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Higgs scalaron mixed inflation

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ABSTRACT

We discuss the inflationary dynamics of a system with a non-minimal coupling between the Higgs and the Ricci scalar as well as a Ricci scalar squared term. There are two scalar modes in this system, *i.e.* the Higgs and the spin-zero mode of the graviton, or the scalaron. We study the two-field dynamics of the Higgs and the scalaron during inflation, and clarify the condition where inflation is dominated by the Higgs/scalaron. We also find that the cut-off scale at around the vacuum is as large as the Planck scale, and hence there is no unitarity issue, although there is a constraint on the couplings from the perturbativity of the theory at around the vacuum.

1. Introduction

After the observation of the cosmic microwave background (CMB) anisotropy, inflation plays a central role in the modern cosmology. It is usually assumed that inflation is caused by potential energy of a scalar field, or the inflaton, but there is no candidate within the standard model (SM). Hence we need to go beyond the SM to cause inflation. Among a variety of such inflation models, the Higgs-inflation [1–3] and the R^2-inflation [4–7] models are intriguing because of their minimality as well as consistency with the CMB observation. In the Higgs-inflation model, the SM Higgs boson plays the role of the inflaton thanks to a large non-minimal coupling to the Ricci scalar. In the R^2-inflation model, a spin-zero component of the metric (or the scaralon) obtains a kinetic term and plays the role of the inflaton once we introduce a Ricci scalar squared term in the action. It is known that both models predict a similar value of the spectral index which is in good agreement with the Planck observation [8]. It is also attractive that both models predict the tensor-to-scalar ratio that may be detectable in the future CMB experiment (CMB-S4) [9].

In the actual analysis of these models, it is sometimes assumed that the Higgs or the scalaron is the only scalar degree of freedom during inflation. In reality, however, the Higgs must always be there even if we consider the R^2-inflation model. In addition, if we consider the Higgs-inflation model, the large non-minimal coupling of the Higgs to the Ricci scalar may radiatively induce a large Ricci scalar squared term [10,11] that makes the scalaron dynamical as well. Hence it is more realistic to consider the dynamics of both the Higgs and the scalaron simultaneously.[1] In this paper we will thus study the Higgs-scalaron two-field inflationary dynamics,[2] and derive the parameter dependence of the inflationary predictions in our system. We will clarify the quantitative condition where inflation is dominated by the Higgs or the scalaron. In addition, we will address the unitarity structure of our system, which is much different from that of the Higgs-inflation.

The organization of this paper is as follows. In Sec. 2, we discuss the inflationary dynamics of the Higgs-scalaron two-field system. We first study the dynamics analytically, and later confirm it by numerical calculation. In Sec. 3, we study the unitarity structure of this system. We find that the cut-off scale of our system is as large as the Planck scale, which is similar to the case of the R^2-inflation rather than the Higgs-inflation. In Sec. 4, we concentrate on the dynamics of the Higgs when the electroweak (EW) vacuum is metastable. The last section 5 is devoted to the summary and discussions.

2. Inflationary dynamics

In this section, we study the two-field dynamics of the Higgs and the scalaron during inflation.

[1] A similar study with an additional scalar field instead of the scalaron with a non-minimal coupling to the Ricci scalar has been performed in literature. See, *e.g.* Refs. [12–21] and references therein.

[2] An analysis in this direction is also performed in Ref. [22,10] although some aspects we discuss in this paper such as the unitarity/perturbativity and the implication of the electroweak vacuum metastability are not addressed there. See also Refs. [23–28] as other treatments.

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2.1. Action in Jordan/Einstein frame

We start from the following action in the Jordan frame:

$$S = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(1+\frac{\xi_h h^2}{M_P^2}\right)R_J + \frac{\xi_s}{4}R_J^2 - \frac{1}{2}g_J^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda_h}{4}h^4\right], \tag{1}$$

where $g_{J\mu\nu}$ is the metric (with the "almost-plus" convention), g_J is the determinant of the metric, R_J is the Ricci scalar, M_P is the reduced Planck mass and h is the Higgs in the unitary gauge. We add the subscript J for the quantities in the Jordan frame. We consider only the case

$$\xi_s,\ |\xi_h| \gg 1. \tag{2}$$

In particular, we concentrate on the case $\xi_s > 0$ since otherwise there is a tachyonic mode. On the other hand, we do not specify the signs of ξ_h and λ_h. Concerning the sign of λ_h, the current measurement of the top and Higgs masses indicates that it becomes negative at a high energy region, resulting in the metastable EW vacuum [29–42], although the stable EW vacuum is also still allowed. In view of this, we consider both $\lambda_h > 0$ and $\lambda_h < 0$ in this paper.

By introducing an auxiliary field s, the action (1) is rewritten as [6,43][3]

$$S = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(1+\frac{\xi_h h^2+\xi_s s}{M_P^2}\right)R_J - \frac{\xi_s}{4}s^2 - \frac{1}{2}g_J^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda_h}{4}h^4\right]. \tag{3}$$

Note that the variation with respect to s gives

$$s = R_J, \tag{4}$$

and we restore the original action (1) after substituting it to Eq. (3). The field s corresponds to a spin-zero mode of the graviton that is dynamical due to the presence of the Ricci scalar squared term. We call it a "scalaron" in this paper.

First we perform the Weyl transformation to obtain the action in the Einstein frame. We define the metric in the Einstein frame as

$$g_{\mu\nu} = \Omega^2 g_{J\mu\nu},\quad \Omega^2 = 1+\frac{\xi_h h^2+\xi_s s}{M_P^2}. \tag{5}$$

The Ricci scalar is transformed as

$$R_J = \Omega^2\left[R + 3\Box\ln\Omega^2 - \frac{3}{2}g^{\mu\nu}\partial_\mu\ln\Omega^2\partial_\nu\ln\Omega^2\right], \tag{6}$$

where R and $\Box$ are the Ricci scalar and the d'Alembert operator constructed from $g_{\mu\nu}$, respectively. The action now reads

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{3M_P^2}{4}g^{\mu\nu}\partial_\mu\ln\Omega^2\partial_\nu\ln\Omega^2 - \frac{g^{\mu\nu}}{2\Omega^2}\partial_\mu h\partial_\nu h - U(h,s)\right], \tag{7}$$

where the potential in the Einstein frame is given by

$$U(h,s) \equiv \frac{\lambda_h h^4+\xi_s s^2}{4\Omega^4}. \tag{8}$$

[3] This choice of the dual description is unique up to the shift and the rescaling of the auxiliary field s. For more details, see Appendix A.

We define a new field ϕ as

$$\frac{\phi}{M_P} \equiv \sqrt{\frac{3}{2}}\ln\Omega^2. \tag{9}$$

It corresponds to the inflaton degree of freedom in our system. By eliminating s in terms of ϕ, we finally obtain

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}e^{-\chi}g^{\mu\nu}\partial_\mu h\partial_\nu h - U(\phi,h)\right], \tag{10}$$

where the potential now reads

$$U(\phi,h) = \frac{1}{4}e^{-2\chi}\left[\lambda_h h^4 + \frac{M_P^4}{\xi_s}\left(e^\chi - 1 - \frac{\xi_h h^2}{M_P^2}\right)^2\right], \tag{11}$$

and we have defined

$$\chi \equiv \sqrt{\frac{2}{3}}\frac{\phi}{M_P}. \tag{12}$$

This is the master action in our system. Note that so far we have not used any approximation. In the following, we study the inflationary dynamics of this action in the Einstein frame.

2.2. Two-field dynamics

Now we study the inflationary dynamics of the action (10). An analysis for a similar system is performed in Ref. [13], and we follow that procedure here. The action (10) contains the kinetic mixing term between ϕ and h, and hence we define the following field τ to solve the mixing:

$$\tau \equiv \frac{s}{h^2}. \tag{13}$$

Note that $\tau = 0$ corresponds to the pure Higgs-inflation, while $\tau = \infty$ corresponds to the pure R^2-inflation. The kinetic terms now read

$$\mathcal{L}_{\rm kin} = -\frac{1}{2}\left(1+\frac{1}{6(\xi_h+\xi_s\tau)}\frac{e^\chi}{e^\chi-1}\right)(\partial\phi)^2 - \frac{M_P^2}{8}\frac{\xi_s^2(1-e^{-\chi})}{(\xi_h+\xi_s\tau)^3}(\partial\tau)^2 + \frac{M_P}{2\sqrt{6}}\frac{\xi_s}{(\xi_h+\xi_s\tau)^2}(\partial\phi)(\partial\tau). \tag{14}$$

Since we are interested in the inflationary dynamics, we concentrate on the case

$$\xi_h h^2 + \xi_s s \gg M_P^2,\ \text{ or } e^\chi \gg 1, \tag{15}$$

in this section. Then, the kinetic terms are approximated as

$$\mathcal{L}_{\rm kin} = -\frac{1}{2}\left(1+\frac{1}{6(\xi_h+\xi_s\tau)}\right)(\partial\phi)^2 - \frac{M_P^2}{8}\frac{\xi_s^2}{(\xi_h+\xi_s\tau)^3}(\partial\tau)^2 + \frac{M_P}{2\sqrt{6}}\frac{\xi_s}{(\xi_h+\xi_s\tau)^2}(\partial\phi)(\partial\tau). \tag{16}$$

Note that τ satisfies

$$\xi_h + \xi_s\tau \gg \frac{M_P^2}{h^2} > 0, \tag{17}$$

when the condition (15) is satisfied, and hence the kinetic term of τ has a correct sign. In the following we assume

$$\xi_h + \xi_s\tau \gg 1, \tag{18}$$