Measurement of the Baryon Acoustic Oscillation scale at $z = 1$ with Dark Energy Survey year 1 data

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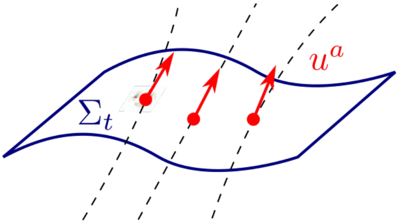
Universidade de São Paulo and LIneA

LINEA webinar. March 8th, 2018

Outline

The cosmological standard model



- Space-time geometry.
  - Fundamental (isotropic) observers, u^a.
  - Constant time (homogeneous) hyper-surfaces, Σ_t.

$$g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -\mathrm{d}t^2 + a^2(t)\mathrm{d}\ell^2$$

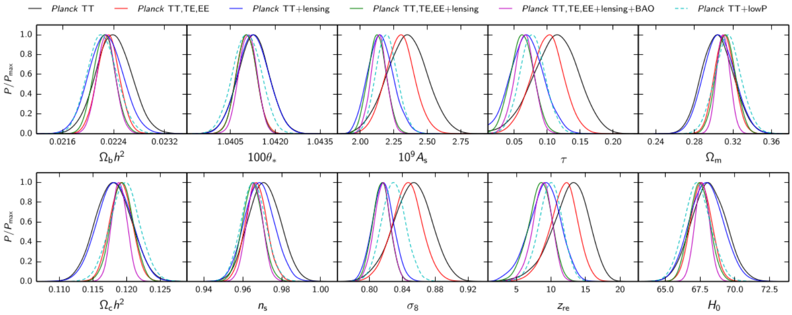
- Matter/energy content.
- Law of gravitation.

$$G_{ab} := R_{ab} - \frac{1}{2}Rg_{ab} = \kappa T_{ab} - \Lambda g_{ab}$$

An actual concordance model

$$E^2(a) := \boxed{\frac{H^2(a)}{H_0^2} = \frac{\Omega_K}{a^2}} + \boxed{\frac{\Omega_\mathrm{m}}{a^3} + \frac{\Omega_\mathrm{r}}{a^4} + \Omega_\mathrm{DE}\frac{\rho_\mathrm{DE}(a)}{\rho_\mathrm{DE0}}}.$$

geometry — matter/energy



Planck Collaboration (2015)

... So the universe is accelerating

- Shortfall on its contents

$$\Omega_{\mathrm{DE}} : \Omega_{\mathrm{m}} : \Omega_{\mathrm{b}} \approx 70 : 26 : 4$$

- Independent observational evidence
  - Supernovae are further away than expected
  - Growth of structure has been slowed
- Tremendous implications for physics/astronomy
  - Current understanding of gravity is incomplete
  - Current understanding of universe constituents is incomplete

How to gain information about DE's nature?

Implications on the recent (observable) universe volume.

- Expansion rate, $H(z)$
- Growth of structure
- Abundance of collapsed/virialized objects
- Light rays deflection by structures

All related directly or indirectly with distance estimation calibration, $d_{\mathrm{L}}, d_{\mathrm{A}}(z)$

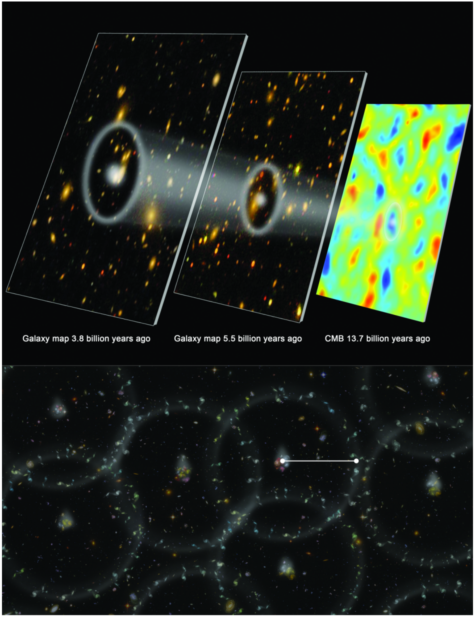
Albrecht et. al. Report of the DEFT (2006)

The Dark Energy Survey (DES)

- International collaboration: USA, OK, Spain, Germany, Chile, Switzerland and Brazil
- Wide field photometric "legacy survey" griz (SDSS) bands $\rightarrow$ largest volume to date: tens of Gpc^3
- Four main cosmological observables:
  - Galaxy cluster counts, ≈ 100000, $0.3 < z < 1.3$
  - Clustering of galaxies, 200 million, same z
  - Weak lensing tomography, up to $z \sim 1$
  - Distance/luminosities of SNIa $0.3 < z < 0.8$

The DES collaboration, The DES (2005)

BAO as standard ruler



two-point statistics

$$\langle \mathrm{d}N_{\mathrm{pairs}}(r, \hat{\mathbf{n}}) \rangle = \bar{n}_{\mathrm{g}}^2 \left[1 + \langle \delta_{\mathrm{g}}(\mathbf{x}) \delta_{\mathrm{g}}(\mathbf{x} + r\hat{\mathbf{n}}) \rangle\right] \mathrm{d}V_1 \; \mathrm{d}V_2$$

Two point correlation function:

$$\xi_{\mathrm{g}}(r, \hat{\mathbf{n}}) = \langle \delta_{\mathrm{g}}(\mathbf{x}) \delta_{\mathrm{g}}(\mathbf{x} + r\hat{\mathbf{n}}) \rangle$$

- Contain information about the scale of BAO!

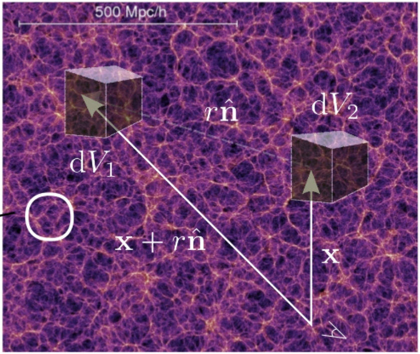
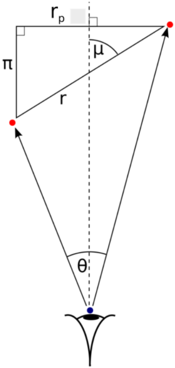


Image credit: M. Blanton and the SDSS

two-point statistics



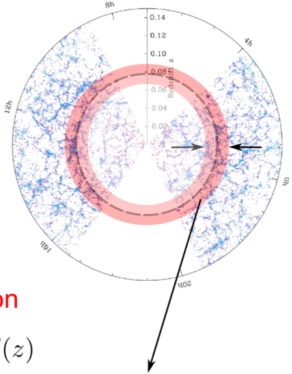
In the DO approximation, $\xi(r, \mu) = \xi(r_\mathrm{p}, \pi)$

$$\begin{cases} r^2 & = \chi^2 = \chi_1^2 + \chi_2^2 - 2\chi_1\chi_2\cos(\theta) \\ \mu & = \cos(\gamma) = \frac{\chi_2 - \chi_1\cos(\theta)}{\chi} \end{cases}$$

$$\begin{cases} \pi & = r\mu \\ r_\mathrm{p} & = \sqrt{r^2 - \pi^2} \end{cases}$$

Alonso (2013)

How to deal with photometric redshifts?



Proper projection of the 3D fluctuation field

$$\delta_{\rm g}^{\rm 2D}(\theta,\varphi) := \int_0^\infty {\rm d}z\, W^{\rm g}(z)\widehat{R}_{\rm g}\delta_0(\chi,\theta,\varphi)$$

- Projection kernel $\leftrightarrow$ galaxy window function

$$W^{\rm g}(z) := \phi^{\rm g}(z) b_{\rm g}(z) G(z)$$

$$\phi^{\rm g} \equiv \textit{radial selection of galaxies}$$

Measuring the BAO scale

An appropriate template for 2pt statistics.

$$P(k,\mu) = (1+\mu^2\beta)^2 \left((P_{\rm lin} - P_{\rm nw})e^{-k^2\Sigma_{\rm nl}^2} + P_{\rm nw}\right)$$

$$\Sigma_{\rm nl}^2 = (1-\mu^2)\Sigma_\perp^2/2 + \mu^2\Sigma_{||}^2/2.$$

- Configuration space

$$w_{\rm BAO}(\theta) = \int dz_1 \int dz_2 \phi(z_1)\phi(z_2)\xi_s(s[z_1,z_2,\theta],\mu[z_1,z_2,\theta]).$$

$$\xi(s_\perp,\mu) = \int {\rm d}z G(z)\xi(s_{\rm true}[s_\perp,\mu,z],\mu_{\rm true}[s_\perp,\mu,z]),$$

- Harmonic space

$$C_{\ell {\rm BAO}} = \frac{2}{\pi}\int dk\, k^2 P_{\rm gal}(k)\left\{\Psi_\ell\right\}^2$$

$$\Psi_\ell = \int dz\, G(z)\phi(z)j_\ell[k\chi(z)] + \Psi_{\rm RSD}$$

Measuring the BAO scale

Each method allow us to infer a $\mathscr{L}(\alpha)$

$$\alpha = \frac{D_A(z_{\text{eff}})r_{\text{d}}^{\text{fid}}}{D_A^{\text{fid}}(z_{\text{eff}})r_{\text{d}}}, \quad \frac{D_A(z_{\text{eff}})}{r_{\text{d}}} = \alpha \frac{D_A^{\text{fid}}(z_{\text{eff}})}{r_{\text{d}}^{\text{fid}}}.$$

$$D_A(z) = \frac{c}{H_0(1+z)} \int_0^z dz' \frac{H_0}{H(z')}, \quad \Delta\theta \propto \frac{r_{\text{d}}}{D_A(z)}$$

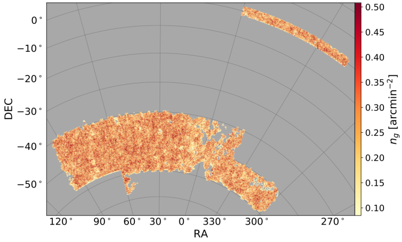
- Configuration space

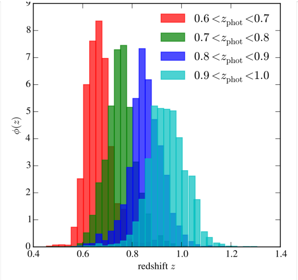
$$M(x) = BT_{\text{BAO}}(x\alpha) + A(x)$$

- Harmonic space

$$C(\ell) = BT_{\text{BAO}}(\ell/\alpha) + A(\ell)$$

DES Y1 BAO galaxy sample



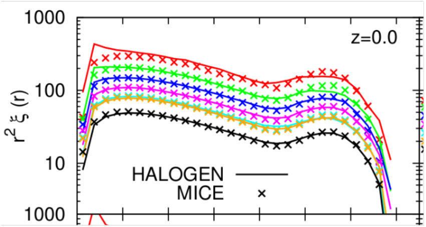


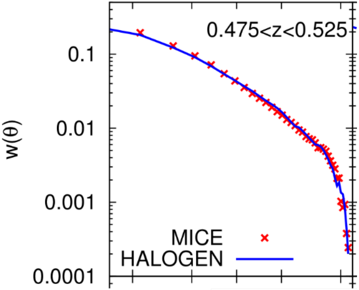
$z_{\rm photo}$	$N_{\rm gal}$	$\sigma_{68}/(1+z)$	$f_{\rm star}$
$0.6 < z < 0.7$	386057 (332242)	0.023 (0.027)	0.004 (0.018)
$0.7 < z < 0.8$	353789 (429366)	0.028 (0.031)	0.037 (0.042)
$0.8 < z < 0.9$	330959 (380059)	0.029 (0.034)	0.012 (0.015)
$0.9 < z < 1.0$	229395 (180560)	0.036 (0.039)	0.015 (0.006)

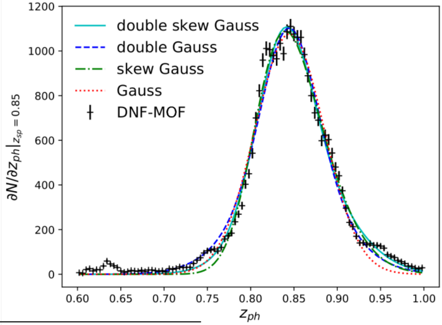
- Extend the selection of LRGs from SDSS to cover the higher redshift and deeper data (DES)
- 1.3 million red galaxies across 1318 deg^2 of area, largely contained in one compact region (SPT)

Crocce et. al. (2018)

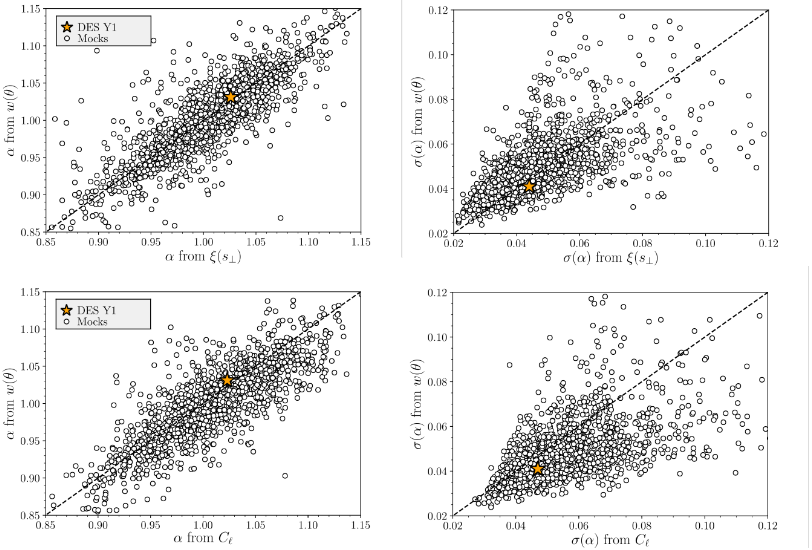
Covariances, 1800 Halogen mocks







Avila et. al. (2018)



Abbot et. al. (2018)

case	$\langle\alpha\rangle$	$\langle\sigma\rangle$	S_α	$f(N_{\rm det})$
$0.6 < z < 1.0$:				
$\xi + w$	1.004	0.050	0.050	0.917
$w(\theta)$	1.001	0.051	0.054	0.898
$w(\theta)$, $\Delta\theta = 0.15$ deg	1.001	0.054	0.055	0.907
$w(\theta)$, $\theta_{\rm min} = 1$ deg	1.002	0.051	0.053	0.898
C_ℓ	1.007	0.058	0.053	0.864
ξ (bins combined)	1.004	0.048	0.050	0.916
ξ, $+0h^{-1}$ Mpc	1.004	0.048	0.050	0.916
ξ, $+3h^{-1}$ Mpc	1.004	0.048	0.051	0.916
ξ, $+6h^{-1}$ Mpc	1.005	0.048	0.050	0.916
ξ, $+9h^{-1}$ Mpc	1.005	0.048	0.050	0.921
ξ, $s_{\perp {\rm min}} = 50h^{-1}$ Mpc	1.005	0.049	0.050	0.913
ξ, $\Delta s_\perp = 5h^{-1}$ Mpc	1.005	0.050	0.051	0.918
ξ, $\Delta s_\perp = 10h^{-1}$ Mpc	1.005	0.049	0.050	0.916
ξ, $\Delta s_\perp = 15h^{-1}$ Mpc	1.004	0.048	0.051	0.911

Abbot et. al. (2018)

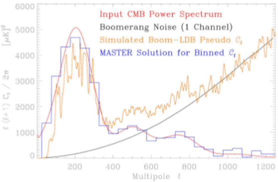
Angular power spectrum measurements. MASTER or PCL approach

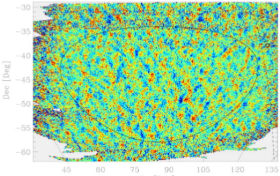
$$\tilde{a}_{\ell m} = \int d\mathbf{n} \Delta T(\mathbf{n}) W(\mathbf{n}) Y^*_{\ell m}(\mathbf{n})$$

$$\approx \Omega_p \sum_p \Delta T(p) W(p) Y^*_{\ell m}(p)$$

$$\widetilde{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2$$

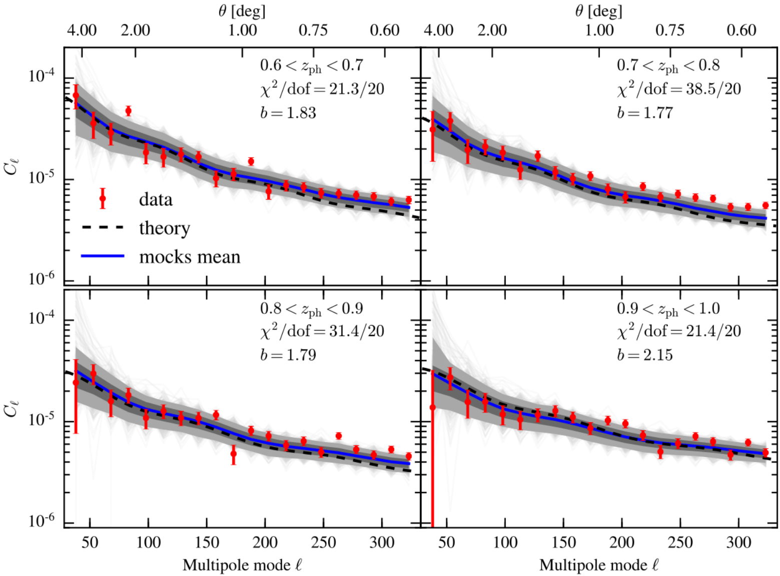
$$\langle \widetilde{C}_\ell \rangle = \sum_{\ell'} M_{\ell\ell'} \langle C_{\ell'} \rangle$$



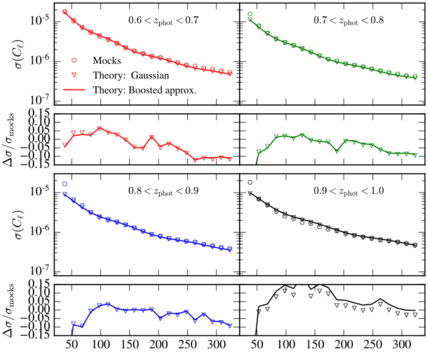


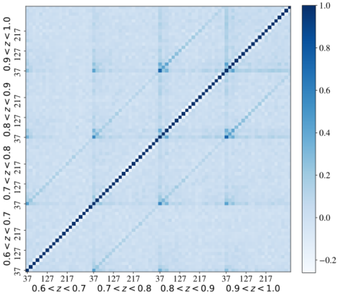
[Hivon et. al.(2001) arXiv:astro-ph/0105302]
[Elsner, Leistedt and Peiris (2016) https://arxiv.org/abs/1609.03577]

Angular power spectrum measurements

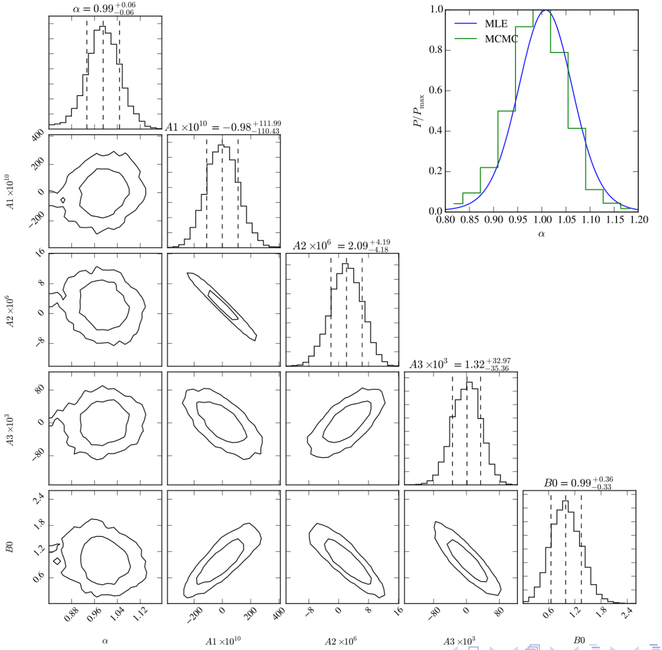


Angular power spectrum covariance

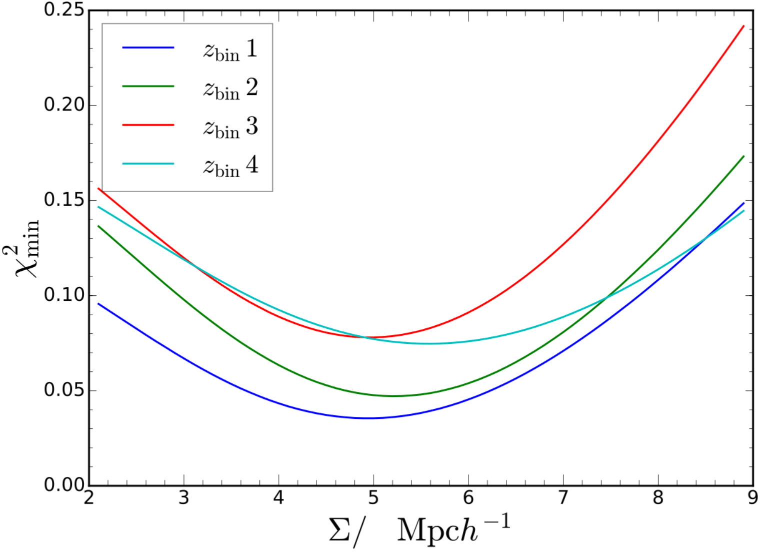




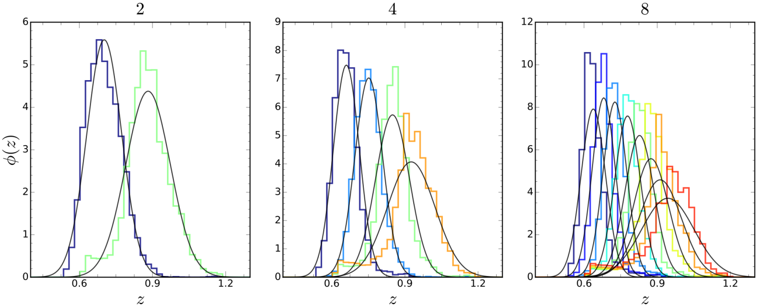
Estimation methods

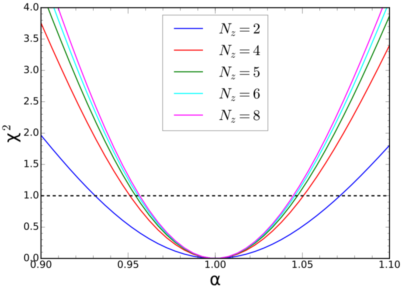


$\Sigma_{\rm nl} = 5.2\ {\rm Mpc}h^{-1}$

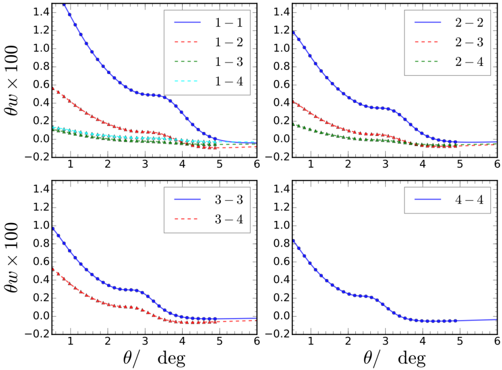


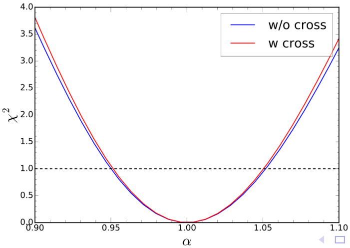
$N(z)$



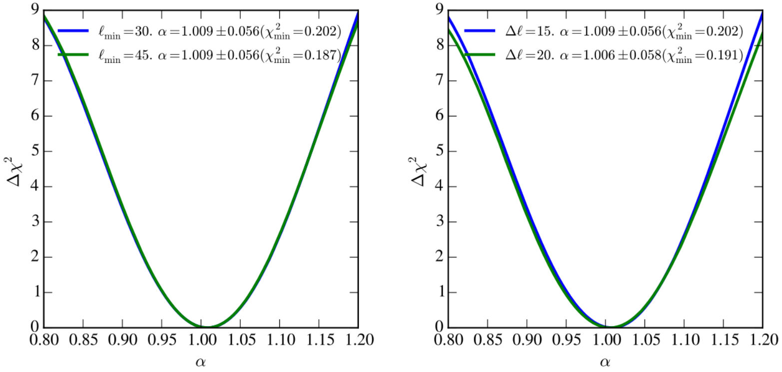


Cross-correlations



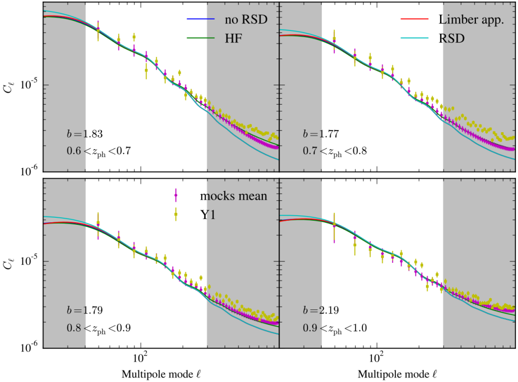


Bandpowers

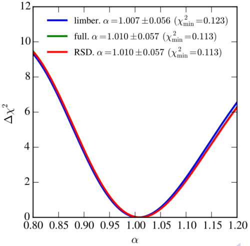


$\ell_{min}=30.\ \alpha=1.009\pm0.056(\chi^2_{min}=0.202)$
$\ell_{min}=45.\ \alpha=1.009\pm0.056(\chi^2_{min}=0.187)$
$\Delta\ell=15.\ \alpha=1.009\pm0.056(\chi^2_{min}=0.202)$
$\Delta\ell=20.\ \alpha=1.006\pm0.058(\chi^2_{min}=0.191)$
$\Delta\chi^2$
α
0.80
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20
0
1
2
3
4
5
6
7
8
9

$P(k)$ model



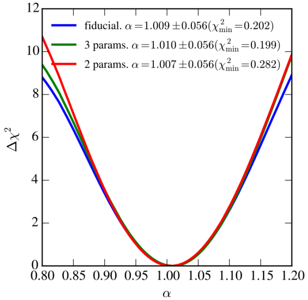
no RSD
HF
Limber app.
RSD
mocks mean
Y1
C_ℓ
10^{-5}
10^{-6}
$b=1.83$
$0.6<z_{\rm ph}<0.7$
$b=1.77$
$0.7<z_{\rm ph}<0.8$
$b=1.79$
$0.8<z_{\rm ph}<0.9$
$b=2.19$
$0.9<z_{\rm ph}<1.0$
10^2
Multipole mode ℓ



limber. $\alpha=1.007\pm0.056$ ($\chi^2_{\rm min}=0.123$)
full. $\alpha=1.010\pm0.057$ ($\chi^2_{\rm min}=0.113$)
RSD. $\alpha=1.010\pm0.057$ ($\chi^2_{\rm min}=0.113$)
$\Delta\chi^2$
α
0.80 0.85 0.90 0.95 1.00 1.05 1.10 1.15 1.20
0 2 4 6 8 10 12

Broadband terms

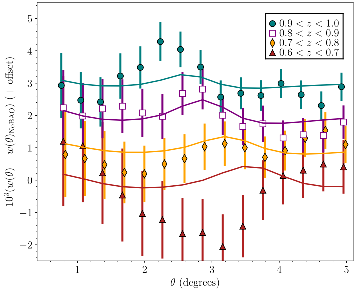
case	$\langle\alpha\rangle$	$\langle\sigma\rangle$	S_α	$f(N_{\rm det})$	mean of mocks
$\Delta\ell = 15,\ 30 < \ell < 330$:					
$A_0 + A_1\ell + A_2\ell^{-1}$	1.003	0.051	0.058	0.752	1.008 ± 0.056
$A_0 + A_1\ell + A_2\ell^{-2}$	1.007	0.058	0.053	0.864	1.009 ± 0.056
$A_0 + A_1\ell + A_2\ell^{2}$	1.011	0.056	0.055	0.851	1.013 ± 0.056
$\Delta\ell = 20,\ 40 < \ell < 300$:					
$A_0 + A_1\ell + A_2\ell^{-1}$	1.003	0.051	0.060	0.734	1.006 ± 0.058
$A_0 + A_1\ell + A_2\ell^{-2}$	1.006	0.059	0.056	0.812	1.006 ± 0.058
$A_0 + A_1\ell + A_2\ell^{2}$	1.009	0.057	0.057	0.790	1.012 ± 0.057
$\Delta\ell = 15,\ 45 < \ell < 330$:					
$A_0 + A_1\ell + A_2\ell^{-1}$	1.004	0.050	0.059	0.736	1.009 ± 0.056
$A_0 + A_1\ell + A_2\ell^{-2}$	1.007	0.057	0.054	0.841	1.009 ± 0.056
$A_0 + A_1\ell + A_2\ell^{2}$	1.011	0.056	0.055	0.839	1.013 ± 0.056
$\Delta\ell = 20,\ 40 < \ell < 320$:					
$A_0 + A_1\ell + A_2\ell^{-1}$	1.004	0.050	0.060	0.731	1.008 ± 0.056
$A_0 + A_1\ell + A_2\ell^{-2}$	1.007	0.058	0.055	0.833	1.008 ± 0.057
$A_0 + A_1\ell + A_2\ell^{2}$	1.011	0.056	0.057	0.831	1.014 ± 0.057

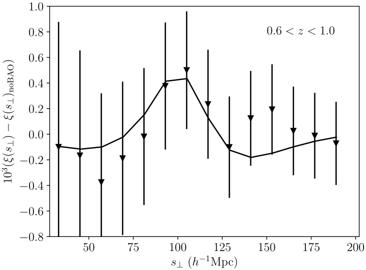


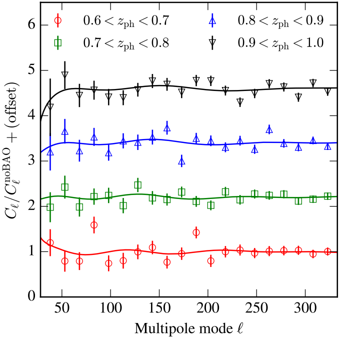
Summary of stress tests

Y1 Measurement	D_A/r_d	
$z_{\rm eff} = 0.81$	10.75 ± 0.43	
case	α	χ^2/dof
$w(\theta)$ [**consensus**]	1.033 ± 0.041	$53/43$
ξ (bins combined)	1.026 ± 0.044	$9/9$
Robustness tests:		
C_ℓ	1.023 ± 0.047	$94/63$
$w(\theta)$ fiducial	1.033 ± 0.041	$53/43$
$w(\theta)$ $\Delta\theta = 0.15$	1.033 ± 0.045	$159/103$
$w(\theta)$ $\theta_{\rm min} = 1$	1.038 ± 0.038	50/39
$w(\theta)$ Planck$\times$1.042	1.034 ± 0.041	52/43
$w(\theta)$ BPZ	1.018 ± 0.043	56/43
$w(\theta)$ z uncal	1.023 ± 0.040	52/43
$w(\theta)$ no $w_{\rm sys}$	1.028 ± 0.039	51/43
$w(\theta)$ $\Sigma_{\rm nl} = 2.6$	1.028 ± 0.035	51/43
$w(\theta)$ $\Sigma_{\rm nl} = 7.8$	1.033 ± 0.056	55/43
$w(\theta)$ free $\Sigma_{\rm nl}$	1.028 ± 0.033	51/42
$w(\theta)$ $0.7 < z < 1.0$	1.053 ± 0.040	$37/32$
ξ fiducial binning	1.031 ± 0.040	$9/9$
ξ -3	1.031 ± 0.045	$12/9$
ξ $+3$	1.017 ± 0.041	$8/9$
ξ $+6$	1.025 ± 0.050	$7/8$
ξ $\Delta s_\perp = 5$	1.021 ± 0.041	$45/29$
ξ $\Delta s_\perp = 8$	1.029 ± 0.046	$31/16$
ξ $\Delta s_\perp = 10$	1.022 ± 0.037	$16/12$
ξ $\Delta s_\perp = 15$	1.012 ± 0.039	$7.5/6$
ξ $s_{\perp,\rm min} = 50$	1.032 ± 0.046	$8/7$
ξ Planck$\times$1.042	1.018 ± 0.041	7/9
ξ BPZ	1.012 ± 0.040	12/9
ξ no $w_{\rm sys}$	1.029 ± 0.040	10/9
ξ $\Sigma_{\rm nl} = 4$	1.023 ± 0.038	9/9
ξ $\Sigma_{\rm nl} = 12$	1.043 ± 0.052	11/9
ξ $\Sigma_{\rm nl}$ free	1.024 ± 0.039	9/9
ξ $0.7 < z < 1.0$	1.052 ± 0.031	$17/9$

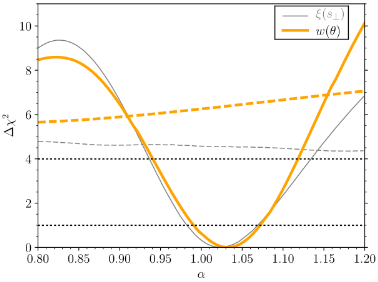
BAO measurements



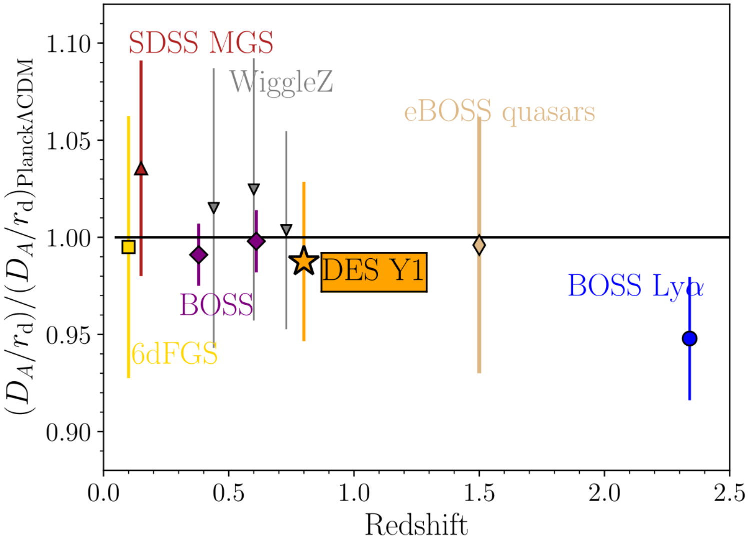




BAO measurements



BAO detection



Conclusions

- Dark energy remains as one of the biggest puzzles and data can give light to solve it.
- BAO detection is robust for wide photo-z surveys like DES.
- BAO measurements had previously been proven to be a robust and precise method for measuring cosmological distances when using spectroscopic redshifts
- Looking forward for Y3