Differentiating dark energy and modified gravity with galaxy redshift surveys

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Abstract. The observed cosmic acceleration today could be due to an unknown energy component (dark energy), or a modification to general relativity (modified gravity). If dark energy models and modified gravity models are required to predict the same cosmic expansion history $H(z)$, they will predict different growth rates for cosmic large scale structure, $f_{g}(z)$. If gravity is not modified, the measured $H(z)$ leads to a unique prediction for $f_{g}(z)$, $f_{g}^{H}(z)$, if dark energy and dark matter are separate. Comparing $f_{g}^{H}(z)$ with the measured $f_{g}(z)$ provides a transparent and straightforward test of gravity. We show that a simple $\chi^2$ test provides a general figure of merit for our ability to distinguish between dark energy and modified gravity given the measured $H(z)$ and $f_{g}(z)$. We find that a magnitude-limited NIR galaxy redshift survey covering $>10000\,\text{deg}^2$ and a redshift range of $0.5 < z < 2$ can be used to measure $H(z)$ to 1–2% accuracy via baryon acoustic oscillation measurements, and $f_{g}(z)$ to the accuracy of a few percent via the measurement of redshift-space distortions and the bias factor which describes how light traces mass. We show that if the $H(z)$ data are fitted by both a DGP gravity model and an equivalent dark energy model that predict the same $H(z)$, a survey area of $11,931\,\text{(deg)}^2$ is required to rule out the DGP gravity model at the 99.99% confidence level. It is feasible for such a galaxy redshift survey to be carried out by the next generation space missions from NASA and ESA, and it will revolutionize our understanding of the universe by differentiating between dark energy and modified gravity.

Keywords: dark energy theory, gravity, surveys of galaxies, power spectrum
Differentiating dark energy and modified gravity with galaxy redshift surveys

1. Introduction

The observed cosmic acceleration today [1,2] could be due to an unknown energy component (dark energy, see, e.g., [3]), or a modification to general relativity (modified gravity, see, e.g., [4,5]). Reference [6] contains reviews with more complete lists of references. Illuminating the nature of dark energy is one of the most exciting challenges in cosmology today.

The cosmic expansion history, \( H(z) = (da/da)(a) \) (where \( a \) is the cosmic scale factor), and the growth rate for cosmic large scale structure, \( f_g(z) = d\ln\delta/d\ln a \) (where \( \delta = (\rho_m - \rho_m)/\rho_m \)), are two functions of redshift \( z \) that can be measured from cosmological data. They provide independent and complementary probes of the nature of the observed cosmic acceleration [7,9]. The precisely measured \( H(z) \) and \( \Omega_m \) lead to a unique prediction for \( f_g(z) \) in the absence of modified gravity, \( f_g^H(z) \), if dark energy and dark matter are separate. Comparing \( f_g^H(z) \) with the measured \( f_g(z)_{\text{obs}} \) provides a transparent and straightforward test of gravity (see figure 1). If gravity is not modified, \( H(z) \) and \( f_g(z) \) together provide stronger constraints on dark energy models [10].

Using the VVDS data, reference [11] demonstrated that a magnitude-limited galaxy redshift survey can be used to measure \( f_g(z) \) via measurements of redshift-space distortion parameter

\[
\beta(z) = \frac{f_g(z)}{b(z)}
\]  

(1)

and the bias parameter \( b(z) \) (which describes how light traces mass) from galaxy clustering. In this paper we show that a feasible, sufficiently wide and deep magnitude-limited galaxy redshift survey will allow us to unambiguously differentiate between dark energy and modified gravity by providing precise measurements of \( H(z) \) and \( f_g(z) \) (see figure 1).

2. Models

If the present cosmic acceleration is caused by dark energy, \( E(z) \equiv H(z)/H_0 = [\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_X X(z)]^{1/2} \), where \( X(z) \equiv \rho_X(z)/\rho_X(0) \), with \( \rho_X(z) \) denoting...
Differentiating dark energy and modified gravity with galaxy redshift surveys

Figure 1. Current and expected future measurements of the cosmic expansion history $H(z) = H_0 E(z)$ and the growth rate of cosmic large scale structure $f_g(z) = d \ln \delta / d \ln a$ ($\delta = (\rho_m - \bar{\rho}_m) / \bar{\rho}_m$; $a$ is the cosmic scale factor). Note that the fiducial model assumed for the future galaxy redshift survey is a dark energy model with the same $H(z)$ as that of the DGP model. These two models have identical expansion histories $H(z)$ (solid line in panel (a)), but very different growth rates $f_g(z)$ (solid and dashed lines in panel (b)).

the dark energy density. The linear growth rate $f_g \equiv d \ln D_1 / d \ln a$ is determined by solving the equation for $D_1 = \delta^{(1)}(x, t) / \delta(x)$,

$$D_1' (\tau) + 2 E(z) D_1' (\tau) - \frac{2}{3} \Omega_m (1 + z)^3 D_1 = 0,$$

where primes denote $d/d(\tau_0 t)$, and we have assumed that dark energy and dark matter are separate.

In the simplest alternatives to dark energy, the present cosmic acceleration is caused by a modification to general relativity. The only rigorously worked example is the DGP gravity model [5, 7], which can be described by a modified Friedmann equation:

$$H^2 - \frac{H}{r_0} = \frac{8 \pi G \rho_m}{3},$$

where $r_0$ is a parameter in DGP gravity, and $\rho_m(z) = \rho_m(0)(1 + z)^3$. Solving equation (3) gives

$$E(z) = \frac{H(z)}{H_0} = \frac{1}{2} \left\{ \frac{1}{H_0 r_0} + \left[ \frac{1}{(H_0 r_0)^2} + 4 \Omega_m^0 (1 + z)^3 \right]^{1/2} \right\},$$

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Differentiating dark energy and modified gravity with galaxy redshift surveys

with \( \Omega_m^0 \equiv \rho_m(0)/\rho_c^0 \), \( \rho_c^0 \equiv 3H_0^2/(8\pi G) \). The added superscript ‘0’ in \( \Omega_m^0 \) denotes that this is the matter fraction today in the DGP gravity model. Note that consistency at \( z = 0 \), \( E(0) = 1 \) requires that

\[
H_0 r_0 = \frac{1}{1 - \Omega_m^0},
\]

so the DGP gravity model is parametrized by a single parameter, \( \Omega_m^0 \). The linear growth factor in the DGP gravity model is given by [7]

\[
D''_1(\tau) + 2E(z)D'_1(\tau) - \frac{3}{2} \Omega_m (1 + z)^3 D_1 \left( 1 + \frac{1}{3\alpha_{DGP}} \right) = 0,
\]

where

\[
\alpha_{DGP} = \frac{1 - 2H_0 r_0 + 2(H_0 r_0)^2}{1 - 2H_0 r_0}.
\]

The dark energy model equivalent of the DGP gravity model is specified by requiring

\[
\frac{8\pi G \rho_{de}^{\text{eff}}}{3} = \frac{H}{r_0}.
\]

Equation (3) and the conservation of energy and momentum equation,

\[
\dot{\rho}_{de}^{\text{eff}} + 3(\rho_{de}^{\text{eff}} + p_{de}^{\text{eff}})H = 0,
\]

imply that [7]

\[
w_{de}^{\text{eff}} = -\frac{1}{1 + \Omega_m(a)},
\]

where

\[
\Omega_m(a) \equiv \frac{8\pi G \rho_m(z)}{3H^2} = \frac{\Omega_m^0(1 + z)^3}{E^2(z)}.
\]

As \( a \to 0 \), \( \Omega_m(a) \to 1 \), and \( w_{de}^{\text{eff}} \to -0.5 \). As \( a \to 1 \), \( \Omega_m(a) \to \Omega_m^0 \), and \( w_{de}^{\text{eff}} \to -1/(1 + \Omega_m^0) \). This means that the matter transfer function for the dark energy model equivalent of the viable DGP gravity model (\( \Omega_m^0 < 0.3 \) and \( w \leq -0.5 \)) is very close to that of the ΛCDM model at \( k \gtrsim 0.001h\text{ Mpc}^{-1} \) [12].

It is very easy and straightforward to integrate equations (2) and (6) to obtain \( f_g \) for dark energy models and DGP gravity models, with the initial condition that for \( a \to 0 \), \( D_1(a) = a \) (which assumes that the dark energy or modified gravity are negligible at sufficiently early times). There are well known approximations to \( f_g \), with \( f_g(z) = \Omega_m(a)^{6/11} \) for dark energy models [13], and \( f_g(z) = \Omega_m(a)^{2/3} \) for DGP gravity models [7]. Figure 2 shows that these power-law approximations of \( f_g \) are not sufficiently accurate for future galaxy redshift surveys that can measure \( f_g \) to a few per cent accuracy in \( \Delta z = 0.2 \) redshift bins.
3. Analysis technique

Galaxy redshift surveys allow us to measure both $H(z)$ and $f_g(z)$ through baryon acoustic oscillation (BAO) measurements (see [15]–[17], [32]) and redshift-space distortion measurements [11]. BAO in the observed galaxy power spectrum has the characteristic scale determined by the comoving sound horizon at recombination, which is precisely measured by the cosmic microwave background (CMB) anisotropy data [14]. Comparing the observed BAO scales with the expected values gives $H(z)$ in the radial direction, and $D_A(z)$ (the angular diameter distance $D_A(z) = r(z)/(1 + z)$, where $r(z)$ is the coordinate or comoving distance) in the transverse direction. We will only estimate the accuracy to which $H(z)$ and $f_g(z)$ can be determined from galaxy redshift surveys in dark energy models (the error bars in figure 1).

The observed power spectrum is reconstructed using a particular reference cosmology, including the effects of bias and redshift-space distortions [16]:

$$P_{\text{obs}}(k_\perp, k_\parallel) = \left[ \frac{D_A(z)}{D_A(z)} \right]^2 H(z) b^2 (1 + \beta \mu^2)^2 \cdot \left[ \frac{G(z)}{G(0)} \right]^2 P_{\text{matter}}(k)_{z=0} + P_{\text{shot}},$$

where the growth factor $G(z)$ and the growth rate $f_g(z) = \beta b(z)$ are related via $f_g(z) = \frac{d \ln G(z)}{d \ln a}$, and $\mu = k \cdot \hat{r}/k$, with $\hat{r}$ denoting the unit vector along the line of sight; $k$ is the wavevector with $|k| = k$. Hence $\mu^2 = k_\parallel^2/k^2 = k_\parallel^2/(k_\perp^2 + k_\parallel^2)$. The

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Figure 2. The accuracy of approximate expressions for $f_g(z)$ for various models.

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1 Reference [18] gives a more precise treatment of redshift-space distortions, and reference [19] studies power spectra in alternative gravity models.
values in the reference cosmology are denoted by the subscript ‘ref’, while those in the true cosmology have no subscript. Note that
\[ k_{\perp}^{\text{ref}} = k_{\perp} \frac{D_{A}(z)}{D_{A}(z)^{\text{ref}}}, \quad k_{\parallel}^{\text{ref}} = k_{\parallel} \frac{H(z)^{\text{ref}}}{H(z)}. \] (13)

Equation (12) characterizes the dependence of the observed galaxy power spectrum on \( H(z) \) and \( D_{A}(z) \) due to BAO, as well as the sensitivity of a galaxy redshift survey to the redshift-space distortion parameter \( \beta \) [21].

To study the expected impact of future galaxy redshift surveys, we use the Fisher matrix formalism. In the limit where the length scale corresponding to the survey volume is much larger than the scale of any features in \( P(k) \), we can assume that the likelihood function for the band powers of a galaxy redshift survey is Gaussian [22]. Then the Fisher matrix can be approximated as [23]
\[ F_{ij} = \int_{k_{\min}}^{k_{\max}} \frac{\partial \ln P(k)}{\partial p_i} \frac{\partial \ln P(k)}{\partial p_j} V_{\text{eff}}(k) \frac{dk^3}{2(2\pi)^3}, \] (14)
where \( p_i \) are the parameters to be estimated from data, and the derivatives are evaluated at parameter values of the fiducial model. The effective volume of the survey
\[ V_{\text{eff}}(k, \mu) = \int \frac{\partial \ln P(k)}{\partial p_i} \frac{\partial \ln P(k)}{\partial p_j} V_{\text{survey}}, \] (15)
where the comoving number density \( n \) is assumed to only depend on the redshift for simplicity. Note that the Fisher matrix \( F_{ij} \) is the inverse of the covariance matrix of the parameters \( p_i \) if the \( p_i \) are Gaussian distributed. Equation (14) propagates the measurement error in \( \ln P(k) \) (which is proportional to \( V_{\text{eff}}(k)^{-1/2} \)) into measurement errors for the parameters \( p_i \).

Since we do not include nonlinear effects, we only consider wavenumbers smaller than a minimum value of nonlinearity. Following [15], we take \( k_{\min} = 0 \), and \( k_{\max} \) given by requiring that the variance of matter fluctuations in a sphere of radius \( R \), \( \sigma^2(R) = 0.35 \), for \( R = \pi/(2k_{\max}) \). We will also give results for \( \sigma^2(R) = 0.2 \) for comparison. In addition, we impose a uniform upper limit of \( k_{\max} \leq 0.2h \, \text{Mpc}^{-1} \), to ensure that we are only considering the conservative linear regime essentially unaffected by nonlinear effects. Reference [25] shows that nonlinear effects can be accurately taken into account. Reference [26] shows that the BAO signal is boosted when these effects are properly included in the Hubble volume simulation. We assume \( \Omega_b = 0.045 \), \( h = 0.7 \), \( b = 1 \), and \( nP = 3 \) [15]; this is conservative since \( nP > 3 \) at any redshift for a magnitude-limited survey.

The observed galaxy power spectrum in a given redshift shell centered at redshift \( z_i \) can be described by a set of parameters, \( \{H(z_i), D_{A}(z_i), G(z_i), \beta(z_i), P_{\text{shot}}, n_{S}, \omega_{m}, \omega_{b}\} \), where \( n_{S} \) is the power-law index of the primordial matter power spectrum, \( \omega_{m} = \Omega_{m}h^2 \), and \( \omega_{b} = \Omega_{b}h^2 \) (\( h \) is the dimensionless Hubble constant). Note that \( P(k) \) does not depend on \( h \) if \( k \) is in units of \( \text{Mpc}^{-1} \), since the matter transfer function \( T(k) \) only depends on \( \omega_{m} \) and \( \omega_{b} [27]^2 \), if the dark energy dependence of \( T(k) \) can be neglected. Since \( G(z), b, \)

\(^{2}\) Massive neutrinos can suppress the galaxy power spectrum amplitudes by \( \geq 4\% \) on BAO scales [24]. It will be important for future work to quantify the effect of massive neutrinos on the measurement of \( H(z) \) and \( f_{\sigma}(z) \).
and the power spectrum normalization $P_0$ are completely degenerate in equation (12), we have defined $G(z_i) \equiv b G(z) P_0^{1/2} / G(0)$.

The square roots of diagonal elements of the inverse of the full Fisher matrix of equation (14) give the estimated smallest possible measurement errors on the assumed parameters. The parameters of interest are $\{H(z_i), D_A(z_i), \beta(z_i)\}$; all other parameters are marginalized over. Note that the estimated errors we obtain here are independent of cosmological priors\(^3\), and thus scale with (area)\(^{-1/2}\) for a fixed survey depth.

Figure 1 shows the errors on $H(z)$ and $f_g(z) = \beta(z)b(z)$ for a dark energy model that gives the same $H(z)$ as a DGP gravity model with the same $\Omega_m^0$, for a redshift survey covering 11 931 (deg)\(^2\), and the redshift range $0.5 < z < 2$ ($\sigma^2(R) = 0.35$ assumed). Note that the $D_A(z)$ measured from the same redshift survey provides additional constraints on $H(z)$ that can be used for cross-checking to eliminate systematic effects. We have neglected the very weak dependence of the transfer function on dark energy at very large scales in this model [12], and added $\Delta \ln b = 0.01 \{ \text{(area)} / [28 600 \text{(deg)}^2] \}^{-1/2}$ in quadrature to the estimated error on $\beta$.\(^4\)

Reference [36] developed the method for measuring $b(z)$ from the galaxy bispectrum, which was applied by [37] to the 2dF data. Assuming that [35]

$$\delta_g = b\delta(x) + \frac{1}{2} b_2 \delta^2(x), \quad \text{(16)}$$

the galaxy bispectrum

$$\langle \delta_{gk_1}\delta_{gk_2}\delta_{gk_3} \rangle = (2\pi)^3 \left\{ P_g(k_1)P_g(k_2) \left[ \frac{J(k_1, k_2)}{b} + b_2 b_3 \right] + \text{cyc.} \right\} \delta^D(k_1 + k_2 + k_3), \quad \text{(17)}$$

where $J$ is a function that depends on the shape of the triangle formed by $(k_1, k_2, k_3)$ in $k$ space, but only depends very weakly on cosmology [36].

Reference [15] used Monte Carlo $N$-body simulation to study the extraction of the BAO scales. For comparison, we calculated $\{H(z_i), D_A(z_i)\}$ for the same fiducial model as considered by [15] (with the same assumptions and cutoffs in $k$), and obtained results that are within 30% of the values given by the fitting formulas from [28]. This is reassuring, as it validates the approach of using the Fisher matrix formalism to forecast the parameter accuracies for future redshift surveys\(^5\).

### 4. Observational methods

$H(z)$ can be probed using multiple techniques. It can be measured using type Ia supernovae (SNe Ia) as cosmological standard candles [29]. CMB and large scale structure data provide constraints on cosmological parameters that help tighten the constraints on $H(z)$ [30]. Figure 1(a) shows the $H(z)$ given by equation (3) with $\Omega_m^0 = 0.25$ (solid line),

\(^3\) Priors on $\omega_m$, $\omega_b$, $\Omega_k$, and $n_S$ will be required to obtain the errors on dark energy parameters.

\(^4\) This $\Delta \ln b$ estimate comes from extrapolating 2dF measurement of $b = 1.04 \pm 0.11$ at $z \sim 0.15$ for an effective survey area of $1300 \times 127 000 / 245 591 = 672$ (deg)\(^2\) [37], and assuming a factor of 1.6 improvement for an NIR space mission that can detect galaxies at a much higher number density. This $\Delta \ln b$ estimate is comparable to (and larger than) that estimated by [38] for imaging surveys at $z < 2$.

\(^5\) Reference [20] found similar agreement in their comparison.
Differentiating dark energy and modified gravity with galaxy redshift surveys

as well as a cosmological constant model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ (dotted line). Clearly, both these fit the constraints on $H(z)$ from current data [30] (no priors assumed)\(^6\).

BAO measurements from a very wide and deep galaxy redshift survey provide a direct precise measurement of $H(z)$ (see figure 1(a)). Suppose $H(z)$ is measured to be $H^2 - H/r_0 = 8\pi G \rho_m/3$ (see solid line in figure 1(a)) and $\Omega_m$ is known accurately, equation (2) yields a unique prediction for $f_g(z)$, $f_g^H(z)$, assuming that gravity is not modified (see the dashed line in figure 1(b)).

The measurement of $f_g(z)$ can be obtained through independent measurements of $\beta = f_g(z)/b$ and $b(z)$ [11]. The parameter $\beta$ can be measured directly from galaxy redshift survey data by studying the observed redshift-space correlation function [33,34]. The bias factor $b(z)$ can be measured by studying galaxy clustering properties (for example, the galaxy bispectrum) from the galaxy redshift survey data [37]. Independent measurements of $\beta(z)$ and $b(z)$ have only been published for the 2dF data [33,37,39].

Figure 1(b) shows the $f_g(z)$ for the DGP gravity model with $\Omega_m^D = 0.25$ (solid line), as well as a dark energy model that gives the same $H(z)$ for the same $\Omega_m^D$ (dashed line). The cosmological constant model from figure 1(a) is also shown (dotted line). Clearly, current data cannot differentiate between dark energy and modified gravity.

A very wide and deep galaxy redshift survey provides measurement of $f_g(z)$ accurate to a few per cent (see figure 1(b)); this will allow an unambiguous distinction between dark energy models and modified gravity models that give identical $H(z)$ (see the solid and dashed lines in figure 1(b)). A simple $\chi^2$ test can provide a general figure of merit for our ability to distinguish between dark energy and modified gravity models that fit the measured $H(z)$ but predict different $f_g(z)$. If the measurement errors are normally distributed, $\Delta \chi^2 \equiv \chi^2(s) - \chi^2(s_0)$ is distributed as a chi-square distribution with $n$ degrees of freedom ($n$ is the number of data points), where $s$ is the test model, and $s_0$ is the best-fit model measured from data. $P(\chi^2|n) = 99.99\%$ corresponds to $\Delta \chi^2 = 29.877$ for $n = 7$. Assuming that $\chi^2(s_0) = n$, we find that $\chi^2(s) = 36.877$. In figure 1, we assume that the true model is a dark energy model with $\Omega_m^D = 0.25$, $H^2 - H/r_0 = 8\pi G \rho_m/3$, with $Hr_0 = 1/(1 - \Omega_m^D)$. For a linear cutoff given by $\sigma^2(R) = 0.35$ (or 0.2), a survey covering $11,931$ (deg)$^2$ would rule out the DGP gravity model that gives the same $H(z)$ and $\Omega_m^0$ at $99.99\%$ (or 95\%) C.L.; a survey covering $13,912$ (deg)$^2$ would rule out the DGP gravity model at $99.999\%$ (or 99\%) C.L.

5. Conclusions

Discovering the nature of dark energy has been identified as a high priority by both NASA and ESA. A magnitude-limited NIR galaxy redshift survey, covering $>10,000$ (deg)$^2$ and the redshift range $0.5 < z < 2$, can be feasibly carried out by a space mission that uses MEMS technology to obtain 5000–10,000 galaxy spectra simultaneously [40,41]. The low background from space enables very short exposure times to obtain galaxy spectra to $z \sim 2$, making it practical to carry out a magnitude-limited NIR galaxy redshift survey over $>10,000$ (deg)$^2$ in only a few years. A magnitude-limited galaxy redshift survey over $>10,000$ (deg)$^2$ will enable robust and precise determination of $b(z)$ using multiple

\(^6\) Reference [30] uses WMAP three year data [14], 182 type Ia supernovae [31], and the SDSS baryon acoustic scale measurement [32].
Differentiating dark energy and modified gravity with galaxy redshift surveys

techniques and with sufficient statistics [11, 36, 37]. This is critical for determining \( f_g(z) \) using measurements of redshift-space distortions. Such a survey will also enable rigorous study of the systematic uncertainties of BAO, and accurate measurements of redshift-space distortions.

Reference [8] studied the use of weak lensing shear maps to differentiate between dark energy and modified gravity, complementary to what we have studied in this paper. While both weak lensing surveys and galaxy redshift surveys can provide accurate measurements of \( H(z) \) (if the systematic uncertainties are properly modeled and controlled), galaxy redshift surveys can potentially provide the most accurate measurement of \( f_g(z) \) (compare figure 2 of [8] with figure 1 of this paper, noting that \( f_g(z) = \frac{d \ln G(z)}{d \ln a} \)).

We have shown that a magnitude-limited NIR galaxy redshift survey covering \( >10,000 \text{ (deg)}^2 \) and \( 0.5 < z < 2 \) can provide precise measurements of the cosmic expansion history \( H(z) \), and the growth rate of cosmic large scale structure \( f_g(z) \). These provide model-independent constraints on dark energy and the nature of gravity. The precisely measured \( H(z) \) can be used to predict \( f_g(z) \) expected in the absence of modified gravity, \( f_{gH}(z) \), if dark energy and dark matter are separate. Comparing \( f_{gH}(z) \) with \( f_g(z) \) provides a transparent and powerful probe of modified gravity. This will allow us to illuminate the nature of the observed cosmic acceleration by differentiating between dark energy and modified gravity (see figure 1). A magnitude-limited survey covering \( 11,931 \text{ (deg)}^2 \) can rule out the DGP gravity model at the 99.99% confidence level\(^7\). If this technologically feasible survey is carried out by a space mission, it will have a revolutionary effect on our understanding of the universe.

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References

[1] Riess A G et al, 1998 Astron. J. 116 1009 [SPIRES]
[2] Perlmutter S et al, 1999 Astrophys. J. 517 565 [SPIRES]
[3] Freese K et al, 1987 Nucl. Phys. B 297 797 [SPIRES]
Wetterich C, 1988 Nucl. Phys. B 302 668 [SPIRES]
Frieman J A et al, 1995 Phys. Rev. Lett. 75 2077 [SPIRES]
Caldwell R, Dave R and Steinhardt P J, 1998 Phys. Rev. Lett. 80 1582 [SPIRES]
[4] Salni V and Babib S, 1998 Phys. Rev. Lett. 81 1766 [SPIRES]
Parker L and Raval A, 1999 Phys. Rev. D 60 063512 [SPIRES]
Delfayet C, 2001 Phys. Lett. B 502 199 [SPIRES]
Uzan J-P and Bernardeau F, 2001 Phys. Rev. D 64 083004 [SPIRES]
Freese K and Lewis M, 2002 Phys. Lett. B 540 1 [SPIRES]
Onemli V K and Woodard R P, 2004 Phys. Rev. D 70 107301 [SPIRES]
[5] Dvali G, Gabadadze G and Porrati M, 2000 Phys. Lett. B 485 208 [SPIRES]
[6] Padmanabhan T, 2003 Phys. Rep. 380 235 [SPIRES]
Peebles P J E and Ratra B, 2003 Rev. Mod. Phys. 75 55 [SPIRES]
Sahni V and Starobinsky A, 2006 Int. J. Mod. Phys. D 15 2105 [SPIRES]

Such a survey would allow us to distinguish between dark energy and modified gravity even if dark energy is clustered such that \( f_g \), bias, and redshift distortions are scale dependent \([42]\), since a dark energy model and a modified gravity model generally have different redshift dependences of the modified growth rate, and the data of such a survey can be analyzed in multi-redshift slices, on multiple scales, and using different populations of galaxies.

\(^7\) Such a survey would allow us to distinguish between dark energy and modified gravity even if dark energy is clustered such that \( f_g \), bias, and redshift distortions are scale dependent \([42]\), since a dark energy model and a modified gravity model generally have different redshift dependences of the modified growth rate, and the data of such a survey can be analyzed in multi-redshift slices, on multiple scales, and using different populations of galaxies.
Differentiating dark energy and modified gravity with galaxy redshift surveys

Copeland E J, Sami M and Tsujikawa S, 2006 Int. J. Mod. Phys. D 15 1753 [SPIRES]
Ruiz-Lapuente P, 2007 Class. Quantum Grav. 24 R91 [SPIRES]
Ratra B and Vogeley M S, 2007 Preprint 0706.1565
Sahni V and Starobinsky A, 2006 Int. J. Mod. Phys. D 15 2105 [SPIRES]
[7] Lue A, Scoccimarro R and Starkman G D, 2004 Phys. Rev. D 69 124015 [SPIRES]
Lue A, 2006 Phys. Rep. 423 1 [SPIRES]
[8] Knox L, Song Y S and Tyson J A, 2006 Phys. Rev. D 74 023512 [SPIRES]
[9] Heavens A F, Kitching T D and Verde L, 2007 Mon. Not. R. Astron. Soc. 380 1029
Zhang P, Liguori M, Bean R and Dodelson S, 2007 Phys. Rev. Lett. 99 141302 [SPIRES]
Sapone D and Amendola L, 2007 Preprint 0709.2792 [ps, pdf, other]
[10] Knop R A et al, 2003 Astrophys. J. 598 102 [SPIRES]
Wang Y and Mukherjee P, 2004 Astrophys. J. 606 654 [SPIRES]
Wang Y and Tegmark T, 2004 Phys. Rev. Lett. 92 241302 [SPIRES]
[11] Guzzo L et al, 2008 Nature 451 541 [SPIRES]
[12] Ma C P, Caldwell R R, Bode P and Wang L, 1999 Astrophys. J. 521 L1 [SPIRES]
[13] Wang L and Steinhardt P J, 1998 Astrophys. J. 508 483 [SPIRES]
[14] Spergel D N et al, 2007 Astrophys. J. Suppl. 170 377
[15] Blake C and Glazebrook K, 2003 Astrophys. J. 594 665 [SPIRES]
[16] Seo H and Eisenstein D J, 2003 Astrophys. J. 598 720 [SPIRES]
[17] See, for example, White M, 2005 Apastrop. Phys. 24 334 [SPIRES]
Huetsi G, 2006 Astron. Astrophys. 449 891 [SPIRES]
Wang Y, 2006 Astrophys. J. 647 1 [SPIRES]
Angulo R et al, 2007 Preprint astro-ph/0702543
[18] Scoccimarro R, 2004 Phys. Rev. D 70 083007 [SPIRES]
[19] Stabenau H F and Jain B, 2006 Phys. Rev. D 74 084007 [SPIRES]
[20] Seo H and Eisenstein D J, 2005 Astrophys. J. 633 575 [SPIRES]
[21] Kaiser N, 1987 Mon. Not. R. Astron. Soc. 227 1
[22] Feldman H A, Kaiser N and Peacock J A, 1994 Astrophys. J. 426 23 [SPIRES]
[23] Tegmark M, 1997 Phys. Rev. Lett. 79 3806 [SPIRES]
[24] Eisenstein D J and Hu W, 1999 Astrophys. J. 511 5 [SPIRES]
[25] Hu W, Eisenstein D J and Tegmark M, 1998 Phys. Rev. Lett. 80 5255 [SPIRES]
[26] Jeong D and Komatsu E, 2006 Astrophys. J. 651 619 [SPIRES]
Crocce M and Scoccimarro R, 2007 Preprint 0704.2783
Smith R E, Scoccimarro R and Sheth R K, 2007 Preprint astro-ph/0703620
[27] Koehler R S, Schuecker P and Gebhardt K, 2007 Astron. Astrophys. 462 7 [SPIRES]
[28] Eisenstein D and Hu W, 1998 Astrophys. J. 496 605 [SPIRES]
[29] Blake C et al, 2006 Mon. Not. R. Astron. Soc. 365 255
[30] Phillips M M, 1993 Astrophys. J. 413 L105 [SPIRES]
[31] Wang Y and Mukherjee P, 2007 Phys. Rev. D 76 103533 [SPIRES]
[32] Astier P et al, 2006 Astron. Astrophys. 447 31 [SPIRES]
Riess A G et al, 2007 Astrophys. J. 659 98 [SPIRES]
[33] Eisenstein D et al, 2005 Astrophys. J. 633 560 [SPIRES]
[34] Hawkins E et al, 2003 Mon. Not. R. Astron. Soc. 346 78
[35] Fry J N and Gaztanaga E, 1993 Astrophys. J. 413 447 [SPIRES]
[36] Matarrese S, Verde L and Heavens A F, 1997 Mon. Not. R. Astron. Soc. 290 651
[37] Verde L et al, 2002 Mon. Not. R. Astron. Soc. 335 432 http://www.mso.anu.edu.au/2dFGRS/
[38] Dolney D, Jain B and Takada M, 2006 Mon. Not. R. Astron. Soc. 366 884
[39] Nesseris S and Perivolaropoulos L, 2007 Preprint 0710.1092
[40] Wang Y et al, 2004 Bull. Am. Astron. Soc. 36 1560 [SPIRES]
Crotts A et al, 2005 Preprint astro-ph/0507043
Cheng E et al, 2006 Proc. SPIE 6265 626529
[41] Robberto M, Cimatti A and the SPACE Science Team, 2008 Venice 2007 Conf. Proc.; Nuovo Cim. at press [0710.3970]
[42] Hu W, 2002 Phys. Rev. D 65 023003 [SPIRES]
Gordon C, Hu W, 2004 Phys. Rev. D 70 083003 [SPIRES]
Hui L, Parfrey K P, 2007 Preprint 0712.1162