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Low temperature electroweak phase transition in the Standard Model with hidden scale invariance

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ABSTRACT

We discuss a cosmological phase transition within the Standard Model which incorporates spontaneously broken scale invariance as a low-energy theory. In addition to the Standard Model fields, the minimal model involves a light dilaton, which acquires a large vacuum expectation value (VEV) through the mechanism of dimensional transmutation. Under the assumption of the cancellation of the vacuum energy, the dilaton develops a very small mass at 2-loop order. As a result, a flat direction is present in the classical dilaton-Higgs potential at zero temperature while the quantum potential admits two (almost) degenerate local minima with unbroken and broken electroweak symmetry. We found that the cosmological electroweak phase transition in this model can only be triggered by a QCD chiral symmetry breaking phase transition at low temperatures, $T \lesssim 132$ MeV. Furthermore, unlike the standard case, the universe settles into the chiral symmetry breaking vacuum via a first-order phase transition which gives rise to a stochastic gravitational background with a peak frequency $\sim 10^{-8}$ Hz as well as triggers the production of approximately solar mass primordial black holes. The observation of these signatures of cosmological phase transitions together with the detection of a light dilaton would provide a strong hint of the fundamental role of scale invariance in particle physics.

1. Introduction

Scale invariance provides an attractive framework for addressing the problem of the origin of mass and hierarchies of mass scales. In this framework, quantum fluctuations result in an overall mass scale via the mechanism of dimensional transmutation [1], while dimensionless couplings are responsible for generating mass hierarchies. The dimensionless couplings in the low-energy sector of the theory are only logarithmically sensitive to the high-energy sector and can be naturally small in the technical sense [2–4]. If high-energy and low-energy sectors interact via feeble interactions, the breaking of scale invariance in the higher energy sector would proliferate in the low-energy sector resulting in a stable mass hierarchy between the two [for an incomplete list of recent works, see [5,6]]. The above scenario is signified by the fact that scale (conformal) invariance is indeed an essential symmetry in string theory that is believed to provide a consistent ultraviolet completion of all fundamental interactions including gravity.

Recently, two of us have proposed a minimal extension of the Standard Model which incorporates spontaneously broken scale invariance as a low energy effective theory [7]. In this approach, non-linearly realised scale invariance is introduced by promoting physical mass parameters (including the ultraviolet cut-off Λ) to a dynamical dilaton field. The dilaton field develops a large vacuum expectation value (VEV) via the quantum mechanical mechanism of dimensional transmutation. The dilaton-Higgs interactions then trigger the electroweak symmetry breaking and generate a stable hierarchy between the Higgs and dilaton VEVs. As a result of the spontaneous breaking of anomalous scale symmetry, the dilaton develops a mass at two loop level, which can be as small as $\sim 10^{-8}$ eV (for a dilaton VEV of the order the Planck scale, $\sim M_P \sim 10^{19}$ GeV). In addition, the Higgs-dilaton potential displays a nearly flat direction.

The formalism of hidden scale invariance is rather generic and can be applied to other effective field theory models, with essentially the same predictions regarding the light dilaton and the Higgs-dilaton potential [8]. Due to these generic features it is interesting to investigate the cosmological phase transition in effective theories with hidden scale invariance. This is the purpose of the present paper.

Witten has pointed out a long time ago [9] that in the Standard Model with Coleman–Weinberg radiative electroweak symmetry breaking, the cosmological electroweak phase transition is

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strongly first-order. The electroweak phase transition is aided by the QCD quark–antiquark condensate and hence occurs at low temperatures, namely around the temperature of the QCD chiral phase transition. See also the follow up work which also introduces the dilaton field [10]. Although these models are no longer phenomenologically viable, one may consider their extensions which exhibit the same features for some range of parameters [11]. We will argue below, that within the framework of hidden scale invariance, the electroweak phase transition is necessarily triggered by QCD chiral phase transition and is completed at a low temperature ~ 130 MeV. We find that the Higgs field transitions to the electroweak vacuum via a second-order phase transition, while the chiral phase transition becomes first-order, similarly to one of the scenarios described in [11]. The later phase transition leads to the generation of stochastic gravitational waves in the $\sim 10^{-8}$ Hz frequency range, which are potentially observable using pulsar timing technique, e.g. at the Square Kilometre Array (SKA) observatory [12]. In addition, production of primordial solar mass black holes are expected during that phase transition.

The paper is organised as follows. In the next section we describe the minimal Standard Model with hidden scale invariance. Calculation of the thermal effective potential and a subsequent analysis of the cosmological phase transition is given is section 3. The last section 4 is reserved for conclusions.

2. The Standard Model with hidden scale invariance

Let us consider the Standard Model as an effective low energy theory valid up to an energy scale, Λ, as introduced in [7]. In the Wilsonian approach, the ultraviolet cut-off Λ is a physical parameter that encapsulates physics (e.g. massive fields) which we are agnostic of. The Higgs potential defined at this ultraviolet scale reads:

$$V(\Phi^\dagger\Phi) = V_0(\Lambda) + \lambda(\Lambda)\left[\Phi^\dagger\Phi - v_{ew}^2(\Lambda)\right]^2 + \ldots, \tag{1}$$

where Φ is the electroweak doublet Higgs field, V_0 is a field-independent constant (bare cosmological constant parameter) and the ellipsis denote all possible dimension > 4 (irrelevant), gauge invariant operators, $\left(\Phi^\dagger\Phi\right)^n$, $n = 3, 4\ldots$ The other bare parameters include the dimensionless couplings $\lambda(\Lambda)$ and a mass dimension parameter $v_{ew}(\Lambda)$ namely the bare Higgs expectation value. In principle, this potential has an infinite number of nonrenormalisable operators and Λ-dependent parameters must fully encode the physics beyond the Standard Model. In practice, however, we usually deal with a truncated theory, which is valid in the low-energy domain only.

We assume now that a fundamental theory maintains spontaneously broken scale invariance, such that all mass parameters have a common origin. To make this symmetry manifest in our effective theory, we promote all mass parameters to a dynamical field χ, the dilaton, as follows:

$$\begin{aligned}&\Lambda \to \Lambda\frac{\chi}{f_\chi} \equiv \alpha\chi, \quad v_{ew}^2(\Lambda) \to \frac{v_{ew}^2(\alpha\chi)}{f_\chi^2}\chi^2 \equiv \frac{\xi(\alpha\chi)}{2}\chi^2,\\ &V_0(\Lambda) \to \frac{V_0(\alpha\chi)}{f_\chi^4}\chi^4 \equiv \frac{\rho(\alpha\chi)}{4}\chi^4,\end{aligned} \tag{2}$$

where f_χ is the dilaton decay constant. Then, Eq. (1) turns into the Higgs-dilaton potential,

$$V(\Phi^\dagger\Phi, \chi) = \lambda(\alpha\chi)\left[\Phi^\dagger\Phi - \frac{\xi(\alpha\chi)}{2}\chi^2\right]^2 + \frac{\rho(\alpha\chi)}{4}\chi^4. \tag{3}$$

This potential is manifestly scale invariant up to the quantum scale anomaly, which is engraved in the χ-dependence of dimensionless couplings.[1] Indeed, the Taylor expansion around an arbitrary fixed scale μ reads:

$$\begin{aligned}\lambda^{(i)}(\alpha\chi) = \lambda^{(i)}(\mu) + \beta_{\lambda^{(i)}}(\mu)\ln(\alpha\chi/\mu)\\ + \beta'_{\lambda^{(i)}}(\mu)\ln^2(\alpha\chi/\mu) + \ldots,\end{aligned} \tag{4}$$

where $\lambda^{(i)} \equiv (\lambda, \xi, \rho)$ and

$$\beta_{\lambda^{(i)}}(\mu) = \left.\frac{\partial\lambda^{(i)}}{\partial\ln\chi}\right|_{\alpha\chi=\mu}, \tag{5}$$

is the renormalisation group (RG) β-functions for the respective coupling $\lambda^{(i)}$ defined at a scale μ, while $\beta'_{\lambda^{(i)}}(\mu) = \left.\frac{\partial^2\lambda^{(i)}}{\partial(\ln\chi)^2}\right|_{\alpha\chi=\mu}$, etc. For convenience, we fix the renormalisation scale at the cut-off scale Λ, which is defined through the dilaton VEV as $\langle\chi\rangle \equiv v_\chi$, i.e. $\mu = \Lambda = \alpha v_\chi$. Note that while the lowest order contribution in β-functions is one-loop, i.e. $\sim \mathcal{O}(\hbar)$, n-th derivative of β is nth order in the perturbative loop expansion, $\sim \mathcal{O}(\hbar^n)$.

The extremum condition $\left.\frac{dV}{d\chi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle} = 0$ together with the phenomenological constraint on vacuum energy $V(v_{ew}, v_\chi) = 0$, lead to the following relations:

$$\rho(\Lambda) = 0\,, \quad \beta_\rho(\Lambda) = 0\,. \tag{6}$$

One of the above relations can be used to define the dilaton VEV (dimensional transmutation) and another represents the tuning of the cosmological constant. The second extremum condition $\left.\frac{dV}{d\Phi}\right|_{\Phi=\langle\Phi\rangle,\chi=\langle\chi\rangle} = 0$ simply sets the hierarchy of VEVs:

$$\xi(\Lambda) = \frac{v_{ew}^2}{v_\chi^2}\,. \tag{7}$$

In the classical limit when all the quantum corrections are zero, i.e., $\beta_{\lambda^{(i)}} = \beta'_{\lambda^{(i)}} = \ldots = 0$, the above vacuum configuration represents a flat direction of the Higgs-dilaton potential (3). The existence of this flat direction is, of course, the direct consequence of the assumed classical scale invariance. In this approximation, the dilaton is the massless Goldstone boson of spontaneously broken scale invariance. The flat direction is lifted by quantum effects and, as we will see below, by thermal effects in the early universe. Note, however, that the dilaton develops a (running) mass in our scenario at two-loop level [7] (see also [14]),

$$m_\chi^2 \simeq \frac{\beta'_\rho(\Lambda)}{4\xi(\Lambda)}v_{ew}^2\,, \tag{8}$$

while the tree-level Higgs mass is given to a high accuracy by the standard formula: $m_h^2 \simeq 2\lambda(\Lambda)v_{ew}^2$. Note that $\beta'_\rho \propto \xi^2$ and hence the dilaton is a very light particle, $m_\chi/m_h \sim \sqrt{\xi}$.

To verify whether the above scalar field configurations correspond to a local minimum of the potential one must evaluate the running masses down to low energy scales. The relations in Eq. (6) provide non-trivial constraints here. In Fig. 1, we have presented our analysis based on solutions of the relevant (one-loop) RG equations (see the appendix section in Ref. [7]). The shaded region in the $\Lambda - m_t$ plane corresponds to a positive dilaton mass squared (minimum of the potential) and the solid curve shows the cut-off scale Λ as a function of the top-quark mass m_t for which the conditions in Eq. (6) are satisfied. Hence, within the given approxima-

[1] In this we differ substantially from the so-called quantum scale-invariant SM [13]. In their approach, the SM is extrapolated to an arbitrary high energy scale and regularized by invoking dilaton-dependent renormalization scale, $\mu = \mu(\chi)$.