GRENOBLE | MODANE

DARK ENERGY SURVEY

Cosmology from the Measurement of the Baryon Acoustic Oscillations Scale in Large Galaxy Surveys

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Thursday 25th January, 2024

Outline

1. The Standard Cosmological Model
2. Baryon Acoustic Oscillations (BAO)
3. The Dark Energy Survey (DES)
4. Measurement of the BAO Scale in DES Y3
5. Conclusions

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The Standard Cosmological Model

The standard cosmological model is also known as the **ΛCDM model**.

- Our Universe is mainly composed of Λ (dark energy) + CDM (cold dark matter)

$$\text{Energy content}\begin{cases}\textbf{dark energy - }\boldsymbol{\Lambda}\ \boldsymbol{(\sim 70\%)}\\ \text{matter } (\sim 30\%)\begin{cases}\text{cold dark matter } (\sim 25\%)\\ \text{baryonic matter } (\sim 5\%)\\ \text{non-relativistic neutrinos } (< 1\%)\end{cases}\\ \text{radiation } (< 1\%)\begin{cases}\text{photons } (< 1\%)\\ \text{relativistic neutrinos } (< 1\%)\end{cases}\end{cases}$$

- Main pillars of ΛCDM:
  - Theory of general relativity.
  - The cosmological principle.
  - Vast observational basis, including:
    - Cosmic microwave background (CMB).
    - Primordial nucleosynthesis and abundance of light elements.
    - **Large-scale structure (LSS)**.

Dark Energy

The Universe is undergoing an **accelerated expansion phase** (Perlmutter et al. 1999):

- the expansion is such that the velocity at which a distant galaxy is receding from the observer is continuously increasing with time.
- this is **caused by dark energy**. Observations tell us that dark energy = cosmological constant.

There are several probes of dark energy, and the measurement of the **baryon acoustic oscillations (BAO)** scale is one of the most important ones. Their study was one of the **main goals of my thesis**.

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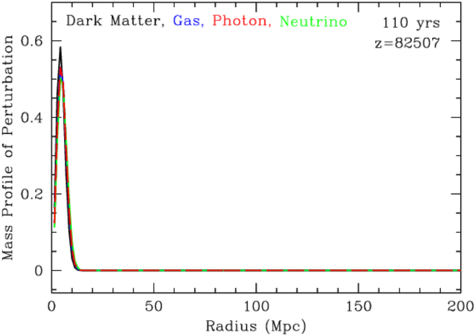
What are Baryon Acoustic Oscillations?

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**.



Credits: Eisenstein *et al* 2006

The BAO provides a **standard ruler** given by the maximum distance r_d these acoustic waves could travel in the primordial plasma before recombination,

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \approx 150 \text{ Mpc}.$$

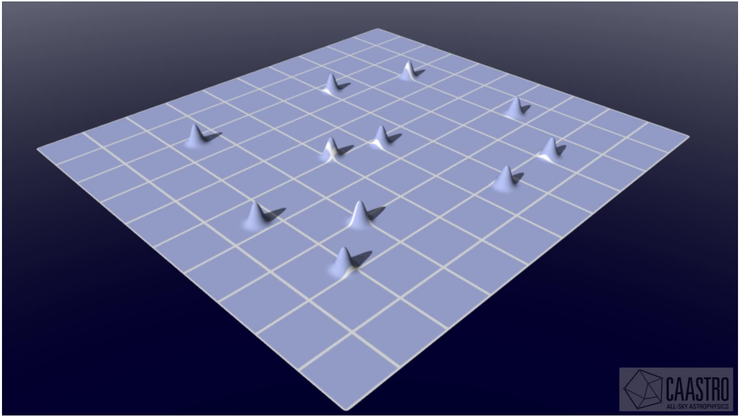
It gives us information about $\boldsymbol{d_M(z)}$ and/or $\boldsymbol{H(z)}$.

Why do We Study BAO?

The BAO plays a crucial role as a cosmological probe because of

- its significance in measuring the **expansion history** of the Universe.
- its significance **constraining cosmological parameters** (Bassett et al. 2010).
- its consistency with the **high-z results from Planck** (Planck Collaboration 2020).
- its robustness against systematics.

How do We Measure the BAO Signal?



Source: `https://www.youtube.com/watch?v=jpXuYc-wzk4`

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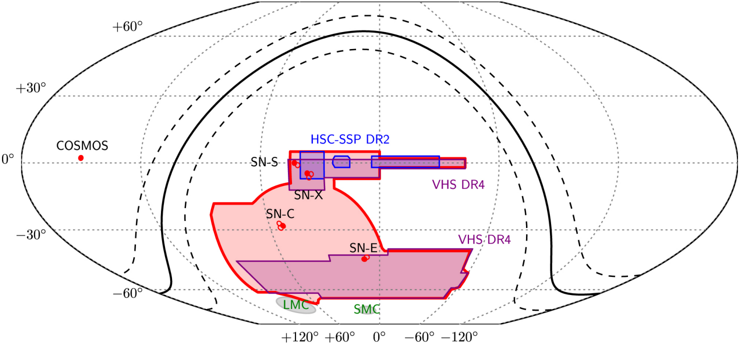
The Dark Energy Survey (DES)

- DES is a **visible and near-infrared photometric survey** that aims to probe the physical nature of dark energy.
- It studies the dynamics of the expansion of the Universe and the growth of large-scale structure.
- It has imaged about 5,000 deg^2 of the southern sky in a 6-year photometric survey from Cerro Tololo (Chile).



Scientific Goals of DES

- 4 main probes of DES:
  - Number of clusters as a function of redshift (CL).
  - Weak lensing (WL) effect in the distribution of galaxies - **3×2pt probe**.
  - The **BAO measurement**.
  - Hubble diagram of type Ia supernovae.
- Periods of time spanned by the data in each DES analysis:

Name	**Period**	**Area (deg^2)**	**Depth (*i* band)**	**Objects**
SV	Nov. 2012 - Feb. 2013	250	23.68	25M
Y1	Aug. 2013 - Feb. 2014	1,800	23.29	137M
Y3	Aug. 2013 - Feb. 2016	5,000	23.44	399M
Y6	Aug. 2013 - Jan. 2019	5,000	23.80	691M

- We are still analyzing the Y6 data.

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Introduction

- **Blind analysis**. To avoid confirmation bias, the analysis is performed blind:
  - the **angular correlation function of the data is blinded**. Only three pre-unblinding points below 1 deg are computed to calibrate the simulations.
  - we require to pass several tests before unblinding our measurements.

- **Photometric redshifts**. Photo-z are estimated from magnitudes (we do not have a direct measurement of redshift).

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The Y3 BAO Sample: Selection Cuts

The Y3 BAO sample is a photometric red galaxy sample that is

- selected using the ***griz* bands** and a **photometric redshift estimate ($z_{\rm ph}$)**.
- built looking for a good compromise between $z_{\rm ph}$ accuracy and number density.

Its selection cuts are given by

$$\begin{aligned} 1.7 &< i - z + 2(r - i) && \text{(color selection)}, \\ 17.5 &< i < 19 + 3z_{\rm ph} && \text{(flux selection)}, \\ 0.6 &< z_{\rm ph} < 1.1 && \text{(photo-z range)}. \end{aligned}$$

- It is divided in **5 redshift bins** with $\Delta z_{\rm ph} = 0.1$.
- The **effective redshift** of the sample is $\boldsymbol{z_{\rm eff} = 0.835}$.
- It has a total of ∼7 million galaxies over ∼4,100 deg^2.

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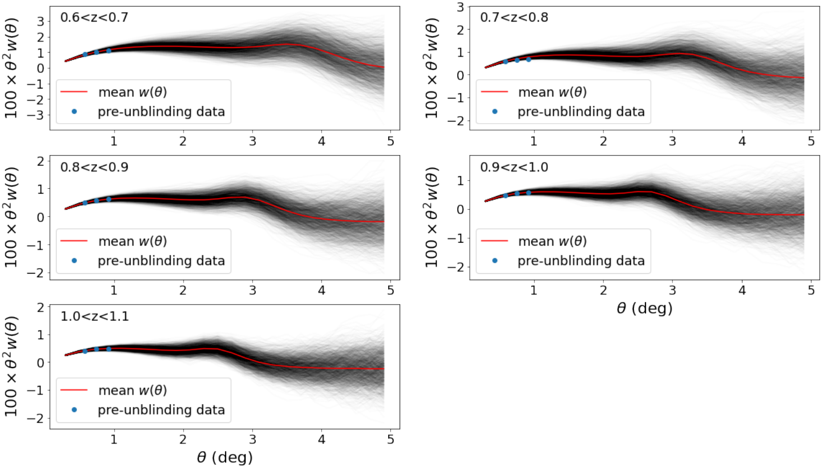
Simulations: the COLA Mocks

1,952 mocks that **resemble the Y3 BAO sample**. Underlying cosmology: Mice ($\Omega_b = 0.044$, $\Omega_c = 0.206$, $h = 0.7$, $\sigma_8 = 0.8$, $n_s = 0.95$).



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The BAO-Fitting Pipeline: Introduction

- Development of a **BAO-fitting pipeline to measure the BAO signal** from the DES data.
- The pipeline uses a **template-based method**.
- The position of the BAO peak is encoded in α, which **measures the shift in the position of the BAO peak between the data and the template**, and is defined by

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

The distance measurement is computed from α as

$$\frac{d_M(z_{\text{eff}})}{r_d} = \frac{d_M^{\text{ref}}(z_{\text{eff}})}{r_d^{\text{ref}}}\alpha(z_{\text{eff}}).$$

The BAO-Fitting Pipeline: Modeling

The χ^2 to be minimized is

$$\chi^2(\boldsymbol{\Theta}) = \sum_{\mathrm{zbin}_1,\mathrm{zbin}_2} \sum_{i,j} \Delta w^{\mathrm{zbin}_1}(\theta_i, \boldsymbol{\Theta})(\mathrm{cov}^{-1})_{i,j}^{\mathrm{zbin}_1,\mathrm{zbin}_2} \Delta w^{\mathrm{zbin}_2}(\theta_j, \boldsymbol{\Theta}),$$

where

$$\Delta w^{\mathrm{zbin}}(\theta, \boldsymbol{\Theta}) = w_{\mathrm{data}}^{\mathrm{zbin}}(\theta) - w_{\mathrm{model}}^{\mathrm{zbin}}(\theta, \boldsymbol{\Theta}).$$

The model is given by

$$w_{\mathrm{model}}^{\mathrm{zbin}}(\theta, \boldsymbol{\Theta}) = B^{\mathrm{zbin}} w_{\mathrm{ref}}^{\mathrm{zbin}}(\alpha\theta) + \sum_i A_i^{\mathrm{zbin}} \theta^{-i}.$$

For the fiducial analysis, we compute the covariance matrices with CosmoLike (Krause et al. 2016).

The BAO-Fitting Pipeline: Minimization Algorithm

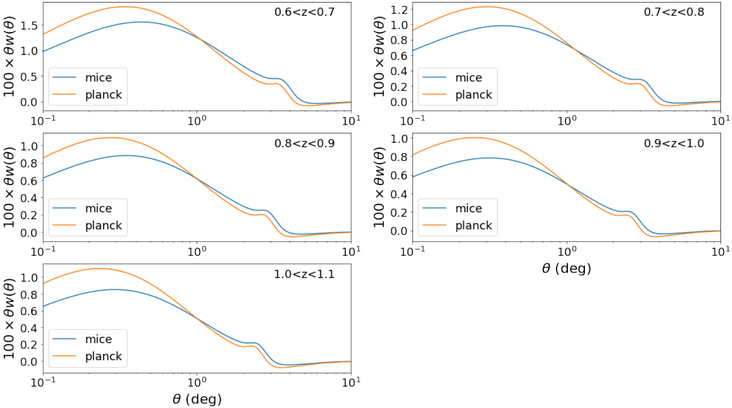
$$w_{\mathrm{model}}^{\mathrm{zbin}}(\theta, \mathbf{\Theta}) = B^{\mathrm{zbin}} w_{\mathrm{ref}}^{\mathrm{zbin}}(\alpha\theta) + \sum_{i} A_i^{\mathrm{zbin}} \theta^{-i}.$$

The minimization algorithm has four steps:

1. The A_i^{zbin} are fit analytically, following Cowan 1998. This leaves us with
$$\chi^2(\alpha, B^{\mathrm{zbin}}, A_i^{\mathrm{zbin}}) \rightarrow \chi^2(\alpha, B^{\mathrm{zbin}}, A_{i,\mathrm{bf}}^{\mathrm{zbin}}).$$
2. Numerically search for the best-fit B^{zbin} with the prior $B^{\mathrm{zbin}} > 0$. This leaves us with
$$\chi^2(\alpha, B^{\mathrm{zbin}}, A_{i,\mathrm{bf}}^{\mathrm{zbin}}) \rightarrow \chi^2(\alpha, B_{\mathrm{bf}}^{\mathrm{zbin}}, A_{i,\mathrm{bf}}^{\mathrm{zbin}}).$$
3. The χ^2 is then **sampled as a function of $\boldsymbol{\alpha}$**. We find the best-fit α, α_0.
4. The $1 - \sigma$ region of α is obtained with the $\Delta\chi^2 = 1$ rule.

The BAO-Fitting Pipeline: the BAO Template

	Ω_b	Ω_c	h	σ_8	n_s
Mice cosmology	0.044	0.206	0.7	0.8	0.95
Planck cosmology	0.048	0.262	0.676	0.8	0.97



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Tests on Simulations: Reference Cosmology

Bins	$\langle\alpha\rangle$	$\sigma_{\rm std}$	$\langle\sigma_\alpha\rangle$	$\langle\chi^2\rangle$/dof
		Mice template		
All	**1.005**	**0.024**	**0.022**	**93.2/89**
1	1.002	0.051	0.049	17.7/17
2	1.002	0.049	0.046	17.0/17
3	1.002	0.046	0.041	17.5/17
4	1.005	0.045	0.040	17.8/17
5	1.008	0.049	0.044	18.3/17
		Planck template		
All	**0.966**	**0.023**	**0.021**	**93.6/89**
1	0.964	0.050	0.048	17.9/17
2	0.965	0.047	0.045	17.2/17
3	0.966	0.044	0.040	17.5/17
4	0.970	0.044	0.039	17.9/17
5	0.976	0.048	0.042	18.3/17

- For the "All" case, $\langle\sigma_\alpha\rangle/\langle\alpha\rangle$ **~2.4% for both Mice and Planck**.
- Using $d_M^{\rm Mice}(z_{\rm eff})/r_d^{\rm Mice} = 19.31$ and $d_M^{\rm Planck}(z_{\rm eff})/r_d^{\rm Planck} = 20.11$, we find

$$\left\langle \frac{d_M(z_{\rm eff})}{r_d} \right\rangle = 19.41 \pm 0.42 \text{ (Mice)}, \quad \left\langle \frac{d_M(z_{\rm eff})}{r_d} \right\rangle = 19.42 \pm 0.42 \text{ (Planck)}.$$

- Removing redshift bins gives larger $\sigma_{\rm std}$ and $\langle\sigma_\alpha\rangle$.

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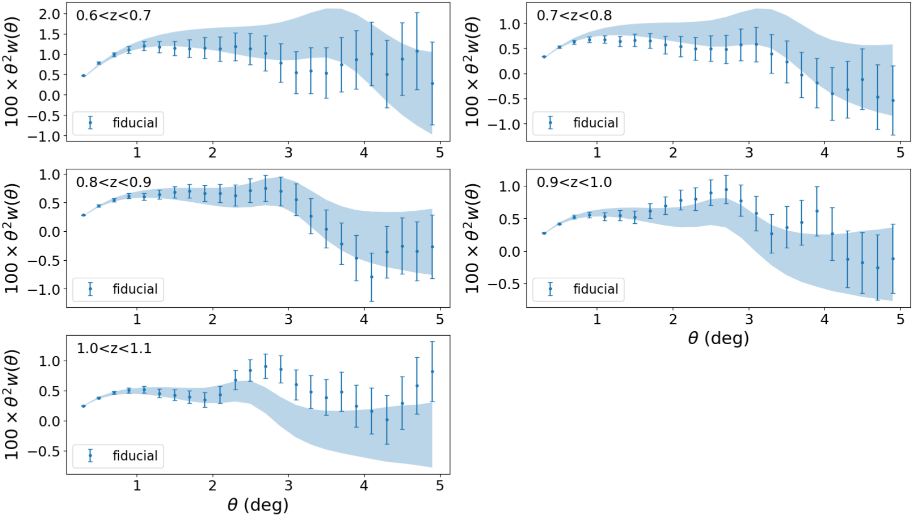
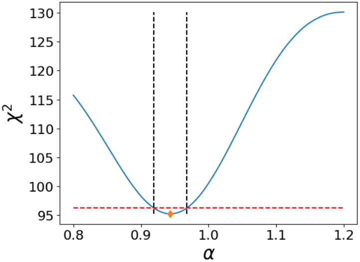
BAO Measurement on the Y3 Data: Clustering Signal



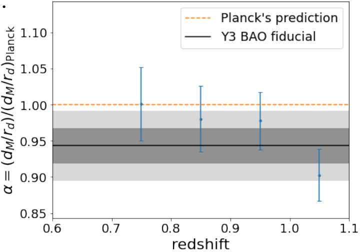
BAO Measurement on the Y3 Data: BAO-Fit Results

Bins	α	σ_α	χ^2/dof	p-value
All	**0.942**	**0.024**	**95.0/89**	**0.313**
1	-	-	-	-
2	1.000	0.050	10.2/17	0.895
3	0.978	0.047	19.7/17	0.288
4	0.978	0.040	23.2/17	0.143
5	0.903	0.036	10.8/17	0.865



Using $d_M^{\rm Planck}(z_{\rm eff})/r_d^{\rm Planck} = 20.11$,

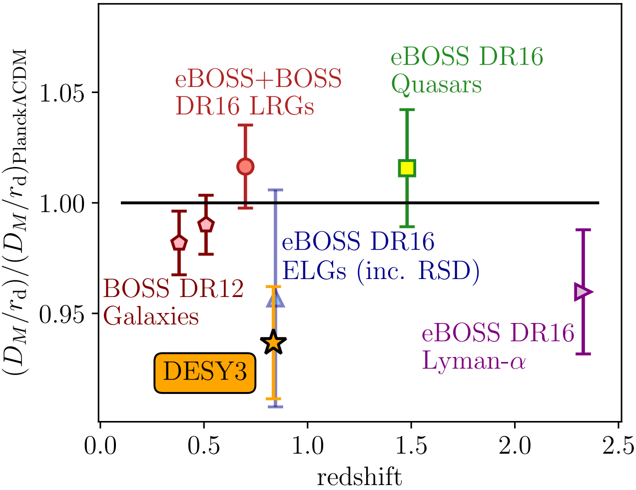
$$\frac{d_M(z_{\rm eff})}{r_d} = (0.942 \pm 0.024) \times 20.11 = 18.94 \pm 0.48.$$



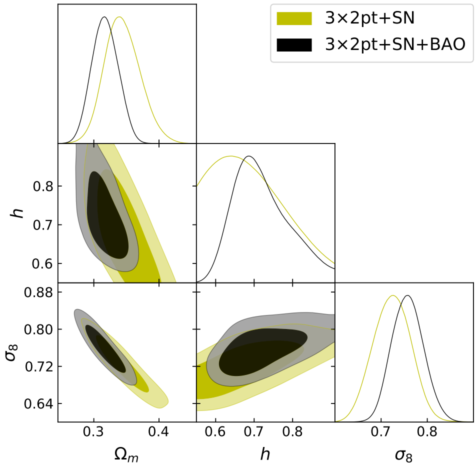
Our measurement is

- **consistent with Planck at the 2.5σ level**.
- the **most precise from a photometric survey ever**, and competitive with spectroscopic.

BAO Measurement on the Y3 Data: BAO Distance Ladder



BAO Measurement on the Y3 Data: Combination with 3×2pt



- DES 3×2pt+SN:

$$\begin{cases} \Omega_m = 0.342^{+0.029}_{-0.025}, \\ h = 0.681^{+0.109}_{-0.082}, \\ \sigma_8 = 0.724^{+0.020}_{-0.042}. \end{cases}$$

- DES 3×2pt+SN+BAO:

$$\begin{cases} \Omega_m = 0.317^{+0.021}_{-0.020}, \\ h = 0.709^{+0.089}_{-0.059}, \\ \sigma_8 = 0.758^{+0.033}_{-0.036}. \end{cases}$$

The posterior in *h* is more symmetrical, with a **gain in constraining power of ∼20%**; the **error in Ω_m is reduced by ∼25%**; and the **constraining power in σ_8 improves by ∼16%** when including the BAO!

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- We developed a **BAO-fitting pipeline** for DES:
  - It was **tested and validated using the Y3 COLA mocks**: robust results when changing the cosmology of the template and the settings for the fits.
  - It was run on the DES Y3 data, for which we obtained

    $$d_M(0.835)/r_d = 18.94 \pm 0.48.$$

    This result is **consistent with Planck at the 2.5σ level**, and represents the **most precise measurement** from a photometric galaxy survey up to date, with a relative error of 2.6%.
- **We combined our BAO likelihood with DES 3×2pt and SN**, finding better constraints in h, Ω_m and σ_8.

Thank You!