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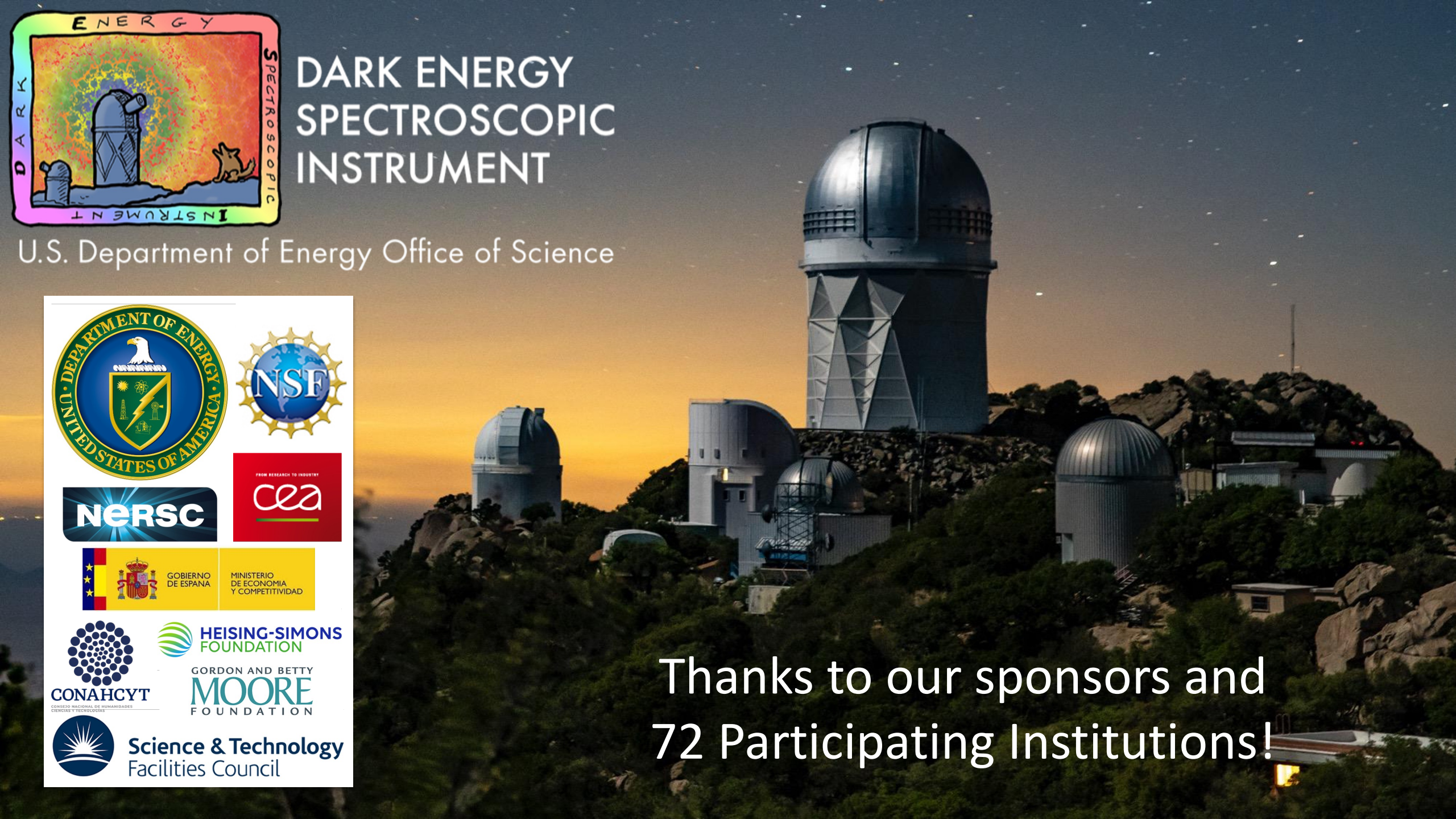
Mapping the Expansion History with DESI Y1 Data

Nikhil Padmanabhan

Yale

For the DESI collaboration

w/ slides from Hee-Jong Seo, Julien Guy, Mustapha Ishak, Etienne Burtin, Sesh Nadathur, Andreu Font-Ribera, Arnaud de Mattia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Key Publications

- DESI Collaboration et al., *DESI 2024 III: Baryon Acoustic Oscillations from Galaxies and Quasars*
- DESI Collaboration et al., *DESI 2024 IV: Baryon Acoustic Oscillations from the Lyman Alpha Forest*
- DESI Collaboration et al., *DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations*

- Chen et al. (2024), *Baryon Acoustic Oscillation Theory and Modelling Systematics for the DI 2024 results*
- Paillas, Ding, Chen et al. (2024), *Optimal Reconstruction of Baryon Acoustic Oscillations for DESI 2024*
- Rashkovetskyi et al. (2024), *Semi-analytical covariance matrices for two-point correlation function for DESI 2024 data*
- Mena-Fernandez et al. (2024), *HOD-Dependent Systematics for Luminous Red Galaxies in tl DESI 2024 BAO Analysis*
- Garcia-Quintero et al. (2024), *HOD-Dependent Systematics in Emission Line Galaxies for the DESI 2024 BAO analysis*

- Ramírez-Pérez et al. (2024), *The Lyman-α forest catalogue from the Dark Energy Spectroscopic Instrument Early Data Release*
- Gordon et al. (2023), *3D correlations in the Lyman-α forest from early DESI data*
- Filbert et al. (2023), *Broad Absorption Line Quasars in the Dark Energy Spectroscopic Instrument Early Data Release*
- Herrera-Alcantar et al. (2024), *Synthetic spectra for Lyman-α forest analysis in the Dark Energy Spectroscopic Instrument*
- Bault et al. (2024), *Impact of Systematic Redshift Errors on the Cross-correlation of the Lyman-α Forest with Quasars at Small Scales Using DESI Early Data*
- Guy, Gontcho A Gontcho et al. (2024), *Characterization of contaminants in the Lyman-alpha forest auto-correlation with DESI*
- Cuceu et al. (2024), *Validation of the DESI 2024 Lyα forest BAO analysis using synthetic datasets*

And more in progress!

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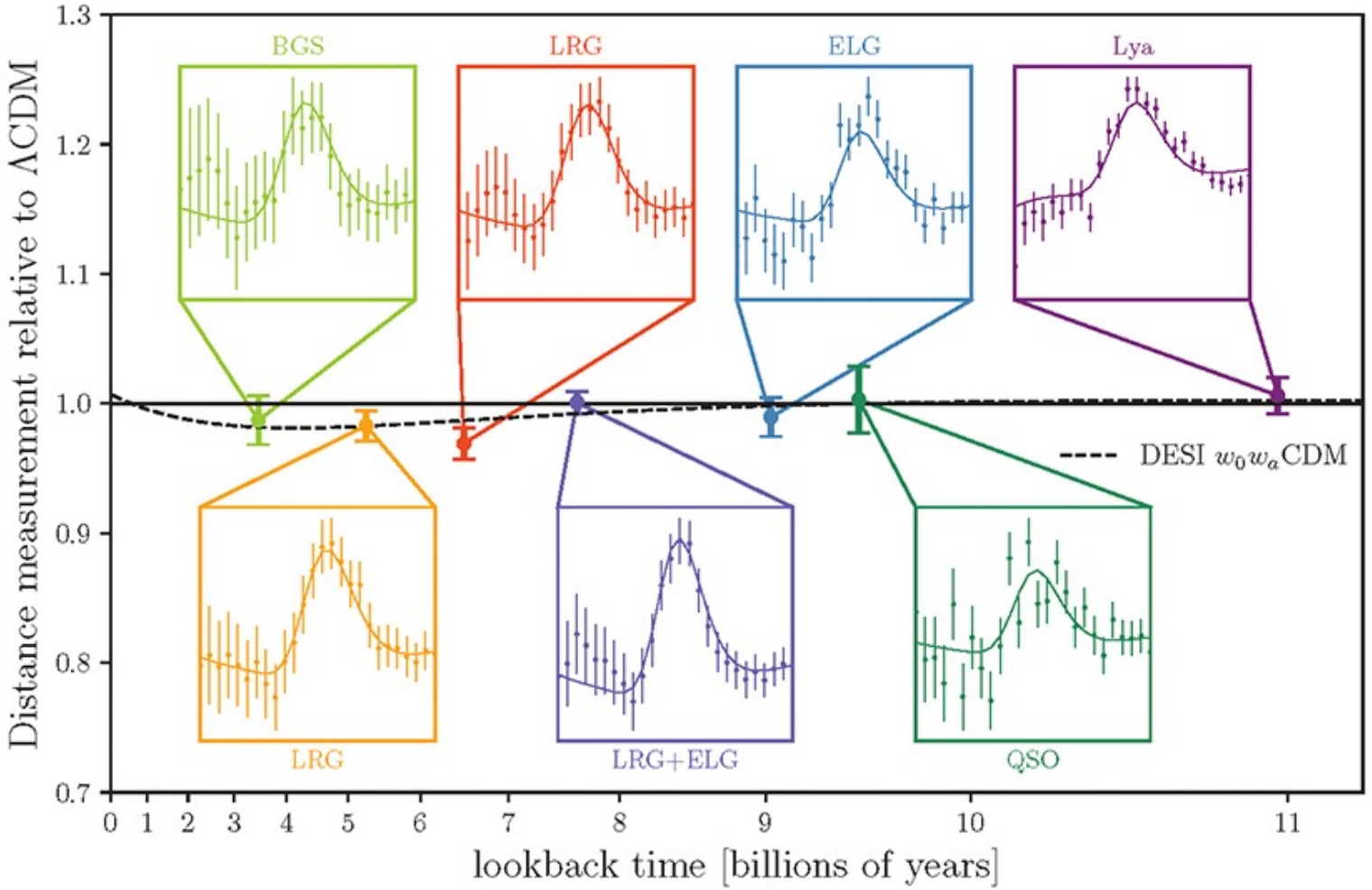
DESI measures the expansion history with BAO



Arnaud de Mattia, DESI Collab

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...and constrains the DE equation of state

Combining all DESI + CMB + SN

$$w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}$$

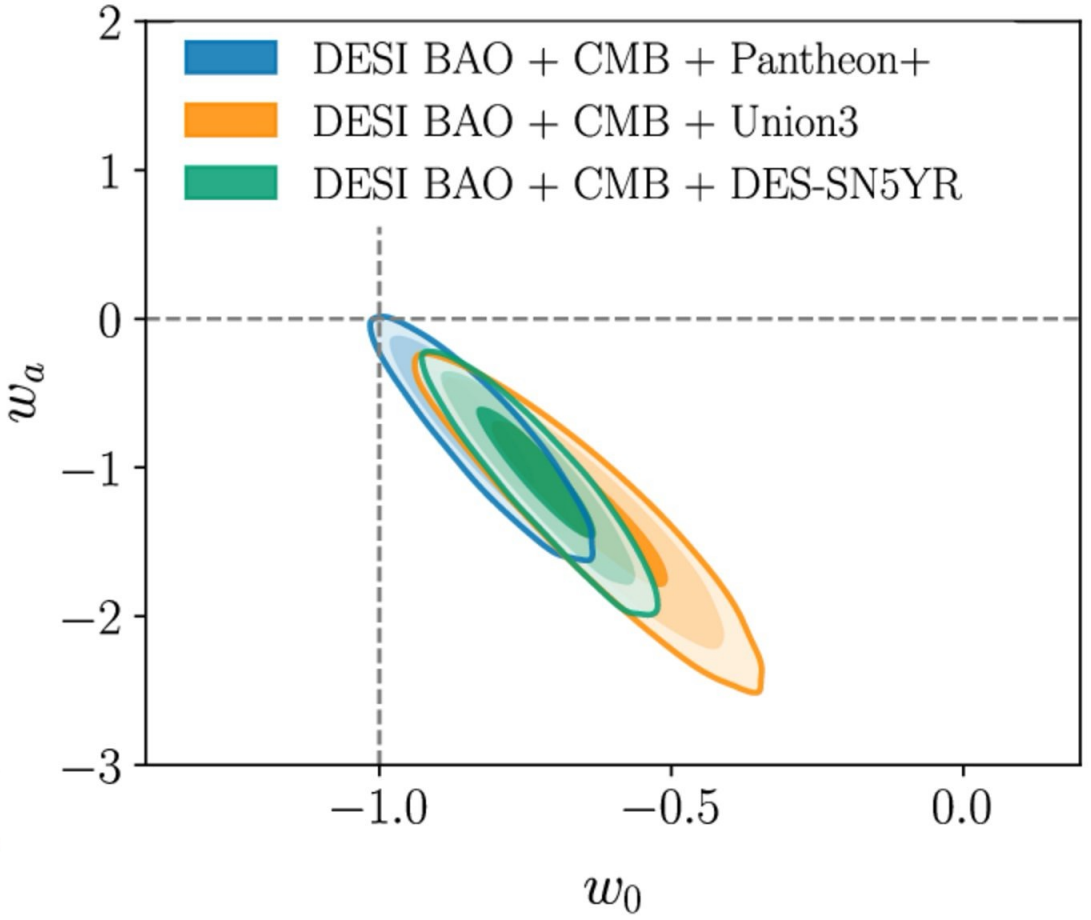
$$\text{DESI} + \text{CMB} + \text{Pantheon+} \implies 2.5\sigma$$

$$w_0 = -0.64 \pm 0.11 \qquad w_a = -1.27^{+0.40}_{-0.34}$$

$$\text{DESI} + \text{CMB} + \text{Union3} \implies 3.5\sigma$$

$$w_0 = -0.727 \pm 0.067 \qquad w_a = -1.05^{+0.31}_{-0.27}$$

$$\text{DESI} + \text{CMB} + \text{DES-SN5YR} \implies 3.9\sigma$$



$w_0 > -1, w_a < 0$ favored, level varying on the SN dataset

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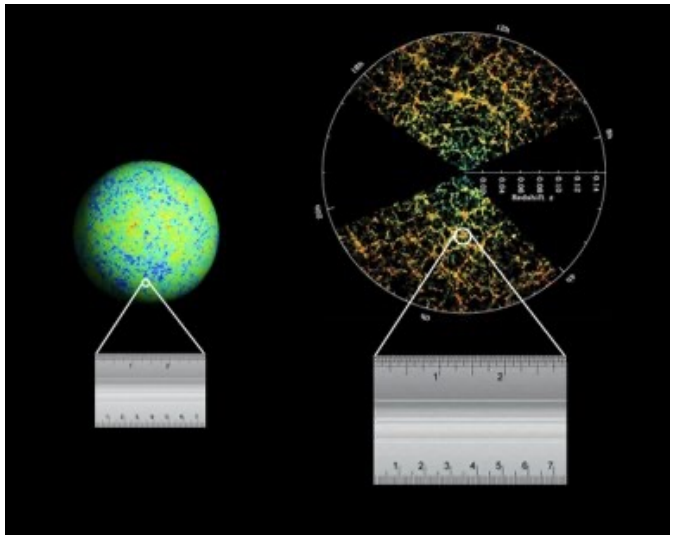
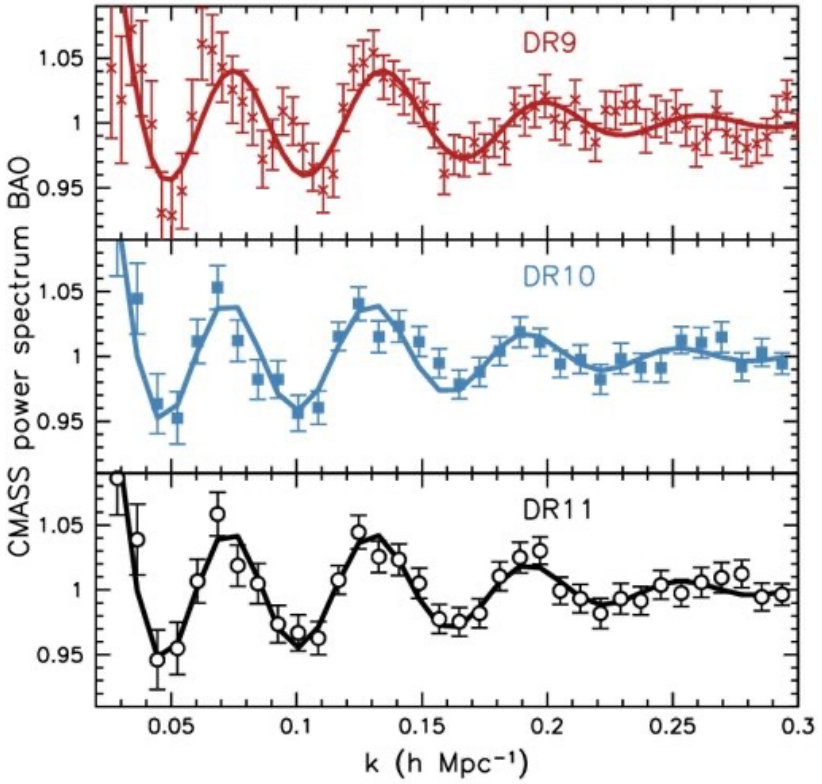
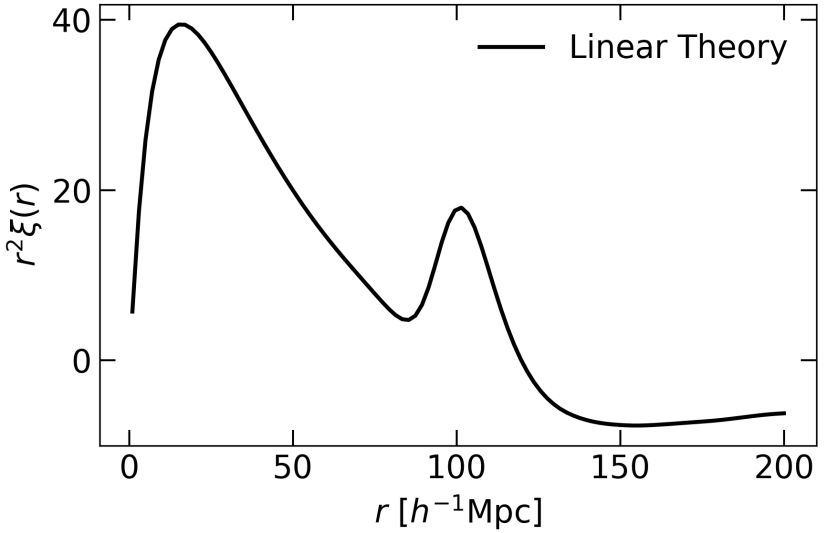
A Standard Ruler : Baryon Acoustic Oscillations







Figures from lbl.gov,
Elisa Ferreira et al
BOSS CMASS measurements

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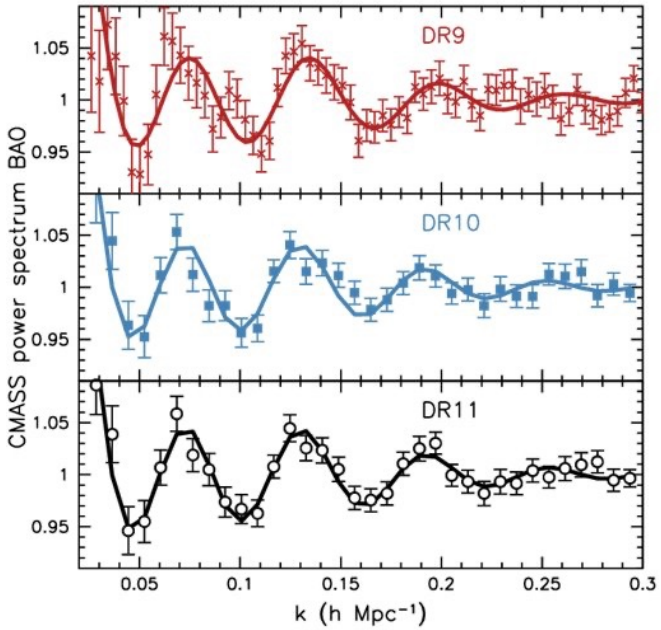
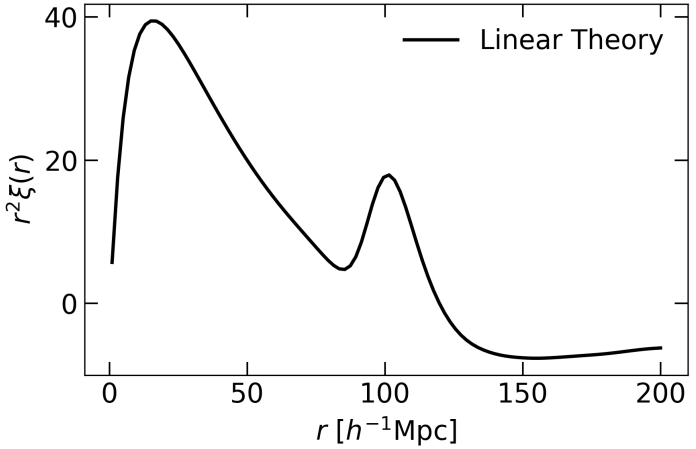
A Naturally Robust Standard Ruler

A Large Scale Feature

- ~150 Mpc
- Nonlinear/galaxy formation scales are much smaller
  - Nonlinear effects/galaxy evolution effects are suppressed on these scales
  - Hard to produce a feature
- 3D feature
  - Hard to mimic with observational systematics





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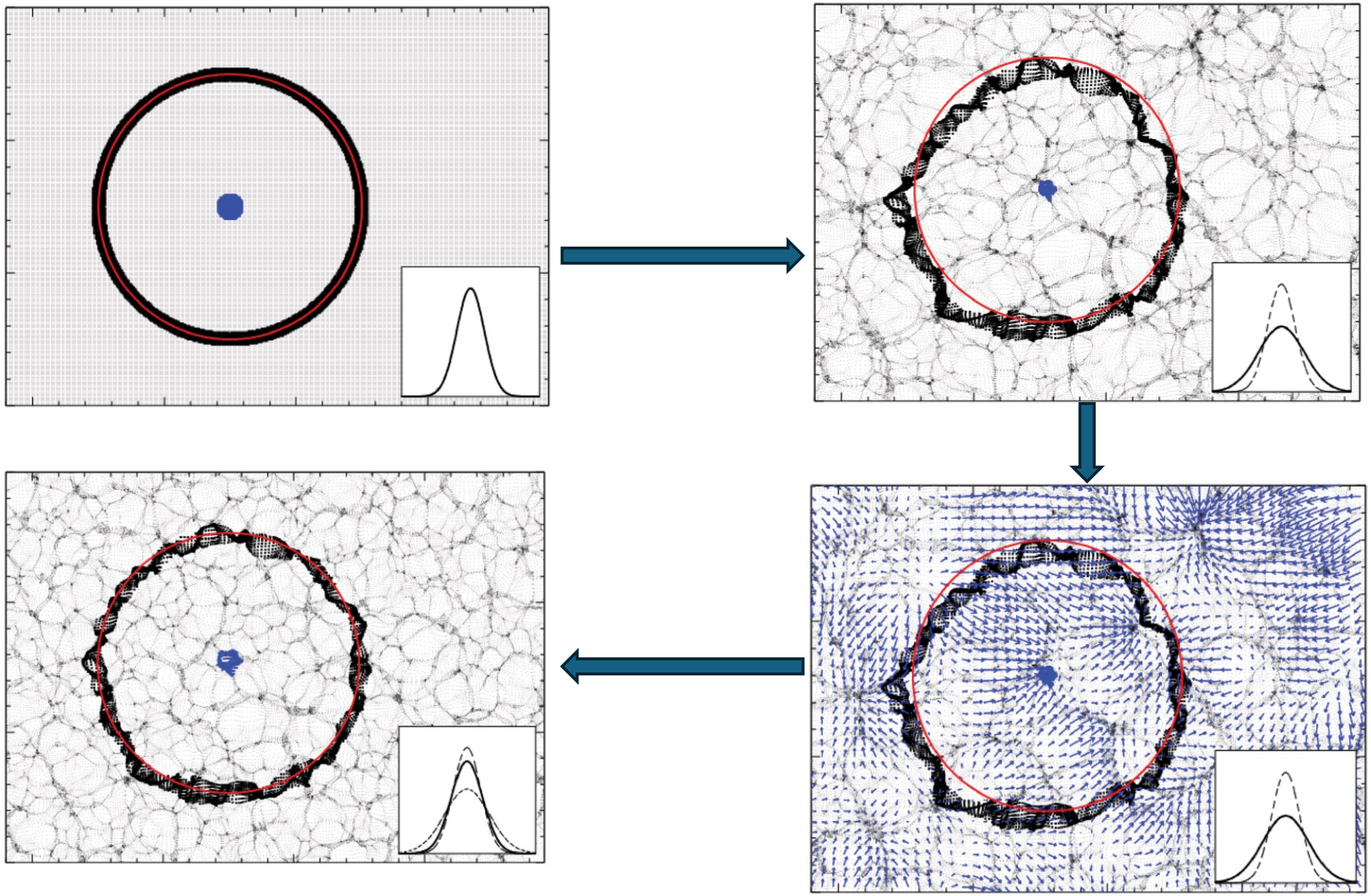
Sharpening the standard ruler



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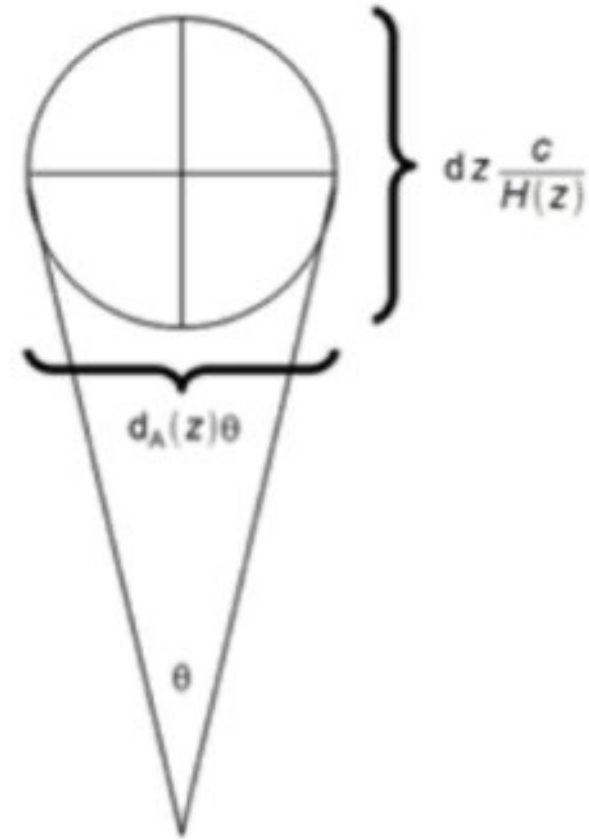
BAO measurements

BAO measures ratios of distances over the sound horizon scale at the drag epoch ["standard ruler"] r_d

- transverse to the line-of-sight: $D_\mathrm{M}(z)/r_\mathrm{d}$
- along the line-of-sight: $D_\mathrm{H}(z)/r_\mathrm{d} = c/(H(z)r_\mathrm{d})$
- isotropic average: $D_\mathrm{V}(z)/r_\mathrm{d} = (zD_\mathrm{M}^2(z)D_\mathrm{H}(z))^{1/3}/r_\mathrm{d}$



Five target classes

40 million redshifts

in 5 years

DESI (2021-2026)

3 million QSOs

Lya z > 2.1

Tracers 0.9 < z < 2.1

16 million ELGs

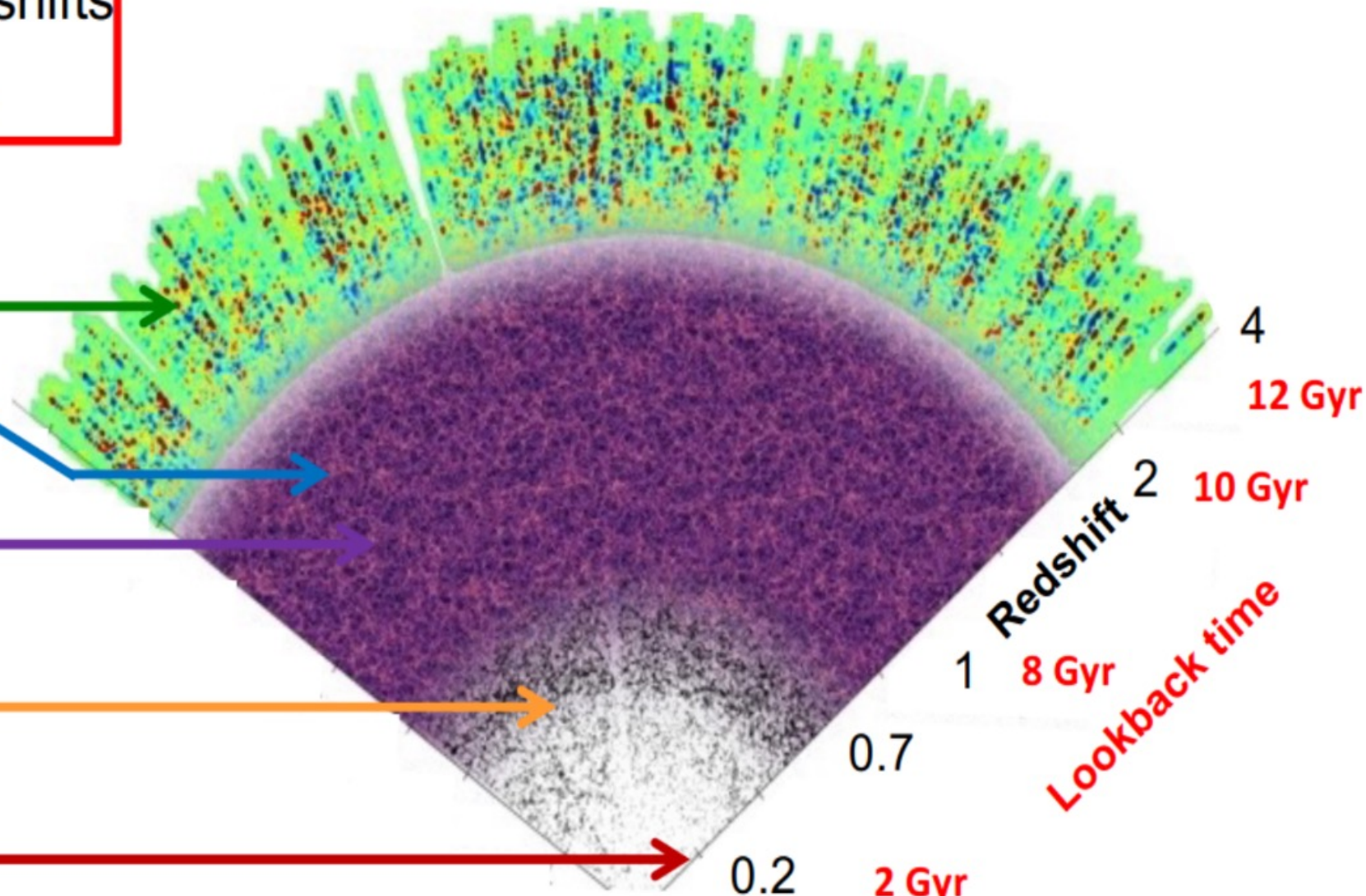
0.6 < z < 1.6

8 million LRGs

0.4 < z < 1.0

13.5 million Brightest galaxies

0.0 < z < 0.4



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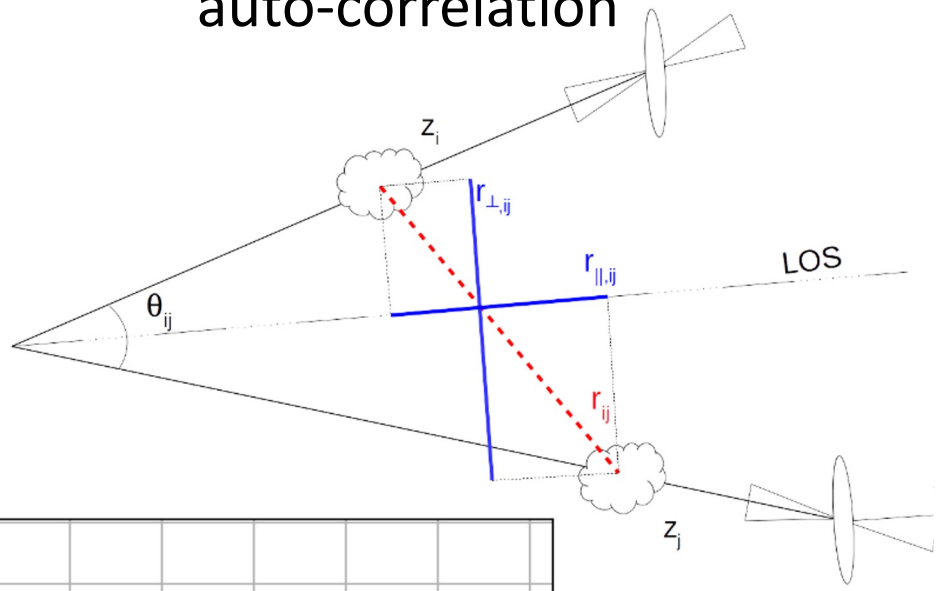
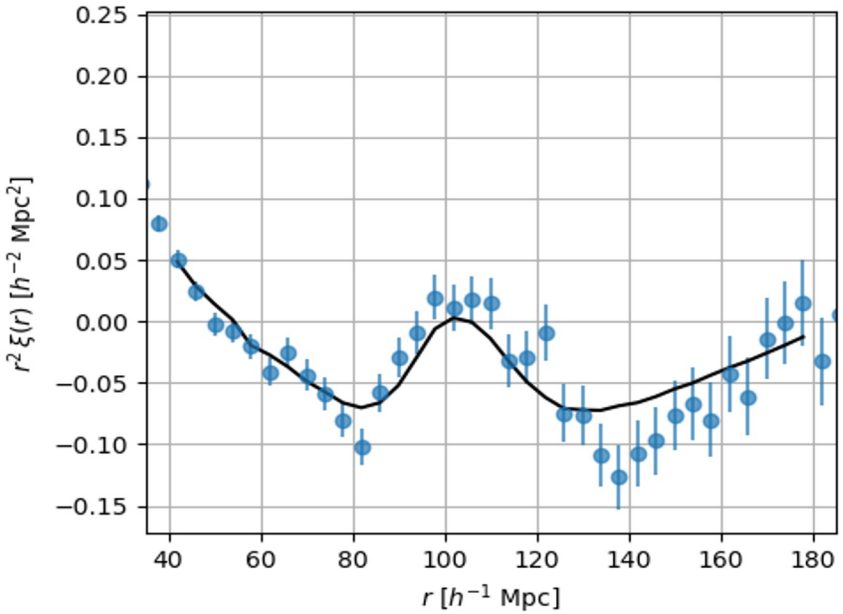
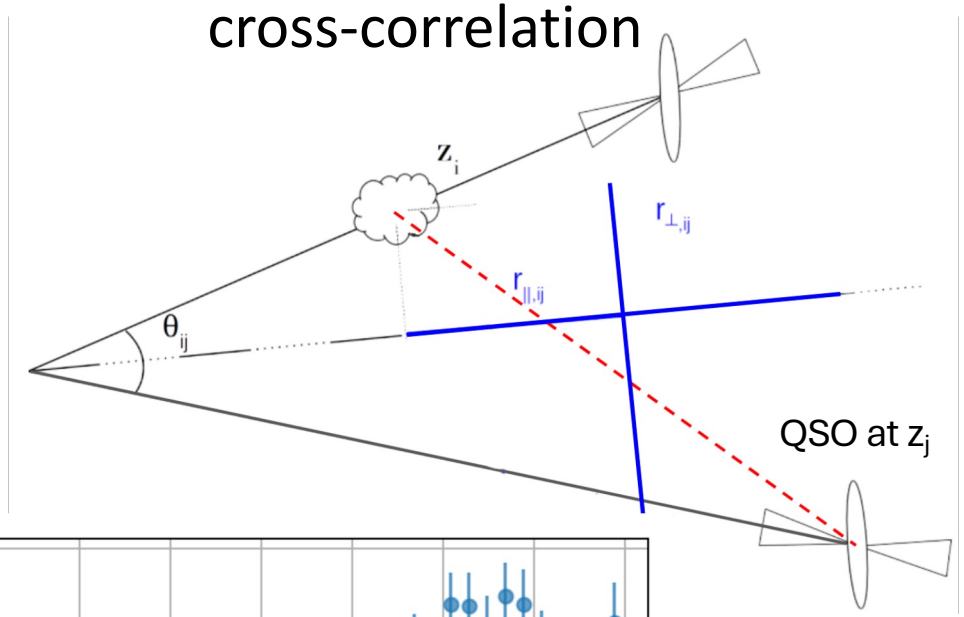
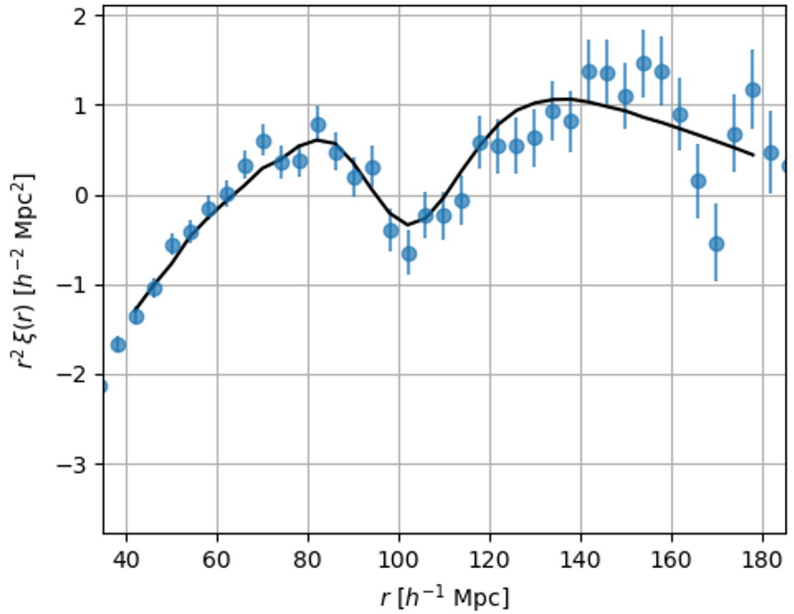
Lyα-Lyα auto-correlation





Lyα-QSO cross-correlation





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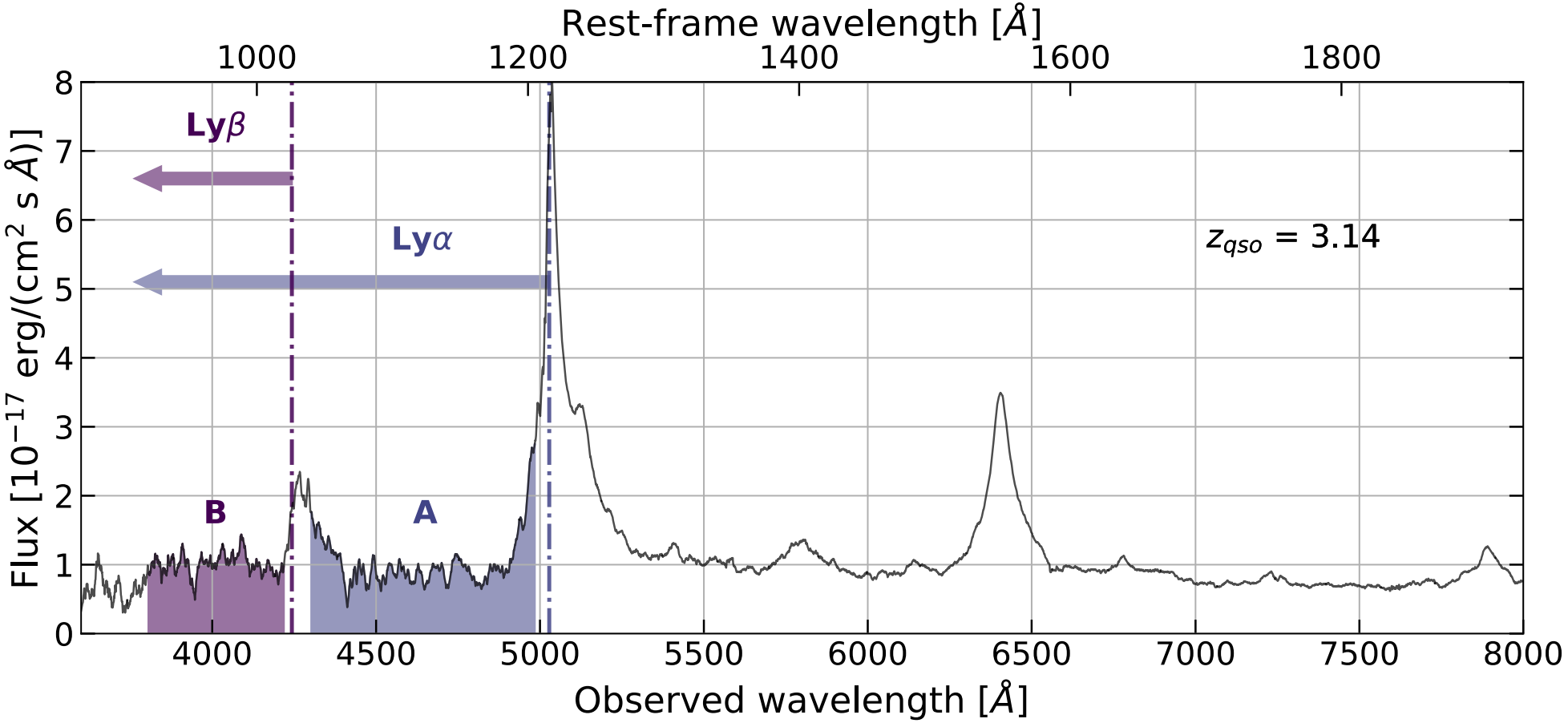
2 spectral regions , 4 correlation functions

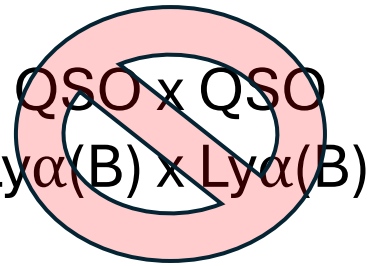


Lyα(A) x Lyα(A)

Lyα(A) x Lyα(B)

Lyα(A) x QSO

Lyα(B) x QSO



Difficult & Low S/N

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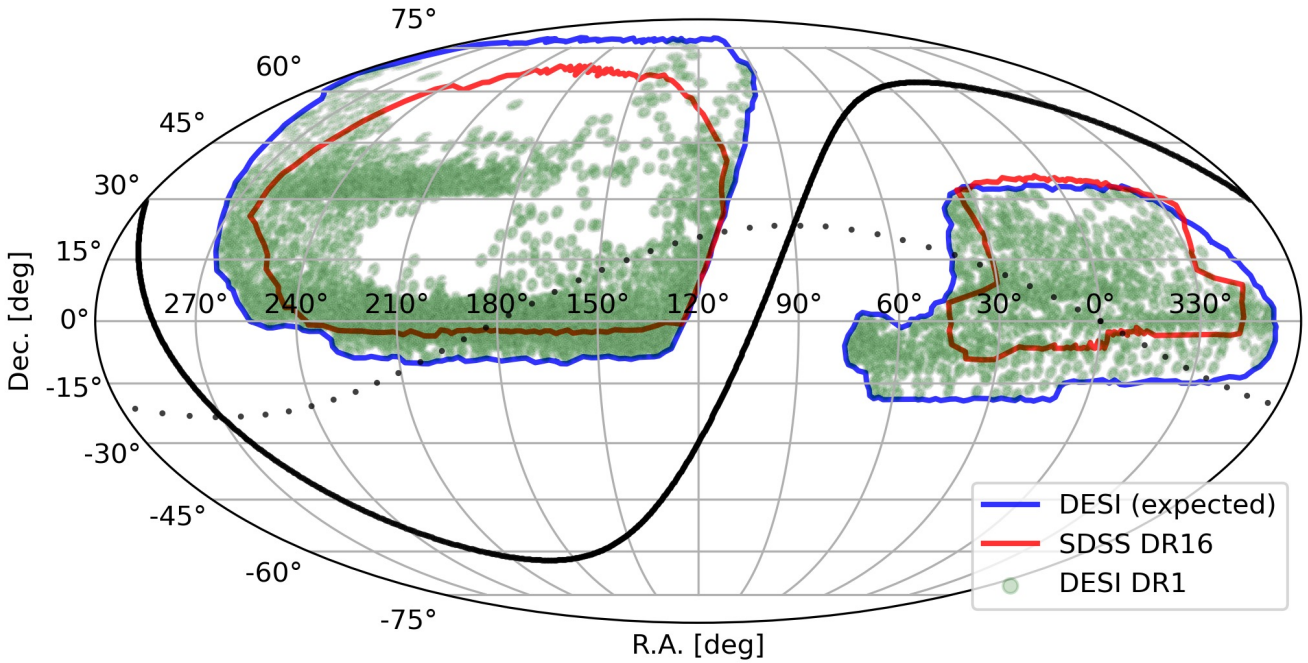
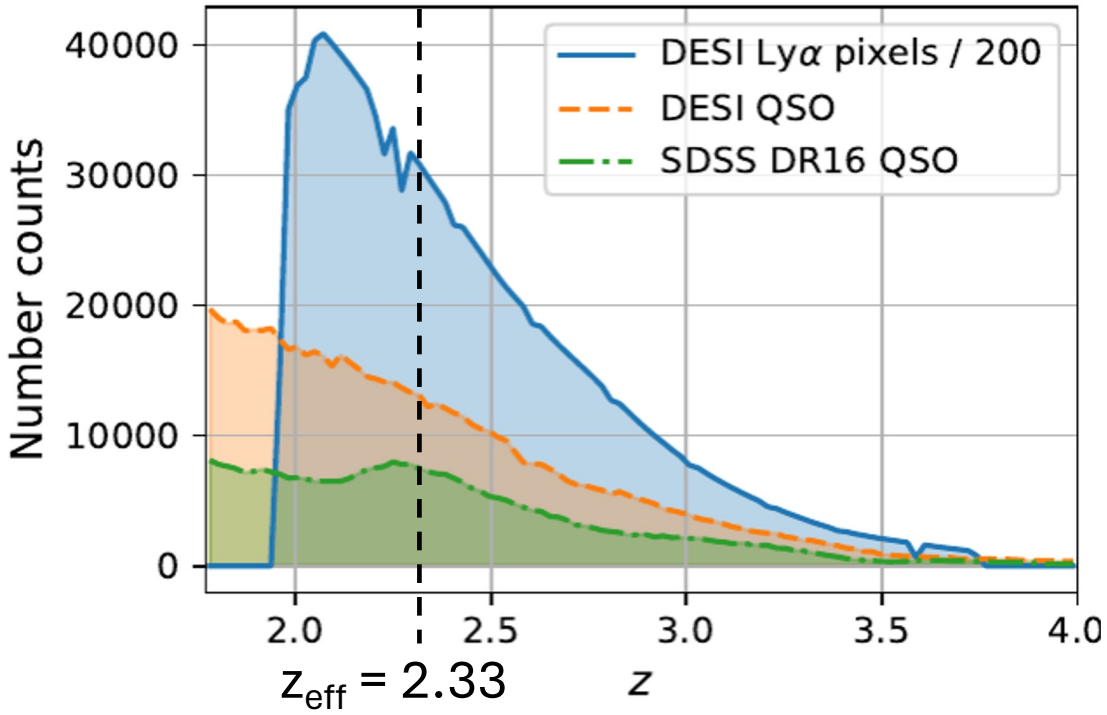
DESI DR1 Quasar and Lyα sample





More than 420,000 Lyα QSOs at z>2.1 (twice as many as in 20 years of SDSS)

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2 spectral regions , 4 correlation functions

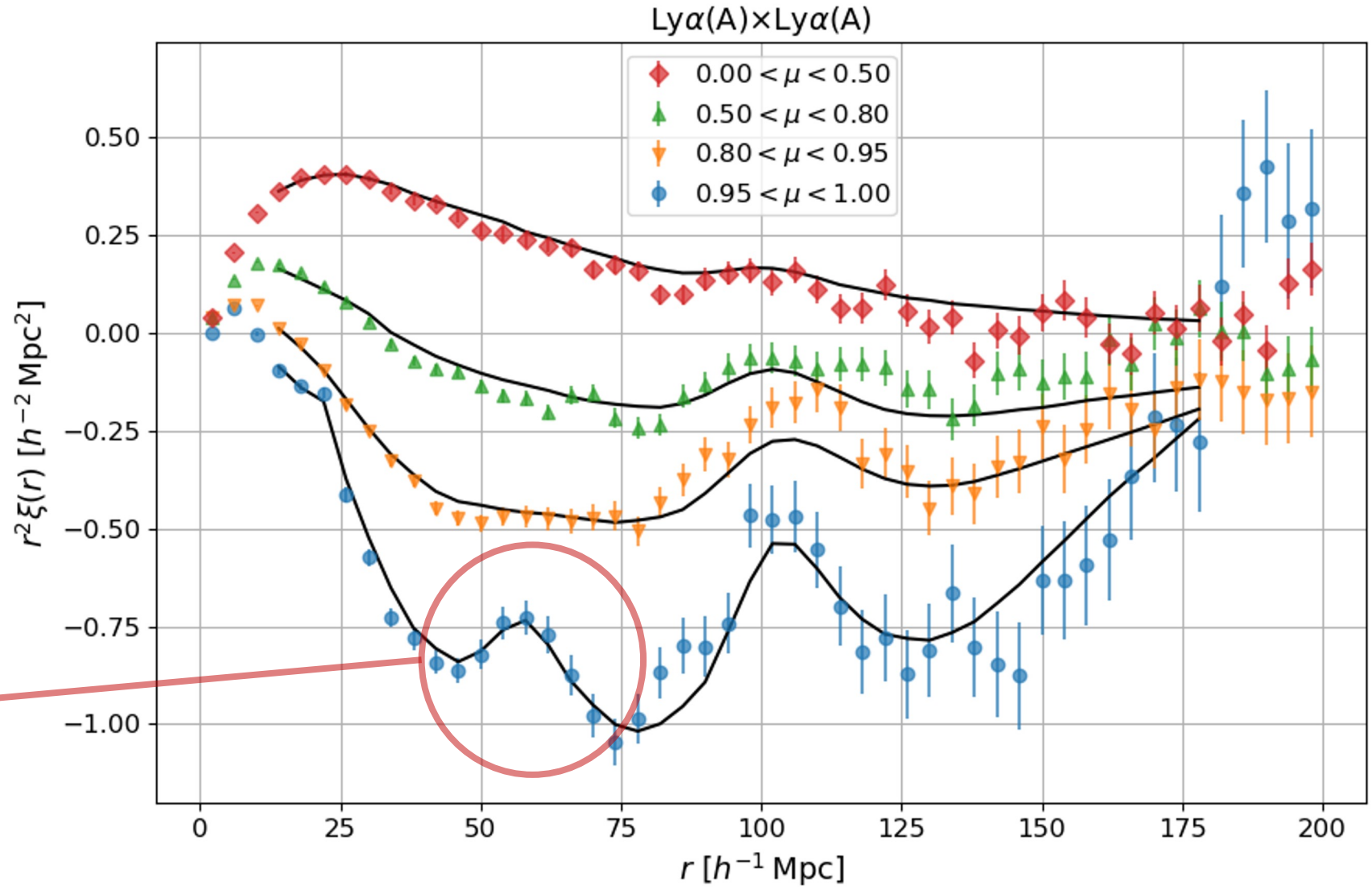
Lyα auto-correlation measured in 50 x 50 bins of 4 Mpc/h

"μ wedges" used in plots only

Very strong RSD

Spurious correlations caused by Silicon

Impact on very small angular separations (included in fits)



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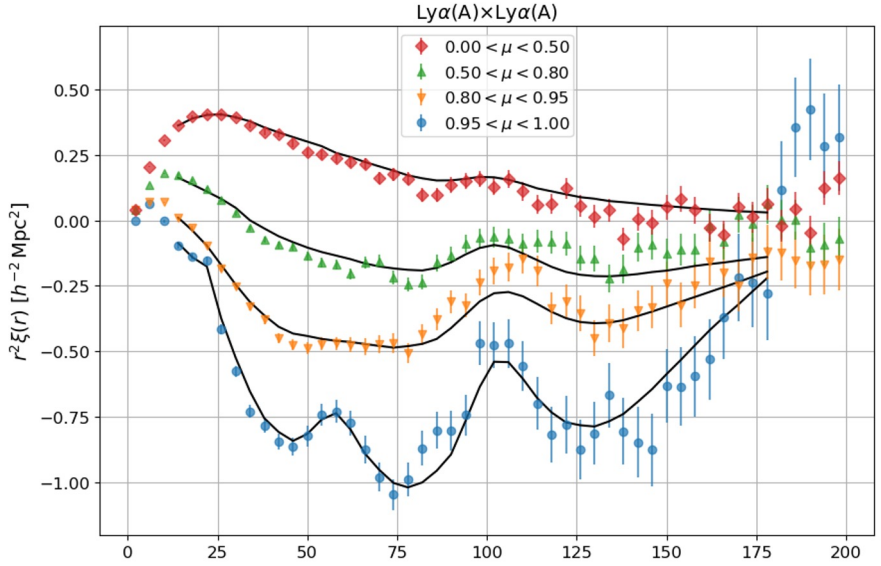
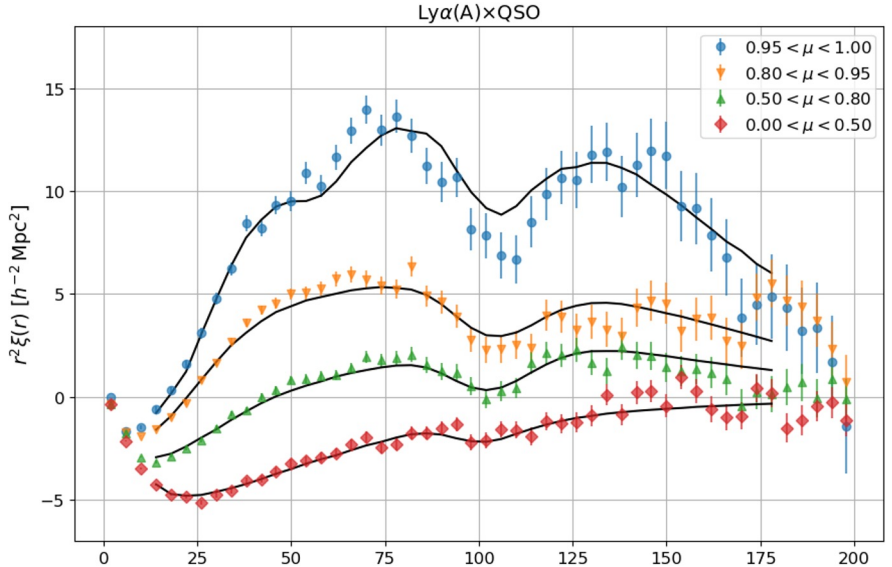
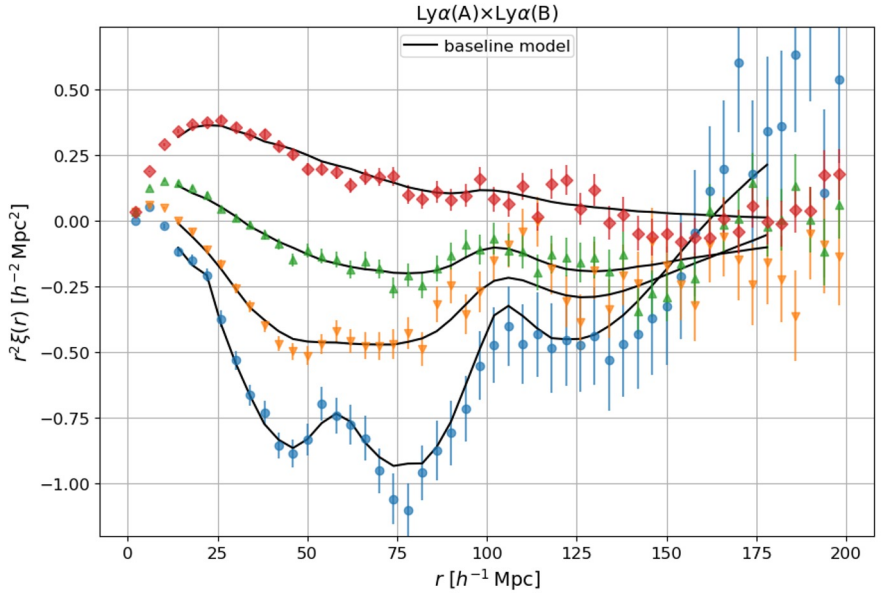
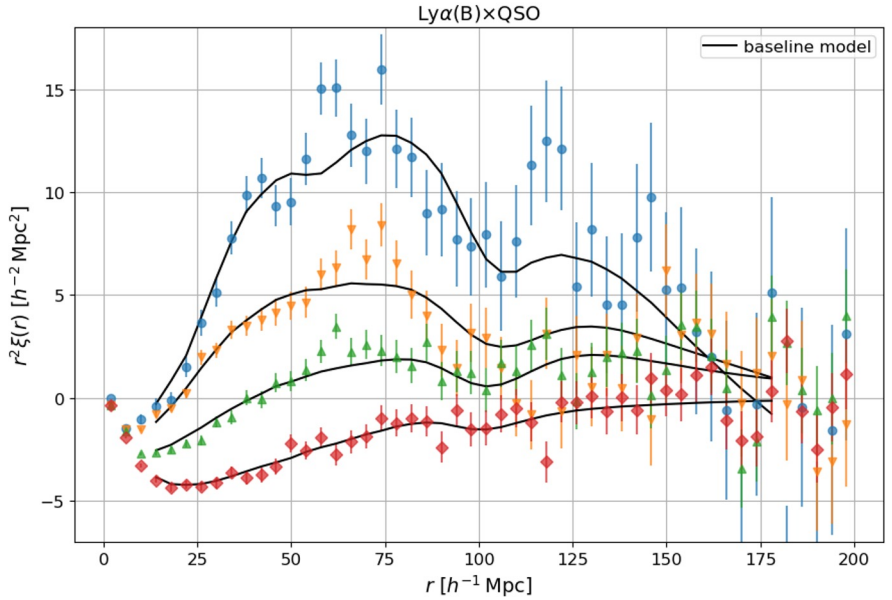
2 spectral regions , 4 correlation functions









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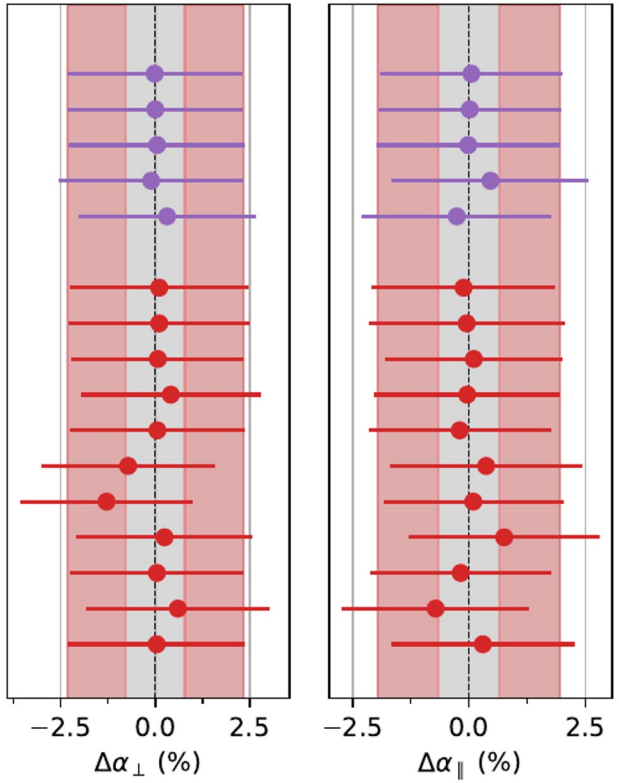
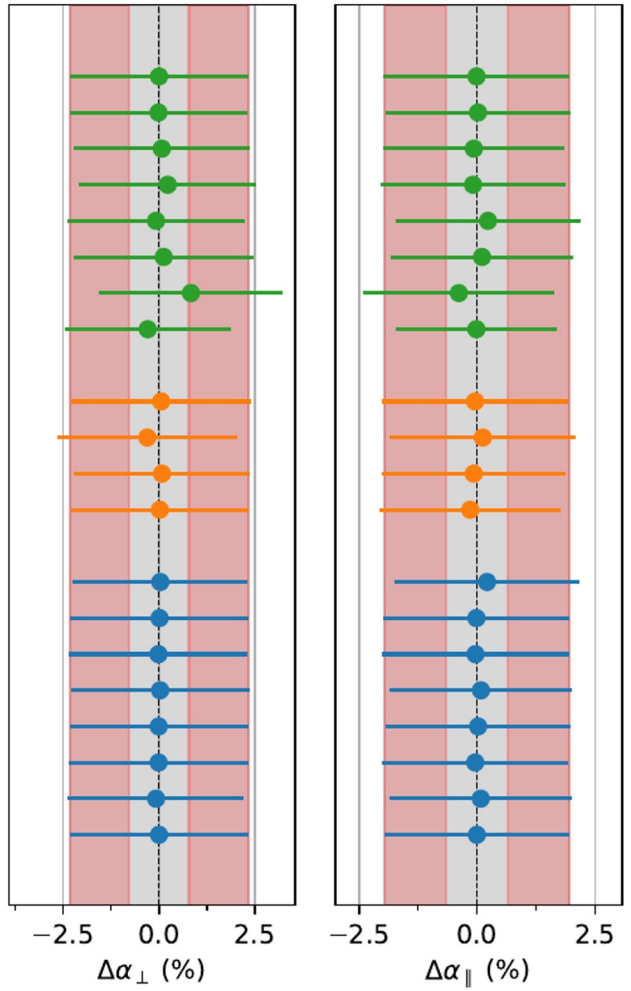
Variations in the analysis



no calibration
$\eta_{pip} = 1$
ϵ free
$\eta_{LSS} = 3.5$
$\Delta\lambda = 2.4\,Å$

$\lambda_{obs} < 5500\,Å$
$\lambda_{obs} > 3650\,Å$
$\lambda_{RF} < 1200\,Å$
$z_Q < 3.78$
> 50 pixels in forest
original redshift estimates
mask-Lya redshift estimates
only quasar targets
DLAs SNR > 1
weak BALs
no sharp lines mask



dmat $r_\parallel < 200$ Mpc/h
dmat 2%
dmat model 4 Mpc/h
$\Delta\lambda = 3.2\,Å$
$\Delta\lambda = 1.6\,Å$
nside = 32
$\Delta r = 5$ Mpc/h
no cross-covariance

$r < 200$ Mpc/h
$r < 160$ Mpc/h
$r > 20$ Mpc/h
$r > 40$ Mpc/h with priors

eBOSS metals
vary L_{HCD}
$L_{HCD} = 10$ Mpc/h
$L_{HCD} = 3$ Mpc/h
Gaussian redshift errors
weak CIV bias prior
no small-scales correction
UV fluctuations

- Tests with same data set (purple, green, orange, blue):
  BAO shifts < ⅓ stat (gray band)
- Tests with varying data sets (red):
  BAO shifts consistent with statistical fluctuations

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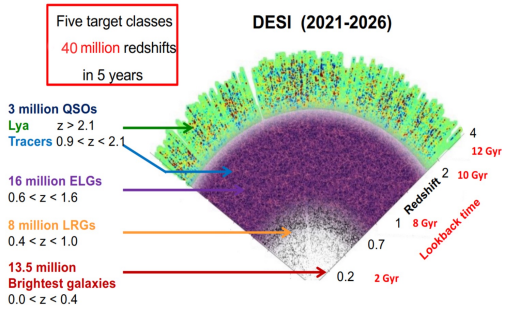
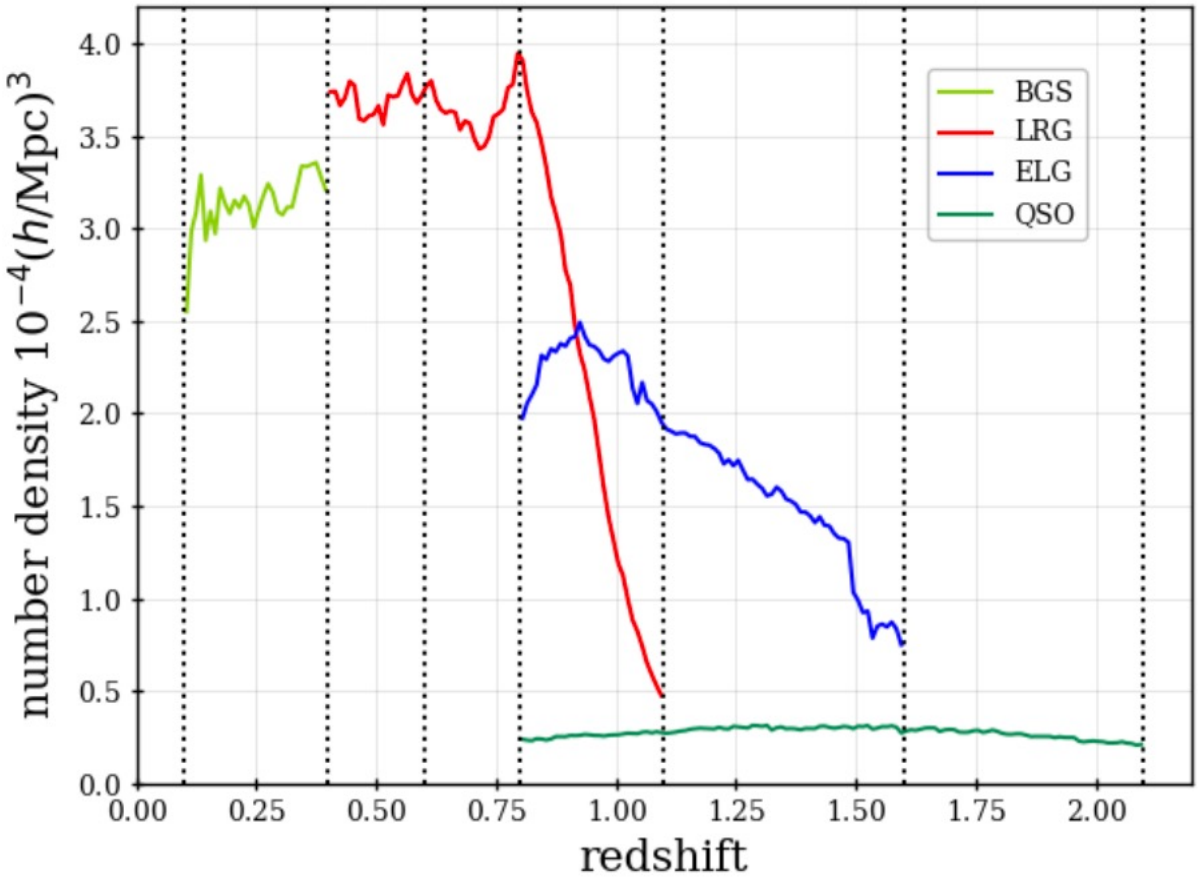
Mapping LSS @ z<2.1





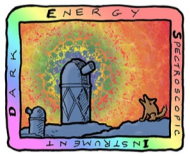
Four different tracers (bright, luminous red, emission line, quasars)

Six redshift bins, including one overlapping bin

5.7M unique redshifts

18 Gpc^3 volume

3x SDSS



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Features of our Y1 analysis

- **The biggest data set both in terms of numbers and volume**
- **Use of a catalog-level blinding scheme to avoid confirmation bias**
  - Pipelines/systematics (largely) determined before unblinding
- **Unified pipeline across all tracers/redshift slices, consistent models in Fourier and configuration space**
- Physically motivated enhancements to the BAO pipeline
- Improvements to reconstruction
- A combined LRG+ELG analysis between $0.8 < z < 1.1$
- **Comprehensive, revisited systematics error budget**

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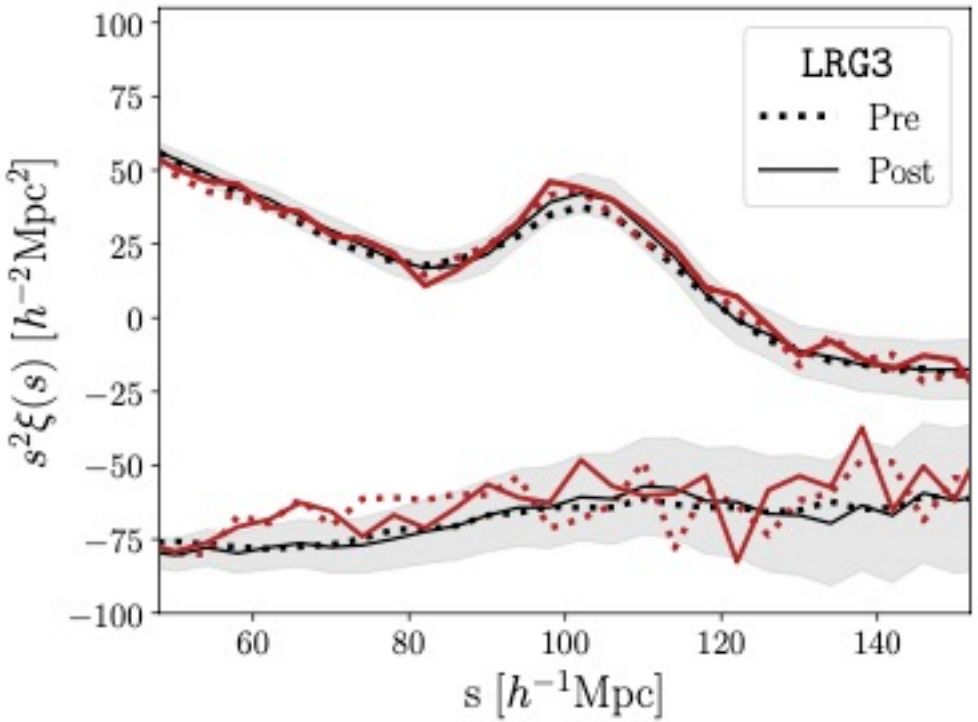
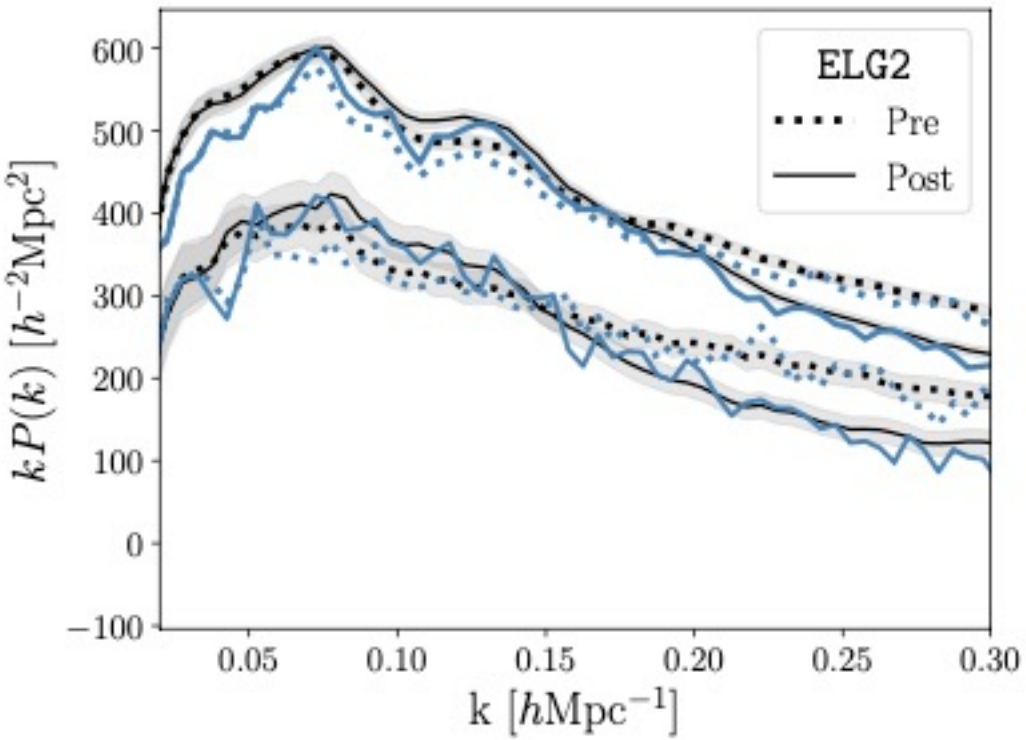
Examples of the observed clustering





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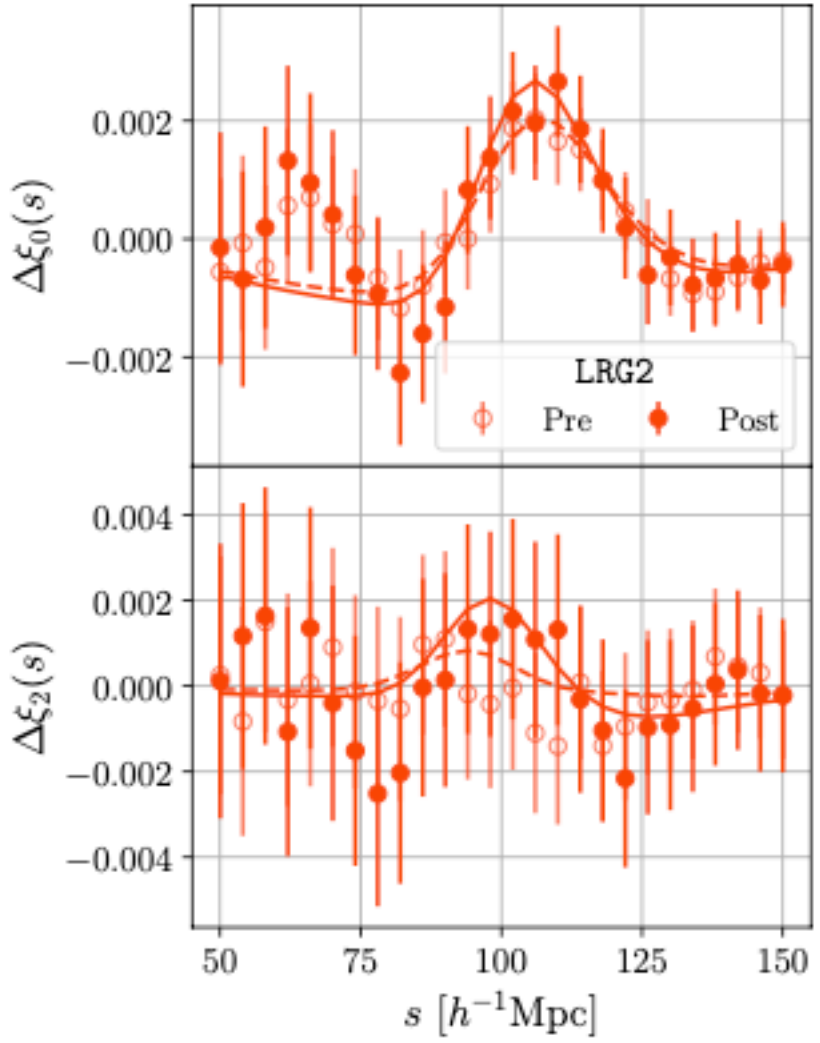
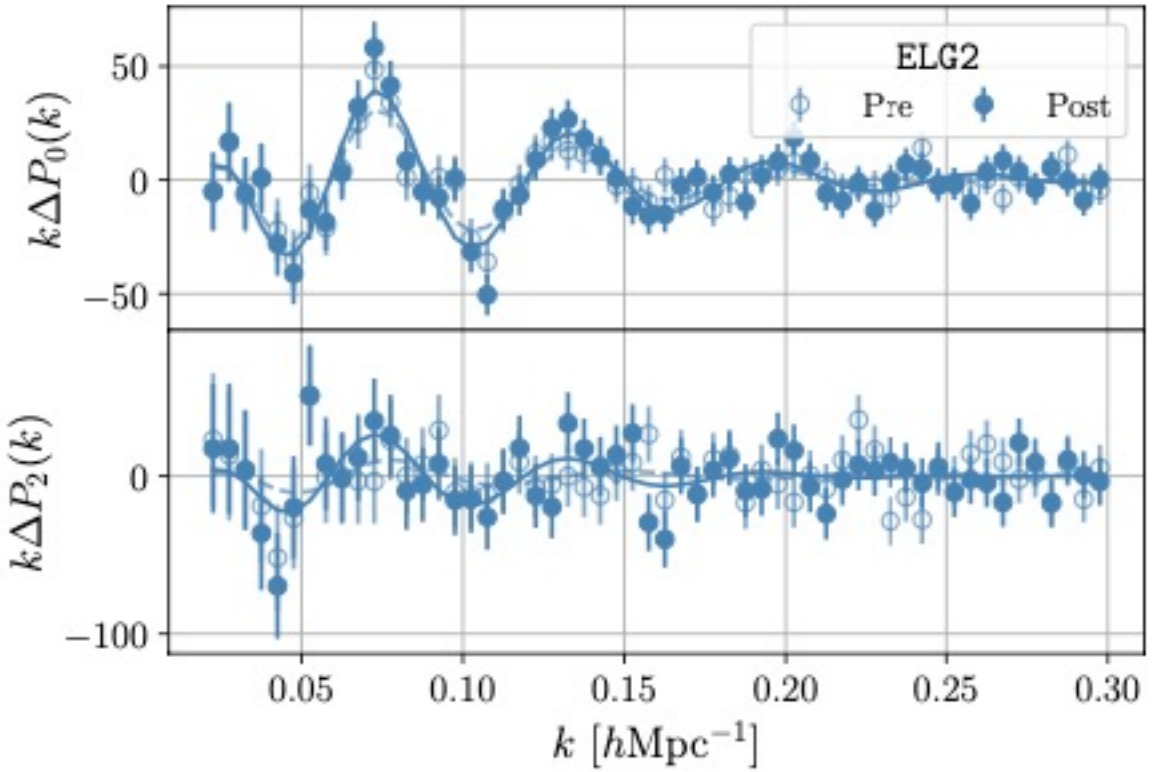
… and the BAO feature





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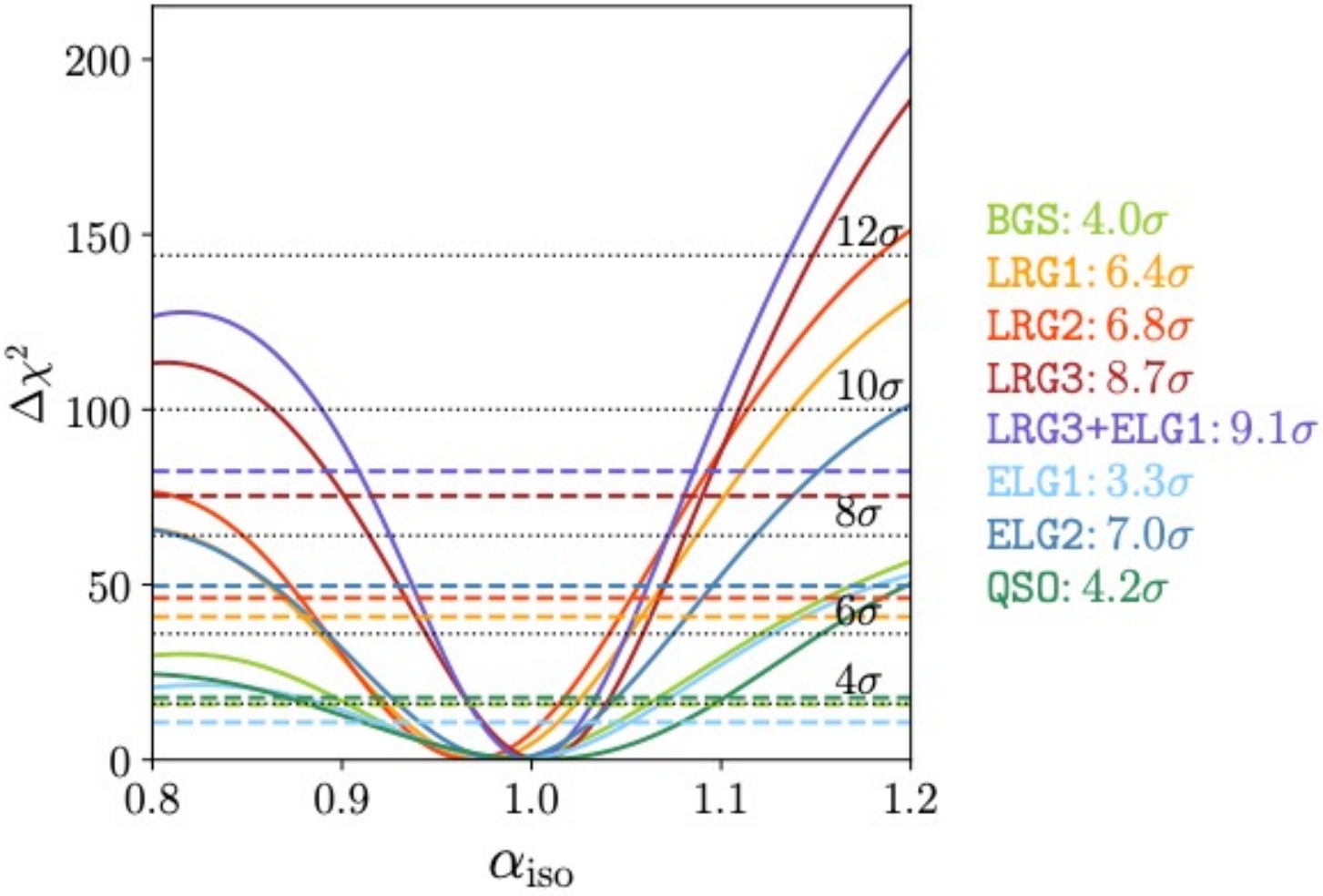
BAOs are significantly detected for all samples



Aggregate distance precision with Year 1 data:

0.52%

Cf. All SDSS galaxy BAOs over two decades:

0.64%

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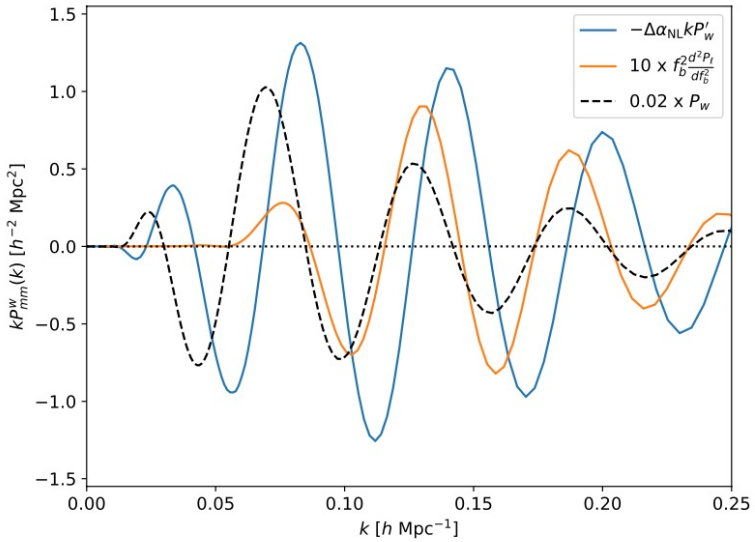
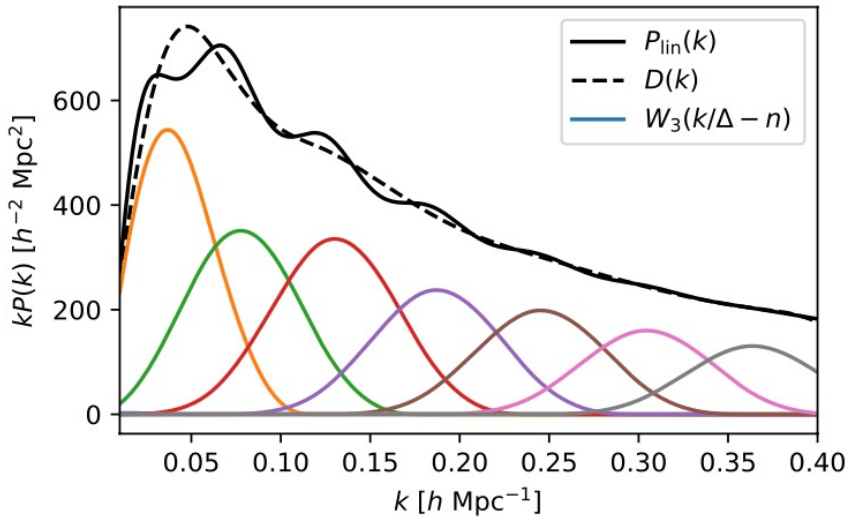
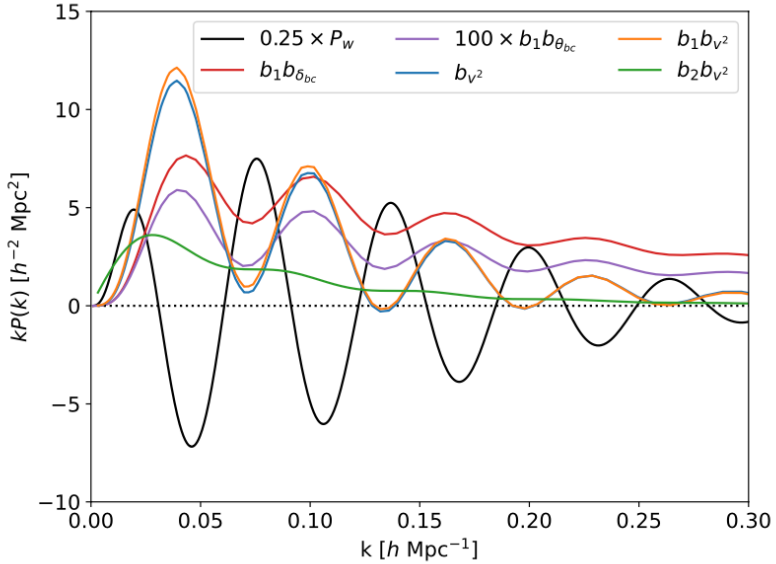
Tracking Theoretical Systematics

Name/Description	$\sigma_{\alpha_{\rm iso}}$	$\sigma_{\alpha_{\rm AP}}$
Non-linear mode-coupling	$< 0.1\%$	$< 0.1\%$
Relative velocity effects	$< 0.05\%$	$< 0.05\%$
Broadband modelling	$< 0.02\%$	0.11%
BAO wiggle extraction	$< 0.02\%$	$< 0.09\%$
Dilating smooth vs. wiggle	$< 0.02\%$	$< 0.09\%$
Modelling $\xi(s)$ from $P(k)$	$< 0.01\%$	0.12%
Combined	0.1%	0.2%







Chen, Howlett et al

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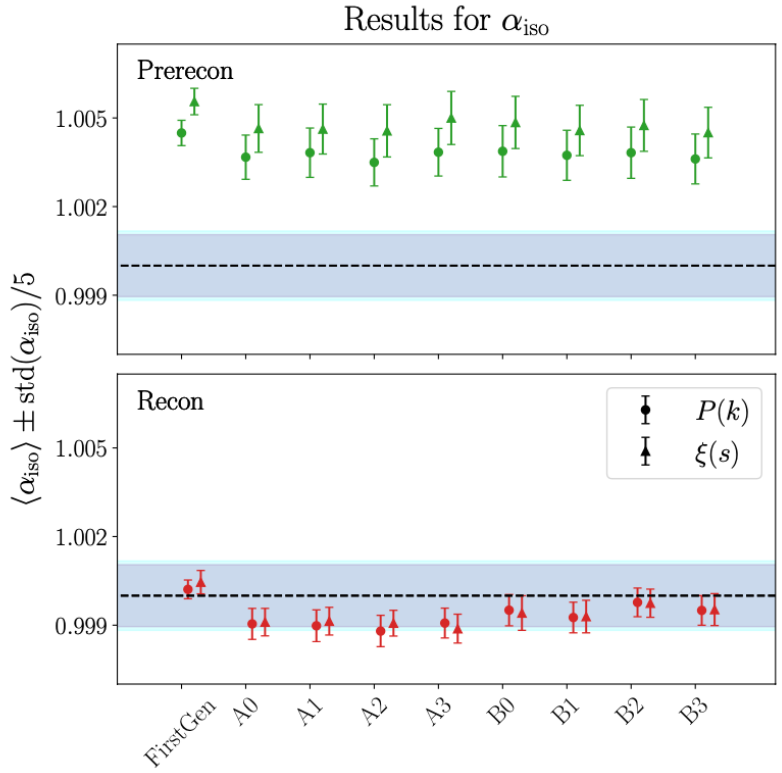
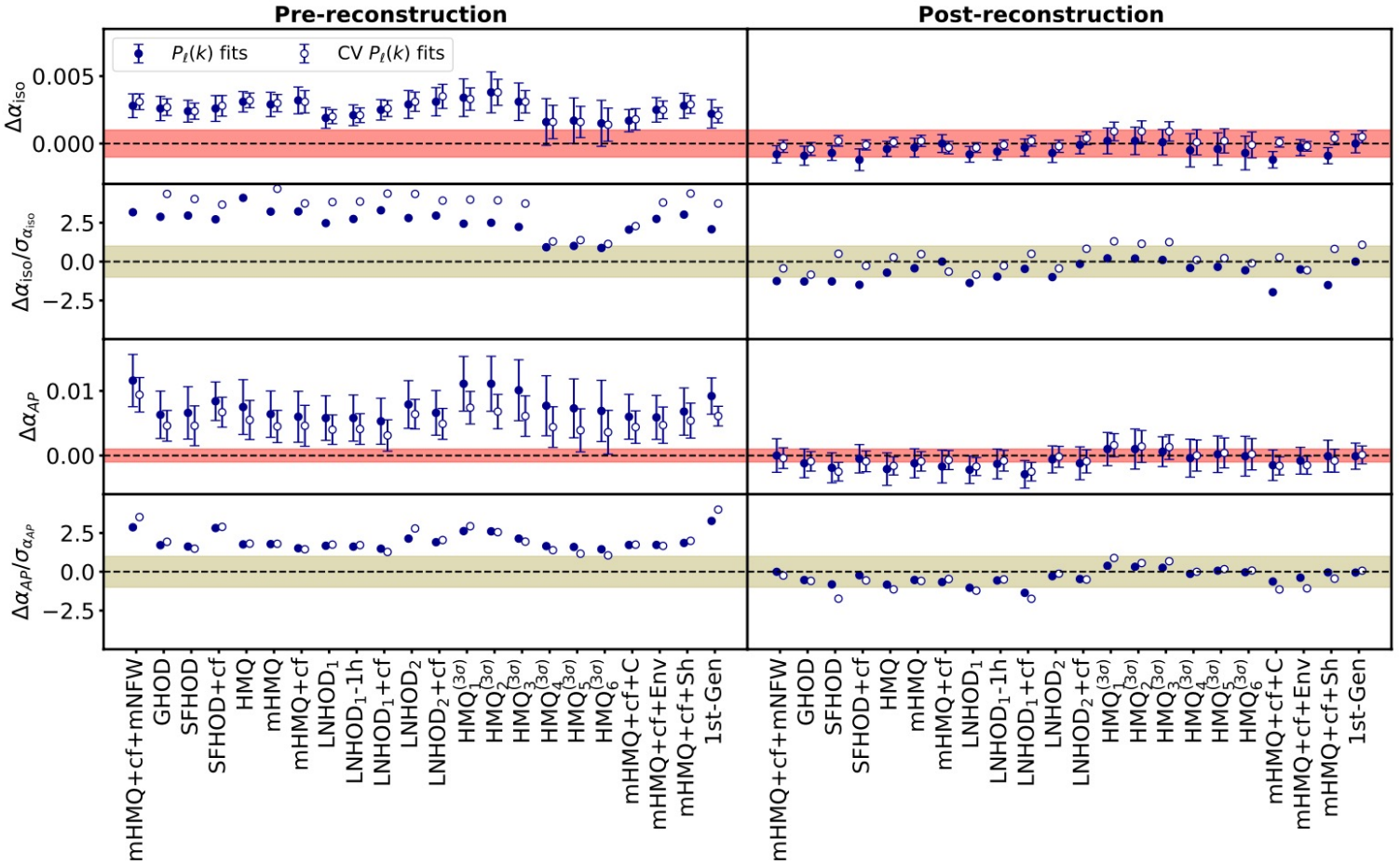
Testing with varying galaxy prescriptions





Used control variates to reduce mock sample variance (B. Hadzhiyska et al, 2023)

Note that reconstruction removes shifts in distance measurements

Mena-Fernandez et al
Garcia Quintero et al

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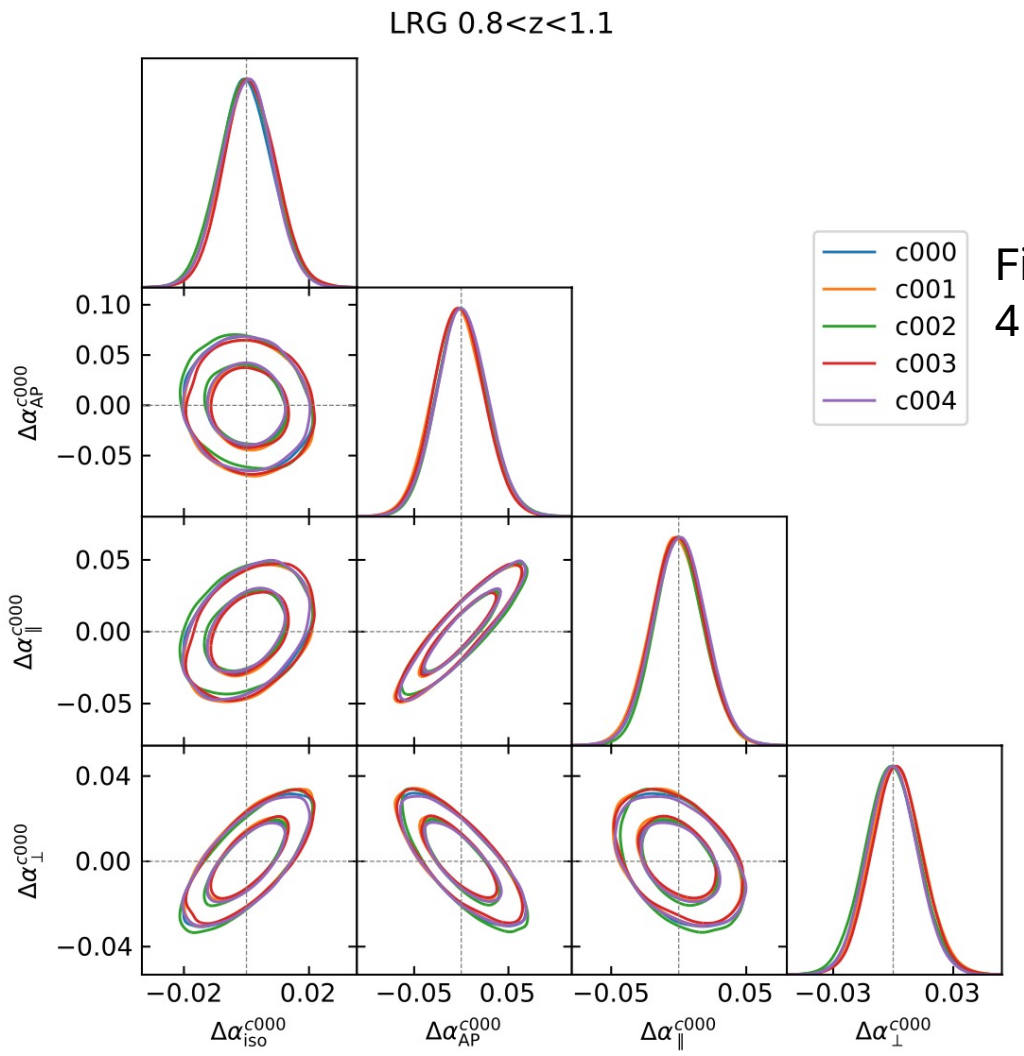
Assumed cosmology makes no difference



Fiducial cosmology +
4 different cosmologies

c003 includes a non-standard Neff

Space	Parameter	c000-c00X	c000-c003
Fourier	α_{iso}	0.1%	0.2%
	α_{AP}	None (0.1%)	None (0.1%)
Config.	α_{iso}	None (0.1%)	0.2-0.3%
	α_{AP}	None (0.1%)	None (0.1%)

Perez-Fernandez et al

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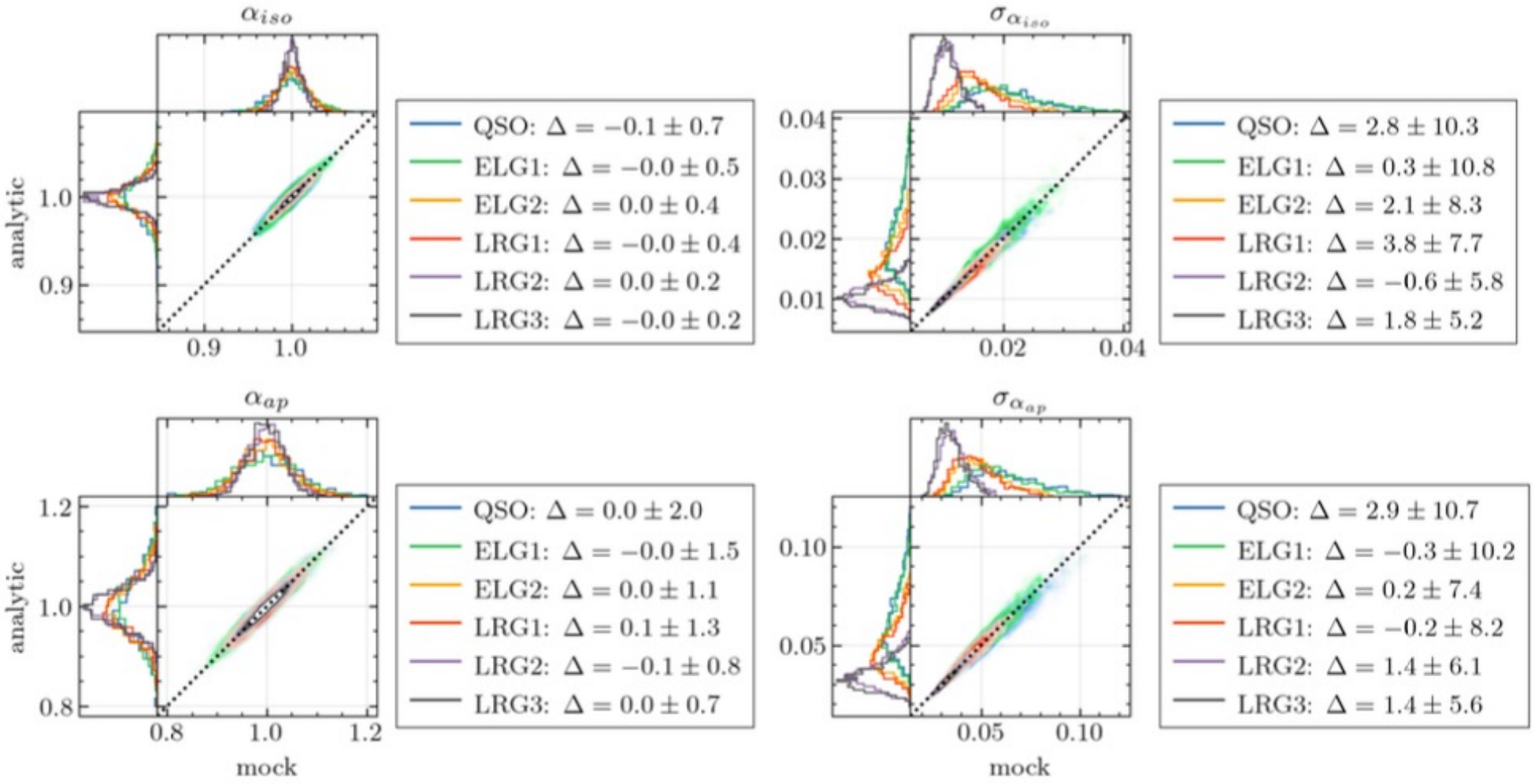
Use of analytic covariances, calibrated with mocks



Wadekar et al
Philcox et al
Rashkovetskyi et al

Alves et al, in prep
Forero-Sanchez et al, in prep

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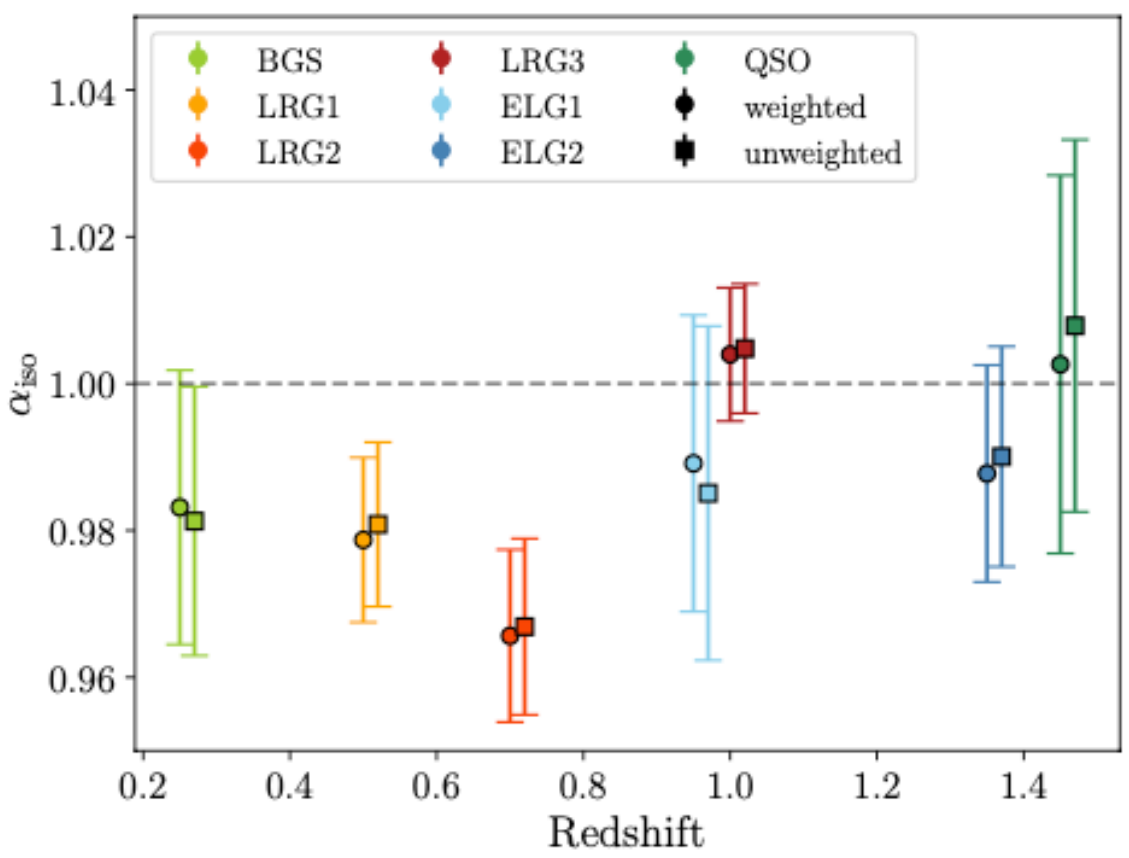
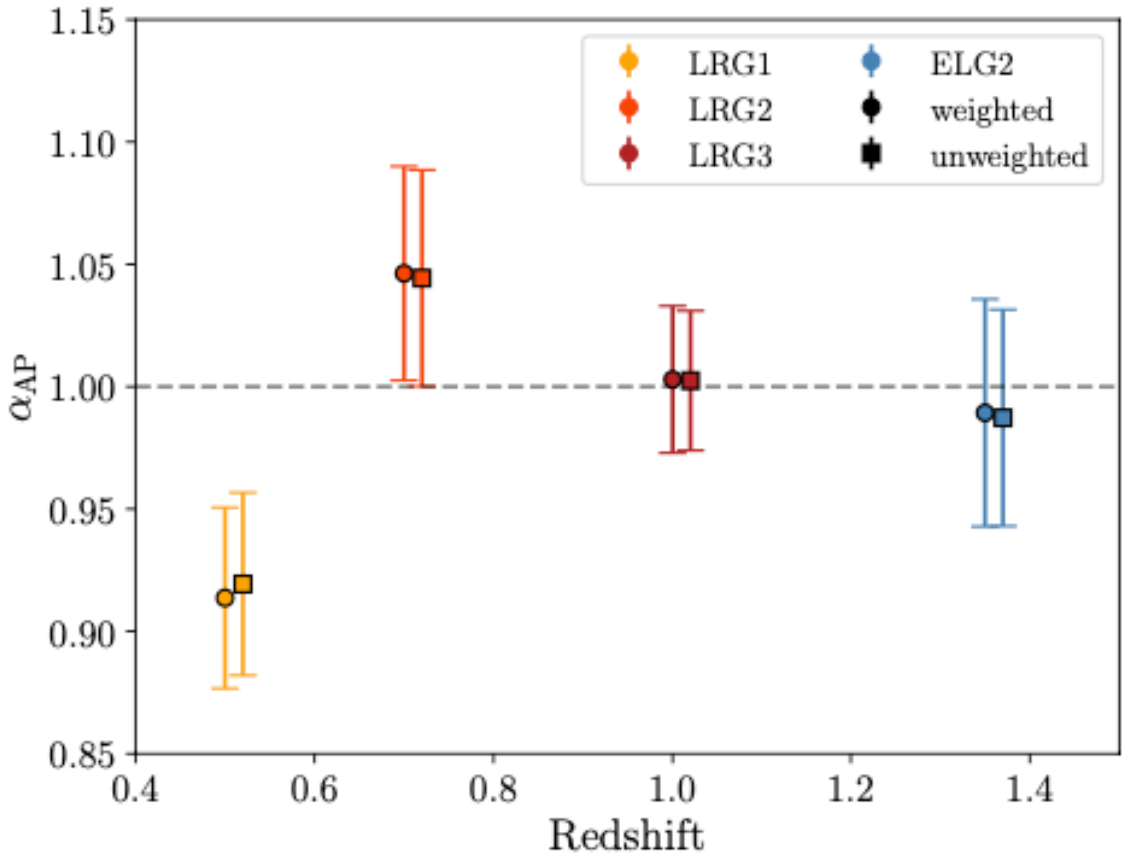
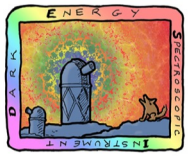
Observational Systematics are subdominant





Yu et al, in prep
Rosado-Marin et al, in prep
Krolewski et al, in prep



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Systematics are subdominant to statistical errors

Systematic	Error (in percent)	Comments
Theoretical	0.1 ($\alpha_{\rm iso}$), 0.2 (α_{AP})	Includes fitting methodology and choices, as well as expected impacts from galaxy bias and cosmology misestimation
Observational		
a. Imaging	Not detected	Tested on the data, with the largest change being 0.3% seen for the `ELG1`, and the rest being 0.1%.
b. Spectroscopic	Not detected	Tested with the mocks on the clustering level.
c. Fiber assignment	Not detected	The test was finalized after unblinding.
HOD	0.2	Only one detected statistically significant pair Limited by statistical precision of mocks Note : some of this error is already included in the theory budget
$N_{\rm eff}$	0.2 ($\alpha_{\rm iso}$)	Bias for $N_{\rm eff} = 3.7$
Fiducial $D_A(z)$	< 0.1	May require iteration post-unblinding if best-fit is far from fiducial Upper limit based on statistical precision
Reconstruction	Not detected	No significant effects from different
		algorithms etc.
Covariances	Not detected	Based on comparisons between analytic and mock covariances

	Tracer	$\sigma_{\rm BGS}$	$\sigma_{\rm LRGs,ELGs}$		$\sigma_{\rm QSO}$
Space	Source	$\alpha_{\rm iso}$ (%)	$\alpha_{\rm iso}$ (%)	$\alpha_{\rm AP}$ (%)	$\alpha_{\rm iso}$ (%)
$\xi(r)$	Theory (Table 7)	0.1	0.1	0.2	0.1
$\xi(r)$	HOD (Table 8)	0.2	0.2	0.2	0.2
$\xi(r)$	Fiducial (Table 11)	0.1	0.1	0.1	0.1
$\xi(r)$	Total	0.245	0.245	0.3	0.245
$P(k)$	Theory (Table 7)	0.1	0.1	0.2	0.1
$P(k)$	HOD (Table 8)	0.2	0.1	0.1	0.12
$P(k)$	Fiducial (Table 11)	0.1	0.1	0.1	0.1
$P(k)$	Total	0.245	0.18	0.245	0.19

Max. effect:

$$\sigma_{\rm stat+sys} = 1.05\sigma_{\rm stat}$$

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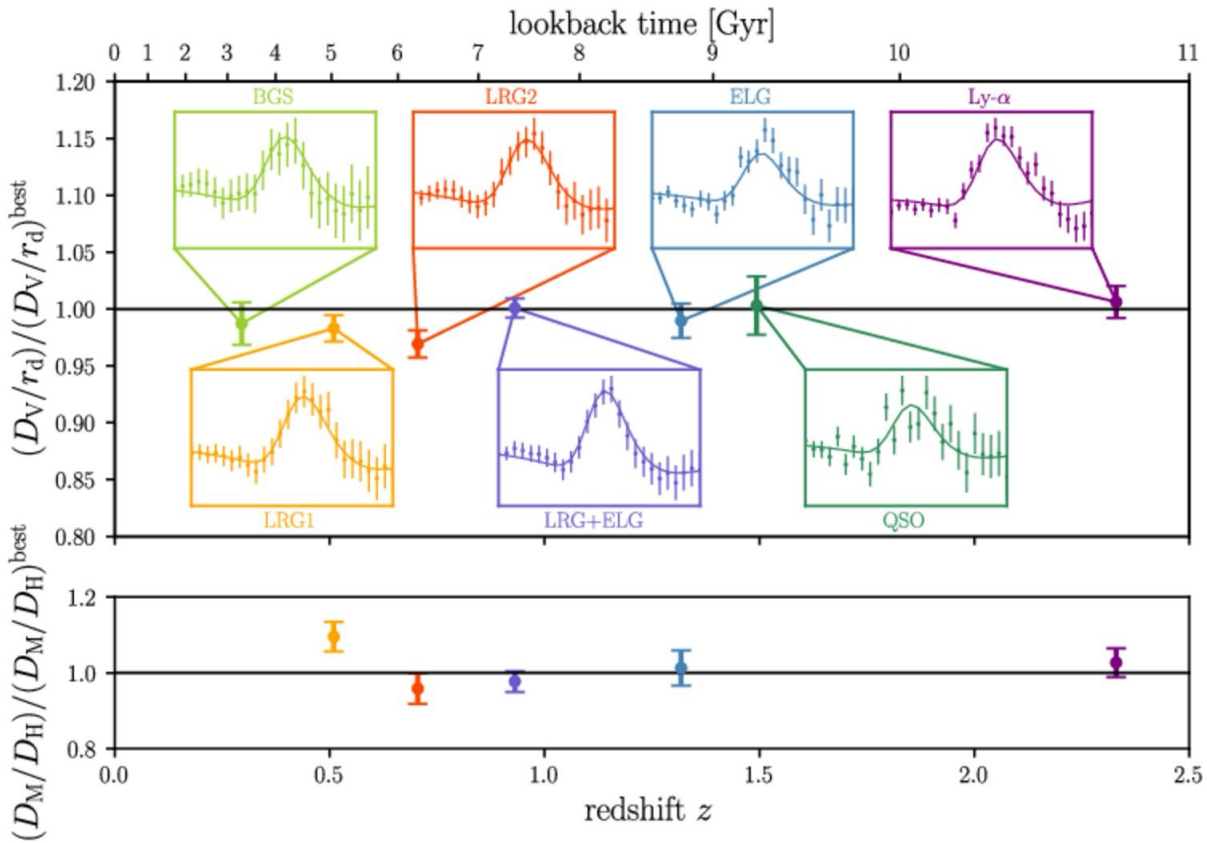
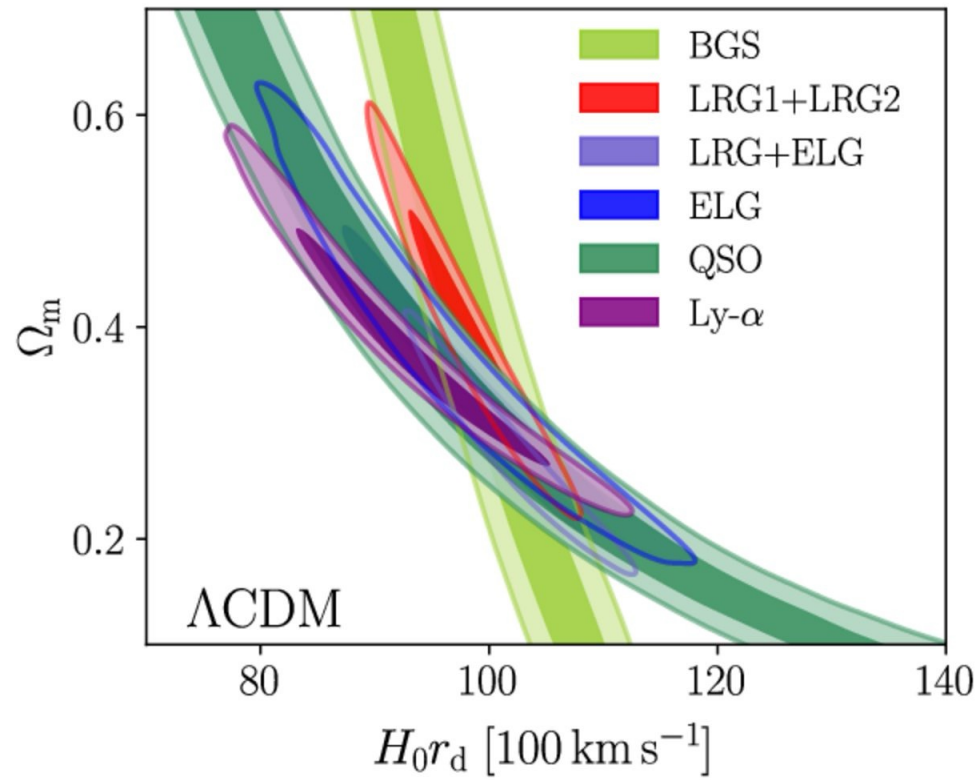
DESI Y1 BAO

DESI BAO measurements





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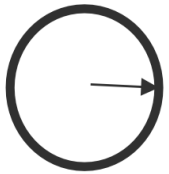
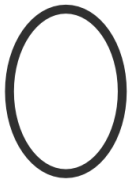
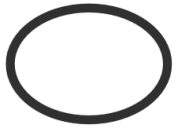
The z<2.1 BAO Hubble Diagram

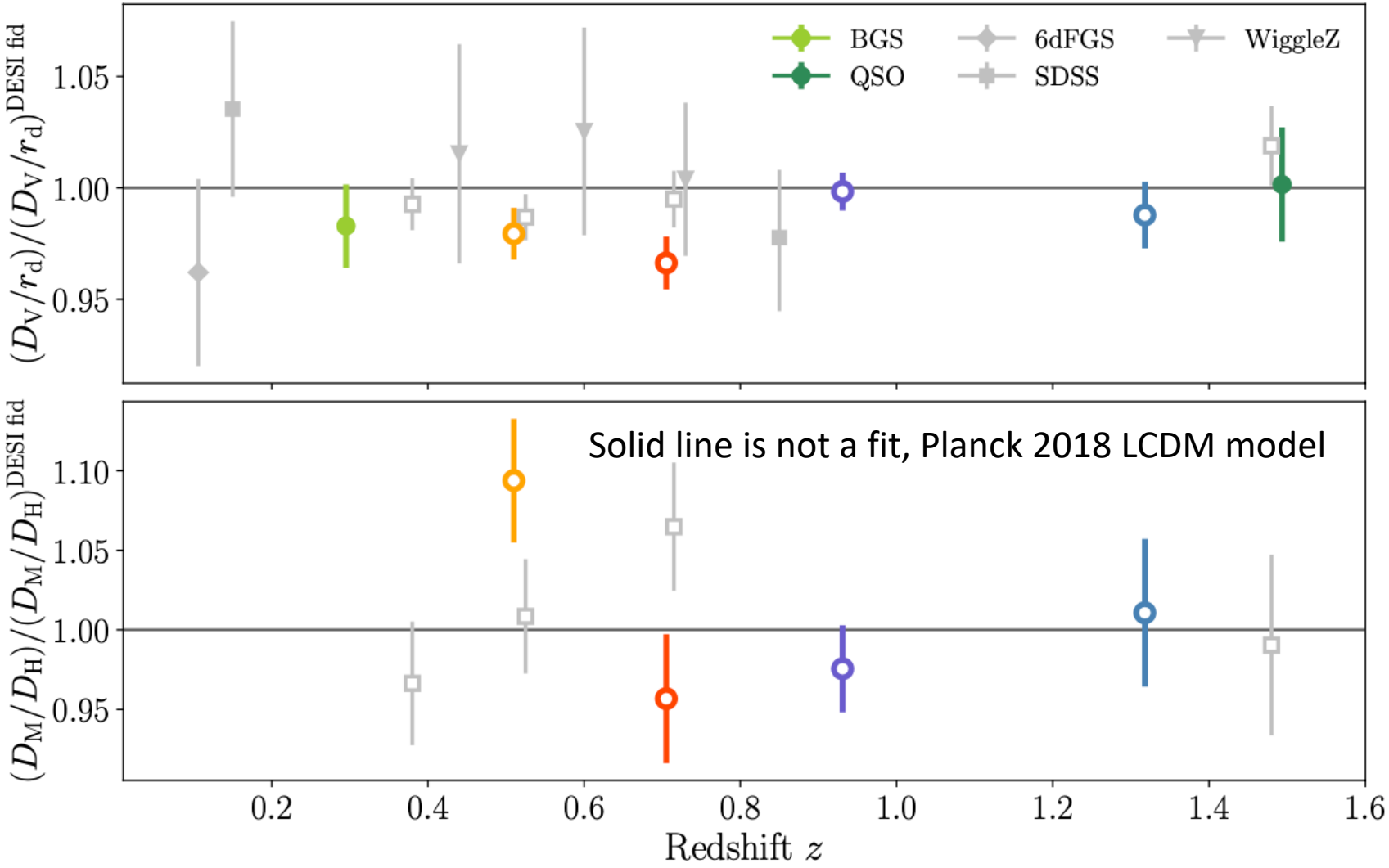
Overall size of the BAO



Anisotropy of the BAO







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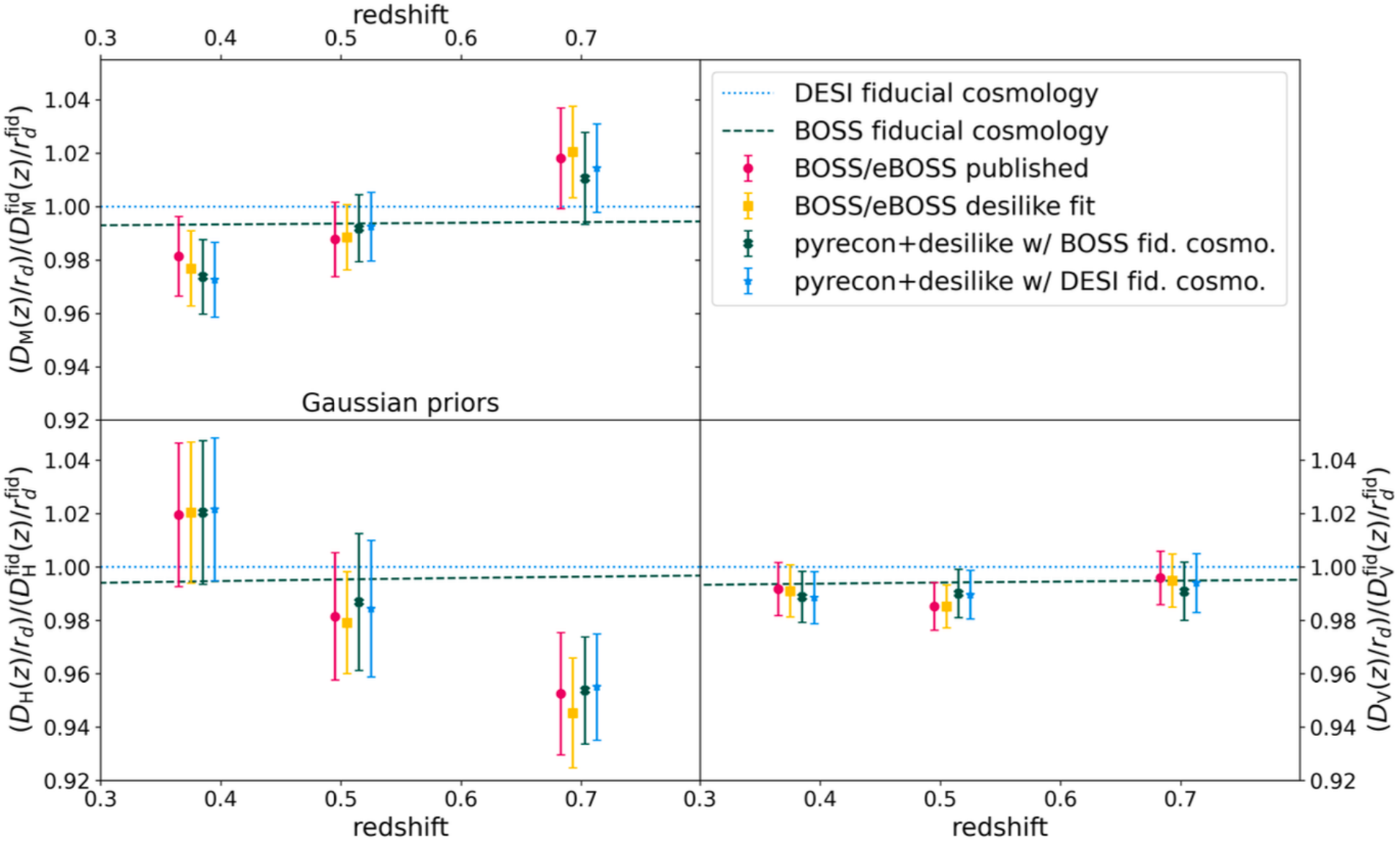
Re-analysing SDSS yields consistent results



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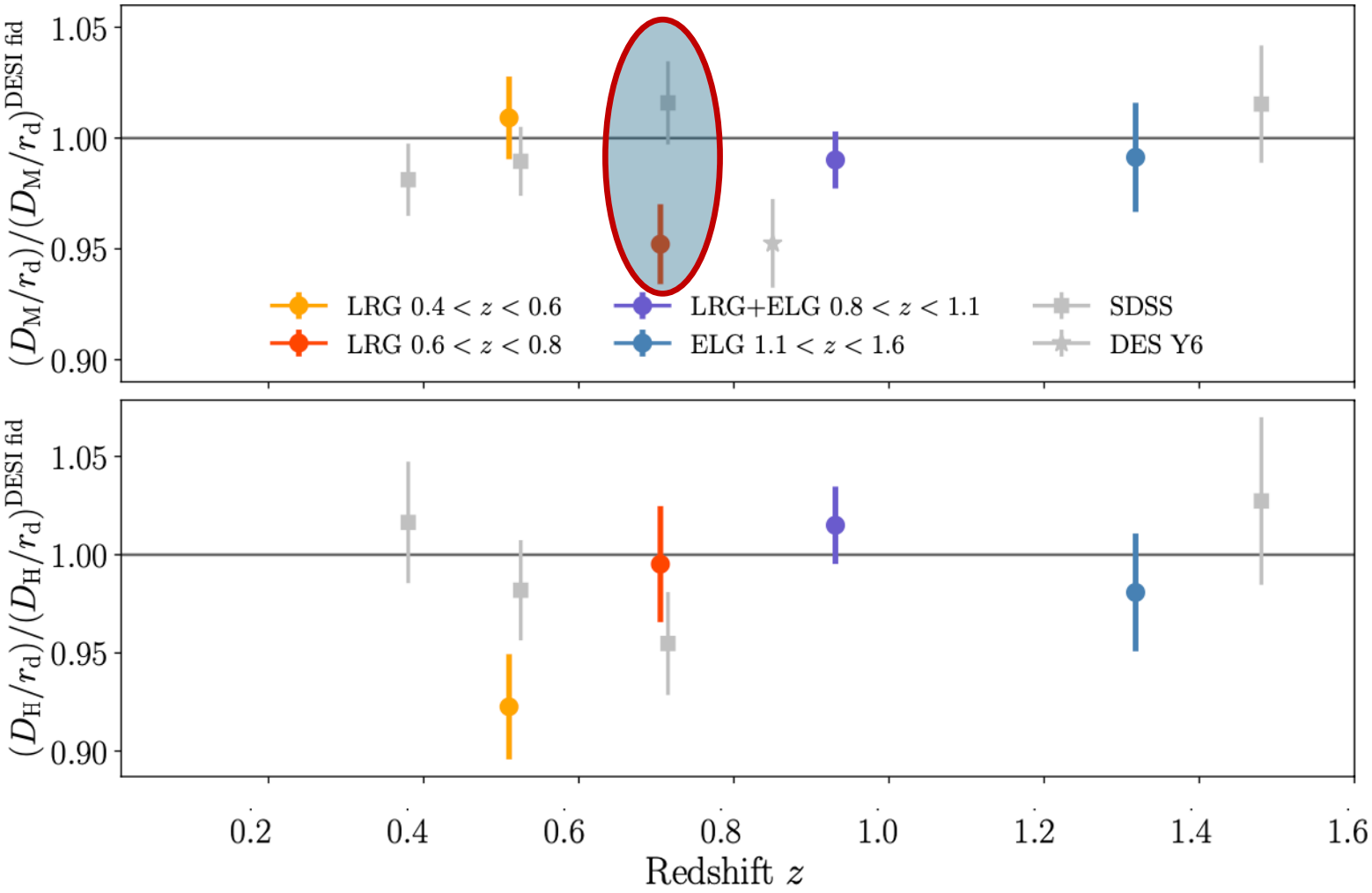
Comparing SDSS with DESI



r<0.2 cross-correlation between the samples based on effective volume

2.7-3 sigma discrepancy at z~0.7; slightly lower with the DESI reanalysis.

Blind analysis, we were not trying to match results (or a cosmology)

We conclude this was a statistical fluctuation; revisit with Y3 data

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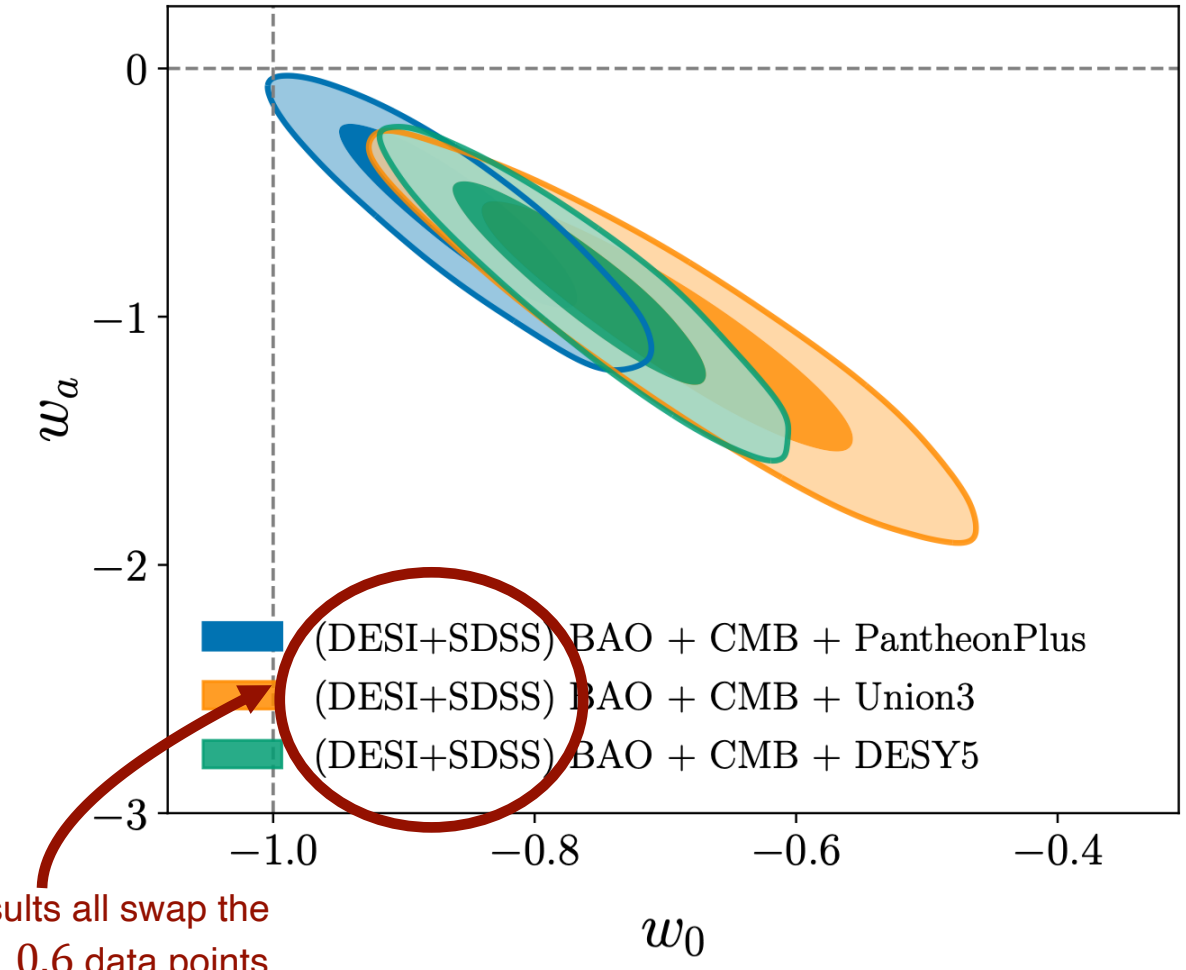
Is the DE result all because of the $z = 0.51$ point?

No! **Fig. 12 of the paper already addressed this.**



These results all swap the DESI $z < 0.6$ data points for SDSS/BOSS ones

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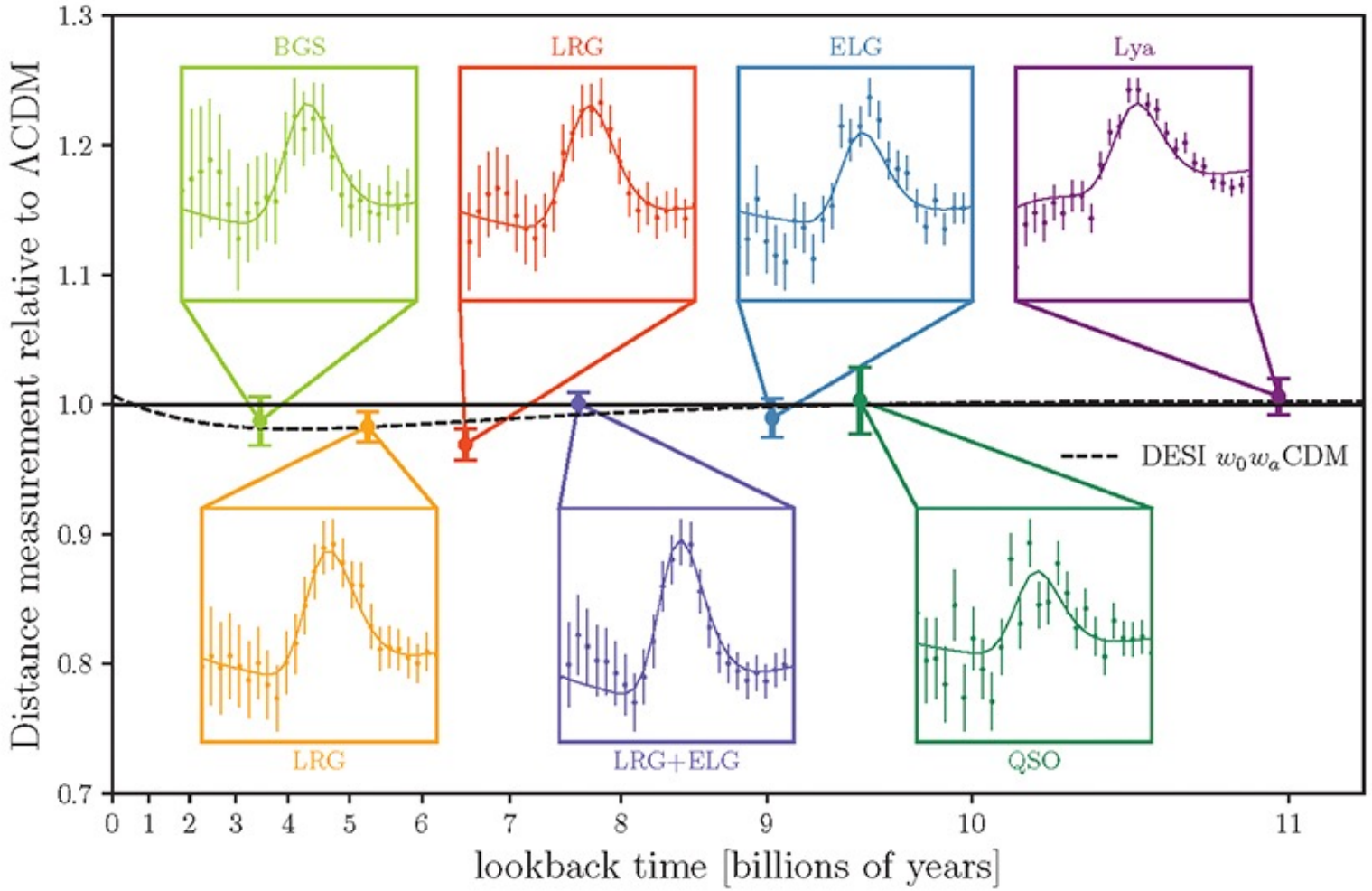
Stay tuned for Y>=3 data and beyond



Arnaud de Mattia, DESI Collab