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Reconstructing inflationary paradigm within Effective Field Theory framework

Sayantan Choudhury [1]

Department of Theoretical Physics, Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India

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ABSTRACT

In this paper my prime objective is to analyse the constraints on a sub-Planckian excursion of a single inflaton field within Effective Field Theory framework in a model independent fashion. For a generic single field inflationary potential, using the various parameterization of the primordial power spectrum I have derived the most general expression for the field excursion in terms of various inflationary observables, applying the observational constraints obtained from recent Planck 2015 and Planck 2015 + BICEP2/Keck Array data. By explicit computation I have reconstructed the structural form of the inflationary potential by constraining the Taylor expansion co-efficients appearing in the generic expansion of the potential within the Effective Field Theory. Next I have explicitly derived, a set of higher order inflationary *consistency* relationships, which would help us to break the degeneracy between various class of inflationary models by differentiating them. I also provided two simple examples of Effective Theory of inflation- *inflection-point* model and *saddle-point* model to check the compatibility of the prescribed methodology in the light of Planck 2015 and Planck 2015 + BICEP2/Keck Array data. Finally, I have also checked the validity of the prescription by estimating the cosmological parameters and fitting the theoretical CMB TT, TE and EE angular power spectra with the observed data within the multipole range $2 < l < 2500$.

1. Introduction

The primordial inflation [1–3] has two *key* predictions—creating the scalar density perturbations and the tensor perturbations during the accelerated phase of expansion [4], for a review, see [5]. One of the predictions, namely the temperature anisotropy due to the scalar density fluctuations has now been tested very accurately by the observations from the temperature anisotropy and polarization in the cosmic microwave background (CMB) radiation [6–8]. In the last year the detection of tensor modes has been initially confirmed by the ground based BICEP2 experiment [9], which according to the initial claim has detected for the first time a non-zero value of the tensor-to-scalar ratio at 7σ C.L. The value obtained by the BICEP2 team in conjunction with Planck+WAMP-9 + high L + BICEP2 put a bound on the primordial gravitational waves, via tensor-to-scalar ratio, within a window:

$$0.15 \leq r(k_\star) \equiv P_T(k_\star)/P_S(k_\star) \leq 0.27, \tag{1.1}$$

at the pivot scale, $k_\star = 0.002\ \mathrm{Mpc}^{-1}$ [9], where P_T and P_S denote the power spectrum for the tensor and scalar modes, respectively. But just after releasing this result BICEP2 analysis was put into question by several works [10–13] on its correctness in the physical ground. Most importantly it accounting for the contribution of foreground dust which will shift the value of tensor-to-scalar ratio r downward by an amount and further better constrained by the joint analysis performed by Planck and BICEP2/Keck Array team [14]. The final result is expressed as a likelihood curve for r, and yields an upper limit:

$$r(k_\star) \equiv P_T(k_\star)/P_S(k_\star) \leq 0.12 \tag{1.2}$$

at the pivot scale, $k_\star = 0.05\ \mathrm{Mpc}^{-1}$ with 2σ confidence. Marginalizing over dust contribution and r, finally it is reported that the lensing B-modes are detected at 7σ significance. Very recently in Ref. [15] the Planck team in 2015 data release also fixed the upper bound on the tensor-to-scalar ratio as:

$$r(k_\star) \equiv P_T(k_\star)/P_S(k_\star) \leq 0.11 \tag{1.3}$$

at the pivot scale, $k_\star = 0.002\ \mathrm{Mpc}^{-1}$ with 2σ C.L. and perfectly consistent with the joint analysis performed by Planck and BICEP2/Keck Array team.

E-mail addresses: sayantan@theory.tifr.res.in, sayanphysicsisi@gmail.com.
[1] Presently working as a Visiting (Post-Doctoral) fellow at DTP, TIFR, Mumbai.

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Note that large $r(k_\star)$ is possible if the initial conditions for gravitational waves is quantum Bunch–Davis vacuum [16],[2] for a classical initial condition the amplitude of the gravitational waves would be very tiny and undetectable, therefore this can be treated as the first observable proof of quantum gravity. However, apart from the importance and applicability of quantum Bunch–Davis vacuum on its theoretical and observational ground it is still not at all clear from the previous works in this area that whether the quantum Bunch–Davies vacuum is the only source of generating large value of $r(k_\star)$ during inflationary epoch or not. One of the prime possibilities comes from the deviation from quantum Bunch–Davies vacuum *aka* consideration of quantum non-Bunch–Davies or arbitrary vacuum in this picture which may also be responsible for the generation of large $r(k_\star)$ during inflation.[3]

In this paper, our aim will be to illustrate that it is possible to explain the current data sets within a sub-Planckian model of inflation, where:

- $\phi_0 \ll M_p$ — vev of the inflaton must be bounded by the cut-off of the particle theory, where $M_p = 2.4 \times 10^{18}$ GeV. We are assuming that 4 dimensions M_p puts a natural cut-off here for any physics beyond the Standard Model.
- $|\Delta\phi| \approx |\phi_\star - \phi_e| \lesssim M_p$ —the inflaton potential has to be flat enough during which a successful inflation can occur. Here

$$\phi_\star \geq \phi_0 \geq \phi_e \tag{1.4}$$

represents the field VEV, and $\Delta\phi$ denotes the range of the field values around which all the relevant inflation occurs, $\phi_\star$ corresponds to the pivot scale and ϕ_e denotes the end of inflation. Note that the flatness of the potential has to be fine tuned and also there is no particle physics symmetry which can maintain the flatness. We will assume

$$V''(\phi_0) \approx 0, \tag{1.5}$$

where $V(\phi)$ denotes the inflaton potential, and prime denotes derivative w.r.t. the ϕ field. Naturally, the potential has to be flat enough within $\Delta\phi$ to support slow roll inflation.

The above requirements are important if the origin of the inflaton has to be embedded within a particle theory, where inflaton is part of a *visible sector* gauge group, i.e. Standard Model gauge group, instead of an arbitrary gauge singlet. If the inflaton is *gauged* under some gauge group, as in the case of a minimal supersymmetric Standard Model (MSSM), Ref. [17], then the inflaton VEV must be bounded by M_p, in order to keep the sanctity of an effective field theory description.[4]

Our prescribed methodology will be very generic, with a Taylor expanded potential around VEV ϕ_0 is given by[5]:

$$V(\phi) = \sum_{n=0}^{\infty} \frac{(\phi-\phi_0)^n}{n!}\left(\frac{d^nV(\phi)}{d\phi^n}\right)_{\phi=\phi_0},$$

$$= V(\phi_0) + V'(\phi_0)(\phi-\phi_0) + \frac{V''(\phi_0)}{2}(\phi-\phi_0)^2 + \frac{V'''(\phi_0)}{6}(\phi-\phi_0)^3 + \frac{V''''(\phi_0)}{24}(\phi-\phi_0)^4 + \cdots, \tag{1.6}$$

where the expansion co-efficients are characterized as follows:

- The first term:

$$V(\phi_0) \ll M_p^4 \tag{1.7}$$

denotes the height of the potential. Also this term will play the most significant role in fixing the scale of inflation within the present framework.
- The Taylor expansion coefficients of the effective potential:

$$V'(\phi_0) \leq M_p^3, \tag{1.8}$$

$$V''(\phi_0) \leq M_p^2, \tag{1.9}$$

$$V'''(\phi_0) \leq M_p, \tag{1.10}$$

$$V''''(\phi_0) \leq \mathcal{O}(1), \tag{1.11}$$

determine the shape of the potential in terms of the model parameters.
- The *prime* denotes the derivative w.r.t. ϕ. In particular, some specific choices of the potential would be a *saddle point*, when

$$V'(\phi_0) = 0 = V''(\phi_0), \tag{1.12}$$

an *inflection point*, when

$$V''(\phi_0) = 0. \tag{1.13}$$

Previous studies regarding obtaining large $r(k_\star)$ within sub-Planckian VEV models of inflation have been studied in Refs. [21–23]. In Ref. [21], the authors could match the amplitude of the power spectrum, P_S, at the pivot point, but not at the entire range of $\Delta\phi$ for the observable window of ΔN, where N is the number of e-foldings of inflation. In Ref. [24], the authors have looked into higher order slow roll corrections by expanding the potential around ϕ_0. They pointed out that large

$$r \sim 0.05 \tag{1.14}$$

could be obtained in an *inflection-point* model of inflation where the slow roll parameter, ϵ_V, changes non-monotonically (for a definition of ϵ_V, see Eq. (2.8)). The ϵ_V parameter first increases within the observational window of ΔN and then decreases before increasing to exit the slow roll inflation by violating the slow roll condition, i.e. $\epsilon_V \approx 1$.[6] The value of r was still small in order to accommodate the WMAP data, which had probed roughly $\Delta N \approx 8$ as compared to the Planck, which has now probed $\Delta N \approx 17$ e-foldings of inflation [23,26–29] can be achieved by the CMB distortion observation. A generic bound on tensor-to-scalar ratio was

2 Apart from the correctness of this argument, it is additionally important to mention here that, still it does not require the initial conditions for the quantum vacuum to be Bunch–Davis strictly.

3 In this article I have not explored the possibility of non Bunch–Davies vacuum.

4 An arbitrary moduli or a gauge singlet inflaton can take large VEVs (super-Planckian) as in the case of a chaotic inflation [2]. Although, in the case of *assisted inflation* [18], see *chaotic assisted inflation* [19], the individual VEVs of the inflatons are sub-Planckian.

5 For the sake of completeness I suggest the readers to see Ref. [20], where I have explicitly studied the inflationary reconstruction technique within the framework of Randall Sundrum single brane set up, using the observational constraints obtained from Planck 2015 and BICPE2/Keck Array joint constraints.

6 The smallness of the observational window on ΔN also allows us to exploit another loophole in the derivation of the Lyth bound [25], namely the assumption that ϵ_V increases monotonically. This seems a natural assumption given that during inflation

$$\epsilon_V \ll 1 \tag{1.15}$$

and at the end of inflation

$$\epsilon_V \sim 1, \tag{1.16}$$

current observational constraints also strongly favour ϵ_V increasing during the $\Delta N \sim 17$ *e*-folds of the window achieved by the CMB distortion observation. However, outside this window the behaviour of ϵ_V is not constrained and the assumption of monotonicity is not strictly necessary. Relaxing this assumption makes it possible to construct a scalar potential for a single field that violates the Lyth bound. For more details see Ref. [24].