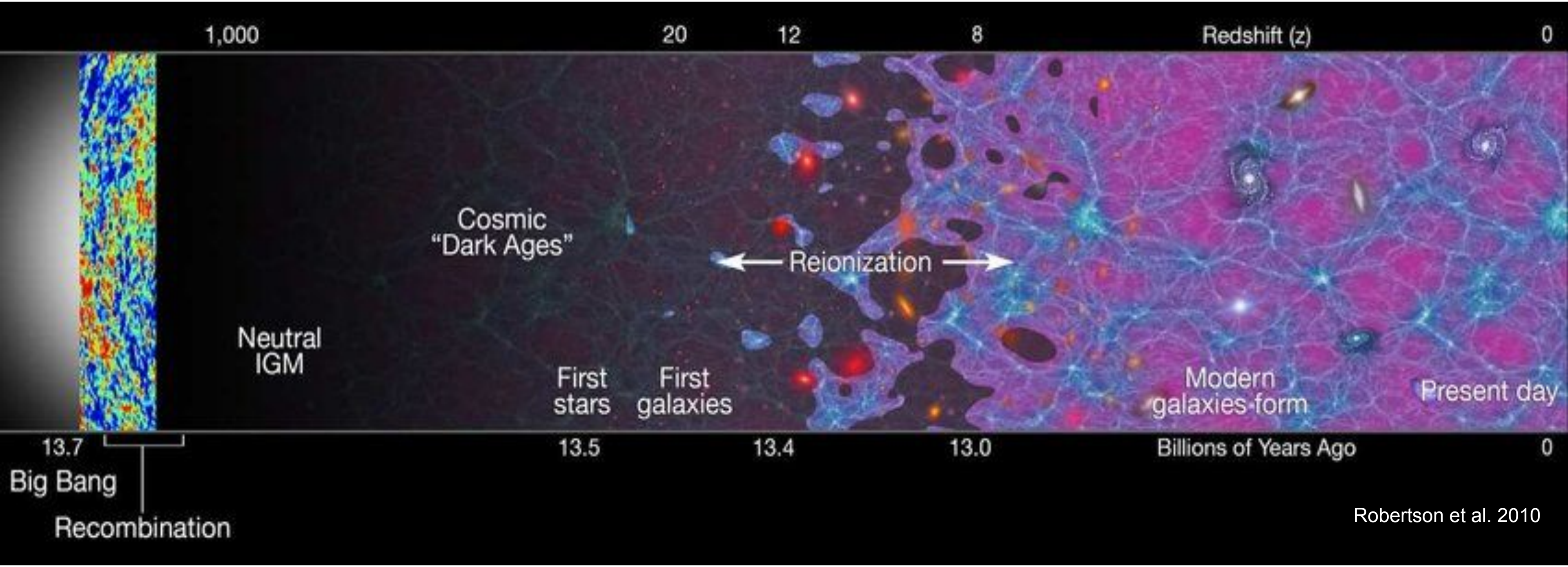
Measuring the 1D Lyman-α forest power at z > 5 (the end of Reionization)

Molly Wolfson (OSU)
CCAPP Sympodium – Sept 17, 2025

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

NASA, ESA and J. Olmsted (STScI)

What is Reionization?



Robertson et al. 2010

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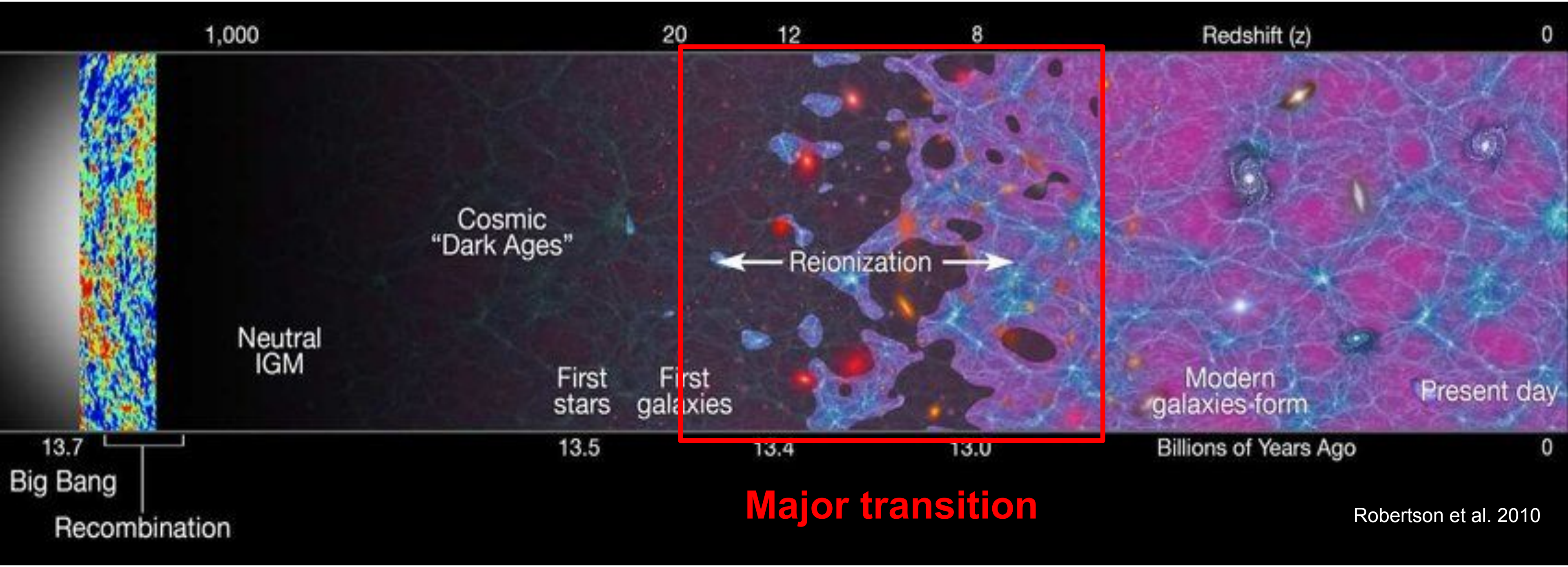
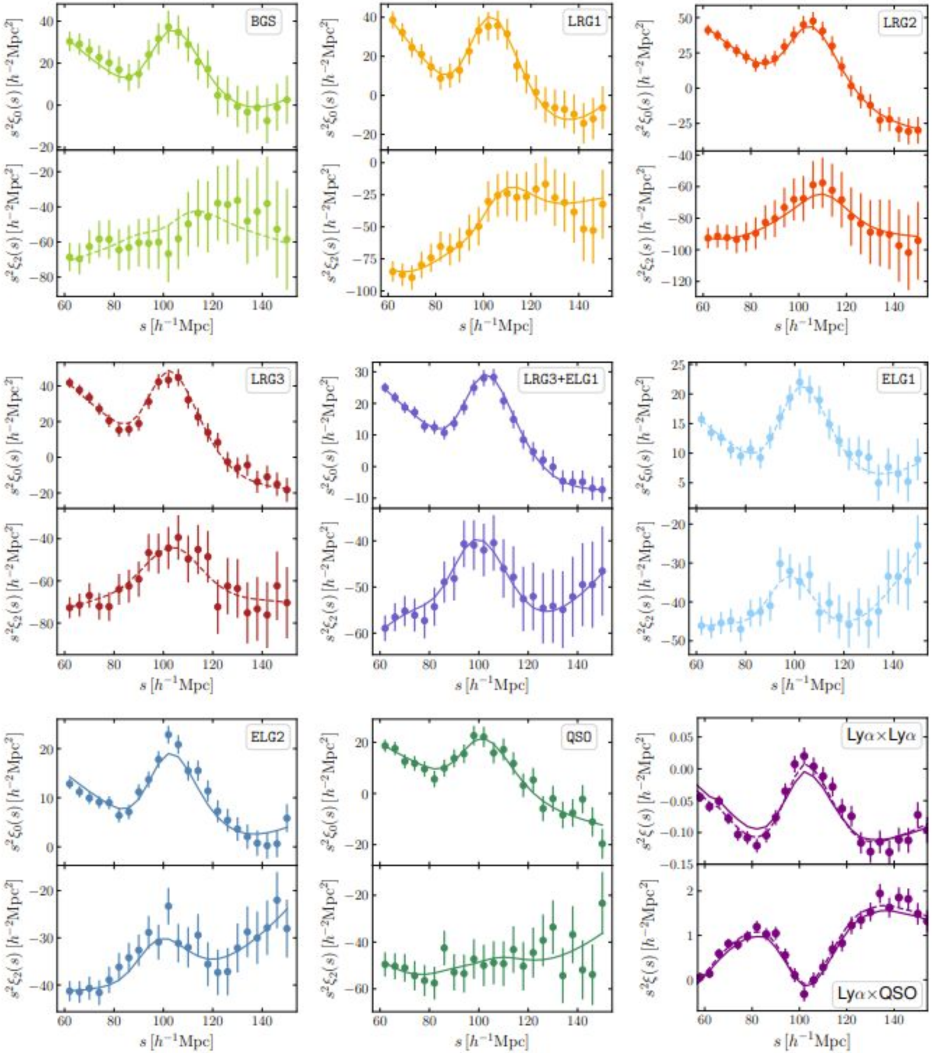
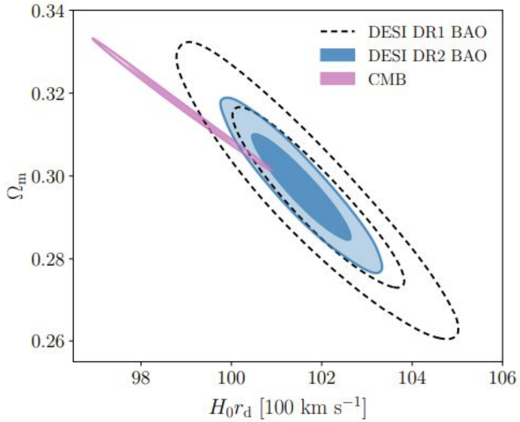
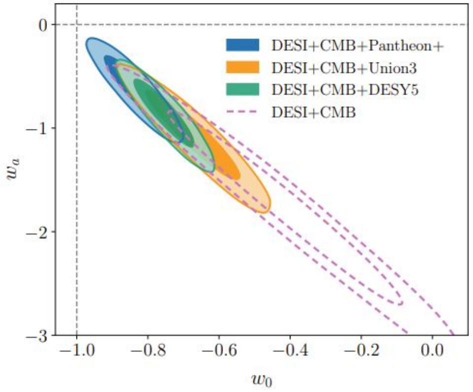


Robertson et al. 2010

DESI BAO Measurement



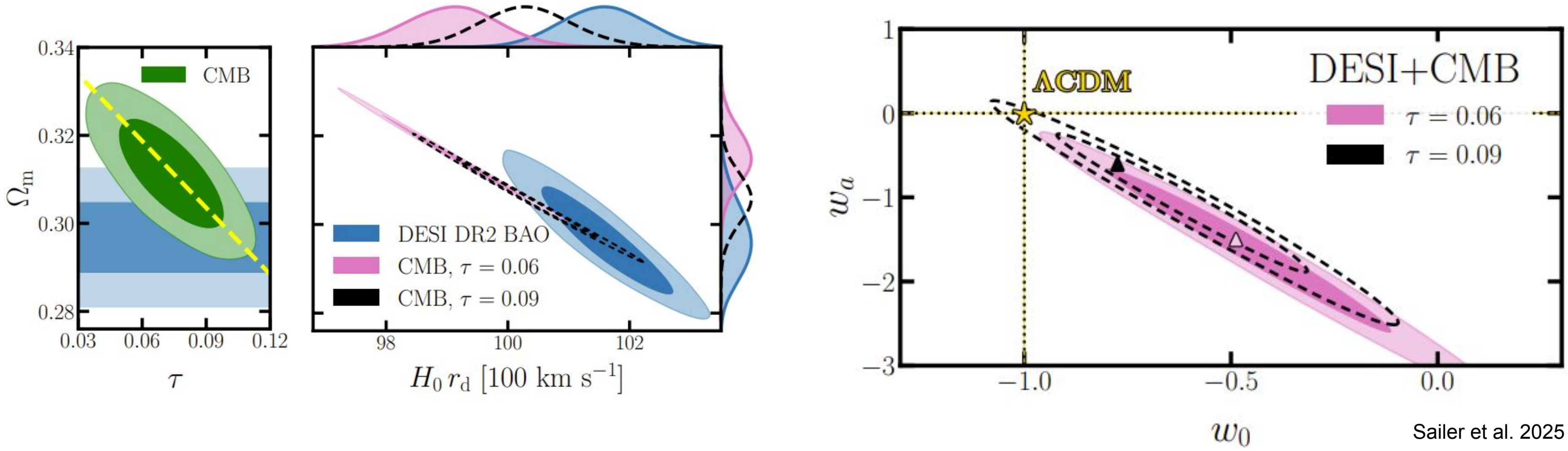




$$w(a) = w_0 + w_a(1 - a)$$

DESI Collaboration 2025
2503.14738

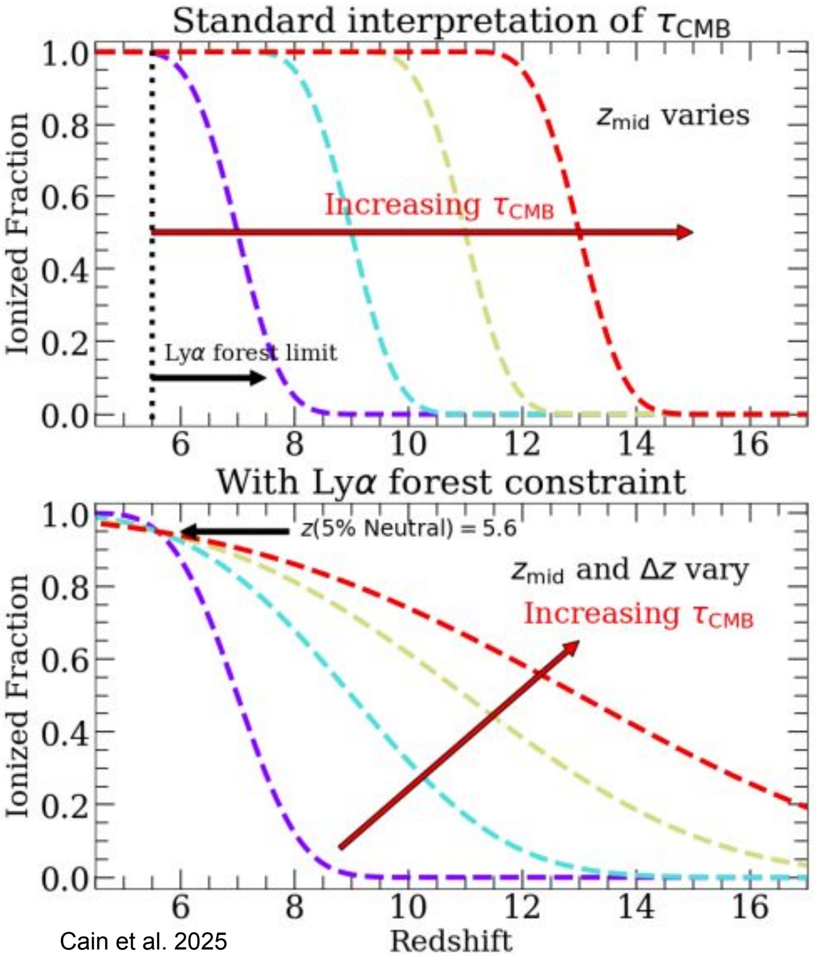
Can the optical depth to Reionization relieve the tension without time-evolving dark energy?



Sailer et al. 2025

Can the optical depth to Reionization relieve the tension without time-evolving dark energy?

What does the optical depth to reionization (τ_{reion} or τ_{CMB}) mean in terms of reionization history?



Cain et al. 2025

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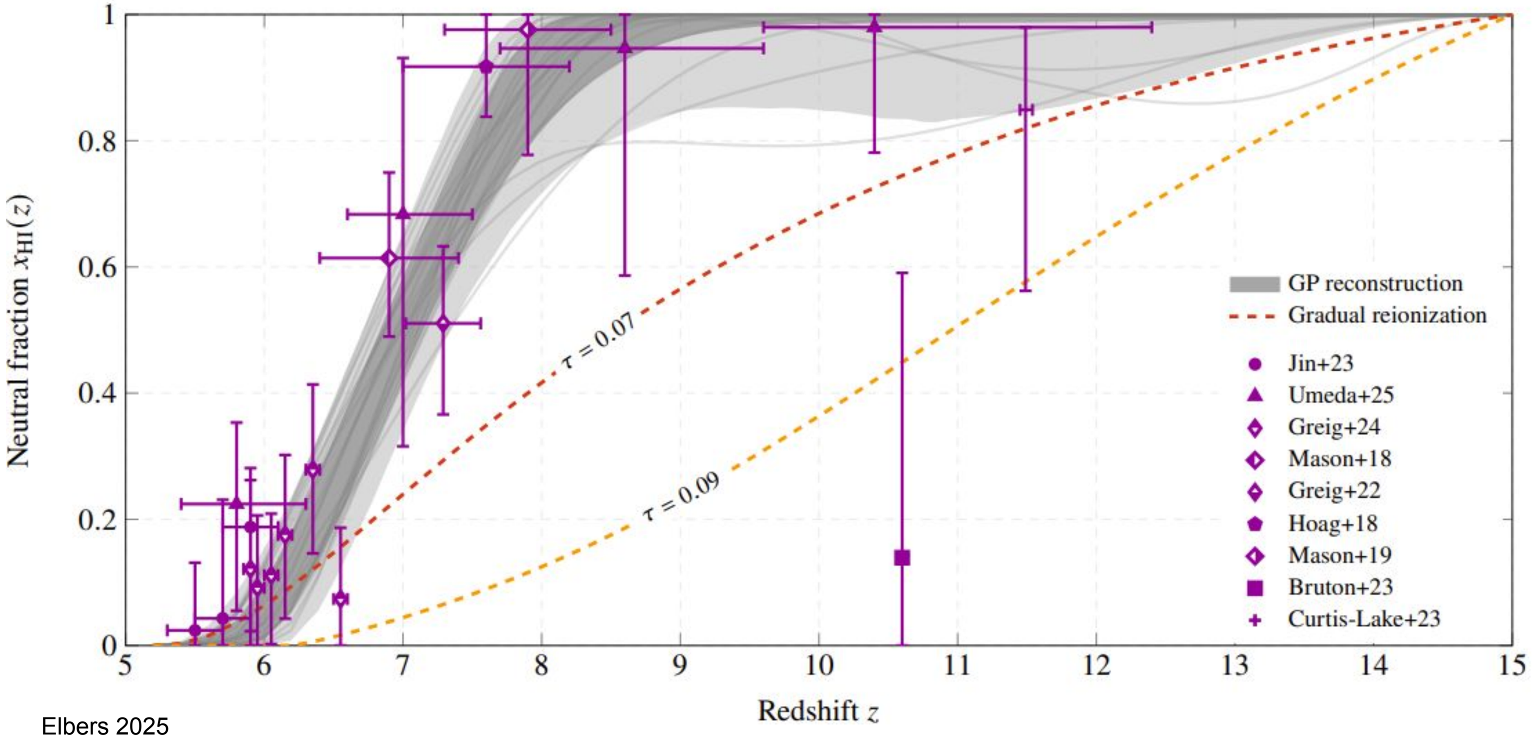

Elbers 2025

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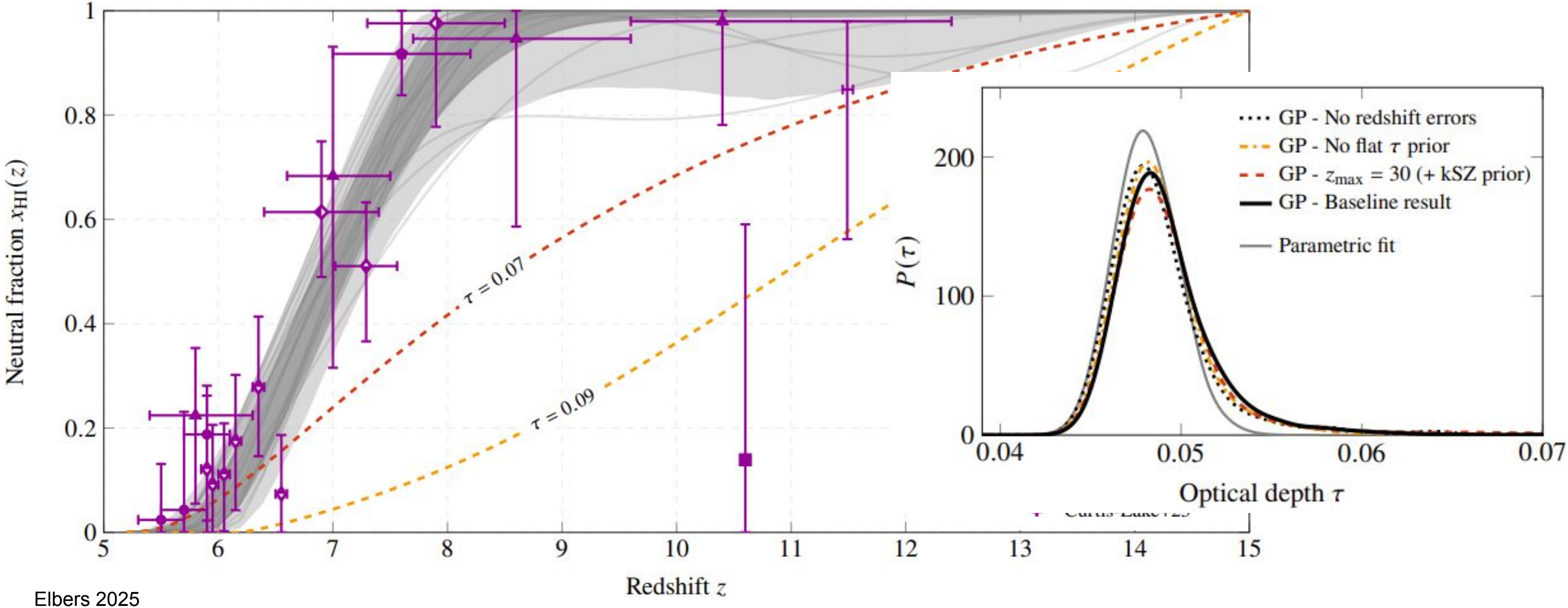

Elbers 2025

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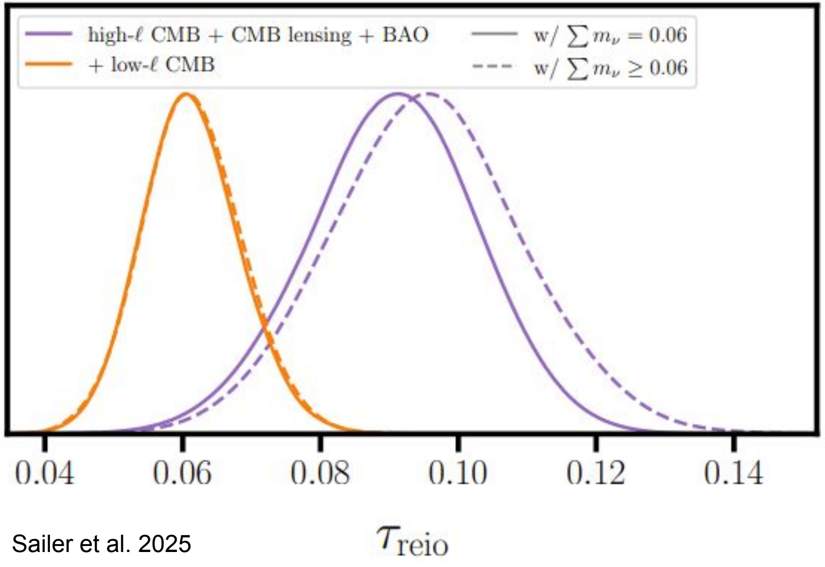
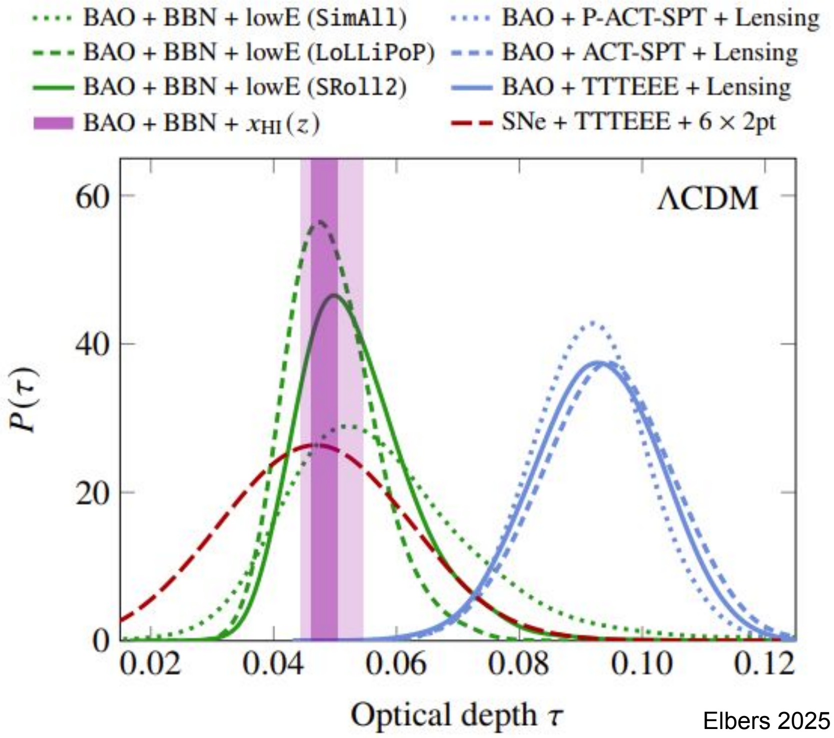
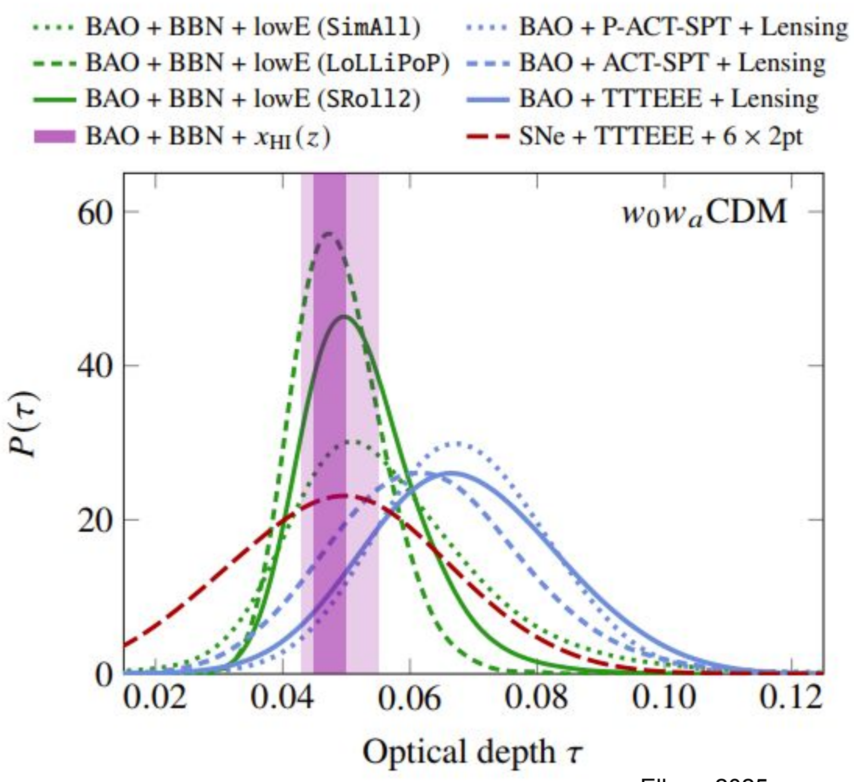


Sailer et al. 2025



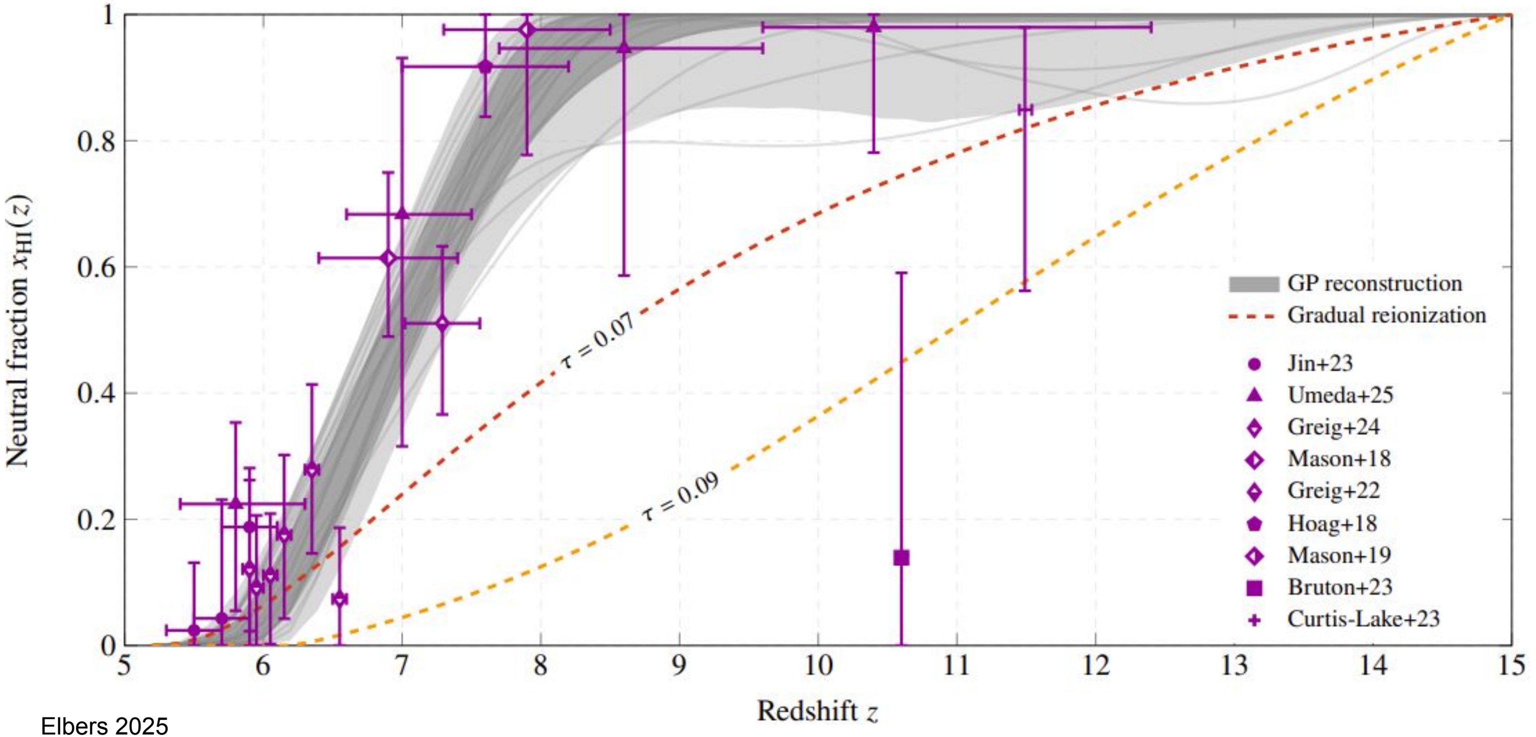
Elbers 2025

But what would this look like in w_0w_aCDM?



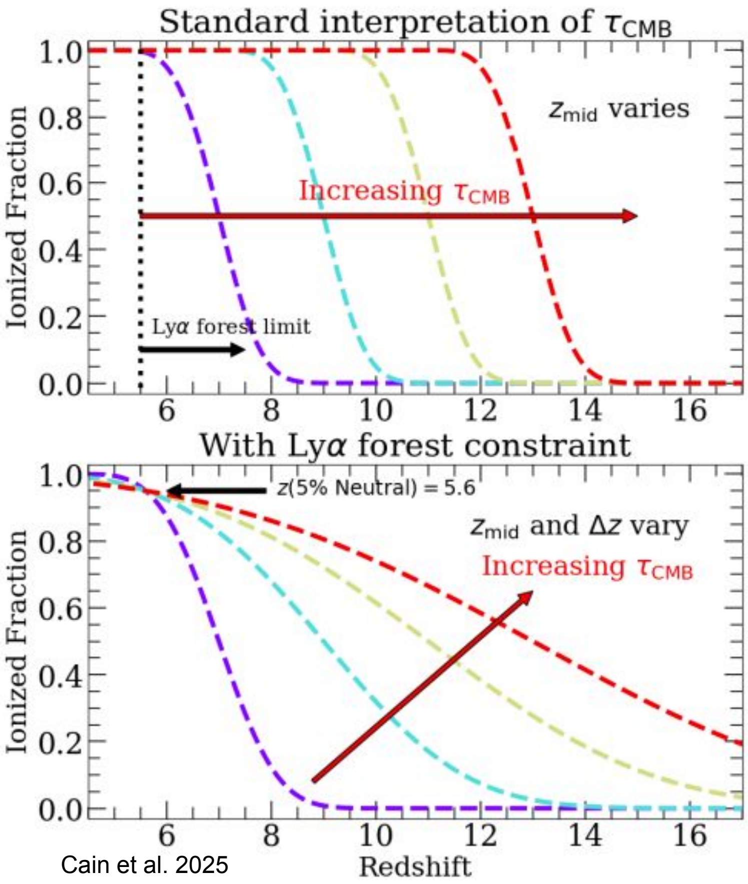
Elbers 2025

Mapping out the end of Reionization provides key insight to cosmological models with BAO and CMB:

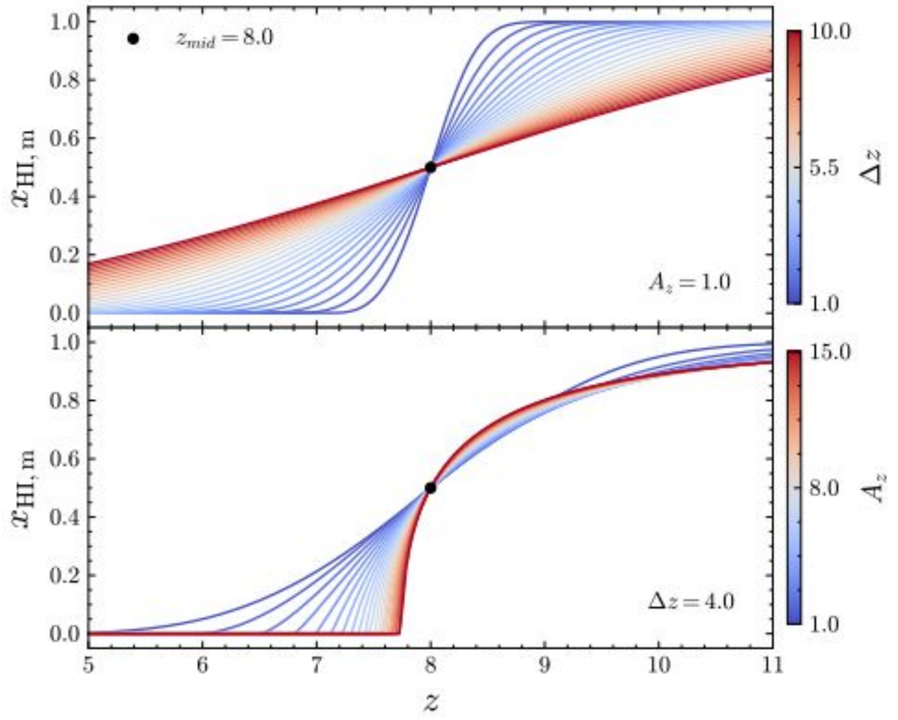


Elbers 2025

How else can we constrain the evolution of Reionization?



Cain et al. 2025



González-Hernández, Doughty, **Wolfson**, et a. submitted!

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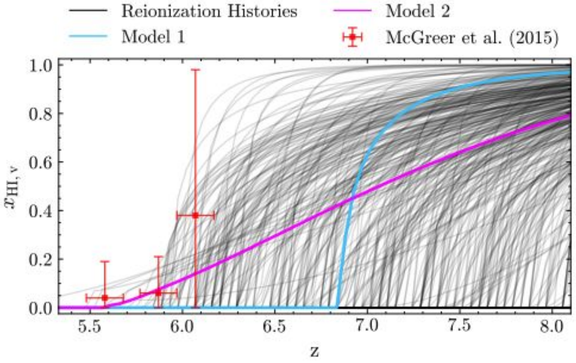
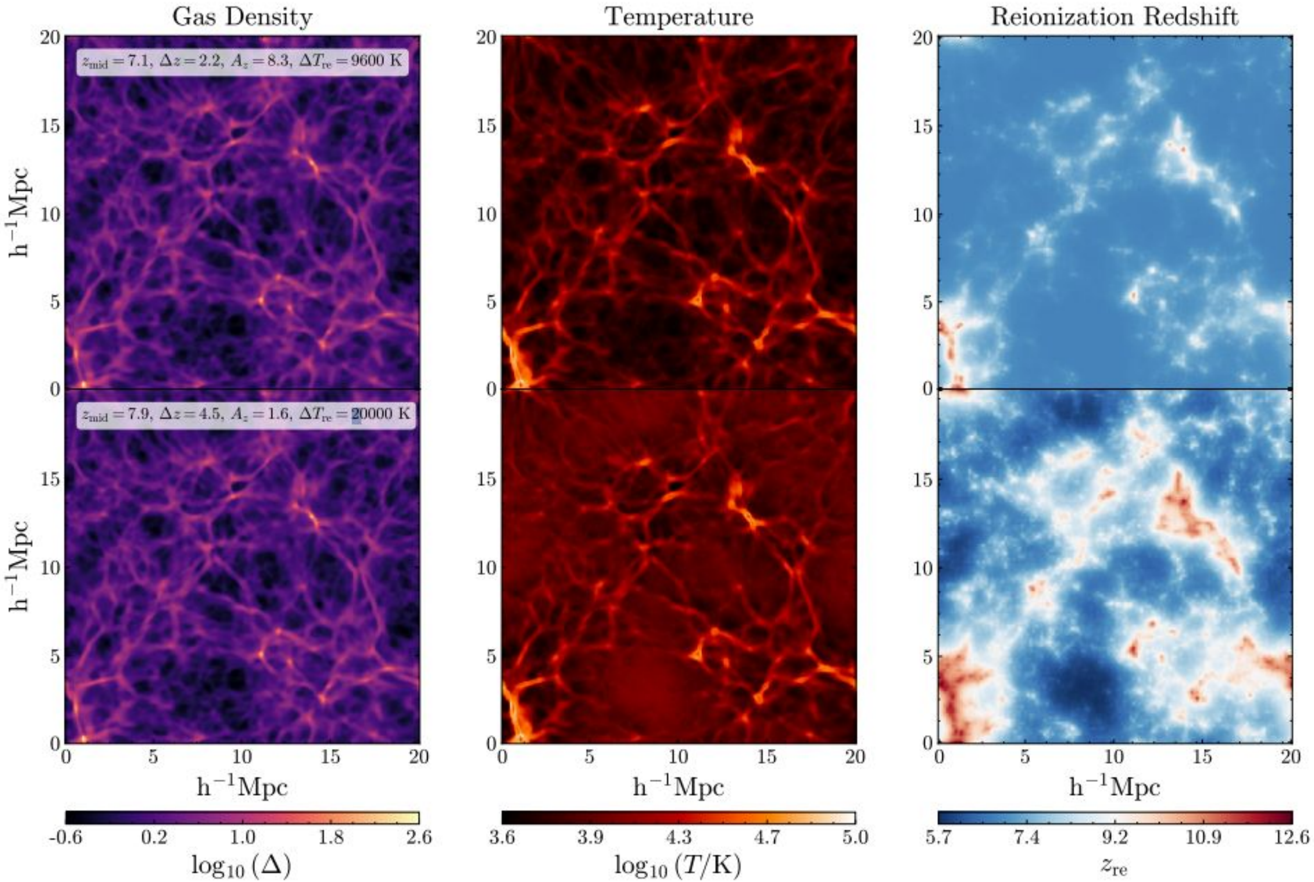
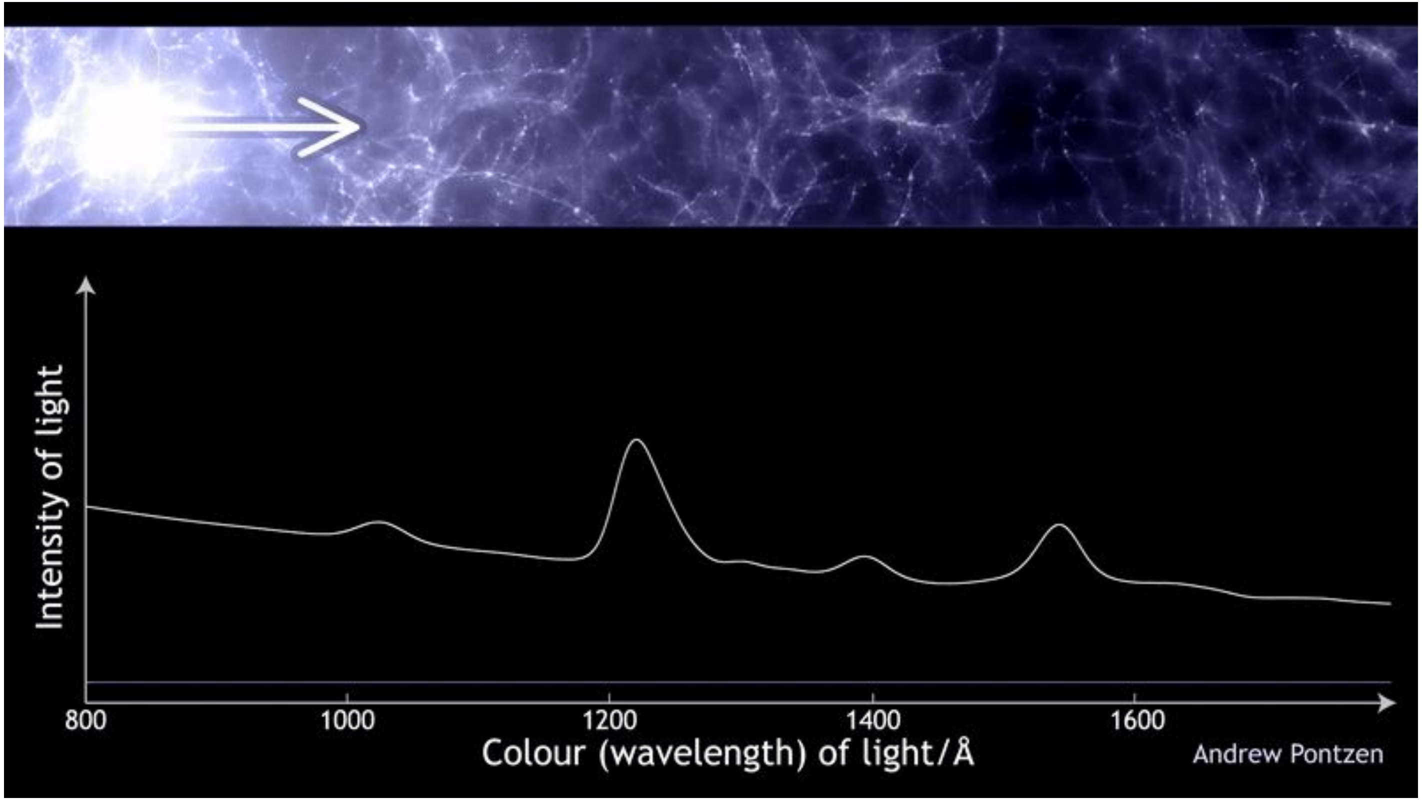
The intergalactic medium (at z ≳ 5)



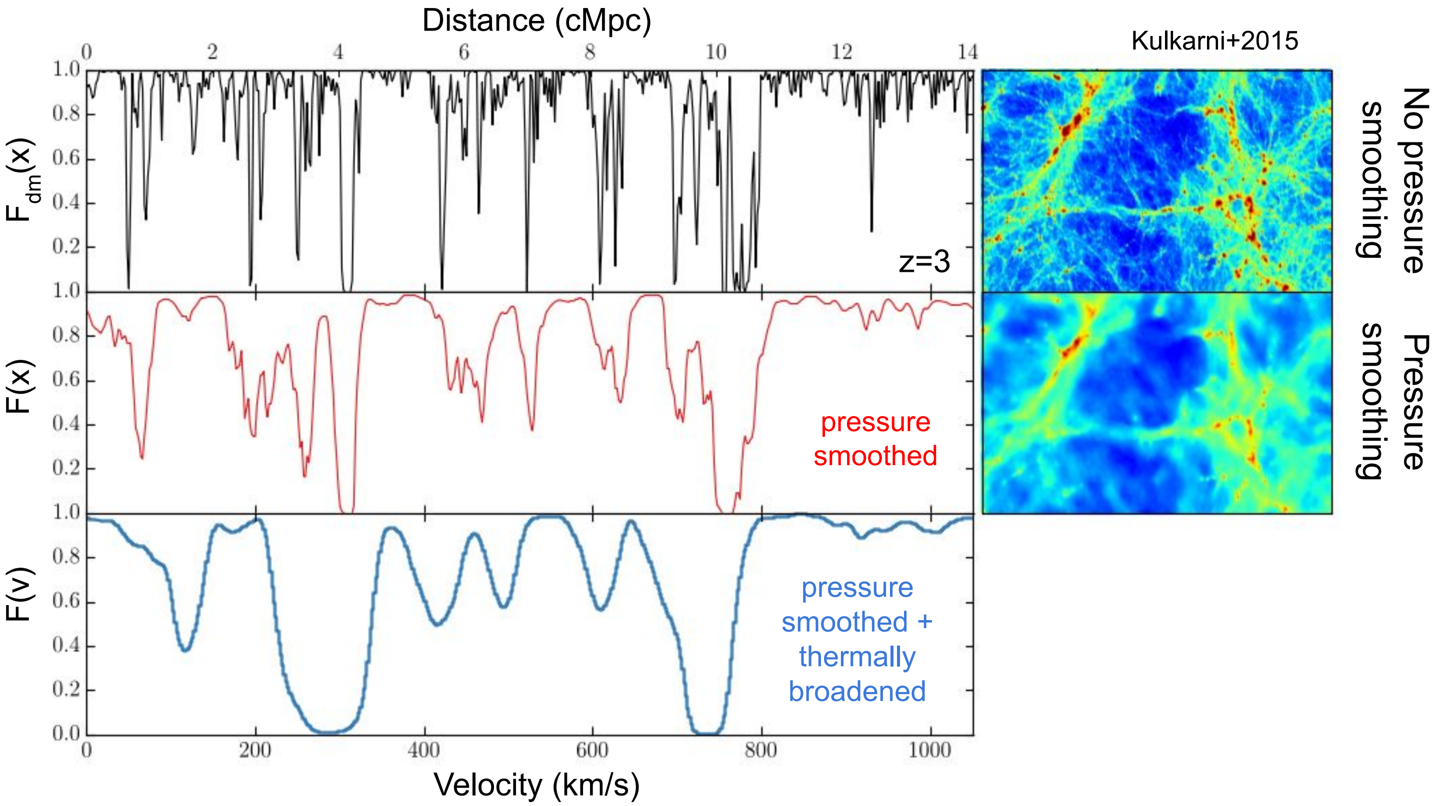
This is z = 5



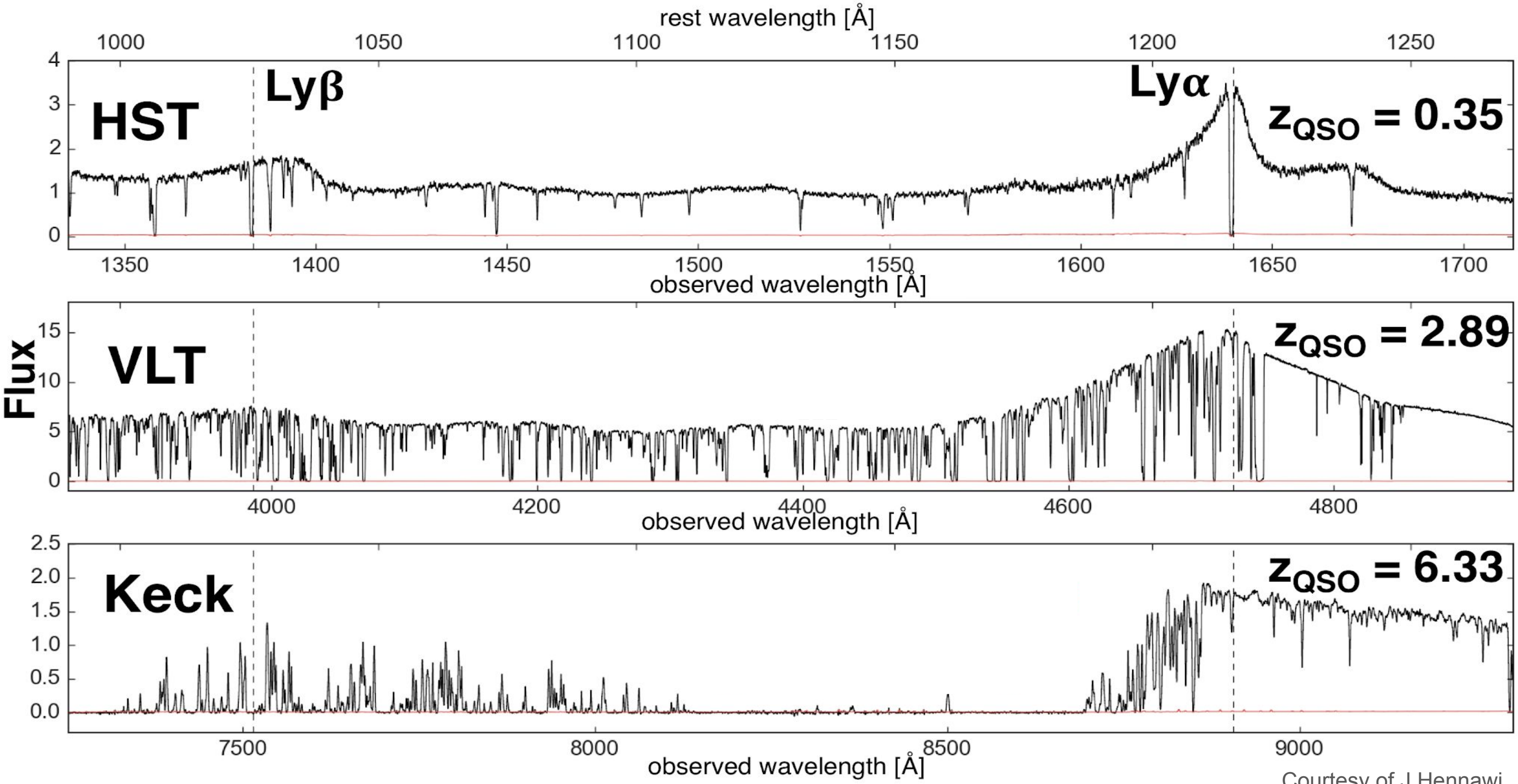
Probing the IGM with the Lyman-α forest:



Lyman alpha absorption lines are set by the physics of the IGM, including…

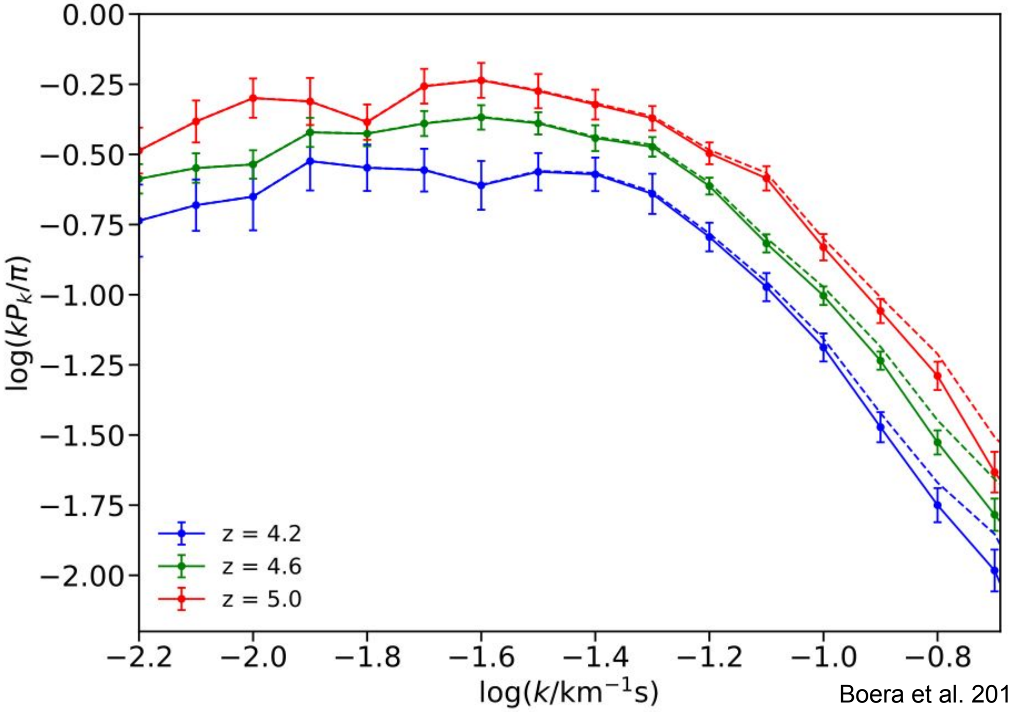


Lyman-α forest flux at high-z:



Courtesy of J.Hennawi

1D Lyman-α forest power spectrum: $P(k) = \frac{1}{2\pi}\langle|\tilde{\delta}(k)|^2\rangle$



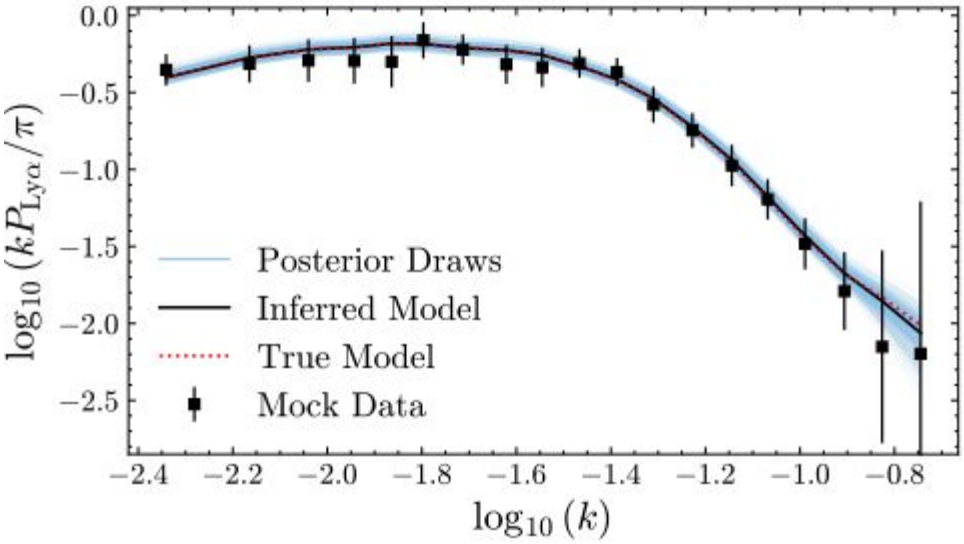
Boera et al. 2019

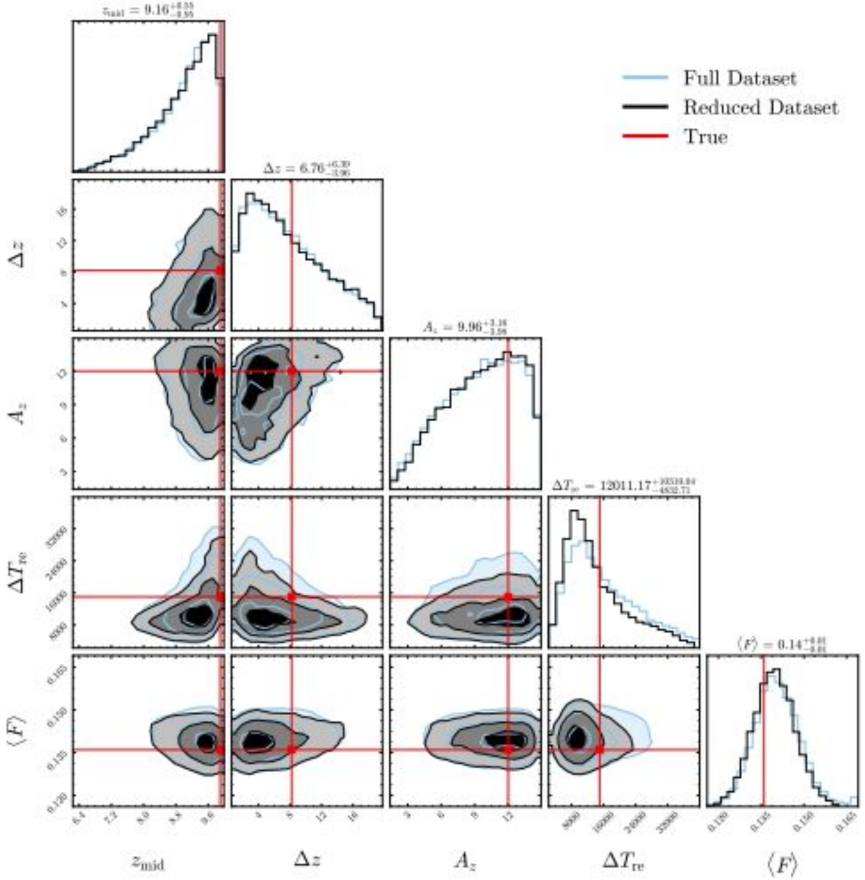
Large Scales

Small Scales

Using the 1D Lyman-α forest power spectrum to constrain Reionization:

Simulation data:

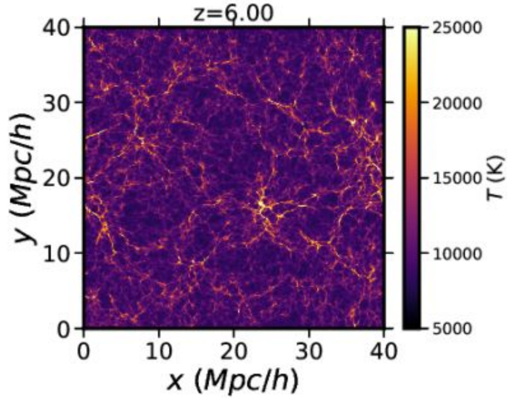




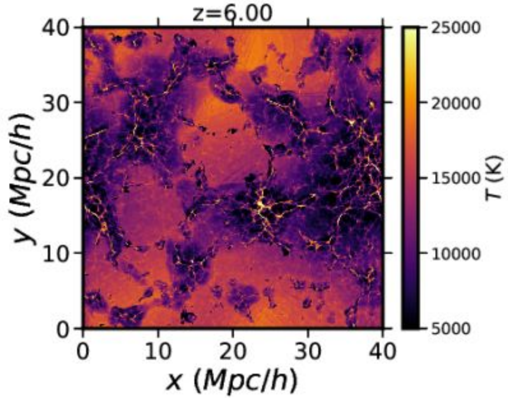
González-Hernández, Doughty, **Wolfson**, et a. submitted!

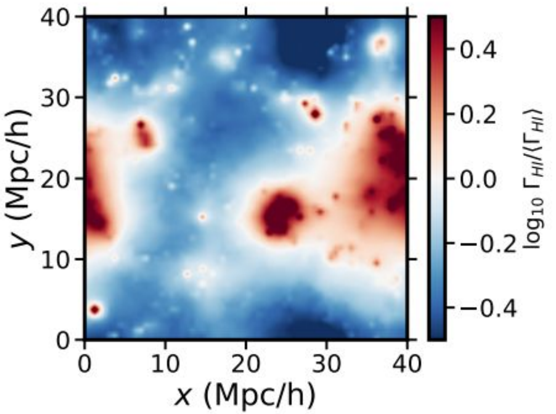
Large-scales of the power spectrum are also of interest for Reionization:

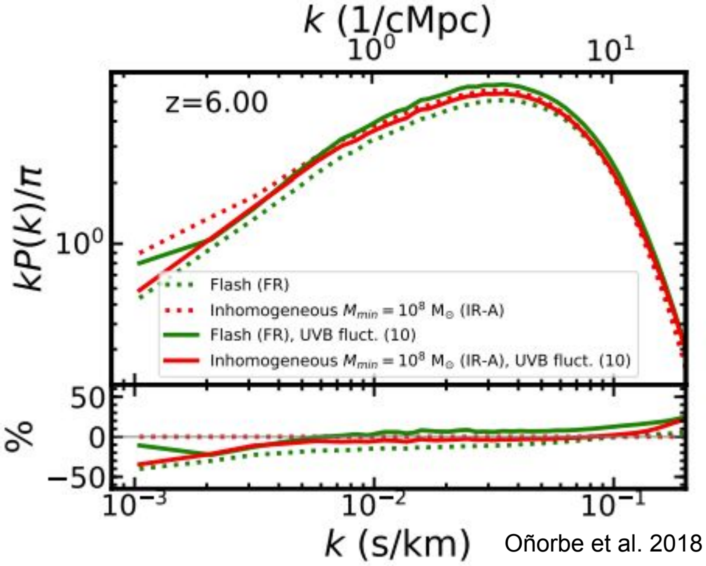
Flash



Inhomogeneous







Oñorbe et al. 2018

How to measure the power spectrum:

$$P(k) = \frac{1}{2\pi}\langle|\tilde{\delta}(k)|^2\rangle$$

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Discrete Fourier transforms assume regularly spaced, periodic inputs

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Also have to correct for noise and window function

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$$P_{\mathrm{F}}(k) = \frac{P_{\mathrm{data}}(k) - P_{\mathrm{N}}(k)}{W_R^2(k, R, dv_p)}$$

$$\xi(r) = \langle \delta(x)\, \delta(x + r) \rangle,$$

$$P(k) = \int_{-\infty}^{\infty} \xi(r)\, e^{-ikr}\, \mathrm{d}r$$

How to measure the power spectrum:

$$\mathcal{L}_{sp}(\mathbf{P}) = \frac{1}{(2\pi)^{N_{sp}^{\mathrm{pix}}/2}\sqrt{\det(C)}} \exp\left(-\frac{\delta^T C^{-1} \delta}{2}\right)$$

C = correlation matrix
(from values of ξ)

δ = delta flux field

Following Palanque-Delabrouille et al. 2013 SDSS measurement

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$$\begin{aligned} C_{ij}^S &= \int_{-\infty}^{+\infty} P_{1D}(k) \cdot \exp\left[-ik\Delta v \times (i-j)\right] dk \\ &= \int_{0}^{+\infty} P_{1D}(k) \cdot 2\cos\left[k\Delta v \times (i-j)\right]\, dk. \end{aligned}$$

Following Palanque-Delabrouille et al. 2013 SDSS measurement

How to measure the power spectrum:

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$$C_{ij}^{S}(\mathbf{P}) = \sum_{\ell=1}^{N_\ell} P_\ell \cdot \int_{k_{\ell-1}}^{k_\ell} 2\cos\left[k\Delta v \times (i-j)\right] dk$$

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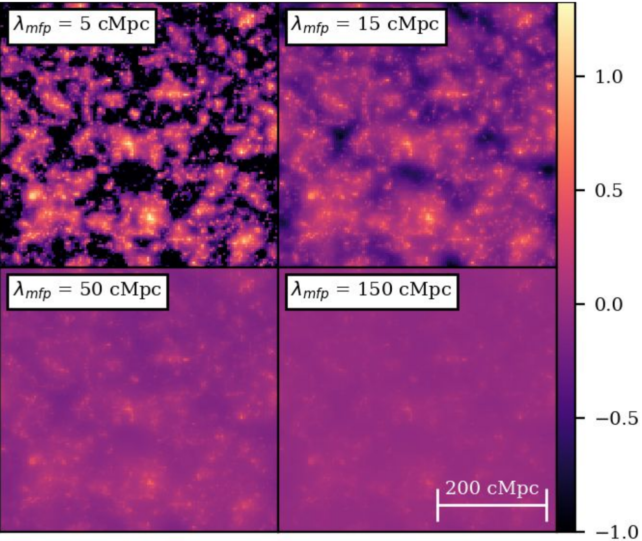
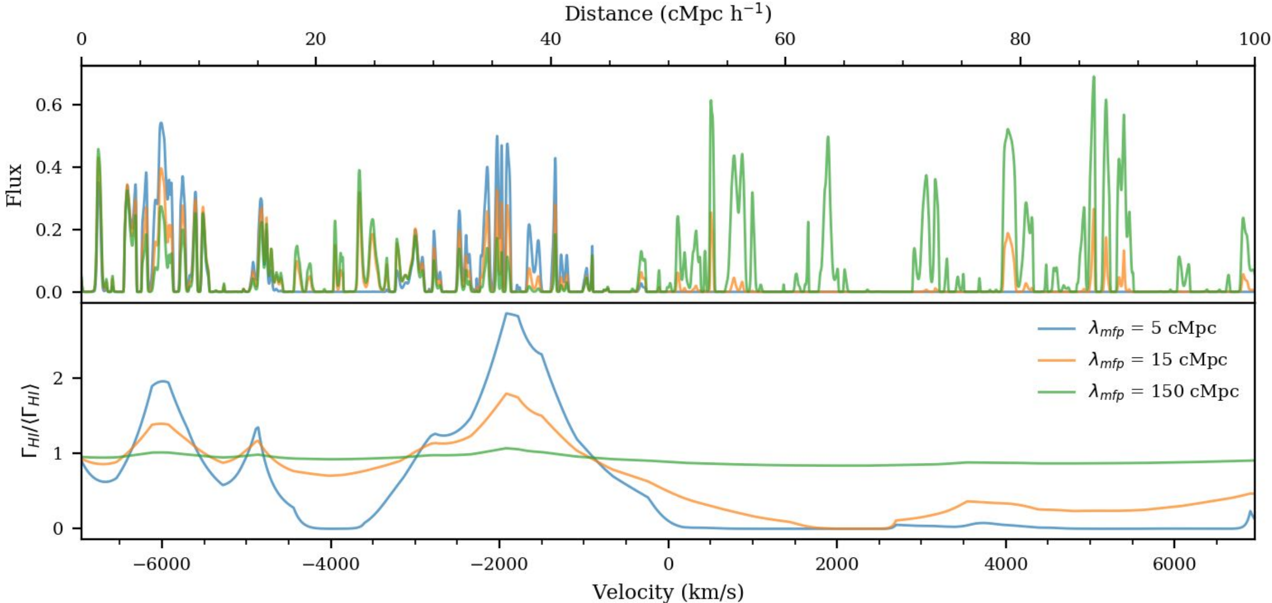
$$C_{ij}^S(\mathbf{P}) = \sum_{\ell=1}^{N_\ell} P_\ell \cdot \int_{k_{\ell-1}}^{k_\ell} 2\cos\left[k\Delta v \times (i-j)\right] \times W(k, R_i, \Delta v) W(k, R_j, \Delta v)\, dk$$

Following Palanque-Delabrouille et al. 2013 SDSS measurement

Implementing this on mock data with fluctuating UVBs:



Wolfson et al. 2023



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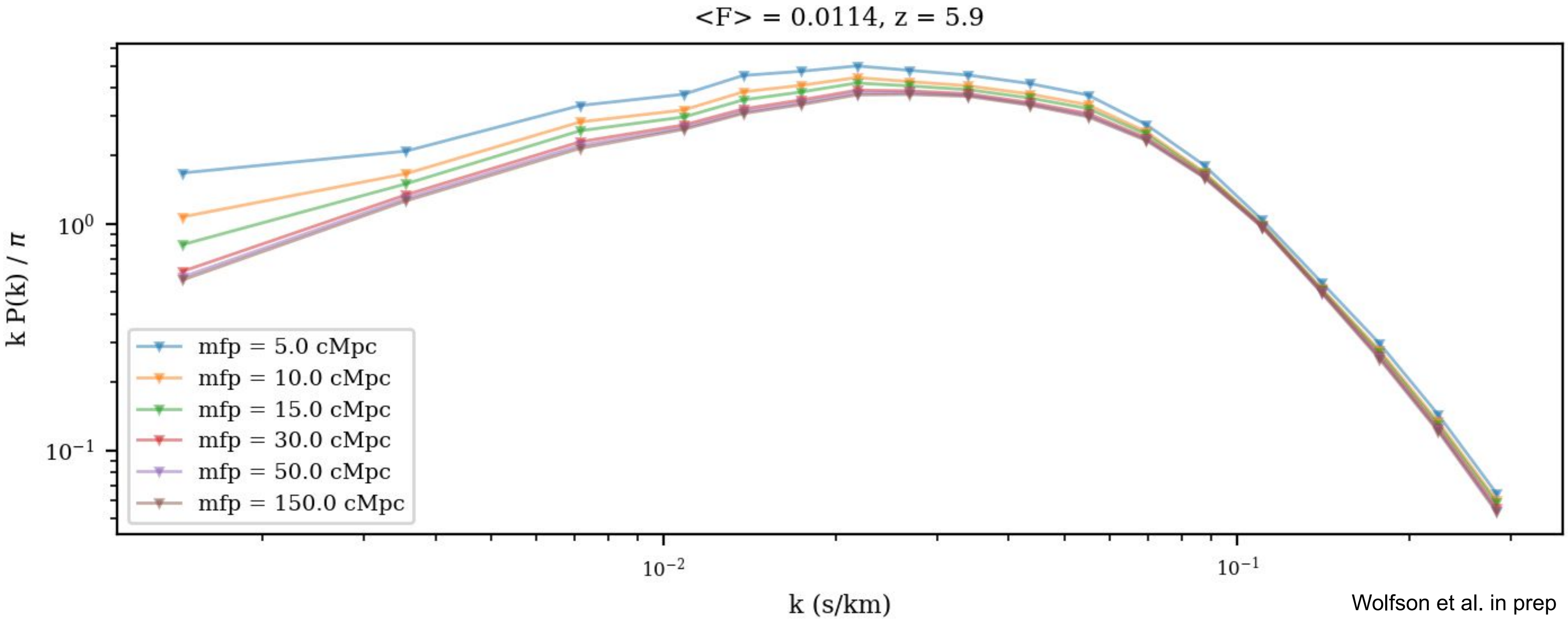
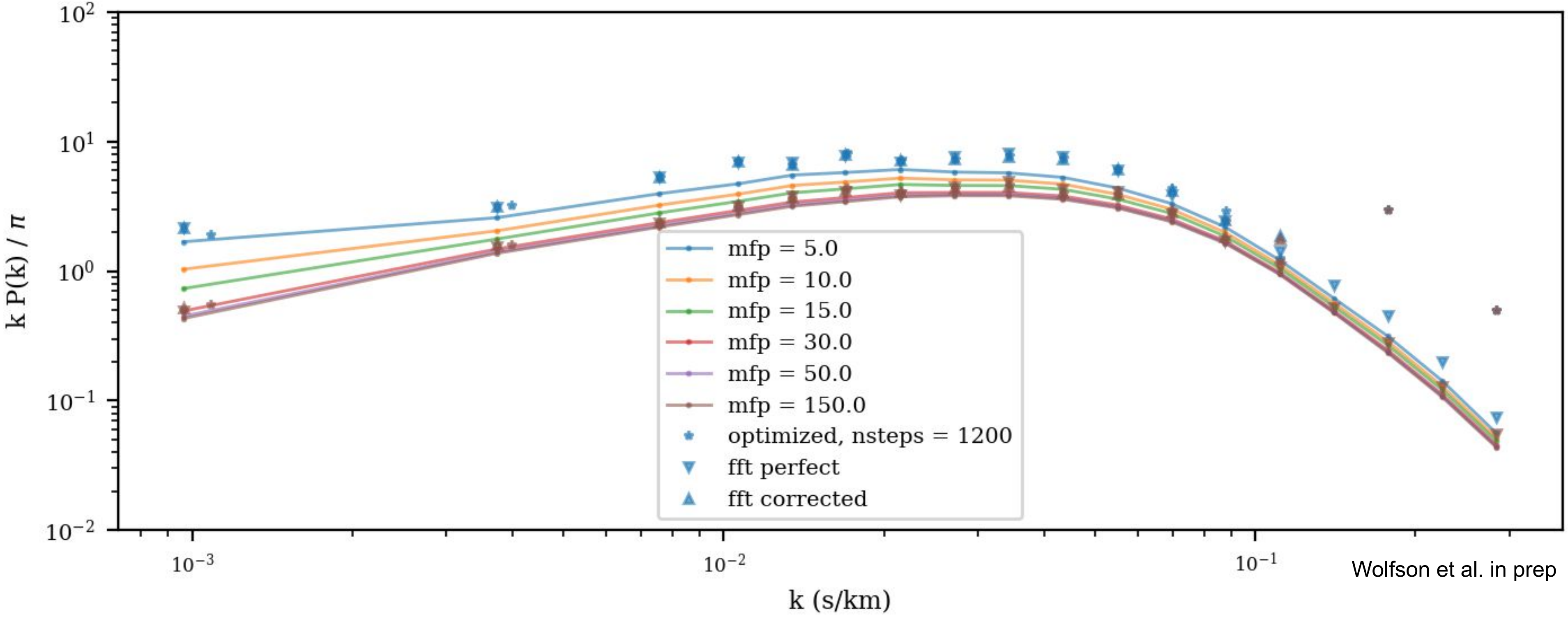


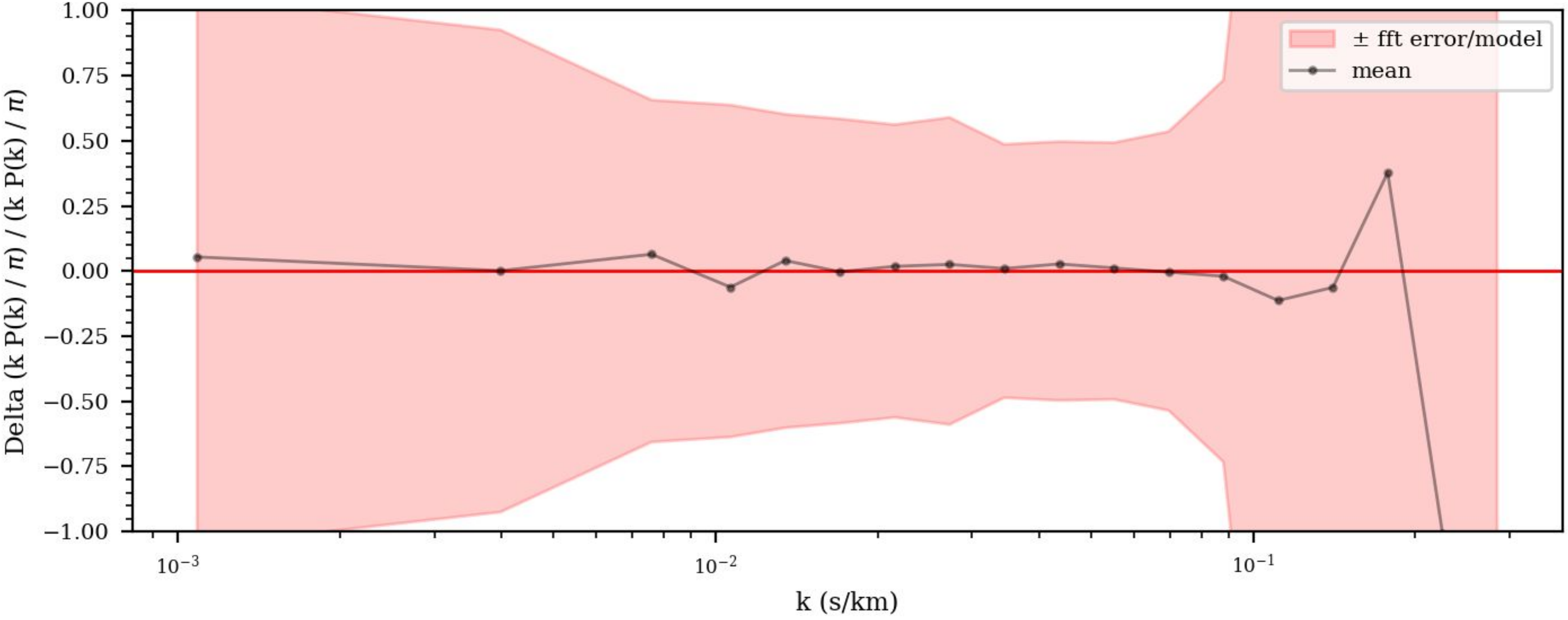
Wolfson et al. in prep

Mock measurement from my implementation:



Wolfson et al. in prep

Difference between the optimization on realistic mock data and FFT on perfect mock data:



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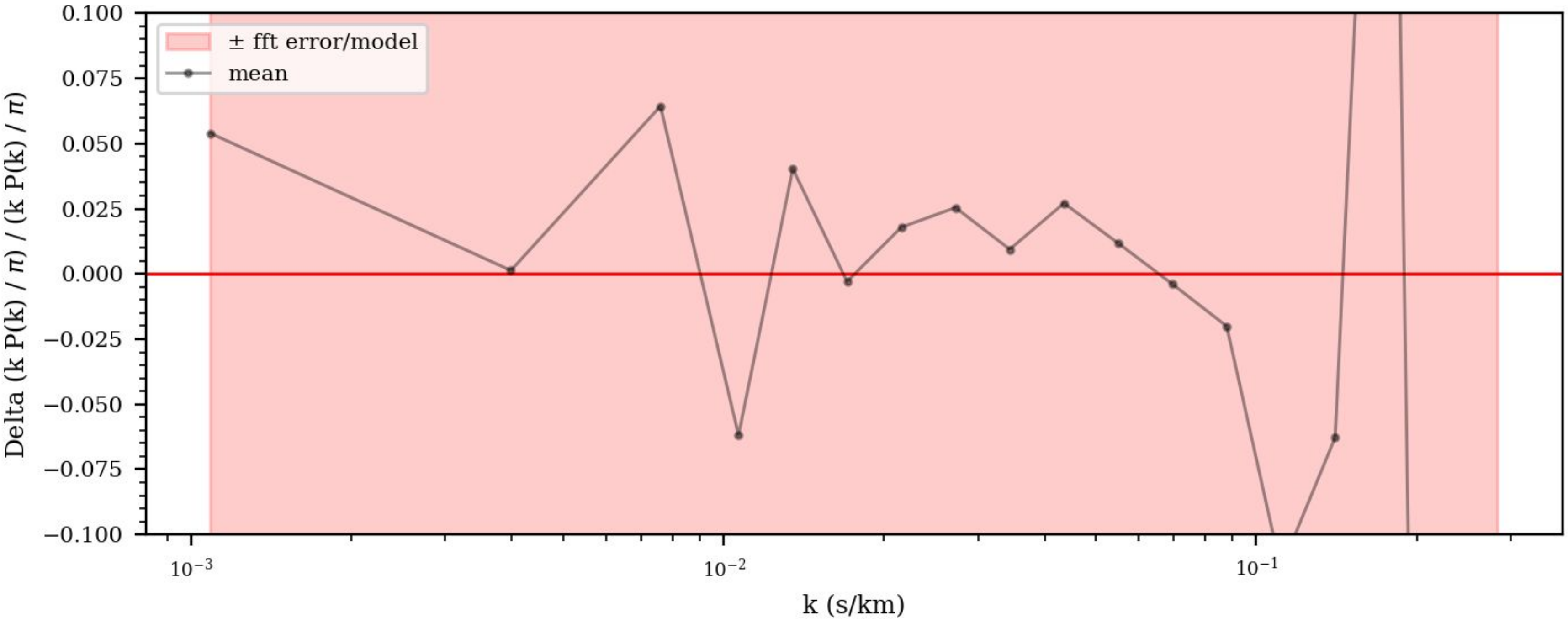
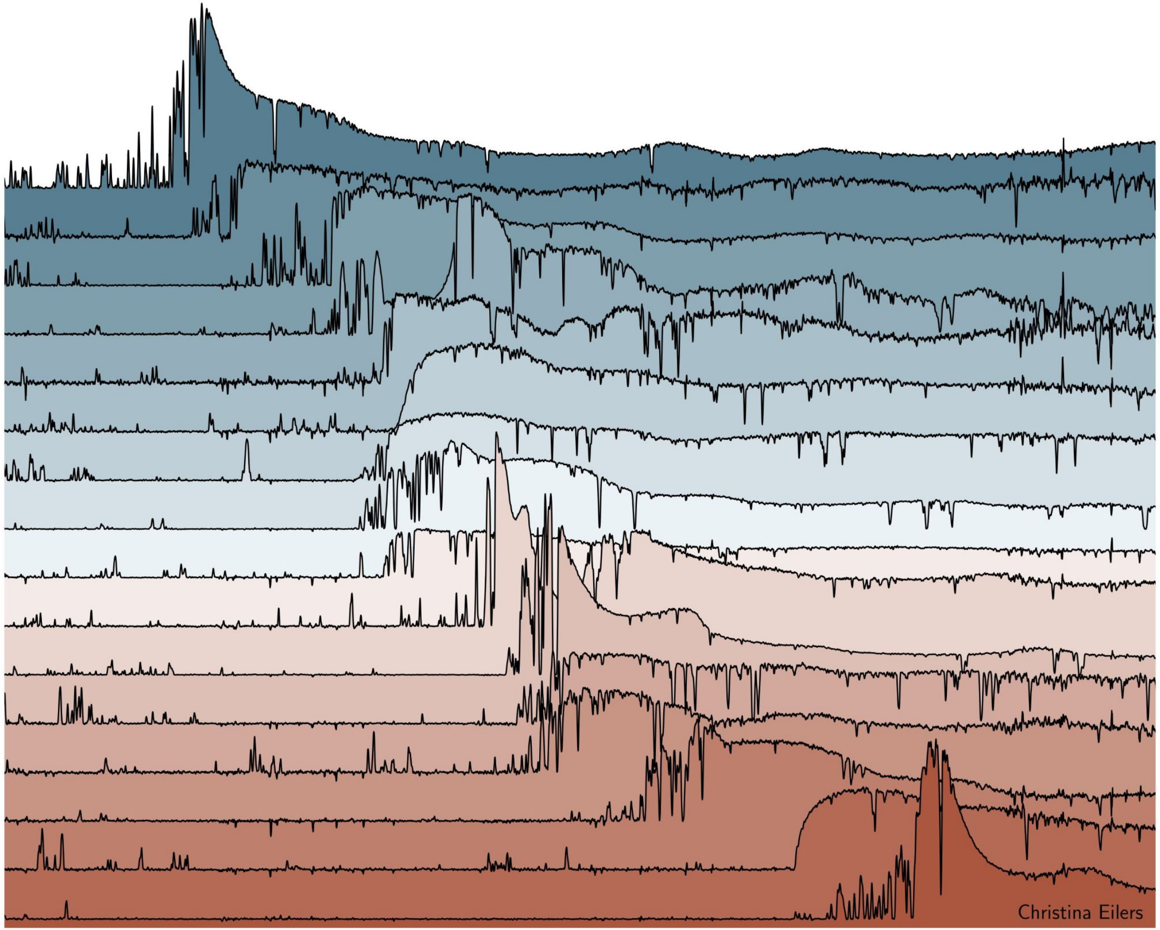


Data measurement to come!

XQR-30

XQR-30 (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

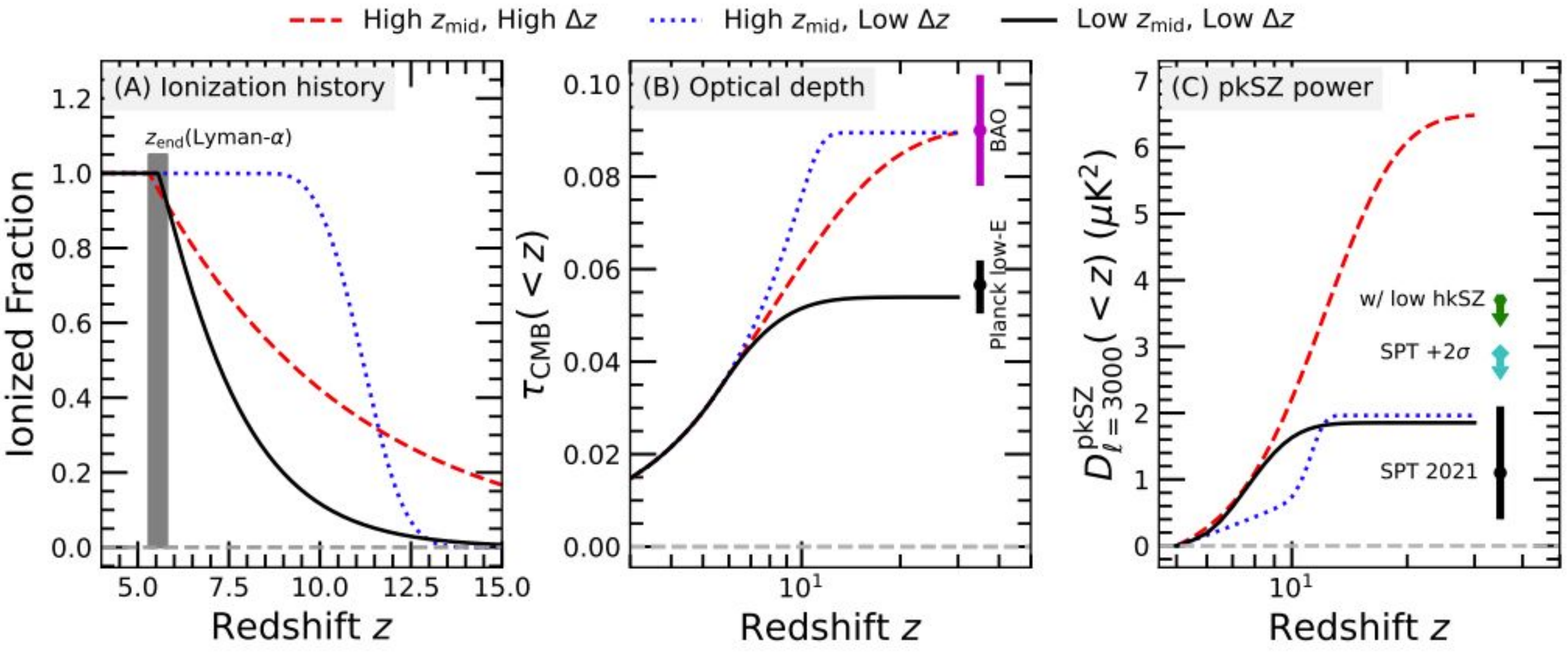


Takeaways:

- There is a lot of interest in fully constraining the timing, duration, and asymmetry of Reionization
- The 1D Lyman-α forest power spectrum can be a powerful probe the effect of reionization on both large and small scales
- Measuring the power from data is tricky, so sophisticated computational methods are needed
- I have implemented a likelihood method to measure the power from data that is robust from tests on mock data with a variety of large-scale power
- Measurement on data expected very soon!

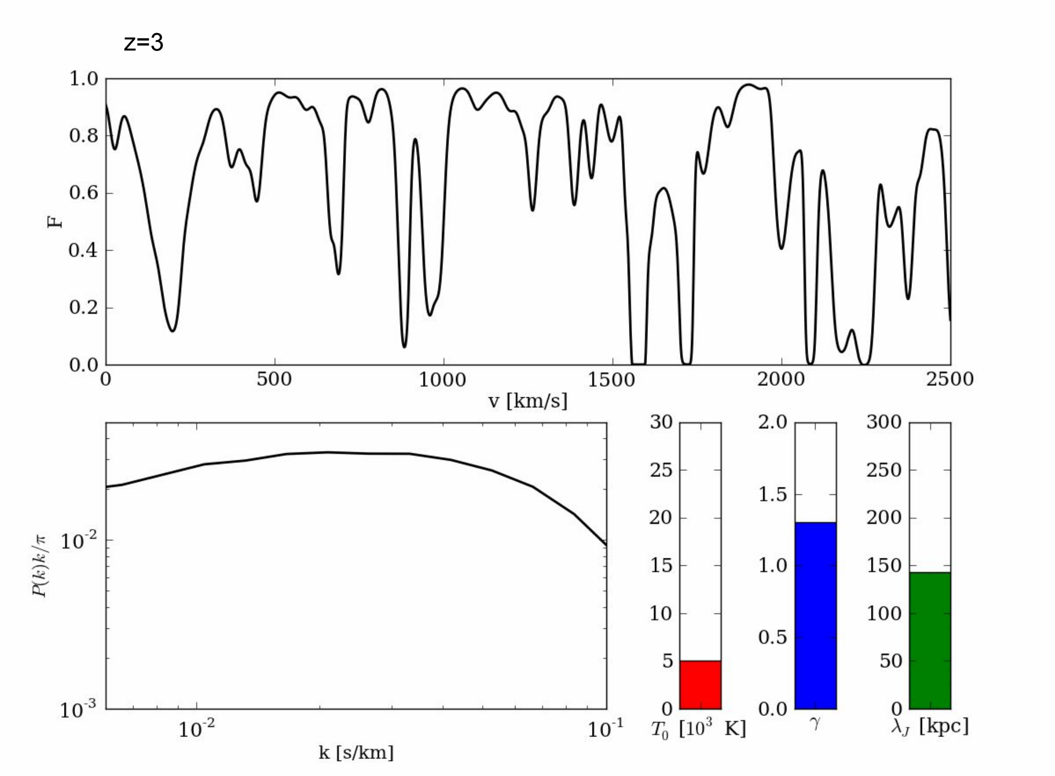
Extra Slides

Can the optical depth to Reionization relieve the tension without time-evolving dark energy?



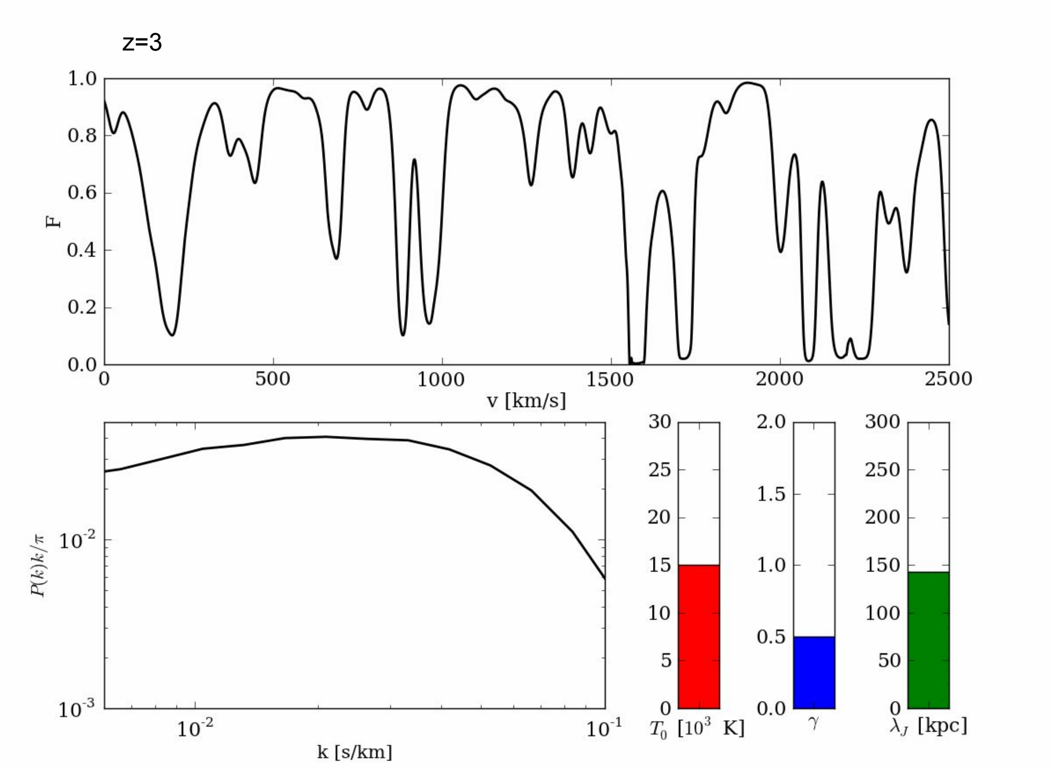
Cain et al. 2025

Changing T_0



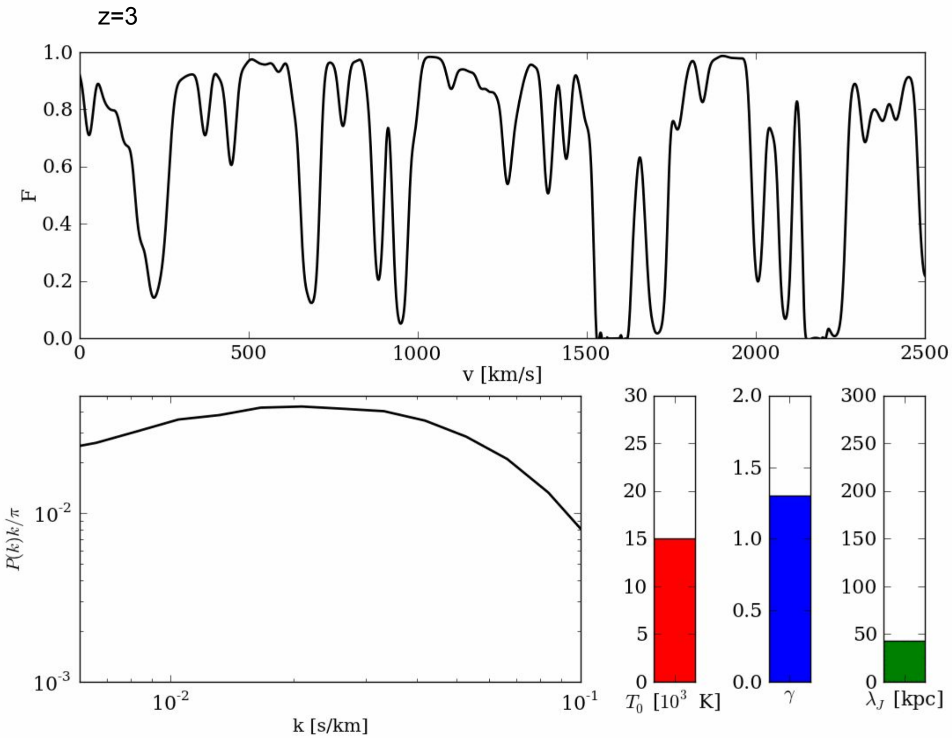
A. Rorai

Changing γ



A. Rorai

Changing λ_p



A. Rorai

How to measure the power spectrum:

$$P(k) = \frac{1}{2\pi}\langle|\tilde{\delta}(k)|^2\rangle$$

Computing the power from the Fourier transform of the delta-Flux field is difficult. Any non-regular grid spacing (for example from masking pixels in the spectrum from high column density systems or sky lines)

The data measurement also needs to be corrected for the noise and window function (arising from finite spectrograph resolution and pixel spacing):

$$P_{\mathrm{F}}(k) = \frac{P_{\mathrm{data}}(k) - P_{\mathrm{N}}(k)}{W_R^2(k, R, dv_p)}$$

Rather than this, one could instead exploit the fact that the power is the Fourier transform of the auto-correlation function, ξ

$$\xi(r) = \langle\delta(x)\,\delta(x+r)\rangle,$$

$$P(k) = \int_{-\infty}^{\infty} \xi(r)\, e^{-ikr}\, \mathrm{d}r$$