HIERARCHICAL CLUSTERING AND THE BAO SIGNATURE

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In this contribution we present the preliminary results regarding the non-linear BAO signal in higher-order statistics of the cosmic density field. We use ensembles of N-body simulations to show that the non-linear evolution changes the amplitudes of the BAO signal, but has a negligible effect on the scale of the BAO feature. The latter observation accompanied by the fact that the BAO feature amplitude roughly doubles as one moves to higher orders, suggests that the higher-order correlation amplitudes can be used as a probe of the BAO signal.

Keywords: baryon acoustic oscillations, non-linear clustering, dark matter

1. Introduction

Thanks to the impressive development in observational astronomy that we have witnessed in the last two decades, we are living now in the era of the precision cosmology. Growing data sets and galaxy catalogues allow for extraction and measurement of percent-level signals. However, this advance of observational data has however not always matched by an accompanying increase in theoretical understanding. Observations of the evolution and the structure of the large-scale clustering pattern of galaxies has left us with the riddle about the nature of the seemingly dominant yet elusive components of cosmic energy: dark matter (DM) and dark energy (DE). One of the main precision probes of 21st century cosmology is that of the Baryon Acoustic Oscillations (BAO).

The BAO feature in the cosmic density field is closely related to the size of the sound horizon during at recombination era. The measurements of the size of the BAO feature in the low-redshift Universe constrain the cosmic expansion history. Such measurements, in principle, should have discriminatory power to distinguish between dynamical DE models and the cosmological constant.

Measurements of the BAO feature have been reported for the power spectrum and the two-point correlation function of galaxies. However there are well-known
systematics and non-linear effects that lower the accuracy of the two-point statistics. The most important among them are the biasing of galaxies with respect to the dark matter distribution and redshift space distortions. Recently, we have proposed that higher-order statistics of clustering could be a useful probe of the BAO signal (hereafter JHvW). Higher-order clustering amplitudes have the advantage that they are less prone to systematics and non-linear effects. On the other hand, in general they have a lower signal-to-noise level. Here we explore the original idea of JHvW using the N-body simulations. Also, we investigate the idea for higher order statistics beyond that of the three-point clustering measure.

2. Hierarchical amplitudes and the BAO

We define the volume-averaged $J$-point correlation function (of the density/galaxy field) as

$$\bar{\xi}_J = V_W^{-J} \int_S d\mathbf{x}_1 ... d\mathbf{x}_J W(\mathbf{x}_1) ... W(\mathbf{x}_J) \xi_J(\mathbf{x}_1, ..., \mathbf{x}_J),$$

(1)

where $\mathbf{x}_i$ is the comoving separation vector, $W(\mathbf{x})$ is a window function with volume $V_W$, and the integral covers the entire volume $S$. The hierarchical amplitudes $S_n(R)$ of order $n$ are conventionally defined as,

$$S_n(R) = \frac{\bar{\xi}_n}{\xi_2} = \bar{\xi}_n \sigma^{-2(n-1)}$$

(2)

with volume-averaged correlation functions $\bar{\xi}_n(R)$ and the variance $\sigma^2(R)$ implicitly depending on the smoothing scale $R$. Using perturbation theory (PT), Juszkiewicz et al. showed that the reduced skewness ($S_3$) of the density field is a function of the logarithmic slope of the variance (power spectrum) at a given smoothing scale $R$. Furthermore, Bernardeau showed that also higher-order clustering amplitudes are functions of higher-order derivatives of the variance. JHvW noticed that the unique feature of the BAO signal, the so-called wiggles, should be imprinted also in the slope of the variance, and hence in the high-order hierarchical amplitudes.

3. Results

Here we present the preliminary results of our N-body simulations. We have conducted high-resolution N-body simulations using the publicly available code by Volker Springel - Gadget2. To assess the exact features resulting from the presence of the BAO signal we have used two ensembles of simulations. In one of these, we applied initial conditions generated with BAO wiggles smoothed-out (dubbed 'no-wiggles'). In the other, we implemented the initial density field with fully consistent BAO features.

Our results are summarised in Figure 1. In the left panel we plot the prediction of the BAO signal for the reduced skewness $S_3$ computed using PT, together with the signal obtained from the simulations. The fully non-linear evolution of the structure
Fig. 1. *Left:* Comparison of the PT prediction and the fully non-linear evolution for the case of $S_3$. *Right:* the shape and the amplitude of the BAO signal for $S_3$, $S_4$ and $S_5$.

formation lowers the amplitude of the BAO signal by $\sim 33\%$ compared to PT. However, an important thing to note here is that the non-linear effects seem to have negligible impact on the *scale* of the BAO feature in the hierarchical amplitude. This has profound consequences, as this is the scale associated with the BAO signature. We should remind that it is the BAO scale that constrains the expansion history, not the amplitude. In the right hand side panel we plot the BAO feature measured from simulations for the first three amplitudes - $S_3$ (skewness), $S_4$ (kurtosis) and the $S_5$. The plot shows that when one moves to statistics of one order higher, the amplitude of the BAO signal doubles. Such a behaviour of the BAO signature in the high-order clustering amplitudes opens a possibility to extract this signal from the current and future large and deep galaxy redshift surveys, avoiding to some extent the systematic effects that lower the accuracy of the two-point statistics.

**Acknowledgements**

Soon after we started working on this project, Roman Juszkiewicz had undergone a dramatic deterioration of health, as a result of which he passed away on 28th January 2012. We leave this contribution as another tribute to a leading scientist and teacher who was a great friend to the entire community.

**References**