Islands of neutral hydrogen below redshift 5.5

Laura Keating

with Girish Kulkarni, Martin Haehnelt, Lewis Weinberger,
Ewald Puchwein, Sarah Bosman,
Jonathan Chardin and Dominique Aubert

At the same redshift, the Lyα forest looks very different along different sightlines

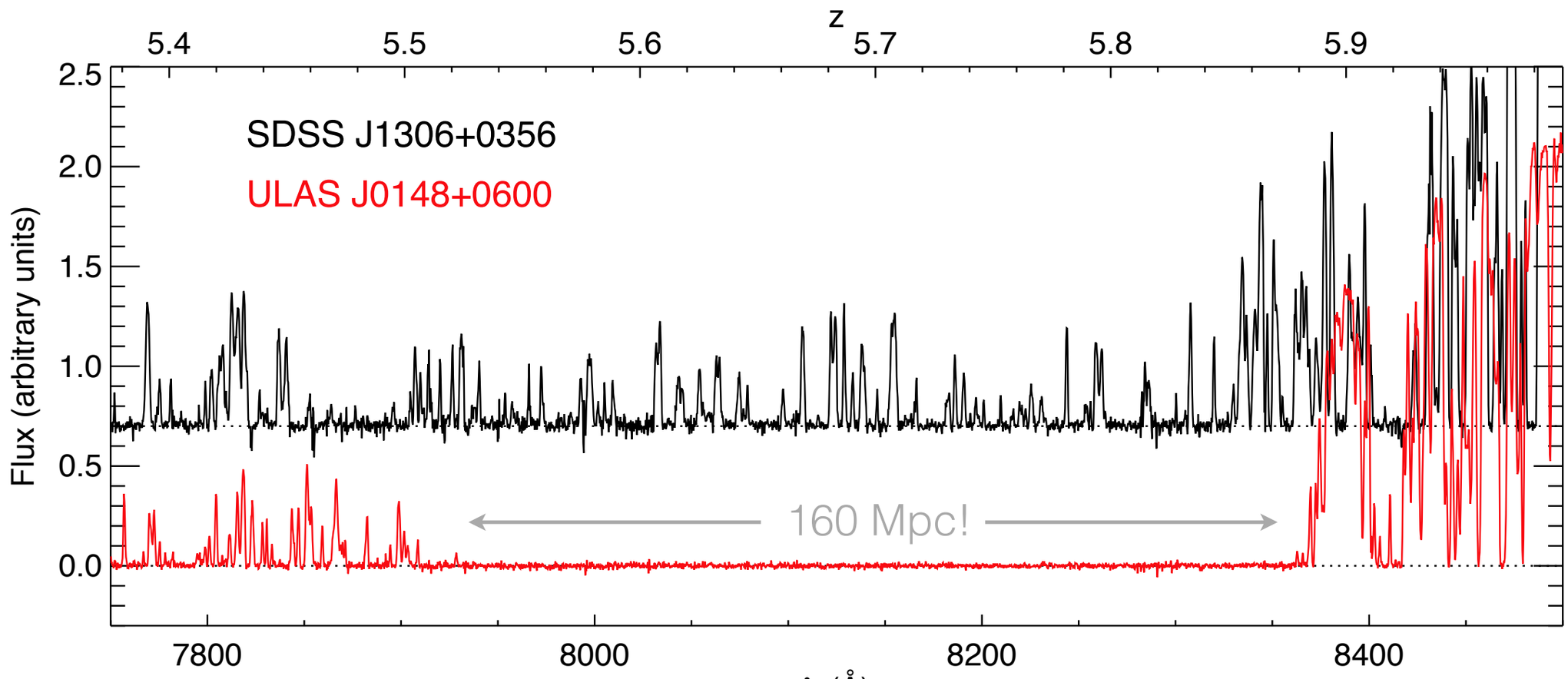


Figure from George Becker

At the same redshift, the Lyα forest looks very different along different sightlines

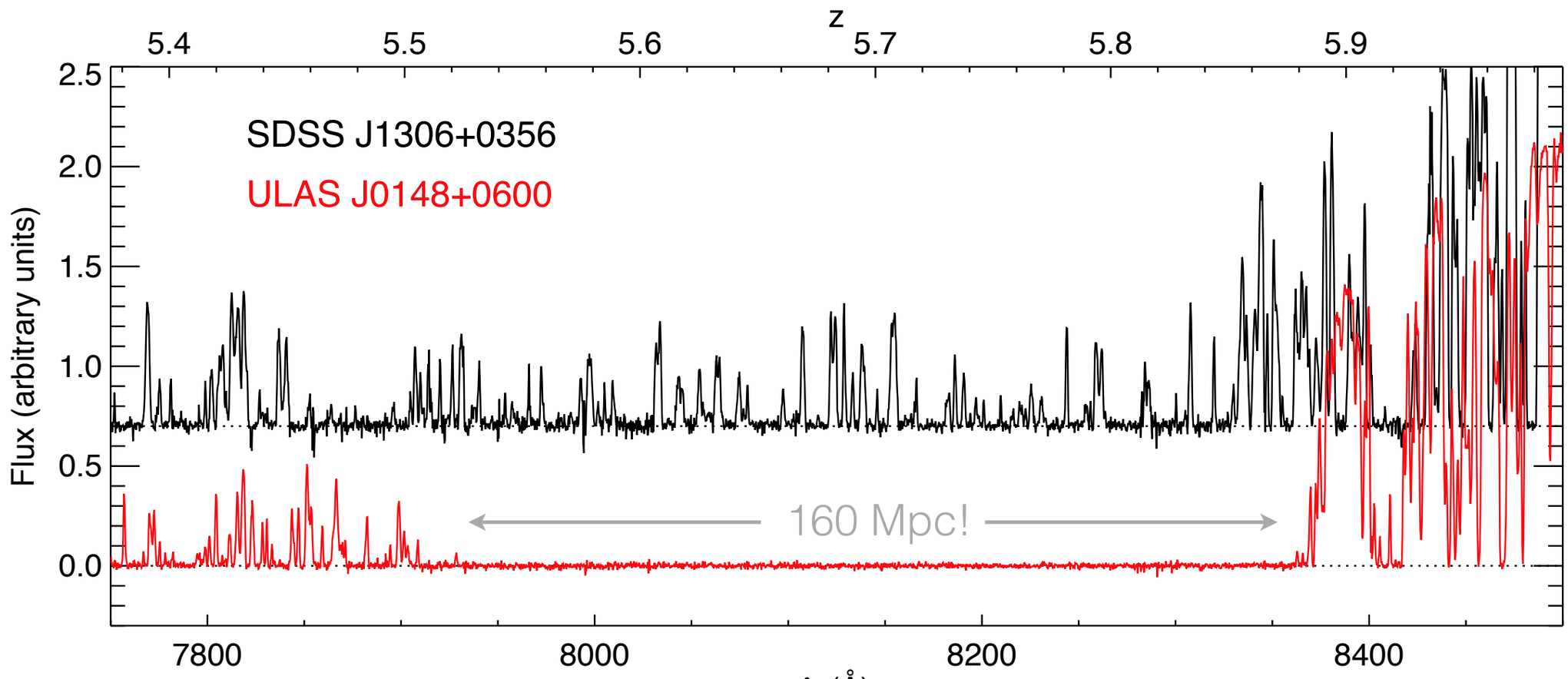
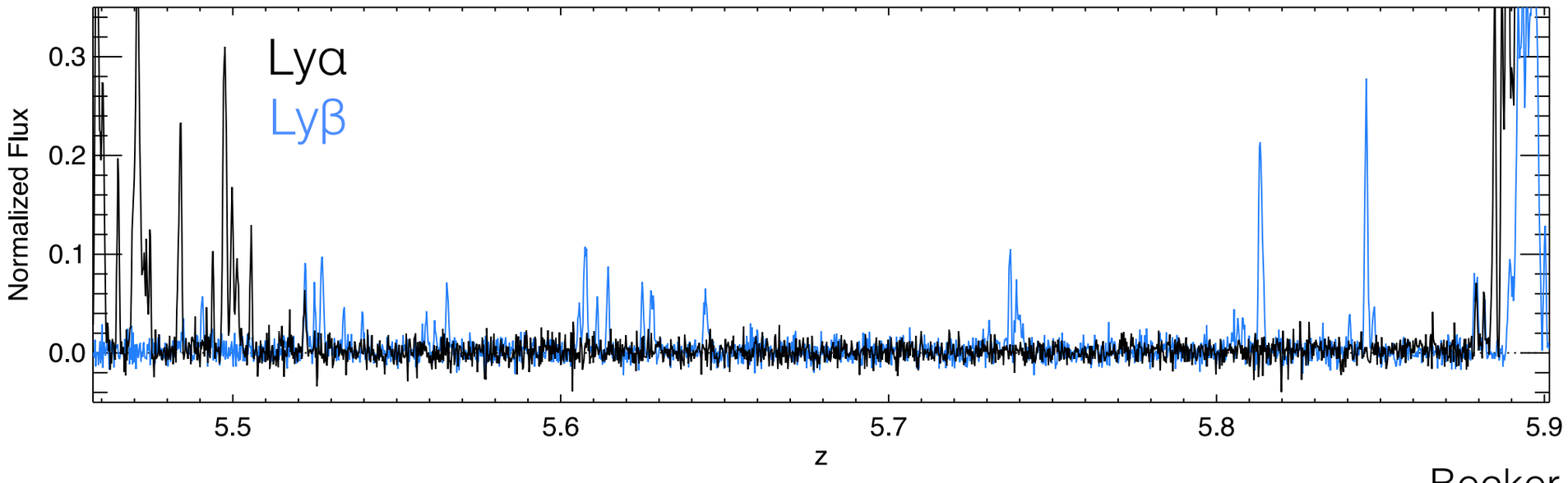


Figure from George Becker

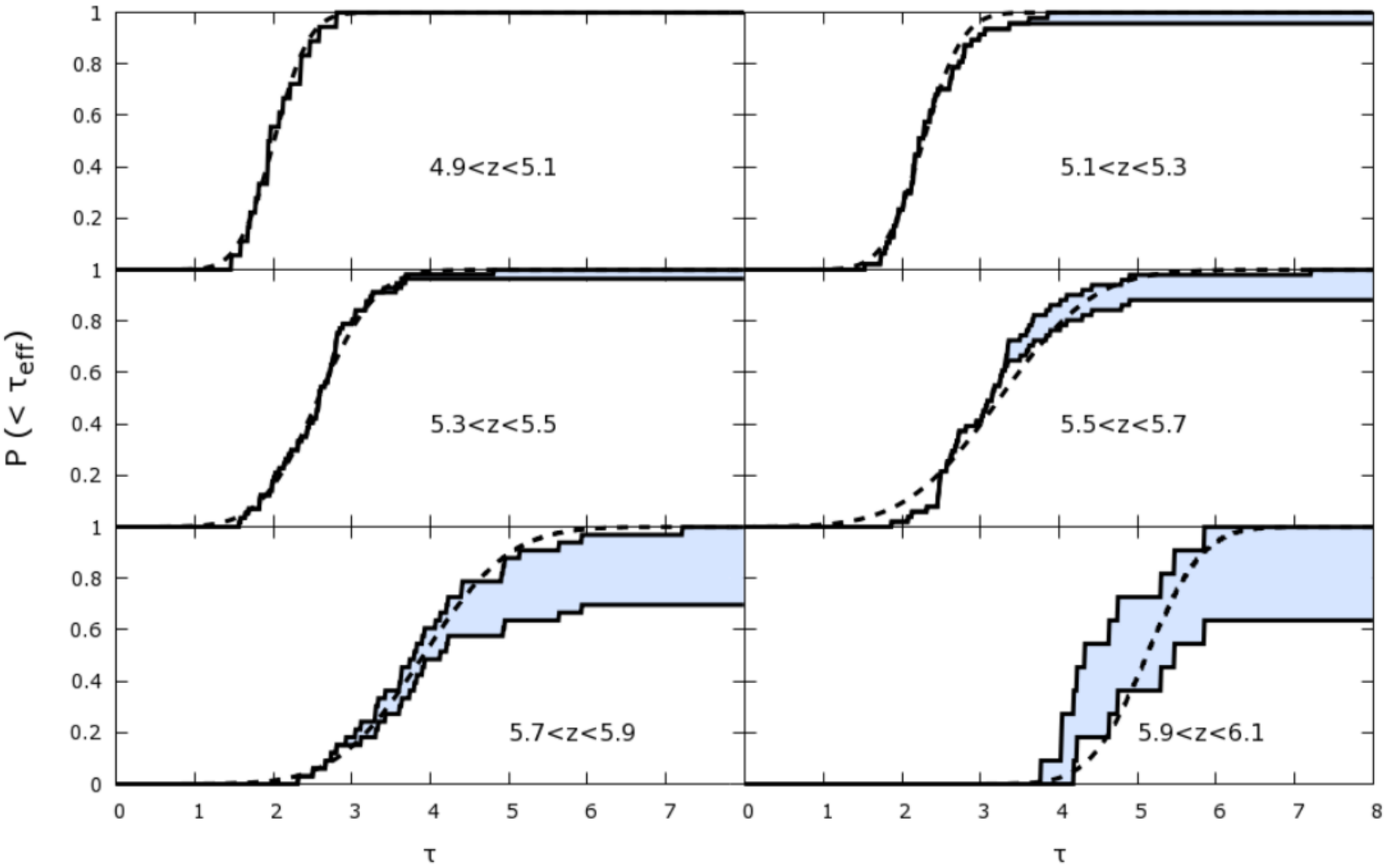
Long troughs show some Lyβ transmission, so can't be completely neutral



Becker+15

Opaque sightlines are already seen below z = 5.5

The scatter among sightlines is larger than expected for fluctuations in density



$$\langle F \rangle = \exp(-\tau_{\rm eff})$$

measured in 50 Mpc/h segments

Bosman+18

see also Fan+06, Becker+15, Eilers+18

Can we learn something about reionization from this data?

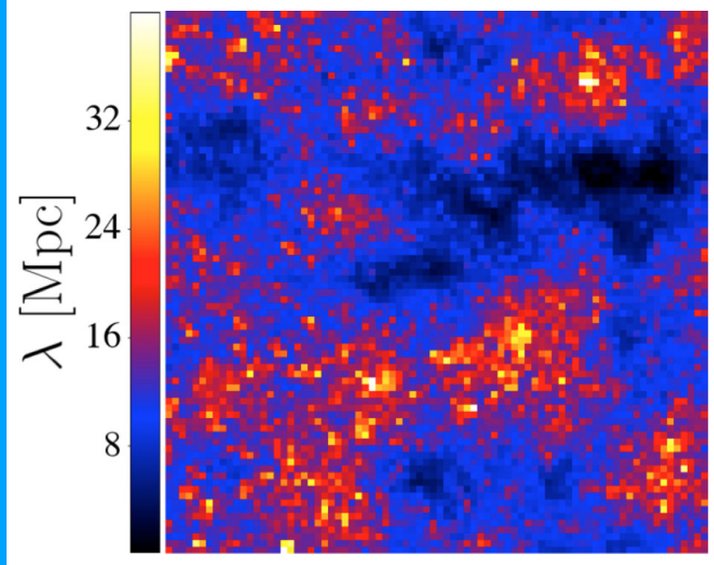
from photoionization equilbrium: $$n_{\rm HI} \propto \frac{\alpha(T) n_e n_{\rm HII}}{\Gamma_{\rm HI}} \propto \frac{T^{-0.7}\Delta^2}{\Gamma_{\rm HI}}$$

Can we learn something about reionization from this data?

from photoionization equilbrium: $$n_{\rm HI} \propto \frac{\alpha(T) n_e n_{\rm HII}}{\Gamma_{\rm HI}} \propto \frac{T^{-0.7}\Delta^2}{\Gamma_{\rm HI}}$$

Fluctuations in the UVB amplitude

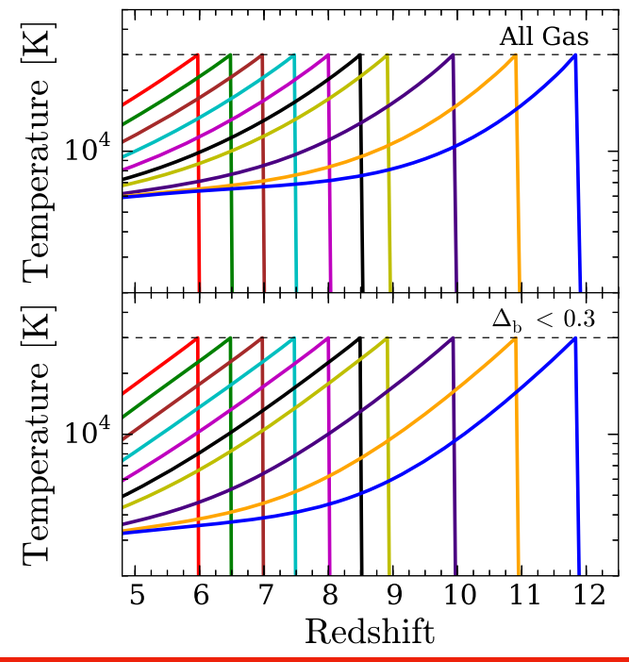
Fluctuations in the mean free path?



Davies+16

Fluctuations in temperature

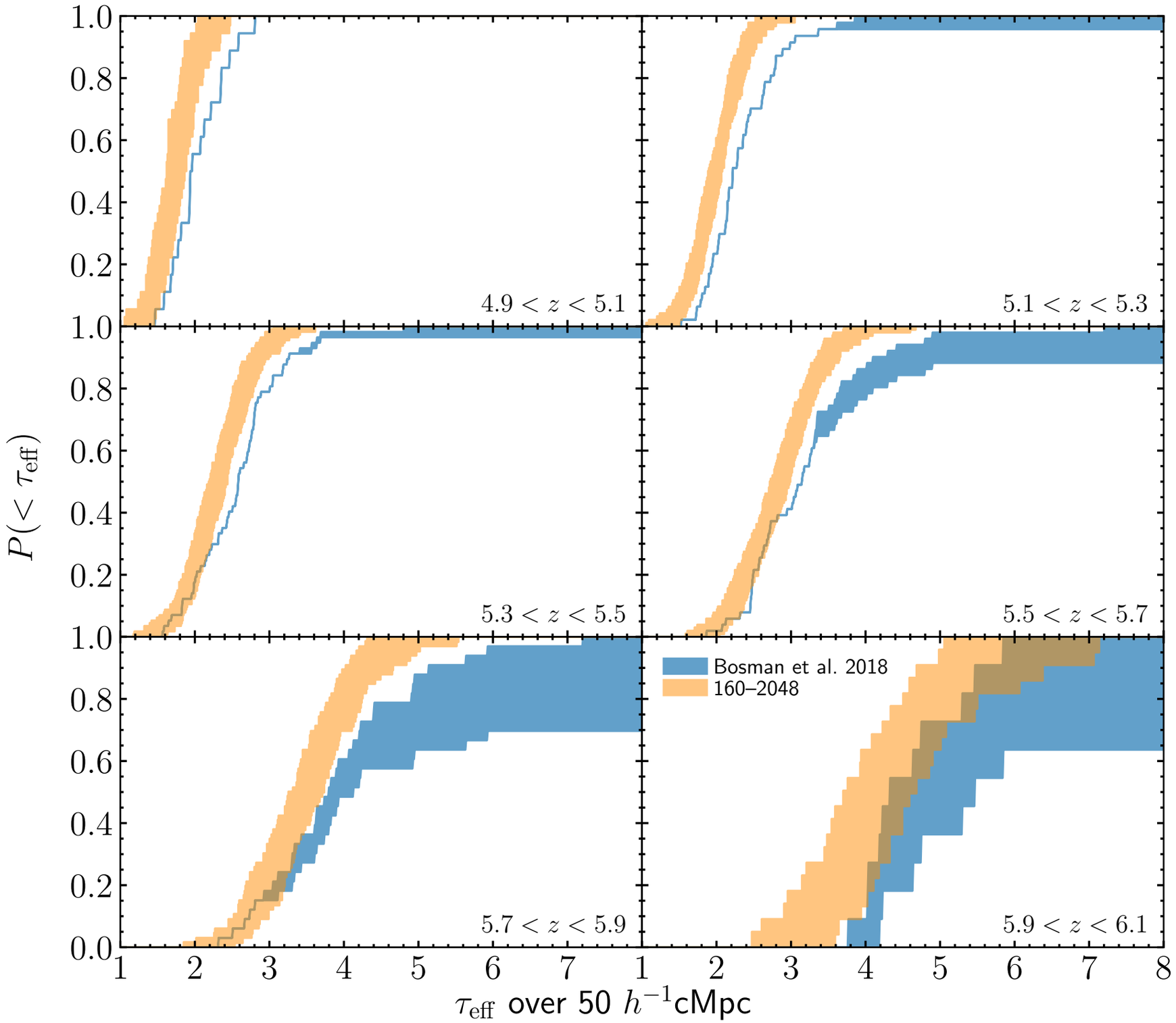
Due to patchy hydrogen reionization



D'Aloisio+15

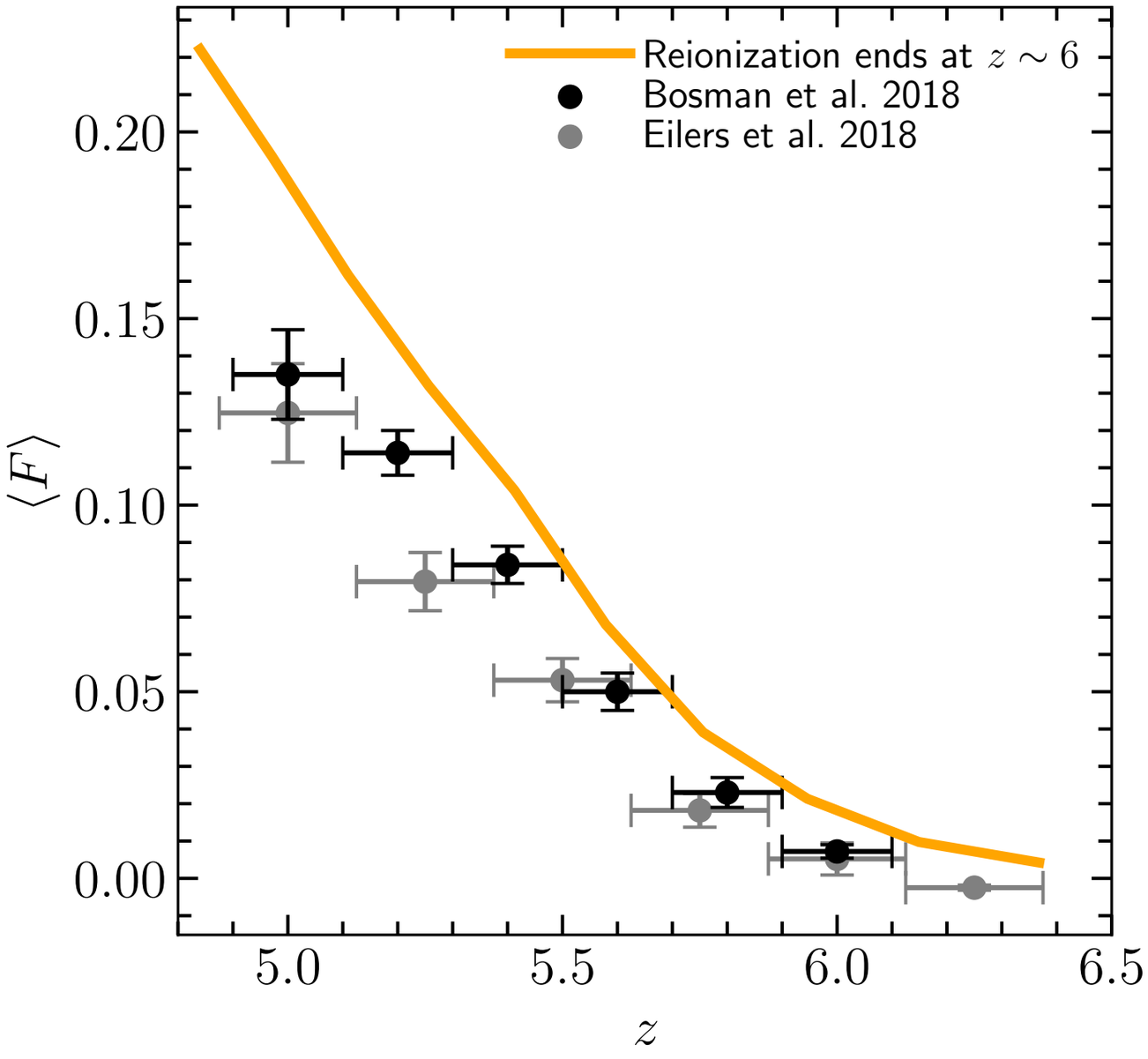
Let’s look in radiative transfer simulations that can model these temperature and UV fluctuations…

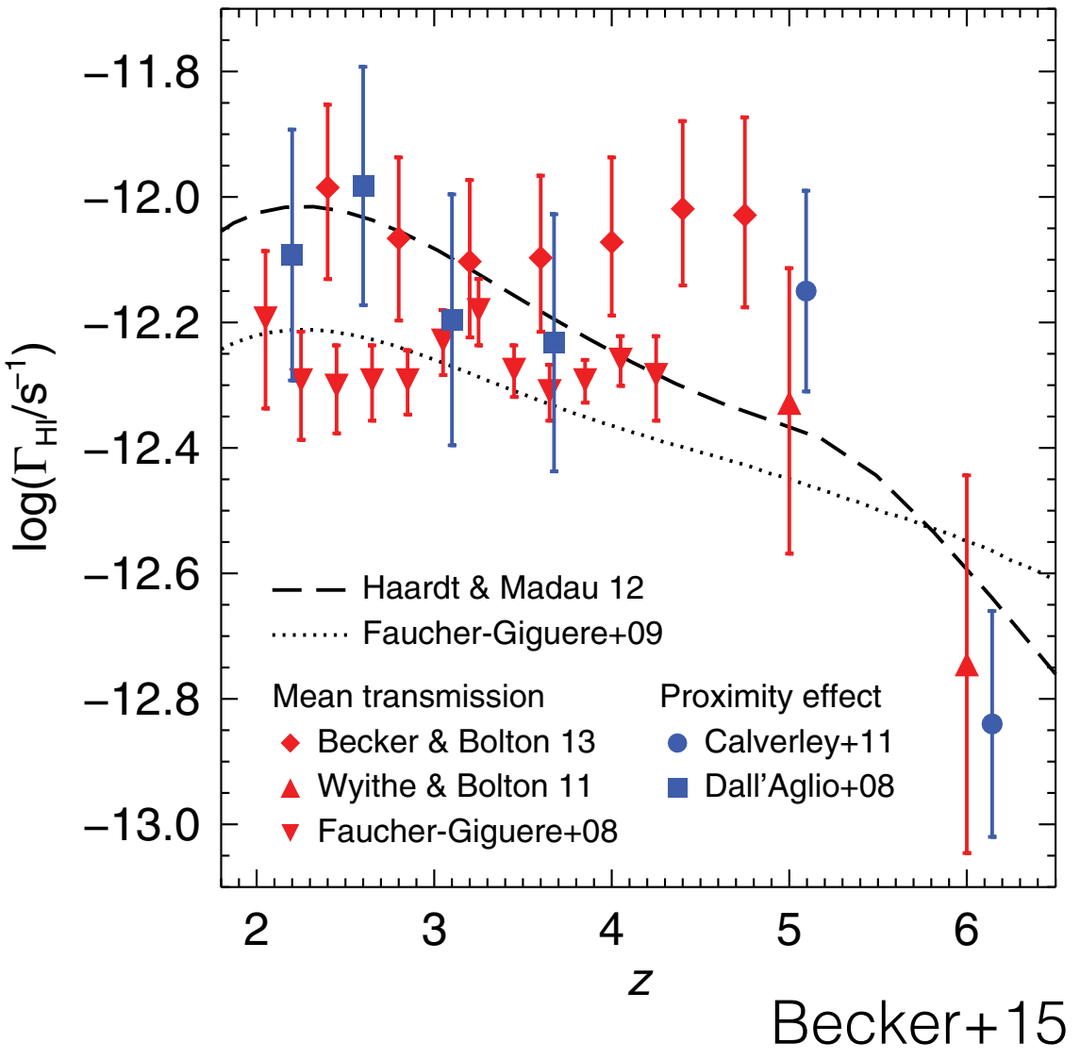
Let's look in radiative transfer simulations that can model these temperature and UV fluctuations…



Previously all our simulations had been calibrated to match the photoionization rate

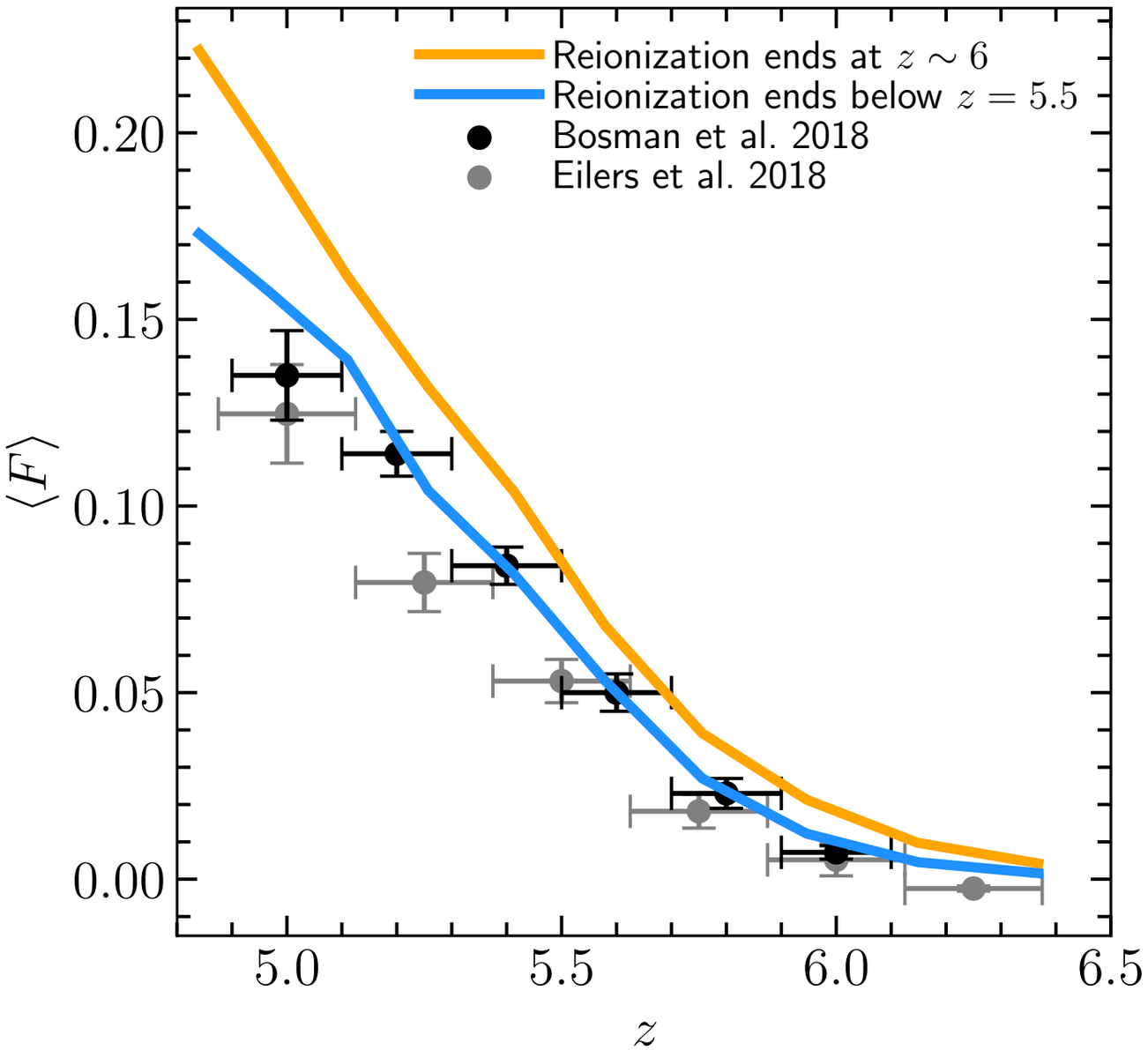
But this is a derived quantity… the real observable is the mean flux

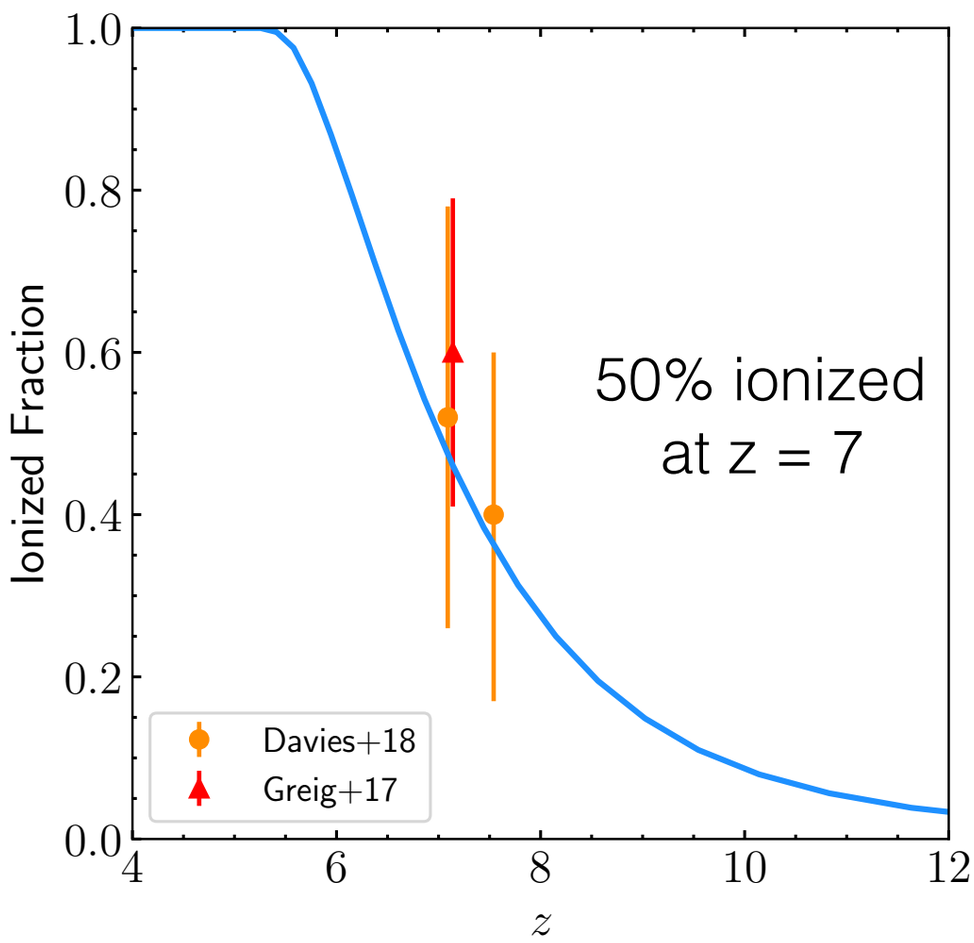




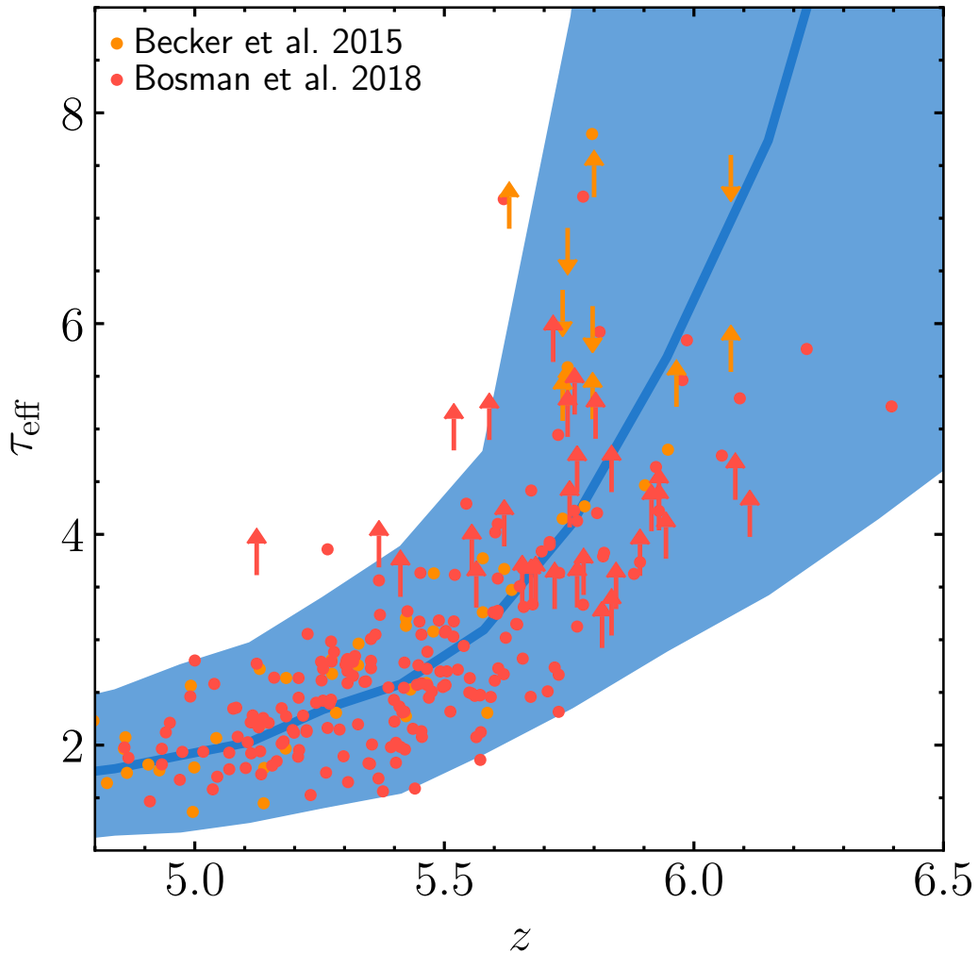
Previously all our simulations had been calibrated to match the photoionization rate

But this is a derived quantity… the real observable is the mean flux

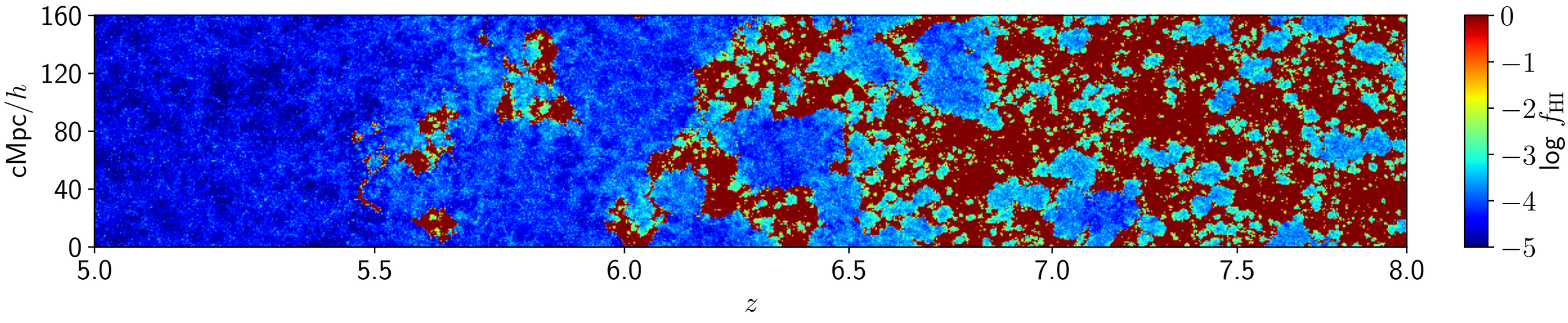




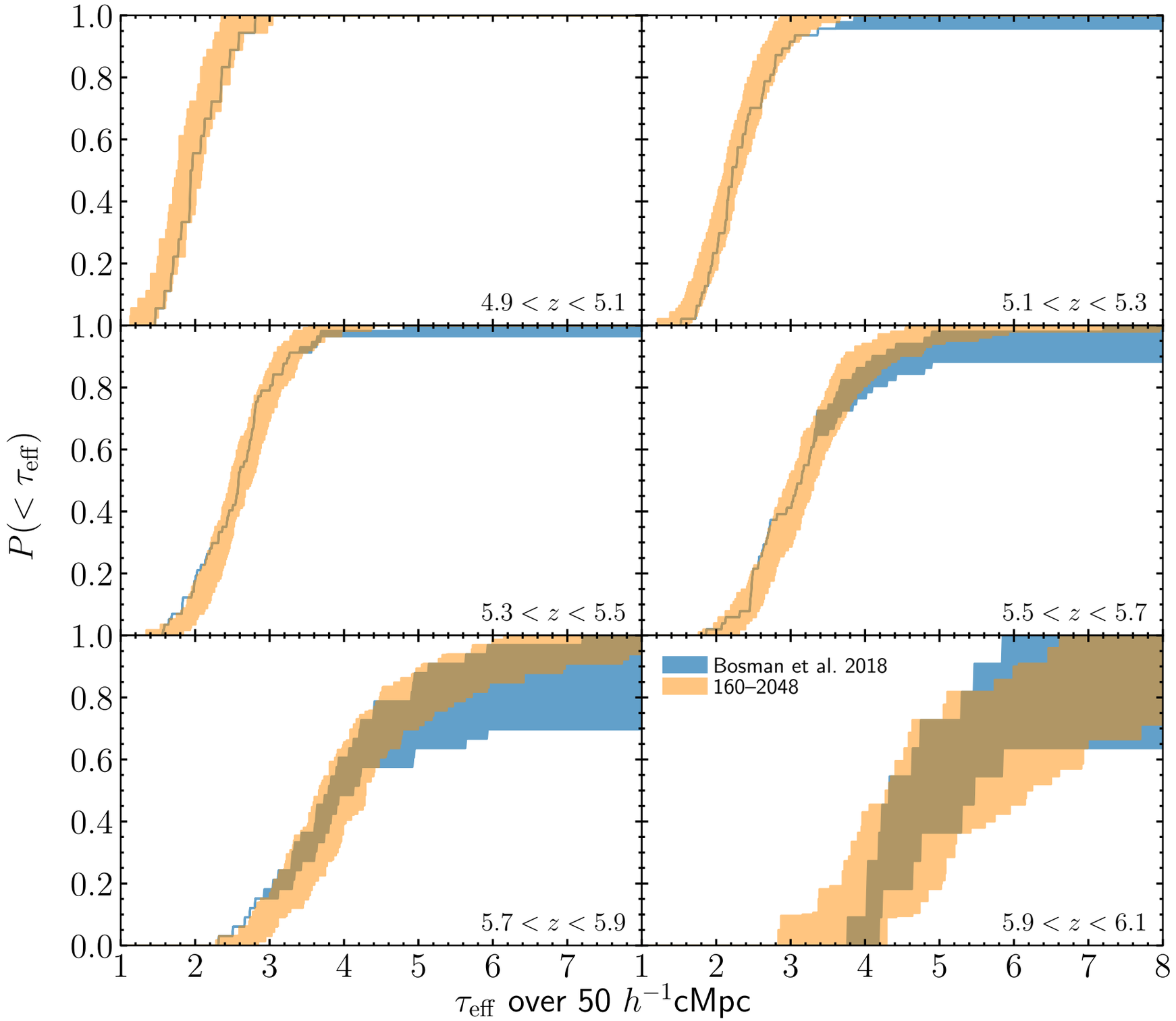
We find that matching the mean flux requires a later reionization (ending at z = 5.3)



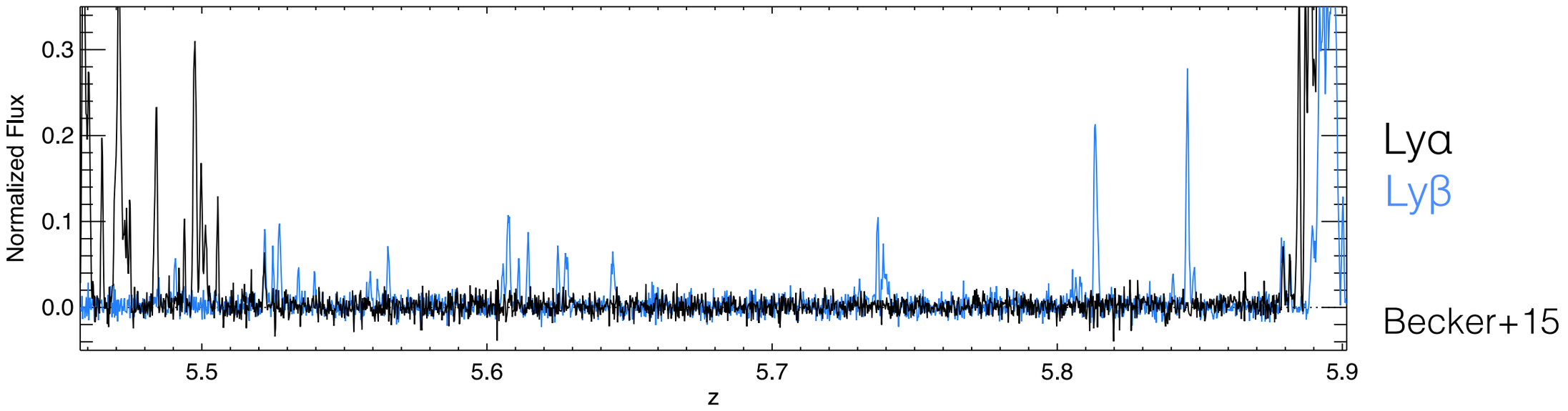
The increasing scatter in the effective optical depth above z = 5.5 is driven by large islands of neutral gas in the IGM at that redshift



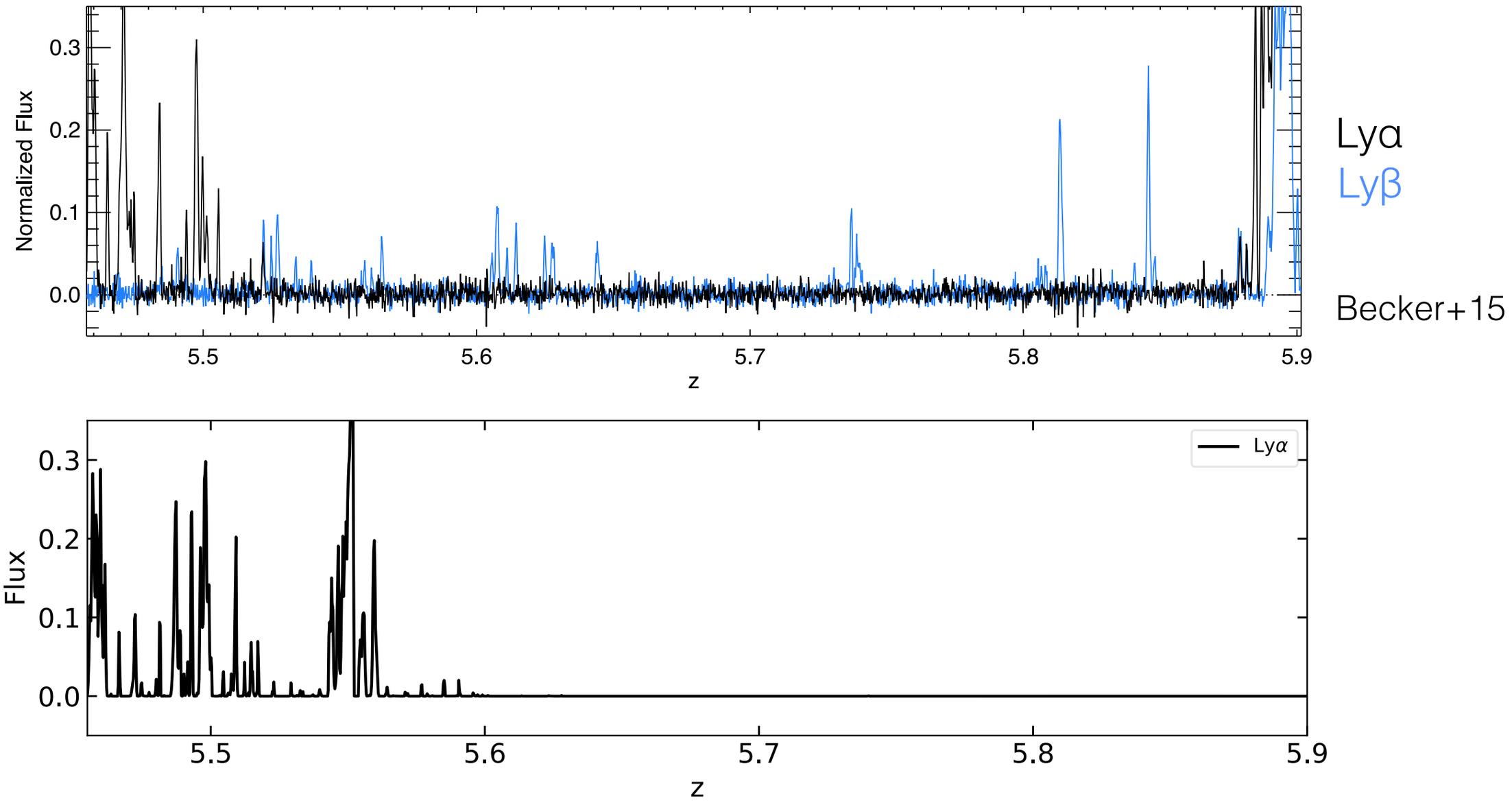
In this late reionization model, we can now produce distributions of Lyα opacities as broad as observed



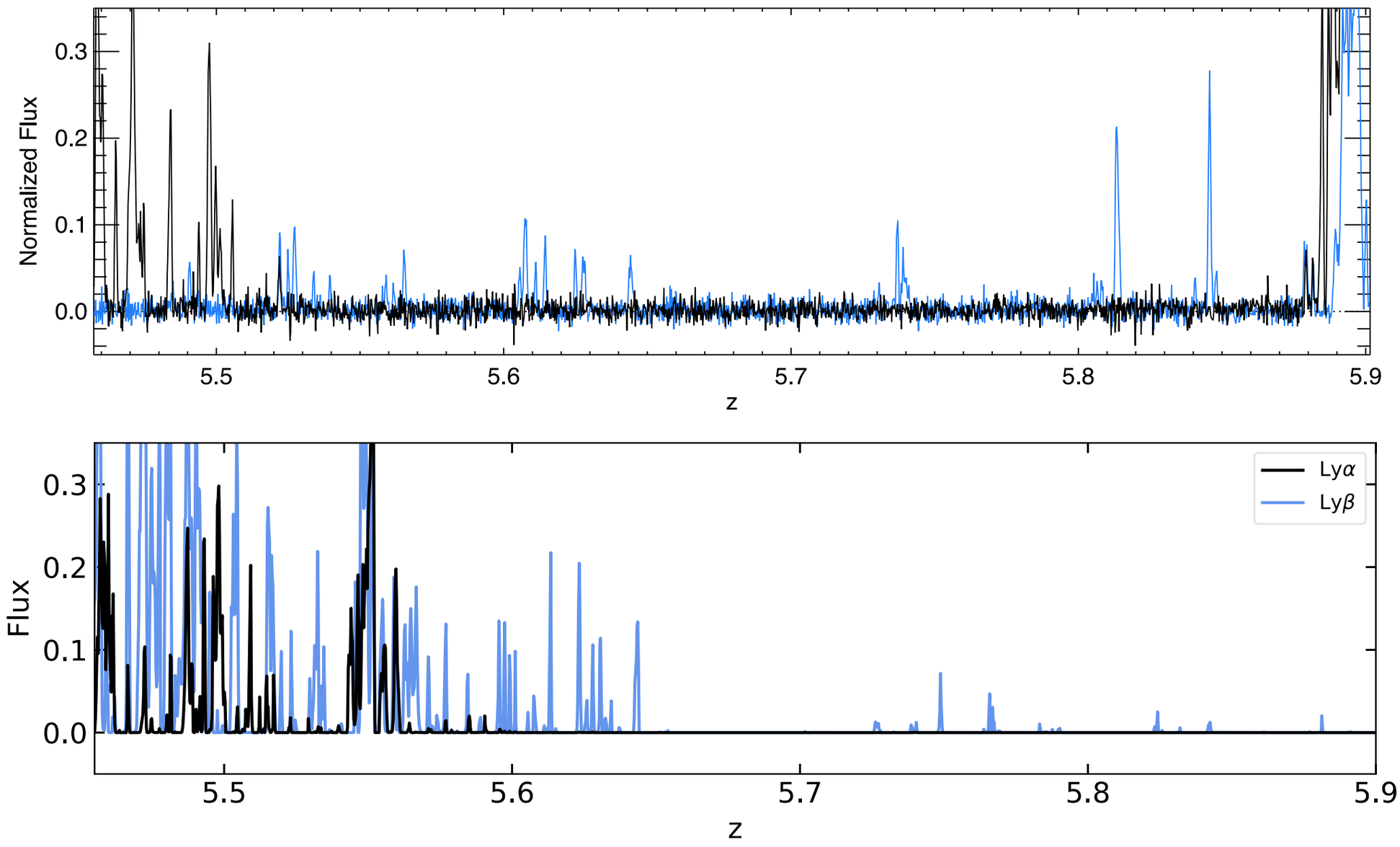
What about the large Lyα absorption troughs that are observed?
Lyβ transmission seen, implying an ionized IGM



What about the large Lyα absorption troughs that are observed?
Lyβ transmission seen, implying an ionized IGM



What about the large Lyα absorption troughs that are observed?
Lyβ transmission seen, implying an ionized IGM

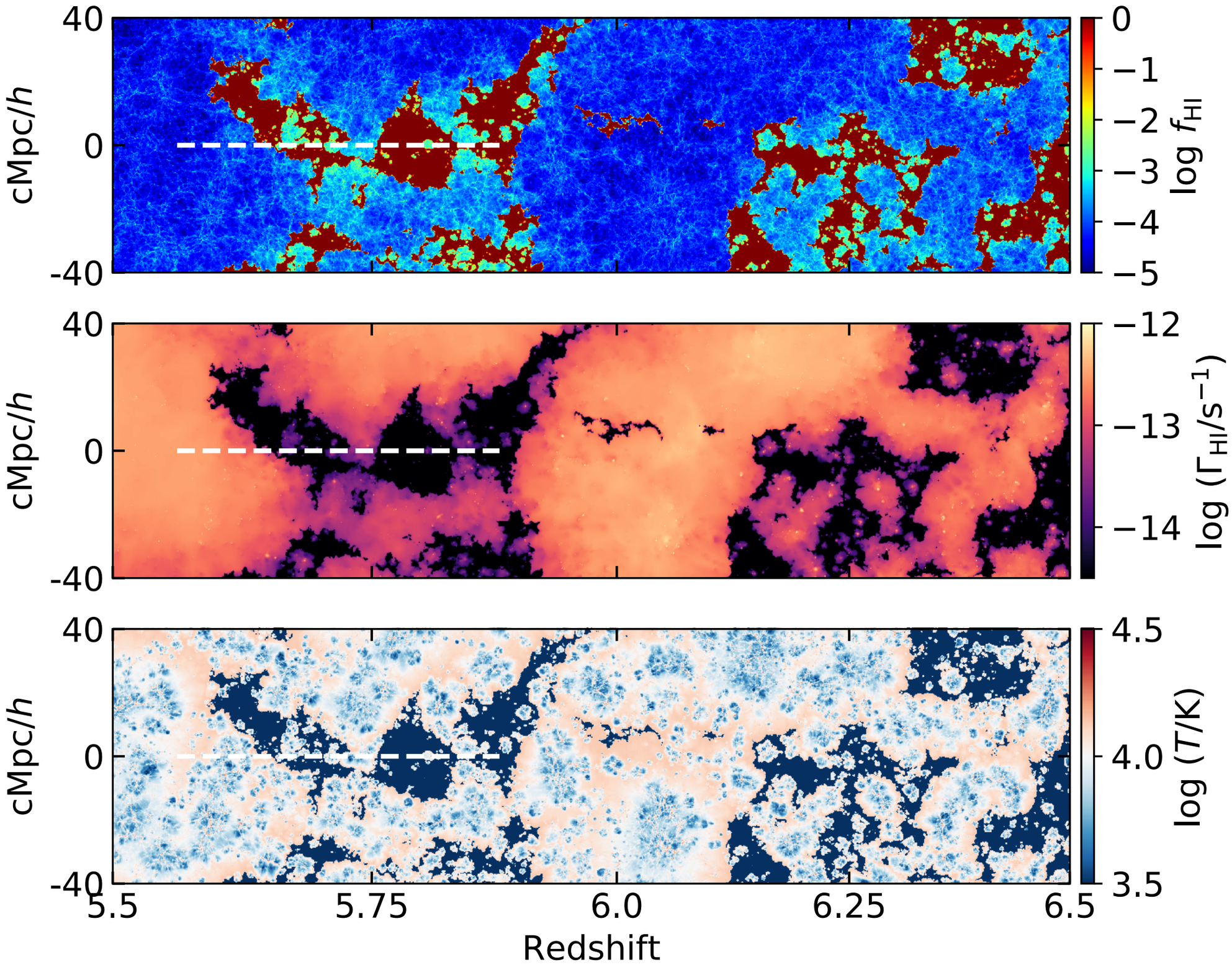


Small ionized bubbles within the neutral islands allow for transmission of Lyβ

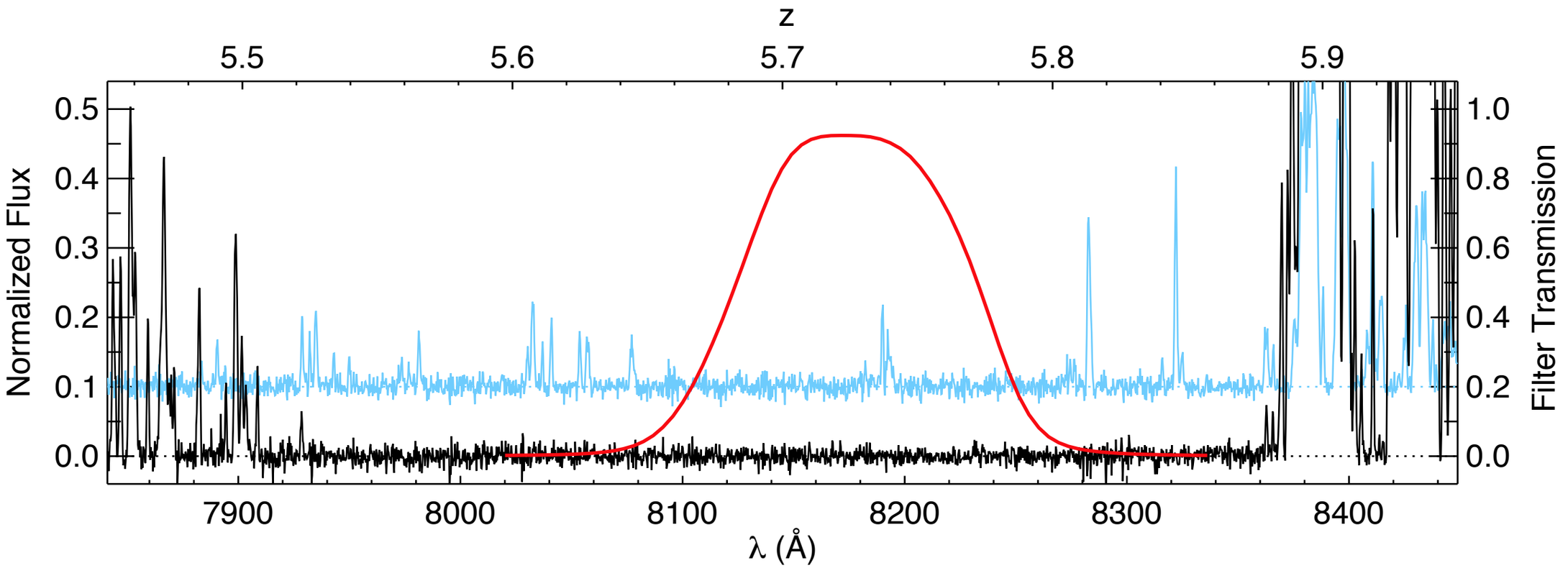
HI fraction

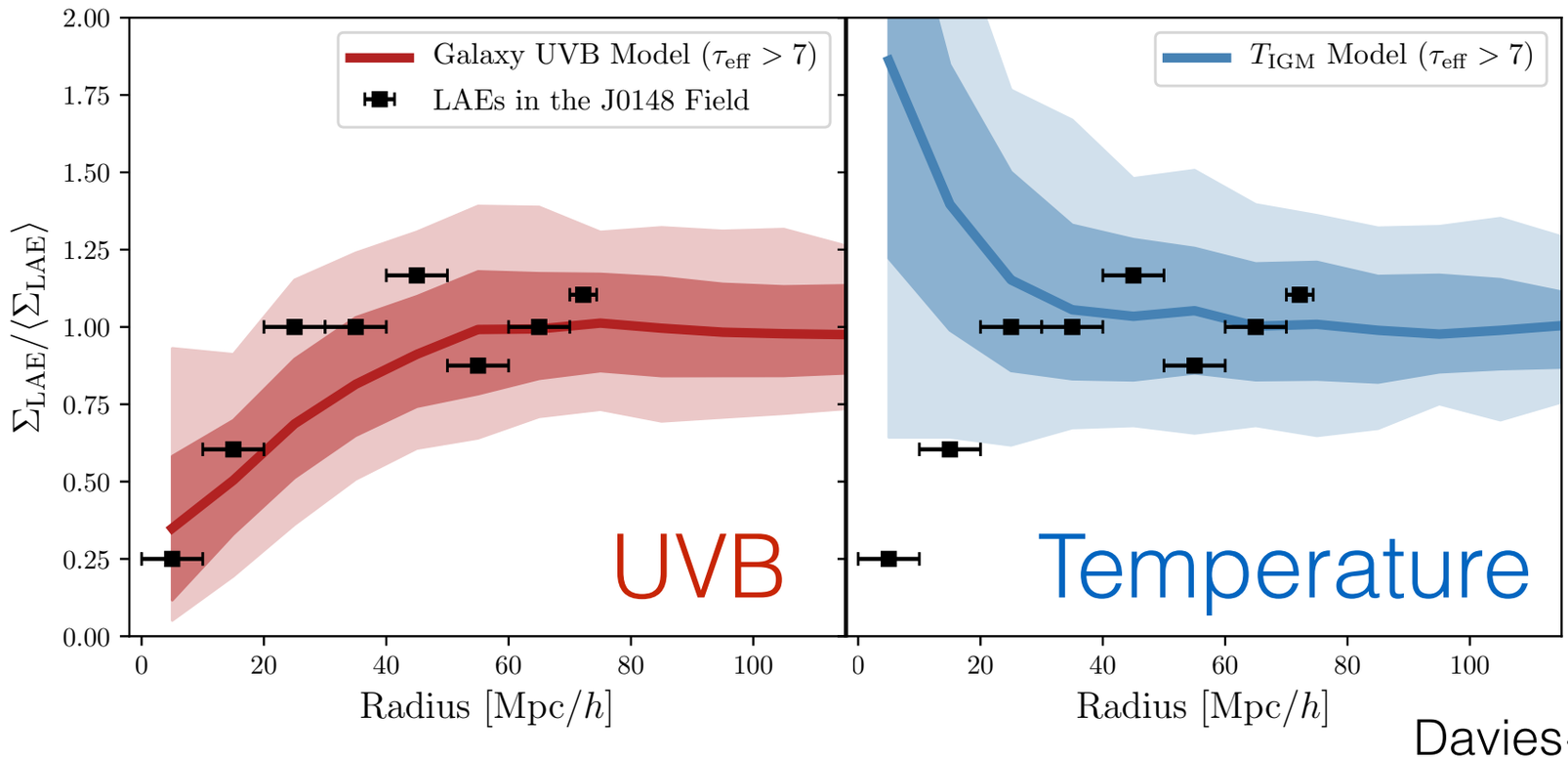
Photoionization rate

Temperature

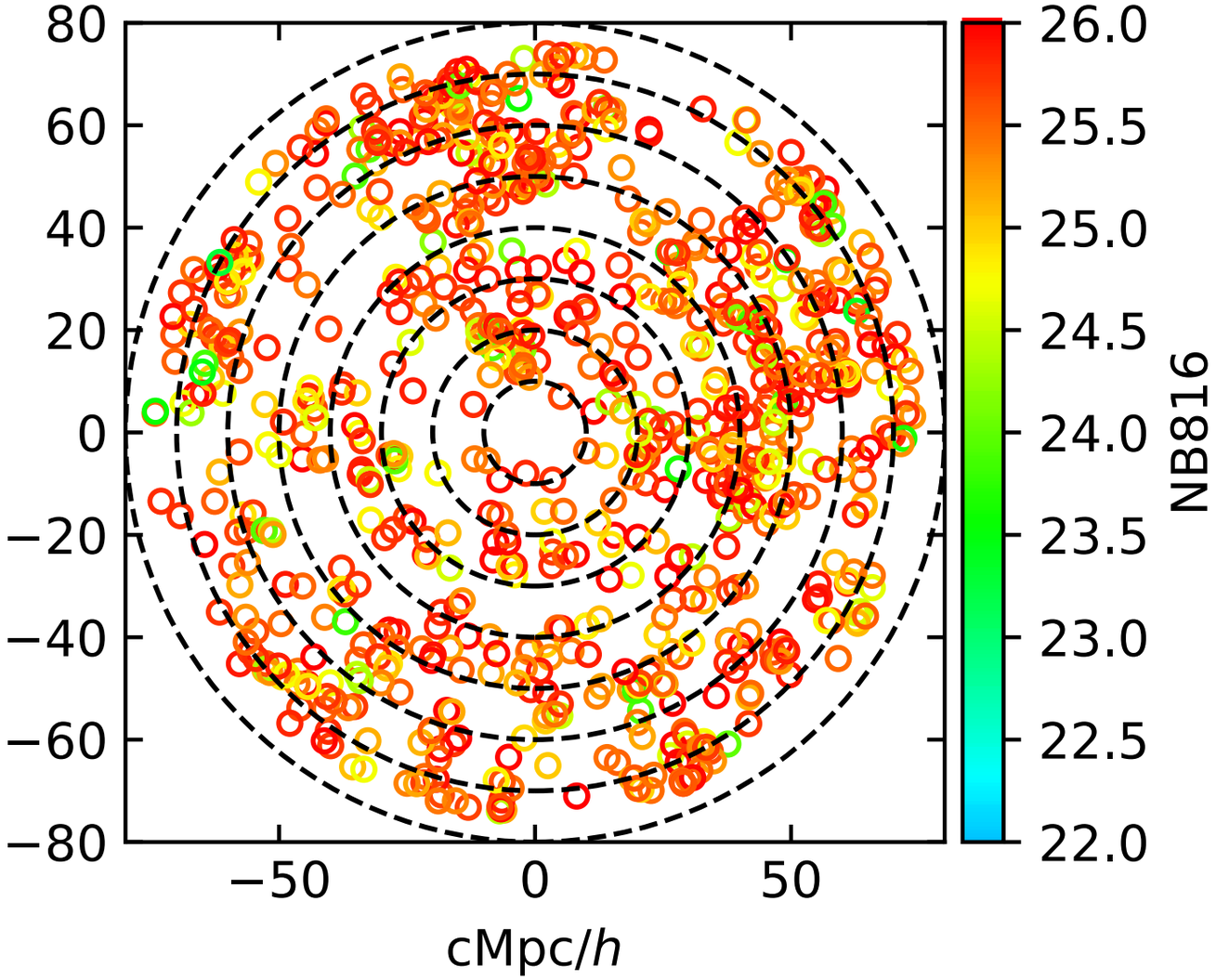


Searches for Lyman-α emitters around the trough can distinguish between different models for the large spatial fluctuations in the Lyman-α forest opacities



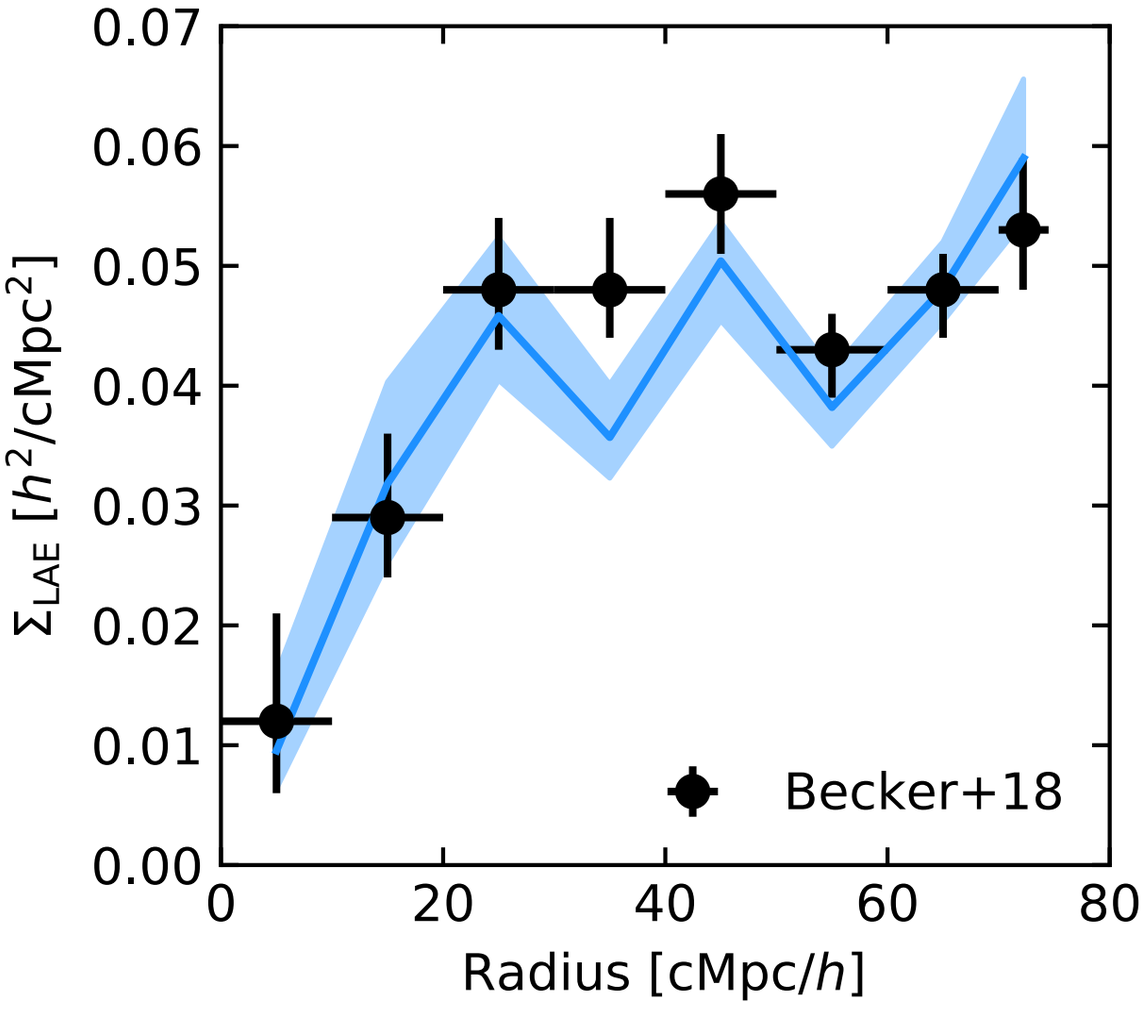


Davies+18/Becker+18

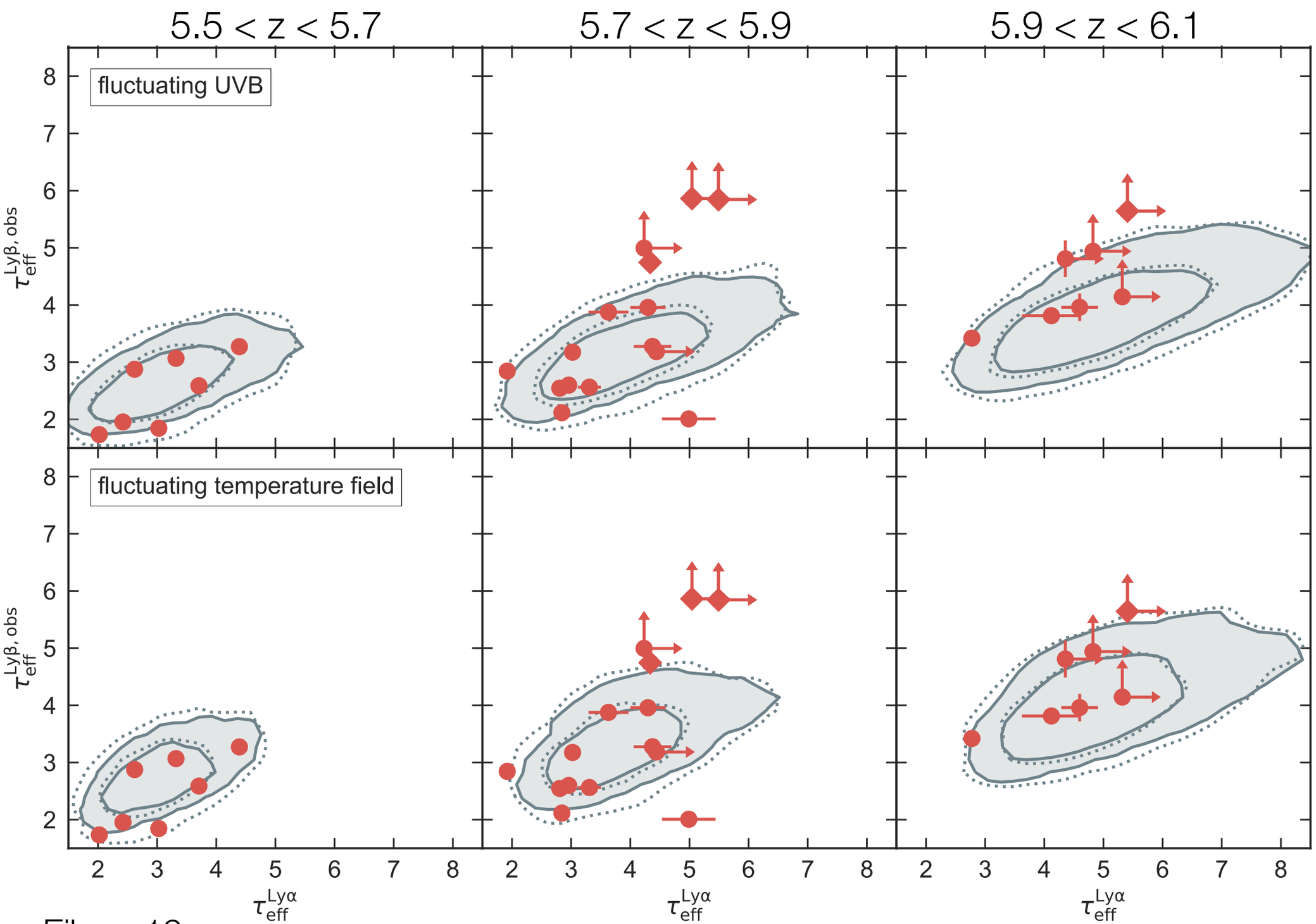


In this model, the troughs are in the last regions to ionize (i.e., voids)

Find a deficit of LAEs around the most opaque sightlines as observed



Observations of the Lyβ forest are also very useful for constraining the properties of the IGM

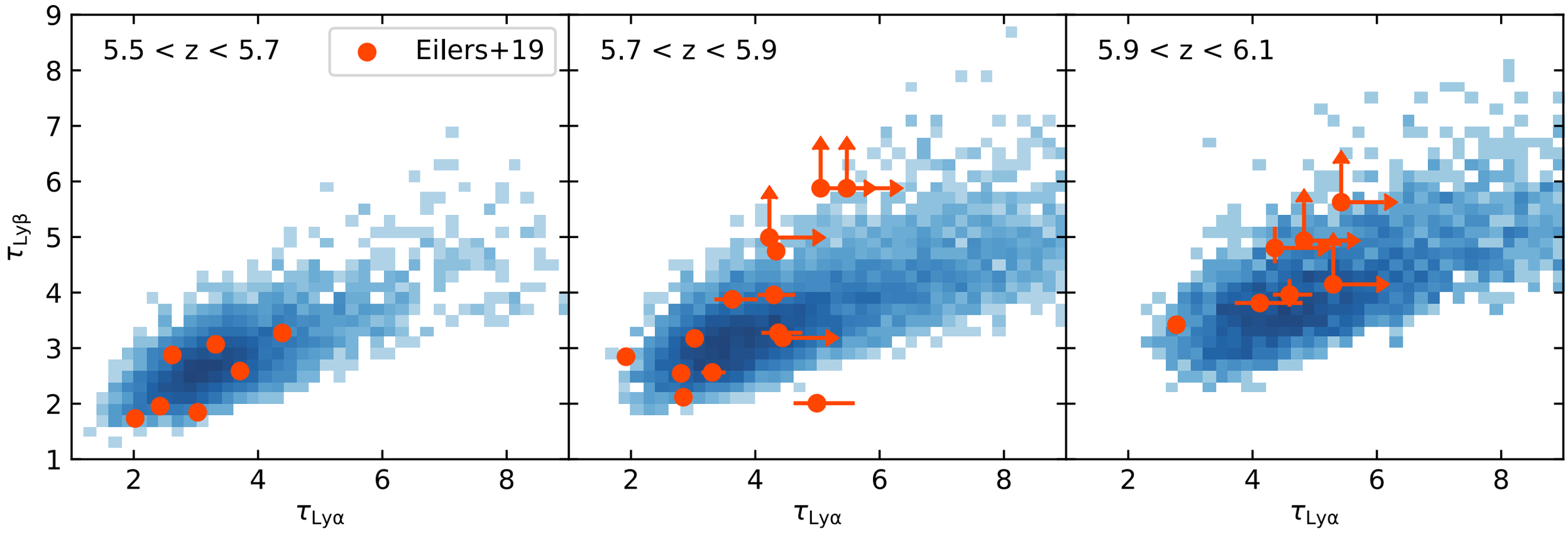


Eilers+19

UV fluctuations

Temperature fluctuations

A late reionization model is consistent with these Lyβ observations



- Matching the mean flux in the Lyman-α forest requires an IGM that is still significantly neutral below redshift 6

- This model naturally reproduces the large spatial fluctuations in the opacity of the Lyman-α forest

- This model also explains the large observed Lyman-α absorption troughs and lack of Lyman-α emitters surrounding them, as well as recent observations of the Lyman-β forest