The Dark Energy Spectroscopic Instrument
Cosmological results from the Data Release 2

Julien Guy (LBNL)
on behalf of the DESI collaboration

Rencontres du Vietnam, Aug 2025

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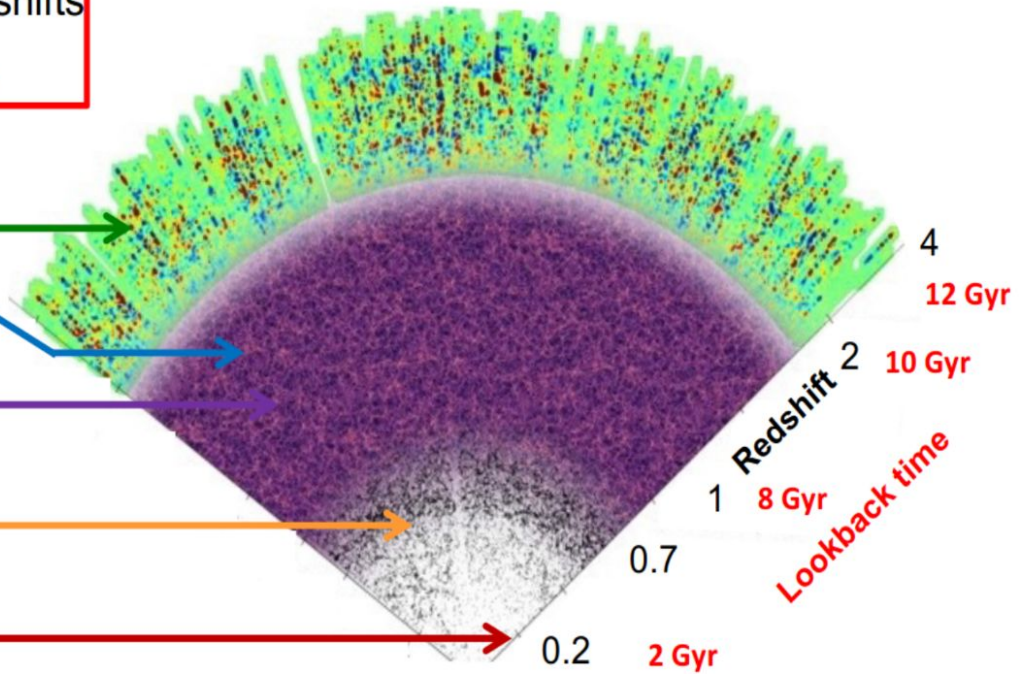
The DESI survey

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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The DESI survey

starts with images (see https://www.legacysurvey.org/)

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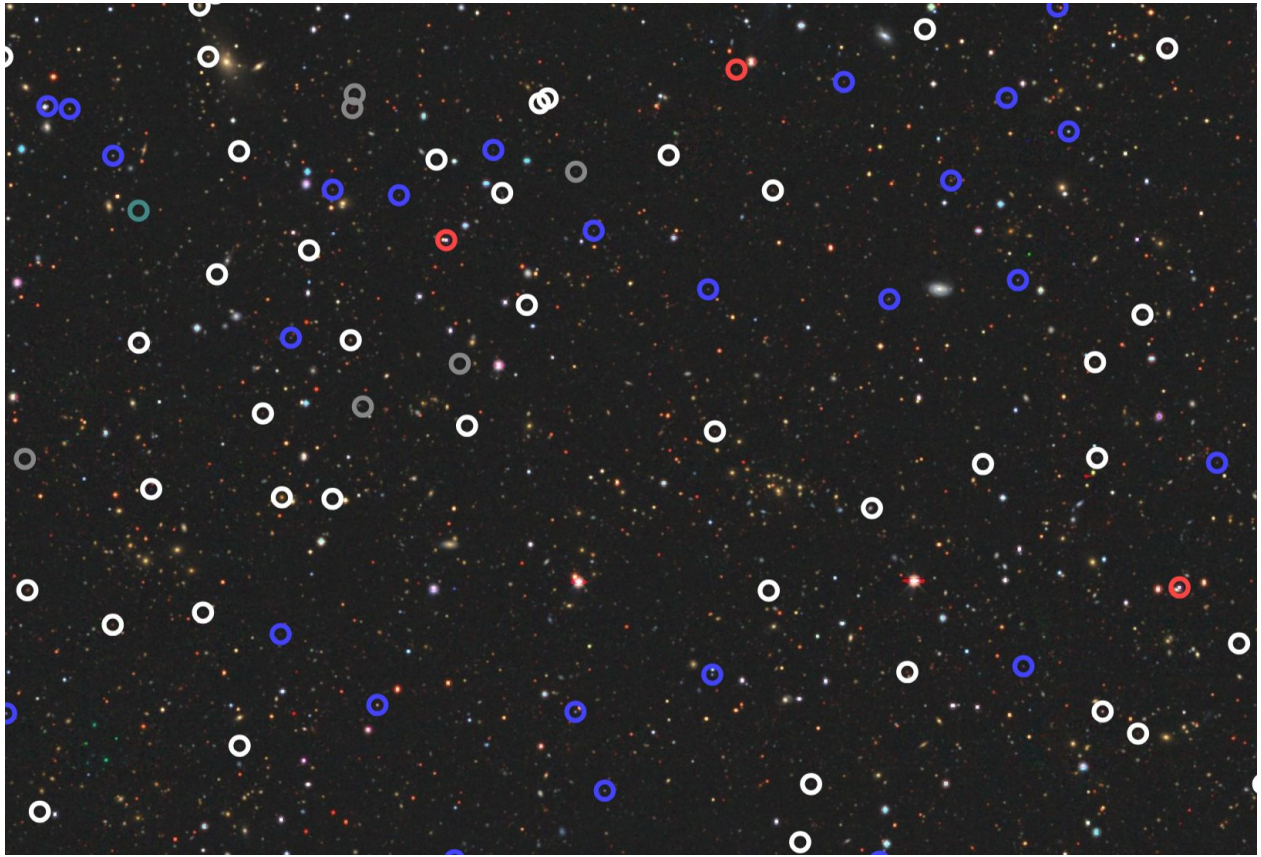
The DESI survey

on which we select targets



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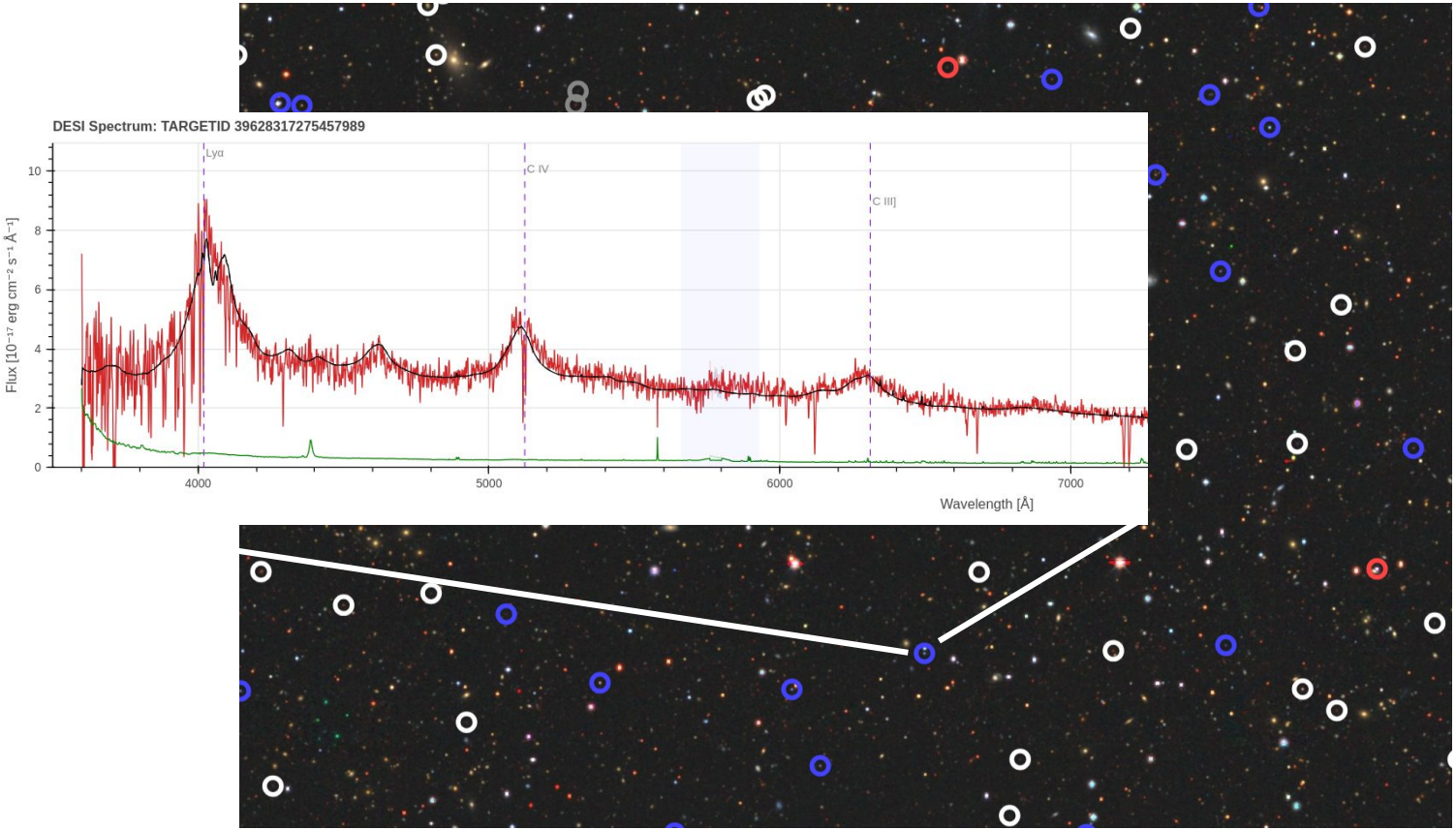
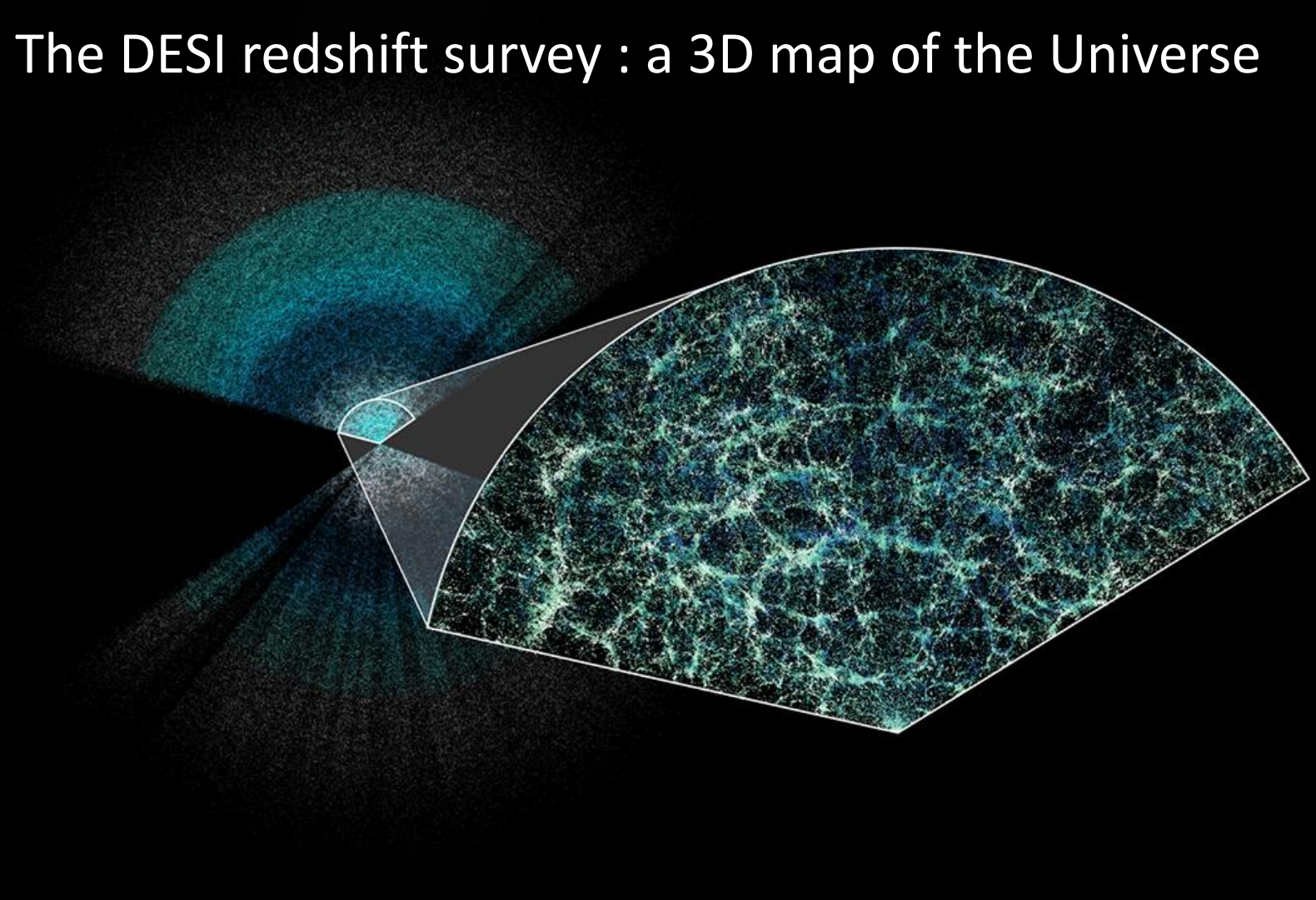
The DESI survey

and measure their spectra



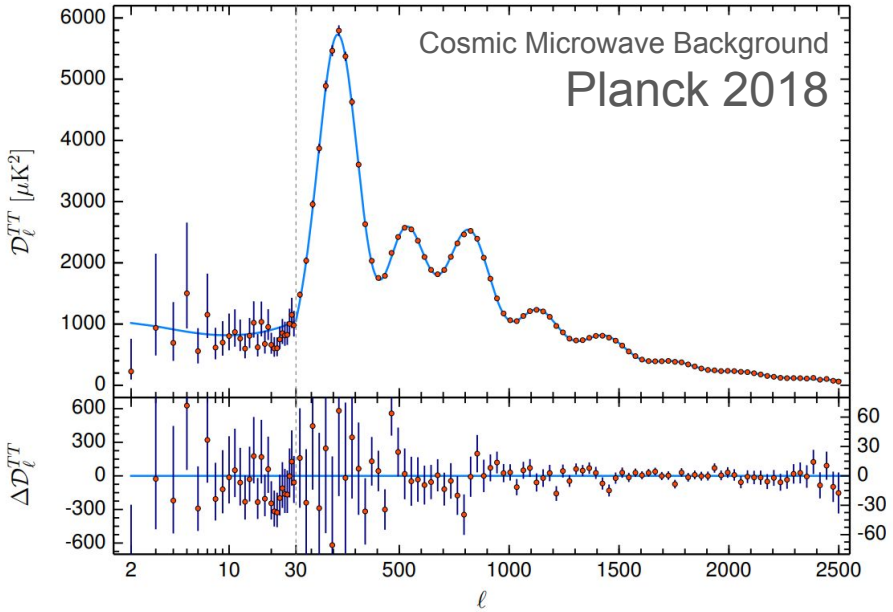
The DESI redshift survey : a 3D map of the Universe

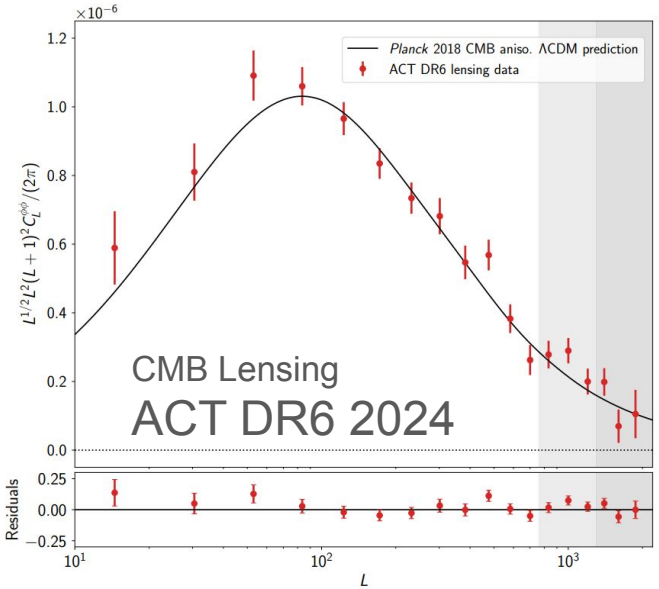


Lambda **C**old **D**ark **M**atter cosmological model

The Cosmic Microwave Background observations (primary temperature anisotropies, polarization, secondary lensing power spectrum) beautifully explained with a **6 parameter model** (1 angular scale, 1 amplitude, 1 power-law index, an optical depth, and 2 densities)

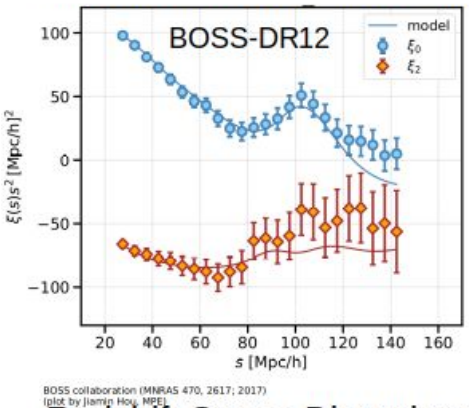
Confirmed to a large extend with several other probes (Big Bang Nucleosynthesis, SNIa, Baryon Acoustic Oscillation, Galaxy Clustering, Cosmic Shear, H0, other secondary CMB probes, and cross-correlations) (see later slides)





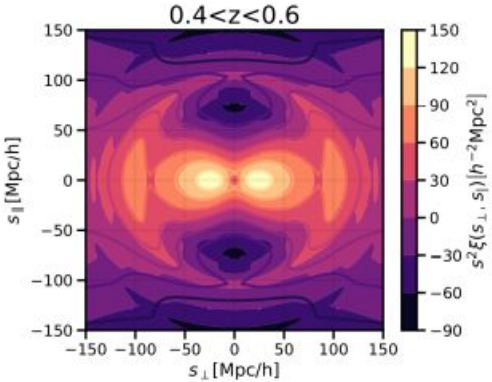
DESI Science goals:

Baryon Acoustic Oscillations



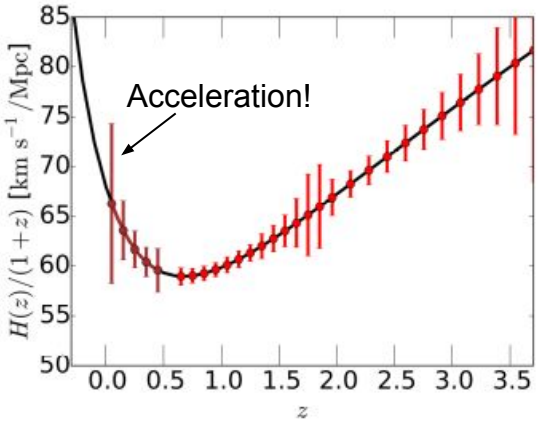
BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)

Redshift Space Distortions

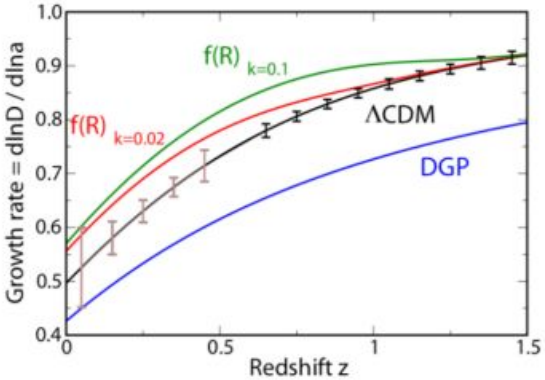


BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)

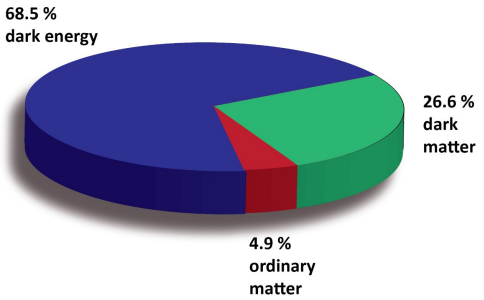
Expansion history



Growth rate of structure



Cosmological constant ?



Modified gravity ?

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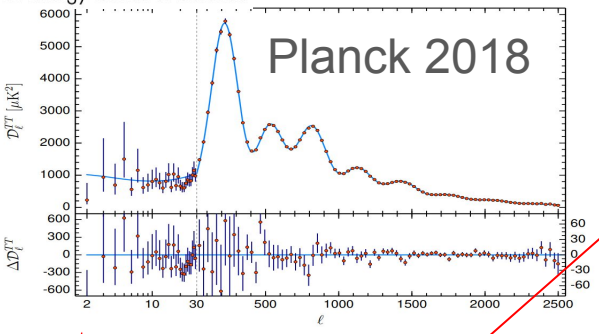
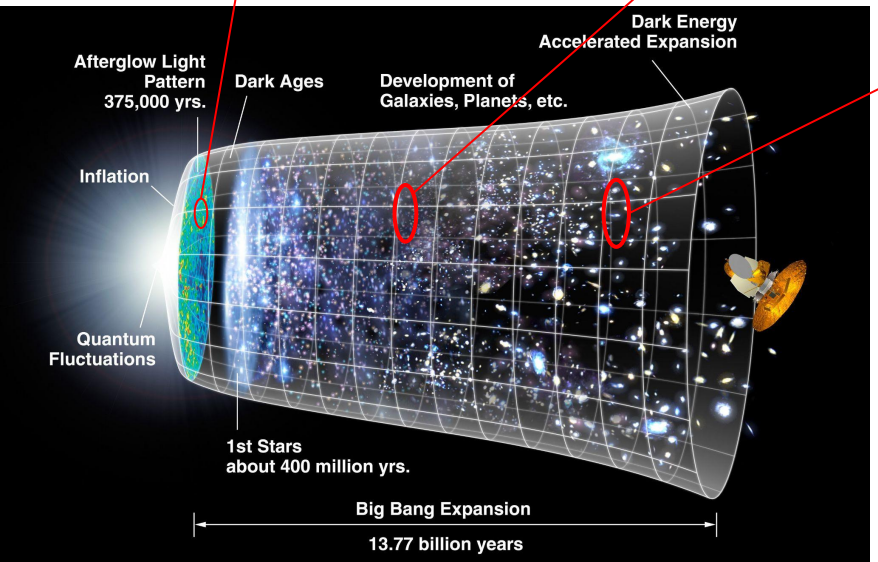
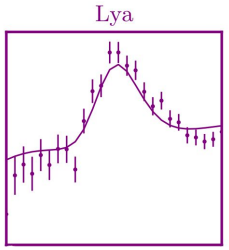
Baryon Acoustic Oscillations

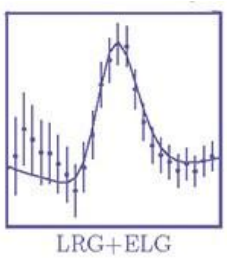




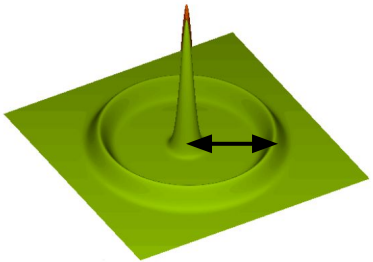
DESI 2024 Lyman-alpha z~2.3

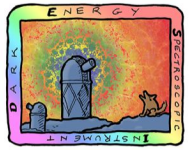


DESI 2024 ELG z~1.3



Imprint of a stalled sound wave in the baryon density





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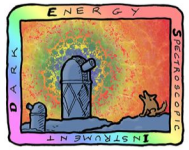
Cosmology at work in DESI

- Baryon Acoustic Oscillation in galaxies and Lyman-alpha forest
- Redshift Space Distortion and “full fit” or “direct fit” of 2pt statistics with EFT
- Constraints on fNL as a test of inflation
- Small scale P(k) of Lyman-alpha forest
- DESI and CMB: cross-correlation with CMB-lensing maps in redshift slices, kSZ to measure baryon distributions in clusters), also with Lyman-alpha forest
- DESI and cosmic shear: calibration of intrinsic alignment, revised n(z) from Photo-Z of several lensing imaging surveys.
- Gravitational magnification from several redshift slices.
- Strong lenses detected with spectroscopy
- Host galaxy redshifts for SNe (and detection of live SNe)

…



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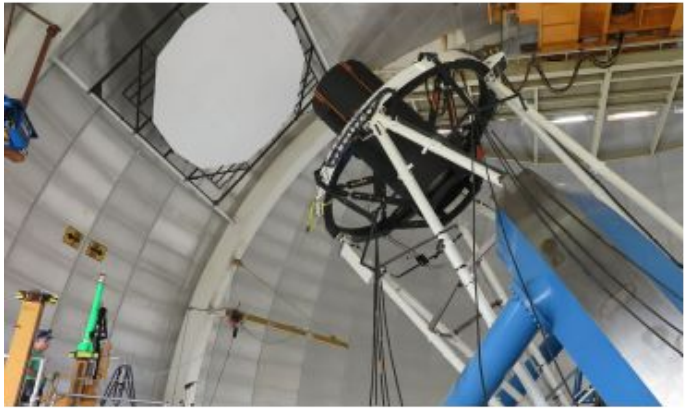
DESI Timeline

- Oct 2019: first light
- May 2021: main survey begins
- April 2024: first year cosmology results “DESI 2024”, BAO
- Dec 2024: first year cosmology results “DESI 2024”, full shape
- March 2025: 3rd year BAO cosmology results “DESI DR2”
- March 2025: Public Data Release of first year data “DESI DR1” (catalogs, spectra)

Today:

- originally planned survey nearly completed
- started running extension until 2028
- planning for a second phase, called DESI-2, not yet funded, aiming at higher-z

DESI instrument overview



Focal plane assembly with
5000 fiber positioners

Calibration Lamp System

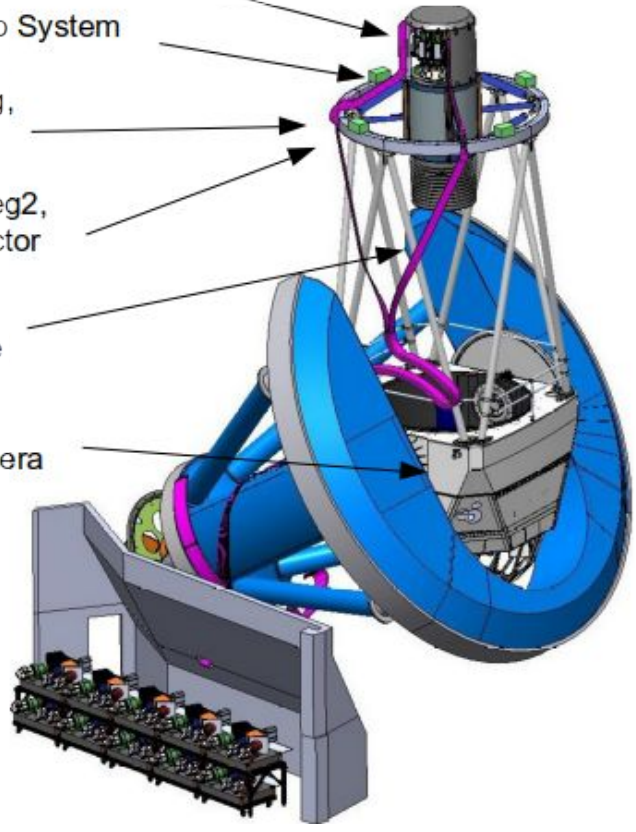
New Upper Ring,
Vanes, Cage

New 6-lens 8 deg2,
wide field corrector
in hexapod

47.5m, 10-cable
fiber run

Fiber View Camera

Ten, thermally-controlled
30channel spectrographs
360-980nm

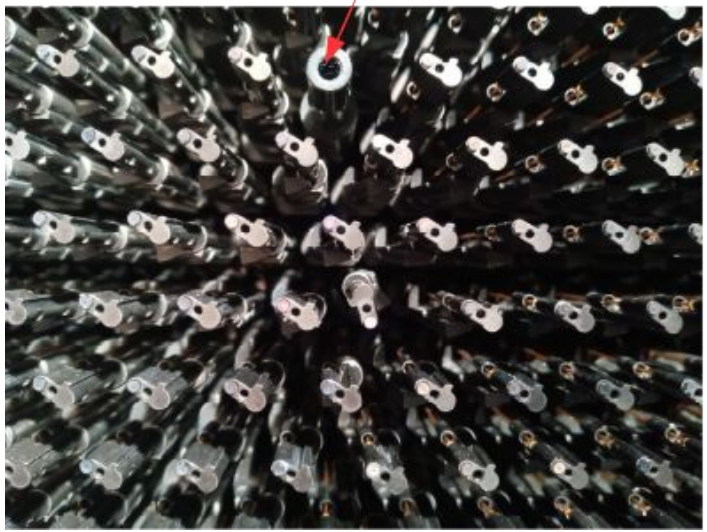


DESI focal plane

5000 positioners
- Two 3-mm long arms
- Pitch 10.4 mm
- Patrol radius 12 mm

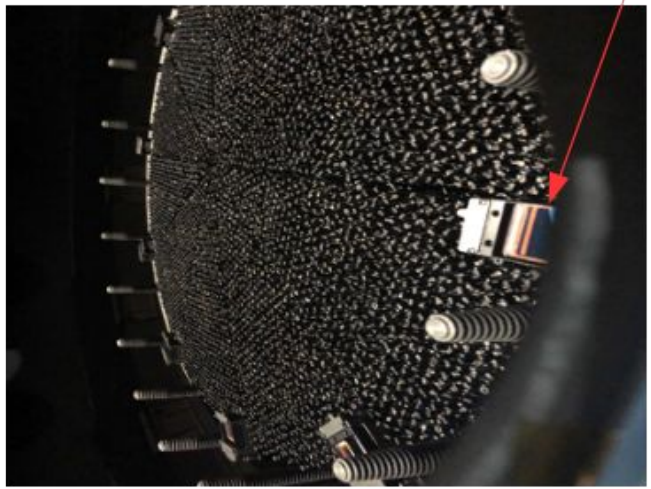
in 10 petals

one fiducial

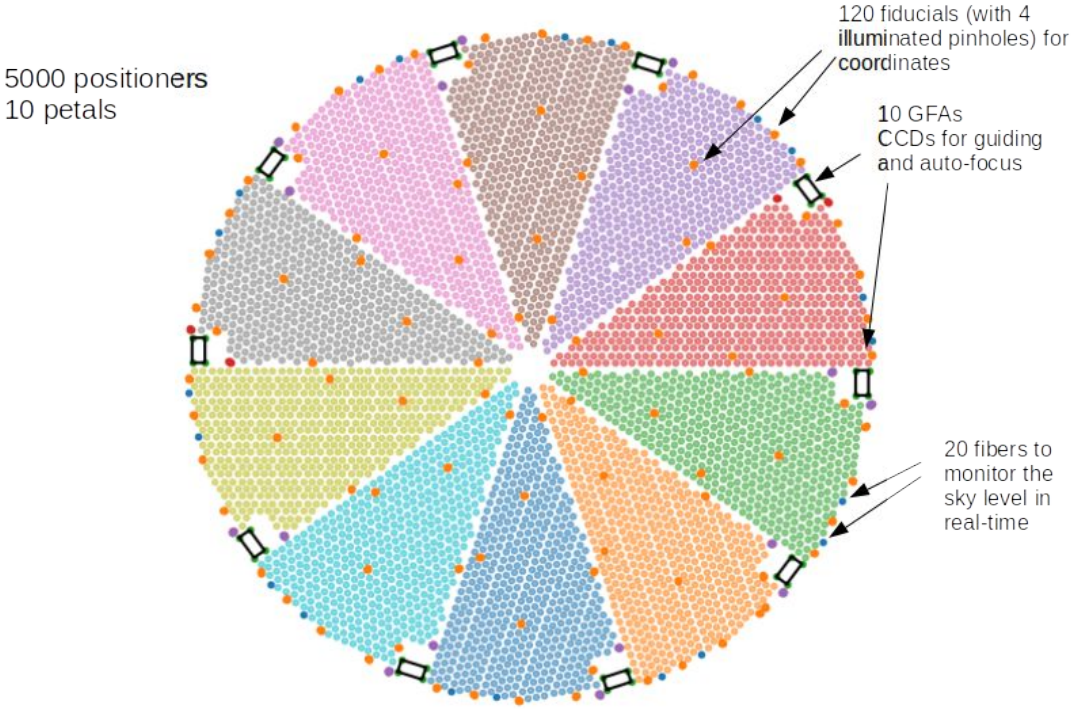


view of the installed focal plane

one GFA

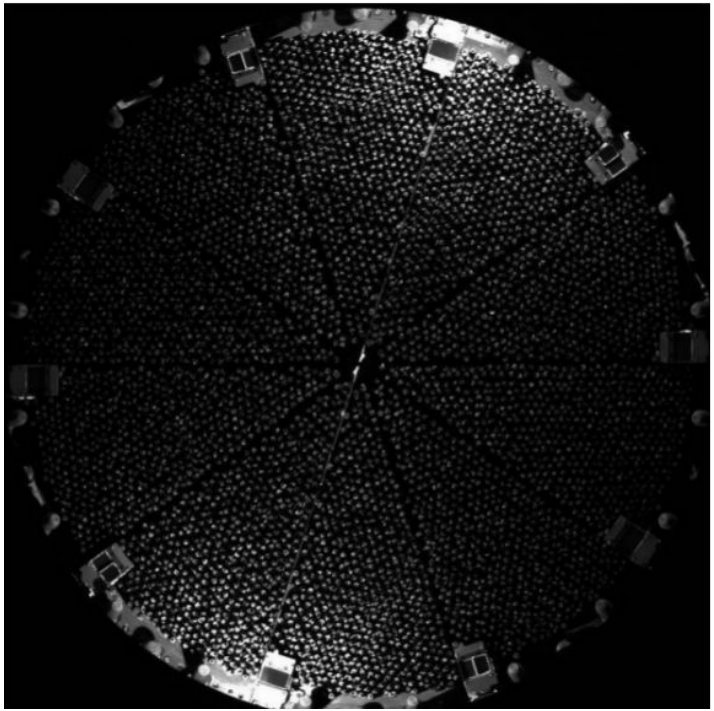


DESI focal plane

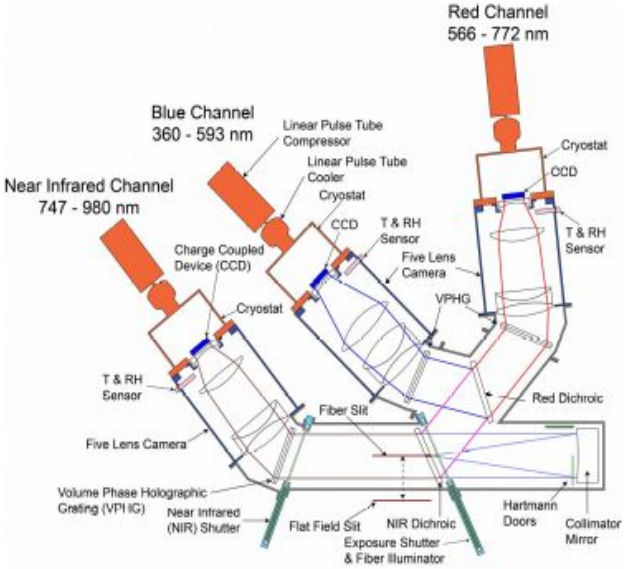


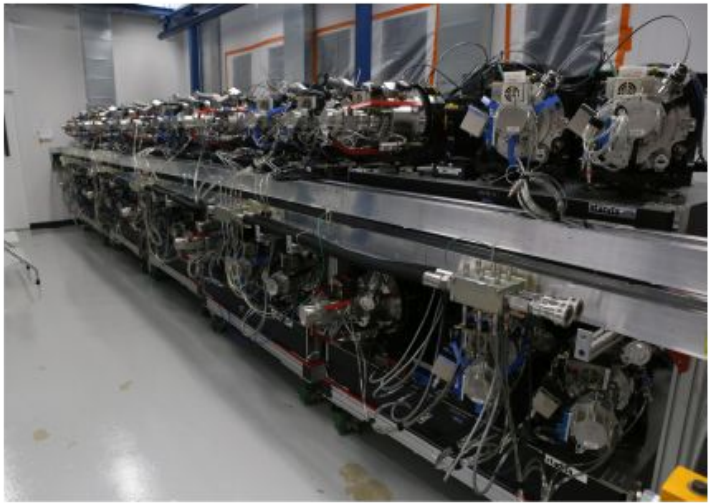
Fiber view camera image

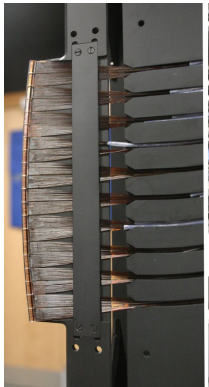
front-illuminated focal plane

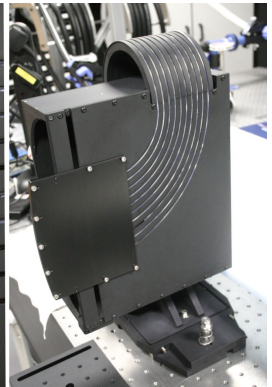


DESI spectrographs





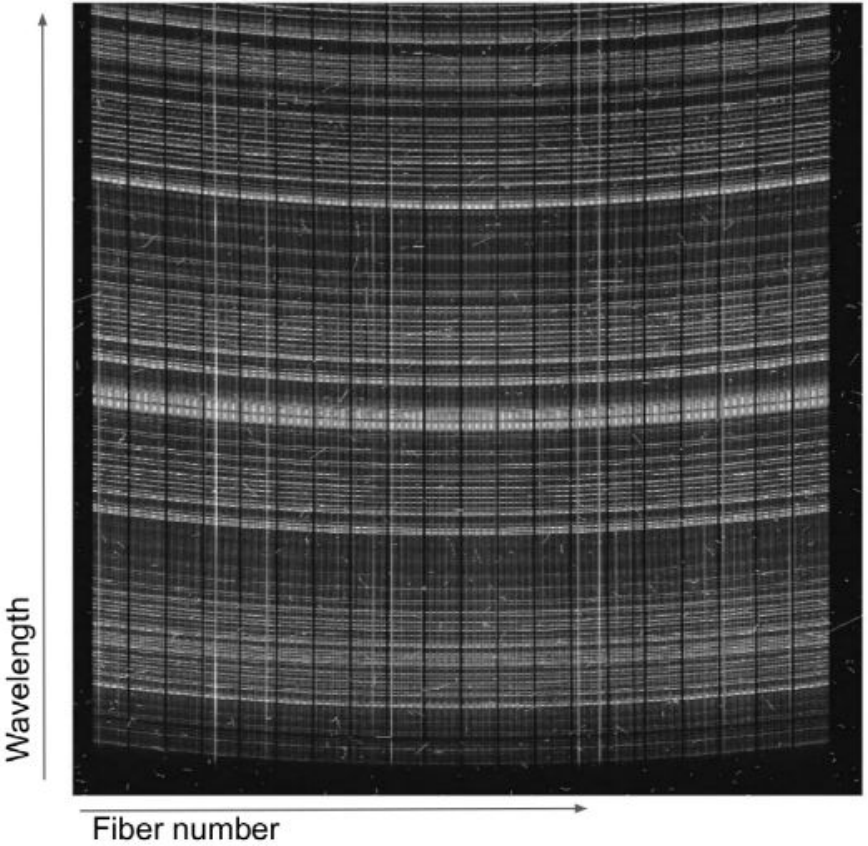




10 spectrographs
- 3 arms : BLUE (ITL CCD)
  RED-NIR (LBNL 250 microns CCD)
- 360-980 nm
- Volume Phase Holographic Gratings
- Resolution adapted to resolve [0II] doublet

Visual illustration

18 min exposure from April 12, one NIR CCD

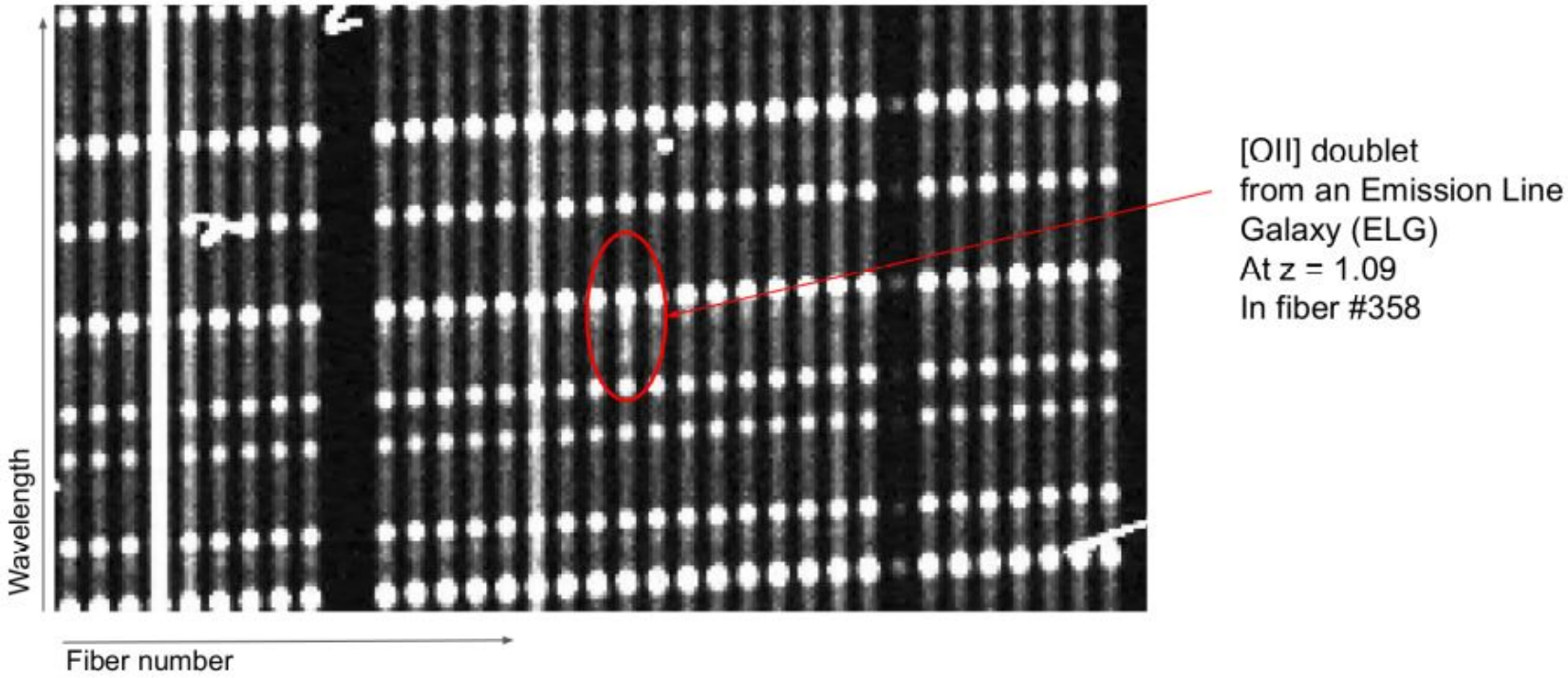


500 vertical fiber traces

Curved horizontal lines
are sky lines

Visual illustration

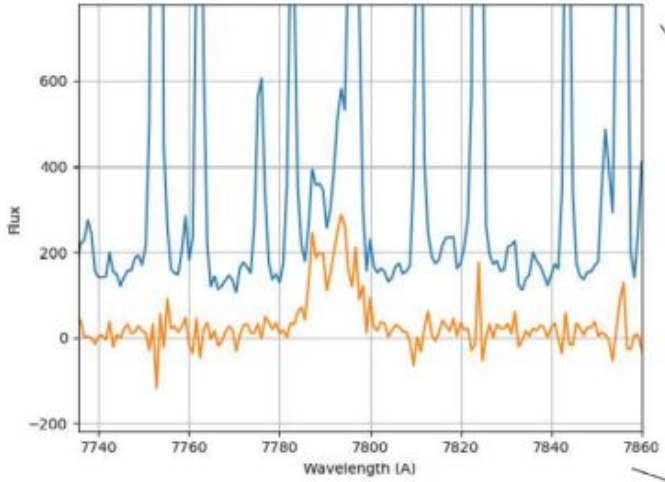
18 min exposure from April 12, one NIR CCD

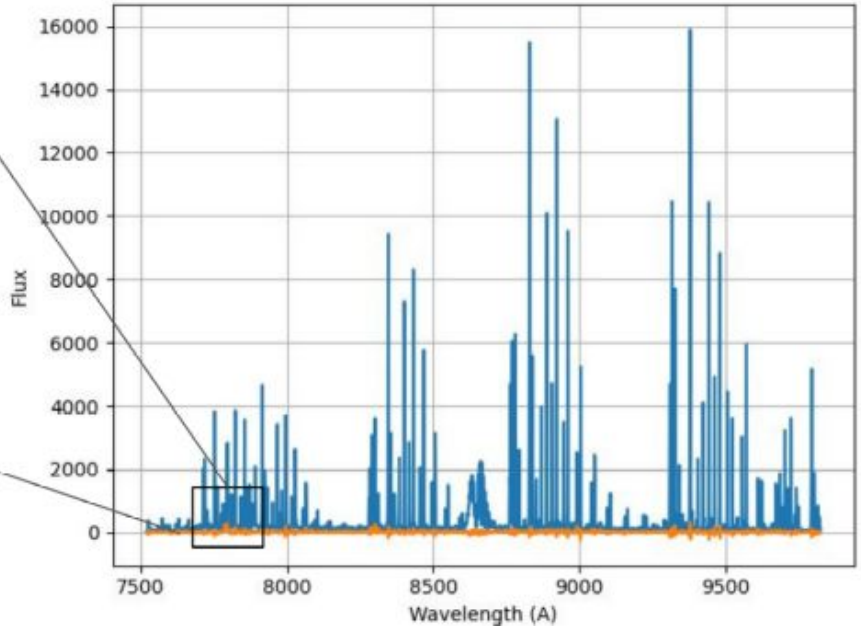


Visual illustration

18 min exposure from April 12, one NIR CCD

Extracted spectrum of fiber #358 for this exposure
before and after the subtraction of the sky background



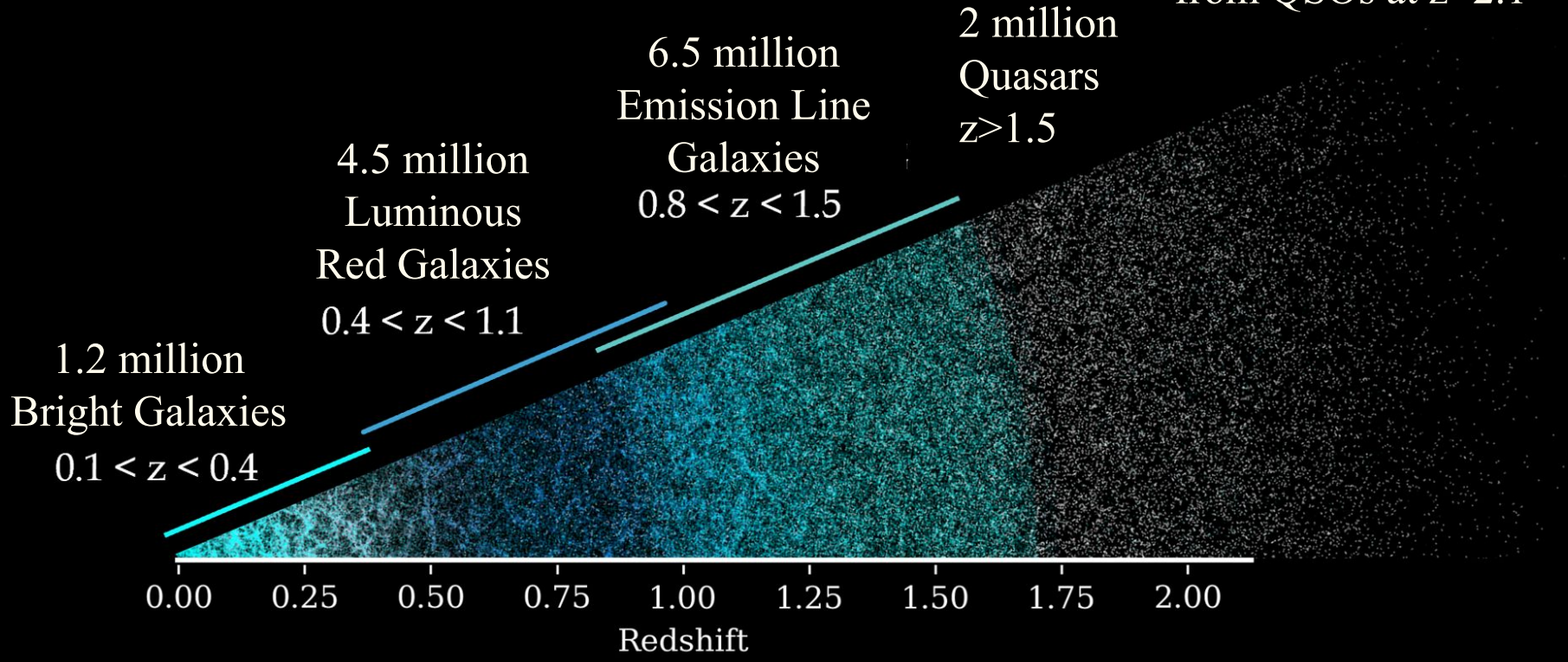


[OII] doublet from an Emission Line Galaxy
between 7780 and 7800A (z = 1.09)
in fiber #358


DESI DATA RELEASE 2
(first 3 years of operations)
67% of the dark time survey
May 2021 - April 2024

DESI DR2

Expected for Y5: > 40 million redshifts



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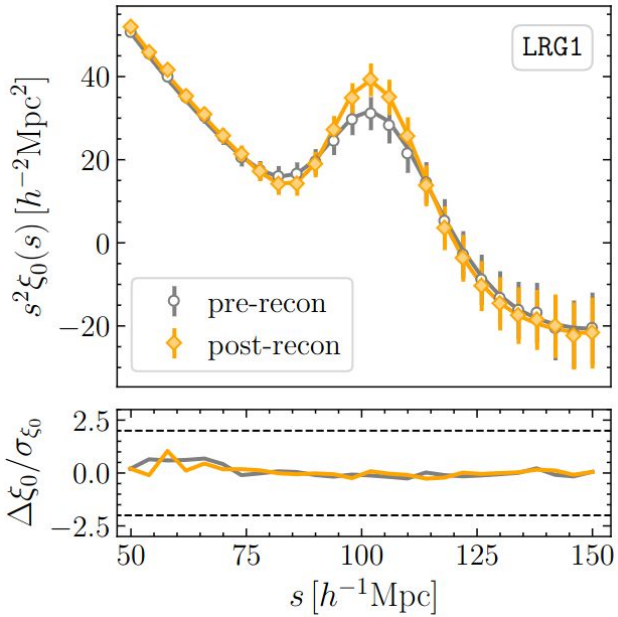
Two point correlation function and BAO

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

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



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

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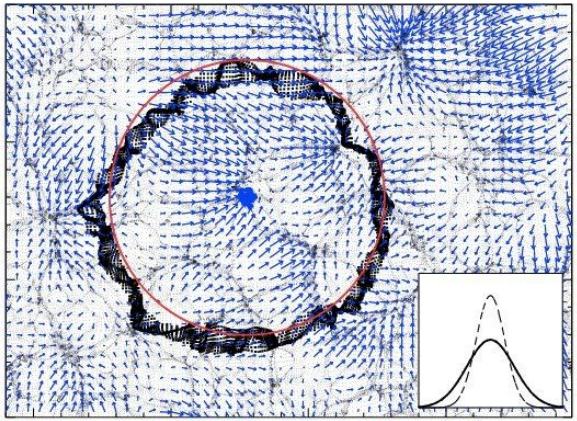
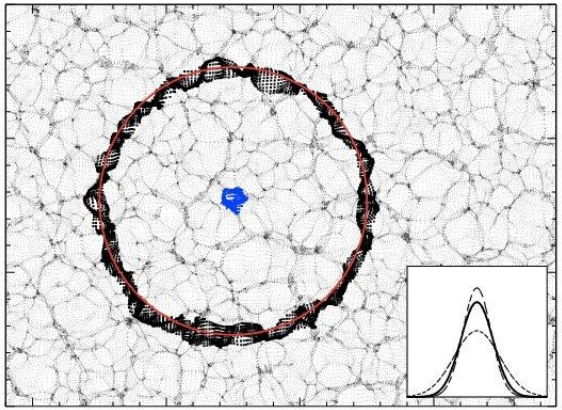
For galaxies and quasar only:

Density-field reconstruction (Eisenstein et al. 2008)

Refurbishes the ruler!



Reconstruction



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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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.

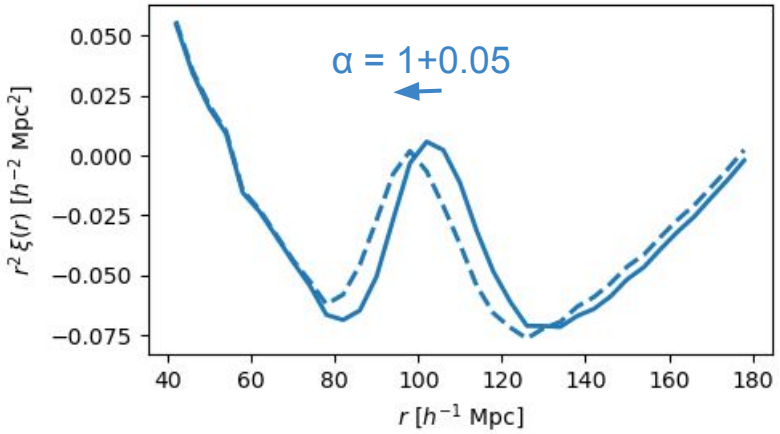
$$\xi(r_{||}, r_{\perp}) = \hat{\xi}_{\rm s}(r_{||}, r_{\perp}) + \hat{\xi}_{\rm p}(\alpha_{||} r_{||}, \alpha_{\perp} r_{\perp})$$

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

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

$$\alpha_{\rm iso} = \left(\alpha_{\perp}^2 \alpha_{\parallel}\right)^{1/3}$$

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



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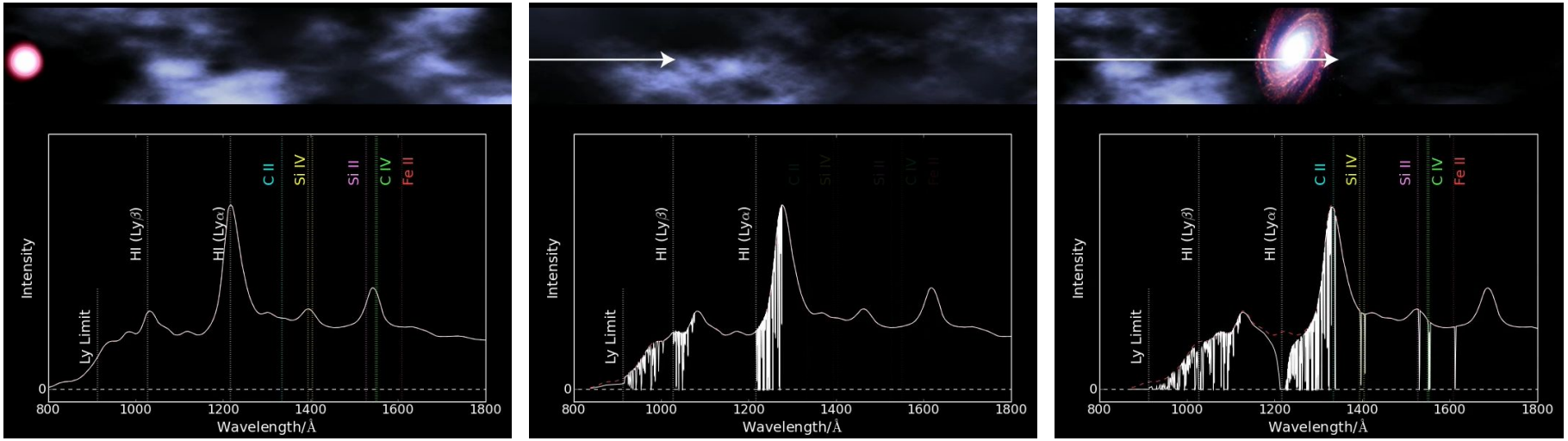
The Lyman-α Forest

credit: Andrew Pontzen



Background quasar → Intervening gas → Earth

- Absorption in QSO spectra by neutral hydrogen in the intergalactic medium

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

- The transmitted flux fraction F is a cosmological probe of the fluctuation in the neutral hydrogen density

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

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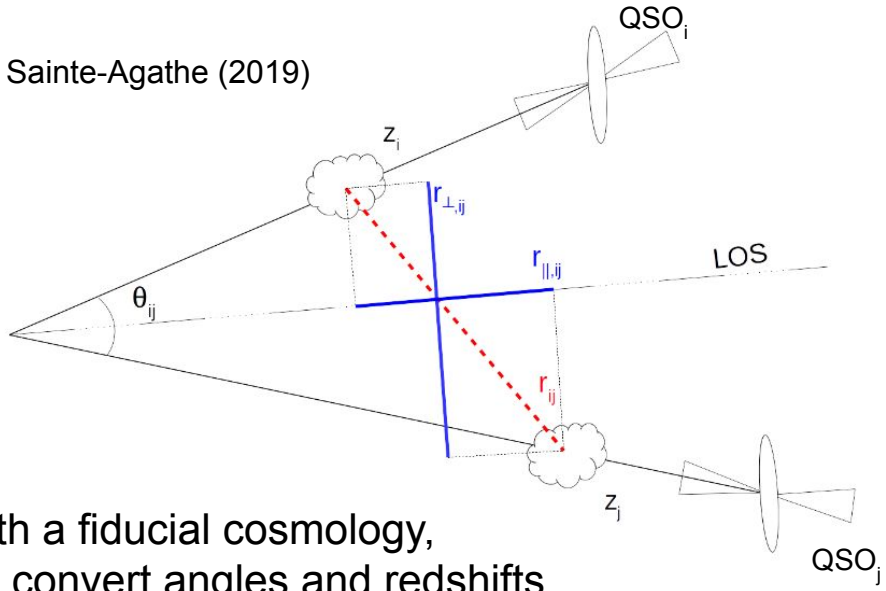
Lyman-alpha (Lya) Auto-Correlation function

de Sainte-Agathe (2019)



Transmitted flux fraction

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

Transmitted flux fraction contrast

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

Auto-correlation function

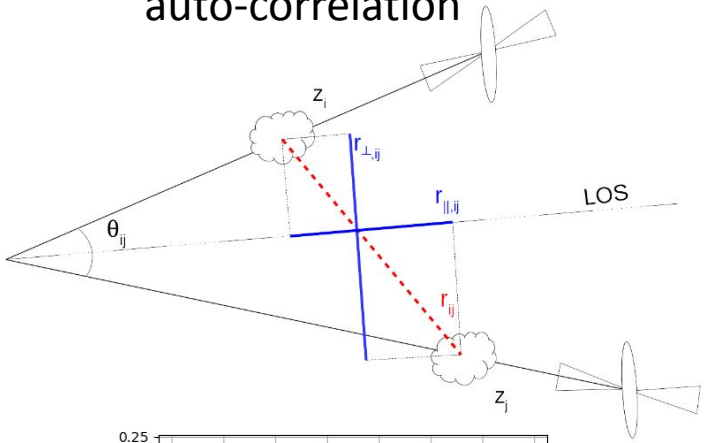
$$\xi(\vec{r}) = \langle \delta_F(\vec{x})\delta_F(\vec{x}+\vec{r}) \rangle$$

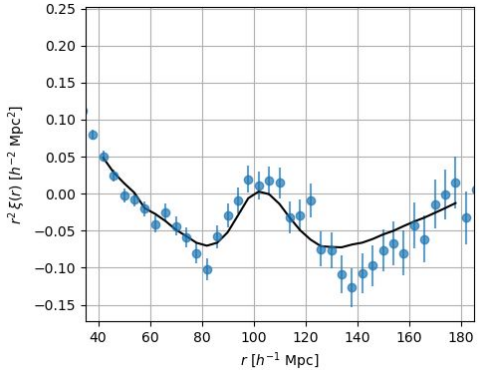
With a fiducial cosmology,
we convert angles and redshifts
into comoving separations

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

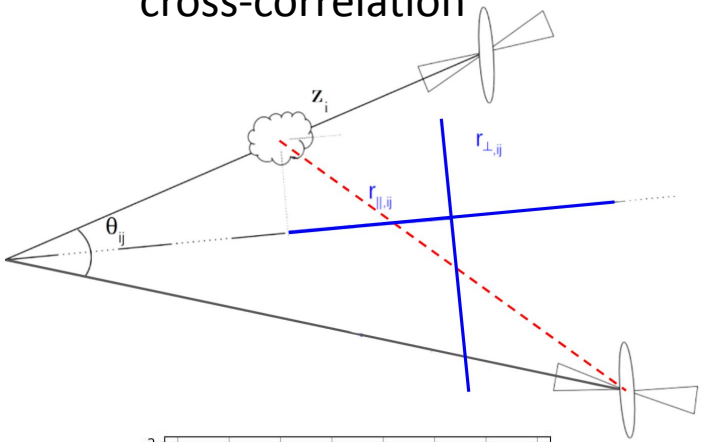
$D_C(z)$: comoving distance
$D_M(z)$: comoving angular distance

Lya-Lya auto-correlation

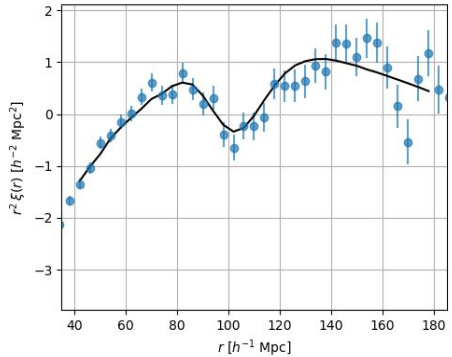




Lya-QSO cross-correlation



QSO at z_j



DESI DR2 BAO: blinded analyses

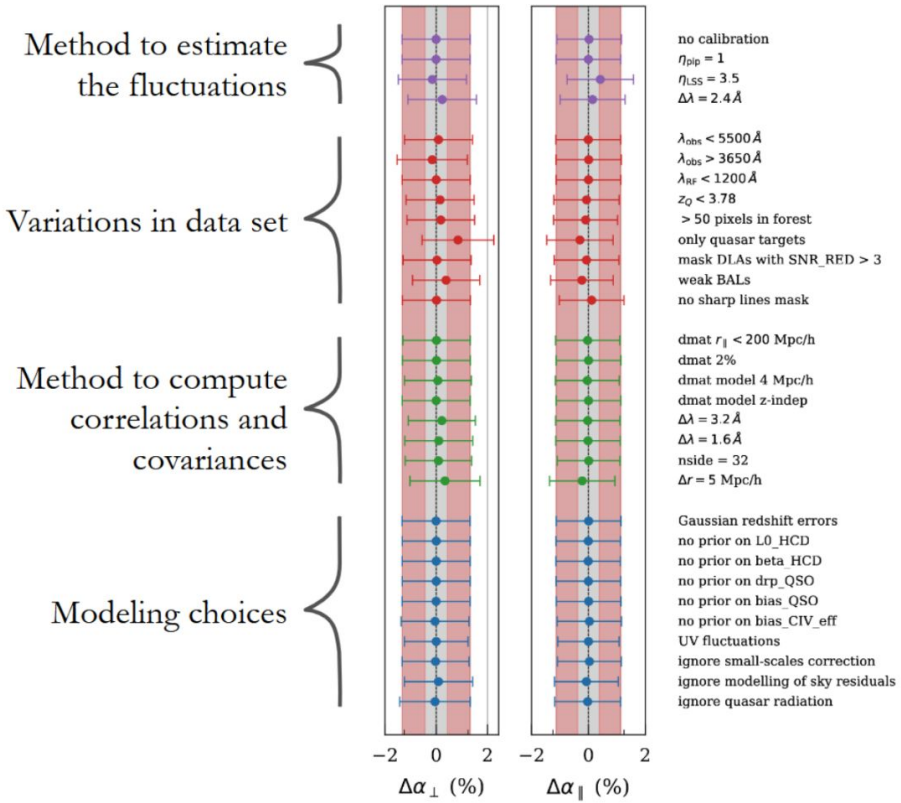
- BAO measurements were kept blinded during the validation process
- For galaxies and quasars: Catalog-level blinding that modifies galaxy redshifts and weights
- For Lyα forest: Data-vector blinding that shifts the BAO peak location

DESI DR2 BAO: Lyman-alpha analysis

DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest

Supporting paper: Validation of the DESI DR2 Lyα BAO analysis using synthetic datasets (Casas++ 2025)

Supporting paper: Construction of the Damped Lyα Absorber Catalog for DESI DR2 Lyα BAO (Brodzeller++ 2025)



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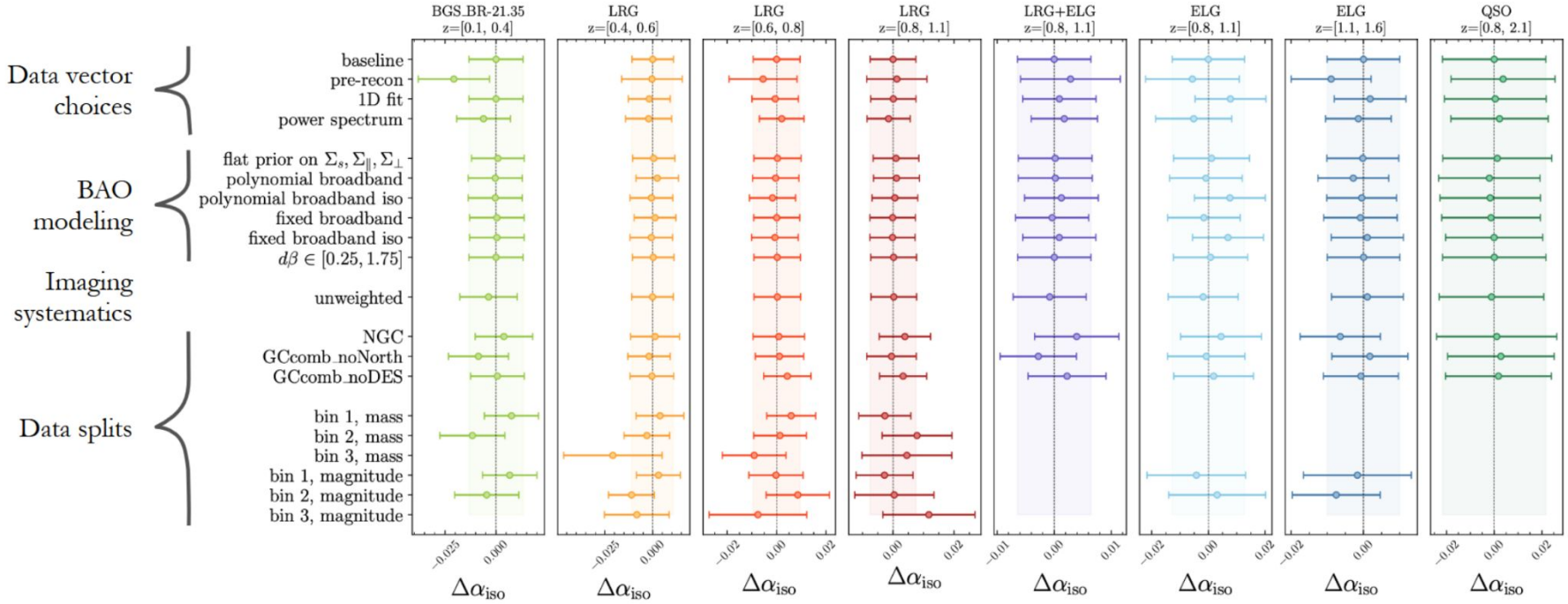
DESI DR2 BAO: galaxy clustering analysis



Differences in the isotropic BAO dilation

Supporting paper: Validation of DESI DR2 BAO from Galaxies and Quasars (Andrade++ 2025)

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DESI DR2 BAO: systematic uncertainties

Galaxy clustering

Tracer	Parameter	Theory (%)	HOD (%)	Fiducial (%)	Total (%)
BGS	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
LRG1	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG2	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG3	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG3+ELG1	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
ELG1	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	No detection	0.1	0.224
ELG2	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	No detection	0.1	0.224
QSO	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329

Lyα forest

$\Delta\alpha_{\parallel} = 0.3\%$

$\Delta\alpha_{\perp} = 0.3\%$

(due to non-linear evolution of the BAO peak)

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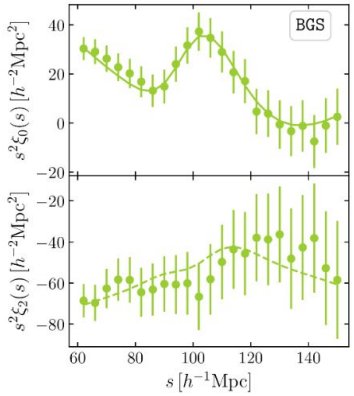
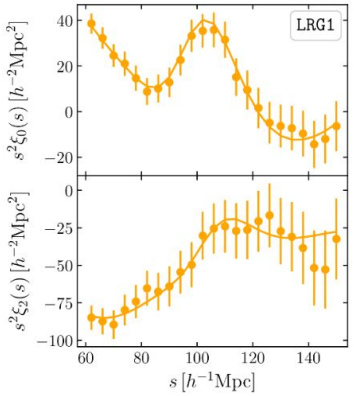
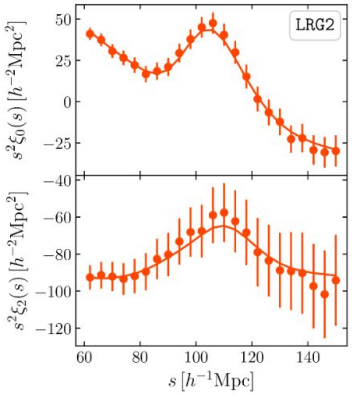
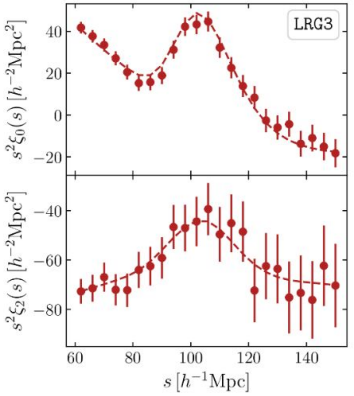
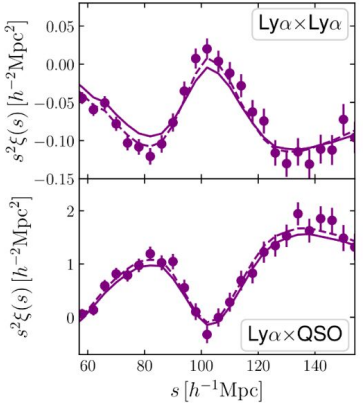
DESI DR2 BAO measurements

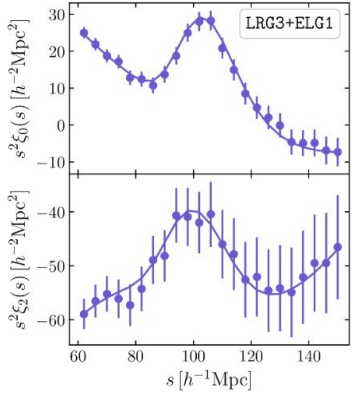


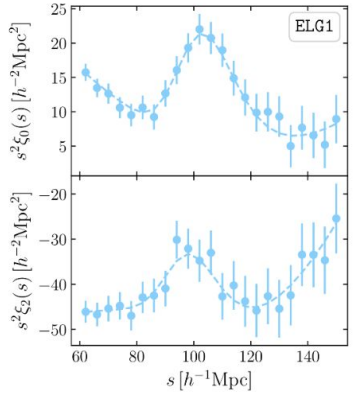


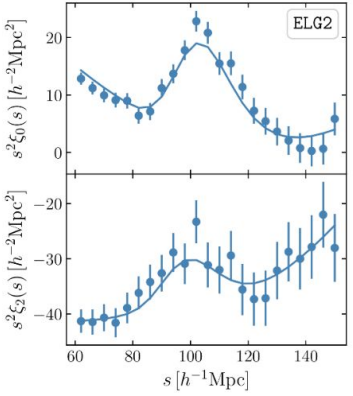


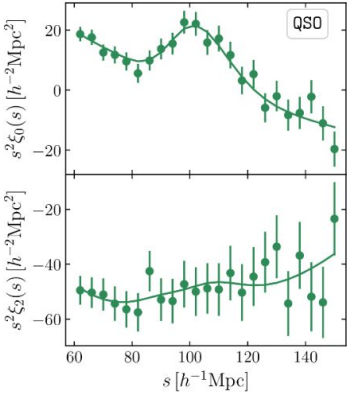












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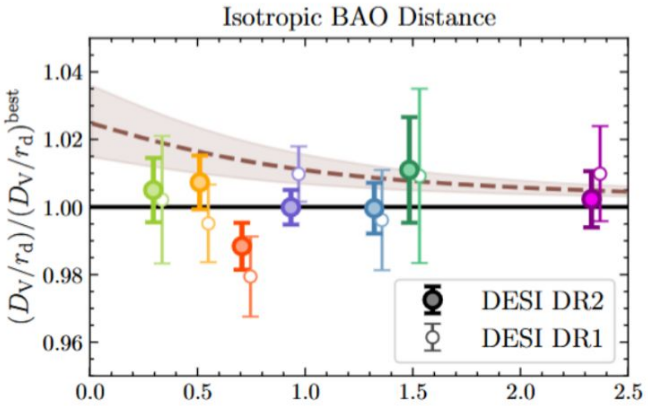
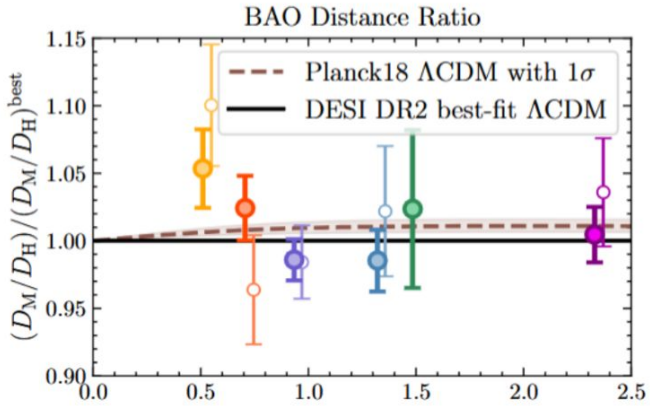
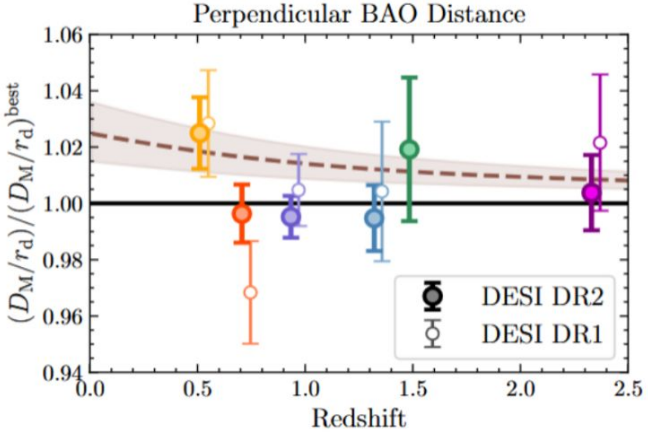
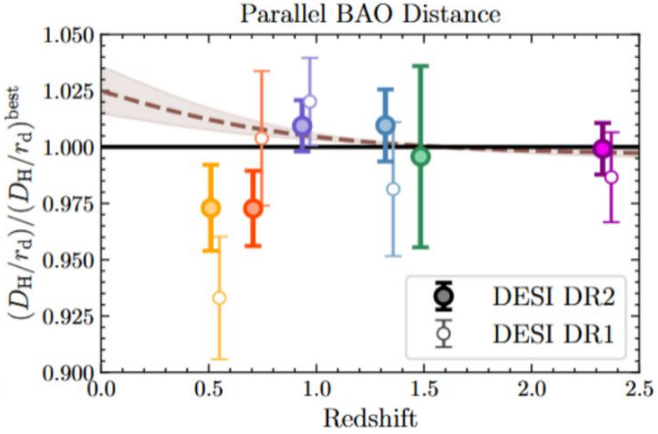
DESI DR2 BAO measurements









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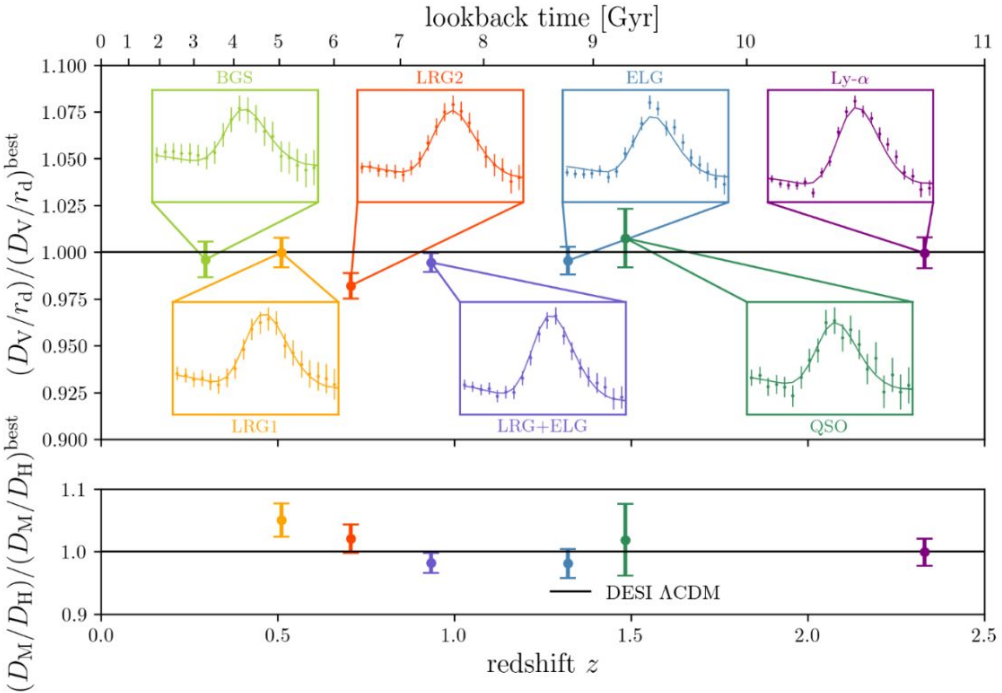
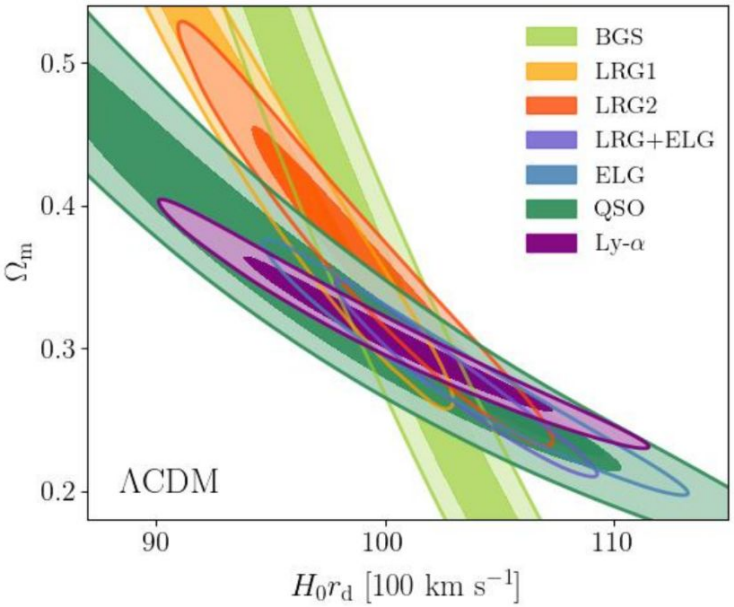
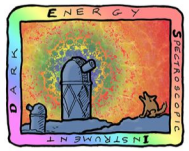
DESI DR2 BAO only: consistent with LCDM

DESI BAO measurements



Flat ΛCDM results





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DESI DR2 BAO only: consistent with LCDM

DESI BAO measurements

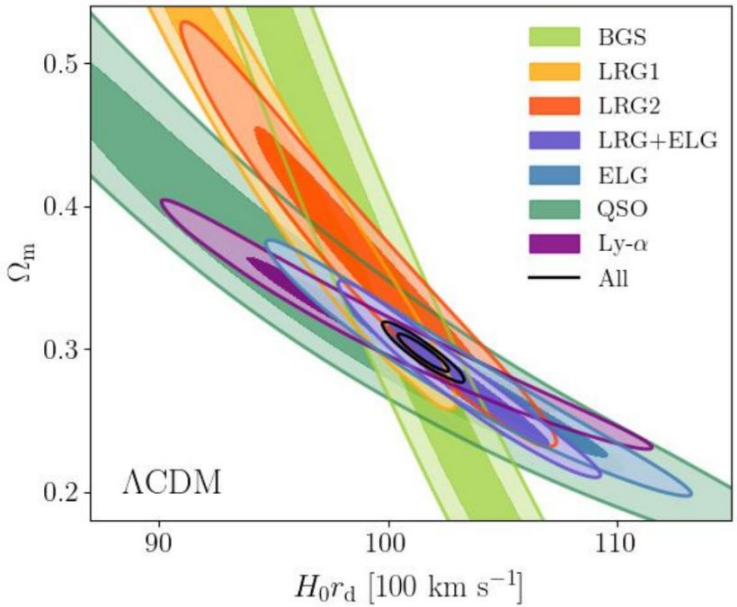
Consistent with each other,
and complementary

$\Omega_m = 0.2975 \pm 0.0086$ **(2.9%)**

$H_0 r_d = (101.54 \pm 0.73)\ [100\ \mathrm{km/s}]$ **(0.7%)**

DESI

Flat ΛCDM results



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DESI DR2 BAO in flat LCDM: tension with CMB

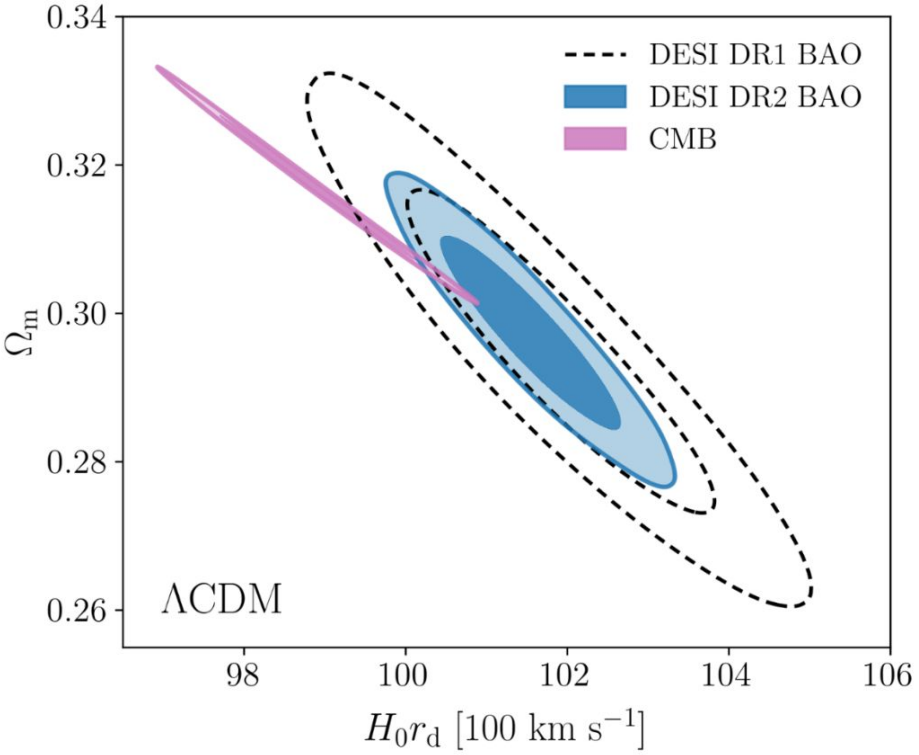
DESI DR1 BAO was 1.9σ from the **CMB**

CMB includes:

- primary CMB from Planck PR4 (CamSpec)
- CMB lensing from Planck PR4 + ACT DR6

DESI DR2 BAO is:

- Consistent with **DESI DR1**
- 2.3σ from the **CMB**



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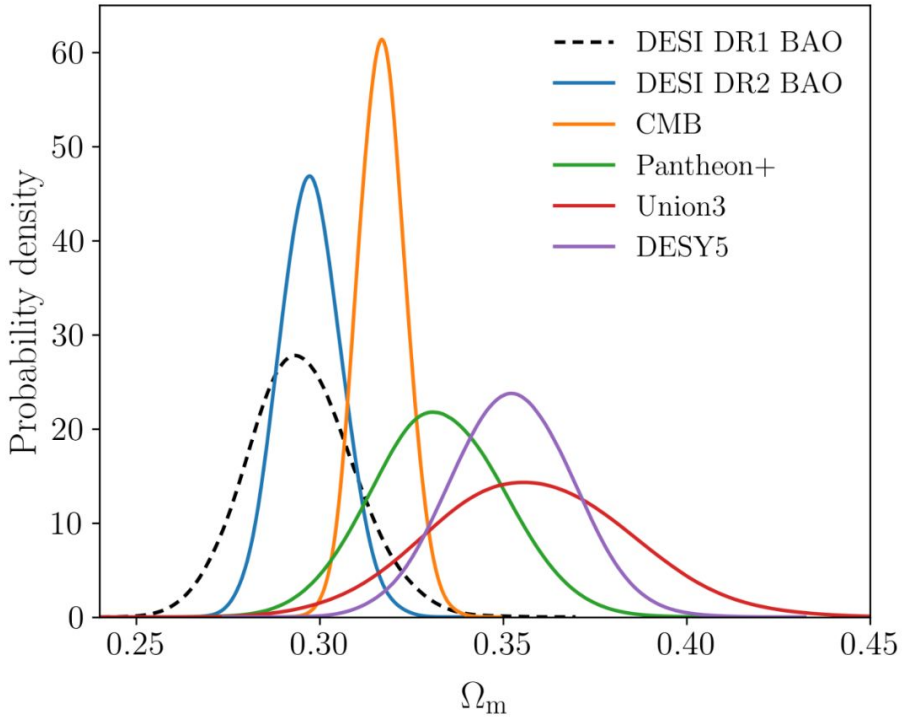
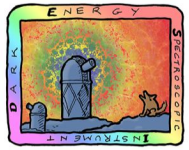
DESI DR2 BAO in flat LCDM: tension with SNeIa

- **DESI DR2** consistent with DESI DR1
- **DESI DR2** is lower than the CMB
- **DESI DR2** is lower than Supernovae:
  - 1.7σ lower than Pantheon+
  - 2.1σ lower than Union3
  - 2.9σ lower than DESY5





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Dynamical Dark Energy

$$w = P / \rho$$

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

DESI DR2 BAO+CMB+SNe favors Dynamical Dark Energy

Combining all DESI + CMB + SN

$w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}$

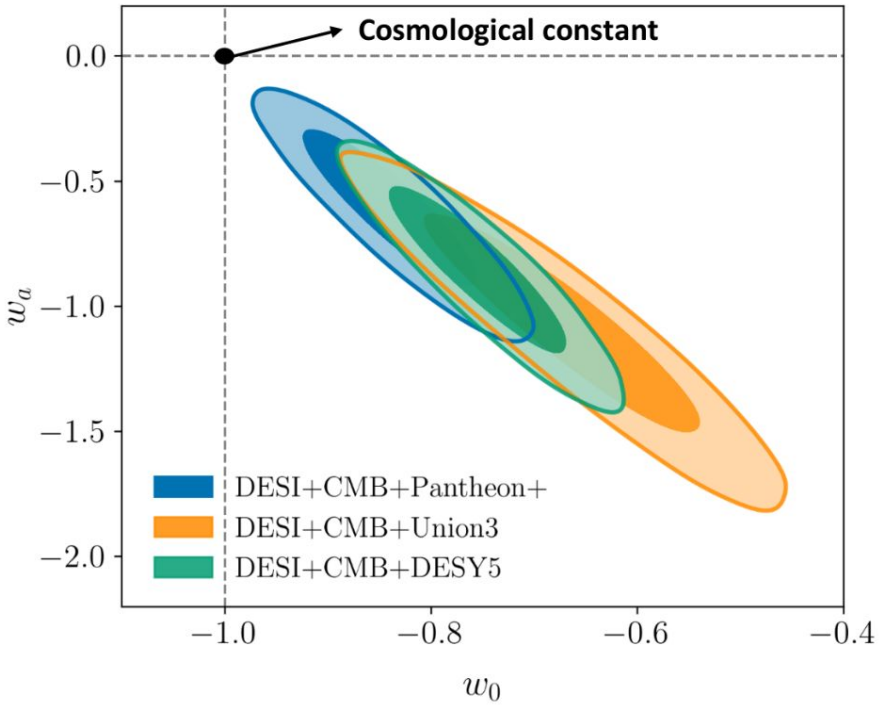
DESI + CMB + Pantheon+ $\Longrightarrow 2.8\sigma$

$w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}$

DESI + CMB + Union3 $\Longrightarrow 3.8\sigma$

$w_0 = -0.752 \pm 0.057 \qquad w_a = -0.86^{+0.23}_{-0.20}$

DESI + CMB + DESY5 $\Longrightarrow 4.2\sigma$



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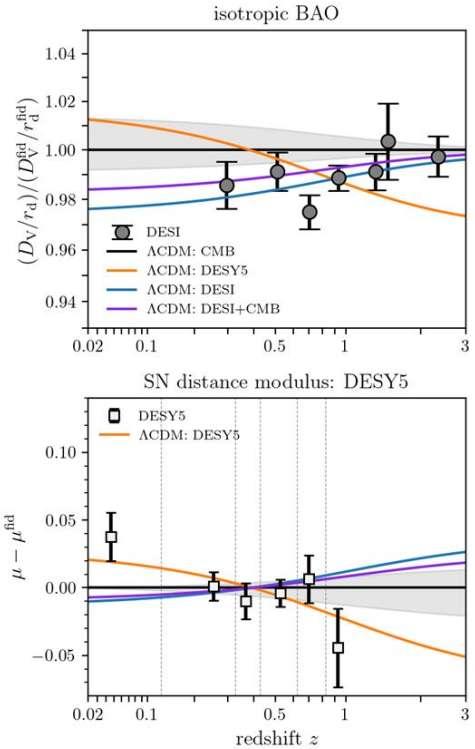
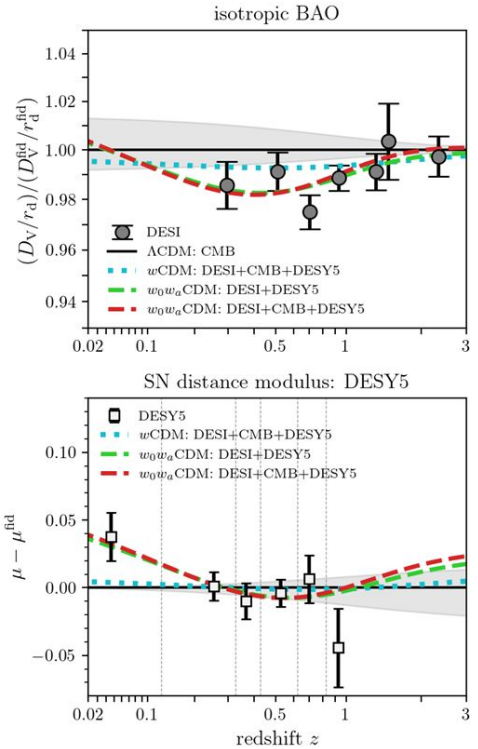
DESI DR2 BAO+CMB+SNe favors Dynamical Dark Energy

Cosmological constant (LCDM)
not a good fit to BAO+CMB+Supernovae



Dynamical dark energy (w0waCDM) is a better fit
(at 2.8 to 4.2 sigma depending on the SN sample)



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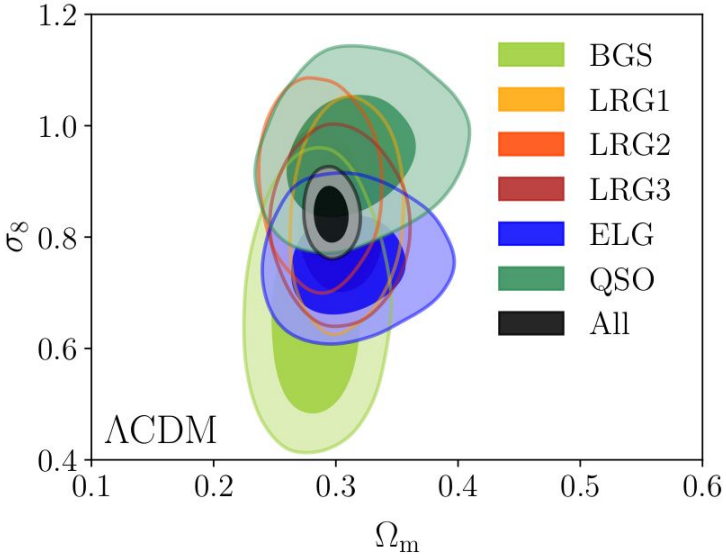
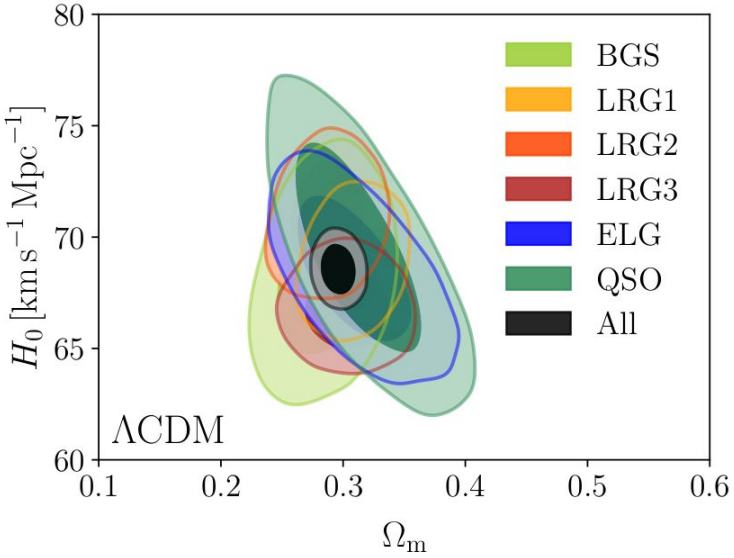
DESI 2024 (DR1) full-shape results





$$\left.\begin{aligned}\Omega_{\rm m} &= 0.2962 \pm 0.0095,\\ \sigma_8 &= 0.842 \pm 0.034,\\ H_0 &= (68.56 \pm 0.75)\ \mathrm{km\,s^{-1}\,Mpc^{-1}},\end{aligned}\right\}\ \text{DESI (FS+BAO)+BBN+}n_{\rm s10}$$

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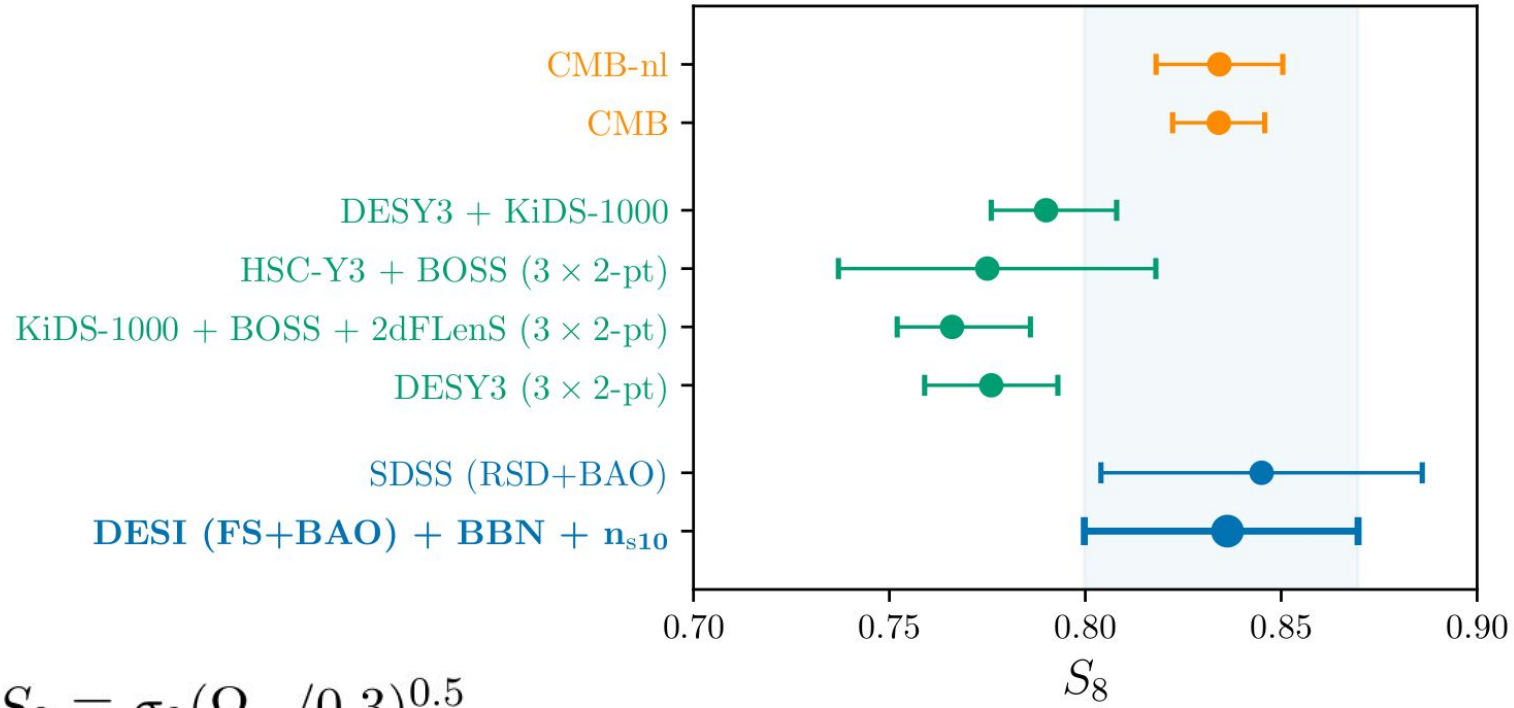
DESI 2024 (DR1) full-shape results



$$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$$

$$S_8 = 0.836 \pm 0.035 \quad (\text{DESI (FS+BAO)+BBN+}n_{\rm s10})$$

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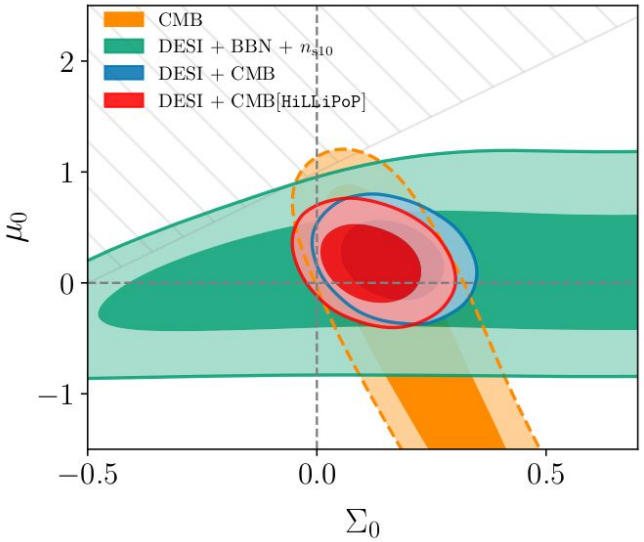
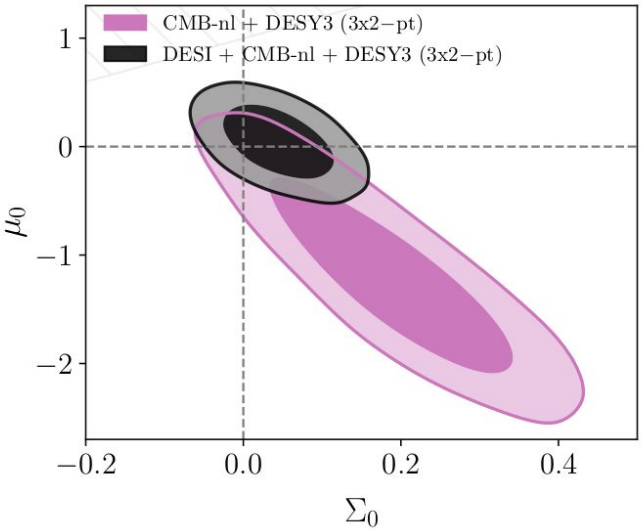
DESI 2024 (DR1) full-shape results
Modified gravity

$$k^2\Psi = -4\pi G a^2 \mu(a,k) \sum \rho_i \Delta_i, \quad k^2(\Phi+\Psi) = -8\pi G a^2 \Sigma(a,k) \sum_i \rho_i \Delta_i$$

$$\mu(a) = 1 + \mu_0 \frac{\Omega_{\rm DE}(a)}{\Omega_\Lambda}, \qquad \Sigma(a) = 1 + \Sigma_0 \frac{\Omega_{\rm DE}(a)}{\Omega_\Lambda}$$





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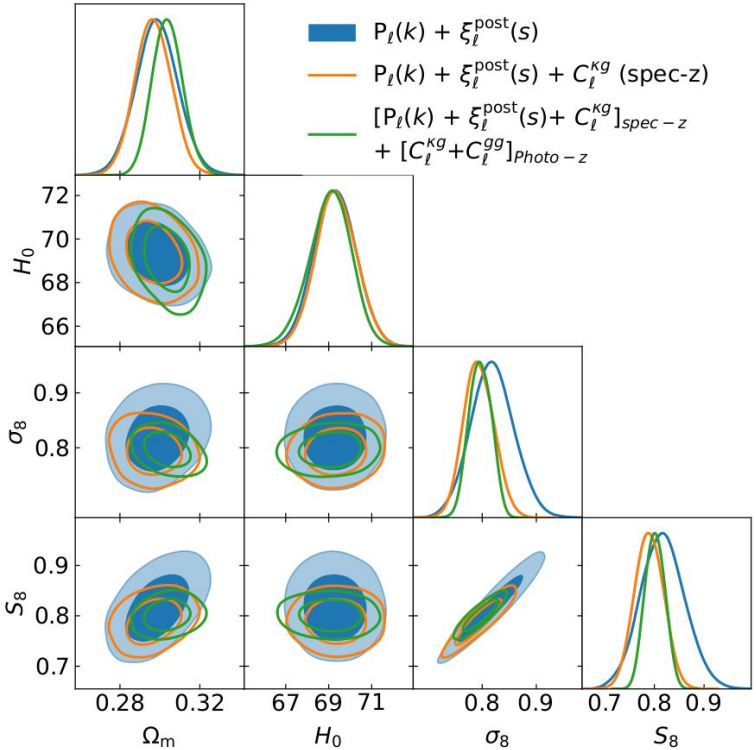
DESI 2024 (DR1) full-shape + CMB lensing x galaxy (spec-z and photo-z)

Maus et al. (2025)

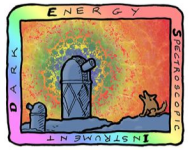


BGS,LRG,ELG,QSO Full-shape+BAO
+ BGS+LRG x CMB Lensing (Planck+ACT)

sigma_8 = 0.803 +- 0.017

(2.1% precision,
gain of ~50% compared to DESI only)

consistent with primary CMB only,
Planck + ACT, which gives
sigma_8 = 0.813 +- 0.005



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Conclusion

- DESI DR2 BAO from 14 million galaxies and QSO + 0.8 million Lya forests
- Aggregate precision of 0.3% on isotropic BAO scale at z<2 with galaxies+QSO, and 0.7% at z>2 with Lyman-alpha forest auto-correlation + QSO cross-corr.
- DESI BAO internally consistent with LCDM
- DESI BAO + BBN: H_0= 68.51 +- 0.58 km/s/Mpc (in tension with SHOES)
- DESI BAO in tension with CMB and/or SNIa in LCDM
  (see next talk for constraints on neutrinos)
- DESI BAO + CMB + SNe favor dynamical dark energy at 2.8 to 4.2 sigma depending on SNIa sample
- DESI DR1 full shape analysis measures sigma8 = 0.842 +- 0.034
  consistent with prediction from CMB in LCDM