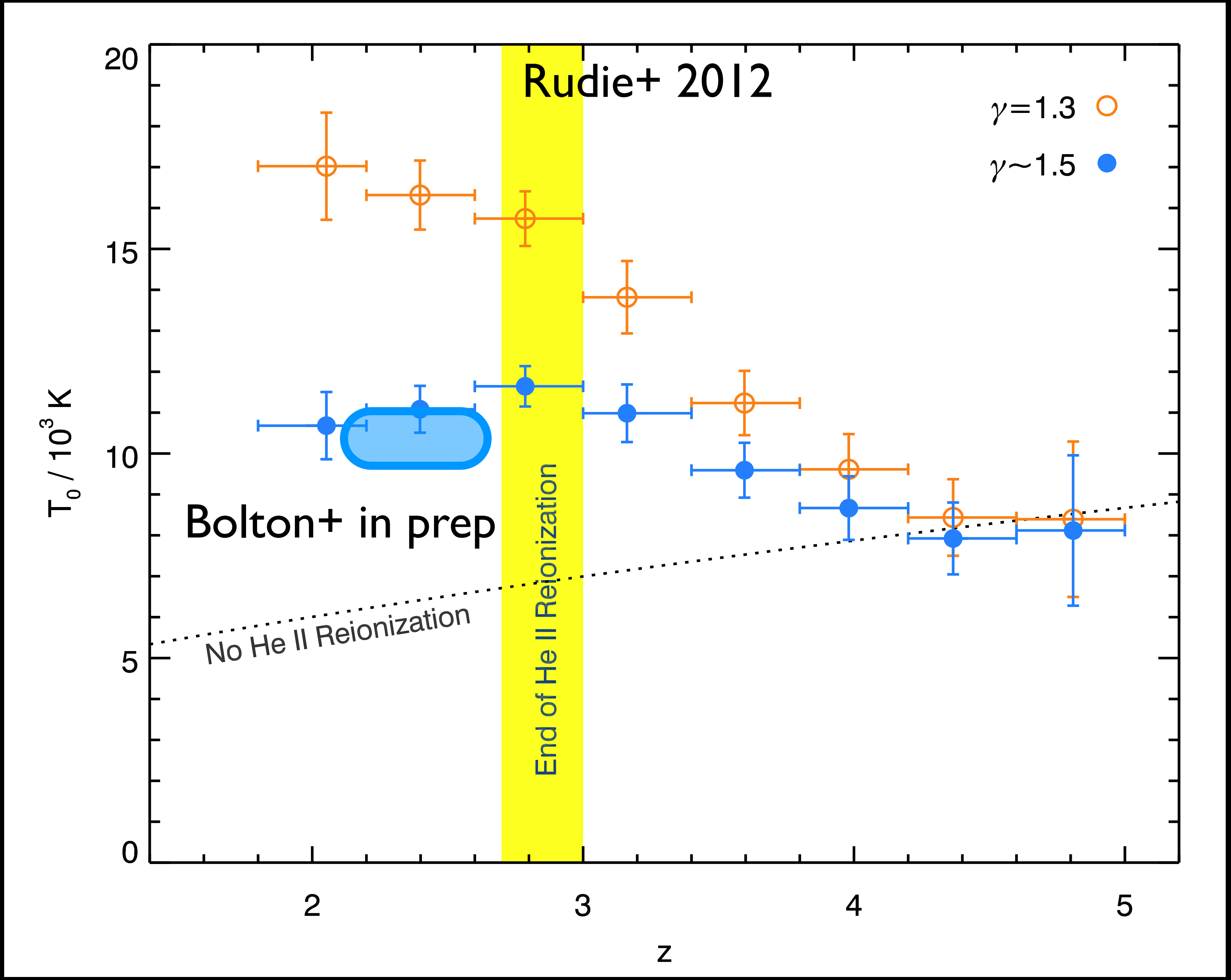
$$T(\Delta) = T_0 \left(\frac{\rho}{\langle \rho \rangle} \right)^{\gamma - 1}$$

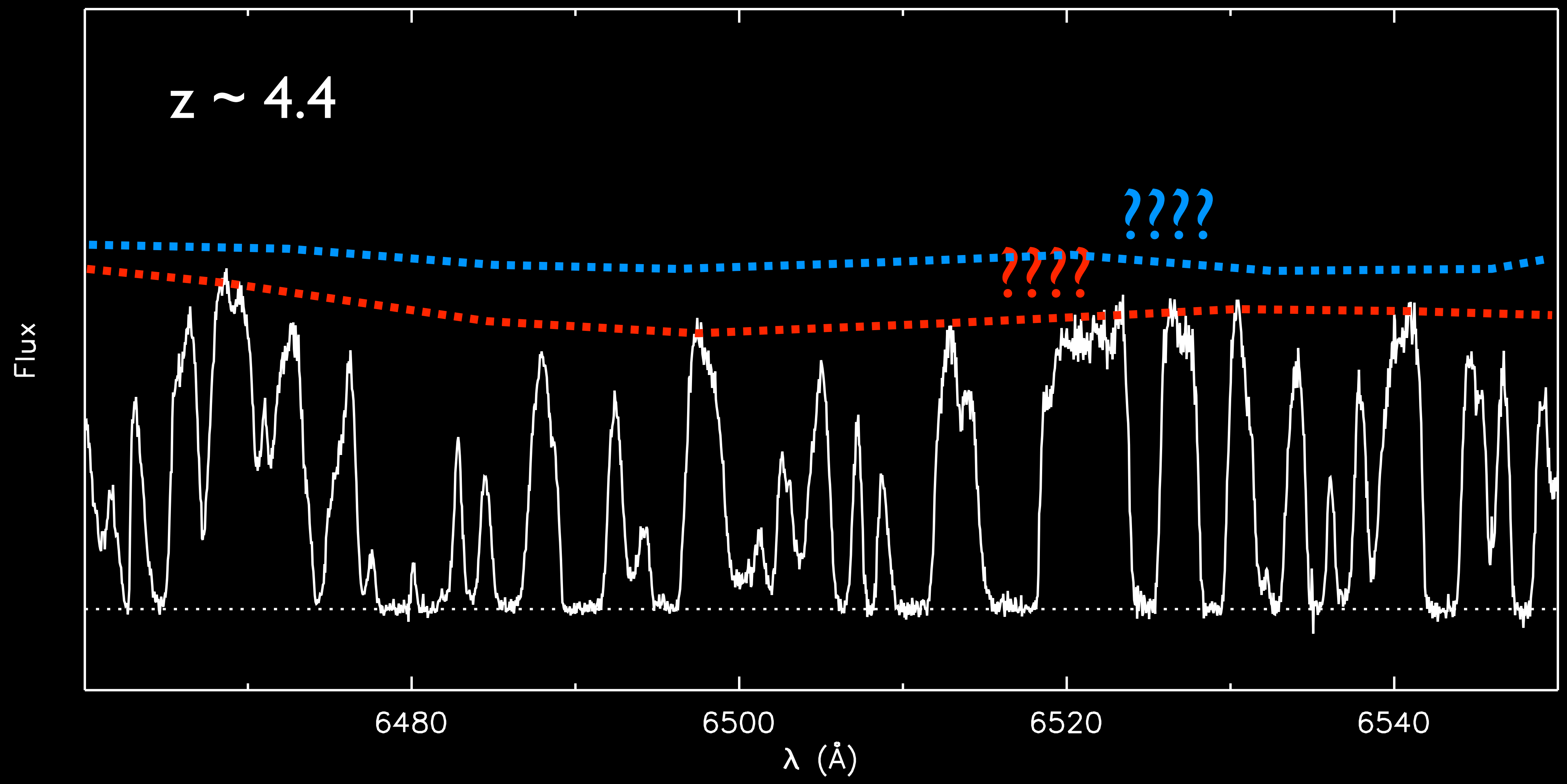


Becker+ 2011

* Extended He II Reionization *

Mean transmitted flux

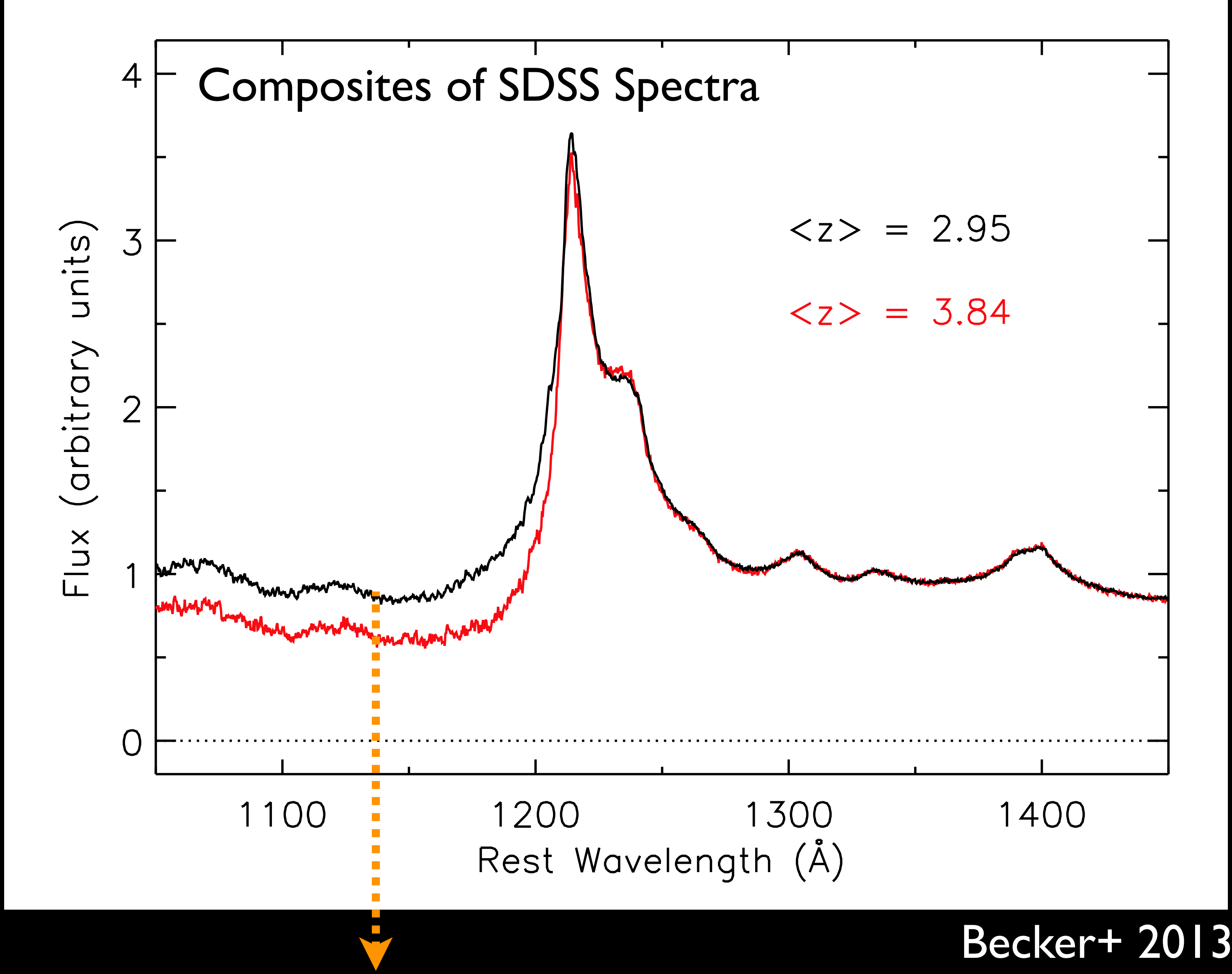
The Continuum Problem



$$\langle F_{\mathrm{trans}} \rangle = \frac{F_{\mathrm{observed}}}{F_{\mathrm{continuum}}}$$

The Continuum Solution

Don’t fit continua.

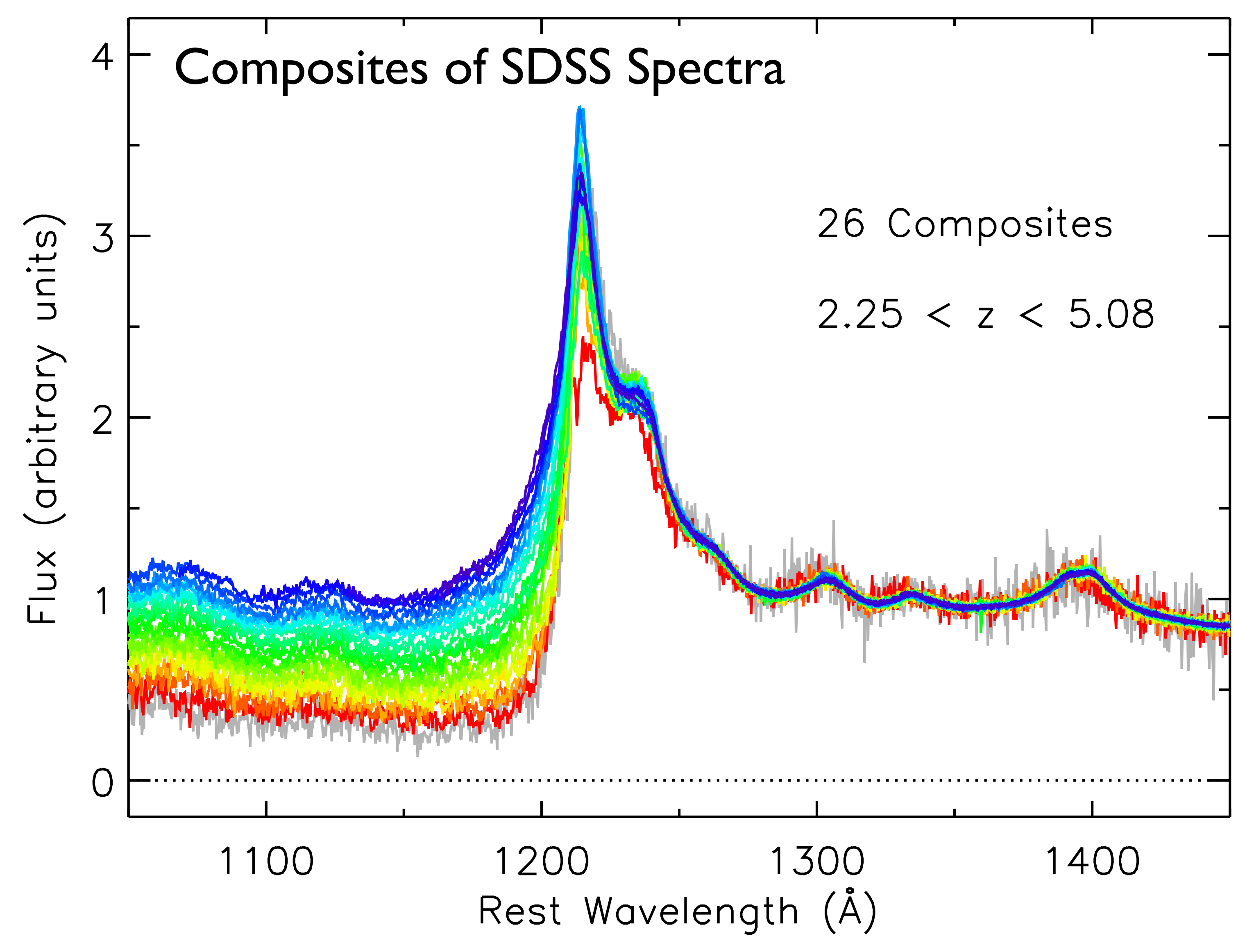


Becker+ 2013

Flux ratio = F_{z_1}/F_{z_2}

The Continuum Solution

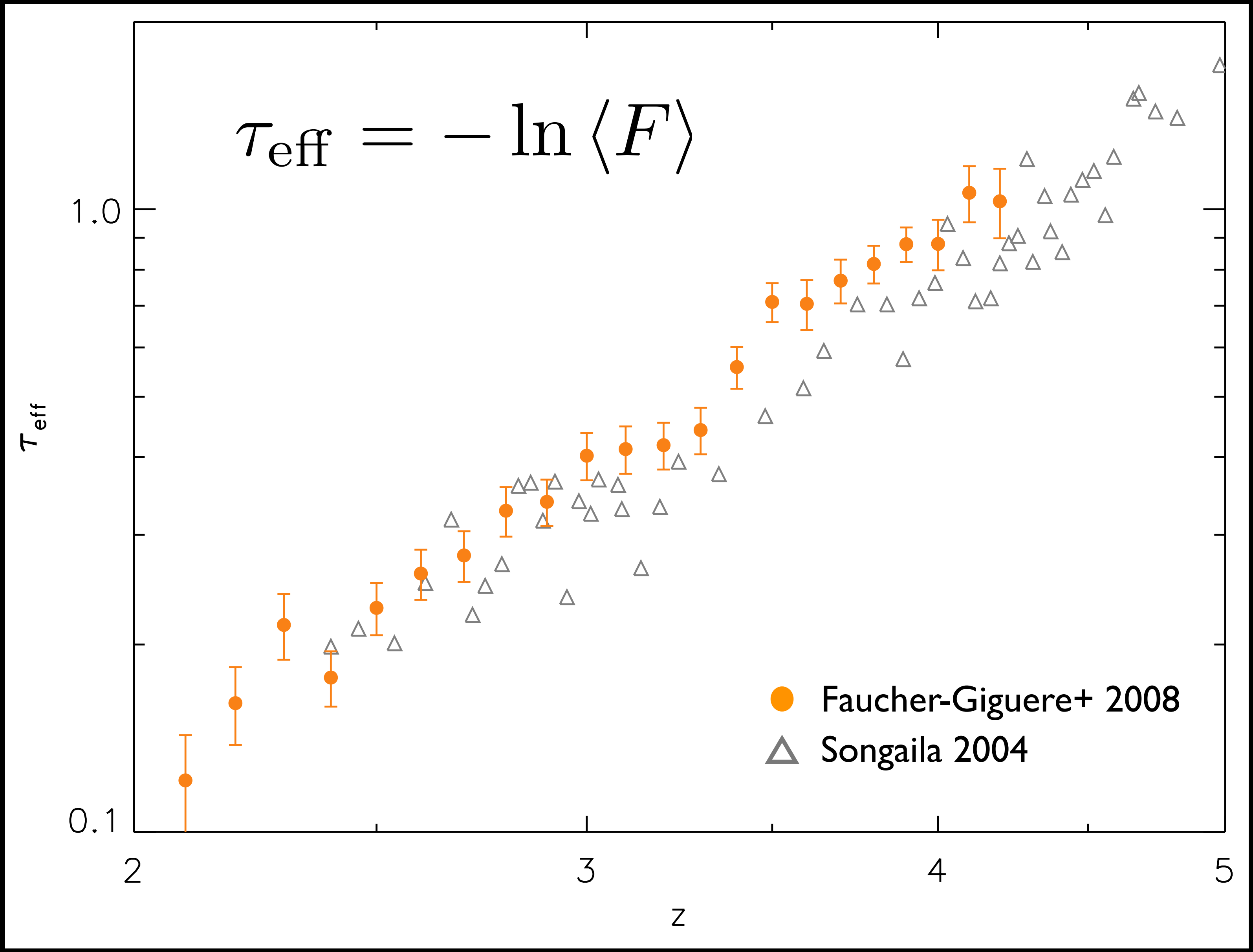
Don’t fit continua. Use composites.



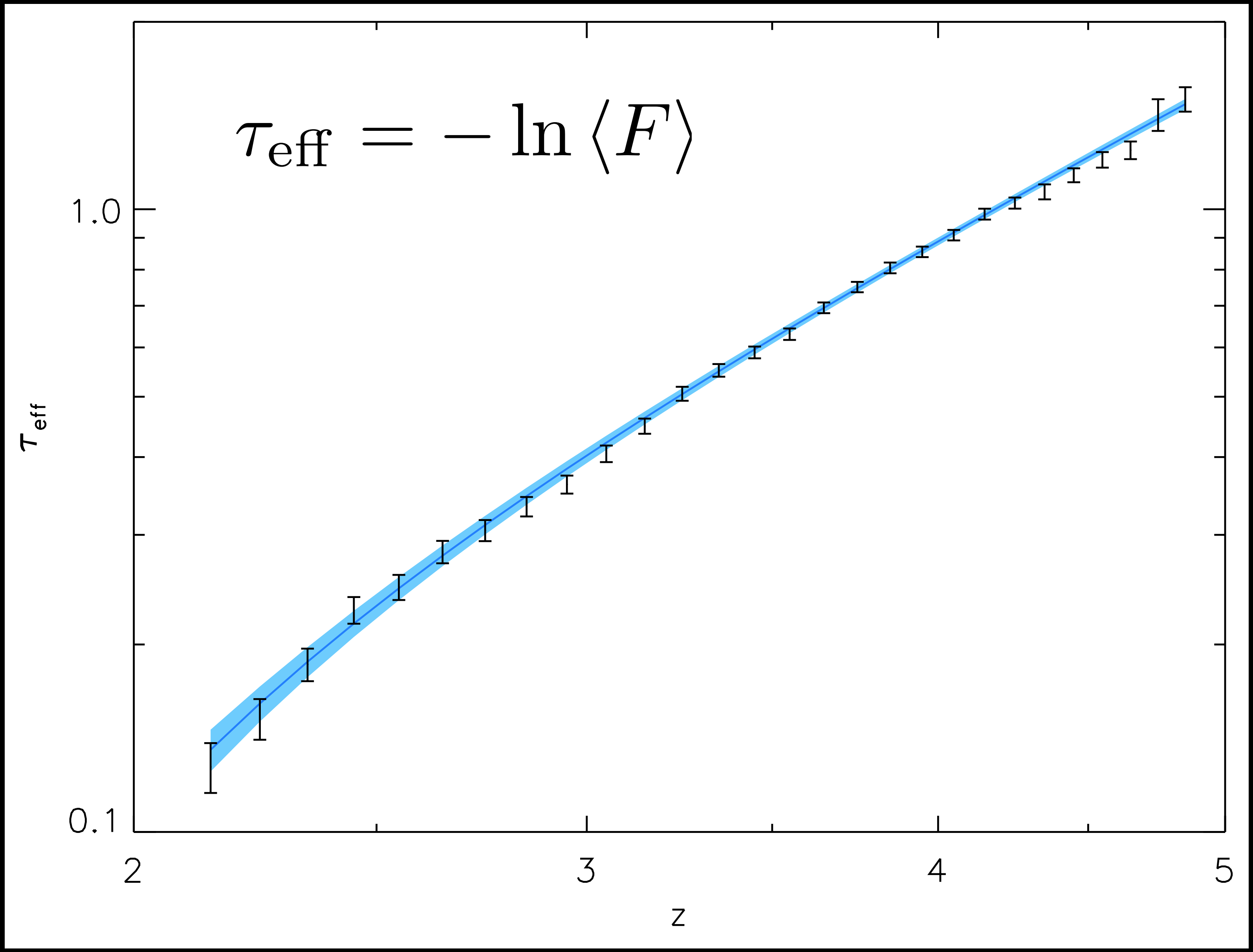
Becker+ 2013

Use flux ratios to get Fz/Fz=2

Lyα Opacity -- Existing

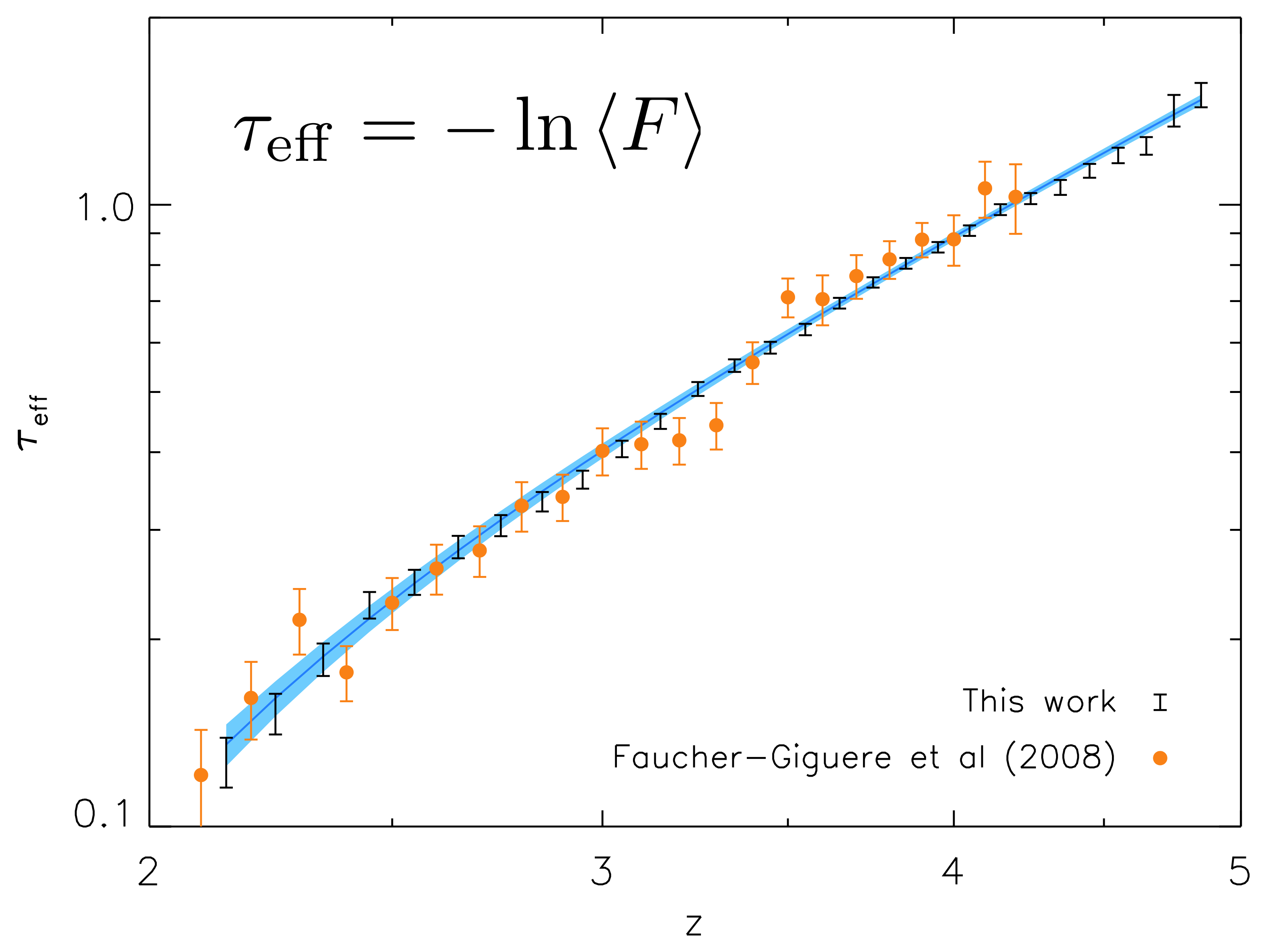


Lyα Opacity -- New



Becker+ 2013

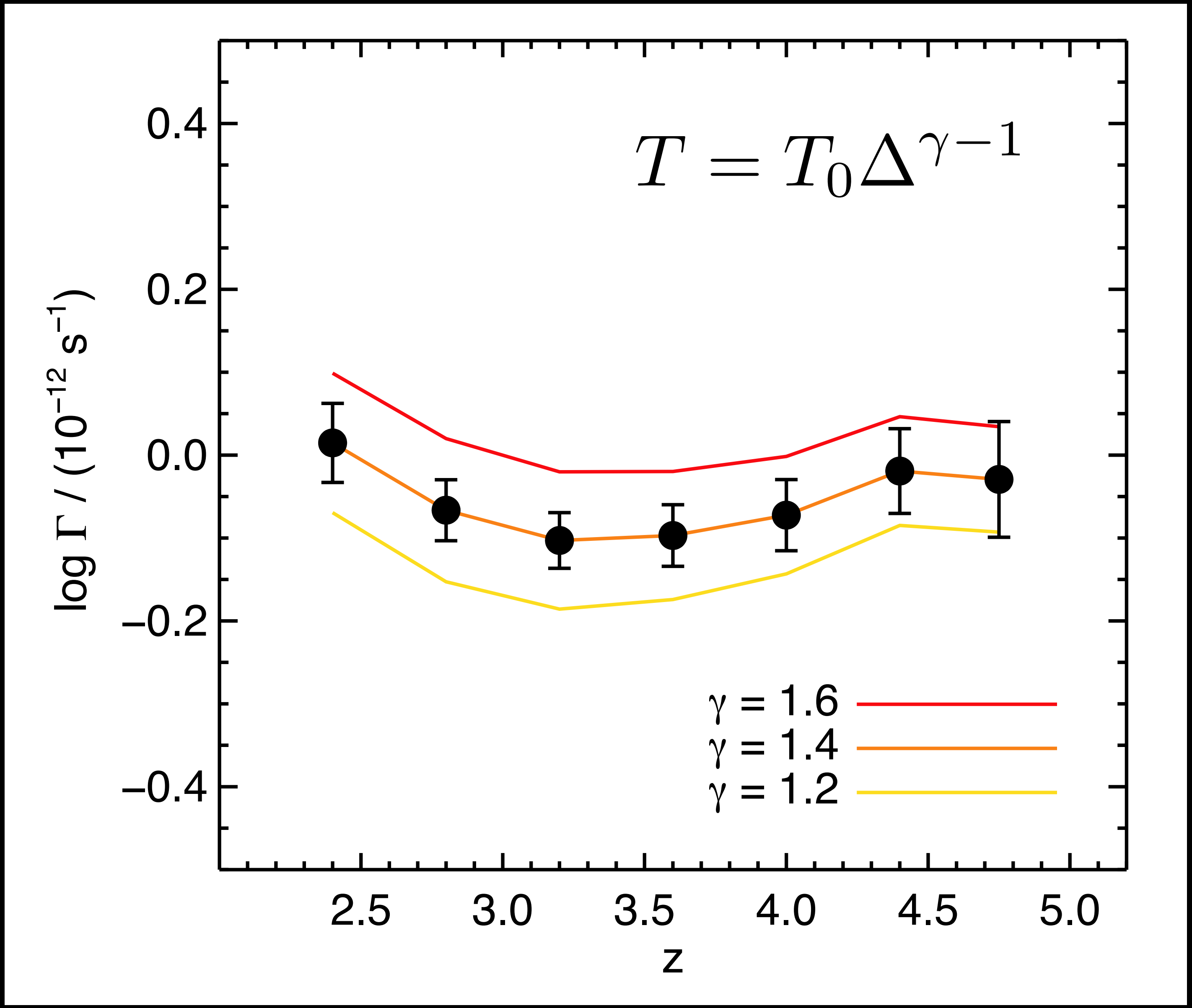
Lyα Opacity -- New



Becker+ 2013

1. Much smaller errors
2. Extends to z=5
3. No bump

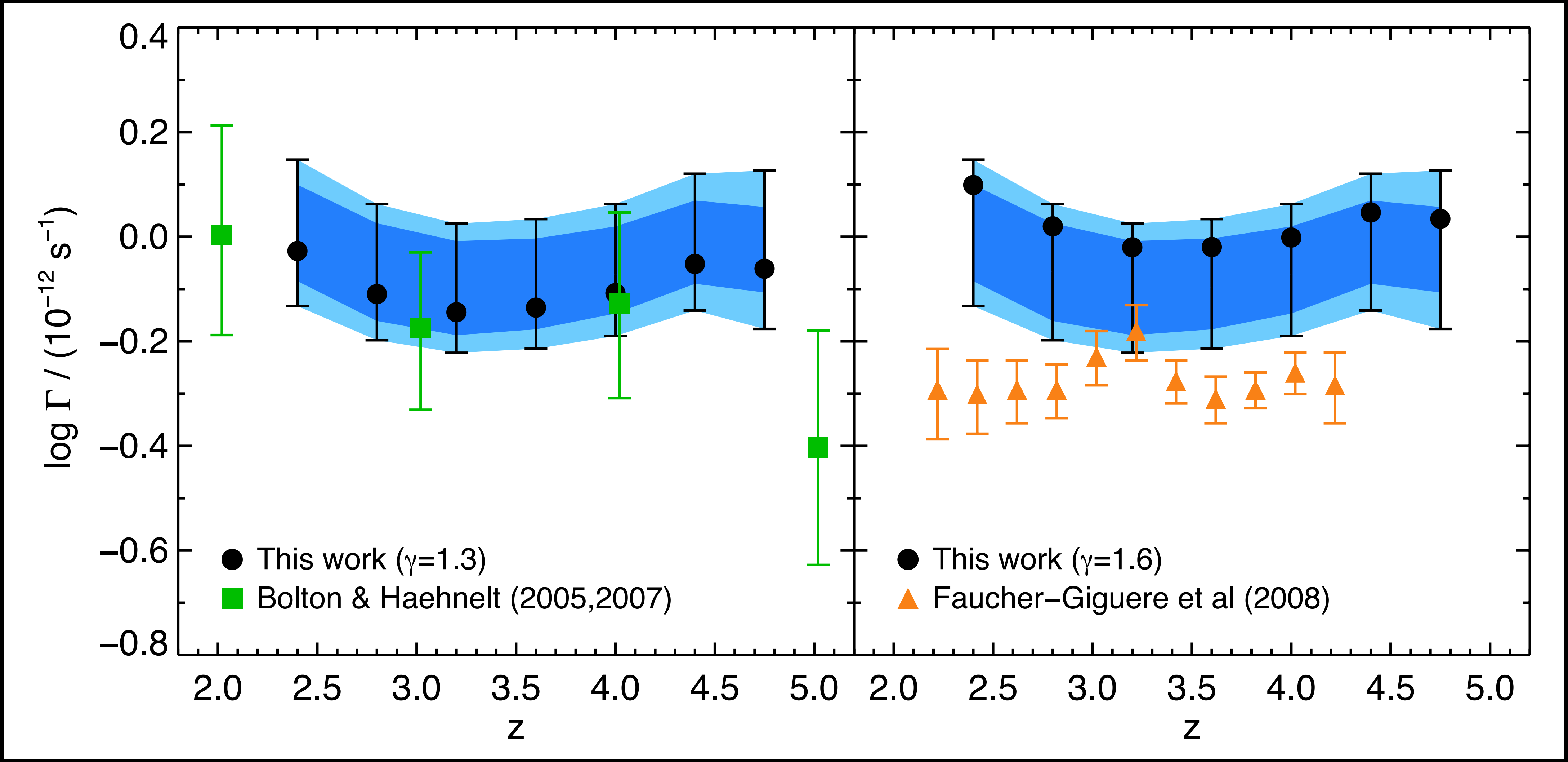
Hydrogen Ionization Rate



Becker & Bolton, in prep

Ionization timescale = 1 / Γ ~ 40,000 years

Hydrogen Ionization Rate

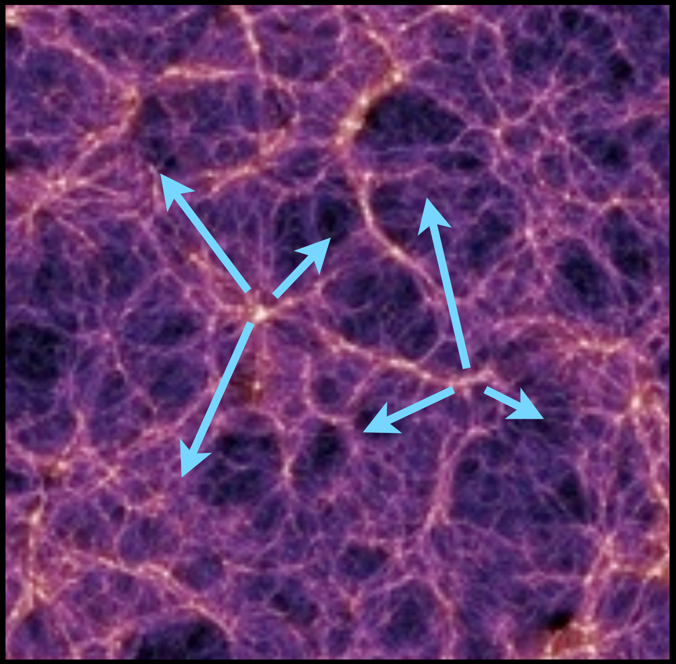


Higher Γ due to

(1) lower temperatures

(2) calibration with artificial spectra

Ionization Rate ⟶ Ionizing Emissivity



Roughly, $\dot{N}_{\rm ion} \propto \frac{\Gamma}{\sigma_{\rm HI}\lambda_{\rm mfp}}$

but exact treatment needed at z~2-3!

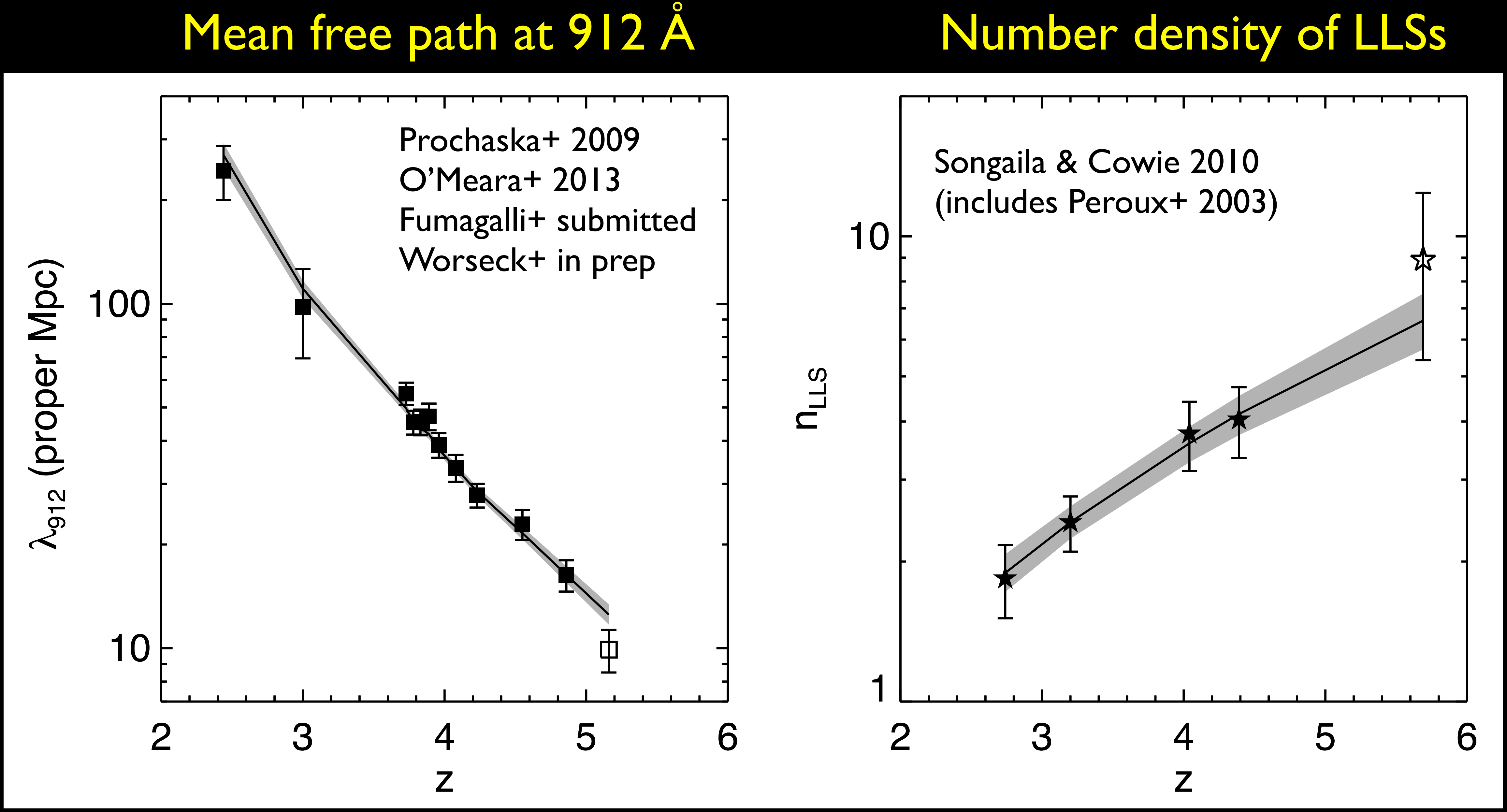
Radiative transfer: $J(\nu_0, z_0) = \frac{1}{4\pi}\int_{z_0}^{\infty} dz \frac{dl}{dz}\frac{(1+z_0)^3}{(1+z)^3}\epsilon(\nu, z)e^{-\tau_{\rm eff}(\nu_0, z_0, z)}$

Intensity

Emissivity

Ionizing opacity: $\tau_{\rm eff}(\nu_0, z_0, z) = \int_{z_0}^{z} dz' \int_0^{\infty} dN_{\rm H\,I} f(N_{\rm H\,I}, z')(1 - e^{-\tau_\nu})$

Ionizing Opacity



Fit simultaneously: $f(N_{\mathrm{H,I}}, z) \propto N_{\mathrm{H\,I}}^{-\beta_{\mathrm{N}}} (1+z)^{\beta_z}$

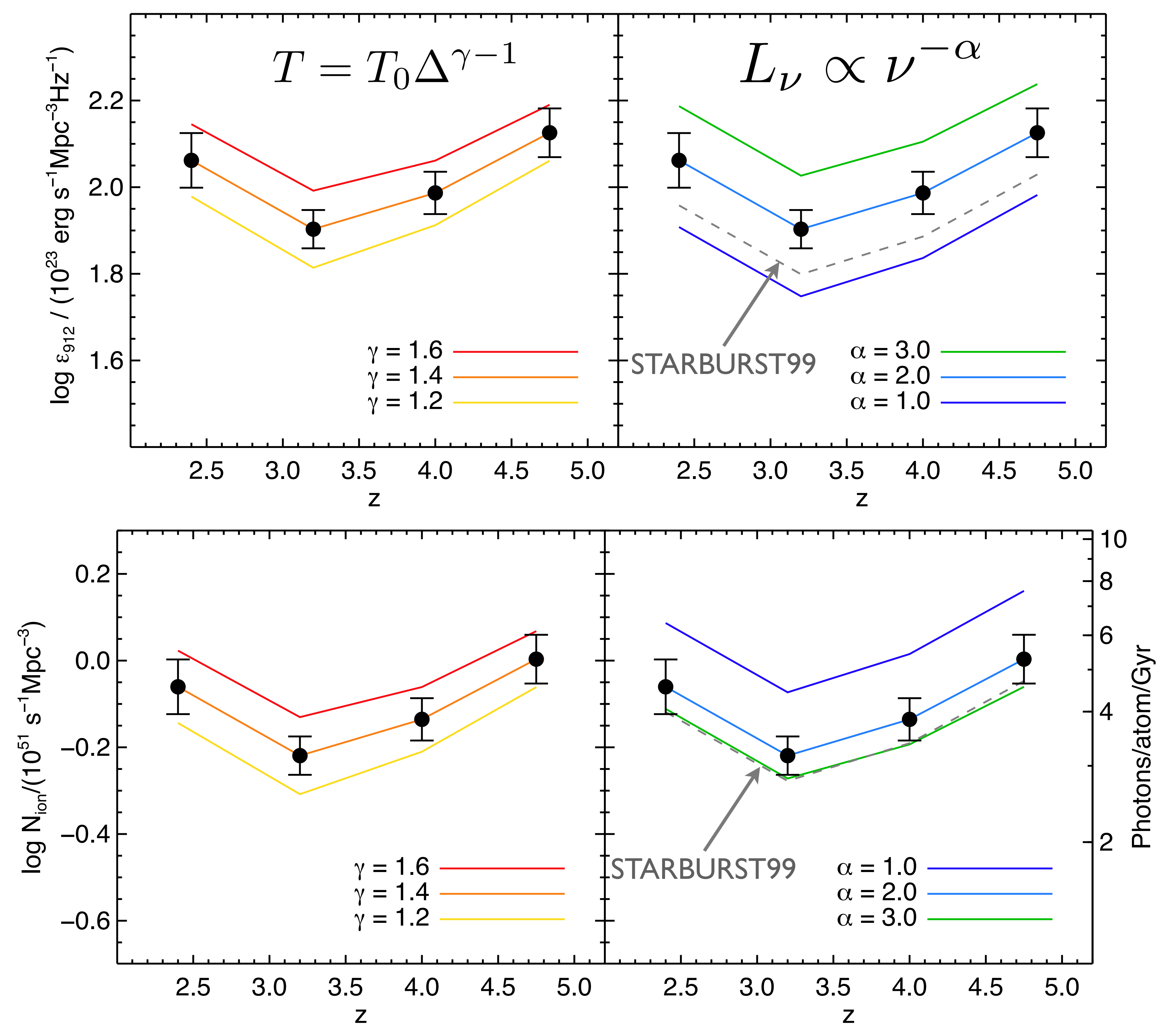
$$\beta_{\mathrm{N}} = 1.32 \pm 0.05$$

$$\beta_z = 2.1 \pm 0.3$$

Emissivity Results

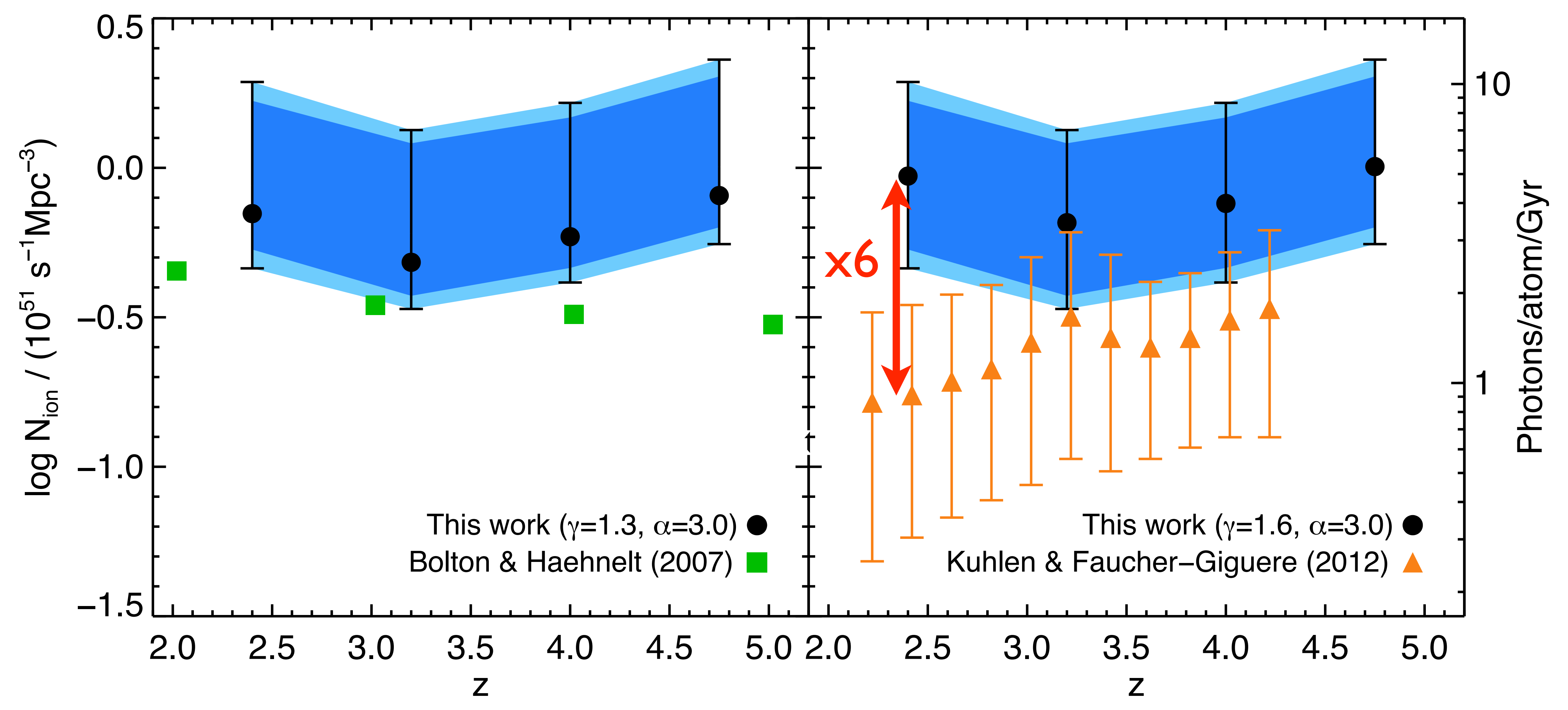
Specific emissivity near 1 Ryd

Total emissivity of ionizing photons



Becker & Bolton, in prep

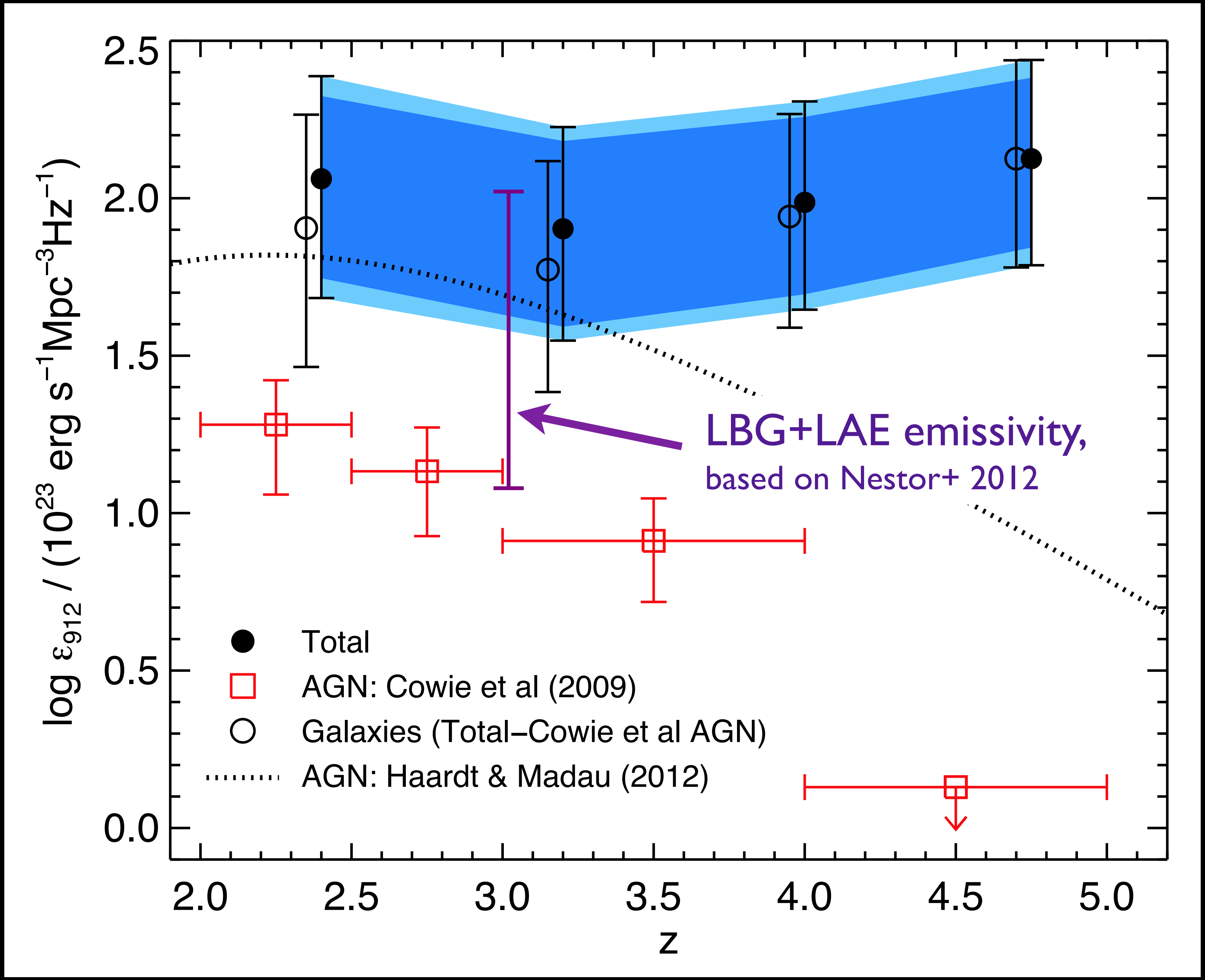
Emissivity Results



Higher values due to (1) Higher Γ
(2) higher ionizing opacity
(3) inclusion of radiative transfer

Becker & Bolton, in prep

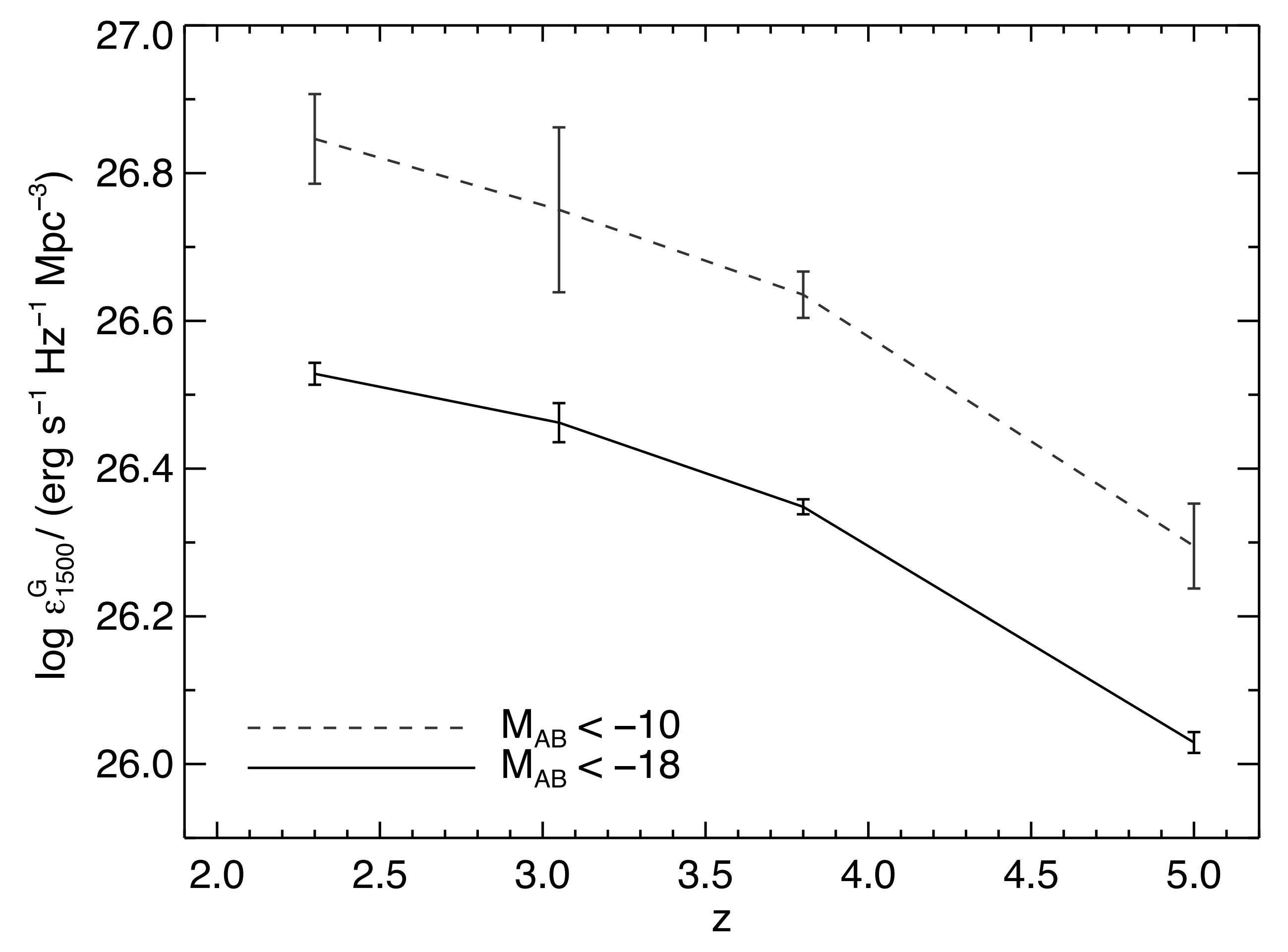
Separating AGN and Stars



Galaxies dominate the emissivity near 1 Ryd at $z > 4$, and possibly at $z > 2.4$

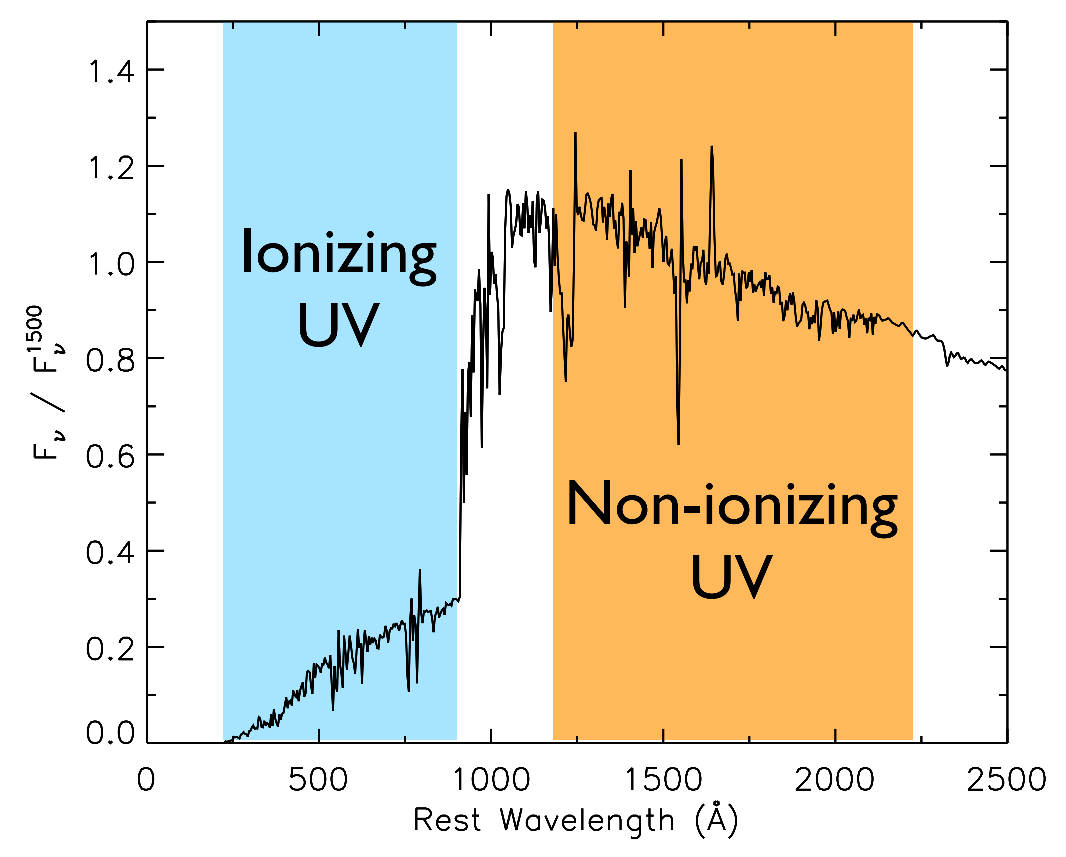
Becker & Bolton, in prep

Ionizing efficiency of galaxies



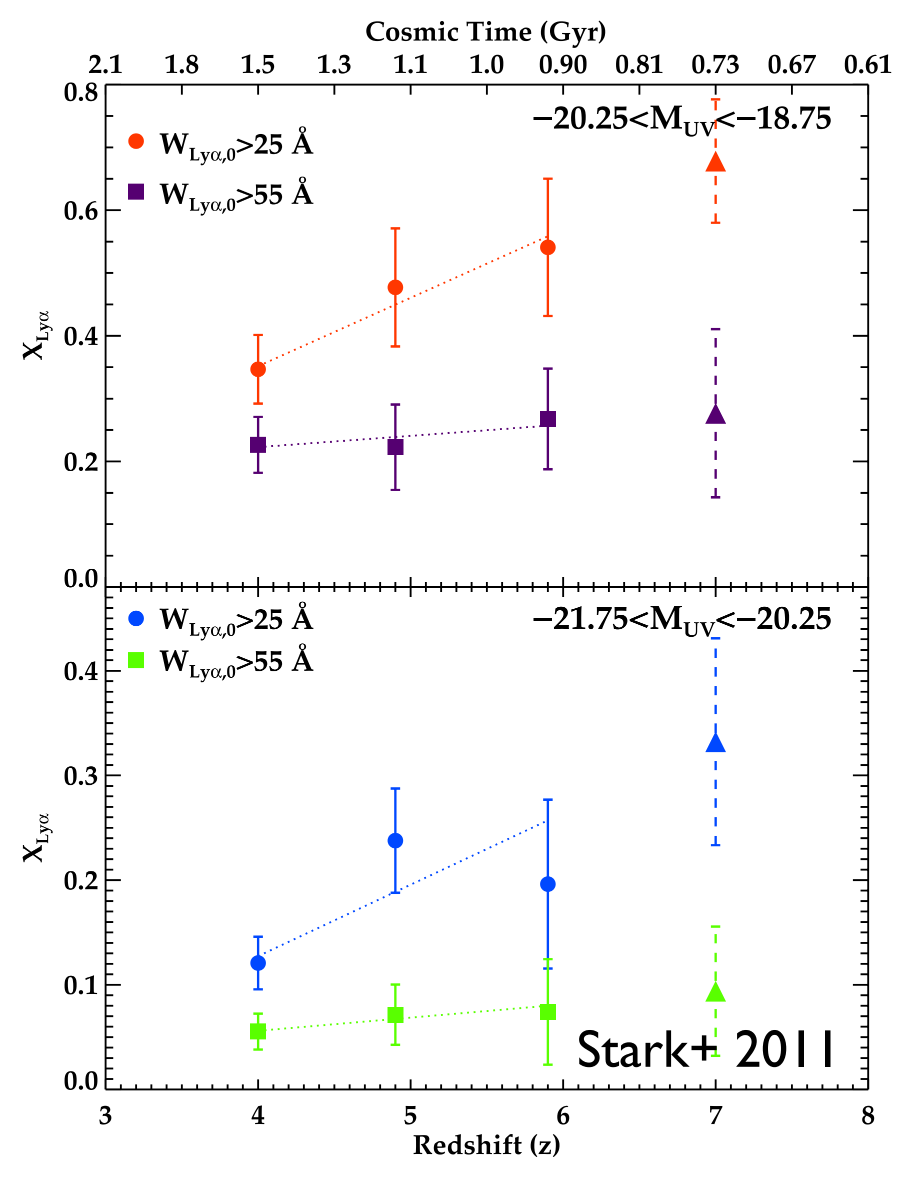
We know:

1. The ionizing emissivity from the IGM
2. The non-ionizing emissivity galaxy surveys

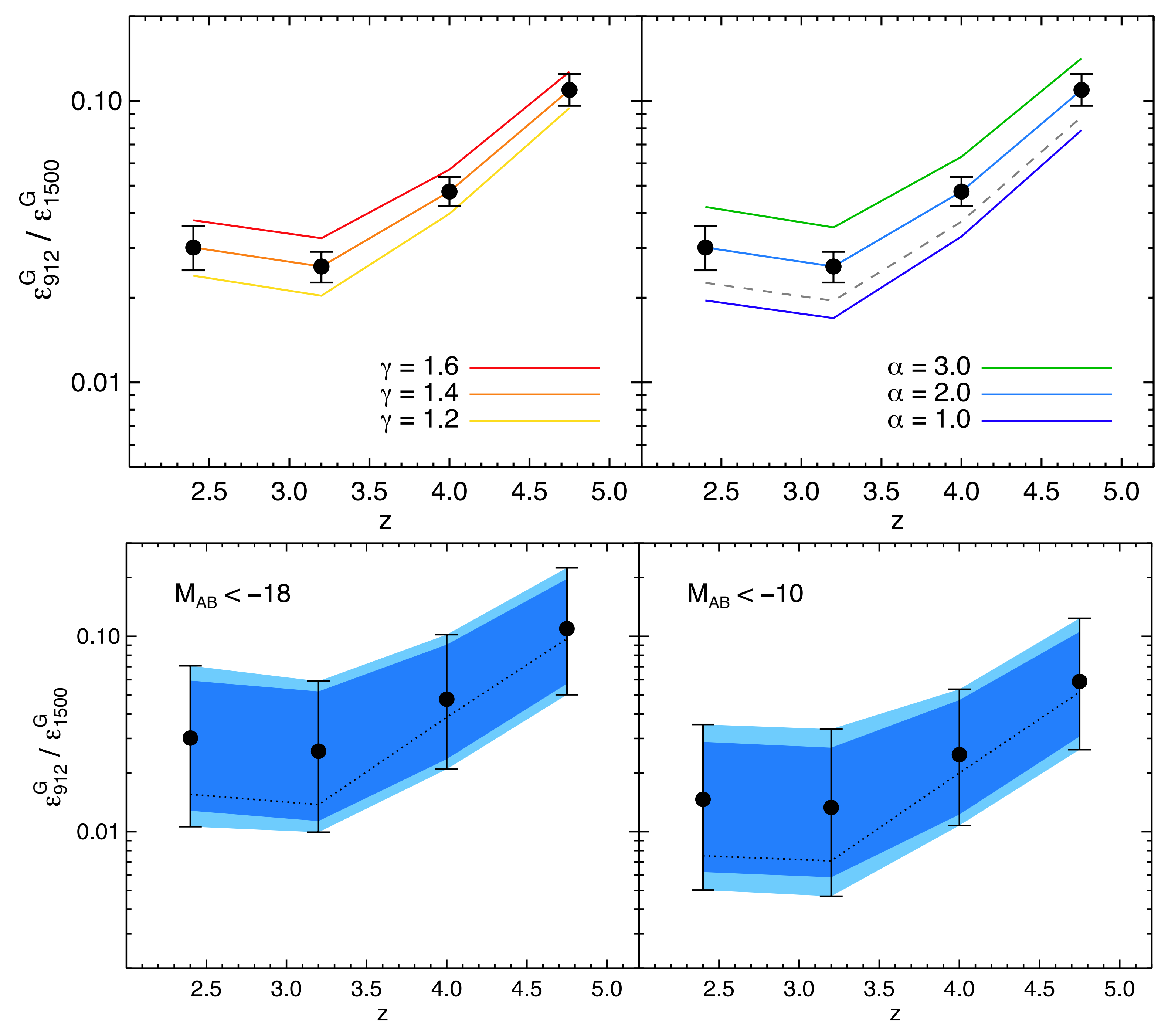


Compute the ionizing efficiency of galaxies...

Ionizing efficiency of galaxies



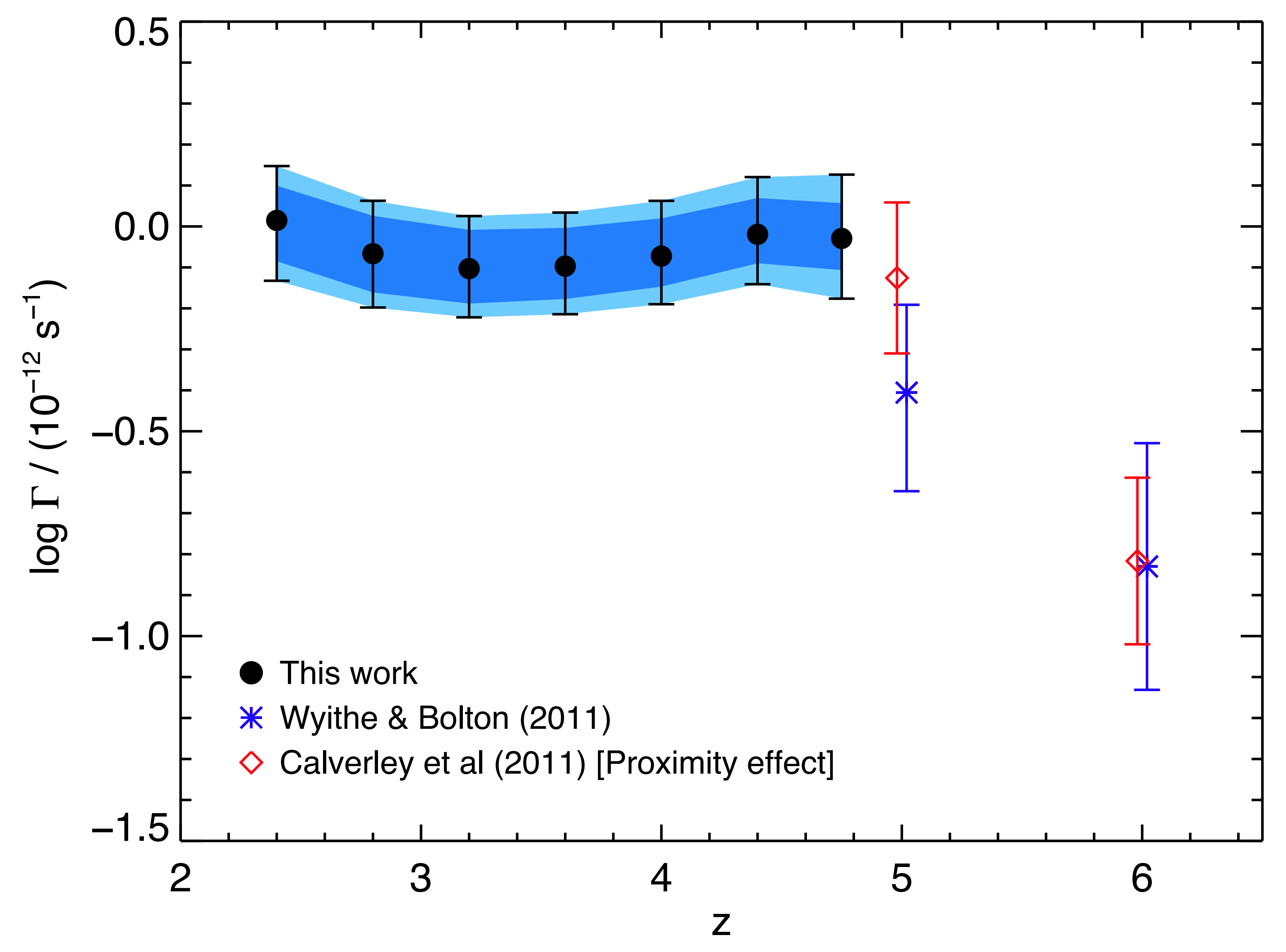
Stark+ 2011



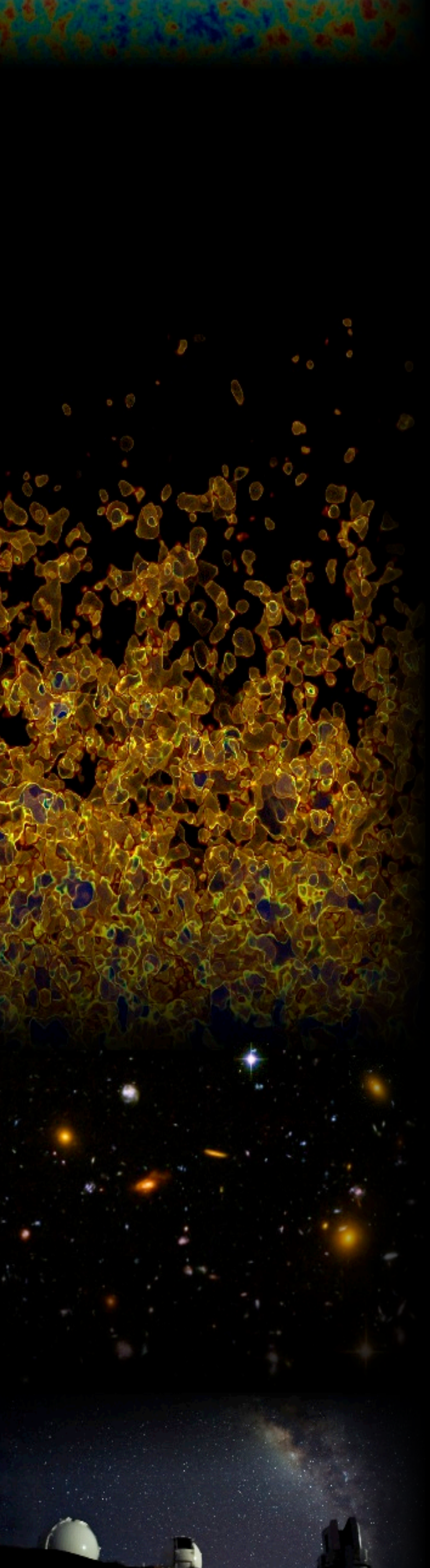
Becker & Bolton, in prep

1. Ionizing efficiency increases with redshift
2. Trend necessary for reionization continues to z~3

UVB at z > 5



Rapid change in the mean free path over $5 < z < 6$?



Summary

- UVB results based on new measurements of IGM properties over $2 < z < 5$
  - Temperature
  - Opacity to Lyα photons
  - Opacity to ionizing photons
- Ionization rate ~flat over $2 < z < 5$, although higher than other results (lower temperatures)
- Emissivity 2-6x higher than previous estimates (temperatures, ionizing opacity, RT)
  - Flat or increasing with redshift
  - More photons near the end of reionization
- Ionizing efficiency of galaxies appears to increase from z~3 to 5, as required for reionization