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A NEW VIABLE REGION OF DARK MATTER IN A MIXED SCALAR DARK MATTER MODEL

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ABSTRACT

In this work we explore the intermediate dark matter mass regime of 400-550 GeV in a mixed scalar dark matter (DM) model. This mass region remains suppressed from dark matter relic abundance observations. In this model, the standard model (SM) is extended by a scalar singlet and an inert doublet field. The lightest neutral Higgs that comprises of the CP-even component of inert doublet and a singlet scalar is the dark matter candidate. We scan over the parameter space consistent with theoretical and latest experimental constraints, as well as dark matter relic abundance and recent searches from experiment like XENON1T. We find that correct relic abundance for the intermediate mass region $400 < M_{DM} < 550$ GeV could be revived by considering the mixed scalar dark matter model with appropriate couplings and mixings.

Keywords: Dark matter, beyond standard model, XENON1T, Inert doublet, relic density

INTRODUCTION

The fact that dark matter (DM) is present in the Universe has been established for many decades from astrophysical and cosmological observations. Some earlier evidences of DM include the galaxy cluster observations by Fritz Zwicky [1] in 1933, observations of the galaxy

rotation curves in 1970's [2] and the observation of the bullet cluster [3]. The latest observation from the Planck satellite [4] indicates that approximately 27% of the present Universe is composed of such non-baryonic DM, which is approximately five times more than the ordinary visible matter.

The present abundance of DM is often expressed in terms of the density parameter Ω as [4] $\Omega_{DM}h^2 = 0.1198 \pm 0.0026$, where $h = H_0/100$ is a parameter of order unity and H_0 is the Hubble parameter. However, the exact composition of DM is still unknown. Motivated by these observations there has been several proposals in last few decades to incorporate DM in models which are beyond standard model (BSM). One such most popular proposals is the so called weakly interacting massive particle (WIMP) paradigm.

The scalar singlet dark matter is one of the simplest scalar extended dark matter models. This model has been extensively studied in literature [5-9]. The scalar singlet dark matter is severely constrained, except around the mass region (with $M_{DM} \sim m_h/2$), from direct detection experiments, such as PandaX-II [10], LUX [11], and XENON1T [12], etc. Here, M_{DM} is the mass of DM candidate and m_h is the Higgs mass. Another DM model is the Inert Doublet Model (IDM) which has been studied extensively as a framework to provide a scalar doublet DM [14–17]. These works have shown that the correct relic abundance could be produced mainly in two regions - one in the lower mass region ($M_{DM} < M_W$, M_W is the W-boson mass) and the other around 550

GeV or above [18]. The low mass and intermediate mass regions are almost excluded by the collider constraints and the DM direct detection limits. These strong bounds limits the allowed DM mass in the low mass region to a funnel shaped region near Higgs resonance ($M_{DM} \sim m_h/2$). The high mass region DM masses (> 500 GeV) is allowed and is quite difficult to probe in the direct detection experiments [19]. Therefore, in this work we consider the possibility of reviving DM mass in the intermediate mass region i.e. within the mass range $M_W < M_{DM} < 550$ GeV by considering a mixed scalar dark matter model.

The paper has been organised as follows. After a brief description of the model and its parameters in section II, we discuss the results of our work in section III. Finally we conclude in section IV.

The Model

In this work we extend the inert doublet ϕ with a real singlet scalar S . Both ϕ and S are odd under a Z_2 symmetry while all the SM fields including Higgs doublet H are even. Further it is assumed that the field ϕ do not develop vacuum expectation value (vev). The combined scalar potential will be then

$$V' = \mu_H^2(H^\dagger H) + \mu_I^2(\phi^\dagger \phi) + \mu_S^2(S^\dagger S) + \lambda_1(H^\dagger H)^2 + \lambda_2(\phi^\dagger \phi)^2 + \lambda_5(S^\dagger S)^2 \lambda_3(H^\dagger H)(\phi^\dagger \phi) + \lambda_4(H^\dagger \phi)(\phi^\dagger H) + \lambda_{HS}(S^\dagger S)(H^\dagger H) + \frac{\lambda_5}{2}[H^\dagger \phi + h.c.] \lambda_{\phi S}(S^\dagger S)(\phi^\dagger \phi) + \rho[(H^\dagger \phi)S + h.c.]$$

(1)

where, μ_i , λ_j and ρ are coupling parameters. After the symmetry breaking the two scalar doublets can be written as $H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$, $\phi = \begin{pmatrix} H^\pm \\ \frac{H_0+iA_0}{\sqrt{2}} \end{pmatrix}$, where H develops a vev , $v = 246 GeV$. The mass terms for the SM

Higgs, the charged scalar H^\pm and pseudo-scalar A_0 can be obtained as

$$m_h^2 = 2\lambda_1 v^2, m_{H^\pm}^2 = \mu_I^2 + \frac{\lambda_3}{2} v^2, m_{A_0}^2 = \mu_I^2 + \lambda_L' v^2$$

(2)

where m_h is the SM Higgs boson mass, m_{H_0} , m_{A_0} and m_{H^\pm} are the masses of the CP even scalar H_0 , CP odd scalar A_0 and charged scalar H^\pm of the inert doublet respectively. After EWSB, neutral component of the inert doublet and the extra singlet mix into the scalar DM. The mixing arises from the couplings to the SM-like Higgs field. The DM-Higgs boson triple and quartic couplings in such model are controlled by the singlet-

doublet scalars mixing. Therefore, DM annihilation and spin-independent DM-nucleon scattering processes can be characterised by the mixing angle, and the thermal DM relic abundance can be achieved with an appropriate magnitude of the mixing. The term $\lambda_{\phi S}(S^\dagger S)(\phi^\dagger \phi)$ is responsible for the mixing of H_0 and S . We obtain a 2×2 mass square matrix for the lightest neutral Z_2 odd scalar as

$$M = \begin{pmatrix} \mu_I^2 + \lambda_L v^2 & \rho v \\ \rho v & 2\mu_S^2 + \lambda_{HS} v^2 \end{pmatrix}$$

(3)

Here, $\lambda_L = \frac{\lambda_3 + \lambda_4 + \lambda_5}{2}$ and $\lambda_L' = \frac{\lambda_3 + \lambda_4 - \lambda_5}{2}$. The physical mass eigenstates can be defined as

$$\chi_1 = H_0 \cos\theta + S \sin\theta, \quad \chi_2 = -H_0 \sin\theta + S \cos\theta$$

(4)

And the corresponding mass and mixing angle θ of the neutral scalars χ_1 and χ_2 are

$$m_{\chi_1}^2 = \frac{m_{H_0}^2 + m_S^2}{2} - \frac{m_{H_0}^2 - m_S^2}{2} \sqrt{1 + \tan^2 2\theta}, \quad m_{\chi_2}^2 = \frac{m_{H_0}^2 + m_S^2}{2} + \frac{m_{H_0}^2 - m_S^2}{2} \sqrt{1 + \tan^2 2\theta}$$

$$\tan(2\theta) = \frac{2m_{H_0}^2 m_S}{m_{H_0}^2 - m_S^2}$$

(5)

The couplings in terms of the masses are (we have denoted $\cos\theta$ ($\sin\theta$) as c_θ (s_θ) from now on),

$$\lambda_1 = \frac{m_h^2}{2v^2}, \lambda_3 = \frac{2(\lambda_L v^2 + m_{H^\pm}^2 - m_{\chi_1}^2 c_\theta^2 - m_{\chi_1}^2 s_\theta^2)}{v^2}, \lambda_4 = \frac{m_{\chi_1}^2 c_\theta^2 + m_{\chi_2}^2 s_\theta^2 + m_{A_0}^2 - 2m_{H^\pm}^2}{v^2},$$

$$\lambda_5 = \frac{m_{\chi_1}^2 c_\theta^2 + m_{\chi_2}^2 s_\theta^2 + m_{A_0}^2}{v^2}, \mu_S^2 = \frac{m_{\chi_1}^2 s_\theta^2 + m_{\chi_2}^2 c_\theta^2 - \lambda_{HS} v^2}{2}, \rho = \frac{(m_{\chi_2}^2 - m_{\chi_1}^2) \sin 2\theta}{2v}$$

$$\mu_I^2 = m_{\chi_1}^2 c_\theta^2 + m_{\chi_2}^2 s_\theta^2 - \lambda_L v^2$$

(6)

RESULTS AND DISCUSSIONS

We consider one of the physical eigenstates χ_1 as the lightest particle which could serve as the DM candidate. We use the package micrOMEGAS 4.3.5 [20] to calculate the relic abundance of DM in our model. The variation of relic abundance of DM with its mass in the mixed scalar model is shown in Fig. 1 for specific values of IHDM parameters. The parameters used are $\lambda_L = \lambda_2 = 0.01$, $\sin\theta = 0.2$, $v = 246\text{GeV}$, $m_h = 125\text{GeV}$. It is seen that there exists a funnel shaped region around ($m_{DM} \sim m_h/2$). This corresponds to the resonance in the s-channel annihilation of DM into the SM fermions mediated by the Higgs boson h . Though the region above the black line is excluded from relic density observations, yet it depends on different couplings and could be shifted for different sets of parameters. In Fig. 2 a scan of coupling constants λ_2 , λ_L and $\sin\theta$ is shown for points which satisfies the relic density constraints.

The other parameters used are $v = 246\text{GeV}$, $m_h = 125\text{GeV}$. The range of variation of the couplings λ_2 , λ_L and mixing angle $\sin\theta$ are : $0.001 \leq \lambda_{L,2} \leq 1$ and $0.01 \leq \sin\theta \leq 0.7$ respectively. The correct observed relic abundance could be produced by appropriate values of couplings and mixing angle.

The spin independent scattering cross section with nucleons in scalar singlet model and IDM is tightly constrained by the recent bounds from direct detection experiments like PandaX-II [10], LUX [11] and XENON1T [13]. We therefore plot the spin-independent scattering cross section of the mixed scalar DM model to compare with that of XENON1T spin-independent curve for the points satisfying the observed relic density. The observed points with mass range around 400-550 GeV are well within the allowed parameter range of XENON1T spin-independent curve.

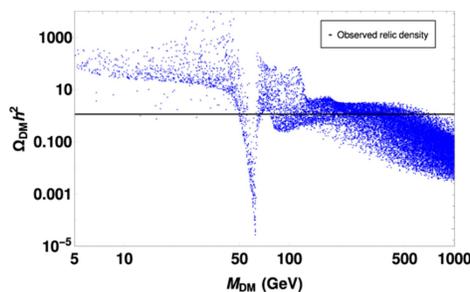


Fig. 1: DM relic abundance with model parameters $m_h = 125\text{GeV}$ and $\lambda_L = \lambda_2 = 0.01$. The black line is the observed relic density

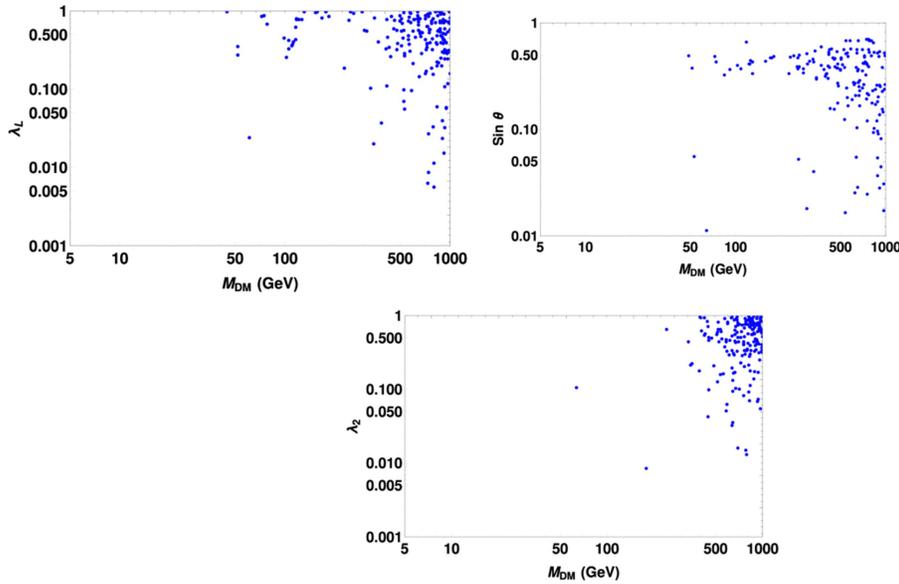


Fig. 2: Variation of coupling constants with mass of the Dark matter

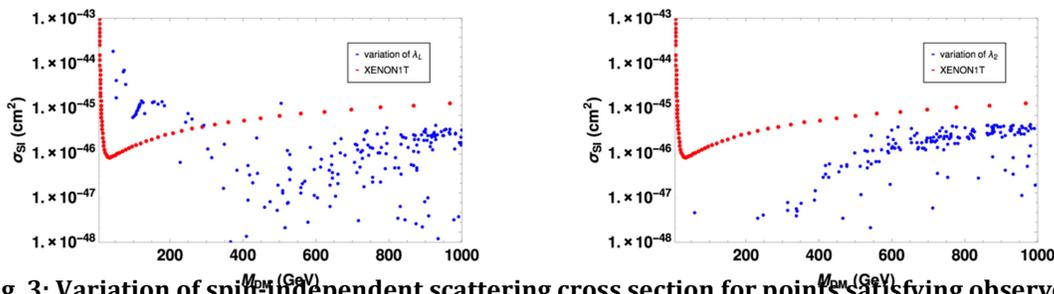


Fig. 3: Variation of spin-independent scattering cross section for points satisfying observed DM relic density

CONCLUSIONS

To conclude, in this work, we studied the possibility of generating correct relic abundance in a mixed scalar dark matter model for a new viable region of mass around 400-550 GeV. This mass range was previously constrained by the requirement of matching observed relic density. The dark matter candidate in this model is the lightest Z_2 odd particle obtained from the mixing of the singlet scalar and CP-even neutral component of the inert doublet model. We have compared our

results and constraints of the mixed scalar DM model with the recent results of spin-independent direct detection experiment XENON1T. The parameter space of the mixed scalar model has the advantage of being less constrained by the spin-independent direct detection experiments. We find that the intermediate mass region of 400-550 GeV, previously excluded by various indirect and direct experimental constraints for both singlet scalar model and inert doublet model could be revived to generate correct DM relic

abundance. Revival of this intermediate mass region could be interesting from the collider and indirect detection prospects.

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