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HIGGS INFLATION AROUND THE SYMMETRIC POINT

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Abstract. *A novel generalized Higgs inflation scenario is studied, where inflation takes place near the symmetric point of the "Mexican hat" potential, as opposed to the standard Higgs inflation which takes place at large field values away from the symmetric point. When minimally coupled to gravity, inflation near the symmetric point leads to large tensor-to-scalar ratio which is ruled out by CMB observations, while requiring super-Planckian Higgs VEV which also acts as the axion decay constant (super-Planckian values of the decay constant are theoretically disfavored, for example by the swampland conjectures). It is shown that both of the aforementioned problems can be resolved by considering non-minimal coupling of the Higgs field to the scalar curvature of spacetime. This requires sufficiently large non-minimal coupling parameter, and produces similar results for the scalar spectral index and tensor-to-scalar ratio to the standard Higgs inflation, and the Starobinsky model. The Higgs field under consideration can in principle be identified with the Standard Model Higgs scalar, in which case an extremely large non-minimal coupling is required (in order to reproduce CMB-aligned predictions), which can also be theoretically problematic. A more likely scenario is a hidden sector Higgs-like field, such as the Peccei–Quinn field, where a smaller non-minimal coupling is acceptable. The proposed model offers an alternative to the simplest single-field models of inflation, especially of Higgs and Peccei-Quinn type, while fitting the CMB observations of primordial power spectra. An advantage of such models in the vast landscape of inflationary theories is simplicity: no ad hoc scalar fields are assumed to exist purely to explain inflation, since both Higgs and Peccei-Quinn fields are motivated by particle physics considerations.*

Keywords: cosmology, inflation, Higgs field, spontaneous symmetry breaking

1. Introduction

Cosmic inflation remains the leading paradigm for explaining the observed large-scale homogeneity and isotropy of the Universe and for generating the primordial perturbations that seed cosmic structure. In the slow-roll framework, a scalar field evolving on a sufficiently flat potential produces an approximately scale-invariant power spectrum with a slightly red tilt and a small tensor contribution. These generic expectations are in impressive agreement with the latest CMB constraints, which continue to favor simple, radiatively stable realizations of single-field inflation with suppressed tensor-to-scalar ratio [1].

A particularly attractive direction is to embed inflation into symmetry-based scalar sectors familiar from particle physics. The idea that the Higgs field (or a Higgs-like field such as the Peccei–Quinn field) can act as the inflaton has been explored extensively, most prominently in the Standard Model context with a non-minimal coupling to gravity [2] (see, e.g., [3, 4] for a review). Subsequent studies investigated the impact of radiative corrections and running couplings on the inflationary regime, clarifying when Higgs-sector potentials can support successful slow-roll dynamics consistent with CMB observables [5, 6]. Some questions still remain, regarding possible violations of perturbative unitarity when the non-minimal coupling of the Higgs field to gravity is large, as required by the standard Higgs inflation scenarios [7–16].

Motivated by these developments, we study an alternative scenario of non-minimally coupled Higgs-like inflation, where inflation takes place around the symmetric point, in contrast to conventional Higgs inflation which happens at large field values and away from the symmetric point of the potential. We consider a simple Abelian symmetry breaking model, where the symmetry can be global or local, as it does not affect inflationary dynamics. Inflation starting sufficiently close to the symmetric configuration shares conceptual features with hilltop inflation scenarios, where slow-roll proceeds near a local maximum of the potential before the system relaxes toward the broken vacuum [17]. If the angular mode (the Goldstone mode of the broken symmetry) remains light during inflation, i.e. no explicit symmetry-breaking terms are generated, axion-like isocurvature perturbations can impose strong constraints on the allowed parameter space [18]. In this respect, gauging the $U(1)$ symmetry provides an appealing option: the axion is absorbed by the gauge field via the Higgs mechanism, which reduces potentially problematic isocurvature contributions.

Investigating inflationary dynamics near the symmetric point of a "Mexican hat" potential provides a crucial alternative to standard large-field scenarios, particularly in addressing the theoretical challenges associated with super-Planckian field excursions and the swampland conjectures [23,27]. By demonstrating that a non-minimal coupling can simultaneously suppress the tensor-to-scalar ratio to observationally viable limits and rescue the model from the swampland, this work establishes a robust framework for a minimal single-field inflation. Furthermore, by utilizing particle-physics-motivated fields like the Higgs or the Peccei–Quinn field, this approach reduces the need for ad hoc cosmological fields, offering a more constrained and well-motivated avenue for connecting early-universe inflation with high-energy particle physics.

The paper is organized as follows. Section 2 presents the minimally coupled Abelian Higgs-like model and discusses the inflationary regime near the symmetric point, where unacceptably large values of tensor-to-scalar ratio, as well as large, super-Planckian VEV of the symmetry breaking field Φ are found. To overcome these drawbacks, in Sec. 3 the same scenario is studied, but in the presence of non-minimal coupling of Φ to the scalar curvature, and find that the aforementioned issues can be resolved for sufficiently large non-minimal coupling. The results are discussed in Sec. 4 and conclusion is given in Sec. 5.

2. Minimal coupling

Consider the Lagrangian for a minimally coupled Abelian Higgs-like field Φ:

$$\sqrt{-g}^{-1}L = \frac{1}{2}R - \partial\Phi\partial\Phi^* - \frac{\lambda}{4}\left(f^2 - 2\Phi\Phi^*\right)^2, \tag{1}$$

where λ is the quartic coupling, and f is the VEV parameter of Φ, which is also the axion decay constant. The complex scalar Φ is parametrized as

$$\Phi = \frac{1}{\sqrt{2}}\phi e^{-i\sigma}, \tag{2}$$

where ϕ is the radial component, and σ is the axion, or the Goldstone boson of a $U(1)$ symmetry. The latter acts on Φ as $\Phi \to \Phi e^{-ic}$, where c is a constant for global $U(1)$, and a function $c(x)$ for local, or gauge $U(1)$ symmetry. The gauging procedure can be done without affecting inflationary dynamics, as in our model inflation is driven by the radial scalar ϕ.

Therefore, we focus on the ϕ -part of the Lagrangian:

$$\sqrt{-g}^{-1}L = \frac{1}{2}R - \frac{1}{2}\partial\phi\partial\phi - \frac{\lambda}{4}(f^2 - \phi^2)^2. \tag{3}$$

For the discussion of inflation it is useful to introduce the potential slow-roll parameters,

$$\epsilon_V \equiv \frac{V_{,\phi}^2}{2V^2}, \quad \eta_V \equiv \frac{V_{,\phi\phi}}{V}, \tag{4}$$

where V is the scalar potential, $V = \frac{1}{\lambda}(f^2 - \phi^2)^2$, and $V_{,\phi}$ denotes its derivative with respect to ϕ. The usual slow-roll inflation requires $\epsilon_{V,}\ |\eta_V| \ll 1$. By using these slow-roll parameters one can estimate the inflationary observables consisting of the amplitude of scalar perturbations A_s, their spectral tilt n_s, and the ratio of tensor to scalar perturbations r:

$$A_s \simeq \frac{V}{24\pi^2\epsilon_V}, \tag{5}$$

$$n_s \simeq 1 + 2\eta_V - 6\epsilon_V, \quad (6)$$

$$r \simeq 16\epsilon_V. \quad (7)$$

Their numerical values are calculated at the field value ϕ_* at which the corresponding perturbation exits the Hubble horizon, and compared to the observations of the Cosmic Microwave Background (CMB). The *Planck* and *BICEP-Keck* data suggest the following values [19, 20],

$$A_s = 2.1 \times 10^{-9}, n_s = 0.9668 \pm 0.0037, \ \ r < 0.036. \quad (8)$$

In addition, the length of inflation can be measured in the number of e-folds $\varDelta N$ from the horizon exit and until the end of inflation where $\epsilon_V \simeq 1$. It is estimated as

$$\varDelta N \simeq \int_{\phi_*}^{\phi_e} \frac{d\phi}{\sqrt{2\epsilon_V}}, \quad (9)$$

where ϕ_e is the value of the inflaton at the end of inflation, which can be found by solving $\epsilon_V(\phi_e) = 1$. For succesful inflation, around $\varDelta N = 50 - 60$ is needed, starting from the horizon exit. Then Eq. (9) can be solved for ϕ_* and the observables (5), (6), and (7) at this field value can be estimated.

For the model (3) one obtains

$$\epsilon_V \simeq \frac{8\phi^2}{f^4}, \ \ \eta_V \simeq \frac{-4}{f^2}, \quad (10)$$

where assume $\phi \ll 1$ is assumed, since inflation is possible only around the hilltop of the potential in this model. Consequently, the length of inflation is calculated as

$$\varDelta N \simeq -\frac{f^2}{4}\left(\frac{1}{2} + log\frac{\phi_*}{f}\right), \quad (11)$$

so that

$$\frac{\phi_*}{f} = e^{-\frac{1}{2} - 4f^{-2}\varDelta N}. \quad (12)$$

By using Eqs. (6), (10), and (12) it can be estimated that $n_s \approx 0.967$ at $\varDelta N = 55$ and $f \approx 21$. Next, r is estimated as

$$r \simeq \frac{128}{f^4}\phi^2. \quad (13)$$

At $\phi = \phi_*$ and for $f = 21$ one gets $r \approx 0.036 - 0.043$ for $\varDelta N$ between 60 and 50, respectively. Our numerical results, however, show even larger values of r (for large f, the approximations (10) and (9) become less and less precise). For example, when $f = 21$ and $\varDelta N = 60$, one gets $r \approx 0.057$ (smaller $\varDelta N$ leads to larger r), which is completely excluded by observations.

In this work, the strategy for obtaining numerical inflationary solutions and the corresponding predictions is the following. First, the equations of motion (27), (28), (29) are solved numerically (for a given field-space metric *G*, which is equal to one in the minimally coupled case, and scalar potential *V;* and using *Mathematica's NDSolve* differential equation solver), in terms of the forward e-fold time *N*. After the solution for the Hubble function *H* is found, one can derive the Hubble-based slow-roll parameters (shown below Eq. (29)) and finally the predictions for n_s and r, calculated via Eq. (30) at the starting time N_* of observable inflation (when the CMB perturbations are generated). In turn, N_* can be found by subtracting $\varDelta N$ (which ranges from 50 to 60) from the time of the end of inflation N_{end}. The latter is often defined by the condition where the Hubble slow-roll parameter, $\epsilon \equiv \frac{-\dot{H}}{H^2}$, reaches unity (this is set as a condition to stop the numerical integration of the equations of motion).

As for the quartic coupling λ, it can be fixed from (5) by using (8) and (12). One obtains $\lambda \sim 10^{-14}$ for $50 - 60$ e-folds, in line with the standard Higgs inflation [2].

In summary, this section is concluded by noting that the minimally coupled Higgs-like inflation is possible around the symmetric point $\phi = 0$, but (a) it leads to unacceptable values of tensor-to-scalar ratio r, and (b) the VEV parameter (which is also the axion decay constant) is super-Planckian at $f \sim O(10M_P)$, which can be theoretically problematic due to a difficulty of finding consistent UV completions of such a theory [21, 22] (also related to the swampland distance conjecture [23]).

In light of these results, we propose a non-minimally coupled extension of this Higgs-like model. It should be emphasized that in our scenario, inflation takes place at small field values, $\frac{\phi}{f} \ll 1$ (as considered in this section for the minimally-coupled model), as opposed to the usual Higgs inflation, where inflation happens at large field values $\frac{\phi}{f} \gg 1$, or away from the symmetric point.

3. Non-minimal coupling

With the inclusion of non-minimal coupling, the Lagrangian reads

$$\sqrt{-g}^{-1}L = \frac{1}{2}A(\Phi\Phi^*)R - \partial\Phi\partial\Phi^* - \frac{\lambda}{4}(f^2 - 2\Phi\Phi^*)^2 \quad (14)$$

where $A(\Phi\Phi^*)$ is some function of the $U(1)$-invariant product $\Phi\Phi^*$.

By rescaling the metric as

$$g_{mn} \to A^{-1}g g_{mn}, \quad (15)$$

one can bring the Jordan frame Lagrangian (14) to the Einstein frame,

$$\frac{L}{\sqrt{-g}} = \frac{1}{2}R - \frac{1}{A}\partial\Phi\partial\Phi^* - \frac{3}{4A^2}\partial A\partial A - \frac{\lambda}{4A^2}(f^2 - 2\Phi\Phi^*)^2, \quad (16)$$

which extends the kinetic term of Φ by adding the derivatives of $A(\Phi\Phi^*)$, and rescales the potential by A^{-2}.

The simplest choice for the non-minimal coupling function A is linear in $\Phi\Phi^*$:

$$A = \mu^2 + 2\xi\Phi\Phi^* = \mu^2 + \xi\phi^2, \quad (17)$$

where μ is a real parameter which can be eliminated by requiring that $A = M_P^2$ at the vacuum (so that the Einstein–Hilbert term is recovered), or in Planck units,

$$\langle A\rangle = \mu^2 + \xi f^2 = 1. \quad (18)$$

Then $\mu^2 = 1 - \xi f^2$, so that one can write

$$A = 1 - \xi(f^2 - \phi^2). \quad (19)$$

With this, the ϕ -sector of the Lagrangian becomes

$$\sqrt{-g}^{-1}L = \frac{1}{2}R - \frac{1}{2}G\partial\phi\partial\phi - \frac{\lambda(f^2-\phi^2)^2}{4[1-\xi(f^2-\phi^2)]^2}, \quad (20)$$

where the field-space metric of ϕ, denoted G, is given by

$$G = \frac{1-\xi f^2+(1+6\xi)\xi\phi^2}{[1-\xi(f^2-\phi^2)]^2}. \quad (21)$$

The canonically parametrized scalar φ can be found by solving

$$\frac{d\varphi}{d\phi} = \sqrt{G}, \quad (22)$$

and inverting the solution should give us $\phi(\varphi)$ in order to express the Lagrangian in terms of the canonical scalar. Analytical solutions to (22) and/or the analytical inverse $\phi(\varphi)$ does not always exist, so it can be more convenient to work directly with the non-canonical scalar ϕ.

To understand the impact of the non-minimal coupling on the scalar potential, one can analyze second derivative of the scalar potential of Eq. (20) at $\phi = 0$:

$$V_{,\phi\phi}(\phi = 0) = \frac{-\lambda f^2}{(1-\xi f^2)^3}. \quad (23)$$

This shows that large negative value of ξf^2 can flatten the potential (reduce $V_{,\phi\phi}$) while keeping the negative sign of $V_{,\phi\phi}$ around $\phi = 0$. At the same time the correct sign of the kinetic term of ϕ requires $\xi f^2 < 1$, as can be seen from (20) and (21).

Taking into account Eq. (22), the potential slow-roll parameters can be written in terms of the non-canonical scalar ϕ as

$$\epsilon_V = \frac{V_{,\varphi}^2}{2V^2} = \frac{V_{,\varphi}^2}{2GV^2} = \frac{8\phi^2}{(f^2-\phi^2)^2(A+6\xi^2\phi^2)}. \quad (24)$$

and

$$\eta_V = \frac{V_{,\varphi\varphi}}{V} = \frac{V_{,\varphi\varphi}}{GV} - \frac{G_{,\phi}V_{,\phi}}{2G^2V}, \quad (25)$$

where A is given by (19). For $|\xi|f^2 \gg 1$, ϵ_V is suppressed compared to its expression in the minimally coupled model (10). For η_V in Eq. (25) the situation is more interesting. At $\phi = 0$ (and when $6|\xi|\phi^2 \ll f^2$), it reduces to $\eta_V = \frac{-4}{f^2}$, which is the same value as in the minimally coupled model. Nonetheless, as ϕ moves away from the origin, η can be suppressed once $6\xi\phi^2$ becomes much larger than $|\xi|f^2$ (this can happen while $\frac{\phi}{f}$ is still small if one assumes $|\xi| \gg f^{-2} \gg 1$). These results imply that the non-minimal coupling can help to reduce the value of f, and the value of tensor-to-scalar ratio r (which is proportional to ϵ_V) if the non-minimal coupling is sufficiently large. Let us also estimate the number of e -folds between some small ϕ_1 (start of inflation) and $\phi_2 = f$ (end of inflation):

$$\Delta N \simeq \int_{\varphi_1}^{\varphi_2}\frac{d\varphi}{\sqrt{2\epsilon_V}} = \int_{\varphi_1}^{\varphi_2} d\phi\sqrt{\frac{G}{2\epsilon_V}} \simeq \frac{f^2}{4}\left(log\frac{f}{\phi_1} - \frac{1}{2}\right) + \frac{3}{4}[|\xi|f^2 - log(1 + |\xi|f^2)], \quad (26)$$

where $\phi_1 \ll f$ and $\xi = -|\xi|$ are assumed. As can be seen, for large values of $|\xi| f^2$ the number of e-folds is roughly proportional to $|\xi| f^2$, so that f does not need to be large, unlike in the minimally coupled case. In fact, as will be shown, f can be much smaller than one (or much smaller than M_P when restoring Planck mass).

Since the analytical results discussed above can become inaccurate depending on the parameter values and the hierarchies between them, the equations of motion (Klein–Gordon and Friedmann) will be numerically solved and more precise results for the observables n_s and r will be derived. It is convenient to use the number of e-folds N (related to the Hubble function as $\dot{N} = H$) as a time variable when deriving inflationary solutions. The equations of motion for the Lagrangian (20) can be written as

$$\phi'' + (3-\epsilon)\phi' + \frac{V_{,\phi}}{GH^2} = 0, \tag{27}$$

$$(3-\epsilon)H^2 = V, \tag{28}$$

$$\epsilon = \frac{1}{2} G \phi'^2, \tag{29}$$

where $' \equiv \frac{d}{dN}$ and $\epsilon \equiv \frac{-\dot{H}}{H^2}$ is the Hubble slow-roll parameter, which can be related to the kinetic term of ϕ via the second Friedmann equation (29). Another useful slow-roll parameter is $\eta \equiv \frac{\dot{\epsilon}}{(H\epsilon)} = \frac{\epsilon'}{\epsilon}$, which shows the rate of change of ϵ. With the Hubble slow-roll parameters one can calculate the spectral index and tensor-to-scalar ratio as

$$n_s \simeq 1 - 2\epsilon - \eta, n_s \simeq 1 - 2\epsilon - \eta, \tag{30}$$

under the slow-roll approximation where $\epsilon \ll 1, |\eta| \ll 1$ (i.e., higher-order terms in ϵ and η are ignored).

After numerically solving the system (27), (28), and (29), the resulting values of n_s and r are plotted in Fig. 1. It can be seen that for $|\xi| f^2 = 90$, the predictions for $n_s$and r differ significantly depending on the value of f. As one increases the effective parameter $|\xi| f^2$, this difference quickly reduces, and for $|\xi| f^2 > 100$ the predictions are practically independent of f as long as f is around Planck mass or smaller (it can be much smaller in principle).

Let us comment on physical interpretation of the parameters and their variation. As mentioned above, the effective parameter $|\xi| f^2$ (assuming negative ξ) flattens the "Mexican hat" potential (in the Einstein frame) near the top, while f controls the VEV of the Higgs (-like) field, and therefore the distance between the top of the potential (symmetric point) and its minimum. As is well-known, flatter potentials (i.e., larger $|\xi| f^2$ in our case) allow the inflaton to travel smaller field-space distances while maintaining the required amount of inflation (50 to 60 e-folds). At the same time, they lead to a decrease in tensor-to-scalar ratio. Given that $|\xi| f^2 \gg 1$ is required in order to sufficiently decrease the value of r, one has $|\xi| \gg f^{-2}$. In addition, $f < 1$ can be required by theoretical motivations, i.e. a sub-Planckian VEV of the inflaton/Higgs field. This necessarily leads to $|\xi| \gg 1$.

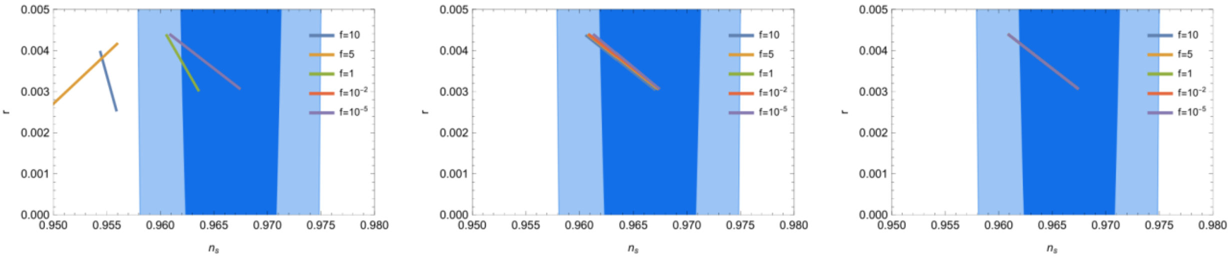

Fig.1. Predictions of Higgs inflation for the spectral index ns and tensor-to-scalar ratio r compared to the Planck constraints [1] (*GetDist* package [28] is use to generate the observational bounds on $n_s - r$ plane). The calculations are done for ΔN from 50 to 60. Values of the composite parameter $|\xi| f^2$ are -90 (left), −200 (middle) and −1000 (right).

4. Results and discussion

This work studies generalized Higgs inflation with non-minimal coupling to gravity, where inflation happens near the symmetric point of the potential. First, inflationary solution without the non-minimal coupling was derived, and it was shown that it leads to large values of tensor-to-scalar ratio that are ruled out by observations. Furthermore, observational constraints on n_s require super-Planckian axion decay constant/VEV of ϕ, around $f \approx 21M_P$, which is problematic from theoretical point of view, even if the scalar ϕ is not identified with the Standard Model Higgs scalar.

These problems can be resolved by considering large negative non-minimal coupling at least of order $|\xi| \sim \frac{100}{f^2}$. This leads to the predictions for the inflationary observables very close to the Starobinsky model or conventional Higgs inflation, where n_s and r can be approximated as

$$n_s \simeq 1 - \frac{2}{\Delta N}, \quad r \simeq \frac{12}{\Delta N^2}. \tag{31}$$

At the same time the decay constant f can be arbitrarily small, but at the expense of large $|\xi|$ which scales as $|\xi| \propto \frac{1}{f^2}$ if one requires viable inflationary scenario. For the Standard Model Higgs field, $f \sim 100$GeV, or in Planck units, $f \sim 10^{-16}$, leading to an extremely large $|\xi| \sim 10^{34}$. This is problematic from theoretical point of view, in light of unitarity arguments. For example, in the case of the conventional Higgs inflation it has been shown that with the Standard Model Higgs field as the inflaton, the inflationary energy density reaches the perturbative unitarity violation scale unless $|\xi|$ is well below 10^4 [10] (at the same time CMB measurements require $|\xi| \sim 10^4$ or even larger, implying an inconsistency). However, a more careful analysis of tree-level scattering diagrams conducted in [29] (see also more recent works [15,16,30]) has shown that for a single-field case (such as our proposal), the unitarity violation scale is pushed all the way up to the (reduced) Planck mass M_P, so that such models are well-behaved as effective field theories during the inflationary phase, where the energy density is two or three orders of magnitude below the Planck scale.

On the other hand, for a more general Higgs-like field (not from the Standard Model), the VEV f can be close to the Planck scale, or around the possible Grand Unification scale of $10^{15} - 10^{16}$GeV, in which case ξ takes much more reasonable values compared to $|\xi| \sim 10^{34}$. One example of such a model is Peccei–Quinn theory where f can take the values up to the Planck mass in principle [24] (in this case, the axion σ, introduced in (2), can act as dark matter). When f is at the Planck mass (or in Planck units, $f \sim 1$), to satisfy the CMB data, the non-minimal coupling parameter should be of order $|\xi| \sim 100$, which is much below than in the conventional Higgs inflation with $|\xi| \sim 10^4$, making our model somewhat more natural.

5. Conclusion

This work establishes Higgs-type inflation around the symmetric point as a viable candidate for simple single-field inflationary model. By using the example of a complex Higgs-type field with the radial component ϕ, it is found that a non-minimal coupling $\xi\phi^2 R$ to scalar curvature can facilitate the alignment of the model with the CMB measurements as well as reduce super-Planckian field excursions, with the condition that ξ is negative and satisfies $|\xi| f^2 \gg 1$. The novelty of this approach is that it differs in principle from the standard Higgs inflation, which also utilizes the non-minimal coupling, but takes place at large field values, i.e. $\phi \gg f$. By contrast, in our model inflation happens at $\phi < f$, when ϕ is close to the symmetric point $\phi = 0$. Our model belongs to the class of hilltop inflation in a broad sense, where one usually expands the potential around the symmetric point, and discards the corrections which become important near the VEV of the inflaton. More specific hilltop models considered in the literature include specific realizations of string inflation, natural inflation (where the potential is periodic), and some supergravity models (an overview of such models can be found in [17] and Refs. therein). A crucial difference with all these hilltop models is that our approach relies on non-minimal coupling of the inflaton for the flattening of the potential, rather than ad hoc corrections to the potential itself.

In future works it can be interesting to extend our framework by including higher-derivative corrections, such as the Gauss–Bonnet term and Horndeski-type derivative corrections, which can be expected from the effective field theory point of view, without introducing Ostrogradski instability and new degrees of freedom. These corrections can change inflationary dynamics (see, e.g., [25, 26]) and potentially further relax the constraints on ξ and f. On the other hand, more recent activity in the area of inflationary model building is in large part related to the recent Atacama Cosmology Telescope (ACT) results [31] suggesting a mild deviation from the PLANCK constraint on n_s (towards slightly larger values). For instance, in [32] the authors revisit the general hilltop models (minimally-coupled) and further constrain the parameters of the models, while in [33-35] non-minimally coupled Higgs inflation (at large field values) is studied in this context. This also motivates further studies of our model in light of the ACT data, for example, by calculating the effects of the aforementioned Gauss-Bonnet term, along the lines of [36,37].

Conflict of interest statement
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement
Berkimbayev D.: Investigation, Software, Writing - Original Draft. **Aldabergenov Y.**: Conceptualization, Methodology, Writing - Review & Editing.

Statement on the use of Artificial Intelligence.
The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement
The data that support the findings of this article are openly available.

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