Observatório Nacional

Measuring the acoustic scale from the SDSS luminous galaxies angular correlation function

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in collaboration with
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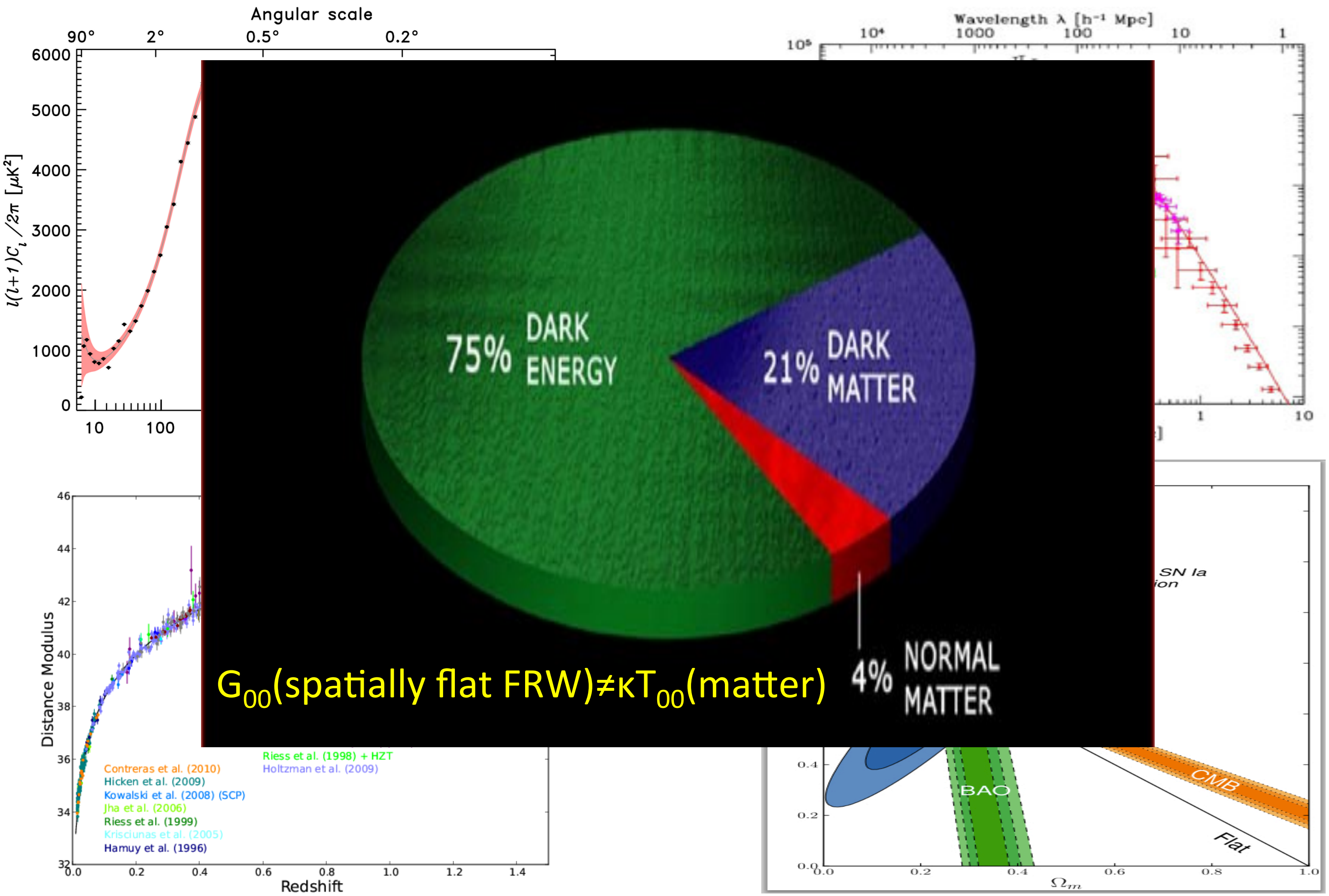
Outline

- Introduction
- Probes of cosmic acceleration
- Baryon acoustic oscillations (BAO)
- BAO from the 2PACF
- Application to SDSS-III DR7/DR10/DR11
- An independent estimate of the acoustic scale and cosmological constraints
- Conclusions

- G. Carvalho, A. Bernui, M. Benetti, J. Carvalho & JSA, Phys. Rev. D93, 023530 (2016)
- G. Carvalho, A. Bernui, M. Benetti, J. Carvalho & JSA, Submitted to Phys. Rev. D (2017)

Composition of the cosmos



A true cosmological constant -- but why this value?

Vacuum decay.

Hiding the cosmological constant – it is there all the time but just doesn't gravitate (Ellis et al 2010).

Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence [w(z)].

...ortant questions:

...gy consistent with a ...cuum Energy (w = -1)?

Does General Rela... Consistently Descri... Acceleratio...

Large-scale modifications of Einstein's General Relativity leading to cosmic acceleration today.

Ex. f(R), Extra dimensions, etc.

Perhaps GR but Universe is inhomogeneous

Probing dark energy

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

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

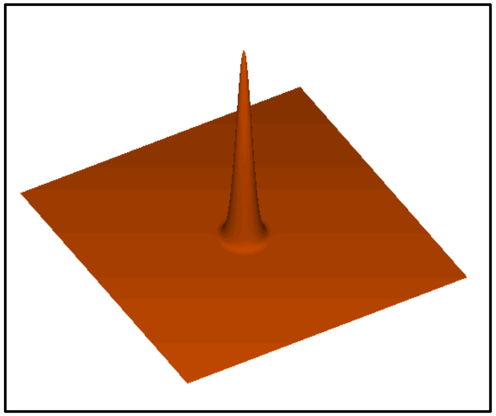
Main approaches:

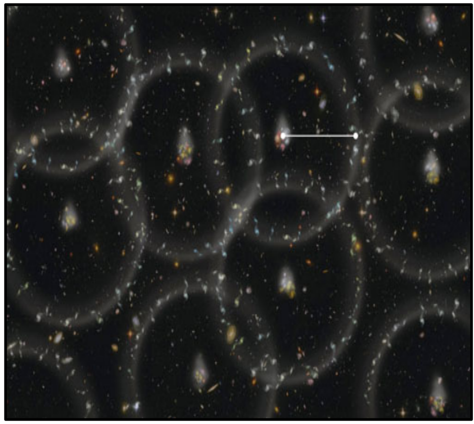
- **Standard Candles:** measure $d_L \propto \int dz / H(z)$
- **Standard Rulers:** measure $d_A \propto \int dz / H(z)$ and $H(z)$

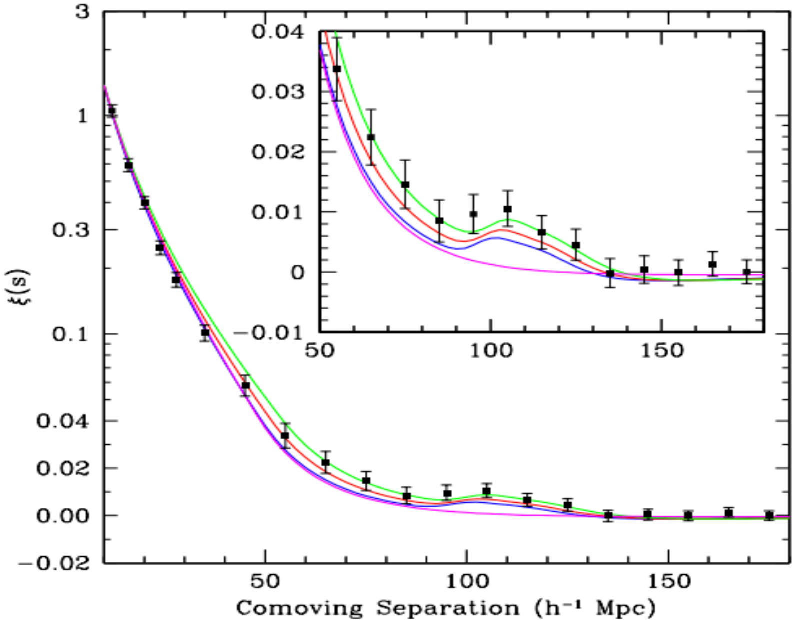
- **Cosmic Chronometers:** measure $t \propto \int dz / (1+z)H(z)$ and $H(z)$
- **Growth of fluctuations:** Crucial for testing extra ρ components vs modified gravity.

BAO: cosmological ruler

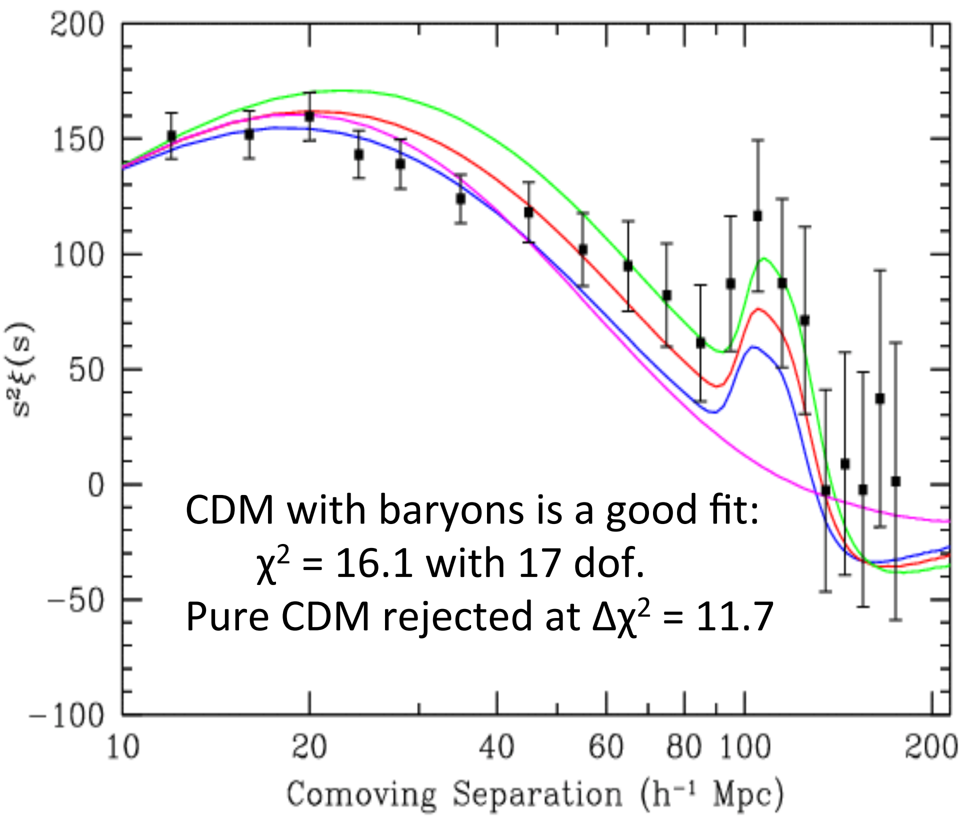
- Primordial perturbations generated acoustic waves in the photon-baryon fluid until decoupling at z ~ 1100 (Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970).
- At this time the photons decouple from the baryons creating a high density region from the original source of perturbation, at a distance given 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.



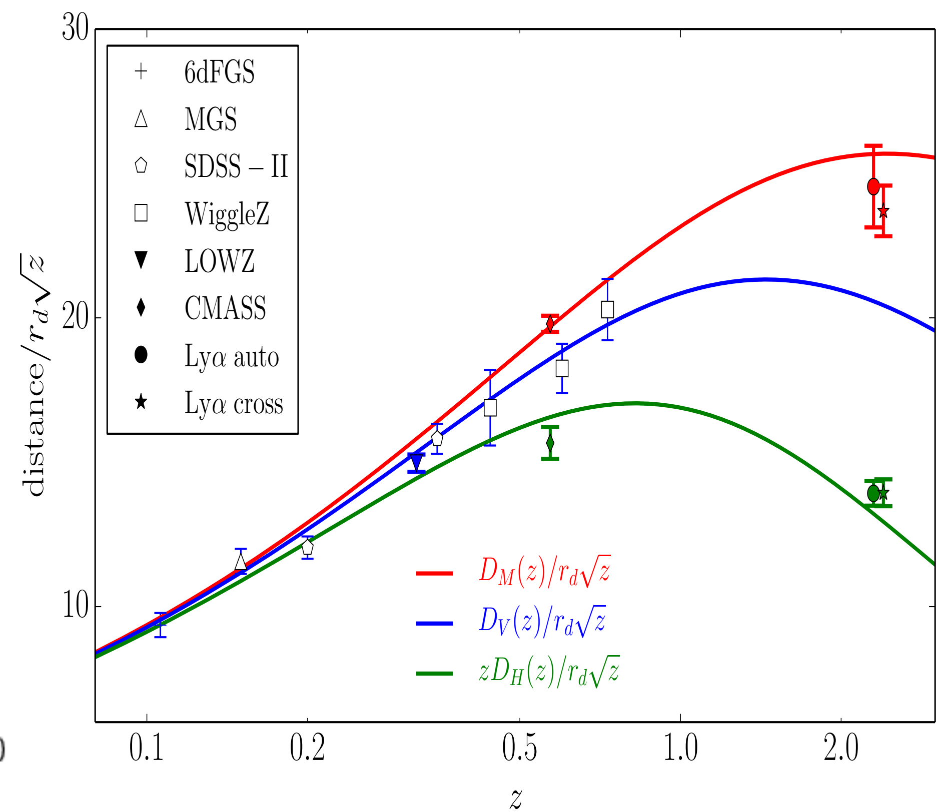




Detection of the Acoustic Peak



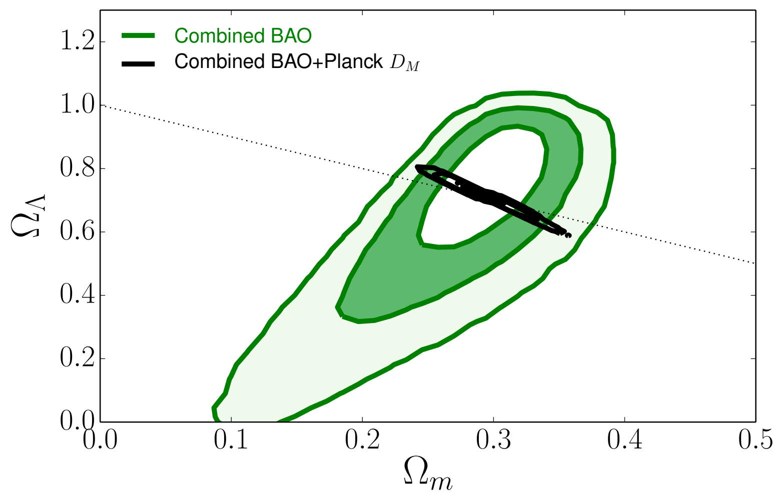
Current measurements:

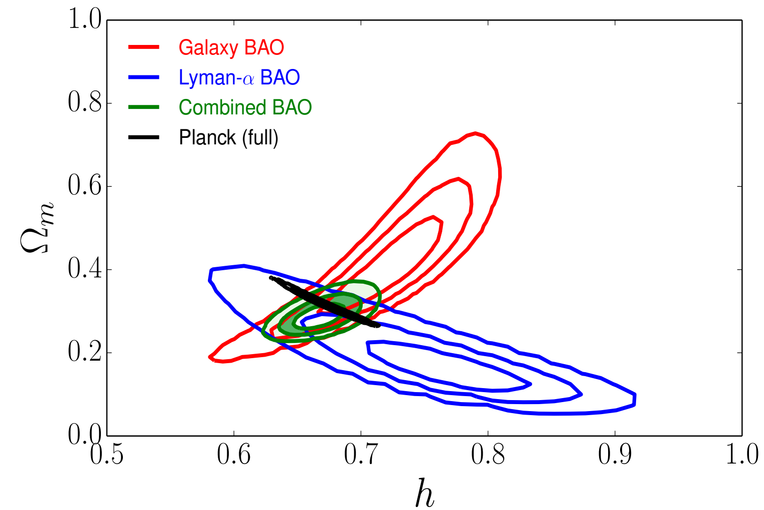


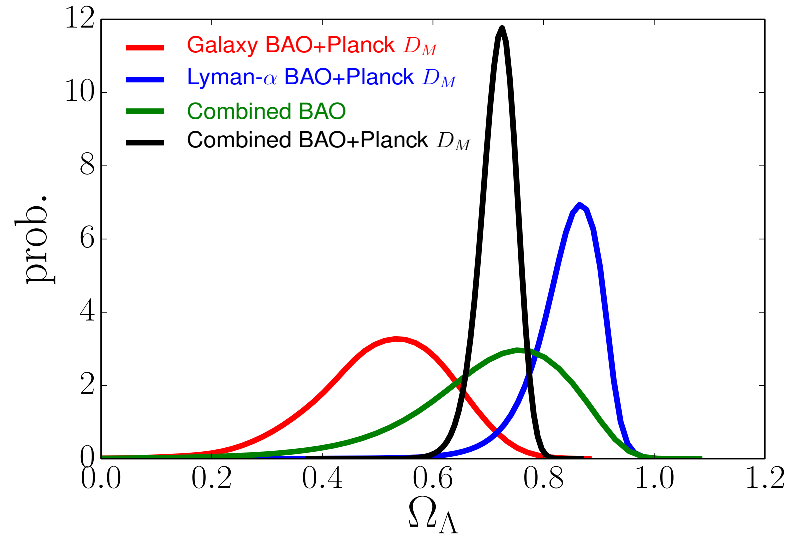
Eisenstein et al. (2005)

Aubourg et al. (2014)
arXiv:1411.1074 [astro-ph.CO]

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)

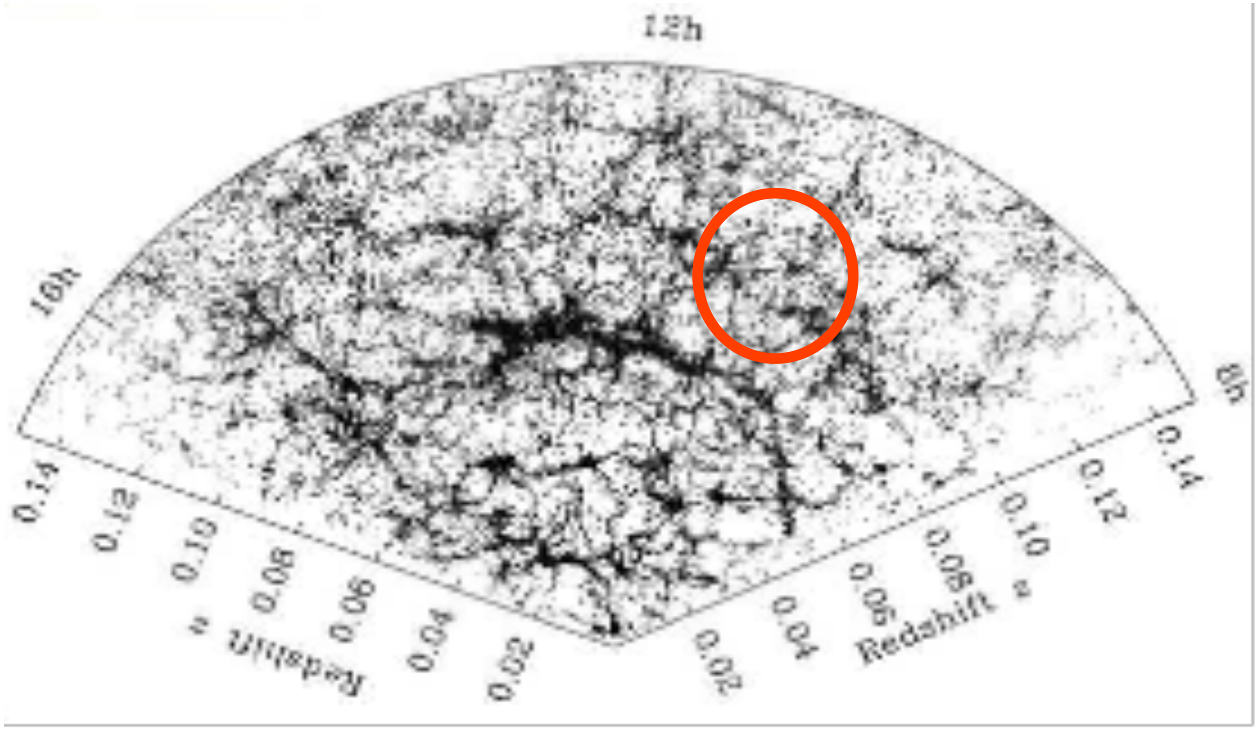
Virtues of the Acoustic Peaks

- The acoustic signature is created by physics at z=1000 when the perturbations are << 1. Linear perturbation theory is excellent.
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since D_A is an integral of H.

D. Eisenstein (JTS, 2010)

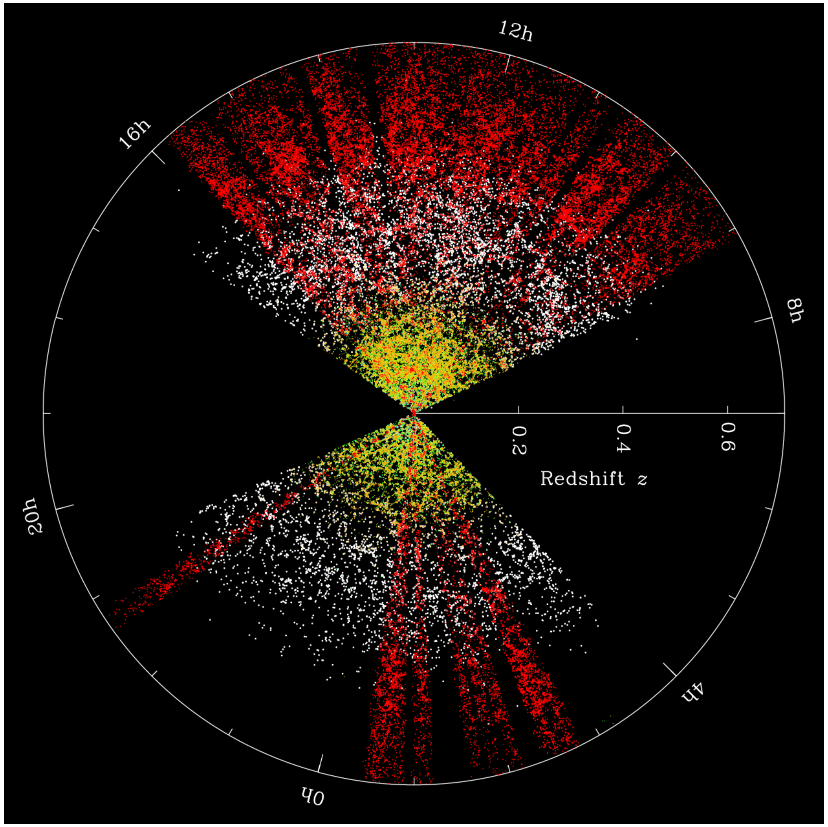
2PACF

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



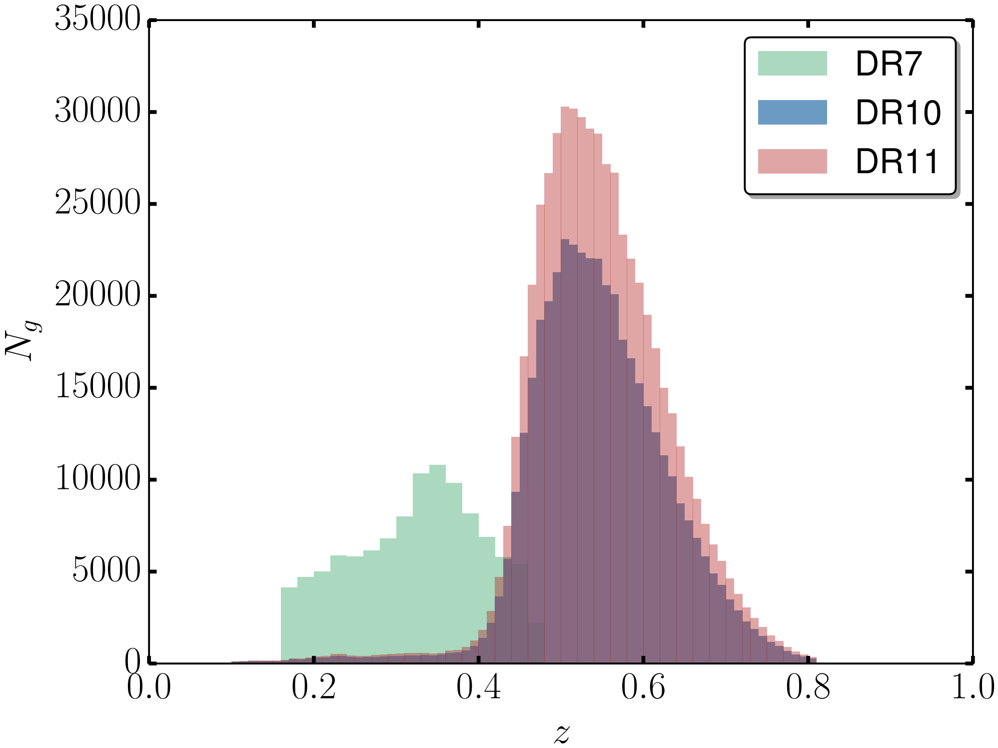
We obtain precise measurements of $D_A(z)$ <u>without assuming a fiducial cosmology</u> and restrict cosmological parameters <u>in an almost model-independent way</u>

The data set

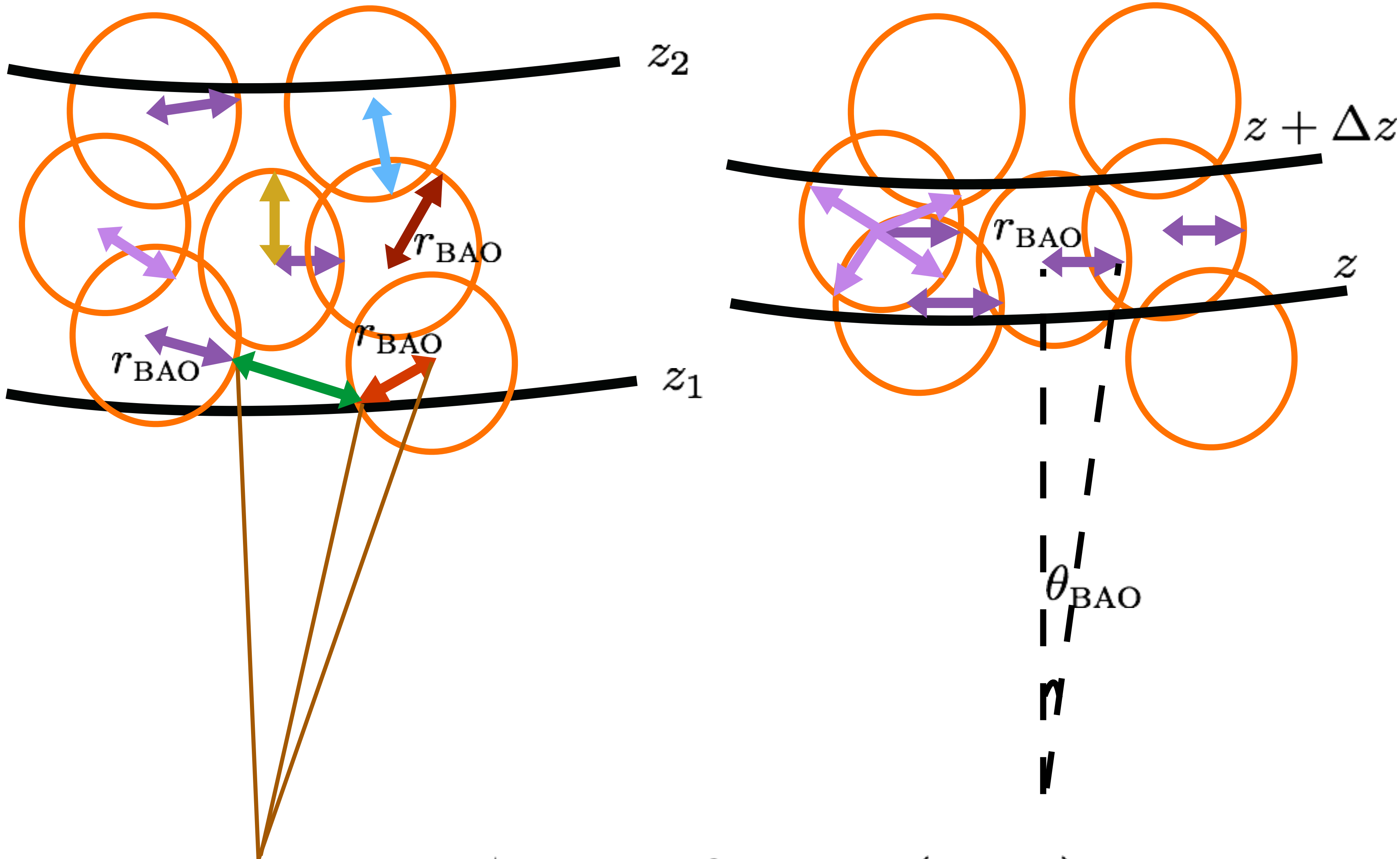


Baryon Oscillation Spectroscopic Survey (BOSS)

- **1.35 million galaxies (z <0.7)**
- **10,000 deg2**
- **150.000 Quasars (z = 2.15 – 3.50)**



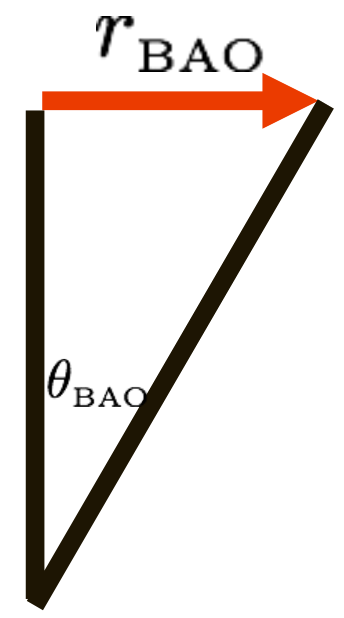
- SDSS-DR7: contains 105,831 LRG's
- SDSS-DR10: contains 409,337 LRG's
- SDSS-DR11: contains 543,116 LRG's



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

$$r_{\rm BAO}^{\rm radial} = \frac{c}{H(z)}\Delta z$$

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



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

(CMB data)

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

The data set

- The SDSS-DR10 contains 409,337 LRG's with redshifts $0.43 \leq z \leq 0.7$.

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

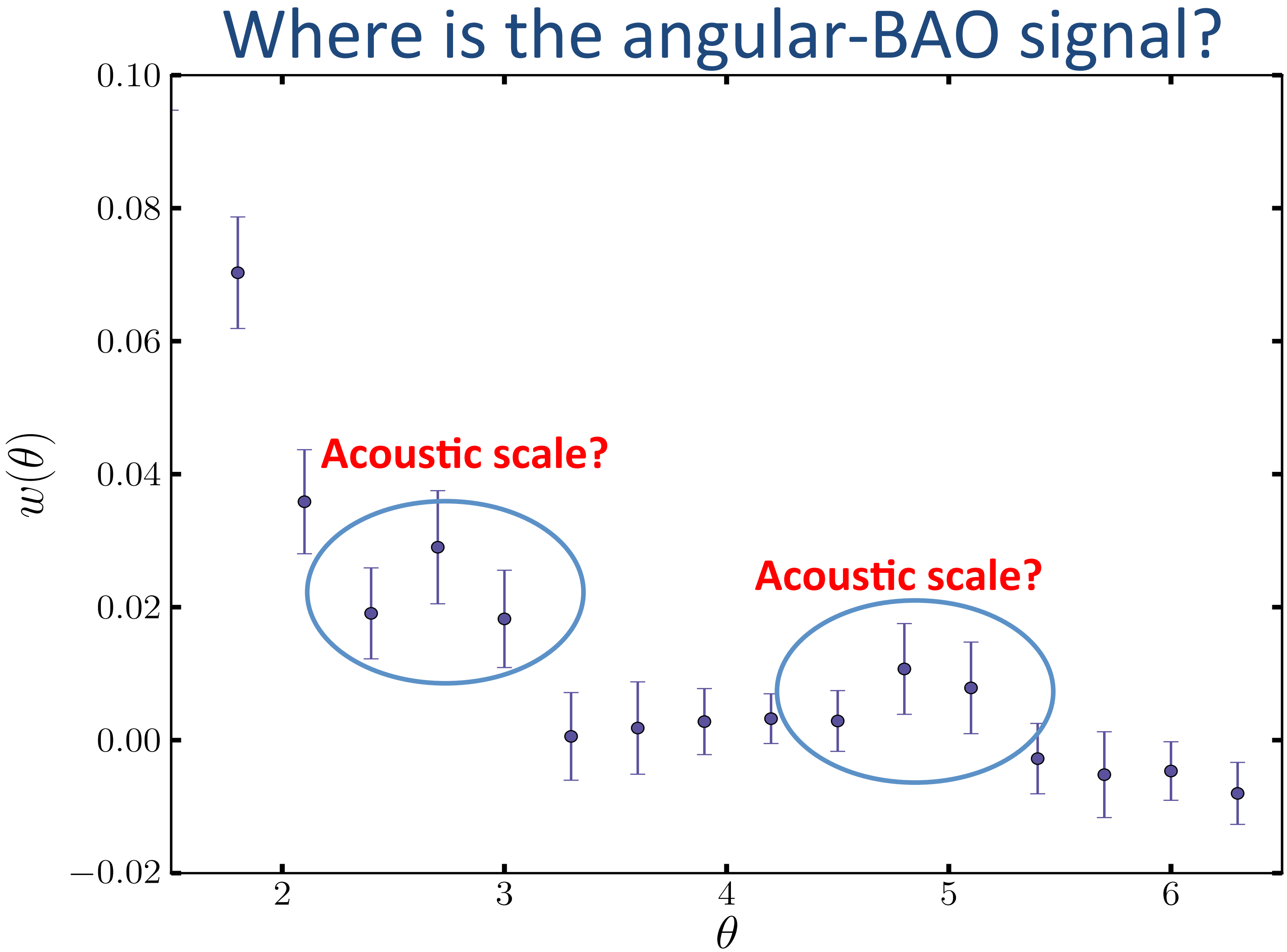
TABLE I: The six bin-redshift intervals and their properties: number of galaxies, mean redshift of the sample, $\bar{z}$, and bin-width, δz. Notice that contiguous intervals are separated by a redshift interval of size 0.005 to avoid correlation between neighbours.

The data set

- The SDSS-DR11 contains 543,116 LRG's with redshifts $0.43 \leq z \leq 0.7$.

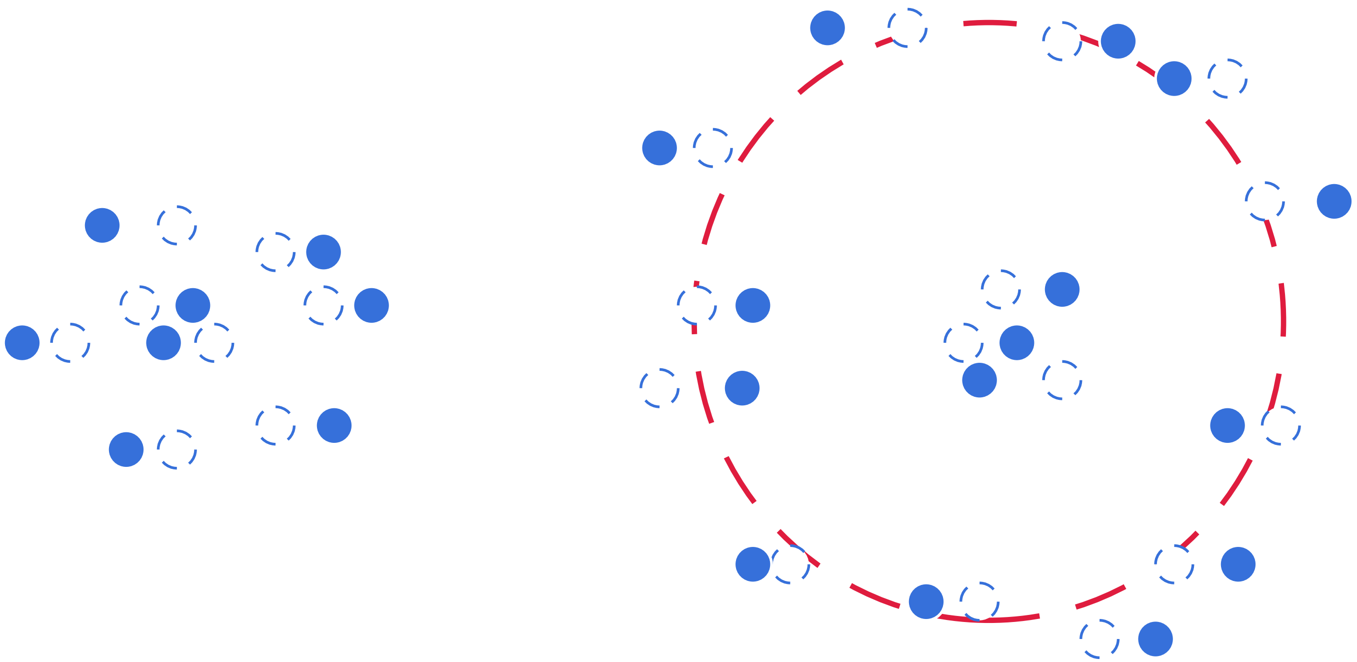
$\bar{z}$	z range	N_g
0.57	[0.565 , 0.575]	24,967
0.59	[0.585 , 0.595]	21,292
0.61	[0.605 , 0.615]	18,003
0.63	[0.625 , 0.635]	14,275
0.65	[0.640 , 0.660]	21,949

Finding Θ_{BAO} in the 2PACF

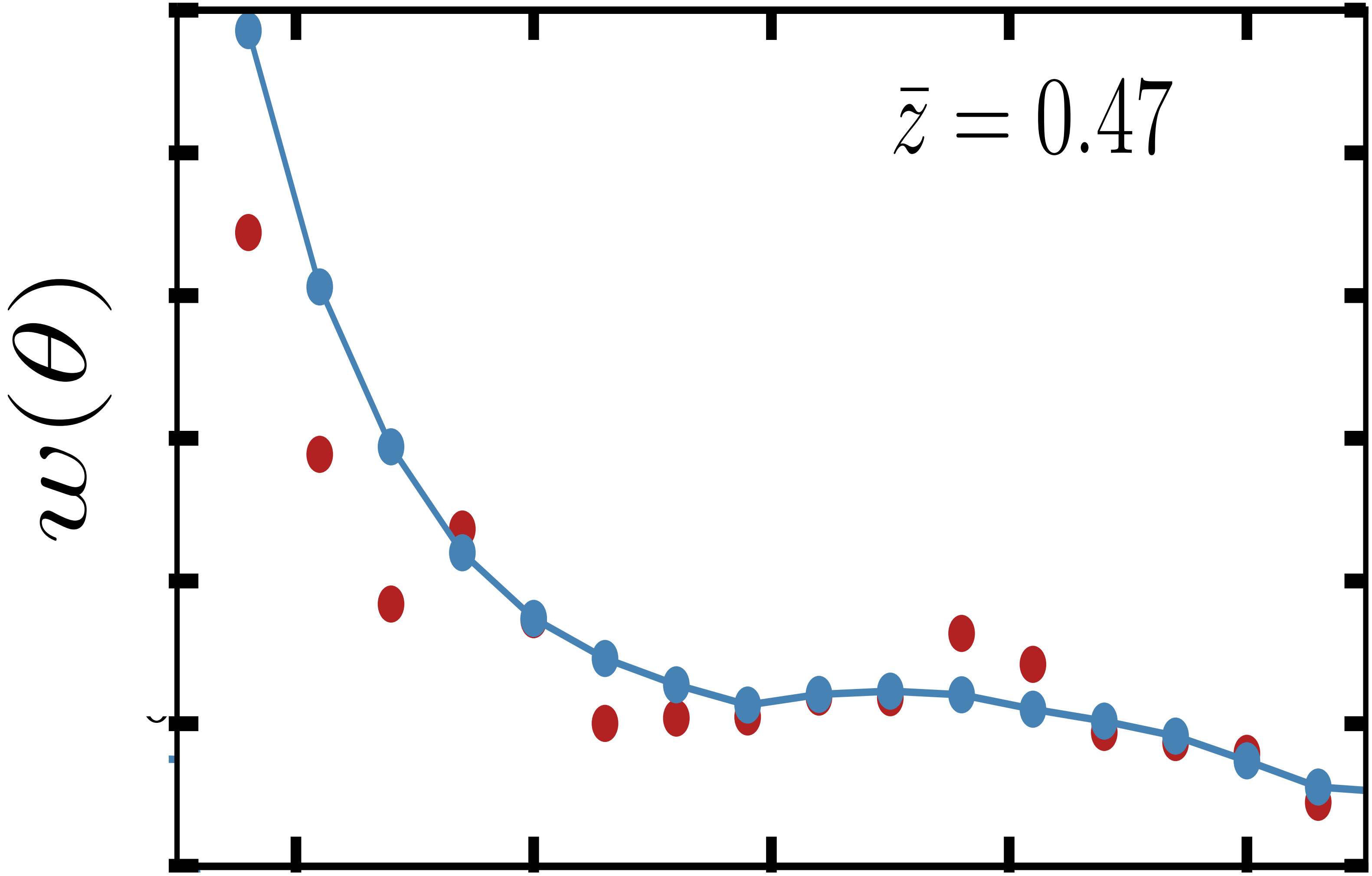


A model-independent way to find θ_{BAO}

- Changing galaxies coordinates

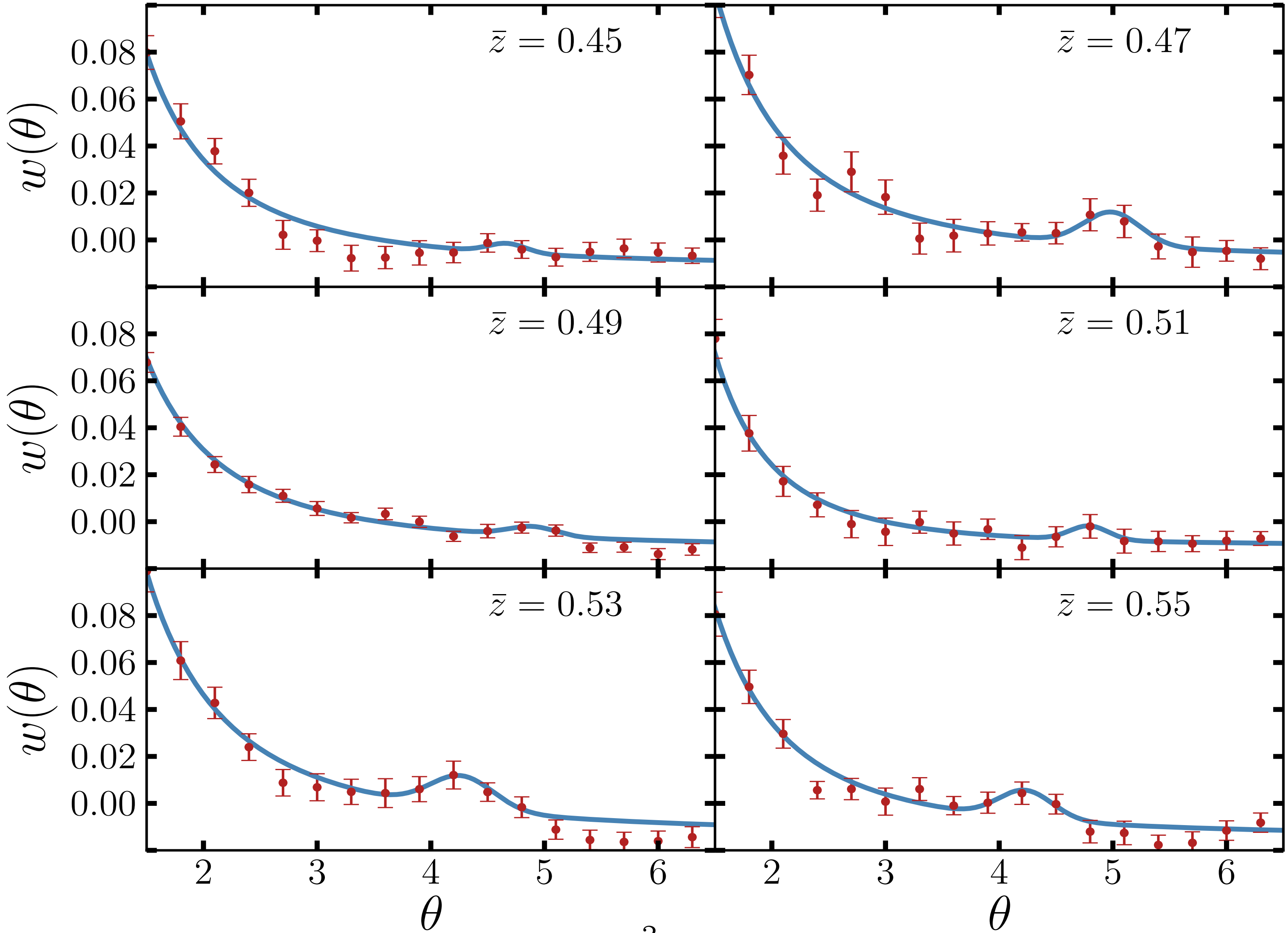


Example



The blue curve is obtained averaging 100 2PACFs, each one obtained by changing the angular positions of the galaxies by a random amount after understanding systematics...the results

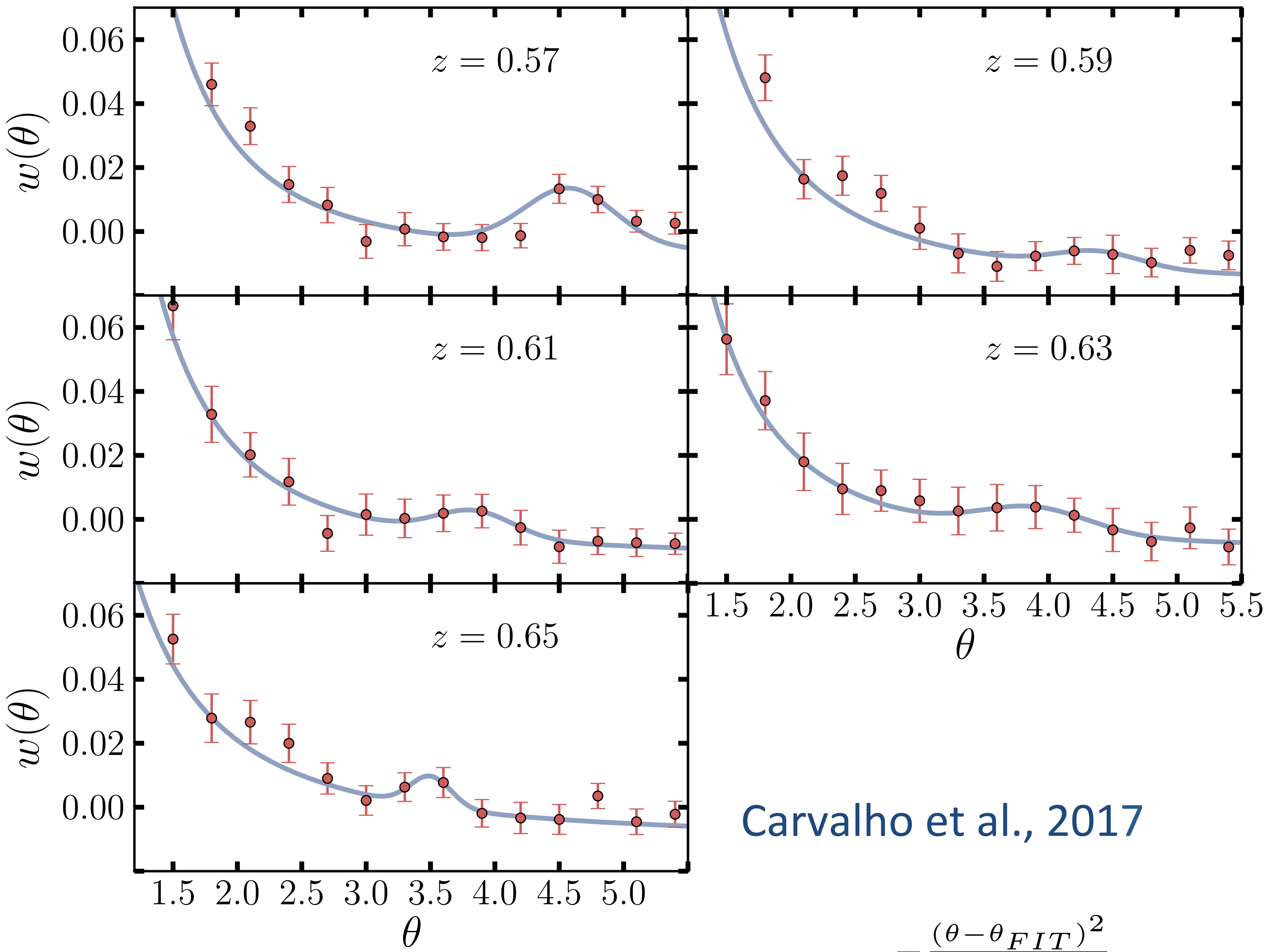
Carvalho et al., PRD (2016)
Carvalho et al., PRD (2017)



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

(Sanchez et al. 2011)

Carvalho et al., 2016

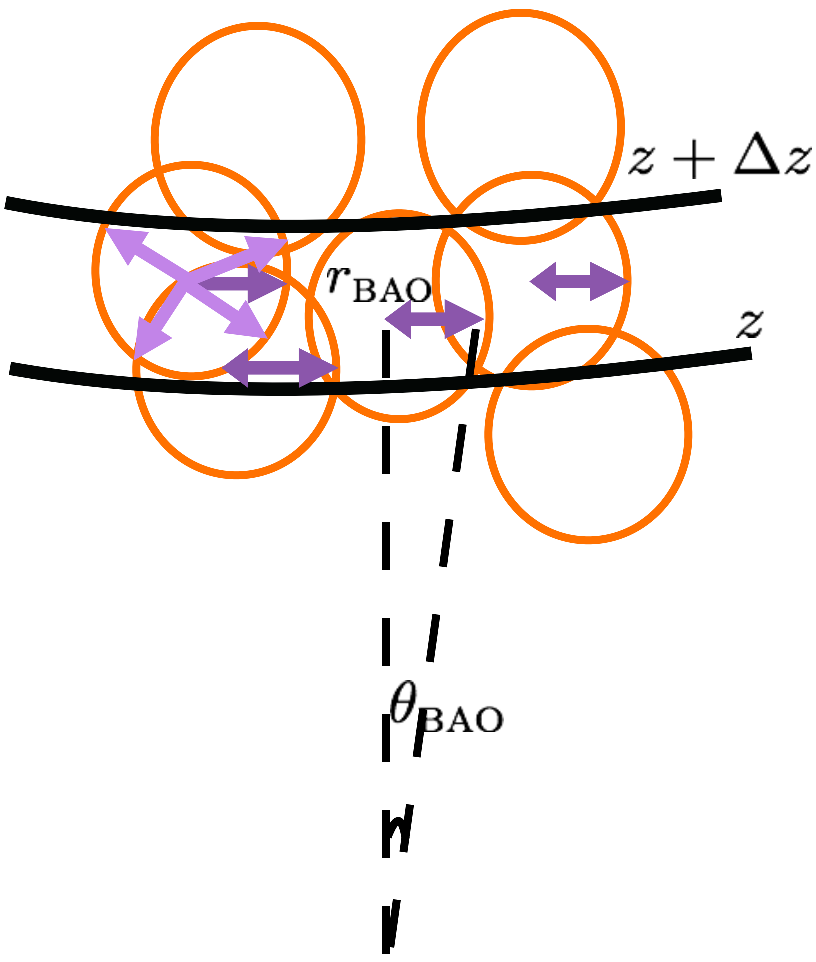


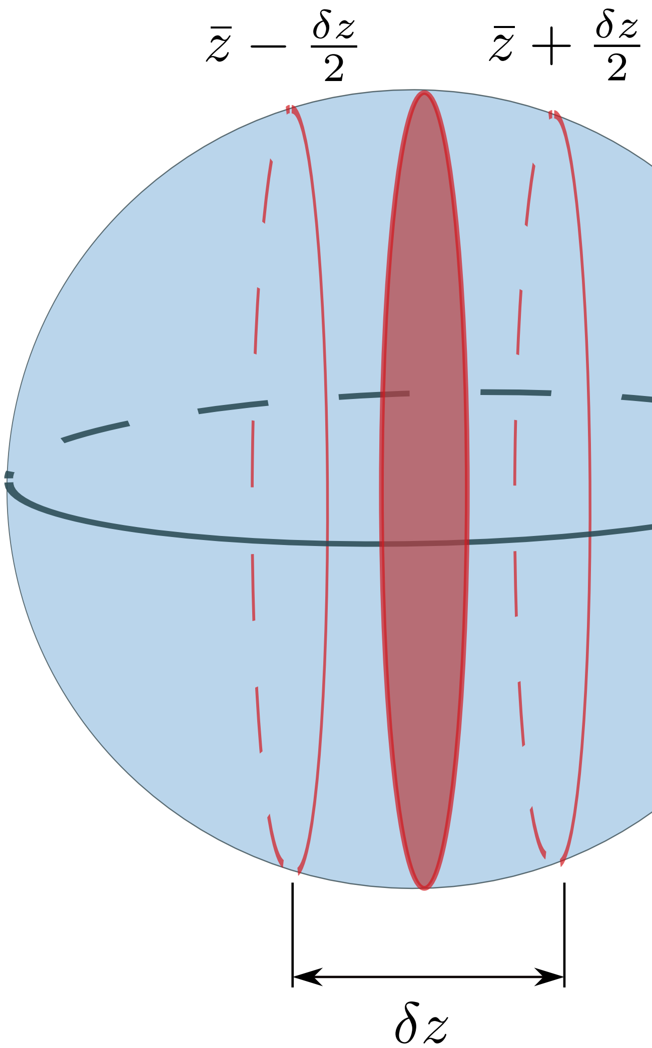
Carvalho et al., 2017

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

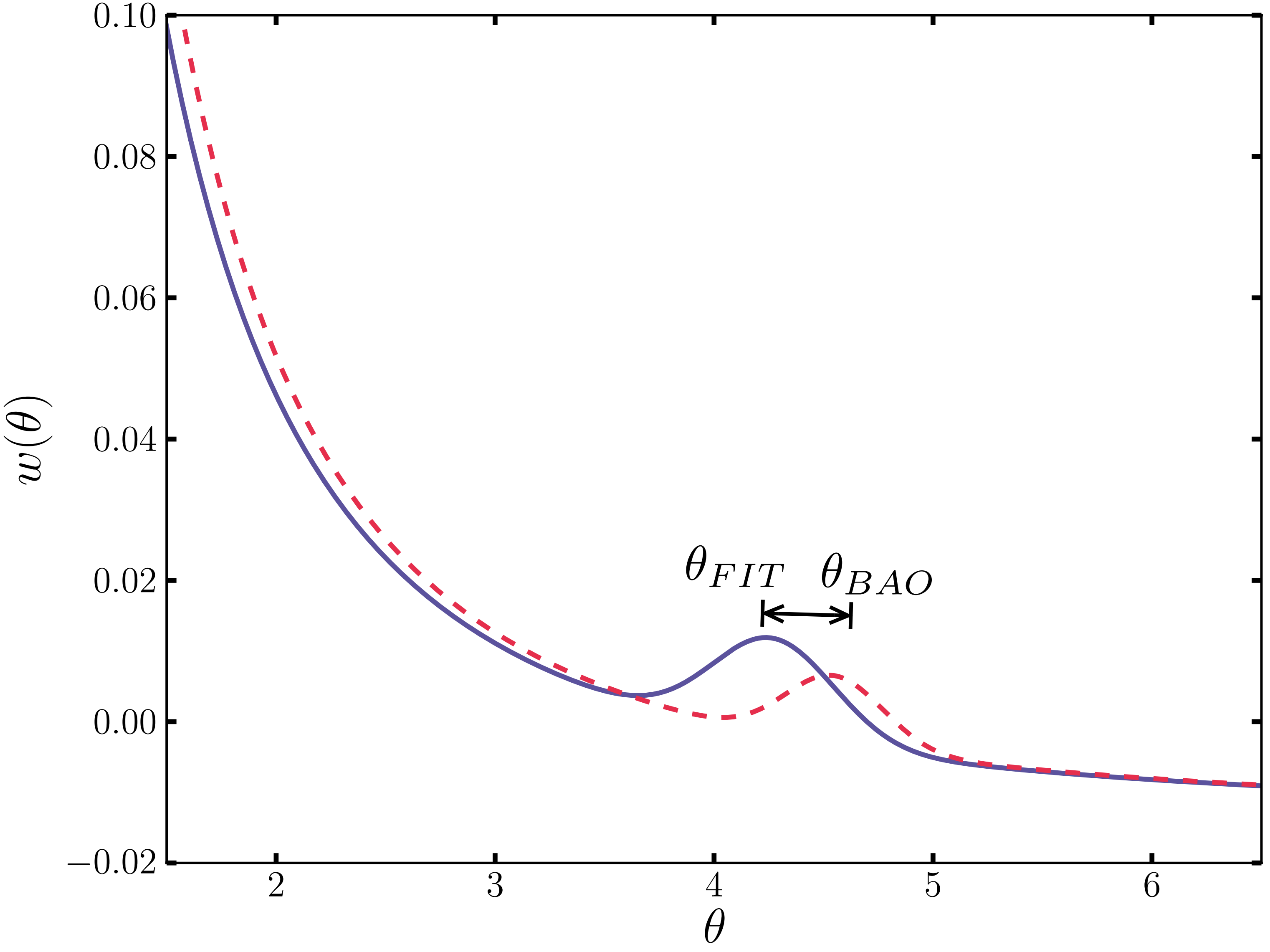
(Sanchez et al. 2011)

- Projection effects: $\theta_{FIT} \neq \theta_{BAO}$ ($\delta z \neq 0$)





- Shift factor (α)



- Projection effects:

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

$$\alpha = \frac{\theta_E^{\delta z=0}(z) - \theta_E^{\delta z}(z)}{\theta_E^{\delta z=0}(z)}$$

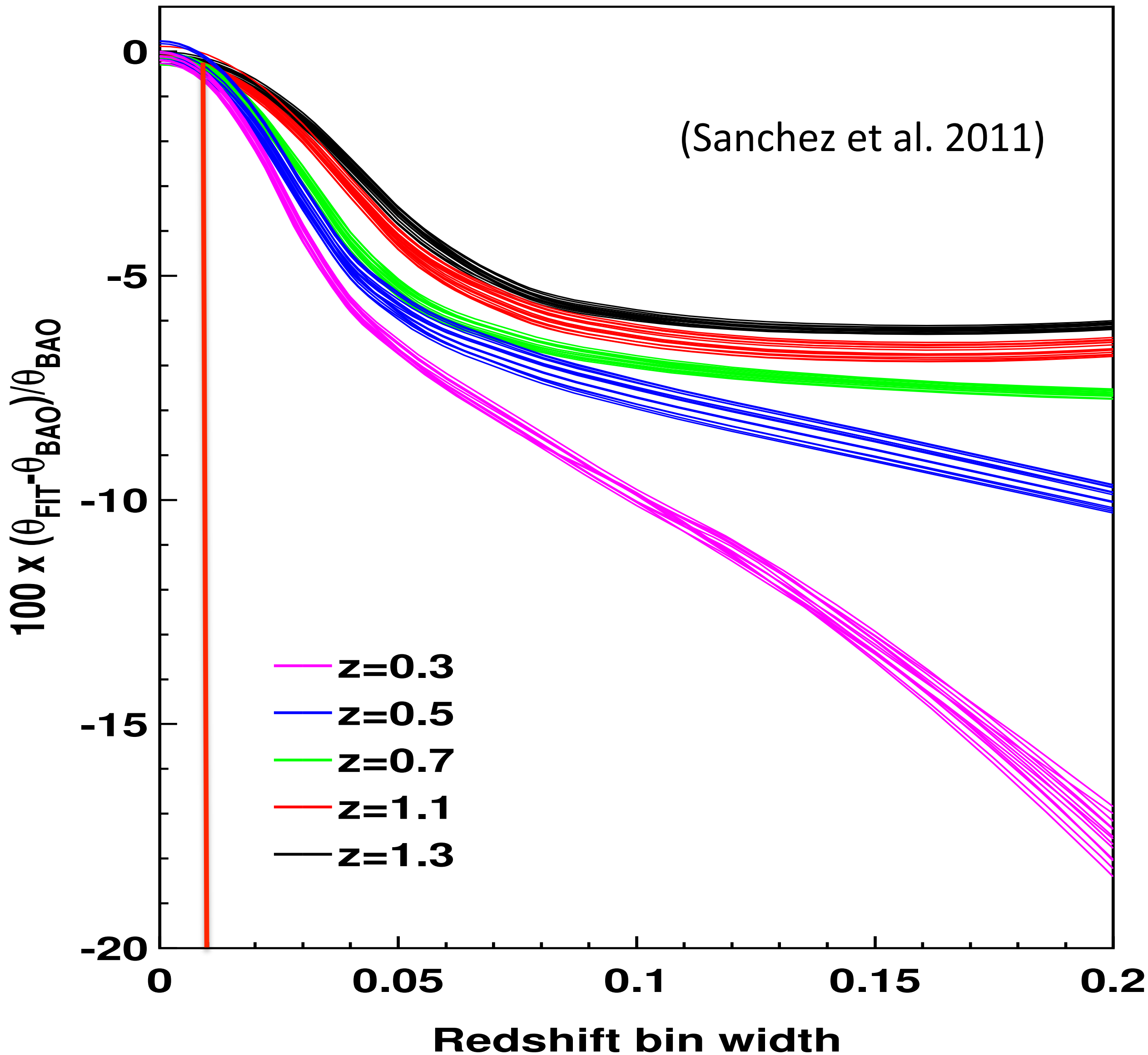
$$w_E(\theta,\tilde{z}) = \int_0^\infty dz_1 \phi(z_1) \int_0^\infty dz_2 \phi(z_2) \xi_E(s,\tilde{z})$$

$$\xi_E(s,z) = \int_0^\infty \frac{dk}{2\pi^2} k^2 j_0(ks) b^2 P_m(k,z)$$

$$s = \sqrt{r^2(z_1) + r^2(z_2) - 2r(z_1)r(z_2)\cos\theta_{12}}$$

$$r(z_i) = cH_0^{-1} \int_0^{z_i} \frac{dz}{E(z)}$$

- Projection effects:



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 is modified to
Include w = $w_0 + w_a\,(1\text{-}a)$

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

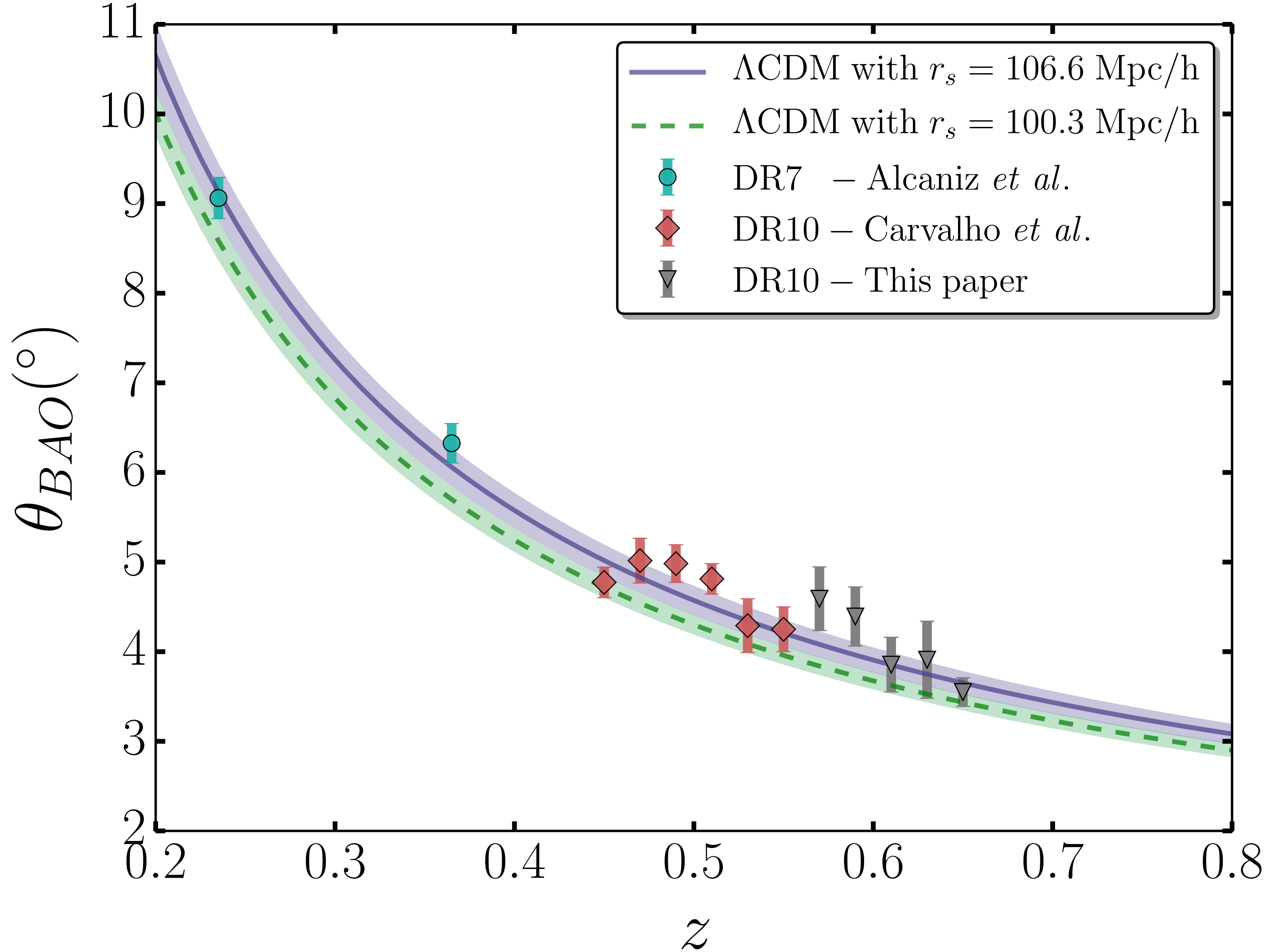
Measurements of $\theta_{BAO}(z)$

DR10

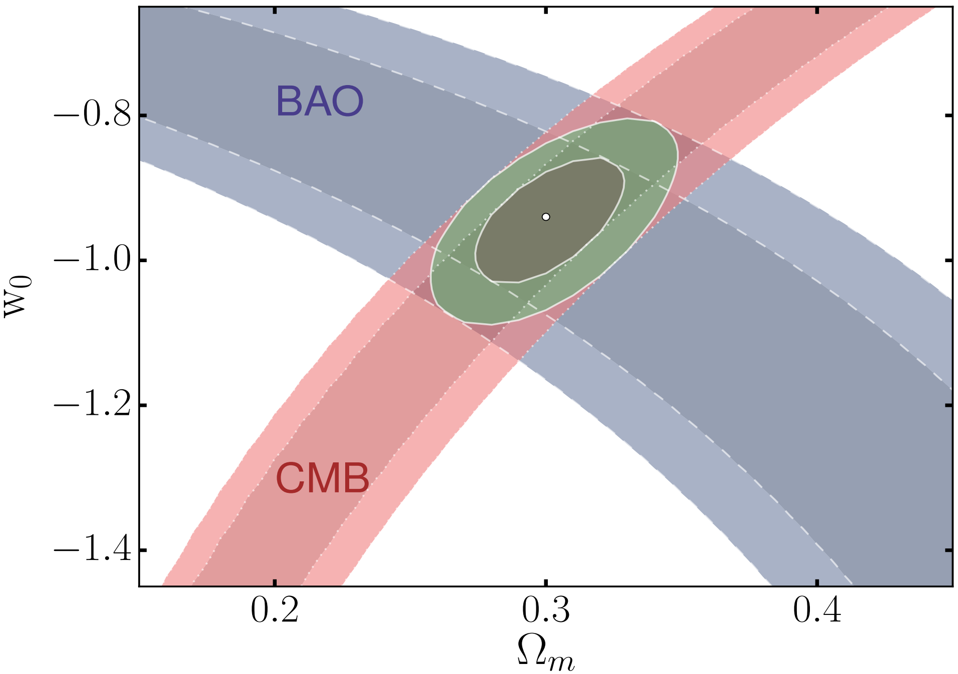
z interval	$\langle z \rangle$	α (%)	θ_{FIT} ($^\circ$)	θ_{BAO} ($^\circ$)	σ_{BAO}
0.440-0.460	0.45	2.0815	4.67	4.77	0.17
0.465-0.475	0.47	0.5367	4.99	5.02	0.25
0.480-0.500	0.49	2.0197	4.89	4.99	0.21
0.505-0.515	0.51	0.5002	4.79	4.81	0.17
0.525-0.535	0.53	0.4847	4.27	4.29	0.30
0.545-0.555	0.55	0.4789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

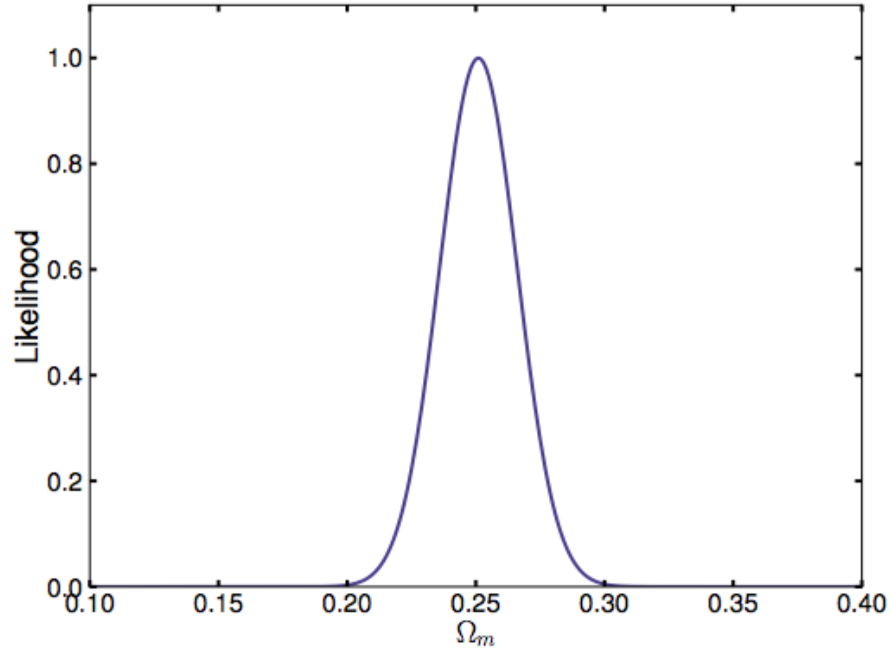
$\alpha \leq 2\%$

DR7 + DR10 + DR11



Cosmological Constraints





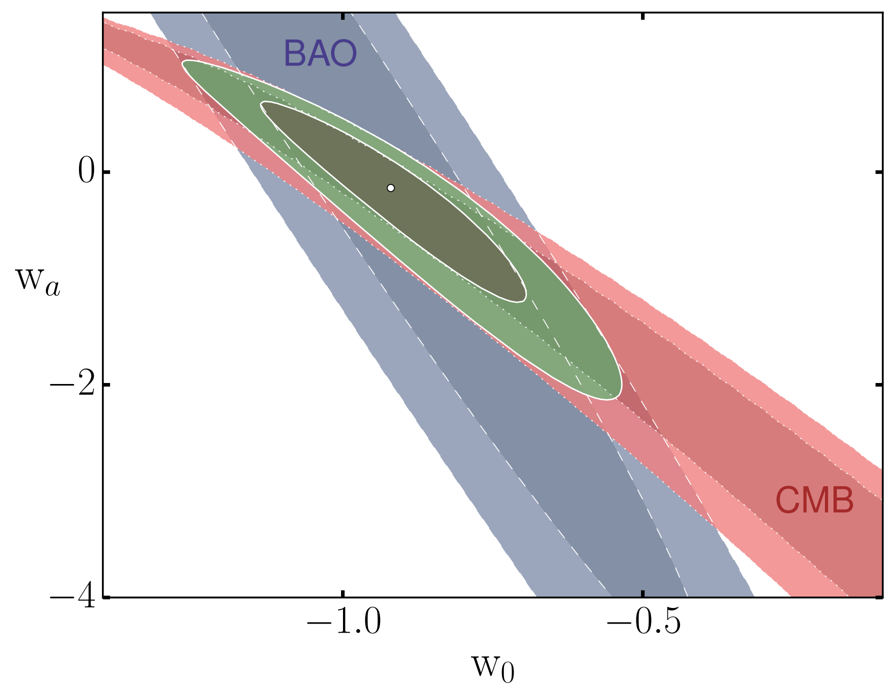
$$\Omega_m = 0.30 \pm 0.02; \quad w_0 = -0.94 \pm 0.06$$

$$w_0 = -0.92 \pm 0.14; \quad w_a = -0.15 \pm 0.61$$

$$\Omega_m = 0.26 \pm 0.03 \quad (\Lambda CDM)$$

r_s = 106.61 ± 3.47 Mpc/h (WMAP9)

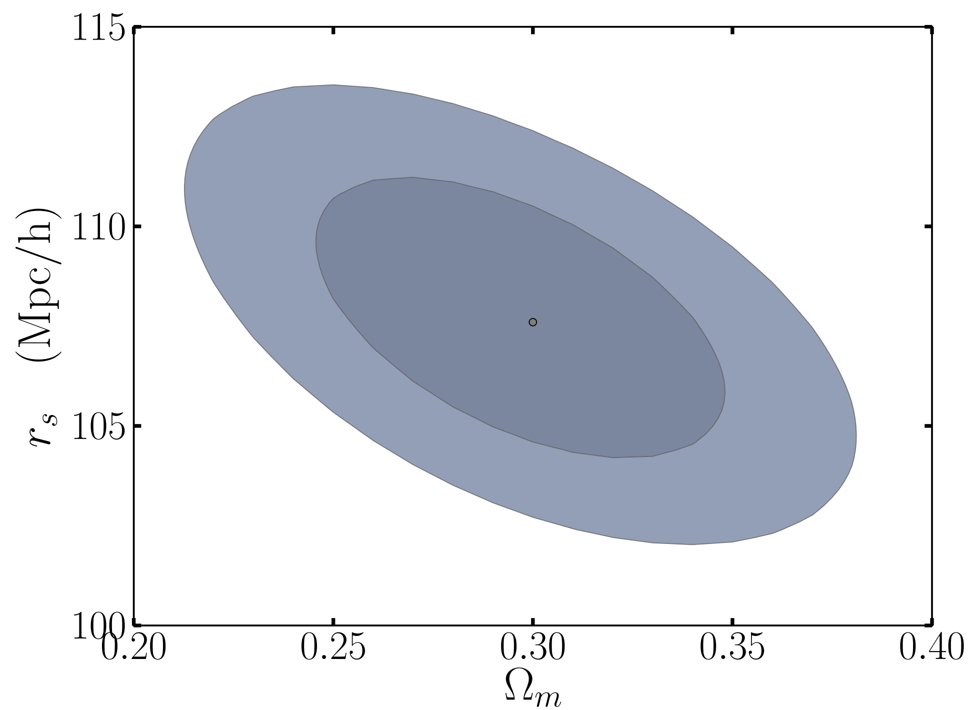
Planck Data (CMB)



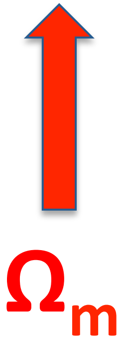
An independent estimate of the acoustic scale

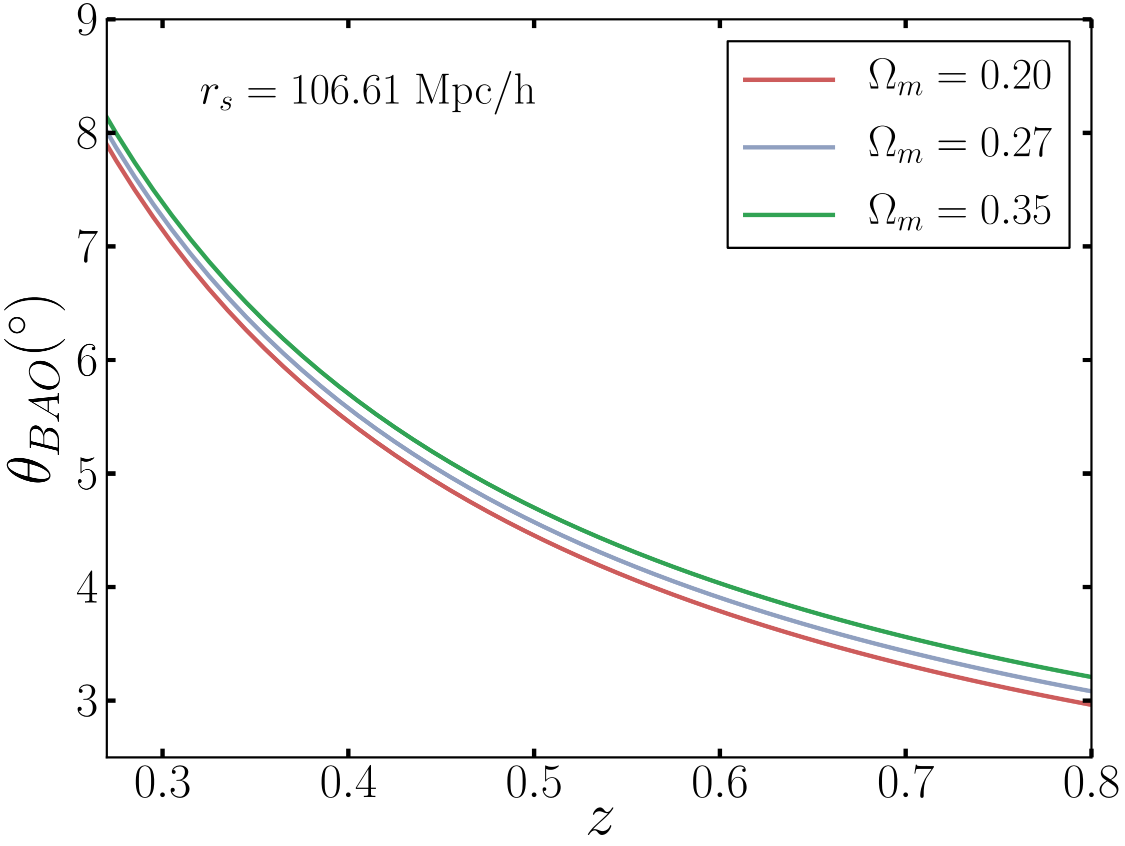
- r_s = 106.61 ± 3.47 Mpc/h (WMAP9)
- r_s = 100.29 ± 2.26 Mpc/h (Planck)
- r_s = 101.90 ± 1.90 Mpc/h (Heavens, Verde, Jimenez, PRL, 2015)
- r_s = 107.60 ± 4.40 Mpc/h (Carvalho et al. 2017)

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



Tension with Planck data?





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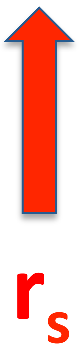

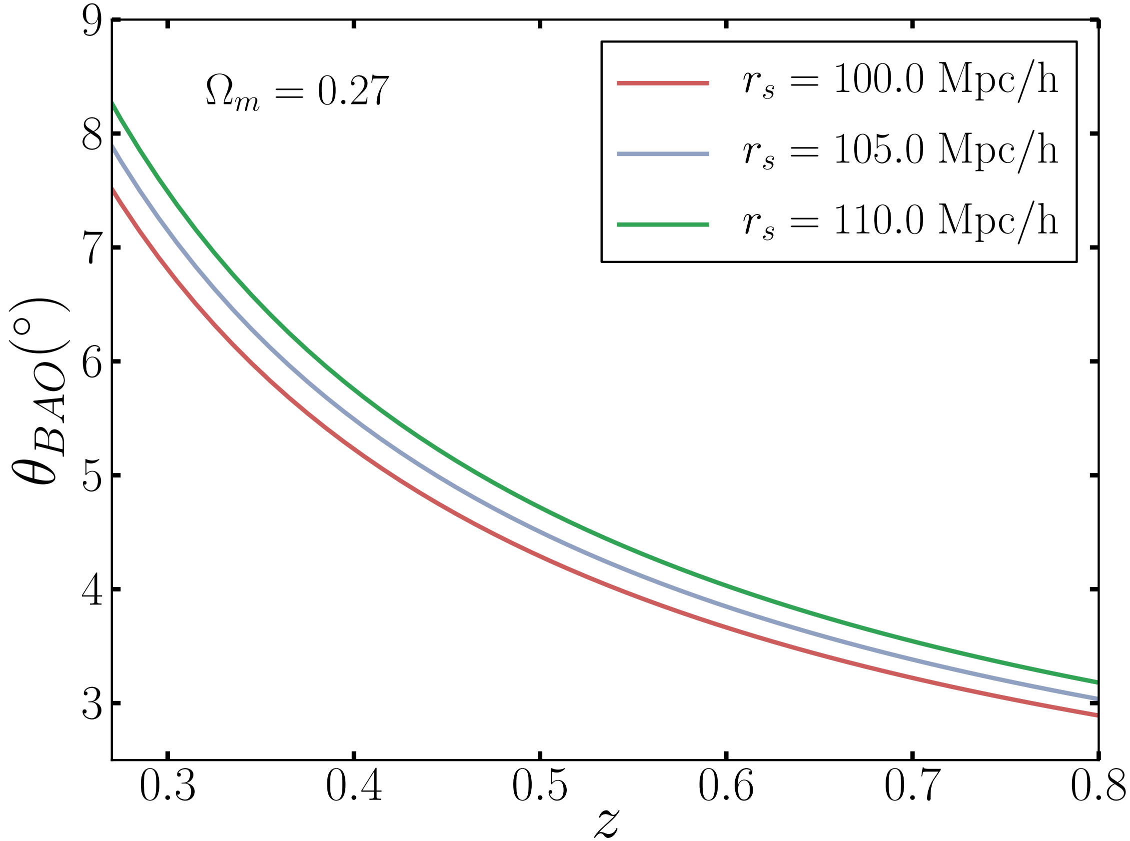

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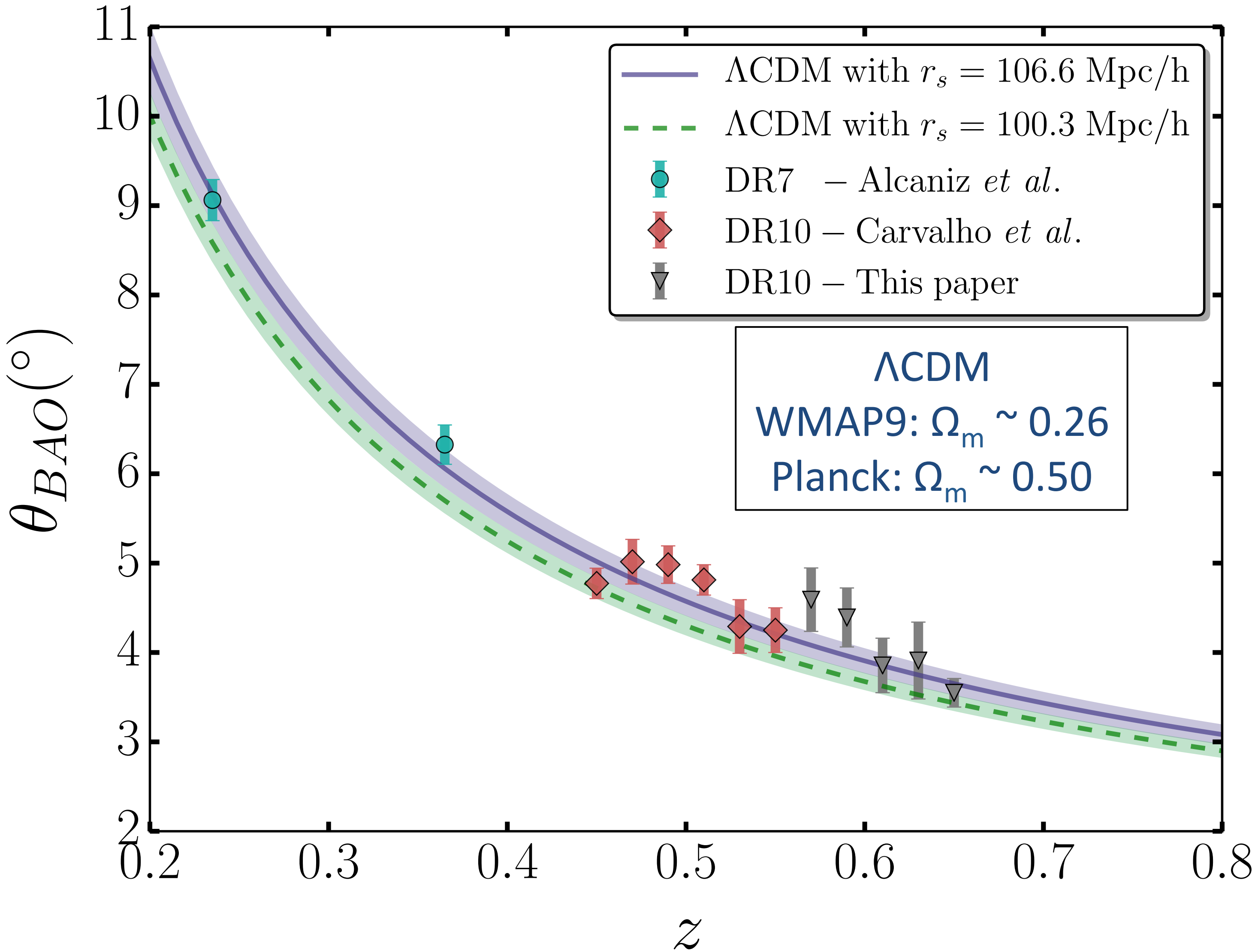

Conclusions

- The mechanism behind cosmic acceleration is an open question; Many candidates (GR or MG).
- 2PACF analysis of SDSS-III DR7+10+11 luminous galaxies.
- BAO peaks: model-independent methodology.
- BAO peak position: α shift (model-dependent correction ≤ 2%).
- Cosmological constraints: dependence with r_s. Good agreement with WMAP9 data.
- We have extended the present number of θ_{BAO} data and provide an *independent estimate of r_s*.
- Current data are compatible with both ΛCDM and some of its extensions.
- Work in progress with DR14 and J-PAS.