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The inflation point in $U(1)_{de}$ hilltop potential assisted by chaoton, BICEP2 data, and trans-Planckian decay constant

Jihn E. Kim

Department of Physics, Kyung Hee University, 26 Gyungheedaero, Dongdaemun-Gu, Seoul 130-701, Republic of Korea

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A B S T R A C T

The recent BICEP2 report on the CMB B-mode polarization hints an early Universe energy density at the GUT scale. We add a new 'chaoton' term to our recently proposed hilltop potential to have a large tensor mode fluctuation. The chaoton field slides down from the hilltop when the inflaton field value is small so that an enough e-folding is possible. We also comment how the trans-Planckian decay constant is obtained from some discrete symmetries of ultra-violet completed models.

1. Introduction

The recent report of the tensor modes on a large CMB B-mode polarization by the BICEP2 group [1] has attracted a great deal of attention. The reported tensor-to-scalar ratio is $r = 0.2^{+0.07}_{-0.05}$ (after dust reduction to $r = 0.16^{+0.06}_{-0.05}$). But, the previously reported Planck data presented an upper bound on $r < 0.11$ [2] which is about 2σ away from the BICEP2 report. At present, therefore, we need to wait a final confirmation on the BICEP2 report. However, this large value of r is so profound if true, here we investigate a possible outcome from our recently published *hilltop inflation* model [3,4].

A large r seems against hilltop inflation scenario rolling down from the origin [5]. However, a hilltop potential is quite generic from the top-down approach [6]. In Ref. [3], the hilltop inflation was suggested on the way to understand a very tiny dark energy (DE) scale 10^{-47} GeV^4 [7,8], by closing the shift symmetry $a_{de} \to a_{de} +$ constant of the DE Goldstone boson direction. The field a_{de} is a pseudo-Goldstone boson because any global symmetry must be broken at some level [3,9]. For a_{de} to generate the DE scale, theory must allow the leading contribution to DE density at the level of 10^{-46} GeV^4. A top-down approach such as string theory introduces the defining scale ($M_P \simeq 2.44 \times 10^{18}$ GeV or string scale), and the next possible scale is the grand unification (GUT) scale M_{GUT}. If a_{de} is a pseudo-Goldstone boson with its decay constant at a Planckian (or trans-Planckian) value, its potential can be parametrically expressed as a power series of M_{GUT}/M_P. However, if a_{de} couples to the QCD anomaly, then it is the QCD axion.[1] Since the QCD axion cannot be a_{de}, we must introduce two spontaneously broken global symmetries, one $U(1)_{PQ}$ and the other $U(1)_{de}$, where $U(1)_{de}$ is chosen not to carry the QCD anomaly. If the leading term of a_{de} is chosen at the 10^{-46} GeV^4 level, its potential looks like Fig. 1, where this tiny energy scale is shown as the red band (exaggerated in the figure), and the decay constant of a_{de}, f_{DE}, can be larger than the Planck mass $M_P \simeq 2.44 \times 10^{18}$ GeV. The decay constant f_{DE} is required to be trans-Planckian so that a_{de} has survived until now [10]. One inevitable aspect of this study is that it is necessary to consider $U(1)_{de}$ (and hence the QCD axion [11]) together with the $U(1)_{de}$ symmetry.

The field a_{de} is a pseudoscalar field, *i.e.* the phase of some complex scalar Φ. In the top-down approach, the height of the potential at the origin is expected to be of order ${M_{GUT}}^4$ as shown in Fig. 1. Since a_{de} is the phase of Φ, the potential along the a_{de} direction is flat if we do not consider the explicit breaking terms of order 10^{-46} GeV^4. Of course, at the intermediate scale or at the electroweak scale, there are additional $U(1)_{de}$ breaking terms, but their effect is just changing f_{DE} by a tiny amount, $f_{DE} \to \sqrt{{f_{DE}}^2 + M^2_{int}}$. In this top-down approach, we must consider the potential shown in Fig. 1, and the very early Universe might have started at the black bullet point of Fig. 1 due to high temperature effects [12,13]. This leads to the hilltop inflation. Our 'hilltop inflaton' is a scalar field.

[1] We can neglect the coupling to the $SU(2)_{weak}$ anomaly, whose effect is negligible compared to the potential energy term we consider as powers of M_{GUT}/M_P.

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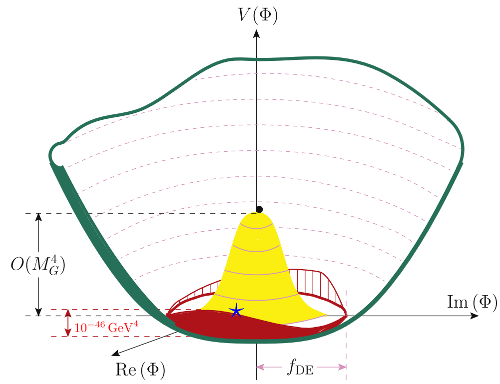

Fig. 1. The dark energy potential. The blue star marks a typical field value of the phase field of Φ. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

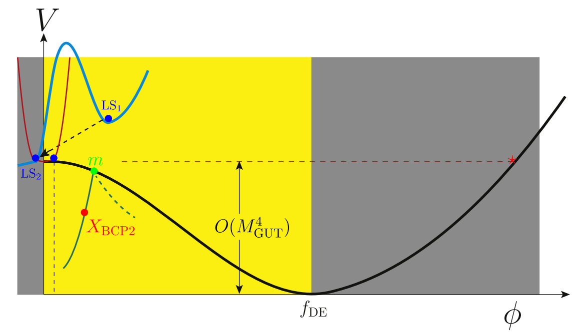

Fig. 2. The $U(1)_{de}$-hilltop inflation. The cyan curve is the potential showing tunneling to the blue bullet. The blue bullets in the gray and yellow are the equivalent points. The temperature dependent potential before spontaneous symmetry breaking of $U(1)_{de}$ is shown as the red curve. The green curve direction from m, orthogonal to that of ϕ, is the chaoton direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The 'natural inflation' [14,15] is also using a potential of a pseudo-Goldstone boson, but it is not a hilltop inflation because at the origin of $\text{Im}\,(\Phi)$ the potential is a local minimum and the 'natural inflaton' is a pseudoscalar field. Nevertheless, the possibility of large r from the BICEP2 data may rule out the hilltop inflation, even though a (3–4) σ allowance may be acceptable. On the other hand, if the height of hilltop is much lower than the GUT scale energy density, the inflation history may not be affected by the hilltop potential. A more attractive possibility will be that the inflaton may not be a vanilla type single field but involves more than one field.

In the Einstein equation $G_{\mu\nu} = T_{\mu\nu}$, the Einstein tensor responds to the energy–momentum tensor and the GUT energy density can be considered small enough to use the Einstein equation for the evolution of the Universe. If there exists a trans-Planckian vacuum expectation value (VEV) or decay constant, one should check a possible generation of Planck scale $T_{\mu\nu}$ in which case a proper discussion of the Universe evolution by the Einstein equation is impossible. But, if the energy scale during inflation is small (*i.e.* $(10^{16}\ \text{GeV})^4$) compared to the Planck energy density M_P^4, the trans-Planckian field values (*i.e.* the DE decay constant $f_{\rm DE} > M_P$) are allowed during inflation [16].

One possible trans-Planckian decay constant is some combination of axion decay constants [15,17] where the potential energy never exceeds M_P^4 due to the shift symmetries of axions. The form of the potential of Fig. 1 is also appropriate for inflation if we let $|\Phi| < f_{\rm DE}$. Usually, the cutoff scale of Planck mass allows higher dimensional operators ϕ^n/M_P^{n-4} for field value of ϕ less than the cutoff scale. With the trans-Planckian $f_{\rm DE}$, it corresponds to $\frac{\lambda\phi^n}{M_P^{n-4}}$ (the vacuum energy at $\phi = 0$) $< M_P^4$, or the trans-Planckian decay constant satisfies, $f_{\rm DE} < M_P/\lambda^{1/n}$. This corresponds to allowing only smaller and smaller couplings for higher order terms of ϕ such as $\cos\phi$ [14,15]. We will also point out that even without shift symmetries an appropriate choice of discrete quantum numbers of the inflaton and GUT scale fields can be adequate to describe a trans-Planckian VEV of the inflaton.

2. Spontaneously broken U(1) hilltop inflation

Let us introduce dimensionless energy variables in units of $M_P \simeq 2.44 \times 10^{18}$ GeV and a dimensionless time t in units of M_P^{-1}. A GUT scale reported in Ref. [1] is $(2 \times 10^{16}\ \text{GeV})^4$ which is about 10^{-8}. Models from (heterotic-)string compactifications leading to the unification of gauge couplings at the GUT scale [18–23] do not necessarily imply renormalizable couplings in the effective potential V below the Planck scale M_P. There are two well-known hilltop forms for the potential, which are very flat near the top.

The first example is the quartic potential with an extremely small λ. With the symmetry $\phi \to -\phi$, it can be written with two parameters, λ, and $f_{\rm DE}$, with three conditions, $V'(0) = 0$, $V'(f_{\rm DE}) = 0$, and $V(f_{\rm DE}) = 0$,

$$V = \frac{\lambda M_P^4}{4!}\left(\phi^2 - {f_{\rm DE}}^2\right)^2 \equiv \frac{\lambda}{4!}\left(\phi^2 - {f_{\rm DE}}^2\right)^2 \tag{1}$$

where λ is the quartic coupling constant and ϕ is the radial field of Fig. 1.

The second example is the non-supersymmetric Coleman–Weinberg (CW) type potential [24,25], originally considered in the new inflation scenario [13],

$$\text{CW}\begin{cases} V = B\left(\phi^4 \ln\frac{\phi^2}{M_f^2} + \frac{1}{2}e^{-1}M_f^4\right), \\ V' = 4B\phi^3\left(\ln\frac{\phi^2}{M_f^2} + \frac{1}{2}\right), \\ V'' = 12B\phi^2\left(\ln\frac{\phi^2}{M_f^2} + \frac{7}{6}\right), \end{cases} \tag{2}$$

where M_f is a mass parameter chosen to absorb all ϕ^4 coupling in $V(\phi)$, and

$$B = \frac{3}{64\pi^2\phi^4}\text{Tr}\,\mu_\phi^4 = \frac{3}{64\pi^2\langle\phi\rangle^4}\sum_v \mu_v^4 \tag{3}$$

where for simplicity we did not include the fermion and scalar couplings and the sum running over all massive vector bosons at the GUT scale. With the CW potential, it is known that the Higgs mass is $O(\alpha)$ times smaller [25] than the VEV of the Higgs field. In the $U(1)_{de}$ case, the VEV or $f_{\rm DE}$ is required to be trans-Planckian and a GUT scale scalar mass perfectly fits with a trans-Planckian DE decay constant. If the BICEP2 data is explainable with the CW potential, it is a very attractive one relating the scales of $f_{\rm DE}$ and $M_{\rm GUT}$. There are more examples of inflatons, mostly with large field values for inflation.

A year ago the small field inflation was looked plausible with the Planck data [2], possibly disfavoring a large field value, but the situation has changed after the report by the BICEP2 group. In each case, Eq. (1) or Eq. (2), the potential is schematically drawn in Fig. 2. But, there is a problem with the hilltop potential with a large r if inflation starts from the origin. This is because with the BICEP2 value of r, $1 - \frac{3}{8}r \simeq 0.925$. With Eqs. (1) and (2), we have a very small η, and the relation $n_s = 1 - \frac{3}{8}r + 2\eta$ cannot be raised to ~ 0.96. This is even before calculating the e-folding number in a