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Coupling dark energy to dark matter inhomogeneities

Valerio Marra

Departamento de Física, Universidade Federal do Espírito Santo, 29075-910, Vitória, ES, Brazil

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ABSTRACT

We propose that dark energy in the form of a scalar field could effectively couple to dark matter inhomogeneities. Through this coupling energy could be transferred to/from the scalar field, which could possibly enter an accelerated regime. Though phenomenological, this scenario is interesting as it provides a natural trigger for the onset of the acceleration of the universe, since dark energy starts driving the expansion of the universe when matter inhomogeneities become sufficiently strong. Here we study a possible realization of this idea by coupling dark energy to dark matter via the linear growth function of matter perturbations. The numerical results show that it is indeed possible to obtain a viable cosmology with the expected series of radiation, matter and dark-energy dominated eras. In particular, the current density of dark energy is given by the value of the coupling parameters rather than by very special initial conditions for the scalar field. In other words, this model – unlike standard models of cosmic late acceleration – does not suffer from the so-called "coincidence problem" and its related fine tuning of initial conditions.

1. Introduction

According to the standard model of cosmology – confirmed by the latest results from ESA's Planck mission [1] – about 5% of the energy content of the universe is made of ordinary baryons, that is, of particles belonging to the standard model of particle physics, recently glorified by the discovery of the Higgs boson [2,3]. The dark sector accounts for the remaining 95%. More precisely, roughly 25% consists of a yet-undetected matter component, which is thought to be a massive particle of non-baryonic nature that interacts through weak interaction and gravity only. It is dubbed "cold dark matter". Finally, dark energy is responsible for the missing 70% of the energy content. The best candidate for dark energy to date is the so-called "cosmological constant", which is basically the energy of the vacuum and, in general relativity, is an arbitrary constant of nature. Its fundamental property – gravitational repulsion – causes the acceleration of the expansion of the universe [4,5].

Faced with the formidable challenge of accounting for not only one but two unknown components, cosmologists studied at great depth dynamical models of dark energy [6,7] and a possible interaction between dark energy and the other fields (see [8–10] and references therein), hoping to shed light on the nature of the dark sector. In particular, a coupling between dark energy and dark matter [11–14] is suggested by the fact that the individual energy densities of the two components are today of the same order of magnitude. The latter is the so-called "coincidence problem", as an incredible fine tuning of the value of the cosmological constant is necessary for the standard model to explain observations. However, a careful dynamical analysis of coupled dark energy models has shown that a fine tuning of the dark energy potential is unavoidable in order to have a viable cosmology (see, for example, [9]).

Here we propose that dark energy could effectively couple to dark matter inhomogeneities. Indeed, if this is the case, the dark energy evolution will be altered – possibly causing the universe acceleration – at late time when inhomogeneities become strong. In other words, the trigger for acceleration is not given by tuned initial conditions but rather by the natural evolution of inhomogeneities. We then take a phenomenological approach and consider a possible realization of this general idea by coupling dark energy to dark matter via the linear growth function of matter perturbations. Our aim is to understand if such interaction can indeed give a viable dark energy dynamics free of fine tuning.

The outline of this paper is as follows. First we introduce the model in Sections 2–4. Next we discuss the limiting cases in Section 5 and the evolution in Section 6. Conclusions are given in Section 7.

2. Model

Within General Relativity the total energy–momentum tensor is conserved and a possible interaction between dark matter and a scalar field can be modeled through an interaction current Q^β

E-mail address: valerio.marra@me.com.

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which transfers energy and momentum from one source to the other:

$$\nabla_\alpha T_m^{\alpha\beta} = Q^\beta \qquad \nabla_\alpha T_\phi^{\alpha\beta} = -Q^\beta. \tag{1}$$

In the individual conservation equations the interaction current has opposite sign so that the total energy–momentum tensor is conserved.

From Eq. (1) ($Q^i = 0$ because of homogeneity and isotropy) one can derive the following system of dynamical field equations describing the background evolution of the well known Coupled Dark Energy model (see, e.g., [9]):

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_\phi + \rho_r)\,, \tag{2}$$

$$\dot H + H^2 = -\frac{4\pi G}{3}(\rho_m + \rho_\phi + 3p_\phi + 2\rho_r)\,, \tag{3}$$

$$\dot\rho_\phi + 3H(\rho_\phi + p_\phi) = -Q^0\,, \tag{4}$$

$$\dot\rho_m + 3H\rho_m = Q^0\,, \tag{5}$$

$$\dot\rho_r + 4H\rho_r = 0\,. \tag{6}$$

Curvature and the (subdominant) baryons are neglected, an overdot represents a derivative with respect to the cosmic time t, $H \equiv \dot a/a$ is the Hubble function, and $M_{\rm Pl} \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass with G the Newton constant (we set $c = \hbar = 1$). The first two equations are, respectively, the Friedmann and the acceleration equation, while the last three equations are the continuity equations for the scalar field, matter and radiation, respectively. The scalar field energy density, pressure and equation of state are, respectively:

$$\rho_\phi = \frac{1}{2}\dot\phi^2 + V(\phi), \qquad p_\phi = \frac{1}{2}\dot\phi^2 - V(\phi), \qquad w_\phi = \frac{p_\phi}{\rho_\phi}. \tag{7}$$

3. Interaction

In the literature two classes of interactions – with several variations – have been studied:

$$Q_I^\beta = Q\, T_m \nabla^\beta \phi / M_{\rm Pl}\,, \tag{8}$$

$$Q_{II}^\beta = Q\, T_m H\, u_m^\beta\,, \tag{9}$$

where $T_m = -\rho_m$ is the trace of the dark-matter energy–momentum tensor so that in Eqs. (4) and (5) one has:

$$Q_I^0 = Q\, \rho_m\, \dot\phi / M_{\rm Pl}\,, \tag{10}$$

$$Q_{II}^0 = Q\, \rho_m\, H\,. \tag{11}$$

The first class follows from the interaction Lagrangian $\mathcal{L}_{\rm int} = m(\phi)\bar\psi\psi$ with $m(\phi) = m_0 e^{Q\phi/M_{\rm Pl}}$,[1] that is, the mass of the dark matter field ψ is a function of the scalar field ϕ, (see [11] for details). The second class is instead an arbitrary parametrization, and Eq. (1) is seen as a phenomenological description for an effective interaction [14]. As said earlier, careful dynamical analyses have shown that fine tuning of initial conditions is unavoidable in order to have a viable cosmology (see, for example, [9]).

Motivated by the fact that the evolution of inhomogeneities could trigger at the right time the onset of a dark-energy dominated universe, we now discuss the possibility that the dark-energy scalar field effectively couples to matter inhomogeneities.[2]

[1] Generally, the coupling is $Q = \partial \ln m(\phi)/\partial\phi$.

[2] The idea that the evolution of inhomogeneities could trigger the acceleration of the universe has been discussed in the literature regarding the so-called backreaction proposal, according to which late-time inhomogeneities could affect the average expansion rate of the universe, possibly explaining away dark energy (see, e.g., the special focus issue [15]).

The coupling is realized by considering an interaction like (10), in which the coupling is a function of the linear growth function of density perturbations δ_m, $Q = \nu\, \delta_m^n$, so that:

$$Q^0 = \nu\, \delta_m^n\, \rho_m\, \dot\phi / M_{\rm Pl}\,. \tag{12}$$

The interaction (12) couples Eqs. (4)–(5) to the linear perturbation Eq. (13). The use of δ_m is perhaps the simplest way to quantify the overall growth of inhomogeneities in the universe. The dimensionless coupling parameter ν sets the strength of this interaction. The exponent n parametrizes the dependence of the effective coupling parameter $Q = \nu\, \delta_m^n$ on the linear growth function δ_m. For the sub-horizon scales at which a canonical scalar field remains homogeneous, the growth function does not depend on the wavenumber k and can be obtained numerically from the standard equation [9]:

$$\ddot\delta_m + 2H\dot\delta_m - 4\pi G\rho_m\delta_m = 0. \tag{13}$$

As usual, we normalize δ_m to unity at the present time, $\delta_m(t_0) = 1$. It is interesting to note that the coupling parameter ν does not appear as the correction due to ν is of order $n+1$ in δ_m. Therefore, the growth of perturbation is altered only by the different background evolution, meaning that this model could agree with growth data for arbitrarily large values of ν.

3.1. Discussion

Although in the following we take the phenomenological approach in which we assume the validity of (12) and examine its cosmological implications, it is interesting to discuss which mechanism could be behind such an interaction.

Physical processes that are linked to the growth of δ_m are necessarily nonlinear, such as collapse and shell crossing. However, quantities associated to scalar perturbations do not seem suitable for the coupling (12). Indeed, local values of e.g. matter density and velocity divergence can be arbitrary high in the past even if δ_m was initially very small. The obvious quantity that at early times is absent (or negligible) is the vorticity (or curl) of the velocity field,[3] which is generated at very non-linear stages of the dark matter collapse. More precisely, it is produced when, at shell crossing, the single-stream irrotational description of the dark matter fluid ceases to be valid [17]. Therefore, as time progresses, vorticity is produced on ever larger scales. It is difficult to study analytically the production of vorticity and many works have used dedicated N-body simulations in order to obtain its magnitude and time/scale dependence [18–20]. In particular, the results of [19,20] show how vorticity is correlated with the density contrast and that it becomes important (as compared to the velocity divergence) at small scales and/or at early times.

The coupling of (12) could then arise if the scalar field is coupled to the vector perturbations associated with vorticity. Phenomenologically, the coupling Q will be proportional to an invariant contraction of the gradient tensor of the velocity field $\partial v_i/\partial x_j$ (see [18] for a discussion of possible invariants), which, based on the results from numerical simulations [19,20], we can parametrize through a power of δ_m, as in the expression $Q = \nu\, \delta_m^n$ above. Note, however, that we are parametrizing the nonlinear growth of perturbations (the one correlated with the vorticity) with the linear growth function of Eq. (13). Although this is similar in spirit to what is usually done within the spherical top-hat model for nonlinear collapse, it is also clear that this approach will only be able to describe qualitatively the growth of vorticity.

[3] Not to be confused with the halo spin, see e.g. [16].