Constraining Reionization with the $z > 5$ Lyman-α forest

Molly Wolfson

CCAPP Symposium – September 25, 2024

NASA, ESA and J. Olmsted (STScI)

Overview:

1. What is Reionization and why is it important?

2. How does the IGM evolve during the end of Reionization?
   Fluctuations in the UVB characterized by λ_{mfp}

3. Can we measure this evolution?
   Auto-correlation function of Lyman-α flux

4. Have I made this measurement?
   Why or why not?

Conclude/Future Plans

Overview:

1. **What is Reionization and why is it important?**

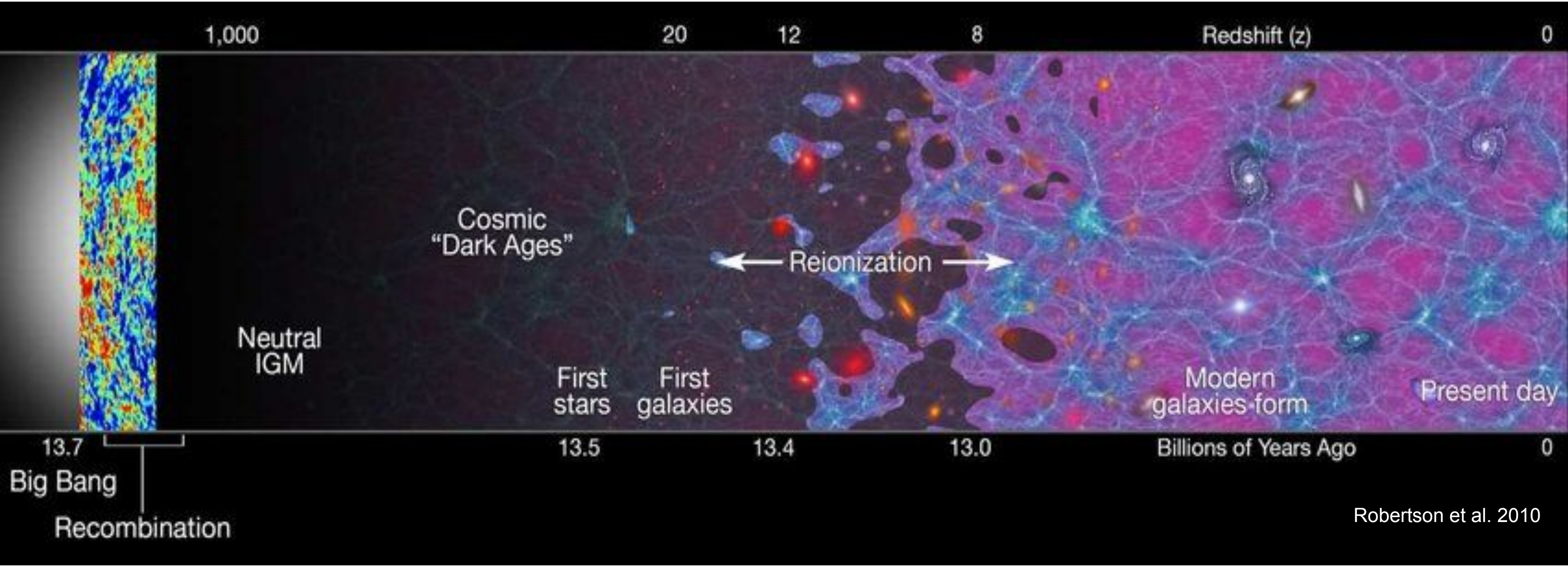
2. How does the IGM evolve during the end of Reionization?
   Fluctuations in the UVB characterized by λ_{mfp}

3. Can we measure this evolution?
   Auto-correlation function of Lyman-α flux

4. Have I made this measurement?
   Why or why not?

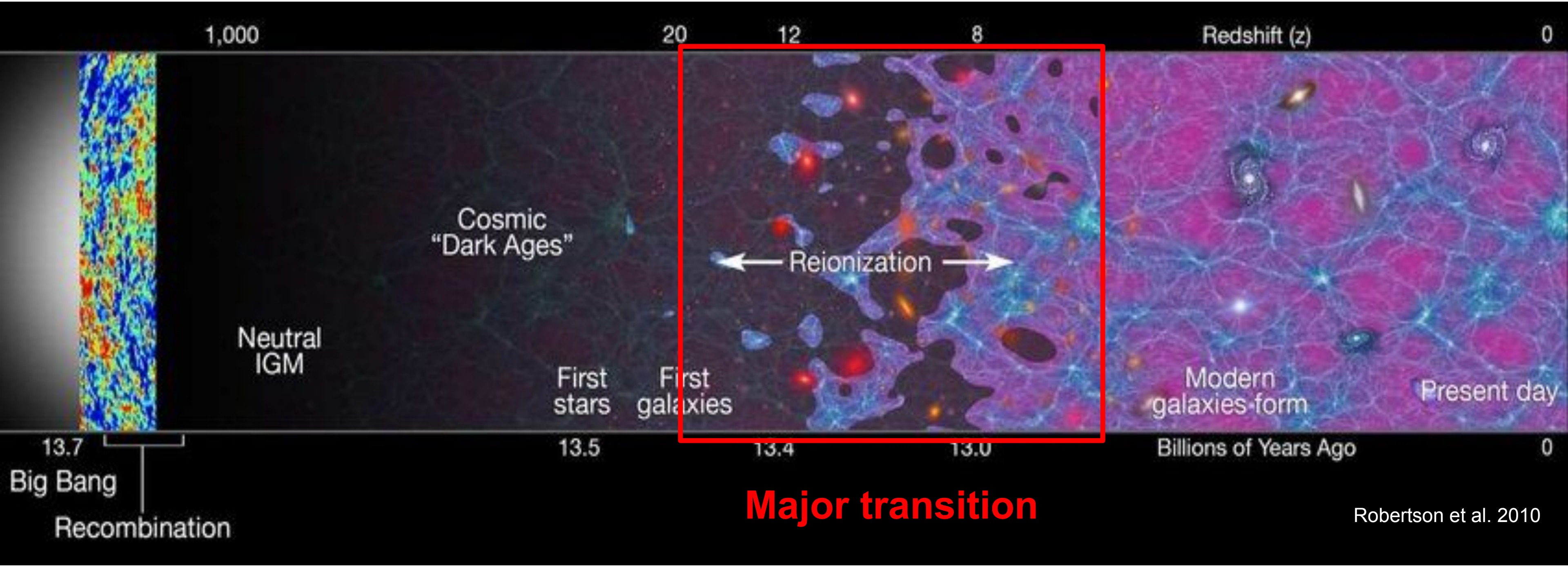
Conclude/Future Plans

What is Reionization?

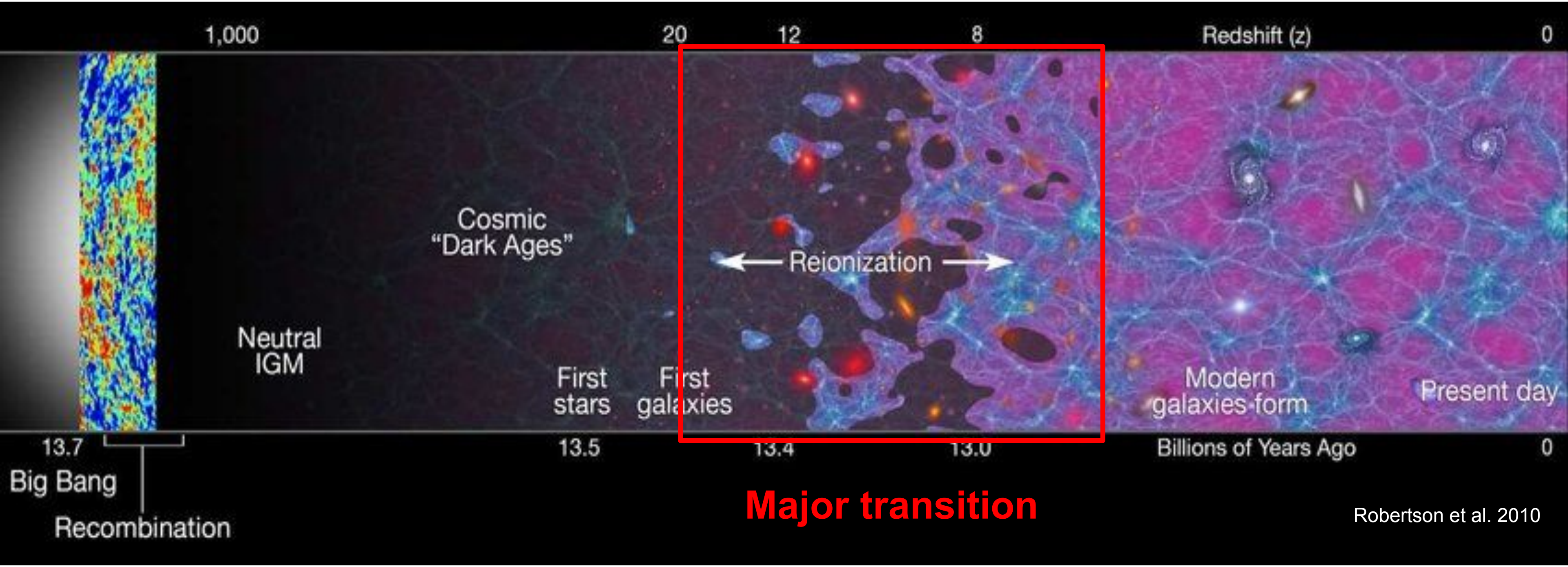


Robertson et al. 2010

What is Reionization?



What is Reionization?



What we know: z_{mid} ~ 7.7 (Planck), complete at z < 6, driven by galaxies

What we don't know: exact timing, # of photons required, impact on thermal state, details on sources, and more

Overview:

1. What is Reionization and why is it important?

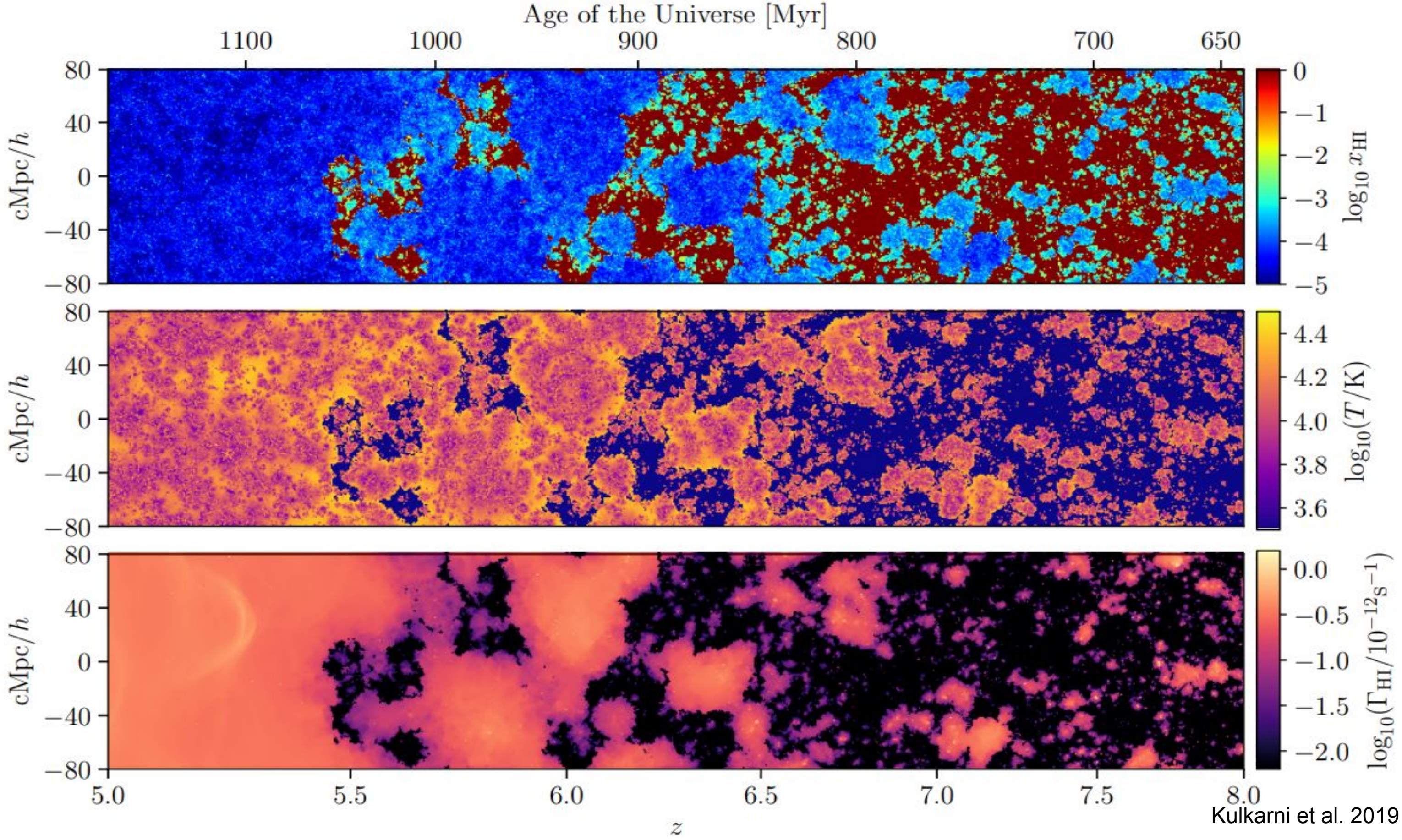
2. **How does the IGM evolve during the end of Reionization?**
   Fluctuations in the UVB characterized by λ_{mfp}

3. Can we measure this evolution?
   Auto-correlation function of Lyman-α flux

4. Have I made this measurement?
   Why or why not?

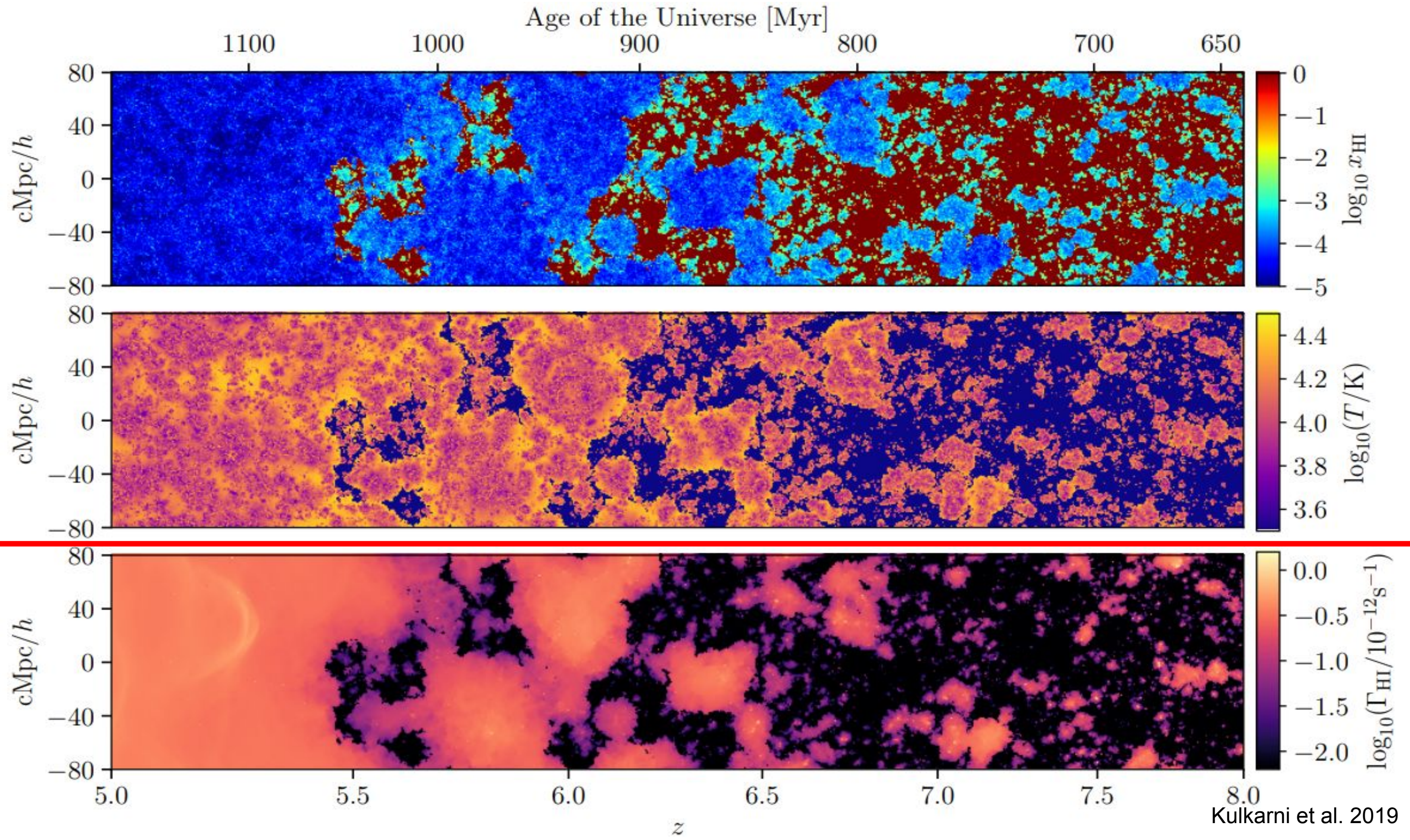
Conclude/Future Plans

The evolution of the thermal state of the IGM and UVB:



Kulkarni et al. 2019

The evolution of the thermal state of the IGM and UVB:

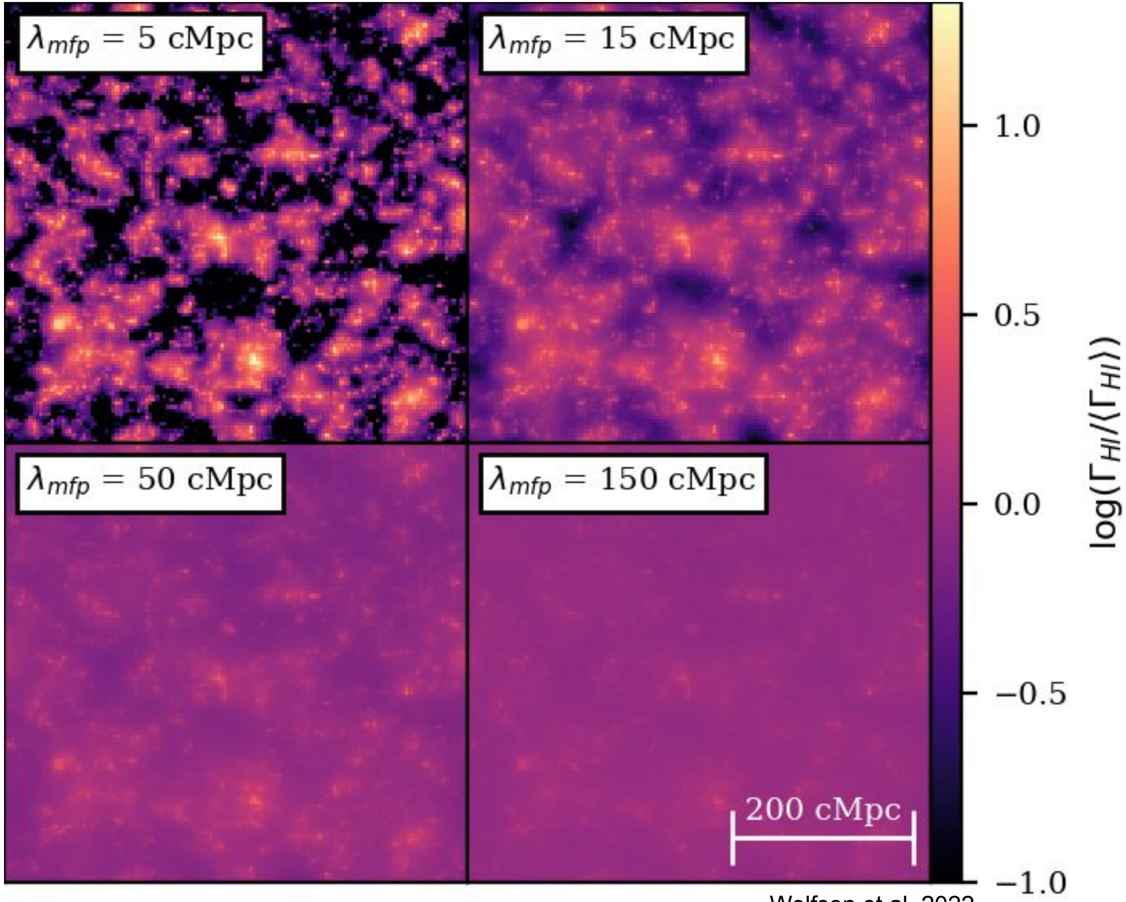


UVB

Kulkarni et al. 2019

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

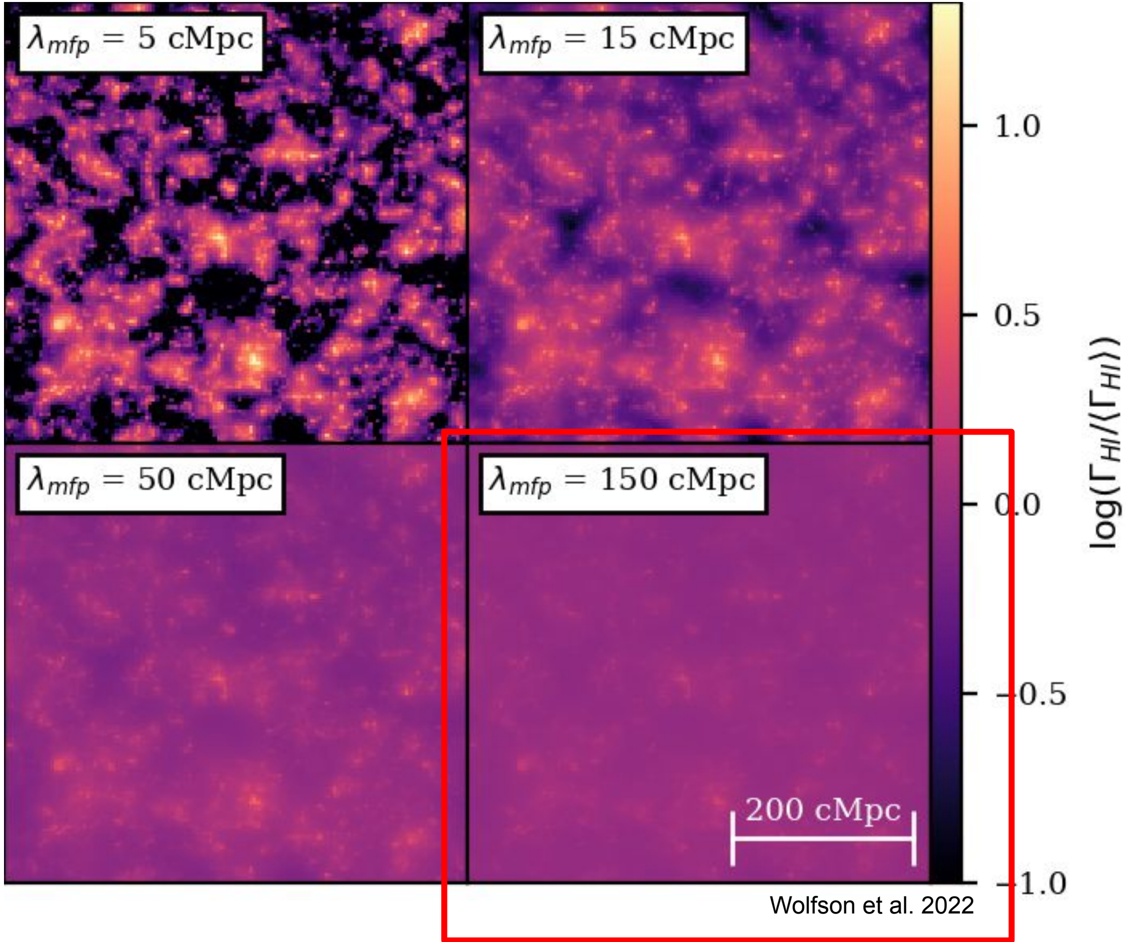
λ_{mfp} - the average distance ionizing photons travel before interacting with neutral hydrogen



Wolfson et al. 2022

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

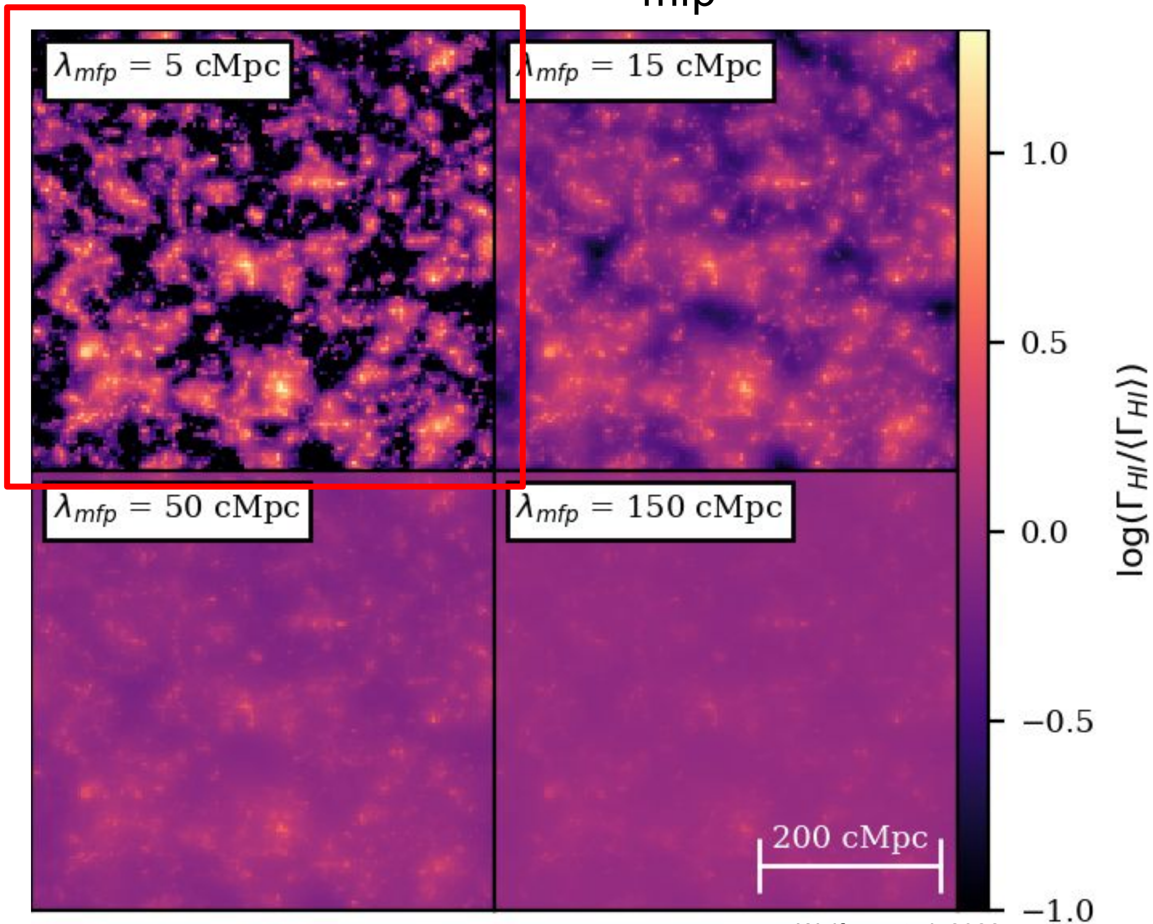
λ_{mfp} - the average distance ionizing photons travel before interacting with neutral hydrogen



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

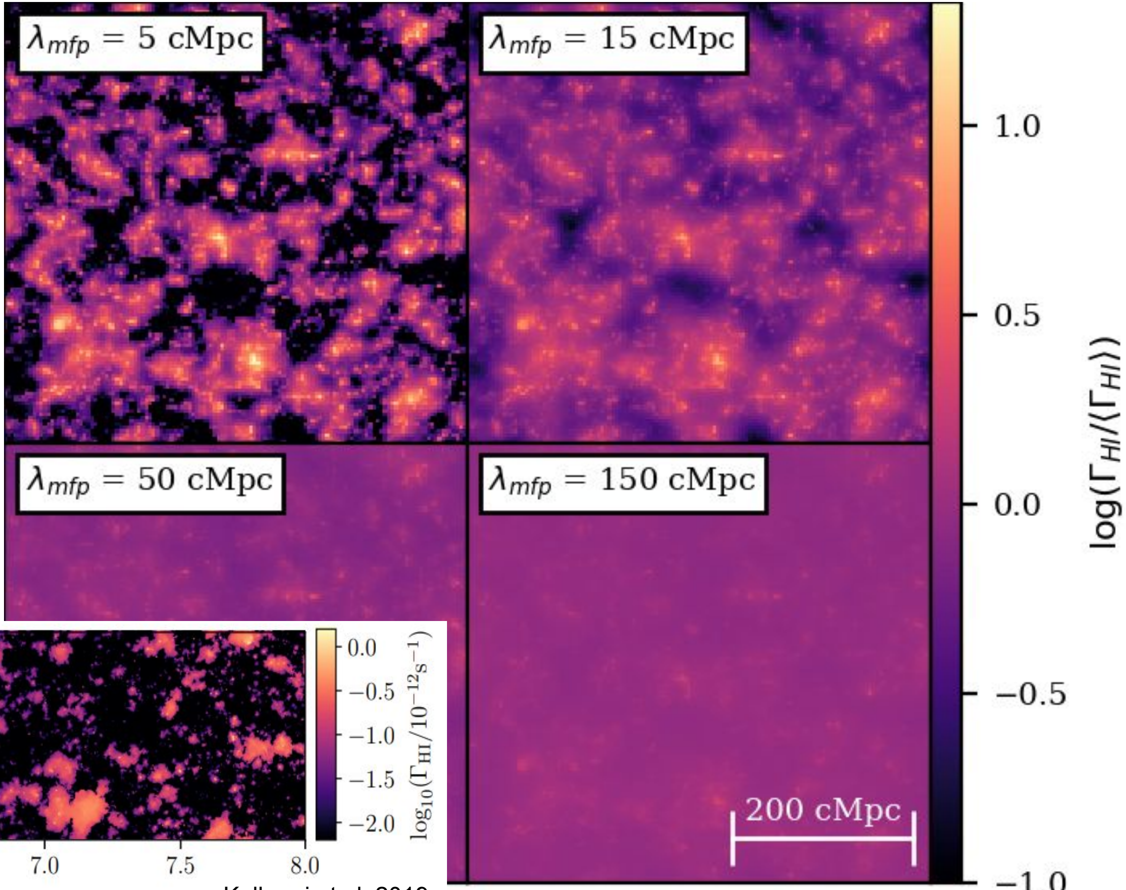


Wolfson et al. 2022

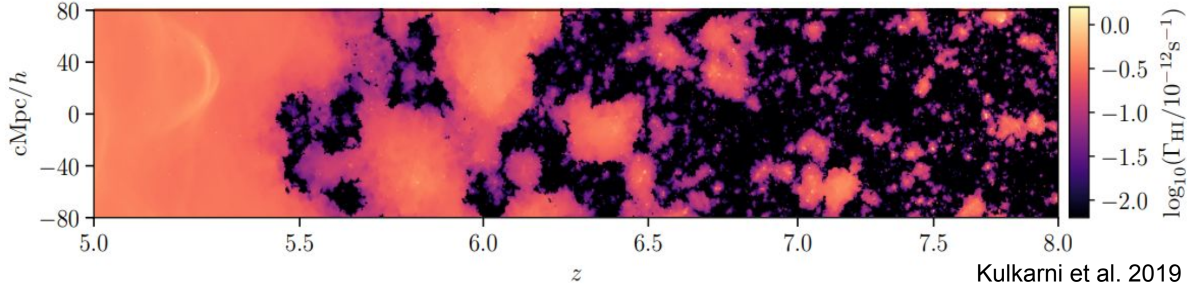
Fluctuations in the UVB can be described by λ_{mfp}

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

Overview:

1. What is Reionization and why is it important?

2. How does the IGM evolve during the end of Reionization?
   Fluctuations in the UVB characterized by λ_{mfp}

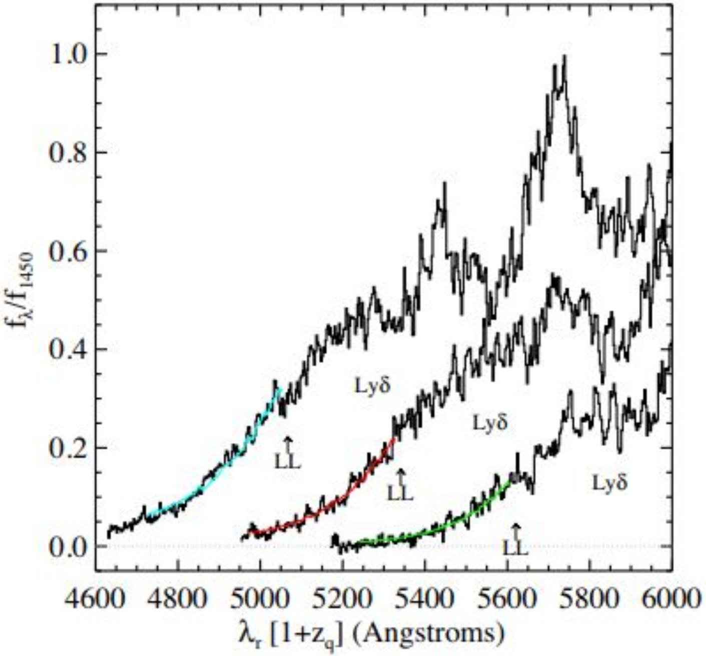
3. **Can we measure this evolution?**
   Auto-correlation function of Lyman-α flux

4. Have I made this measurement?
   Why or why not?

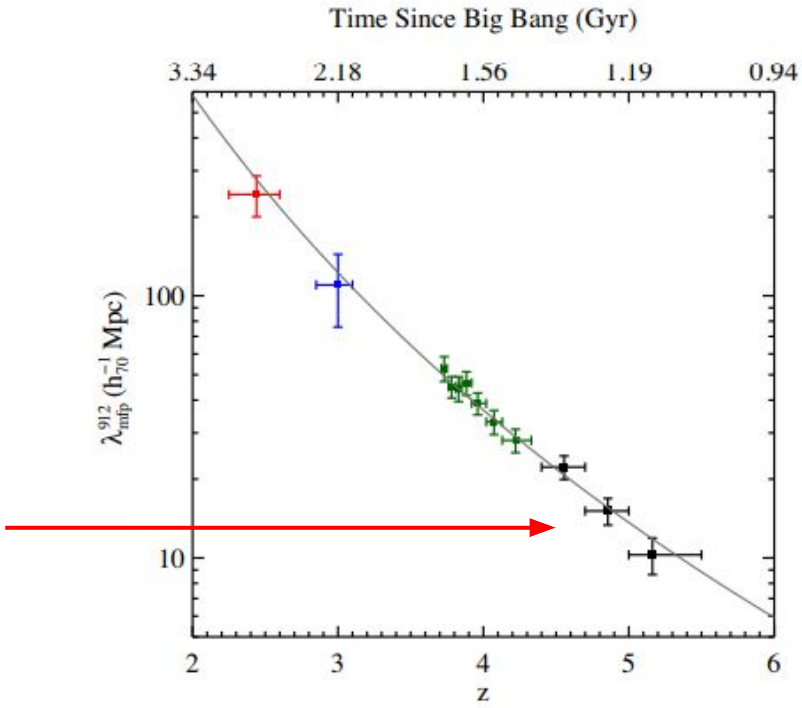
Conclude/Future Plans

Existing measurements of λ_{mfp}

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



Worseck et al. 2014

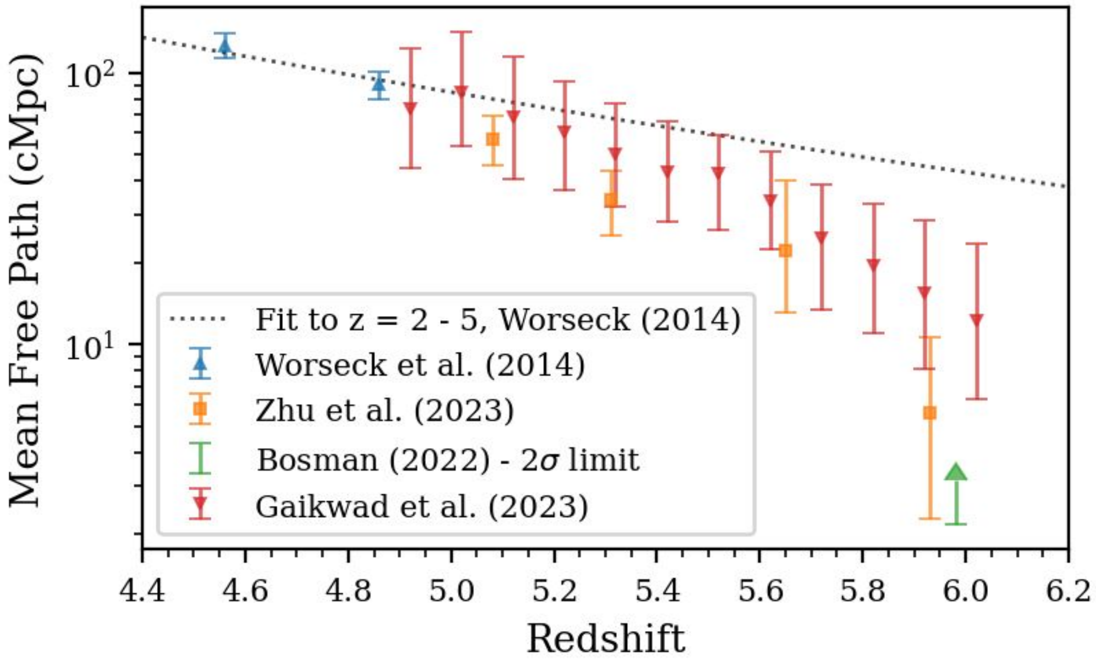


Worseck et al. 2014

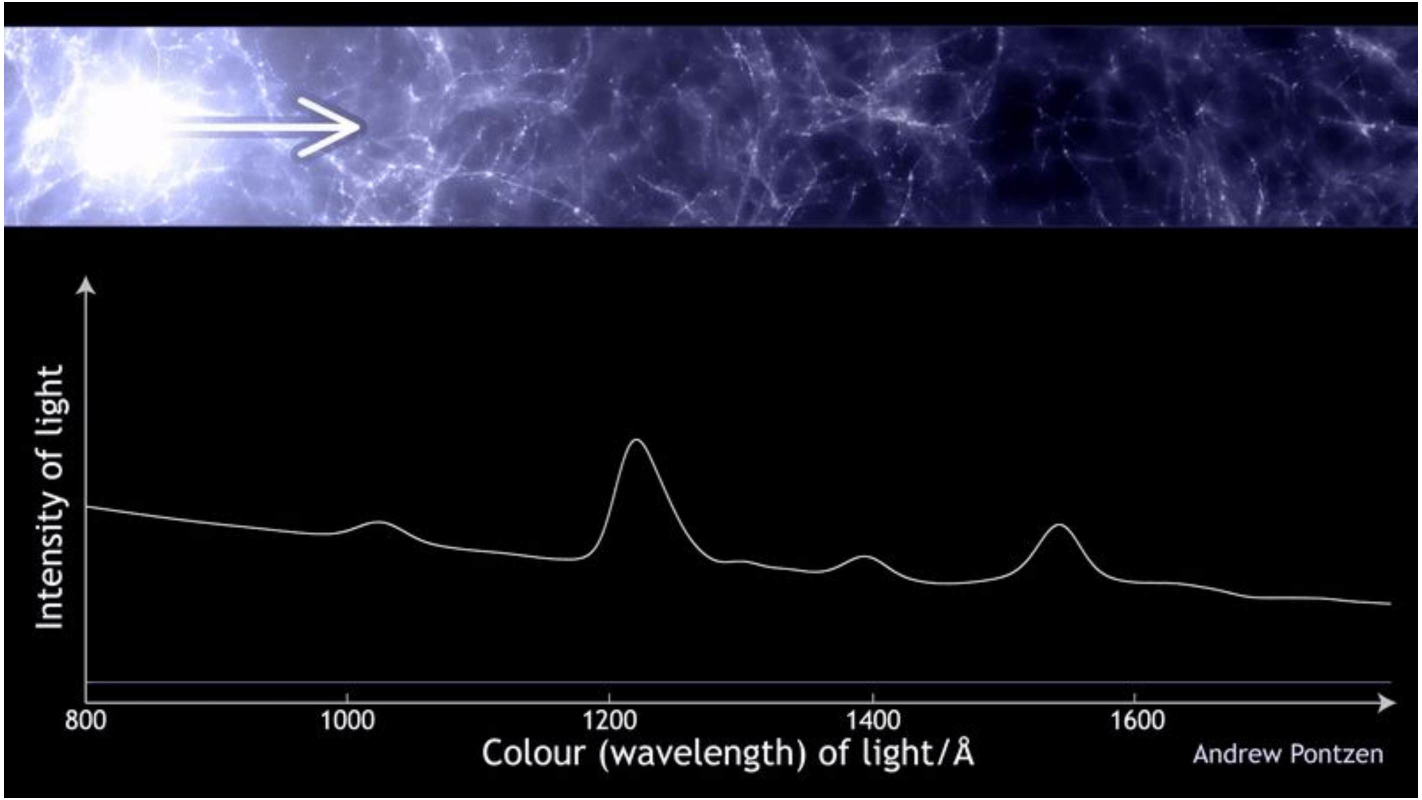
Existing measurements of λ_{mfp}

Blue and Orange points are from flux beyond the Lyman limit in stacked quasar spectra

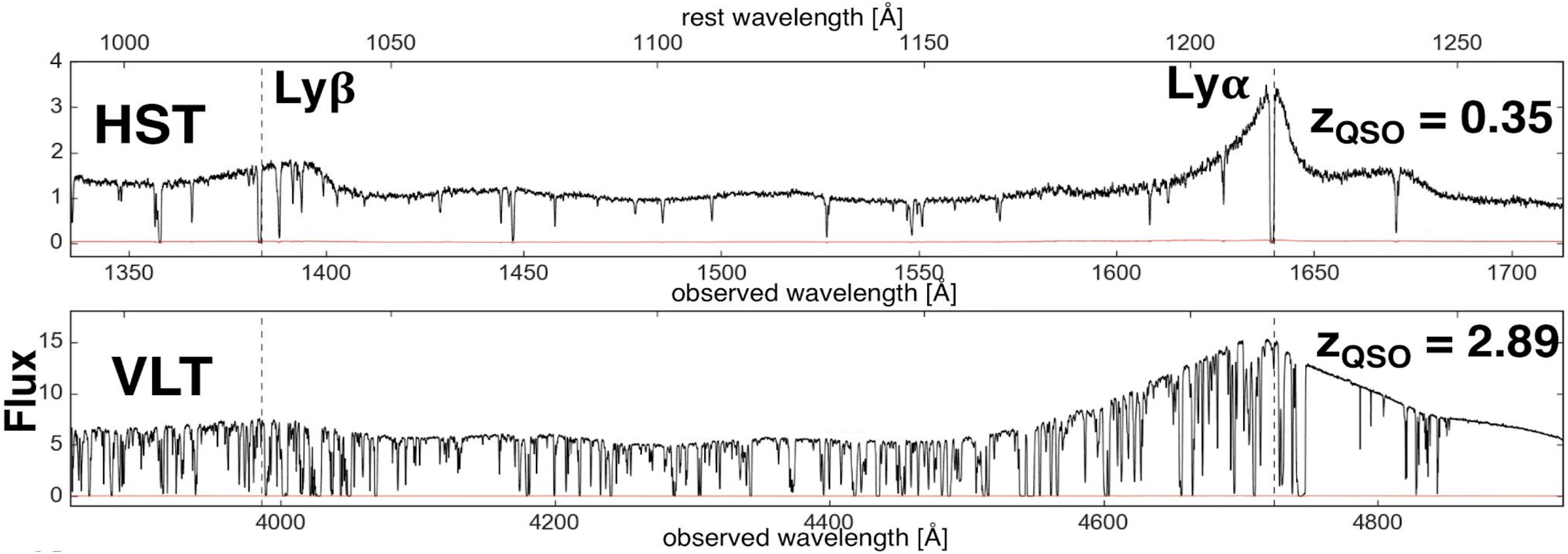
Red points come from the the Lyman-α forest optical depth CDF



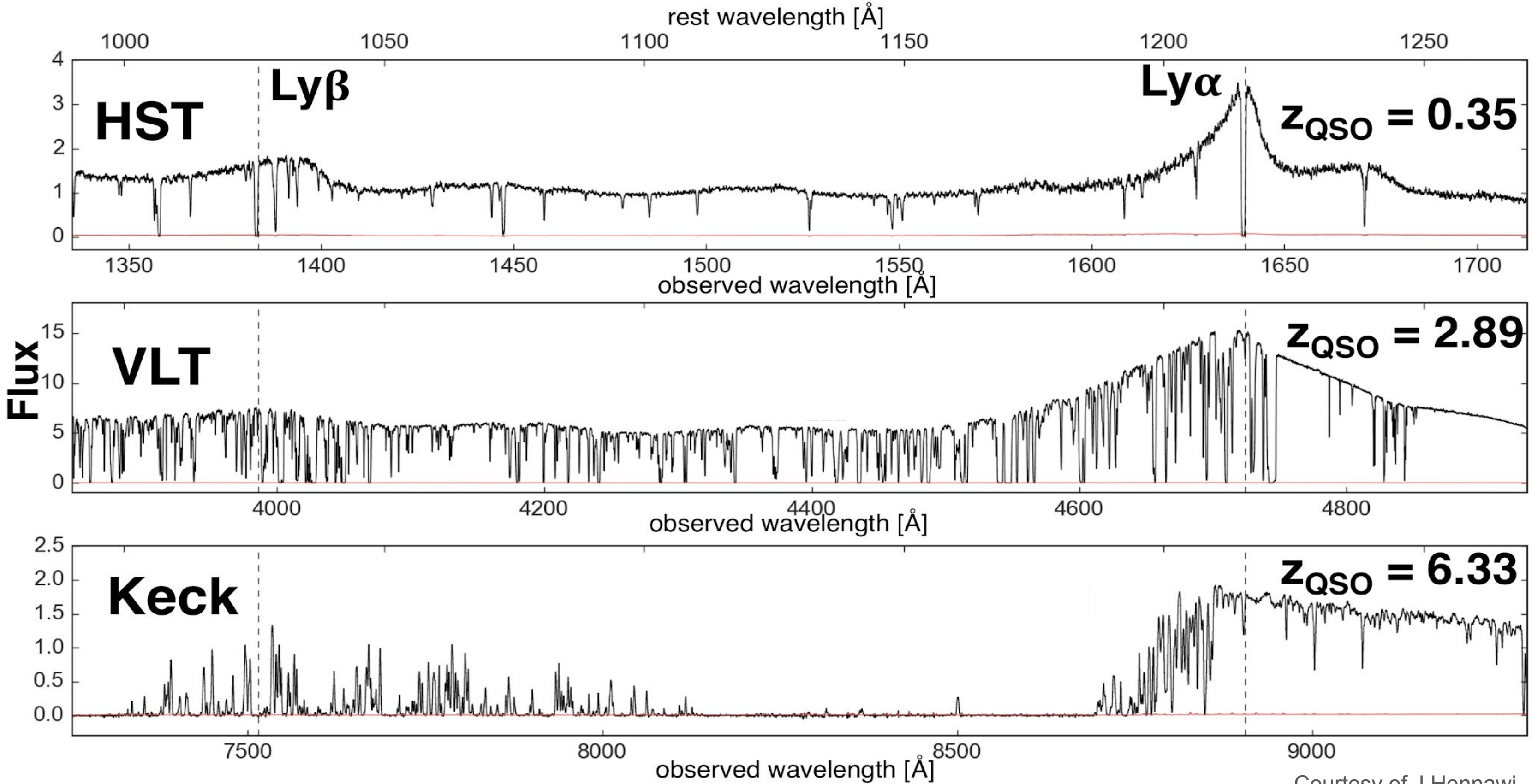
Probing the IGM with the Lyman-α forest:



Lyman-α forest flux at high-z:

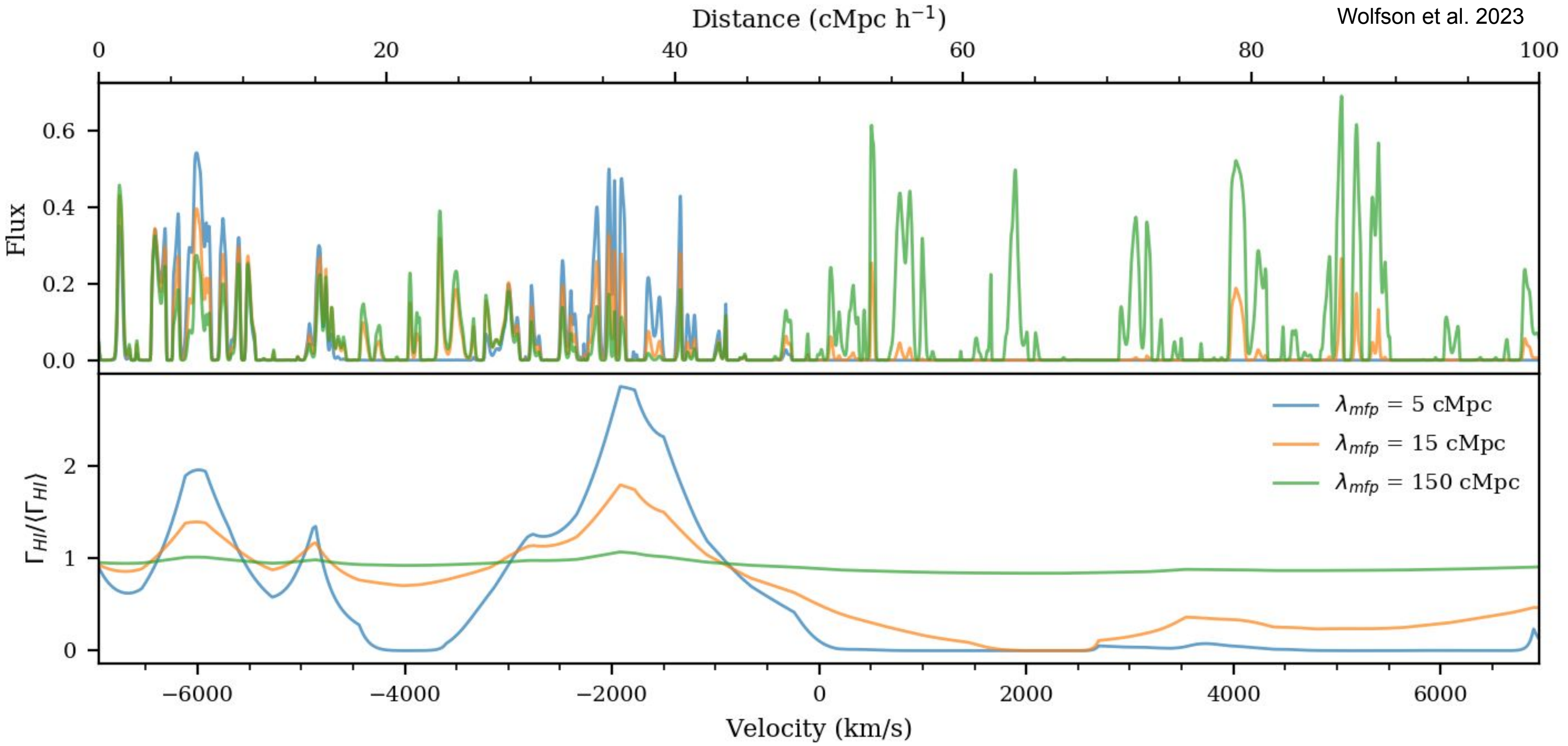


Lyman-α forest flux at high-z:



Courtesy of J.Hennawi

Can you use Lyman-α forest observations to constrain λ_{mfp}?



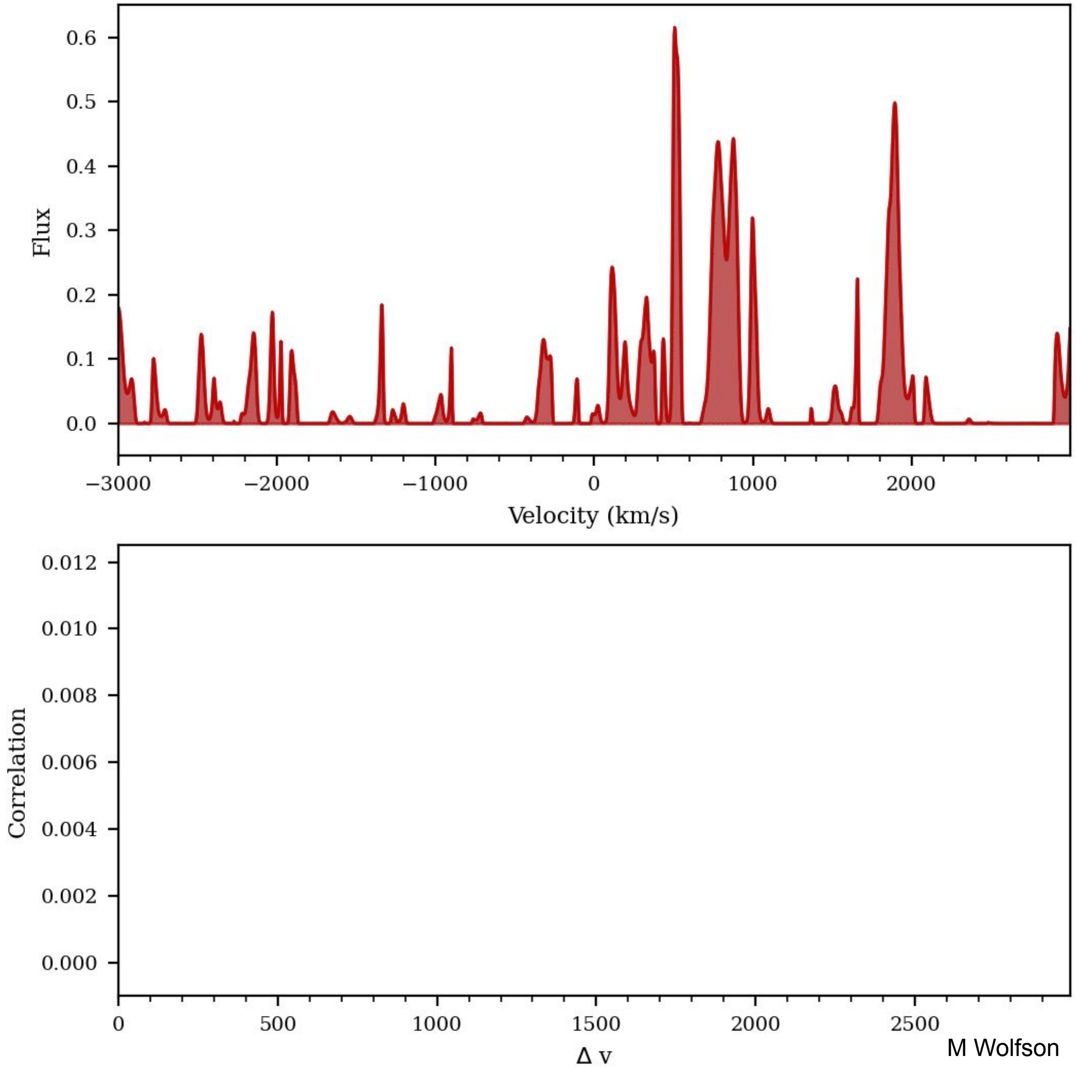
Auto-correlation function:

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

The fourier transform of the 1D power spectrum

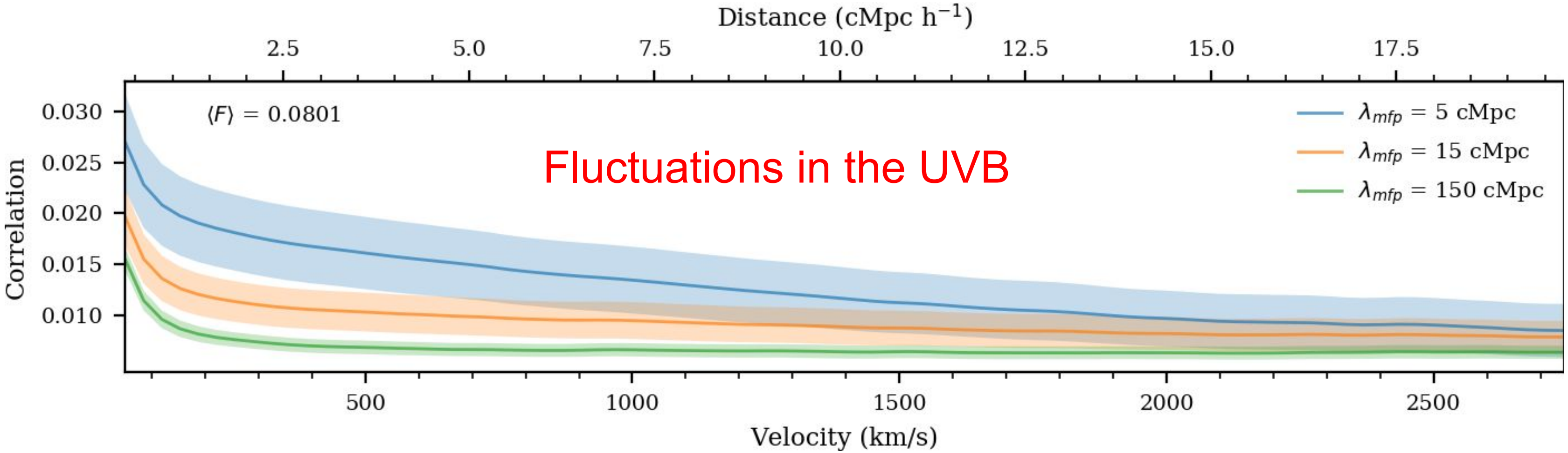
Uncorrelated gaussian noise averages out

Easy to mask out DLAs etc

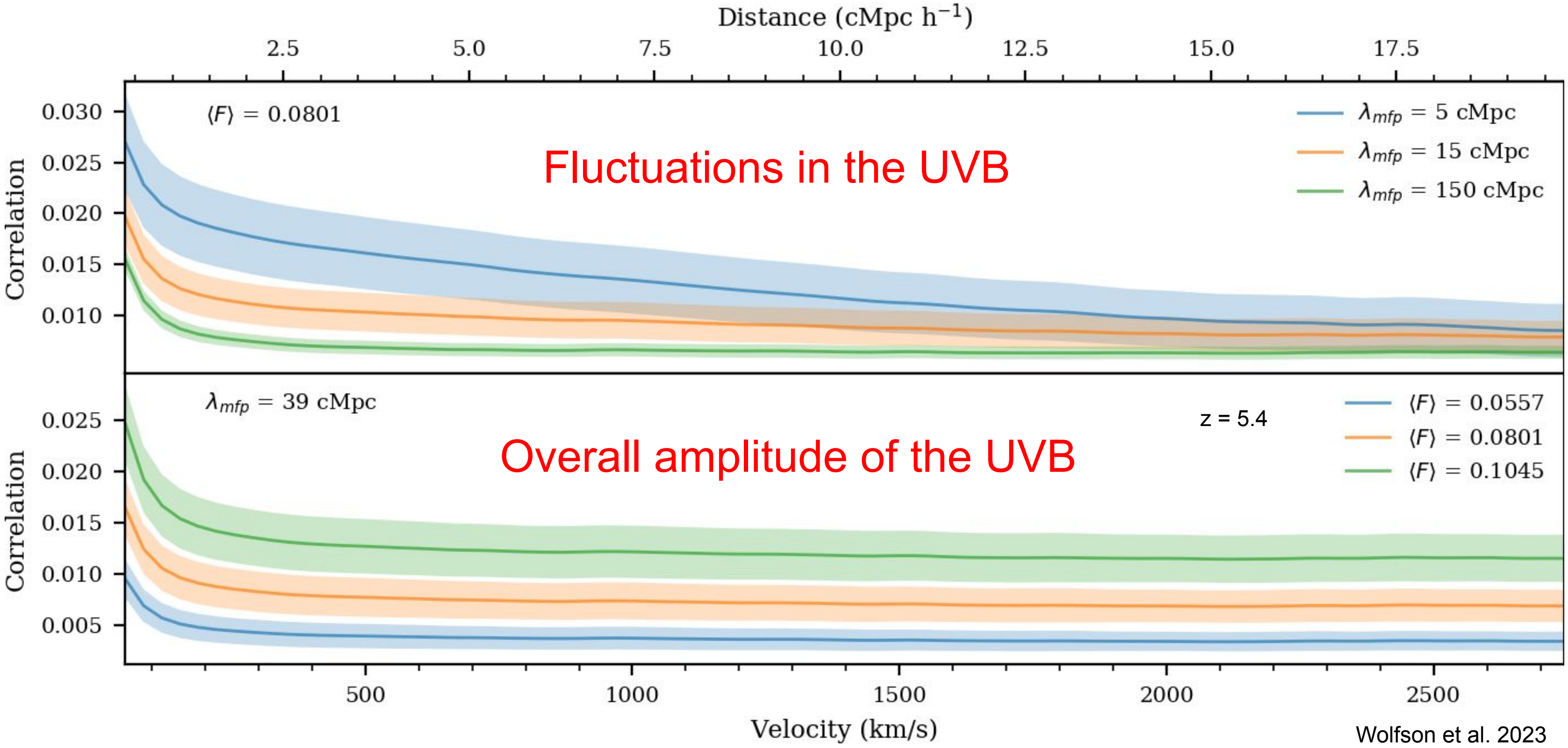


M Wolfson

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



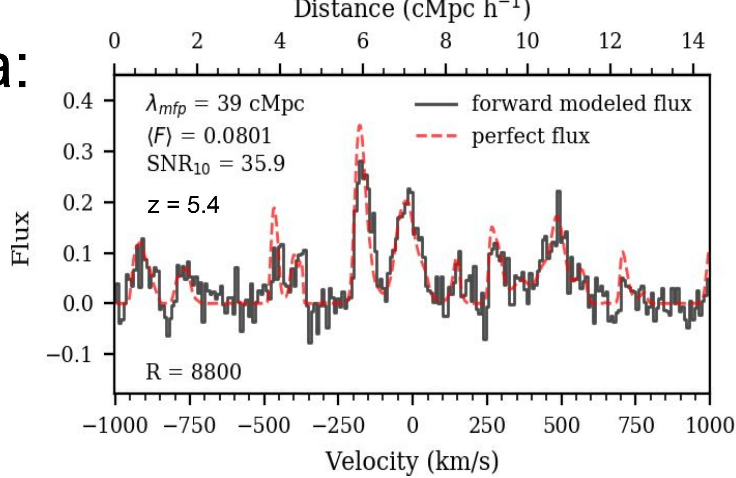
Effect of λ_{mfp} on the auto-correlation function



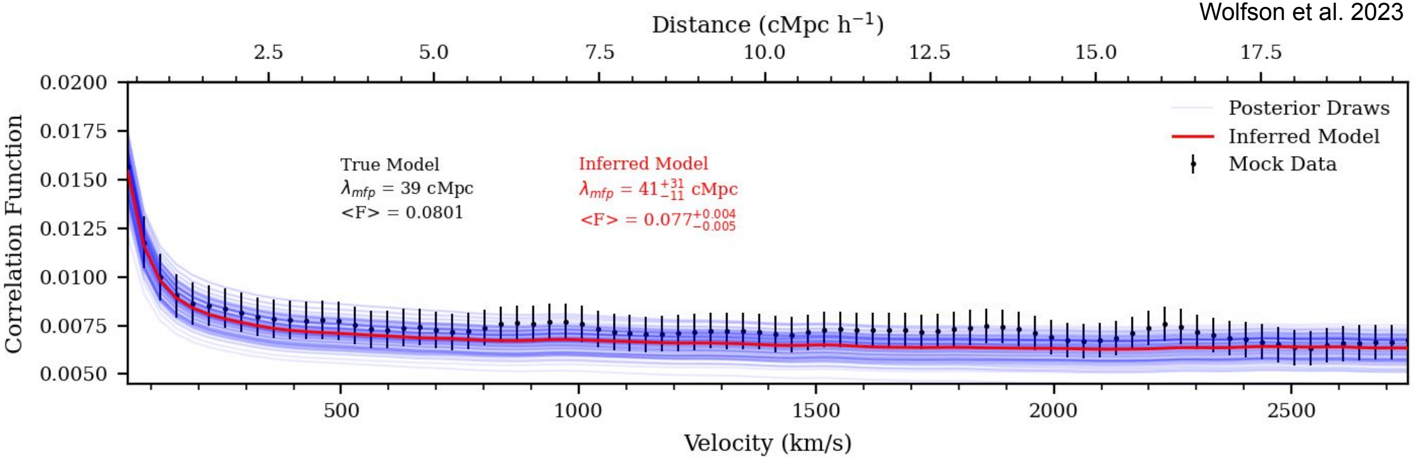
Wolfson et al. 2023

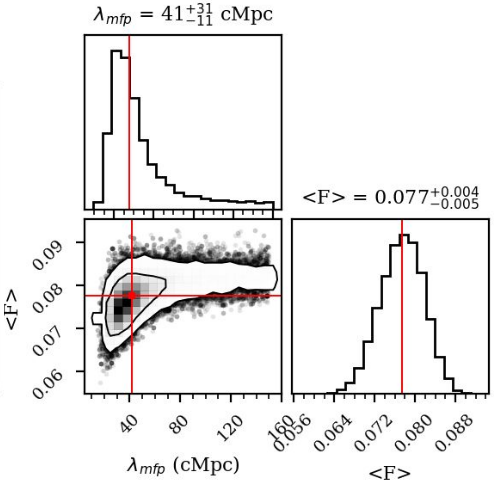
Measuring λ_{mfp} from simulated mock data:

1. Forward model simulation skewers to match observations
2. Use a Gaussian likelihood and MCMC
3. Get constraints on λ_{mfp} and <F>



Wolfson et al. 2023





Overview:

1. What is Reionization and why is it important?

2. How does the IGM evolve during the end of Reionization?
   Fluctuations in the UVB characterized by λ_{mfp}

3. Can we measure this evolution?
   Auto-correlation function of Lyman-α flux

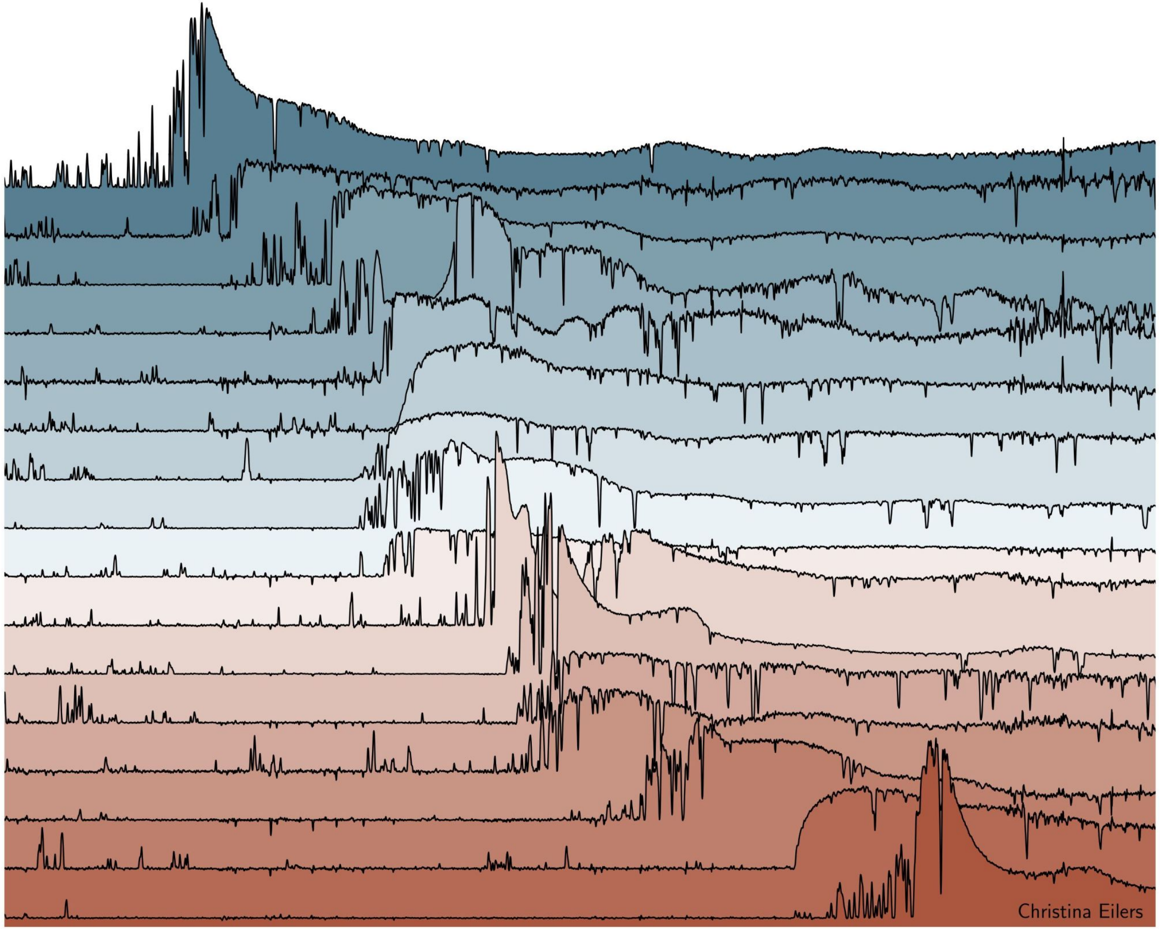
4. **Have I made this measurement?**
   Why or why not?

Conclude/Future Plans

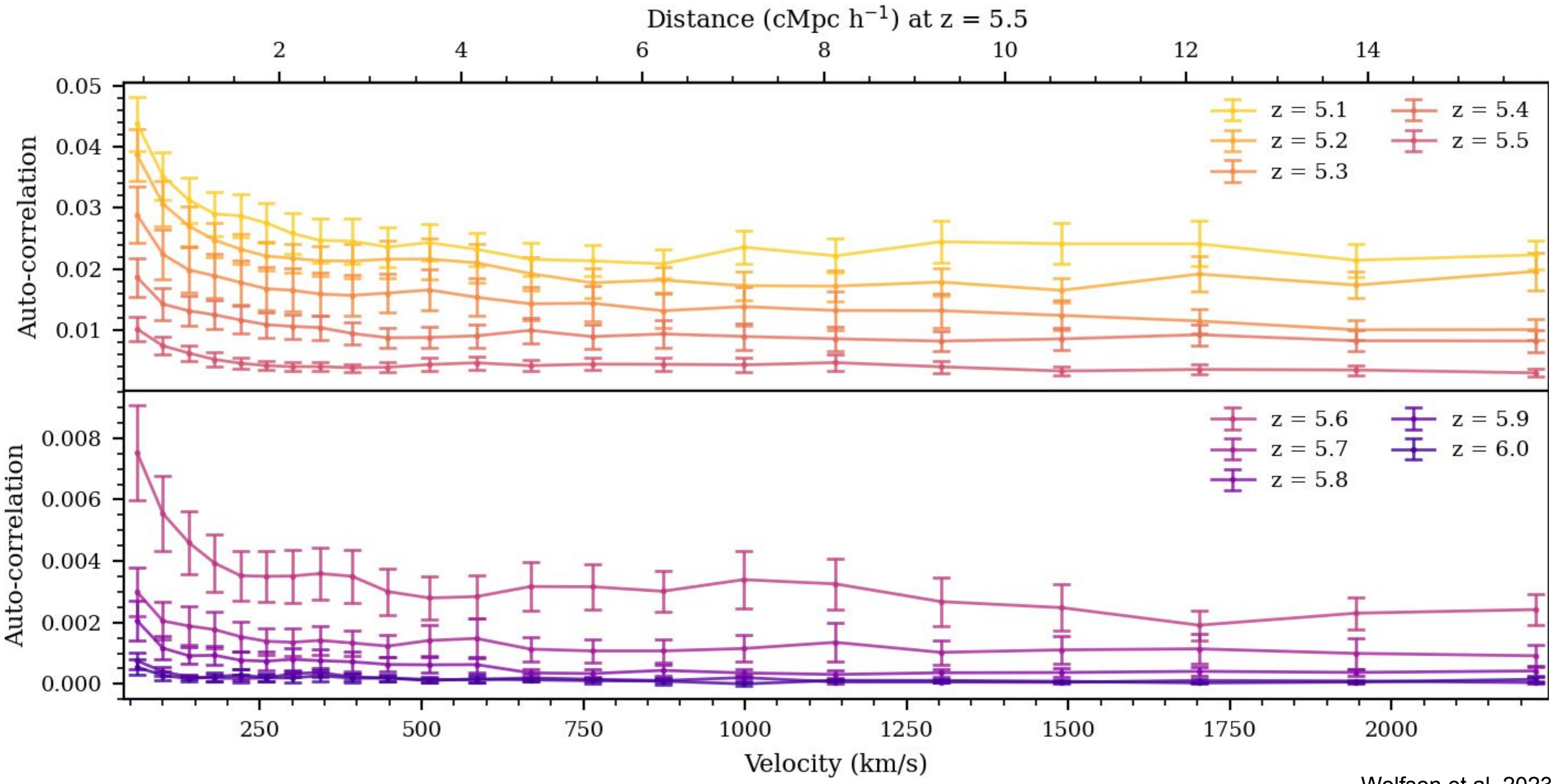
XQR-30 Quasars:

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

- dedicated ~250 hours of observations
- Uses VLT/X-Shooter (R ~ 8800 in the visible)
- 30 new observations of some of the most luminous z > 5.8 quasars observed
- Supplemented with 12 archival observations

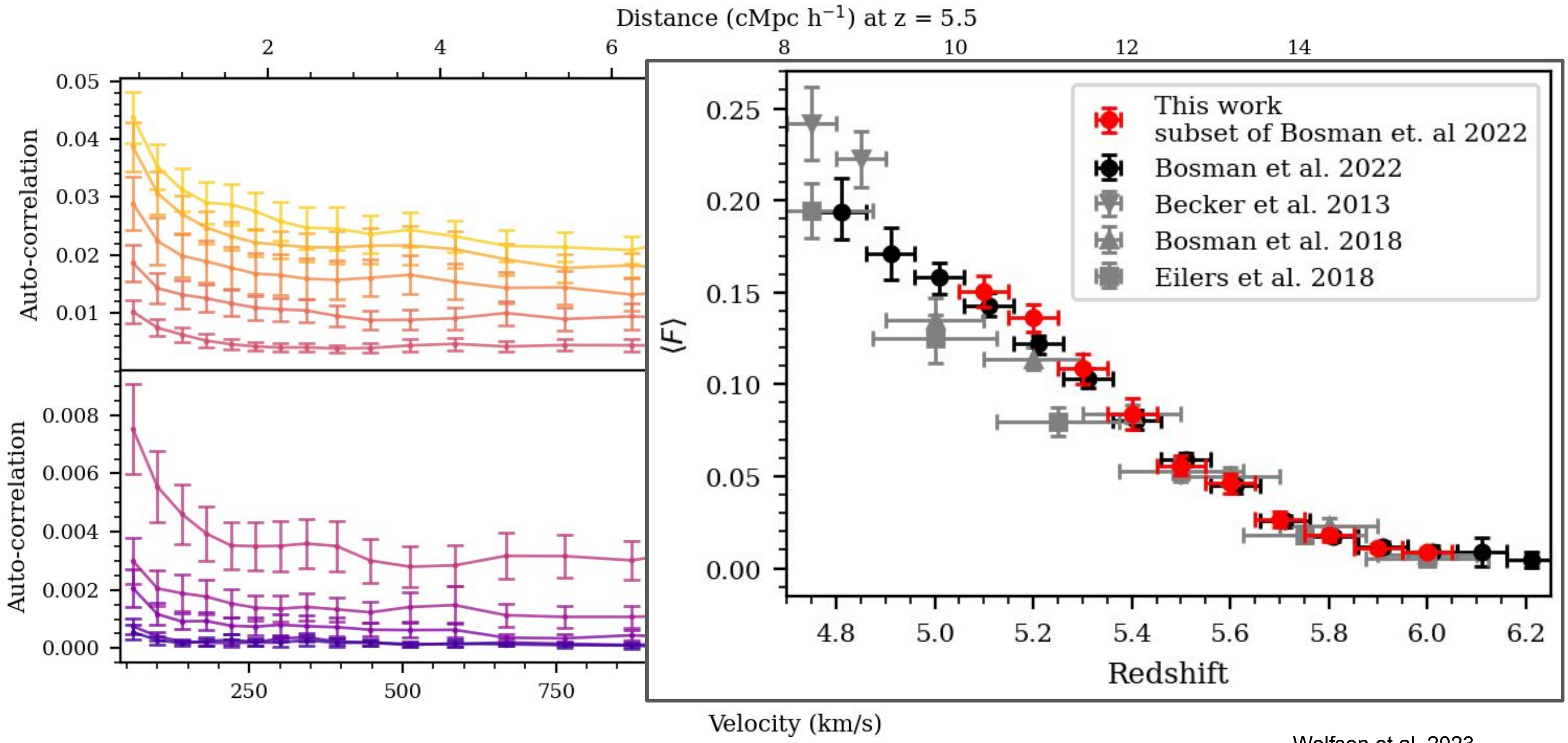


Auto-correlation function from XQR-30



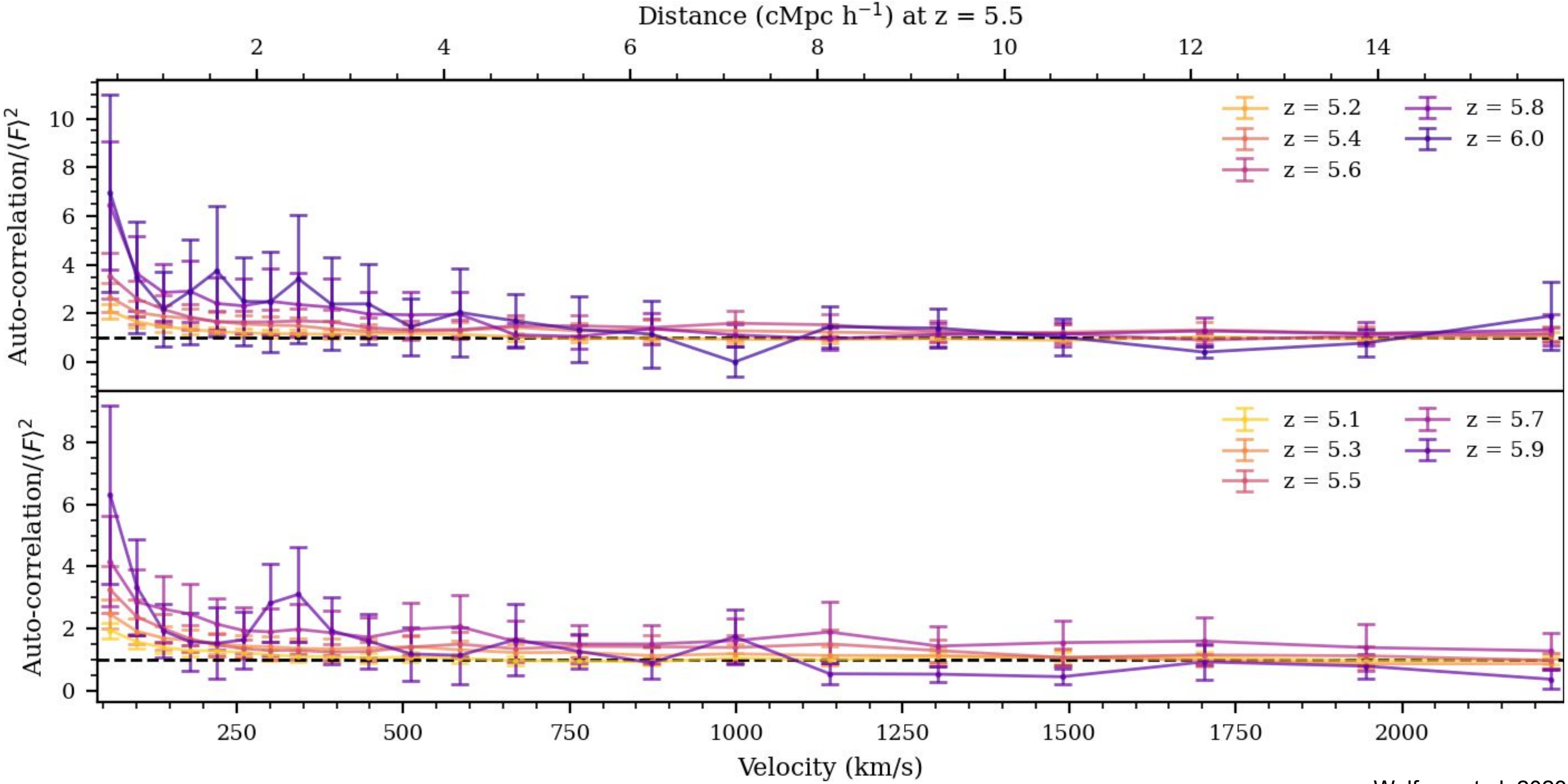
Wolfson et al. 2023

Auto-correlation function from XQR-30



Wolfson et al. 2023

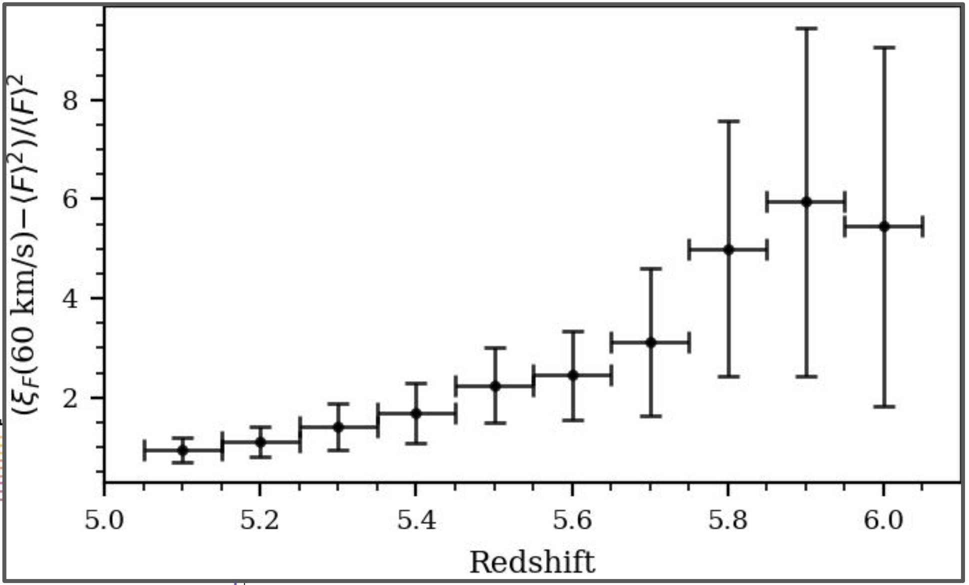
Auto-correlation function from XQR-30



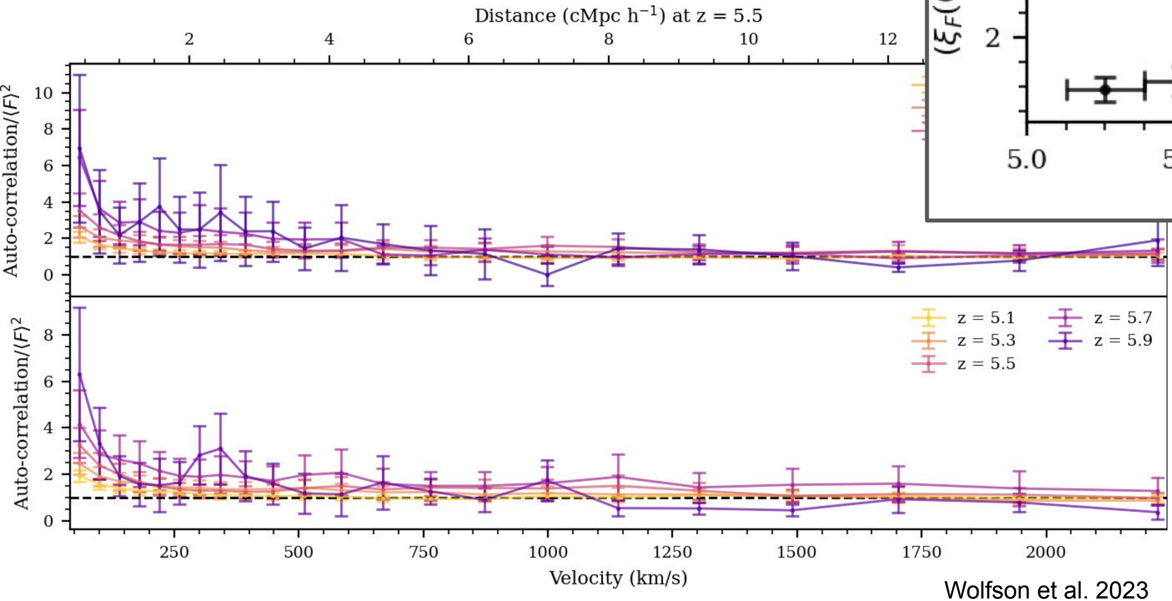
Wolfson et al. 2023

Auto-correlation function from XQR-30

Smallest scale:



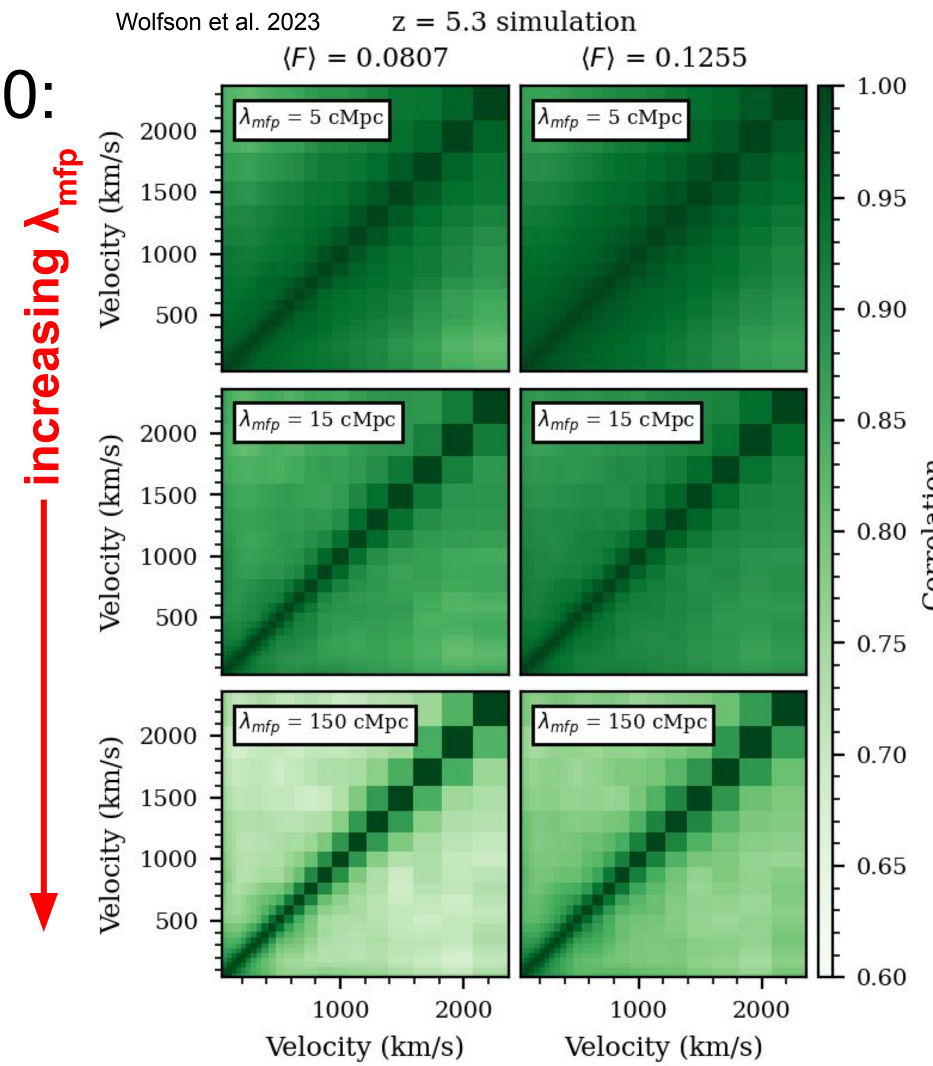
Wolfson et al. 2023



Wolfson et al. 2023

Constraints on λ_{mfp} from XQR-30:

Constraints on λ_{mfp} from XQR-30:



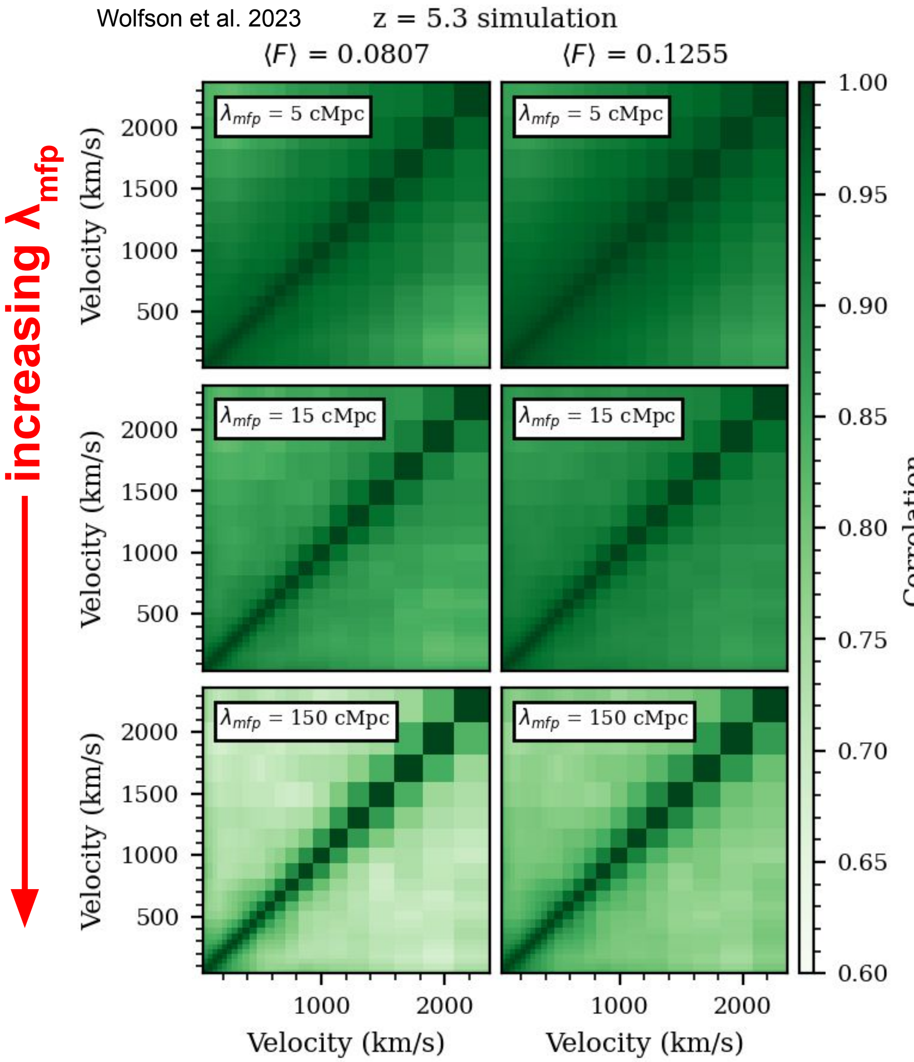
Conclusions:

- Understanding the thermal state of the IGM and characterizing the UVB at $z > 5$ can provide **numerical constraints** on Reionization
- Both the thermal state and λ_{mfp} can be constrained with the **auto-correlation function of the Lyα forest flux**
- Presented the **first measurement** of these auto-correlation functions at $z > 5$
  - Initial naive fits are not performing as well as fits to mock data – more physics?
- The auto-correlation function mixes scales, meaning that this measurement requires simulating **many orders of magnitudes** correctly

Questions?

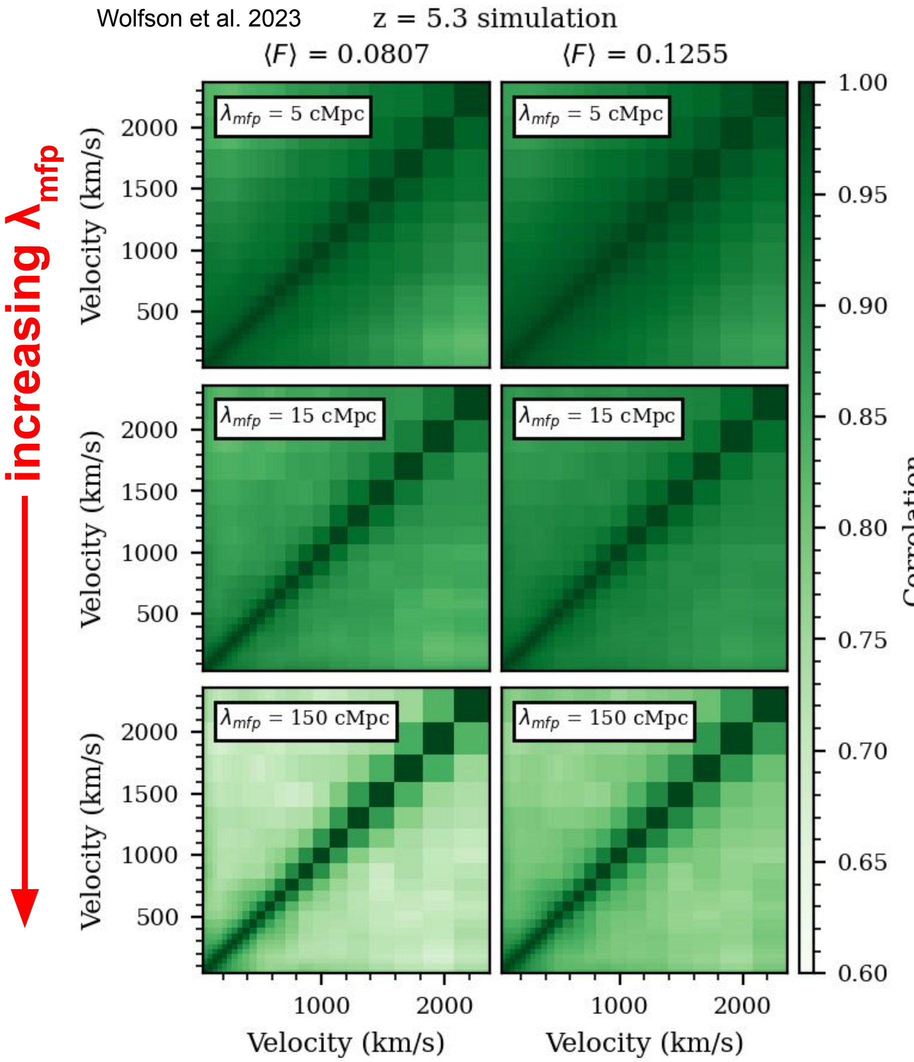
Extra Slides

The covariance matrix also evolves with λ_{mfp}:



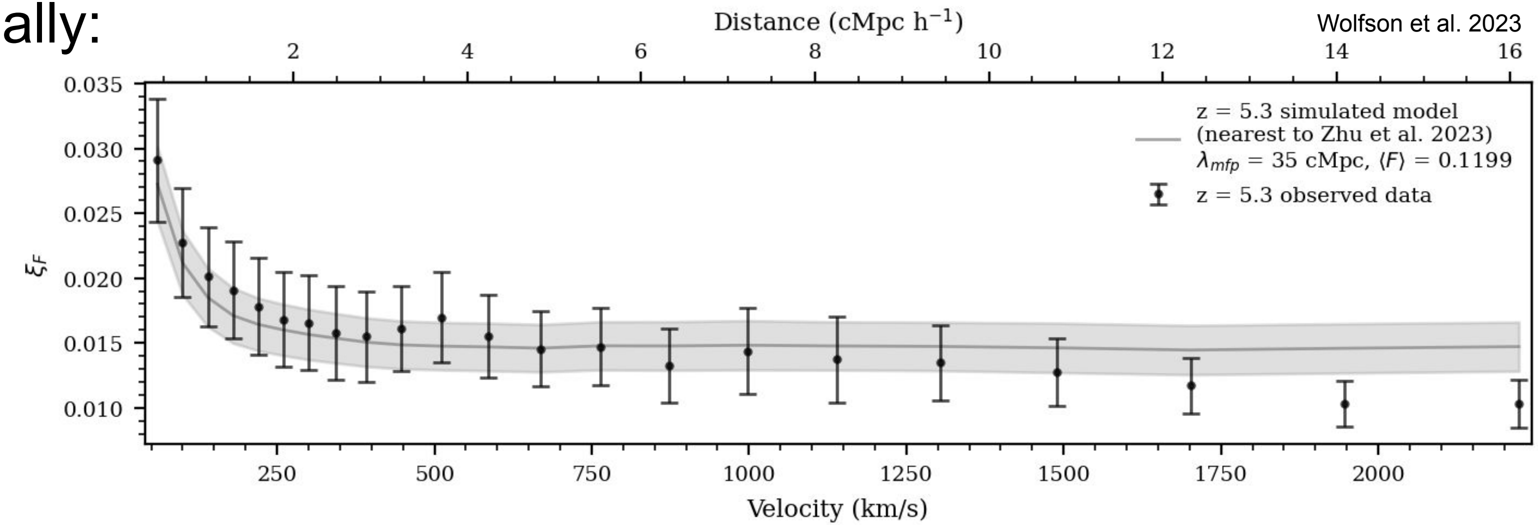
The covariance matrix also evolves with λ_{mfp}:

We are not only fitting the model line but also this covariance matrix structure



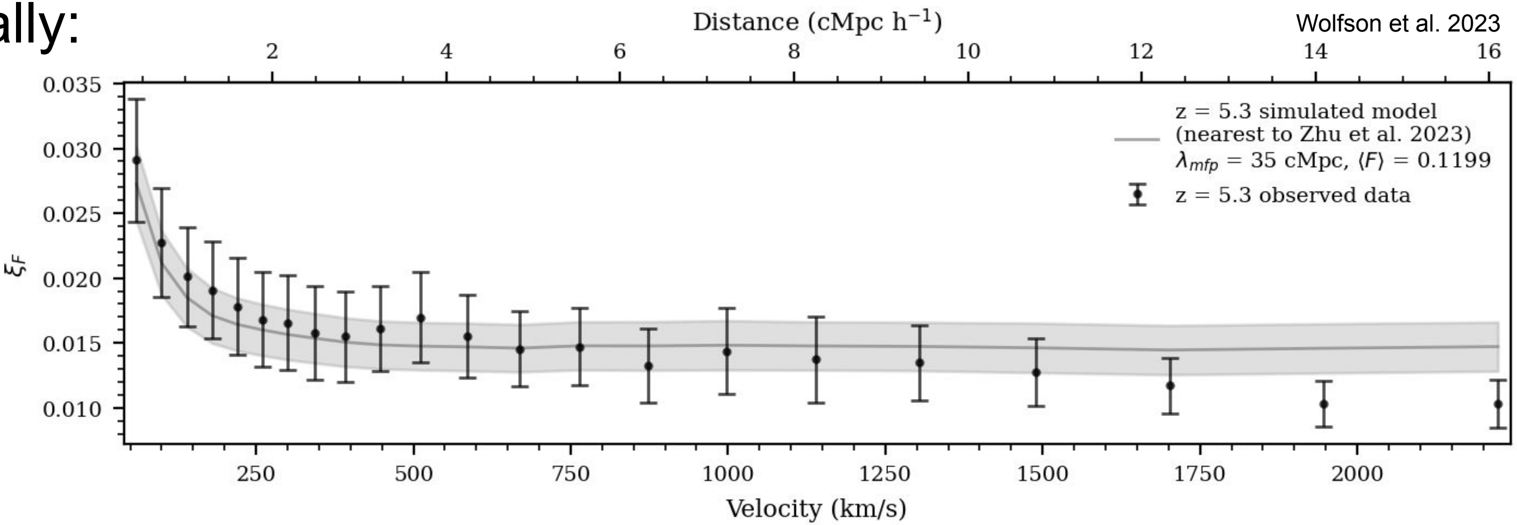
A model value of the auto-correlation function may seem like a good fit visually:

Wolfson et al. 2023

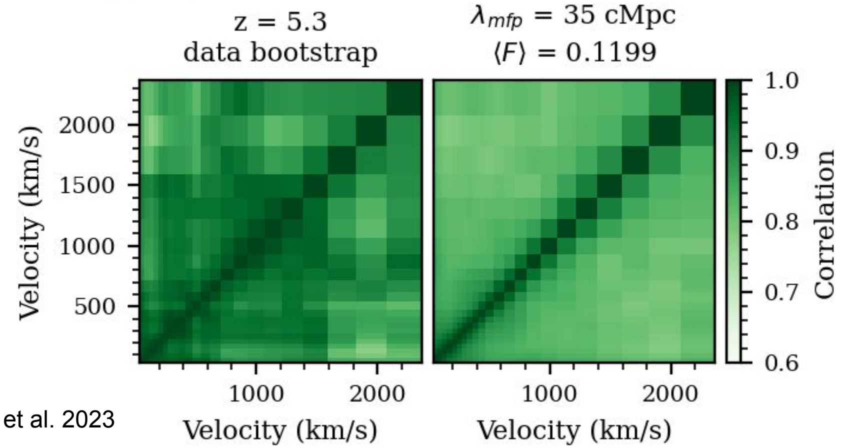


A model value of the auto-correlation function may seem like a good fit visually:

Wolfson et al. 2023



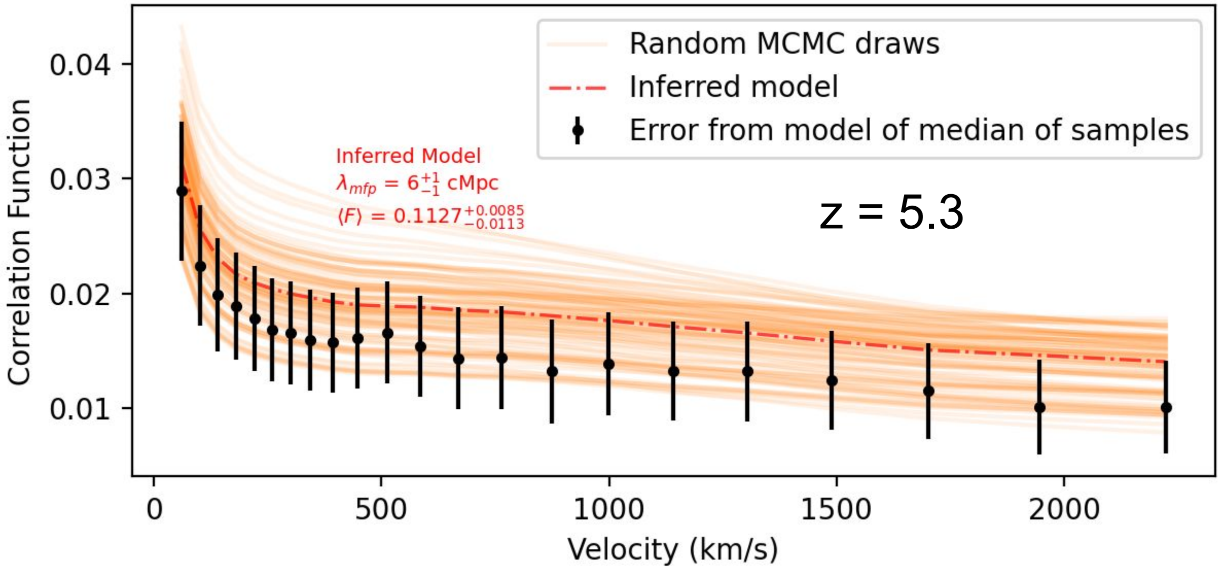
But the covariance matrix may disagree:

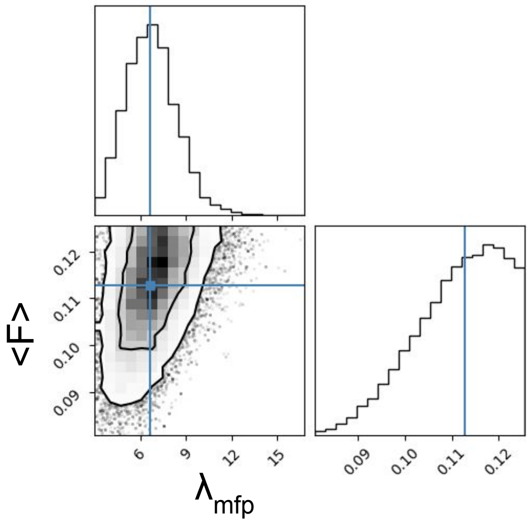


Wolfson et al. 2023

Attempting a fit on XQR-30 data at z = 5.3

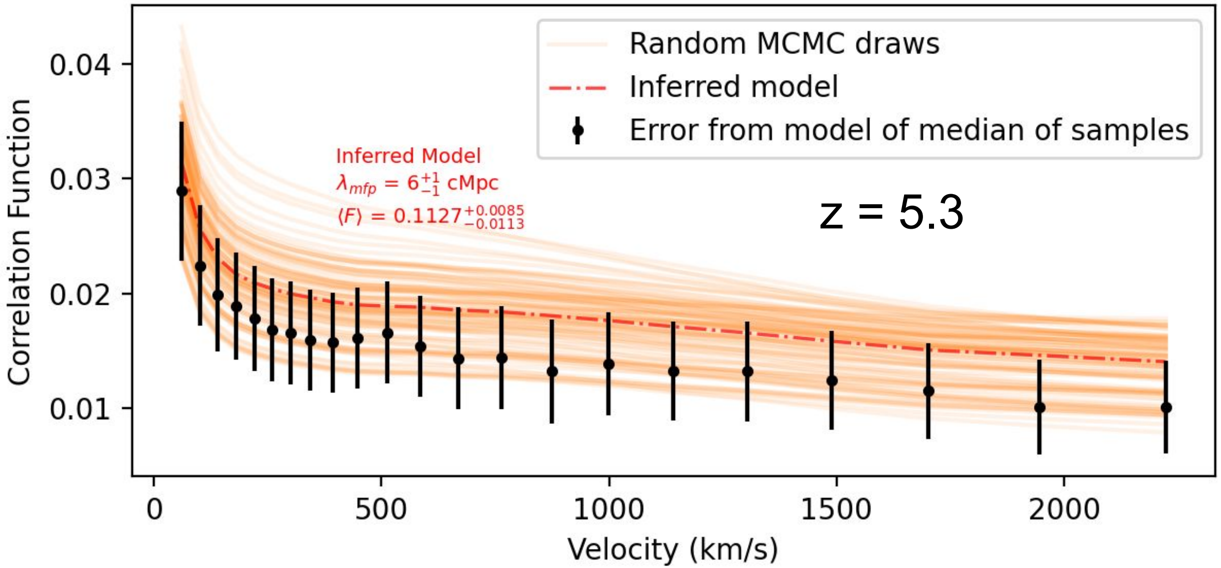
Wolfson et al. in prep.

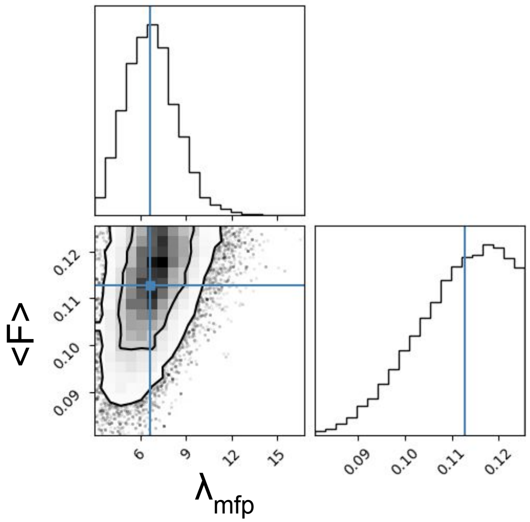




Attempting a fit on XQR-30 data at z = 5.3

Wolfson et al. in prep.

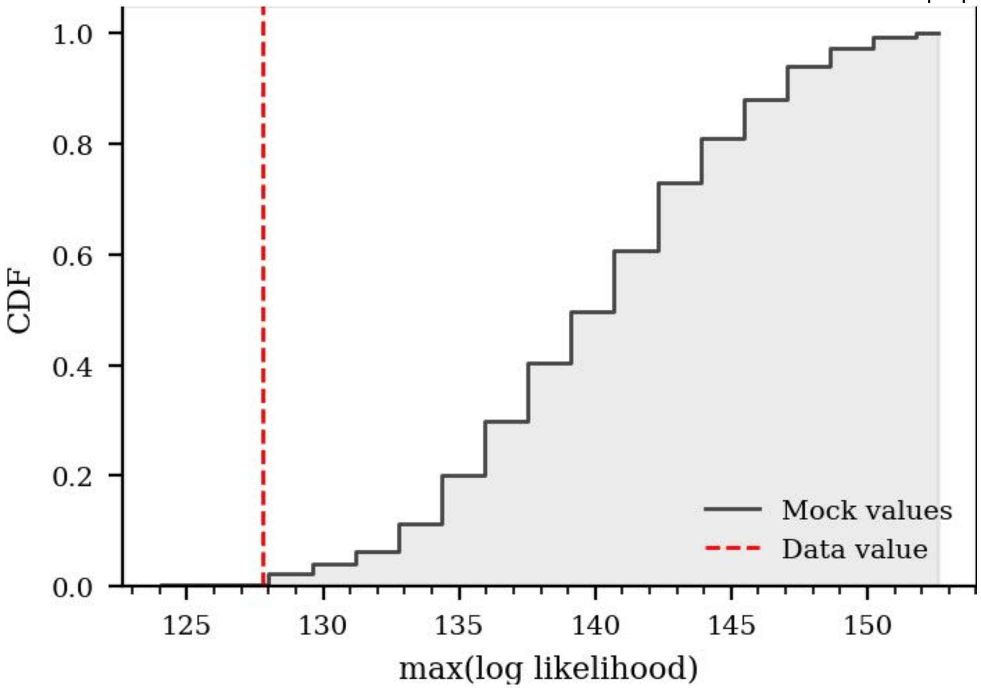




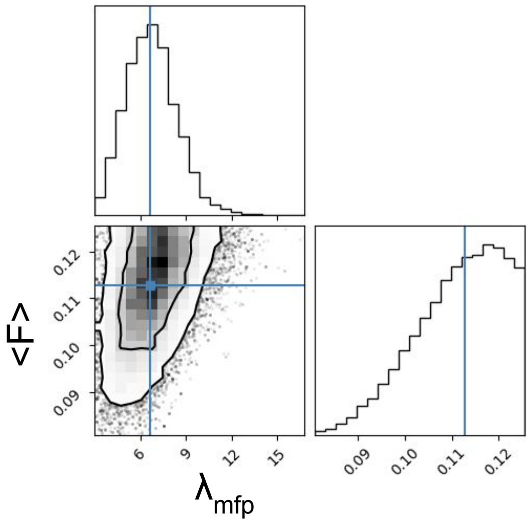
Can we quantify how 'good' this fit is compared to the mock data?

Attempting a fit on XQR-30 data at z = 5.3

Wolfson et al. in prep.

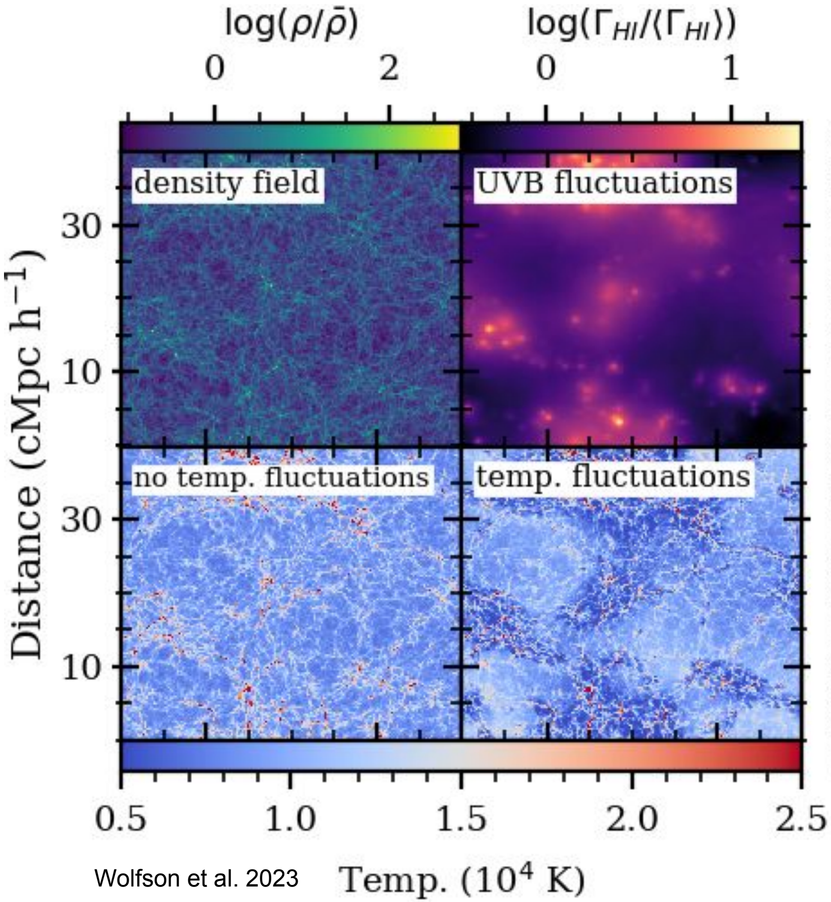


Wolfson et al. in prep.



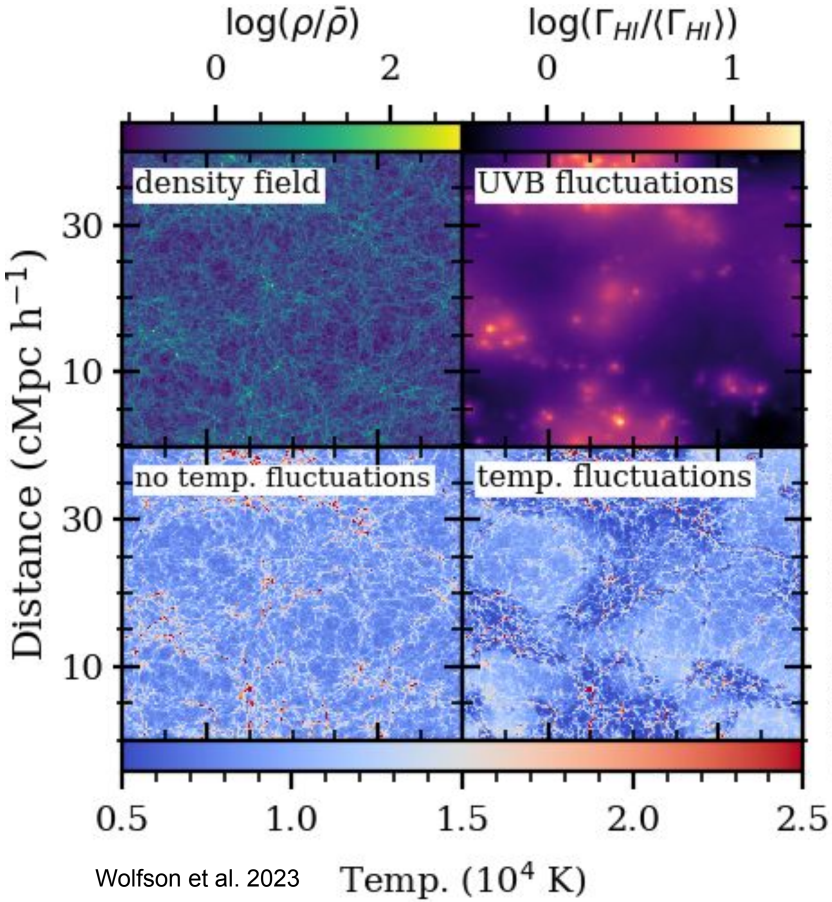
Can we quantify how ‘good’ this fit is compared to the mock data?

How does adding temperature fluctuations change things?

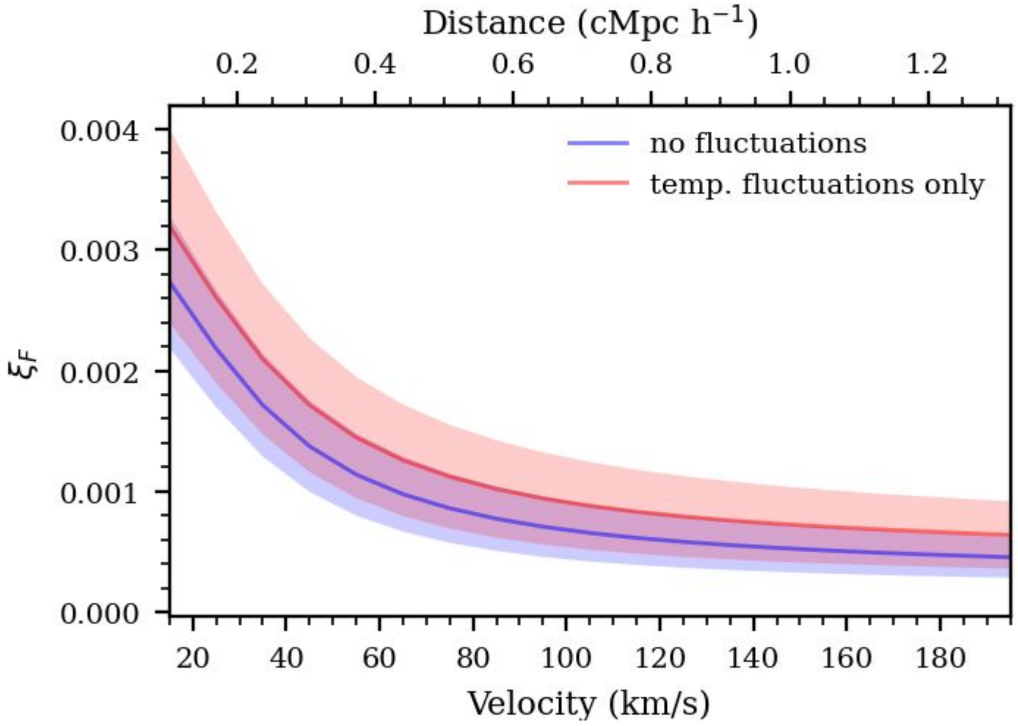


Wolfson et al. 2023

How does adding temperature fluctuations change things?

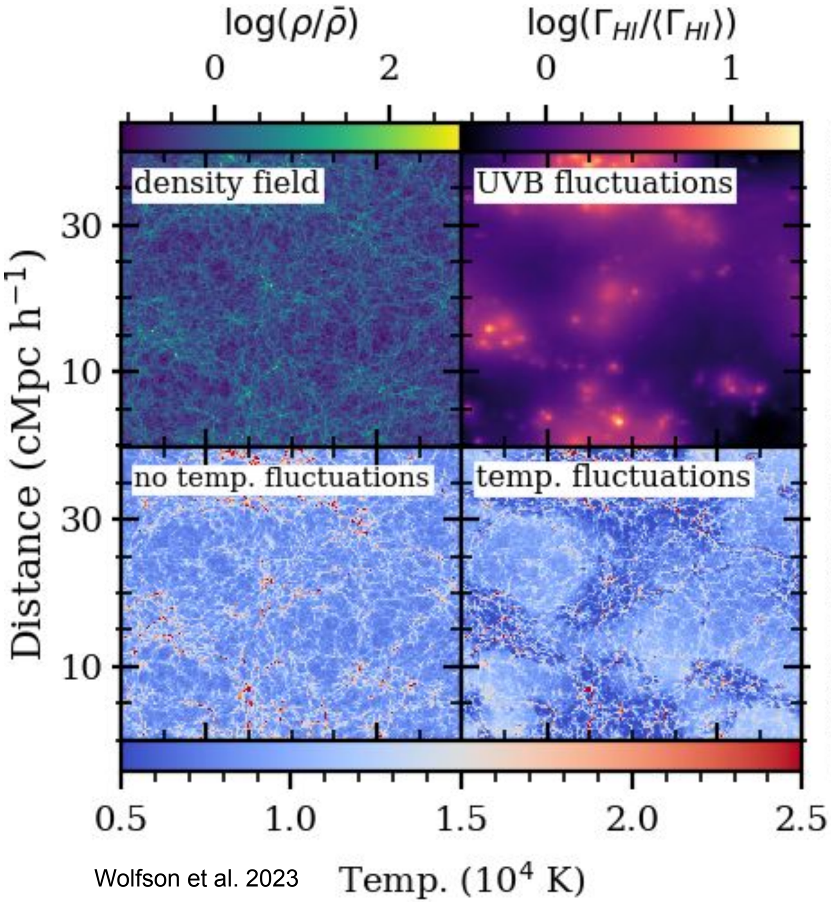


Wolfson et al. 2023

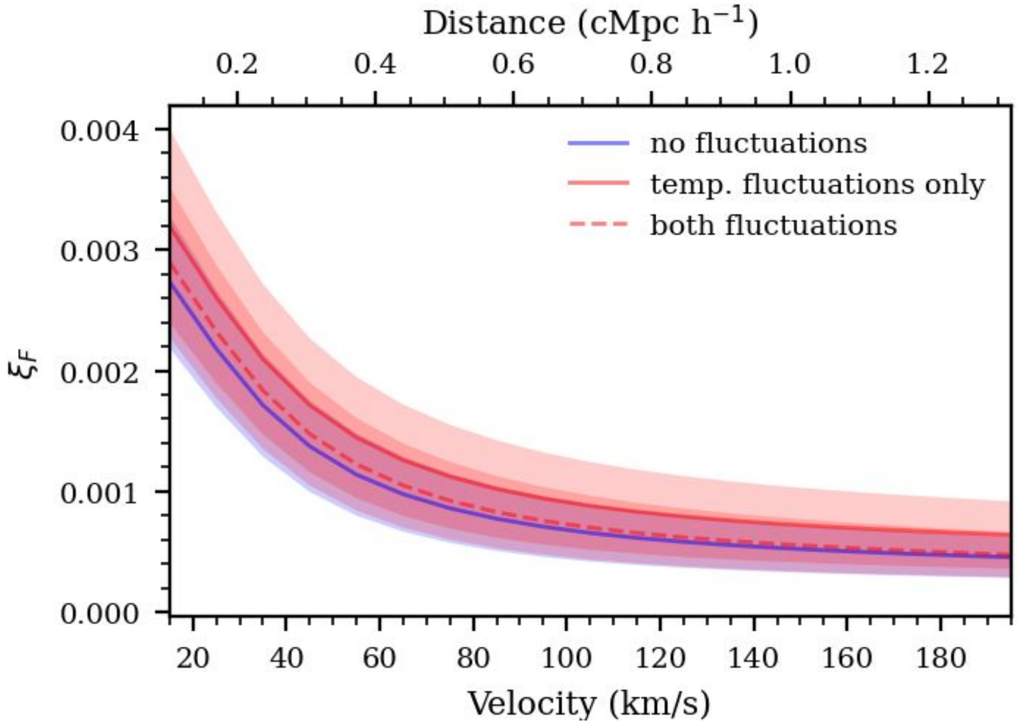


Wolfson et al. 2023

How does adding temperature fluctuations change things?

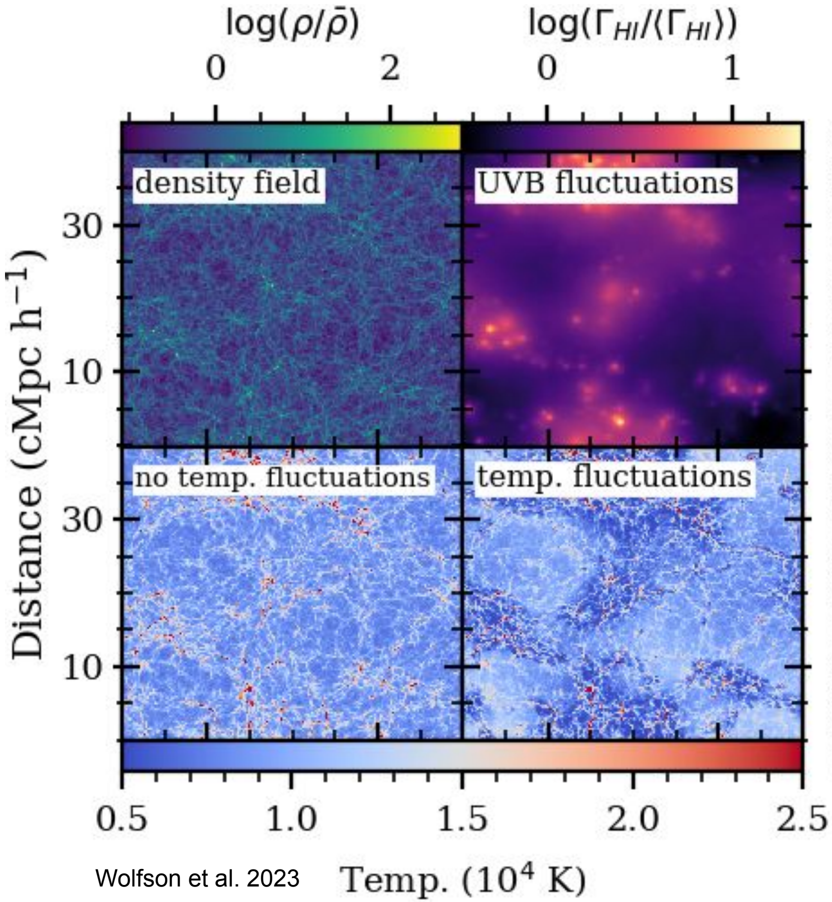


Wolfson et al. 2023



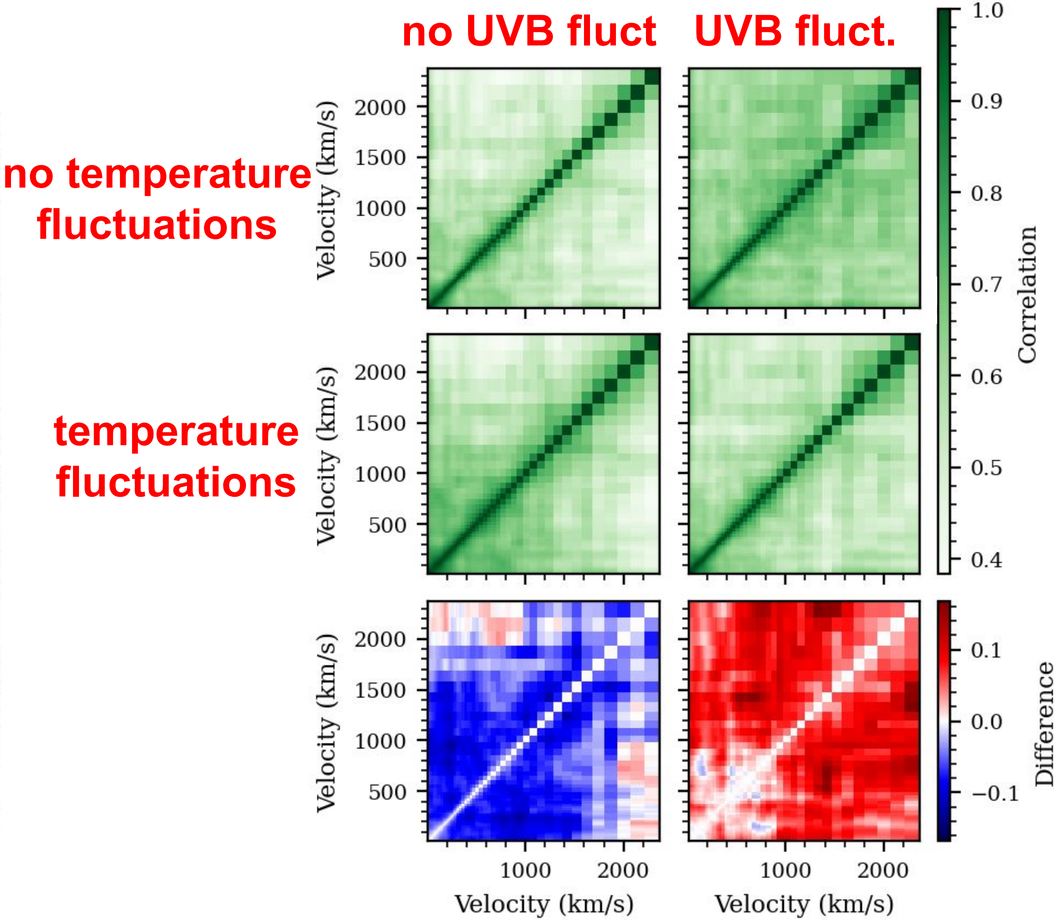
Wolfson et al. 2023

How does adding temperature fluctuations change things?



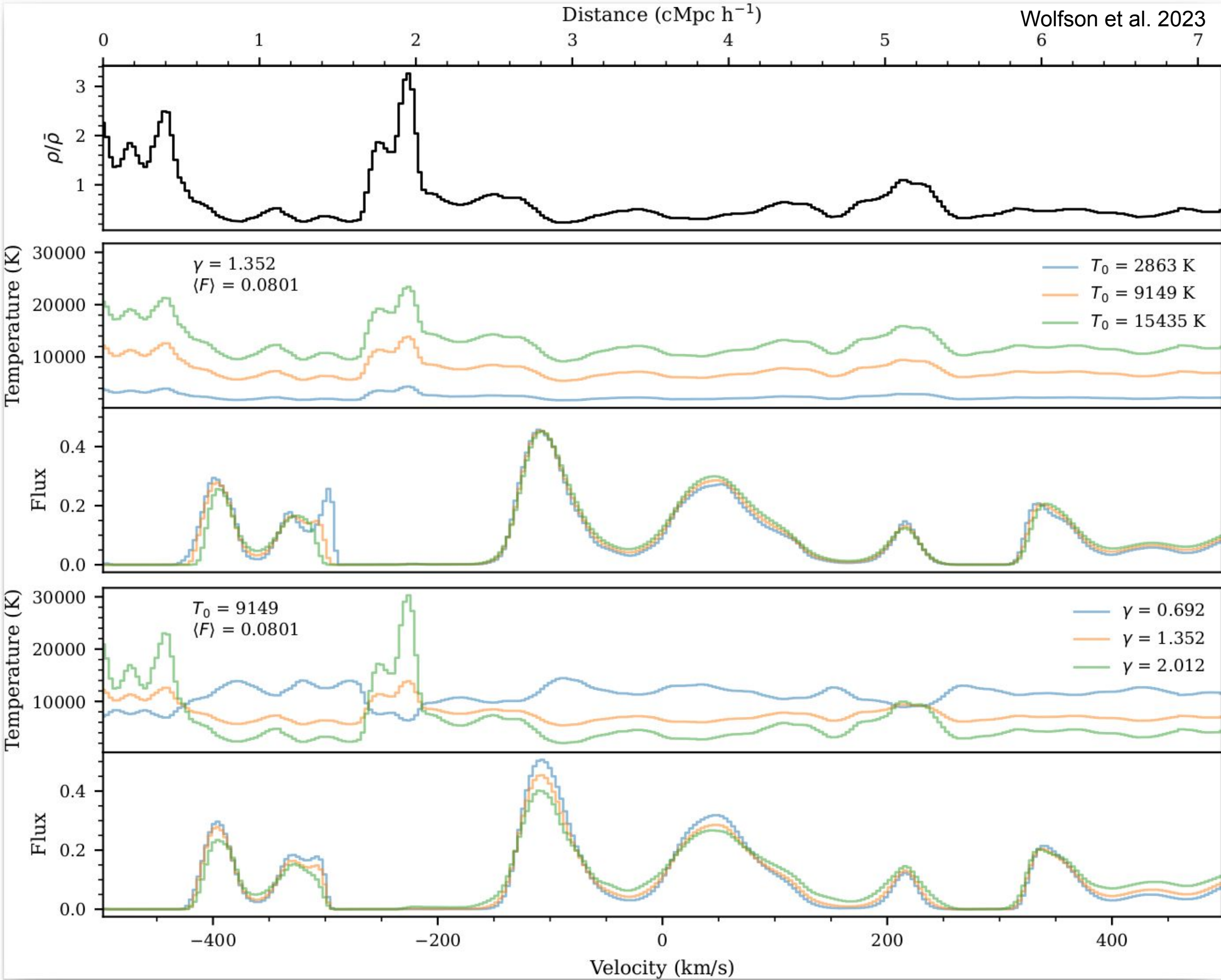
Wolfson et al. 2023

Wolfson et al. in prep.



Can you use high-resolution measurements to constrain the thermal state?

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



Thermal state effect on the correlation function: