Observatório
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Baryon acoustic oscillations from the SDSS luminous galaxies angular correlation function

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Outline

- Cosmic acceleration and standard rulers
- Baryon acoustic oscillations (BAO)
- BAO from the 2PACF
- Application to SDSS-III DR10/DR11
- Cosmological constraints
- Conclusions

G. Carvalho, A. Bernui, M. Benetti, J. Carvalho & JSA, Phys. Rev. D93, 023530 (2016)

Two important questions:

Is Dark Energy Consistent with a Cosmological Constant (w = -1)?

Does GR Self Consistently Describe Cosmic Acceleration?

For a recent review, see Weinberg et al. Phys. Rept. 530, 87 (2013)

Probing dark energy

We "see" dark energy through its effects on the expansion of the universe:

$$H^2(z) = \frac{8\pi G}{3}\sum_i \rho_i(z)$$

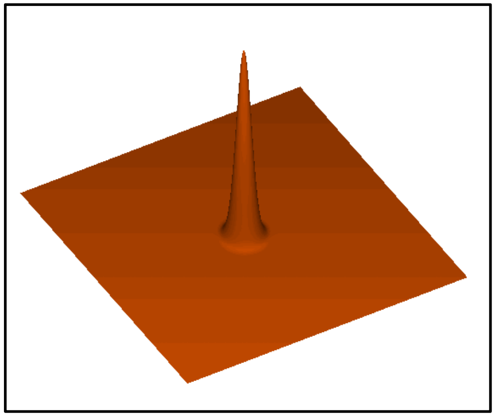
Main approaches:

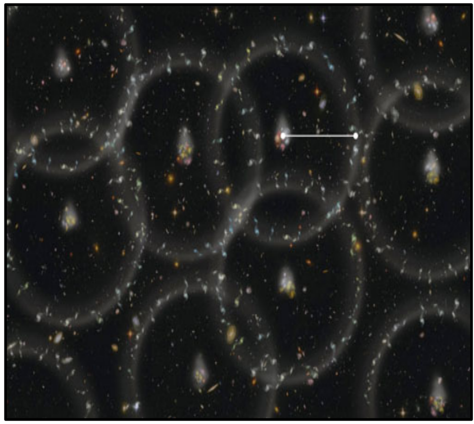
- **Standard Candles:** measure $d_L \propto \int dz / H(z)$
- **Standard Rulers:** measure $d_A \propto \int dz / H(z)$ and $H(z)$

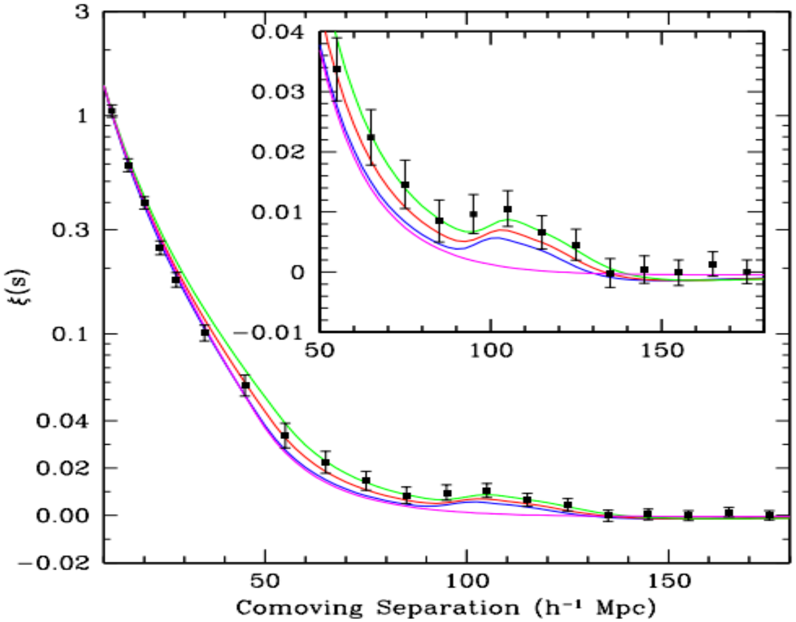
- **Cosmic Chronometers:** measure $t \propto \int dz / (1+z)H(z)$ and $H(z)$
- **Growth of fluctuations:** Crucial for testing extra ρ components vs modified gravity.

BAO: cosmological ruler

- Primordial perturbations generated acoustic waves in the photon-baryon fluid until decoupling at z ~ 1100 (Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970).
- At this time the photons decouple from the baryons creating a high density region from the original source of perturbation, at a distance given by the sound horizon length.
- This high density profile shows as a peak associated to the sound horizon scale in the galaxies spatial two-point statistics in the configuration space, which can be used as a cosmological standard ruler.

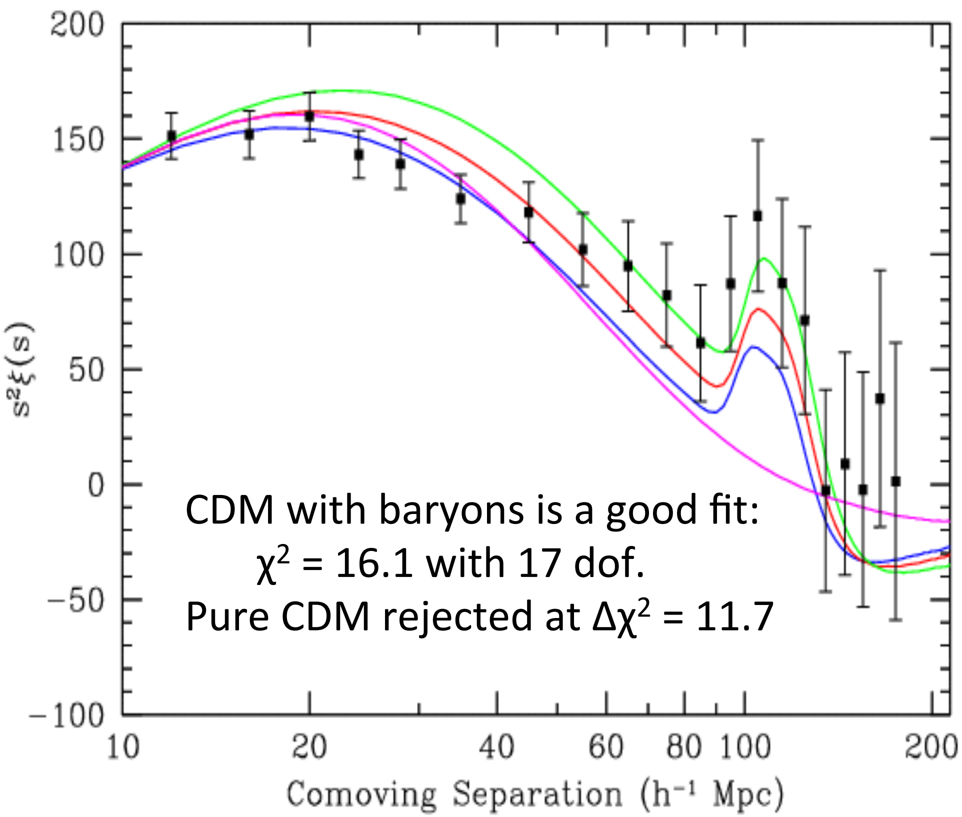


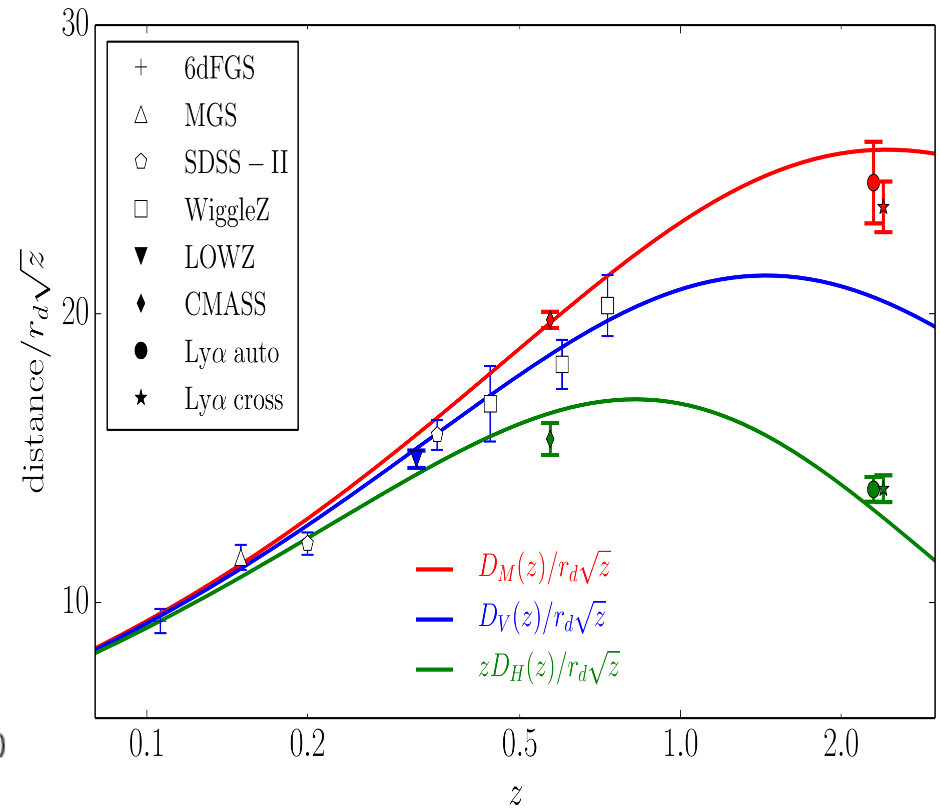




Detection of the Acoustic Peak

Current measurements:

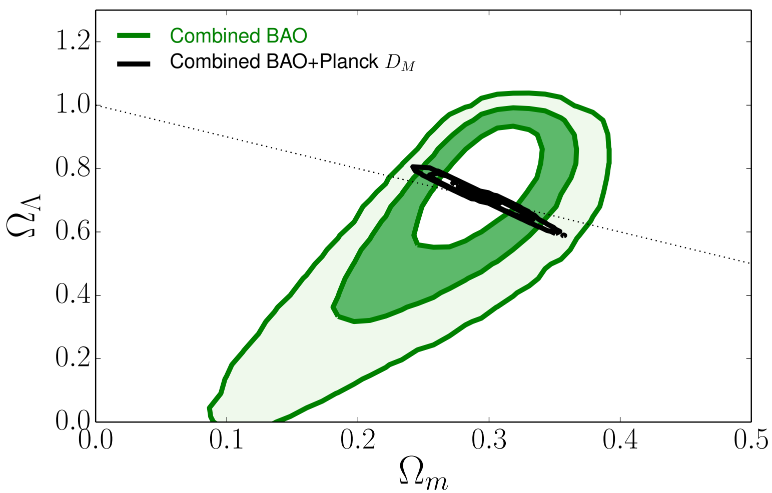


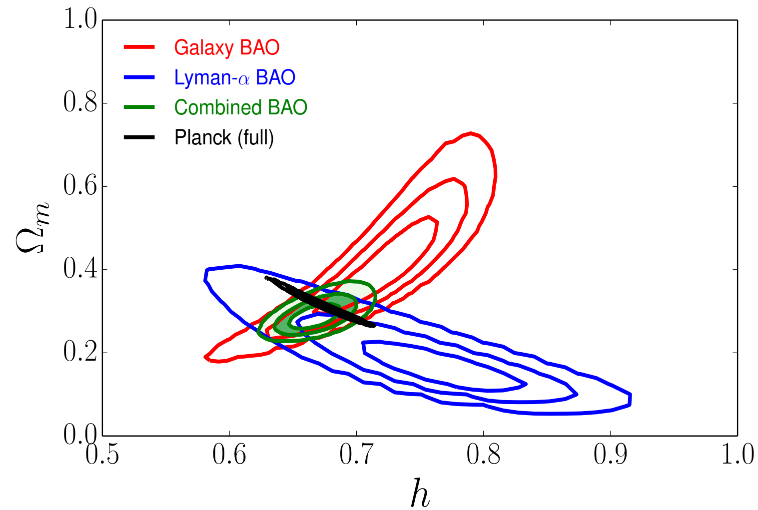


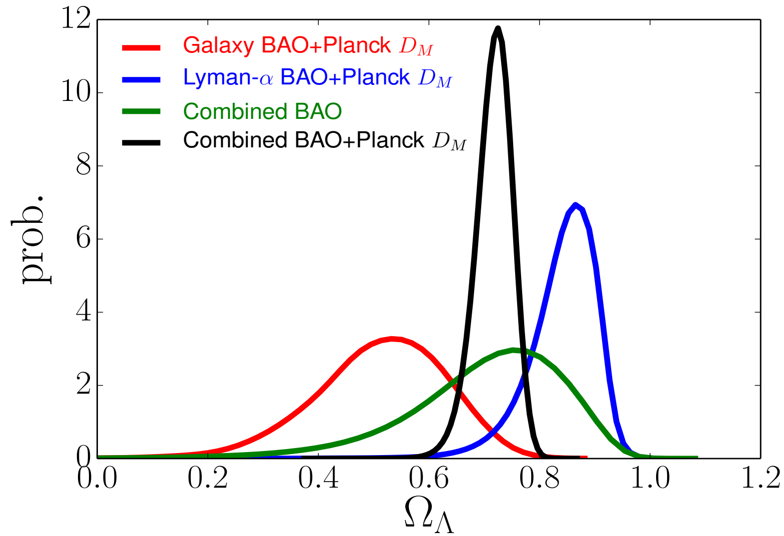
Eisenstein et al. (2005)

Aubourg et al. (2014)

Current measurements







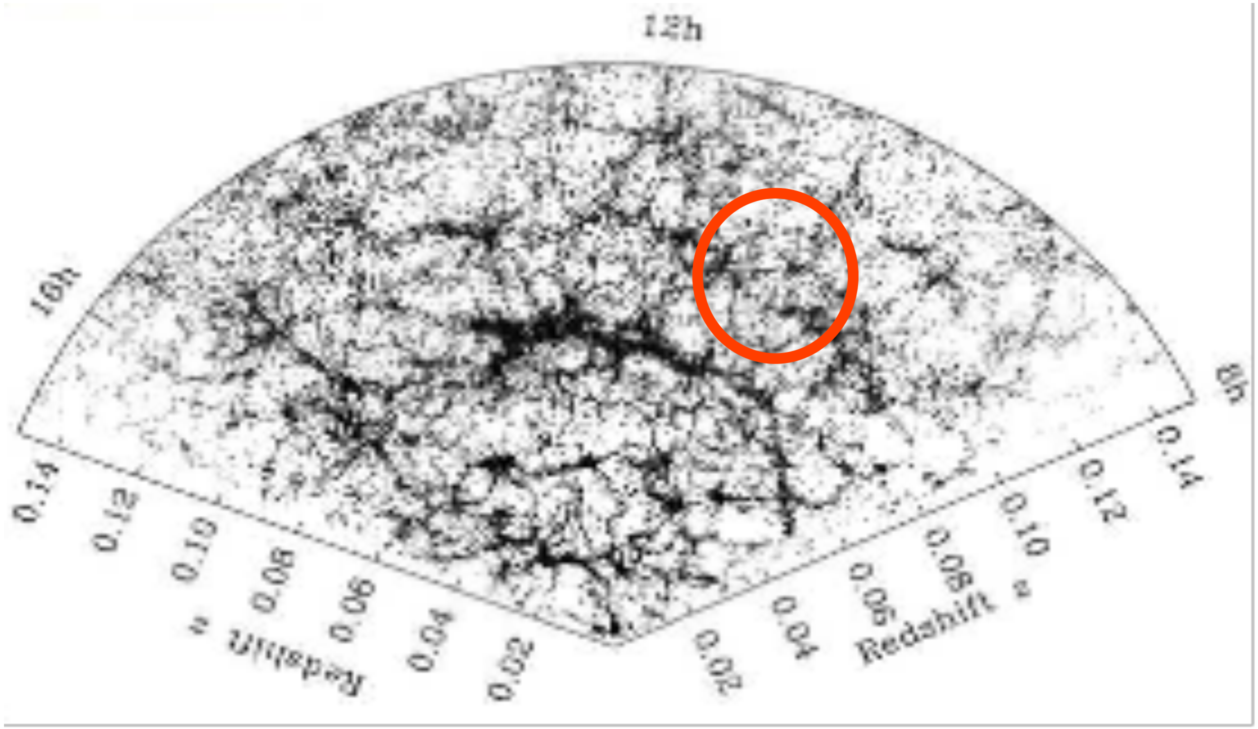
$$\Omega_\Lambda = 0.73^{+0.25}_{-0.68}\ (99.7\%)$$

~ 3σ detection of dark energy from BAO data alone.

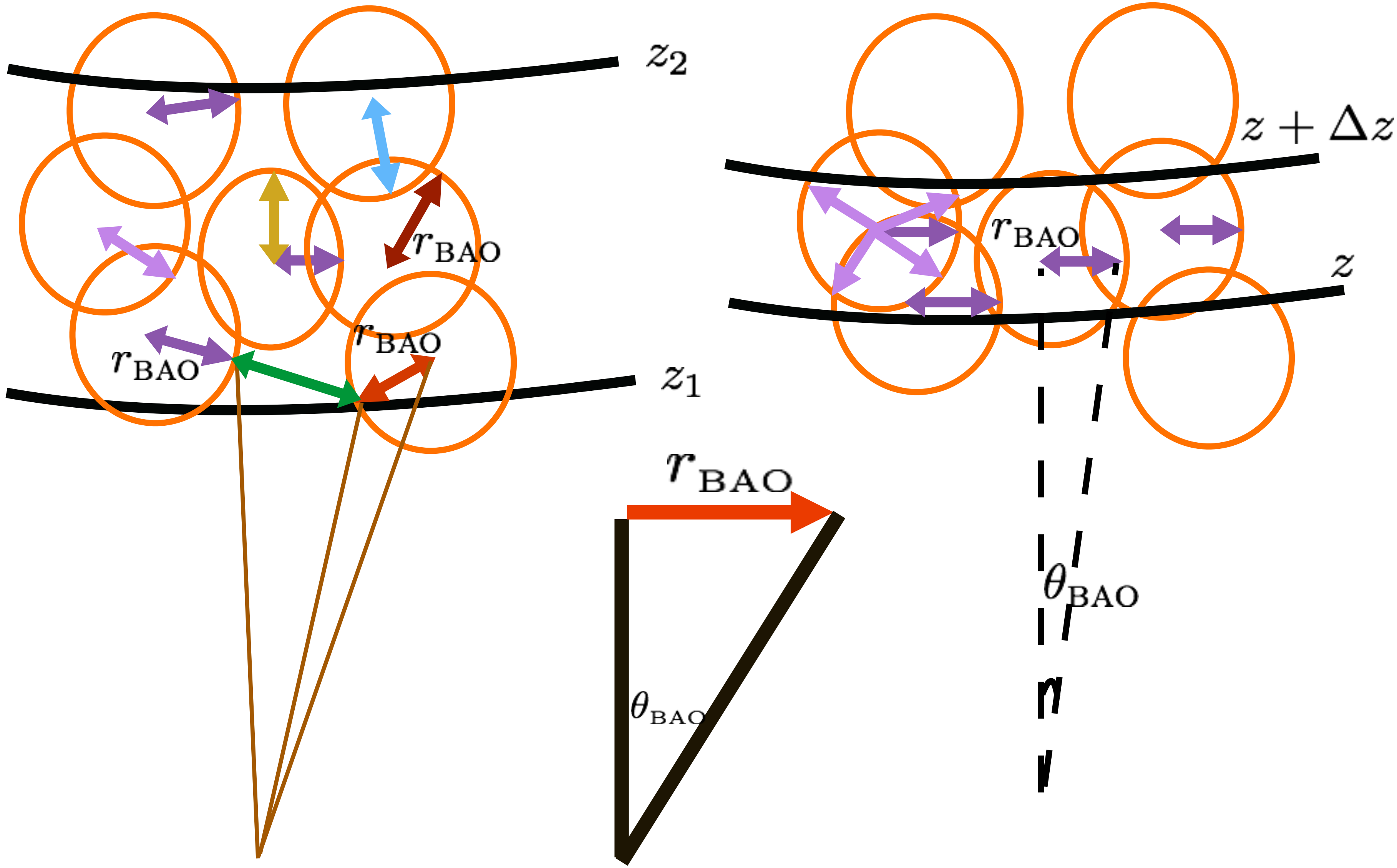
Aubourg et al. (2014)

2PACF

$\omega(\theta)$ = The excess probability (above random) of finding two point sources with a given angular separation θ.



We obtain precise measurements of $D_A(z)$ without assuming a fiducial cosmology and restrict cosmological parameters in an almost model-independent way



$$\theta_{\rm BAO} = \frac{r_{\rm BAO}}{(1+z)\,D_A}$$

$$r_{\rm BAO} \simeq 105\,{\rm Mpc}/h$$

The data set

- SDSS-DR10: contains 409,337 LRG's
- SDSS-DR11: contains 543,116 LRG's

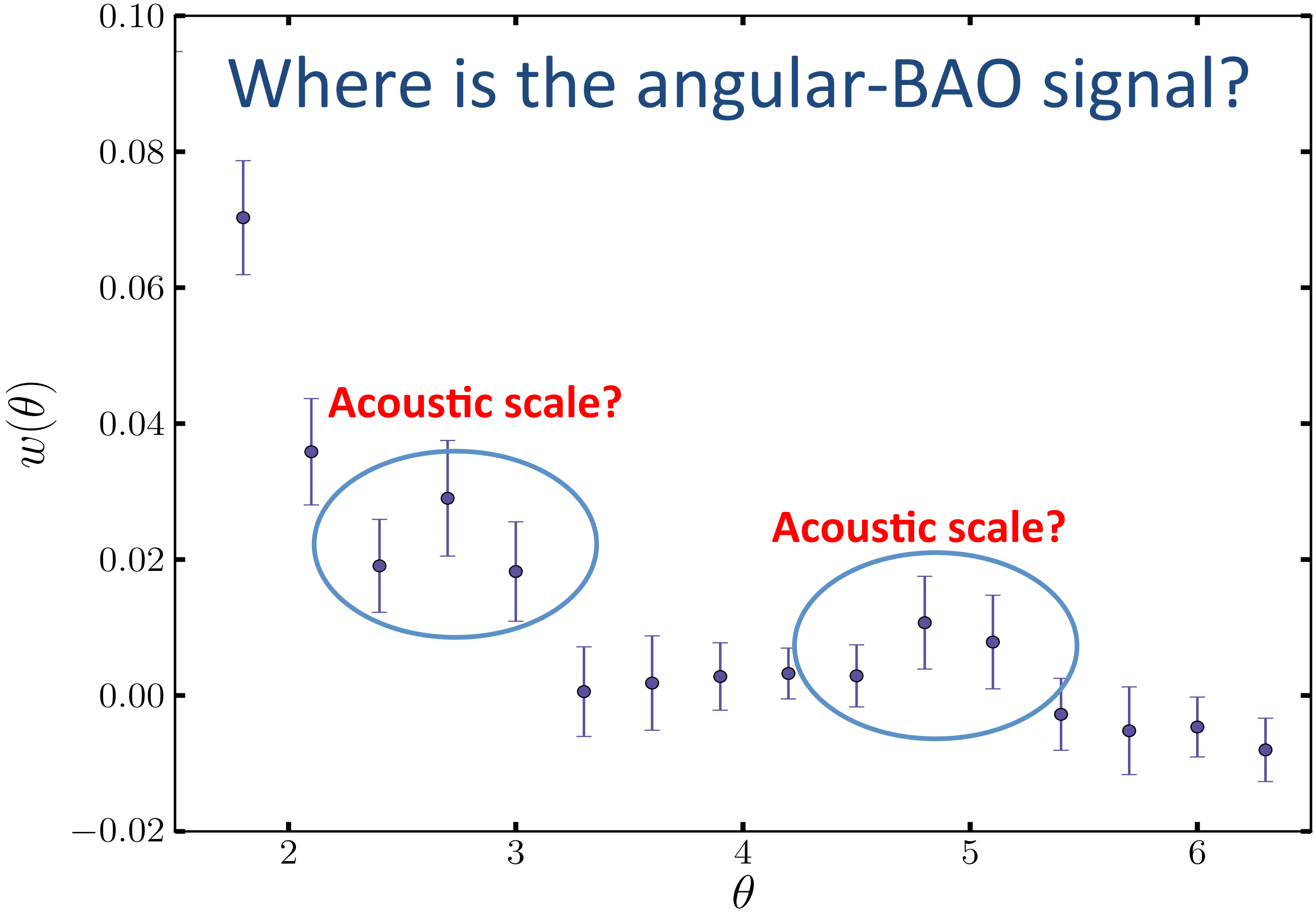
($0.43 \leq z \leq 0.7$)

DR10

redshift intervals	number of LRGs	$\bar{z}$	δz
0.440 - 0.460	21,862	0.45	0.02
0.465 - 0.475	17,536	0.47	0.01
0.480 - 0.500	40,957	0.49	0.02
0.505 - 0.515	21,046	0.51	0.01
0.525 - 0.535	22,147	0.53	0.01
0.545 - 0.555	21,048	0.55	0.01

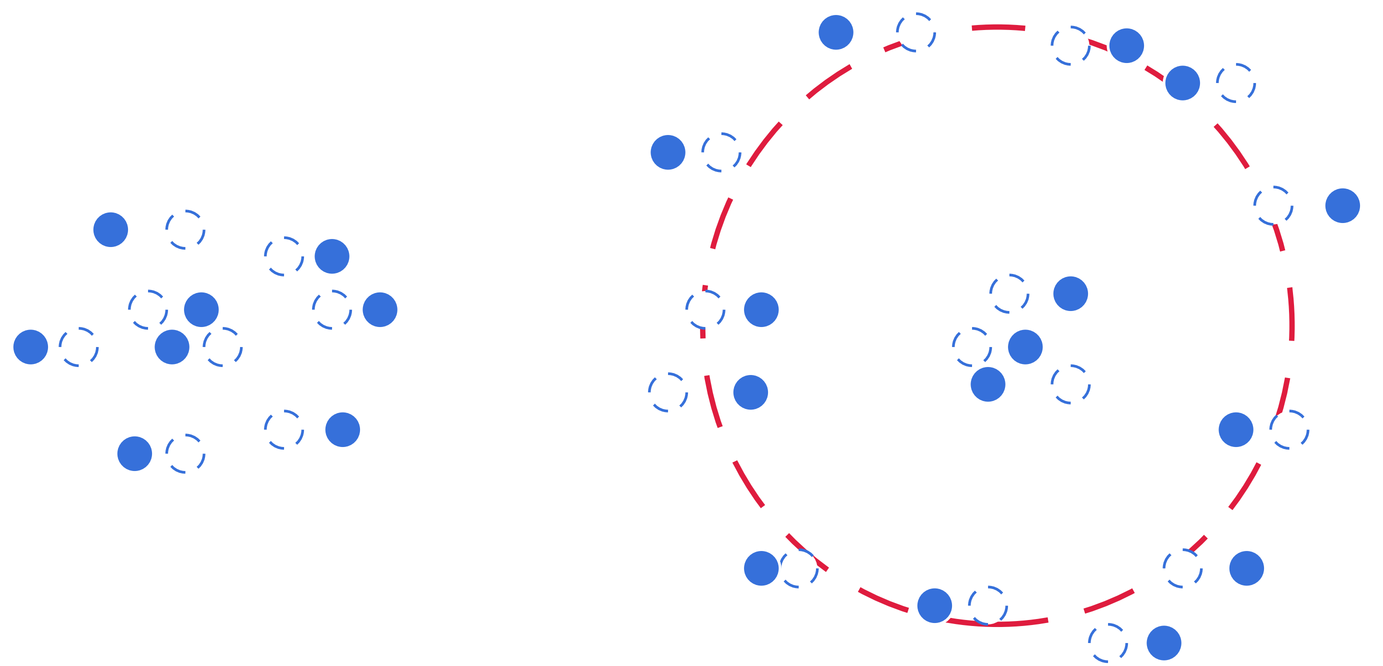
TABLE I: The six bin-redshift intervals and their properties: number of galaxies, mean redshift of the sample, $\bar{z}$, and bin-width, δz. Notice that contiguous intervals are separated by a redshift interval of size 0.005 to avoid correlation between neighbours.

Finding Θ_{BAO} in the 2PACF

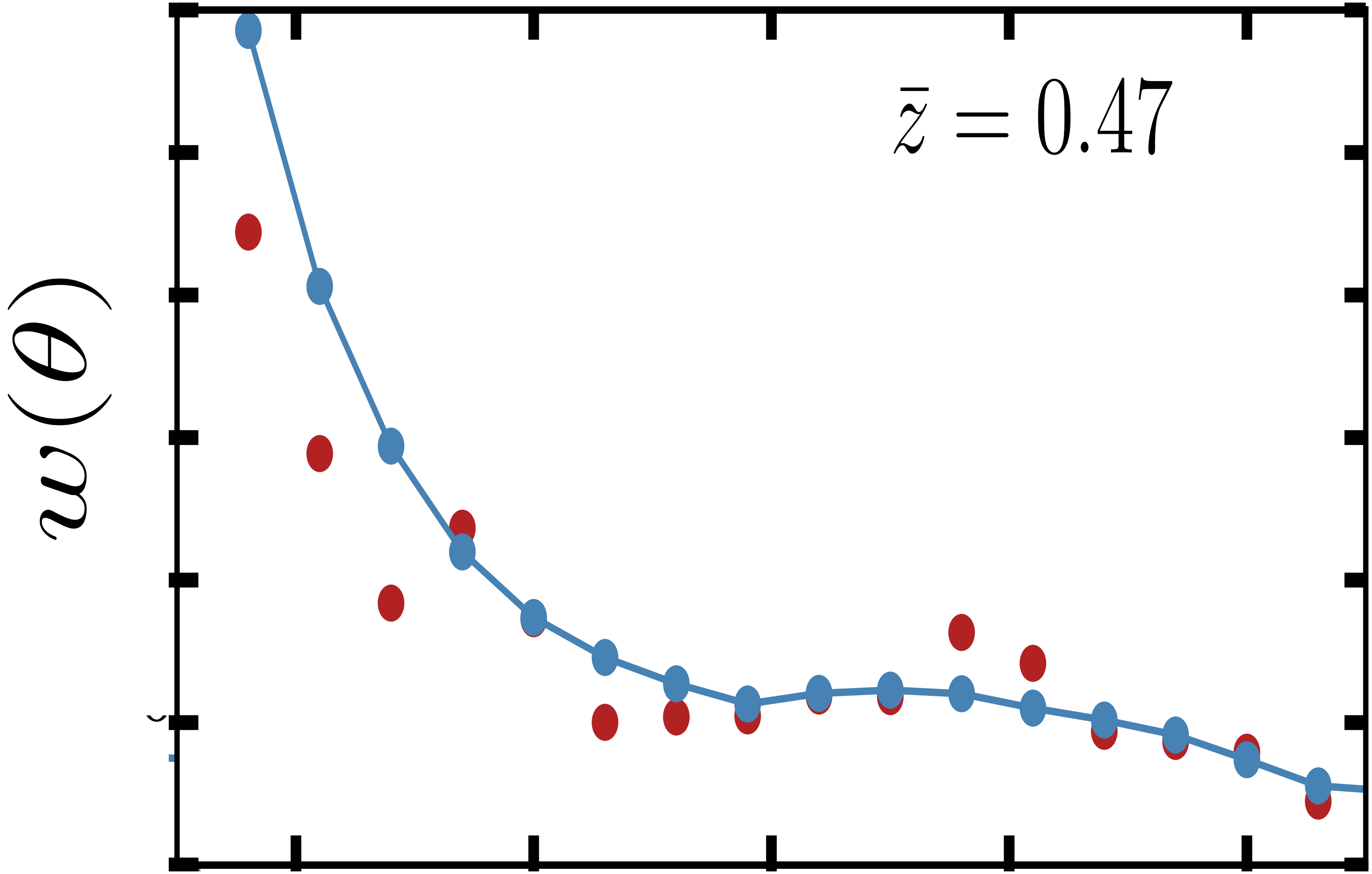


A model-independent way to find θ_{BAO}

- Changing galaxies coordinates



Example

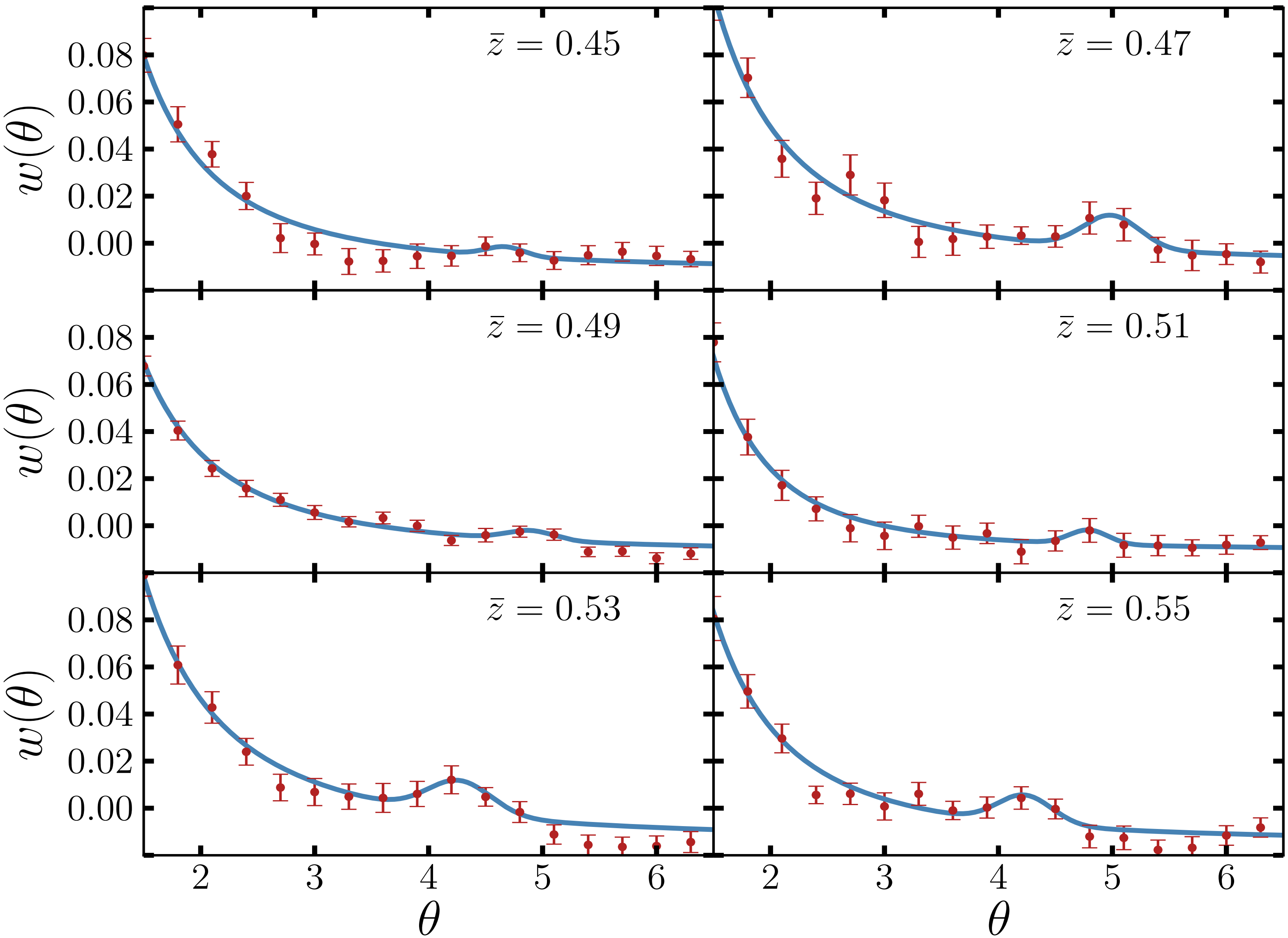


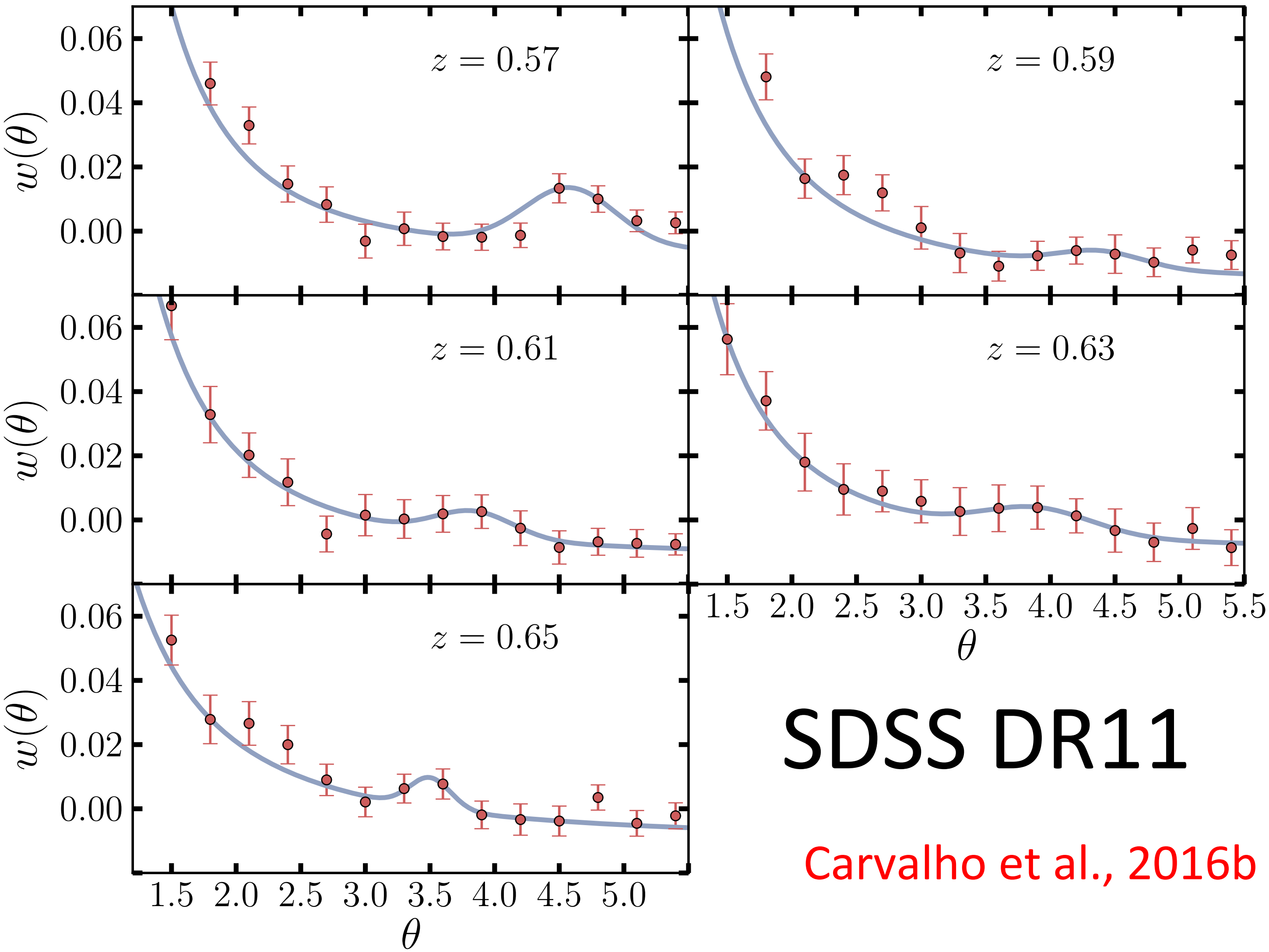
Results

Carvalho et al., Phys. Rev. D93, 023530 (2016a)
Carvalho et al. 2016b (in preparation)

SDSS DR10

Carvalho et al., 2016a





SDSS DR11

Carvalho et al., 2016b

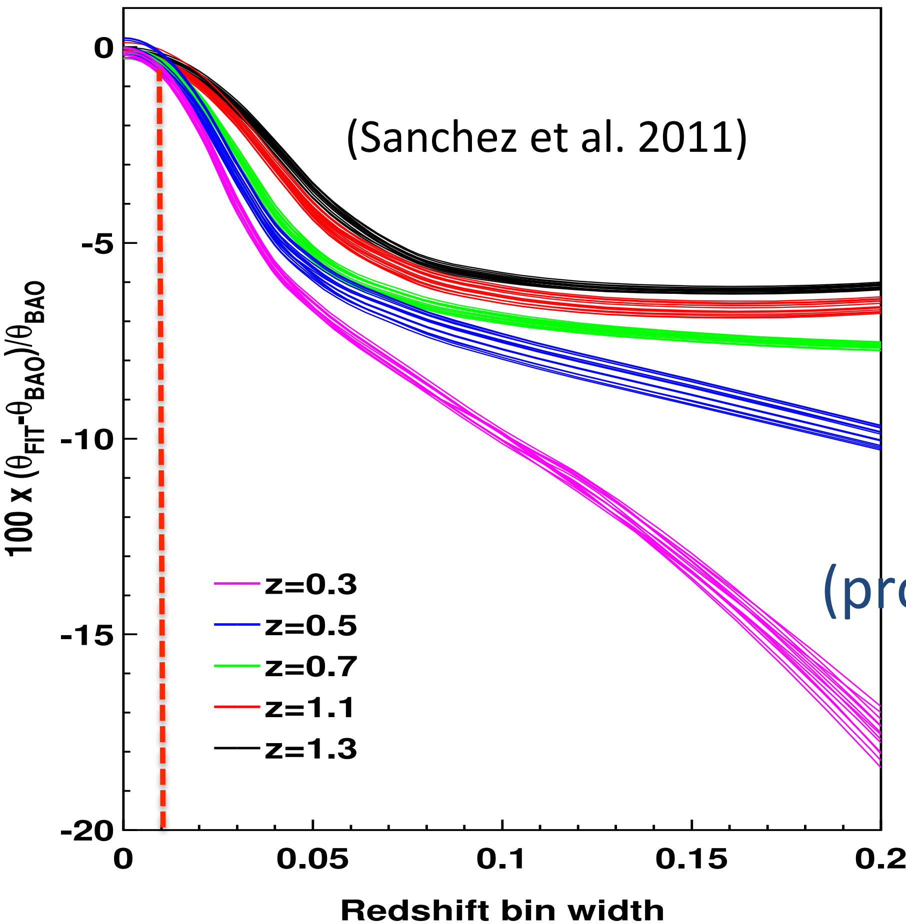
$$w_{FIT}(\theta) = A + B\theta^{\nu} + Ce^{-\frac{(\theta-\theta_{FIT})^2}{2\sigma^2_{FIT}}}$$

(Sanchez et al. 2011)

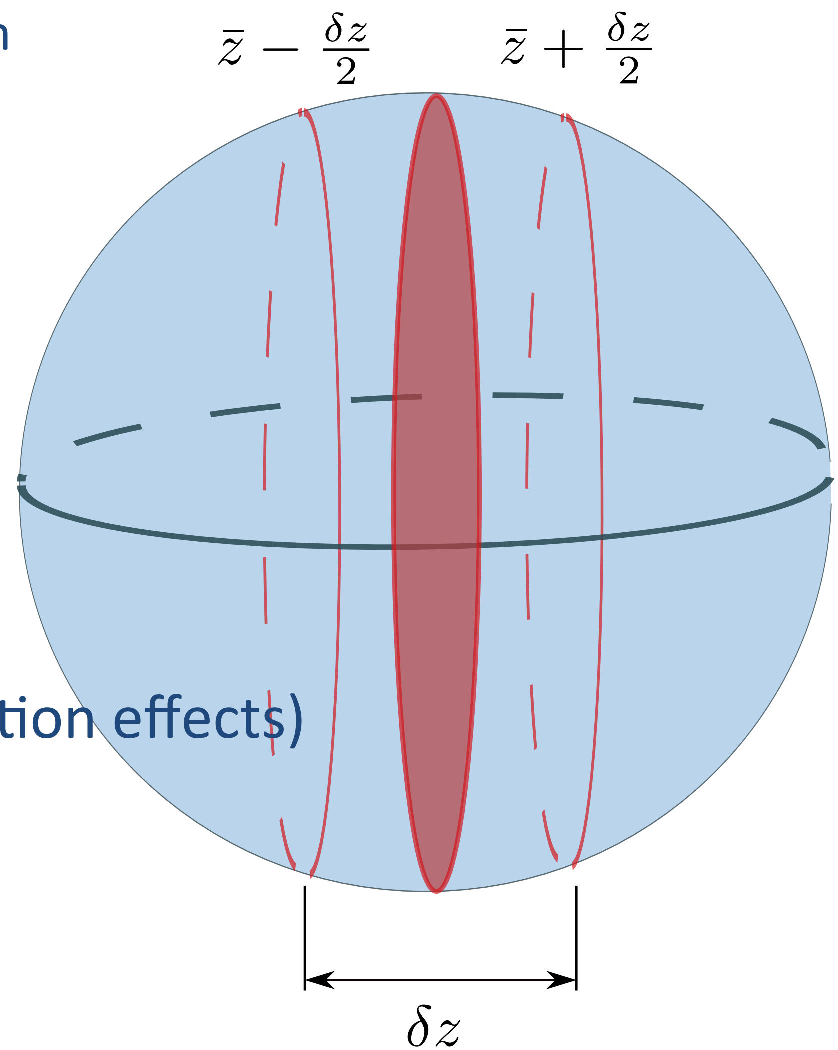
- Shift factor (α): $\theta_{FIT} \neq \theta_{BAO}$ (δz ≠ 0)

$$\theta_{BAO}(z,\delta z) = \theta_{FIT}(z) + \alpha(z,\delta z,P_m(k,z))\theta_E^{\delta z=0}(z)$$

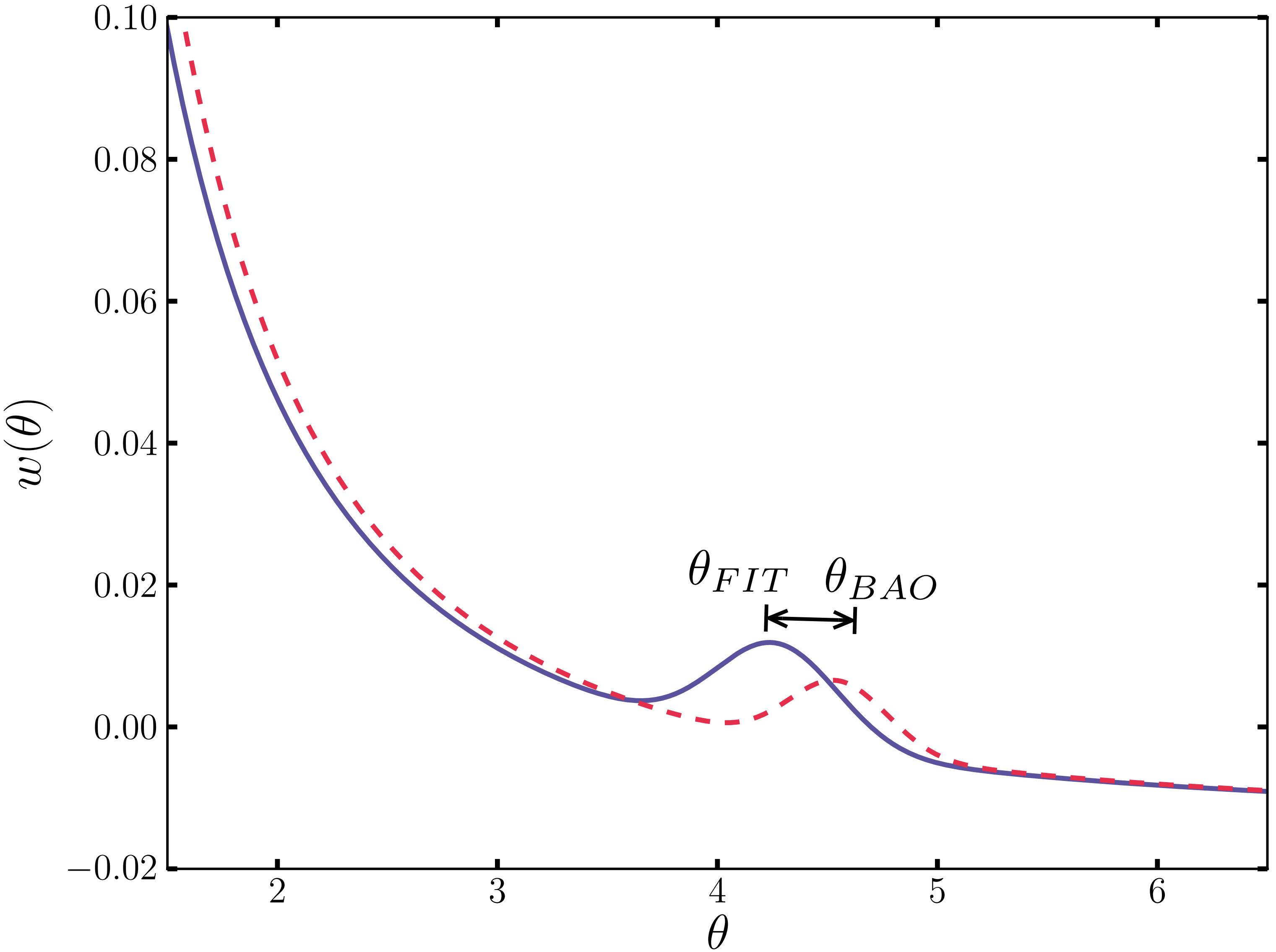
$P_m(k,z)$ = is the matter power spectrum



(projection effects)



- Shift factor (α)



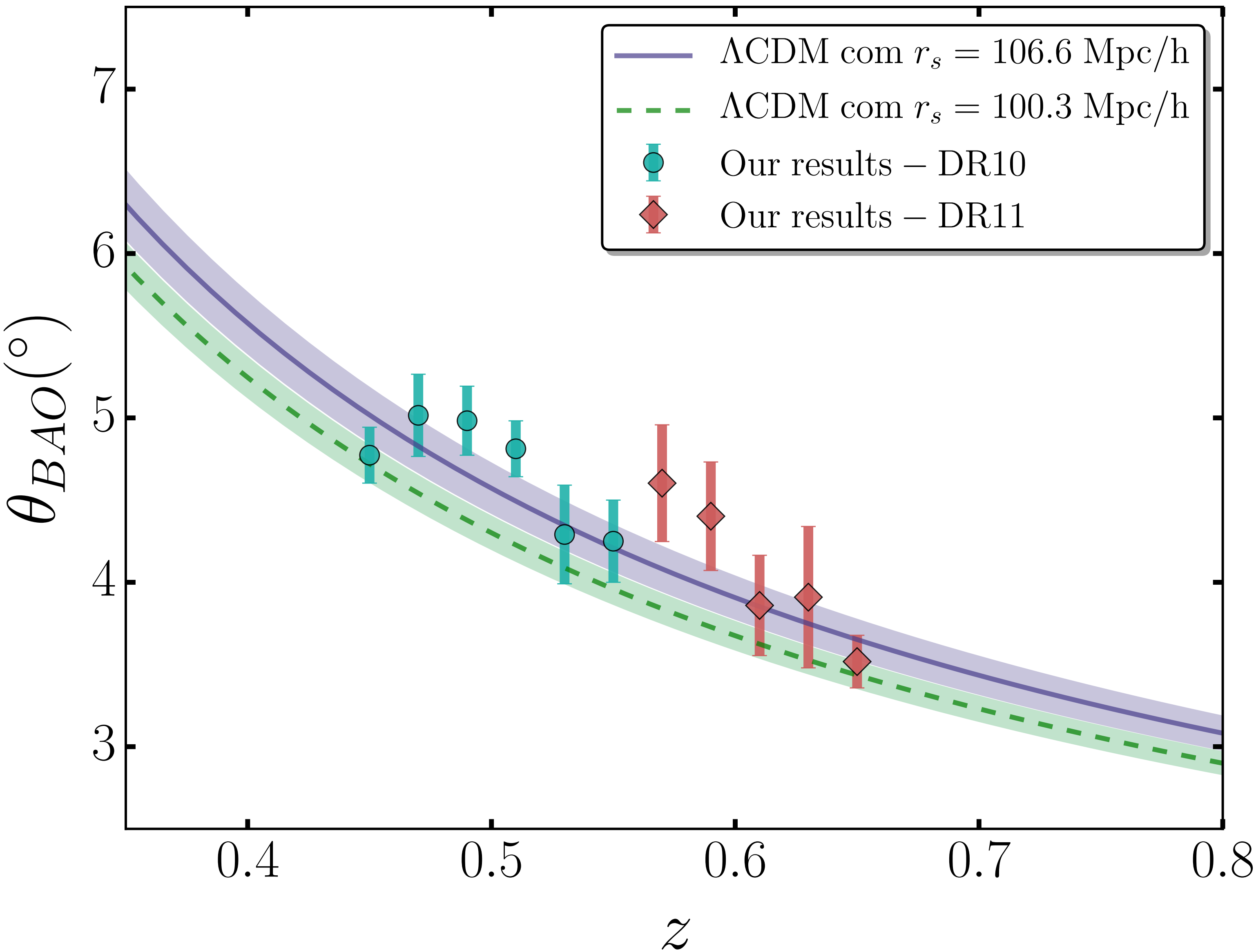
Measurements of $\theta_{BAO}(z)$

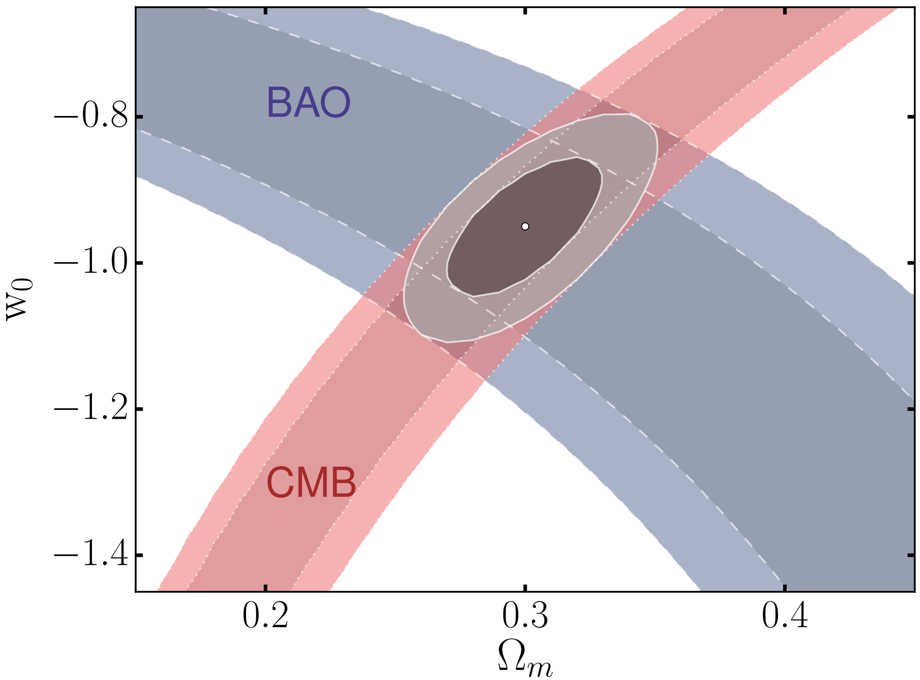
DR10

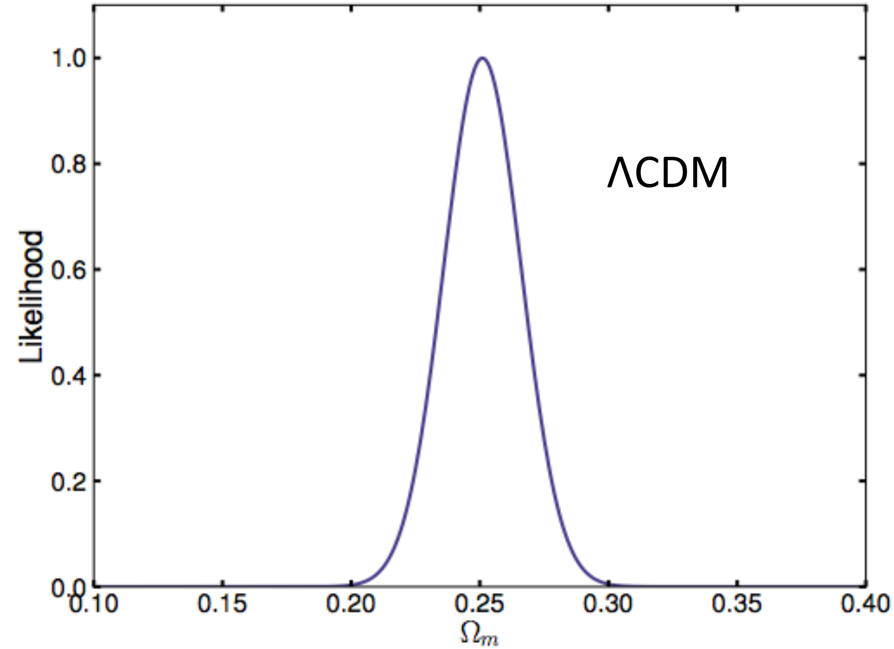
z interval	$\langle z \rangle$	α (%)	θ_{FIT} ($^\circ$)	θ_{BAO} ($^\circ$)	σ_{BAO}
0.440-0.460	0.45	2.0815	4.67	4.77	0.17
0.465-0.475	0.47	0.5367	4.99	5.02	0.25
0.480-0.500	0.49	2.0197	4.89	4.99	0.21
0.505-0.515	0.51	0.5002	4.79	4.81	0.17
0.525-0.535	0.53	0.4847	4.27	4.29	0.30
0.545-0.555	0.55	0.4789	4.23	4.25	0.25

$\alpha \leq 2\%$

The $\Theta_{BAO} - z$ plane



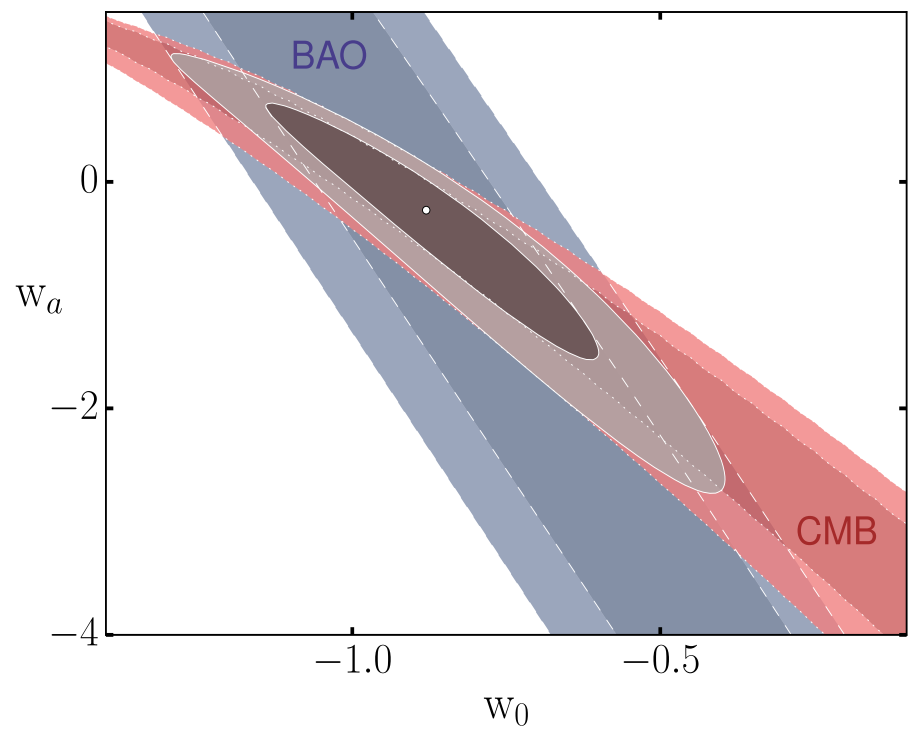




$$\Omega_m = 0.30 \pm 0.02; \quad w_0 = -0.95 \pm 0.06$$

$$w_0 = -0.88 \pm 0.17; \quad w_a = -0.25 \pm 0.74$$

$$\Omega_m = 0.26 \pm 0.02 \quad \left(\Lambda CDM\right)$$

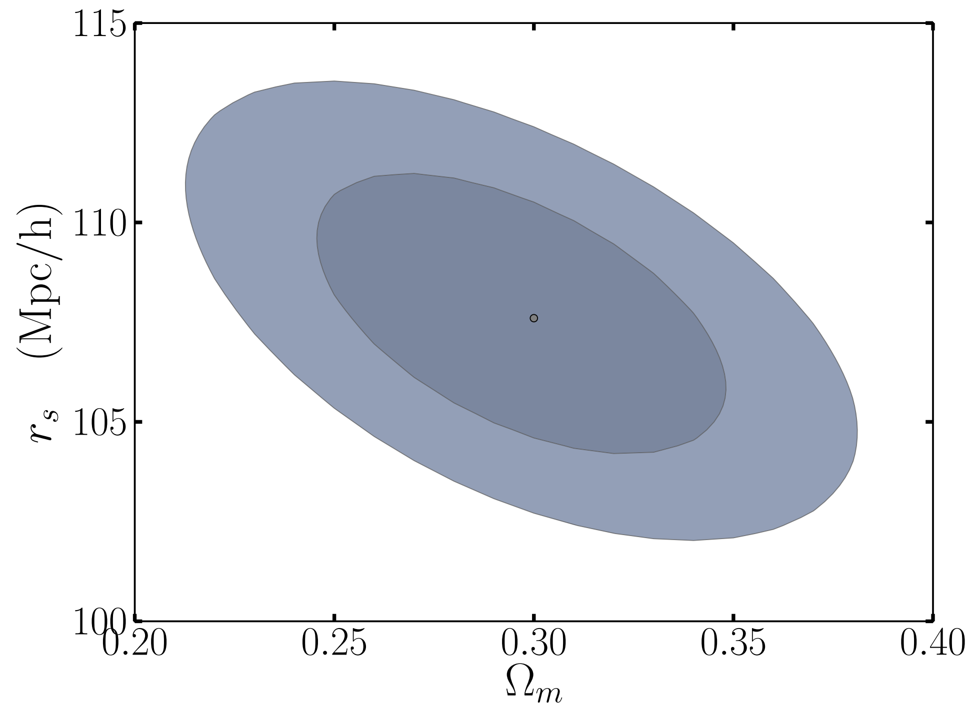


An independent estimate of the acoustic scale

$$\theta_{\rm BAO} = \frac{r_{\rm BAO}}{(1+z)\,D_A}$$

- r_s = 106.61 ± 3.47 Mpc/h (WMAP9 - LCDM)
- r_s = 100.29 ± 2.26 Mpc/h (Planck - LCDM)
- r_s = 101.90 ± 1.90 Mpc/h (Heavens, Verde, Jimenez, PRL, 2015)
- r_s = 107.80 ± 2.0 Mpc/h (Carvalho et al. 2016b- LCDM)

Tension with Planck



Conclusions

- The mechanism behind cosmic acceleration is an open question; Many candidates (GR or MG).
- 2PACF analysis of SDSS-III DR10/DR11 luminous galaxies.
- BAO peaks: model-independent methodology.
- BAO peak position: α shift (model-dependent correction $\leq 2\%$).
- Cosmological constraints: dependence with r_s. Good agreement with WMAP9 data.
- We have extended the present number of θ_{BAO} data. It can be used to provide an independent estimate of r_s.
- Current data are compatible with both ΛCDM but do not rule out some of its extensions.

Dependence on P(k,z)

$$\{\Omega_b h^2, \Omega_c h^2, 100\Theta, \tau, A_s e^9, n_s\}$$

↓

$$\{0.0226, 0.112, 1.04, 0.09, 2.2, 0.96\}$$

CAMB was modified to Include $w = w_0 + w_a (1-a)$

Models	$\omega_b h^2$	$\omega_c h^2$	w_0	w_a	$H_0{}^a$
Reference	0.0226	0.112	-1	0	70
Varying $\omega_c h^2$	0.0226	0.100	-1	0	70
	0.0226	0.140	-1	0	70
Varying state equation	0.0226	0.112	-2	0	70
	0.0226	0.112	-0.8	0	70
	0.0226	0.112	-1	1	70
	0.0226	0.112	-1	-1	70
Varying H_0	0.0226	0.112	-1	0	65
	0.0226	0.112	-1	0	68
	0.0226	0.112	-1	0	72
	0.0226	0.112	-1	0	75

[a] in units of km/s/Mpc

Carvalho et al., Phys. Rev. D93, 023530 (2016)