Systematics in Baryon Acoustic Oscillations

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(Prada et al. 2016; Klypin et al. 2016)

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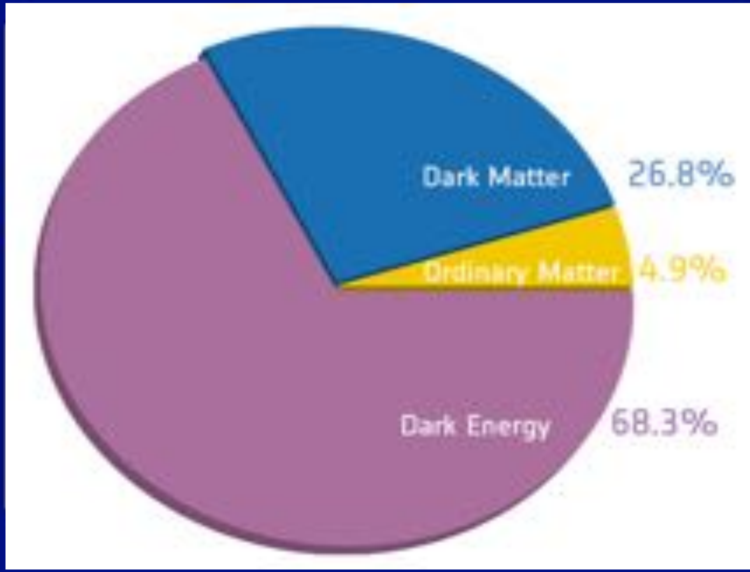
Top Scientific Objectives

Physics of the Universe

Understanding Scientific Principles

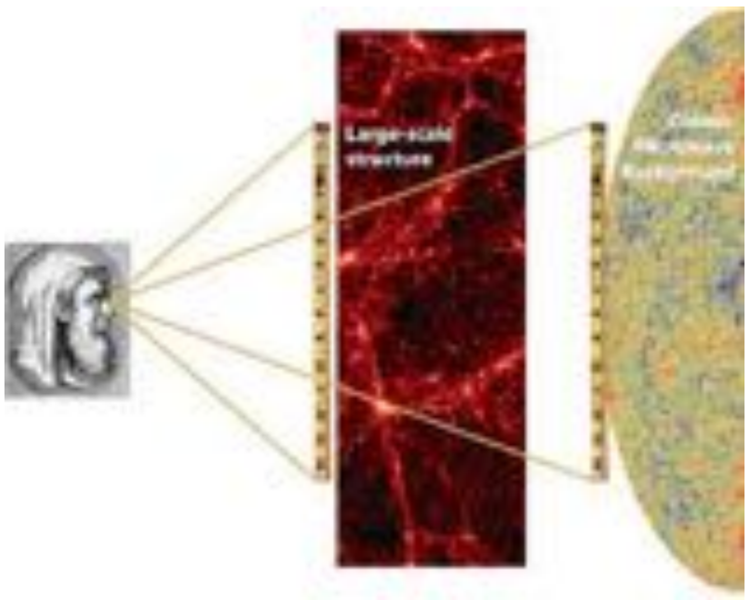


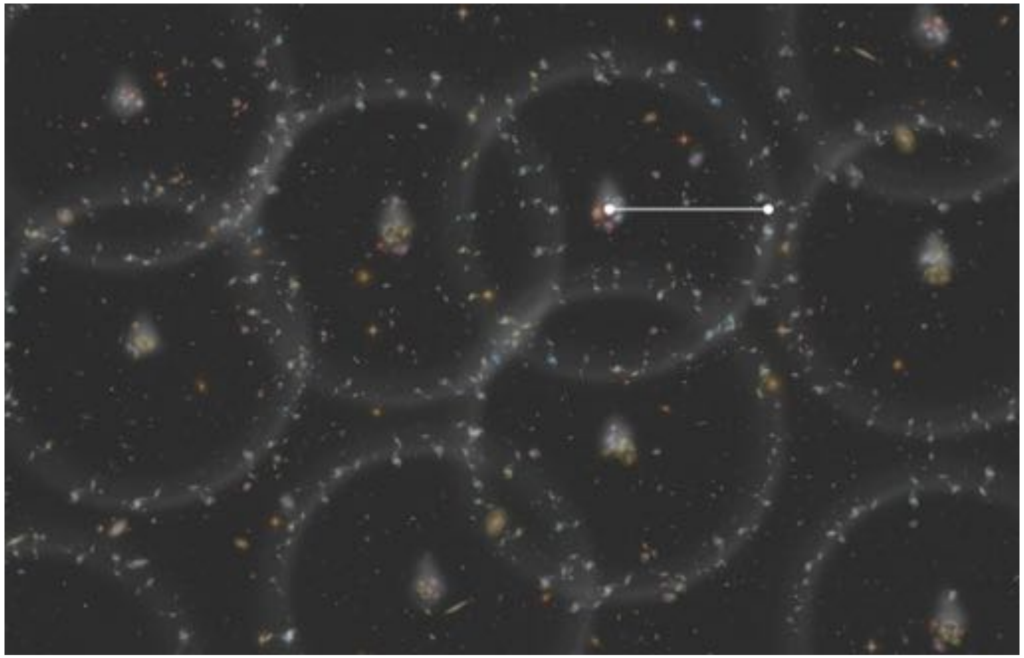
The two highest level questions in the field are the following:

- Is cosmic acceleration caused by a breakdown of Einstein General Relativity on cosmological scales, or is it caused by a new energy component with negative pressure ("dark energy") within General Relativity?
- If the acceleration is caused by "dark energy," is its energy density constant in space and time and thus consistent with quantum vacuum energy or does its energy density evolve in time and/or vary in space?

How to measure Dark Energy?

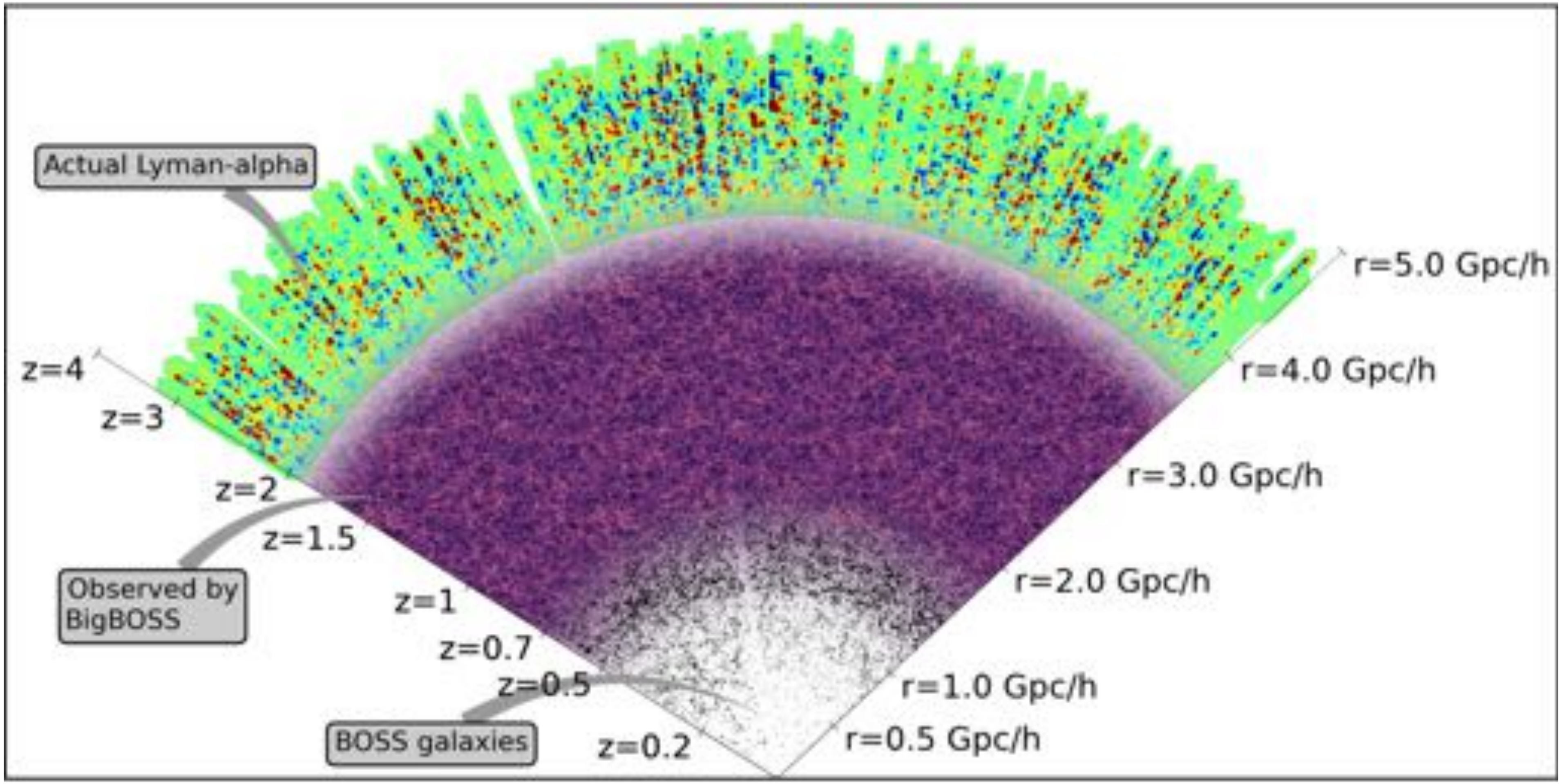
Baryonic Acoustic Oscillations as standard ruler



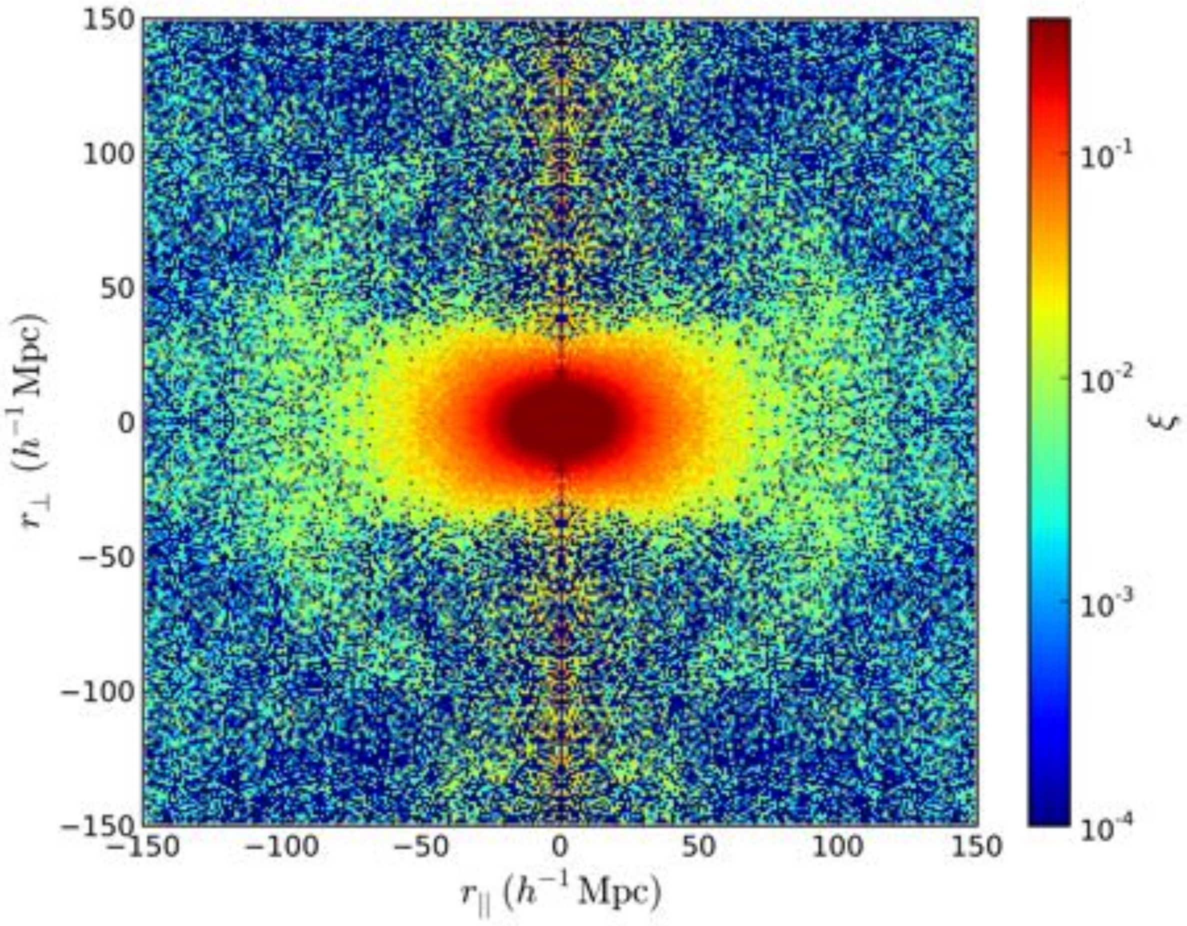


LSS catalogs provides a picture of the distribution of matter such that one can search for a BAO signal by seeing if there is a larger number of galaxies separated at the sound horizon.

Large Scale Structure Spectroscopic Surveys



Baryonic Acoustic Oscillations in BOSS



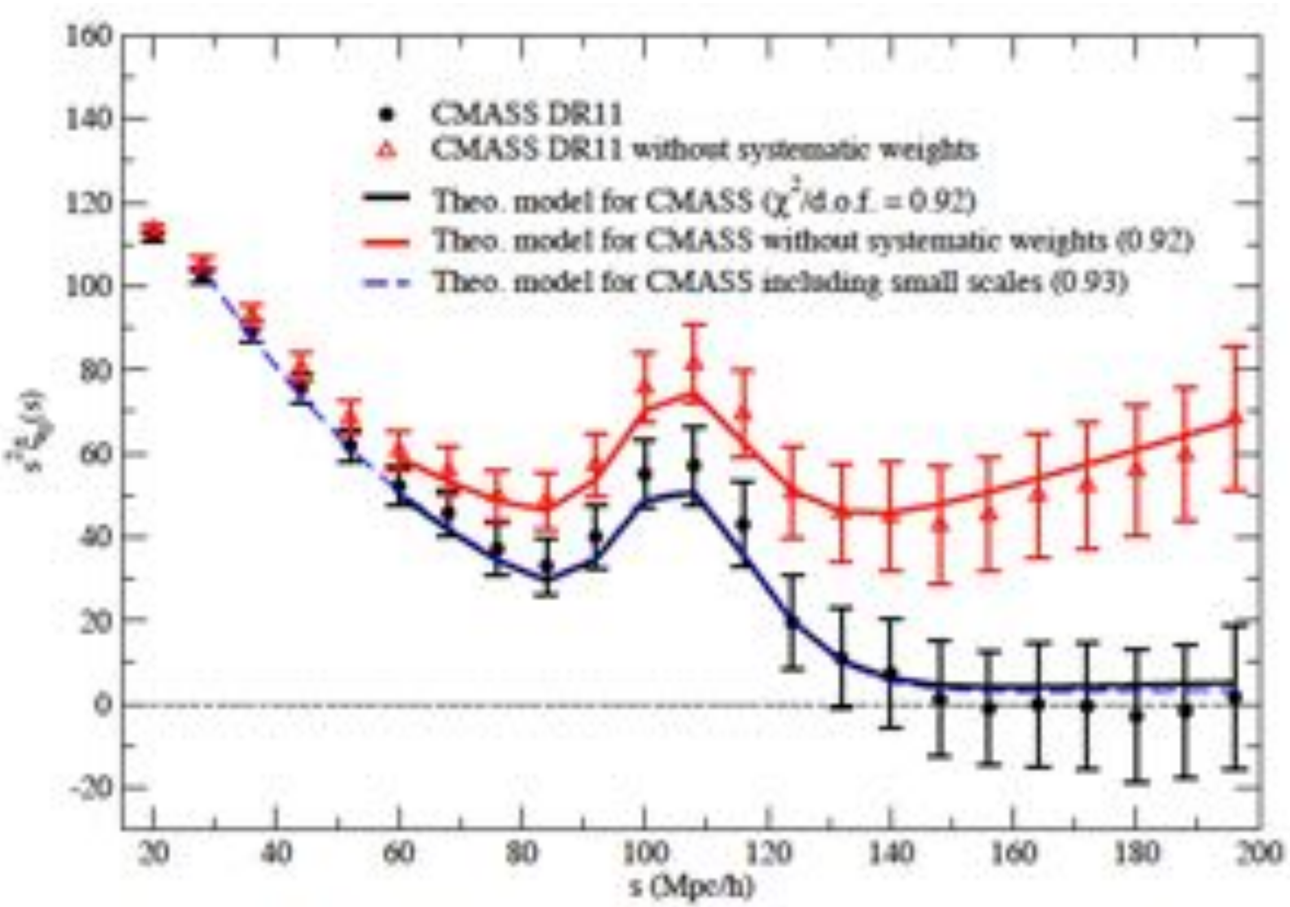
Two-dimensional correlation function of DR11 CMASS galaxies in BOSS. Colors indicate amplitude of the correlation function (Samushia et al. 2013)

BAO feature in both the transverse and line-of-sight directions. These shifts are typically parameterized by

$$\alpha_{\perp} = \frac{D_A(z) r_d^{\mathrm{fid}}}{D_A^{\mathrm{fid}}(z) r_d}, \quad \alpha_{\|} = \frac{H^{\mathrm{fid}}(z) r_d^{\mathrm{fid}}}{H(z) r_d}$$

Together, they allow us to measure the Angular diameter distance (relative to the sound horizon at the drag epoch r_d) $D_A(z)/r_d$, and the Hubble parameter $H(z)$ via $cz/(H(z)\ r_d)$ separately.

BOSS Galaxy Clustering results at z=0.55



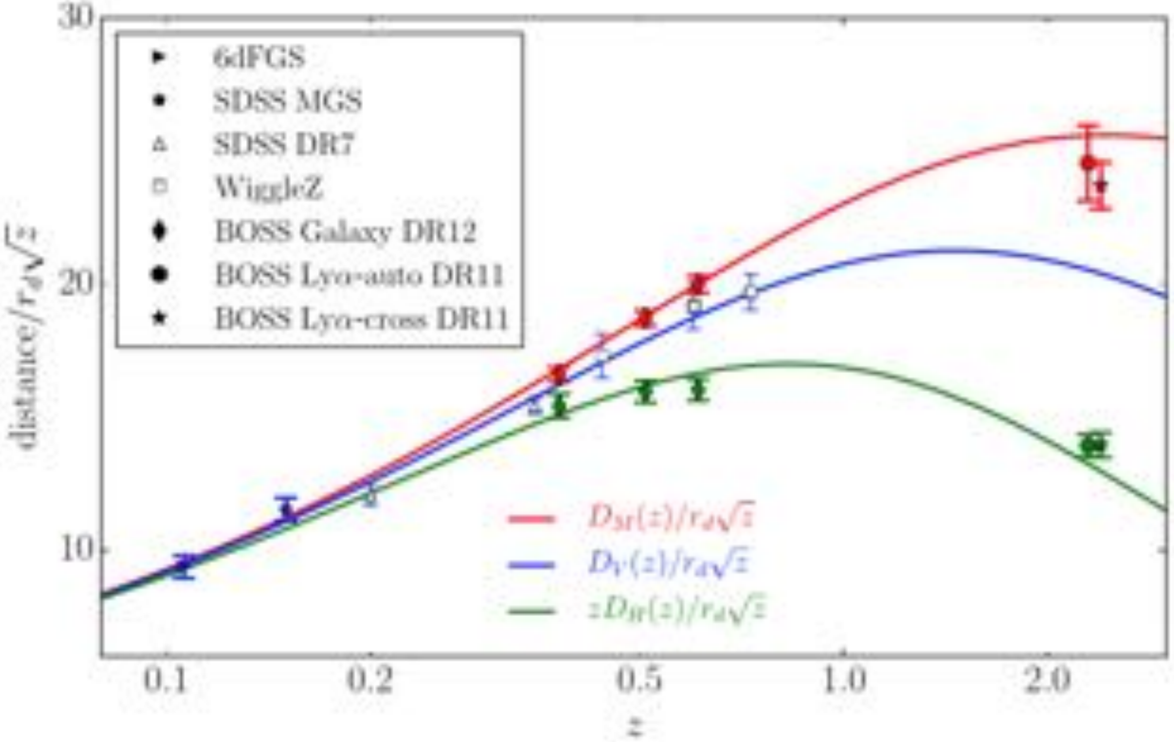
The observed BAO position depends simply on the scale dilation parameter

$$\alpha \equiv \frac{D_V(z) r_{d,\mathrm{fid}}}{D_V^{\mathrm{fid}}(z) r_d}$$

which measures the relative position of the acoustic peak in the data versus the model, thereby characterising any observed shift.

If $\alpha > 1$, the acoustic peak is shifted towards smaller scales, and $\alpha < 1$ shifts the observed peak to larger scales.

Measurement of effective monopole of the correlation function from the BOSS DR11 CMASS galaxy sample with/without systematics weights for star and seeing (black/red points), compared to the theoretical models given the parameters measured (solid lines). Chuang, Prada et al. (2013).



$$D_V(0.38) = (1477 \pm 16\ \mathrm{Mpc})\left(\frac{r_\mathrm{d}}{r_\mathrm{d,fid}}\right)$$

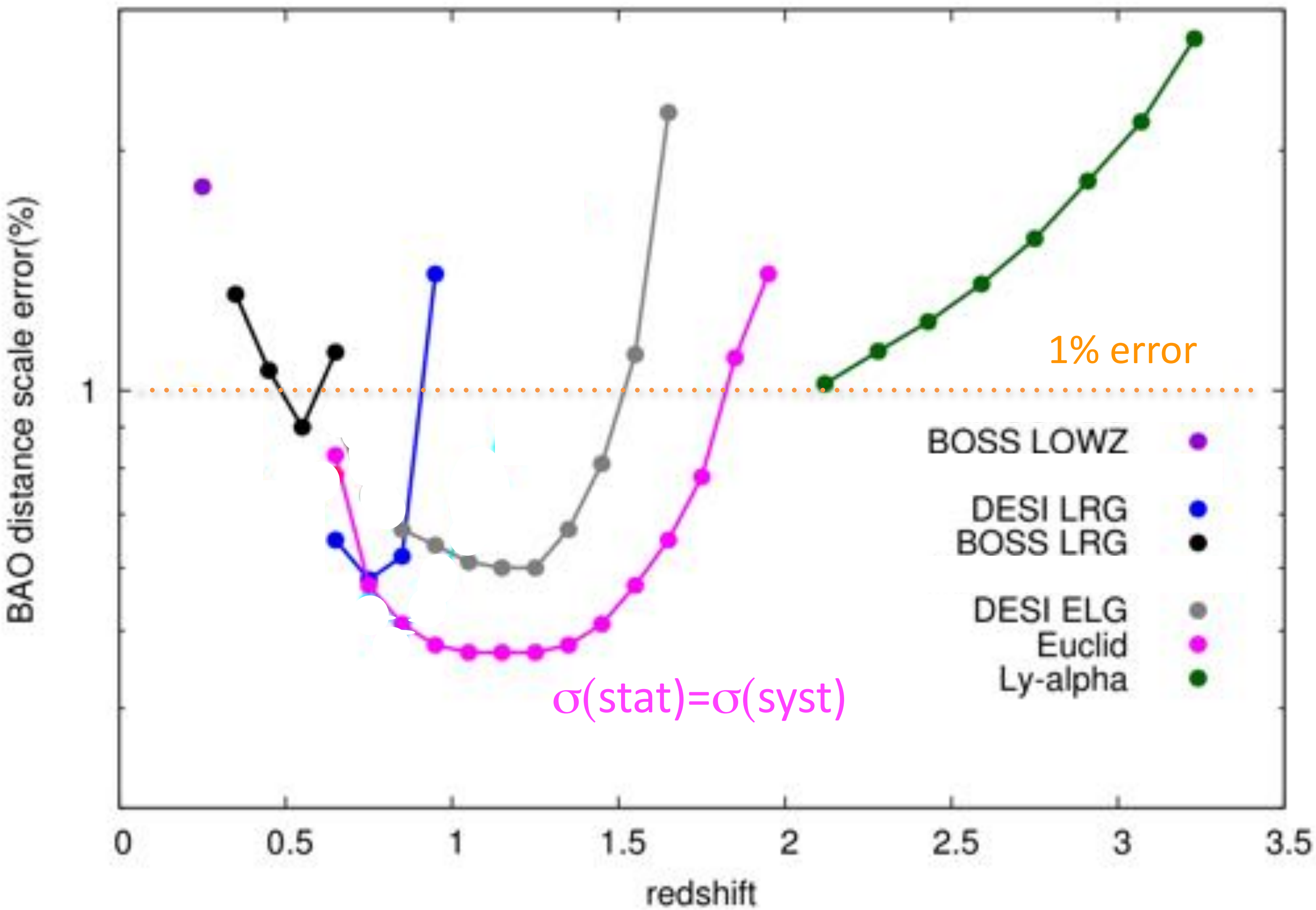
$$D_V(0.51) = (1877 \pm 19\ \mathrm{Mpc})\left(\frac{r_\mathrm{d}}{r_\mathrm{d,fid}}\right)$$

$$D_V(0.61) = (2140 \pm 22\ \mathrm{Mpc})\left(\frac{r_\mathrm{d}}{r_\mathrm{d,fid}}\right)$$

Alam et al. 2017

These values correspond to the distance BOSS measurements of 1.1 per cent precision for low-redshift bin and 1.0 per cent for the intermediate- and high-redshift bins

BAO forecast



Theory design to study BAO systematics

- Modelling non-linearity and galaxy bias to use BAO, RSDs, weak-lensing and the power spectrum broad-band shape at the 0.1-0.3% level.
- Using Halo Abundance Matching and SAMs for accurate modelling of galaxy bias
- Providing clustering and bias model useful to calibrate fast-methods for the massive production of mock galaxy catalogs (GLAM + MultiDark).
- **Studying BAO systematics: shift and damping for biased tracers.**

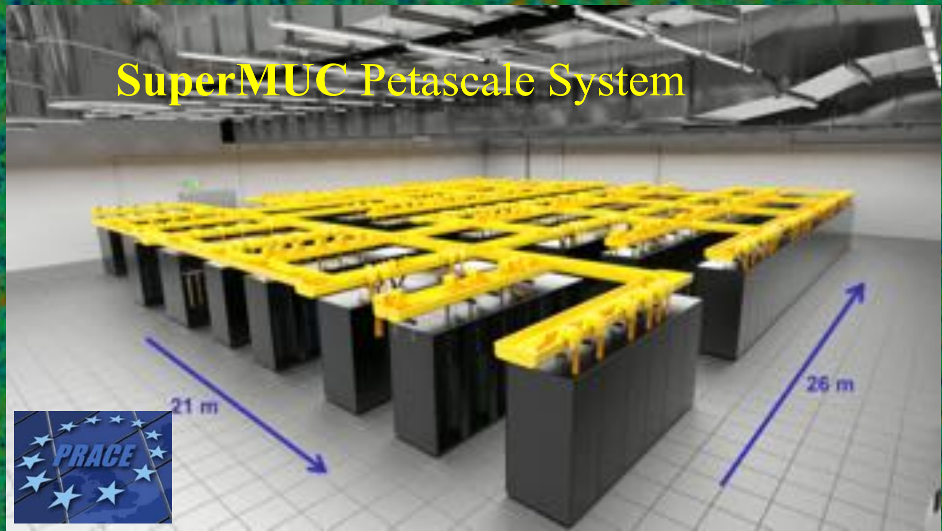
2.5 Gpc/h

>> The MultiDark Project <<

www.skiesanduniverses.org

www.cosmosim.org

Klypin et al. 2016



BigMultiDark runs designed for BOSS LRGs:

L_{box}= 2500 h^{-1} Mpc; N_{part}= 3840^3

Force res.= 10 kpc/h comoving; M_{part}=2.08 10^{10} h^{-1} M_{sun}

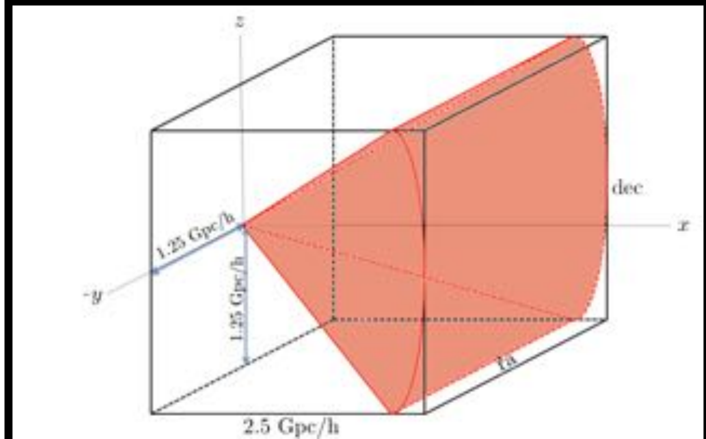
4.7 10^{15} $h^{-1}M_{sun}$

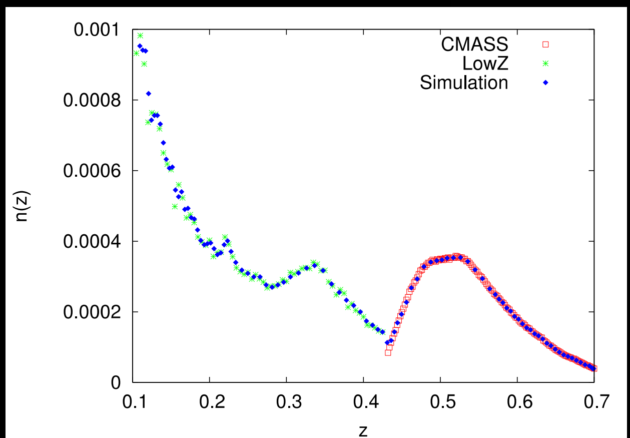
>> BigMultiDark products <<

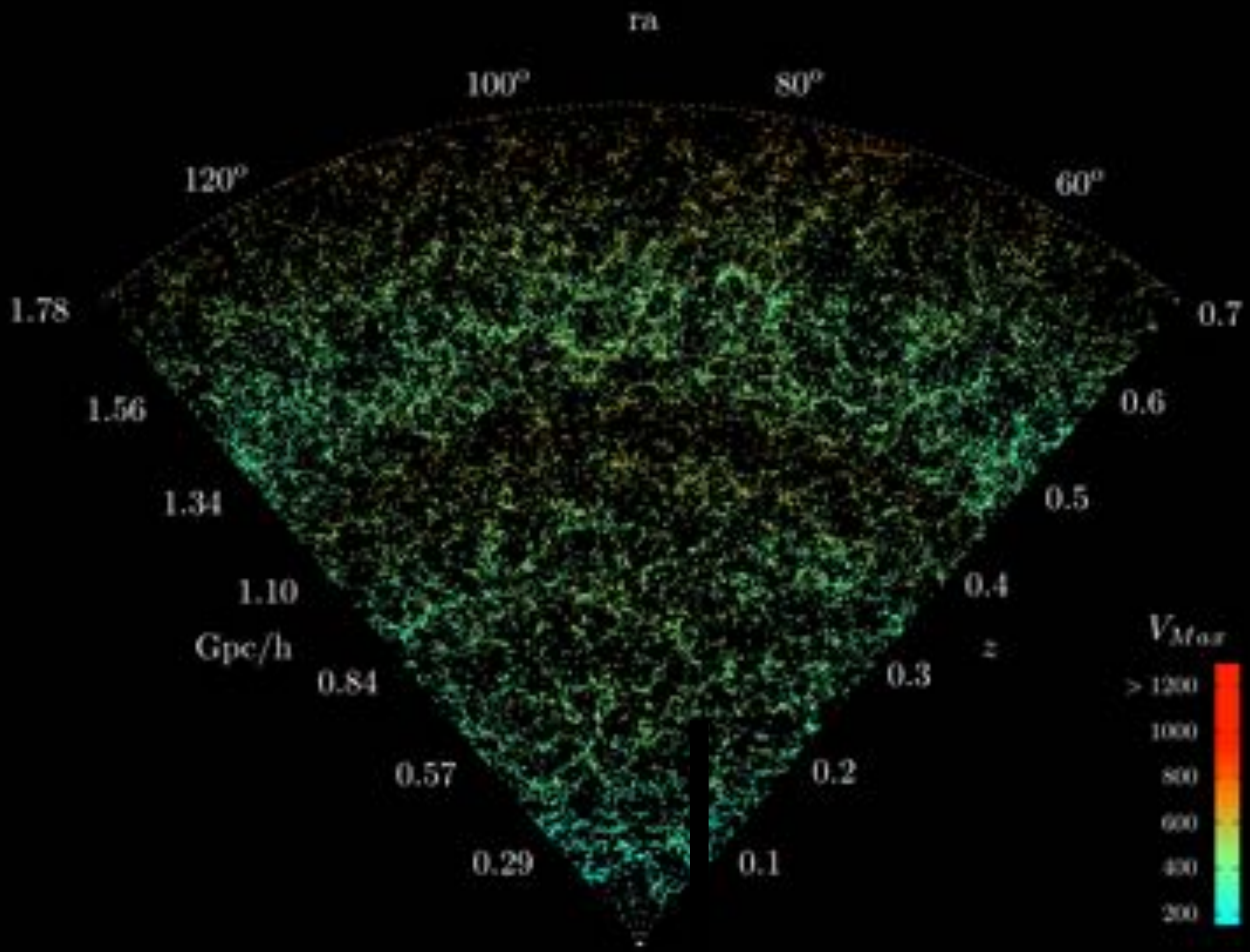
www.skiesanduniverses.org

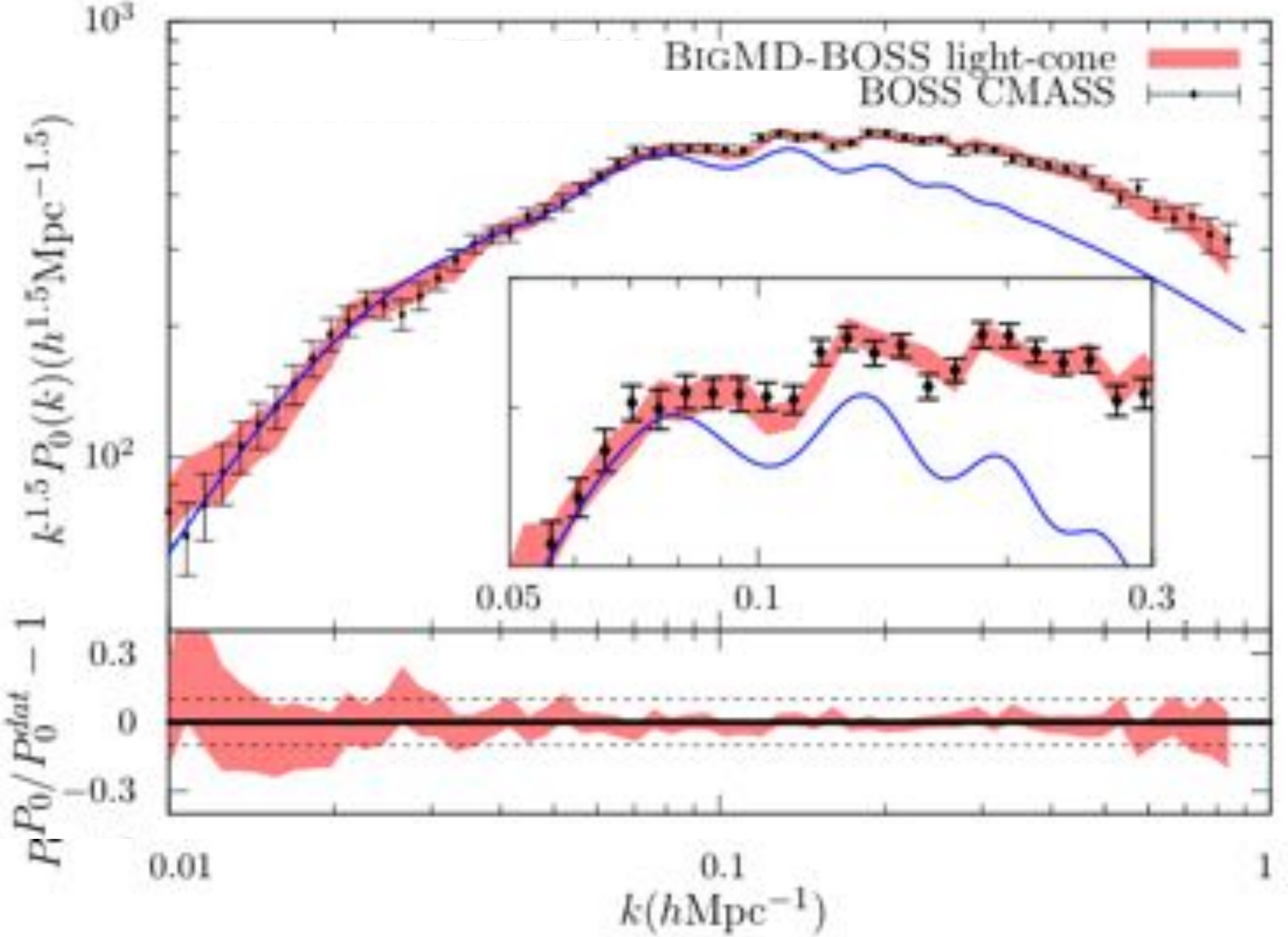
Products:

- Row particle data
- FOF & BDM halo catalogs
- (sub)Halo profiles
- Merging Trees
- **BOSS galaxy light-cones**
- MultiDark-Galaxies





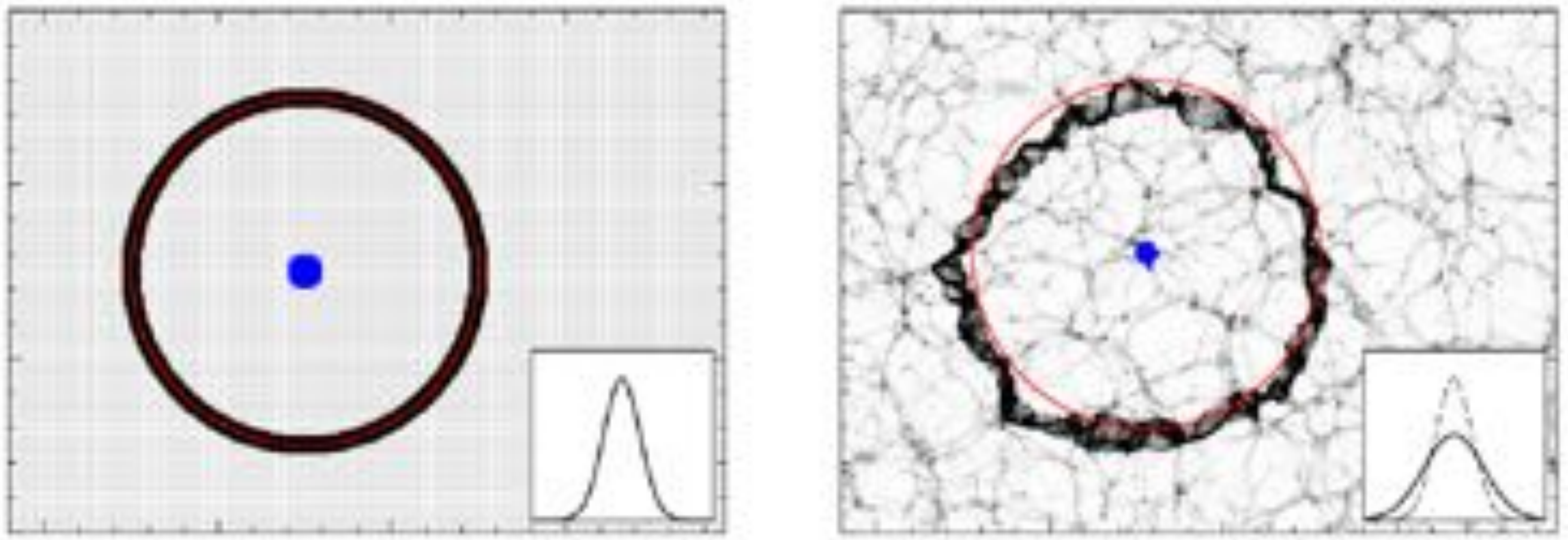




Rodríguez-Torres et al. 2016

Figure 11. Monopole of power spectrum from the BIGMD-BOSS light-cone and the CMASS DR12 sample.

Physics of BAO

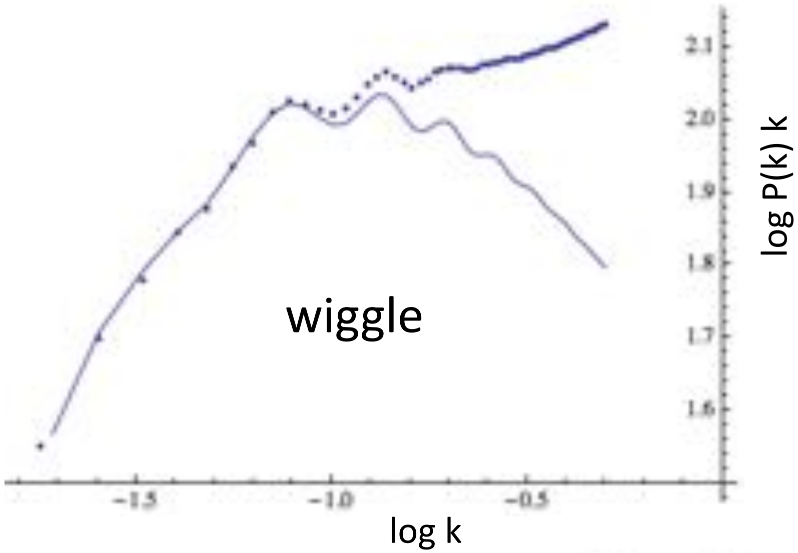


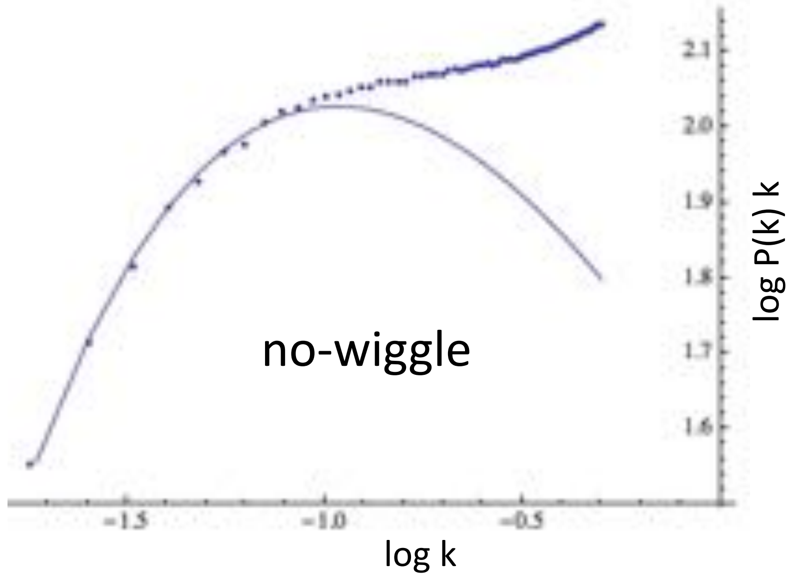
A sketch explanation of how the BAO shifts and broadened since the early universe to the present day. In each panel, we show a thin slice of a simulated cosmological density field. (top left) In the early universe, the initial densities are very smooth. We mark the acoustic feature with a ring of 150 Mpc radius from the central points. A Gaussian with the same rms width as the radial distribution of the black points from the centroid of the blue points is shown in the inset. (top right) We evolve the particles to the present day, here by the Zel'dovich approximation. The red circle shows the initial radius of the ring, centered on the current centroid of the blue points. The large-scale velocity field has caused the black points to spread out; this causes the acoustic feature to be broader (Padmanabhan 2012).

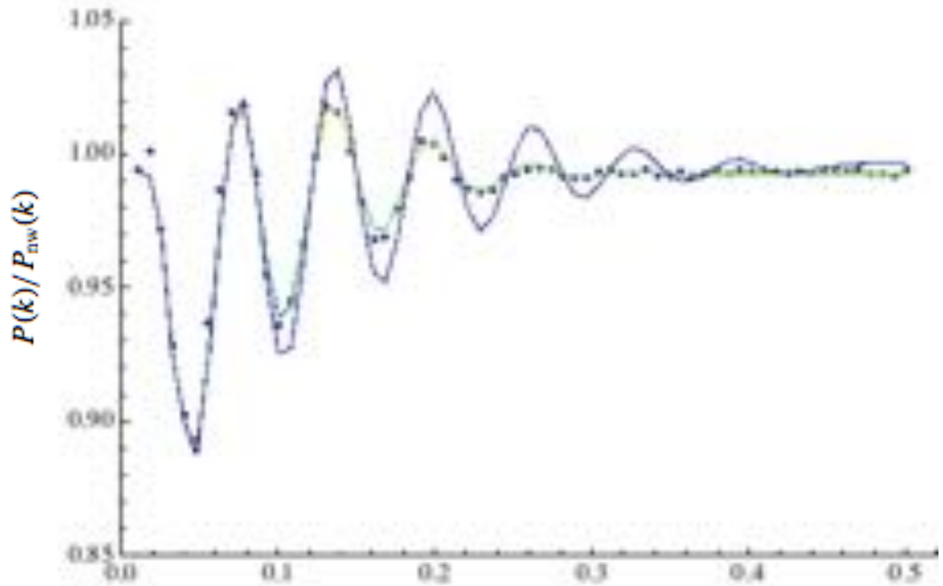
Accurate measurement of the BAO shift and damping

Prada et al. 2016

Simulation	Box	Particles	m_p	ϵ	Ω_M	Ω_B	Ω_Λ	σ_8	n_s	H_0	Code
BigMDPL	2.5	3840^3	2.4×10^{10}	10.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2
BigMDPLnw	2.5	3840^3	2.4×10^{10}	10.0	0.307	0.048	0.693	0.829	0.96	67.8	GADGET-2







Fitting model:

$$P(k)/P_{\rm nw}(k) = \left[\left(\frac{P^{\rm lin}(k/\alpha)}{A(k)P^{\rm lin}_{\rm nw}(k/\alpha)} - 1\right)\exp\left(-k^2\Sigma_{\rm nl}^2/2\right)+1\right]C(k)$$

Accurate measurement of the BAO shift and damping

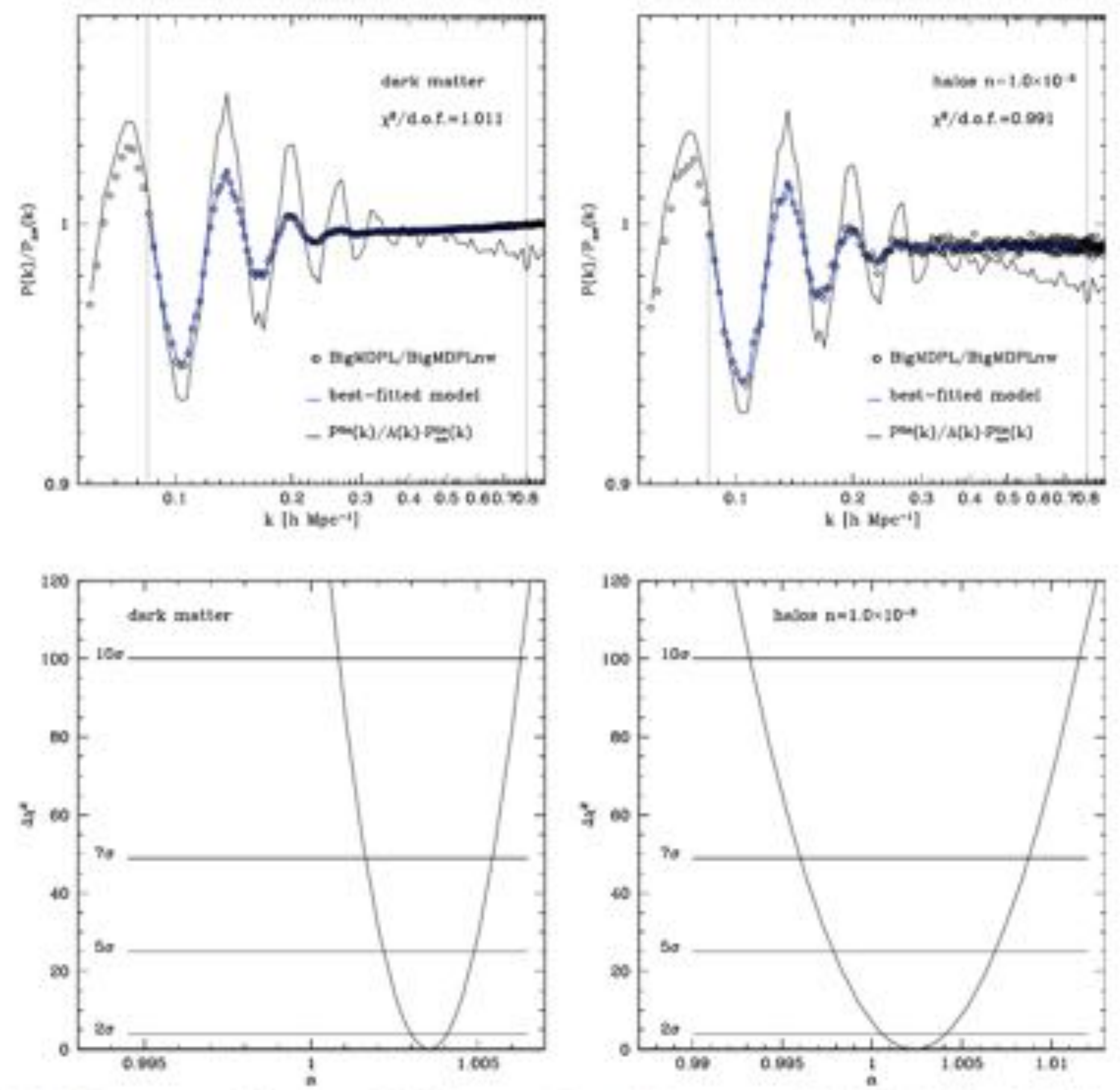


Figure 3. Power spectra at $z = 0$, in real-space, divided by the corresponding non-wiggle power spectrum obtained from BigMDPL and BigMDPLnw, respectively, for dark matter (top-left panel) and a typical halo sample with number density 1×10^{-3} Mpc^{-3} h^3 (top-right panel). The thick solid line corresponds to the best-fitted model given by equation (2) in the wavenumber range $0.085 < k < 0.8\ h$ Mpc^{-1} shown by the vertical dotted lines. The ratio of wiggle and non-wiggle linear matter power spectrum is also shown in both cases (thin solid line). The bottom panels show the likelihood χ^2 distributions for the BAO shift α parameter both for dark matter (left-hand panel) and the halo sample (right-hand panel).

BAO shift & damping for Dark Matter

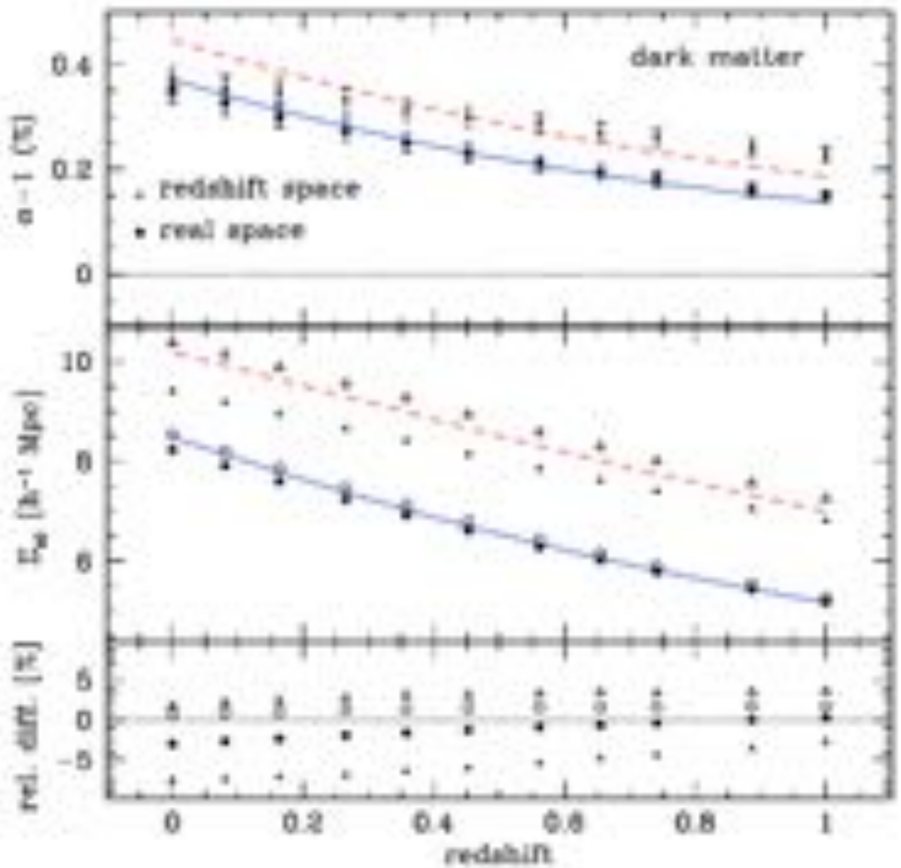


Figure 5. Non-linear evolution of the BAO shift and damping with redshift for dark matter in real- and redshift-space (solid circles and triangles, respectively). The solid line in the top and middle panel are our best fit to $\alpha(z) - 1 \propto [D(z)/D(0)]^2$ and the linear theory estimate of the damping given by equation (3), respectively. Errors for the damping measurements are smaller than the size of the symbols. The dashed lines correspond to redshift-space predictions. The open circles and triangles are representing the dispersion of the dark matter pair separation at BAO scales measured from the BigMD simulation (see the text). The bottom panel shows the relative ratio of the damping measurements as compared to linear theory.

Redshift	$\alpha - 1$[per cent]	Σ_{nl} (Mpc h^{-1})	Σ_{100}	$\chi^2/d.o.f.$
1.000	$0.228^{+0.013}_{-0.015}$	$6.814^{+0.017}_{-0.016}$	7.257	0.98
0.887	$0.241^{+0.013}_{-0.015}$	$7.056^{+0.016}_{-0.017}$	7.572	1.04
0.741	$0.256^{+0.015}_{-0.016}$	$7.406^{+0.017}_{-0.016}$	8.010	1.14
0.655	$0.271^{+0.018}_{-0.016}$	$7.626^{+0.018}_{-0.017}$	8.291	1.06
0.562	$0.287^{+0.017}_{-0.019}$	$7.858^{+0.017}_{-0.018}$	8.584	1.06
0.453	$0.301^{+0.018}_{-0.019}$	$8.147^{+0.019}_{-0.019}$	8.942	1.02
0.358	$0.313^{+0.021}_{-0.020}$	$8.415^{+0.018}_{-0.021}$	9.268	1.06
0.265	$0.332^{+0.023}_{-0.023}$	$8.657^{+0.021}_{-0.021}$	9.553	1.02
0.164	$0.349^{+0.023}_{-0.024}$	$8.959^{+0.021}_{-0.023}$	9.881	1.08
0.081	$0.353^{+0.026}_{-0.025}$	$9.185^{+0.024}_{-0.022}$	10.135	1.02
0.000	$0.369^{+0.026}_{-0.027}$	$9.410^{+0.024}_{-0.025}$	10.358	1.01

Redshit-space

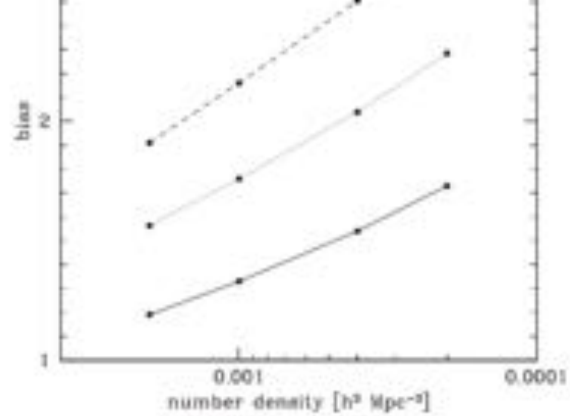


Figure 2. Bias as a function of number density at $z = 0$, 0.562, and 1, for four different samples of dark matter haloes selected accordingly to their maximum circular velocities V_{max} from our BigMD Planck simulations.

Halo Tracers
BAO shift & damping as a function of bias

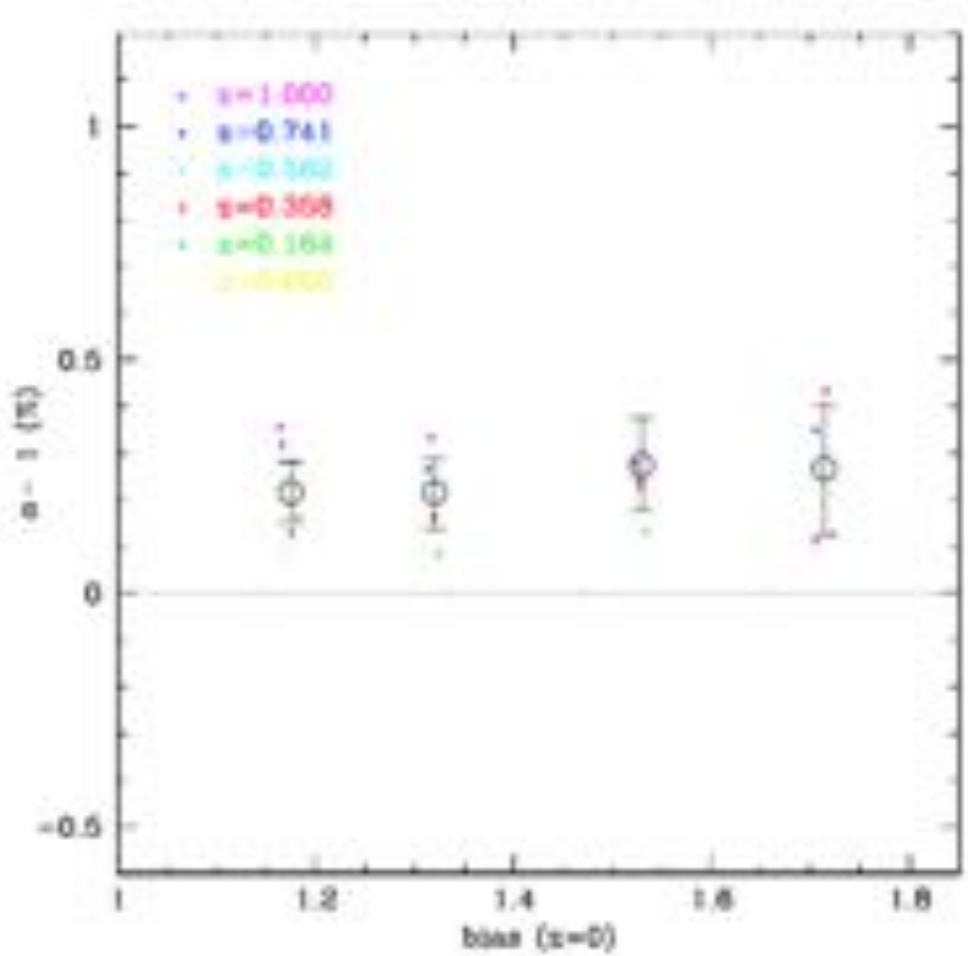


Figure 7. Measurements of the BAO shift as a function of halo bias for our BigMD Planck data. Each of the individual shift estimates are shown

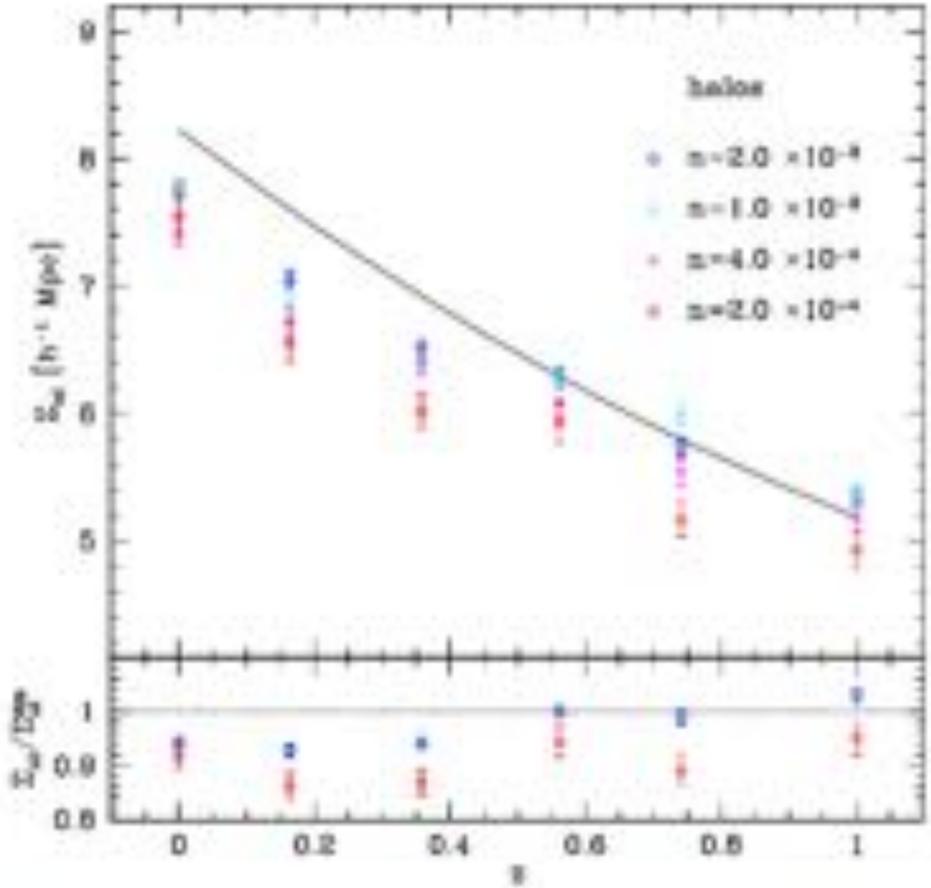
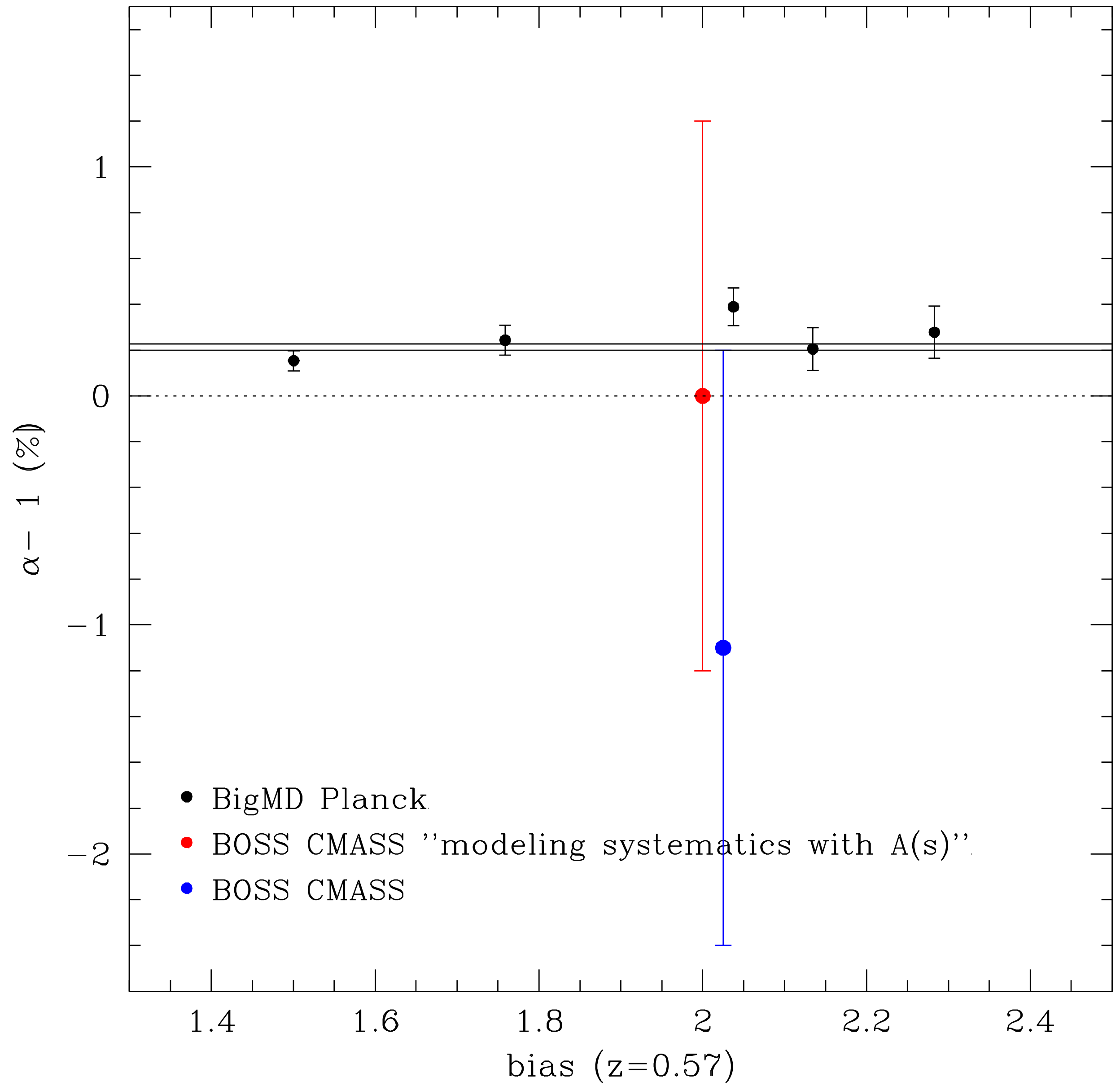
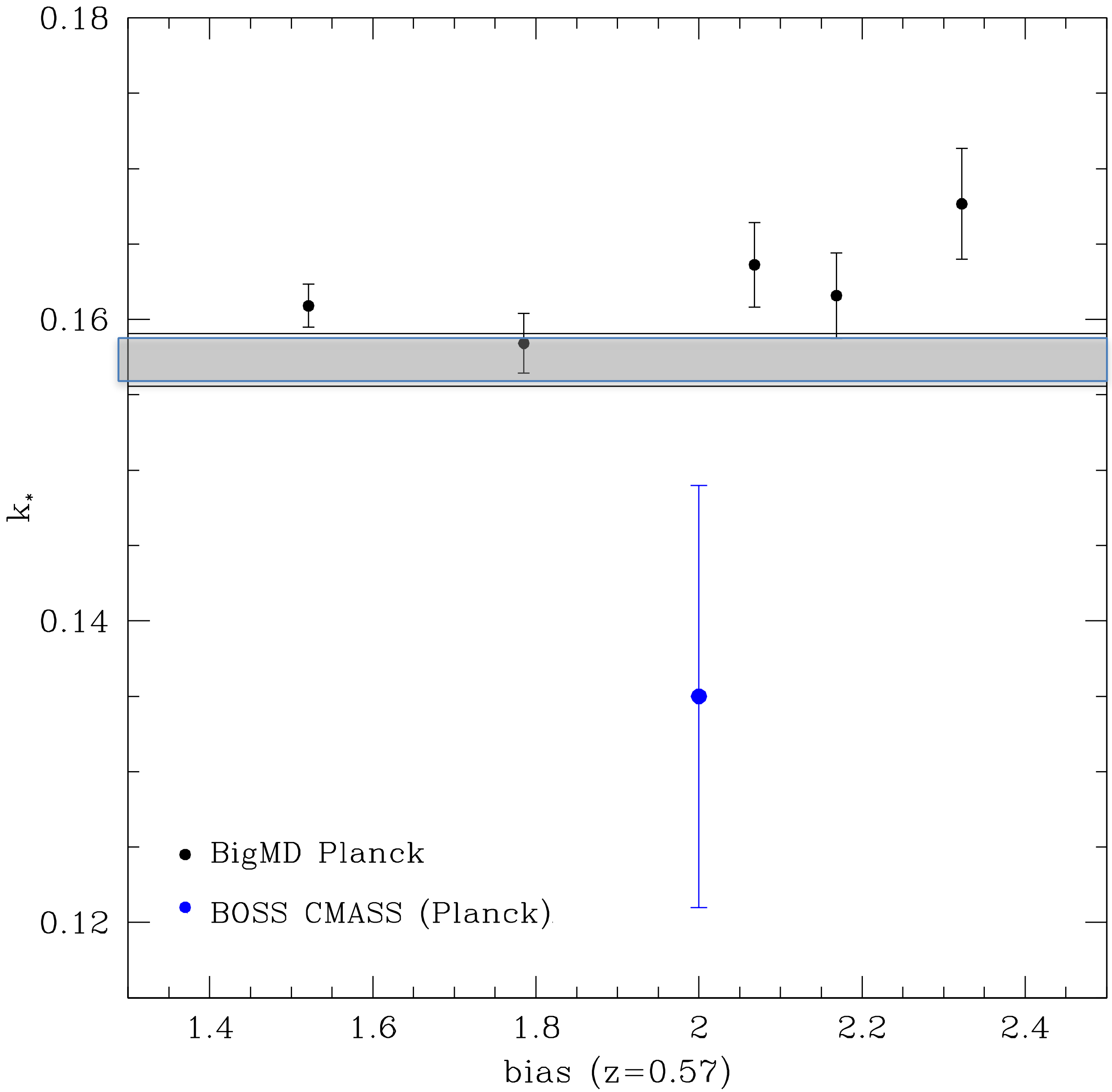


Figure 8. Non-linear evolution of the BAO damping with redshift, in real-space, for our four different halo samples (open symbols). The solid line connects the measurements for the dark matter tracer provided in Table 2

BAO shift as a function of bias



BAO damping as a function of bias



Conclusions

- MultiDark is designed to study LSS and BAO systematics. The suite of MultiDark simulation products is available at *www.skiesanduniverses.org and www.cosmosim.org*
- BAO shift & damping scale, and their evolution with redshift, has been studied both for dark matter and different halo number densities
- Level of BAO systematics in halos and dark matter tracers seems different, and about the same level than observational statistical errors from the new planned surveys such as DESI and Euclid
- It remains to be understood the impact of this study on the BAO modelling and reconstruction