Cosmological interaction of vacuum energy and dark matter

Author: Clara Hormigos Feliu
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Joan Solà Peracaula

Models which allow for an evolving cosmological constant Λ are an alternative to the ΛCDM model, with a rigid Λ term. An evolving Λ leads to a coupling of dark energy (associated with the vacuum energy ρ_Λ) either to matter or to the gravitational constant G, which hints that an interaction of dark energy could be present. We study the dynamical vacuum models proposed by (Salvatelli *et al*, 2014) and (Solà *et al*, 2015 and 2016), which are based on different assumptions on the evolution of ρ_Λ. We solve both models and find an effective equation of state for dark energy in each case, recovering the results found by (Solà *et al*, 2015 and 2016), and find that their effective behavior can be related to that of phantom fields or quintessence models. A recent reanalysis of the (Salvatelli et al, 2014) scenario by the last authors leads to different conclusions more in accordance with observations. Interestingly, the dynamical vacuum models are currently challenging the ΛCDM.

I. Introduction

The accelerated expansion of the universe is currently explained with the existence of a negative-pressure component, what we know as "dark energy". The nature of dark energy (DE) is far from understood, and it has been associated with the cosmological constant in Einstein's field equations, Λ, with $\rho_\Lambda = \Lambda/8\pi G$ being the vacuum denisty. Other proposals, such as quintessence or phantom fields, have been made [1]. The equation of state (EoS) associated to the vacuum is $p_\Lambda = -\rho_\Lambda$ so that $\omega_\Lambda = -1$, a value that falls within recent observational constraints [2], but in general the EoS of DE can take any value between -1 and -1/3. Quintessence models, which postulate a scalar field with a positive interaction potential, lead to larger values of ω_Λ, whereas the introduction of phantom scalar fields, with negative kinetic energy, permit values smaller than -1.

DE must not be confused with dark matter (DM), since the latter has zero pressure, clusters and interacts weakly with baryonic matter [1]. The contribution of DM to the density of the Universe is, in units of the critical density, $\Omega_{DM} \simeq 0.25$ whereas baryonic matter contributes $\Omega_B \simeq 0.05$ only. DE, in contrast, is completely smooth and does not cluster, and its contribution to the total energy budget of the Universe is $\Omega_{DE} \simeq 0.7$ [3].

The dynamics of the universe are currently described in the ΛCDM model through Einstein's field equations with a cosmological constant and a (nearly) flat Friedmann-Lemaître-Robertson-Walker (FLRW) metric [2]. However, the equations allow for an evolution with time of the Λ term and the gravitational constant, G, which has been motivated in the literature in the context of quantum field theory and the running of coupling constants [4]. Models which allow for this provide an alternative explanation of the nature of DE as an evolving vacuum, without the need of external fields or the assumption of a negative kinetic energy. These models can lead to anomalous conservation laws, with the equations showing a coupling of the vacuum density to matter or to G. Recently there has been evidence in the literature that dynamic vacuum models can provide a significantly better agreement with observations than the more rigid concordance model [5][6][7][8].

We study the dynamic vacuum models proposed by (Salvatelli *et al*, 2014) and (Solà *et al*, 2015 and 2016) and solve them, finding the evolution with the scale factor of the densities and the Hubble function. We also find an effective EoS for DE in each model by associating it to a scalar field, which allows us to compare the behavior of the studied models with other theories of scalar fields. We obtain as well the redshift of the transition from a decelerated to an accelerated expansion in each model and compare it to that of the ΛCDM model.

II. Studied Models

Allowing for an evolution with cosmic time of the factors G and Λ, which are constant in the ΛCDM model, leads to the same form of the two independent Friedmann's equations [4]:

$$3H^2 = 8\pi G(a)\big(\rho_m + \rho_r + \rho_\Lambda(a)\big) \tag{1}$$

$$3H^2 + 2\dot{H} = -8\pi G(a)\Big(\frac{\rho_r}{3} - \rho_\Lambda(a)\Big), \tag{2}$$

where we explicitly denote the dependence on the scale factor a rather than time, which we use from now on, and the dot indicates the time derivative. We take a to be normalized so that $a = 1$ at present. A useful equation (the local energy conservation law), though not independent from (1) and (2), is

$$\frac{d}{dt}\big(G\rho\big) + 3GH(\rho + p) = 0, \tag{3}$$

where ρ and p are the total density and pressure, and G can be simplified if it is constant. Matter is assumed to have zero pressure ($\omega_m = 0$) and radiation follows the equation of state $p_r = \rho_r/3$ dictated by statistical mechanics. In our notation ρ_m refers generically to non-relativistic matter, both baryonic and DM, assuming that if an interaction with DE is present it is carried by the

DM component. It is useful to notice that an EoS will lead to an accelerated expansion ($\ddot{a} > 0$) only if $\omega < -1/3$, so that we must demand that any EoS for DE fulfill this condition. In the ΛCDM model, with strictly constant G and Λ, equation (3) leads to the densities evolving as $\rho_m = \rho_m^0 a^{-3}$ and $\rho_r = \rho_r^0 a^{-4}$, where ρ_m^0 and ρ_r^0 are the current matter and radiation densities. The Hubble function ($H = \dot{a}/a$) evolves as $H^2 = H_0^2(\Omega_r^0 a^{-4} + \Omega_m^0 a^{-3} + \Omega_\Lambda^0)$ in terms of the cosmological parameters $\Omega_i^0 = \rho_i^0/\rho_c^0$ with the current critical density being $\rho_c^0 = 3H_0^2/8\pi G_0$. (Solà *et al*, 2015 and 2016) proposed that the vacuum energy density evolve with H in the form

$$\rho_\Lambda(H;\nu,\alpha) = \frac{3}{8\pi G}\Big(c_0 + \nu H^2 + \frac{2}{3}\alpha \dot{H}\Big), \qquad (4)$$

where G can also have a dependence on the Hubble function, and ν and α are two parameters which can be fit to observational data. The models (4) are generically called running vacuuum models (RVM's); (Solà *et al*, 2015 and 2016) distinguish between RVM's type G, where G is allowed to depend on time, and type A, where G is constant. On the other hand, (Salvatelli *et al*, 2014) proposed that the vacuum density obey the relation

$$\dot{\rho}_\Lambda = -q_V H \rho_\Lambda, \qquad (5)$$

where q_V is the only free parameter, and G is taken to be constant. We refer to their model as the S model. In both cases the models can be solved analytically.

Both (Solà *et al*, 2016) and (Salvatelli *et al*, 2014) fit their models to experimental data in order to compute the best-fit values of the free parameters and the cosmological functions in the models, and found that the parameters take values different from zero (hence departing from the ΛCDM case) with a high level of confidence. (Solà *et al*, 2016) fit their models taking only the parameter ν into account and setting $\alpha = 0$ (models G1 and A1), and using both parameters (models G2 and A2). They show their results in terms of a single parameter, $\nu_{eff} = \alpha - \nu$. (Salvatelli *et al*, 2014) fit their model using different redshift bins; we use the parameter q_V they computed for $z < 0.9$, which leads to their most significant results. The values of these parameters, which we use in our computations, are found in tables I and II.

III. G model

For G models (Solà *et al*, 2015 and 2016) assume that matter and radiation follow the conventional conservation laws, that is $\dot{\rho}_m + 3H\rho_m = 0$ and $\dot{\rho}_r + 4H\rho_r = 0$. Using the change of variables $d/dt = aHd/da$ and imposing that the densities match the current ones at present we obtain $\rho_m(a) = \rho_m^0 a^{-3}$ and $\rho_r(a) = \rho_r^0 a^{-4}$, which correspond to the evolution of densities in the ΛCDM model. We notice that the vacuum does not couple to matter or radiation but only to the gravitational factor G; if $G = const.$ equation (3) leads to $\dot{\rho}_\Lambda = 0$, so that the coupling to G is essential in this case. By combining equations (1) and (2) ρ_Λ cancels and we obtain an expression of $G(a)$ in terms of the derivative of the Hubble function and the matter and radiation densities, whose expressions we already know:

$$G(a) = -G_0 \frac{a dE^2/da}{4\Omega_r^0 a^{-4} + 3\Omega_m^0 a^{-3}}\,. \qquad (6)$$

G_0 is the current value of the gravitational constant and we have defined a normalized Hubble function $E = H/H_0$. Substituting both the above expression of G and the explicit form of ρ_Λ given by equation (4) in equation (1) we obtain a differential equation for $E^2(a)$,

$$E^2(1-\nu) + \frac{dE^2}{da}\frac{a(1-\alpha) + \frac{\Omega_r^0}{\Omega_m^0}(1-\frac{4}{3}\alpha)}{3 + 4\frac{\Omega_r^0}{\Omega_m^0}a^{-1}} - \frac{c_0}{H_0^2} = 0\,, \quad (7)$$

which can be directly integrated by separation of variables. The constant c_0 can be obtained by imposing that $\rho_\Lambda(a=1) = \rho_\Lambda^0$ and using equation (2) to compute $\dot{H}(a=1)$, and the result is $c_0 = H_0^2\big(\Omega_\Lambda^0 - \nu + \alpha(\Omega_m^0 + \frac{4}{3}\Omega_r^0)\big)$. We have also used that $\Omega_m^0 + \Omega_{\Lambda^0} = 1$. The result of the integration using this expression of c_0 and fixing the integration constant with $E^2(a=1) = 1$ leads to

$$E^2(a) = 1 + \left(\frac{\Omega_m}{\xi} + \frac{\Omega_r}{\xi'}\right)\left[-1 + a^{-4\xi}\left(\frac{a + \frac{\Omega_r}{\Omega_m}\frac{\xi}{\xi'}}{1 + \frac{\Omega_r}{\Omega_m}\frac{\xi}{\xi'}}\right)^{\frac{\xi'}{1-\alpha}}\right], \qquad (8)$$

where we have defined the parameters $\xi = \frac{1-\nu}{1-\alpha}$ and $\xi' = \frac{1-\nu}{1-\frac{3}{4}\alpha}$. From equation (8) we can directly compute the explicit forms of $G(a)$ and ρ_Λ, which are rather lengthy and not shown here. If we assume that, near our present time, the radiation density is much smaller than the matter density, the expressions simplify and we obtain

$$E^2(a) \simeq 1 + \frac{\Omega_m^0}{\xi}\Big(a^{-3\xi} - 1\Big), \quad G(a) \simeq G_0 a^{-3(\xi-1)}$$
$$\rho_\Lambda(a) = \rho_c^0 a^{-3}\Big(a^{3\xi}(1 - \frac{\Omega_m^0}{\xi}) + \Omega_m^0(\xi^{-1} - 1)\Big)\,. \qquad (9)$$

We use these expressions later on in computing the effective EoS. The evolution of the adimensional parameter $\Omega_\Lambda(z) = \rho_\Lambda(z)/\rho_c^0$ is shown in figure 1; and it is seen to increase with redshift, differing from the ΛCDM result (a constant Ω_Λ).

The redshift at which the expansion became accelerated (inflection point z_I) is that at which the deceleration parameter q is zero. Using that $q = -\frac{\ddot{a}}{aH^2} = -1 - \frac{a}{2H^2}\frac{dH^2}{da}$ we find a_I (scale factor at $q = 0$) imposing that

$$E^2(a_I) = -\frac{a}{2}\frac{dE^2}{da}\bigg|_{a_I}\,. \qquad (10)$$

Model	G1	G2	ΛCDM
ν_{eff}	0.0009 ± 0.0003	0.0011 ± 0.0003	0
Ω_m	0.296 ± 0.005	0.296 ± 0.005	0.288 ± 0.009
z_I	0.683 ± 0.014	0.684 ± 0.014	0.70 ± 0.02

TABLE I: Parameters of the G model found by (Solà *et al*, 2016) and transition redshift computed from equation (11) and results for the ΛCDM case [3].

Neglecting radiation a_I can be found analytically, and taking into account that $z = a^{-1} - 1$ we find that for the G model acceleration began at redshift z_I given by

$$z_I = \left[\frac{1 - \frac{\Omega_m^0}{\xi}}{\Omega_m^0(\frac{3}{2} - \xi^{-1})}\right]^{\frac{1}{3\xi}} - 1\,. \tag{11}$$

The result of evaluating this expression with the parameters of the model is found in table I. In the limit $\xi \to 1$ we obtain $z_I = (2\Omega_\Lambda^0/\Omega_m^0)^{1/3} - 1$, which is the ΛCDM result, also shown in table I. The fact that the model shows a value of z_I close to that of the ΛCDM case hints that it provides reasonable predictions; however, z_I has not been measured with high precision and cannot be used as a reference to check the validity of the models.

IV. A Model

In this model we consider $G = const.$, and from equation (3) we obtain $\dot\rho_m + \dot\rho_r + 3H(\rho_m + \rho_r) = -\dot\rho_\Lambda$. The conservation law is anomalous and indicates an interaction between DE and DM. Using the explicit form of ρ_Λ in (4) and a combination of equations (1) and (2) we obtain a differential equation for the matter and radiation densities,

$$a\frac{d\rho_r}{da}\Big(1-\frac{4}{3}\alpha\Big)+(1-\alpha)\frac{d\rho_m}{da}+4(1-\nu)\rho_r+3(1-\nu)\rho_m = 0\,. \tag{12}$$

We consider that ρ_m and ρ_r evolve separately and obtain $\rho_m(a) = \rho_m^0 a^{-3\xi}$ and $\rho_r(a) = \rho_r^0 a^{-4\xi'}$, which lead to the ΛCDM expressions when $\xi, \xi' \to 1$. The equation we obtain for $E(a)$ by combining (1) and (2) as in the previous section is

$$\frac{dE^2}{da} + 4\Omega_r^0 a^{-4\xi'-1} + 3\Omega_m^0 a^{-3\xi-1} = 0\,, \tag{13}$$

and integration leads to

$$E^2(a) = 1 + \frac{\Omega_r^0}{\xi'}\big(a^{-4\xi'} - 1\big) + \frac{\Omega_m^0}{\xi}\big(a^{-3\xi} - 1\big)\,. \tag{14}$$

The explicit expression of ρ_Λ, using the above and equation (4), is $\rho_\Lambda(a) = \rho_\Lambda^0 + \rho_m^0(\xi^{-1}-1)(a^{-3\xi}-1) + \rho_r^0(\xi'^{-1} - 1)(a^{-4\xi'} - 1)$. The evolution of $\Omega_\Lambda(z)$ is similar to the previous case, as seen in figure 1. In the limit $\rho_r << \rho_m$ the Hubble function takes the same form as in the G model, so that applying equation (10) the expression we obtain for the redshift of the transition is the same as in (11). The numerical result is shown in table II and it is in agreement with the ΛCDM result.

Model	A1	A2	S
ν_{eff}, q_V	0.0009 ± 0.0003	0.0012 ± 0.0004	-0.128 ± 0.070
Ω_m	0.296 ± 0.005	0.296 ± 0.005	0.303 ± 0.001
z_I	0.683 ± 0.014	0.684 ± 0.014	0.592 ± 0.013

TABLE II: Parameters of the A (ν_{eff}) and S (q_V) models found by (Solà *et al*, 2016) and (Salvatelli *et al*, 2014) and transition redshift computed from equations (11) (A model) and (17) (S model).

V. S Model

The evolution of ρ_Λ in this model can be found integrating equation (5), which delivers $\rho_\Lambda(a) = \rho_\Lambda^0 a^{-q_V}$. (Salvatelli *et al*, 2014) work with a density ρ_c that refers to cold dark matter and neglect radiation; we use ρ_m instead to relate to our notation. Using equation (3) we find $\dot\rho_m + 3H\rho_m = -\dot\rho_\Lambda$, again an anomalous conservation law. Substituting ρ_Λ by the expression we found leads to the following differential equation for ρ_m:

$$\frac{d\rho_m}{da} + \frac{3}{a}\rho_m - q_V\rho_\Lambda^0 a^{-q_V-1} = 0\,. \tag{15}$$

After integration we obtain $\rho_m(a) = \rho_m^0 a^{-3} + \rho_\Lambda^0\eta(a^{-q_V} - a^{-3})$, where we have defined $\eta = \frac{q_V}{3-q_V}$. Substituting in equation (1) we obtain, for the Hubble function,

$$E^2(a) = \Omega_m^0 a^{-3} + \Omega_\Lambda^0\Big((\eta+1)a^{-q_V} - \eta a^{-3}\Big)\,. \tag{16}$$

Using again equation (10) the redshift at $q = 0$ is found to be

$$z_I = \left[\frac{\Omega_m^0 - \eta\Omega_\Lambda^0}{2\Omega_\Lambda^0(\eta+1)(1-q_V)}\right]^{\frac{1}{q_V-3}} - 1\,. \tag{17}$$

The numerical result shown in table II has a relative error of 16% when comparing it to the ΛCDM result, which is not negligible. (Salvatelli *et al*, 2014) found a negative parameter q_V in all their fits, which leads to ρ_Λ increasing with time as seen in figure 1, so that $\dot\rho_\Lambda > 0$. With time the term a^{-q_V} in ρ_m will dominate, and since $\eta < 0$ eventually ρ_m becomes increasingly negative. This represents a decay of matter into vacuum, which is not thermodynamically favored. Recent results from (Solà *et al*, 2016) indicate that the parameter q_V is actually positive, with a value $q_V = 0.0180 \pm 0.0075$. In figure 1 we plot as well $\Omega_\Lambda(z)$ with this value under the label S', and observe that it decreases mildly with time.

VI. Effective equation of state

In order to show the behavior of our models we find an effective EoS for DE, $p_D = \omega_D\rho_D$, in the supposition that its origin was an external field not interacting

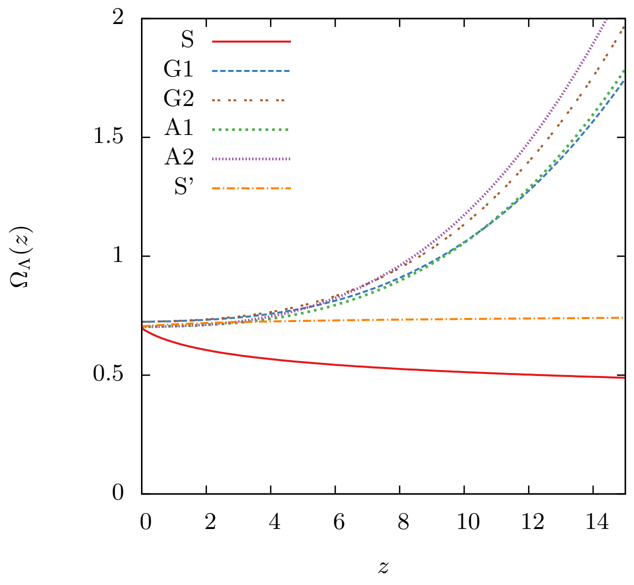

FIG. 1: Evolution with redshift of the parameter $\Omega_\Lambda(z) = \rho_\Lambda(z)/\rho_c^0$ for the different RVM's and the two S variants.

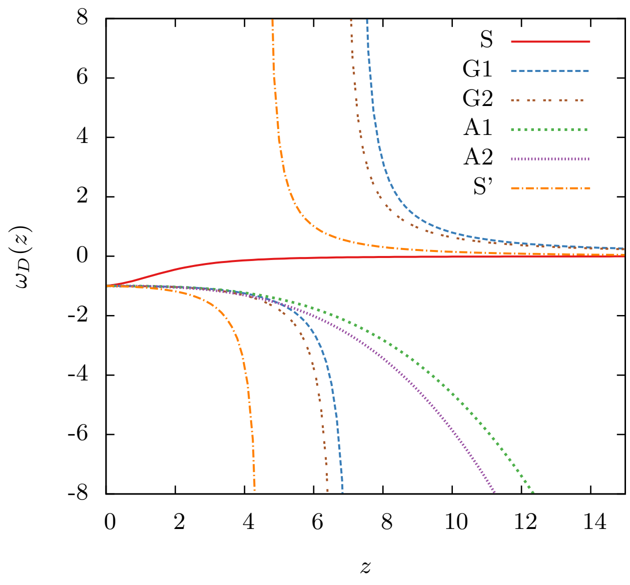

FIG. 2: Evolution with redshift of the parameter $\omega_D(z)$ of the effective equation of state for the different RVM's and the two S variants.

with DM. In this hypothesis all density components fulfill equation (3) separately, so that for matter we have $\rho_m = \rho_m^0 a^{-3(1+\omega_m)} = \rho_m^0(1+z)^{3(1+\omega_m)}$, but for DE we allow ω_D to vary with redshift, so that its density can be expressed as

$$\rho_D(z) = \rho_D^0 \exp\left[3\int_0^z \frac{1+\omega(z')}{1+z'}\right] = \rho_D^0\zeta(z)\,. \qquad (18)$$

In this scenario, which (Basilakos & Solà, 2013) call the DE picture, the Hubble function given by equation (1) is $E_D^2(z) = \tilde{\Omega}_m^0(1+z)^{\alpha_m} + \tilde{\Omega}_D^0\zeta(z)$, where the tildes indicate the values of the cosmological parameters in the DE picture, which we take to be very similar to the ones in our description. (Basilakos & Solà, 2013) showed that in the DE picture the Hubble function of a generalized vacuum model can be written as

$$E^2(z) = \Omega_m^0 f_m(z, r_i)(1+z)^{\alpha_m} + \Omega_\Lambda^0 f_\Lambda(z, r_i)\,. \qquad (19)$$

where $\alpha_m = 3(1+\omega_m)$ and f_m and f_Λ are two functions that depend on the redshift and the model's free parameters, r_i, and which must satisfy $f_j(0, r_i) = f_j(z, 0) = 1$ in order to fulfill the initial conditions and to recover the ΛCDM limit when the parameters are set to zero. Imposing that the Hubble function be the same in the two pictures, they showed that $\omega_D(z)$ could be found as $\omega_D(z) = -1 + \frac{1}{3}\alpha_m(1+z)^{\alpha_m}\epsilon(z)$, with

$$\epsilon(z) = \frac{\Omega_m^0 f_m(z, p_i) - \tilde{\Omega}_m^0}{(\Omega_m^0 f_m(z, p_i) - \tilde{\Omega}_m^0)(1+z)^{\alpha_m} + \Omega_\Lambda^0 f_\Lambda(z, p_i)}\,. \qquad (20)$$

We now identify the functions f_m and f_Λ in each of our models in order to find $\omega_D(z)$, checking that they fulfill the conditions mentioned before. Because we are interested in the behavior of ω_D near our present time, we use always the limits $\rho_r << \rho_m$ of the expressions we obtained in solving the models, and we take $\alpha_m = 3$ $(\omega_m = 0)$.

A. G Model

For the G model we find

$$f_m(z) = \frac{G(z)}{G_0}\,, \qquad f_\Lambda(z) = \frac{\Omega_\Lambda(z)}{\Omega_\Lambda^0}$$
$$\omega_D(z) = -\frac{1}{1 + \frac{G(z)-G_0}{G(z)}\frac{\Omega_m(z)}{\Omega_\Lambda(z)}}\,, \qquad (21)$$

in terms of the expressions in section III and assuming that $\tilde{\Omega}_m^0/\Omega_m^0 \simeq 1$. At present time $G(z) = G_0$ and we recover $\omega_D = -1$. In figure 2 we see that ω_D becomes more negative with increasing redshift, and it presents an asymptote that can be an artifact of the model. Since ω_D is always negative and smaller than -1, model G has phantom-field behavior, and the condition $\omega_D < -1/3$ for an accelerated expansion is fulfilled.

B. A Model

In the A model we find the following functions:

$$f_m(z) = (1+z)^{3(\xi-1)}$$
$$f_\Lambda(z) = 1 + \frac{\Omega_m^0}{\Omega_\Lambda^0}(\xi^{-1} - 1)\big((1 + z^{3\xi}) - 1\big)$$

$$\omega_D(z) = -1 + \xi \frac{\Omega_m^0 (1+z)^{3\xi} - \tilde{\Omega}_m^0 (1+z)^3}{\left(1 - \tilde{\Omega}_m^0 (1+z)^3\right)\xi + \Omega_m \left((1+z)^{3\xi} - 1\right)}$$

$$\simeq -1 + 3 \frac{\Omega_m^0}{\Omega_\Lambda^0} (1+z)^3 (\alpha - \nu) \ln(1+z) \,, \qquad (22)$$

where we have expanded ω_D in the limit $\alpha, \nu \to 0$ and neglected $1 - \tilde{\Omega}_m^0 / \Omega_m^0$. In figure 2 we see that its behavior is phantom-field like, as in the previous case. The model also presents asymptotes at higher redshifts, which are not seen in figure 2 .

C. S Model

For the S model we find

$$f_m(z) = 1 + \eta \frac{\Omega_\Lambda^0}{\Omega_m^0} \Big((1+z)^{q_V - 3} - 1\Big), \quad f_\Lambda(z) = (1+z)^{q_V}$$

$$\omega_D(z) = -\frac{1}{1 + \eta\big(1 - (1+z)^{3-q_V}\big)}$$

$$\simeq -1 + \eta\big(1 - (1+z)^{3-q_V}\big). \qquad (23)$$

In the last line we have expanded for a small η. In this case $\omega_D(z)$ has a very different behavior; it departs from -1 and goes to zero with increasing redshift, as seen in figure 2. We have checked that, for redshifts lower than z_I, the effective EoS fulfills $\omega_D < -1/3$, so that an accelerated expansion is possible. The fact that $\omega_D(z)$ is greater than -1 at higher redshifts indicates a quintessence-like behavior. Figure 2 also shows $\omega_D(z)$ computed with the parameter found by (Solà *et al*, 2016), and the effective behavior becomes phantom-field like as in models G and A. With a positive q_V all models have the same effective behavior, so that the results do not depend dramatically on the postulated evolution of ρ_Λ and describe the decay of vacuum into matter.

VII. Conclusions

We have studied three different dynamic vacuum models and solved them, recovering the expressions of $E^2(a)$, $\rho_m(a)$, $\rho_\Lambda(a)$ and $G(a)$ found by (Solà *et al*, 2015 and 2016) for models G and A. In models A and S the conservation laws obtained indicate an interaction between DE and DM while, in model G, DE does not couple to matter but to G. The density $\Omega_\Lambda(z)$ is found to increase with redshift for models G and A and to decrease for model S, thus differing from the ΛCDM case, with a constant Ω_Λ. The prediction made by each model of the redshift at the inflection point is in agreement with the ΛCDM result except for model S, which delivers a too low value of z_I as compared to ΛCDM. For this model the parameter q_V found by (Salvatelli *et al*, 2014) is negative, which indicates a decay of matter into vacuum. However, very recent results [8] indicate that q_V is actually positive, leading to the expected situation of vacuum decaying into matter.

In all cases the ΛCDM limit is recovered when the models' parameters are set to zero, and the results we obtain provide only small variations in the values of the cosmological functions near our present time. However, these small differences turn out to be crucial to improve the quality of the fits to observational data of the RVM's as compared to the ΛCDM, therefore supporting the possibility of a dynamical vacuum in interaction with matter [7][8].

The behavior of dynamic vacuum models can be compared with scalar-field theories by imposing an equality of their theoretical Hubble functions. Models G and A show an effective EoS for DE with $\omega_D(z) < -1$ and increasingly negative at higher redshifts, thus showing a phantom-like behavior. On the other hand, model S shows an $\omega_D(z)$ evolving towards zero with increasing redshift, so that its behavior is analogue to that of quintessence; the model fulfills the condition $\omega_D < -1/3$ for redshifts lower than its prediction of z_I, ensuring that an accelerated expansion is possible. For the positive q_V found by (Solà *et al*, 2016), however, the effective EoS of model S has a similar behavior to RVM's. This indicates that most dynamical vacuum models have a similar behavior if the proposed evolution of ρ_Λ describes a decay of vacuum into matter. In these cases the dynamical models can improve significantly the description of the cosmological data as compared to the ΛCDM case [8].

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