GravitationalWave Signals of Electroweak Phase Transition Triggered by Dark Matter Postprint

Authors: Wei Chao, Huai-Ke Guo, Jing Shu

Date: 2017-08-02T00:00:00+00:00

Abstract

We study in this work a scenario that the universe undergoes a two step phase transition with the first step happened to the dark matter sector and the second step being the transition between the dark matter and the electroweak vacuums, where the barrier between the two vacuums, that is necessary for a strongly first order electroweak phase transition (EWPT) as required by the electroweak baryogenesis mechanism, arises at the tree-level. We illustrate this idea by working with the standard model (SM) augmented by a scalar singlet dark matter and an extra scalar singlet which mixes with the SM Higgs boson. We study the conditions for such pattern of phase transition to occur and especially for the strongly first order EWPT to take place, as well as its compatibility with the basic requirements of a successful dark matter, such as observed relic density and constraints of direct detections. We further explore the discovery possibility of this pattern EWPT by searching for the gravitational waves generated during this process in spaced based interferometer, by showing a representative benchmark point of the parameter space that the generated gravitational waves fall within the sensitivity of eLISA, DECIGO and BBO.

Full Text

Gravitational Wave Signals of Electroweak Phase Transition Triggered by Dark Matter

Wei Chao,[1] Huai-Ke Guo,[2] and Jing Shu[2],[3]

[1]Center for Advanced Quantum Studies, Department of Physics, Beijing Normal University, Beijing, 100875, China
[2]CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
[3]CAS Center for Excellence in Particle Physics, Beijing 100049, China

Abstract

We study a scenario in which the universe undergoes a two-step phase transition: the first step occurs in the dark matter sector, and the second step involves a transition between the dark matter and electroweak vacua. In this framework, the barrier between the two vacuums—necessary for a strongly first-order electroweak phase transition (EWPT) as required by the electroweak baryogenesis mechanism—arises at tree level. We illustrate this idea using the Standard Model (SM) augmented by a scalar singlet dark matter field S and an additional scalar singlet Φ that mixes with the SM Higgs boson. We investigate the conditions for such a pattern of phase transition to occur, particularly for achieving a strongly first-order EWPT, and examine its compatibility with basic dark matter requirements such as the observed relic density and direct detection constraints. We further explore the discovery prospects for this pattern of EWPT by searching for gravitational waves generated during this process with space-based interferometers, showing a representative benchmark point in parameter space where the generated gravitational waves fall within the sensitivity ranges of eLISA, DECIGO, and BBO.

PACS numbers: 11.30.Er, 11.30.Fs, 11.30.Hv, 12.60.Fr, 31.30.jp

---

I. INTRODUCTION

The Standard Model (SM) of particle physics provides an excellent description of a wide variety of experimental observations. Nevertheless, it must be extended because it fails to explain at least two cosmological puzzles: it does not provide a dark matter (DM) candidate, and it cannot generate the observed baryon asymmetry of the universe (BAU). The latter requires a strongly first-order electroweak phase transition (EWPT) to provide a non-equilibrium environment if the BAU is generated via the electroweak baryogenesis mechanism [?, ?, ?, ?]. Since the 125 GeV Higgs boson is too heavy to give rise to a first-order EWPT [?, ?], new ingredients beyond the SM Higgs interactions may be needed. On the other hand, how DM interacts with SM particles remains unknown. The Higgs portal is particularly attractive since it may kill two birds with one stone —addressing both DM and the strongly first-order EWPT [?].

The characteristics of a scalar DM-triggered strongly first-order EWPT are twofold: (i) It is a two-step phase transition [?, ?, ?, ?, ?, ?, ?] and the barrier between electroweak symmetric and broken phases arises at tree level, which may avoid the problem of gauge dependence [?]; (ii) The parameter space of the model is strongly constrained by the exclusion limits of direct detection experiments and cannot explain the observed relic density. It was pointed out in Ref. [?] that, for the SM plus a real scalar DM S scenario, S could only constitute up to 3% of the total DM relic density while still being relevant for direct detection because of its sizable coupling with the SM Higgs as required by the two-step EWPT.

In this paper, we revisit this type of EWPT by extending the SM with a scalar singlet DM S and another scalar singlet Φ that can mix with the SM-like Higgs boson. Due to the mixing of Φ with the SM Higgs, there are two separate contributions to DM-nucleon scattering, which may cancel each other and lead to a negligible cross section. This results in a mechanism to suppress the direct detection signal and evade the currently most stringent experimental constraints from direct detection experiments [?, ?]. Furthermore, the quartic interaction $\Phi^2 S^2$ may contribute to the mass of S, which can lead to a relatively small quartic coupling of S with the SM-like Higgs and result in a sizable relic density. Consequently, the tension between DM relic density and direct detection that occurs for the SM plus singlet case [?, ?] can be significantly loosened in this scenario.

Regarding the thermal history of the universe, the presence of the two additional scalars allows a two-step EWPT. This occurs as follows: As the universe cools down, S acquires a vacuum expectation value (VEV) first and the universe transitions to this phase. As the temperature gets lower, a second minimum appears in the SM-like Higgs and Φ subspace. The universe then tunnels to this electroweak minimum, resulting in a strongly first-order EWPT with gravitational waves (GWs) generated. We calculate the GW signals from this two-step EWPT using a benchmark point in parameter space, and our results show that the corresponding GW signals are testable by the Evolved Laser Interferometer Space Antenna (eLISA), DECi-hertz Interferometer Gravitational wave Observatory (DECIGO), Ultimate-DECIGO, and Big Bang Observer (BBO).

The remainder of this paper is organized as follows. We define the model conventions in Sec. II. We then study the DM phenomenology in Sec. III and the capability for a strongly first-order EWPT in Sec. IV. The GW calculations and discovery prospects are explored in Sec. V, after which we present a brief summary in Sec. VI.

II. THE MODEL

We present the model for two-step phase transition and scalar DM in this section. The model extends the SM with two real scalar singlets: S and Φ, where S is the DM candidate, while Φ gets a non-zero VEV at zero temperature and thus mixes with the SM Higgs [?]. The Higgs potential can be written as:

$$V = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\mu_\Phi^2 \Phi^2 + \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \lambda_1 S^2 H^\dagger H + \lambda_2 \Phi^2 H^\dagger H + \frac{1}{4}\lambda_S S^4 + \frac{1}{4}\lambda_\Phi \Phi^4 + \lambda_3 S^2 \Phi^2,$$

where H is the SM Higgs doublet. The effective potential, critical for the EWPT, can be written as:

$$V_{\text{eff}} = V_0 + V_{\text{CW}} + V_T,$$

where V_0 is the tree-level potential, V_{CW} is the Coleman-Weinberg term [?], and V_T includes finite temperature contributions from loops [?] and bosonic ring diagrams [?, ?].

For one-step phase transitions, where the Higgs potential contains no tree-level cubic term, the barrier between the electroweak symmetric and broken phases usually arises from loop corrections, and according to the Nielsen identity [?], the resulting effective potential is gauge dependent. For the two-step phase transition, the barrier arises at tree level. Therefore, we include in the effective potential the standard one-loop $T = 0$ corrections but retain only terms proportional to T^2 for the consideration of gauge invariance. The thermal masses of scalars take the following forms:

$$\Pi_h = \left(\frac{3g^2 + g'^2}{16} + \frac{\lambda}{2} + \frac{\lambda_1 + \lambda_2}{12}\right) T^2,$$
$$\Pi_\phi = \left(\frac{\lambda_2}{3} + \frac{\lambda_\Phi}{4} + \frac{\lambda_3}{6}\right) T^2,$$
$$\Pi_s = \left(\frac{\lambda_1}{3} + \frac{\lambda_S}{4} + \frac{\lambda_3}{6}\right) T^2.$$

We require S to have zero VEV at $T = 0$ for DM stability and parametrize the other two fields by $H = (0, (v_{\text{EW}} + h)/\sqrt{2})$ and $\phi = v_\Phi + \varphi$.

Minimization conditions around $(v_{\text{EW}}, v_\Phi, 0)$ in the (h, φ, s) space allow us to trade the two VEVs v_{EW} and v_Φ for μ^2 and μ_Φ^2:

$$\mu^2 = \lambda v_{\text{EW}}^2 + \lambda_2 v_\Phi^2,$$
$$\mu_\Phi^2 = \lambda_2 v_{\text{EW}}^2 + \lambda_\Phi v_\Phi^2.$$

We also replace μ_S^2 by the physical DM mass $m_S^2 = \lambda_1 v_{\text{EW}}^2 + 2\lambda_3 v_\Phi^2$. With these substitutions, the mass matrix for (h, φ) is then given by:

$$\mathcal{M}^2 = 2 \begin{pmatrix} \lambda v_{\text{EW}}^2 & v_{\text{EW}} v_\Phi \lambda_2 \\ v_{\text{EW}} v_\Phi \lambda_2 & \lambda_\Phi v_\Phi^2 \end{pmatrix},$$

which can be diagonalized by a 2 × 2 orthogonal matrix parametrized by a rotation angle θ. The mass eigenstates $(\hat{h}, \hat{\varphi})$ can then be written as:

$$\hat{h} = c_\theta h + s_\theta \varphi,$$
$$\hat{\varphi} = -s_\theta h + c_\theta \varphi,$$

where $c_\theta = \cos\theta$ and $s_\theta = \sin\theta$. We define $\hat{h}$ as the SM-like Higgs boson and therefore when $\theta = 0$, $\hat{h}$ is purely the SM Higgs. With this definition, three of the parameters in the potential λ, λ_2, λ_Φ can be replaced by the physical masses $m_{\hat{h}}$, $m_{\hat{\varphi}}$ and θ:

$$\begin{aligned}
\lambda &= \frac{m_{\hat{h}}^2 c_\theta^2 + m_{\hat{\varphi}}^2 s_\theta^2}{2v_{\mathrm{EW}}^2}, \\
\lambda_\Phi &= \frac{m_{\hat{h}}^2 s_\theta^2 + m_{\hat{\varphi}}^2 c_\theta^2}{2v_\Phi^2}, \\
\lambda_2 &= \frac{\sin(2\theta)}{4v_{\mathrm{EW}}v_\Phi}(m_{\hat{\varphi}}^2 - m_{\hat{h}}^2).
\end{aligned}$$

In summary, we have a total of 7 free parameters: v_Φ, $m_{\hat{\varphi}}$, m_S, λ_S, θ, λ_1, and λ_3, where λ_1 and λ_3 are relevant for DM phenomenology.

Before proceeding to study the EWPT and DM phenomenology, we discuss constraints on the mixing angle θ from Higgs measurements and electroweak precision measurements. Couplings of the SM-like Higgs to all SM particles are rescaled by the factor c_θ due to the mixing. As a result, signal rates—the ratio of Higgs measurements relative to SM predictions—equal c_θ^2. Performing a universal Higgs fit to the data given by the ATLAS and CMS collaborations yields $c_\theta^2 > 0.526$ at 95% CL [?]. It was shown in Ref. [?] that the constraint from electroweak precision measurements is closely related to the mass of $\hat{\varphi}$, being weaker than that from Higgs measurements for a light $\hat{\varphi}$ but becoming much stronger as $m_{\hat{\varphi}}$ gets heavier. For constraints from vacuum stability and perturbativity, we refer the reader to Refs. [?, ?] for details.

III. DARK MATTER

The fact that about 26.8% of the universe consists of DM, with relic abundance $\Omega_c h^2 = 0.1189$ [?], is well established, while the nature of DM remains unknown. The Higgs potential in Eq. (1) has Z_2 discrete symmetry for S and Φ respectively. At zero temperature, Φ gets a non-zero VEV and thus its corresponding Z_2 is broken. On the other hand, we require that the global minimum at $T = 0$ forbids a non-zero VEV in the s direction. As a result, s can serve as a DM candidate, which interacts with SM particles via Higgs portal interactions.

The couplings between the DM and the physical scalars are:

$$\begin{aligned}
s^2\hat{h}^2 &: \lambda_1 v_{\mathrm{EW}} c_\theta + 2\lambda_3 v_\Phi s_\theta, \\
s^2\hat{\varphi}^2 &: -\lambda_1 v_{\mathrm{EW}} s_\theta + 2\lambda_3 v_\Phi c_\theta, \\
s^2\hat{h}\hat{\varphi} &: c_\theta s_\theta(2\lambda_3 v_\Phi - \lambda_1 v_{\mathrm{EW}}).
\end{aligned}$$

The relic density of DM is governed by the Boltzmann equation:

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{EQ}}^2),$$

where H is the Hubble constant and $\langle \sigma v \rangle$ is the thermal average of the reduced annihilation cross section, which will be adopted in the following numerical analysis for simplicity.

In our model, DM can annihilate into $\bar{f}f$, ZZ/WW, $\hat{h}\hat{h}$, $\hat{\varphi}\hat{\varphi}$, and $\hat{h}\hat{\varphi}$ final states via s-channel Higgs mediation, where di-scalar processes also receive contributions from four-point interactions in Eq. (17). Compared with the simplest Higgs portal, there are more annihilation channels for heavy DM. Couplings in Eqs. (13) and (14) are both relevant for DM direct detection, while the contribution from $\hat{\varphi}$-mediated processes is suppressed by the factor s_θ^2 and thus is negligible for small θ.

For numerical simulations, we implement the model in LanHEP [**?**, **?**] and use MicrOMEGAs [**?**, **?**] to calculate the relic density. For direct detection, the spin-independent scattering cross section off nucleons is given by:

$$\sigma_n = \frac{m_n^4}{4\pi(m_S + m_n)^2 v_{\mathrm{EW}}^2} \left| \sum_{q=u,d,s} f_{T_q}^n \left(\frac{c_\theta a_{\hat{h}}}{m_{\hat{h}}^2} + \frac{s_\theta a_{\hat{\varphi}}}{m_{\hat{\varphi}}^2} \right) \right|^2,$$

where $a_{\hat{h}}$, $a_{\hat{\varphi}}$ are effective couplings from Eqs. (13) and (14) respectively, and $f_{T_q}^n$ are nucleon form factors for light quarks [**?**]. The inclusion of Φ that mixes with the SM Higgs can lead to complete cancellation in contributions to σ_n at tree level. This occurs when the effective coupling of DM with quarks vanishes, that is, when the expression in $|\cdots|$ vanishes. Imposing this condition allows us to eliminate one more parameter:

$$\lambda_3 = \frac{v_{\mathrm{EW}} \lambda_1 (m_{\hat{\varphi}}^2 - m_{\hat{h}}^2)}{2 v_\Phi (m_{\hat{\varphi}}^2 \tan\theta + m_{\hat{h}}^2 \cot\theta)}.$$

For a detailed survey of the parameter space, we perform a parameter scan and show the results in Fig. 1 [Figure 1: see original paper] in the (m_S, λ_1) plane (left panel) and in the (θ, λ_1) plane (right panel). In these plots, the green points give the relic density within the range $\Omega_c h^2 \in (0.03, 0.12)$ allowed by current Planck results [**?**], in addition to being able to induce the two-step EWPT pattern discussed later. The red points, in addition to generating relic density falling into this interval, also satisfy the strong first-order EWPT condition $v_h(T_C)/T_C \gtrsim 1$.

From the left panel, we see that the coupling λ_1 that can give a relic density within this range is of magnitude $(0.005, 0.02)$ for relatively heavy DM, while it can be as large as 0.06 for relatively light DM. In the right panel, the mixing angle is mostly negative since most scanned points have $m_{\hat{\varphi}} > m_{\hat{h}}$, and therefore a negative θ is needed to give a positive λ_2 according to Eq. (10).

IV. ELECTROWEAK PHASE TRANSITION

The barrier between the electroweak symmetric and broken phases emerges at tree level in our two-step phase transition scenario. As a result, the effective potential, which includes the standard one-loop $T = 0$ corrections but retains only the leading terms (thermal mass terms) in the high-T expansion to avoid problems related to gauge dependence, can be written as:

$$V_{\text{eff}} = \frac{1}{2}(\mu_S^2+\Pi_s)s^2+\frac{1}{2}(\mu_\Phi^2+\Pi_\phi)\phi^2+\frac{1}{2}(\mu^2+\Pi_h)h^2+\frac{\lambda}{4}h^4+\frac{\lambda_\Phi}{4}\phi^4+\frac{\lambda_S}{4}s^4+\frac{\lambda_1}{4}s^2h^2+\frac{\lambda_2}{2}\phi^2h^2+\lambda_3 s^2\phi^2.$$

The VEV of the SM Higgs at finite temperature can be written as:

$$v_h(T) = \sqrt{\frac{\lambda_2\Pi_\phi - \lambda_\Phi(\mu^2+\Pi_h)}{\lambda\lambda_\Phi - \lambda_2^2}}.$$

The critical temperature T_C can be calculated analytically from the following equation:

$$2\lambda_2(\mu^2+\Pi_h)(\mu_\Phi^2+\Pi_\phi) + \lambda_\Phi(\mu^2+\Pi_h)^2 = \lambda(\mu_\Phi^2+\Pi_\phi)^2,$$

where μ^2, μ_Φ^2, and μ_S^2 can be written in terms of physical parameters.

[Figure 2: see original paper] gives an illustrative picture of the two-step EWPT with the first step in the s direction and the subsequent one from the s direction to the (h, ϕ) direction, in terms of background fields h, ϕ, and s.

Given Eq. (21), one can trace the evolution of the universe' s phase as temperature drops. Our desired pattern of EWPT is illustrated in Fig. 2 [Figure 2: see original paper]. At sufficiently high temperature, the universe sits at the global minimum $(0, 0, 0)$ where electroweak symmetry is restored. As the temperature drops to T_s, a minimum develops in the s direction and, due to the absence of a barrier with the one at the origin, the universe transits to this minimum through a second-order phase transition. As T continues decreasing to T_h, a second minimum develops in the (h, ϕ) direction but its free energy is initially higher than the one in the s direction. As T further decreases, the free energy of the minimum in the (h, ϕ) direction drops faster than the one in the s direction, and at the critical temperature T_C, these two minima become degenerate. Slightly below T_C, the universe makes a second transition to the global minimum in the (h, ϕ) direction. Due to the existence of a barrier between these two minima, the transition may occur as a first-order EWPT via a tunneling process and proceeds through nucleations of electroweak bubbles [**?**, **?**, **?**] which expand, collide, and coalesce, eventually leaving the universe in the electroweak broken phase. To avoid washing out the generated baryons by sphaleron processes inside the electroweak bubble, the sphaleron process needs to be sufficiently suppressed inside the bubble, which translates into the generally adopted criterion [**?**, **?**, **?**]:

$$\frac{v_h(T_C)}{T_C} \gtrsim 1.$$

Note that due to the reflection symmetry of the effective potential under $h \leftrightarrow -h$ and $s \leftrightarrow -s$, there are identical phase structures and we focus on the region with $h, \phi, s > 0$.

As a concrete example, we show in the left panel of Fig. 3 [Figure 3: see original paper] the evolution of V at the two minima as the temperature drops from right to left, for the parameter choice $v_\Phi = 65$ GeV, $m_{\hat{\varphi}} = 82$ GeV, $m_S = 71$ GeV, $\lambda_S = 0.015$, $\theta = 0.12$, $\lambda_1 = 0.046$, and $\lambda_3 = 0.57$. The horizontal green line on the far right denotes the symmetric phase at high temperature when the universe sits at the origin, the magenta dashed line represents the minimum in the s direction, and the blue line is the minimum in the (h, ϕ) direction which eventually evolves to the electroweak minimum at zero temperature labeled by a red dot. The s-direction phase appears at $T_s = 150$ GeV continuously away from the origin, while the (h, ϕ)-direction phase starts from $(159 \text{ GeV}, 9.15 \text{ GeV}, 0)$ at $T_h = 108$ GeV, above which it is a saddle point. The temperature at which the blue and magenta lines intersect is the critical temperature $T_C = 78.8$ GeV and is labeled by a black dot. At T_C, the two minima are $(205 \text{ GeV}, 45 \text{ GeV}, 0)$ and $(0, 0, 352 \text{ GeV})$.

For more details on the evolution of the minimum in the (h, ϕ) direction, we plot in the right panel the track of this minimum (blue dotted line) for the whole thermal history, with the red arrow denoting the direction as temperature drops. The contours in this plot give a measure of the value of V at $T = 0$, and the electroweak vacuum labeled by the red point sits at the deepest location. For this parameter choice, the strongly first-order EWPT criterion Eq. (22) is achieved since $v_h(T_C)/T_C = 2.6$.

A more comprehensive survey of the model is given by a scan over the parameter space as shown in Fig. 1 [Figure 1: see original paper], where all plotted points give the above-described pattern of EWPT by imposing various conditions during the scan. These conditions include: (i) there are two minima in field space, one in the s direction and the other in the (h, ϕ) direction; (ii) the electroweak minimum needs to be lower than the one in the s direction at $T = 0$ should the s-direction minimum persist at $T = 0$; (iii) the minimum in the s direction occurs earlier than the one in the (h, ϕ) direction, that is, $T_s > T_h$. After imposing these conditions, the points are further filtered to give a relic density in the range $(0.03, 0.12)$, with the remaining points plotted in green. At this stage, these points can produce a two-step EWPT and a sizable relic density, but the second-step EWPT is not necessarily strongly first order. Therefore, we further calculate the critical temperature T_C and $v_h(T_C)$ corresponding to the black intersection point of the blue and magenta lines for each green point. The points that satisfy the condition in Eq. (22) are shown in red in Fig. 1 [Figure 1: see original paper]. We can see that there is sufficient parameter space in this model where the desired strongly first-order EWPT pattern can be realized. We note in passing that the second-order phase transition for the first step could also be strongly first order should a more complete effective potential be adopted.

V. GRAVITATIONAL WAVES

The calculation of GWs generated during the second-step EWPT requires a numerical analysis of the tunneling process at finite temperature and particularly involves solving the critical bubble profiles. As mentioned in the previous section, after the universe cools down to a temperature below T_C, the second transition from $(0, 0, v_s)$ to the true vacuum $(v_h, v_\phi, 0)$ takes place via nucleation of true vacuum bubbles. This tunneling rate per unit time per unit volume reads [**?**]:

$$\Gamma(T) \approx A(T) e^{-S_3/T},$$

where S_3 is the Euclidean action of the critical bubble which minimizes the action:

$$S_3(\vec{\phi}, T) = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2} \left(\frac{d\vec{\phi}}{dr} \right)^2 + V(\vec{\phi}, T) \right],$$

and the prefactor $A(T)$ is roughly of $\mathcal{O}(T^4)$, whose precise evaluation requires integrating out fluctuations around the bounce solution [**?**]. From this rate formula, the bubble nucleation temperature T_n is defined as the temperature at which the probability for a single bubble to be nucleated within one horizon volume equals one, i.e.,

$$\int_{t_n}^{t_n+\Delta t} dt\, \Gamma(t) V_H(t) = 1,$$

which leads numerically to [**?**]:

$$\frac{S_3(T_n)}{T_n} \approx 140.$$

This equation serves as our definition of T_n.

From the bounce solutions, two other important parameters α and β, which are directly relevant for GW calculations, are defined by:

$$\alpha \equiv \frac{\rho_{\text{vac}}}{\rho^*_{\text{rad}}},$$
$$\beta \equiv H_n T_n \left. \frac{d(S_3/T)}{dT} \right|_{T=T_n},$$

where ρ_{vac} is the vacuum energy density released in the phase transition, H_n is the Hubble parameter at T_n, and $\rho^*_{\text{rad}} = g_* \pi^2 T_n^4/30$ with g_* being the relativistic degrees of freedom in the plasma at T_n. A small β/H_n triggers a strong phase transition and consequently a significant stochastic background of gravitational waves.

The observable characterizing the GW background is the energy spectrum $h^2\Omega_{\text{GW}}(f)$ and is given by [?]:

$$h^2\Omega_{\text{GW}}(f) = \frac{h^2}{\rho_c}\frac{d\rho_{\text{gw}}}{d\log f},$$

where ρ_{gw} is the energy density of GWs with frequency f and ρ_c is the critical energy density today. The sources of stochastic GW signals arising from first-order EWPT can be classified into three categories: (1) collisions of bubble walls; (2) sound waves in the plasma after bubble collision; and (3) magnetohydrodynamic (MHD) turbulence in the plasma [?]. The total energy spectrum is given approximately by the sum of these three sources:

$$h^2\Omega_{\text{GW}} \approx h^2\Omega_{\text{coll}} + h^2\Omega_{\text{sw}} + h^2\Omega_{\text{turb}}.$$

The GW contribution from bubble collisions can be calculated using the envelope approximation [?, ?, ?], which numerically results in the following contribution to the spectrum [?]:

$$h^2\Omega_{\text{coll}}(f) = 1.67 \times 10^{-5} \left(\frac{0.11 v_w^3}{0.42 + v_w^2}\right) \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \frac{3.8(f/f_{\text{coll}})^{2.8}}{1 + 2.8(f/f_{\text{coll}})^{3.8}},$$

where v_w is the bubble wall velocity, κ characterizes the fraction of latent heat deposited in a thin shell, and f_{coll} is the peak frequency produced by bubble collisions. At the time of the phase transition, $f^n_{\text{coll}} = 0.1 v_w \beta/(1.8 - 0.1 v_w + v_w^2)$, which is redshifted to give the peak frequency today:

$$f_{\rm coll} = f^n_{\rm coll} \times \frac{a(T_n)}{a_0} = 16.5 \times 10^{-6}\,{\rm Hz}\left(\frac{f^n_{\rm coll}/\beta}{H_n}\right)\left(\frac{T_n}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}.$$

Both v_w and κ are functions of α, which read as [**?**]:

$$v_w(\alpha) = \frac{1/\sqrt{3} + \sqrt{\alpha^2 + 2\alpha/3}}{1+\alpha},$$
$$\kappa(\alpha) = \frac{0.7\alpha + 0.2\sqrt{\alpha}}{1+0.7\alpha}.$$

The sound wave contribution to the GW intensity is numerically fitted by [**?**]:

$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} v_w \left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2},$$

where κ_v denotes the fraction of latent heat transformed into bulk motion of the fluid, and $f_{\rm sw}$ is the peak frequency that can be obtained from rescaling its value at the phase transition, i.e., $f_{\rm sw} = f^n_{\rm sw} \times a(T_n)/a_0$ with $f^n_{\rm sw} = (2/\sqrt{3})(\beta/v_w)$. We refer the reader to Refs. [**?**, **?**] for the value of κ_v in the small and large v_w limits.

The MHD turbulence contribution to the GW spectrum can be written as [**?**]:

$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{\kappa_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{1/3} v_w \frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f/h_n)},$$

where $\kappa_{\rm tu} \approx 0.1\kappa_v$ [**?**], $f_{\rm tu} = (3.5/2)(\beta/v_w) \times a(T_n)/a_0$, and h_n is the Hubble parameter today.

We use the package CosmoTransitions [**?**] to solve for profiles of the critical bubble and the nucleation temperature for the benchmark point used earlier. This parameter choice gives $\Omega_c h^2 = 0.04$, constituting about 34% of the total DM relic density. For this benchmark parameter point, we show in the left panel of Fig. 4 [Figure 4: see original paper] the quantity $S_3(T)/T$ as a function of T and find $T_n = 41.2$ GeV. The resulting GW signals are shown in the right panel of Fig. 4 [Figure 4: see original paper], where the three contributions are displayed with details in the caption. As can be seen from this figure, the blue sound wave contribution dominates and is almost indistinguishable from the sum of the three sources, which is denoted by the cyan line.

For comparison with experiments, we show first four sensitive regions corresponding to four configurations of the eLISA detector. These four regions are labeled in the format NiAjMkLl and are plotted as red shaded regions at the top, following conventions from Refs. [?, ?]. We can see that for this parameter set, the GWs can be detected by the configuration N2A5M5L6 while being unreachable by the others. We further add the sensitive regions of several other proposed decihertz GW experiments: Advanced Laser Interferometer Antenna (ALIA) [?, ?], BBO, DECIGO, and Ultimate-DECIGO [?]. The data are taken from Refs. [?, ?, ?] and plotted as gray, green, yellow, and purple regions respectively [?]. From the plot, we see that the GW signals from the benchmark point fall within the detectable ranges of BBO, DECIGO, and Ultimate-DECIGO. It should be noted that there might be other points in the model parameter space where the generated GWs have much larger energy density spectra and are therefore within reach of the other three eLISA configurations as well as ALIA, while also giving a sufficiently large DM relic density. However, this requires a dedicated survey of the parameter space including all considerations, which we leave for future work.

For GWs from one-step EWPT in the SM extended with scalar singlet(s) [?], we refer the reader to Refs. [?, ?, ?, ?, ?, ?] and references therein for details. Alternatively, first-order phase transitions may lead to the formation of primordial black holes, which can be captured by neutron stars or astrophysical black holes [?], resulting in GWs that may be detected by Advanced LIGO or Advanced Virgo.

VI. SUMMARY

Working in a simple model with the SM extended by a scalar singlet DM and another scalar singlet that mixes with the SM-like Higgs boson, we studied a possible connection between DM phenomenology and the EWPT, particularly the detectability of GW signals generated during DM-assisted EWPT. Through both analytical and numerical studies, we find that this model may admit strongly first-order two-step EWPT in certain parameter space, which may also give rise to viable DM relic density and a negligible direct detection cross section. We further exemplified, using one representative benchmark point, the discovery prospects for this EWPT pattern through generated GW signals during the second-step EWPT, and found that the GW signals can be detected by eLISA in the configuration N2A5M5L6, as well as by BBO, DECIGO, and Ultimate-DECIGO. This scenario can readily be generalized to other models where DM can have nontrivial effects on baryon number generation and is helpful for understanding and testing the origin of these two cosmological puzzles.

VII. ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China under grant Nos. 11647601, 11690022, and 11675243, and also supported by the Strategic Priority Research Program of the Chinese Academy of Sciences under grant No. XDB23030100. Part of the results described in this paper were obtained on the HPC Cluster of SKLTP/ITP-CAS.

REFERENCES

[1] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, "On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe,"Phys. Lett. B155 (1985) 36.

[2] M. E. Shaposhnikov, "Possible Appearance of the Baryon Asymmetry of the Universe in an Electroweak Theory," JETP Lett. 44 (1986) 465–468. [Pisma Zh. Eksp. Teor. Fiz.44,364(1986)].

[3] M. E. Shaposhnikov, "Baryon Asymmetry of the Universe in Standard Electroweak Theory," Nucl. Phys. B287 (1987) 757–775.

[4] D. E. Morrissey and M. J. Ramsey-Musolf, "Electroweak baryogenesis," New J. Phys. 14 (2012) 125003, arXiv:1206.2942 [hep-ph].

[5] A. I. Bochkarev and M. E. Shaposhnikov, "Electroweak Production of Baryon Asymmetry and Upper Bounds on the Higgs and Top Masses," Mod. Phys. Lett. A2 (1987) 417.

[6] K. Kajantie, M. Laine, K. Rummukainen, and M. E. Shaposhnikov, "The Electroweak phase transition: A Nonperturbative analysis," Nucl. Phys. B466 (1996) 189–258, arXiv:hep-lat/9510020 [hep-lat].

[7] J. R. Espinosa, T. Konstandin, and F. Riva, "Strong Electroweak Phase Transitions in the Standard Model with a Singlet," Nucl. Phys. B854 (2012) 592–630, arXiv:1107.5441 [hep-ph].

[8] C. Cheung and Y. Zhang, "Electroweak Cogenesis," JHEP 09 (2013) 002, arXiv:1306.4321 [hep-ph].

[9] H. H. Patel and M. J. Ramsey-Musolf, "Stepping Into Electroweak Symmetry Breaking: Phase Transitions and Higgs Phenomenology," Phys. Rev. D88 (2013) 035013, arXiv:1212.5652 [hep-ph].

[10] S. Inoue, G. Ovanesyan, and M. J. Ramsey-Musolf, "Two-Step Electroweak Baryogenesis," Phys. Rev. D93 (2016) 015013, arXiv:1508.05404 [hep-ph].

[11] H. H. Patel, M. J. Ramsey-Musolf, and M. B. Wise, "Color Breaking in the Early Universe," Phys. Rev. D88 no. 1, (2013) 015003, arXiv:1303.1140 [hep-ph].

[12] M. Chala, G. Nardini, and I. Sobolev, "Unified explanation for dark matter and electroweak baryogenesis with direct detection and gravitational wave signatures," Phys. Rev. D94 no. 5, (2016) 055006, arXiv:1605.08663 [hep-ph].

[13] V. Vaskonen, "Electroweak baryogenesis and gravitational waves from a real scalar singlet," arXiv:1611.02073 [hep-ph].

[14] S. J. Huber, T. Konstandin, G. Nardini, and I. Rues, "Detectable Gravitational Waves from Very Strong Phase Transitions in the General NMSSM," JCAP 1603 no. 03, (2016) 036, arXiv:1512.06357 [hep-ph].

[15] H. H. Patel and M. J. Ramsey-Musolf, "Baryon Washout, Electroweak Phase Transition, and Perturbation Theory," JHEP 07 (2011) 029, arXiv:1101.4665 [hep-ph].

[16] J. M. Cline and K. Kainulainen, "Electroweak baryogenesis and dark matter from a singlet Higgs," JCAP 1301 (2013) 012, arXiv:1210.4196 [hep-ph].

[17] LUX Collaboration, D. S. Akerib et al., "Results from a search for dark matter in the complete LUX exposure," Phys. Rev. Lett. 118 no. 2, (2017) 021303, arXiv:1608.07648 [astro-ph.CO].

[18] PandaX-II Collaboration, A. Tan et al., "Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment," Phys. Rev. Lett. 117 no. 12, (2016) 121303, arXiv:1607.07400 [hep-ex].

[19] L. Feng, S. Profumo, and L. Ubaldi, "Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines," JHEP 03 (2015) 045, arXiv:1412.1105 [hep-ph].

[20] A. De Simone, G. F. Giudice, and A. Strumia, "Benchmarks for Dark Matter Searches at the LHC," JHEP 06 (2014) 081, arXiv:1402.6287 [hep-ph].

[21] S. R. Coleman and E. J. Weinberg, "Radiative Corrections as the Origin of Spontaneous Symmetry Breaking," Phys. Rev. D7 (1973) 1888–1910.

[22] M. Quiros, "Finite temperature field theory and phase transitions," in Proceedings, Summer School in High-energy physics and cosmology: Trieste, Italy, June 29-July 17, 1998, pp. 187–259. 1999. arXiv:hep-ph/9901312 [hep-ph].

[23] R. R. Parwani, "Resummation in a hot scalar field theory," Phys. Rev. D45 (1992) 4695, arXiv:hep-ph/9204216 [hep-ph]. [Erratum: Phys. Rev.D48,5965(1993)].

[24] D. J. Gross, R. D. Pisarski, and L. G. Yaffe, "QCD and Instantons at Finite Temperature," Rev. Mod. Phys. 53 (1981) 43.

[25] N. K. Nielsen, "On the Gauge Dependence of Spontaneous Symmetry Breaking in Gauge Theories," Nucl. Phys. B101 (1975) 173–188.

[26] W. Chao, "Hiding Scalar Higgs Portal Dark Matter," arXiv:1601.06714 [hep-ph].

[27] S. Profumo, M. J. Ramsey-Musolf, C. L. Wainwright, and P. Winslow, “Singlet-catalyzed electroweak phase transitions and precision Higgs boson studies,” Phys. Rev. D91 no. 3, (2015) 035018, arXiv:1407.5342 [hep-ph].

[28] M. Gonderinger, Y. Li, H. Patel, and M. J. Ramsey-Musolf, “Vacuum Stability, Perturbativity, and Scalar Singlet Dark Matter,” JHEP 01 (2010) 053, arXiv:0910.3167 [hep-ph].

[29] W. Chao, M. Gonderinger, and M. J. Ramsey-Musolf, “Higgs Vacuum Stability, Neutrino Mass, and Dark Matter,” Phys. Rev. D86 (2012) 113017, arXiv:1210.0491 [hep-ph].

[30] Planck Collaboration, P. A. R. Ade et al., “Planck 2015 results. XIII. Cosmological parameters,” Astron. Astrophys. 594 (2016) A13, arXiv:1502.01589 [astro-ph.CO].

[31] A. V. Semenov, “LanHEP: A Package for automatic generation of Feynman rules in gauge models,” arXiv:hep-ph/9608488 [hep-ph].

[32] A. Semenov, “LanHEP - a package for automatic generation of Feynman rules from the Lagrangian. Updated version 3.1,” arXiv:1005.1909 [hep-ph].

[33] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “MicrOMEGAs: A Program for calculating the relic density in the MSSM,” Comput. Phys. Commun. 149 (2002) 103–120, arXiv:hep-ph/0112278 [hep-ph].

[34] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “micrOMEGAs-3: A program for calculating dark matter observables,” Comput. Phys. Commun. 185 (2014) 960–985, arXiv:1305.0237 [hep-ph].

[35] H.-Y. Cheng and C.-W. Chiang, “Revisiting Scalar and Pseudoscalar Couplings with Nucleons,” JHEP 07 (2012) 009, arXiv:1202.1292 [hep-ph].

[36] S. R. Coleman, “The Fate of the False Vacuum. 1. Semiclassical Theory,” Phys. Rev. D15 (1977) 2929–2936. [Erratum: Phys. Rev.D16,1248(1977)].

[37] A. D. Linde, “Fate of the False Vacuum at Finite Temperature: Theory and Applications,” Phys. Lett. B100 (1981) 37–40.

[38] A. D. Linde, “Decay of the False Vacuum at Finite Temperature,” Nucl. Phys. B216 (1983) 421. [Erratum: Nucl. Phys.B223,544(1983)].

[39] J. M. Cline, “Baryogenesis,” in Les Houches Summer School - Session 86: Particle Physics and Cosmology: The Fabric of Spacetime Les Houches, France, July 31-August 25, 2006. 2006. arXiv:hep-ph/0609145 [hep-ph].

[40] G. D. Moore and T. Prokopec, “How fast can the wall move? A Study of the electroweak phase transition dynamics,” Phys. Rev. D52 (1995) 7182–7204, arXiv:hep-ph/9506475 [hep-ph].

[41] G. V. Dunne and H. Min, “Beyond the thin-wall approximation: Precise numerical computation of prefactors in false vacuum decay,” Phys. Rev. D72 (2005) 125004, arXiv:hep-th/0511156 [hep-th].

[42] R. Apreda, M. Maggiore, A. Nicolis, and A. Riotto, "Gravitational waves from electroweak phase transitions," Nucl. Phys. B631 (2002) 342–368, arXiv:gr-qc/0107033 [gr-qc].

[43] C. Caprini et al., "Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions," JCAP 1604 no. 04, (2016) 001, arXiv:1512.06239 [astro-ph.CO].

[44] S. W. Hawking, I. G. Moss, and J. M. Stewart, "Bubble Collisions in the Very Early Universe," Phys. Rev. D26 (1982) 2681.

[45] C. Caprini, R. Durrer, and G. Servant, "Gravitational wave generation from bubble collisions in first-order phase transitions: An analytic approach," Phys. Rev. D77 (2008) 124015, arXiv:0711.2593 [astro-ph].

[46] R. Jinno and M. Takimoto, "Gravitational waves from bubble collisions: analytic derivation," Phys. Rev. D95 no. 2, (2017) 024009, arXiv:1605.01403 [astro-ph.CO].

[47] S. J. Huber and T. Konstandin, "Gravitational Wave Production by Collisions: More Bubbles," JCAP 0809 (2008) 022, arXiv:0806.1828 [hep-ph].

[48] M. Kamionkowski, A. Kosowsky, and M. S. Turner, "Gravitational radiation from first order phase transitions," Phys. Rev. D49 (1994) 2837–2851, arXiv:astro-ph/9310044 [astro-ph].

[49] J. R. Espinosa, T. Konstandin, J. M. No, and G. Servant, "Energy Budget of Cosmological First-order Phase Transitions," JCAP 1006 (2010) 028, arXiv:1004.4187 [hep-ph].

[50] M. Hindmarsh, S. J. Huber, K. Rummukainen, and D. J. Weir, "Numerical simulations of acoustically generated gravitational waves at a first order phase transition," Phys. Rev. D92 no. 12, (2015) 123009, arXiv:1504.03291 [astro-ph.CO].

[51] C. L. Wainwright, "CosmoTransitions: Computing Cosmological Phase Transition Temperatures and Bubble Profiles with Multiple Fields," Comput. Phys. Commun. 183 (2012) 2006–2013, arXiv:1109.4189 [hep-ph].

[52] A. Klein et al., "Science with the space-based interferometer eLISA: Supermassive black hole binaries," Phys. Rev. D93 no. 2, (2016) 024003, arXiv:1511.05581 [gr-qc].

[53] X. Gong et al., "Descope of the ALIA mission," J. Phys. Conf. Ser. 610 no. 1, (2015) 012011, arXiv:1410.7296 [gr-qc].

[54] H. Kudoh, A. Taruya, T. Hiramatsu, and Y. Himemoto, "Detecting a gravitational-wave background with next-generation space interferometers," Phys. Rev. D73 (2006) 064006, arXiv:gr-qc/0511145 [gr-qc].

[55] C. J. Moore, R. H. Cole, and C. P. L. Berry, "Gravitational-wave sensitivity curves," Class. Quant. Grav. 32 no. 1, (2015) 015014, arXiv:1408.0740 [gr-qc].

[56] K. Yagi and N. Seto, "Detector configuration of DECIGO/BBO and identification of cosmological neutron-star binaries," Phys. Rev. D83 (2011) 044011, arXiv:1101.3940 [astro-ph.CO].

[57] M. Artymowski, M. Lewicki, and J. D. Wells, "Gravitational wave and collider implications of electroweak baryogenesis aided by non-standard cosmology," arXiv:1609.07143 [hep-ph].

[58] R. Jinno and M. Takimoto, "Probing classically conformal $\mathrm{B}-\mathrm{L}$ model with gravitational waves," Phys. Rev. D95 no. 1, (2017) 015020, arXiv:1604.05035 [hep-ph].

[59] P. Huang, A. J. Long, and L.-T. Wang, "Probing the Electroweak Phase Transition with Higgs Factories and Gravitational Waves," Phys. Rev. D94 no. 7, (2016) 075008, arXiv:1608.06619 [hep-ph].

[60] K. Hashino, M. Kakizaki, S. Kanemura, P. Ko, and T. Matsui, "Gravitational waves and Higgs boson couplings for exploring first order phase transition in the model with a singlet scalar field," Phys. Lett. B766 (2017) 49–54, arXiv:1609.00297 [hep-ph].

[61] M. Kakizaki, S. Kanemura, and T. Matsui, "Gravitational waves as a probe of extended scalar sectors with the first order electroweak phase transition,"Phys. Rev. D92 no. 11, (2015) 115007, arXiv:1509.08394 [hep-ph].

[62] C. Balazs, A. Fowlie, A. Mazumdar, and G. White, "Gravitational waves at aLIGO and vacuum stability with a scalar singlet extension of the Standard Model," arXiv:1611.01617 [hep-ph].

[63] R. Jinno, K. Nakayama, and M. Takimoto, "Gravitational waves from the first order phase transition of the Higgs field at high energy scales," Phys. Rev. D93 no. 4, (2016) 045024, arXiv:1510.02697 [hep-ph].

[64] H. Davoudiasl and P. P. Giardino, "Gravitational Waves from Primordial Black Holes and New Weak Scale Phenomena," arXiv:1609.00907 [gr-qc].

[65] F. P. Huang, Y. Wan, D.-G. Wang, Y.-F. Cai, and X. Zhang, "Hearing the echoes of electroweak baryogenesis with gravitational wave detectors," Phys. Rev. D94 no. 4, (2016) 041702, arXiv:1601.01640 [hep-ph].

[66] I. Baldes, "Gravitational waves from the asymmetric-dark-matter generating phase transition," arXiv:1702.02117 [hep-ph].

[67] A. Addazi, "Limiting First Order Phase Transitions in Dark Gauge Sectors from Gravitational Waves experiments," arXiv:1607.08057 [hep-ph].

[68] Our particle settings are similar to those in Ref. [11] where color breaking from two-step phase transition was proposed.

[69] The ALIA program is the upgraded version of the Chinese Taiji Program in space of gravitational wave physics.

[70] The ALIA, BBO, and DECIGO data are taken from the website http://rhcole.com/apps/GWplotter/ where these sensitivity curves are collected in one place. We also checked that these curves are consistent with those used in Ref. [57].

[71] GWs can be generated from EWPT in SM extended with dimension-six operators [**?**, **?**, **?**], where no scalar singlet is needed.

Note: Figure translations are in progress. See original paper for figures.