L5-1

Publ. Astron. Soc. Japan (2018) 70 (5), L5 (1–6)
doi: 10.1093/pasj/psy083
Advance Access Publication Date: 2018 August 9
Letter

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Letter

Are redshift-space distortions actually a probe of growth of structure?

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Received 2018 June 18; Accepted 2018 July 9

Abstract

Although multiple cosmological observations indicate the existence of dark matter and dark energy, cosmological tests of interactions between them have not yet been established. We point out that, in the presence of a coupling between dark matter and dark energy, a peculiar velocity of total matter field is determined not only by a logarithmic time-derivative of its density perturbation but also by density perturbations for both dark matter and baryonic matter, leading to a large modification of the physical interpretation of observed data obtained by measurements of redshift-space distortions. We reformulate a galaxy two-point correlation function in the redshift space based on the modified continuity and Euler equations. We conclude from the resultant formula that redshift space distortions provide us information on the coupling between dark matter and the scalar field by combining weak lensing measurements.

Key words: cosmology: observations — cosmology: theory — dark energy — dark matter — large-scale structure of universe

1 Introduction

The current cosmological observations, such as type Ia supernovae (Perlmutter et al. 1997; Riess et al. 1998) and cosmic microwave background (Planck Collaboration 2016), indicate the presence of dark matter and dark energy, which have not been identified yet. The existence of dark matter is also well established by astrophysical observations, which indicate dark matter as a non-luminous and pressure-less fluid with small dispersion velocity (Zwicky 1933; Bowen & Wyse 1939; Kahn & Woltjer 1959; Clowe et al. 2004). The dark energy is responsible for explaining the late-time accelerated expansion of the Universe, and numerous attempts to identify it have been intensively proposed in much of the literature. One such candidate is to introduce a scalar degree of freedom as a new contribution to the energy–momentum tensor or

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modification in a gravitational sector (see, e.g., Tsujikawa 2010; Clifton et al. 2012 for reviews).

When the ordinary matter, baryons, directly couples with such a scalar degree of freedom, it induces a fifth force. While the fifth force in the baryonic sector is tightly constrained by the solar-system experiments (Will 2006), this is not true for the dark force that is active only in the cold dark matter (CDM) sector since the solar-system experiments do not probe such an interaction. Therefore, the natural arena for probing such interactions is cosmology. When additional interaction is present only in the CDM sector, the growth rate of the CDM density perturbations would be generically different from that of the baryonic matter density perturbations (van de Bruck & Morrice 2015; Mifsud & van de Bruck 2017; van de Bruck & Mifsud 2018; Amendola 2000; Koivisto et al. 2012; Zumalacarregui et al. 2013). We then expect that observing the growth of the CDM density perturbation provides us with rich information about such an interaction.

In the standard treatments, the linear growth rate is mainly obtained by observing a galaxy peculiar velocity field through measurements of redshift-space distortions (RSDs) in galaxy survey. Due to RSDs, the galaxy power spectrum on large scales is known to be enhanced by a factor $(1 + \beta\mu^2)^2$ (named the "Kaiser formula"), where $\beta \equiv f_{\rm m}/b_{\rm g}$ with $f_{\rm m}$ the linear growth rate, $b_{\rm g}$ the linear galaxy bias factor, and μ the cosine of the angle between the line of sight and the Fourier momentum (Kaiser 1987). The degeneracy between the growth rate and the linear bias factor can in principle be broken by using, e.g., higher-order statistics (Scoccimarro et al. 1999) and cross-correlations between other observables (Hashimoto et al. 2016). Hence, it is widely believed that measurements of RSDs even at single redshift allow direct constraints on the growth rate. Moreover, several attempts show that the relation between the peculiar velocity and the growth rate for each species, which is based on the continuity equation, is valid even for the wide range of cosmological scenarios including modified theories of gravity (see, e.g., Gleyzes et al. 2016). However, as we will show below, this relation is not necessarily correct in more general situations.

2 Setup

Let us consider the following invertible metric transformation (Bekenstein 1993),

$$\bar{g}_{\mu\nu} = A(\phi, X)g_{\mu\nu} + B(\phi, X)\partial_\mu\phi\partial_\nu\phi\,, \tag{1}$$

where $g_{\mu\nu}$ is the original frame metric, and $A(\phi, X)$ and $B(\phi, X)$ are called, respectively, the conformal and disformal factors, and are functions of the scalar field ϕ and its kinetic term $X \equiv -g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi/2$. Here and hereafter, ϕ is a generic scalar field, and we do not specify it (though the case with ϕ being responsible for dark energy is the most interesting). The action is given by

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}(R[g] - 2\Lambda) + \mathcal{L}_\phi[g, \phi]\right\} + S_{\rm m}\,, \tag{2}$$

where $\mathcal{L}_\phi$ represents a Lagrangian for the scalar field and $S_{\rm m}$ is a total matter action. For simplicity, we consider the canonical scalar field, $\mathcal{L}_\phi = -(1/2)(\partial\phi)^2 - V(\phi)$, and assume the scalar field does not modify the gravitational sector, i.e., the absence of kinetic braiding (Deffayet et al. 2010). As for the matter sector, we assume that the baryonic matter is minimally coupled for simplicity while the CDM couples with the scalar field through the barred metric $\bar{g}_{\mu\nu}$ defined in equation (1). The total matter action is given by

$$\begin{aligned} S_{\rm m} &= S_{\rm b} + S_{\rm c} \\ &= \int d^4x\left(\sqrt{-g}\mathcal{L}_{\rm b}[g_{\mu\nu}, \psi_{\rm b}] + \sqrt{-\bar{g}}\mathcal{L}_{\rm c}[\bar{g}_{\mu\nu}, \psi_{\rm c}]\right)\,, \end{aligned} \tag{3}$$

where $S_{\rm b}$ and $S_{\rm c}$ represent the actions for baryonic matter and CDM, respectively. Due to the non-minimal coupling between the dark matter and the scalar field, baryonic matter and dark matter do not move in the same way.

The variation with respect to the metric $g^{\mu\nu}$ leads to the Einstein equations as usual,

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = (1/M_{\rm Pl}^2)\left(T^{(\rm b)}_{\mu\nu} + T^{(\rm c)}_{\mu\nu} + T^{(\phi)}_{\mu\nu}\right). \tag{4}$$

Here and hereafter, $T^{(\rm I)}_{\mu\nu} = -(2/\sqrt{-g})(\delta S_{\rm I}/\delta g^{\mu\nu})$ and $T^{(\phi)}_{\mu\nu} = -(2/\sqrt{-g})[\delta(\sqrt{-g}\mathcal{L}_\phi)/\delta g^{\mu\nu}]$.

The superscript "I" represents b, c, or m for baryonic matter, dark matter, and total matter, respectively. The combination of the energy–momentum tensor for total matter $T^{(\rm m)}_{\mu\nu} := T^{(\rm b)}_{\mu\nu} + T^{(\rm c)}_{\mu\nu}$ and the scalar sector $T^{(\phi)}_{\mu\nu}$ is conserved as $\nabla^\mu[T^{(\rm m)}_{\mu\nu} + T^{(\phi)}_{\mu\nu}] = 0$. The energy–momentum conservation for baryonic matter also takes the familiar form, $\nabla^\mu T^{(\rm b)}_{\mu\nu} = 0$. On the other hand, the energy–momentum tensors for the scalar field and dark matter no longer satisfy the conservation law individually, and it instead takes the form, $\nabla^\mu T^{(\rm c)}_{\mu\nu} = -\nabla^\mu T^{(\phi)}_{\mu\nu}$. The scalar equation is given by

$$\Box\phi - V_\phi = Q, \tag{5}$$

where Q, which characterizes the coupling between CDM and the scalar field, is defined as

$$Q \equiv -\frac{1}{\sqrt{-g}}\frac{\delta(\sqrt{-\bar{g}}\mathcal{L}_{\rm c})}{\delta\phi} = \nabla_\mu W^\mu - Z\,, \tag{6}$$

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with

$$Z = \frac{1}{2A}\left\{\left[A_\phi + \frac{A_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right] T_{(c)} + \left[B_\phi + \frac{B_X X(A_\phi - 2B_\phi X)}{A - A_X X + 2B_X X^2}\right] T_{(c)}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right\}, \quad (7)$$

$$W^\mu = \frac{1}{2A}\left[2B\, T_{(c)}^{\mu\nu}\partial_\nu\phi - \frac{A - 2BX}{A - A_X X + 2B_X X^2} \times \left(A_X T_{(c)} + B_X T_{(c)}^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi\right)\partial^\mu\phi\right], \quad (8)$$

where $U_\phi = \partial U/\partial\phi$ and $U_X = \partial U/\partial X$ for $U = A, B$. By using of equation (5), the energy–momentum conservation for CDM and total matter can be recast as

$$\nabla^\mu T_{\mu\nu}^{(c)} = \nabla^\mu T_{\mu\nu}^{(m)} = -Q\partial_\nu\phi\,. \quad (9)$$

3 Basic equations

We work on a spatially flat Friedman-Lemaître-Robertson-Walker metric in Newtonian gauge, $ds^2 = -[1 + 2\Phi(t, \boldsymbol{x})]dt^2 + a^2(t)[1 - 2\Psi(t, \boldsymbol{x})]d\boldsymbol{x}^2$, and define the background and perturbations of the energy–momentum tensor for the baryonic matter, the dark matter, and the total matter as $T^0_{(\mathrm{I})0} = -\rho_\mathrm{I}(t)[1 + \delta_\mathrm{I}(t, \boldsymbol{x})]$, $T^0_{(\mathrm{I})i} = -\rho_\mathrm{I}(t)\,\partial_i v_\mathrm{I}(t, \boldsymbol{x})$, $T^{(\mathrm{I})i}{}_j = 0$, and (otherwise) $= 0$.[1] Based on these equations, we can find the relations

$$\delta_\mathrm{m} = \omega_\mathrm{c}\delta_\mathrm{c} + \omega_\mathrm{b}\delta_\mathrm{b}\,, \qquad v_\mathrm{m} = \omega_\mathrm{c}v_\mathrm{c} + \omega_\mathrm{b}v_\mathrm{b}\,, \quad (10)$$

where $\omega_\mathrm{I} = \rho_\mathrm{I}/\rho_\mathrm{m}$. We also split the scalar field as $\phi(t, \boldsymbol{x}) \to \phi(t) + \delta\phi(t, \boldsymbol{x})$. The background part of the Einstein equation gives

$$H^2 = (1/3M_\mathrm{Pl}^2)[\rho_\mathrm{c} + \rho_\mathrm{b} + \Lambda + (1/2)\dot\phi^2 + V]\,, \quad (11)$$

$$3H^2 + 2\dot H = (1/M_\mathrm{Pl}^2)[\Lambda - (1/2)\dot\phi^2 + V]\,. \quad (12)$$

The background equation of motion for ϕ [equation (5)] yields

$$\ddot\phi + 3H\dot\phi + V_\phi = -Q_0\,, \quad (13)$$

and the energy–momentum conservation for baryonic matter and CDM lead to the background equations

$$\dot\rho_\mathrm{b} + 3H\rho_\mathrm{b} = 0\,, \qquad \dot\rho_\mathrm{c} + 3H\rho_\mathrm{c} = Q_0\dot\phi\,, \quad (14)$$

where Q_0 is a background value of Q. We can rewrite Q_0 from the definitions (6)–(8) together with equation (14),

$$\frac{\dot\phi}{\rho_\mathrm{c}}Q_0 = \frac{1}{2}\frac{d}{dt}\log\left[\frac{(2A - A_X\dot\phi^2 + B_X\dot\phi^4)^2}{A - B\dot\phi^2}\right], \quad (15)$$

where A, A_X, B, and B_X are evaluated at background fields.

In deriving perturbed equations, we use the quasi-static approximation, which is applicable when the wavelength of perturbations is well inside the sound horizon of the scalar field, $k^{-1} \ll c_s/(aH)$, where c_s is the sound speed of the scalar field (Sawicki & Bellini 2015). Although the sound speed of the scalar field generally differs from unity in our setup (F. Chibana et al. in preparation) we assume $c_s = \mathcal{O}(1)$ for simplicity. Then we can neglect time-derivative terms of perturbations while keeping spatial derivative terms,[2] and we obtain the linearized perturbed Einstein equations in the Fourier space,

$$(k^2/a^2)\Psi = (k^2/a^2)\Phi = -4\pi G\rho_\mathrm{m}\delta_\mathrm{m}\,. \quad (16)$$

The continuity and Euler equations for baryonic matter are the standard form:

$$\dot\delta_\mathrm{b} + (k^2/a^2)v_b = 0, \quad \dot v_\mathrm{b} - \Phi = 0, \quad (17)$$

while those for CDM get modified as follows:

$$\dot\delta_\mathrm{c} + (k^2/a^2)v_\mathrm{c} = (\dot\phi/\rho_\mathrm{c})(\delta Q - Q_0\delta_\mathrm{c})\,, \quad (18)$$

$$\dot v_\mathrm{c} - \Phi = (Q_0/\rho_\mathrm{c})(\delta\phi - \dot\phi v_\mathrm{c})\,, \quad (19)$$

where the scalar field perturbation is determined by

$$-(k^2/a^2)\delta\phi = \delta Q. \quad (20)$$

In the quasi-static limit, the most relevant terms in Q can be extracted as

$$\delta Q = Q_0\delta_\mathrm{c} + (R_1 + R_2)\,\dot\phi\dot\delta_\mathrm{c} + R_1\dot\phi\frac{k^2}{a^2}v_\mathrm{c} + R_2\frac{k^2}{a^2}\delta\phi\,, \quad (21)$$

where

$$R_1 = \frac{B\rho_\mathrm{c}}{A}\,, \quad R_2 = -\frac{(A - B\dot\phi^2)(A_X - B_X\dot\phi^2)\rho_\mathrm{c}}{A(2A - A_X\dot\phi^2 + B_X\dot\phi^4)}\,. \quad (22)$$

We emphasize that the R_2 term gives the non-vanishing contributions only if the conformal and/or disformal factors depend on the kinetic term.

After eliminating the scalar field perturbations using equation (20), we can rewrite the modified continuity

[1] Note that the pressureless feature of the CDM is robust at least at the first order of perturbations even if we take other definitions of energy–momentum tensor, such as $\overline{T}^{(c)}_{\mu\nu} = -(2/\sqrt{-\bar g})\delta(\sqrt{-\bar g}\mathcal{L}_\mathrm{c})/\delta\bar g^{\mu\nu}$ and $\widetilde{T}^{(c)}_{\mu\nu} = -(2/\sqrt{-g})\delta(\sqrt{-g}\mathcal{L}_\mathrm{c})/\delta g^{\mu\nu}$. The property of CDM of being pressureless at the background level was first mentioned in Koivisto (2008).

[2] We also neglect the mass m_ϕ of the scalar field, which could be crucial when the mass of the scalar field is large enough, i.e., $m_\phi \gtrsim k/a$.

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equation in terms of the CDM density contrast and velocity field as

$$(1-\Upsilon_1)\left(\dot{\delta}_c+\frac{k^2}{a^2}v_c\right)=\Upsilon_2\left(\dot{\delta}_c-\frac{Q_0}{\dot{\phi}}\delta_c\right), \tag{23}$$

with

$$\Upsilon_1=\frac{\dot{\phi}^2}{\rho_c}\frac{R_1}{1+R_2}, \quad \Upsilon_2=\frac{\dot{\phi}^2}{\rho_c}\frac{R_2}{1+R_2}. \tag{24}$$

In the minimal coupling case ($A=1$, $B=0$), all time-dependent coefficients are zero, $Q_0=R_1=R_2=0$. When conformal and disformal factors depend only on ϕ, we have $Q_0\neq 0$, $R_1\neq 0$, and $R_2=0$. Thus the continuity equation is the same as the one in the minimal coupling case. One can verify this property even for a wider class of scalar–tensor theories (Gleyzes et al. 2016). When at least one of A and B depend on X, there arises a new contribution of R_2 in the continuity equation, and the CDM velocity can significantly differ from the standard case. An important implication from these equations is that the continuity equation for the total matter fluctuations, equation (10), is given by

$$\dot{\delta}_m+\frac{k^2}{a^2}v_m=\omega_c\frac{\Upsilon_2}{1-\Upsilon_1}\left(\dot{\delta}_c-\frac{Q_0}{\dot{\phi}}\delta_c\right)+\omega_b\frac{Q_0\dot{\phi}}{\rho_m}(\delta_c-\delta_b), \tag{25}$$

which differs from the standard form by the presence of the non-minimal coupling. We also found that the standard form of the continuity equation cannot be reproduced even when the R_2 contribution is negligible, due to the second term on the right-hand side of the second equation, which originates from the deviation of the background energy density from the standard matter [see equation (14)]. Therefore, we conclude that there are two possibilities to break the standard relation of the continuity equation for the total matter field: one comes from the R_2 term in the CDM continuity equation, which appears only when the coupling depends on the kinetic term, and the other corresponds to the deviation of the background dynamics from the standard one characterized by Q_0 (Gleyzes et al. 2016).

Combining all the perturbed equations to eliminate velocities as usual, we obtain two coupled second-order differential equation for the baryonic matter and CDM density contrasts. Since the evolution equations for the baryonic matter and CDM density contrasts are independent of the wavenumber k, one can decompose the density contrasts into the (normalized) k-independent linear growth factors $D_{\rm I}$ and initial density contrasts δ_0 for the baryonic matter, CDM, and total matter as $d_{\rm I}(t,\boldsymbol{k})=D_{\rm I}(t)\delta_0(\boldsymbol{k})$.

Here, we have chosen the initial time to be much after the time of cosmic microwave backgroun (CMB) decoupling ($z\approx 1100$) but much before the effect of the dark interaction becomes important ($z\sim 1$), and assumed that the baryonic density contrast has caught up with the CDM density contrast by the initial time. We also define the growth rate for each species, $f_{\rm I}$, as the logarithmic derivative of the linear growth, that is, $f_{\rm I}(t)\equiv d\ln D_{\rm I}/d\ln a$. Rewriting the continuity equations for the baryonic matter, CDM, and total matter in terms of the growth factors, we obtain a form of velocity potentials:

$$v_{\rm I}(t,\boldsymbol{k})=-\frac{a^2H}{k^2}f_{\rm I}^{\rm eff}(t)\delta_{\rm I}(t,\boldsymbol{k}). \tag{26}$$

Although one can easily see $f_b^{\rm eff}=f_b$, from equation (23) the *effective* linear growth rate of the CDM, $f_c^{\rm eff}$, can significantly differ from the standard one due to the R_2 contribution as

$$f_c^{\rm eff}=f_c-\frac{\Upsilon_2}{1-\Upsilon_1}\left(f_c-\frac{Q_0}{H\dot{\phi}}\right)\equiv f_c+\Delta f_c. \tag{27}$$

Moreover, by the use of equation (25), the *effective* growth rate of the total matter fluctuations can be written as

$$f_m^{\rm eff}=f_m+\omega_c\frac{D_c}{D_m}\Delta f_c-\omega_b\frac{Q_0\dot{\phi}}{H\rho_m}\frac{D_c-D_b}{D_m}. \tag{28}$$

with $D_m=\omega_cD_c+\omega_bD_b$. Although $f_m^{\rm eff}$ is naturally given by the growth-factor-weighted average of the effective growth rates for CDM and baryonic matter, it does not in general coincide with f_m. As discussed above, its deviation is due to the non-trivial terms in the CDM continuity equation and the background dynamics that produce the second and third terms in equation (28).

4 Modified interpretation of Kaiser formula

In the above investigation, we found that the *effective* growth rate $f_m^{\rm eff}$ inferred from the peculiar velocities no longer coincides with the actual growth rate f_m; namely, measurements of the peculiar velocity field do not necessarily provide the growth rate of clustering directly. Our example vividly demonstrates that the standard dictionary translating the RSD measurements into the growth rate is not universal and fails for some classes of theories beyond the ΛCDM model. To see the impact of the breaking of the relation between the peculiar velocities and the actual growth rate, we now focus on the modification of the Kaiser formula as the simplest and most important observable effect of RSDs. The mapping of the observed redshift position $\boldsymbol{s}$ from the real space position $\boldsymbol{x}$ is given by $\boldsymbol{s}=\boldsymbol{x}+(v_{g,z}/aH)\hat{\boldsymbol{z}}$ (see, e.g., Bernardeau et al. 2002).

Here, $v_{g,z}$ is a line-of-sight component of the peculiar velocity of a galaxy and $\hat{\boldsymbol{z}}$ is a unit vector of the line-of-sight. In this equation, we have assumed the plane–parallel approximation, so that the line-of-sight is taken as a fixed direction, $\hat{\boldsymbol{z}}$. Recalling that the number of galaxies in the

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infinitesimal volume of both spaces is invariant, the overdensities in the redshift space $\delta_{\mathrm{g,s}}$ and the real space δ_{g} are related through $\delta_{\mathrm{g,s}} = \delta_{\mathrm{g}} - (1/aH)\nabla_z v_{\mathrm{g},z}$.

The galaxy density contrast in the real space, δ_{g}, is related to the total matter density contrast δ_{m} given by equation (10), through the standard linear bias model $\delta_{\mathrm{g}} = b_{\mathrm{g}}\delta_{\mathrm{m}}$ on large scales. The peculiar velocity fields of the galaxies, v_{g}, on large scales are expected to be related to the CDM and baryonic matter fluid velocities, and the explicit relation is determined by imposing the reasonable physical condition, e.g., momentum conservation law for each galaxy (Gleyzes et al. 2016). For simplicity, here, we assume that the peculiar velocity fields of galaxies on large scales are given by the total matter fluid velocities, v_{m}, given in equation (10), as in the standard case: $v_{\mathrm{g}} = v_{\mathrm{m}} = -(a^2H/k^2)\, f_{\mathrm{m}}^{\mathrm{eff}}\delta_{\mathrm{m}}$ (see, e.g., Chan et al. 2012).[3] Therefore, the resultant galaxy power spectrum in redshift space is given by

$$P_{\mathrm{g,s}}(\boldsymbol{k};t) = \left[1 + \beta_{\mathrm{eff}}(t)\,\mu^2\right]^2 P_{\mathrm{g}}(k;t), \tag{29}$$

where $P_{\mathrm{g}} = b_{\mathrm{g}}^2\, P_{\mathrm{m}}$ is the real-space galaxy power spectrum, $P_{\mathrm{m}} = D_{\mathrm{m}}^2 P_0$ is the power spectrum for the total matter density contrast, and

$$\beta_{\mathrm{eff}} \equiv \frac{f_{\mathrm{m}}^{\mathrm{eff}}}{b_{\mathrm{g}}} = \beta + \frac{1}{b_{\mathrm{g}} D_{\mathrm{m}}}\left[\omega_{\mathrm{c}} D_{\mathrm{c}} \Delta f_{\mathrm{c}} - \omega_{\mathrm{b}} \frac{Q_0\dot{\phi}}{H\rho_{\mathrm{m}}}\,(D_{\mathrm{c}} - D_{\mathrm{b}})\right]. \tag{30}$$

This is a generalization of the Kaiser formula. In fact, in the minimal coupling case, we have $D_{\mathrm{m}} = D_{\mathrm{c}} = D_{\mathrm{b}}$ and $f_{\mathrm{m}}^{\mathrm{eff}} = f_{\mathrm{m}} = f_{\mathrm{c}}^{\mathrm{eff}} = f_{\mathrm{c}} = f_{\mathrm{b}}$, and hence equation (29) is reduced to the standard Kaiser formula. However, we found that in the presence of the coupling between the CDM and the scalar sector we no longer have the relation $f_{\mathrm{m}}^{\mathrm{eff}} = f_{\mathrm{m}}$ as we have discussed, and it means that the RSDs are not reliable probes of growth of structure. It is notable that the RSDs cannot provide the true value of the growth rate f_{m} even in the simple case where the conformal and disformal factors depend only on ϕ. Since in this case the deviation from the standard formula is proportional to Q_0, this effect is suppressed when the background evolution of the dark matter is almost same as that of the baryonic matter. On the other hand, there is wider room for a sizable modification of the standard Kaiser formula in our general setup, even when either Q_0 or the baryonic contamination is negligibly small, i.e., $\omega_{\mathrm{b}} \simeq 0$, $f_{\mathrm{m}}^{\mathrm{eff}}$ can differ from f_{m} by $\mathcal{O}(1)$. To see this clearly, let us consider a toy model with $A = 1$ and $B = \alpha/2X$, where α is a coupling constant. In this case, the background evolution of CDM is diluted at the usual rate, $\rho_c \propto a^{-3}$, since $Q_0 = 0$. Let us then expand the formula (31) in terms of the baryonic matter–CDM ratio to neglect the ambiguity from the baryonic matter contribution. Assuming that the coupling α is tiny, i.e., $\alpha\rho_c/\dot{\phi}^2 \ll 1$, the effective growth rate becomes $f_{\mathrm{m}}^{\mathrm{eff}} \simeq (1+\alpha)\, f_{\mathrm{c}}$. This immediately shows that the single-redshift RSD measurements cannot give a constraint on the linear growth rate f_{c} unless the contributions from the couplings Δf_{c} is fixed by using other observables.[4] This fact demonstrates that one has to keep this new effect in mind when testing beyond ΛCDM theories using the RSD measurements. Even if a growth index $\gamma \approx 0.55$ is obtained from RSDs in future galaxy survey, it is still possible that the true theory is different from the ΛCDM model. In addition, in our example, the quantity E_{G}, which is related to the ratio of the Laplacian of the Newtonian potentials to the peculiar velocity divergence (Zhang et al. 2007), can be written as $E_{\mathrm{G}} \simeq (1 - \alpha)\Omega_{\mathrm{m0}}/f_{\mathrm{m}}$, where Ω_{m0} is the present density parameter for the total matter. Although E_{G} is extremely useful for discriminating the ΛCDM model and modified gravity models, it only measures the effective growth rate in our setup.[5]

One way to obtain the actual growth rate of large-scale structure is to observe the time-evolution of structure directly by, e.g., tomographic weak lensing power spectra, since the gravitational potential is sourced by only the total matter density [see the Poisson equation (16)]. After fixing the linear bias for each redshift by using other observations, i.e., cross-correlation between the clustering of galaxies and weak lensing (see, e.g., Hashimoto et al. 2016), one can measure the coupling between the CDM and scalar field from RSD measurements.

Now let us give a forecast for the accuracy of constraining the coupling from future galaxy redshift surveys represented by Euclid (Amendola et al. 2018) and the Square Kilometre Array (SKA) (Yahya et al. 2015). For simplicity, we assume that the background dynamics are identical to those in the Planck best-fitting ΛCDM. We use the model based on the choice of the coupling $A = 1$ and $B = \alpha/2X$, and then the effective growth rate is given by $f_{\mathrm{m}}^{\mathrm{eff}} \simeq (1+\alpha)\, f_{\mathrm{c}}$. We also parametrize the growth rate of the dark matter as $f_{\mathrm{c}} = \Omega_{\mathrm{m}}^{\gamma}$. In the Fisher matrix analysis, our forecast is performed for the parameters $\{w_0, w_a, \Omega_\Lambda, b(z)\}$ with the redshift smearing parameter and the target

[3] We stress that even if this assumption is not valid, the coupling effect on RSDs is still present as long as the peculiar velocity field of galaxy v_{g} constains the CDM peculiar velocity v_{c}, i.e., $v_{\mathrm{g}} \neq v_{\mathrm{b}}$.

[4] The model considered in Marcondes et al. (2016) is described by two parameters, the equation of state w and the (background) energy transfer parameter ξ (δQ in our analysis is neglected). Once the constraints on background dynamics from the observations such as type Ia supernovae and CMB are taken into account, only ξ characterizes both the actual growth rate $f_{\mathrm{c}}/b_{\mathrm{g}}$ and the deviation $\Delta f_{\mathrm{c}}/b_{\mathrm{g}}$. Thus in such a model, it is enough to measure the single-redshift RSDs, however, this does not hold in a general setup.

[5] In a general setup, the quantities E_{G} can be written as $E_{\mathrm{G}} = a^3(\rho_{\mathrm{m}}/\rho_{\mathrm{m0}})\Omega_{\mathrm{m0}}/f_{\mathrm{m}}^{\mathrm{eff}}$ and thus, strictly speaking, measure the combination of the effective linear growth rate and the (background) coupling Q_0. Therefore, the actual growth rate and the coupling cannot be separated.

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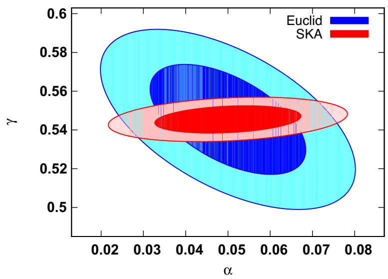

Fig. 1. The 1σ and 2σ contours in the γ–α plane for the Euclid and SKA2 HI galaxy surveys. (Color online)

parameters are $\alpha = 0.05$ and $\gamma = 0.545$. In figure 1, the 1σ and 2σ contours are plotted. As one can see, the future galaxy surveys will be able to detect the effect of the coupling α, the natural value of which would be of the order of unity, if $|\alpha| \gtrsim 0.05$. Furthermore, once the actual growth rate f_c is determined by the use of tomographic weak lensing power spectra, the galaxy surveys can improve constraints on the coupling parameter.

5 Conclusion

We have shown that the additional interaction mediated by the scalar field that operates only between dark matter through conformal and disformal couplings changes the continuity and Euler equations for cosmological perturbations in a non-trivial manner, and investigated its impact on RSD measurements in galaxy surveys. We found that the effects of such modifications appear even at sub-horizon scales in the presence of ϕ and $X(= -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi/2)$-dependence of the conformal and/or disformal couplings. The *effective* linear growth rate, which is inferred from measurements of the peculiar velocities of the distributed galaxies, no longer corresponds to the logarithmic time derivative of the density perturbation and is rather characterized by both the density perturbations and their derivatives for each species in a general situation.[6] In other words, information on the coupling is encoded in the peculiar velocity fields and the true value of the growth rate of large-scale structure cannot necessarily be constrained by the RSD measurements themselves. The actual growth can instead be extracted from weak lensing measurements, and the coupling between dark matter and the scalar field can be measured by using multiple power spectra of the galaxy distribution. This fact will play a vital role in the RSD measurement, and it will provide us a rich source of information on dark matter and dark energy.

[6] While this paper was being completed, Borges and Wands (2017) published their work, in which the redshift space distortions in the context of interacting dark matter and vacuum energy are discussed.

Acknowledgments

We thank Elcio Abdalla, Toshifumi Noumi, Masamune Oguri, Jiro Soda, Masahiro Takada, and Kazuhiro Yamamoto for many useful comments and discussions. This work was supported in part by JSPS Grant-in-Aid for Scientific Research Nos. JP17K14304 (D.Y.), JP17K14276 (R.K.), JP25287054 (R.K. & M.Y.), JP26610062 (M.Y.), JP15K17632 (T.S.), and JP15K17659 (S.Y.), MEXT KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas "Cosmic Acceleration" Nos. JP15H05888 (M.Y.) and JP16H01103 (S.Y.), MEXT KAKENHI Grant Numbers JP17H06359 (T.S.).

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