Preheating and Dark Sector of Universe

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Abstract

Regarding long life particles produced during preheating after inflation as dark matter, we find that its back reaction on the field $\varphi$ could lock $\varphi$ in a false vacuum up to today. This false vacuum can drive the accelerated expansion of universe at late time and play the role of dark energy. When the number density of dark matter particles is dilute to some value, the field $\varphi$ becomes tachyonic and rolls to its true minima rapidly, and the acceleration of universe ceases. We discuss the constraints on the parameters of model from the observations of dark energy and dark matter halos on subgalactic scale.

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Recent data from observations have given a possible picture where we live in a spatially flat universe consisting of predominantly unknown dark sector. In particular, at present about 1/3 of the energy density of universe behaves as pressureless matter, which is not luminous and has litter interactions with the usual baryon matter, dubbed dark matter. The remaining about 2/3 is named dark energy, which drives the current accelerated expansion of universe. Recently, relevant issues of dark matter and dark energy have received increased attentions, see [1, 2, 3, 4, 5] for reviews.

The simplest form of dark energy is a small positive cosmological constant, which can fit data nicely and might be phenomenologically the most appealing choice. But in this case, its value of cosmological constant has to be fine tuned extremely to an incredible level, in the meantime the coincidence problem is also required to explain. Furthermore, a constant positive vacuum energy will lead inevitably to eternal acceleration of universe and the existence of future causal horizon, which may be most undesirable in string theory, because it inhibits the construction of S-matrix. The alternative is Quintessence [6, 7], which is a rolling light scalar field with a normal dynamical term and not interacts with other matters. It could terminate accelerated expansion by reaching the minimum of its potential or by gravitational back reaction [8]. It is generally assumed that due to some as yet not understanding mechanism the fundamental vacuum energy of universe is 0. The dark energy observed is dominated by some fields that have not yet relaxed to their vacuum state. The scalar field involving Quintessence is required to have a very shallow potential, which can be make its evolution overdamped by the expansion of universe until recently. But it suffers from certain problems [9, 10]. For generical potentials the field is nearly massless $m_Q \sim h_0 \sim 10^{-33}$eV, where $h_0$ is present Hubble parameter. Such a small mass may be inconsistent with radiation corrections.

In this note, we attempts to provides a single theoretical framework for dark sector of universe. The other ones with this aim can be found in Ref. [12, 13, 14]. Regarding long life particles produced during preheating after inflation as dark matter, we find that its back reaction on the field $\varphi$ can lock $\varphi$ in a false vacuum up to today. This false vacuum can play the role of dark energy at late time. When the number density of dark matter particles is dilute to some value, the field $\varphi$ rolls to its true minima and dark energy disappears. This model avoids some problems mentioned above. Further, dark matter particles produced during the nonthermal production [11] could be relativistic, and their
comoving free streaming scales could be as large as of the order 0.1 Mpc, which lead to a severe suppression of the density fluctuations on scales less than the free streaming scale. Thus under certain conditions the discrepancies between the observations of dark matter halos on the subgalactic scales and the predictions of the standard cold dark matter scenario could also be resolved in this model.

The reheating theory is one of the most important parts of inflation cosmology, which has been developed extensively several years ago [15]. During preheating after inflation, parameteric resonance [15] or instant preheating [16] will lead to the production of many particles. The universe is reheated after these particles decay. But if particles have a long enough life, the back reaction produced by them can significantly affect the motion of oscillating inflaton, for example, which may reduced to a temporary symmetry restoration for a double well potential [17, 18]. Trapping moduli at enhanced symmetry points by quantum production of light particles has been studied in Ref. [19]. Trapping of a scalar field which has a potential can lead to a short period of accelerated expansion in situations with steeper potentials than would otherwise allow this has been shown. We assume, for our purpose, that other particles except $\chi$ particles produced during preheating decays into radiation and reheats the universe, thus their backreactions can not affect the shape of $\phi$ potential. But $\chi$ particles still surviving until today will lead to a correction to the effective potential of $\phi$ and make $\phi = 0$ become a local false vacuum when its backreaction effect is enough large. We expect that the energy density of this false vacuum could be responsible for the observed accelerated expansion while the $\chi$ particles produced could be regarded as dark matter, which locks the $\phi$ field in the false vacuum equal to the cosmological constant observed. Since the number density of $\chi$ particles decreases with the expansion of universe, at some time when its back reaction is no more large than the techyonic mass of $\phi$, the field $\phi$ will be released and roll down to its true minimum rapidly. Thus the system reaches true vacuum and accelerated expansion of universe ceases, see Fig.1 for an illustration.

To implement this model, we consider such an effective potential of field $\phi$ as follows

$$V(\phi) = \begin{cases} 
\alpha \phi^4 & \text{for } \phi \gg \phi_* \\
\beta (\phi^2 - \phi_*^2)^2 & \text{for } \phi \sim \phi_*
\end{cases} \quad (1)$$

where the scalar field $\phi$ has a chaotic inflation potential for large $\phi$, which is regarded as an asymptotic one here, where inflation occurs, and has a double well potential for small $\phi$, whose global minima are at $\phi = \phi_*$, and the $\phi = 0$ is an unstable saddle point, whose
FIG. 1: Illustration of model. Initially $\varphi > m_p$, inflation occurs, and after inflation, the field will roll down along its potential, see solid line. When the $\varphi$ field reaches a small region about $\varphi = 0$, the adiabaticity condition will be violated and the productions of $\chi$ particles leads to a correction to the potential of $\varphi$, see dashed line, which makes $\varphi$ local in $\varphi = 0$. The energy density of false vacuum of $\varphi$ field and $\chi$ particles produced are regarded as dark energy and dark matter respectively in this model.

tachyonic mass $\sim -\beta \varphi^2_*$. Suppose that an universe is initially in inflation regime, where $\varphi \gtrsim m_p$, after inflation ends, the field $\varphi$ will roll down and oscillate around $\varphi = 0$, then finally cease in some minimum of its potential.

But when considering the interactions of $\varphi$ with other scalar fields, the case will be different. When the $\varphi$ field reaches a small region about $\varphi = 0$, the adiabaticity condition will be violated and the productions of $\chi$ particles and other particles with fields coupling to inflaton field $\varphi$ will occur. We consider an interaction between a massive $\chi$ field $\frac{1}{2}m^2\chi^2$ and inflaton as follows $\frac{1}{2}g^2\chi^2\varphi^2$. Thus the effective mass of $\chi$ field is $m_{\chi eff}^2 = m^2_\chi + g^2\varphi^2$, which decreases with the rolling down of $\varphi$ after the end of inflation. When the field $\varphi$ arrives at about $\varphi = 0$, where $m_{\chi eff} \gtrsim m_{\chi eff}^2$, relevant process becomes non adiabatic. For $v \ll g$, $|\varphi| \lesssim (v/g)^{1/2}$ is in a narrow region, where $v$ is the velocity of $\varphi$ about $\varphi = 0$. Thus the process of particle production occurs nearly instantaneously, $\Delta t_* \sim (gv)^{-1/2}$. In this case the uncertainty principle implies that the particles produced have typical momenta $k \sim (\Delta t_*)^{-1} \sim (gv)^{1/2}$ Thus following [15, 16], the occupation number $n_k$ of $\chi$ particles with
momenta $k$ suddenly acquires the value
\[ n_k = \exp \left( -\frac{\pi(k^2 + m_{\chi}^2)}{g v} \right) \] (2)

This value does not change until the field $\varphi$ rolls to the point $\varphi = 0$ again. We expect that instant preheating and decay of other particles may be very effective, which can make the universe reheat to some temperature rapidly. Though long life $\chi$ particles produced during initial oscillation is negligible for the evolution of background, its back reaction will provide a correction to the effective potential of $\varphi$, which makes $\varphi = 0$ become a temporal minimum. During radiation dominated the $\varphi$ field may gently lands in $\varphi = 0$ without many oscillations with large velocity. Thus in this case the parametric resonance may not occur and only a few initial oscillations may be important. We simply estimate the particle number density $n_\chi$ produced as
\[ n_\chi = \frac{1}{2\pi^2} \int dk k^2 n_k = \frac{(gv)^{3/2}}{8\pi^3} \exp \left( -\frac{\pi m_{\chi}^2}{gv} \right) \] (3)

For $m_{\chi}^2 \ll gv$, which is reasonable and can be seen from following calculations, we have
\[ n_\chi \simeq \frac{(gv)^{3/2}}{8\pi^3} \] (4)

The kinetic energy of $\varphi$ field after reheating locked at $\varphi = 0$ is larger than its potential energy and is relativistic. But since the $\chi$ particles has a bare mass, this can make it become non relativistic before its energy overpasses radiation. Considering the particle number density $n_\chi \sim a^{-3} \sim T^3$, where we have neglected tiny difference between coefficients during different periods, thus after the $\chi$ particles become non relativistic, its energy density can be written as
\[ \rho_\chi \sim n_\chi m_\chi \left( \frac{T}{T_r} \right)^3 \] (5)

where $T_r$ is the reheating temperature resulting from the decay of other particles produced during preheating. From (1) and (5), that at present the energy density of dark matter is approximately equal to dark energy’s requires
\[ n_\chi m_{\chi} \left( \frac{T_0}{T_r} \right)^3 \sim \beta \varphi_*^4 \sim \Lambda \] (6)

where $T_0$ is CMB temperature and $\Lambda$ is the cosmological constant observed at present. Furthermore, to make $\varphi$ stay in a false vacuum up to today requires
\[ g^2 \langle \chi^2 \rangle \gtrsim \beta \varphi_*^2 \] (7)
For non relativistic $\chi$ particles, $\langle \chi^2 \rangle$ can be reduced as

$$\langle \chi^2 \rangle \simeq \frac{1}{2\pi^2} \int \frac{n_k k^2 dk}{\sqrt{k^2 + m^2_\chi}} \simeq \frac{n_\chi}{m_\chi}$$

(8)

Thus substituting (8) into (7), one obtain

$$\frac{g n_\chi}{m_\chi} \left( \frac{T_0}{T_r} \right)^3 \gtrsim \beta \varphi^2$$

(9)

Combining (6) and (9),

$$m_\chi \lesssim g \varphi_*$$

(10)

is given. In this model, the energy density of false vacuum is regarded as dark energy observed, thus $\beta \varphi^4_* \sim \Lambda \sim 10^{-120} m^4_p$, where $m_p$ is the Planck scale, which implies $\varphi_* \sim \beta^{-\frac{1}{4}} 10^{-30} m_p$. Regarding the $\varphi$ field as a modulus, a natural value of $\beta$ could be

$$\beta \sim \left( \frac{m_s}{m_p} \right)^4$$

(11)

where $m_s$ may be the supersymmetry breaking scale. Thus one obtain $\varphi_* \sim 10^{-30} m^2_p/m_s$. Thus for $m_s \sim \text{Tev}$, $\varphi_*$ can be Tev order, i.e. $\varphi_* \sim m_s$. In this case, one can further obtain

$$\Lambda \sim \beta \varphi^4_* \sim \left( \frac{m_s}{m_p} \right)^4 m^4_s$$

(12)

which has been mentioned as a possible suggestions for value of observed cosmological constant [20], where supersymmetry is assumed as breaking at Tev scale by an order parameter chiral superfield which makes that electroweak symmetry breaking become a direct consequence of supersymmetry breaking. In their argument, the vacuum energy is given by $(m^2_s/m_p)^4$.

Combining (6) and (10),

$$n_\chi \gtrsim \frac{\beta \varphi^3_*}{g} \left( \frac{T_r}{T_0} \right)^3$$

(13)

is given. Instituting it into (4), one obtain

$$g \gtrsim (8\pi)^{\frac{6}{5}} \frac{\beta^{\frac{2}{5}} \varphi^\frac{6}{5}_(r)}{v^{\frac{6}{5}} \left( \frac{T_r}{T_0} \right)^{\frac{6}{5}}}$$

(14)

During initial oscillation after inflation the kinetic energy of $\varphi$ at the bottom of valley is far larger than its potential energy. Thus the velocity at $\varphi = 0$ is hardly affected by potential at small $\varphi$. For large $\varphi$, the potential is $\alpha \varphi^4$. The numerical calculation shows $v \sim 0.01 \sqrt{\alpha m^2_p}$
at $\varphi = 0$ for the first oscillation. The proper fluctuation amplitude responsible for large scale structure requires $\alpha \sim 10^{-13}$. Thus $v \sim 10^{-8}m_p^2$. Considering (11),

$$g \gtrsim 10^{-3}\left(\frac{m_s}{m_p}\right)^{14/5}\left(\frac{T_r}{T_0}\right)^{6/5}$$

(15)

For example, taking $T_0 \sim 10^{-13}$ Gev and $T_r \sim 10^{15}$ Gev, we have $g \gtrsim 10^{-4}$.

The standard cold dark matter scenario predicts too much power on small scale. Several possible resolutions have been proposed to this apparent discrepancy [11, 21]. It is known that below the free streaming scale, the power spectrum can be severely damped. The studies shows that to explain dark matter halos on the subgalactic scales, the free streaming scale should be $\sim 0.1$ Mpc [23]. The comoving free streaming scale $R_f$ for nonthermal particles can be calculated as [11, 22]

$$R_f = \int_{t_i}^{t_{eq}} \frac{u(t')}{a(t')} dt' \approx \int_0^{t_{eq}} \frac{u(t')}{a(t')} dt'$$

$$\approx 2rt_{eq}(1 + z_{eq})^2 \ln \left( \frac{1}{r^2(1 + z_{eq})^2 + \frac{1}{r(1 + z_{eq})}} \right)$$

(16)

where $r \equiv ak/m$ is defined, which is a constant during the evolution of universe, and the subscript eq denotes when the energy density of radiation equals to that of matter. For $R_f \sim 0.1$ Mpc, from (16), one obtain $r \sim 10^{-7}$, which gives rise to a further constraint on parameter of the model. Instituting

$$r \approx \frac{T_0}{T_r} \frac{(gv)^{1/2}}{m_\chi} \sim 10^{-7}$$

(17)

into (15), we have

$$T_r \lesssim \left(\frac{\sqrt{v}}{10^{-8} \varphi_*}\right)^{5/8}\left(\frac{m_p}{m_s}\right)^{7/8}T_0 \sim 10^{26}T_0 \sim 10^{13}$ Gev$$

(18)

Thus for $T_r \gg 10^{13}$ Gev, $r \ll 10^{-7}$, which means that the $\chi$ particle produced during preheating serves as a good candidate for cold dark matter. However, a lower reheating temperature will be more required to solve the subgalactic scale problem of cold dark matter. For example, taking $T_r \sim 10^7$ Gev and $g \sim 10^{-2}$, we obtain $r \sim 10^{-7}$.

The $\chi$ particles will still not decay until today requires that its decay rate satisfies the conditions $\Gamma_\chi < h_0 \sim \sqrt{\Lambda}/m_p$. The coupling $g_\chi$ of $\chi$ with its decay products generally lies in the range $m_\chi/m_p \lesssim g_\chi \lesssim 1$, where the lower bound is given by the gravitational decay
of $\chi$ particles. Thus for $\Gamma_\chi \sim g_\chi^2 m_\chi$, the bound $m_\chi \lesssim 10^{-20} m_p$ is obtained, which can be consistent with (10).

When the energy of false vacuum dominate dark matter’s at late time, the universe will expand more fast. Thus the number density of dark matter particles will be diluted more rapidly and its back reaction on the effective potential of $\varphi$ field will be weakened more fast than that during radiation or matter dominated periods. From (15), at some time in the future, when CMB temperature decreases to

$$T \sim 10^{-3} \left( \frac{m_s}{m_p} \right)^\frac{2}{3} \frac{T_r}{g_\star}$$

\[ (19) \]

$\varphi = 0$ will become an unstable saddle point. From (12), the tachyonic mass of $\varphi$ about $\varphi = 0$ is $m_\varphi \sim (m_s/m_p)^2 m_s \sim 10^{15} h_0 \gg h_0$. Thus the $\varphi$ field will roll to its true minima rapidly, where its potential energy is 0. In this case the accelerated expansion will cease and the universe will be eventually dominated by massive $\chi$ particles with mass square $m_{\chi\text{eff}}^2 = m_\chi^2 + g \varphi_*^2$. From (10), we have $m_{\chi\text{eff}} \simeq g \varphi_*$. The efficient reheating requires $g \gg 10^{-4}$, thus the $\chi$ particle will eventually gravitationally decay, whose products will dominate the universe in the final.

From (10), (11) and (12), we see that the parameters $\beta$, $\varphi_*$ and $m_\chi$ can be connected to only two natural mass scale $m_s$ and $m_p$ with $\alpha \sim 10^{-13}$ for a successful inflation and $g$ for an enough dark particles produced. Therefor, we can be placed in a false vacuum leaded to by the back reaction of dark matter particles without special fine tuning.

In conclusion, we proposed a single model of dark sector of universe. The long life particles produced during preheating after inflation are regarded as dark matter, whose back reaction on $\varphi$ field locks $\varphi$ in a false vacuum, which drive the accelerated expansion of universe at late time. When the number density of dark matter particles is dilute to some value, the field $\varphi$ rolls to its true minima and the acceleration of universe ceases. This model not only retains basic predictions of standard dark energy and cold dark matter scenario, but avoids eternal acceleration. Further, for a lower reheating temperature, the problem of cold dark matter on subgalactic scale is also cured. Moreover, since $m_\varphi \sim 10^{15} h_0 \sim 10^9 h_{eq}$, compared with quintessence model, the correction from supergravity is negligible. In addition, this model may be also applied to where the potential has rich vacuum structures at small $\varphi$. Trapping effect reduced by particles production may help to give a dynamical selection mechanism for vacua [19]. In this process one with a little mass and long life among kind of produced
particles may play a role of dark matter, which traps $\varphi$ in some vacuum with observed dark energy.

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