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Some studies on dark energy related problems

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Abstract. In this work we perform some studies related to dark energy. Firstly, we propose a dynamical approach to explain the dark energy contents of the universe. We assume that a massless scalar field couples to the Hubble parameter with some Planck-mass suppressed interactions. This scalar field develops a Hubble parameter-dependent (thus time-dependent) vacuum expectation value, which renders a time-independent relative density for the dark energy and thus can explain the coincidence of the dark energy density of the universe. Furthermore, we assume that the dark matter particle is metastable and decays very late into the dark energy scalar field. Such a conversion of matter to dark energy can give an explanation for the starting time of the accelerating expansion of the universe. Secondly, we introduce multiple Affleck–Dine fields to the landscape scenario of dark energy in order to have the required baryon-asymmetrical universe.

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1 Introduction

The nature of the contents of the universe is a great mystery in today's physical science. The Wilkinson Microwave Anisotropy Probe (WMAP) collaboration gives fairly accurate values on the contents of the universe [1]:

$$\begin{aligned}&\Omega_m = 0.27^{+0.04}_{-0.04}, \quad \Omega_b = 0.044^{+0.004}_{-0.004},\\ &\Omega_\Lambda = 0.73^{+0.04}_{-0.04}, \qquad \eta = (6.14 \pm 0.25) \times 10^{-10}, \qquad (1)\end{aligned}$$

where Ω_m, Ω_b and Ω_Λ denotes the density of total matter, baryonic matter and dark energy, respectively. η denotes the baryon to photon ratio. We see that, coincidentally, the dark matter density is comparable to the dark energy density as well as to the baryonic matter density. Such a coincidence needs to be understood.

For the explanation of such a coincidence, some phenomenologically dynamical approaches have been proposed, such as the quintessence [2, 3], phantom [4] and k-essence [5] ones. In this note we propose a new dynamical approach to explain the dark energy coincidence in the contents of the universe. In this approach a massless scalar field is assumed to couple to the Hubble parameter with some Planck-mass suppressed interactions. This scalar field develops a Hubble parameter-dependent (thus time-dependent) vacuum expectation value, which renders a time-independent dark energy density and thus can explain the coincidence of the dark energy density of the universe. We further assume that the dark matter particle is metastable and decays very late into the dark energy scalar field. Such a conversion of matter to dark energy can give an explanation for another puzzle, namely the starting time of the accelerating expansion of the universe.

Another puzzle related to the dark energy is the smallness of dark energy (or cosmological constant). Weinberg used the anthropic principle [6] to argue that fine-tuning is needed by the existence of human beings. Such an approach is based on the hypothesis of multiple vacua, each of which has identical physical properties but different values of vacuum energy. Motivated by such an approach, landscape from string theory is used to provide the vast amount of vacua. In such a landscape scenario, the vast amount ($\sim 10^{120}$) of vacua of the potential arises from a large number of fields (say $100 \sim 300$), which ensures the statistical selection to give a plausible vacuum energy. However, the baryon contents may be over-washed out by sphaleron effects even at temperature moderately beneath $\Lambda_{\rm QCD}$ and give a small baryon to photon ratio to be consistent with baryon-symmetrical universe [7]. In order to give the required baryon-asymmetrical universe, we propose to use multiple Affleck–Dine fields. We find that with multiple Affleck–Dine fields the baryon contents can be much higher, which has a large range to ensure the present asymmetric baryon abundance.

This article is organized as follows. In Sect. 2 we elucidate the new dynamical approach to dark energy. Then we discuss the conversion of dark matter to dark energy, which causes the accelerating expansion of the universe. In Sect. 3 we introduce multiple Affleck–Dine fields to the landscape scenario in order to give the required baryon-asymmetrical universe. The conclusion is given in Sect. 4.

2 Dynamical approach to dark energy

The smallness of the dark energy (cosmological constant) may imply the existence of some new fundamental law of nature. It is possible for dark energy to have dynamical behaviors. We know that dark energy can be related to the Hubble constant H_0 and the Planck scale $M_{\rm Pl}$ by a see-saw mechanism[1]

$$\frac{\Lambda}{H_0} \sim \frac{M_{\rm Pl}}{\Lambda}, \tag{2}$$

where Λ is related to the dark energy density by $\rho_{\rm DE} \sim \Lambda^4$. We can attribute the varying of the dark energy to a massless scalar field ϕ. Such a massless scalar can be the Nambu–Goldstone boson from the breaking of the global $U(1)$ R-symmetry [8] by gravity effects. We can phenomenologically adopt a potential of the form [9]

$$V(\phi) = H^2\phi^2 f\left(\frac{\phi^2}{M_{\rm Pl}^2}\right). \tag{3}$$

It is quite possible for the second derivative of the potential to be negative. As an effective theory, the flatness of the potential for the massless scalar can be lifted by a higher order gravitational force. We introduce the Planck scale-suppressed terms which preserve $-\phi \leftrightarrow \phi$ symmetry,

$$V(\phi) \approx -H^2\phi^2 + \frac{\lambda}{M_{\rm Pl}^2}\phi^6, \tag{4}$$

where λ is a dimensionless constant or variable of $\mathcal{O}(1)$, characterizing the coupling of ϕ.

The vacuum expectation value of ϕ is then given by

$$\langle\phi\rangle^4 \sim \frac{1}{3\lambda}H^2(t)M_{\rm Pl}^2. \tag{5}$$

Here we can see two features for our approach.
(1) The dark energy density $\rho_{\rm DE} \sim \langle\phi\rangle^4$ is time-dependent, which makes the relevant density $\Omega_\Lambda = \rho_{\rm DE}/(\rho_m + \rho_{\rm DE})$ almost time independent.
(2) When $t = t_0$ (present time), $\rho_{\rm DE} \sim \langle\phi\rangle^4$ can naturally take the required value $\sim H_0^2 M_{\rm Pl}^2$.

So, in this way, the dark energy coincidence in the contents of the universe can be understood.

[1] Our universe can be described by the Robertson–Walker metric

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\varphi^2\right).$$

Here $a(t)$ is the scale factor, k can be chosen to be $+1$, -1, or 0 for spaces of constant positive, negative or zero curvature, respectively. The see-saw relation can also be seen in the Friedmann equation

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_{\rm DE}).$$

The gravitational constant is related to the Planck scale by $G = \hbar c^5/M_{\rm Pl}^2$. H is the Hubble parameter defined by $H(t) = \dot{a}(t)/a(t)$, where $t = t_0$ gives the Hubble constant.

We also note that the coincidence of dark matter density and baryonic matter density can be understood in the Affleck–Dine mechanism for baryogenesis. In this mechanism, the baryonic number can be generated dynamically. The oscillation of the field is generically unstable with spatial perturbations and can condense into non-topological solitons called Q-balls [10–13]. The late decays of these Q-balls into dark matter relate baryonic matter density to dark matter density [14, 15].

For the dynamical scalar field ϕ introduced in the preceding section, we can also introduce some subdominate terms for its interaction with the dark matter particle, which is assumed to be a scalar $\tilde{f}$ (say the super-partner of a sterile neutrino),

$$\frac{1}{M_{\rm Pl}^3}\phi^6\tilde{f}. \tag{6}$$

It will not cause any phenomenological problems in particle physics since it is much suppressed. Through this interaction the scalar $\tilde{f}$ decays into ϕ and its lifetime τ can be estimated to be

$$\tau^{-1} \sim \left(\frac{m_{\tilde{f}}}{M_{\rm Pl}}\right)^6 m_{\tilde{f}}. \tag{7}$$

Suppose $m_{\tilde{f}}$ is large, $\sim 10^9$ GeV, and such a decay occurs at the time scale

$$\tau \sim 10^{18}\,\mathrm{s}, \tag{8}$$

which is of the order of the age of the universe. Thus such metastable particles can be a component of the relic dark matter (for some extensive studies on the cosmology of metastable sfermions, see [16]).

Through such decays, dark matter particles are being converted to dark energy field particles, which can explain the starting time ($z \sim 1$) of the accelerating expansion of the universe, as explained in the following.

From the Friedmann equation

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3P\ ), \tag{9}$$

we know that the accelerating expansion of the universe starts when $\rho+3P$ becomes negative. Here $\rho = \rho_m + \rho_{\rm DE}$ is the total energy density and P is the presure. The equation of state is given by

$$\omega = \frac{P}{\rho} = \frac{T-V}{T+V}, \tag{10}$$

where T and V are the kinematic and potential energy, respectively. ω is vanishing for matter. Generally, the equation of state for dark energy is similar to that of the quintessence model and $\omega > -1$. The decay of the dark matter can alter the equation of state for dark energy by kinematic terms.

Then we get

$$\begin{aligned}\rho + 3P &= \rho_m + \rho_{\rm DE} + 3(P_m + P_{\rm DE}) \\ &= \rho_m + (1+3\omega)\rho_{\rm DE}.\end{aligned} \tag{11}$$

As the decay of $\tilde{f}$ into ϕ proceeds, ρ_m is getting smaller and $\rho_{\rm DE}$ is getting larger, and at some point $\rho_m + (1+3\omega)\rho_{\rm DE}$ becomes negative since $1+3\omega$ is negative. Such a point is called the critical point; at this point $\rho_m + \rho_{\rm DE} = \Omega\rho_{\rm critical}$ ($\Omega \equiv \rho/\rho_{\rm critical}$) and[2]

$$\frac{\rho_{\rm DE}}{\Omega\rho_{\rm critical}} = \frac{1}{-3\omega}. \tag{12}$$

Since in our scenario such a critical point occurs as a result of the decay of the metastable dark matter particle and the decay occurs at a time scale of 10^{18} s, we get an understanding of why the universe starts the accelerating expansion quite late ($z \sim 1$).

Note that in our scenario the dynamical field ϕ may couple to the graviton. The radiation of gravitons can slowly decrease the kinematic energy. So the transition of dark matter to dark energy causes a slow loss of universe contents. In this way our scenario predicts that the universe is evolving toward an anti-de Sitter universe. If the universe is flat till now ($\Omega = 1$), it will evolve to be open ($\Omega < 1$).

3 Multiple Affleck–Dine fields in landscape

In the Affleck–Dine mechanism, a complex scalar field has $U(1)$ symmetry, which correponds to a conserved current and is regarded as baryon number. It has potential interactions that violate CP. It can develop a large vacuum expectation value and when oscillation begins, it can give a net baryon number. Supersymmetry provides the natural candidates for such scalar fields. The vast number of flat directions [17] that carry baryon or lepton number can have vanishing quartic terms. Non-renormalizable higher-dimensional terms can lift the flat directions which then can give a large vacuum expectation value. Here we propose to use multiple flat directions (each of which denoted by Φ_i) to generate the net baryon number in our universe.

We consider a superpotential, which can lift such flat directions from supersymmetry breaking terms, to have the following leading form:

$$W_n^i = \frac{1}{M^n}{\Phi_i}^{n+3}, \tag{13}$$

where M is the scale of new physics and n is some integer. So the corresponding potential takes the form

$$V = -H^2|\Phi_i|^2 + \frac{1}{M^{2n}}|\Phi_i|^{2n+4}. \tag{14}$$

The leading sources of B and CP violations come from supersymmetry breaking terms (by gravity)

$$am_{3/2}W_n^i + bHW_n^i, \tag{15}$$

where a and b are complex dimensionless constants and $m_{3/2}$ is the gravitino mass. The relative phase in these two terms, $\delta = \tan^{-1}(ab^*/|ab|)$, violates CP. We can choose n and a, b to ensure each potential to have several metastable vacuum expectation values with very different magnitudes as illustrated in Fig. 1 (acceptable selection in natural consideration may require that the magnitudes be different by $10^3 \sim 10^4$). The two vacuum expectation values of Φ_i are given by

$$\Phi_{i,0} \approx M\left(\frac{H}{M}\right)^{1/(n+1)} \tag{16}$$

and

$$\Phi_{i,0} \approx M\left(\frac{2[\mathrm{Re}(a)m_{3/2} + \mathrm{Re}(b)H]}{M}\right)^{1/(n+1)}. \tag{17}$$

So we can get more than 10^{120} vacua for $100 \sim 300$ Affleck–Dine fields.

The evolution of the baryon number is

$$\frac{\mathrm{d}n_B^i}{\mathrm{d}t} = \frac{\sin(\delta)m_{3/2}}{M^n}\Phi_i^{n+3}. \tag{18}$$

Naive estimation gives (we assume $H \sim 1/t$)

$$n_B = \sum_i \frac{\sin(\delta)}{M^n}\Phi_{i,0}^{n+3}. \tag{19}$$

As each of the two metastable vacua differs significantly, the combination of multiple fields can give a large range for the baryonic contents. The rate of washing out baryon asymmetry is given by [7]

$$\frac{\mathrm{d}n_B}{\mathrm{d}t} = -\Gamma. \tag{20}$$

Here Γ is given by

$$\Gamma = {\alpha_W}^4 T\left(\frac{M_W(T)}{\alpha_W T}\right)^7 \mathrm{e}^{-\frac{M_W(T)}{\alpha_W T}}, \tag{21}$$

where at zero temperature M_W is given by

$$M_W \sim g_W f \sim g_W\frac{\Lambda_{\rm QCD}}{4\pi}. \tag{22}$$

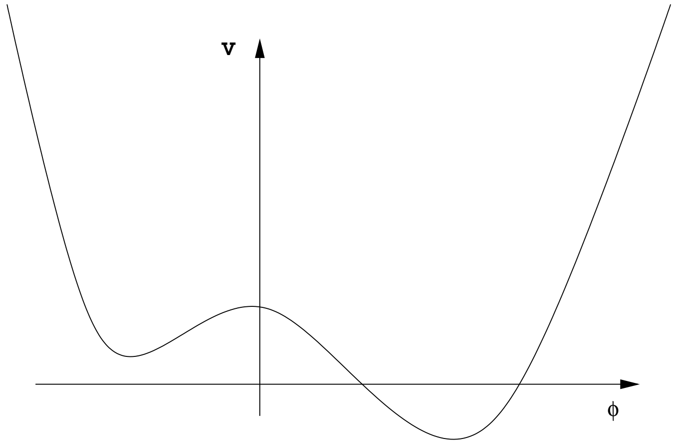

Fig. 1. The illustrative plot of different vacuum expectation values in the flat direction potential which can generate different baryonic contents

[2] At the critical point, if we naively use $\omega = -1$, we find that the dark energy constitutes about 1/3 of the total contents of the universe. However, such a portion can be increased when ω is larger than -1, which is highly justified.

The residue abundance in our multiple fields case can be several orders higher[3] than the ordinary approach, which can greatly enhance the residue value for baryon contents and thus make it possible to be consistent with a baryon-asymmetrical universe.

4 Conclusion

We performed some studies related to dark energy. Firstly, we proposed a dynamical approach to explain the dark energy contents of the universe. We assumed that a massless scalar field couples to the Hubble parameter with some Planck-mass suppressed interactions. Such a scalar field develops a Hubble parameter-dependent (thus time-dependent) vacuum expectation value, which renders a time-independent relative density for dark energy and thus can explain the coincidence of the dark energy density of the universe. Furthermore, we assumed that the dark matter particle is metastable and decays very late into the dark energy scalar field. Such a conversion of matter to dark energy can give an explanation for the starting time of the accelerating expansion of the universe. Finally, we introduced multiple Affleck–Dine fields to the landscape scenario of dark energy in order to have the required baryon-asymmetrical universe.

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[3] $n_{\rm total} \sim n_{\rm field} \times n_{\rm differ}$ can be as high as $10^3 \sim 10^{3(n+3)}$. Here $n_{\rm field}$ is the number of Affleck–Dine fields and $n_{\rm differ}$ is the order of difference between the metastable vacuum values.