Cumhuriyet Science Journal
e-ISSN: 2587-246X
ISSN: 2587-2680
Cumhuriyet Sci. J., 42(3) (2021) 728-734
http://dx.doi.org/10.17776/csj.892438

# Preheating in radiatively corrected $\phi^4$ inflation with non-minimal coupling in Palatini formulation

***Nilay BOSTAN*** [1, *]

[1]*The University of Iowa, Department of Physics and Astronomy, Iowa City, IA 52242/U.S.A.*

**Abstract**

We discuss the impact of the preheating stage due to the interaction of the inflaton to fermions in Palatini formulation. In Palatini inflation with large non-minimal coupling, the field is allowed to return to the plateau region during the reheating stage, therefore the average equation of state per oscillations is closer to $-1$ rather than $1/3$. The incursion in the plateau, however, leads to a highly efficient tachyonic instability, which is able to reheat the Universe in less than one e-fold. By taking prescription II into account, which is discussed in the literature, we calculate the spectral index $n_s$ and the tensor-to-scalar ratio r in the wide range of $\kappa - \xi$. We will show the results which are compatible with the data given by the Keck Array/BICEP2 and Planck collaborations.

**Article info**

*History:*
Received:07.03.2021
Accepted:20.07.2021

*Keywords:*
Non-minimal inflation,
Palatini gravity,
Preheating,
Radiative corrections.

## 1. Introduction

Inflation [1-4] is an early period of nearly exponential expansion of the universe, and it has become a solution for several shortcomings such as the horizon, flatness, and unobserved magnetic monopoles since its proposal around 1980. The theory of cosmic inflation gives an acceptable explanation of the large-scale homogeneity of the universe, as well as the primordial density perturbations that grow into the cosmic structure. These primordial perturbations evolve in order to produce the observed large-scale structure and the cosmic microwave background (CMB) temperature anisotropy. In addition to this, several inflationary models have been suggested [5], and most of them are defined by the slow-rolling scalar field which is called the inflaton. Predictions of these models are currently being tested by polarization observations and CMB temperature anisotropies [6, 7]. In particular, the last results released by the Keck Array/BICEP2 and Planck collaborations [8] cast robust constraints on the tensor-to-scalar ratio ($r$), which explains the amplitude of primordial gravitational waves and the scale of inflation. As a result, the predictions of the simple monomial inflation models are ruled out at level, thus the models of non-minimally coupled to gravity become the most popular ones.

In this work, we take models of inflation with non-minimal coupling to gravity ($\xi\phi^2 R$) into account, where $\xi$ is the non-minimal coupling parameter, $\phi$ is the scalar field (inflaton) and $R$ is the Ricci scalar. $\xi\phi^2 R$ term is necessary to provide the renormalizability of the scalar field theory in curved space-time [9]. In addition, the predictions of the inflationary models can change significantly according to the coefficient of this coupling term [5]. We show how the values of $n_s$ and $r$ change for the preheating stage due to the interactions of the inflaton to fermions in Palatini formulation by using prescription II, in the presence of the non-minimal coupling parameter $\xi$. In the literature, many articles have already studied inflation with non-minimal coupling in Metric formalism [10–12]. In particular, the most favorite one is the scenario where the Standard Model Higgs scalar [12] is the inflaton. Furthermore, in the Metric formulation, all model's asymptote to a universal attractor [13], which is called the Starobinsky model, for the large values of $\xi$ independent of the original scalar potential. On the other hand, the attractor behavior of the Starobinsky model is lost in the Palatini formulation, and $r$ can be much smaller in the Palatini formulation compared to the Metric one [14]. Also, consideration of the gravitational degrees of freedom is necessary for the presence of non-minimal coupling to gravity. In the metric formulation of gravity, the independent variables are the metric and its first derivatives [15], while in the Palatini formulation, the independent variables are the connection and the metric [16]. The predictions of these two formalisms correspond to the same equations of motion, therefore they describe equivalent physical theories. However,

*Corresponding author. *e-mail address: nilay-bostan@uiowa.edu*

in the case of non-minimal coupling between gravity and matter, such equivalence disappears, and the two formulations illustrate different gravity theories [14, 17–19]. In the literature, the Palatini formulation of inflation with non-minimal coupling was discussed in refs. [14, 19-21]. The Palatini self-interaction potential $V(\phi)$ was analyzed in ref. [14], and they figured out the observational parameters $n_s \simeq 0.968$ and $r \simeq 10^{-14}$ in the large-field limit. Also, Palatini Higgs inflation was examined in ref. [19], and they showed the range of the tensor-to-scalar ratio as $1 \times 10^{-13} < r < 2 \times 10^{-5}$. According to these papers, $r$ takes very small values in Palatini formulation. In addition to this, it was showed that the radiative corrections to the inflationary potential can play a pivotal role [22–24], in the case of non-minimal coupling to gravity, generating the Planck scale dynamically [25].

In this paper, we study the impact of the preheating stage in Palatini radiatively corrected $\phi^4$ inflation by using prescription II and the coupling of the inflaton to fermions. As compared to the metric formulation, the entropy production in Palatini Higgs inflation appears significantly more effective [20], decreasing the number of e-folds required to solve the flatness and horizon problems, producing a less spectral tilt for the primordial density perturbations. Furthermore, ref. [20] showed that after inflation, the slow decay of the Higgs oscillations allows the field to return to the plateau of the potential periodically during the reheating stage. In addition, in the large-field limit, the effective mass of the Higgs becomes negative, allowing for the exponential creation of Higgs excitations. Consequently, the preheating stage of the Palatini Higgs inflation is primarily instantaneous and this case decreases the value of $N_*$ required to solve the Hot Big-Bang shortcomings [20]. The paper is organized as follows: the non-minimal inflation with Palatini formalism is presented in section 2. In section 3, we explain the radiatively corrected $\phi^4$ potential with radiative corrections. In section 4, we numerically calculate the impact of the preheating stage in Palatini radiatively corrected $\phi^4$ inflation for prescription II and the coupling of inflaton to fermions, and finally, we discuss our results in section 5.

## 2. Non-minimal inflation in Palatini formulation

Assuming the following Lagrangian density for a scalar-tensor theory in the Jordan frame with non-minimally coupled scalar field $\phi$:

$$\frac{\mathcal{L}_J}{\sqrt{-g}} = \frac{1}{2}F(\phi)R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_J(\phi)\,, \tag{1}$$

where the subscript $J$ indicates that the Lagrangian is described in a Jordan frame. In addition, $g^{\mu\nu}$ is a metric tensor, $F(\phi)$ is a non-minimal coupling function and $F(\phi) = 1 + \xi\phi^2$. The Lagrangian consists of a canonical kinetic term and a potential $V_J(\phi)$ in the Jordan frame. We consider the units where the reduced Planck scale, $m_P = 1/\sqrt{8\pi G} \approx 2.4 \times 10^{18}$ GeV, is fixed equal to unity, thus we require $F(\phi) \to 1$ after inflation. Here, $G$ is a gravitational constant. Furthermore, to avoid repulsive gravity, we suppose $F(\phi) > 0$. This property of $F(\phi)$ is independent of the formulation of gravity, such as Metric and Palatini.

In the metric formulation, the connection is described as a function of a metric tensor called Levi-Civita connection $\bar{\Gamma} = \bar{\Gamma}(g^{\mu\nu})$:

$$\bar{\Gamma}^\lambda_{\alpha\beta} = \frac{1}{2}g^{\lambda\rho}\left(\partial_\alpha g_{\beta\rho} + \partial_\beta g_{\rho\alpha} - \partial_\rho g_{\alpha\beta}\right). \tag{2}$$

Unlike the metric formulation, $g_{\mu\nu}$ and $\Gamma$ are independent variables in the Palatini formalism, and the only constraint is that the connection is torsion-free, $\Gamma^\lambda_{\alpha\beta} = \Gamma^\lambda_{\beta\alpha}$. By solving the EoM, we obtain [14]

$$\Gamma^\lambda_{\alpha\beta} = \overline{\Gamma}^\lambda_{\alpha\beta} + \delta^\lambda_\alpha\partial_\beta\omega(\phi) + \delta^\lambda_\beta\partial_\alpha\omega(\phi) - g_{\alpha\beta}\partial^\lambda\omega(\phi), \tag{3}$$

where

$$\omega(\phi) = \ln\sqrt{F(\phi)}. \tag{4}$$

Due to the fact that the connections (Eqs. (2) and (3)) are different, the metric and Palatini formalisms correspond to two different theories of gravity. On the one hand, we can explain the differences by taking into account the problem in the Einstein frame by means of the conformal transformation.

In order to calculate the observational parameters, it is more efficient to switch to the Einstein frame by using a Weyl rescaling $g_{E,\mu\nu} = g_{J,\mu\nu}/F(\phi)$. Then the Einstein frame Lagrangian density becomes [26]

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = \frac{1}{2}R_E - \frac{1}{2Z(\phi)}g_E^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_E(\phi)\,, \tag{5}$$

where

$$Z^{-1}(\phi) = \frac{1}{F(\phi)}\,, \qquad V_E(\phi) = \frac{V_J(\phi)}{F(\phi)^2}, \tag{6}$$

in the Palatini formalism. By making a field redefinition

$$\mathrm{d}\sigma = \frac{\mathrm{d}\phi}{\sqrt{Z(\phi)}}. \tag{7}$$

We find the Lagrangian density for a minimally coupled scalar field $\sigma$ with a canonical kinetic term. Here, $\sigma$ is a canonical scalar field. As a consequence, for the Palatini formalism, the field redefinition is induced just by rescaling the inflaton kinetic term, and it does not include the Jordan frame Ricci scalar. On the other hand, in the Metric formalism, the field redefinition consists of the transformation of the Jordan frame Ricci scalar and the rescaling of the kinetic term of the Jordan frame scalar field [14]. Therefore, we can say that the difference between the metric and Palatini formalisms correspond to the different definitions of $\sigma$ with the different non-minimal kinetic terms including $\phi$.

In the large-field limit, for $F(\phi)=1+\xi\phi^2$, ($|\xi|\phi^2\gg 1$), we can find

$$\phi\simeq\frac{1}{\sqrt{\xi}}\sinh\left(\sigma\sqrt{\xi}\right), \tag{8}$$

in the Palatini formalism. By using eq. (8), the inflationary potential can be described in terms of $\sigma$, so that we can obtain the slow-roll parameters in Palatini formalism for the $|\xi|\phi^2\gg 1$ limit in terms of $\sigma$.

The observational parameters for the inflationary dynamics can be defined by the following slow-roll parameters [27],

$$\epsilon=\frac{1}{2}\left(\frac{V_\sigma}{V}\right)^2, \quad \eta=\frac{V_{\sigma\sigma}}{V}, \tag{9}$$

where $\sigma$'s in the subscript denote derivatives with respect to the canonical scalar field. Observational parameters, i.e. the spectral index $n_s$ and the tensor-to-scalar ratio $r$ can be expressed in terms of the slow-roll parameters as,

$$n_s=1-6\epsilon+2\eta\,, \quad r=16\epsilon. \tag{10}$$

The number of e-folds in the slow-roll approximation is

$$N_*=\int_{\sigma_e}^{\sigma_*}\frac{V\,d\sigma}{V_\sigma}, \tag{11}$$

where the subscript "$_*$" indicates that the scale corresponding to $k_*$ exited the horizon for that quantity, $k_*=0.002$ Mpc$^{-1}$ and $\sigma_e$ is the inflaton value at the end of inflation, which we obtain by using $\epsilon(\sigma_e)=1$.

The amplitude of the curvature power spectrum is given in the form

$$\Delta_{\mathcal{R}}=\frac{1}{2\sqrt{3}\pi}\frac{V^{3/2}}{|V_\sigma|}. \tag{12}$$

The best fit value for the pivot scale $k_*=0.002$ Mpc$^{-1}$ is $\Delta_{\mathcal{R}}^2\approx 2.1\times10^{-9}$ [6] from the Planck results.

Furthermore, we reproduce the slow-roll parameters in terms of the original scalar field $\phi$ to use them in numerical calculations. By using them together with the Eqs. (7) and (9), slow-roll parameters can be figured out in terms of $\phi$ [28]

$$\epsilon=Z\epsilon_\phi\,, \ \eta=Z\eta_\phi+\mathrm{sgn}(V')Z'\sqrt{\frac{\epsilon_\phi}{2}}, \tag{13}$$

where we defined

$$\epsilon_\phi=\frac{1}{2}\left(\frac{V'}{V}\right)^2, \quad \eta_\phi=\frac{V''}{V}\ . \tag{14}$$

Here, $V'\equiv dV/d\phi$. Similarly, Eqs. (11) and (12) can be found in terms of $\phi$ by using

$$N_*=\mathrm{sgn}(V')\int_{\phi_e}^{\phi_*}\frac{\mathrm{d}\phi}{Z(\phi)\sqrt{2\epsilon_\phi}}, \tag{15}$$

$$\Delta_{\mathcal{R}}=\frac{1}{2\sqrt{3}\pi}\frac{V^{3/2}}{\sqrt{Z}|V'|}. \tag{16}$$

These observable parameters that depend on the number of e-folds of inflation are required to solve such problems, i.e. the flatness and horizon. Following the standard method, we need

$$1=a_0=\frac{a_0}{a_{\mathrm{RH}}}\frac{a_{\mathrm{RH}}}{a_e}\frac{a_e}{a_*}a_*=\left(\frac{g_{*s\,\mathrm{RH}}}{g_{*s\,\mathrm{now}}}\right)^{1/3}\frac{T_{\mathrm{RH}}}{T_0}\frac{k_*}{H_*}\exp(\Delta N+N_*), \tag{17}$$

where "0" denotes that the value of the corresponding quantity is the one at the present time (as used throughout this paper), and ("RH") indicates that the value of the quantity is the one at the end of the reheating stage. In addition, ("$e$") indicates at the end of inflation, and ("*") illustrates the pivot scale corresponding to $k_*=0.002$ Mpc$^{-1}$ crosses the horizon. The quantity $\Delta N$ indicates the number of e-folds of reheating, $g_{*s}$ is the effective number of entropy degrees of freedom with $g_{*s\,\mathrm{RH}}=g_{*\,\mathrm{RH}}$, as well as $g_{*s\,now}=3.94$ [29] and $T_0\simeq 2.7$ K. $T_{\mathrm{RH}}$ is the reheating temperature [30]. In ref. [20], $N_*$ is defined in the preheating stage of the Palatini Higgs inflation, which is necessarily instantaneous. Here, $g_{*s\,now}$ shows the current value of the effective number of entropy degrees of freedom. After the inflation, almost all of the background energy density is converted to the radiation, and by solving eq. (17) for the condition of $\Delta N\ll 1$, $N_*$ can be found in the form [20]

$$N_*\simeq 54.9-\frac{1}{4}\log\xi, \tag{18}$$

this result is precise to an integer order of $N_*$. In section 4, we numerically figure out the impact of the preheating stage in Palatini radiatively corrected $\phi^4$ inflation for prescription II and inflaton to fermions coupling by using eq. (18).

## 3. Radiatively corrected $\phi^4$ potential with radiative corrections

For the description of the couplings of the inflaton with other fields, it is necessary to produce radiative corrections in the inflationary potential for effective reheating. These corrections can be defined at the leading order in the form [31–33],

$$\Delta V(\phi) = \sum_i \frac{(-1)^\nu}{64\pi^2} M_i(\phi)^4 \ln\left(\frac{M_i(\phi)^2}{\mu^2}\right). \quad (19)$$

Here, $\nu$ is +1 (−1) for bosons (fermions), $\mu$ is a renormalization scale and $M_i(\phi)$ corresponds to the field-dependent mass.

We consider the minimally coupled $\phi^4$ potential interacting with another scalar $\chi$ and a Dirac fermion $\Psi$ in the form,

$$V(\phi,\chi,\Psi) = \frac{\lambda}{4}\phi^4 + h\phi\bar{\Psi}\Psi + m_\Psi\bar{\Psi}\Psi + \frac{1}{2}g^2\phi^2\chi^2 + \frac{1}{2}m_\chi^2\chi^2. \quad (20)$$

Here, $\lambda$ is a self-coupling constant, $g$ ($h$) are bosons (fermions) coupling constants, and $m_\Psi$ ($m_\chi$) are the mass terms for Dirac fermions (scalars). We assume that, with these approximations

$$g^2\phi^2 \gg m_\chi^2, \qquad g^2 \gg \lambda,$$
$$h\phi \gg m_\Psi, \qquad h^2 \gg \lambda, \quad (21)$$

the inflationary potential consisting of the Coleman-Weinberg one-loop corrections given by eq. (19) can be found in the form

$$V(\phi) \simeq \frac{\lambda}{4}\phi^4 \pm \kappa\phi^4 \ln\left(\frac{\phi}{\mu}\right), \quad (22)$$

where + (−) sign indicates the inflaton coupling to bosons (fermions). We can describe the coupling parameter as follows

$$\kappa \equiv \frac{1}{32\pi^2}|(g^4 - 4h^4)|. \quad (23)$$

Here, the potential in eq. (22) is just an approximation of the one-loop RG improved effective actions [34].

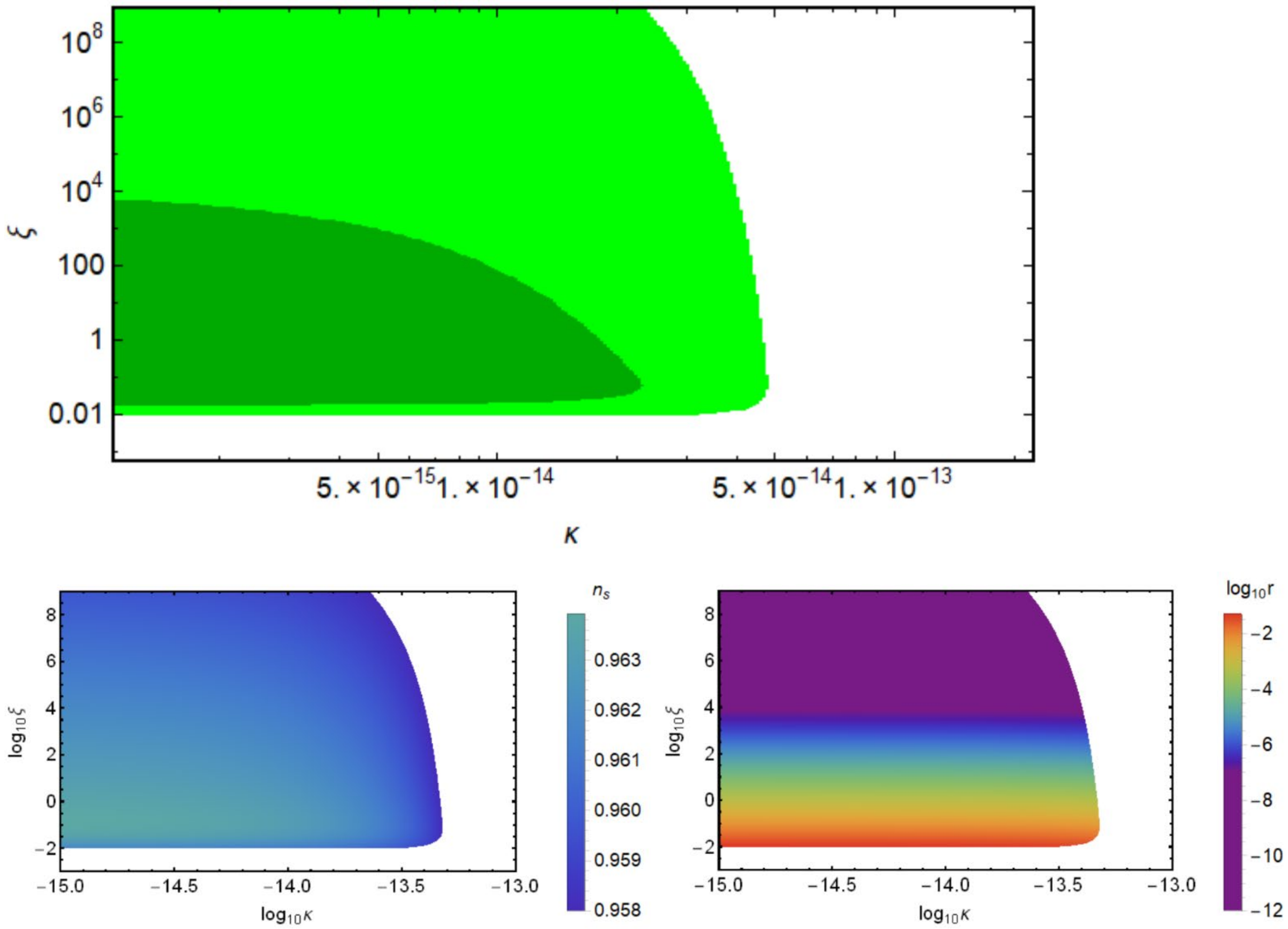


**Figure 1**. The top figure in light green (green) illustrates the regions in the $\kappa - \xi$ plane where the $n_s$ and r values are inside the 95% (68%) CL contours based on data given by the Keck Array/BICEP2 and Planck collaborations [8]. Bottom figures display $n_s$ and r values in these regions.

As discussed in the literature, one of the two different prescriptions is prescription II that is typically used for the calculation of radiative corrections [35–38]. In prescription II, the field-dependent masses in the one-loop Coleman-Weinberg potential are described in the Jordan frame, therefore eq. (22) corresponds to the one-loop Coleman-Weinberg potential in the Jordan frame. As a consequence, the Einstein frame potential for the interactions of the inflaton and fermions in prescription II is described by

$$V(\phi) = \frac{\frac{\lambda}{4}\phi^4 - \kappa\phi^4 \ln\left(\frac{\phi}{\mu}\right)}{(1+\xi\phi^2)^2} . \tag{24}$$

We can say that the variation of the value of the renormalization scale does not affect the form of the potential in eq. (24). The form of the potential only changes with a shift in $\lambda$. As a result, observational parameters do not change depending upon $\mu$ as well.

## 4. Inflationary results

In this section, we numerically investigate the effect of the preheating stage in Palatini radiatively corrected $\phi^4$ inflation for prescription II and coupling of the inflaton to fermions. Figure 1 displays the regions in the κ-ξ plane where the $n_s$ and $r$ values are inside the 95% (68%) CL (confidence levels) contours based on data given by the Keck Array/BICEP2 and Planck collaborations. As it can be seen from Fig.1, for the values of $10^{-2} \lesssim \xi \lesssim 10^4$ and $10^{-15} \lesssim \kappa \lesssim 2.2 \times 10^{-14}$, observational parameters can be within the 68% CL contour based on the data given by the Keck Array/BICEP2 and Planck collaborations, and their values are $n_s \simeq 0.963$ and $10^{-7} \lesssim r \lesssim 10^{-2}$. On the other hand, as $\kappa$ increases, it reaches a maximum value, $\kappa_{\max}$, for each $\xi$ value. For $\kappa > \kappa_{\max}$, there are no solutions that provide the inflationary dynamics. Furthermore, in the range of $10^4 \lesssim \xi \lesssim 10^8$ and $10^{-15} \lesssim \kappa \lesssim 5 \times 10^{-14}$, we find $0.958 \lesssim n_s \lesssim 0.961$ and $10^{-12} \lesssim r \lesssim 10^{-7}$. These values are in the 95% CL contour based on the data given by the Keck Array/BICEP2 and Planck collaborations. As a result, for $10^4 \lesssim \xi \lesssim 10^8$ and $N_* \simeq 52$, we obtain $0.958 \lesssim n_s \lesssim 0.961$. Although still in $2\sigma$ confidence limits, these $n_s$ values slightly disagreed with the observational results given by the Keck Array/BICEP2 and Planck collaborations, as well as the values of $r$ are extremely tiny in the large $\xi$ limits. Ref. [20] also showed that for the preheating stage of Higgs inflation in Palatini formulation, $n_s \simeq 0.961$ and $r$ values are very tiny for large $\xi$ values for the $N_* \simeq 51$ and finally, the behavior of Starobinsky attractor in metric formulation for large $\xi$ values is lost for the potential we take into account.

## 5. Conclusion

In this paper, we described the non-minimal inflation in Palatini formulation in section 2, and then in section 3, we briefly presented the radiatively corrected $\phi^4$ potential with radiative corrections. We numerically investigated the impact of the preheating stage on the observational parameters for this type of potential for fermions coupling in section 4.

In general, we found that $r$ values are too small in the large-field limit, and the behavior of Starobinsky attractor in metric formulation for the large $\xi$ values disappears for the potential which we considered. Furthermore, we found that for the cases of $\kappa > \kappa_{\max}$, there are no solutions that provide inflationary dynamics and for the values of $10^4 \lesssim \xi \lesssim 10^8$ and $N_* \simeq 52$, $n_s$ values are in $2\sigma$ CL but marginally incompatible with the observational results.

In the large-field limit, for the Palatini formulation, the process of entropy production emerges very efficiently and leads to the complete reduction of the inflaton condensate in an e-fold expansion of smaller than one [20]. As a consequence, in the preheating stage, Palatini inflation with the radiative corrections to the coupling of fermions in prescription II is necessarily instantaneous, and after the inflation, almost all of the background energy density is converted to the radiation. This decreases the value of $N_*$ required to solve the common Hot Big-Bang shortcomings, while an insignificantly smaller value for the spectral tilt produces.

Finally, by the consideration of $\mathcal{O}(10^{-3})$ accuracy of future precision measurements [38], the predictions of Palatini formulation could be distinguished from the metric ones within forthcoming results, and assuming larger values of $r$ are obtained, the Palatini formulation can be ruled out.

## Acknowledgements

The author thanks Javier Rubio and Ohannes Kamer Koseyan for their useful discussions.

## Conflicts of interest

The author states that did not have conflict of interests.

## References

[1] Guth A. H., The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems, *Phys. Rev. D*, 23 (1981) 347-356.

[2] Linde A. D., A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems, *Phys. Lett.*, 108B (1982) 389-393.

[3] Albrecht A., Steinhardt P. J., Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking, *Phys. Rev. Lett.*, 48 (1982) 1220-1223.

[4] Linde A. D., Chaotic Inflation, *Phys. Lett.*, 129B (1983) 177-181.

[5] Martin J., Ringeval C., Vennin V., Encyclopædia Inflationaris, *Phys. Dark Univ.*, 5-6 (2014) 75-235, arXiv:1303.3787.

[6] Aghanim N. et al. [Planck Collaboration], Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.*, 641 (2020) A6, arXiv:1807.06209.

[7] Akrami Y. et al. [Planck Collaboration], Planck 2018 results. X. Constraints on inflation, *Astron. Astrophys.*, 641 (2020) A10, arXiv:1807.06211.

[8] Ade P. A. R. et al. [BICEP2 and Keck Array Collaborations], BICEP2 / Keck Array x: Constraints on Primordial Gravitational Waves using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season, *Phys. Rev. Lett.*, 121 (2018) 221301, arXiv:1810.05216.

[9] Callan, Jr. C. G., Coleman S. R., Jackiw R., A New improved energy-momentum tensor, *Annals Phys.*, 59 (1970) 42-73.

[10] Bezrukov F., Magnin A., Shaposhnikov M., Sibiryakov S., Higgs inflation: consistency and generalisations, *JHEP*, 1101 (2011) 016, arXiv:1008.5157.

[11] Bostan N., Güleryüz Ö., Şenoğuz V. N., Inflationary predictions of double-well, Coleman-Weinberg, and hilltop potentials with non-minimal coupling, *JCAP*, 1805 no. 05 (2018) 046, arXiv:1802.04160.

[12] Bezrukov F. L., Shaposhnikov M., The Standard Model Higgs boson as the inflaton, *Phys. Lett. B*, 659 (2008) 703-706, arXiv:0710.3755.

[13] Kallosh R., Linde A., Roest D., Universal Attractor for Inflation at Strong Coupling, *Phys. Rev. Lett.*, 112 no. 1 (2014) 011303, arXiv:1310.3950.

[14] Bauer F., Demir D. A., Inflation with Non-Minimal Coupling: Metric versus Palatini Formulations, *Phys. Lett. B*, 665 (2008) 222-226, arXiv:0803.2664.

[15] Padmanabhan T., Holographic gravity and the surface term in the Einstein-Hilbert action, *Braz. J. Phys.*, 35 (2005) 362-372, arXiv:gr-qc/0412068.

[16] Palatini A., Deduzione invariantiva delle equazioni gravitazionali dal principio di Hamilton, *Rendiconti del Circolo Matematico di Palermo (1884-1940)*, 43(1) (1919) 203-212.

[17] York, Jr J. W., Role of conformal three geometry in the dynamics of gravitation, *Phys. Rev. Lett.*, 28 (1972) 1082-1085.

[18] Tenkanen T., Resurrecting Quadratic Inflation with a non-minimal coupling to gravity, *JCAP*, 1712 no. 12 (2017) 001, arXiv:1710.02758.

[19] Rasanen S., Wahlman P., Higgs inflation with loop corrections in the Palatini formulation, *JCAP*, 1711 no. 11 (2017) 047, arXiv:1709.07853.

[20] Rubio J., Tomberg E. S., Preheating in Palatini Higgs inflation, *JCAP*, 1904 (2019) 021.

[21] Fu C., Wu P., Yu H., Inflationary dynamics and preheating of the nonminimally coupled inflaton field in the metric and Palatini formalisms, *Phys. Rev. D*, 96 no. 10 (2017) 103542, arXiv:1801.04089.

[22] Marzola L., Racioppi A., Raidal M., Urban F. R., Veermäe H., Non-minimal CW inflation, electroweak symmetry breaking and the 750 GeV anomaly, *JHEP*, 1603 (2016) 190, arXiv:1512.09136.

[23] Marzola L., Racioppi A., Minimal but non-minimal inflation and electroweak symmetry breaking, *JCAP*, 1610 no. 10 (2016) 010, arXiv:1606.06887.

[24] Dimopoulos K., Owen C., Racioppi A., Loop inflection-point inflation, *Astropart. Phys.*, 103 (2018) 16-20, arXiv:1706.09735.

[25] Kannike K., Racioppi A., Raidal M., Linear inflation from quartic potential, *JHEP*, 1601 (2016) 035, arXiv:1509.05423.

[26] Fujii Y., Maeda K., The scalar-tensor theory of gravitation, Cambridge, UK: Cambridge University Press, (2007).

[27] Lyth D. H., Liddle A. R., The primordial density perturbation: Cosmology, inflation and the origin of structure, Cambridge, UK: Cambridge Univ. Pr., (2009).

[28] Linde A., Noorbala M., Westphal A., Observational consequences of chaotic inflation with nonminimal coupling to gravity, *JCAP*, 1103 (2011) 013, arXiv:1101.2652.

[29] Husdal L., On Effective Degrees of Freedom in the Early Universe, *Galaxies*, 4 no. 4 (2016) 78, arXiv:1609.04979.

[30] Gialamas I. D., Lahanas A. B., Reheating in $R^2$ Palatini inflationary models, *Phys. Rev. D*, 101 no. 8 (2020) 084007, arXiv:1911.11513.

[31] Coleman S. R., Weinberg E. J., Radiative Corrections as the Origin of Spontaneous Symmetry Breaking, *Phys. Rev. D*, 7 (1973) 1888-1910.

[32] Enqvist K., Karciauskas M., Does Planck really rule out monomial inflation?, *JCAP*, 1402 (2014) 034, arXiv:1312.5944.

[33] Weinberg E. J., Radiative corrections as the origin of spontaneous symmetry breaking, Ph.D. Thesis, Harvard University, Department of Physics, April 1973, arXiv: hep-th/0507214, arXiv:1005.5161.

[34] Okada N., Rehman M. U., Shafi Q., Tensor to Scalar Ratio in Non-Minimal $\phi^4$ Inflation, *Phys. Rev. D*, 82 (2010) 043502, arXiv:1005.5161.

[35] De Simone A., Hertzberg M. P., Wilczek F., Running Inflation in the Standard Model, *Phys. Lett. B*, 678 (2009) 1-8, arXiv:0812.4946.

[36] Barvinsky A. O., Kamenshchik A. Y., Kiefer C., Starobinsky A. A., Steinwachs C., Asymptotic freedom in inflationary cosmology with a non-minimally coupled Higgs field, *JCAP*, 0912 (2009) 003, arXiv:0904.1698.

[37] Barvinsky A. O., Kamenshchik A. Y., Kiefer C., Starobinsky A. A., Steinwachs C. F., Higgs boson, renormalization group, and naturalness in cosmology, *Eur. Phys. J. C*, 72 (2012) 2219, arXiv:0910.1041.

[38] M. Remazeilles et al. [CORE Collaboration], Exploring cosmic origins with CORE: B-mode component separation, *JCAP*, 1804 no. 04 (2018) 023, arXiv:1704.04501.