New coupled quintessence cosmology

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A component of dark energy has been recently proposed to explain the current acceleration of the Universe. Unless some unknown symmetry in Nature prevents or suppresses it, such a field may interact with the pressureless component of dark matter, giving rise to the so-called models of coupled quintessence. In this paper we propose a new cosmological scenario where radiation and baryons are conserved, while the dark energy component is decaying into cold dark matter (CDM). The dilution of CDM particles, attenuated with respect to the usual $a^{-3}$ scaling due to the interacting process, is characterized by a positive parameter $\epsilon$, whereas the dark energy satisfies the equation of state $p_x = \omega \rho_x$ ($\omega < 0$). We carry out a joint statistical analysis involving recent observations from type Ia supernovae, baryon acoustic oscillation peak, and Cosmic Microwave Background shift parameter to check the observational viability of the coupled quintessence scenario here proposed.

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I. INTRODUCTION

According to Einstein’s general theory of relativity, the dynamic properties of a given spacetime are determined by its total energy content. In the cosmological context, for instance, this amounts to saying that to understand the spacetime structure of the Universe one needs to identify the relevant sources of energy and their contributions to the total energy momentum tensor. Matter fields (e.g., baryonic matter and radiation), are obvious sources of energy. Nevertheless, according to current observations, two other components, namely, dark matter and dark energy, whose origin and nature are completely unknown, are governing the late time dynamic properties of the Universe. Although fundamental to our understanding of the Universe, several important questions involving these dark components and their roles in the dynamics of the Universe remain unanswered (see, e.g., [1] for some recent reviews).

Among these questions, the possibility of interaction in the dark sector (dark matter-dark energy), which gave origin to the so-called models of coupled quintessence, has been largely explored in the literature [2, 3]. These scenarios are based on the premise that, unless some special and unknown symmetry in Nature prevents or suppresses a non-minimal coupling between these components (which has not been found – see, e.g., [4] for a discussion), such interaction is in principle possible, and although no observational piece of evidence has so far been unambiguously presented, a weak coupling still below detection cannot be completely excluded.

From the observational viewpoint, these models are capable of explaining the current cosmic acceleration, as well as other recent observational results [2]. From the theoretical point of view, however, critiques to these scenarios do exist and are mainly related to the fact that in order to establish a model and study their observational and theoretical predictions, one needs first to specify a phenomenological coupling between the cosmic components.

In this concern, an interesting step towards a realistic interaction law was given recently by Wang & Meng in Ref. [5] (see also [6]) in the context of models with vacuum decay, a class of coupled quintessence in which the dark energy equation of state (EoS) is $w = -1$. Actually, in certain sense, one may say that coupled dark energy or quintessence models are the natural inheritors of the so-called time-varying $\Lambda(t)$-cosmologies [7, 8, 9, 10]. However, instead of the traditional approach, Refs. [5, 6] deduced a new interaction law from a simple argument about the effect of the dark energy on the cold dark matter (CDM) expansion rate. The resulting expression is a very general law that has many of the previous phenomenological approaches as a particular case.

In this paper, we extend the arguments of Refs. [5, 6] to a dark energy/dark matter interaction, where the dark energy component is described by an equation of state $p_x = \omega \rho_x$ ($\omega < 0$), and explore theoretical and observational consequences of a new scenario of coupled quintessence. Differently from other interacting quintessence models, we do not consider interaction between the dark sector and the baryonic content of the Universe. We also emphasize that this process of interaction is completely different from the physical point of view from unification scenarios of the dark sector, an idea that has been widely discussed in the recent literature [11].

We have organized this paper as follows. In Sec. II the interaction law and the basic field equations of the
model are presented. The influence of the dark energy-dark matter coupling on the epoch of cosmic acceleration is also discussed. In order to test the observational viability of the model, Sec. III presents a statistical analysis involving the most recent type Ia supernovae (SNe Ia) data [12, 13, 14, 15, 16], observations of the baryon acoustic oscillation (BAO) peak (measured from the correlation function of luminous red galaxies) [17] and the current estimate of the Cosmic Microwave Background (CMB) shift parameter from WMAP-5 [18]. In Sec. IV we end this paper by summarizing our main results.

II. THE MODEL

For a spatially flat, homogeneous and isotropic scenario driven by matter (baryonic + dark) and radiation fields and a negative-pressure dark energy component, the Einstein field equations can be written as

\[8\pi G (\rho_\gamma + \rho_b + \rho_{dm} + \rho_x) = \frac{3a^2}{a^2},\]

(1)

\[8\pi G (p_\gamma + p_x) = -\frac{\dot{a}}{a} + \frac{\dot{a}^2}{a^2},\]

(2)

where \(\rho_\gamma\), \(\rho_b\), \(\rho_{dm}\) and \(p_x\) are the energy densities of the radiation, baryons, cold dark matter and dark energy, respectively, while \(p_\gamma\) and \(p_x\) are the radiation and dark energy pressures. We will always refer to the dark matter quantities with the subscript \((dm)\), in order to distinguish them to total matter quantities, for which we will use the subscript \((m)\). Thus, in our notation, \(\rho_m = \rho_b + \rho_{dm}\).

By assuming that the radiation and baryonic fluids are separately conserved, the energy conservation law for the two interacting components \((u_{\alpha T}^{(\alpha\beta)} = 0\), where \(T^{(\alpha\beta)} = T^{(\alpha\beta)}_{dm} + T^{(\alpha\beta)}_x\)) reads

\[\dot{\rho}_{dm} + 3\frac{\dot{a}}{a}\rho_{dm} = -\dot{\rho}_x - 3\frac{\dot{a}}{a}(\rho_x + p_x).\]

(3)

Now, to complete the description of our interacting quintessence scenario we need to specify the interaction law. In principle, if the quintessence component is decaying into CDM particles, the CDM component will dilute more slowly compared to its standard (conserved) evolution, \(\rho_m \propto a^{-3}\). Therefore, if the deviation from the standard evolution is characterized by a positive constant \(\epsilon\) we may write

\[\rho_{dm} = \rho_{dm0}a^{-3+\epsilon},\]

(4)

where \(\epsilon\) is a constant parameter and we have set the present-day value of the cosmological scale factor \(a_0 = 1\).

In what follows we also consider that the dark energy component is described by an equation of state \(p_x = \omega \rho_x\), where the constant \(\omega\) is a negative quantity.

Now, by integrating Eq. (3) it is straightforward to show that the energy density of the dark energy component is given by

\[\rho_x = \rho_{x0}a^{-3(1+\omega)} + \frac{\epsilon \rho_{dm0}}{3|\omega| - \epsilon}a^{-3+\epsilon},\]

(5)

where the integration constant \(\rho_{x0}\) is the present-day fraction of the dark energy density. Clearly, in the absence of a coupling with the CDM component, i.e., \(\epsilon = 0\),

\[\rho_x = \rho_{x0}a^{-3(1+\omega)} + \frac{\epsilon \rho_{dm0}}{3|\omega|}a^{-3},\]

\[\rho_x = \rho_{x0}a^{-3(1+\omega)} + \frac{\epsilon \rho_{dm0}}{3|\omega| - \epsilon}a^{-3},\]

FIG. 1: \(q(z)\) in the scenario of coupled quintessence. a) Deceleration parameter as a function of redshift for the phantom case in which \(\omega = -1.2\) and selected values of \(\epsilon\). b) The same as in the previous Panel for the quintessence case \(\omega = -0.8\). As discussed in the text, the effect of a positive \(\epsilon\) parameter is to decrease the value of \(q(z)\), therefore increasing the value of the transition redshift \(z_t\). \(q(z)\) versus redshift for the specific value of \(\epsilon = 0.1\) and selected values of EoS parameter.
the conventional non-interacting quintessence scenario is fully recovered. For \( \omega = -1 \) and \( \epsilon \neq 0 \), we may identify \( \rho_{x0} \equiv \rho_{x0}^{\infty} \) (the current value of the vacuum contribution), and the above expression reduces to the vacuum decaying scenario recently discussed in Refs. \([5, 6]\).

Neglecting the radiation contribution, the Friedmann equation (1) for this interacting dark matter-dark energy cosmology can be rewritten as

\[
\mathcal{H} = \left( \Omega_x a^{-3} + 3|\omega|\Omega_{dm} a^{-3} + \tilde{\Omega}_x a^{-3(1+\omega)} \right)^{1/2},
\]

where \( \mathcal{H} = H(z)/H_0 \), \( \Omega_x \) and \( \Omega_{dm} \) are, respectively, the normalized Hubble parameter, and the baryons and CDM present-day density parameters (for these quantities, we have dropped the subscript ‘0’ for convenience). The parameter \( \tilde{\Omega}_x \) is defined, in terms of the density parameter of the dark energy component \( \Omega_x \), as

\[
\tilde{\Omega}_x = \Omega_x - \frac{\epsilon \Omega_{dm}}{3|\omega| - \epsilon}, \tag{7}
\]

and, therefore

\[
\tilde{\Omega}_x = 1 - \Omega_b - \frac{3|\omega|\Omega_{dm}}{3|\omega| - \epsilon}. \tag{8}
\]

The above expression clearly shows that the conventional (non-interacting) quintessence scenario is considerably modified due to the dark energy decay into CDM particles. It is also worth noticing the importance of the baryonic contribution to this sort of scenario. Going back to high redshifts we see that the presence of an explicit baryon term – redshifting as \((1+z)^3\) – is well justified since the decaying dark energy component slows down the variation of CDM density. Although being subdominant at the present stage of cosmic evolution, the baryonic content will be dominant (in comparison to CDM) at very high redshifts. Actually, it becomes subdominant just before nucleosynthesis \((z \simeq 10^{10} \text{ for } \epsilon \sim 0.1)\), so that the CDM component drives the evolution after the radiation phase. However, even at late times, baryons have several dynamical effects. In particular, they alter considerably the transition redshift, i.e., the redshift where the current accelerating regime begins \([6]\).

To quantify this latter effect, let us consider the transition redshift, \(z_t\), at which the Universe switches from deceleration to acceleration or, equivalently, the redshift at which the deceleration parameter vanishes. From Eq. (1), it is straightforward to show that the deceleration parameter, defined as \(q(t) = -a\ddot{a}/\dot{a}^2\), now takes the following form

\[
q(z) = \left( \frac{1 + \frac{3|\omega|+3\epsilon}{3|\omega| - \epsilon} \frac{\Omega_{dm}}{\tilde{\Omega}_x}(1+z)^{-\epsilon} + (1 + 3\omega)\frac{\tilde{\Omega}_x}{\Omega_b}(1+z)^{3\omega}}{1 + \frac{3|\omega|}{3|\omega| - \epsilon} \frac{\Omega_{dm}}{\Omega_b}(1+z)^{-\epsilon} + \frac{\tilde{\Omega}_x}{\Omega_b}(1+z)^{3\omega}} \right)^2. \tag{9}
\]

Some interesting features of the above expression must be explored. First, if \(\tilde{\Omega}_x = \Omega_x = \epsilon = 0\) one finds \(q = 1/2\), as expected for a flat matter-dominated model (\(\Omega_b + \Omega_{dm} = 1\)). Note that the expression of \(\tilde{\Omega}_x\) has been defined by Eq. (8). In comparison with the conventional non-interacting quintessence scenario, the coupling term (\(\epsilon\)) modifies considerably the transition deceleration/acceleration. In principle, since the CDM density scales as \(a^{-3}\), while the baryon density scales with \(a^{-3+\epsilon}\), the latter becomes dynamically more important in comparison with the non-decaying scenario. The overall baryon effect is to delay the transition epoch relative to previous cases (including

![FIG. 2: The transition redshift \(z_t\) in the scenario of coupled quintessence. a) \(z_t\) as a function of \(\omega\) for some selected values of the coupling parameter \(\epsilon\). b) The plane \((\epsilon - \omega)\) for some selected values of \(\omega\). In both diagrams, the horizontal lines represent the 2\(\sigma\) limits on \(z_t\) as given in Ref. [14].](image-url)
the standard ΛCDM model), which seems to be in better agreement with some recent SNe results indicating $z_t = 0.46 \pm 0.13$ at 1σ [14]. Besides this effect, we also have in our model the effect of the dark energy EOS $\omega$, which introduces a new parameter relative to the decaying vacuum model [6]. To better visualize the effect of the dark energy EOS, as well as the effect of the dark energy-dark matter interaction parameter $\epsilon$, we plot in Figure 1 the deceleration parameter as a function of redshift $z$ for some selected values of the EoS $(w = -1.1$ and $-0.8)$ and decaying $(\epsilon = 0.1)$ parameters.

Figures (1a) and (1b) show that the effect of a positive $\epsilon$ parameter, as required by thermodynamical arguments [6], is to decrease the value of the deceleration parameter, then increasing the value of the transition redshift. The net effect of the dark energy EOS, however, is not monotonic as the effect of the interaction. We have in general, for values of the dark energy EOS close to the vacuum value ($\omega = -1$), that the present value of the deceleration parameter increases for increasing $\omega$, although this behavior may change for values of $\omega$ much different from the standard value, or at high redshifts, as seen in Figure (1c).

Figures (2a) and (2b) show the direct effect of the $\epsilon$ and $\omega$ parameters on the transition redshift ($z_t$). In agreement with Figure (1), we see from Panel (2a) that the effect of the interacting parameter is in general to increase $z_t$. We can also see that the transition redshift has a maximum for values of the $\omega$ parameter a little larger than $-1$. Similar result can also be taken from Panel (2b), although $z_t$ has a more complicated dependence on $\omega$. We also show in both panels the 2σ limits given by Riess et al. (2004) [14]. It is clear that values of $\omega$ larger than $-1$ as well as smaller than $-1$ are favoured by these limits, whereas larger values of the $\epsilon$ parameter are disfavoured by these limits when $\omega \approx -1$. This latter result is in full agreement with the results of our statistical analyses discussed in the next section.

### III. ANALYSIS AND DISCUSSION

The description of the model discussed in the previous Section clearly shows that it comprises a multitude of cosmological solutions. In a model with such a wealth of different possibilities constraints on the parameter space arising from current observational data are likely to rule out many of the possible scenarios (combinations of $\epsilon$, $w$ and $\Omega_{dm}$) for the evolution of the Universe. In this Section we investigate such observational constraints by placing cosmological bounds on the parametric spaces $\epsilon - w$ and $\epsilon - \Omega_{dm}$ from statistical analyses involving a large set of cosmological observations. To this end we use the most recent distance measurements to SNe Ia [12] and the current estimates of the baryon acoustic oscillations found in the SDSS data [17], as well as, the shift parameter from WMAP observations [18]. In our analysis we fix $\Omega_b = 0.0416$ also from WMAP results, a value in good agreement with the constraints derived from primordial nucleosynthesis [19]. Now, concerning the Hubble parameter, it should be recalled that the estimates of $H_0$ through different methods fall on the range 62-74 km/s/Mpc with an uncertainty of about 10% [20]. In what follows, we consider the Hubble Space Telescope (HST) Key Project final result, i.e., $h = 0.71 \pm 0.08$ [21], as a Gaussian prior on the Hubble parameter.

#### A. SNe Ia

The predicted distance modulus for a supernova at redshift $z$, given a set of parameters $s$, is

$$\mu_p(z|s) = m - M = 5 \log d_L + 25,$$

where $m$ and $M$ are, respectively, the apparent and absolute magnitudes, the complete set of parameters is $s \equiv (H_0, \Omega_{dm}, \epsilon, w)$ and $d_L$ stands for the luminosity distance (in units of megaparsecs).

We estimate the best fit to the set of parameters $s$ by using a $\chi^2$ statistics, with

$$\chi^2 = \frac{\sum_{i=1}^{N} [\mu_p^i(z|s) - \mu_p^i(z|s)]^2}{\sigma_i^2},$$

where $\mu_p^i(z|s)$ is given by Eq. (10), $\mu_p^i(z|s)$ is the extinction corrected distance modulus for a given SNe Ia at $z_i$, and $\sigma_i$ is the uncertainty in the individual distance moduli.

In our analysis, we use a combined sample with $N = 192$ SNe also used by Davis et al. (2007) [12]. This sample consists of the best quality light-curves SNs of Wood-Vasey et al. (2007) [13], which are 60 ESSENCE supernovae [13], 57 SNLS supernovae [15], and 45 nearby supernovae. We also include, as in [12], 30 new released SNe Ia, classified as "gold" supernovae by Riess et al. (2007) [16].

#### B. BAO

The Baryon Acoustic Oscillations (BAO) given by the acoustic oscillations of baryons in the primordial plasma, leave a signature on the correlation function of galaxies as observed by Eisenstein et al. (2005) [17]. This signature furnishes a standard rule which can be used to constrain the following quantity [17]:

$$A \equiv \frac{\Omega_m^{1/2}}{H(z_s)^{1/3}} \left[\frac{1}{z_s} \Gamma(z_s)\right]^{2/3} = 0.469 \pm 0.017,$$

where $H$ is given by Eq. (4), $z_s = 0.35$ is a typical redshift of the SDSS data, and $\Gamma(z_s)$ is the dimensionless comoving distance to the redshift $z_s$. As has been shown in Ref. [22], this quantity can be used for models which do not have a large contribution of dark energy at early times.
values very close to zero ($\epsilon \approx 0$), which is given, for a flat Universe, by (23):

$$C_{\text{MB}} \text{ power spectrum first peak is the shift parameter,}$$

\[ \epsilon \text{ respectively,} \]

At 68.3%, 95.4% and 99.7% c.l., we have found, as discussed in the text, this analysis constrains $\epsilon$ to values very close to zero ($\approx 0.09$ at 3$\sigma$).

b) Same as Panel a for the plane $\omega - \epsilon$.

C. CMB shift parameter

A useful quantity to characterize the position of the CMB power spectrum first peak is the shift parameter, which is given, for a flat Universe, by (23):

$$\mathcal{R} = \sqrt{\Omega_m} \int_{z_e}^{z_r} \frac{dz}{H(z)} = 1.71 \pm 0.03 , \quad (13)$$

where $z_r = 1089$ is the recombination redshift and the value for $\mathcal{R}$ above is calculated from the MCMC of the WMAP 3-yr in the standard flat $\Lambda$CDM model [24].

As mentioned above, we also include a Gaussian prior on $h$, as given by the final results of HST Key Project [21]. Thus, in our statistical analysis we minimize the following quantity:

$$\chi^2 = \sum_{i=1}^{192} \left( \frac{\mu_{\text{obs}, i} - \mu_{\text{th}, i}}{\sigma_{\mu, i}} \right)^2 + \left( A - 0.469 \right)^2 \left( \frac{0.017}{0.017} \right)^2 + \left( \frac{R - 1.71}{0.03} \right)^2 + \left( \frac{h - 0.72}{0.08} \right)^2 , \quad (14)$$

D. Results

In Figure (3) we show the main results of our statistical analyses. As usual, the total likelihood is written as $\mathcal{L} \propto e^{-\chi^2/2}$, where $\chi^2$ is given by Eq. (14). By marginalizing $\mathcal{L}$ over the EoS parameter $\omega$, we can quantify how much the plane ($\epsilon$-$\Omega_m$) can be constrained by the data. The contour levels for this analysis are shown on Figure (3a). At 68.3%, 95.4% and 99.7% c.l., we have found, respectively,

$$\Omega_m = 0.269^{+0.028+0.047+0.066}_{-0.026-0.042-0.058} \quad \text{and}$$

$$\epsilon = 0.000^{+0.027+0.057+0.088}_{-0.000-0.000-0.000} ,$$

with the relative $\chi^2/\nu \approx 1.03$, where $\nu$ is the number of degrees of freedom. These results are much more constraining than those obtained in Ref. [6] for the case $\omega = -1$, as we have used more recent CMB and SNe Ia data. While in the above reference the bounds on the interacting parameter were $\epsilon = 0.06 \pm 0.10$ at 95.4% c.l., we have found, at the same level, $\epsilon = 0.000^{+0.057}_{-0.000}$ which clearly constrains this parameter to values very close to the standard non-interacting case ($\epsilon = 0$).

In Figure (3b) we show the plane ($\omega - \epsilon$) when the total likelihood is marginalized over the density parameter $\Omega_m$. For this analysis, we have found

$$\omega = -1.006^{+0.117+0.188+0.258}_{-0.119-0.205-0.296} ,$$

whereas the bounds for $\epsilon$ are very similar to those found in the previous analysis (Fig. 3a). Clearly, the standard $\Lambda$CDM is preferred by this analysis, although much space is left for an EoS distinct from $-1$. The so-called phantom models ($\omega < -1$) are slightly more favoured by this analysis than quintessence ($\omega > -1$) scenarios.

IV. FINAL REMARKS

The current standard cosmological model, i.e., a flat, accelerating Universe composed of $\simeq 1/3$ of matter (baryonic + dark) and $\simeq 2/3$ of a dark energy component in the form of the vacuum energy density ($\Lambda$), is fully consistent with a variety of observational data. Even so, given the complexity of the involved phenomena, it is clear that in order to obtain a deeper insight into the nature of the dark energy and dark matter, it is worth consider, both
from the observational and theoretical viewpoint, more complex scenarios as, for instance, models with interaction between these two components.

In this paper we have discussed some cosmological consequences of an alternative mechanism of cosmic acceleration based on a general class of coupled quintessence scenarios whose interaction term is deduced from the effect of the dark energy on the CDM expansion rate. The resulting expressions for the model, parameterized by a small positive parameter ($\epsilon$), are very general and have many of the previous phenomenological approaches as a particular case. In particular, the coupled quintessence models proposed here may be thought as a natural extension of the decay vacuum scenarios discussed a couple of years ago [2].

By combining the most recent SNe Ia, BAO, CMB shift parameter data and the HST results on $H_0$, we have shown that strong constraints can be placed on this kind of scenario. We have shown that the free parameters of the model are constrained to assume values very close to the standard ΛCDM values, i.e., $\omega \simeq -1$ and $\epsilon \simeq 0$, although space is still left for an EoS distinct from $-1$ and the interacting parameter slightly different from zero. It is worth emphasizing that in our analysis the EoS $w$ and interacting $\epsilon$ parameters have been set as constants. In a more realistic case, however, such parameters must vary with redshift. The theoretical and observational consequences of this more realistic interacting $w(z)$ scenario, as well as a full comparison with the case discussed in the present analysis, will appear in a forthcoming communication.

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