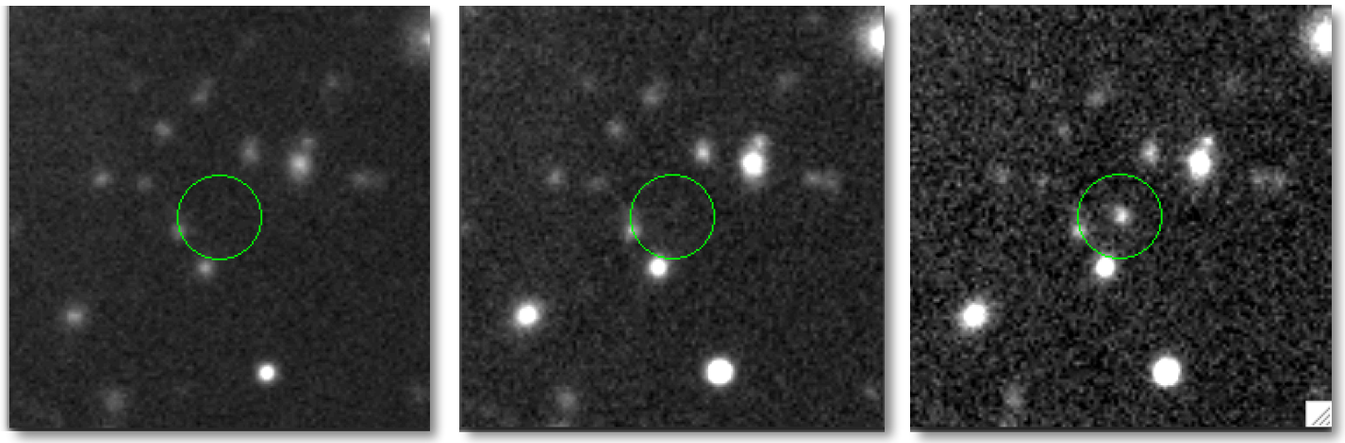
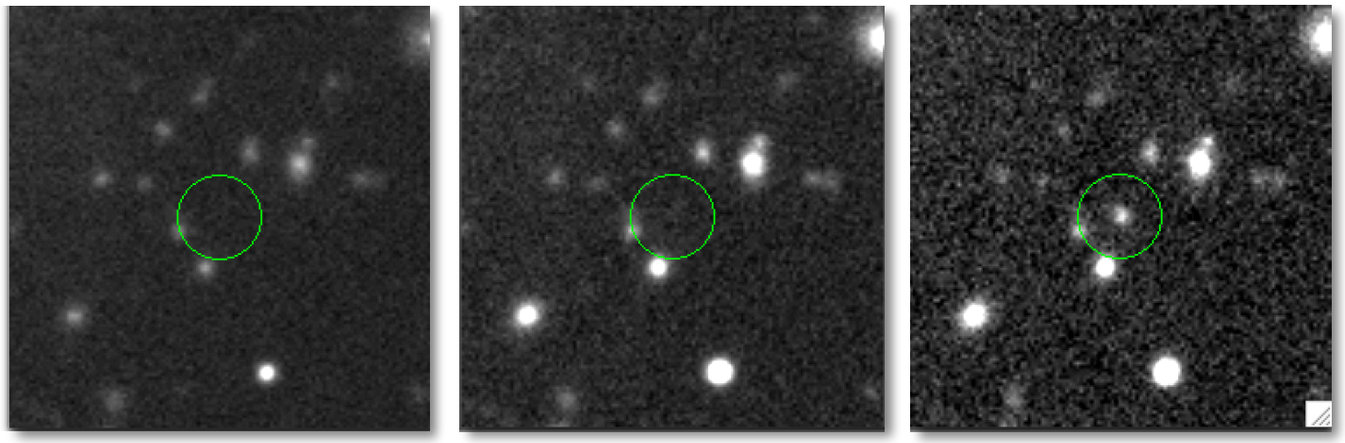


Connecting the IGM and Galaxies Close to Reionization

George Becker (UC Riverside)

UCB

September 13, 2018

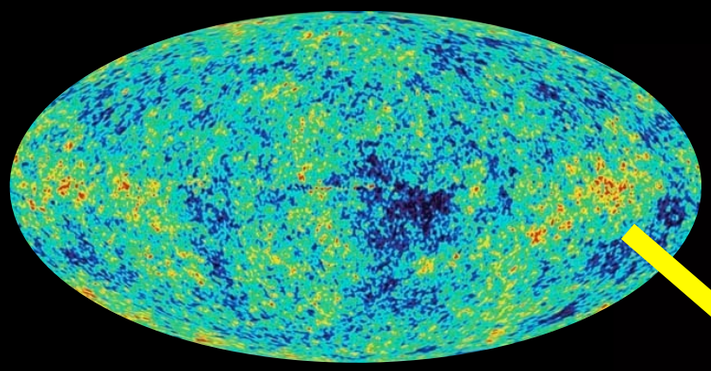


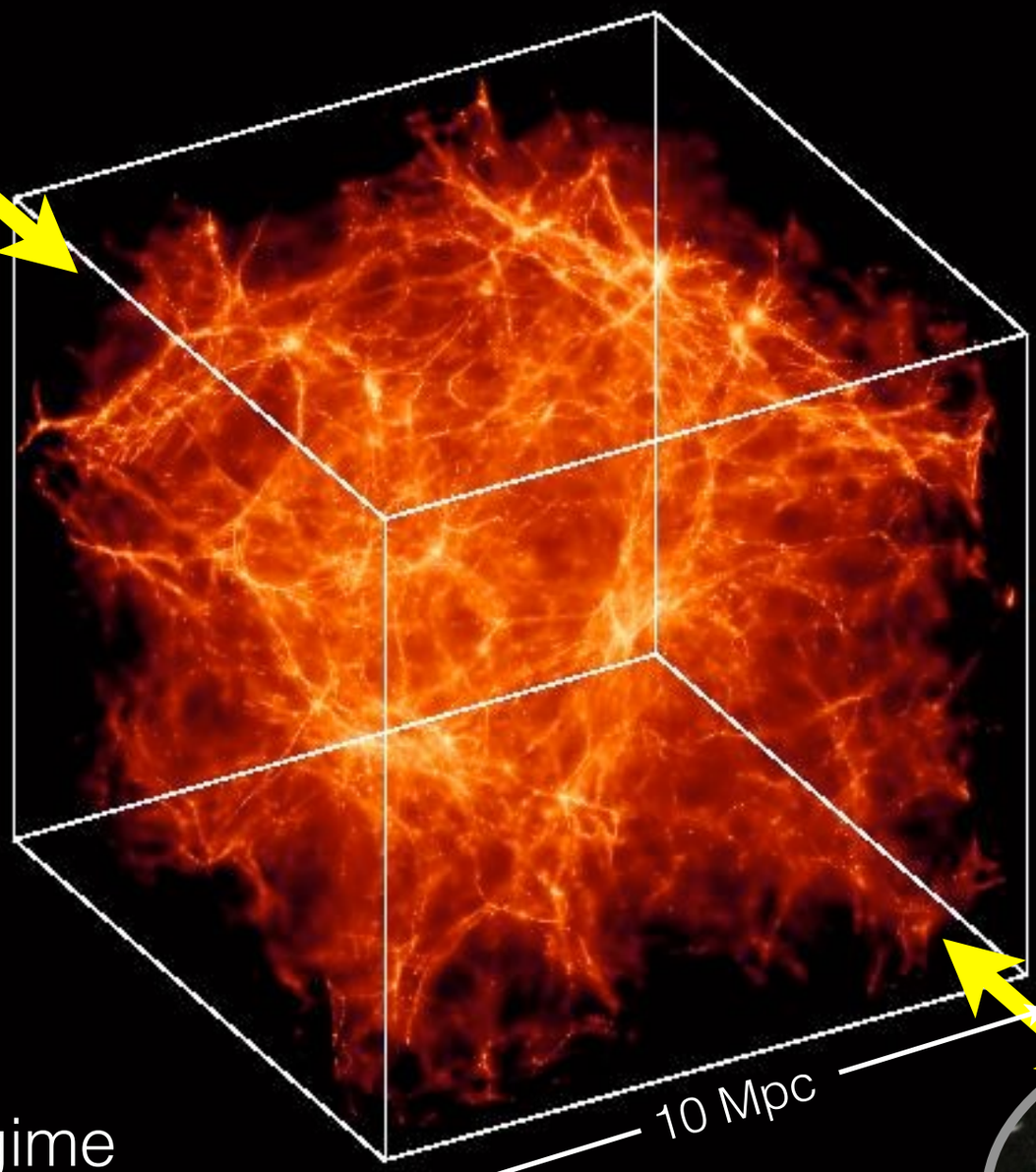
Connecting the IGM and Galaxies Close to Reionization

1. IGM Overview
2. Current Picture of Reionization
3. Large-scale fluctuations in the IGM neutral fraction at z < 6

The Intergalactic Medium

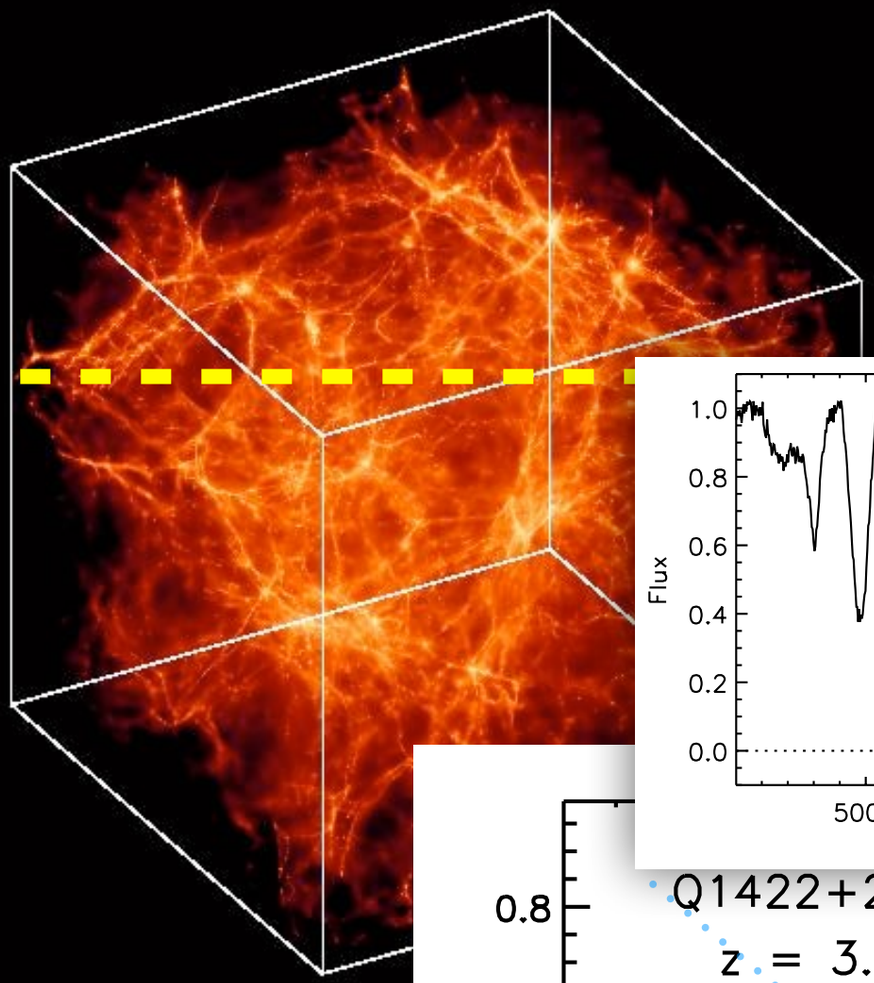
>90% of all baryons

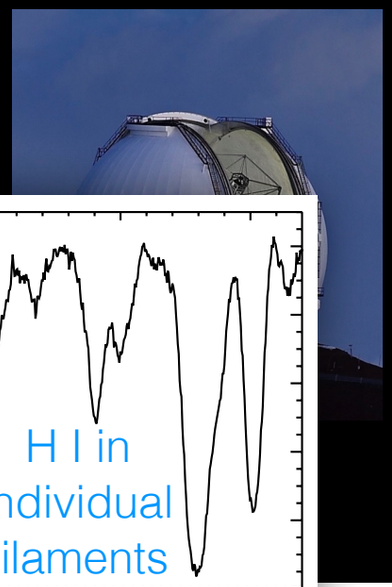


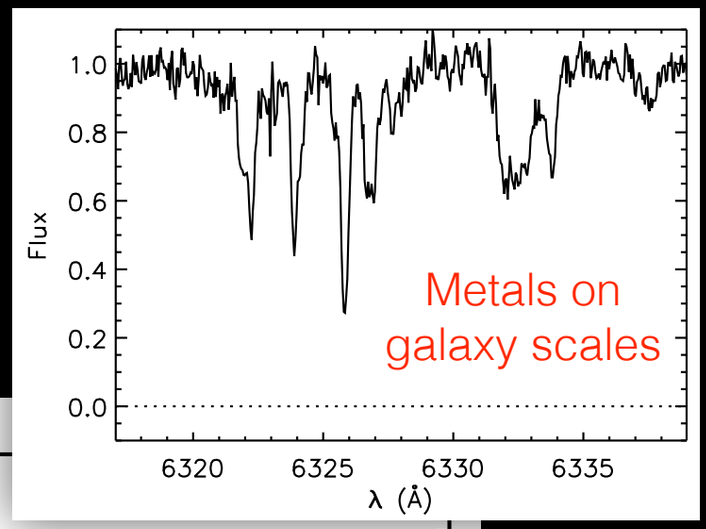


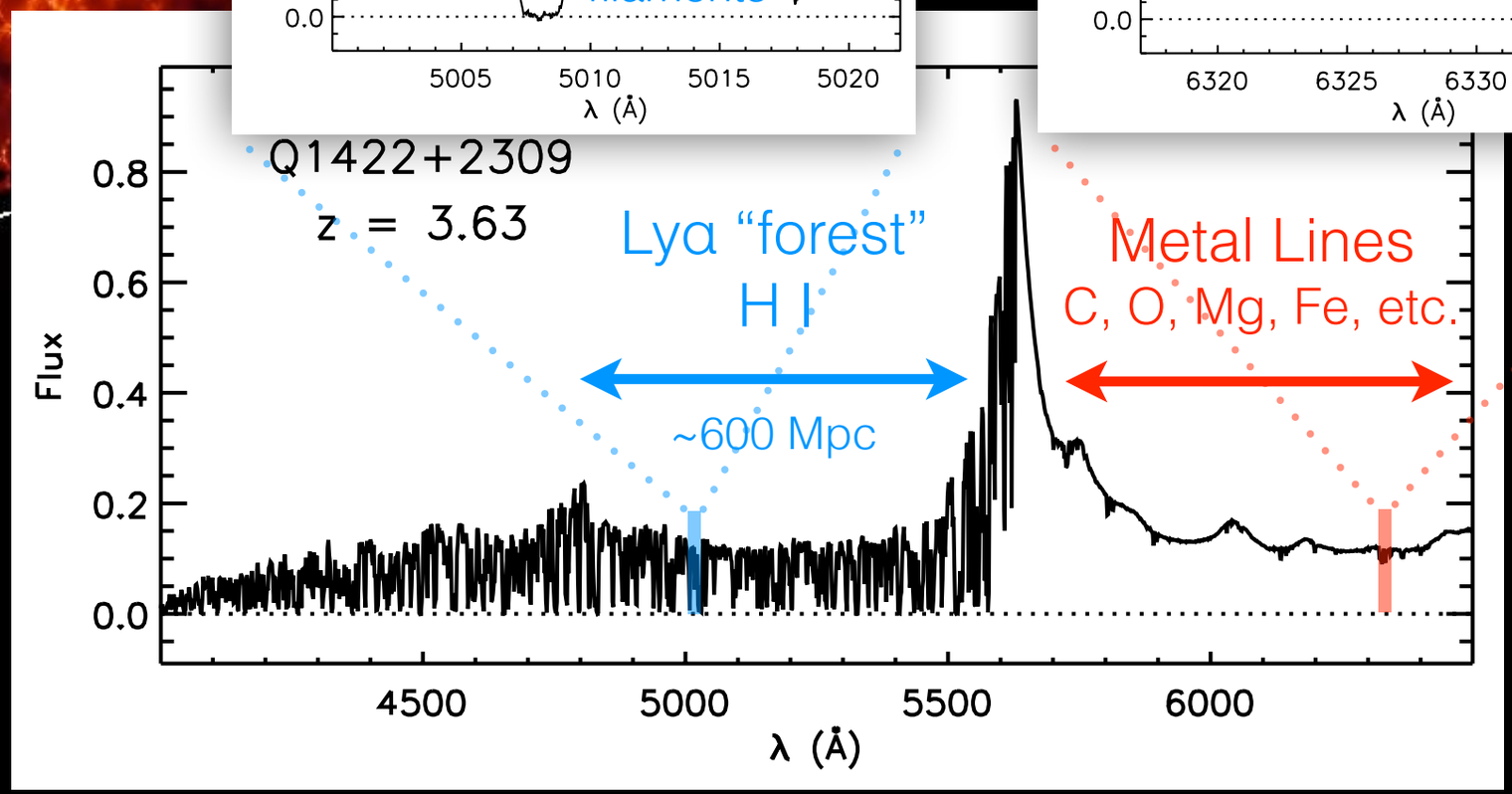
- Mildly non-linear regime
- Baryons reflect the physics of galaxy formation

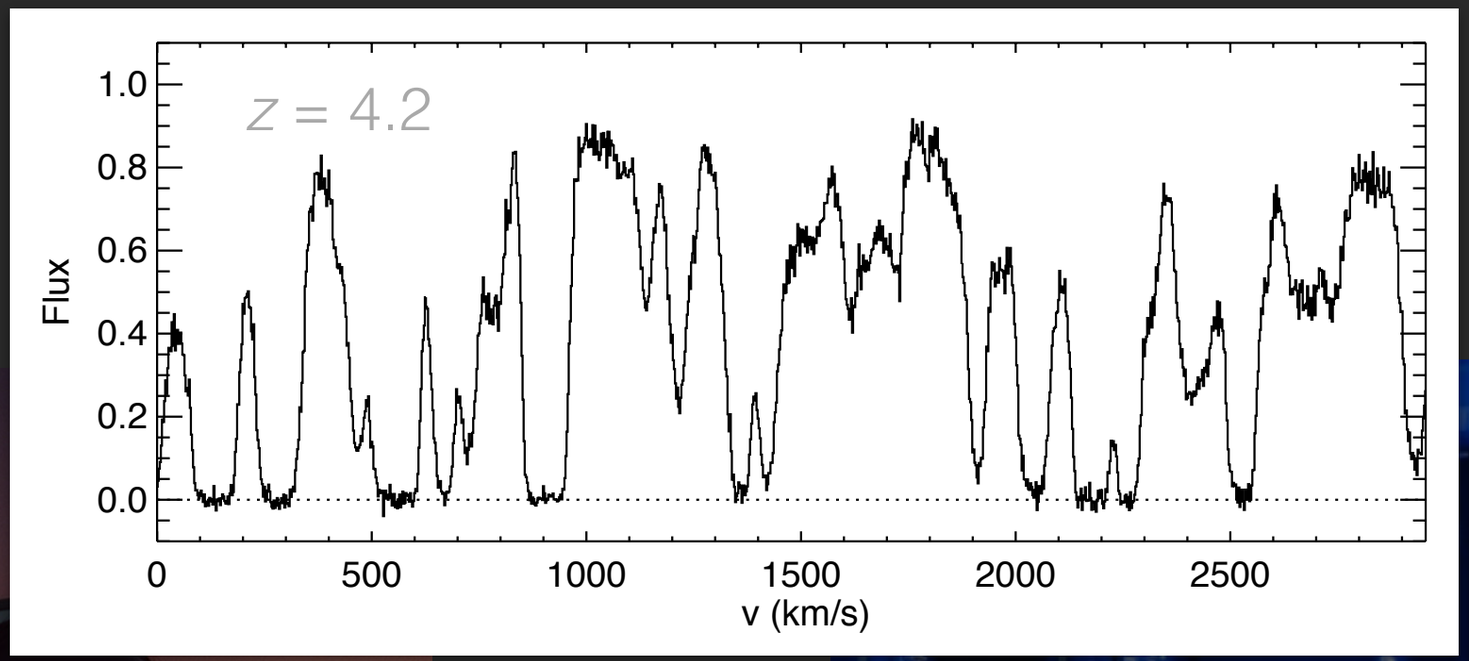
Quasar Absorption Lines

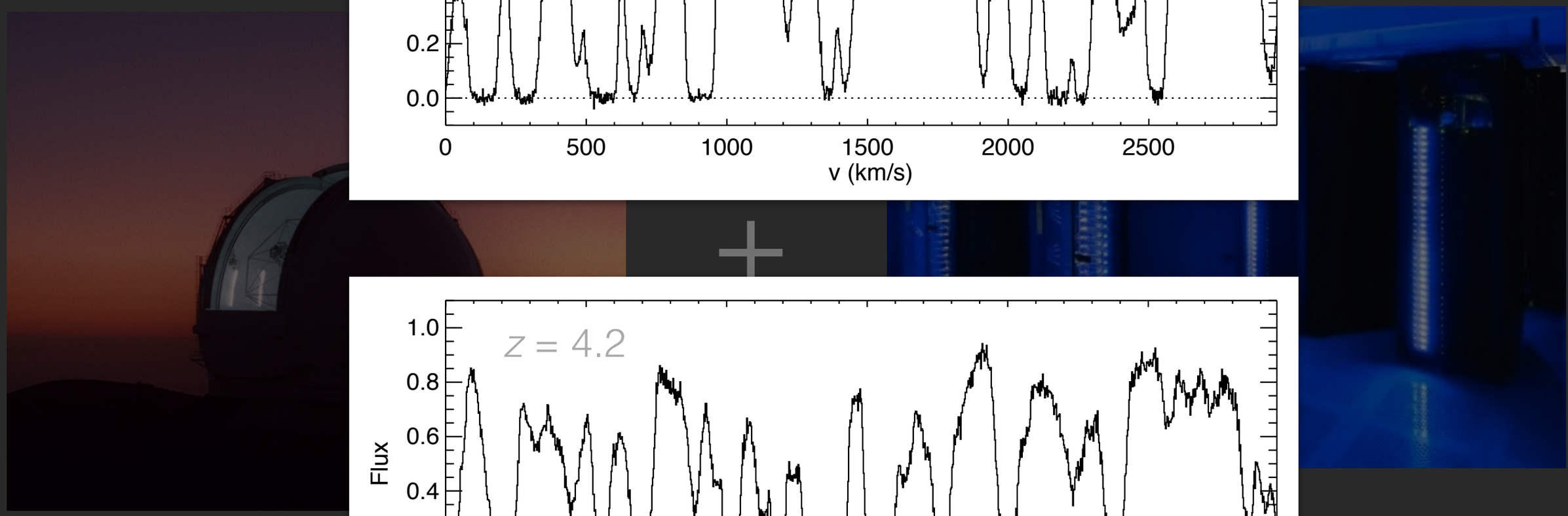








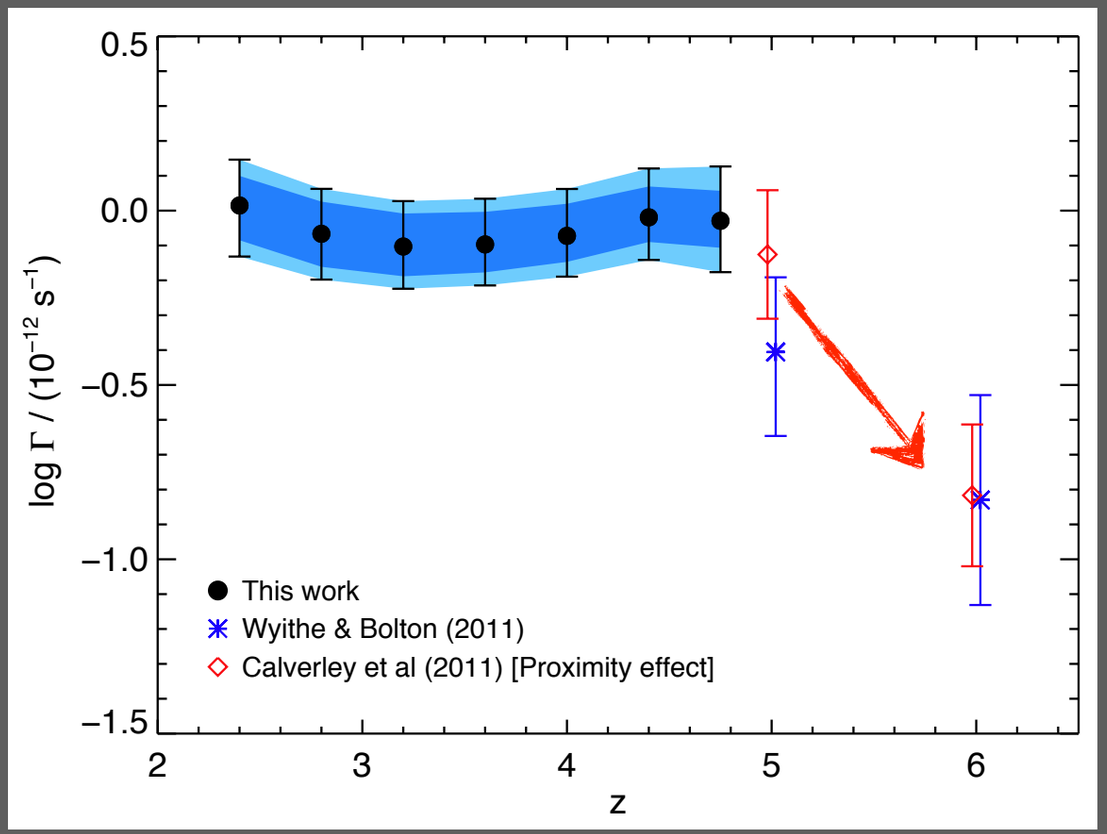

z = 4.2
Flux
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
v (km/s)



z = 4.2
Flux
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
v (km/s)

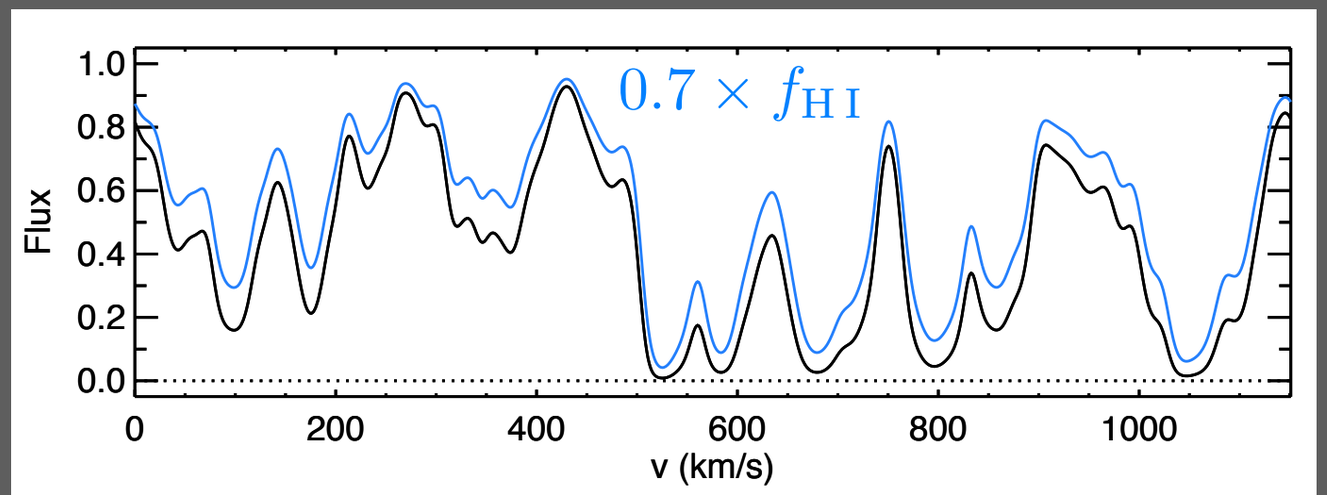
Perturbations to the IGM 1:
UV Background

Ionization rate

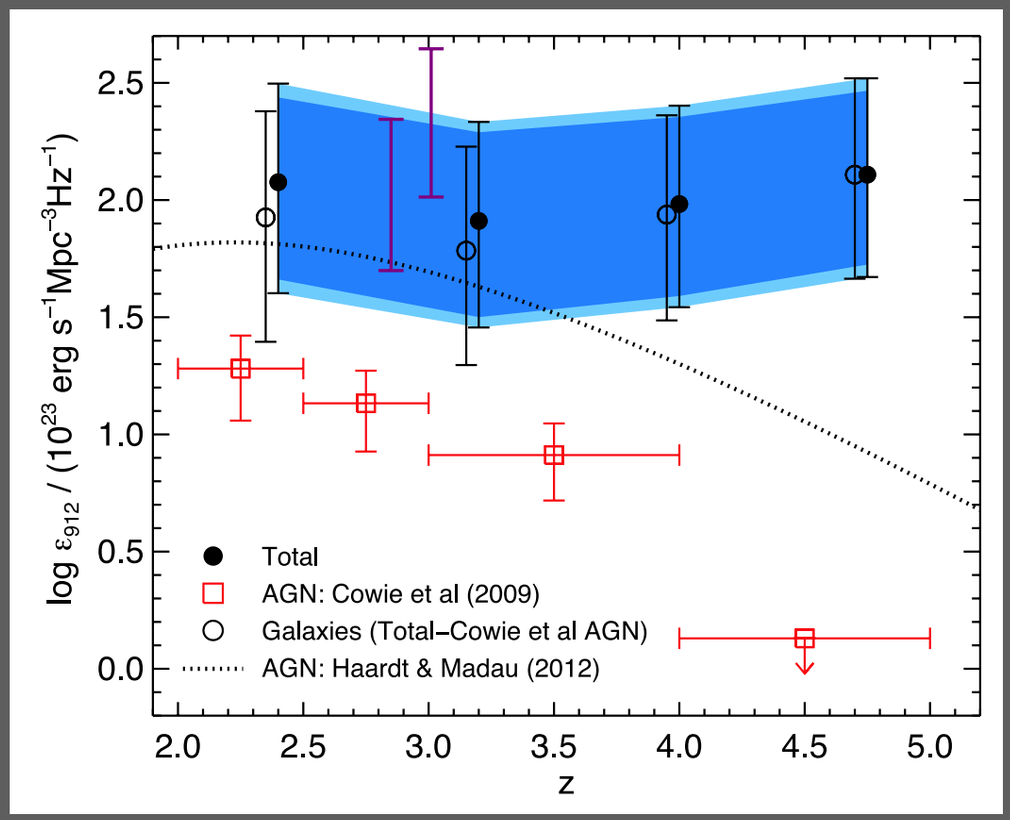


GB & Bolton 2013

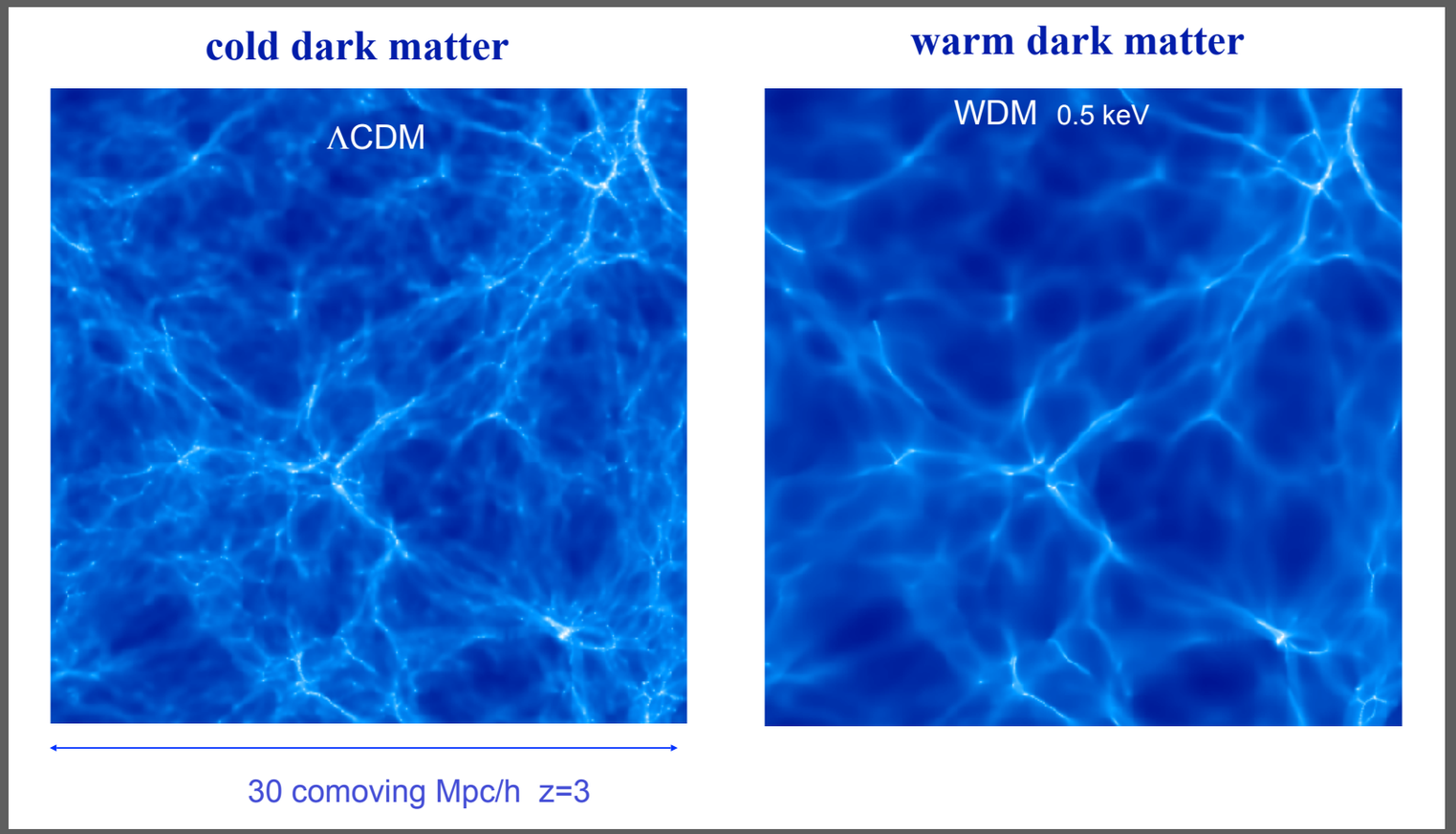
See also Davies+2018

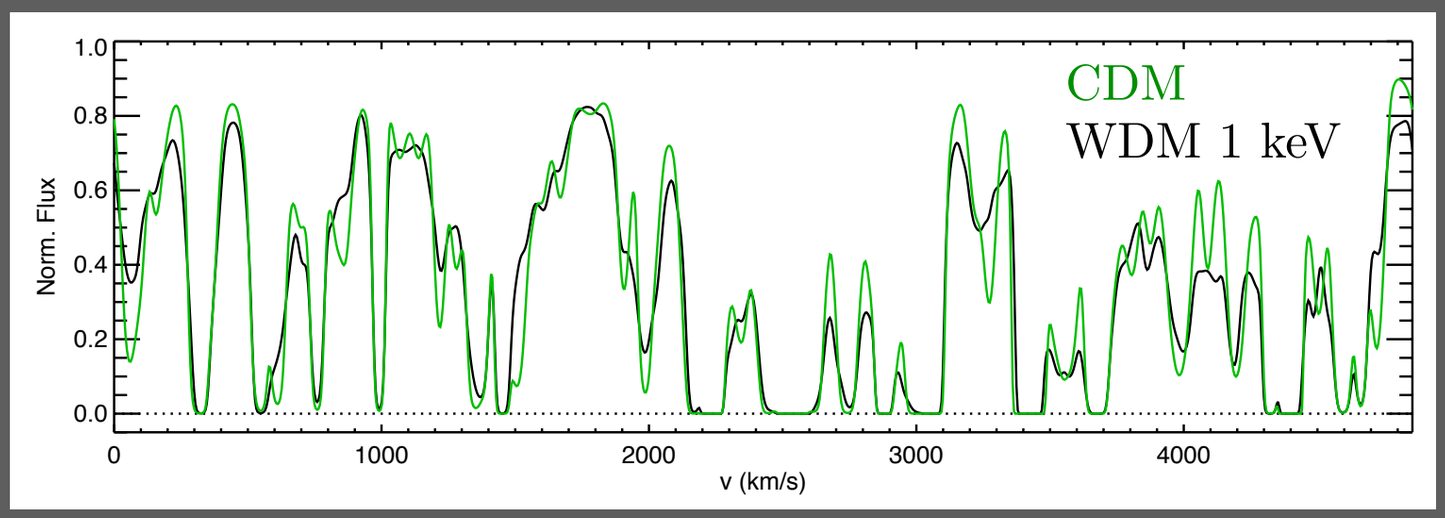


Ionizing emissivity



Perturbations to the IGM 2:
Warm Dark Matter



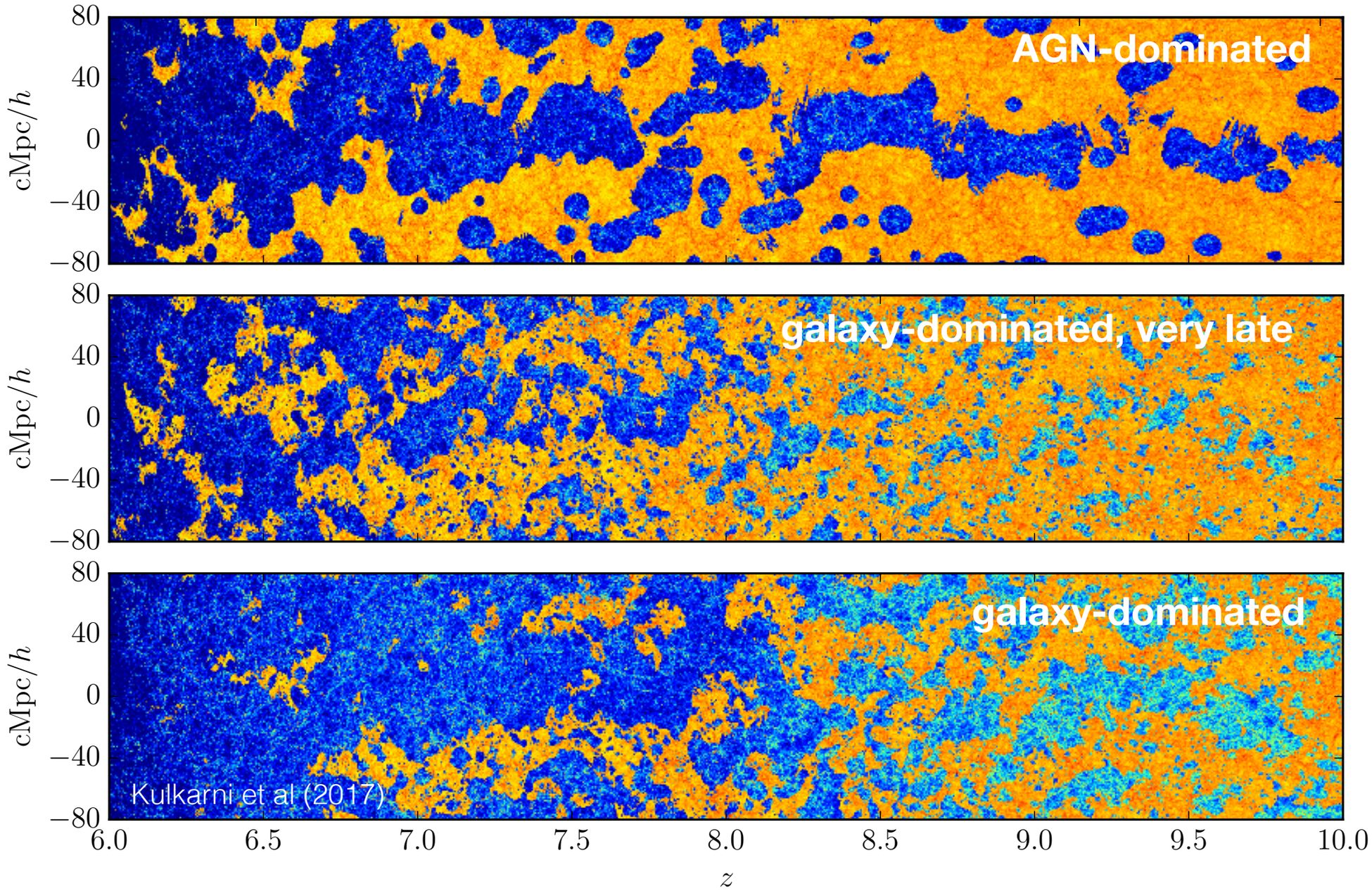


Newest constraint:

$$m_{\rm WDM} > 5.3 \text{ keV } (2\sigma)$$

Irsic+ 2017

Cosmic Reionization



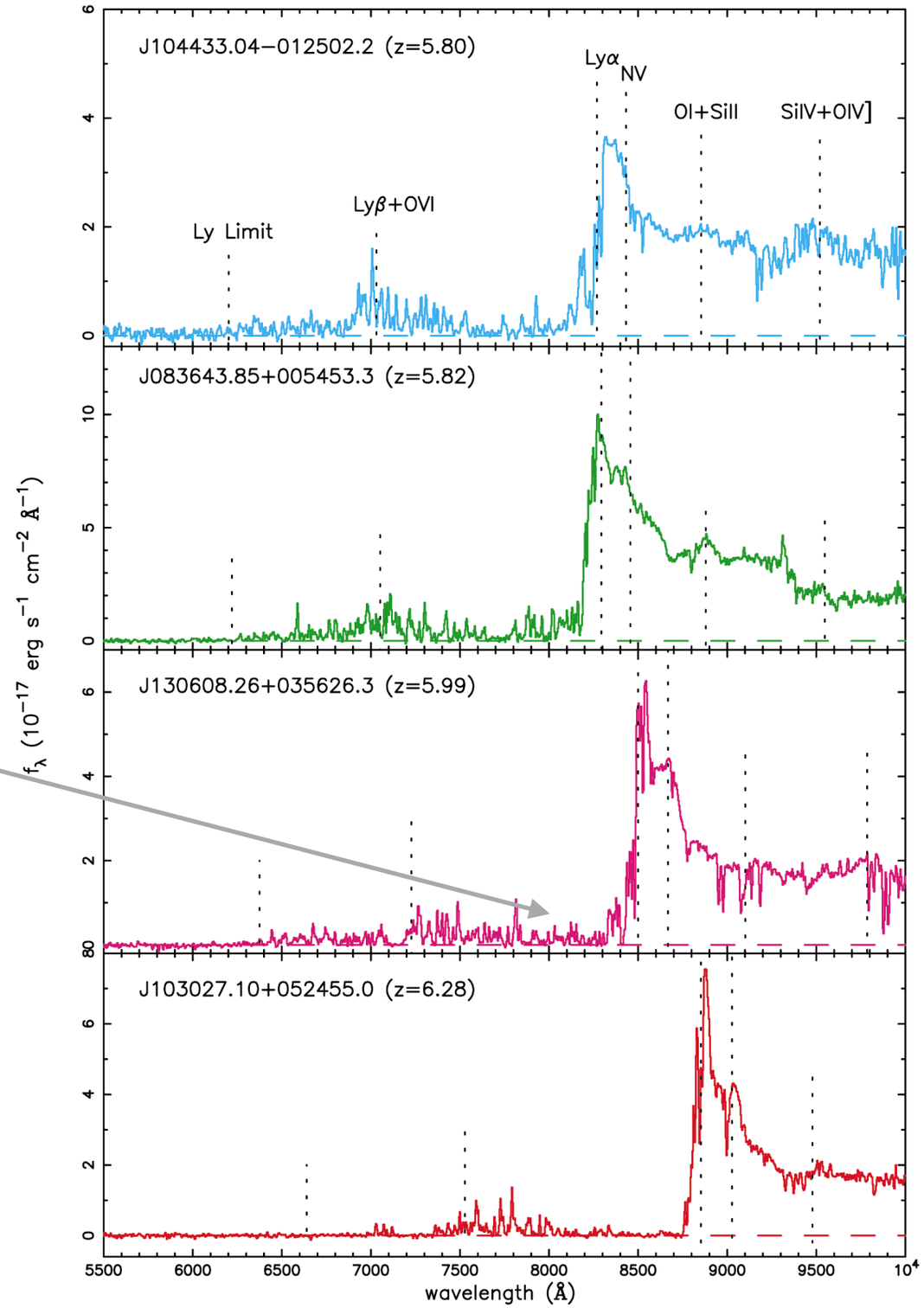
1. **When did it happen?**
2. **What sources are responsible (stars or AGN)?**

Current best constraints…

1. Lyα forest: Reionization essentially ended (by volume) by z~6

   (e.g., Fan+2006, McGreer+2015)

$$\tau_{\mathrm{Ly}\alpha} \sim 10^5 f_{\mathrm{HI}}$$

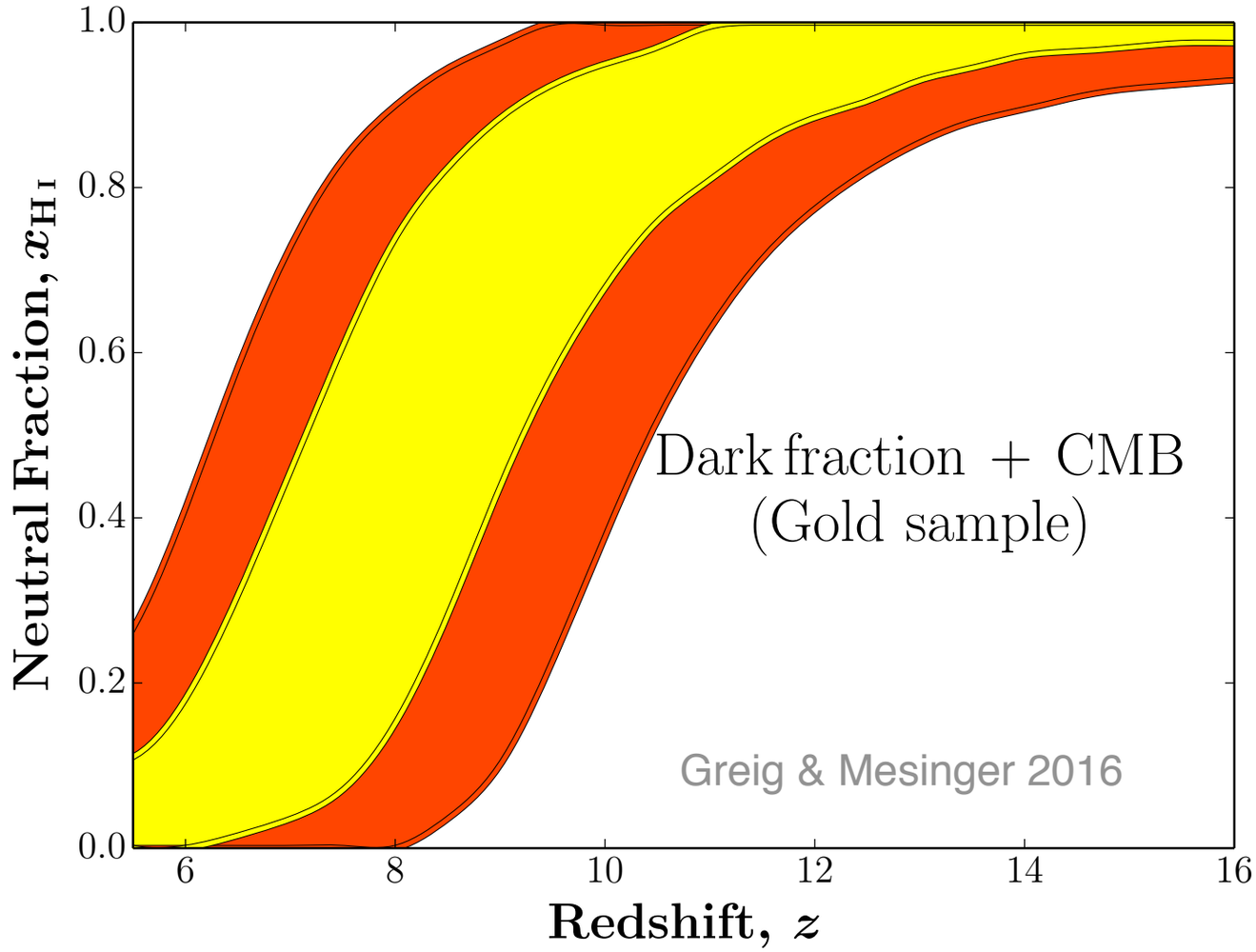


Becker+ 2001

Current best constraints…

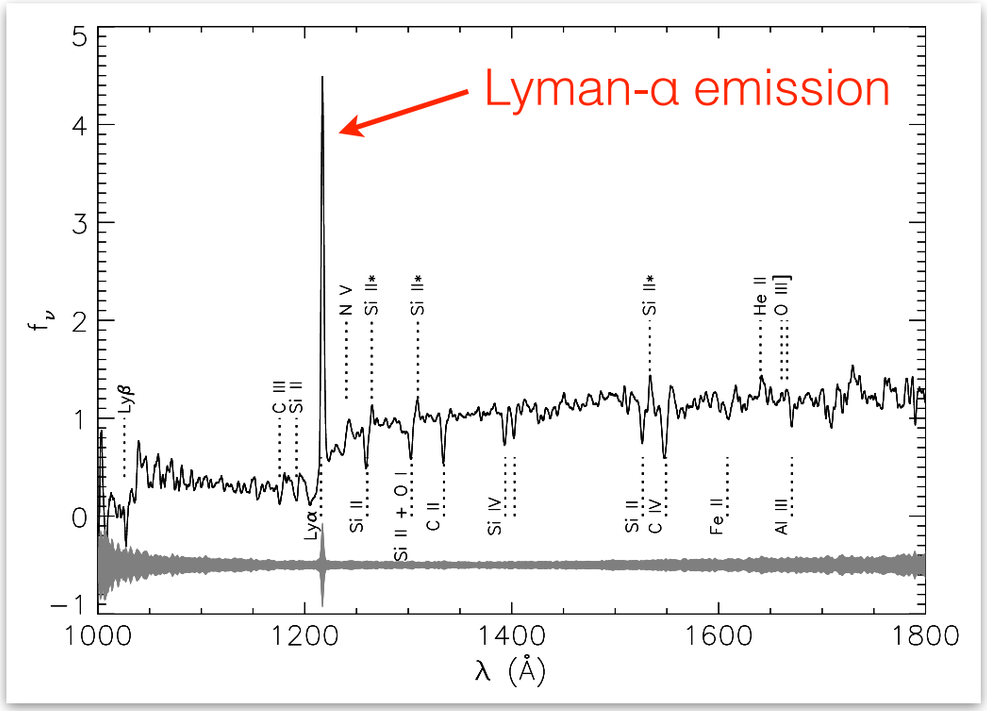
1. Lyα forest: Reionization essentially ended (by volume) by z~6
   (e.g., Fan+2006, McGreer+2015)

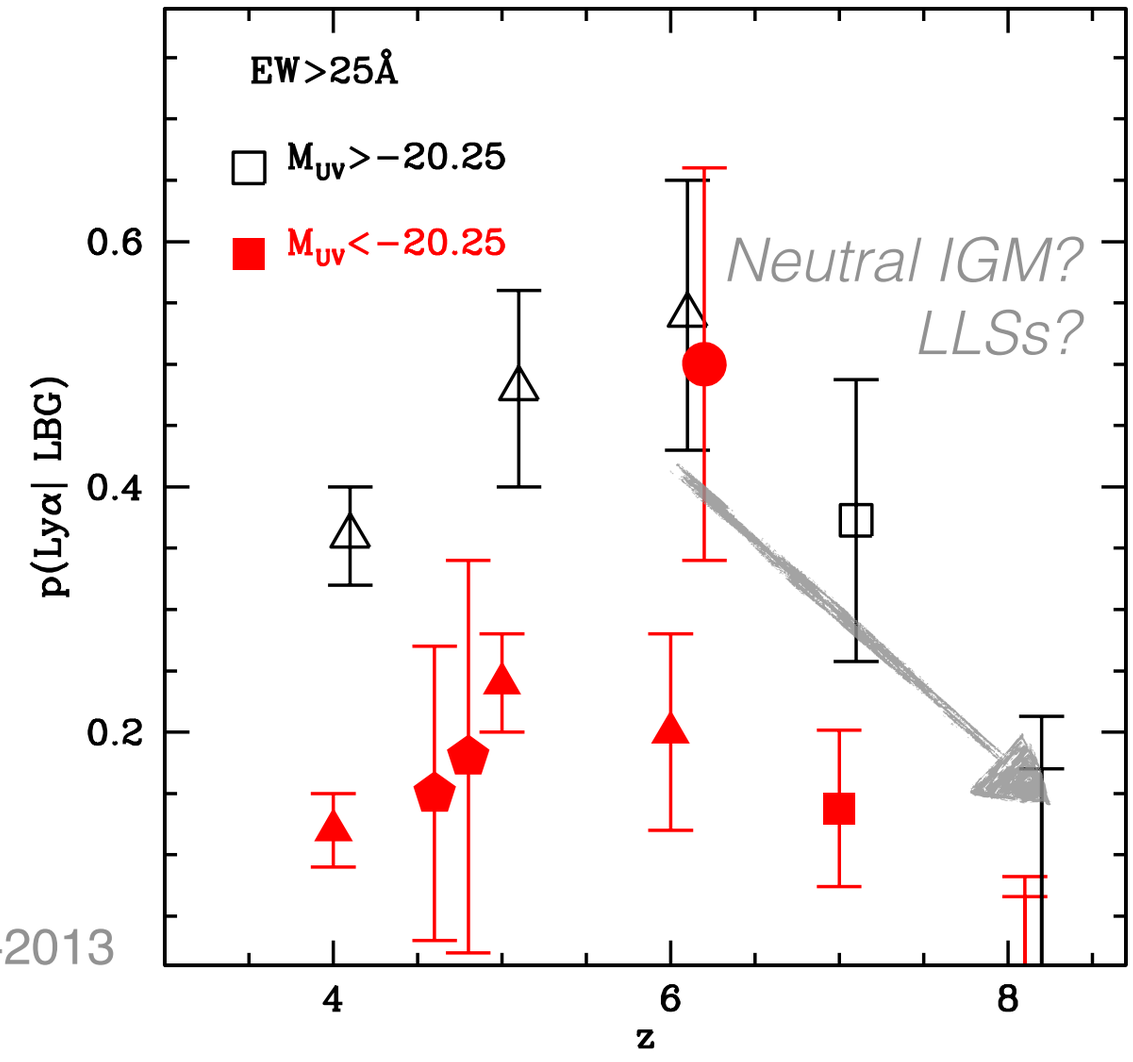
2. CMB: $\tau_e = 0.054 \pm 0.007$ (1σ)
   (Planck 2018)



Galaxy Lyα Fraction

Jones+2012 z~4 LBG Composite



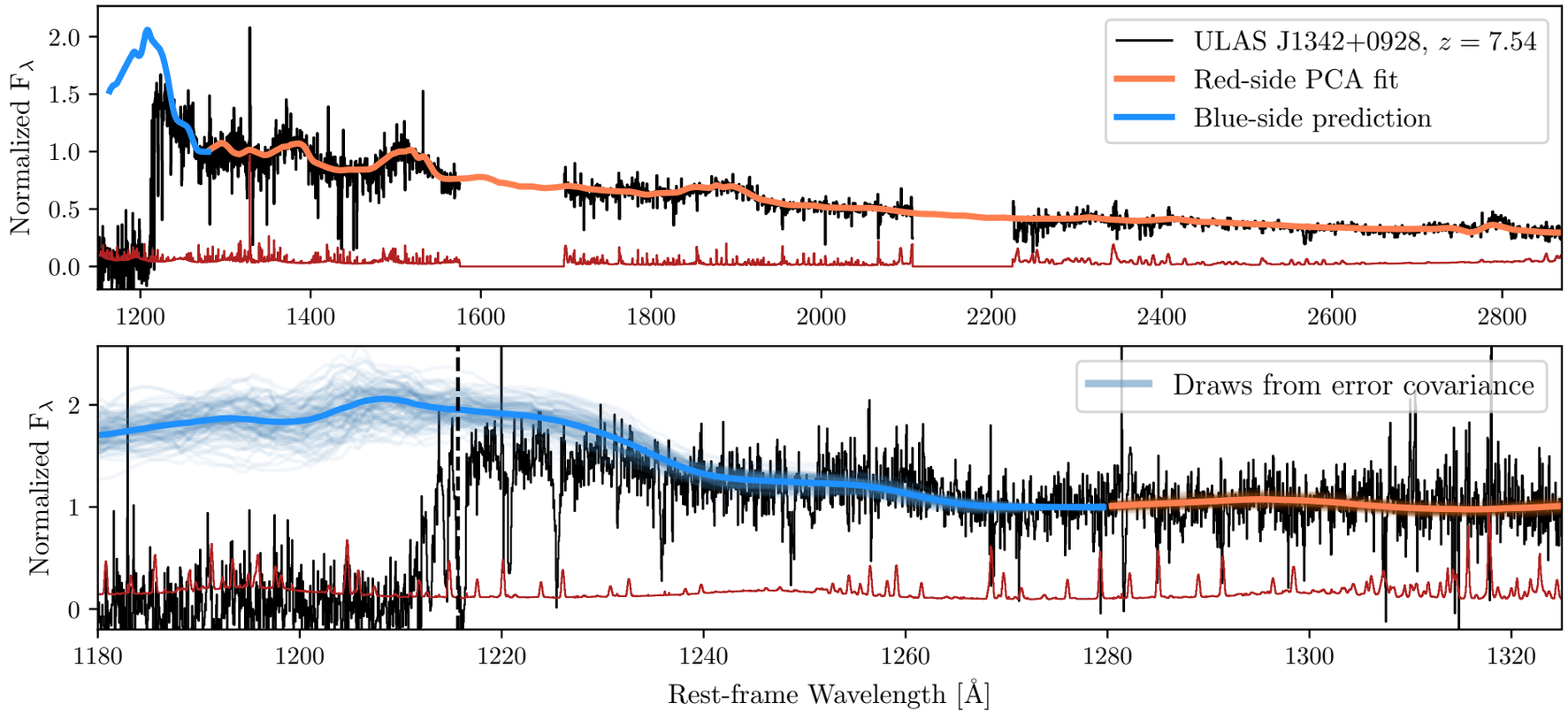


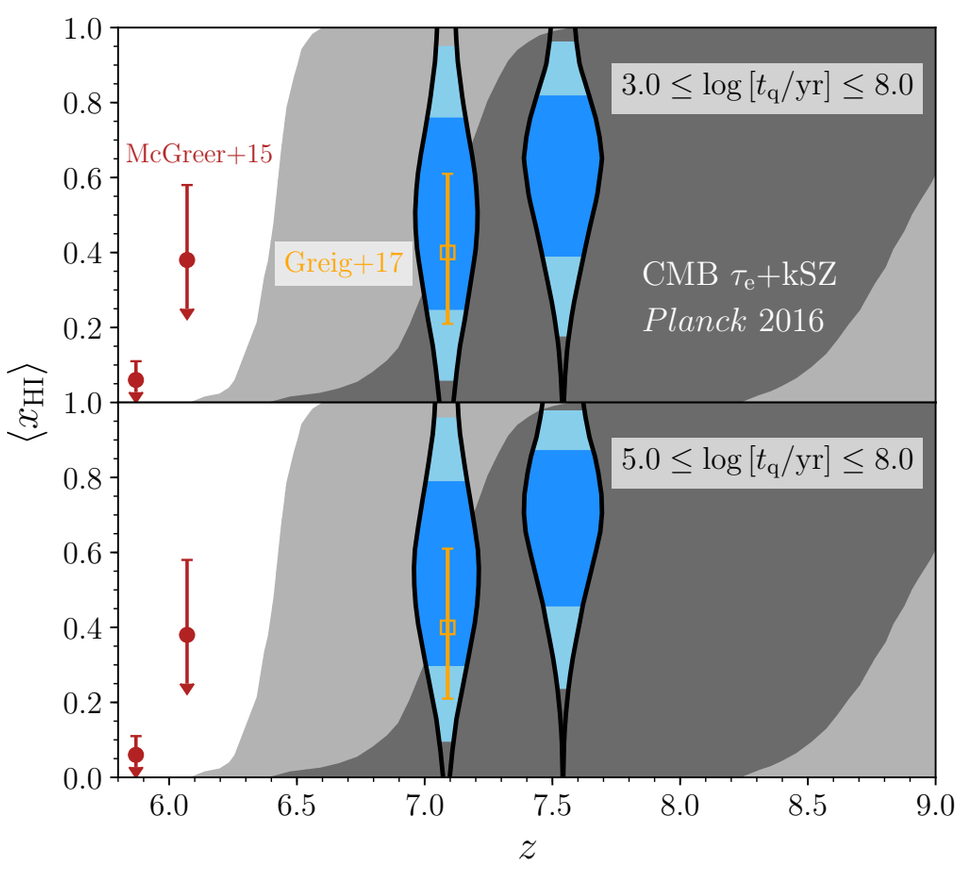
Treu+2013

Decline in the fraction of galaxies with Lyα emission at z > 6 may indicate scattering by a significantly neutral IGM.

(Observations: e.g., Stark+2010; Pentericci+2011; Ono+2012; Treu+2013; Caruna+2014; Schenker+2014; Modeling: Bolton & Haehnelt 2013; Mesinger+2015, see also Dijkstra+2014)

Damping wings in z > 7 QSO spectra





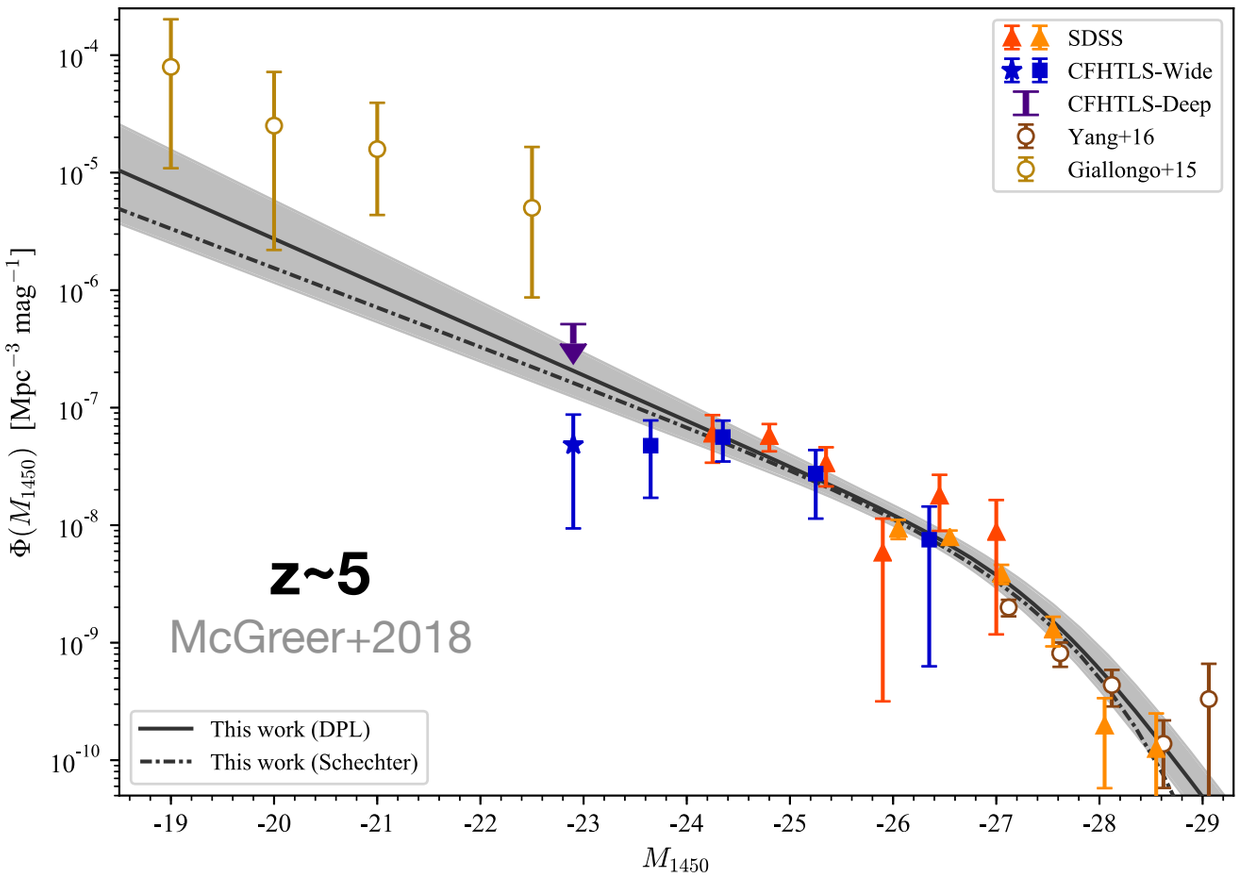
Tend to favor significant neutral fractions at z > 7.

(Mortlock+2011, Bolton+2011, Bosman+2015, Grieg+2017, Davies+2018a,b)

Figures from Davies+2018b

Sources

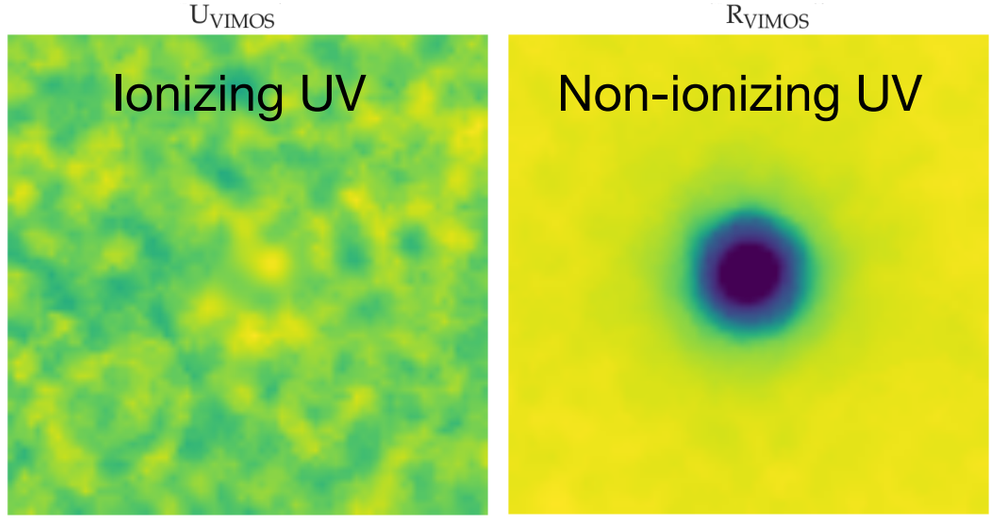
AGN?

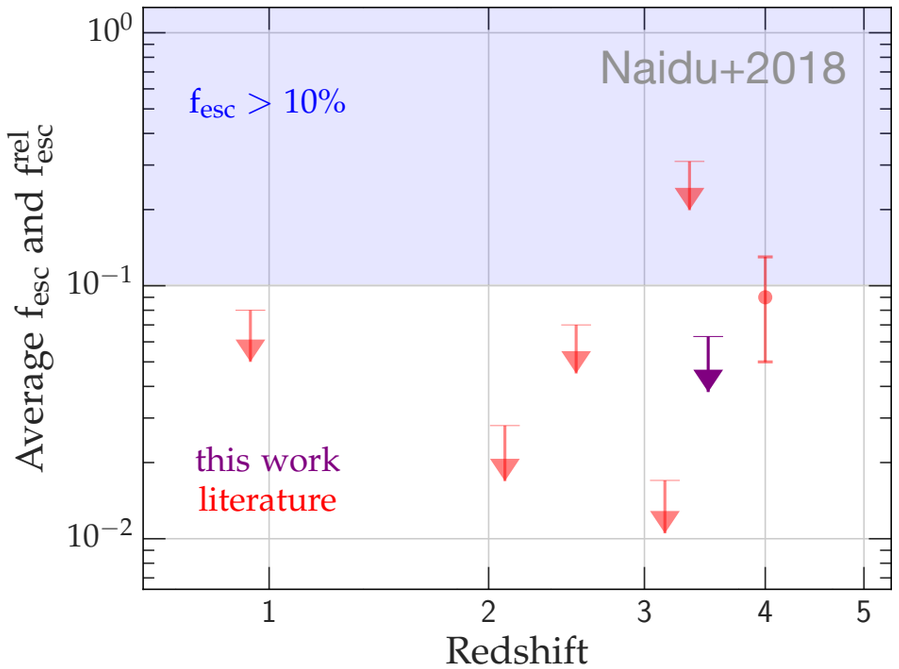


AGN definitely emit ionizing photons, but are there enough at z > 6?

(e.g., Madau & Haardt 2015)

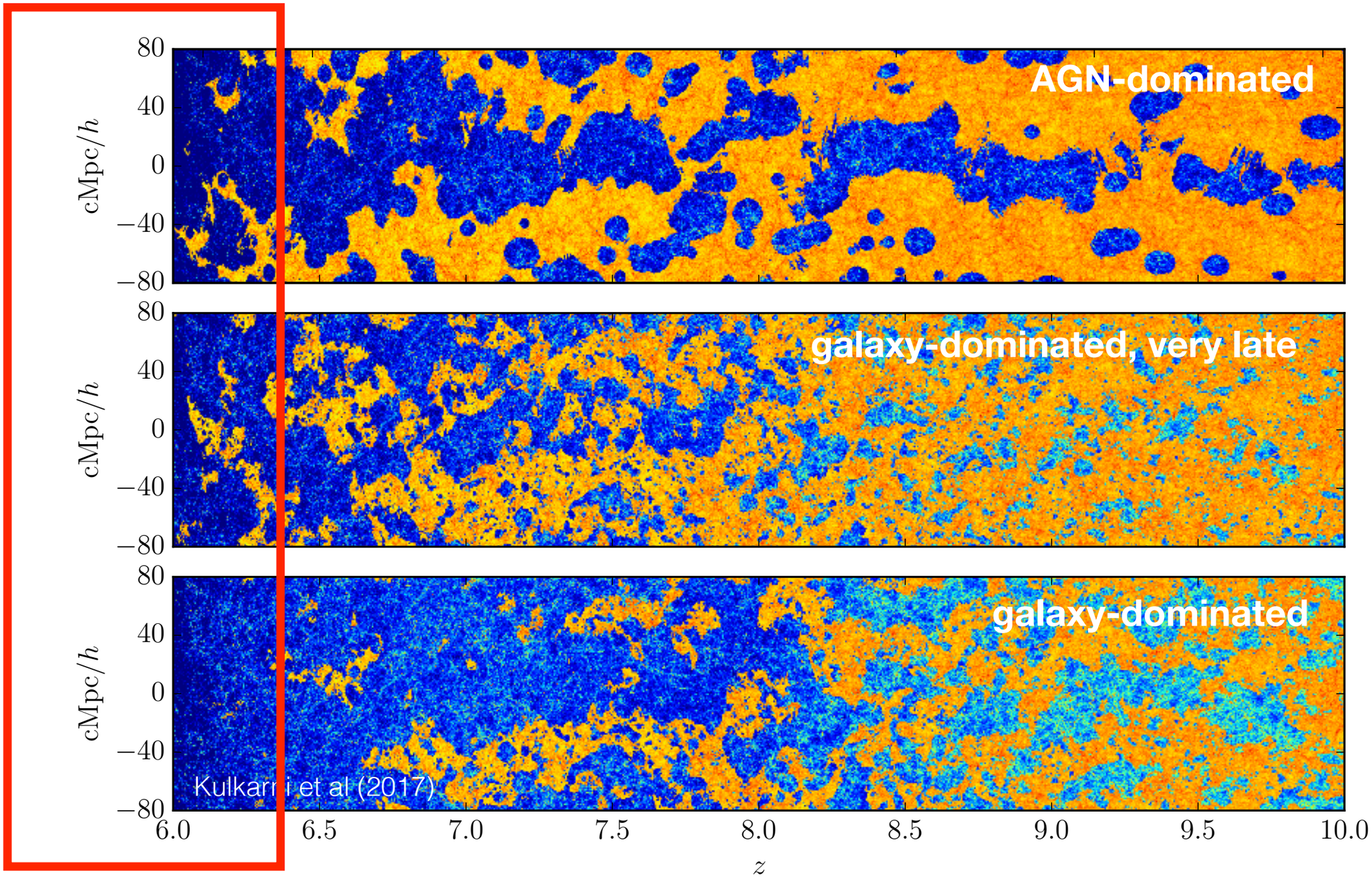
Star-forming galaxies?





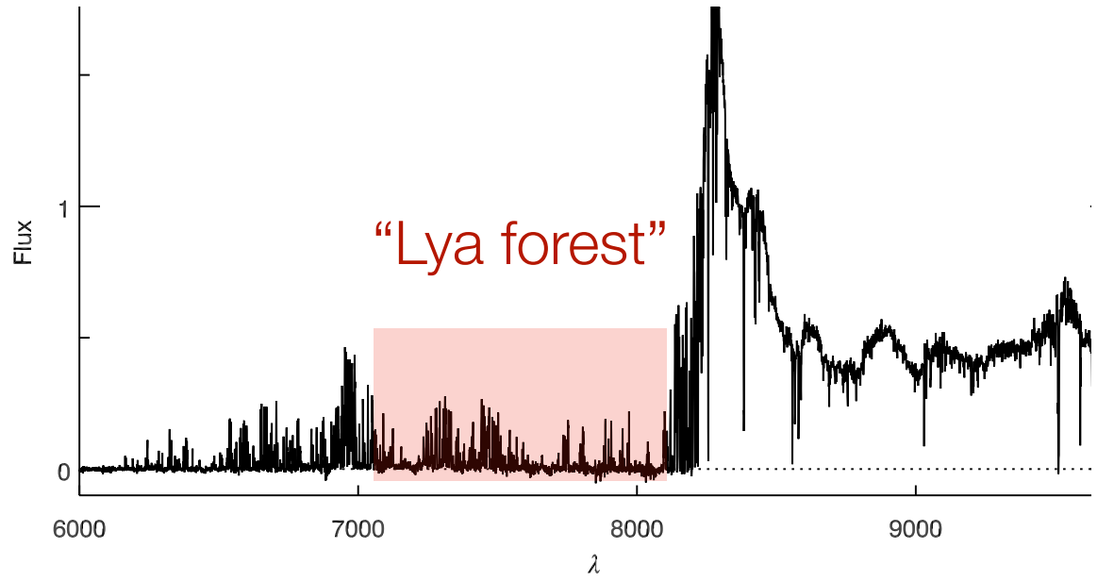
Plenty of star formation at z > 6, but do the ionizing photons escape?

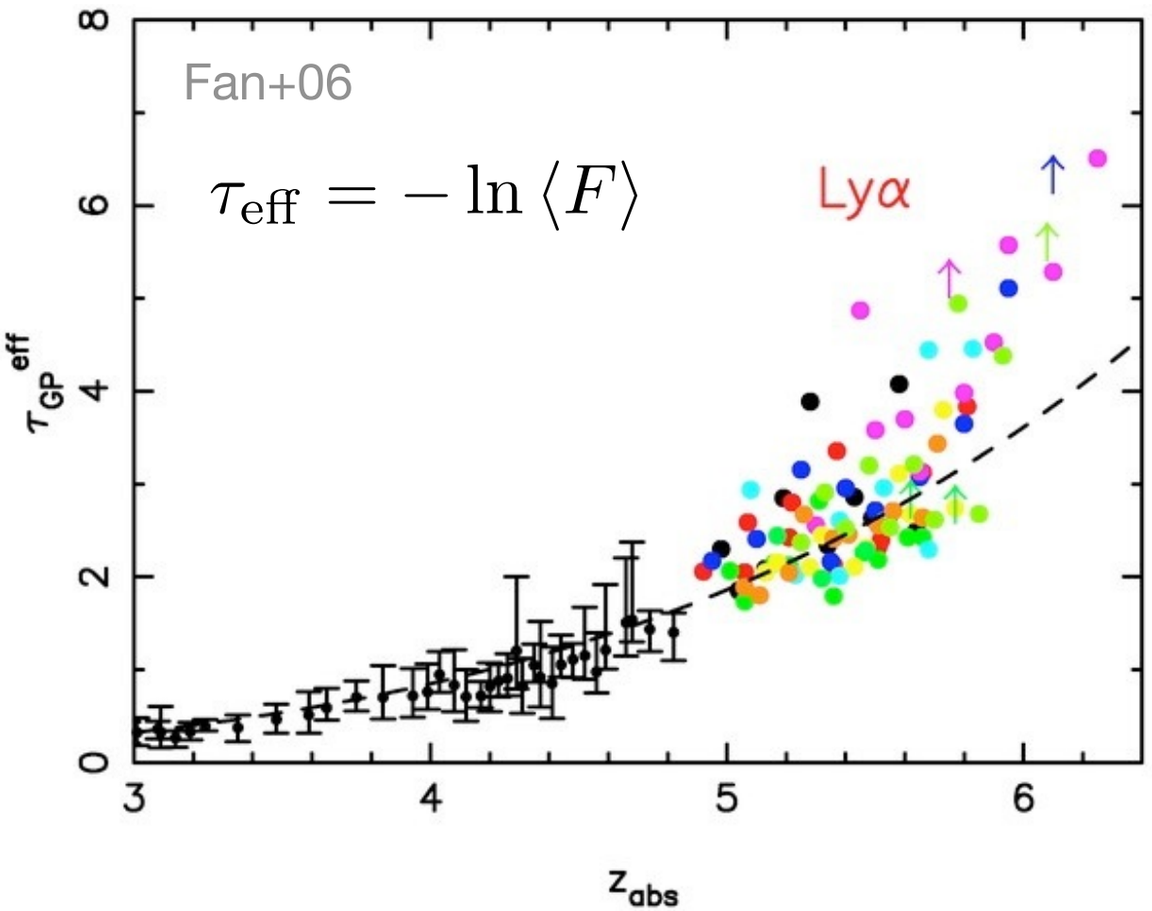
Cosmic Reionization



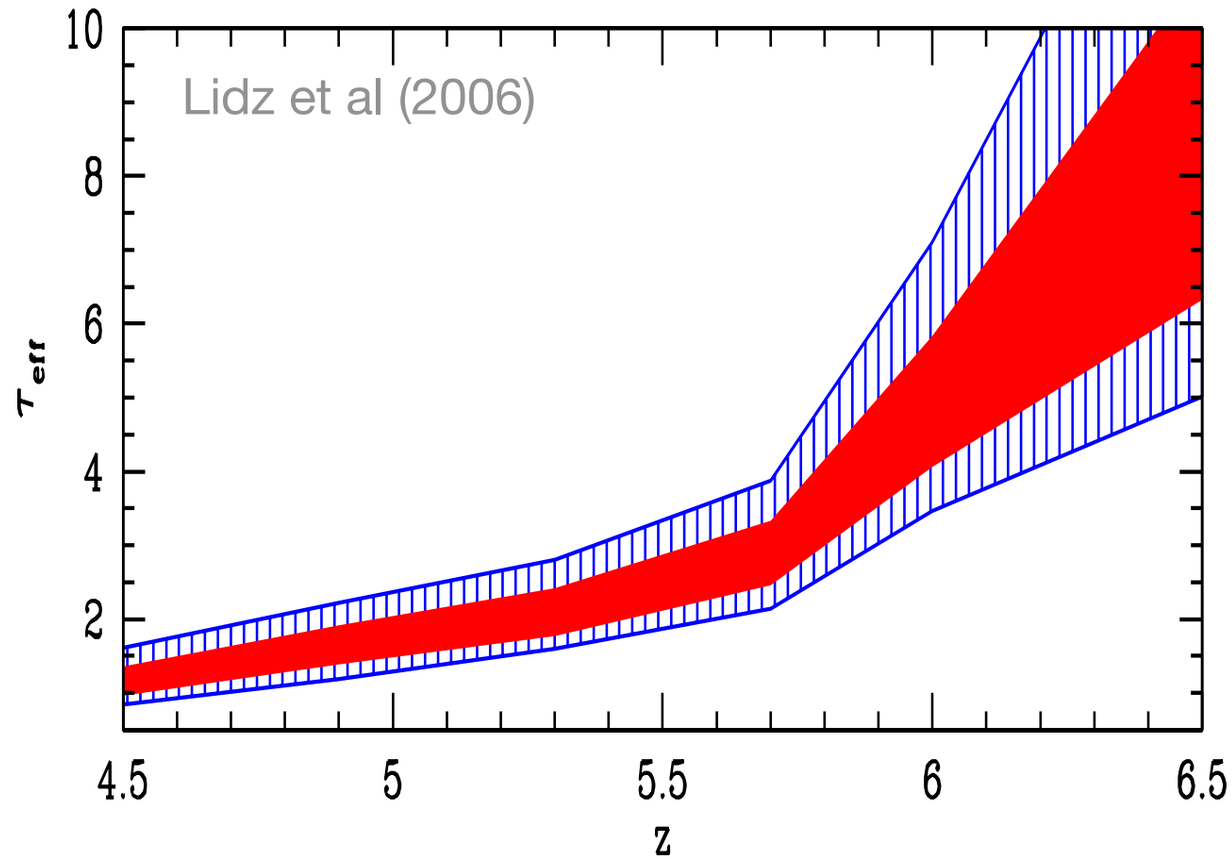
What more can we learn from the post-reionization IGM?

IGM opacity from the Lyα forest

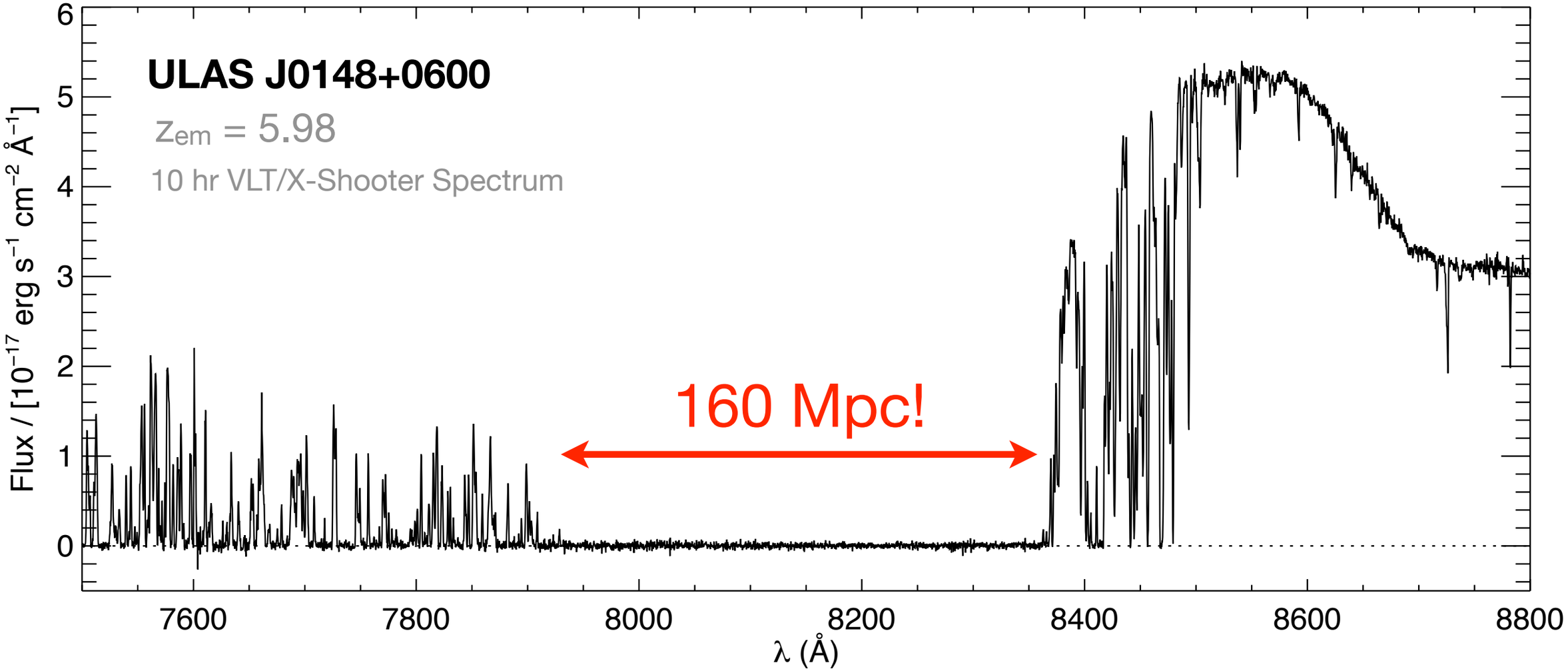


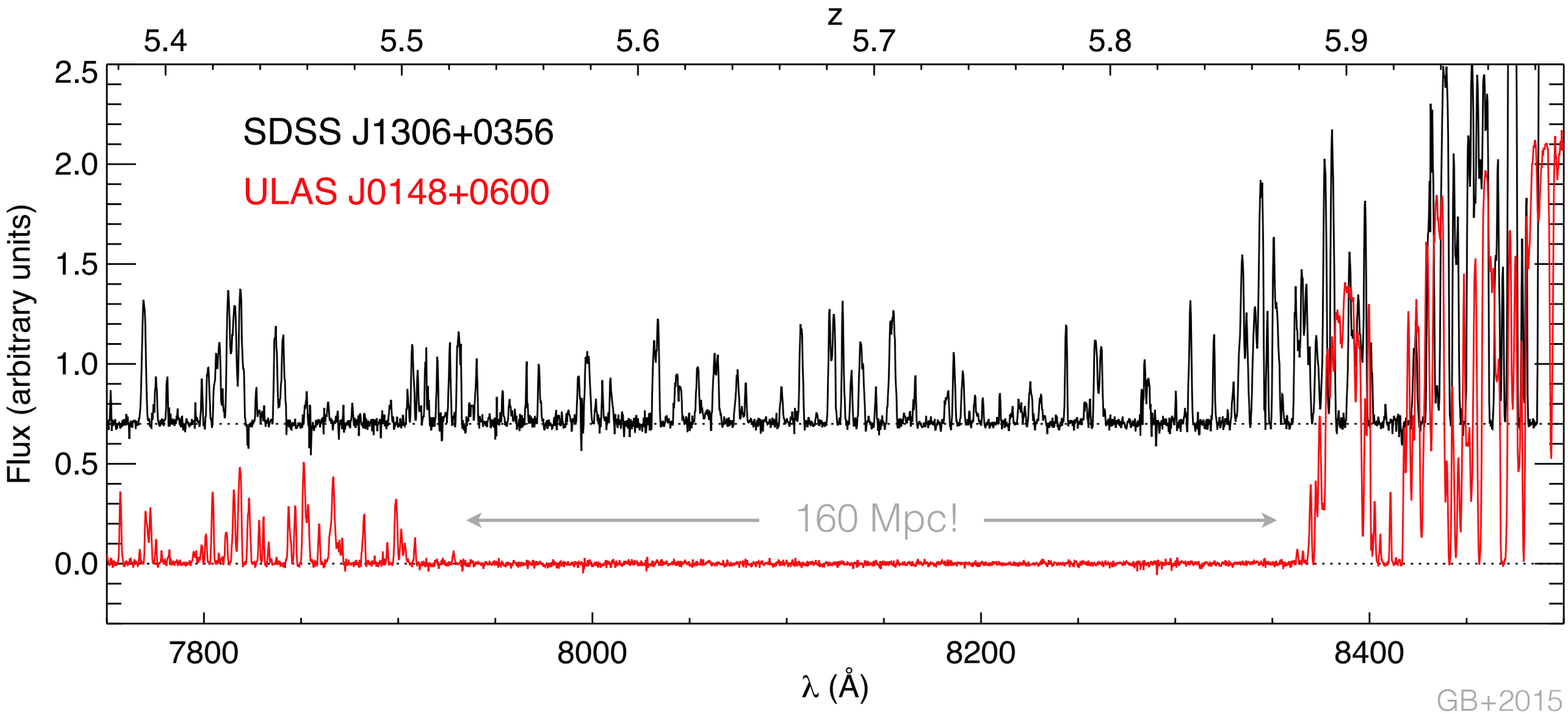


The Lya forest at z < 6 is patchy…



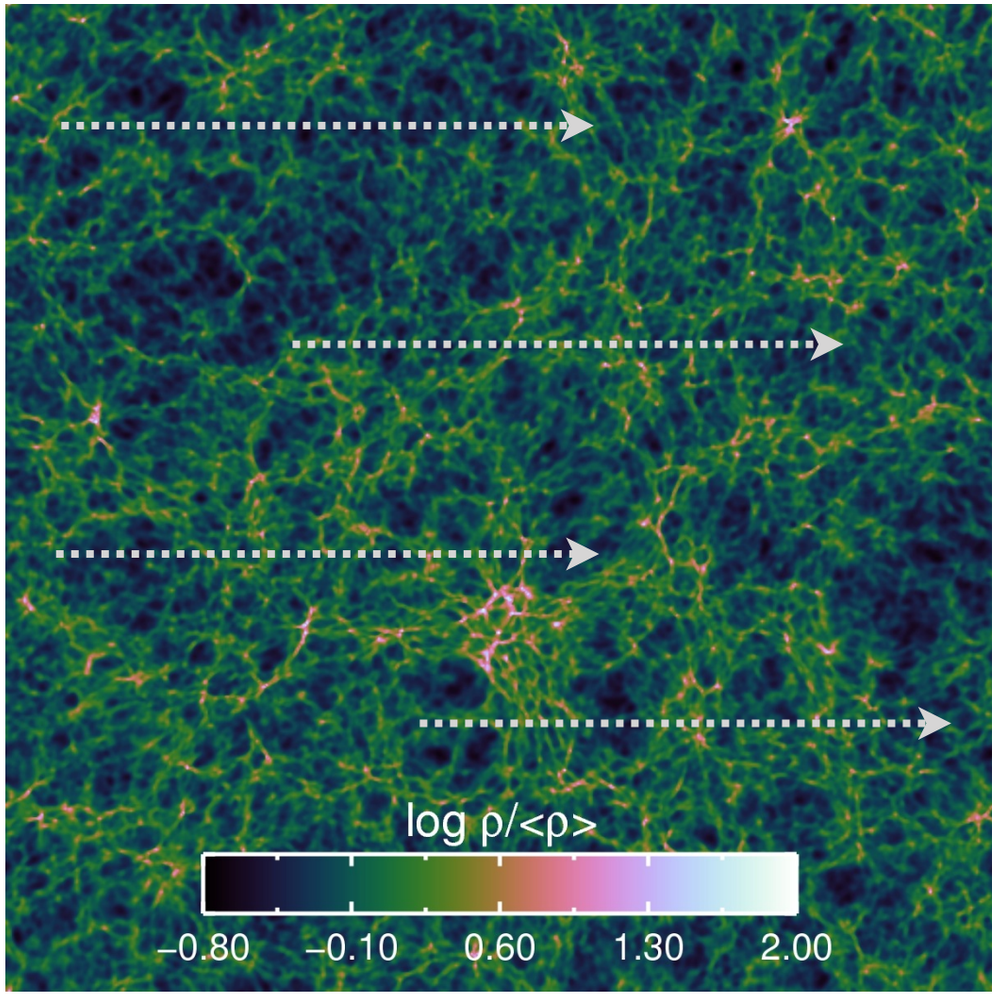
…but there will be patchiness from density fluctuations alone.

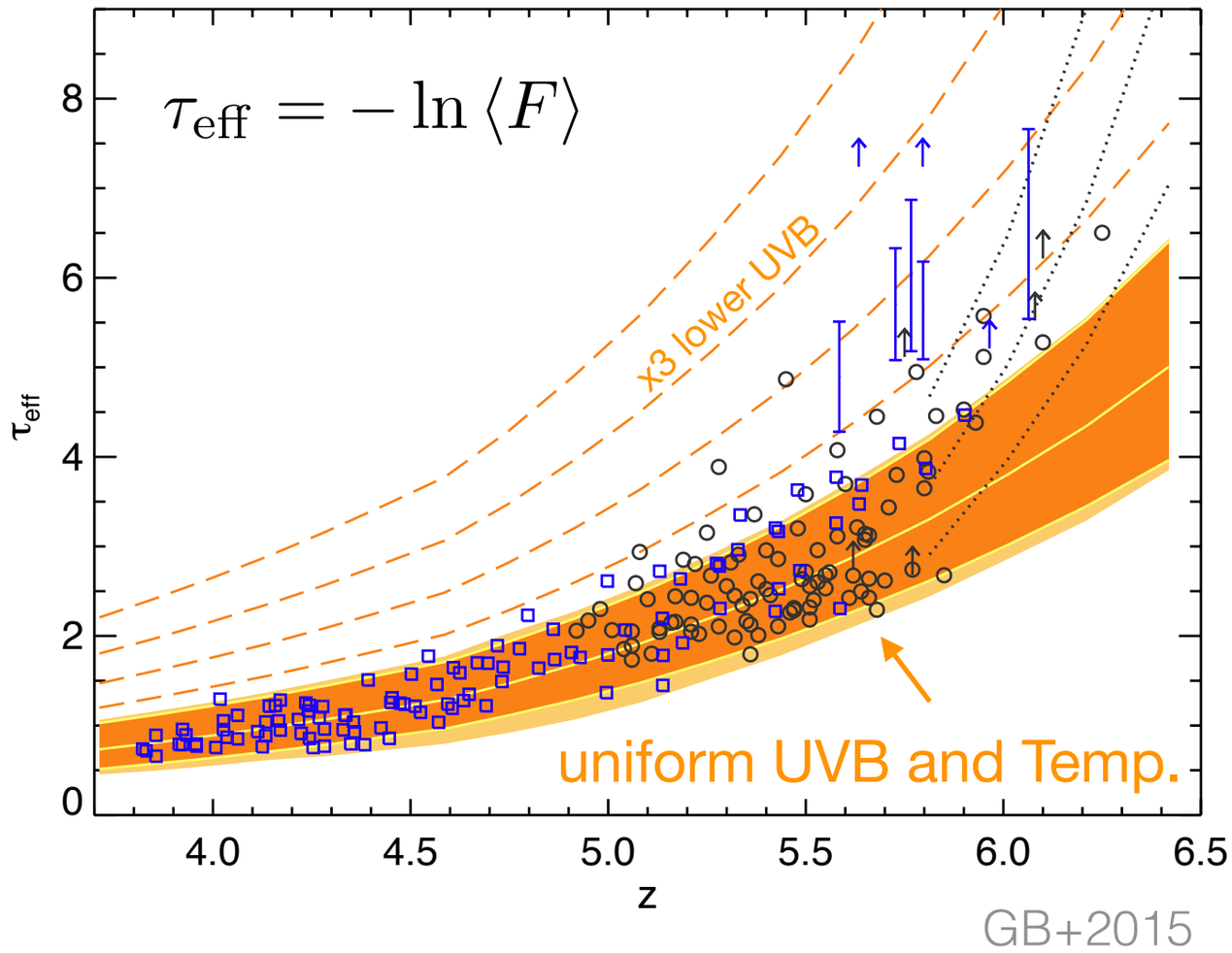

ULAS J0148+0600
z_{em} = 5.98
10 hr VLT/X-Shooter Spectrum
160 Mpc!
Flux / [10^{-17} erg s^{-1} cm^{-2} Å^{-1}]
λ (Å)
0
1
2
3
4
5
6
7600
7800
8000
8200
8400
8600
8800



What drives the large scatter in Lyα opacity z > 5?

It must be more than density fluctuations.





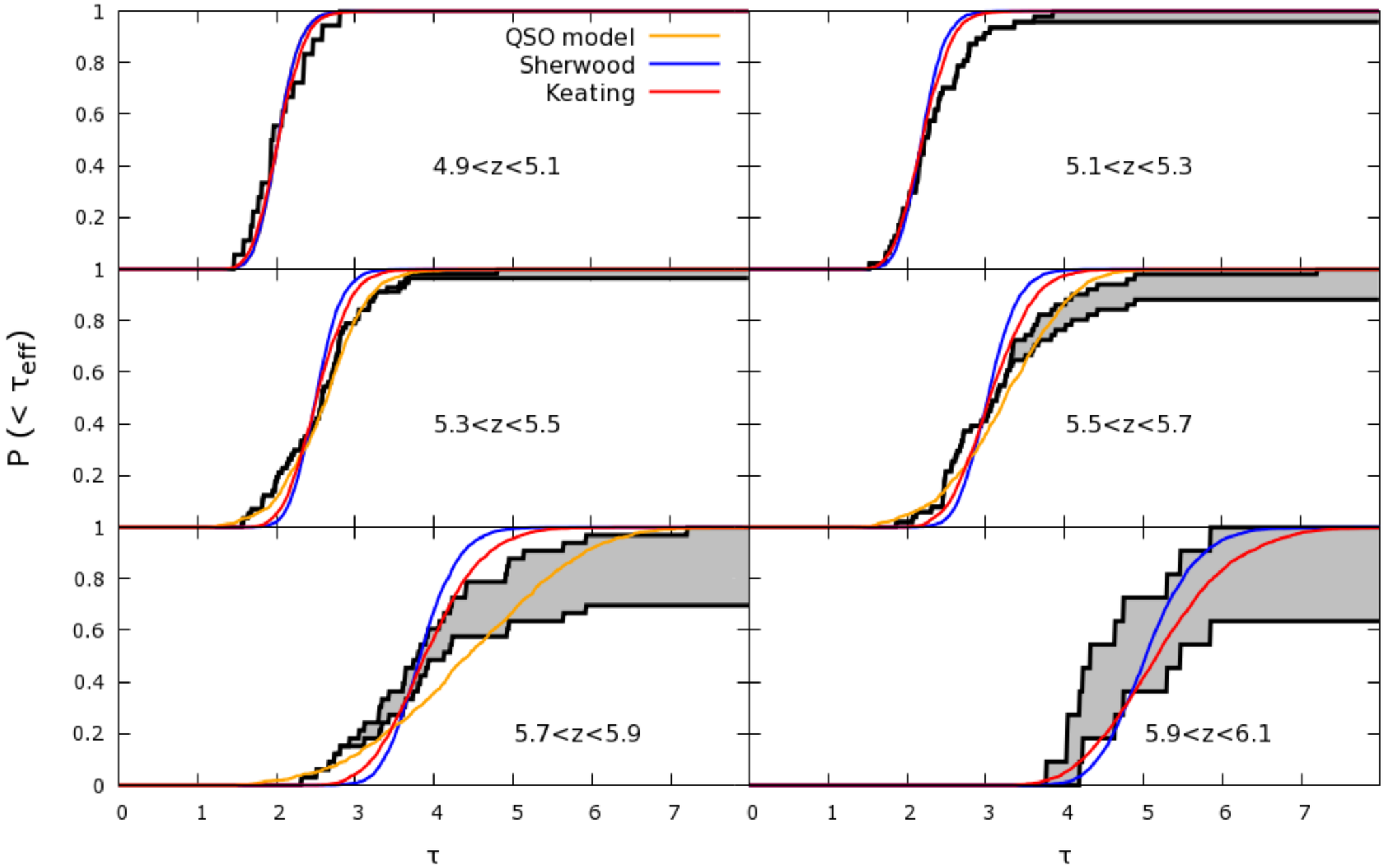
GB+2015

…and see Bosman+2018, Eilers+2018

Factor of >3 fluctuations in neutral fraction required.

62 QSOs at z > 5.7

Bosman+2018



Lyα opacity

Uniform UVB, T-ρ relation

Possible models…

Neutral fraction: $$f_{\mathrm{H\,I}} \propto n_{\mathrm{H}} \Gamma^{-1} T^{-0.7}$$

Density **UVB** **Temperature**

Possible models…

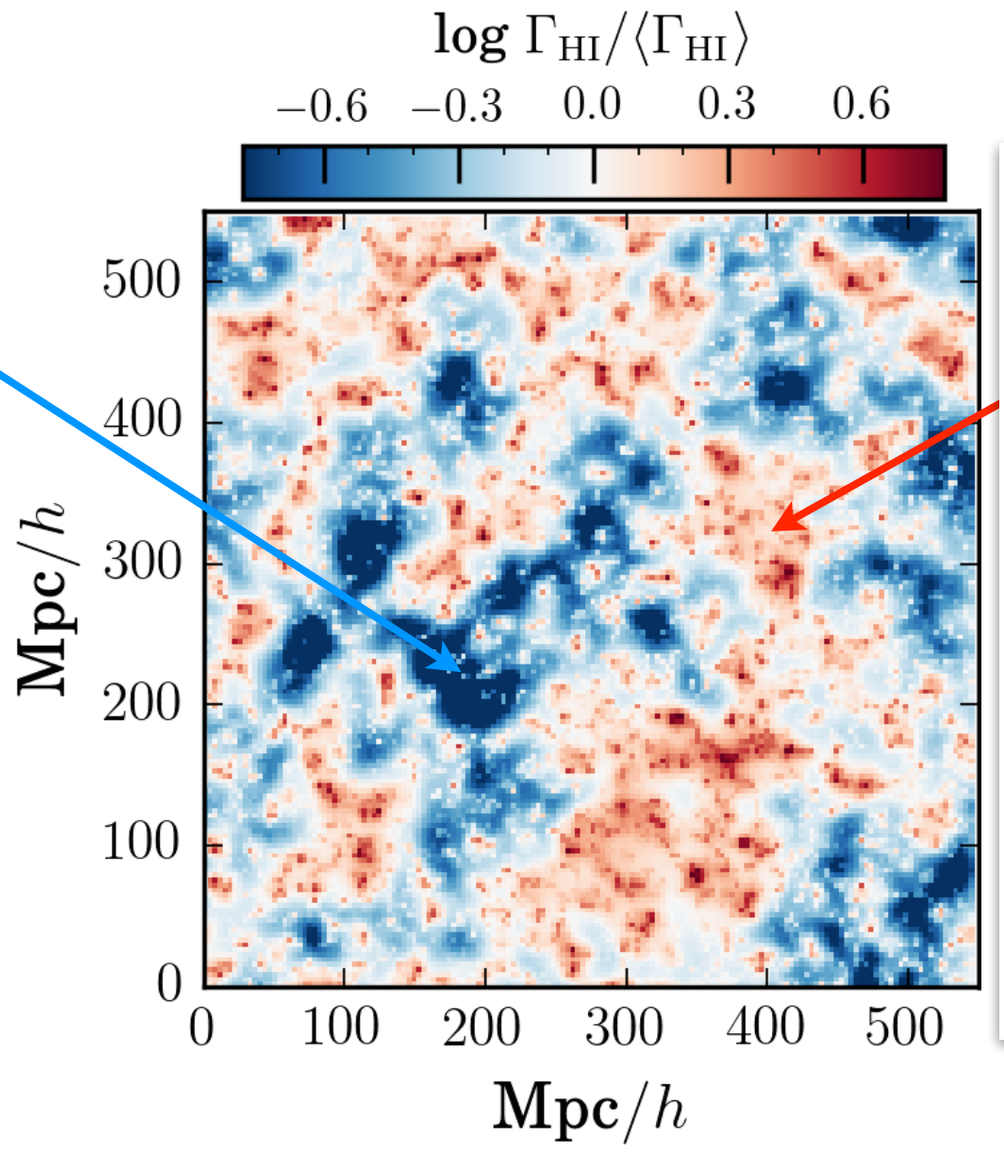
$$f_{\mathrm{H\,I}} \propto n_{\mathrm{H}} \Gamma^{-1} T^{-0.7}$$

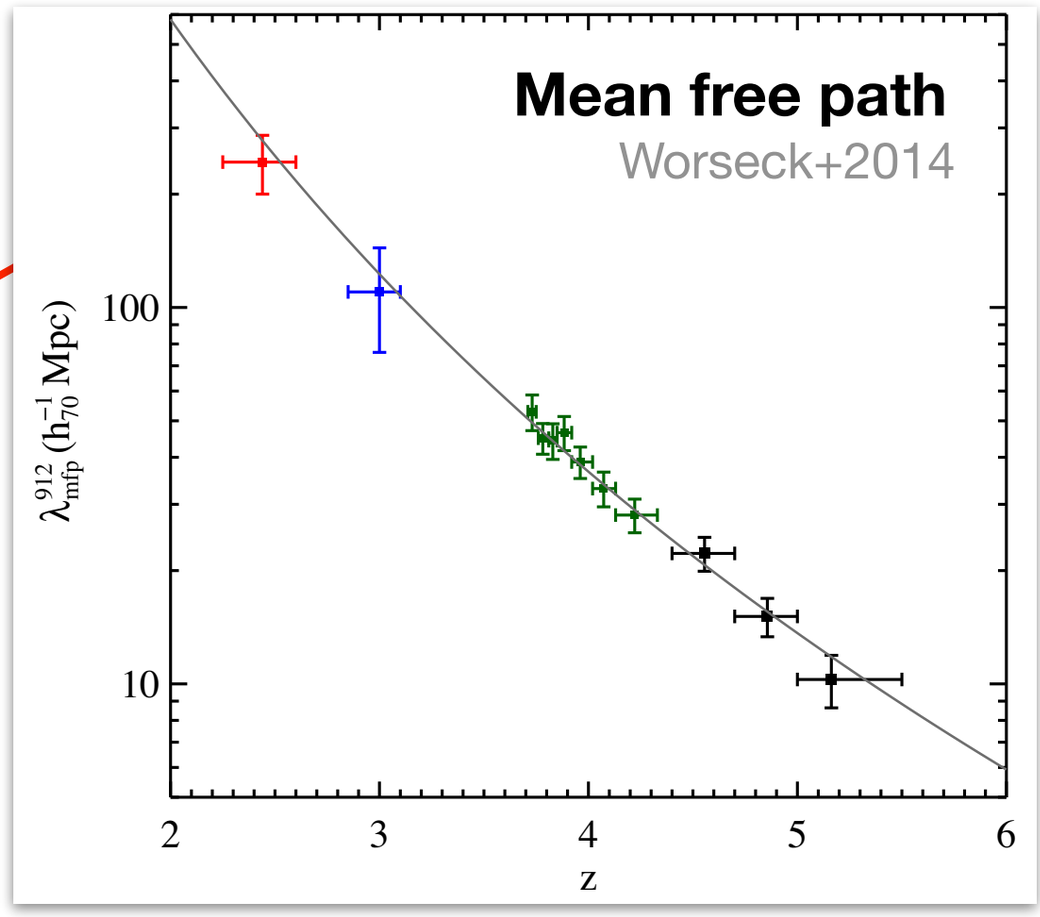
1. Fluctuating UV Background (Galaxies)

(Davies & Furlanetto 2016, D'Aloisio et al. 2018)

Dark troughs trace **low-density** regions with few ionizing sources and a short mean free path.

Low density





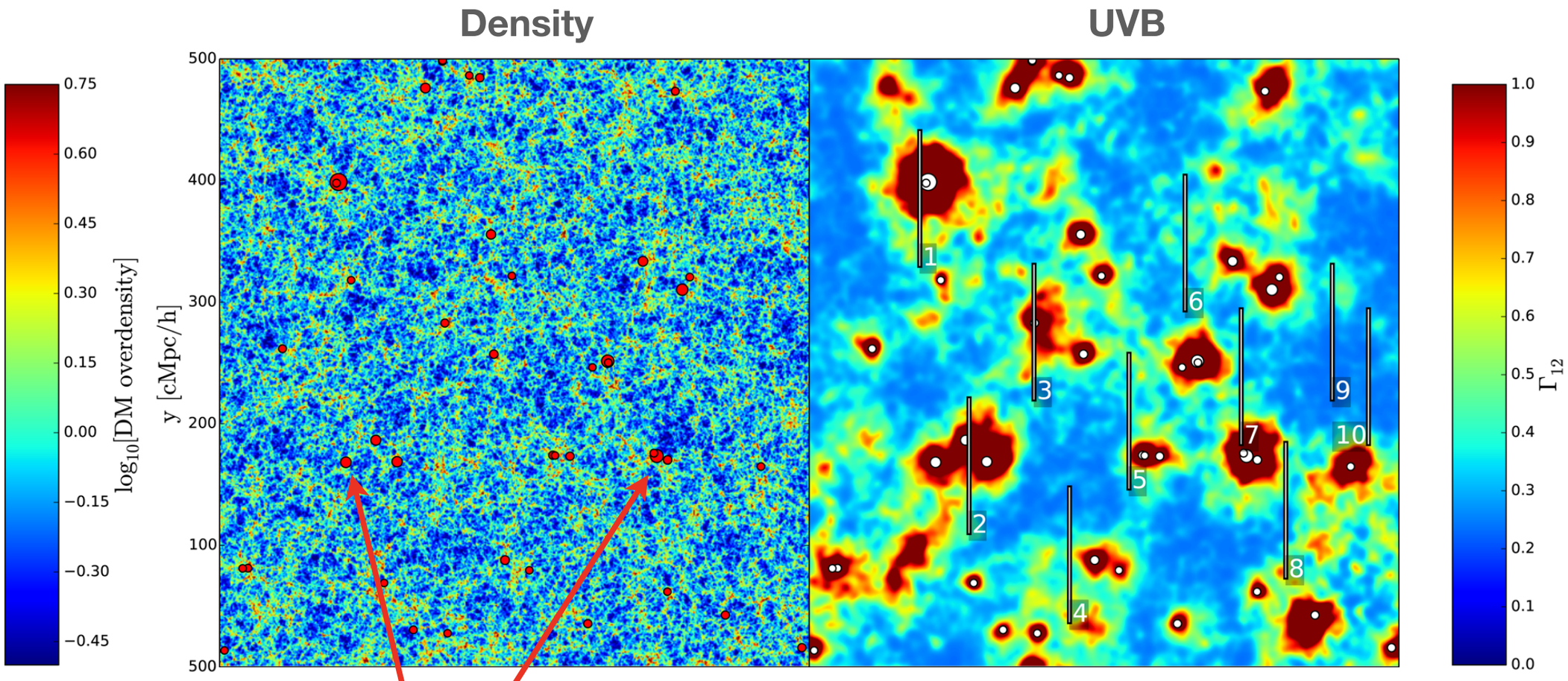
Figures: Davies+2017

$$f_{\mathrm{H\,I}} \propto n_{\mathrm{H}} \Gamma^{-1} T^{-0.7}$$

2. Fluctuating UV Background (QSOs)

(Chardin et al. 2015, 2017)

Dark troughs trace **any** regions far from ionizing sources.



Difficulties: Are there enough QSOs?
Helium reionization too early?

(see D'Aloisio et al. 2017)

Chardin et al. (2017)

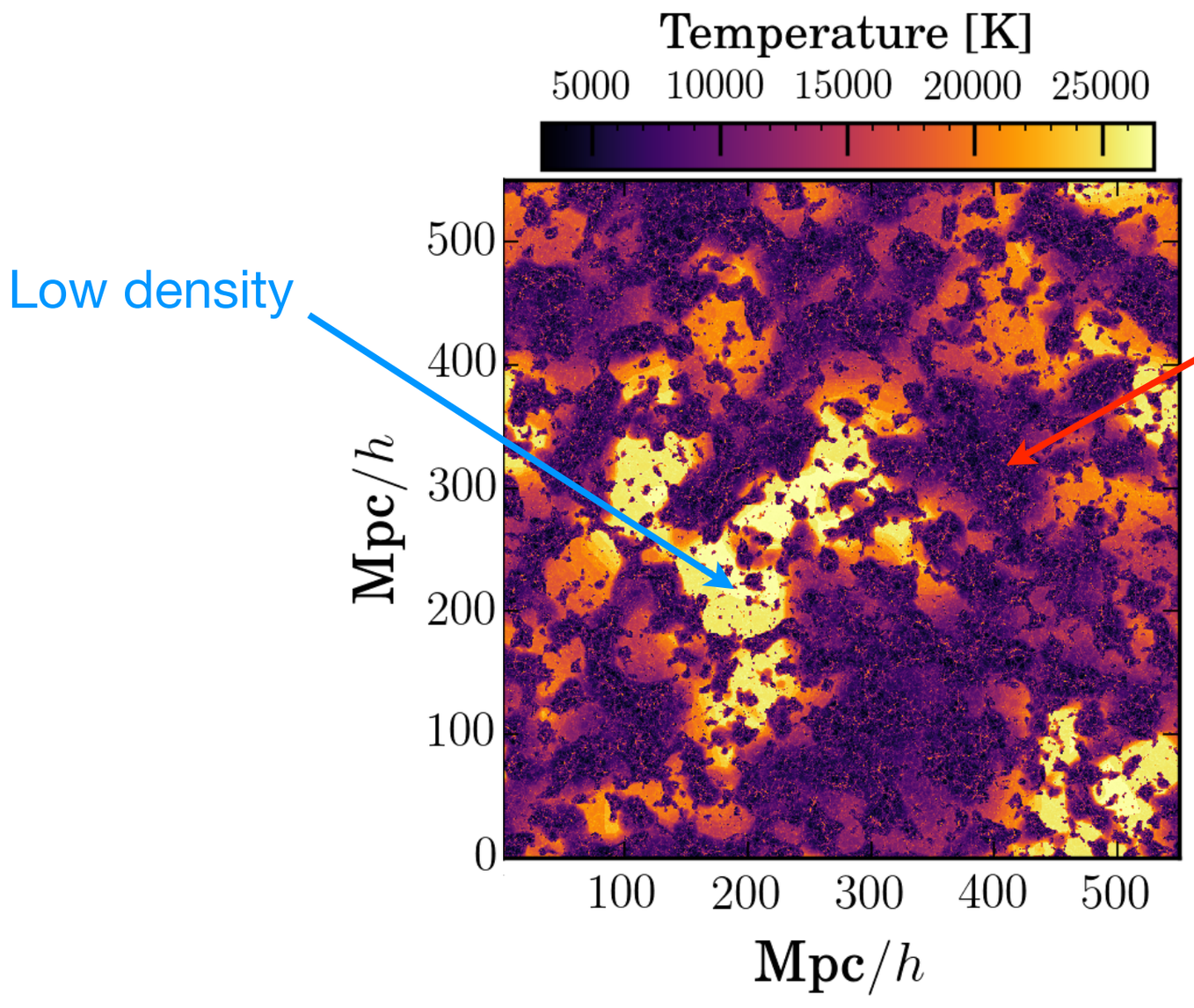
Possible models…

$$f_{\mathrm{H\,I}} \propto n_{\mathrm{H}} \Gamma^{-1} T^{-0.7}$$

3. Fluctuating IGM Temperature

(D'Aloisio et al. 2016a)

Dark troughs trace **high-density** regions, where reionization ended early and the gas has had time to cool.

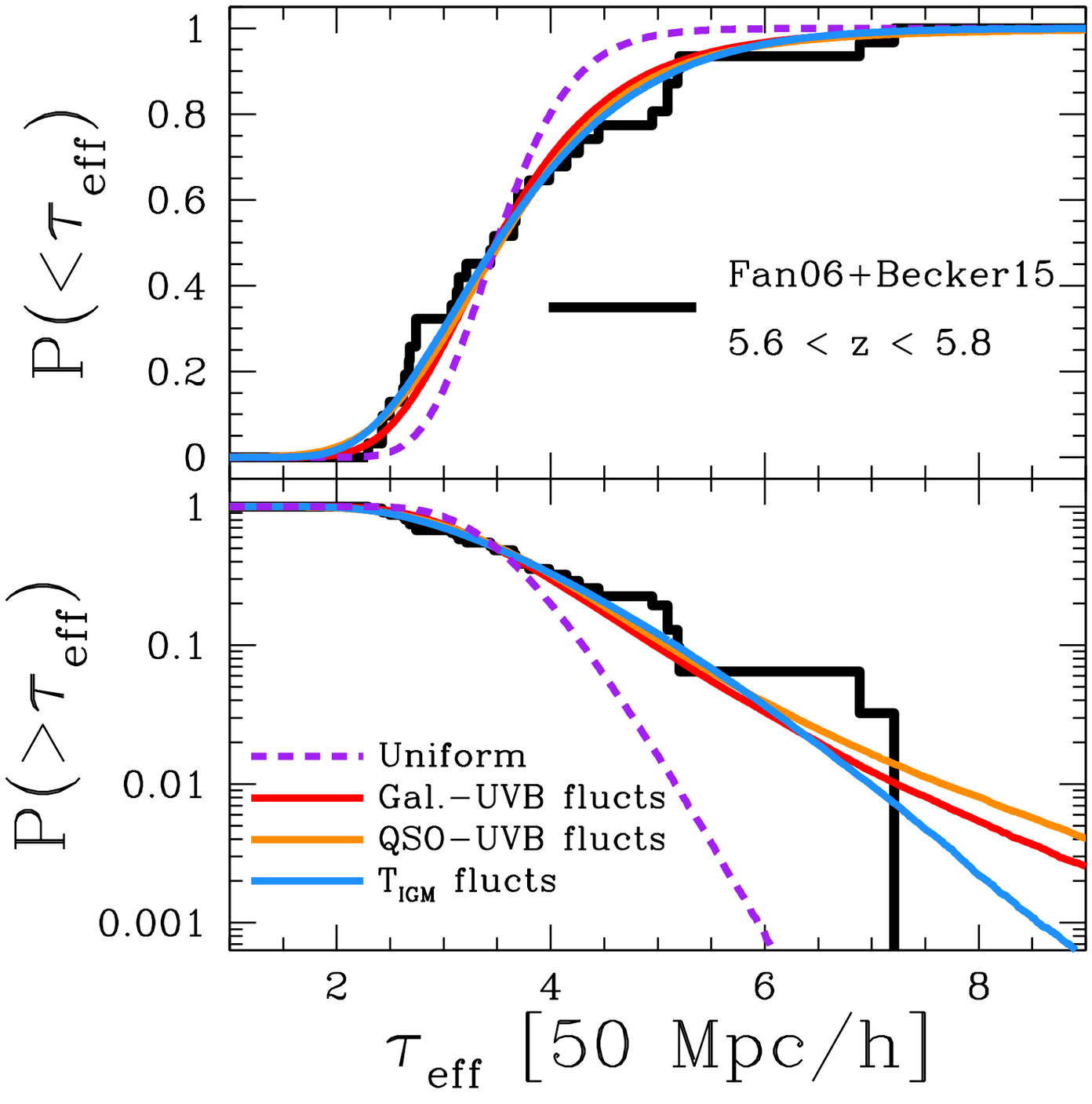


Difficulty:

Temperature boost from reionization must be extreme (Δ*T* ~ 30,000 K).

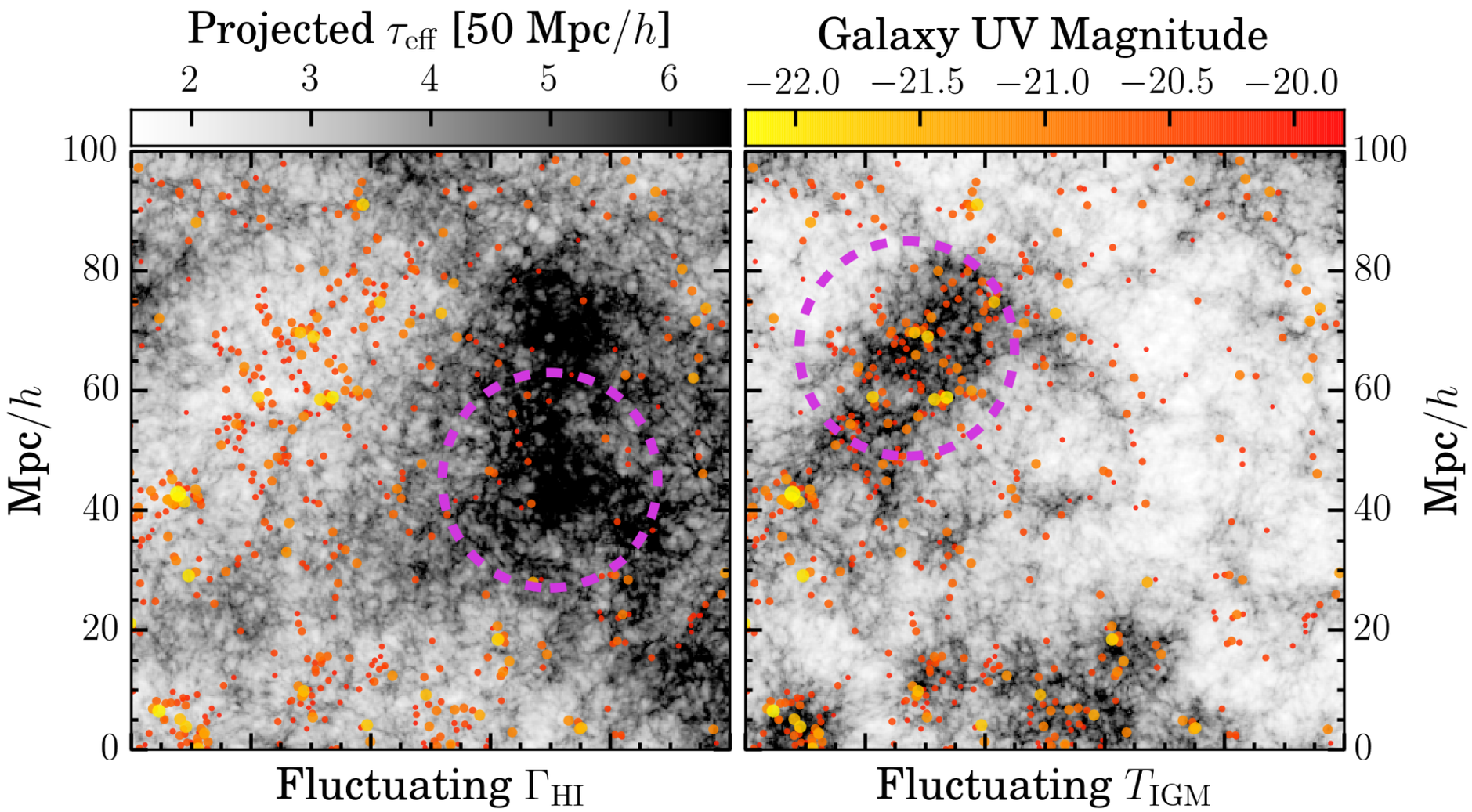
(See also Keating et al. 2017)

All three models can be tuned to match the opacity distribution.



GB+2018

The Test: **Use galaxies to trace the density field.**



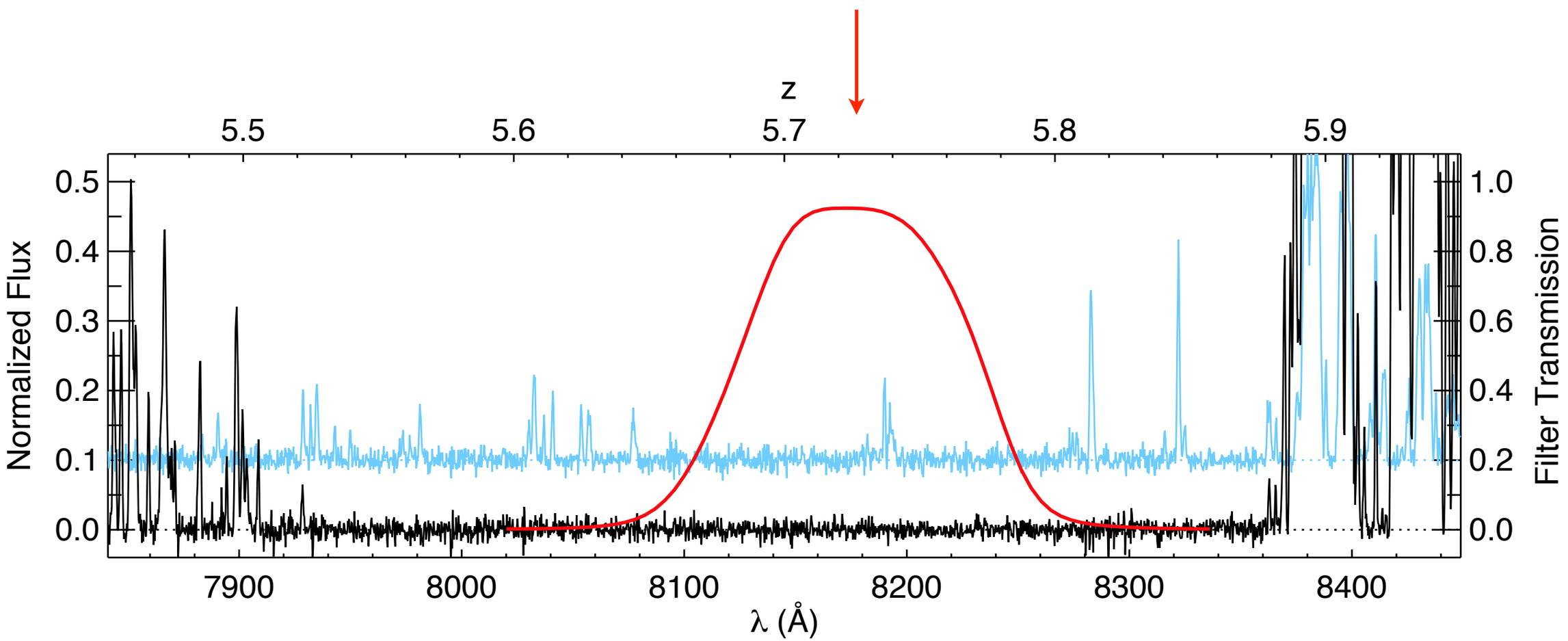
UVB model:
Galaxies avoid high-opacity regions.

Temperature model:
Galaxies trace high-opacity regions.

Figures: Davies+2017

Davies, GB & Furlanetto 2017

Narrow band filter tuned to Lyα at z=5.7



Lyβ forest

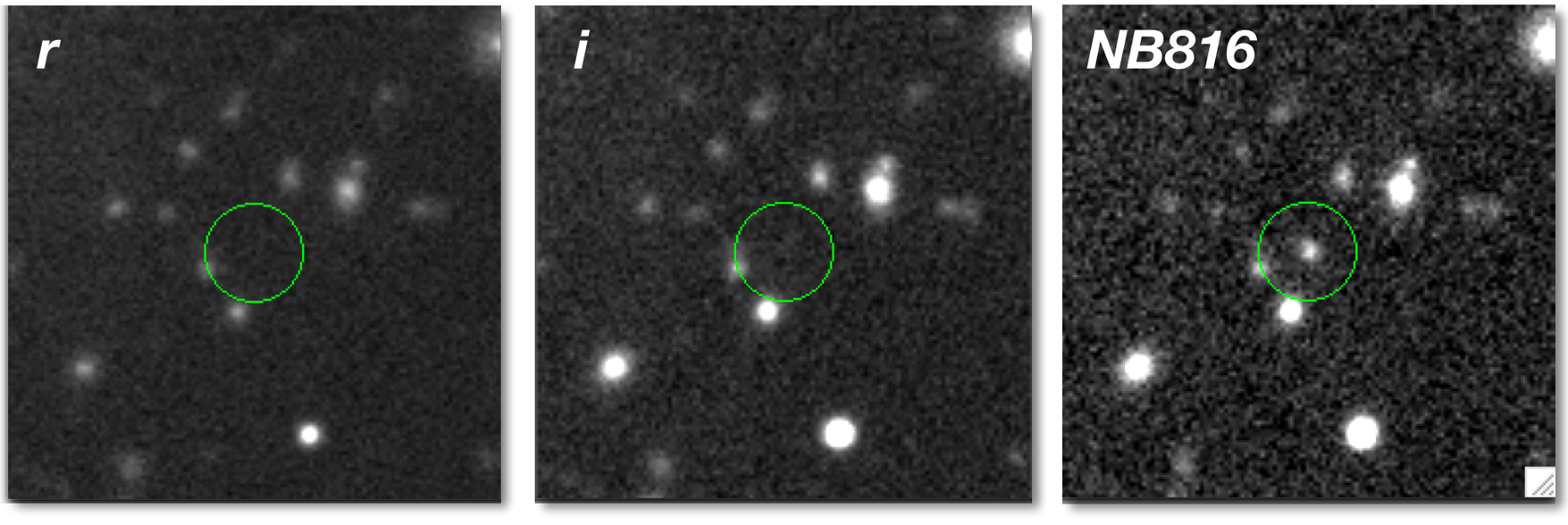
Lyα forest

Narrow-band search for Lyα emitters in the field around J0148+0600 (giant Lyα trough).

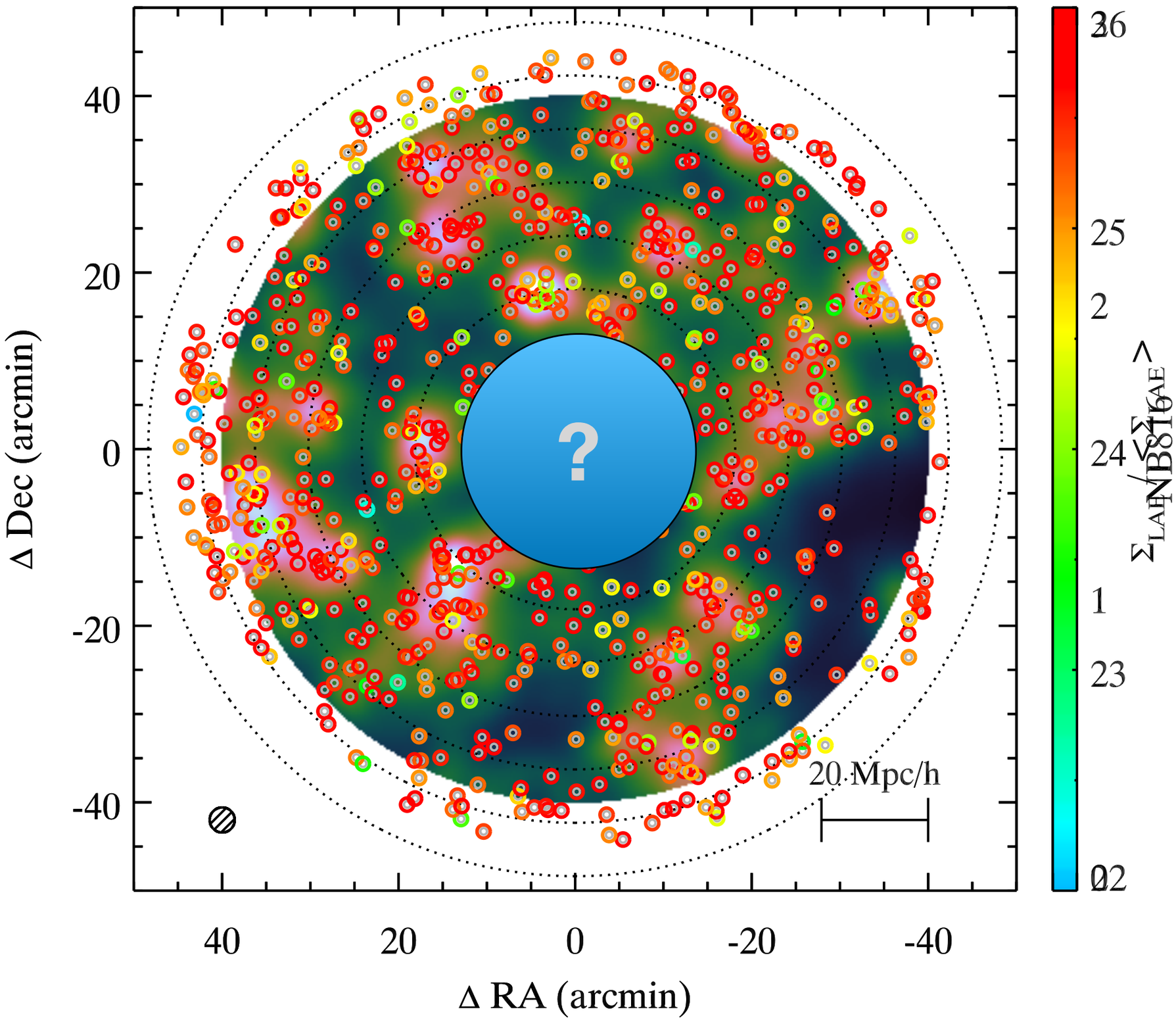
Subaru Hyper-Suprime Cam data acquired August 2017.

Deep (m_{NB} = 26): High number density of sources to probe density.

Large Field (90’): Self-consistently compare region around QSO line of sight to the surrounding field.

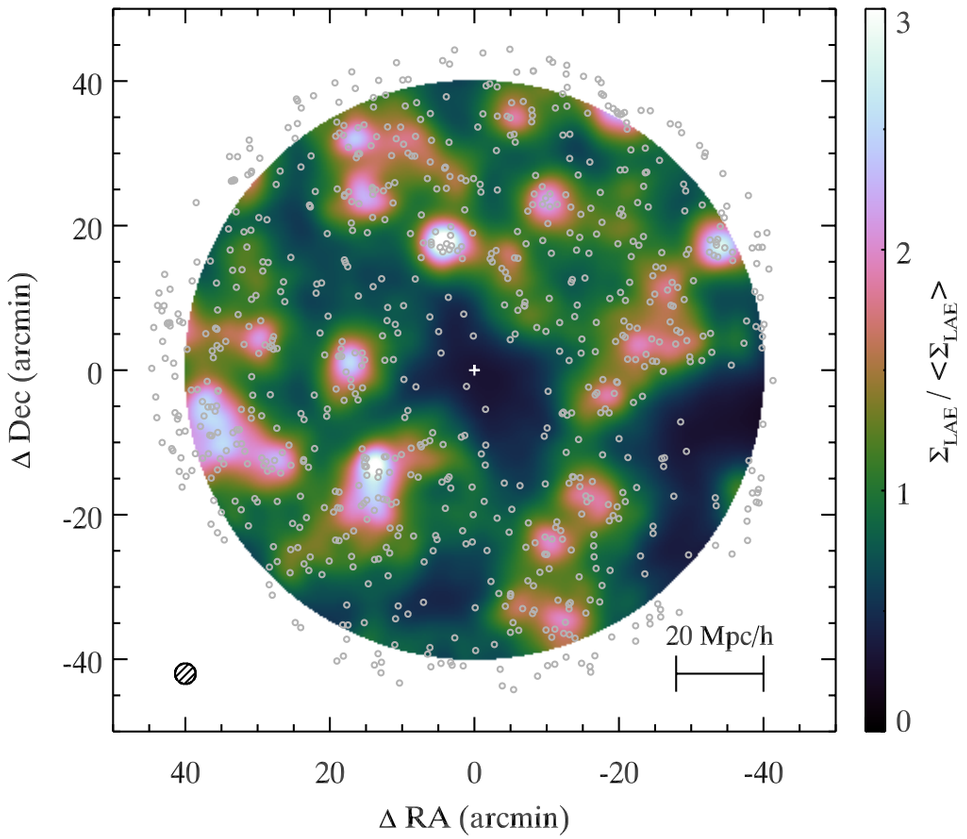


LAEs around giant Lyα trough

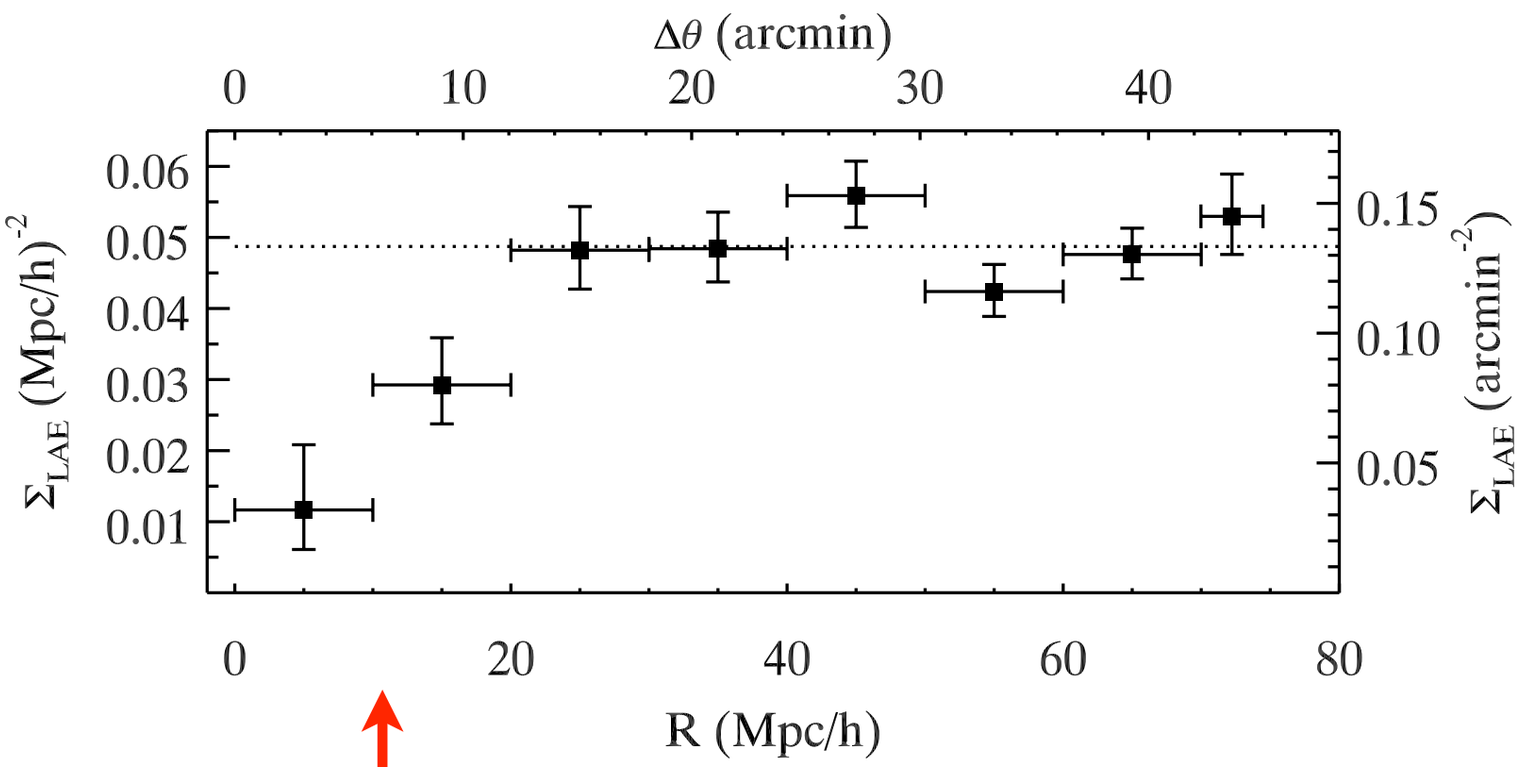


GB+2018

LAEs around giant Lyα trough

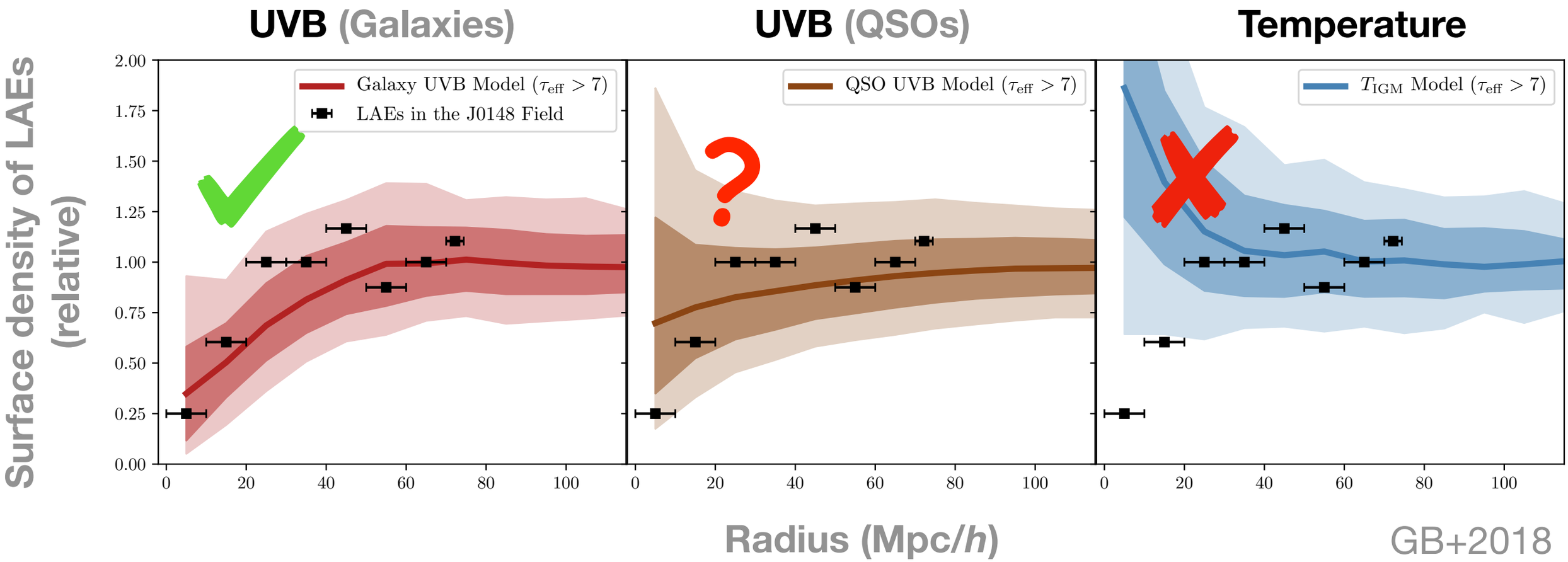


Surface density of LAEs



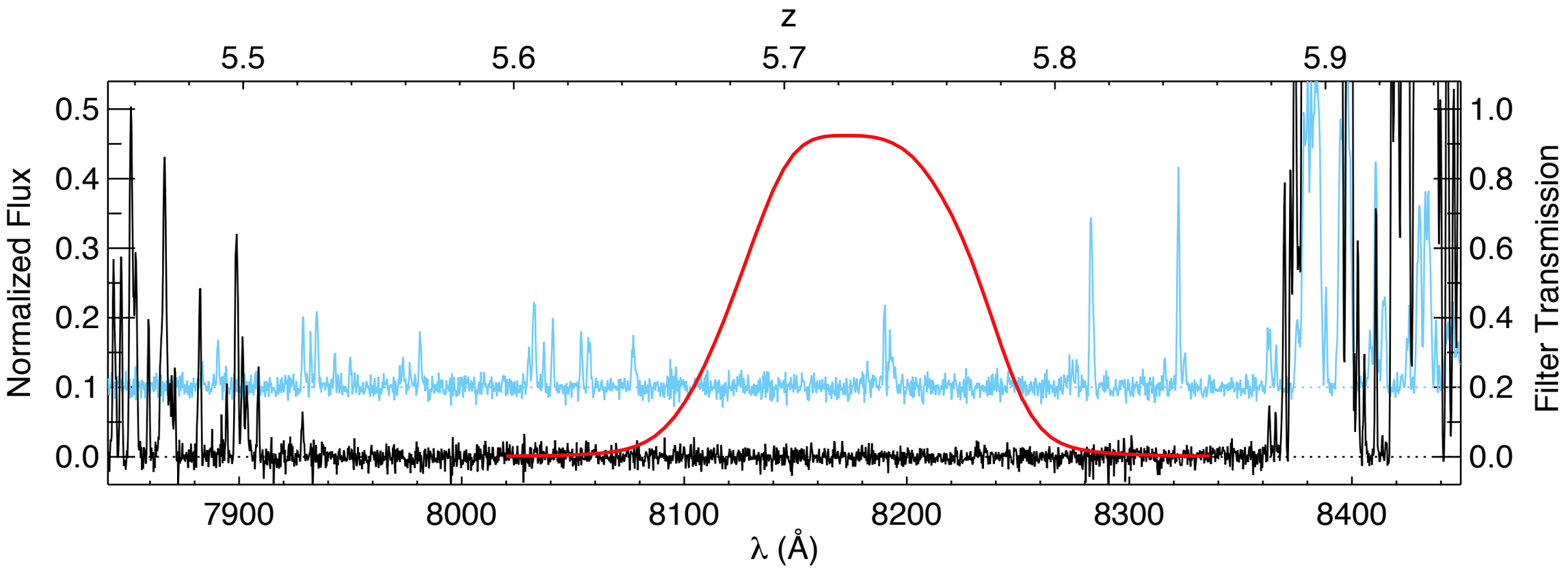
Deficit of LAEs close to QSO line of sight.

GB+2018



- **At first glance, results support fluctuations in a UVB dominated by galaxies.**
- **Model details may be important.**
- **Could galaxy Lyα emission be suppressed along the trough?**

Could there be neutral gas?



Summary

- Multiple lines of evidence now point to a relatively late hydrogen reionization, but the timing and sources remain uncertain.
- The z < 6 IGM places strong boundary conditions on reionization.
- Multiple models attempt to explain the large-scale fluctuations in IGM Lyα opacity at z~6.
- Deficit of LAEs around a deep Lyα trough supports large-scale fluctuations in the ionizing UV background. *Ultimately a way to identify reionization sources.*
- UVB fluctuations left over from recent reionization?
- Other models possible? Reionization not complete at z=5.7?