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Higgs–Dilaton cosmology: Are there extra relativistic species?

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ABSTRACT

Recent analyses of cosmological data suggest the presence of an extra relativistic component beyond the Standard Model content. The Higgs–Dilaton cosmological model predicts the existence of a massless particle – the dilaton – associated with the spontaneous symmetry breaking of scale invariance and undetectable by any accelerator experiment. Its ultrarelativistic character makes it a suitable candidate for contributing to the effective number of light degrees of freedom in the Universe. In this Letter we analyze the dilaton production at the (p)reheating stage right after inflation and conclude that no extra relativistic degrees of freedom beyond those already present in the Standard Model are expected within the simplest Higgs–Dilaton scenario. The elusive dilaton remains thus essentially undetectable by any particle physics experiment or cosmological observation.

1. Introduction

Cosmology is entering in a precision era where the interplay with particle physics is becoming more and more important. A noteworthy example is the effective number of light degrees of freedom appearing in the different extensions of the Standard Model (SM). Any extra radiation component in the Universe is usually parametrized, independently of its statistics, in terms of an effective number of neutrino species, $N_{\rm eff} = N_{\rm eff}^{\rm SM} + \Delta N_{\rm eff}$ [1], where $N_{\rm eff}^{\rm SM}$ stands for the number of active neutrinos in the SM.[1]

The strongest constraints on the effective number of neutrino species come from Big Bang Nucleosynthesis (BBN). A non-standard value of $N_{\rm eff}$ increases the expansion rate, which results on an enhancement of the primordial helium abundance. Assuming zero lepton asymmetry, the number of effective degrees of freedom at BBN turns out to be $N_{\rm eff} = 3.71^{+0.47}_{-0.45}$ (68% C.L.) [4]. Note that, although the existence of extra species is somehow favored, the obtained value is still compatible with the SM prediction within the 95% C.L.

Some constraints on $N_{\rm eff}$ can be also obtained from the analysis of the Cosmic Microwave Background (CMB), although the current limits are significantly weaker than those of BBN. The combined analysis of WMAP7 results, Hubble constant measurements and baryon acoustic oscillations [5] provides a value $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68% C.L.). Similar and complementary results for smaller CMB scales have been also reported by the Atacama Cosmology Telescope [6] and the South Pole Telescope [7]. It is interesting to notice the dependence of the effective number of neutrino species on the priors considered in the different Bayesian analysis existing in the literature. While in some references the SM value, $N_{\rm eff}^{\rm SM} = 3$, is ruled out at 95% C.L. [8,9], in others, such as [10], it is not. Besides, if the helium abundance obtained from CMB measures is taken into account, together with the most precise primordial deuterium abundance [11], the BBN result becomes perfectly consistent with the SM one at the 2σ level, $N_{\rm eff} = 3.22 \pm 0.55$ [4]. The number of extra degrees of freedom is therefore an open question to be solved by the Planck satellite, which is expected to determine $N_{\rm eff}$ with an accuracy of ~ 0.3 at 2σ [12], breaking thereby the degeneracies with nonzero neutrino masses and dynamical dark energy [13].

In order to account for the apparent radiation excess one can consider several possibilities. It could be, for instance, the indication of an extra sterile neutrino [14,15], of relic gravitational waves [16], or arise from other exotic possibilities such as a decaying particle [17–19], or the interaction between dark energy and dark matter [20] or the reheating of the neutrino thermal bath [21]. In this Letter we will consider a different possibility within the minimalistic framework of Higgs–Dilaton cosmology [22–24]. This constitutes an extension of the Higgs inflation idea [25], where the Standard Model Higgs doublet H is non-minimally coupled to gravity. The novel ingredient of Higgs–Dilaton cosmology is

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[1] In the standard cosmological model with three neutrino flavors and zero chemical potential we have $N_{\rm eff}^{\rm SM} = 3$ at BBN, and $N_{\rm eff}^{\rm SM} = 3.046$ at CMB. The small excess in the last case with respect to the LEP result [2] is due to the entropy transfer between neutrino species and the thermal bath during electron–positron annihilation [3].

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the invariance of the action under scale transformations. This extra symmetry leads to the absence of any dimensional parameters or scales.[2] The simplest phenomenologically viable theory of this kind requires the existence of a new scalar singlet under the SM gauge group [22], the dilaton χ, non-minimally coupled to gravity. It corresponds to the Goldstone boson associated with the spontaneous symmetry breaking of scale invariance and it is therefore massless. This property makes it a potential candidate for contributing to the effective number of relativistic degrees of freedom at BBN and recombination. Indeed, this cosmological test seems to be the only available probe for determining the existence of the dilaton particle. The coupling between the dilaton and all the SM fields (apart from the Higgs) is forbidden by quantum numbers, which, together with the Goldstone boson nature of this particle, excludes the possibility of a direct detection in an accelerator experiment [22].

In this Letter we study the (p)reheating stage in Higgs–Dilaton cosmology, paying special attention to the dilaton production. This Letter is organized as follows. In Sections 2 and 3 we review the Higgs–Dilaton inflationary model and show that, given the hierarchical structure of the non-minimal couplings to gravity, the production of SM particles takes place, up to some small corrections, as in the simplest Higgs inflationary scenario [26–28]. The difference between the two models is described in Section 4, where we compute the dilaton production, compare it with the total energy density of SM particles at the end of the preheating stage and determine its contribution to the effective number of relativistic degrees of freedom. The conclusions are presented in Section 5.

2. Higgs–Dilaton inflation

We start by reviewing the Higgs–Dilaton model [22,23]. In the unitary gauge $H^T=(0,h/\sqrt{2})$, it is described by the following Lagrangian density

$$\frac{\mathscr{L}}{\sqrt{-g}}=\frac{1}{2}(\xi_\chi\chi^2+\xi_h h^2)R-\frac{1}{2}(\partial\chi)^2-U(\chi,h), \tag{1}$$

where we have omitted the part of the SM Lagrangian not involving the Higgs potential, $\mathscr{L}_{\mathrm{SM}[\lambda\to 0]}$. The values of the non-minimal couplings to gravity can be determined from CMB observations and turn out to be highly hierarchical ($\xi_\chi\sim 10^{-3}$, $\xi_h\sim 10^3$–10^5) [23,29]. The scale-invariant potential $U(\chi,h)$ is given by

$$U(\chi,h)=\frac{\lambda}{4}\left(h^2-\frac{\alpha}{\lambda}\chi^2\right)^2+\beta\chi^4, \tag{2}$$

with λ the self-coupling of the Higgs field. The parameters α and β must be properly tuned in order to reproduce the correct hierarchy between the electroweak, Planck and cosmological constant scales. In particular, we must require $\beta\ll\alpha\ll 1$. The smallness of all the couplings involving the dilaton field gives rise to an approximate shift symmetry $\chi\to\chi+\mathrm{const.}$, which, as described in Ref. [30], has important consequences for the analysis of quantum effects. For the typical energy scales involved in the (p)reheating stage we can safely set $\alpha=\beta=0$ in all the following developments.

We study here the (p)reheating of the universe after Higgs–Dilaton inflation. As emphasized in Ref. [23], particle production is more easily analyzed in the so-called Einstein-frame, where the Higgs and dilaton fields are minimally coupled to gravity. Performing a conformal redefinition of the metric, $\tilde g_{\mu\nu}=\Omega^2 g_{\mu\nu}$, with conformal factor $\Omega^2=M_P^{-2}(\xi_\chi\chi^2+\xi_h h^2)$, we obtain

$$\frac{\mathscr{L}}{\sqrt{-\tilde g}}=\frac{M_P^2}{2}\tilde R-\frac{1}{2}\tilde K(\chi,h)-\tilde U(\chi,h). \tag{3}$$

Here $\tilde K(\chi,h)$ is a non-canonical kinetic term in the basis $(\phi^1,\phi^2)=(\chi,h)$

$$\tilde K(\chi,h)=\frac{\kappa_{ij}}{\Omega^2}\tilde g^{\mu\nu}\partial_\mu\phi^i\partial_\nu\phi^j, \tag{4}$$

with

$$\kappa_{ij}=\left(\delta_{ij}+\frac{3}{2}M_P^2\frac{\partial_i\Omega^2\partial_j\Omega^2}{\Omega^2}\right), \tag{5}$$

and $\tilde U(\chi,h)\equiv U(\chi,h)/\Omega^4$ is the Einstein-frame potential. In order to diagonalize the kinetic term we can make use of the conserved Noether's current associated to scale invariance. It can be easily shown, via the homogeneous Friedmann and Klein–Gordon equations in the slow-roll approximation, that the field combination $(1+6\xi_\chi)\chi^2+(1+6\xi_h)h^2$ is time-independent in the absence of any explicit symmetry breaking term [23]. This conservation suggests a field redefinition to polar variables in the (h,χ) plane

$$r=\frac{M_P}{2}\log\left[\frac{(1+6\xi_\chi)\chi^2+(1+6\xi_h)h^2}{M_P^2}\right], \tag{6}$$

$$\tan\theta=\sqrt{\frac{1+6\xi_h}{1+6\xi_\chi}}\frac{h}{\chi}. \tag{7}$$

In terms of the new coordinates, the kinetic term (4) becomes diagonal, although non-canonical,

$$\tilde K=\left(\frac{1+6\xi_h}{\xi_h}\right)\frac{1}{\sin^2\theta+\varsigma\cos^2\theta}(\partial r)^2 + \frac{M_P^2\varsigma}{\xi_\chi}\frac{\tan^2\theta+\mu}{\cos^2\theta(\tan^2\theta+\varsigma)^2}(\partial\theta)^2, \tag{8}$$

where we have defined

$$\mu=\frac{\xi_\chi}{\xi_h}\quad\text{and}\quad\varsigma=\frac{(1+6\xi_h)\xi_\chi}{(1+6\xi_\chi)\xi_h}. \tag{9}$$

The dilatonic field r is massless, as corresponds to the Goldstone boson associated with the spontaneously broken scale symmetry. The inflationary potential depends only on the angular variable θ and it is symmetric around $\theta=0$

$$\tilde U(\theta)=\frac{\lambda M_P^4}{4\xi_h^2}\left(\frac{\sin^2\theta}{\sin^2\theta+\varsigma\cos^2\theta}\right)^2. \tag{10}$$

It can be easily seen that during the (p)reheating stage the values of the oscillating field θ are much larger than the μ parameter for a large number of oscillations, $\tan^2\theta\gg\mu$. This allows us to neglect the μ term in Eq. (8) and perform an extra field redefinition

$$\rho=\gamma^{-1}r,\qquad |\phi|=\phi_0-\frac{M_P}{a}\tanh^{-1}[\sqrt{1-\varsigma}\cos\theta], \tag{11}$$

with

$$\gamma=\sqrt{\frac{\xi_\chi}{1+6\xi_\chi}}\quad\text{and}\quad a=\sqrt{\frac{\xi_\chi(1-\varsigma)}{\varsigma}}. \tag{12}$$

[2] In particular it forbids the appearance of a cosmological constant term in the action. In Higgs–Dilaton cosmology, the late dark energy dominated period of the Universe is recovered, at the level of the equations of motion, by replacing General Relativity with Unimodular Gravity. However, both the inflationary and preheating stages considered in this Letter take place in field space regions where the dark energy contribution is completely negligible. We will thus omit this point here. The reader is referred to Ref. [23] for details about the phenomenological consequences of Unimodular Gravity in the Higgs–Dilaton scenario.