BAO signature in Galaxy Bispectrum

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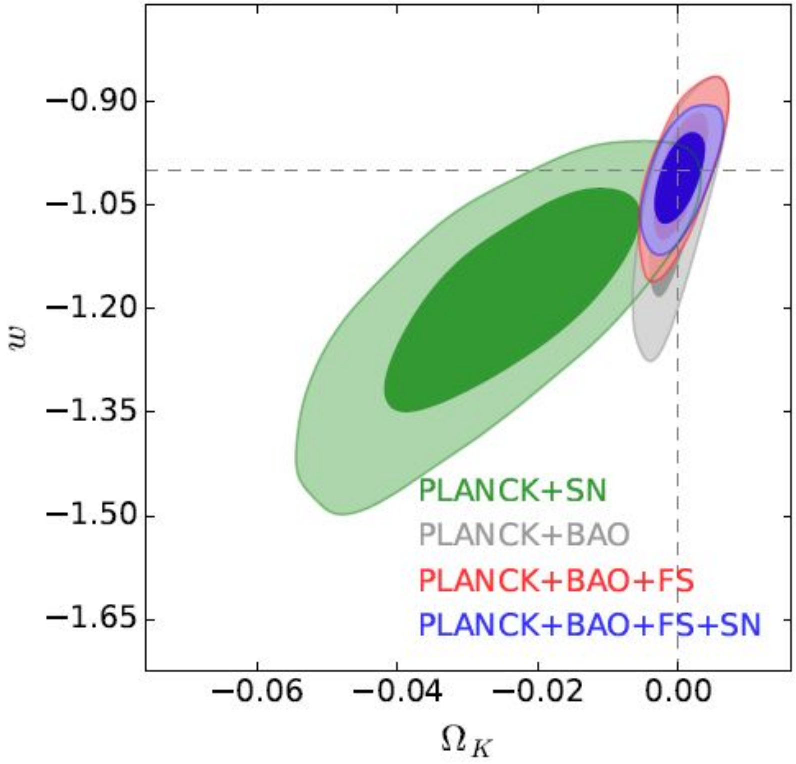
Precision Cosmology Now

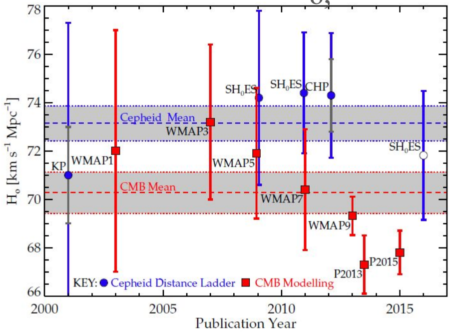
Everything seems to be consistent with the simple LCDM + GR model so far.

Some interesting tensions are present but not statistically significant

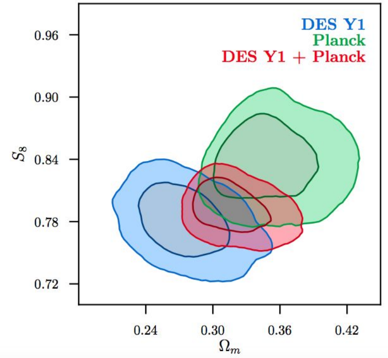
- Discrepancy between local and high redshift H_o values
- Discrepancy between high redshift and low redshift $\boldsymbol{\sigma}_{8,}$ values



BOSS DR12

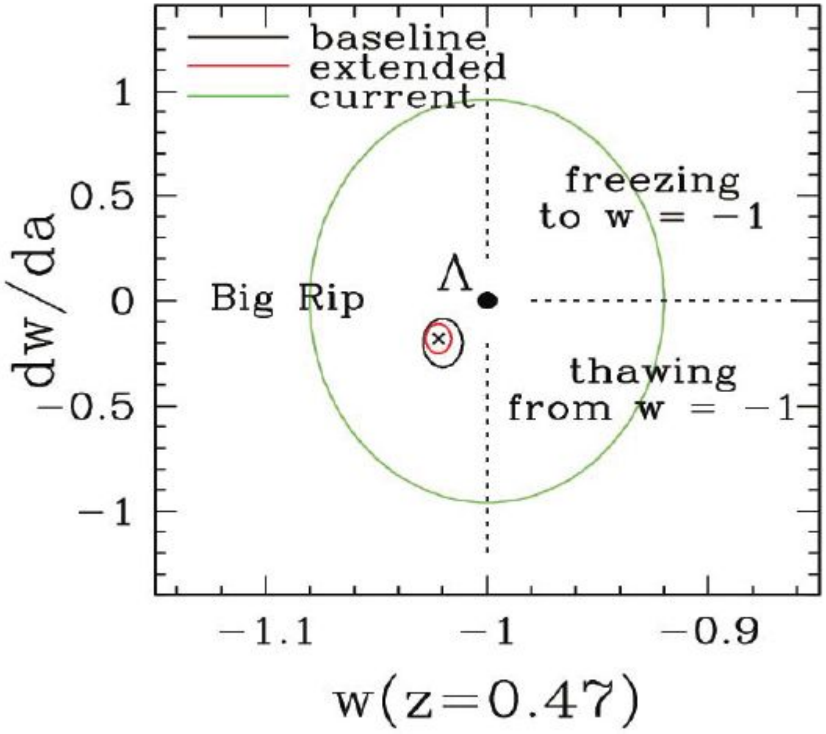


Beaton et al. (2016)



DES Y1

Precision Cosmology 2025



WFIRST SDT (2015)

If there is an interesting deviation from LCDM + GR we should be able to detect it within next decade

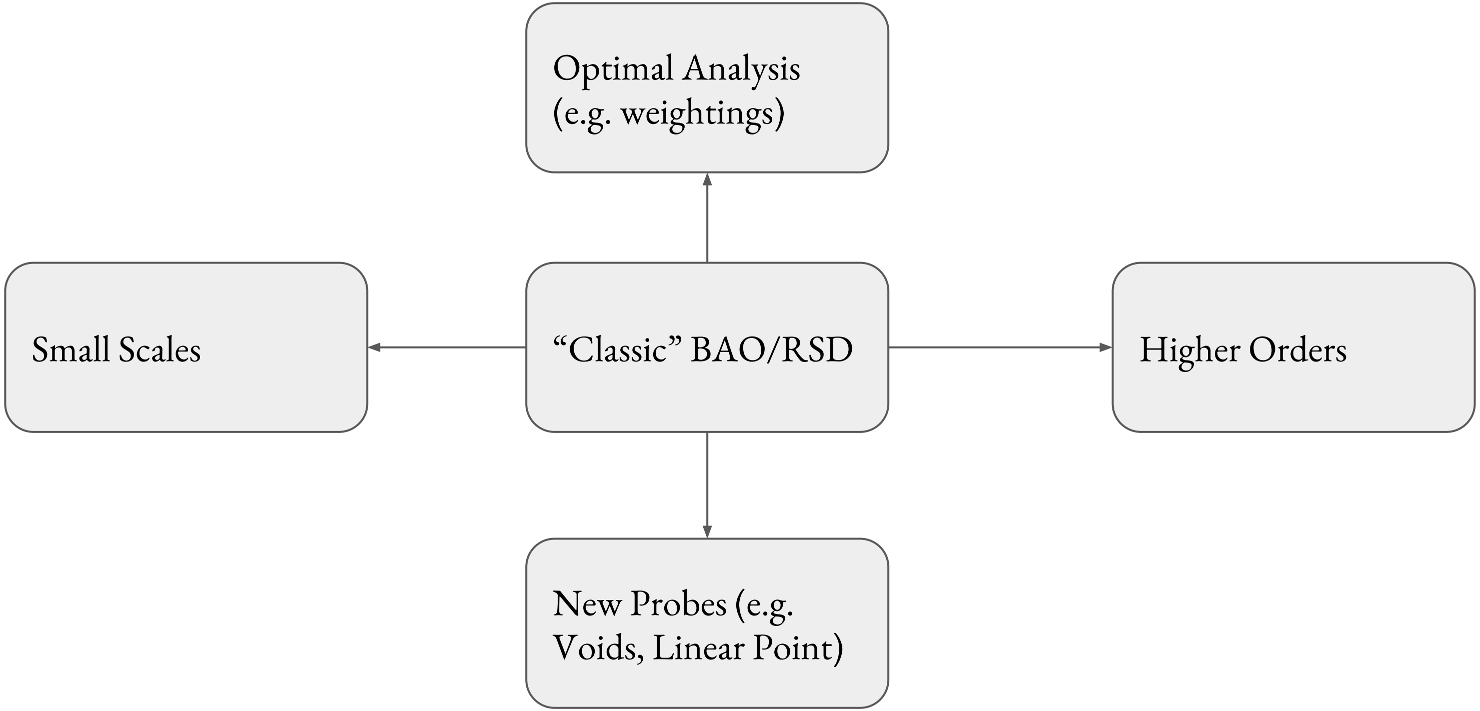
If we get a convincing (~5sigma) detection it will be amazing. 2 to 3 sigma features are not going to be taken seriously.

What if we have 3-5 sigma detections of non-LCDM behaviour?

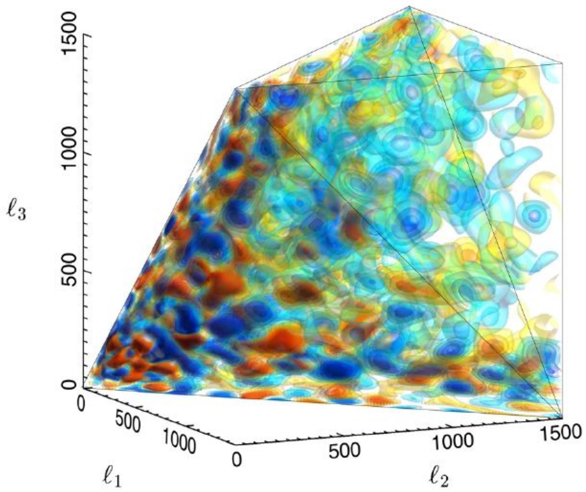
There isn't much room to improve statistical errorbars.

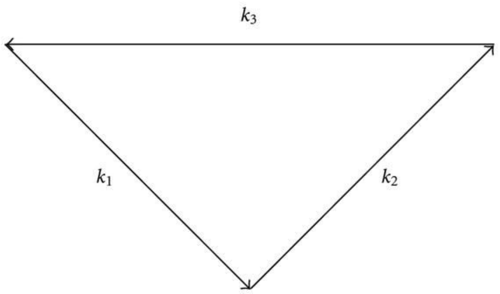
<u>We need to squeeze out as much information as possible from the clustering measurements</u>.

Fishing for More Information

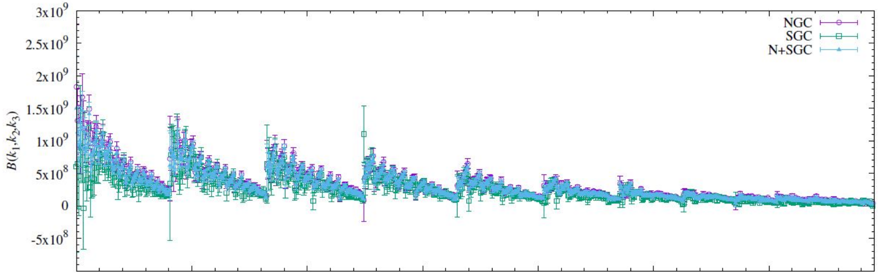


Bispectrum Shape





Planck



Bispectrum is a function of 5 variables

3 wavenumbers determining the triangle “shape”

1 line-of-sight angle

1 angle of rotation around one side

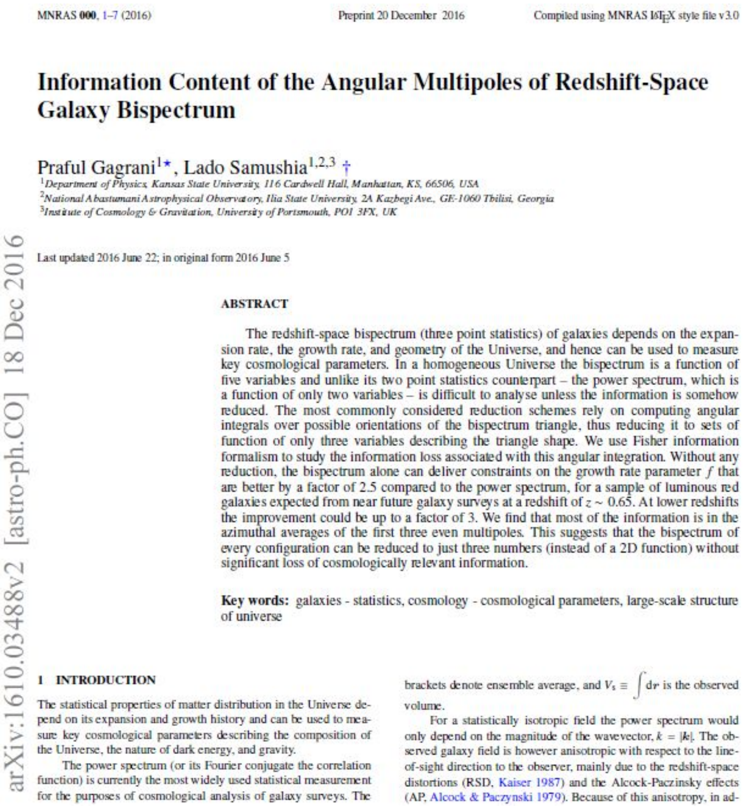
Distortions in this 5D function can yield very powerful cosmological constraints

Cosmological Parameters from Bispectrum

- Bispectrum Shape
  - Initial non-Gaussianities (f_{nl})
  - Gravitational Evolution (low redshift, small scales)
  - Halo/Galaxy bias (b_2)
- Distortions
  - RSD (sensitive to G_{eff} and Ω_m)
  - AP (sensitive to Ω_m, Ω_k, H_0)

Since density fields tend to be close to Gaussian on large-scales the Bispectrum shape may not contain significant (independent of Power spectrum) cosmological information. But low redshift "distortion" effects make the measured bispectrum sensitive to cosmological parameters (in a way that's independent of the power spectrum) even in this case.

Gagrani & Samushia (2017) MNRAS



MNRAS 000, 1–7 (2016) Preprint 20 December 2016 Compiled using MNRAS LaTeX style file v3.0

Information Content of the Angular Multipoles of Redshift-Space Galaxy Bispectrum

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Last updated 2016 June 22; in original form 2016 June 5

ABSTRACT

The redshift-space bispectrum (three point statistics) of galaxies depends on the expansion rate, the growth rate, and geometry of the Universe, and hence can be used to measure key cosmological parameters. In a homogeneous Universe the bispectrum is a function of five variables and unlike its two point statistics counterpart – the power spectrum, which is a function of only two variables – is difficult to analyse unless the information is somehow reduced. The most commonly considered reduction schemes rely on computing angular integrals over possible orientations of the bispectrum triangle, thus reducing it to sets of function of only three variables describing the triangle shape. We use Fisher information formalism to study the information loss associated with this angular integration. Without any reduction, the bispectrum alone can deliver constraints on the growth rate parameter f that are better by a factor of 2.5 compared to the power spectrum, for a sample of luminous red galaxies expected from near future galaxy surveys at a redshift of $z \sim 0.65$. At lower redshifts the improvement could be up to a factor of 3. We find that most of the information is in the azimuthal averages of the first three even multipoles. This suggests that the bispectrum of every configuration can be reduced to just three numbers (instead of a 2D function) without significant loss of cosmologically relevant information.

Key words: galaxies - statistics, cosmology - cosmological parameters, large-scale structure of universe

1 INTRODUCTION

The statistical properties of matter distribution in the Universe depend on its expansion and growth history and can be used to measure key cosmological parameters describing the composition of the Universe, the nature of dark energy, and gravity.

The power spectrum (or its Fourier conjugate the correlation function) is currently the most widely used statistical measurement for the purposes of cosmological analysis of galaxy surveys. The

brackets denote ensemble average, and $V_s \equiv \int d\mathbf{r}$ is the observed volume.

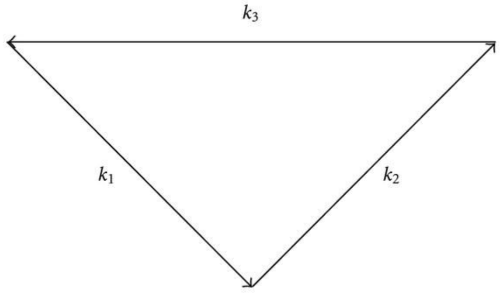
For a statistically isotropic field the power spectrum would only depend on the magnitude of the wavevector, $k = |\mathbf{k}|$. The observed galaxy field is however anisotropic with respect to the line-of-sight direction to the observer, mainly due to the redshift-space distortions (RSD, Kaiser 1987) and the Alcock-Paczinsky effects (AP, Alcock & Paczynski 1979). Because of this anisotropy, in ad-

Power spectrum can be fully described by just a 1D function (or rather 3x1D functions, multipoles)

Bispectrum is a 5D function (3 scales, 2 angles) that is not formally reducible to a finite number of multipoles

- Can we somehow compress raw bispectrum data without losing information?
- How much information is in the WFIRST, Euclid, DESI, bispectrum?

Reducing Bispectrum



Keep three “shape” parameters.

Expand angular dependence in spherical harmonics.

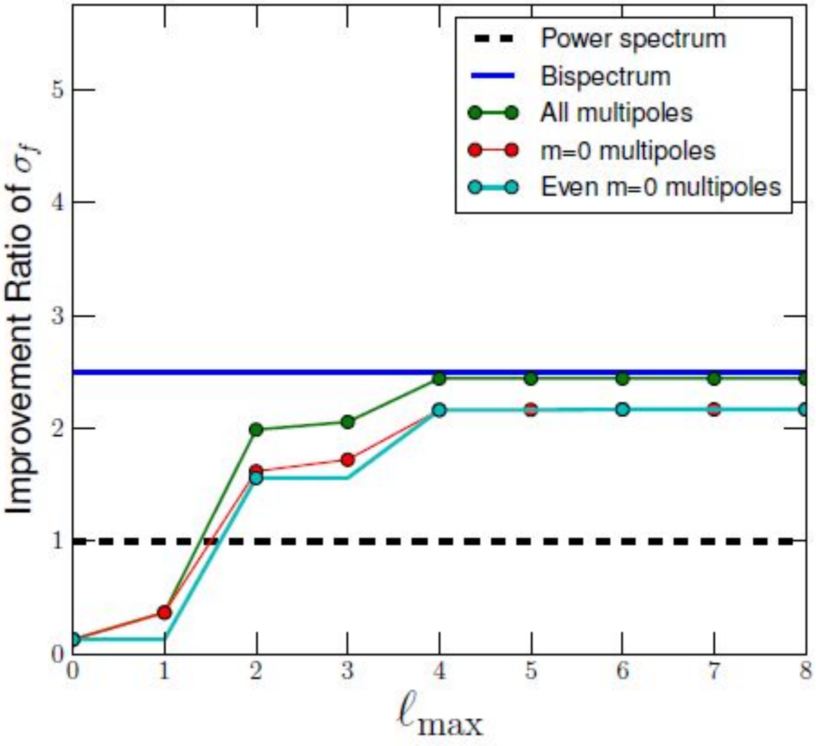
One could go further and expand the “triangle” into two side-lengths and Legendre expansion of the angle in between.

How much information is lost compared to the full 5D bispectrum?

This is difficult to see analytically.

We investigated this question numerically with Fisher matrices.

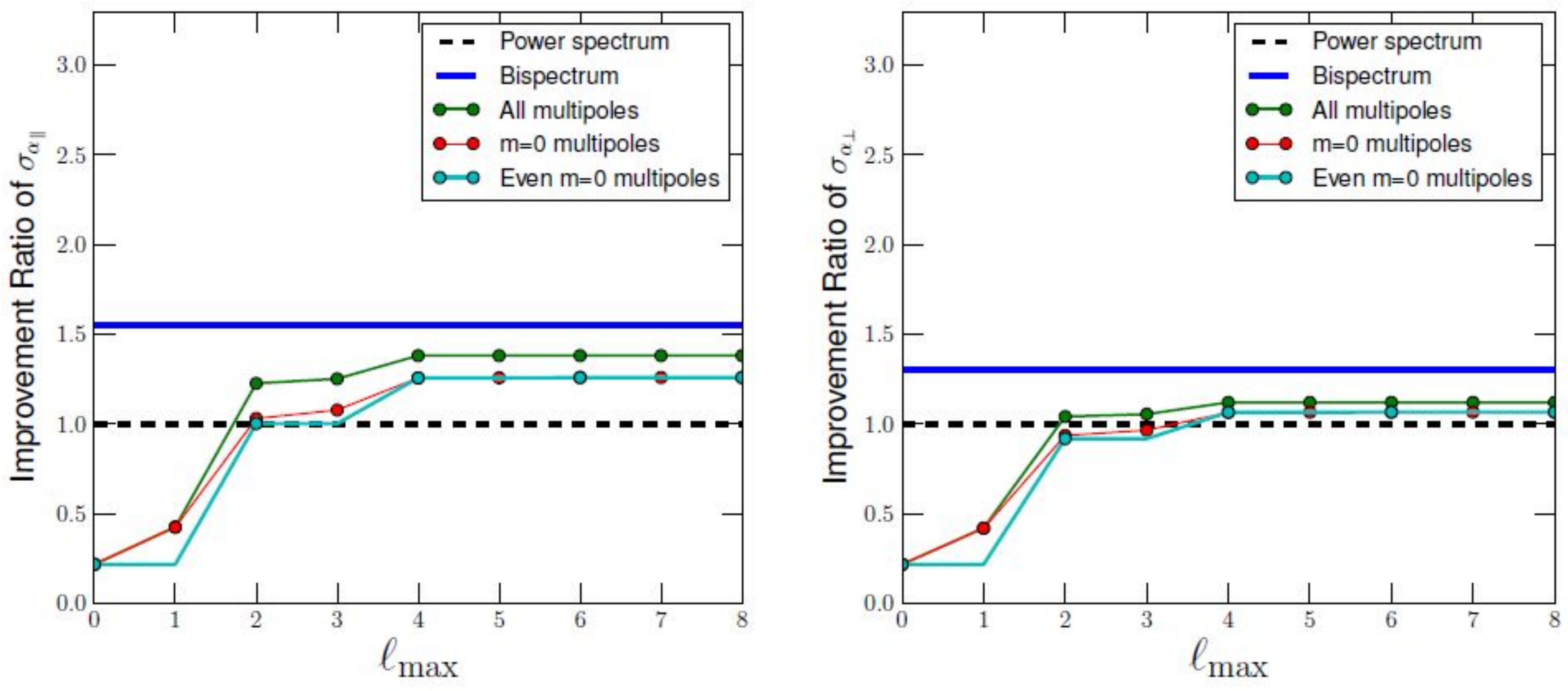
Bispectrum Multipoles - RSD



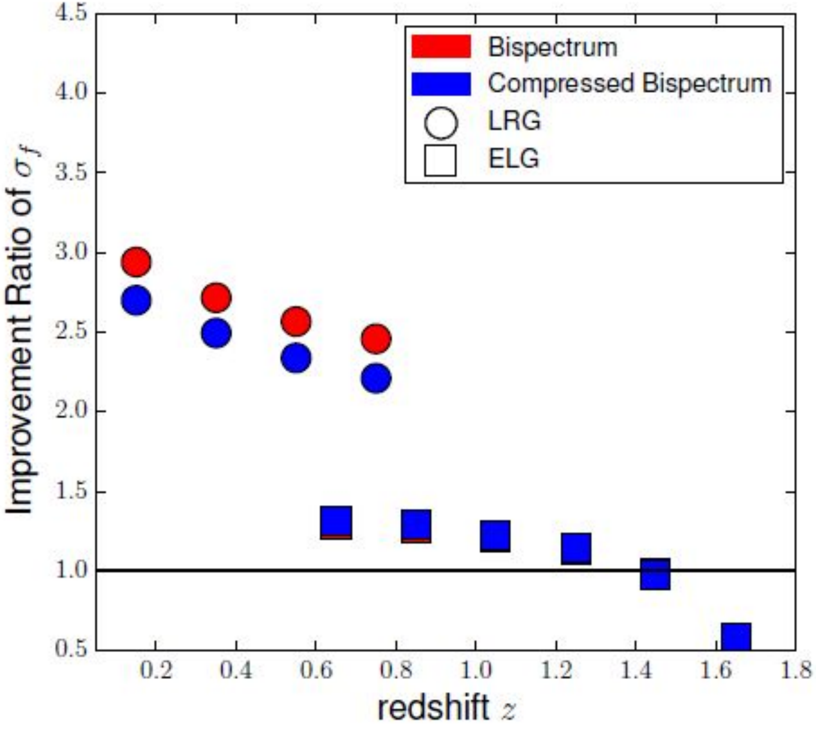
- Even multipoles in LOS angle have most information
- Taking average over the rotational angle does not seem to lose a lot of information
- Information content saturates at l=4

This suggests that taking four multipoles (l=0,2,4) with m=0 conserves most of cosmologically relevant information reducing 5D function to three functions of triangular shape.

Bispectrum Multipoles - BAO



Future Prospects



More importantly, in some cases bispectrum may contain more information than the corresponding power spectrum by a factor of few!

E.g. DESI BGS has a very high density of tracers and the expected RSD errorbars are tighter by a factor of 3 compared to the classic power spectrum based RSD for $k_{max} = 0.2$

DISCLAIMER: As it always is with Fisher matrices those are potential constraints that we may not be able to fully harvest because of modeling systematics.

Where does the information come from?

Bispectrum information content depends very steeply on number density. It also depends very steeply on k_{max}.

The number of triangles scales as k^3_{max} while number of pairs scales as k^2_{max}

High number density allows going to higher k-values.

$(P_k + n^{-1})$ vs $(B_{kk} + n^{-2})$.

For dense surveys (WFIRST, DESI BGS) bispectrum has a lot of constraining power.

Pearson & Samushia (2018) MNRAS

MNRAS 000, 1–13 (2017) Preprint 18 December 2017 Compiled using MNRAS LaTeX style file v3.0

A Detection of the Baryon Acoustic Oscillation Features in the SDSS BOSS DR12 Galaxy Bispectrum

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Accepted XXX. Received YYY; in original form 2017 December 12

ABSTRACT
We present the first high significance detection (4.1σ) of the Baryon Acoustic Oscillations (BAO) feature in the galaxy bispectrum of the twelfth data release (DR12) of the Baryon Oscillation Spectroscopic Survey (BOSS) CMASS sample ($0.43 \leq z \leq 0.7$). We measured the scale dilation parameter, α, using the power spectrum, bispectrum, and both simultaneously for DR12, plus 2048 MultiDark-PATCHY mocks in the North and South Galactic Caps (NGC and SGC, respectively), and the volume weighted averages of those two samples (N+SGC). The fitting to the mocks validated our analysis pipeline, yielding values consistent with the mock cosmology. By fitting to the power spectrum and bispectrum separately, we tested the robustness of our results, finding consistent values from the NGC, SGC and N+SGC in all cases. We found $D_V = 2032 \pm 24(\mathrm{stat.}) \pm 15(\mathrm{sys.})$ Mpc, $D_V = 2038 \pm 55(\mathrm{stat.}) \pm 15(\mathrm{sys.})$ Mpc, and $D_V = 2031 \pm 22(\mathrm{stat.}) \pm 10(\mathrm{sys.})$ Mpc from the N+SGC power spectrum, bispectrum and simultaneous fitting, respectively. Our bispectrum measurement precision was mainly limited by the size of the covariance matrix. Based on the fits to the mocks, we showed that if a less noisy estimator of the covariance were available, from either a theoretical computation or a larger suite of mocks, the constraints from the bispectrum and simultaneous fits would improve to 1.1 per cent (1.3 per cent with systematics) and 0.7 per cent (0.9 per cent with systematics), respectively, with the latter being slightly more precise than the power spectrum only constraints from the reconstructed field.

Key words: large-scale structure of Universe – distance scale – cosmology: observations

1 INTRODUCTION

The bispectrum is sensitive to non-Gaussianities in the galaxy density field from primordial physics, gravitational dynamics, velocity distortions and biasing. However, bispectrum estimates are quite noisy since one can only average

DESI Collaboration et al. 2016), will simultaneously cover a large volume and have a high number density, making the constraining power of the bispectrum comparable to that of the power spectrum (Gagrani & Samushia 2017).

Recent studies, making use of the Sloan Digital Sky

Test BAO detection analyses on BOSS DR12 mocks. Check whether there are biases.

Measure BAO signature in BOSS DR12 Bispectrum monopole.

- How strong is the BAO detection?
- Is the scale consistent with other, more conventional measurements?
- How much information does the Bispectrum BAO add?

2pt constraints

BAO only

- Virtually free of systematics
- Only uses the BAO feature, less information

Full shape (RSD)

- Potential systematics, especially on smaller scales
- Uses full shape, much more information

BAO only measurements schematics

- Take a correlation function/power spectrum model
- marginalize over amplitude parameters
- marginalize over all sensible smooth functions (different positive and negative powers of scale)

Since the shape/amplitude are marginalized over we do not need to worry about the broadband model as long as the “BAO shape” in the model is roughly correct.

The nuisance parameters will absorb any systematics in the incorrect modeling of shape.

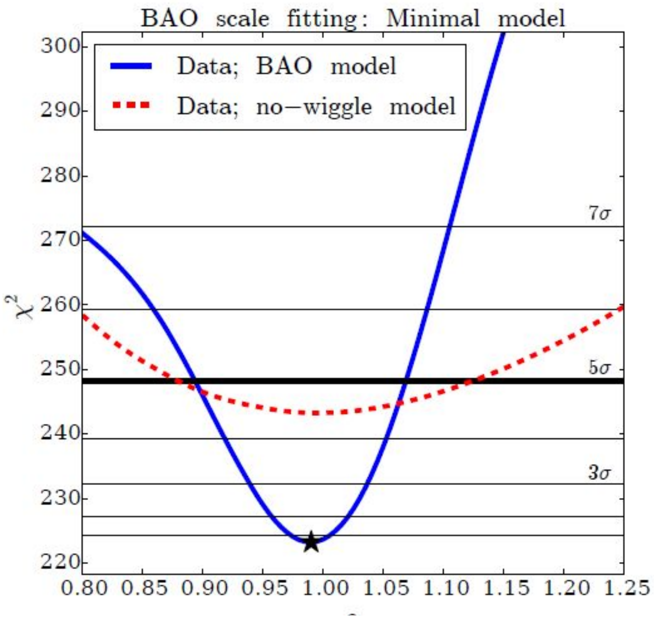
Recent 3pt analyses

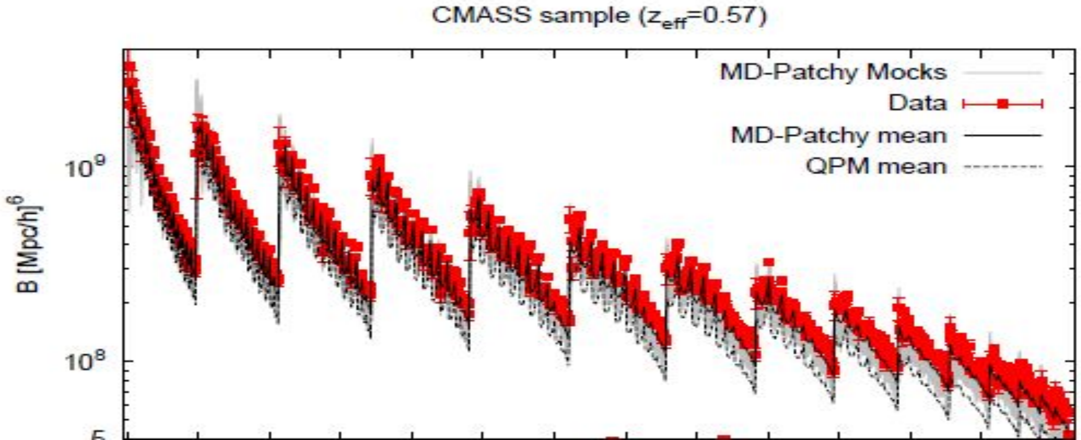
BOSS Power Spectrum + Bispectrum monopole to constrain growth rate and second order bias

Gil-Marin 2015, 2017

BOSS three point function monopole to measure BAO peak position

Slepian (2017a,b)

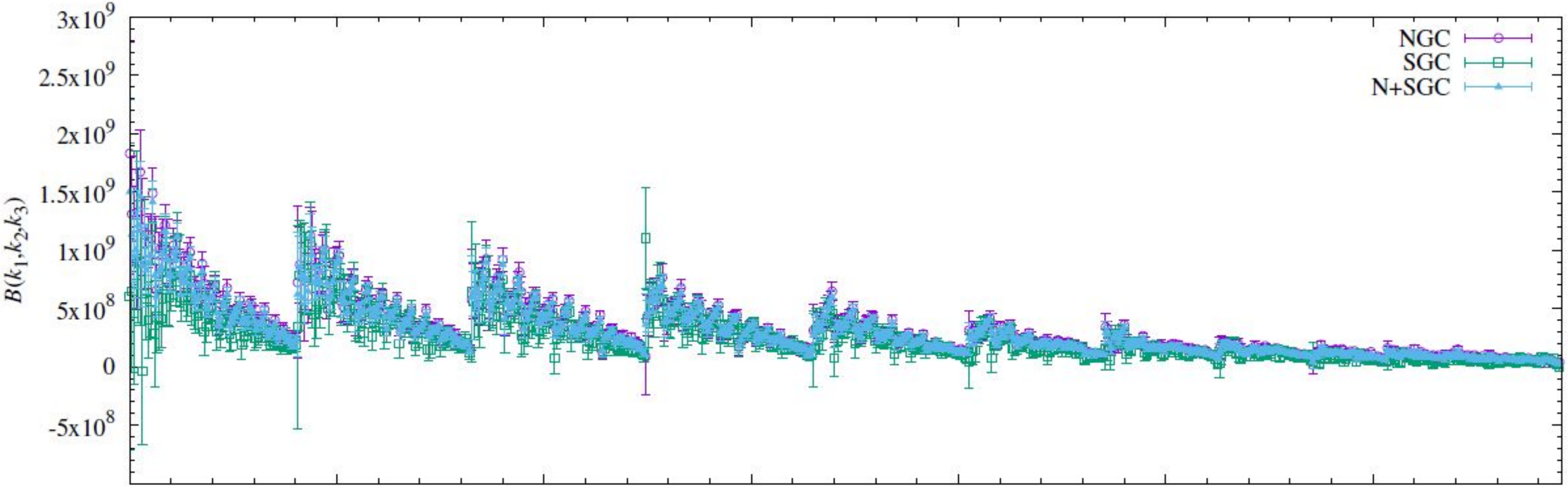




BOSS BAO measurements

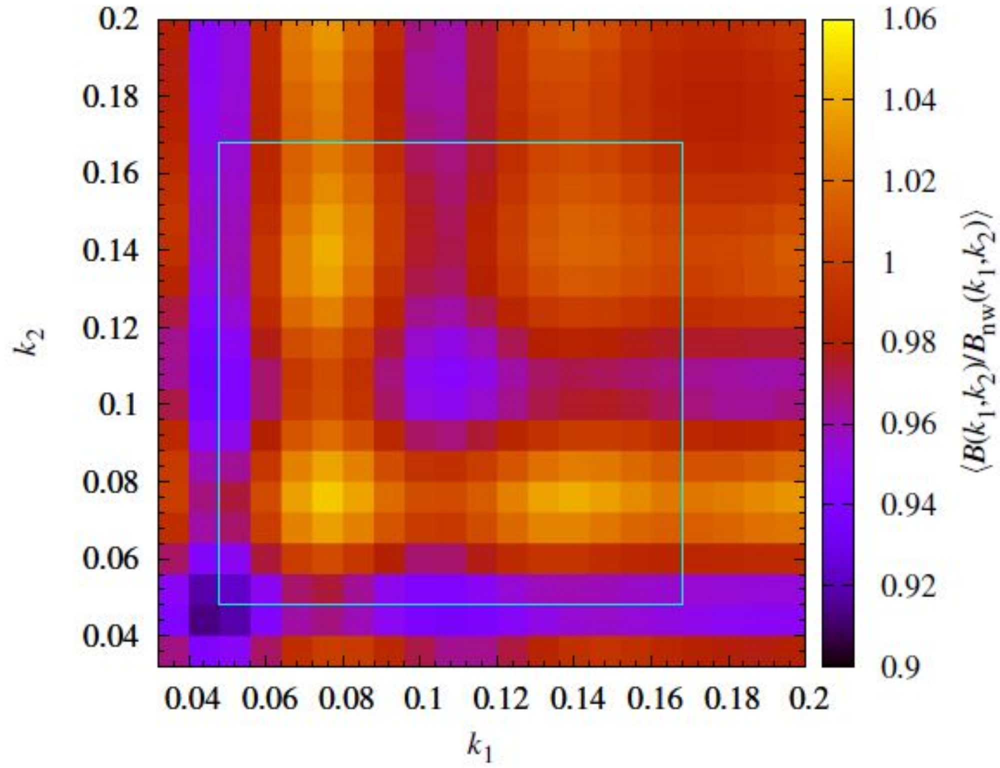
Power Spectrum	Correlation Function
Bispectrum	Three Point Function

Bispectrum of BOSS CMASS



Bispectrum of BOSS CMASS galaxies

BAO Signature in the Bispectrum



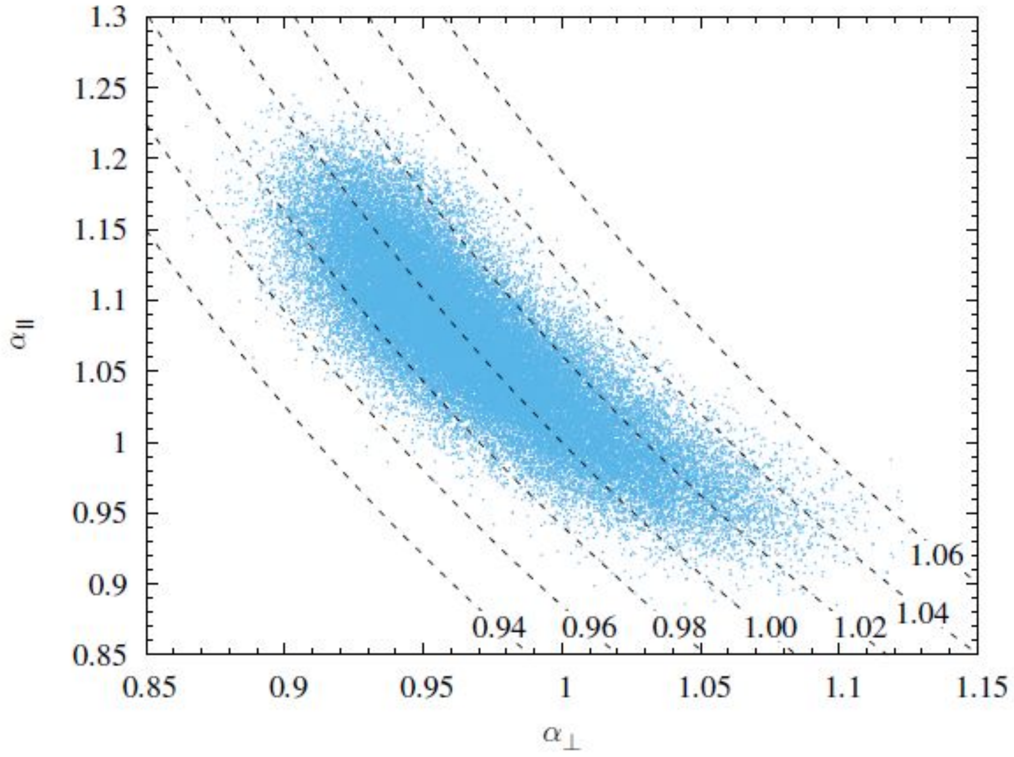
Since we are fitting to a very specific signal it would be nice to “see” where the best-fit values come from.

Bispectrum marginalized over one of the wavenumbers clearly displays a 2D pattern of BAO hills and valleys.

We used the raw data in the previous slide in the k-range inside cyan box.

Fitting anisotropic BAO

$$D_V(z) = \left[cz(1+z)^2 D_A^2(z) H^{-1}(z)\right]^{1/3}$$



Bispectrum monopole can only constrain one combination of transverse and line-of-sight BAO scales.

Not clear a priori what that scale should be.

Our MCMC chains suggest it is the same combination D_V as the one constrained by the power spectrum.

Results

4.5 sigma detection of the BAO peak

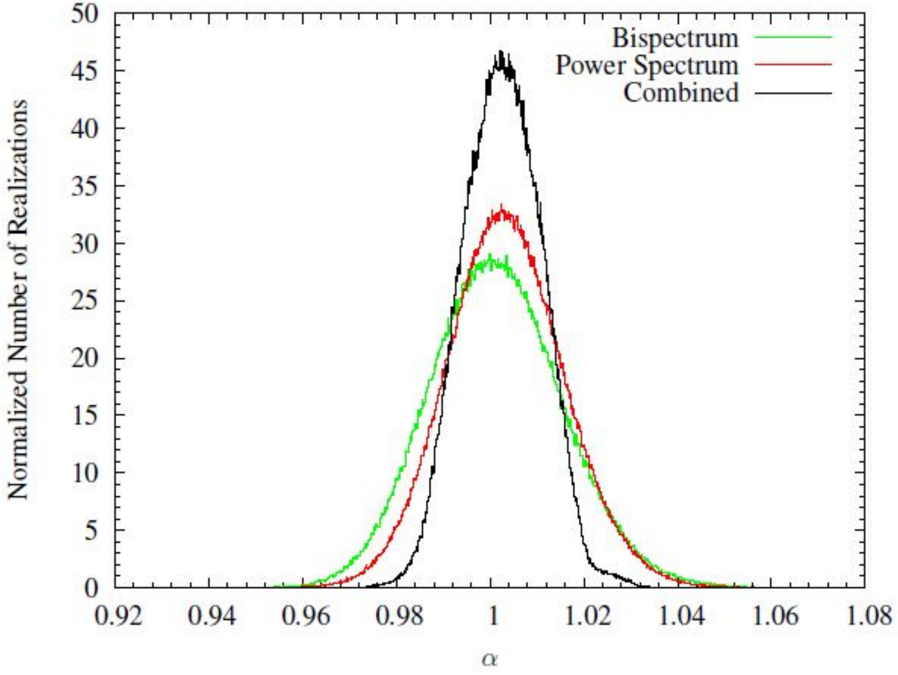
~ 2 per cent precision on the BAO peak position (distance scale)

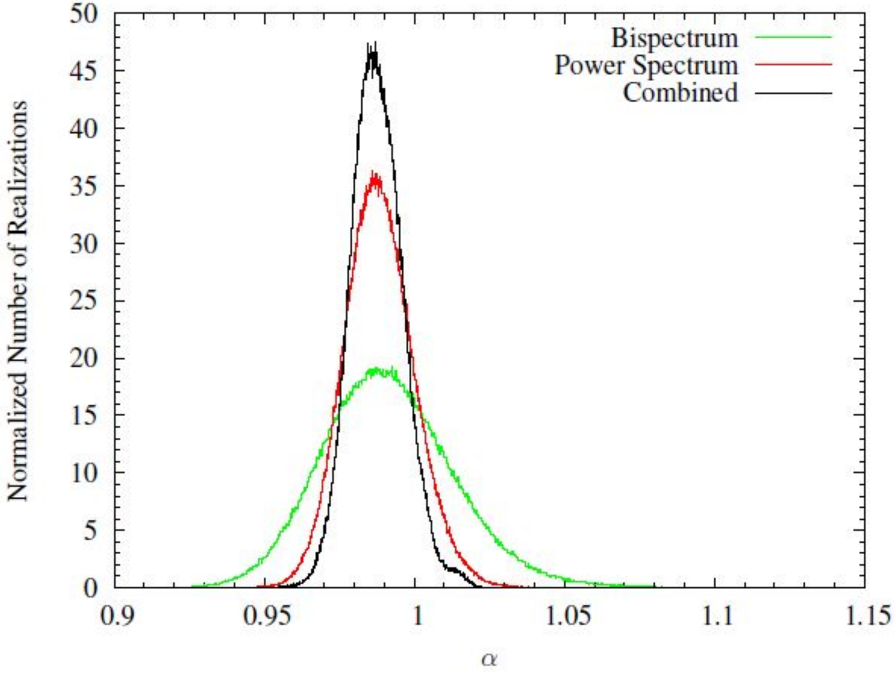
Consistent with all previous BOSS measurements

Joint fits improve the BAO scale by ~ 30 per cent compared to the power spectrum only results

The cross correlation between Bkk BAO and Pk BAO is somewhere between 20 and 40 per cent

BAO scale constraints





~ 2% precision

Reconstruction vs 2pt+3pt

Reconstruction partially removes nonlinearities by moving galaxies back to their linear displacement.

Clearly sharpens the BAO measurements.

Can not be used with the full shape (RSD) measurements, since it is unclear exactly how to model its effects.

We believe that reconstruction is equivalent to extracting higher order information, or in other words joint bispectrum/power spectrum analysis may be an alternative to reconstruction + full shape 2pt. (Why?)

Could it be better?

Things to improve

- For our analysis the limiting factor was accuracy of covariance (and joint covariance) matrices. More mocks or a good covariance model would reduce the systematic error
- Nonlinear shifts in the bispectrum will need to be better understood for a higher precision data
- Fitting to the full shape will be a much complicated task because we can not sweep the model deficiencies under the rug anymore
- Fitting higher order multipoles will enable to measure H and D_A separately

Summary

- Bispectrum analysis can strongly enhance the clustering constraints from galaxy surveys
- For some surveys (e.g. WFIRST, DESI BGS) the bispectrum is formally superior in terms of information content
- We have made quite a lot of recent progress in this direction (bispectrum estimators, BAO measurements)
- BOSS bispectrum BAO provides a 4.5 sigma detection, and a 30 per cent improvement over power spectrum only measurements