

Does Current Data Prefer a Non-minimally Coupled Inflaton?

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We examine the impact of a non-minimal coupling of the inflaton to the Ricci scalar, $\frac{1}{2}\xi R\phi^2$, on the inflationary predictions. Such a non-minimal coupling is expected to be present in the inflaton Lagrangian on fairly general grounds. As a case study, we focus on the simplest inflationary model governed by the potential $V \propto \phi^2$, using the latest combined 2015 analysis of *Planck* and BICEP2/*Keck* Array. We find that the presence of a coupling ξ is favoured at a significance of 99% CL, assuming that nature has chosen the potential $V \propto \phi^2$ to generate the primordial perturbations and a number of e-foldings $N = 60$. Within the context of the same scenario, we find that the value of ξ is different from zero at the 2σ level. When considering the cross-correlation polarization spectra from BICEP2/*Keck* Array and *Planck*, a value of $r = 0.038_{-0.030}^{+0.039}$ is predicted in this particular non-minimally coupled scenario. Future cosmological observations may therefore test these values of r and verify or falsify the non-minimally coupled model explored here.

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I. INTRODUCTION

Inflation provides the most theoretically attractive and observationally successful cosmological scenario able to generate the initial conditions of our universe, while solving the standard cosmological problems. Despite this remarkable success, the inflationary paradigm is still lacking firm observational confirmation. The picture that emerges from the latest data from *Planck*, including also the joint analysis of *B*-mode polarization measurements from the BICEP2 collaboration [1–4], is compatible with the inflationary paradigm. According to these observations, structure grows from Gaussian and adiabatic primordial perturbations. From the theoretical viewpoint, this picture is usually understood as the dynamics of a single new scalar degree of freedom, *the inflaton*, minimally coupled to Einstein gravity. However, the inflaton ϕ is expected to have a non-minimal coupling to the Ricci scalar through the operator $\frac{1}{2}\xi R\phi^2$, where ξ is a dimensionless coupling. Indeed, successful reheating requires that the inflaton is coupled to the light degrees of freedom. Such couplings, though weak, will induce a non-trivial running for ξ . Thus, even starting from a vanishing value of ξ (away from the conformal fixed point $\xi = -1/6$) at some energy scale, a non-trivial non-minimal coupling will be generated radiatively at some other scale (see *e.g.* Ref. [5]). Therefore, it is important to study the impact of such a coupling on the inflationary predictions, especially in view of the latest *Planck* 2015 data.

Generically, for successful inflation, the inflaton should be very weakly coupled¹. It follows that the magnitude

of ξ is expected to be small. Yet, even with such a suppressed coupling, the inflationary predictions are significantly altered [6–16]. For instance, and as we will see, a small and positive ξ can enlarge considerably the space of phenomenologically acceptable scenarios (see also [17]). In this paper, we will focus on the simplest inflationary scenario with a potential $V \propto \phi^2$ [18], and a non-zero non-minimal coupling. According to the very recent *Planck* 2015 full mission results, the minimally-coupled version of this scenario (*i.e.* $\xi = 0$) is ruled out at more than 99% confidence level [2, 4], for 50 e-folds of inflation. Nevertheless, the $N = 60$ case is only moderately disfavoured at 95% CL. Thus, before discarding it definitely from the range of theoretical possibilities, it is worthwhile to explore this scenario in all generality (considering as well different possibilities for the number of e-folds), given that, as explained earlier, the presence of non-minimal couplings in the inflaton Lagrangian is quite generic.

II. NON-MINIMALLY COUPLED INFLATON

The dynamics of a non-minimally coupled scalar field ϕ with a potential $U(\phi)$ is governed, in the *Jordan frame*, by the following action²

$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{\xi}{2} R\phi^2 - \frac{1}{2}(\partial\phi)^2 - U(\phi) \right], \quad (1)$$

primordial non-Gaussianities [3] and the soft breaking of the shift symmetry $\phi \rightarrow \phi + c$, necessary to protect the flatness of the potential.

² As usual, $M_P = 1/\sqrt{8\pi G_N} \simeq 2.43 \times 10^{18}$ GeV is the reduced Planck mass.

¹ This requirement is also dictated by the non-detection of large

where indices are contracted with the metric $g_{\mu\nu}$, defined as $ds^2 = -dt^2 + a^2(t)dx^2$. Inflation can be conveniently studied in the *Einstein frame*, after performing a conformal transformation $g_{\mu\nu}^E = \Omega(\phi)g_{\mu\nu}$, with $\Omega \equiv 1 + \xi\phi^2/M_P^2$ and canonically-normalizing the scalar field. Up to a total derivative, the action takes the familiar form

$$S = \int d^4x \sqrt{-g_E} \left(\frac{M_P^2}{2} R_E - \frac{1}{2} g_E^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - V[\phi(\varphi)] \right), \quad (2)$$

where now φ is the canonically-normalized inflaton, related to the original non-minimally coupled scalar field ϕ through

$$\left(\frac{d\varphi}{d\phi} \right)^2 = \frac{1}{\Omega} + \frac{3}{2} M_P^2 \left(\frac{\Omega'}{\Omega} \right)^2. \quad (3)$$

In terms of the original scalar field ϕ , the *physical potential* takes the simple form

$$V[\varphi(\phi)] = U(\phi)/\Omega^2(\phi). \quad (4)$$

In the following, as previously stated, we shall focus on the simplest inflationary model. A generalization to other interesting inflationary scenarios, as for instance, the Higgs inflation model [19], will be carried out elsewhere [20]. The simplest scenario is given by the quadratic potential $U(\phi) = \frac{1}{2}m^2\phi^2$, with a non-vanishing coupling ξ . In order to derive the primordial scalar and tensor perturbation spectra within the non-minimally coupled ϕ^2 theory, we shall make use of the slow-roll parameters³:

$$\epsilon \equiv \frac{M_P^2}{2} \left(\frac{V_\varphi}{V} \right)^2, \quad \eta \equiv M_P^2 \frac{V_{\varphi\varphi}}{V}, \quad \xi_{\text{SR}} \equiv M_P^4 \frac{V_\varphi V_{\varphi\varphi\varphi}}{V^2}. \quad (5)$$

It is straightforward to derive the expressions for the spectral index of the primordial scalar perturbations $n_s \equiv 1 + 2\eta - 6\epsilon$, its running $\alpha \equiv dn_s/d\ln k \equiv -24\epsilon^2 + 16\epsilon\eta - 2\xi_{\text{SR}}$, and the tensor-to-scalar ratio $r \equiv 16\epsilon$ from the above slow-roll parameters⁴.

Within the slow-roll approximation, one can easily solve numerically the inflationary dynamics governed by the action Eq. (2). The number of e-folds is given by

$$N = \frac{1}{M_P} \int_{\varphi_{\text{end}}}^{\varphi_*} \frac{d\varphi}{\sqrt{2\epsilon(\varphi)}} = \frac{1}{M_P} \int_{\phi_{\text{end}}}^{\phi_*} \frac{d\phi}{\sqrt{2\epsilon(\phi)}} \left(\frac{d\varphi}{d\phi} \right), \quad (6)$$

³ Here, we use the notation $\xi_{\text{SR}}(\varphi)$ to refer to the usual slow-roll parameter ξ , in order to avoid confusion with the non-minimal coupling to gravity ξ .

⁴ Notice that the expressions for both n_s and r are first-order in slow-roll, while α involves second order slow-roll terms. However, we have checked numerically that such second order corrections in slow-roll leave unchanged the constraints on the inflationary observables (n_s, r) . Therefore, higher order slow-roll corrections can be safely neglected.

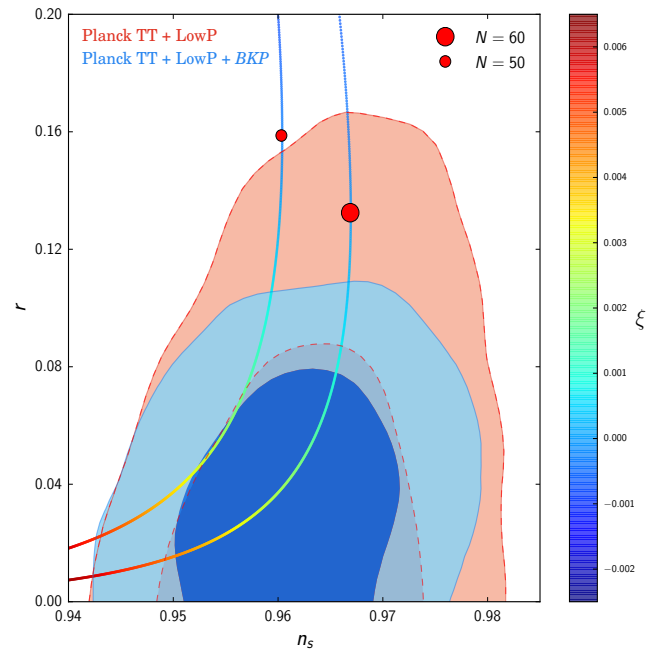


FIG. 1. Theoretical predictions for the chaotic model $V \propto \phi^2$ with a non-minimal coupling ξ in the (n_s, r) plane for $N = 50$ and $N = 60$. The red circles represent the $\xi = 0$ case, corresponding to the usual predictions of the chaotic inflationary scenario. We show as well the 68% and 95% confidence level regions arising from the usual analyses in the (n_s, r) plane using the various data combinations considered here.

where $\epsilon(\phi) \equiv \frac{M_P^2}{2} [V'(\phi)/V(\phi)]^2$.

The inflationary theoretical predictions for the $N = 50$ and $N = 60$ cases are depicted in Fig. 1, in the (n_s, r) plane, for both positive and negative values of the coupling ξ . The case of $\xi = 0$ corresponds to the usual predictions of the chaotic inflationary scenario, with $n_s = 1 - 2/N \simeq 0.967$ ($n_s \simeq 0.96$) and $r = 8/N \simeq 0.13$ ($r \simeq 0.16$) for $N = 60$ ($N = 50$), and it is represented by red circles. Notice that negative values of ξ lead to a larger tensor-to-scalar ratio. Positive values of ξ , on the other hand, will reduce the tensor contribution, while also pushing n_s significantly below scale invariance as ξ increases. For instance, for $\xi > 0.002$ and $N = 60$, the scalar spectral index will always be smaller than the observationally preferred value $n_s \simeq 0.96$.

The predicted running of the spectral index α is shown in Fig. 2 as a function of the non-minimal coupling ξ . In general, negative (positive) values of ξ lead to positive (negative) values of the running. Although the large positive values of the running shown in Fig. 2 are compatible with the recent *Planck* 2015 constraints [2], $\alpha = -0.0065 \pm 0.0076$, they are nevertheless associated with values of the tensor-to-scalar ratio $r > 0.5$, which are excluded observationally. The red circle in Fig. 2 refers to the $\xi = 0$ case, corresponding to $\alpha = -2/N^2 \simeq -0.00056$ for $N = 60$.

III. OBSERVATIONAL CONSTRAINTS ON ξ IN THE QUADRATIC INFLATIONARY MODEL

In this paper, we restrict our numerical fits to Cosmic Microwave Background (CMB) measurements. The inclusion of external data sets, such as Baryon Acoustic Oscillation measurements, or a Hubble constant prior from the HST team will not affect the constraints presented in the following. Our data sets are the *Planck* temperature data (hereafter *TT*) [21–23], together with the low- ℓ WMAP 9-year polarization likelihood, that includes multipoles up to $\ell = 23$, see Ref. [24] (hereafter *WP*), and the recent multi-component likelihood of the joint analysis of BICEP2/*Keck* Array and *Planck* polarization maps (hereafter *BKP*), following the data selection and foreground parameters of the fiducial analysis presented in Ref. [1]⁵. However, variations of this fiducial model will not change significantly the results presented here.

These data sets are combined to constrain the cosmological model explored here, and described by the parameters⁶:

$$\{\omega_b, \omega_c, \Theta_s, \tau, \log[10^{10} A_s], \xi\} \quad (7)$$

In Table I, we summarize the definition as well as the priors on these parameters. We use the Boltzmann code *CAMB* [25] and the cosmological parameters are extracted from the data described above by means of a Monte Carlo Markov Chain (MCMC) analysis based on the most recent version of *cosmomc* [26]. The constraints obtained on the non-minimal coupling ξ are then translated into bounds on the usual inflationary parameters n_s , r and α .

Table II shows the 95% CL constraints on the parameter ξ as well as on the derived inflationary parameters

Parameter	Physical Meaning	Prior
$\omega_b \equiv \Omega_b h^2$	Present baryon density.	0.005 \rightarrow 0.1
$\omega_c \equiv \Omega_c h^2$	Present Cold dark matter density.	0.01 \rightarrow 0.99
Θ_s	$r_s/D_A(z_{\text{dec}})$ ^a .	0.5 \rightarrow 10
τ	Reionization optical depth.	0.01 \rightarrow 0.8
$\ln(10^{10} A_s)$	Primordial scalar amplitude.	2.7 \rightarrow 4
ξ	Non-minimal coupling.	-0.002 \rightarrow 0.0065

^a The parameter Θ_s is the ratio between the sound horizon r_s and the angular diameter distance $D_A(z_{\text{dec}})$ at decoupling z_{dec} .

TABLE I. Uniform priors for the cosmological parameters considered in the present analysis.

⁵ This fiducial analysis assumes a tensor spectral index $n_T = 0$, the *BB* bandpowers of BICEP2/*Keck* Array and the 217 and 353 GHz bands of *Planck*, in the multipole range $20 < \ell < 200$.

⁶ Notice that the inflationary cosmology under study contains less parameters than the standard Λ CDM picture, as once the non-minimal coupling ξ is fixed, n_s , r and α are fully determined, and are thus *derived* parameters.

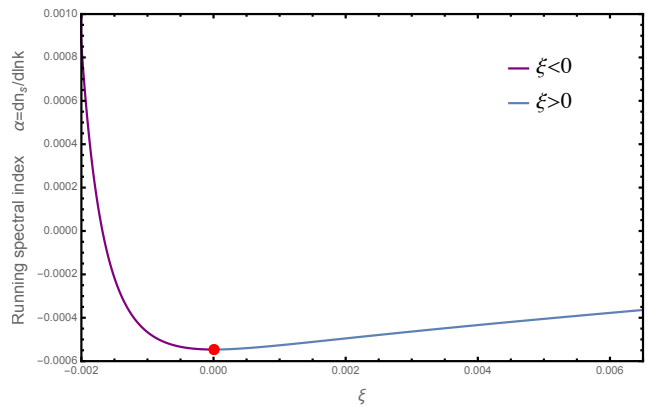


FIG. 2. The running α as a function of the non-minimal coupling ξ . The red circle represents the minimal coupling case $\xi = 0$.

n_s , r and the running α arising from our numerical analyses using the two CMB data combinations used here and assuming that n_s and r are univocally determined by ξ (for a fixed number of e-folds N , that we consider to be either 60 or 50). For $N = 60$, the preferred value of the non-minimal coupling ξ from *Planck TT* plus *WP* measurements is positive and slightly larger than the mean value obtained when the cross-correlated polarized maps from BICEP2/*Keck* and *Planck* (*BKP*) experiments are included in the numerical analyses. This preference for a slightly larger ξ (and consequently, smaller r) is clear from the one-dimensional posterior probability distribution of ξ shown in the left panel of Fig. 4. The mean value of $\xi = 0.0028$ obtained from *Planck TT* plus *WP* data is translated into a 95% CL constraint of the tensor-to-scalar-ratio $r = 0.038^{+0.051}_{-0.031}$, as can be seen from the right panel of Fig. 4. When considering BICEP2/*Keck* and *Planck* cross-spectra polarization data, the former constraint on the tensor-to-scalar ratio is very similar to the one quoted above. Concerning the running of the spectral index, the two data combinations seem to have a preference for a small negative running $\alpha = -0.0005$, associated to small values of $|\xi|$, as shown in Fig. 2.

Let us now comment on the sensitivity of our constraints to changes in the number of e-folds N . Setting $N = 50$ leads to different, though almost insignificant, changes in the constraints obtained using the two CMB data sets. The theoretically allowed regions in the (n_s, r) plane as a function of ξ for $N = 50$ are indeed slightly different from those corresponding to the $N = 60$ case, see Fig. 1. The net result is a smaller (larger) values of n_s (r) than in the $N = 60$ case. The BICEP2/*Keck* and *Planck* cross-spectra polarization data yield a value $r = 0.053^{+0.038}_{-0.037}$ for the tensor-to-scalar ratio in the context of the non-minimally coupled ϕ^2 model. On the other hand, the resulting central value for the scalar spectral index is only half a σ away (towards smaller values) from the corresponding one for $N = 60$, as expected from the theoretical predictions illustrated in Fig. 1.

	Planck TT+WP		BK+Planck TT+WP	
N	60	50	60	50
ξ	$0.0028^{+0.0023}_{-0.0025}$	$0.0024^{+0.0023}_{-0.0023}$	$0.0027^{+0.0023}_{-0.0022}$	$0.0027^{+0.0020}_{-0.0019}$
n_s	$0.958^{+0.010}_{-0.011}$	$0.954^{+0.007}_{-0.009}$	$0.958^{+0.009}_{-0.011}$	$0.953^{+0.007}_{-0.009}$
r	$0.038^{+0.051}_{-0.031}$	$0.063^{+0.056}_{-0.048}$	$0.038^{+0.039}_{-0.030}$	$0.053^{+0.038}_{-0.037}$
$\alpha \equiv dn_s/d \ln k$	$-0.0005^{+0.0001}_{-0.0001}$	$-0.0007^{+0.0001}_{-0.0001}$	$-0.0005^{+0.0001}_{-0.0001}$	$-0.0007^{+0.0001}_{-0.0001}$

TABLE II. **Inflationary constraints in the context of non-minimally coupled chaotic potential ϕ^2** : The upper block of the table refers to the 95% CL limits on the non-minimal coupling ξ (the parameter varied in the MCMC analyses) from the two possible CMB data combinations used in this study, for both $N = 60$ and $N = 50$. The lower block of the table contains the 95% CL derived ranges of the inflationary parameters n_s , r and α from the limits of ξ illustrated above, in the context of the non-minimally coupled chaotic potential ϕ^2 , for both $N = 60$ and $N = 50$.

Figure 1 shows the 68% and 95% CL allowed regions in the (n_s, r) plane resulting from our MCMC analyses to *Planck TT* plus *WP* data and to the combined *BKP* in the usual (n_s, r) plane, together with the theoretical predictions for $N = 50$ and $N = 60$ for the non-minimally coupled ϕ^2 scenario.

To address the question of whether or not a non-minimal coupling ξ is favoured by current CMB data, we compare the χ^2 test statistics function for the ϕ^2 model in its minimally and non-minimally coupled versions for $N = 60$, albeit very similar results are obtained for

$N = 50$. The χ^2 for the case of *Planck TT* plus *WP* data, evaluated at the best-fit-point of the ϕ^2 model minimally coupled to gravity is $\chi^2[\xi = 0] = 9812.8$. On the other hand, the non-minimally coupled version has a lower χ^2 value at the best-fit-point due to the extra parameter ξ introduced in the model, with $\chi^2[\xi \neq 0] = 9806.8$. The difference between these two χ^2 values is $\Delta\chi^2 = 6$, which, for a distribution of one degree of freedom, has a p -value of 0.014, and is considered as statistically significant. For the case of the combined *BKP* likelihood, the difference between the test-statistics for the minimally coupled and non-minimally coupled ϕ^2 models is $\Delta\chi^2 = 10$, which, for one degree of freedom, has a p -value of 0.0016, and is considered as very statistically significant. Therefore, according to the most recent CMB data, the presence of a non-minimal coupling ξ within the ϕ^2 model is favoured at a significance equal or larger than $\sim 99\%$ CL.

Let us now turn to future constraints on ξ . Future observations, as those expected from *PIXIE* [27], *Euclid* [28], *CORe* [29] and *PRISM* [30], could be able to reach an accuracy of $\sigma_r = \sigma_{n_s-1} = 10^{-3}$. With such precision, one could hope to test deviations from the quadratic potential [31], as the one studied here, by constructing quantities independent of N , up to subleading $\mathcal{O}(1/N^3)$ corrections. It is straightforward to get for our case,

$$n_s - 1 + \frac{r}{4} = -20\xi, \quad (8)$$

at leading order both in slow-roll and ξ . If it turns out that nature had chosen a very small value of r , future constraints on ξ would be as strong as $\xi \lesssim 10^{-4}$; one order of magnitude stronger than the ones obtained in this analysis. Concerning the running α , it is interesting to note that futuristic observations like *SPHEREx* [32] with a forecasted error of $\sigma_\alpha = 10^{-3}$, will be able to falsify the present scenario.

Finally, it is also interesting to explore the impact of the non-minimal coupling on the inflaton excursion. It is

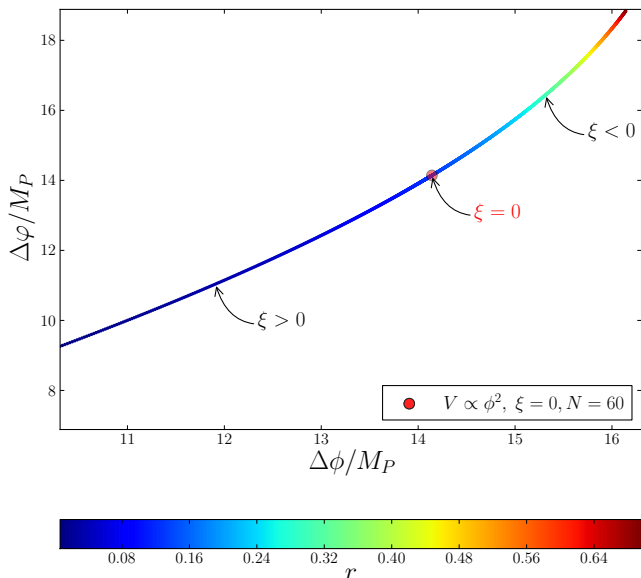


FIG. 3. Excursion of the canonically-normalized inflaton φ versus the one of the original scalar ϕ . The magnitude of the tensor-to-scalar ratio is encoded in the curve through the color bar. Notice that, in both frames, large r correlates with large excursions.

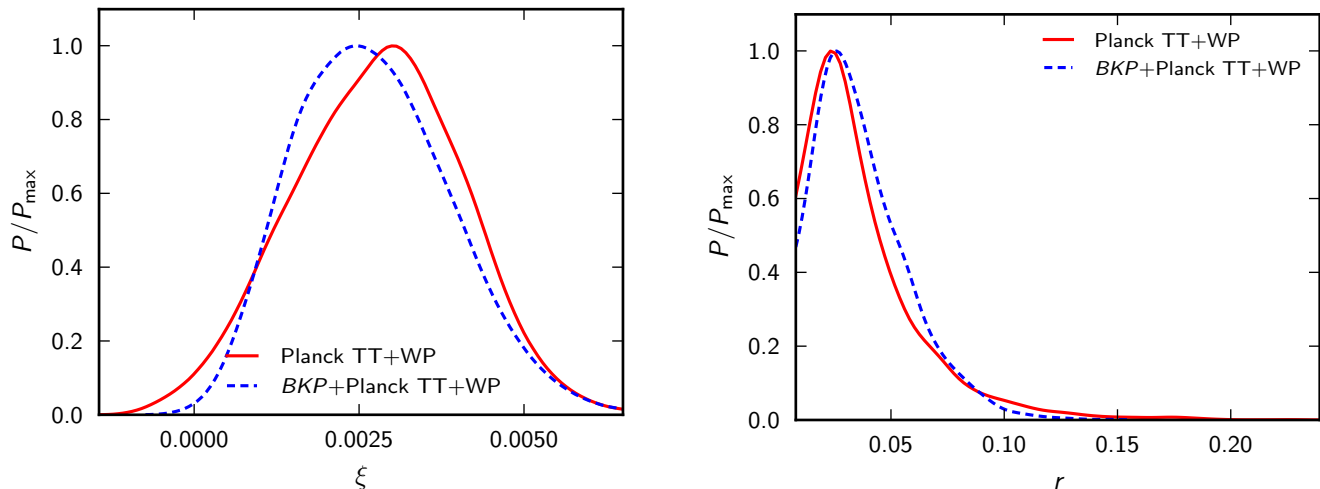


FIG. 4. The left (right) panel shows the one-dimensional posterior probability distributions of the non-minimal coupling ξ (the tensor-to-scalar ratio r) in the context of a non-minimally coupled chaotic potential ϕ^2 , with r a function of ξ , and therefore, a prediction within the model.

well-know that large values of the tensor-to-scalar ratio r , as those found by previous BICEP2 measurements ⁷ [33, 34] yield large inflaton excursions $\phi \gg M_P$ [35–38], which are hard to understand in the context of a consistent effective field theory. In particular, successful inflation requires that higher order non-renormalizable operators, which are expected to be naturally present in the inflationary potential, are sufficiently suppressed. A number of phenomenological studies have recently been devoted to address this problem [39–42]. In Fig. 3, we plot the excursion of both ϕ and φ , together with the corresponding tensor-to-scalar ratio r . It is clear that the excursion of the canonically-normalized inflaton φ is lowered for positive values of ξ *i.e.* $\Delta\varphi < \Delta\phi$. However, this decrease is rather mild and the excursion still takes on super-Planckian values for the phenomenologically acceptable values of ξ . Conversely, negative values of ξ lead to an increase of the excursion of φ . Figure 3 also shows that super-Planckian values of both ϕ and φ are *still* associated with large values of the tensor-to-scalar ratio r , in agreement with the Lyth bound [35]. Thus, once a small non-zero and positive value of the coupling ξ is turned on, both the inflaton excursion and r are slightly lowered, but without alleviating completely the super-Planckian excursion problem.

IV. CONCLUSIONS

A small, non-minimal coupling $\frac{1}{2}\xi R\phi^2$ is expected to be present in the inflaton Lagrangian, and modifies the

inflationary predictions in an interesting way. Focusing on the simplest quadratic potential scenario, and using the very recent joint analysis of BICEP2/*Keck* Array and *Planck* polarization maps, we found that a small, positive value of the coupling ξ is favoured at the 2σ level, assuming that nature has chosen the ϕ^2 scenario for the generation of primordial perturbations. If only *Planck TT* plus *WP* data are used in the analyses, the significance is milder. These conclusions have been obtained for a number of e-foldings within the $N = 50 - 60$ range. It would be interesting to see if upcoming *B*-modes measurements can reinforce or weaken the statistical significance of these findings. In particular, it would be crucial to discriminate between the presence of a non-minimal coupling in the theory and other departures from the quadratic approximation.

V. ACKNOWLEDGMENTS

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⁷ The joint BKP analysis finds however no evidence for primordial

B-modes, but a robust limit of $r < 0.12$ at 95% CL, see Ref. [1].

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