Large scale density profiles surrounding halos as cosmological probe

Paul de Fromont* and J.-M. Alimi

CNRS, Laboratoire Univers et Théories (LUTh), UMR 8102 CNRS, Observatoire de Paris, Université Paris Diderot ; 5 Place Jules Janssen, 92190 Meudon, France
*Email : *paul.de-fromont@obspm.fr*

The understanding of the cosmic acceleration led to the introduction of the cosmological constant behind the standard ΛCDM model. However, there are many hints of the possibility of more complex Dark Energy which could be understand, at first order, as a Dark Fluid with constant equation of state $p_{DE} = w \times \rho_{DE}$. It could also results from a modification of the essence of Gravity such as described in modified gravity models.

In this work we show that it is possible to constraint those models using the large scale density profiles surrounding extrema in the density field such as Dark Matter (DM) Halos or their symmetric, Cosmic Voids. Those profiles can be parametrized in such a way that they conserve, *whatever the underlying dynamics*, some properties in their evolution. Using this property we are able to reconstruct the profile from its analytical expectation from the Gaussian Random Field statistics.

Keywords: Cosmology; dark energy; large scale structures; numerical simulations.

1. Introduction

Here we present a method to reconstruct the mass and velocity profiles of the large scale matter field surrounding extrema in the density field and in particular around cosmic Halos (central over-densities).

We show that, from the compensation property of each profile (the central over/under density has to be compensated), each profile is surrounded by a compensation belt whose shape and amplitude can be predicted in a given cosmology and can be used to constrain cosmological parameters such as the matter density Ω_m and the Dark Energy equation of state w.

One key point of this work is the immediate application to the study of Cosmic Voids. From the symmetry of the initial density field statistics, the initial profiles seeding Halos are the exact symmetric of the voids progenitor (with $\nu \to -\nu$). Indeed, Cosmic Voids have been recently used to probe cosmology from their shape and statistics[4–6] and this work takes place in this seek for cosmological informations from those observables.

The work presented here is developed de Fromont & Alimi[7] and its following papers.

2. Large scale density profiles surrounding halos

N-body simulations

In this work, we used N-body simulations from the "Dark Energy Universe Simulation" (DEUS)[a] (see Rasera et al.[2], Alimi et al.[3] for an introduction to the DEUS simulations).

[a]http://www.deus-consortium.org/

In this study we considered only the flat ΛCDM model with parameters calibrated from *WMAP*-5 data. The reduced Hubble constant is set to $h = 0.72$ and the cosmological parameters are : $\Omega_{DE} = 0.74$, $\Omega_b = 0.044$, $\sigma_8 = 0.79$ and $n_s = 0.963$.

In this paper we use data from simulation with $2592\,h^{-1}$ Mpc boxlength and 2048^3 particles.

Dark matter halos as tracers for cosmic maximums in the density field

From the numerical simulation we have access to the halos as detected by the FOF algorithm[b]. Typically, selecting a halo with mass M_h is in first approximation equivalent to select an initial over-density with a $\nu \simeq \delta_c/\sigma_0(m)$ where δ_c is $\delta_c \simeq 1.686$ for ΛCDM cosmology. The halos selected for this work have physical masses of $M_h \sim 1.5 \times 10^{13}\ h^{-1} M_\odot$ (see Fig. 1)

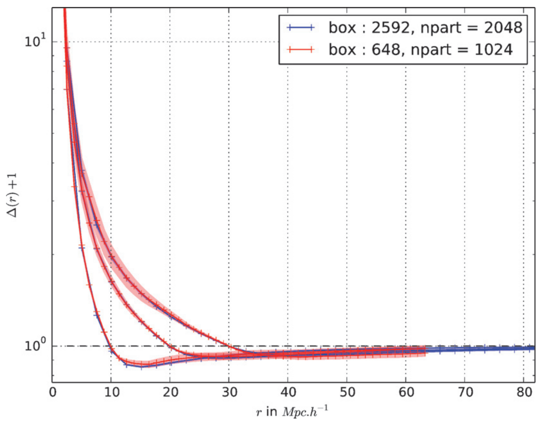

Fig. 1. Mass contrast profile as defined in Eq.(1) for different mass radius R_1 and two different simulations with the same halo mass. This illustrates the coherence of the measured profiles which does not depends on the simulation parameters once the physical properties are set, *i.e.* for fixed halo mass and radius.

In this context, halos are used to spot the maximums in the underlying dark matter density field. From the position of a halo, we compute the total mass profile in concentric shells around the center of the halo for radius far beyond the size of the halo (as defined by r_{200} or any radius convention). This leads to the averaged mass contrast profile $\Delta(r)$ defined through

$$\Delta(r) + 1 \equiv \frac{m(r)}{\bar{m}(r)} = \frac{3m(r)}{4\pi\bar{\rho}_m r^3} \tag{1}$$

[b]With a linking factor $b = 0.2$.

where $m(r)$ is the mass enclosed in the sphere of radius r. For each profile we show that there exist a single radius R_1 such as $\Delta(R_1) = 0$. Physically, it corresponds to the sphere where the enclosed mean density reaches the background density[c].

The mass profiles are then completely defined by two independent parameters: the mass of the halo M_h and the radius R_1 where the mass recovers the background mass.

Stacking the profiles

Although the density profile around one single halo is far from being spherically symmetric[d], we construct spherically symmetric profiles by stacking profiles with the same physical parameters, *i.e.* with the same mass M_h and the same mass radius R_1.

This stacking procedure can be seen as an average on a large number of statistical realizations of the same region surrounding halo.

Dynamical properties of stacked profiles

It is important to note that from the definition of R_1, the mass enclosed in this sphere is *compensated* in the sense that the over-mass in exactly compensated by the under-density such as the mean density in this sphere is exactly the background one. Formally, this isolated *bubble Universes* which size will growth proportionally to the scale factor. This is illustrated in the following figure.

3. Reconstructing density profiles from initial conditions

Initial conditions

The initial conditions are assumed to correspond to the Last Scattering Surface where first photons decoupled from the matter soup at redshift $z_{init} \sim 1100$. At this redshift, the DM density field follows a Gaussian Random Field statistics[e]. This Gaussian field is fully determined by its Linear Power-Spectrum $P_{lin}(k)$ and the level of fluctuations σ_0.

From Bardeen et al. [1], we have access to the spherically averaged initial profile $\langle\delta\rangle$ from Gaussian Random Field assuming it is centred on an extremum in the density field. It is given by the two-points correlation function of the field $\xi(r) = \sigma_0^2(r)$ and its second derivative $r^{-2}\partial_r(r^2\partial_r\xi(r)) = \sigma_1^2(r)$.

If we want to make the link with the observed numerical profiles, we must introduce a new parametrisation of the initial profile which includes the condition

[c] One have to note that it is bigger than the radius where the *local* density reaches the background density.
[d] Even in the initial condition, see Bardeen et al. [1]
[e] At least assuming that the non-Gaussianity are negligible at first order.

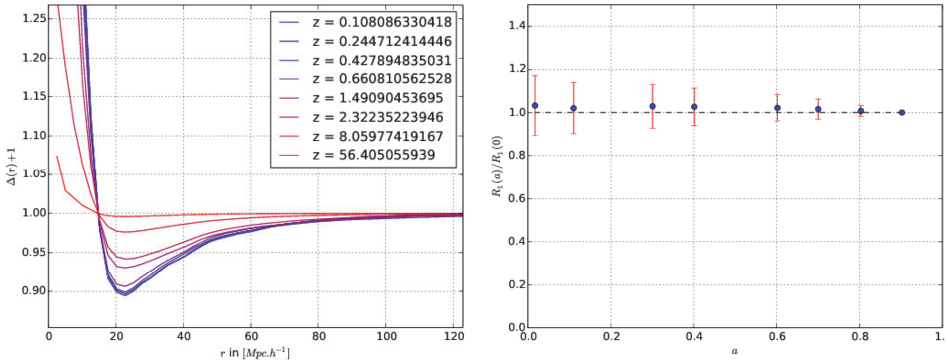

Fig. 2. On the left, plot of the mean mass contrast profile for a fixed radius $R_1 = 15\ h^{-1}Mpc$ and for various redshift in comoving coordinates. On the right, measure of $R_1(z)/R_1(0)$ using 10000 halos. We used the reference simulation with halos of mass $M_{halo} \sim 3 \times 10^{13}\ h^{-1}Mpc$. Since R_1 is measured in *comoving* coordinates, this shows that this radius evolves exactly as the scale factor $R_1(t) \propto a(t)$.

$\Delta(R_1) = 0$. The corresponding profile can then be written as

$$\langle\delta\rangle(r) \propto \sigma_0^2(r) - \frac{\bar{\sigma}_0^2(R_1)}{\bar{\sigma}_1^2(R_1)}\sigma_1^2(r)$$

where $\bar{\sigma}_i^2(r) = 3r^{-3}\int u^2\sigma_i^2(u)du$ and using an appropriate smoothing of the Power Spectrum that we detail in de Fromont & Alimi[7]. The advantage of this new formulation lies in the immediate link with the dynamics. Indeed, as spotted out before, the mass radius R_1 is conserved in comoving coordinates and is thus a global invariant of the profile in cosmology.

This leads only one free parameter to reconstruct the corresponding initial profile, the initial heigh of the peak ν which can be addressed from the density at the particular point R_1.

Dynamics

The dynamics is assumed to be spherical, indeed, from the stacking procedure that selects objects with the same mass radius R_1, we stack together structures with the *same dynamical properties*. It turns out that the spherical dynamics is sufficient to describe the full dynamics of the profile.

From the Spherical Collapse dynamics, we are able to compute the evolved mass and density profile at any redshift assuming the absence of shell-crossing[f]. The resulting profile is illustrated in Fig.(3).

[f]This hypothesis can be tested independently by evaluating the shell-crossing redshift at every radius from the initial mass profile and it turns out that at the scales we are looking at, this redshift is always $z_{SC} < 0$.

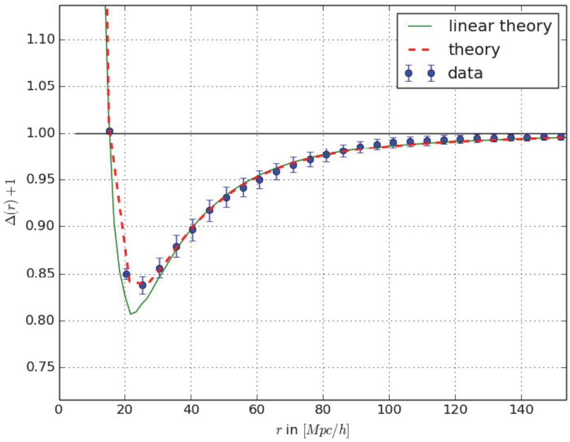

Fig. 3. Comparison between the numerical profile (in blue) together with the analytical profile evolved by spherical dynamic (in red) and the linear theory expectation (in green). Here we only show a zoom on the compensation belt surroundng the halo. Although the linear evolution is not completely ruled out, it is clearly not sufficient for precision cosmology.

4. Probing the cosmology

The dynamic of each shell is fully determined by the inner mass and the background content of the Universe. Also, this dynamics is intimately linked to the nature of Gravity itself which determines the coupling between the massive particles and the underlying space time metric.

It is thus clear that the dynamics of those profiles will be very sensitive to Dark Energy and/or Modified Gravity. In de Fromont & Alimi [9] we use this under-density to measure precisely the background history and show that we can obtain direct measure on the expansion rate factor $f(a) = \partial \log(D)/\partial \log(a)$ and thus probe cosmology and Modifications of Gravity (see Fig. 4).

Conclusion

In this paper I briefly presented the principles of using the large scale density profiles surrounding cosmic structures for probing the underlying Cosmology and the nature of Gravity.

We show in de Fromont et al. [8], how the new parametrisation in term of the threshold ν and the radius R_1 in the primordial Gaussian Field allows to reconstruct also the full statistics of those objects as a function only of R_1. We use then those statistics to probe the cosmology in a complementary way.

References

1. Bardeen, J.M., Bond, J.R., Kaiser, N., Szalay, A.S., 1986, ApJ, 304, 15
2. Rasera, Y., et al., 2010, AIP Conf. Proc. 1251, 1134

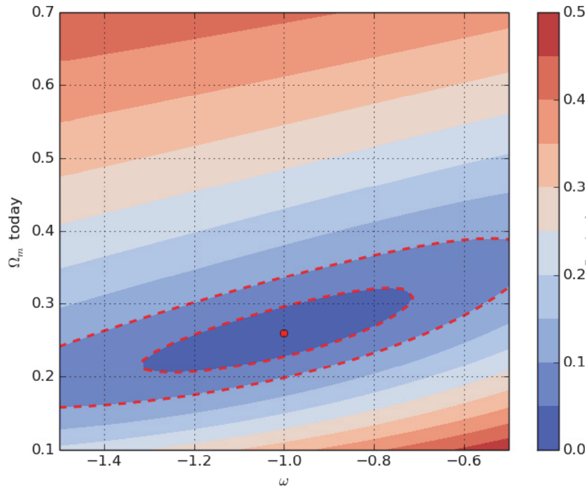

Fig. 4. Theoretical relative difference for the growth rate $f(z) = \partial \log(D)/\partial \log(a)$ between the ΛCDM reference cosmology (red dot) in the (Ω_m, w) plane (with w being the Dark Fluid parameter $p_{DE} = w\rho_{DE}$). The difference is simply evaluated by $\Delta = |f_{w,\Omega_m}/f_{ref} - 1|$. The parameter degeneracy is broken by using several redshift, here we used $z \in [0, 1]$. The dashed lines represent respectively the 5% and 10% surfaces. Those constrained come from the analysis of the density and velocity profiles around the particular radius R_1 in which all quantities *mimic* the background evolution

3. Alimi, J.-M. and Fuzfa, A. and Boucher, V. and Rasera, Y. and Courtin, J. and Corasaniti, P.-S., 2010, MNRAS, 401, Issue 2, 775-790., 2010
4. Sheth R. K., van der Waygaert R., 2004, Mon.Not.Roy.Astron.Soc.350:517
5. Hamaus N, Sutter P. M., Wandelt B. D., 2014, Phys. Rev. Lett. 112, 251302
6. Hamaus N, Sutter P. M., Lavaux G., Wandelt B. D., 2015, arXiv:1507.04363
7. de Fromont, P. and Alimi, J.-M., 2016, Large Scale Density Profiles Surrounding Extrema in ΛCDM Cosmology, to be submitted to MNRAS
8. de Fromont, P. and Alimi, J.-M. and Pasdeloup, J., 2016, Counting Statistics of Cosmic Structures Based on their Large Scale Density Profile, to be submitted to MNRAS
9. de Fromont, P. and Alimi, 2016, Constraining Cosmology and Modified Gravity from Large Scale Density Profiles, to be submitted to MNRAS