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Scalar field dark matter and the Higgs field

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ABSTRACT

We discuss the possibility that dark matter corresponds to an oscillating scalar field coupled to the Higgs boson. We argue that the initial field amplitude should generically be of the order of the Hubble parameter during inflation, as a result of its quasi-de Sitter fluctuations. This implies that such a field may account for the present dark matter abundance for masses in the range 10^{-6}–10^{-4} eV, if the tensor-to-scalar ratio is within the range of planned CMB experiments. We show that such mass values can naturally be obtained through either Planck-suppressed non-renormalizable interactions with the Higgs boson or, alternatively, through renormalizable interactions within the Randall–Sundrum scenario, where the dark matter scalar resides in the bulk of the warped extra-dimension and the Higgs is confined to the infrared brane.

1. Introduction

The existence of a significantly undetected non-relativistic matter component in the Universe is widely accepted, with plenty of evidence arising from different sources. In particular, the flatness of the rotational curves of galaxies requires a significant dark matter component to account for the inferred dynamical galactic mass. In addition, the invisible mass of galaxy clusters and the temperature and polarization anisotropies of the Cosmic Microwave Background (CMB) radiation indicate a dark matter component that accounts for about 26% of the present energy balance in the Universe. The origin and the constitution of dark matter remain, however, unknown, despite the large number of candidates that arise in theories beyond the Standard Model of Particle Physics (see e.g. [1] for a review).

The recent discovery of the Higgs boson at the Large Hadron Collider [2,3] has opened up new possibilities for understanding the nature of dark matter. In fact, several works in the literature have already considered the possibility that dark matter interacts with the Higgs field in a variety of forms. The first models [4–8] considered an extension of the Standard Model with an additional singlet scalar field, ϕ, with renormalizable interactions with the Higgs field of the form:

$$V(\phi, h) = \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{1}{2}g^2\phi^2 h^\dagger h\,, \tag{1}$$

where m_ϕ is the field mass, λ_ϕ its self-coupling term and g the coupling term between the "phion" and the Higgs field. Several analyses of this and related models have been performed in the literature [9–22] and this possibility has become widely known as "Higgs-portal" dark matter. A connection to dark energy has also been suggested in [23,24].

Most of the works in the literature focus, however, on dark matter candidates whose abundance is set by the standard decoupling and freeze-out mechanism, with masses in the GeV–TeV range. In this work, we consider an alternative possibility in which the scalar field ϕ acquires a large expectation value during inflation and begins oscillating after the electroweak phase transition, behaving as non-relativistic matter. Although a related scenario was considered e.g. in Ref. [19], in the latter case interactions are sufficiently large to lead to the decay of the scalar condensate and thermalization of the ϕ-particles, so that the present-day dark matter abundance also corresponds to a GeV–TeV WIMP thermal relic.

Our proposal considers a scenario where the dark matter field is part of a hidden/sequestered sector with an inherent conformal symmetry/scale invariance, which is broken only by feeble inter-

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actions with the Higgs boson. This implies that the field's mass and self-couplings are extremely small, which in particular leads to a long-lived oscillating scalar condensate that is never in thermal equilibrium in the cosmic history. We will consider particular models where this generic idea can be realized, and show that such a field can naturally account for the present dark matter abundance.

The article is organized as follows. In Sec. 2 we describe the main properties of our scenario, focusing on the dynamics of an oscillating scalar field in the post-inflationary Universe and considering that the field only acquires mass through the Higgs mechanism after the electroweak phase transition. We determine, in particular, the relation between the field's mass and initial amplitude required in order to explain the observed dark matter abundance. In Sec. 3 we discuss the dynamics of the field during inflation and compute the average field amplitude that results from quasi-de Sitter fluctuations and sets the initial conditions for the post-inflationary evolution. Finally, in Sec. 4 and Sec. 5 we describe particular realizations of a weak coupling between the ϕ and Higgs fields leading to the required field mass to account for dark matter, considering firstly the case of non-renormalizable operators and secondly a bulk scalar field in the Randall–Sundrum scenario for a warped extra-dimension. We summarize our conclusions and prospects for future work in Sec. 6.

2. Oscillating scalar field as dark matter

Let us start by reviewing why a homogeneous oscillating field, ϕ, with a potential dominated by a quadratic term, $V(\phi) = \frac{1}{2}m_\phi^2\phi^2$, behaves as non-relativistic matter. In a generic cosmological epoch where the scale factor evolves as $a(t) = (t/t_i)^p$, with $p > 0$ and $a(t_i) = 1$, the Hubble parameter is simply $H = p/t$. The field ϕ then satisfies the Klein–Gordon equation:

$$\ddot{\phi} + 3\frac{p}{t}\dot{\phi} + m_\phi^2\phi = 0 \,. \tag{2}$$

For $m_\phi t \gg 1$, the solution of this equation is then approximately given by:

$$\phi(t) \simeq \frac{\phi_i}{a(t)^{3/2}}\cos(m_\phi t + \delta_\phi) \,, \tag{3}$$

where we have defined the initial field amplitude, ϕ_i, and phase, δ_ϕ. The energy density of the oscillating field thus evolves, after a few oscillations, as:

$$\rho_\phi \simeq \frac{1}{2}\frac{m^2\phi_i^2}{a^3} \,, \tag{4}$$

which corresponds to the behavior of non-relativistic matter.

We may therefore consider an oscillating scalar field as a plausible dark matter candidate, provided that it is stable and yields the correct present abundance. In general, the field will begin to oscillate after inflation when $m_\phi \simeq H$. If we consider that the field only acquires mass through the Higgs mechanism, its mass vanishes before electroweak symmetry breaking and, consequently, $H > m_\phi$ and the field is overdamped, such that its amplitude remains approximately constant. After the electroweak phase transition at temperatures around 100 GeV, the field acquires a mass that eventually becomes larger than the Hubble parameter. The field then becomes underdamped and begins to oscillate as obtained above. This will generically occur during the radiation-dominated epoch, where the Hubble expansion rate is given by:

$$H = \frac{\pi}{\sqrt{90}}\sqrt{g_*}\frac{T^2}{M_{Pl}} \,, \tag{5}$$

where M_{Pl} is the reduced mass Planck, $M_{Pl} = 1/\sqrt{8\pi G}$, T is the cosmic temperature and $g_* = N_B + (7/8)N_F$ is the total number of relativistic degrees of freedom, including N_B and N_F bosonic and fermionic degrees of freedom, respectively.

From Eq. (4), we may define an effective number density of ϕ particles in the oscillating scalar condensate:

$$n_\phi = \frac{\rho_\phi}{m_\phi} = \frac{m_\phi\phi_i^2}{2a^3} \,. \tag{6}$$

The total entropy density of radiation in the early Universe is given by:

$$s = \frac{2\pi^2}{45}g_{*S}T^3 \,, \tag{7}$$

where $g_{*S} = N_B + \frac{3}{4}N_F$ is the effective number of relativistic degrees of freedom contributing to the entropy. Using Eqs. (6) and (7), it is easy to see that the number of particles in a comoving volume is:

$$\frac{n_\phi}{s} = \frac{m_\phi\phi_i^2/(2a^3)}{\frac{2\pi^2}{45}\,g_{*S}\,T^3} = \text{const.} \tag{8}$$

This is a conserved quantity since, due to the entropy conservation, $S = sa^3$ remains constant throughout the history of the Universe.

We consider now two separate cases, since the field only acquires its mass after the electroweak phase transition at $T_{EW} \sim 100$ GeV. If, on the one hand, the field mass is smaller than the Hubble rate $H_{EW} = \pi/\sqrt{90}g_*T_{EW}^2/M_P \sim 10^{-5}$ eV, with $g_* \sim 100$,[1] the field will only start to oscillate after the phase transition. If, on the other hand, $m_\phi \gtrsim H_{EW}$, oscillations start as soon as the Higgs field acquires its vacuum expectation value, which we take approximately to be at T_{EW}.

In the first case, for $m_\phi \lesssim H_{EW}$, the temperature at which $m_\phi = H$ is given by:

$$T = \left(\frac{90}{\pi^2}\right)^{1/4} g_*^{-1/4}\sqrt{M_{Pl}m_\phi} \,, \tag{9}$$

which is valid for temperatures below T_{EW}. Introducing this temperature into the relation Eq. (8), we get:

$$\frac{n_\phi}{s} = \frac{1}{8}\left(\frac{90}{\pi^2}\right)^{1/4} g_*^{-1/4}\frac{\phi_i^2}{\sqrt{m_\phi M_{Pl}^3}} \,, \tag{10}$$

where we have taken $g_* = g_{*S}$ when field oscillations begin. We may then use this to compute the present dark matter abundance, $\Omega_{\phi,0}$, defined as:

$$\begin{aligned}\Omega_{\phi,0} &\equiv \frac{\rho_{\phi,0}}{\rho_{c,0}} = \frac{m_\phi}{3H_0^2M_{Pl}^2}\left(\frac{n_\phi}{s}\right)s_0 \\ &\simeq \frac{1}{6}\left(\frac{\pi^2}{90}\right)^{3/4}\frac{g_{*S0}}{g_*^{1/4}}\frac{T_0^3m_\phi^{1/2}\phi_i^2}{H_0^2M_{Pl}^{7/2}} \,, \qquad m_\phi < H_{EW} \,,\end{aligned} \tag{11}$$

where $H_0 \simeq 1.45 \times 10^{-33}$ eV is the present Hubble parameter, $T_0 \simeq 2.58 \times 10^{-4}$ eV is the present CMB temperature and $g_{*S0} \simeq 3.91$.

For the case where the field starts oscillating immediately after the electroweak phase transition, for $m_\phi \gtrsim H_{EW}$, we take the temperature at the beginning of field oscillations to be T_{EW} and, following the same steps as for the previous case, we obtain:

[1] Note that the electroweak phase transition is not instantaneous, and both the temperature and the number of relativistic species vary during the phase transition. This simplified approach to consider a given temperature and g_*, it gives nevertheless a sufficiently good approximation for determining the main properties of the dark matter field.