An update on the two singlet dark matter model

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ABSTRACT: We revisit the two real singlet extension of the Standard Model with a $Z_2 \times Z'_2$ symmetry. One of the singlet scalars S_2 , by virtue of an unbroken Z'_2 symmetry, plays the role of a stable dark matter candidate. The other scalar S_1 , with spontaneously broken Z_2 -symmetry, mixes with the SM Higgs boson and acts as the scalar mediator. We analyze the model by putting in the entire set of theoretical and recent experimental constraints. The latest bounds from direct detection Xenon1T experiment severely restricts the allowed region of parameter space of couplings. To ensure the dark matter satisfies the relic abundance criterion, we rely on the Breit-Wigner enhanced annihilation cross-section. Further, we study the viability of explaining the observed gamma-ray excess in the galactic center in this model with a dark matter of mass in the $\sim 36 - 51$ GeV window and present our conclusions.

KEYWORDS: Beyond Standard Model, Cosmology of Theories beyond the SM

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Contents

1	Introduction	1
2	The two-singlet model	2
3	Constraints on the two-singlet model	4
3.1	Vacuum stability	4
3.2	Collider constraints	6
3.3	LHC Higgs searches	7
4	Dark matter phenomenology in the two-singlet model	8
4.1	Direct detection	9
4.2	Relic abundance	11
4.3	Explaining gamma-ray excess in two-singlet model	13
5	Conclusion	14
A	Relevant Couplings	16

1 Introduction

The elusive dark matter, consisting of 24% of the universe [1, 2], finds no explanation in the Standard Model (SM) of particle physics. Although there are several evidences [3–6] for the existence of dark matter (DM) on cosmological scales, direct evidences such as scattering of DM particles off nuclei are still lacking. The properties and interaction of dark matter are still unknown, except that it must be electrically neutral and stable on cosmic time scales. Therefore, the quest for identifying dark matter continues to motivate extensions beyond the SM. A popular choice for DM is the weakly interacting massive particle (WIMP) [7–9] scenario with the DM mass ranging from a few GeV to a few hundred GeVs. It is imperative that the WIMPs do not have sizable couplings to the SM sector lest they decay. A discrete symmetry under which the dark matter and the SM behave differently is a convenient mechanism with which to prohibit such decays. There is a large literature of WIMP candidates from various well-motivated Beyond the SM (BSM) scenarios. For example, in this context supersymmetry (SUSY), neutralinos are widely studied in the literature [10] as possible WIMPs. Neutralinos being the lightest supersymmetric particles (LSP) are odd under R-parity enabling them to be stable DM candidates. But it is quite challenging to achieve a light dark matter below 100 GeV in minimal SUSY model owing to various phenomenological and experimental constraints [11–15].

In the context of minimal non-supersymmetric scenarios, the real singlet extension of the SM has been extensively studied [16–23], where an imposed Z_2 -symmetry ensures the

stability of the extra singlet rendering it a viable dark matter candidate. In such models, it has been observed that only a dark matter with mass nearly half that of the SM Higgs boson can survive the relic abundance constraints, which makes light DM with mass less than 60 GeV or so not viable even if they are consistent with direct detection bounds. A possible way out of this leads one to the next to minimal approach: a two singlet extension of the SM with an added $Z_2 \times Z'_2$ discrete symmetry (for both singlets charged under same Z_2 see ref. [24]). Previous studies on two singlet model in the pre-LHC era [25, 26] have shown that a DM with mass $\sim 10 - 20$ GeV and a light mediator is consistent with the CDMSII [27] and XENON100 [28] bounds. Ref. [29], considers similar models but in the context of slightly complicated multi component DM while ref. [30] focusses on Higgs phenomenology in the two singlet model. In a recent study [31], the authors have taken into account self interactions of the DM and with a light mediator to explain the observed density profiles of dwarf galaxies and galaxies of the size of our Milky way.

The paper is organized as follows: in section 2, we review the two-singlet model [25, 31] with a $Z_2 \times Z'_2$ symmetry and compute the relevant couplings and mixings. Then in section 3, we study the implications of imposing various constraints on the model from collider searches and the vacuum stability bound. The invisible decay width of SM Higgs boson restricts the choice of certain parameters like the dark matter self coupling and its coupling to the SM Higgs. Section 4 deals with the detailed dark matter phenomenology — we demonstrate in section 4.1 that in order to be consistent with recent Xenon1T exclusion limits, the parameter space for couplings are quite tightly constrained. Relic abundance (section 4.2) criteria are found to be satisfied only near the regions where the mass of the DM is almost half the mass of either the SM Higgs boson (h) or the other scalar (H) where the Breit-Wigner enhancement is significant — elsewhere the annihilation cross-section is too low leading to over-abundance. In section 4.3, we discuss the reported gamma ray excess observed in the galactic center which has grabbed a lot of attention lately. Choosing the DM mass in the range $\sim 36 - 51$ GeV with m_H ranging between 70 – 104 GeV, we demonstrate that the galactic center gamma ray excess [32–36] can be accommodated in this model. This again is because the annihilation cross-section of DM-DM into $b\bar{b}$ is enhanced by virtue of the scalar resonance. Finally in section 5, we conclude with remarks on the future scope of this model.

2 The two-singlet model

One of the simplest ways to incorporate a dark matter candidate is by extending the scalar sector of the SM. In this paper, we concentrate on the extension of the SM with two real scalars S_1 and S_2 with an imposed $Z_2 \times Z'_2$ symmetry. Here we capture the essential elements of the model pertaining to the symmetry breaking pattern — more details about the model can be found in refs. [25, 31, 37].

The model is constructed such that all SM particles are even under both the Z_2 's while the extra scalar singlets transform in the following manner:

$$\begin{aligned} S_1 &\xrightarrow{Z_2} -S_1, & S_1 &\xrightarrow{Z'_2} S_1, \\ S_2 &\xrightarrow{Z_2} S_2, & S_2 &\xrightarrow{Z'_2} -S_2. \end{aligned} \tag{2.1}$$

Both S_1 and S_2 interact with the SM particles solely through a Higgs-portal. The Z_2 symmetry is broken spontaneously while the Z'_2 remains unbroken which continues to insure the stability of S_2 , thus making it a potential dark matter candidate (we will consider the WIMP scenario in this paper). As we will see below, as a consequence of the Higgs-portal structure, interactions of the DM with the SM particles arise purely from the DM-Higgs boson couplings. We begin by writing down the Lagrangian of the scalar sector:

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + \frac{1}{2} \partial^\mu S_1 \partial_\mu S_1 + \frac{1}{2} \partial^\mu S_2 \partial_\mu S_2 - V(\Phi, S_1, S_2), \quad (2.2)$$

where Φ is the usual SM Higgs doublet. The scalar potential admits all terms respecting the gauge and the discrete $Z_2 \times Z'_2$ symmetries:

$$V = -\frac{m_0^2}{2}(\Phi^\dagger \Phi) - \frac{m_1^2}{2}S_1^2 + \frac{m_2^2}{2}S_2^2 + \frac{\lambda_0}{4}(\Phi^\dagger \Phi)^2 + \frac{\lambda_1}{4}S_1^4 + \frac{\lambda_2}{4}S_2^4 + \lambda_{01}(\Phi^\dagger \Phi)S_1^2 + \lambda_{02}(\Phi^\dagger \Phi)S_2^2 + \lambda_{12}S_1^2S_2^2. \quad (2.3)$$

The scalar doublet Φ develops a vacuum expectation value (vev) v_0 breaking the $SU(2)_L \times U(1)_Y$ spontaneously. Denoting the vev of S_1 by v_1 , the two fields can be written in unitary gauge after symmetry breaking in the form

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 + h_0 \end{pmatrix}; \quad S_1 = v_1 + h_1, \quad (2.4)$$

where both v_0 and v_1 are real and positive and h_0 and h_1 are excitations around the respective vevs. The Domain Wall problem [38] can be evaded by explicitly breaking the Z_2 symmetry corresponding to S_1 by introducing in the Lagrangian a term linear in S_1 [31]. Assuming the corresponding coupling with cubic mass dimension to be Planck mass suppressed, we have not explicitly shown such a term in eq. (2.3) as it becomes important only at energies close to the Planck scale. Extremization of the potential gives the following relations between the different parameters:

$$m_0^2 = \frac{\lambda_0 v_0^2}{2} + 2\lambda_{01}v_1^2; \quad m_1^2 = \lambda_1 v_1^2 + \lambda_{01}v_0^2. \quad (2.5)$$

After symmetry breaking, the mass matrix for the scalar sector can be written as

$$\mathcal{M}_s = \begin{pmatrix} h_0 & h_1 \end{pmatrix} \begin{pmatrix} \frac{\lambda_0 v_0^2}{4} & \lambda_{01}v_0v_1 \\ \lambda_{01}v_0v_1 & \lambda_1 v_1^2 \end{pmatrix} \begin{pmatrix} h_0 \\ h_1 \end{pmatrix} + \frac{1}{2}(m_2^2 + \lambda_{02}v_0^2 + 2\lambda_{12}v_1^2)S_2^2. \quad (2.6)$$

The off-diagonal terms indicate mixing — the mass matrix can be diagonalized by a unitary rotation in the usual manner and the mass eigenstates can be written as

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_0 \\ h_1 \end{pmatrix}, \quad (2.7)$$

where h and H are the two mass eigenstates and the mixing angle α is given by

$$\tan 2\alpha = \frac{2\lambda_{01}v_0v_1}{\frac{\lambda_0 v_0^2}{4} - \lambda_1 v_1^2}. \quad (2.8)$$

While one could directly write down the mass eigenvalues $m_{h,H}$ from eq. (2.6), for our purposes it is more useful to use these as inputs so we can use them to re-express other Lagrangian parameters. In particular, the quartic self-couplings λ_0 and λ_1 can be written as

$$\begin{aligned}\lambda_0 &= \frac{2}{v_0^2} \left(\frac{m_h^2 + m_H^2}{2} + \sqrt{\frac{(m_h^2 - m_H^2)^2}{4} - 4\lambda_{01}^2 v_0^2 v_1^2} \right), \\ \lambda_1 &= \frac{1}{2v_1^2} \left(\frac{m_h^2 + m_H^2}{2} - \sqrt{\frac{(m_h^2 - m_H^2)^2}{4} - 4\lambda_{01}^2 v_0^2 v_1^2} \right).\end{aligned}\tag{2.9}$$

We will use these formulas extensively while analyzing the parameter space of this model in what follows. Finally, rewriting the Lagrangian in the mass basis, we can collect the cubic and quartic interaction terms of the scalars:

$$\begin{aligned}V_{\text{cubic}} &= \lambda_{HHH}H^3 + \lambda_{hhh}h^3 + \lambda_{HHh}H^2h + \lambda_{Hhh}Hh^2 + \lambda_{HS_2S_2}HS_2^2 + \lambda_{hS_2S_2}hS_2^2, \\ V_{\text{quartic}} &= \lambda_{HHHH}H^4 + \lambda_{hhhh}h^4 + \lambda_{S_2S_2S_2S_2}S_2^4 + \lambda_{HHhh}H^2h^2 + \lambda_{HH S_2S_2}H^2S_2^2 \\ &\quad + \lambda_{hh S_2S_2}h^2S_2^2 + \lambda_{HHHh}H^3h + \lambda_{Hhhh}Hh^3 + \lambda_{Hh S_2S_2}HhS_2^2.\end{aligned}\tag{2.10}$$

The explicit form of the various couplings in the expressions above are given in detail in tables 2, 3 of appendix A.

3 Constraints on the two-singlet model

In this section, we will impose all theoretical and experimental constraints upon the parameter space of the model to figure out the surviving areas. Before we begin, we note that we will need to fix the values of certain parameters from either experimental observations or from phenomenological requirements: specifically, we fix $v_0 = 246$ GeV, the scale of Electroweak Symmetry Breaking (EWSB) and one of the two Higgses in the model to be the observed 126 GeV Higgs boson. We do the analysis for two choices: fixing the lighter of the two to be the SM Higgs and choosing the other to have a mass $m_H = 250$ GeV, and choosing the heavier one to be the SM Higgs fixing the lighter Higgs at $m_h = 80$ GeV. For both these cases, we will analyze and scan the parameter space of the couplings (λ_{01} , λ_{02} , λ_{12}) and put bounds on their values from various constraints. λ_{01} and λ_{02} are the Higgs portal couplings while the λ_{12} represents the DM interaction with the other scalar S_1 . While it would certainly be more useful to directly constrain the physical couplings as given in appendix A, as can be seen from that table, the expressions can be rather unwieldy and hence in this paper we restrict ourselves to analyzing the Lagrangian parameters instead. We begin with the vacuum stability conditions.

3.1 Vacuum stability

Calculating the vacuum stability conditions analytically for any model is in general quite involved. However, in lieu of doing a detailed analysis [29, 39], we use a graphical analysis to get an idea of the upper bound on λ_{01} . An important criteria for SSB is the ‘wrong’ sign of the mass term: there has to be a relative sign difference between the mass term and

Figure 1. Bound on λ_{01} (top left) due to positivity constraints on λ_0 for various values of v_1 : 1 TeV (solid), 0.5 TeV (dashed) and 0.3 TeV (dotted) and that on λ_1 (top right) for the $m_H = 125$ GeV case for the same set of v_1 values (colors online). The bottom panel shows the bounds on these parameters for the $m_h = 125$ GeV case. Note that these are *not* contour plots — only those points displayed on each curve is allowed and the rest of the parameter space is unphysical.

the term containing the fourth power of the scalar field in the Lagrangian. Thus ensuring that both Φ and S_1 engineer the breaking of $SU(2) \times U(1)$ down to $U(1)_{\text{em}}$ demands that the parameters λ_0 and λ_1 be real and positive. With the chosen benchmark values of m_h , m_H , and v_0 , and using eqs. (2.9), we display the extent of λ_{01} values consistent with the positivity condition of λ_0 and λ_1 for various values of v_1 in figure 1. To understand the nature of these plots, we first note from eqs. (2.9) that in the limit $\lambda_{01} \rightarrow 0$, $\lambda_0 \approx 2m_h^2/v_0^2$ and $\lambda_1 \approx m_H^2/2v_1^2$. For the chosen benchmark points, we expect λ_1 to be more constrained than λ_0 for a given λ_{01} , particularly for larger v_1 values. Looking at the $\lambda_0 - \lambda_{01}$ parameter space for instance, we see that for $v_1 = 1$ TeV, for a λ_{01} value of around ~ 0.008 for the $m_H = 125$ GeV case λ_0 can reach a value of around 0.4, while the upper limit on λ_1 for the same λ_{01} is around 0.004. This trend is consistent with the $m_h = 125$ GeV case as well as can be readily seen in figure 1. In fact, turning this argument around, we see that the parameter λ_{01} is itself highly constrained even from this simple analysis — if one forces the value of λ_{01} higher, the couplings λ_0 (or λ_1) quickly become imaginary thus affecting the symmetry breaking structure of the model. For the purposes of our analysis, conclusions drawn on λ_{01} are highly relevant as this higgs portal coupling (see eq. (2.3)) will play a

crucial role in dark matter phenomenology. We note, however, that the couplings λ_{02} and λ_{12} are unaffected by this analysis as S_2 does not mix with the other scalars in the model.¹

3.2 Collider constraints

A major collider constraint on Higgs-portal dark matter sector comes from the Branching Ratio (BR) of the Higgs invisible decays:

$$\text{BR}_{h \rightarrow \text{inv}} = \frac{\Gamma_{h \rightarrow \text{inv}}}{\Gamma_{h \rightarrow \text{SM}} + \Gamma_{h \rightarrow \text{inv}}}.$$

Given the presence of extra scalars that couple to the SM Higgs, this constraint becomes an important one for the present model. ATLAS [40] and CMS [41] have provided experimental limits on the branching ratio of invisible Higgs decays — the bound from ATLAS is the strongest till date with an observed value of around 11%. To translate this bound to the present model, we need to first fix the masses. In anticipation of future results (laid out in sections 4.2 and 4.3), we choose $m_{S_2} = 40 \text{ GeV}$. In the $m_H = 125 \text{ GeV}$ case with both h and S_2 lighter, both decays $H \rightarrow hh$ and $H \rightarrow S_2 S_2$ need to be considered — however, for the chosen benchmark point ($m_h = 80 \text{ GeV}$), the only tree-level decay that is relevant is the latter. For the other case ($m_h = 125 \text{ GeV}$), only the decay $h \rightarrow S_2 S_2$ is relevant as we have chosen the mass of the H to be higher than that of the h . Thus, the relevant couplings in these two cases are $\lambda_{HS_2 S_2}$ and $\lambda_{hS_2 S_2}$. Referring to appendix A, we see that these couplings involve the four parameters² λ_{02} , λ_{12} , the mixing angle α , and v_1 . Of these, with the use of eqs. (2.8) and (2.9), the parameter α can be traded for the masses, λ_{01} , and v_1 . We choose the lowest admissible value of λ_{01} (0.008 for the $m_H = 125 \text{ GeV}$ case and 0.04 for the $m_h = 125 \text{ GeV}$ case) from figure 1. While other values of λ_{01} could certainly be considered, the numerical difference in this coupling (as seen from figure 1) is not very large, and the chosen λ_{01} value is consistent for all three choices of v_1 that we consider here.

In figure 2, we illustrate the invisible decay constraints in this model by displaying contours of 11% BR³ in the $\lambda_{02} - \lambda_{12}$ parameter space for three different values of v_1 for both the $m_H = 125 \text{ GeV}$ (left) and $m_h = 125 \text{ GeV}$ (right) cases. In the former case, it is seen that lowering the scale v_1 increases the range of allowed values of λ_{12} while in the latter it has the opposite effect — in this case it is seen that lowering v_1 shifts the allowed band toward a more restricted range for λ_{12} . In general, we see that the $m_H = 125 \text{ GeV}$ case prefers larger λ_{12} and slightly smaller λ_{02} values compared to the $m_h = 125 \text{ GeV}$ case. We see from the nature of the couplings (see appendix A)

$$\begin{aligned}\lambda_{HS_2 S_2} &= \lambda_{02} v_0 \cos \alpha + 2\lambda_{12} v_1 \sin \alpha \\ \lambda_{hS_2 S_2} &= -\lambda_{02} v_0 \sin \alpha + 2\lambda_{12} v_1 \cos \alpha\end{aligned}\tag{3.1}$$

that for a given α , the relative importance of the λ_{02} and λ_{12} pieces will be different in the two cases.

¹Note that we have considered λ_0 values > 1 in the $m_h = 125 \text{ GeV}$ case — however this is only a Lagrangian parameter and *not* a physical coupling.

²The couplings also involve v_0 which is fixed at 246 GeV .

³To calculate these BRs, we considered the dominant decays of the higgs: $b\bar{b}$, $\tau\bar{\tau}$, and $S_2 S_2$, and neglected off-shell decays like WW and ZZ .

Figure 2. Contours of $\text{BR}=11\%$ for $v_1 = 1$ TeV (solid), 0.5 TeV (dashed) and 0.3 TeV (dotted) for the $m_H = 125$ GeV case (left) and the $m_h = 125$ GeV case (right) (colors online). The allowed region for the $m_h = 125$ GeV case on the right is the band between the corresponding lines.

A couple of general features arise from these two constraints put together:

- In spite of being a rather minimal extension of the SM, this model has quite a few independent parameters. We observe that while lowering v_1 shifts the allowed regions in the parameter space, the numerical values of the couplings do not change significantly for the different choices of v_1 employed. Thus, we will fix $v_1 = 1$ TeV henceforth.
- Fixing $\lambda_{01} = 0.008$ (0.04) for $m_H = 80$ GeV (250 GeV) and looking at the $\lambda_{02} - \lambda_{12}$ parameter space, we conclude that all these couplings are roughly constrained to lie in the numerical range $10^{-3} - 10^{-2}$.

3.3 LHC Higgs searches

After the discovery of the SM-like Higgs, the LHC experiments have continued to look for heavier scalars in a variety of final states. Non-observation of such particles constrains the parameter space of theoretical models that admit such states in their spectrum, and thus we need to understand how this affects the present model. For the first benchmark point ($m_h = 80$ GeV, $m_H = 125$ GeV), there are not many direct searches that impact the model. However, for the second choice ($m_h = 125$ GeV, $m_H = 250$ GeV), searches for a heavy scalar in the channel $gg \rightarrow H \rightarrow WW/ZZ$ provide useful constraints, with the gauge bosons further decaying to various hadronic and leptonic states whose combined effect [42, 43] has been taken into account. In translating this bound, we should also account for the fact that the HWW coupling (mentioned in table 5) is scaled by a factor of $\cos \alpha$ relative to the SM Higgs coupling — however, like in the previous section we trade the parameter α for λ_{01} and v_1 , choosing $\lambda_{01} = 0.04$ as before. In figure 3, we present the direct bounds from the LHC searches in the $\lambda_{02} - \lambda_{12}$ parameter space from both the 8 TeV and the 13 TeV data. Understandably, the 13 TeV bounds are tighter — however, we note

Figure 3. Allowed regions in the $\lambda_{02} - \lambda_{12}$ parameter space from searches for the heavy scalar H at the LHC in the diboson channel $gg \rightarrow H \rightarrow WW/ZZ$ with the gauge bosons decaying either leptonically or hadronically (left) and a magnified view of the 13 TeV constraints (right).

that the Higgs invisible decay limits (figure 2) constrain this parameter space much more than the results of the direct search experiments.

4 Dark matter phenomenology in the two-singlet model

The two-singlet extension of the scalar sector of the SM has been studied in the literature from the dark matter point of view for different symmetry breaking patterns of the discrete $Z_2 \times Z'_2$. Our work complements these and aims to address the results of the latest experimental efforts. The direct detection constraints being comparatively less restrictive for lighter (< 10 GeV) dark matter masses can give rise to very exciting phenomenology [44]. Investigations [25, 26, 30] have been carried out in good detail to restrict this model with various constraints from collider and direct searches — however some of these bounds are presently outdated. The two-singlet extension scenarios have also been explored in some other contexts such as the exchange-driven freeze out mechanism [45], dwarf galaxy density profiles [31], MeV scale SIMP dark matter with a $3 \rightarrow 2$ process dictating the relic [46], and mitigating direct detection bounds under a mix of annihilation and co-annihilation of multicomponent dark matter [47]. In this work, we update the exclusion limits from the latest collider and direct search results with a focus on relaxing the direct detection constraints taking advantage of the destructive interference between the two higgs exchange diagrams and its implications for possible future results. In addition, we also address the gamma-ray excess observation from the galactic center [32–36] and Fermi bubble — while this been explored in the light of a multicomponent dark matter scenario (see for example [29]), we demonstrate here that two-singlet extension models can also account for this excess reasonably well taking advantage of the Breit-Wigner resonance.

4.1 Direct detection

The direct detection experiments probe the cross-section for the scattering of the DM particle off a nucleon at non-relativistic limits. The effective lagrangian for nucleon-dark matter interaction is given by

$$L_{\text{eff}} = a_N N \bar{N} S_2^2, \quad (4.1)$$

where a_N is the effective coupling constant between the DM and the nucleon. The spin-independent scattering cross-section for the scattering of the DM off a proton or neutron goes as $\sigma_{p,n}^{\text{SI}} \sim \mu^2 f_{p,n}^2$ [48], where μ is the reduced mass and $f_{p,n}$ is the hadronic matrix element:

$$f_{p,n} = \sum_{q=u,d,s} f_{Tq}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q},$$

where a_q is the (model-dependent) coupling between the DM and quarks and the quantities $f_{Tq}^{(p,n)}$ and $f_{TG}^{(p,n)}$ [49] are defined as

$$f_{Tq}^p m_p \langle p|p \rangle \equiv \langle p|m_q \bar{q}q|p \rangle; \quad f_{TG}^{(p,n)} = 1 - \sum_{q=u,d,s} f_{Tq}^{(p,n)}, \quad (4.2)$$

and similarly for neutrons. The numerical values of the matrix elements are [48]:

$$\begin{aligned} f_{Tu}^{(p)} &= 0.020 \pm 0.004, & f_{Td}^{(p)} &= 0.026 \pm 0.005, & f_{Ts}^{(p)} &= 0.118 \pm 0.062, \\ f_{Tu}^{(n)} &= 0.014 \pm 0.003, & f_{Td}^{(n)} &= 0.036 \pm 0.008, & f_{Ts}^{(n)} &= 0.118 \pm 0.062. \end{aligned}$$

In this model, the elastic scattering of the DM candidate S_2 with a nucleon happens via two t -channel diagrams with h and H as propagators. The resulting spin independent scattering cross-section with the assumption of the quark contribution being approximately equal for both the nucleons (i.e., $f_{Tq}^{(n)} \approx f_{Tq}^{(p)} = f_{Tq}^N$) can be written as

$$\begin{aligned} \sigma_N^{\text{SI}} = \frac{\mu^2}{4\pi m_{S_2}^2} & \left[\frac{\lambda_{HS_2S_2}}{m_H^2} \left(\sum_{q=u,d,s} \frac{m_q}{v_0} \cos \alpha \frac{m_N}{m_q} f_{Tq}^N + \frac{2}{27} f_{TG}^N \sum_{q=c,b,t} \frac{m_q}{v_0} \cos \alpha \frac{m_N}{m_q} \right) \right. \\ & \left. - \frac{\lambda_{hS_2S_2}}{m_h^2} \left(\sum_{q=u,d,s} \frac{m_q}{v_0} \sin \alpha \frac{m_N}{m_q} f_{Tq}^N + \frac{2}{27} f_{TG}^N \sum_{q=c,b,t} \frac{m_q}{v_0} \sin \alpha \frac{m_N}{m_q} \right) \right]^2, \quad (4.3) \end{aligned}$$

where the reduced mass $\mu = \frac{m_N m_{S_2}}{m_N + m_{S_2}}$. This formula is an extension of the expression corresponding to the singlet scalar dark matter case [20]. The relative negative sign between the h and H contribution arises because of the nature of their Yukawa couplings (see table 4). Given the presence of the two different channels, we can accommodate the direct detection constraints by appealing to a destructive interference between these two channels (see also ref. [50]).

The present limit from the Xenon1T result restricts a DM particle of mass 40 GeV (30 GeV) to have a spin independent cross-section lower than $\sim 4.5 \times 10^{-47} \text{ cm}^2$ ($\sim 4.1 \times 10^{-47} \text{ cm}^2$) [51]. Thus, direct detection bounds put very stringent constraints on λ_{02} and λ_{12} (since the hS_2S_2 and HS_2S_2 couplings depend directly on these two parameters). However,

Figure 4. The surviving $\lambda_{02} - \lambda_{12}$ parameter space with the twin constraints coming from direct detection (solid lines) and the invisible BR of the higgs (dashed line) imposed for $v_1 = 1$ TeV (green regions) and $v_1 = 0.5$ TeV (grey). We have set $\lambda_{01} = 0.008$ (0.04) for the $m_H = 125$ GeV ($m_h = 125$ GeV) case.

λ_{01} is not bounded by direct detection directly since the dependence on λ_{01} comes only through α . In figure 4, we have combined the bounds on the parameter space of λ_{02} and λ_{12} from the BR of invisible higgs decay and the direct detection limits together for a 40 GeV S_2 ,⁴ for two different choices of v_1 and for the lowest permissible λ_{01} for the two cases $m_h = 125$ GeV and $m_H = 125$ GeV. In the plots, the solid lines show the allowed range of λ_{02} and λ_{12} while taking into account the constraint on σ^{SI} and the dashed lines, on the other hand shows the bound on both the couplings complying with the constraint on the BR of invisible higgs decay (as given in figure 2). The shaded region in the intersection of these two constraints is the allowed parameter space in this model — specifically, it can be seen that λ_{12} (λ_{02}) up to 1.1×10^{-3} (4.5×10^{-3}) can be probed for the $m_H = 125$ GeV case for $v_1 = 1$ TeV.

In table 1, we indicate a couple of representative benchmark values that can be derived from figure 4 for $m_{S_2} = 40$ GeV. As expected,⁵ benchmark points near the edge (of the solid lines) of the contour (BP-1 & BP-3) provide relatively higher values of σ_N^{SI} and benchmark points from a more central region (i.e., equidistant points from the two straight lines of the contour like in BP-2 & BP-4) can significantly lower the cross-section as evidenced in table 1. We will use these benchmark points for further analysis in the subsequent sections.

In figure 5 below, we have shown, for the two sets of benchmark points from table 1, the variation of the spin-independent cross-section with the DM mass⁶ — overlaid on the

⁴Note that in the one-singlet extension of the SM, a dark matter mass below $\simeq 60$ GeV is not feasible [18] — the choice here is deliberately one in this window to emphasize the difference in this model.

⁵In figure 4, the two solid lines represent the upper bound of σ_N^{SI} and the regions toward the center of the shaded portions accommodate lower values of σ_N^{SI} .

⁶Note that the cross-section values quoted in table 1 are for $m_{S_2} = 40$ GeV, while in figure 5, we choose the same benchmark points as far as the couplings are considered and vary the DM mass.

	Masses (GeV)	v_1 (GeV)	λ_{01}	λ_{02}	λ_{12}	$\sigma_N^{\text{SI}}(\text{cm}^2)$
BP-1	$m_h = 80, m_H = 125$	1000	0.008	0.002	0.0010	3.86×10^{-47}
BP-2	$m_h = 80, m_H = 125$	1000	0.008	0.002	0.0005	2.61×10^{-49}
BP-3	$m_h = 125, m_H = 250$	1000	0.04	0.010	0.001	1.98×10^{-47}
BP-4	$m_h = 125, m_H = 250$	1000	0.04	0.005	0.0006	2.35×10^{-48}

Table 1. Representative benchmark points shown along with the corresponding spin independent cross-section values they admit for a dark matter mass of 40 GeV. It is seen that this model offers scope to admit values allowed by the latest Xenon-1T data.

Figure 5. Variation of $\sigma_N^{\text{SI}}(\text{cm}^2)$ with $m_{S_2}(\text{GeV})$ for the benchmark points in table 1 — overlaid on the plots are the constraints from the Xenon-1T and LUX results.

plot are the exclusion limits of Xenon1T [51] and LUX [52]. It can be seen that while BP2 and BP4 can conveniently evade the bound for a wide range of DM masses, BP1 and BP3 cannot do so for lighter S_2 — this is so because as these values of couplings aid higher cross-sections, m_{S_2} has to be correspondingly a little higher to bring down the value as $\sigma_N^{\text{SI}} \propto m_{S_2}^{-2}$ (see eq. (4.3)).

4.2 Relic abundance

In the early universe, temperature was very high and all the particles including the DM were in thermal equilibrium in the cosmic soup. But as the universe cooled down due to expansion and the interaction rate went below the Hubble expansion rate, the annihilation rate of the DM dropped and thus the number density of the DM froze to a constant. This remaining *relic abundance* — now measured to be $\Omega h^2 = 0.120 \pm 0.001$ [1] — is given by the expression [53]

$$\Omega h^2 = 1.07 \times 10^9 \frac{x_f}{\sqrt{g^*} m_{\text{pl}} \langle \sigma v \rangle}, \quad (4.4)$$

Figure 6. Plot of $w(s)$ vs. m_{S_2} showing the contribution of $b\bar{b}$ and $\tau\bar{\tau}$ channels for the benchmark points in table 1. The two resonances correspond to $m_h = 80$ GeV and $m_H = 125$ GeV (left) and $m_h = 125$ GeV and $m_H = 250$ GeV (right).

where $x_f = \frac{m_{S_2}}{T}$, m_{Pl} is the Planck mass, and g^* is the effective degrees of freedom. The velocity averaged cross section $\langle\sigma v\rangle$ up to second order is given by [54]

$$\begin{aligned} \langle\sigma v\rangle = & \frac{1}{m_{S_2}^2} \left[w(s) - \frac{3}{2} \left(2w(s) - 4m_{S_2}^2 w'(s) \right) \frac{1}{x_f} \right. \\ & \left. + \frac{3}{8} \left(16w(s) - 32m_{S_2}^2 w'(s) + 5(4m_{S_2}^2)^2 w''(s) \right) \frac{1}{x_f^2} \right] \Big|_{s=(2m_{S_2})^2}, \end{aligned} \quad (4.5)$$

with $w'(s) = \frac{dw(s)}{ds}$ and [54, 55]

$$w(s) = \frac{1}{32\pi} \sqrt{\frac{s - 4m_{S_2}^2}{s}} \int \frac{d(\cos\phi)}{2} \sum_{\text{all channels}} |\mathcal{M}|^2, \quad (4.6)$$

where s is the center of mass energy.

In this model, the DM annihilates to SM particles only through scalar portal interactions. The relevant channels to consider here are s -channel diagrams with h and H as propagators and $b\bar{b}$, $\tau\bar{\tau}$, W^+W^- , ZZ , hH , hh and HH as final states. However, given the DM mass we consider here (40 GeV), the gauge and higgs channels will all be highly off-shell and thus the dominant contributions to the annihilation cross section will arise from the $b\bar{b}$ and $\tau\bar{\tau}$ channels. In figure 6, we have display $w(s)$ as a function of DM mass depicting the contribution of $b\bar{b}$ (solid line) and $\tau\bar{\tau}$ (dashed line) channels in the annihilation cross section for two of the representative benchmark points listed in table 1⁷ — the plot clearly shows the effect of the resonances at $m_h/2$ and $m_H/2$. We observe that away from resonance, the $b\bar{b}$ channel dominates the $\tau\bar{\tau}$ for much of the parameter space.

In figure 7, we display the relic abundance as a function of the dark matter mass for the set of four benchmark points listed in table 1. Due to the Breit-Wigner resonance, an enhancement in the velocity averaged cross section of DM-DM annihilation [56, 57] is obtained in certain regions of dark matter mass. Thus, the measured relic abundance can

⁷The other two benchmark points also show similar behavior and hence are not displayed here.

Figure 7. Plot of relic abundance as a function of the DM mass for the benchmark points listed in table 1. The horizontal dotted line shows the measured value of $\Omega h^2 = 0.120 \pm 0.001$.

be realized at only the narrow mass regions where the dark matter mass is around half of the mass of either Higgses h and H . This is a general feature of such scalar extension Higgs-portal dark matter models — given the low couplings, one has to resort to a Breit-Wigner enhancement to reproduce the correct relic abundance and hence there is a certain amount of fine-tuning that is necessarily introduced in the model.

Having consistently explained the dark matter phenomenology in the model consistent with the latest bounds, we now move on to the observed gamma ray excess observed in the Fermi-LAT data and check to see if this simple DM model can account for it.

4.3 Explaining gamma-ray excess in two-singlet model

The observed gamma-ray excess found in the Fermi-LAT data points toward a spatially extended excess of 1 – 3 GeV gamma rays [32–36] from the regions surrounding the galactic center, the morphology and spectrum of which is best fitted with that predicted from the annihilations of a 36 – 51 GeV WIMP into $b\bar{b}$ with an annihilation cross section of $\sigma v = (1 - 3) \times 10^{-26} \text{cm}^3 \text{sec}^{-1}$ [58] (normalized to a local dark matter density of 0.4 GeVcm^{-3}). The desired value of the cross-section is accidentally close to the one required to obtain correct relic abundance. Earlier studies showed that in the simplest one real singlet extension of the SM with a DM mass in this window fails to explain the gamma-ray excess [59] as the annihilation cross-section could not be sufficiently enhanced to the desired value. However, in the two singlet extension model again with the aid of the Breit-Wigner enhancement, the required cross section can be enhanced enough to accommodate the gamma ray excess data as shown in figure 8 (where we have chosen $m_h = 80 \text{ GeV}$). Given the minimal particle spectrum addition, the two singlet model can thus be regarded as the simplest possible extension of the SM to explain both the dark matter and the gamma ray observation consistently.

While the specific mass point $m_{S_2} = 40 \text{ GeV}$ certainly works, it is nevertheless interesting to ask if the entire predicted WIMP range of 36 – 51 GeV can still accommodate the gamma-ray excess in this model while still complying with all the other constraints put in thus far. Since we will be scanning a slightly wide mass region, constraints from figure 1

Figure 8. Enhancement in the $\langle\sigma v\rangle_{b\bar{b}}$ values around resonance, shown here as a function of the dark matter mass.

also have to be modified accordingly — specifically, a lowering of the λ_{01} value is necessary to keep the analysis consistent with the vacuum stability bounds across the mass region of interest while also being consistent with $BR_{h \rightarrow \text{inv}}$ and the Xenon1T bounds. In this respect, we find the value $\lambda_{01} = 0.004$ to be consistent with all the given constraints. In figure 9, we show the allowed region in the $m_{S_2} - m_h$ plane that can explain the gamma ray excess observations⁸ while respecting all the other bounds. The nature of the plot in figure 9 can be understood by appealing to figure 8 — note that there are two sets of mass points that can each accommodate the lower or the higher σv in the range. Specifically, $m_{S_2} \simeq 38.6$ and 41.3 GeV correspond to $\sigma v = 1 \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1}$ and $m_{S_2} \simeq 38.9$ and 41 GeV correspond to $\sigma v = 3 \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1}$. This same feature carries over in figure 9 — the borders of each thick colored line represents the two ends of the range in $\sigma v = (1 - 3) \times 10^{-26} \text{ cm}^3 \text{ sec}^{-1}$, and the upper and lower colored lines indicate that these ranges can correspond to two different masses. The regions shaded in blue and orange can accommodate the Gamma ray excess while still conforming to all the other constraints. The reliance on the Breit-Wigner resonance thus limits the parameter space to one in which the two masses are highly correlated. Also, since we want an enhancement in the low mass region, the possibility that the lighter of the two Higgses is the observed 125 GeV Higgs cannot be considered and we are forced to choose the $m_h = 80$ GeV scenario.

5 Conclusion

In this work, we studied a simple scalar extension of the SM with two real singlets S_1 and S_2 with a $Z_2 \times Z_2'$ symmetry. While the Z_2 is broken, the other discrete Z_2' remains unbroken enabling the scalar S_2 to be a potential dark matter candidate. The interaction strength of the singlet scalars with the SM sector is dictated via a Higgs portal term in the Lagrangian of the form $\lambda_{0i}(\Phi^\dagger \Phi)S_i^2$. The model has the advantage that with a minimal addition to the SM particle spectrum, it provides a dark matter candidate consistent with the latest experimental bounds while also simultaneously accommodating the observed gamma ray excess.

⁸While we have continued to use the terms BP1 and BP2 in figure 9, we remind that reader that this is the same set of values as in table 1 with the one exception of a slightly smaller value of λ_{01} .

Figure 9. The region allowed by the gamma ray excess observation in mass space for $\lambda_{01} = 0.004$ and $v_1, \lambda_{02}, \lambda_{12}$ from table 1 — the surviving regions is shown in the shaded blue and orange lines for the benchmark points BP1 and BP2.

After putting in the vacuum stability constraints on the Higgs potential, we find that the coupling λ_{01} is constrained to lie in the $10^{-1} - 10^{-2}$ range (depending on whether the light or the heavier Higgs is associated with the 125 GeV Higgs). While λ_{02} is unconstrained by vacuum stability considerations as it does not mix with the other CP-even scalars, direct bounds from the Higgs invisible branching ratios forces $\lambda_{02} \approx 10^{-2} - 10^{-3}$ thus severely restricting the couplings of the singlets to the SM sector. Interestingly, even though the direct detection exclusion limits coming from experiments like Xenon1T shrink the coupling parameter space appreciably, the model still has potential discoverable regions. Typically, a model can be ruled out if the upper limit on the couplings imposed by the direct detection experiments are insufficient to generate the required relic density values. However, in the two singlet model, the direct detection constraint is relaxed to a great extent by the destructive interference between the two t -channel h and H propagators while the Breit-Wigner resonance helps to get the correct relic abundance. In addition, we have also demonstrated that the two singlet model can also account for the gamma-ray excess for an S_2 in the range 36 – 51 GeV — however it has to be noted that this explanation imposes the restriction that we cannot consider the possibility of the observed 125 GeV Higgs to be the lighter of the two CP-even eigenstates and are forced to choose $m_h = 80$ GeV and $m_H = 125$ GeV.

The two singlet extension thus remains an attractive possibility from a dark matter perspective. Future limits from the Higgs invisible branching ratio estimates and the Xenon-1T experiment would undoubtedly constrain the parameter space further. The model is also interesting from a collider physics angle. While the restriction of the coupling strength of the extra scalars to the SM fermions would make direct collider searches of these scalars at the LHC difficult, it nevertheless is interesting to ask if one could uncover these Higgs portal signatures by appealing to unique multi-Higgs final states that have a relatively low SM background — these remain interesting avenues to explore.

A Relevant Couplings

In this appendix, we list all the relevant couplings of the extra scalars in tables 2 to 5, that have been used in this study.

λ_{abc}	Couplings in terms of Lagrangian parameters
HHH	$\frac{\lambda_0 v_0}{4} \cos^3 \alpha + \lambda_1 v_1 \sin^3 \alpha + \lambda_{01} v_0 \cos \alpha \sin^2 \alpha + \lambda_{01} v_1 \sin \alpha \cos^2 \alpha$
hhh	$-\frac{\lambda_0 v_0}{4} \sin^3 \alpha + \lambda_1 v_1 \cos^3 \alpha - \lambda_{01} v_0 \sin \alpha \cos^2 \alpha + \lambda_{01} v_1 \cos \alpha \sin^2 \alpha$
HHh	$-\frac{3\lambda_0 v_0}{4} \cos^2 \alpha \sin \alpha + 3\lambda_1 v_1 \sin^2 \alpha \cos \alpha$ $+ \lambda_{01} v_0 (2 \sin \alpha \cos^2 \alpha - \sin^3 \alpha) + \lambda_{01} v_1 (\cos^3 \alpha - 2 \sin^2 \alpha \cos \alpha)$
Hhh	$\frac{3\lambda_0 v_0}{4} \cos \alpha \sin^2 \alpha + 3\lambda_1 v_1 \sin \alpha \cos^2 \alpha$ $+ \lambda_{01} v_0 (\cos^3 \alpha - 2 \sin^2 \alpha \cos \alpha) + \lambda_{01} v_1 (\sin^3 \alpha - 2 \sin \alpha \cos^2 \alpha)$
HS_2S_2	$\lambda_{02} v_0 \cos \alpha + 2\lambda_{12} v_1 \sin \alpha$
hS_2S_2	$-\lambda_{02} v_0 \sin \alpha + 2\lambda_{12} v_1 \cos \alpha$

Table 2. The cubic couplings of the various Higgs bosons in the two singlet model.

λ_{abcd}	Couplings in terms of Lagrangian parameters
$HHHH$	$\frac{\lambda_0}{16} \cos^4 \alpha + \frac{\lambda_1}{4} \sin^4 \alpha + \frac{\lambda_{01}}{2} \cos^2 \alpha \sin^2 \alpha$
$hhhh$	$\frac{\lambda_0}{16} \sin^4 \alpha + \frac{\lambda_1}{4} \cos^4 \alpha + \frac{\lambda_{01}}{2} \cos^2 \alpha \sin^2 \alpha$
$S_2S_2S_2S_2$	$\frac{\lambda_2}{4}$
$HHhh$	$\frac{3\lambda_0}{8} \sin^2 \alpha \cos^2 \alpha + \frac{3\lambda_1}{2} \sin^2 \alpha \cos^2 \alpha + \frac{\lambda_{01}}{2} (\cos^4 \alpha + \sin^4 \alpha - 4 \sin^2 \alpha \cos^2 \alpha)$
HHS_2S_2	$\frac{\lambda_{02}}{2} \cos^2 \alpha + \lambda_{12} \sin^2 \alpha$
hhS_2S_2	$\frac{\lambda_{02}}{2} \sin^2 \alpha + \lambda_{12} \cos^2 \alpha$
$HHHh$	$-\frac{\lambda_0}{4} \sin \alpha \cos^3 \alpha + \lambda_1 \sin^3 \alpha \cos \alpha + \lambda_{01} (\sin \alpha \cos^3 \alpha - \sin^3 \alpha \cos \alpha)$
$Hhhh$	$-\frac{\lambda_0}{4} \sin^3 \alpha \cos \alpha + \lambda_1 \sin \alpha \cos^3 \alpha + \lambda_{01} (\sin^3 \alpha \cos \alpha - \sin \alpha \cos^3 \alpha)$
HhS_2S_2	$-\lambda_{02} \sin \alpha \cos \alpha + 2\lambda_{12} \sin \alpha \cos \alpha$

Table 3. The quartic scalar couplings of the various Higgs bosons in the two singlet model.

λ_{abc}	Couplings
$Hb\bar{b}$	$\frac{-em_b}{2 \sin \theta_\omega m_W} \cos \alpha$
$hb\bar{b}$	$\frac{em_b}{2 \sin \theta_\omega m_W} \sin \alpha$
$H\tau\bar{\tau}$	$\frac{-em_\tau}{2 \sin \theta_\omega m_W} \cos \alpha$
$h\tau\bar{\tau}$	$\frac{em_\tau}{2 \sin \theta_\omega m_W} \sin \alpha$

Table 4. The relevant Yukawa couplings of the h and H with the SM fermions.

λ_{abc}	Couplings
HWW	$\frac{em_W \cos \alpha}{\sin \theta_w}$
hWW	$-\frac{em_W \sin \alpha}{\sin \theta_w}$
HZZ	$\frac{em_Z \cos \alpha}{2 \sin \theta_w \cos \theta_w}$
hZZ	$-\frac{em_Z \sin \alpha}{2 \sin \theta_w \cos \theta_w}$

Table 5. The relevant scalar-gauge boson couplings in the two singlet model.

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