DESI 2024: Cosmic Expansion History with Baryon Acoustic Oscillations

Julien Guy (LBNL)
on behalf of the DESI collaboration

Slides from presentations at APS and Moriond conferences

Papers: https://data.desi.lbl.gov/doc/papers/

52nd SLAC Summer Institute 08/13/2024

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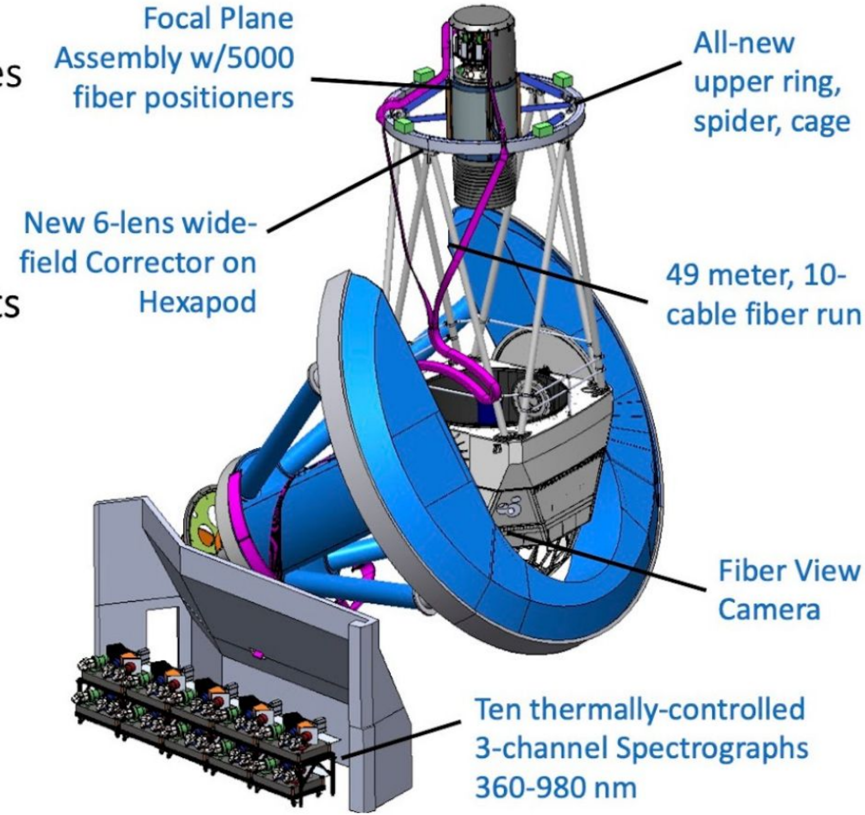
Thanks to our sponsors and 72 Participating Institutions!

The DESI instrument

- DESI is a Fiber-fed multi-object spectrograph. It uses robotic control to position optical fibers onto the location of a known galaxy
- 5000 fiber positioner robots on the focal plane
- 8 sq. deg. FOV
- Ten 3-channel spectrographs



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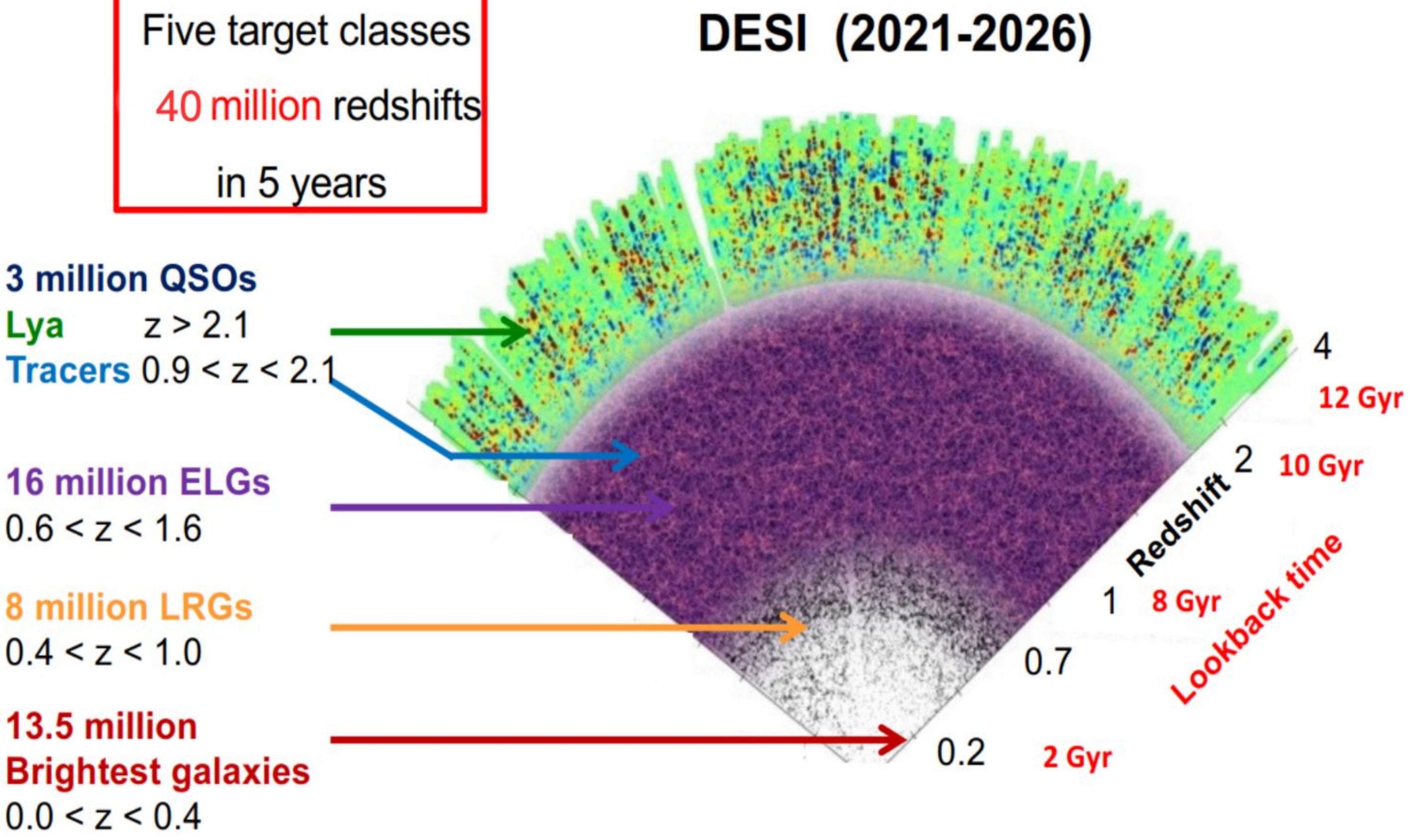
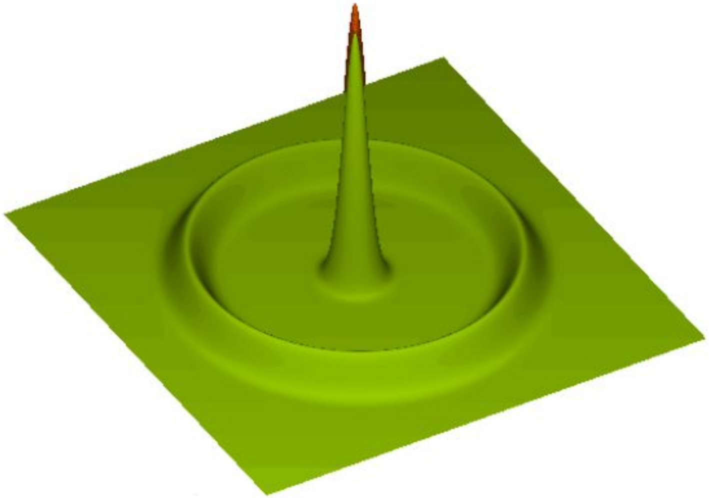
The DESI survey

Five target classes
40 million redshifts
in 5 years



Baryon Acoustic Oscillations (BAO)

Sound waves in the baryon density



Eisenstein, Seo, White et al. 2007

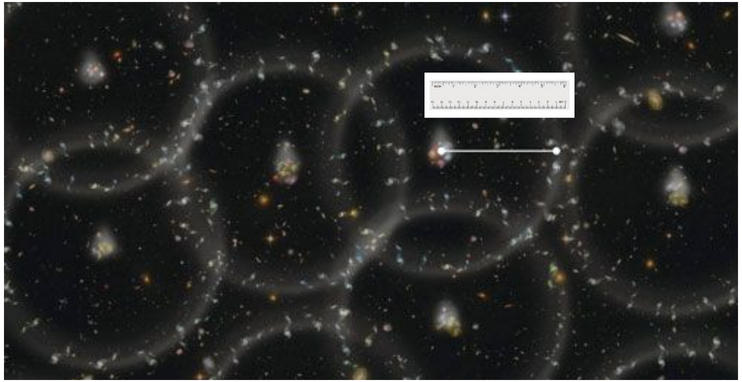
At recombination (z~1000),

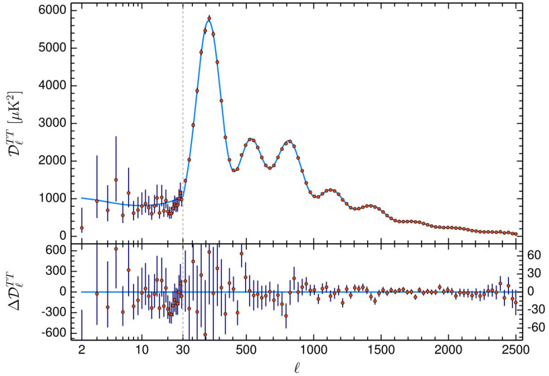
- Optically thick → optically thin
- Baryons decouple from photons.
- Sound speed of gas decreases.
- The traveling wave stalls.

A spherical peak at the distance that the wave has travelled before the recombination

→ **the sound horizon scale** at recombination (~150 Mpc).

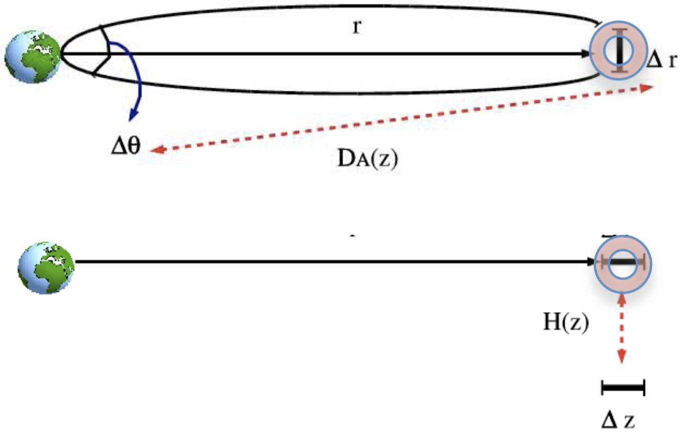
Standard ruler to measure the distances





Planck 2018

The size of the BAO is precisely measured from the CMB data.

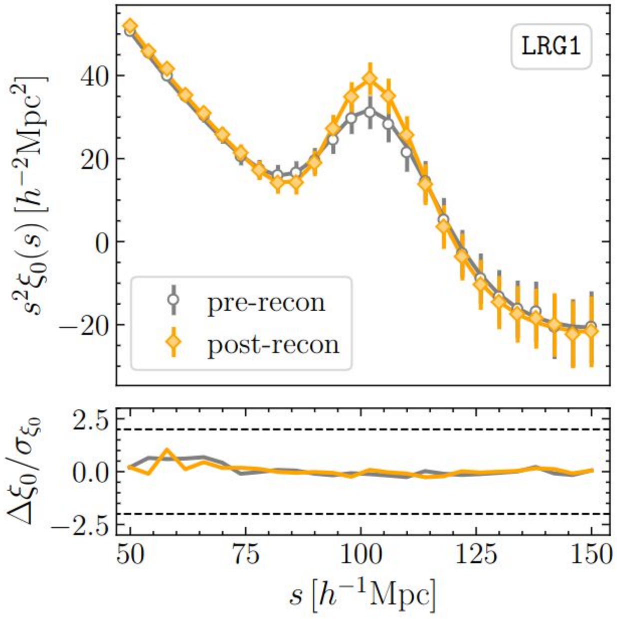


DA(z) and H(z) encode the expansion history of the Universe.

Two point correlation function and BAO

$$\delta(\vec{x}) = \frac{\rho(\vec{x})}{\bar{\rho}} - 1$$

$$\xi(\vec{r}) = \langle\, \delta(\vec{x})\delta(\vec{x}+\vec{r})\,\rangle$$



With a fiducial cosmology,
we convert angles and redshifts
into comoving separations

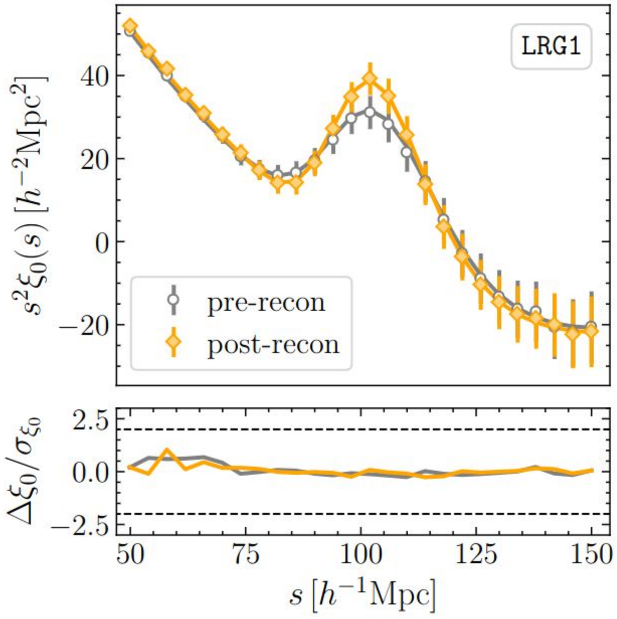
$$r_\parallel = [D_C(z_i) - D_C(z_j)]\cos(\theta_{ij}/2)$$
$$r_\perp = [D_M(z_i) + D_M(z_j)]\sin(\theta_{ij}/2)$$

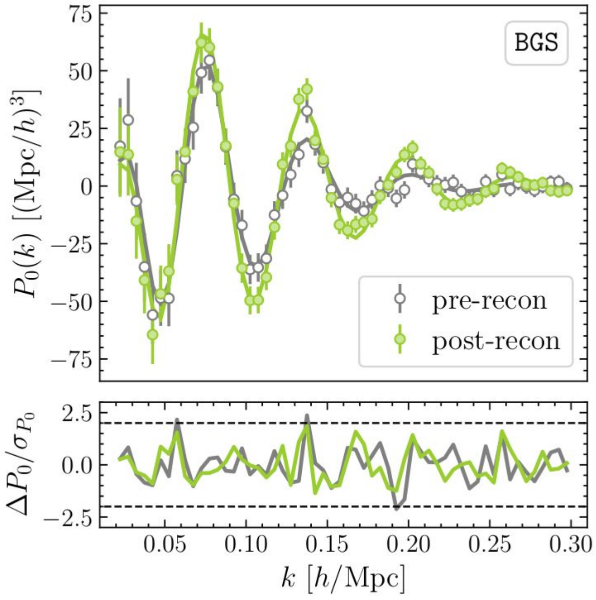
$D_C(z)$: comoving distance
$D_M(z)$: comoving angular distance

Two point correlation function and BAO

$$\delta(\vec{x}) = \frac{\rho(\vec{x})}{\bar{\rho}} - 1$$

$$\xi(\vec{r}) = \langle\, \delta(\vec{x})\delta(\vec{x}+\vec{r})\, \rangle \qquad P(\vec{k}) = \int d^3r\, \xi(\vec{r}) e^{-i\vec{k}.\vec{r}}$$



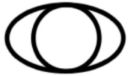


BAO Fit Method

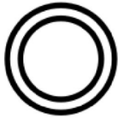
- The correlation function model is decomposed into a smooth and a peak component.
- Only the peak component is stretched with the BAO parameters.
- There are additional nuisance parameters in the model.
- All of them are fitted simultaneously.

$$\xi(r_{||}, r_\perp) = \hat{\xi}_{\mathrm{s}}(r_{||}, r_\perp) + \hat{\xi}_{\mathrm{p}}(\alpha_{||} r_{||}, \alpha_\perp r_\perp)$$

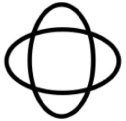
$$\alpha_{||} = \frac{D_H(z_{\mathrm{eff}})/r_d}{[D_H(z_{\mathrm{eff}})/r_d]_{\mathrm{fid}}}$$



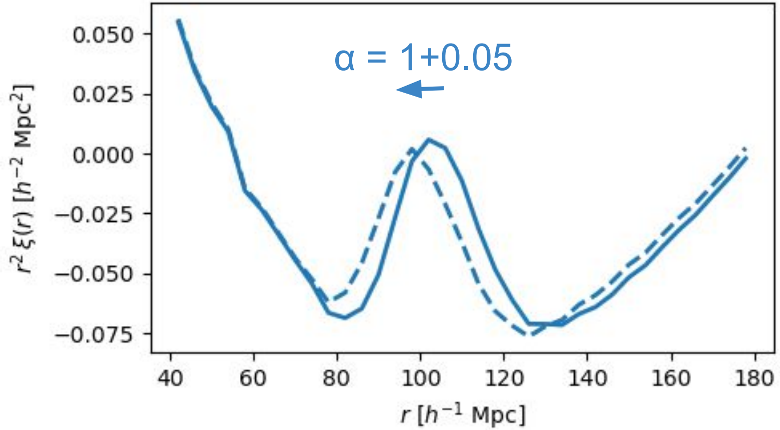
$$\alpha_\perp = \frac{D_M(z_{\mathrm{eff}})/r_d}{[(D_M(z_{\mathrm{eff}})/r_d]_{\mathrm{fid}}}$$



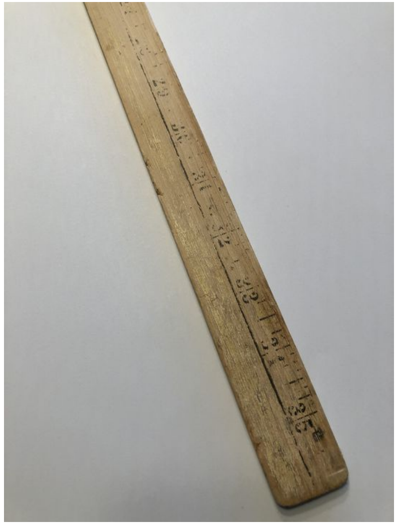
$$\alpha_{\mathrm{iso}} = (\alpha_\perp^2 \alpha_{||})^{1/3}$$



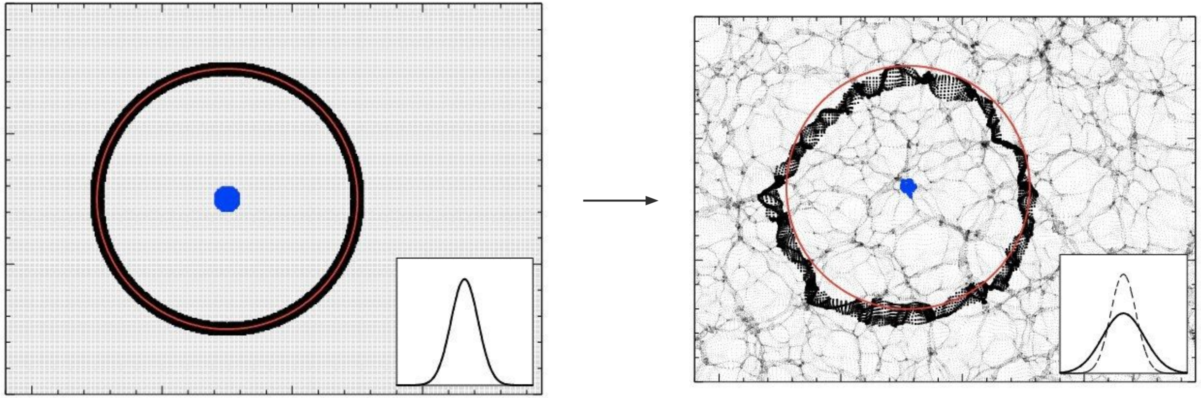
$$\alpha_{\mathrm{AP}} = \frac{D_H}{D_M} \frac{D_M^{\mathrm{fid}}}{D_H^{\mathrm{fid}}}$$



Nonlinear evolution of the standard ruler



The ruler gets blurred and shrinks during the structure growth and also due to the distortions by peculiar velocities.



Padmanabhan et al. 2012

This will degrade the accuracy and precision of the standard ruler test.

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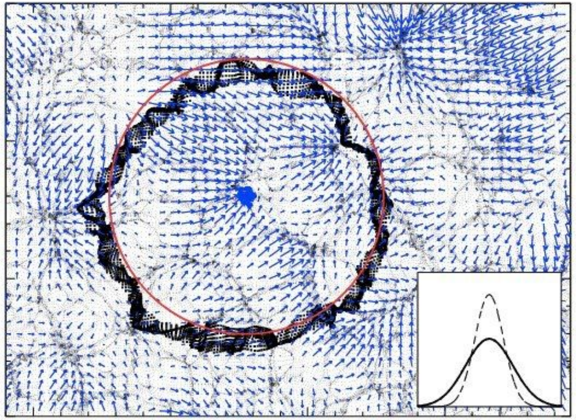
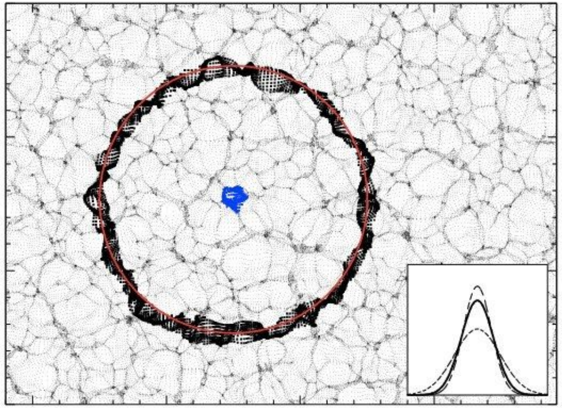
For galaxies and quasar only:
Density-field reconstruction (Eisenstein et al. 2008)

Refurbishes the ruler!





Estimates the displacement field applying the continuity equation on the observed field.
And reverse the displacement.

Improves both precision and accuracy.

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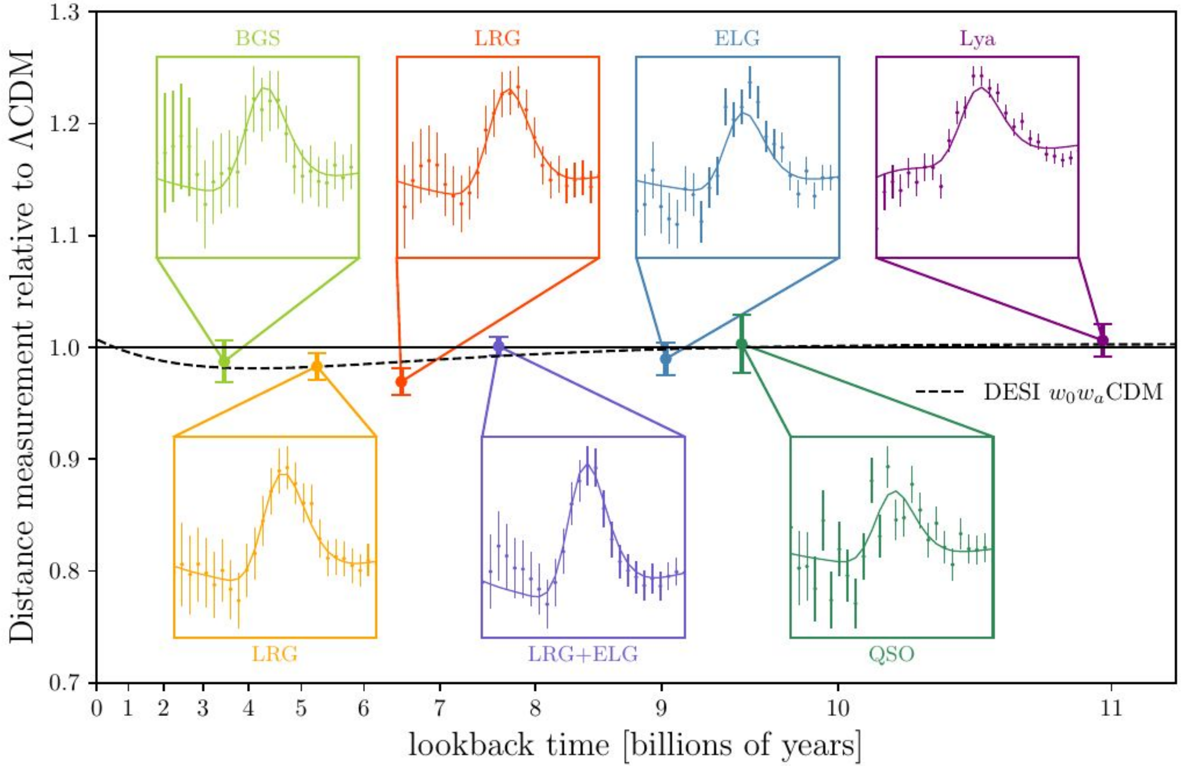
DESI 2024 BAO measurements



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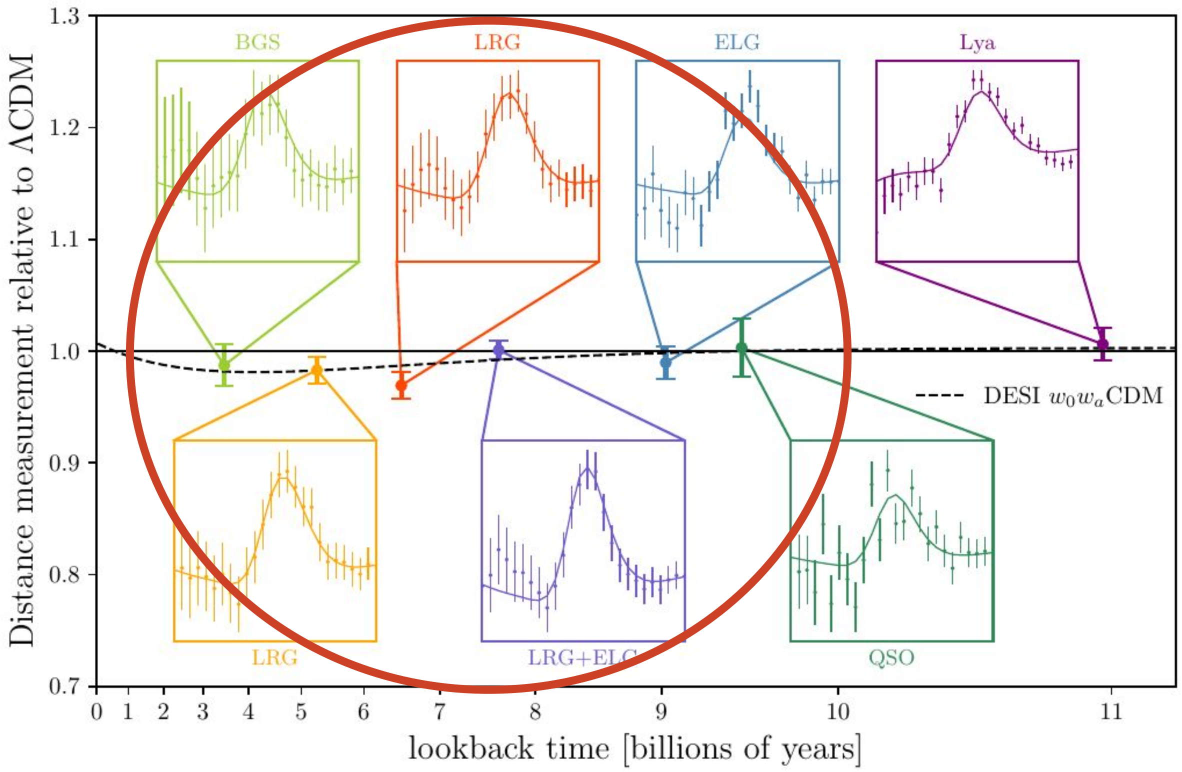
DESI 2024 BAO measurements Part 1 : Galaxies and QSOs (z<2.1)



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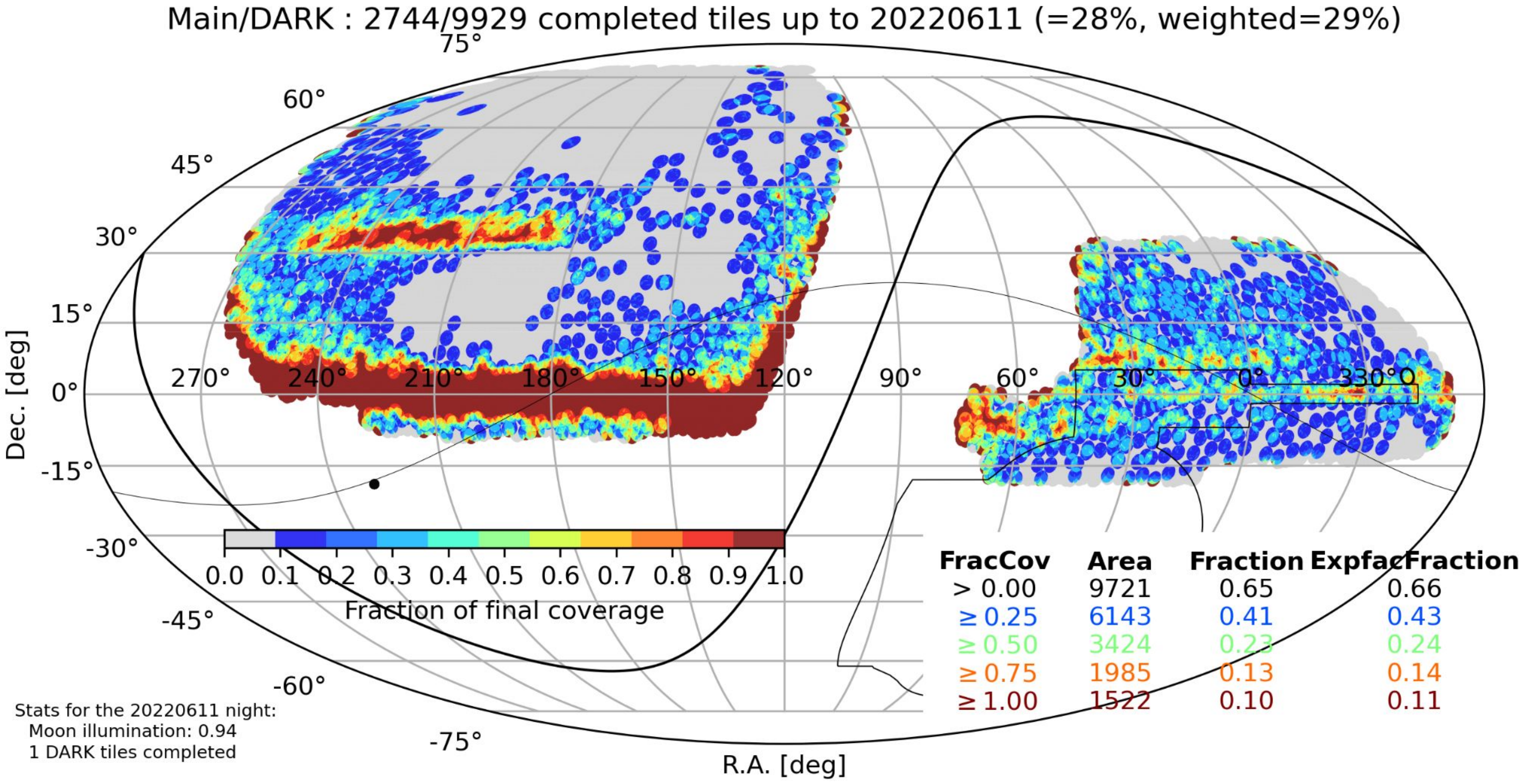
DESI Data Release 1 footprint



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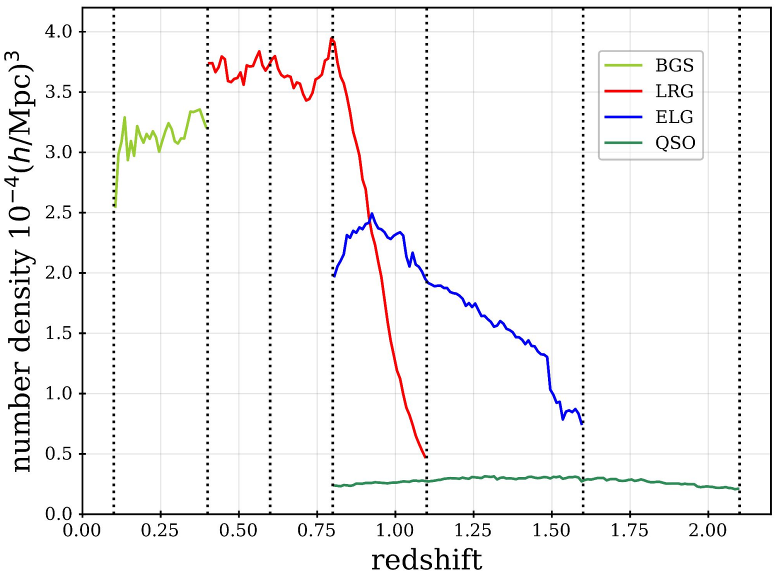
DESI 2024 galaxy and quasar BAO at z < 2.1



Four different large-scale tracers, including emission line galaxies.

5.7 million unique redshifts with the effective cosmic volume of **18 Gpc^3**

A factor of 3 times bigger than SDSS.

Split to six redshift bins to probe the expansion history as a function of lookback time.

How is the DESI BAO analysis different?

- **The biggest data set both in terms of the number and the volume.**
- **First time a catalog-level blinded BAO analysis to mitigate the confirmation bias.**

$$(\mathrm{ra}, \mathrm{dec}, z) \xrightarrow{\text{fiducial cosmology}} (X, Y, Z) \xrightarrow{\text{blind cosmology } w_0,\, w_a,\, \Omega_m \text{ (not revealed!)}} (\mathrm{ra}, \mathrm{dec}, z')$$

+ change to peculiar velocity contributions to redshift to blind growth rate

+ weights-based blinding for primordial non-Gaussianity f_{NL}

How is the DESI BAO analysis different?

- **The biggest data set both in terms of the number and the volume.**
- **First time a catalog-level blinded BAO analysis to mitigate the confirmation bias.**
- Almost all systematics and the baseline methods are determined before unblinding.
- **Unified BAO framework/pipeline/systematic test on all tracers over a wide redshift range as well as between the Fourier space and the configuration space.**
- Physically-motivated enhancements to the BAO fitting method.
- A new reconstruction method.
- A combined tracer to deal with the tracers over the same redshift range (LRG and ELG 0.8<z<1.1).

Systematics test summary

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- No systematics detected for
  - Observational effects,
  - Reconstruction choice,
  - Analytic covariance matrix.

The rest are assigned with systematics

Systematics << Statistical errors.

Max. effect:

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

	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

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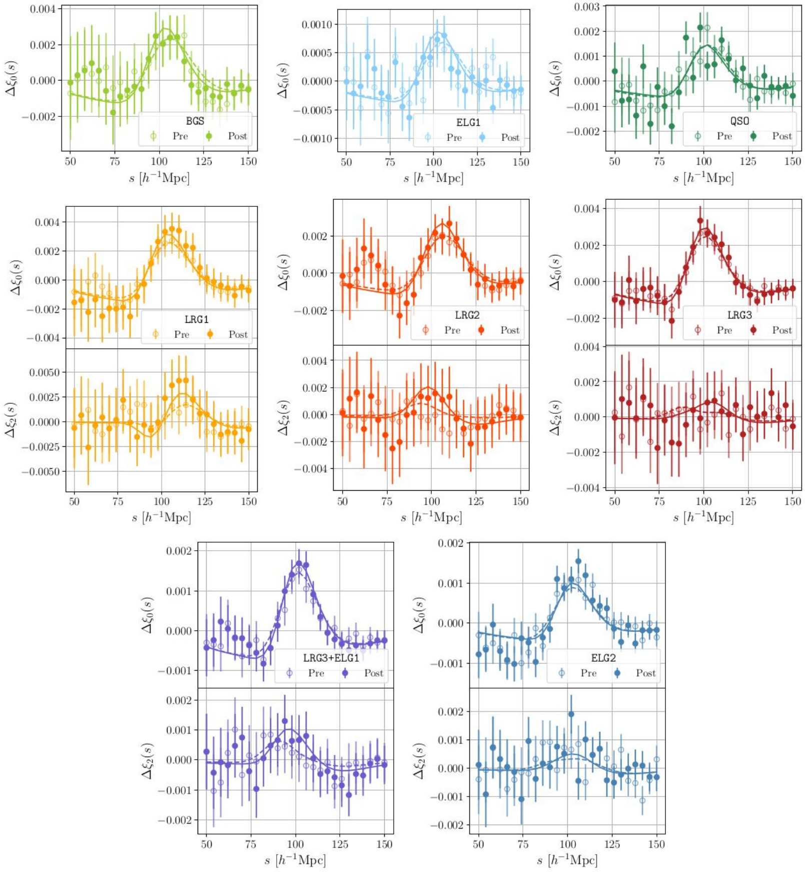
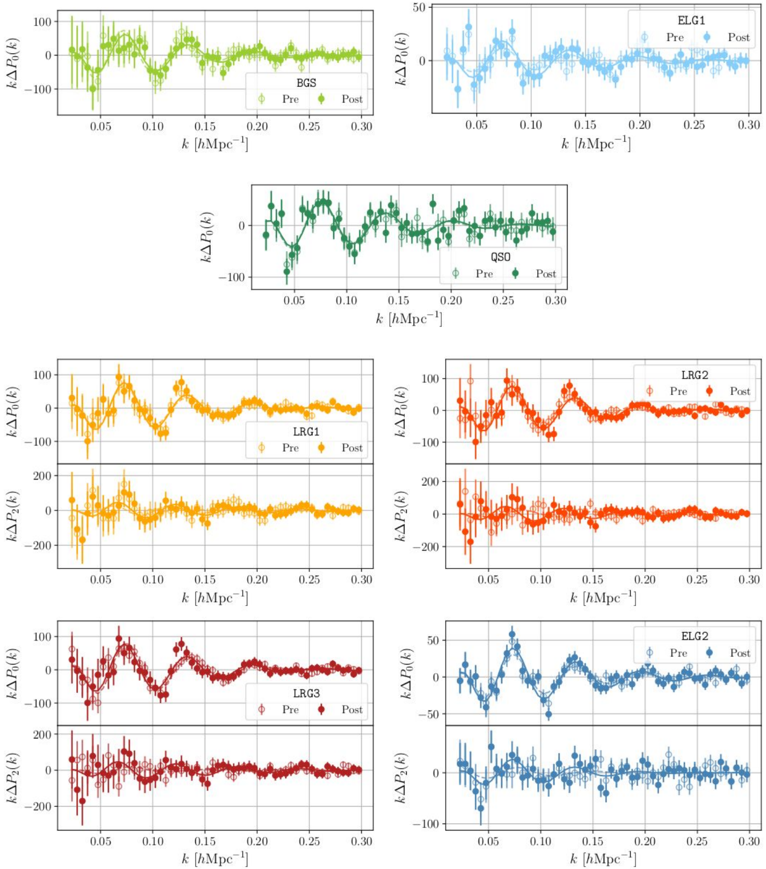
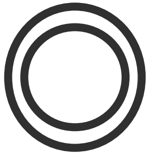
Unblinded galaxy BAO feature highlights



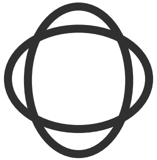


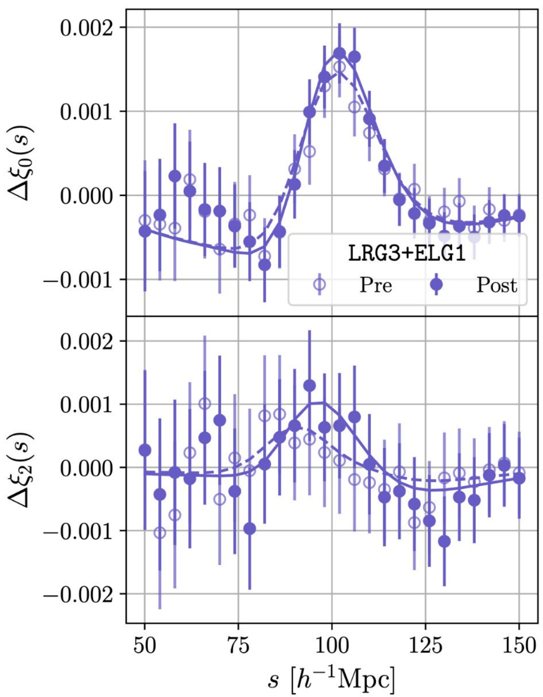
Unblinded galaxy BAO feature highlights

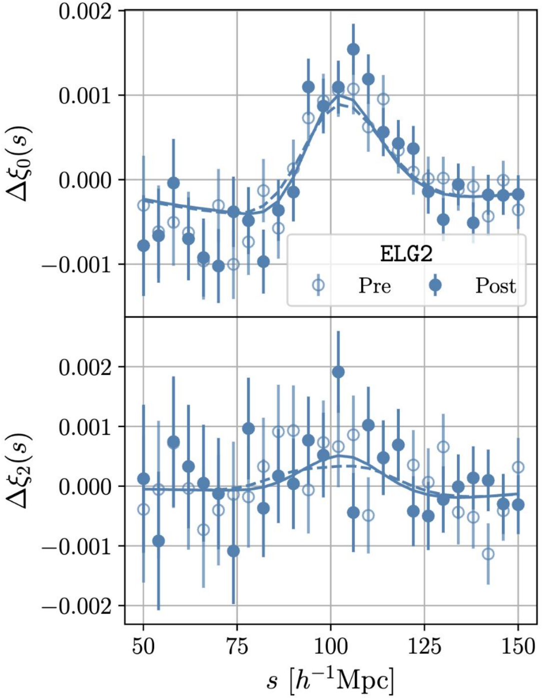
Overall size of the BAO



Anisotropy of the BAO







BAO feature singled out

Combined tracer
at $z_{eff} = 0.93$
Distance measured at 0.8%

Emission Line Galaxies
at $z_{eff} = 1.32$
Distance measured at 1.5%.

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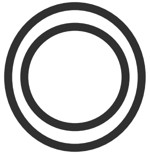
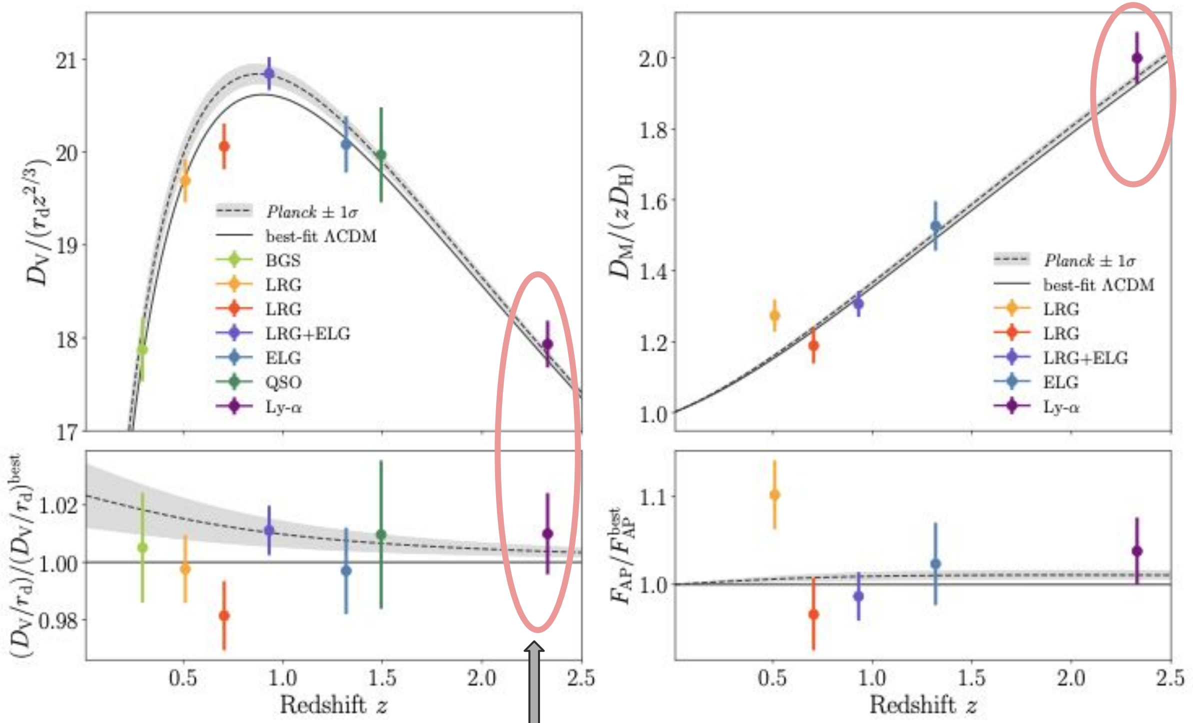
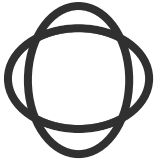
BAO Hubble diagram using DESI 2024



Overall size of the BAO





Anisotropy of the BAO

LyA- BAO (next slides)

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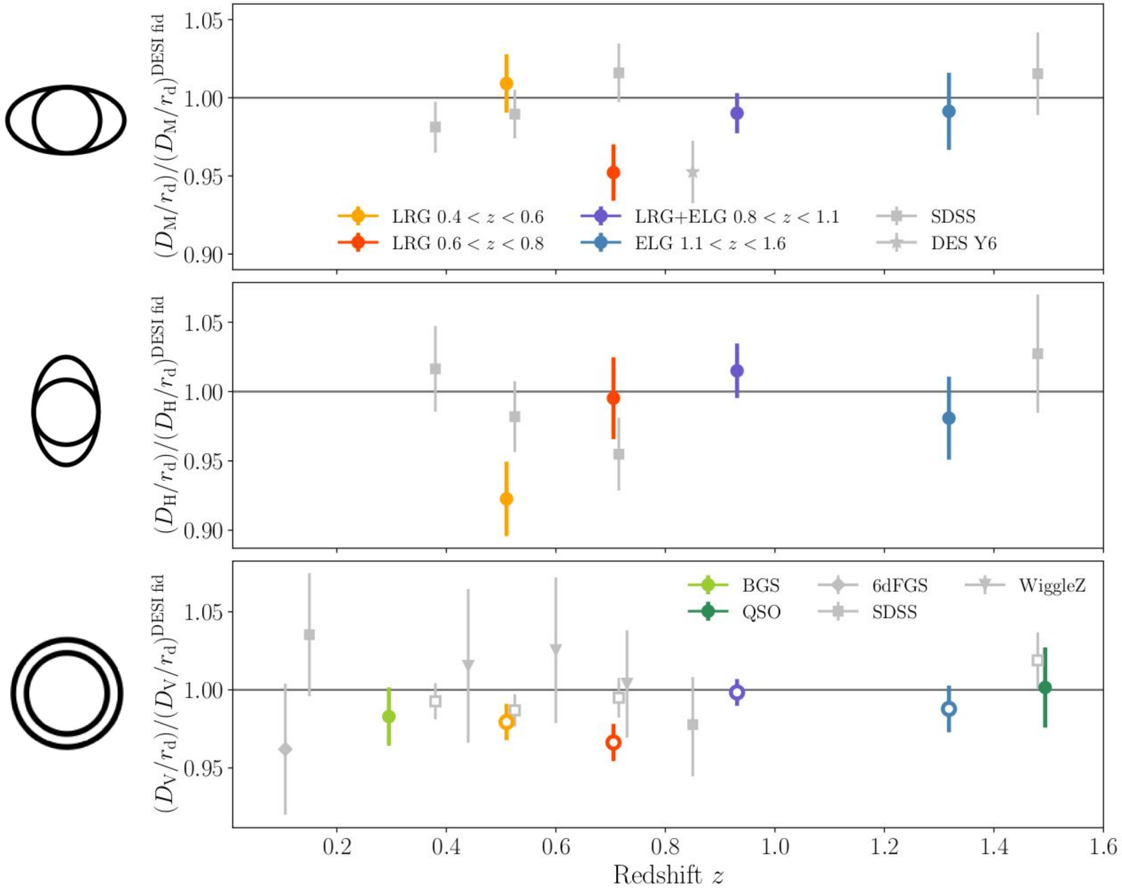
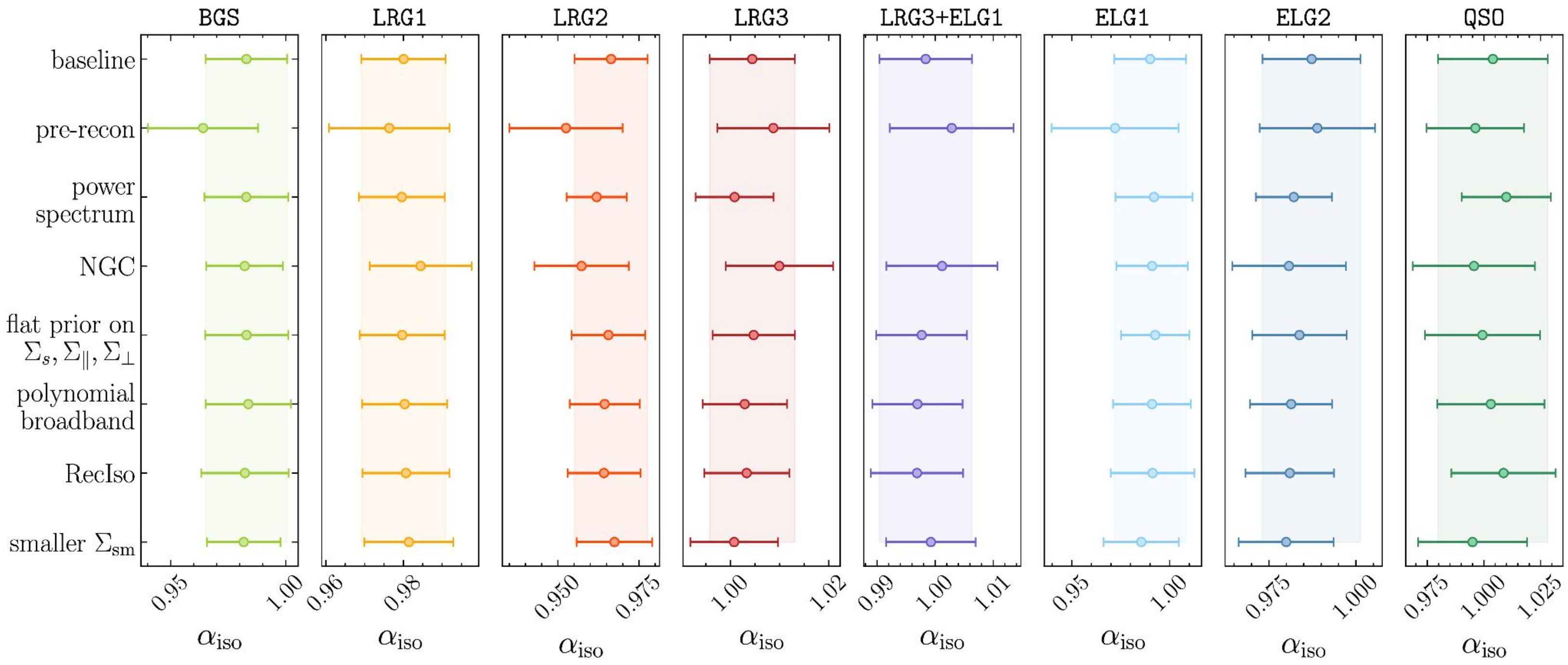
BAO Hubble diagram : 0.52% aggregate precision

Fiducial cosmology :
(solid lines)
Planck 2018 LCDM

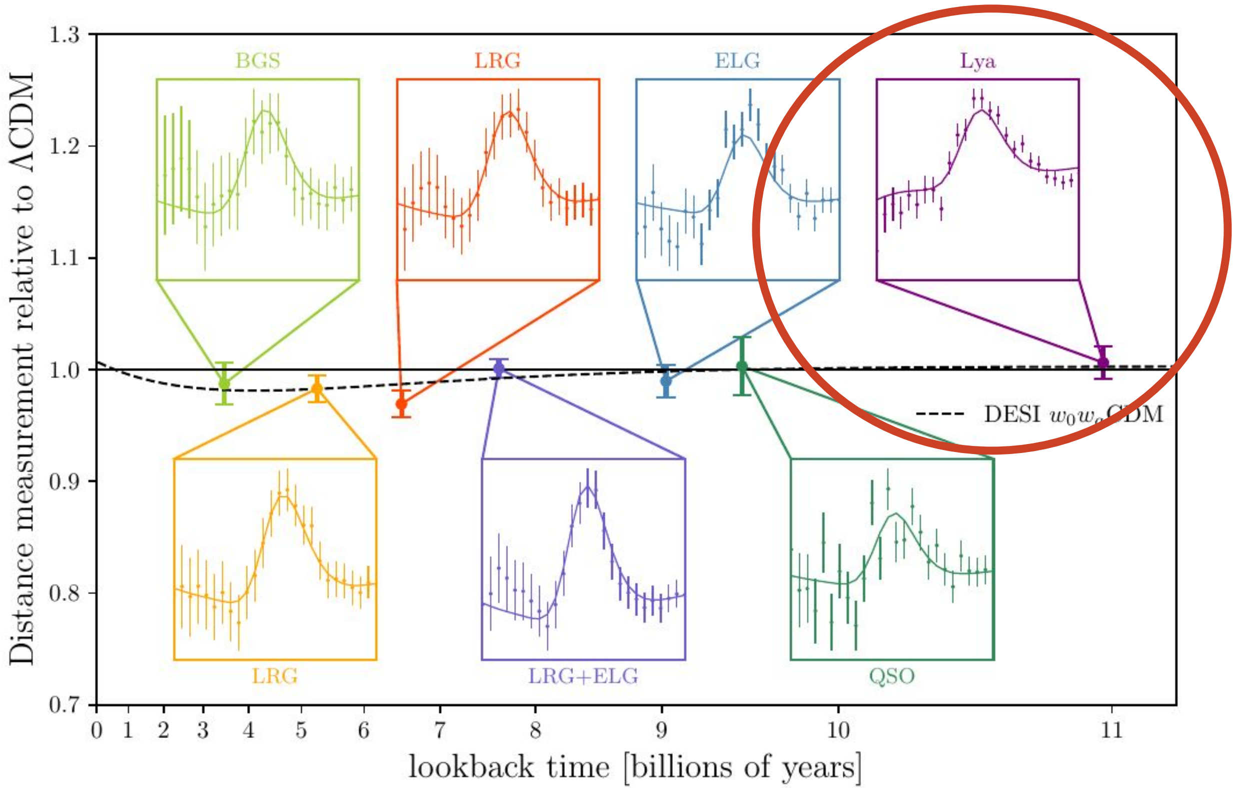
Parameter	Planck (2018) cosmology (TT,TE,EE+lowE+lensing)
Ω_m	0.31509
Ω_r	7.9638e-05
$\sigma_8(z=0)$	0.8119
r_d [Mpc]	147.09
r_d [h^{-1}Mpc]	99.08
$D_\mathrm{H}(z_\mathrm{eff}=2.33)/r_\mathrm{d}$	8.6172
$D_\mathrm{M}(z_\mathrm{eff}=2.33)/r_\mathrm{d}$	39.1879



Consistency tests with the unblinded data

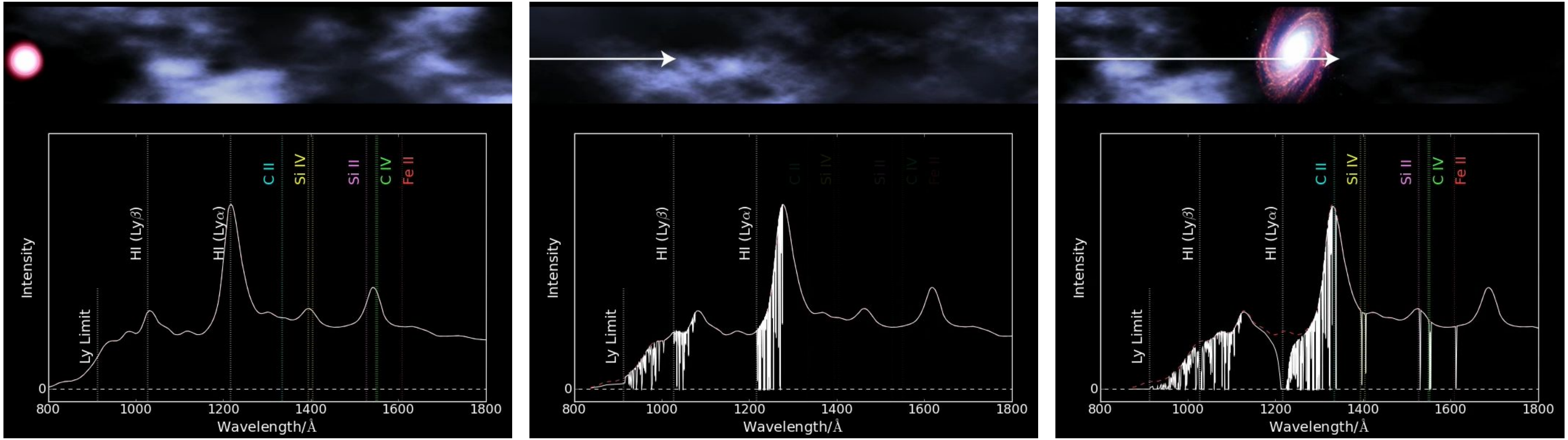


DESI 2024 BAO measurements
Part 2 : Lyman-alpha forest (z>2)



The Lyman-α Forest

credit: Andrew Pontzen



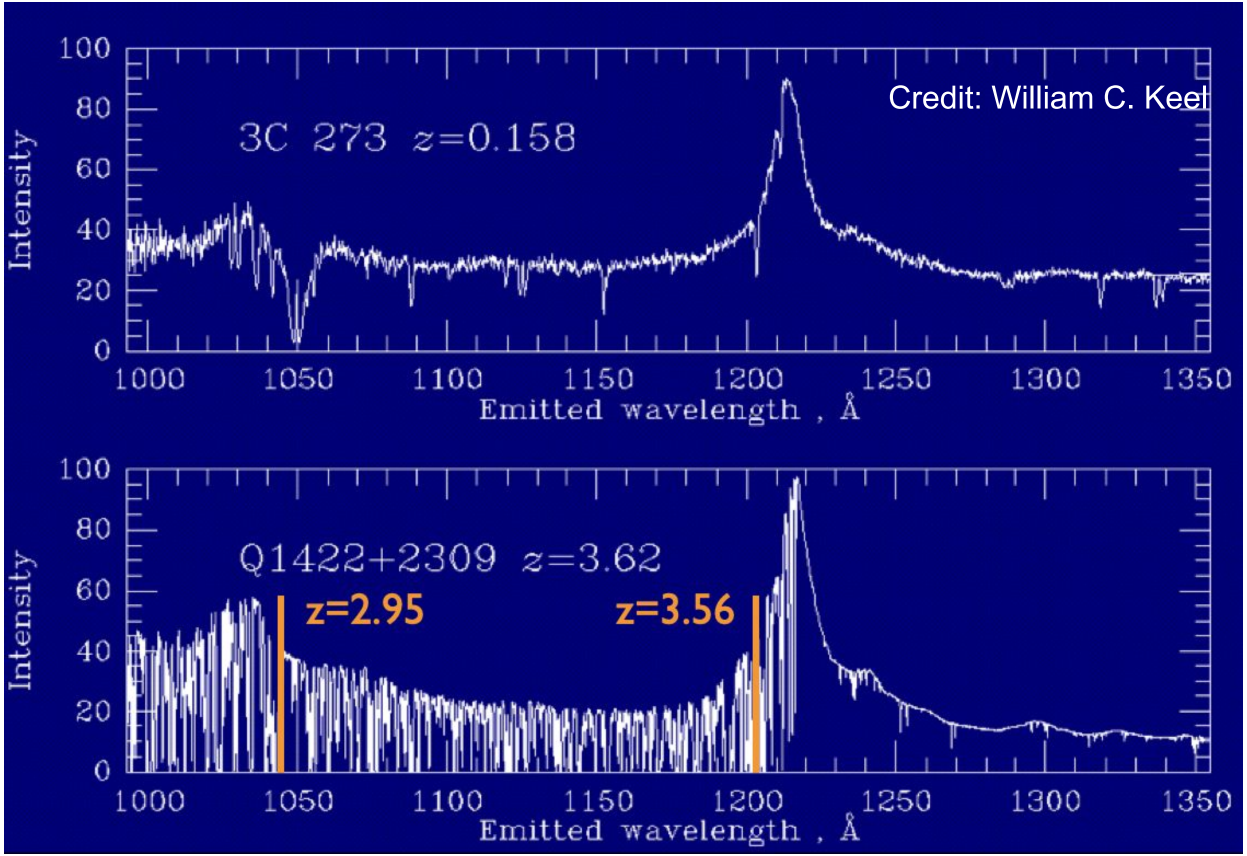
Background quasar — Intervening gas → Earth

$$F = e^{-\tau}$$

$$\tau \propto n_{HI}$$

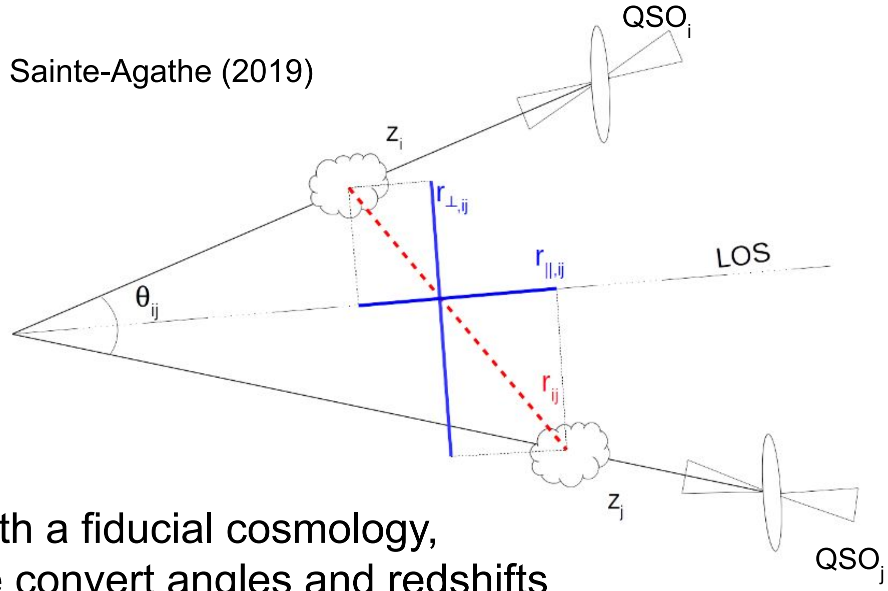
- Absorption in QSO spectra by neutral hydrogen in the intergalactic medium
- The transmitted flux fraction F is a cosmological probe of the fluctuation in the neutral hydrogen density

The Lyman-α Forest



Lyman-alpha (Lya) Auto-Correlation function

de Sainte-Agathe (2019)



Transmitted flux fraction

$$F = e^{-\tau}$$

Transmitted flux fraction contrast

$$\delta_F = \frac{F}{\overline{F}} - 1$$

Auto-correlation function

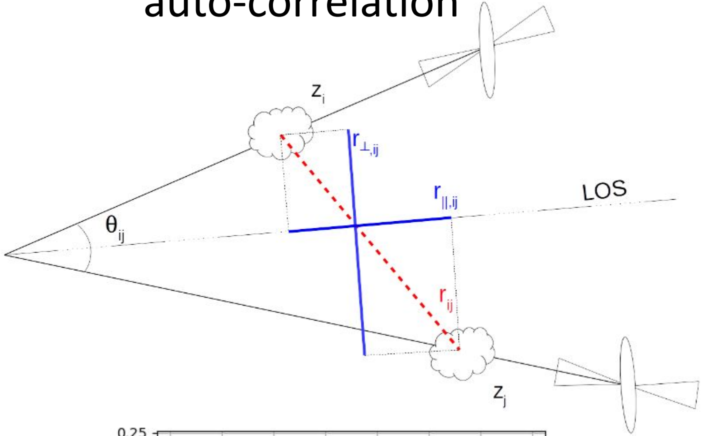
$$\xi(\vec{r}) = \langle\, \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r})\,\rangle$$

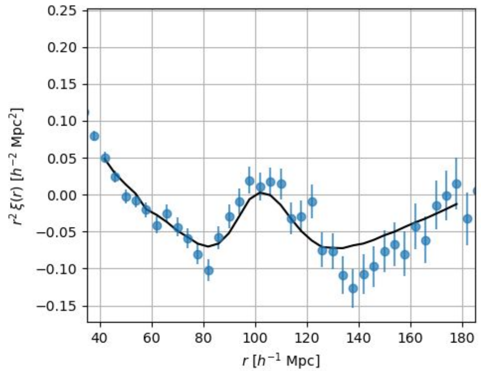
With a fiducial cosmology,
we convert angles and redshifts
into comoving separations

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

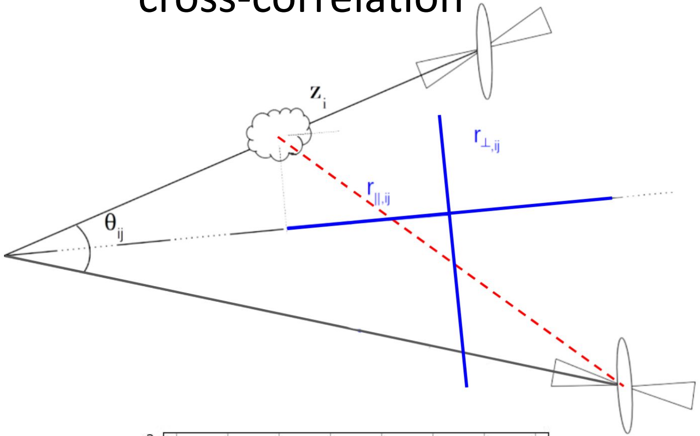
$D_C(z)$: comoving distance
$D_M(z)$: comoving angular distance

Lya-Lya auto-correlation

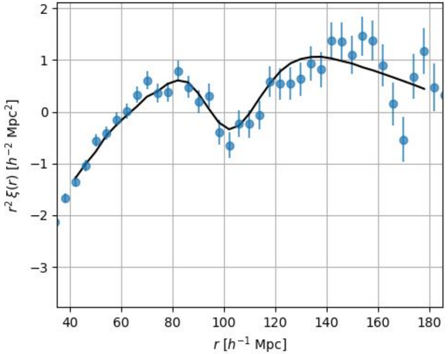




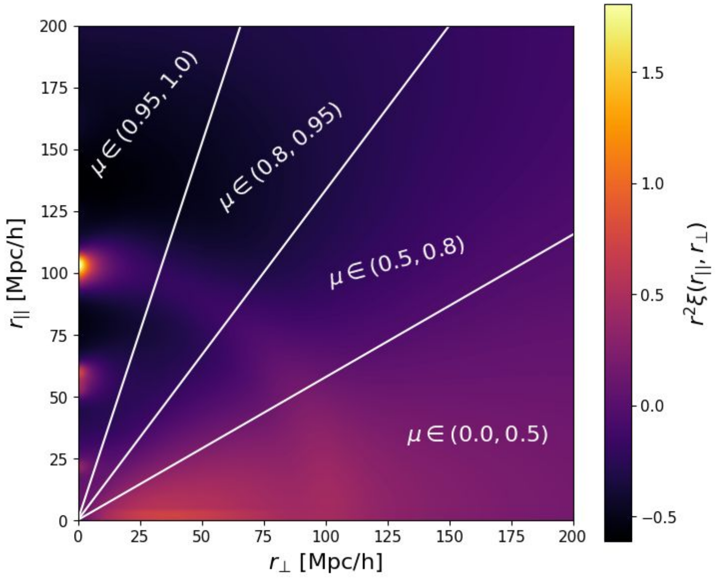
Lya-QSO cross-correlation

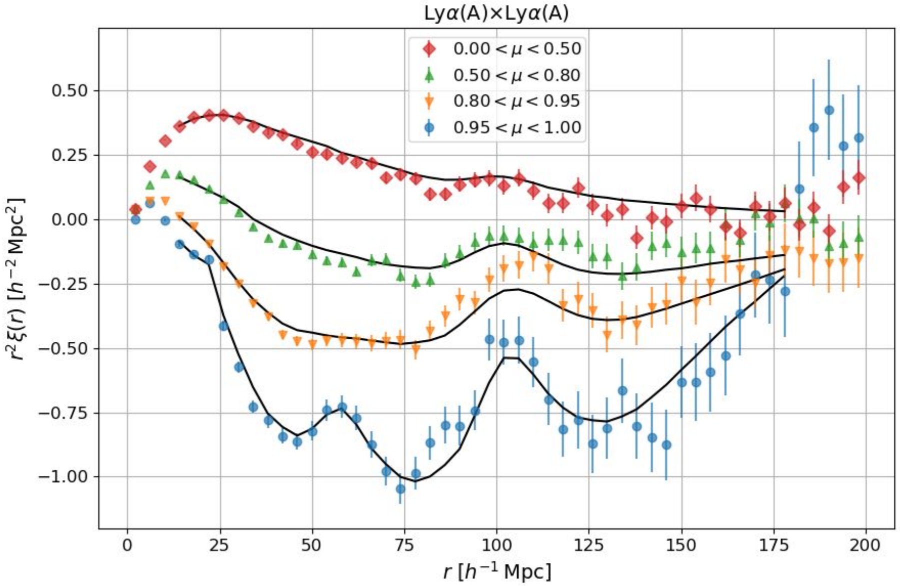


QSO at z_j



2D correlation function





- measurement: 2D rectangular grid, with bins of (4 Mpc/h) x (4 Mpc/h)
- represented with 'wedges' , as a function of r, average over mu
- large redshift space distortion effect for Lyman-alpha
- presence of spurious correlations because of metals (more details later)

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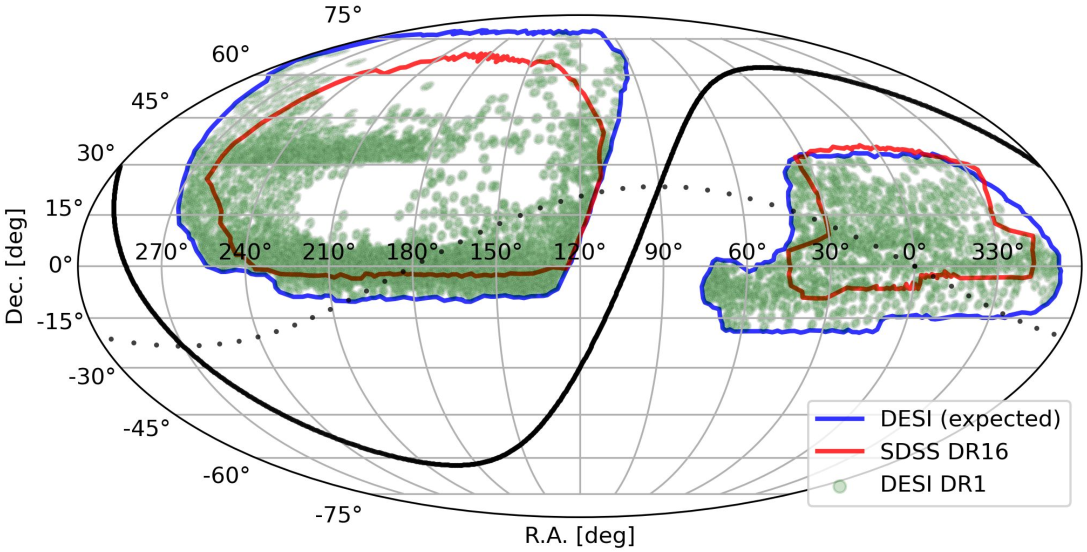
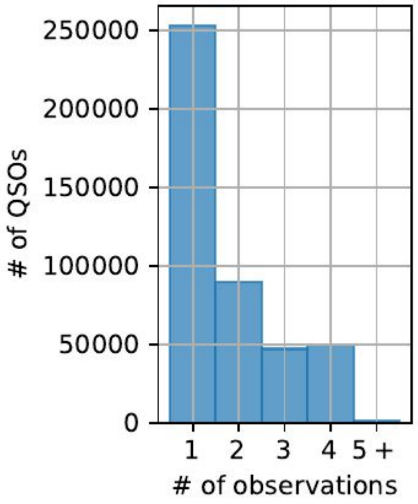
DESI Year 1 Quasar and Lyman-alpha sample

0.71 million tracer QSOs (z>1.77)
0.42 million Lya QSOs (z>2.1)
(after selection cuts)
Already twice as large as the full SDSS sample of Lya QSOs





DESI-Y1 Quasar and Lya sample

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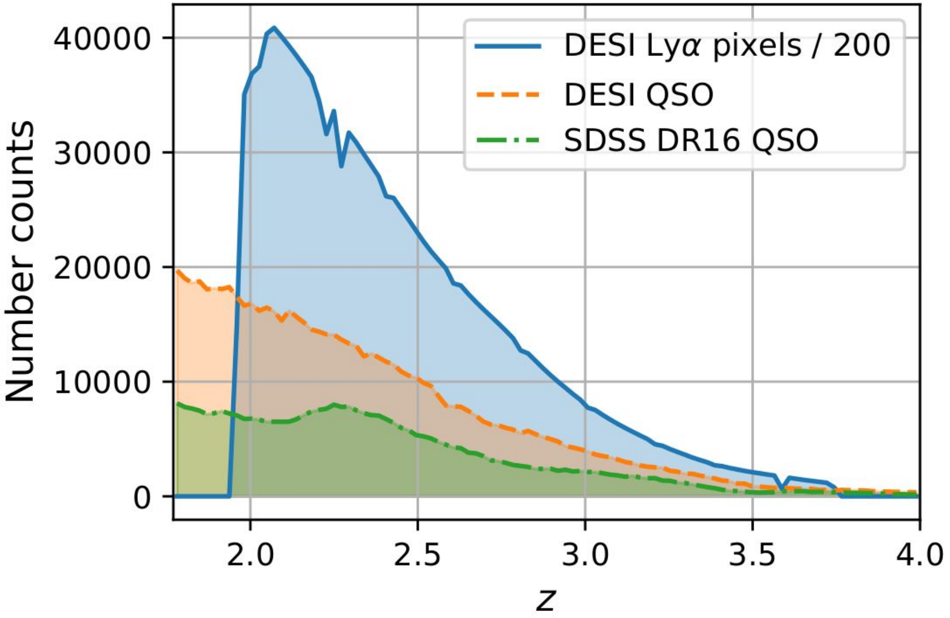
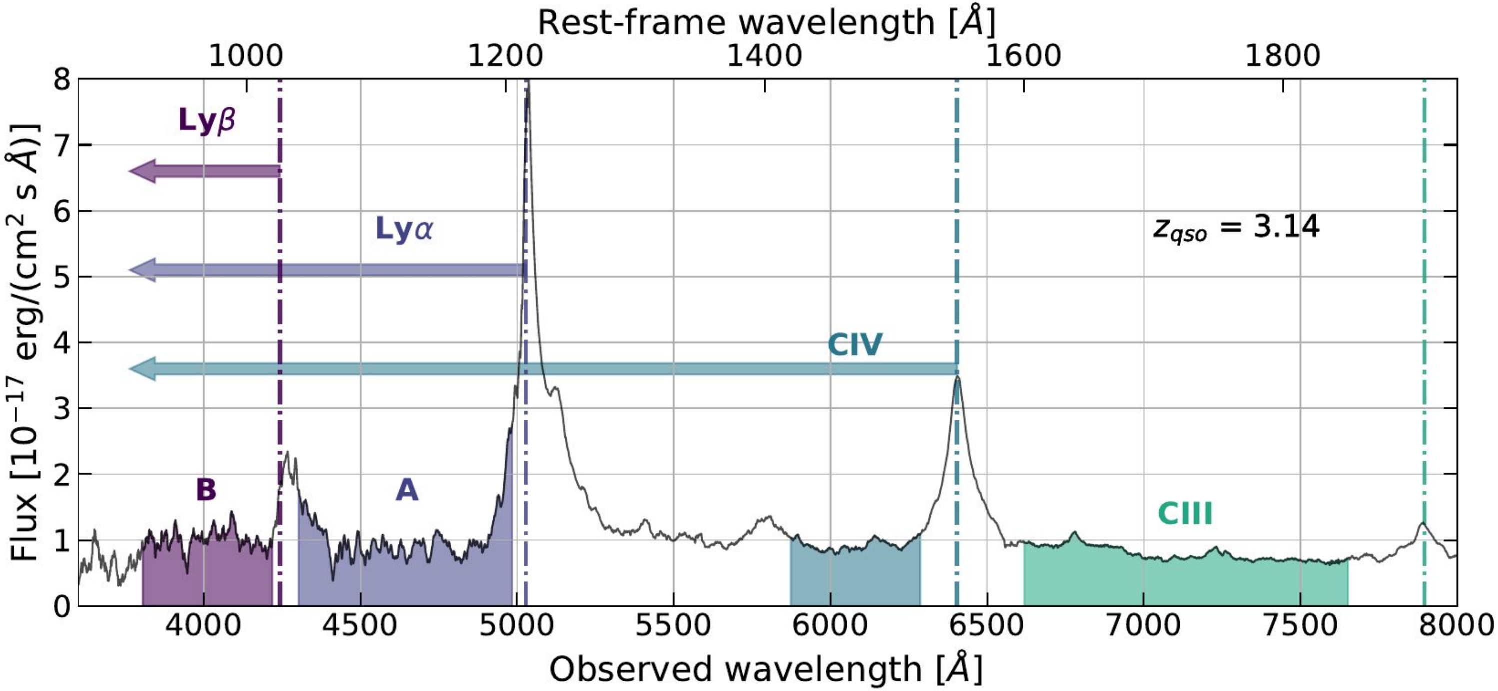
95% of signal from 1.96 < z < 2.8 (2.95) for LyaxLya (LyaxQSO)
Effective redshift: z=2.33

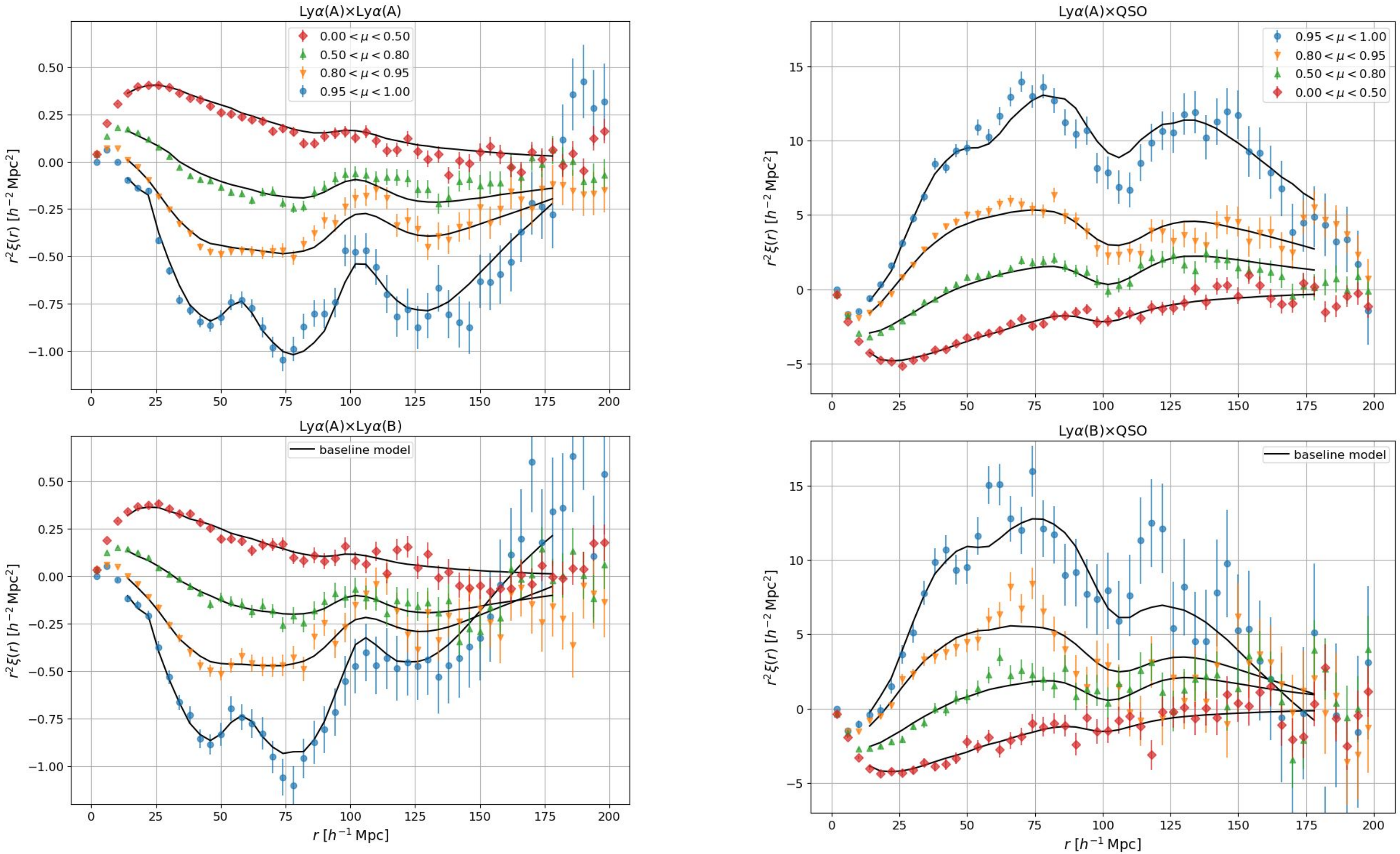


2 spectral regions , 4 correlation functions

Lya(A) x Lya(A)
Lya(A) x Lya(B)
Lya(A) x QSO
Lya(B) X QSO



4 correlation functions



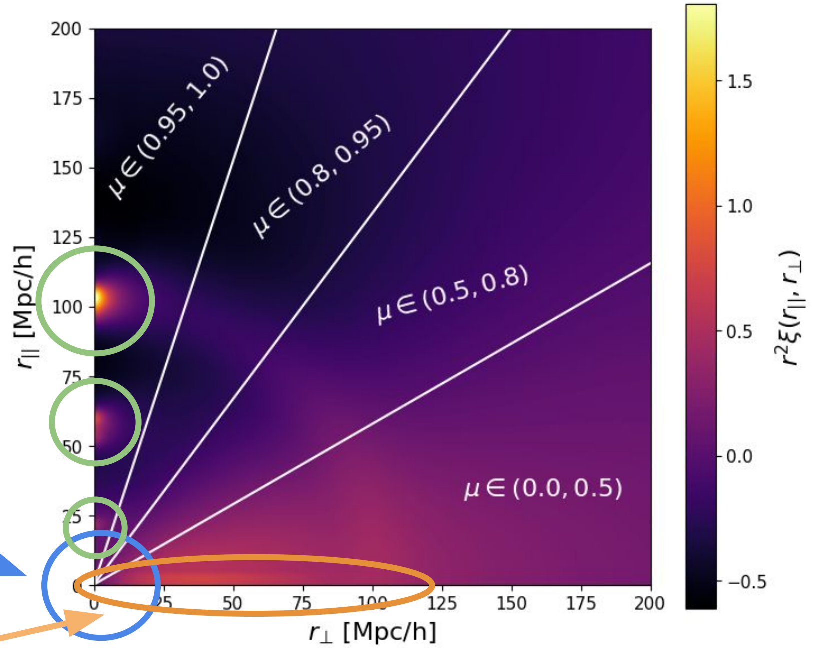
Contaminants to Lyman-alpha forest

- "Metal lines" seen in cross-correlation with Lyman alpha
  Si III (1207A) , Si II (1191,1193A) , Si II (1260A) peaking at

$$r_{\parallel} \sim \frac{c}{H(z)} \left| \frac{\lambda_{\rm obs}}{\lambda_{\rm Ly\alpha}} - \frac{\lambda_{\rm obs}}{\lambda_{\rm metal}} \right|$$

- Other foreground absorbers contributing only with their auto-correlation (Mg II, C IV, Si IV)

- Correlated noise introduced with the data processing (sky model noise) [Guy, Gontcho A Gontcho et al 2024]



All contaminants are modelled and part of the simultaneous fit

A blinded analysis from end-to-end

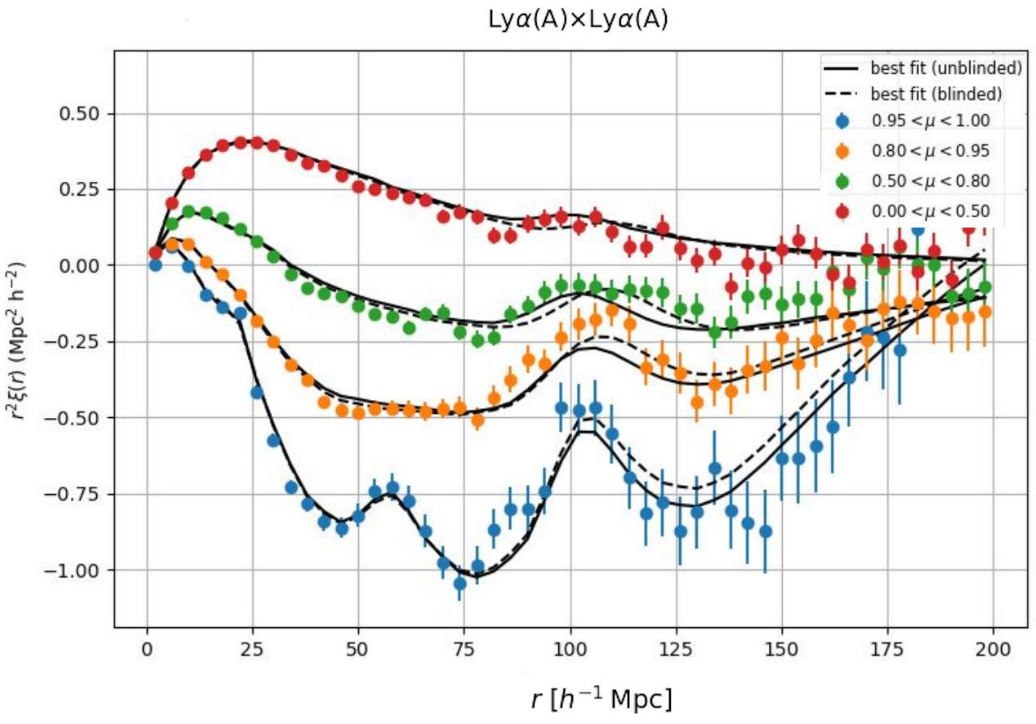
Analysis fully developed with mocks and blinded data

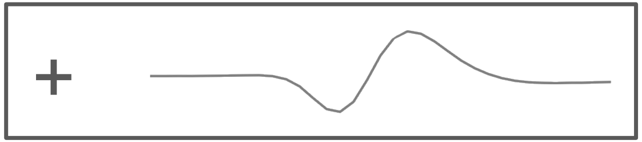
List of validation tests defined in advance

Report to the collaboration on the validation tests on blinded data

Unblinding in Dec. 2023

A blinded analysis from end-to-end





Blinding method :

- Additive perturbation to all correlation functions
- Corresponds to a secret shift of BAO scale
- Based on best fit Lya model from SDSS DR16

A blinded analysis from end-to-end

Tests run before unblinding

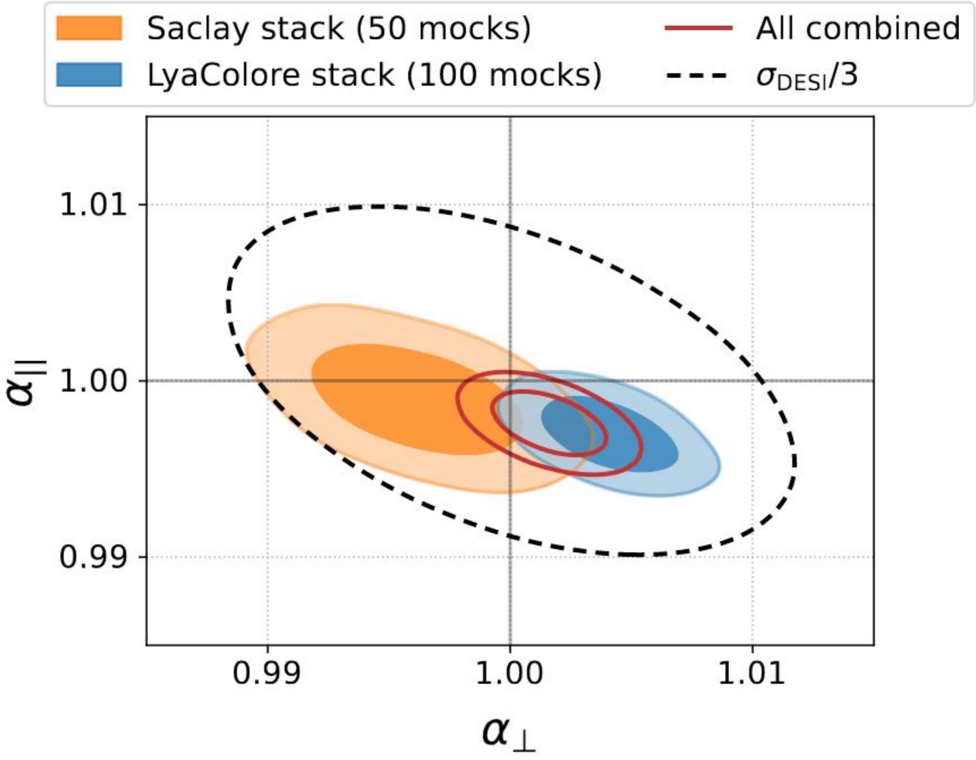
1. Validation with mocks (synthetic data sets):
    a. recover unbiased BAO parameters (**< ⅓ of statistical uncertainty**)
    b. good understanding of statistical uncertainties on BAO

2. Data splits on the blinded data set

3. Variation in the choice of analysis parameters

1. Validation with mocks

[Cuceu, Herrera-Alcantar et al. 2024]
Synthetic data sets of the Year 1 sample



Best fit BAO parameters offsets from truth:

< ⅓ of DESI Y1 statistical uncertainty (dashed ellipse)
< 0.4% (not significant, but treated as conservative systematic uncertainty)

(contours are 68% and 95% C.L.)

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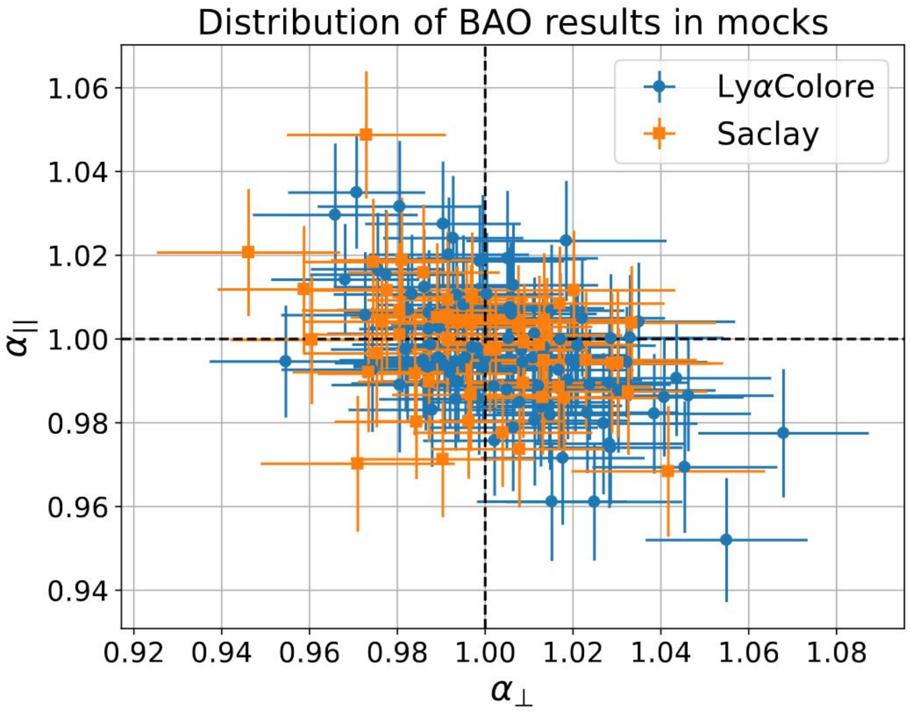
1. Validation with mocks

[Cuceu, Herrera-Alcantar et al. 2024]
Synthetic data sets of the Year 1 sample

Best fit BAO parameters scatter found consistent with expected statistical uncertainties:
rms values

$$\Delta\alpha_{||}/\sigma_{\alpha_{||}} = 1.01 \pm 0.07$$

$$\Delta\alpha_{\perp}/\sigma_{\alpha_{\perp}} = 1.11 \pm 0.06$$



2. Data splits

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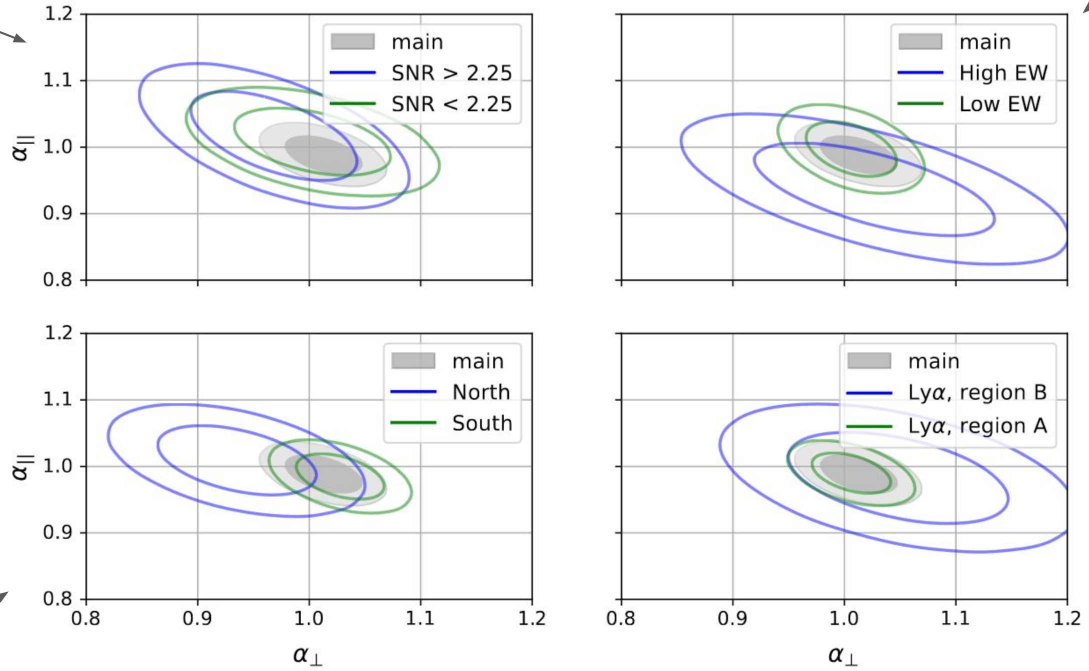
All found consistent within statistical uncertainties

test: spectroscopic data reduction systematics

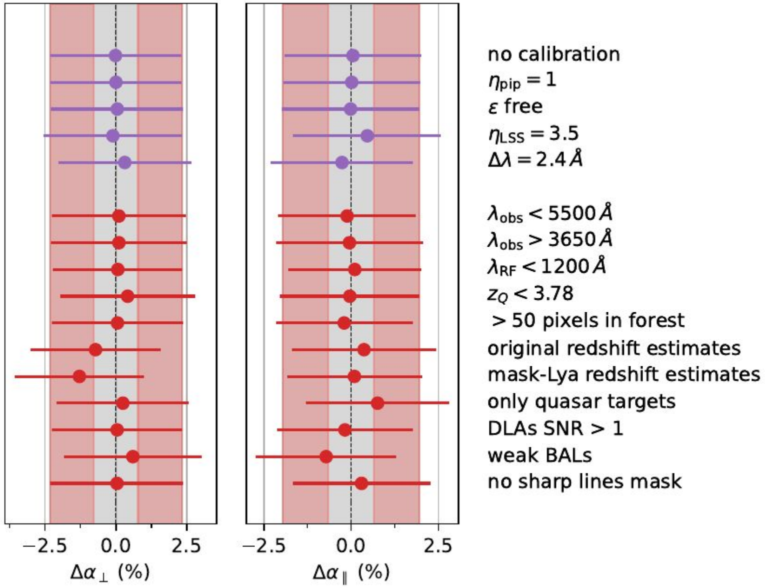
test: systematics from QSO continuum coupled to bias variations

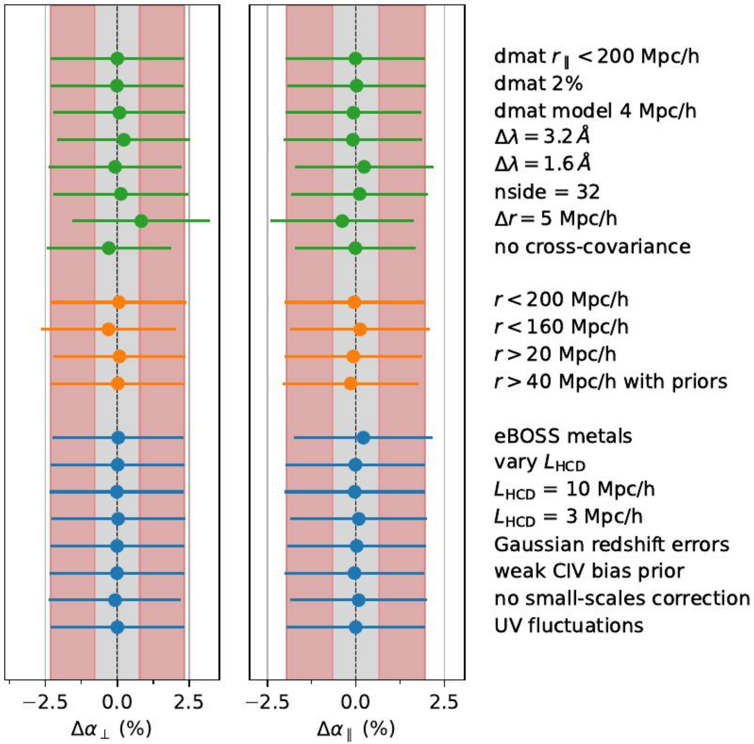


test: target selection systematics

test: continuum systematics, contaminants

3. Variation in the choice of analysis parameters





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

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Unblinding the DESI DR1 Lyman-alpha Results

$$\alpha_{\parallel} = \frac{D_H(z_{\rm eff})/r_d}{[D_H(z_{\rm eff})/r_d]_{\rm fid}}$$

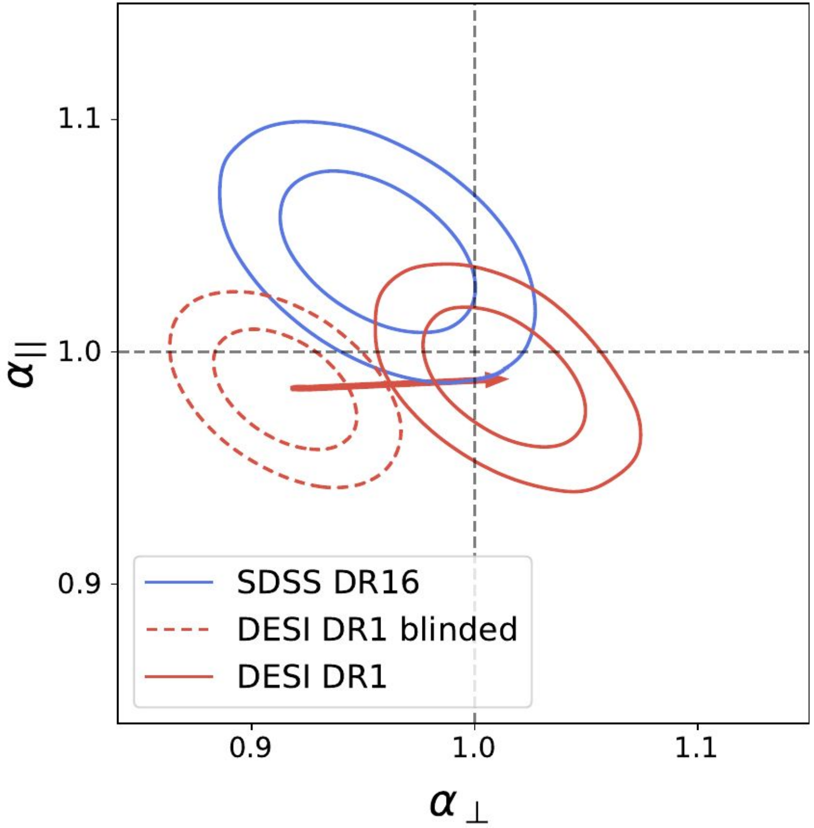
$$\alpha_{\perp} = \frac{D_M(z_{\rm eff})/r_d}{[(D_M(z_{\rm eff})/r_d]_{\rm fid}}$$

$$\alpha_{\parallel} = 0.989 \pm 0.020$$

$$\alpha_{\perp} = 1.013 \pm 0.024$$

Fiducial cosmology:

Parameter	Planck (2018) cosmology (TT,TE,EE+lowE+lensing)
$\Omega_{\rm m}$	0.31509
$\Omega_{\rm r}$	7.9638e-05
$\sigma_8(z=0)$	0.8119
$r_{\rm d}$ [Mpc]	147.09
$r_{\rm d}$ [h^{-1}Mpc]	99.08
$D_{\rm H}(z_{\rm eff}=2.33)/r_{\rm d}$	8.6172
$D_{\rm M}(z_{\rm eff}=2.33)/r_{\rm d}$	39.1879



DESI DR1 Lyman-alpha Results

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$$D_H(z_{\rm eff})/r_d = 8.52 \pm 0.17$$

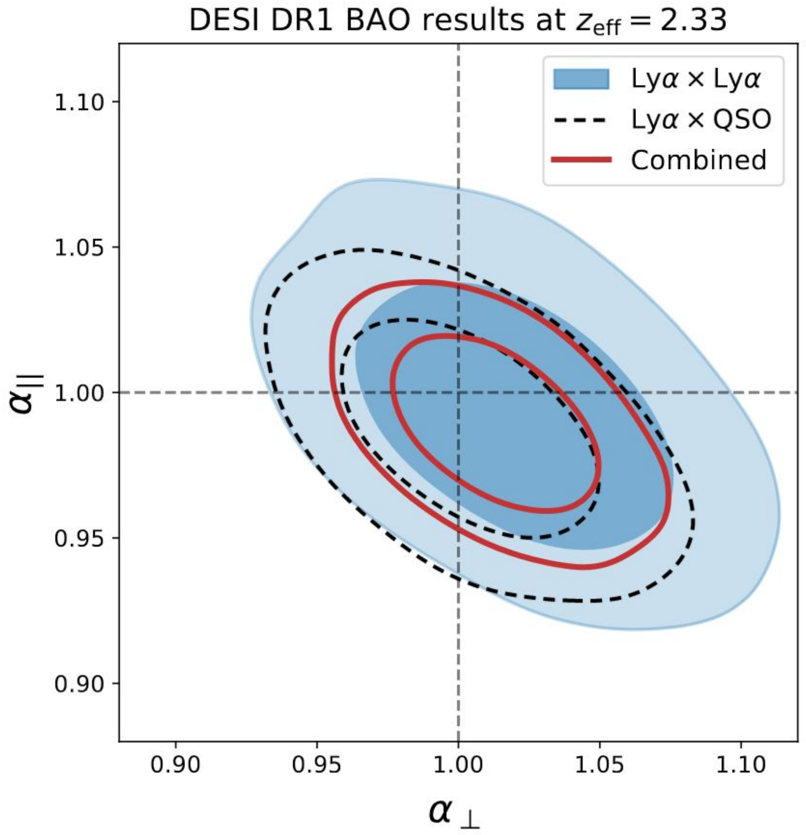
$$D_M(z_{\rm eff})/r_d = 39.71 \pm 0.95$$

with a correlation coefficient $\rho = -0.48$

Optimal combination:

$$D_M(z_{\rm eff})^{9/20} D_H(z_{\rm eff})^{11/20}/r_d = 17.03 \pm 0.19$$

1.1% precision on BAO scale at $z_{\rm eff}$=2.33



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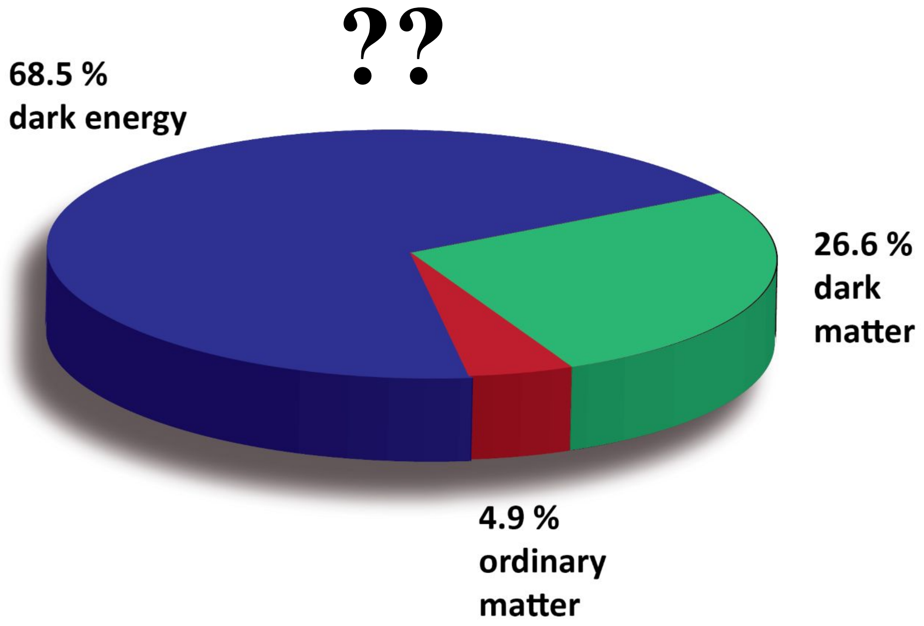
DESI 2024 BAO measurements
Part 3 : cosmological implications



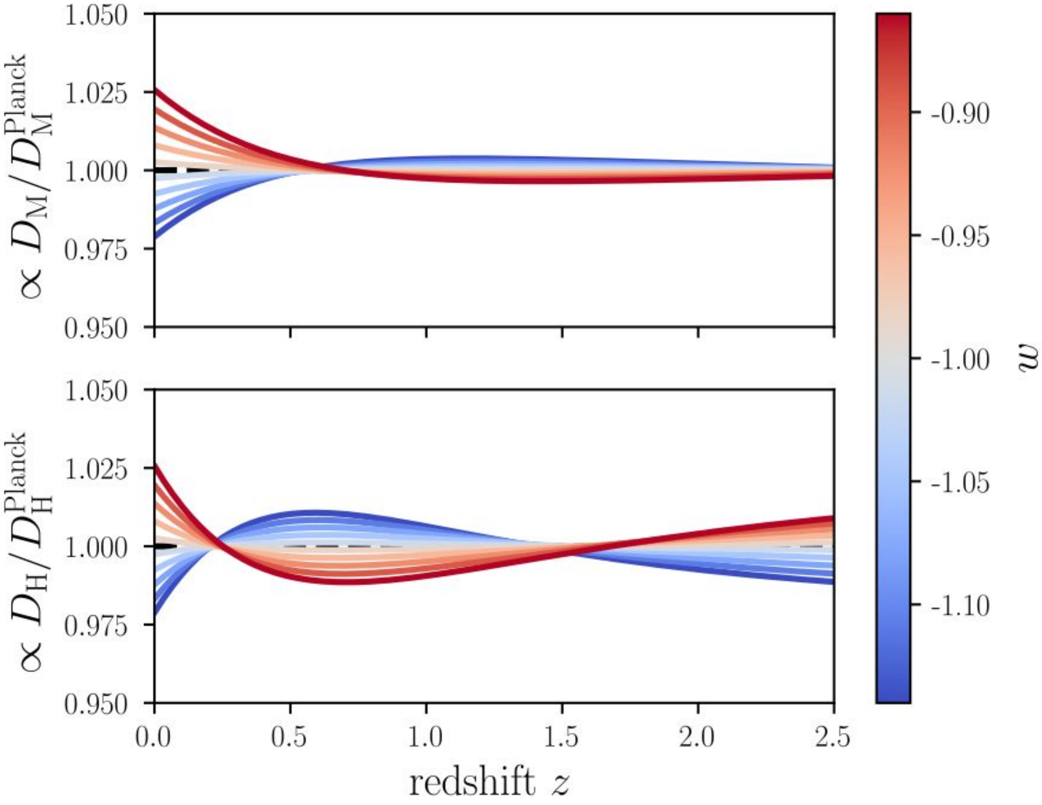
Dark Energy

Dark energy equation of state:

$$P = w\rho$$

- w = constant

w=-1 for cosmological constant in LCDM



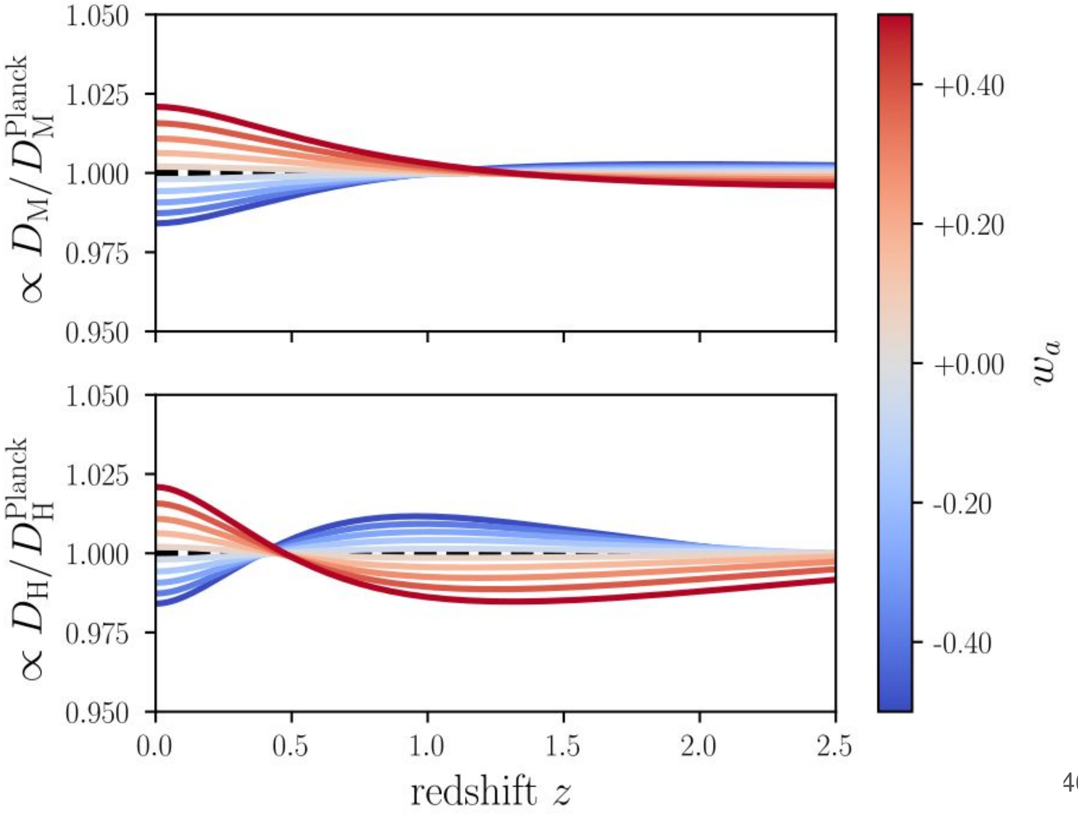
Dark Energy

Dark energy equation of state:

$$P = w\rho$$

- CPL parameterization:

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



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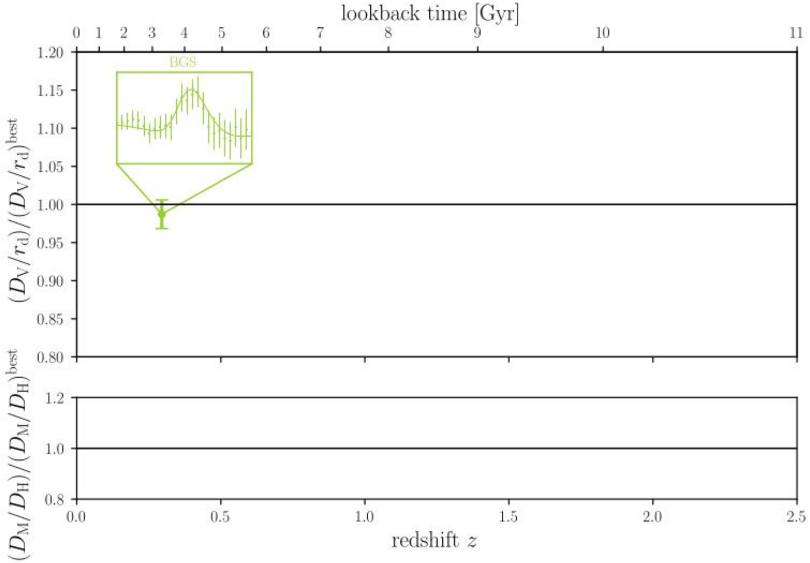
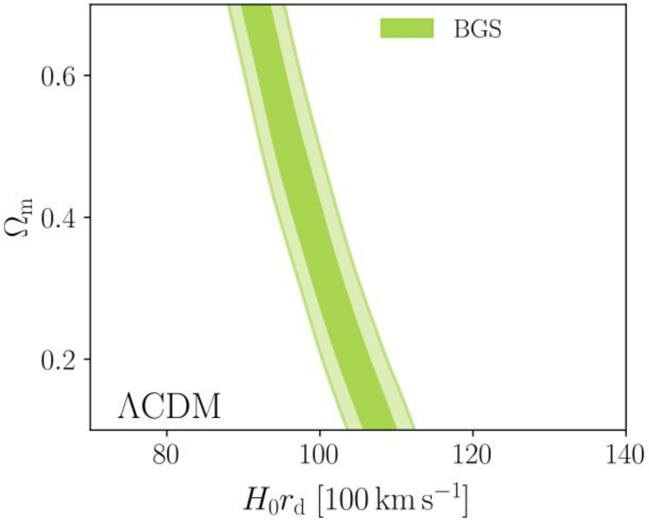
DESI Y1 BAO

DESI BAO measurements





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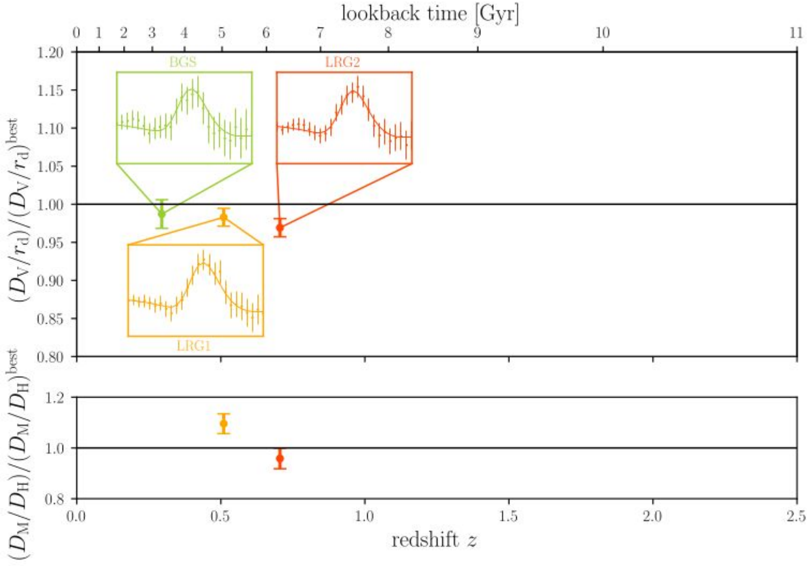
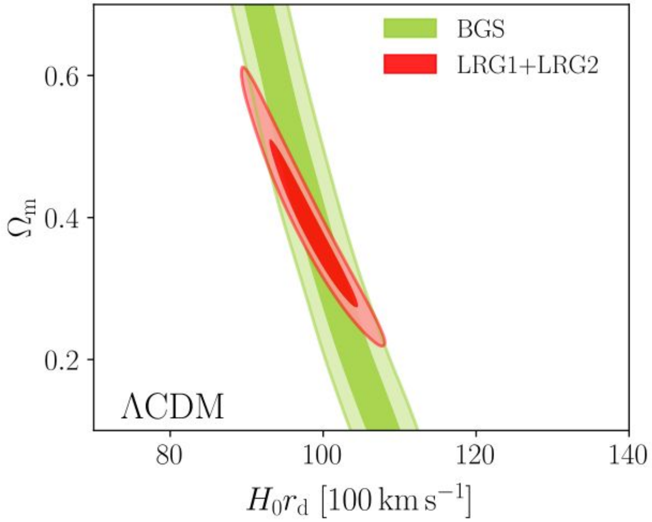
DESI Y1 BAO

DESI BAO measurements





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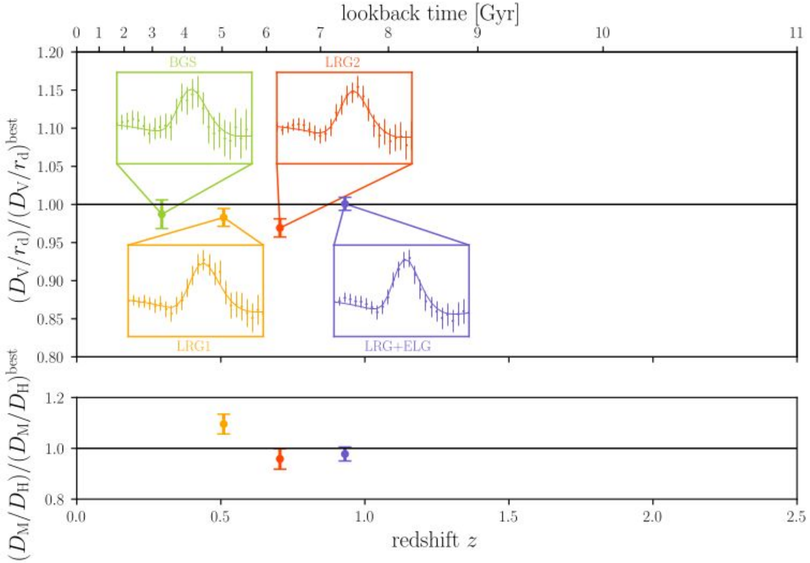
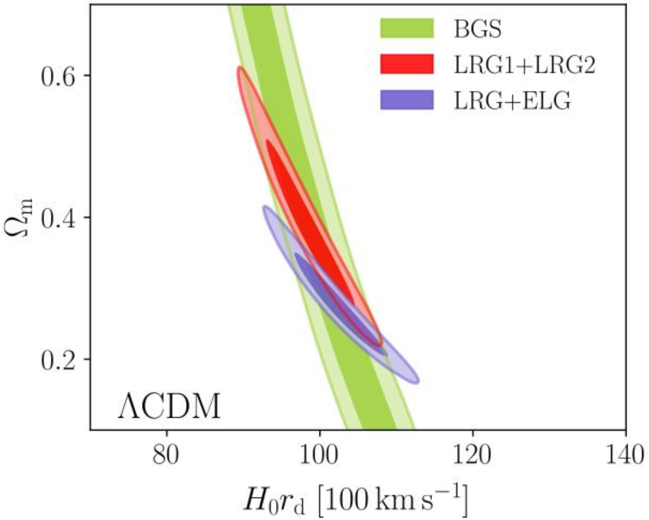
DESI Y1 BAO

DESI BAO measurements





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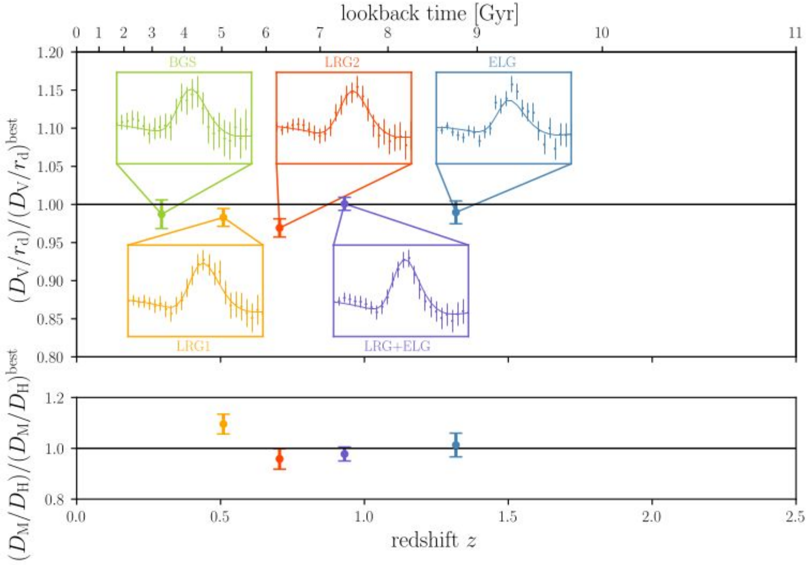
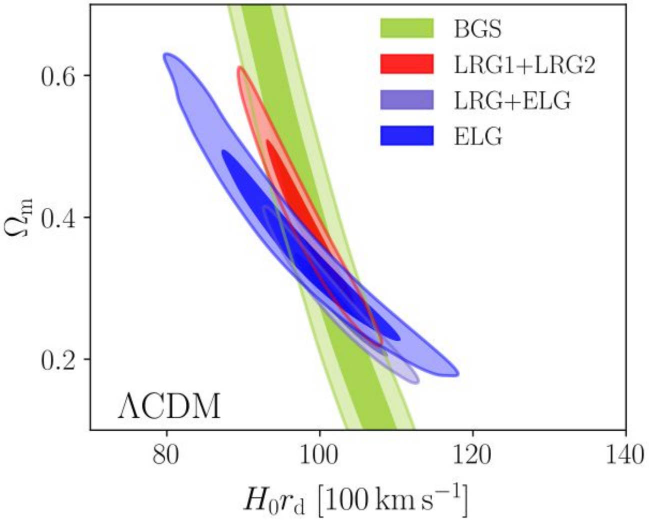
DESI Y1 BAO

DESI BAO measurements





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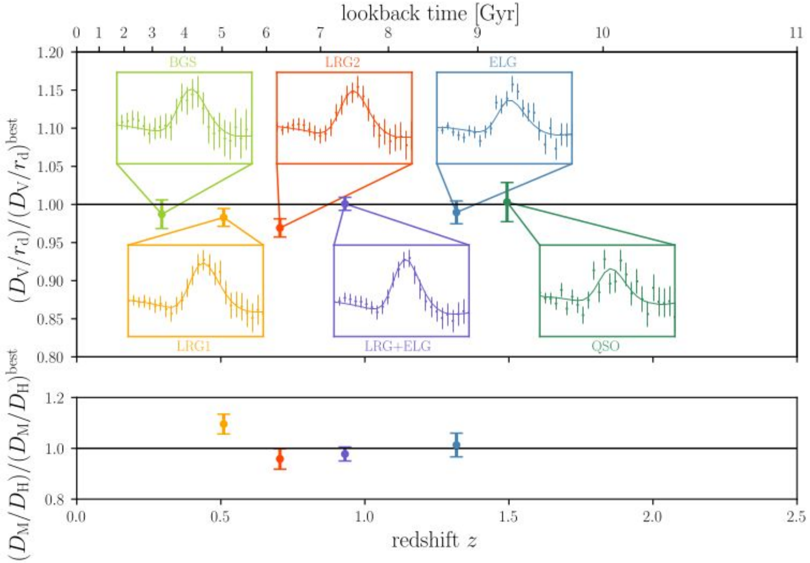
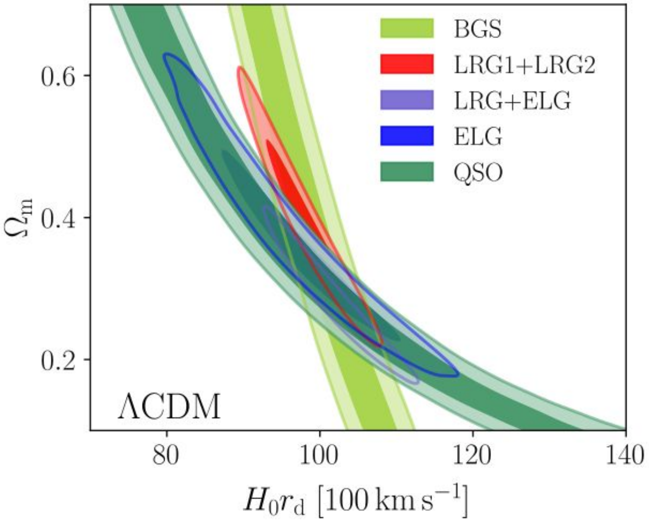
DESI Y1 BAO

DESI BAO measurements





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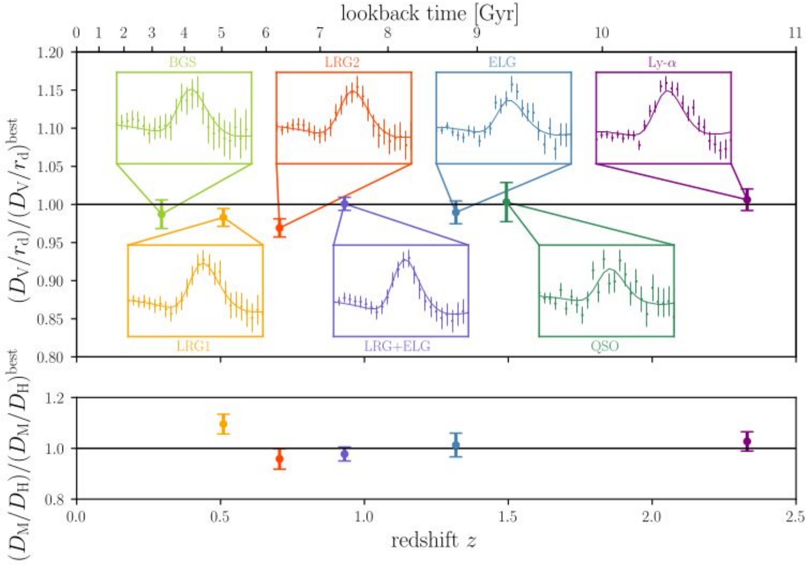
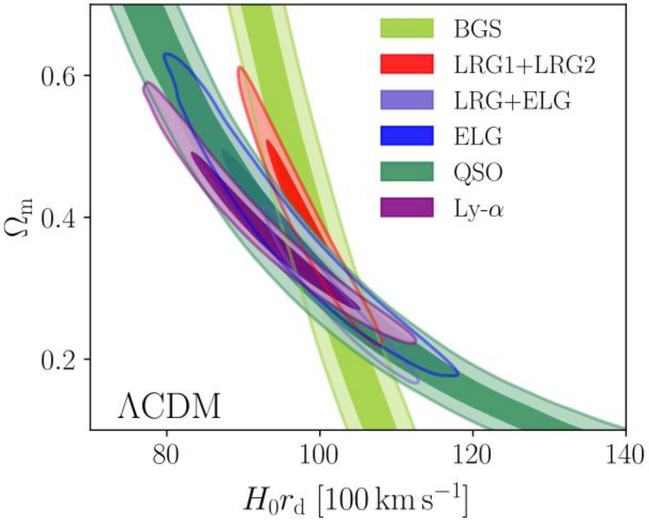
DESI Y1 BAO

DESI BAO measurements





DESI Y1 BAO

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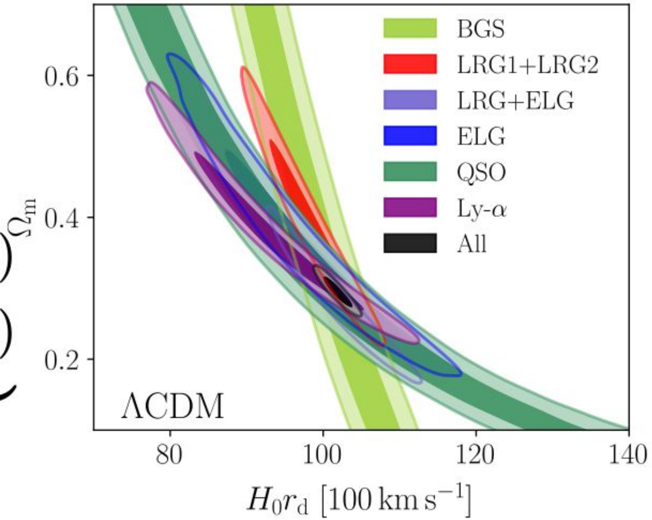
DESI BAO measurements

Consistent with each other,
and complementary

$$\underbrace{\begin{aligned} \Omega_\mathrm{m} &= 0.295 \pm 0.015 & \mathbf{(5.1\%)} \\ H_0 r_\mathrm{d} &= (101.8 \pm 1.3)\,[100\,\mathrm{km\,s^{-1}}] & \mathbf{(1.3\%)} \end{aligned}}_{\text{DESI}}$$



chi2 = 12.66 for 12 data points and 2 parameters

DESI Y1 BAO

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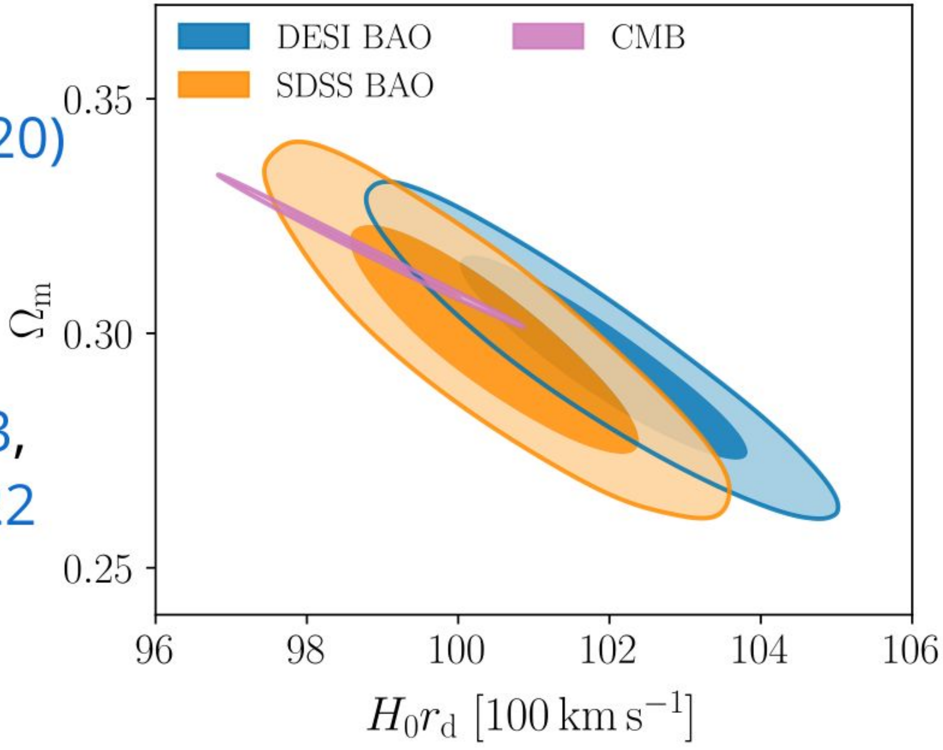
DESI Y1 BAO consistent with:

- SDSS (eBOSS Collaboration, 2020)
- primary CMB: Planck Collaboration, 2018 and CMB lensing: Planck PR4 + ACT DR6 lensing ACT Collaboration, 2023, Carron, Mirmelstein, Lewis, 2022



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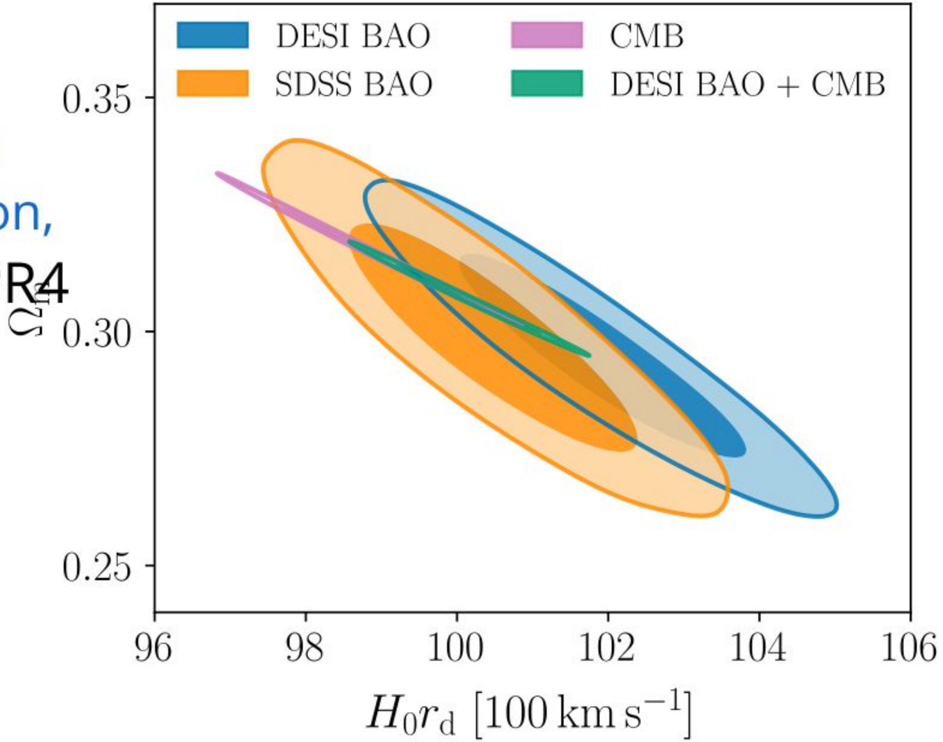
DESI Y1 BAO

DESI Y1 BAO consistent with:

- SDSS (eBOSS Collaboration, 2020)
- primary CMB: Planck Collaboration, 2018 and CMB lensing: Planck PR4 + ACT DR6 lensing ACT Collaboration, 2023, Carron, Mirmelstein, Lewis, 2022

$$\underbrace{\Omega_{\rm m} = 0.3069 \pm 0.0050\ (\mathbf{1.6\%})}_{\text{DESI + CMB}}$$



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Hubble Constant

- BAO constrains $r_{\mathrm{d}}(\Omega_{\mathrm{m}}h^2, \Omega_{\mathrm{b}}h^2)h$
- Ω_{m} constrained by BAO at different z
- $\Omega_{\mathrm{b}}h^2$ can be constrained by BBN: Schöneberg et al., 2024

$\Longrightarrow$ constraints on h i.e. H_0

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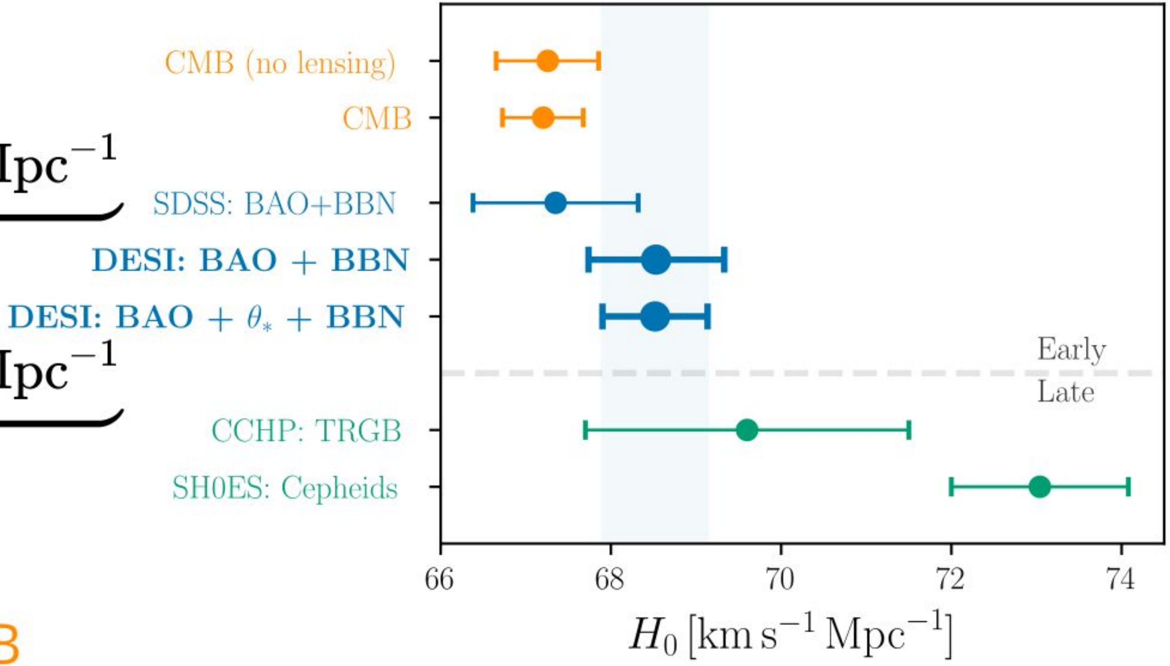
Hubble Constant

$$\underbrace{H_0 = (68.53 \pm 0.80)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\text{DESI + BBN}}$$

$$\underbrace{H_0 = (68.52 \pm 0.62)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\text{DESI} + \theta_* + \text{BBN}}$$

- Consistency with SDSS
- In agreement with CMB
- In 3.7σ tension with SH0ES



Brand new result from CCHP (with JWST):
H_0 = 69.1 +- 1.5 km/s/Mpc

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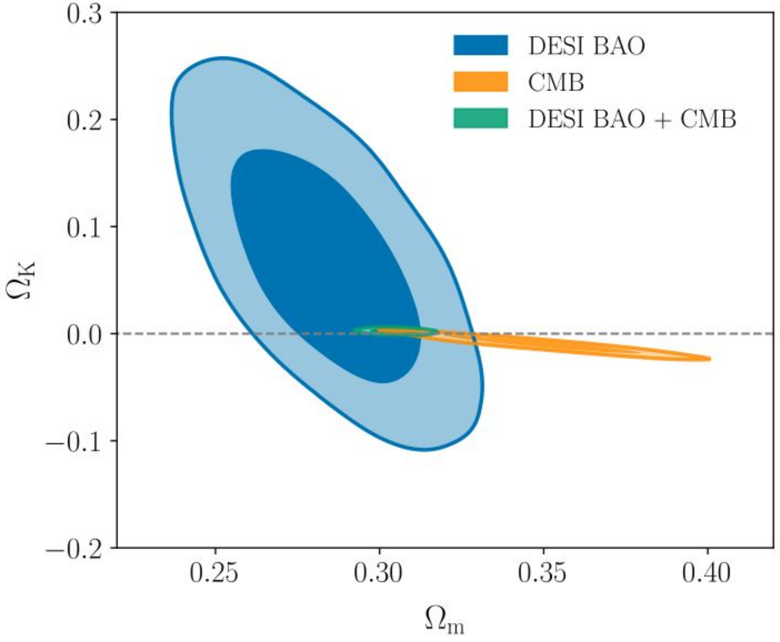
Spatial Curvature

DESI + CMB measurements favor a flat Universe

$$\Omega_K = 0.0024 \pm 0.0016 \text{ (DESI + CMB)}$$



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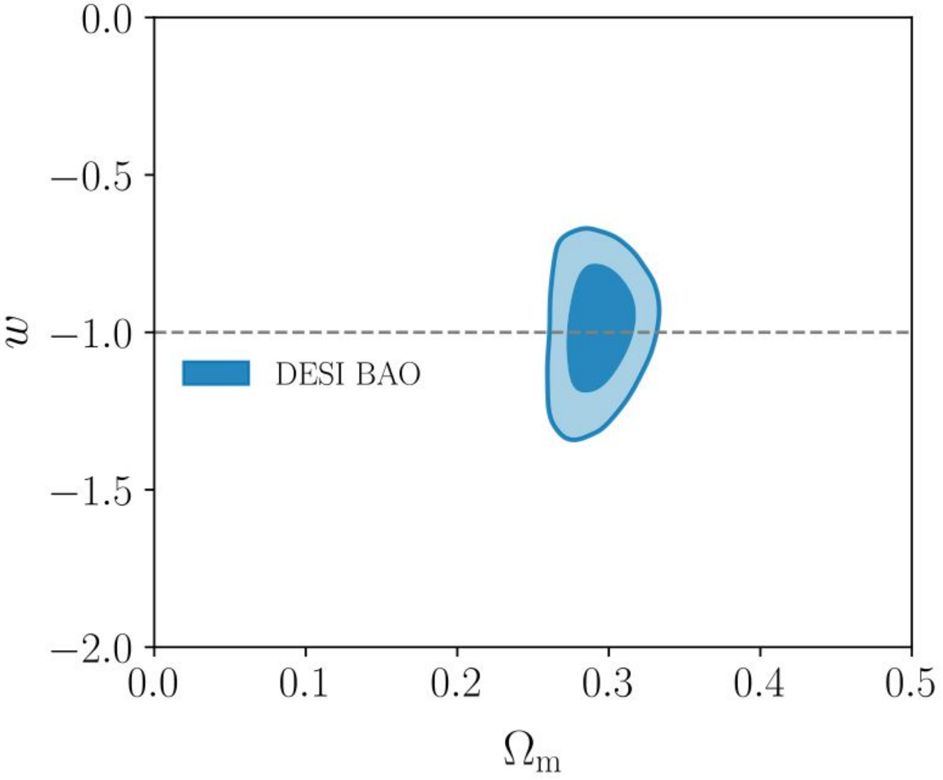
Dark Energy Equation of State

Constant EoS parameter w

$$\Omega_\mathrm{m} = 0.293 \pm 0.015 \quad (\mathbf{5.1\%})$$

$$w = -0.99^{+0.15}_{-0.13} \quad (\mathbf{15\%})$$

DESI



Dark Energy Equation of State

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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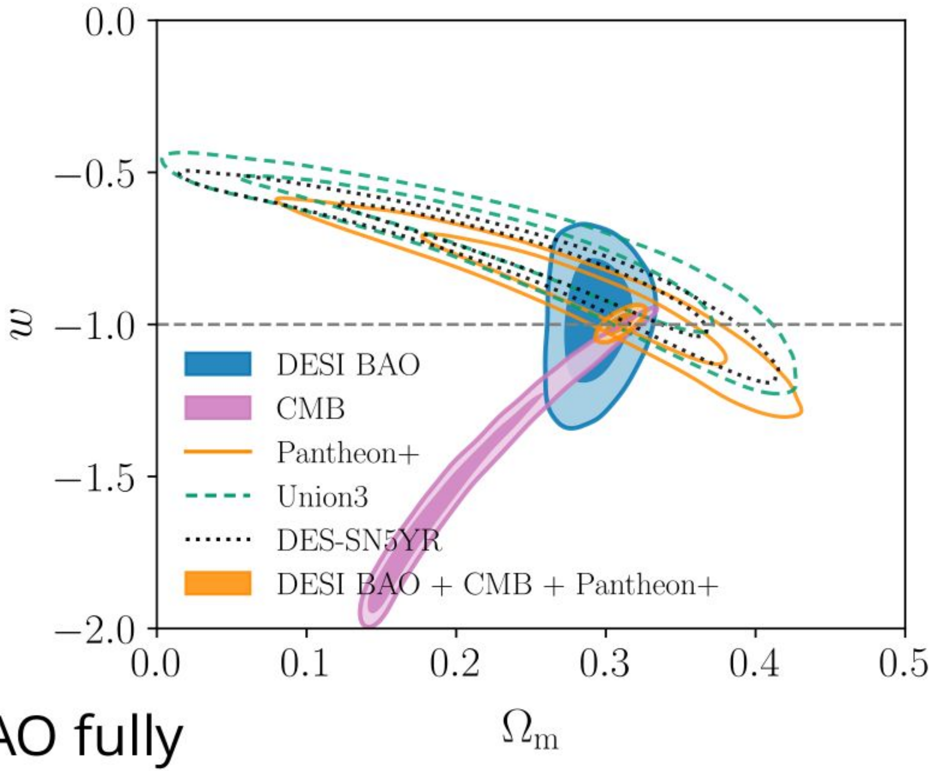
Constant EoS parameter w

$$\Omega_\mathrm{m} = 0.293 \pm 0.015 \quad (\mathbf{5.1\%})$$
$$w = -0.99^{+0.15}_{-0.13} \quad (\mathbf{15\%})$$

DESI

$$\Omega_\mathrm{m} = 0.3095 \pm 0.0065 \quad (\mathbf{2.1\%})$$
$$w = -0.997 \pm 0.025 \quad (\mathbf{2.5\%})$$

DESI + CMB + Pantheon+



Assuming a **constant** EoS, DESI BAO fully compatible with a cosmological constant…

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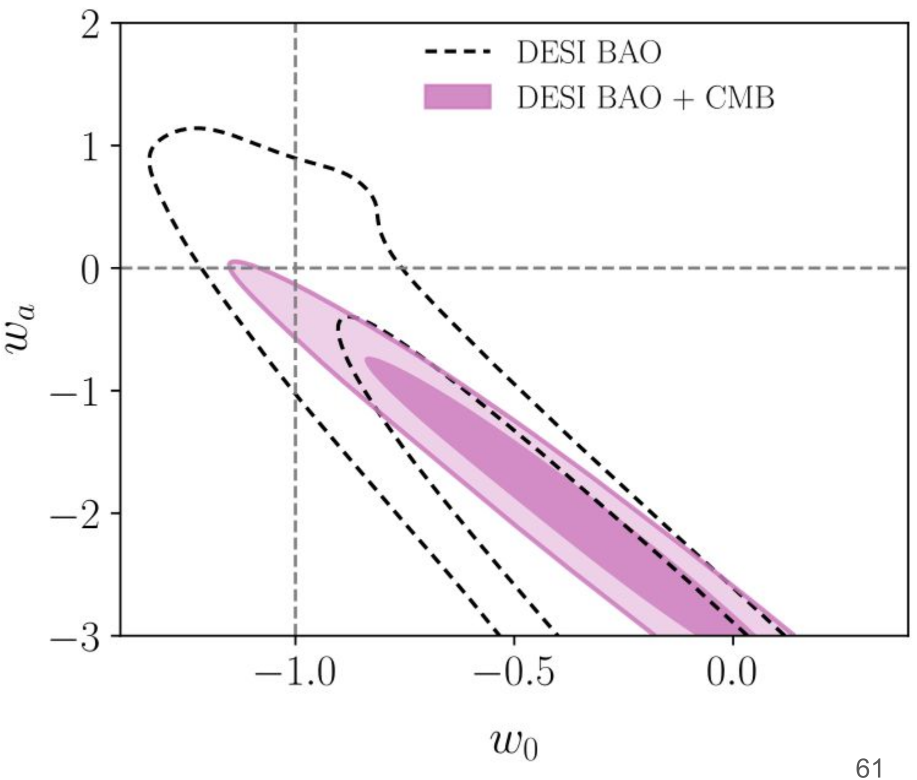
Dark Energy Equation of State

Varying EoS

$$w(a) = w_0 + (1-a)w_a \qquad \text{(CPL)}$$

$$\underbrace{w_0 = -0.45^{+0.34}_{-0.21} \qquad w_a = -1.79^{+0.48}_{-1.00}}_{\text{DESI + CMB} \implies 2.6\sigma}$$



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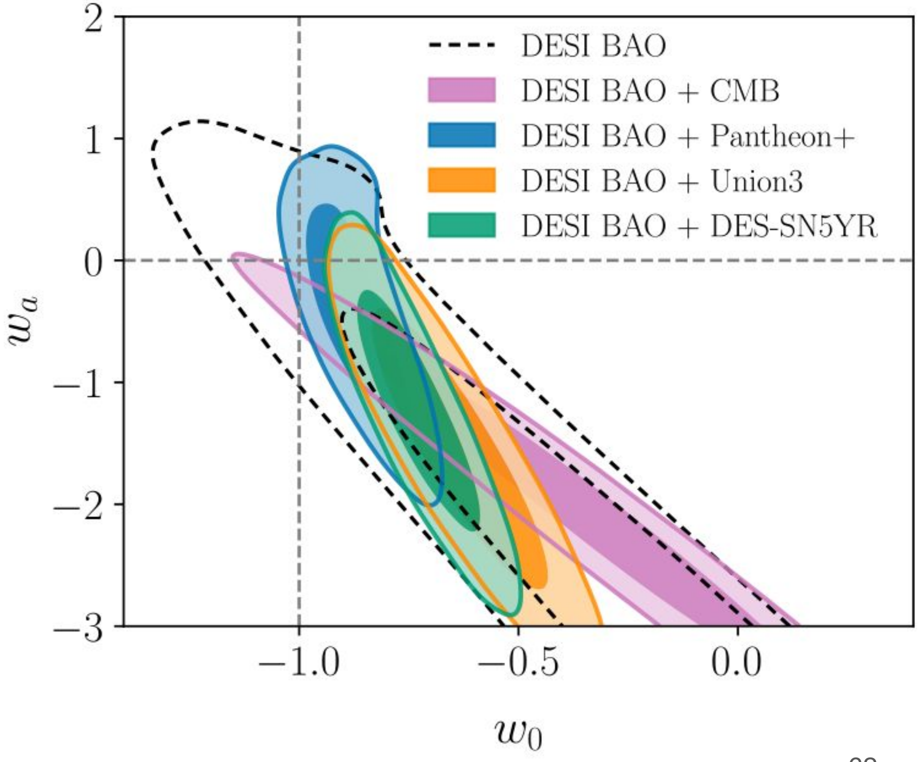


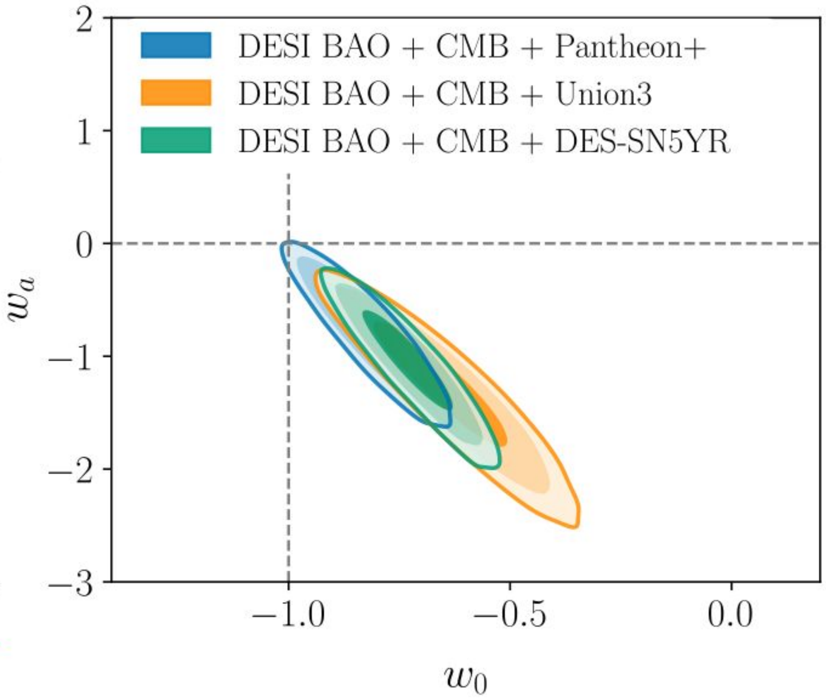
Dark Energy Equation of State

Combining all DESI + CMB + SN

$$\underbrace{w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}}_{\text{DESI + CMB + Pantheon+} \implies 2.5\sigma}$$

$$\underbrace{w_0 = -0.64 \pm 0.11 \qquad w_a = -1.27^{+0.40}_{-0.34}}_{\text{DESI + CMB + Union3} \implies 3.5\sigma}$$

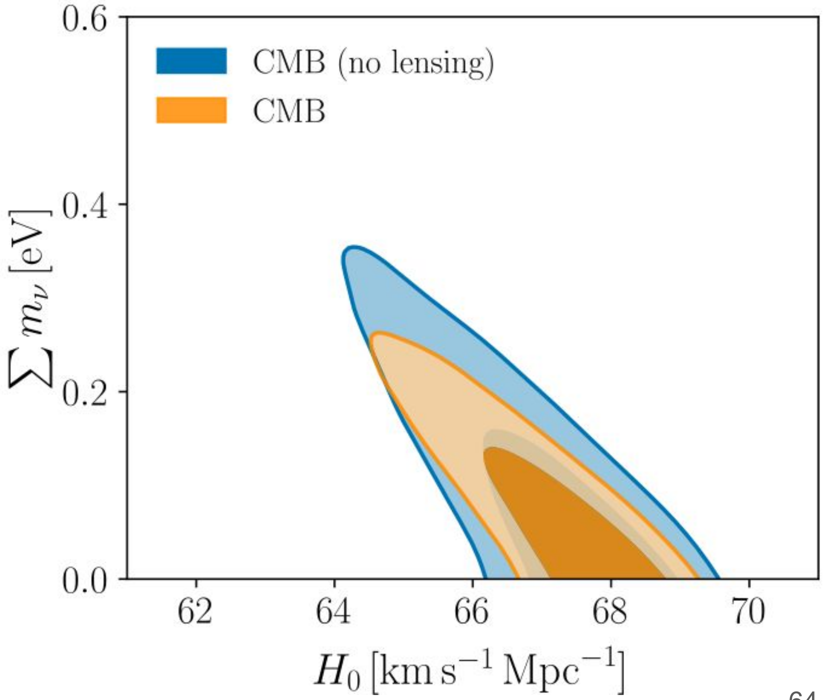
$$\underbrace{w_0 = -0.727 \pm 0.067 \qquad w_a = -1.05^{+0.31}_{-0.27}}_{\text{DESI + CMB + DES-SN5YR} \implies 3.9\sigma}$$



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

Neutrino Masses

Internal CMB degeneracies limiting precision on the sum of neutrino masses



Neutrino Masses

Internal CMB degeneracies limiting precision on the sum of neutrino masses

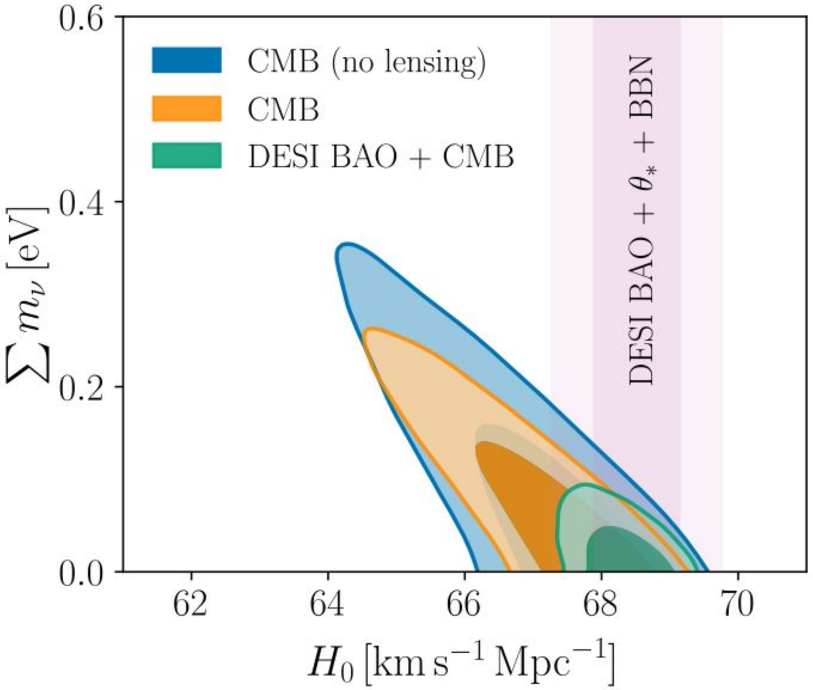
Broken by BAO, especially through H_0

Low preferred value of H_0 yields

$\sum m_\nu < 0.072\,\mathrm{eV}$ (95%, DESI + CMB)

Limit relaxed for extensions to ΛCDM

$\sum m_\nu < 0.195\,\mathrm{eV}$ for $w_0 w_a$CDM



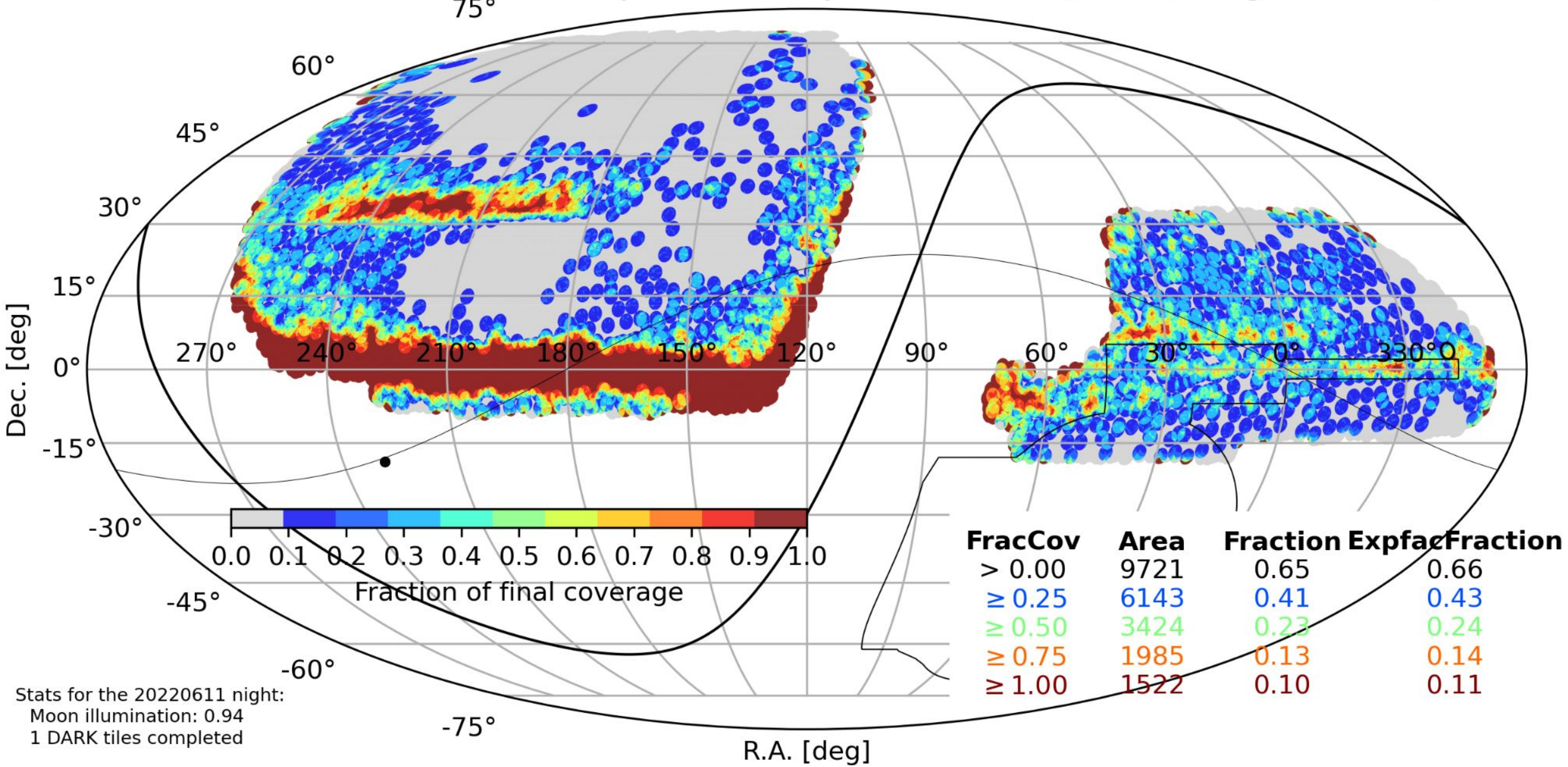
Conclusion

- DESI Year 1 dataset
  - 3 x SDSS (2 decades) with 5.7 million galaxies and QSOs at $z<2.1$
  - 2 x SDSS with 420,000 Lyman-alpha QSOs at $z>2.1$

- Most precise BAO measurement to date with aggregate BAO precision of 0.52% for $z<2.1$ and 1.1% at $z>2.1$

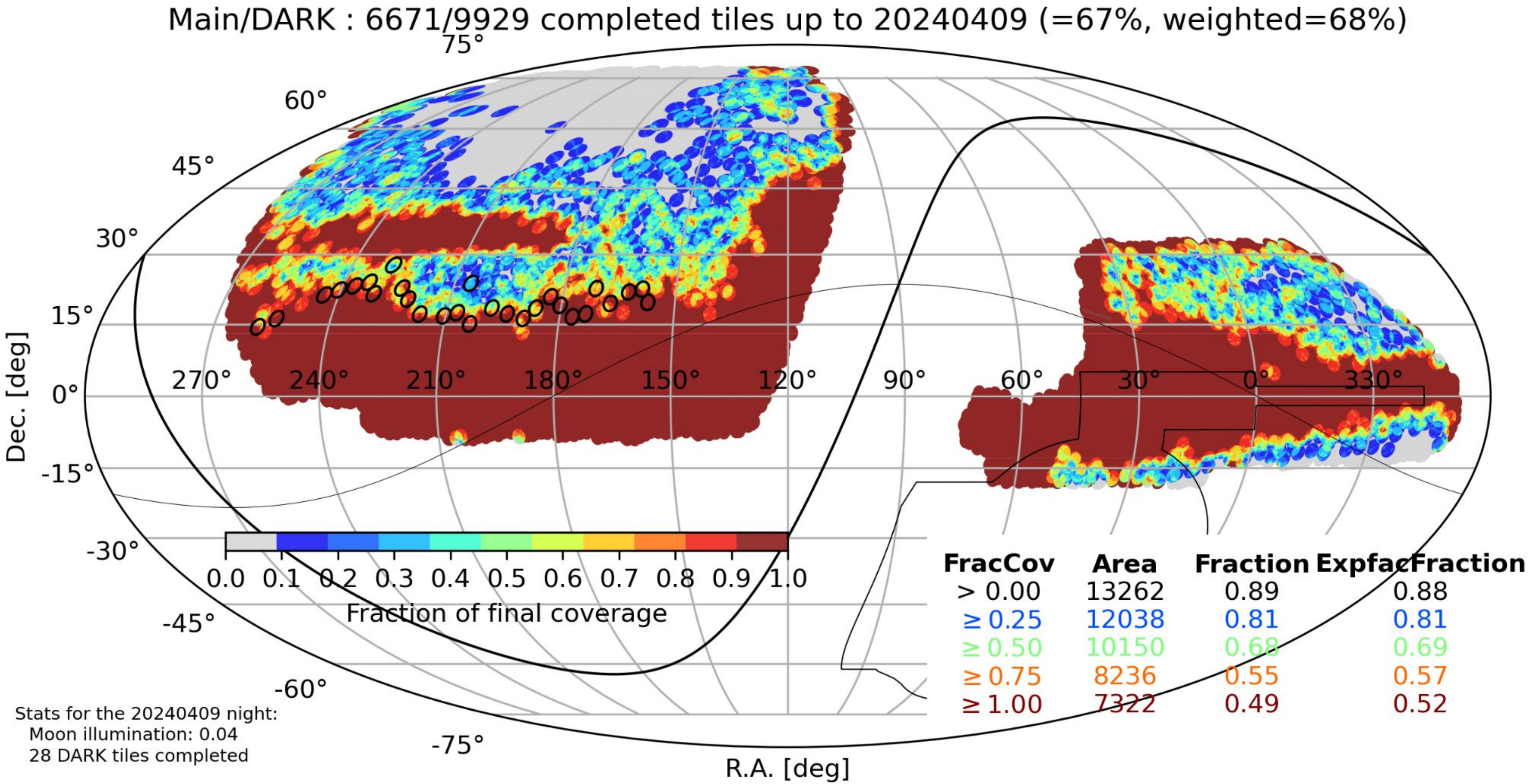
- DESI + BBN (+ θ_*) constraints H0 to ~1%, in tension with SH0ES
- DESI, in combination with CMB data, favors zero spatial curvature
- DESI is consistent with $w = -1$ when assumed constant
- When allowing w to vary with time, DESI combined with CMB: 2.6σ and SN: 2.5 to 3.9σ w.r.t. LCDM
- Limit on $\sum m_\nu$ improves to <0.072 eV (95%, ΛCDM)
  <0.195 eV (95%, w0waCDM)

Main/DARK : 2744/9929 completed tiles up to 20220611 (=28%, weighted=29%)



FracCov	Area	Fraction	ExpfacFraction
> 0.00	9721	0.65	0.66
≥ 0.25	6143	0.41	0.43
≥ 0.50	3424	0.23	0.24
≥ 0.75	1985	0.13	0.14
≥ 1.00	1522	0.10	0.11

DESI Year 1



FracCov	Area	Fraction	ExpfacFraction
> 0.00	13262	0.89	0.88
≥ 0.25	12038	0.81	0.81
≥ 0.50	10150	0.68	0.69
≥ 0.75	8236	0.55	0.57
≥ 1.00	7322	0.49	0.52

BACK UP

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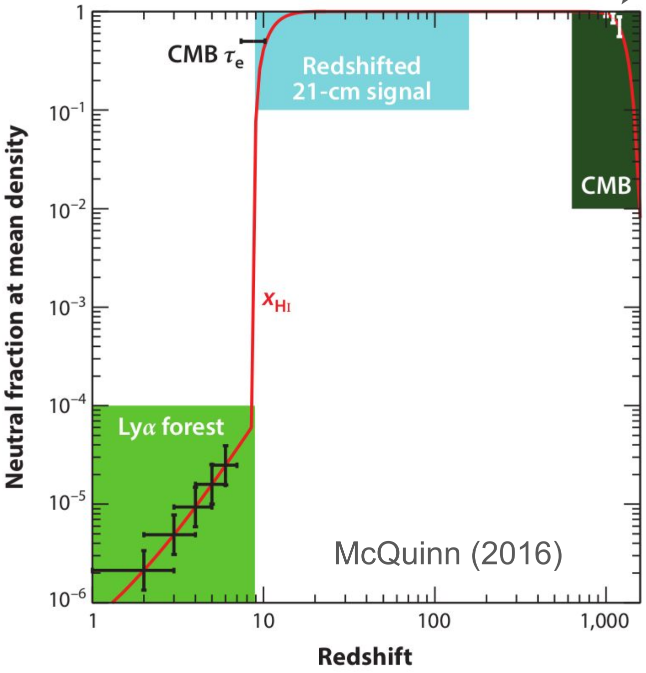
The Lyman-α Forest

reionization with formation of galaxies and quasars

recombination as universe expands

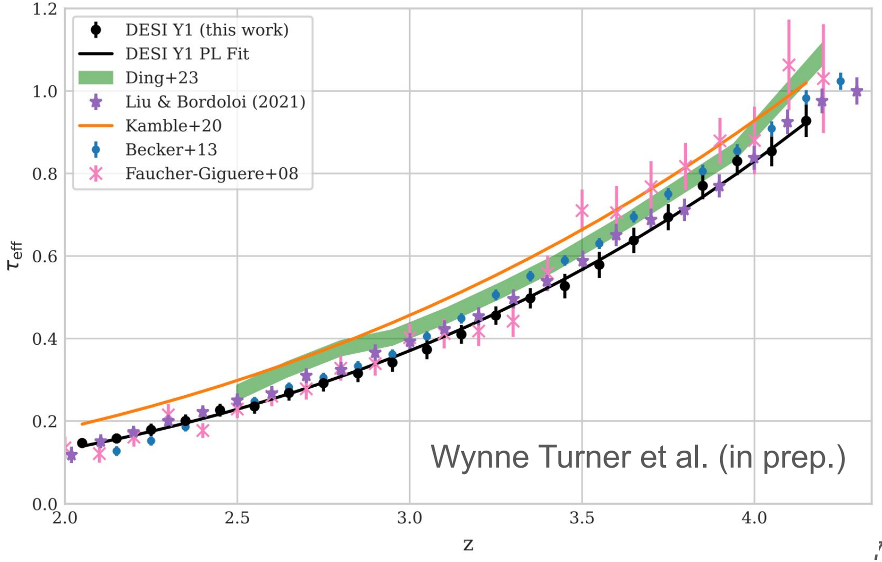


Optical depth to Lyman-alpha transition

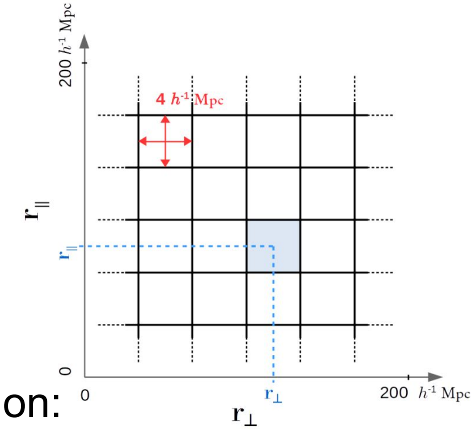
(at 121.6 nm, 1216 A)

$$\tau \propto n_{HI} \qquad \tau \lesssim 1 \text{ for } z < 4$$

great probe of matter density fluctuations



Correlation function estimators



Correlation function estimators are simple weighted means in (r_par,r_perp) separation bins *M* of (4 Mpc/h) x (4 Mpc/h)

Lya x Lya auto-correlation:

$$\xi_M = \sum_{(i,j)\in M} w_i w_j \tilde{\delta}_i \tilde{\delta}_j / \sum_{(i,j)\in M} w_i w_j$$

Lya x QSO cross-correlation:

$$\xi_M = \sum_{(i,j)\in M} w_i w_j^{\mathrm{Q}} \tilde{\delta}_i / \sum_{(i,j)\in M} w_i w_j^{\mathrm{Q}}$$

Optimized weights:

$$w_q(\lambda) = \left(\frac{1+z_\lambda}{1+z_0}\right)^{\gamma_\alpha - 1} \left[\eta_{\mathrm{pip}}(\lambda) \left(\frac{\sigma_{\mathrm{pip},q}(\lambda)}{\overline{F}C_q(\lambda)}\right)^2 + \eta_{\mathrm{LSS}}\, \sigma^2_{\mathrm{LSS}}(\lambda)\right]^{-1}$$

$$w_j^Q = [(1+z_Q)/(1+z_0)]^{\gamma_Q - 1}$$

Covariance matrix

- Cross-covariance between the 4 correlation functions is not negligible (10% change in BAO uncertainties)

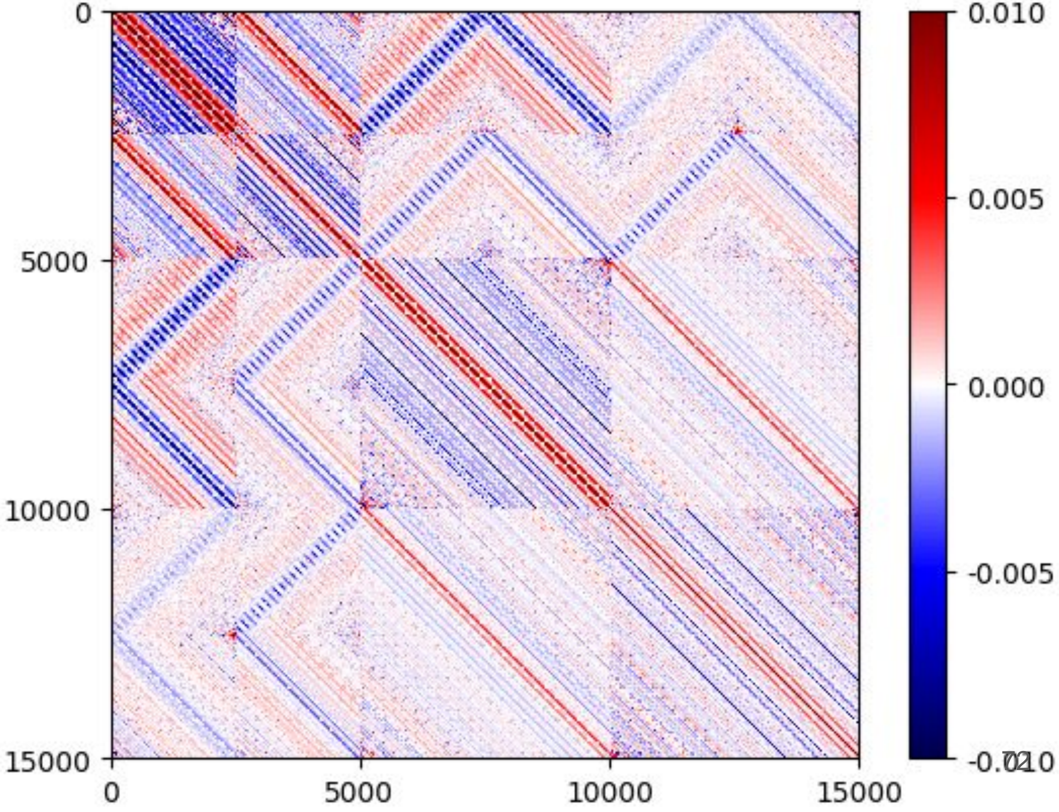
- Combined data array is large 15000 data points = (2x(50x50+100x50))

- Full covariance from sub-sampling with (250 Mpc/h)x(250 Mpc/h) patches on the sky

- Smoothing scheme validated with mocks

(note scale of +-0.01 in color bar)

Correlation matrix



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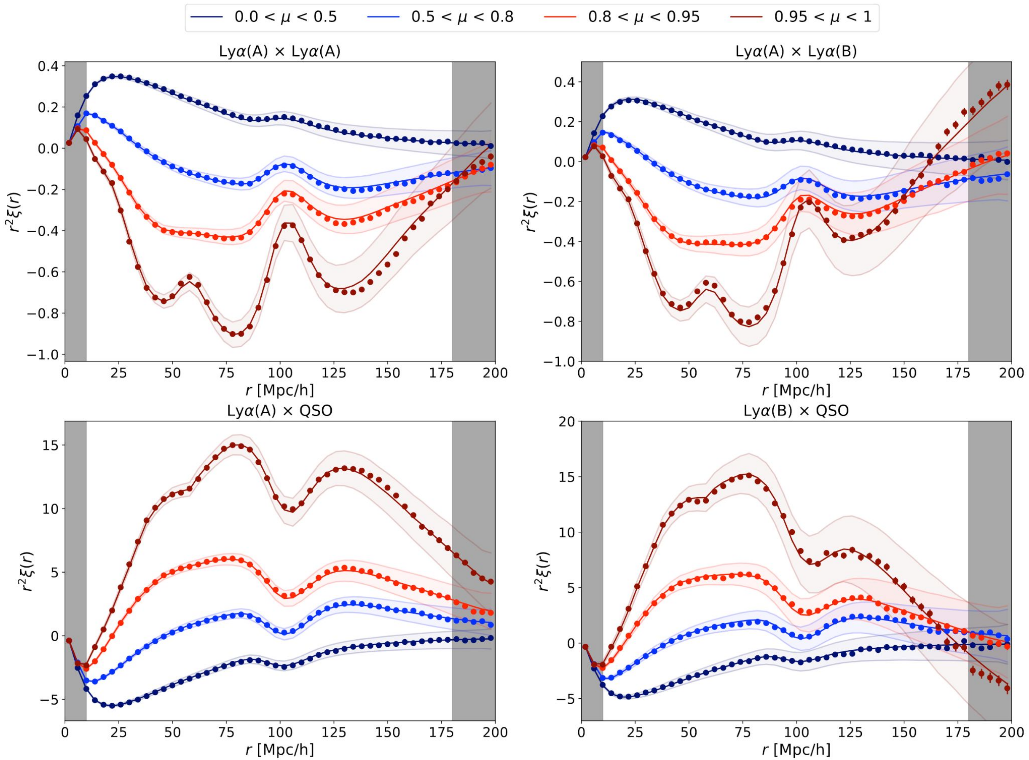
1. Validation with mocks

[Cuceu, Herrera-Alcantar et al. 2024]
Synthetic data sets of the Year 1 sample

- $(10\ h^{-1}\mathrm{Gpc})^3$ boxes of log-normal mocks (FFT based)
- realistic survey footprint, inc. exposure times
- realistic noise and resolution from instrument simulation

x 100 for the 'LyaColore' mocks
x 50 for the 'Saclay' mocks
(not shown,independent code but same principles)

Stack of LyaColore mocks



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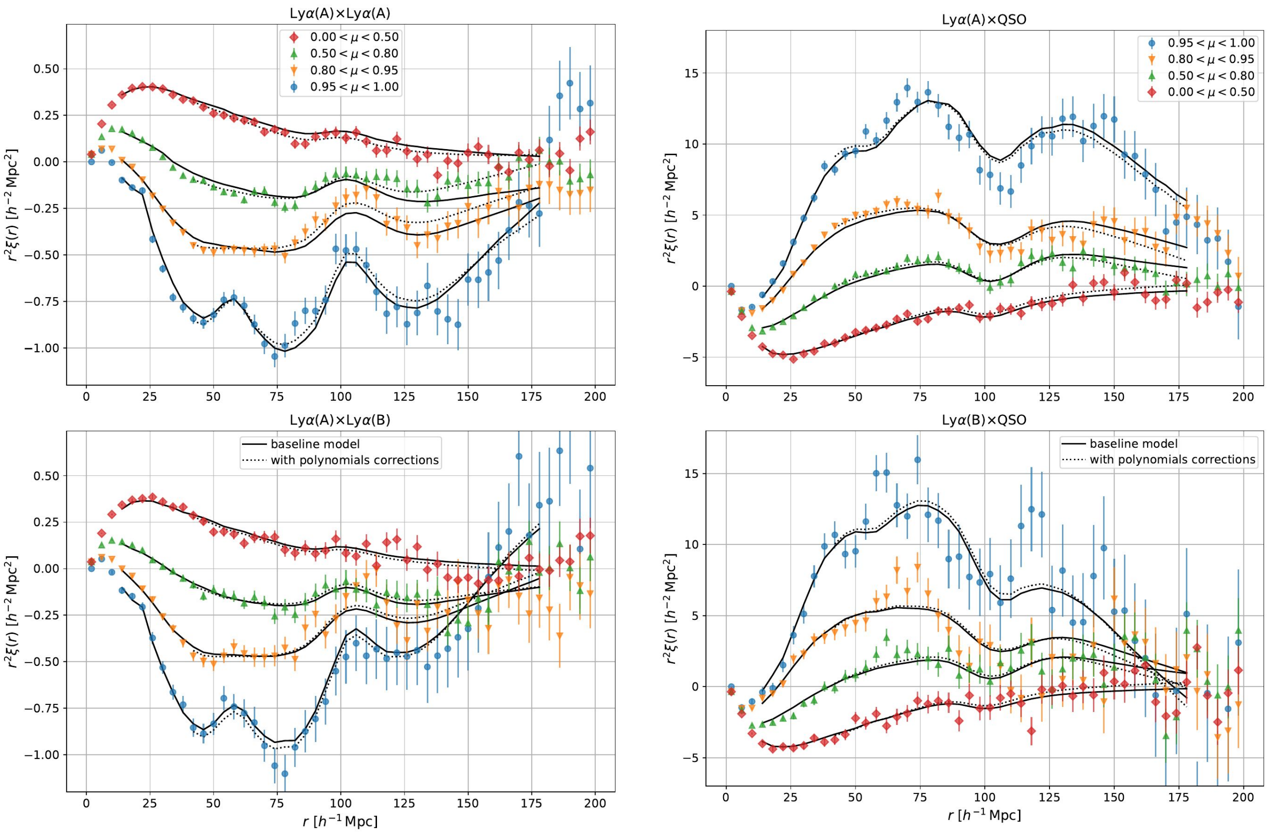
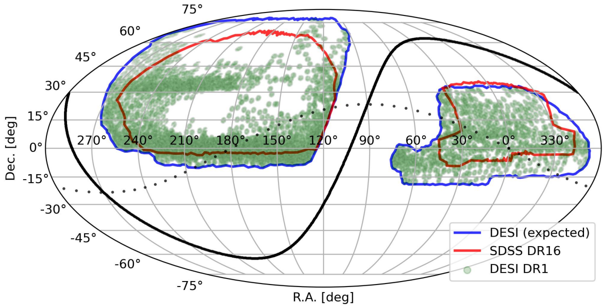
Analysis Validation: broadbands

Added 48 extra free parameters to adjust empirically the correlation function model (dotted curves)

<0.1% impact on BAO



Results: Combined DESI DR1 and SDSS DR16



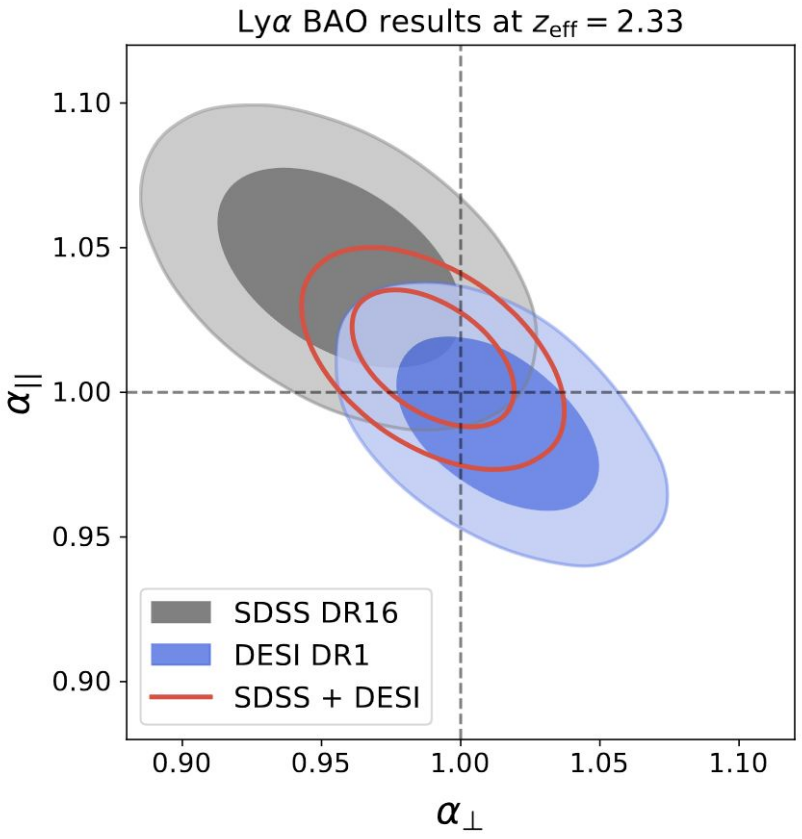
- Estimated covariance of correlation functions between SDSS and DESI with sub-sampling.
- Propagation to covariance of BAO parameters with Monte Carlo realizations drawn from the empirical covariance
- Correlation coefficient between SDSS and DESI ~ 10%

DESI DR1 + SDSS DR16:

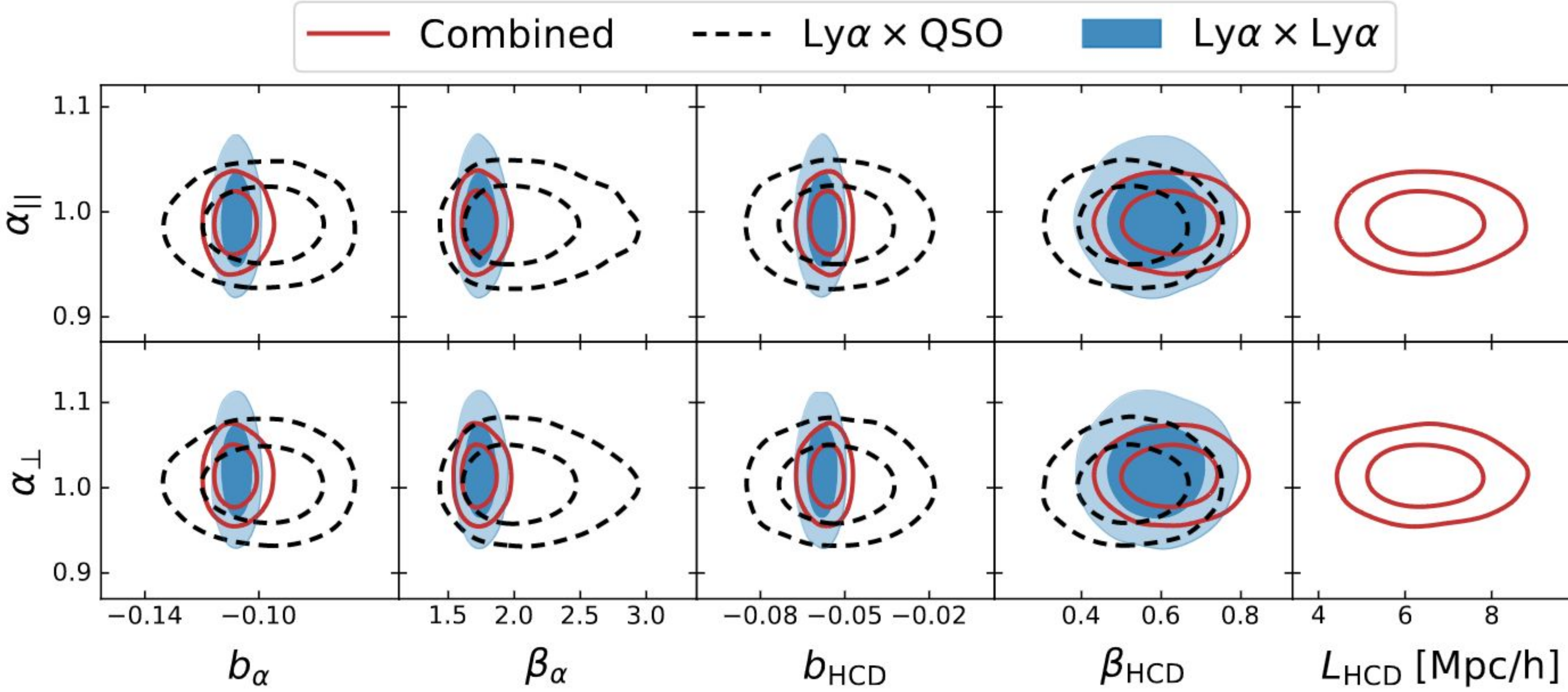
$$D_H(z_{\rm eff})/r_d = 8.72 \pm 0.14$$

$$D_M(z_{\rm eff})/r_d = 38.80 \pm 0.76$$

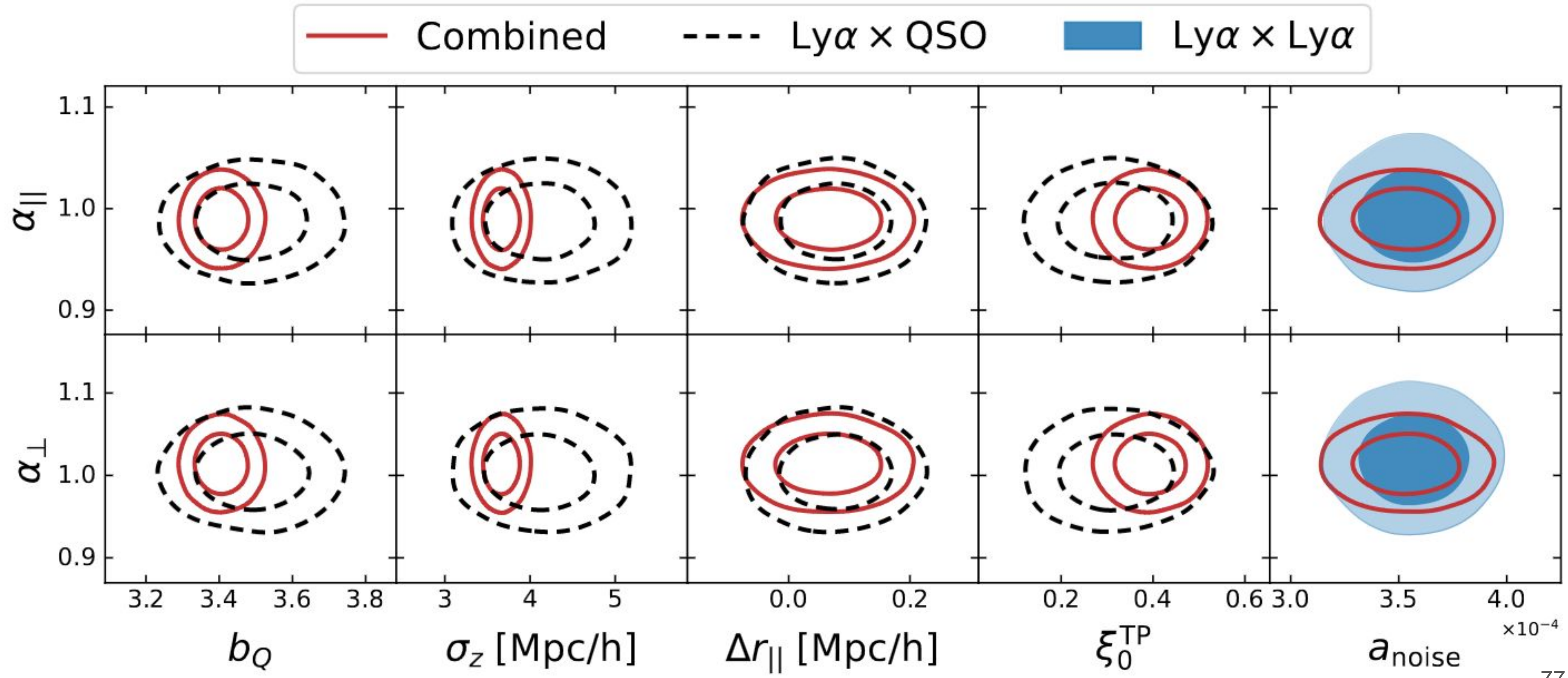
with a correlation coefficient $\rho = -0.47$



Correlations with nuisance parameters (I)



Correlations with nuisance parameters (II)



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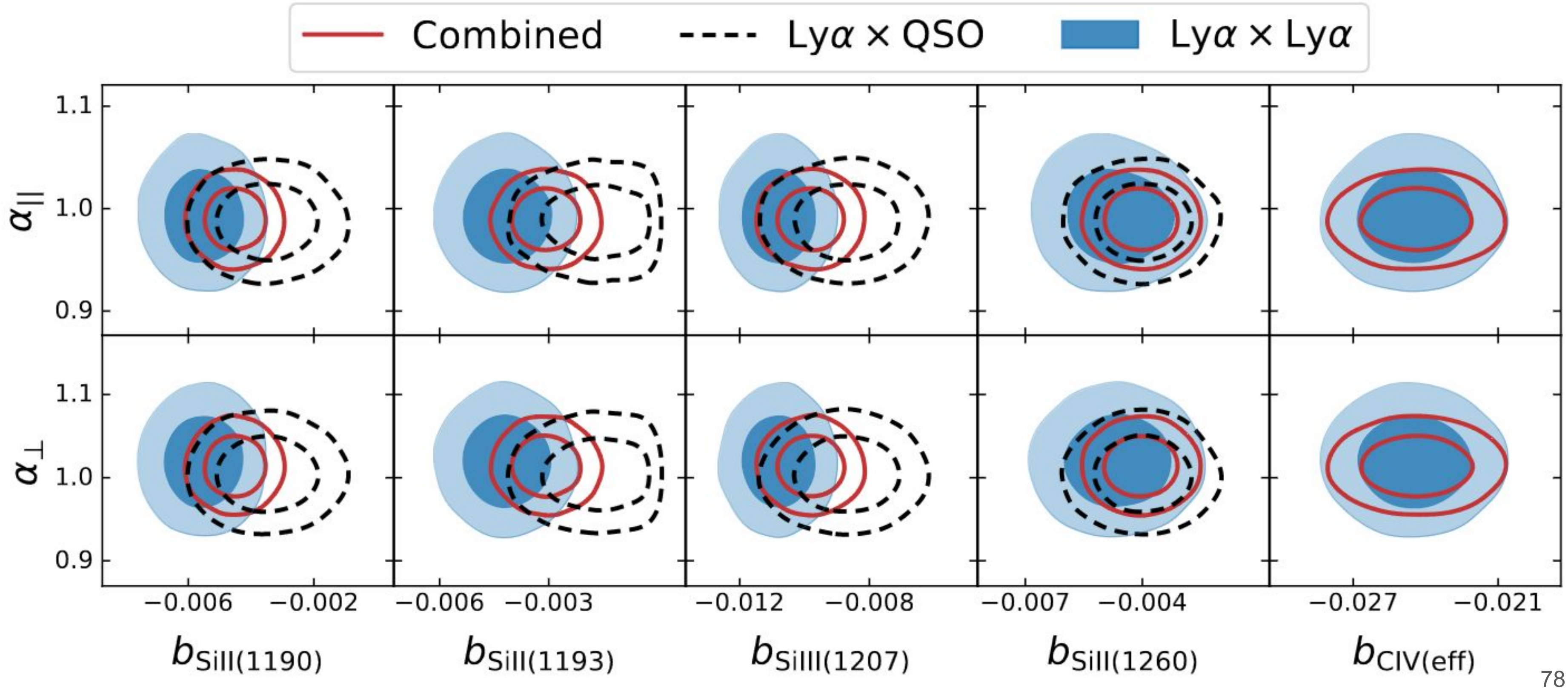
Correlations with nuisance parameters (III)



Fiducial Cosmology (I): coordinates

Fixed r_d

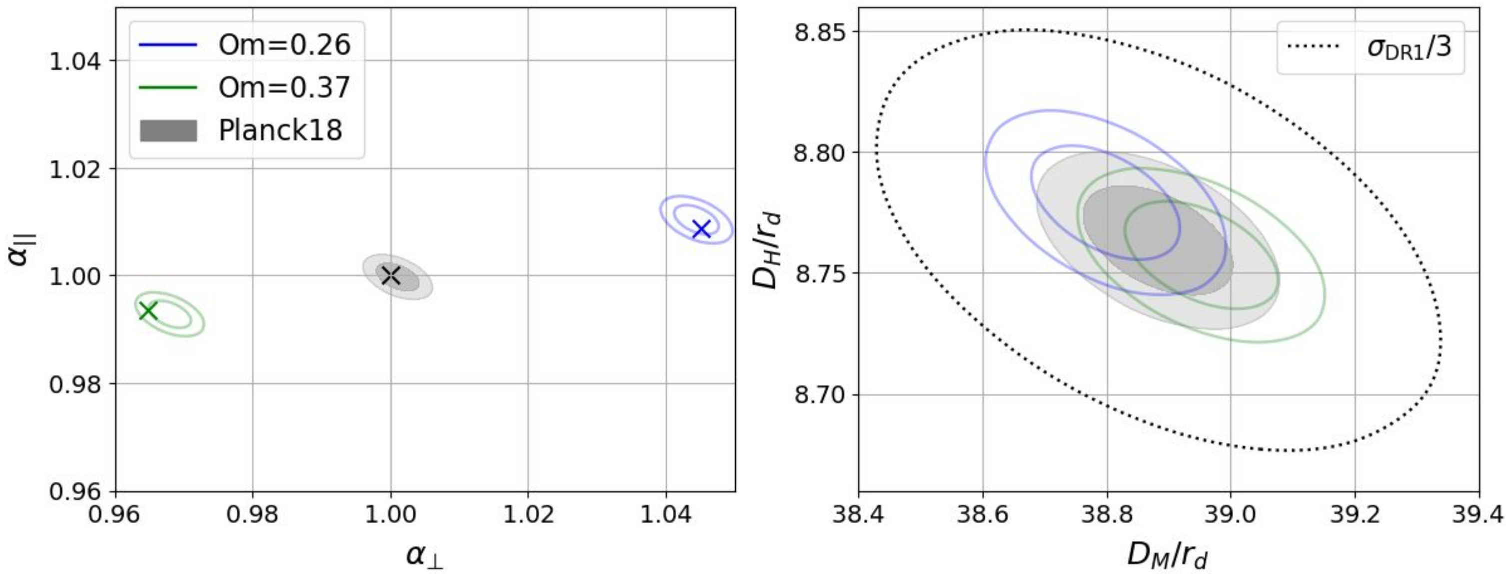


Figure 18: (left) Scale parameters obtained from measurements with the three fiducial cosmologies with fixed $r_{\rm d}$ and different Ω_m and h values. We also include crosses to mark the expected positions of the scale parameters, based on the ratio of their template BAO to that of the template used to create the mocks (Planck 2015). (right) Measured BAO distances obtained by multiplying the scale parameters with the template BAO position. This shows we are able to recover the true BAO position independent of the cosmology used to compute comoving coordinates.

Fiducial Cosmology (II): template

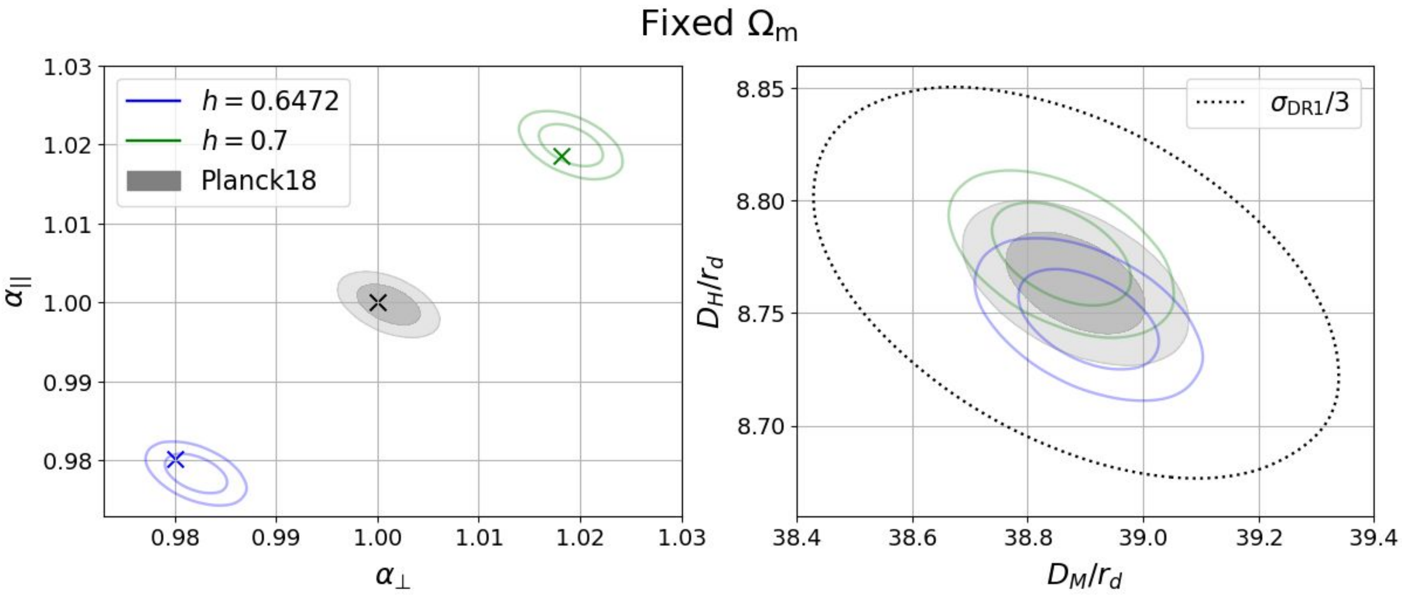
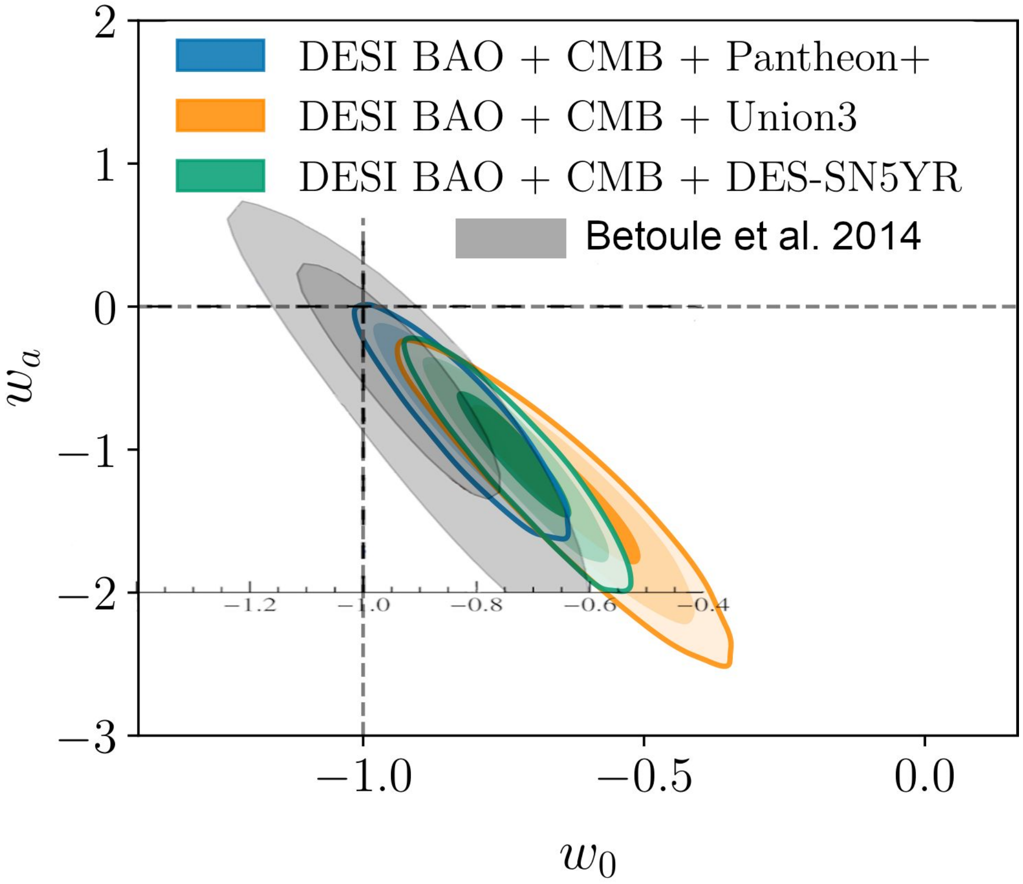


Figure 19: Similar to Figure 18, but using three fiducial cosmologies with fixed coordinate transformation (i.e. Ω_m), and different r_d values. This shows that we are able to recover the true BAO position independent of the cosmology used to create the template.

Comparison with SNLS SDSS JLA SNe



Dark Energy Equation of State