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Superconformal subcritical hybrid inflation

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ABSTRACT

We consider D-term hybrid inflation in the framework of superconformal supergravity. In part of the parameter space, inflation continues for subcritical inflaton field value. Consequently, a new type of inflation emerges, which gives predictions for the scalar spectral index and the tensor-to-scalar ratio that are consistent with the Planck 2015 results. The potential in the subcritical regime is found to have a similar structure to one in the simplest class of superconformal α attractors.

1. Introduction

The observations of the cosmic microwave background (CMB) strongly support inflation as the paradigm of early universe. To discover the nature of inflation, intensive analysis of the CMB has been performed. The latest results by the Planck collaboration [1,2] provide the bounds on the scalar spectral index n_s and the tensor-to-scalar ratio r of the primordial density fluctuations,

$$n_s = 0.9655 \pm 0.0062 \ (68\%\ \mathrm{CL}) ,$$
$$r < 0.10 \ (95\%\ \mathrm{CL}) . \tag{1}$$

In fact, some inflation models, such as canonical chaotic inflation [3] and hybrid inflation [4], are already disfavored due to the bounds. Although they are not supported by the current observations, the models are simple and still attractive in theoretical point of view.

Recently Refs. [5,6] studied the hybrid inflation in the framework of superconformal supergravity [7–10]. It was found that the Starobinsky model [11] emerges in the supersymmetric D-term hybrid inflation [12–14], to give a good accordance with the Planck observations. On the other hand, the D-term hybrid inflation was considered in a different context. In a shift symmetric Kähler potential [15], a 'chaotic regime' was found in the subcritical value of the inflaton field [16]. In the framework, inflation lasts even after the critical point of the hybrid inflation to give rise to different predictions from chaotic inflation. The following study [17] showed that the energy scale of inflation coincides with the Grand Unification (GUT) scale using the Planck 2013 data [18]. However, there is a tension between the predictions and the observations, especially the Planck 2015 data [1,2].

In this letter we revisit D-term hybrid inflation in superconformal framework. It will be shown that there exists a single slow-rolling field in the subcritical value of the inflaton field. Since inflation continues for sufficiently long period, cosmic strings are unobservable as in Refs. [16,17]. The potential in the subcritical region turns out to be in a general class of superconformal α attractors [19,20], especially similar to the simplest version of the model. Consequently, non-trivial behavior and different predictions from the simplest ones are discovered.

2. Subcritical regime in superconformal D-term inflation

We consider D-term hybrid inflation in supergravity with superconformal matter [5,6]. In the model three chiral superfields $S_\pm$ and Φ, which have local U(1) charge $\pm q$ $(q > 0)$ and 0, respectively, are introduced. The superpotential and Kähler potential after fixing a gauge for the local conformal symmetry are respectively given by

$$W = \lambda S_+ S_- \Phi , \tag{2}$$
$$K = -3 \log \Omega^{-2} , \tag{3}$$

with

$$\Omega^{-2} = 1 - \frac{1}{3}\left(|S_+|^2 + |S_-|^2 + |\Phi|^2\right) - \frac{\chi}{6}\left(\Phi^2 + \bar{\Phi}^2\right) , \tag{4}$$

where λ and χ are constants.[1] The term proportional to χ in the Kähler potential breaks superconformal symmetry explicitly. In the

[1] Throughout this letter we use the same notation for chiral superfields and scalar fields and take the reduced Planck mass $M_{\rm pl} = 1$ unit.

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model the Fayet–Iliopoulos (FI) term can be accommodated. Then, the D-term potential in the Einstein frame is [5],

$$V_D = \frac{1}{2} g^2 \left(q\Omega^2 (|S_+|^2 - |S_-|^2) - \xi \right)^2 , \tag{5}$$

where g is the gauge coupling and ξ is the FI term, which is taken as a constant. (See Refs. [21–26] for the subtleties of this issue in supergravity.) The F-term potential in the Einstein frame, on the other hand, is given in a simple form without exponentially growing terms [5,27],

$$V_F = \Omega^4 \lambda^2 \left[|\Phi|^2 \left(|S_+|^2 + |S_-|^2 \right) + |S_+ S_-|^2 - \frac{\chi^2 |S_+ S_- \Phi|^2}{3 + \frac{\chi}{2}\left(\Phi^2 + \bar{\Phi}^2\right) + \chi^2 |\Phi|^2} \right] . \tag{6}$$

As in the canonical hybrid inflation, S_- is stabilized to its origin meanwhile S_+ suffers from the tachyonic instability depending on the field value of Φ. The nature of Φ depends on the value of χ. In the Kähler potential there is a shift symmetry under $\mathrm{Re}\,\Phi\,(\mathrm{Im}\,\Phi) \to \mathrm{Re}\,\Phi\,(\mathrm{Im}\,\Phi) + \mathrm{const.}$ for $\chi = -1\,(+1)$, and $\mathrm{Re}\,\Phi\,(\mathrm{Im}\,\Phi)$ can play a role of inflaton, as mentioned in Ref. [5]. We consider $\chi \leq -1$ in the later discussion without loss of generality. Then, the total potential is given by the waterfall field $s \equiv \sqrt{2}|S_+|$ and the inflaton field $\phi \equiv \sqrt{2}\mathrm{Re}\,\Phi$,

$$V_{\rm tot}(\phi, s) = V_F + V_D = \frac{\Omega^4(\phi, s)\lambda^2}{4} s^2 \phi^2 + \frac{g^2}{8}\left(q\Omega^2(\phi, s) s^2 - 2\xi \right)^2 , \tag{7}$$

$$\Omega^{-2}(\phi, s) = 1 - \frac{1}{6}\left(s^2 + (1+\chi)\phi^2 \right) . \tag{8}$$

The waterfall field becomes tachyonic below the critical value ϕ_c of the inflaton field,

$$\phi_c^2 = \frac{6qg^2\xi}{3\lambda^2 + (1+\chi) q g^2 \xi} . \tag{9}$$

After the tachyonic growth, the waterfall field is expected to reach its local minimum, which is obtained by $\partial V_{\rm tot}(\phi, s)/\partial s = 0$,

$$s_{\rm min}^2 = \frac{2\xi \Omega^{-2}(\phi, 0)}{q(1+\tilde{\xi})} \frac{1 - \Psi^2}{1 + \frac{\tilde{\xi}}{1+\tilde{\xi}}\Psi^2} , \tag{10}$$

where $\tilde{\xi} \equiv \xi/3q$ and

$$\Psi \equiv \frac{\Omega(\phi, 0)\phi}{\Omega(\phi_c, 0)\phi_c} = \frac{\Omega(\phi, 0)\phi}{\sqrt{2qg^2\xi/\lambda^2}} . \tag{11}$$

The expression for the local minimum given in Refs. [16,17] corresponds to the case for $\chi = -1$ (and $q = 1$) from the facts that $\Omega(\phi, 0)|_{\chi=-1} = 1$ and $\tilde{\xi} \sim \mathcal{O}(10^{-4})$ in our targeted parameter space. Following Refs. [16,28] (see also Appendix), we have confirmed numerically that the waterfall field reaches to the local minimum after $\mathcal{O}(1/H_c)$ where $H_c (= g\xi/\sqrt{6})$ is the Hubble parameter at the critical point, and then it becomes a single field inflation. Since the inflation lasts well over $\mathcal{O}(10^2/H_c)$, cosmic strings, which are produced during the tachyonic growth, are unobservable. After the waterfall field relaxed to the local minimum, the dynamics of the inflaton is described by the potential,

$$V \equiv V_{\rm tot}(\phi, s_{\rm min}) = g^2\xi^2(1+\tilde{\xi})\Psi^2 \frac{1 - \frac{\Psi^2}{2(1+\tilde{\xi})}}{1 + 2\tilde{\xi}\Psi^2} . \tag{12}$$

As in Eq. (10), it is easily to see that the potential V with $\chi = -1$ agrees with one given in Refs. [16,17] up to $\mathcal{O}(\xi)$.[2]

We note that non-zero λ explicitly breaks the shift symmetry for $\mathrm{Re}\,\Phi$ as well as χ that deviates from -1 does. Thus, a parameter $\lambda \ll 1$ and $\chi \simeq -1$ is consistent with each other under the approximate shift symmetry. In addition, $\chi \simeq -1$ is required for $\lambda \ll 1$ otherwise ϕ_c^2 gets negative. As it will be seen, the observational data indeed implies such a parameter space.

3. Cosmological consequences

The slow roll parameters for the inflaton dynamics are given as

$$\epsilon(\phi) = \frac{1}{2}\left(\frac{V'}{V} \right)^2 , \qquad \eta(\phi) = \frac{V''}{V} , \tag{13}$$

where $V' = dV/d\hat{\phi}$ and $V'' = d^2V/d\hat{\phi}^2$. Here $\hat{\phi}$ is canonically-normalized inflaton field that is related to ϕ as

$$\frac{d\phi}{d\hat{\phi}} = K_{\Phi\bar{\Phi}}^{-1/2} , \tag{14}$$

where $K_{\alpha\bar{\alpha}} \equiv \partial^2 K/\partial\alpha\partial\bar{\alpha}$. $|S_-| = 0$, $\Phi = \bar{\Phi} = \phi/\sqrt{2}$, and $|S_+| = s_{\rm min}/\sqrt{2}$ are implicit here. (Parametrically $s_{\rm min} \simeq 0$ is a good approximation as discussed later.) Inflation ends at $\phi = \phi_f \equiv \mathrm{Max}\{\phi_\epsilon, \phi_\eta\}$ where $\epsilon(\phi_\epsilon) = 1$ and $|\eta(\phi_\eta)| = 1$, and the last e-folds N_* before the end of inflation is obtained by

$$N_* = \int_{\phi_f}^{\phi_*} d\phi \frac{V}{dV/d\phi} K_{\Phi\bar{\Phi}} . \tag{15}$$

The cosmological observables, *i.e.*, the scalar amplitude A_s, the spectral index, and the tensor-to-scalar ratio, are then determined by

$$A_s = \frac{V(\phi_*)}{24\pi^2 \epsilon(\phi_*)} , \tag{16}$$

$$n_s = 1 + 2\eta(\phi_*) - 6\epsilon(\phi_*) , \qquad r = 16\epsilon(\phi_*) . \tag{17}$$

We normalize the scalar amplitude by using the Planck 2015 data [2] $A_s = 2.198^{+0.076}_{-0.085} \times 10^{-9}$ and compute n_s and r for a given N_*.

As we have stated before, our target is the parameter space $\lambda \ll 1$. To search such a region, it is convenient to parametrize χ as

$$\chi = -1 - \frac{3\lambda^2}{qg^2\xi}\delta\chi \qquad (0 < \delta\chi < 1) , \tag{18}$$

to satisfy $\phi_c^2 = 2qg^2\xi/\lambda^2(1 - \delta\chi) > 0$.

Now we are ready to discuss the cosmological consequences. Fig. 1 shows the predictions of n_s and r in our model. Here $q = g = 1$ is taken (see footnote 2), and λ and ξ are determined for a $\delta\chi$ and N_* by using the scalar amplitude observed by the Planck collaboration. In Fig. 2, the allowed regions due to the bounds on n_s and r are shown for $N_* = 55$–60.[3] The upper and lower bounds on ξ corresponds to the upper limit on r and lower limit on n_s, respectively. In the n_s-r plane, smaller values of n_s and r are obtained for larger λ (and smaller ξ). In Fig. 1 the result in

[2] q and g can be absorbed by the redefinition of λ and ξ, $\bar{\lambda} \equiv \lambda/\sqrt{qg}$ and $\bar{\xi} \equiv g\xi$ if we ignore terms proportional to $\tilde{\xi}$ that are irrelevant numerically. Although we will use λ and ξ in the following discussion, the results in terms of $\bar{\lambda}$ and $\bar{\xi}$ can be obtained by $q \to 1$, $g \to 1$, $\lambda \to \bar{\lambda}$, and $\xi \to \bar{\xi}$.

[3] There is no allowed region for $N_* = 50$ except for $\delta\chi = 0.9$.