

PAPER

# Strongly first-order phase transition in real singlet scalar dark matter model

To cite this article: Karim Ghorbani and Parsa Hossein Ghorbani 2020 *J. Phys. G: Nucl. Part. Phys.* **47** 015201

View the [article online](#) for updates and enhancements.



**IOP** Astronomy ebooks

Part of your publishing universe and your first choice for astronomy, astrophysics, solar physics and planetary science ebooks.

[iopscience.org/books/aas](http://iopscience.org/books/aas)

# Strongly first-order phase transition in real singlet scalar dark matter model

Karim Ghorbani<sup>1</sup>  and Parsa Hossein Ghorbani<sup>2,3</sup> 

<sup>1</sup> Physics Department, Faculty of Sciences, Arak University, Arak 38156-8-8349, Iran

<sup>2</sup> Applied Physics Inc., Center for Cosmological Research, 300 Park Avenue, New York, NY 10022, United States of America

E-mail: [karim1.ghorbani@gmail.com](mailto:karim1.ghorbani@gmail.com) and [parsaghorbani@gmail.com](mailto:parsaghorbani@gmail.com)

Received 5 July 2019, revised 5 September 2019

Accepted for publication 26 September 2019

Published 16 December 2019



CrossMark

## Abstract

The extension of the standard model by a real gauge singlet scalar is the simplest but the most studied model with sometimes controversial ideas on the ability of the model to address the dark matter (DM) and the electroweak phase transition (EWPT) issues simultaneously. For this model, we obtain analytically slightly different conditions for strongly first-order EWPT and apply that in computation of the DM relic density where the real scalar plays the role of the DM particle. We show that the scalar in this model before imposing the invisible Higgs decay constraint, can be responsible for all or part of the DM abundance, while at the same time gives rise to a strongly first-order EWPT required for the baryogenesis. When the constraints from the direct detection experiments such as XENON100 or LUX/XENON1t are considered, the model is excluded completely.

Keywords: dark matter, electroweak phase transition, beyond the standard model, early universe

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Apart from the discovery of the Higgs particle—the last elementary particle and the first scalar field discovered in nature—at the Large Hadron Collider (LHC) [1, 2], the search for a footprint of beyond the Standard Model (BSM) of elementary particles by the experiments at the LHC has ended up to null results so far [3]. However, there are strong motivations to look for BSM. Some examples are the absence of a well-established mechanism on how the Higgs

<sup>3</sup> Author to whom correspondence should be addressed.

gets a non-zero vacuum expectation value ( $v_{ev}$ ) in the early universe, the matter-antimatter asymmetry observed today in the Universe, and the mystery of dark matter (DM), which in all cases the existence of at least one more degree of freedom in the SM seems inevitable. On the other hand, the Higgs might not be the only scalar field in nature and the existence of further scalar degrees of freedom is not unlikely. The first possible addition of such a scalar would be the standard model (SM) plus a gauge-singlet scalar field. This is the simplest model BSM and has been studied vastly from various aspects in the past. These investigations may be divided in two categories. Once when the scalar field is stable under a  $\mathbb{Z}_2$  discrete symmetry and gets employed solely to explain the observed DM abundance and is constrained by direct and indirect searches, [4–25], or alternatively when the extra singlet scalar is used to give a first-order electroweak phase transition (EWPT) required by the Baryogenesis [26–35]. In the latter case, the singlet scalar is not necessarily required to get zero  $v_{ev}$  after the EWPT.

In the most recent work on the status of the singlet scalar DM by the GAMBIT collaboration [36], the Bayesian and frequentist global fits on the nuisance parameters, after imposing the constraints from the Planck for the relic density, the LUX, PandaX, SuperCDMS, XENON100 in direct searches, the invisible Higgs decay at the LHC, the IceCube for the DM annihilation to high energy neutrinos in the Sun, and the *Fermi*-LAT for DM annihilation into gamma rays in dwarf galaxies, show that the viable DM mass in the singlet scalar model sits either in the range  $\sim 125$ – $300$  GeV or is about  $\sim 1$  TeV if the scalar constitutes all the DM abundance. A global fit of the  $\gamma$ -ray galactic center excess in the real singlet scalar DM model is accomplished in [37]. These status reports on singlet scalar model have been only on DM part.

There are a few works that have addressed separately or simultaneously both the DM and the EWPT in the singlet scalar model [38–42]. For instance, in [39] it is argued that the scalar can be responsible for only 3% of the DM relic density and to give a first-order EWPT while evading the XENON100 direct detection (DD) bound. [41] however reports a slightly different result from [39] arguing that the model is completely unable to account for both the DM relic density and a first-order EWPT without considering the constraint from the DD experiments.

In this paper we scrutinize the question of the first-order EWPT in the real singlet scalar model and realize that the previous literature use *unnecessary* stronger first-order conditions which make the results slightly different. We elaborate this point in the paper and analytically compute the first-order EWPT conditions. Then we use the `micrOMEGAs` package for embedding both problems of the DM relic density and the electroweak EWPT in one code to explore the viable regions of the parameter space. We also impose the washout criterion as a requirement for the phase transition to be strongly enough for the baryogenesis. Finally we update the DD constraint to the recent results from LUX and XENON1t.

The paper is organized as the following. In section 2 we introduce the model and obtain analytically the first-order phase transition conditions and the washout criterion, then in section 3 we numerically compute the DM relic density and the DM-nucleon cross section while imposing the strongly first-order phase transition. We summarize the results in section 4.

## 2. First-order phase transition

The model is the simplest renormalizable extension of the SM with an additional real singlet scalar denoted by  $s$  here. The real scalar  $s$  interacts with the SM through the Higgs portal having a quadratic interaction with the Higgs particle. Therefore, beside the Higgs and the

scalar potentials

$$\begin{aligned} V_H &= -\mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2 \\ V_s &= -\frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4, \end{aligned} \quad (1)$$

the total potential includes also the interaction part

$$V_{\text{int}} = \lambda_{hs} s^2 H^\dagger H, \quad (2)$$

where  $H$  denotes the Higgs  $SU(2)$  doublet and  $\lambda_{hs}$  is the scalar-Higgs interaction coupling playing an important role in our analysis. There are only two free parameters in the model, i.e. the scalar mass and the coupling,  $\lambda_{hs}$ . Note that we are not considering the terms in the potential that do not respect the  $\mathbb{Z}_2$  discrete symmetry, such that the scalar can be a stable DM particle in the so-called *freeze-out* mechanism. Gauging away three components of the Higgs doublet, only one real component,  $h$ , remains and the Higgs field in equations (1) and (2) can be replaced by  $H^\dagger = \frac{1}{\sqrt{2}}(0 \ h \ v_h)$  after the electroweak symmetry breaking. When the temperature is very high the theory consisting of the SM and the new real scalar, lives in its symmetric phase. In this energy scale, the Higgs takes zero vacuum expectation value while the scalar could have zero or non-zero  $vev$ <sup>4</sup>. The tree-level the total potential at high temperature can then be written as

$$V_{\text{tr}}(h, s) = -\frac{1}{2}\mu_h^2 h^2 - \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_{hs} s^2 h^2. \quad (3)$$

As the Universe cools down, at the time of electroweak symmetry breaking at lower temperatures, we assume a one-step phase transition that the  $vevs$  of the scalars,  $h$  and  $s$ , change from  $(v_0 = 0, w_0 \neq 0)$  to  $(v \neq 0, w = 0)$  at temperature  $T_c$  where  $v \equiv \langle h \rangle$  and  $w \equiv \langle s \rangle$ <sup>5</sup>. We require that after the phase transition  $w = 0$  because otherwise the  $\mathbb{Z}_2$  symmetry is broken and the scalar  $s$  can no longer be taken as the DM candidate.

Along the lines of [33], in addition to the tree-level barrier we include also the one-loop thermal potential in order to get a strong EWPT

$$V_T^{1-\text{loop}}(h, s; T) \simeq \left( \frac{1}{2}c_h h^2 + \frac{1}{2}c_s s^2 \right) T^2, \quad (4)$$

where the parameters  $c_h$  and  $c_s$  are the following

$$\begin{aligned} c_h &= \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 12\lambda_h + 4\lambda_{hs}) \\ c_s &= \frac{1}{12}(\lambda_{hs} + 3\lambda_s). \end{aligned} \quad (5)$$

The one-loop correction at zero-temperature in the effective potential as pointed out in [43, 44] is negligible, therefore the thermal one-loop effective potential can approximately be written as

<sup>4</sup> Note that in the early universe, the DM freezes out from plasma of particles in a temperature much lower than the electroweak phase transition temperature,  $T_c$ . Therefore, to be more accurate, it only suffices that the real scalar takes zero  $vev$  just above the freeze-out temperature,  $T_f$ .

<sup>5</sup> At very high temperature the  $vev$  of the scalar must be vanishing, as can be seen easily from the thermal effective potential. However at intermediate temperatures the  $w_0 \neq 0$  can be a deeper minimum. We ignore the transition from  $w_0 = 0$  to  $w_0 \neq 0$  which does not change the nature of EWPT.

$$V_{\text{eff}}(h, s; T) = V_{\text{tr}}(h, s) + V_T^{1-\text{loop}}(h, s; T). \quad (6)$$

The critical temperature  $T_c$  of the electroweak phase transition, is the temperature at which the free energy (thermal effective potential in equation (6)) in the symmetric phase equals the free energy in the broken phase. In other words, the thermal effective potential gets two degenerate minima at  $T = T_c$ . Note the fact that we deal with two types of symmetries here. One is the  $\mathbb{Z}_2$  discrete symmetry in  $s$  which must exist below the freeze-out temperature,  $T_f$ , and the  $SU(2)$  electroweak symmetry which is unbroken in high temperatures. The phase transition process we consider here is a transition from  $(\langle h \rangle, \langle s \rangle) = (v_{\text{sym}} = 0, w_{\text{brk}})$  to  $(\langle h \rangle, \langle s \rangle) = (v_{\text{brk}}, w_{\text{sym}} = 0)$ . We recall that at temperatures above  $T_c$ , the scalar field  $s$ , can always have non-zero vacuum expectation value. The minima of the thermal effective potential in equation (6) read

$$v_{\text{sym}} = 0 \text{ and } v_{\text{brk}}^2(T) = \frac{\mu_h^2 - c_h T^2}{\lambda_h} \equiv \frac{\mu_h^2(T)}{\lambda_h}, \quad (7)$$

where  $v_{\text{brk}}$  is the  $T$ -dependent Higgs  $vev$ , and

$$w_{\text{sym}} = 0 \text{ and } w_{\text{brk}}^2(T) = \frac{\mu_s^2 - c_s T^2}{\lambda_s} \equiv \frac{\mu_s^2(T)}{\lambda_s}, \quad (8)$$

with  $w_{\text{brk}}$  being the  $T$ -dependent  $vev$  of the scalar  $s$ .

Now the critical temperature below which the transition from  $(v_{\text{sym}} = 0, w_{\text{brk}})$  to  $(v_{\text{brk}}, w_{\text{sym}} = 0)$  takes place is obtained by solving  $V_{\text{eff}}(0, w_{\text{brk}}; T_c) = V_{\text{eff}}(v_{\text{brk}}, 0; T_c)$ . The answer can be expressed as

$$T_c = \sqrt{\frac{a - b}{c}}, \quad (9)$$

with the parameters  $a$ ,  $b$  and  $c$  defined as

$$\begin{aligned} a &= c_h \mu_h^2 \lambda_s - c_s \mu_s^2 \lambda_h, \\ b &= |c_h \mu_s^2 - c_s \mu_h^2| \sqrt{\lambda_h \lambda_s}, \\ c &= c_s^2 \lambda_h - c_h^2 \lambda_s. \end{aligned} \quad (10)$$

At temperatures lower than the critical temperature,  $T < T_c$  the minimum at  $(v(T) = \sqrt{\mu_h^2(T)/\lambda_h}, 0)$  must be the global minimum down to  $T = 0$ . This means that the  $T^2$ -derivative of  $\Delta V_{\text{brk-sym}}(T)$

$$\Delta V_{\text{brk-sym}}(T) = V(0, w(T)) - V(v(T), 0) > 0, \quad (11)$$

must satisfy

$$\left. \frac{d\Delta V_{\text{brk-sym}}(T)}{dT^2} \right|_{T=T_c} < 0, \quad (12)$$

which leads to

$$c_h \sqrt{\frac{\lambda_s}{\lambda_h}} > c_s. \quad (13)$$

It is assumed in the literature (see e.g. [41]) that the minimum  $(0, w_0)$  must exist for all temperatures from  $T = 0$  to very large  $T$ , say  $T \rightarrow \infty$ . This puts strong constraints on  $c_s$  and  $\mu_s^2$ :  $c_s < 0$  and  $\mu_s^2 > 0$ , which we explain in a moment that are not the correct conditions. On the other hand, the minimum  $(v, 0)$  should coexist together with the minimum  $(0, w_0)$  for

temperatures  $T \leq T_c$ , while the minimum  $(v, 0)$  must remain the deepest minima until  $T = 0$ . The latter condition is given by equation (13). The global minimum condition for  $(v, 0)$  given in equation (13) and the (not very correct) local minimum conditions for  $(0, w_0)$  mentioned above, have no overlap in the space of parameter, hence it has been inferred in [41] that the EWPT cannot be of first-order.

Now we explain why the local minimum condition considered e.g. in [41] does not necessarily hold. Although, the local minimum condition at  $(0, w_0)$  for  $T \in [0, \infty)$  is sufficient, but it is not necessary. In fact, it is enough that the local minimum  $(0, w_0)$ , exist for even a short time before the EWPT, say from  $T_c + \delta T$  to  $T_c$  with  $\delta T$  an arbitrary small value and  $T_c$  being the critical temperature. Above the temperature  $T_c + \delta T$ , the minimum may be either  $(0, w_0)$  or  $(0, 0)$ . Any possible change in  $w_0$  above  $T_c + \delta T$ , has no effect on the electroweak phase transition. Considering this fact and in the limit  $\delta T \rightarrow 0$ , the local minimum condition for  $(0, w_0)$  becomes

$$c_s < \frac{\mu_s^2}{T_c^2}. \quad (14)$$

One of the Sakharov's condition for the baryon asymmetry is guaranteed by the suppressed sphaleron rate in the Higgs broken phase. This is equivalent to the condition  $v_c/T_c > 1$  that is called the *washout criterion* in which  $v_c \equiv v_{\text{brk}}(T_c)$ . For the solution we found in equation (9) we have therefore the following condition

$$\frac{v_c(T_c)}{T_c} > 1 \quad (15)$$

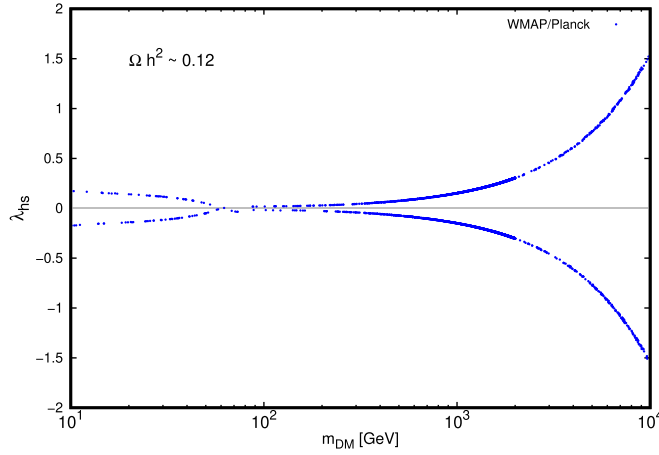
with

$$v_c = \frac{c_s \mu_h^2 - c_h \mu_s^2}{c_s \sqrt{\lambda_h} - c_h \sqrt{\lambda_s}}. \quad (16)$$

The stability conditions at  $T = 0$  still reduces the number of independent parameters. The Higgs physical mass fixes the parameter  $\mu_h^2$  as  $\mu_h^2 = m_H^2/2$  with  $m_H = 125$  GeV. The Higgs quartic coupling is also fixed as  $\lambda_h = m_H^2/2v_h^2 \simeq 0.129$ . Then from equation (10),  $\lambda_s > 0$ . The physical mass of the scalar  $s$  (DM mass) is given by  $m_{\text{DM}}^2 \equiv m_s^2 = -\mu_s^2 + \lambda_{hs} v_h^2$ . The positivity of the DM mass then requires  $\mu_s^2 < \lambda_{hs} v_h^2$ .

### 3. Dark matter

Another important issue we take into account in the simple model of the real scalar extension of the SM is the problem of the DM. Because of the  $\mathbb{Z}_2$  discrete symmetry on the scalar  $s$  we considered in equation (3), the scalar is stable and is taken as the *weakly interacting massive particle*. The DM particle is in thermal equilibrium with the SM particles in the early universe, but it detaches from other particles at the freeze-out temperature,  $T_f$  after the Universe is expanded enough with the Hubble rate. The  $v_{ev}$  of the Higgs particle at zero temperature is  $v_h = 246$  GeV and for the singlet scalar is  $v_s = 0$ , hence there is no mixing between the Higgs and the DM particle. The only annihilation channel we deal with in this model is  $ss \rightarrow \text{Higgs} \rightarrow \text{SM}$ , therefore the only independent coupling in the Lagrangian that enters in the DM annihilation process and the DM elastic scattering off the nuclei is the  $\lambda_{hs}$  in equation (3). Other parameters in the theory does not affect the computation of the relic density and the DM-nucleon elastic scattering cross section. Nevertheless, they are present in the EWPT conditions as was discussed in the previous section. In our computations, we



**Figure 1.** The plot shows the viable range of the coupling  $\lambda_{hs}$  and the DM mass which gives rise to the correct relic density for the DM in the real singlet scalar model.

confirm that the EWPT occurs before the DM freezes-out from the thermal equilibrium. This means that at the time of freeze-out the Higgs is already in a non-zero  $v_{ev}$  or equivalently the theory is already in its broken phase (the Higgs and the SM fermions are massive) and the singlet scalar has got the  $\mathbb{Z}_2$  symmetry.

The time evolution of the DM density is obtained by solving the Boltzmann differential equation

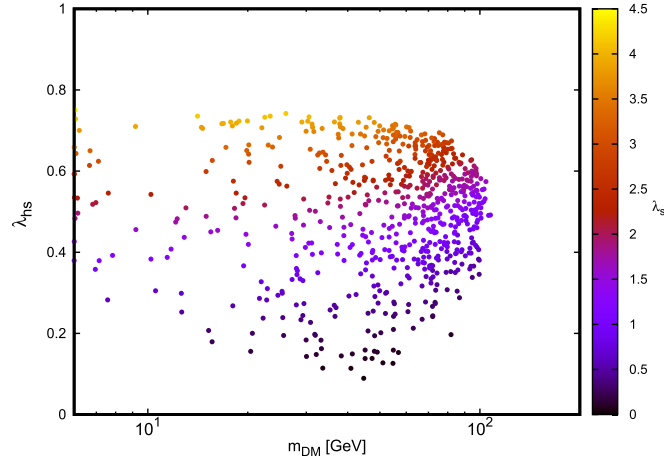
$$\frac{dn_s}{dt} = -3Hn_s - \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle [n_s^2 - (n_s^{\text{eq}})^2], \quad (17)$$

where  $H$  stands for the Hubble expansion rate of the Universe (not to be confused with the Higgs doublet denoted in section 2),  $\sigma_{\text{ann}}$  is the DM annihilation cross section,  $v_{\text{rel}}$  is the DM relative velocity and the bracket means the thermal average. Exploiting the `micrOMEGAs` package [45], we obtained the relic density. Having applied the stability conditions, we scanned over all DM masses in the range 10 GeV–10 TeV while the only relevant coupling  $\lambda_{hs}$  being in the interval  $-2 < \lambda_{hs} < 2$ . The result is demonstrated in figure 1. As seen in the plot, the DM particle,  $s$ , enjoys a viable space of the coupling  $\lambda_{hs}$  to account for all the relic abundance observed in the Universe by WMAP/Planck [46, 47] to be  $\Omega_{\text{DM}} h^2 \sim 0.12$ . Furthermore, we observe from figure 1 that the coupling  $\lambda_{hs}$  has is decreasing until  $m_s \equiv m_{\text{DM}} = m_h/2$  and it gets larger for smaller masses afterwards. After imposing the first-order EWPT conditions, the coupling  $\lambda_{hs}$  can only be positive and as seen in figure 2 its allowed value is within 0.1–0.8.

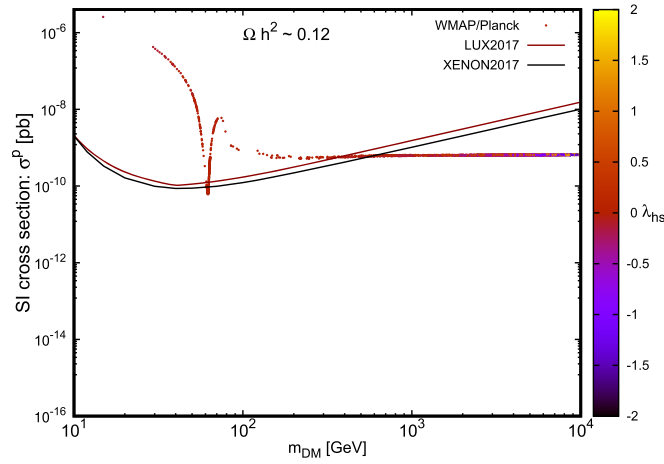
To calculate the DM-nucleon elastic scattering cross section, there is only one  $t$ -channel  $ss\bar{q}q$  Feynman diagram which can be easily read from the Lagrangian. However, one needs to use the effective operator for the interaction  $ss\bar{N}N$  which requires the use of the nucleon form factors. The DM-nucleon spin-independent elastic scattering cross section is then as follows

$$\sigma_{\text{SI}}^N = \frac{\alpha_N^2 \mu_N^2}{\pi m_{\text{DM}}^2}, \quad (18)$$

where  $\alpha_N$  is the effective coupling given in terms of the form factors and  $\mu_N$  is the DM-nucleon reduced mass (see e.g. [48] for more details). The DM-nucleon cross section can also be computed in the `micrOMEGAs` package. For each set of the parameters that lead



**Figure 2.** The allowed values of the couplings  $\lambda_{hs}$  and  $\lambda_s$  in terms of DM mass after imposing first-order EWPT conditions.

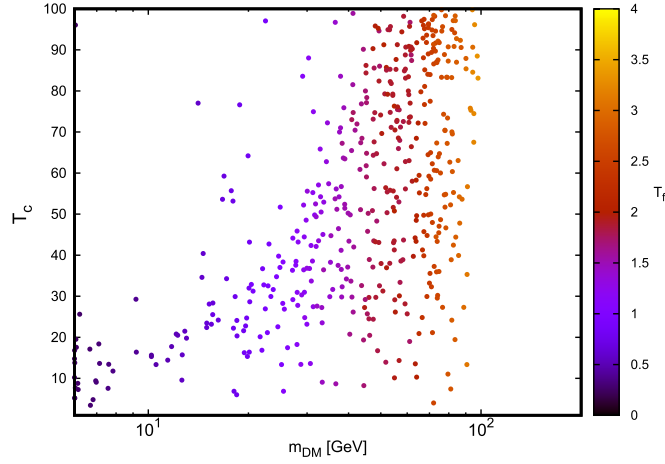


**Figure 3.** The relic density viable space saturates the spin-independent DM-nucleon cross section limit provided by LUX/XENON1t at DM mass of  $\sim 600$  GeV.

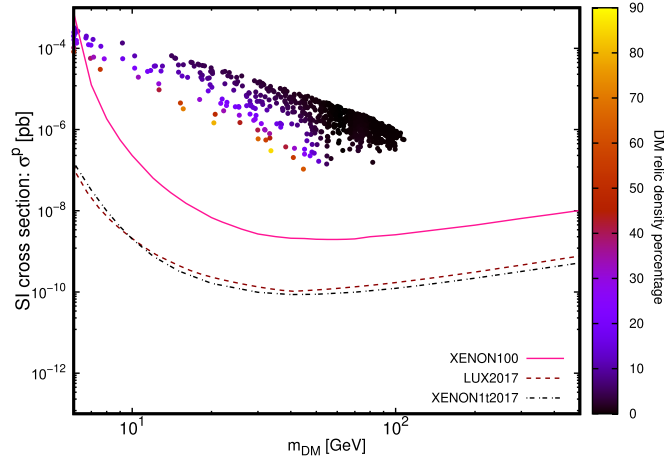
to the correct DM relic abundance, we have computed the scattering cross section. The result in figure 3 shows that the cross section saturates the LUX bound [49] at  $\sim m_s \equiv m_{DM} \sim 350$  GeV and the XENON1t limit [50] at  $\sim m_{DM} \sim 600$  GeV and of course for the resonance region. We do not focus on the resonance region because it is excluded when we add the washout criterion into our computation as comes later on. We therefore conservatively can impose the DM mass to be  $m_{DM} \gtrsim 600$  GeV if only the total relic density and the DD bounds are taken into consideration. This is consistent with the results in [36] suggesting a viable DM mass of order  $\sim 1$  TeV. Note that we have not considered all the constraints in [36] that is why the viable DM mass seen in figure 3 has only a lower bound. In figure 1 the coupling is of order of one as has been mentioned in the results of the GAMBIT global fit [36].

We finally take into account the first-order electroweak phase transition conditions and the washout criterion obtained in equations (9), (13)–(15). In figure 4, the critical and





**Figure 4.** Shown is the critical and freeze-out temperatures,  $T_c$  and  $T_f$  in terms of DM mass.



**Figure 5.** The DM mass against the DM-nucleon cross section when the electroweak phase transition is strongly first-order and the singlet scalar constitutes 0%–100% of the total DM relic density  $\Omega_{\text{DM}} h^2 \sim 0.12$ . The DM relic density and the strongly EWPT can be explained simultaneously by singlet scalar model with DM mass smaller than 130 GeV. The XENON100 cross section bound excludes almost all the parameter space except for a small DM mass range 6–8 GeV.

freeze-out temperatures are shown in terms of the viable DM mass while the first-order EWPT conditions are satisfied. From this figure, it is obvious that  $T_f < T_c$ . In figure 5, the spin-independent DM-nucleon cross section against the DM mass is shown where all the constraints from the strongly first-order EWPT are imposed. The DM relic density condition is relaxed to take all values from 0% to 100% of the DM relic density observed by WMAP/Planck. As seen in figure 5, we find regions of the parameter space that the singlet scalar covers from 0% to 100% of the DM relic density in a range of DM mass  $\sim 6$ –130 GeV. We therefore have demonstrated that before imposing any constraint from the invisible Higgs

decay width, the singlet scalar can be a subdominant DM from 0% to 100%. This result has not been pointed out before in the literature. When we impose also the invisible Higgs decay bound the scalar can then cover less than 3% of the relic abundance, as reported in [39].

Except for DM mass  $\sim 6\text{--}8$  GeV, where the sensitivity of the current DD experiments is low, we have shown in figure 5 that all the parameter space is excluded by the cross section bounds provided by XENON100/XENON1T experiments. This result is different from that of [39] where a DM mass of  $\sim 100\text{--}170$  GeV can evade the XENON100 bound. In fact, it is seen promptly from figure 5 that the smaller the fraction of the DM relic density is covered by the singlet scalar model, the more strongly it is excluded by the XENON100 limit. In figure 5 we have included also the updated DM-nucleon cross section bound from LUX/XENON1T.

#### 4. Conclusion

In this article we have studied the real singlet scalar DM model which possesses only two additional independent parameters compared to the SM. The extra scalar in the model is used to simultaneously play the role of the DM particle and to make the electroweak phase transition strongly first-order. By introducing a weaker first-order EWPT condition that usually is considered in the literature, we have shown that the singlet scalar model is capable of explaining partially or the whole DM relic abundance observed by the WMAP/Planck, and giving rise at the same time to strongly first-order EWPT. The model is excluded entirely by the XENON1t experiment but if we consider the XENON100 limit, the viable DM mass sits in a region of 6–8 GeV to which the DD experiments are not very sensitive.

#### Acknowledgments

The authors would like to thank the CERN Theoretical Physics Department (CERN-TH), for the hospitality and support where this work was finalized during their visits. Arak University is acknowledged for financial support under contract No. 98/664

#### ORCID iDs

Karim Ghorbani  <https://orcid.org/0000-0002-1441-0014>

Parsa Hossein Ghorbani  <https://orcid.org/0000-0002-1489-5568>

#### References

- [1] Aad G *et al* 2012 Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC *Phys. Lett. B* **716** 1–29
- [2] Chatrchyan S *et al* 2012 Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC *Phys. Lett. B* **716** 30–61
- [3] Baak M, Goebel M, Haller J, Hoecker A, Kennedy D, Kogler R, Moenig K, Schott M and Stelzer J 2012 The electroweak fit of the standard model after the discovery of a new boson at the LHC *Eur. Phys. J. C* **72** 2205
- [4] Hill C T and Simmons E H 2003 Strong dynamics and electroweak symmetry breaking *Phys. Rep.* **381** 235–402  
Hill C T and Simmons E H 2004 *Phys. Rept.* **390** 553 erratum
- [5] Silveira V and Zee A 1985 Scalar phantoms *Phys. Lett.* **161B** 136–40
- [6] McDonald J 1994 Gauge singlet scalars as cold dark matter *Phys. Rev. D* **50** 3637–49

- [7] McDonald J 2002 Thermally generated gauge singlet scalars as selfinteracting dark matter *Phys. Rev. Lett.* **88** 091304
- [8] Bento M C, Bertolami O, Rosenfeld R and Teodoro L 2000 Selfinteracting dark matter and invisibly decaying Higgs *Phys. Rev. D* **62** 041302
- [9] Burgess C P, Pospelov M and ter Veldhuis T 2001 The Minimal model of nonbaryonic dark matter: a singlet scalar *Nucl. Phys. B* **619** 709–28
- [10] He X-G, Li T, Li X-Q, Tandean J and Tsai H-C 2009 Constraints on scalar dark matter from direct experimental searches *Phys. Rev. D* **79** 023521
- [11] Lerner R N and McDonald J 2009 Gauge singlet scalar as inflaton and thermal relic dark matter *Phys. Rev. D* **80** 123507
- [12] Gonderinger M, Li Y, Patel H and Ramsey-Musolf M J 2010 Vacuum stability, perturbativity, and scalar singlet dark matter *J. High Energy Phys.* [JHEP01\(2010\)053](#)
- [13] Farina M, Pappadopulo D and Strumia A 2010 CDMS stands for constrained dark matter singlet *Phys. Lett. B* **688** 329–31
- [14] Guo W-L and Wu Y-L 2010 The Real singlet scalar dark matter model *J. High Energy Phys.* [JHEP10\(2010\)083](#)
- [15] Profumo S, Ubaldi L and Wainwright C 2010 Singlet scalar dark matter: monochromatic gamma rays and metastable vacua *Phys. Rev. D* **82** 123514
- [16] Biswas A and Majumdar D 2013 The real Gauge singlet scalar extension of standard model: a possible candidate of cold dark matter *Pramana* **80** 539–57
- [17] Djouadi A, Falkowski A, Mambrini Y and Quevillon J 2013 Direct detection of Higgs-portal dark matter at the LHC *Eur. Phys. J. C* **73** 2455
- [18] Feng L, Profumo S and Ubaldi L 2015 Closing in on singlet scalar dark matter: LUX, invisible Higgs decays and gamma-ray lines *J. High Energy Phys.* [JHEP03\(2015\)045](#)
- [19] Profumo S, Ramsey-Musolf M J, Wainwright C L and Winslow P 2015 Singlet-catalyzed electroweak phase transitions and precision Higgs boson studies *Phys. Rev. D* **91** 035018
- [20] Duerr M, Fileviez Perez P and Smirnov J 2016 Scalar dark matter: direct versus indirect detection *J. High Energy Phys.* [JHEP06\(2016\)152](#)
- [21] Han H, Yang J M, Zhang Y and Zheng S 2016 Collider signatures of Higgs-portal scalar dark matter *Phys. Lett. B* **756** 109–12
- [22] Sage F S and Dick R 2016 Gamma ray signals of the annihilation of Higgs-portal singlet dark matter [arXiv:1604.04589 \[astro-ph.HE\]](#)
- [23] Wu H and Zheng S 2017 Scalar dark matter: real versus complex *J. High Energy Phys.* [JHEP03\(2017\)142](#)
- [24] Casas J A, Cerdeno D G, Moreno J M and Quilis J 2017 Reopening the Higgs portal for single scalar dark matter *J. High Energy Phys.* [JHEP05\(2017\)036](#)
- [25] Athron P, Cornell J M, Kahlhoefer F, McKay J, Scott P and Wild S 2018 Impact of vacuum stability, perturbativity and XENON1T on global fits of  $\mathbb{Z}_2$  and  $\mathbb{Z}_3$  scalar singlet dark matter *Eur. Phys. J. C* **78** 830
- [26] Espinosa J R and Quiros M 1993 The Electroweak phase transition with a singlet *Phys. Lett. B* **305** 98–105
- [27] Choi J and Volkas R R 1993 Real Higgs singlet and the electroweak phase transition in the standard model *Phys. Lett. B* **317** 385–91
- [28] Brustein R and Oaknin D H 1999 Electroweak baryogenesis induced by a scalar field *Phys. Rev. Lett.* **82** 2628–31
- [29] Ham S W, Jeong Y S and Oh S K 2005 Electroweak phase transition in an extension of the standard model with a real Higgs singlet *J. Phys. G: Nucl. Part. Phys.* **31** 857–71
- [30] Ahriche A 2007 What is the criterion for a strong first order electroweak phase transition in singlet models? *Phys. Rev. D* **75** 083522
- [31] Profumo S, Ramsey-Musolf M J and Shaughnessy G 2007 Singlet Higgs phenomenology and the electroweak phase transition *J. High Energy Phys.* [JHEP08\(2007\)010](#)
- [32] Das S, Fox P J, Kumar A and Weiner N 2010 The dark side of the electroweak phase transition *J. High Energy Phys.* [JHEP11\(2010\)108](#)
- [33] Espinosa J R, Konstandin T and Riva F 2012 Strong electroweak phase transitions in the standard model with a singlet *Nucl. Phys. B* **854** 592–630
- [34] Fuyuto K and Senaha E 2014 Improved sphaleron decoupling condition and the Higgs coupling constants in the real singlet-extended standard model *Phys. Rev. D* **90** 015015

- [35] Kurup G and Perelstein M 2017 Dynamics of electroweak phase transition in singlet-scalar extension of the standard model *Phys. Rev. D* **96** 015036
- [36] Athron P *et al* 2017 Status of the scalar singlet dark matter model *Eur. Phys. J. C* **77** 568
- [37] Cuoco A, Eiteneuer B, Heisig J and Kramer M 2016 A global fit of the  $\gamma$ -ray galactic center excess within the scalar singlet Higgs portal model *J. Cosmol. Astropart. Phys.* **JCAP06(2016)050**
- [38] Barger V, Langacker P, McCaskey M, Ramsey-Musolf M J and Shaughnessy G 2008 LHC phenomenology of an extended standard model with a real scalar singlet *Phys. Rev. D* **77** 035005
- [39] Cline J M and Kainulainen K 2013 Electroweak baryogenesis and dark matter from a singlet Higgs *J. Cosmol. Astropart. Phys.* **JCAP01(2013)012**
- [40] Alanne T, Tuominen K and Vaskonen V 2014 Strong phase transition, dark matter and vacuum stability from simple hidden sectors *Nucl. Phys. B* **889** 692–711
- [41] Vaskonen V 2017 Electroweak baryogenesis and gravitational waves from a real scalar singlet *Phys. Rev. D* **95** 123515
- [42] Beniwal A, Lewicki M, Wells J D, White M and Williams A G 2017 Gravitational wave, collider and dark matter signals from a scalar singlet electroweak baryogenesis *J. High Energy Phys.* **JHEP08(2017)108**
- [43] Ghorbani P H 2017 Electroweak Baryogenesis and dark matter via a Pseudoscalar versus scalar *J. High Energy Phys.* **JHEP08(2017)058**
- [44] Ghorbani P H 2018 Electroweak phase transition in the scale invariant standard model *Phys. Rev. D* **98** 115016
- [45] Barducci D, Belanger G, Bernon J, Boudjema F, Da Silva J, Kraml S, Laa U and Pukhov A 2018 Collider limits on new physics within micrOMEGAs4.3 *Comput. Phys. Commun.* **222** 327–38
- [46] Hinshaw G *et al* 2013 Nine-year Wilkinson microwave anisotropy probe (WMAP) observations: cosmological parameter results *Astrophys. J. Suppl.* **208** 19
- [47] Ade P A R *et al* 2014 Planck 2013 results: XVI. Cosmological parameters *Astron. Astrophys.* **571** A16
- [48] Ghorbani K and Ghorbani H 2016 Scalar split WIMPs in future direct detection experiments *Phys. Rev. D* **93** 055012
- [49] Akerib D S *et al* 2017 Results from a search for dark matter in the complete LUX exposure *Phys. Rev. Lett.* **118** 021303
- [50] Aprile E *et al* 2017 First dark matter search results from the XENON1T experiment *Phys. Rev. Lett.* **119** 181301