Illuminating the Dark Ages, 28.06.16

Exploring reionisation with Lyman-α absorption

Jamie Bolton

With thanks to:
George Becker (UC Riverside), **Fahad Nasir** (Nottingham)

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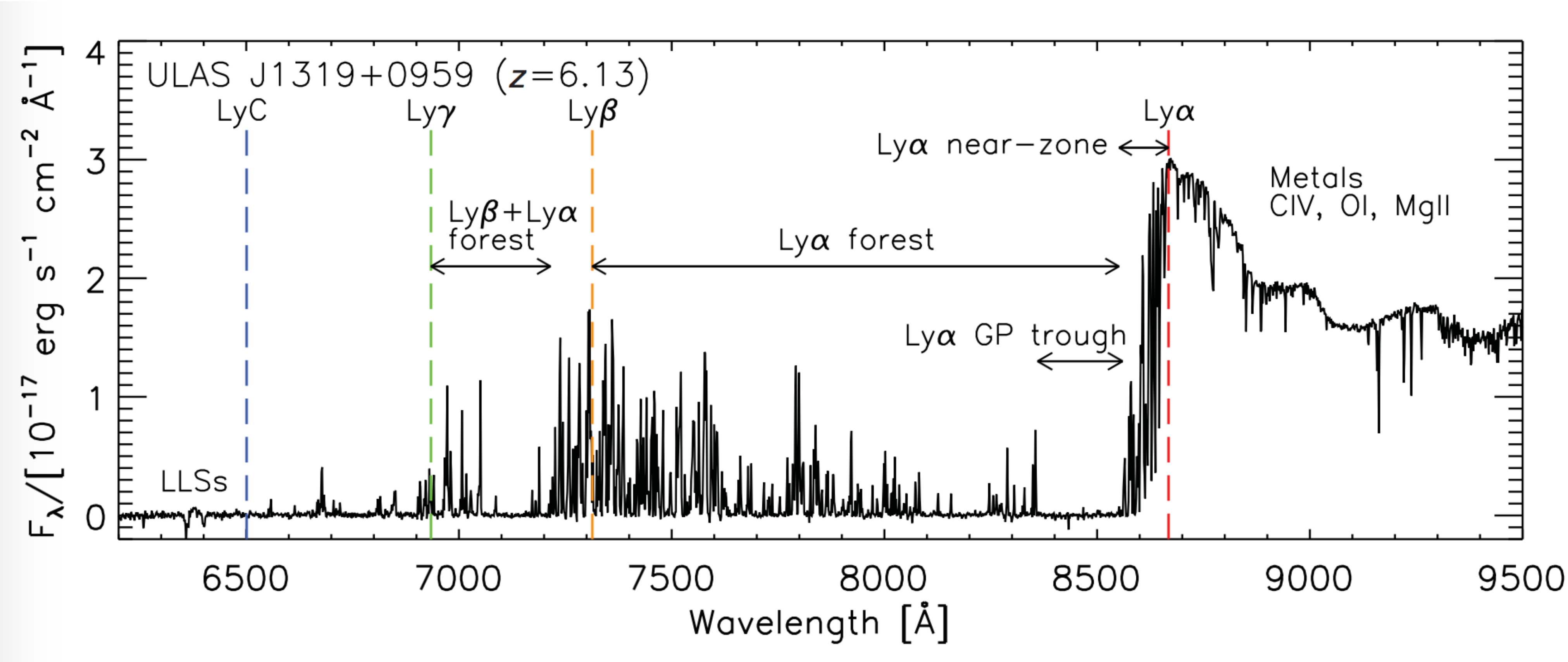
Anatomy of a z~6 quasar spectrum

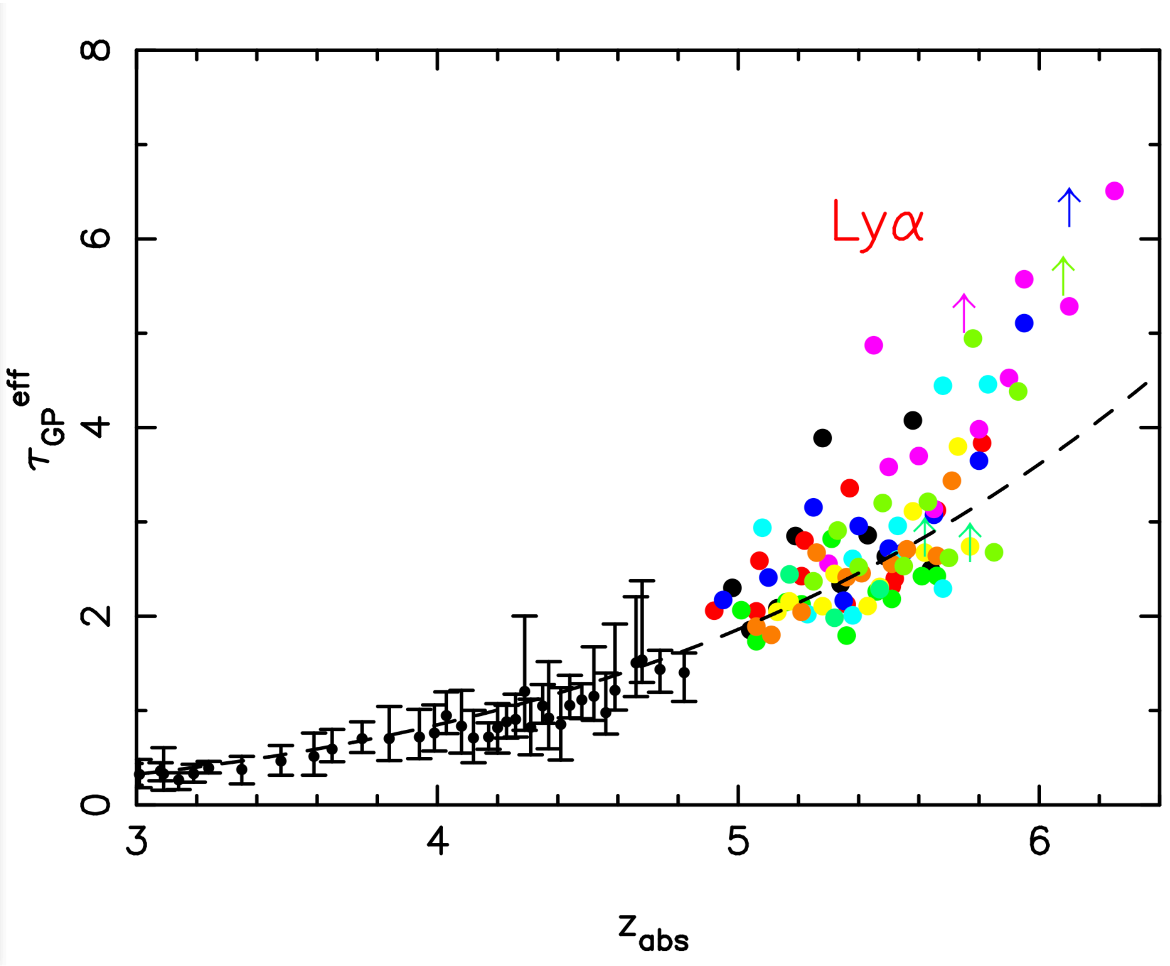


Becker, Bolton & Lidz (2015)

Overview

- Observations of the Ly-α forest opacity at z=5-6 (Becker et al. 2015);
- Updated estimates of the ionising emissivity at z~6 (Becker & Bolton in prep.)
- Constraining the thermal history with the Ly-α forest power spectrum at z=5 (Nasir et al. 2016 + poster)

Scatter in Ly-α opacity

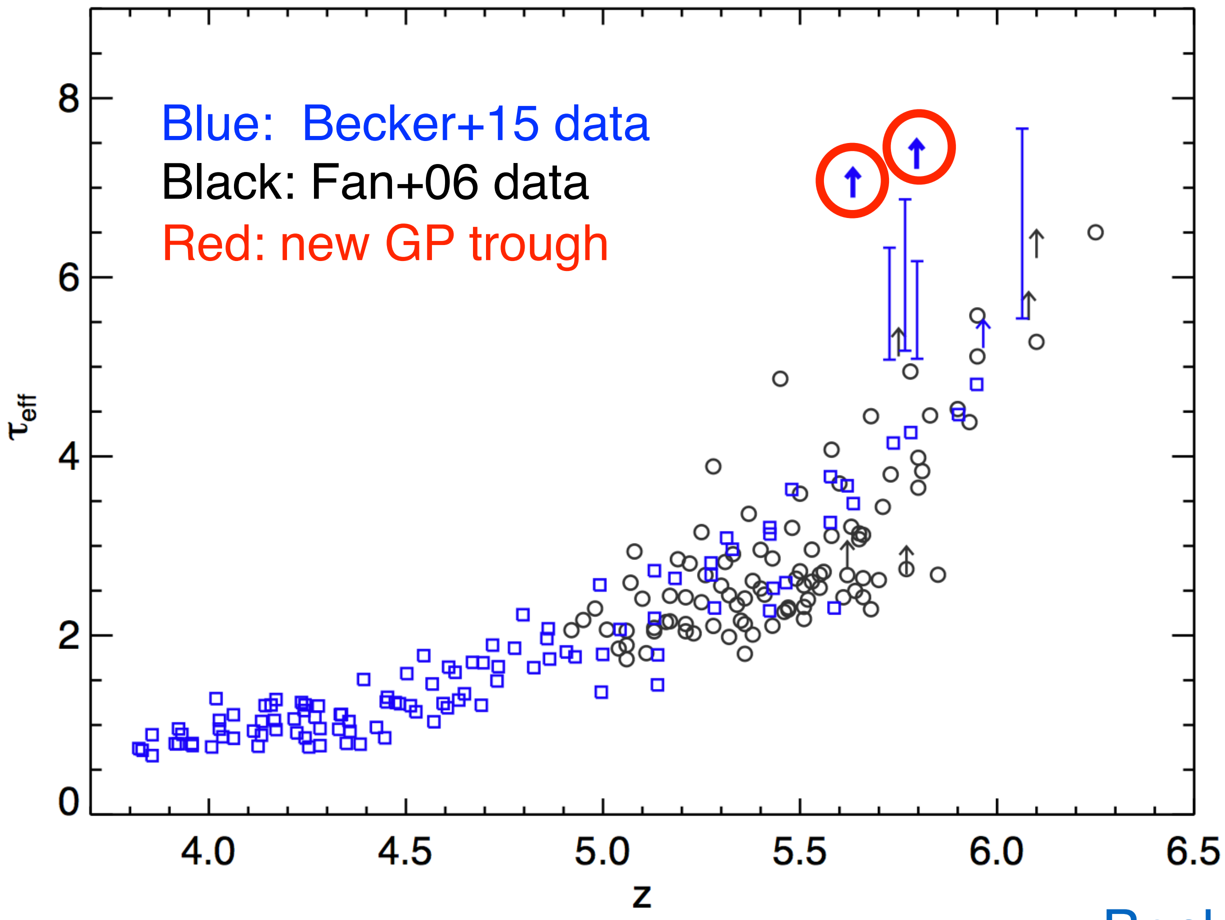


Fan et al. (2006)

- Signature of patchy reionisation? (Wyithe & Loeb 2005)
- Scatter explained by variations in IGM density? (Lidz et al. 2006)

$$\tau \simeq 4.3 \times 10^5 f_{\rm HI} \left(\frac{1+z}{7}\right)^{3/2}$$

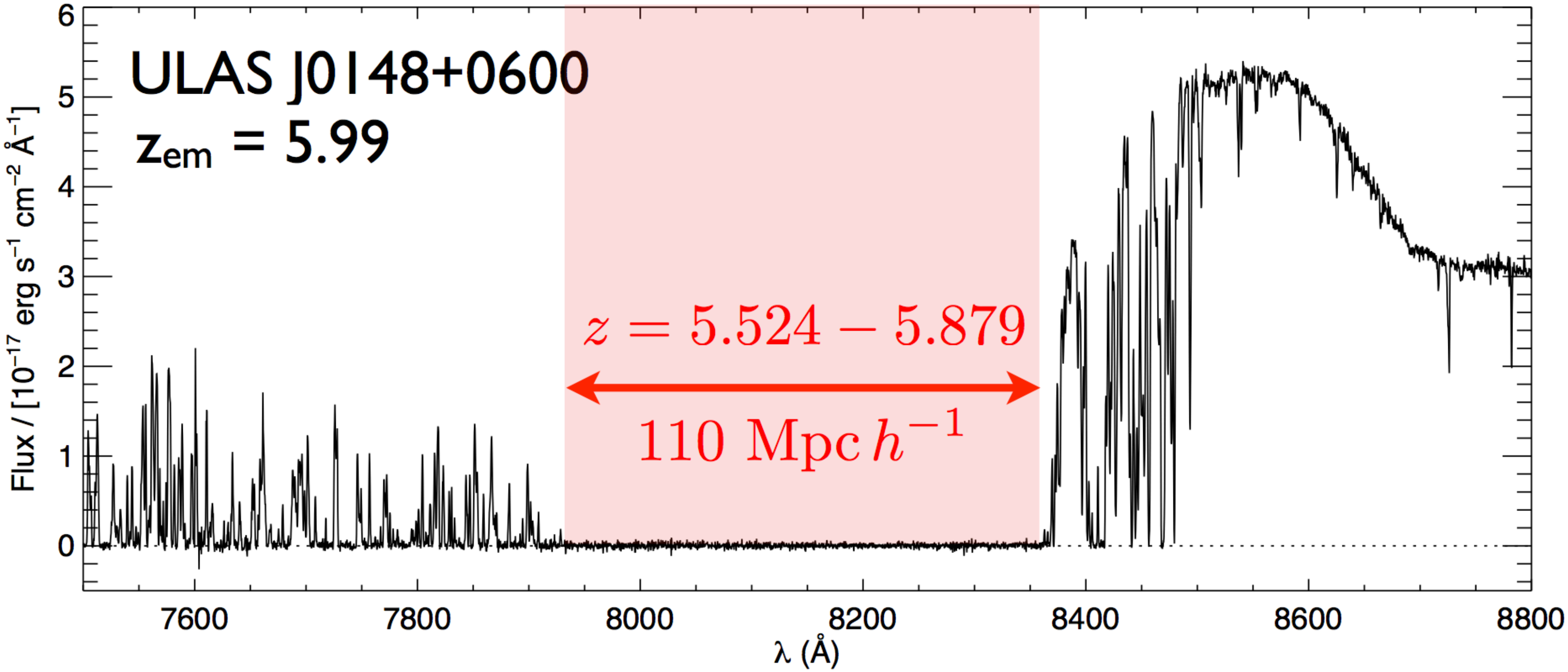
Scatter in Ly-α opacity



Becker et al. (2015)

SDSS + 23 additional quasar spectra (MIKE, ESI, HIRES, X-shooter)

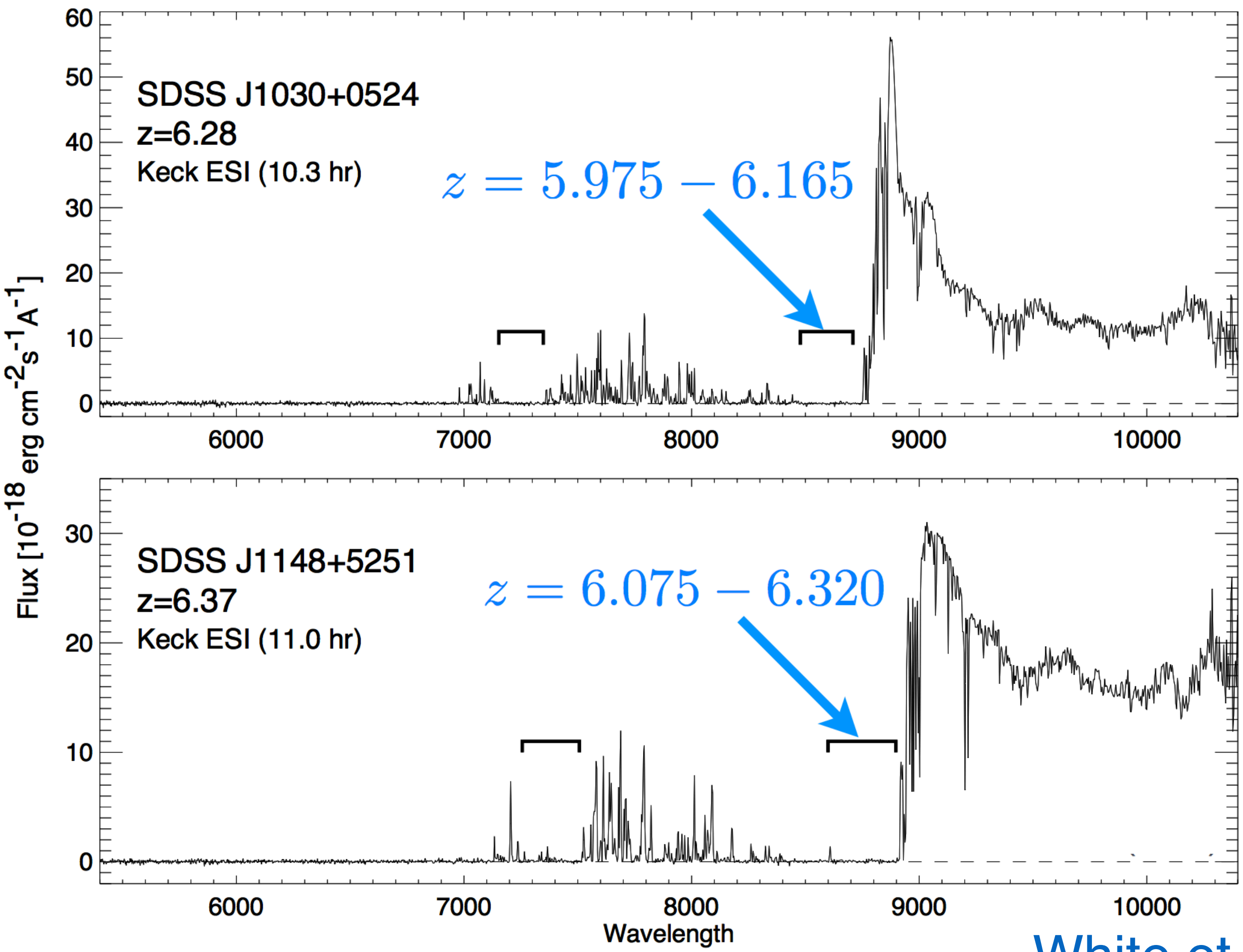
ULAS J0148+0600



VLT/X-shooter (10 hr)

Becker et al. (2015)

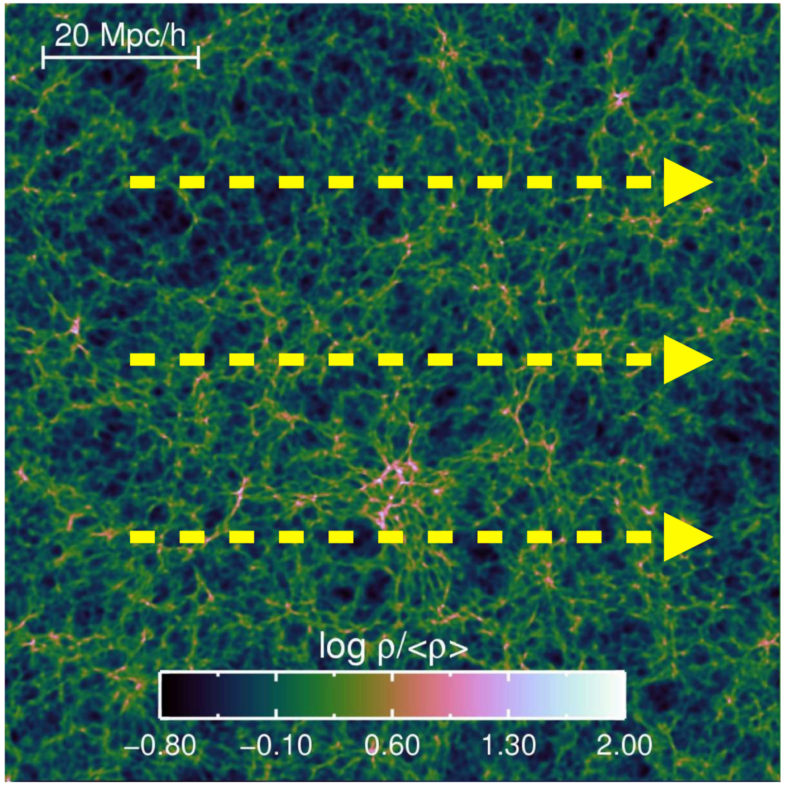
Other dark GP troughs at z~6

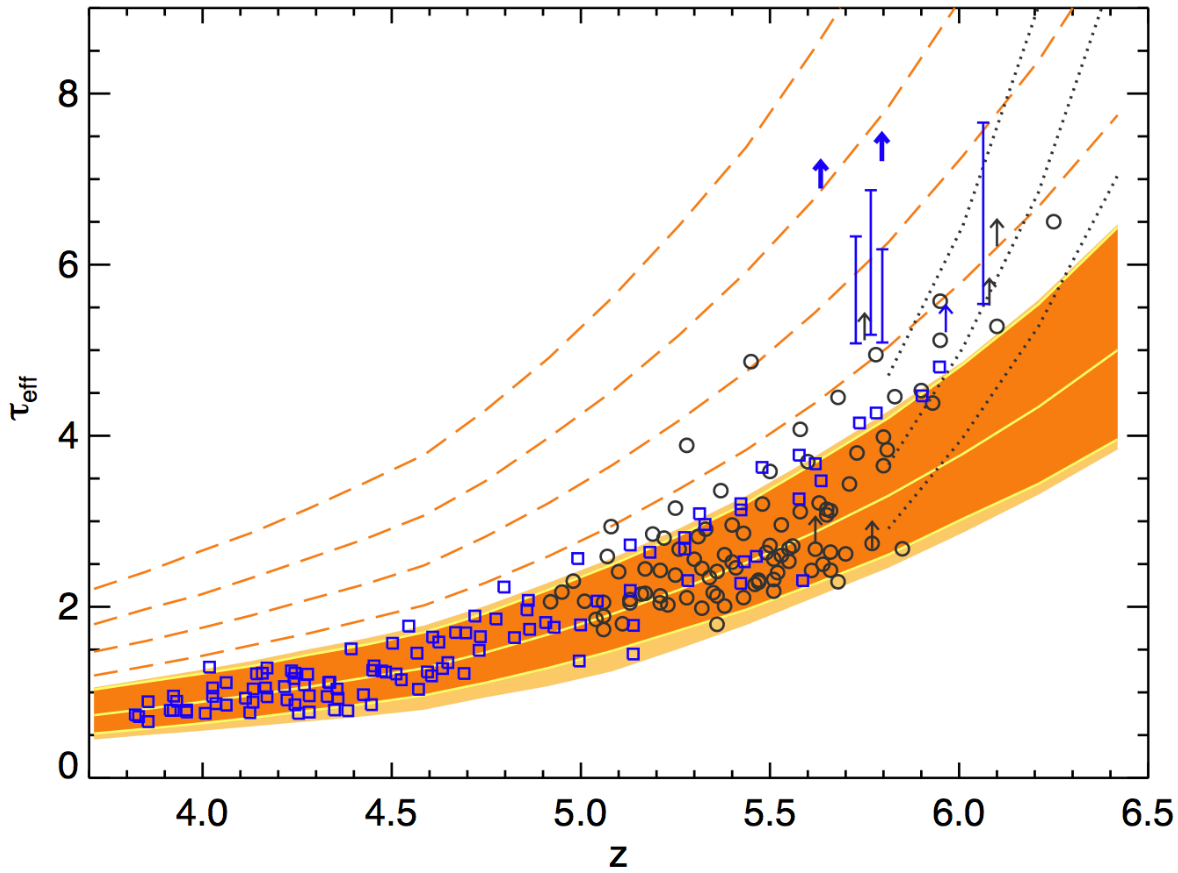


White et al. (2003)

The ULAS J0148+0600 trough is longer and at lower redshift.

Uniform UV background?

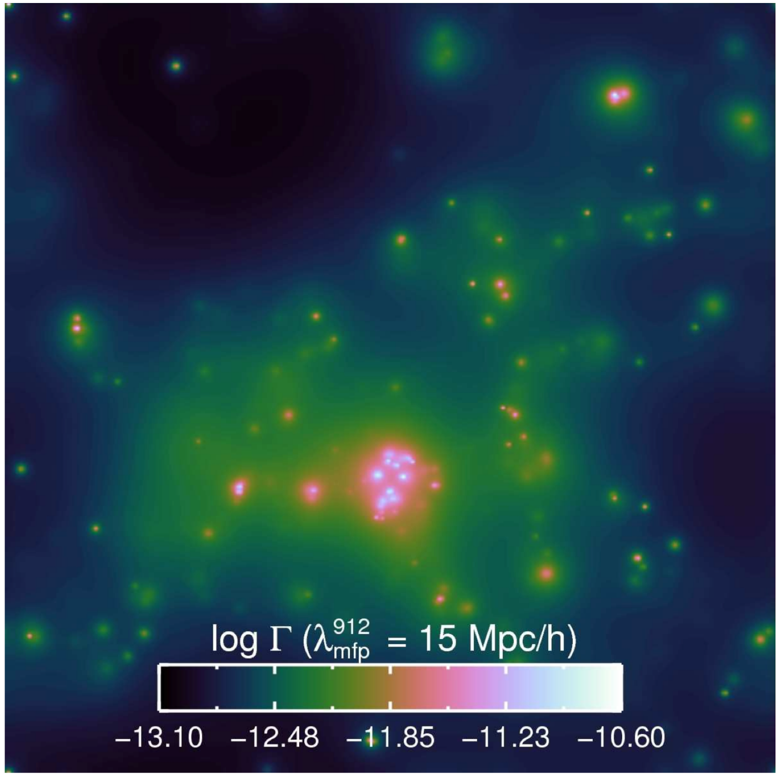


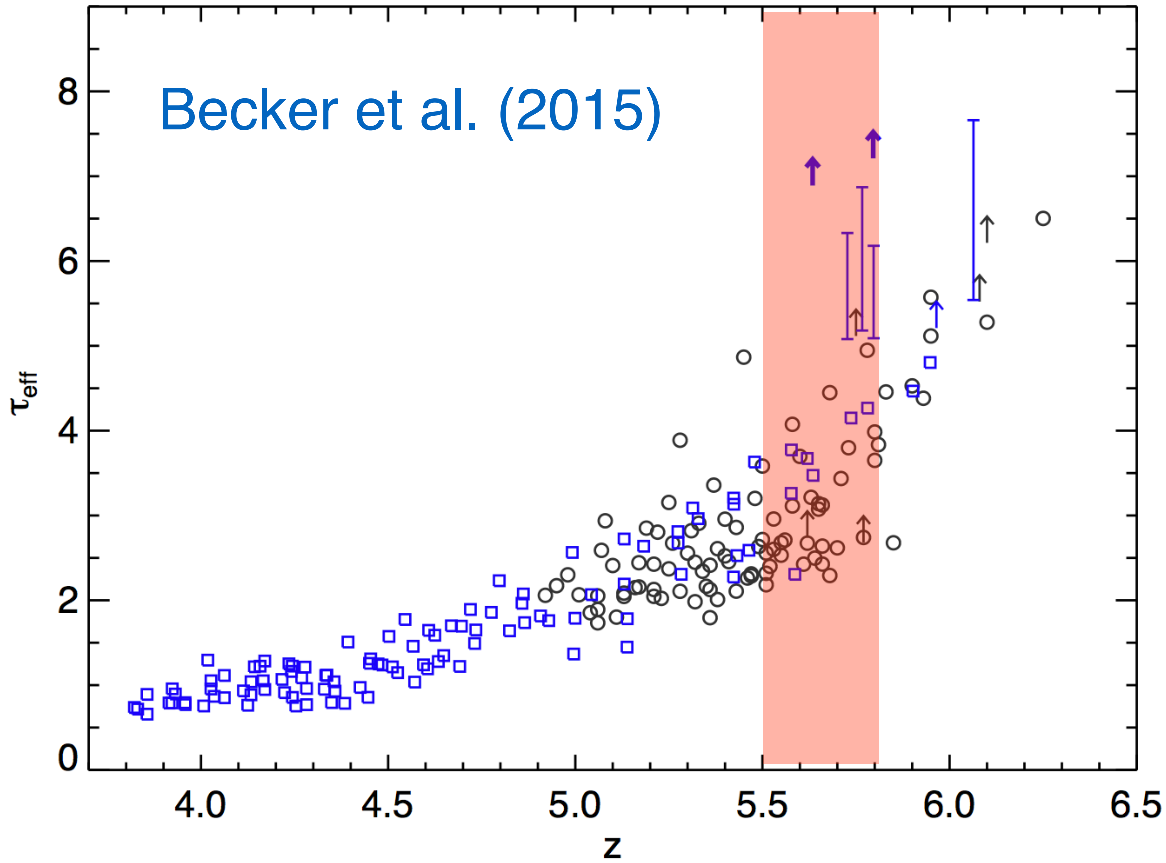


Becker et al. (2015)

Possible additional factor of ~3 variation in f_{HI} required.

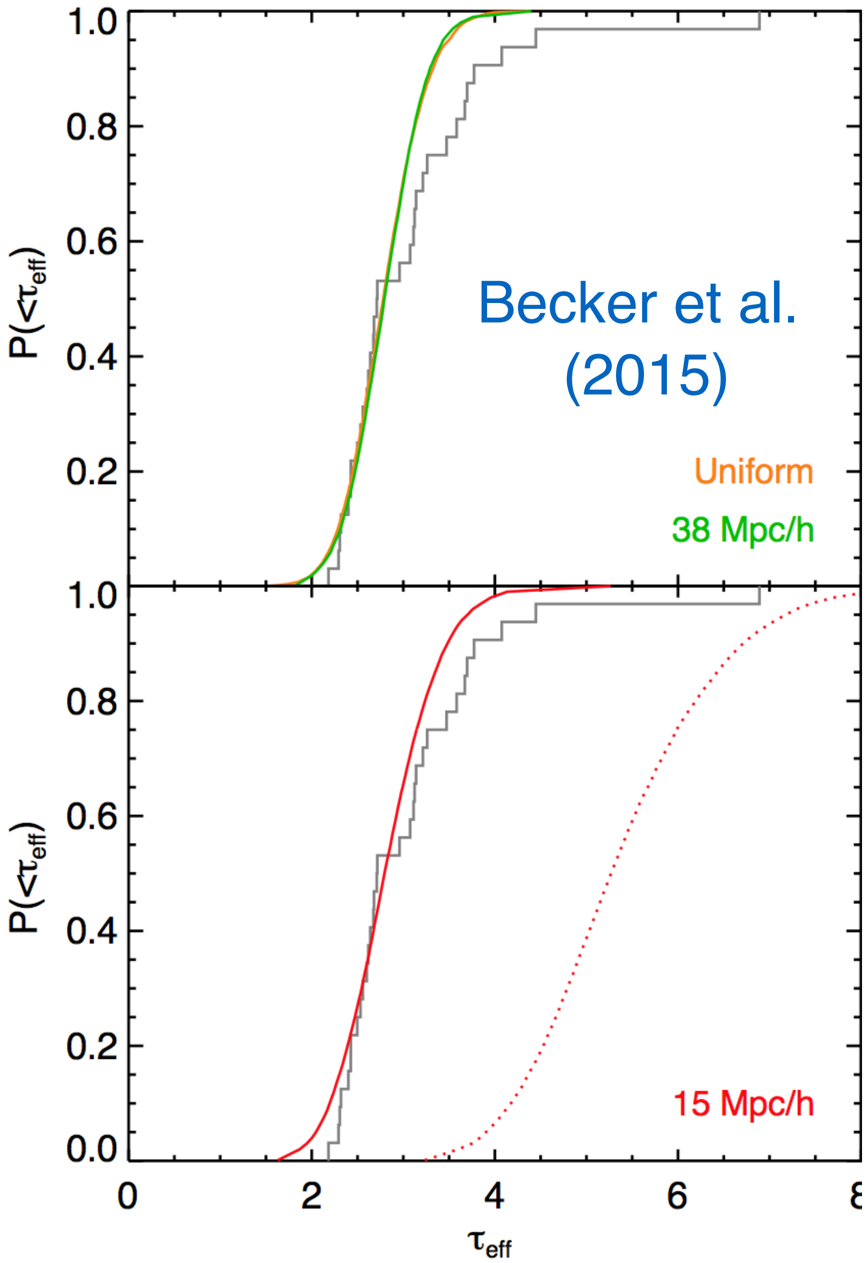
Inhomogeneous UV background?





Fluctuating background from galaxies with spatially invariant mean free path.

Inhomogeneous UV background?

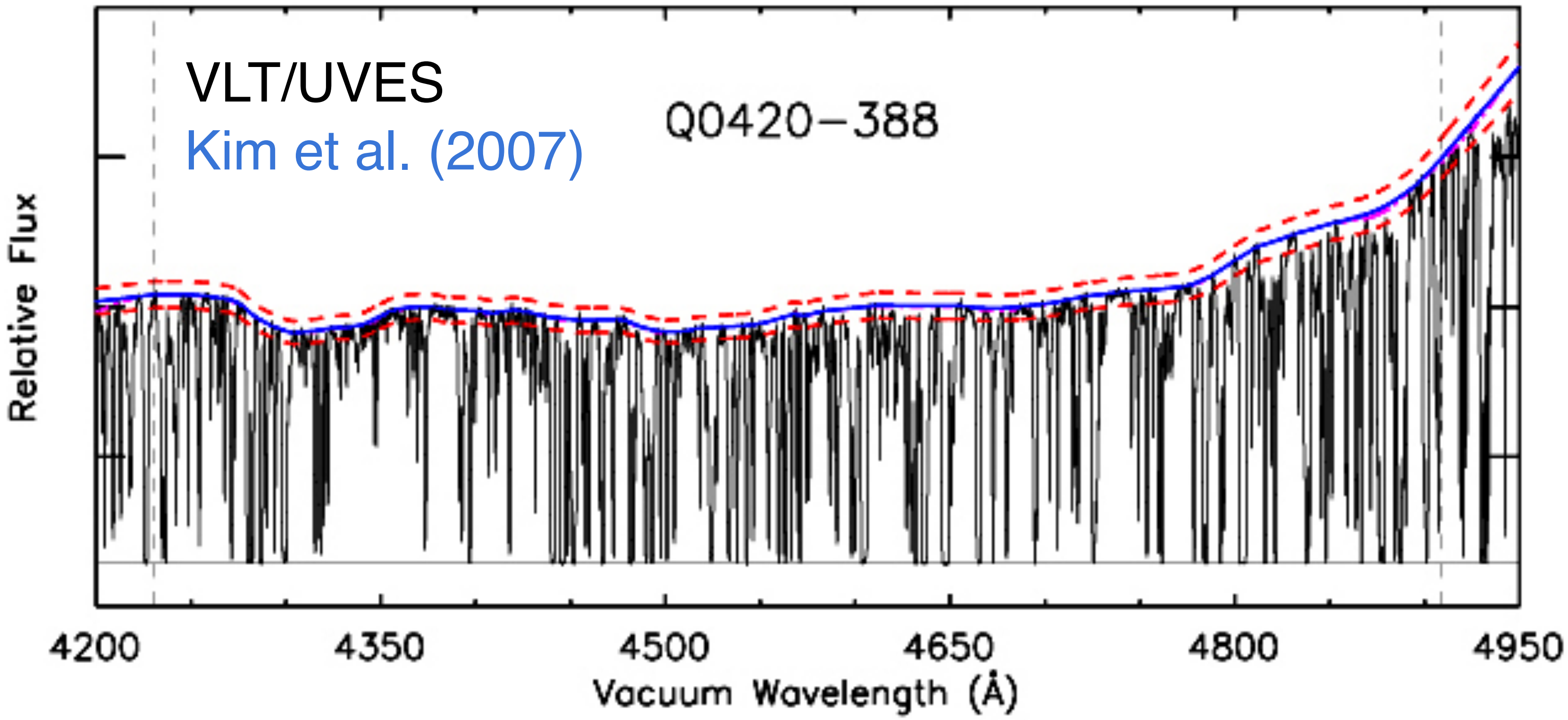


- Simple fluctuating UVB models do better, although not perfect.
- Mean free path may also vary spatially; indicative of patchy reionisation?

For possible explanations, see:

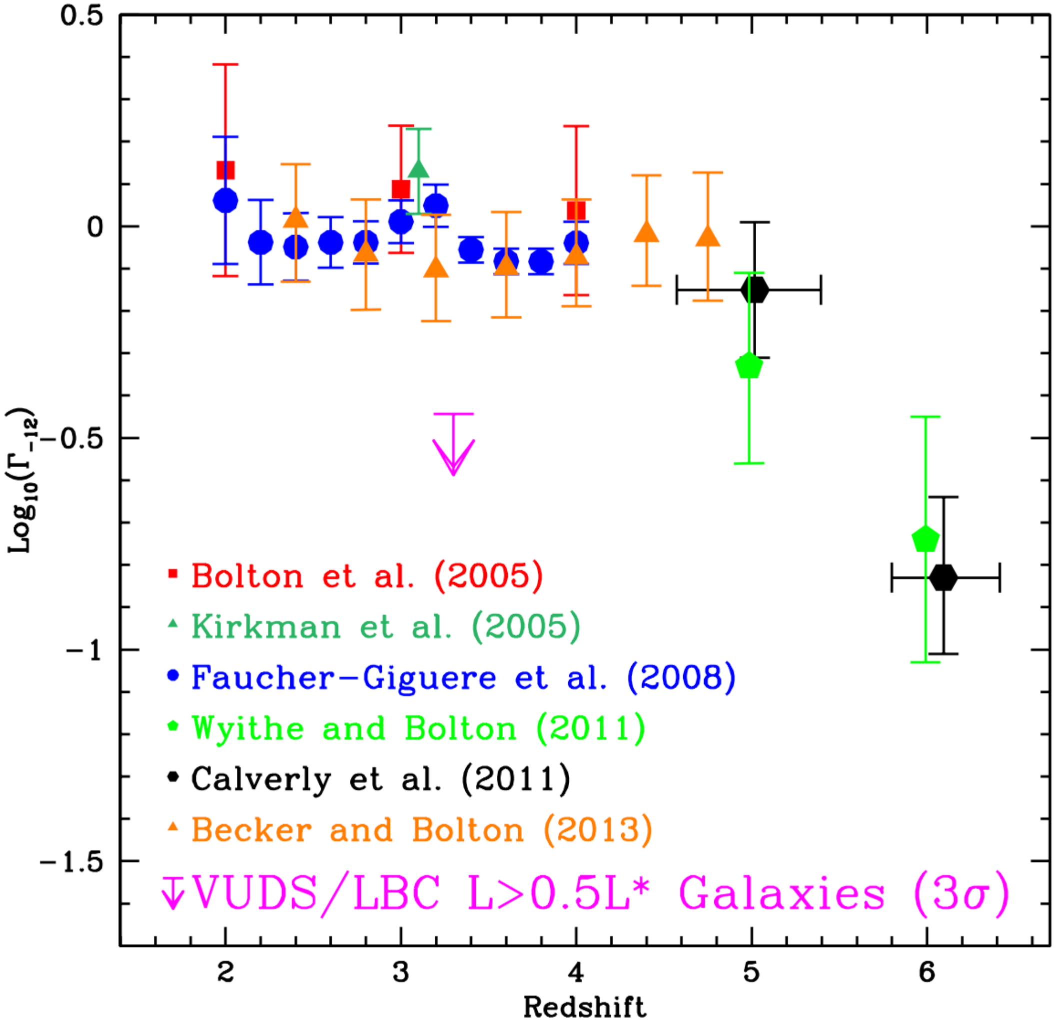
Chardin et al. (2015) + talk
D'Aloisio et al. (2015)
Davies & Furlanetto (2016) + talk
Gnedin et al. (2016)

The amplitude of the UVB



Opacity $$\tau_{\mathrm{Ly}\alpha} \propto \frac{1}{\Gamma_{\mathrm{HI}}(z)}$$ Hydrogen photo-ionisation rate

The photo-ionisation rate Γ_{HI}



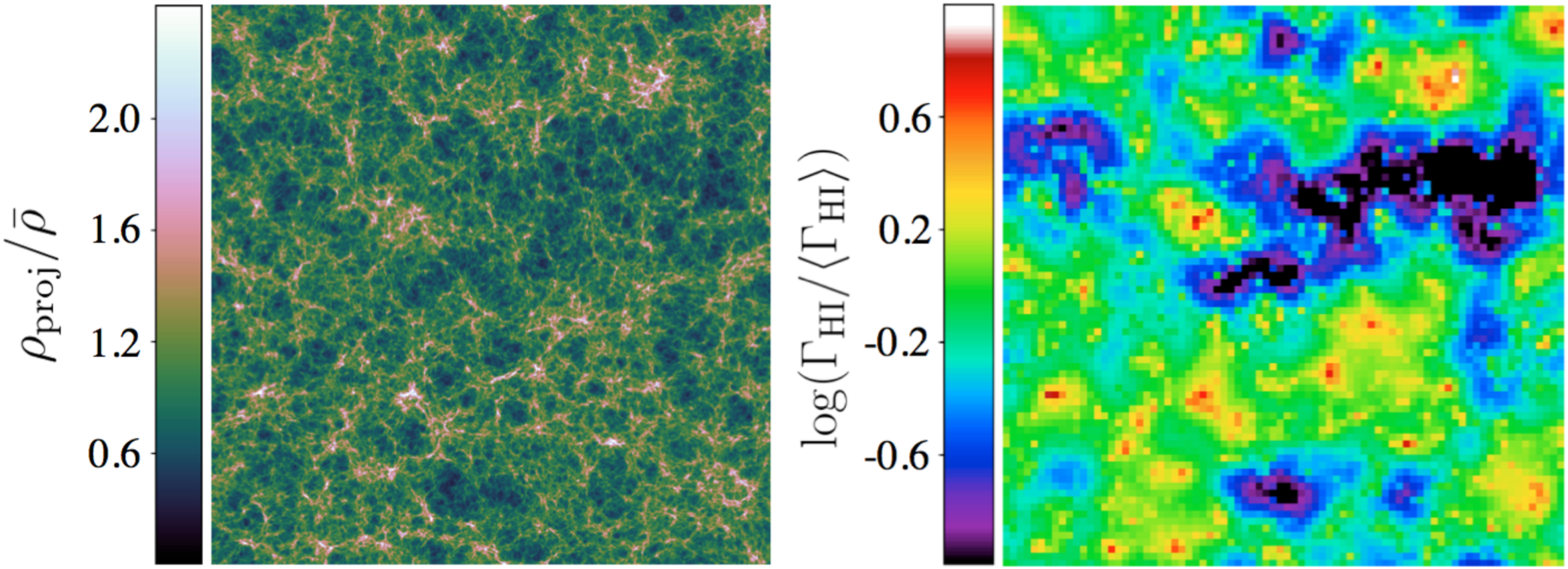
Grazian et al. (2016)

Decline in photo-ionisation rate by factor of 4-5 over 4<z<6

For discussion see e.g.: Munoz et al. (2016)

Spatial fluctuations in Γ_{HI}

Ionisation rate lower in underdense regions probed by the Ly-α forest



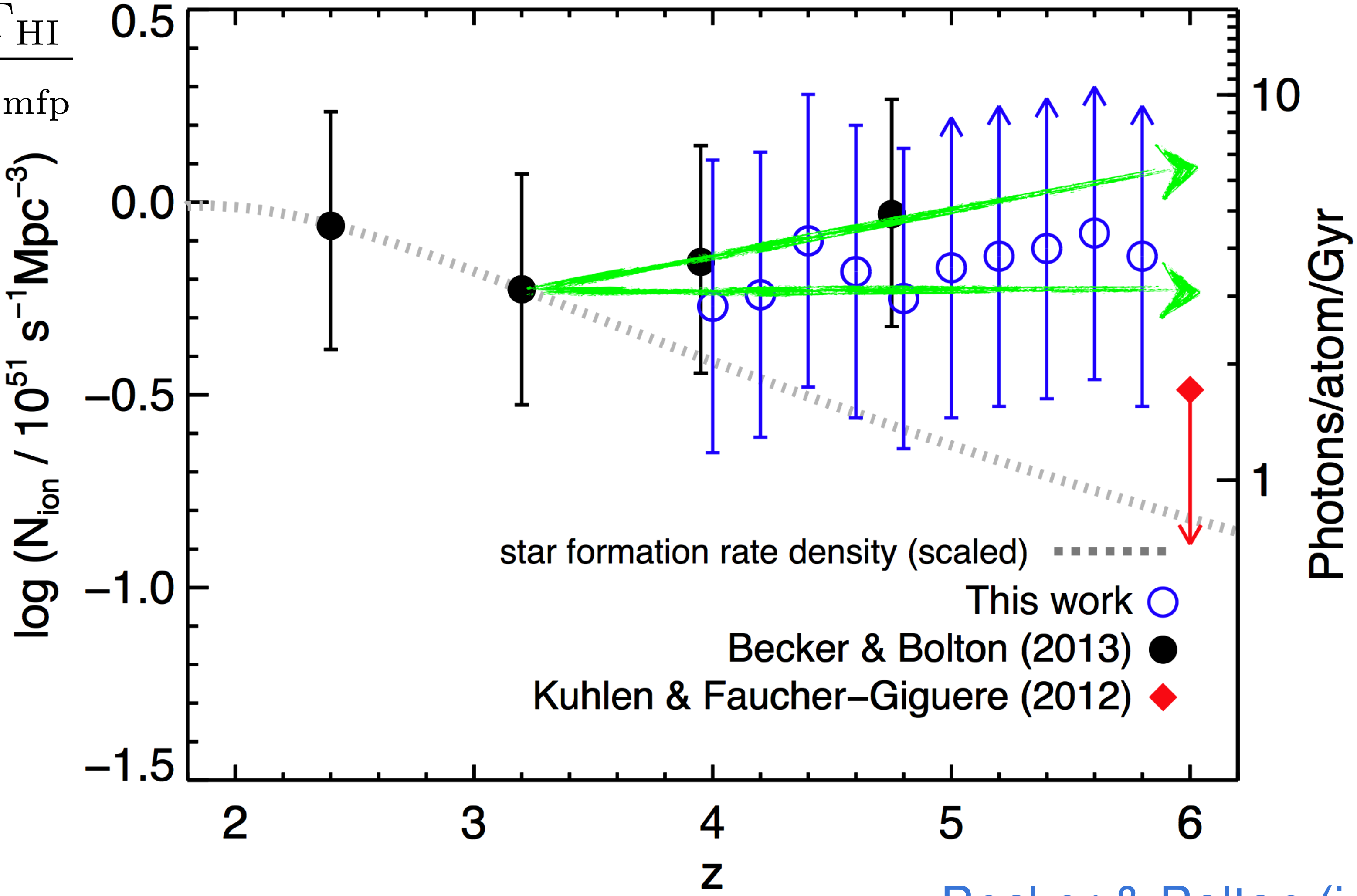
$$\Gamma_{\mathrm{HI}} \propto \dot{N}_{\mathrm{ion}}\lambda_{\mathrm{mfp}}$$

Davies & Furlanetto (2016)

see also Gnedin & Hamilton (2002), Meiksin & White (2003)

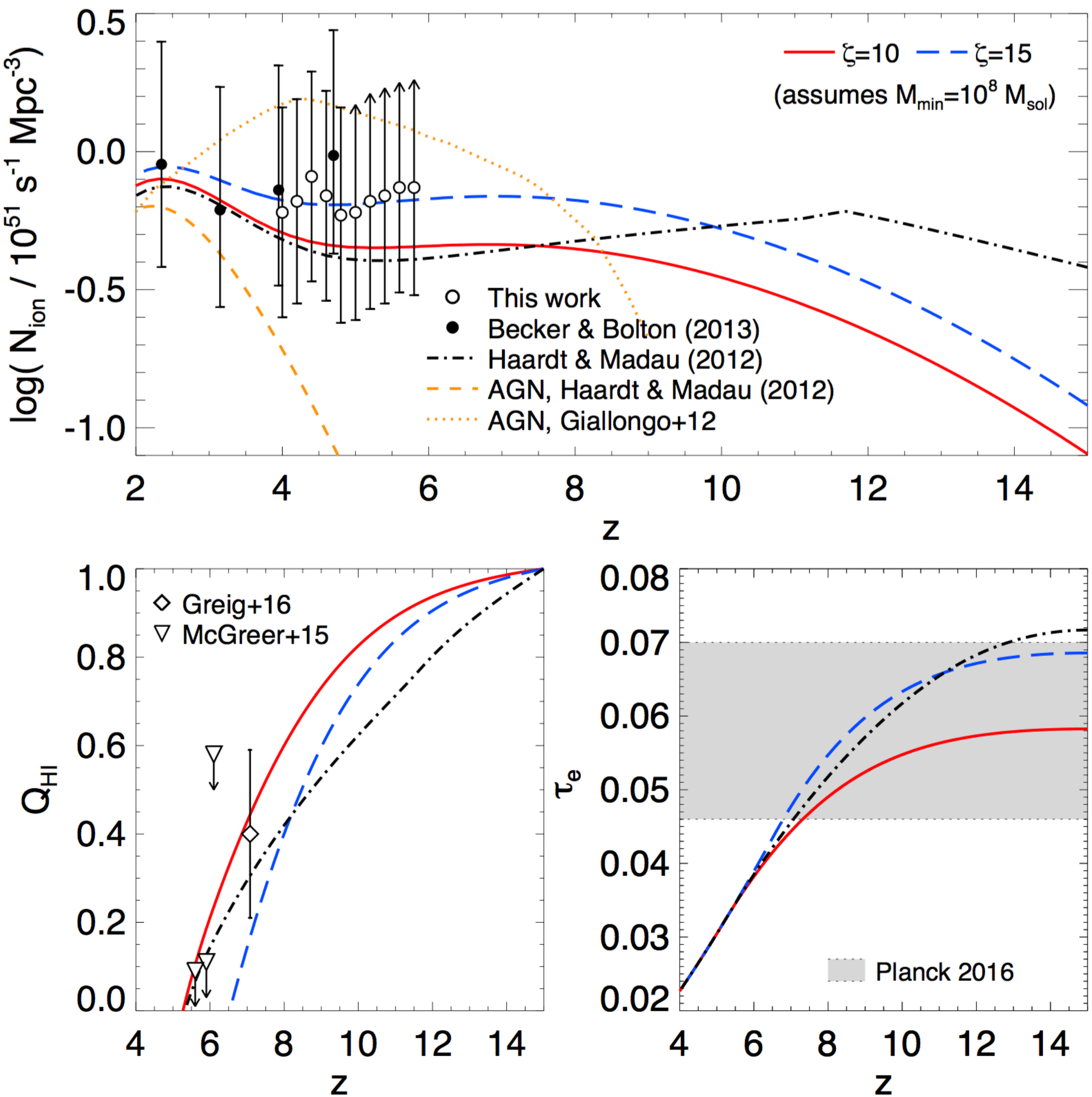
Ionising emissivity **PRELIMINARY**

$$\dot{N}_{\rm ion} \propto \frac{\Gamma_{\rm HI}}{\lambda_{\rm mfp}}$$



Becker & Bolton (in prep.)

Ionising emissivity is ~4 photons/atom/Gyr from 2<z<6.



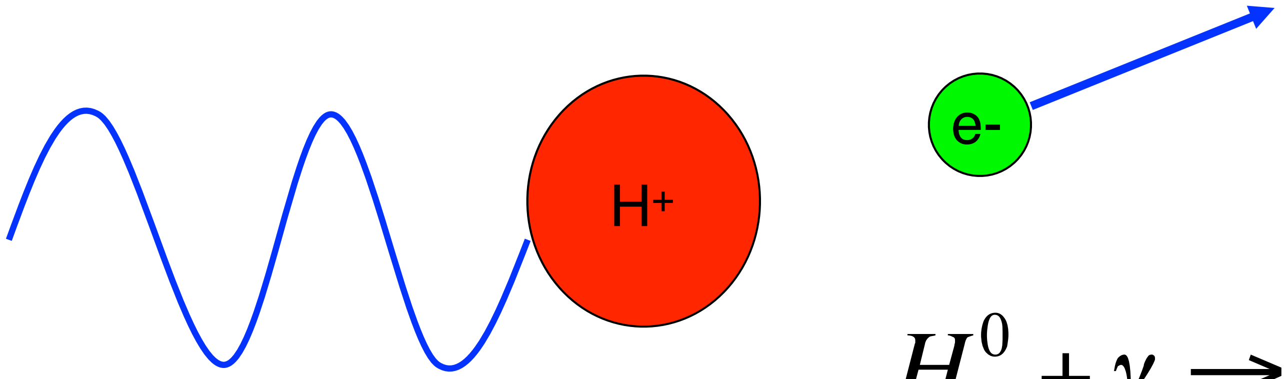
Becker & Bolton (in prep.)

PRELIMINARY

- Emissivity at z~5.5 around 3x larger;
- Thomson optical depth lowered by Planck;
- Consistent with simple models with constant ionising efficiency.

see also e.g.
Robertson et al. (2015)
Bouwens et al. (2015)
Mitra et al. (2015)
Madau & Haardt (2015)
Giallongo et al. (2015)
Khaire et al. (2016)
+ talks

Photo-ionisation heating

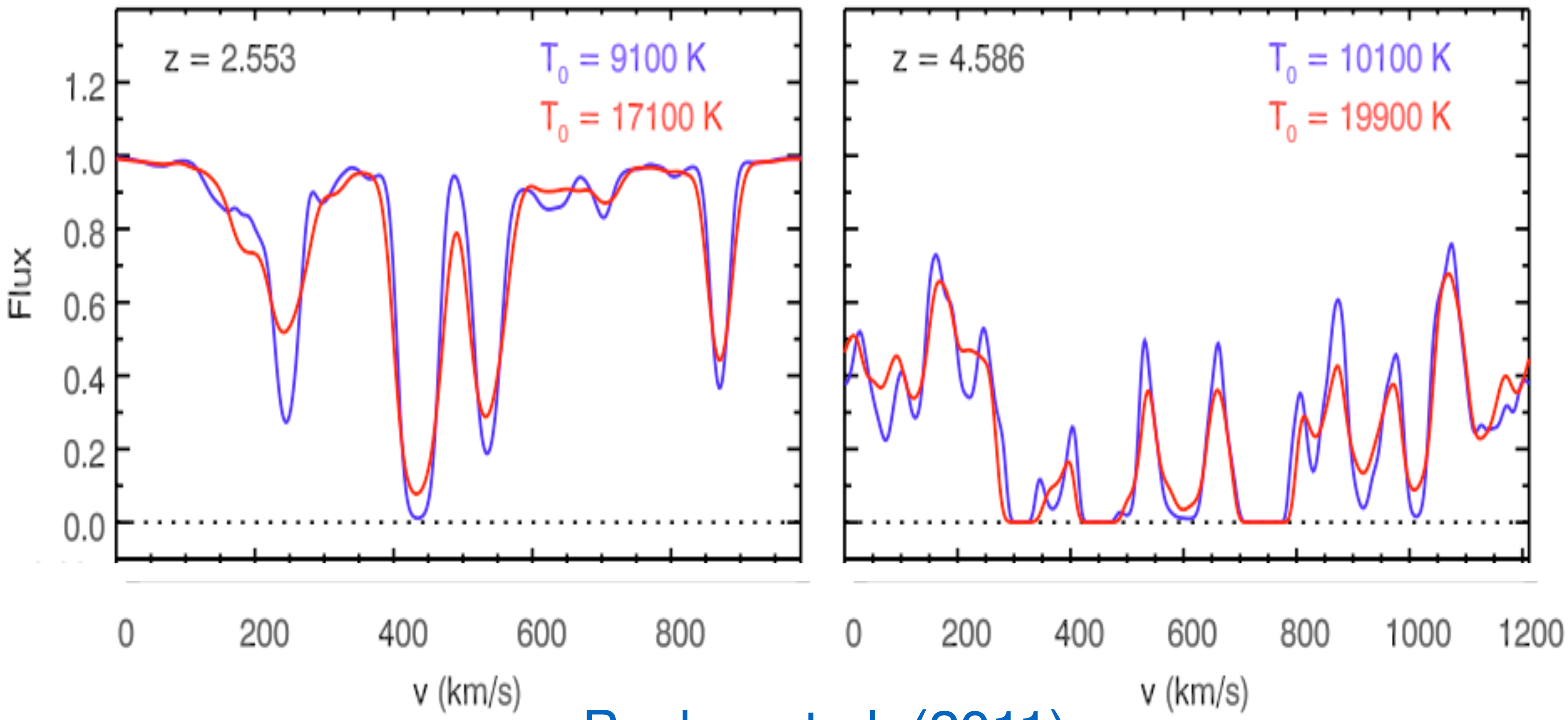


E > 13.6 eV photon

$$H^0 + \gamma \rightarrow H^+ + e^-$$

Ejected photo-electrons share their energy with neutrals via scattering and raise the temperature of the residual H-I.

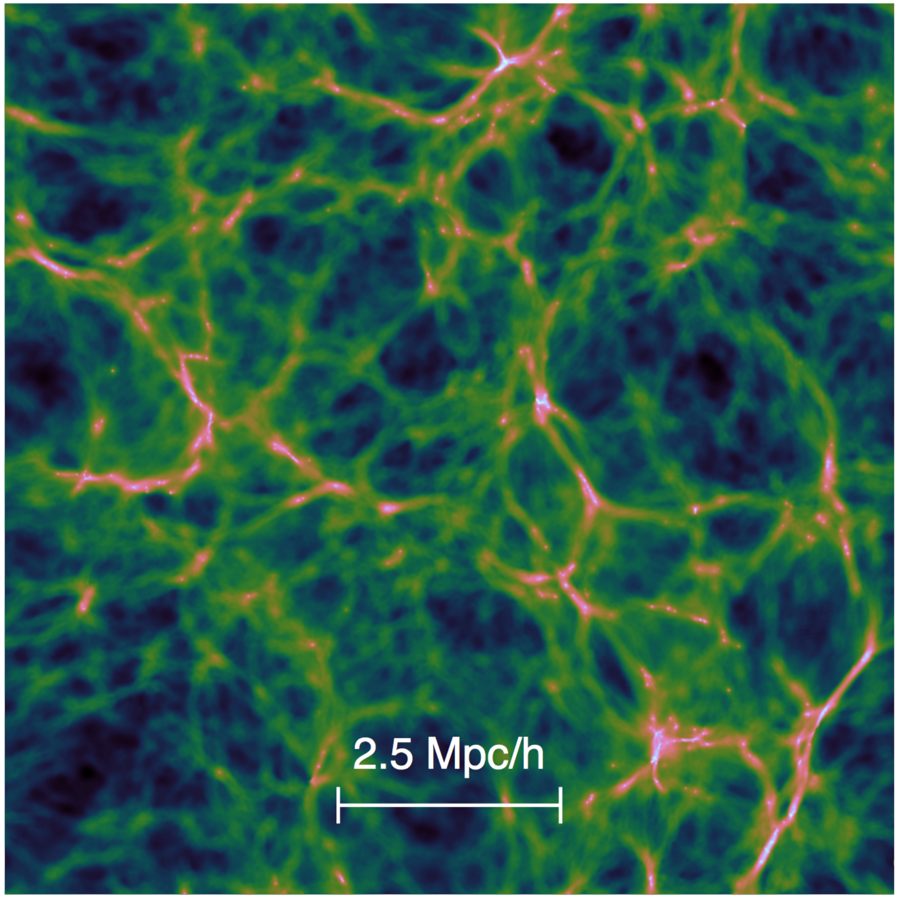
The Ly-α forest as a thermometer

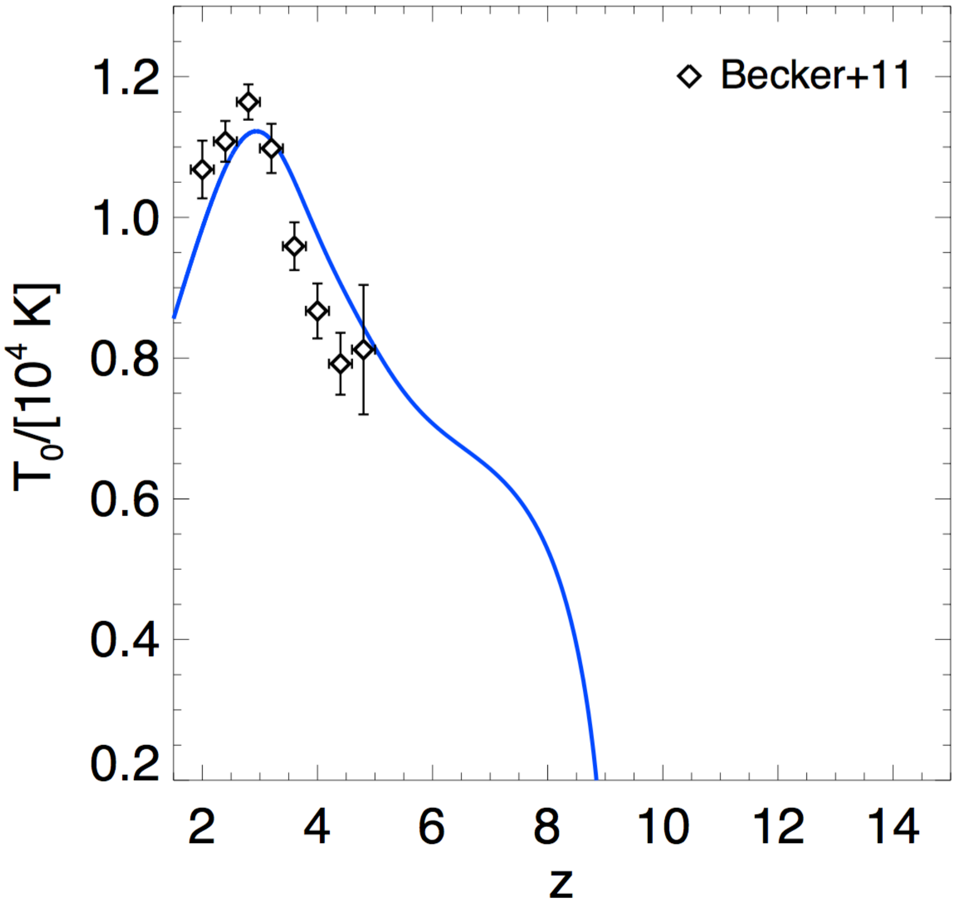


Becker et al. (2011)

1) Thermal broadening by instantaneous temperature (along the line of sight only);
2) Jeans smoothing via integrated heating history (in three dimensions).

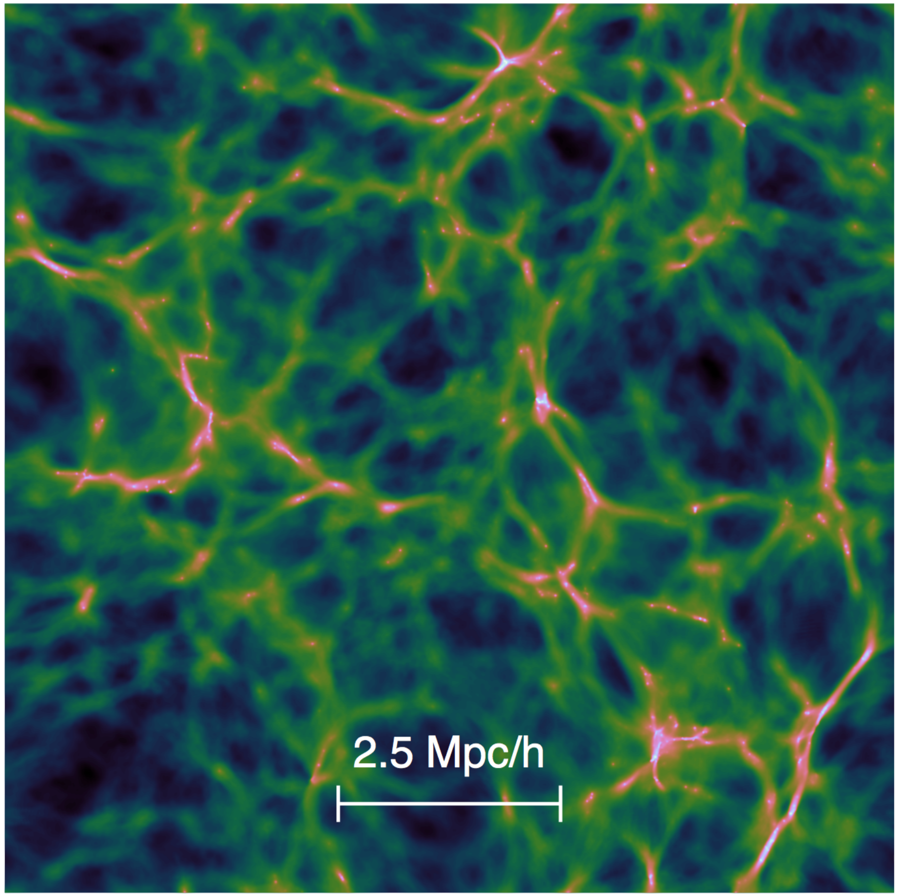
Gas pressure (Jeans) smoothing

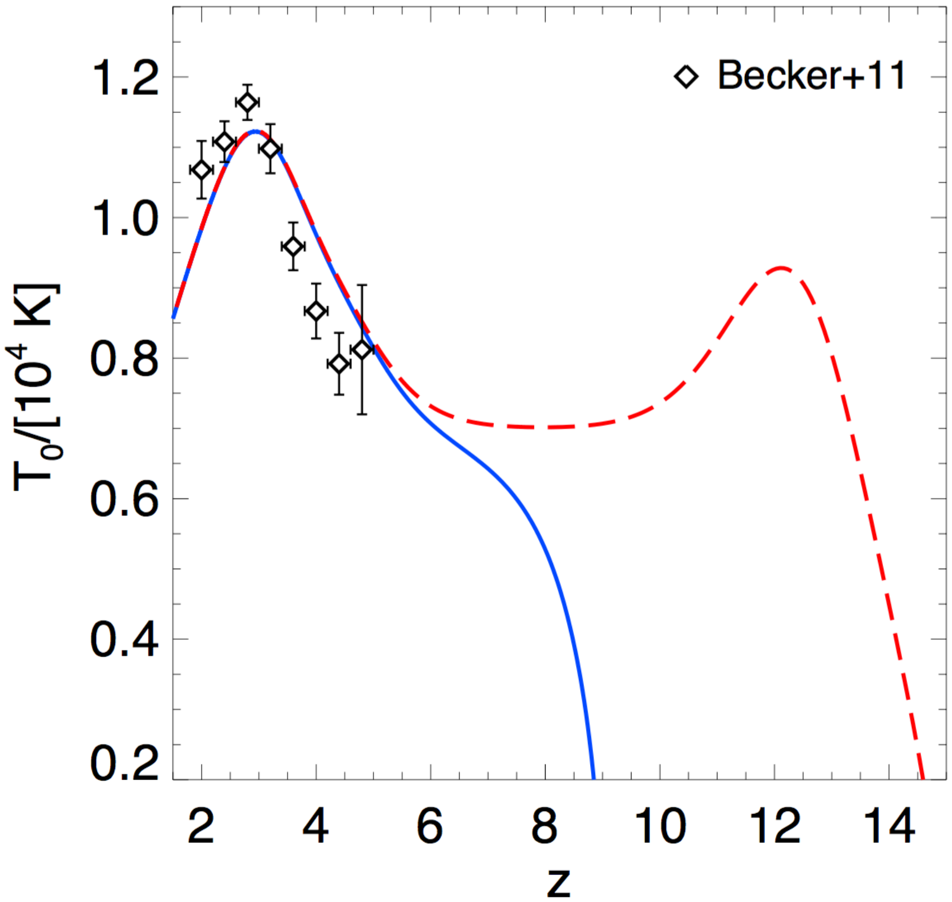




see also e.g. Hui & Gnedin 98, Pawlik+09, Peeples+10, Rorai+13, Kulkarni+15

Gas pressure (Jeans) smoothing



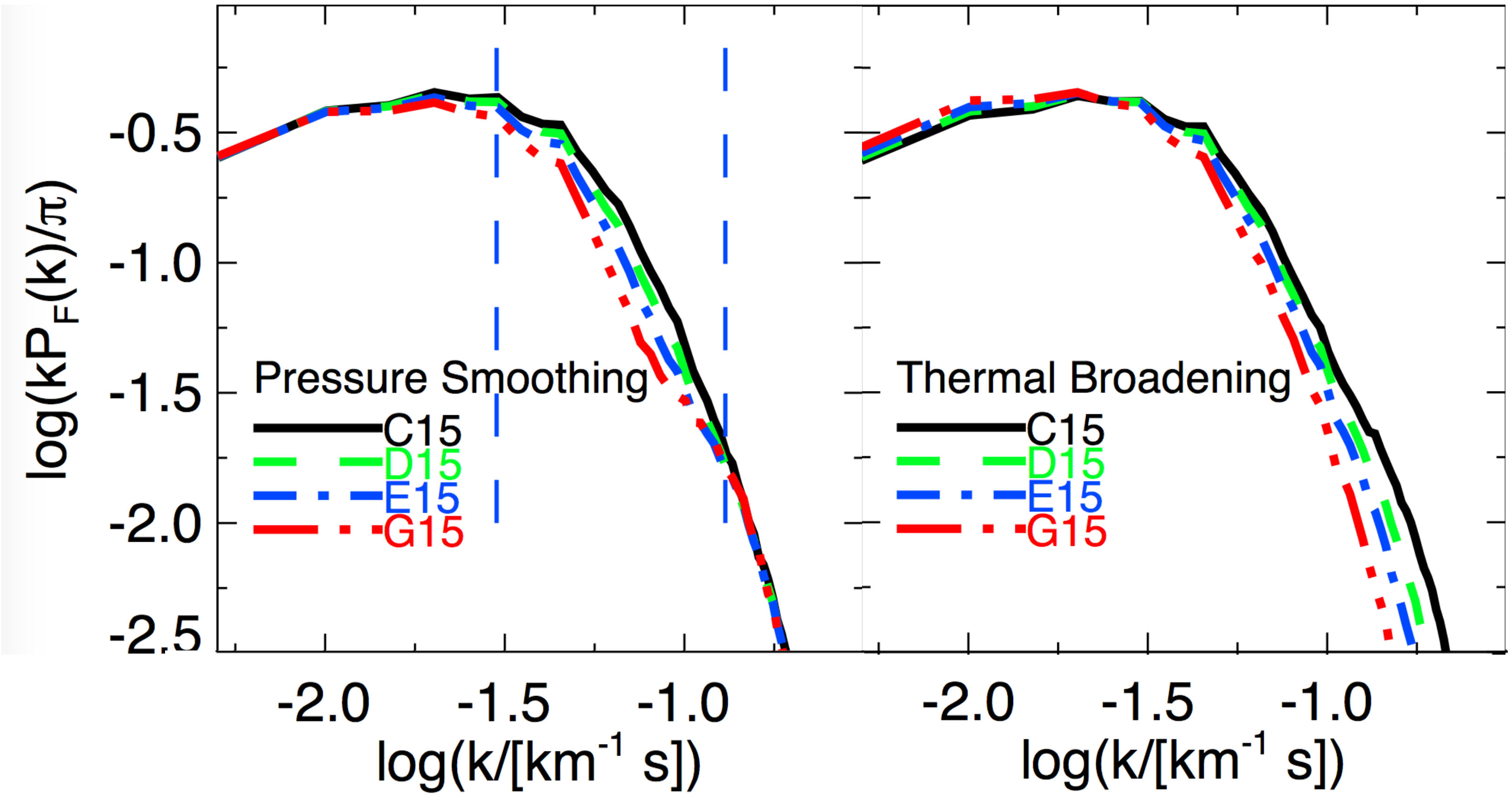


see also e.g. Hui & Gnedin 98, Pawlik+09, Peeples+10, Rorai+13, Kulkarni+15

The observable

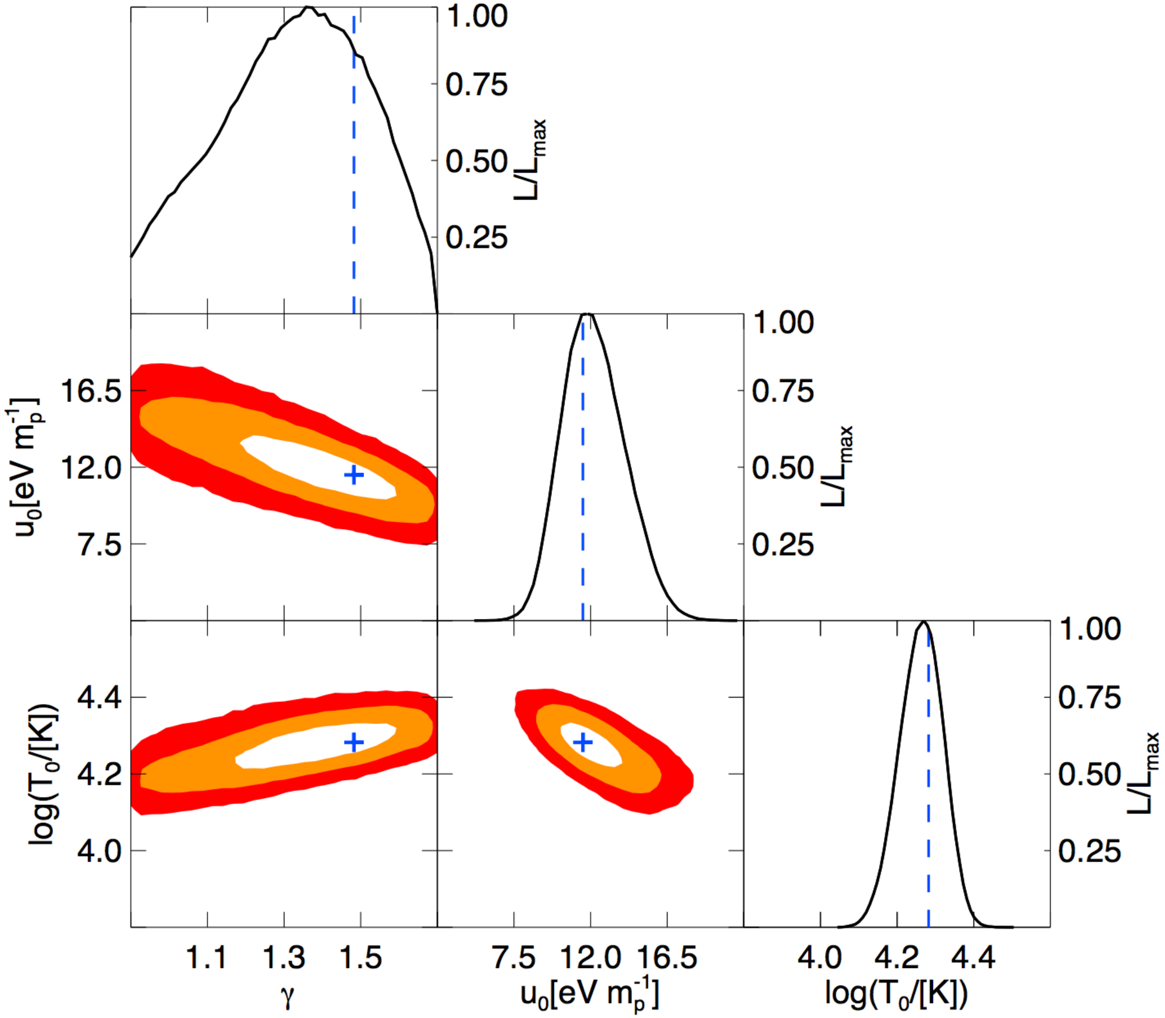
Separate the broadening mechanisms with the transmitted flux power spectrum at z~5

see e.g. Croft+02, McDonald+06, Zaroubi+06, Viel+13



Nasir et al. (2016) + poster

MCMC analysis

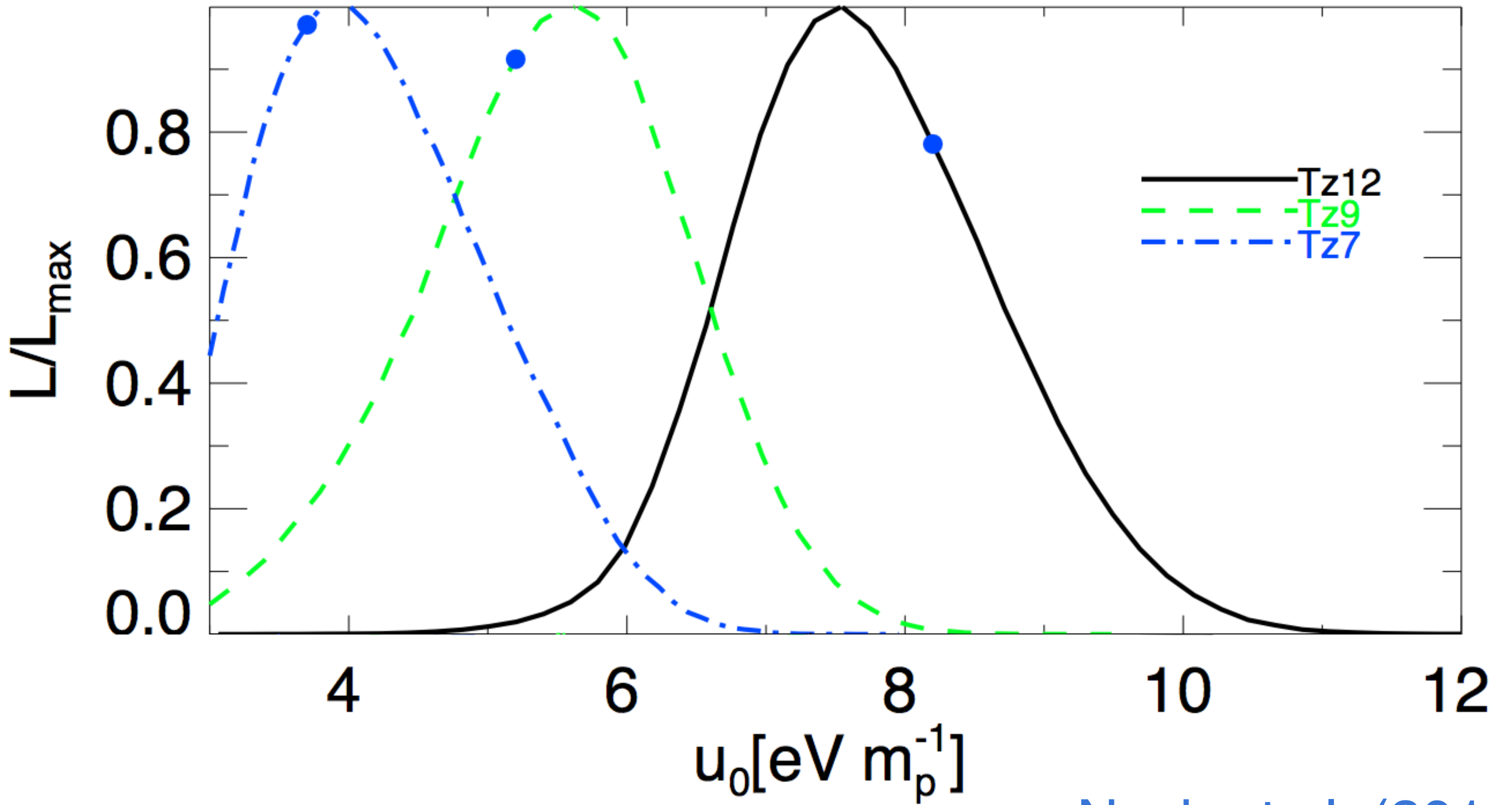


Nasir et al. (2016) + poster

- Statistical uncertainty of ~20% on u_0 with currently available data.
- Systematics are likely comparable, however.
- Total uncertainty around ~30%

MCMC analysis

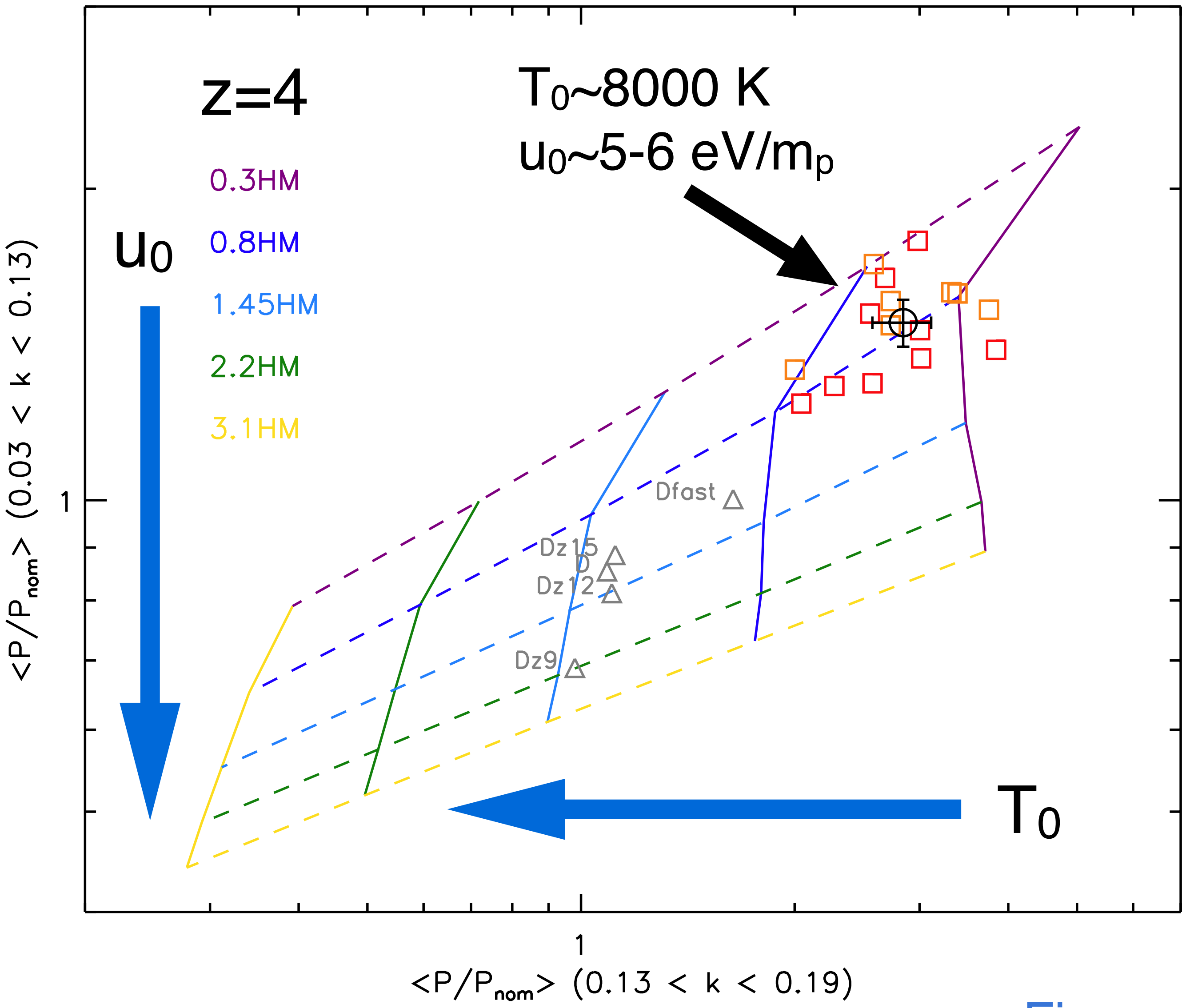
Should distinguish between models where u_0 varies by 2-3 eV per proton over 5<z<12



Nasir et al. (2016) + poster

A first look at data

PRELIMINARY



- Data prefer low values of u_0;
- T_0 similar to earlier measurements at z~4-5, e.g. Schaye +00, Becker+11

Figure courtesy of G.D. Becker

Summary

- The Ly-α forest opacity at $5<z<6$ exhibits large fluctuations that are most likely related to the latter stages of reionisation;

- Updated emissivity measurements and Planck 2016 data do not require the ionising efficiency of galaxies to evolve at $z>6$;

- Power spectrum of the Ly-α forest transmitted flux should distinguish between reionisation heating that varies by 2-3 eV per proton over $5<z<12$.