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Modeling the galaxy distribution with perturbation theory and nonlinear stochastic biasing

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The distribution of galaxies contains valueable cosmological information about the underlying dark matter field and the primordial fluctuations of the Universe. Understanding the physical and statistical nature of galaxies is fundamental to make a precision analysis of the Large-Scale Structure and infer cosmological quantities from them. We use a combination of perturbation theory and nonlinear deterministic and stochastic bias descriptions to study and reproduce the halo distribution from N-body simulations.

In particular, we have developed a new fast and efficient approach to model structure formation with Augmented Lagrangian Perturbation Theory (ALPT, *KH13*). Our method is based on splitting the displacement field into a long and a short-range component. The long-range component is computed by second order LPT (2LPT). This approximation contains a tidal nonlocal and nonlinear term. 2LPT fails on small scales due to severe shell crossing and a crude quadratic behaviour in the low density regime. The spherical collapse (SC) approximation has been recently reported to correct for both effects by adding an ideal collapse truncation. However, this approach fails to reproduce the structures on large scales where it is significantly less correlated with the *N*-body result than 2LPT or linear LPT (the Zeldovich approximation) (see Fig. 1). We propose to combine both approximations using for the short-range displacement field the SC solution. A Gaussian filter with a smoothing radius r_S is used to separate between both regimes. We use the result of 25 dark matter only *N*-body simulations to benchmark at $z = 0$ the different approximations: 1st, 2nd, 3rd order LPT, SC and our novel combined ALPT model. This comparison demonstrates that our method improves previous approximations at all scales showing ∼25% and ∼75% higher correlation than 2LPT with the *N*-body solution at $k = 1$ and $2\ h\ \mathrm{Mpc}^{-1}$, respectively.

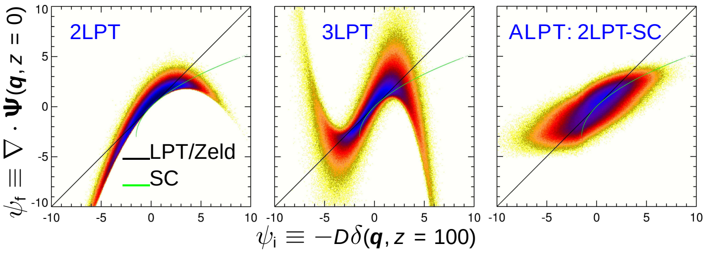

Figure 1: Cell-to-cell correlation between the linear initial overdensity field $D\delta(\mathbf{q}, z = 100)$ (D: growth factor) and the corresponding approximations for the divergence of the displacement field for the 10th realisation of our set of simulations. The solid black line represents the LPT/Zeldovich approximation and the green curve the local SC model, which approximately fits the mean *N*-body relation. The nonlocal relations are given by the contours for various approximations: **left panel:** 2LPT (quadratic relation). **Middle panel:** 3LPT (cubic relation) and **right panel:** combined 2LPT-SC with $r_S = 4\ h^{-1}$ Mpc. The dark colour-code indicates a high number and the light colour-code a low number of cells.

ALPT was implemented in the KIGEN-code (*K13; Ketal12*) and has enabled us to reconstruct the primordial fluctuations of the Local Universe with high precision, and perform constrained simulations (*HKG13*) and to search for the WHIM (SKAM13).

Based on ALPT we have developed the PATCHY-code to perform mock galaxy catalogs (*KYP13*). We account for the systematic deviation of perturbative approaches from N-body simulations together with halo biasing adopting an exponential bias. We then account for stochastic biasing by defining three regimes: a low, an intermediate and a high density regime, using a Poisson distribution in the intermediate regime and the negative binomial distribution including an additional parameter to model over-dispersion in the high density regime (*KM13*). Since we focus in this study on massive halos, we suppress the generation of halos in the low density regime. The various nonlinear biasing parameters, stochastic biasing parameter and density thresholds are calibrated with the large BigMultiDark N-body simulation to match the power spectrum of the corresponding halo population (see Fig. 2).

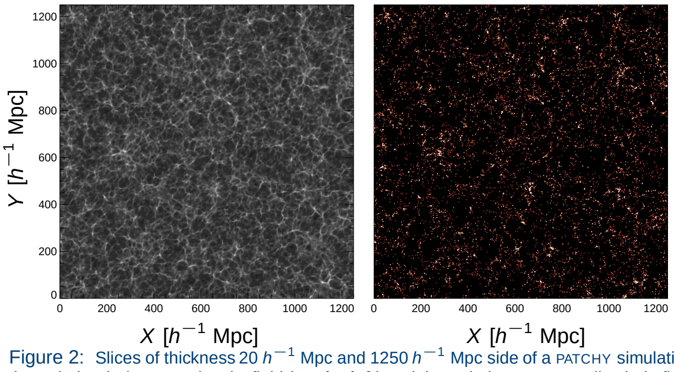

Figure 2: Slices of thickness 20 h^{-1} Mpc and 1250 h^{-1} Mpc side of a PATCHY simulation through the dark matter density field (**on the left**) and through the corresponding halo field (**on the right**). The logarithm of the density fields are shown. Lighter regions represent higher densities.

Our model effectively includes only 4 parameters, as they are additionally constrained by the number density. Our mock catalogs show power spectra which are compatible with N-body simulations within about 2% up to k ∼ 1 h Mpc^{-1} at redshift z = 0.577 for a sample of halos with the typical BOSS CMASS galaxy number density (see Fig. 3). The corresponding correlation functions are compatible down to a few Mpc (see Fig. 4). We also find that neglecting over-dispersion in high density regions produces power spectra with deviations of 10% at k ∼ 0.4 h Mpc^{-1}. These results indicate the need to account for an accurate statistical description of the galaxy clustering for precise studies of large-scale surveys.

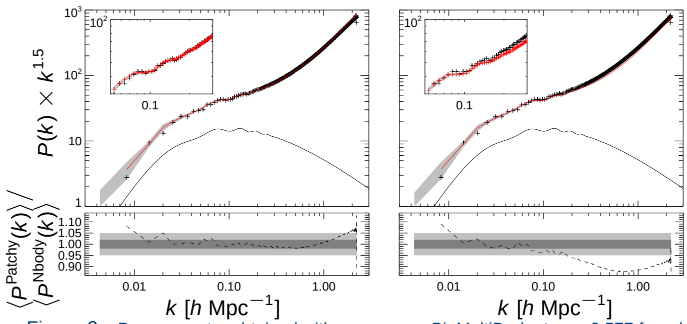

Figure 3: Power spectra obtained with PATCHY vs. BigMultiDark at $z = 0.577$ for a halo sample with number density $3.6 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ h^3$. The red line corresponds to the mean of 50 PATCHY realizations with the corresponding 1-sigma region in grey. The linear power spectrum is also shown (solid black line) as well as the mean over 8 sub-volumes of the BigMultiDark simulation. **Bottom**: Ratio between the mean of the PATCHY realizations and the mean of the N-body sub-volumes. Regions within 2% are inidcated by the dark grey area and 5 % by the lighter one. **On the left** we show the modeling with over-dispersion in high density regions, and **on the right** we perform the modeling only with a Poisson PDF.

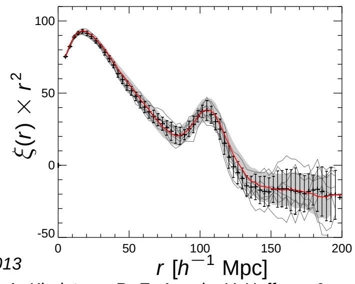

Figure 4: Correlation functions of the PATCHY simulations vs the BigMultiDark N-body simulations. The red line corresponds to the mean of 50 PATCHY realization with the corresponding 1-sigma region in grey. Black crosses: mean over 8 sub-volumes of the BigMultiDark simulation. The error bars indicate 1-sigma regions for the N-body case. Each of the 8 sub-volumes from the N-body simulation is represented by a dashed line.

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