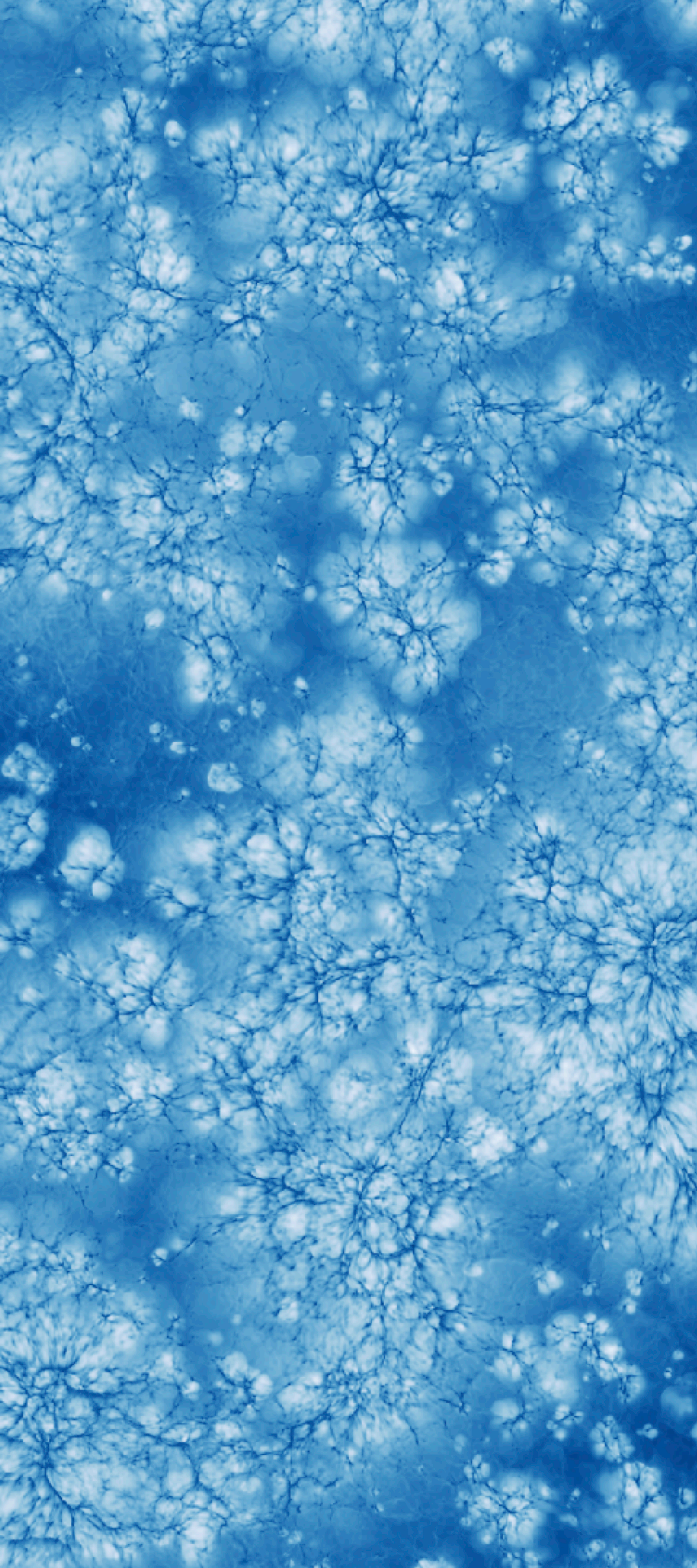

Hints of a concordant reionization model from the Lyman-α forest

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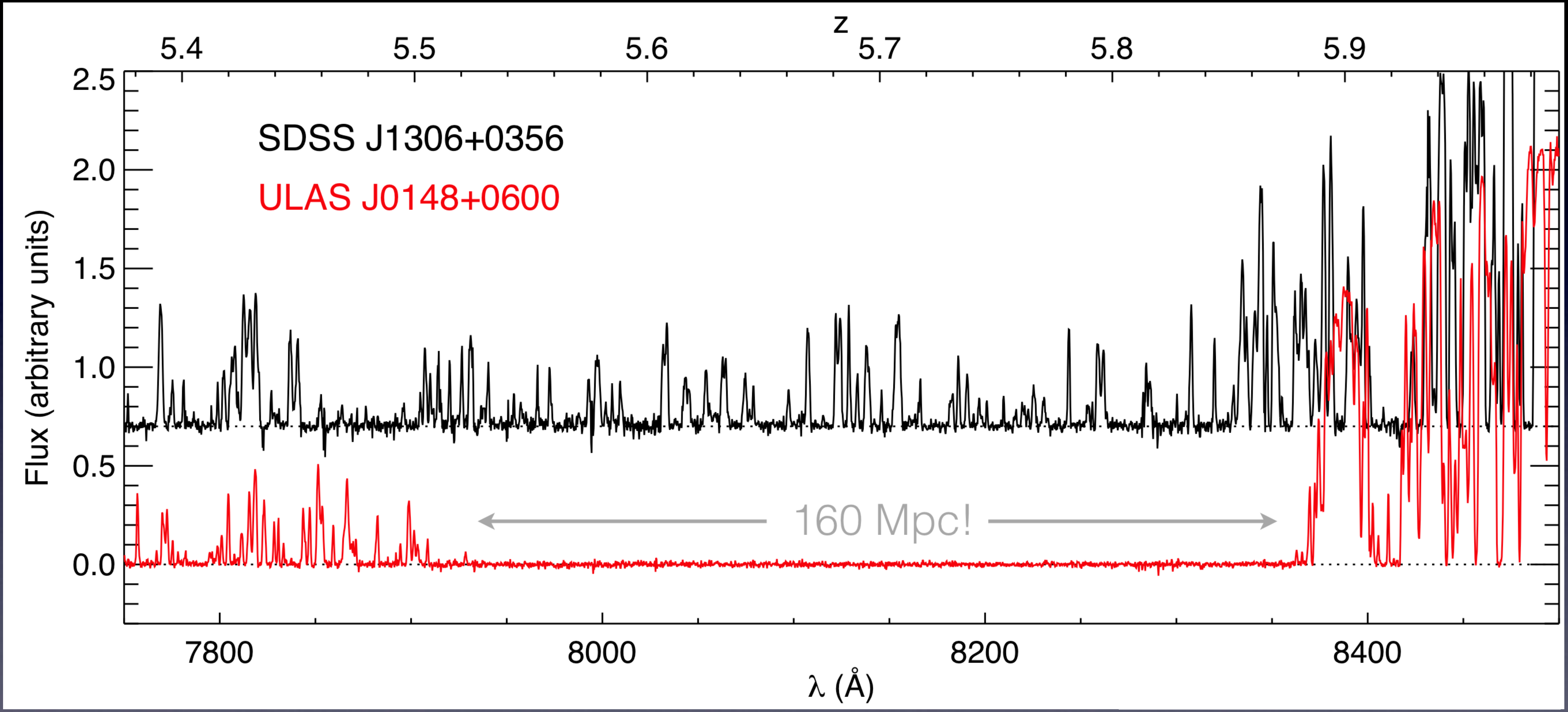
7 October 2019
Second Global 21-cm Workshop

We are seeing the emergence of a model of reionization that is consistent with almost every high-redshift observation

Lyα forest shows spatial fluctuations

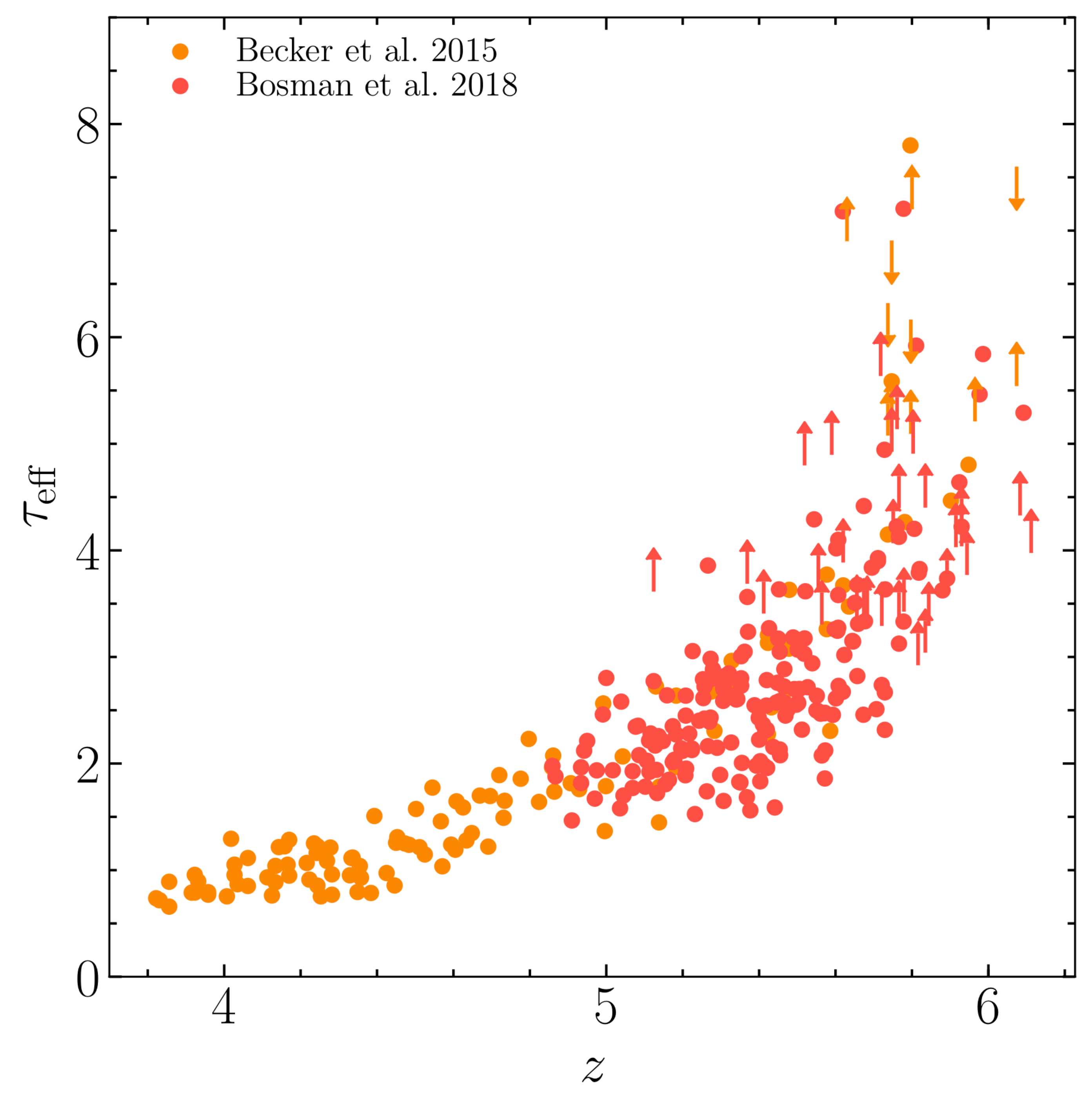


Becker et al. 2015

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

Quantify this by defining an effective optical depth over 50 cMpc/h segments of the forest

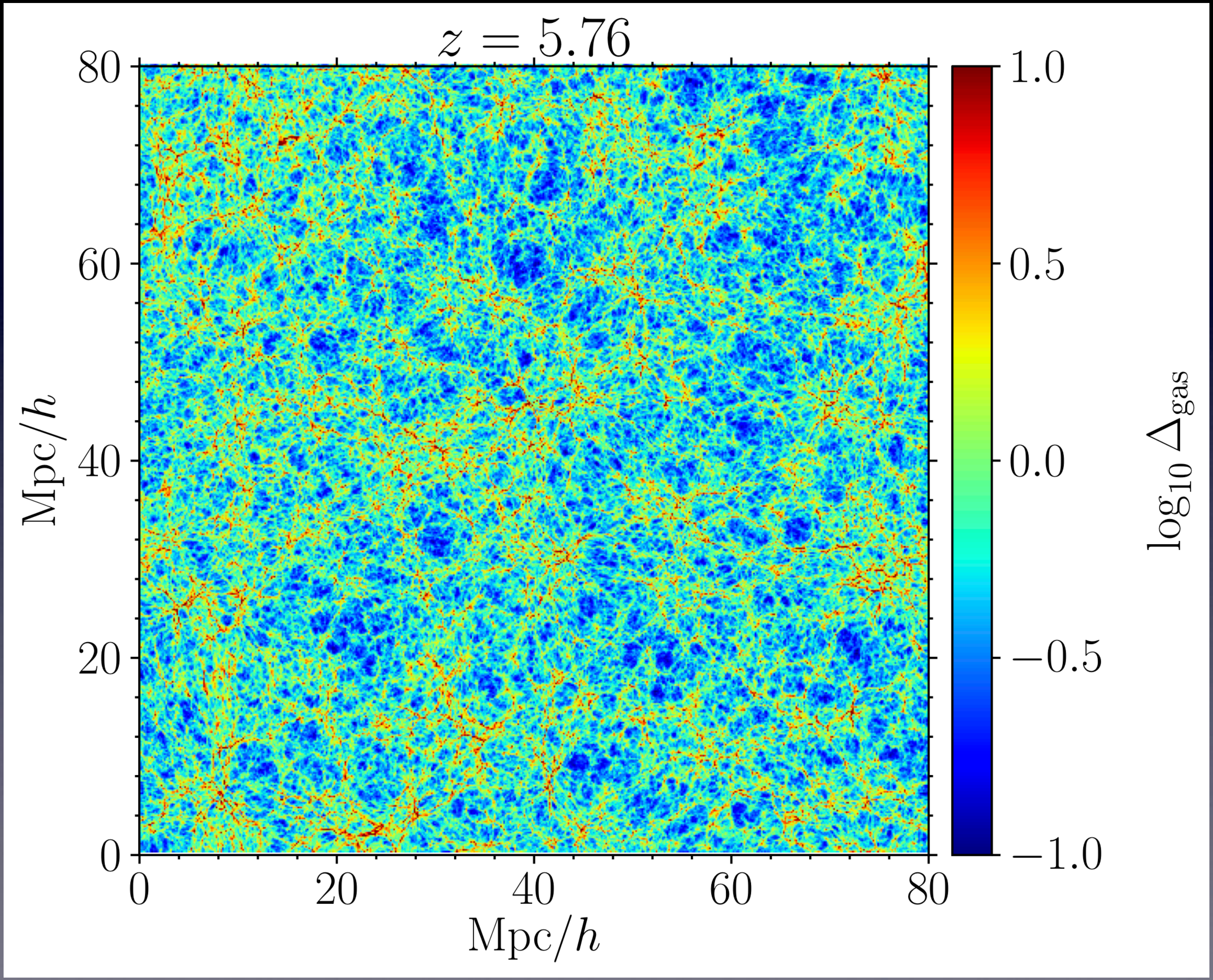
Lyα forest shows spatial fluctuations



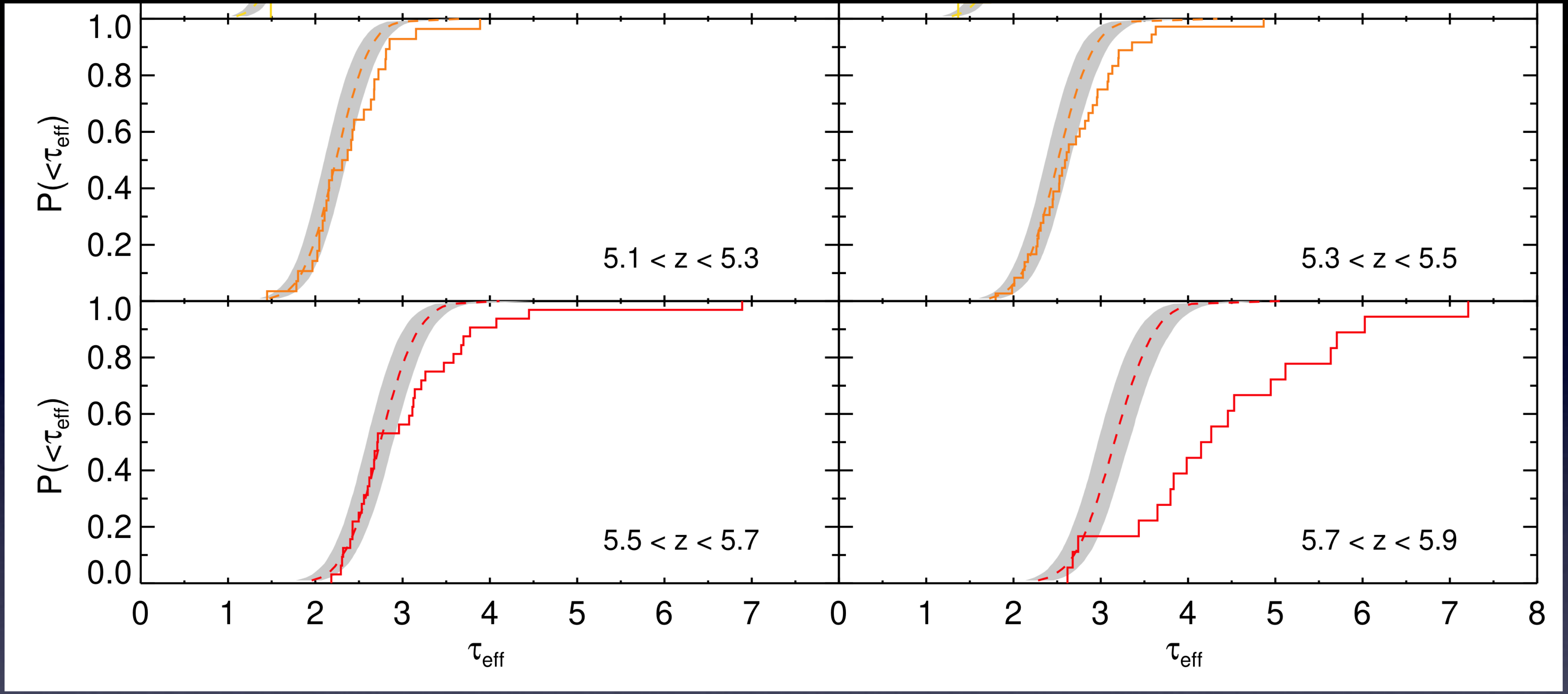
cf. Fan et al. 2006, Eilers e al. 2018

Factor of 2 scatter in mean transmission at z = 4 but ≳500 scatter at z = 5.6

We do expect spatial fluctuations



Cosmic density does not explain fluctuations

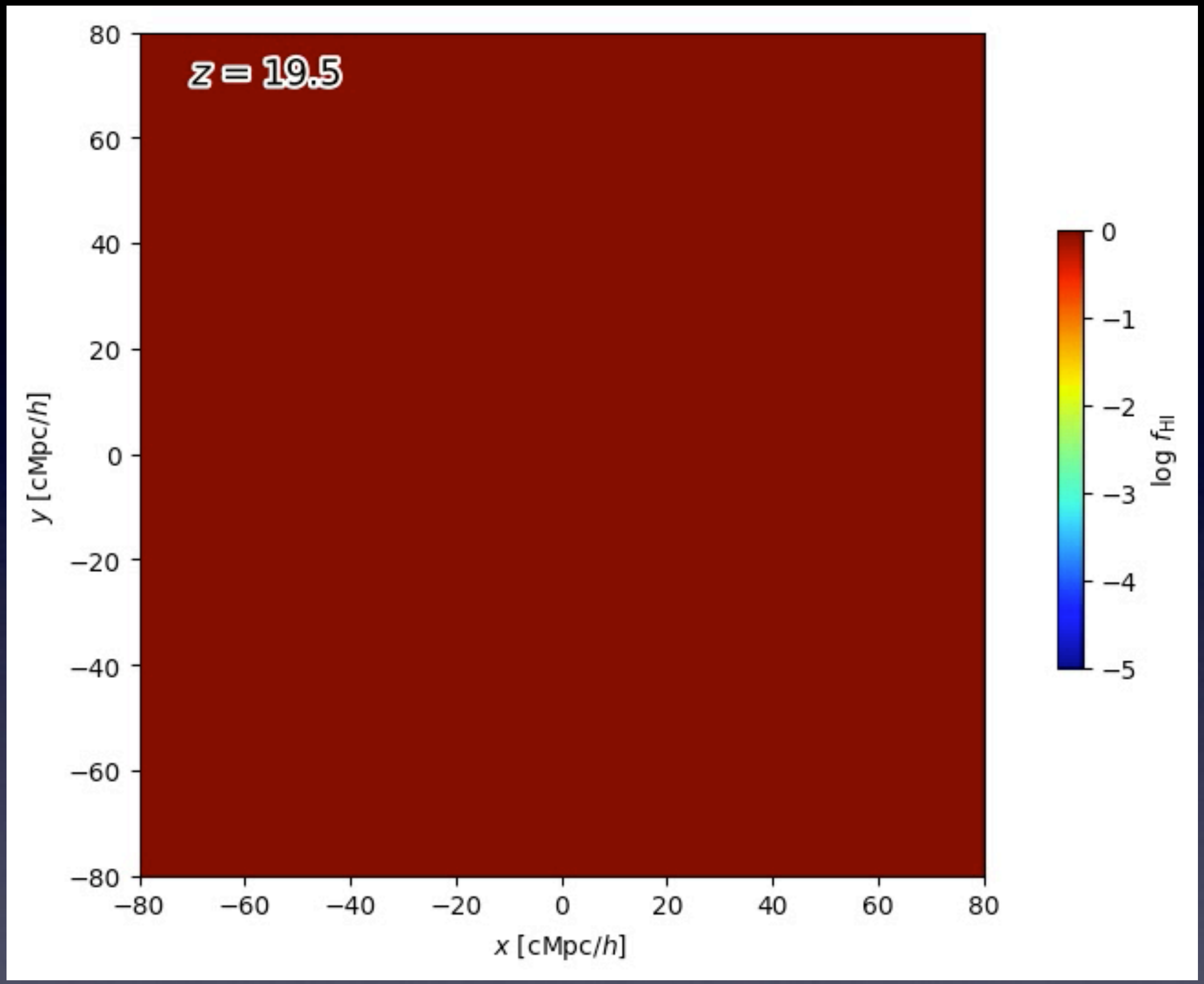


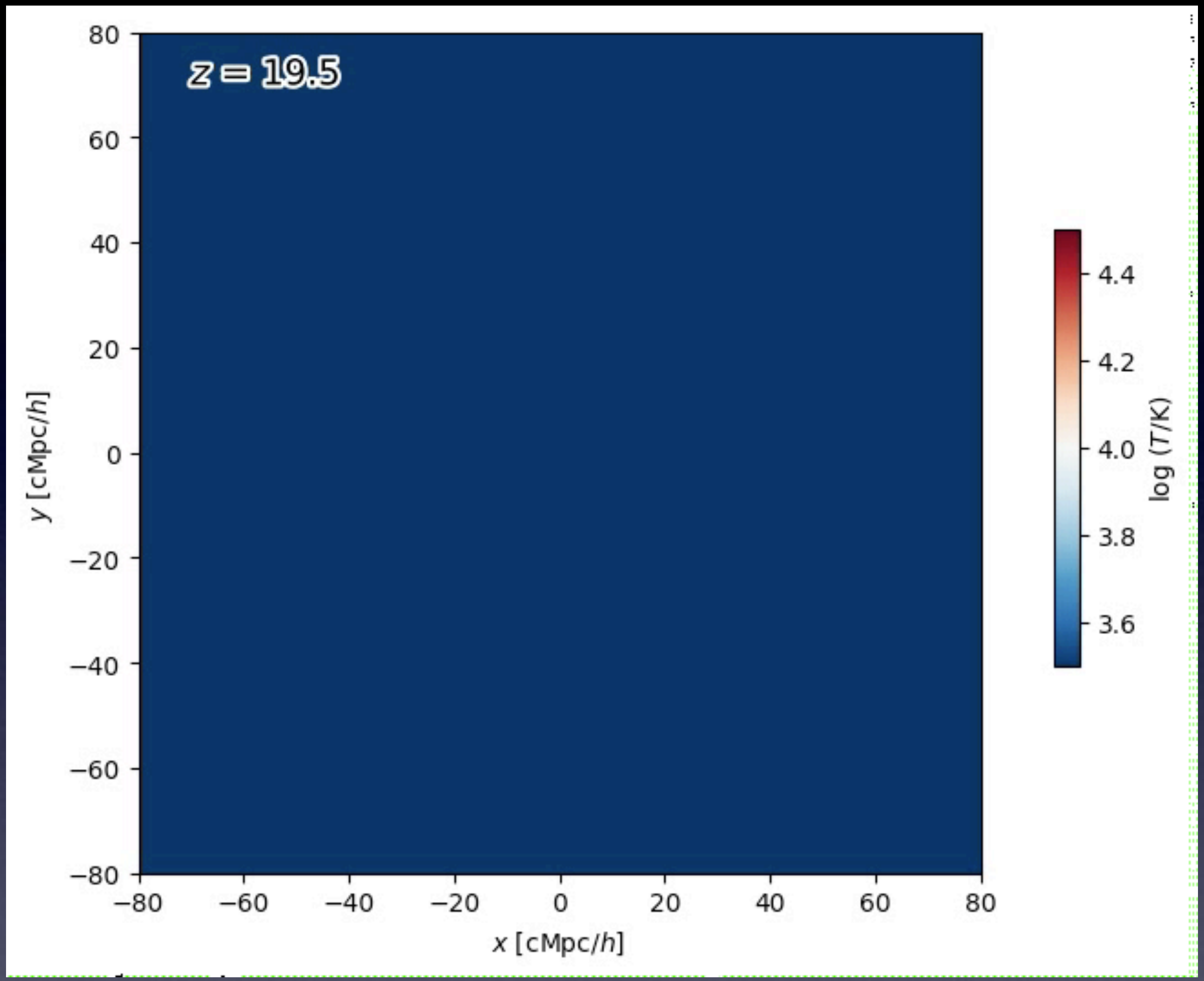
Becker et al. 2015

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

- Temperature fluctuations (D’Aloisio et al. 2015): too high temperatures
- Ionization rate fluctuations (Davies et al. 2016): too small mean free path
- Rare sources, such as QSOs (Chardin et al. 2015): not sure if these exist

Carefully calibrated reionization simulation suite

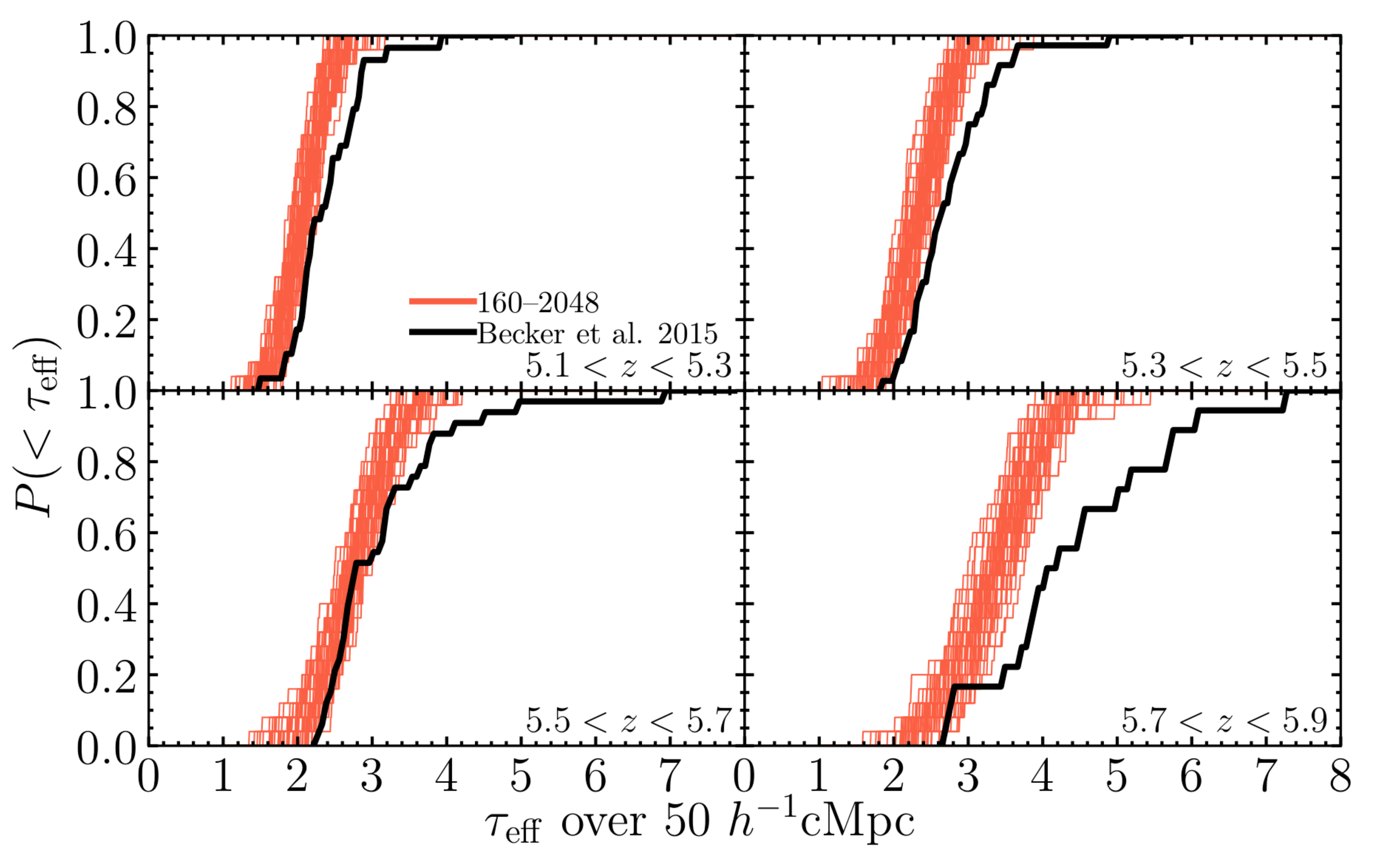




Kulkarni et al. 2019

- Cosmological simulations + GPU-enabled radiative transfer
- Highest dynamic-range reionization simulations in the world: 80 kpc/h–320 Mpc/*h*! Box size greater than the mean free path.
- Sources are galaxies that reside in haloes down to 10^9 $M_\odot$ halos

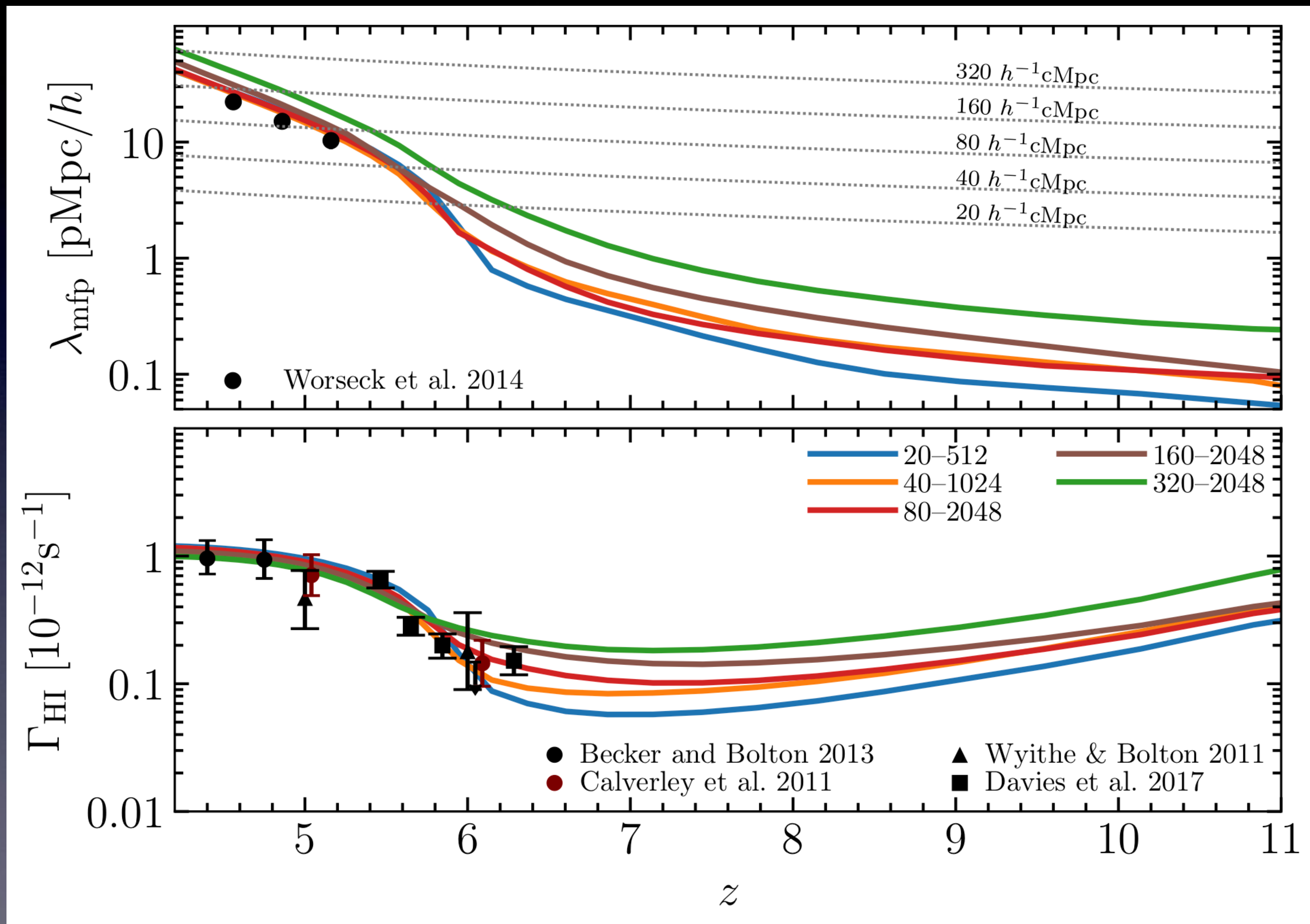
Another bad surprise?



Kulkarni et al. 2019

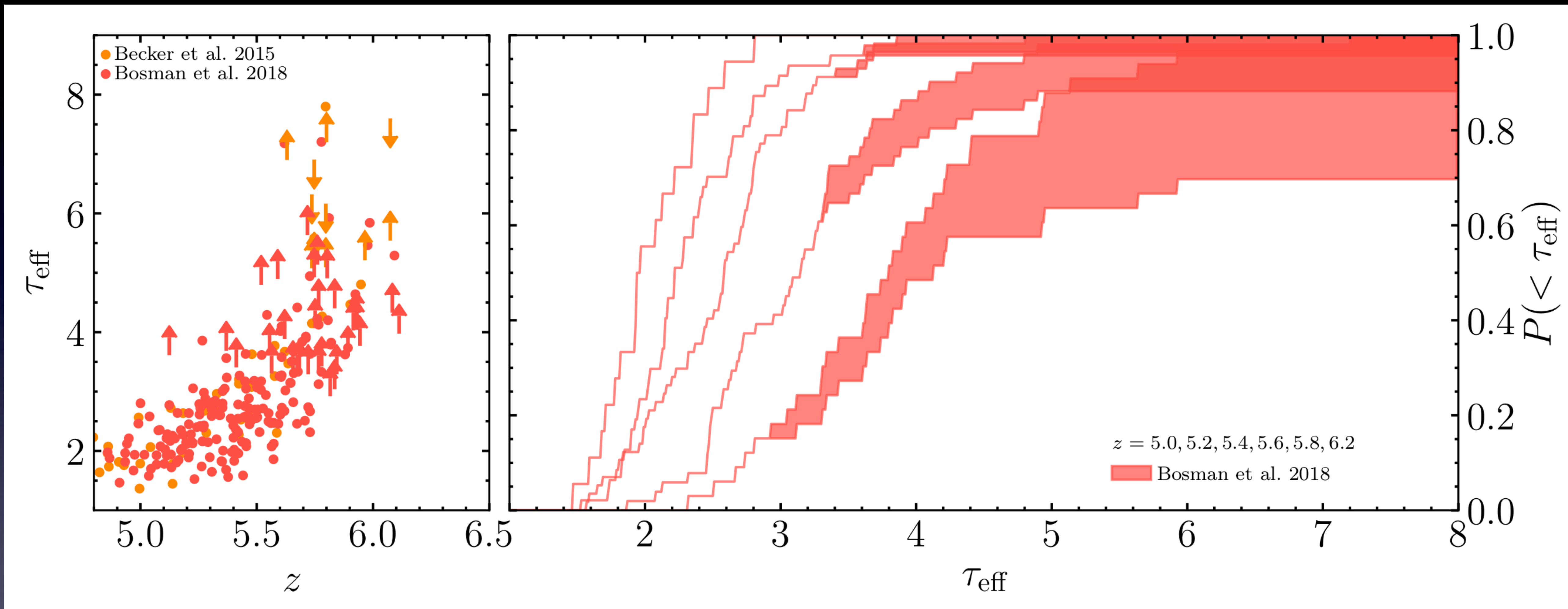
Distributions were much narrower in our initial runs.

How are these simulations calibrated?

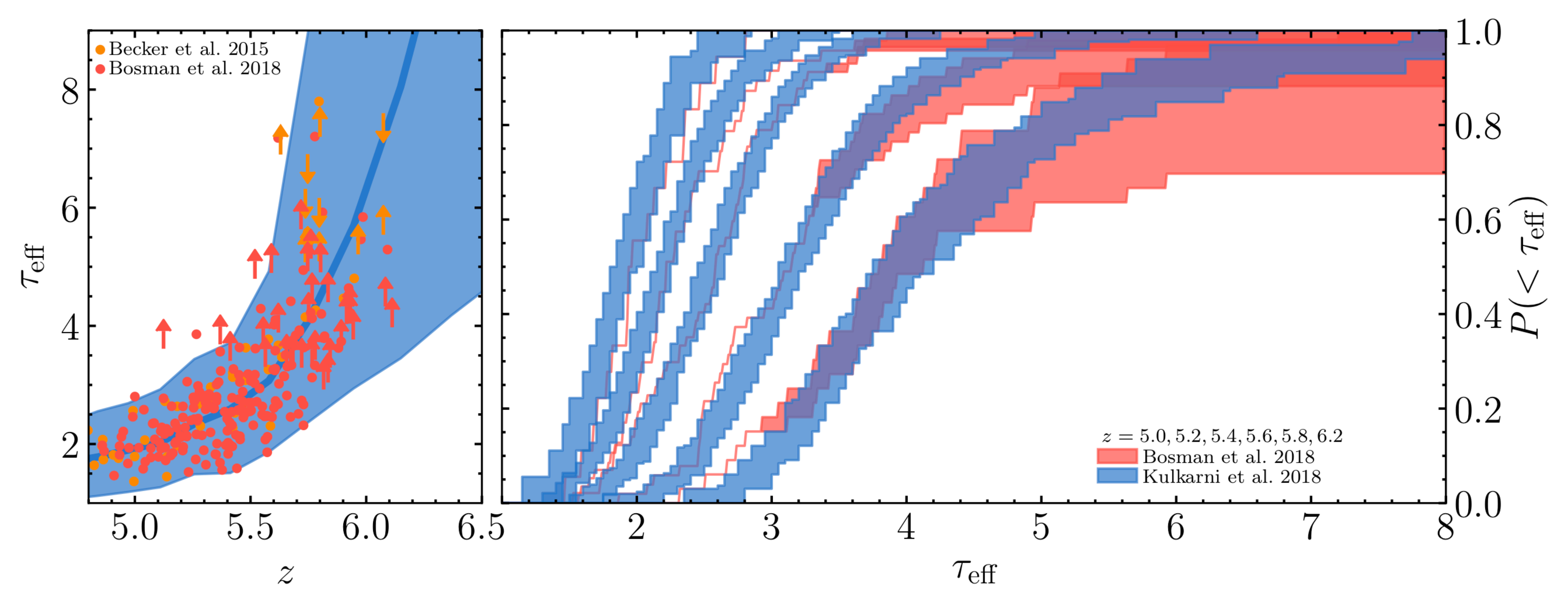


Reionization simulations are traditionally calibrated to reproduce the mean IGM photoionization rate

Lyα fluctuations



Lyα fluctuations explained

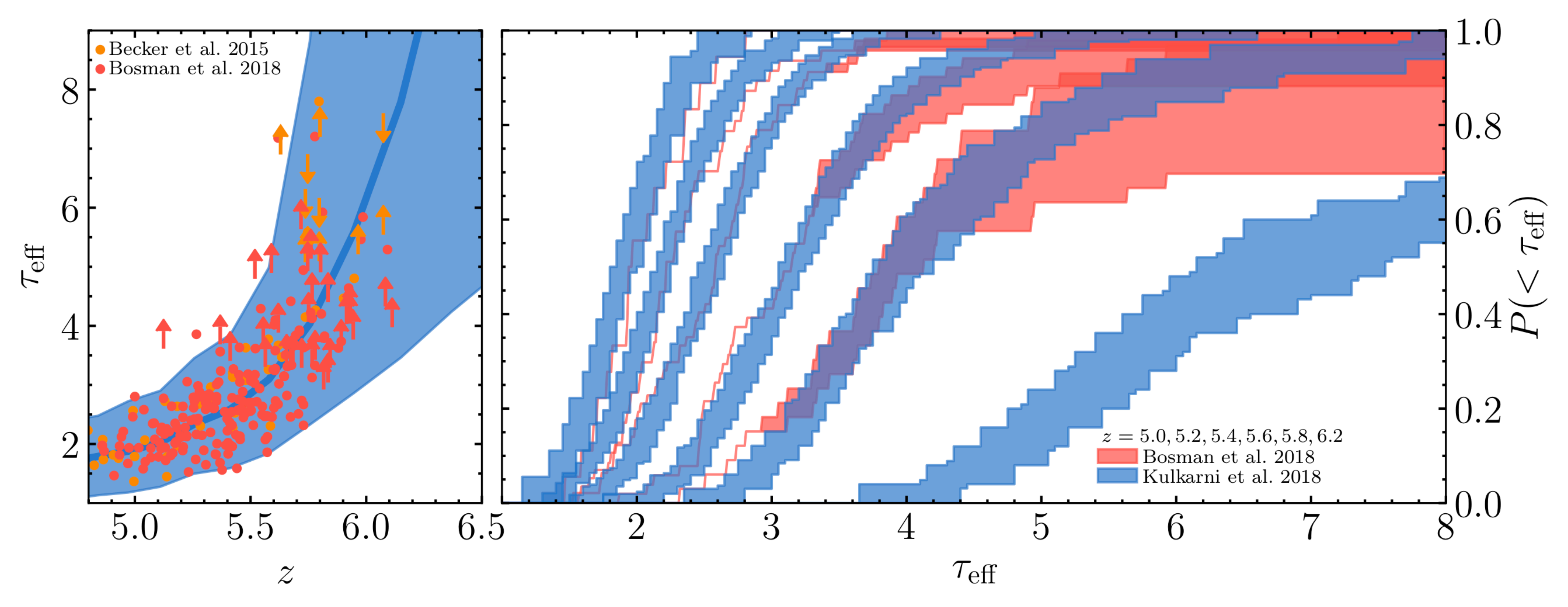


Kulkarni et al. 2019

Key to success: correct calibration of simulations.

Previous simulations were calibrated to match the photoionization rate but that is a derived quantity. Use the mean flux instead.

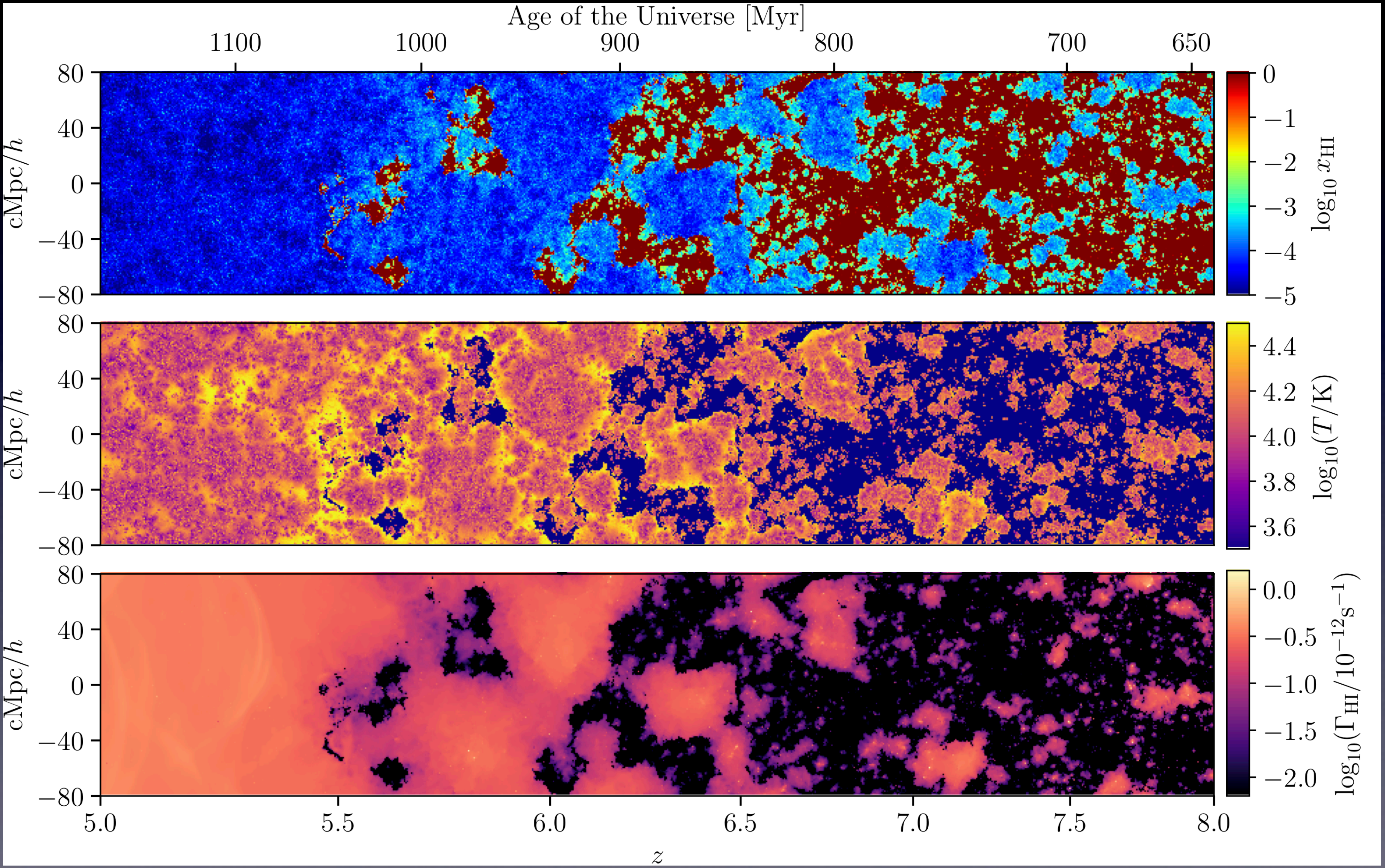
Lyα fluctuations explained



Kulkarni et al. 2019

112.5 hr on VLT to target 29 z > 5.8 quasars

Delayed reionization

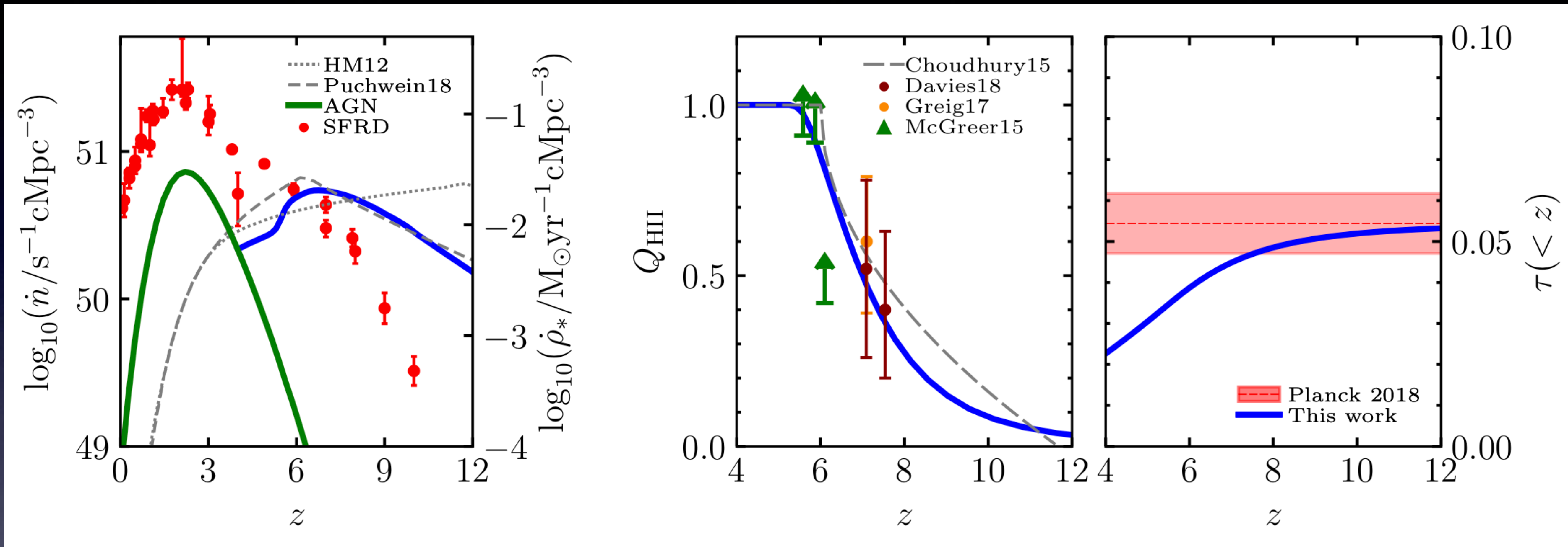


Kulkarni et al. 2019

Reionization is half-finished at z ~ 7.5 and ends at z ~ 5.3, with long-lasting neutral "islands". (Good news for 21-cm experiments.)

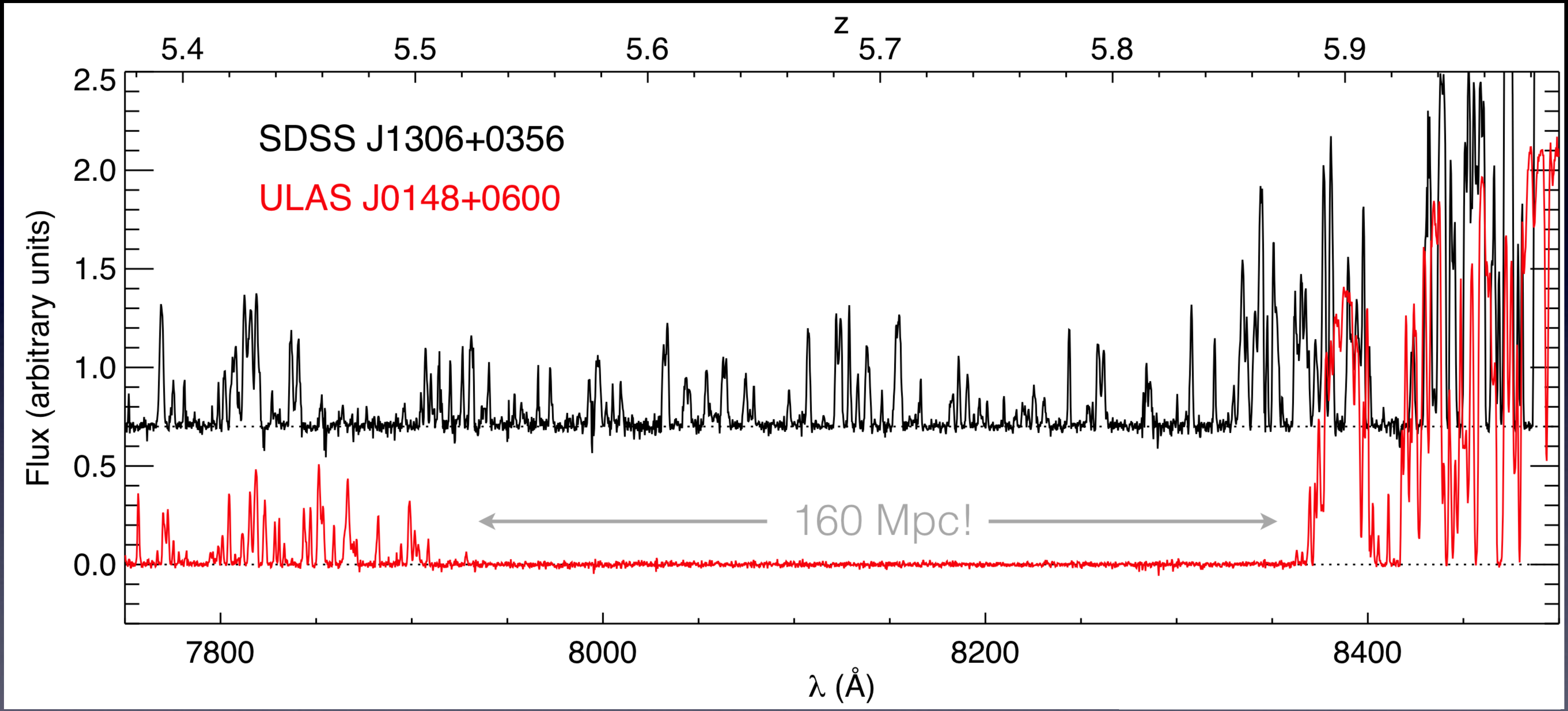
Towards a concordant reionization model

Kulkarni et al. 2019



- Good agreement with Lyα emitter data (Choudhury et al. 2015), IGM damping wing (Greig et al. 2017 and Davies et al. 2018), statistics of dark Lyα forest pixels (McGreer et al. 2015), and CMB (Planck 2018)
- Ionizing emissivity peaks at redshift z ~ 7
- Very little freedom at least out to z ~ 7.5

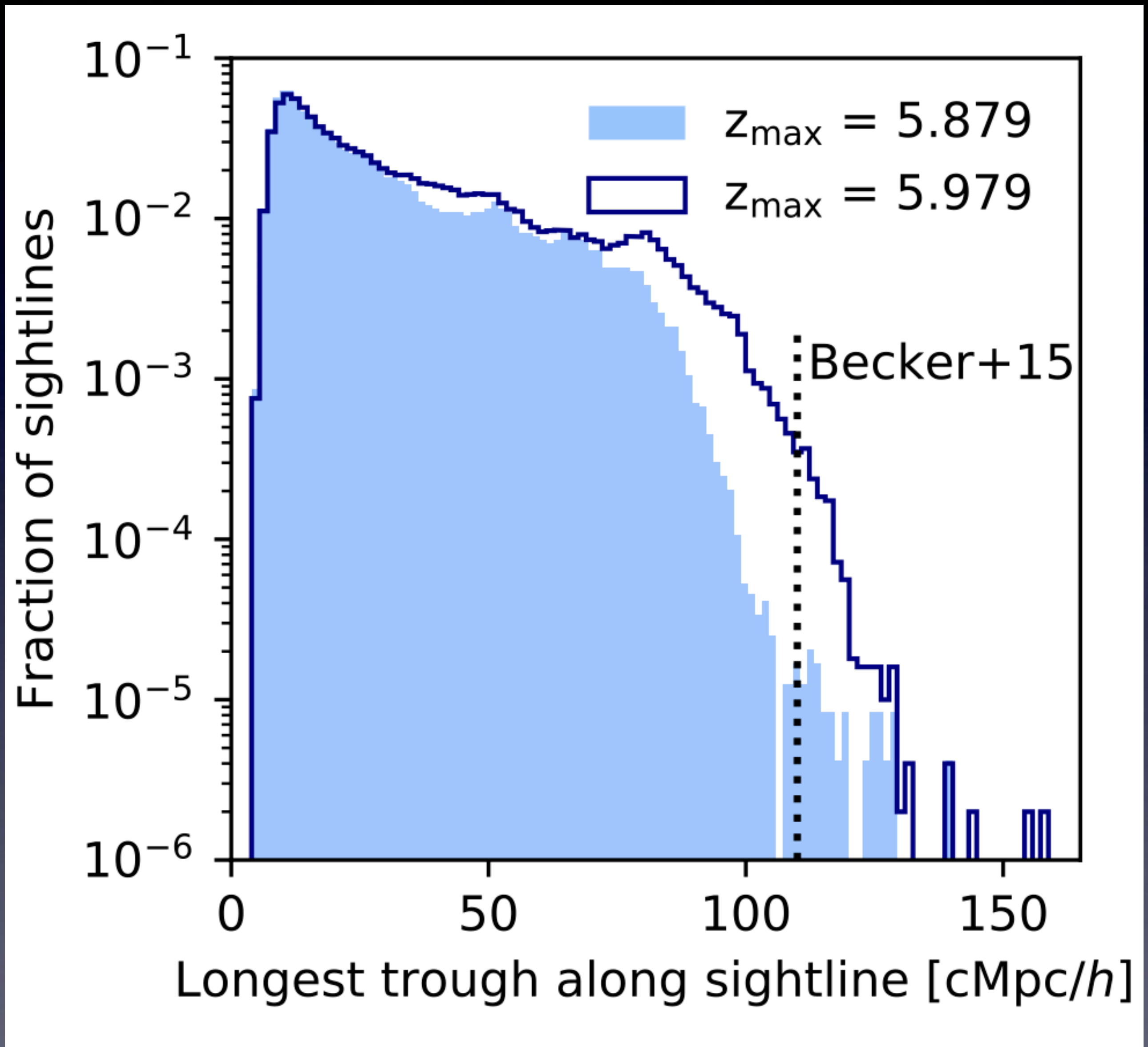
Long Lyα troughs in late reionization models

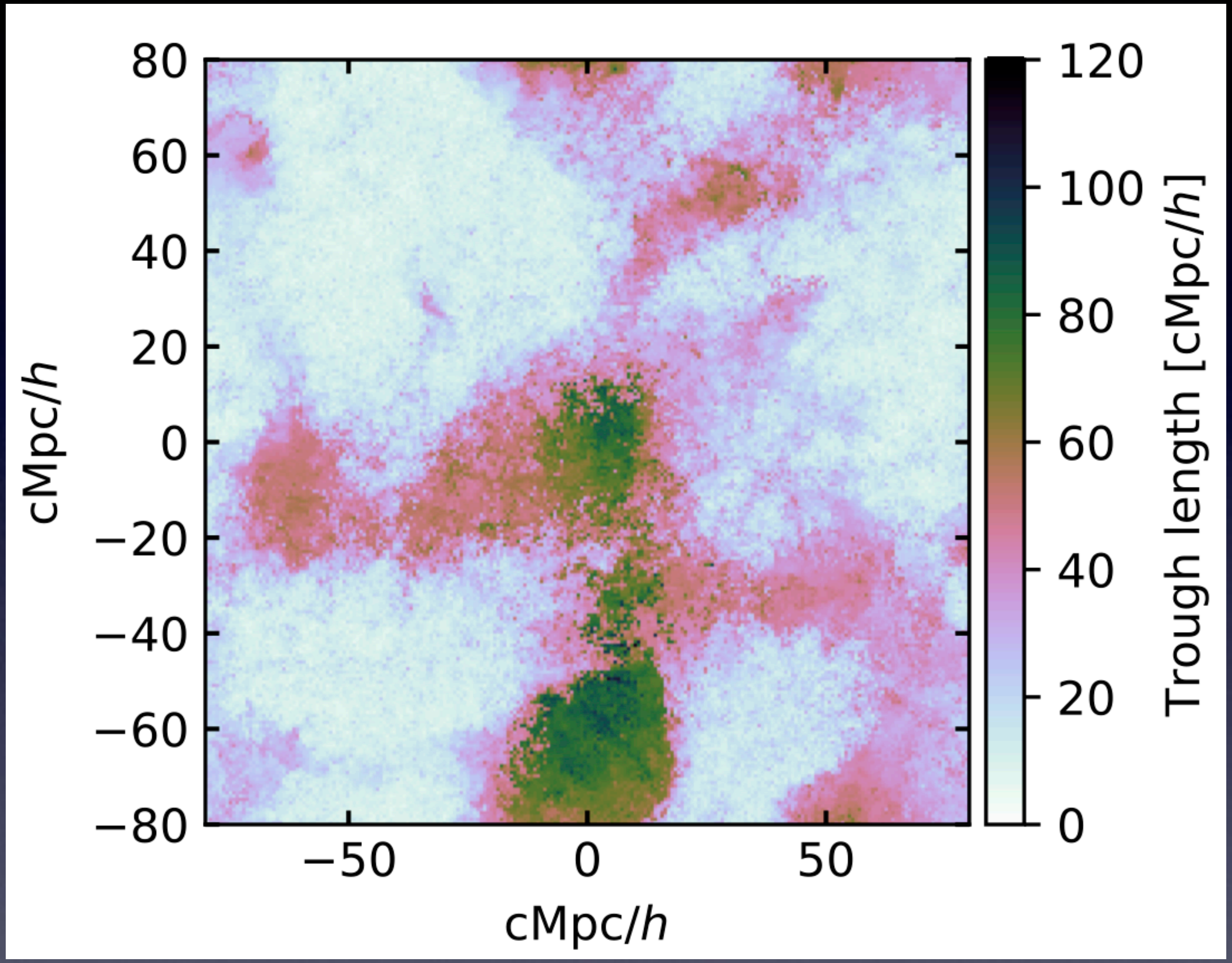


Becker et al. 2015

Incidence of long troughs and the density structure around them are good model discriminants.

Long Lyα troughs in late reionization models

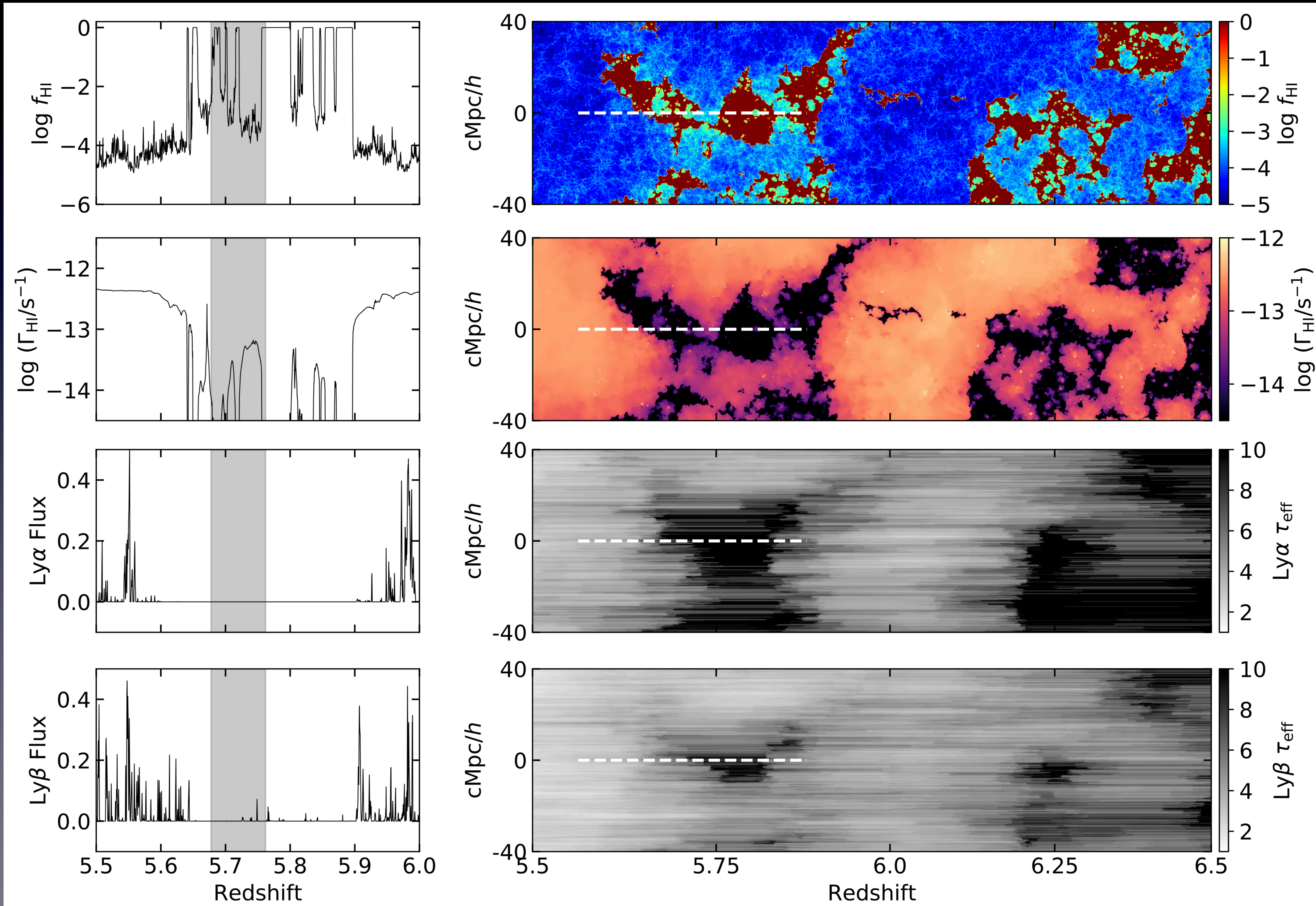




Keating, Kulkarni et al. 2019

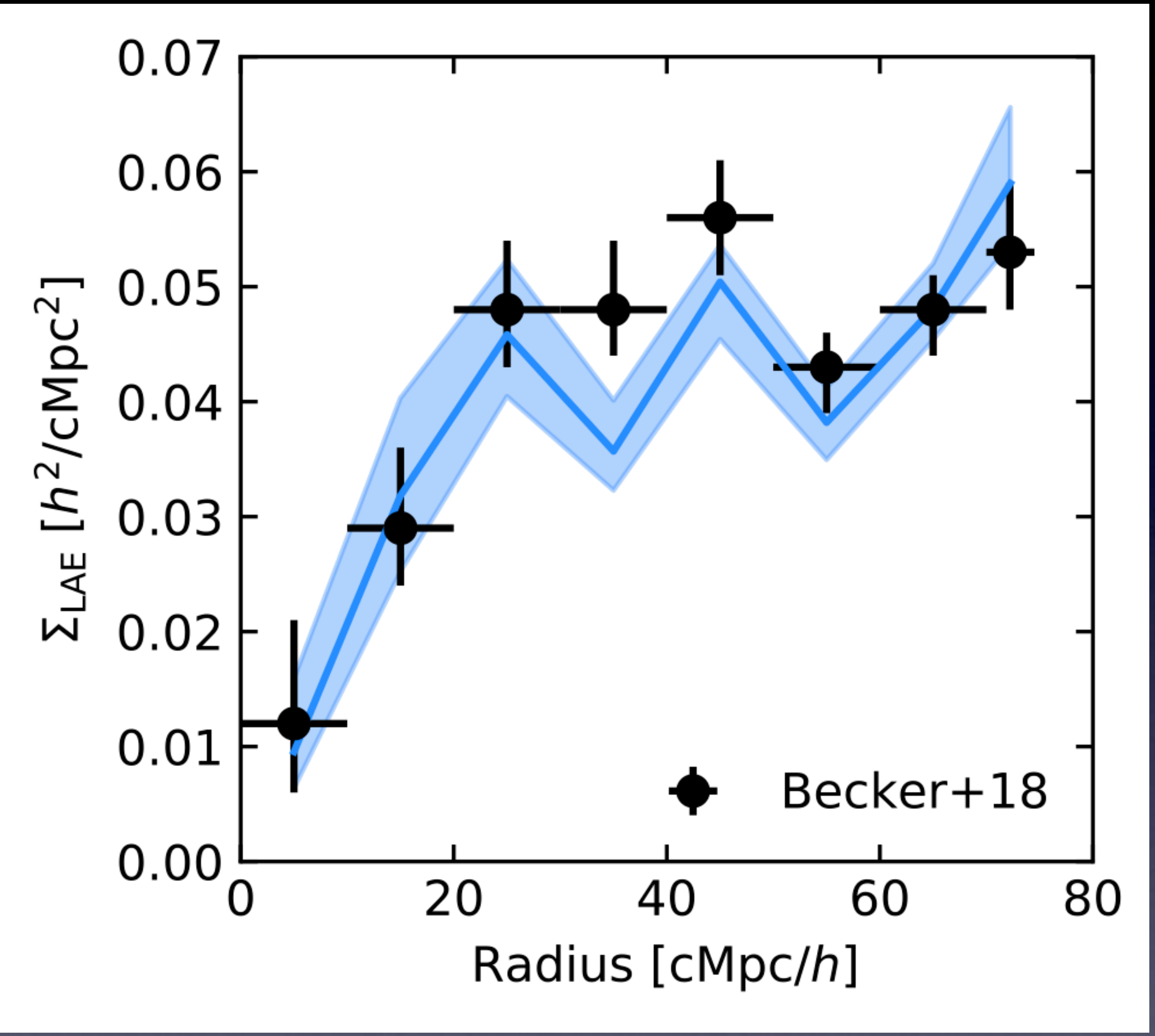
- Derive spectra over lightcones; add instrument profile and noise
- Define trough length following Becker et al. 2015
- Incidence rate falls above 80 cMpc/h (reionization still early? small volume?)

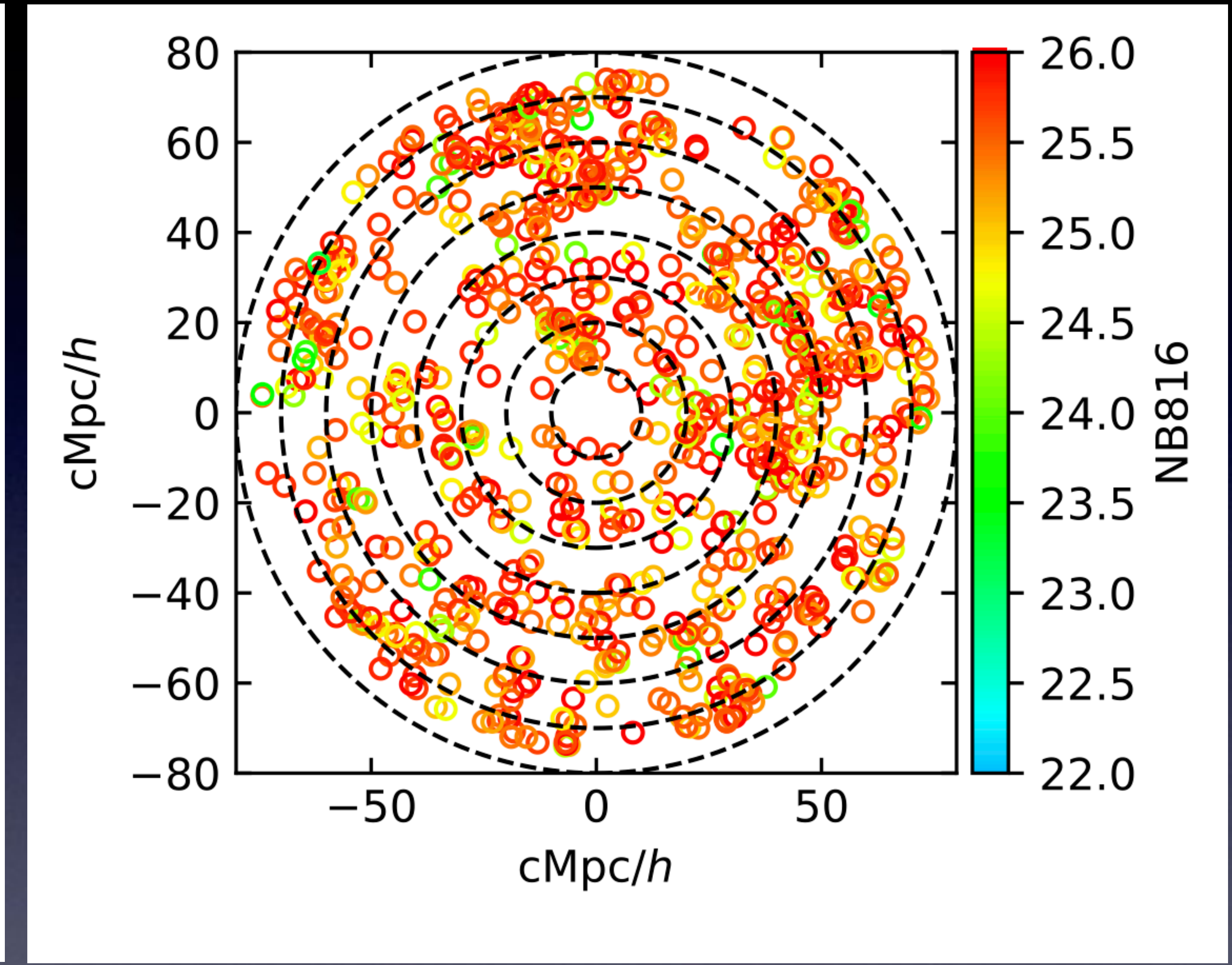
‘Neutral islands’ cause long troughs



Keating, Kulkarni et al. 2019

LAE counts show decrement near the trough

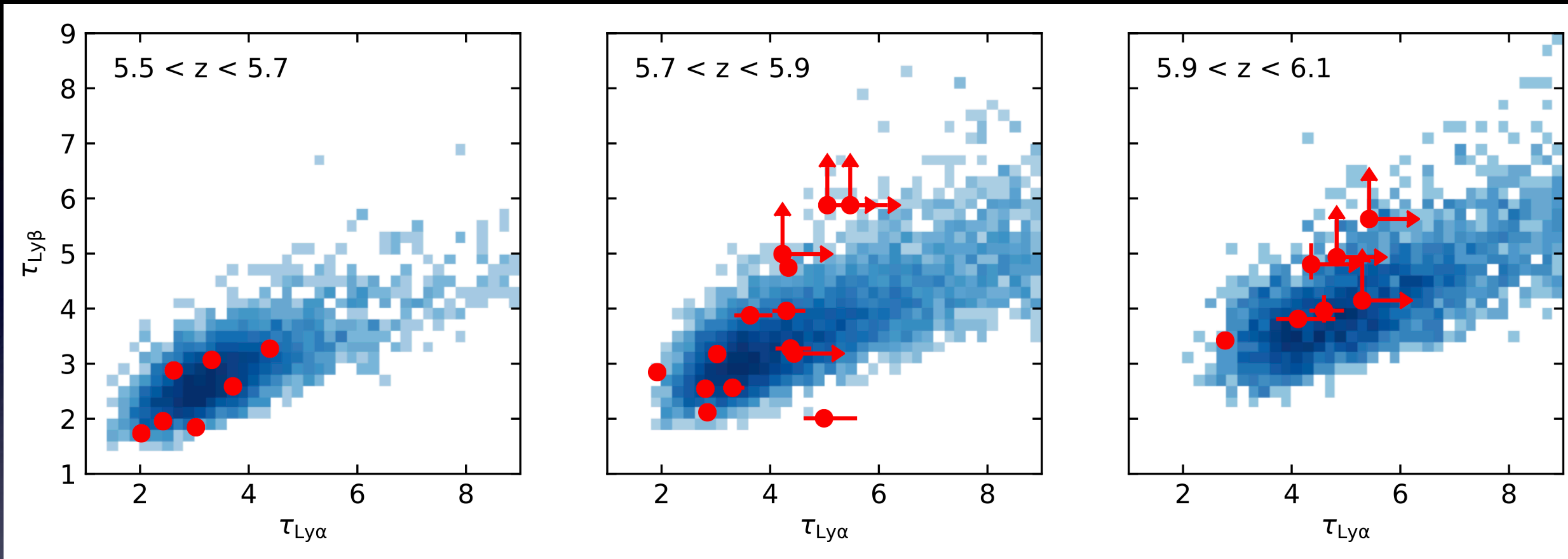




Keating, Kulkarni et al. 2019

- Model LAEs following Weinberger et al. 2019
- Deficit in LAEs near the trough in agreement with Becker et al. 2018
- Combination of low density and high Lya opacity of environment

Lyman-β opacity at z = 5.5–6.1



- Measurements from 19 quasar sightlines by Eilers et al. 2019
- Effective opacity derived over 40 cMpc.
- Late reionization model seems to be in better agreement with high-opacity data points than other models

Conclusion

- **Reionization is late** (ends at $z < 5.5$)
- Late reionization explains a variety of high-z data: Lyα opacities, long Lyα troughs, Lyβ opacities, and 2018 τ measurement from Planck
- Implications for the global 21-cm signal?