Observatório
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Baryon acoustic oscillations from the SDSS galaxies angular correlation function

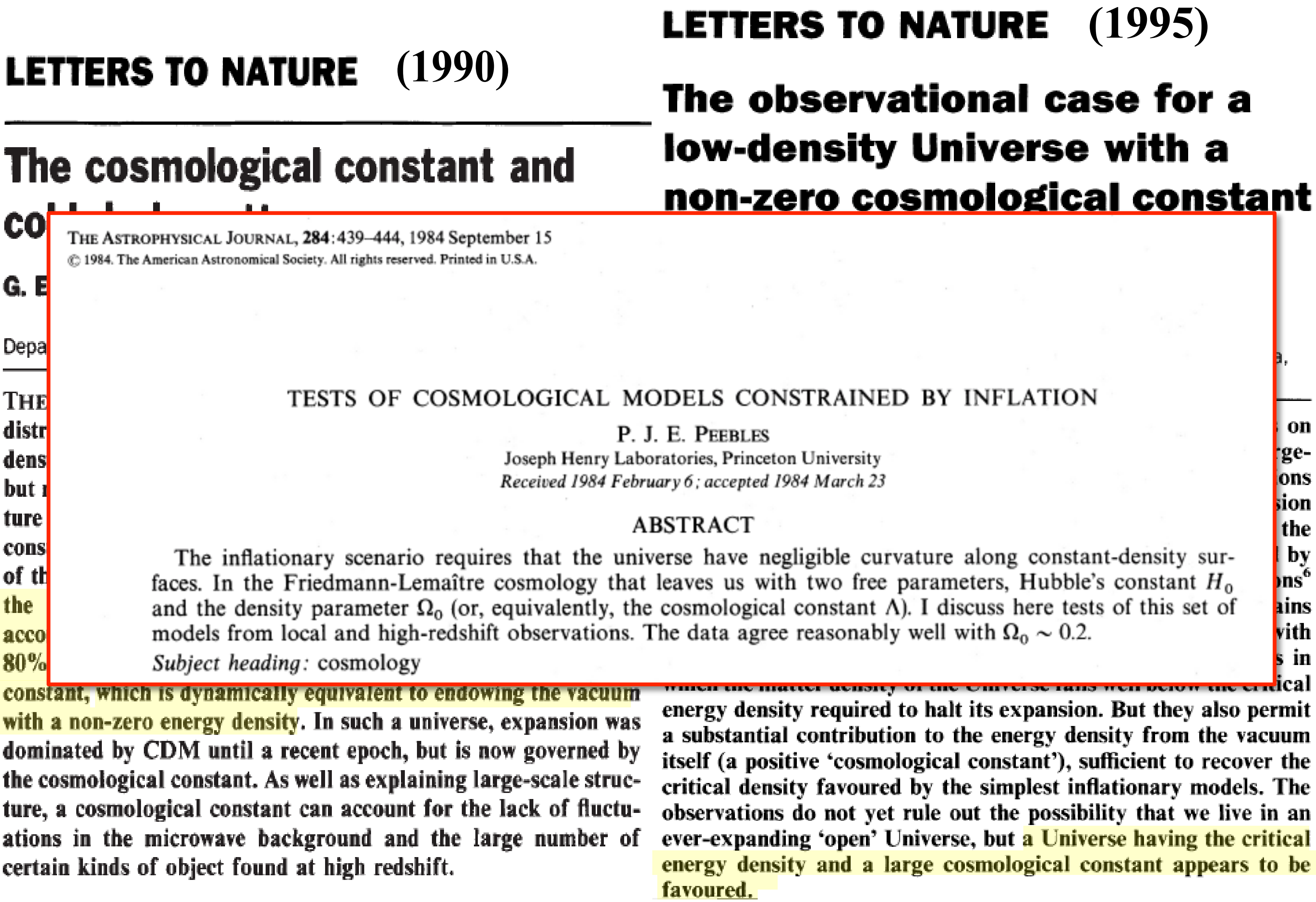
J. S. Alcaniz

Observatório Nacional

&

McGill University

HEP Theory Group JC / Montreal, Oct. 18th 2017



LETTERS TO NATURE (1990)

The cosmological constant and co

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constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

LETTERS TO NATURE (1995)

The observational case for a low-density Universe with a non-zero cosmological constant

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energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive 'cosmological constant'), sufficient to recover the critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

THE ASTROPHYSICAL JOURNAL, **284**:439–444, 1984 September 15

TESTS OF COSMOLOGICAL MODELS CONSTRAINED BY INFLATION

P. J. E. PEEBLES
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Received 1984 February 6; accepted 1984 March 23

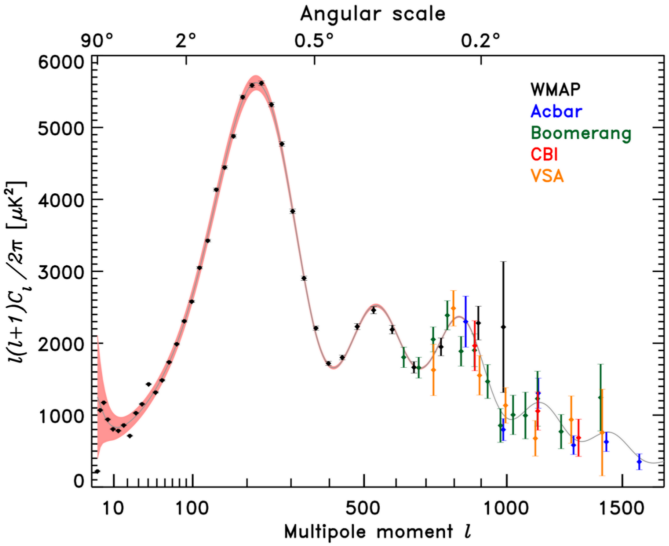
ABSTRACT

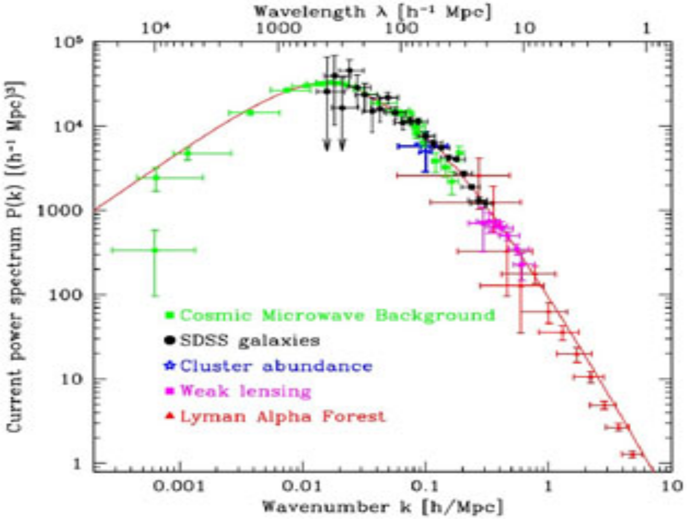
The inflationary scenario requires that the universe have negligible curvature along constant-density surfaces. In the Friedmann-Lemaître cosmology that leaves us with two free parameters, Hubble's constant H_0 and the density parameter Ω_0 (or, equivalently, the cosmological constant Λ). I discuss here tests of this set of models from local and high-redshift observations. The data agree reasonably well with $\Omega_0 \sim 0.2$.

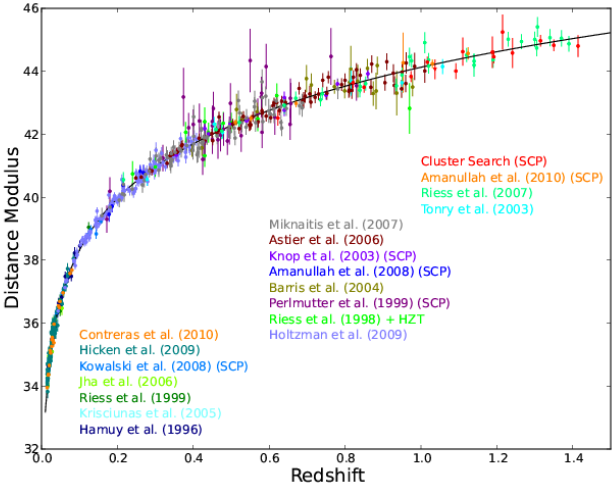
Subject heading: cosmology

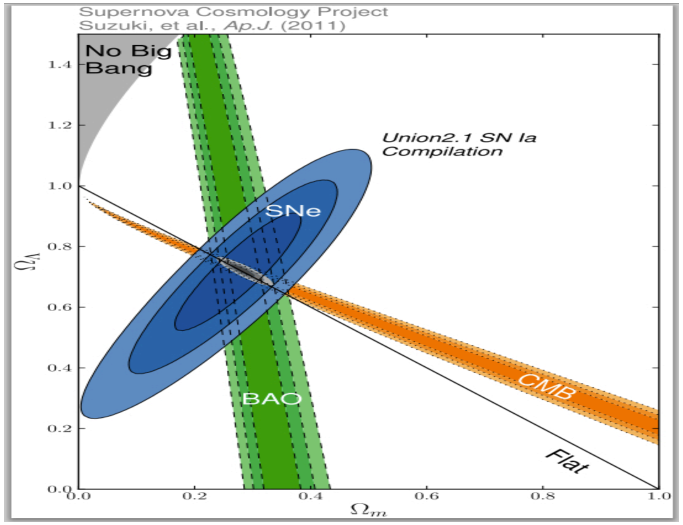
White, 2009

Composition of the cosmos









The Standard Cosmological Model

The Universe is spatially flat, accelerating and described by the FLRW metric; composed of baryons, dark matter, and dark energy; underwent a hot, dense, early phase of expansion that produced the light elements via big bang nucleosynthesis and the CMB radiation; and experienced a much earlier epoch of accelerated expansion, known as inflation, which produced density perturbations from quantum fluctuations, leaving an imprint on the CMB anisotropy and leading by gravitational instability to the formation of large-scale structure.

For some reviews, see Sahni & Starobinsky 2000, Peebles & Ratra 2003, Padmanabhan 2003, Copeland et al. 2006; Frieman et al. 2008; Weinberg et al. (2013).

rtant questions:

A true cosmological constant -- but why this value?

Vacuum decay - interacting models.

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)].

y consistent with a
uum 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…

Outline

- Probes of cosmic acceleration
- Baryon acoustic oscillations (BAO)
- BAO from the 2PACF
- Application to SDSS-III 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)

Probing dark energy

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

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

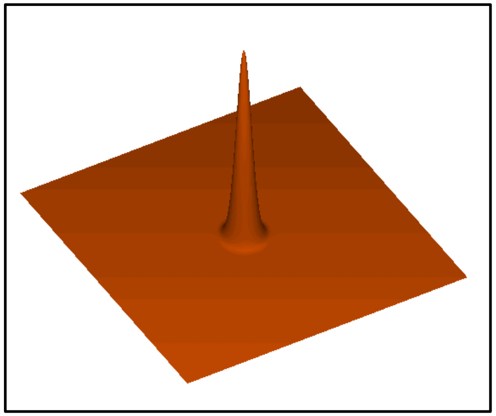
Main approaches:

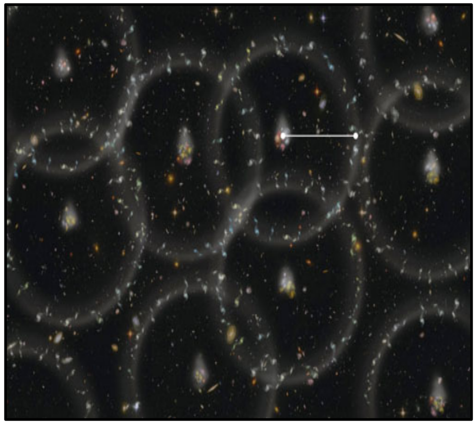
- **Standard Candles:** measure $d_L \propto \int dz / H(z)$
- **Standard Rulers:** measure $d_A \propto \int dz / H(z)$ and $H(z)$

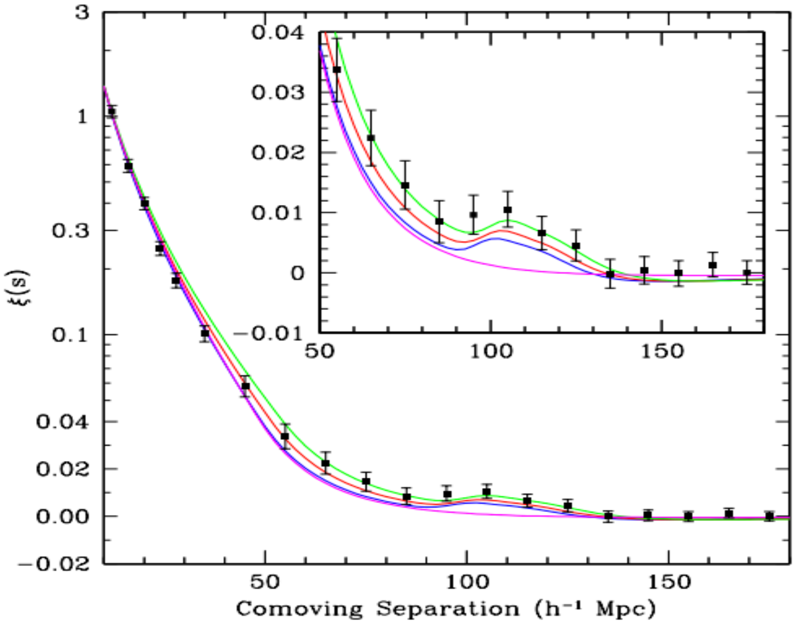
- **Cosmic Chronometers:** measure $t \propto \int dz / (1+z)H(z)$ and $H(z)$
- **Growth of fluctuations:** Crucial for testing extra ρ components vs modified gravity.

BAO: cosmological ruler

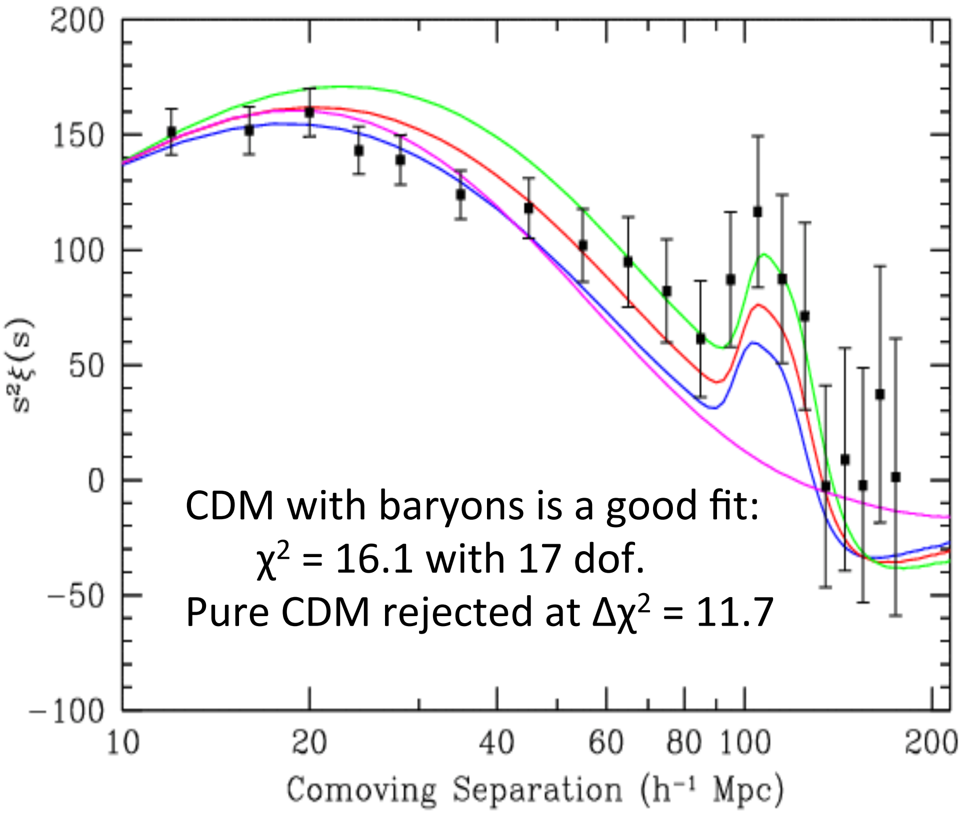
- Primordial perturbations generated acoustic waves in the photon-baryon fluid until decoupling at z ~ 1100 (Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970).
- At this time the photons decouple from the baryons creating a high density region from the original source of perturbation, at a distance given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







Detection of the Acoustic Peak



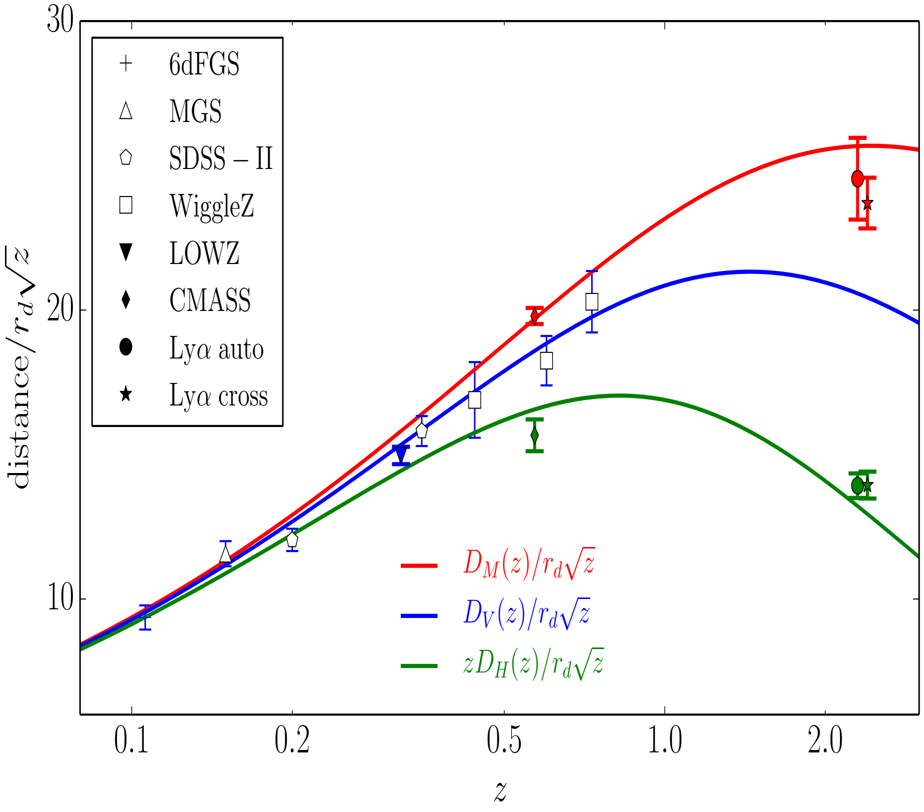
CDM with baryons is a good fit:

χ^2 = 16.1 with 17 dof.

Pure CDM rejected at $\Delta\chi^2$ = 11.7

Eisenstein et al. (2005)

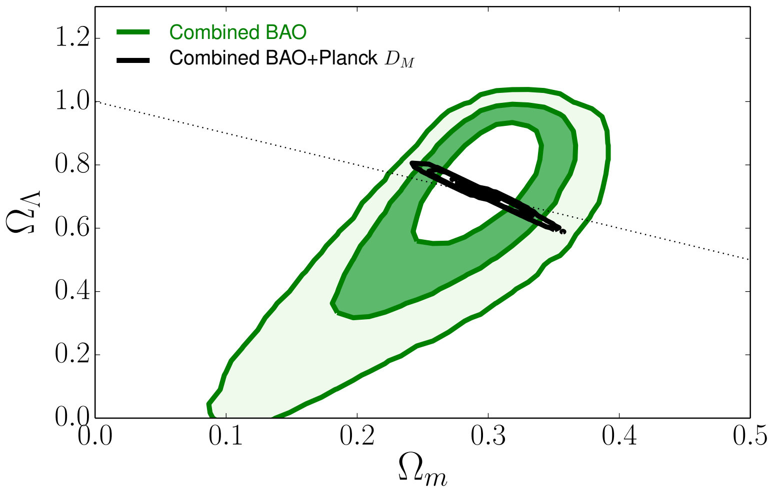
Current measurements:

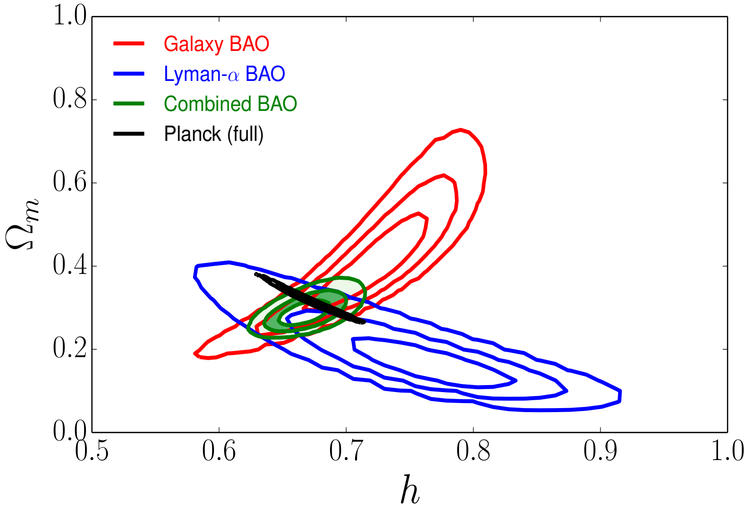


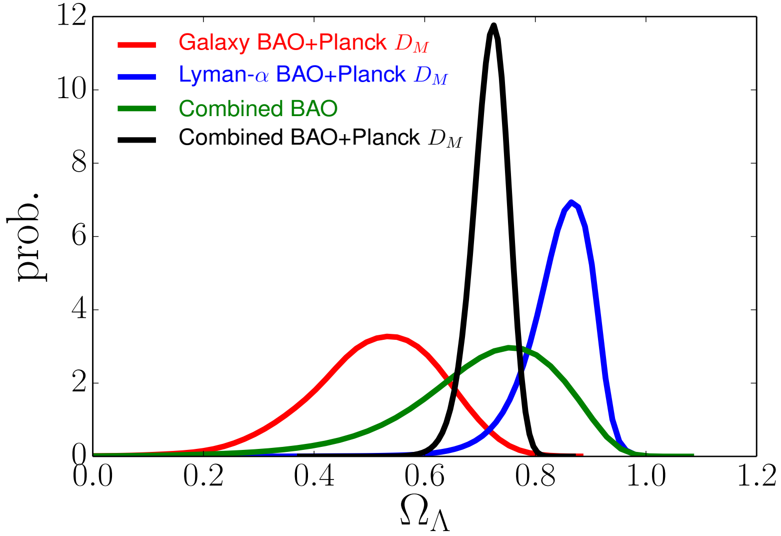
Aubourg et al. (2014)

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.

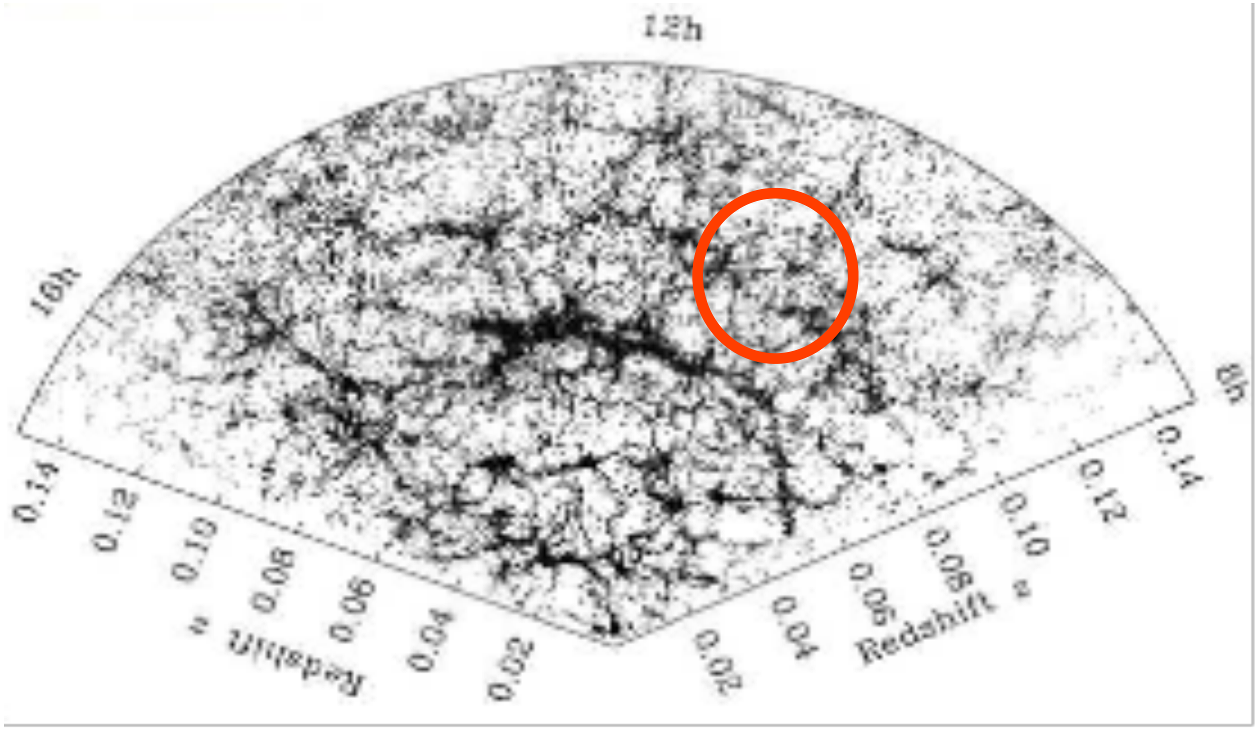
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.

- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since D_A is an integral of H.

D. Eisenstein (JTS, 2010)

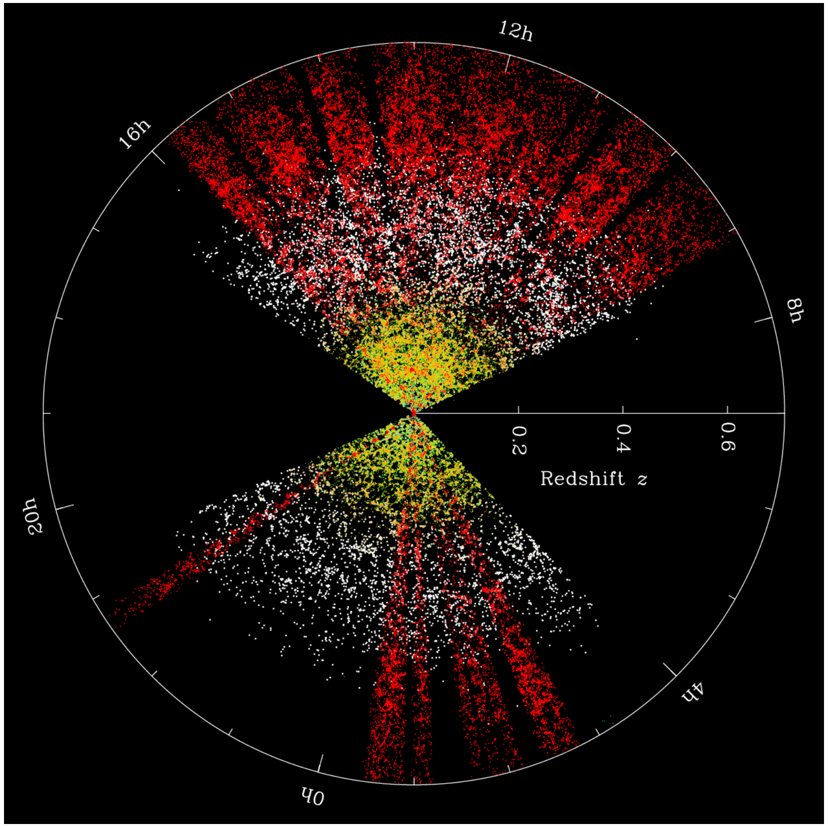
2PACF

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



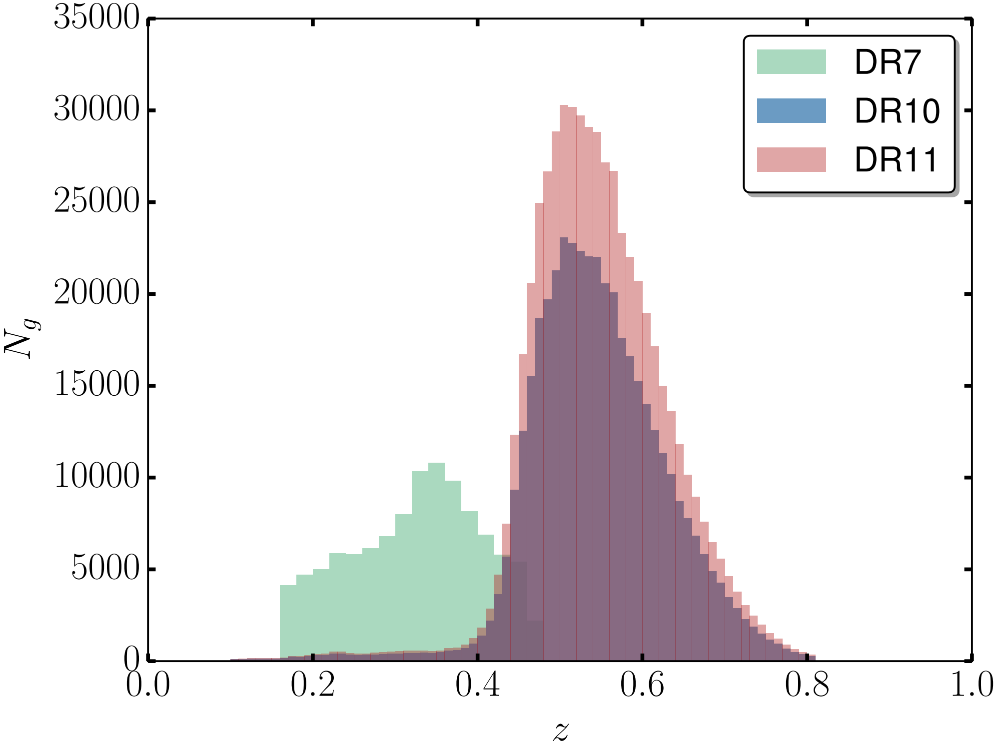
We obtain precise measurements of $D_A(z)$ <u>without assuming a fiducial cosmology</u> and restrict cosmological parameters <u>in an almost model-independent way</u>

The data set

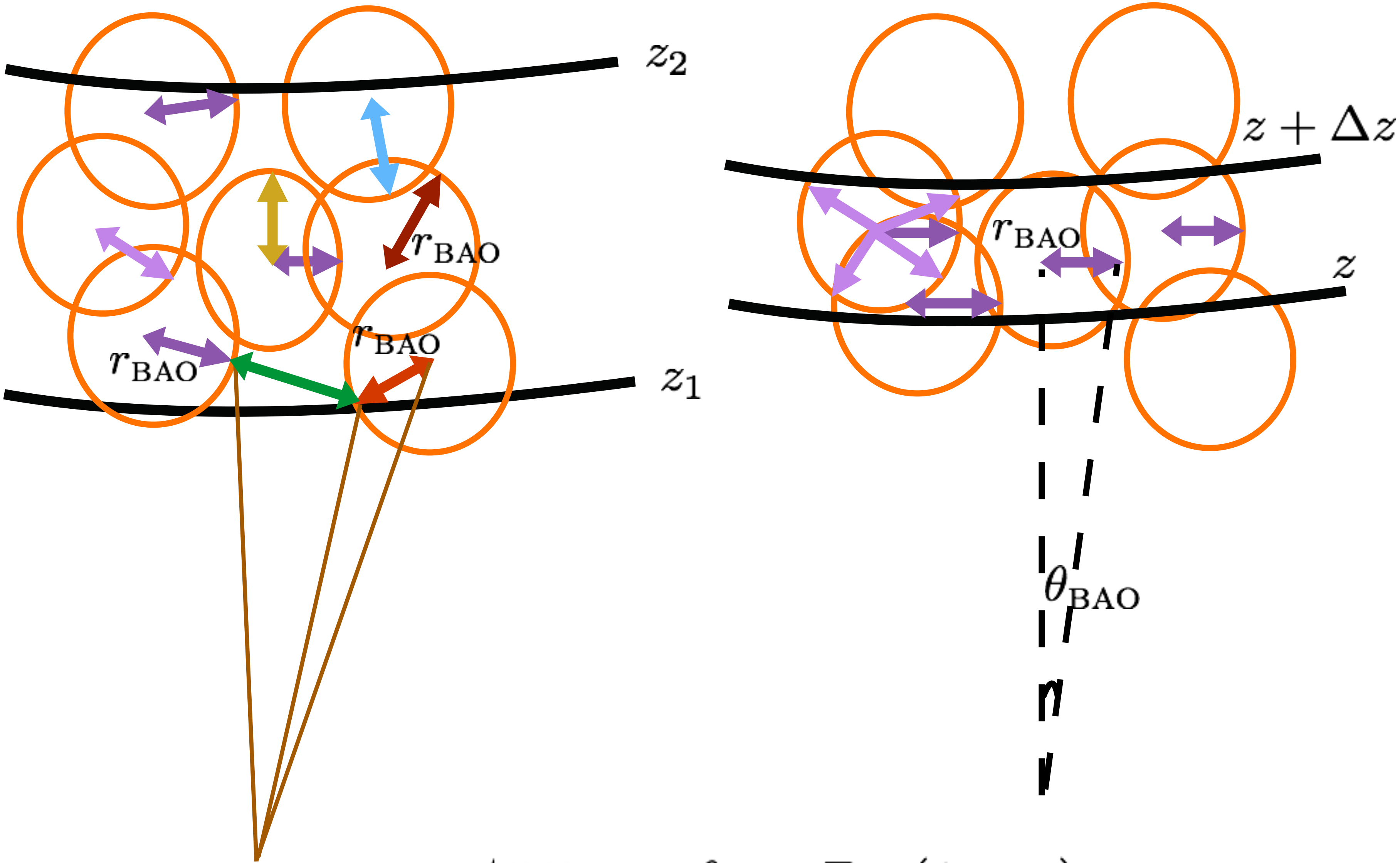


Baryon Oscillation Spectroscopic Survey (BOSS)

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



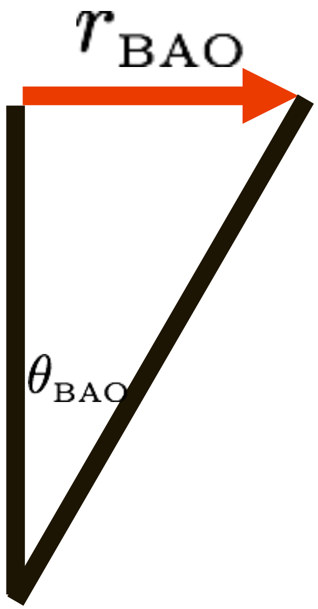
- SDSS-DR7: contains 105,831 LRG's
- SDSS-DR10: contains 409,337 LRG's
- SDSS-DR11: contains 543,116 LRG's



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

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

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



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

(CMB data)

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

The data set

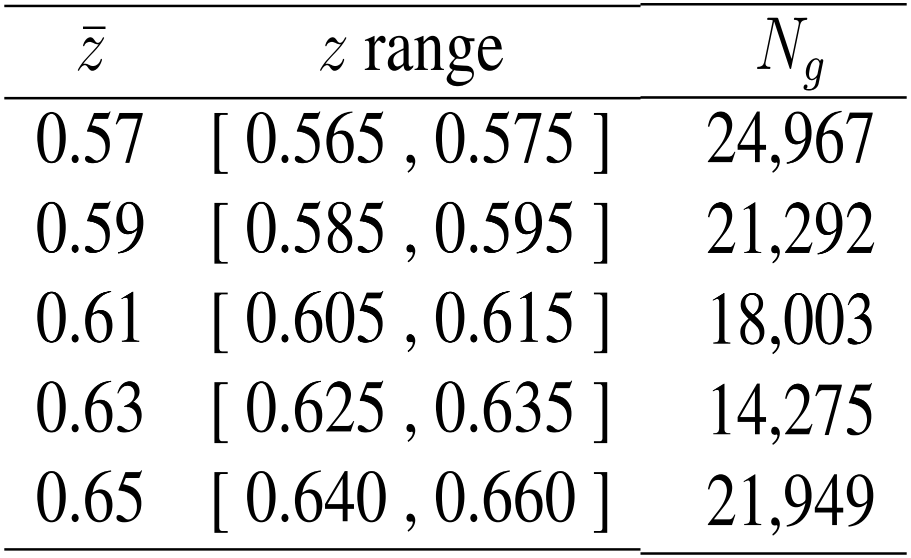
- The SDSS-DR10 contains 409,337 LRG’s with redshifts $0.43 \leq z \leq 0.7$.

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.

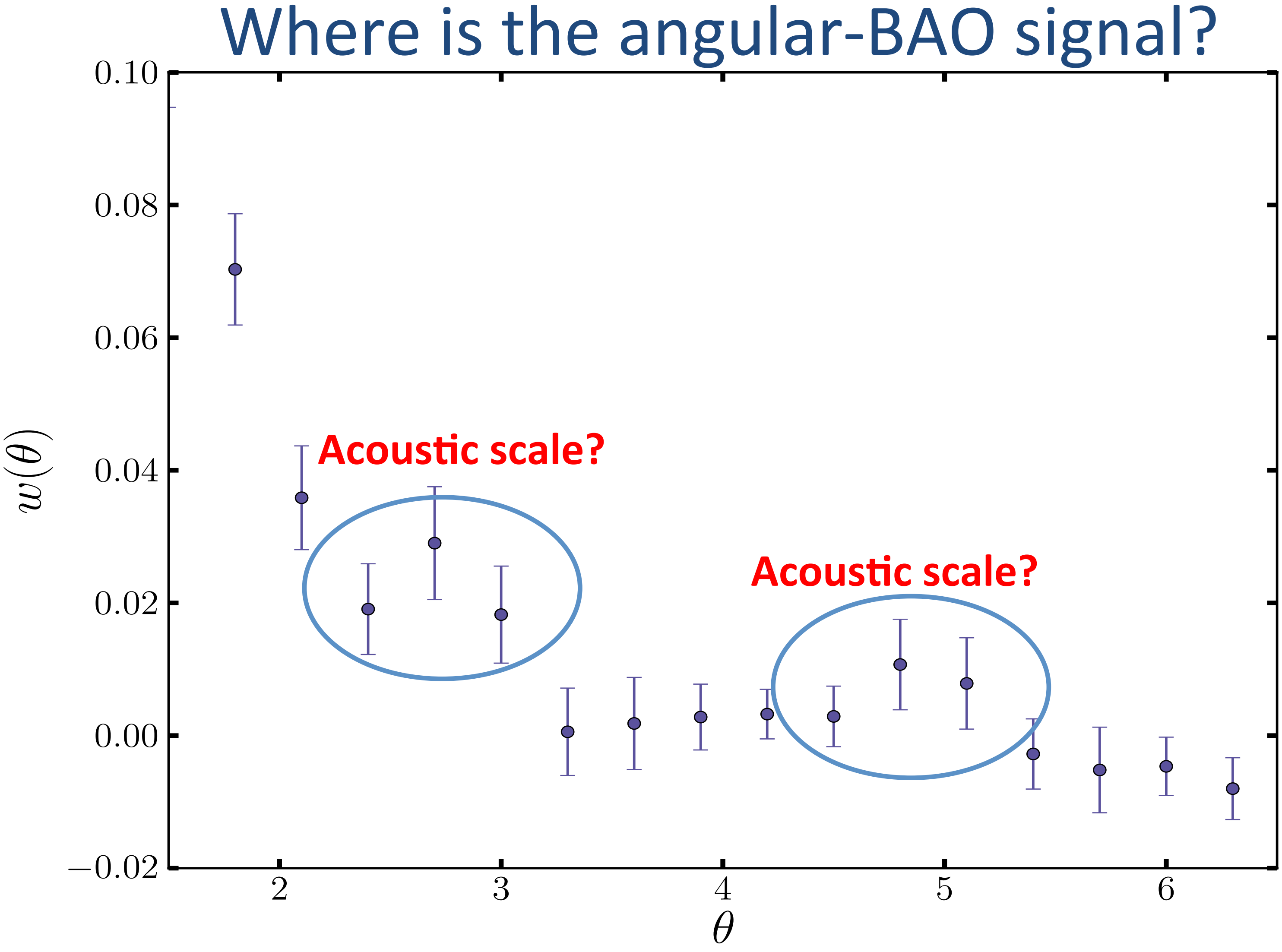
The data set

- 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



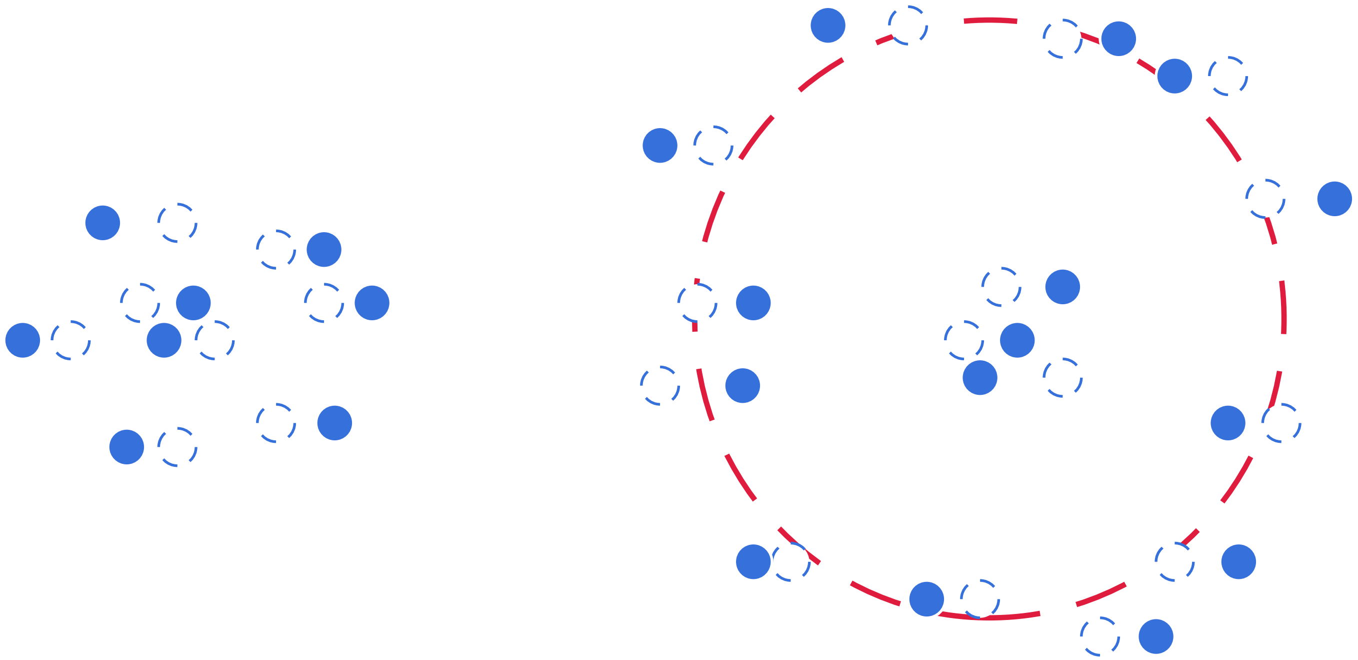
Where is the angular-BAO signal?

Acoustic scale?

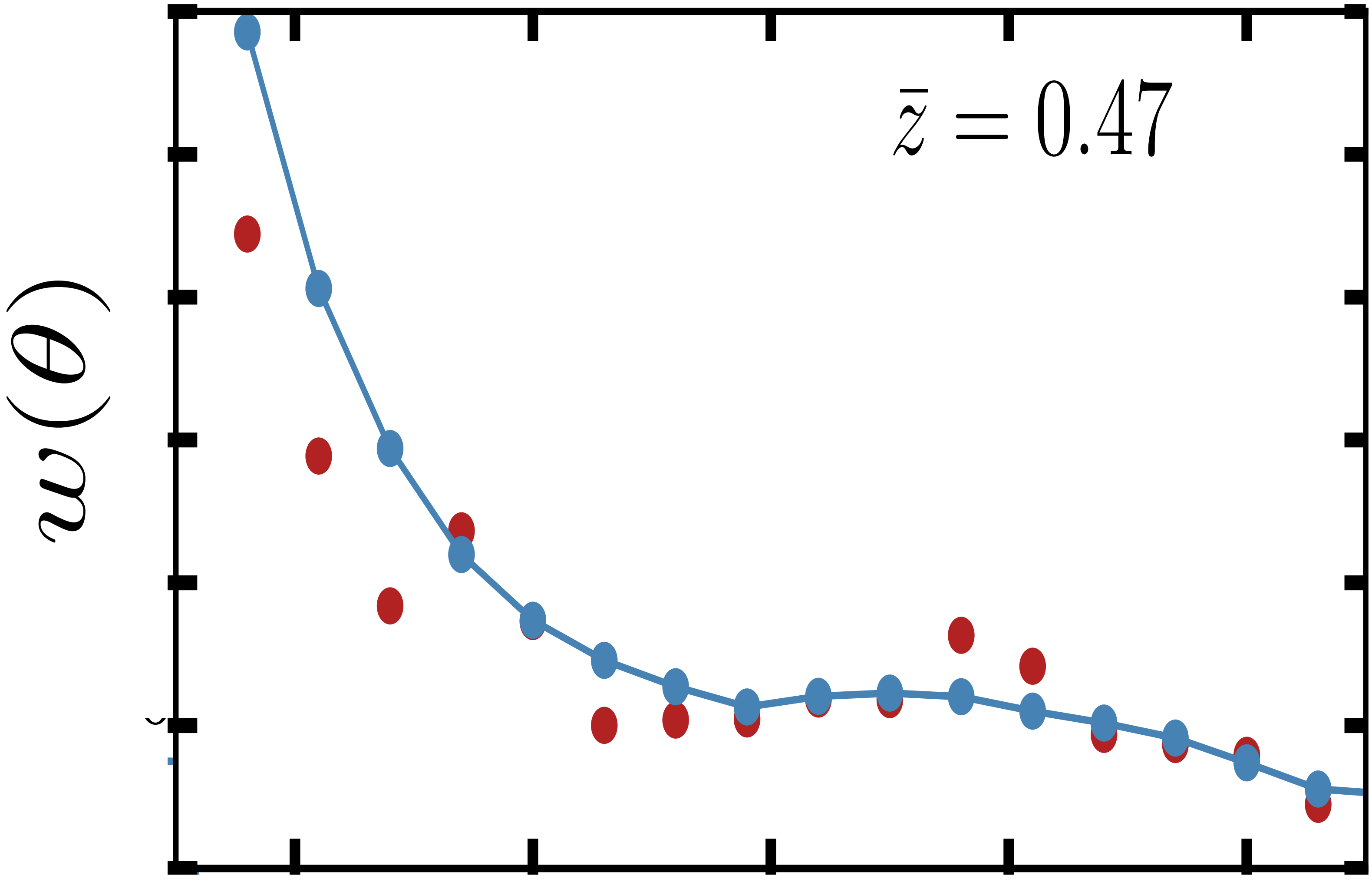
Acoustic scale?

A model-independent way to find θ_{BAO}

- Changing galaxies coordinates



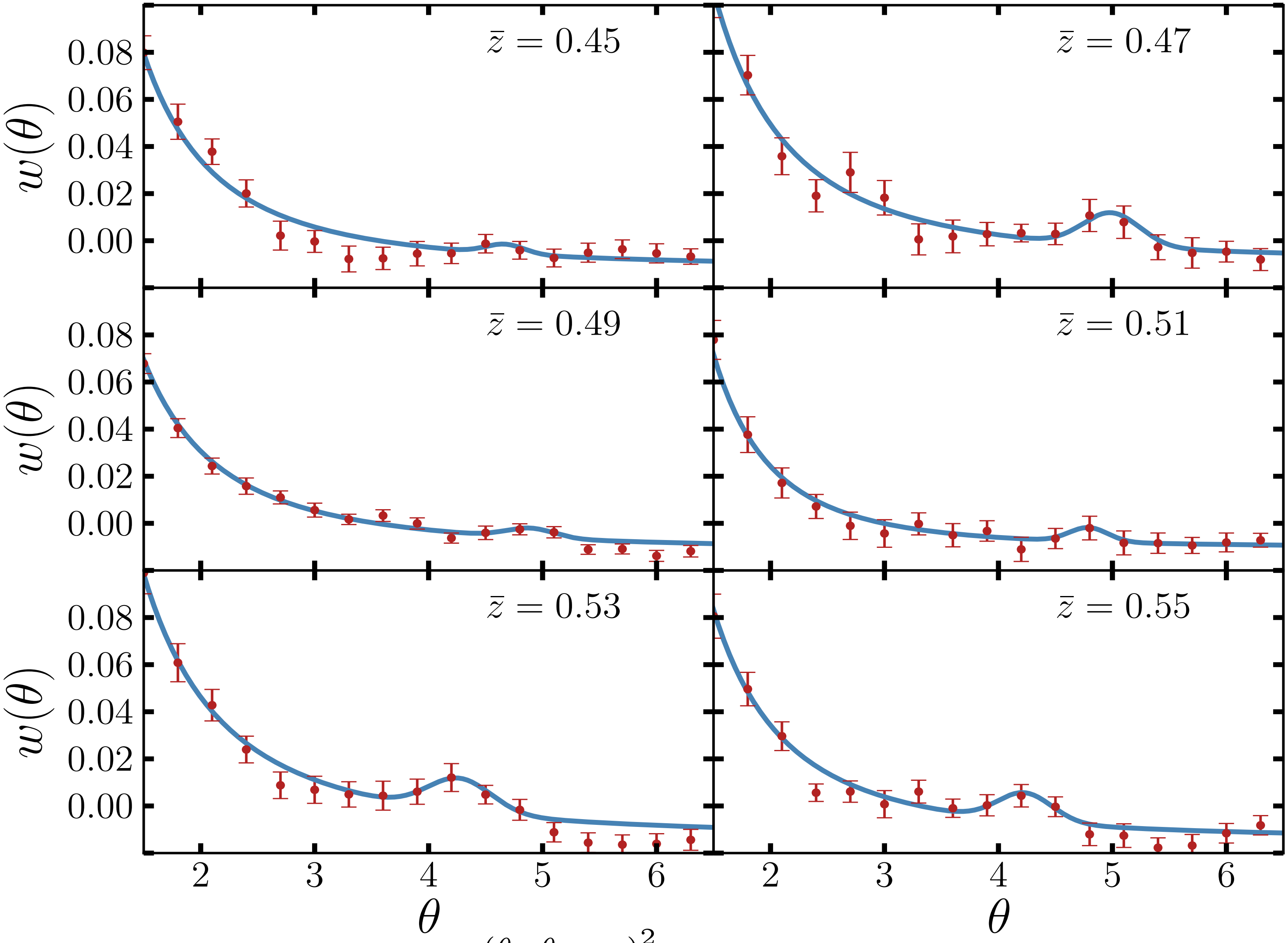
Example



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

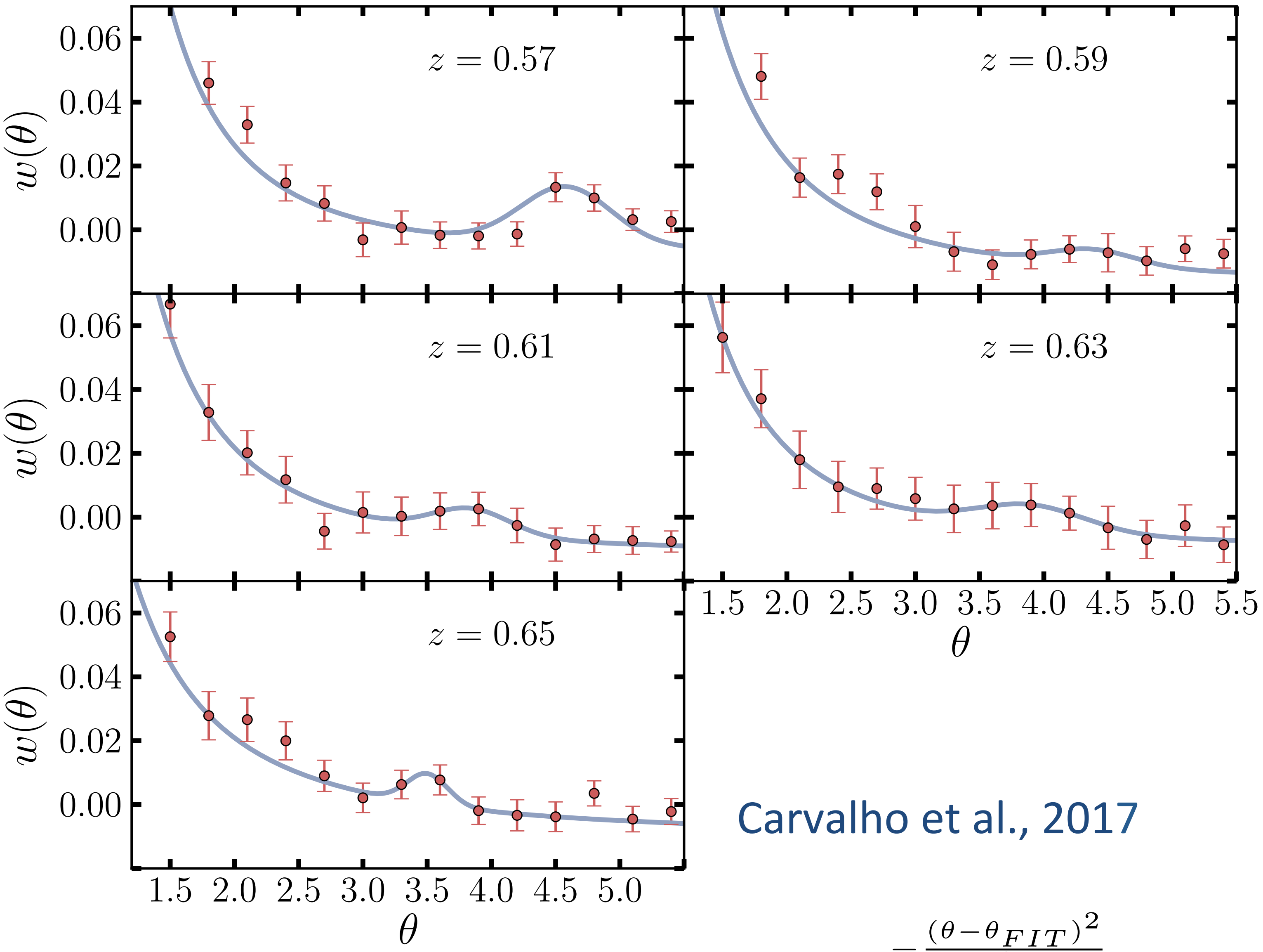
Carvalho et al., PRD (2016)
Carvalho et al., PRD (2017)



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

Carvalho et al., 2016

(Sanchez et al. 2011)

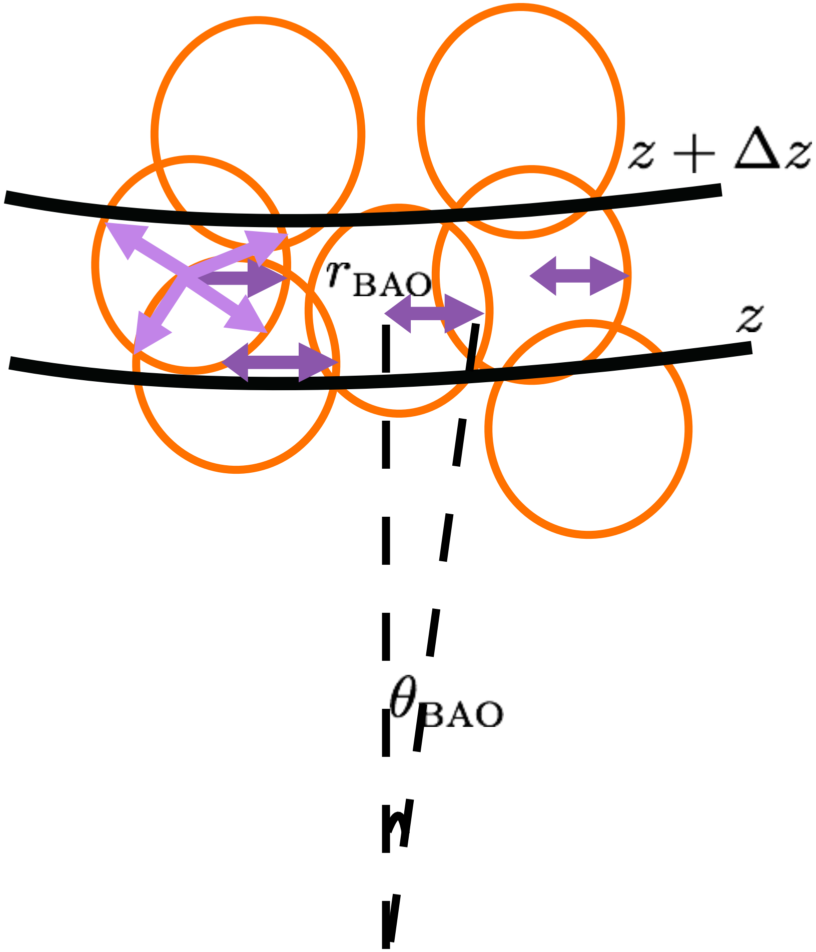


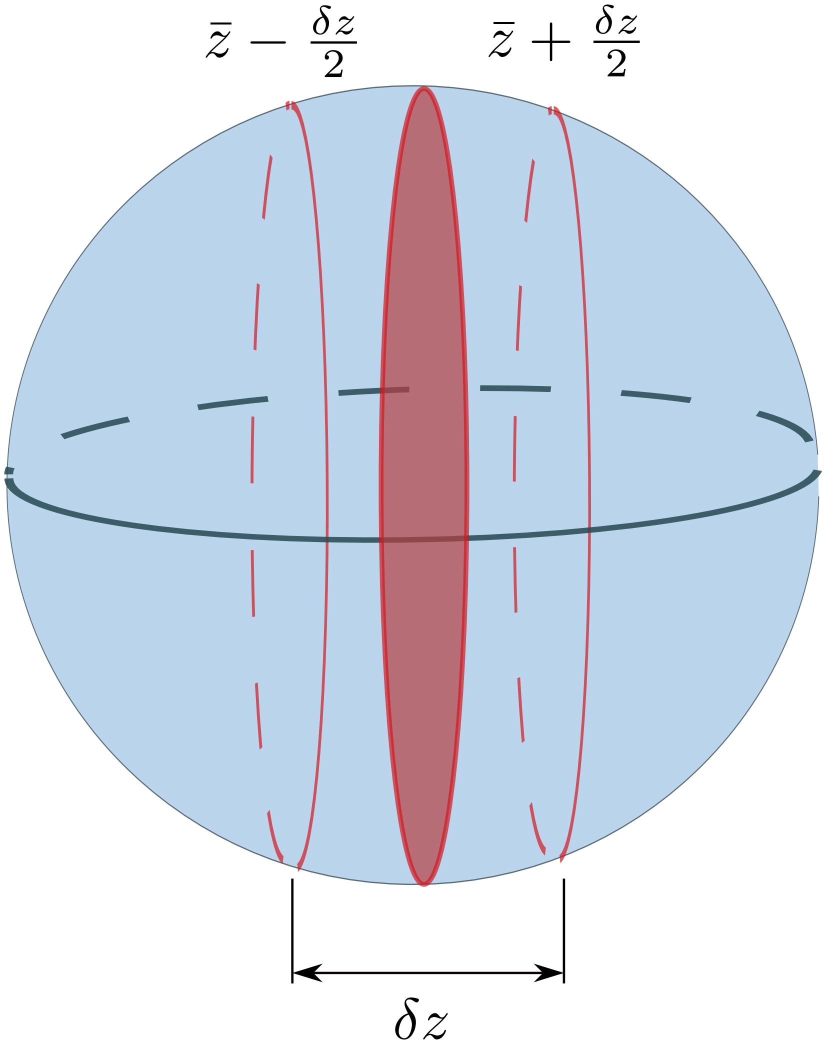
Carvalho et al., 2017

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

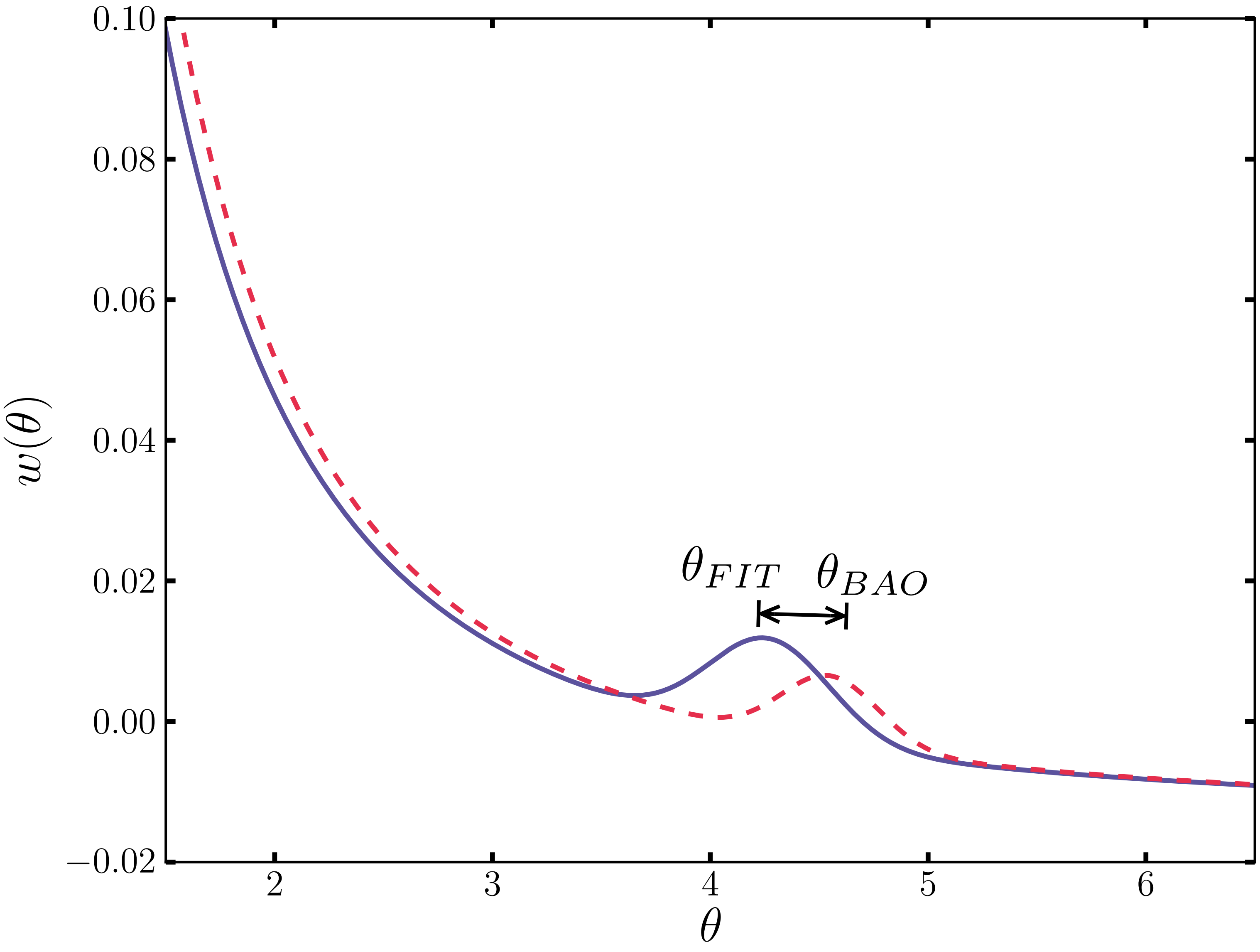
(Sanchez et al. 2011)

- Projection effects: $\theta_{FIT} \neq \theta_{BAO}$ (δz ≠ 0)





- Shift factor (α)



- Projection effects:

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

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

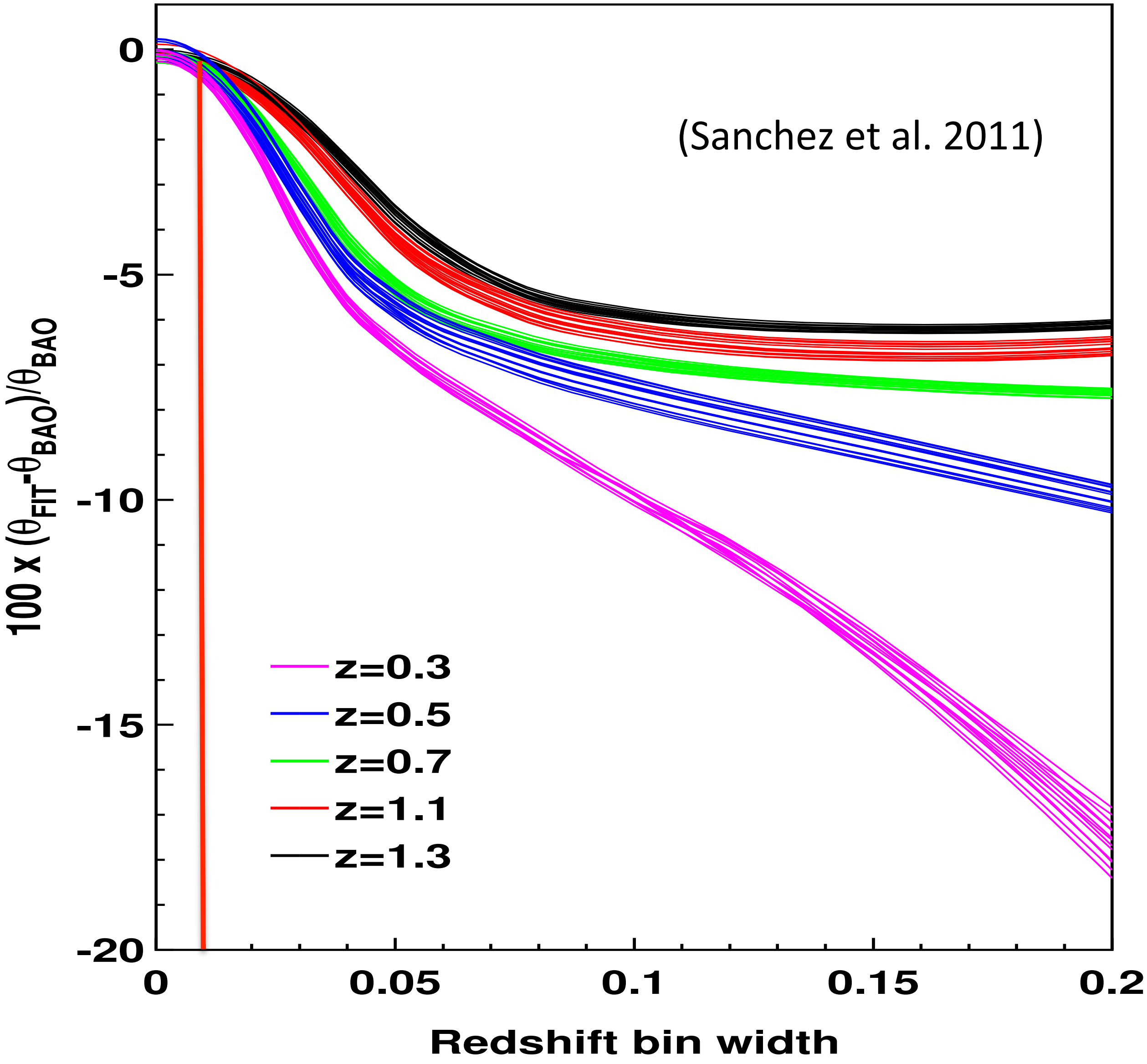
$$w_E(\theta,\tilde{z}) = \int_0^\infty dz_1 \phi(z_1) \int_0^\infty dz_2 \phi(z_2) \xi_E(s,\tilde{z})$$

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

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

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

- Projection effects:



Dependence on P(k,z)

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

$$\Big\downarrow$$

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

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} (°)	θ_{BAO} (°)	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

$\alpha \leq 2\%$

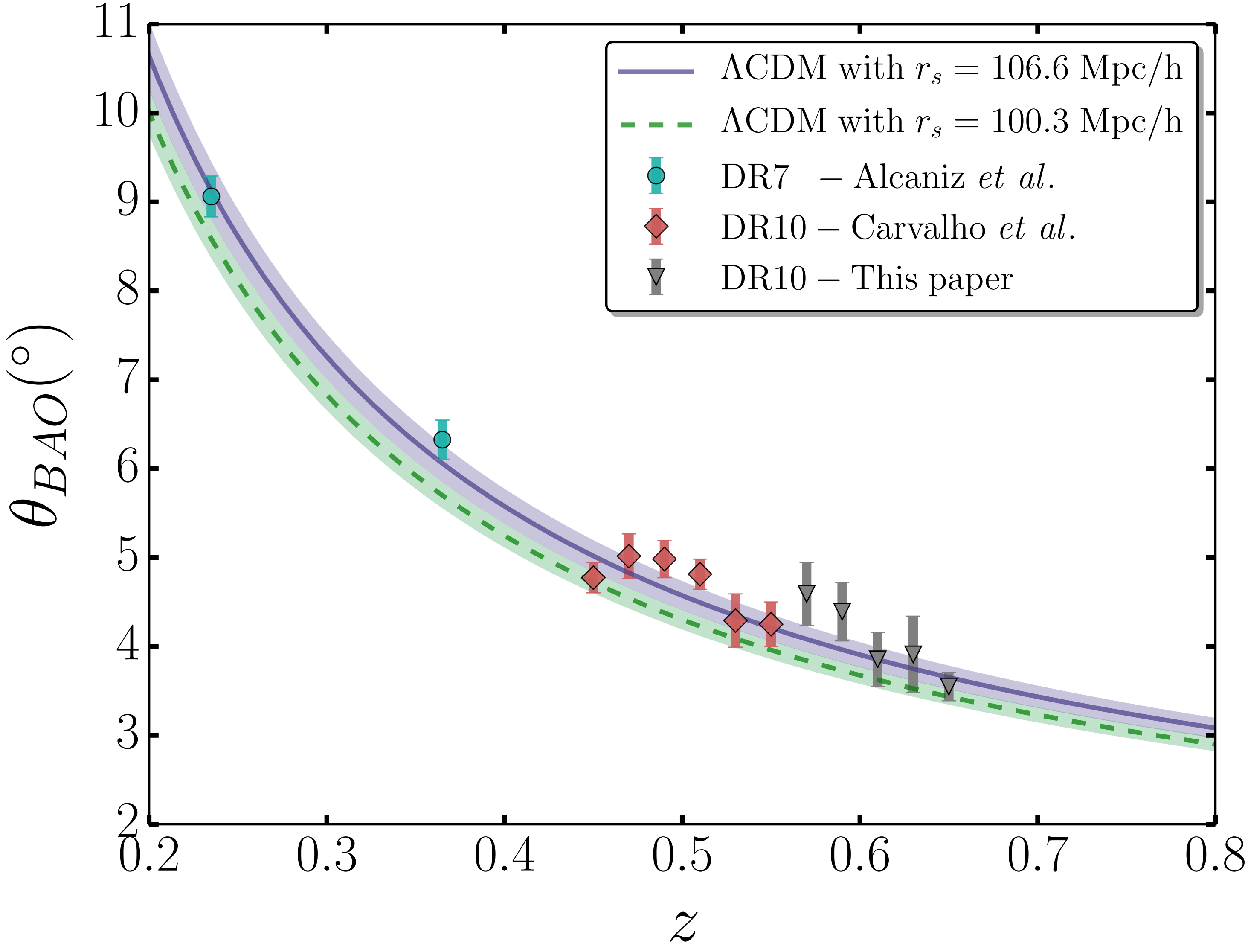
Measurements of $\theta_{BAO}(z)$

DR11

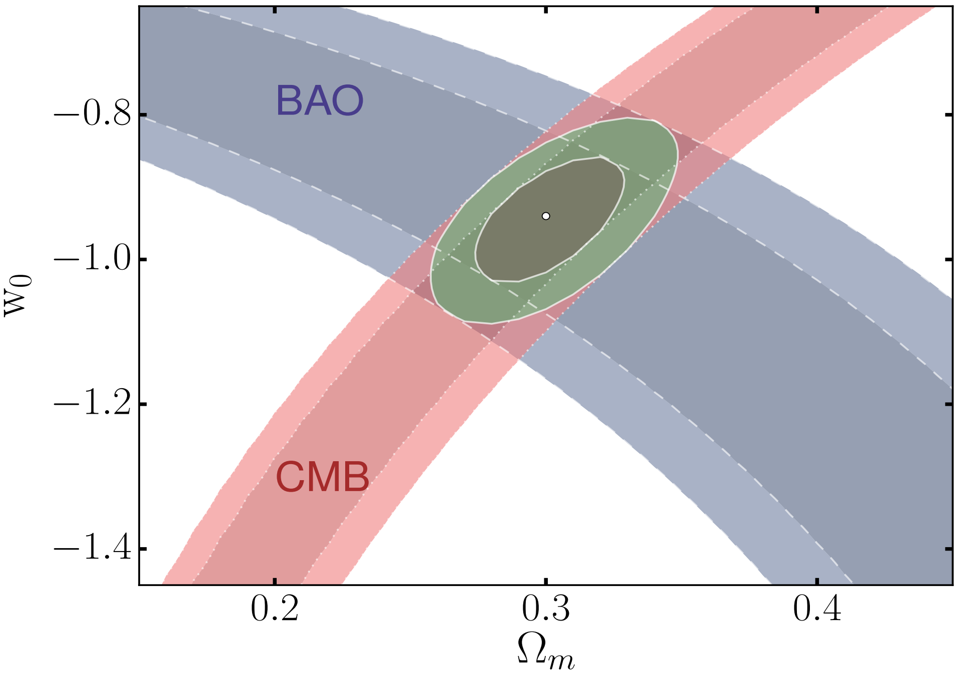
$\bar{z}$	z range	$\alpha(z, \delta z)[\%]$	$\theta_{FIT}[\mathrm{deg}]$	$\sigma_{\theta_{BAO}}$	$\theta_{BAO}[\mathrm{deg}]$	N_g
0.57	[0.565 , 0.575]	0.28	4.58	0.36	4.59	24,967
0.59	[0.585 , 0.595]	0.32	4.38	0.33	4.39	21,292
0.61	[0.605 , 0.615]	0.41	3.84	0.31	3.85	18,003
0.63	[0.625 , 0.635]	0.56	3.89	0.43	3.90	14,275
0.65	[0.640 , 0.660]	1.44	3.50	0.16	3.55	21,949

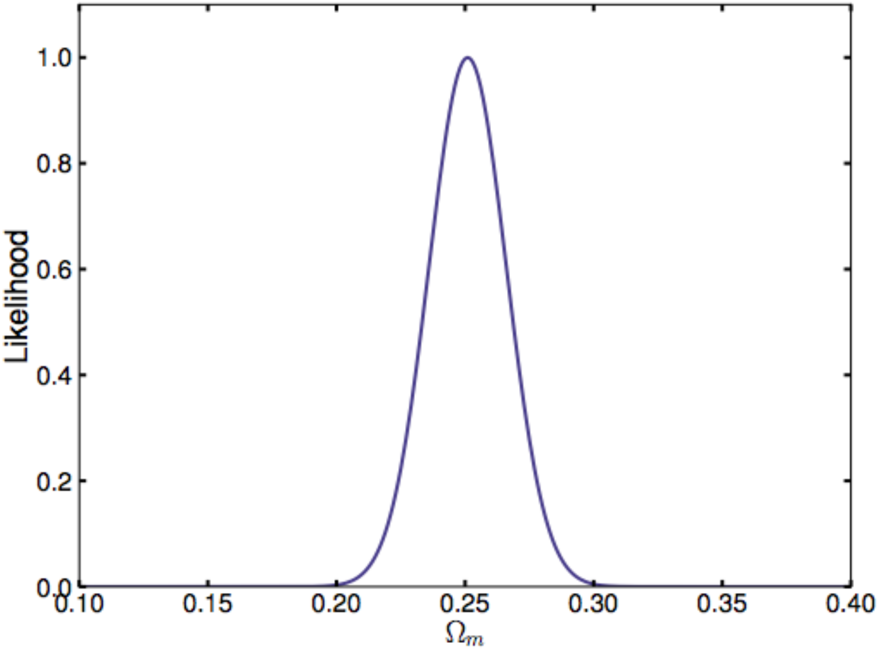
$\alpha \leq 1.4\%$

DR7 + DR10 + DR11



Cosmological Constraints



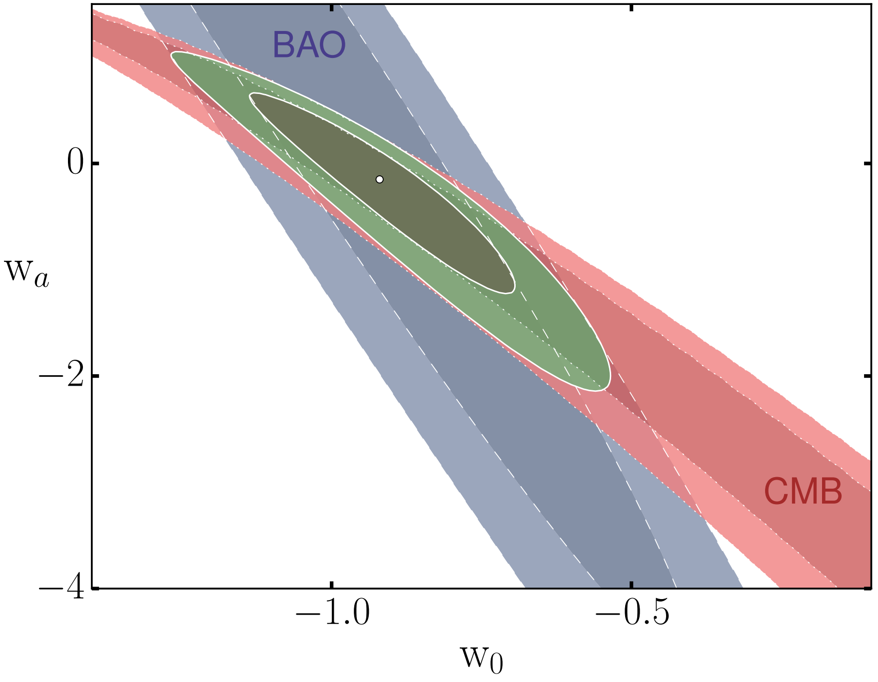


$$\Omega_m = 0.30 \pm 0.02; \quad w_0 = -0.94 \pm 0.06$$

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

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

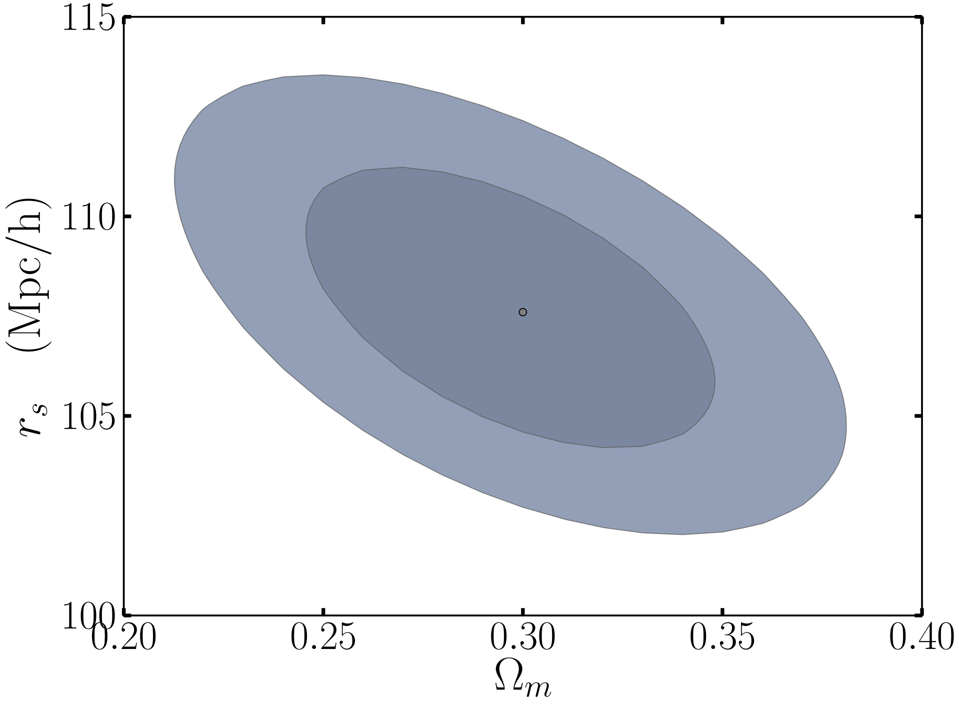
r_s = 106.61 ± 3.47 Mpc/h (WMAP9)
Planck Data (CMB)



An independent estimate of the acoustic scale

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

- 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)



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: *almost* 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 SDSS DR14 and J-PAS. Non-linear effects (reconstruction).