DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Novel methods for Lyman-alpha forest cosmology

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BCCP Seminar – 11/18/25

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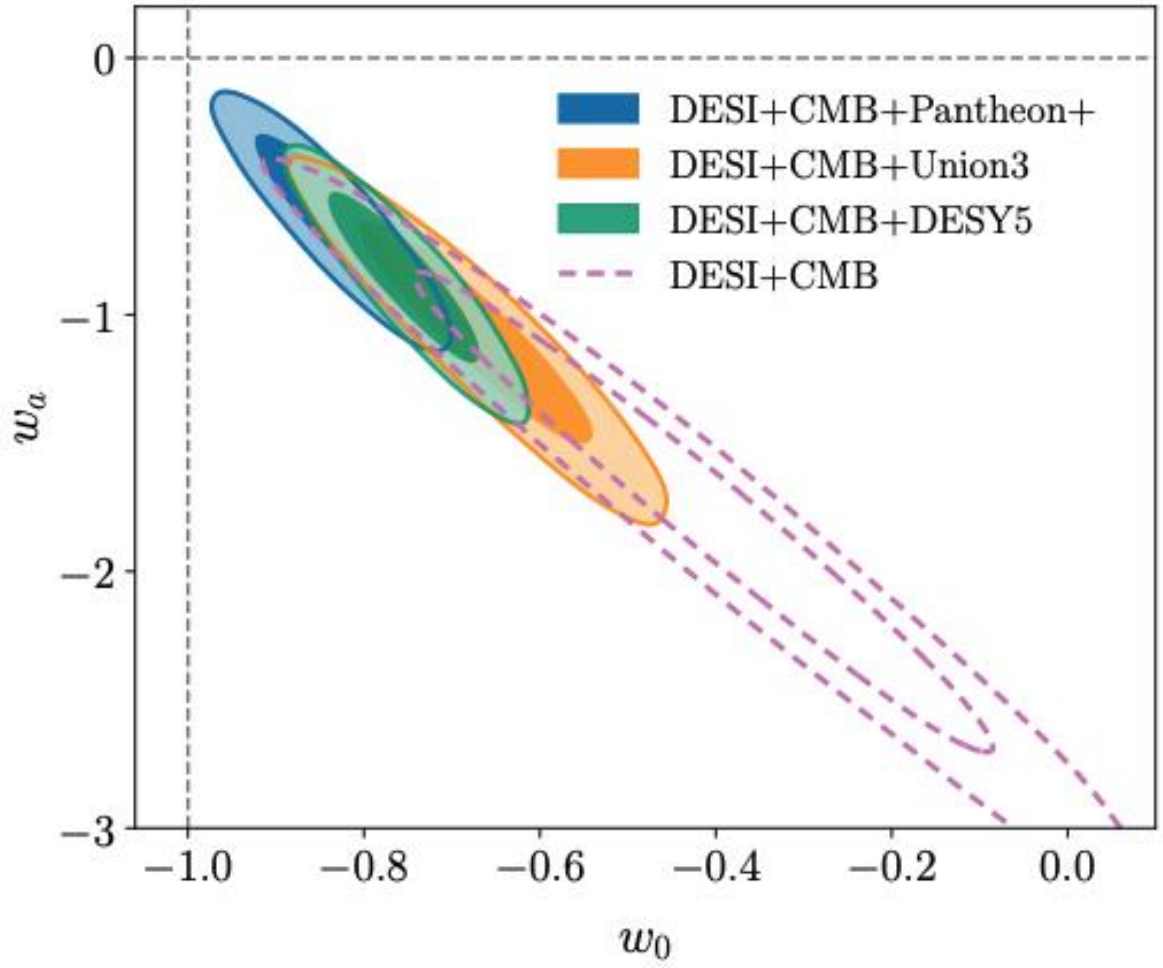
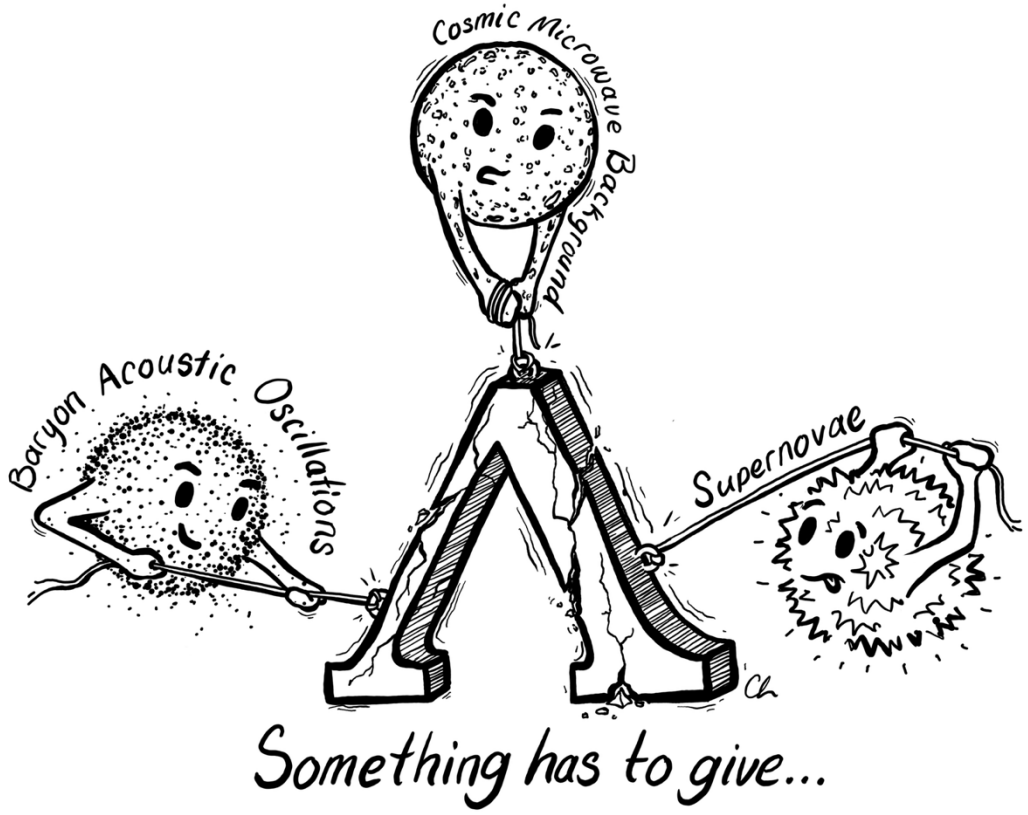
Motivation

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



DESI Collaboration (incl. **Turner**) et al. 2025



Credit: Claire Lamman

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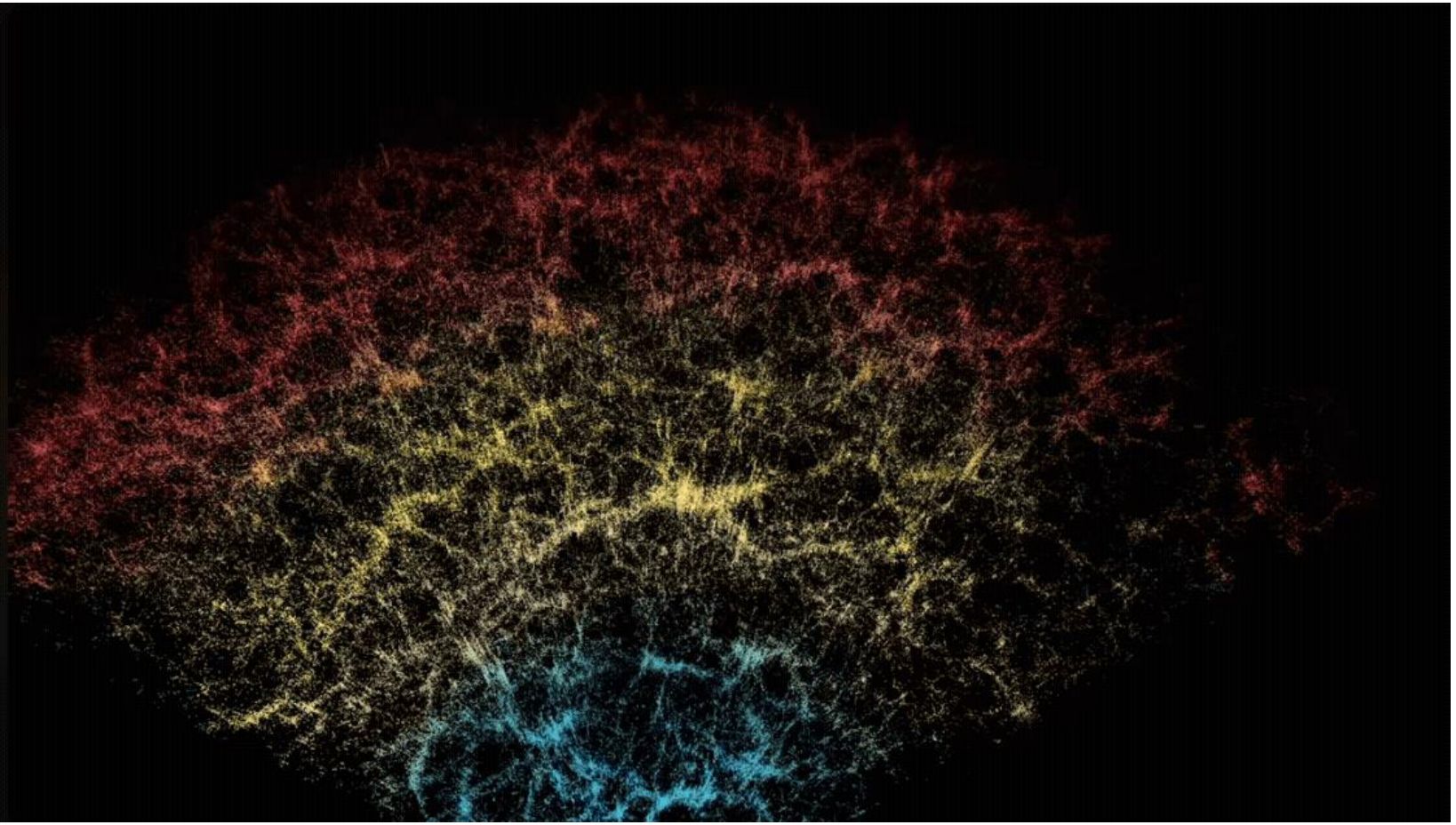
DESI overview



- Robotic positioners enable observations of 5000 objects simultaneously
- 8-year survey measuring 63M extragalactic redshifts
- Roughly one million $z \geq 2.1$ Lyα forest quasars

Credit: DESI Collaboration/NOIRLab/NSF/AURA/R. Proctor

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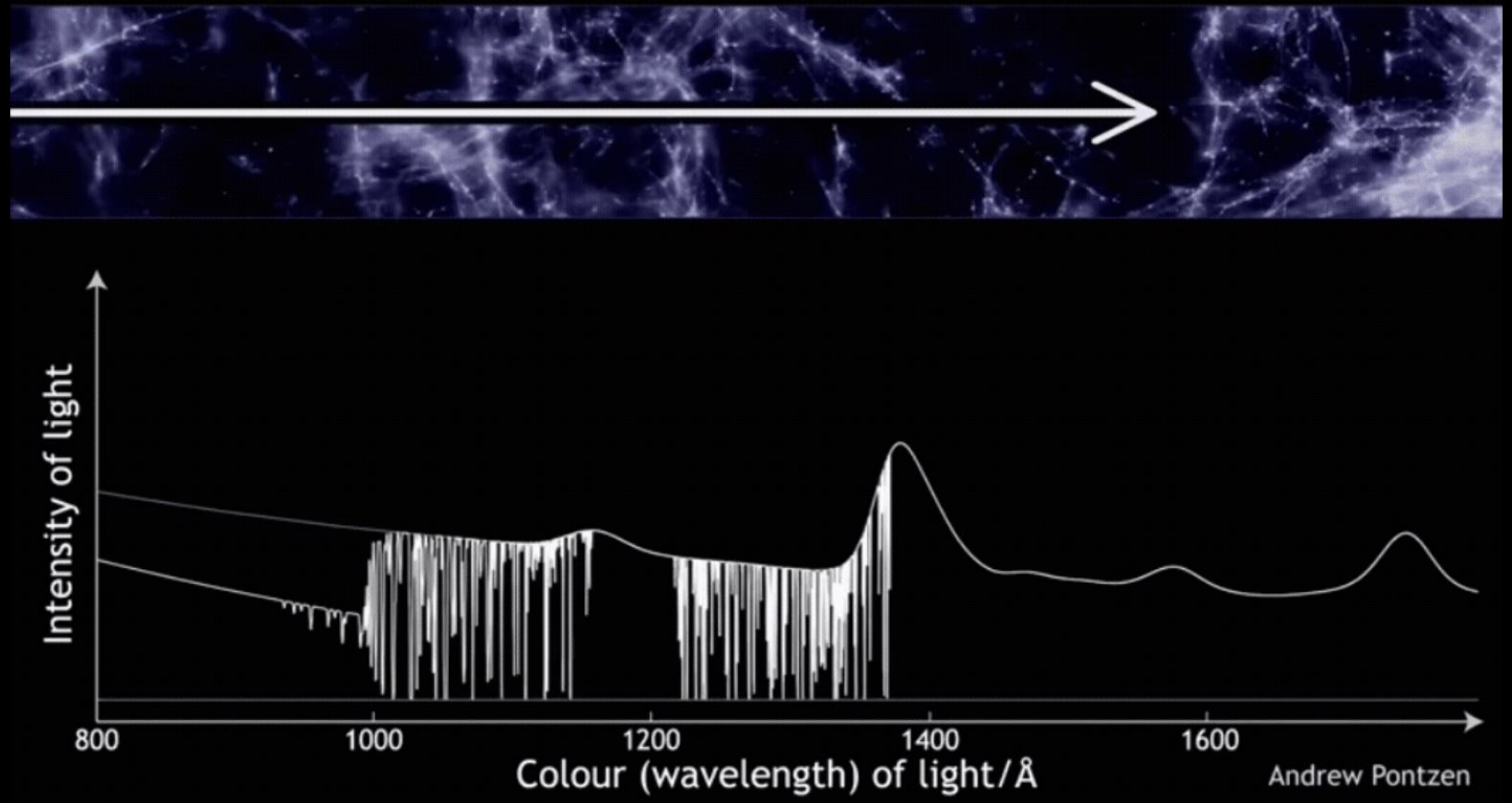
Why the Lyα forest?



- Probes ionization state, temperature, density of IGM
- Traces large-scale structure: great for z > 2 cosmology!

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Lyα forest correlations

- Two-point correlations:
  - Lyα auto-correlation
  - Cross-correlation with quasars
- Must assume a fiducial cosmology

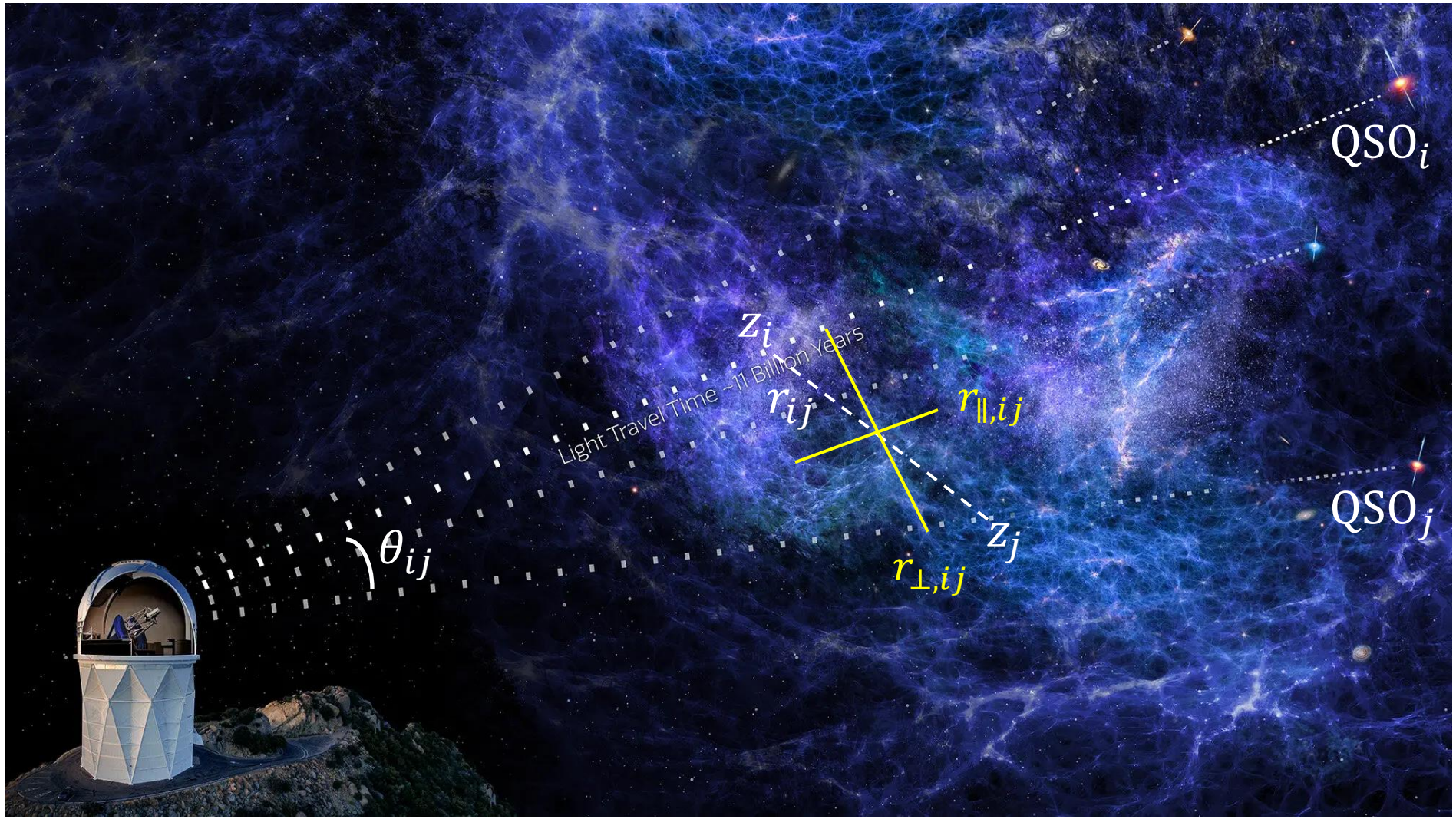

Image Credit: NOIRLab/NSF/AURA/P. Marenfeld and DESI Collaboration

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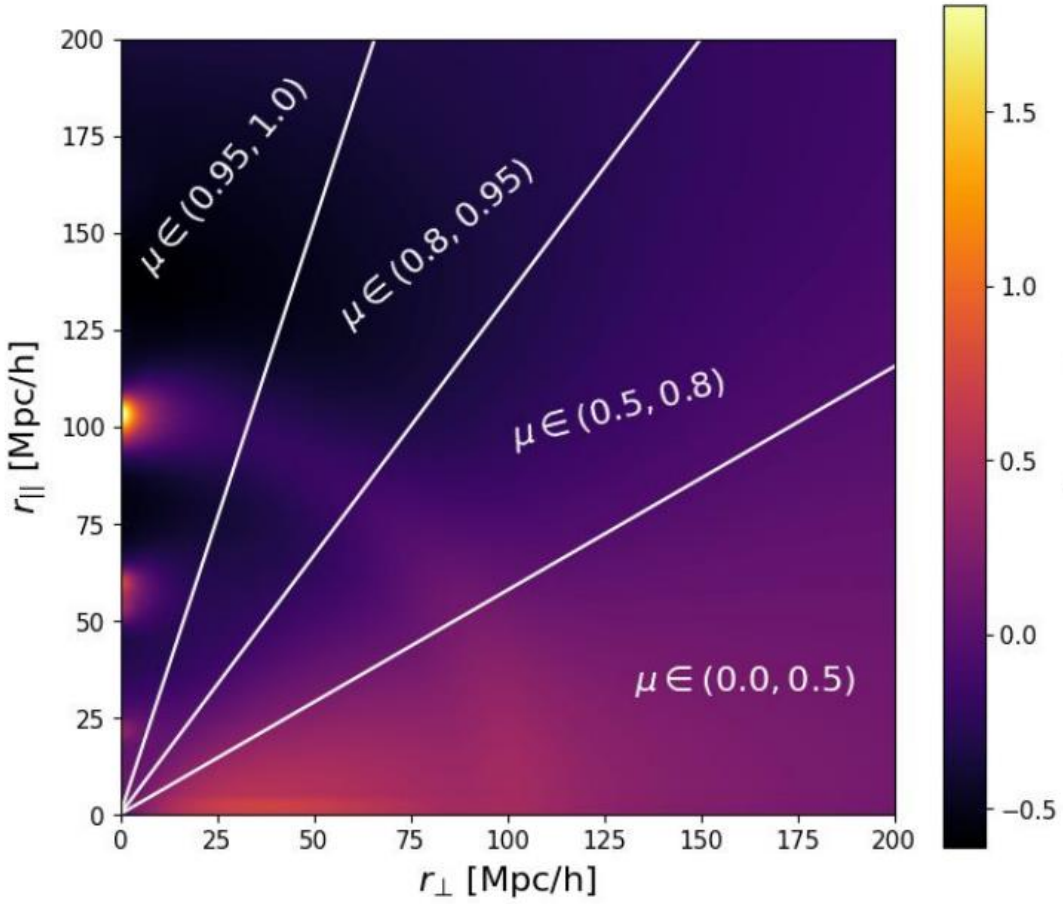
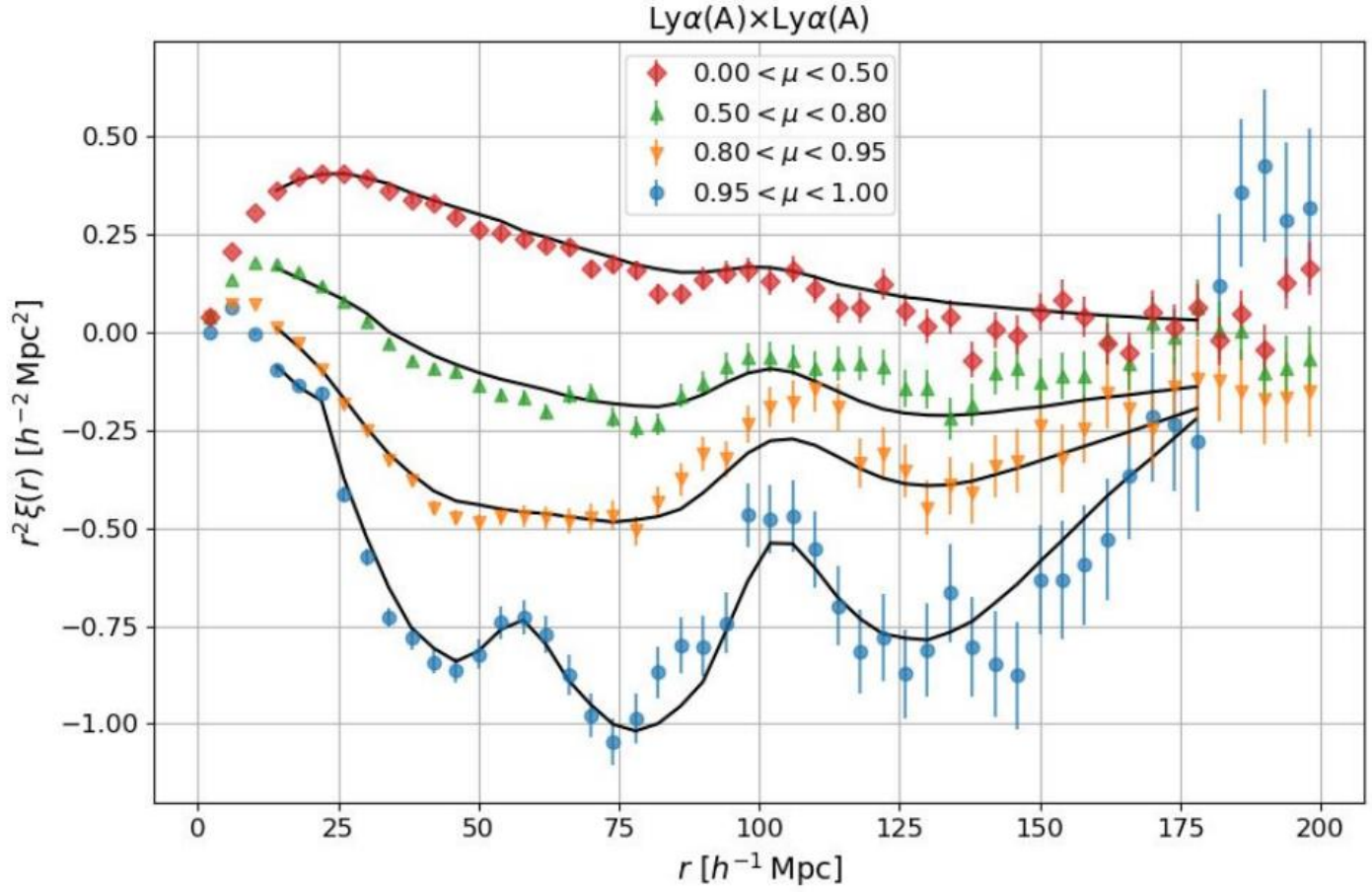
Lyα forest correlations





Credit: Andrei Cuceu and the DESI Collaboration

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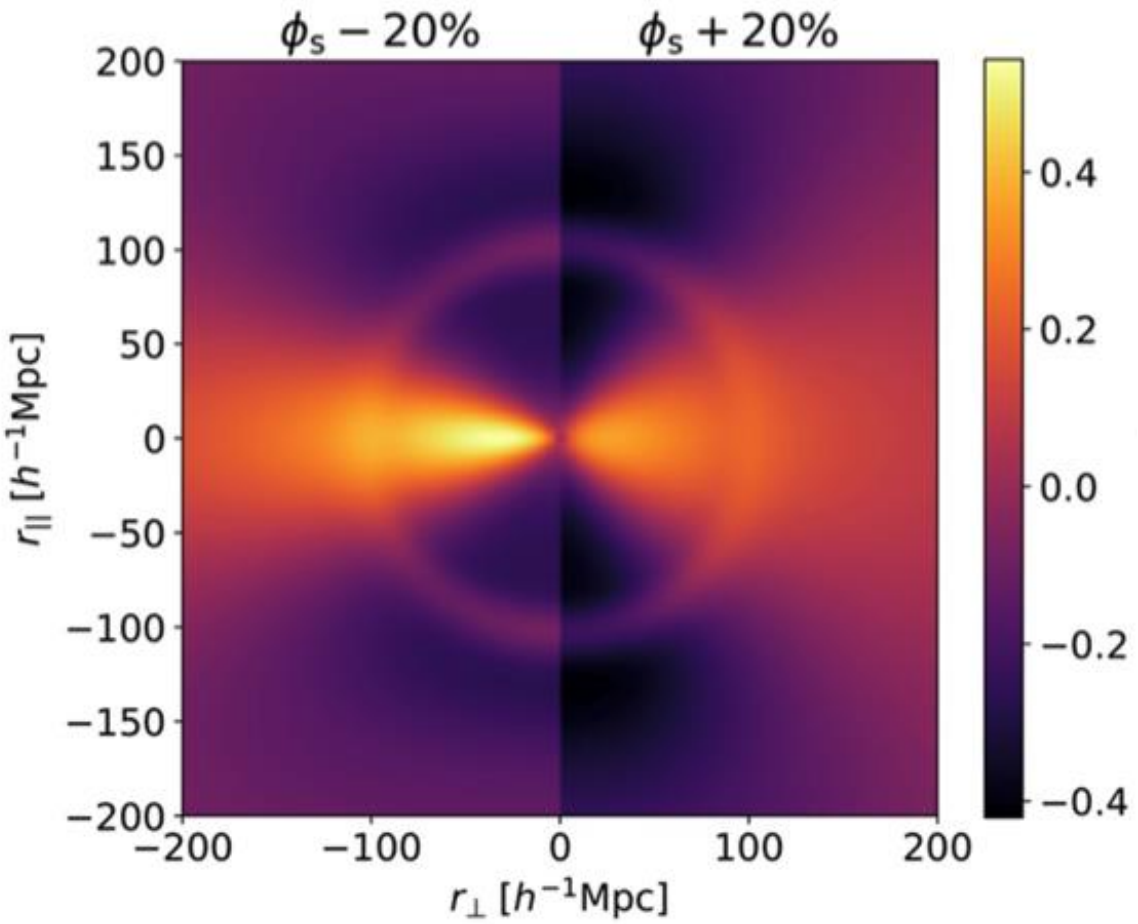
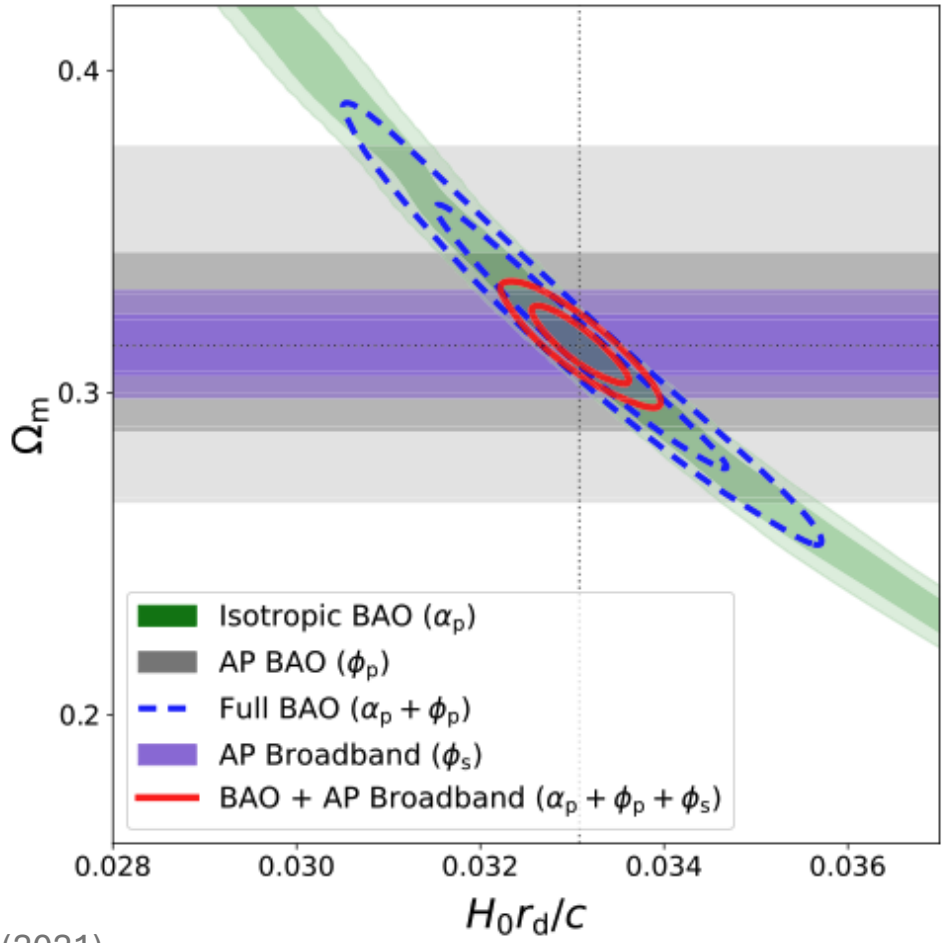
Beyond BAO

- More to be gained from the Alcock-Paczyński (AP) effect: factor of ~2 improvement
- Arises from anisotropy introduced by incorrect fiducial cosmology





Cuceu et al. (2021)

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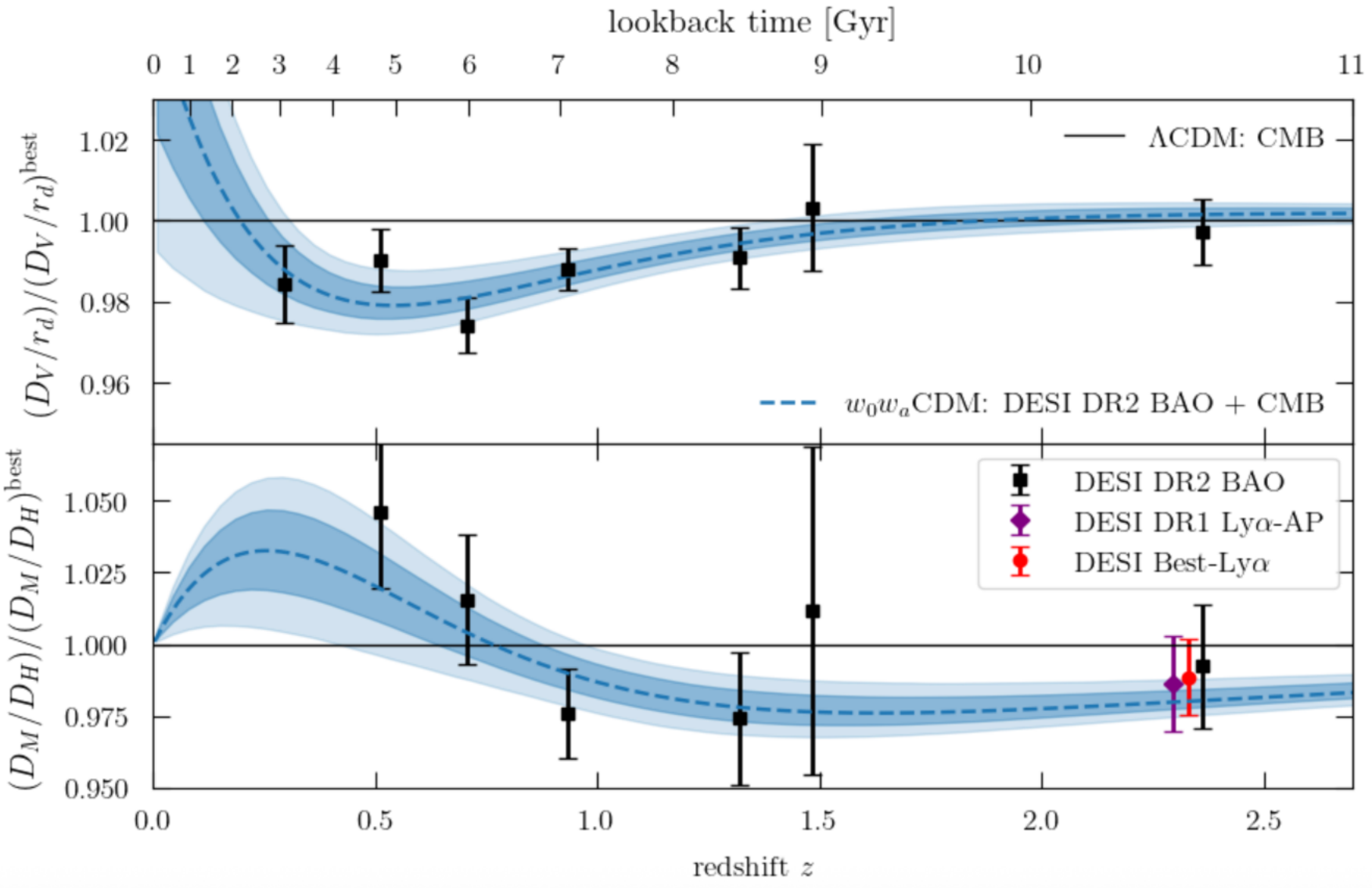
DR1 Lyα full shape

Isotropic BAO

AP



Adapted from Cuceu et al. (2025)

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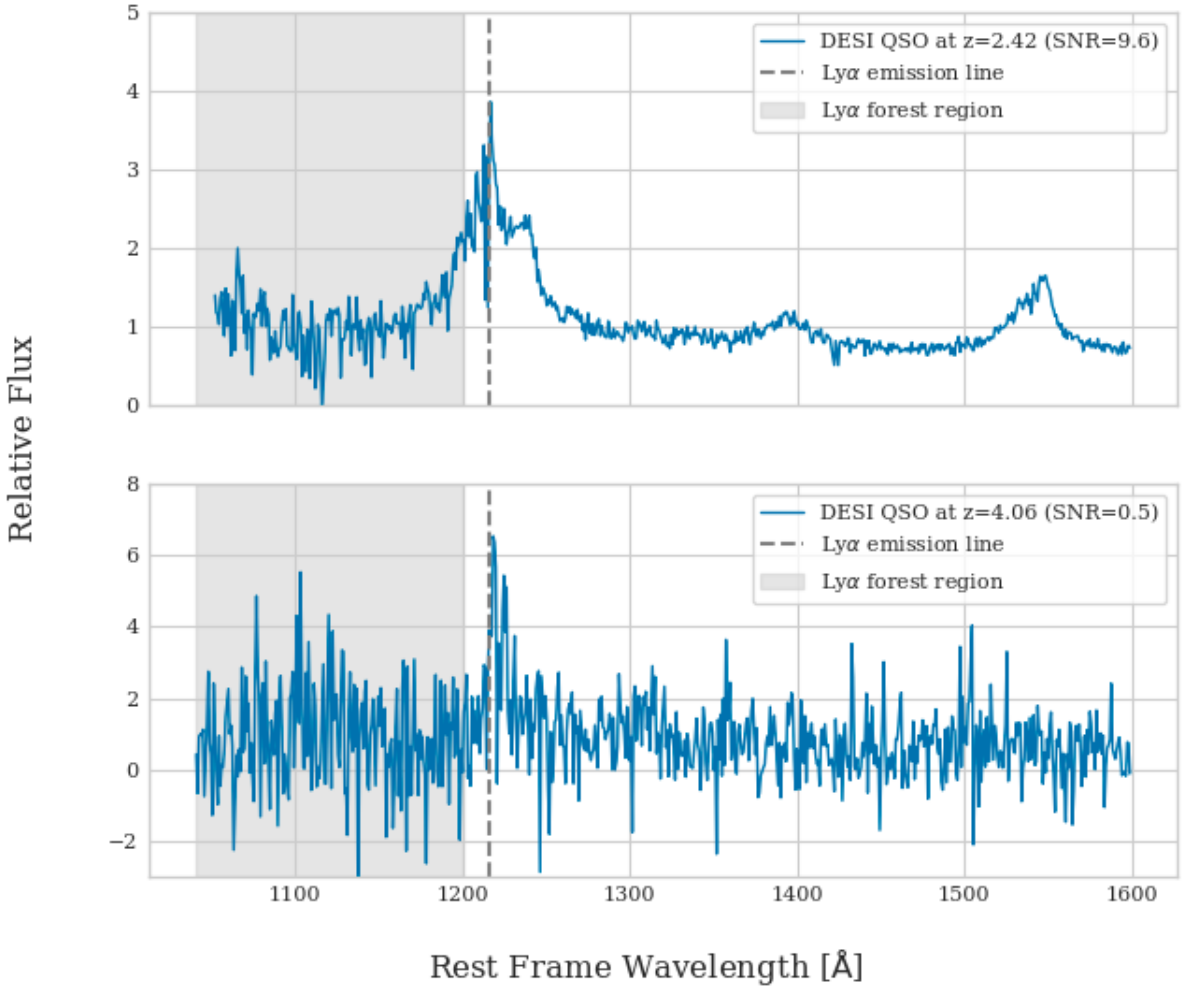
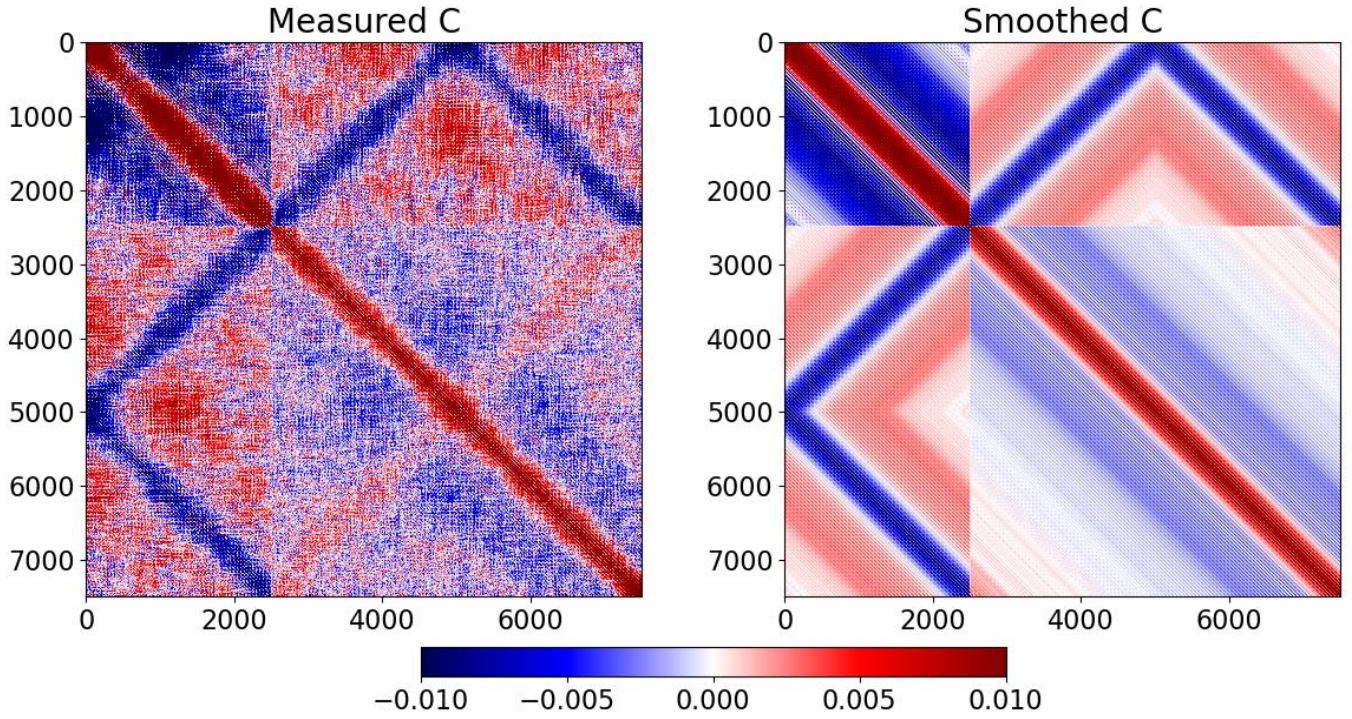
Challenges in Lyα forest cosmology

Requires estimates of the quasar continuum



Covariance estimation: ad-hoc smoothing procedure



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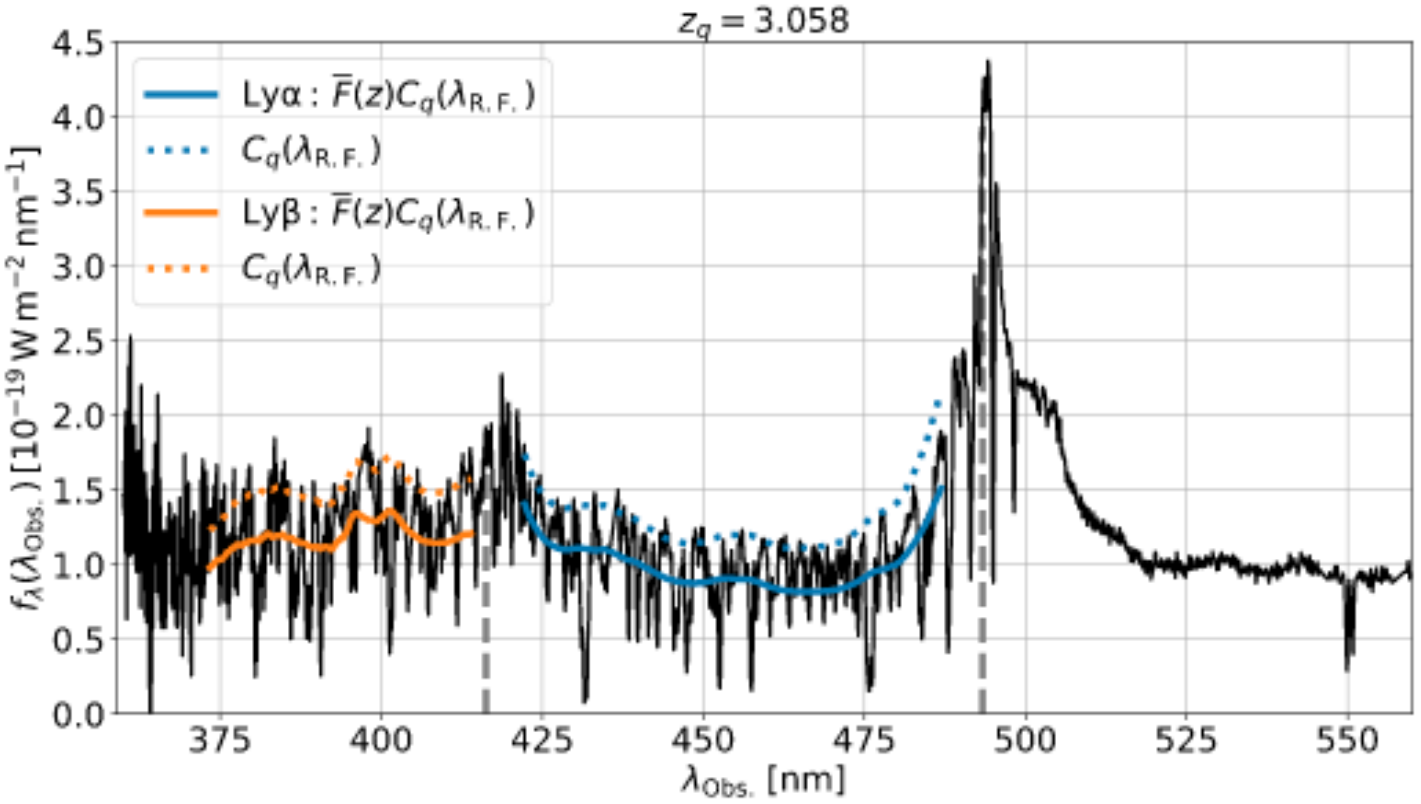
Current continuum fitting method

$$\bar{F}(\lambda)C_q(\lambda) = \bar{C}(\lambda_{\mathrm{RF}})\left(a_q + b_q \log\lambda\right)$$

- Forest continuum cannot be measured directly in DESI data
- Current method estimates the expected flux $\bar{F}(\lambda)C_q(\lambda)$ for each quasar
  - Mean continuum $\bar{C}(\lambda_{\mathrm{RF}})$ is measured from data
- Removes some information on large scales
  - Distorts correlation function on all scales
  - Not recovering all the information in the two-point correlation functions



du Mas des Bourboux et al. (2020)

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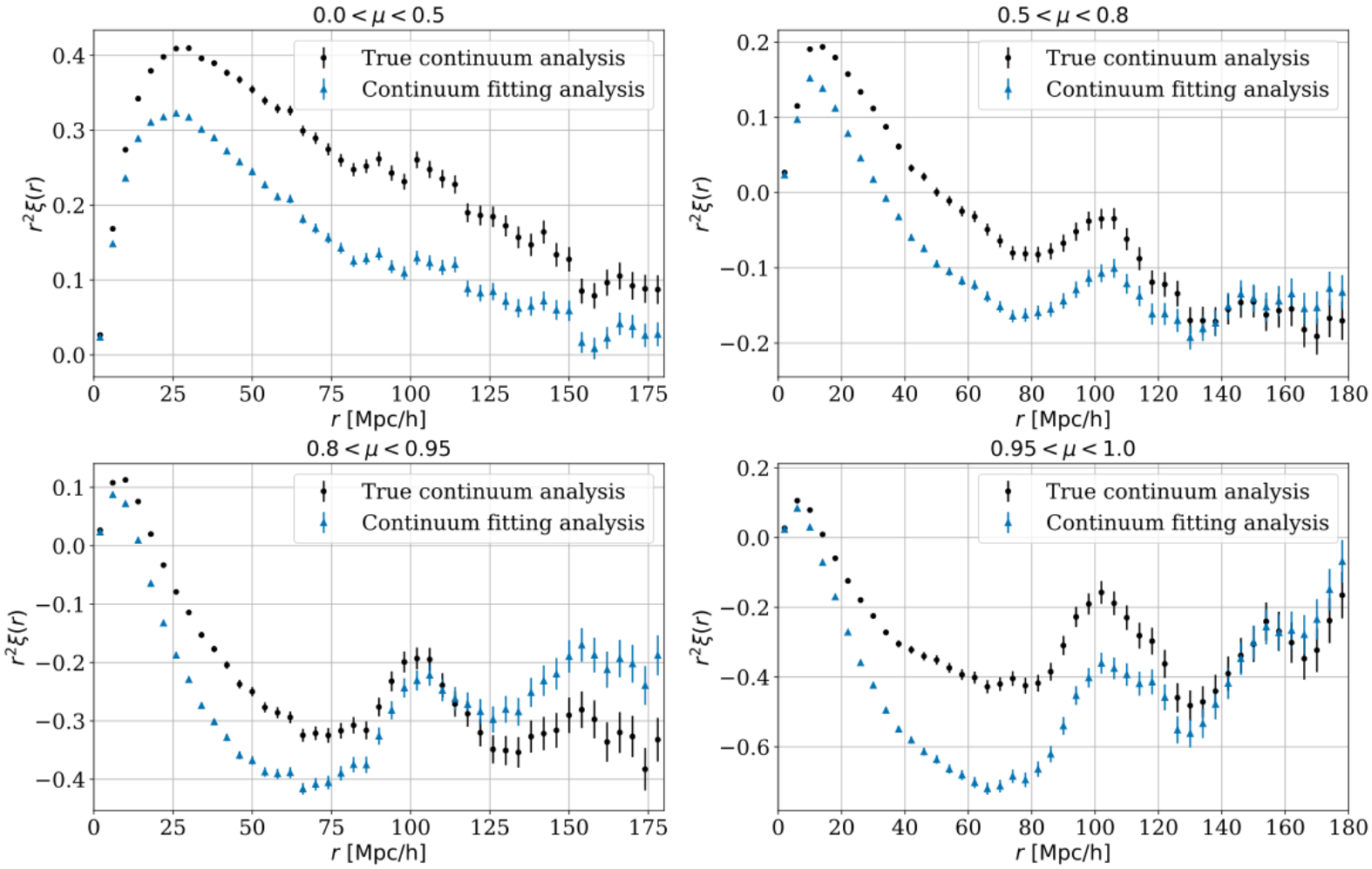

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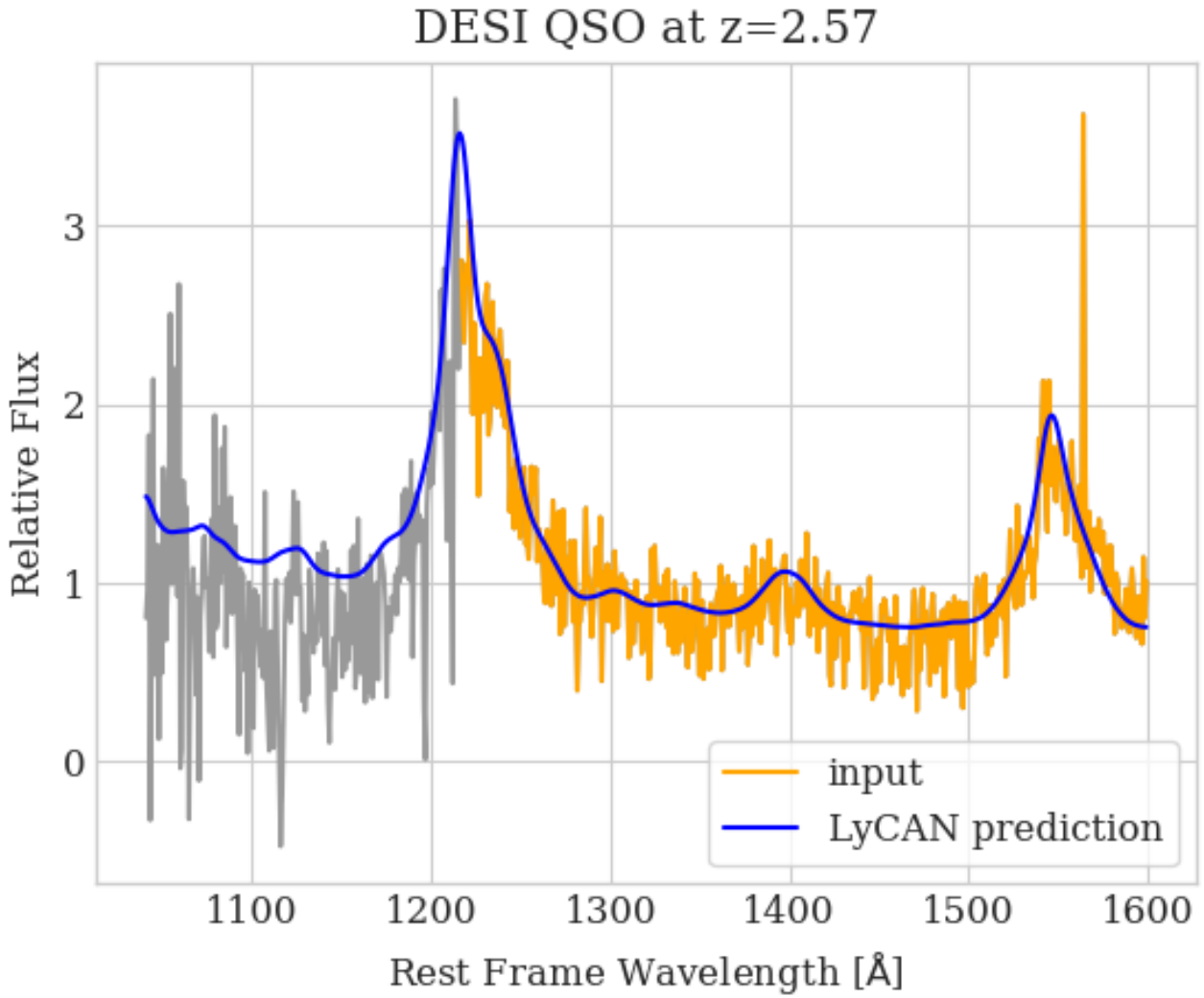
LyCAN

Lyα **C**ontinuum **A**nalysis **N**etwork

- CNN that predicts unabsorbed continuum from 1040-1600Å based only on red side (1216-1600Å)
- Trained on low-z COS spectra + DESI Y5 mocks



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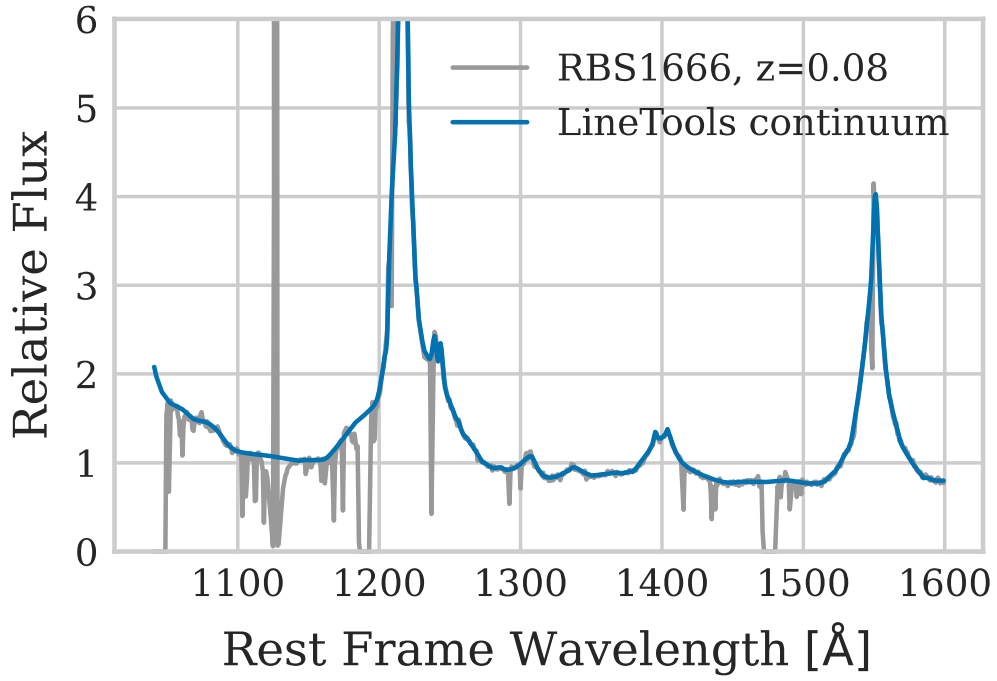
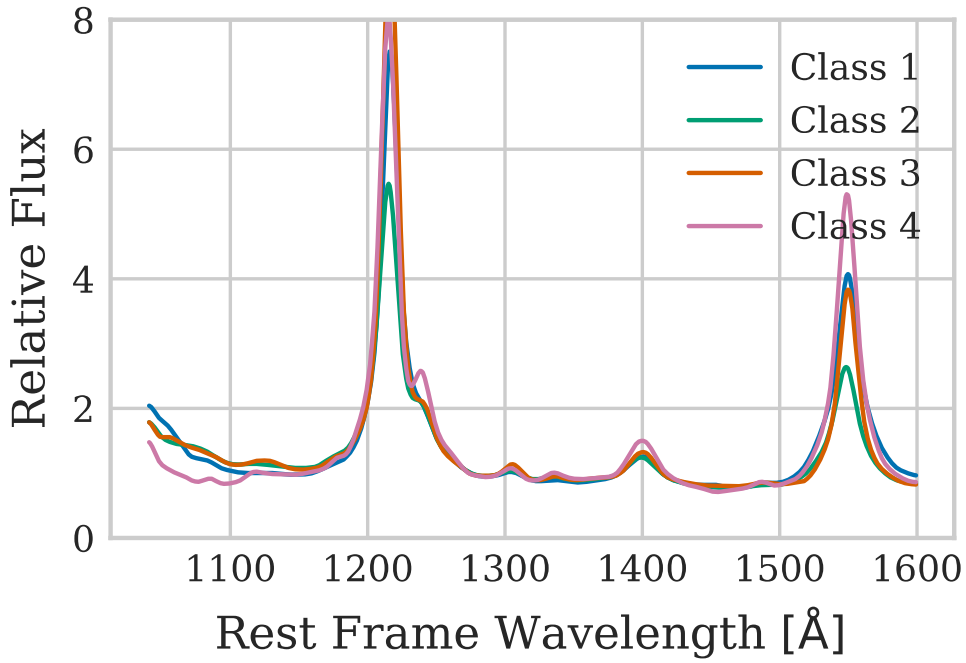
LyCAN training

Cosmic Origins Spectrograph (COS) spectrum



Gaussian Mixture Model representation of 38 COS spectra



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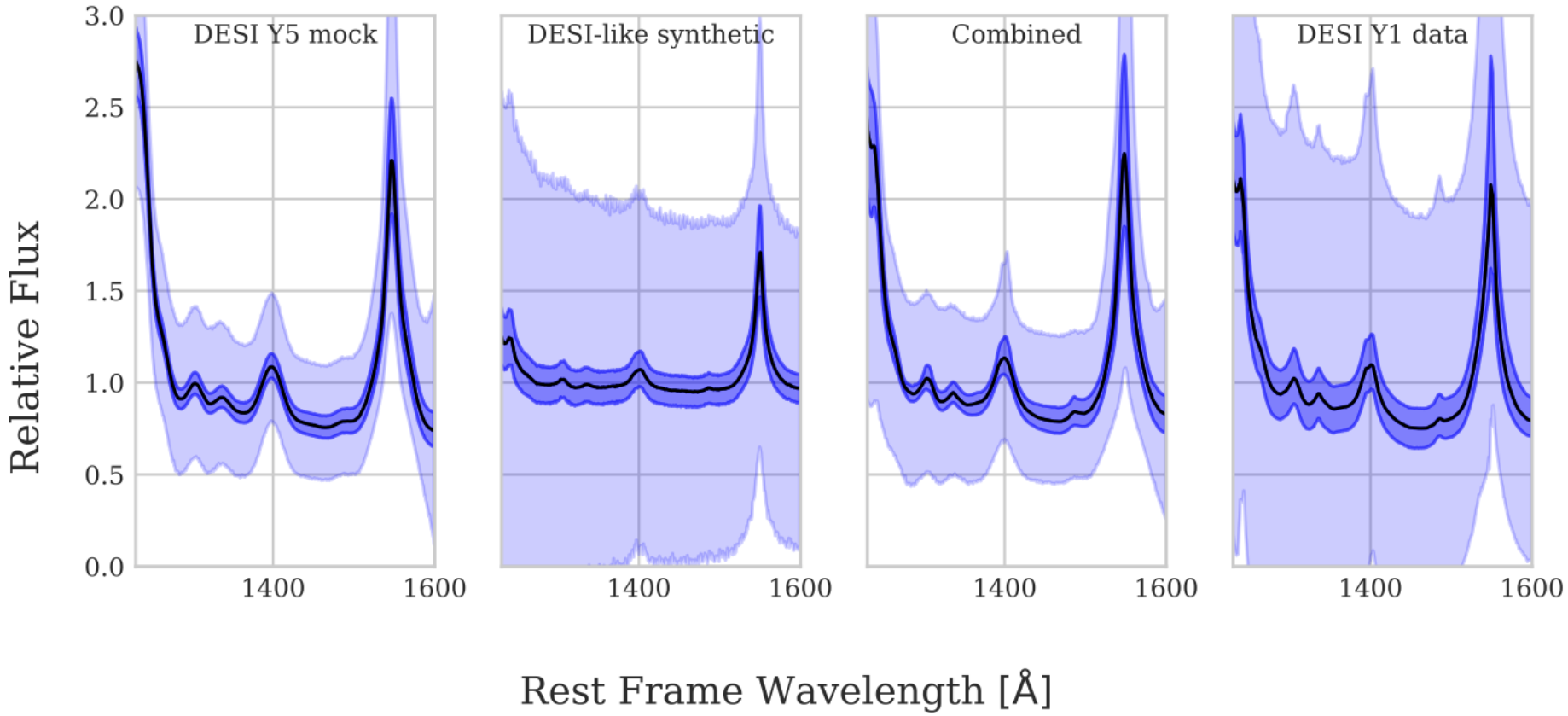
LyCAN training

- 40k COS-based synthetic spectra + 40k DESI Y5 mock spectra
- Perturbations, metal lines, and noise added to COS-based spectra



Turner et al. (2024)

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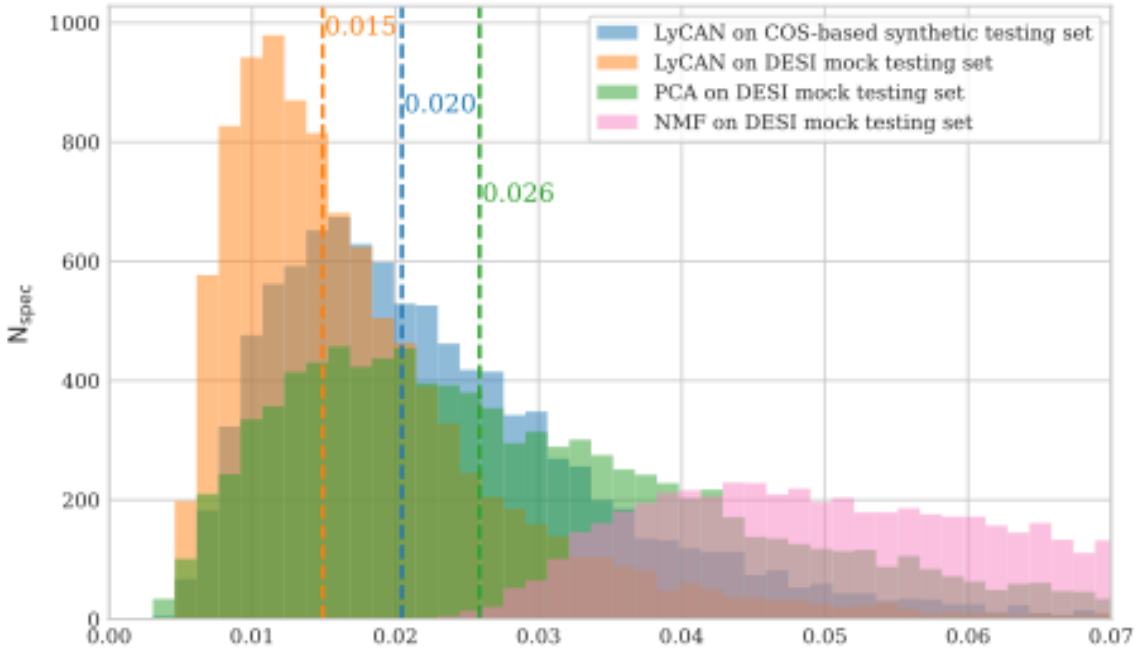
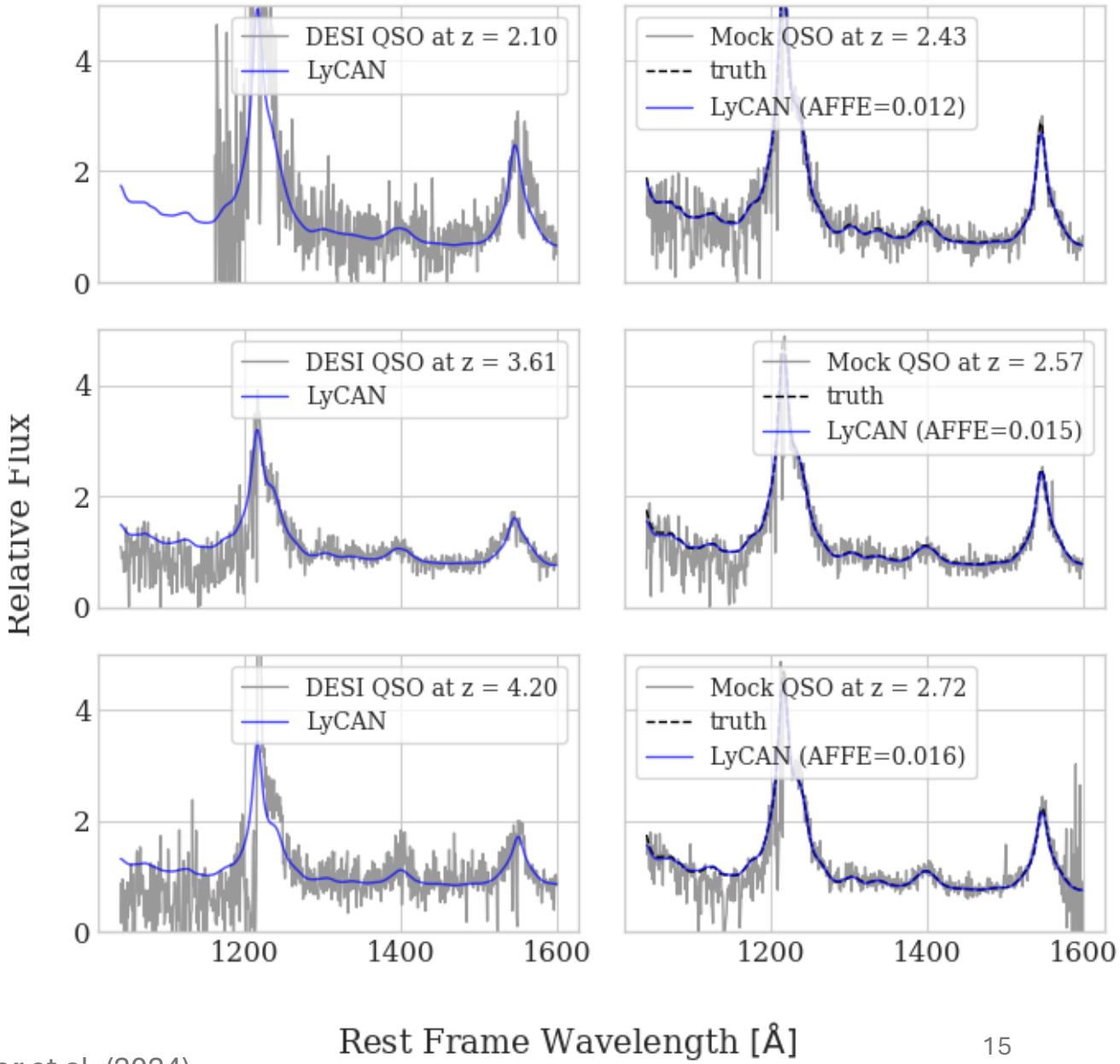
LyCAN performance



$$\mathrm{AFFE} = \frac{\int_{1040\text{Å}}^{1200\text{Å}} \left| \frac{F_{pred}(\lambda) - F_{true}(\lambda)}{F_{true}(\lambda)} \right| d\lambda}{\int_{1040\text{Å}}^{1200\text{Å}} d\lambda}$$

LyCAN outperforms these PCA and NMF models by 40% or more



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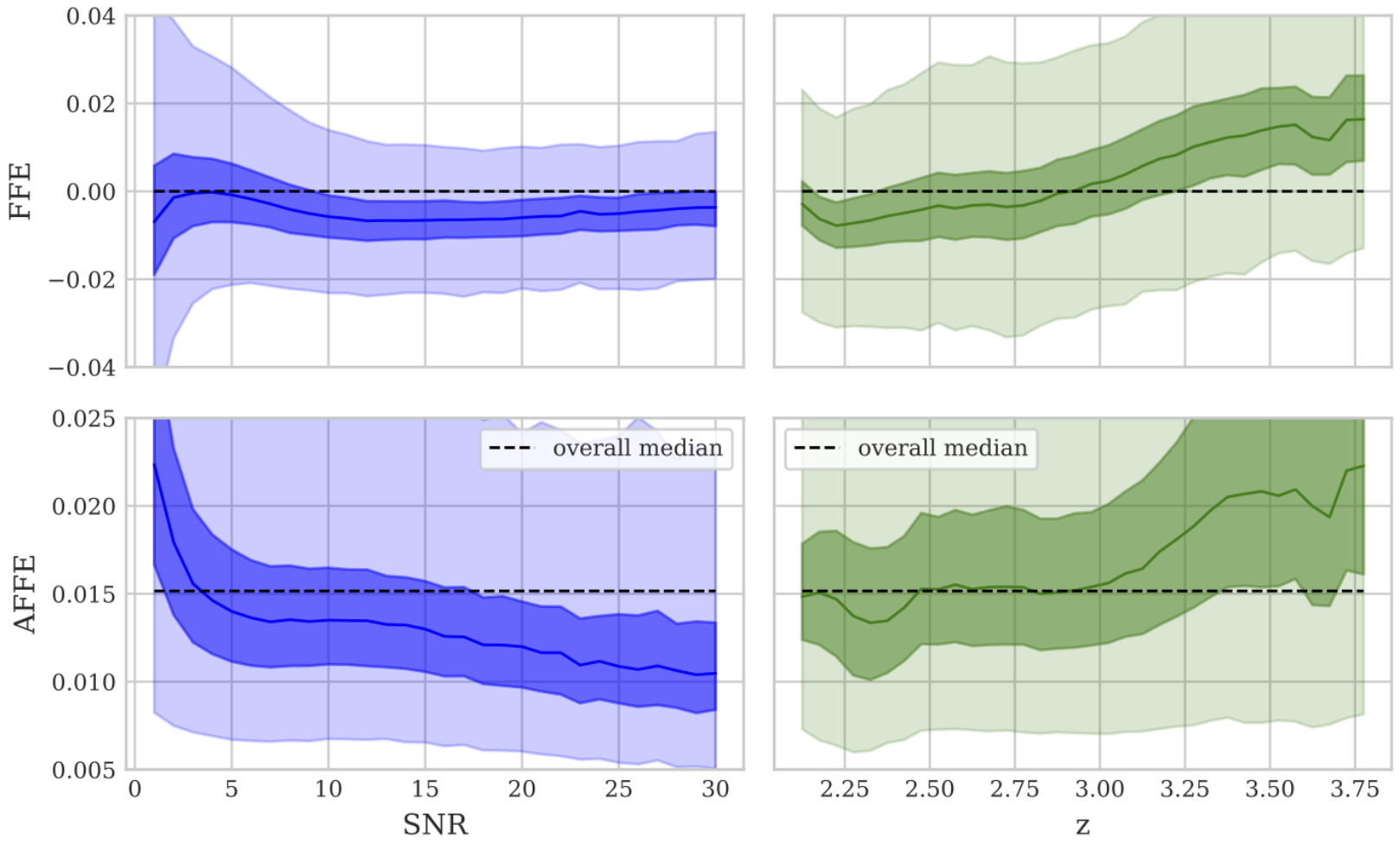
Bias

LyCAN tends to over-predict the continuum at high-z (~1% in FFE)



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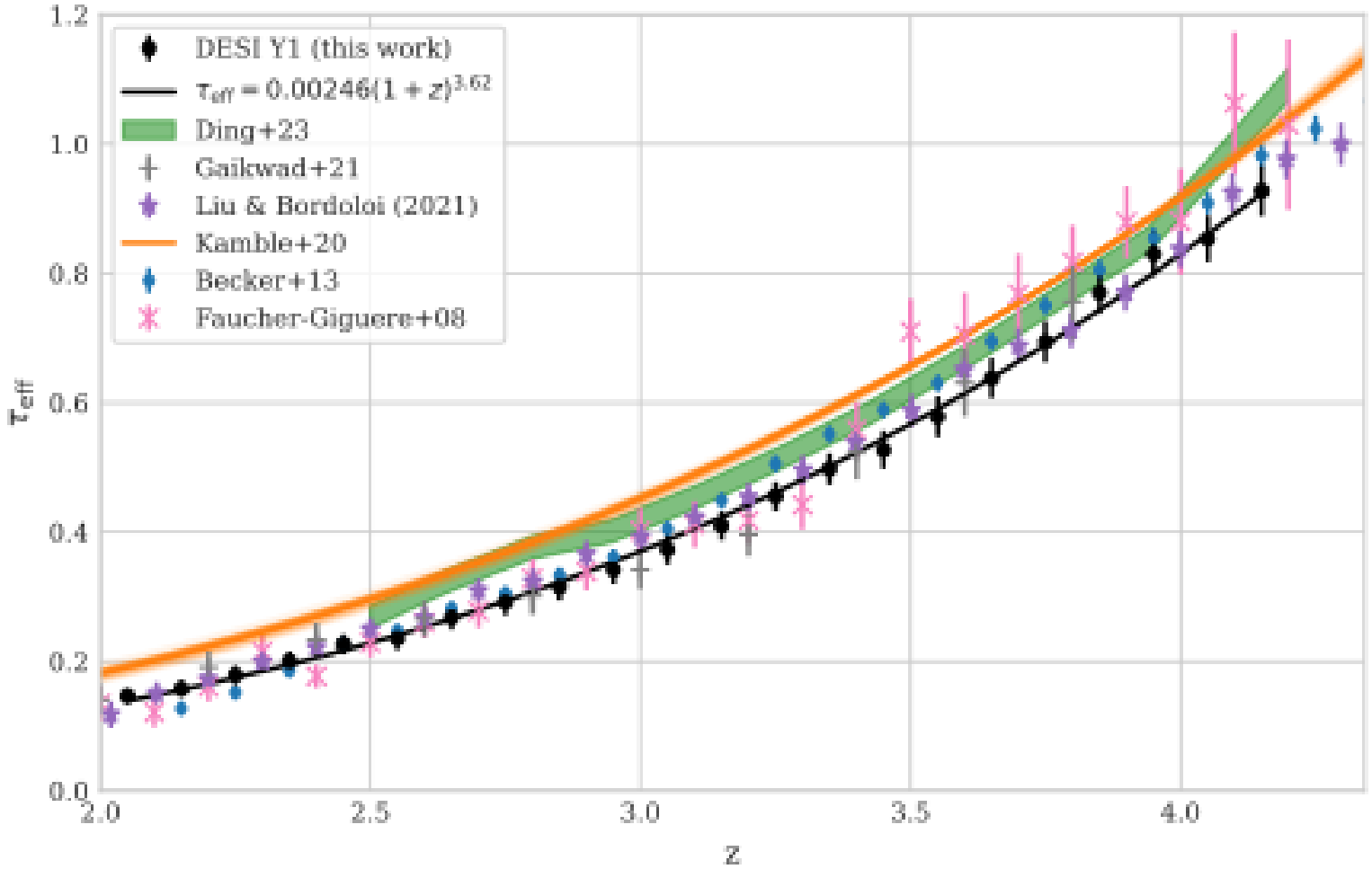
Application: optical depth evolution

- Probes the evolution of the IGM, including possible signatures of He II reionization
- Largest sample to date for measurement of $\tau_{\rm eff}$ (~84,000 QSOs, SNR ≥ 5 only)
  - Error bars dominated by metal correction scheme (Schaye+03)
  - Best agreement with low-z measurements based on high-resolution spectra (e.g. Faucher-Giguere+08; Gaikwad+21)



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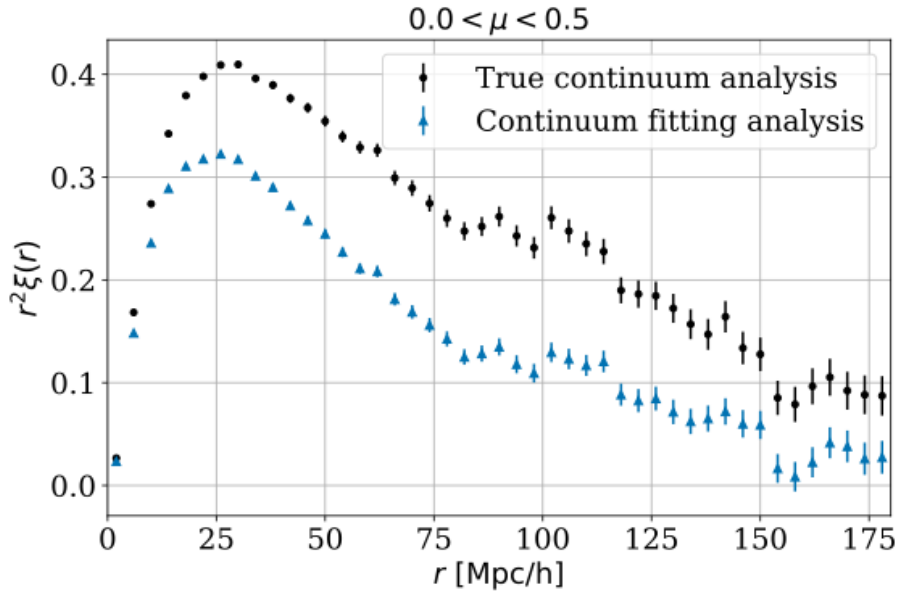
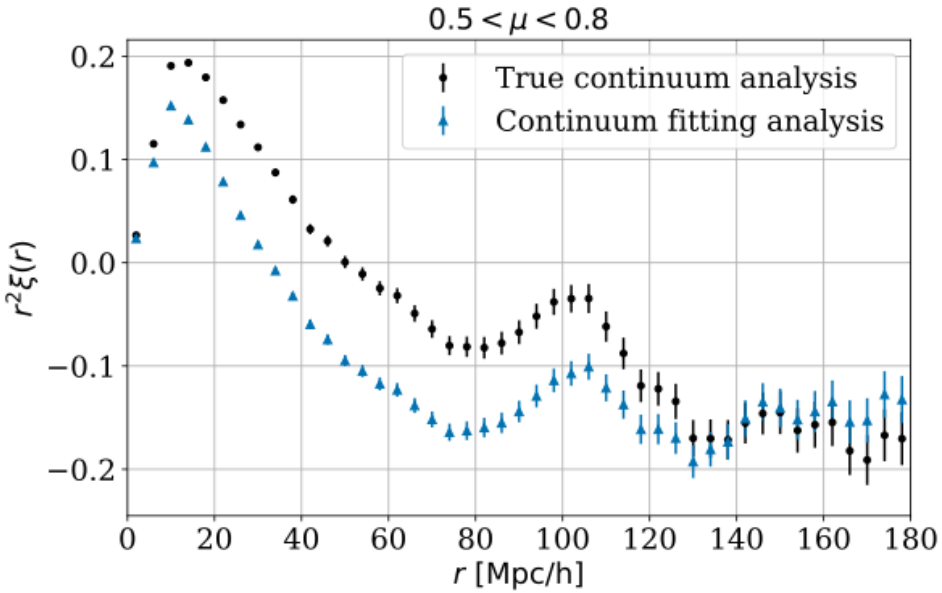
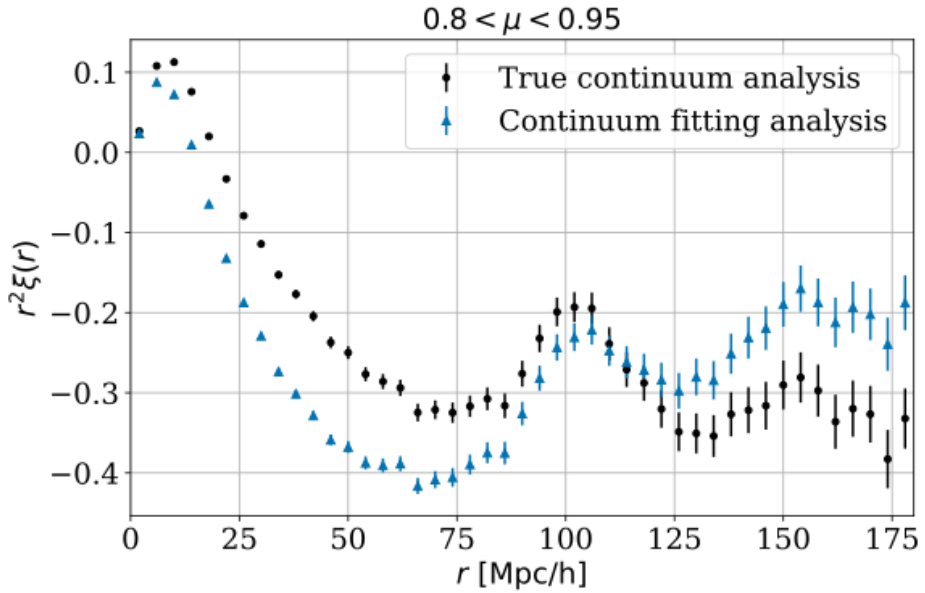
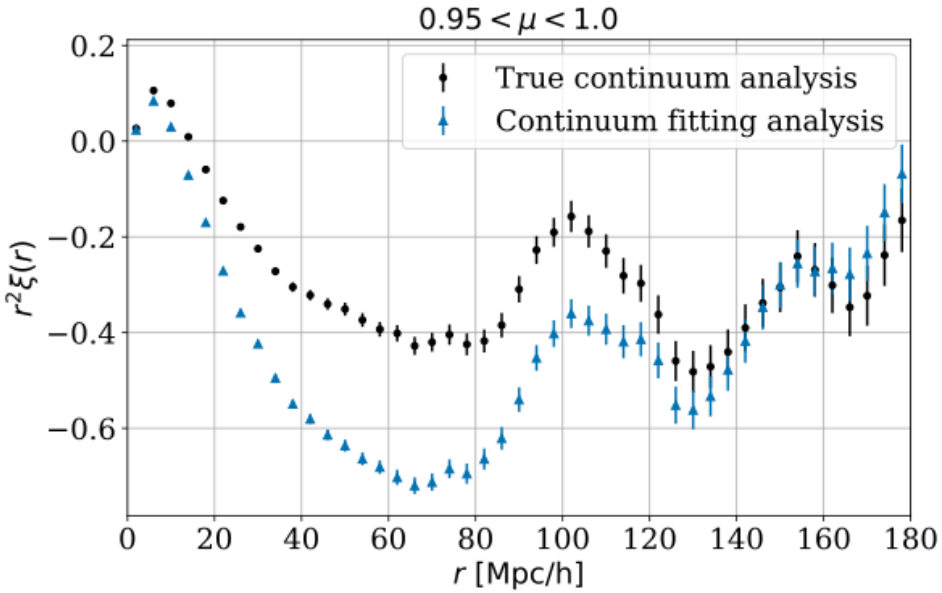
Can we measure undistorted correlation functions?









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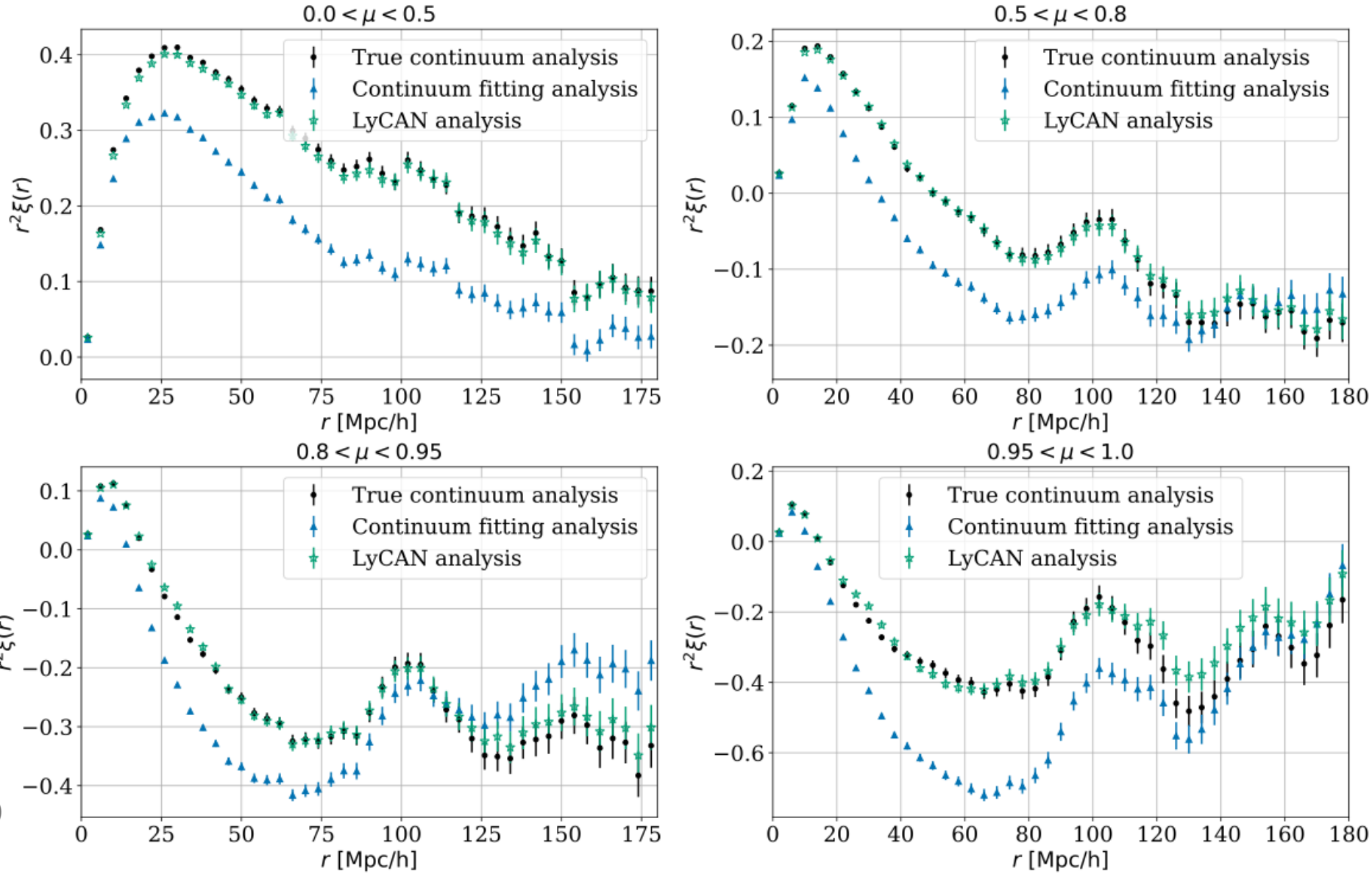

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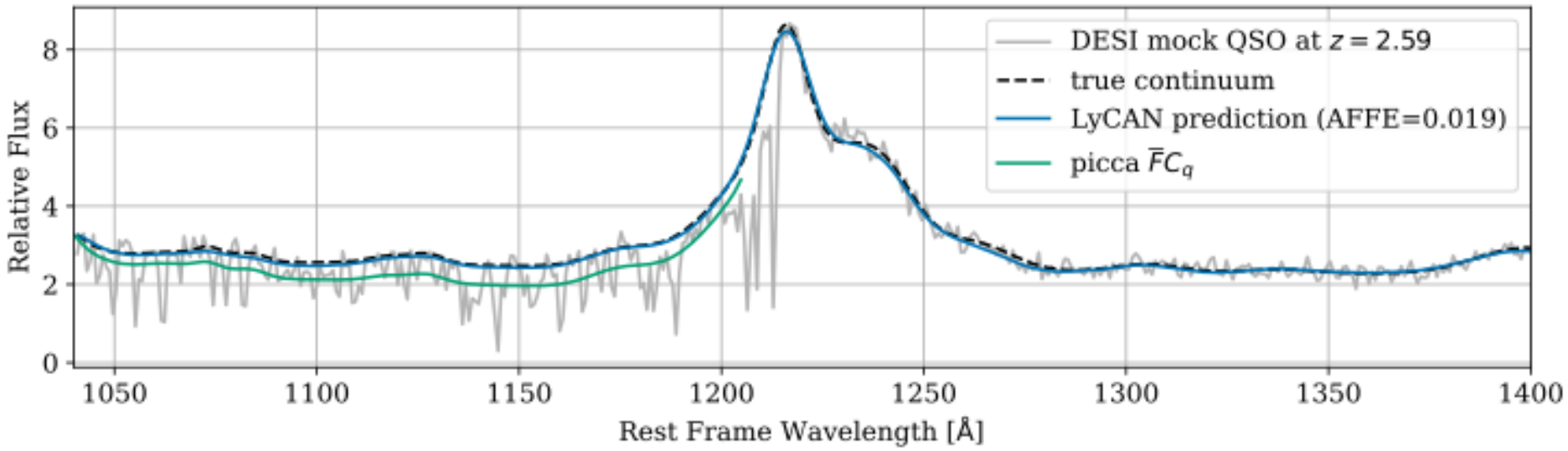
Impact on cosmology

- **Question:** how much better can we measure cosmological parameters with knowledge of the true continuum?
- **Method:** full-shape forecasts using DESI DR2 mocks (idealized case without contaminants)



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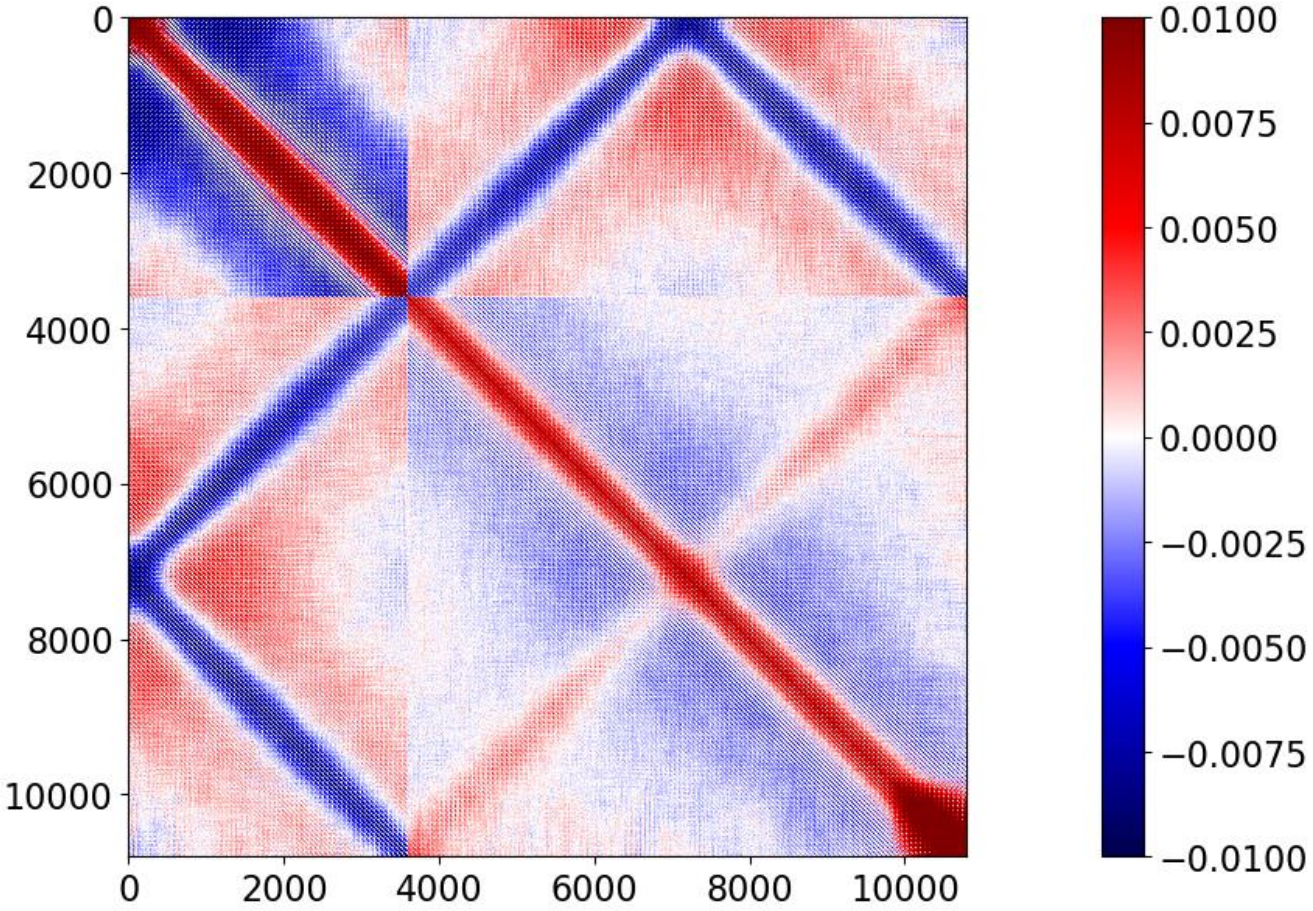
Method

- Forecasts assume Planck 2018 fiducial model
- Computed covariance matrices from mocks with the true vs fitted continuum up to $r_{\max} = 240\ h^{-1}\mathrm{Mpc}$
- Results compared to current baseline: continuum fitting (distorted) analysis, $30 < r < 180\ h^{-1}\mathrm{Mpc}$



Correlation matrix from 50 mocks (~875 subsamples per mock)

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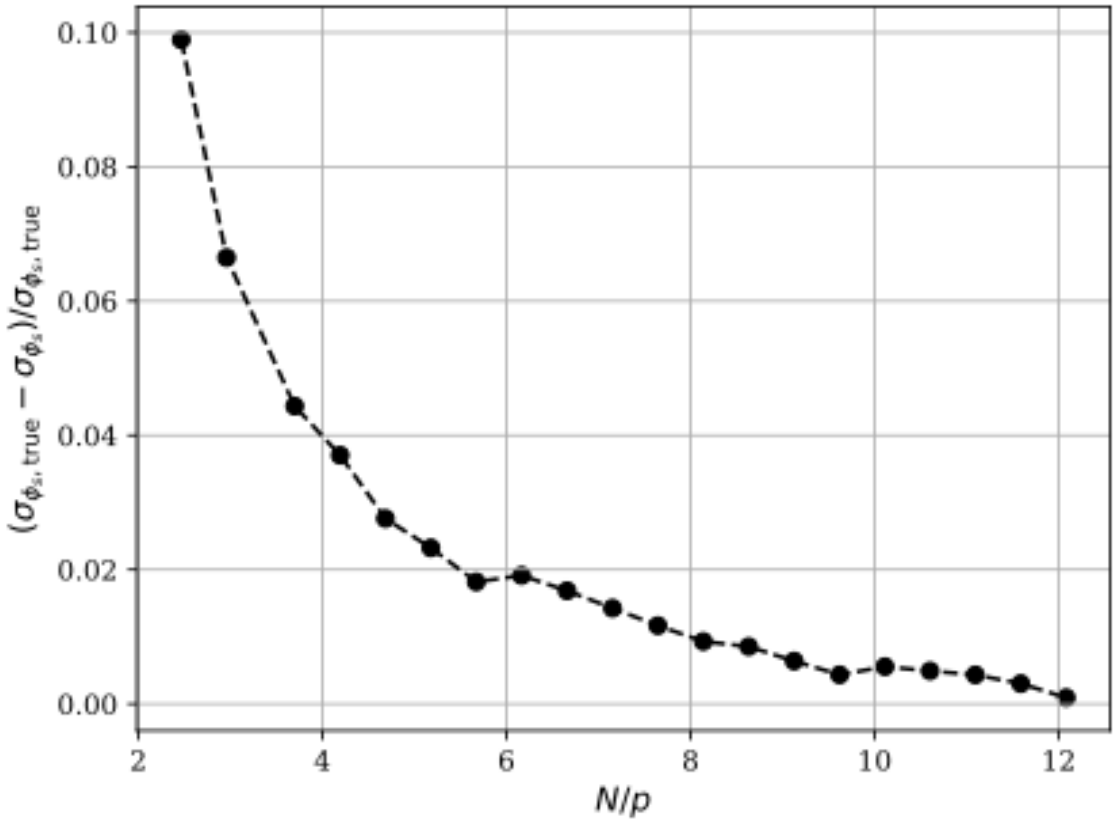
Covariance estimation

- Applied and validated the Hartlap correction to ensure robustness of the covariance matrix
- Balance between:
  - N_{hp} and size of data vector
  - HEALPix pixel size and largest transverse separations probed
- Also investigated impact of extending analysis to larger scales
  - Within limit allowed by robustness of covariance matrix

Error on the Hartlap correction



N: number of samples used for covariance measurement
p: length of data vector

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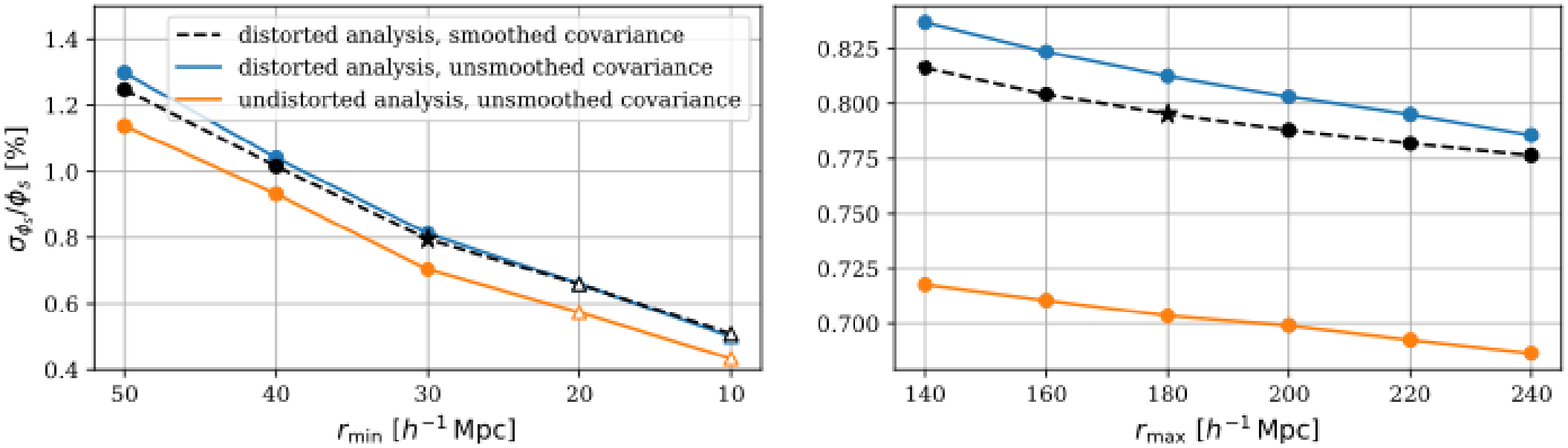
Forecast results

- ~10-15% improved AP constraints with the true continuum
  - → ~40% extension in area
- More information available at larger scales, but dominant effect is the true continuum



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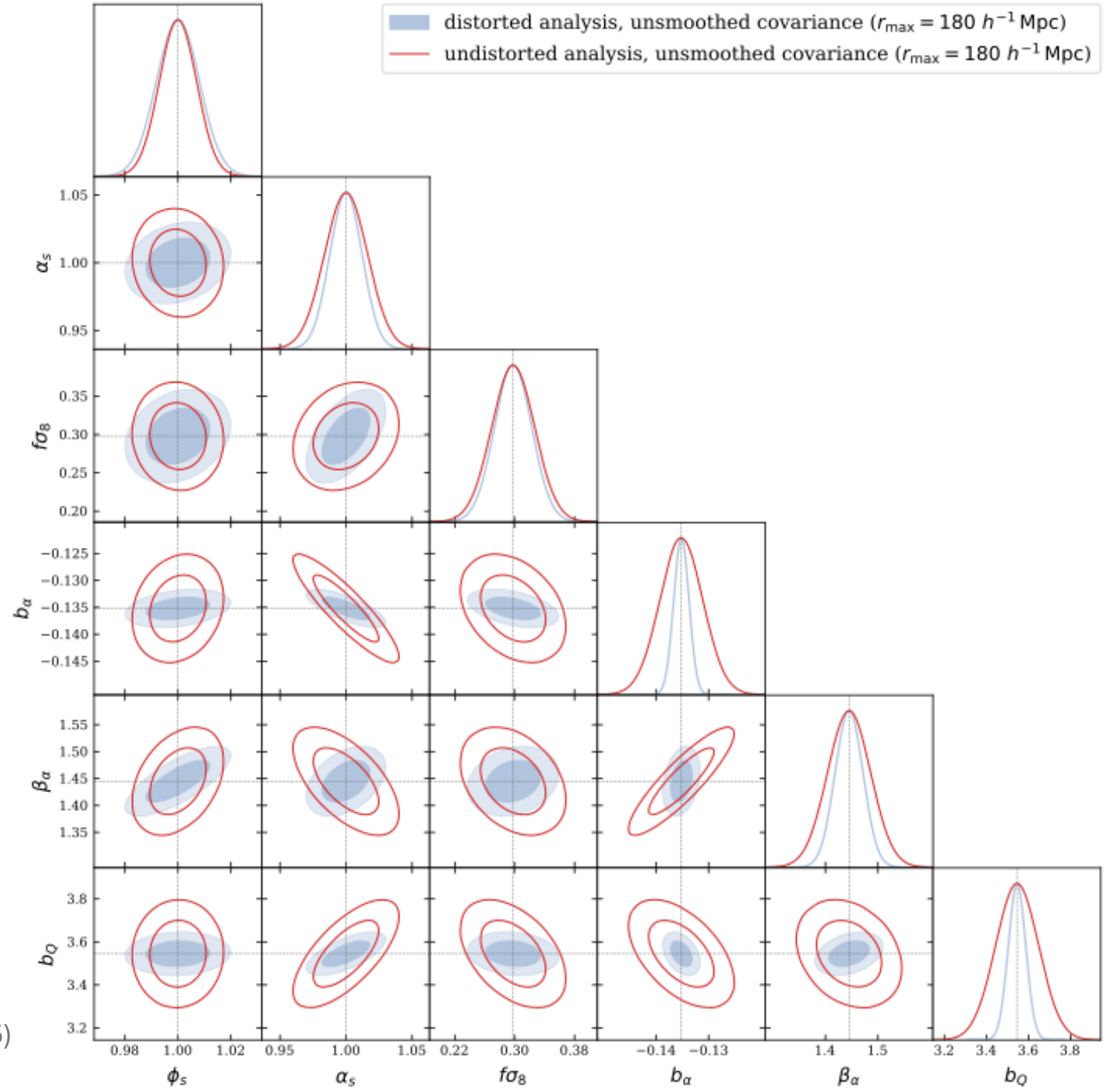
Other parameters

- Improvement seen in ϕ_s, ϕ_p
- $f\sigma_8$ and bias parameters degrade
- Caveats:
  - Sub-optimal estimator
  - Distorted analysis brings in smaller scale information
  - $f\sigma_8$ is not well-constrained by the Lyα forest



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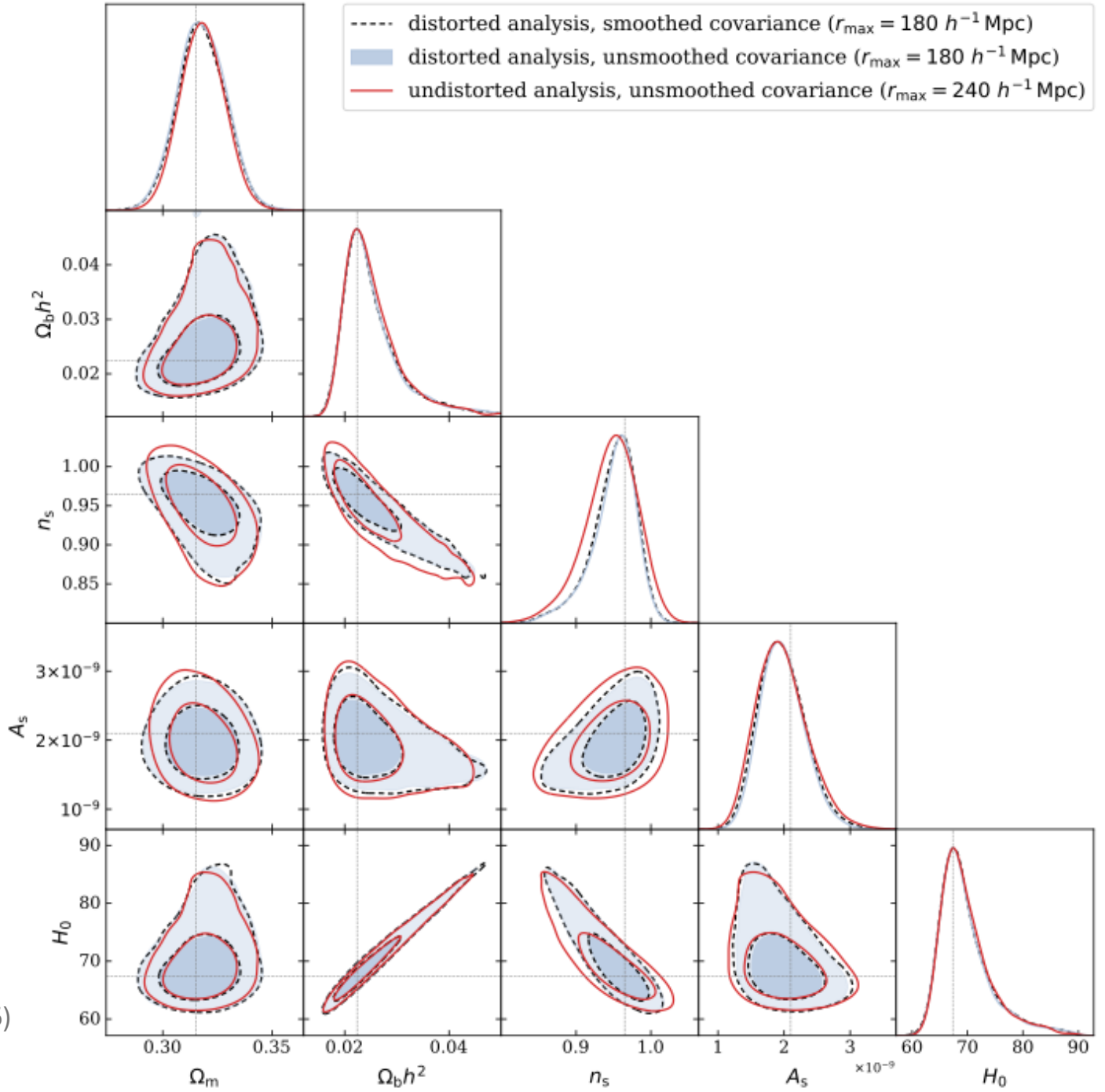
Direct cosmological inference

- Direct fit to full power spectrum instead of template fitting approach
- Improvement on AP translates to improvement on Ω_m
- Parameters with degradation are not well-constrained by the forest



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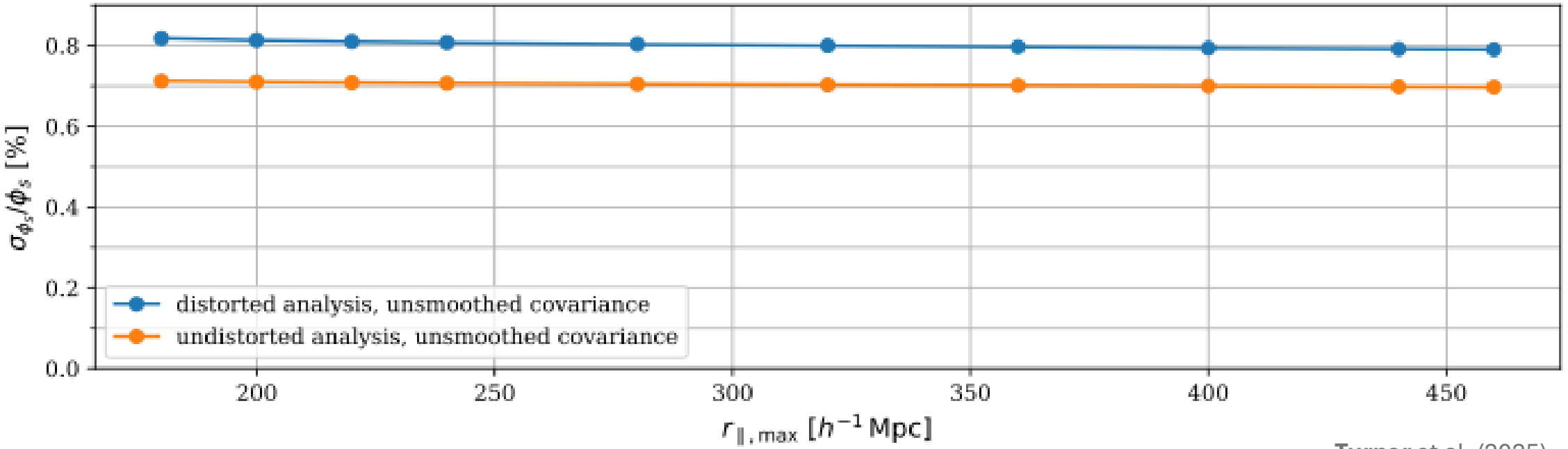
Impact of larger scales

(Along the line of sight)



Turner et al. (2025)

Some additional information available, but minimal

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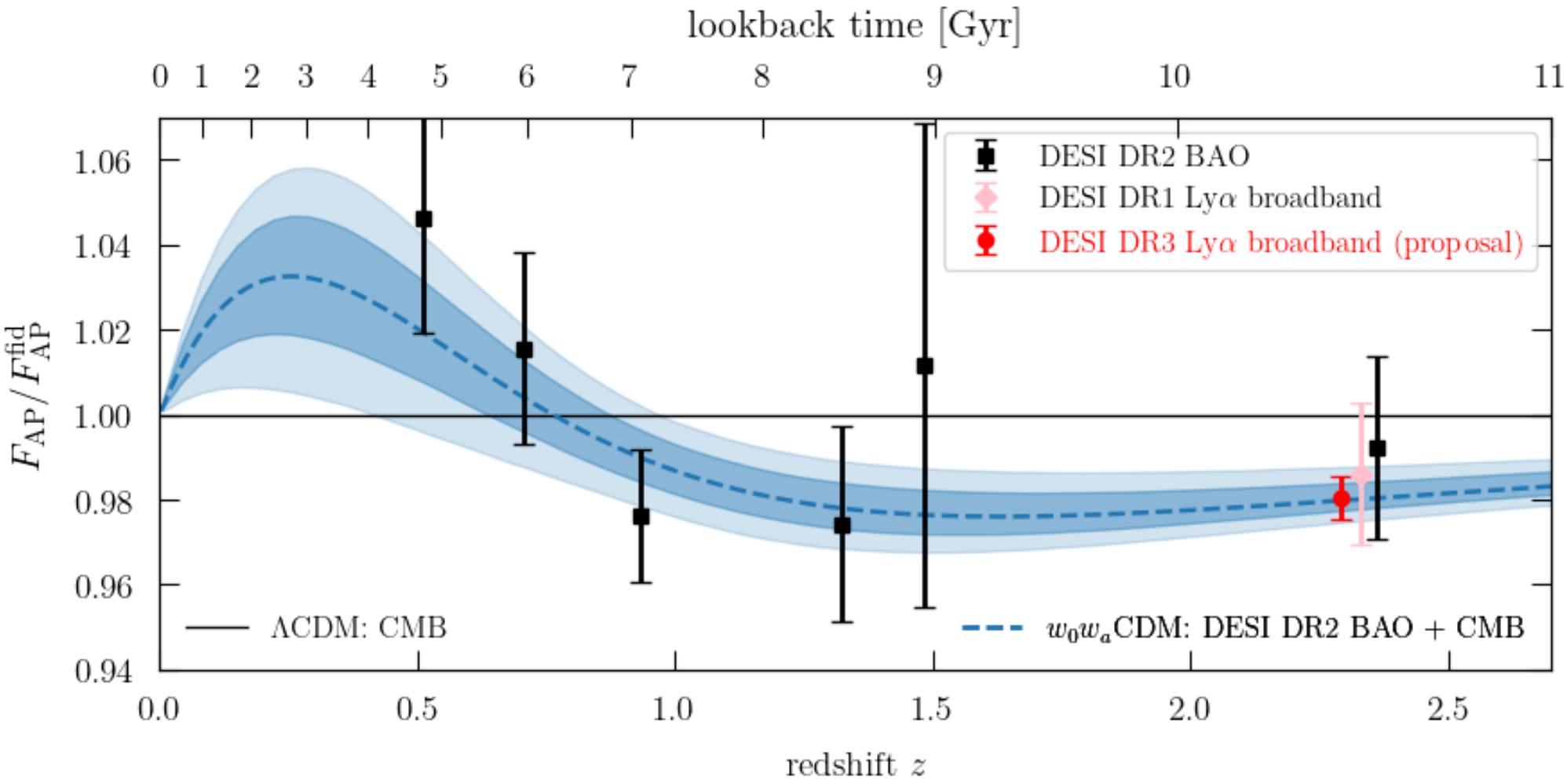
Future prospects



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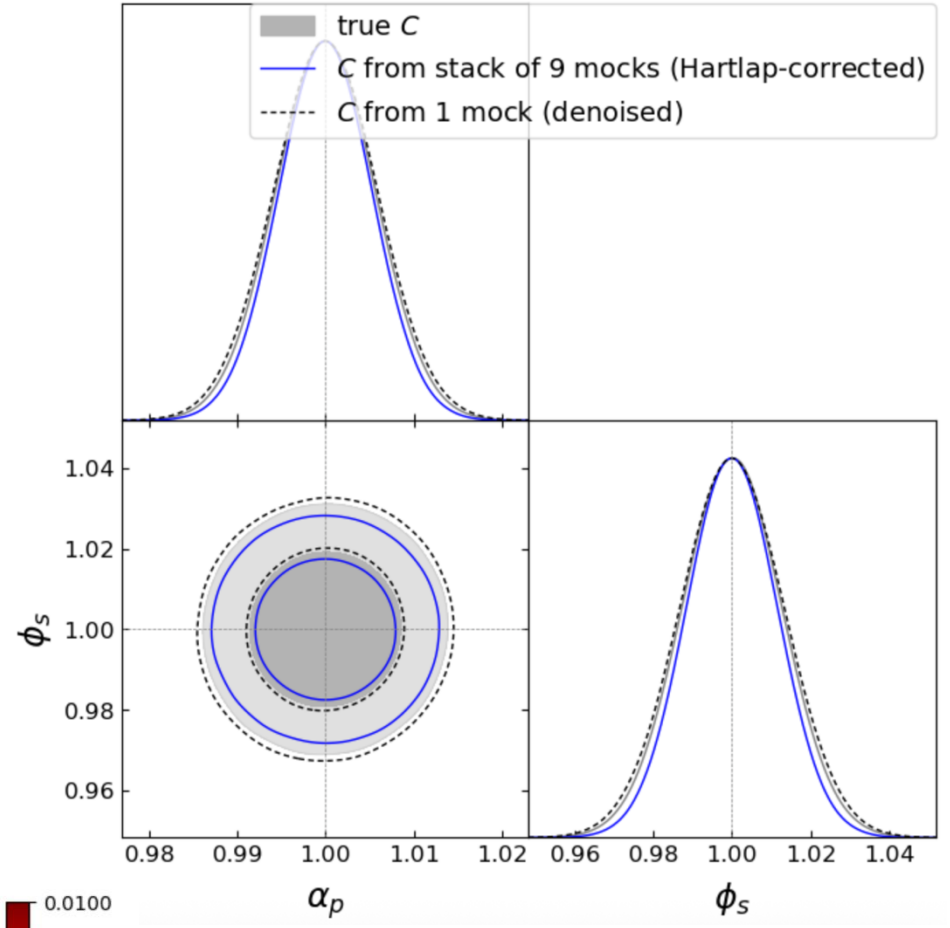
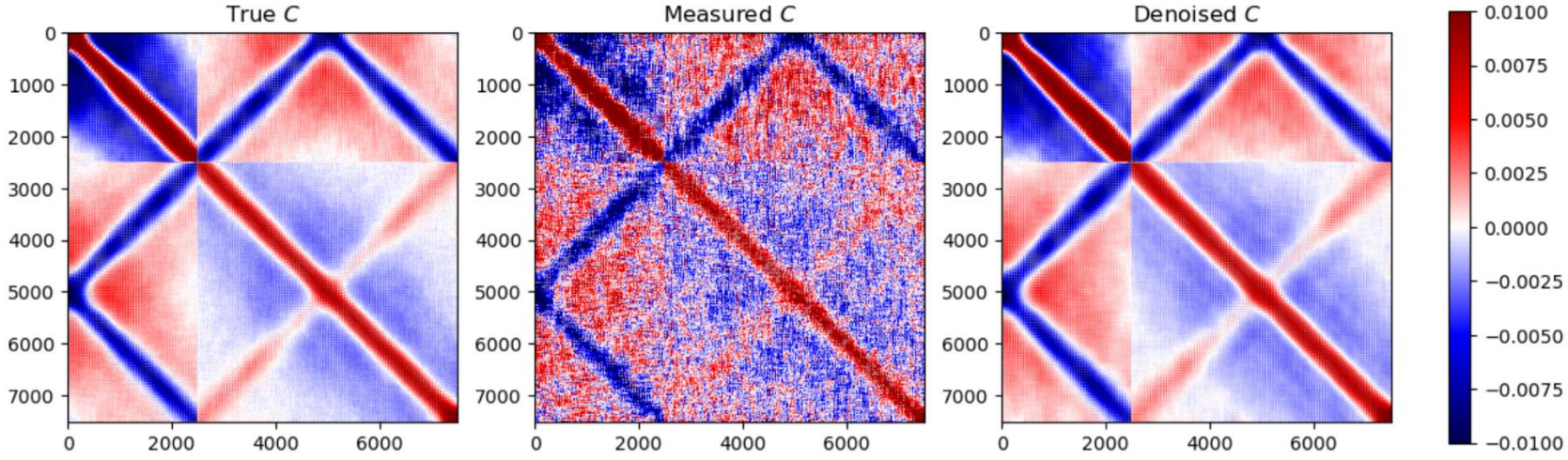
Current work: covariance denoising

- Covariance matrix can be expressed in the eigenbasis of a mock-based reference
- Robust uncertainties demonstrated by forecasts
- Neural network to learn corrections to this reconstruction





Turner (in prep)

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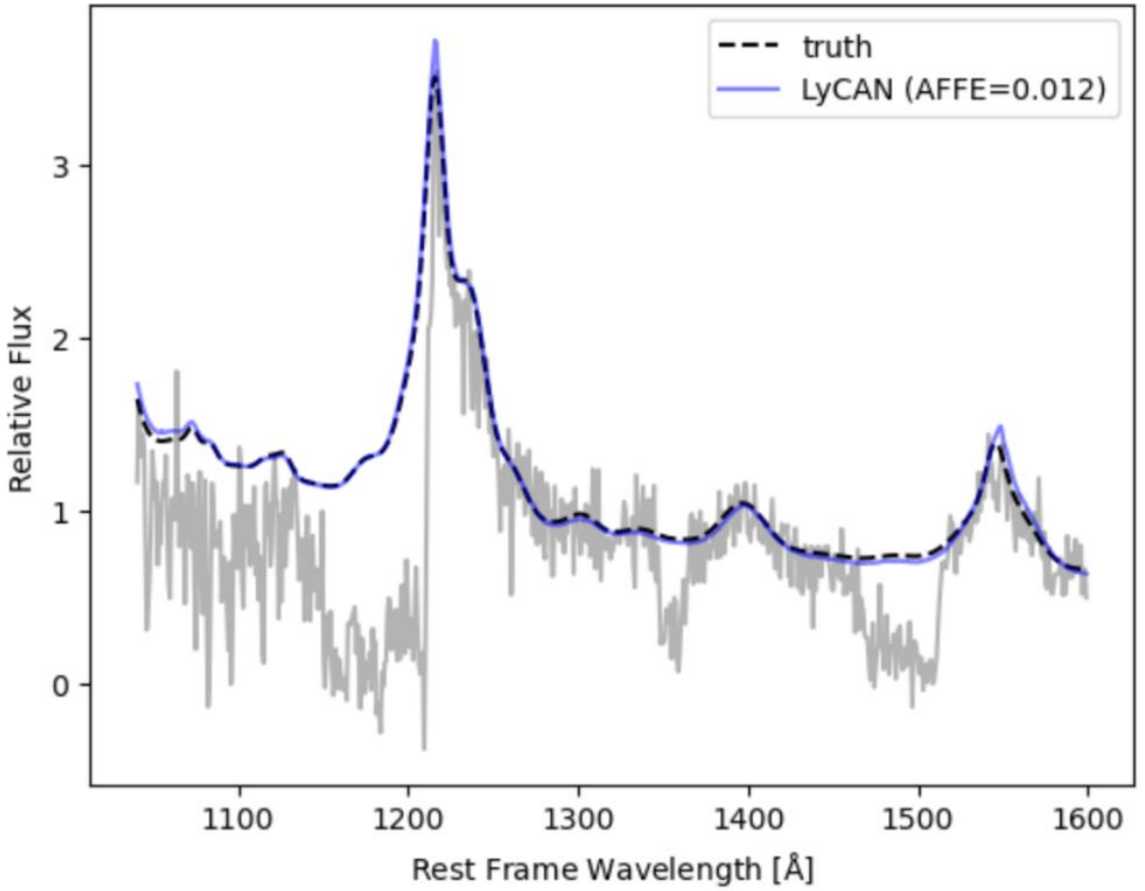
Other ongoing and future work

- Improvements to LyCAN
  - Incorporating broad absorption line (BAL) quasars in training set and adding pixel masking (Deeti Patel)
  - Uncertainty prediction
- Validation on mocks, including impact of contaminants and continuum errors
- Other applications of LyCAN
  - Cross-correlation with CIB
  - Calibrating photo-z distributions through cross-correlation with Lyα forest
- Potential new cosmological analyses
  - Primordial non-Gaussianity with the Lyα forest
  - Cross-correlation with CMB lensing



Credit: Deeti Patel

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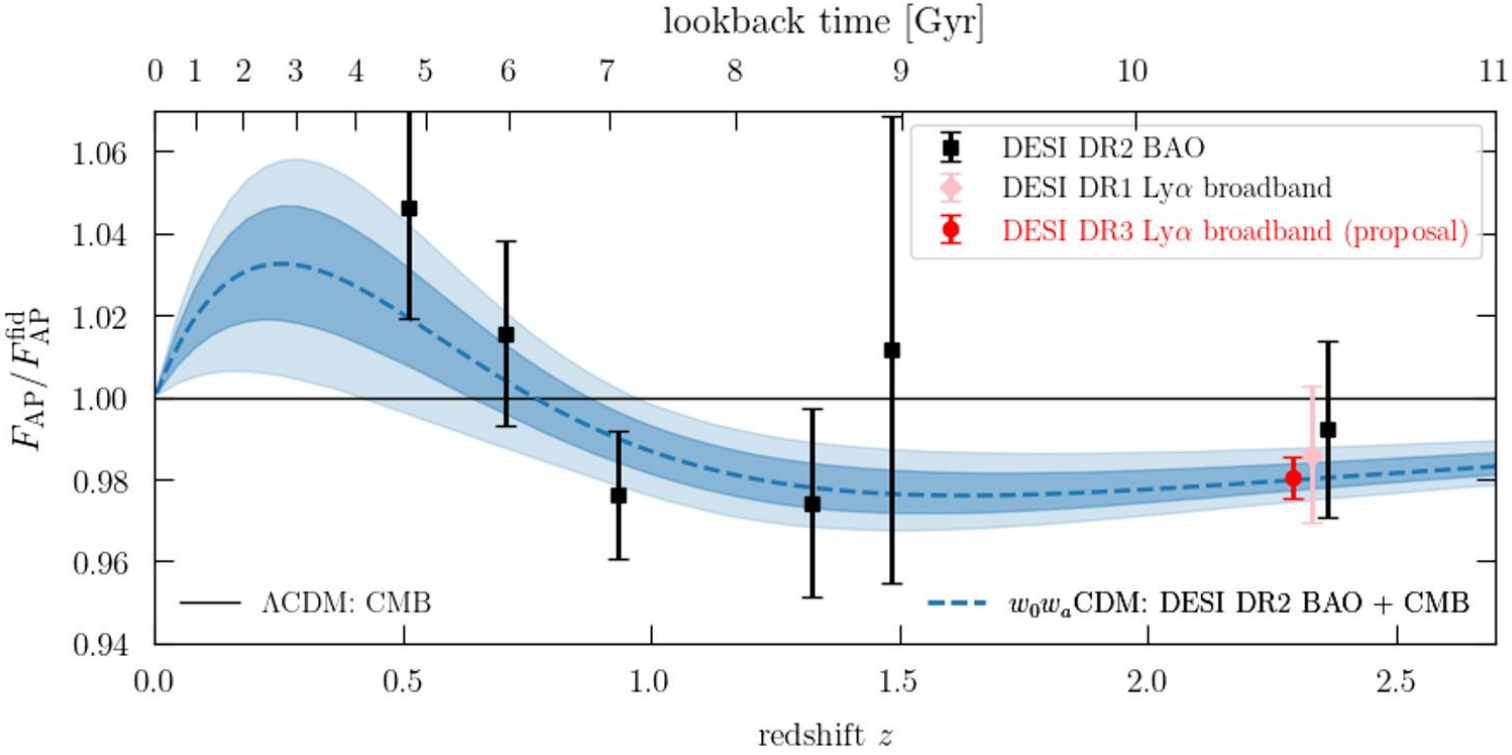
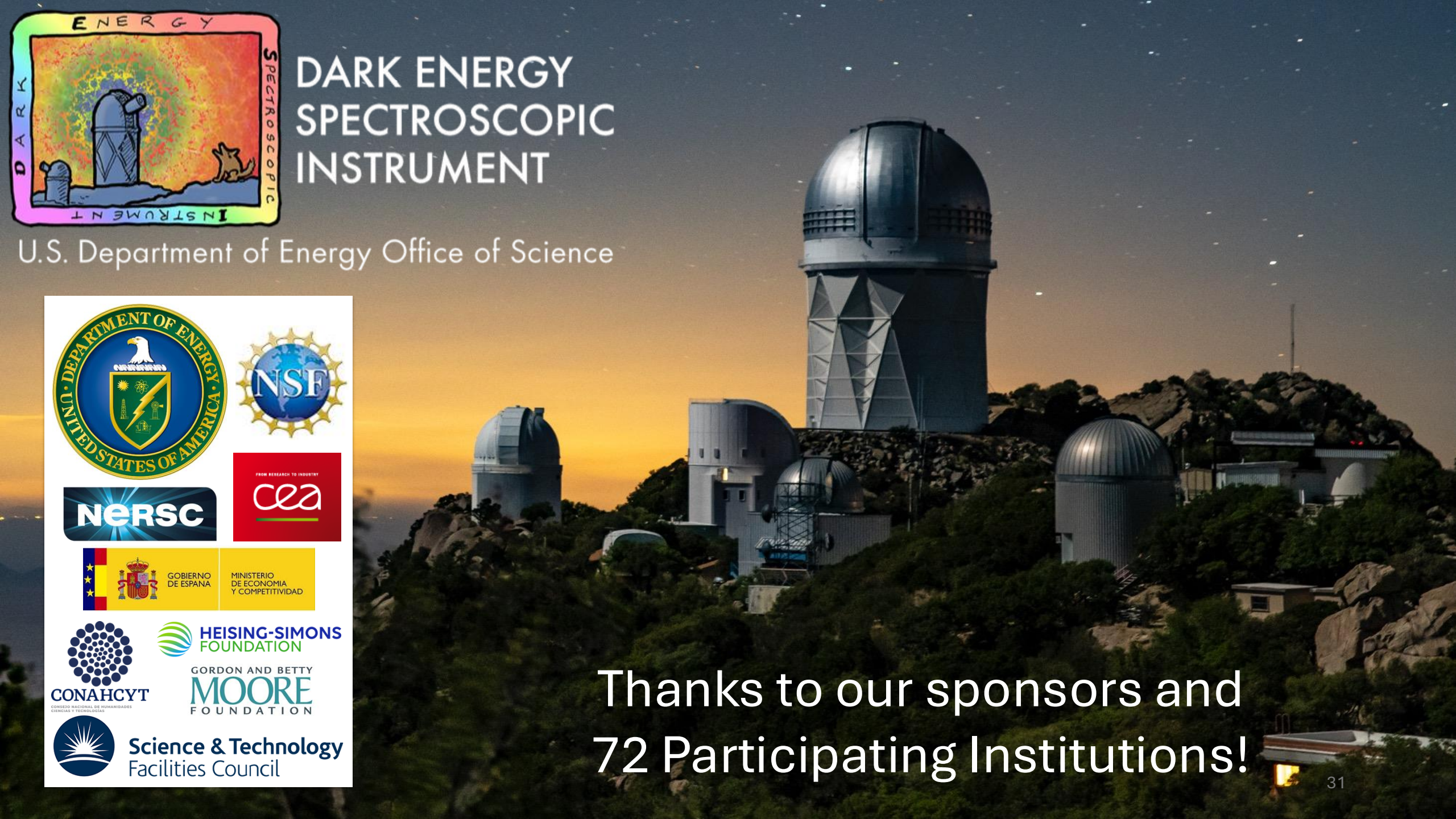
Summary

- Access to the unabsorbed continuum could enable ~10-15% tighter constraints on the AP parameter
  - May be feasible with a method like LyCAN
- Will help the Lyα forest distinguish between different dark energy models at high redshift – will apply to DESI DR3
- LyCAN's preserved large-scale information may enable new cosmological analyses

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