Phase Transitions and Gravitational Wave Tests of Pseudo-Goldstone Dark Matter in the Softly Broken $U(1)$ Scalar Singlet Model

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Abstract

We study phase transitions in a softly broken $U(1)$ complex singlet scalar model in which the dark matter is the pseudoscalar part of a singlet whose direct detection coupling to matter is strongly suppressed. Our aim is to find ways to test this model with the stochastic gravitational wave background from the scalar phase transition. We find that the phase transition which induces vacuum expectation values for both the Higgs boson and the singlet – necessary to provide a realistic dark matter candidate – is always of the second order. If the stochastic gravitational wave background characteristic to a first order phase transition will be discovered by interferometers, the soft breaking of $U(1)$ cannot be the explanation to the suppressed dark matter-baryon coupling, providing a conclusive negative test for this class of singlet models.

1. Introduction

Scalar singlet is one of the most generic candidates for the dark matter (DM) of Universe [1, 2], whose properties have been exhaustively studied [3–6] (see [7] for a recent review and references). However, the recent results from direct detection experiments [8–10] have pushed the singlet scalar DM mass above a TeV-scale (except in a narrow region around the Higgs resonance). Thus, the singlet scalar models with the simplest scalar potential, in which the DM is stabilised by a $Z_2$ symmetry, appear to be strongly constrained, less natural and less attractive.

This conclusion need not hold for specific realisations of the singlet scalar DM idea. A neat observation was made in [11] that for the case of a less general scalar potential obtained by imposing an $U(1)$ symmetry that is softly broken, the direct detection cross section is strongly suppressed at tree level by the destructive interference between two contributing amplitudes. This result persists even if loop-level corrections to the direct detection cross section are considered [12, 13], making the softly broken scalar singlet model really interesting. This has motivated follow-up studies demonstrating that it is possible for pseudo-Goldstone DM to show up at the LHC [14] or in indirect detection [15].

Is there any other way to test the softly broken $U(1)$ singlet DM model experimentally and to distinguish the particular model from more general versions of singlet scalar DM? A new probe of physics beyond the Standard Model (SM) became experimentally available due to the discovery of gravitational waves (GWs) by LIGO experiment [16, 17]. It is well known that first order phase transitions generate a stochastic GW background [18–20] which can potentially be probed in future space based GW interferometers [21, 22]. While the Higgs phase transition in the SM is of second-order [23, 24] and, thus, does not generate the GW signal, in models with extended scalar sector the first order phase transition in the early Universe can become experimentally testable by the GW experiments.

GWs from the extension of the SM with a scalar singlet have been extensively studied. In general a two-step phase transition will take place in those models that can be of the first order [25, 30] and be testable with GWs [31, 38]. In general a two-step phase transition will take place in those models that can be of the first order and be testable with GWs. The aim of this work is to study the properties of the phase transition in the scalar singlet model with a softly broken $U(1)$ symmetry in order to find out whether the GW signal can distin-
guish between different versions of the singlet DM models. We reach a definitive conclusion: in this class of models with a suppressed direct detection cross section, the phase transition is necessarily of the second order and no testable GW background will be generated. Therefore, if the stochastic GW background characteristic to the first order phase transition due to scalar singlets will be discovered, the softly broken singlet model cannot be responsible for that. In this case, as a consequence, the negative results from DM direct detection experiments cannot be explained with the ideas presented in [11].

This Letter is organised as follows. We describe the model in Section 2. The phase transition in this framework is studied in Section 3. We conclude in Section 4.

2. The Model

We consider the scalar potential of the SM Higgs boson $H$ together with a complex singlet $S$,  
\[
V = \frac{1}{2} \mu_H^2 |H|^2 + \frac{1}{2} \mu_S^2 |S|^2 + \frac{1}{4} \lambda_S (S^2 + S^*S)^2
\]
\[+ \frac{1}{2} \lambda_H |H|^4 + \lambda_{HS} |H|^2 |S|^2 + \frac{1}{2} \lambda_S |S|^4,
\]
where the $\mu_S^2$ term is the only one that softly breaks the $U(1)$ symmetry $S \rightarrow e^{i\alpha} S$. Without loss of generality, the parameter $\mu_S^2$ can be taken to be real and positive.

We decompose the fields in the electroweak vacuum as  
\[
S = \frac{v_s + s + i\chi}{\sqrt{2}}, \quad H = \left( \begin{array}{c} 0 \\ v_h + h \end{array} \right).
\]

Note that both the Higgs boson and the singlet will get a vacuum expectation value (VEV) (the Higgs VEV is $v_h = 246.22$ GeV). The mixing of the CP-even states $h$ and $s$ will yield two CP-even mass eigenstates $h_1$ and $h_2$. We identify $h_1$ with the SM Higgs boson with mass $m_1 = 125.09$ GeV [39]. Notice that the pseudo-Goldstone $\chi$ is the DM candidate with a mass determined by $\mu_S^2$.

We express the potential parameters in terms of physical quantities in the zero-temperature vacuum, such as the masses $m_{1,2}^2$ of real scalars, their mixing angle $\theta$, pseudoscalar mass $m_\chi^2$, and the VEVs $v_h$ and $v_s$:  
\[
\lambda_H = \frac{m_1^2 + m_2^2 + (m_1^2 - m_2^2) \cos \theta}{2v_h}, 
\]
\[
\lambda_S = \frac{m_1^2 + m_2^2 + (m_1^2 - m_2^2) \cos \theta}{2v_s}, 
\]
\[
\lambda_{HS} = \frac{(m_1^2 - m_2^2) \sin \theta}{2v_sv_h}, 
\]
\[
\mu_H^2 = -\frac{1}{2}(m_1^2 + m_2^2) + \frac{1}{2v_h}(m_2^2 - m_1^2)
\]
\[\times (v_h \cos \theta + v_s \sin \theta),
\]
\[
\mu_S^2 = -\frac{1}{2}(m_1^2 + m_2^2) + 2m_\chi^2 + \frac{1}{2v_s}(m_1^2 - m_2^2)
\]
\[\times (v_s \cos \theta - v_h \sin \theta),
\]
\[
\mu_{HS}^2 = m_\chi^2.
\]

The tree-level direct detection DM amplitude vanishes at zero momentum transfer,  
\[
A_{dd}(t) \propto \sin \theta \cos \theta \left( \frac{m_2^2}{t - m_2^2} - \frac{m_1^2}{t - m_1^2} \right) \approx 0,
\]
which allows one to explain the negative experimental results from DM direct detection experiments while still keeping the pseudo-Goldstone DM mass in the reach of collider searches.

3. Phase Transition

In the high temperature limit, the $U(1)$-symmetric mass terms take on temperature-dependent corrections:  
\[
\mu_H^2(T) = \mu_H^2(0) + c_HT^2,
\]
\[
\mu_S^2(T) = \mu_S^2(0) + c_ST^2,
\]
where  
\[
c_H = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_H + 4\lambda_{HS}),
\]
\[
c_S = \frac{1}{6}(\lambda_S + \lambda_{HS}).
\]

The thermal correction to $\mu_S^2$ is zero, because the quartic couplings do not break the $U(1)$ symmetry.

For the cancellation mechanism [9] to work, the fields must end up in the $(v_h, v_s, 0)$ vacuum at zero temperature. Then the phase transition pattern consistent with the DM relic density is  
\[
(0, 0, 0) \rightarrow (0, v_s, 0) \rightarrow (v_h, v_s, 0).
\]
Both steps are second-order phase transitions.
There is no possibility to engineer a first-order phase transition. The only alternative second step, which could potentially be first-order \cite{40}, would be

\[ (0, 0, v_\chi) \rightarrow (v_h, v_s, 0). \]  

(13)

For a first-order phase transition, however, both extrema must be minima at the same time. But if the \((v_h, v_s, 0)\) vacuum is a minimum, the \((0, 0, v_\chi)\) vacuum can only be a saddle point or maximum, because the mass squared of the \(s\) particle is \(-m_\chi^2 < 0\) in this vacuum.\footnote{When the potential contains a cubic term \cite{41}, then the phase transition \cite{41} into \((v_h, v_s, 0)\) can be first order, but such a term explicitly breaks the \(Z_2\) symmetry.}

The phase diagram for one particular point of the parameter space with correct relic density \cite{39} with the mixing angle \(\sin \theta = 0.1\), the ratio \(v_h/v_s = 0.291\), and masses \(m_2 = 1000\) GeV and \(m_\chi = 100\) GeV is shown in Fig. 1. The phase diagram in the left panel shows the evolution of fields (black line) from the \((0, 0, 0)\) vacuum (white) through the \((0, v_s, 0)\) vacuum (red) to the \((v_h, v_s, 0)\) vacuum (yellow). The phase where only the Higgs has a VEV is shown in green. The right panel demonstrates the second phase transition. The phase transition is of second-order: the Higgs VEV begins to grow continuously at the critical temperature, marked by the thin vertical line.

4. Conclusions

Pseudo-Goldstone DM in singlet scalar models with softly broken \(U(1)\) presents an appealing possibility to sidestep constraints from direct detection on more general class of scalar singlet DM with a \(Z_2\) symmetry. Motivated by the aim to find additional tests of this framework we study the thermal phase transition pattern of the model. In order the model to work, the mechanism that cancels the direct detection cross section needs both the Higgs boson and the singlet to have VEVs. For that reason, the possible phase transitions in this model are necessarily of the second order and, therefore, cannot produce any detectable gravitational wave signal.

Thus, a possible future discovery of a stochastic gravitational wave background characteristic to strong first order phase transition would strongly disfavor or even rule out this class of models. In this case the suppression of DM scattering cross section off nuclei must be explained by other means.

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