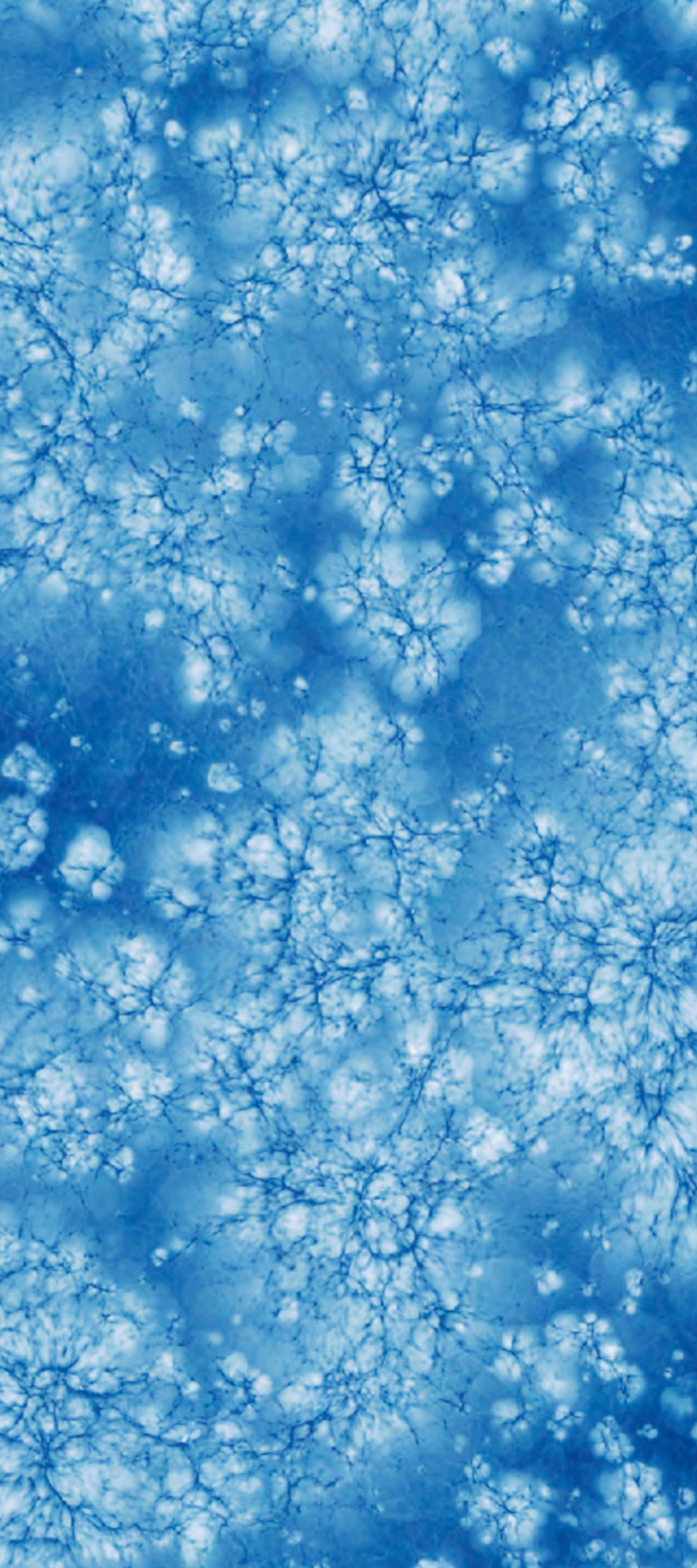


When did reionization happen?

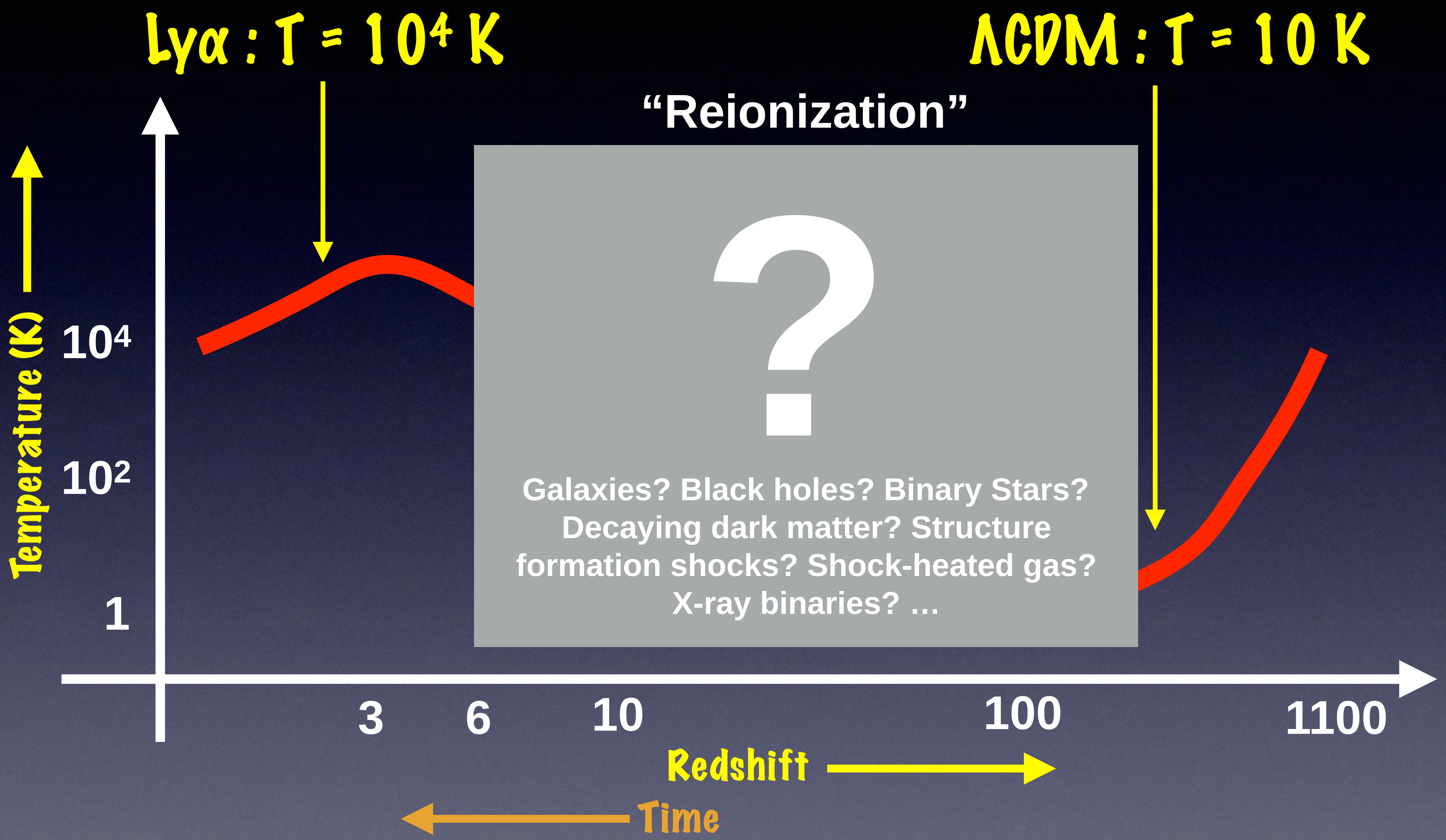
Girish Kulkarni

Tata Institute of Fundamental Research

with Dominique Aubert (Strasbourg), Sarah Bosman (UCL), Jonathan Chardin (Strasbourg), Sebastian Dumitru (UPenn), Martin Haehnelt (Cambridge), Joe Hennawi (UCSB), Laura Keating (CITA), Guillaine Lagache (Marseille), Ewald Puchwein (Potsdam), Lewis Weinberger (Cambridge), Gabor Worseck (Potsdam)

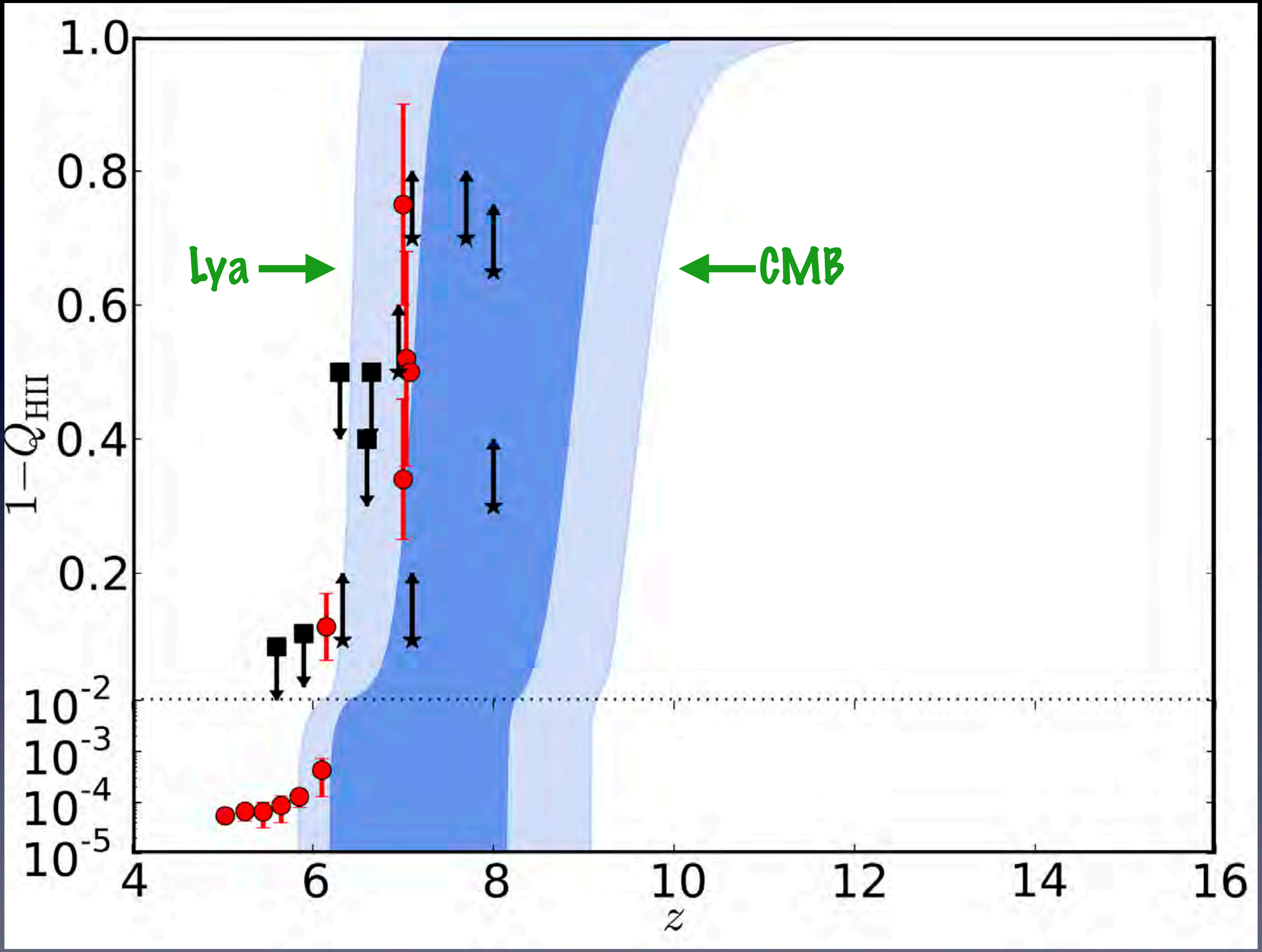
26 September 2019
Kavli IPMU

How did the IGM heat up?



1. When did reionization happen?
2. What caused it?

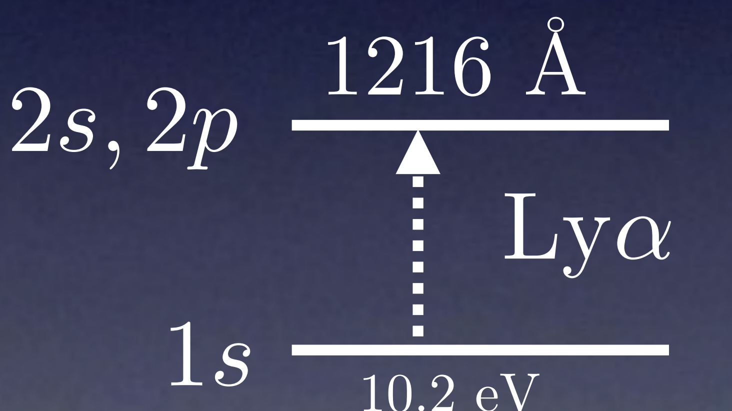
How to probe reionization?



Planck Collaboration 2016

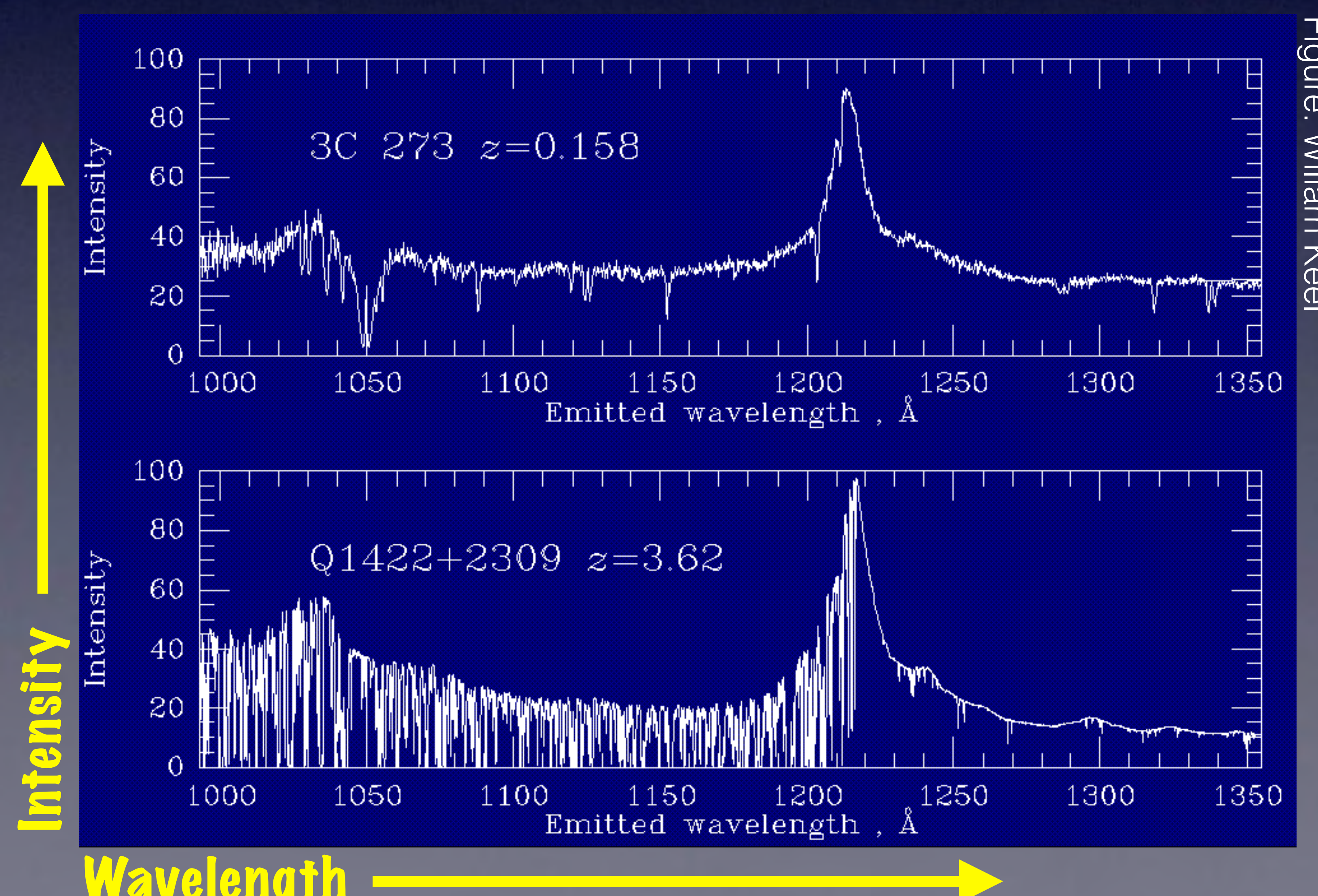
• CMB • Lya absorption • Lya emitters • 21-cm absorption/emission

Lyman-α Forest probes IGM at low *z*

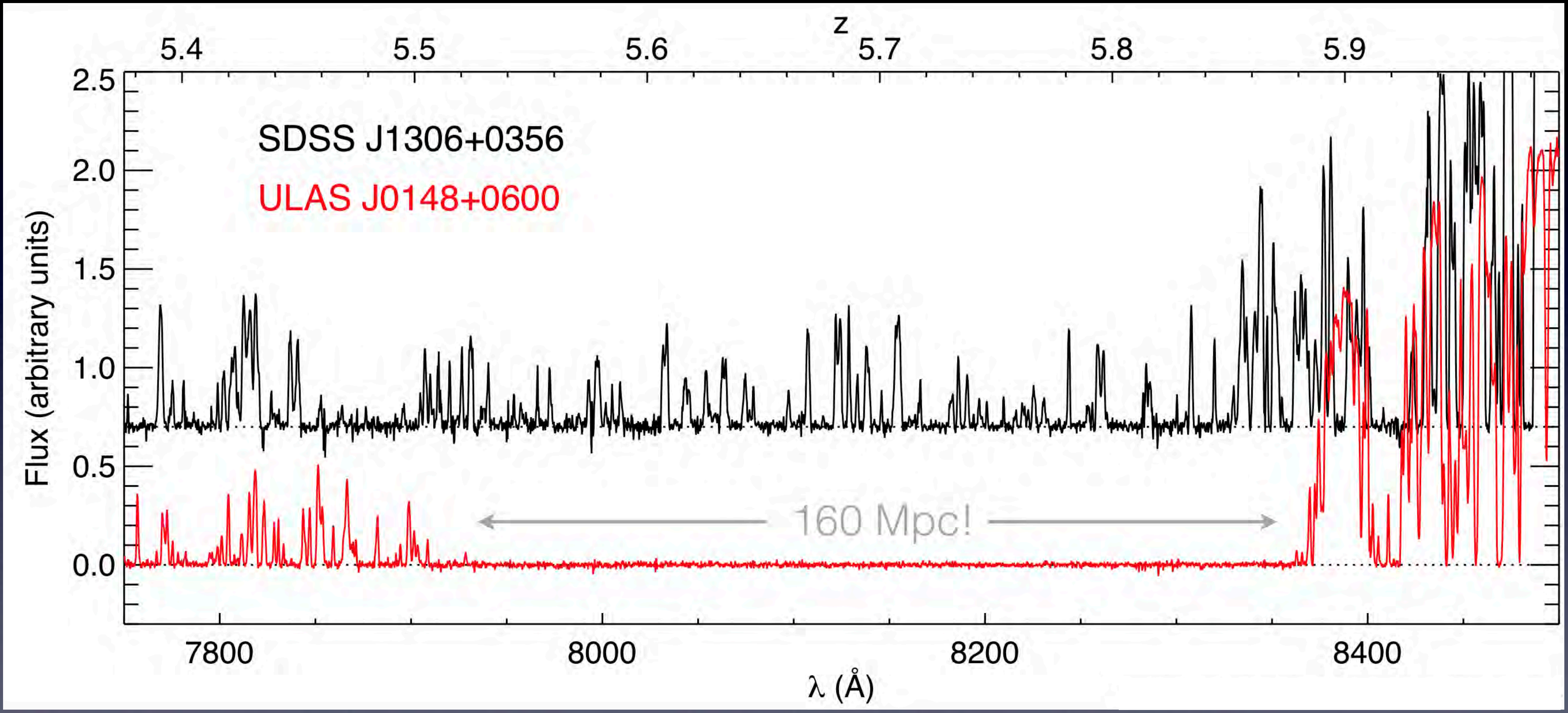


$$F_{\rm obs} = F_{\rm int} e^{-\tau}$$

$$b = \left[\frac{2k_{\rm B}T}{mc^2}\right]^{1/2}$$



Lyα forest shows spatial fluctuations

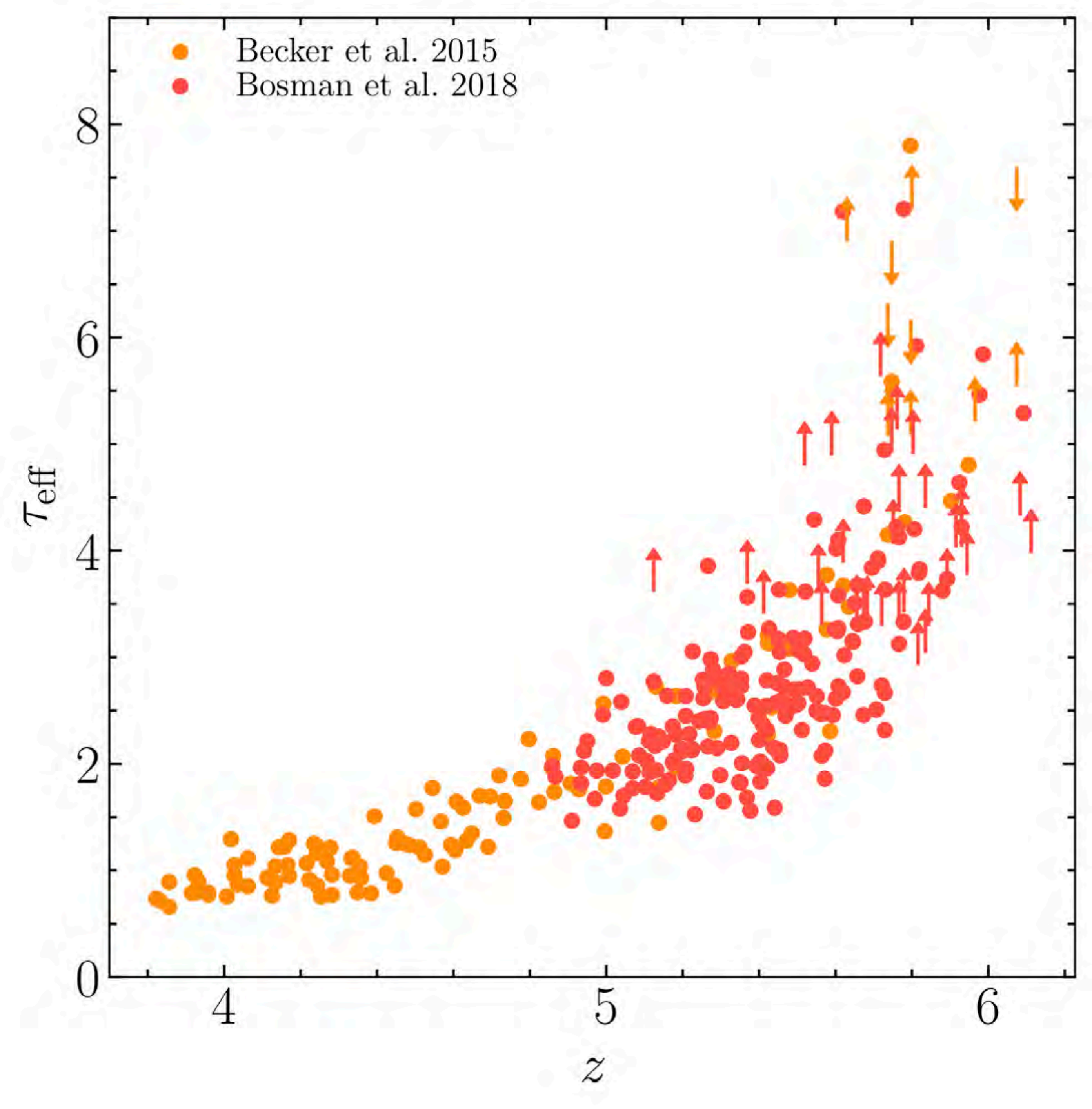


Becker et al. 2015

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

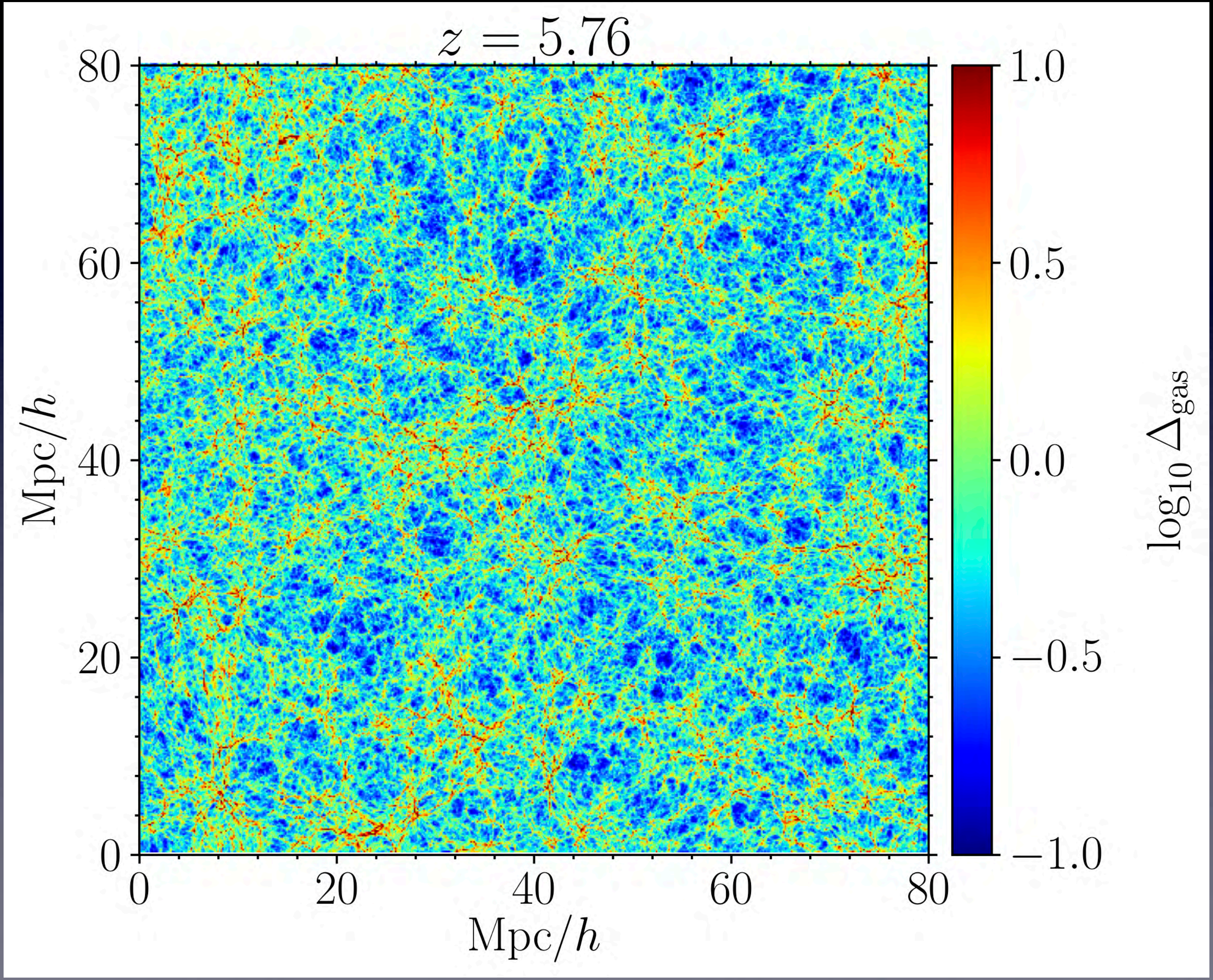
Quantify this by defining an effective optical depth over 50 cMpc/h segments of the forest

Lyα forest shows spatial fluctuations

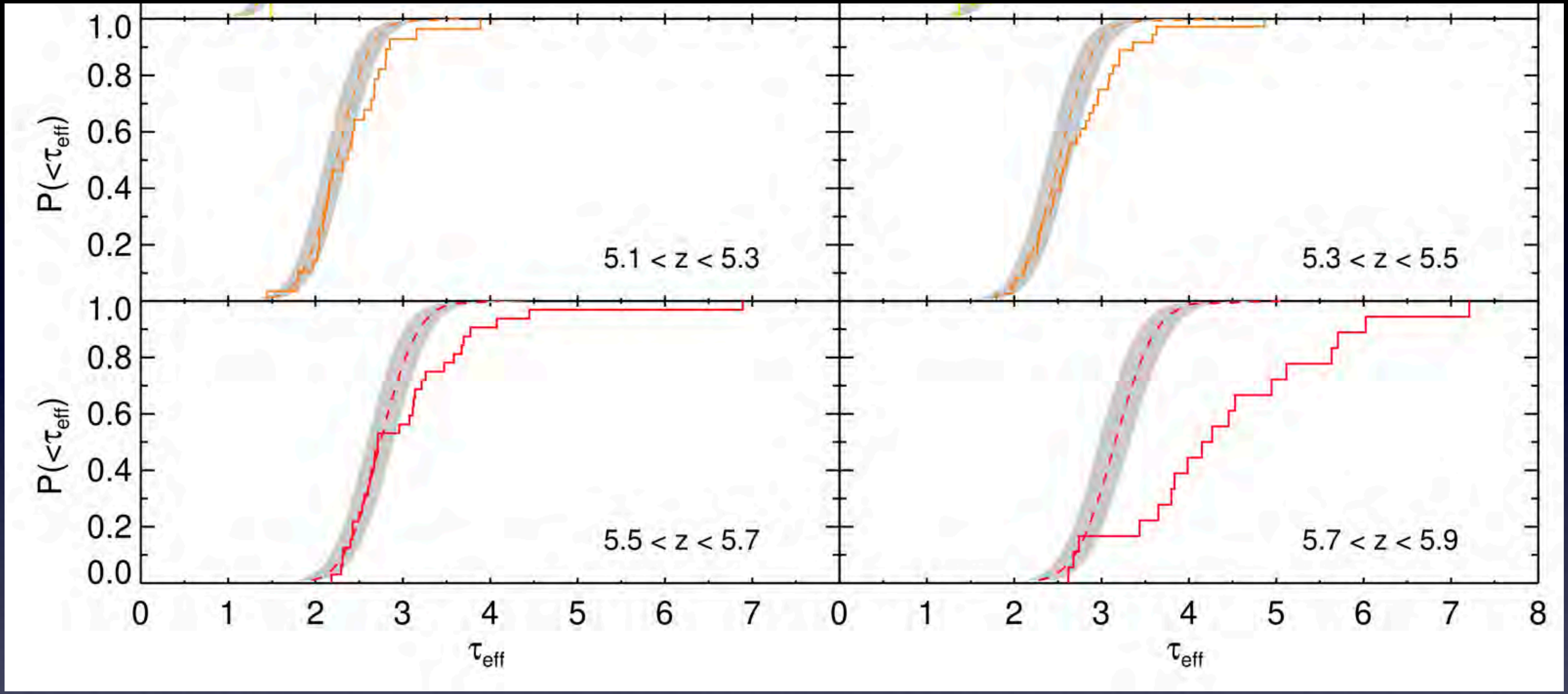


Factor of 2 scatter in mean transmission at z = 4 but ≳500 scatter at z = 5.6

We do expect spatial fluctuations



Cosmic density does not explain fluctuations

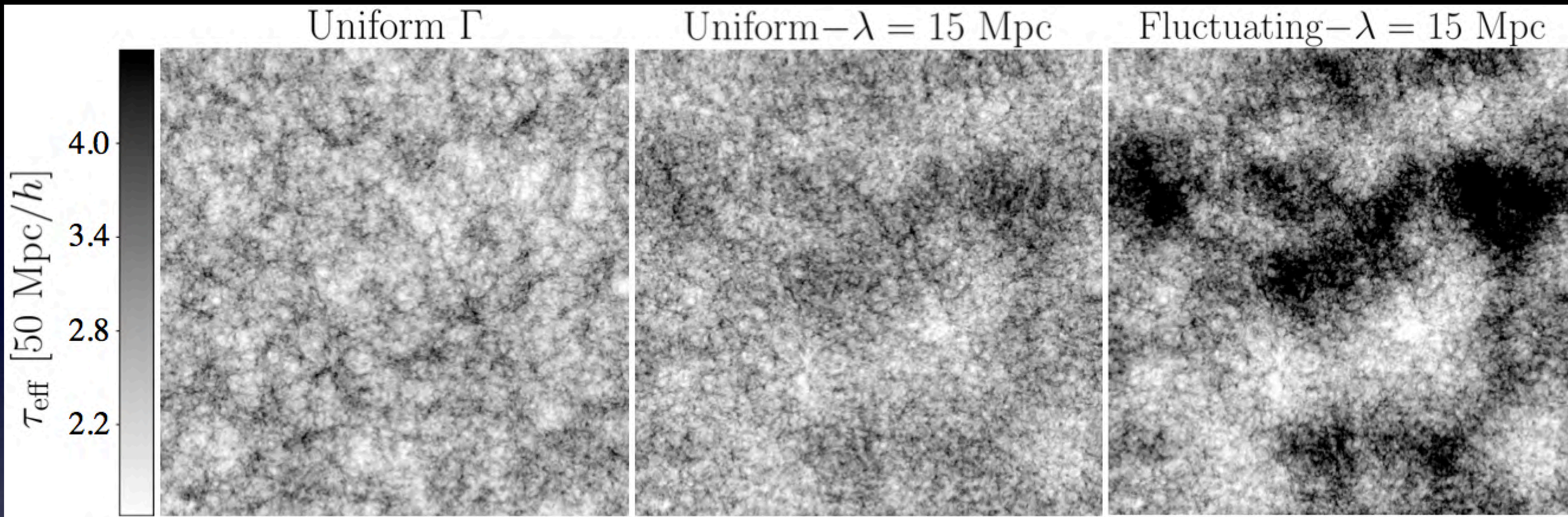


Becker et al. 2015

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

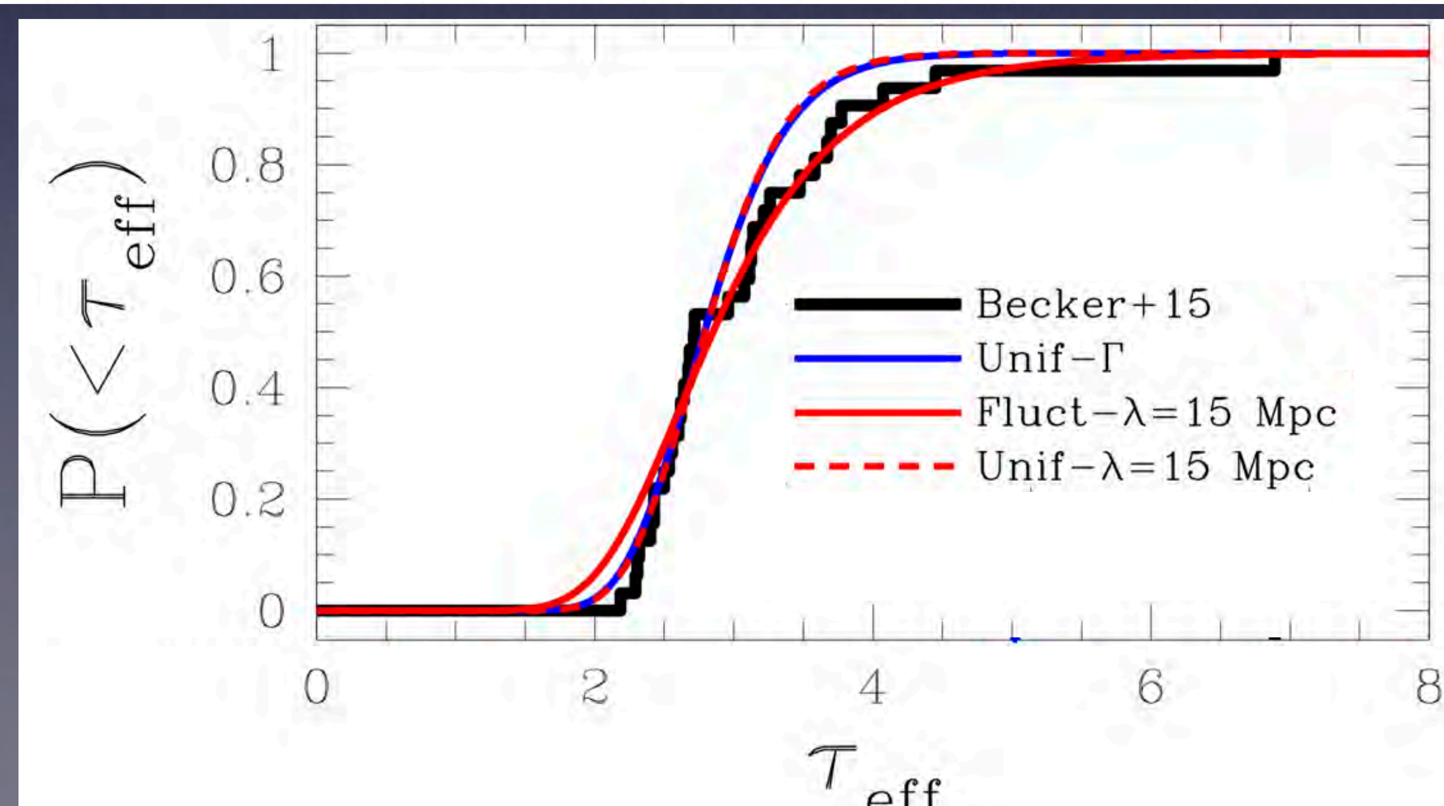
- Temperature fluctuations (D'Aloisio et al. 2015): too high temperatures
- Ionization rate fluctuations (Davies et al. 2016): too small mean free path
- Rare sources, such as QSOs (Chardin et al. 2015): not sure if these exist

Fluctuations in photoionization rate?



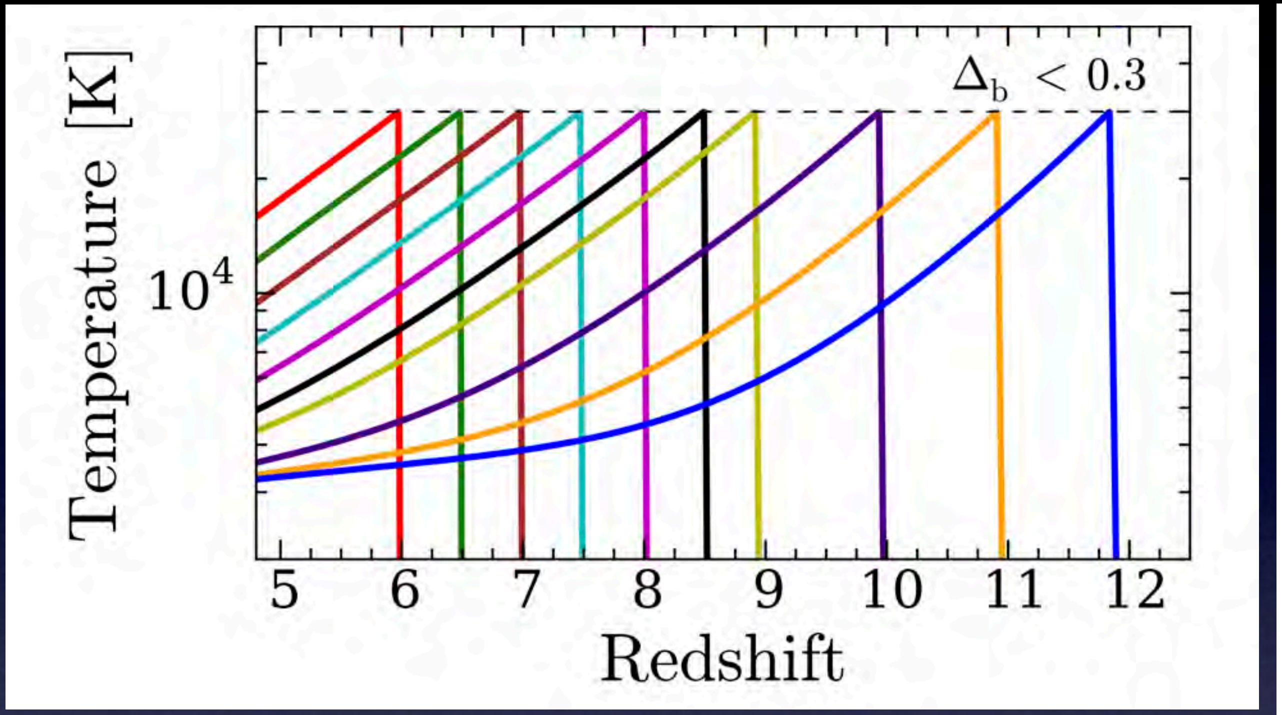
Davies et al. 2016

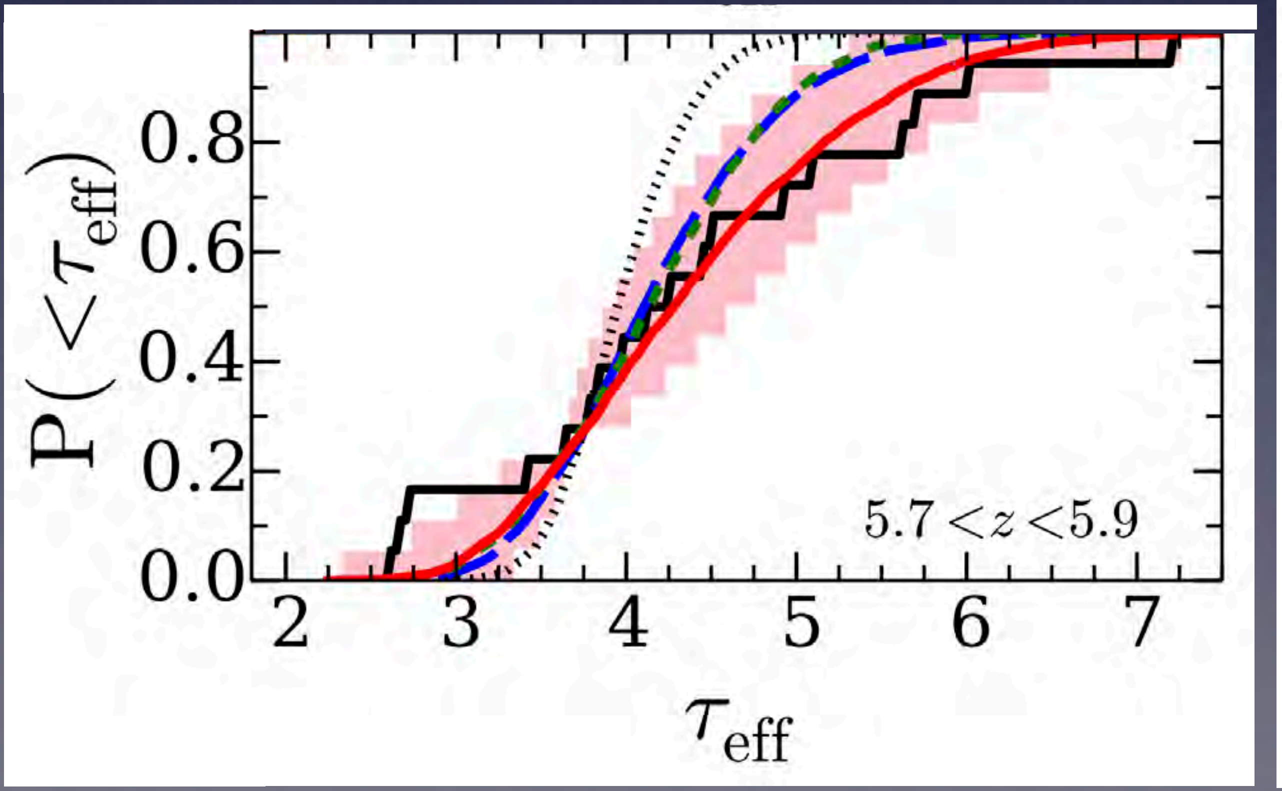
- Required mean free path is too small?
- High opacity regions are associated with **underdensities**

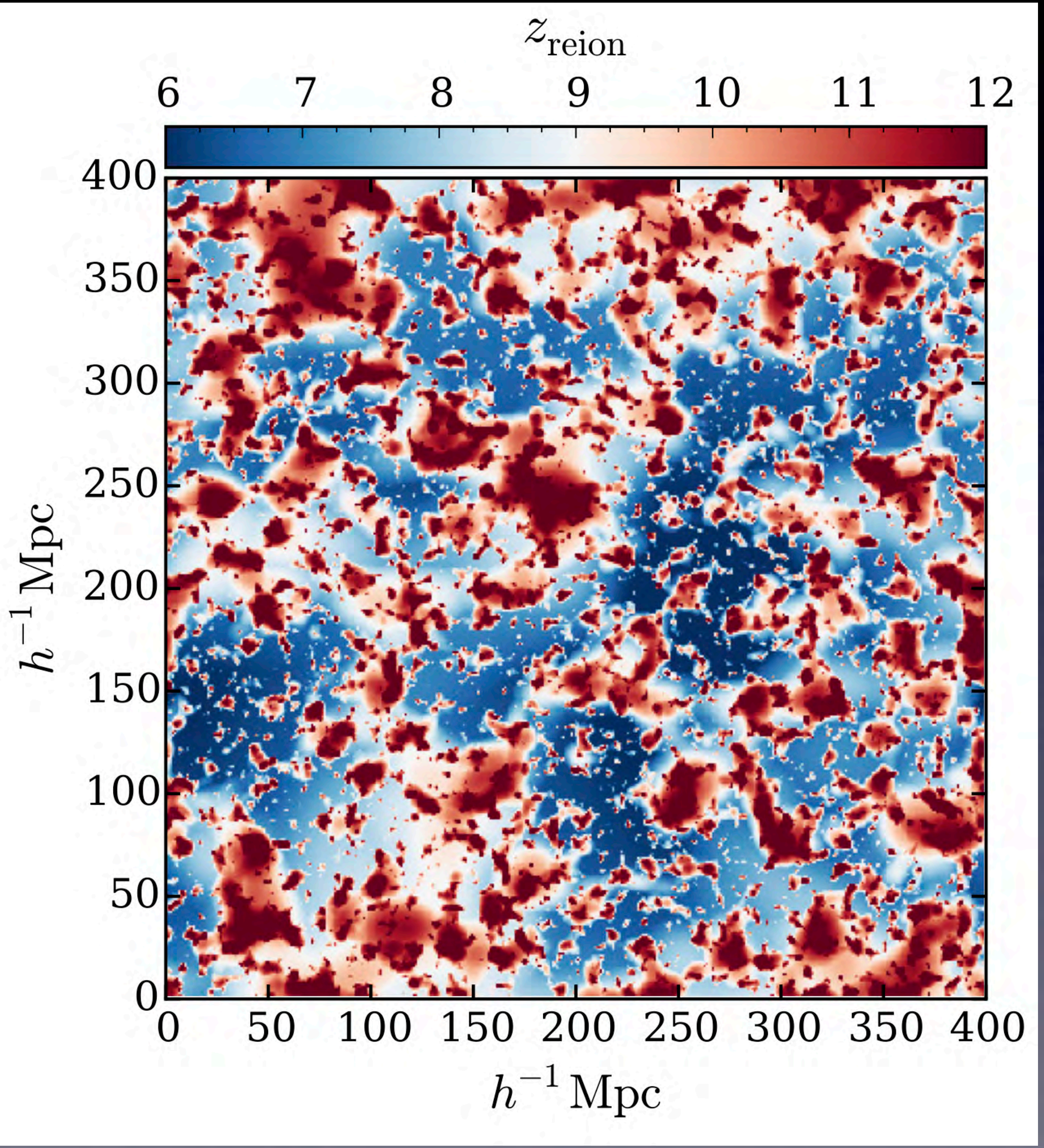


Fluctuations in temperature?

D'Aloisio et al. 2016

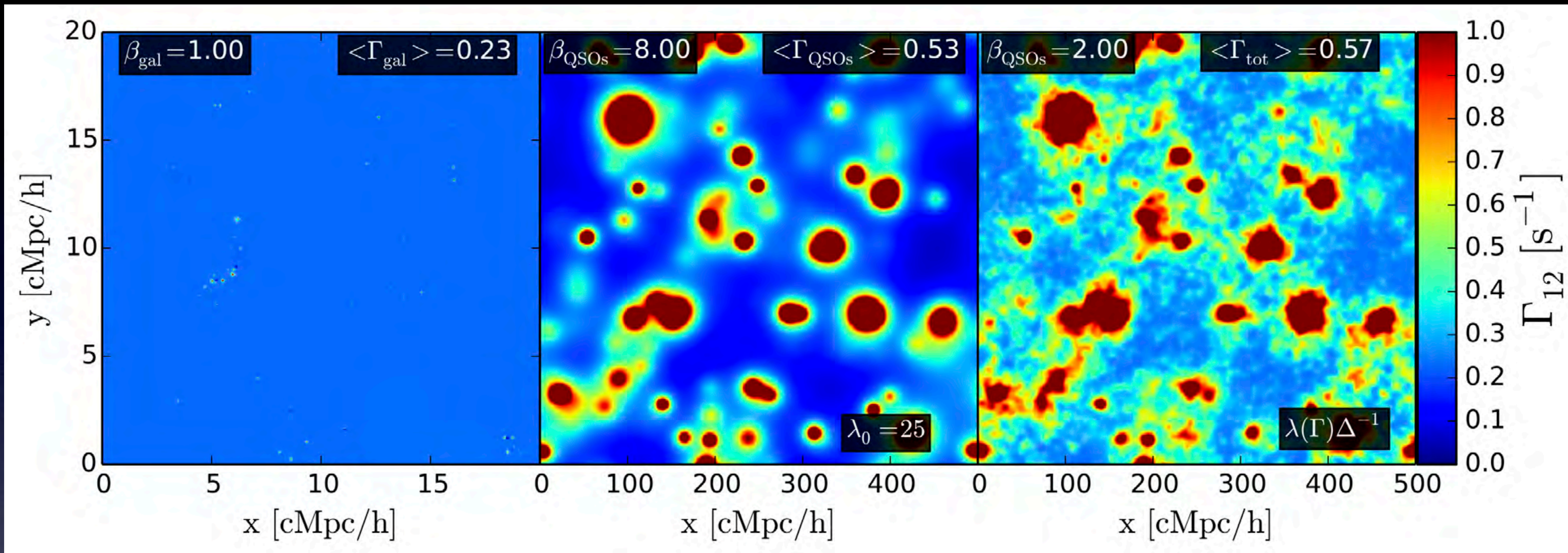






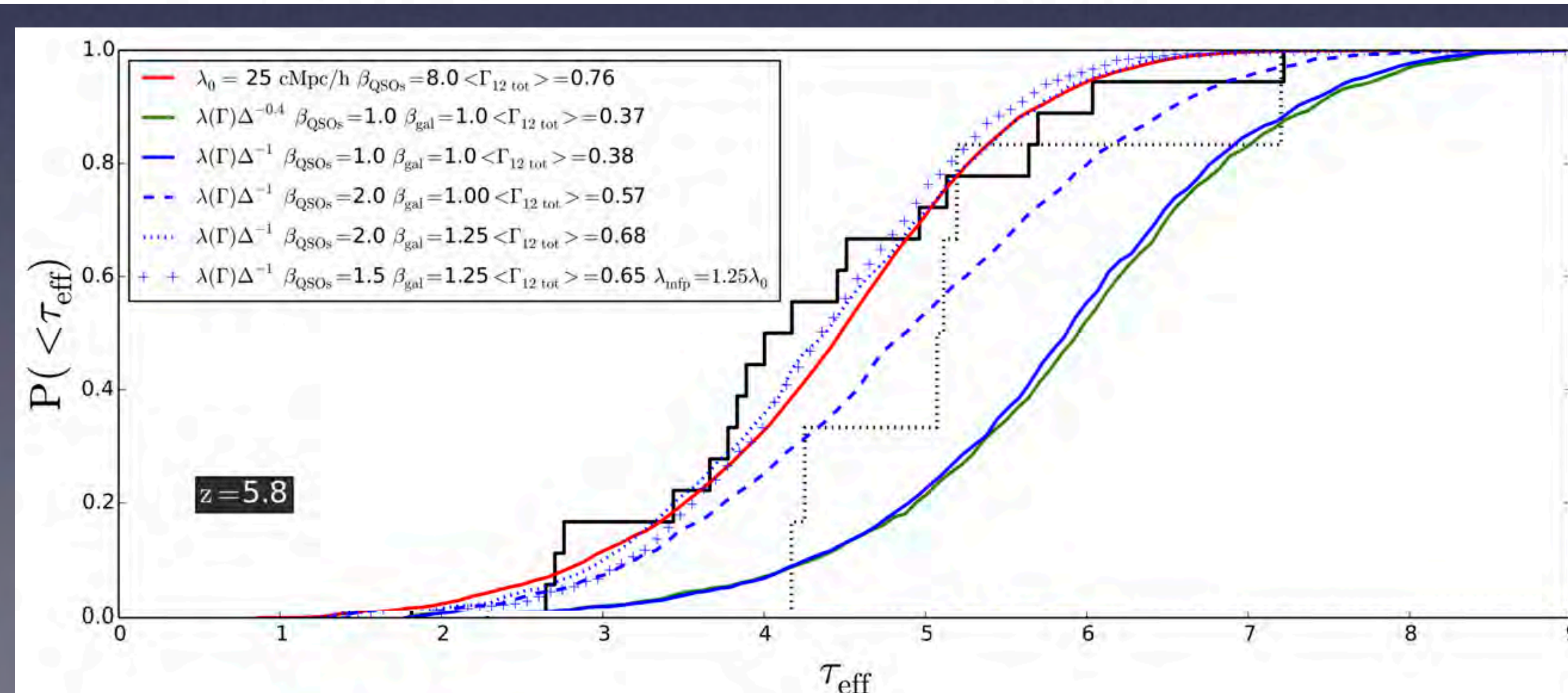
High opacity regions are associated with **overdensities**

Increased source clustering?

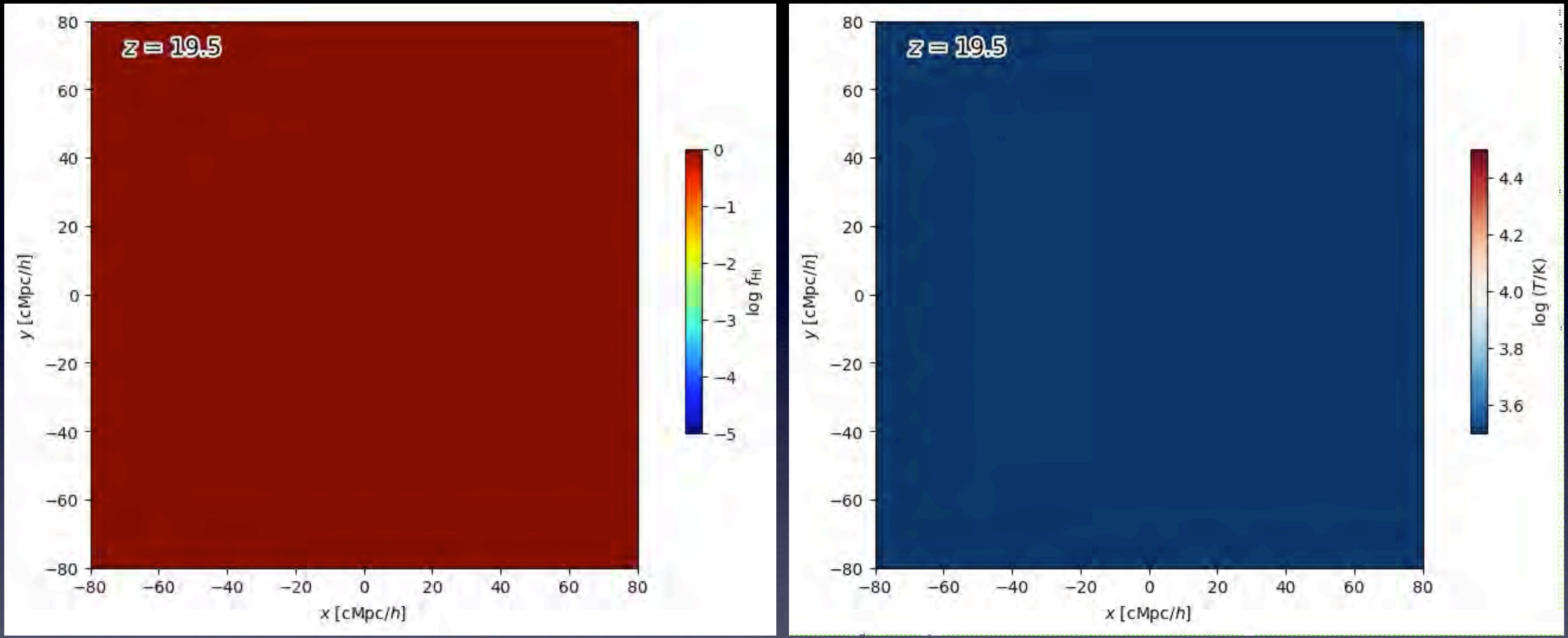


Chardin et al. 2016

More than 50% contribution from quasars leads to large Lya opacity fluctuations; but **do such objects exist?**



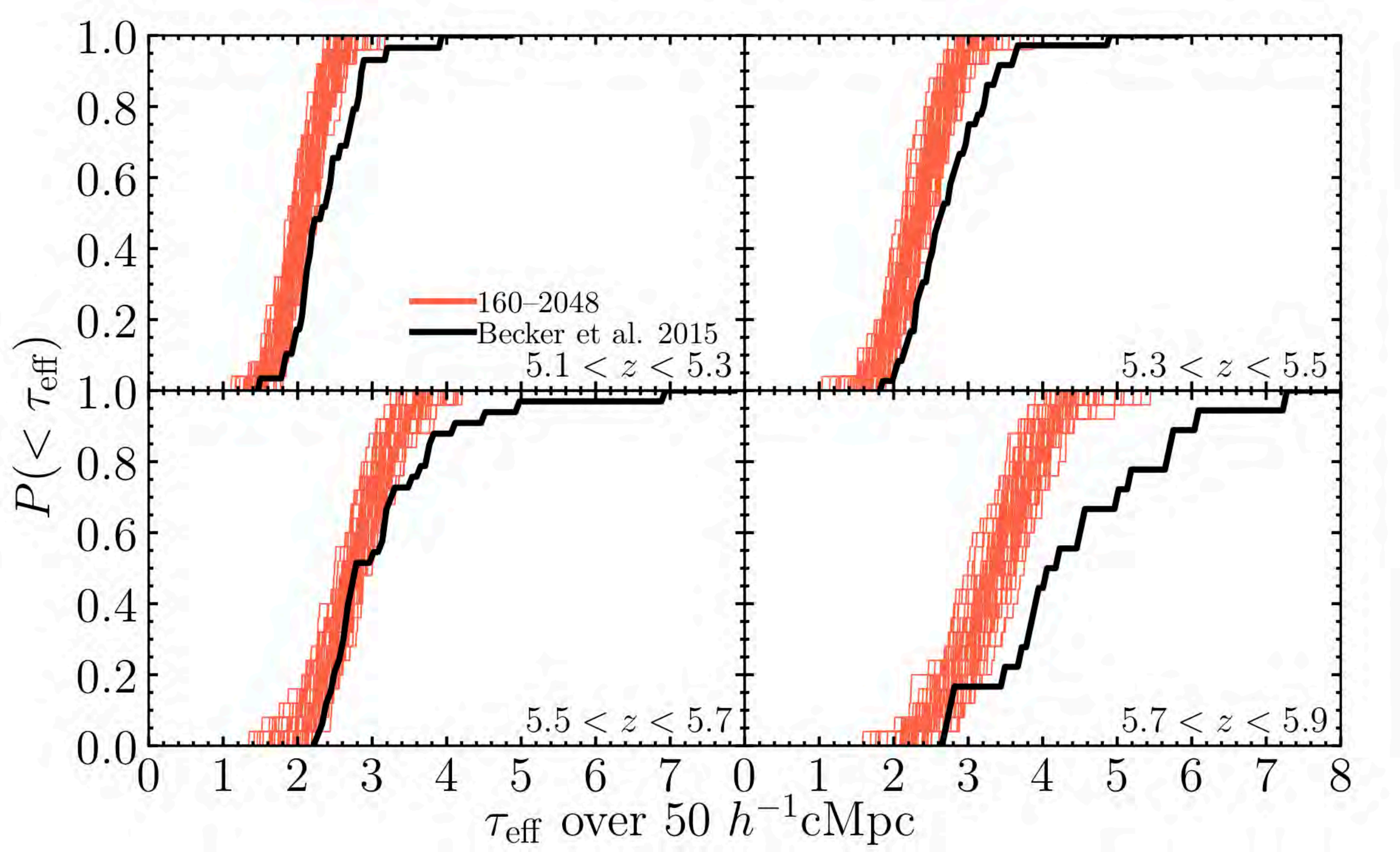
Carefully calibrated reionization simulation suite



Kulkarni et al. 2018

- 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

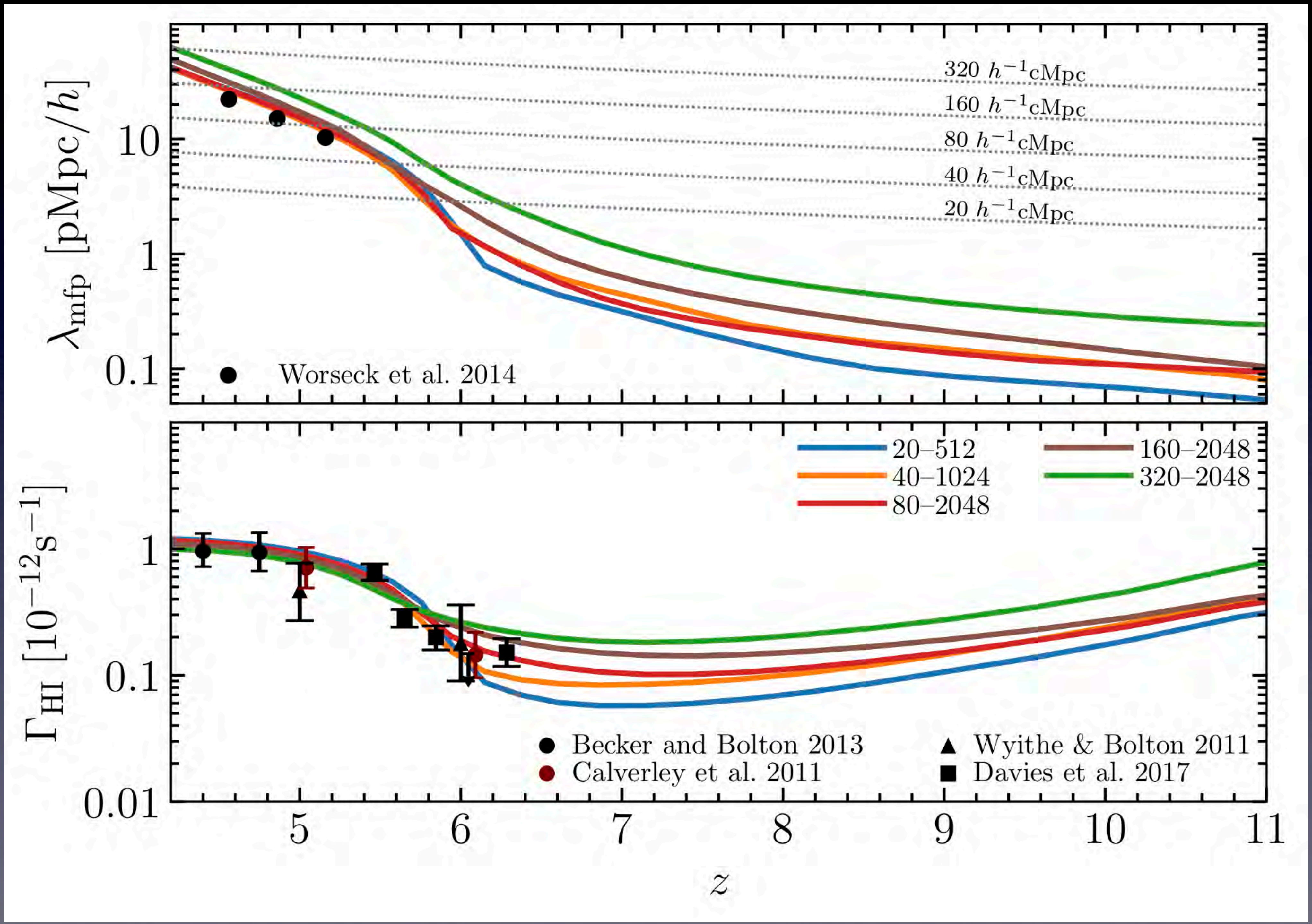
Another bad surprise?



Kulkarni et al. 2018

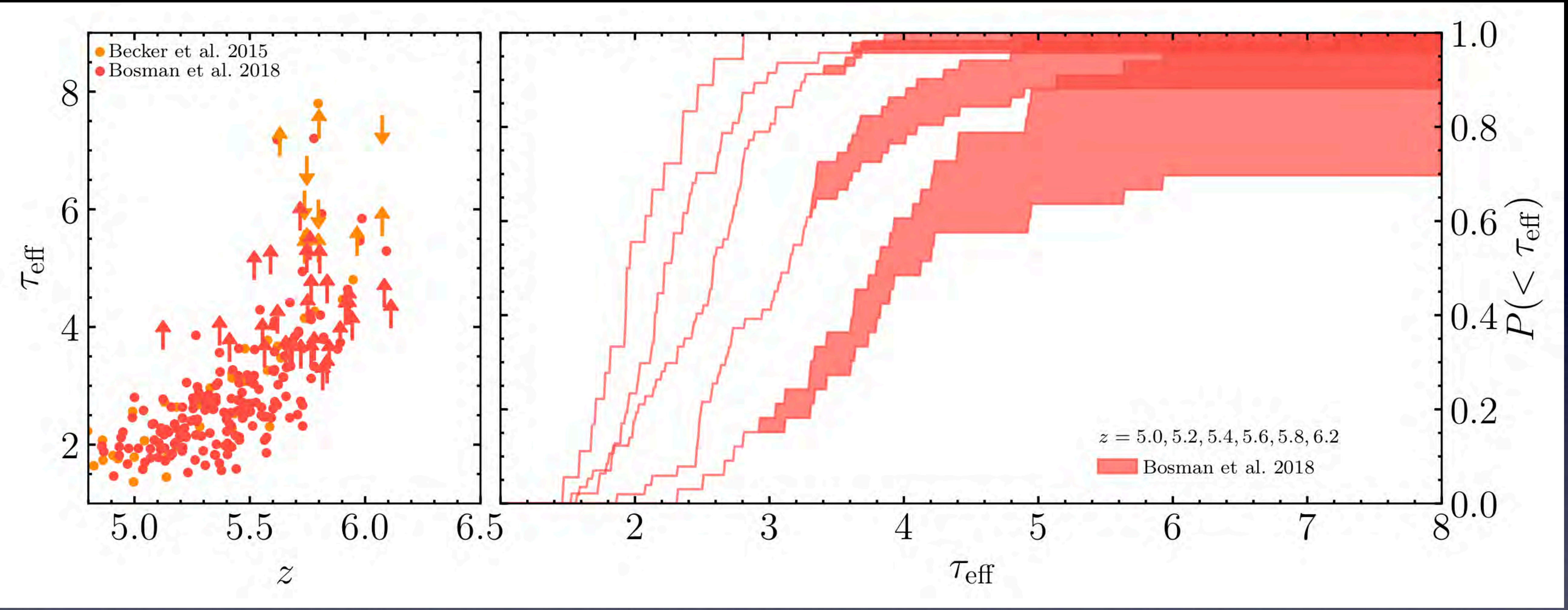
Distributions were much narrower in our initial runs.

How are these simulations calibrated?

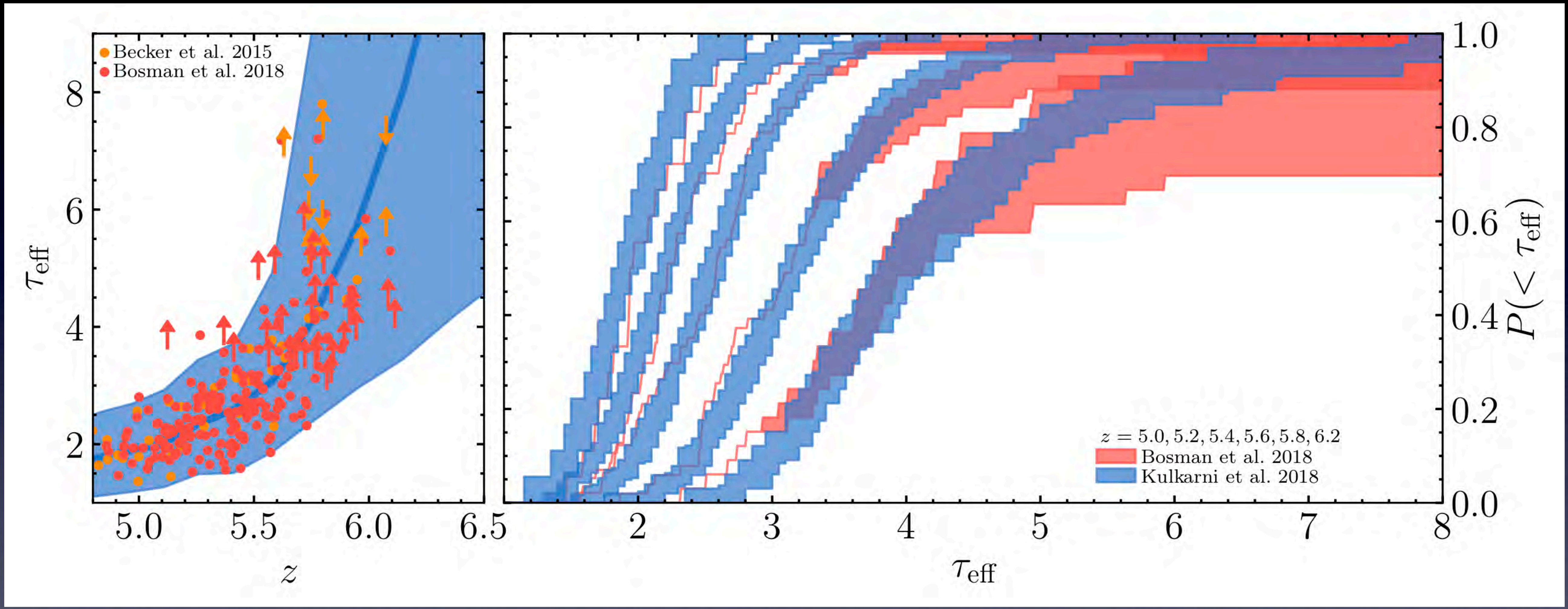


Reionization simulations are traditionally calibrated to reproduce the mean IGM photoionization rate

Lyα fluctuations



Lyα fluctuations explained

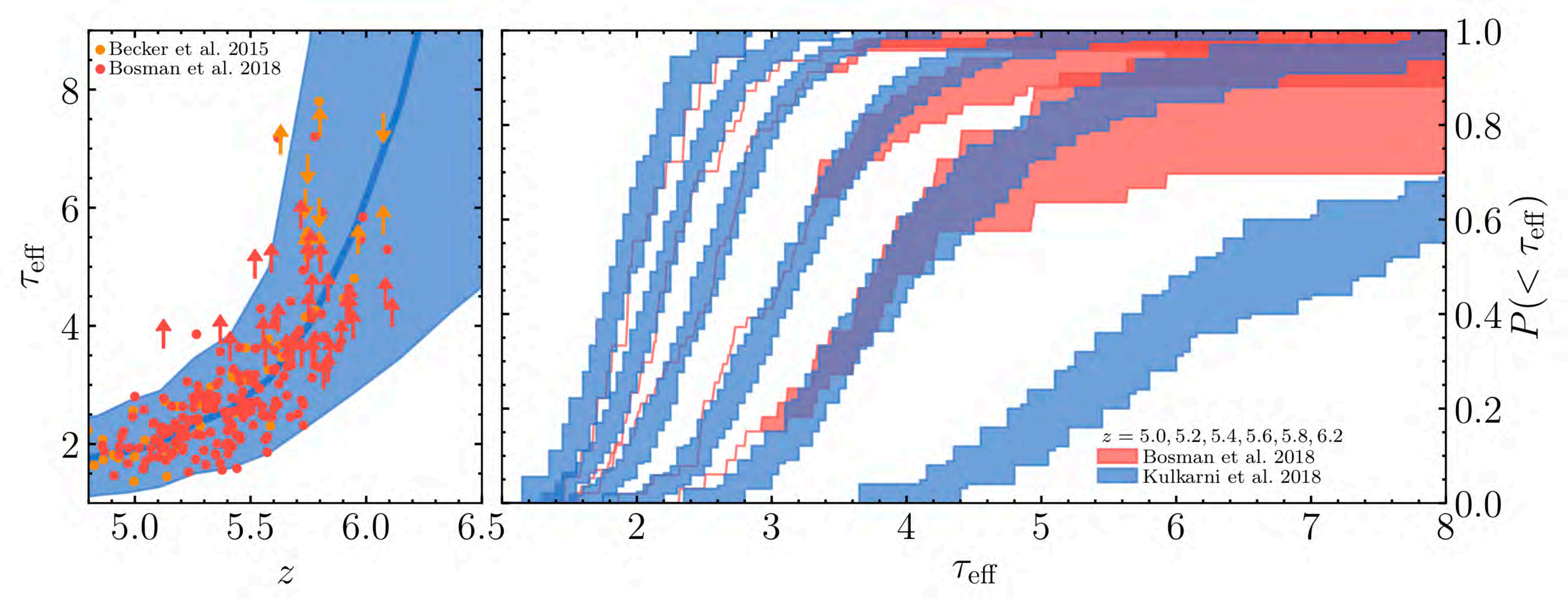


Kulkarni et al. 2018

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.

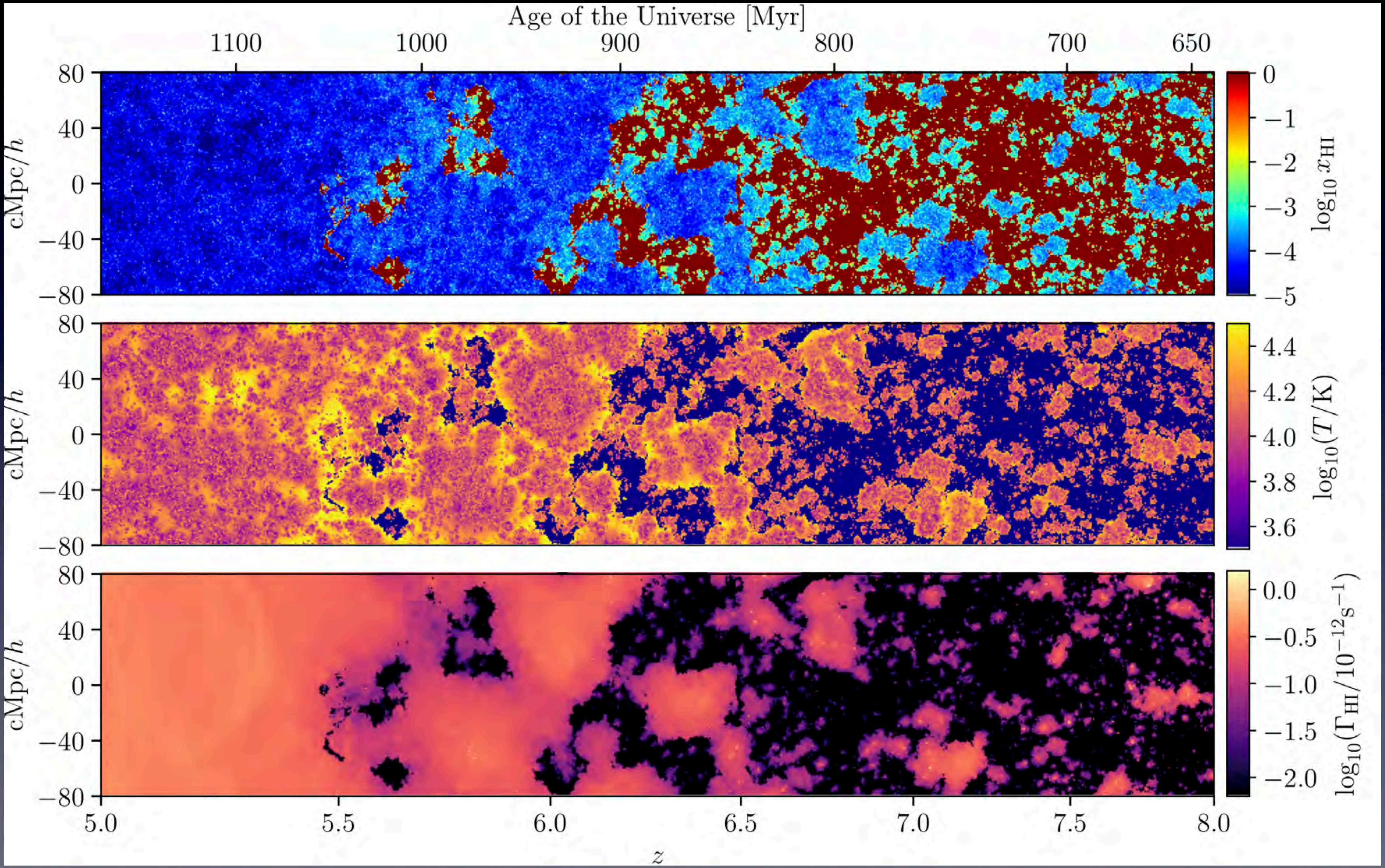
Lyα fluctuations explained



Kulkarni et al. 2018

Just been awarded 112.5 hr on VLT to target 29 z > 5.8 quasars

Delayed reionization

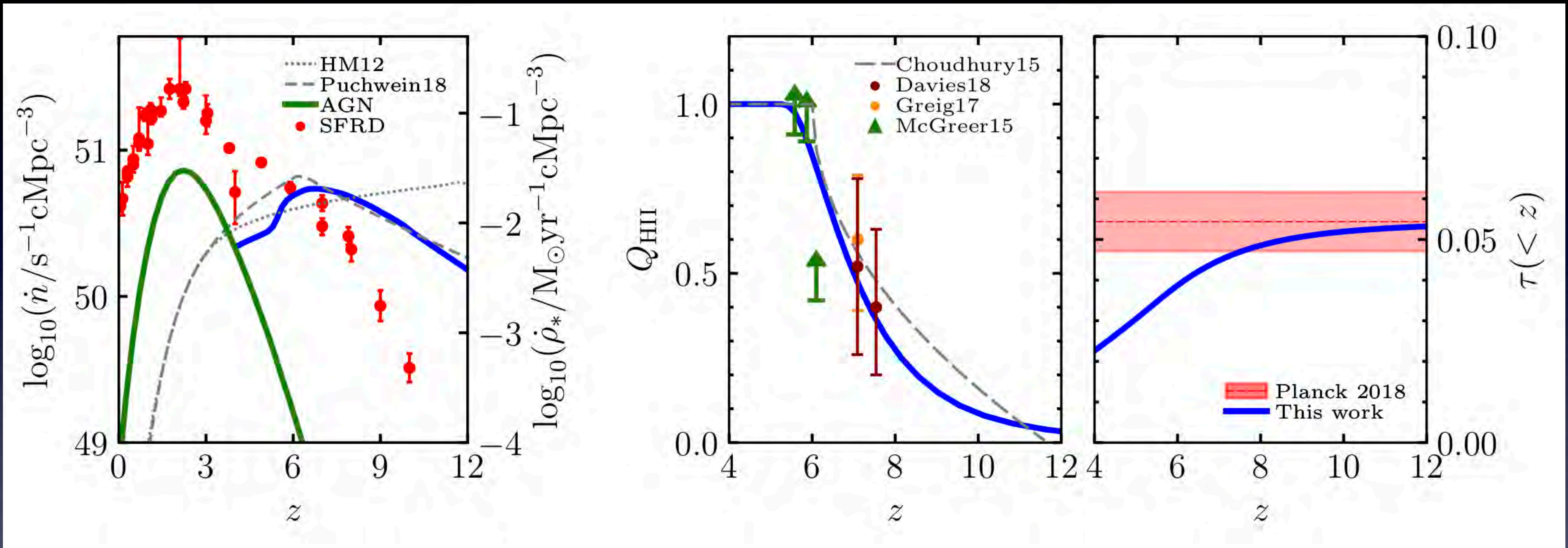


Kulkarni et al. 2018

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.)

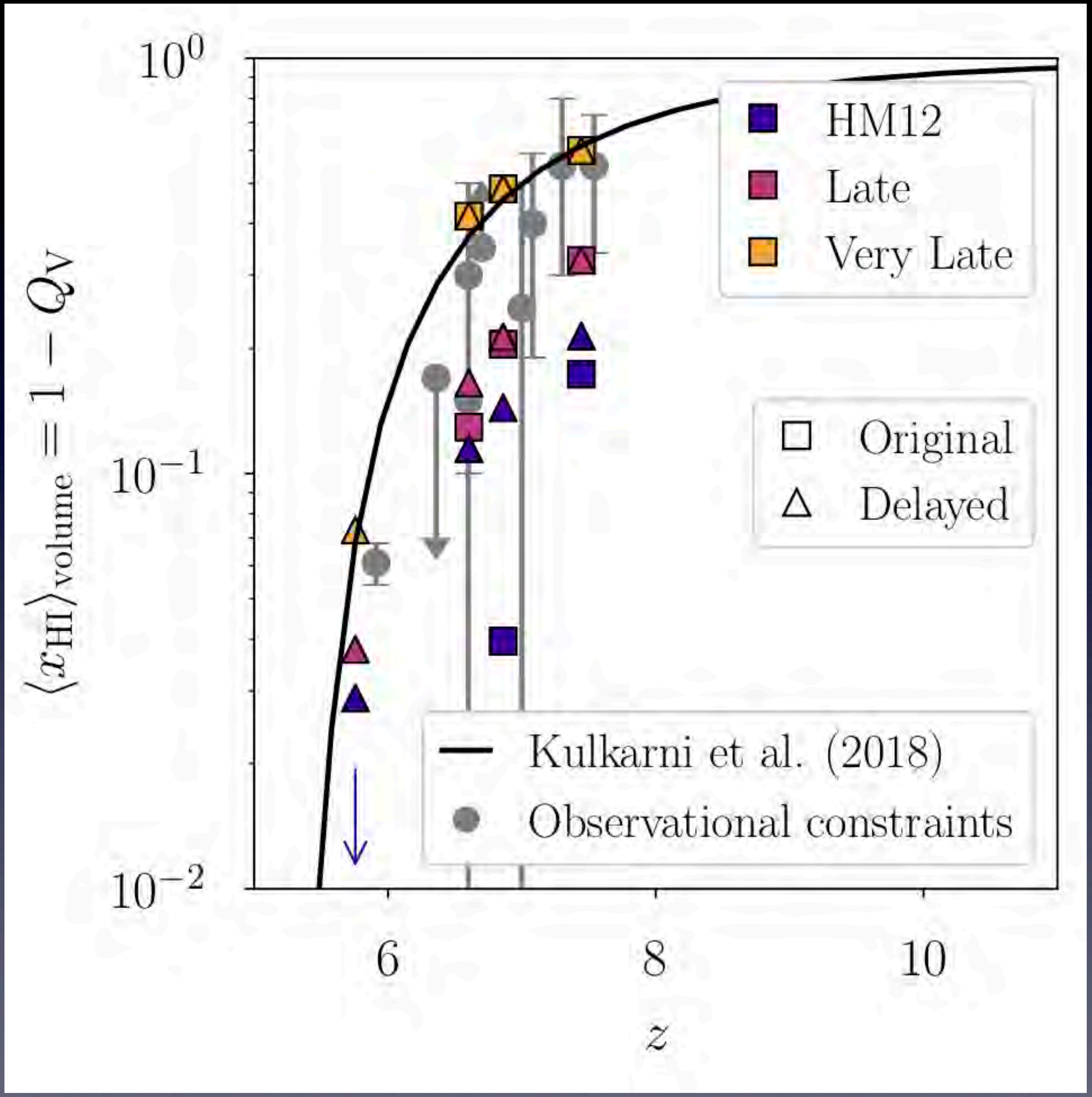
Towards a concordant reionization model

Kulkarni et al. 2018



- 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

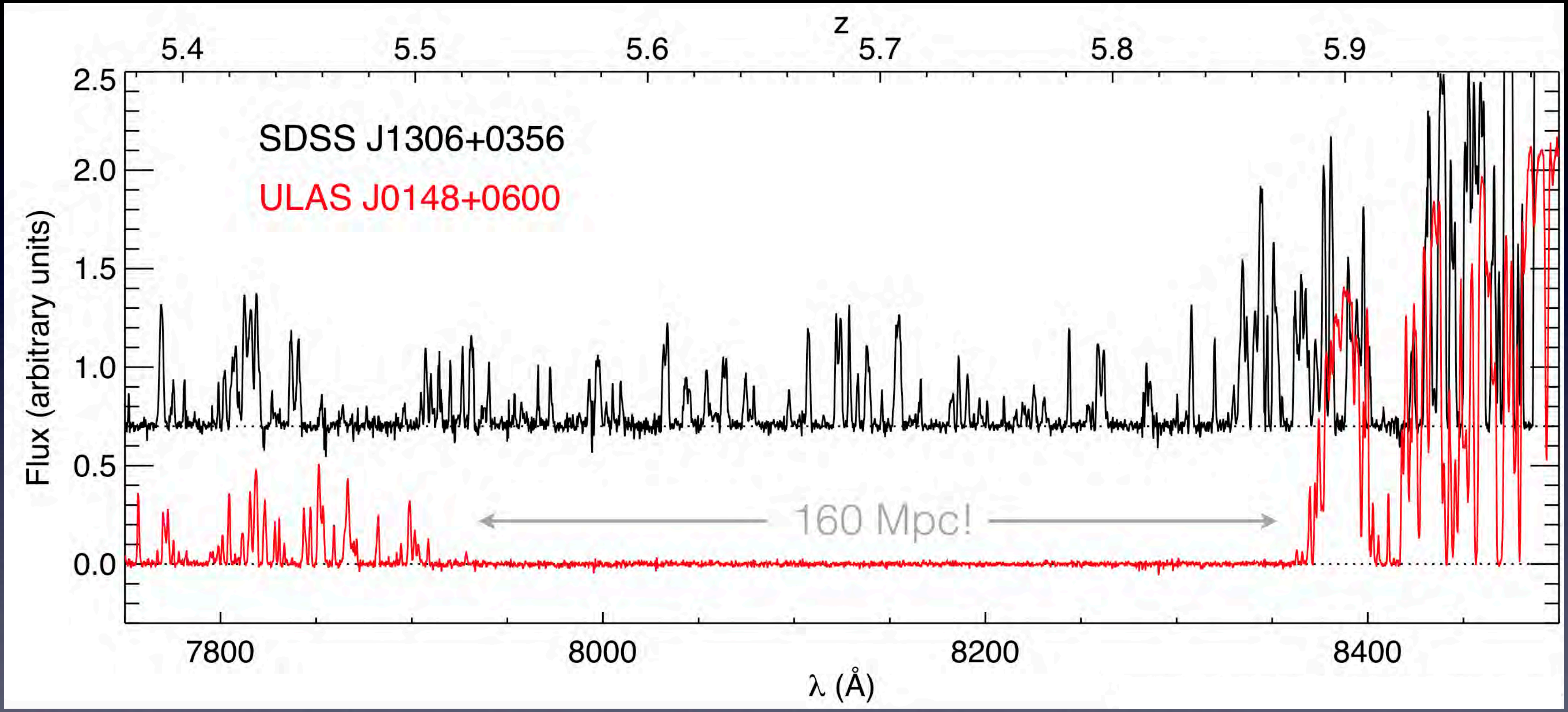
View from Lyα emitters



Weinberger, Kulkarni et al. 2018, 2019
cf. Mason et al. 2019

- Lyα-selected galaxies seem to disappear rapidly at z > 6
- Lyα radiative transfer is complex
- But detailed modelling supports delayed reionization

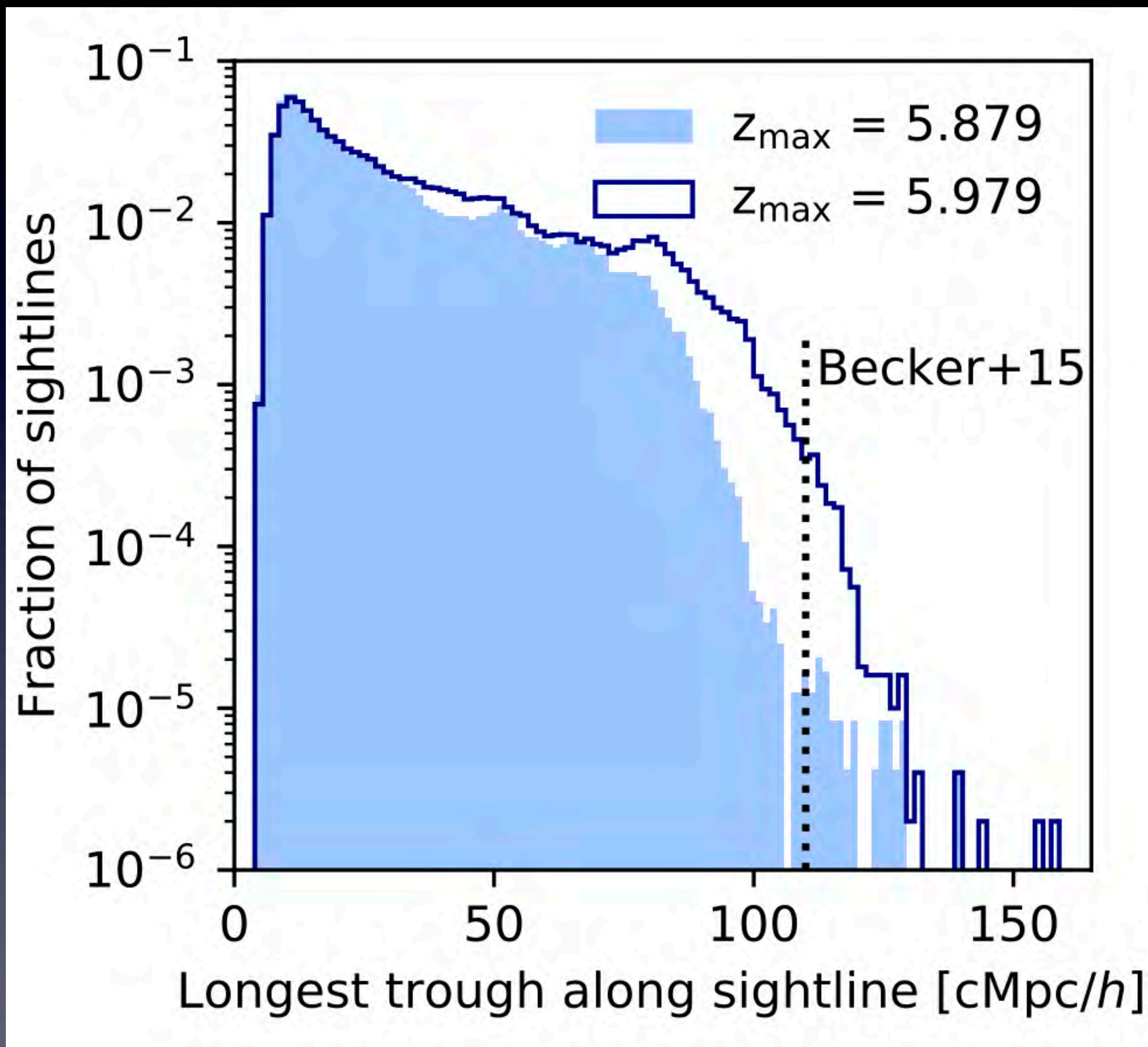
Structure of the longest trough

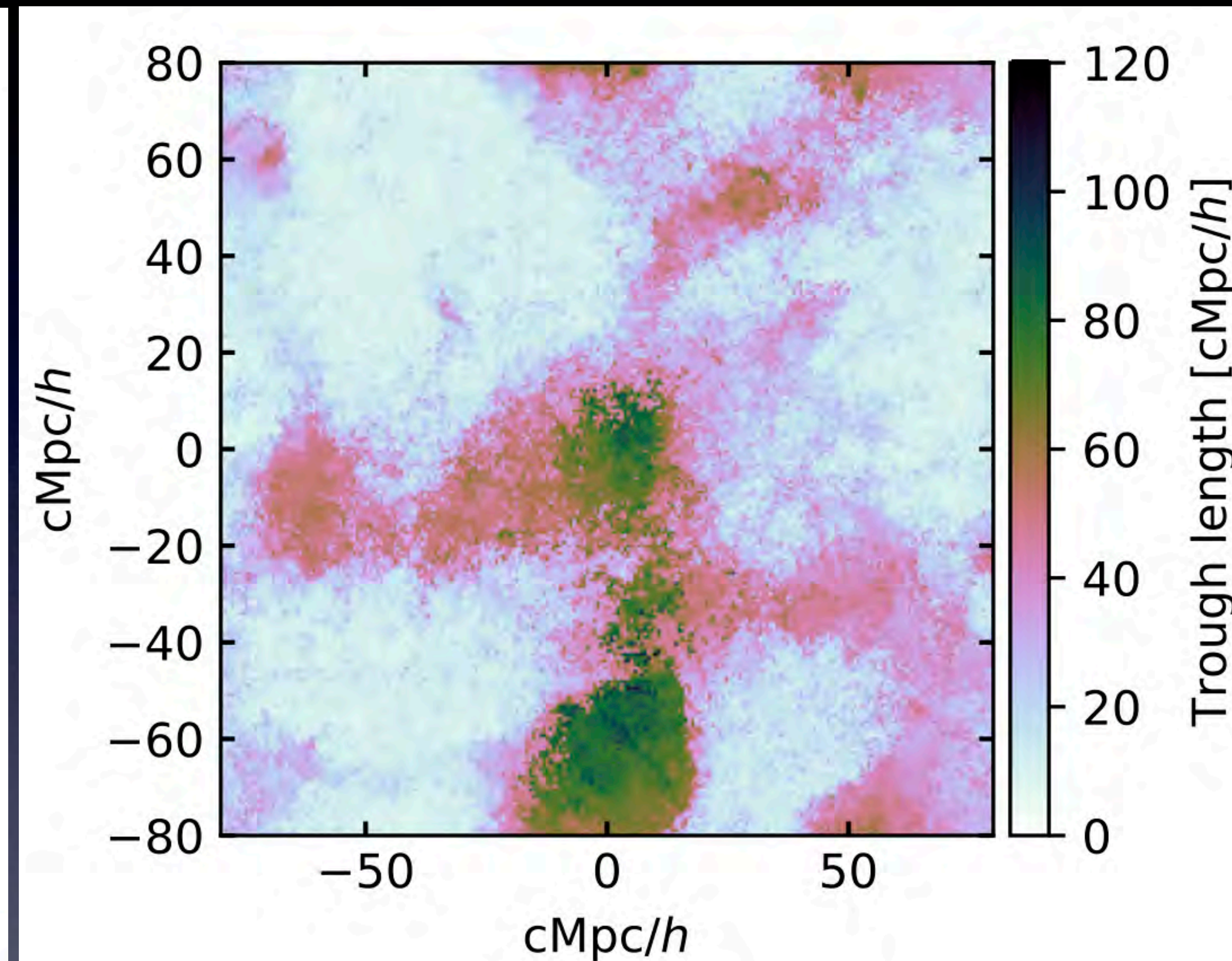


Becker et al. 2015

Models differ in their prediction for the large-scale structure near the long trough.

Long Lyα troughs in late reionization models

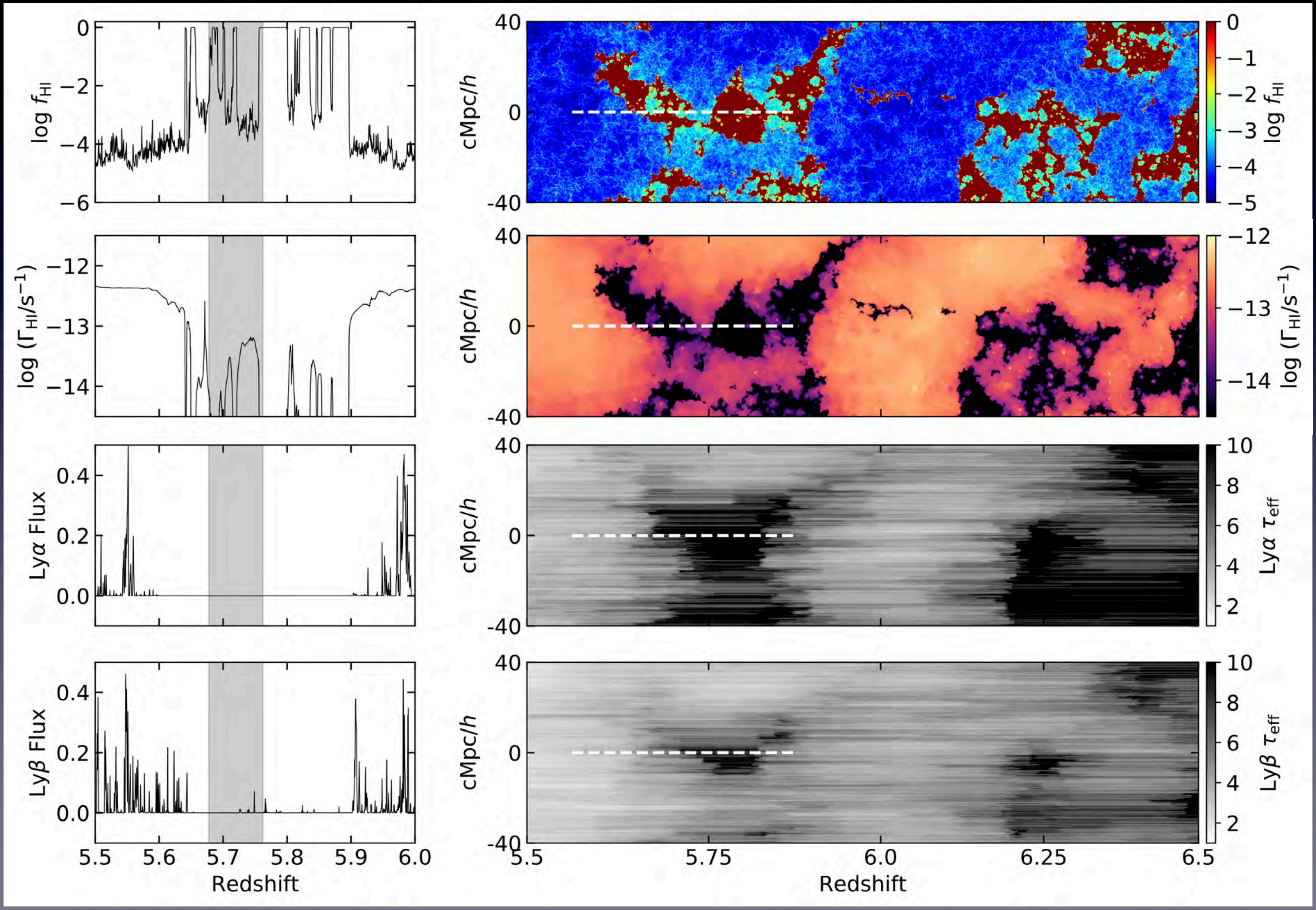




Keating, Kulkarni et al. 2019

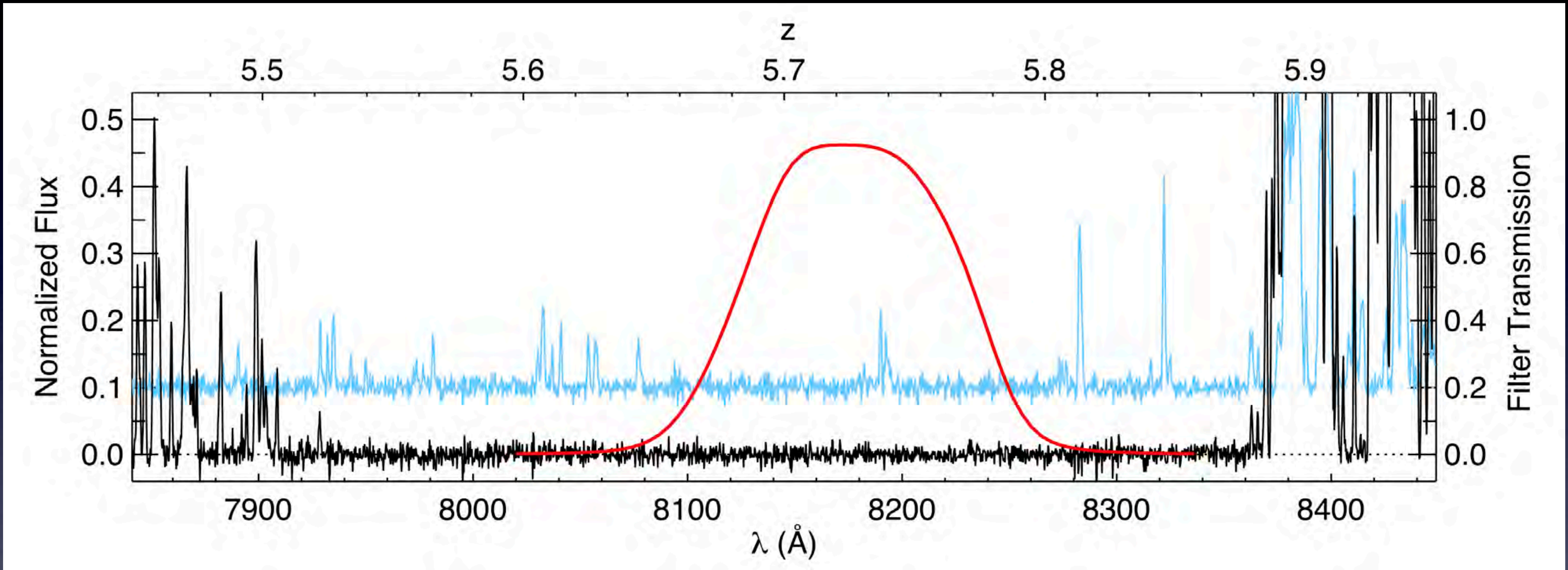
- Derive spectra over lightcones; add instrument profile and noise
- Define trough length following Becker et al. 2015
- Incidence rate falls above 80 cMpc/h (reionization still early? small volume?

‘Neutral islands’ cause long troughs



Keating, Kulkarni et al. 2019

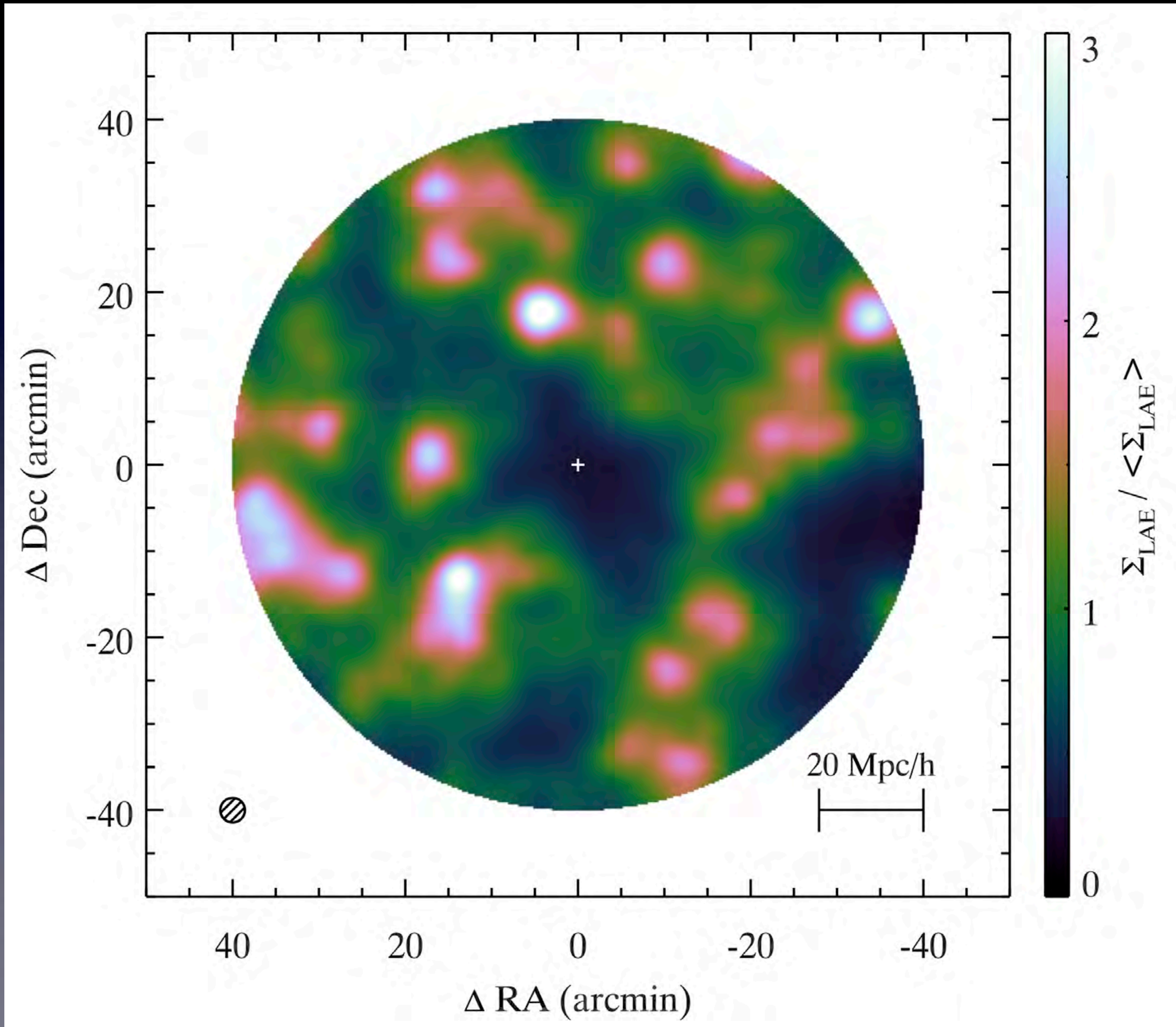
Structure of the longest trough



Becker et al. 2018

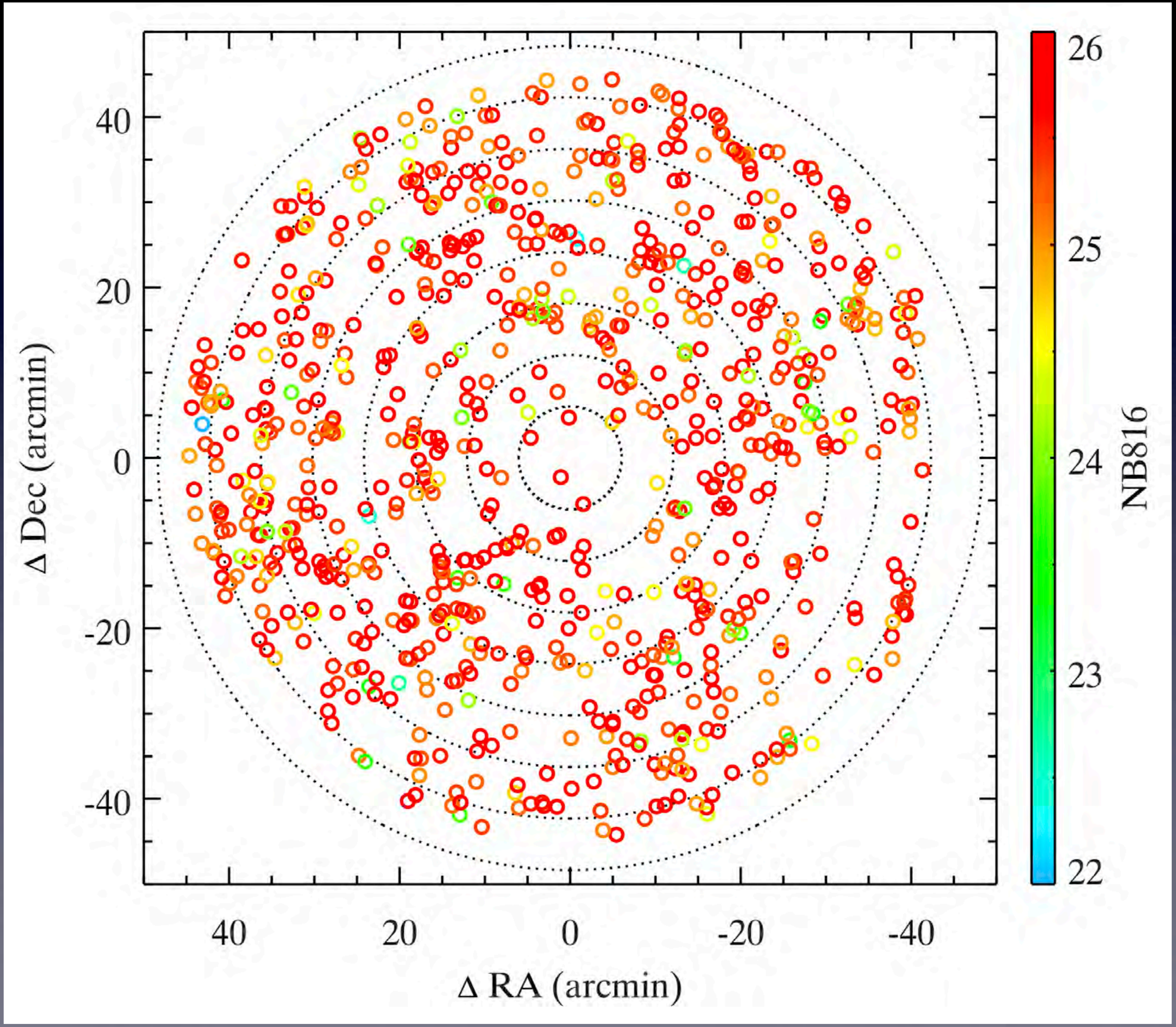
Place a narrow-band filter at the trough at count Lyman-α emitting galaxies (LAEs).

LAEs are depleted around the trough



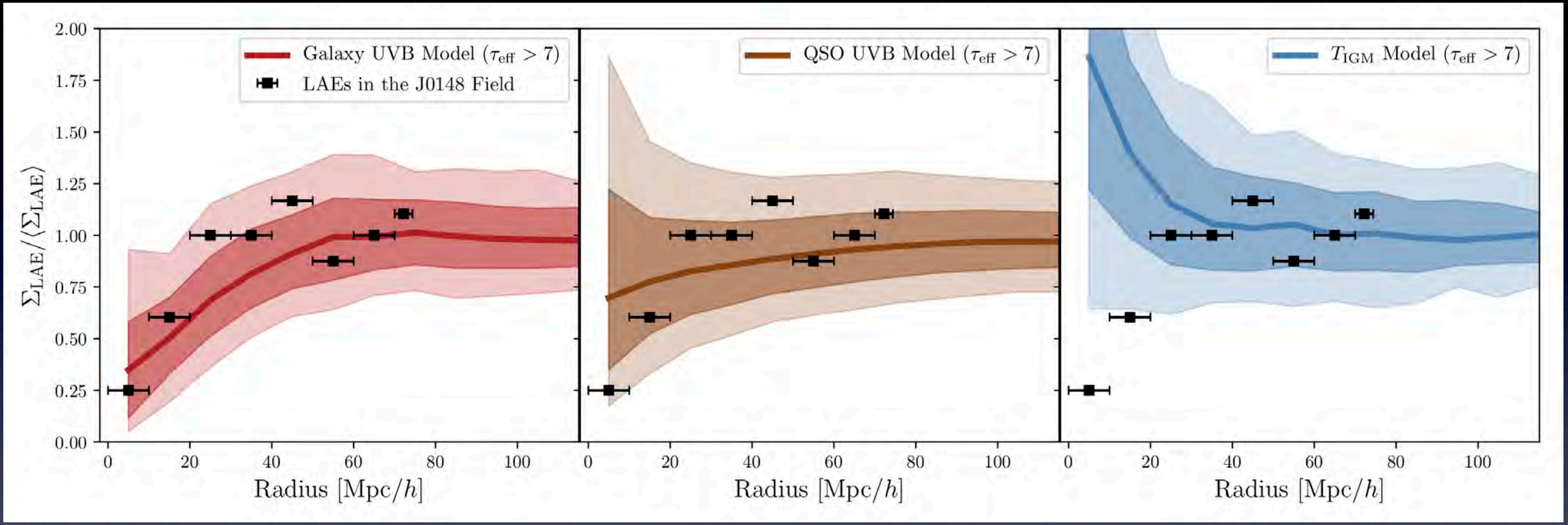
Becker et al. 2018

LAEs are depleted around the trough



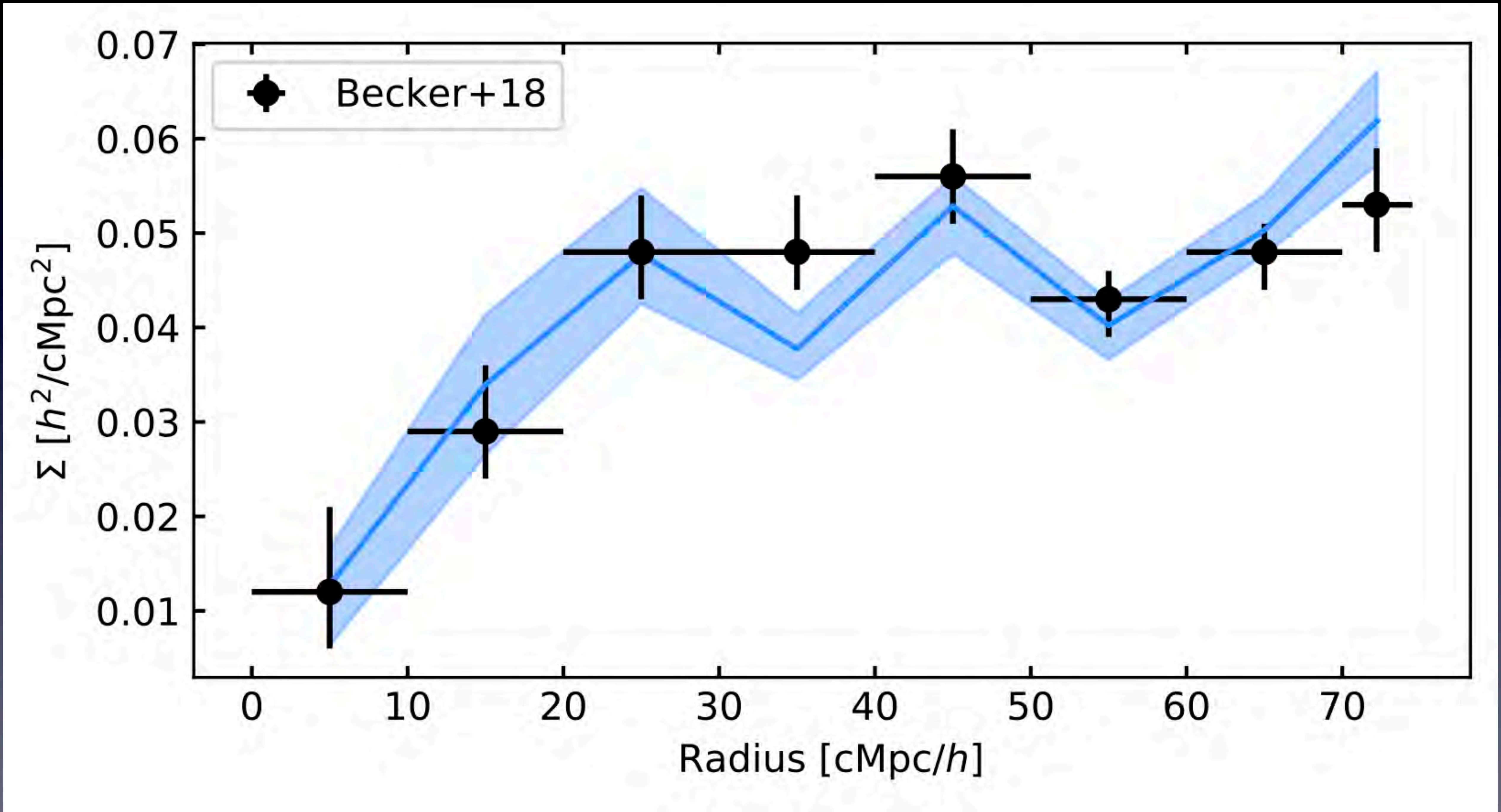
Becker et al. 2018

Can seem to rule out models



- Temperature fluctuations model predicts overdensity on the trough.
- Other models predict underdensities.

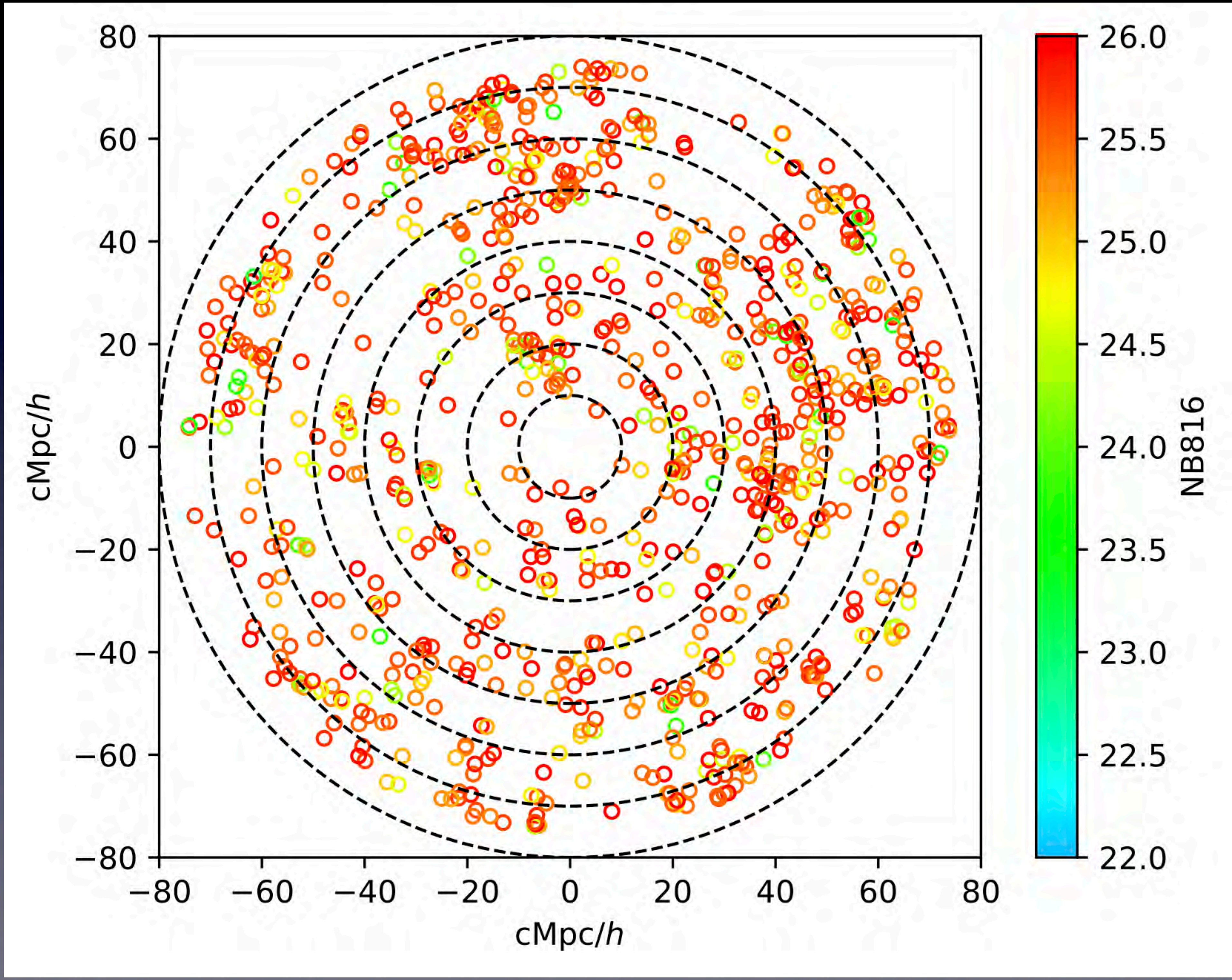
How does our model perform?



Keating, Kulkarni et al. 2019

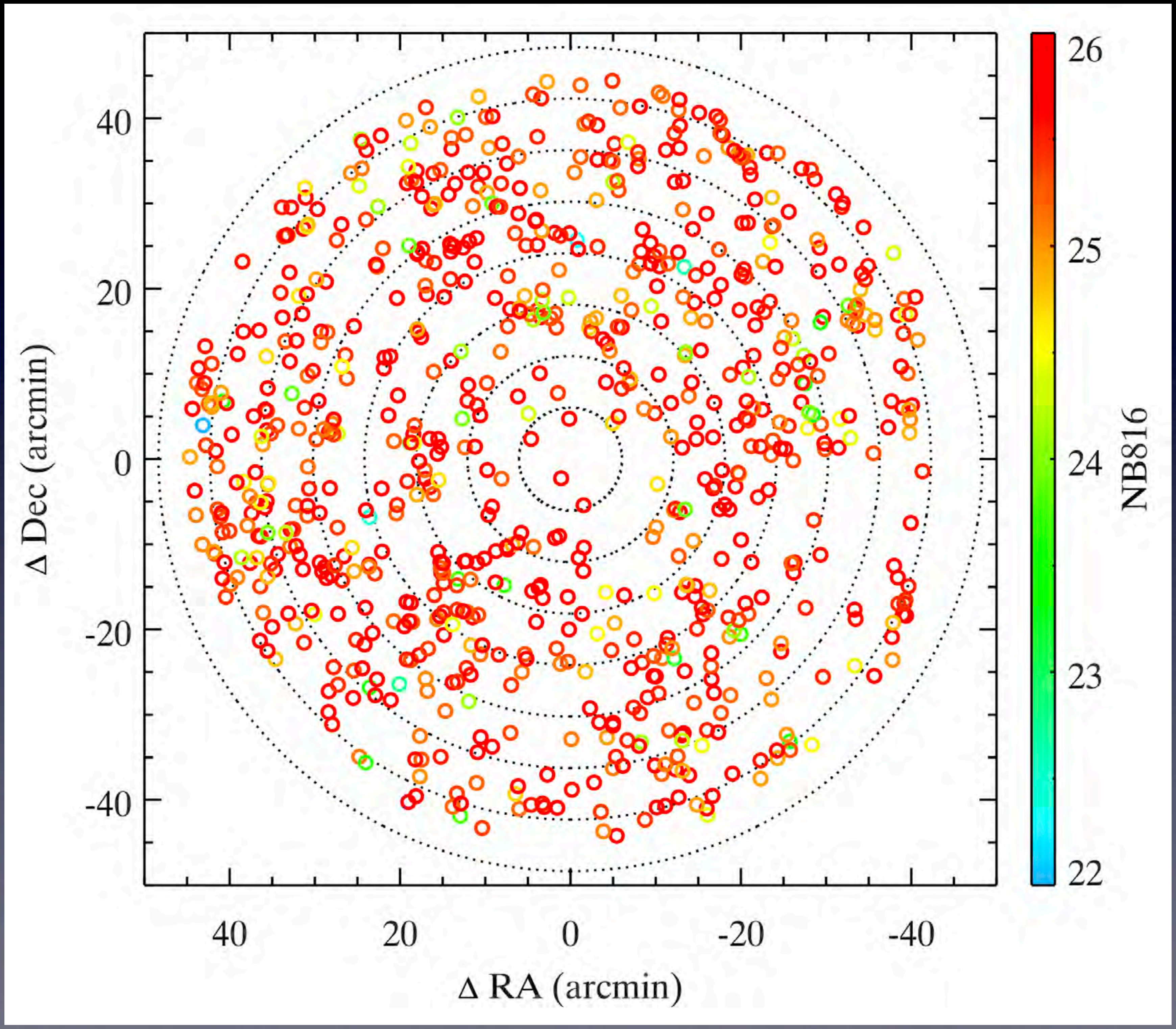
LAEs are attenuated by the neutral islands. LAE counts agree with observations.

Simulation matches data



Keating, Kulkarni et al. 2019

Simulation matches data



Becker et al. 2018

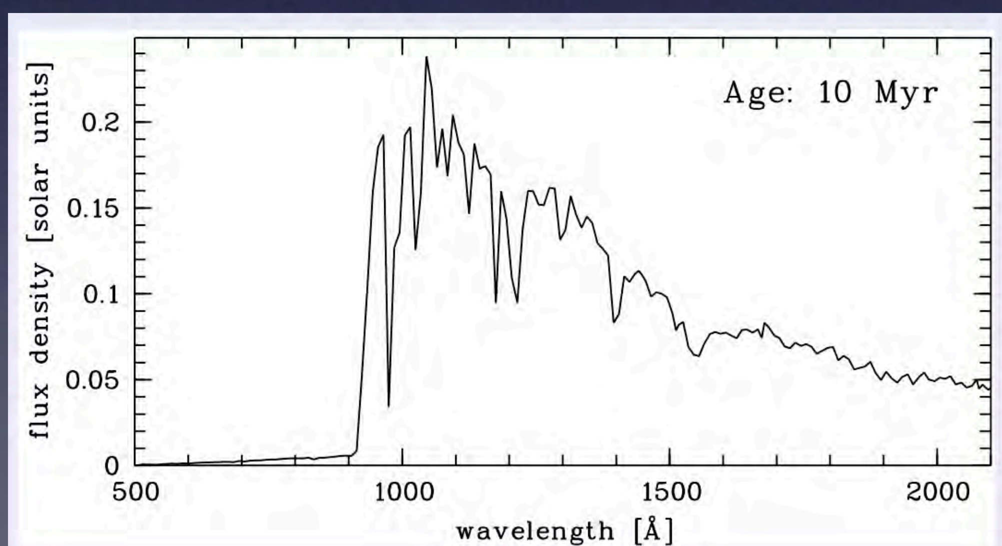
LBGs even better (Kashiwa et al. 2019)

Towards a concordant reionization model

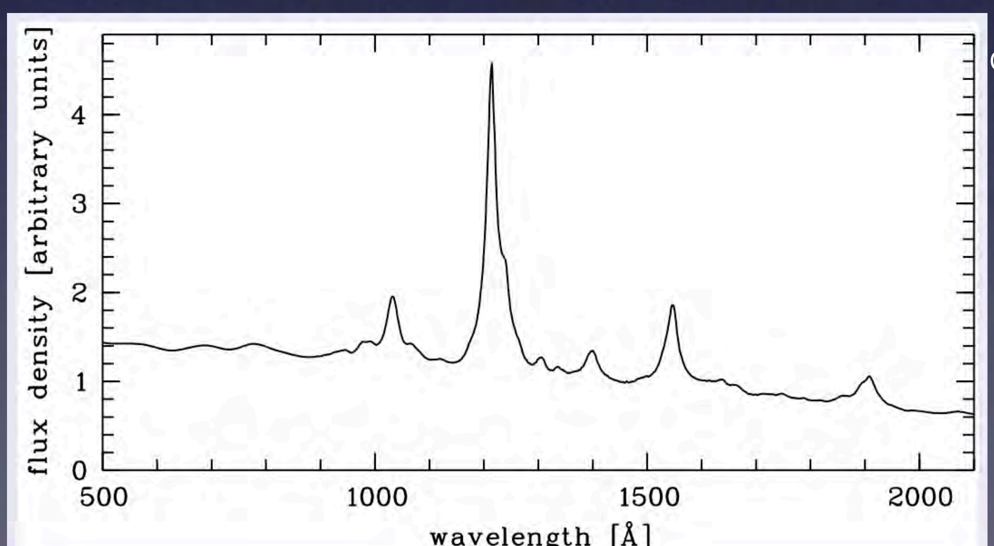
1. CMB
2. IGM damping wing
3. LAEs
4. Quasar near zones
5. Structure of the longest trough
6. Metal-poor DLA at $z = 6.43$

What caused reionization?

- Our model prefers that galaxies reionized the Universe
- But galaxies show very little escape of hydrogen-ionizing photons



Galaxy



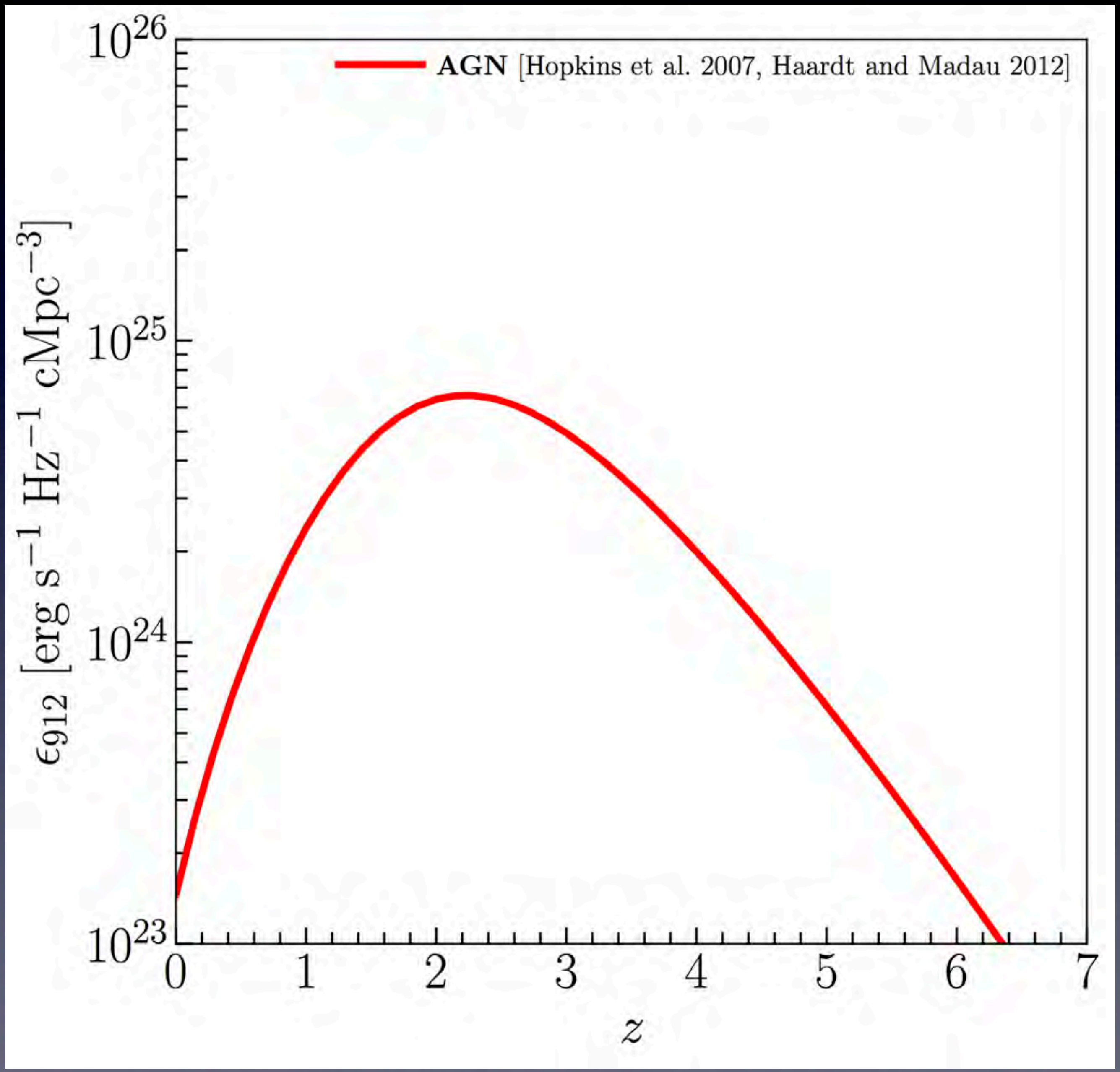
AGN

Figure: Gabor Worseck

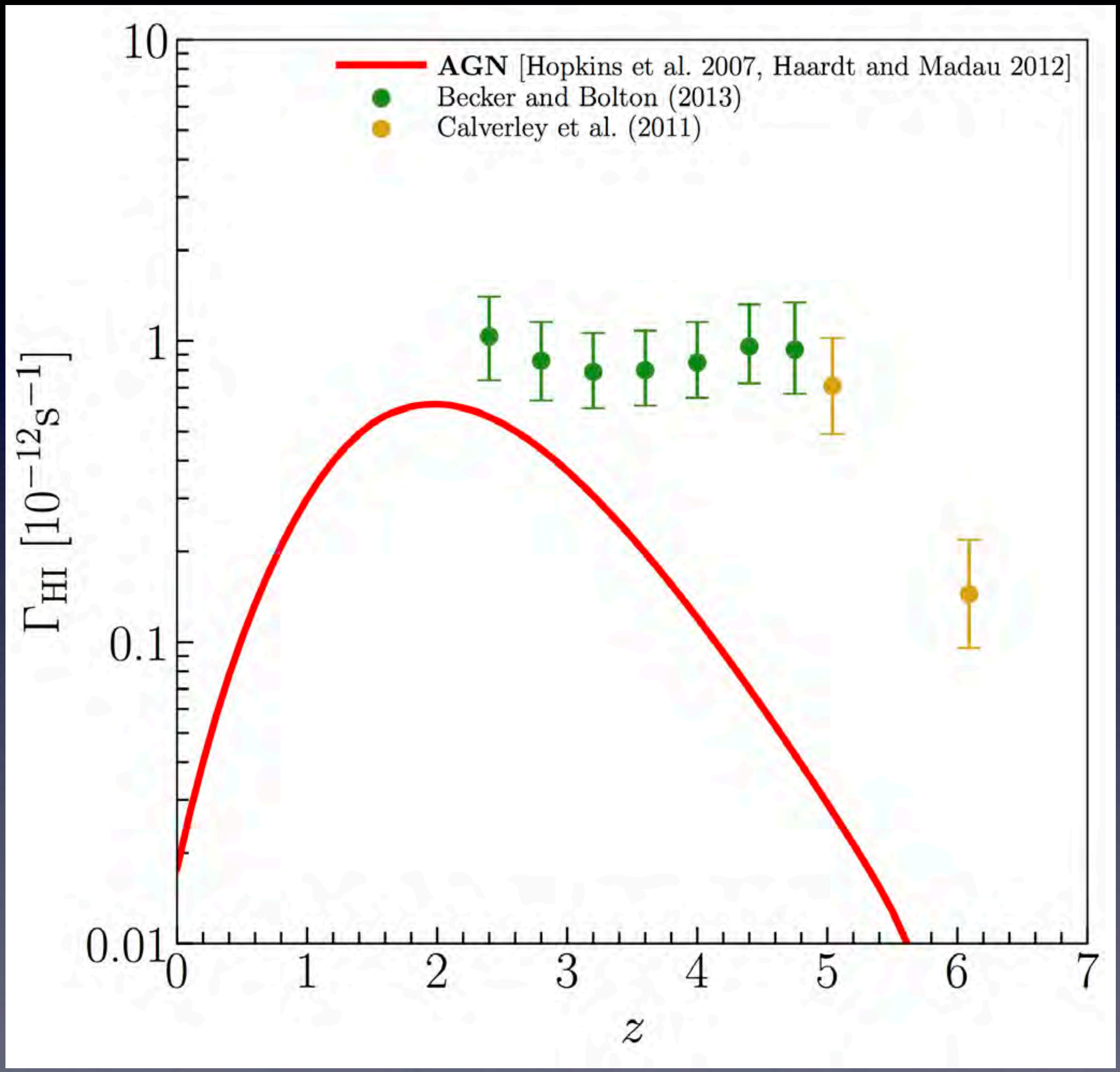
Could AGN have provided reionizing photons?

Reionization by Quasars—c. 2012

Ionizing Emissivity



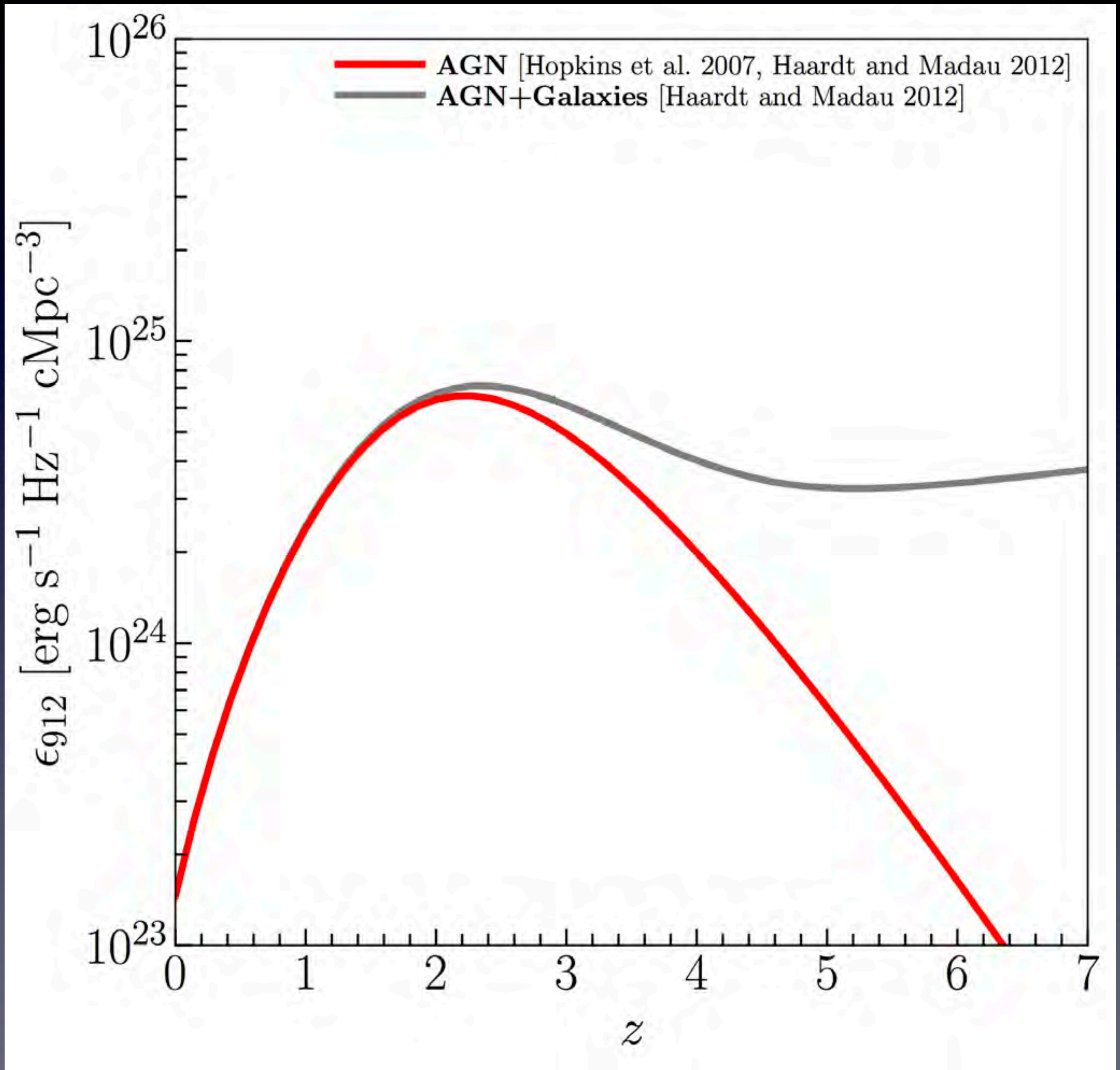
Photoionization Rate



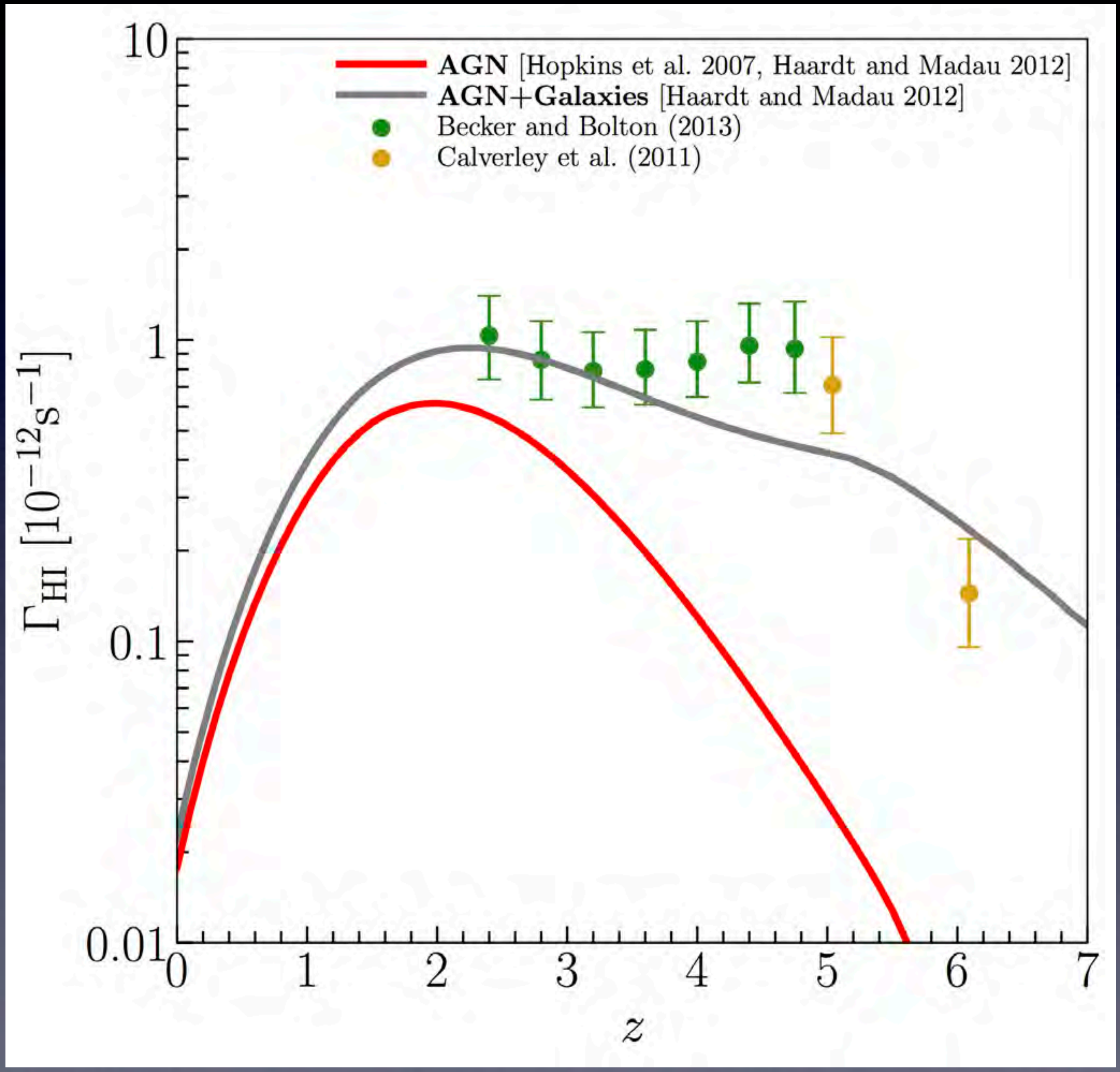
Quasar contribution falls short of the photon budget implied by Lyα data (e.g., Becker and Bolton 2013; Calverley et al. 2011)

Reionization by Quasars—c. 2012

Ionizing Emissivity



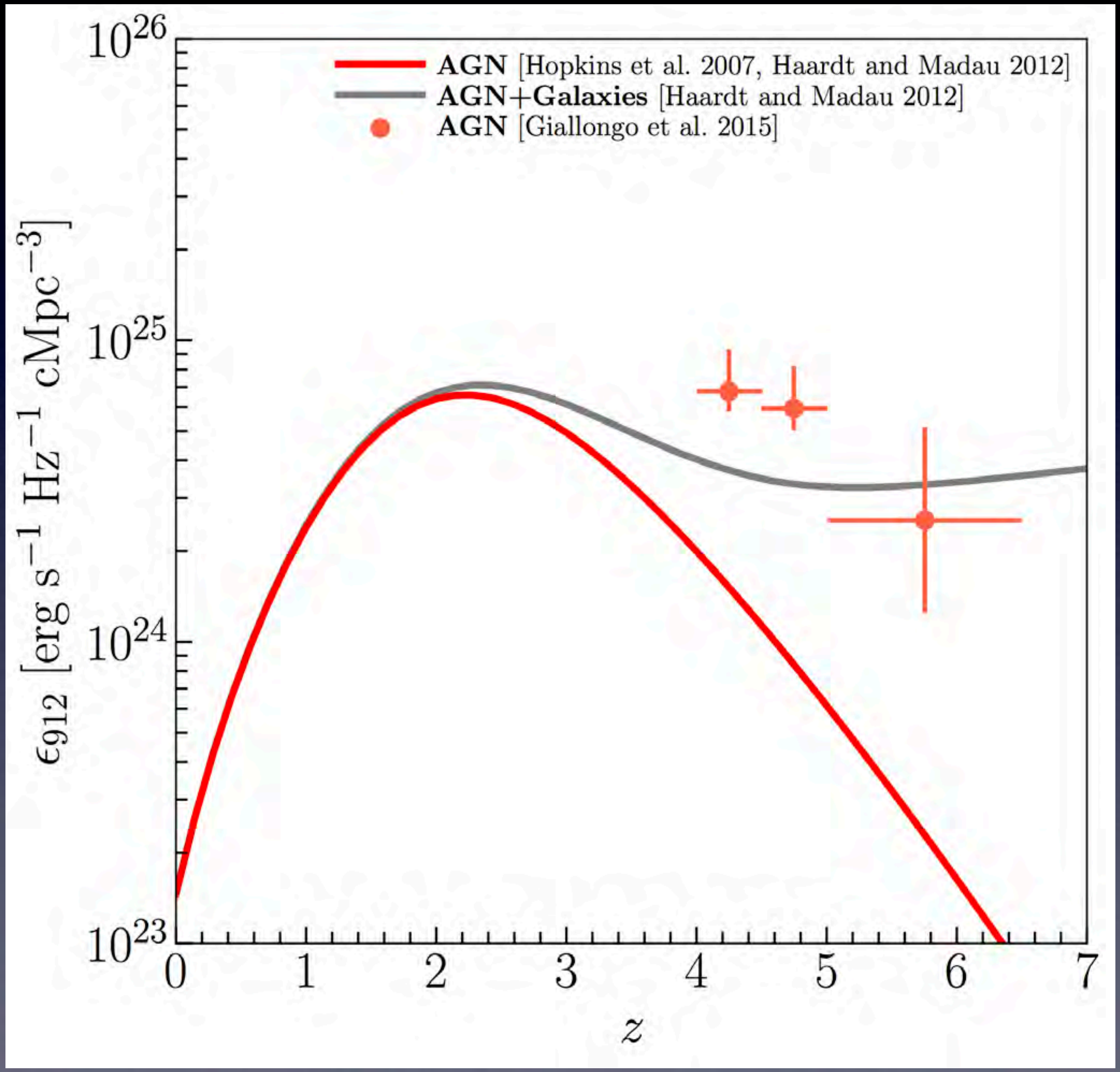
Photoionization Rate



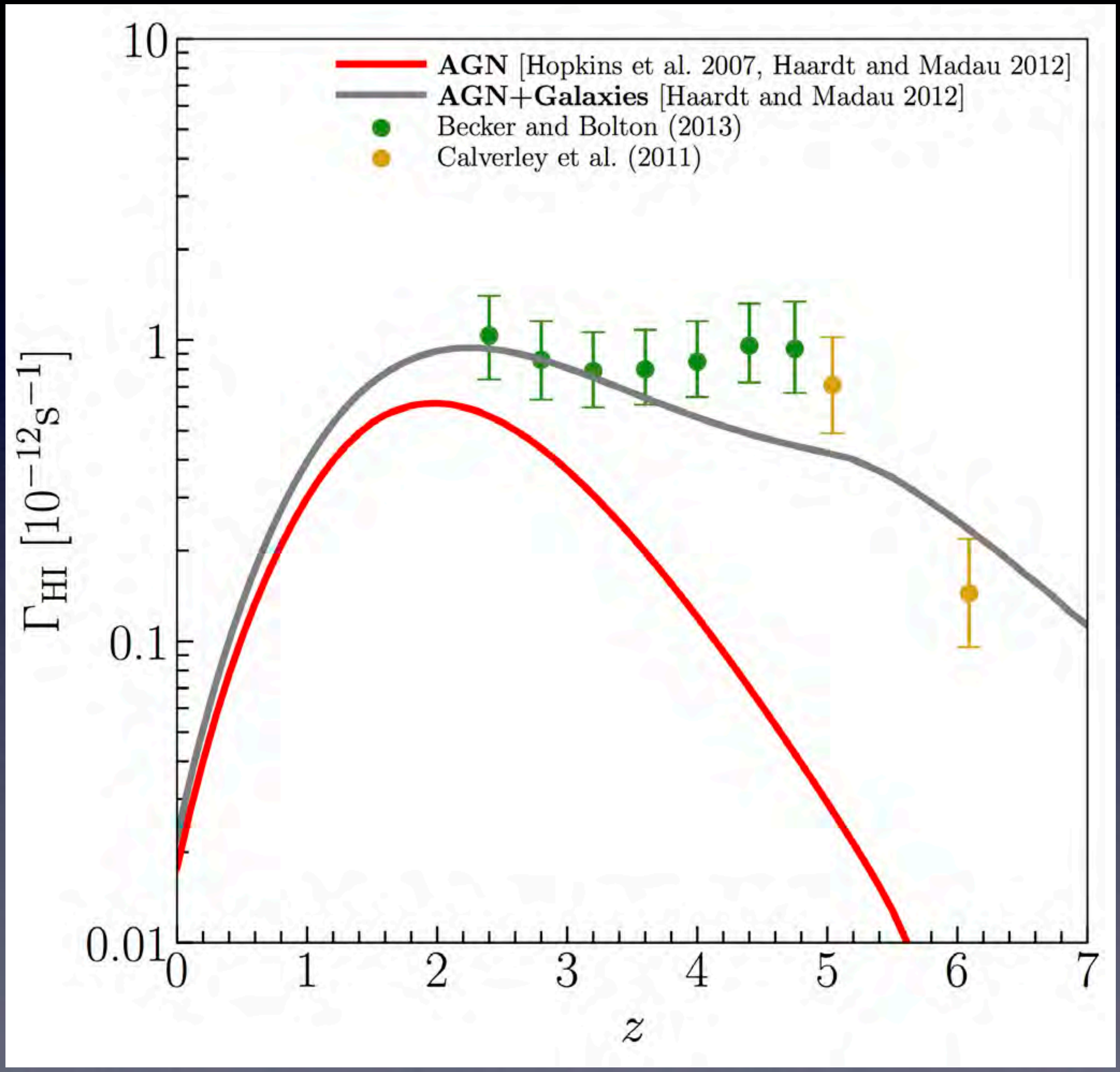
Deficit can be balanced by invoking escape of LyC photons from galaxies (e.g., Haardt and Madau 2012; Mitra et al. 2016)

Reionization by Quasars—today

Ionizing Emissivity

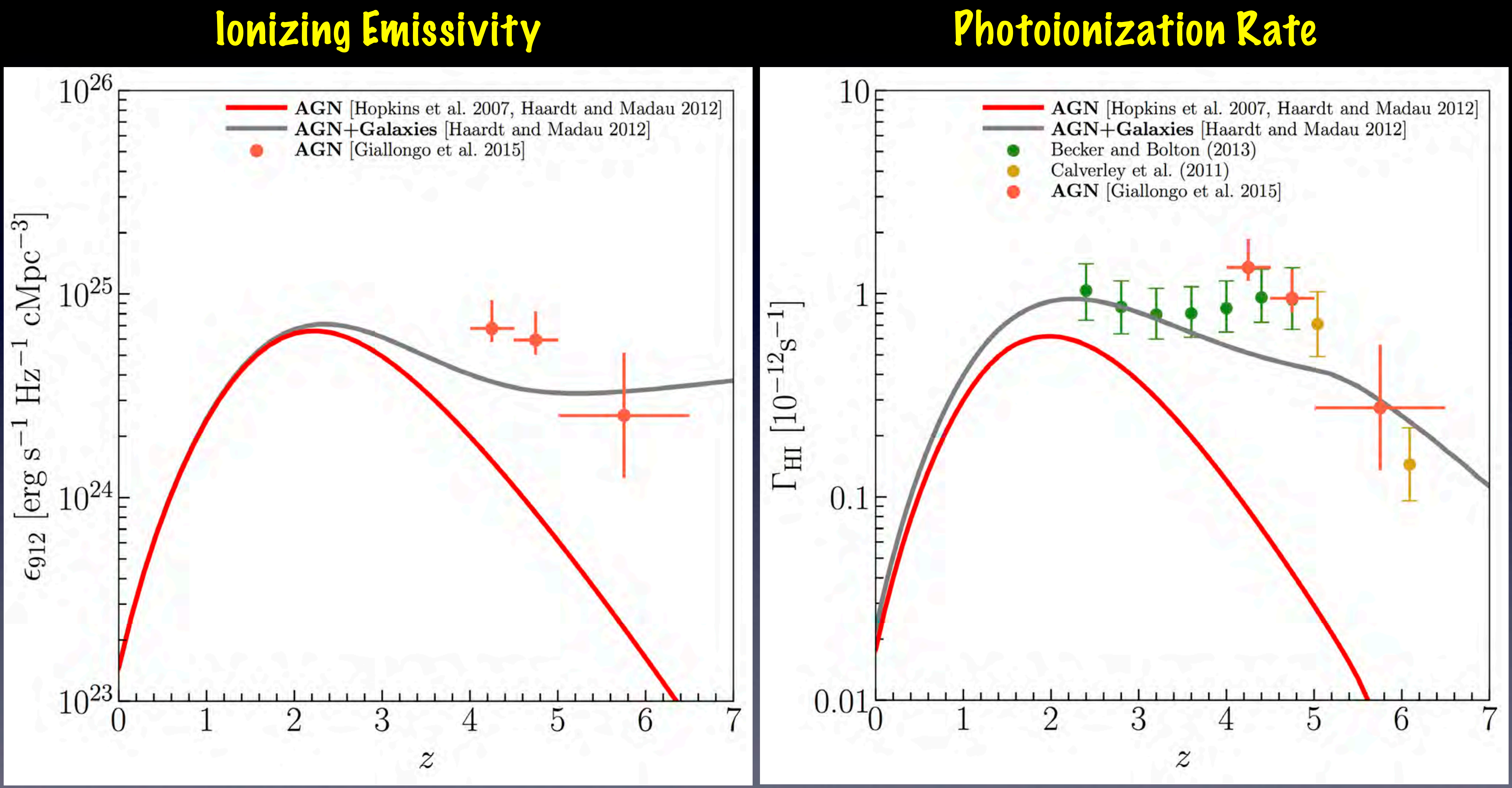


Photoionization Rate



19 new faint AGN at z = 4–6 via photometric X-ray/NIR selection suggest much higher AGN number density (Giallongo et al. 2015)

Reionization by Quasars—today



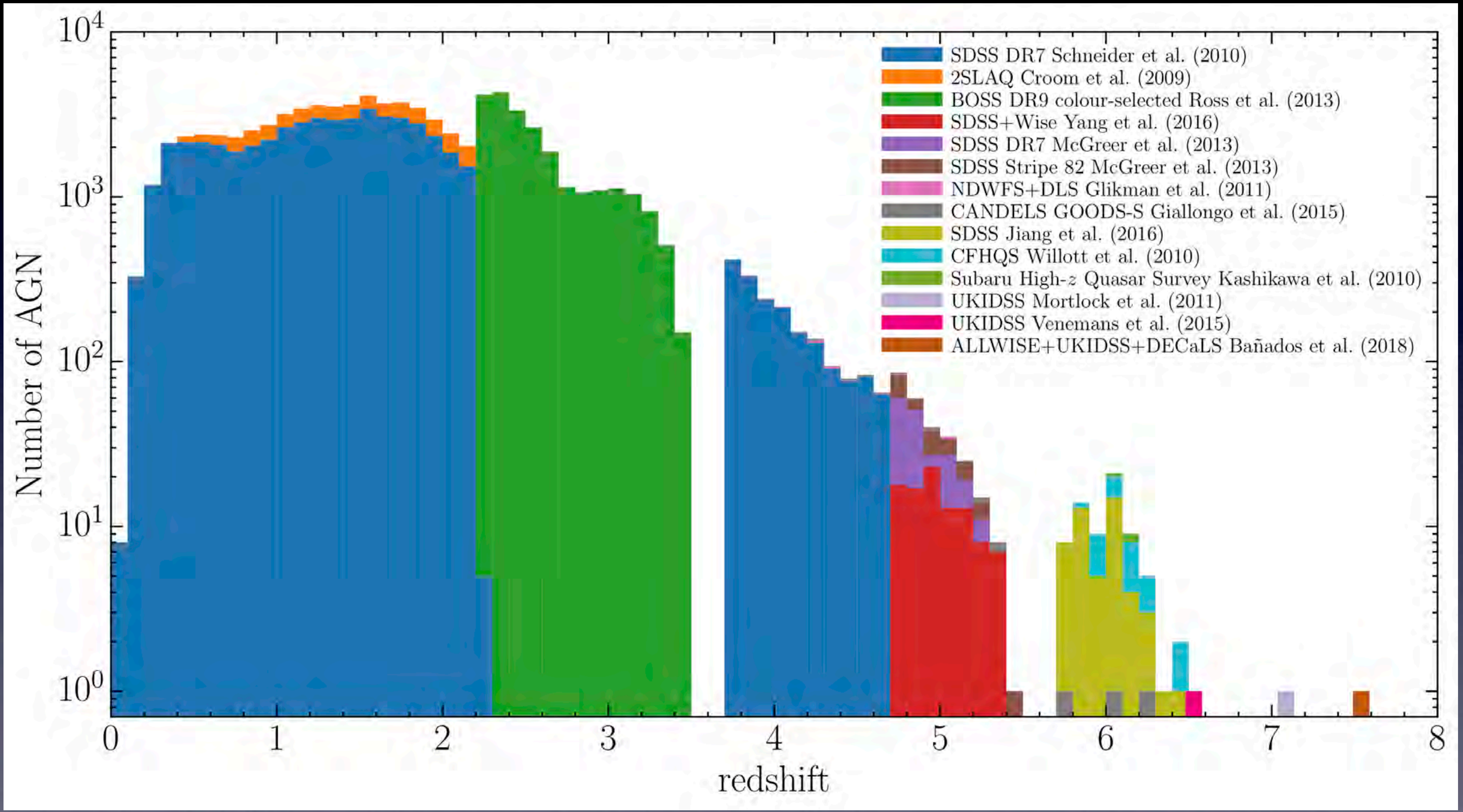
Consistency with Lyα data all the way up to z = 6 suggests that **AGN *can* reionize the universe** (Giallongo et al. 2015)

Issues with current analyses

- Inhomogeneous mixing of data sets
- Restrictive priors
- Arbitrary selection of data sets
- Non-uniform data quality

Response: Construct a homogenous sample of good quality data and derive AGN UV luminosity function

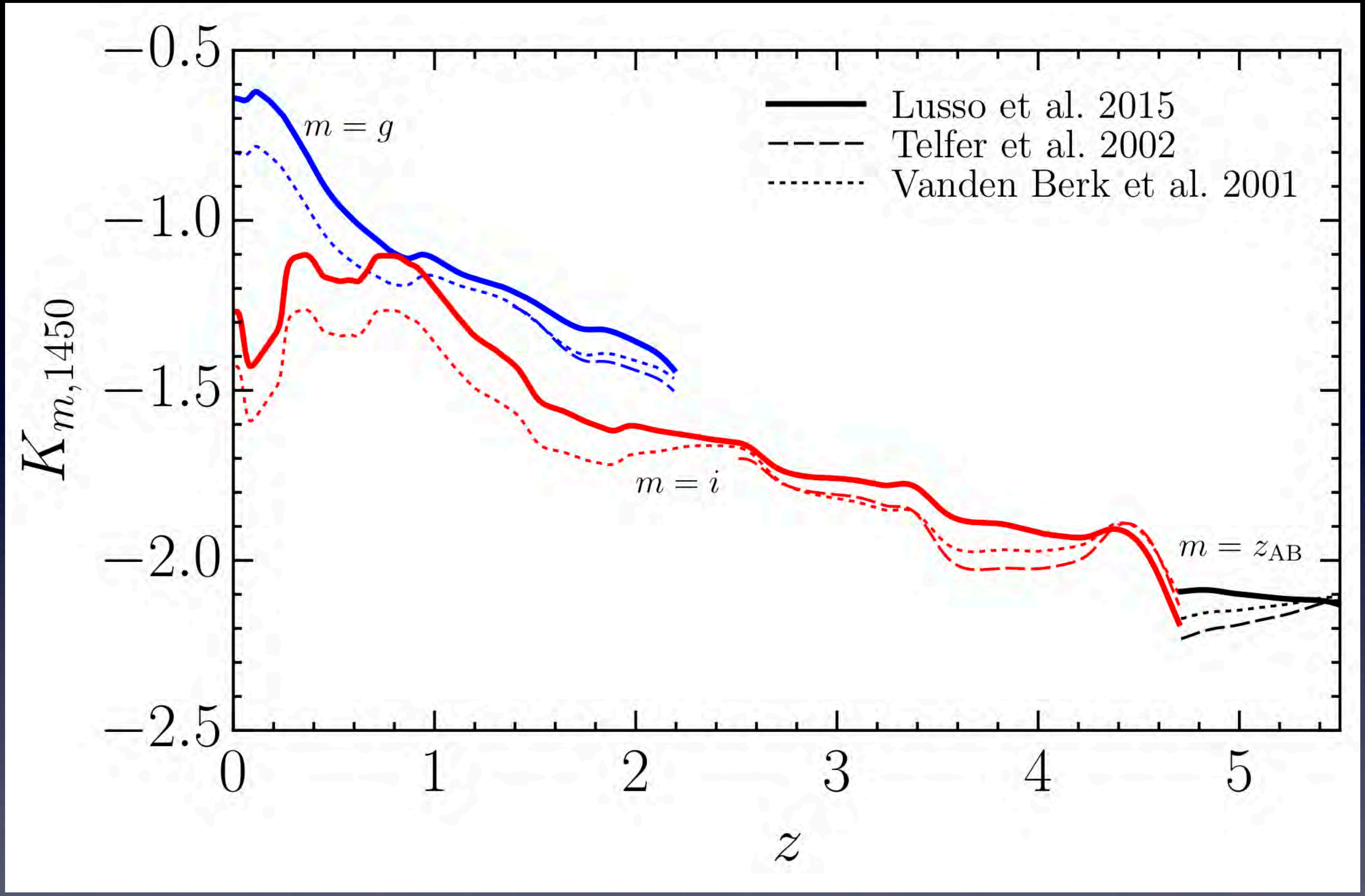
Prepare largest homogeneous quasar dataset



Kulkarni et al. 2018

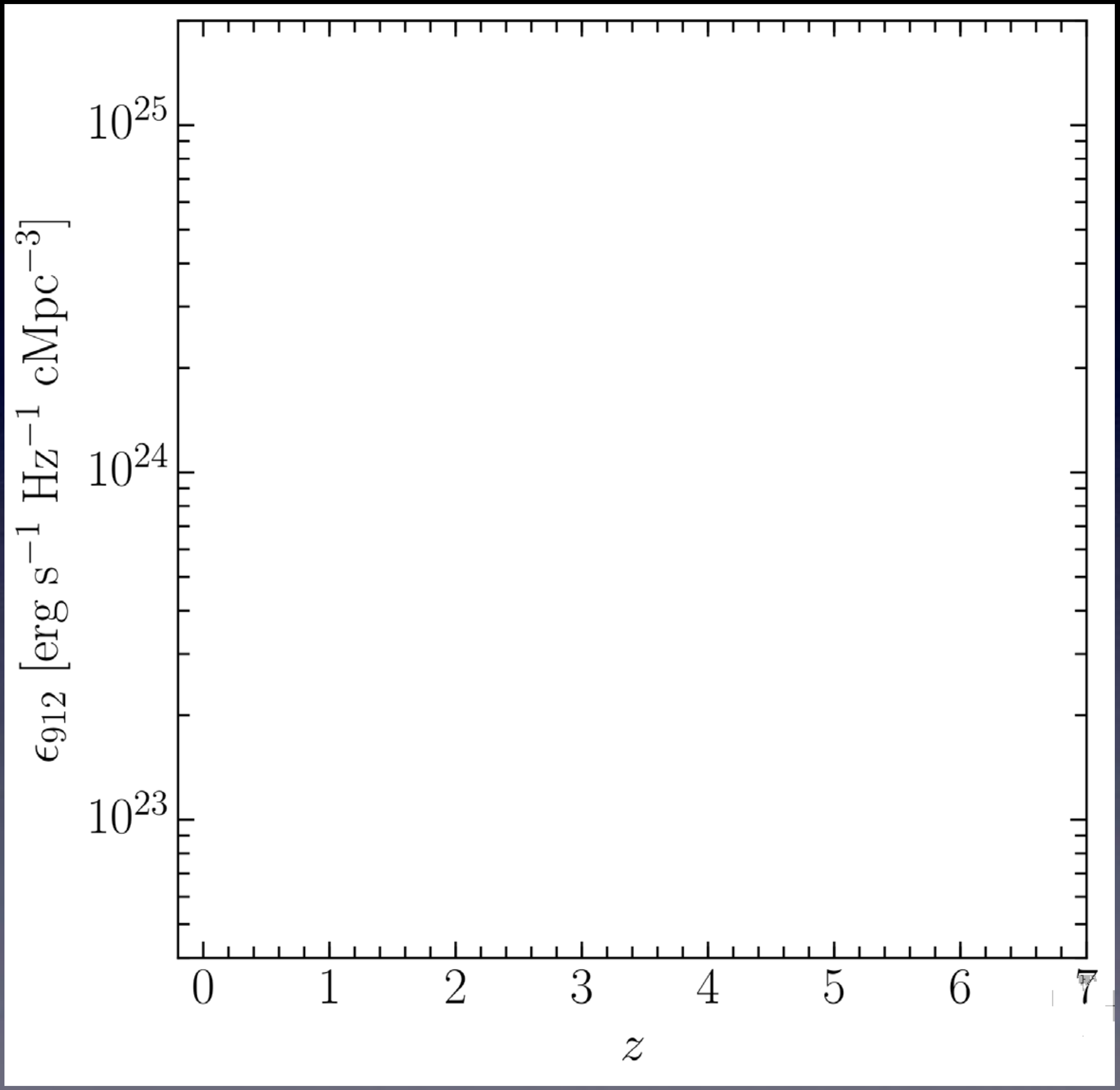
83,488 quasars with spectroscopic redshifts and completeness estimates

Homogenisation

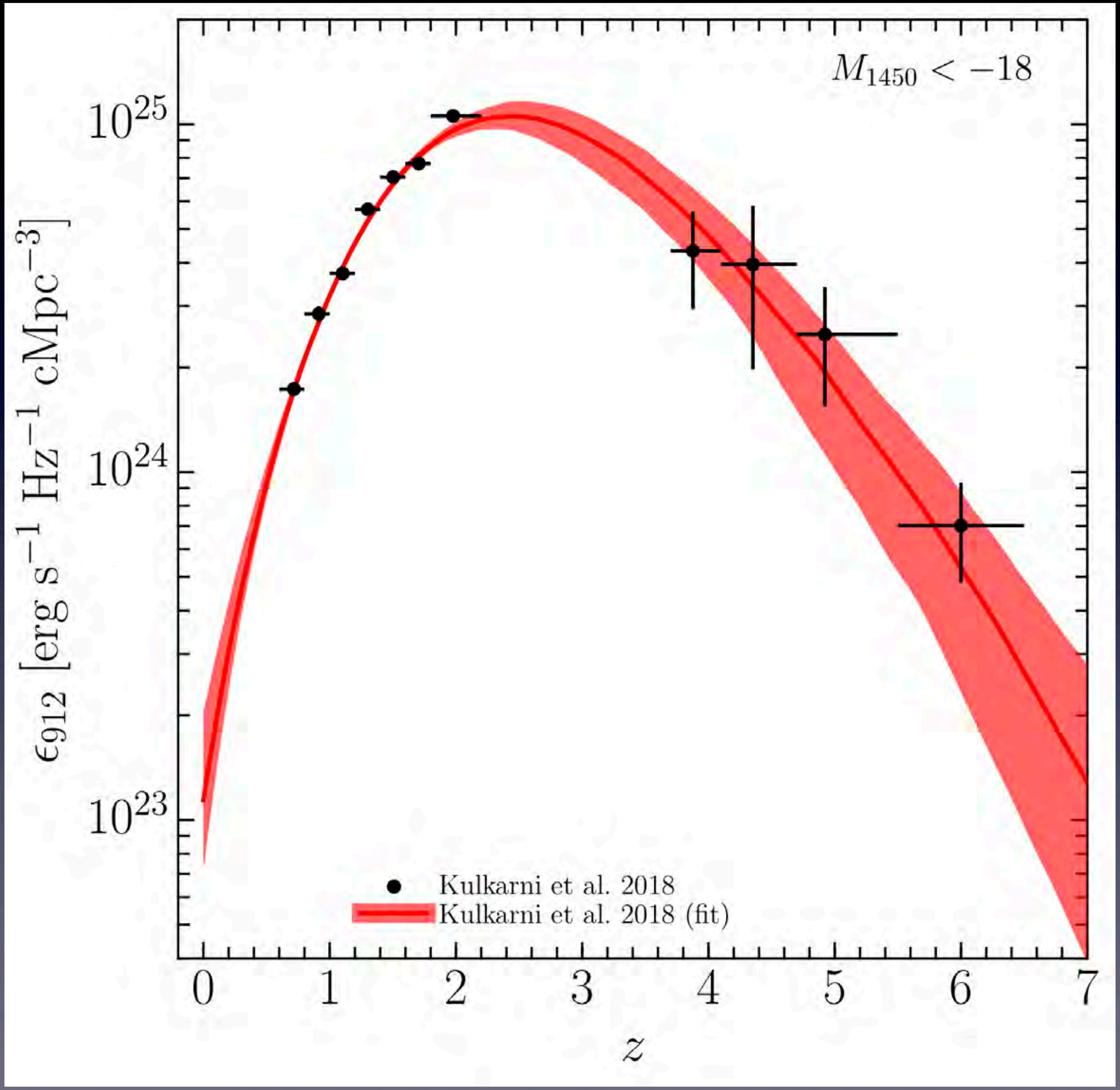


- Change quasar luminosities and completeness maps to M1450 and homogeneous K-correction and cosmology
- Corrected z < 2.2 sample for host-galaxy contamination (Croom et al. 2009)—negligible contamination for z > 0.8

Quasar contribution sub-dominant

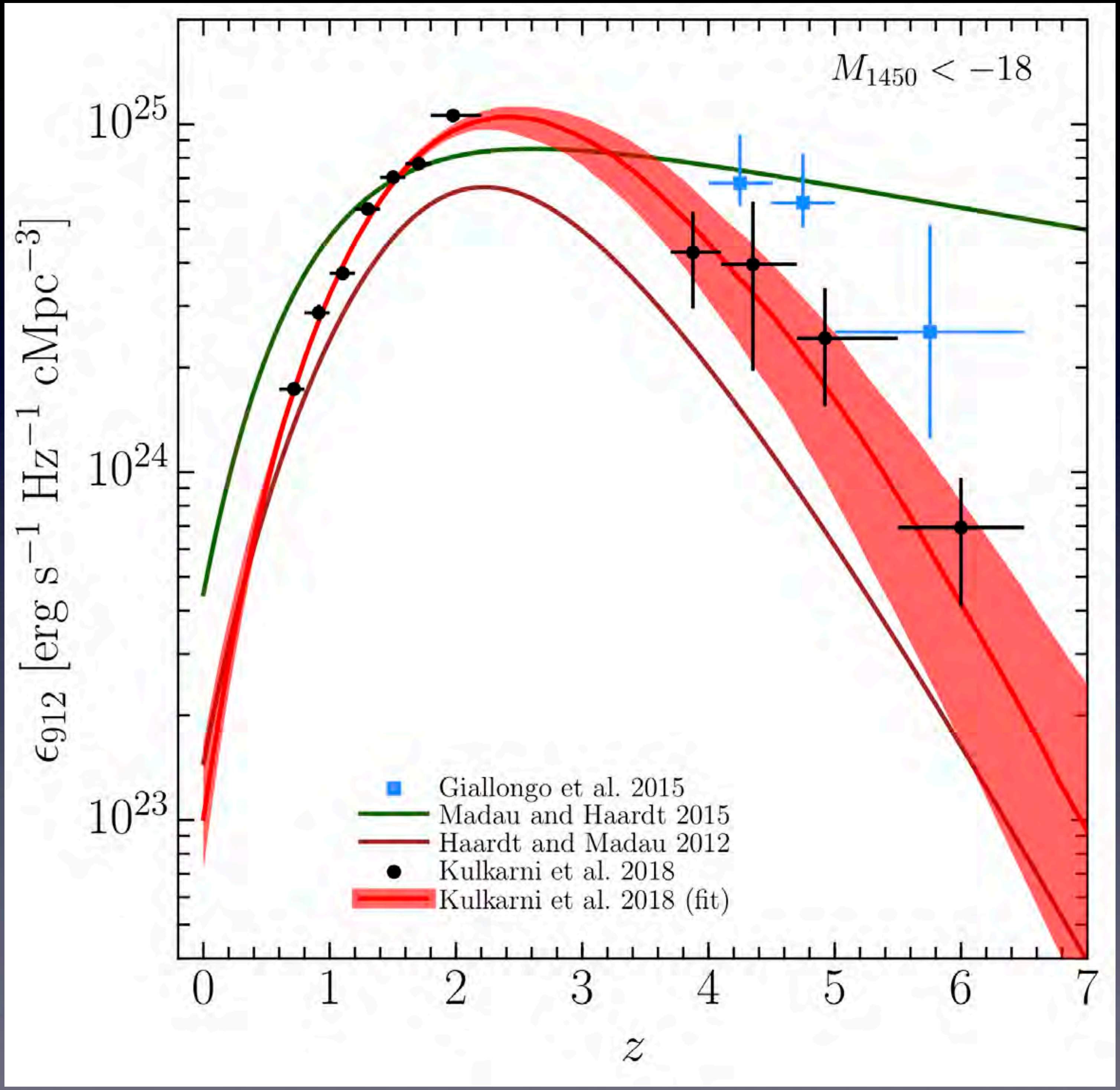


Quasar contribution sub-dominant



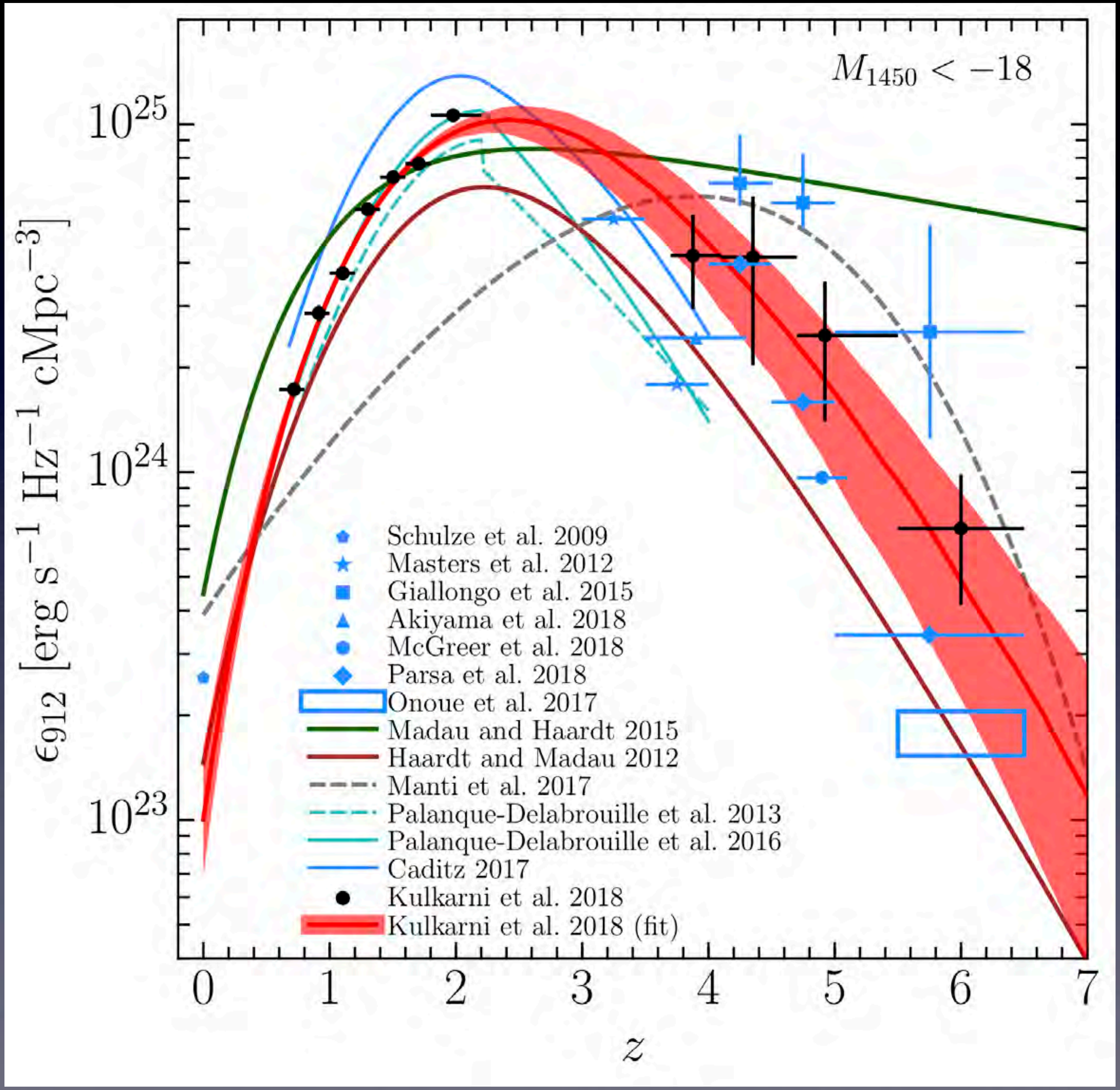
Quasar contribution to UV background less than the Giallongo inference

Quasar contribution sub-dominant



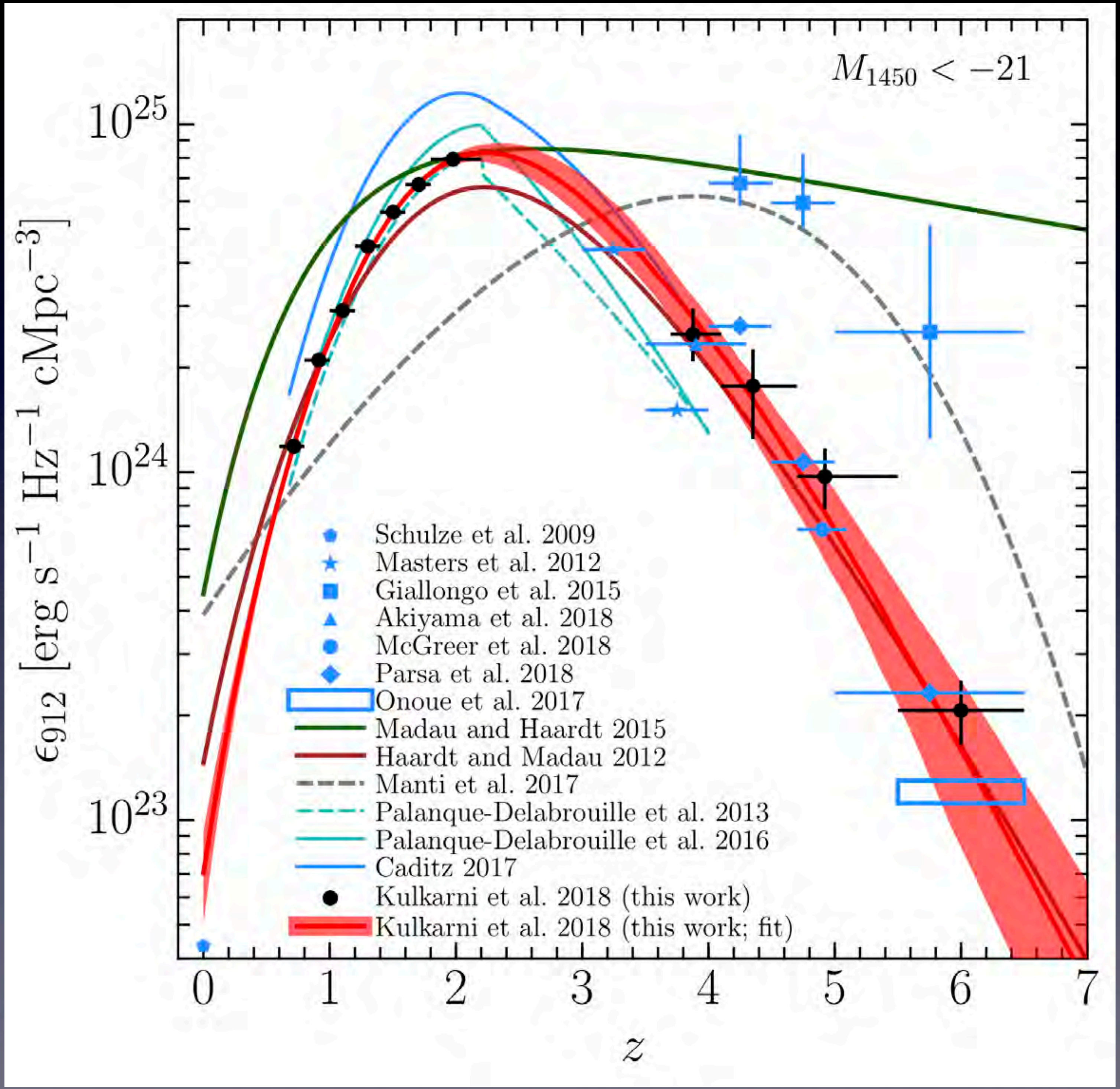
Quasar contribution could still be higher than previously thought at $z \sim 4$–5

Models differs from recent results



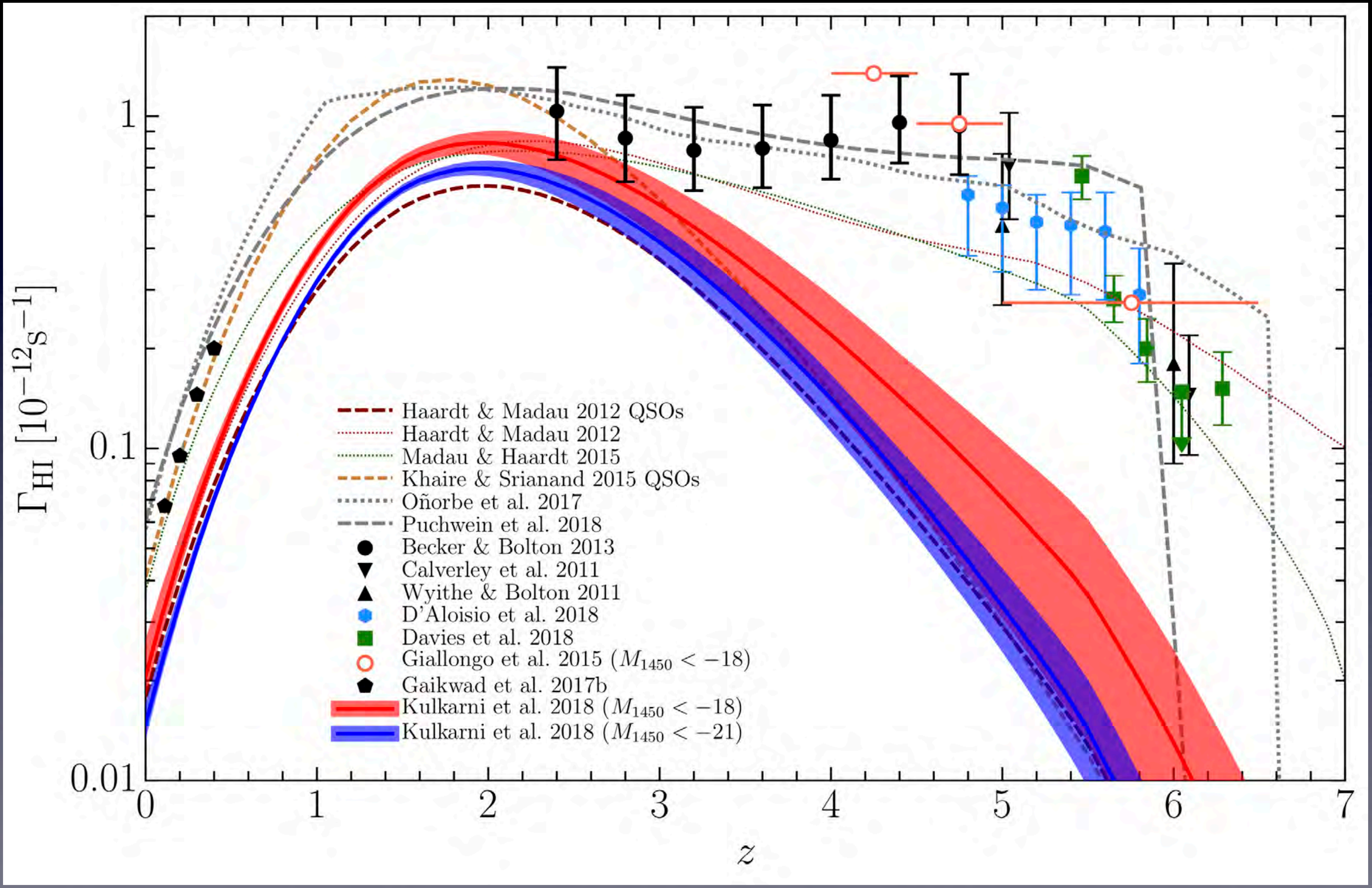
Photoionisation rate derivation requires treatment of IGM opacity and radiative transfer

Contribution of 'reliable' quasars even lower



Spectroscopic data only go down to M ~ –21. These quasars contribute even less to the total emissivity.

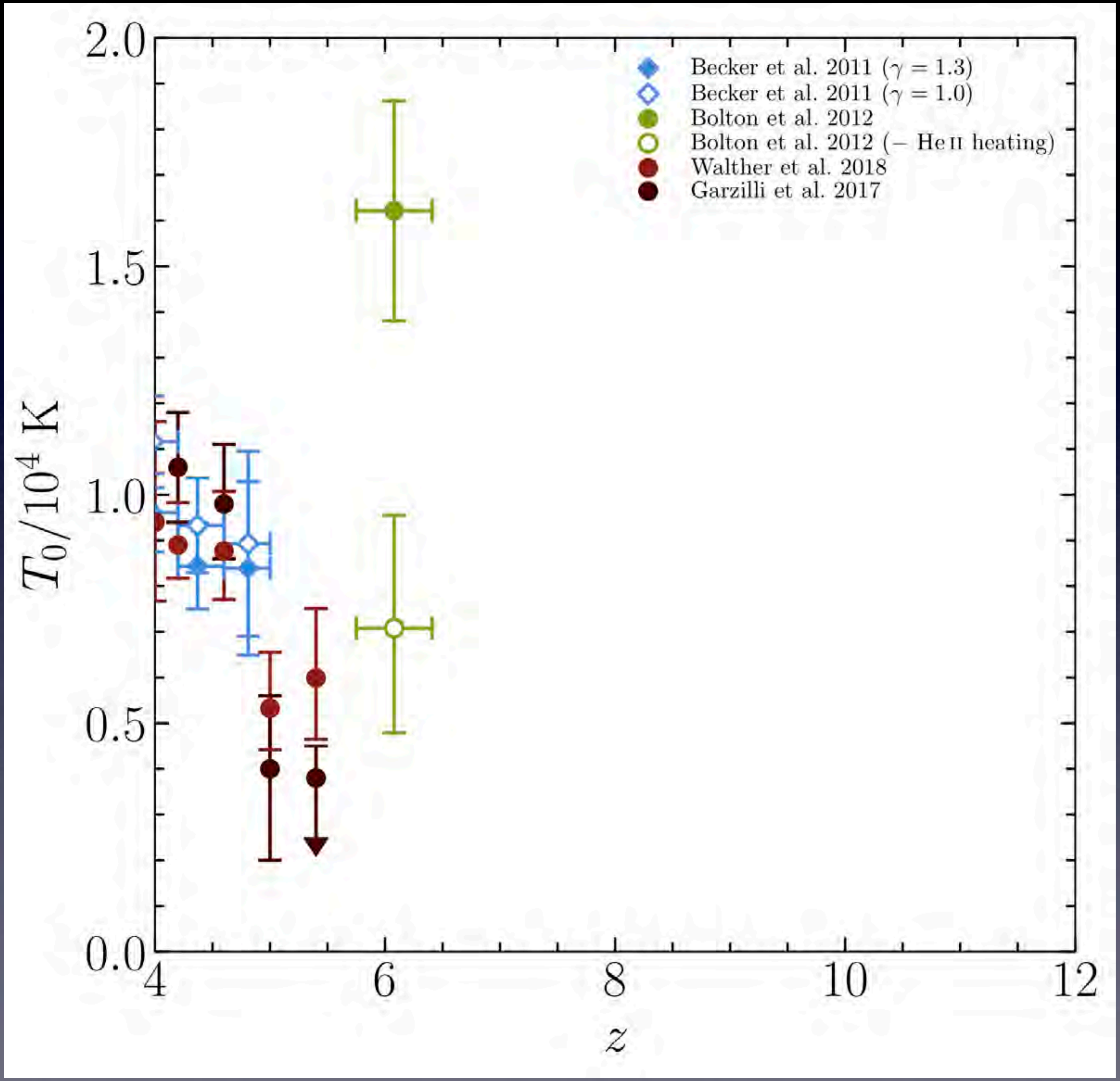
AGN contribution to reionization subdominant



Kulkarni et al. 2018

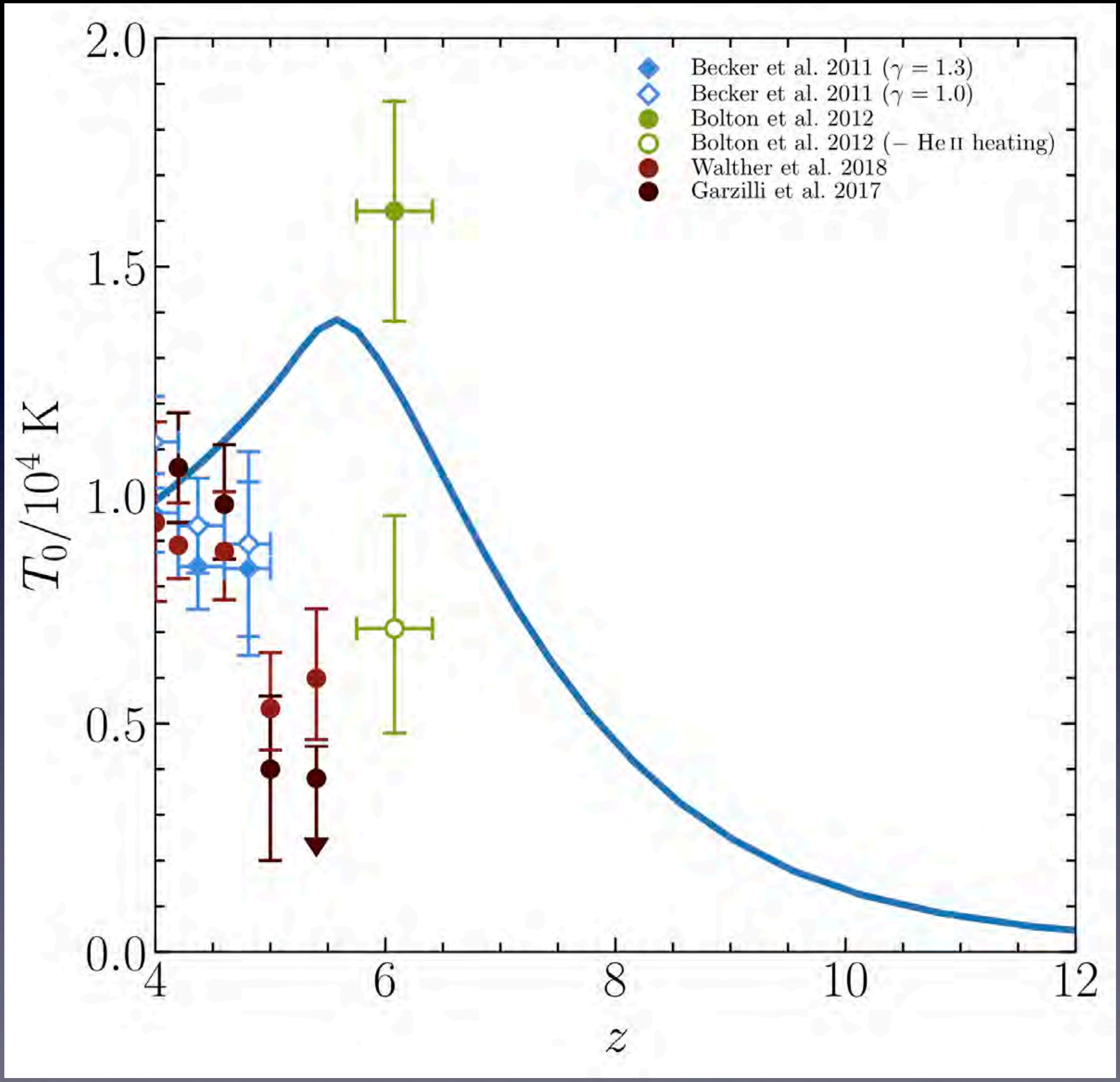
What next?

Can we get the temperature now?



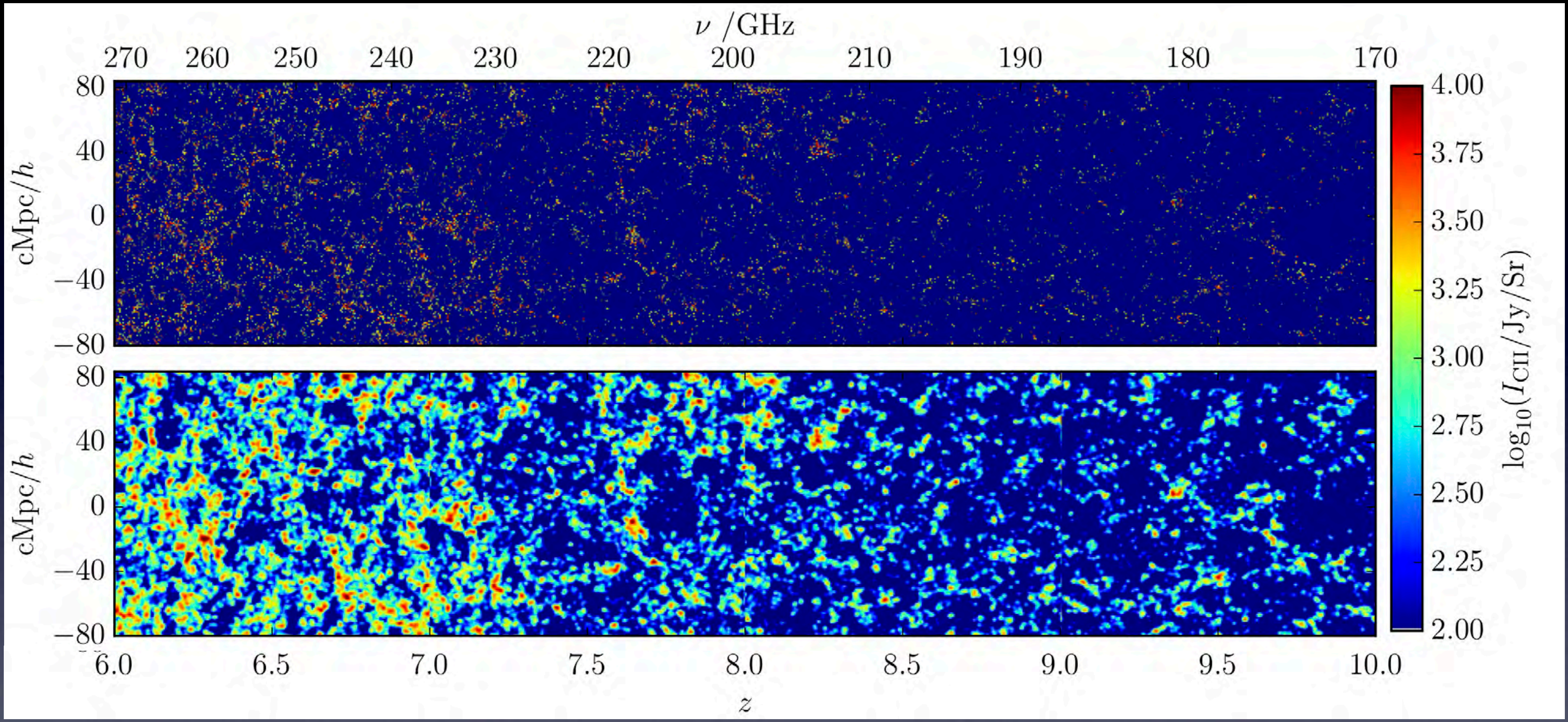
IGM temperature measurements at high-redshifts are notoriously hard and model-dependent

Can we get the temperature now?



By combining radiative transfer and hydrodynamics, we can derive relatively robust temperature measurements

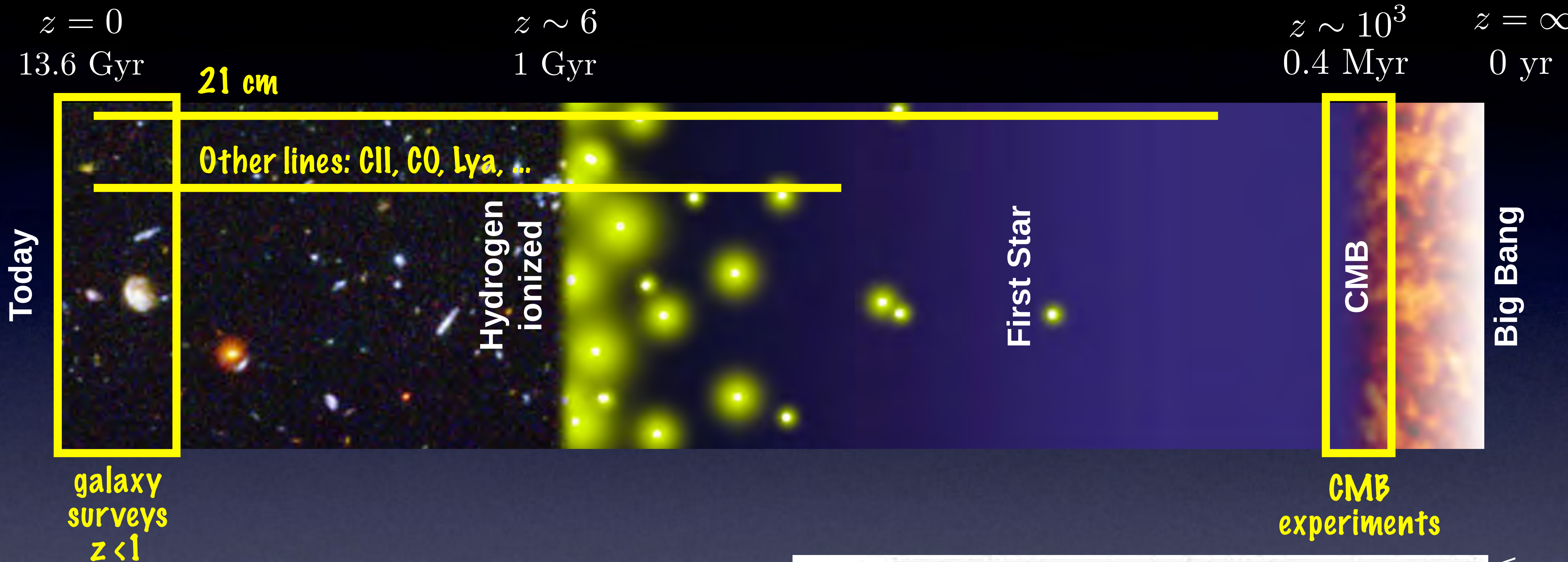
Higher redshifts: Intensity Mapping

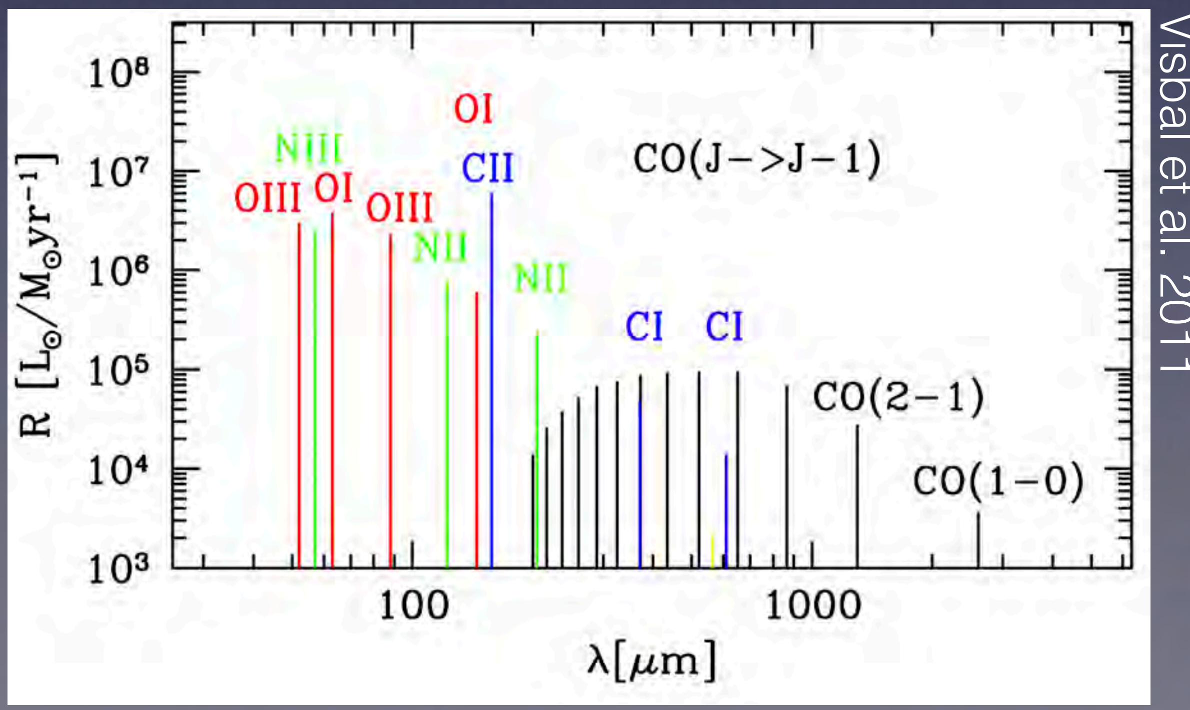


Dumitru, Kulkarni et al. 2018

- Measure spatial fluctuation in line emission from unresolved sources (“Forest, not the trees”)
- More economical than traditional galaxy surveys
- Commonly targeted lines: HI 21 cm, [CII] 160 μm, CO, and Lyα

Targets for Intensity Mapping

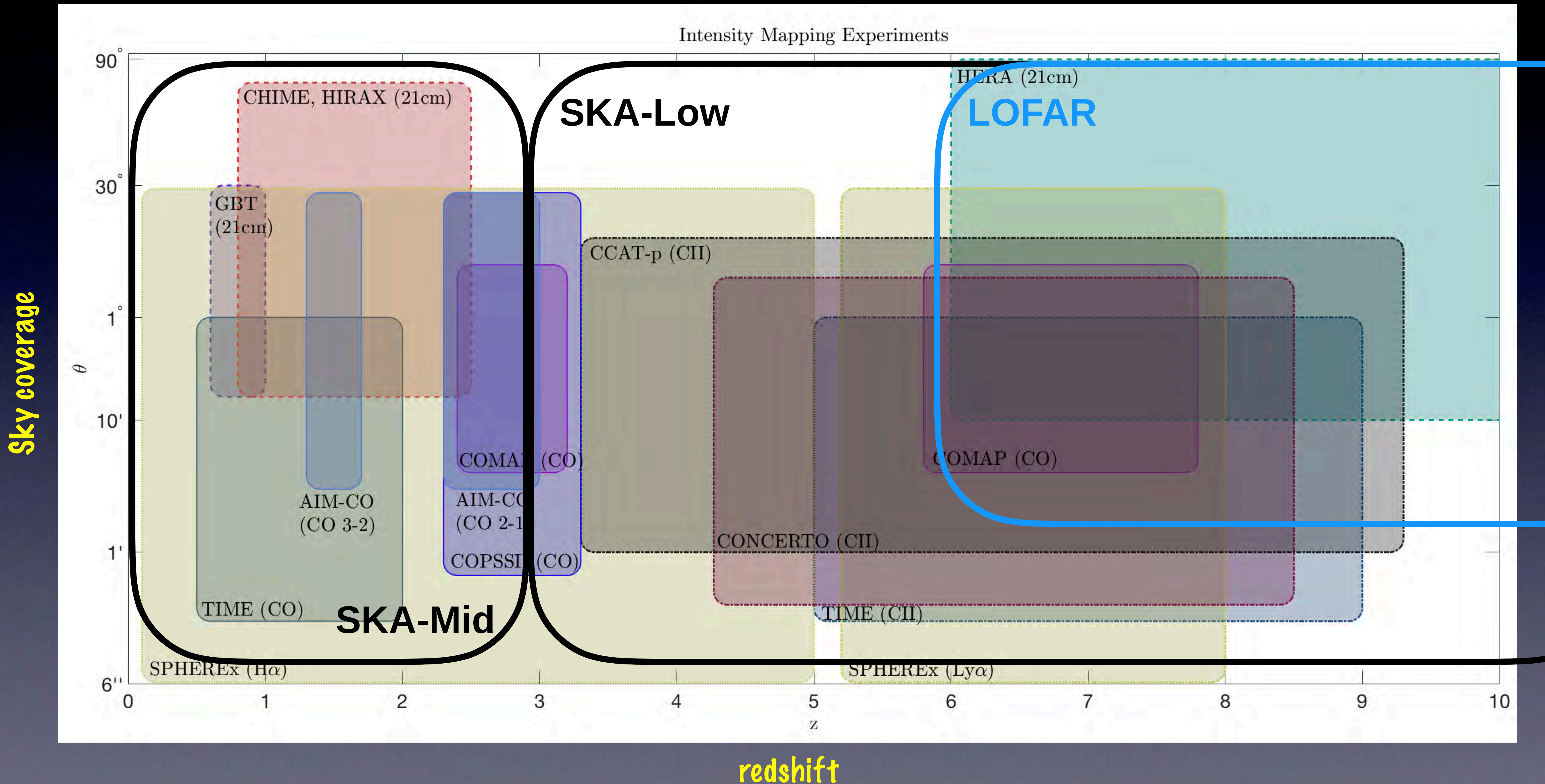




- Most early interest in HI 21-cm for reionization
- Growing interest in CII, CO, Lya
- Increased awareness of low-z possibilities

Planned experiments

Kovetz et al. 2017

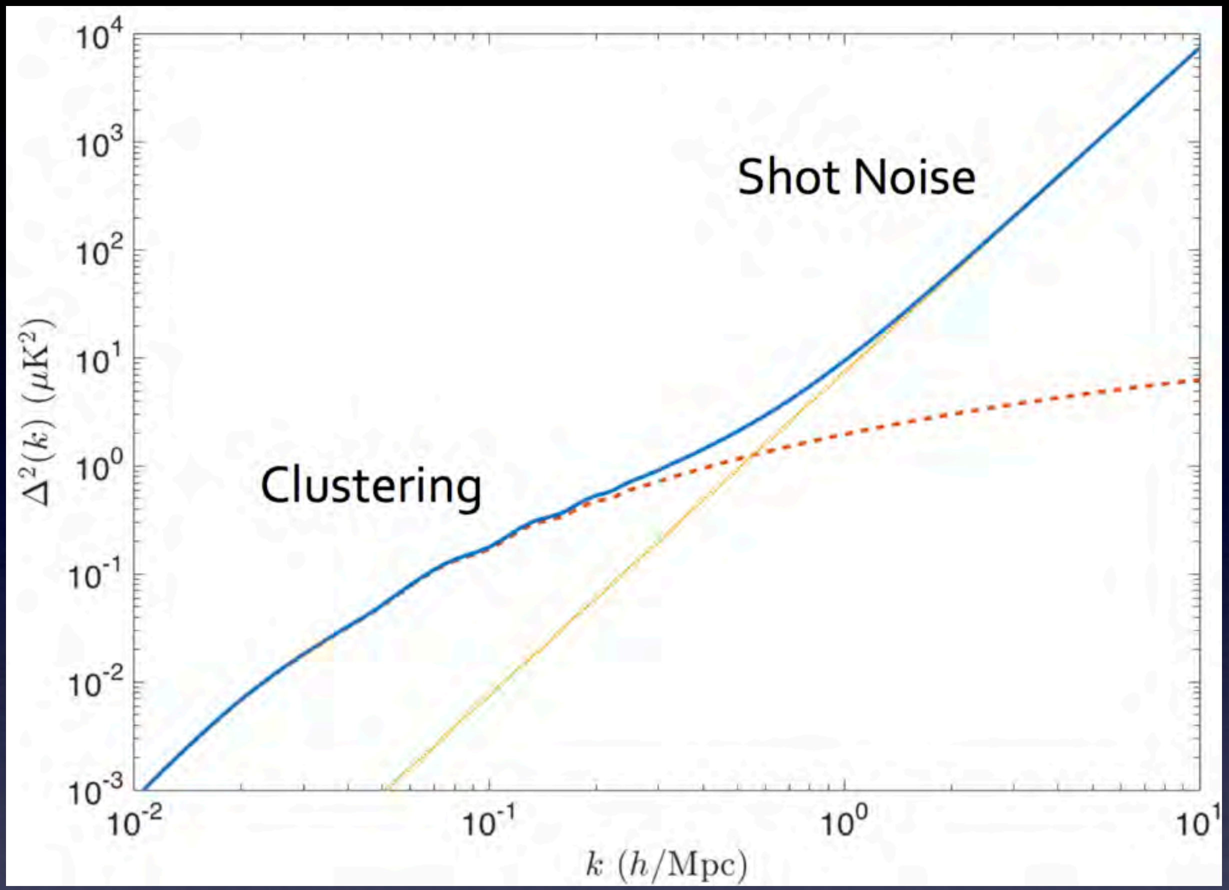


More than 15 experiments aiming at z = 0–30.

Science Goals

- **Cosmology**: parameter constraints, neutrino masses, non-Gaussianity, dark energy
- **Astrophysics**: epoch of reionization, galaxy formation

Expected signal



Koveetz et al. 2017

$$P_k(z) = \langle I(z) \rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}(z)$$

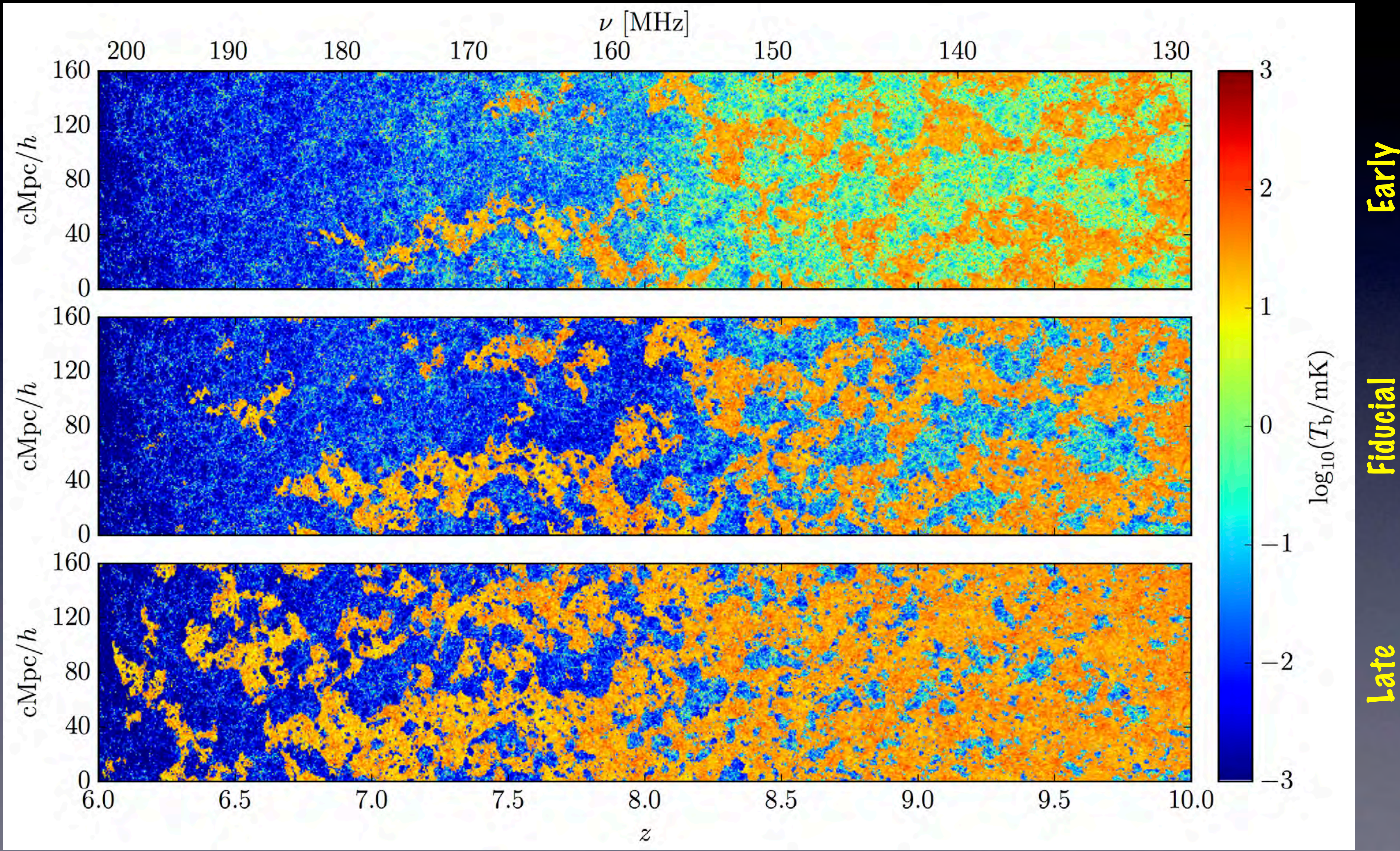
Avg. line intensity

bias

shot noise

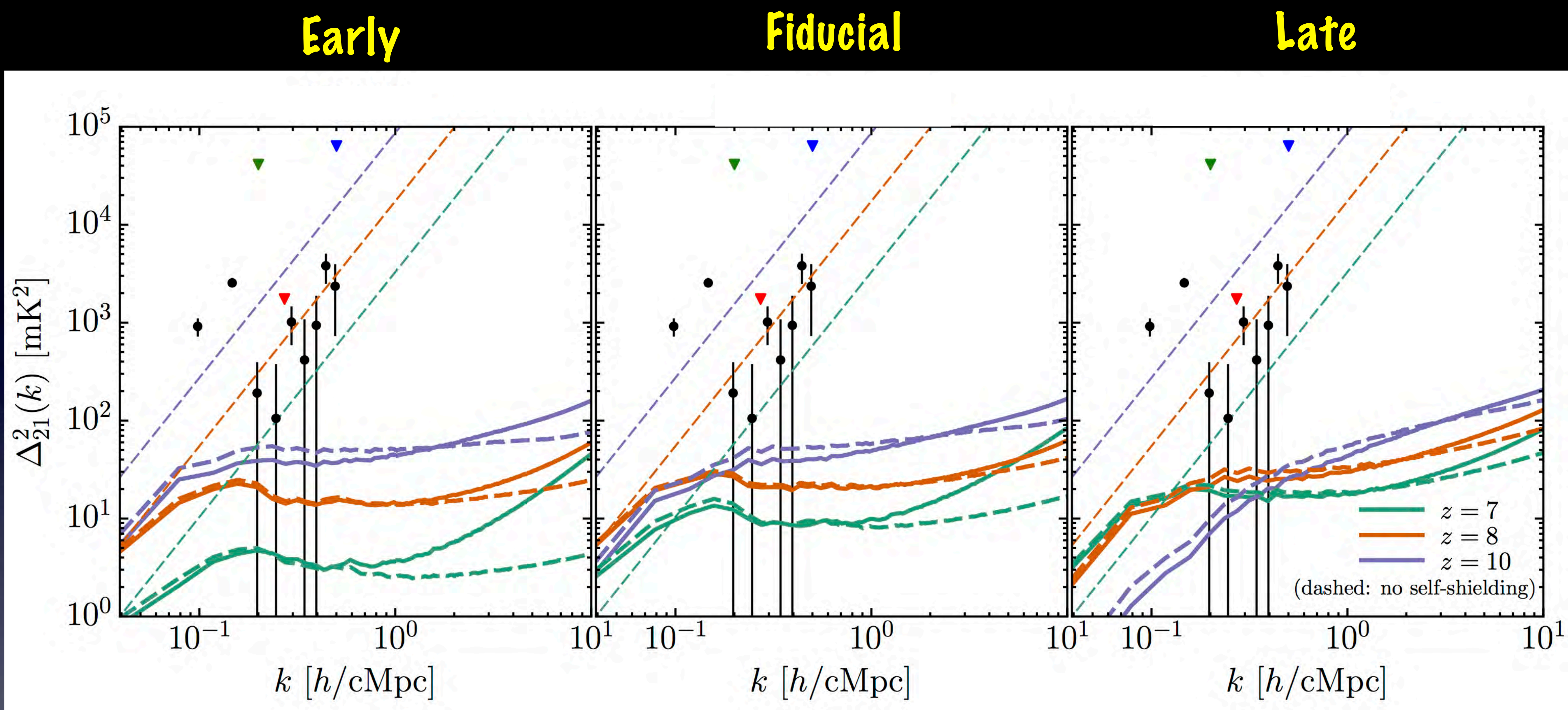
Signal dominated by shot noise on small scales. Need to model line luminosity function and bias.

Expected signal: reionization HI



Kulkarni et al. 2016

Power spectrum predictions



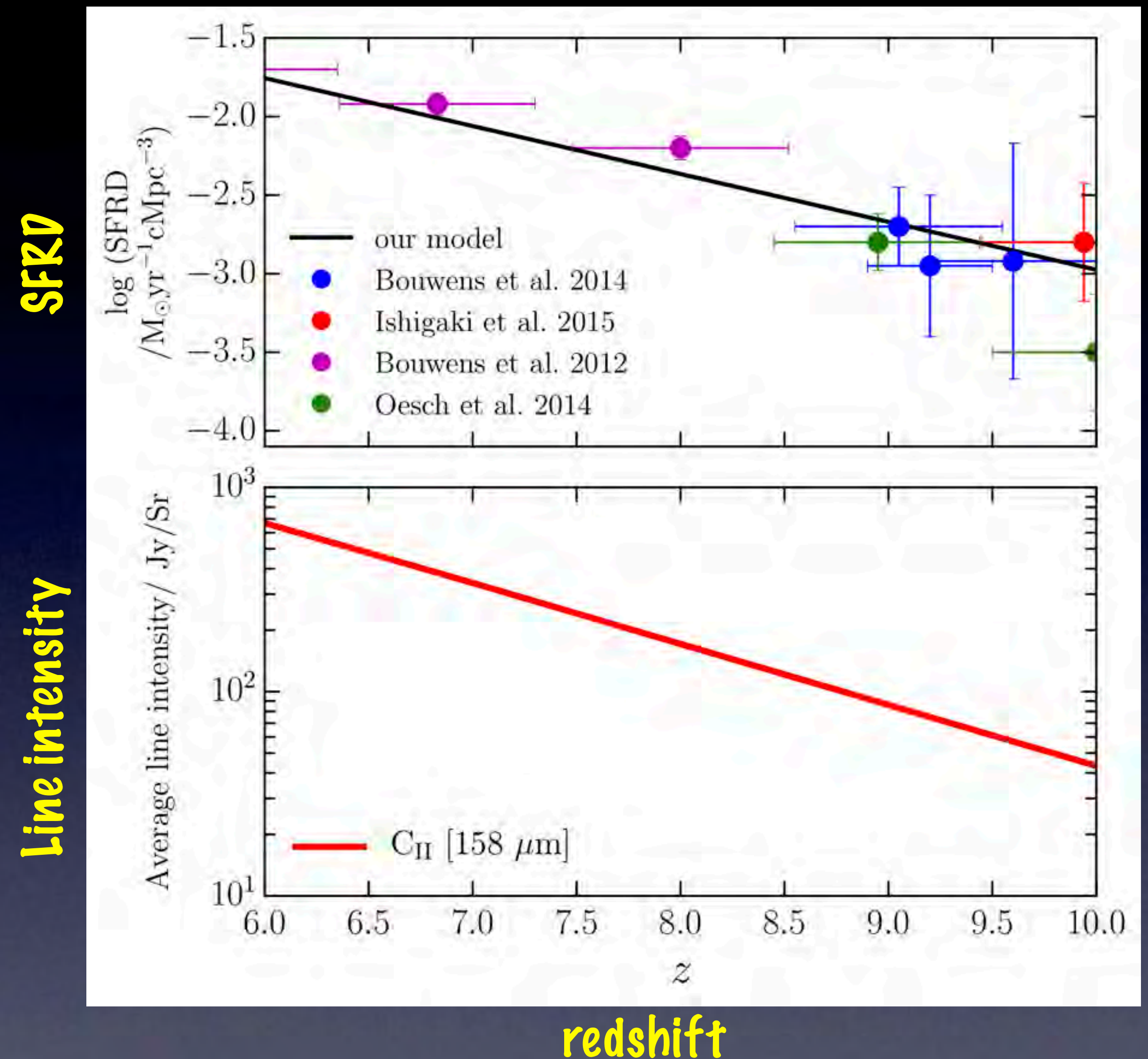
Kulkarni et al. 2016

$$\Delta^2_{21}(k) = b_1(Q,k)\Delta^2_{\mathrm{sources}}(k) + b_2(Q,k)\Delta^2_{\mathrm{matter}}(k)$$

Source clustering fixes large-scale power. **Matter clustering** fixes small-scale power. Reionization astrophysics decides how the two mix.

Epoch-of-reionization C II intensity mapping

$\mathrm{SFR} = f_* \frac{\Omega_\mathrm{b}}{\Omega_\mathrm{m}} \frac{M}{t_\mathrm{s}}$

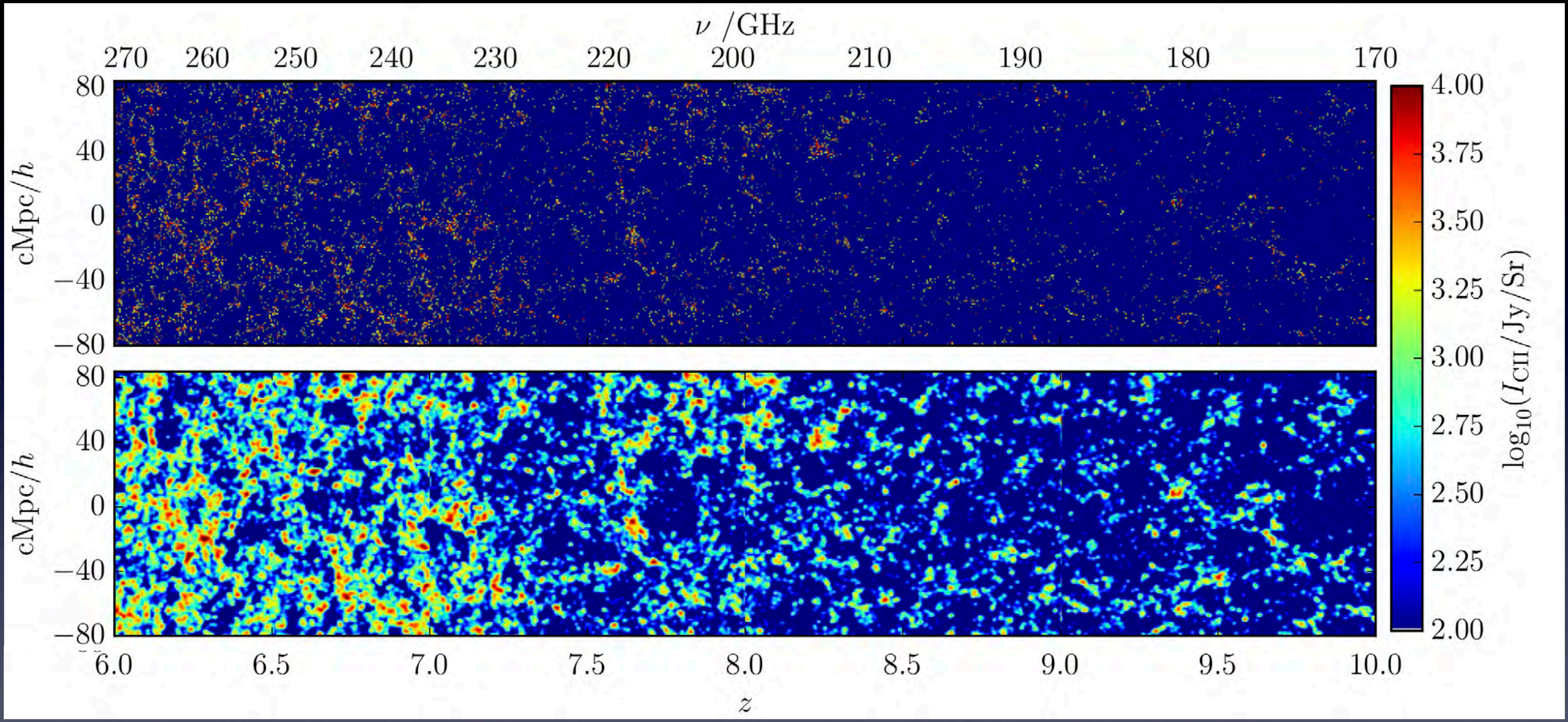


Dumitru, Kulkarni et al., 2018

Model line emission intensity using analytical model of Lagache et al. 2007 and summing over simulation lightcones

$$\log\left(\frac{\mathrm{L}_{[\mathrm{CII}]}}{L_\odot}\right) = (1.4 - 0.07z) \times \log\left(\frac{\mathrm{SFR}}{\mathrm{M}_\odot \mathrm{yr}^{-1}}\right) + 7.1 - 0.07z\,.$$

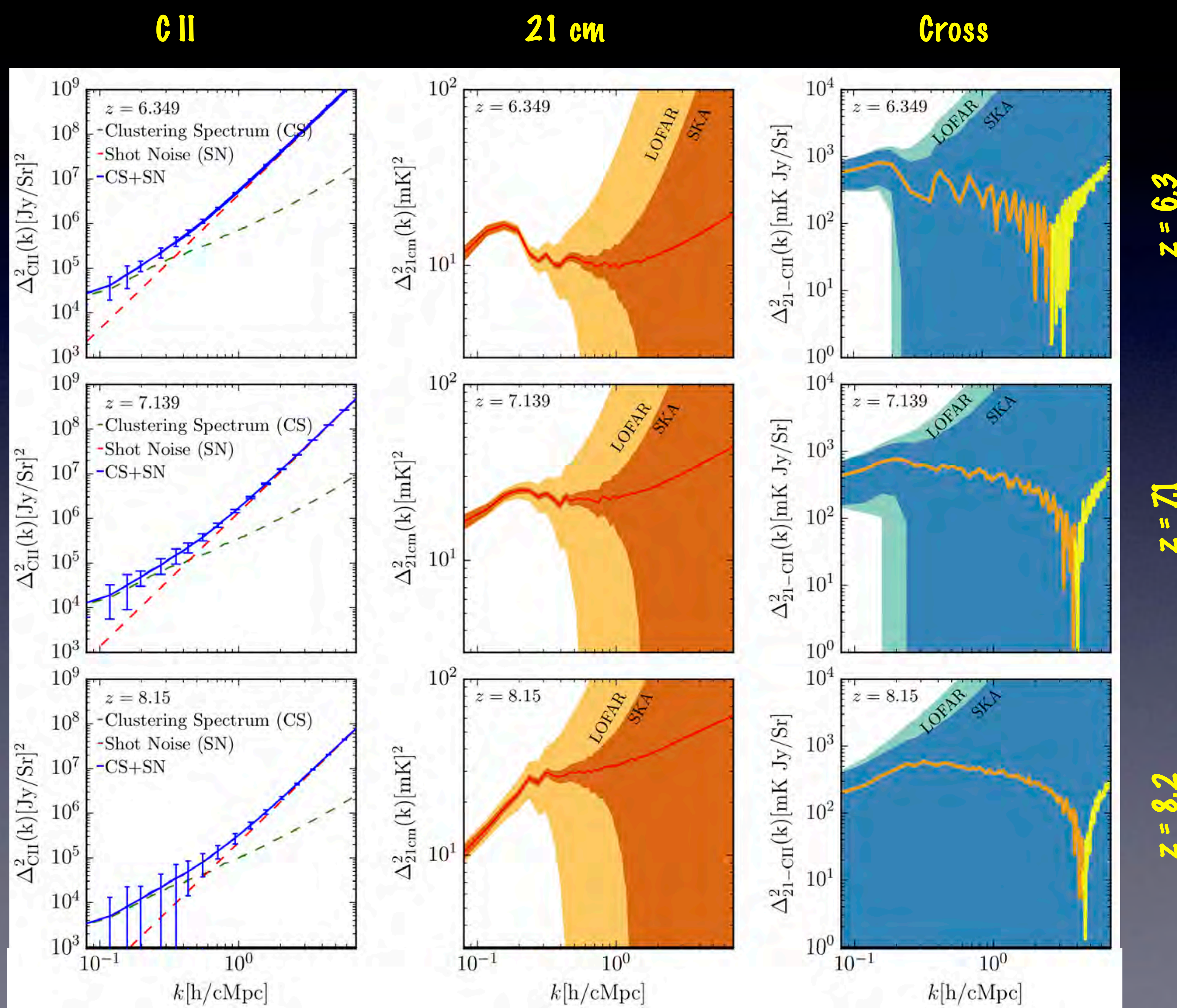
Epoch-of-reionization C II intensity mapping



Dumitru, Kulkarni et al. 2018

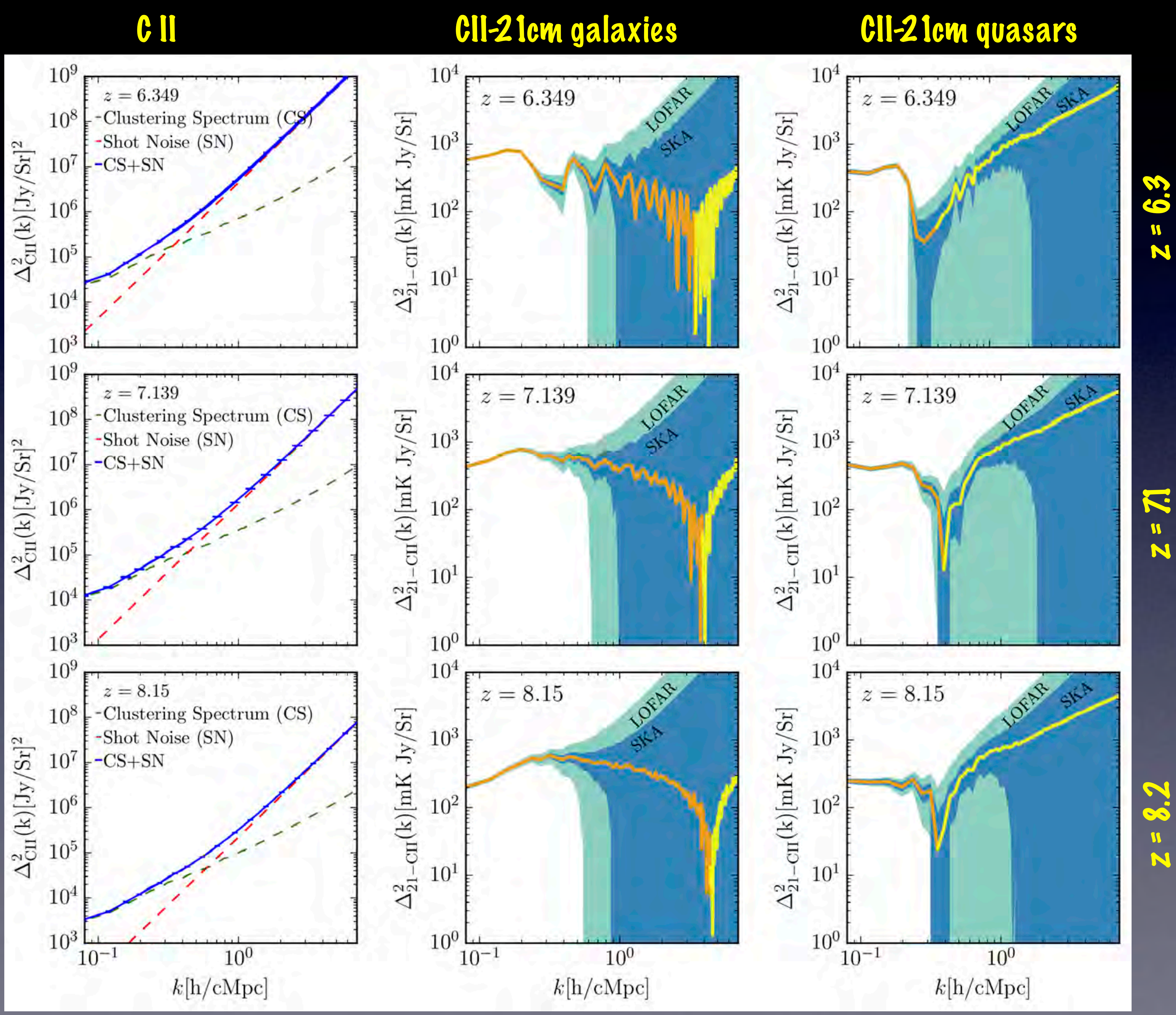
- Model C II using PDR model of Lagache et al. 2017—consistent with C II measurements at z > 4.
- Consider 1500 hr on CONCERTO (Serra et al. 2016) 2 deg^2 map, z = 6–9, 0.4 arcmin resolution.

C II power spectra measurable up to z ~ 8



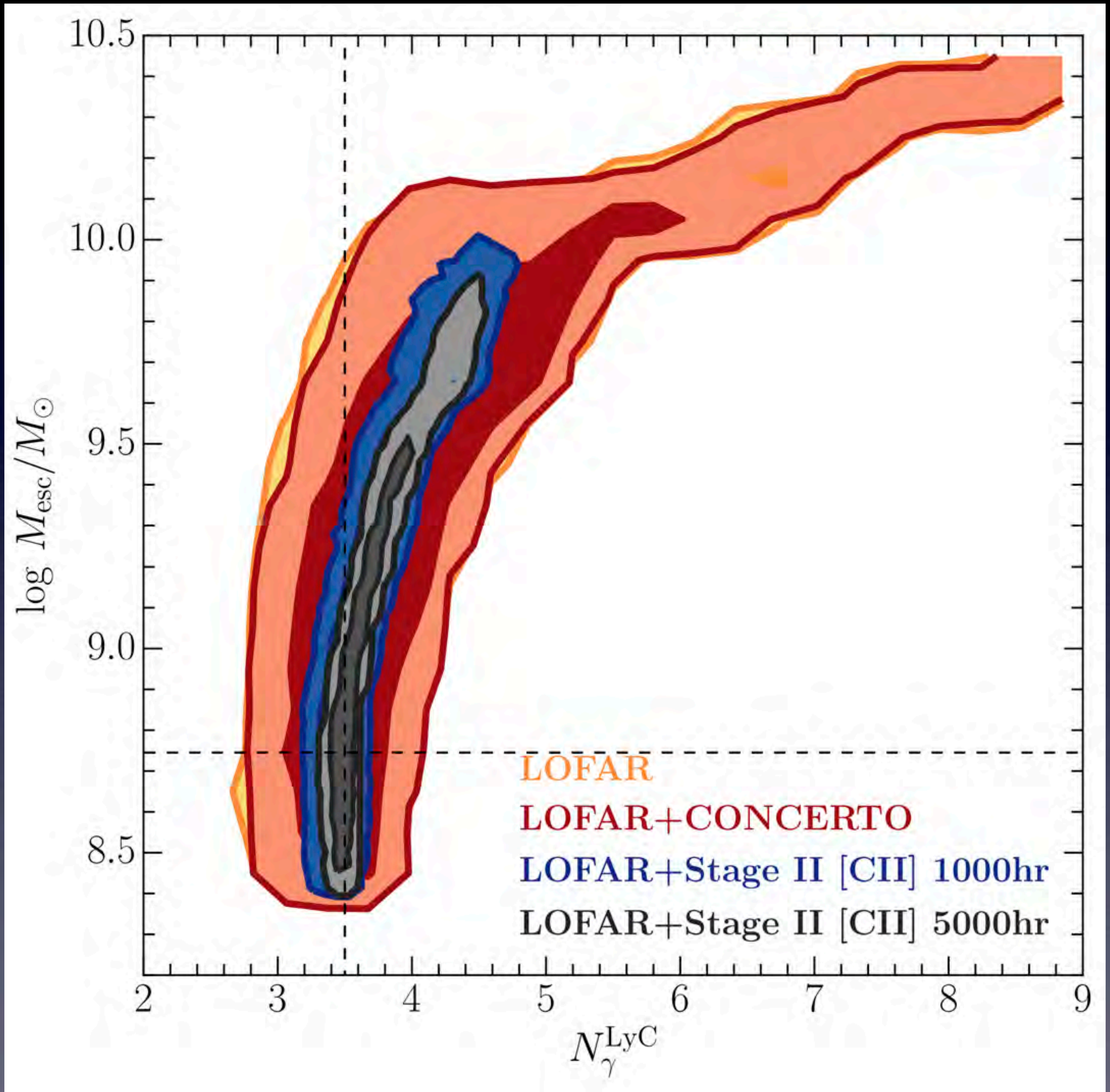
Dumitru, Kulkarni et al. 2018

Improvement with a Stage II experiment



Dumitru, Kulkarni et al. 2018

Constrain sources of reionization



Minimum mass of ionizing sources

Brightness of ionizing sources

Dumitru, Kulkarni et al. 2018

Cross-correlating C II with 21 cm can help measure astrophysical parameters

Still higher redshifts: REACH

- Radio Experiment for the Analysis of Cosmic Hydrogen
- PI: Eloy de Lera Acedo (Cambridge)
- Somewhere between 50–200 MHz
- Location: Karoo, South Africa
- First season of observations begins 2020

Conclusion

- **Reionization is late** (ends at $z \sim 5.2$) and can be caused by radiation from star-forming galaxies
- Consistent with various other constraints, including 2018 τ measurement from Planck
- Future lies in pushing the redshift frontier