Turkish Journal of Physics

http://journals.tubitak.gov.tr/physics/

Research Article

Turk J Phys
(2024) 48: 28 – 39
© TÜBİTAK
doi:10.55730/1300-0101.2754

Reheating constraints to Palatini Coleman-Weinberg inflation

Nilay BOSTAN*
Proton Accelerator Facility, Turkish Energy Nuclear and Mineral Research Agency
Nuclear Energy Research Institute, Ankara, Turkiye

Received: 16.08.2023 • **Accepted/Published Online:** 16.02.2024 • **Final Version:** 21.02.2024

Abstract: In this work, we examine the reheating constraints to symmetry-breaking mechanism, which is associated with Coleman-Weinberg inflation in the early universe. We consider the Coleman-Weinberg inflation potential, where the inflaton has a $v \neq 0$ after inflation. Setting $T_{reh} = 10^5$ GeV, we first show w_{reh} dependency on n_s, r, and N_* for AV case. Then, we demonstrate the results of n_s, r, N_*, $\alpha = \mathrm{d}n_s/\mathrm{d}\ln k$ for different reheating temperatures and compare the results with the latest BICEP/Keck data. We also present that $n_s - r$ and $n_s - N_*$ planes and the effect of reheating temperature which is in a wide range, on inflationary predictions for both AV and BV cases. Finally, we indicate how N_* and α change according to the reheating temperature values.

Keywords: Cosmology, inflation, reheating

1. Introduction

The theory of inflation was first proposed in 1979 by Guth, and the theory began to develop in the early 1980s [1–4]. Inflation is thought to explain the origin of the large-scale structure of the universe, why the universe is isotropic, homogeneous and flat, as well as why no magnetic monopole has occurred in the universe. Inflation also causes dilution of objects such as magnetic monopoles, which are likely to result from symmetry-breaking in the early universe, thus providing an explanation for why such objects are not currently observed. Furthermore, inflationary models are based on the scalar field which is slowly-rolling ϕ, with a require flat potential $V(\phi)$. Most of the inflationary scenarios that have been examined so far are based on inflaton, see [5].

On the other hand, when inflationary epoch ends, the energy density of the inflaton field (ϕ) turns into radiation, and the radiation phase in standard cosmology begins. This transfer process is called reheating [6–12]. When this reheating process completes, the universe becomes completely filled with radiation in thermal equilibrium. The temperature at which the universe is in thermal equilibrium and radiation dominates is called the reheating temperature, T_{reh}. At the end of inflationary period, until the universe is reheated, ϕ oscillates around the minimum of inflation potential. This happens within the reheating phase, at which ϕ decays into Standard Model (SM) particles which populate the universe, they interact with each other, and finally reaching thermal equilibrium. In addition to this, as the inflaton oscillates, either the inflaton decays directly into SM particles or the inflaton decays into

*Correspondence: nilay.bostan@tenmak.gov.tr

other particles and these particles into SM particles. Thus, reheating process is essential for standard hot Big Bang, it provides remarkable explanation for the origin of the particles in the universe. This phase is also the conversion period, until the inflation ends, where the ϕ decays and it passes its all energy to the SM particles. In addition, in general, the inflation models can reach the reheating temperature up to large values of $T_{reh} \sim 10^{16}$ GeV, which is the GUT scale and for lower values, such as $T_{reh} = 1$ MeV, which is the scale of Big Bang nucleosynthesis (BBN). In addition, reheating phase is parameterized with w_{reh}, called equation-of-state parameter. For instance, $w_{reh} = -1/3$ at which the inflation end, and then radiation dominated period begins at $w_{reh} = 1/3$, it also indicates the instantaneous reheating. Moreover, $w_{reh} = 0$ means that reheating happens by means of the decay of inflaton to particles with mass. In the case of $w_{reh} = 0$, coherent oscillations of the inflaton dominates the reheating process and $w_{reh} = 0$ is equivalent to the value of presureless dust, matter which also has $w_{reh} = 0$.

In this work, we have given the inflationary predictions for the Coleman-Weinberg potential, which is one of the pivotal symmetry-breaking type potentials, we calculate the predictions for different T_{reh} values. We present the results of n_s and r with the consideration of the standard thermal history after inflation. We also show the compatible regions of the n_s and r within the recent BICEP/Keck data. Furthermore, we consider the nonminimal coupling of gravity, including $\xi\phi^2 R$ term between the Ricci scalar and inflaton. In curved space-time, this term is essential for the renormalizable scalar field theory [13–15]. In addition, regarding ξ parameter in this term, the inflationary predictions vary, it also directly effects whether inflation takes place or not accordingly [16–24]. It is important to mention here, in this work, we analyze the Coleman-Weinberg potential in Palatini formulation of gravity. As is widely known, for a nonminimally coupled inflation, the predictions of metric formulation of gravity gives different results for the cosmological parameters than the Palatini one. In the literature, a vast number of studies consider inflation with nonminimal coupling in metric or Palatini formulation, for details, see the following papers [25–37]. Furthermore, there are another methods in the literature for the inflation. One of them is the affine approach, affine inflation, see [38, 39]. Affine gravity [40] is based on the connection with no notion of metric. This framework needs the scalar fields which have nonvanishing potentials, as a result it is deemed that affine gravity is important while working on inflation. Another one is the inflation in symmergent metric-Palatini gravity that is the new framework that combines gravity and the standard model so that the gravity arises from the matter loops and restores the broken gauge symmetries all the way, for the recent study, see [41].

The paper is organized as follows: we first briefly explain the nonminimally coupled inflation to gravity by considering Palatini formulation (Section 2), we then discuss symmetry-breaking type Coleman-Weinberg inflation potential and show our results for this potential in Palatini gravity with details for different T_{reh} values in Section 3. Finally, in Section 4, we discuss our results and conclude the paper.

2. Inflation with nonminimal coupling to gravity

In this section, we begin considering nonminimally coupled inflation with a canonical kinetic term and a potential $V_J(\phi)$ in Jordan frame. In this instance, Lagrangian density in Jordan frame is described as follows:

$$\mathcal{L}_J/\sqrt{-g} = \frac{1}{2}K(\phi)R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_J(\phi), \tag{2.1}$$

here, we use the units, with the reduced Planck scale $M_P = 1/\sqrt{8\pi G} \approx 2.4 \times 10^{18}$ GeV equals to 1, G is the gravitational constant. $K(\phi)$ is the nonminimal coupling function, and in this work, we define this function with the following form [27]

$$K(\phi) = 1 + \xi(\phi^2 - v^2), \tag{2.2}$$

where v is the vacuum expectation value (VEV) of the inflaton. $V_J(\phi)$ is the Jordan frame potential. Note that, here, ξ is the dimensionless numbers. Also, after inflation, $K(\phi) \to 1$ or $\phi \to 0$. In this work, we consider the well-known inflationary potential, which is one of the important symmetry-breaking potentials, namely the Coleman-Weinberg (CW) potential. We examine this potential for two different cases:

- *Above the VEV (AV):* $\phi > v$,
- *Below the VEV (BV):* $\phi < v$.

On the other hand, it is more convenient to compute the inflationary predictions in the Einstein frame. Utilizing Weyl rescaling, $g_{E,\mu\nu} = g_{J,\mu\nu}/K(\phi)$, we can convert the Jordan frame to Einstein frame (E). It is noteworthy that in the Einstein frame, all matter couplings become ϕ dependent. Consequently, since $g_{J,\mu\nu} = K(\phi) g_{E,\mu\nu}$, the inflaton can decay into matter by $K(\phi)$ during the reheating phase at the end of inflation. By using Weyl rescaling, one can obtain Einstein frame Lagrangian density from Jordan frame with the following form

$$\mathcal{L}_E/\sqrt{-g_E} = \frac{1}{2}R_E - \frac{1}{2K(\phi)} g_E^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_E(\phi) \to \text{in Palatini formulation}, \tag{2.3}$$

where

$$V_E(\phi) = \frac{V_J(\phi)}{K(\phi)^2} \to \text{Einstein frame potential}. \tag{2.4}$$

In the next section, we introduce observable parameters of inflation with detail.

2.1. Observable parameters of inflation

The slow-roll parameters in terms of canonical scalar field (σ) can be found by using Einstein frame potential with the following descriptions [42]

$$\epsilon = \frac{1}{2}\left(\frac{V_\sigma}{V}\right)^2, \quad \eta = \frac{V_{\sigma\sigma}}{V}, \quad \zeta^2 = \frac{V_\sigma V_{\sigma\sigma\sigma}}{V^2}, \tag{2.5}$$

where the subscripts σ's indicate derivatives. In the case of the slow-roll approximation, inflationary predictions can be expressed in the following forms

$$\begin{aligned} n_s &= 1 - 6\epsilon + 2\eta, \quad r = 16\epsilon, \\ \alpha &= \frac{\mathrm{d}n_s}{\mathrm{d}\ln k} = 16\epsilon\eta - 24\epsilon^2 - 2\zeta^2, \end{aligned} \tag{2.6}$$

where n_s is the (scalar) spectral index, r, the tensor-to-scalar ratio, and α is the running of the spectral index. In addition, in the slow-roll approximation, the number of e-folds is given with this form

$$N_* = \int_{\sigma_e}^{\sigma_*} \frac{V \mathrm{d}\sigma}{V_\sigma}\,. \tag{2.7}$$

The subscript "$_*$" indicates the quantities at the scale corresponding to k_* exited the horizon. σ_e gives the inflaton value at the end of inflation, its value can be found by using $\epsilon(\sigma_e) = 1$.

Furthermore, N_* should be within approximately $55-60$ to solve the horizon problem. The exact value of N_* should depend on the evolution of the universe, thus we assume a standard thermal history after inflation and consider that N_* takes the following form [43]

$$N_* \approx 64.7 + \frac{1}{2}\ln\rho_* - \frac{1}{3(1+\omega_{reh})}\ln\rho_e + \Big(\frac{1}{3(1+\omega_{reh})} - \frac{1}{4}\Big)\ln\rho_{reh}, \tag{2.8}$$

where $\rho_e = (3/2)V(\phi_e)$ and ρ_{reh} are the energy densities at the end of inflation and at the end of reheating, respectively. ρ_{reh} can be found by using the Standard Model value of the number of relativistic degrees of freedom, $g_* = 106.75$. Also, $\rho_* \approx V(\phi_*)$ is the energy density at the pivot scale. ρ_{reh} and ρ_* have the definitions as follows:

$$\rho_{reh} = \Big(\frac{\pi^2}{30}106.75\Big)T_{reh}^4, \qquad \rho_* = \frac{3\pi^2\Delta_\mathcal{R}^2 r}{2}, \tag{2.9}$$

here, T_{reh} is the reheating temperature, r, the tensor-to-scalar ratio, which we already defined above. Also, $\Delta_\mathcal{R}^2$ corresponds to the amplitude of curvature perturbation that is given as follows:

$$\Delta_\mathcal{R}^2 = \frac{1}{12\pi^2}\frac{V^3}{V_\sigma^2}, \tag{2.10}$$

which should be consistent with $\Delta_\mathcal{R}^2 \approx 2.1 \times 10^{-9}$ from the Planck results [44] for the pivot scale $k_* = 0.002$ Mpc^{-1}. As the last one, ω_{reh} is the equation-of-state parameter during reheating. In this work, particularly, we will show the inflationary predictions, n_s, r, N_*, α of Coleman-Weinberg potential taking $\omega_{reh} = 1/3$ and $\omega_{reh} = 0$ for different T_{reh} values by using Eq. (2.8), we display the results for very broad ranges of T_{reh}. The potential, which is considered in this work, is related to symmetry-breaking in the early universe; therefore, we take $v \neq 0$ after inflation, as well as, we display the results in the broad ranges of v for both AV and BV cases.

Moreover, we can write the slow-roll parameters in terms of ϕ, and the definitions can be written as follows [45]:

$$\epsilon = K\epsilon_\phi\,, \quad \eta = K\eta_\phi + \mathrm{sgn}(V')K'\sqrt{\frac{\epsilon_\phi}{2}},$$
$$\zeta^2 = K\left(K\zeta_\phi^2 + 3\mathrm{sgn}(V')K'\eta_\phi\sqrt{\frac{\epsilon_\phi}{2}} + K''\epsilon_\phi\right), \tag{2.11}$$

here, we define

$$\epsilon_\phi = \frac{1}{2}\left(\frac{V'}{V}\right)^2, \quad \eta_\phi = \frac{V''}{V}, \quad \zeta_\phi^2 = \frac{V'V'''}{V^2}\,. \tag{2.12}$$

Also, Eqs. (2.7) and (2.10) can be found in terms of ϕ in these forms

$$N_* = \mathrm{sgn}(\mathrm{V}') \int_{\phi_\mathrm{e}}^{\phi_*} \frac{\mathrm{d}\phi}{\mathrm{K}(\phi)\sqrt{2\epsilon_\phi}}, \tag{2.13}$$

$$\Delta_\mathcal{R} = \frac{1}{2\sqrt{3}\pi} \frac{V^{3/2}}{\sqrt{K}|V'|}. \tag{2.14}$$

3. Coleman-Weinberg inflation

The symmetry-breaking due to the Coleman-Weinberg mechanism has been related with inflation since 1980s at which new inflation models were first introduced [2, 3, 46–48]. The effective potential in Jordan frame is written as follows:

$$V_J(\phi) = A\phi^4 \left[\ln\left(\frac{\phi}{v}\right) - \frac{1}{4}\right] + \frac{Av^4}{4}. \tag{3.1}$$

We can write the potential in Einstein frame by using the nonminimal coupling function which is defined in Eq. (2.2) as

$$V_E(\phi) = \frac{A\phi^4 \left[\ln\left(\frac{\phi}{v}\right) - \frac{1}{4}\right] + \frac{Av^4}{4}}{\left[1 + \xi(\phi^2 - v^2)\right]^2}. \tag{3.2}$$

For this potential, minimal coupling ($\xi = 0$) case is already considered in several works [49–52]. This potential in Palatini and metric formulation is also examined in these studies [35, 53] by using the assumption of instant reheating, $w_{reh} = 1/3$. Note that here, for $w_{reh} = 1/3$, N_* does not depend on the reheating temperature at all. Furthermore, the Coleman-Weinberg potential with nonminimal coupling to gravity for $w_{reh} = 0$ and different T_{reh} values are considered with detail in [54], they use metric formulation of gravity and only for selected v values. On the other hand, in this work, we present our results for Palatini formulation. We first show how to vary n_s, r, and N_* according to the w_{reh} values, we show the results while setting $T_{reh} = 10^5$ GeV and for AV case. Then, we show our results for both AV and BV cases for $w_{reh} = 1/3$ and $w_{reh} = 0$ for different T_{reh} values, and the effect of wide ranges of T_{reh} values on the inflationary predictions. As a final step, we show T_{reh} dependency on N_* and α by taking $w_{reh} = 0$.

3.1. Results

In this section, we present our results for the Coleman-Weinberg potential in Palatini formulation using the Einstein frame potential which is given in Eq. (3.2). We first display $w_{reh} - n_s$, $w_{reh} - r$ and $w_{reh} - N_*$ predictions for $\phi > v$, $\xi = 10^{-1.5}$ and $v = 0.01$ in Figure 1 by setting $T_{reh} = 10^5$ GeV. According to Figure 1, n_s and N_* increase while increasing w_{reh}, but r decreases accordingly. For instance, we find that for $w_{reh} = 1 \to n_s \sim 0.974$, $r \sim 0.021$ and $N_* \sim 65$ but for $w_{reh} = 1/5$ $\to n_s \sim 0.969$, $r \sim 0.027$ and $N_* \sim 57$. In addition to this, for the Coleman-Weinberg potential, in Figures 2 and 3, we display $n_s - r$ predictions and $v - n_s$ values for different T_{reh} values for $\phi > v$, $\xi = 10^{-1.5}$ cases in Figure 2, and $\phi < v$, $\xi = -10^{-3}$ in Figure 3. In the figures, we select the v

ranges widely, for AV case: v in approximately $\left[10^{-15} - 10^{2}\right]$, and for BV case: v in approximately $\left[8 - 10^{5}\right]$. Also, we compare our results with the latest data given by BICEP/Keck [55], where blue (red) contours indicate the 95% (68%) CL contour. For $\phi > v$, the predictions can be inside the 68% CL only for $w_r = 1/3$ and $w_r = 0$ with $T_{reh} = 10^9$ GeV for $v \lesssim 1$ values. While v increasing, $n_s - r$ predictions increase, and the results are ruled out for the BICEP/KECK data. Also, for smaller T_{reh} values, $T_{reh} \lesssim 10^7$ GeV, the predictions cannot enter the 1-σ region, but the predictions can remain inside 95% CL for $v \lesssim 1$ values. On the other hand, for $\phi < v$, the $n_s - r$ predictions can be inside 68% CL contour at $v \gtrsim 25$. In addition, for both lower and higher T_{reh} values, the patterns of $n_s - r$ predictions are quite similar for the results of $\phi < v$. Contrary to $\phi > v$ values, there is no solution to have a reasonable inflationary predictions for $v \lesssim 1$ values and r takes very smaller values than the results of $\phi > v$ cases.

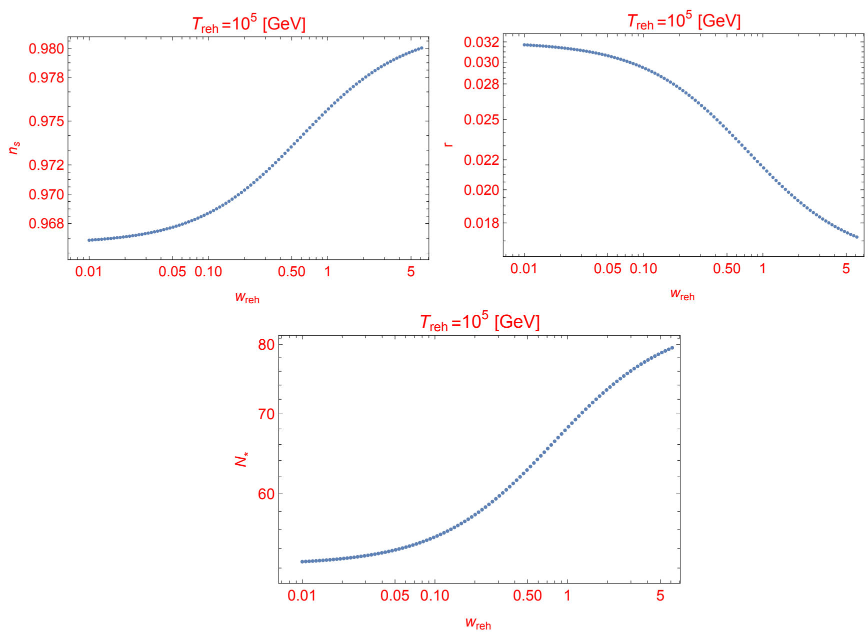

Figure 1. $w_{reh} - n_s$, $w_{reh} - r$, and $w_{reh} - N_*$ predictions for $\phi > v$, $\xi = 10^{-1.5}$ and $v = 0.01$, and here we set $T_{reh} = 10^5$ GeV.

Figure 4 shows that $n_s - r$ and $n_s - N_*$ predictions for $\phi > v$, $v = 0.01$ and $\xi = 10^{-1.5}$ values in top panel, and bottom panel shows the same predictions but for $\phi < v$, $v = 60$ and $\xi = -10^{-3}$. In these figures, color coded represents the corresponding T_{reh} values in the regions. According to our results, for $\phi > v$ values, $n_s - r$ predictions can be inside the CL regions depending on T_{reh} values. Clearly, for higher T_{reh} values, $n_s - r$ predictions are more consistent with the data than smaller values of T_{reh} for $\phi > v$ case. On the other hand, the predictions slightly change depending on T_{reh} values for $\phi < v$ case and for this case, the predictions are very close to each other for both high and low T_{reh} values, such as for $T_{reh} = 10^{16}$ GeV and $T_{reh} = 10^2$ GeV. Also, for both $\phi > v$ and $\phi < v$ cases, depending on the increase of T_{reh} values, both n_s and N_* increase but r values decrease accordingly.

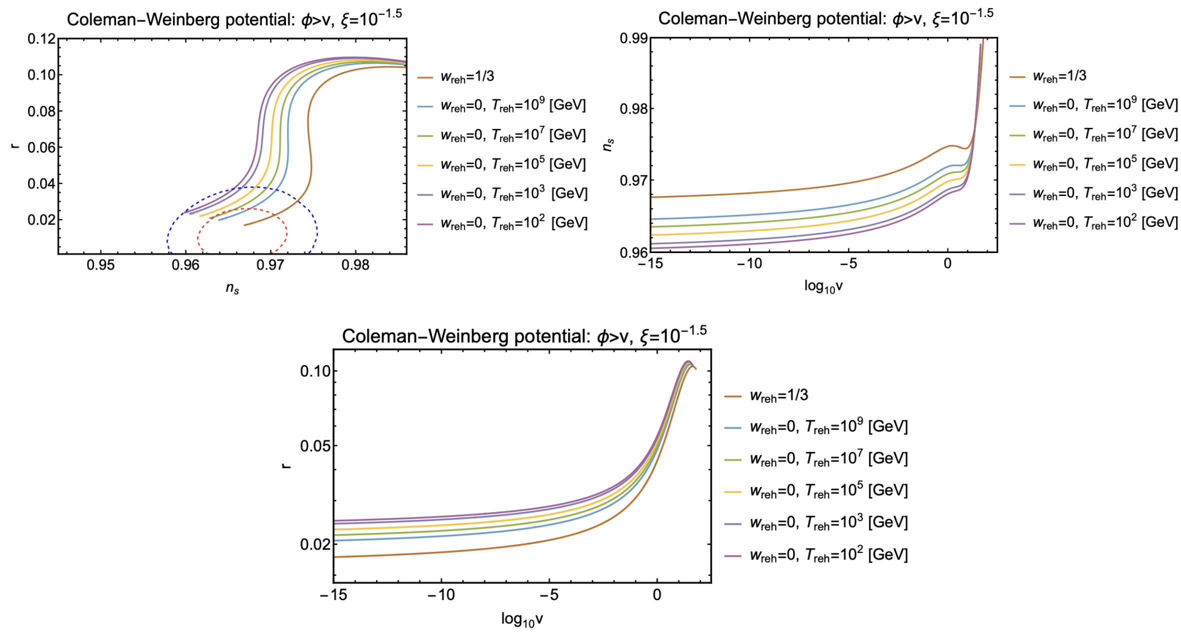

Figure 2. The results of $n_s - r$, $v - n_s$, and $v - r$ for different T_{reh} values and $\phi > v$, $\xi = 10^{-1.5}$ cases. In the top left panel, we compare the predictions with the latest data given by BICEP/Keck [55], where blue (red) contours indicate the 95% (68%) CL contour.

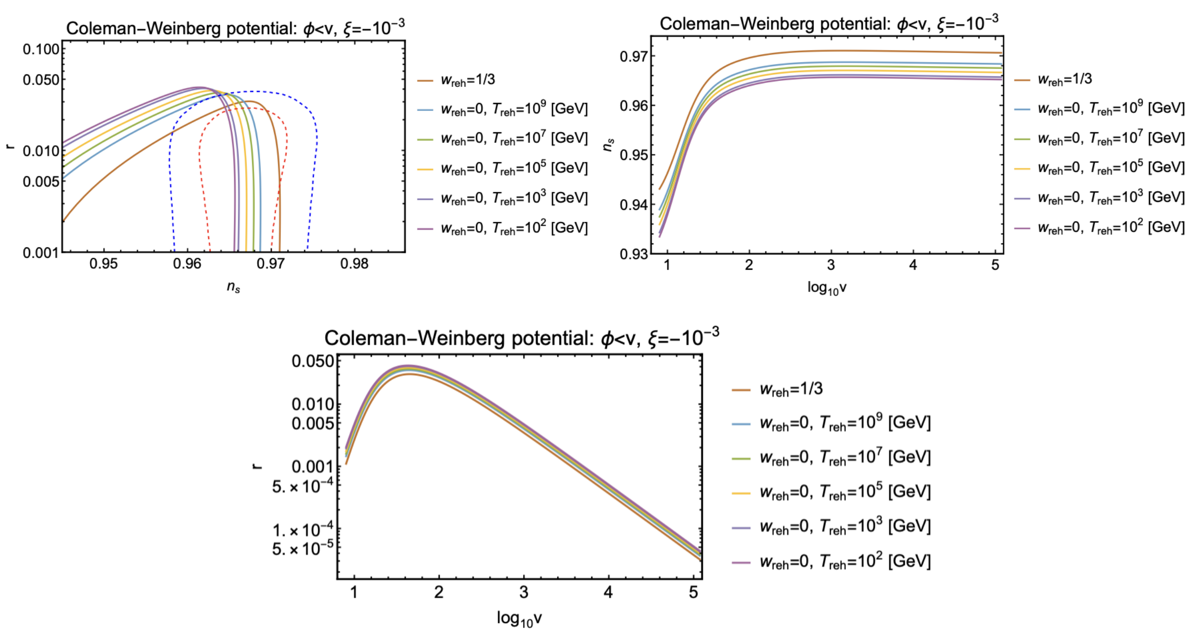

Figure 3. The results of $n_s - r$, $v - n_s$, and $v - r$ for different T_{reh} values and $\phi < v$, $\xi = -10^{-3}$ cases. In the top left panel, we compare the predictions with the latest data given by BICEP/Keck [55], where blue (red) contours indicate the 95% (68%) CL contour.

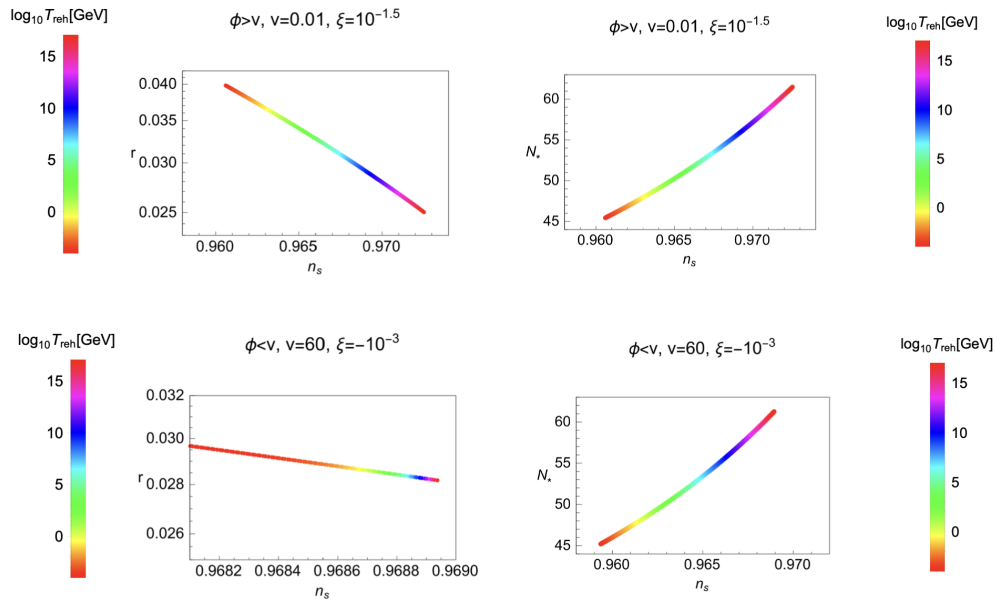

Figure 4. Top panel shows $n_s - r$ (left) and $n_s - N_*$ (right) predictions for $\phi > v$, $v = 0.01$ and $\xi = 10^{-1.5}$ values, bottom panel shows the same predictions but for $\phi < v$, $v = 60$ and $\xi = -10^{-3}$. Color coded represents the corresponding T_{reh} values in the regions.

We also present that $T_{reh} - N_*$ and $T_{reh} - \alpha$ values for $\phi > v$, $v = 0.01$ and $\xi = 10^{-1.5}$ values for Coleman-Weinberg potential in Palatini formulation for $w_{reh} = 0$. The results are shown in Figure 5. It is clearly seen that while T_{reh} increasing, N_* increases accordingly. To be able to satisfy $N_* \sim 55 - 60$ values, $T_{reh} \gtrsim 10^{13}$ GeV. Also, for $N_* \sim 45 - 50$, T_{reh} values are in the regions, approximately $\left[10^{-3}, 10^{5}\right]$ GeV. It can be concluded that for lower T_{reh} values, we have lower e-fold numbers accordingly. Finally, T_{reh} dependency is very tiny on the α predictions. The change is not very sharp, thus we can say that α values are close to each other for both higher and lower T_{reh} values.

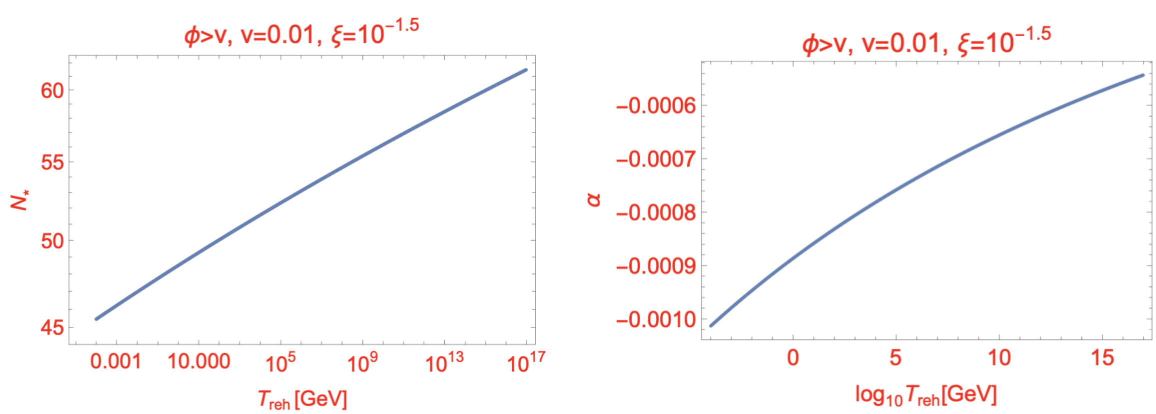

Figure 5. The plots show $T_{reh} - N_*$ (left) and $T_{reh} - \alpha$ (right) for $\phi > v$, $v = 0.01$ and $\xi = 10^{-1.5}$ values for $w_{reh} = 0$.

4. Conclusion

We present the results of the symmetry-breaking type Coleman-Weinberg inflation potential in Palatini formulation. Regarding our results, we find that n_s and N_* increase while increasing w_{reh}, but r decreases accordingly. In addition, we show the inflationary predictions in the wide ranges of v for both AV and BV cases. According to our results, the $n_s - r$ predictions are only within the 1-σ CL region for $w_{reh} = 1/3$ and $w_{reh} = 0$ with $T_{reh} = 10^9$ GeV for $v \lesssim 1$ values in AV case. For the BV case, the behavior of $n_s - r$ predictions in broad ranges of T_{reh} values are very similar to each other, remaining in 1-σ CL region at $v \gtrsim 25$. We also show the results of inflationary parameters, n_s, r, and N_*, at $v = 0.01$ (symmetry-breaking scale) for $\phi > v$ and $v = 60$ for $\phi < v$ with the corresponding T_{reh} values in the regions. We find that for higher T_{reh} values, $n_s - r$ predictions are in a good agreement with the data than smaller values of T_{reh} for both AV and BV cases. In addition, the predictions have a tiny change depending on T_{reh} values for $\phi < v$ case and for this case, the predictions are very close to each other for both high and low T_{reh} values. We also present for both $\phi > v$ and $\phi < v$ cases, depending on the increase of T_{reh} values, both n_s and N_* increase but r values decrease accordingly.

We finally show the results of $T_{reh} - N_*$ and $T_{reh} - \alpha$ values for AV case and for $w_{reh} = 0$, it can be seen that as T_{reh} grows, N_* grows accordingly. To satisfy $N_* \sim 55 - 60$ values, $T_{reh} \gtrsim 10^{13}$ GeV. Also, for $N_* \sim 45 - 50$, T_{reh} values are in the regions, $\sim \left[10^{-3}, 10^5\right]$ GeV. We can conclude that for smaller T_{reh} values, we have smaller e-fold numbers accordingly. Last but not least, T_{reh} dependency on α is very small, as well as, α predictions are very close to each other if we compare the α values in low and high T_{reh} values.

References

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

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

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

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

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

[6] L. Kofman, A. D. Linde and A. A. Starobinsky, *Towards the theory of reheating after inflation*, Phys. Rev. D **56**, 3258-3295 (1997) [arXiv:9704452].

[7] D. J. H. Chung, E. W. Kolb and A. Riotto, *Production of massive particles during reheating*, Phys. Rev. D **60**, 063504 (1999) [arXiv:9809453].

[8] B. A. Bassett, S. Tsujikawa and D. Wands, *Inflation dynamics and reheating*, Rev. Mod. Phys. **78**, 537-589 (2006) [arXiv:0507632].

[9] L. Dai, M. Kamionkowski and J. Wang, *Reheating constraints to inflationary models*, Phys. Rev. Lett. **113, 041302 (2014)** [arXiv:1404.6704].

[10] J. L. Cook, E. Dimastrogiovanni, D. A. Easson and L. M. Krauss, *Reheating predictions in single field inflation*, JCAP **04, 047 (2015)** [arXiv:1502.04673].

[11] J. B. Munoz and M. Kamionkowski, *Equation-of-State Parameter for Reheating*, Phys. Rev. D **91, no.4, 043521 (2015)** [arXiv:1412.0656].

[12] A. Hanin, K. El Bourakadi, M. Ferricha-Alami, Z. Sakhi and M. Bennai, *Reheating Mechanism from Tree Level Potential in Standard Cosmology*, Int. J. Theor. Phys. **62**, no.7, 143 (2023).

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

[14] D. Z. Freedman and E. J. Weinberg, *The Energy-Momentum Tensor in Scalar and Gauge Field Theories*, Annals Phys. **87**, 354 (1974).

[15] I. L. Buchbinder, S. D. Odintsov and I. L. Shapiro, *Effective action in quantum gravity*, Bristol, UK: IOP (1992) 413 p.

[16] L. F. Abbott, *Gravitational Effects on the SU(5) Breaking Phase Transition for a Coleman-Weinberg Potential*, Nucl. Phys. B **185**, 233 (1981).

[17] B. L. Spokoiny, *Inflation And Generation Of Perturbations In Broken Symmetric Theory Of Gravity*, Phys. Lett. **147B**, 39 (1984).

[18] F. Lucchin, S. Matarrese and M. D. Pollock, *Inflation With a Nonminimally Coupled Scalar Field*, Phys. Lett. **167B**, 163 (1986).

[19] T. Futamase and K. i. Maeda, *Chaotic Inflationary Scenario in Models Having Nonminimal Coupling With Curvature*, Phys. Rev. D **39**, 399 (1989).

[20] R. Fakir and W. G. Unruh, *Improvement on cosmological chaotic inflation through nonminimal coupling*, Phys. Rev. D **41**, 1783 (1990).

[21] D. S. Salopek, J. R. Bond and J. M. Bardeen, *Designing Density Fluctuation Spectra in Inflation*, Phys. Rev. D **40**, 1753 (1989).

[22] L. Amendola, M. Litterio and F. Occhionero, *The Phase space view of inflation. 1: The nonminimally coupled scalar field*, Int. J. Mod. Phys. A **5**, 3861 (1990).

[23] V. Faraoni, *Nonminimal coupling of the scalar field and inflation*, Phys. Rev. D **53**, 6813 (1996) [astro-ph/9602111].

[24] V. Faraoni, *Cosmology in scalar tensor gravity*, Fundam. Theor. Phys. **139** (2004).

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

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

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

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

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

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

[31] R. Jinno, M. Kubota, K. y. Oda and S. C. Park, *Higgs inflation in metric and Palatini formalisms: Required suppression of higher dimensional operators*, JCAP **03**, no. 063, (2020) [arXiv:1904.05699].

[32] J. Rubio and E. S. Tomberg, *Preheating in Palatini Higgs inflation*, JCAP **1904**, no. 04, 021 (2019) [arXiv:1902.10148].

[33] V. M. Enckell, K. Enqvist, S. Rasanen and E. Tomberg, *Higgs inflation at the hilltop*, JCAP **1**806, no. 06, 005 (2018) [arXiv:1802.09299].

[34] N. Bostan, *Non-minimally coupled Natural Inflation: Palatini and Metric formalism with the recent BICEP/Keck*," JCAP **02**, 063 (2023) [arXiv:2209.02434].

[35] N. Bostan, *Quadratic, Higgs and hilltop potentials in Palatini gravity*, Commun. Theor. Phys. **1**806, no. 8, 085401 (2020) [arXiv:1908.09674].

[36] T. Tenkanen, *Minimal Higgs inflation with an R^2 term in Palatini gravity*, Phys. Rev. D **99**, no. 6, 063528 (2019) [arXiv:1901.01794].

[37] L. Järv, A. Karam, A. Kozak, A. Lykkas, A. Racioppi and M. Saal, *Equivalence of inflationary models between the metric and Palatini formulation of scalar-tensor theories*, Phys. Rev. D **102**, no.4, 044029 (2020) [arXiv:2005.14571].

[38] H. Azri and D. Demir, *Affine Inflation*, Phys. Rev. D **95**, 124007 (2017) [arXiv:1705.05822].

[39] H. Azri and D. Demir, *Induced Affine Inflation*, Phys. Rev. D **97**, 044025 (2018) [arXiv:1802.00590].

[40] J. Kijowski and R. Werpachowski, *Universality of affine formulation in general relativity theory*, Rept. Math. Phys. **59**, 1 (2007) [arXiv:gr-qc/0406088].

[41] N. Bostan, C. Karahan and O. Sargın, *Inflation in Symmergent Metric-Palatini Gravity*, [arXiv:2308.04507], (accepted for publication in JCAP).

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

[43] A. R. Liddle and S. M. Leach, *How long before the end of inflation were observable perturbations produced?*, Phys. Rev. D **68**, 103503 (2003) [arXiv:0305263].

[44] N. Aghanim *et al.* [Planck Collaboration], *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641**, A10 (2020) [arXiv:1807.06209].

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

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

[47] A. Albrecht and R. H. Brandenberger, *On the Realization of New Inflation*, Phys. Rev. D **31**, 1225 (1985).

[48] A. D. Linde, *Particle physics and inflationary cosmology*, Contemp. Concepts Phys. **5**, 1-362 (1990) [arXiv:0503203].

[49] Q. Shafi and V. N. Senoguz, *Coleman-Weinberg potential in good agreement with wmap*, Phys. Rev. D **73**, 127301 (2006) [arXiv:0603830].

[50] G. Barenboim, E. J. Chun and H. M. Lee, *Coleman-Weinberg Inflation in light of Planck*, Phys. Lett. B **730**, 81-88 (2014) [arXiv:1309.1695].

[51] K. Kannike, A. Racioppi and M. Raidal, *Embedding inflation into the Standard Model - more evidence for classical scale invariance*, JHEP **06**, 154 (2014) [arXiv:1405.3987].

[52] V. N. Şenoğuz and Q. Shafi, *Primordial monopoles, proton decay, gravity waves and GUT inflation*, Phys. Lett. B **752**, 169-174 (2016) [arXiv:1510.04442].

[53] N. Bostan, *Palatini double-well and Coleman-Weinberg potentials with non-minimal coupling*, JCAP **04**, 042 (2021) [arXiv:2009.04406].

[54] R. Maji and Q. Shafi, *Monopoles, strings and gravitational waves in non-minimal inflation*, JCAP **03**, 007 (2023) [arXiv:2208.08137].

[55] Ade, P. A. R. *et al.* [BICEP, Keck], *Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season*, Phys. Rev. Lett **151301**, 127, 15 (2021) [arXiv:2110.00483].