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What we can learn from the spectral index of the tensor mode

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A B S T R A C T

If the beginning of inflation is defined at the moment when the vacuum energy of the inflaton starts to dominate, the energy density of the other fields at that moment is (by definition) comparable to the inflaton. Although the fraction will be small at the horizon exit due to the inflationary expansion, they can alter the scale dependence of the spectrum. At the same time, velocity of the inflaton field may not coincide with the slow-roll (attractor) velocity. Those dynamics could be ubiquitous but can easily alter the scale dependence of the spectrum. Since the scale dependence is currently used to constrain or even exclude inflation models, it is very important to measure its shift, which is due to the dynamics that does not appear in the original inflation model. Considering typical examples, we show that the spectral index of the tensor mode is a useful measure of such effect. Precise measurement of the higher runnings of the scalar mode will be helpful in discriminating the source.

1. Introduction

Scale-dependence of the spectrum of the curvature perturbation has been used to discriminate inflationary scenarios [1,2]. In addition to the scalar mode, recent discovery of the B-mode polarization [3–6] has ignited studies of the tensor modes. Although the detection of the inflationary tensor mode by the BICEP2 was not successful, it stimulated study of the mechanism of generating peculiar scale-dependence [7–9]. Besides those recent trends in inflationary cosmology, models of particle physics (e.g., supersymmetric models and string theory) are expecting a large amount of scalar fields that may be dynamical in the very early stage of inflation. In the light of multi-field inflation, those extra degrees of freedom may alter the scale-dependence of both the tensor and the scalar perturbations. Consequently, they may bring in a kind of ambiguity to the inflationary parameters. Even if one is able to assume that the inflaton is the only dynamical field, it is still hard to believe that the inflaton velocity "before" inflation coincides with the slow-roll velocity "during" inflation. Initially the inflaton velocity could deviate from the slow-roll (attractor) velocity and it will lead to the shift of the scale-dependence. These effects are very common and they can be responsible for the scale dependence of the spectrum.

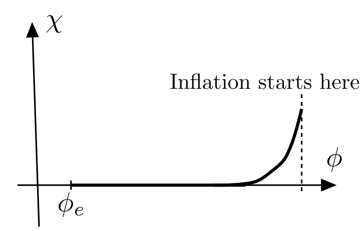

Fig. 1. Schematic picture of the "modest" multi-field inflation model. The scalon soon disappears and the number of e-foldings is determined by ϕ. Mixing in the spectrum is negligible.

We start with the obvious situation. The model shown in Fig. 1 is a textbook example, which helps understand why it is very easy to shift the scale-dependence of the spectrum. We focus on the simple and common dynamics. Since the scale dependence is currently used to constrain inflation models, it is very important to consider the shift of the scale dependence which could be caused by the dynamics that does not appear in the original inflation model. We call such dynamics the "scalon", since it contributes only to the generation of the scale dependence. Our study can be discriminated from other attempts in which non-trivial interactions play the key role. We are considering ubiquitous remnants. We also consider the case in which the field is not negligible at the end of inflation. The model is presented in Fig. 2. Finally we consider single-field inflation in which small deviation from the slow-roll

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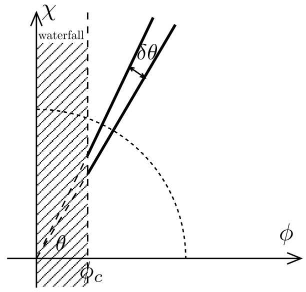

Fig. 2. Hybrid inflation with a ubiquitous (non-interacting) scalar field. Entropy perturbation ($\delta\theta$) causes δN at the end.

velocity can cause significant shift of the scale dependence. We show that in those cases the observation of the spectral index of the tensor mode will play important role in finding the scalon contribution. More precise measurement of the higher runnings of the scalar spectrum will be helpful for the discrimination.

2. How to measure and remove the scalon contribution in the spectrum

We briefly explain the overview before the details. We are focusing on the generality of the situation and considering simple dynamics of a scalar field. We thus avoid introduction of specific interactions and non-trivial kinetic terms. This point could be distinguishable from the other recent attempts [7].

Single-field inflation "usually" expects $r + 8n_t = 0$, where r is the tensor-to-scalar ratio and n_t is the spectral index of the tensor mode. The relation could be violated if there are multiple scalar fields during inflation.[1] Intuitively we are expecting simple cases for multi-field inflation explained below.

- Consider trajectory of Fig. 1. In this scenario the scalon is short-lived. The curvature perturbation evolves during inflation [10].
- Consider trajectory of Fig. 2. In this scenario the scalon remains dynamical until the end of inflation. The curvature perturbation is generated at the end.

In both cases the curvature perturbation at the pivot scale is unchanged, while the scale dependence is shifted by the scalon.

Before explaining more details, we point out that similar (but opposite) situation already appeared in the curvaton model. In the simplest curvaton model, in which the slow-roll parameters of the curvaton field are negligible (i.e., the curvaton dynamics cannot generate the scale dependence), the scale dependence is generated by the dynamics of the inflaton field whose perturbation is negligible in the curvaton model. In that case the inflaton dynamics contributes only to the scale dependence. Note that the field (or the dynamics) that contributes only to the scale dependence may commonly appear in any inflationary model. Similar effect may appear without adding a scalar field, as we will describe the situation below for single-field inflation.

- Inflaton velocity may have deviation from the slow-roll velocity. In that case the curvature perturbation is known to evolve after horizon exit, since the additional degree of freedom (i.e., the deviation) forms the decaying mode. In that case $r + 8n_t = 0$ is not satisfied in single-field inflation.

[1] Later we will show that it is possible to violate the relation in single-field inflation.

Deviation from the slow-roll velocity may have serious impact on the scale dependence. We will consider this possibility in Sec. 2.3. The sign of the spectral index could be reversed.

The relation $r+8n_t = 0$ is useless in the curvaton scenario, since the form of the curvature perturbation is completely different. We are not discussing those "alternative" models, including modulation (e.g. modulated reheating).

In general, "multi-field inflation" includes models in which multiple perturbations contribute the curvature perturbation. Such models are extensively studied since they may have a significant evidence of multi-field inflation in the relation among non-linear parameters [11]. To avoid confusions in this paper, those models are specifically called "mixed perturbation scenario". In this paper we are avoiding mixed perturbation scenarios since the non-Gaussianity parameter is small.

One might notice that the current CMB data is sometimes used to distinguish multi and single-field inflation. The major reason could be that there is the stringent upper bound on the isocurvature perturbation. Although an additional field "can" generate significant isocurvature perturbations, it is not mandatory. In other cases, as we have stated above, "multi-field inflation" sometimes means "mixed perturbation scenario". To avoid those confusions we emphasize that "inflation with the scalon dynamics" will not be distinguishable at this moment; we mean that the experimental plans at hand will hardly find the distinction. However, since what we call "the scalon" is the very common dynamics that could appear in the early Universe, we claim that it has to be identified and removed by more future experiments.

2.1. "Modest" multi-field inflation

We start with the simplest case. We introduce the scalon field (additional free scalar field χ), which is dynamical at the beginning of inflation. One can imagine the case in which $\dot{\chi}_* \gg \dot{\phi}_*$ at horizon exit but $\dot{\chi} \ll \dot{\phi}$ at the end. Here "$*$" denotes the value at the horizon exit. See also Fig. 1. Using the standard definition of the curvature perturbation, the scalon determine the initial adiabatic curvature perturbation. We also consider the case with $\dot{\chi}_* < \dot{\phi}_*$, which can also shift the scale dependence.

We are considering multi-field inflation. However, since we are considering a "temporal" field in this section, the derivative of the e-foldings with respect to the extra field ($N_{,\chi}$) is negligible.[2] Here the subscript with comma denotes derivative with respect to the field. Cases with significant $N_{,\chi}$ has been considered in Ref. [13]. Remember that we are focusing on the simple dynamics that does not assume specific interactions. We will assume canonical kinetic term for the fields. We are avoiding mixing of the fields in the potential. The scalon field is separated from the inflaton ϕ and ceases to be dynamical before the end of inflation. In that way our analysis does not depend on specific inflationary model. One can add χ to any (single-field, canonical kinetic term) inflationary model on one's choice.

When a couple of fields ϕ and χ are dynamical during inflation, the spectral index of the curvature perturbation is calculated as [12]

$$n_s - 1 \simeq -(6 - 4\cos^2 K_A)\epsilon_H + 2\eta_{\sigma\sigma}\sin^2 K_A + 4\eta_{\sigma s}\sin K_A \cos K_A + 2\eta_{ss}\cos^2 K_A, \quad (1)$$

where the subscripts σ and s denote the adiabatic and entropy directions at the horizon exit. We choose $\dot{\sigma}^2 = \dot{\chi}^2 + \dot{\phi}^2$. Here the definitions of the slow-roll parameters are

[2] In this section we are trying to explain the situation as intuitively as possible. See Ref. [12] if details are needed.