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Physics Letters B 659 (2008) 703–706
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

The Standard Model Higgs boson as the inflaton

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Received 26 October 2007; received in revised form 12 November 2007; accepted 14 November 2007

Available online 4 December 2007

Editor: A. Ringwald

Abstract

We argue that the Higgs boson of the Standard Model can lead to inflation and produce cosmological perturbations in accordance with observations. An essential requirement is the non-minimal coupling of the Higgs scalar field to gravity; no new particle besides already present in the electroweak theory is required.

PACS: 98.80.Cq; 14.80.Bn

Keywords: Inflation; Higgs field; Standard Model; Variable Planck mass; Non-minimal coupling

1. Introduction

The fact that our universe is almost flat, homogeneous and isotropic is often considered as a strong indication that the Standard Model (SM) of elementary particles is not complete. Indeed, these puzzles, together with the problem of generation of (almost) scale invariant spectrum of perturbations, necessary for structure formation, are most elegantly solved by inflation [1–6]. The majority of present models of inflation require an introduction of an additional scalar—the "inflaton". This hypothetical particle may appear in a natural or not so natural way in different extensions of the SM, involving Grand Unified Theories (GUTs), supersymmetry, string theory, extra dimensions, etc. Inflaton properties are constrained by the observations of fluctuations of the Cosmic Microwave Background (CMB) and the matter distribution in the universe. Though the mass and the interaction of the inflaton with matter fields are not fixed, the well-known considerations prefer a heavy scalar field with a mass $\sim 10^{13}$ GeV and extremely small self-interacting quartic coupling constant $\lambda \sim 10^{-13}$ [7]. This value of the mass is close to the GUT scale, which is often considered as an argument in favour of existence of new physics between the electroweak and Planck scales.

The aim of the present Letter is to demonstrate that the SM itself can give rise to inflation. The spectral index and the amplitude of tensor perturbations can be predicted and be used to distinguish this possibility from other models for inflation; these parameters for the SM fall within the 1σ confidence contours of the WMAP-3 observations [8].

To explain our main idea, consider Lagrangian of the SM non-minimally coupled to gravity,

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R, \tag{1}$$

where $L_{\rm SM}$ is the SM part, M is some mass parameter, R is the scalar curvature, H is the Higgs field, and ξ is an unknown constant to be fixed later.[1] The third term in (1) is in fact required by the renormalization properties of the scalar field in a curved space–time background [9]. If $\xi = 0$, the coupling of the Higgs field to gravity is said to be "minimal". Then M can be identified with Planck scale M_P related to the Newton's constant as

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[1] In our notations the conformal coupling is $\xi = -1/6$.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2007.11.072

$M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV. This model has "good" particle physics phenomenology but gives "bad" inflation since the self-coupling of the Higgs field is too large and matter fluctuations are many orders of magnitude larger than those observed. Another extreme is to put M to zero and consider the "induced" gravity [10–14], in which the electroweak symmetry breaking generates the Planck mass [15–17]. This happens if $\sqrt{\xi} \sim 1/(\sqrt{G_N} M_W) \sim 10^{17}$, where $M_W \sim 100$ GeV is the electroweak scale. This model may give "good" inflation [12–14,18–20] even if the scalar self-coupling is of the order of one, but most probably fails to describe particle physics experiments. Indeed, the Higgs field in this case almost completely decouples from other fields of the SM[2] [15–17], which corresponds formally to the infinite Higgs mass m_H. This is in conflict with the precision tests of the electroweak theory which tell that m_H must be below 285 GeV [21] or even 200 GeV [22] if less conservative point of view is taken.

These arguments indicate that there may exist some intermediate choice of M and ξ which is "good" for particle physics and for inflation at the same time. Indeed, if the parameter ξ is sufficiently small, $\sqrt{\xi} \lll 10^{17}$, we are very far from the regime of induced gravity and the low energy limit of the theory (1) is just the SM with the usual Higgs boson. At the same time, if ξ is sufficiently large, $\xi \gg 1$, the scalar field behaviour, relevant for chaotic inflation scenario [7], drastically changes, and successful inflation becomes possible. We should note, that models of chaotic inflation with both nonzero M and ξ were considered in literature [12,14,19,20,23–25], but in the context of either GUT or with an additional inflaton having nothing to do with the Higgs field of the Standard Model.

The Letter is organized as follows. We start from discussion of inflation in the model, and use the slow-roll approximation to find the perturbation spectra parameters. Then we will argue in Section 3 that quantum corrections are unlikely to spoil the classical analysis we used in Section 2. We conclude in Section 4.

2. Inflation and CMB fluctuations

Let us consider the scalar sector of the Standard Model, coupled to gravity in a non-minimal way. We will use the unitary gauge $H = h/\sqrt{2}$ and neglect all gauge interactions for the time being, they will be discussed later in Section 3. Then the Lagrangian has the form:

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M^2 + \xi h^2}{2} R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \right\}. \quad (2)$$

This Lagrangian has been studied in detail in many papers on inflation [14,19,20,24], we will reproduce here the main results of [14,19]. To simplify the formulae, we will consider only ξ in the region $1 \ll \sqrt{\xi} \lll 10^{17}$, in which $M \simeq M_P$ with very good accuracy.

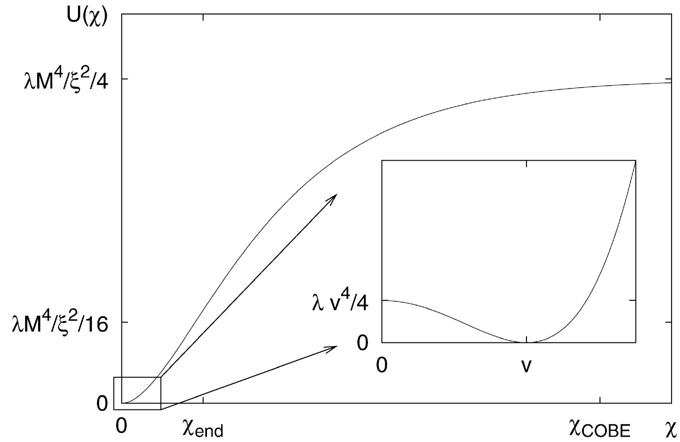

Fig. 1. Effective potential in the Einstein frame.

It is possible to get rid of the non-minimal coupling to gravity by making the conformal transformation from the Jordan frame to the Einstein frame

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}. \quad (3)$$

This transformation leads to a non-minimal kinetic term for the Higgs field. So, it is convenient to make the change to the new scalar field χ with

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}}. \quad (4)$$

Finally, the action in the Einstein frame is

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi) \right\}, \quad (5)$$

where $\hat{R}$ is calculated using the metric $\hat{g}_{\mu\nu}$ and the potential is

$$U(\chi) = \frac{1}{\Omega(\chi)^4} \frac{\lambda}{4}\left(h(\chi)^2 - v^2\right)^2. \quad (6)$$

For small field values $h \simeq \chi$ and $\Omega^2 \simeq 1$, so the potential for the field χ is the same as that for the initial Higgs field. However, for large values of $h \gg M_P/\sqrt{\xi}$ (or $\chi \gg \sqrt{6} M_P$) the situation changes a lot. In this limit

$$h \simeq \frac{M_P}{\sqrt{\xi}} \exp\left(\frac{\chi}{\sqrt{6} M_P}\right). \quad (7)$$

This means that the potential for the Higgs field is exponentially flat and has the form

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6} M_P}\right)\right)^{-2}. \quad (8)$$

The full effective potential in the Einstein frame is presented in Fig. 1. It is the flatness of the potential at $\chi \gg M_P$ which makes the successful (chaotic) inflation possible.

Analysis of the inflation in the Einstein frame[3] can be performed in standard way using the slow-roll approximation. The

[2] This can be seen most easily by rewriting the Lagrangian (1), given in the Jordan frame, to the Einstein frame, see also below.

[3] The same results can be obtained in the Jordan frame [26,27].