ISW-galaxy cross-correlation in K-mouflage

G Benevento$^{1,2}$, N Bartolo$^{1,2,3}$, M Liguori$^{1,2,3}$

$^1$ Dipartimento di Fisica e Astronomia “G. Galilei”, Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
$^2$ INFN, Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy
$^3$ INAF-Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy
E-mail: benevent@pd.infn.it

Abstract. Cross-correlations between the cosmic microwave background and the galaxy distribution can probe the linear growth rate of cosmic structures, thus providing a powerful tool to investigate different Dark Energy and Modified Gravity models. We explore the possibility of using this observable to probe a particular class of Modified Gravity models, called K-mouflage.

1. Introduction
In a Universe undergoing accelerating expansion, the gravitational potentials associated to large scale structures decay. A photon of the Cosmic Microwave Background (CMB) travelling through a decaying potential will experience a net change in energy [1], which leads to a secondary anisotropy in the CMB temperature distribution. Such particular gravitational redshift effect is called Integrated Sachs Wolfe (ISW) [2], as it has to be integrated along the line of sight. This effect can be used to discriminate between different Dark Energy (DE) and Modified Gravity (MG) scenarios [3, 4, 5]. The ISW signal is not detectable using only CMB temperature data, due to the noise arising from other sources of anisotropies on large angular scales and from the cosmic variance. Cross-correlation between the CMB and a tracer of the gravitational potential, like the projected galaxy number counts, can extract the ISW signal, making it detectable with high significance using the upcoming galaxy surveys [5].

In this paper we investigate the power of this probe to discriminate between the Λ-Cold Dark Matter model (ΛCDM) and the K-mouflage models of modified gravity [6]. K-mouflage models, that we present in Section 2, predict a considerable deviation from the ΛCDM model in the growth rate of cosmic structures [7], this feature makes them suitable to be tested through cross-correlation between CMB and galaxies. In Section 3 we perform a cross-correlation analysis for two different K-mouflage models, with the aim of forecasting their detectability using two upcoming cosmological surveys: Euclid [8] and LSST [9]. We draw our conclusions in Section 4.

2. Growth of linear perturbations in K-mouflage models
K-mouflage models assume the presence of an additional scalar field ($\phi$) non-minimally coupled to the space-time metric ($g_{\mu \nu}$) [6]. The action in the Einstein frame can be expressed in the following form:

$$S = \int d^4x \sqrt{-g} \left[ \frac{M^2_{Pl}}{2} R + M^4 K(\chi) \right] + \int d^4x \sqrt{-g} C_m(\psi^{(i)}_m, g_{\mu \nu}),$$

(1)
The perturbed Robertson-Walker metric in the Einstein frame, using the Newtonian conformal here only the main results of the perturbative treatment at the linear level.

The cosmological perturbation theory for K-mouflage models has been studied in [7]. We report and different choices are possible. Here, we consider two simple models, for which the kinetic and coupling functions are given in Table 1.

| Model 1 | Kinetic term | Coupling function | \( \beta \) | \( m \) | \( K_0 \) |
|---------|--------------|------------------|------|------|------|
| -1 + \( \chi + K_0 \chi^m \) | \( A = e^{\beta \varphi \sqrt{8\pi G}/M^4} \) | 0.3 | 3 | 1 |
| Model 2 | -1 + \( \chi + K_0 \chi^m \) | \( A = e^{\beta \varphi \sqrt{8\pi G}/M^4} \) | 0.3 | 3 | -5 |

Table 1. Definition of the K-mouflage models we adopt in our analysis.

\[
\chi = -\frac{1}{2M^4}g_{\mu\nu}\partial^\mu\varphi\partial^\nu\varphi, \quad \bar{g}_{\mu\nu} = A^2(\varphi)g_{\mu\nu},
\]

where \( M_{Pl} \) is the Planck mass, \( M^4 \) is the energy scale of the field \( \varphi \) and \( \mathcal{L}_m \) is the Lagrangian of the matter fields \( \psi_i^{(m)} \). This action involves two metrics, the Einstein-frame metric \( g_{\mu\nu} \) and the Jordan-frame metric \( \bar{g}_{\mu\nu} \), related to the former by the conformal transformation in Eq. (2).

K-mouflage models are characterized by a scalar field Lagrangian with a non-canonical kinetic term \( K(\chi) \). The form of the kinetic function and of the coupling function needs to be specified and different choices are possible. Here, we consider two simple models, for which the kinetic and coupling functions are given in Table 1.

The growing mode of the gravitational potential is related to the growth factor by the Poisson equation. In the \( \Lambda \)CDM model, this relation simply reads \( D_{\Psi,N} = \frac{D_{\Psi}}{a} \), whereas in K-mouflage we can write the linear growing mode \( D_{\Psi,N} \) of the gravitational potential as:

\[
D_{\Psi,N} = \bar{A} \frac{D}{a},
\]
3. ISW-galaxy cross-correlation

In a Dark Energy dominated universe the gravitational potential varies with time unlike the case of a matter dominated universe [3]. This leaves an imprint on the CMB power spectrum. This phenomenon, the so-called late Integrated Sachs-Wolfe (late ISW) effect, can play a primary role in discriminating between different dynamical DE or MG models, since it is sensitive to the evolution of the gravitational potential, which is encoded in the growth factor.

Solving Eq. (5), as done e.g. in [7], shows that K-mouflage models predict substantial deviations in the growth factor, as well as in its derivative, w.r.t. ΛCDM. In particular the gravitational potential in K-mouflage is expected to evolve even during the matter-dominated era, at redshift $z > 2$, when it is constant in the standard cosmological scenario. This peculiar growth of matter perturbations produces a signature in the late ISW anisotropies, which can be used as an observational probe for this class of models.

The cross-correlation between galaxy distribution and CMB anisotropies can enhance the late ISW signal, making it detectable, thus it can be successfully used to constrain K-mouflage models. The key quantity to describe the amount of cross-correlation between the CMB and the ISW signal, making it detectable, thus it can be successfully used to constrain K-mouflage models. In analogy with the definition of the CMB angular power spectrum, we can define the ISW-galaxy cross-correlation power spectrum. In models with those of ΛCDM and estimating the significance of a possible future detection.

3.1. Analysis

We now develop a cross-correlation analysis, comparing the predictions for different K-mouflage models with those of ΛCDM and estimating the significance of a possible future detection. Extremely deep and wide surveys will gather an exceptional catalogue of sources in the next
few years (e.g. [8, 9]). In particular their high limiting magnitude (e.g. 24.5 for Euclid and 27.5 for LSST) will allow to map the galaxy distribution up to very high redshifts. This makes them ideal for a tomographic study of the ISW effect through CMB-galaxy cross-correlation. For our purpose we concentrate on two promising surveys, Euclid and LSST, that are optimized for CMB-galaxy cross-correlation as shown in [8, 9].

The main goal of this analysis is to forecast the possibility of investigating K-mouflage using the differences in the late ISW effect predicted by such theory, opening the way to more detailed studies. With this aim we want to compute the signal to noise ratio for a possible detection of the ISW-galaxy correlation, assuming the ΛCDM prediction as null hypothesis.

Following the standard procedure for similar forecasts [10, 11, 12], we bin the (predicted) redshift distribution of galaxies for Euclid and LSST and we then compute ISW-galaxy cross-correlation power spectra solving numerically Eq. (9) (or Eq. (12) for $l > 20$), for the K-mouflage models defined in Table 1 and for ΛCDM.

The redshift distribution of galaxies for the upcoming surveys Euclid and LSST, can be well approximated by the following analytic form [13]:

$$\frac{dN}{dz} = \frac{1}{\Gamma(\alpha+1)} \beta z^\alpha z_0^{\alpha+1} \exp \left[ -\left( \frac{z}{z_0} \right) ^\beta \right].$$

The above parametrization gives the normalized distribution of galaxies per steradian. The parameters $\alpha$, $\beta$ and $z_0$ are characteristic of each survey and determine the shape of the distribution as well as its median redshift. Their values are given in Table 2. To simulate a tomographic analysis we arbitrarily chose to divide the Euclid-like galaxy distribution in 3 redshift bins, and the LSST-like survey in 5 redshift bins, following the procedure of [13].

Assuming a Gaussian distribution, we can estimate the error associated to $C_l^{ISW-gal}$ in a given redshift bin for a single multipole $l$ as [10]:

$$\sigma^2(C_l^{ISW-gal}) = \frac{1}{f_s (2l+1)} \left[ (C_l^{ISW-gal})^2 + \left( C_l^{gg} + \frac{1}{n_g} \right) (C_l^{TT}) \right],$$

where $C_l^{TT}$ and $C_l^{gg}$ are the auto-correlation power spectra of CMB temperature anisotropies and of galaxies number counts respectively. $f_s$ is the fraction of sky covered by the survey, while $n_g$ is the number density of galaxies per steradian in the considered redshift bin.

Assuming that different $l$ multipoles are uncorrelated, we can compute the cumulative squared signal to noise ratio of the deviation between K-mouflage models and the ΛCDM as:

$$\left( \frac{S}{N} \right)^2 = \sum_l \left[ (C_l^{ISW-gal})_{Km} - (C_l^{ISW-gal})_{ΛCDM} \right]^2, \quad \sigma^2 = \sigma^2_{Km} + \sigma^2_{ΛCDM}. $$

### Table 2. Properties of the upcoming surveys considered in this analysis. We consider photometric surveys, for Euclid we assume the same predictions given in [8], while for LSST we follow the forecast of [9].

| Parameter                      | Euclid-like survey | LSST-like survey |
|--------------------------------|--------------------|------------------|
| Number density                 | $n_g = 30$ arcmin$^{-2}$ | $n_g = 50$ arcmin$^{-2}$ |
| Sky coverage                   | 15,000 deg$^2$     | 20,000 deg$^2$   |
| Redshift distribution          | $\alpha = 2$, $\beta = 1.5$, $z_0 = 0.64$ | $\alpha = 2$, $\beta = 1$, $z_0 = 0.5$ |
| Median redshift                | $z_m = 0.9$        | $z_m = 1.34$     |
| photo-z errors                 | $\sigma_z = 0.05(1+z)$ | $\sigma_z = 0.02(1+z)$ |
| galaxy bias                    | $b = \sqrt{1+z}$  | $b = 1 + 0.84z$  |
Figure 1. ISW-galaxies cross-correlation power spectra and $S/N$ for Model 1 of Table 1 as expected to be measured by Euclid and LSST. The four panels on the left represent quantities computed using the Euclid-like survey divided in 3 redshift bins, while the four panels on the right have been obtained considering the LSST-like survey divided in 5 redshift bins. Each bin is labelled with its median redshift $z_m$.

Figure 2. ISW-galaxies cross-correlation power spectra and $S/N$ for Model 2 of Table 1. The same quantities computed for Model 1 are shown.

In Fig. 1 and Fig. 2 we show our results for the cross-correlation power spectra (adopting the compact notation $C^K_m = (C^{ISW-gal})_Km$ and $C_i^{ΛCDM} = (C^{ISW-gal})_ΛCDM$) computed for the K-mouflage models of Table 1, their relative difference w.r.t. the ΛCDM prediction $|C^K_m - C_i^{ΛCDM}| / C_i^{ΛCDM}$, the signal to noise ratio per multipole $|C^K_m - C_i^{ΛCDM}| / σ$, and the total signal to noise ratio obtained using Eq. (15).
The signal to noise ratio per multipole peaks at $l \sim 10 - 60$: at low multipole orders the uncertainty on the power spectrum is dominated by the cosmic variance, while at large $l$ the signal decreases due to the decay of the ISW on small angular scales. Our result for the cumulative $S/N$ shows that the significance of the deviation of Model 1 from $\Lambda$CDM would reach $\sim 0.5\sigma$ for the Euclid-like survey and $\sim 0.8\sigma$ using the LSST-like survey. For Model 2 we obtain an higher significance, $\sim 2.2\sigma$ for the Euclid-like survey and $\sim 3.5\sigma$ for the LSST-like survey. This is due to the peculiar behaviour of $C_{l}^{ISW-gal}$ in Model 2, that shows an anti-correlation at high redshift. This feature makes the model significantly different from $\Lambda$CDM that predicts a positive correlation.

We observe that, especially for Model 1, we gain significance by splitting the galaxy distribution in redshift bins. The tomographic analysis allows to select sharp redshift intervals in which the correlation signal is high enough to overcome the increase in shot noise due to the reduced number of galaxies considered. Finally, we observe that the results obtained using the Euclid-like and the LSST-like survey are consistent with our expectations. In our forecast the LSST-like survey is supposed to cover a larger area of sky and reduce the shot noise in Eq. (14) observing an higher number of galaxies with respect to Euclid (see Table 2), these differences improve the detectability of K-mouflage models.

4. Conclusions
The measurement of the late-ISW signal through the cross-correlation between the CMB and the projected distribution of galaxies, observed by wide cosmological surveys, constitutes a promising method of investigation to discriminate between different DE and MG theories. In this work we have computed the ISW-galaxy cross-correlation power spectra for two different K-mouflage scenarios. We found the striking result that Model 2 predicts a negative ISW-galaxy cross-correlation, this could represent a smoking-gun signature for similar models. In order to forecast the detectability of K-mouflage models using future surveys like Euclid and LSST we performed an error analysis, computing the signal to noise ratio in several redshift bins. Our results confirm that the probing power of CMB-galaxies cross-correlations will increase with the upcoming generation of surveys, also thanks to the possibility to perform tomographic analysis. A more general analysis of the K-mouflage phenomenology, including all the observable effects on CMB anisotropies, requires the full solution of the linearised Einstein-Boltzmann equations for this theory. This can be done e.g. using the EFTCAMB Einstein-Boltzmann solver [14]. Including K-mouflage models in the EFTCAMB code allows to study different observational signatures and to perform the comparison with data in a systematic way. The work based on this method is currently under development [15].

References
[1] Hu W and Dodelson S 2002 ARA&A 40 171
[2] Sachs R K and Wolfe A M 1967 ApJ 147 73
[3] Crittenden R, Boughn S and Turok N 1996 Bull. Am. Astron. Soc. 28 1341
[4] Khosravi S, Mollazadeh A and Baghram S 2016 JCAP 9 003
[5] Hu W and Scranton R 2004 Phys. Rev. D 70 123002
[6] Brax P and Valageas P 2014 Phys. Rev. D 90 023507
[7] Brax P and Valageas P 2014 Phys. Rev. D 90 023508
[8] Amendola L, Appleby S, Avgoustidis A et al 2013 Living Rev. Relativ. 16 6
[9] LSST Science Collaboration, Abell P A, Allison J et al 2009 preprint arXiv:0912.0201
[10] Schmidt F, Liguori M and Dodelson S 2007 Phys. Rev. D 76 083518
[11] Bertacca D, Raccanelli A, Piatella O F et al 2011 JCAP 3 039
[12] Douspis M, Castro P G, Caprini C and Aghanim N 2008 Astron. Astrophys. 485 395
[13] de Putter R, Doré O and Das S 2014 ApJ 780 185
[14] Raveri M, Hu B, Frusciante N and Silvestri A 2014 Phys. Rev. D 90 043513
[15] Benevento G, Bartolo N, Brax P, Lazanu A, Liguori M, Raveri M and Valageas P in preparation.