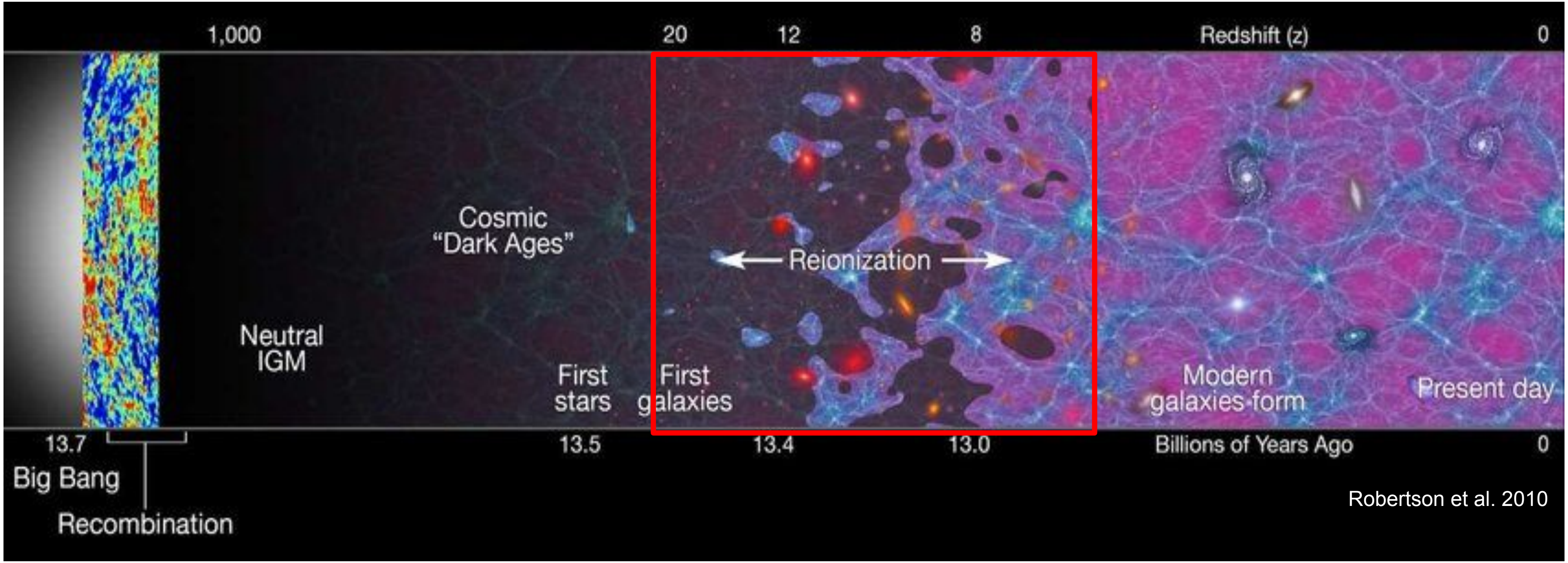
Constraining the mean free path of ionizing photons (λ_{mfp}) at z > 5 from the Lyman-α forest flux auto-correlation function

2208.09013

Molly Wolfson (UCSB)

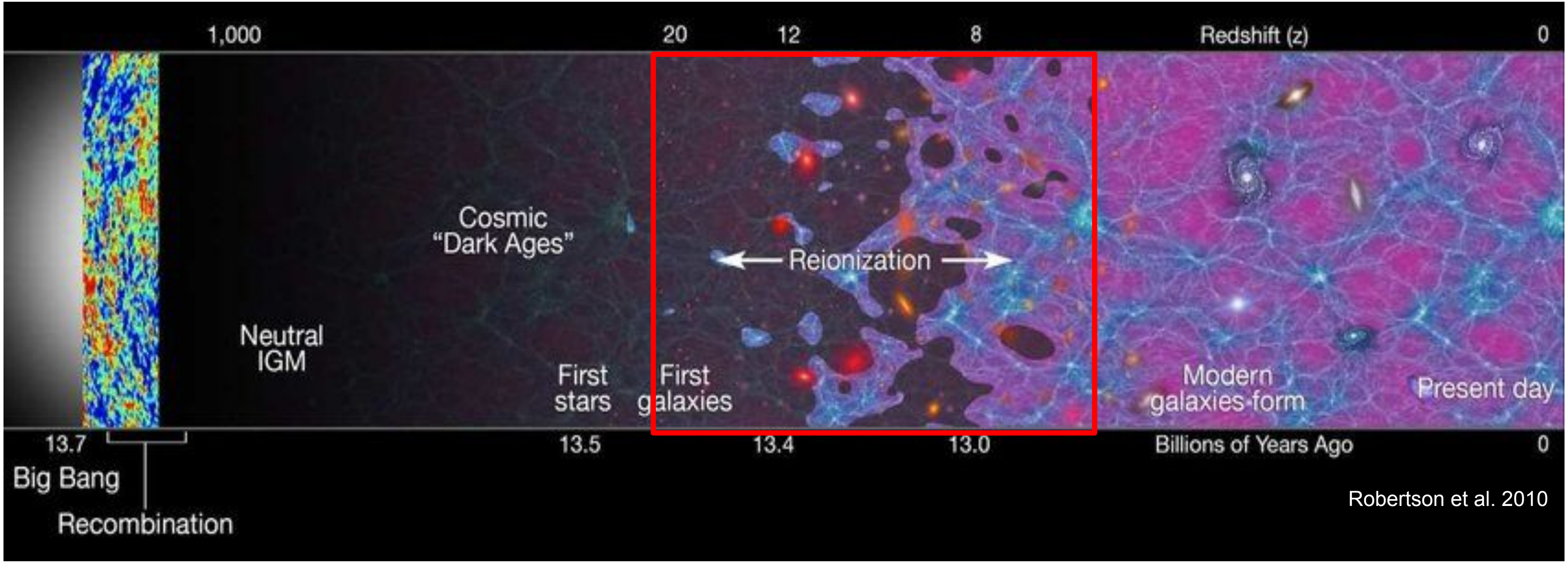
What is reionization?



Planck gives the midpoint: $z_{re} \sim 7.7$

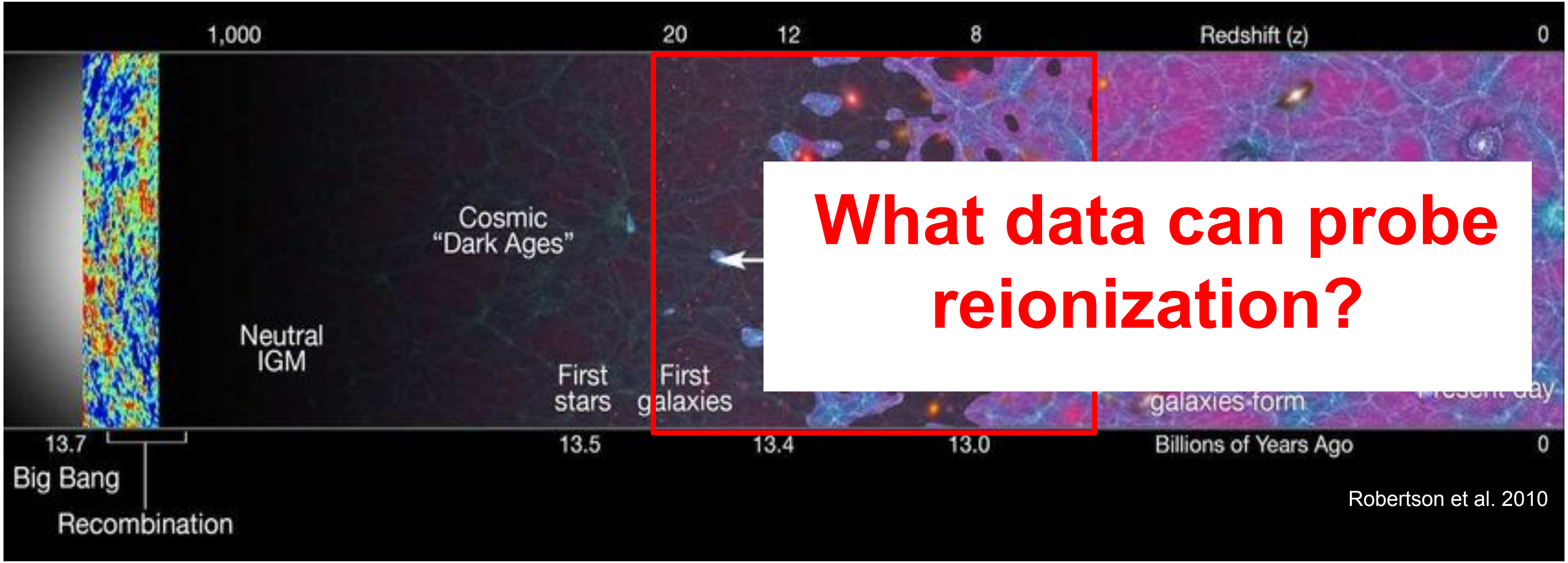
Recent measurements suggest that it is not complete until $z < 6$

What is reionization?



A lot still unknown (driving sources, number of photons required, impact on thermal state of IGM, and more)

What is reionization?



A lot still unknown (driving sources, number of photons required, impact on thermal state of IGM, and more)

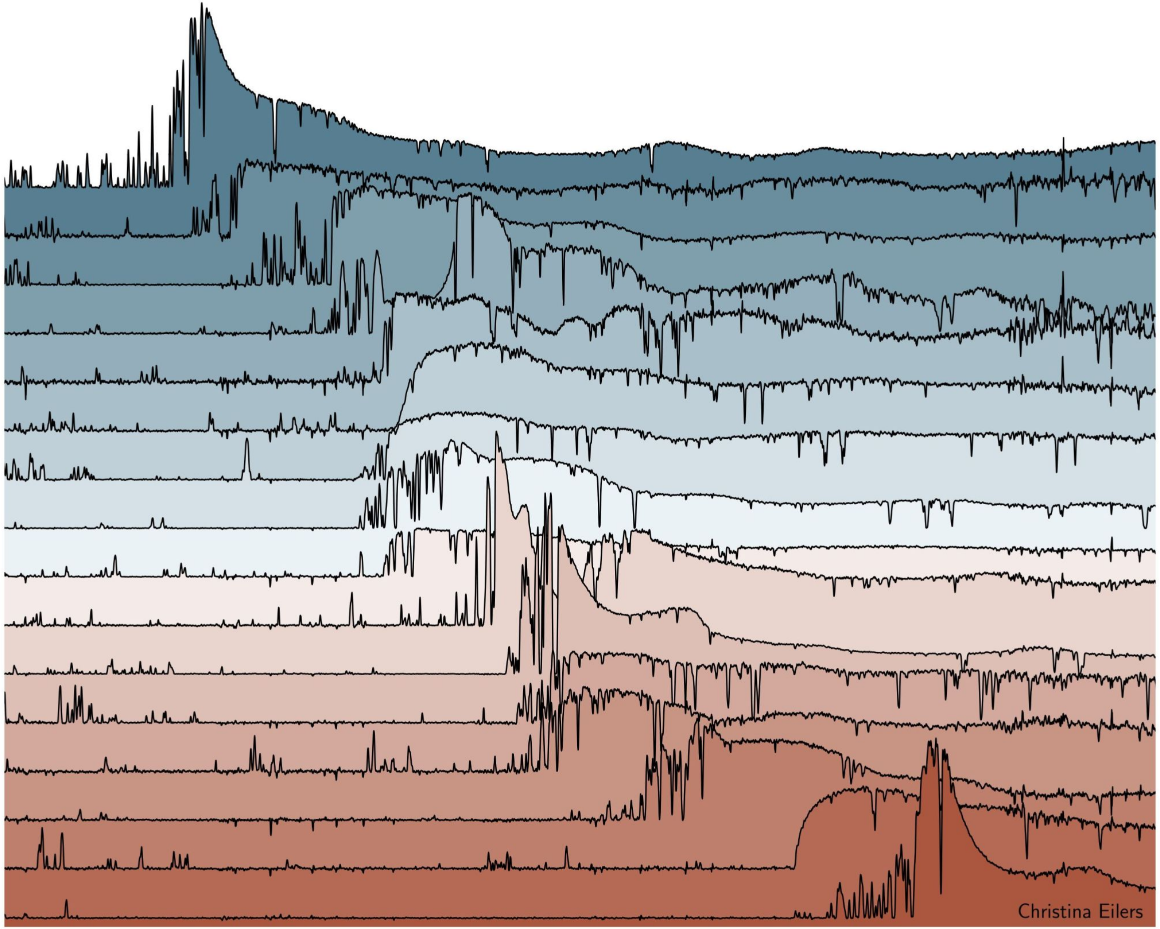
High redshift quasars

NASA, ESA and J. Olmsted (STScI)

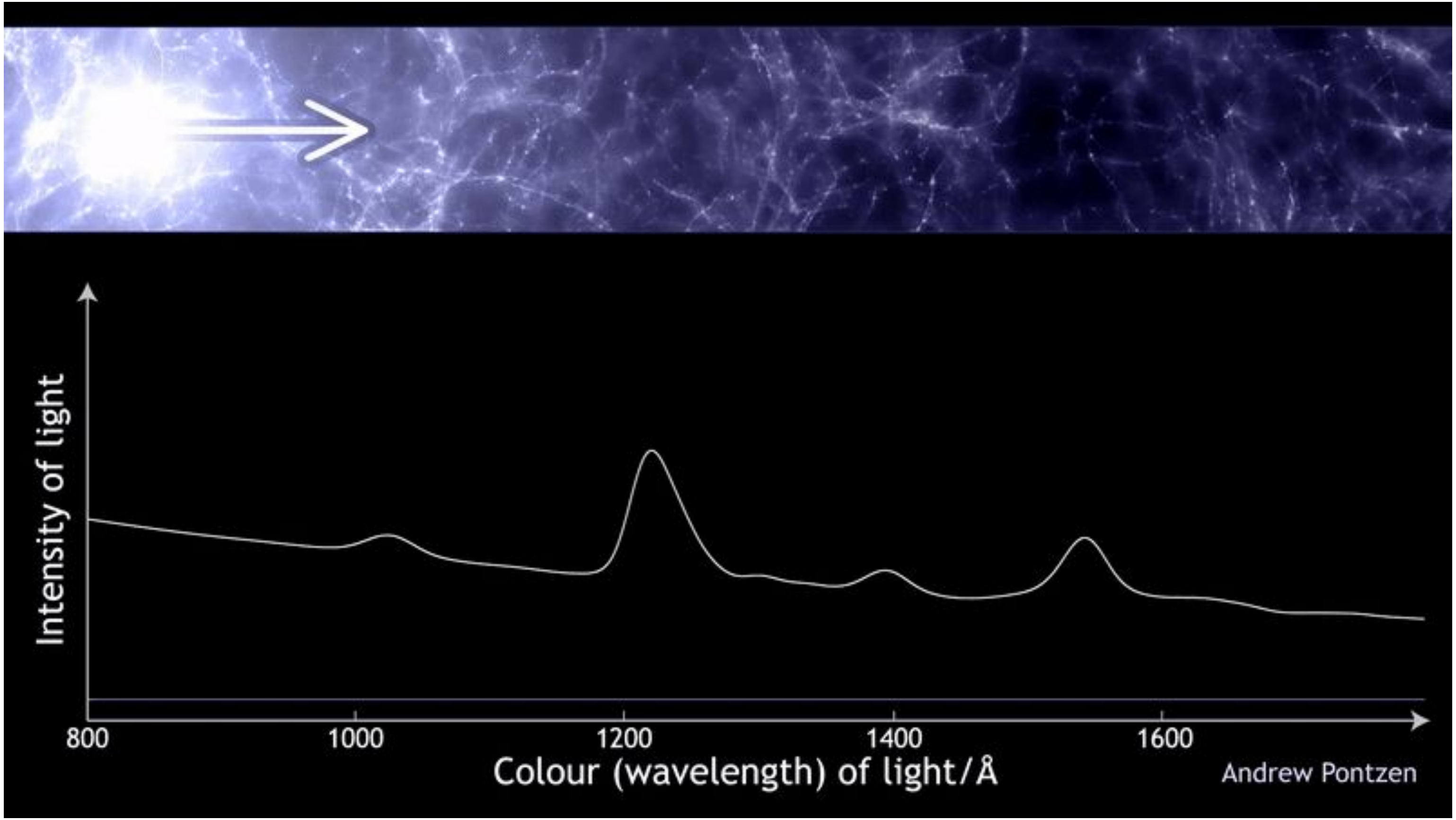
XQR-30 Collaboration

XQR-30 data (xqr30.inaf.it):

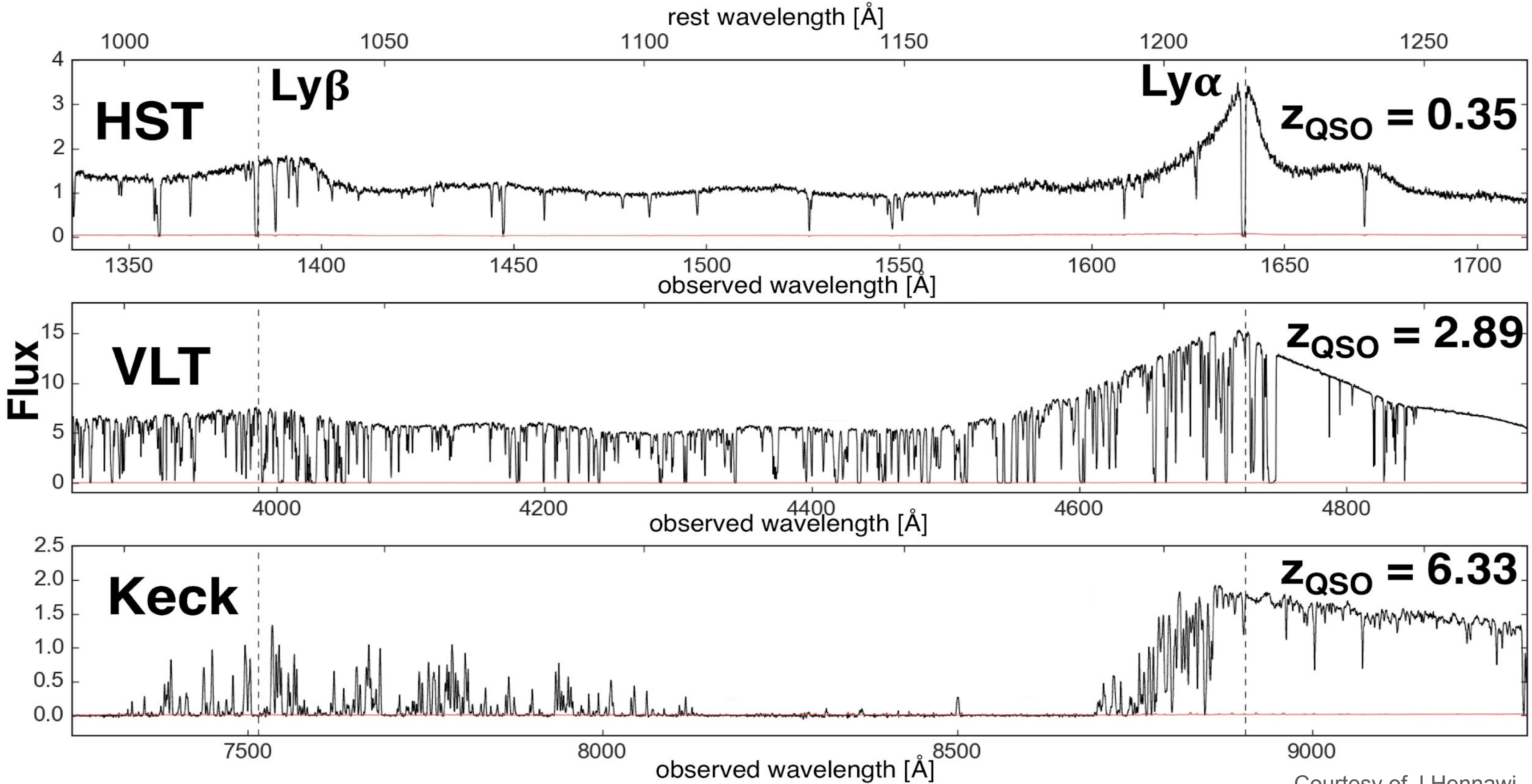
- Uses VLT/X-Shooter (R ~ 8800 in the visible)
- 30 new observations of some of the brightest z > 5.8 quasars observed
- Supplemented with 12 archival observations



Probing the IGM with the Lyman-α forest



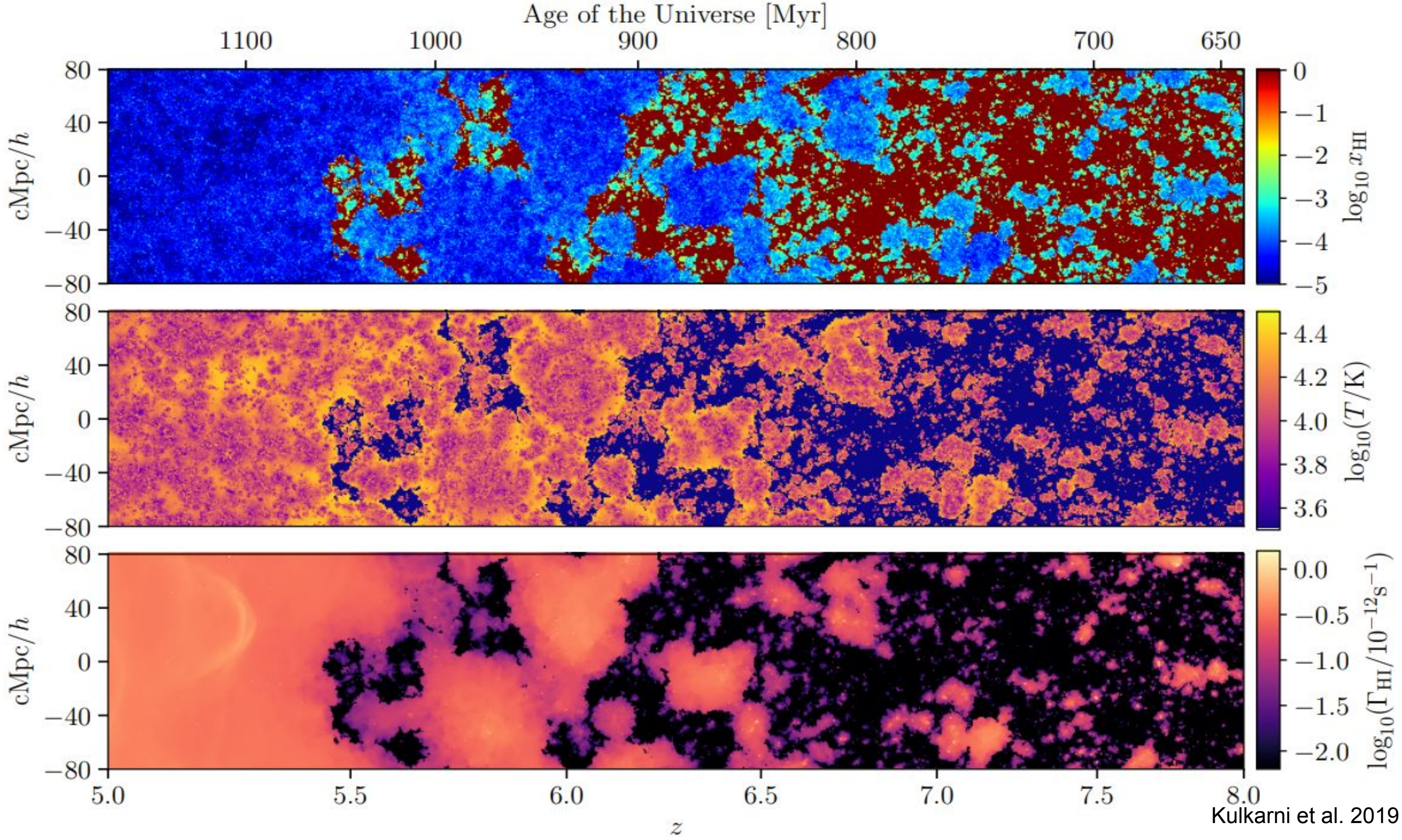
Probing the IGM with the Lyman-α forest



Courtesy of J.Hennawi

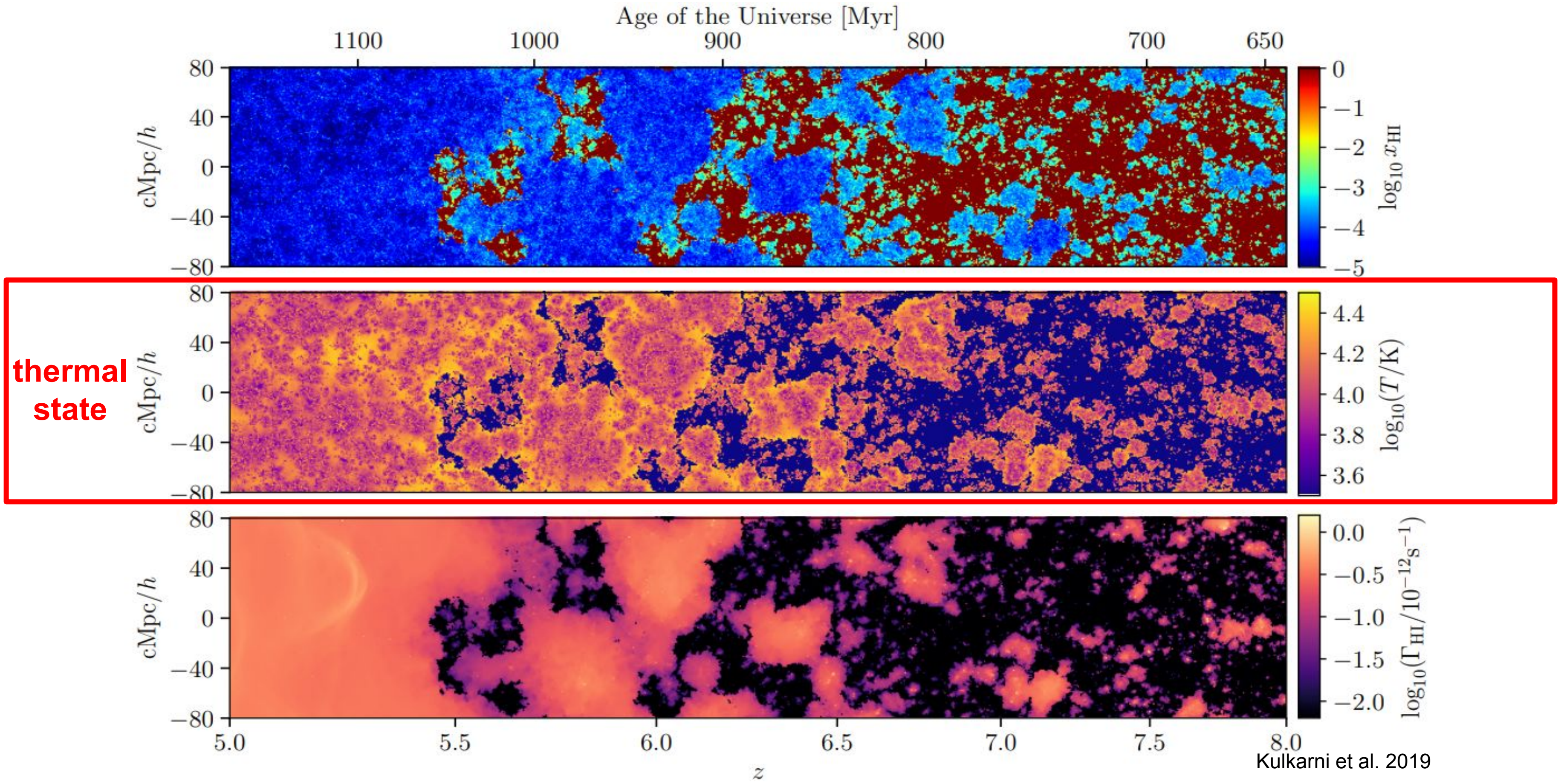
Saturates for $\langle x_{\rm HI}(z) \rangle \gtrsim 10^{-4}$

Some signatures of reionization in the IGM



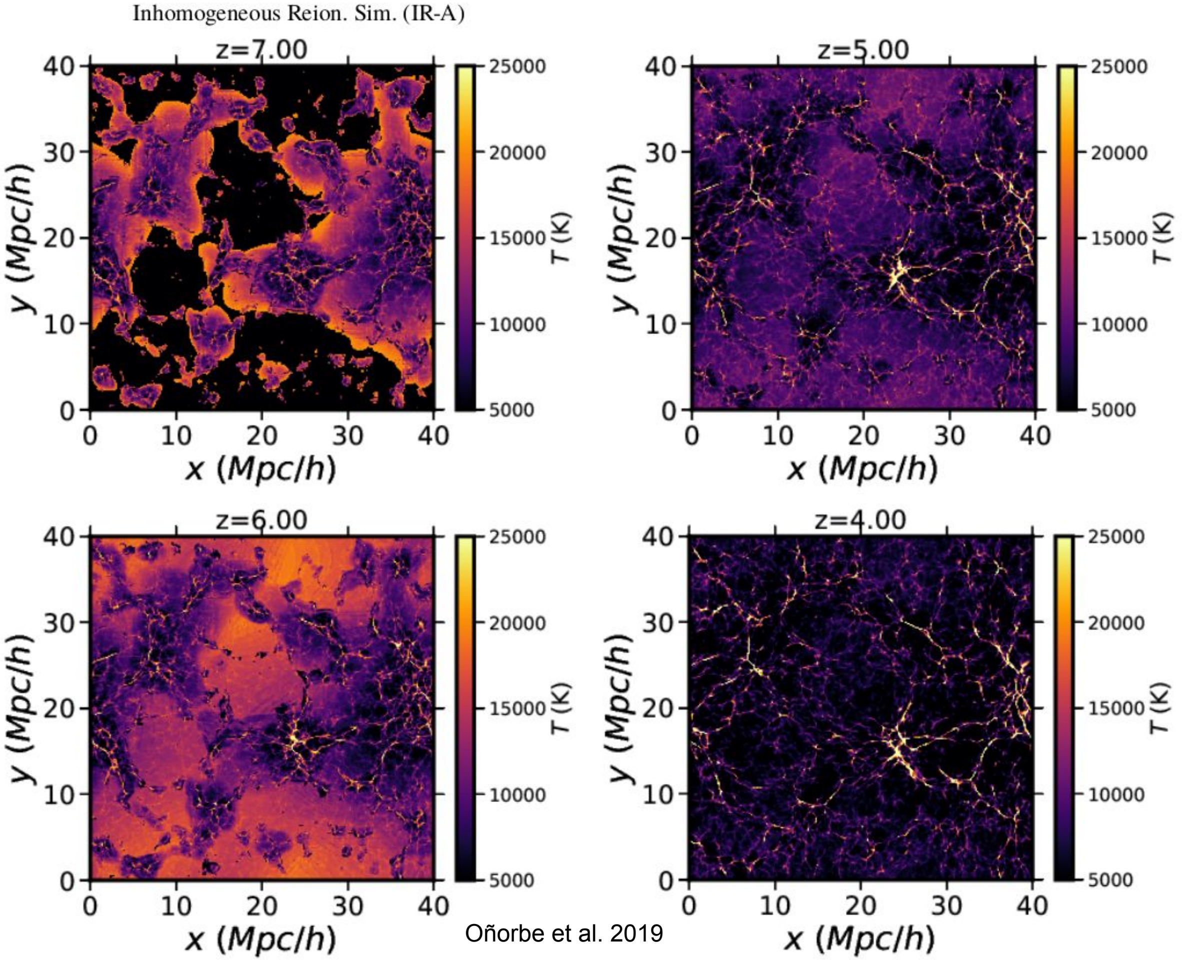
Kulkarni et al. 2019

Some signatures of reionization in the IGM



Kulkarni et al. 2019

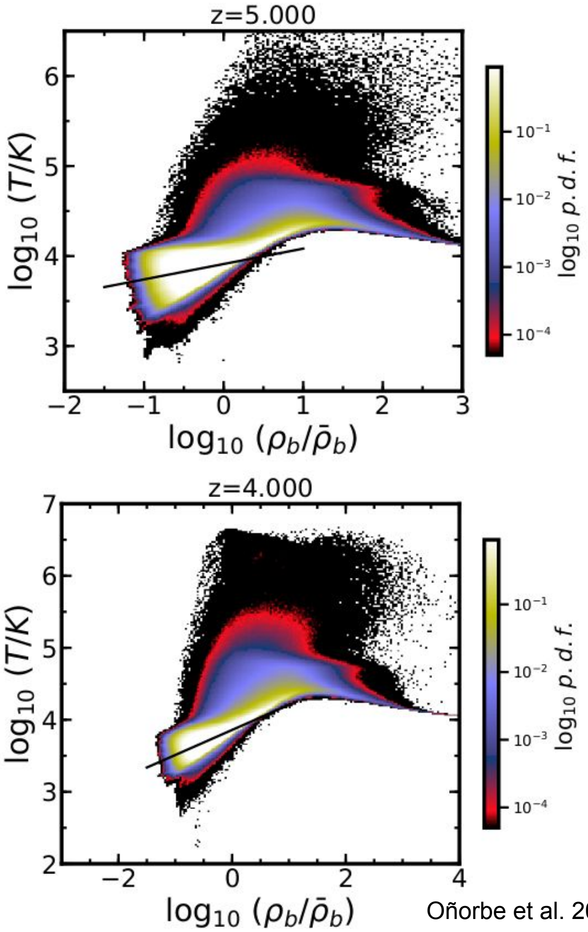
Thermal state evolution in simulations



z_{mid} = 7.75
z_{end} = 6.05

Oñorbe et al. 2019

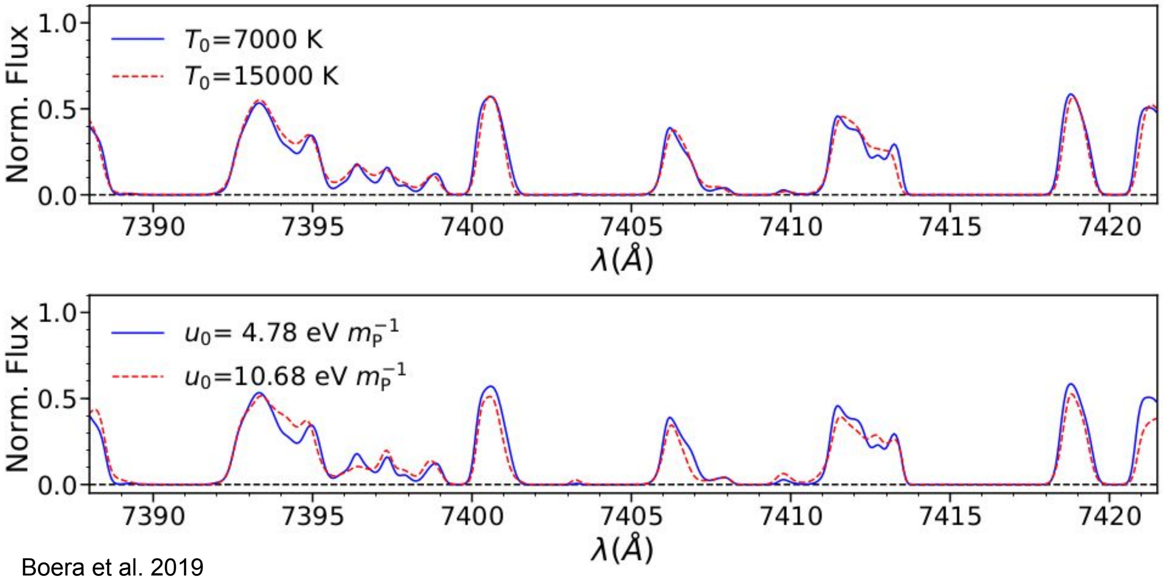
Parameters for the thermal state



Oñorbe et al. 2019

$$T = T_0(\rho/\bar{\rho})^{\gamma-1}$$

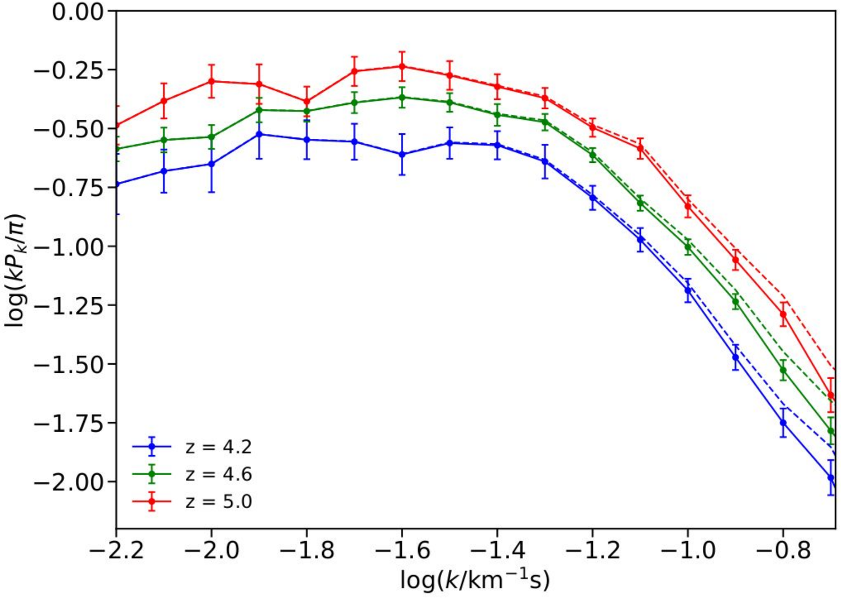
Also pressure smoothing (here u_0)

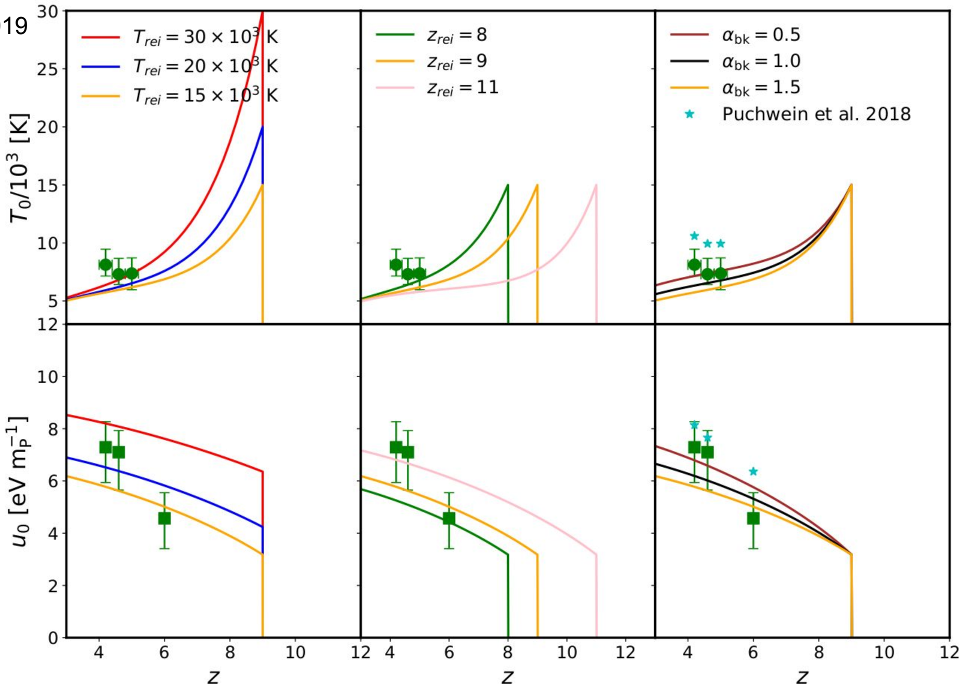


Boera et al. 2019

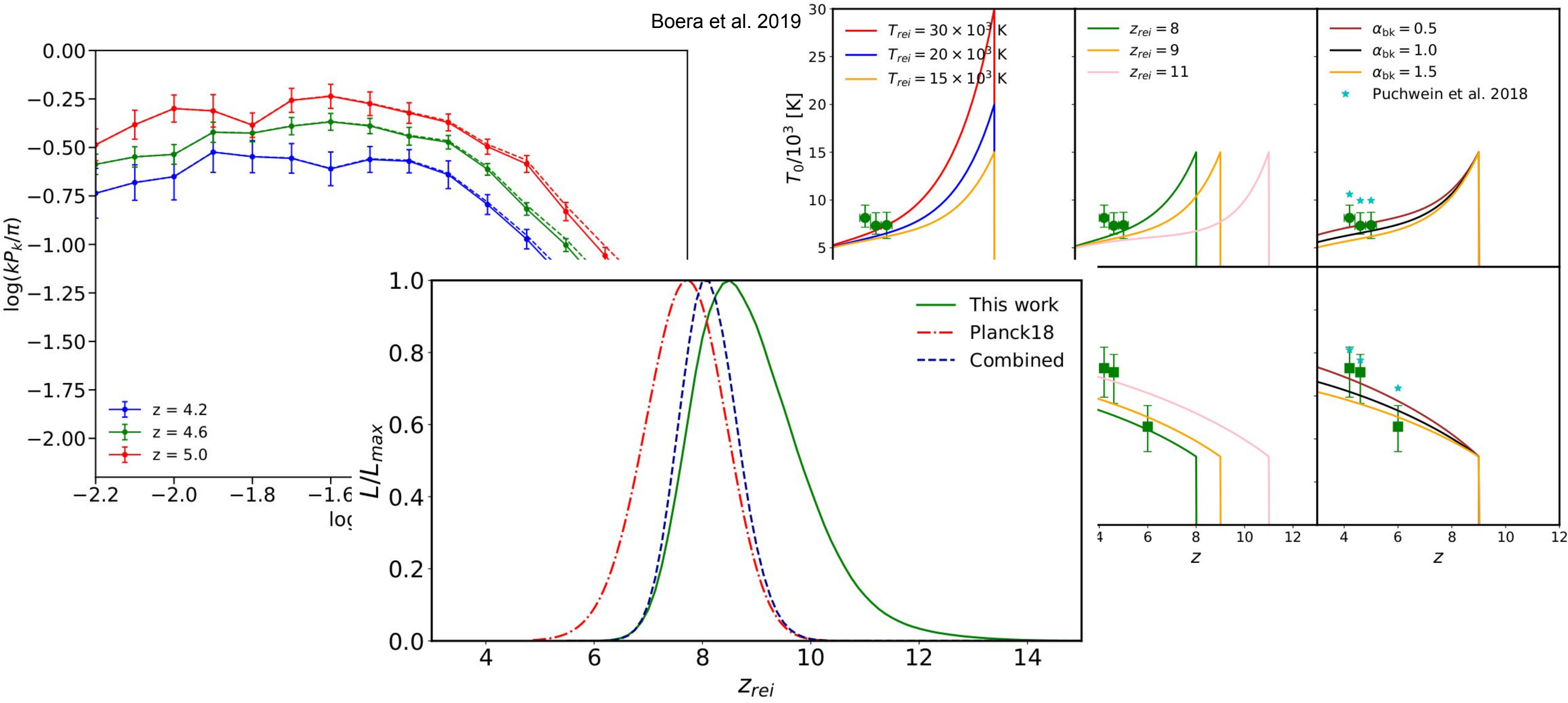
Existing measurements of the thermal state

Boera et al. 2019

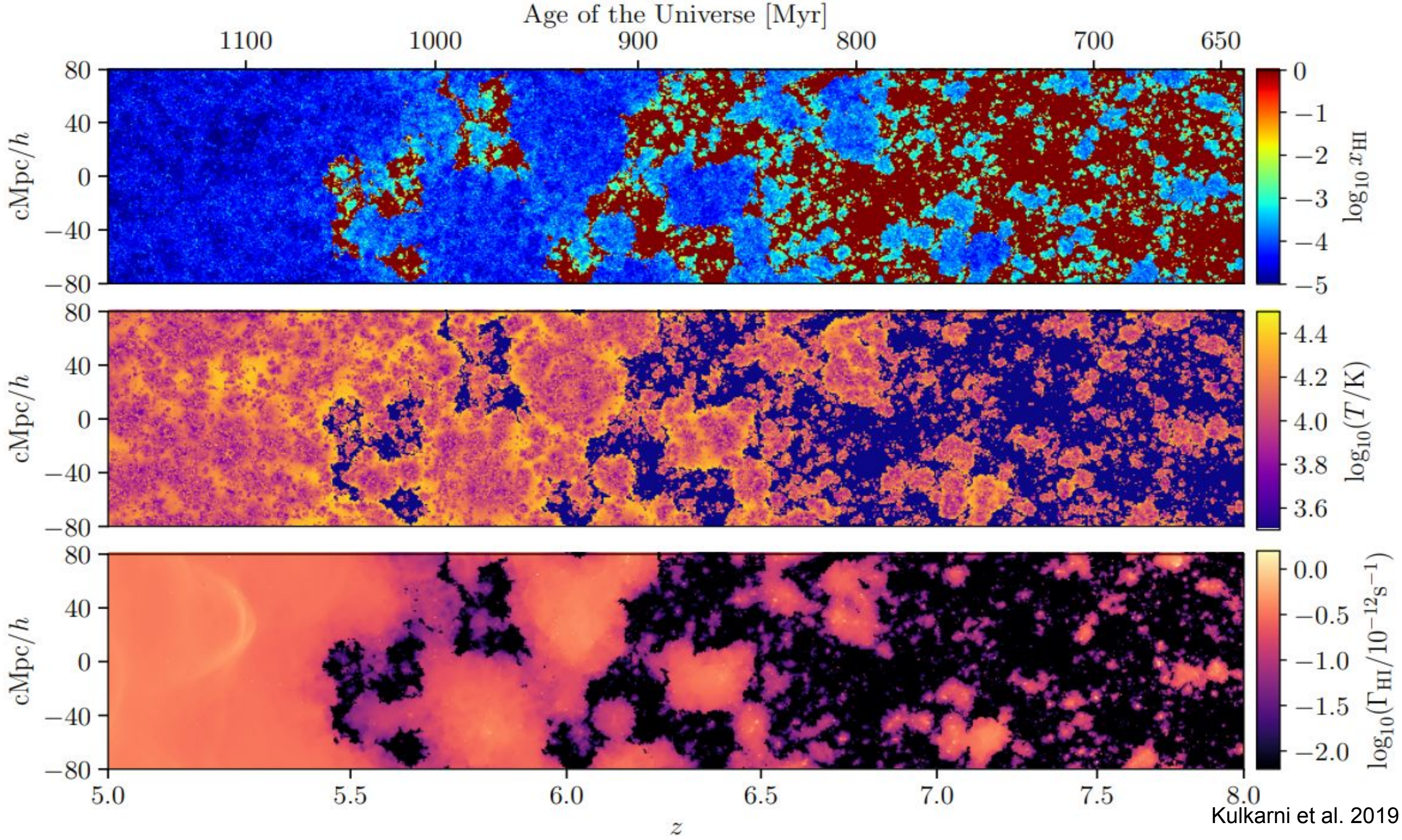




Existing measurements of the thermal state

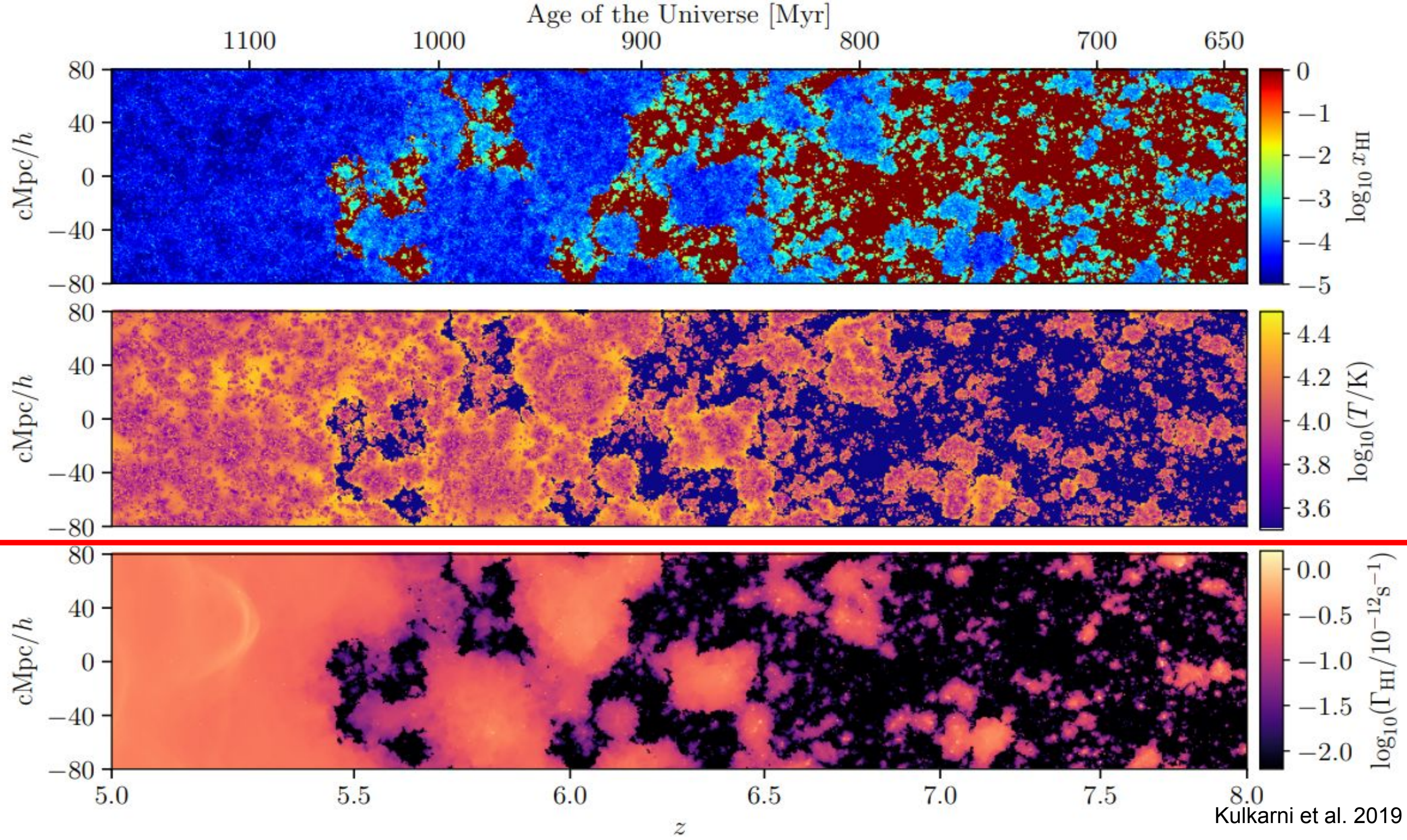


Some signatures of reionization in the IGM



Kulkarni et al. 2019

Some signatures of reionization in the IGM

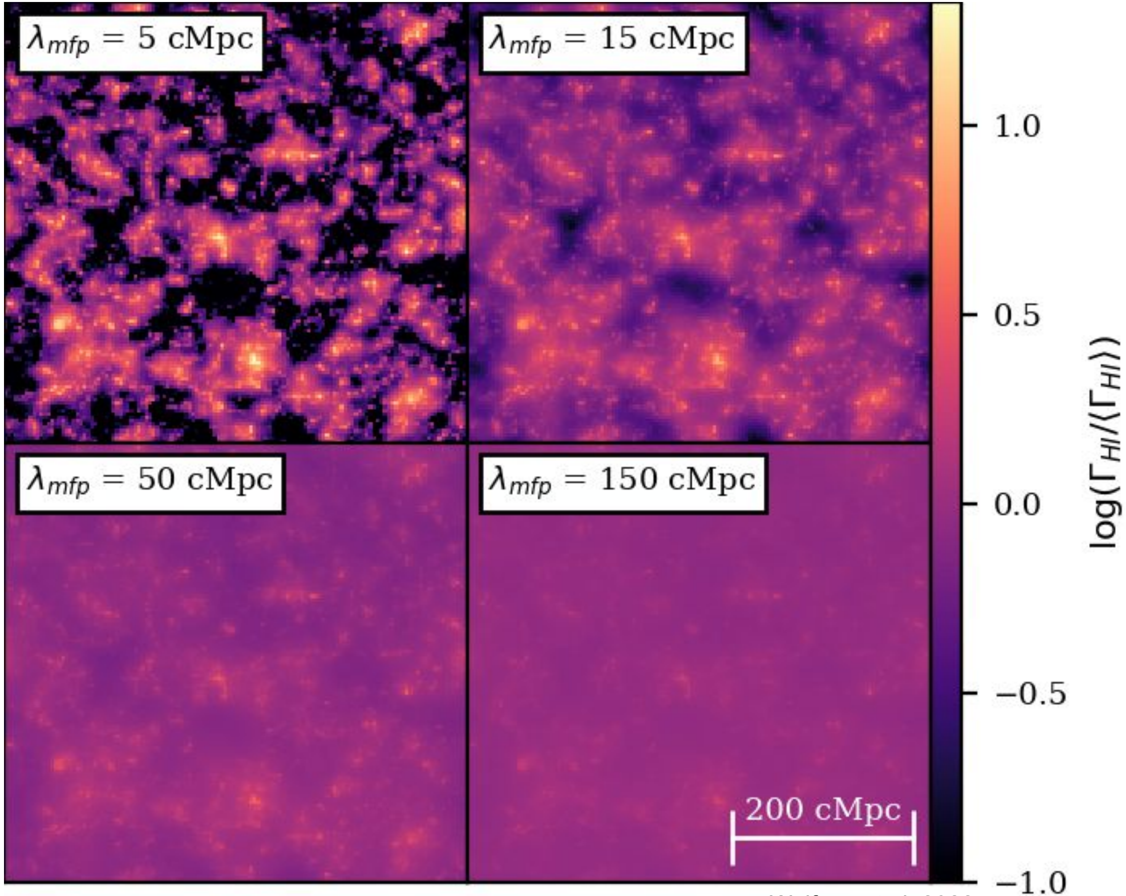


UVB

Kulkarni et al. 2019

Fluctuations in the UVB can be described by λ_{mfp}

λ_{mfp} - the average distance ionizing photons travel before interacting with neutral hydrogen

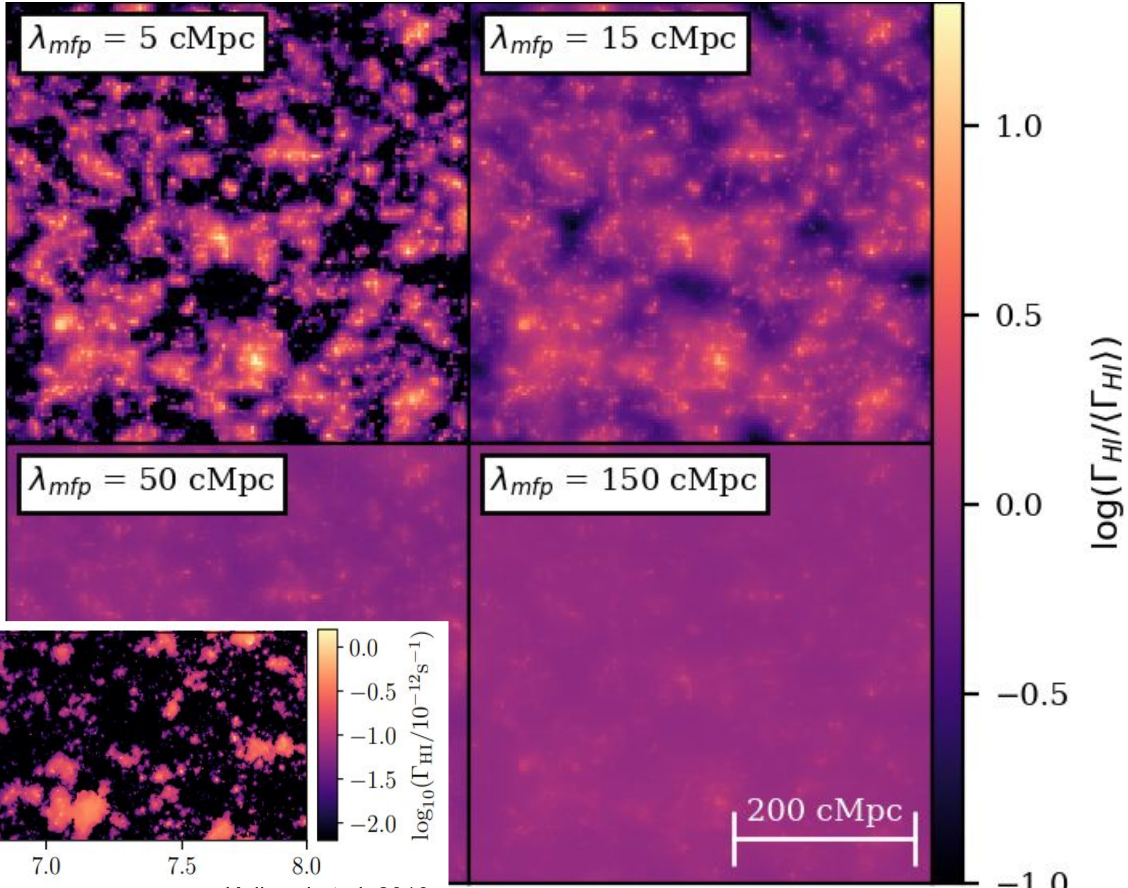


Wolfson et al. 2022

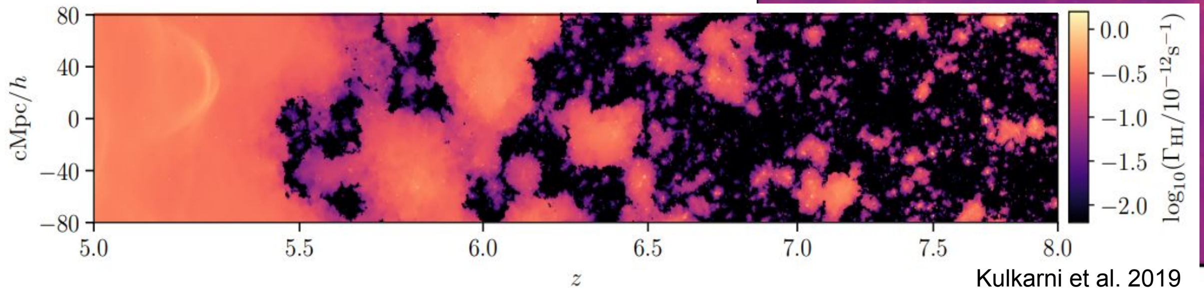
Fluctuations in the UVB can be described by λ_{mfp}

λ_{mfp} - the average distance ionizing photons travel before interacting with neutral hydrogen

Rapid increase signals the end of reionization



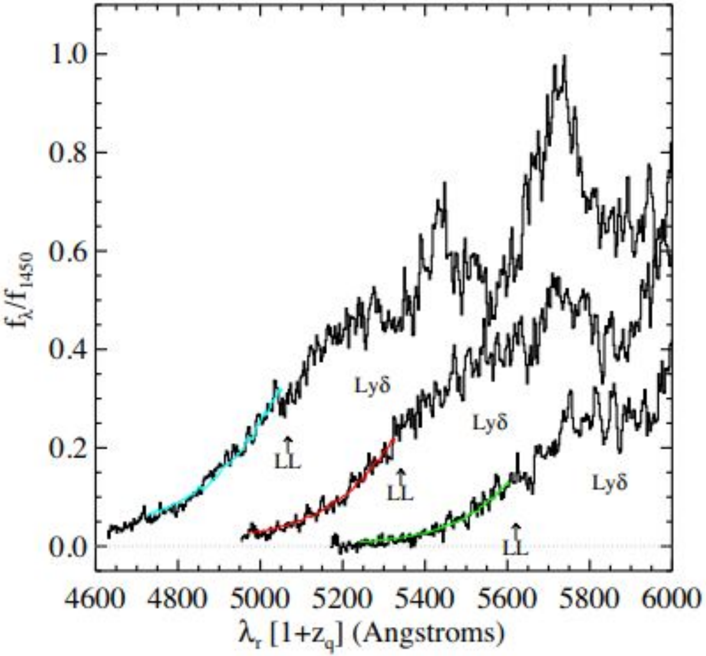
Wolfson et al. 2022



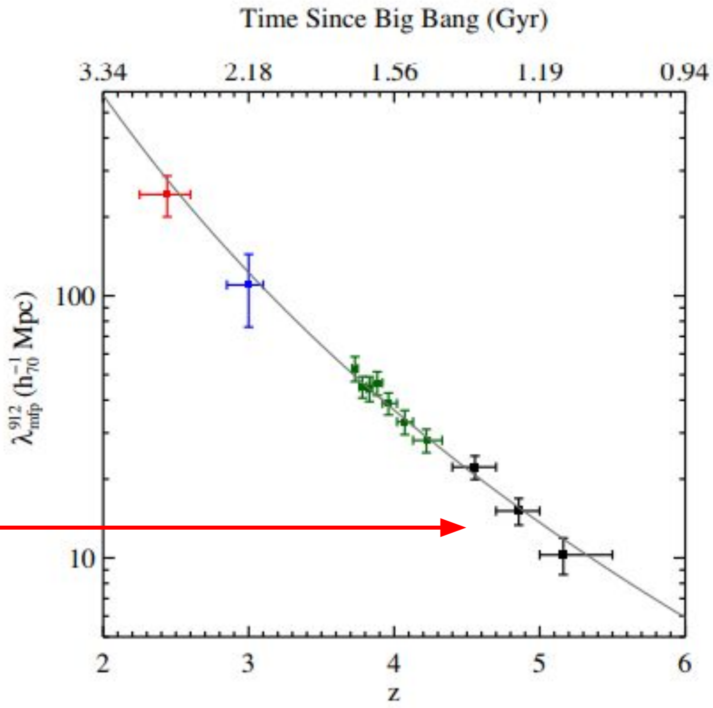
Kulkarni et al. 2019

Existing measurements of λ_{mfp}

Most constraining method has been from flux beyond the Lyman limit in stacked quasar spectra



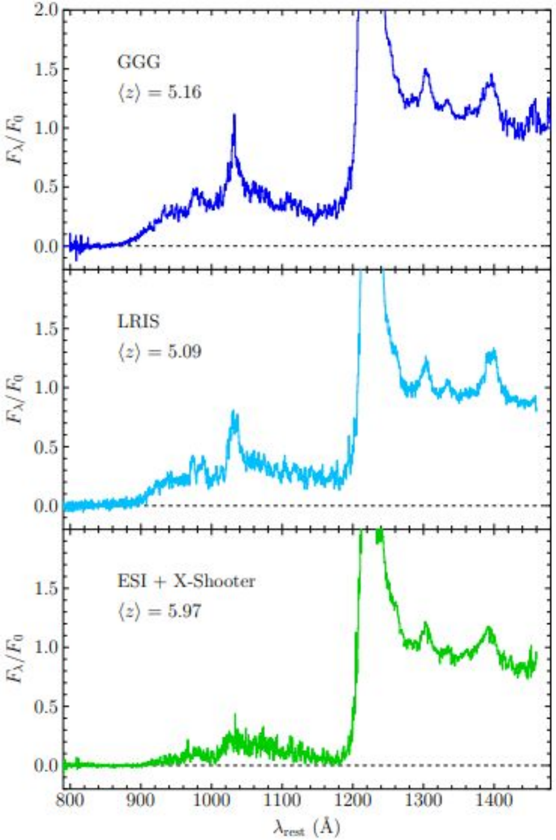
Worseck et al. 2014



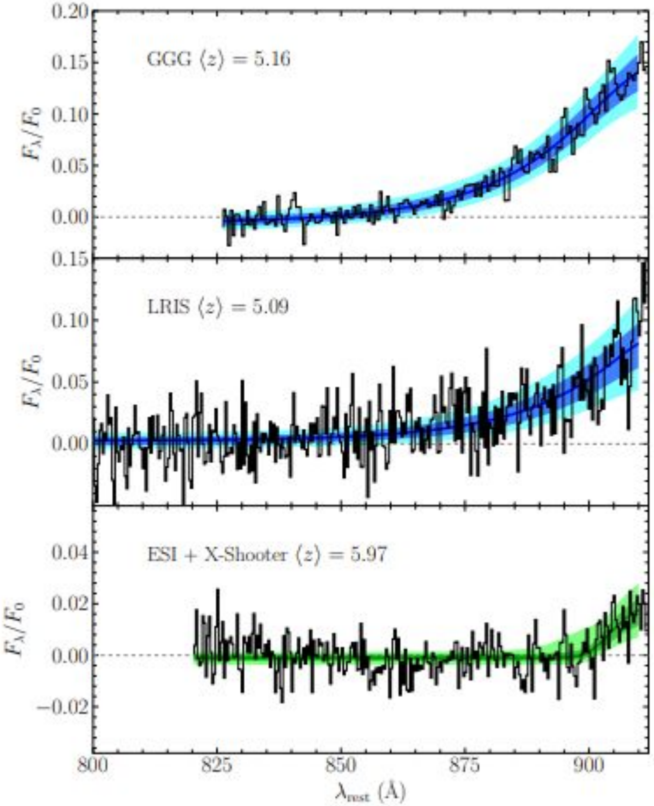
Worseck et al. 2014

Existing measurements of λ_{mfp}

Most constraining method has been from flux beyond the Lyman limit in stacked quasar spectra



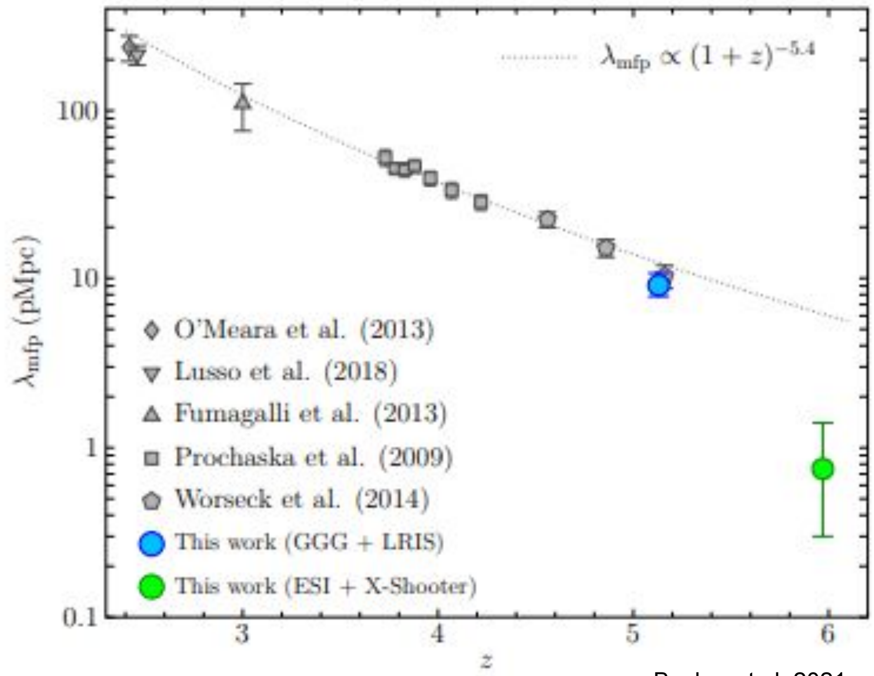
Becker et al. 2021



Becker et al. 2021

Existing measurements of λ_{mfp}

Most constraining method has been from flux beyond the Lyman limit in stacked quasar spectra



Becker et al. 2021

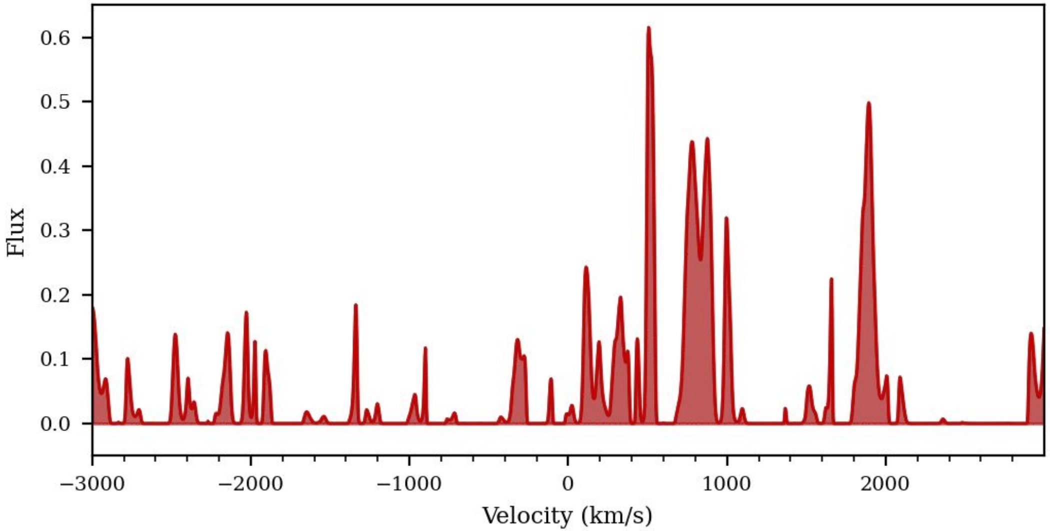
Auto-correlation function

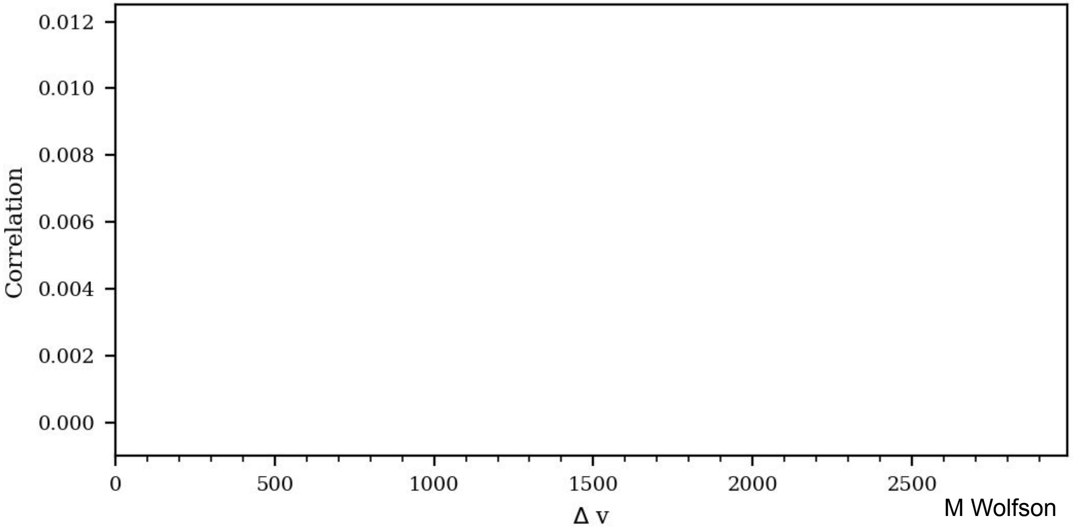
$$\xi_F(\Delta v) = \langle F(v) F(v + \Delta v) \rangle$$

The fourier transform of the power spectrum

Uncorrelated gaussian noise averages out

Easy to mask out DLAs etc





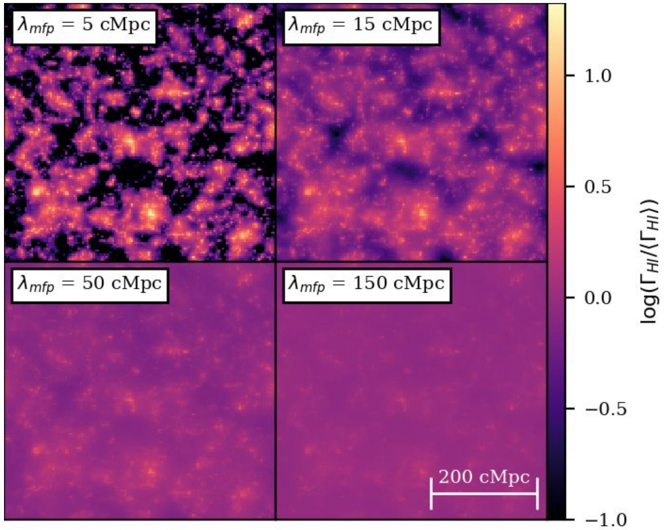
M Wolfson

Is the auto-correlation function of the Lyman-α forest sensitive to λ_{mfp}?

Simulation box properties

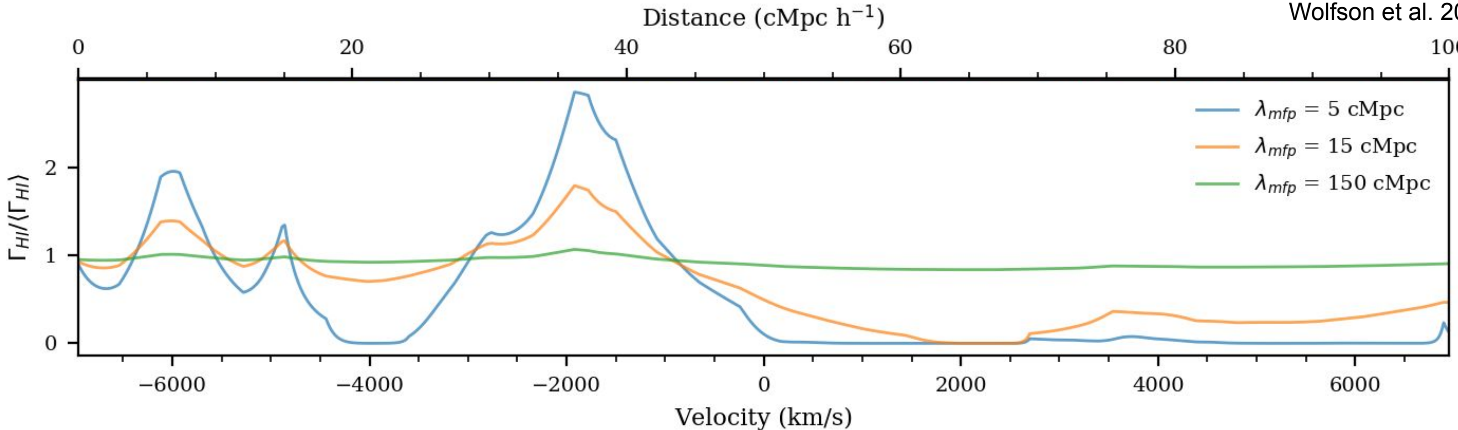
UVB boxes with L_{box} = 512 cMpc

- Method of Davies & Furlanetto 2016
- 128^3 pixels



Wolfson et al. 2022

Wolfson et al. 2022



Simulation box properties

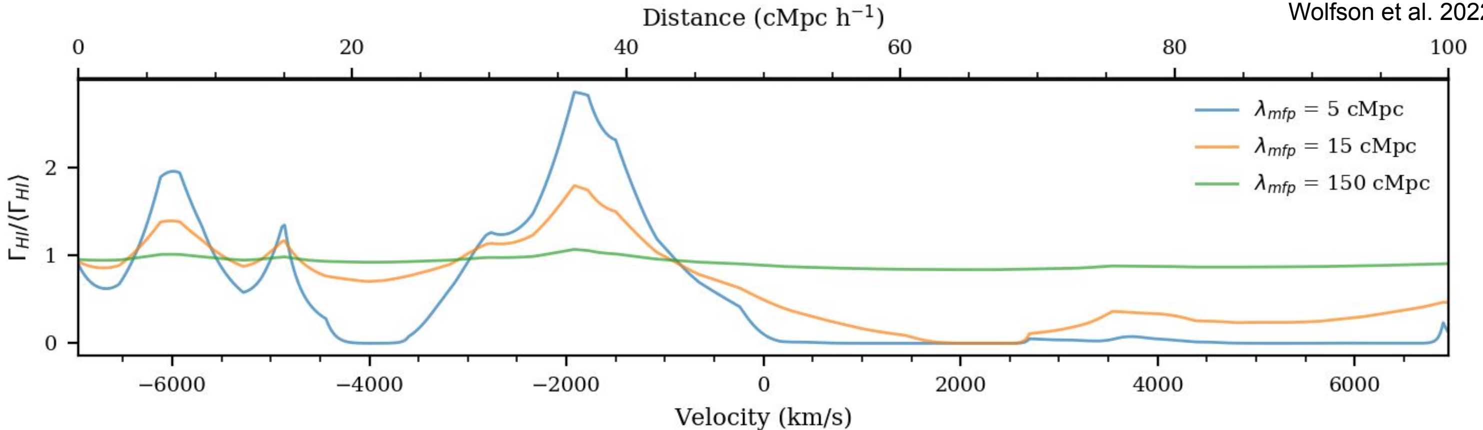
UVB boxes with L_{box} = 512 cMpc

- Method of Davies & Furlanetto 2016
- 128^3 pixels

Nyx box with L_{box} = 100 cMpc h^{-1}

- Hydrodynamical code designed for the Lyα forest
- 4096^3 dark matter particles, 4096^3 baryon grid cells

Wolfson et al. 2022



Simulation box properties

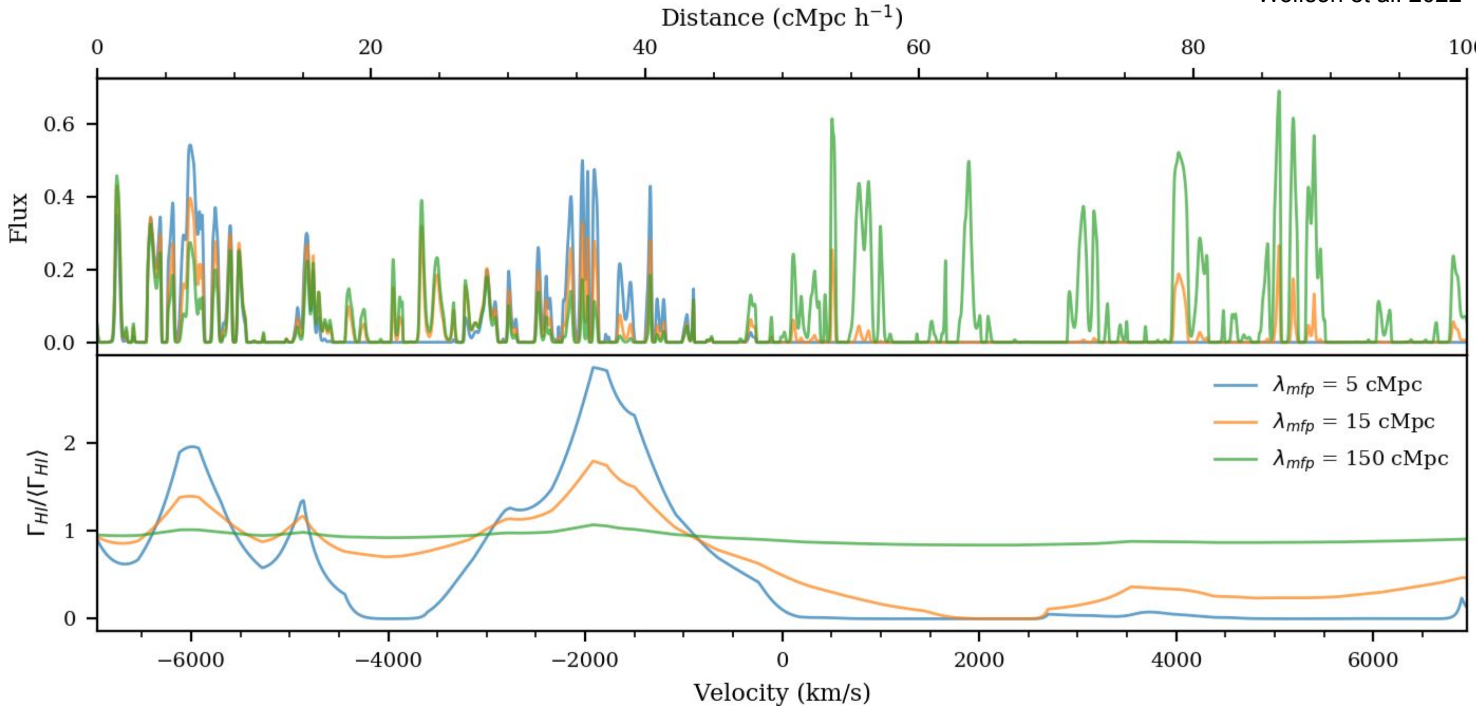
UVB boxes with L_{box} = 512 cMpc

- Method of Davies & Furlanetto 2016
- 128^3 pixels

Nyx box with L_{box} = 100 cMpc h^{-1}

- Hydrodynamical code designed for the Lyα forest
- 4096^3 dark matter particles, 4096^3 baryon grid cells

Wolfson et al. 2022



Simulation box properties

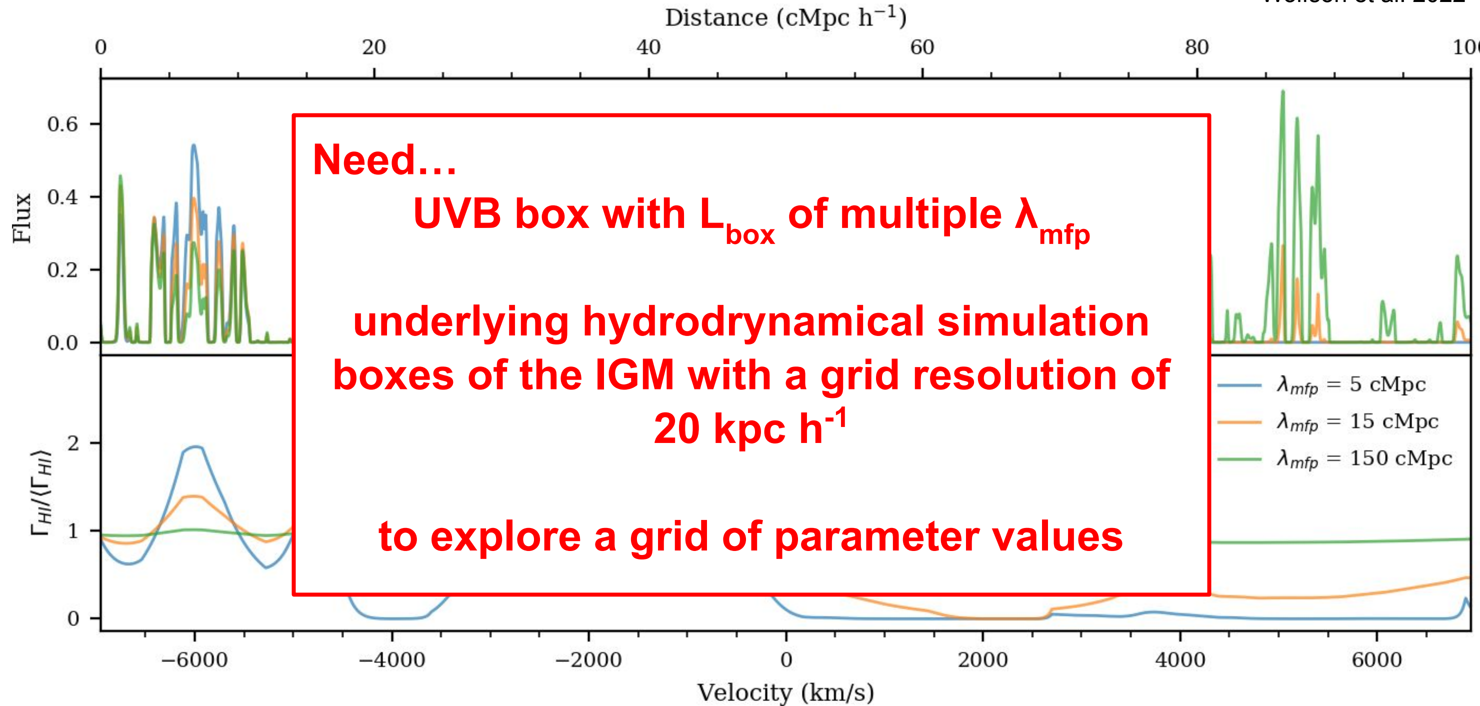
UVB boxes with L_{box} = 512 cMpc

- Method of Davies & Furlanetto 2016
- 128^3 pixels

Nyx box with L_{box} = 100 cMpc h^{-1}

- Hydrodynamical code designed for the Lyα forest
- 4096^3 dark matter particles, 4096^3 baryon grid cells

Wolfson et al. 2022



Need…

UVB box with L_{box} of multiple λ_{mfp}

underlying hydrodrynamical simulation boxes of the IGM with a grid resolution of 20 kpc h^{-1}

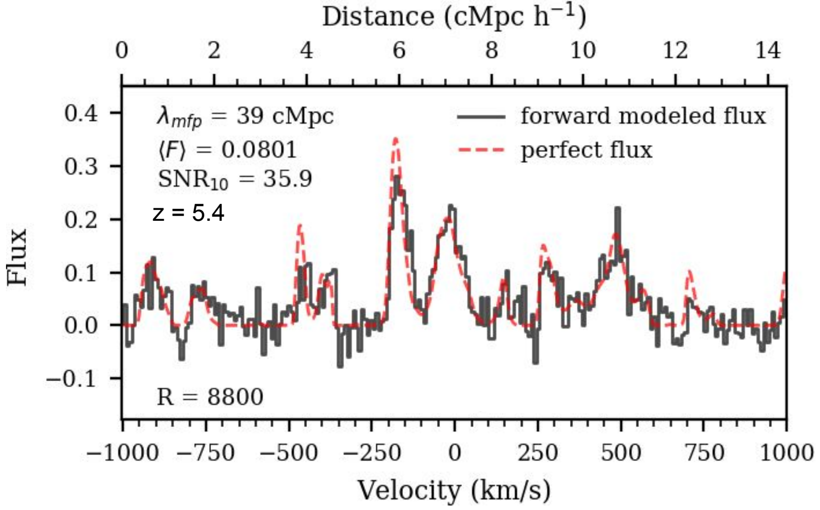
to explore a grid of parameter values

Forward modeling realistic data

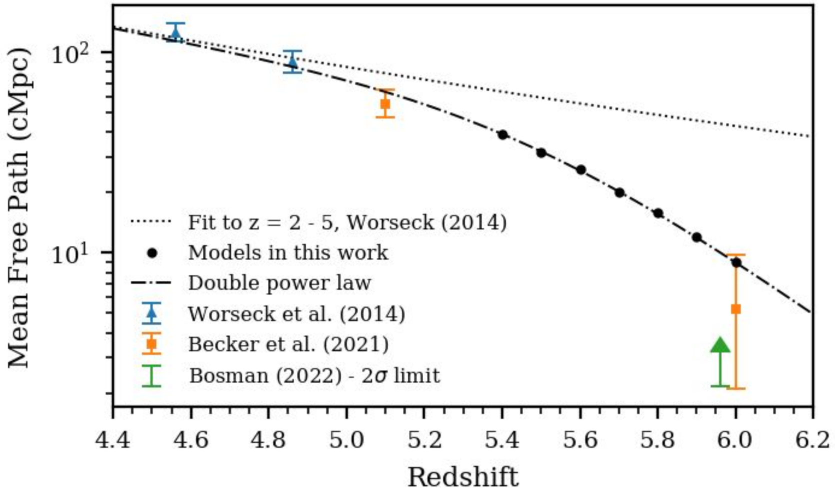
Forward modeling properties:

- Resolution of 8800
  - The resolution of X-Shooter
  - Convolve with a gaussian filter
- Gaussian noise with SNR_{10} = 35.9
  - Median of data in Bosman et al. 2021
- 12-60 quasars in each redshift bin

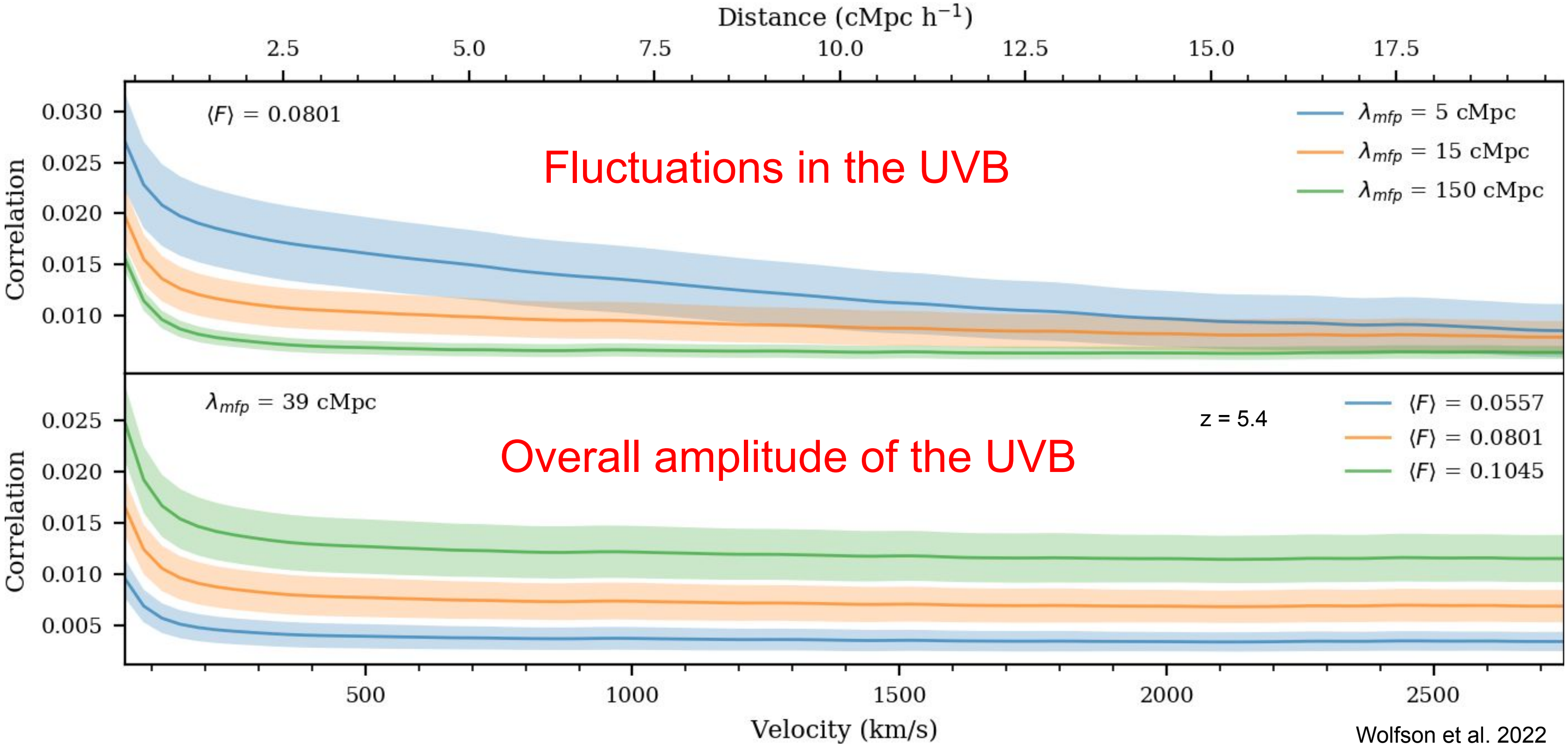
Double power law - fit by eye - of the evolution of λ_{mfp}



Wolfson et al. 2022



Effect of λ_{mfp} on the auto-correlation function

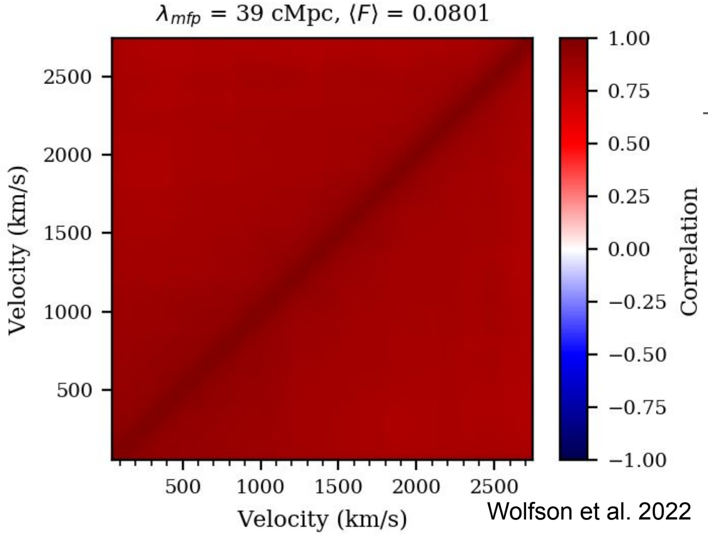


Differences between the models for different λ_{mfp} values are non-linear!

Measuring λ_{mfp} from mock data

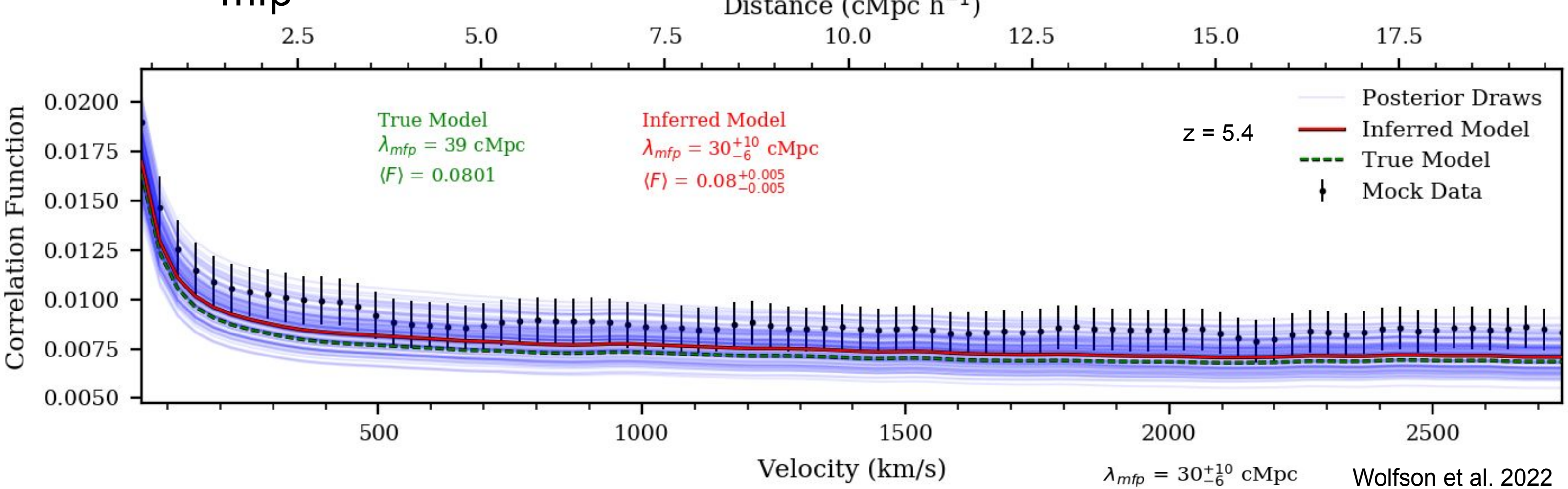
Gaussian likelihood:

$$\mathcal{L} = \frac{1}{\sqrt{\det(\Sigma)(2\pi)^n}} \exp\left(-\frac{1}{2}\left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\rm model}(\lambda_{\rm mfp}, \langle F\rangle)\right)^{\rm T} \Sigma^{-1} \left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\rm model}(\lambda_{\rm mfp}, \langle F\rangle)\right)\right)$$

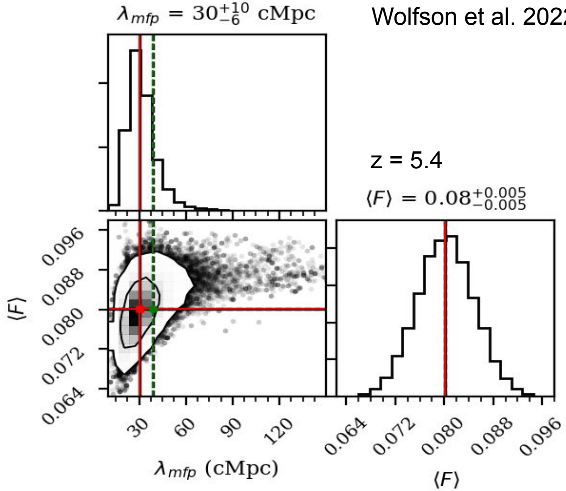


Wolfson et al. 2022

Measuring λ_{mfp} from mock data



MCMC



Wolfson et al. 2022

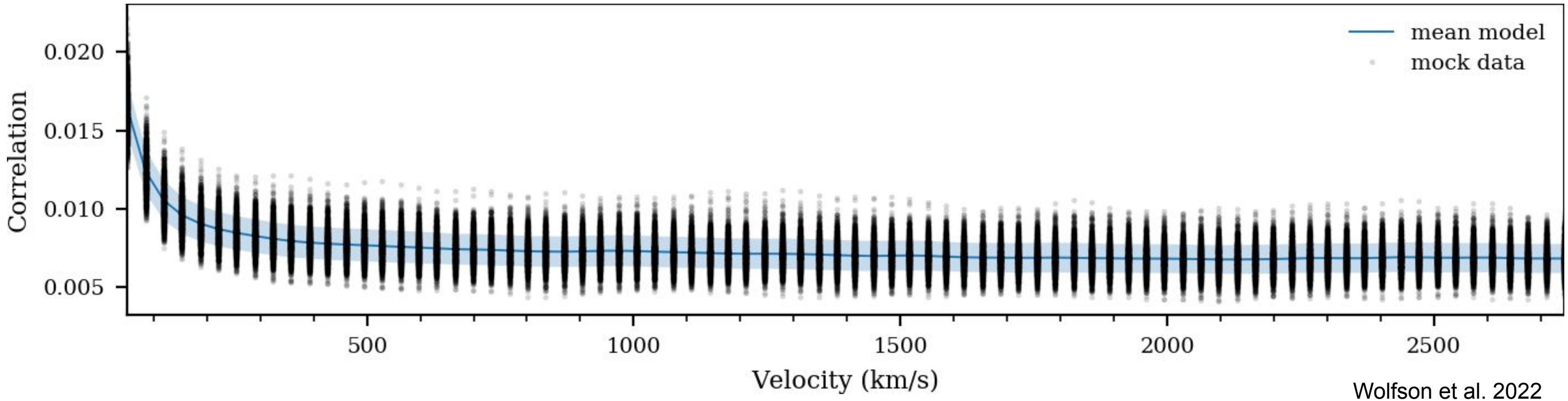
Can we check that our assumptions are correct?

Do we know our posteriors accurately reflect the true probabilities of our measurements?

Is the assumption of gaussian distributed data correct?

$$\mathcal{L} = \frac{1}{\sqrt{\det(\Sigma)(2\pi)^n}} \exp\left(-\frac{1}{2} \left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\rm model}(\lambda_{\rm mfp}, \langle F \rangle)\right)^{\rm T} \Sigma^{-1} \left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\rm model}(\lambda_{\rm mfp}, \langle F \rangle)\right) \right)$$

- Flux PDF is not gaussian but assume averaging to auto-correlation gaussianizes data
- Commonly done with weak lensing, other Lyα forest statistics

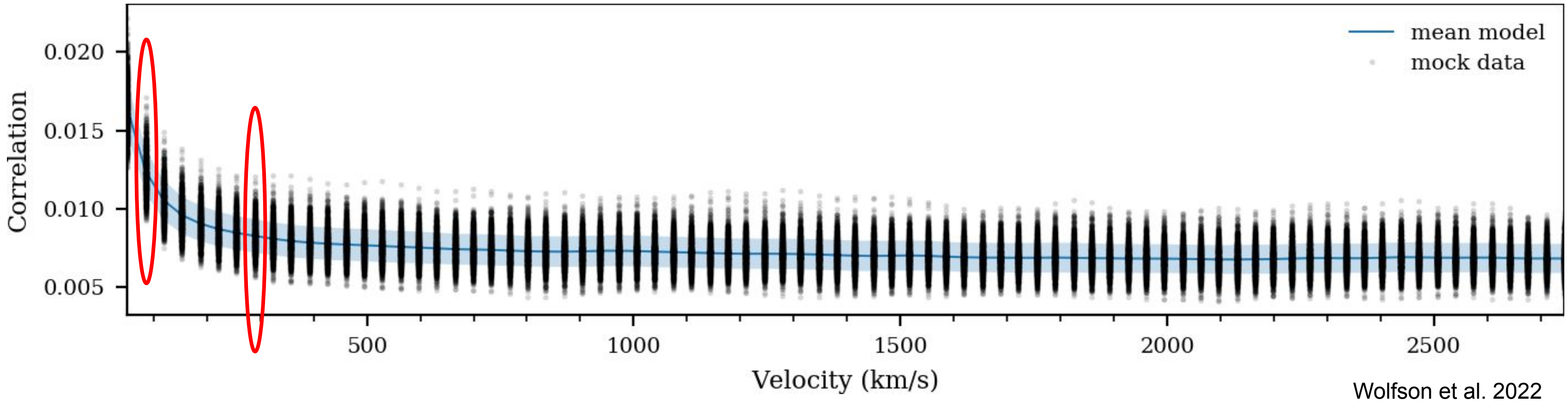


Wolfson et al. 2022

Is the assumption of gaussian distributed data correct?

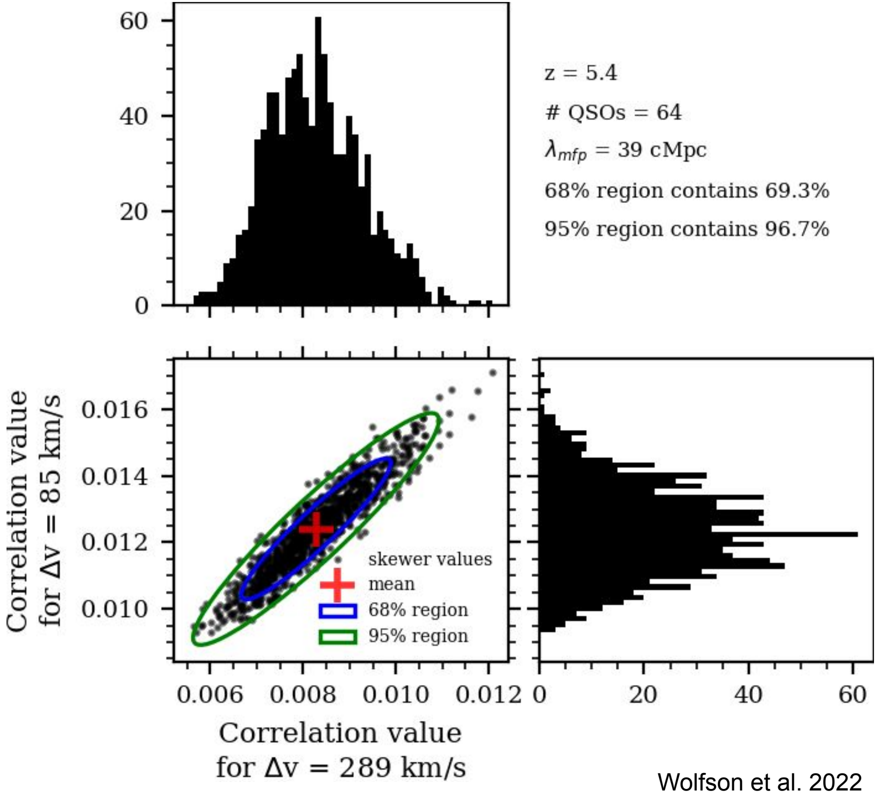
$$\mathcal{L} = \frac{1}{\sqrt{\det(\Sigma)(2\pi)^n}} \exp\left(-\frac{1}{2}\left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\mathrm{model}}(\lambda_{\mathrm{mfp}}, \langle F \rangle)\right)^{\mathrm{T}} \Sigma^{-1} \left(\boldsymbol{\xi} - \boldsymbol{\xi}_{\mathrm{model}}(\lambda_{\mathrm{mfp}}, \langle F \rangle)\right)\right)$$

- Flux PDF is not gaussian but assume averaging to auto-correlation gaussianizes data
- Commonly done with weak lensing, other Lyα forest statistics



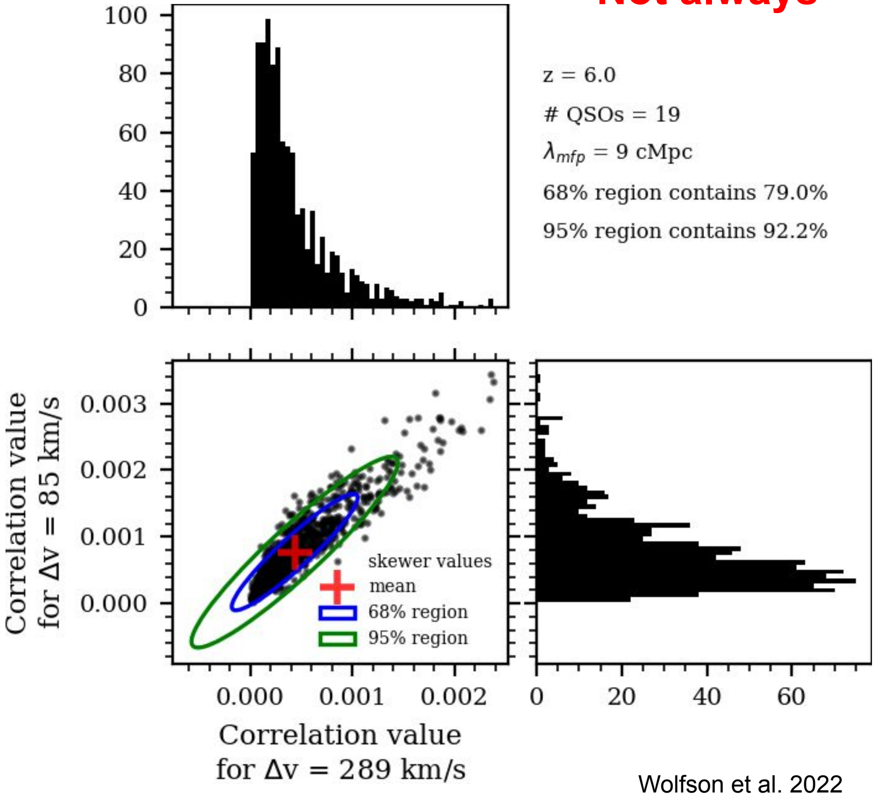
Wolfson et al. 2022

Is the assumption of gaussian distributed data correct?



Wolfson et al. 2022

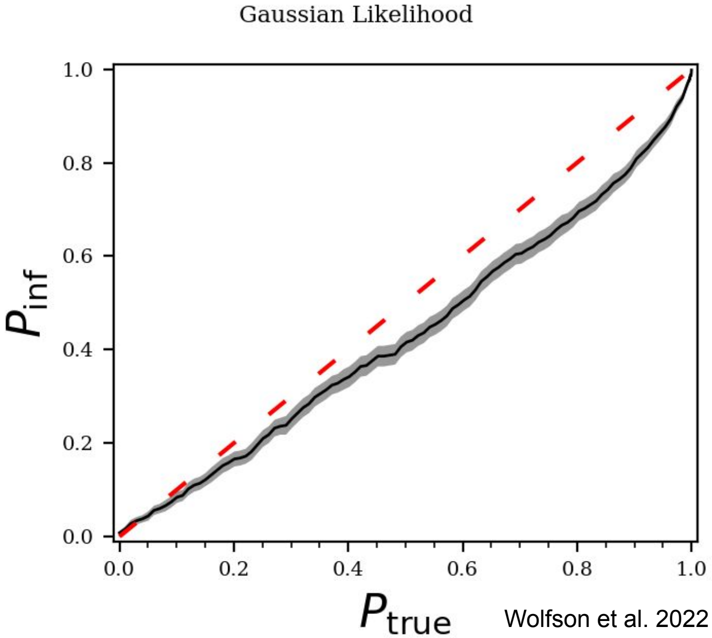
Not always



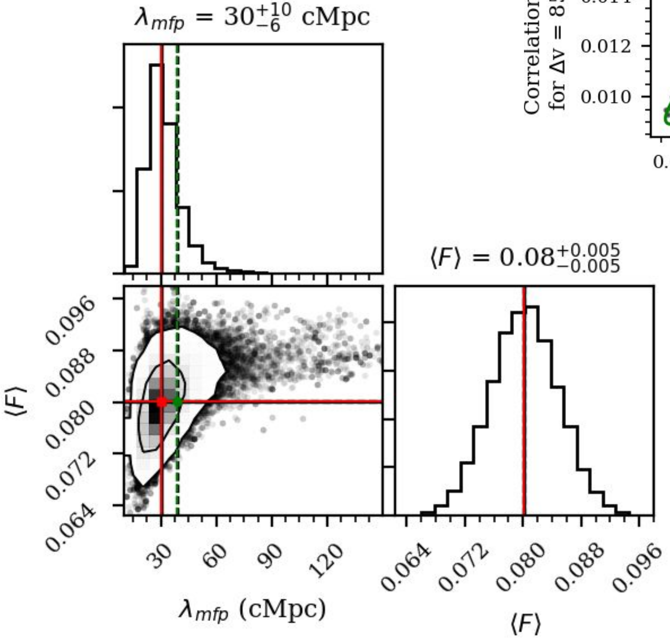
Wolfson et al. 2022

Can we quantify how correct our assumptions are?

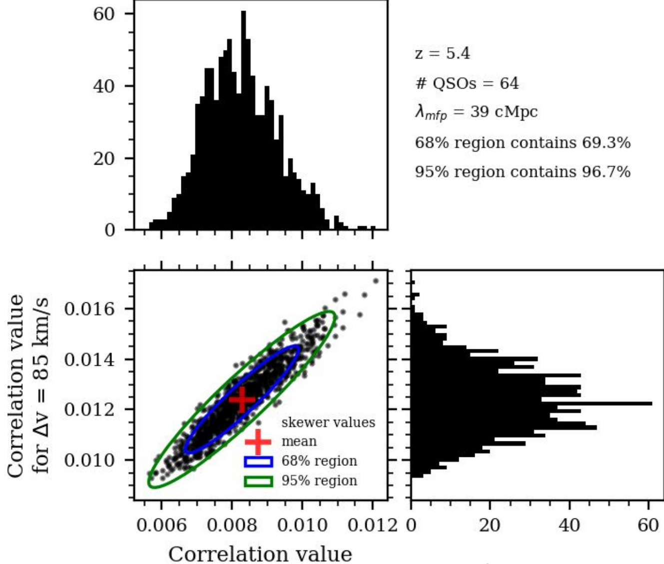
Look at the posteriors for 500 mock data sets



Wolfson et al. 2022



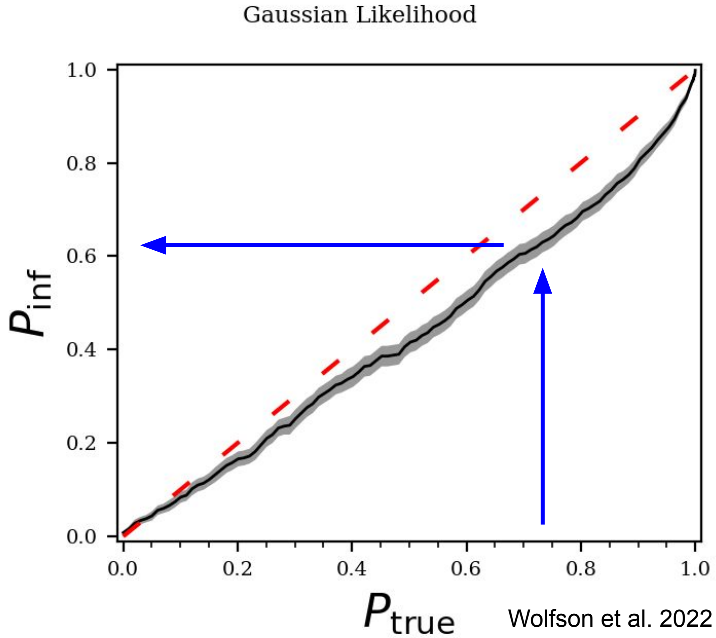
Wolfson et al. 2022



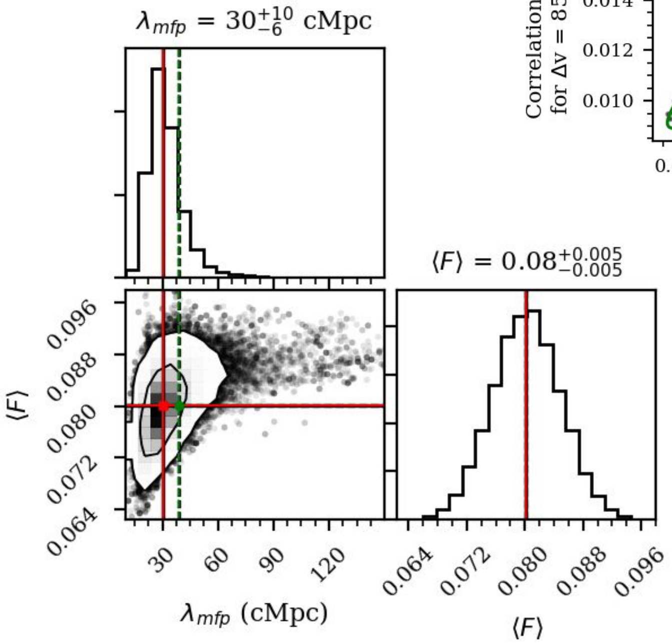
Wolfson et al. 2022

Can we quantify how correct our assumptions are?

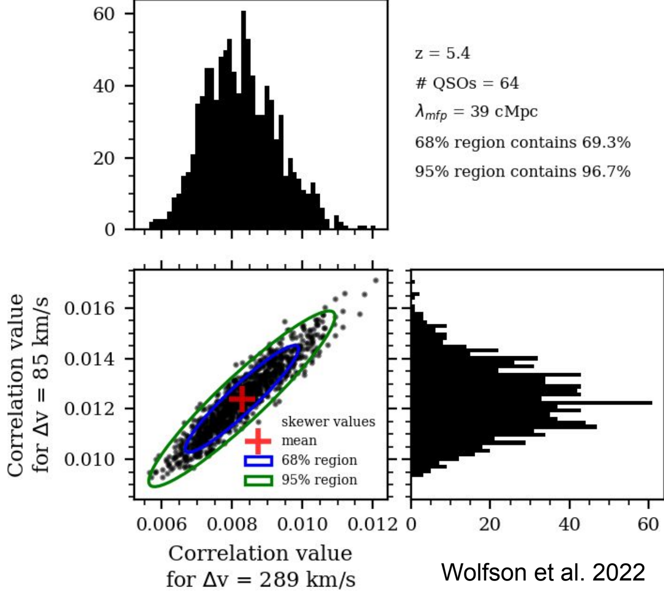
Look at the posteriors for 500 mock data sets



Wolfson et al. 2022



Wolfson et al. 2022

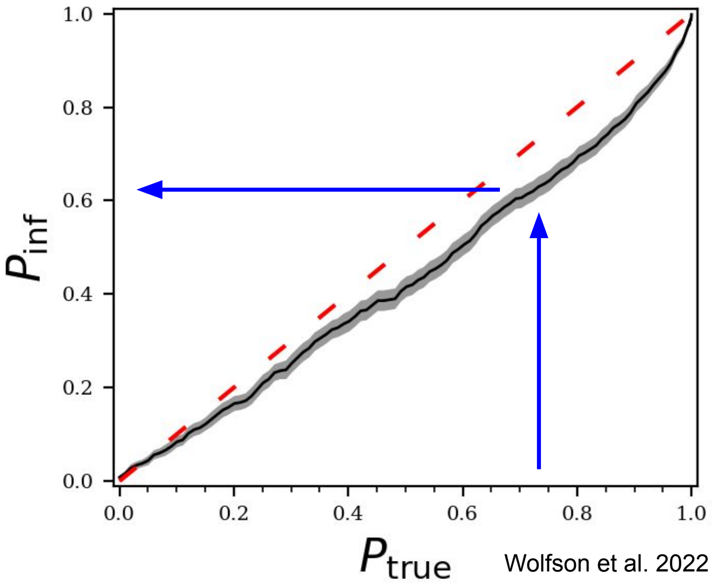


Wolfson et al. 2022

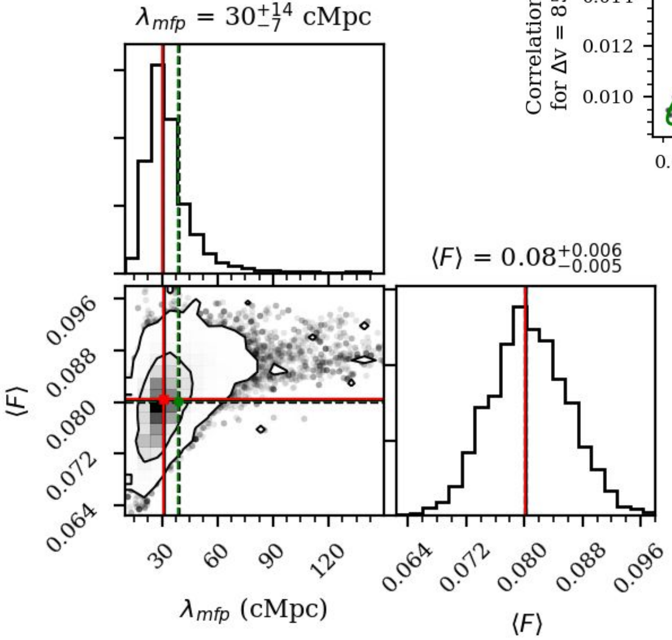
Can we quantify how correct our assumptions are?

Look at the posteriors for 500 mock data sets

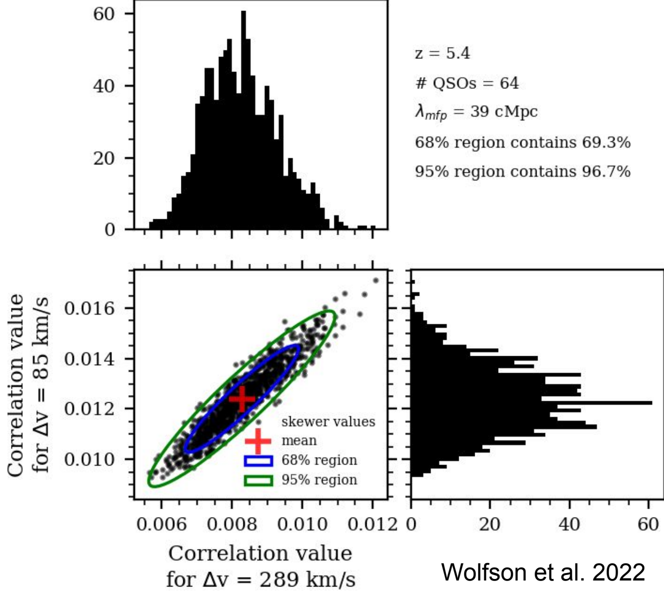
Calculate one set of weights for all posteriors to pass



Wolfson et al. 2022



Wolfson et al. 2022

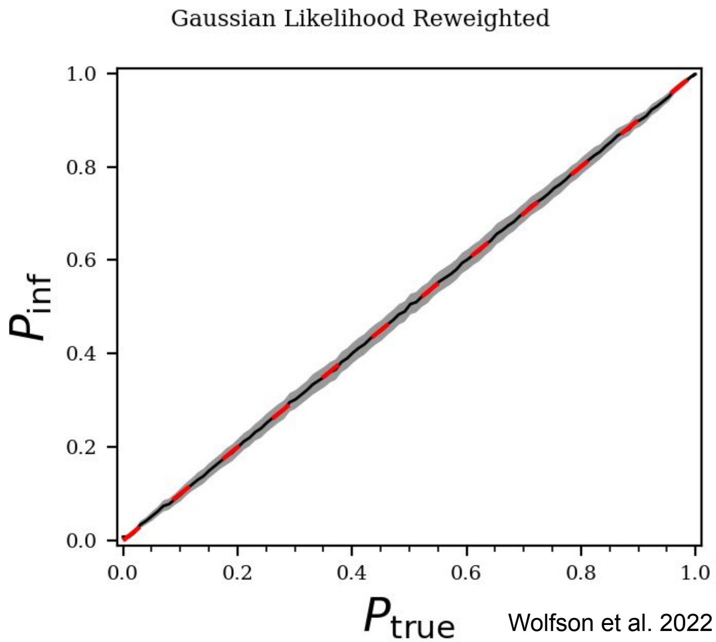


Wolfson et al. 2022

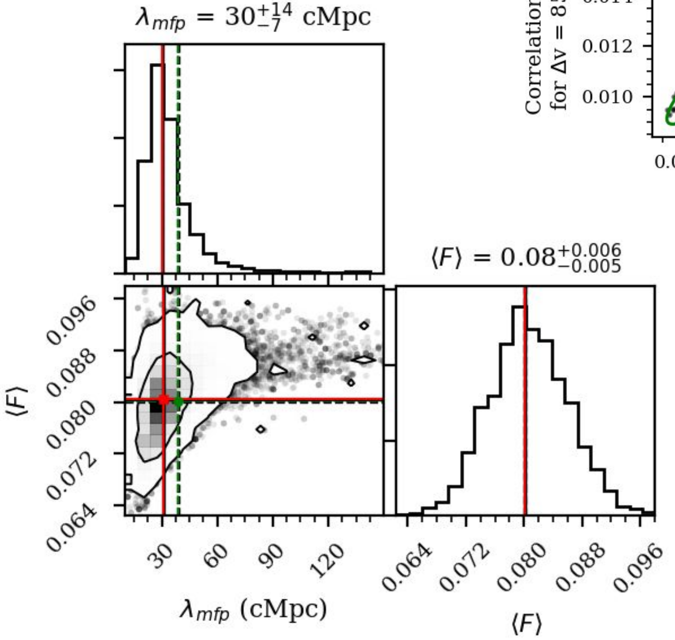
Can we quantify how correct our assumptions are?

Look at the posteriors for 500 mock data sets

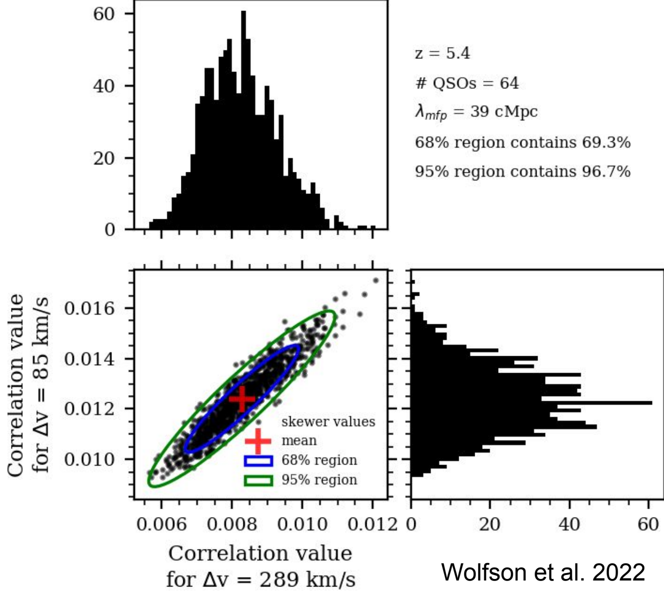
Calculate one set of weights for all posteriors to pass



Wolfson et al. 2022



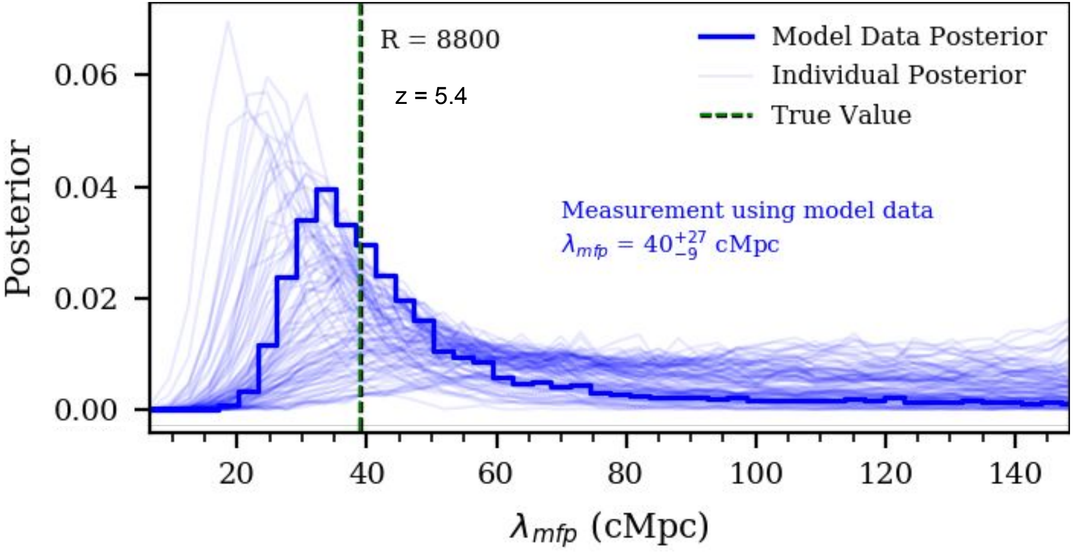
Wolfson et al. 2022



Wolfson et al. 2022

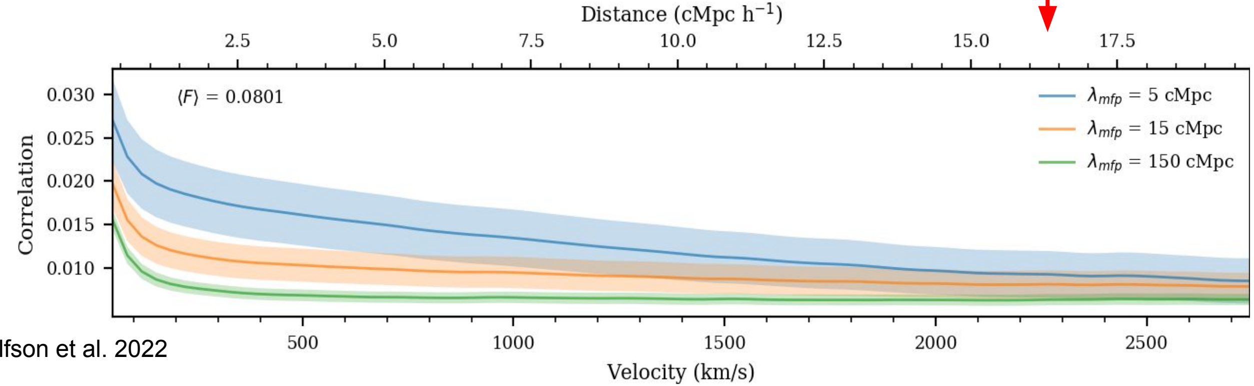
Measuring λ_{mfp} from mock data

Wolfson et al. 2022



Luck of the draw for the chosen mock data set dictates the precision of the posterior

Remove this by using the model value as the data

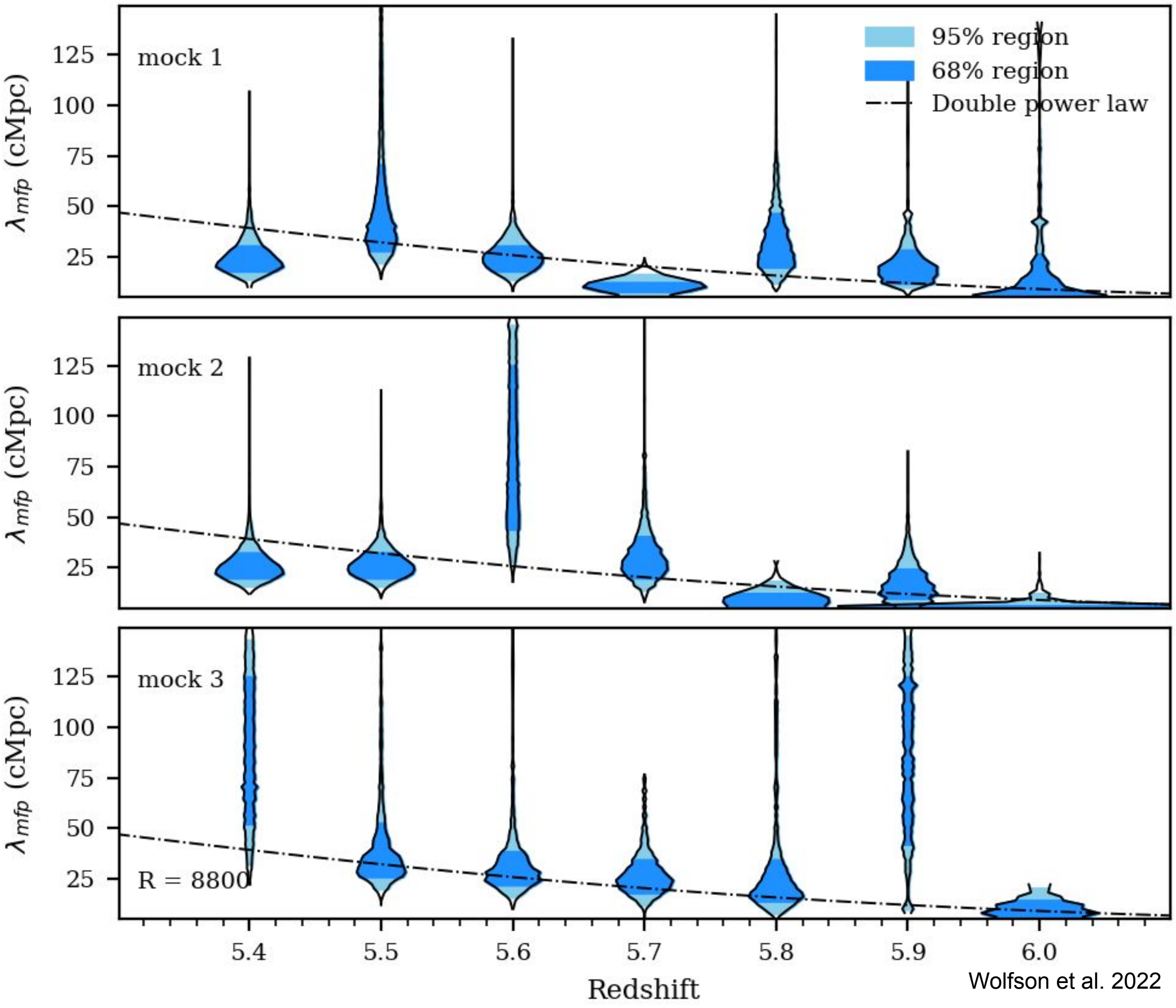


Wolfson et al. 2022

Measuring λ_{mfp} from mock data

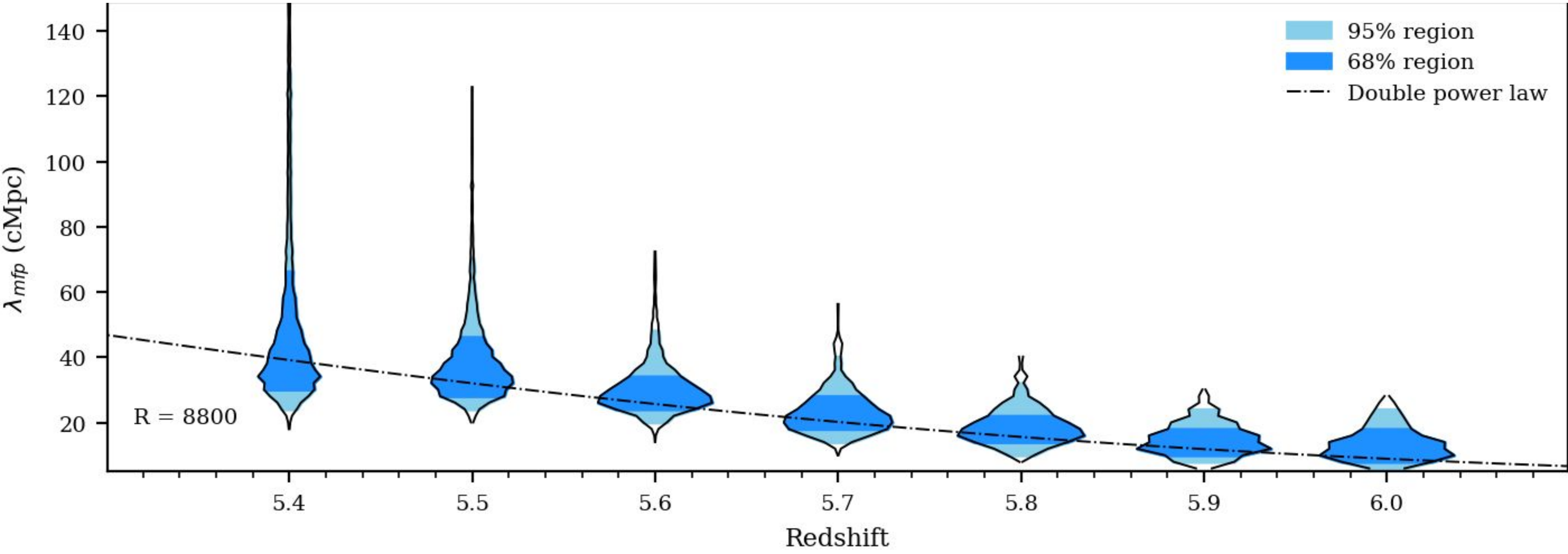
Different redshifts have different precision due to:

- Size of the mock data
- The sensitivity of the autocorrelation function at the inferred λ_{mfp}
- The luck of the draw



Wolfson et al. 2022

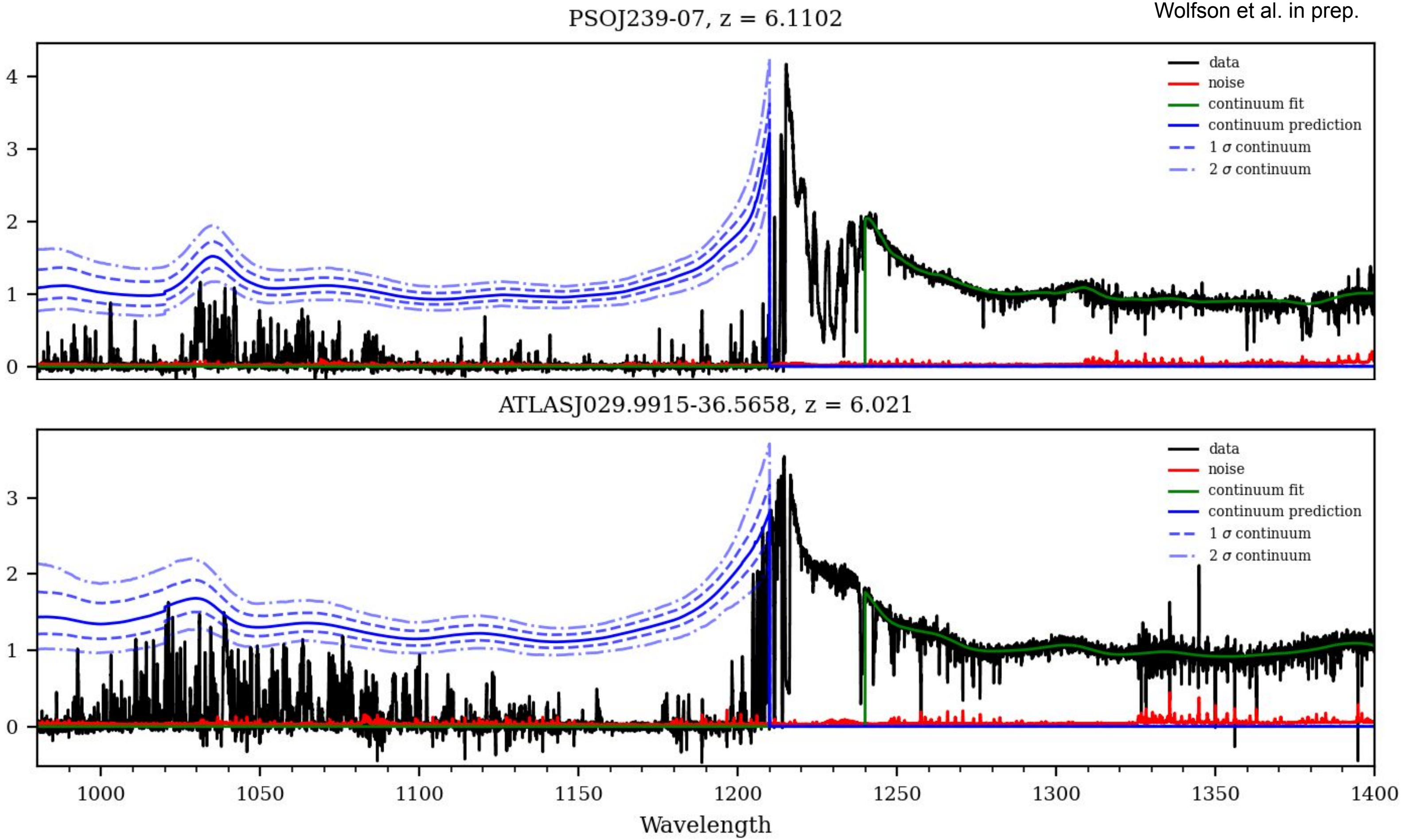
Measuring λ_{mfp} from mock data (removing "luck of the draw")



Wolfson et al. 2022

Now with XQR-30 data:

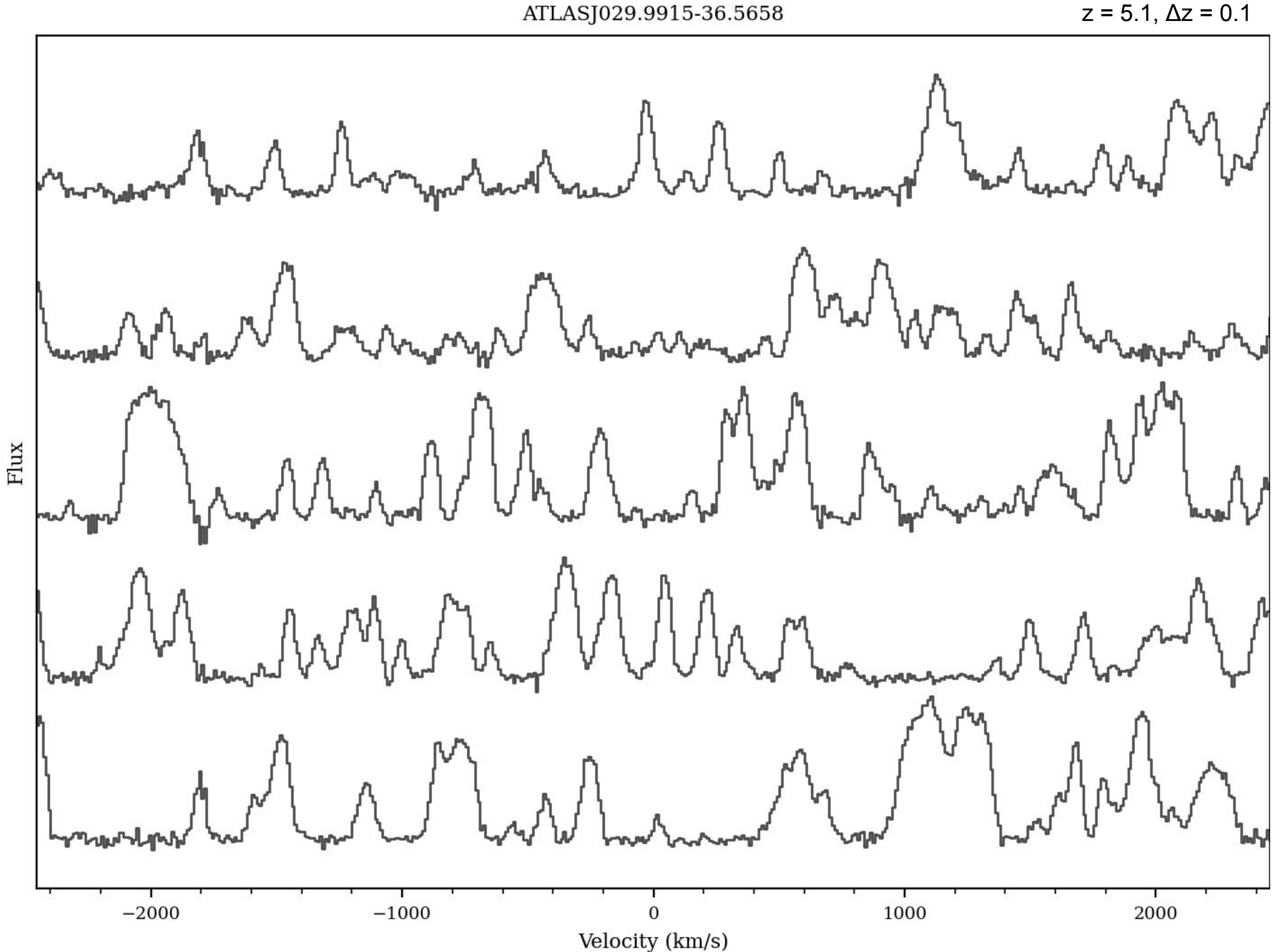
Wolfson et al. in prep.



Forward modeling XQR-30 data

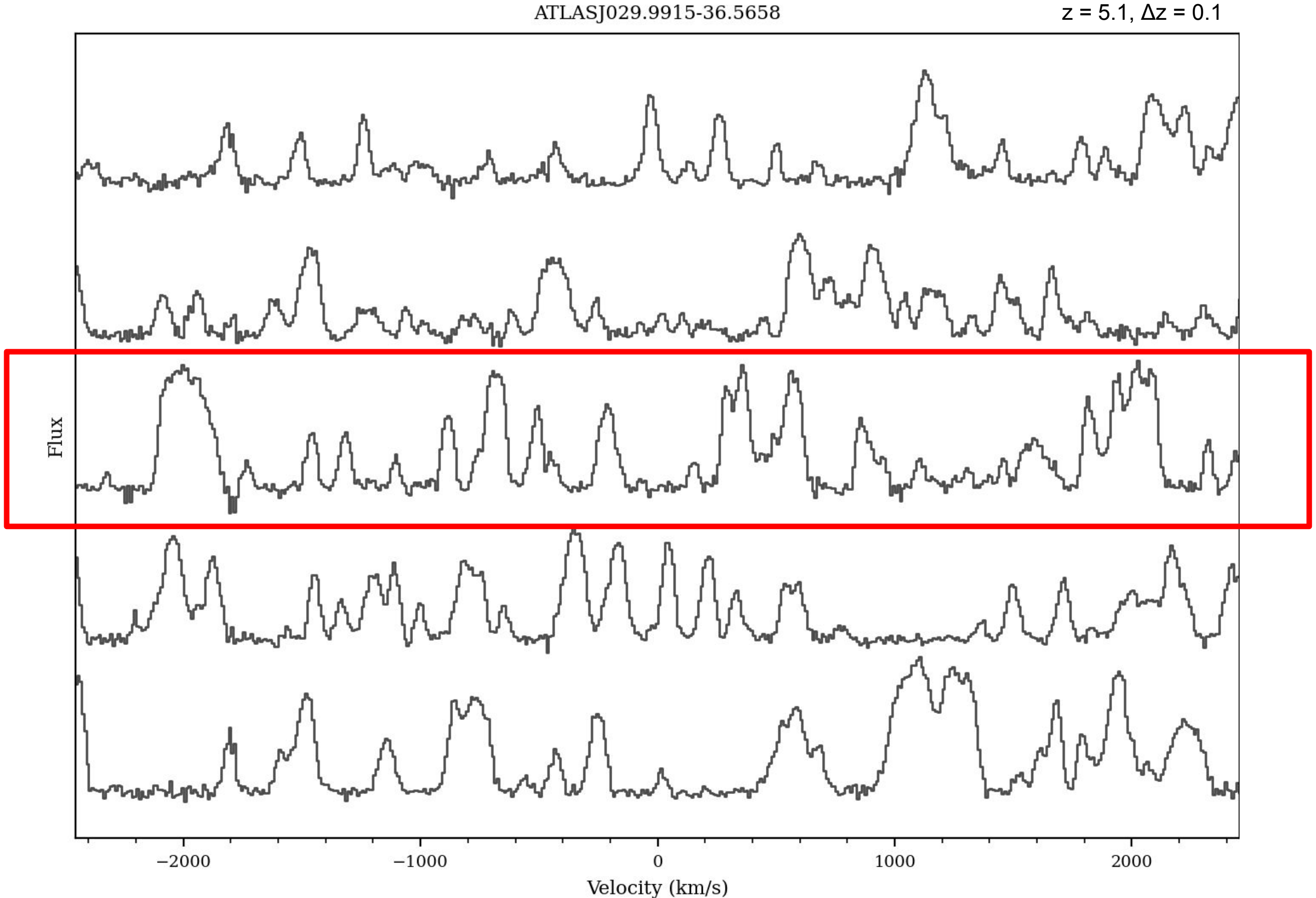
Wolfson et al. in prep.

z = 5.1, Δz = 0.1

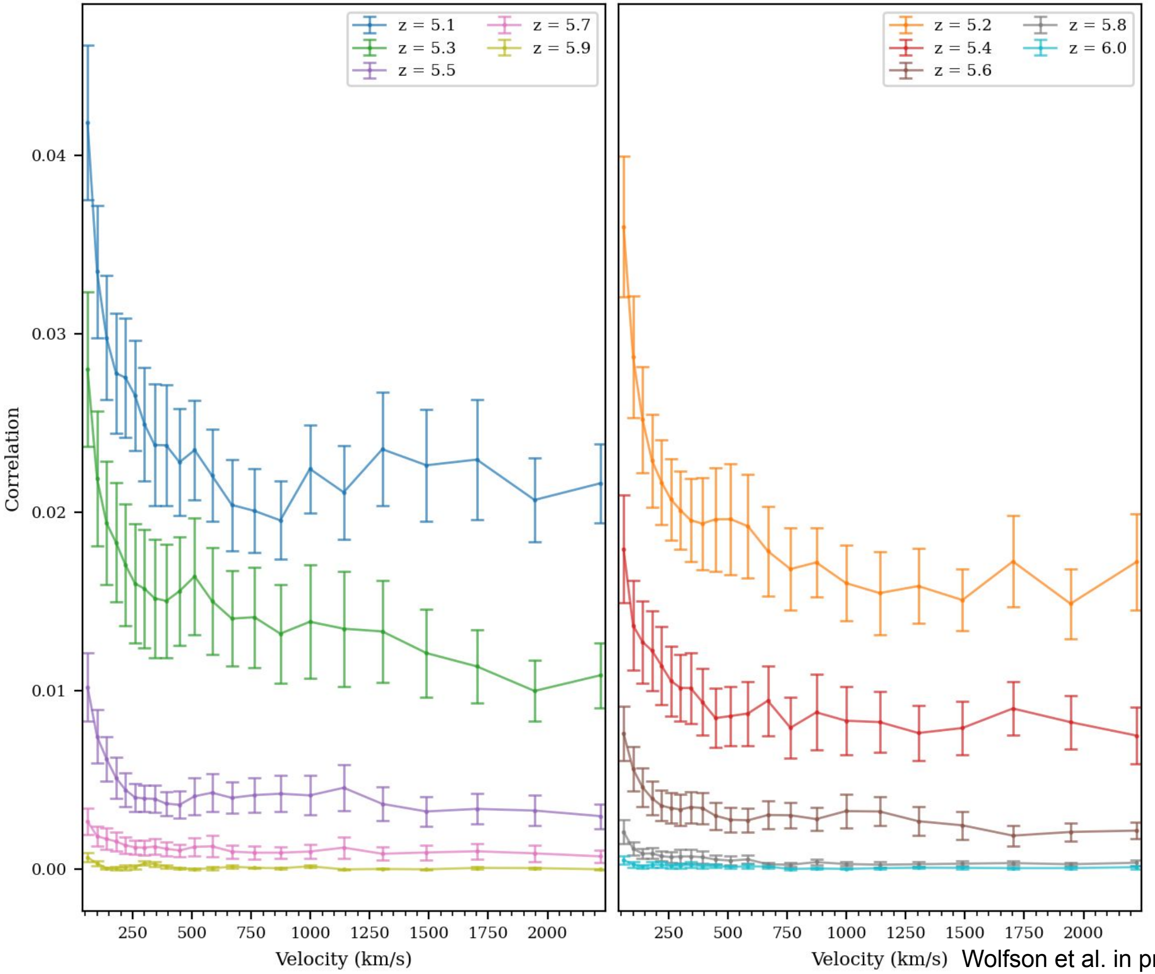


Forward modeling XQR-30 data

Wolfson et al. in prep.

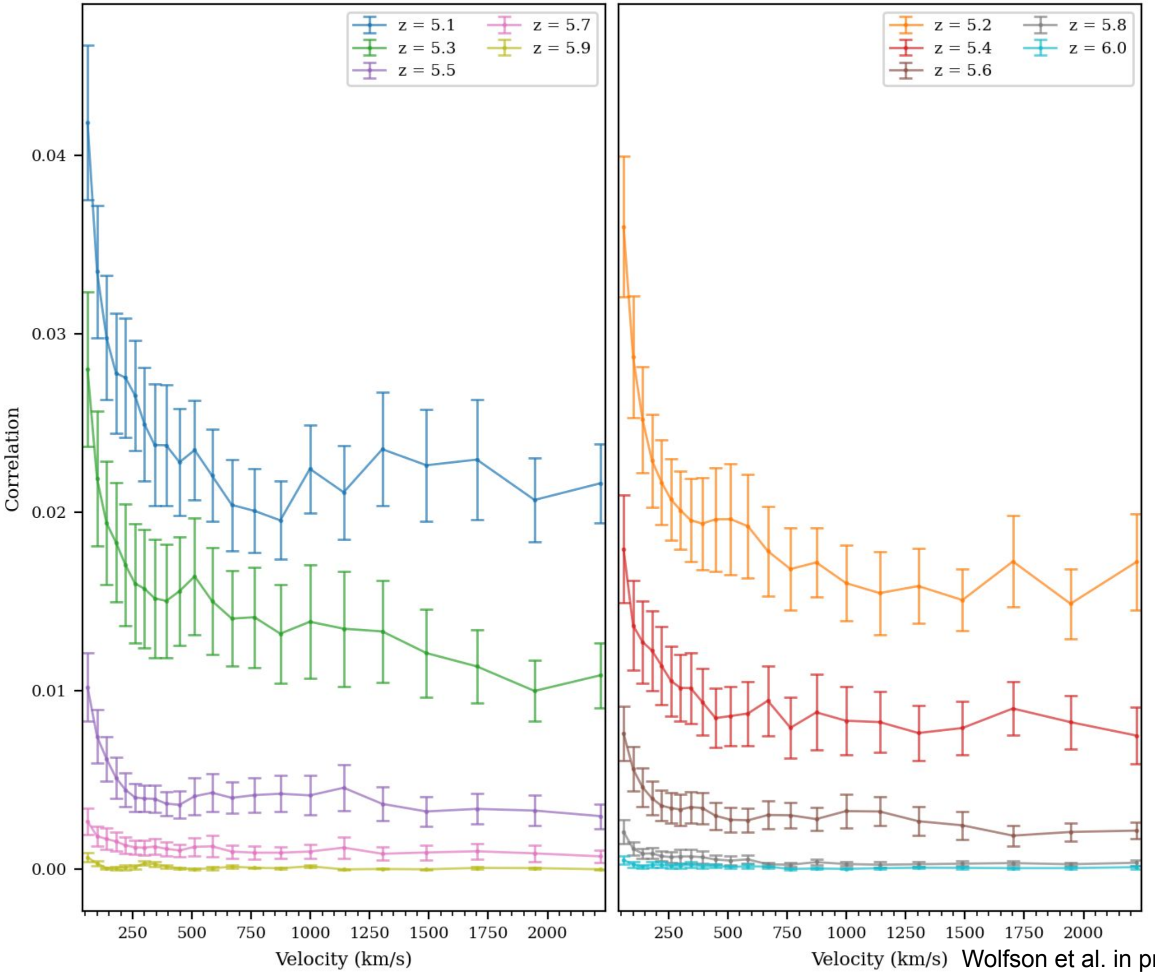


Auto-correlation function from XQR-30

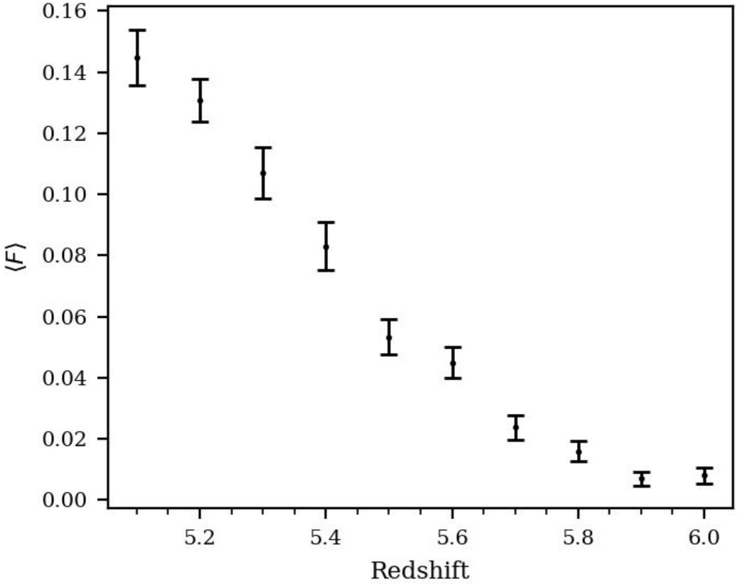


Wolfson et al. in prep.

Auto-correlation function from XQR-30

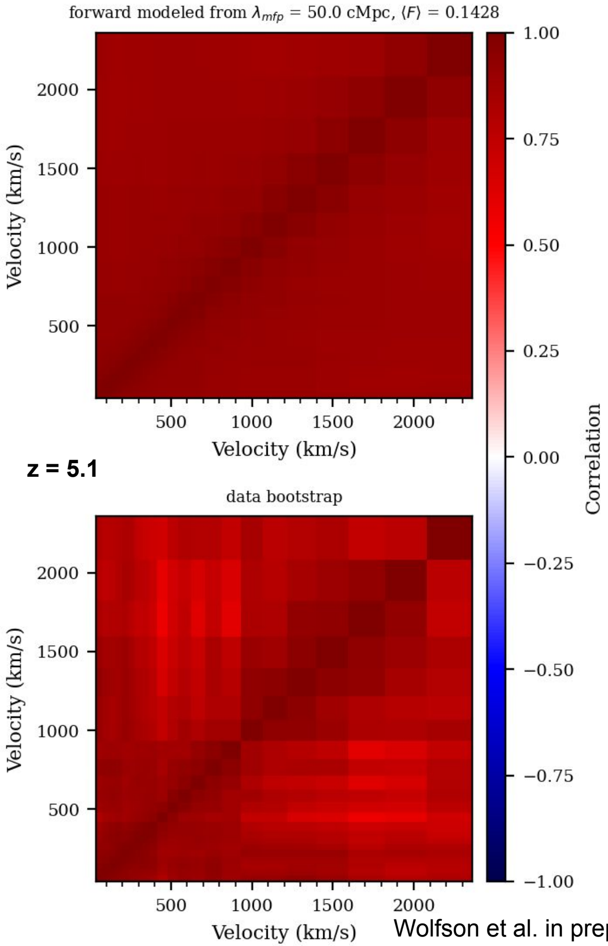


Wolfson et al. in prep.

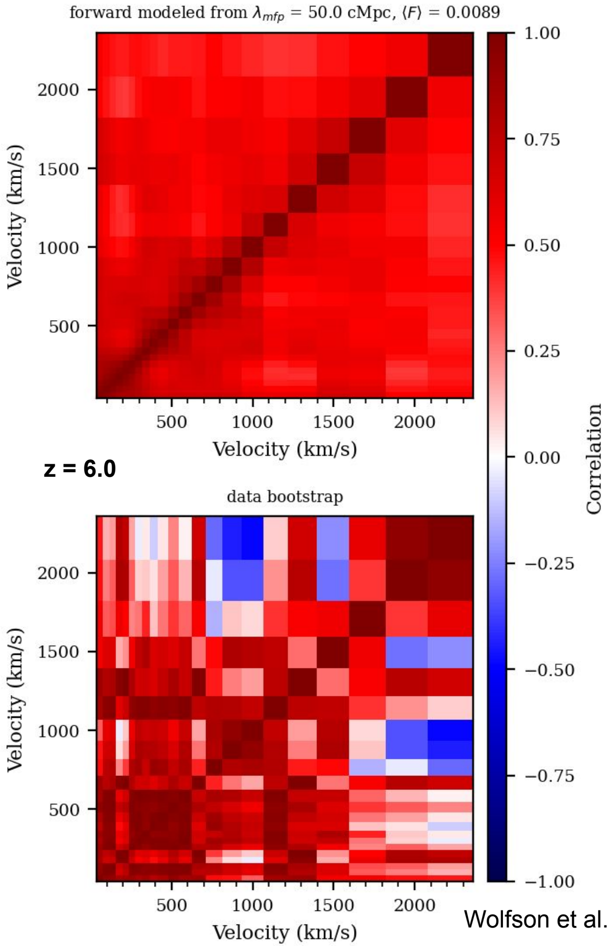


Wolfson et al. in prep.

Calculating the covariance from noisy data is difficult



Wolfson et al. in prep.



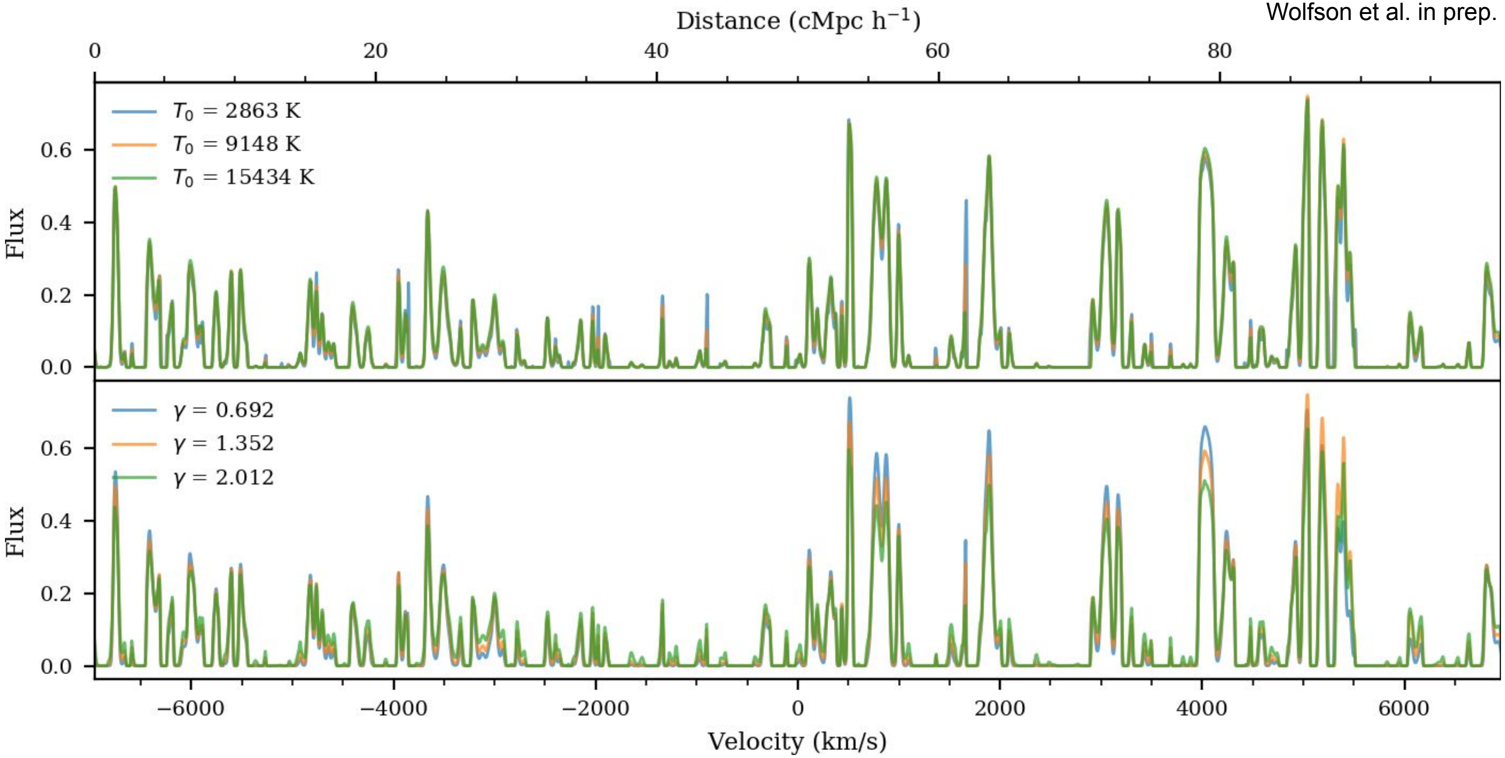
Wolfson et al. in prep.

Is the auto-correlation function sensitive to the thermal state?

Modeling the thermal state

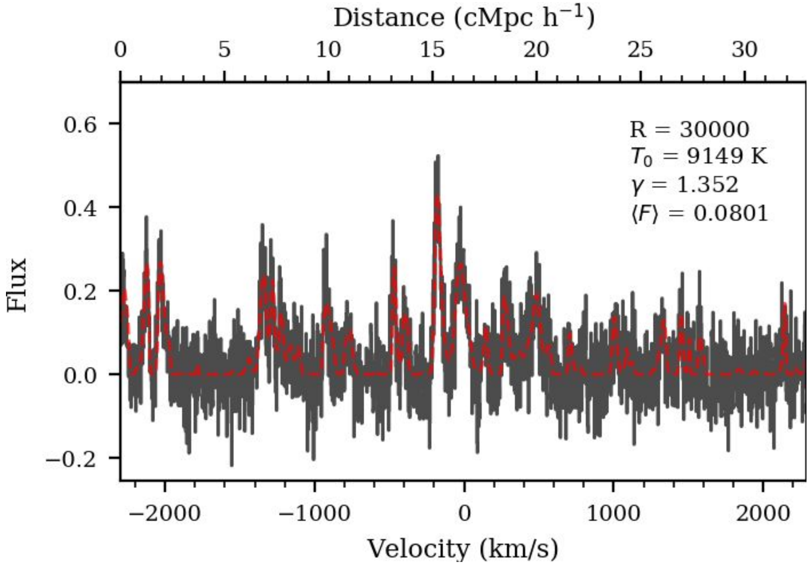
- Same Nyx box with L_{box} = 100 cMpc h^{-1}
- Paint on different temperature-density relationships $T = T_0(\rho/\bar{\rho})^{\gamma-1}$

Wolfson et al. in prep.



Modeling the thermal state

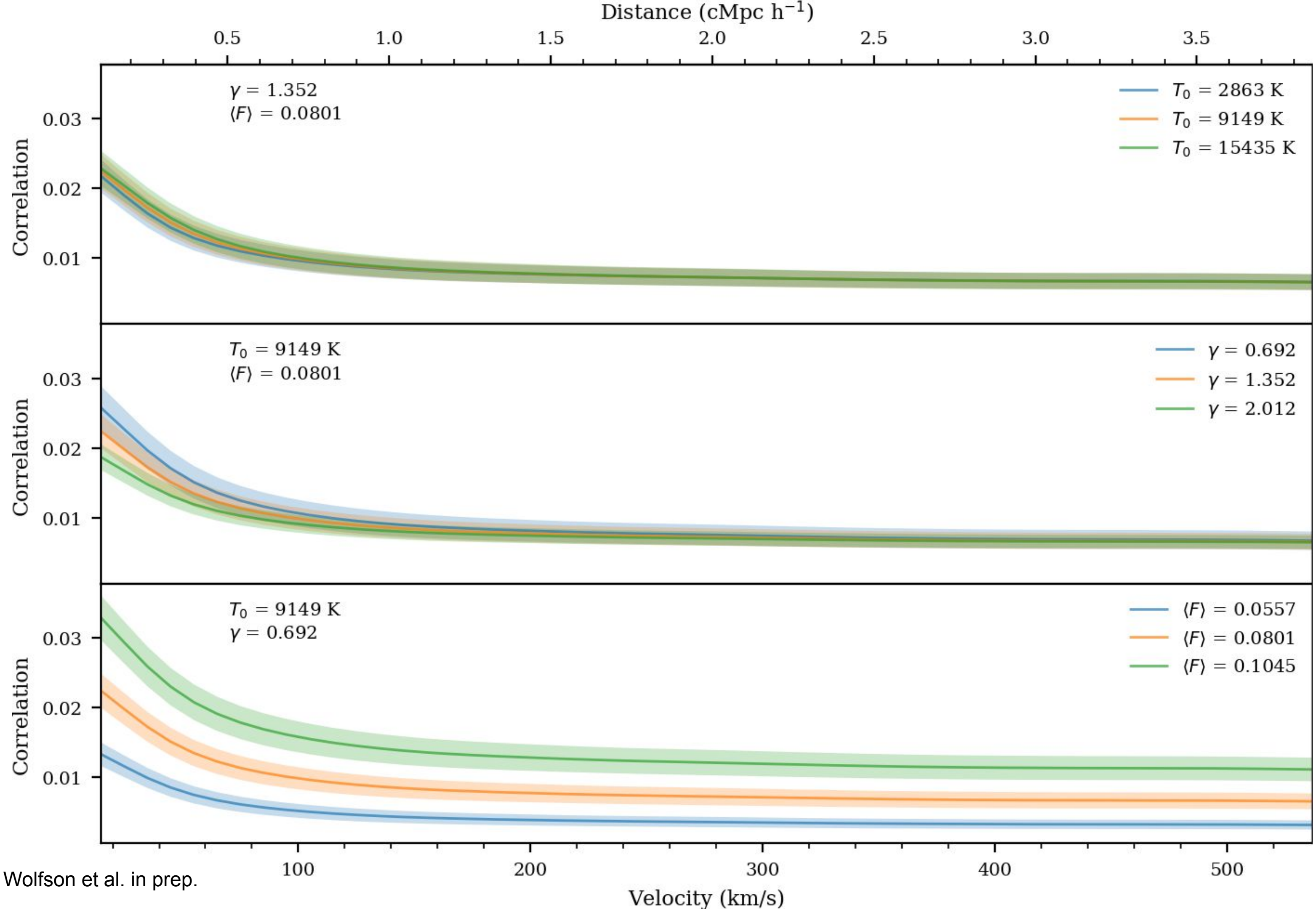
- Same Nyx box with L_{box} = 100 cMpc h^{-1}
- Paint on different temperature-density relationships $T = T_0(\rho/\bar{\rho})^{\gamma-1}$



Wolfson et al. in prep.

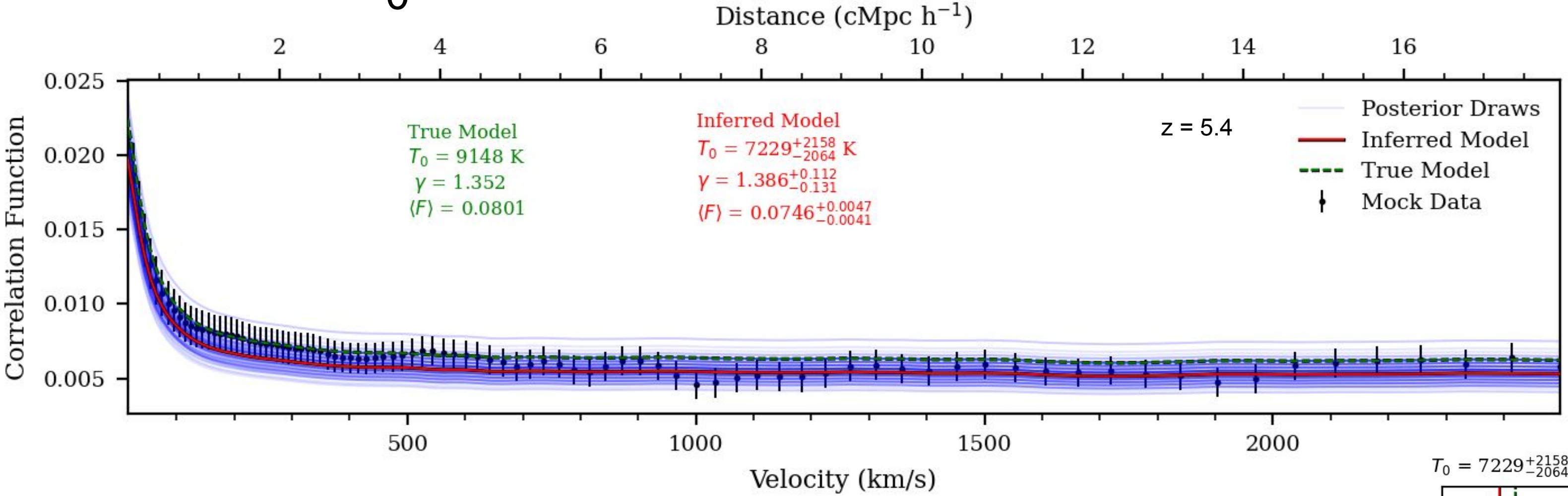
Mock data properties:

- High-resolution data R ~ 30000
  - Resolution of Keck/HIRES
  - Convolve with a gaussian filter
- Gaussian noise with SNR_{pixel} = 10
- 10 quasars in each z bin

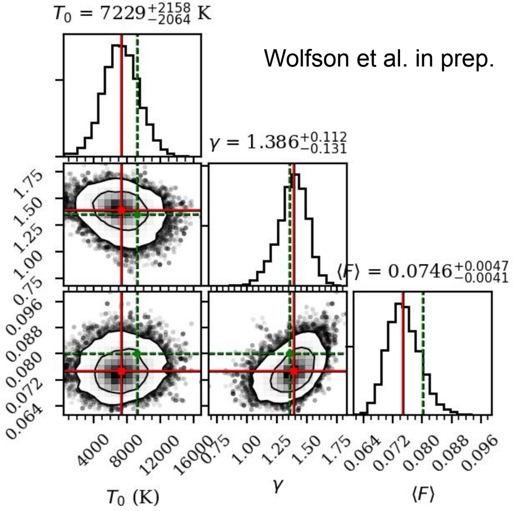


Wolfson et al. in prep.

Measuring T_0 and γ from mock data:

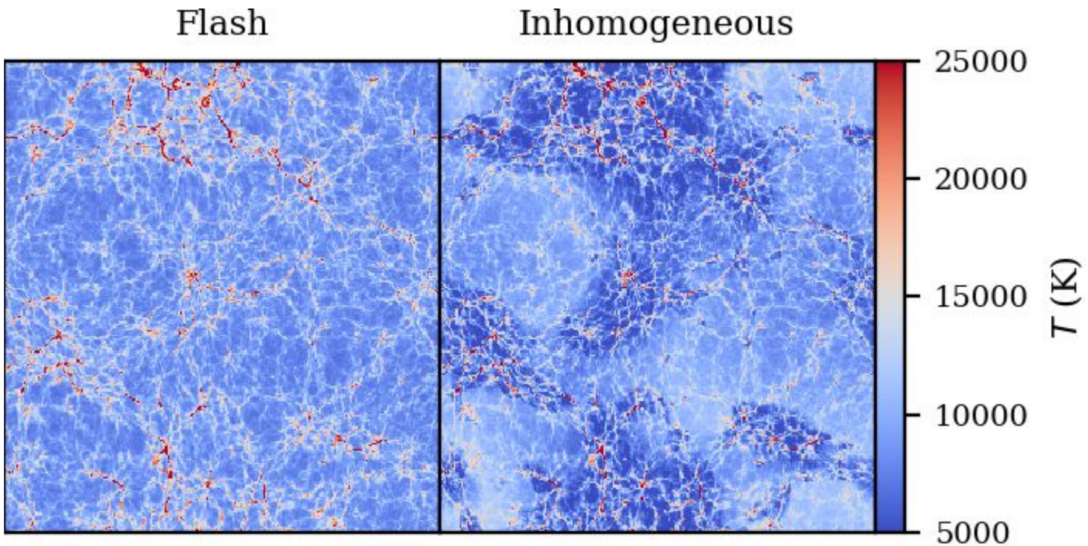


MCMC

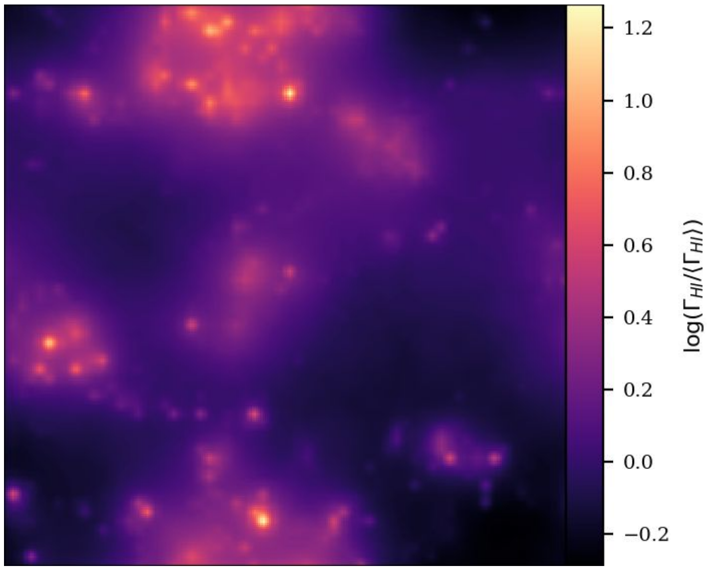


Wolfson et al. in prep.

Modeling different reionization scenarios



Wolfson et al. in prep.

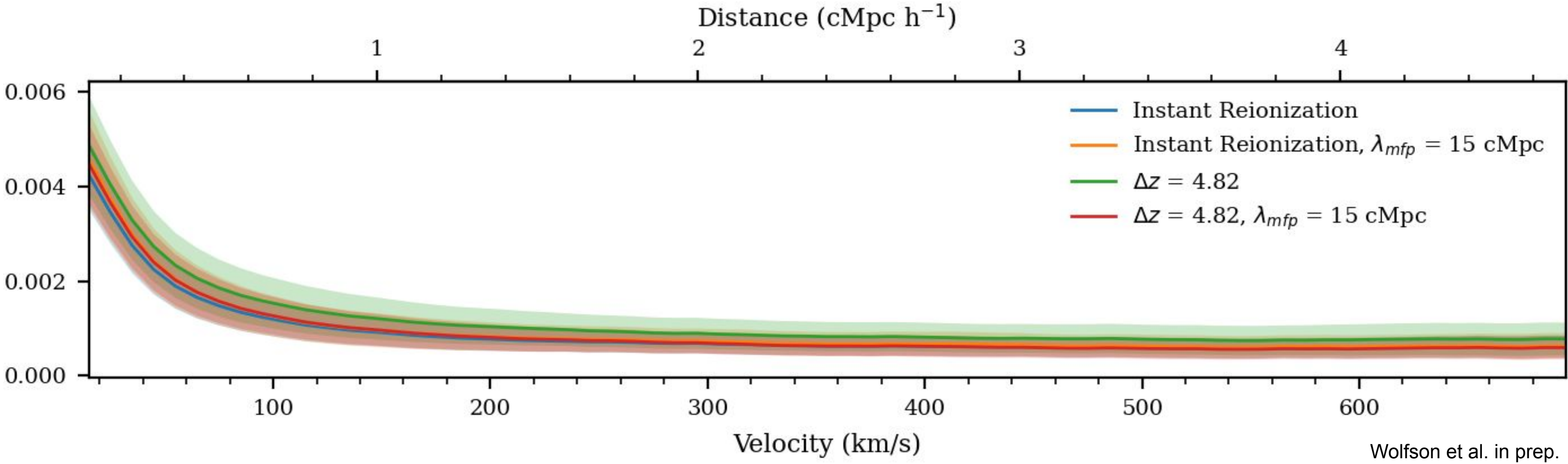


Wolfson et al. in prep.

Reionization models from Oñorbe et al. 2019

UVB box matching the IGM simulation with λ_{mfp} = 15 cMpc

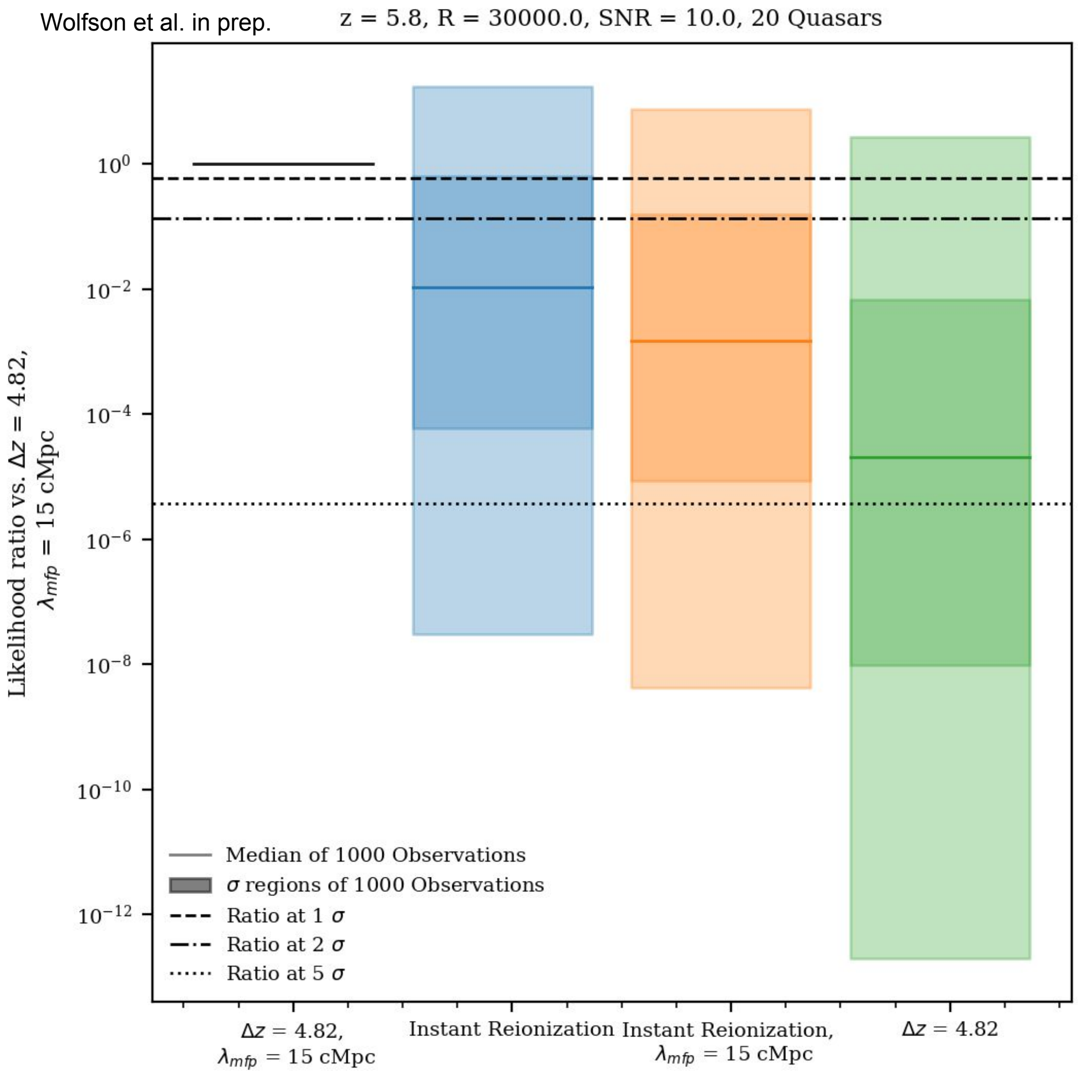
Auto-correlation from the four scenarios



Wolfson et al. in prep.

Likelihood ratio results

Can rule out other models at over 2σ level for over 50% of the mock data sets considered



Summary

- The auto-correlation function provides a new way to competitively constrain the evolution with redshift of λ_{mfp} with existing data
- Practical considerations make the auto-correlation function a particularly useful statistic
  - Ex: not needing to model the noise or calculate the window function from DLA mask
- We can reweight the posteriors from mock data to correct for assumptions in our likelihood function (such as using a multivariate gaussian distribution)
  - However, further work on likelihood-free inference (LFI) should further improve precision of measurements
- Measurement of λ_{mfp} from XQR-30 data is ongoing
  - Estimating covariance matrix from limited data has been challenging
- The auto-correlation function will also provide a new way to constrain the thermal state of the IGM with high-resolution data

Future work – measure the auto-correlation function with high resolution data, WDM sensitivity, LFI