DARK ENERGY SURVEY
On behalf of the DES collaboration

LPSC GRENOBLE | MODANE

CoΦ Cosmological Physics GDR

2.1% measurement of the Baryon Acoustic Oscillation scale using the Dark Energy Survey final dataset

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On behalf of the LSS working group of the DES collaboration
In particular, special thanks to S. Avila, A. Porredon, K. C. Chan, H. Camacho, M. Rodríguez-Monroy, I. Ferrero.

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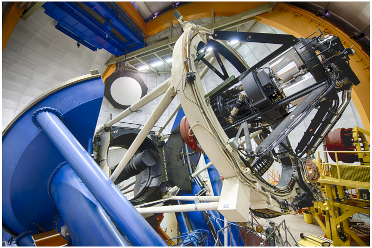
Content

The Dark Energy Survey

The **Dark Energy Survey (DES)**

- is a visible and near-infrared **photometric** galaxy survey.
- has imaged about **5,000 deg^2** of the southern sky in a **6-year survey**.



DES relies on 4 dark energy probes:

- the number of clusters as a function of redshift (CL).
- the weak lensing effect in the distribution of galaxies (WL).
- the Hubble diagram of type Ia supernovae (SN).
- **the baryon acoustic oscillation measurement (BAO)**.

The Dark Energy Survey

Periods DES data:

Name	Period	Area (deg^2)	Objects (millions)
SV	Nov. 2012 - Feb. 2013	250	25
Y1	Aug. 2013 - Feb. 2014	1,800	137
Y3	Aug. 2013 - Feb. 2016	5,000	399
Y6	**Aug. 2013 - Jan. 2019**	**5,000**	**691**

Here, we present the **measurement of the BAO using the Y6 data**.

This presentation is based on two papers (both accepted for publication in PRD):

- BAO measurement (Y6): DES collaboration (2024) - arXiv:2402.10696.
- BAO sample (Y6): Mena-Fernández et al. (2024) - arXiv:2402.10697.

Content

What are baryon acoustic oscillations?

Baryon acoustic oscillations (BAO) are fluctuations in the density of the baryonic matter of the Universe caused by acoustic density waves in the **primordial plasma of the early Universe**.

The BAO provides a **"standard ruler"** given by the sound horizon scale at recombination,

$$r_d \equiv r_s(z_d) = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \approx 100 \text{ Mpc}/h.$$

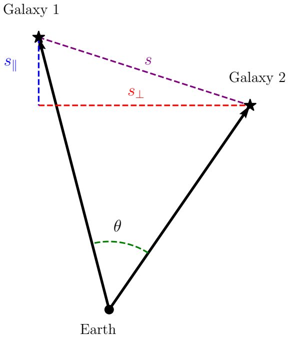
It gives us information about

- $H(z)$, if measured along the line of sight.
- $D_M(z)$, if measured **across the line of sight**.

How do we measure the BAO signal in DES?

The BAO appears as a **peak in the 2-point correlation function** of galaxy positions. In photometric surveys such as DES:

- we have low z accuracy, but a large number of galaxies.
- we use **angular estimators** to measure the clustering signal.



Here, we measure the BAO using

- the **angular correlation function (ACF)** or $w(\theta)$.
- the **angular power spectrum (APS)** or C_ℓ.
- the **projected correlation function (PCF)** or $\xi_p(s_\perp)$.

We, then, **combine the three (AVG)**.

Content

The DES Y6 BAO sample

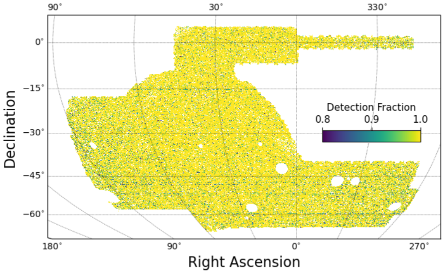
The DES Y6 BAO sample

- is a red galaxy sample selected using the ***griz* bands** and a **photo-*z*** estimate.
- has a good compromise between **photo-*z* accuracy and number density**.

Selection cuts:

$$
\begin{aligned}
&1.7 < i - z + 2(r - i) && \text{(color selection)},\\
&17.5 < i < 19.64 + 2.894 z_{\rm ph} && \text{(flux selection)},\\
&i < 22.5 && (i - \text{mag limit}),\\
&0.6 < z_{\rm ph} < 1.2 && \text{(photo-}z\text{ range)}.
\end{aligned}
$$

- It is divided in **6 redshift bins** with $\Delta z_{\rm ph} = 0.1$.
- The **effective redshift** of the sample is $\boldsymbol{z_{\rm eff} = 0.85}$.
- It has a total of ∼16 million galaxies over ∼4,300 deg^2.



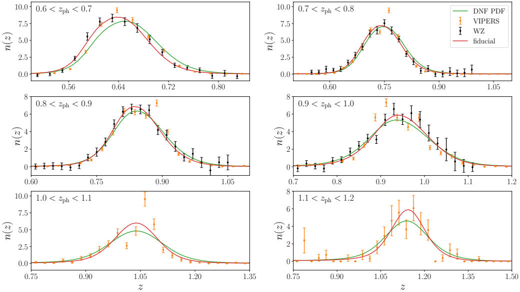
Redshift calibration

We use three different methods to estimate the true redshift distributions:

- **DNF** (Directional Neighborhood Fitting) - De Vicente et al. (2016)
- Direct **calibration with VIPERS z_{spec}** (16 deg^2 overlap; complete at $z > 0.6$, $i < 22.5$) - Scodeggio et al. (2018)
- **Clustering redshifts (WZ)** with SDSS galaxies - Cawthon et al. (2022)

The **fiducial method combines the three**:

- DNF+WZ at $z < 1$.
- DNF+VIPERS at $z > 1$.



Content

Methodology

1. Simulations

We created a set of **1,952 mock catalogs** of the BAO sample, based on **ICE-COLA fast simulations**, which reproduce with high accuracy the main properties of the data:

- Sample observational volume.
- Abundance of galaxies, redshift distributions and photo-z errors.
- Clustering as a function of redshift.

Mocks are key to

- **validate the modeling**.
- run our **pre-unblinding tests**.
- quantify how likely some features we find in the data are.

Methodology

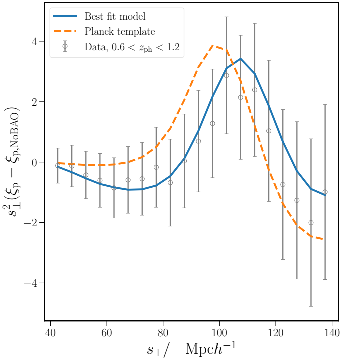
2. The BAO fit

- We use a **template-based method**:

$$M(x) = BT_{\mathrm{BAO},\alpha}(x') + A(x).$$

- The position of the BAO feature is given in terms of the **BAO-scaling parameter α**,

$$\alpha(z_{\mathrm{eff}}) = \frac{D_M(z_{\mathrm{eff}})}{r_d}\left[\frac{D_M^{\mathrm{ref}}(z_{\mathrm{eff}})}{r_d^{\mathrm{ref}}}\right]^{-1}.$$



- We use Planck collaboration (2018) results as our reference cosmology, for which $D_M(z_{\mathrm{eff}} = 0.85)/r_d = 20.39$.
- The fiducial result is the combination of our three estimators:

$$\alpha_{\mathrm{AVG}} = w_{\mathrm{ACF}}\alpha_{\mathrm{ACF}} + w_{\mathrm{APS}}\alpha_{\mathrm{APS}} + w_{\mathrm{PCF}}\alpha_{\mathrm{PCF}}.$$

Methodology

3. Pre-unblinding tests

The analysis and most of the paper writing were performed **blind**. Some of the pre-unblinding tests are:

- Do we have a BAO detection
  - in the combined fit? Yes
  - in each redshift bin? No: non-detection in the first bin (but this is consistent with ~20% of the mocks)
- Is our measurement robust to
  - removing redshift bins? Yes
  - changing analysis choices? Yes
- Are our three estimators compatible (ACF, APS and PCF)? Yes
- And our consensus measurement (AVG)? Yes

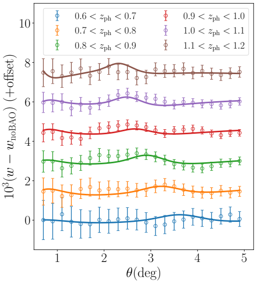
All these tests pointed to the robustness of our measurement, so **we unblinded**.

Content

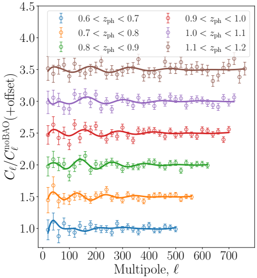
The BAO signal

Isolated BAO feature: data vs best fit.

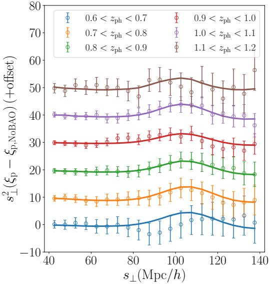
ACF



APS



PCF



Each plot shows the fit to the **6 redshift bins simultaneously**, taking into account their covariances.

The BAO measurement

Our fiducial BAO-fit results are

$$\alpha(0.85) = 0.9517 \pm 0.0227 \quad (\text{ACF}),$$
$$\alpha(0.85) = 0.9617 \pm 0.0224 \quad (\text{APS}),$$
$$\alpha(0.85) = 0.9553 \pm 0.0201 \quad (\text{PCF}),$$

and our consensus combined measurement (AVG) is

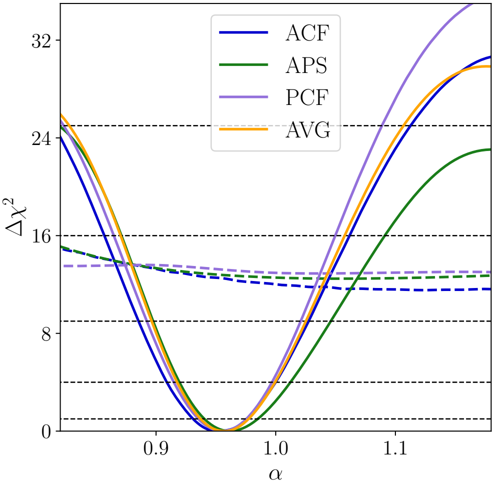
$$\alpha(0.85) = 0.9571 \pm 0.0196 \ [\text{stat.}],$$
$$\pm 0.0041 \ [\text{sys.}],$$
$$\alpha(0.85) = 0.9571 \pm 0.0201 \ [\text{tot.}].$$

- **Fractional error of 2.1%**, the lowest for a photometric survey ever.
- **Compatible with Planck at the level of 2.13σ**.

We can also compute D_M/r_d from α,

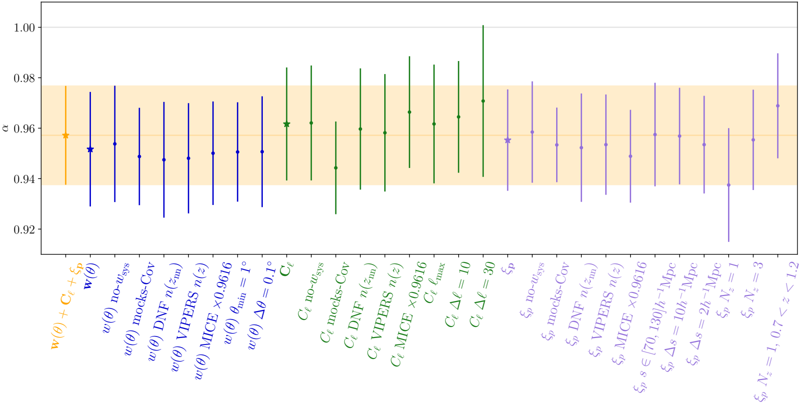
$$\frac{D_M(0.85)}{r_d} = 19.51 \pm 0.41.$$

The BAO likelihood



- **Significance of the detection at the level of $\sim$3.5σ** for the three estimators.

Robustness tests



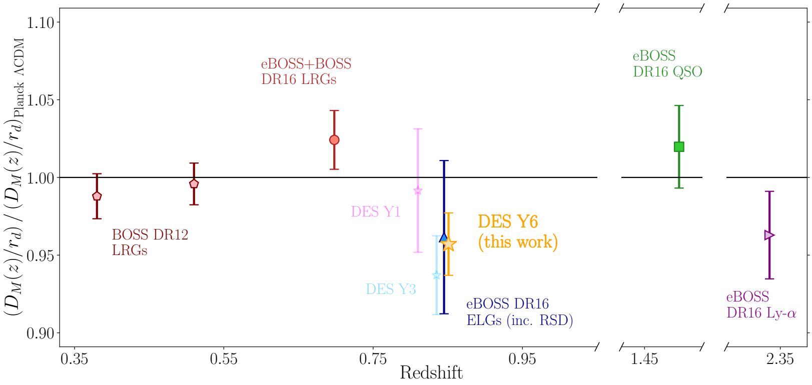
Our measurement is robust against

- variations in the fiducial settings.
- different clustering estimators.
- data calibration (systematics).

The angular BAO distance ladder at the end of Stage III

Our fiducial BAO distance measurement is

$$\alpha(z = 0.85) = 0.957 \pm 0.020.$$

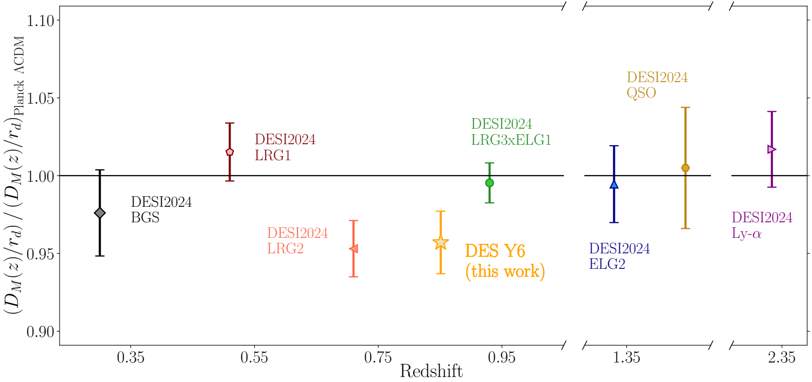


- **Competitive with Stage-III spectroscopic surveys**.
- Most precise measurement at $z > 0.75$ at the end of Stage III.

The angular BAO distance ladder including DESI2024

Our fiducial BAO distance measurement is

$$\alpha(z = 0.85) = 0.957 \pm 0.020.$$



Content

Conclusions

- The fiducial comoving angular diameter distance measurement for the DES Y6 BAO analysis is

$$\frac{D_M(z=0.85)}{r_d} = 19.51 \pm 0.41.$$

  In terms of α,

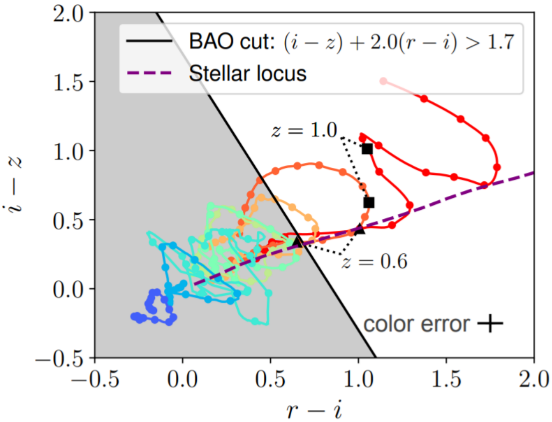
$$\alpha(z=0.85) = 0.957 \pm 0.020.$$

  This measurement
  - represents a **fractional error of $\sim$ 2.1%**.
  - is the most precise from a photometric redshift survey up to date.
  - is **compatible with Planck at the level of 2.13σ**.
  - is robust against observational systematics and modeling choices.
- It helps to construct the **most up-to-date angular BAO distance ladder**.

Thank You!

Backup slides

Color cuts


BAO cut: $(i - z) + 2.0(r - i) > 1.7$
Stellar locus
$z = 1.0$
$z = 0.6$
color error
$i - z$
$r - i$
2.0
1.5
1.0
0.5
0.0
−0.5
−0.5
0.0
0.5
1.0
1.5
2.0

Redshift calibration

bin	method	fid.	DNF z_{mc}	VIPERS	WZ
1	ACF	1.0001 ± 0.0548	0.9899 ± 0.0550	0.9931 ± 0.0530	1.0014 ± 0.0548
1	APS	1.0000 ± 0.0617	0.9899 ± 0.0612	0.9927 ± 0.0610	1.0009 ± 0.0623
1	PCF	0.9998 ± 0.0446	0.9922 ± 0.0458	0.9930 ± 0.0426	0.9994 ± 0.0440
2	ACF	1.0001 ± 0.0483	0.9921 ± 0.0481	0.9950 ± 0.0463	0.9987 ± 0.0486
2	APS	1.0000 ± 0.0518	0.9920 ± 0.0514	0.9945 ± 0.0512	0.9987 ± 0.0518
2	PCF	0.9998 ± 0.0426	0.9938 ± 0.0432	0.9954 ± 0.0408	1.0002 ± 0.0426
3	ACF	1.0001 ± 0.0420	0.9957 ± 0.0422	0.9918 ± 0.0410	0.9993 ± 0.0417
3	APS	1.0000 ± 0.0438	0.9957 ± 0.0438	0.9914 ± 0.0435	0.9991 ± 0.0440
3	PCF	0.9998 ± 0.0412	0.9982 ± 0.0418	0.9942 ± 0.0392	0.9994 ± 0.0406
4	ACF	1.0001 ± 0.0410	1.0019 ± 0.0419	1.0112 ± 0.0398	0.9983 ± 0.0398
4	APS	1.0000 ± 0.0402	1.0017 ± 0.0408	1.0106 ± 0.0405	0.9981 ± 0.0403
4	PCF	0.9998 ± 0.0404	1.0026 ± 0.0422	1.0082 ± 0.0390	1.0010 ± 0.0388
5	ACF	1.0001 ± 0.0472	1.0030 ± 0.0494	0.9985 ± 0.0452	—
5	APS	1.0000 ± 0.0401	1.0030 ± 0.0409	0.9971 ± 0.0402	—
5	PCF	0.9994 ± 0.0446	1.0018 ± 0.0509	1.0026 ± 0.0434	—
6	ACF	1.0001 ± 0.0683	1.0062 ± 0.0741	1.0048 ± 0.0699	—
6	APS	1.0000 ± 0.0458	1.0067 ± 0.0475	1.0047 ± 0.0466	—
6	PCF	0.9998 ± 0.0831	1.0130 ± 0.0941	1.0234 ± 0.0773	—
All	ACF	1.0001 ± 0.0201	0.9972 ± 0.0206	0.9985 ± 0.0195	—
All	APS	1.0000 ± 0.0190	0.9988 ± 0.0194	0.9989 ± 0.0192	—
All	PCF	0.9998 ± 0.0202	0.9982 ± 0.0214	1.0002 ± 0.0196	—
All	**AVG**	0.9998 ± 0.0193	0.9984 ± 0.0204	1.0001 ± 0.0189	—

Fits to the mocks: ACF

case	$\langle\alpha\rangle$	$\sigma_{\rm std}$	σ_{68}	$\langle\sigma_\alpha\rangle$
$i = 0$	1.0039	0.0187	0.0183	0.0180
$i = 0, 1$	1.0051	0.0202	0.0200	0.0190
$\boldsymbol{i = 0, 1, 2}$	**1.0057**	**0.0201**	**0.0202**	**0.0187**
$i = -1, 0, 1, 2$	1.0058	0.0202	0.0200	0.0188
Planck template $i = 0, 1$	0.9675	0.0197	0.0197	0.0205
Planck template $i = 0, 1, 2$	0.9680	0.0193	0.0191	0.0182
Planck template $i = -1, 0, 1, 2$	0.9680	0.0195	0.0193	0.0182
$\Delta\theta = 0.05$ deg	1.0058	0.0202	0.0200	0.0188
$\Delta\theta = 0.15$ deg	1.0057	0.0202	0.0199	0.0188
$\theta_{\rm min} = 1$ deg	1.0061	0.0203	0.0200	0.0189
Planck Cov. + Templ.	0.9686	0.0194	0.0191	0.0209
COLA cov	1.0063	0.0193	0.0187	0.0184

Fits to the mocks: combination

case	meth.	$\langle\alpha\rangle$	$\sigma_{\rm std}$	σ_{68}	$\langle\sigma_\alpha\rangle$	mocks $\in \langle\alpha\rangle \pm \langle\sigma_\alpha\rangle$
MICE	ACF	1.0057	0.0202	0.0202	0.0187	65.2%
	APS	1.0063	0.0216	0.0204	0.0178	62.3%
	PCF	1.0012	0.0187	0.0182	0.0189	69.6%
	AVG	1.0019	0.0185	0.0180	0.0181	68.6%
Planck	ACF	0.9680	0.0193	0.0191	0.0181	65.3%
	APS	0.9685	0.0225	0.0203	0.0187	64.5%
	PCF	0.9631	0.0180	0.0176	0.0182	69.5%
	AVG	0.9638	0.0180	0.0177	0.0175	67.6%

Pre-unblinding tests: detection

Bin	ACF	APS	PCF
All	99.95 % [Y]	99.49 % [Y]	100 % [Y]
1	90.32 % [N]	74.49 % [N]	95.39 % [N]
2	94.98 % [Y]	82.12 % [Y]	97.34 % [Y]
3	97.39 % [Y]	86.73 % [Y]	97.69 % [Y]
4	97.59 % [Y]	91.55 % [Y]	97.84 % [Y]
5	96.67 % [Y]	90.73 % [Y]	95.39 % [Y]
6	91.19 % [Y]	87.76 % [Y]	86.22 % [Y]
Non-detections			
0	72.90 %	41.80 %	73.77 %
1	**22.85** %	**36.42** %	**22.69** %
2	3.84 %	16.03 %	3.23 %
3	0.31 %	4.82 %	0.26 %
4	0.10 %	0.92 %	0.05 %

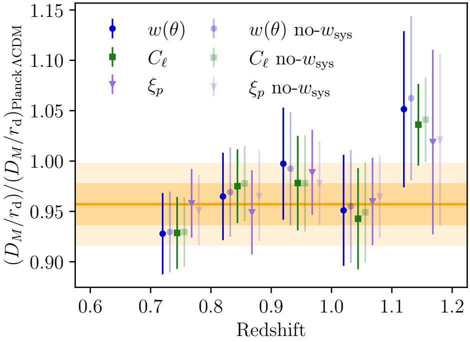
Pre-unblinding tests: combination

$\Delta\alpha \times 100$	Data	90%-mocks
ACF-APS	-1.00	[-1.36, 1.12]
ACF-PCF	-0.36	[-0.58, 1.51]
APS-PCF	0.64	[-1.04, 2.15]
ACF-{APS+PCF}	-0.48	[-0.52, 1.24]
APS-{ACF+PCF}	0.68	[-1.02, 2.02]
PCF-{ACF+APS}	0.10	[-1.58, 0.61]
AVG-ACF	0.54	[-1.34, 0.58]
AVG-APS	-0.45	[-1.78, 0.81]
AVG-PCF	0.19	[-0.23, 0.39]

Pre-unblinding tests: varying settings

Threshold (Fraction of mocks)	90 % min	90 % max	95 % min	95 % max	97 % min	97 % max	99 % min	99 % max	data MICE	data **Planck**
	$10^2(\alpha - \alpha_{\rm fiducial})$									
Bins 23456	-1.33	1.43	-1.79	1.86	-2.10	2.17	-2.44	2.76	0.75	1.15
Bins 13456	-1.39	1.63	-1.83	1.99	-2.03	2.30	-2.80	3.13	1.03	1.47
Bins 12456	-1.37	1.51	-1.71	2.00	-2.03	2.35	-2.52	3.23	-0.21	-0.39
Bins 12356	-1.45	1.27	-1.81	1.57	-2.19	1.88	-2.80	2.76	-0.66	-0.27
Bins 12346	-1.21	1.11	-1.51	1.41	-1.79	1.72	-2.48	2.02	0.37	0.30
Bins 12345	-0.86	0.76	-1.07	0.96	-1.30	1.15	-1.63	1.65	-0.68	-0.76
Bins 456	-2.85	3.73	-3.42	4.85	-3.86	5.54	-5.00	7.90	3.26	3.41
Bins 123	-3.30	2.65	-4.27	3.45	-5.04	4.26	-6.80	5.56	-1.55	-1.58
Bins 1234	-1.83	1.67	-2.25	2.13	-2.55	2.35	-3.67	3.22	-0.39	-0.70
Template Cosmo	-0.33	0.48	-0.40	0.60	-0.44	0.68	-0.55	0.89	×	0.17
Covariance	-0.46	0.42	-0.58	0.54	-0.68	0.64	-0.83	0.82	×	-0.42
$n(z)$ $z_{\rm mc}$ − fid	-0.56	0.08	-0.60	0.14	-0.64	0.20	-0.72	0.31	×	-0.42
	$100\ (\sigma - \sigma_{\rm All\ Bins})/\sigma_{\rm All\ Bins}$									
Bins 23456	-2.47	25.15	-4.33	30.34	-6.09	35.42	-9.08	41.50	5.37	3.96
Bins 13456	-1.60	26.16	-3.55	31.21	-5.18	35.18	-8.95	45.61	18.05	14.54
Bins 12456	-2.00	26.22	-4.53	31.44	-5.84	36.80	-8.93	45.86	18.05	14.98
Bins 12356	-2.29	25.17	-4.09	30.79	-5.51	35.11	-9.35	41.35	8.29	4.41
Bins 12346	-1.39	19.89	-2.84	24.51	-4.07	27.92	-6.22	34.80	7.32	7.93
Bins 12345	-0.66	11.94	-1.45	14.87	**-1.97**	17.79	-3.56	22.50	0.49	**-3.08**
Bins 456	12.08	94.25	8.20	114.76	5.13	128.50	-1.76	166.46	66.34	57.71
Bins 123	10.14	80.86	5.92	95.62	3.02	109.42	-2.36	144.43	21.95	18.50
Bins 1234	1.37	35.50	-0.99	42.58	-1.84	45.70	-4.23	55.74	7.80	3.96

The BAO measurement in individual bins



- non-detection in the first bin ($0.6 < z_{\text{ph}} < 0.7$), as in Y1 and Y3.
- consistency between the different estimators.
- fluctuations across bins compatible with mock catalogs.

Ross Cawthon, J Elvin-Poole, A Porredon, M Crocce, G Giannini, M Gatti, AJ Ross, ES Rykoff, A Carnero Rosell, J DeRose, et al. Dark Energy Survey Year 3 results: calibration of lens sample redshift distributions using clustering redshifts with BOSS/eBOSS. *Monthly Notices of the Royal Astronomical Society*, 513(4): 5517–5539, 2022.

Juan De Vicente, Eusebio Sánchez, and Ignacio Sevilla-Noarbe. DNF–Galaxy photometric redshift by Directional Neighbourhood Fitting. *Monthly Notices of the Royal Astronomical Society*, 459(3):3078–3088, 2016.

The DES collaboration. Dark Energy Survey: A 2.1% measurement of the angular Baryonic Acoustic Oscillation scale at redshift $z_{\mathrm{eff}}=0.85$ from the final dataset, 2024.

J. Mena-Fernández et al. Dark Energy Survey: Galaxy Sample for the Baryonic Acoustic Oscillation Measurement from the Final Dataset, 2024.

The Planck collaboration. Planck 2018 results. VI. Cosmological parameters. *arXiv preprint arXiv:1807.06209*, 2018.

MARCO Scodeggio, L Guzzo, BIANCA Garilli, BR Granett, M Bolzonella, S De La Torre, U Abbas, C Adami, S Arnouts, D Bottini, et al. The VIMOS Public Extragalactic Redshift Survey (VIPERS)-Full spectroscopic data and auxiliary information release (PDR-2). *Astronomy & Astrophysics*, 609:A84, 2018.