

Independent connection in action during inflation

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The Atacama Cosmology Telescope (ACT) has recently released new measurements and constraints on inflationary observables. In this paper, it is shown that a component of a dynamical affine connection, which is independent of the metric, can easily drive inflation in agreement with these observations. Such geometrical explanation of inflation is analyzed in detail here in the minimal model, including the predictions for the scalar spectral index n_s and its running α_s , the amplitude of the scalar perturbations, and the tensor-to-scalar ratio r . Furthermore, this minimal model is shown to provide an inflationary attractor: arbitrary initial values of the kinetic energy density are dynamically attracted down to negligible values compared to the potential energy density in homogeneous and isotropic metrics. Also, the role of the Higgs boson during and after inflation is briefly discussed.

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Introduction. In Refs. [1,2], the ACT Collaboration has provided new determinations of several inflationary observables. One of the most evident differences with respect to the values previously furnished by the Planck and BICEP/Keck (BK18) Collaborations [3,4] is a higher favored value for n_s : when the new ACT observations are combined with Planck data and baryon acoustic oscillation data from the Dark Energy Spectroscopic Instrument (DESI) [5] (this combination is denoted P-ACT-LB) Ref. [1] finds $n_s = 0.9743 \pm 0.0034$.

This new result has attracted much attention [6–11] as several inflationary models that were in perfect agreement with the previous Planck and BICEP/Keck results are in tension with the new determination.

The main purpose of this paper is to offer a well-motivated scenario that can explain the new results of Refs. [1,2]. While Einstein's general relativity (GR) explains gravity in geometrical terms (the distances are measured through the metric and the gravitational force is determined by the affine connection), inflation is usually accounted for by adding an *ad hoc* scalar field, which is unrelated to geometry. However, from the purely geometrical point of view, the metric and the connection, unlike in GR, can be completely independent objects and, moreover, can contain extra degrees of freedom besides the spin-2 graviton. This generalized scenario is known as metric-affine gravity (see [12,13] for detailed discussions and

further references). The extra degrees of freedom carried by the affine connection can include the inflaton [14–16], and this provides a geometrical origin also for this scalar field and the subsequent period of reheating too [14,15], which sets the initial conditions for the radiation dominated phase of the Universe.

Addressing the compatibility of such scenario with the new ACT results is not the only purpose of this work. Other new goals include studying the implications of the couplings between the inflaton and the Standard Model particles for reheating and inflation, investigating the presence of an inflationary attractor and studying the running of the spectral index in this scenario.

The model. An explanation of the new results of Refs. [1,2] can already been obtained in the simplest model where the inflaton is a dynamical scalar component of the affine connection (see [13,14] for an introduction to this model). The part of the action that is relevant for inflation in this case is

$$S_I = \int d^4x \sqrt{-g} (\alpha \mathcal{R} + \beta \mathcal{R}' + c \mathcal{R}'^2), \quad (1)$$

where [17] $\mathcal{R} \equiv \mathcal{R}_{\mu\nu}^{\mu\nu}$ and $\mathcal{R}' \equiv \epsilon^{\mu\nu\rho\sigma} \mathcal{R}_{\mu\nu\rho\sigma} / \sqrt{-g}$ is the parity-odd Holst invariant [18–20]. Here,

$$\mathcal{R}_{\mu\nu}^{\rho\sigma} \equiv \partial_\mu \mathcal{A}_\nu^\rho{}_\sigma + \mathcal{A}_\mu^\rho{}_\lambda \mathcal{A}_\nu^\lambda{}_\sigma - (\mu \leftrightarrow \nu) \quad (2)$$

is the curvature built with the affine connection $\mathcal{A}_\mu^\rho{}_\sigma$, also $\epsilon^{\mu\nu\rho\sigma}$ is the totally antisymmetric Levi-Civita symbol with $\epsilon^{0123} = 1$ and g is the determinant of the metric. The invariants $\mathcal{R}$ and $\mathcal{R}'$ generically appear in low-energy metric-affine effective field theories [21]. In the GR case,

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where $\mathcal{A}_\mu{}^\rho{}_\sigma$ equals the Levi-Civita connection, $\mathcal{R}$ coincides with the Ricci scalar, R , but $\mathcal{R}'$ vanishes. Thus, in metric-affine gravity, $\mathcal{R}'$ can be understood as a component of the connection. The coefficients α and β have dimensions of energy squared, while c is a dimensionless coefficient. The quantity $M_P^2/(4\beta)$ is called the Barbero-Immirzi parameter [22,23]. These coefficients can be determined as follows.

After introducing an auxiliary field ω , which trades the curvature-squared term in (1) with a linear-in-curvature term, and solving exactly the $\mathcal{A}_\mu{}^\rho{}_\sigma$ field equations, one obtains the equivalent form,

$$S_I = \int d^4x \sqrt{-g} \left[\alpha \mathcal{R} - \frac{(\partial\omega)^2}{2} - \mathcal{U}(\omega) \right], \quad (3)$$

where

$$\mathcal{U}(\omega) \equiv \frac{(\beta - \frac{g}{2} \sinh(X(\omega)))^2}{4c} \quad (4)$$

and

$$X(\omega) \equiv \frac{\omega}{\sqrt{3\alpha}} + \tanh^{-1} \left(\frac{4\beta}{\sqrt{16\beta^2 + 4\alpha^2}} \right). \quad (5)$$

Thus, one reproduces GR coupled to an ordinary scalar for $\alpha = M_P^2/2$, where M_P is the reduced Planck mass. So, from now on $\alpha = M_P^2/2$. The coefficients c and β can be determined by requiring $\mathcal{U}$ to be a good inflationary potential.

The field ω , the candidate inflaton, has the same symmetry properties of $\mathcal{R}'$ [13,24,25], so it is a spin-0 field with odd parity. For this reason, it is named the pseudoscalaron. The squared mass of ω can be obtained by evaluating the second derivative of $\mathcal{U}$ at $\omega = 0$, which is the only stationary point of $\mathcal{U}$. The result is

$$m_\omega^2 = \frac{16\beta^2 + M_P^4}{48cM_P^2}. \quad (6)$$

Therefore, requiring the absence of tachyons, $c > 0$. Also note that $\mathcal{U}(\omega)$ is symmetric in the exchange $\{\omega, \beta\} \rightarrow \{-\omega, -\beta\}$. Thus, an arbitrary value of β and its opposite are physically equivalent.

For $\sqrt{|\beta|} \gtrsim M_P$, a plateau appears in $\mathcal{U}$ (see the blue line in Fig. 1), which is suitable for inflation.

Despite its simplicity, this minimal model predicts inflationary observables that are quite robust under extensions of the inflationary action in (1). First, the same inflationary predictions emerge if one substitutes $c\mathcal{R}^2$ with a general quadratic function of both $\mathcal{R}$ and $\mathcal{R}'$. This is because such more general function leads to the same potential [13] (see also [26]). Second, a variation of this idea where the action includes *only* a quadratic function of both $\mathcal{R}$ and $\mathcal{R}'$, and so it is invariant under $g_{\mu\nu} \rightarrow \Omega^2 g_{\mu\nu}$, for

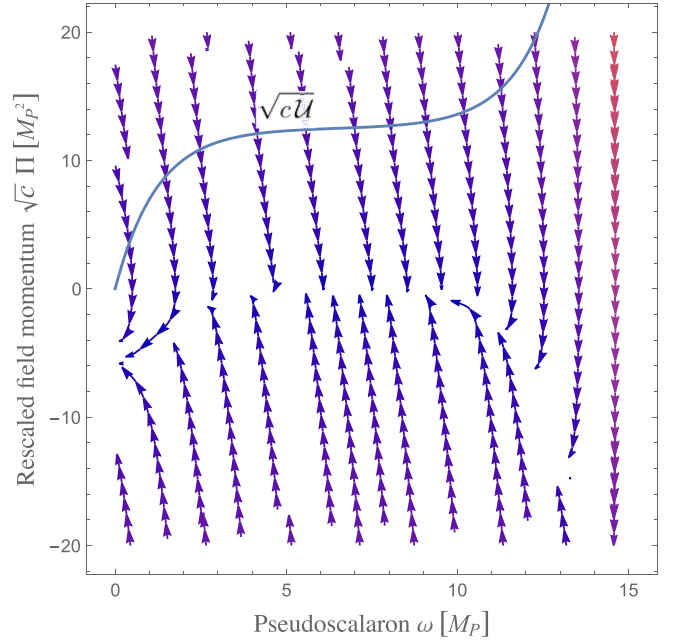


FIG. 1. Phase space of the inflationary dynamical system in (13) together with the square root of the potential energy density, $\sqrt{c}\mathcal{U}$, for comparison. The arrows indicate the directions of motion. The field momentum Π and $\sqrt{c}\mathcal{U}$ have been multiplied by $\sqrt{c}$ to obtain a c -independent plot. Here, $\beta = -25M_P^2$, but for other values of β a qualitatively similar situation is obtained.

a generically spacetime dependent Ω (Weyl invariance), leads again to the same potential [16].

Inflationary predictions. The slow-roll approximation can be used when

$$\epsilon \equiv \frac{M_P^2}{2} \left(\frac{1}{\mathcal{U}} \frac{d\mathcal{U}}{d\omega} \right)^2 \ll 1, \quad \eta \equiv \frac{M_P^2}{\mathcal{U}} \frac{d^2\mathcal{U}}{d\omega^2} \ll 1. \quad (7)$$

If so, the number of e-folds N_e as a function of ω is

$$N_e(\omega) = N(\omega) - N(\omega_{\text{end}}), \quad (8)$$

where

$$N(\omega) = \frac{1}{M_P^2} \int^\omega d\omega' \mathcal{U} \left(\frac{d\mathcal{U}}{d\omega'} \right)^{-1} \quad (9)$$

and ω_{end} is the field value where inflation ends. The quantities n_s , r and the curvature power spectrum P_R (at horizon exit) are then given by

$$n_s = 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon, \quad P_R = \frac{\mathcal{U}/\epsilon}{24\pi^2 M_P^4}. \quad (10)$$

One finds analytic expressions not only for ϵ , η , n_s , r , and P_R , but also for the e-fold function N and ω_{end} , so N_e can

be computed analytically in terms of the generic field value ω (these analytic expressions can be found in [14]).

Here, we are also interested in predicting α_s (at horizon exit), which in the slow-roll approximation is

$$\alpha_s = 16\epsilon\eta - 24\epsilon^2 - 2\xi_2, \quad (11)$$

where the extra slow-roll parameter ξ_2 reads

$$\xi_2 \equiv \frac{M_P^4}{\mathcal{U}^2} \frac{d\mathcal{U}}{d\omega} \frac{d^2\mathcal{U}}{d\omega^2}. \quad (12)$$

Using the explicit expression of $\mathcal{U}$, one finds

$$\xi_2(\omega) = \frac{64M_P^4 \cosh^2(X(\omega))(M_P^2 \sinh(X(\omega)) - \beta)}{9(M_P^2 \sinh(X(\omega)) - 4\beta)^3}.$$

Before comparing these inflationary predictions with observational bounds let us recall that, in using the slow-roll approximation, one is implicitly assuming the initial condition for the field momentum $\Pi \equiv \dot{\omega}$, where a dot is the cosmic-time derivative, to be small compared to the square root of the potential energy density, at least for the relevant values of ω on the inflationary plateau. In general, one wants to explain why this is a reasonable assumption. In the present model, for homogeneous and isotropic metrics [27], initial values of the kinetic energy density Π^2 of order of, or even much larger than, $\mathcal{U}$ are dynamically attracted to small values, where the above-mentioned assumption is automatically verified.

To show this, first note that for inflationary actions of the form (3), with $\mathcal{U}$ not necessarily given by Eq. (4), initial values of Π^2 much larger than $\mathcal{U}$ are always dynamically brought at least down to values comparable to $\mathcal{U}$ [28–30]. There is no model-independent argument showing that Π^2 continues to decrease to values much smaller than the potential energy density, so the explicit form of $\mathcal{U}$ should be considered. The Einstein and inflaton field equations imply the following dynamical system:

$$\begin{cases} \Pi' = -3\Pi - \frac{1}{H} \frac{d\mathcal{U}}{d\omega}, \\ \chi' = \frac{\Pi}{H}, \\ H^2 = \frac{\Pi^2 + 2\mathcal{U}}{6M_P^2}, \end{cases} \quad (13)$$

where a prime is a derivative with respect to N_e and the spatial curvature has been neglected as the energy density is expected to be dominated by the inflaton during inflation. Figure 1 shows the phase space of this system with the directions of motion, illustrating how, even starting from values of Π^2 that are not small compared to $\mathcal{U}$, the dynamics brings the system to negligible values of Π for ω on the inflationary plateau. Slow-roll then takes over as will be shown in Sec. IV.

Facing observational bounds. Note that, as always the case in slow-roll inflation, ϵ , η , and ξ_2 (so also n_s , α_s , and r) are independent of the overall constant in the potential, while P_R is proportional to it. This overall constant is $1/c$ in the present case; see Eq. (4). So, the observed value of P_R (Ref. [3] gives $(2.10 \pm 0.03) \times 10^{-9}$) can always be obtained by choosing c appropriately.

In Fig. 2, it is shown that slow-roll inflation not only occurs but can also remarkably accommodate the recent ACT bounds [1,2] for an appropriate number of e-folds N_e . In Fig. 2, the previous Planck and BK18 bounds of Refs. [3,4] are also shown. In that figure, $r_{0.002}$ is the value of r at the reference momentum scale 0.002 Mpc^{-1} , used by Planck and BK18. One can note that the ACT results [1,2] favor values of $\sqrt{|\beta|}$ closer to M_P compared to the Planck and BK18 bounds of Refs. [3,4]. Values of $\sqrt{|\beta|}$ closer to the other dimensionful scale in the model, M_P , appear to be a more natural setting. For example, the minimal values of $\sqrt{|\beta|}$ to stay in the 1σ region of [1,2] for $N_e = 60$ and $N_e = 49$, respectively, are approximately $4M_P$ and $3M_P$, both of order M_P . The inset in the upper plot of Fig. 2 shows that for these values of β the slow-roll approximation is still valid.

In Fig. 3, $\mathcal{U}$ is plotted as a function of ω for $\beta = -20M_P^2$. One can note that the values of the energy density, $\sim \mathcal{U}$, are well below the Planck scale, the maximal cutoff of the theory (as Einstein's gravity breaks down at that scale). Therefore, if the UV completion of the present model occurs at energies not much smaller than M_P , the effective field theory approach used here is expected to provide a good approximation for the observable quantities.

In Fig. 4, the predictions for α_s (and for ξ_2 in the inset) as a function of β are shown. The predicted α_s is so small to be within approximately the 1σ bounds from both [2] and [32]. The inset of Fig. 4 shows that the extra slow-roll parameter ξ_2 remains small for all relevant values of β .

The values of β favored by ACT [1,2] are compatible with the reheating mechanisms previously proposed in [14] up to a reheating temperature above the electroweak scale. Such efficient reheating can take place even without including extra degrees of freedom besides the Standard Model ones if one just adds to the action the following nonminimal coupling:

$$S_{\text{nm}} = \int \sqrt{-g} \frac{\xi \phi^2}{2} \mathcal{R}, \quad (14)$$

where ϕ is the (canonically normalized) Higgs field in the unitary gauge and ξ is a dimensionless coefficient. This is true even for values of ξ that are not large, guaranteeing perturbative unitarity up to scales close to M_P , where an ultraviolet completion of the effective field theory we are considering should be unavoidably taken into account. Indeed, the term (14) allows for the decay of the pseudo-scalar into two Higgs bosons after inflation, leading to a

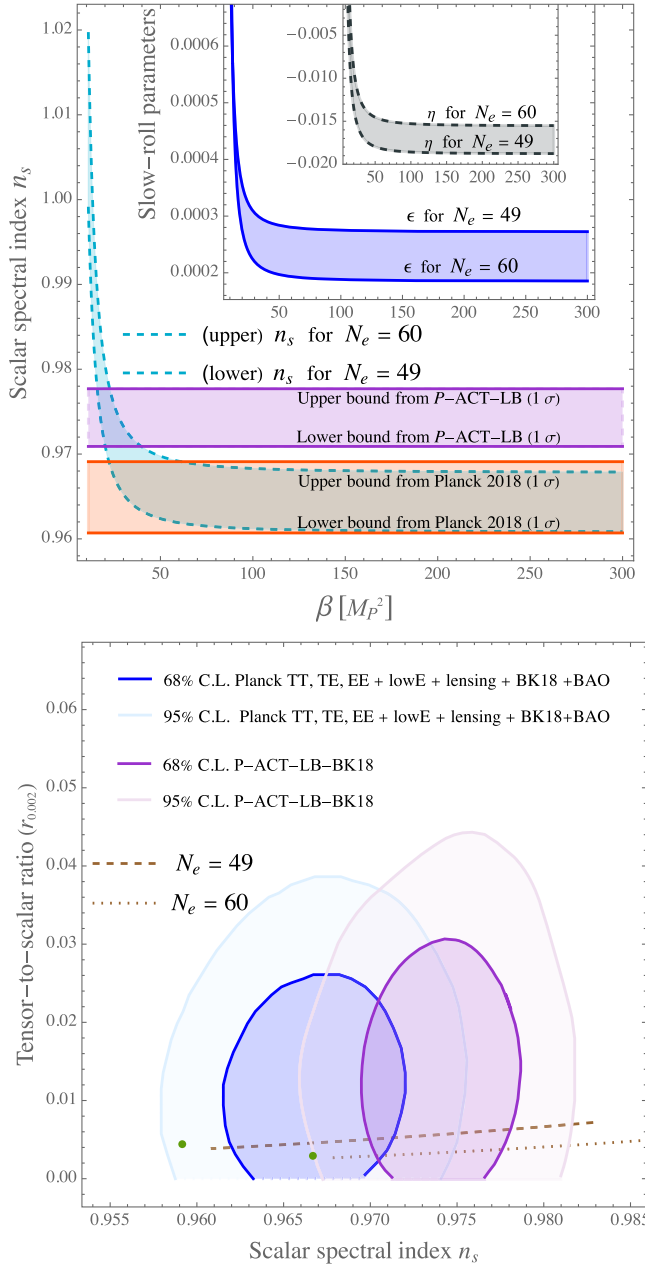


FIG. 2. *Upper plot:* the scalar spectral index n_s predicted by pseudoscalar inflation as a function of β together with the 1σ bounds from P-ACT-LB and Planck 2018 (the second paper in [3]). The inset shows the slow-roll parameters ϵ and η . *Lower plot:* the predictions of pseudoscalaron inflation in the (n_s, r) plane together with the bounds from [3,4] (in blue) and the more recent ones from [1,2]. The green dots in the bottom plot are the predictions of Starobinsky inflation [31].

reheating temperature $T_{\text{RH}} \gtrsim 10^9 |\xi|$ GeV (in the minimal setup considered here and for $|\beta| \gtrsim M_P^2$) [14]. Note that for $|\xi| \gtrsim 1$, the reheating temperature is very large, $T_{\text{RH}} \gtrsim 10^9$ GeV, and even for a very small $|\xi|$, the reheating temperature remains much larger than what is required by observations.

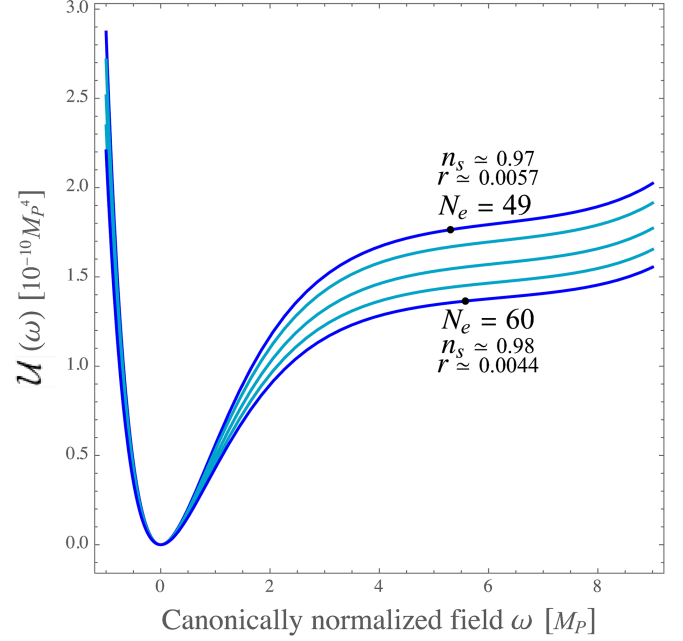


FIG. 3. The potential density as a function of the canonically normalized field. Here, $\beta = -20M_P^2$. For all curves, c is fixed to reproduce $P_R = 2.1 \times 10^{-9}$. Also, the black points correspond to the values of the inflaton for which $N_e = 49$ (upper curve) and $N_e = 60$ (lower curve); the corresponding predictions for n_s and r are also shown.

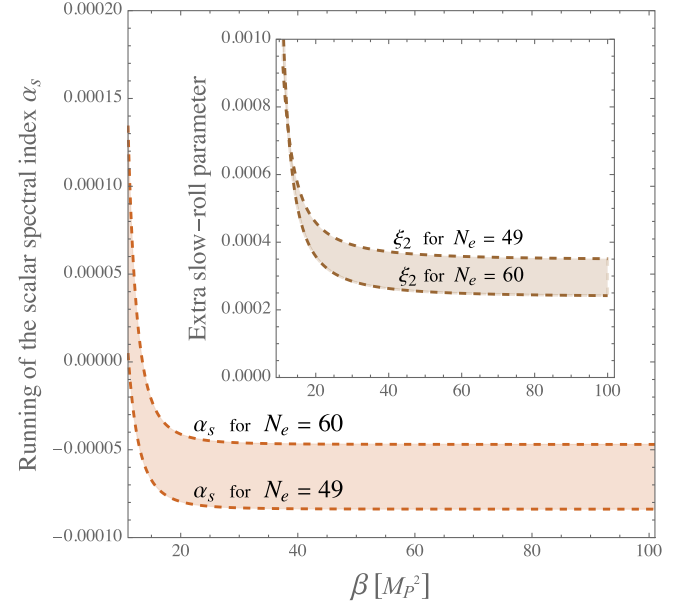


FIG. 4. Running α_s of the scalar spectral index as a function of β . The index shows the extra slow-roll parameter ξ_2 .

The term in (14) is known to be generated by quantum corrections, and, therefore, it is more natural to include it. However, quantum corrections in a perturbative setup are loop suppressed and, therefore, one does not expect a large ξ .

Higgs inflation in both metric gravity (when $\mathcal{A}_\mu^\rho$ equals the Levi-Civita connection) and metric-affine gravity typically uses $\xi \gg 1$ [33] to flatten and suppress the Higgs potential at inflationary scales. As a result, for values of ξ that are sufficiently small (but sufficiently large to have a large-enough T_{RH}) the dynamics of the Higgs boson during inflation is negligible in the minimal setup considered here. In some extended models, however, Higgs inflation can take place even for $\xi = 0$ [34].

Conclusions. According to the new measurements and constraints provided by ACT [1,2] the class of observationally favored inflationary models has significantly changed compared to the previous Planck and BK18 determinations [3,4].

In this work, it has been shown that a simple explanation of the ACT determinations may be provided if the inflaton is a component of a dynamical connection that is independent of the metric. In this way, not only gravity but also inflation has a geometrical origin. This conclusion has been reached by performing a detailed analysis of the inflationary predictions of the minimal model of this sort, whose inflationary action appears in Eq. (1), including n_s , r , P_R , and α_s , and by comparing them with the observational constraints.

Furthermore, here this minimal model has been shown to provide an inflationary attractor: arbitrary initial values of the kinetic energy density are dynamically attracted down

to negligible values compared to the potential energy density in homogeneous and isotropic metrics, for ω on the inflationary plateau.

An interesting aspect is that the new data favor values of $\sqrt{|\beta|}$ closer to the other dimensionful quantity in the model, M_P . This appears to be a more natural setting. For these values of β , however, it is still easy to reheat the Universe up to a temperature much larger than the electroweak scale if a nonminimal coupling of the Higgs boson is introduced, Eq. (14). Such term is generically induced by perturbative quantum corrections, providing a value of ξ typically large enough to establish such reheating, but small enough to neglect the dynamics of the Higgs boson during inflation in the minimal setup considered here.

The values of α_s predicted by the model are very small: as illustrated in Fig. 4, any evidence for α_s significantly above the 10^{-4} order of magnitude would falsify the model.

Interestingly, the requirement that the two scales of the model with mass dimension, M_P and $|\sqrt{\beta}|$, be close to each other (which appears natural) favors values of n_s close to the upper observational bound. This can be tested by future experiments such as LiteBIRD [35].

Data availability. The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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