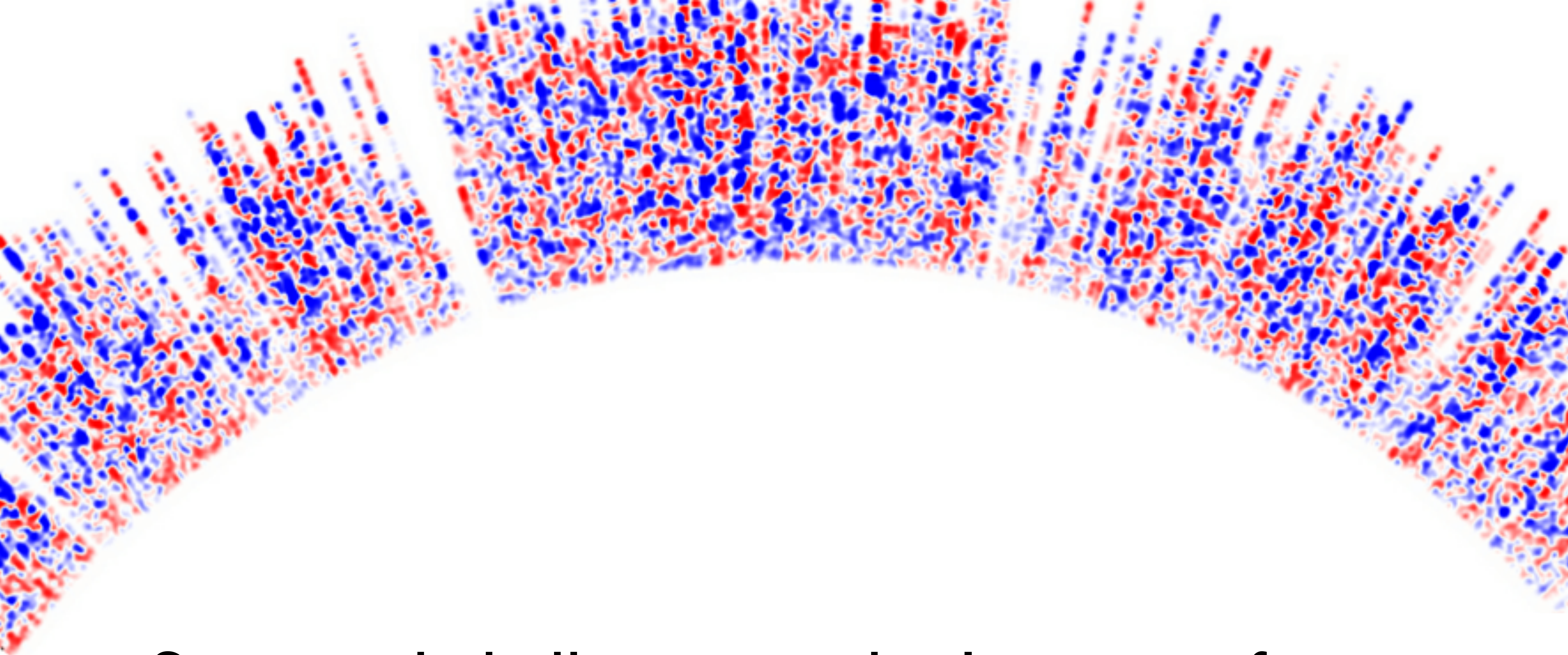


Statistical challenges in the Lyman-α forest

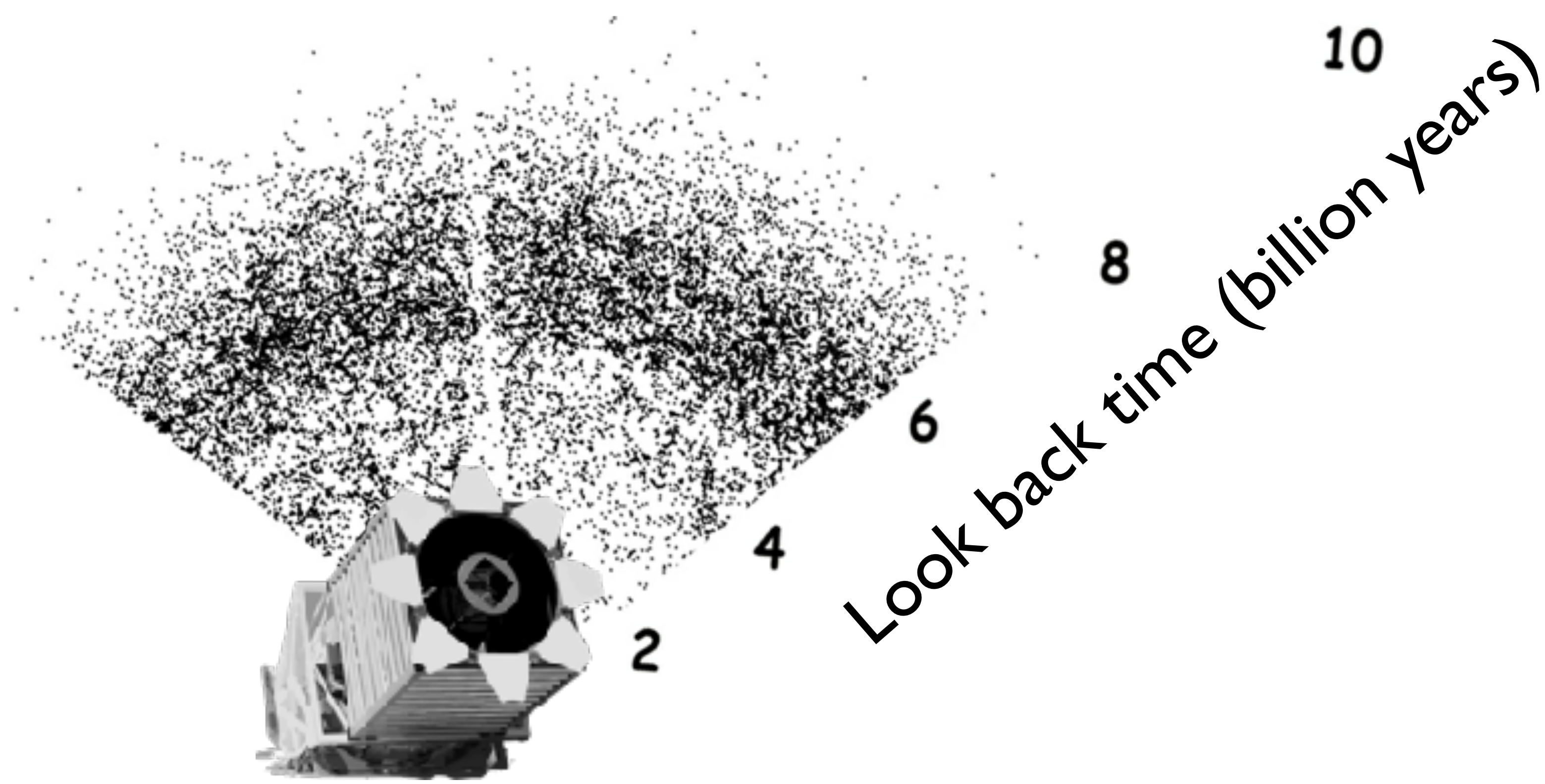
Andreu Font-Ribera

STFC Ernest Rutherford Fellow at University College London

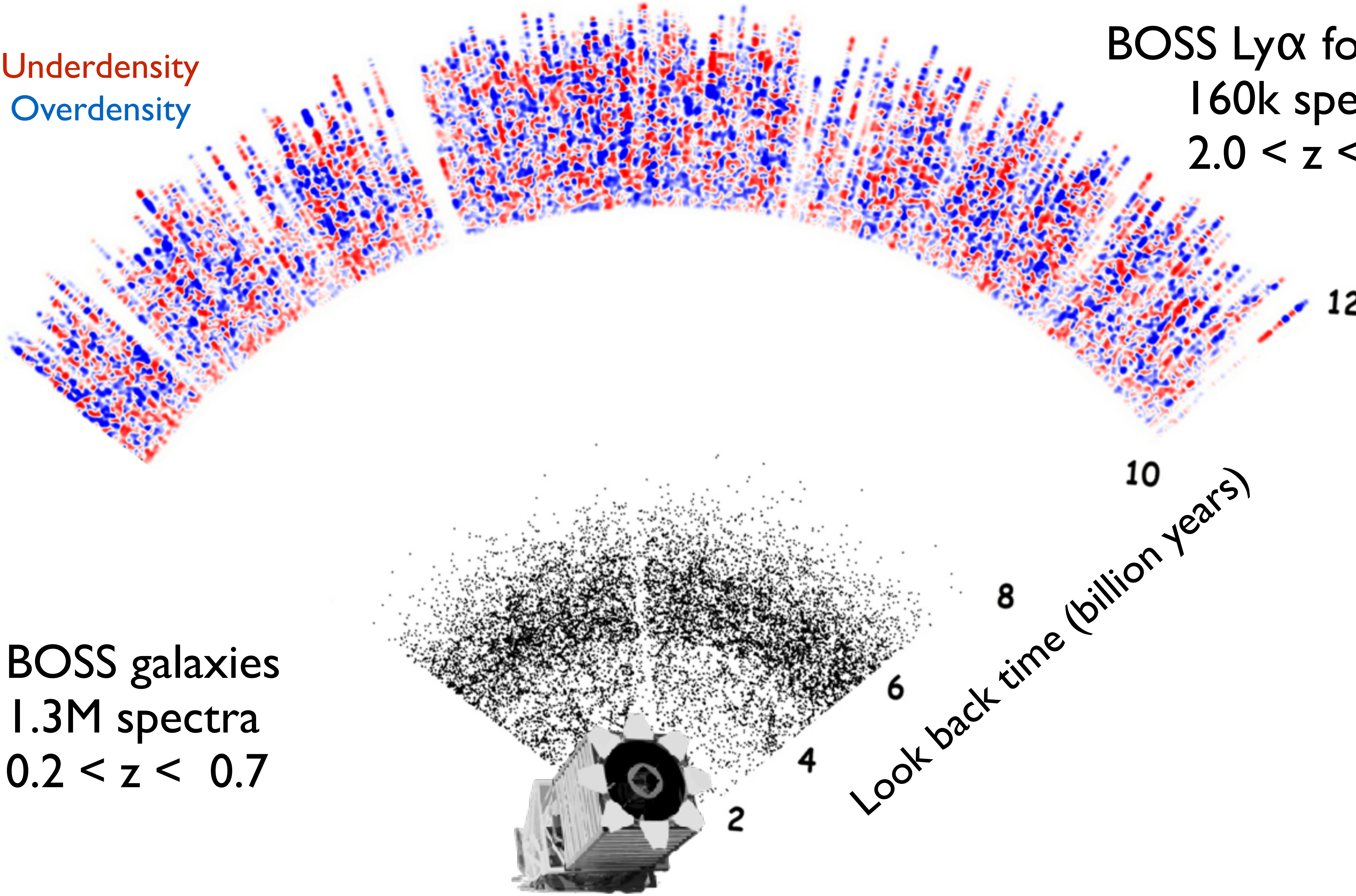
In collaboration with Pat McDonald (LBL) and Anže Slosar (BNL)

Redshift Surveys

BOSS galaxies
1.3M spectra
0.2 < z < 0.7



Redshift Surveys



BOSS Lyα forest
160k spectra
$2.0 < z < 3.5$

BOSS galaxies
1.3M spectra
$0.2 < z < 0.7$

Outline

- Baryon Acoustic Oscillations in the Lyman-α (Lyα) forest
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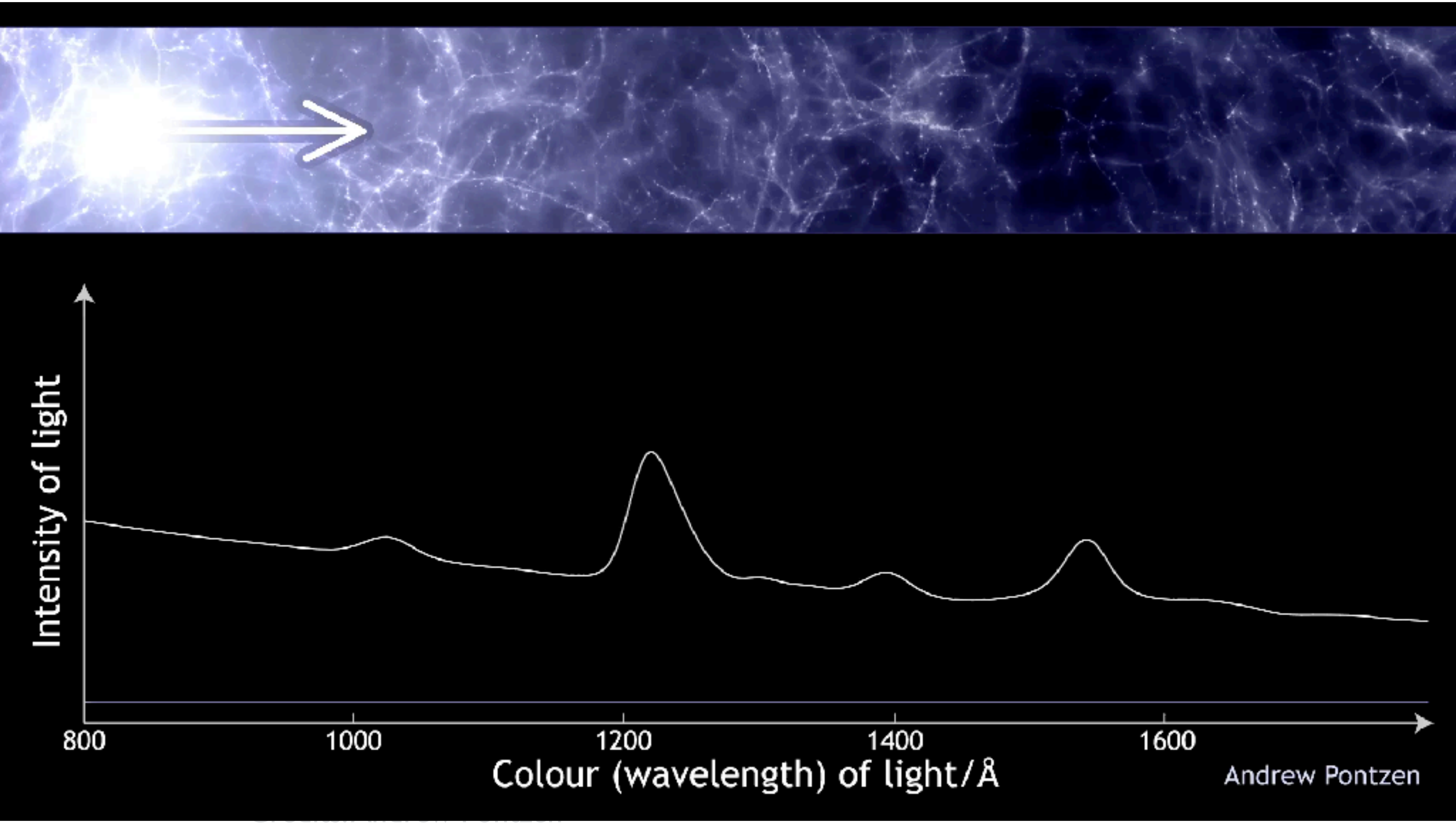
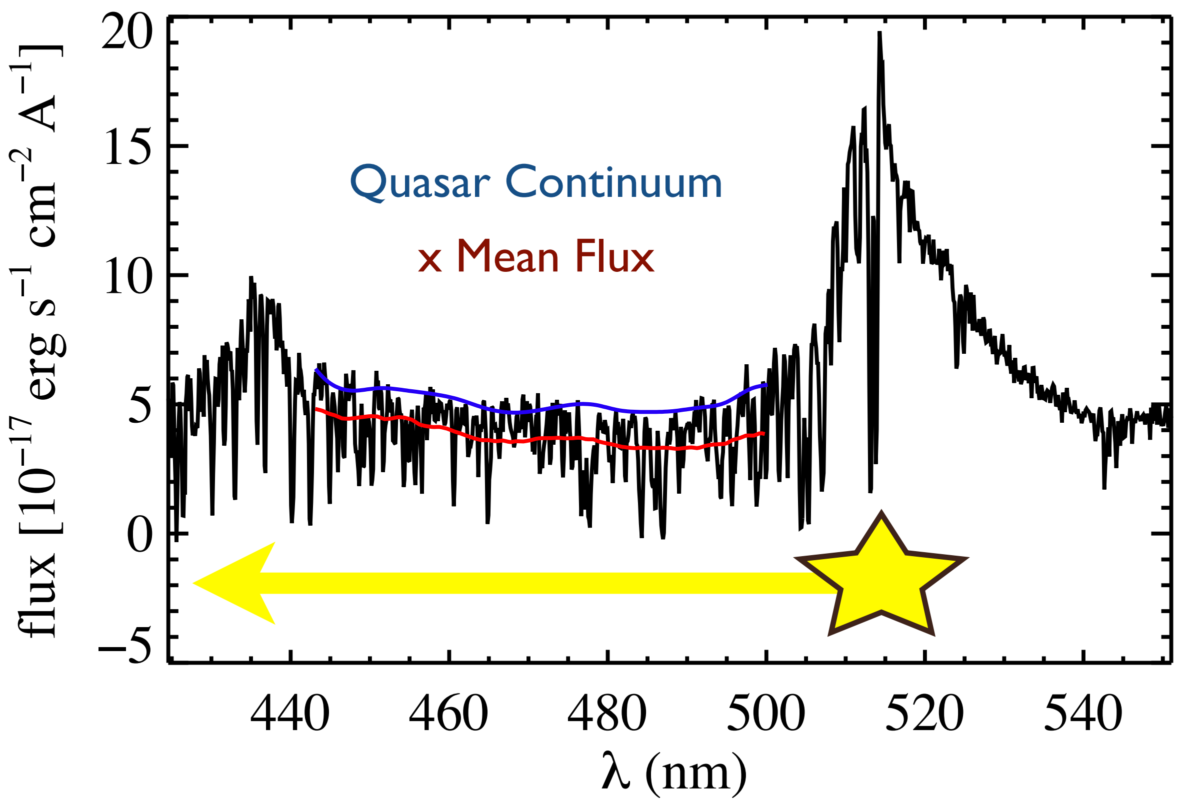
  - BAO results from BOSS Lyα
  - BAO forecasts for DESI Lyα
- Small scale clustering of the Lyα forest
  - Opportunities (neutrinos, running, warm dark matter)
  - State of the art (one-dimensional power spectrum)
  - Statistical challenges (three-dimensional clustering)

The Lyman-α forest



The Lyman-α forest

1st step: from observed flux to cosmological fluctuations



Observed flux — Transmitted fraction

$$f_q(\lambda) = C_q(\lambda) F_q(\lambda)$$

Quasar continuum

Observed wavelength — Absorption redshift

$$\lambda = \lambda_\alpha (1 + z)$$

LyaF wavelength (121.6 nm)

$$\delta_F(\mathbf{x}) = \frac{F(\mathbf{x}) - \bar{F}}{\bar{F}}$$

Flux fluctuations in pixels trace the density along the line of sight to the quasar

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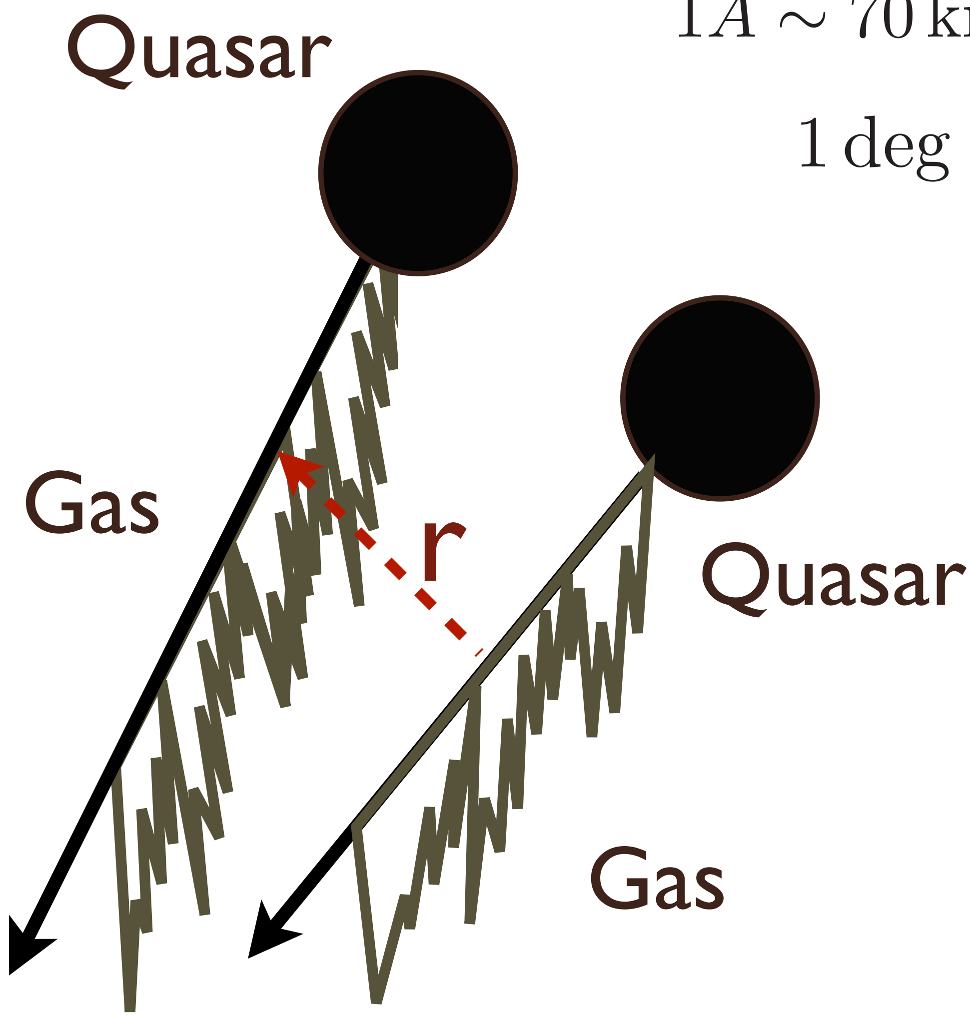
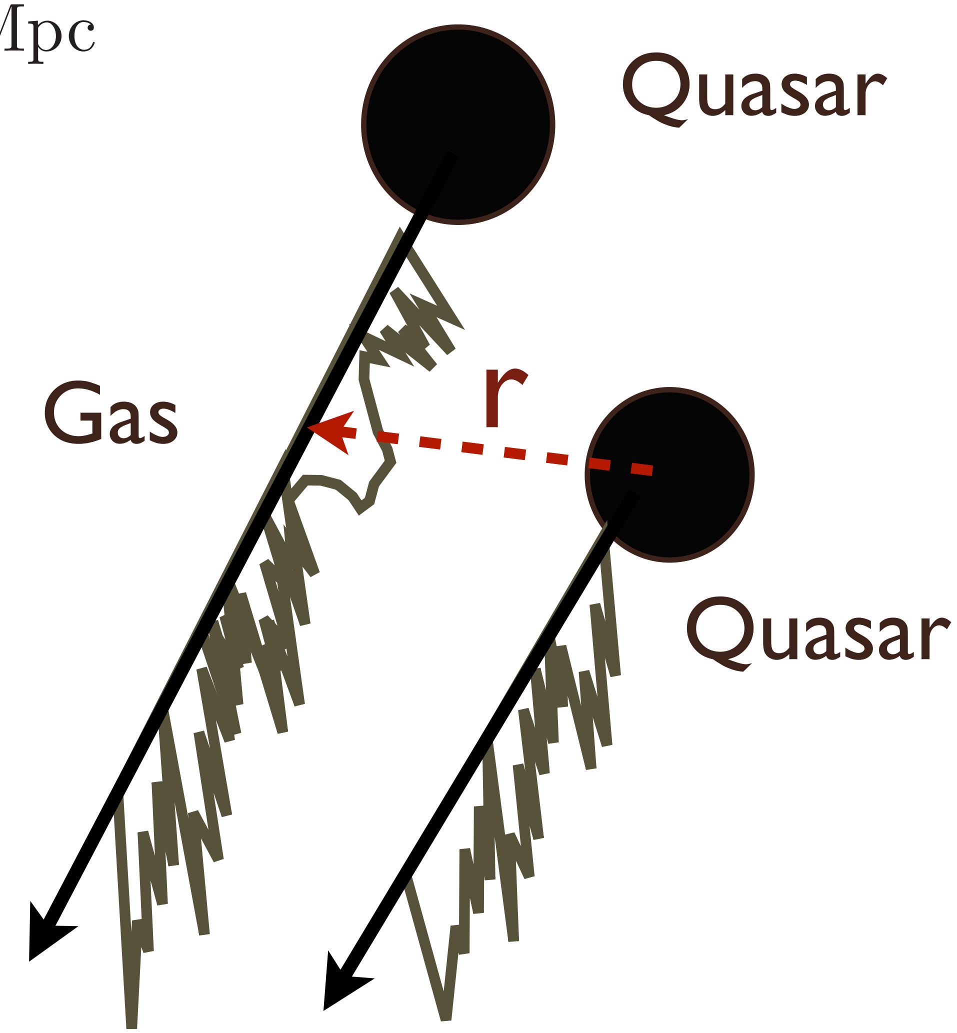
BOSS Lyman-α BAO

Two independent ways of measuring the BAO scale

$$1\mathring{A} \sim 70\,\mathrm{km\,s^{-1}} \sim 0.7\,h^{-1}\,\mathrm{Mpc}$$

$$1\,\mathrm{deg} \sim 70\,h^{-1}\,\mathrm{Mpc}$$





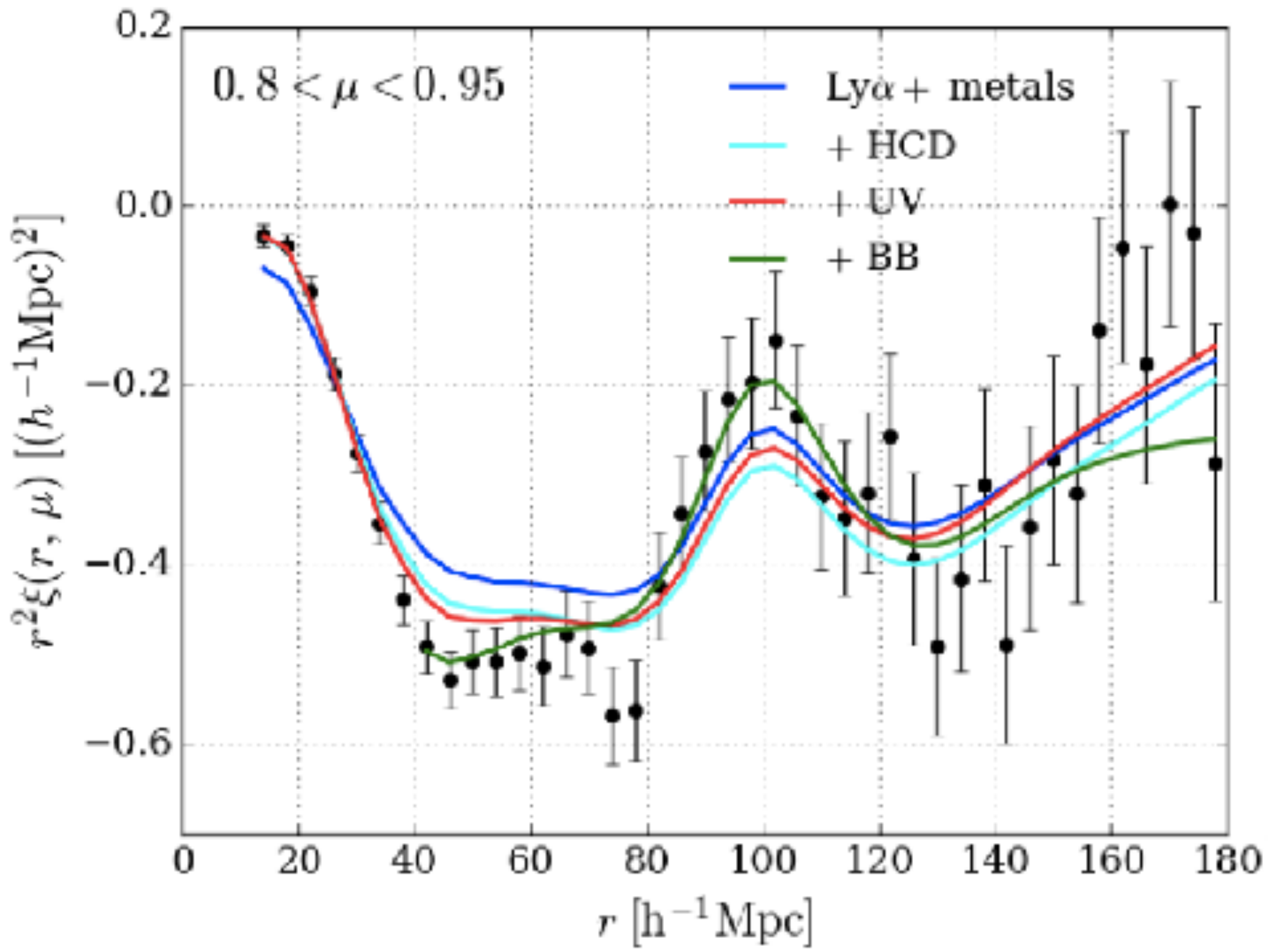
Lyα auto-correlation

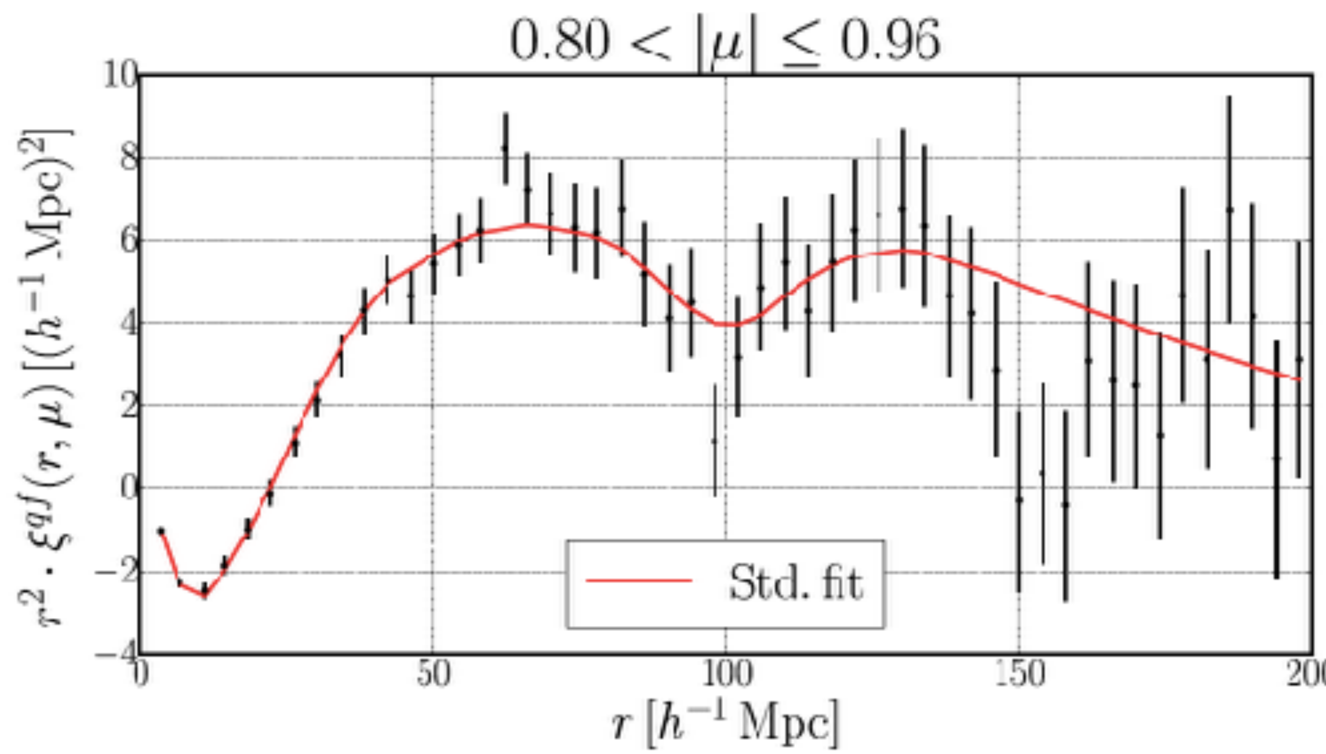
Lyα-quasar cross-correlation

Bautista et al. (2017) —— DR12 —— du Mas des Bourboux (2017)

BOSS Lyman-α BAO

Two independent ways of measuring the BAO scale

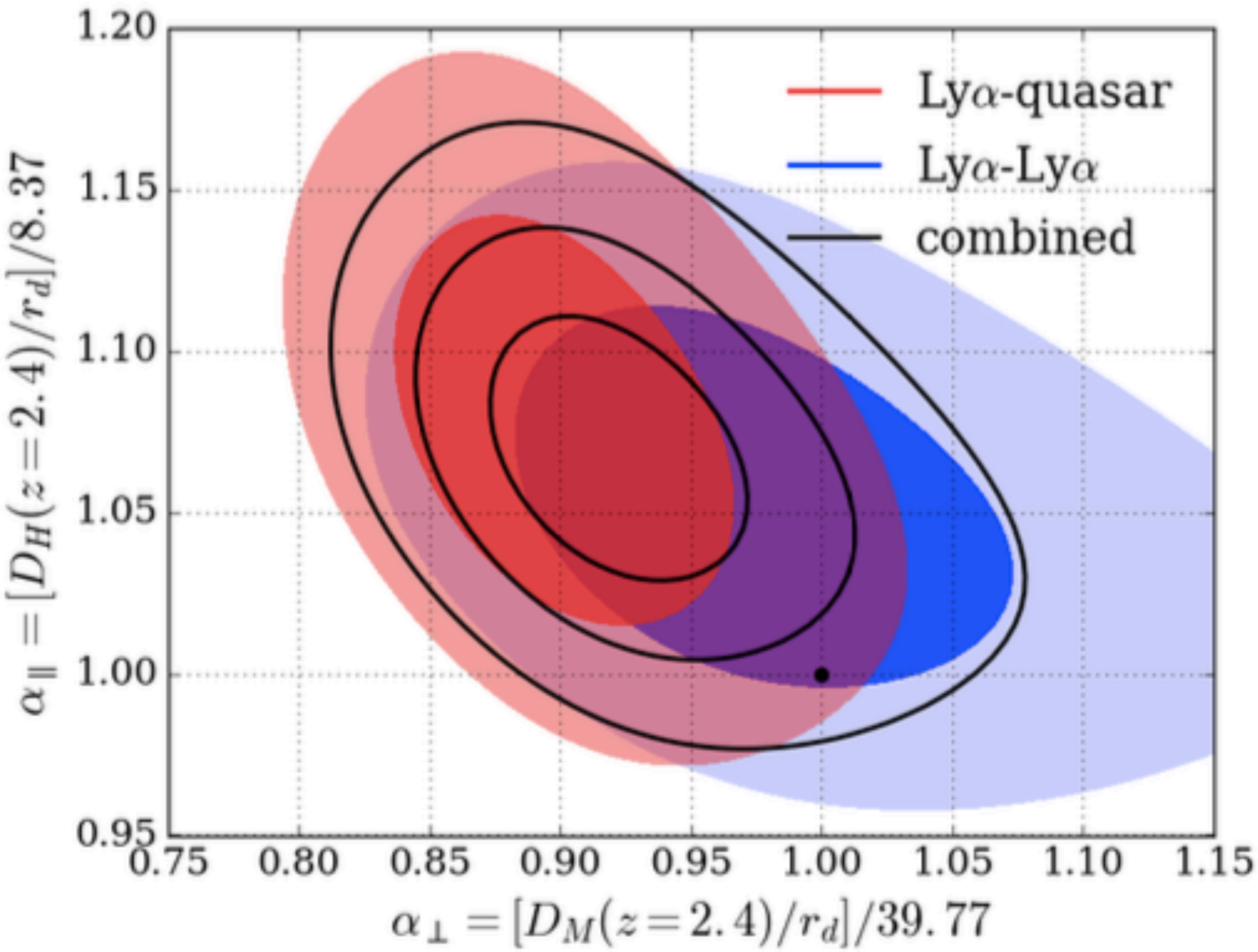


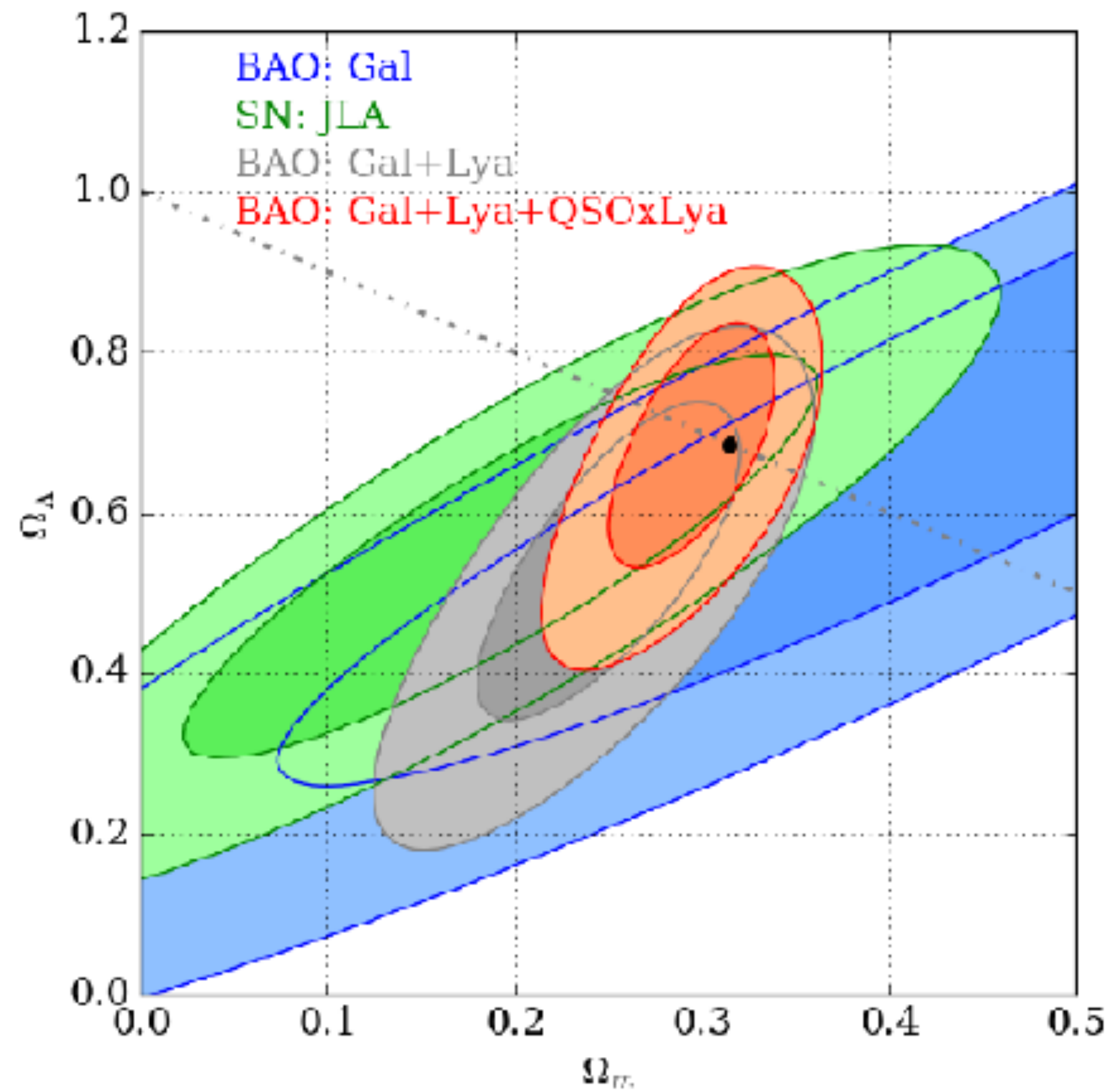


Lyα auto-correlation — Lyα-quasar cross-correlation

Bautista et al. (2017) —— DR12 —— du Mas des Bourboux (2017)

Combined BOSS BAO





In a flat ΛCDM model

$$\Omega_m = 0.292 \pm 0.019 \quad \text{BAO}$$

$$\Omega_m = 0.315 \pm 0.017 \quad \text{Planck}$$

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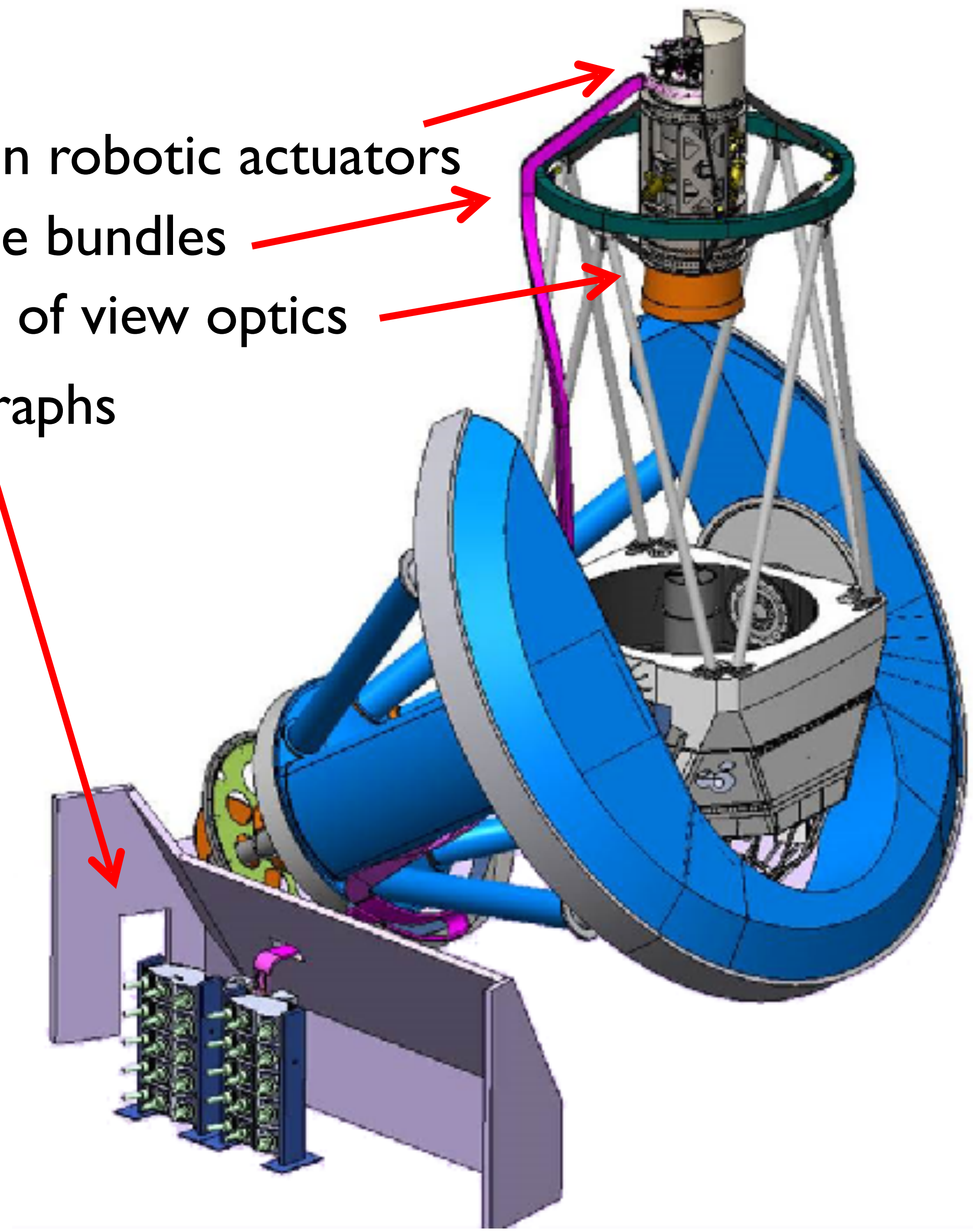
Dark Energy Spectroscopic Instrument

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



Readout
& Control

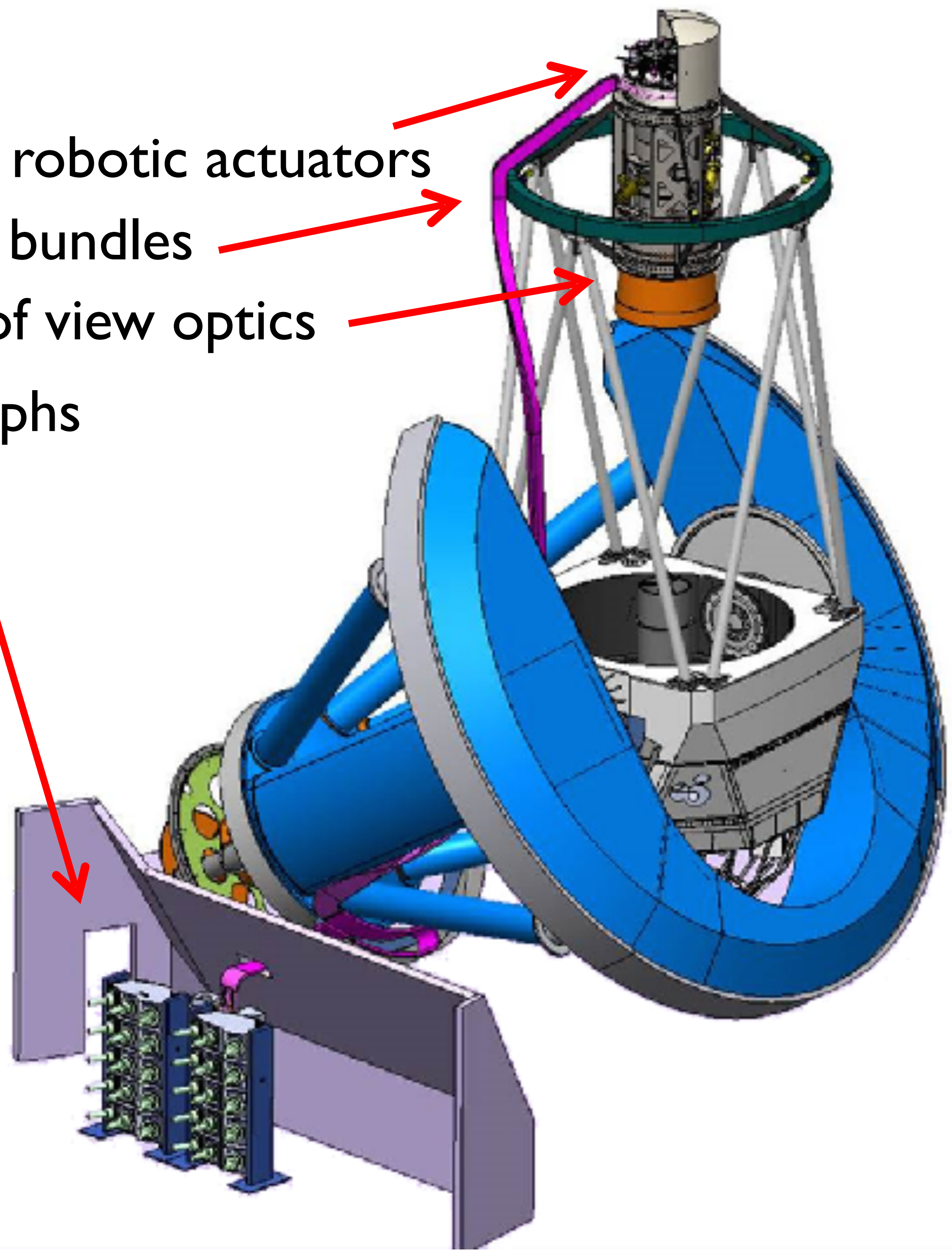
Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS dataset by an order of magnitude

Scheduled to start in 2019

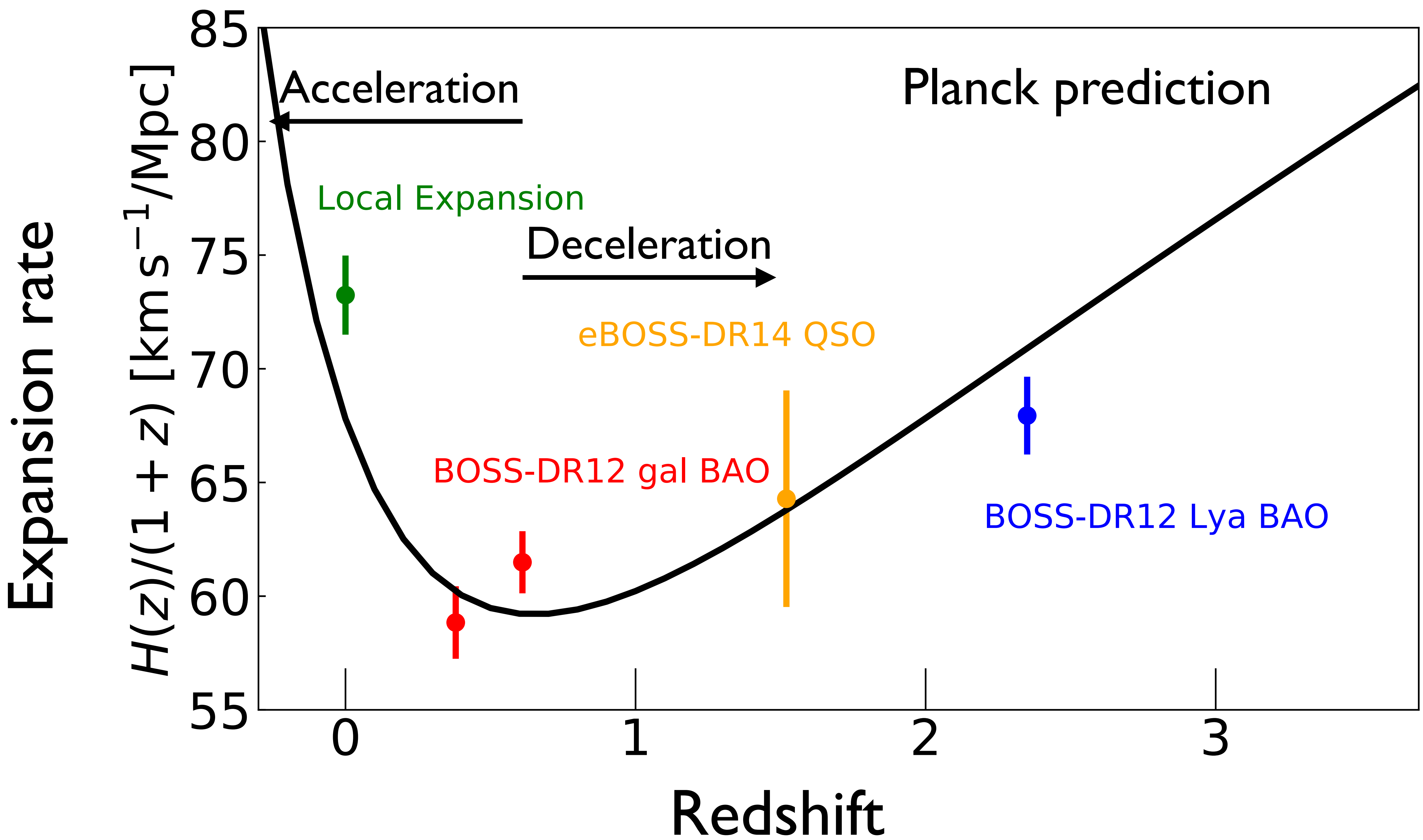
Dark Energy Spectroscopic Instrument

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs

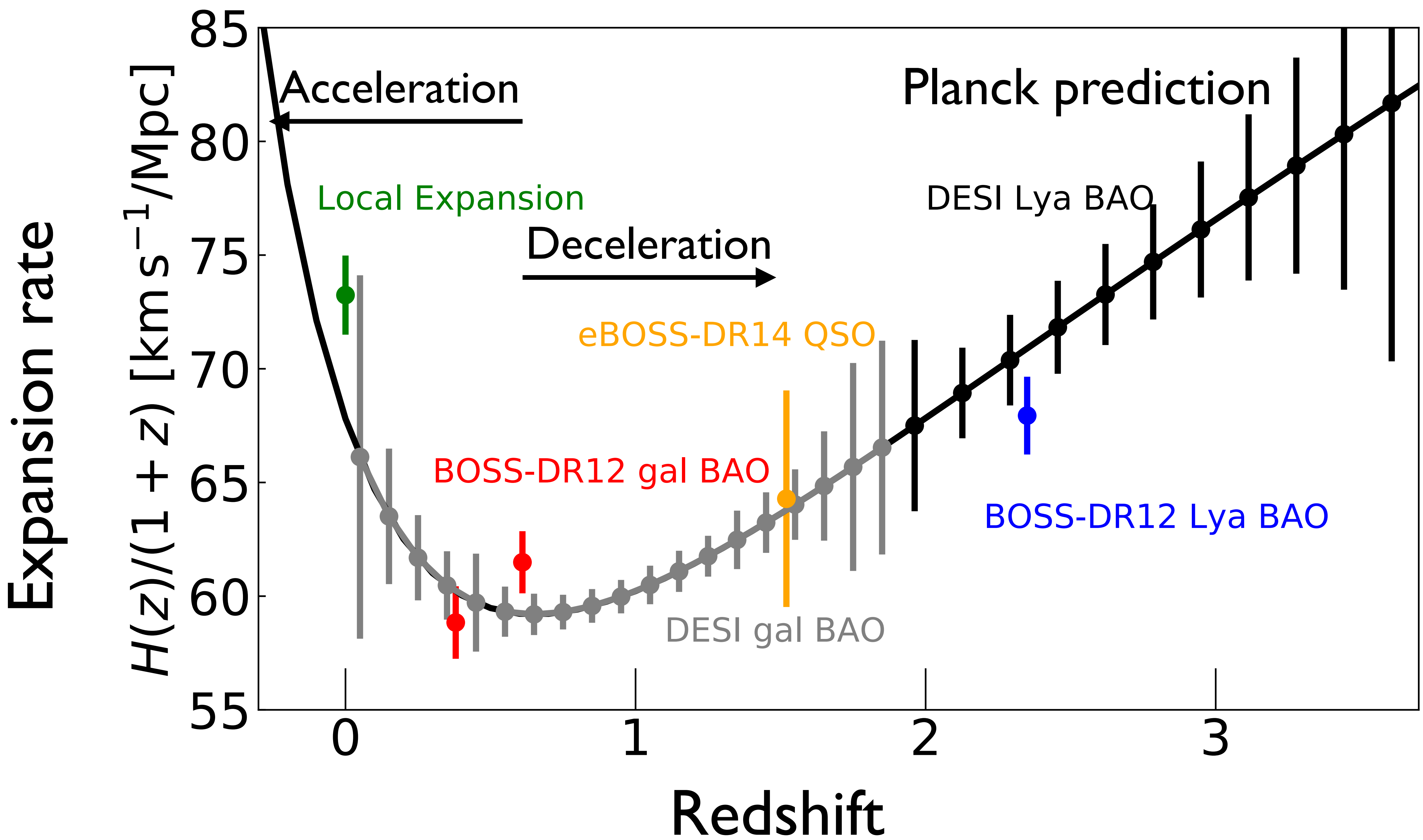


Readout
& Control

Dark Energy Spectroscopic Instrument



DESI projections (Font-Ribera++ 2014b)



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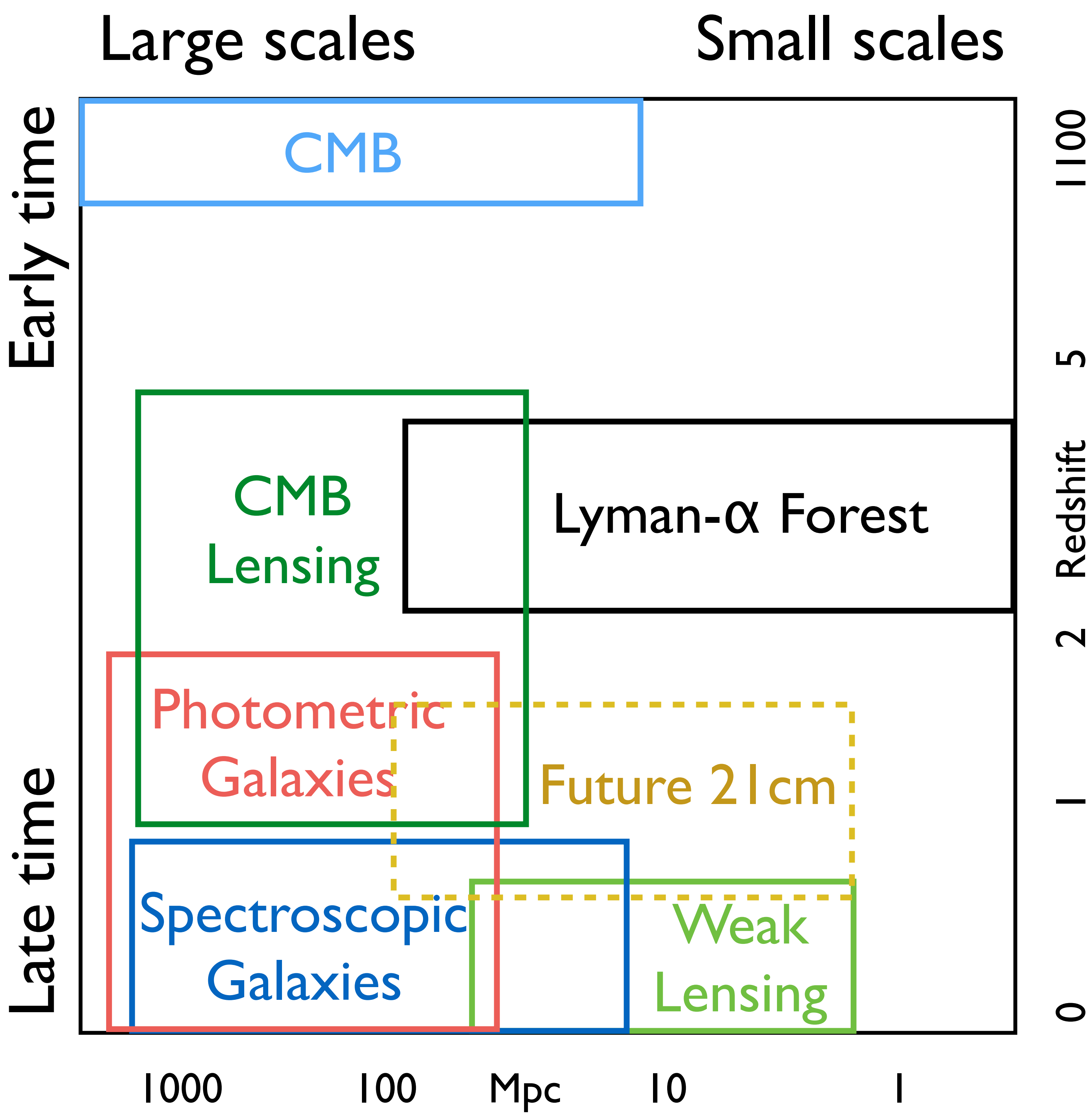
Small scale clustering

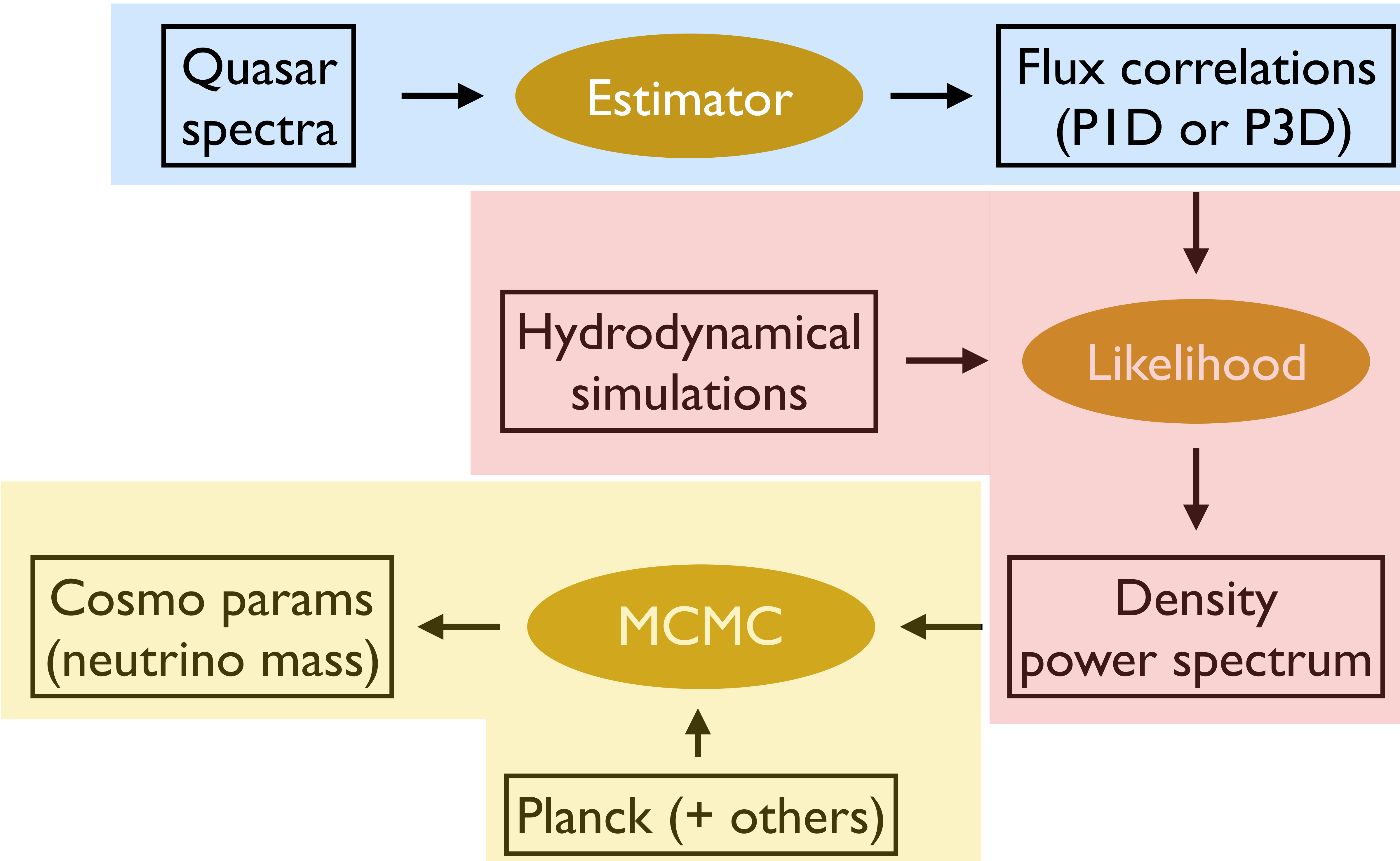


Lyman-α forest offers a unique window to study small scale clustering

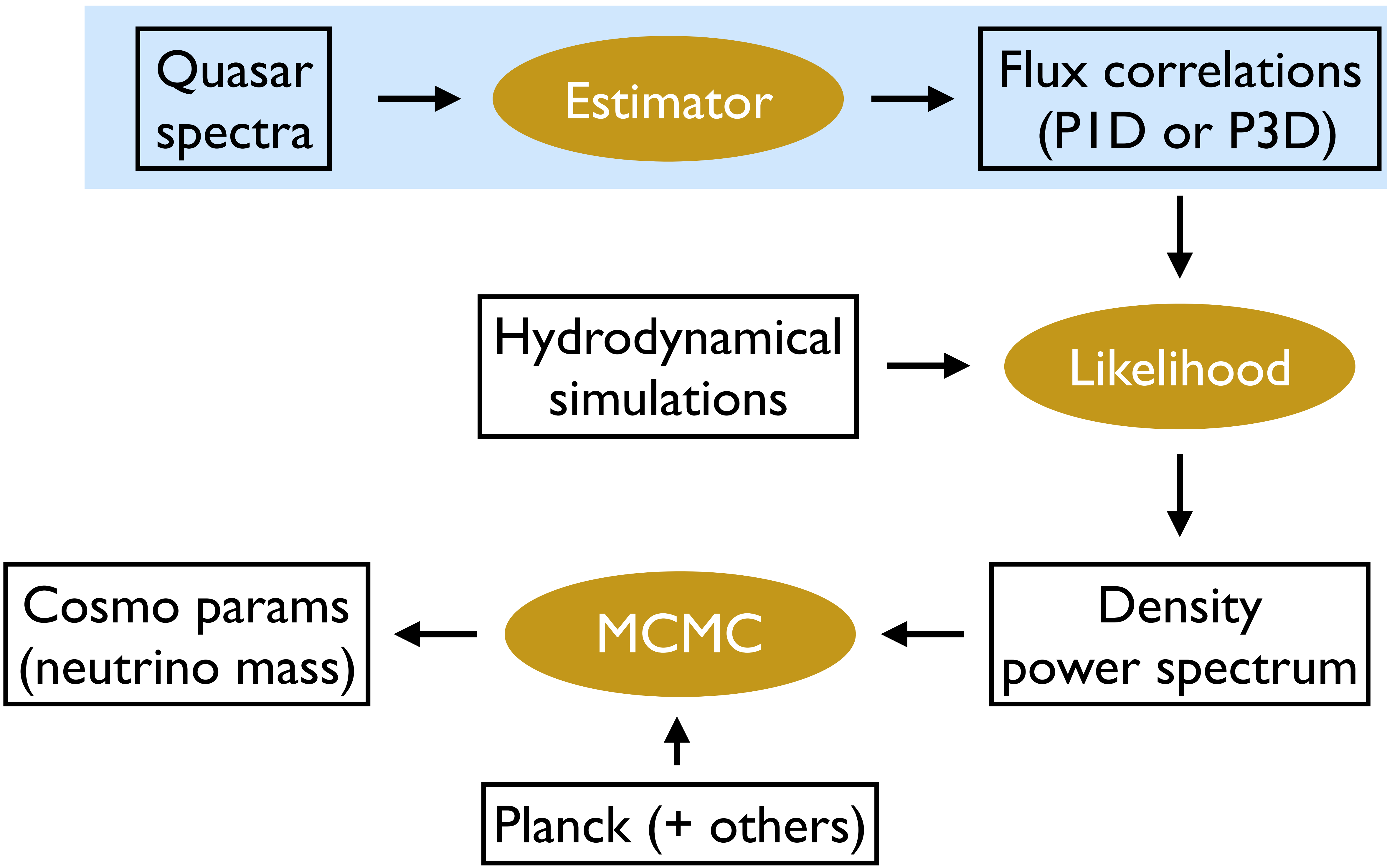
Combined with CMB, it allows us to study:

- shape of primordial P(k)
- dark matter properties
- neutrino mass

Small scale clustering



Small scale clustering



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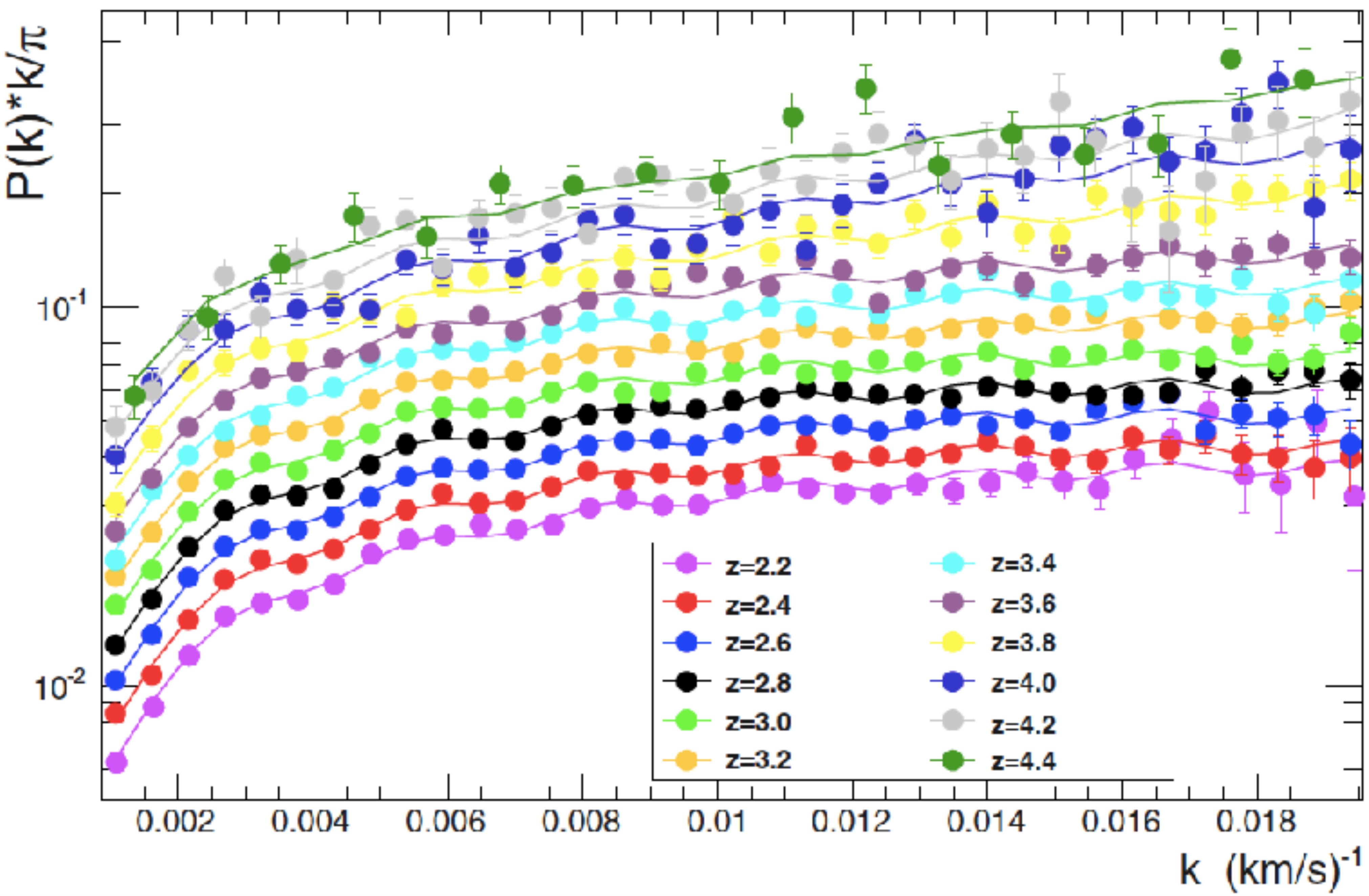
Estimators: 1D P(k)

1D correlations, one skewer at a time (Palanque-Delabrouille et al. 2013)



~ 0.1 h/Mpc | Line of sight (1D) wavenumber | ~ 2 h/Mpc

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Estimators: 3D P(k)

Motivation

- Good to have an alternative way to study BAO
- Constraint cosmology from the Lyα clustering, beyond BAO (DESI Lyα forecasts dominated by P3D, not P1D)

1D analyses have used both FFT / *Pseudo-Cl* and Maximum Likelihood

However, current 3D studies in BOSS/eBOSS only try to measure BAO

$$\bar{\xi}_F(r,\mu) = \frac{\sum_{\text{pairs } i,j} w_i w_j \, \delta_{Fi} \delta_{Fj}}{\sum_{\text{pairs } i,j} w_i w_j}$$

Estimators: 3D P(k)

Likelihood-based

$$L(\delta|\mathbf{p}) \propto \det(\mathbf{C})^{-1/2} \exp\left[-\frac{1}{2}\delta^t \mathbf{C}^{-1}\delta\right] = \exp\mathcal{L} \ ,$$

$$\mathcal{L}(\mathbf{p}) \simeq \mathcal{L}(\mathbf{p}_0) + \frac{d\mathcal{L}}{dp_i}\delta p_i + \frac{1}{2}\frac{d^2\mathcal{L}}{dp_i dp_j}\delta p_i \delta p_j + ... \equiv \mathcal{L}(\mathbf{p}_0) + \mathcal{L}_{,i}\delta p_i + \frac{1}{2}\mathcal{L}_{,ij}\delta p_i \delta p_j + ...$$

Optimal Quadratic Estimator

$$p_i^{\max} = p_i^0 - \mathcal{L}_{,ij}^{-1}\mathcal{L}_{,j} \ ,$$

$$\mathcal{L}_{,i} = \frac{1}{2}\delta^t \mathbf{C}^{-1}\mathbf{S}_{,i}\mathbf{C}^{-1}\delta - \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\mathbf{S}_{,i}\right]$$

$$F_{ij} \equiv -\langle \mathcal{L}_{,ij} \rangle = \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\mathbf{S}_{,i}\mathbf{C}^{-1}\mathbf{S}_{,j}\right]$$

- Can't evaluate by brute force (roughly a billion correlated pixels)
- We need to make controlled approximations for speed
    - Assume uncorrelated skewers (block-diagonal covariance)
    - Rotate data into eigenvectors of response matrices $\mathbf{S}_{,i}$
    - Use special parameterization, change variables later

Estimators: 3D P(k)

Configuration or Fourier space?

- Off-diagonal covariance
- low-k line of sight modes (continuum errors) spread over all scales

- Funky window function in transverse direction
- Non-stationary field (z-evolution)

Cross-spectrum (hybrid)

$$P_\times(\mathbf{r}_\perp, k_\parallel) = \int dx_\parallel \, e^{ik_\parallel x_\parallel} \, \xi(r_\parallel, \mathbf{r}_\perp)$$
$$= \frac{1}{(2\pi)^2} \int d\mathbf{k}_\perp \, e^{-i\mathbf{k}_\perp \mathbf{r}_\perp} \, P(k_\parallel, \mathbf{k}_\perp)$$

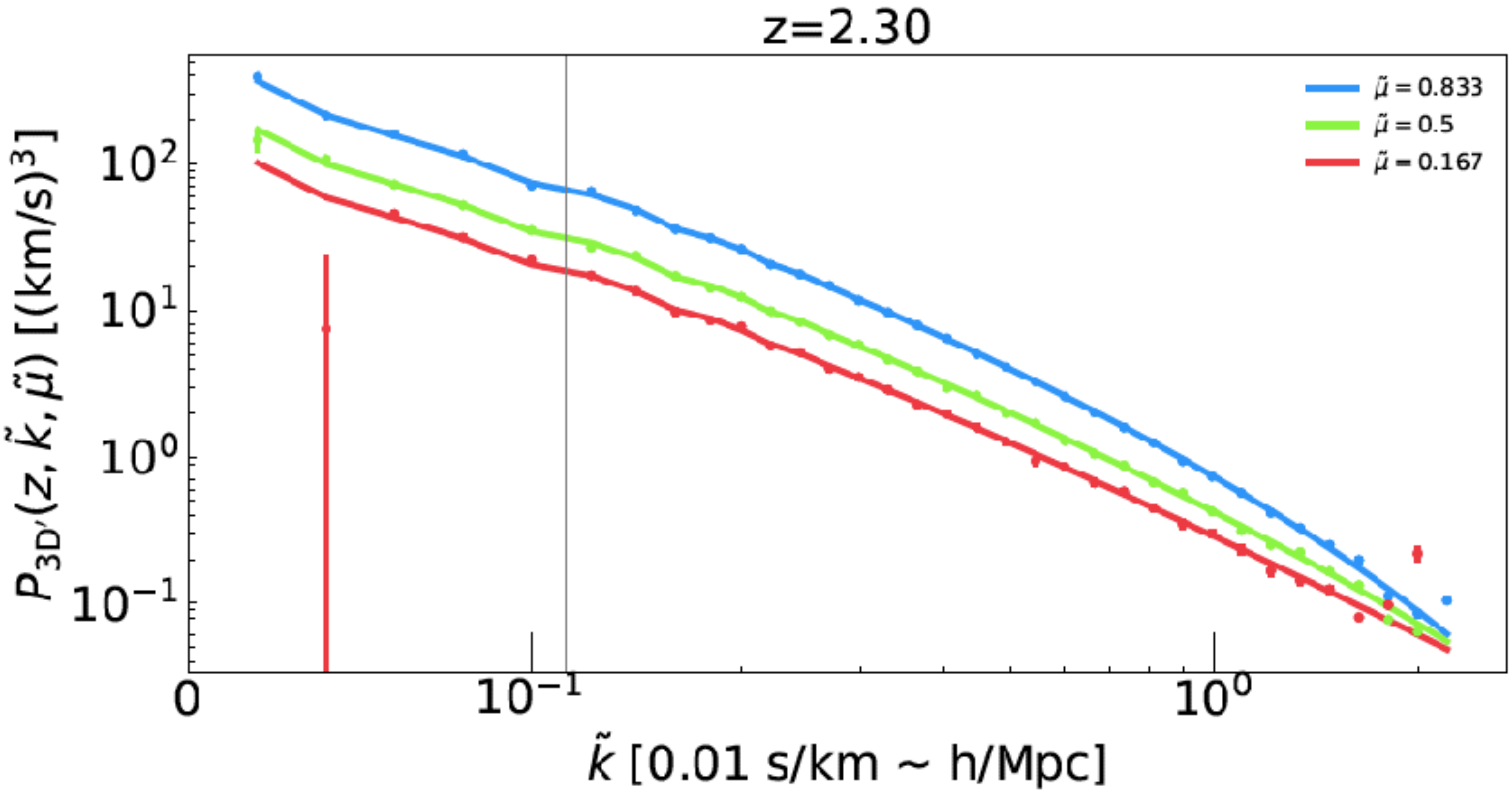
1D power is just one of the bins of the cross-spectrum with $r_\perp = 0$

Estimators: 3D P(k)

An efficient algorithm for estimating the 3D Lyα forest power spectrum

Andreu Font-Ribera [a,1,†] Patrick McDonald,[2,‡] and Anže Slosar[3,§]

JCAP (2018)
1710.11036v2



Measurement from 40 mock realizations of BOSS

Summary

BAO in the Lyα forest

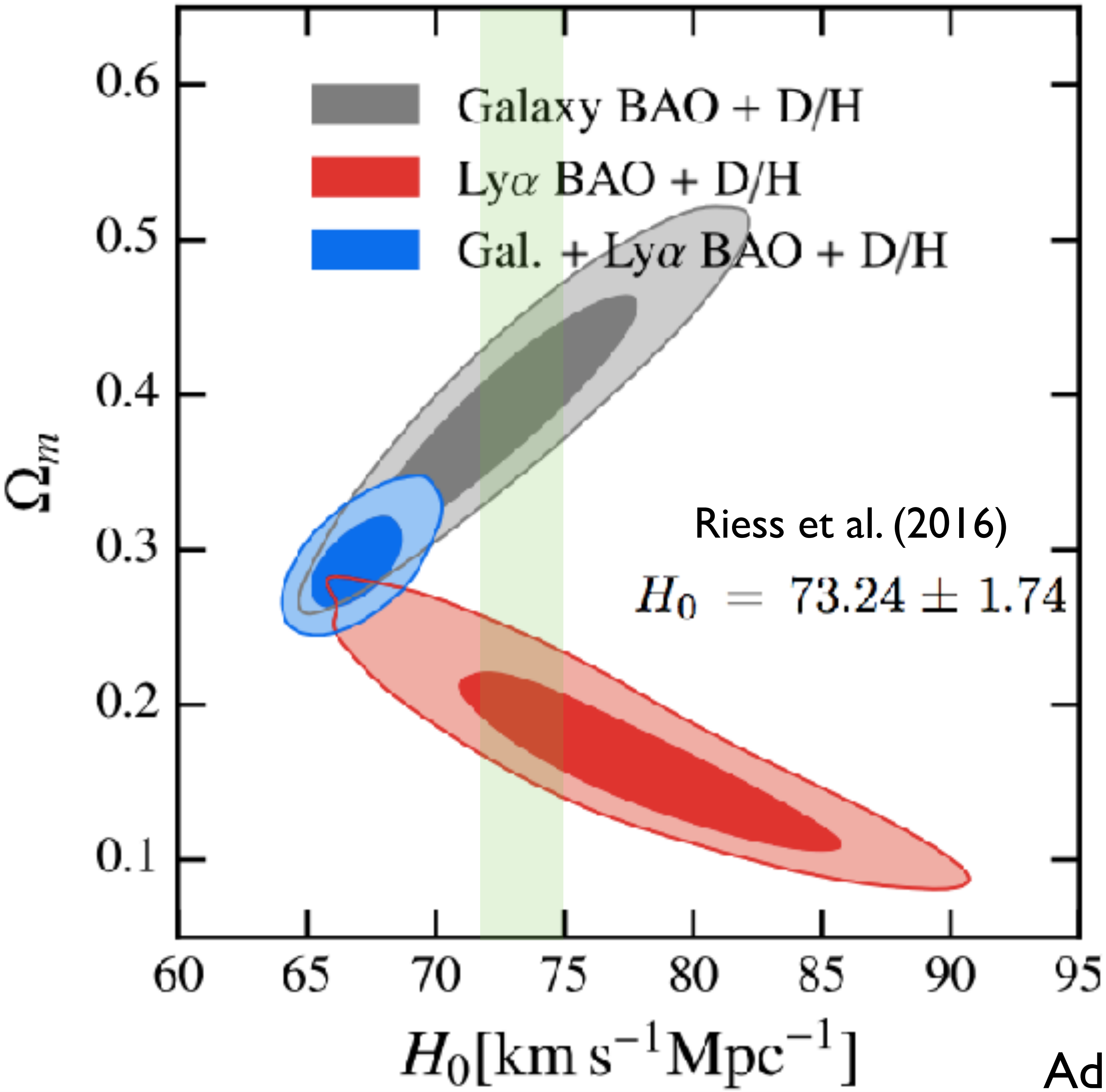
- 2% measurement at z~2.3 (quasars and the Lyman-α forest)
- BOSS Ly-α showed the forest is ready for precision cosmology
- DESI will represent an order of magnitude jump in precision

Small scale clustering of the Lyα forest

- Ly-α offers a unique window to small scales
- Strong constraints on warm dark matter, neutrinos or running
- Several statistical and computational challenges
- Many interesting projects, very few people working on it!

Extra slides

BAO and the H_0 tension



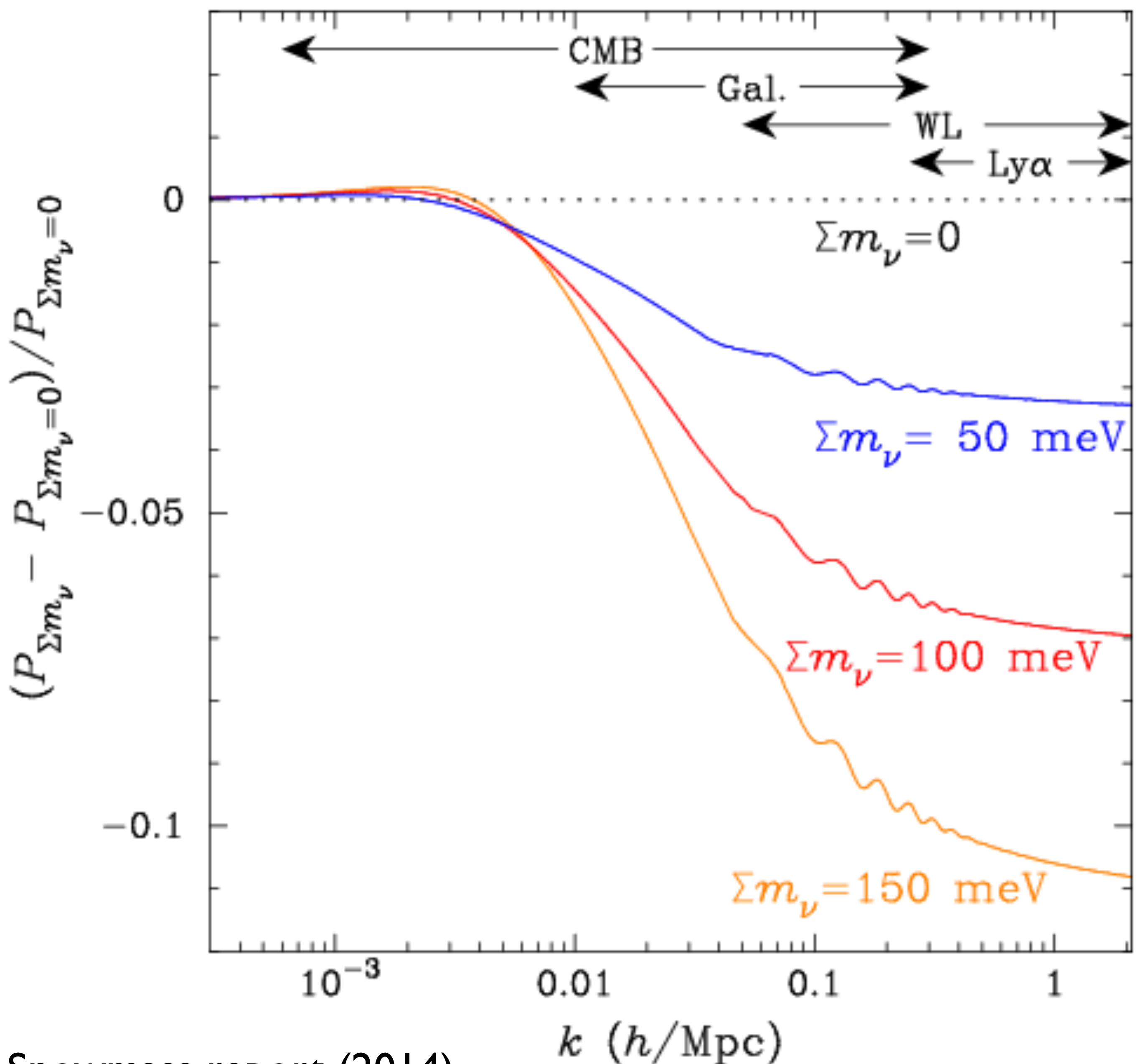
Addison et al. (2017)

Planck + LCDM predicts value of H_0 lower than that from local expansion (Riess et al. 2016)

BAO + LCDM constraint Ω_m and $H_0 r_s$ (sound horizon, size of ruler)

With BBN prior on Ω_b we can break degeneracy and measure H_0 from BAO

Small scale clustering



Snowmass report (2014)

Massive neutrinos are hot dark matter, do not cluster on small scales

Comparing the power on large and small scales we can constraint neutrino masses

Best constraints from Planck + BOSS Lyα
$\Sigma m_\nu < 0.12$ eV (95%)
(Palanque-Delabrouille++ 2015)