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Higgs inflation with singlet scalar dark matter and right-handed neutrino in light of BICEP2

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We discuss the Higgs inflation scenario with singlet scalar dark matter and a right-handed neutrino. The singlet scalar and the right-handed neutrino play crucial roles for realizing a suitable plateau of Higgs potential with the center value of the top mass of Tevatron and LHC measurements. This Higgs inflation scenario predicts about a 1 TeV scalar dark matter and an $\mathcal{O}(10^{14})$ GeV right-handed neutrino by use of a 125.6 GeV Higgs mass, 173.34 GeV top mass, and a nonminimal gravity coupling $\xi \simeq 10.1$. This inflation model is consistent with the recent result of the tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ by the BICEP2 Collaboration.

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I. INTRODUCTION

The Higgs particle has been discovered at the CERN Large Hadron Collider experiment, and their results are almost consistent with the standard model (SM) [1,2]. In addition, since the experiment has not obtained evidence of new physics so far [e.g., supersymmetry, extra dimension(s), etc.], one might consider a scenario such that the SM is valid up to a very high energy scale (GUT, string, or Planck scales). In fact, there have been several curious research results for this scenario. For example, Ref. [3] showed that the multiple point criticality principle[1] predicts 135 ± 9GeV Higgs and 173 ± 5 GeV top masses. Reference [4] also pointed out that a 126 GeV Higgs mass can be realized with a few GeV uncertainty in an asymptotic safety scenario of gravity. They clarified that the vanishing Higgs self-coupling and its β function at the Planck scale, $\lambda(M_{\rm pl}) = \beta_\lambda(M_{\rm pl}) = 0$, lead to the above values of the Higgs and top masses, which are close to the current experimental values. Reference [5] investigated the realization of the Veltman condition, ${\rm Str}M^2(M_{\rm pl}) = 0$, and the vanishing anomalous dimension of the Higgs mass, $\gamma_{m_h}(M_{\rm pl}) = 0$, at the Planck scale in addition to $\lambda(M_{\rm pl}) = \beta_\lambda(M_{\rm pl}) = 0$. As a result, the authors could find that the realization of the boundary conditions (BCs) predicts a 127–142 GeV Higgs mass. It is interesting that the above BCs can lead to close values of the Higgs and top masses to the experimental ones, but it seems difficult to reproduce the experimental center values of the top and Higgs masses at the same time (see also Refs. [6–13] for the recent analyses). Since the realization of BCs means that the Higgs potential is almost flat near the Planck scale, an application of the flat potential to the inflation, the so-called Higgs inflation [14–24], is intriguing. In addition, recently, the tensor-to-scalar ratio,

$$r = 0.20^{+0.07}_{-0.05}, \tag{1}$$

was reported by the BICEP2 Collaboration [25], and several researchers have investigated the ordinary Higgs inflation and models related to the Higgs field [26–37]. In particular, the authors of Ref. [28] pointed out that the Higgs potential with the small top mass and a nonminimal coupling $\xi = 7$ can make the ordinary Higgs inflation consistent with the BICEP2 result.

In this paper, we will investigate the Higgs inflation with the singlets extension of the SM. The gauge singlet fields can play various roles in models/theories beyond the SM. For instance, a singlet real scalar field can rescue the SM from the vacuum instability, and it can be a candidate for dark matter (DM) with odd parity under an additional Z_2 symmetry (e.g., see [38–48]). In addition, a scalar can play an important role of electroweak and conformal symmetry breaking through a strongly coupled hidden sector (see [49–51] for more recent discussion). It is also well known that the right-handed neutrinos can generate tiny active neutrino masses through a seesaw mechanism and the baryon asymmetry of the Universe (BAU) through the leptogenesis.

The singlet scalar and the right-handed neutrino play crucial roles for realizing a suitable plateau of Higgs potential with the center value of the top mass of Tevatron and LHC measurements [52]. We will show that this Higgs inflation scenario predicts about a 1 TeV scalar DM and an $\mathcal{O}(10^{14})$ GeV right-handed neutrino by use of a 125.6 GeV Higgs mass, a 173.34 GeV top mass, and a nonminimal gravity coupling $\xi \simeq 10.1$. We stress that the inflation model is consistent with the recent result of the tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ by the BICEP2 Collaboration.

II. SINGLETS EXTENSION OF THE SM

We discuss the SM with a real singlet scalar and a right-handed neutrino. The relevant Lagrangians of the model are given by

[1]The principle says that there are two degenerate vacua in the Higgs potential of SM. One is at the Planck scale and another one is at the electroweak (EW) scale where we live.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_S + \mathcal{L}_N, \tag{2}$$

$$\mathcal{L}_{\rm SM} \supset -\lambda\left(|H|^2 - \frac{v^2}{2}\right)^2, \tag{3}$$

$$\mathcal{L}_S = -\frac{\bar{m}_S^2}{2}S^2 - \frac{k}{2}|H|^2S^2 - \frac{\lambda_S}{4!}S^4 + (\text{kinetic term}), \tag{4}$$

$$\mathcal{L}_N = -\left(\frac{M_R}{2}\overline{N^c}N + y_N\bar{N}L\tilde{H} + \text{c.c.}\right) + (\text{kinetic term}), \tag{5}$$

with $\tilde{H} = -i\sigma_2 H^*$, where $\mathcal{L}_{\rm SM}$ is the SM Lagrangian including the Higgs potential. H is the Higgs doublet, v is the vacuum expectation value of the Higgs, L is the left-handed lepton doublet in the SM, S is a gauge singlet real scalar, and N is a right-handed neutrino. We omit the flavor index of left-handed lepton doublets and assume that only the singlet real scalar has odd parity under an additional Z_2. Thus, the singlet scalar can be DM if the scalar has suitable values of the mass and coupling k. The right-handed neutrino can generate the tiny neutrino mass through the type-I seesaw mechanism.

The renormalization group equations (RGEs) of (λ, k, λ_S) are given by

$$(4\pi)^2\frac{dX}{dt} = \beta_X(X = \lambda, k, \lambda_S), \tag{6}$$

with

$$\beta_\lambda = 24\lambda^2 + 4\lambda(3y^2 + y_N^2) - 2(3y^4 + y_N^4) - 3\lambda(g'^2 + 3g^2) + \frac{3}{8}[2g^4 + (g'^2 + g^2)^2] + \frac{k^2}{2}, \tag{7}$$

$$\beta_k = k\left[4k + 12\lambda + 2(3y^2 + y_N^2) - \frac{3}{2}(g'^2 + 3g^2) + \lambda_S\right], \tag{8}$$

$$\beta_{\lambda_S} = 3\lambda_S^2 + 12k^2, \tag{9}$$

at the one-loop level, where y (y_N) is the top (neutrino) Yukawa coupling, g and g' are gauge couplings, t is defined as $t \equiv \ln(\mu/1\ \text{GeV})$, μ is a renormalization scale within $M_Z \leq \mu \leq M_{\rm pl}$, M_Z is the Z boson mass, and $M_{\rm pl}$ is the reduced Planck mass as $M_{\rm pl} = 2.435 \times 10^{18}$ GeV. When μ is smaller than a mass of the particle, contribution to the β functions from the particle should be subtracted. For example, the terms proportional to y_N in Eqs. (7) and (8) disappear in an energy range of $\mu < M_R$. Typical properties of evolutions of scalar quartic couplings are listed as follows:

(i) An evolution of k is small when $k(M_Z)$ is small, because β_k is proportional to k itself. In this case, the evolution of $\lambda(\mu)$ resembles that of the SM, closely.

(ii) When one takes the experimental center values of the Higgs and top masses, $\lambda(\mu)$ is negative within a region of $\mathcal{O}(10^{10})$ GeV $\lesssim \mu \leq M_{\rm pl}$ [see the dotted curve in Fig. 1(a)]. It is known as the vacuum instability or metastability. This is caused by the negative contribution, which is proportional to the top Yukawa coupling $-6y^4$ to β_λ in Eq. (7). There exists a minimum in the evolution of $\lambda(\mu)$ around $\mu \sim \mathcal{O}(10^{17})$ GeV. But, for taking a heavier Higgs mass as $127 \lesssim m_H \lesssim 130$ GeV with $M_t = 173.1 \pm 0.6$ GeV or a lighter top mass as $171.3 \lesssim M_t \lesssim 171.7$ GeV with $m_H = 126$ GeV, $\lambda(\mu)$ can be positive

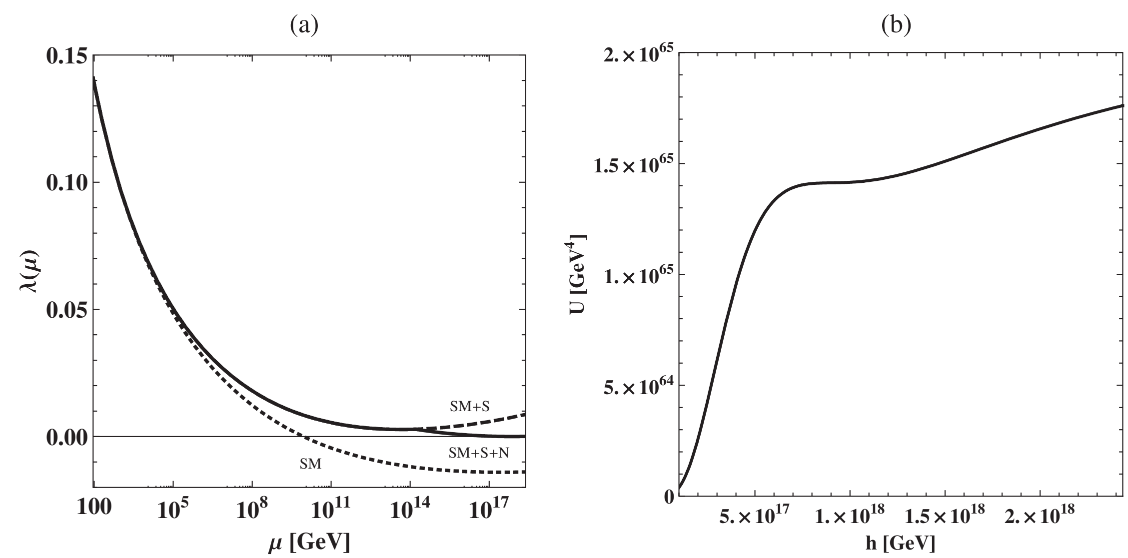

FIG. 1. (a) A typical evolution of $\lambda(\mu)$, and (b) the scalar potential in the singlets extension of the SM. We take $M_t = 173.34$ GeV, $m_H = 125.6$ GeV, $m_S \simeq 1029$ GeV, $M_R \simeq 1.58 \times 10^{14}$ GeV, $k(M_Z) \simeq 0.325$, and $y_N(M_Z) = \sqrt{m_\nu M_R}/v \simeq 0.512$. In (a), dotted, dashed, and solid curves indicate typical evolutions of $\lambda(\mu)$ in the SM, SM with a singlet scalar (SM + S), and SM with a singlet scalar and a right-handed neutrino (SM + S + N), respectively.

over a region of $M_Z \le \mu \le M_{\rm pl}$ in next to next to leading order calculations [6].

(iii) The additional term $+k^2/2$ contributes to β_λ, which makes the value of $\lambda(\mu)$ positive up to the Planck [see the dashed curve in Fig. 1(a)]. On the other hand, the contribution from the Yukawa coupling $-2y_N^4$ pushes down the evolution of $\lambda(\mu)$ like the top Yukawa coupling [compare the dashed curve with the solid one in Fig. 1(a)]. The value of $\mu_{\rm min}$, where $\lambda_{\rm min} \equiv \lambda(\mu_{\rm min}) = \min\{\lambda(\mu)\}$, shifts smaller (larger) than $\mathcal{O}(10^{17})$ GeV by introducing S (N) because the positive (negative) term $+k^2/2$ ($-2y_N^4$) contributes to β_λ. These features will be crucial in our realization of the successful Higgs inflation in singlets extension of the SM; i.e., we will fine-tune between these two contributions to obtain the suitable plateau in the Higgs inflation potential which is consistent with the recent BICEP2 result within the experimental range as $M_t = 173.34 \pm 0.76$ GeV [52].

(iv) The evolution of $\lambda_S(\mu)$ is a monotonical increasing function of the renormalization scale, and $\lambda_S(\mu)$ does not contribute to β_λ directly.

Let us show that the Higgs inflation works well in this model as below.

III. HIGGS INFLATION IN SINGLETS EXTENSION OF THE SM

We start with the relevant action of the ordinary Higgs inflation [14] as

$$S_J \supset \int d^4x\sqrt{-g}\left(-\frac{M_{\rm pl}^2 + \xi h^2}{2}R + \mathcal{L}_{\rm SM}\right), \quad (10)$$

in the Jordan frame, where ξ is the nonminimal coupling to the Ricci scalar R, $H = (0, h)^T/\sqrt{2}$ is taken in the unitary gauge, and $\mathcal{L}_{\rm SM}$ includes the Higgs potential given in Eq. (3). After the conformal transformation from the Jordan frame to the Einstein one ($\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$ and $\Omega^2 \equiv 1 + \xi h^2/M_{\rm pl}^2$), one can write down the relevant action as

$$S_E \supset \int d^4x\sqrt{-\hat{g}}\left(-\frac{M_{\rm pl}^2}{2}\hat{R} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} - \frac{\lambda}{4\Omega(\chi)^4}(h(\chi)^2 - v^2)^2\right), \quad (11)$$

where $\hat{R}$ is given by R and $\hat{g}_{\mu\nu}$, and χ is a canonically normalized field as

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_{\rm pl}}{\Omega^4}}. \quad (12)$$

The slow roll parameters for the inflation are calculated as

$$\epsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{dU/d\chi}{U}\right)^2, \qquad \eta = M_{\rm pl}^2 \frac{d^2U/d\chi^2}{U}, \quad (13)$$

with

$$U(\chi) \equiv \frac{\lambda}{4\Omega(\chi)^4}(h(\chi)^2 - v^2)^2. \quad (14)$$

Then, the spectral index and the tensor-to-scalar ratio are given by $n_s = 1 - 6\epsilon + 2\eta$ and $r = 16\epsilon$, respectively. The number of e-foldings is

$$N = \int_{h_{\rm end}}^{h_0} \frac{1}{M_{\rm pl}^2}\frac{U}{dU/dh}\left(\frac{d\chi}{dh}\right)^2 dh, \quad (15)$$

where h_0 ($h_{\rm end}$) is the initial (final) value when the inflation starts (ends). $h_{\rm end}$ is given as the slow roll conditions ($\epsilon, |\eta| \ll 1$) are broken.

It is known that the SM Higgs potential can have a plateau by taking a fine-tuned *small* top mass of $M_t = 171.0789(171.0578)$ GeV for $m_H = 125.6(125)$ GeV [24,28,33]. By using this plateau, the authors of Ref. [28] pointed out that $r \simeq 0.2$ can be achieved by introducing $\xi = 7$ in the Higgs inflation. On the other hand, if the plateau in not used, the value of ξ should be as large as $\xi \sim \mathcal{O}(10^4)$ in order to have enough e-foldings. However, in this case, r becomes too tiny as $r \simeq 3.3 \times 10^{-3}$ to be consistent with the recent BICEP2 result, since the potential is too flat at the beginning of the inflation. The Higgs inflation with the plateau induced from $M_t \simeq 171.1$ GeV and $\xi = 7$ does not suffer from this problem, since a suitable e-foldings ($50 \lesssim N \lesssim 60$) and $r \simeq 0.2$ are realized at the same time. But, this top mass is out of $M_t = 173.34 \pm 0.76$ GeV [52], anyhow.

Now let us try to obtain a suitable Higgs inflation to realize $m_H \simeq 125.6$ GeV, $M_t \simeq 173.34$ GeV, $r \simeq 0.2$, and $50 \lesssim N \lesssim 60$, as well as suitable DM and neutrino masses in the singlet extension of the SM. The realization of the scenario can be understood by investigating the behavior of $\lambda(\mu)$. A typical evolution of $\lambda(\mu)$ in the model is shown in Fig. 1(a):

(i) At first, $\lambda(\mu)$ in the SM is depicted by the dotted curve when $M_t = 173.34$ GeV and $m_H = 125.6$ GeV.

(ii) Next, we add S with mass $m_S \simeq 1029$ GeV and coupling $k(M_Z) \simeq 0.325$ into the SM. $\lambda(\mu)$ in this case is shown by the dashed curve. It is seen that the model can avoid the vacuum instability, but the value of $\mu_{\rm min}$ becomes smaller than that of the SM. This is problematic for the inflation because one cannot have a plateau around $\mu \sim \mathcal{O}(10^{17-18})$ GeV.

(iii) Next is the case of introducing a heavy right-handed neutrino of $M_R \sim \mathcal{O}(10^{14})$ GeV with a suitable y_N, where the evolution of $\lambda(\mu)$ is pushed down again.

Then, $\mu_{\rm min} \sim \mathcal{O}(10^{17-18})$ GeV and $10^{-6} < \lambda(\mu_{\rm min}) \lesssim 10^{-5}$ can be realized by a fine-tuning of M_R. In Figs. 1(a) and 1(b), values of M_R and $y_N(M_Z)$ are taken to reproduce a typical active neutrino mass of $m_\nu = 0.1$ eV.

The resultant scalar potential for the inflation is shown in Fig. 1(b). Stress that the experimental center value of the top mass $M_t = 173.34$ GeV can be used due to the effects of S and N.

Finally, we show explicit magnitudes of all parameters which realize the successful Higgs inflation. They are

$$m_S \simeq 1029.492\,\text{GeV}, \quad M_R \simeq 1.583687 \times 10^{14}\,\text{GeV},$$
$$m_\nu = 0.1\,\text{eV}, \quad k(M_Z) \simeq 0.3249353,$$
$$\lambda_S(M_Z) = 0.1, \quad \xi|_{\mu=h_0} = 10.097,$$

with the experimental center values of

$$m_H = 125.6\,\text{GeV}, \;\; M_t = 173.34\,\text{GeV}, \;\; \alpha_s(M_Z)^{-1} = 0.1184.$$

They reproduce[2]

$$r \simeq 0.200, \qquad n_s \simeq 0.955, \qquad N \simeq 50.6.$$

The value of $k(M_Z)$ is determined by the condition that the S can account for the relic abundance of DM (e.g., see [46,53]), i.e., $\Omega_S \bar{h}^2 = 0.119$, where Ω_S and $\bar{h}$ are the density parameters of the singlet scalar DM and the Hubble constant, respectively. The value of $\lambda_S(M_Z)$ is irrelevant to our result, as long as $0 \leq \lambda_S(M_Z) < 1$, as discussed in [46]. The value of y_N is determined by the seesaw formula, $m_\nu = (y_N v)^2/M_R$ with $m_\nu = 0.1$ eV and $v = 246$ GeV, where the right-handed neutrino can generate one active neutrino mass. Other neutrino masses can be realized by introducing lighter right-handed neutrinos with smaller neutrino Yukawa couplings. It is because the neutrino Yukawa couplings do not affect the RGE evolution when they are smaller than the bottom Yukawa coupling. With the above conditions, the values of (m_S, M_R, ξ) are uniquely determined to achieve realistic magnitudes of the cosmological parameters (r, n_s, N) under given values of $(m_H, M_t, m_\nu, \lambda_S, \alpha_S)$. Our solution also indicates

$$\mu_{\rm min} \simeq 7.50 \times 10^{17}\ \text{GeV}, \qquad \lambda_{\rm min} \simeq 2.44 \times 10^{-6},$$
$$h_0 \simeq 1.86 \times 10^{18}\ \text{GeV}, \qquad h_{\rm end} \simeq 4.61 \times 10^{17}\ \text{GeV},$$
$$U(h_0) = 1.6 \times 10^{65}\ \text{GeV}^4,$$

which realize the successful Higgs inflation. If one considers a slightly lighter (heavier) DM mass, then $\mu_{\rm min}$ or $\lambda_{\rm min}$ becomes too small (large) to achieve a realistic inflation, even by fine-tuning M_R and ξ. This model has a 1029 GeV DM mass, which is consistent with DM experiments [54] (see also [53]). It might be detected by a future experiment such as XENON1T, XENON100 with 20 times sensitivity, a combined analysis of Fermi + CTA + Planck observations, etc. [53]. When we take care of experimental uncertainties (and a tiny effect from λ_S), we can draw allowed regions around the typical point shown above.

[2]Here we include two-loop SM contributions to β_λ.

IV. SUMMARY

We have investigated the Higgs inflation scenario with singlet scalar dark matter and the right- handed neutrino. The singlet scalar and the right-handed neutrino play crucial roles for realizing the suitable plateau of Higgs potential with the center value of the top mass of Tevatron and LHC measurements. We have shown that this Higgs inflation scenario predicts a 1029 GeV scalar DM and an $\mathcal{O}(10^{14})$ GeV right-handed neutrino by use of a 125.6 GeV Higgs mass, 173.34 GeV top mass, and a nonminimal gravity coupling $\xi \simeq 10.1$. This inflation model works well completely, and it is consistent with the recent result of the tensor-to-scalar ratio $r = 0.20^{+0.07}_{-0.05}$ by the BICEP2 Collaboration.

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