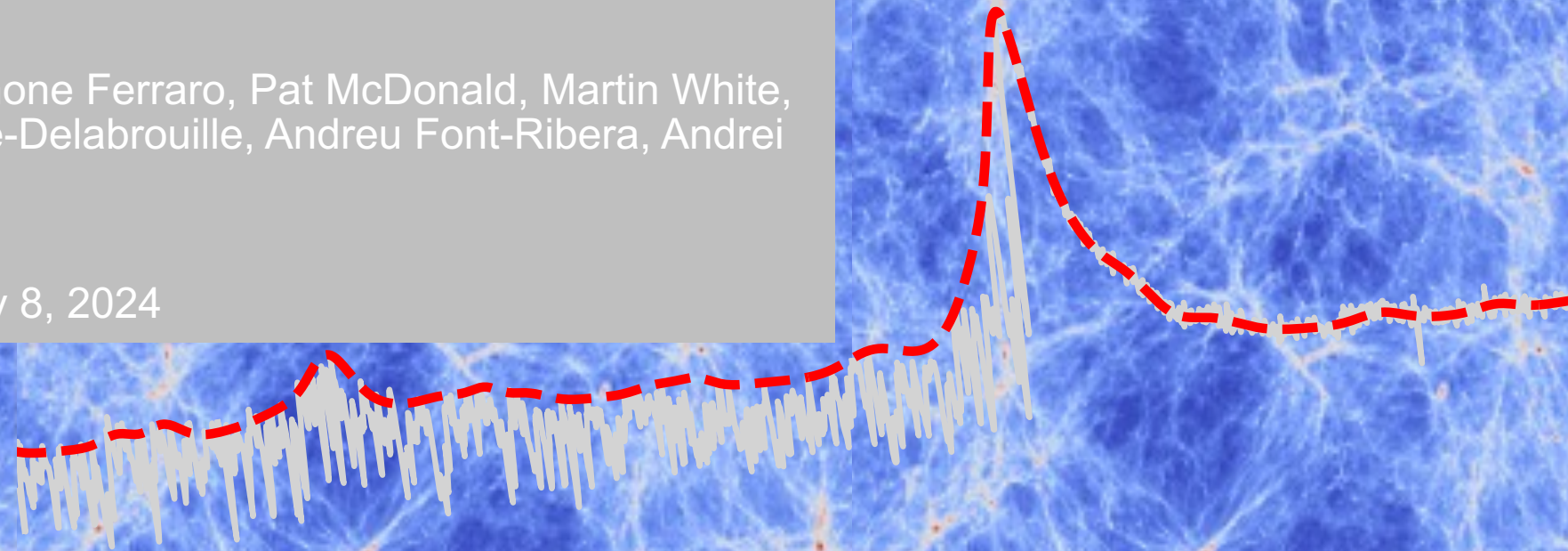


Cosmology with the Lyman- α Forest

Roger de Belsunce

+ Vid Irsic, Oliver Philcox, Simone Ferraro, Pat McDonald, Martin White, Julien Guy, Nathalie Palanque-Delabrouille, Andreu Font-Ribera, Andrei Cuceu, Naim Karacayli

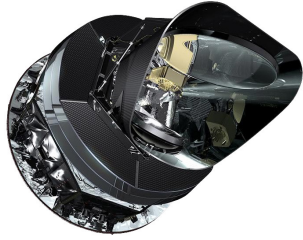
Spec-S5 meeting @ LBL: May 8, 2024



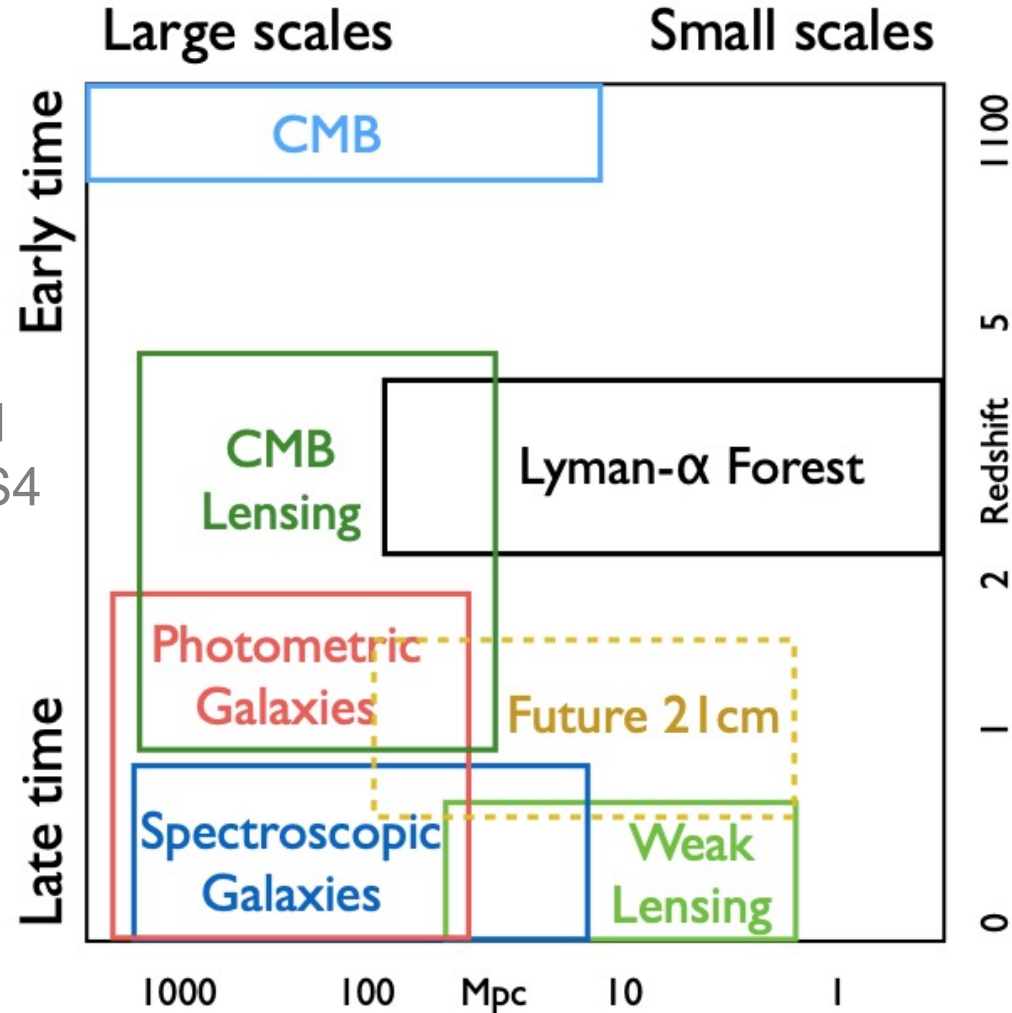
Probing cosmology at different scales

Breaking degeneracies

¹ DESI presentation (Font-Ribera)



Space: Planck, WMAP, Litebird
Ground: ACT, SPT, SO, CMB-S4

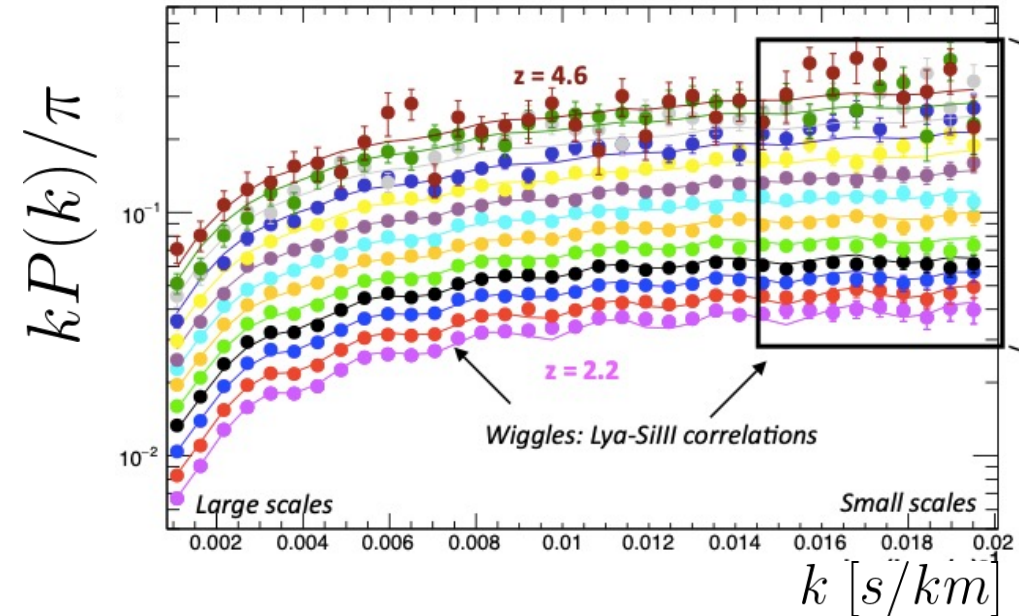
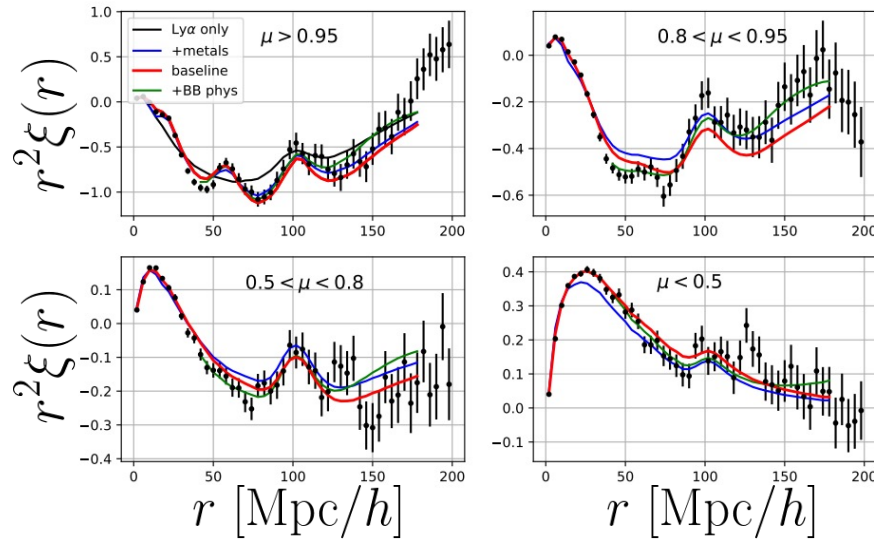


eBOSS DR16: ~200k spectra
DESI year-1: ~500k spectra
DESI year-5: ~840k spectra
Spec S-5: >>1M spectra (?)

The Lyman- α forest - scales

Probe of LSS at high- z down to small scales

- ¹ du Mas des Bourboux et al. (2020)
- ² Font-Ribera et al. (2017)
- ³ Zaldarriaga et al. (2001)
- ⁴ Palanque-Delabrouille et al. (2013)



$\sim 100 \text{ Mpc}/h$

$\sim 10 \text{ Mpc}/h$

$\sim 1 \text{ Mpc}/h$

$\sim 100 \text{ kpc}/h$

Large scales: $\xi(r) \leftrightarrow P_{3D}(k)$

Intermediate scales: $C_l^{\kappa F}$

Small scales: $P_{1D}(k)$

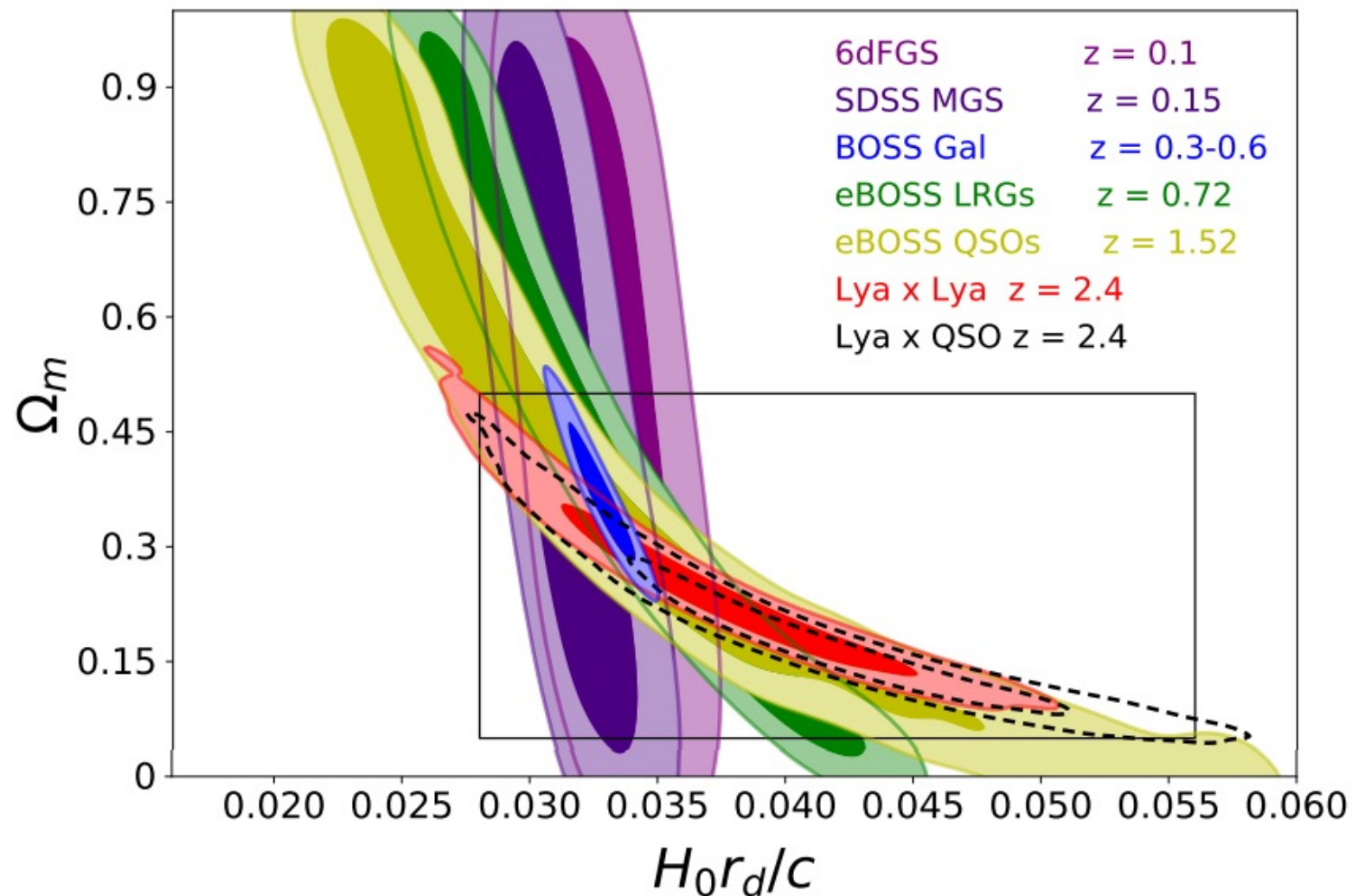
- BAO: Expansion history
- Full-shape: Amplitude (σ_8) & matter ($\Omega_m h$)

- Amplitude & shape of matter clustering
- Sum of neutrino masses $\sum m_\nu$

- Neutrino mass
- IGM thermal parameters
- Warm DM models

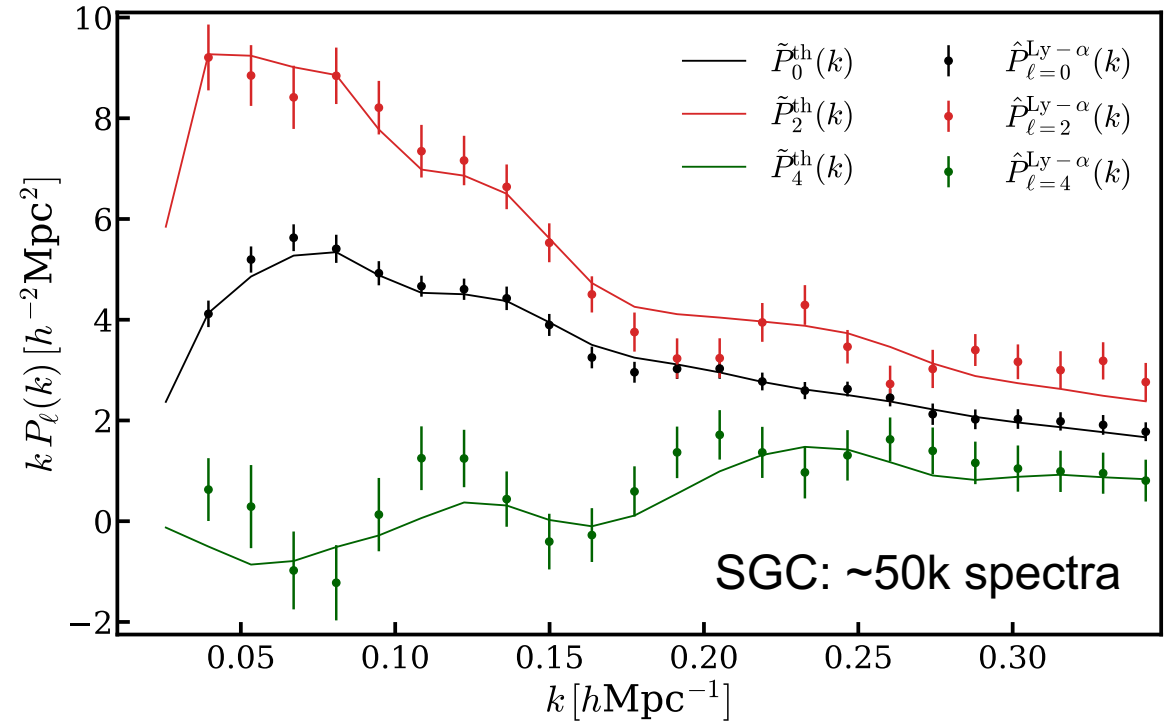
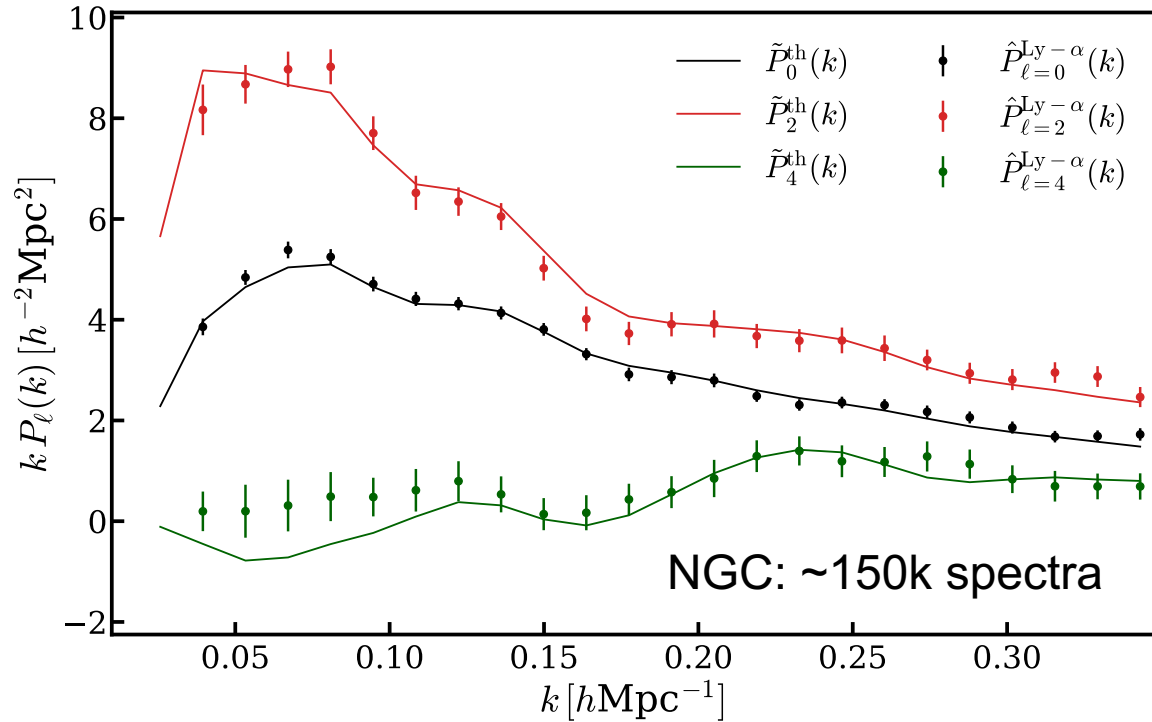
Why do we need a high-z measurement?

Break degeneracies from BAO measurements



Lyman-a forest 3D power spectrum

Comparison to best-fit theory prediction from 2PCF measurement¹



Consistent anisotropic P3D from eBOSS at z~2.33 for NGC and SGC at 1-2 σ level

Theory vs. simulation-based analyses

¹ Chen, Vlah & White (2022)

² Ivanov (2023)

³ Bird+ (2018)

⁴ Pedersen+ (2020, 2023)

⁵ Cabayol-Garcia+ (2023)

Perturbative models^{1,2}

- Theoretically well motivated (EFTofLSS)
- Fast but difficult to compute
 - Higher-order terms / N-PCF
- High $z \rightarrow$ high k reach

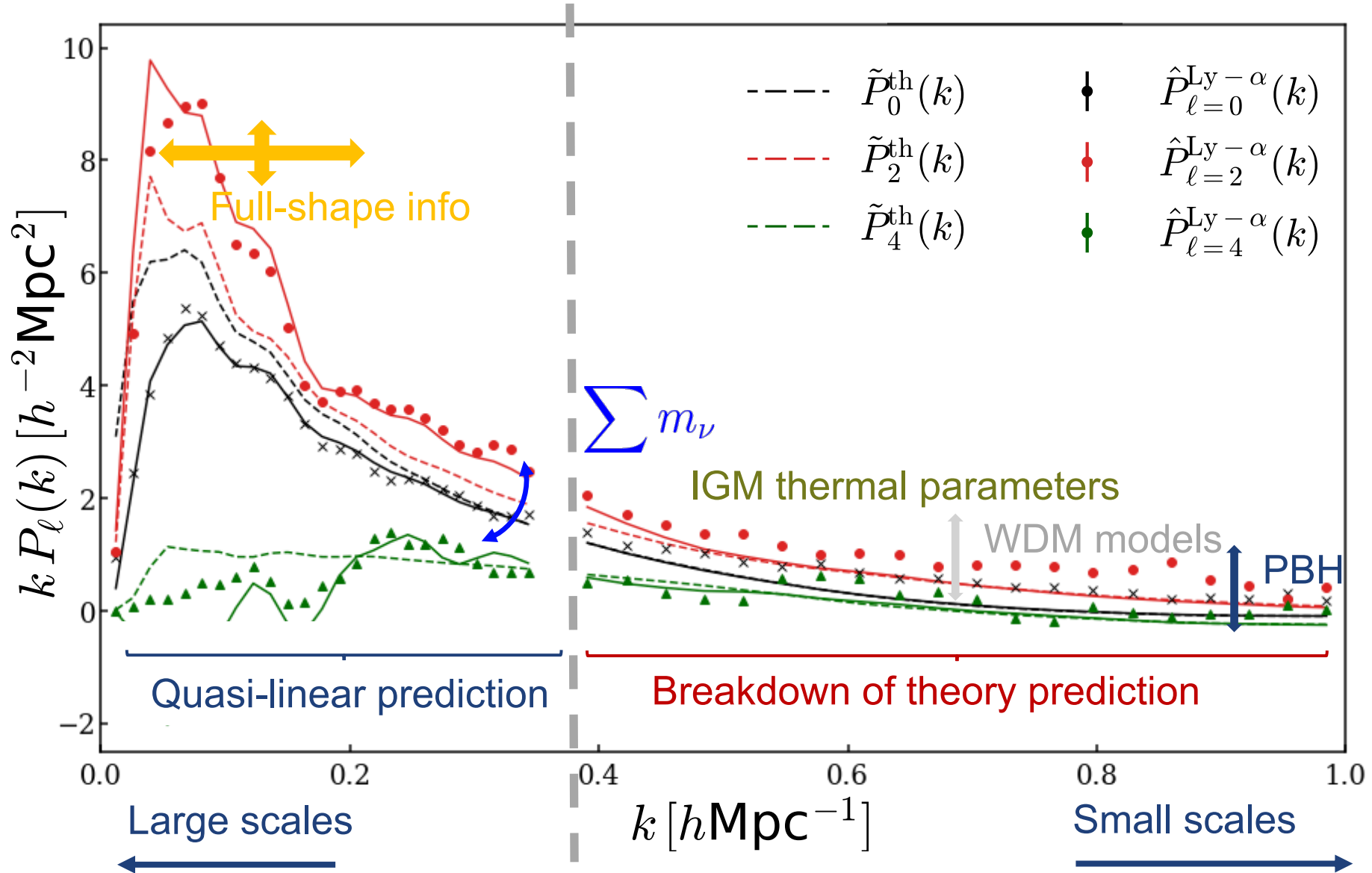
Emulator model^{3,4}

- Simulation-based model
 - Ly- α forest resolution at all scales required
 - Can extend to non-perturbative regimes
- Field-level inference
 - (Potentially) extract all the available information

Hybrid model: (EFT + simulation-based model)

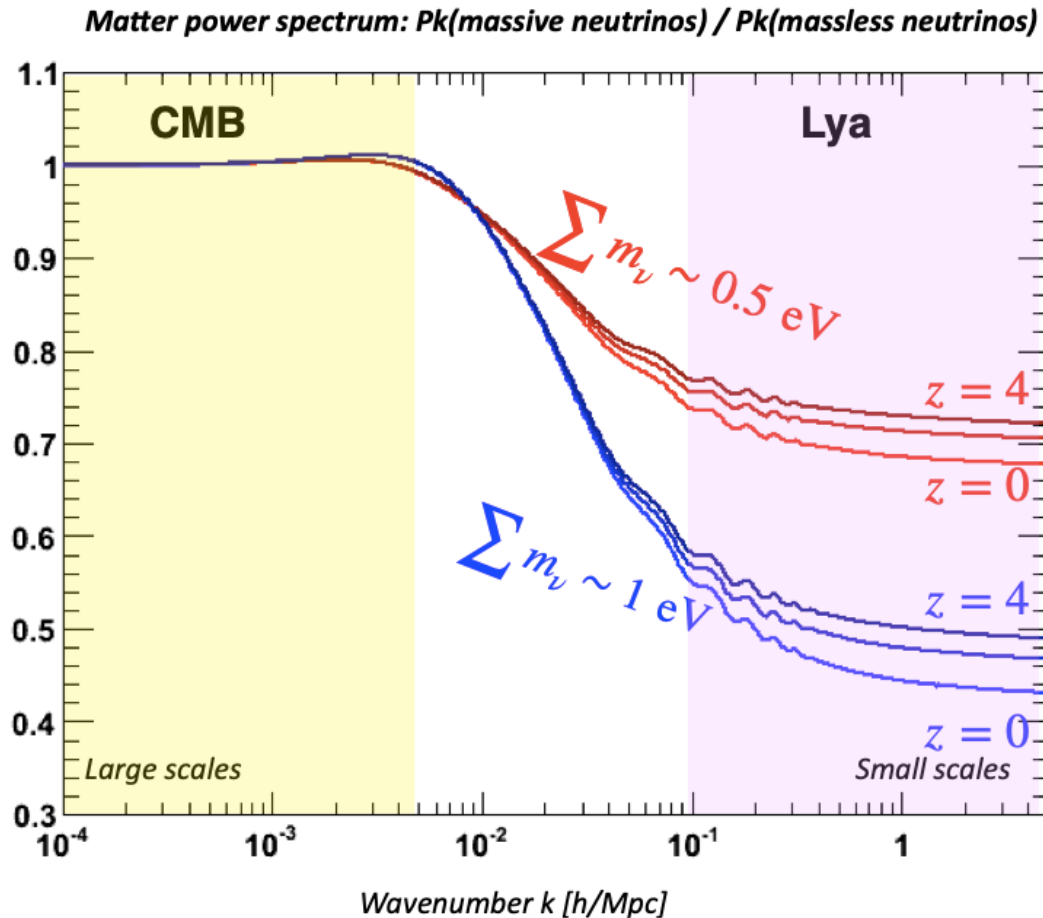
Full-shape analysis of Lyman- α forest data

Accurate model down to smaller scales?



Probe scales from CMB to Lyman- α

From large to small scales



- CMB
 - Sensitive to large scales
 - Traces projected matter density
 - Probe reionization & inflation
 - **Probe amplitude of matter fluctuations**
- Lyman- α forest
 - Sensitive to small scales
 - Suppression of matter clustering $\rightarrow M_\nu$
- Break degeneracies with bias
 - **CMB x Lyman- α**
 - QSO x Lyman- α

CMB lensing x Lyman-a forest: power spectrum

Break degeneracies to measure S_8 : $\sigma_8^2 \sim \langle \delta_m^2 \rangle$

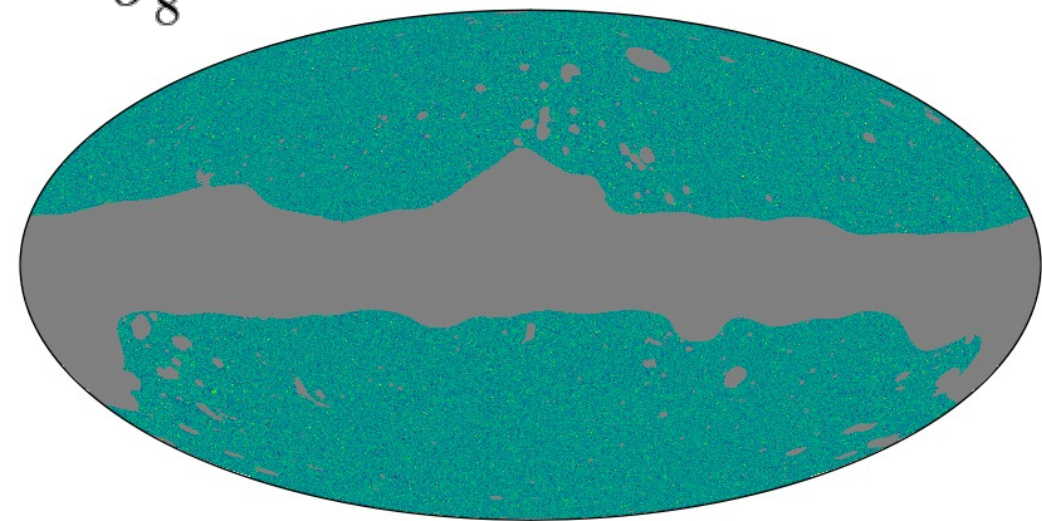
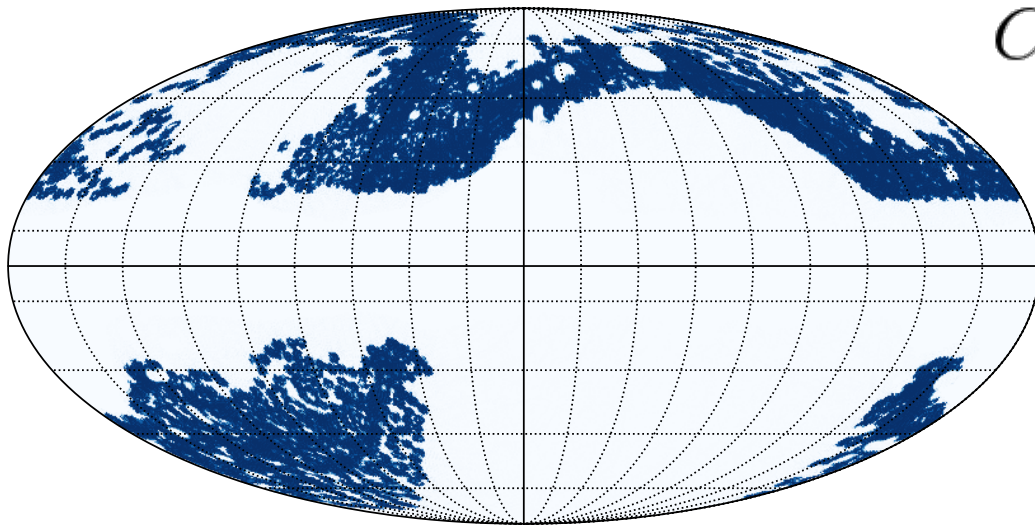
¹ Zaldarriaga et al. (2001)

² Valinotto et al. (2009)

³ Doux et al. (2016)

$$C_l^{FF} \sim b_F^2 \sigma_8^2 \quad C_l^{\kappa F} \sim b_F \sigma_8^2$$

$$\frac{(C_l^{\kappa F})^2}{C_l^{FF}} \sim \sigma_8^2$$

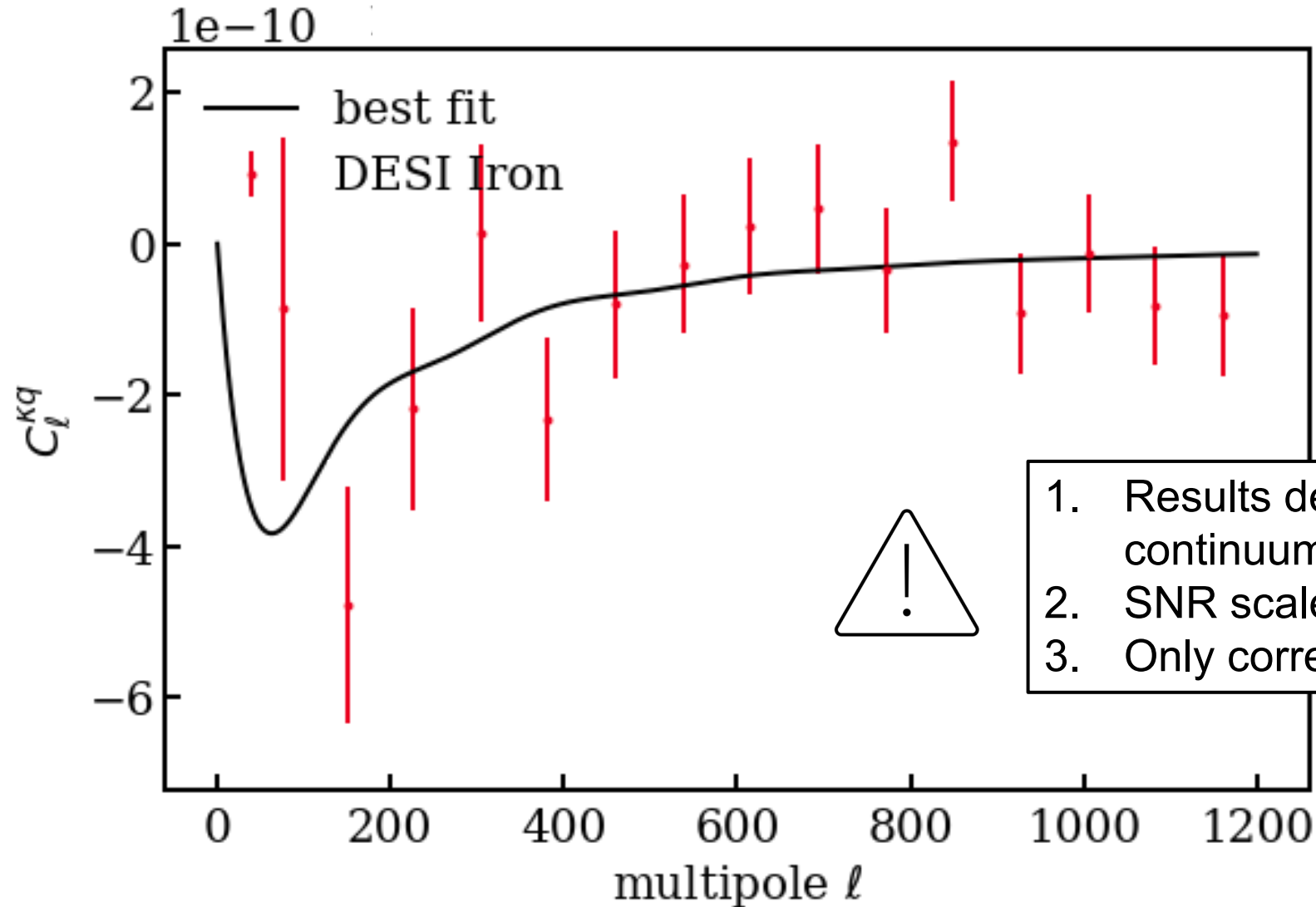


- Mean Lyman-a forest in $2 < z < 4$; $f_{\text{sky}} \sim 1/4$

- CMB lensing (kappa) map from Planck PR3

~4 σ detection of CMB lensing x Ly α forest: power spectrum

First signal from DESI year-1 data

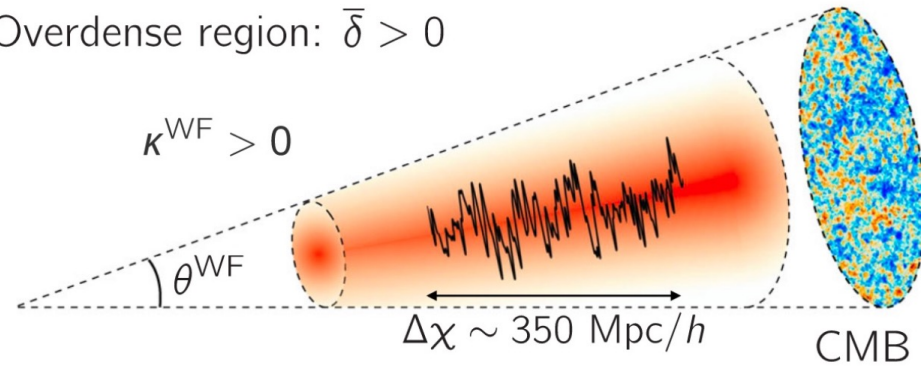


1. Results depend on continuum fitting
2. SNR scales as a function of z
3. Only correlations along LOS

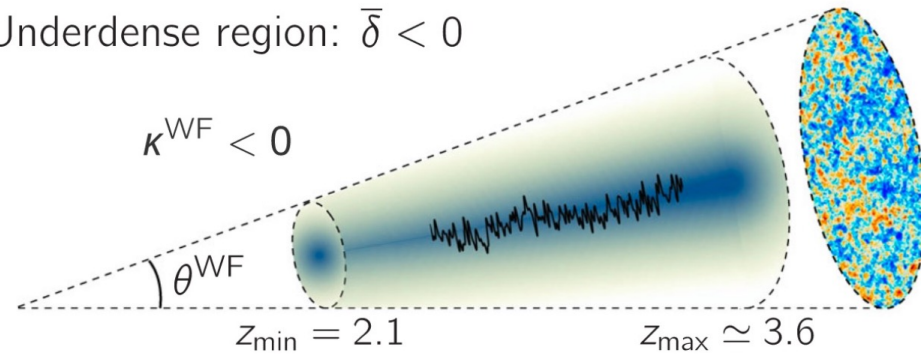
~4.8 σ detection of CMB lensing x Lyman-a P1D

Measuring a squeezed bispectrum

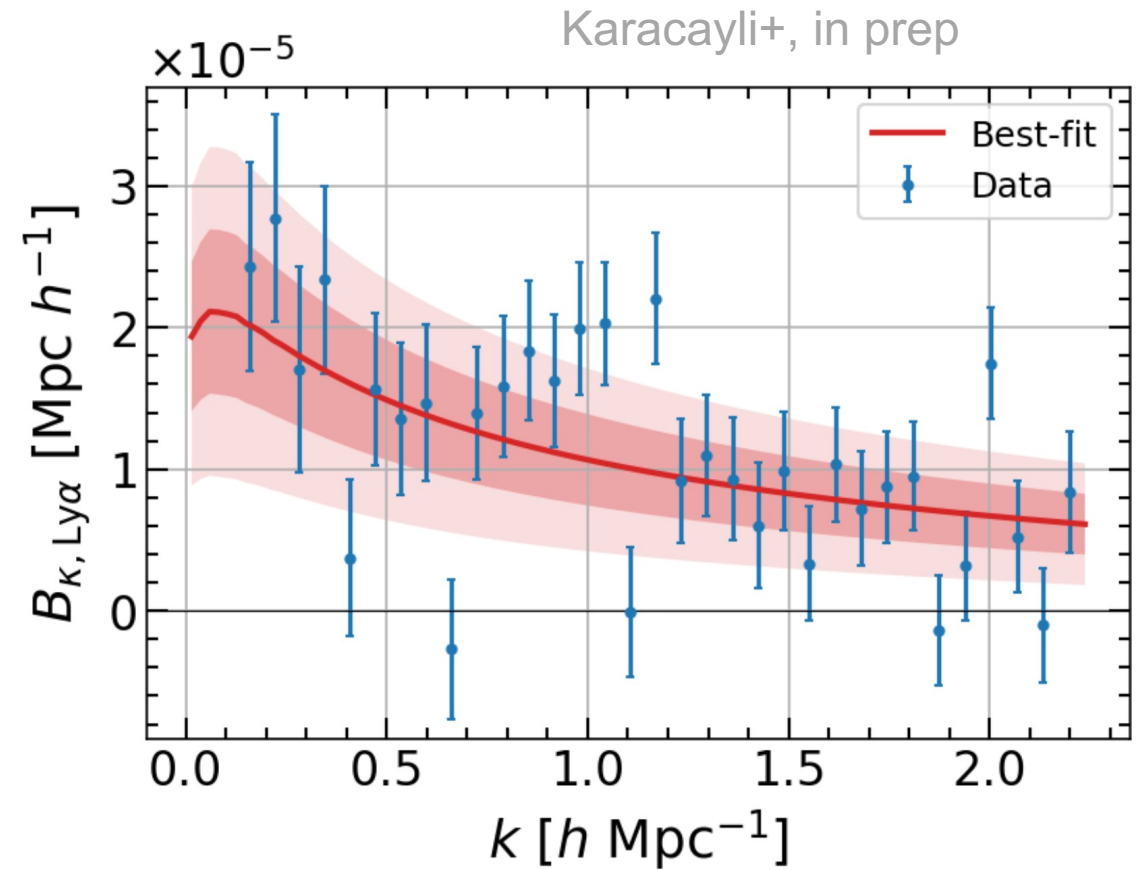
Overdense region: $\bar{\delta} > 0$



Underdense region: $\bar{\delta} < 0$



Doux et al. (2016)



Signal from 290,000 Lyman-a forests at $z^* \sim 2.4$ but cosmology interpretation difficult

What do gain from Spec-S5?

More lines of sight + cross-correlations with high-z galaxies

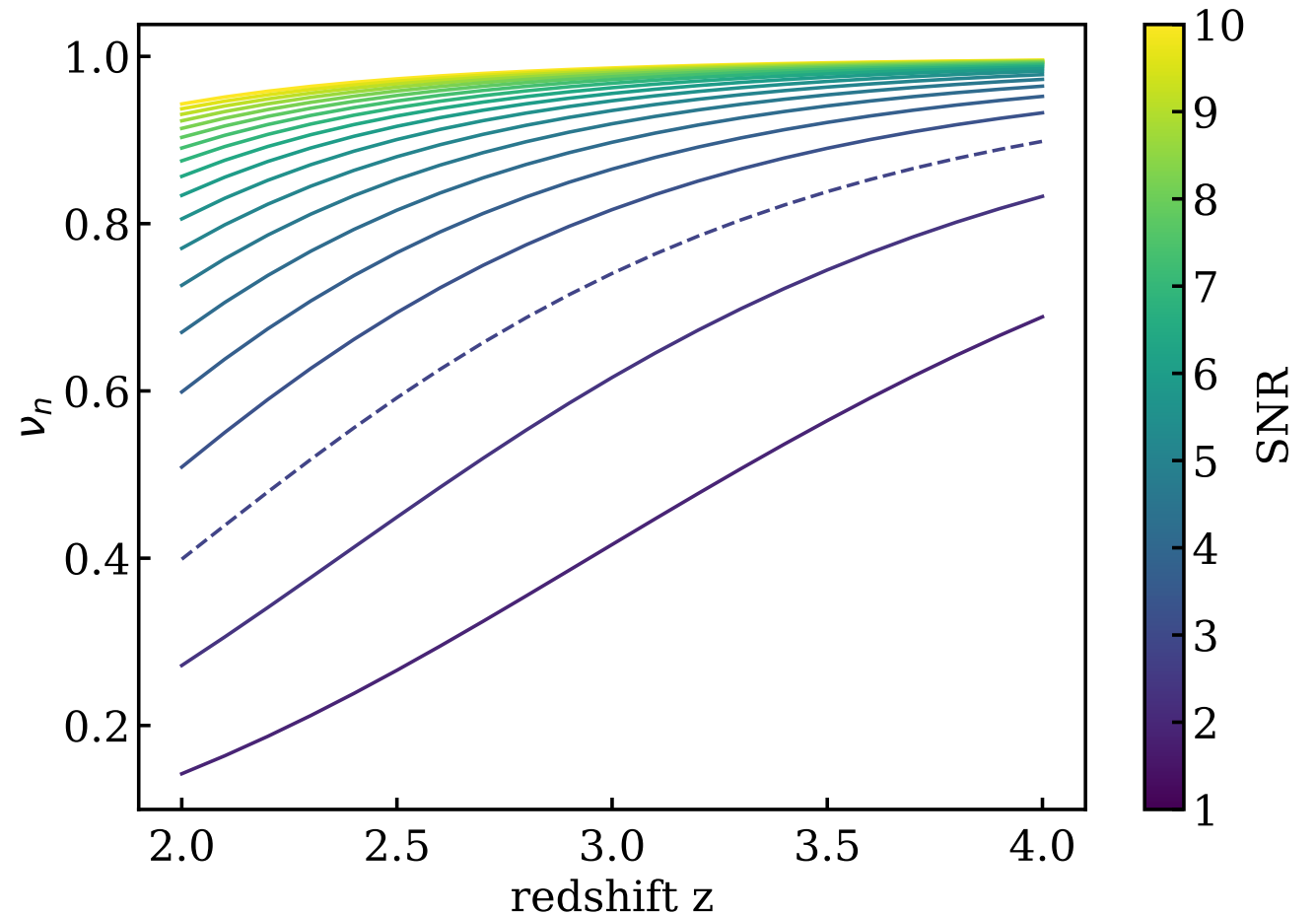
¹ McDonald & Eisenstein (2007)

² McQuinn & White (2011)

$$\hat{P}_{3D}^F(\mathbf{k}) = P_{3D}^F(\mathbf{k}) + \frac{P_{1D}(k_{\parallel})}{\bar{n}_{\text{eff}}}$$

$$\bar{n}_{\text{eff}} \equiv \frac{1}{A} \sum_{n=1}^{N_q} \nu_n$$

$$\nu_n \equiv \frac{P_{1D}(k_{\parallel})}{P_{1D}(k_{\parallel}) + P_{N,n}}$$



Summary & next steps

- Lyman- α forest probes:
 - small scale clustering
 - high redshift: $2 < z < 5$
 - **early-Universe physics**
- Robust **P3D estimator** to extract information at **all scales** from Lyman- α forest
 - sensitive to large-scale intensity and temperature fluctuations^{1,2}
- **Detection of CMB lensing x Ly α forest power spectrum signal**

Lyman- α : high $z \rightarrow$ high k

¹ White+ (2010)

² Zaldarriaga+ (2001)

