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Oscillating scalar-field dark matter in supergravity

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Abstract: We show that an oscillating scalar field in supergravity of mass of the order of $\sim$ TeV with a non-zero vacuum expectation value ($\sim 10^{10}$ GeV) can be a candidate of cold dark matter (CDM). To avoid the gravitino problem, we need a low reheating temperature after the primordial inflation. Then, the energy density of the oscillating scalar field satisfies all the requirements for CDM at present in the universe.

Keywords: Cosmology of Theories beyond the SM, Dark Matter.

Contents

1. Introduction

It is widely believed that a significant fraction of energy density in the universe is in the form of cold dark matter (CDM). Recently it was reported that the contribution of CDM to density parameter is approximately $\Omega \simeq 0.3$ (for a review, see ref. [1]). It is one of the most important problems in cosmology and particle physics to clarify the nature and the origin of dark matter.

In this paper, we consider stable scalar fields with an electroweak scale mass $\sim \mathcal{O}\,(\mathrm{TeV})$ and a large vacuum expectation value (VEV) $\sim \mathcal{O}(10^{10})\,\mathrm{GeV}$. These scalar fields naturally appear in supergravity. It is interesting that such a scalar field can have a net oscillation energy after inflation because of the coupling with the inflaton field through Kähler potential and an additional SUSY breaking effect during the inflation [2, 3]. On the other hand, however, whenever we consider a model based on supergravity within the framework of inflationary cosmology, we are faced with some sticky problems. In particular, "gravitino problem" would be one of the severest problems in cosmology [4, 5]. To avoid the gravitino problem, i.e. to restrain the production of gravitinos and the photodissociation of light elements due to their late-time decays, we need a low reheating temperature after the primordial inflation [6]. In this situation, we show that the energy density of the oscillation of the scalar field satisfies the requirements for CDM at present in the universe.

2. Model

In supergravity, we know there exist a lot of scalar fields with an almost flat potential. These scalar fields are expected to acquire masses of the order of the electroweak scale from a supersymmetry breaking effect and might have a non-zero VEV.

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We consider a chiral superfield Φ which is the gauge singlet and contains a scalar field ϕ. We assume that it has a minimal Kähler potential $K = |\Phi|^2 M_G^{-2}$ and a superpotential,

$$W = \frac{\lambda}{n+3}\frac{\Phi^{n+3}}{M_G^n} + C\,, \tag{2.1}$$

where $M_G = M_{Pl}/\sqrt{8\pi} \simeq 2.4\times 10^{18}\,\mathrm{GeV}$ is the reduced Planck mass, $\lambda \sim \mathcal{O}(1)$, and C is a constant. The superpotential and the Kähler potential give a scalar potential,

$$V(\phi) = -3\frac{C^2}{M_G^2} - 2\frac{C^2}{M_G^4}|\phi|^2 + \frac{n}{n+3}\frac{\lambda C}{M_G^2}\frac{\phi^{n+3}+\phi^{*n+3}}{M_G^n} + \lambda^2\frac{|\phi|^{2n+4}}{M_{Pl}^{2n}}\,, \tag{2.2}$$

at low energy limit($\phi \ll M_G$). In addition, the scalar field acquires a soft mass ($\sim 1\,\mathrm{TeV}$) through a SUSY breaking effect. When we assume that the cosmological constant vanishes at the VEV, it is natural to take $C \simeq m_{3/2}M_G^2$, where $m_{3/2}$ is the gravitino mass ($\sim 1\,\mathrm{TeV}$). Then, we obtain the following low energy effective potential,

$$V(\phi) = V_0 - m_0^2|\phi|^2 + \frac{n}{n+3}\frac{\lambda C}{M_G^2}\frac{\phi^{n+3}+\phi^{*n+3}}{M_G^n} + \lambda^2\frac{|\phi|^{2n+4}}{M_G^{2n}}\,, \tag{2.3}$$

where the second term means the negative mass term ($m_0^2 \sim C^2/M_G^4 \sim 1\,\mathrm{TeV}^2$) which comes from the negative mass squared in eq. (2.2) and the soft mass. Notice that this potential does not have a term $\kappa\phi^4$ with $\kappa \sim \mathcal{O}(1)$. One finds that the VEV of the scalar field $M \equiv \langle\phi\rangle$ is given by

$$\frac{M^{n+1}}{M_G^n} = \frac{1}{2(n+2)\lambda}\left[\frac{nC}{M_G^2} + \sqrt{\left(\frac{nC}{M_G^2}\right)^2 + 4(n+2)m_0^2}\right]\,, \tag{2.4}$$

and the vacuum energy at $\phi = 0$ becomes

$$V_0 = \frac{n+1}{n+2}M^2\left[m_0^2 + \frac{nC}{2(n+2)(n+3)M_G^2}\times \right.$$
$$\left.\times\left(\frac{nC}{M_G^2} + \sqrt{\left(\frac{nC}{M_G^2}\right)^2 + 4(n+2)m_0^2}\right)\right]\,. \tag{2.5}$$

From eq. (2.4), we see that $M \sim \sqrt{m_0 M_G} \sim \mathcal{O}(10^{10})\,\mathrm{GeV}$ in the case of $n = 1$.

After the primordial inflation, the inflaton field oscillates around its minimum and dominates the energy density in the universe until the reheating time $t \sim \Gamma_I^{-1}$, where Γ_I is the decay rate of the inflaton field. While the Hubble expansion rate is large $H \gg m_0$, the scalar field ϕ would be trapped dynamically at the origin by an additional SUSY breaking effect which is explained in the following reason [2, 3].

In supergravity, the scalar potential of the inflaton field I and the scalar field ϕ is expressed by

$$V(\phi, I) = e^{G(\phi,I)}\left[G_i(G^i_j)^{-1}G^j - 3\right], \tag{2.6}$$

where $G = K + \ln|W|^2$ and $G_i = \partial G/\partial\phi^i, G^j = \partial G/\partial\phi^*_j$ and $G^j_i = \partial^2 G/\partial\phi^i\partial\phi^*_j$. During the oscillation of the inflaton field, the scaler potential is related to the Hubble expansion rate as $V(\phi, I) \simeq \rho_I \simeq 3M_G^2H^2$ through the Friedmann equation, because the energy density in the universe is dominated by the inflaton field. Then, the scalar potential is modified as

$$V(\phi) \simeq V_0 + 3H^2|\phi|^2, \tag{2.7}$$

and ϕ would be trapped at $\phi = 0$.

On the other hand, when the Hubble expansion rate becomes smaller than the mass of the scalar field, i.e. $H \lesssim m_0$, the additional SUSY breaking effect disappears and the scalar field begins to roll down to its VEV while the oscillating inflaton field still dominates in the energy density in the universe because of the low reheating temperature in order to avoid the gravitino problem.

The scalar potential is expanded around the VEV as

$$V(x) \sim V''(M)x^2 + \lambda_3 x^3 + \lambda_4 x^4 + \cdots, \tag{2.8}$$

where x expresses the deviation from the VEV, i.e. $x = \phi - M$. The mass squared in the VEV, $V''(M)$, is of the order of $\sim \mathcal{O}(\mathrm{TeV}^2)$ while λ_3 and λ_4, are of the order of $V''(M)/M$ and $V''(M)/M^2$, respectively. Note that the initial amplitude of the oscillation is approximately $\mathcal{O}(M)$. Then, we see that the oscillation induced by the mass term, i.e. the first term in eq. (2.8), dominates the oscillating energy because $x \lesssim M$. Therefore, we find that both the energy density of ϕ and the inflaton field I decrease as $\propto a(t)^{-3}$ where $a(t)$ is the scale factor. Namely the ratio of the energy density of the inflaton field to that of the scalar field does not change until the reheating time. This means that the vacuum energy of the scalar field V_0 is transfered to the oscillation energy of ϕ.

Hereafter we mainly consider the case of n = 1. The energy density of the scalar field at the reheating time ($t = t_R$) is estimated as

$$\rho_\phi(t_R) = \left.\frac{\rho_\phi}{\rho_I}\right|_{H=m_0} \rho_I(t_R), \tag{2.9}$$

with the energy density of the inflaton field,

$$\rho_I(t_R) = \frac{\pi^2 g_* T_R^4}{30}, \tag{2.10}$$

where T_R is reheating temperature and g_* is the degree of freedom in the thermal bath. When the reheating process finished, the ratio of the energy density of ϕ to the entropy density s is estimated as

$$\begin{aligned}\frac{\rho_\phi}{s} &= \frac{V_0 T_R}{4M_G^2 m_0^2} \\ &\simeq 0.5\times 10^{-9}\,\mathrm{GeV}\left(\frac{T_R}{10^7\,\mathrm{GeV}}\right)\left(\frac{M}{10^{10}\,\mathrm{GeV}}\right)^2 ,\end{aligned} \tag{2.11}$$

where $s = 2\pi^2 g_* T_R^3/45$. Both ρ_ϕ and s decrease as $a(t)^{-3}$, so that the ratio ρ_ϕ/s is constant unless the additional entropy is produced after the reheating. If we adopt inflation models with a low reheating temperature, e.g. $T_R \lesssim 10^7\,\mathrm{GeV}$, in order to avoid the gravitino problem [6], the energy density of the dark matter cannot be larger than the critical density and does not overclose the universe.

The present value of the energy density of dark matter to entropy density ratio is given by

$$\begin{aligned}\frac{\rho_{\mathrm{DM}}}{s_0} &= \frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{cr}}}{s_0} \\ &\simeq 3.6\times 10^{-9}\Omega_{\mathrm{DM}} h^2\,\mathrm{GeV}\,,\end{aligned} \tag{2.12}$$

where ρ_{cr} is the present critical density of the universe, s_0 is the present entropy density, Ω_{DM} is the density parameter of dark matter (~ 0.3) [1], and h is the present Hubble parameter normalized as $H_0 = 100h\,\mathrm{km/sec\,Mpc}^{-1}$. From eq. (2.12) we see that the energy density of the oscillating scalar field almost coincides with the energy density of dark matter. Namely the contribution of ρ_ϕ to density parameter Ω is estimated as

$$\begin{aligned}\Omega_\phi &= \frac{\rho_\phi}{\rho_{\mathrm{cr}}} \\ &\simeq 0.28\times\left(\frac{T_R}{10^7\,\mathrm{GeV}}\right)\left(\frac{M}{10^{10}\,\mathrm{GeV}}\right)^2\left(\frac{0.7}{h}\right)^2 .\end{aligned} \tag{2.13}$$

From eq. (2.13) we see that $\Omega_\phi \simeq 0.3$ (0.03) for $T_R \simeq 10^7$ $(10^6)\,\mathrm{GeV}$. On the other hand, for the case of $n = 2$, the VEV of the scalar field is of the order of 10^{13} GeV. Then, we obtain $\Omega_\phi \simeq 0.3$ (0.03) for $T_R \simeq 10$ (1) GeV.

3. Conclusion

In this paper, within the framework of inflationary cosmology we have shown that the stable scalar field with the electroweak scale mass and the large VEV is now oscillating, and the energy density of the oscillation significantly contributes to the density parameter Ω and satisfies the requirements for CDM at present in the universe. It is interesting that such a scalar field naturally appears in supergravity. In addition, it is also fascinating that when we require the low reheating temperature after the primordial inflation to avoid the gravitino problem ($T_R \lesssim 10^7$ GeV), it automatically

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ensures the appropriate energy density for CDM ($\Omega_\phi \simeq 0.3$). The potential we considered has degenerate minima and may cause a domain wall problem. However the difficulty can be solved by a few modification, as was shown in ref. [7].

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