Interacting dark energy in the dark $SU(2)_R$ model

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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 $\Lambda$CDM 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 $\Lambda$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.

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 lifetime 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, 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. Sect. 2 presents the dark $SU(2)_R$ model, introduced in [89]. In Sect. 3 we derive its cosmological equations and discuss the outcome of confronting it with observational data from the standard cosmic probes. Sect. 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 \( \psi \), a dark matter neutrino \( \nu_d \) (which can be much lighter than \( \psi \)), and the dark energy doublet \( \varphi \), with \( \varphi^0 \) and \( \varphi^+ \), the latter being the heaviest particle by definition. The scalar potential for the dark energy doublet is

\[
V(\Phi) = \frac{m^2}{2} \Phi^\dagger \Phi - \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + \frac{g'}{\Lambda^2} (\Phi^\dagger \Phi)^3 ,
\]

where \( \lambda \) and \( g' \) are positive constants and \( \Lambda \) is the cutoff scale. There are also terms which involve couplings with the Higgs boson \( \phi \) being the heaviest particle by definition. The scalar potential for the dark energy doublet is no longer the same, but \( m_{\varphi^0} \) and \( m_{\varphi^+} \).

The dimension six interaction term can be split into

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

where \( g' = \frac{\Lambda^2}{32 m_i^2} - g \) and \( i \) stands for \( \varphi^0 \) or \( \varphi^+ \).

The mass term, the quartic interaction and the first term of the dimension six operator can be grouped as a perfect square, \( \left[ m_{\varphi^0}^2 - \lambda (\varphi^0)^2 \right] \), which has an absolute minimum at \( V(\varphi^0) = 0 \). The extra term \( g \Lambda^{-2} (\varphi^0)^6 \) brings the minimum \( V(\pm 2 m_i/\sqrt{\Lambda}) \) down, 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 \( (gM_{\text{Pl}}^2 (\varphi^0)^6) \), 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, \( \sim O(\text{GeV}) \) for \( \lambda \sim 1 \) 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, \( m_i \), \( \lambda \), or \( g \).

The interaction between the fields are given by the Lagrangian

\[
\mathcal{L}_{\text{int}} = g \left( W^\mu_{\mu} T^\mu_{\text{dw}} + W^\mu_{\text{dw}} T^\mu_{\text{dw}} + Z^\mu_{\mu} \rho^\mu_{\text{zw}} \right) ,
\]

(3)

where the currents are

\[
J^\mu_{\text{dw}} = \frac{1}{\sqrt{2}} \left[ \bar{\nu}_d \gamma^\mu \psi_r + i (\varphi^0 \mu \psi_r - \bar{\psi}^0 \mu \varphi^0) \right] ,
\]

(4)

\[
J^\mu_{\text{dw}} = \frac{1}{\sqrt{2}} \left[ \bar{\nu}_d \gamma^\mu \psi_r + i (\varphi^+ \mu \psi_r - \bar{\psi}^0 \mu \varphi^+) \right] ,
\]

(5)

\[
J^\mu_{\text{zw}} = \frac{1}{\sqrt{2}} \left[ \bar{\nu}_d \gamma^\mu \psi_r - i (\varphi^0 \mu \bar{\psi}^0 - \bar{\psi}^0 \mu \varphi^0) \right] - i (\varphi^+ \mu \bar{\psi}^0 - \bar{\psi}^0 \mu \varphi^+) .
\]

(6)

The behaviour of this system is two fold. If we place the bosonic field on the (metastable) vacuum at \( \varphi^0 = 0 \) 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 \( \varphi^0 \), if trapped by a large enough barrier, can only decay by means of the Lagrangian, Eq. (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 \( \varphi^+ \) into fermions plus \( \varphi^0 \) 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 \( \varphi^+ \to \varphi^0 + \psi + v_d \) [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]

\[
\frac{\partial(a^3 n_\alpha)}{\partial t} = -a^3 \int d\Pi a d\Pi_b d\Pi_c d\Pi_{\Pi} (2\pi)^4 \times \\
\times \delta^4(p_a - p_b - p_c - p_\Pi) |\mathcal{M}|^2 e^{-E_\Pi/2k_B T} \Gamma_{\alpha \to a + b + c} f_\Pi ,
\]

(7)

where \( d\Pi \equiv \frac{1}{(2\pi)^4} d^4 k_a \) and \( f_\Pi = e^{-E_\Pi/2k_B T} \) 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 Eq. (7) becomes

\[
\int d\Pi_{\varphi^+} d\Pi_\varphi d\Pi_{\varphi^0} d\Pi_\varphi d\Pi_{\varphi^0} (2\pi)^4 \delta^4(p_{\varphi^+} - p_{\varphi^0} - p_{\varphi^0} - p_{\varphi^0}) \times \\
\times |\mathcal{M}|^2 e^{-E_{\varphi^+}/2k_B T} = -\Gamma_{\varphi^0 \varphi^0} ,
\]

(8)

where \( \Gamma \) is the integral of the scattering amplitude, which in turn does not depend on \( P \). The number density is \( n_{\varphi^0} = \int e^{-E_\varphi^0/2k_B T} d^4 p_{\varphi^0} \). Eqs. (7) and (8) lead to the following equations for the particles in the decay process

\[
\frac{\partial(a^3 n_\alpha)}{\partial t} = -\Gamma a^3 n_\alpha ,
\]

(9)

\[
\frac{\partial(a^3 n_{\alpha,b,c})}{\partial t} = \Gamma a^3 n_\alpha .
\]

(10)
Once the field is at rest in the minimum of the potential, from Eq. (9) we see that the term \(a^n\) 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 \(\rho = a^3 m_i\), 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 \(\rho_i \equiv \int \frac{d^3p}{(2\pi)^3} E_i f_i \approx m_i n_i\), where the last equality holds for non-relativistic fluids. Hence, the continuity equation for the \(\psi^+\) fluid is

\[ \dot{\rho}_{\psi^+} = -\Gamma \rho_{\psi^+}, \]

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

\[ \dot{\rho}_{\psi^+} + 3H(1 + \omega_{\psi}) \rho_{\psi^+} = 0, \]

where \(\omega_{\psi} = -1 + \Gamma/3H\). The second term gives rise to a kinetic contribution for the dark energy.

The other fluids (\(\Phi^0\), \(\psi\), and \(\nu\)) have similar continuity equations, with the equations of state \(w_{\Phi^0} = -1\), \(w_{\psi} = 0\) 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

\[ \dot{\rho}_{\Phi^0} = \mu_{\Phi^0} \dot{\rho}_{\psi^+}, \]

\[ \dot{\rho}_{\psi} + 3H(1 + \omega_{\psi}) \rho_{\psi} = (1 - \omega_{\psi}) \Gamma \rho_{\psi^+}, \]

\[ \dot{\rho}_{\nu} + 3H(1 + \omega_{\nu}) \rho_{\nu} = (1 - \omega_{\nu}) \dot{\rho}_{\psi^+}, \]

where \(\omega_{\psi}\) and \(\omega_{\nu}\) are the mass ratios \(m_{\Phi^0}/m_{\psi}, m_{\nu}/m_{\psi}\), respectively. The right-hand side of the continuity equations above are a leading-order approximation since we are considering non-relativistic fluids for \(\psi^+, \Phi^0\) and \(\psi\).

### 3.2 Cosmological perturbations

Once the equation of state parameters \(\omega_i\) are constant for all fluids, their sound speeds are \(c_{ij}^2 = \Theta \partial_i / \partial \rho_j = \omega_i\), where \(\Theta\) is the pressure of the fluid \(i\). The sound speed for a scalar field is, in turn, \(c_{\phi \phi}^2 = 1\) [92]. Following the definitions of [93], in the synchronous gauge the energy conservation leads to the following equations for the dark fluids

\[ \delta_{\Phi^+} + 6H \delta_{\Phi^+} = -\Gamma \delta_{\Phi^+}, \]

\[ \delta_{\Phi^0} + 6H \delta_{\Phi^0} = \mu_{\Phi^0} \Gamma \delta_{\Phi^+}, \]

\[ \delta_{\nu} + \theta_{\nu} + \frac{h}{2} = \mu_{\nu} \Gamma \delta_{\psi^+}, \]

\[ \delta_{\psi} + (1 + w_{\nu}) \left( \theta_{\psi} + \frac{h}{2} \right) = (1 - \mu_{\psi} - \mu_{\nu}) \Gamma \delta_{\psi^+}, \]

where \(\delta_i \equiv \delta \rho_i / \rho_i\). The right-hand sides of the equations above follow from Eqs. (12–15). Eq. (16) has the solution \(\delta_{\Phi^+} \propto a^{-6} e^{-\Gamma t}\), in agreement with the fact that dark energy does not cluster on sub-horizon scales [94]. Since the \(\Phi^+\) fluid is diluted in the universe faster than radiation, the couplings in the right side of Eqs. (17–19) are negligible. As a result, \(\delta \rho_{\psi^0} \propto a^{-6}\) 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 Eq. (8) by \(\rho_{\psi^+}/E_{\psi^+} = \rho_{\psi^+}/m_{\psi^+}\) before integrating it. The field velocity is defined as \(v_i \equiv \frac{1}{3} \int d^3 p \frac{p_i}{E} e^{-E/T}\), thus the Navier-Stokes equation in momentum space for \(\psi^+\) is

\[ k^2 \delta \phi^+ + \theta \phi^+ \Gamma, \]

where \(\theta \equiv \frac{k}{3} v_i\). The field velocity for \(\psi^+\) is also negligible because the left-hand side of Eq. (20) goes to zero. Thus the momentum transfer is irrelevant and the Navier-Stokes equation for dark matter is the usual one from the $\Lambda$CDM 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 \(\Phi^+\) and \(\Phi^0\) have \(\omega_i = -1\) 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 equations (14) and (15) can be combined into

\[ \dot{\rho}_{\dm} + 3H \rho_{\dm} = (1 - \omega_{\phi^0}) \Gamma \rho_{\phi^+}, \]

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

\[ \frac{d \rho_{\phi^0}}{da} = -\frac{\Gamma}{aH} \rho_{\phi^0}, \]

\[ \frac{d \rho_{\phi^+}}{da} = \frac{\mu_{\phi^+} \Gamma}{aH} \rho_{\phi^+}, \]

\[ \frac{d \rho_{\dm}}{da} = -\frac{3}{a} \rho_{\dm} + (1 - \omega_{\phi^0}) \frac{\Gamma}{aH} \rho_{\phi^+}, \]

backwards in time with the current values 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 \(\Gamma\) and the density of \(\Phi^+\) is evident from these equations. The two parameters always appear multiplied. Writing them in terms of a new “density” \(\rho_T \equiv \Gamma \rho_{\phi^+}\) gives

\[ \frac{d \rho_T}{da} = -\frac{\Gamma}{aH} \rho_T, \]

\[ \frac{d \rho_{\phi^0}}{da} = \frac{\mu_{\phi^0}}{aH} \rho_T, \]

\[ \frac{d \rho_{\dm}}{da} = -\frac{3}{a} \rho_{\dm} + \frac{1 - \omega_{\phi^0}}{aH} \rho_T, \]
in this paper we investigated the interactions among 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 $\phi^+$ and $\phi^0$, 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 ($\phi^+$).

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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
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