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
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
The DESI survey

Five target classes
40 million redshifts in 5 years

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 \( < z < 0.4 \)
Baryon Acoustic Oscillations (BAO)

Sound waves in the baryon density

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).

Eisenstein, Seo, White et al. 2007
Standard ruler to measure the distances

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

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

\[ \xi(\vec{r}) = \langle \delta(\vec{x}) \delta(\vec{x} + \vec{r}) \rangle \]

\[ P(\vec{k}) = \int d^3r \; \xi(\vec{r}) e^{-i\vec{k}.\vec{r}} \]
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.

\[ \xi(r_\parallel, r_\perp) = \hat{\xi}_s(r_\parallel, r_\perp) + \hat{\xi}_p(\alpha_\parallel r_\parallel, \alpha_\perp r_\perp) \]

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

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

\[ \alpha_{\text{iso}} = (\alpha_\perp \alpha_\parallel)^{1/3} \]

\[ \alpha_{\text{AP}} = \frac{D_H D_{\text{M fid}}}{D_M D_H^{\text{fid}}} \]

\[ \alpha = 1 + 0.05 \]
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.

This will degrade the accuracy and precision of the standard ruler test.
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.**
DESI 2024 BAO measurements
DESI 2024 BAO measurements
Part 1: Galaxies and QSOs (z<2.1)
DESI Data Release 1 footprint

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

Stats for the 20220611 night:
Moon illumination: 0.94
1 DARK tiles completed
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 $18 \text{ Gpc}^3$

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.

\[(ra, \, dec, \, z) \quad \rightarrow \quad (X, \, Y, \, Z) \quad \rightarrow \quad (ra, \, dec, \, z')\]

- Fiducial cosmology
- **blind** cosmology $w_0, \, w_a, \, \Omega_m$ (not revealed!)
- + 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

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

Systematics $\ll$ Statistical errors.

Max. effect:

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

<table>
<thead>
<tr>
<th>Space</th>
<th>Tracer</th>
<th>$\sigma_{\text{BGS}}$</th>
<th>$\sigma_{\text{LRG,ELG}}$</th>
<th>$\sigma_{\text{QSO}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi(r)$</td>
<td>Theory (Table 7)</td>
<td>0.1</td>
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<td>0.2</td>
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<td>$\xi(r)$</td>
<td>HOD (Table 8)</td>
<td>0.2</td>
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<td>$\xi(r)$</td>
<td>Fiducial (Table 11)</td>
<td>0.1</td>
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<tr>
<td>$\xi(r)$</td>
<td>Total</td>
<td>0.245</td>
<td>0.245</td>
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<tr>
<td>$P(k)$</td>
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<td>0.1</td>
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<td>0.18</td>
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</table>
Unblinded galaxy BAO feature highlights
Unblinded galaxy BAO feature highlights

Overall size of the BAO

Anisotropy of the BAO

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

Emission Line Galaxies at $z_{\text{eff}} = 1.32$
Distance measured at 1.5%.
Overall size of the BAO

Anisotropy of the BAO

LyA- BAO (next slides)
Fiducial cosmology:
(solid lines)
Planck 2018 LCDM

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<tr>
<td>$\Omega_r$</td>
<td>7.9638e-05</td>
</tr>
<tr>
<td>$\sigma_8(z=0)$</td>
<td>0.8119</td>
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<tr>
<td>$r_d$ [Mpc]</td>
<td>147.09</td>
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<td>99.08</td>
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<td>$D_M(z_{\text{eff}}=2.33)/r_d$</td>
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BAO Hubble diagram: 0.52% aggregate precision
Consistency tests with the unblinded data

<table>
<thead>
<tr>
<th></th>
<th>BGS</th>
<th>LRG1</th>
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<th>LRG3</th>
<th>LRG3+ELG1</th>
<th>ELG1</th>
<th>ELG2</th>
<th>QS0</th>
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<td>flat prior on ( \Sigma_{g}, \Sigma_{</td>
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<td>smaller ( \Sigma_{\text{emp}} )</td>
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\( \alpha_{\text{iso}} \)

\( 0.95 \) to \( 1.00 \), \( 0.95 \) to \( 1.025 \)
DESI 2024 BAO measurements
Part 2: Lyman-alpha forest (z>2)
The Lyman-α Forest

- 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

\[ \tau \propto n_{HI} \]
The Lyman-α Forest

Credit: William C. Keel
Lyman-alpha (Lya) Auto-Correlation function

de Sainte-Agathe (2019)

Transmitted flux fraction
\[ F = e^{-\tau} \]

Transmitted flux fraction contrast
\[ \delta_F = \frac{F}{F_0} - 1 \]

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

\(D_C(z)\) : 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)
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
DES1-Y1 Quasar and Lya sample

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

Rest-frame wavelength [Å]

Flux [10^{-17} erg/(cm^2 s Å)]

Observed wavelength [Å]

Lyα  Lyβ  CIV  CIII

Z_{qso} = 3.14
4 correlation functions
Contaminants to Lyman-alpha forest

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

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

- 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]
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 Lyα 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 (\(< \frac{1}{3} \text{ of statistical uncertainty}\))
   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:

\(< \frac{1}{3} \text{ of DESI Y1 statistical uncertainty (dashed ellipse)}\)
\(< 0.4\% \text{ (not significant, but treated as conservative systematic uncertainty)}\)

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

\[
\frac{\Delta \alpha||}{\sigma_{\alpha||}} = 1.01 \pm 0.07 \\
\frac{\Delta \alpha_{\perp}}{\sigma_{\alpha_{\perp}}} = 1.11 \pm 0.06
\]
2. Data splits

All found consistent within statistical uncertainties

Test: spectroscopic data reduction systematics

Test: target selection systematics

Test: systematics from QSO continuum coupled to bias variations

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

- no calibration
  \( \eta_{\text{pip}} = 1 \)
  \( \varepsilon \) free
  \( \eta_{\text{LS}} = 3.5 \)
  \( \Delta \lambda = 2.4 \text{ Å} \)
  \( \lambda_{\text{obs}} < 5500 \text{ Å} \)
  \( \lambda_{\text{obs}} > 3650 \text{ Å} \)
  \( \lambda_{\text{AF}} < 1200 \text{ Å} \)
  \( z_0 < 3.78 \)
  > 50 pixels in forest
  original redshift estimates
  mask-LyA redshift estimates
  only quasar targets
  DLAs SNR > 1
  weak BALs
  no sharp lines mask

- dmat \( r_1 < 200 \text{ Mpc/h} \)
  dmat 2%
  dmat model 4 Mpc/h
  \( \Delta \lambda = 3.2 \text{ Å} \)
  \( \Delta \lambda = 1.6 \text{ Å} \)
  nsides = 32
  \( \Delta r = 5 \text{ Mpc/h} \)
  no cross-covariance
  \( r < 200 \text{ Mpc/h} \)
  \( r < 160 \text{ Mpc/h} \)
  \( r > 20 \text{ Mpc/h} \)
  \( r > 40 \text{ Mpc/h} \) with priors

- eBOSS metals
  vary \( L_{\text{HGD}} \)
  \( L_{\text{HGd}} = 10 \text{ Mpc/h} \)
  \( L_{\text{HGD}} = 3 \text{ Mpc/h} \)
  Gaussian redshift errors
  weak CIV bias prior
  no small-scales correction
  UV fluctuations
Unblinding the DESI DR1 Lyman-alpha Results

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

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

\[\alpha_{||} = 0.989 \pm 0.020\]

\[\alpha_{\perp} = 1.013 \pm 0.024\]

Fiducial cosmology:

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DESI DR1 Lyman-alpha Results

Optimal combination:

\[
\frac{D_H(z_{\text{eff}})}{r_d} = 8.52 \pm 0.17 \\
\frac{D_M(z_{\text{eff}})}{r_d} = 39.71 \pm 0.95
\]

with a correlation coefficient \( \rho = -0.48 \)

\[
D_M(z_{\text{eff}})^{9/20} D_H(z_{\text{eff}})^{11/20} / r_d = 17.03 \pm 0.19
\]

1.1% precision on BAO scale at \( z_{\text{eff}} = 2.33 \)
DESI 2024 BAO measurements
Part 3: cosmological implications

- 68.5% dark energy
- 26.6% dark matter
- 4.9% ordinary matter
Dark energy equation of state:

\[ P = w\rho \]

- \( w = \) constant

\( w = -1 \) for cosmological constant in LCDM
Dark energy equation of state:

\[ P = w \rho \]

- **CPL parameterization:**
  \[ w(a) = w_0 + (1 - a)w_a \]
DESI BAO measurements
DESI BAO measurements
DESI BAO measurements
DESI BAO measurements
DESI Y1 BAO

DESI BAO measurements

[Graph showing BAO measurements with data points and error bars for different redshifts and lookback times.]
DESI BAO measurements
DESI Y1 BAO

DESI BAO measurements

Consistent with each other, and complementary

\[ \Omega_m = 0.295 \pm 0.015 \quad (5.1\%) \]

\[ H_0 r_d = (101.8 \pm 1.3) \ [100 \text{ km s}^{-1}] \quad (1.3\%) \]

\[ \chi^2 = 12.66 \text{ for 12 data points and 2 parameters} \]
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
DESI Y1 BAO consistent with:

- SDSS (eBOSS Collaboration, 2020)
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$$\Omega_m = 0.3069 \pm 0.0050 \,(1.6\%)$$

DESI + CMB
Hubble Constant

- BAO constrains $r_d(\Omega_m h^2, \Omega_b h^2)h$
- $\Omega_m$ constrained by BAO at different $z$
- $\Omega_b h^2$ can be constrained by BBN: Schöneberg et al., 2024

$\Rightarrow$ constraints on $h$ i.e. $H_0$
Hubble Constant

\[ H_0 = (68.53 \pm 0.80) \text{ km s}^{-1} \text{ Mpc}^{-1} \]

\[ H_0 = (68.52 \pm 0.62) \text{ km s}^{-1} \text{ Mpc}^{-1} \]

- Consistency with SDSS
- In agreement with CMB
- In 3.7\( \sigma \) tension with SH0ES

Brand new result from CCHP (with JWST):
\[ H_0 = 69.1 \pm 1.5 \text{ km/s/Mpc} \]
Spatial Curvature

DESI + CMB measurements favor a flat Universe

\( \Omega_K = 0.0024 \pm 0.0016 \) (DESI + CMB)
**Dark Energy Equation of State**

**Constant EoS parameter** \( w \)

\[
\Omega_m = 0.293 \pm 0.015 \quad (5.1\%)
\]

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

**DESI**
Dark Energy Equation of State

**Constant EoS parameter $w$**

\[
\Omega_m = 0.293 \pm 0.015 \quad (5.1\%)
\]

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

---

**DESI**

\[
\Omega_m = 0.3095 \pm 0.0065 \quad (2.1\%)
\]

\[
w = -0.997 \pm 0.025 \quad (2.5\%)
\]

---

**DESI + CMB + Pantheon+**

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

\[ w(a) = w_0 + (1 - a)w_a \quad \text{(CPL)} \]

\[ w_0 = -0.45^{+0.34}_{-0.21} \quad w_a = -1.79^{+0.48}_{-1.00} \]

DESI + CMB \implies 2.6\sigma
Dark Energy Equation of State

**Varying EoS**

\[ w(a) = w_0 + (1 - a) w_a \]  
(CPL)

\[ w_0 = -0.45^{+0.34}_{-0.21} \quad w_a = -1.79^{+0.48}_{-1.00} \]

DESI + CMB  \( \Rightarrow \)  2.6\( \sigma \)
Dark Energy Equation of State

Combining all DESI + CMB + SN

\[
\begin{align*}
  w_0 &= -0.827 \pm 0.063 & w_a &= -0.75^{+0.29}_{-0.25} \\
  \text{DESI + CMB + Pantheon+} &\implies 2.5\sigma
\end{align*}
\]

\[
\begin{align*}
  w_0 &= -0.64 \pm 0.11 & w_a &= -1.27^{+0.40}_{-0.34} \\
  \text{DESI + CMB + Union3} &\implies 3.5\sigma
\end{align*}
\]

\[
\begin{align*}
  w_0 &= -0.727 \pm 0.067 & w_a &= -1.05^{+0.31}_{-0.27} \\
  \text{DESI + CMB + DES-SN5YR} &\implies 3.9\sigma
\end{align*}
\]

\[w_0 > -1, w_a < 0\] 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

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

Limit relaxed for extensions to $\Lambda$CDM

$$\sum m_\nu < 0.195 \text{ eV} \text{ for } w_0w_a \text{ CDM}$$
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%, $\Lambda$CDM)
  <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

Stats for the 20220611 night:
Moon illumination: 0.94
1 DARK tiles completed
Main/DARK : 6671/9929 completed tiles up to 20240409 (=67%, weighted=68%)

Stats for the 20240409 night:
Moon illumination: 0.04
28 DARK tiles completed
BACK UP
The Lyman-α Forest

Recombination as universe expands
Reionization with formation of galaxies and quasars

Optical depth to Lyman-alpha transition
(at 121.6 nm, 1216 Å)

\[ \tau \propto n_{HI} \quad \tau \lesssim 1 \text{ for } z < 4 \]

great probe of matter density fluctuations

McQuinn (2016)

Wynne Turner et al. (in prep.)
Correlation function estimators

Correlation function estimators are simple weighted means in $(r_{\text{par}}, r_{\text{perp}})$ separation bins $M$ of $(4 \, \text{Mpc}/h) \times (4 \, \text{Mpc}/h)$

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:

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

Optimized weights:

$$w_q(\lambda) = \left( \frac{1 + z_\lambda}{1 + z_0} \right)^{\gamma_q^{-1}} \left[ \eta_{\text{pip}}(\lambda) \left( \frac{\sigma_{\text{pip},q}(\lambda)}{F C_q(\lambda)} \right)^2 + \eta_{\text{LSS}} \sigma_{\text{LSS}}^2(\lambda) \right]^{-1}$$

$$w_j^Q = \left[ (1 + z_Q)/(1 + z_0) \right]^{\gamma_q^{-1}}$$
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 = \(2 \times (50 \times 50 + 100 \times 50)\)

- Full covariance from sub-sampling with \((250 \text{ Mpc/h}) \times (250 \text{ Mpc/h})\) patches on the sky

- Smoothing scheme validated with mocks

(note scale of +-0.01 in color bar)
1. Validation with mocks

[Cuceu, Herrera-Alcantar et al. 2024]
Synthetic data sets of the Year 1 sample
- $(10\ h^{-1}\text{Gpc})^3$ 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)
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 \( \sim 10\% \)

DESI DR1 + SDSS DR16:

\[
\frac{D_H(z_{\text{eff}})}{r_d} = 8.72 \pm 0.14
\]

\[
\frac{D_M(z_{\text{eff}})}{r_d} = 38.80 \pm 0.76
\]

with a correlation coefficient \( \rho = -0.47 \)
Correlations with nuisance parameters (I)

![Graph showing correlations between various parameters with different lines representing different combinations of Lyα.]
Correlations with nuisance parameters (II)

- **Combined**
- **Lyα × QSO**
- **Lyα × Lyα**

**Axes:**
- \( \alpha_{\parallel} \) and \( \alpha_{\perp} \)
- \( b_Q \), \( \sigma_z \text{ [Mpc/h]} \), \( \Delta r_{\parallel} \text{ [Mpc/h]} \), \( \xi_0^{TP} \), \( a_{\text{noise}} \times 10^{-4} \)
Correlations with nuisance parameters (III)

![Graph showing correlations with nuisance parameters](image-url)
Figure 18: (left) Scale parameters obtained from measurements with the three fiducial cosmologies with fixed $r_d$ and different $\Omega_m$ 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. $\Omega_m$), 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

- DESI BAO + CMB + Pantheon+
- DESI BAO + CMB + Union3
- DESI BAO + CMB + DES-SN5YR

Betoule et al. 2014
Dark Energy Equation of State