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PARTICLES AND FIELDS

Interacting Dark Energy in the Dark $SU(2)_R$ Model

Ricardo G. Landim[1,2] · **Rafael J. F. Marcondes**[1] · **Fabrízio F. Bernardi**[1] · **Elcio Abdalla**[1]

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Abstract

We explore the cosmological implications of the interactions among the dark particles in the dark $SU(2)_R$ model. It turns out that the relevant interaction is between dark energy and dark matter, through a decay process. With respect to the standard ΛCDM model, it changes only the background equations. We note that the observational aspects of the model are dominated by degeneracies between the parameters that describe the process. Thus, only the usual Λ CDM parameters such as the Hubble expansion rate and the dark energy density parameter (interpreted as the combination of the densities of the dark energy doublet) could be constrained by observations at this moment.

Keywords Dark matter · Dark energy · Cosmological observations

1 Introduction

Understanding the nature of dark energy and dark matter is a puzzling challenge that has motivated physicists to develop huge observational programs. This is one of the biggest concerns in modern cosmology. The simplest dark energy candidate is a cosmological constant, in agreement with the Planck satellite results [1]. Such attempt, however, suffers from a huge discrepancy of 120 orders of magnitude between a theoretical prediction and the observed data [2]. The origin of such a constant is still an open issue which motivates physicists to look into more sophisticated models. The plethora of dark energy candidates include scalar fields [3–14], vector fields [15–21], holographic dark energy [22–39], models of false vacuum decay [40–45], modifications of gravity and different kinds of cosmological fluids [46–48]. In addition, the two components of the dark sector may interact with each other [14, 25–28, 44, 48–68], since their densities are comparable and the interaction can eventually alleviate the coincidence problem [69, 70].

Much closer to the Standard Model (SM) of particle physics are models based on gauge groups which aim to take dark matter into account. Those with $SU(2)_R$ symmetry, for instance, are known in the literature as extensions of the SM, in the so-called left-right symmetric models [71–77], where, recently, dark matter has been considered as well [78–88], but with no attempt to insert dark energy in it.

The dark $SU(2)_R$ model was built to have the two elements of the dark sector [89] and it is similar to the well-known model of weak interactions. In principle, the hidden sector interacts with the SM particles only through gravity. Dark energy is interpreted as a scalar field whose potential is a sum of even self-interactions up to order six. The scalar field is at the local minimum of the potential, and such false vacuum might decay into the true one through the barrier penetration. However, in order to explain the current cosmic acceleration, the false vacuum should be long-lived (with a life time of the order of the age of the universe, as shown in [89]) and therefore, the scalar field behaves as a cosmological constant. On the other hand, it differs from the latter due to the presence of interactions among the dark particles.

In this work, we explore the interactions among the dark particles from the cosmological point of view. The relevant interaction is among dark energy and dark matter,

✉ Ricardo G. Landim
rlandim@if.usp.br

Rafael J. F. Marcondes
rafaelmarcondes@usp.br

Fabrízio F. Bernardi
bernardiff@gmail.com

Elcio Abdalla
eabdalla@if.usp.br

1 Instituto de Física, Universidade de São Paulo, Rua do Matão, 1371, Butantã, Sao Paulo, CEP 05508-090, Brazil

2 Departamento de Física e Astronomia, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre 687, 4169-007, Porto, Portugal

through the decay process calculated in [89]. It turns out that the coupling changes only the background equations, since the dark energy perturbation decreases faster than radiation. The paper is organized in the following manner. Section 2 presents the dark $SU(2)_R$ model, introduced in [89]. In Section 3, we derive its cosmological equations and discuss the outcome of confronting it with observational data from the standard cosmic probes. Section 4 is reserved for conclusions.

2 The Dark $SU(2)_R$ Model

In the dark $SU(2)_R$ model [89], dark energy and dark matter are doublets under $SU(2)_R$ and singlets under any other symmetry. The model contains a dark matter candidate ψ, a dark matter neutrino ν_d (which can be much lighter than ψ), and the dark energy doublet φ, with φ^0 and φ^+, the latter being the heaviest particle by definition. The scalar potential for the dark energy doublet is

$$V(\Phi) = \frac{m^2}{2}\Phi^\dagger\Phi - \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + \frac{g'}{\Lambda^2}(\Phi^\dagger\Phi)^3 \quad , \qquad (1)$$

where λ and g' are positive constants and Λ is the cutoff scale. There are also terms which involve couplings with the dark Higgs so that after the spontaneous symmetry breaking the physical mass of the dark energy doublet is no longer the same, but m_{φ^0} and m_{φ^+}.

The dimension six interaction term can be split into

$$\frac{g'}{\Lambda^2}(\Phi^\dagger\Phi)^3 = \left[\frac{\lambda}{32m_i^2} + \frac{g}{\Lambda^2}\right](\Phi^\dagger\Phi)^3 \quad , \qquad (2)$$

where $g' = \frac{\lambda^2}{32m_i^2}\Lambda^2 - g$ and i stands for φ^0 or φ^+.

The mass term, the quartic interaction and the first term of the dimension six operator can be grouped as a perfect square, $\left[\frac{m_i\varphi^i}{\sqrt{2}} - \frac{\lambda(\varphi^i)^3}{\sqrt{32}\,m_i}\right]^2$, which has an absolute minimum at $V(\varphi^i) = 0$. The extra term $g\Lambda^{-2}(\varphi^i)^6$ brings the minimum $V(\pm 2m/\sqrt{\lambda})$ downwards, thus the difference between the true vacuum and the false one, given by $V(0) - V(\pm 2\,m_i/\sqrt{\lambda}) = 64\,m_i^6\lambda^{-3}g\Lambda^{-2}$, is the observed vacuum energy. A gravity-induced term $(gM_{pl}^{-2}(\varphi^i)^6)$, which may parametrizes a graviton loop contribution [90], is a natural option since we are dealing with gravitational effects, therefore, the reduced Planck mass is the cutoff scale.[1] The mass of the scalar field should be, for instance, $\sim \mathcal{O}(\mathrm{GeV})$ for $\lambda \sim g \sim 1$ in order to explain the observed value of 10^{-47} GeV^4. The value of the observed vacuum energy constrains one of the three parameters, namely, m_i, λ, or g.

[1] It is possible to get the scalar potential (1) from minimal supergravity, for instance. However, as usual in supergravity theories, we ended up with a negative cosmological constant.

The interaction between the fields are given by the Lagrangian

$$\mathcal{L}_{int} = g\left(W^+_{d\mu}J^{+\mu}_{dW} + W^-_{d\mu}J^{-\mu}_{dW} + Z^0_{d\mu}J^{0\mu}_{dZ}\right) \quad , \qquad (3)$$

where the currents are

$$J^{+\mu}_{dW} = \frac{1}{\sqrt{2}}[\bar{\nu}_{dR}\gamma^\mu\psi_R + i(\varphi^0\partial^\mu\bar{\varphi}^+ - \bar{\varphi}^+\partial^\mu\varphi^0)] \quad , \qquad (4)$$

$$J^{-\mu}_{dW} = \frac{1}{\sqrt{2}}[\bar{\psi}_R\gamma^\mu\nu_{dR} + i(\varphi^+\partial^\mu\bar{\varphi}^0 - \bar{\varphi}^0\partial^\mu\varphi^+)] \quad , \qquad (5)$$

$$J^{0\mu}_{dZ} = \frac{1}{2}[\bar{\nu}_{dR}\gamma^\mu\nu_{dR} - \bar{\psi}_R\gamma^\mu\psi_R + i(\varphi^+\partial^\mu\bar{\varphi}^+ - \bar{\varphi}^+\partial^\mu\varphi^+) - i(\varphi^0\partial^\mu\bar{\varphi}^0 - \bar{\varphi}^0\partial^\mu\varphi^0)] \quad . \qquad (6)$$

The behavior of this system is two fold. If we place the bosonic field on the (metastable) vacuum at $\varphi^i = 0$, it might decay or remain there in case the height and width of the barrier is large enough. We suppose that is the case here [89]. In such a case, making a background-perturbation split of the fields, they get expanded around the vacuum and the perturbations act as quantum fields in the interactions. The bosonic field φ^+, if trapped by a large enough barrier, can only decay by means of the Lagrangian, (3). Notice that since the false vacuum is at $\varphi^+ = 0$, the expanded Lagrangian coincides with the original one. Therefore, in the decay of the bosonic field φ^+ into fermions plus φ^0 there is no potential barriers, thus the dark energy decays into dark matter and other particles. This mechanism is the one responsible for the dark energy decay into cold (or even warm) dark matter and it is what we are going to pursue now.

From a cosmological point of view, the relevant interactions among the dark particles are the decay $\varphi^+ \to \varphi^0 + \psi + \nu_d$ [89] and the annihilation of two scalars into two fermions. The last process, however, gives a zero cross section after expanding it in even powers of p/m for a fermionic cold dark matter, while the previous (decay) process has already non relativistic contributions; generally speaking, it has more important contributions. The other annihilation processes belong to the hidden sector and do not play a major role in current observations.

3 Model Predictions

3.1 Background Equations

The Boltzmann equation for a process $\alpha \to a + b + c$ is given by [91]

$$\frac{\partial(a^3 n_\alpha)}{\partial t} = -a^3\int d\Pi_\alpha\, d\Pi_a\, d\Pi_b\, d\Pi_c\,(2\pi^4) \times\delta^4(p_\alpha - p_a - p_b - p_c)|\mathcal{M}|^2_{\alpha\to a+b+c}f_\alpha \quad , \qquad (7)$$

where $d\Pi_i \equiv \frac{1}{(2\pi)^3}\frac{d^3 p_i}{2E_i}$ and $f_i = e^{-E_i/k_B T}$ and the $a = a(t)$ is the scale factor. We neglect the factors due to Bose condensation or Fermi degeneracy. The right-hand side of (7) becomes

$$\int d\Pi_{\varphi^+}\, d\Pi_{\varphi^0}\, d\Pi_\psi\, d\Pi_\nu\, (2\pi^4)\delta^4(p_{\varphi^+} - p_{\varphi^0} - p_\psi - p_\nu) \times |\mathcal{M}|^2 e^{-E_{\varphi^+}/k_B T} = -\Gamma n_{\varphi^+} \quad , \tag{8}$$

where Γ is the integral of the scattering amplitude, which in turn does not depend on P. The number density is $n_{\varphi^+} = \int e^{-E_{\varphi^+}/k_B T}\frac{d^3 p_{\varphi^+}}{(2\pi)^3}$. Equations (7) and (8) lead to the following equations for the particles in the decay process

$$\frac{\partial(a^3 n_\alpha)}{\partial t} = -\Gamma a^3 n_\alpha \quad , \tag{9}$$

$$\frac{\partial(a^3 n_{a,b,c})}{\partial t} = \Gamma a^3 n_\alpha \quad . \tag{10}$$

Once the field is at rest in the minimum of the potential, from (9) we see that the term $a^3 n$ should be constant (in the absence of decay) to describe the cosmological constant, therefore the energy density for a fluid with equation of state -1 should be $\rho = a^3 mn$, that is, a non-relativistic fluid that is not diluted as the universe expands.

The continuity equation for a cosmological fluid is obtained from the definition $\rho_i \equiv \int \frac{d^3 p_i}{(2\pi)^3} E_i f_i \approx m_i n_i$, where the last equality holds for non-relativistic fluids. Hence, the continuity equation for the φ^+ fluid is

$$\dot\rho_{\varphi^+} = -\Gamma\rho_{\varphi^+} \quad , \tag{11}$$

which has the usual exponential decay solution $\rho_{\varphi^+} \propto e^{-\Gamma t}$. The decay rate can be seen as part of an effective equation of state for φ^+, since

$$\dot\rho_{\varphi^+} + 3H(1 + w_{\mathrm{eff}})\rho_{\varphi^+} = 0 \quad , \tag{12}$$

where $w_{\mathrm{eff}} = -1 + \Gamma/3H$. The second term gives rise to a kinetic contribution for the dark energy.

The other fluids (φ^0, ψ, and ν_d) have similar continuity equations, with the equations of state $w_{\varphi^+} = -1$, $w_\psi = 0$ and either $w_\nu = 0$ or $w_\nu = 1/3$. The two particles of the dark energy doublet and the dark matter candidate are non-relativistic, which implies that the continuity equations for the remaining fluids are

$$\dot\rho_{\varphi^0} = \mu_{\varphi^0}\Gamma\rho_{\varphi^+} \quad , \tag{13}$$

$$\dot\rho_\psi + 3H\rho_\psi = \mu_\psi\Gamma\rho_{\varphi^+} \quad , \tag{14}$$

$$\dot\rho_\nu + 3H(1 + w_\nu)\rho_\nu = \left(1 - \mu_{\varphi^0} - \mu_\psi\right)\Gamma\rho_{\varphi^+} \quad , \tag{15}$$

where in the last equation we have used the energy conservation $E_\nu = m_{\varphi^+} - m_{\varphi^0} - m_\psi$, which is also evident from the energy-momentum tensor conservation, and μ_{φ^0}, μ_ψ are the mass ratios $m_{\varphi^0}/m_{\varphi^+}$, m_ψ/m_{φ^+}, respectively. The right-hand side of the continuity equations above are a leading-order approximation since we are considering non-relativistic fluids for φ^+, φ^0 and ψ.

3.2 Cosmological Perturbations

Once the equation of state parameters w_i are constant for all fluids, their sound speeds are $c^2_{s,\,i} = \delta\mathcal{P}_i/\delta\rho_i = w_i$, where $\mathcal{P}_i$ is the pressure of the fluid 'i'. The sound speed for a scalar field is, in turn, $c^2_{s,\,\varphi} = 1$ [92]. Following the definitions of [93], in the synchronous gauge the energy conservation leads to the following equations for the dark fluids

$$\dot\delta_{\varphi^+} + 6H\delta_{\varphi^+} = -\Gamma\delta_{\varphi^+} \quad , \tag{16}$$

$$\dot\delta_{\varphi^0} + 6H\delta_{\varphi^0} = \mu_{\varphi^0}\Gamma\delta_{\varphi^+} \quad , \tag{17}$$

$$\dot\delta_\psi + \theta_\psi + \frac{\dot h}{2} = \mu_\psi\Gamma\delta_{\varphi^+} \quad , \tag{18}$$

$$\dot\delta_\nu + (1 + w_\nu)\left(\theta_\nu + \frac{\dot h}{2}\right) = \left(1 - \mu_{\varphi^0} - \mu_\psi\right)\Gamma\delta_{\varphi^+} \quad , \tag{19}$$

where $\delta_i \equiv \delta\rho_i/\bar\rho_i$. The right-hand sides of the equations above follow from (12–15). Equation (16) has the solution $\delta_{\varphi^+} \propto a^{-6}e^{-\Gamma t}$, in agreement with the fact that dark energy does not cluster on sub-horizon scales [94]. Since the φ^+ fluid is diluted in the universe faster than radiation, the couplings in the right side of (17–19) are negligible. As a result, $\delta\varphi^0 \propto a^{-6}$ and the continuity equation for the dark matter perturbation is the same as in the uncoupled case.

In order to get the interacting term in the momentum conservation equations, we multiply the right-hand side of (8) by $p_{\varphi^+}/E_{\varphi^+} = p_{\varphi^+}/m_{\varphi^+}$ before integrating it. The field velocity is defined as $v^i \equiv \frac{1}{n}\int d^3 p \frac{p\hat p^i}{E} e^{-E/T}$, thus the Navier-Stokes equation in momentum space for φ^+ is

$$k^2\delta_{\varphi^+} = \theta_{\varphi^+}\Gamma \quad , \tag{20}$$

where $\theta \equiv ik_j v^j$. The field velocity for φ^+ is also negligible because the left-hand side of (20) goes to zero. Thus, the momentum transfer is irrelevant and the Navier-Stokes equation for dark matter is the usual one from the ΛCDM model. Therefore, the decay process changes only the background equations.

3.3 Comparison with Observations

From the observational point of view, the two scalar fields φ^+ and φ^0 have $w_i = -1$ and effectively behave like one "dark energy" fluid. The same happens with the two particles in the dark matter doublet in the case that the dark neutrino is non-relativistic ($w_\nu = 0$). For this doublet, the background (14) and (15) can be combined into

$$\dot{\rho}_{\rm dm} + 3H\rho_{\rm dm} = \left(1 - \mu_{\varphi^0}\right)\Gamma\rho_{\varphi^+} \quad . \tag{21}$$

It is then straightforward to solve numerically the background cosmology in terms of the scale factor,

$$\frac{d\rho_{\phi^+}}{da} = -\frac{\Gamma}{aH}\rho_{\varphi^+}, \tag{22}$$
$$\frac{d\rho_{\varphi^0}}{da} = \mu_{\varphi^0}\frac{\Gamma}{aH}\rho_{\varphi^+}, \tag{23}$$
$$\frac{d\rho_{\rm dm}}{da} = -\frac{3}{a}\rho_{\rm dm} + \left(1 - \mu_{\varphi^0}\right)\frac{\Gamma}{aH}\rho_{\varphi^+}, \tag{24}$$

backwards in time with the current densities as “initial” conditions, together with the usual equations for the standard model fluids. Rewriting the equations in terms of the scale factor eases the numerics. A degeneracy between Γ and the density of φ^+ is evident from these equations. The two parameters always appear multiplied. Writing them in terms of a new “density” $\rho_\Gamma \equiv \Gamma\rho_{\varphi^+}$ gives

$$\frac{d\rho_\Gamma}{da} = -\frac{\Gamma}{aH}\rho_\Gamma, \tag{25}$$
$$\frac{d\rho_{\varphi^0}}{da} = \frac{\mu_{\varphi^0}}{aH}\rho_\Gamma, \tag{26}$$
$$\frac{d\rho_{\rm dm}}{da} = -\frac{3}{a}\rho_{\rm dm} + \frac{1 - \mu_{\varphi^0}}{aH}\rho_\Gamma, \tag{27}$$

which partially amends the problem. However, we fail to obtain constraints on the relevant parameters of the decay (now Γ, Ω_Γ, $\Omega_{\rm dm}$, μ_{φ^0}, and Ω_{φ^0} determined from the flatness condition on the sum of the density parameters) when we compare the predicted evolution with the standard cosmic probes using Markov Chain Monte Carlo (MCMC) simulations. Despite this, the derived parameter $\Omega_{\rm de} \equiv \Omega_{\varphi^+} + \Omega_{\varphi^0}$, with $\Omega_{\varphi^+} = \Omega_\Gamma/\Gamma$ is verified to mimic the standard model‘s dark energy with $\Omega_{\rm de} = 0.68183^{+0.00668}_{-0.00564}$ at 1σ confidence level (see Fig. 1). For this analysis, we employed observational data from the Planck Cosmic Microwave Background (CMB) distance priors [95], the Joint Light-curve Analysis (JLA) of type-Ia supernovae [96], Baryon Acoustic Oscillation (BAO) from various surveys [97–100], $H(z)$ from cosmic clocks [101, and references therein], and the local value of the Hubble constant [102]. Because the parameters Ω_Γ, Γ and μ_{φ^0} are expected to be small, we adopted conservative flat priors restricting them to the interval [0, 0.5].

The difficulties discourage any further attempt to constrain the parameters of this model in the case $w_\nu = 1/3$, which adds two more parameters, Ω_ν and μ_ψ (the dark matter doublet cannot be described as a single fluid anymore), potentially making the degeneracy even more serious.

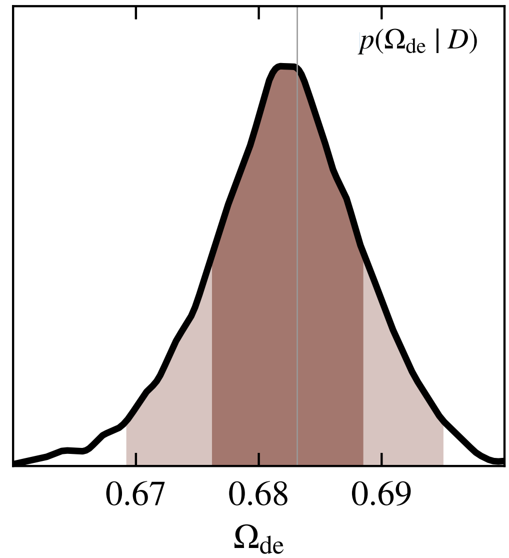

Fig. 1 Marginalized posterior probability p of the derived parameter $\Omega_{\rm de} \equiv \Omega_{\varphi^+} + \Omega_{\varphi^0}$ given the data D from standard cosmic probes. The shaded areas under the curve mark the 1σ and 2σ confidence levels; the thin grey line marks the parameter value at the best-fit (bf) point, $\Omega_{\rm de}^{\rm (bf)} = 0.68313$

4 Conclusions

In this paper, we investigated the interactions among the dark particles in the dark $SU(2)_R$ model from a cosmological point of view. The most relevant interaction is the decay of one particle in the dark energy doublet into the other three particles in the dark energy and dark matter doublet. This process consists of a new form of interacting dark energy and it changes only the background equations. Although the comparison with data constrained very well the dark energy density parameter today, defined as the sum of the density parameters of φ^+ and φ^0, the other free parameters in the process (decay rate and masses of the particles) are not constrained mainly due to the strong degeneracy between the decay rate and the density of the progenitor (φ^+).

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