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Cosmology at high-redshift with the Lyman-α forest

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Outline

- **Introduction and background**
- The Lyman-α forest
- Baryon Acoustic Oscillations (BAO)
- The Alcock-Paczynski (AP) effect
- Redshift Space Distortions (RSD)

Measuring the expansion and growth

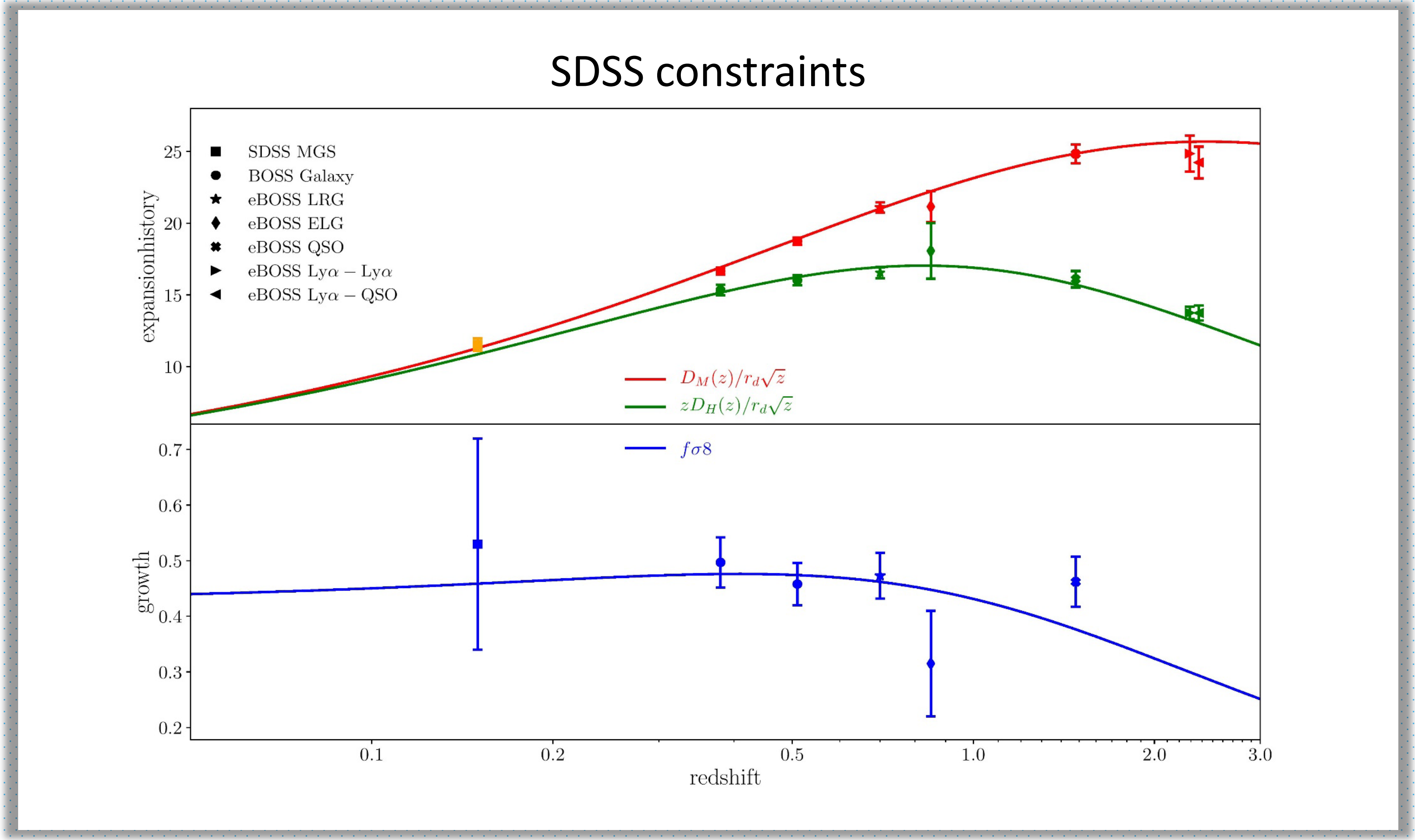

Figure from Alam et al. 2021 (2007.08991)

Measuring the expansion and growth

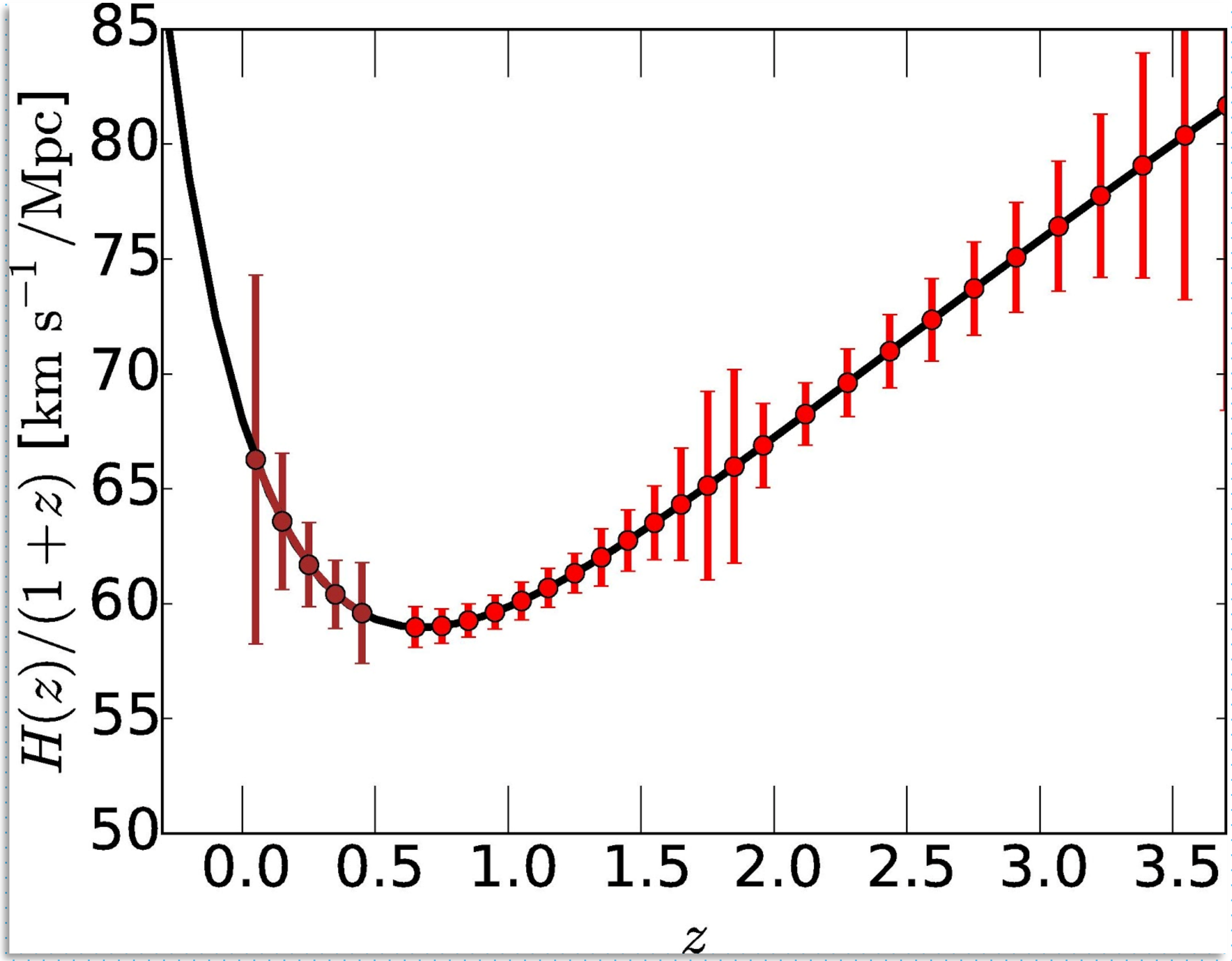

Figure from DESI Collaboration et al. 2016 (1611.00036)

- The Dark Energy Spectroscopic Instrument (DESI) is comprehensively measuring the expansion history all the way to redshift $z\sim 4$

Why so many measurements?

Flat ΛCDM

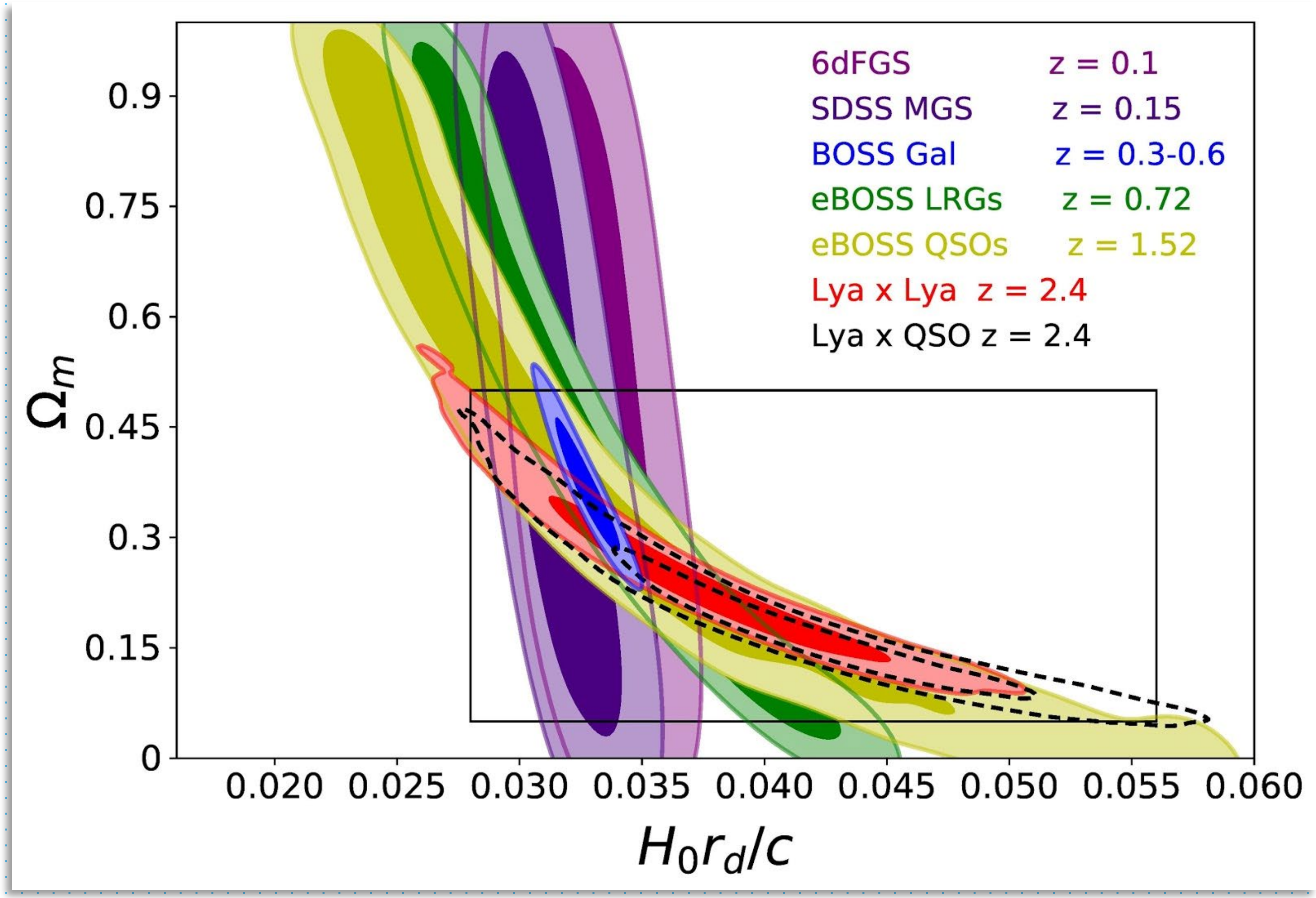

Figure from Cuceu et al. 2019 (1906.11628)

- Measurements at different redshifts lead to different degeneracies
- Low-z ⟶ Dark energy dominated Universe
- High-z ⟶ Matter dominated Universe

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The Lyman-α forest

The Lyman-α forest

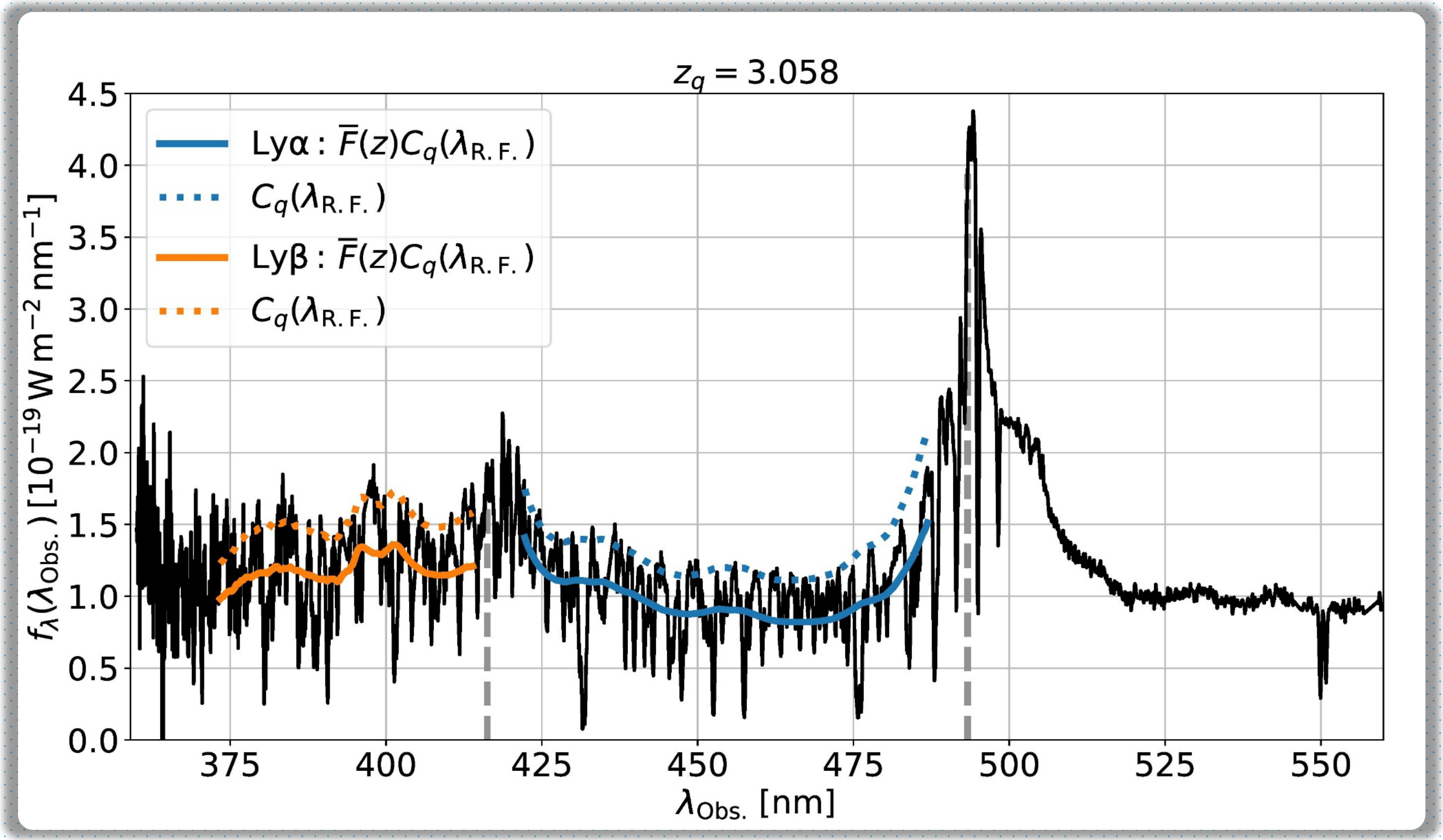


Figure from du Mas des Bourboux et al. 2020 (2007.08995)

The flux overdensity field

- For cosmology we use the statistics of the flux delta field, defined as:

$$\delta_q(\lambda_i) = \frac{f_q(\lambda_i)}{C_q(\lambda_i)\overline{F}(z_i)} - 1$$

- In general, we do not know the quasar continuum, $C_q(\lambda_i)$, and the global mean transmission, $\overline{F}(z_i)$.

- Therefore, we usually have to fit the product $C_q(\lambda_i)\overline{F}(z_i)$ directly from the data.

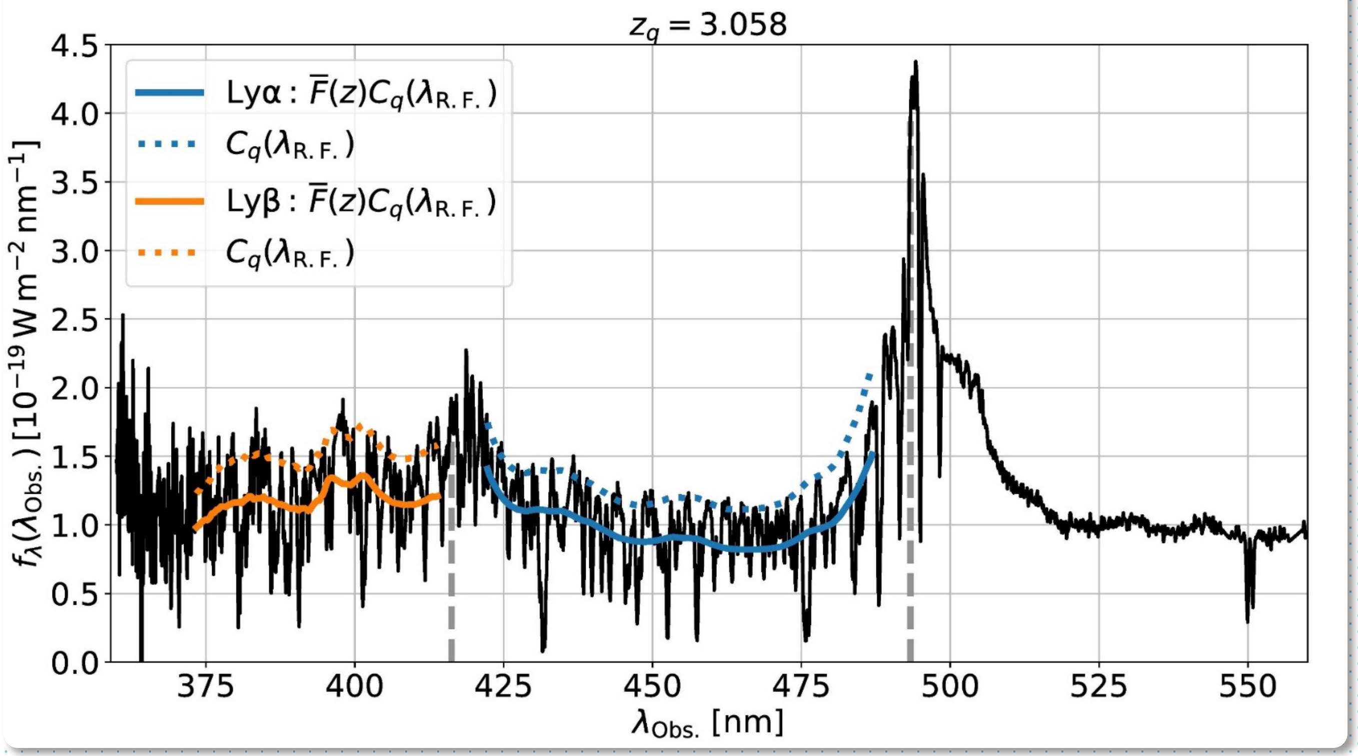


Figure from du Mas des Bourboux et al. 2020 (2007.08995)

Lyman-α forest correlations

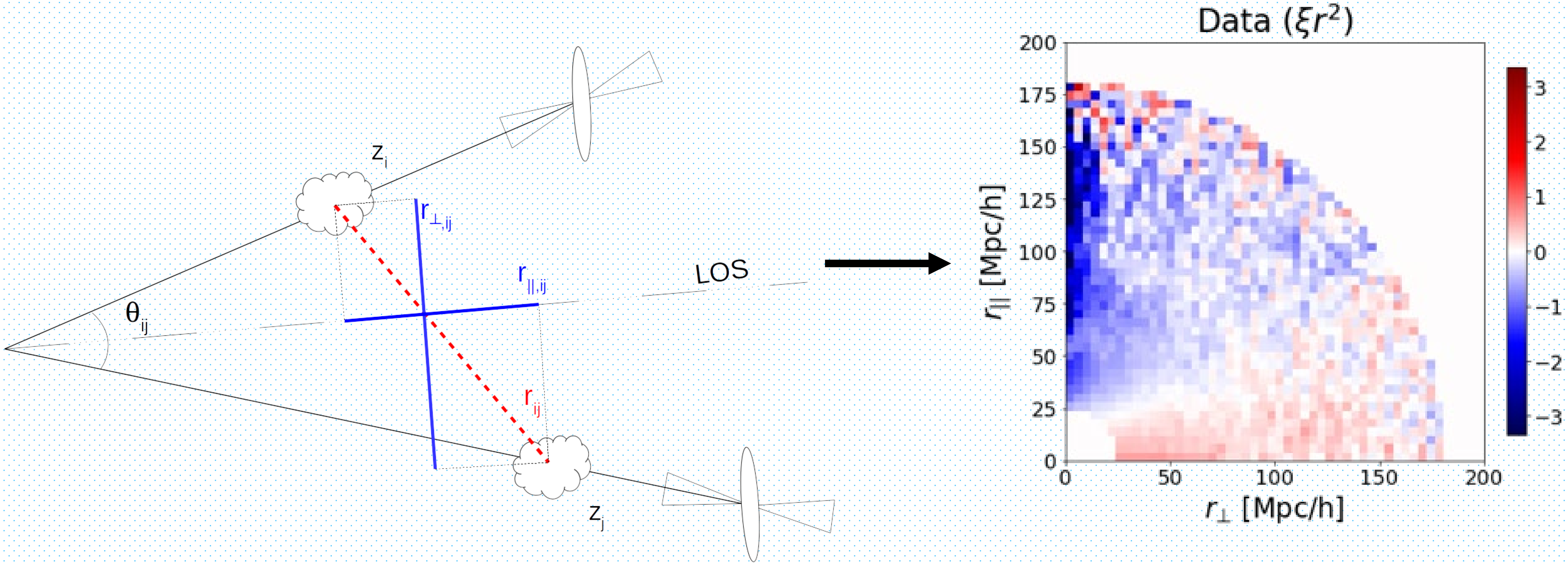
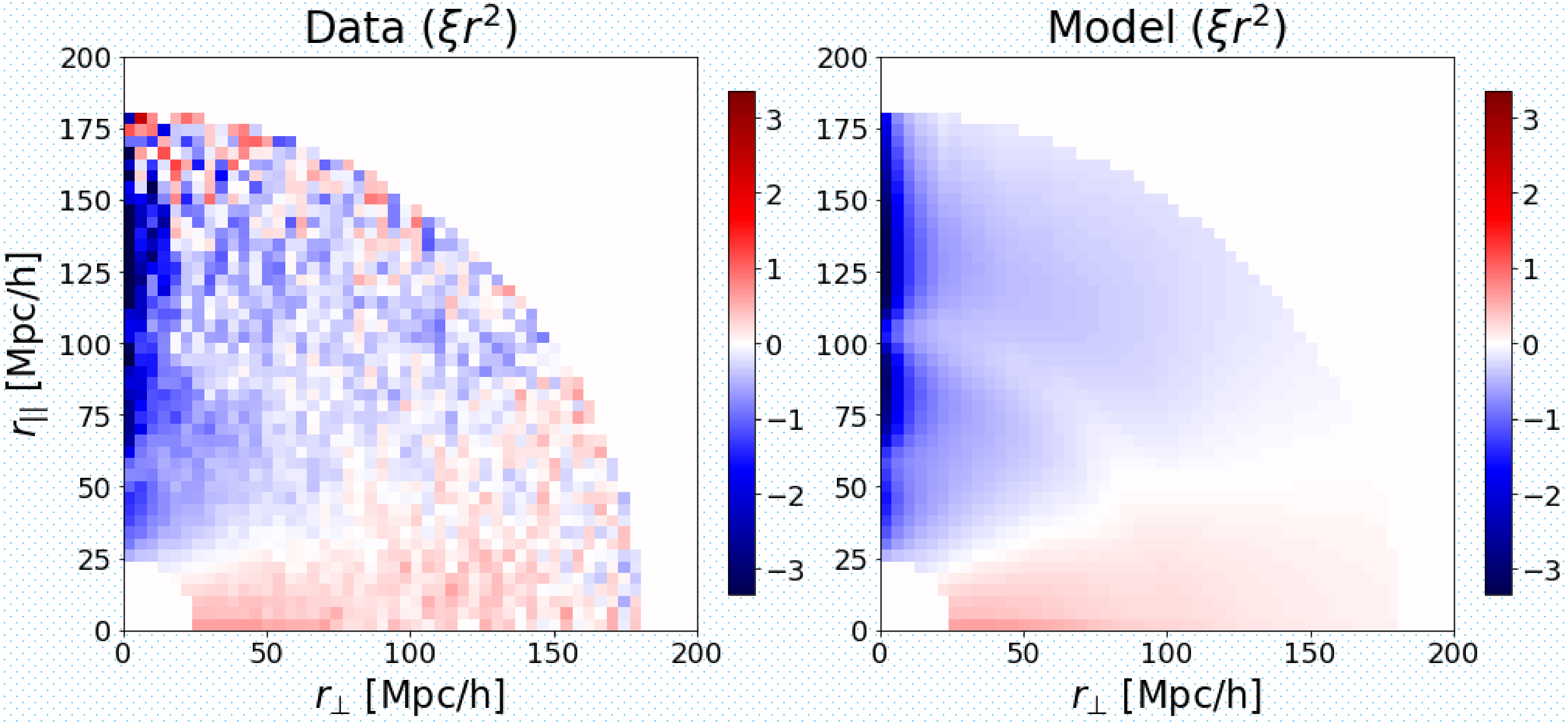
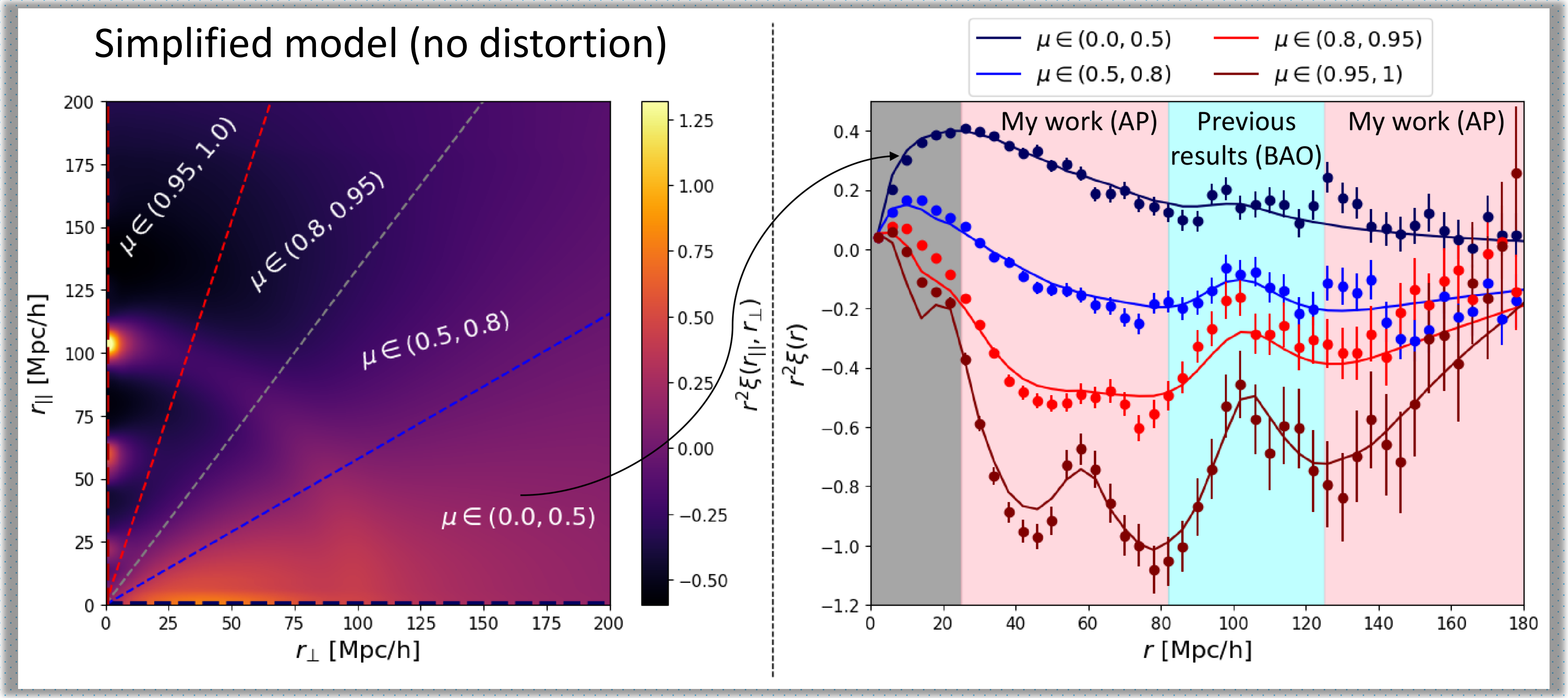


Figure from de Sainte Agathe et al. 2019 (1904.03400)

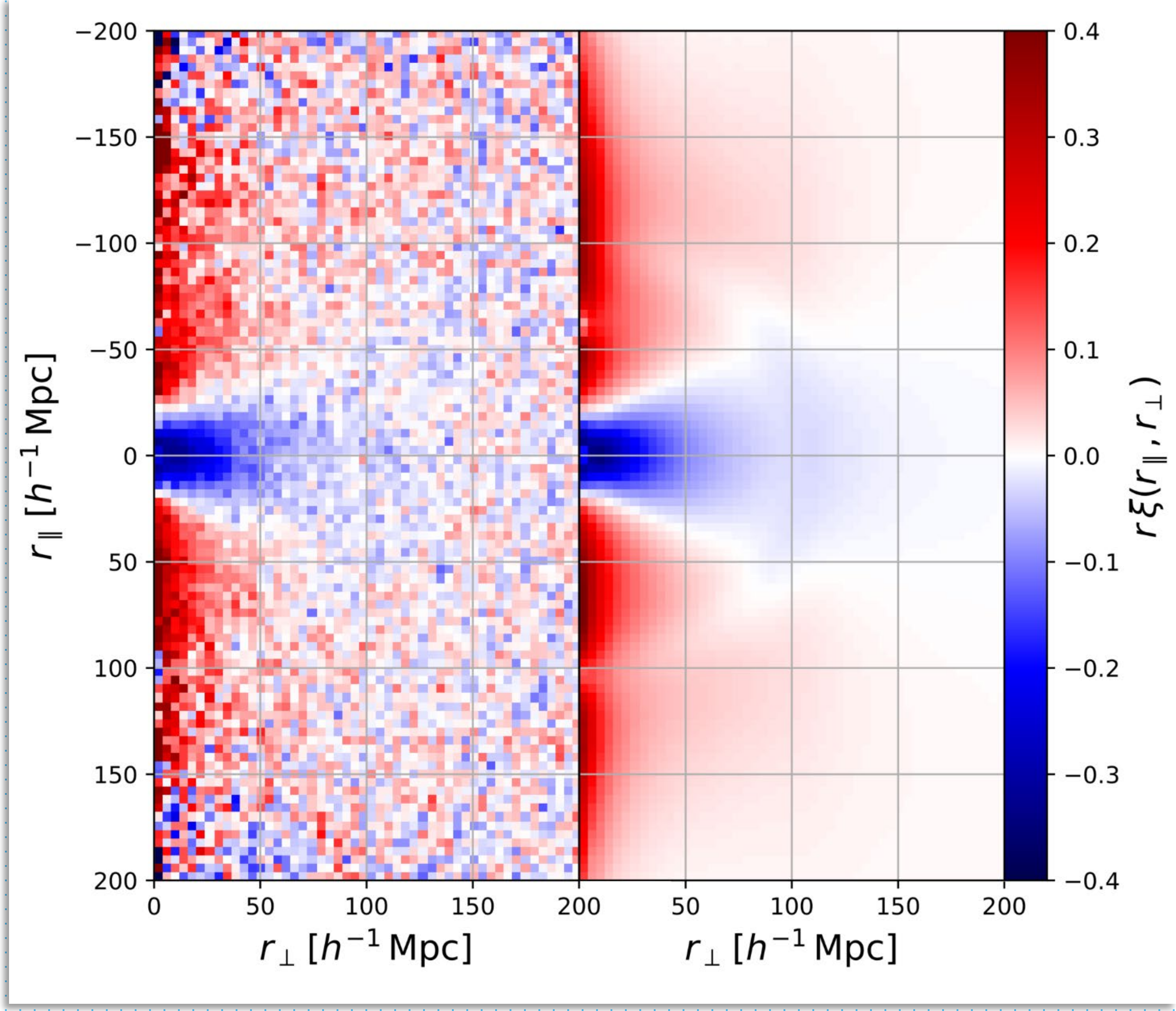
Lyman-α forest correlations: data vs model



Compressing into wedges



Lyα-quasar cross-correlation



- Also compute the cross-correlation between the Lyα forest and the quasar distribution
- Distinguish between forest pixels in front or behind the quasar

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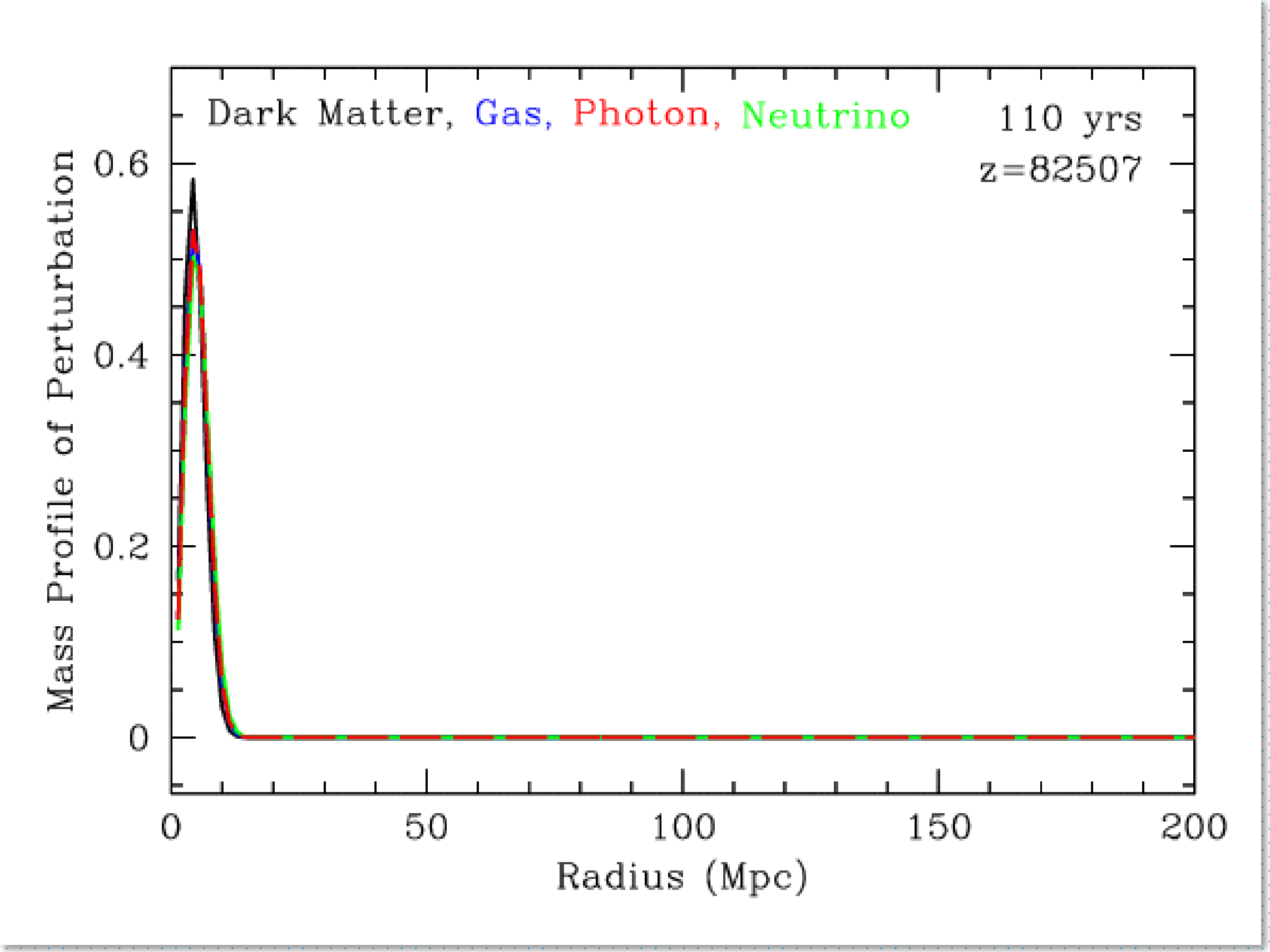
Baryon acoustic oscillations (BAO)

- We can detect BAO in the two point correlation function of galaxies, as a peak at around $\sim 100\ h^{-1}Mpc$

- We can also detect them in the power spectrum as an oscillation



https://lweb.cfa.harvard.edu/~deisenst/acousticpeak/acoustic_anim.html

BAO with the Lyman-α forest

- We use a template power spectrum decomposed into a peak and a smooth component

- We fit two scale parameters that shift the BAO peak along and across the line of sight:

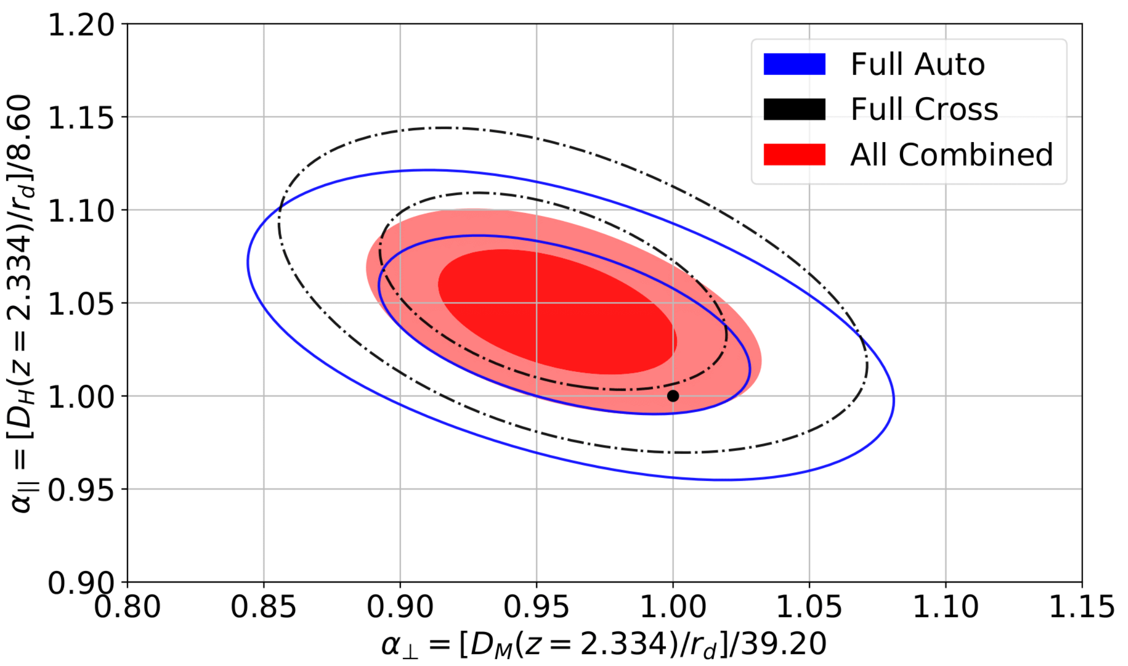
$$\alpha_{\parallel} = \frac{[H(z)\, r_d]_{fid}}{H(z)\, r_d}, \qquad \alpha_{\perp} = \frac{D_A/r_d}{[D_A/r_d]_{fid}}$$

- In a flat ΛCDM cosmology, these two parameters measure the matter fraction (Ω_m) and a combination of the Hubble constant and the size of the sound horizon ($H_0 r_d$)

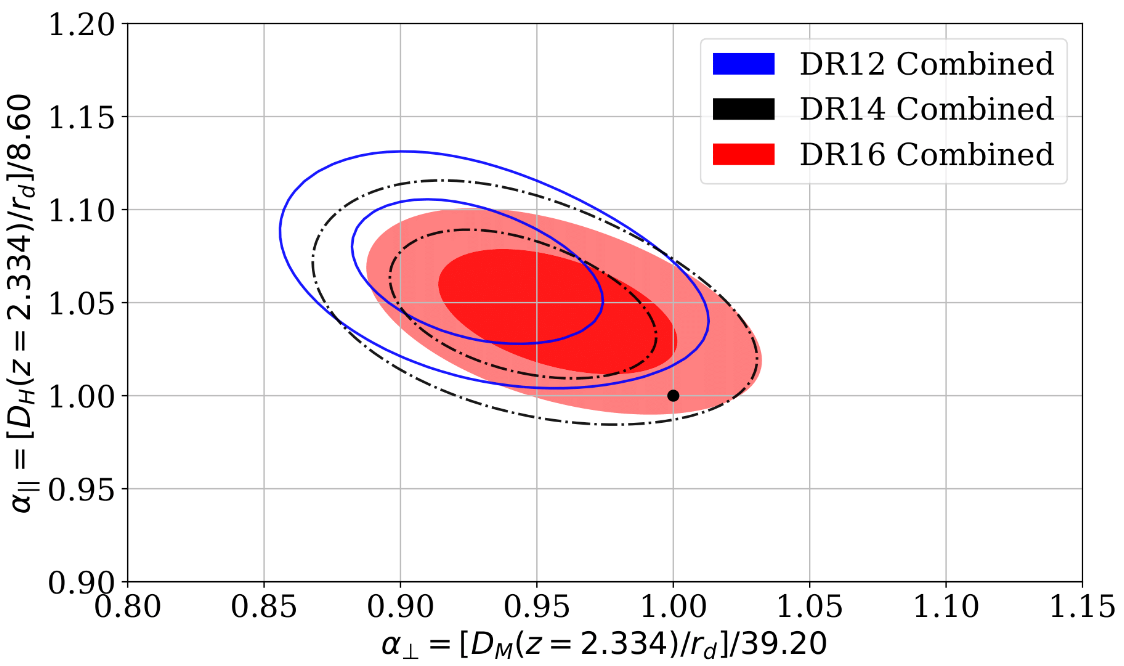
- However, because of the compression, you can use these parameters to constrain other cosmological models as well

Lyα BAO from BOSS and eBOSS

eBOSS DR16 measurements

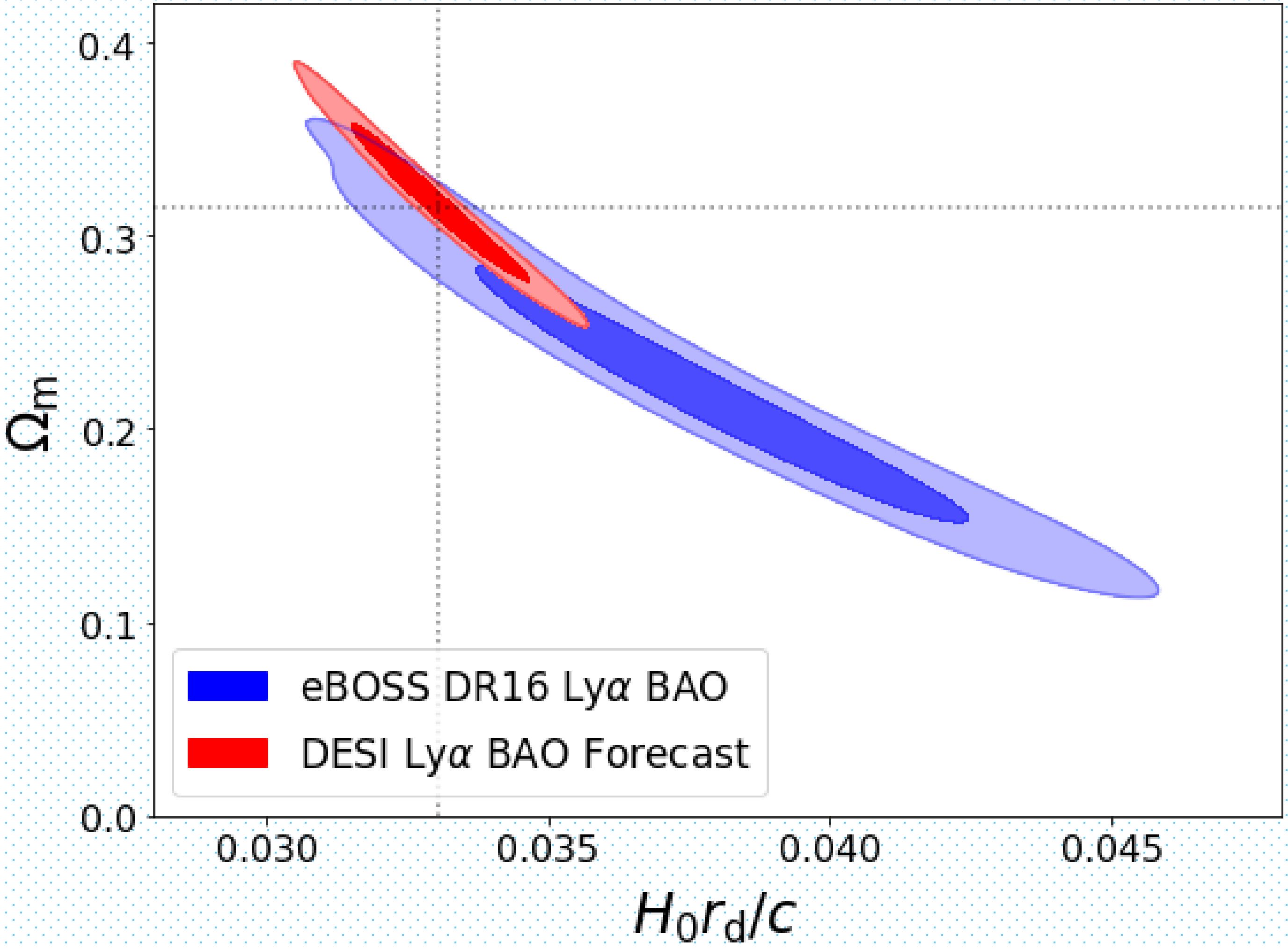


Comparison of SDSS measurements



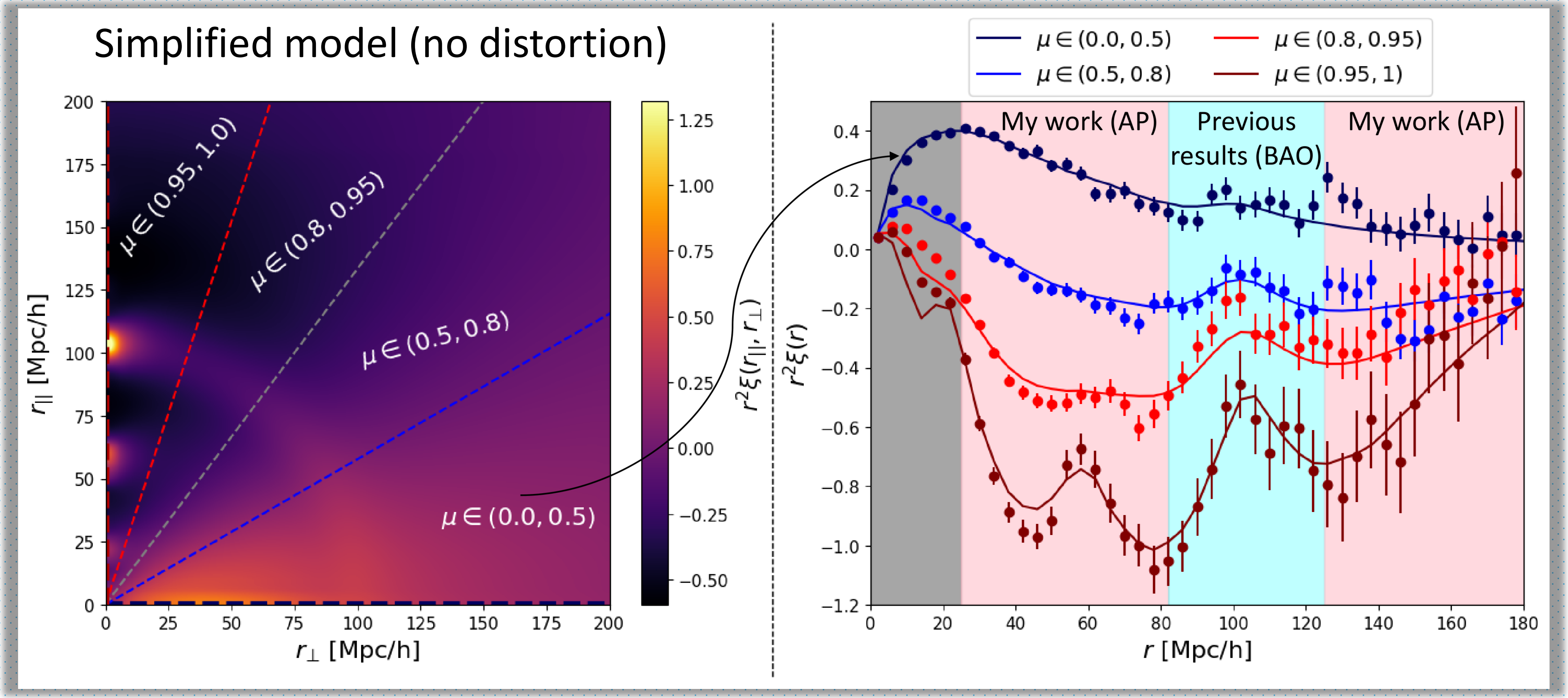
Figures from du Mas des Bourboux et al. 2020 (2007.08995)

DESI Lyα BAO forecast



- In flat ΛCDM, BAO measurements correspond to constraints in the $\Omega_m - H_0 r_d$ plane
- Currently, the best BAO measurement from the Lyα forest is given by eBOSS DR16
- DESI will provide the first sub-percent BAO measurements from LSS at $z > 2$

Beyond BAO with Lyα correlations



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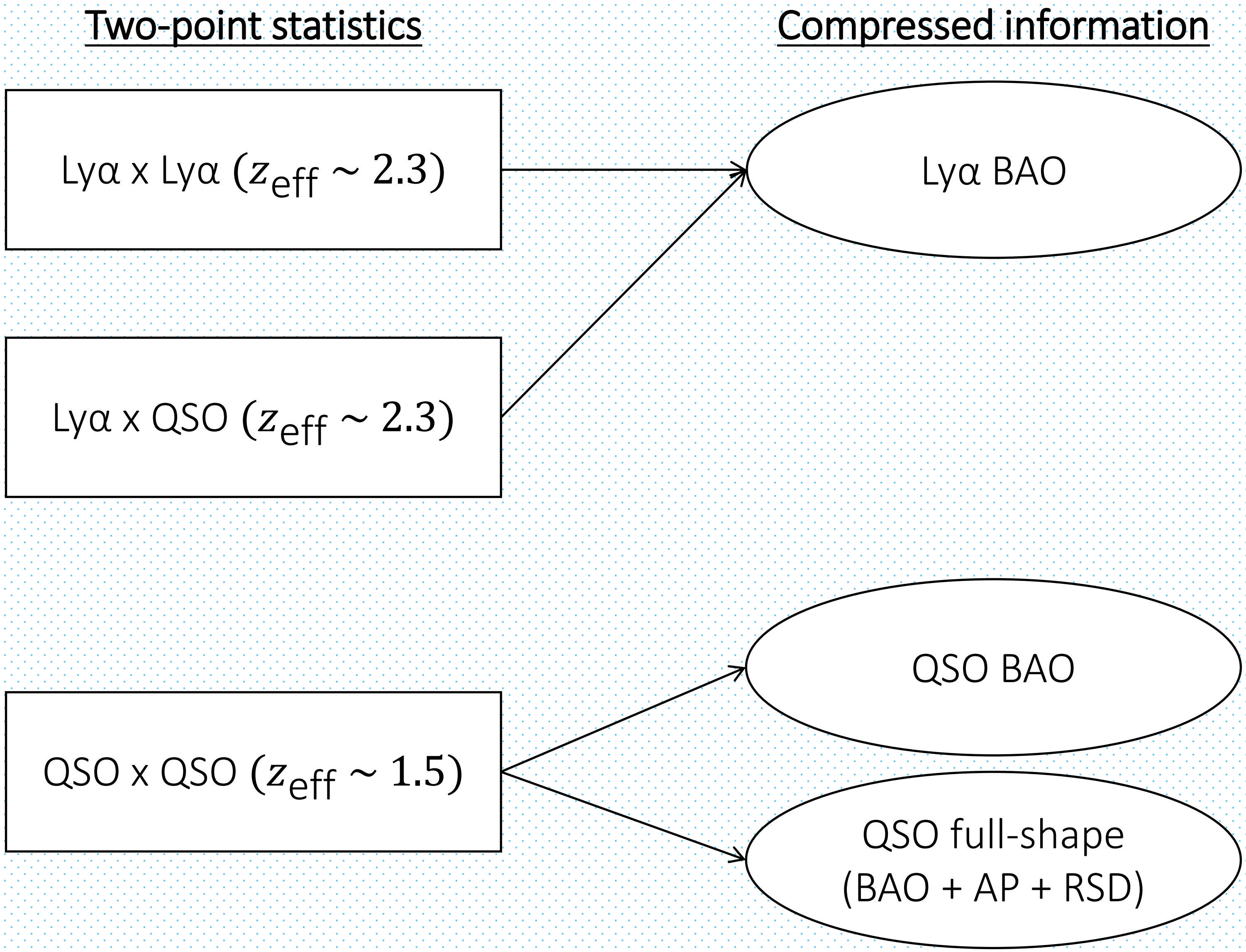
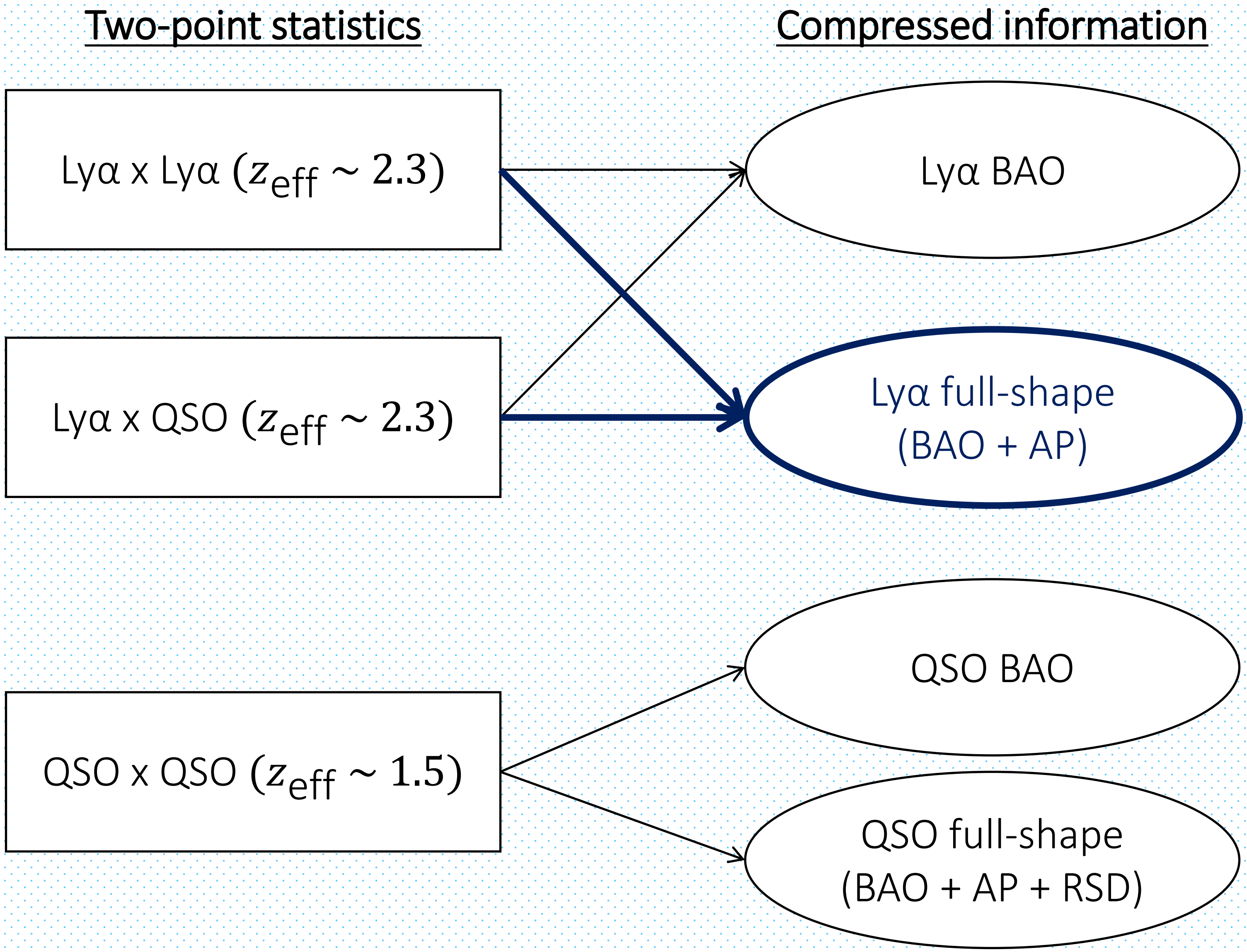
The story so far (BOSS/eBOSS)



- Only BAO from the 3D distribution of the Lyα forest in BOSS and eBOSS
- Galaxies were used for both BAO and full-shape analyses, which include redshift space distortions (RSD) and Alcock-Paczyński (AP).

Lyα full-shape from eBOSS (my work)



- In this talk, I will present results from the first full-shape analysis of the Lyα forest 3D correlations
- We use BOSS and eBOSS data from SDSS data release 16 (DR16)

The Alcock-Paczynski (AP) effect

- Assume a fiducial cosmology to transform angles and redshifts $(\Delta\theta, \Delta z)$ to comoving distances $(r_\parallel, r_\perp)$.

- Fiducial cosmology ≠ true cosmology $\longrightarrow$ anisotropy in the measured 3D correlation.

- Generally use $(\alpha_\parallel, \alpha_\perp)$ to measure this by rescaling the coordinates of the template:

$$r'_\parallel = \alpha_\parallel r_\parallel \text{ and } r'_\perp = \alpha_\perp r_\perp$$

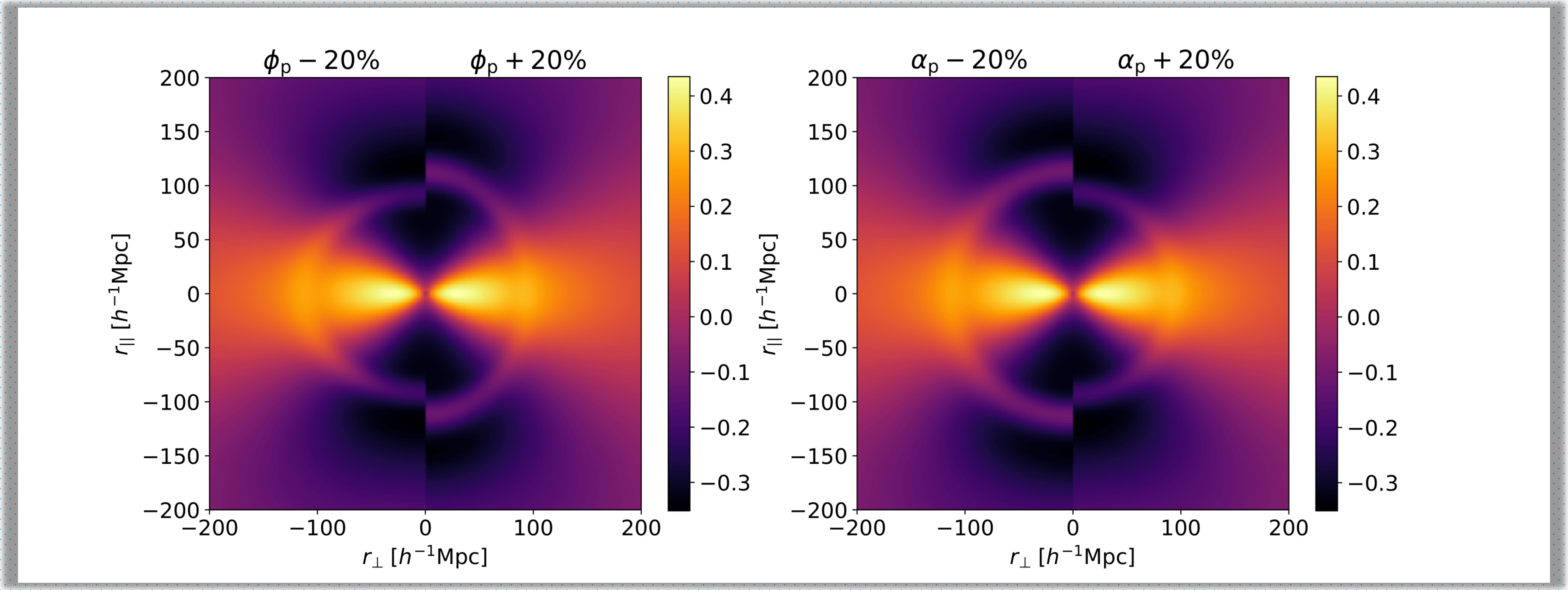
- For our analysis, we redefined these parameters to isolate the AP effect:

$$\phi = \frac{\alpha_\perp}{\alpha_\parallel} \text{ and } \alpha = \sqrt{\alpha_\perp \alpha_\parallel}$$

- Measurements of ϕ and α correspond to:

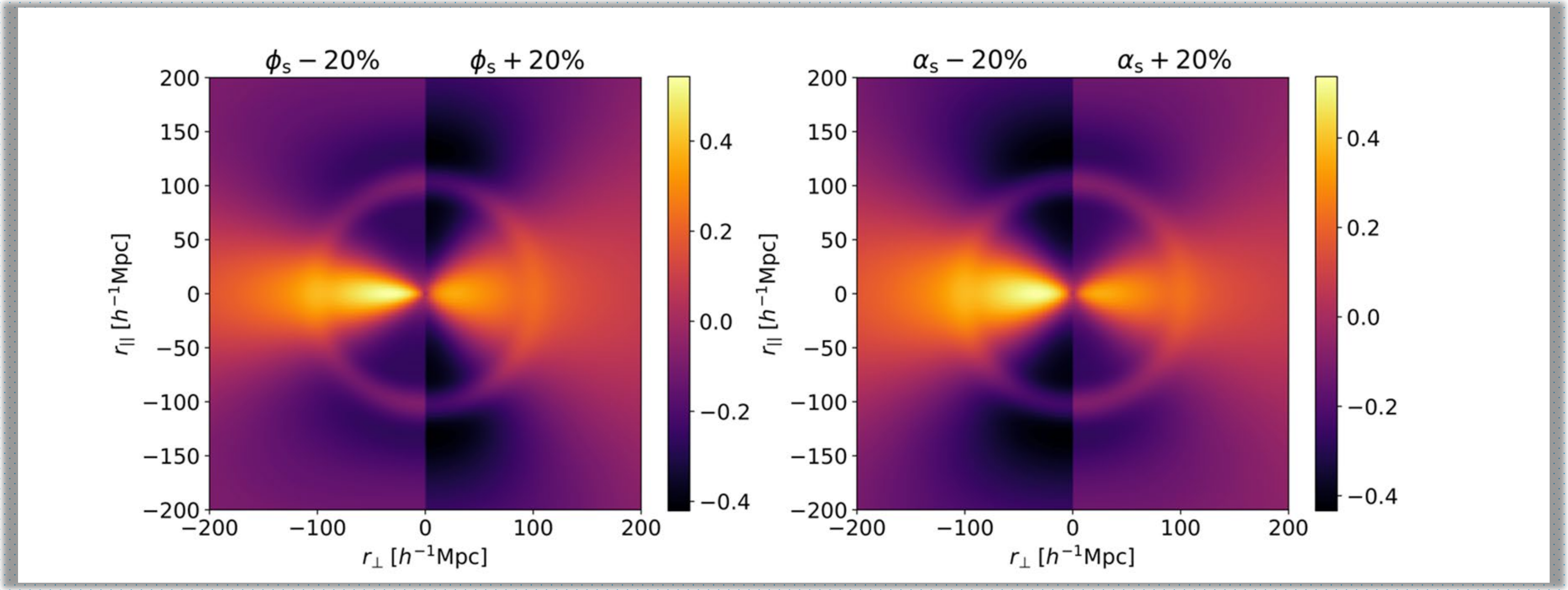
$$\phi = \frac{D_M(z)H(z)}{[D_M(z)H(z)]_{fid}} \text{ and } \alpha = \sqrt{\frac{D_M(z)D_H(z)/r_d^2}{[D_M(z)D_H(z)/r_d^2]_{fid}}}$$

Rescaling the peak component



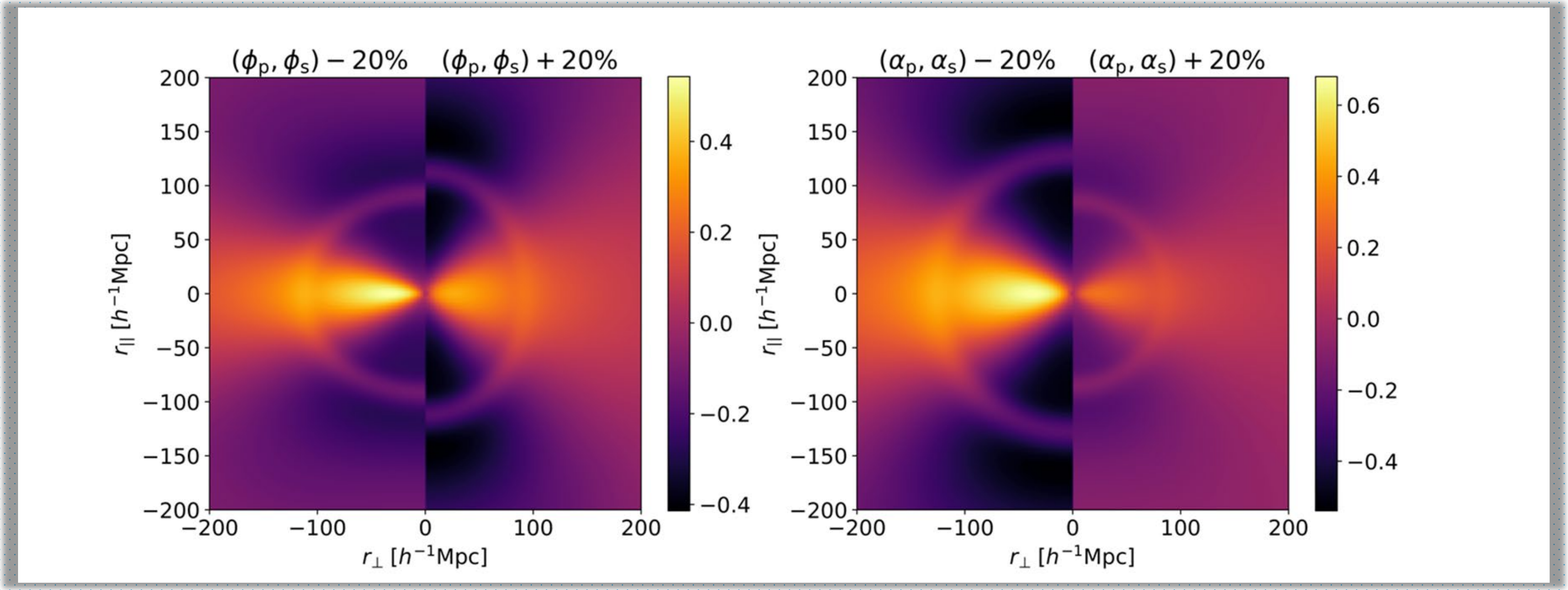
From Cuceu et al. 2021 (2103.14075)

Rescaling the smooth component



From Cuceu et al. 2021 (2103.14075)

Rescaling the full shape



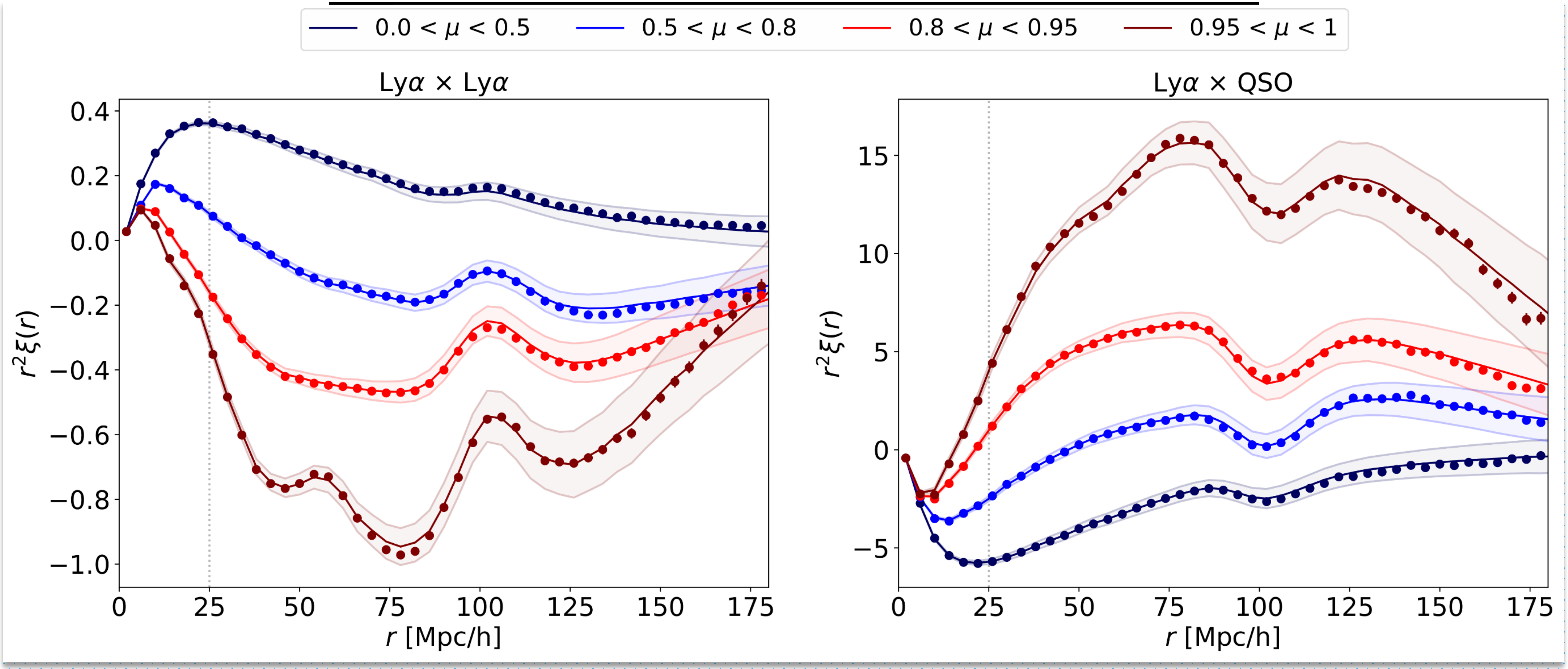
From Cuceu et al. 2021 (2103.14075)

Analysis validation using mocks

- To validate our measurement, we used synthetic data (mocks)
- Set of 100 eBOSS mocks created for the DR16 Lyα BAO analysis
- Mocks use a Gaussian field with quasars drawn from its log-normal transformation
- Include all the major contaminants affecting Lyα forest correlations

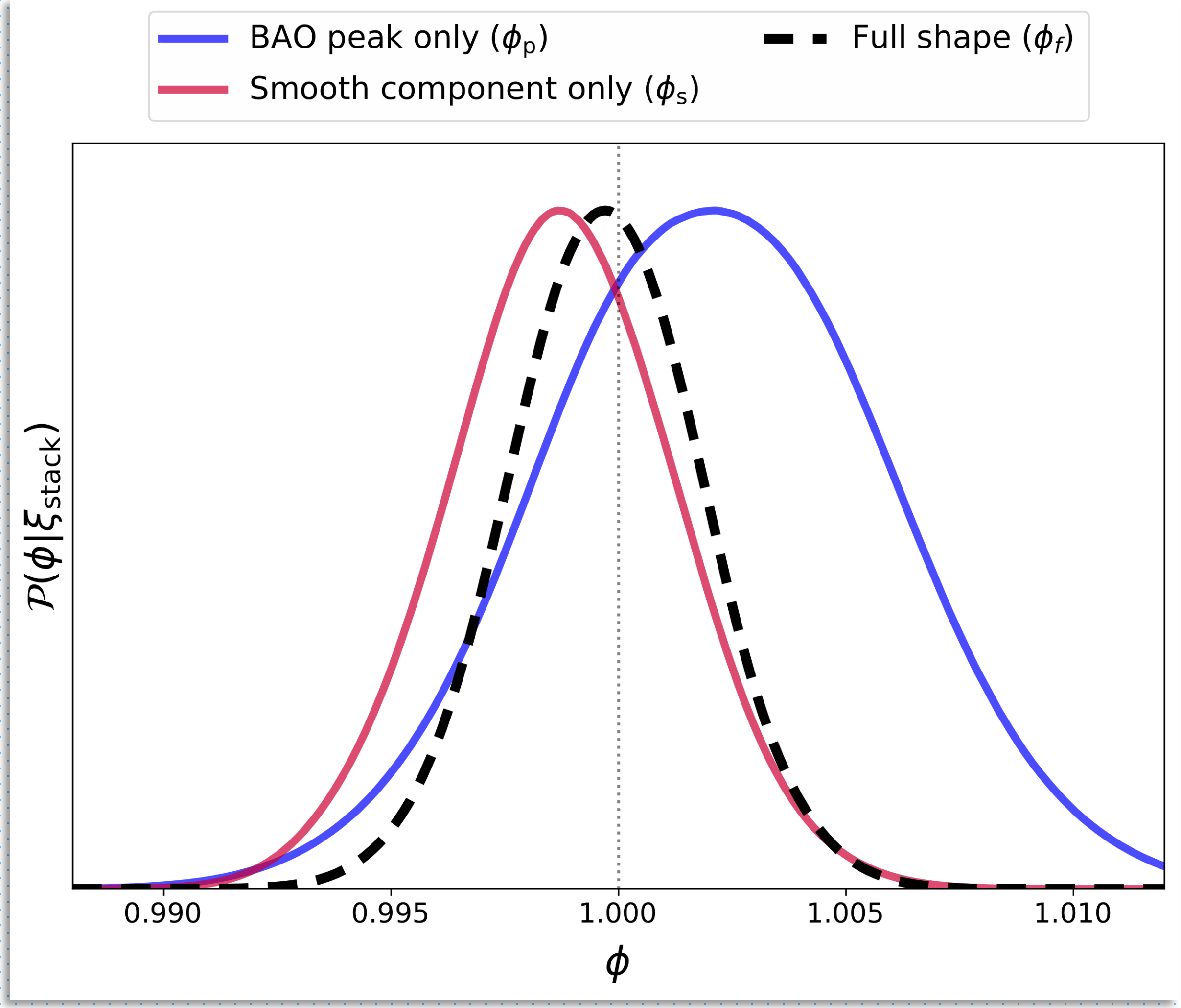
Analysis validation using mocks

Measurements from mean of 100 eBOSS mocks



From Cuceu et al. 2022a (2209.12931)

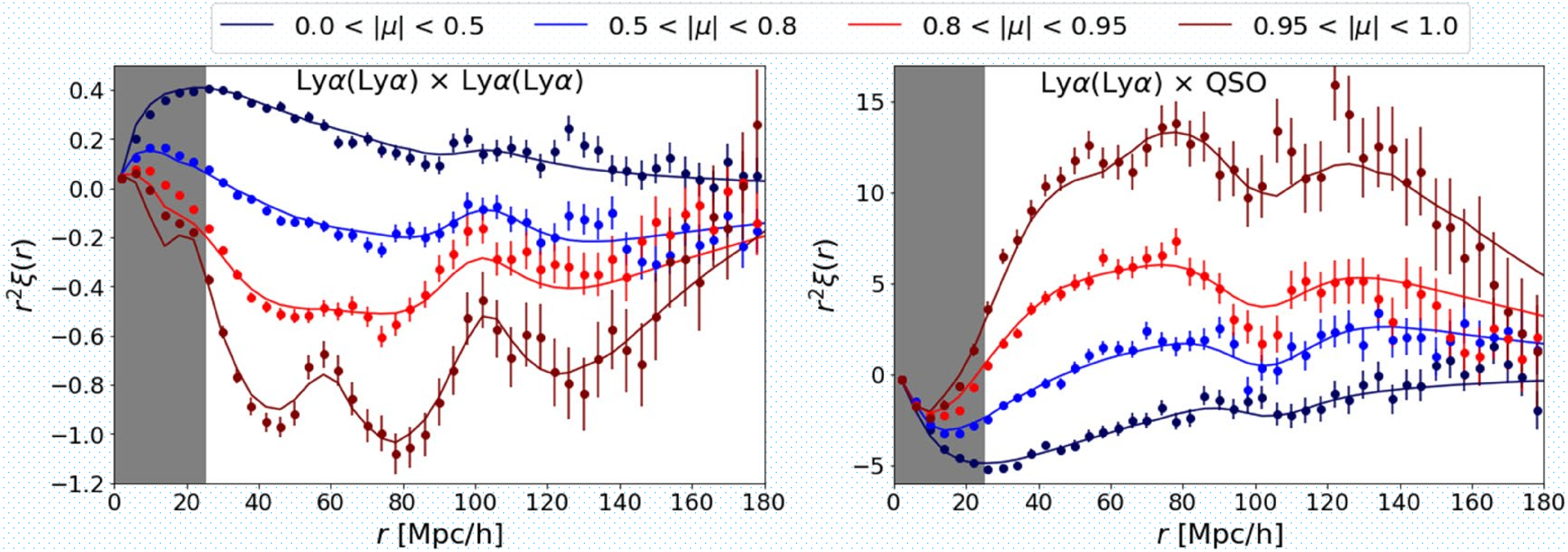
Results from analysis of 100 eBOSS mocks



From Cuceu et al. 2022a (2209.12931)

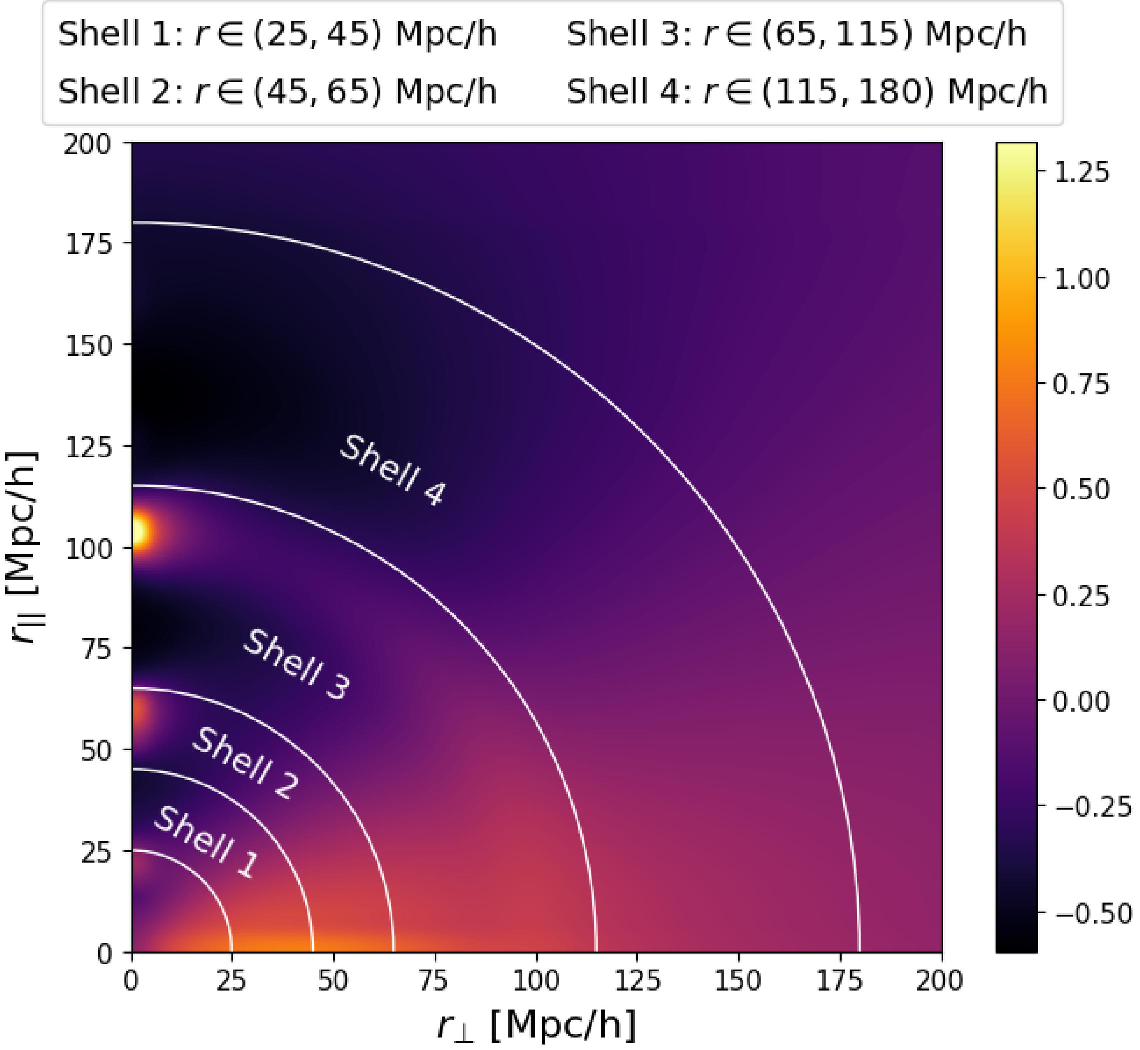
- We used 100 eBOSS DR16 log-normal mocks to validate our analysis
- These mocks include all the major contaminants affecting Lyα forest correlations
- Recovering the cosmology in the mocks corresponds to $\phi = 1$

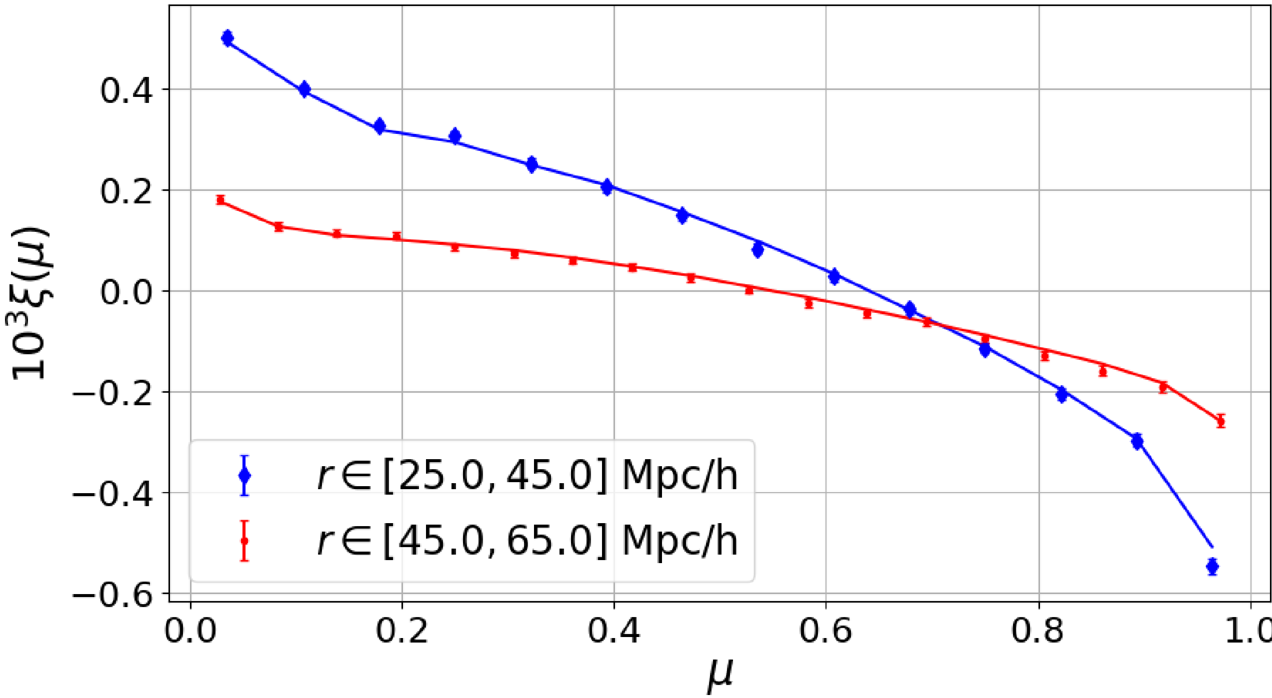
eBOSS data and best-fit model

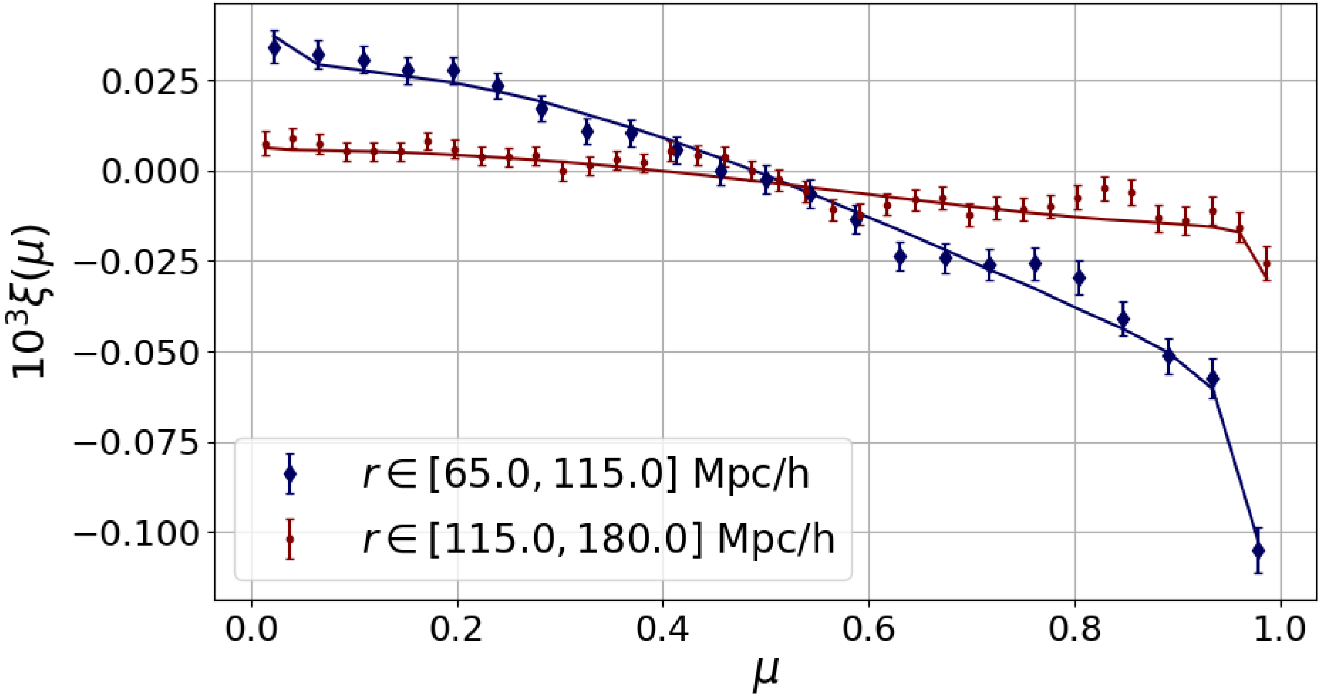


From Cuceu et al. 2022b (2209.13942)

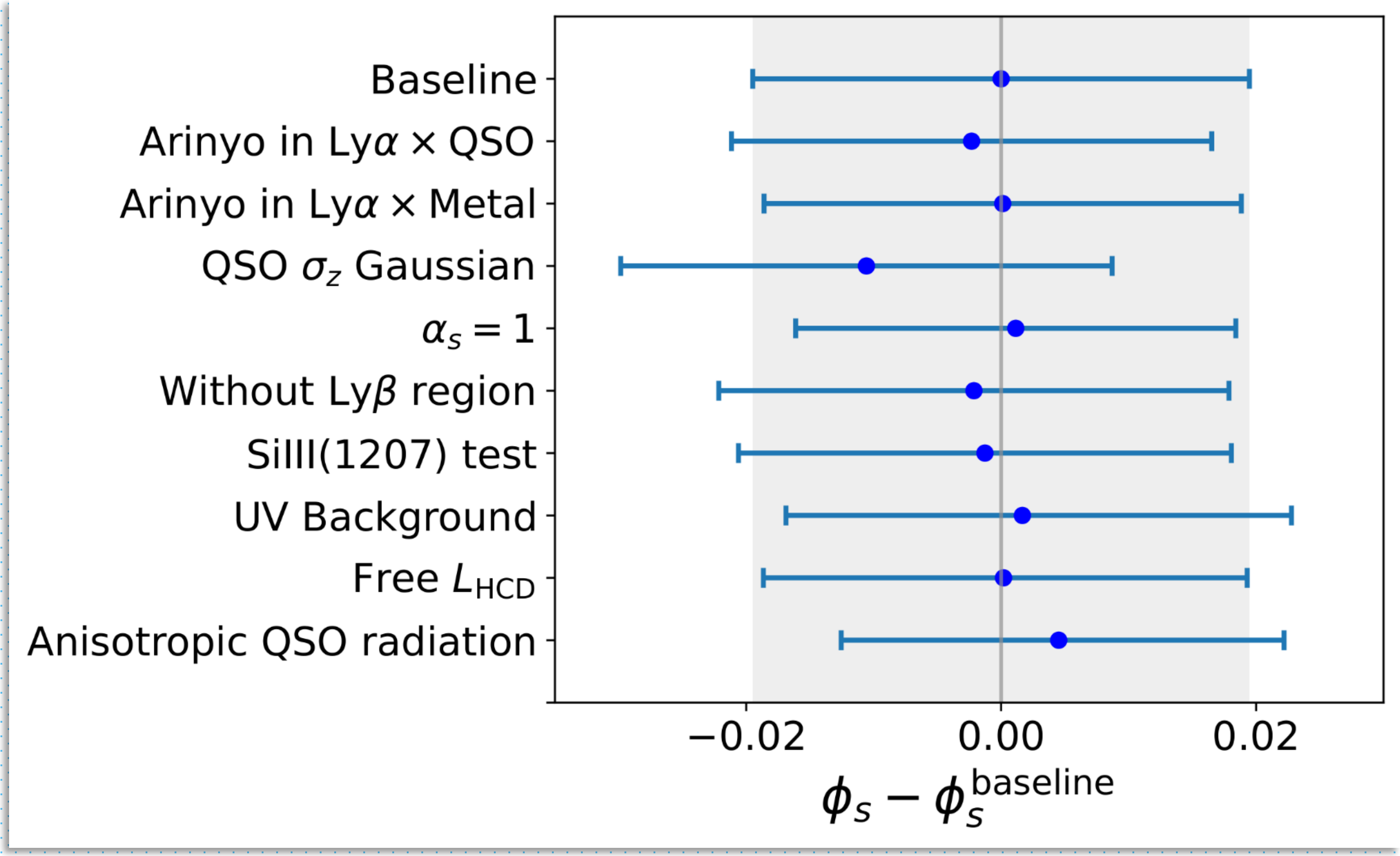
Compressing into shells







Robustness tests

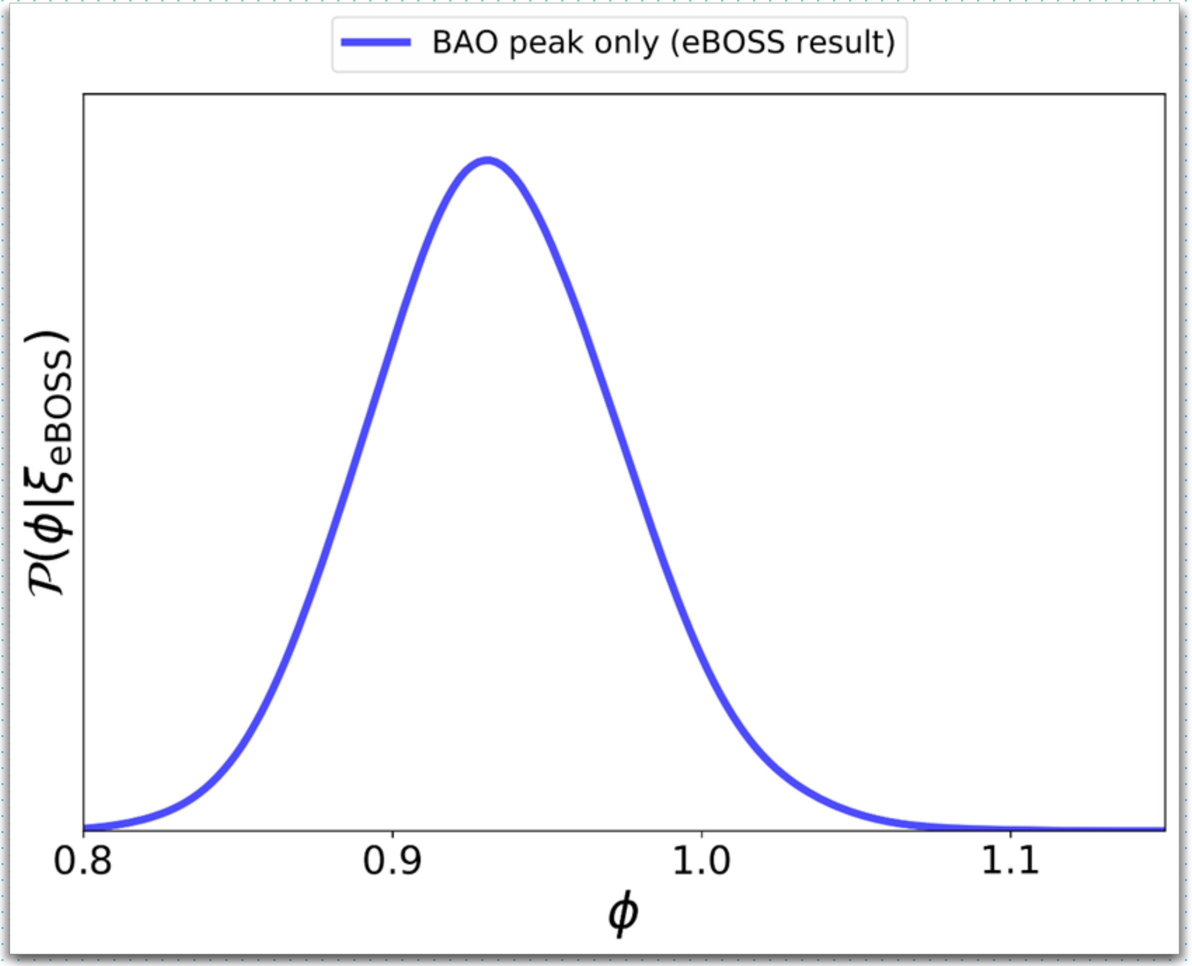


- Performed a blind analysis to test robustness of result
- Focused on effects that we could not study with mocks
- Only found minor shifts in the AP constraint

From Cuceu et al. 2022b (2209.13942)

Lyα BAO from eBOSS

Results from eBOSS DR16 data

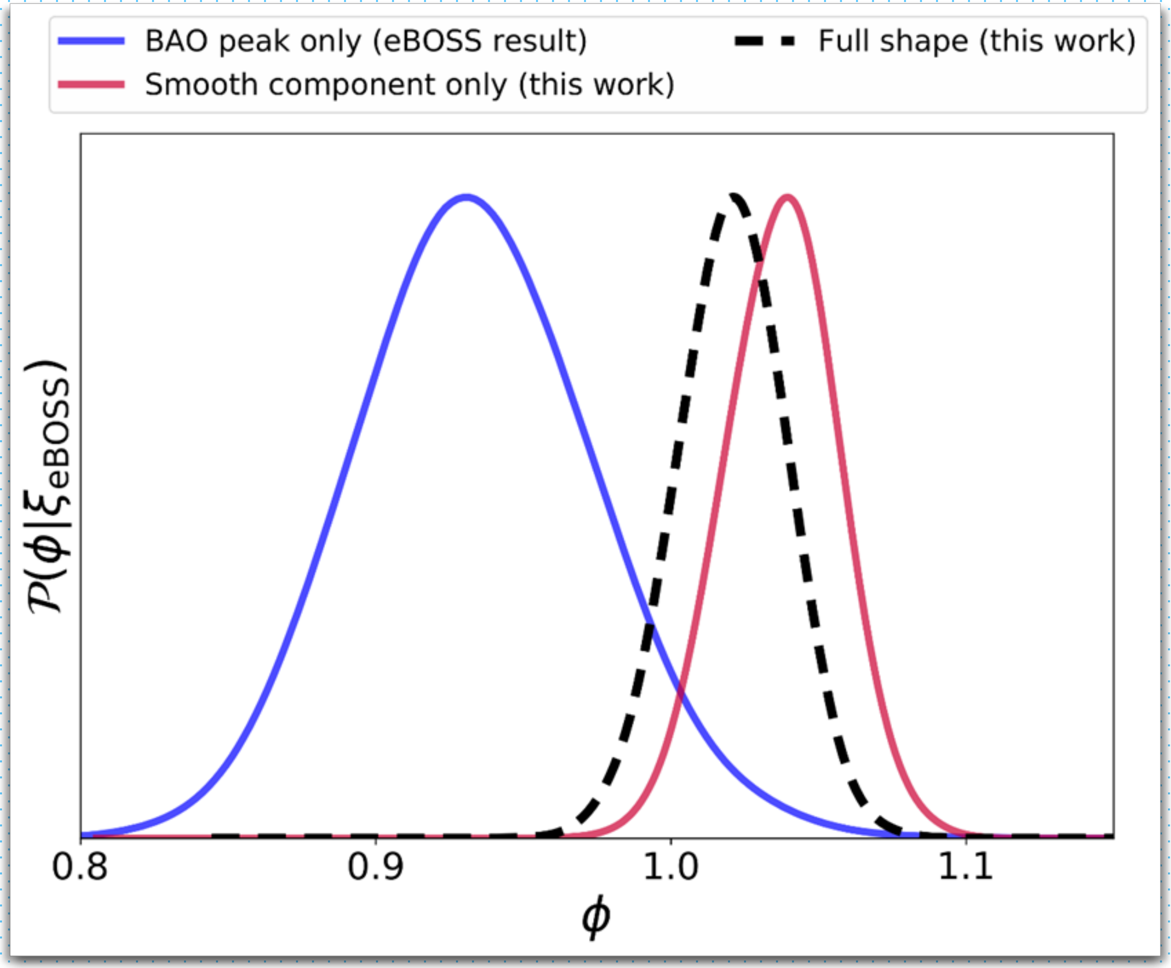


From Cuceu et al. 2022b (2209.13942)

- This is the Lyα BAO measurement from eBOSS DR16

Lyα BAO from eBOSS

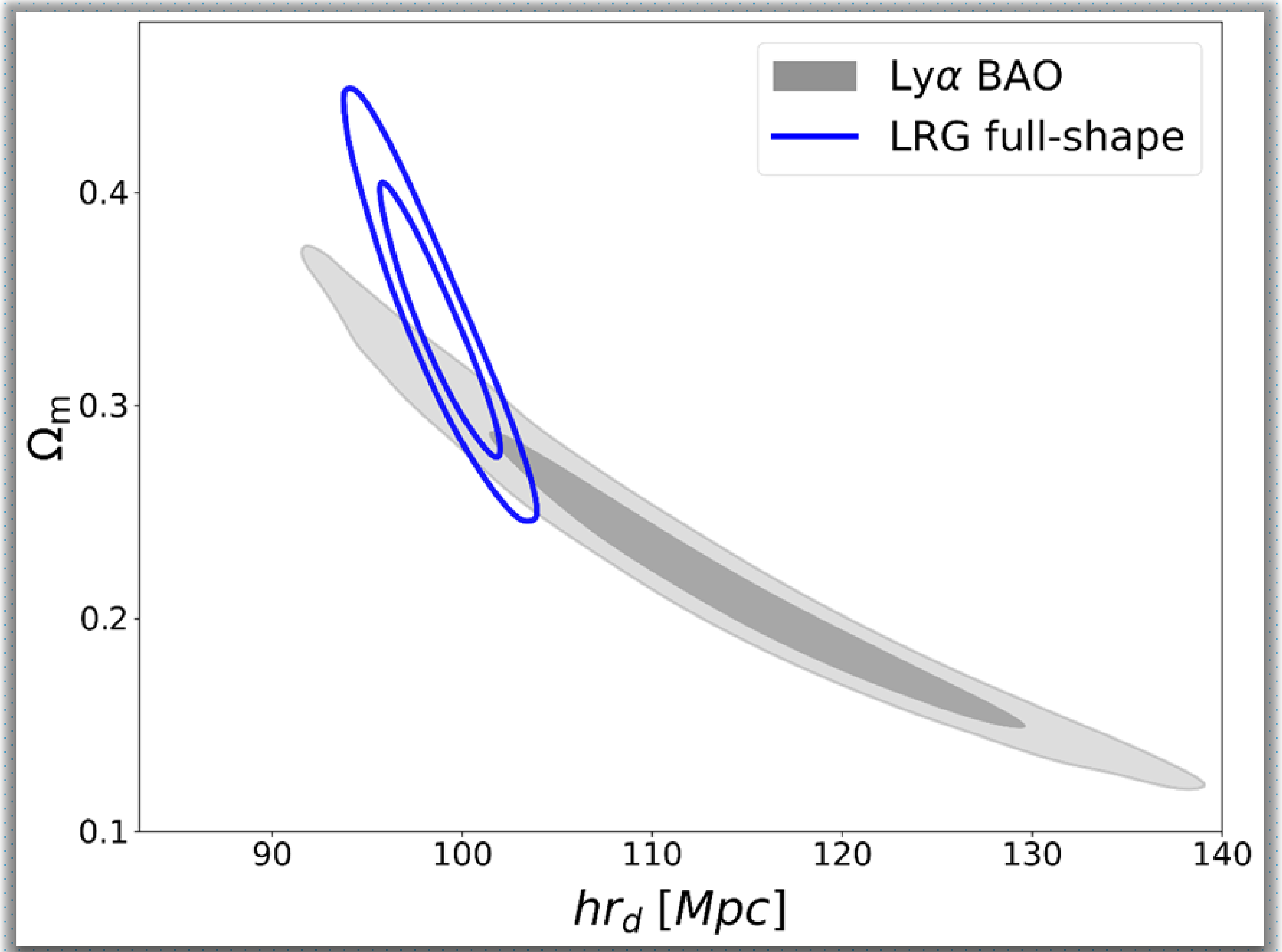
Results from eBOSS DR16 data



From Cuceu et al. 2022b (2209.13942)

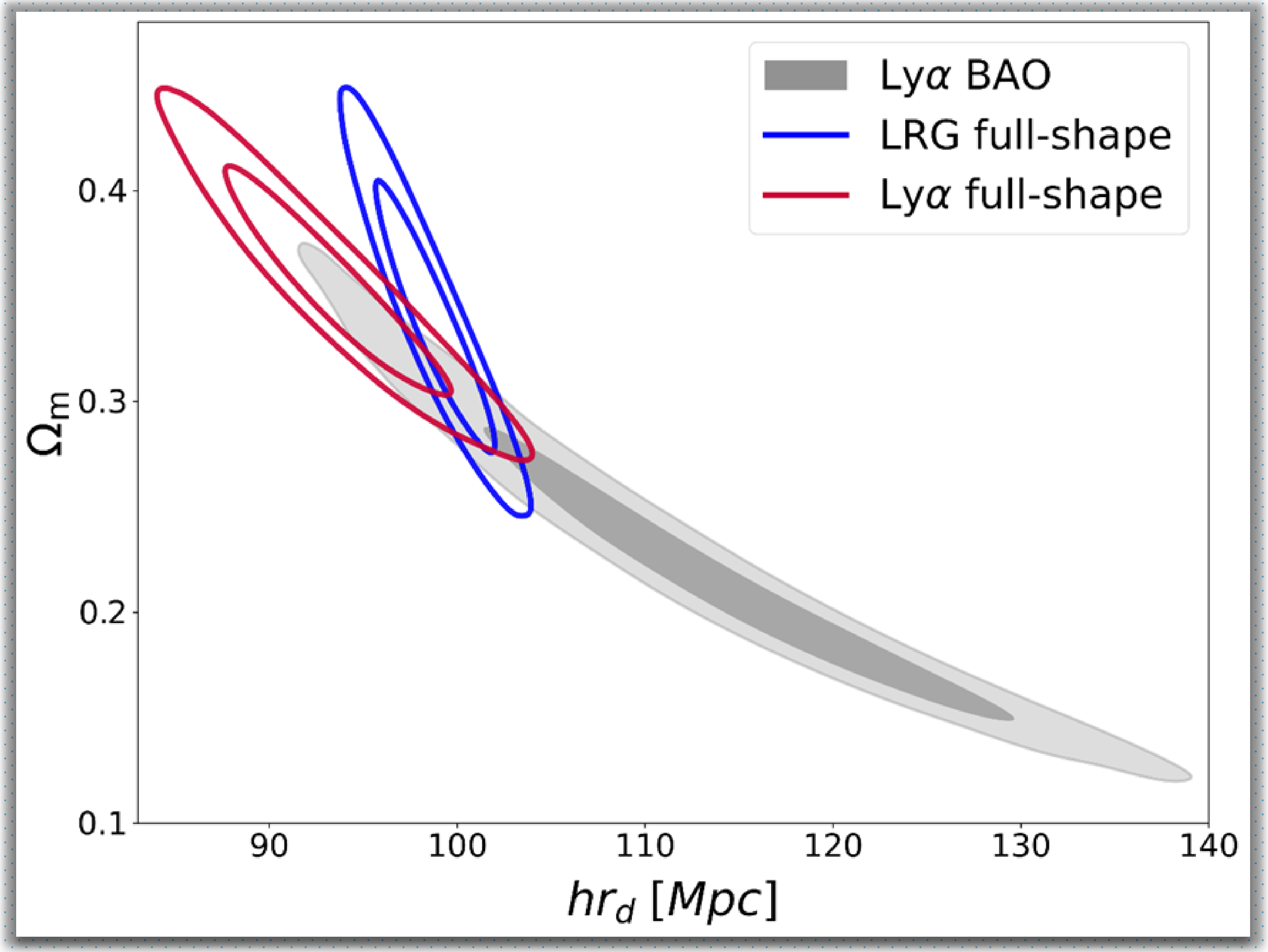
- First ever cosmology measurement from the full-shape of Lyα correlations
- The AP constraint from the full-shape gives a factor of 2 improvement over the BAO constraint

Results in flat ΛCDM



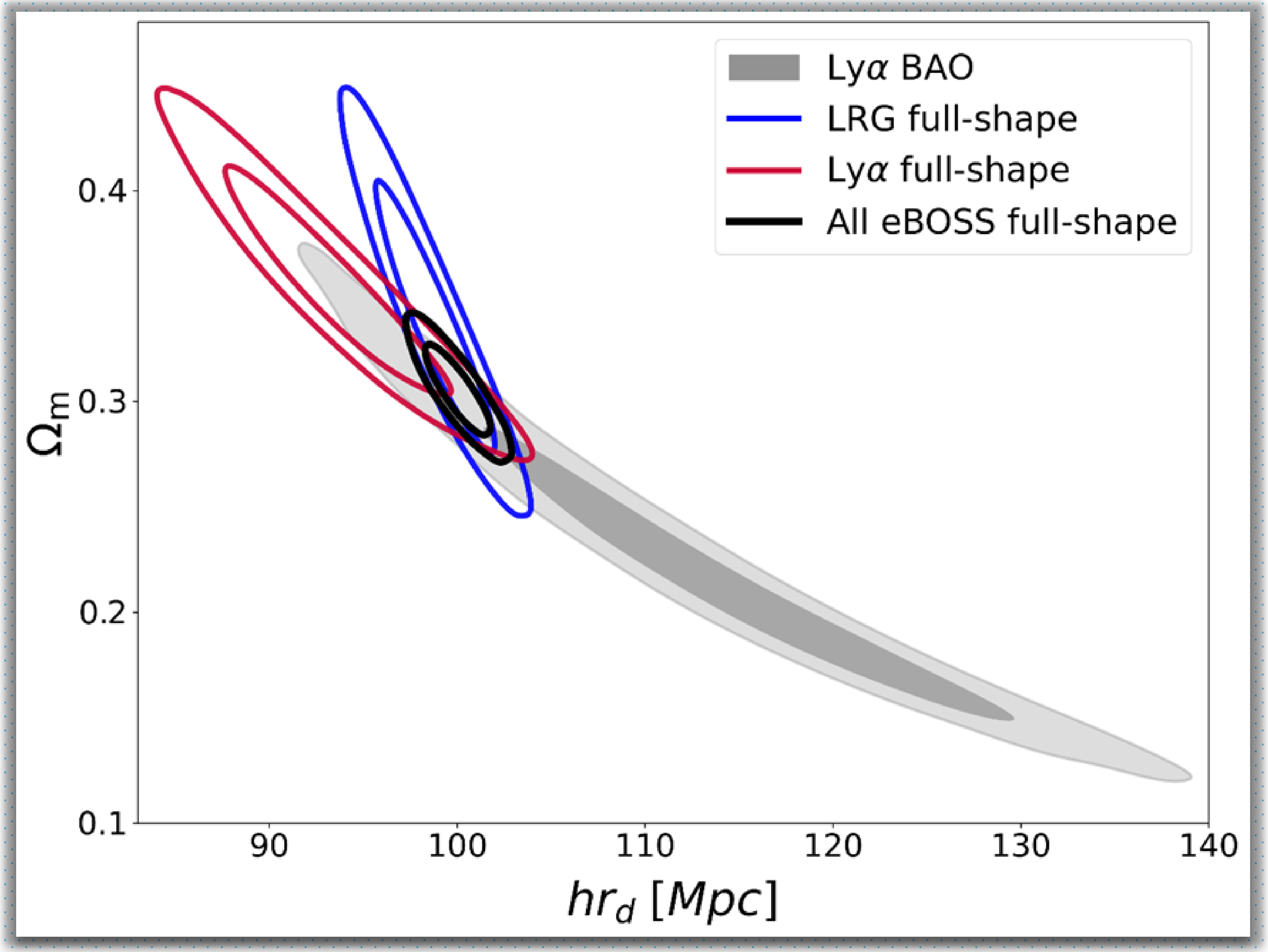
Cuceu et al. 2022b (2209.13942)

Results in flat ΛCDM



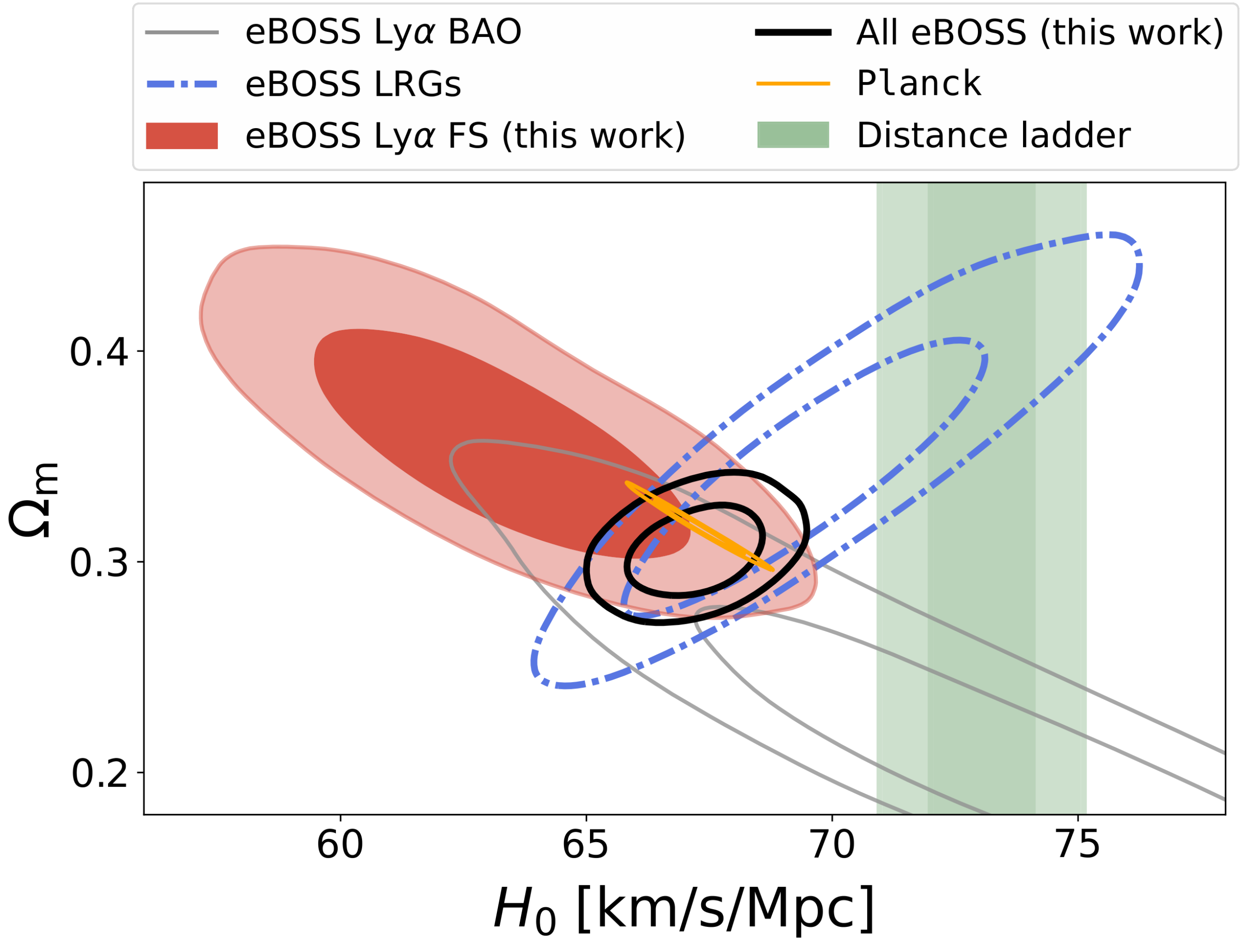
Cuceu et al. 2022b (2209.13942)

Results in flat ΛCDM



Cuceu et al. 2022b (2209.13942)

Measuring the Hubble constant

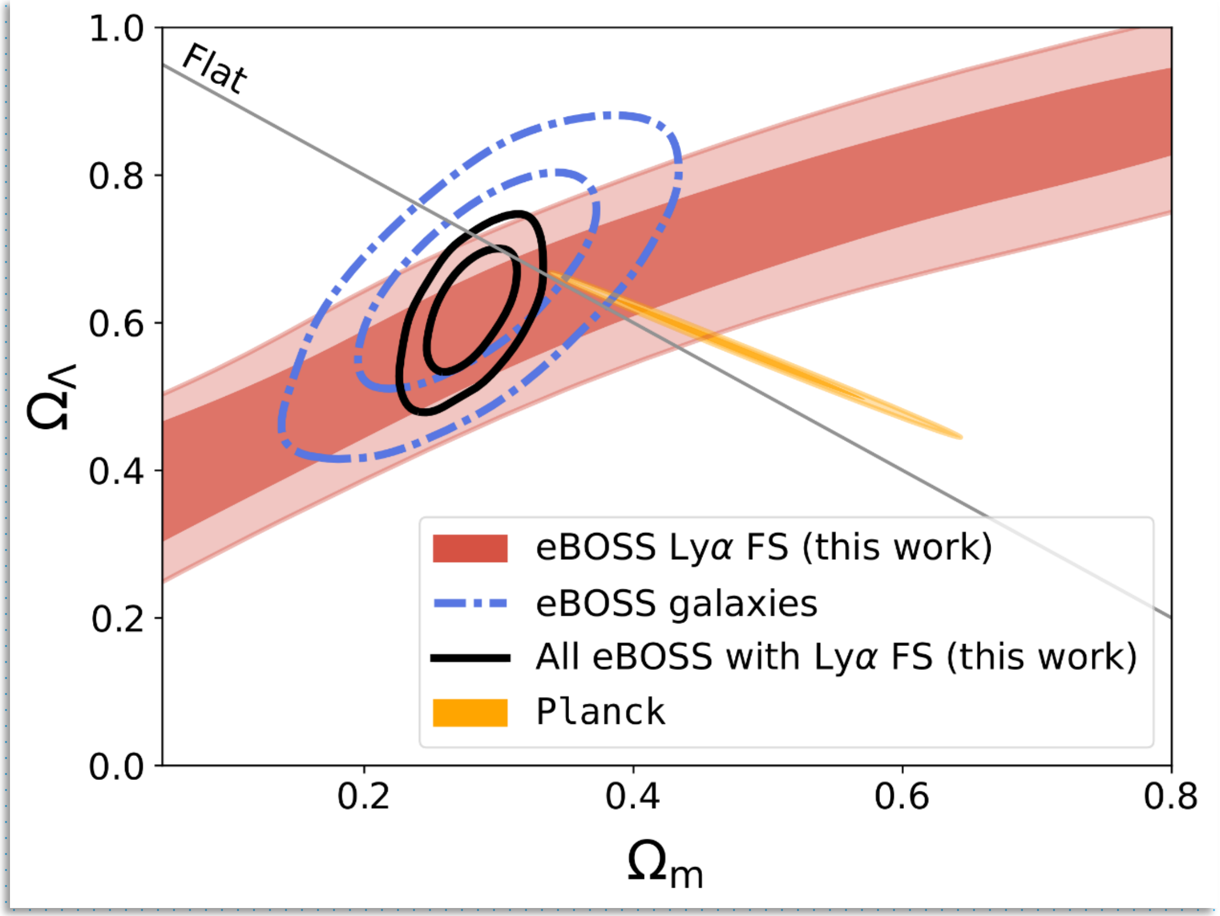


From Cuceu et al. 2022b (2209.13942)

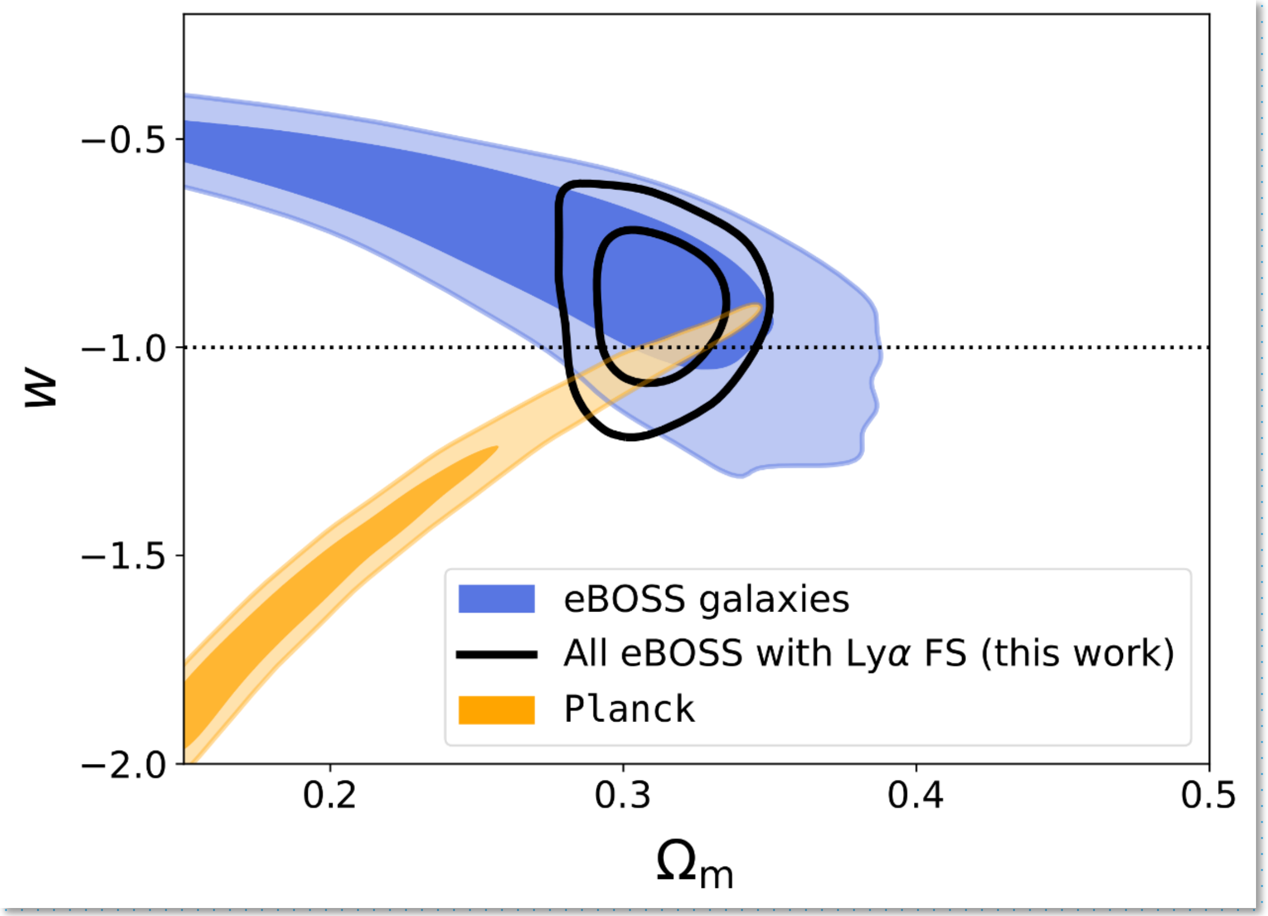
- In flat ΛCDM, Alcock-Paczynski $\longrightarrow \Omega_m$
- Adding isotropic BAO $\longrightarrow H_0 r_d$
- Adding a prior on $\Omega_b h^2$ from Big Bang Nucleosynthesis (BBN) $\longrightarrow H_0$
- Lyα constraint: $H_0 = 63.2 \pm 2.5$ km/s/Mpc
- Full eBOSS: $H_0 = 67.2 \pm 0.9$ km/s/Mpc

Dark energy

Measuring dark energy with free curvature



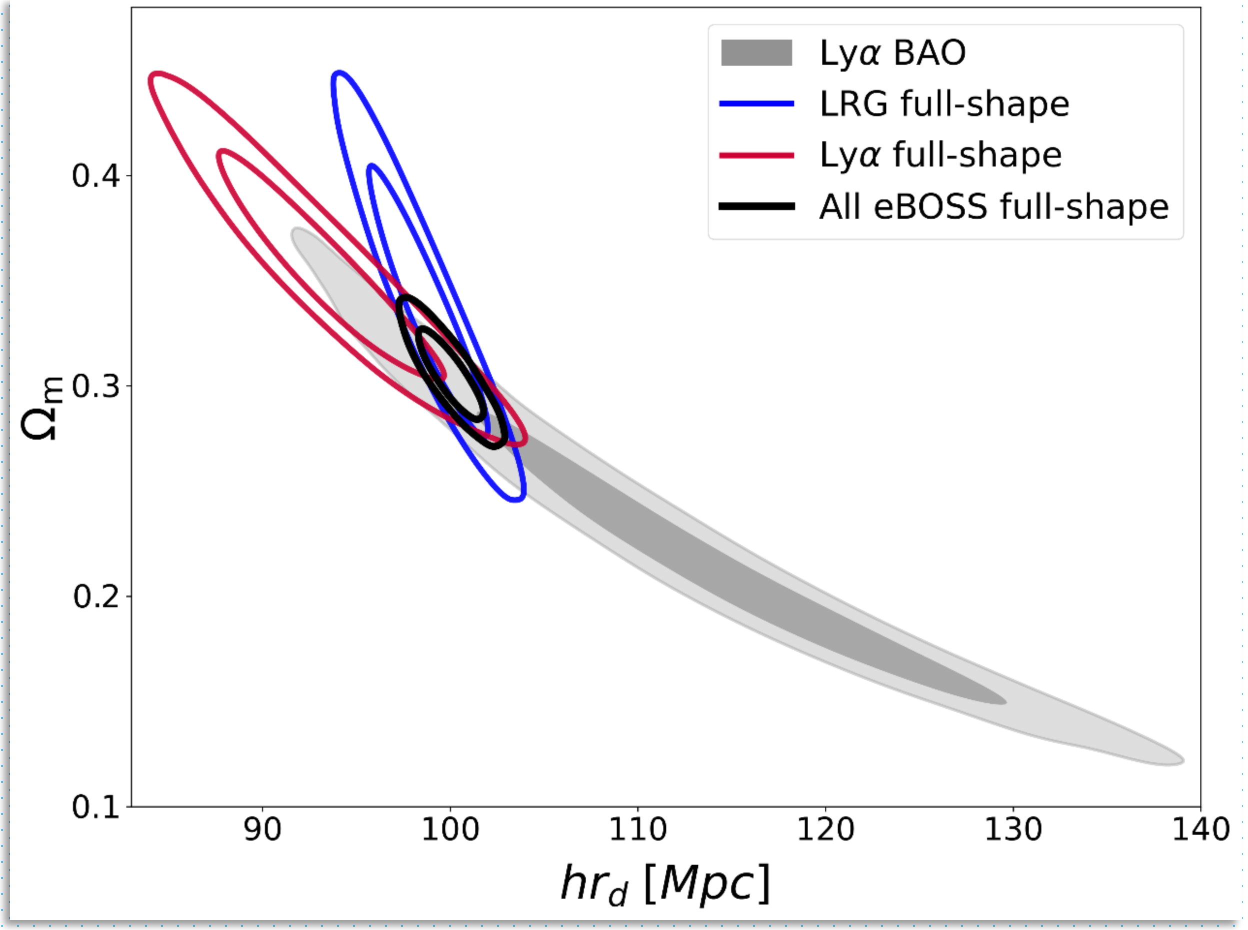
Measuring dark energy equation of state



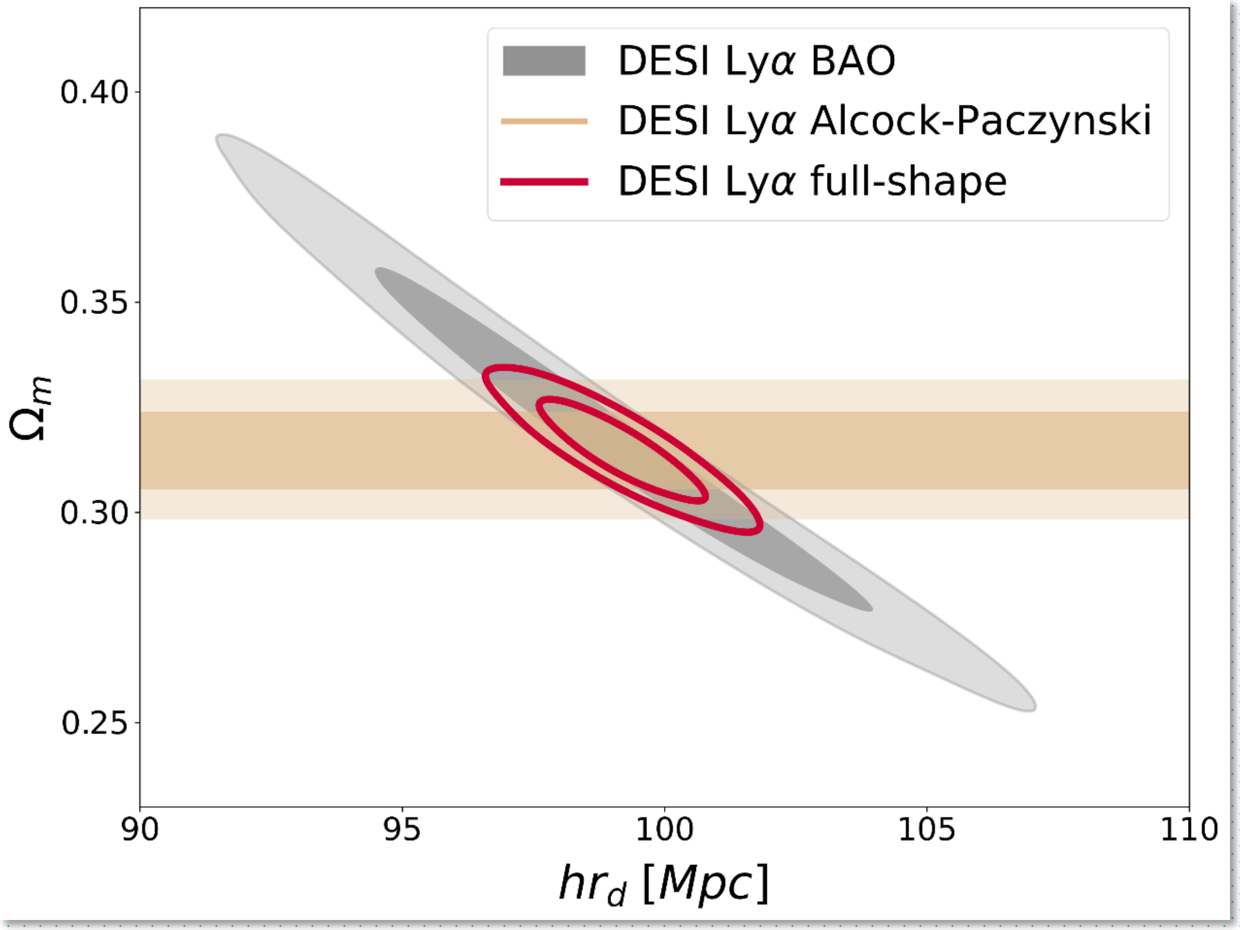
From Cuceu et al. 2022b (2209.13942)

DESI forecasts

eBOSS results



DESI Lyα forecasts



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Why no Lyα RSD measurement?

- Linear theory terms:

Lyα x Lyα : $$P(k,\mu,z) = \left(b_F + b_{\eta,F} f\mu^2\right)^2 P(k,z)$$

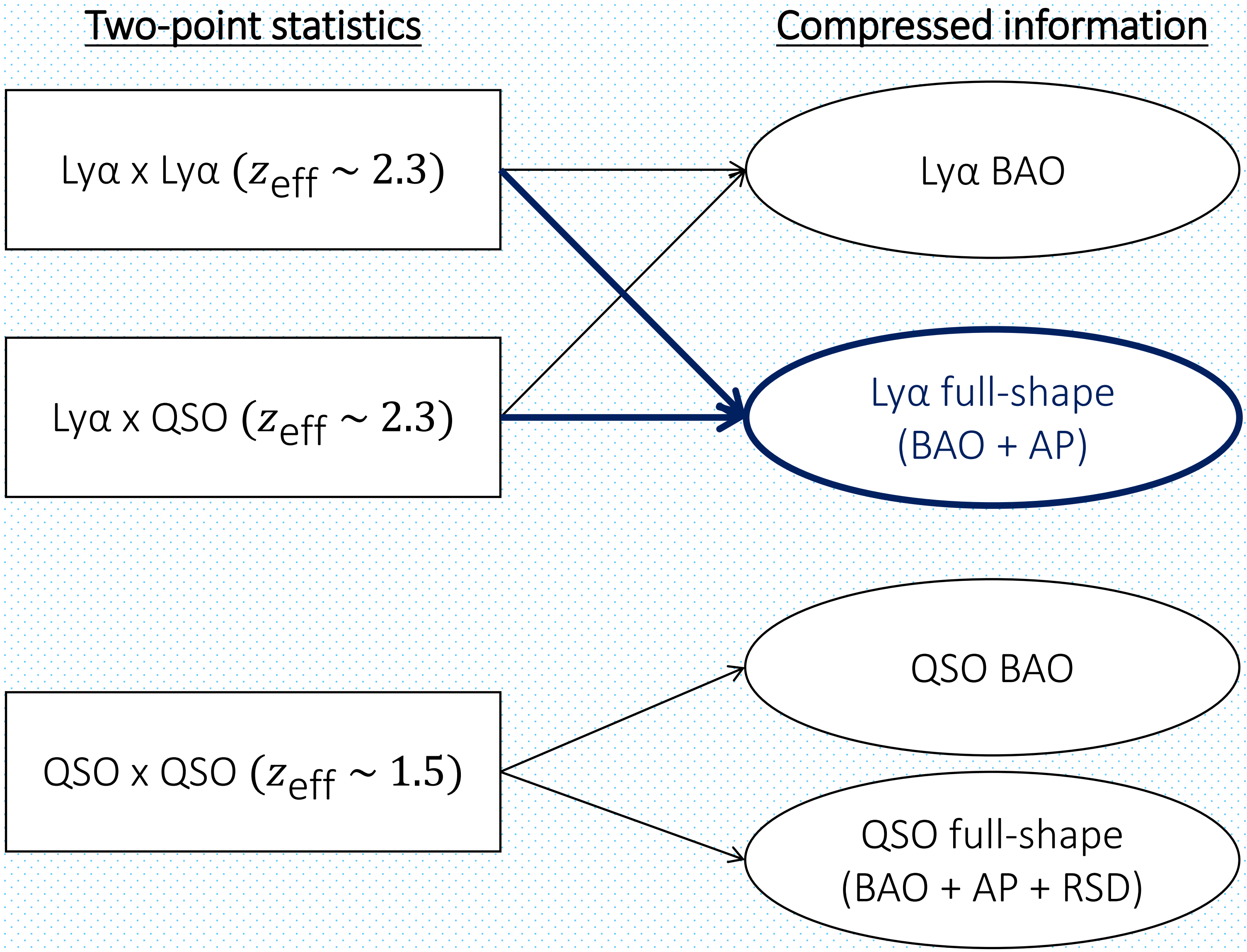
Lyα x QSO : $$P(k,\mu,z) = \left(b_F + b_{\eta,F} f\mu^2\right)\left(b_Q + f\mu^2\right) P(k,z)$$

QSO x QSO: $$P(k,\mu,z) = \left(b_Q + f\mu^2\right)^2 P(k,z)$$

- For the forest, the growth rate (f) is degenerate with an unknown velocity divergence bias ($b_{\eta,F}$).

- However, a joint analysis of Lyα x Lyα and Lyα x QSO would be able to measure f.

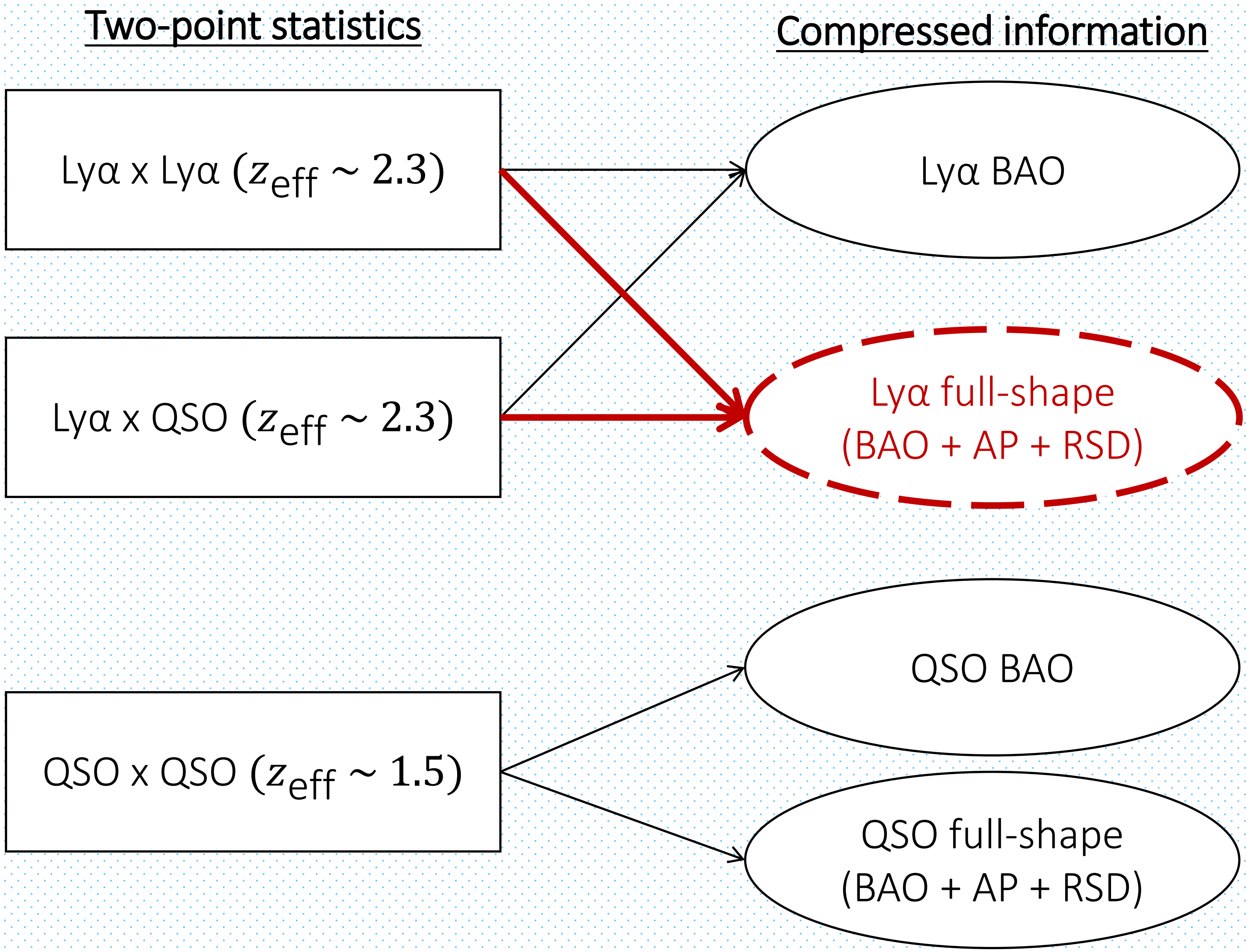
Lyα full-shape from eBOSS (my work)



- We have now measured the Alcock-Paczynski effect from the full-shape of Lyα correlations

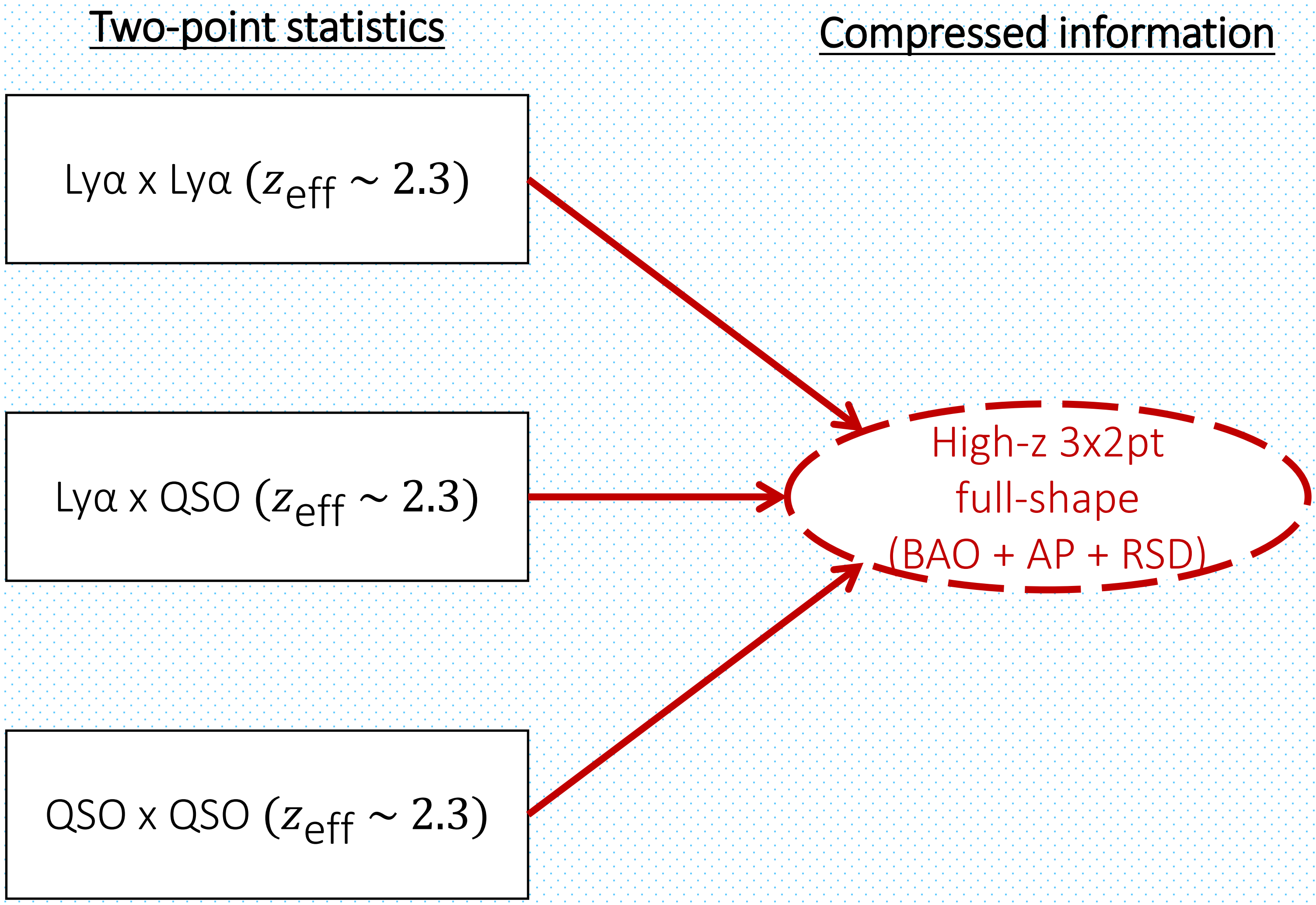
- Next step is to also measure redshift space distortions (RSD)

Lyα full-shape from eBOSS (my work)



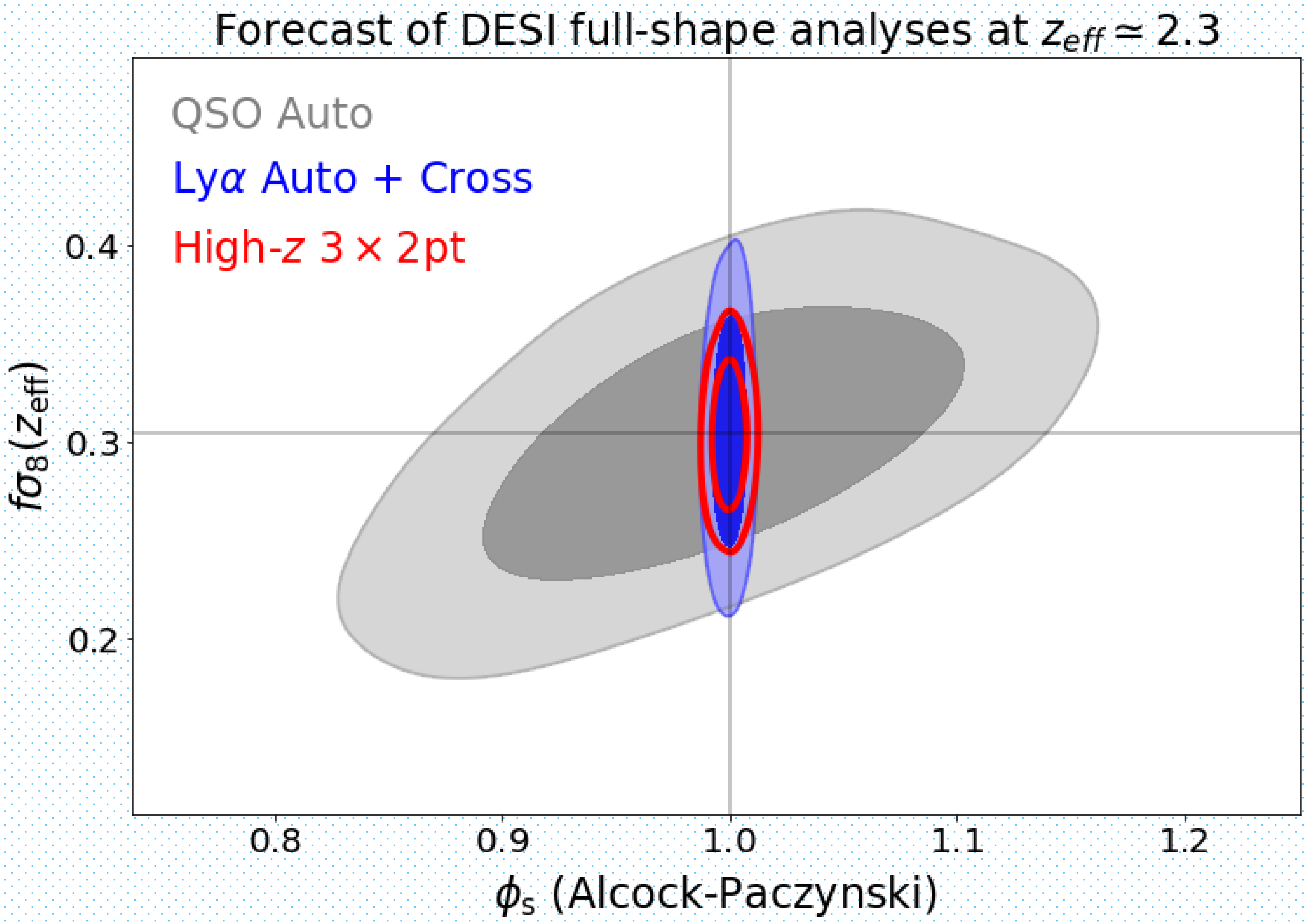
- In Cuceu et. al. 2021 (arxiv:2103.14075) we showed that the Lyα correlations could also be used to measure growth through RSD
- However, this only works in a joint analysis of the Lyα auto and cross-correlation with QSOs.

Lyα full-shape from eBOSS (my work)



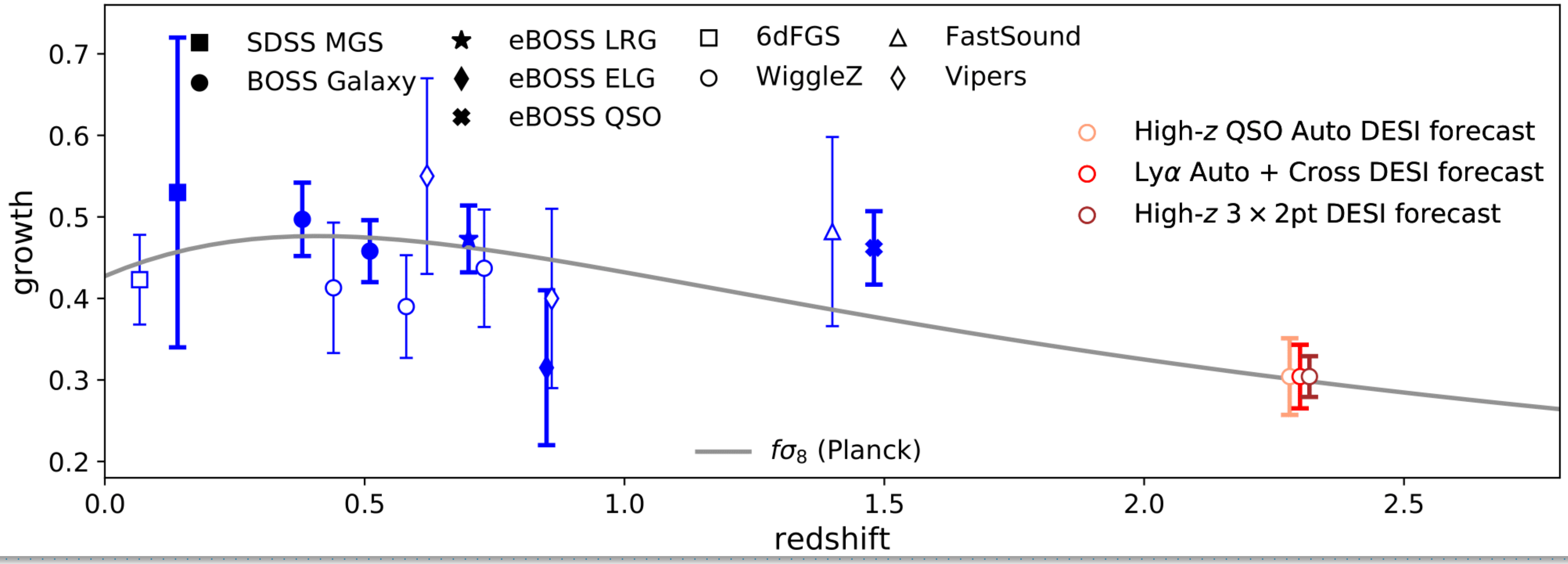
- With DESI we could also perform a joint analysis of the 3 high redshift 2pt statistics (high-z 3x2pt)
- This would help break parameter degeneracies and lead to greatly improved constraints

Towards a high-z 3x2pt analysis



Cuceu et al. 2021 (2103.14075)

Measuring growth with the Lyα forest



Cuceu et al. 2021 (2103.14075)

Summary

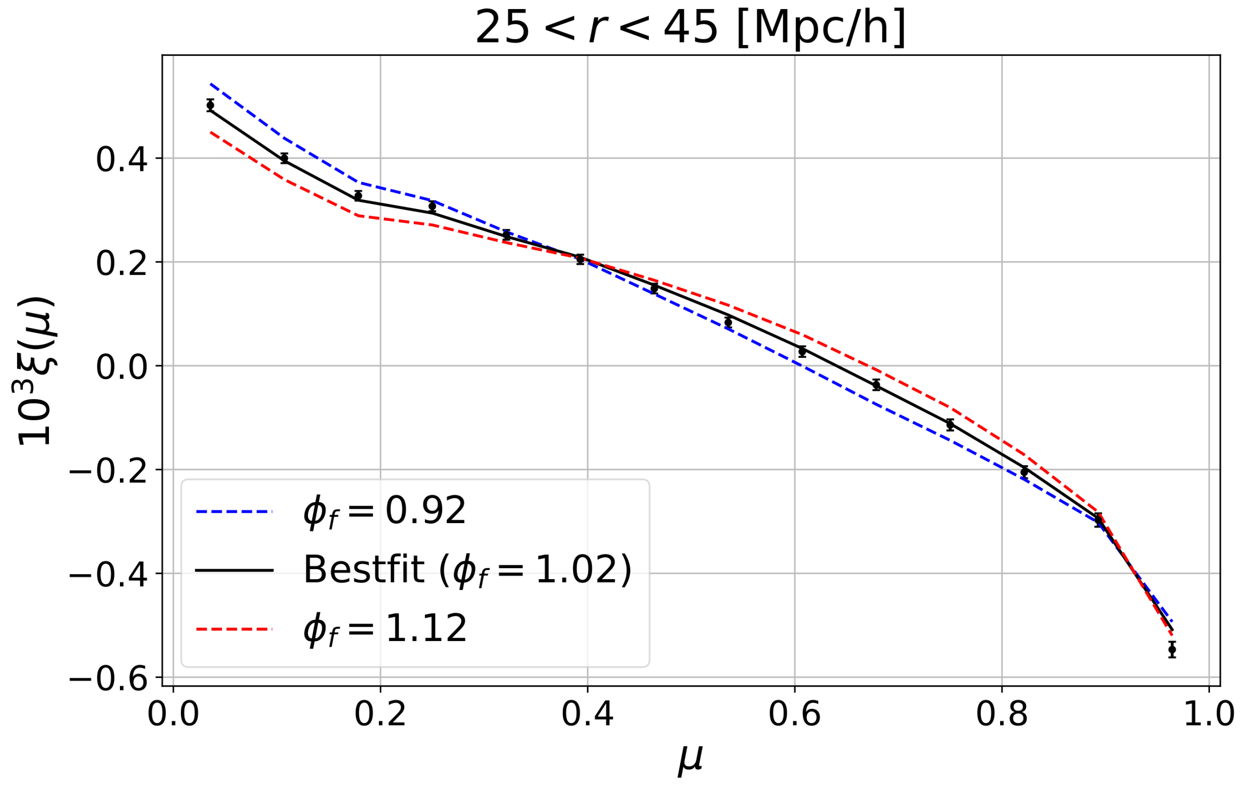
- We performed the first full-shape analysis of Lyα forest 3D correlations.

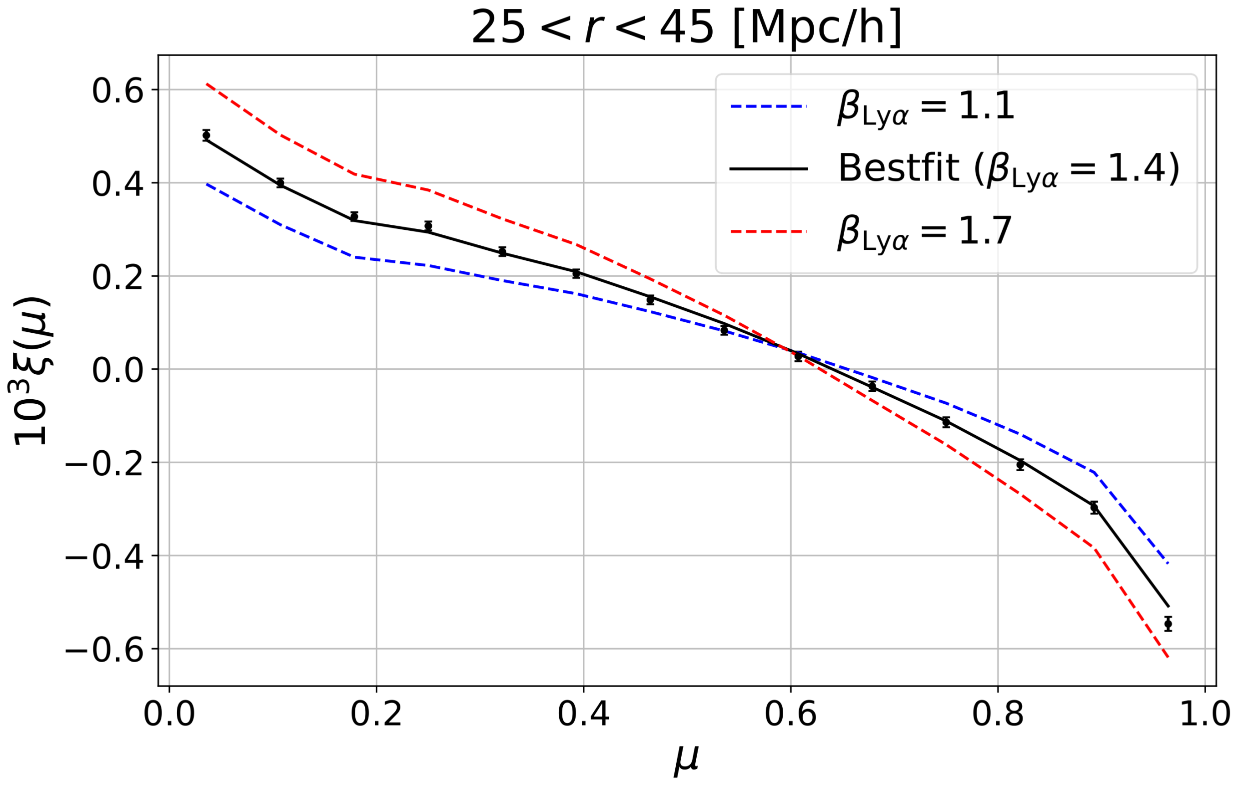
- Most precise expansion rate constraint from large-scale structure at $z > 1$, and a factor of two tighter than the BAO-only constraint.

- Key areas of improvement for DESI include modelling of QSO redshift errors and non-linearities.

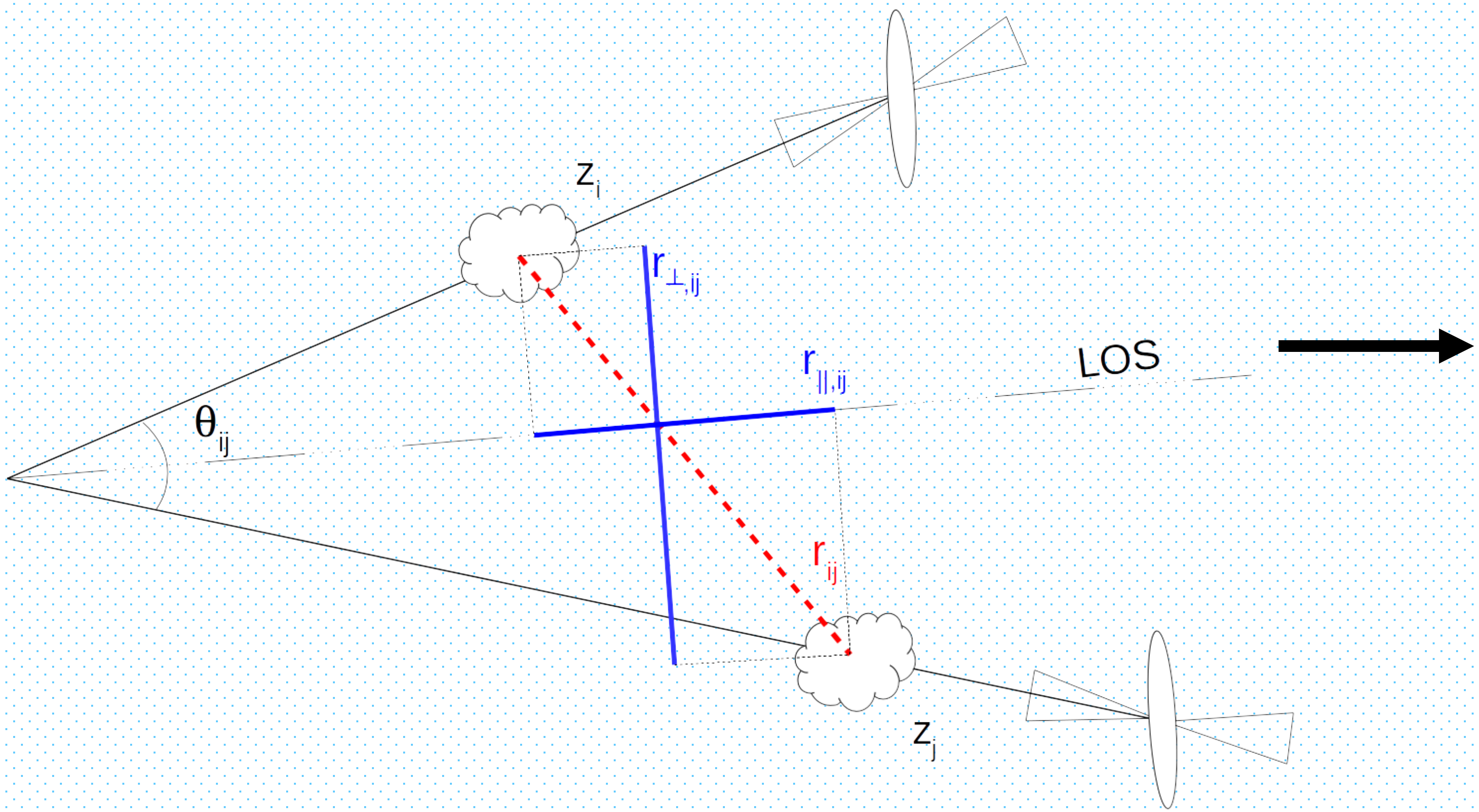
- Opens the way for growth rate measurements from the 3D distribution of the Lyα forest.

Alcock-Paczynski vs redshift space distortions





Lyman-α forest correlations



Comoving coordinates:

$$r_{\parallel} = [D_C(z_i) - D_C(z_j)] \cos(\theta_{ij}/2)$$

$$r_{\perp} = [D_M(z_i) + D_M(z_j)] \sin(\theta_{ij}/2)$$

In flat ΛCDM, $D_M(z) = D_C(z)$, with:

$$D_C(z) = c \int_0^z \frac{dz'}{H(z')}$$

Figure from de Sainte Agathe et al. 2019 (1904.03400)