Modified Einstein versus modified Euler for dark matter

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Modifications of general relativity generically contain additional degrees of freedom that can mediate forces between matter particles. One of the common manifestations of a fifth force in alternative gravity theories is a difference between the gravitational potentials felt by relativistic and non-relativistic particles, also known as ‘the gravitational slip’. In contrast, a fifth force between dark matter particles, owing to dark sector interaction, does not cause a gravitational slip, making the latter a possible ‘smoking gun’ of modified gravity. Here we point out that a force acting on dark matter particles, as in models of coupled quintessence, would also manifest itself as a measurement of an effective gravitational slip by cosmological surveys of large-scale structure. This is linked to the fact that redshift-space distortions owing to peculiar motion of galaxies do not provide a measurement of the true gravitational potential if dark matter is affected by a fifth force. Hence, it is extremely challenging to distinguish a dark sector interaction from a modification of gravity with cosmological data alone. Future observations of gravitational redshift from galaxy surveys can help to break the degeneracy between these possibilities, by providing a direct measurement of the distortion of time. We discuss this and other possible ways to resolve this important question.

The discovery of cosmic acceleration and the unknown nature of dark matter (DM) prompted extensive studies of modified gravity theories. Generically, such theories involve, in addition to the metric tensor, new dynamical degrees of freedom, with a scalar field being the most commonly studied example. In these scalar-tensor theories, gravitational attraction between matter particles is mediated by the curvature of spacetime as well as the scalar field. At the level of linear cosmological perturbations, this ‘fifth force’ not only enhances the rate of gravitational clustering of matter but also manifests itself as a non-zero ‘gravitational slip’, namely, a difference between the Newtonian potential and the curvature perturbation . One can search for evidence of by combining observations of galaxy redshift-space distortions (RSDs) and weak gravitational lensing (WL), along with other cosmological data. A measurement of is often considered to be the ‘smoking gun’ of modified gravity.

What if instead of having modifications of gravity affecting all matter, only the DM particles experience an attractive force owing to some non-gravitational dark sector interaction? Can cosmological observations distinguish a dark sector force, that affects only DM, from a modification of gravity for all matter? Phrasing it in mathematical terms, can one distinguish a modification of the Einstein equations from a modification of the Euler equation for DM? While finding any evidence of a fifth force would be of profound importance by itself, knowing whether it is of gravitational or particle origin is an equally fundamental question.

This question is not new and has been discussed, for example, in the context of scalar-field dark energy. A minimally coupled scalar field is usually referred to as quintessence, whereas a scalar field coupled only to DM would be classified as coupled quintessence (CQ). (Note that in the earlier literature, for example, ref. 16, the term CQ was also used to refer to coupling to all matter, but in more recent years...
CQ has been generally used to refer to the DM-only coupled case. In contrast, a scalar field universally coupled to all matter would be referred to as a scalar-tensor theory and, hence, considered to be modified gravity. Several publications have suggested that a way to differentiate between CQ and scalar-tensor gravity would be to measure the gravitational slip. This expectation, however, relies on our ability to measure the perturbation of the velocity field of the normal matter (‘baryons’) and use it to infer the underlying large-scale dark matter.

In this Analysis, we argue that this is not possible with current observations. The reason is that the baryons we observe are confined in galaxies and clusters. As such their velocity is linked to the velocity of galaxies and, therefore, they do not trace the large-scale dark matter. If DM experiences a fifth force. The effective Newtonian potential inferred from RSDs, when compared with WL measurements, would consequently yield a non-zero measured gravitational slip indistinguishable from that coming from modified gravity.

Fortunately, the next generation of large-scale structure surveys has the potential to break this degeneracy between modified gravity and a dark force acting on DM (hereafter called dark force), by providing a measurement of the distortion of time. This novel observable has the advantage of being directly sensitive to Ψ, even in the presence of a dark force.

The smoking gun argument

We start by comparing two models: a scalar-tensor theory of generalized Brans–Dicke (GBD) type and a CQ model. While the equations of motion and the perturbations we show are specific to these two models, the argument is general and holds for any modified gravity theory and dark force model.

For the GBD model, the action takes the form

$$S^{GBD} = \int d^4\sqrt{-g} \left[ \frac{A^{-2}(\phi)}{16\pi G} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_m(\phi_{DM}, \Psi_{SM, DM}) \right],$$

where \(g\) is the Newton constant, \(R\) is the Ricci scalar built from \(g_{\mu\nu}\) and its derivatives, \(g\) is the metric determinant, \(A\) is a generic function of the scalar field \(\phi\) and \(V\) is its potential. \(\mathcal{L}_m(\phi_{DM}, \Psi_{SM, DM})\) is the Lagrangian density of all matter that includes the standard model (SM) particle fields, collectively denoted as \(\Psi_{SM}\) and the DM particles, denoted as \(\phi_{DM}\) with both following the geodesics of the metric \(g_{\mu\nu}\). Throughout this paper, \(g_{\mu\nu}\) denotes the metric of the ‘baryon frame’; that is, the metric whose geodesics are followed by the SM particles (which, in the case of the scalar-tensor theories, is the same for baryons and DM).

Let us compare the GBD action (equation (1)) with the action of CQ, with the scalar field conformally coupled only to DM

$$S^{CQ} = \int d^4\sqrt{-g} \left[ \frac{\lambda}{16\pi G} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \mathcal{L}_m(\phi_{DM}, \Psi_{SM, DM}) \right]$$

$$+ \mathcal{L}_m(\phi_{DM}, A^2(\phi) g_{\mu\nu}) \right],$$

in which the gravitational part of the action is not modified in the baryon frame \(g_{\mu\nu}\), and with DM following geodesics of \(A^2(\phi) g_{\mu\nu}\).

We always interpret the observations in the ‘baryon frame’, in which the masses of the SM particles are constant. With that in mind, let us compare the equations governing linear cosmological perturbations in GBD and CQ theories. We work with the linearly perturbed flat Friedmann–Lemaître–Robertson–Walker (FLRW) metric in the conformal Newtonian gauge, with the line element given by

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = a^2(\tau) \left[ -(1 + 2\psi) dt^2 + (1 - 2\phi) dx^2 \right],$$

where \(\tau\) denotes conformal time and \(a\) is the scale factor. Neglecting radiation, the relevant variables are \(\Psi, \phi, \) the baryon and (cold) DM density contrasts, \(\delta_\Psi = \delta \rho_\Psi/\rho_\Psi\) and \(\delta_\phi = \delta \rho_\phi/\rho_\phi\), (here \(\rho\) denotes the linear perturbation of the energy density \(\rho\) and their velocity divergences, \(\delta_\psi\) and \(\theta_\phi\). As shown in Methods, in both GBD and CQ, the equations governing the evolution of these variables can be combined into an evolution equation for the matter density contrast

$$\ddot{\delta} + 3H\dot{\delta} = 4\pi G\rho m^2 \delta \Psi,$$

where the overdots denote derivatives with respect to \(\tau\), \(H\) is the Hubble parameter in conformal time, \(\rho \equiv \rho_\Psi + \rho_\phi\) and \(G\) is the effective gravitational coupling that takes the following forms

$$G_{\text{GBD}} = G \left[ 1 + \frac{2\beta^2 k^4}{\gamma^2 m^2 + k^2} \right]$$

and

$$G_{\text{CQ}} = G \left[ 1 + \frac{2\beta^2 k^4}{\gamma^2 m^2 + k^2} (\rho/\rho) \frac{\delta_\phi}{\delta} \right],$$

where \(\beta^2 = \beta^2/8\pi G\beta = A_\phi/A\) is the scalar-field coupling strength and \(m^2\) is the effective mass that sets the range of the fifth force. We see that the effective gravitational couplings are very similar in the two models. The only difference is a small suppression of the impact of the fifth force in \(G_{\text{CQ}}\), owing to the fact that \(-15\%\) of matter does not feel the fifth force. This difference is, however, degenerate with the unknown coupling \(\beta\). We see, therefore, that GBD and CQ are impossible to distinguish through the growth of structure alone. An observer looking for departures from the cold dark matter model (where \(A\) is the cosmological constant by fitting \(G\) to the galaxy growth data (for example, using MGCAMB\(^2\)) would measure a \(G_{\text{eff}} > 1\) either way. Note that the argument derived here in the case of a scalar field holds in general: modifications to the Poisson equation (due to modified gravity) and modifications to the Euler equation (due to a dark fifth force) are generically indistinguishable at the level of the growth rate\(^3\), which is the quantity measured by RSD.

However, the two types of theory differ at the level of the gravitational potentials. In GBD, the two potentials differ, \(\phi \neq \Psi\), hence \(\eta = \phi/\Psi \neq 1\), whereas in CQ the Einstein equations are not modified, and therefore, at late times, \(\eta = 1\). This suggests that one could differentiate the two cases by measuring \(\eta\) (refs. 13, 19), making it a smoking gun for modified gravity. Note that modified gravity effects on linear perturbations can, in principle, be mimicked by a dark fluid with appropriately tuned state functions (see, for example, refs. 22, 23). Here, rather than aiming to distinguish between a modified gravity and a hypothetical fluid, we compare a modified gravity in which a fifth force affects all matter with a theory in which the same type of force acts only on DM, with no additional dark ingredients.

In practice, deviations from general relativity are often parameterized with two functions \(\mu\) and \(\Sigma\) that depend on \(a\) and on the wavenumber \(k\)

$$k^2 \Psi = -4\pi G(a_0 k^2 \mu \delta),$$

$$k^2 (\phi + \Psi) = -8\pi G\Sigma(a_0 k^2 \mu \delta),$$

where, in GBD

$$\mu = G_{\text{GBD}} (G/\Sigma) \mu$$

and \(\Sigma = 1/2(1 + \eta) = 1\).

While in CQ, \(\mu = \Sigma = 1\). In theory, combining a measurement of baryon velocities, determined by the Newtonian potential \(\Psi\), with WL data that measure \(\phi + \Psi\), would yield a measurement of both \(\mu\) and \(\Sigma\) and, therefore, determine \(\eta\). However, as we show below, this test would not work in practice because the baryons we observe are confined to galaxies and, hence, move together with the galactic DM. This means an observer would measure an effective \(\eta^g = 1\) even if there is no intrinsic gravitational slip.
The observed gravitational slip

To understand how the gravitational slip is measured from RSDs and WL, let us first review how these observables are constructed. Redshift surveys map the distribution of galaxies and measure the fluctuation in the galaxy number counts, given in Fourier space by

\[
\Delta(k, z) = \delta_g(k, z) - \frac{1}{\pi^2} \mu(k, z),
\]

where \(z\) is the redshift, \(\mu \equiv \mathbf{k} \cdot \mathbf{n}\), and \(\mathbf{n}\) is the direction of observation (considered fixed in the flat-sky approximation). The first term is the intrinsic fluctuation in the distribution of galaxies \(\delta_g\), related to the (total) matter density contrast through the bias \(b\): \(\delta_g = b \delta \). The second term is due to RSDs, accounting for the fact that the redshift of the galaxies is affected by the peculiar velocity of the baryons (from which the light that we receive is emitted) with respect to us. As shown in Methods, the velocity of baryons can be decomposed into two terms: the velocity of the baryons with respect to the centre of mass of the galaxy, and the galactic centre-of-mass velocity with respect to the Hubble flow. These two terms are sensitive to different ingredients. As illustrated in Fig. 1, the velocity of the baryons with respect to the centre of mass is governed by the local gravitational potential of the galaxy, whereas the velocity of the centre of mass is driven by the large-scale gravitational potential. As RSD surveys measure correlations of galaxy number counts at large separations (well above the size of a galaxy), the first velocity contribution vanishes, since it is not correlated on large scales. Consequently, the RSD power spectrum is affected by only the motion of the galactic centre of mass, and we can effectively replace \(\theta_g\) in equation (9) by the centre-of-mass velocity, denoted by \(\theta_c\). In GBD, the centre of mass moves according to the large-scale gravitational potential \(\Psi_g\). In the CQ model however, the centre-of-mass velocity is also affected by the fifth force:

\[
\text{GBD:} \quad \theta_g + 3 \zeta \theta_c = k^2 \Psi_g,
\]

\[
\text{CQ:} \quad \theta_g + 3 \zeta \theta_c = k^2 \Psi_g + \frac{\rho_b}{\rho} k^2 \delta \phi \equiv k^2 \psi_{\text{eff}}.
\]

Therefore, we see that in the CQ case, RSDs do not allow us to reconstruct the large-scale gravitational potential \(\Psi_g\), even though the fifth force does not act directly on baryons.

To link this to standard RSD analyses, we relate the galaxy velocity to the matter density contrast, assuming that the continuity equation is valid in both models (Methods). With this, the RSD power spectrum becomes

\[
P_{\text{GBD}}(k, \mu_k, z) = \left( f^2 + \mu_k^2 \right) P_{\delta\delta}(k, z),
\]

where \(f \equiv d \ln \delta / d \ln a\) is the growth rate and \(P_{\delta\delta}\) is the matter power spectrum. Both \(f\) and \(P_{\delta\delta}\) are determined by the solution to equation (4) and, therefore, directly affected by \(G_{\text{eff}}\) that has similar forms in GBD and CQ (equation (5)).
\[ \eta^{\text{fit}} = \frac{2\Delta^{\text{fit}}}{\mu^{\text{fit}}} - 1 = \frac{2}{\mu^{\text{fit}}} - 1 < 1. \]  

(18)

Hence, even though the gravitational slip is zero in CQ, one would still measure \( \eta < 1 \) by combining RSD with WL. This clearly demonstrates that measuring \( \eta \neq 1 \) from RSD and WL is not a smoking gun for modified gravity—it can also be due to a fifth force acting solely on DM.

While we used CQ as our example, the effective gravitational slip is present in any model that breaks the weak equivalence principle for DM, that is, any model where a dark force is acting solely on DM. As is schematically shown in Fig. 2, RSDs provide constraints on \( \mu^{\text{fit}} \) (green region), whereas WL constrains both \( \mu^{\text{fit}} \) and \( \Delta^{\text{fit}} \) (blue region). As lensing probes the geometry of the Universe, \( \Delta^{\text{fit}} \) is always equal to the true \( \Delta \) entering in equation (14). Therefore, even if there is a dark fifth force, \( \Delta^{\text{fit}} \) is related to the true \( \Delta \) and \( \mu \). In contrast, \( \mu^{\text{fit}} \) is fitted using the evolution equation for the density contrast, which depends on \( G_{\text{fit}} \). Therefore, if there is a dark fifth force, \( \mu^{\text{fit}} \) differs from the true \( \mu \). As a consequence, when combining \( \Delta^{\text{fit}} = \mu(1 + \eta)/2 = 1 \) with \( \mu^{\text{fit}} > 1 \) in models with a dark force, we automatically obtain \( \eta^{\text{fit}} < 1 \).

In ref. 19, it was argued that this problem could be circumvented by using RSDs to measure directly the Newtonian potential \( \Psi \), instead of constraining \( G_{\text{fit}} \) (and hence \( \mu^{\text{fit}} \)) through the growth rate. However, as the RSD power spectrum is governed by the galaxy centre of mass, \( \Theta \), which is affected by the effective gravitational potential \( \Psi^{\text{eff}} \) (equation (11)), this method would also lead to a measurement of \( \eta^{\text{fit}} < 1 \) (see Methods for a detailed derivation).

**Distinguishing modified gravity from a dark force with gravitational redshift**

Fortunately, the coming generation of galaxy surveys will allow us to measure a new observable, gravitational redshift, which can be used to unambiguously distinguish between a dark fifth force and a modification of gravity.

As explained above, the main problem with measuring \( \eta \) from RSDs and WL is that RSDs are not a tracer of the true large-scale gravitational potential, \( \Psi^{\text{fit}} \), if DM is affected by a fifth force. However, there are other distortions contributing to the observed galaxy number counts \( \Delta \) (refs. 25–27). Among these effects, one is particularly important for testing gravity: the effect of gravitational redshift. This effect encodes the fact that when light escapes a gravitational potential, its energy is redshifted. Contrary to WL, which is sensitive to the sum of the two gravitational potentials (both time and space distortions deviate the trajectory of light), the shift in energy is due only to the time distortion. Therefore, gravitational redshift provides a measurement of the true \( \Psi \), even in the presence of a fifth force. Combining this with WL will allow us to measure the true gravitational slip and, consequently, distinguish a dark fifth force from a modification of gravity.

In practice, the gravitational redshift contribution to \( \Delta \) is very small, and contributes in a negligible way to standard analyses. However, this effect has the specificity to generate asymmetries in the distribution of galaxies\(^{22}\). For this reason, it was proposed to isolate it by searching for asymmetries in the cross-correlation of two populations of galaxies, for example a bright (B) and faint (F) population\(^{29,30}\). Gravitational redshift is, however, not the only contribution that generates asymmetries in the correlation function: there are also Doppler effects, proportional to the galaxy centre-of-mass velocity, that have the same property\(^{29,30}\). Any measured asymmetry will, therefore, be due to a combination of these Doppler terms and gravitational redshift. These terms are generally called relativistic effects in the literature, even though, in reality, only gravitational redshift is a pure effect of general relativity. They contribute to the galaxy number counts as:

\[ \Delta^{\text{tr}}(k, z) = i\mu \left[ -\frac{1}{3} \Psi(k, z) + \left( 1 - 5s + \frac{5s^2}{3c^2} + \frac{2s}{3c^2} + f^{\text{rel}} \right) \delta_g(k, z) + \Theta(k, z)k^{2c} \right]. \]

where \( s \) is the magnification bias and \( f^{\text{rel}} \) is the evolution bias. Contrary to RSDs, these relativistic effects generate contributions to the galaxy power spectrum with odd powers of \( \mu \), and can be isolated by looking for a dipole and octupole. The dipole, which is the dominant contribution, is given by

\[ \mu^{\text{rel}}(k, z) = i\left( f_B + \Theta_B \right) \frac{k}{k_c} P_{\delta_s}(k, z) + i\left( b_B - b_T \right) \frac{k}{k_c} P_{\varphi_{\text{fil}}}(k, z). \]

(19)

where \( \alpha \) is a generic function of the growth rate and its time derivative as well as of \( \Theta_B \) and \( \Theta_T \) that encode the dependence of the dipole on the bias, magnification bias and evolution bias of the bright and faint population, respectively. The dipole is suppressed by one power of \( \kappa / k \) with respect to the even multipoles (Methods), and it is consequently too small to be measured in current surveys\(^{31}\). However, forecasts have shown that it will be detectable with high significance with the coming generation of surveys, such as the Dark Energy Spectroscopic Instrument (DESI) and the Square Kilometer Array (SKA2)\(^{32}\).

From equation (19), we see that combining the dipole with the even multipoles (that depend on \( P_{\delta_s} \)) allows one to directly measure \( P_{\varphi_{\text{fil}}}(k, z) \) (refs. 35,36), which can be used to unambiguously distinguish between modified gravity and a dark fifth force. In practice, this can be done in two complementary ways. The first possibility is to look directly for modifications of gravity by combining \( P_{\varphi_{\text{fil}}}(k, z) \) with galaxy–galaxy lensing (see, for example, ref. 37), which measures the correlation of density with lensing: \( P_{\delta_s \varphi_{\text{fil}}}(k, z) \). The ratio of these two measured quantities gives \( \eta \):

\[ \frac{P_{\varphi_{\text{fil}}}(k, z)}{P_{\delta_s}(k, z)} = 1 + \eta(k, z). \]

(20)

In ref. 38 it was shown that, with this method, \( \eta \) can be measured with a precision of \( 20\% \) at low redshift (in 4 bins, between \( z = 0.2 \) and \( z = 0.7 \), by combining spectroscopic measurements from SKA2 and photometric measurements from the Vera Rubin Observatory\(^{39}\)). Since the denominator of equation (20) depends on the true gravitational potential, a detection of \( \eta = 1 \) with this method would truly be a smoking gun for modified gravity. Models with a dark fifth force would give \( \eta = 1 \).

The second way of using \( P_{\varphi_{\text{fil}}}(k, z) \) to distinguish between modified gravity and a dark fifth force is to combine it with RSDs to directly test the validity of the weak equivalence principle, that is, to constrain the strength of the fifth force\(^{41}\). More precisely, one can compare \( P_{\varphi_{\text{fil}}}(k, z) \) with \( P_{\delta_s}(k, z) \) measured from RSD, to directly probe Euler equation for galaxies in equations (10) and (11), and measure the fifth force, proportional to \( \beta \) in the case of CQ. In ref. 21, it was shown that, with this method, modifications of Euler equation can be constrained and disentangled from a change in the Poisson equation at the level of 15%, with SKA2. Note that these forecasts were based on a particular parameterization in which modifications were proportional to the dark energy density fraction, as commonly assumed in other literature\(^{40}\). The constraints would be tighter in models where deviations could occur at earlier epochs.

**Conclusions**

Current data are not able to distinguish unambiguously between modifications to Einstein equations and modifications to Euler equation. The limitation is due to the fact that large-scale structure is described by four fields, \( \delta_g, \Theta_g, \Phi \) and \( \Psi \), whereas current observations can measure only three quantities, \( \delta_g, \Theta_g \) and \( \Phi + \Psi \). Measuring the galaxy dipole with future surveys will add the missing information, allowing one to differentiate between a dark fifth force and a modification of gravity.
Analysis

Methods

Effective gravitational couplings in GBD and CQ

To derive equations (4) and (5), for simplicity, we will adopt the quasi-static approximation, in which one restricts to subhorizon scales and assumes that the time derivatives of the metric and the scalar-field perturbations are much smaller than their spatial derivatives. Under the quasi-static approximation, in Fourier space, the relevant equations in the baryon frame are as follows.

Generalized Brans–Dicke (GBD):

\[ k^2 \phi = -4\pi Ga^2 \left( \rho_b \delta_b + \rho_c \delta_c \right) - \beta k^2 \delta \phi \]  \hspace{1cm} (21)

\[ k^2 (\phi - \Psi) = -2\beta \kappa k^2 \delta \phi \]  \hspace{1cm} (22)

\[ \delta_b + \theta_b = 0 \]  \hspace{1cm} (23)

\[ \delta_b + \kappa \theta_b = k^2 \Psi \]  \hspace{1cm} (24)

\[ \delta_c + \theta_c = 0 \]  \hspace{1cm} (25)

\[ \delta_c + \kappa \theta_c = k^2 \Psi \]  \hspace{1cm} (26)

\[ \delta \phi = -\frac{\beta (\rho_c \delta_c + \rho_b \delta_b)}{m^2 + k^2/\alpha^2} \]  \hspace{1cm} (27)

\[ \Box \phi = V_\phi + \beta (\rho_c + \rho_b) \equiv V^{\text{eff, } \phi} \]  \hspace{1cm} (28)

\[ \delta + \kappa \delta = 4\pi Ga^2 p \delta \left[ 1 + \frac{2\beta k^2}{a^2 m^2 + k^2} \right] \]  \hspace{1cm} (29)

Coupled quintessence (CQ):

\[ k^2 \phi = -4\pi Ga^2 \left( \rho_b \delta_b + \rho_c \delta_c \right) \]  \hspace{1cm} (30)

\[ k^2 (\phi - \Psi) = -2\beta \kappa k^2 \delta \phi \]  \hspace{1cm} (31)

\[ \delta_b + \theta_b = 0 \]  \hspace{1cm} (32)

\[ \delta_b + \kappa \theta_b = k^2 \Psi \]  \hspace{1cm} (33)

\[ \delta_c + \theta_c = 0 \]  \hspace{1cm} (34)

\[ \delta_c + \kappa \theta_c = k^2 \Psi \]  \hspace{1cm} (35)

\[ \delta \phi = -\frac{\beta \rho_c \delta_c}{m^2 + k^2/\alpha^2} \]  \hspace{1cm} (36)

\[ \Box \phi = V_\phi + \beta \rho_c \equiv V^{\text{eff, } \phi} \]  \hspace{1cm} (37)

\[ \delta + \kappa \delta = 4\pi Ga^2 p \delta \left[ 1 + \frac{2\beta k^2}{a^2 m^2 + k^2} \right] \]  \hspace{1cm} (38)

where the overdots denote derivatives with respect to the conformal time \( \tau \), \( \Box = \nabla^\mu \nabla^\nu \), \( \kappa = a^{-1} \partial_a / \partial \tau \), \( \beta = (\partial \rho / \partial \phi) / (\partial \rho / \partial \phi) \) is the scalar-field coupling strength, \( \beta^2 = (\partial \phi / \partial \Phi)^2 / 8\pi G \) and \( m^2 = V_\phi / \beta^2 \), with the effective potentials defined via equations (28) and (37). Note that the effective potential in CQ depends on only DM. For simplicity, we assume here that \( A^2 = 1 \) and neglect it in our equations. In the case of GBD, this implies that our \( G \) is the \( G \) today, while the overall change in the gravitational coupling with redshift is constrained to be very small in screened GBD theories\(^{41}\). In the case of CQ, an \( A^2 = 1 \) would simply re-scale \( \beta \) in our equations.

We see that the Euler equation for DM in CQ (equation (35)) contains a friction term \( \beta \phi \theta \), this term can be important in CQ models in which \( \phi = \kappa \) (ref. \( 42 \)). It is, however, negligible in theories such as the chameleon\(^{43} \) or the symmetron\(^{44} \) models, in which the scalar field remains near the minimum of a slowly changing effective potential. In what follows, we ignore this term for simplicity, as, for our purposes, it is sufficient to find one example where one cannot distinguish GBD from CQ. Either way, the presence of this term would not affect our arguments, as any modification of the Euler equation would yield an effective potential that is different from the true \( \Psi \) if the RSD measurements are interpreted assuming an unmodified Euler equation.

One can see that in GBD theories, there is an extra term in the Poisson equation (21), and in addition the two potentials are different (equation (22)), \( \phi \neq \Psi \), hence \( \eta = \Phi/\Psi = 1 \). One can combine equations (21), (22) and (27) to write separate Poisson equations for the potential \( \Psi \), which affects the motion of non-relativistic matter (through equations (24) and (26)), and the Weyl potential \( \Phi + \Psi \) felt by relativistic particles:

\[ k^2 \phi = -4\pi G \beta \kappa \rho \left( \rho_b \delta_b + \rho_c \delta_c \right) \]  \hspace{1cm} (39)

\[ k^2 (\phi + \Psi) = -8\pi G \beta \kappa \rho \left( \rho_b \delta_b + \rho_c \delta_c \right) \]  \hspace{1cm} (40)

Comparing the above to the commonly used phenomenological parameterization of modified gravity effects on cosmological perturbations

\[ k^2 \phi = -4\pi \mu (a, k) G \beta \kappa \rho \left( \rho_b \delta_b + \rho_c \delta_c \right) \]  \hspace{1cm} (41)

\[ k^2 (\phi + \Psi) = -8\pi \Sigma (a, k) G \beta \kappa \rho \left( \rho_b \delta_b + \rho_c \delta_c \right) \]  \hspace{1cm} (42)

we have

\[ \mu = 1 + \frac{2\beta k^2}{a^2 m^2 + k^2} \]  \hspace{1cm} (43)

Thus, GBD theories predict \( \mu > \Sigma \). Note that this is true even if we do not assume \( A^2 = 1 \), in which case \( \mu = A^2 (1 + 2\beta^2 k^2 / (a^2 m^2 + k^2)) \) and \( \Sigma = A^2 \). Moreover, we can combine the continuity and Euler equations, and use equation (27), to derive a second-order equation describing the evolution of the total matter density contrast \( \delta = (\rho_b \delta_b + \rho_c \delta_c) / (\rho_b + \rho_c) \), given by equation (29), which can be interpreted as growth in the presence of an effective gravitational coupling, \( G_{\text{eff}}^{\text{GBD}} \), defined as

\[ \frac{G_{\text{eff}}^{\text{GBD}}}{G} = \mu = 1 + \frac{2\beta k^2}{a^2 m^2 + k^2} \]  \hspace{1cm} (44)

In contrast, in the case of CQ, the Einstein equations are not modified and, formally, \( \mu = \Sigma = \eta = 1 \). The effect of scalar field on structure growth comes through the new term in the Euler equation for DM (equation (35)). The second-order equation for the total matter density contrast, \( \delta \), in this case, is given by equation (38), which can also be interpreted as growth in the presence of an effective gravitational coupling, \( G_{\text{eff}}^{\text{CQ}} \), defined as

\[ \frac{G_{\text{eff}}^{\text{CQ}}}{G} = 1 + \frac{2\beta k^2}{a^2 m^2 + k^2} \left( \frac{\rho_c}{\rho_b} \right)^2 \left( \frac{\delta_c}{\delta_b} \right) \]  \hspace{1cm} (45)
We see that $C^{\text{GVD}}_{\text{eff}}/G$ and $C^{\text{GBD}}_{\text{eff}}/G$ are very similar to each other. The only difference is a small suppression of the impact of the fifth force in $C^{\text{GVD}}_{\text{eff}}$, due to the fact that ~15% of matter does not feel the fifth force.

**Gravitational slip measured from galaxy peculiar velocities and weak lensing**

The fact that $\Phi \neq \Psi$ in GBD, while $\Phi = \Psi$ in CQ, suggests that one could differentiate the two cases by measuring $\eta$ (refs. 13, 19), making it a smoking gun for modified gravity. Note that there exist scalar-tensor theories with no gravitational slip, such as cubic Galileons\(^{45}\), kinetic gravity braiding\(^{46}\) and the ‘no-slip gravity’\(^{47}\), but these can be viewed as rare exceptions within the broad class of Horndeski theories\(^{16}\). To measure $\eta$, one can, in principle, combine weak lensing data, that measure $\Phi$ and $\Psi$, and are, consequently, sensitive to $z$, with a measurement of the baryon velocities, that are driven by $\Psi$ and are, consequently, sensitive to $\mu$. The problem with this method is that, in CQ, the baryons too are affected by the fifth force on DM because they are confined in galaxies. Therefore, baryon velocities are not a true tracer of the gravitational potential $\Psi$ in this case, and using them would lead to a measured $\eta^{\text{int}} \neq 1$ even if there is no intrinsic gravitational slip.

To see this, let us start by writing the observed fluctuation in the galaxy number counts as

$$
\Delta(n, z) = \delta_k - \frac{1}{3} \frac{\partial}{\partial r} \left( V_b \cdot n \right),
$$

where $r$ is the comoving distance to the galaxies and $n$ is the direction of observation. Equation (46) can be Fourier transformed

$$
\Delta(k, z) = b \delta_b(k, z) - \frac{1}{3} k^2 \theta_b(k, z),
$$

where $\mu_k = k \cdot n$ is the cosine of the angle between the vector $k$ and the direction of observation $n$ (which is considered fixed in the flat-sky approximation), and $b$ is the bias. The power spectrum of $\Delta$ is then given by

$$
P_{\text{gal}}(k, \mu, z) = b^2 P_{\delta \delta}(k, z) - \frac{2b}{3} \mu^2 P_{\delta \theta_b}(k, z) + \frac{1}{3} \mu^2 P_{\theta_b \theta_b}(k, z).
$$

Since we are interested in the galaxy power spectrum on large scales, in the linear regime $k < k_{\text{cut}}$, we need to model the correlations of the baryon velocity at those scales. For this, we split the baryon velocity into two parts: the velocity of the baryons with respect to the centre of mass of the galaxy, that we call $\theta_{\text{loc}}$, and the velocity of the centre of mass of the galaxy with respect to the Hubble flow, that we call $\theta_{\text{glob}}$:

$$
\theta_b = \theta_{\text{loc}} + \theta_{\text{glob}}.
$$

In both GBD and CQ models, the velocity of the baryons with respect to the centre of mass obeys

$$
\theta_{\text{loc}} + \mathcal{H} \theta_{\text{loc}} = k^2 \Psi + F_{\text{int}},
$$

where $F_{\text{int}}$ accounts for the non-gravitational interactions affecting the motion of baryons inside the galaxy. The gravitational potential can be decomposed into a local part, due to the presence of the galaxy, and a large-scale part, due to the large-scale structure of the Universe, as shown in Fig. 1

$$
\Psi = \psi_{\text{loc}} + \psi_{\text{LS}}.
$$

Equation (50) depends on the total gravitational potential $\Psi$. However, as the galaxy is a localized object of size that is small compared with the extent of $\psi_{\text{LS}}$, the centre of mass of the galaxy and the baryons are situated at almost the same value of $\Psi$. Consequently, $\psi_{\text{LS}}$ does not impact the motion of baryons inside the galaxy, that is, with respect to the centre of mass. In contrast, $\psi_{\text{loc}}$ varies significantly over the extent of the galaxy and does contribute to equation (50). We therefore obtain

$$
\theta_{\text{loc}} + \mathcal{H} \theta_{\text{loc}} = k^2 \psi_{\text{loc}} + F_{\text{int}}.
$$

From this equation, we see that the local velocity is uncorrelated on scales larger than the size of the galaxy. The internal forces in two different galaxies are indeed uncorrelated, and the local gravitational potentials are also uncorrelated at large distance. Therefore

$$
P_{\text{gal}}^{\text{int}}(k, z) = 0, \quad \text{for} \quad k \leq 1/s_{\text{galaxy}},
$$

where $s_{\text{galaxy}}$ denotes the typical size of a galaxy. As a consequence, the RSD power spectrum is affected only by the motion of the centre of mass of the galaxy

$$
P_{\text{gal}}(k, \mu, z) = b^2 P_{\delta \delta}(k, z) - \frac{2b}{3} \mu^2 P_{\delta \theta_b}(k, z) + \frac{1}{3} \mu^2 P_{\theta_b \theta_b}(k, z).
$$

The power spectrum can be further simplified by using that in both GBD and CQ, baryons and DM obey the continuity equation, leading to

$$
\theta_{\text{glob}} = -\delta = -\mathcal{H} \psi_{\text{glob}},
$$

where the (total) matter growth rate is defined as

$$
f = \frac{d \ln \delta}{d \ln a}.
$$

Inserting this into equation (54), we obtain equation (12). From this equation, we see that the RSD power spectrum can be used to measure the growth rate $f$ and constrain $G_{\text{eff}}$. Alternatively, it can also be used to probe $\psi_{\text{LS}}$. In GBD, the galaxy centre of mass, $\theta_{\text{glob}}$, obeys equation (10) and can therefore directly be used to reconstruct $\psi_{\text{LS}}$. In CQ however, $\theta_{\text{glob}}$ obeys equation (11), meaning that RSD provide a measurement of $\psi_{\text{glob}} > \psi_{\text{LS}}$ due to the fifth force. Comparing $\psi_{\text{glob}}$ with $\psi_{\text{LS}}$ inferred from lensing would give

$$
\frac{\psi_{\text{glob}} + \psi_{\text{LS}}}{\psi_{\text{eff}}} \leq \left| \frac{\psi_{\text{glob}} + \psi_{\text{LS}}}{\psi_{\text{LS}}} \right| = 2, \quad \text{leading to} \quad \eta^{\text{int}} = \frac{\psi_{\text{glob}} + \psi_{\text{LS}}}{\psi_{\text{eff}}} - 1 < 1,
$$

that is, a detection of non-vanishing gravitational slip. Again, while we used CQ to illustrate the point, the argument holds for a general dark force.

**Galaxy distribution multipoles**

In addition to RSDs, the observed fluctuation in the galaxy number counts is affected by several other distortions\(^{25–27}\):

$$
\Delta_{\text{eff}}(n, z) = \frac{1}{3} \frac{\partial}{\partial r} V_b \cdot n + \left( 1 - 5x + \frac{5x - 2}{3} \mathcal{H} + \frac{f^{\text{evol}}}{f_{\text{eff}}} \right) V \cdot n.
$$

where the first term on the right-hand side is the gravitational redshift that probe the true Newtonian potential $\Psi$. Note that other relativistic effects contribute to $\Delta$, such as Shapiro time delay, integrated Sachs–Wolfe and gravitational lensing\(^{35–37}\). However, these effects are negligible at the scales and redshifts relevant for the analyses we describe here\(^{38}\).

To separate the relativistic effects from the standard density and RSD, one can expand the power spectrum in multipoles of $\mu_b$

$$
P_{\text{gal}}^{\text{eff}}(k, \mu, z) = \sum_{\mu_b} P_{\text{gal}}^{\mu_b}(k, z) C_{\ell}(\mu_b).
$$
where \( \mathcal{L}_\ell(\mu_k) \) denotes the Legendre polynomial of order \( \ell \). Using the continuity equation (55), the multipoles can be written as

\[
P_{\text{BF}}^{(0)}(k, z) = \left[ b_b b_f + \frac{1}{3} (b_b + b_f) y_m + \frac{4}{7} y_m^2 \right] P_{\text{gal}}(k, z). \tag{60}
\]

Quadrupole: \( P_{\text{BF}}^{(2)}(k, z) = \left[ \frac{2}{3} (b_b + b_f) y_m + \frac{4}{7} y_m^2 \right] P_{\text{gal}}(k, z). \tag{61} \)

Hexadecapole: \( P_{\text{BF}}^{(4)}(k, z) = \frac{8}{35} y_m^2 P_{\text{gal}}(k, z). \tag{62} \)

Dipole: \( P_{\text{BF}}^{(0)}(k, z) = i \left[ \mu_k f_m, \Theta_b, \Theta_f \right] \frac{\Psi}{k} P_{\text{gal}}(k, z) + i (b_b - b_f) \frac{\Psi}{k} P_{\text{gal}}(k, z). \tag{63} \)

Octupole: \( P_{\text{BF}}^{(0)}(k, z) = i \left[ \mu_k f_m, \Theta_b, \Theta_f \right] \frac{\Psi}{k} P_{\text{gal}}(k, z). \tag{64} \)

where \( \Theta_b \) and \( \Theta_f \) encode the dependence of the multipoles on the bias, magnification bias and evolution bias of the bright and faint population, respectively. These multipoles can be measured separately by weighting the galaxy power spectrum with the appropriate Legendre polynomial

\[
P_{\text{BF}}^{(0)}(k, z) = \frac{2 \ell + 1}{2} \int_{-1}^{1} \mu_k \mathcal{L}_\ell(\mu_k) \mathcal{P}_{\text{BF}}^{(0)}(k, \mu_k, z). \tag{65} \]

The monopole, quadrupole and hexadecapole are routinely measured for one population of galaxies, see, for example, ref. 49, and also for multiple populations\cite{48,49}. Measuring these multipoles is actually the optimal way to extract information from RSD and to infer the growth rate \( \sigma_8 \). Measuring the dipole is significantly more difficult, as its signal-to-noise ratio must be much smaller than that of the even multipoles. This is due to the fact that the dipole is suppressed by a factor \( \sqrt{\ell}/k \) with respect to the even multipoles. Note that here we show the multipoles of the power spectrum. In practice, when including relativistic effects, it is better to work with the multipoles of the correlation function, as wide-angle corrections can be correctly accounted for in this case.

**Data availability**

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

**References**

1. Perlmutter, S. et al. Measurements of omega and lambda from 42 high redshift supernovae. *Astrophys. J.* **517**, 565–586 (1999).
2. Riess, A. G. et al. Observational evidence from supernovae for an accelerating universe and a cosmological constant. *Astron. J.* **116**, 1009–1038 (1998).
3. Lovelock, D. The Einstein tensor and its generalizations. *J. Math. Phys.* **12**, 498–501 (1971).
4. Lovelock, D. The four-dimensionality of space and the einstein tensor. *J. Math. Phys.* **13**, 874–876 (1972).
5. Horndeski, G. W. Second-order scalar-tensor field equations in a four-dimensional space. *Int. J. Theor. Phys.* **10**, 363–384 (1974).
6. Deffayet, C., Gao, X., Steer, D. A. & Zahariade, G. From k-essence to generalised Galileons. *Phys. Rev. D* **84**, 064039 (2011).
7. Amendola, L., Kunz, M. & Sapone, D. Measuring the dark side (with weak lensing). *J. Cosmol. Astropart. Phys.* **004**, 013 (2008).
8. Daniel, S. F., Caldwell, R. R., Cooray, A. & Melchiorri, A. Large scale structure as a probe of gravitational slip. *Phys. Rev. D* **77**, 103513 (2008).
9. Zhang, P., Ligori, M., Bean, R. & Dodelson, S. Probing gravity at cosmological scales by measurements which test the relationship between gravitational lensing and matter overdensity. *Phys. Rev. Lett.* **99**, 141302 (2007).
10. Song, Y.-S. et al. Complementarity of weak lensing and peculiar velocity measurements in testing general relativity. *Phys. Rev. D* **84**, 083523 (2011).
11. Amendola, L., Kunz, M., Motta, I. D. & Sawicki, I. Observables and unobservables in dark energy cosmologies. *Phys. Rev. Lett.* **87**, 023501 (2001).
12. Amendola, L. et al. Cosmology and fundamental physics with the Euclid satellite. *Living Rev. Relativ.* **16**, 6 (2013).
13. Amendola, L. et al. Cosmology and fundamental physics with the Euclid satellite. *Living Rev. Relativ.* **21**, 2 (2018).
14. Wetterich, C. The Cosmon model for an asymptotically vanishing time dependent cosmological constant. *Astron. Astrophys.* **301**, 321–328 (1995).
15. Zlatev, I., Wang, L.-M. & Steinhardt, P. J. Quintessence, cosmic coincidence, and the cosmological constant. *Phys. Rev. Lett.* **82**, 896–899 (1999).
16. Amendola, L. Coupled quintessence. *Phys. Rev. D* **62**, 043511 (2000).
17. Barros, B. J., Amendola, L., Barreiro, T. & Nunes, N. J. Coupled quintessence with a $\Lambda$CDM background: removing the $\sigma_8$ tension. *J. Cosmol. Astropart. Phys.* **01**, 007 (2019).
18. Song, Y.-S., Hollenstein, L., Caldera-Cabral, G. & Koyama, K. Theoretical priors on modified growth parameterizations. *J. Cosmol. Astropart. Phys.* **04**, 018 (2010).
19. Motta, M., Sawicki, I., Sawicki, I. D., Amendola, L. & Kunz, M. Probing dark energy through scale dependence. *Phys. Rev. D* **88**, 124035 (2013).
20. Zucca, A., Pogosian, L., Silvestri, A. & Zhao, G.-B. MGAMCMB with massive neutrinos and dynamical dark energy. *J. Cosmol. Astropart. Phys.* **05**, 001 (2019).
21. Castelló, S., Grimm, N. & Bonvin, C. Rescuing constraints on modified gravity using gravitational redshift in large-scale structure. *Phys. Rev. D* **106**, 083511 (2023).
22. Kunz, M. & Sapone, D. Dark energy versus modified gravity. *Phys. Rev. Lett.* **98**, 121301 (2007).
23. Battye, R. A. & Pearson, J. A. Effective action approach to cosmological perturbations in dark energy and modified gravity. *J. Cosmol. Astropart. Phys.* **07**, 019 (2012).
24. Kaiser, N. Clustering in real space and in redshift space. *Mon. Not. R. Astron. Soc.* **227**, 1–27 (1987).
25. Bonvin, C. & Durrer, R. What galaxy surveys really measure. *Phys. Rev. D* **84**, 063505 (2011).
26. Yoo, J., Fitzpatrick, A. L. & Zaldarriaga, M. A new perspective on galaxy clustering as a cosmic probe: general relativistic effects. *Phys. Rev. D* **80**, 083514 (2009).
27. Challinor, A. & Lewis, A. The linear power spectrum of observed source number counts. *Phys. Rev. D* **84**, 043516 (2011).
28. Bonvin, C., Hui, L. & Gaztanaga, E. Asymmetric galaxy correlation functions. *Phys. Rev. D* **89**, 083535 (2014).
29. McDonald, P. Gravitational redshift and other redshift-space distortions of the imaginary part of the power spectrum. *J. Cosmol. Astropart. Phys.* **11**, 026 (2009).
30. Croft, R. A. C. Gravitational redshifts from large-scale structure. *Mon. Not. R. Astron. Soc.* **434**, 3008–3017 (2013).
31. Yoo, J., Hamaus, N., Seljak, U. & Zaldarriaga, M. Going beyond the Kaiser redshift-space distortion formula: a full general relativistic account of the effects and their detectability in galaxy clustering. *Phys. Rev. D* **86**, 063514 (2012).
32. Gaztanaga, E., Bonvin, C. & Hui, L. Measurement of the dipole in the cross-correlation function of galaxies. *J. Cosmol. Astropart. Phys.* **01**, 032 (2017).
33. Beutler, F. & Di Dio, E. Modeling relativistic contributions to the halo power spectrum dipole. *J. Cosmol. Astropart. Phys.* **07**, 048 (2020).
34. Bonvin, C. & Fleury, P. Testing the equivalence principle on cosmological scales. *J. Cosmol. Astropart. Phys.* **05**, 061 (2018).
35. Sobral-Blanco, D. & Bonvin, C. Measuring anisotropic stress with relativistic effects. *Phys. Rev. D* **104**, 063516 (2021).
36. Sobral-Blanco, D. & Bonvin, C. Measuring the distortion of time with relativistic effects in large-scale structure. *Mon. Not. R. Astron. Soc. Letters* **519**, 39 (2023).
37. Prat, J. et al. Dark energy survey year 3 results: high-precision measurement and modeling of galaxy–galaxy lensing. *Phys. Rev. D* **105**, 083528 (2022).
38. Tutusaus, I., Sobral-Blanco, D. & Bonvin, C. Combining gravitational lensing and gravitational redshift to measure the anisotropic stress with future galaxy surveys. *Phys. Rev. D* **107**, 083526 (2023).
39. Ivezić, v et al. LSST: from science drivers to reference design and anticipated data products. *Astrophys. J.* **873**, 11 (2019).
40. Planck Collaboration Planck 2015 results. XIV. Dark energy and modified gravity. *Astron. Astrophys.* **594**, A14 (2016).
41. Wang, J., Hui, L. & Khoury, J. No-go theorems for generalized chameleon field theories. *Phys. Rev. Lett.* **109**, 241301 (2012).
42. Baldi, M. Clarifying the effects of interacting dark energy on linear and nonlinear structure formation processes. *Mon. Not. R. Astron. Soc.* **414**, 116 (2011).
43. Khoury, J. & Weltman, A. Chameleon fields: awaiting surprises for tests of gravity in space. *Phys. Rev. Lett.* **93**, 171104 (2004).
44. Hinterbichler, K. & Khoury, J. Symmetron fields: screening long-range forces through local symmetry restoration. *Phys. Rev. Lett.* **104**, 231301 (2010).
45. Deffayet, C., Esposito-Farese, G. & Vikman, A. Covariant Galileon. *Phys. Rev. D* **79**, 084003 (2009).
46. Deffayet, C., Pujolos, O., Sawicki, I. & Vikman, A. Imperfect dark energy from kinetic gravity braiding. *J. Cosmol. Astropart. Phys.* **1010**, 026 (2010).
47. Linder, E. V. No slip gravity. *J. Cosmol. Astropart. Phys.* **03**, 005 (2018).
48. Jelic-Cizmek, G., Lepori, F., Bonvin, C. & Durrer, R. On the importance of lensing for galaxy clustering in photometric and spectroscopic surveys. *J. Cosmol. Astropart. Phys.* **04**, 055 (2021).
49. Alam, S. et al. Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory. *Phys. Rev. D* **103**, 083533 (2021).
50. Blake, C. et al. Galaxy And Mass Assembly (GAMA): improved cosmic growth measurements using multiple tracers of large-scale structure. *Mon. Not. R. Astron. Soc.* **436**, 3089 (2013).
51. Zhao, G.-B. et al. The completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: a multitracer analysis in Fourier space for measuring the cosmic structure growth and expansion rate. *Mon. Not. R. Astron. Soc.* **504**, 33–52 (2021).

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**Author contributions**

The authors contributed equally to all aspects of the project and writing the paper.

**Competing interests**

The authors declare competing interests.

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