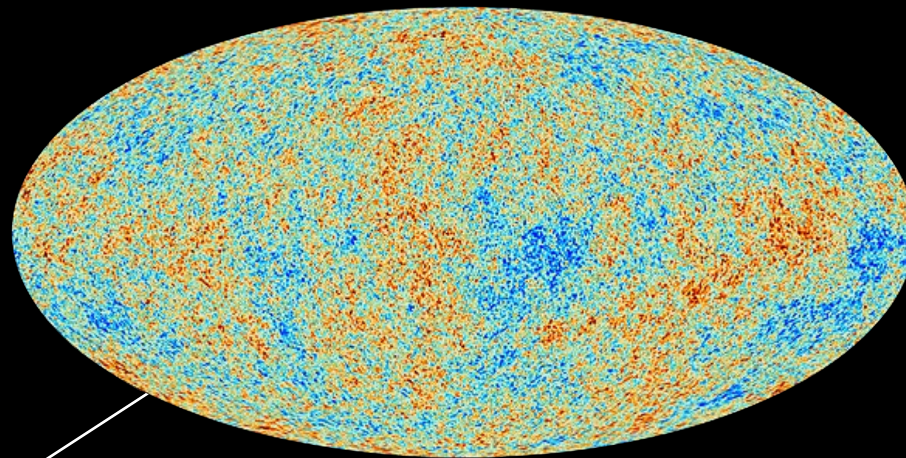
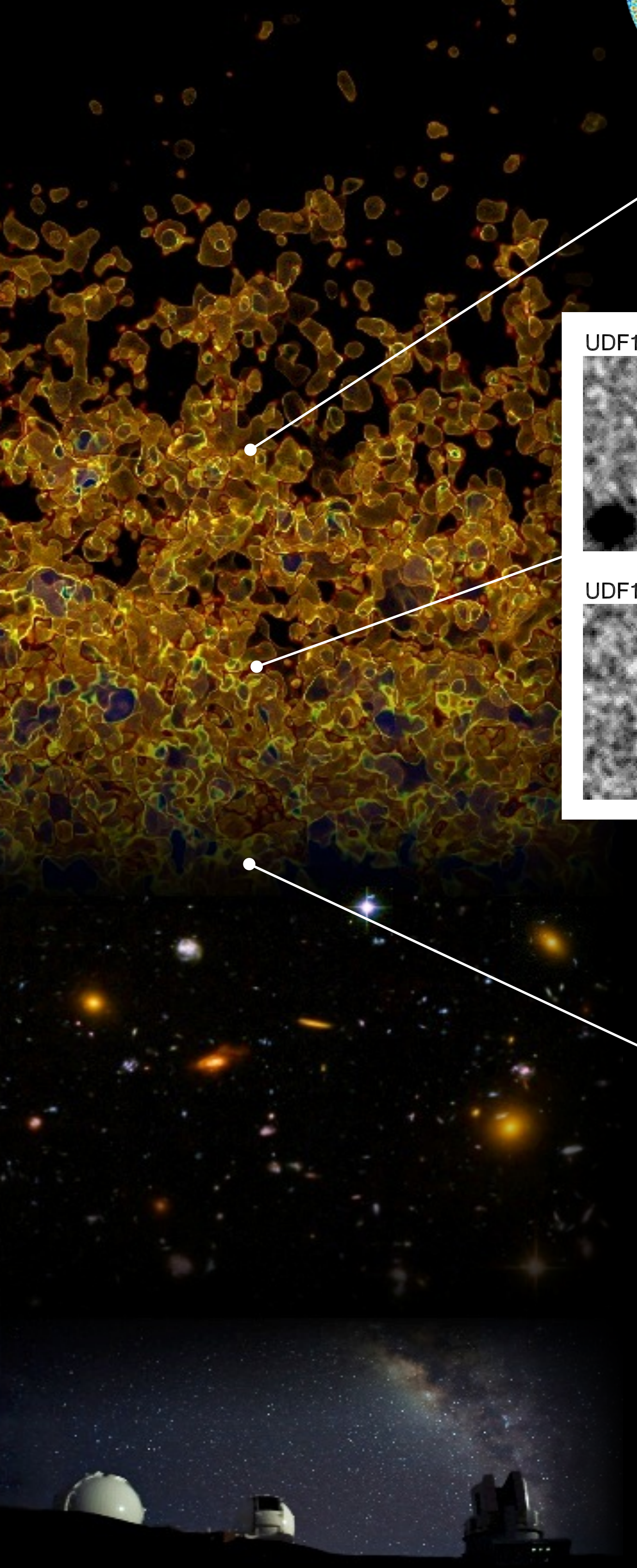
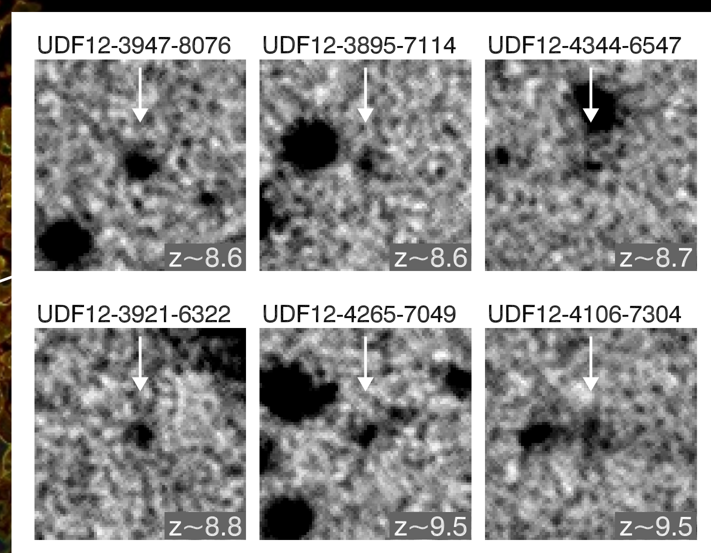
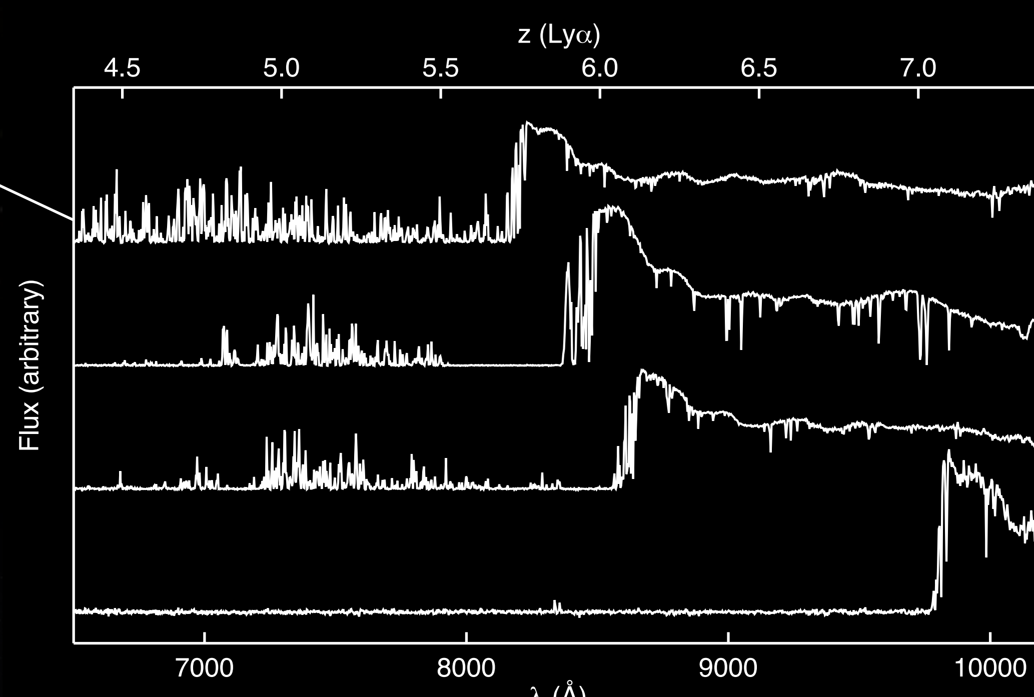






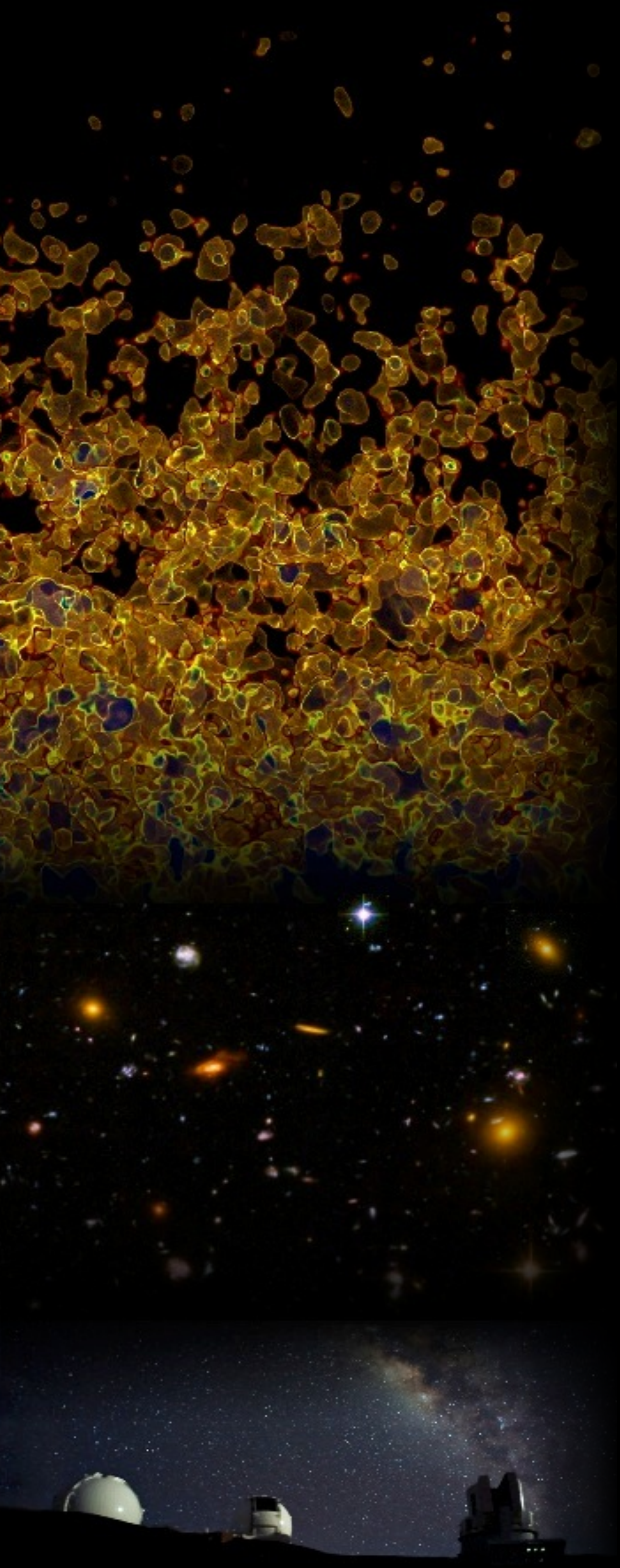


A Consensus Picture of Reionization?

George Becker

STScI

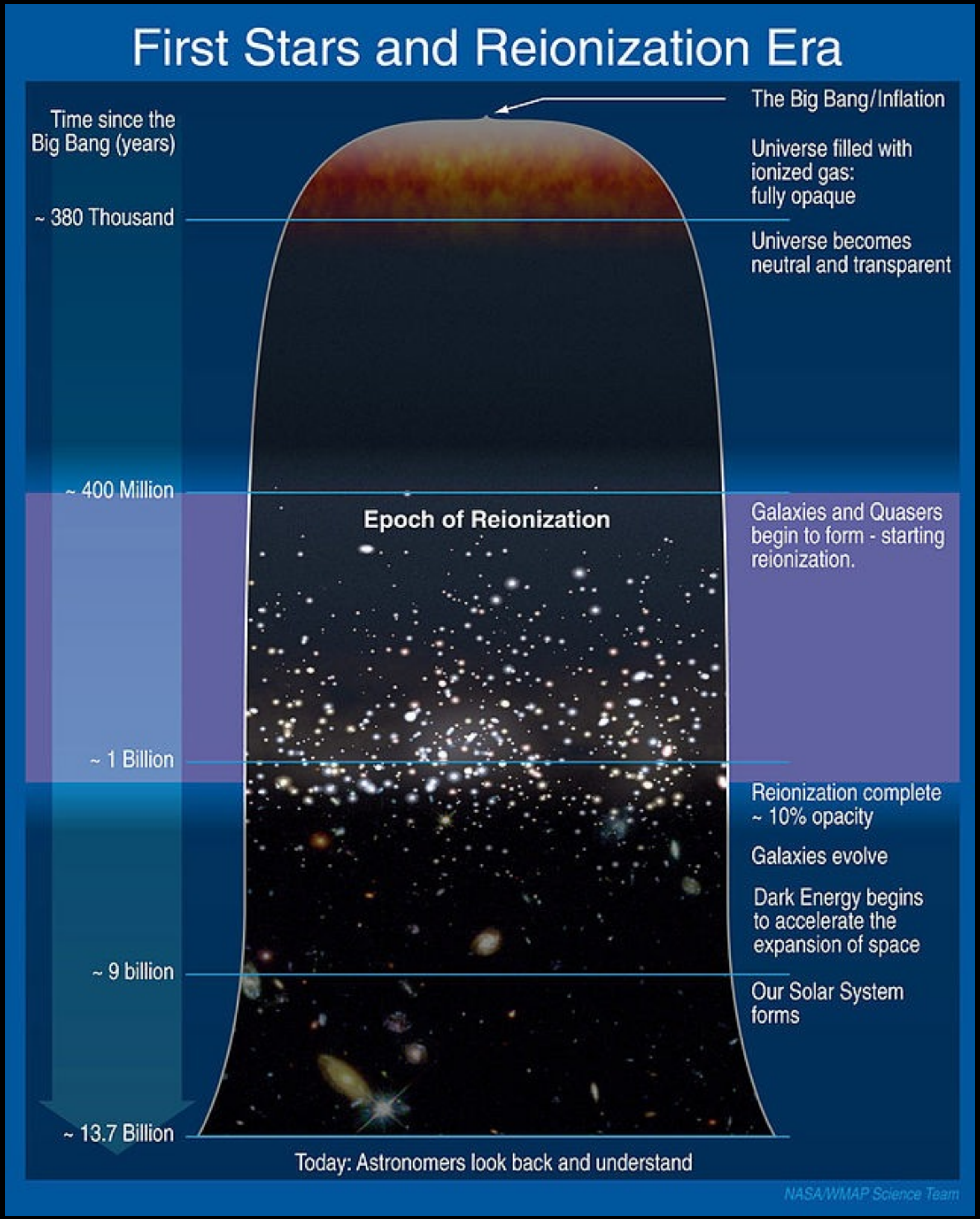
3.10.2015



Outline

- New results from Planck — Problem solved?
- The ionizing photon budget over $2 < z < 6$
- Have we detected reionization at $z\sim6$? $z\sim7$?

Reionization



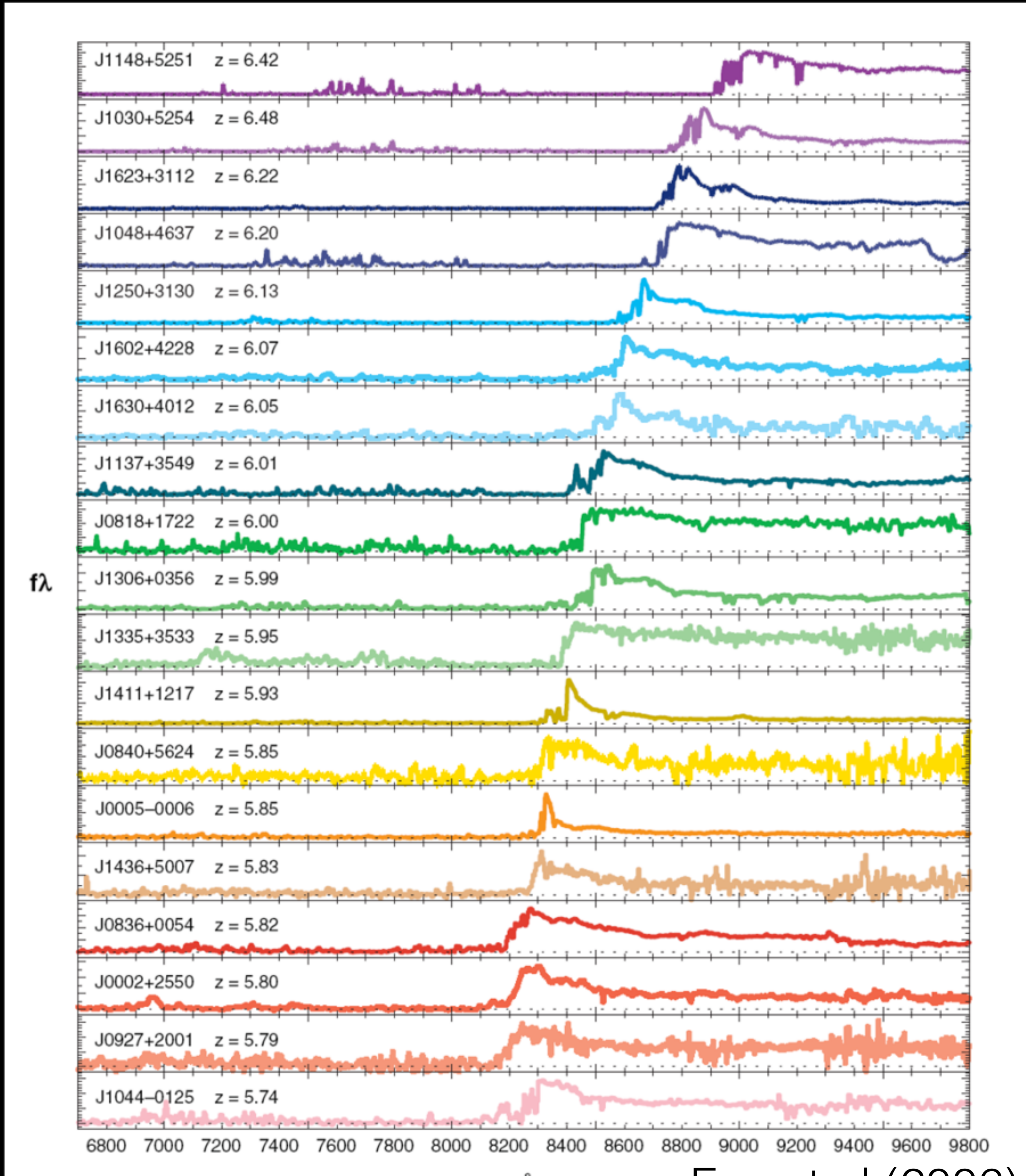
- What are the first stars like?
- When do the first galaxies form?
- What are the properties of the earliest galaxies, and how do they evolve?
- How and when do the first super-massive black holes form?
- How does non-linear structure evolve in the IGM?
- How do galaxies and the IGM interact?

Boundary condition: Lyα Forest

IGM Lyα opacity:

$$\tau_{\mathrm{Ly}\alpha} \sim 10^5 f_{\mathrm{H\,I}}$$

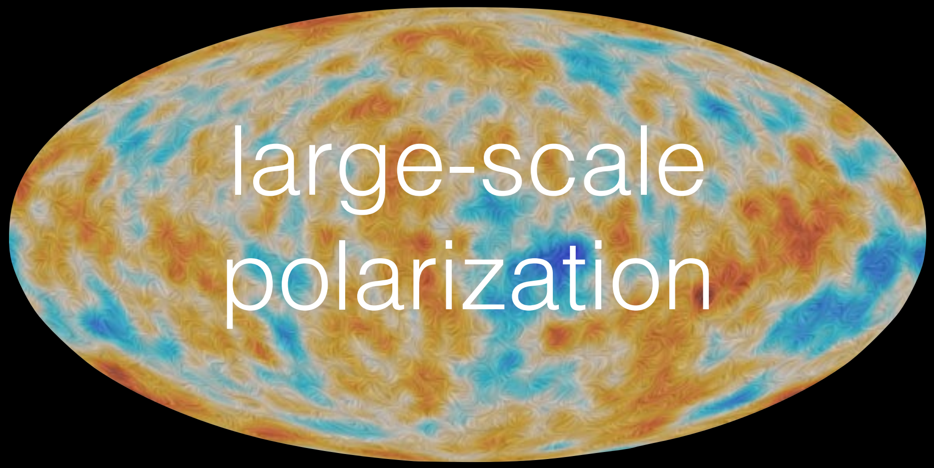
Transmission at z~6 means reionization *largely* complete within 1 Gyr (but see later in the talk).



Fan et al (2006)

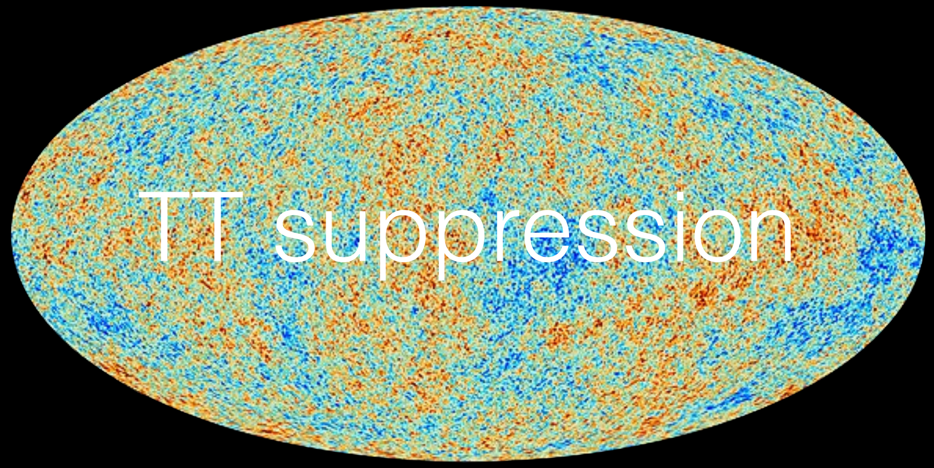
z

Planck 2015



Electron optical depth: $\tau_\mathrm{e} \propto N_\mathrm{e}$

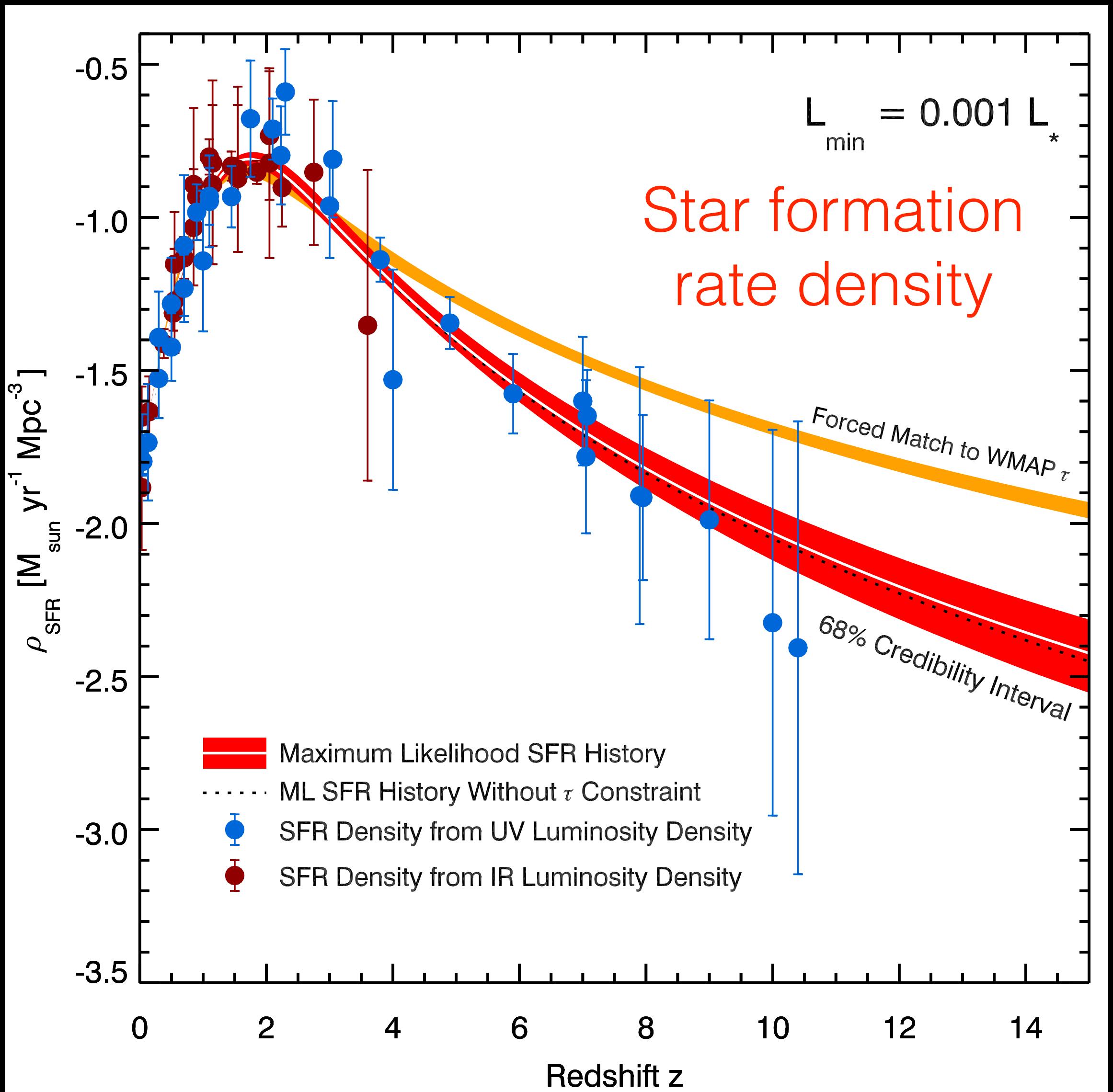
earlier reionization $\longrightarrow$ higher τ_e

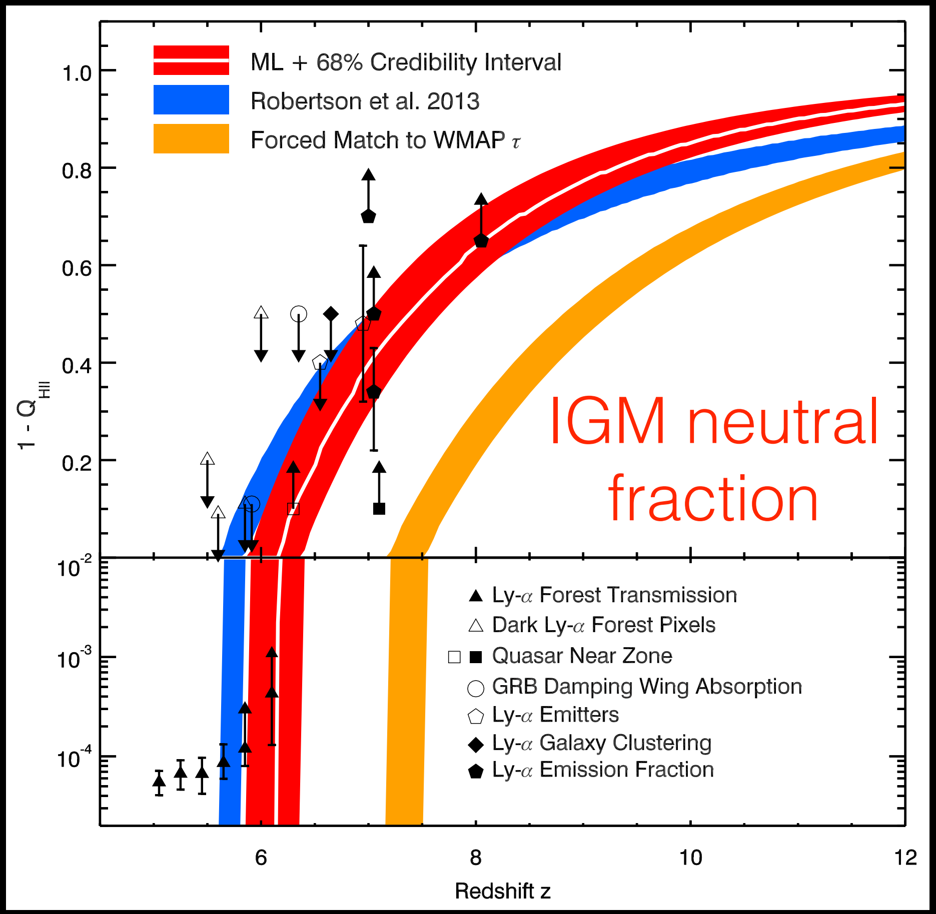


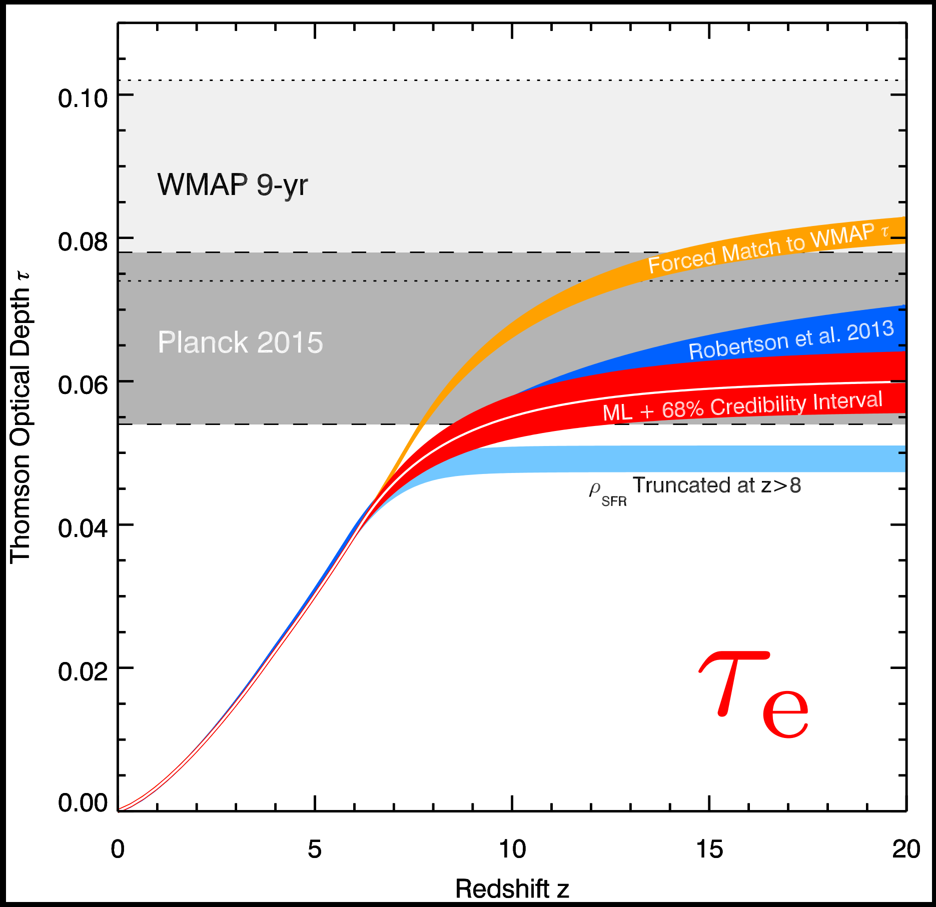
WMAP1	$\tau_\mathrm{e} = 0.17 \pm 0.06$	$z_\mathrm{reion} = 17 \pm 5$	*required "non-standard" star-formation history*
WMAP9	$\tau_\mathrm{e} = 0.089 \pm 0.014$	$z_\mathrm{reion} = 10.6 \pm 1.1$	*still uncomfortably high*
Planck 2015	$\tau_\mathrm{e} = 0.066 \pm 0.016$	$z_\mathrm{reion} = 8.8^{+1.7}_{-1.4}$	*better dust maps + constraints from CMB lensing*

A consensus model?

Robertson+2015







Lower τ_e from Planck reconciles reionization with high-z star formation rate. Right?

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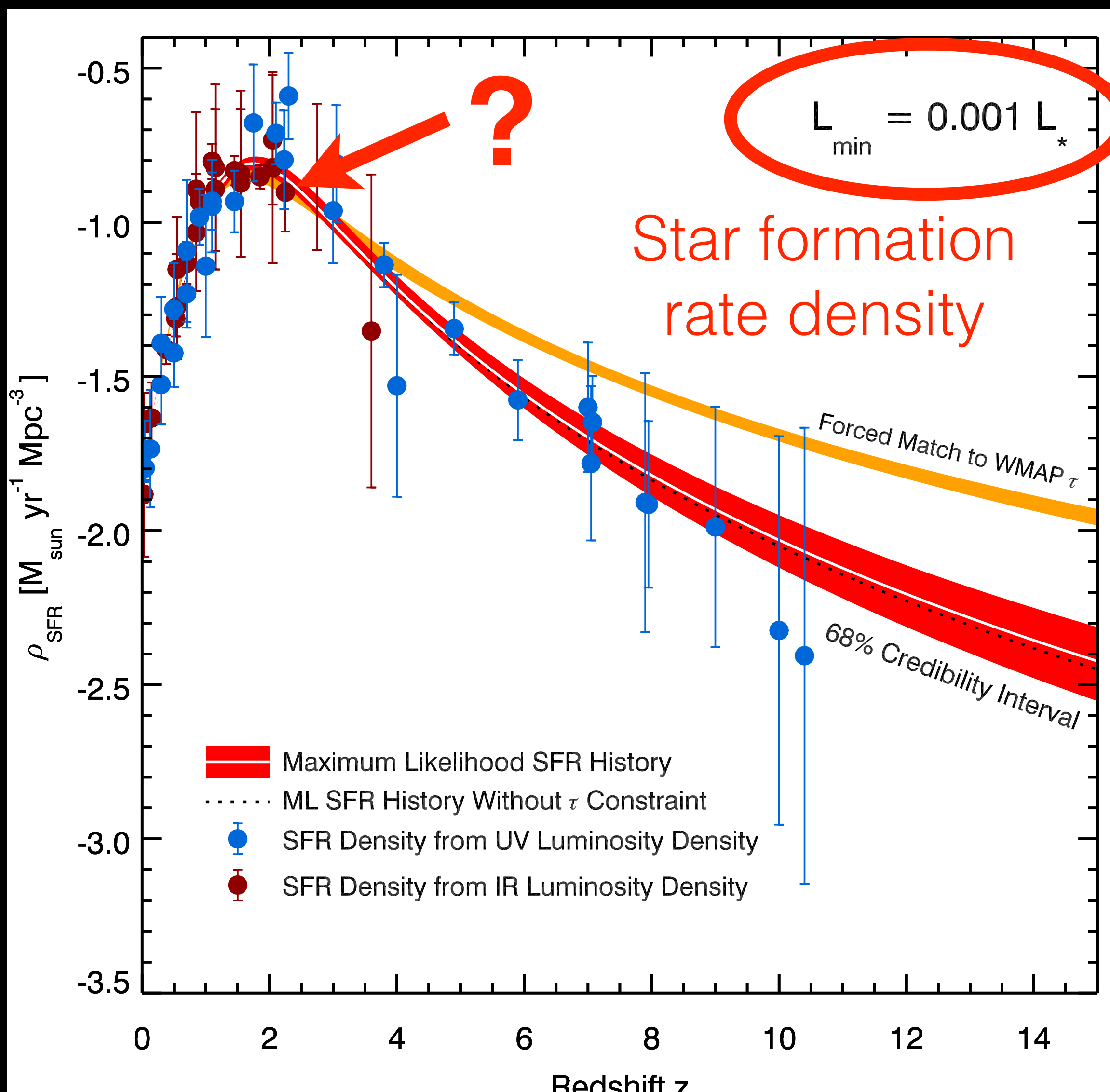
Consistency?

Robertson+2015



To complete reionization, need ~3 ionizing photons/atom.

Ionizing emissivity:

$$\dot{N}_{\rm ion} = f_{\rm esc}\xi_{\rm ion}\rho_{\rm SFR}$$

Escape fraction

ionizing photons / unit SFR

Star formation rate density

Model assumes $f_{\rm esc} = 0.2$, fixed $\xi_{\rm ion}$

Model @ z=2.5 😀

$\dot{N}_{\rm ion} \simeq 19$ LyC photons atom^{-1} Gyr^{-1}

stars only

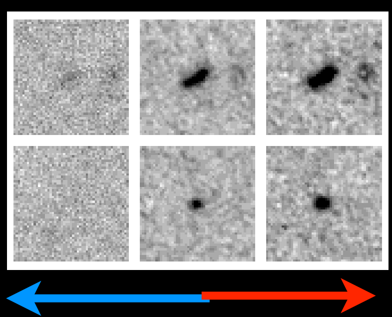
Reality @ z=2.5 😬

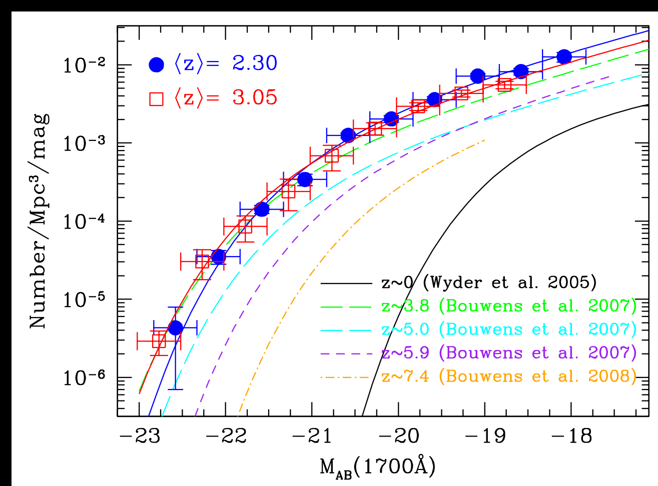
$\dot{N}_{\rm ion} \simeq 4$ LyC photons atom^{-1} Gyr^{-1}

stars + AGN!

Ionizing Emissivity

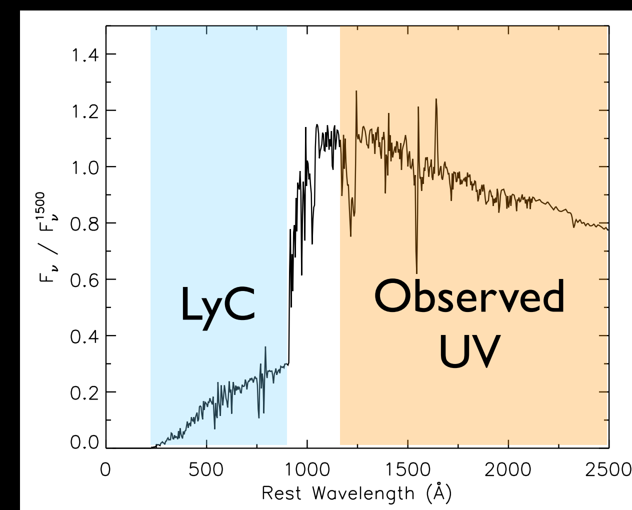
Galaxy UV Luminosity Fn





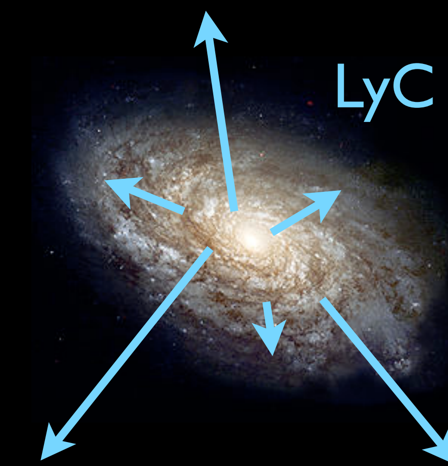
+

SED



+

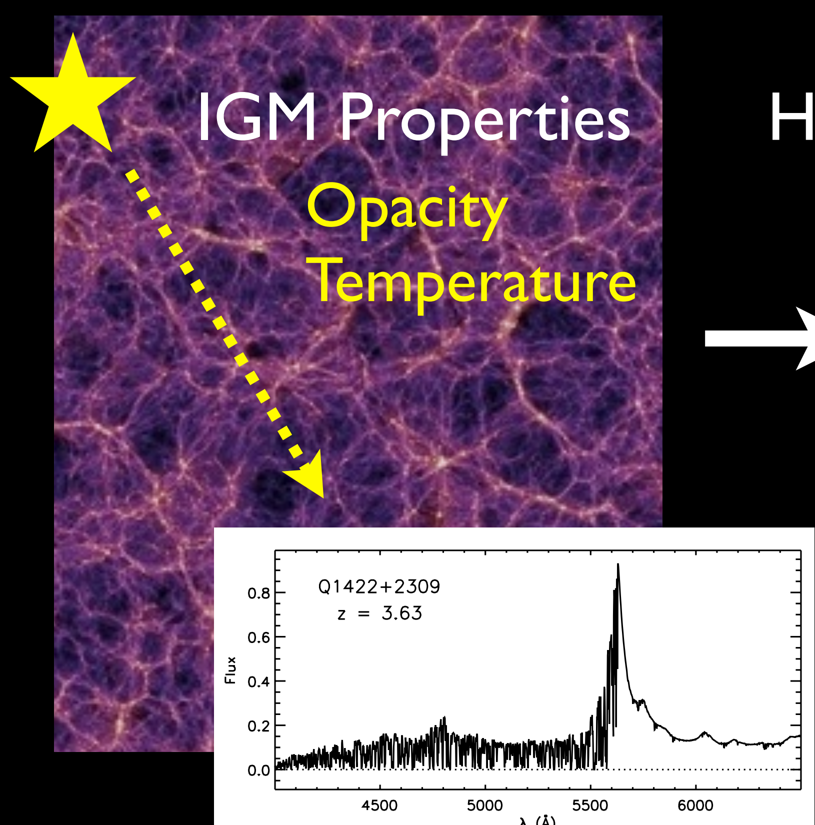
Escape fraction



IGM Properties

Opacity

Temperature



→

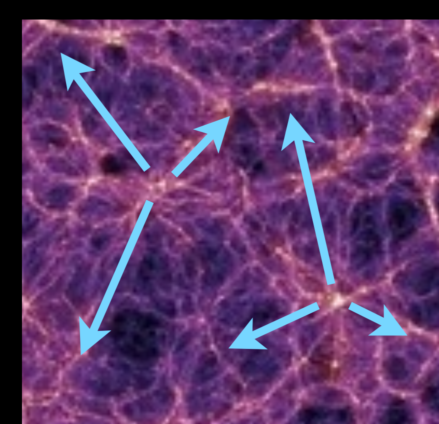
H I Ionization rate

$$\Gamma$$

s^{-1}

+

IGM opacity



→

Emissivity

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

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

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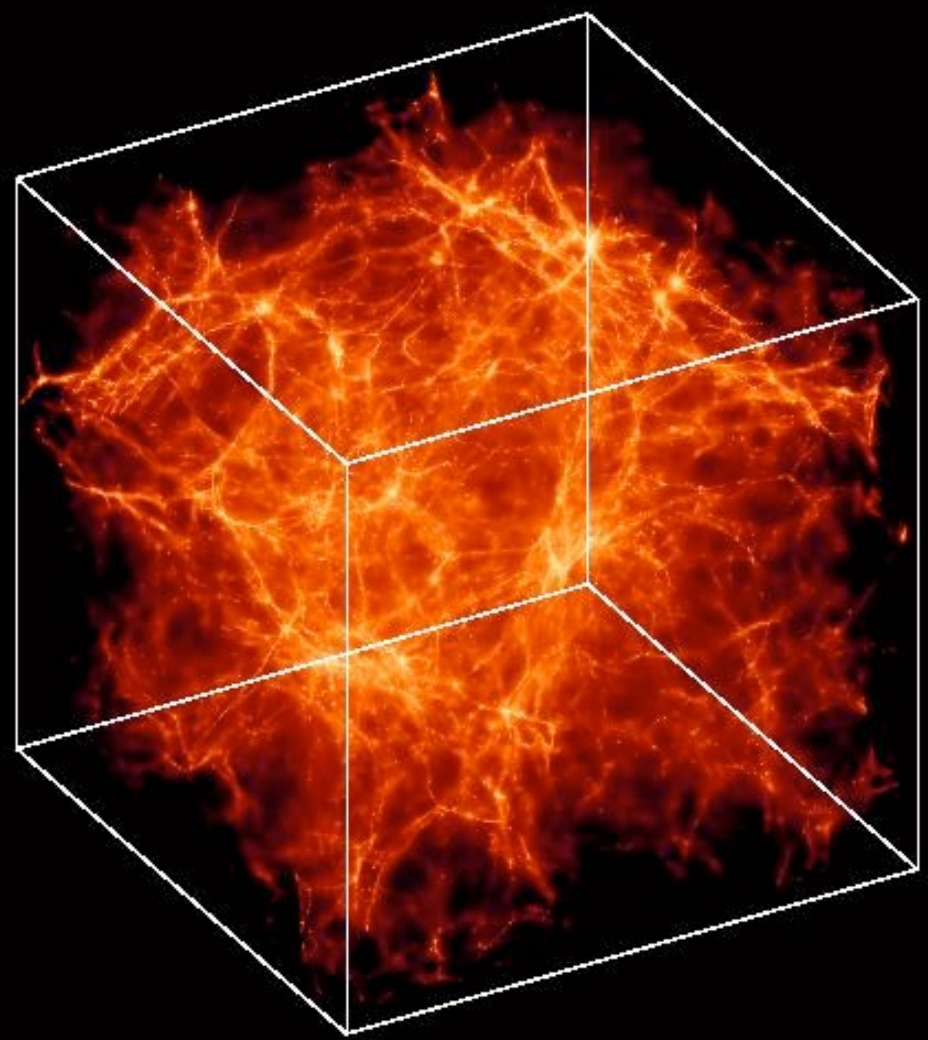
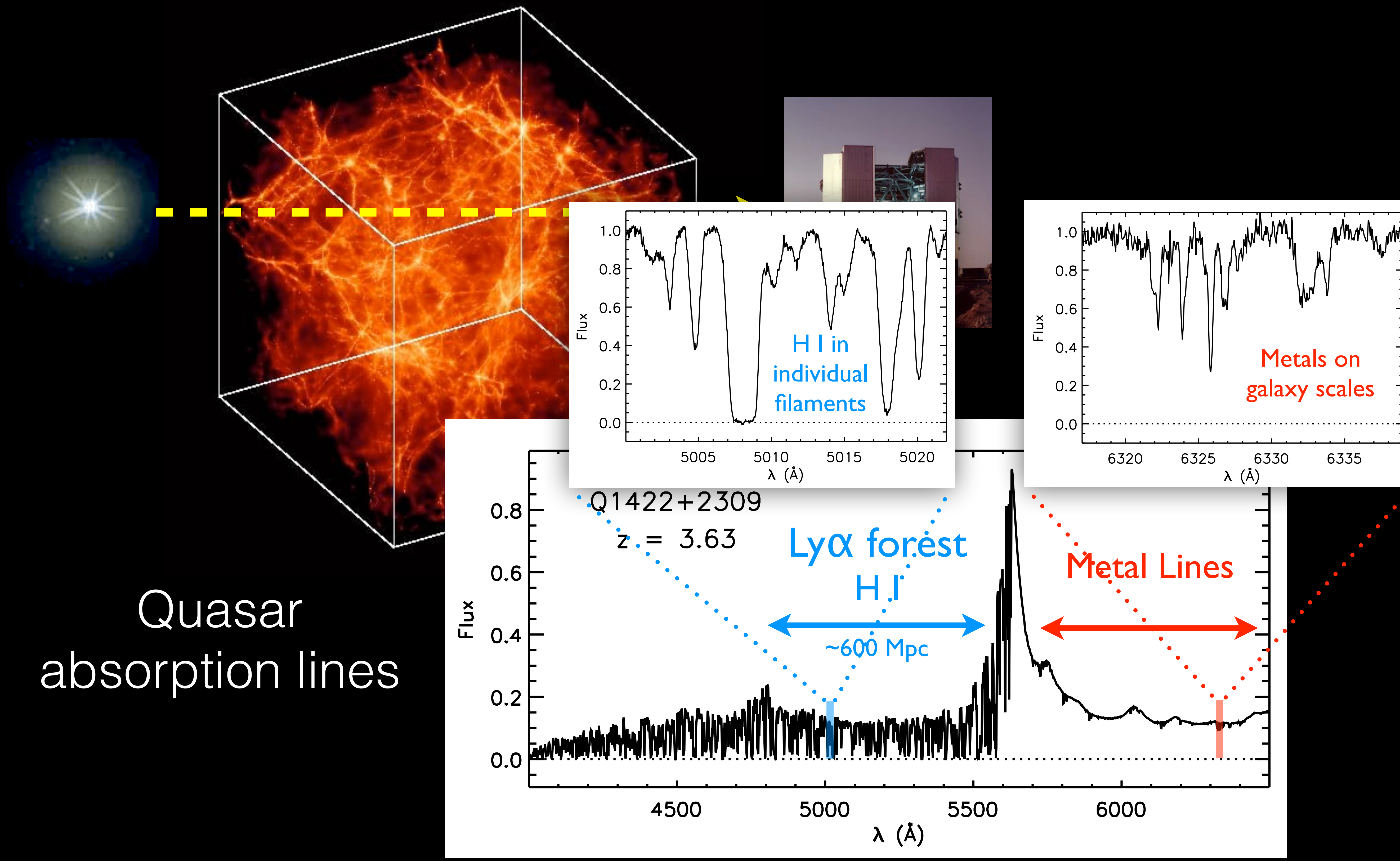
The Intergalactic Medium



- Main reservoir of matter in the universe (>90% baryons)
- Low density $0.1 \lesssim \rho/\bar{\rho} \lesssim 10$
- After reionization: warm, photo-ionized

$$T \sim 10^4 \text{ K}$$
$$f_{\mathrm{H\,I}} \sim 10^{-5}$$

The Intergalactic Medium



Quasar
absorption lines

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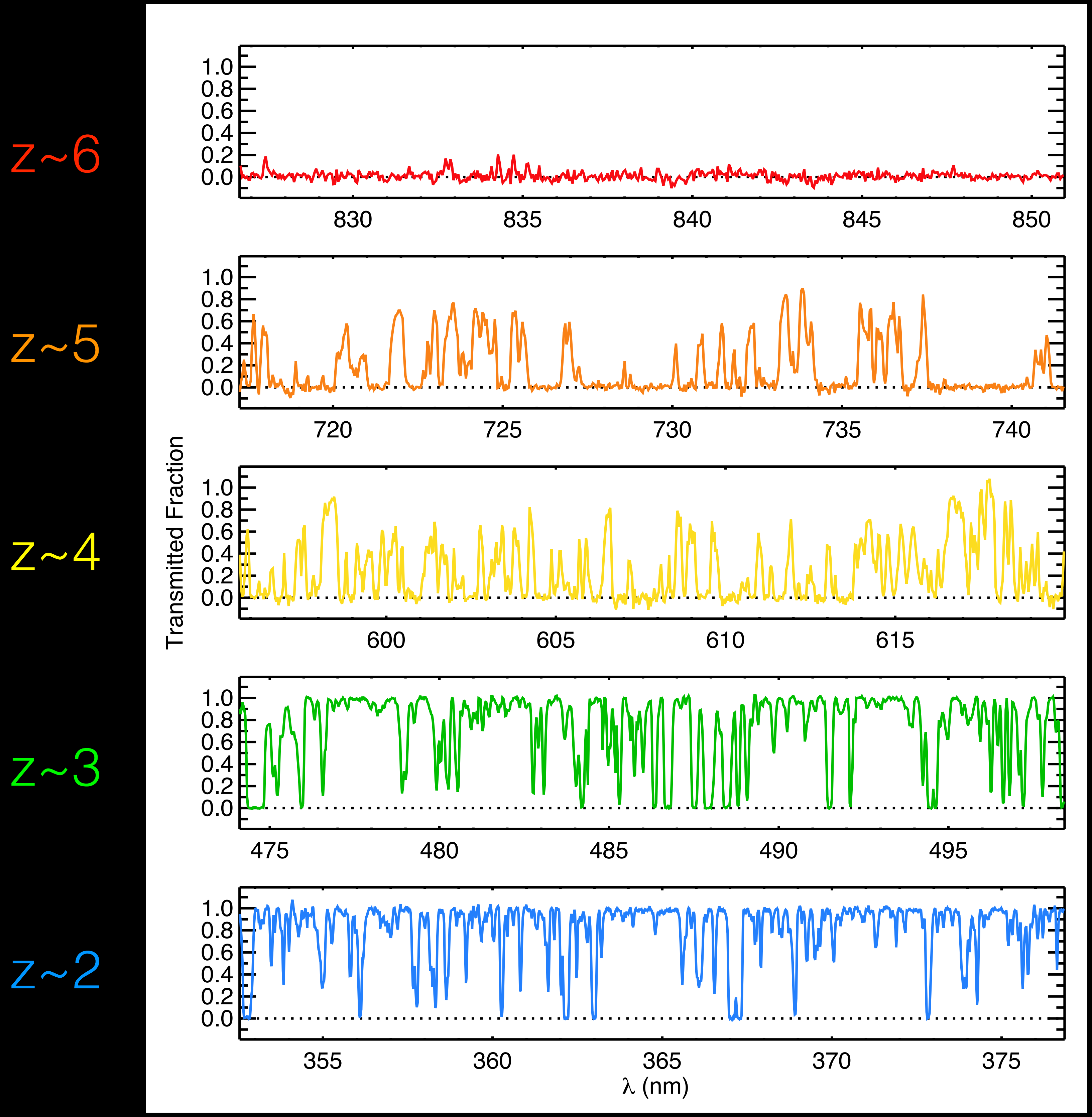
Lya Forest



$\rho/\bar{\rho} \sim 1$

(nearly linear)

$\rho/\bar{\rho} \sim 10$

(mildly non-linear)

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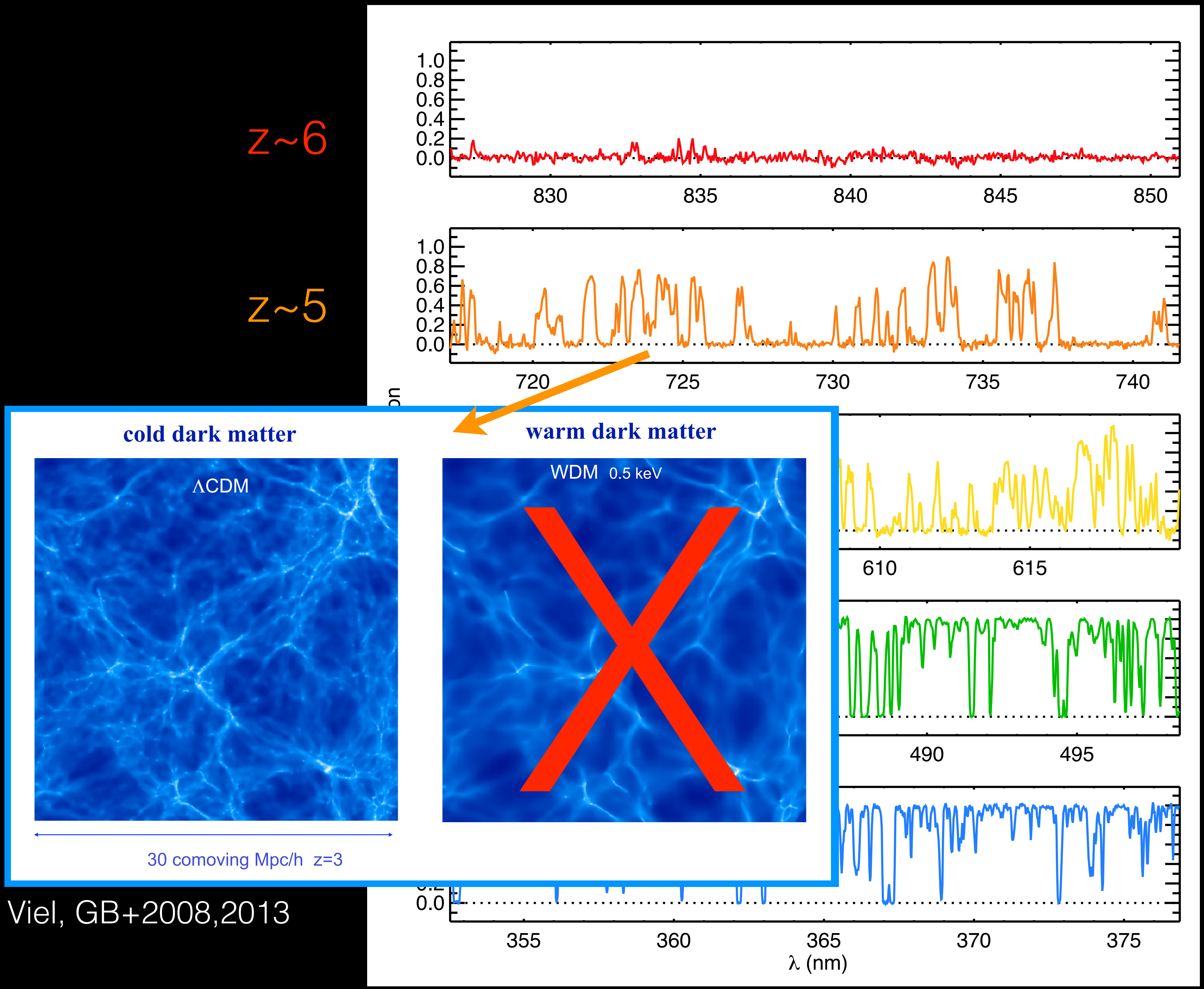
Lya Forest

z~6

z~5



Viel, GB+2008,2013

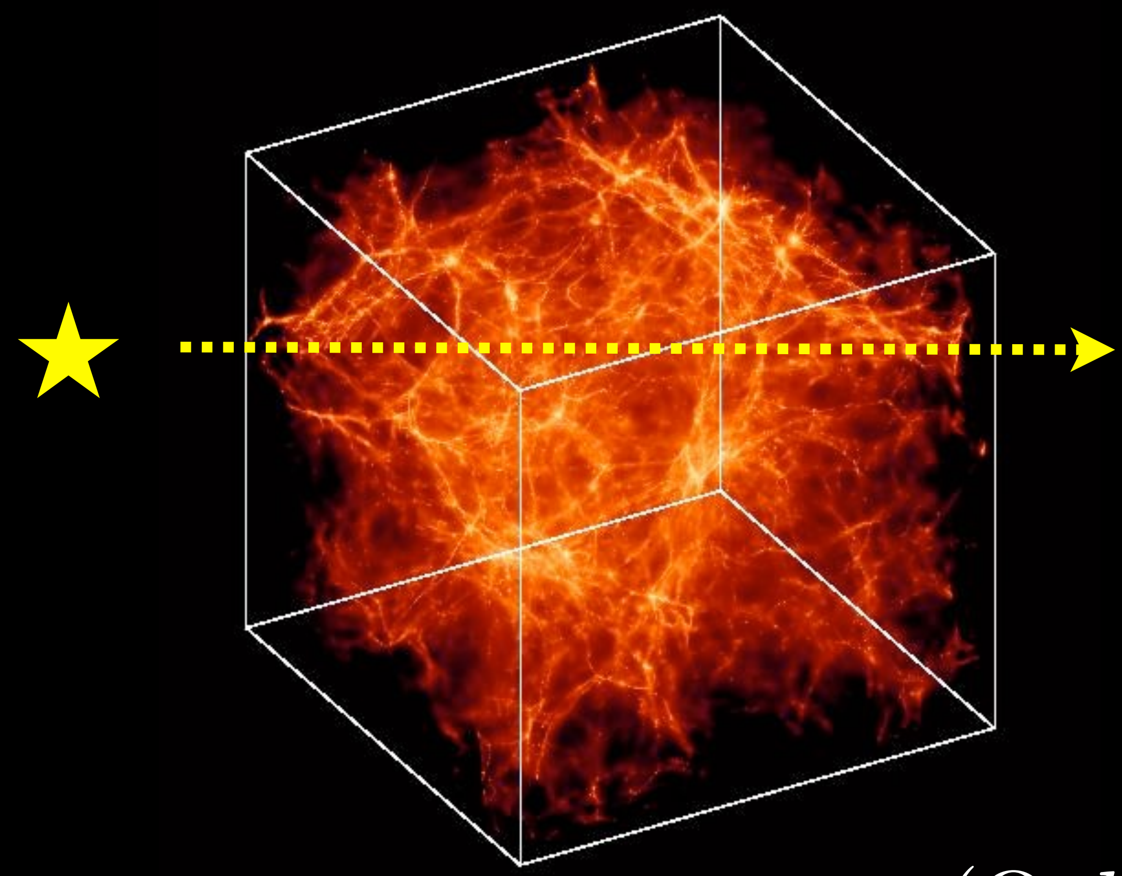
$\rho/\bar{\rho} \sim 1$

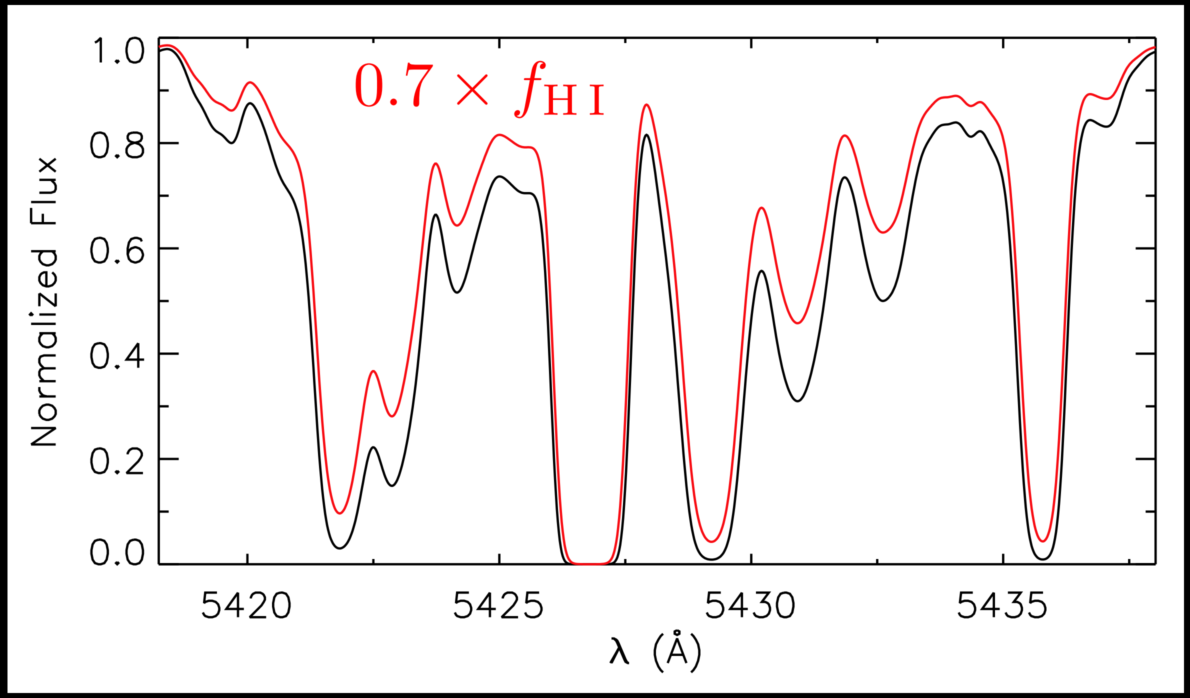
(nearly linear)

$\rho/\bar{\rho} \sim 10$

(mildly non-linear)

Counting photons





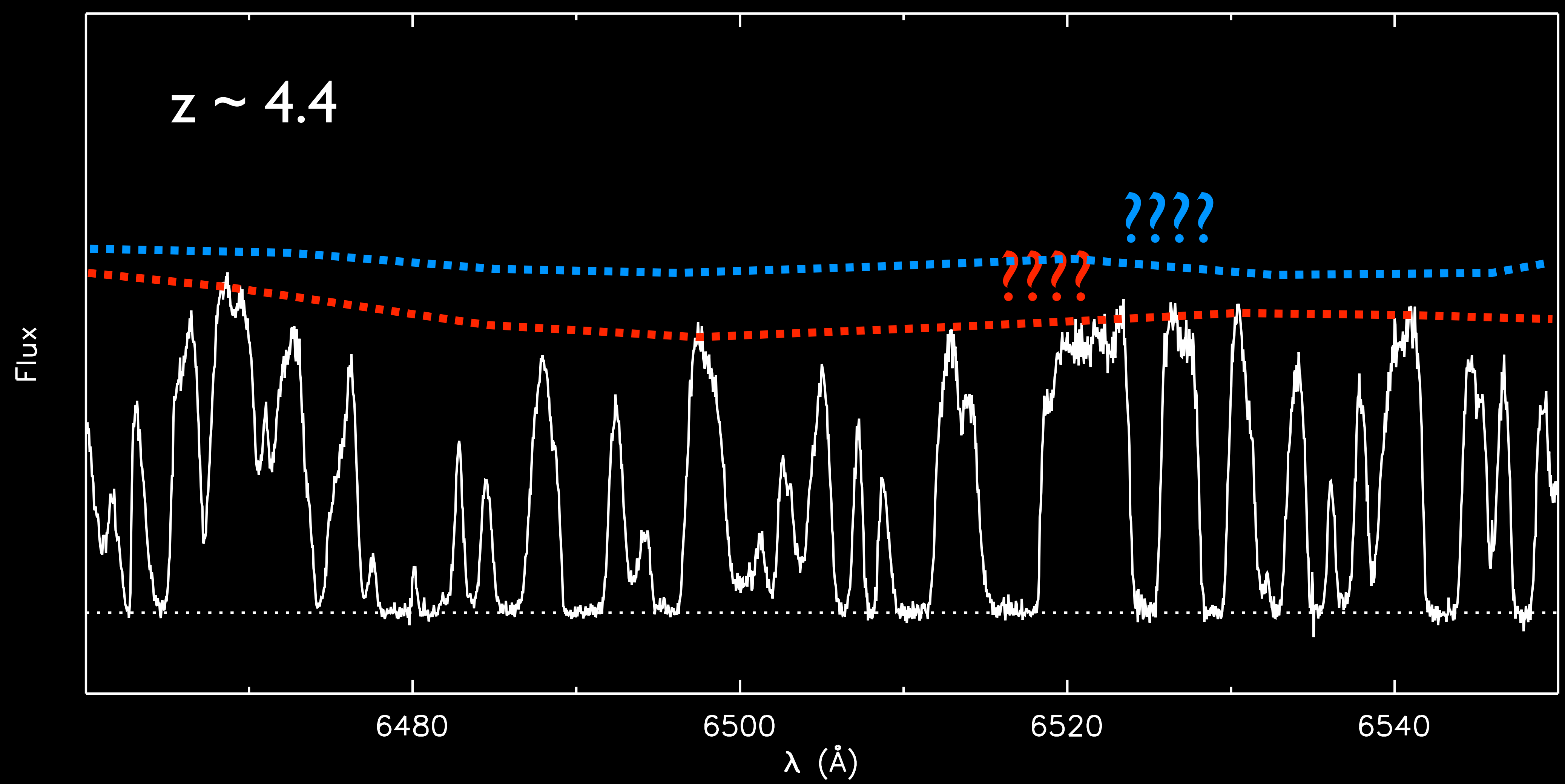
$$\tau \propto \frac{(\Omega_b h^2)^2\,(1+z)^6}{T^{0.7}\,H(z)\,\Gamma(z)}$$

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

H I ionization rate s^{-1}

IGM Lyα Opacity

The Continuum Problem



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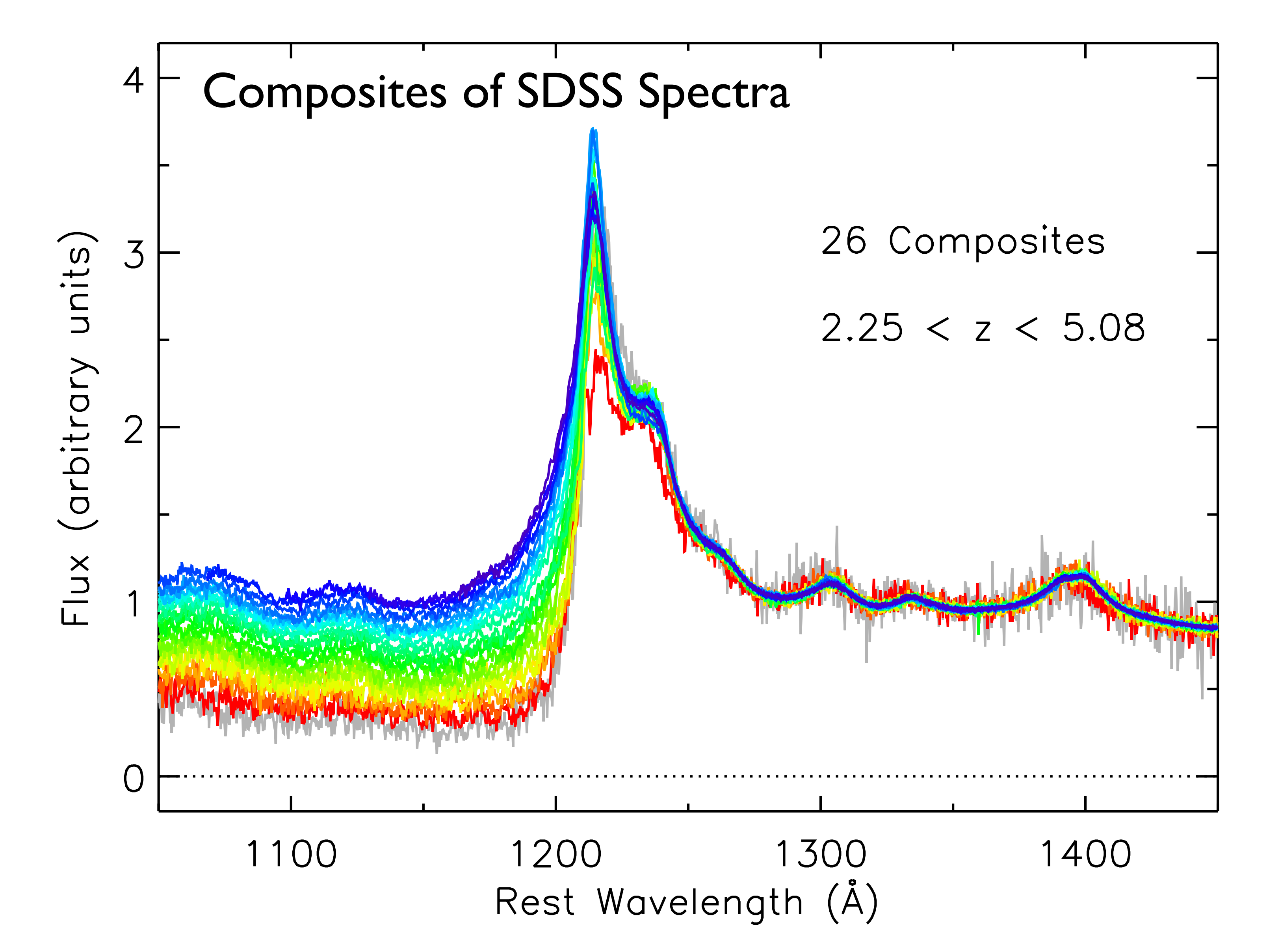
Solution: Don't fit continua

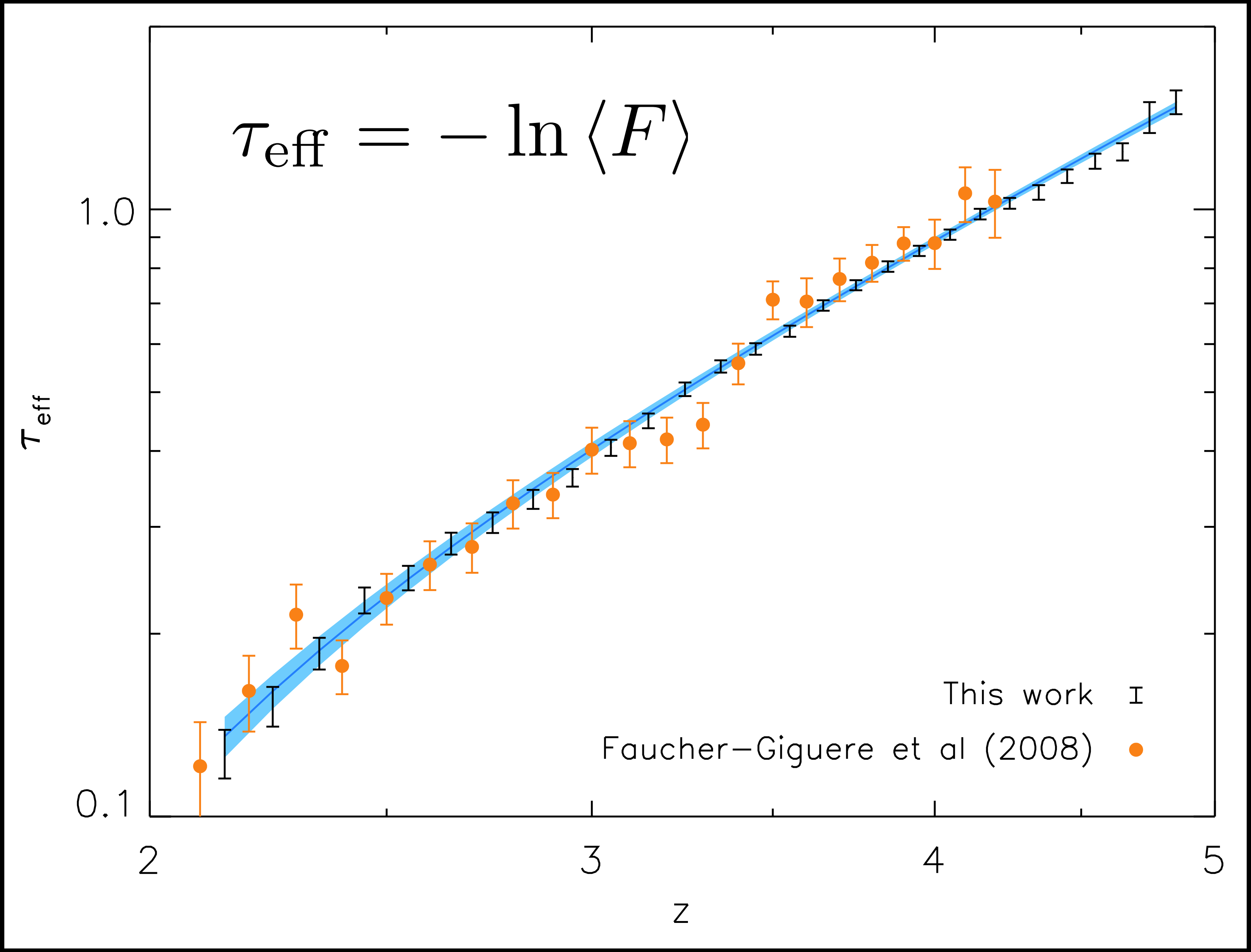
Use composites.



Becker+ 2013

Use flux ratios to get F(z)/F(z=2)

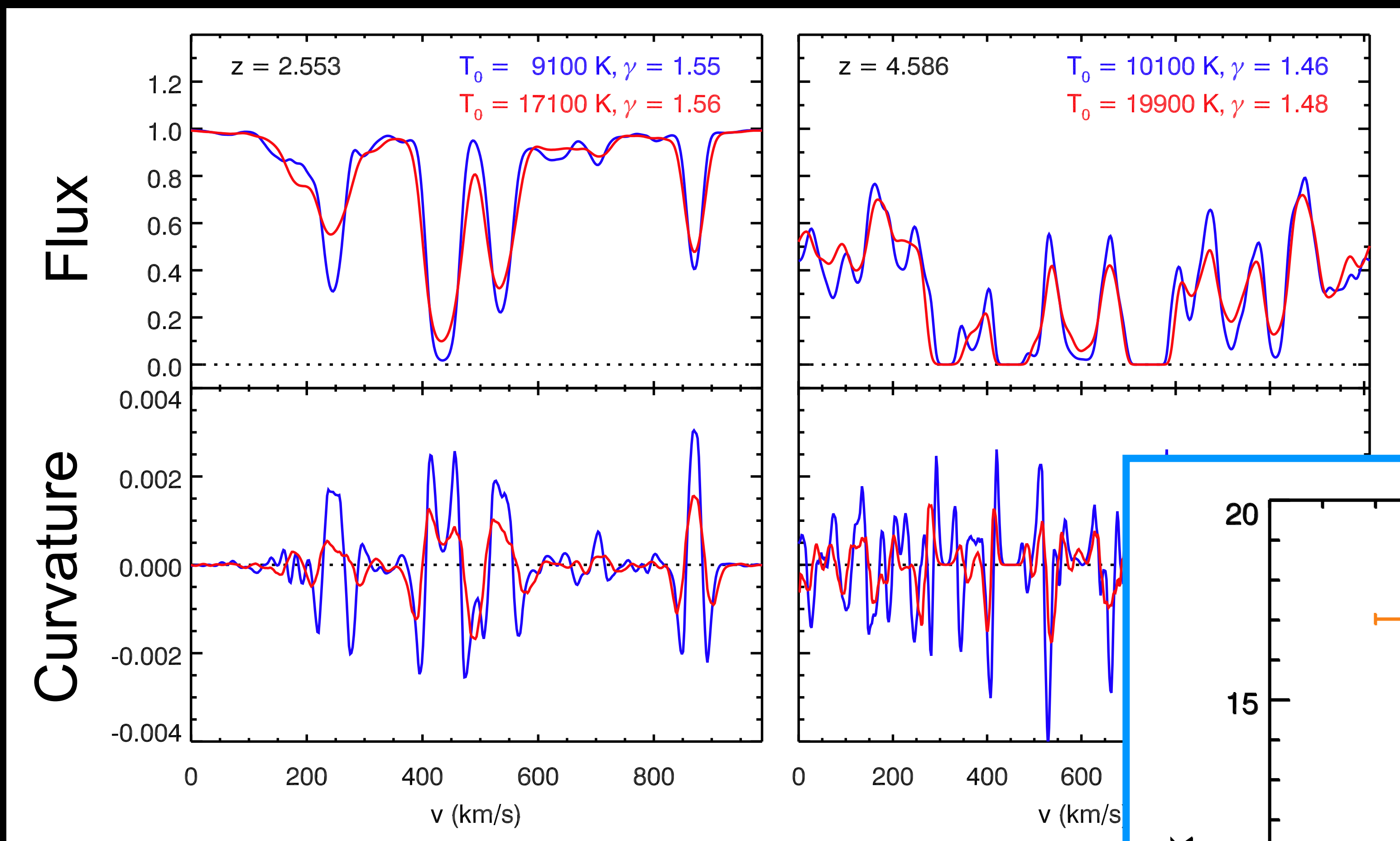
Lyα Opacity



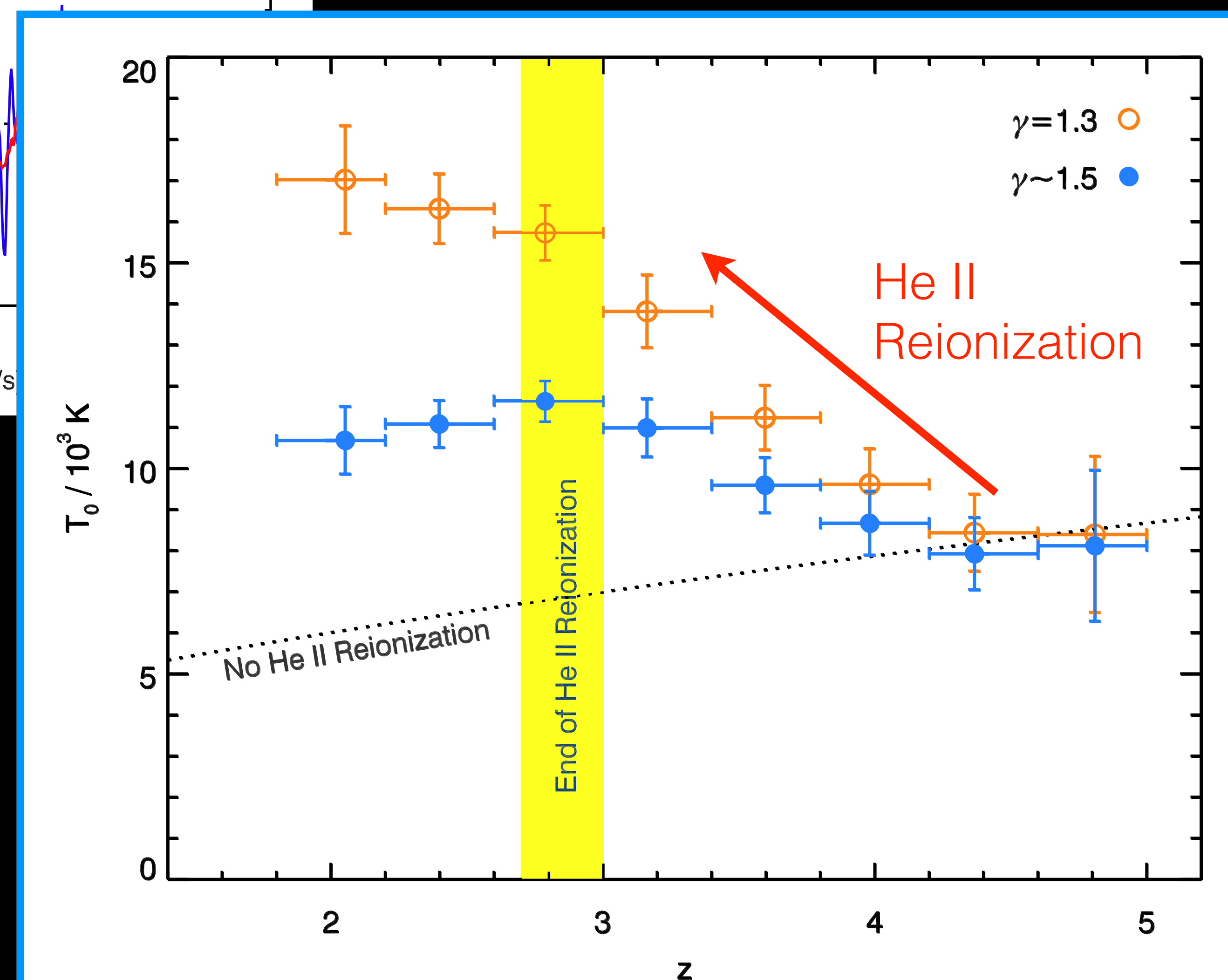
Becker+ 2013

1. Reduced errors
2. Extends to z=5
3. No bump at z=3

IGM Temperatures



Temperature at mean density

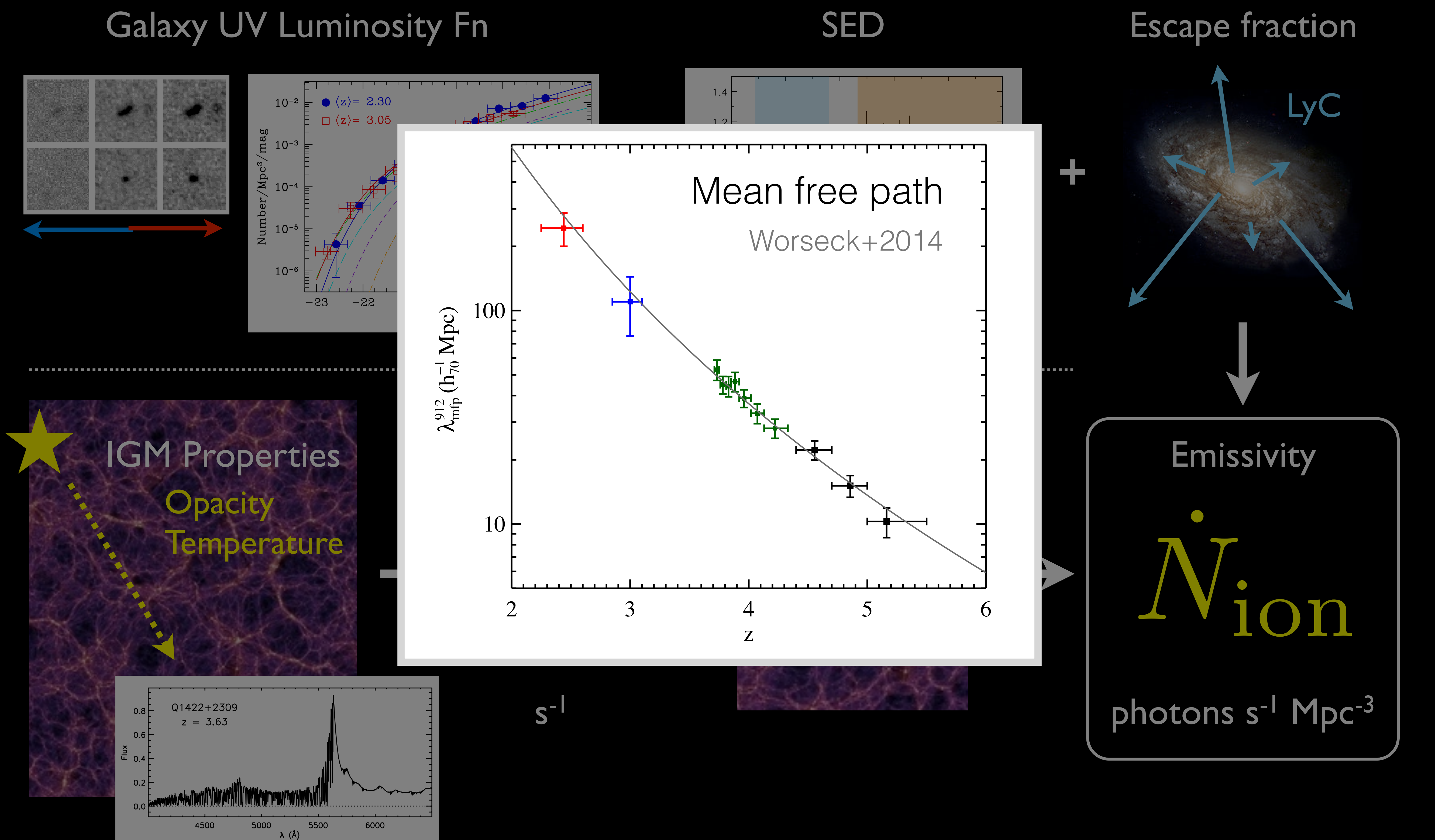


Curvature ≃ *F*''

Higher curvature = *Colder*

Becker+ 2011a

Ionizing Emissivity



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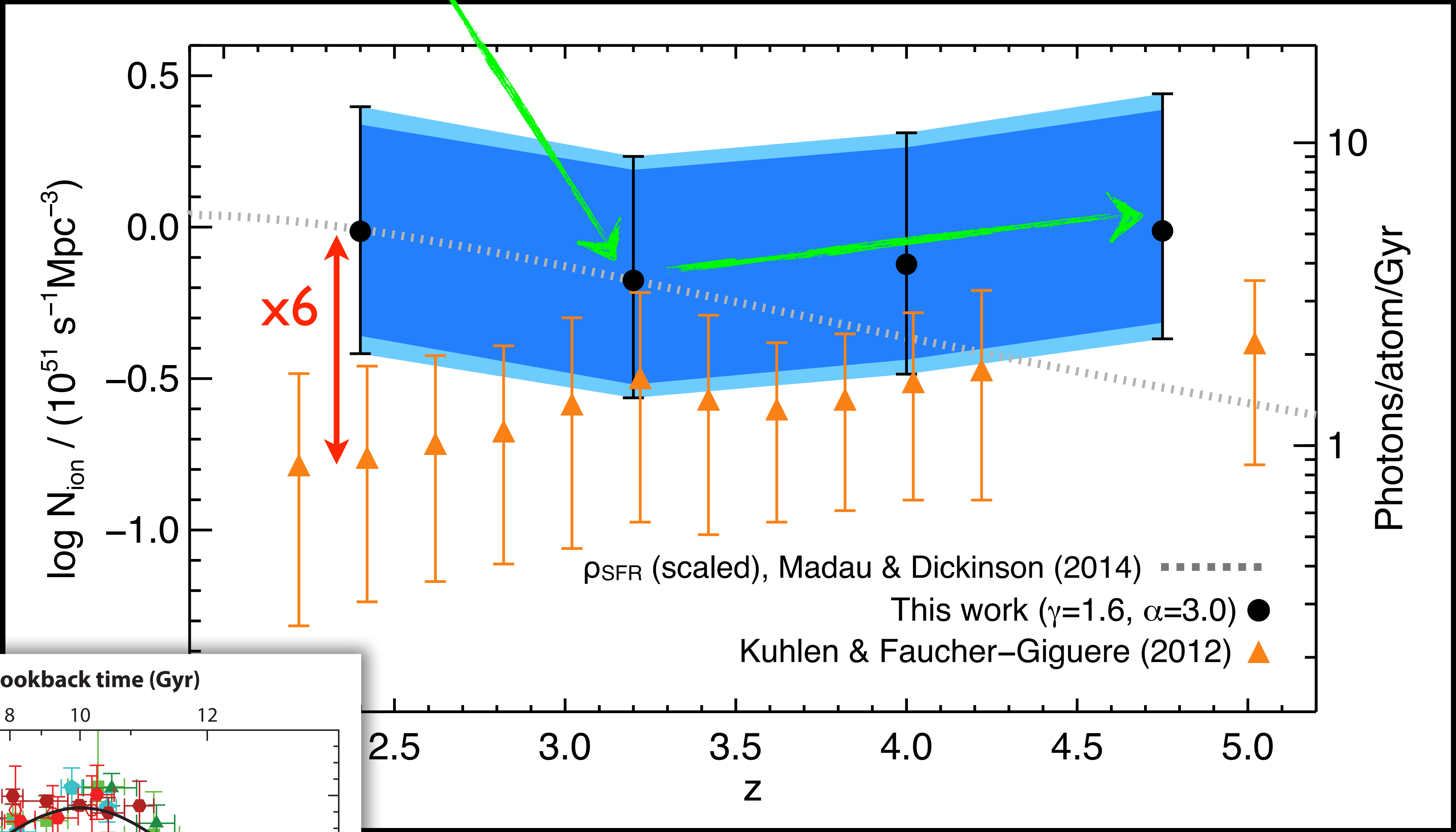
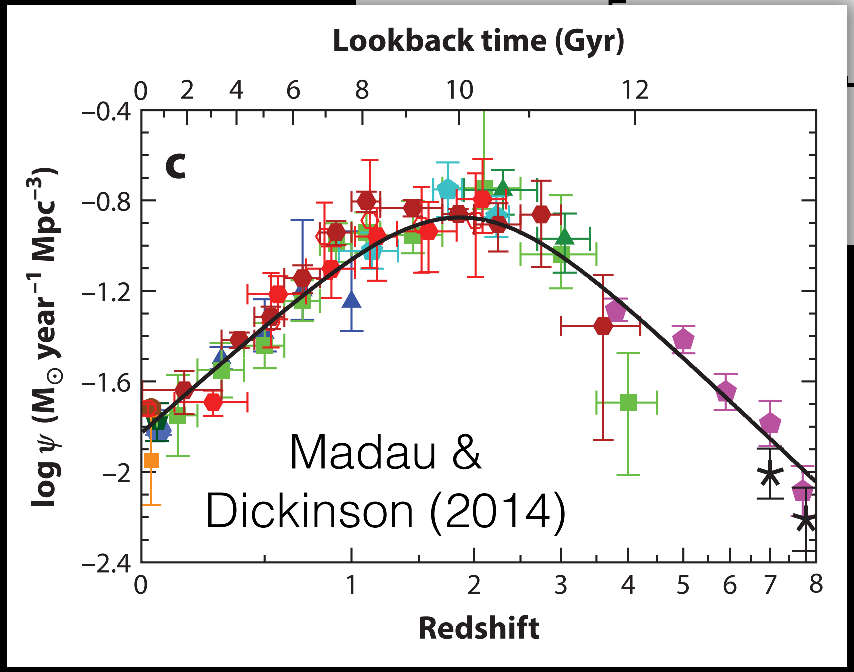
Emissivity Results

Modest emissivity at z~3

Rising as SFR density decreases?





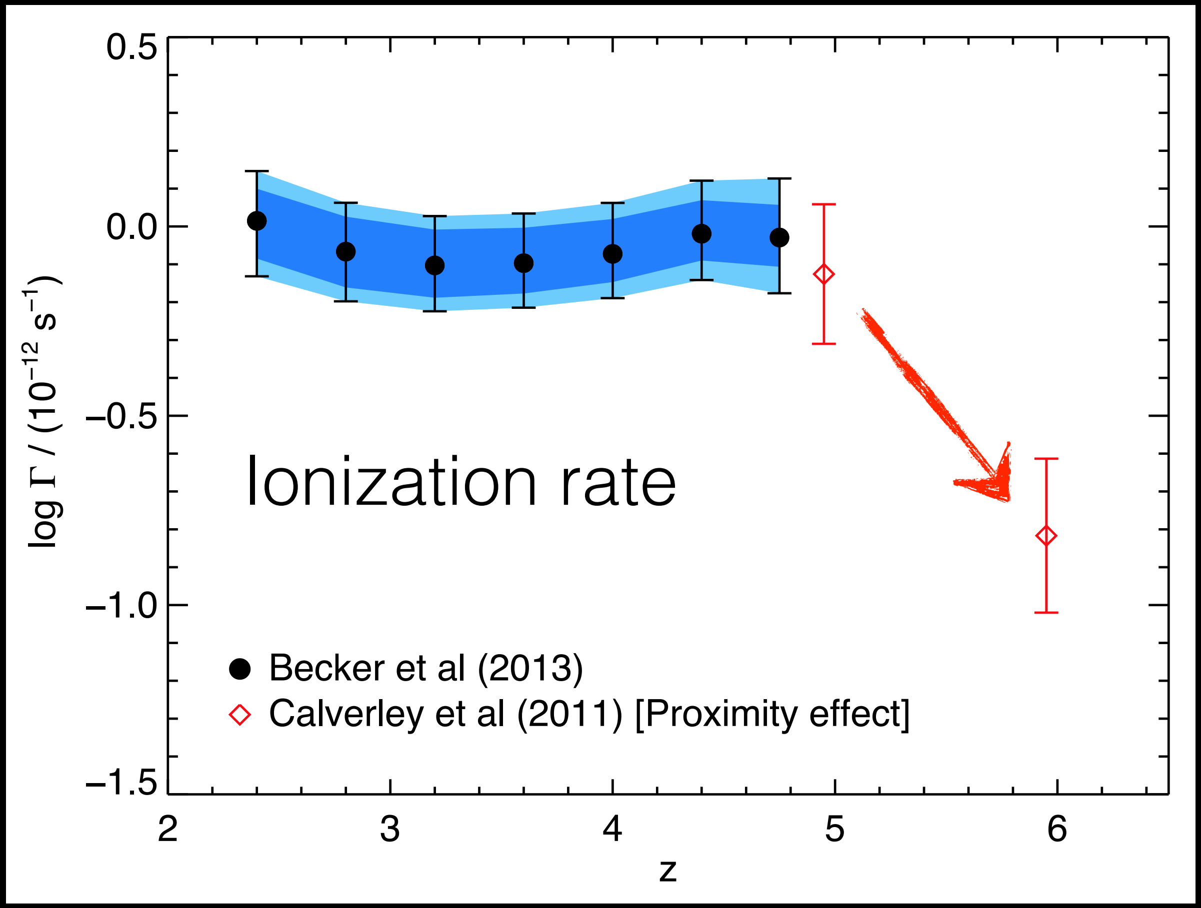
Higher ionizing emissivity from

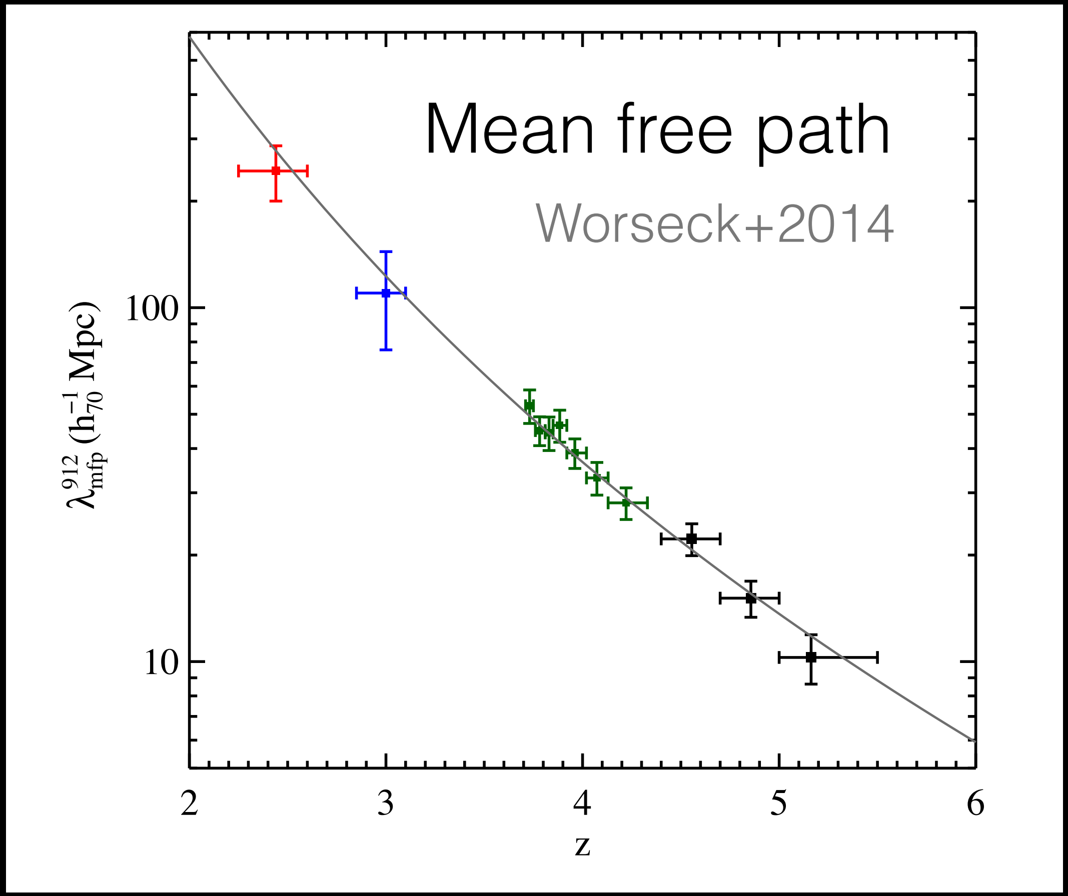
1. Lower temperatures
2. Radiative transfer
3. Shorter mean free path

Becker & Bolton (2013)

But a problem at z~6…

$$\dot{N}_{\rm ion} \propto \Gamma / \lambda_{\rm mfp}$$





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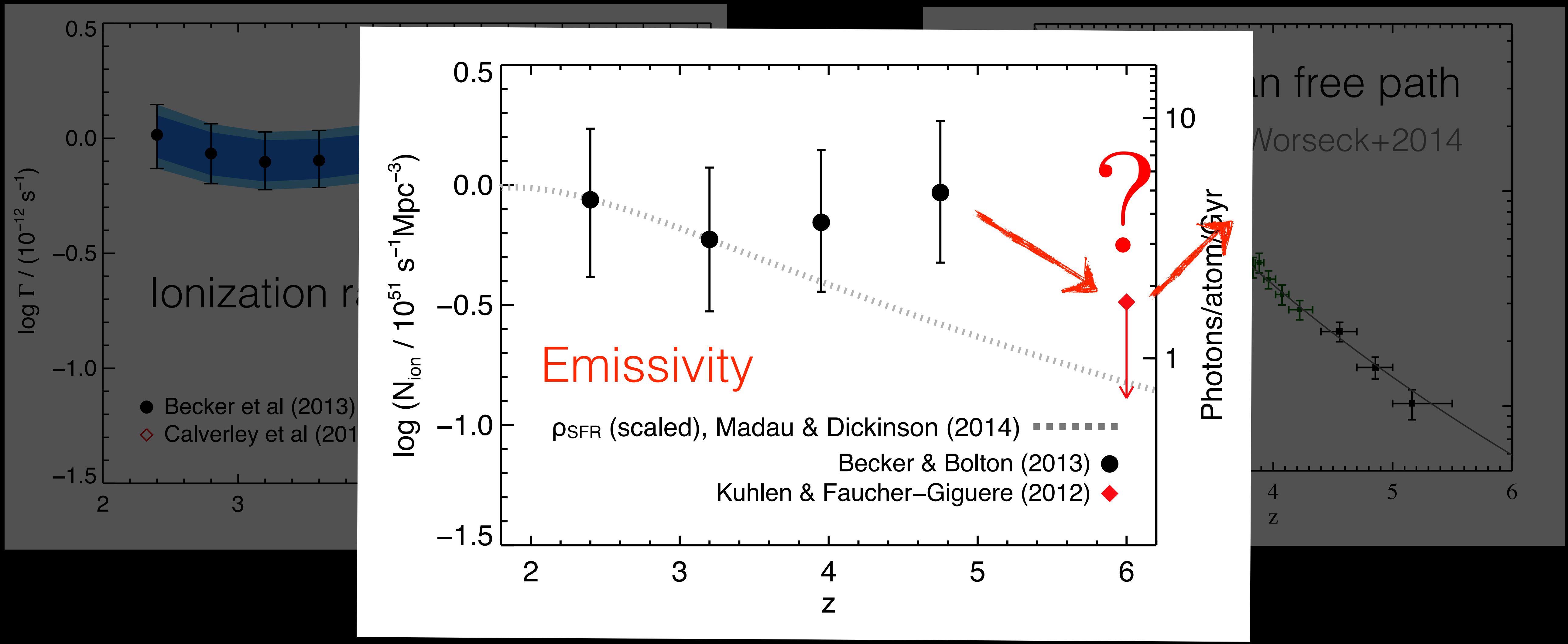
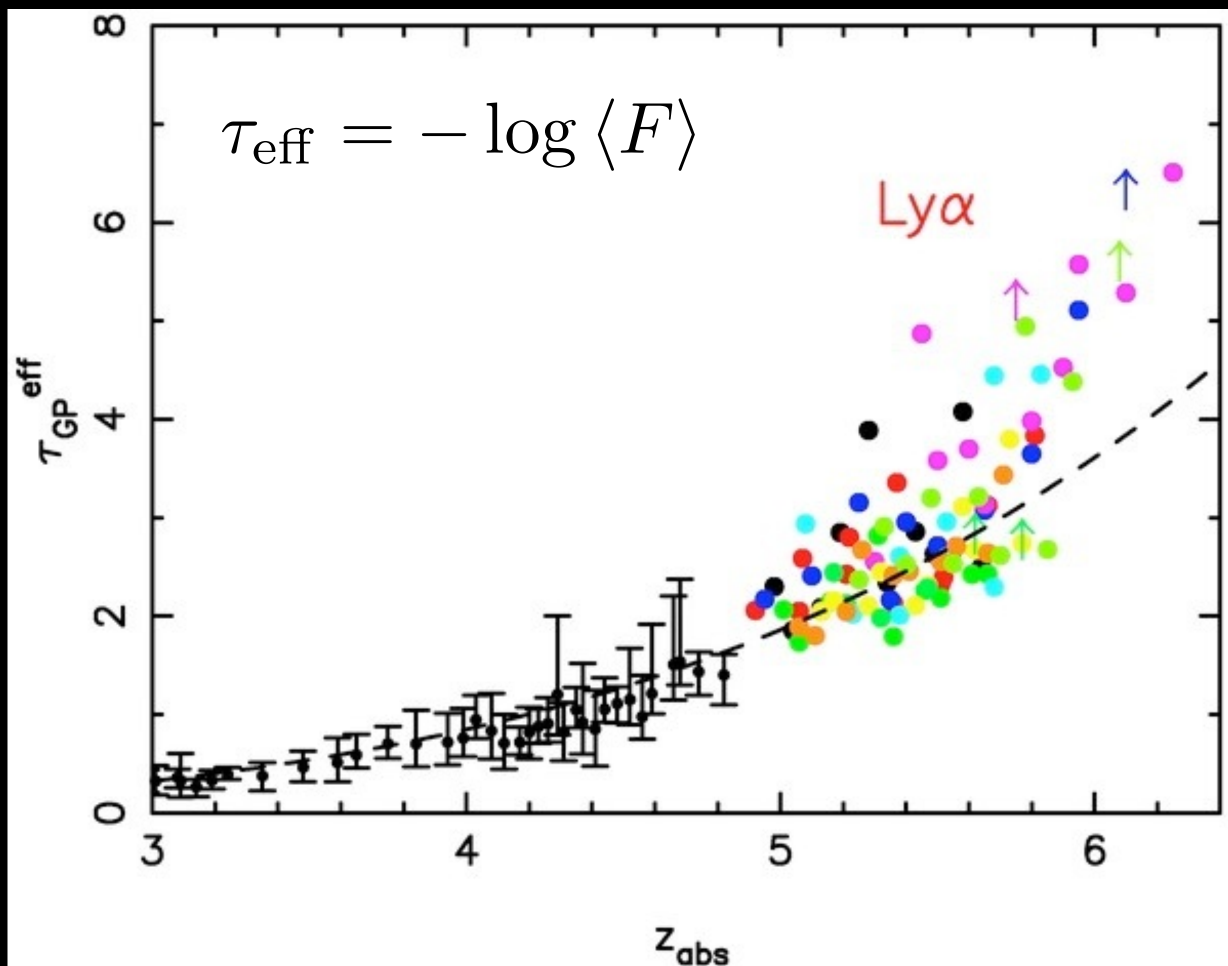
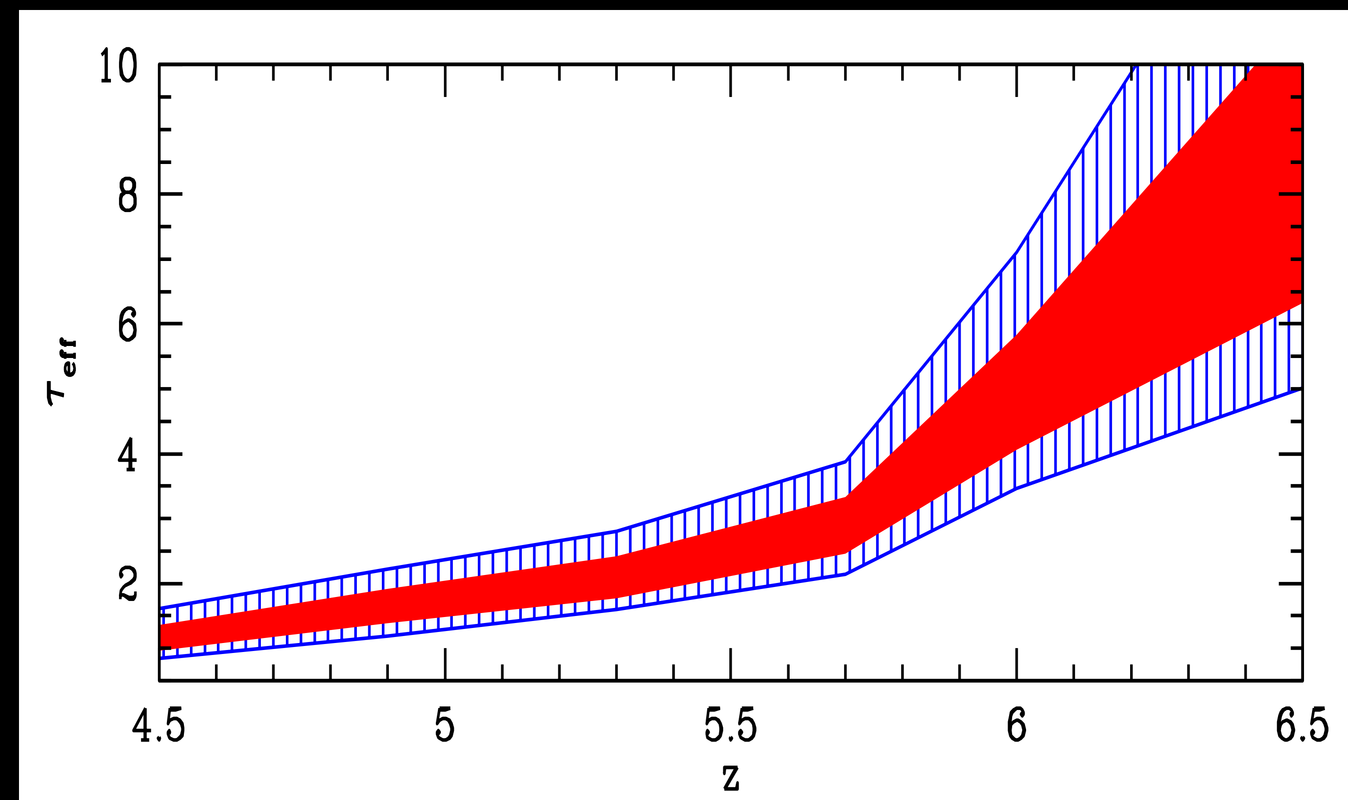


Does the emissivity have to rise at z > 6?

Scatter in Lyα opacity



Fan et al (2006)



Lidz et al (2006)

Get large scatter in Lyα opacity from the density field ***alone***.

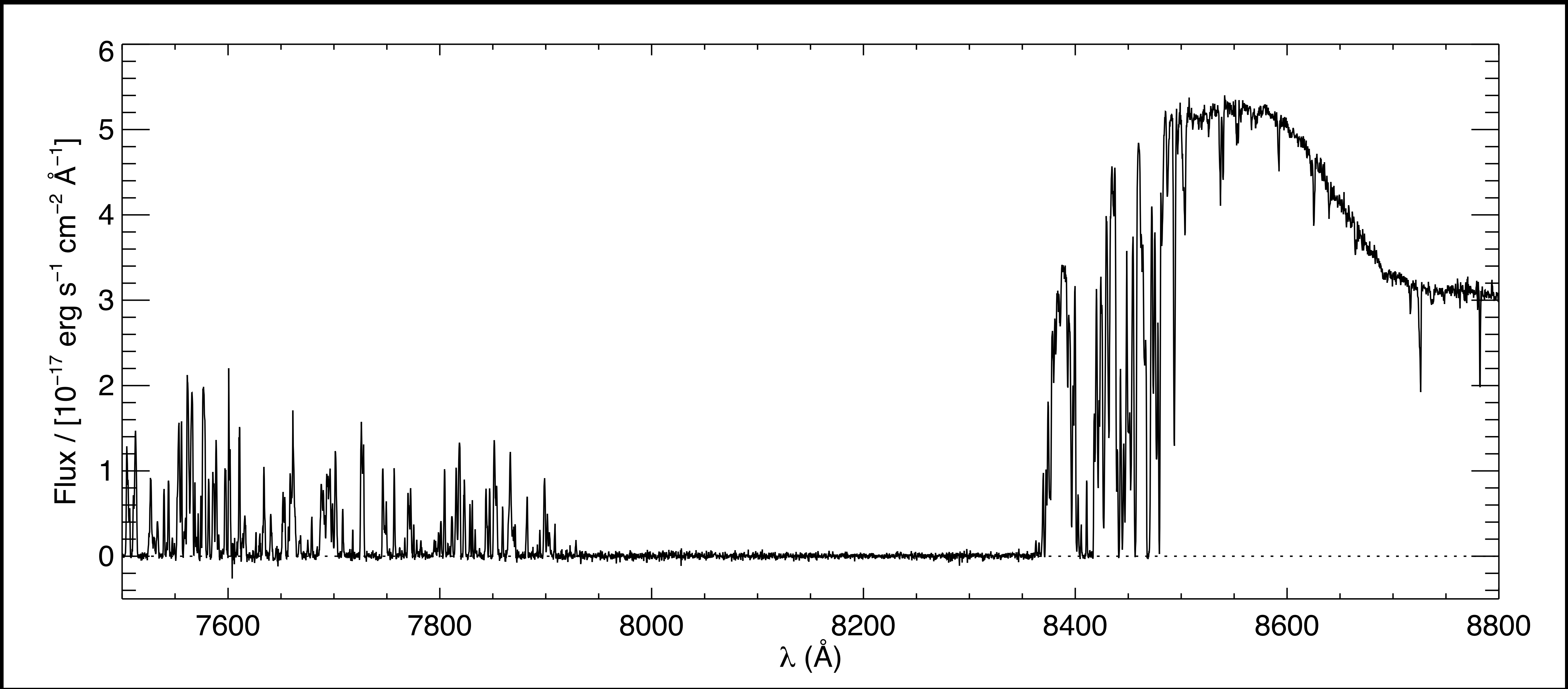
HAVE WE DETECTED PATCHY REIONIZATION IN QUASAR SPECTRA?

ADAM LIDZ,[1] S. PENG OH,[2] AND STEVEN R. FURLANETTO[3]

Received 2005 December 15; accepted 2006 January 26; published 2006 February 14

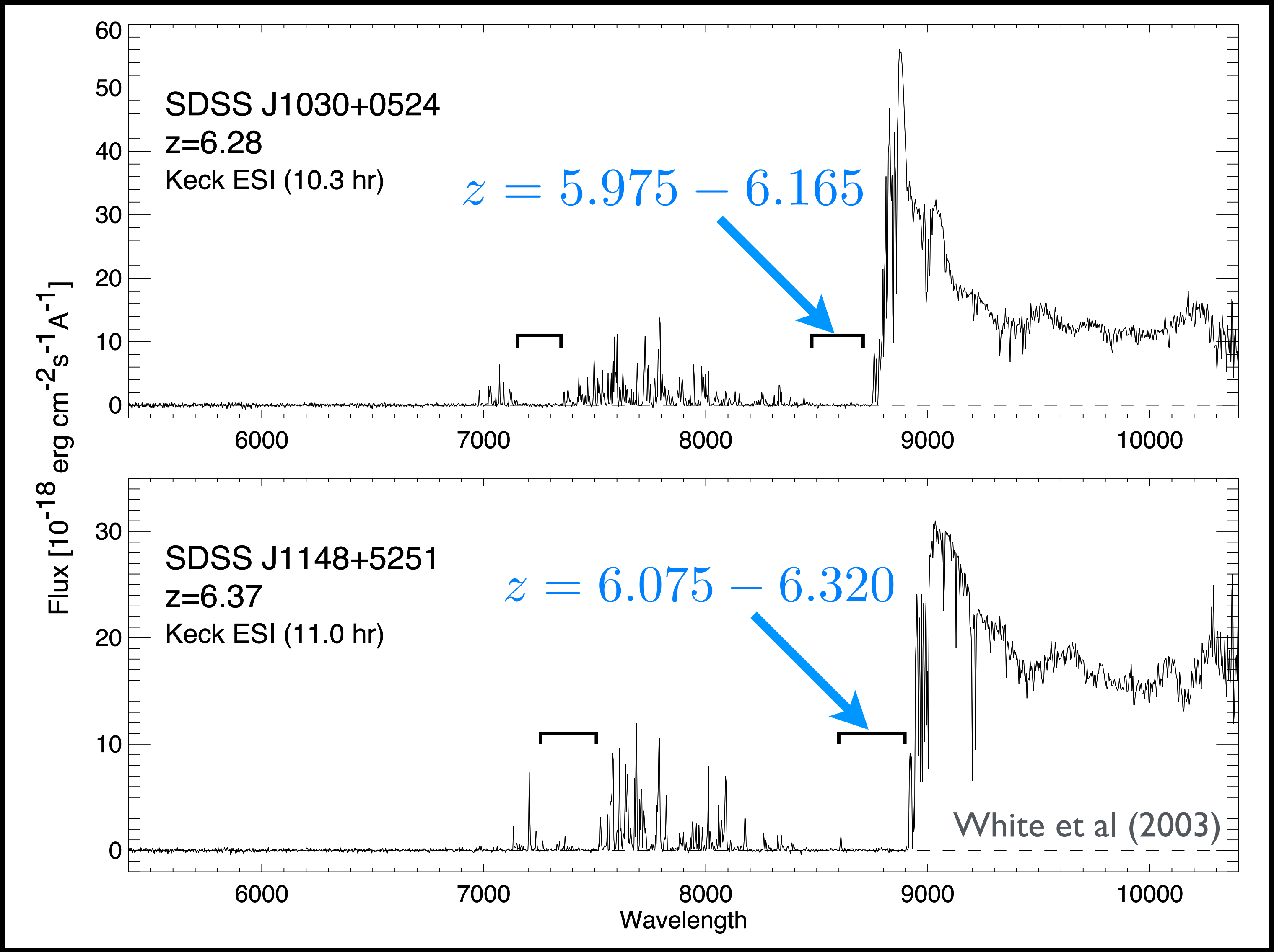
ULAS J0148+0600

$z_{em} = 5.98$

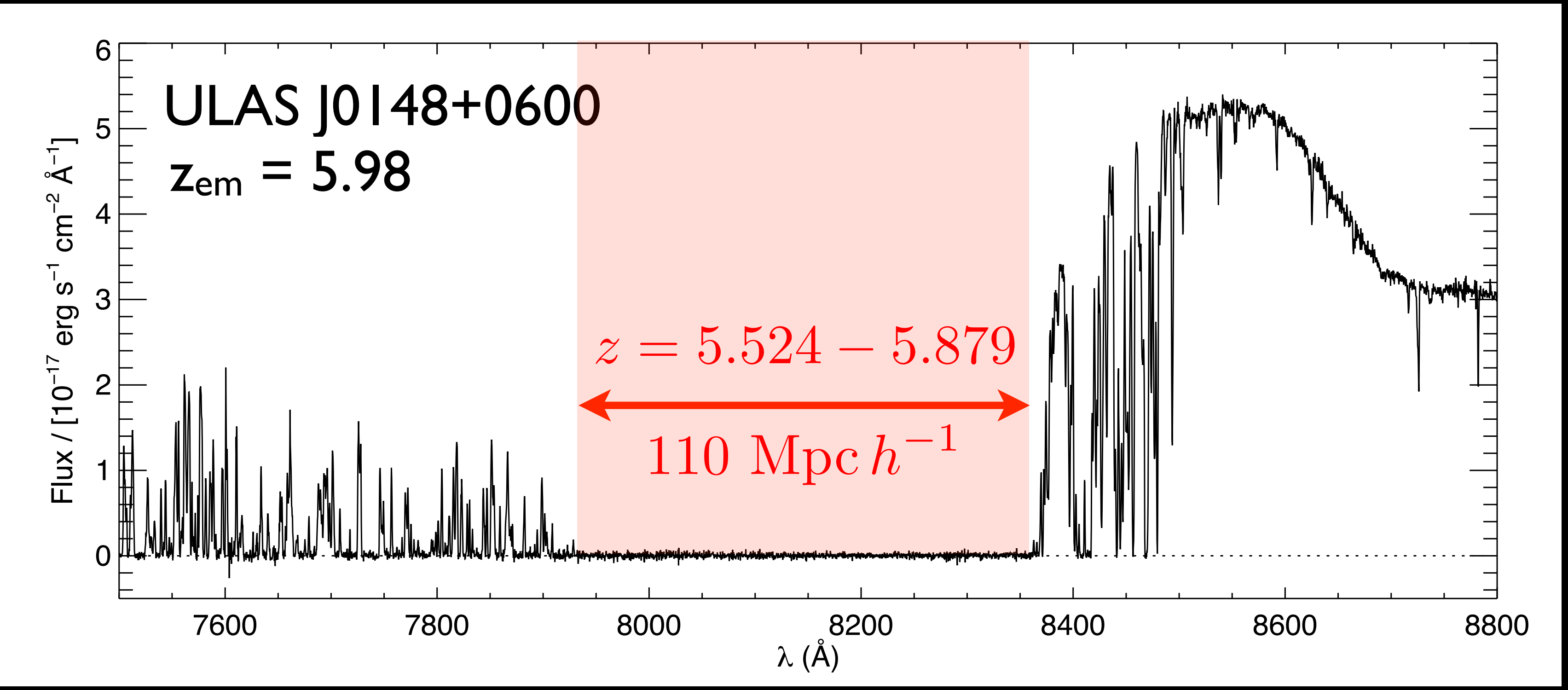


10 hr VLT/X-Shooter Spectrum

Compared to other Lyα troughs…

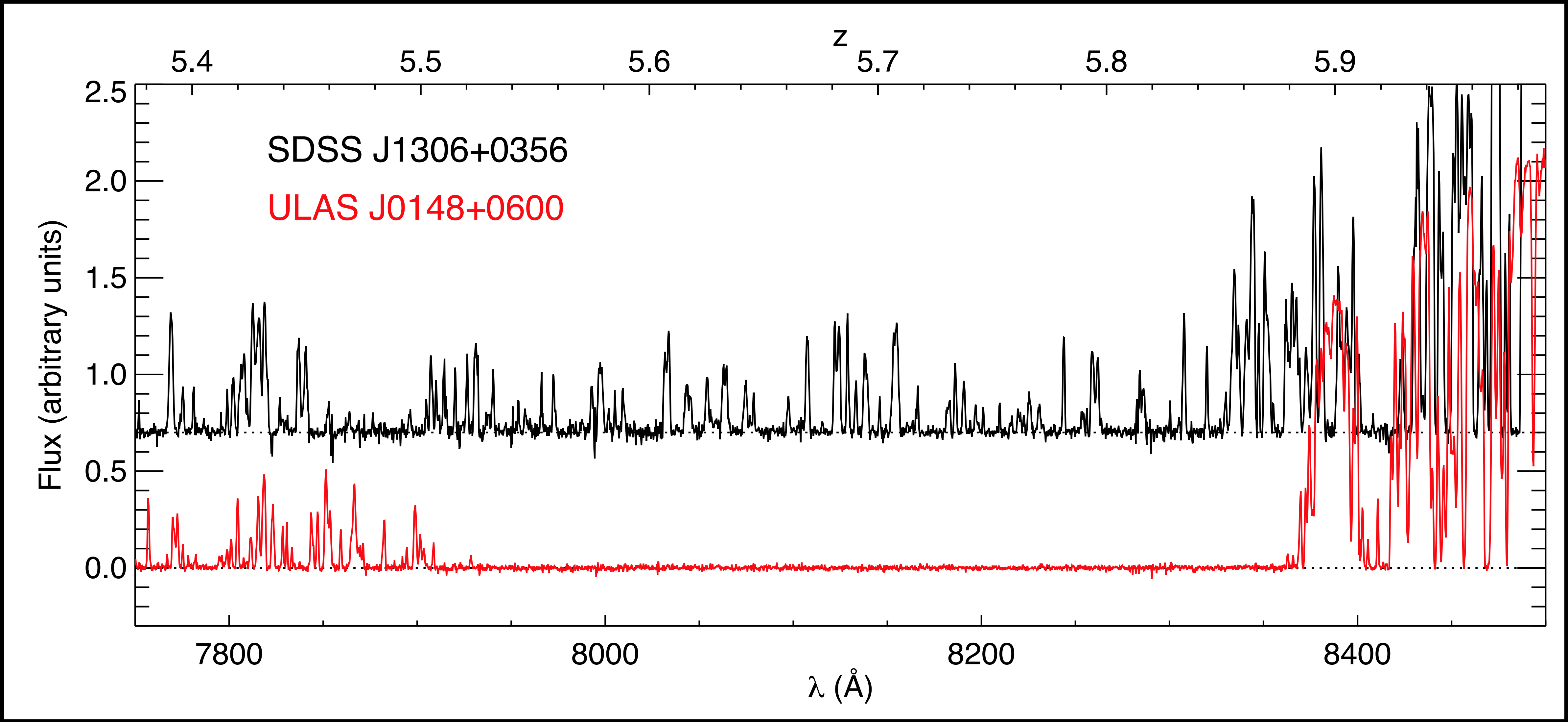


ULAS J0148 trough is longer and at substantially lower redshifts.



Becker+2015

How can these live in the same universe?



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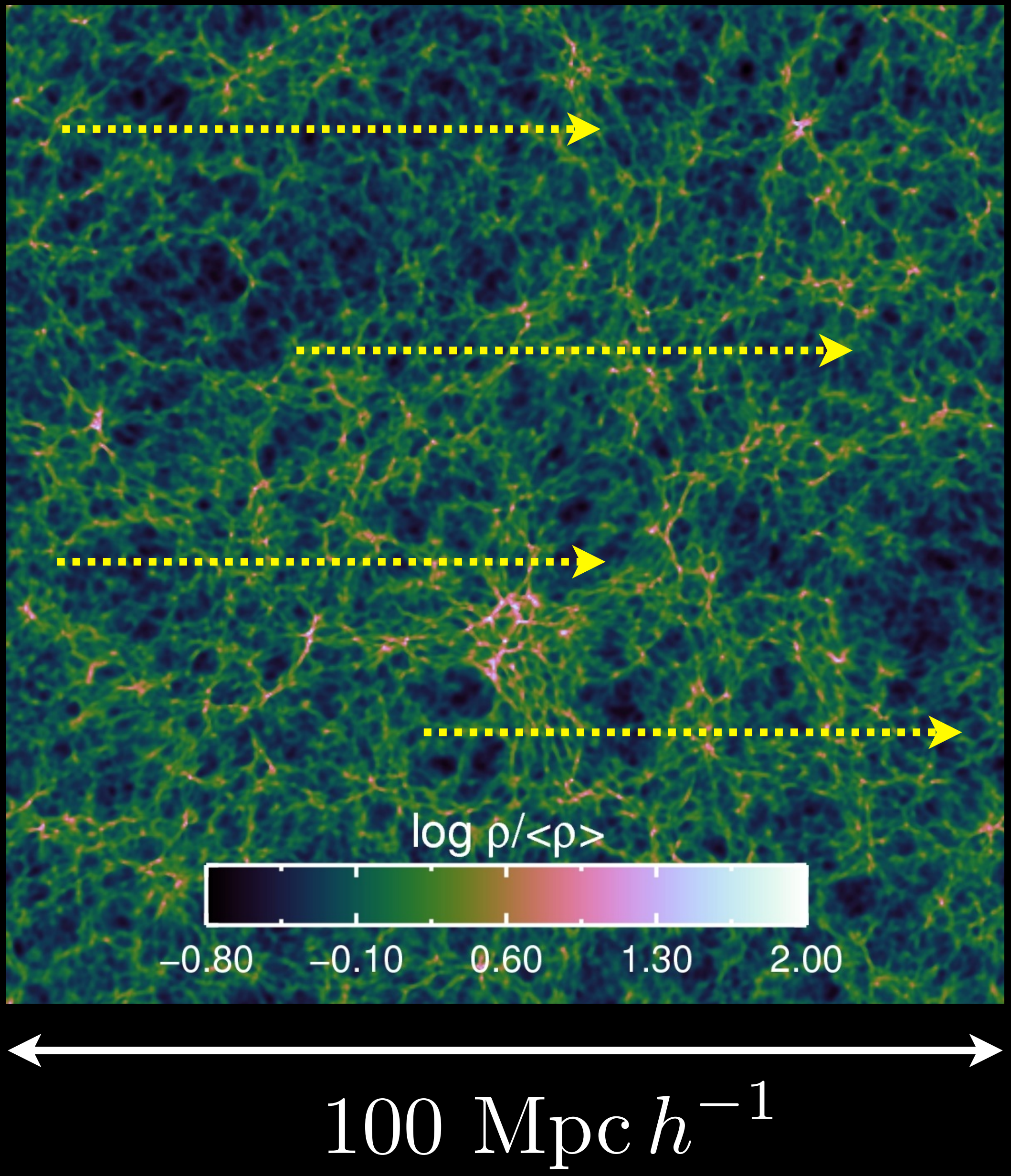
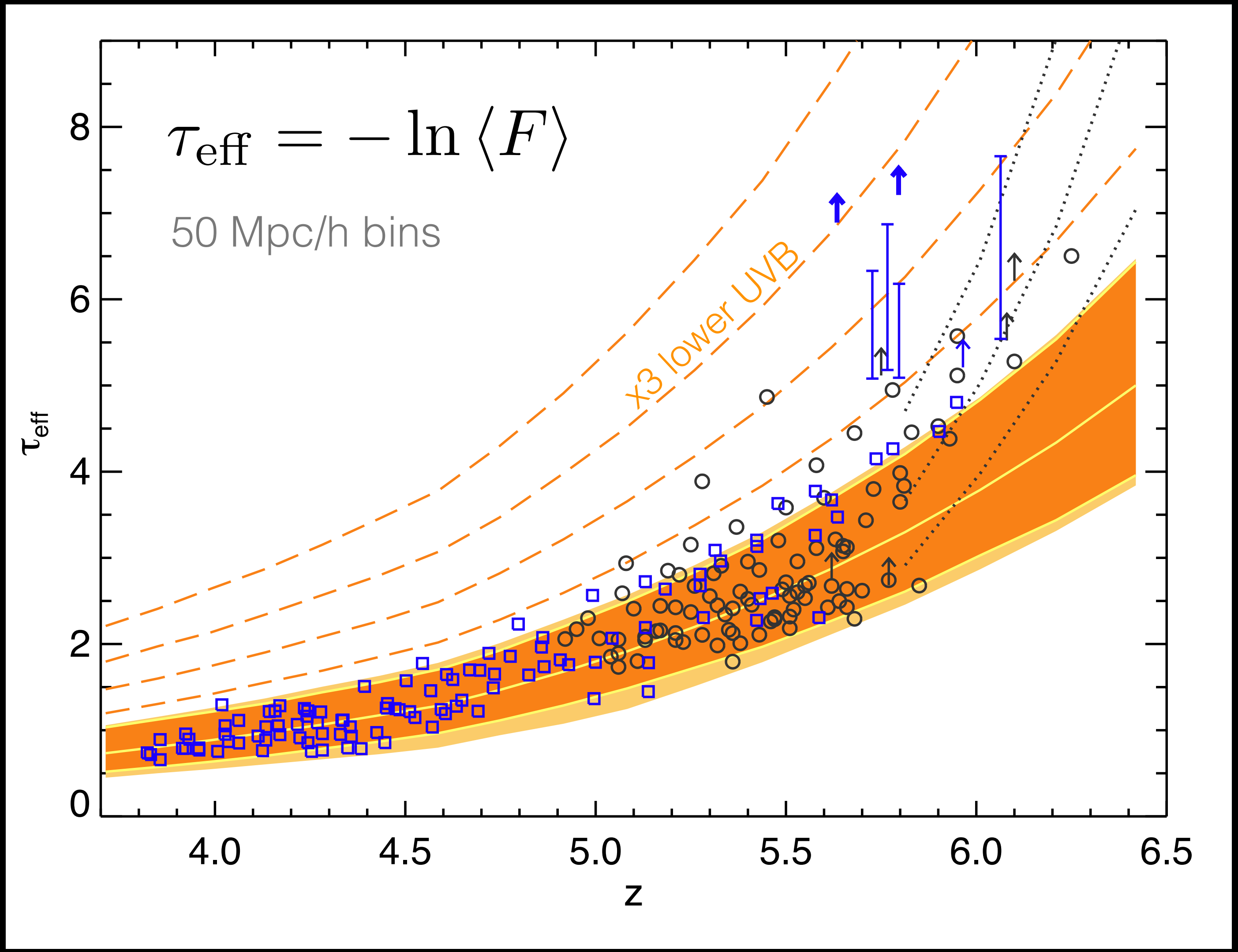
The problem: Assumption of a uniform UVB



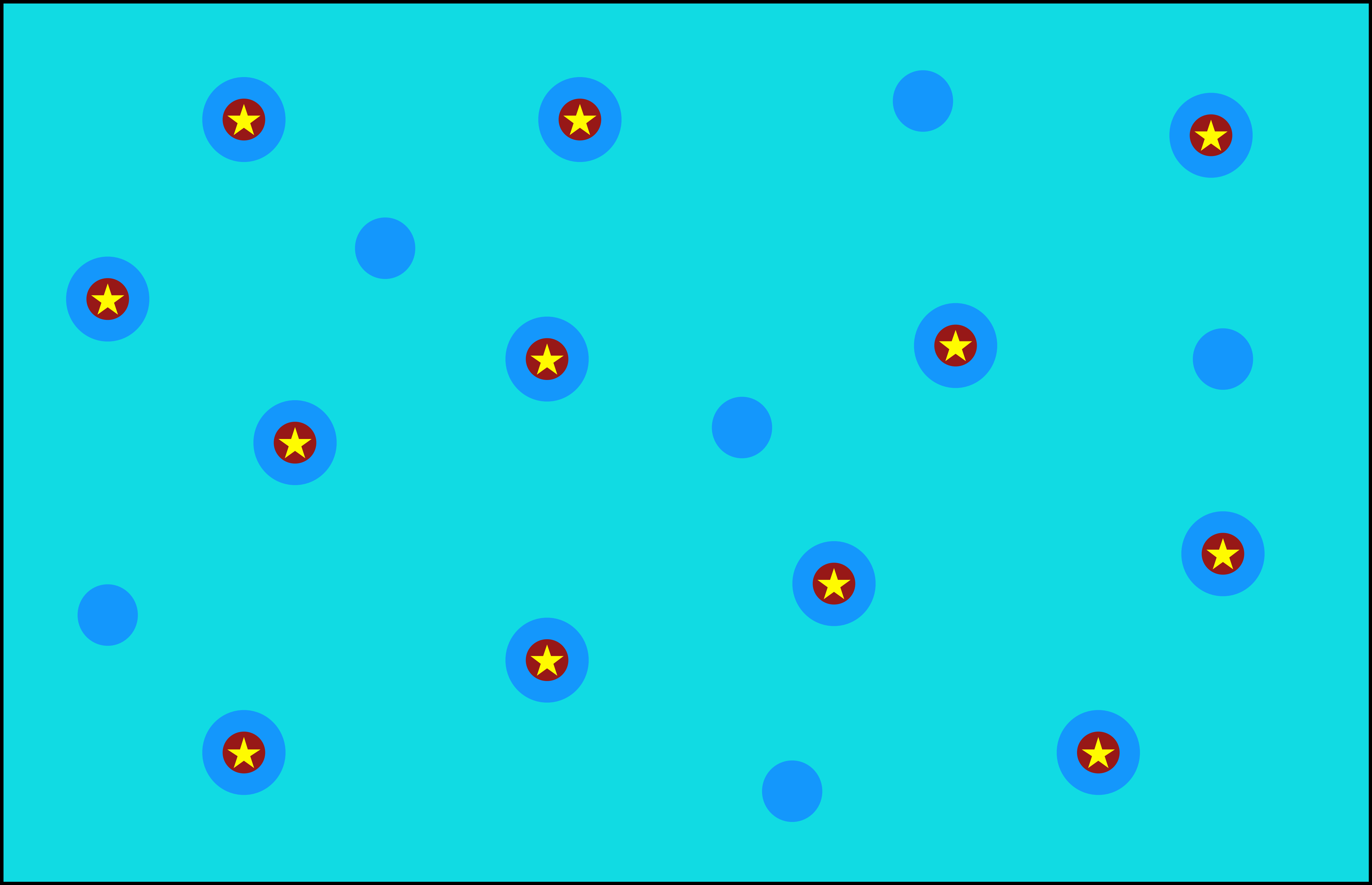
Lyα forest opacities



Uniform UVB does not reproduce observed IGM Lya opacities at z > 5

Becker+2015

“Post-Overlap” phase of Reionization



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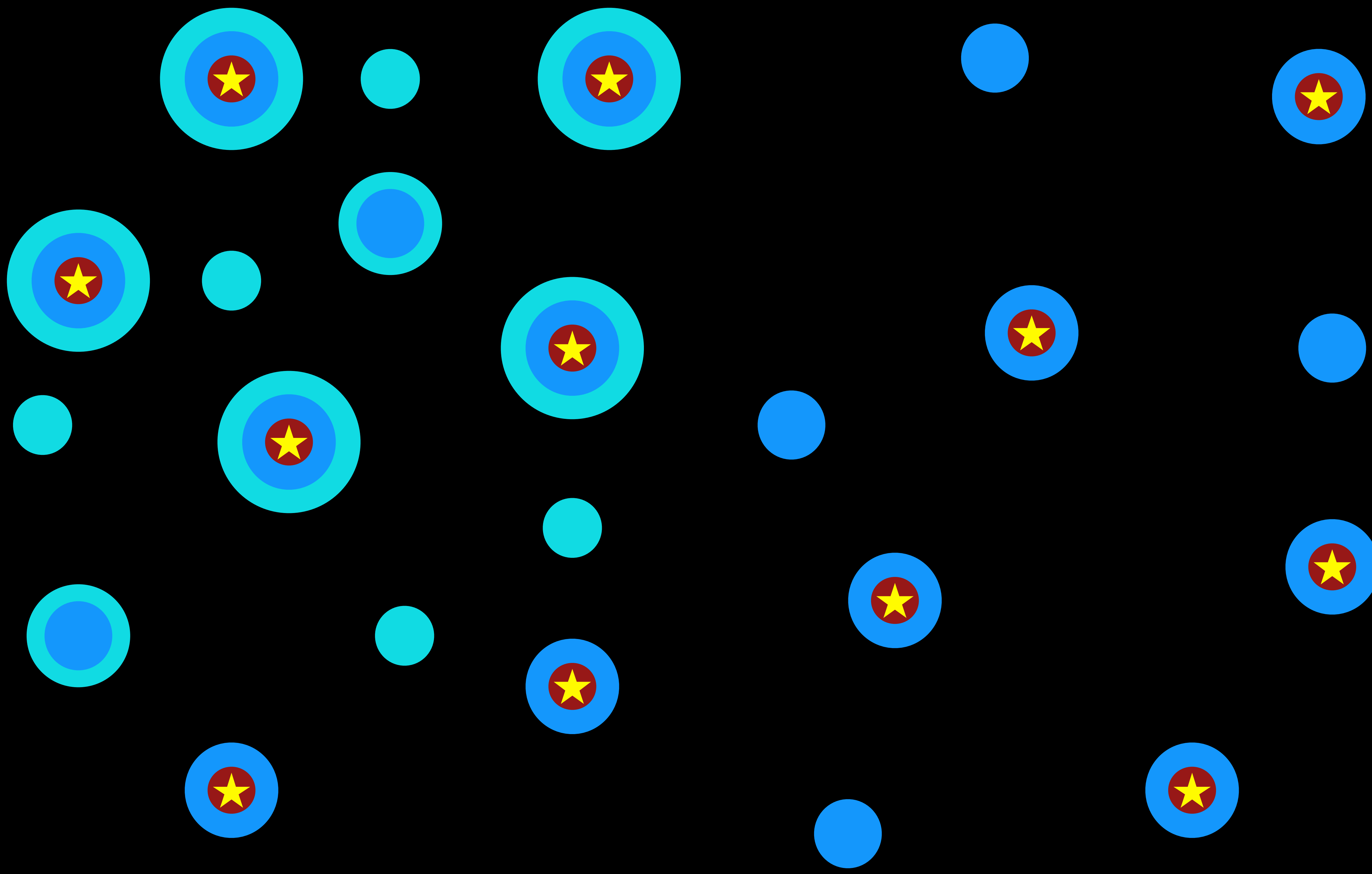
“Post-Overlap” phase of Reionization



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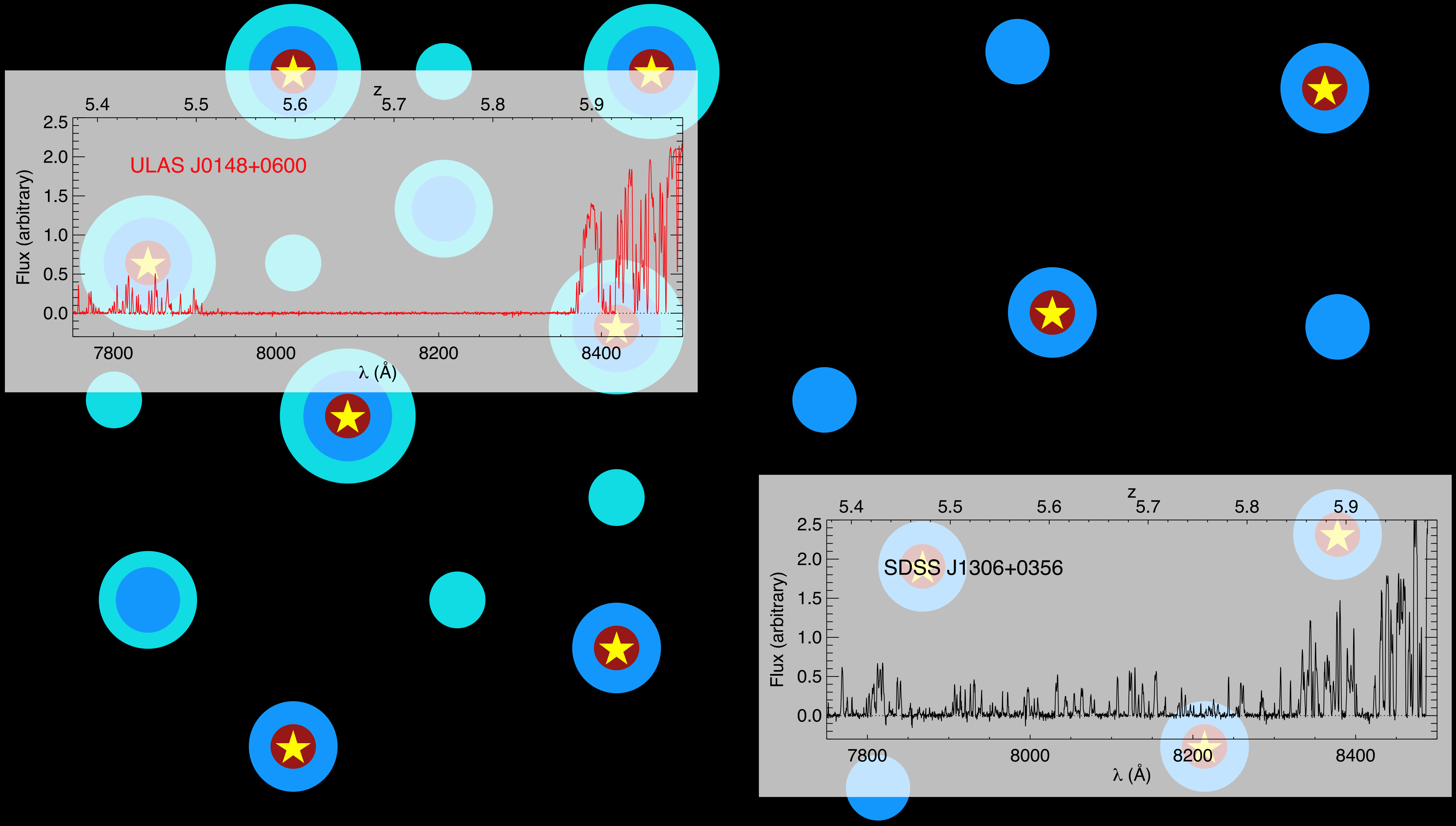
"Post-Overlap" phase of Reionization



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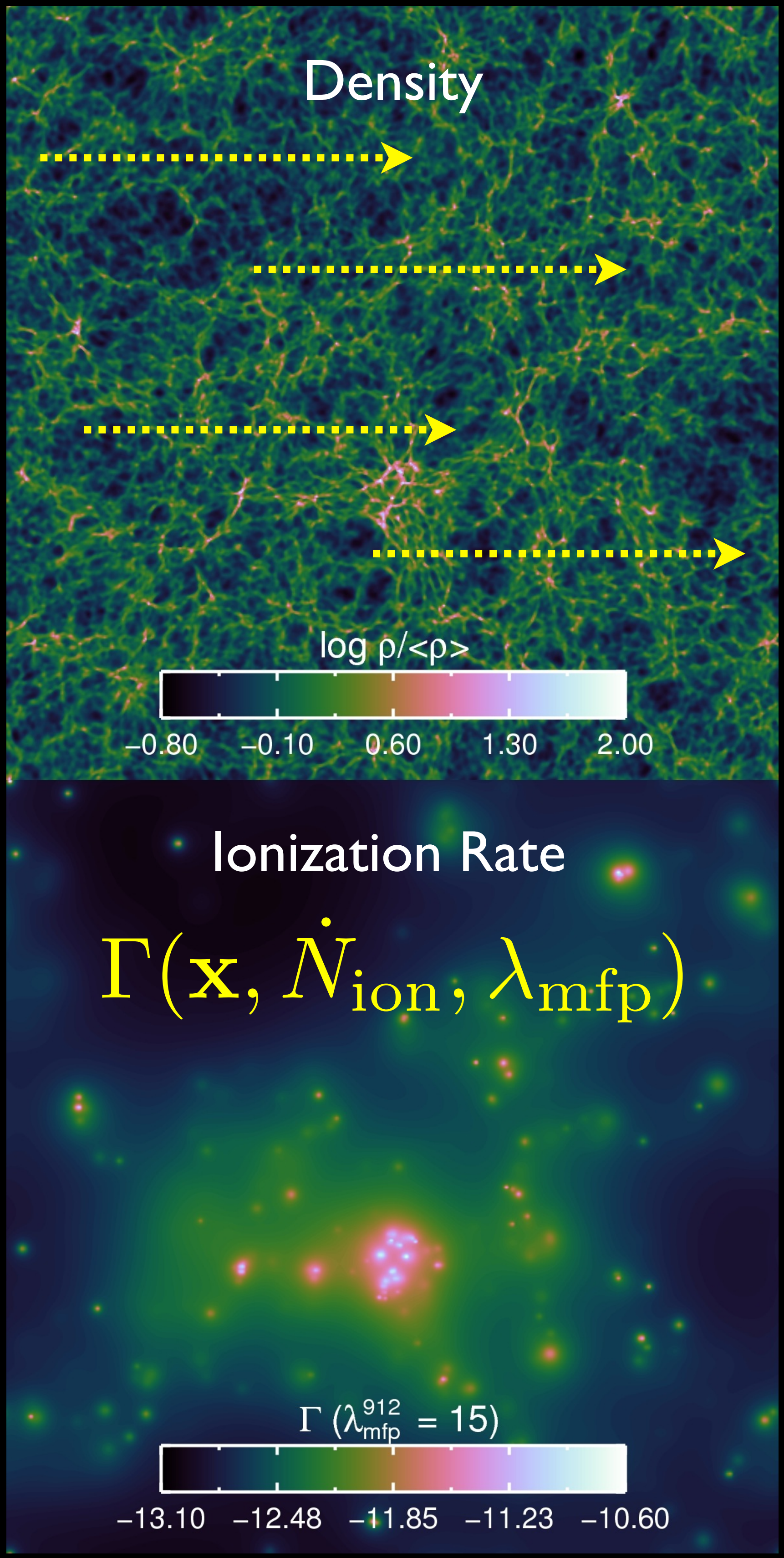
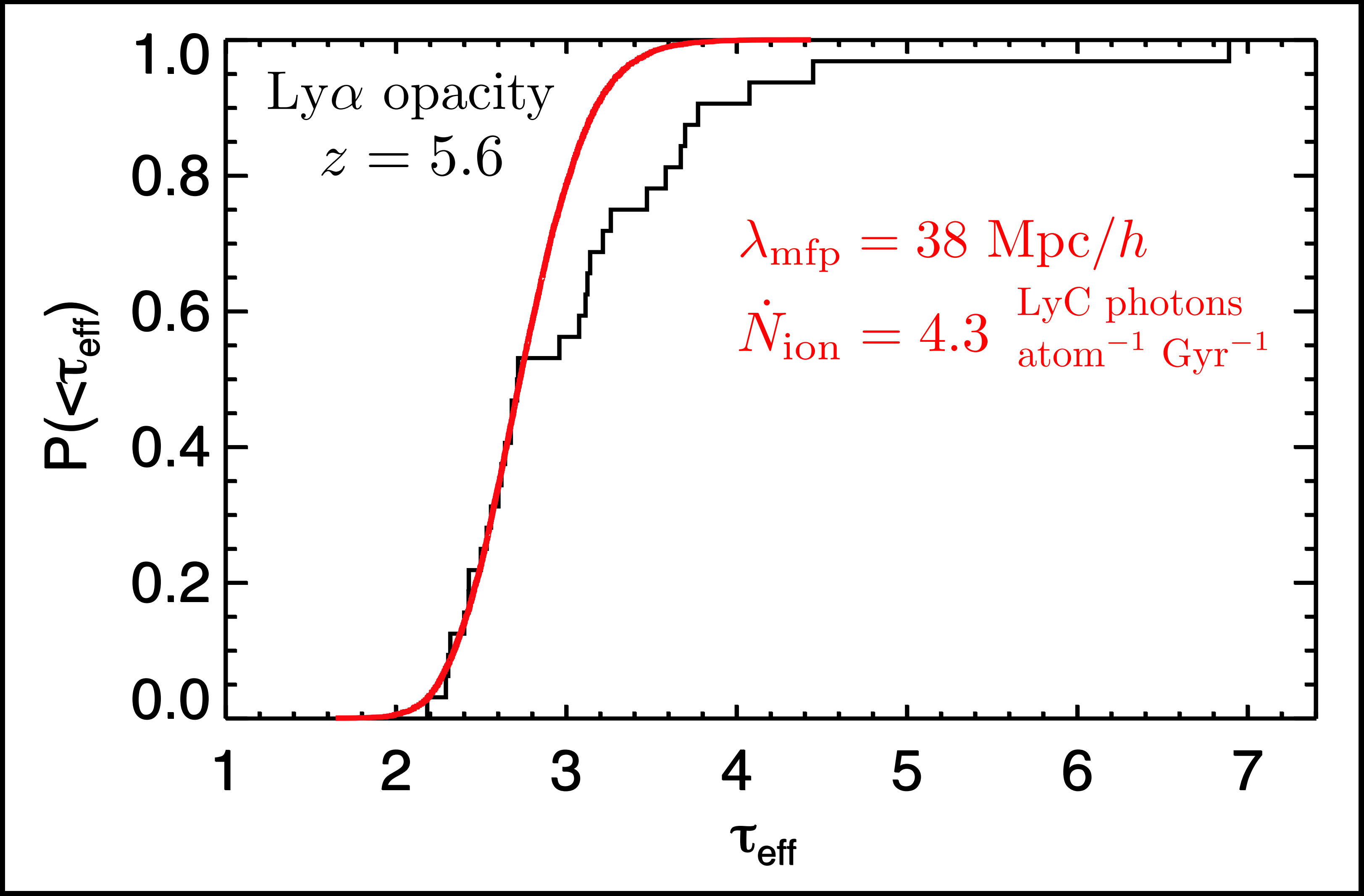
Galaxy UV background



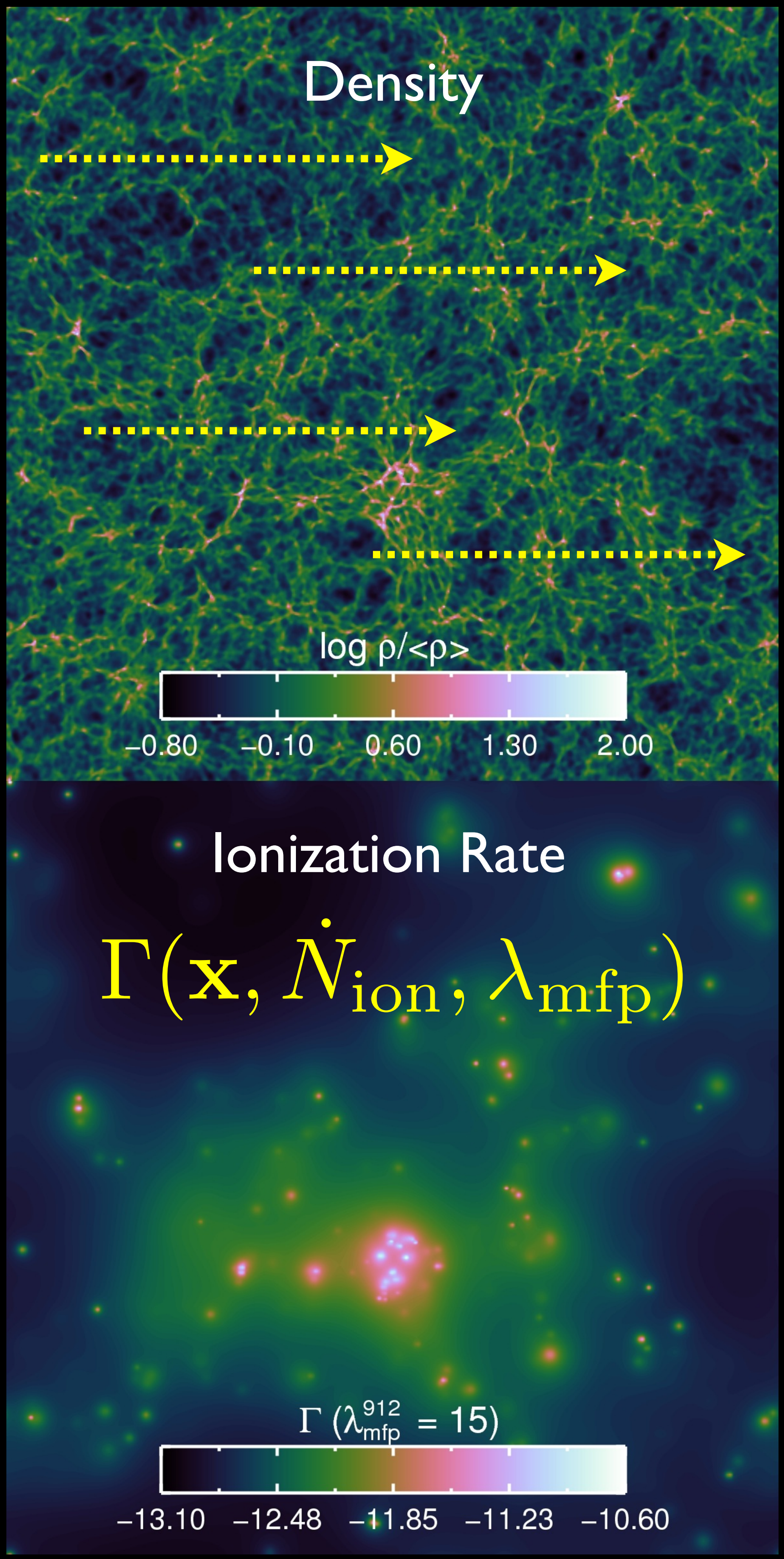


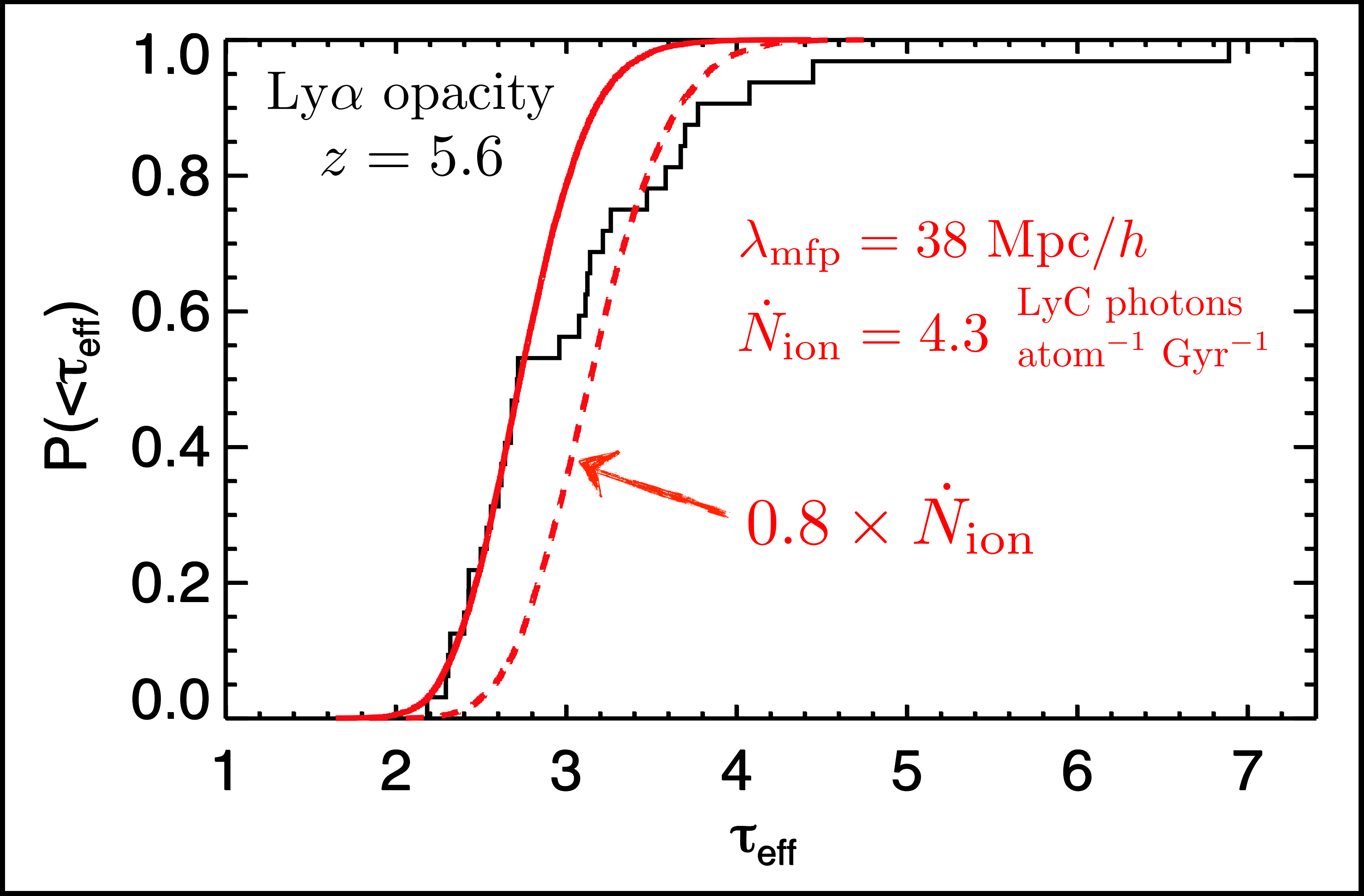
$$\tau_{\rm eff} = -\ln \langle F \rangle$$

50 Mpc/h regions

Becker & Bolton, in prep

Galaxy UV background





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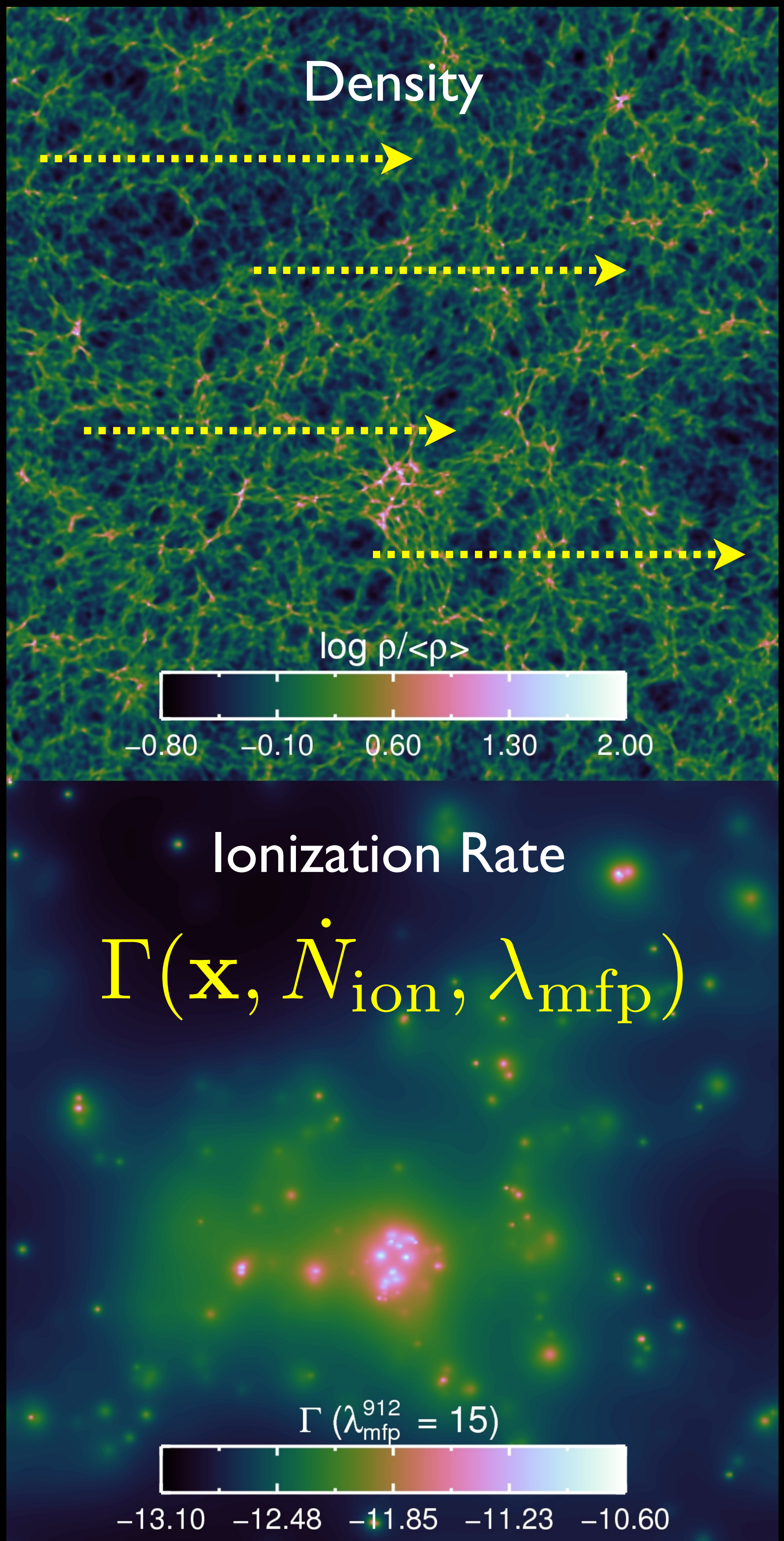
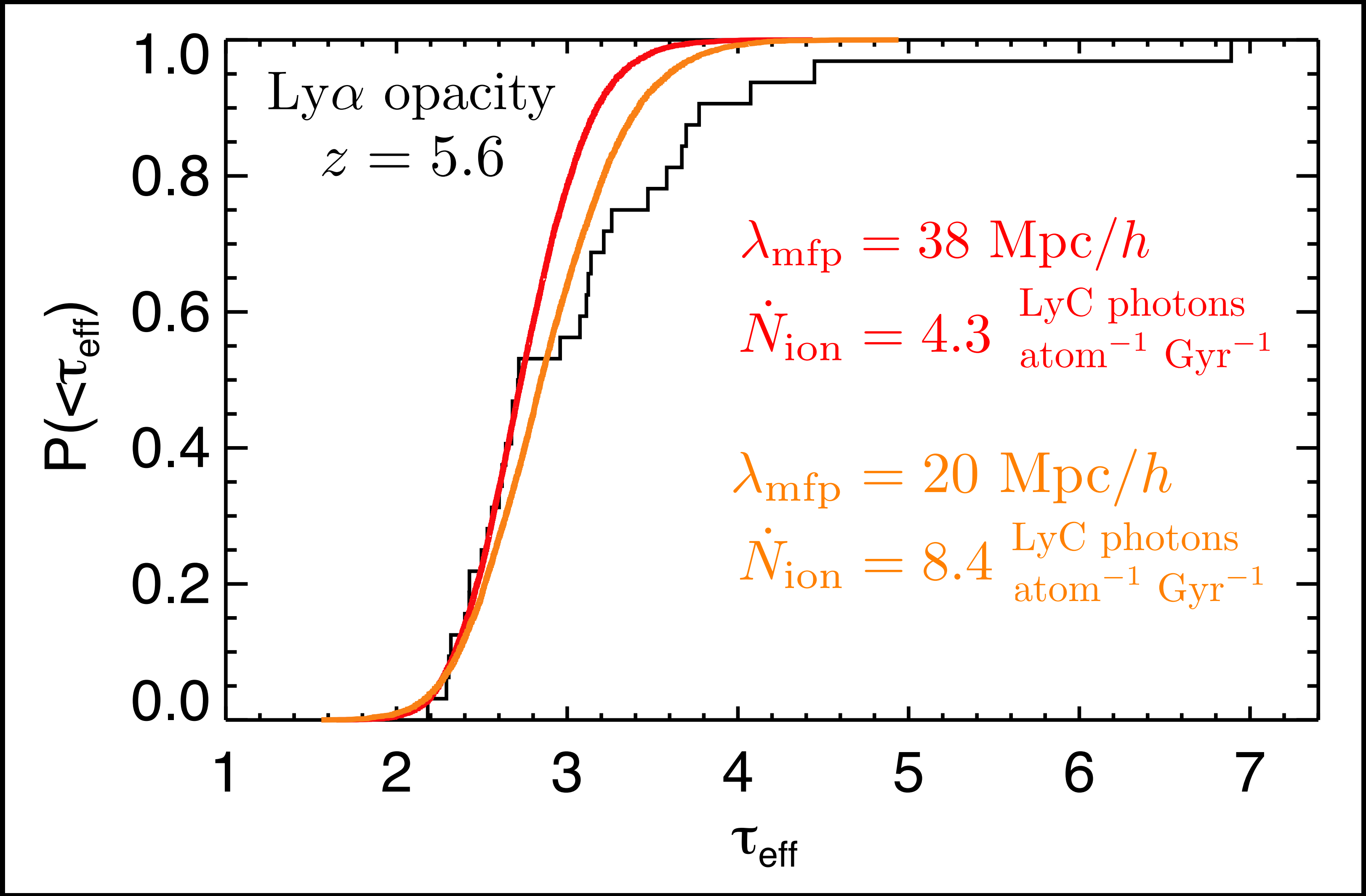
Galaxy UV background





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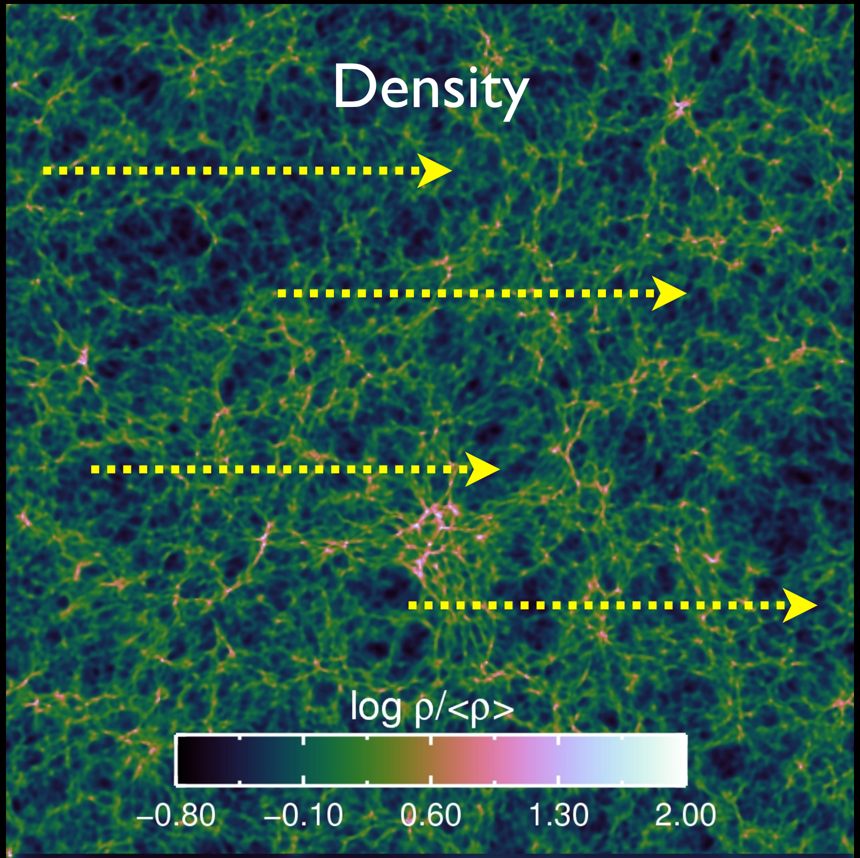

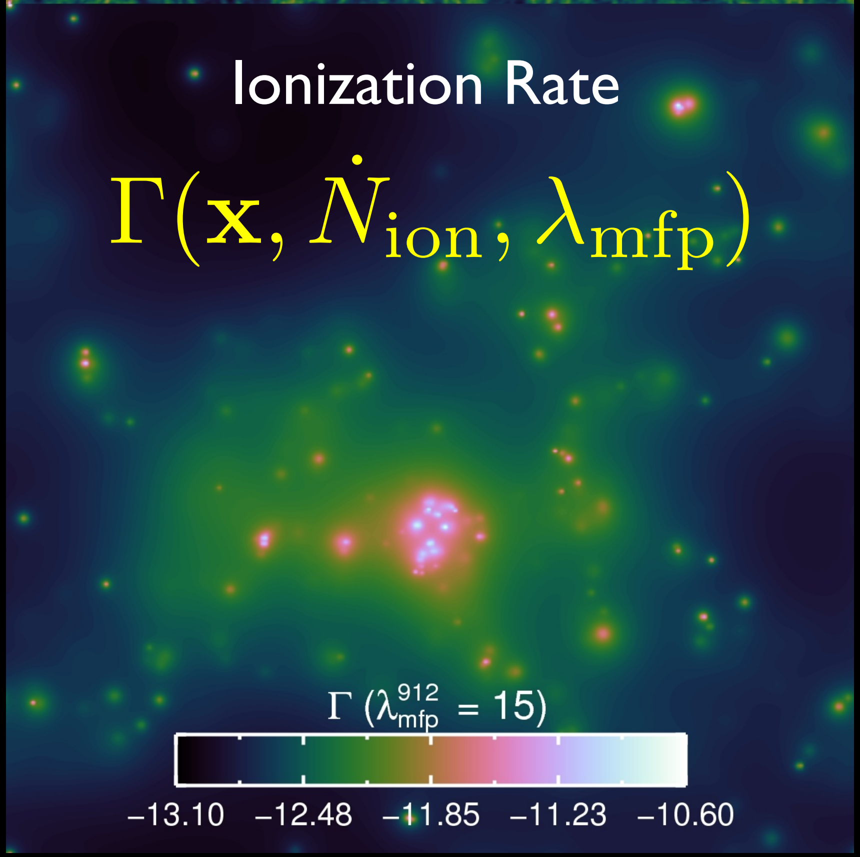

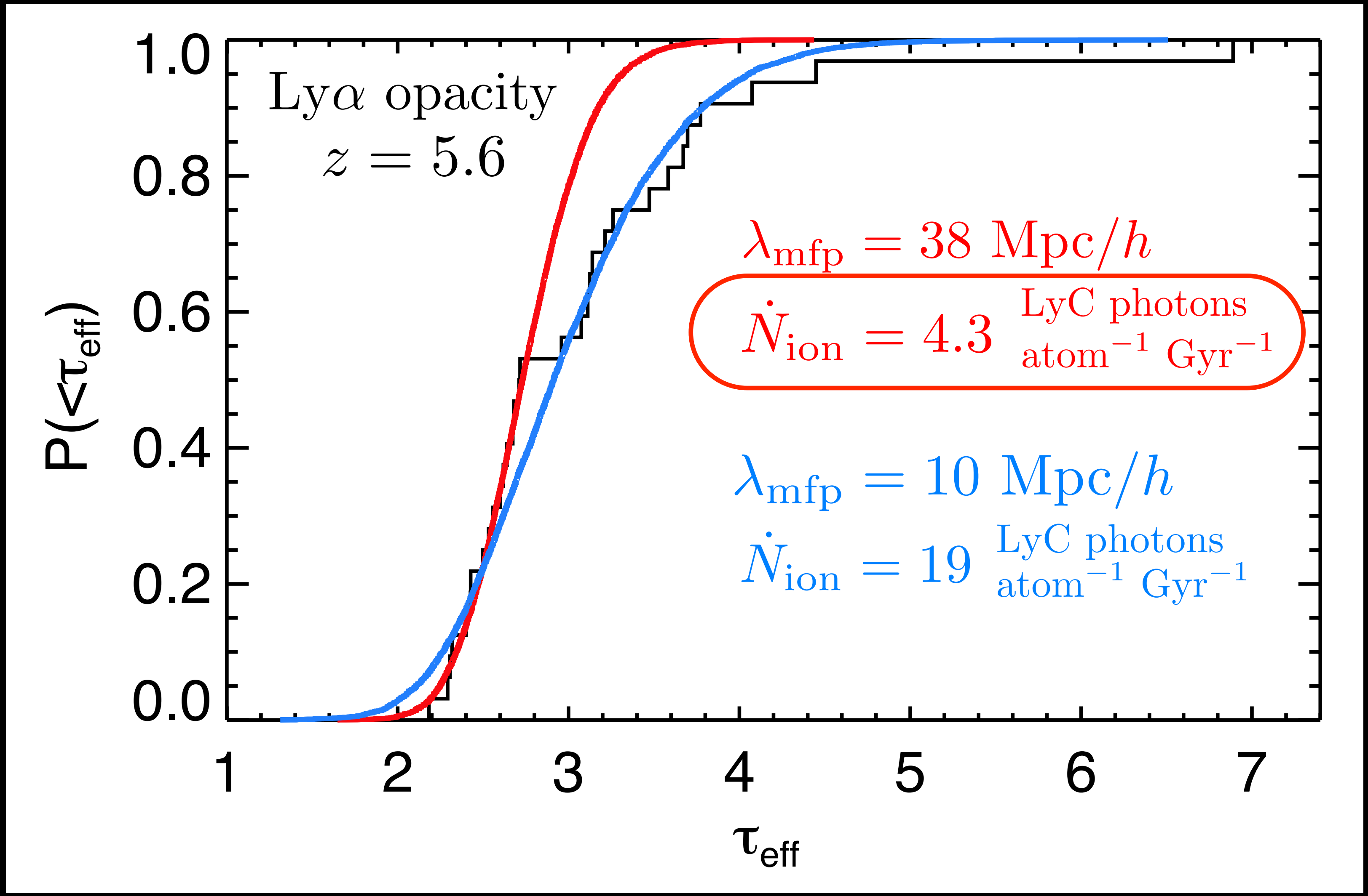

$\tau_{\rm eff} = -\ln \langle F \rangle$

50 Mpc/h regions

Becker & Bolton, in prep

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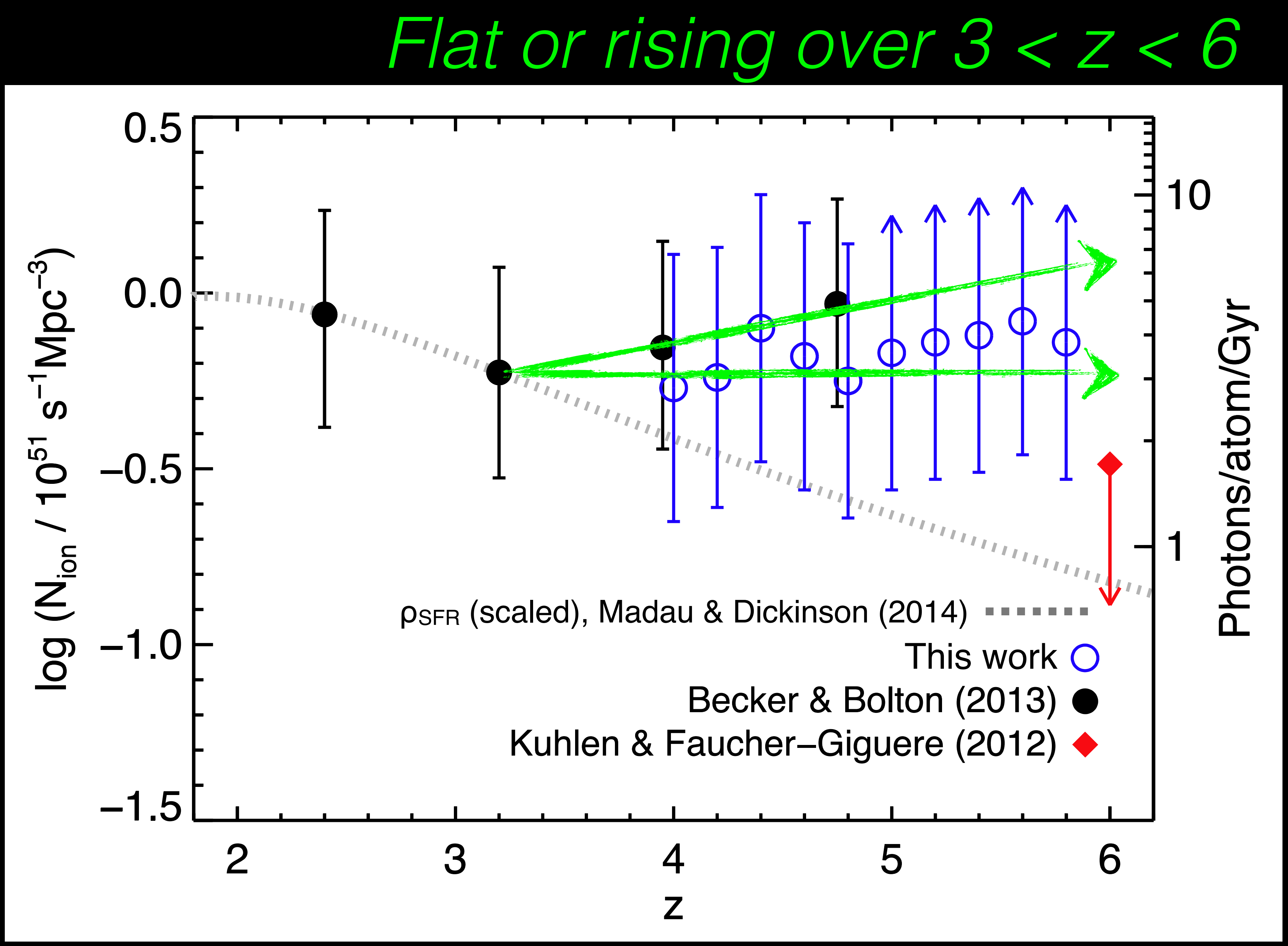
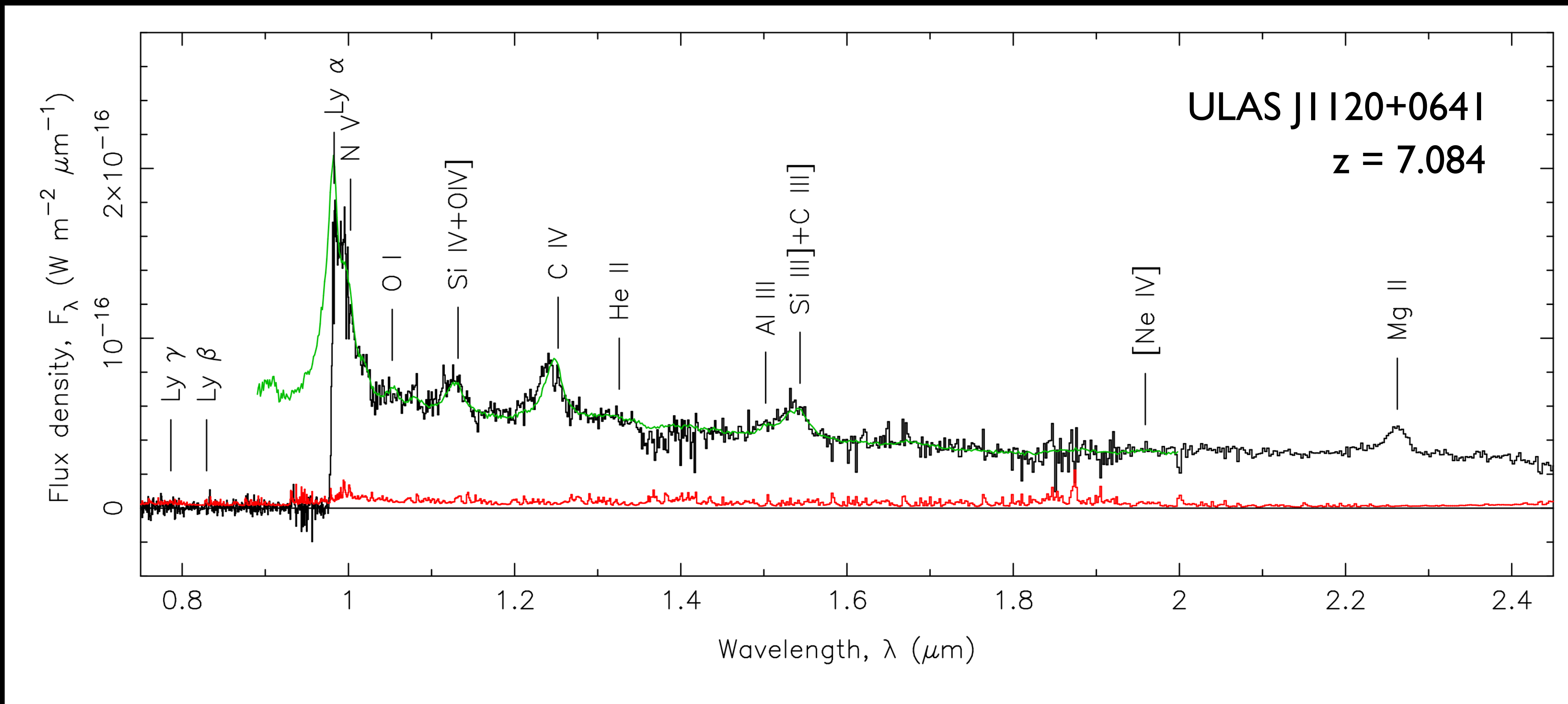
Ionizing Emissivity



1. Abundant photons for reionization.
2. Galaxy ionizing efficiency ($f_{esc}*\xi_{ion}$) must increase with redshift

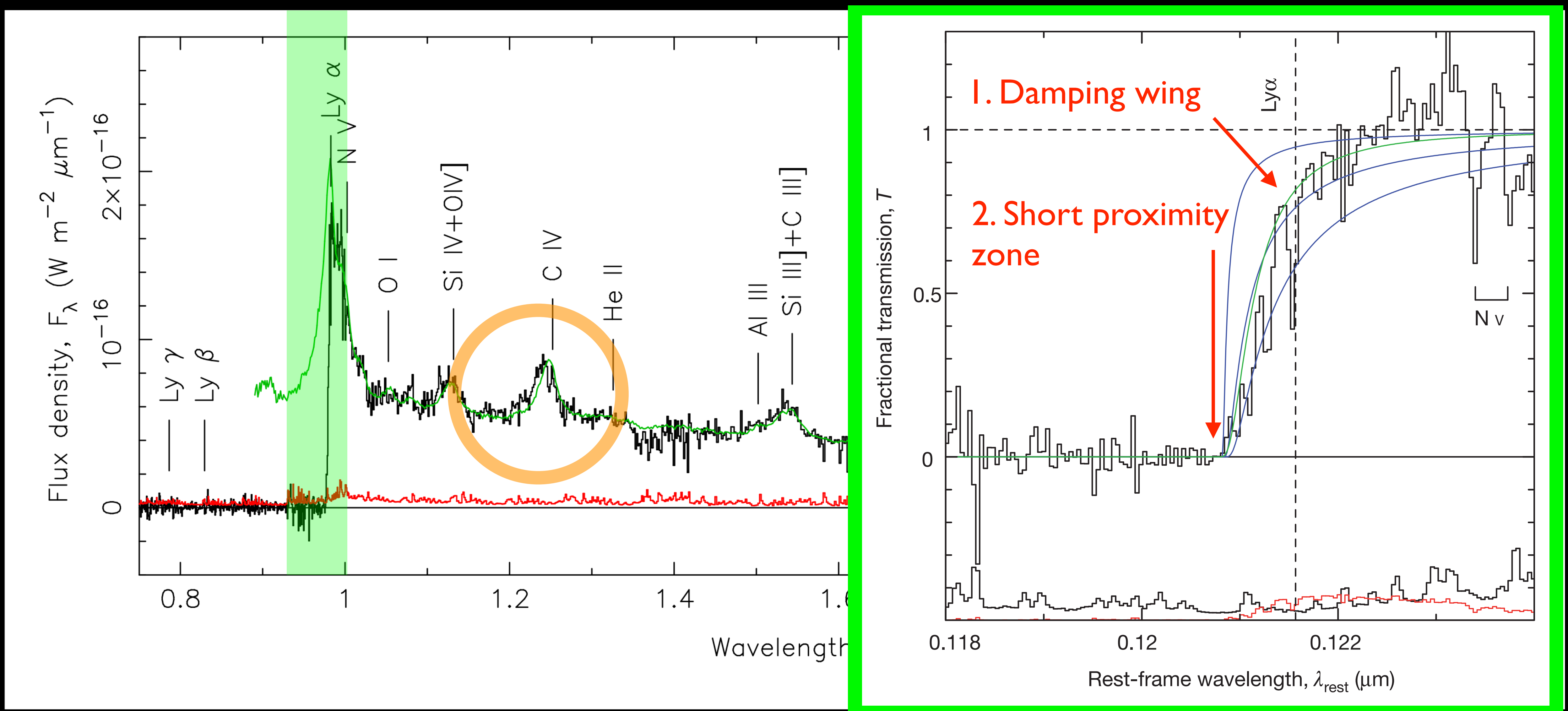
Becker & Bolton, in prep

Constraints from z~7 quasar?



Proximity zone suggests >10% neutral IGM (Mortlock+2011, Bolton+2011)

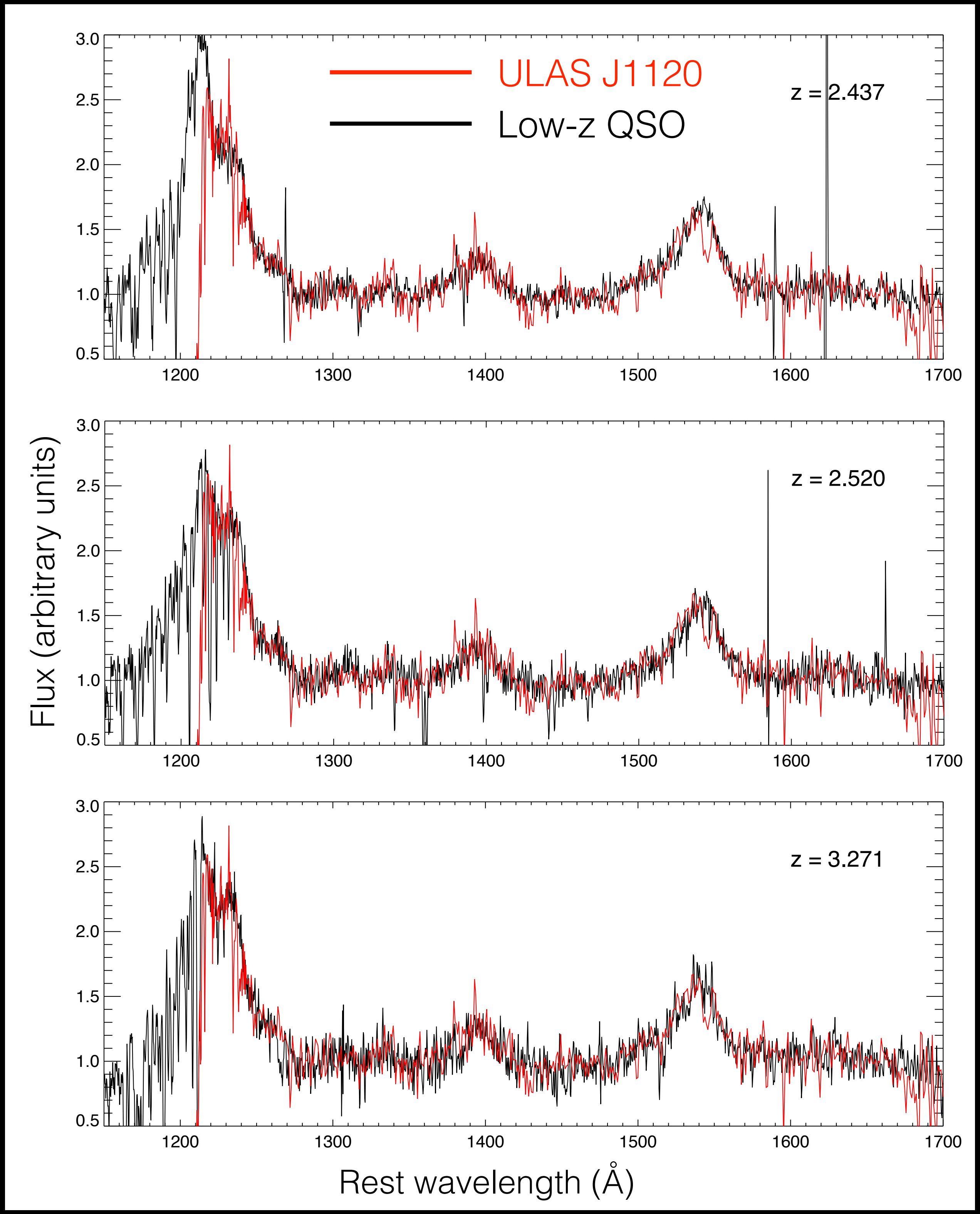
Constraints from z~7 quasar?



Proximity zone suggests >10% neutral IGM (Mortlock+2011, Bolton+2011)

Reasons to be skeptical…

z~7 Damping Wing?

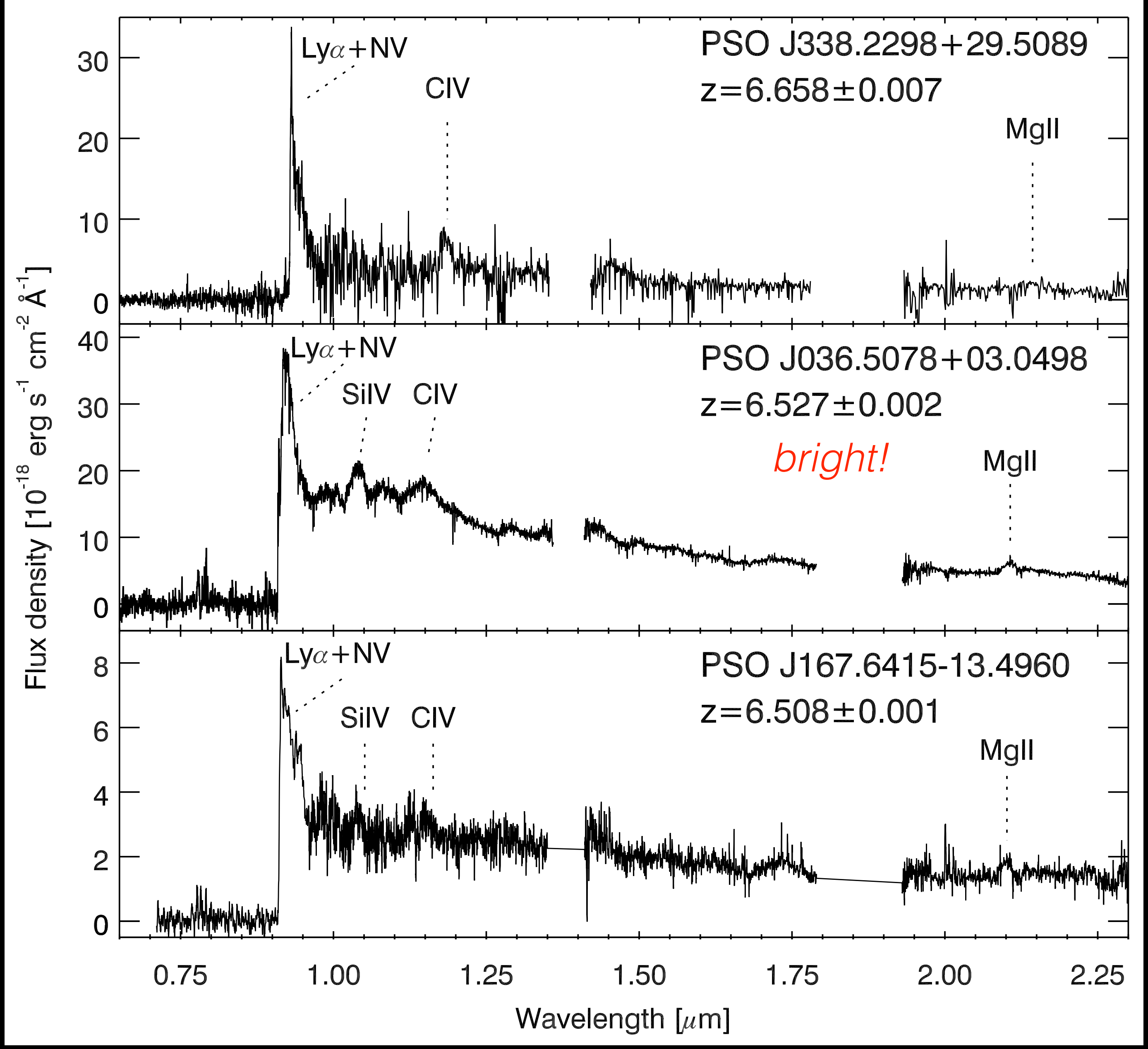


- Among objects that match in C IV, ULAS J1120 is not a strong outlier
- Easy to find similar lower-redshift objects *without damping wings*
- No need for neutral IGM

Bosman & Becker, submitted

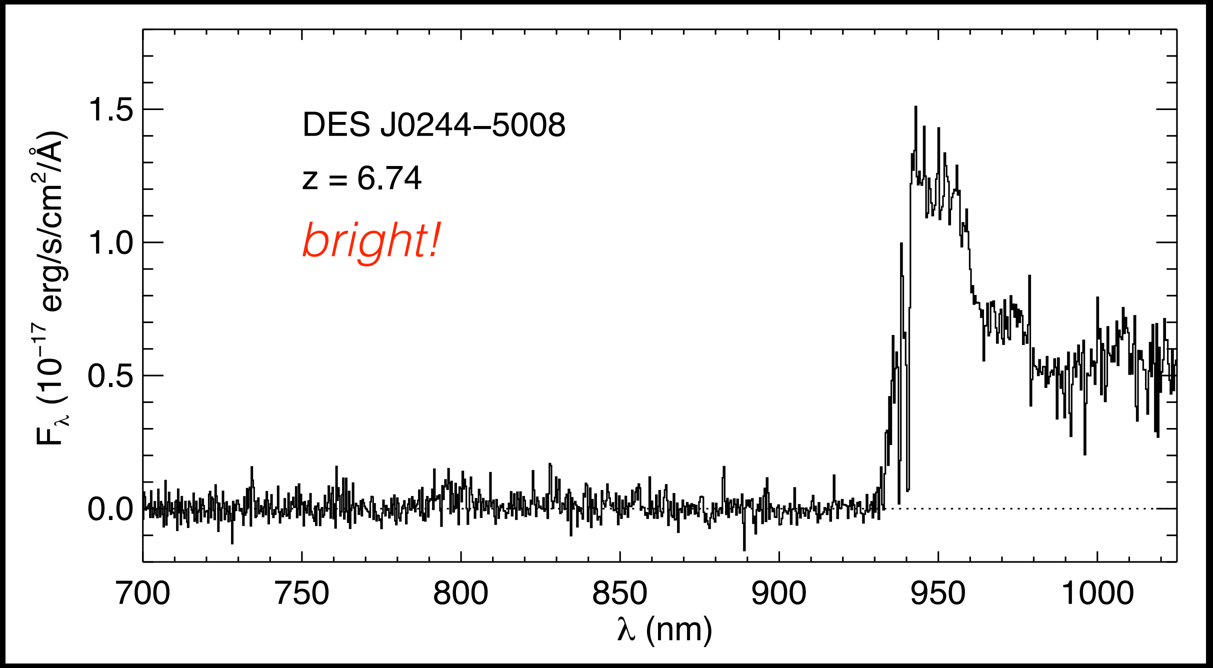
New z > 6.5 quasars!

Pan-STARRS



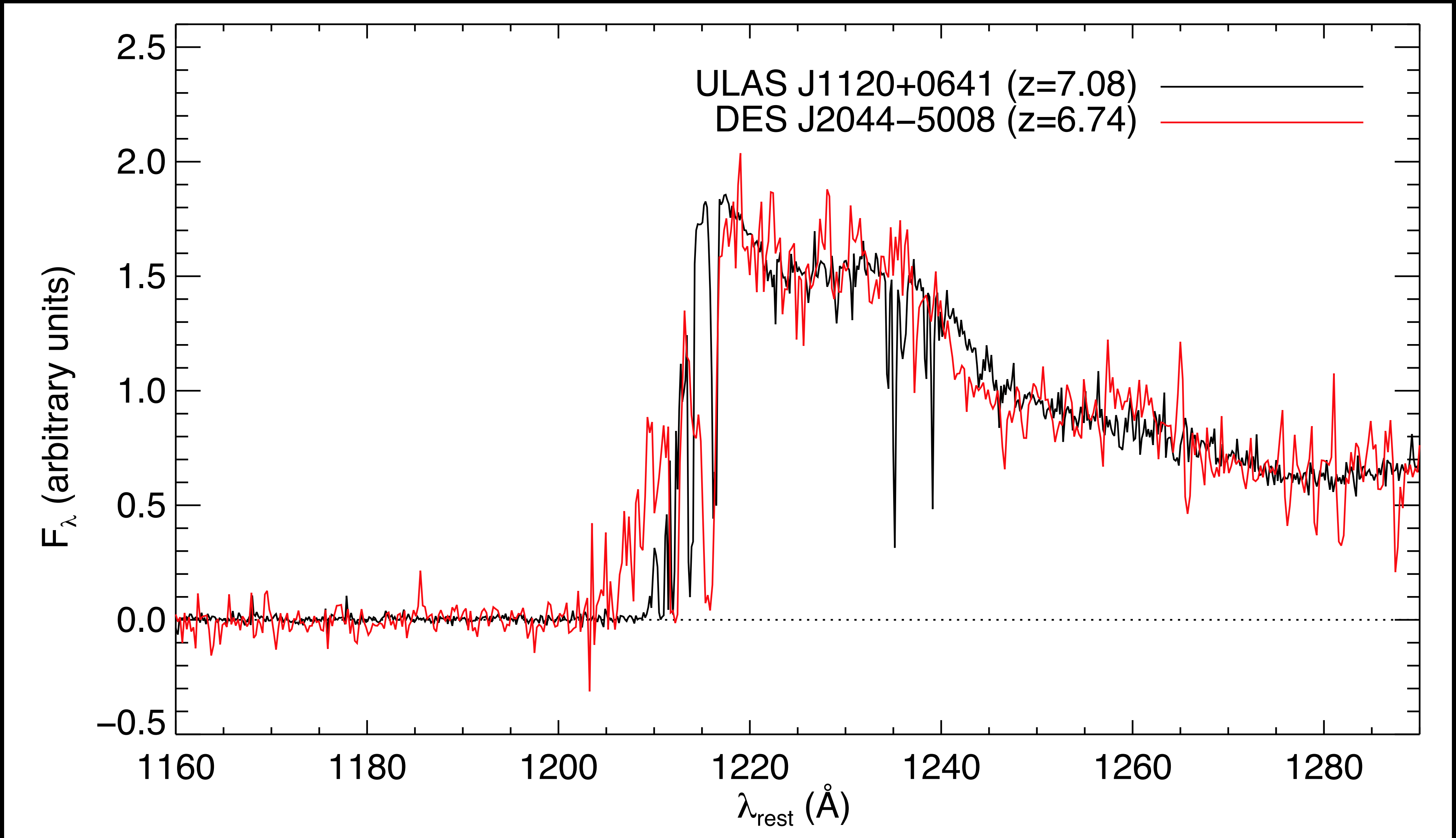
Venemans+2015

DES+VISTA



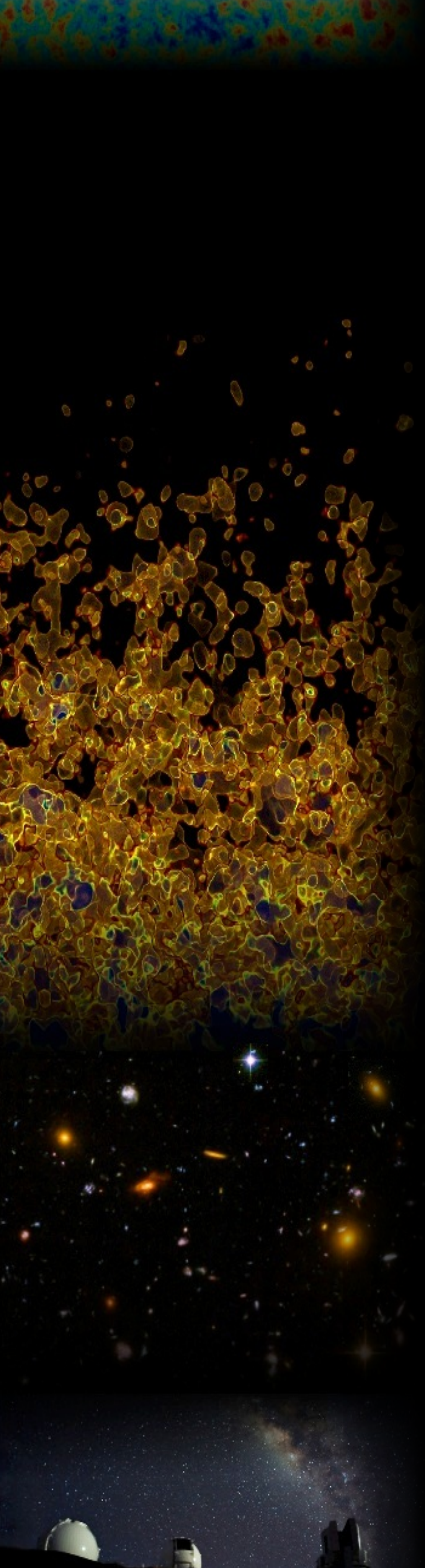
George Becker 3.10.15

The latest DES quasar



More extended proximity zone than J1120, consistent with an ionized IGM near z~7.

George Becker 3.10.15



Summary

- Planck data suggest a somewhat later reionization than WMAP, but a consensus model remains elusive
- Ionizing emissivity remains flat or increases with redshift over $2 < z < 6$, even as global star formation rate declines — escape fractions, IMF may evolve
- Lyα forest shows evidence of large-scale UVB fluctuations near $z \sim 6$, consistent with patchy reionization
- Neutral fraction at $z \sim 7$ still unclear, but larger $z > 6.5$ quasar samples becoming available

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