Physics of the Dark Universe 18 (2017) 73–104

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

Linear and non-linear Modified Gravity forecasts with future surveys

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ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form 14 September 2017
Accepted 17 September 2017

Keywords:
Modified gravity
Non-linearities
Large scale structure
Cosmology
Galaxy surveys
Fisher matrix formalism

ABSTRACT

Modified Gravity theories generally affect the Poisson equation and the gravitational slip in an observable way, that can be parameterized by two generic functions (η and μ) of time and space. We bin their time dependence in redshift and present forecasts on each bin for future surveys like Euclid. We consider both Galaxy Clustering and Weak Lensing surveys, showing the impact of the non-linear regime, with two different semi-analytical approximations. In addition to these future observables, we use a prior covariance matrix derived from the *Planck* observations of the Cosmic Microwave Background. In this work we neglect the information from the cross correlation of these observables, and treat them as independent. Our results show that η and μ in different redshift bins are significantly correlated, but including non-linear scales reduces or even eliminates the correlation, breaking the degeneracy between Modified Gravity parameters and the overall amplitude of the matter power spectrum. We further apply a Zero-phase Component Analysis and identify which combinations of the Modified Gravity parameter amplitudes, in different redshift bins, are best constrained by future surveys. We extend the analysis to two particular parameterizations of μ and η and consider, in addition to Euclid, also SKA1, SKA2, DESI: we find in this case that future surveys will be able to constrain the current values of η and μ at the 2–5% level when using only linear scales (wavevector $k < 0.15$ h/Mpc), depending on the specific time parameterization; sensitivity improves to about 1% when non-linearities are included.

1. Introduction

Future large scale structure surveys will be able to measure with percent precision the parameters governing the evolution of matter perturbations. While we have the tools to investigate the standard model, the next challenge is to be able to compare those data with cosmologies that go beyond General Relativity, in order to test whether a fluid component like Dark Energy or similarly a Modified Gravity scenario can better fit the data. On the theoretical side, while many Modified Gravity models are still allowed by type Ia supernova (SNIa) and Cosmic Microwave Background (CMB) data [1]; structure formation can help us to distinguish among them and the standard scenario, thanks to their signatures on the matter power spectrum, in the linear and mildly non-linear regimes (for some examples of forecasts, see [2–4]).

The evolution of matter perturbations can be fully described by two generic functions of time and space [5,6], which can be measured via Galaxy Clustering and Weak Lensing surveys. In this work we want to forecast how well we can measure those functions, in different redshift bins.

While any two independent functions of the gravitational potentials would do, we follow the notation of [1] and consider μ and η: the first modifies the Poisson equation for Ψ while the second is equal to the ratio of the gravitational potentials (and is therefore also a direct observable [6]). We will consider forecasts for the planned surveys Euclid, SKA1 and SKA2 and a subset of DESI, DESI-ELG, using as priors the constraints from recent *Planck* data (see also [7–12] for previous works that address forecasts in Modified Gravity).

In Section 2 we define μ and η and parameterize them in three different ways. First, in a general manner, we let these functions vary freely in different redshift bins. Complementarily, we also consider two specific parameterizations of the time evolution proposed in [1]. Here, we also specify the fiducial values of our cosmology for each of the parameterizations considered. Section 3 discusses our treatment for the linear and mildly non-linear regime. Linear spectra are obtained from a modified Boltzmann code [13]; the mild non-linear regime (up to $k \sim 0.5$ h/Mpc) compares two methods to emulate the non-linear power spectrum: the commonly used Halofit [14,15], and a semi-analytic prescription

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https://doi.org/10.1016/j.dark.2017.09.009
2212-6864/

to model the screening mechanisms present in Modified Gravity models [16]. In Section 4 we explain the method used to produce the Fisher forecasts both for Weak Lensing and Galaxy Clustering. We explain how we compute and add the CMB *Planck* priors to our Fisher matrices. Section 5 discusses the results obtained for the redshift binned parameterization both for Galaxy Clustering and for Weak Lensing in the linear and non-linear cases. We describe our method to decorrelate the errors in Section 5.4. The results for the other two time parameterizations are instead discussed in Sections 6.1 and 6.2, both for Weak Lensing and Galaxy Clustering in the linear and mildly non-linear regimes. To test the effect of our non-linear prescription, we show in Section 6.3 the impact of different choices of the non-linear prescription parameters on the cosmological parameter estimation.

2. Parameterizing modified gravity

In linear perturbation theory, scalar, vector and tensor perturbations do not mix, which allows us to consider only the scalar perturbations in this paper. We work in the conformal Newtonian gauge, with the line element given by

$$ds^2 = -(1+2\Psi)dt^2 + a^2(1-2\Phi)dx^2 \quad . \tag{1}$$

Here Φ and Ψ are two functions of time and scale that coincide with the gauge-invariant Bardeen potentials in the Newtonian gauge.

In theories with extra degrees of freedom (Dark Energy, DE) or modifications of General Relativity (MG) the normal linear perturbation equations are no longer valid, so that for a given matter source the values of Φ and Ψ will differ from their usual values. We can parameterize this change generally with the help of two new functions that encode the modifications. Many different choices are possible and have been adopted in the literature, see e.g. [1] for a limited overview. In this paper we introduce the two functions through a gravitational slip (leading to $\Phi \neq \Psi$ also at linear order and for pure cold dark matter) and as a modification of the Poisson equation for Ψ,

$$-k^2\Psi(a,k) \equiv 4\pi Ga^2\mu(a,k)\rho(a)\Delta(a,k) \;; \tag{2}$$

$$\eta(a,k) \equiv \Phi(a,k)/\Psi(a,k) \;. \tag{3}$$

These expressions define μ and η. Here $\rho(a)$ is the average dark matter density and $\Delta(a,k) = \delta + 3aH\theta$ is the comoving density contrast with δ the fractional overdensity, and θ the peculiar velocity divergence. We will neglect relativistic particles and radiation as we are only interested in modeling the perturbation behavior at late times. In that situation, η, which is effectively an observable [6], is closely related to modifications of GR [17,18], while μ encodes for example deviations in gravitational clustering, especially in redshift-space distortions as non-relativistic particles are accelerated by the gradient of Ψ.

When considering Weak Lensing observations then it is also natural to parameterize deviations in the lensing or Weyl potential $\Phi + \Psi$, since it is this combination that affects null-geodesics (relativistic particles). To this end we introduce a function $\Sigma(t,k)$ so that

$$-k^2(\Phi(a,k)+\Psi(a,k)) \equiv 8\pi Ga^2\Sigma(a,k)\rho(a)\Delta(a,k) \;. \tag{4}$$

Since metric perturbations are fully specified by two functions of time and scale, Σ is not independent from μ and η, and can be obtained from the latter as follows:

$$\Sigma(a,k) = (\mu(a,k)/2)(1+\eta(a,k)) \;. \tag{5}$$

Throughout this work, we will denote the standard Lambda-Cold-Dark-Matter (ΛCDM) model, defined through the Einstein–Hilbert action with a cosmological constant, simply as GR. For this case we have that $\mu = \eta = \Sigma = 1$. All other cases in which these functions are not unity will be labeled as Modified Gravity (MG) models.

Using effective quantities like μ and η has the advantage that they are able to model *any* deviations of the perturbation behavior from ΛCDM expectations, they are relatively close to observations, and they can also be related to other commonly used parameterization [19] On the other hand, they are not easy to map to an action (as opposed to approaches like effective field theories that are based on an explicit action) and in addition they contain so much freedom that we normally restrict their parameterization to a subset of possible functions.

This has however the disadvantage of losing generality and making our constraints on μ and η parameterization-dependent. In this paper, we prefer to complement specific choices of parameterizations adopted in the literature (we will use the choice made in [1]) with a more general approach: we will bin the functions $\mu(a)$ and $\eta(a)$ in redshift bins with index i and we will treat each μ_i and η_i as independent parameters in our forecast; we will then apply a variation of Principal Component Analysis (PCA), called Zero-phase Component Analysis (ZCA). A PCA approach has been considered previously in the literature by [8,9], where they bin μ and η in several redshift and k-scale bins. In these works they study Weak Lensing and Redshift Space distortions or they cross correlate large scale structure observations with CMB temperature, E-modes and polarization data together with Integrated Sachs–Wolfe (ISW) observations to forecast the sensitivity of future surveys to modifications in μ and η. In the present work, we will neglect a possible k-dependence, we will focus on Galaxy Clustering (GC) and weak lensing (WL) surveys and we will show that there are important differences between the linear and non-linear cases; including the non-linear regime generally reduces correlations among the cosmological parameters. In the remainder of this section we will introduce the parameterizations that we will use.

2.1. Parameterizing gravitational potentials in discrete redshift bins

As a first approach we neglect scale dependence and bin the time evolution of the functions μ and η without specifying any parameterized evolution. To this purpose we divide the redshift range $0 \le z \le 3$ in 6 redshift bins and we consider the values $\mu(z_i)$ and $\eta(z_i)$ at the right limiting redshift z_i of each bin as free parameters, thus with the i index spanning the values $\{0.5, 1.0, 1.5, 2.0, 2.5, 3.0\}$. The chosen width of the redshift bins implicitly assumes that evolution effects within this range can be neglected. This might break down for specific models where the functions strongly depend on the redshift, and can be therefore be seen as an optimistic assumption. On top of these assumptions the first bin is assumed to have a constant value, coinciding with the one at $z_1 = 0.5$, i.e. $\mu(z < 0.5) = \mu(z_1)$ and $\eta(z < 0.5) = \eta(z_1)$. The $\mu(z)$ function (and analogously $\eta(z)$) is then reconstructed as

$$\mu(z) = \mu(z_1) + \sum_{i=1}^{N-1} \frac{\mu(z_{i+1}) - \mu(z_i)}{2}\left[1 + \tanh\left(s\frac{z - z_{i+1}}{z_{i+1} - z_i}\right)\right], \tag{6}$$

where the tanh is used to obtain a smooth interpolation between contiguous bin values, $s = 10$ is a smoothing parameter and N is the number of binned values. We assume that both μ and η reach the GR limit at high redshifts: to realize this, the last $\mu(z_6)$ and $\eta(z_6)$ values assume the standard ΛCDM value $\mu = \eta = 1$ and both functions are kept constant at higher redshifts $z > 3$.

The same approach is used to obtain smooth derivatives of the μ and η functions, computed interpolating between $N - 1$ redshift bins where they take the values

$$\mu'(\bar{z}_j) = \frac{\mu(z_{i+1}) - \mu(z_i)}{z_{i+1} - z_i}, \tag{7}$$