Detecting Dark Energy Fluctuations with Gravitational Waves

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Luminosity distance estimates from electromagnetic and gravitational wave sources are generally different in models of dynamical dark energy and gravity beyond the standard cosmological scenario. We show that this leaves a unique imprint on the angular power-spectrum of fluctuations of the luminosity distance of gravitational-wave observations which directly tracks inhomogeneities in the dark energy field. Exploiting in synergy supernovae and gravitational wave distance measurements, it is possible to build a joint estimator that directly probes dark energy fluctuations, providing a conclusive evidence for their existence in case of detection. Moreover, such measurement would also allow to probe the running of the Planck mass. We discuss experimental requirements to detect these signals.

Over the last decades, a variety of cosmological data have confirmed ΛCDM as the standard model of cosmology [1, 2]. Despite its successes, the physical nature of its main components still eludes us. In particular, understanding whether cosmic acceleration is sourced by a cosmological constant, or by more exotic forms of dark energy (DE) or modifications of the laws of gravity (MG) is one of the main science drivers of the next generation of galaxy surveys [3–6]. These surveys aim at detecting DE/MG only indirectly, through their effects on the clustering and growth of large-scale cosmological structures. These effects arise as a consequence of the dynamics and clustering of any new degree of freedom associated with DE or MG. Henceforth, we will broadly refer to such new degree of freedom as the “DE field”. In this paper we propose a method based on fluctuations of the luminosity distance associated to supernovae and gravitational-wave events to investigate whether a direct detection of fluctuations in the DE field is observationally possible.

The detection of gravitational waves (GW) has opened a new observational window onto our Universe, promising to offer complementary probes to shed light on the cosmic expansion and the nature of DE. For instance, GW events at cosmological distances can be used as standard sirens [7–9] for measuring the expansion rate of the universe. This recent approach is complementary to measuring the luminosity distance of standard candles, as Type-Ia supernovae (SN). Multi-messenger observations can also be used to test theories of modified gravity, as recently reviewed in [10].

In presence of DE/MG, the GW luminosity distance generally differs from the one traced by electromagnetic (EM) signals, both at the background level [11, 12] and in its large-scale fluctuations [13, 14]. In fact, anisotropies in the EM luminosity distance constitute an important probe for cosmology and have been well studied [15–19], while the case of GWs has been addressed in General Relativity (GR) in [20–26]. Moreover, in DE/MG models, as first shown in [13], linearized fluctuations of the GW luminosity distance contain contributions directly proportional to the clustering of the DE field.

In this work we show how to combine SN and GW luminosity distance fluctuations in order to directly detect the DE clustering signal. This signal can not be mimicked by other effects, and would provide convincing evidence for the existence of dynamical DE physics. If DE does not directly couple to known particles through non-gravitational interactions, ours would be a promising method to pursue its direct detection. The approach we propose is particularly appealing since it allows us to probe the DE field at large cosmological scales, far from sources that can hide its presence by means of screening mechanisms (see e.g. [27–29] for reviews).

We start by deriving the expression of the fluctuations of the GW luminosity distance in general MG theories characterized by a non-minimal coupling between the DE field and the space-time curvature, and we compute its angular power-spectrum as a function of the sources redshifts, for two representative MG models. Then we construct a novel joint SN and GW estimator, to single out the contributions of the DE field, and investigate the observational requirements for its direct detection, both in the cases of known and of unknown redshift of the GW sources.
The GW luminosity distance power-spectrum in MG: The luminosity distance, as inferred by an EM or GW signal propagating through a universe with structures, depends on the observed redshift, $z$, and on the direction in the sky, $\theta$. We decompose the observed luminosity distance of a source as a sum of its background and fluctuation components, i.e. $d_L(\theta, z) = \bar{d}_L(z) + \Delta d_L(\theta, z)$. We examine a family of DE/MG models with non-minimal coupling of the DE field to space-time curvature. This translates into a running of the Planck mass, $M_P$, as it generally depends on the background configuration of the dark energy field $\varphi$, and on its first derivatives in the combination $X = -\nabla_\mu \varphi \nabla^\mu \varphi/2$. More specifically, we consider DHOST theories [30–32] (see e.g. [33] for a review), focusing on the set-up that ensures luminal speed for GWs and avoids instabilities associated with graviton decay into DE [34]. Section IIID. We also require that high-frequency scalar fluctuations propagate at the same speed of tensor modes, as discussed in [33]. The dependence of $M_P$ on the DE field gives new contributions to the expression of the GW luminosity distance with respect to GR. At the background level one finds $\bar{d}_L^{GW} = [M_P(z)/M_P(0)]\bar{d}_L$, where $\bar{d}_L$ is the electromagnetic luminosity distance. The multiplicative factor $M_P(z)/M_P(0)$ accounts for the extra friction acting on the GWs during their propagation induced by the time dependence of the Planck mass. This fact has been recently used to forecast the capability of future ground-based [35] and space-based [36] interferometers to probe MG models. When discussing linearized perturbations, $\Delta d_L^{GW}$, to the luminosity distance, the phenomenology becomes even richer. Generalizing to DHOST the procedure described in [33], we find:

$$\frac{\Delta d_L^{GW}}{\bar{d}_L^{GW}} = -\kappa - (\phi + \psi) + \frac{1}{\chi} \int_0^\chi d\chi (\phi + \psi)$$

$$+ \phi \left( \frac{1}{\chi H} - \frac{M_P'}{HM_P} \right) + \psi \left( 1 - \frac{1}{\chi H} + \frac{M_P'}{HM_P} \right)$$

$$- \left( 1 - \frac{1}{\chi H} + \frac{M_P'}{HM_P} \right) \int_0^\chi d\chi (\phi' + \psi')$$

$$+ \frac{M_{P,X}}{M_P} \delta \varphi + \frac{M_{P,\varphi}}{M_P} \delta X . \tag{1}$$

where a prime indicates differentiation w.r.t. conformal time, $H = \alpha'/a$, $\kappa$ denotes the weak lensing convergence, $\chi$ is the comoving distance to the source, $\phi$ is the Newtonian potential, $\psi$ the intrinsic spatial curvature potential, and $v_\parallel$ is the component along the line of sight of the peculiar velocity of the source; all in Poisson gauge and following the conventions of [13]. We also use the shorthand notations $M_{P,\varphi}$ and $M_{P,X}$ for the derivative of $M_P(\varphi, X)$ w.r.t. its arguments.

Equation (1) shows that the physical effects contributing to $\Delta d_L^{GW}$ can be divided into three classes. The first class, in the first line of Eq. (1), includes effects that are only indirectly influenced by DE/MG, through a modified growth of gravitational potentials. These effects are lensing convergence, volume dilation, and time delay. A second class, contained in the second and third lines of Eq. (1), encompasses effects that show an additional explicit decay that depends on the background evolution of the Planck mass, peculiar to the GW luminosity distance and absent in the electromagnetic one. These are the Sachs-Wolfe (SW), Doppler shifts, and Integrated Sachs-Wolfe (ISW) effects. A third class of effects is contained in the fourth line of Eq. (1) and are the main interest of this paper: they are directly proportional to fluctuations in the DE field and are unique to the GW luminosity distance fluctuations. Notice that, even though Eq. (1) is written in a model-independent way, these effects are related to the density and velocity fluctuations of $\varphi$ in a way that depends on the specific DE/MG model.

We use Eq. (1) to build the power-spectrum of GW luminosity distance fluctuations from the 2-point correlation function, $\langle \delta d_L^{GW}/\bar{d}_L^{GW} \delta d_L^{GW}/\bar{d}_L^{GW} \rangle$, averaged over a given redshift distribution of the sources, $W(z)$, as in [37]. As usual, we work with its expansion coefficients in Legendre polynomials, that we denote with $C^{GW}_{\ell}$. Note that we use the notation $d_L(z)$ for the background luminosity distance, to indicate its angular average, weighted by the given redshift distribution.

We discuss in detail the impact of MG on $C^{GW}_{\ell}$ in two representative models. We start with a designer $f(R)$ model on a $\Lambda$CDM background [38]. Compatible with current constraints [39], we choose the value for the only model parameter to be $B_0 = 10^{-4}$. In the second case, we opt for an agnostic parametrization of $M_P$, such that the ratio $(M_P'/M_P)$ is a linear function of the scale-factor, $a(z)$, $M_P'/M_P \equiv (M_P'/M_P)\big|_0 a$, where $(M_P'/M_P)\big|_0$ is the value of the ratio today, which we set to 0.05. This minimal parametrization, implemented on a $\Lambda$CDM background, is representative of the Generalized Brans-Dicke (GBD) [40–42] family. In both our representative models, we parametrize the Planck mass $M_P$ as depending on the scalar field value alone. We defer to a future analysis the application of our general formula Eq. (1) to cases where $M_P$ depends also on $X$. We implement the calculation of the angular power-spectrum of Eq. (1) in EFTCAMB [43], and we will make it publicly available in the next code release.

In Figure 1 we show the angular power-spectrum of GW luminosity distance fluctuations. To highlight redshift dependencies we choose a Gaussian redshift distribution for the GW sources centred in various redshifts, as reported in Figure 1 and with width $\Delta z = 0.01$. The total signal significantly changes shape with increasing redshifts. In particular, at low redshifts and large scales, the signal is dominated by the Doppler effect, due to the bulk-flow of the environment in which the GW sources are embedded. The Doppler contribution then decays for growing $\ell$, and the angular power-spectrum at small scales is dominated by lensing convergence; the Doppler...
term also decays in redshift, while lensing grows and eventually dominates the high-redshift part of the signal. In both models considered such relative behaviour between Doppler and lensing convergence is qualitatively unaltered with respect to GR. Figure 1 also shows the direct contribution of $\delta \varphi$ to the total signal, i.e. the last line in Eq. (1). This is of the same order of magnitude in both models and largely subdominant compared to the total signal. For the $f(R)$ model the scalar field contribution has a noticeable scale-dependent feature that evolves in time as the Compton wavelength of the model. At higher redshift, in fact, the Compton scale of the scalar field is smaller and, correspondingly, the feature in the power-spectrum moves to smaller scales. In the GBD case, on the other hand, any feature in the shape of the power-spectrum is less pronounced, as it only leads to the decay of DE fluctuations below the horizon.

The joint SN/GW estimator: The direct contributions of DE fluctuations to the GW luminosity distance power-spectrum is very small compared to other effects, making it impossible to detect their presence in the angular correlations using GW data only. In order to single out the distinctive DE field contributions, we combine standard sirens and standard candles to exploit the differences between GW and photon propagation in DE/MG scenarios. We assume to have measurements of both SN and GW at the same redshifts and positions and subtract the two as:

$$\Delta \varphi(\hat{\theta}, z) = \frac{\Delta d^{SN}_L(\hat{\theta}, z)}{d^{SN}_L} - \frac{\Delta d^{GW}_L(\hat{\theta}, z)}{d^{GW}_L}. \quad (2)$$

As photons are not affected directly by DE or MG, $\Delta d^{SN}_L$ is structurally unchanged w.r.t. GR, hence is obtained by neglecting all the explicit DE/MG terms present in Eq. (1). Thus, for the theories considered here, Eq. (2) takes the form

$$\Delta \varphi(\hat{\theta}, z) = \frac{M_p}{\mathcal{H} M_P} \left( \phi - v_{\parallel} + \int_0^\chi d\chi (\phi' + \psi') \right) + \frac{M_p v_{\parallel}}{M_P} \delta \varphi - \frac{M_p x_{\parallel}}{M_P} \delta X, \quad (3)$$

where only the explicit DE/MG-dependent effects are present. In addition to the purely DE contributions in the second line of Eq. (3), only three effects contribute to $\Delta \varphi$: the residual Doppler, SW and ISW effects. Most importantly lensing convergence, which is the dominant contribution to GW- and SN-radiation anisotropies, cancels out. For particular classes of events, Eq. (2) could be directly evaluated for pairs of sources at the same position and redshift. In our analysis we require this to hold only statistically, by integrating Eq. (2) over a joint redshift distribution and computing its angular power-spectrum:

$$C^\Delta_\ell = C^{SN}_\ell + C^{GW}_\ell - 2C^{SNGW}_\ell, \quad (4)$$

where $C^{SN}_\ell$ ($C^{GW}_\ell$) are the SN (GW) luminosity distance angular power-spectra, and $C^{SNGW}_\ell$ the cross-spectrum between the two. In this form we need the redshift and position of GW/SN sources to be the same only on average, i.e. same redshift distributions and overlapping regions in the sky.

In Fig. 2 we show $C^\Delta_\ell$ as a function of the source redshift for the two DE models under examination. We consider the case of localized SN/GWs sources to study the redshift dependence of $C^\Delta_\ell$. In the $f(R)$ case, the DE clustering component is dominating the total angular power-spectrum, making its features manifest. In the GBD model, on the other hand, the total signal is domi-
nated by the Doppler effect. The DE clustering contribution to the correlation is of the same order of magnitude as in the $f(R)$. Nevertheless, we stress that a detection of this signal would still be a direct proof of the presence of the DE scalar field.

Observational prospects: We next investigate the detection prospects for the fluctuations of the GW luminosity distance via $C_G^{\Delta \varphi}$, and DE clustering via $C_{\Delta \varphi}$. We consider the noise power-spectrum for both SN and GW, as given by only a shot-noise contribution \[43, 46\]:

$$N_i^\ell = \frac{4\pi f_{\text{sky}} \sigma_{d_L}^2}{d_L^2} = \frac{4\pi f_{\text{sky}}}{N_{i}^\text{eff}}$$

where $i = \{\text{SN, GW}\}$. In Eq. (5), $f_{\text{sky}}$ is the sky fraction covered by observations, which we assume to be $f_{\text{sky}} = 1$ for simplicity. We also define the effective number of sources, $N_{i}^\text{eff}$, as the product of the number of events, $N_i$, in a given redshift bin and the ratio $d_L^2/\sigma_{d_L}^2$, related to the magnitude uncertainty on the measurement of each single event through $\sigma_m = (0.2 \log 10) \times (\sigma_{d_L}/d_L)$. In this way $N_{i}^\text{eff}$, which sets the overall noise level, takes into account the number of events detected and the precision of each measurement. As the signal decays in scale faster than $\propto \ell^{-2}$, we expect to have the best chance of measuring it from large-scale observations. For this reason we assume that future localization uncertainties can be neglected \[47\].

The noise for the joint estimator of Eq. (4) is given by the sum of the two noise power-spectra for GW and SN, since we assume that any stochastic contribution is uncorrelated. Consequently, the number of effective events needed for a detection of $C_{\Delta \varphi}^\ell$ is given by the harmonic mean of the two single ones: $N_{\Delta \varphi}^\text{eff} = \left[\left(N_{\text{SN}}^\text{eff}\right)^{-1} + \left(N_{\text{GW}}^\text{eff}\right)^{-1}\right]^{-1}$. The error on the power-spectrum measurement, both $C_G^{\Delta \varphi}$ and $C_{\Delta \varphi}^\ell$, is then given by $\sigma(C_\ell) = \sqrt{2/(2\ell + 1)f_{\text{sky}}C_\ell + N_\ell}$, and the corresponding signal-to-noise ratio is $(S/N)^2 = \sum_\ell (C_\ell/\sigma(C_\ell))^2$.

The noise power-spectrum in Eq. (5) is scale-independent so that we can solve the inverse problem of determining the number of effective events needed to measure the power-spectra with a desired statistical significance. In practice, we fix a target $S/N = 5$, and solve the equation of $S/N$ for $N_{\text{eff}}$ both in the case of GW sources alone and $\Delta \varphi$.

Finally, we investigate the scenario where the GW source redshift is unknown. In this case we assume the shape of the GW redshift distribution as given in \[23\], while the SN one as in \[48\]. Since, to build Eq. (4), the SN and GW redshift distributions need to match, we take the product of the two and build the joint probability of measuring both SN and GW at the same redshift. Intermediate cases in which the EM counterpart is not available, but estimates of the redshift distributions are obtained via statistical methods \[49, 50\], would fall in between the two extreme cases examined here. Table summarizes the results reporting the number of effective sources for a $5\sigma$ detection of the angular power-spectra $C_G^{GW}$ and $C_{\Delta \varphi}^\ell$, both in the case of GW events with known, as well as unknown redshifts (the latter designated as “w/o z”). We also indicate the value of $N_{\text{GW}}^\text{eff}$ in GR, for comparison.

The detection threshold for GW luminosity distance fluctuations, $N_{\text{GW}}^\text{eff}$, does not change appreciably for the different scenarios, since we selected representative models sufficiently close to $\Lambda$CDM to satisfy current constraints. In fact, as shown in Fig. 1, $C_G^{GW}$ is dominated by lensing convergence at high redshifts and by Doppler shift at low redshifts. The former is indirectly modified by DE/MG, while the latter is also sensitive to the back-
TABLE I. The number of effective events $N_{\text{eff}} \equiv N d_{l}^{2} / \sigma_{\Delta z}^2$ for a 5-$\sigma$ detection of the angular power-spectra of GW luminosity distance fluctuations $C_{\ell}^{\text{GW}}$, and its direct DE contribution, $C_{\ell}^{\Delta z}$.

| gw | $N_{\text{eff}}$ | $N_{\Delta z}$ | $N_{\text{eff}}$ | $N_{\Delta z}$ |
|----|----------------|--------------|----------------|--------------|
| $z = 0.1$ | $10^2$ | $10^7$ | $10^{14}$ | $10^7$ |
| $z = 0.3$ | $10^8$ | $10^8$ | $10^{15}$ | $10^8$ |
| $z = 0.7$ | $10^8$ | $10^8$ | $10^{16}$ | $10^8$ |
| $z = 1.5$ | $10^7$ | $10^7$ | $10^{17}$ | $10^7$ |
| w/o $z$ | $10^7$ | $10^7$ | $10^{19}$ | $10^7$ |

Detect large numbers of binary white dwarfs (BWD) [55] on galactic scales and much beyond [56, 57]. BWD are supposed to be progenitors of Type-Ia SN in the so-called double degenerate scenario [58]. Therefore, for GW and SN signals both from BWD, Eq. (2) would hold locally and $\Delta z$ could be directly reconstructed in configuration space, provided that non-linearities and MG screening effects can be properly taken into account. It will also be interesting to use our general formula, Eq. (1), to investigate whether other DE cosmological models based on DHOST (see e.g. [56, 59, 60]) lead to signals easier to detected with fewer sources.
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[52] S. Kawamura et al., Laser interferometer space antenna. Proceedings, 8th International LISA Symposium, Stanford, USA, June 28-July 2, 2010, Class. Quant. Grav. 28, 094011 (2011).

[53] A. Nishizawa, K. Yagi, A. Taruya, and T. Tanaka, Phys. Rev. D85, 044047 (2012) arXiv:1110.2865 [astro-ph.CO].

[54] P. A. Abell et al. (LSST Science, LSST Project), (2009), arXiv:0912.0201 [astro-ph.IM].

[55] L. McNeill, R. A. Mardling, and B. Müller, Mon. Not. Roy. Astron. Soc. 491, 3000 (2020) arXiv:1901.09045 [astro-ph.HE].

[56] A. Maselli, S. Marassi, and M. Branchesi, Astron. Astrophys. 635, A120 (2020) arXiv:1910.00016 [astro-ph.HE].

[57] T. Kinugawa, H. Takeda, and H. Yamaguchi, (2019), arXiv:1910.01063 [astro-ph.HE].

[58] D. Maoz and F. Mannucci, Publ. Astron. Soc. Austral. 29, 447 (2012) arXiv:1111.4492 [astro-ph.CO].

[59] M. Crisostomi and K. Koyama, Phys. Rev. D97, 084004 (2018) arXiv:1712.06556 [astro-ph.CO].

[60] S. Arai, P. Karmakar, and A. Nishizawa, Phys. Rev. D102, 024003 (2020) arXiv:1912.01768 [gr-qc].