Explaining Low Energy $\gamma$–ray Excess from the Galactic Centre using a Two Component Dark Matter Model

Anirban Biswas

Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, Kolkata 700064, India

ABSTRACT

Over the past few years, there has been a hint of the $\gamma$–ray excess observed by the Fermi-LAT satellite borne telescope from the region surrounding the Galactic Centre at an energy range $\sim 1-3$ GeV. The nature of this excess $\gamma$–ray spectrum is found to be consistent with the $\gamma$–ray emission expected from dark matter annihilation at the Galactic Centre while disfavouring other known astrophysical sources as the possible origin of this phenomena. It is also reported that the spectrum and morphology of this excess $\gamma$–rays can well be explained by the dark matter particles having mass in the range 30 $\sim$ 40 GeV annihilating into $b\bar{b}$ final state with an annihilation cross section $\sigma v \sim 1.4 - 2.0 \times 10^{-26}$ cm$^3$/s at the Galactic centre. In this work, we propose a two component dark matter model where two different types of dark matter particles namely a complex scalar and a Dirac fermion are considered. The stability of both the dark sector particles are maintained by virtue of an additional local U(1)$_X$ gauge symmetry. We find that our proposed scenario can provide a viable explanation besides satisfying all the existing relevant theoretical, experimental and observational bounds.
1 Introduction

The existence of the dark matter (DM) in the Universe is now an established fact by various astronomical measurements and observations such as galaxy rotation curves, gravitational lensing, Bullet cluster etc. However, no information is still available to us about the nature and the constituents of dark matter. The most successful hypothesis until now is that the dark matter of the Universe is composed of Weakly Interacting Massive Particles or WIMPs. The particle nature of the dark matter can be explored mainly in two ways. One of them is the process of direct detection where the information about the mass of the dark matter candidate along with its scattering cross section off the detector nuclei can be obtained by measuring the recoil energy of the latter as a result of scattering of the dark matter particles with the nuclei. The DM particles may also be trapped gravitationally within the massive celestial objects like the Sun, galaxy, galaxy cluster etc. Annihilation of these trapped dark matter particles can result in the production of high energy $\gamma$-rays or neutrinos. Detection of such high energy $\gamma$-rays or the neutrinos will provide valuable information about the constituents of the dark matter in the Universe. This is known as the process of indirect detection. More information about the properties of WIMPs and their detection procedures (both direct and indirect) are discussed in Refs. [1, 2].

It has been claimed by several groups [3–10] in last few years after analysing the Fermi-LAT data that a hint of the $\gamma$-ray excess has been observed by the Fermi-LAT satellite borne telescope from the regions surrounding the Galactic Centre (GC) at an energy range $\sim$ 1-3 GeV. More recent analyses of Fermi-LAT data by Daylan et. al. [10] excluded all the known astrophysical sources as the possible origin of this phenomena and strongly indicate that, the spectrum of this anomalous excess $\gamma$-rays is consistent with the emission expected from the dark matter annihilation at the Galactic Centre. It is also reported in the same article [10] that the observed $\gamma$-ray spectrum can be well explained by a dark matter particle having mass in the range $\sim$ 30-40 GeV (or $\sim$ 7-10 GeV) and annihilating significantly into $b \bar{b}$ (or $\tau \bar{\tau}$) final state with an annihilation cross section $\sigma v_{b\bar{b}} \sim (1.4 - 2.0) \times 10^{-26}$ cm$^3$/s$^2$. Although, there are some previous works [11–23] where different particle dark matter models have been proposed to explain this low energy (GeV scale) $\gamma$-ray excess from the neighbourhood regions of the Galactic Centre but in most of these articles the authors have considered single component dark matter model i.e. all the dark matter present in the Universe are constituted by a single stable beyond Standard Model particle. Larger dark matter mass ranges which also give acceptable fits to the Fermi-LAT data for the $b \bar{b}$ annihilation channel are discussed in Refs. [24, 25].

2 annihilation into $\tau \bar{\tau}$ final state the required cross section is $\sigma v_{\tau\bar{\tau}} \sim 2.0 \times 10^{-27}$cm$^3$/s (with local dark matter density = 0.4 GeV/cm$^3$) for a $\sim$ 10 GeV DM particle [8].
In this work we propose a two component dark matter model where the dark sector is composed of two different types of particles namely, a complex scalar \((S)\) and a Dirac fermion \((\psi)\). Our proposed model is an extension of the Standard Model (SM) of particle physics where the scalar sector of the SM is enlarged by the two singlet complex scalar fields \(S\) and \(\Phi_S\). The stability of these dark sector particles are ensured by the application of an additional local \(U(1)_X\) gauge symmetry under which only the two dark sector particles \(S, \psi\) and the complex scalar \(\Phi_S\) transform nontrivially. Therefore, the Lagrangian of this present two component dark matter model remains invariant under the \(SU(2)_L \times U(1)_Y \times U(1)_X\) gauge symmetry which breaks spontaneously to a residual \(U(1)_{\text{em}}\) symmetry when the complex scalars \(\Phi\) (usual SM Higgs doublet) and \(\Phi_S\) acquire Vacuum Expectation Values (VEVs). The effect of spontaneous breaking of the local gauge symmetry is manifested by the presence of five gauge bosons namely, \(W^\pm, Z, Z'\) and \(A\) out of which one neutral gauge field \((A)\) remains massless which is identified as the “photon” (mediator of electromagnetic interaction). Thus, in the present scenario we have one extra neutral gauge boson \((Z')\) compared to the SM as we have considered a larger symmetry group here. The extra neutral gauge boson \(Z'\) plays an important role in this proposed two component dark matter model as it is the main interaction mediator through which both the dark matter candidates interact mutually. In the present two component dark matter model the anomalous \(\gamma\)-ray excess is produced by the hadronisation processes of \(b\) quarks, originated from the self annihilation of the dark matter candidate \(S\) at the GC.

This paper is organised as follows. In Section 2 we propose the present two component dark matter model. Section 3 describes the coupled Boltzmann’s equations, required for computing the individual relic densities of each dark matter candidate and hence the overall relic density of the dark matter in the Universe. The results that we have obtained by solving the coupled Boltzmann’s equations numerically and using various experimental, observational and theoretical constraints are discussed in Section 4. In Section 5 we calculate the \(\gamma\)-ray flux for this proposed two component dark matter scenario and is compared with the available Fermi-LAT data. Finally, in Section 6 we summarise our work.

## 2 The Model

We propose a two component dark matter model where the dark sector is composed of a complex scalar \((S)\) and a Dirac fermion \((\psi)\), both of which are singlets under the Standard Model gauge group \(SU(2)_L \times U(1)_Y\). Thus, in the scalar sector of the model we have the usual Higgs doublet \(\Phi\) and two complex SM gauge singlets \(S, \Phi_S\). Note that the present model is an extension of the Standard Model of particle physics in all three sectors namely, gauge, fermionic as well as scalar...
sector. The gauge symmetry group of the SM is enhanced by an additional local U(1)\textsubscript{X} symmetry under which all particles except the SM particles (including the Higgs doublet Φ) transform nontrivially. Out of the three complex scalars (Φ, Φ\textsubscript{s}, S) present in this model only two, namely Φ and Φ\textsubscript{s} acquire VEVs. Consequently, the local gauge symmetry SU(2)\textsubscript{L} × U(1)\textsubscript{Y} × U(1)\textsubscript{X} is spontaneously broken which gives rise to one extra massive neutral gauge boson Z' in addition to four SM gauge bosons namely W\textsuperscript{±}, Z, A. The assigned gauge charges and VEVs of all the fields are given below in a tabular form,

| Field | SU(2)\textsubscript{L} charge | U(1)\textsubscript{Y} charge | U(1)\textsubscript{X} charge | VEV |
|-------|-----------------|-----------------|-----------------|-----|
| Φ     | 2               | 1               | 0               | v   |
| Φ\textsubscript{s} | 1               | 0               | 1               | v\textsubscript{s} |
| S     | 1               | 0               | 2               | 0   |
| ψ     | 1               | 0               | 2               | 0   |
| l\textsubscript{L} | 2               | -\frac{1}{2}   | 0               | 0   |
| Q\textsubscript{L} | 2               | \frac{1}{6}    | 0               | 0   |
| e\textsubscript{R} | 1               | -1             | 0               | 0   |
| u\textsubscript{R} | 1               | \frac{2}{3}    | 0               | 0   |
| d\textsubscript{R} | 1               | -\frac{1}{3}   | 0               | 0   |

Table 1: SU(2)\textsubscript{L} × U(1)\textsubscript{Y} × U(1)\textsubscript{X} charges and VEVs of all fields (including SM fermions) involved in the present model. Where l\textsubscript{L}, Q\textsubscript{L} are left handed lepton and quark doublet while e\textsubscript{R}, u\textsubscript{R} and d\textsubscript{R} represent right handed charge lepton, up type and down type quark respectively.

The Lagrangian of the present model is then given by,

\[ L \supset L_{\text{gauge}} + L_{\text{fermion}} + L_{\text{scalar}}. \]

Where \( L_{\text{gauge}} \) is the Lagrangian of the gauge fields corresponding to the gauge group U(1)\textsubscript{Y} and U(1)\textsubscript{X}.

\[ L_{\text{gauge}} \supset -\frac{1}{4} \hat{B}_{\mu \nu} \hat{B}^{\mu \nu} - \frac{1}{4} \hat{X}_{\mu \nu} \hat{X}^{\mu \nu} + \frac{\chi}{2} \hat{X}_{\mu \nu} \hat{B}^{\mu \nu}. \]

Here \( \hat{B}_{\mu \nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu \) and \( \hat{X}_{\mu \nu} = \partial_\mu \hat{X}_\nu - \partial_\nu \hat{X}_\mu \). Hat notation on the gauge fields indicate that kinetic terms of U(1)\textsubscript{Y} and U(1)\textsubscript{X} gauge fields are not diagonal. In the above equation (Eq. 2), \( \chi = \frac{\epsilon}{\cos \theta_w} \) is the coefficient of kinetic mixing term between the two U(1) gauge fields, which
is experimentally constrained to be very small. Consider a GL(2, R) rotation from the basis \( \hat{B}_\mu, \hat{X}_\mu \to B_\mu, X_\mu \) in such a way that with respect to new basis kinetic mixing term vanishes.

\[
\begin{pmatrix}
B_\mu \\
X_\mu
\end{pmatrix} =
\begin{pmatrix}
1 & -\chi \\
0 & \sqrt{1 - \chi^2}
\end{pmatrix}
\begin{pmatrix}
\hat{B}_\mu \\
\hat{X}_\mu
\end{pmatrix} .
\]

(3)

After such rotation,

\[
\hat{B}_\mu \simeq B_\mu + \chi X_\mu \quad \text{and} \quad \hat{X}_\mu \simeq X_\mu .
\]

(4)

Since \( \chi \ll 1 \) \([26,28]\), we have ignored \( \mathcal{O}(\chi^2) \) terms in the above equation (Eq. (4)). Spontaneous breaking of SU(2)_L \times U(1)_Y \times U(1)_X symmetry by VEVs of the neutral components of the scalar doublet \( \Phi \) (CP even part) and the complex singlet scalar \( \Phi_s \) respectively (see Table. II), results in a 3 \times 3 mass square mixing matrix between the three neutral gauge bosons namely \( W_{3\mu}, B_\mu, X_\mu \).

\[
M_{\text{gauge}}^2 = \frac{v^2}{4}
\begin{pmatrix}
g^2 & -gg' & \chi gg' \\
-gg' & g'^2 & \chi g'^2 \\
\chi gg' & \chi g'^2 & \frac{v_s^2}{v^2}(\frac{2}{3})^2
\end{pmatrix}.
\]

(5)

After diagonalising this mass square mixing matrix by an orthogonal matrix \( O(\theta_{NB}, \theta_W) \) we obtain three physical neutral gauge fields which are denoted by \( Z_\mu, A_\mu \) and \( Z'_\mu \). The eigenstates of the matrix \( M_{\text{gauge}}^2 \), namely, \( Z_\mu, A_\mu \) and \( Z'_\mu \) are linearly related to \( W_{3\mu}, B_\mu, X_\mu \) by an orthogonal transformation which is given by,

\[
\begin{pmatrix}
Z_\mu \\
A_\mu \\
Z'_\mu
\end{pmatrix} =
O(\theta_{NB}, \theta_W)
\begin{pmatrix}
W^3_\mu \\
B_\mu \\
X_\mu
\end{pmatrix} ,
\]

(6)

with

\[
O(\theta_{NB}, \theta_W) =
\begin{pmatrix}
\cos \theta_{NB} \cos \theta_W & -\cos \theta_{NB} \sin \theta_W & -\sin \theta_{NB} \\
\sin \theta_W & \cos \theta_W & 0 \\
\sin \theta_{NB} \cos \theta_W & -\sin \theta_{NB} \sin \theta_W & \cos \theta_{NB}
\end{pmatrix} ,
\]

(7)

where \( \theta_W \) and \( \theta_{NB} \) are the usual weak mixing angle and the mixing angle between two neutral gauge bosons \( Z \) and \( Z' \) respectively. The expressions of \( \theta_W \) and \( \theta_{NB} \) are given by,

\[
\theta_W = \tan^{-1}\left( \frac{g'}{g} \right) , \quad \theta_{NB} = \frac{1}{2} \tan^{-1}\left( \frac{2^{\epsilon} \tan \theta_W}{\frac{g^2}{g^2 + g'^2} \frac{v_s^2}{v^2}} \right) .
\]

(8)
Out of the three physical neutral gauge bosons one remains massless which is identified as the ‘photon’. The masses of other two neutral bosons namely \( Z \) and \( Z' \) are given by,

\[
M_Z = \sqrt{\frac{g_Z^2 v^2 + g_X^2 v_s^2}{8}} + \frac{1}{8} \sqrt{(g_Z^2 v^2 - g_X^2 v_s^2)^2 + 4(g'g_Z v^2 \chi)^2},
\]

\[
M_{Z'} = \sqrt{\frac{g_Z^2 v^2 + g_X^2 v_s^2}{8}} - \frac{1}{8} \sqrt{(g_Z^2 v^2 - g_X^2 v_s^2)^2 + 4(g'g_Z v^2 \chi)^2},
\]

where

\[
g_Z = \sqrt{g^2 + g'^2},
\]

with \( \chi \ll 1 \) as mentioned before, Eq. (9) reduces to

\[
M_Z^2 \simeq \frac{g_Z^2 v^2}{4},
\]

\[
M_{Z'}^2 \simeq \frac{g_X^2 v_s^2}{4}.
\]

In Eq. (1), \( \mathcal{L}_{\text{fermion}} \) refers to the Lagrangian of the singlet Dirac fermion \( \psi \), which is given by,

\[
\mathcal{L}_{\text{fermion}} = \bar{\psi} \left( i \slashed{D} - M_\psi \right) \psi.
\]

Where the covariant derivative \( \slashed{D} \) for the field \( \psi \) is

\[
\slashed{D}_\psi \psi = \gamma^\mu D_{\mu} \psi,
\]

\[
= \gamma^\mu \left( \partial_\mu + i2 g_X X_\mu \right) \psi.
\]

The scalar sector Lagrangian \( \mathcal{L}_{\text{scalar}} \) (in Eq. (1)) of the present model has the following form

\[
\mathcal{L}_{\text{scalar}} = (D_{\phi_\mu} \Phi) \dagger (D_{\phi_\mu} \Phi) + (D_{\phi_{s\mu}} \Phi_s) \dagger (D_{\phi_{s\mu}} \Phi_s) + (D_{s\mu} S) \dagger (D_{s\mu} S)
\]

\[
- V(\Phi, \Phi_s, S),
\]

with

\[
V(\Phi, \Phi_s, S) = \mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \mu_s^2 (\Phi_s^\dagger \Phi_s) + \lambda_s (\Phi_s^\dagger \Phi_s)^2 + \mu_S (S^\dagger S) + \mu_{1S} (S^\dagger S)^2 + \lambda_1 (\Phi^\dagger \Phi)(\Phi_s^\dagger \Phi_s) + \lambda_2 (\Phi^\dagger \Phi)(S^\dagger S)
\]

\[
+ \lambda_3 (\Phi_s^\dagger \Phi_s)(S^\dagger S).
\]

Where

\[
D_{\phi_\mu} \Phi = \left( \partial_\mu + i\frac{g}{2} \sigma^a W_{a\mu} + i\frac{g'}{2} (B_\mu + \chi X_\mu) \right) \Phi,
\]

\[
D_{\phi_{s\mu}} \Phi_s = \left( \partial_\mu + i\frac{g_X}{2} X_\mu \right) \Phi_s,
\]

\[
D_{s\mu} S = \left( \partial_\mu + i2 g_X X_\mu \right) S.
\]
are the covariant derivatives for the scalar doublet $\Phi$ and two complex scalar singlets $\Phi_s, S$ respectively. Similar to the gauge sector, the scalar sector also exhibits mixing between two real scalars namely $\phi^0$ (neutral CP even part of the doublet $\Phi$) and $\phi_s^0$ (real part of the complex scalar $\Phi_s$) after spontaneous breaking of gauge symmetry ($SU(2)_L \times U(1)_Y \times U(1)_X$). The mass square mixing matrix between these two real scalars are given by,

$$M^2_{\text{scalar}} = \begin{pmatrix} 2\lambda v^2 & \lambda_1 v_s v \\ \lambda_1 v_s v & 2\lambda_s v_s^2 \end{pmatrix}. \quad (16)$$

Diagonalising $M^2_{\text{scalar}}$ by an orthogonal matrix $O(\alpha)$, we obtain two real physical scalars namely $h$ and $H$. The old basis states ($\phi^0$, $\phi_s^0$) and the eigenstates ($h$, $H$) of the matrix $M^2_{\text{scalar}}$ are linearly related by the orthogonal matrix $O(\alpha)$ which is given by,

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \phi^0 \\ \phi_s^0 \end{pmatrix}. \quad (17)$$

The mixing angle $\alpha$ and the masses of the physical real scalars $h$ and $H$ are

$$\alpha = \frac{1}{2} \tan^{-1} \left( \frac{\lambda_1 v_s}{1 - \frac{\lambda_s v_s^2}{\lambda_1 v^2}} \right), \quad (18)$$

$$M_h = \sqrt{\lambda v^2 + \lambda_s v_s^2 + \sqrt{(\lambda v^2 - \lambda_s v_s^2)^2 + (\lambda_1 v v_s)^2}},$$

$$M_H = \sqrt{\lambda v^2 + \lambda_s v_s^2 - \sqrt{(\lambda v^2 - \lambda_s v_s^2)^2 + (\lambda_1 v v_s)^2}}. \quad (19)$$

Between these two real scalars, $h$ plays the role of SM Higgs boson. The mass term of the scalar field $S$ which does not mix with other components of the scalar sector is given by,

$$M_S = \sqrt{\rho^2 + \frac{\lambda_2 v^2}{2} + \frac{\lambda_3 v_s^2}{2}}. \quad (20)$$

Both the fermionic field $\psi$ and complex scalar field $S$ remain decoupled from the visible sector of the model. Thus, they can be viable components of dark matter. From the above discussion it is evident that the present scenario involves 9 unknown parameters namely, masses of two dark matter components namely $M_S$ and $M_\psi$, mass of one neutral scalar ($M_H$), mass of extra neutral gauge boson ($M_{Z'}$), the gauge coupling $g_X$ corresponding to the gauge group $U(1)_X$, neutral scalars mixing angle ($\alpha$), coefficient of kinetic mixing term ($\epsilon$) and two quartic couplings $\lambda_2, \lambda_3$. The allowed ranges of these parameters will be restricted by imposing both experimental, observational as well as theoretical bounds mentioned below.

---

3as we identify one of the neutral scalars namely $h$ with the SM Higgs boson, therefore its mass is fixed at $\sim 125.5 \text{ GeV}$ [29,30].
• **Vacuum Stability** - In order to obtain a stable vacuum, the scalar potential $V(\Phi, \Phi_s, S)$ (Eq. (14)) of the present model must be bounded from below. This will be maintained if the following conditions are satisfied,

\[
\begin{align*}
\lambda &\geq 0, \lambda_s \geq 0, \kappa \geq 0, \\
\lambda_1 &\geq -2\sqrt{\lambda \lambda_s}, \\
\lambda_2 &\geq -2\sqrt{\lambda \kappa}, \\
\lambda_3 &\geq -2\sqrt{\lambda_s \kappa}, \\
\sqrt{\lambda_1 + 2\sqrt{\lambda \lambda_s}} + \sqrt{\lambda_2 + 2\sqrt{\lambda \kappa}} + \sqrt{\lambda_3 + 2\sqrt{\lambda_s \kappa}} + 2\sqrt{\lambda \lambda_s \kappa} &\geq 0 .
\end{align*}
\]  

(21)

• **Zero VEV of $S$** - In the present scenario we assume that one among the three scalars, namely $S$ does not possess any vacuum expectation value. The VEV of other two scalars are $v$ and $v_s$ respectively (see Table 1). Hence the ground state of the model is $(v, v_s, 0)$ which requires

\[
\mu^2 < 0, \quad \mu_s^2 < 0 \quad \text{and} \quad \rho^2 > 0 .
\]

(22)

• **PLANCK Limit** - The total relic density ($\Omega_T h^2$) of the dark matter components must lie within the range [31] specified by the PLANCK experiment. The PLANCK limit for the relic density of the dark matter in the Universe is

\[
0.1172 < \Omega_{DM} h^2 < 0.1226 \quad \text{at } 68\% \text{ C.L.}
\]

(23)

• **Limits from Dark Matter Direct Detection Experiments** - In our two component dark matter model both the dark matter components namely $S$ and $\psi$ can interact with detector nuclei placed at various underground laboratories. The component $\psi$ scatters off the detector nuclei only via exchange of $Z$ and $Z'$ bosons, while for the other component $S$, the dominant contribution comes mainly through the exchange of scalar particles such as SM like Higgs boson ($h$) and $H$. Fig. 1 shows the Feynman diagrams for the scattering of both the dark matter components with the detector nucleon ($N$). The spin independent scattering cross section between the dark matter component $\psi$ and nucleon $N$ is given by [32],

\[
\sigma_{SI}^{\psi N \rightarrow \psi N} \approx \frac{\sqrt{2} G_F M_Z^2 g_X^2 Q_X(\psi)^2 \sin^2 \theta_{NB} \cos^2 \theta_{NB} \mu_{\psi N}^2}{16\pi} F_1^2 \left( \frac{1}{M_Z^2} - \frac{1}{M_{Z'}^2} \right) .
\]

(24)
Figure 1: Feynman diagrams for the elastic scattering between both the dark matter candidates $S$, $\psi$ and the nucleon $N$ of the detector material.

where,

\[ \mu_{\psi N} = \frac{M_\psi M_N}{(M_\psi + M_N)} \]

is the reduced mass between $\psi$ and $N$, $F_1^z = -0.5$ is the form factor for neutron and $Q_X(\psi) = \frac{1}{2}$ is the U(1)$_X$ charge of $\psi$. The expression of spin independent scattering cross section for the process $SN \rightarrow SN$ is given by,

\[ \sigma_{SI}^{SN \rightarrow SN} \simeq \frac{\mu_{SN}^2}{4\pi} \left( \frac{M_N f}{M_S v} \right)^2 \left( \frac{g_{SSH} \cos \alpha}{M_h^2} + \frac{g_{SSH} \sin \alpha}{M_H^2} \right)^2, \tag{25} \]

with

\[ \mu_{SN} = \frac{M_S M_N}{(M_S + M_N)} . \]

Where

\[ g_{SSH} = - (\lambda_2 v \cos \alpha - \lambda_3 v_s \sin \alpha) , \]
\[ g_{SSH} = - (\lambda_2 v \sin \alpha + \lambda_3 v_s \cos \alpha) \tag{26} \]

are the couplings for the vertex $SSH$ and $SSH$ respectively. $f$ is the relevant form factor. Throughout this work, we have adopted the value of $f = 0.3$ [33][35].

The Dark sector in our model is composed of two kinds of particles, one of which is scalar (however, it has different antiparticle (complex scalar)) while the other component is fermionic (Dirac fermion) in nature. Their masses as well as the contributions to the total relic density of the dark matter are different in general. Consequently the number densities $n_S$, $n_\psi$ for these two components are also different. Therefore when we compare the spin

---

$^4$particle and antiparticle possess different U(1)$_X$ charges.
independent scattering cross sections of both the components \((S\) and \(\psi\)) obtained from the model with the available experimental data (exclusion plots from various ongoing dark matter direct detection experiments such as LUX [36], XENON-100 [37] etc.), one has to keep in mind that the exclusion plots are computed with the assumption that all the dark matter present in the Universe are same in nature i.e. interaction rates with the detector nuclei are same for all the dark matter particles. However, this assumption is certainly not true in our case as we have two component dark matter scenario. Hence we need to rescale both \(\sigma_{SI}^{\psi N \to \psi N}\) and \(\sigma_{SI}^{SN \to SN}\) (Eqs. (24)-(25)) by appropriate factors consistent with the present consideration that we have two types of dark matter in the Universe. We define the spin independent “effective scattering cross section” between the detector nucleon \(N\) and the dark matter component \(i\) as,

\[
\sigma_{SI}^{iN \to iN} = \frac{n_i}{n_i + n_j} \sigma_{SI}^{iN \to iN},
\]

(27)

with \(i, j = S, \psi\) and \(i \neq j\), \(n_i\) is the number density of the dark mater component \(i\) at the present time. For a viable two component dark matter model it is desirable that

\[
\sigma_{SI}^{iN \to iN} < \sigma_{SI}^{Exp}(M_i).
\]

(28)

In the above \(M_i\) is the mass of the \(i^{th}\) type dark mater and \(\sigma_{SI}^{Exp}(M_i)\) is the experimental upper bound for the spin independent scattering cross section between dark matter particle of mass \(M_i\) and the nucleon \(N\). In this work we have used results only from LUX experiment for constraining the parameter space of this model since LUX imposes strongest limits (exclusion plot) in \(\sigma_{SI} - M_{DM}\) plane until now.

- **Invisible decay width of Higgs boson** \((\Gamma_{inv})\) - In this present two component dark matter model Higgs boson \(h\) can decay into two \(S\), if the condition \(M_h > 2M_S\) is satisfied. Such decay channel is known as invisible decay mode of Higgs boson. Throughout the work we assume that the invisible branching ratio \((BR_{inv})\) of Higgs boson is less than 20\% [38].

- **Constraint from LHC results** The signal strength ratio of Higgs boson for a particular decay channel \((h \to X\bar{X})\) is given by,

\[
R_{h \to X\bar{X}} = \frac{\sigma}{\sigma_{SM}} \frac{BR(h \to X\bar{X})}{BR(h \to X\bar{X})_{SM}},
\]

(29)

where \(X\) is any SM fermion / gauge boson. In Eq. (29) \(\sigma\) and \(BR(h \to X\bar{X})\) are the Higgs production cross section and the branching ratio of the decay channel \(h \to X\bar{X}\) for this present model respectively. Similar quantities for the SM are denoted by \(\sigma_{SM}\) and
BR \langle h \rightarrow X \bar{X} \rangle^{\text{SM}} \) respectively. In order to satisfy LHC results \([39]\) we take \( R_{h \rightarrow X \bar{X}} \geq 0.8 \) for any SM particle \( X \). This condition imposes severe constraint on the mixing angle \( \alpha \) between the two neutral scalars of the model namely, \( h \) and \( H \).

### 3 Solution of Coupled Boltzmann’s Equations of two Dark Matter Components \( \psi \) and \( S \)

In the present model, the dark sector has two different types of particles namely, a Dirac fermion \( \psi \) and a complex scalar \( S \). Therefore, the total relic density of the dark matter in the Universe must have contributions from both of these dark sector particles. In order to compute the total relic density as well as individual relic densities of each dark matter candidate, it is essential to solve two coupled Boltzmann’s equations \([40,41]\) which describe the evolution of number densities of both the dark matter candidates. The equations are given by,

\[
\frac{dn_\psi}{dt} + 3n_\psi H = -\langle \sigma v_{\psi \bar{\psi} \rightarrow SS} \rangle \left( n_\psi^2 - \left( \frac{n_{eq_\psi}^2}{n_{eq_S}^2} \right)^2 n_S^2 \right) \tag{30}
\]

\[
\frac{dn_S}{dt} + 3n_S H = -\langle \sigma v_{SS \rightarrow X \bar{X}} \rangle \left( n_S^2 - \left( \frac{n_{eq_S}^2}{n_{eq_S}^2} \right)^2 n_\psi^2 \right) + \langle \sigma v_{\psi \bar{\psi} \rightarrow SS} \rangle \left( n_\psi^2 - \left( \frac{n_{eq_\psi}^2}{n_{eq_S}^2} \right)^2 n_S^2 \right) \tag{31}
\]

Where \( n_\psi, n_S \) denote the number densities of \( \psi \) and \( S \) while their equilibrium values are denoted by \( n_{eq_\psi}^2, n_{eq_S}^2 \) respectively, \( H \) is the Hubble’s constant and \( \sigma v_{SS \rightarrow X \bar{X}} \) describes the self annihilation cross section of the dark matter component \( S \) into SM particles \((X)\). The interaction between the two components of dark matter, \( \psi \) and \( S \) is described by the annihilation cross section \( \sigma v_{\psi \bar{\psi} \rightarrow SS} \) where the heavier dark matter component (say \( \psi \)) annihilates to produce other component \( S \). New gauge boson \( Z' \) is the main exchange particle for this interaction. The Feynman diagrams for all the processes (self annihilation of dark matter component \( S \) and dark matter conversion from heavier to lighter) which are relevant for the evolution of number densities of both the dark matter component \( S \) and \( \psi \) are given in Fig. [2]. The annihilation cross sections

\[ X \] is any SM particle subjected to satisfy the kinematic condition \( s > 4M_X^2 \), where \( s \) is the centre of mass energy.
Figure 2: Feynman diagrams for the self annihilation of the dark matter components $S$, $\psi$.

for the processes shown in Fig. 2 are given by,

$$
\sigma_{SS^\dagger \rightarrow ff} = \frac{n_c m_f^2}{8\pi s} \left( s - 4m_f^2 \right)^{1/2} \frac{\left( \frac{g_{SSh}}{\sqrt{s}} \right)^2 \cos^2 \alpha}{\left( s - M_h^2 \right)^2 + (\Gamma_h M_h)^2} \left( \frac{\left( \frac{g_{SSh}}{\sqrt{s}} \right)^2 \sin^2 \alpha}{\left( s - M_H^2 \right)^2 + (\Gamma_H M_H)^2} \right) + \frac{\langle ... \rangle_{\psi \psi^\dagger}}{\langle ... \rangle_{S S^\dagger}},
$$

(32)

$$
\sigma_{\psi \bar{\psi} \rightarrow SS^\dagger} = \frac{\langle \frac{g_X^2 Q_X(S) \sin^2 \theta in \rangle \frac{\langle ... \rangle_{\psi \psi^\dagger}}{\langle ... \rangle_{S S^\dagger}} \rangle}{48\pi} \frac{(s - 4M_{S^2})}{(s - M_{S^2})^2} \sqrt{s} K_1 \left( \frac{\sqrt{s}}{T} \right) ds,
$$

(33)

where $\Gamma_h$, $\Gamma_H$ are the decay widths corresponding to the scalars $h$, $H$ and $Q_X(\psi) = Q_X(S) = 2$ are the U(1)$_X$ gauge charges of $\psi$ and $S$ respectively (see Table 1). In Eqs. (30, 31) the symbol $\langle ... \rangle$ implies the quantity within the curly bracket is thermally averaged. A general expression of thermally averaged annihilation cross section for the annihilation channel $AA^\dagger \rightarrow BB$ is given by [42],

$$
\langle \sigma_{AA^\dagger \rightarrow BB} \rangle = \frac{1}{8M_A^2 T K_2 \left( \frac{MA}{T} \right)} \int_{\frac{MA}{T}}^{\infty} \frac{1}{2} \sigma_{AA^\dagger \rightarrow BB}(s - 4M_{A^2}) \sqrt{s} K_1 \left( \frac{\sqrt{s}}{T} \right) ds,
$$

(34)

where $K_1$, $K_2$ are the modified Bessel functions of order 1, 2 and $T$ is the temperature of the Universe. The Extra $\frac{1}{2}$ factor before $\sigma_{AA^\dagger \rightarrow BB}$ arises due to the fact that the initial state particles of the annihilation channel ($AA^\dagger \rightarrow BB$) are not identical (see Refs. [42,43] for more discussions). More specifically, no extra $\frac{1}{2}$ factor would be needed if the particle and its antiparticle involve in the initial state of an annihilation process are identical in nature (e.g. Majorana fermion or real scalar field). Note that there will be a term in Eq. (30) which is similar to the first term of Eq. (31) and it represents the contribution arises from self annihilation of the heavier dark matter.
component $\psi$ into SM particles. Since $\psi$ can interact with the visible world (SM particles) only through the exchange of $Z$ and $Z'$ bosons, the resulting annihilation cross section of the channel $\psi\overline{\psi} \rightarrow XX$ is proportional to $\sin^2 \theta_{NB}$ ($\theta_{NB}$ is the mixing between the two neutral gauge bosons). Now for small values of $\theta_{NB}$, which is required to satisfy experimental constraints [44], one can use the approximation $\sin \theta_{NB} \simeq \theta_{NB}$. Thus, under this circumstance the term $\sin \theta_{NB} \propto \epsilon$, the kinetic mixing parameter between $U(1)_Y$ and $U(1)_X$ gauge fields (see Eq. (8)). Therefore, $\langle \sigma v_{\psi\overline{\psi} \rightarrow XX} \rangle \ll \langle \sigma v_{\psi\overline{\psi} \rightarrow SS} \rangle$ as the value of $\epsilon$ is severely constrained to be very small [26–28,44].

Which implies that the probability of producing two $S$ in the final state is much more than that for SM particles from the self annihilation of the dark matter candidate $\psi$. Hence, we can neglect the contribution of this term in Eq. (30).

Let us introduce two dimensionless variables namely $Y_i = \frac{n_i}{s}$ and $x_i = \frac{M_i}{T}$ for $i = \psi, S$. $Y_i$ and $M_i$ are the comoving number density and mass of the dark matter component $i$. The entropy density of the Universe is denoted by $s$. In terms of these two dimensionless variables Eq. (30) and Eq. (31) take the following forms,

$$\frac{dY_\psi}{dx_\psi} = - \left( \frac{45G}{\pi} \right)^{-\frac{1}{2}} \frac{m_\psi}{x_\psi} \sqrt{g_*} \langle \sigma v_{\psi\overline{\psi} \rightarrow SS} \rangle \left( Y_\psi^2 - \frac{(Y_\psi^{eq})^2}{(Y_S^{eq})^2} Y_S^2 \right),$$

$$\frac{dY_S}{dx_S} = - \left( \frac{45G}{\pi} \right)^{-\frac{1}{2}} \frac{M_S}{x_S} \sqrt{g_*} \left( \langle \sigma v_{SS} \rightarrow XX \rangle (Y_S^2 - (Y_S^{eq})^2) - \langle \sigma v_{\psi\overline{\psi} \rightarrow SS} \rangle \left( Y_\psi^2 - \frac{(Y_\psi^{eq})^2}{(Y_S^{eq})^2} Y_S^2 \right) \right),$$

where $G$ is the Gravitational constant. The quantity $g_*$ is defined as [42],

$$\sqrt{g_*} = \frac{h_{eff}(T)}{\sqrt{g_{eff}(T)}} \left( 1 + \frac{1}{3} \frac{d \ln (h_{eff}(T))}{d \ln (T)} \right),$$

with $g_{eff}(T)$ and $h_{eff}(T)$ are the effective degrees of freedom corresponding to the energy and entropy densities of the Universe. They are related to energy and entropy densities through the relations $\rho = g_{eff}(T) \frac{\pi^2}{30} T^4$, $s = h_{eff}(T) \frac{2\pi^2}{45} T^3$.

We have solved Eqs. (35, 36) numerically to obtain the values of comoving number densities ($Y_\psi, Y_S$) for both the dark matter components $\psi$ and $S$ respectively at the present temperature $T_0$ of the Universe. Using these values of $Y_i$ ($i = \psi, S$) at $T_0$ the relic density of each dark matter component can then be computed using the following equation [45, 46]

$$\Omega_i h^2 = 2.755 \times 10^8 \left( \frac{M_i}{\text{GeV}} \right) Y_i(T_0).$$

\(^6\)In this work we adopt $\epsilon \sim 10^{-3}$.
The total relic density \( \Omega_T h^2 \) of the dark matter is simply the sum of the relic densities of each dark matter component which can be written as [40],

\[
\Omega_T h^2 = \Omega_\psi h^2 + \Omega_S h^2.
\]

4 Results

In this section we describe the effects of the model parameters namely \( M_S, M_\psi, M_H, M_{Z^\prime}, \alpha, \lambda_2, \lambda_3 \) on the relic densities of both the dark matter components. In this present two component dark matter scenario the role of heavier dark matter is played by the component \( \psi \). Hence throughout the work we assume \( M_\psi > M_S \) and the value of \( M_S \) is taken in the range 30 \( \sim \) 40 GeV as this would be required to explain the observed \( \gamma \)-ray excess from the regions close to the GC at an energy range 1 \( \sim \) 3 GeV by the annihilation of the dark matter component \( S \). The ranges of the model parameters adopted in this work are given below,

\[
\begin{align*}
0.001 & \leq \lambda_2, \lambda_3 \leq 0.01, \\
0.01 & \leq \alpha \leq 0.1, \\
25 \text{ GeV} & \leq M_{Z^\prime} \leq 75 \text{ GeV}, \\
40 \text{ GeV} & \leq M_H \leq 100 \text{ GeV}, \\
60 \text{ GeV} & \leq M_\psi \leq 150 \text{ GeV}, \\
30 \text{ GeV} & \leq M_S \leq 40 \text{ GeV}.
\end{align*}
\]

From now on, whenever we use any specific values of the model parameters, we mention it explicitly with the other parameters scanned over their entire considered range given in Eq. (40). In order to study the variations of the relic densities of each of the dark matter component namely, \( S \) and \( \psi \) with the model parameters given in the Section 2 we define a ratio \( \frac{\Omega_i h^2}{\Omega_T h^2} \) which represent the fractional contribution of the dark matter component \( i \) (\( i = S, \psi \)) to the overall dark matter relic density \( (\Omega_T h^2) \). As mentioned earlier, for the computations of individual relic densities (\( \Omega_i h^2 \)) of both the dark matter candidates we need to solve two coupled Boltzmann’s equations (Eqs. (35), (36)) numerically given in previous section (Section 3) using Eqs. (32)-(34) and Eq. (37).

In left panel of Fig. 3 we plot the variations of fractional contributions of both the dark matter components \( \psi \) and \( S \) with the gauge coupling \( g_X \) of the U(1)\(_X\) gauge group for \( M_S = 30 \) GeV, \( M_\psi = 100 \) GeV, \( M_{Z^\prime} = 50 \) GeV and \( M_H = 65 \) GeV. From the left panel of Fig. 3 it is seen that the fractional contribution (\( \frac{\Omega_S h^2}{\Omega_T h^2} \)) of the dark matter component \( S \) increases with gauge coupling \( g_X \). This nature can be explained from the fact that \( \sigma v_{\psi\bar{\psi} \rightarrow SS} \) is directly proportional to \( g_X^2 \) (see Eq. (33)) and therefore as \( g_X \) increases the annihilation cross section of \( \psi \) for the channel
\( \psi \bar{\psi} \rightarrow SS^\dagger \) increases. This results in more and more \( S \) particle production in the final state from the pair annihilation of the heavier dark matter component \( \psi \). Hence the individual relic density of \( S \) as well as the fractional contribution of \( S \) to the total relic density increases (decreases). The variations of the fractional contributions of the dark matter component \( S \) with the neutral scalars mixing angle \( \alpha \) are shown in the right panel of Fig. 3. In this plot (right panel of Fig. 3) the red coloured region describes the allowed zone in the \( \Omega_S h^2 / \Omega_T h^2 \)-Vs-\( \alpha \) plane which satisfies all the constraints listed in Section 2 for \( M_S = 30 \) GeV, \( M_H = 65 \) GeV while the green coloured region is for the case when \( M_S = 35 \) GeV, \( M_H = 75 \) GeV. Both of these plots are computed for heavier dark matter mass \( M_\psi = 100 \) GeV.

Figure 3: Left panel : Variations of \( \Omega_S h^2 / \Omega_T h^2 \) \text{and} \( \Omega_\psi h^2 / \Omega_T h^2 \) with the gauge coupling \( g_X \) for \( M_S = 30 \) GeV and \( M_\psi = 100 \) GeV. Right Panel : Variations of \( \Omega_S h^2 / \Omega_T h^2 \) with the mixing angle \( \alpha \) between the neutral scalars \( h, H \) for \( M_S = 30 \) GeV, \( M_\psi = 100 \) GeV and \( M_S = 35 \) GeV, \( M_\psi = 100 \) GeV respectively.

We also calculate the variations of the ratios \( \Omega_S h^2 / \Omega_T h^2 \), \( \Omega_\psi h^2 / \Omega_T h^2 \) with the mass of the lighter dark matter component \( S \) for two different values of \( M_\psi \) and the results are plotted in both the panels of Fig. 4. In the left panel of Fig. 4 we show the variations of the fractional contribution of \( S \) to the total dark matter relic density with \( M_S \) for \( M_\psi = 80 \) GeV (green coloured band) and 100 GeV (red coloured band). The right panel of the same figure (Fig. 4) shows how the fractional contribution of the heavier dark matter component \( \psi \) to the total relic density varies with the mass of lighter dark matter component \( S \). Similar to the plots in the left panel of Fig. 4 in the right panel too, the green and red coloured band represent allowed zones for \( M_\psi = 80 \) GeV and 100 GeV respectively. From the left panel of Fig. 4 it appears that the contribution of \( S \) to the overall relic density of the dark matter decreases as its mass increases. A possible reason of
Figure 4: Variations of $\Omega_S h^2 / \Omega_T h^2$ (left panel) and $\Omega_S h^2 / \Omega_T h^2$ (right panel) with the mass of $S$ for $M_\psi = 80, 100 \text{ GeV}$ respectively.

this nature could be the annihilation cross section of the dark matter component $S$ into the final states comprised of fermion and antifermion pair ($SS^\dagger \rightarrow ff$, $f$ is any SM fermion except top quark) increases with $M_S$ (see Eq. (32)). Therefore the relic density of $S$ decreases. This results in an increment of the contribution of $\psi$ to the total density since the overall relic density of the dark matter candidates should fall within the range provided by the PLANCK experiment. Also, the annihilation cross section of $\psi$ for the channel $\psi \bar{\psi} \rightarrow SS^\dagger$ decreases with $M_S$ (see Eq. (33)) which further increases the individual density of $\psi$ and hence, its contribution to the overall density. This feature is revealed in the plots of the right panel of Fig. 4.

It has been discussed earlier that the dark matter component $\psi$ can interact with both the visible (SM particles) and invisible (other dark matter component $S$) world mainly through the exchange of gauge boson $Z'$. Therefore, the number density of the heavier dark matter component $\psi$ at present epoch (the relic density of $\psi$) should depend on the mass of $Z'$. Eq. (33) shows that the annihilation cross section for the interaction in which heavier dark matter components annihilate to produce lighter dark matter components ($\psi \bar{\psi} \rightarrow SS^\dagger$), increases with the mass of $Z'$ boson as long as $M_{Z'} < \sqrt{s}_{\min}$ condition holds. Hence, the present day abundance of the dark matter component $\psi$ would be less for the heavier $Z'$ boson as the dark matter conversion process (heavier $\rightarrow$ lighter) is the dominant interaction channel of $\psi$. The change in the mass of the $Z'$ boson has no significant effect on the interactions of the lighter dark matter component $S$ with the SM fermions as those occur mainly through the exchange of neutral scalars namely $h$.

\footnote{which is the case we are considering.}
Figure 5: Variations of $\Omega_s h^2$ (left panel) and $\Omega_{\psi} h^2$ (right panel) with the mass ($M_{Z'}$) of $Z'$ for $M_S = 35$ GeV, $M_\psi = 80$ GeV and $M_S = 35$ GeV, $M_\psi = 100$ GeV.

and $H$. However, as we have mentioned above, the mutual interaction between the dark matter components depends on the mass of $Z'$ which results in an increase of relic density of $S$ with the mass of $Z'$. The variations of fractional relic densities of both the dark matter components $S$ and $\psi$ with the mass of $Z'$ are shown in left and right panels of Fig. 5. In both the panels of Fig. 5 the red coloured bands indicate the variations for $M_S = 35$ GeV and $M_\psi = 100$ GeV while the green bands represent the allowed zone for $M_S = 35$ GeV and $M_\psi = 80$ GeV respectively.

Left panel of Fig. 6 describes the variations of the ratio $\Omega_{\psi} h^2 / \Omega_T h^2$ with the mass ($M_{\psi}$) of the dark matter component $\psi$ for different values of the gauge coupling $g_X$ and the mass ($M_S$) of $S$. The green band represents the variations for $g_X = 0.20$, $M_S = 35$ GeV while the red and blue coloured bands are for two different values of $M_S$ namely, 35 and 30 GeV respectively with the same gauge coupling $g_X = 0.25$. From this figure (left panel of Fig. 6) it appears that the contributions of the heavier dark matter component $\psi$ to the overall dark matter density increase with its mass $M_\psi$ and gauge coupling $g_X$. However, the quantity $\Omega_{\psi} h^2 / \Omega_T h^2$ remains nearly same for the variations of the mass of the lighter dark matter component $S$ from 30 GeV to 35 GeV. This increment of $\Omega_{\psi} h^2 / \Omega_T h^2$ is evident from Eq. (33) which indicates that the annihilation cross section of $\psi$ for the channel $\psi \bar{\psi} \rightarrow SS^\dagger$ increases with both $M_\psi$ and $g_X$. The right panel of Fig. 6 represents how the range of allowed values of $M_H$ vary with the mass of $S$ for $M_\psi = 100$ GeV. Needless to mention that, for not only each point in the right panel of Fig. 6 but for every other plots given in both panels of Figs. 3 - 6 all the possible constraints discussed in the Section 2 namely, the vacuum stability bounds, the relic density constraints, the constraints obtain from the results of dark
Figure 6: Left panel: Variations of the fractional contributions of the dark matter component \( \psi \) with its mass \( M_\psi \) for different values of the gauge coupling \( g_X \) and the mass of \( S \) (\( M_S \)).

Right panel: Variations of the allowed ranges of \( M_H \) with \( M_S \) while the mass of heavier dark matter is fixed at 100 GeV.

Figure 7: Spin independent “effective scattering cross sections” of the dark matter component \( S \) (red coloured region) and \( \psi \) (green coloured region). Limits obtained from LUX experiment are denoted by black solid line.
We have already discussed in the Section 2 that in order to compare the direct detection results computed using a multicomponent dark matter model, one should rescale the spin independent scattering cross sections for both the dark matter components by an appropriate factor (see Eq. 27) which manifest the existence of multicomponent dark matter. In view of this, the spin independent “effective scattering cross sections” between each of the dark matter candidate $(S, \phi)$ and the nucleon are plotted in Fig. 7. Here red coloured zone represents $\sigma^{\prime}_{SI} iN \rightarrow iN$ for the candidate $S$ ($i = S$) however, for the heavier dark matter candidate $\psi$ it is indicated by the green coloured band. For the comparison with the direct detection experimental results the data [36] obtained from the LUX experiment are superimposed on the same figure (Fig. 7). From the Fig. 7 it appears that although some portions of the present two component dark matter model are already excluded by the LUX experiment, still there exists enough allowed regions in the $\sigma_{SI} - M_{DM}$ plane which can be tested by more sensitive (“ton-scale”) direct detection experiments in near future.

5 1-3 GeV $\gamma$ excess from Galactic Centre.

In this section our endeavour is to explain recently observed excess $\gamma$–rays at an energy range 1-3 GeV by Fermi-LAT from the Galactic Centre region within the framework of the proposed two component dark matter model. In the present two component DM scenario, lighter dark matter component namely, $S$ having mass in the range $30 \sim 40$ GeV annihilates with its own antiparticle $S^\dagger$ and thereby produces $b, \bar{b}$ pair in the final state with branching ratio $\sim 85\% - 90\%$. Thereafter those $b$-quarks hadronise to produce $\gamma$–rays that can be detected by Fermi-LAT. The annihilation process $(SS \rightarrow b\bar{b})$ of the dark matter component $S$ proceeds mainly through the exchange of SM like Higgs boson $h$ and $H$. The Feynman diagram for this annihilation process is shown in the left panel of Fig. 2. The differential $\gamma$–ray flux due to self annihilation of $S$ in the GC region is given by [47],

$$\frac{d\Phi_\gamma}{d\Omega dE} = \frac{r_\odot}{8\pi} \left( \frac{\rho_\odot}{M_S} \right)^2 \bar{J} \left( \sigma v_{SS^\dagger \rightarrow b\bar{b}} \right) \frac{dN_b}{dE},$$

(41)

where $\frac{dN_b}{dE}$ is the energy spectrum of photons produced from the hadronisation processes of $b$ quarks [47]. We have used the numerical values of the photon spectrum for different values of photon energy $E_\gamma$, given in Ref. [47]. In the above $\rho_\odot = 0.3$ GeV/cm$^3$ is the dark matter density at the solar location which is nearly $r_\odot \approx 8.5$ Kpc away from the Galactic Centre. The quantity $\bar{J}$ for

---

*originates from the self annihilation of $S$ through the process $SS^\dagger \rightarrow b\bar{b}$. 

---

19
the case of dark matter annihilation in the GC can be expressed as,

\[ \bar{J} = \frac{4}{\Delta \Omega} \int \int db \, dl \cos b \, J(b, l) , \]  

(42)

with

\[ J(l, b) = \int_{l.o.s} ds \left( \frac{\rho(r)}{\rho_\odot} \right)^2 , \]  

(43)

and

\[ \Omega = 4 \int dl \int db \cos b , \]  

(44)

\[ r = \left( r_\odot^2 + s^2 - 2r_\odot s \cos b \cos l \right)^{1/2} . \]  

(45)

In Eqs. (42, 44, 45), \( l \) and \( b \) represent the galactic longitude and latitude respectively. While computing the values of \( \bar{J} \) we perform the integral over a region which is situated within a radius of 5° around the GC. Integral over \( s \) in Eq. (43) is along the line of sight (l.o.s) distance. The quantity \( \langle \sigma v_{SS^\dagger \to bb} \rangle' \) in Eq. (41) is the “effective annihilation cross section” which is in the product of annihilation cross section of the channel \( SS^\dagger \to bb \) and square of the contribution of the component \( S \) to the total dark matter relic density \( (\Omega_T h^2) \) i.e.

\[ \langle \sigma v_{SS^\dagger \to bb} \rangle' = \xi_S^2 \langle \sigma v_{SS^\dagger \to bb} \rangle , \]  

(46)

where

\[ \xi_S = \frac{\Omega_S h^2}{\Omega_T h^2} \]  

(47)

is the fractional relic density of the component \( S \). The use of \( \langle \sigma v_{SS^\dagger \to bb} \rangle' \) (“effective annihilation cross section”) instead of actual annihilation cross section for the channel \( SS^\dagger \to bb \) in Eq. (41) is needed since we are working in a framework with more than one component of the dark matter. Note that if the entire dark sector is composed by only one type of particle (say \( S \)) then \( \xi_S = 1 \), therefore \( \langle \sigma v_{SS^\dagger \to bb} \rangle' \) and \( \langle \sigma v_{SS^\dagger \to bb} \rangle \) are identical. The expression of \( \langle \sigma v_{SS^\dagger \to bb} \rangle \) is given in Eq. (32) of Section 3. Computation of \( \gamma \)-ray flux using Eq. (41) requires the nature of the variation of the dark matter density in the neighbourhood regions of the Galactic Centre with the distance \( r \). In short one needs to know the DM halo profile \( \rho(r) \) as a function of \( r \). In the present work we use the NFW profile [18] with \( \gamma = 1.26 \) [10]. The general expression of NFW profile is given by,

\[ \rho_{\text{NFW}} = \rho_s \frac{\left( \frac{r}{r_s} \right)^{-\gamma}}{\left( 1 + \frac{r}{r_s} \right)^{\delta - \gamma}} , \]  

(48)
Figure 8: Left-Panel : Variations of $\langle \sigma v_{SS^\dagger \to bb} \rangle'$ with the mass of the dark matter component $S$ for different values of the mass of heavier dark matter component $\psi$. where scale radius $r_s = 20$ Kpc. The normalisation constant $\rho_s$ (scale density) is obtained by demanding that at the solar location ($r = r_\odot$) the dark matter density should be $0.3$ GeV/cm$^3$.

In Fig. 8(a-c) we show the variations of “effective annihilation cross section” $\langle \sigma v_{SS^\dagger \to bb} \rangle'$ (defined in Eq. (46)) for the annihilation channel $SS^\dagger \to bb$ with the mass of the the dark matter component $S$ in the range of $30$ GeV - $40$ GeV for three different values of $M_\psi$ namely, $60$, $80$ and $100$ GeV. Since the quantity $\langle \sigma v_{SS^\dagger \to bb} \rangle'$ is the product of annihilation cross section of $S$ for the channel $SS^\dagger \to bb$ and the fractional contribution of $S$ to the total relic density ($\xi_s$) (see Eq. (46)), therefore in the plots (a-c) of Fig. 8 we have taken only those values of both the quantities $\langle \sigma v_{SS^\dagger \to bb} \rangle'$ and $\xi_s$ for which the total dark matter density lies within the range predicted by the PLANCK experiment (Eq. (23)). All the plots in Fig. 8 show that the “effective
annihilation cross section” of the channel $SS^\dagger \to b\bar{b}$ decreases as the mass of the heavier dark matter component $M_\psi$ increases. Since $\xi_\psi$ increases with $M_\psi$ (see left panel of Fig. 6) which results in an enhancement in the pair annihilation rate ($\langle \sigma v_{SS^\dagger \rightarrow f\bar{f}} \rangle$, $f$ is any SM fermion except top quark) of the dark matter component $S$ and hence, the individual relic density ($\Omega_S h^2$) as well as the fractional contribution of $S$ to the overall density ($\xi_S$) decreases with the increase of $M_\psi$. Therefore, the “effective annihilation cross section” of $S$ for the channel $SS^\dagger \to b\bar{b}$ decreases with $M_\psi$ as it is proportional to $\xi_S^2$ (see Eq. (47)). Similarly, one can understand the variations of $\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle$ with the mass of $S$ using left panel of Fig. 4.

The plots (a-c) in Fig. 9 show the variations of the $\gamma$–ray flux obtained from the regions

\begin{align*}
\text{(a) } M_\psi &= 100 \text{ GeV} \\
\text{(b) } M_\psi &= 80 \text{ GeV} \\
\text{(c) } M_\psi &= 60 \text{ GeV}
\end{align*}

Figure 9: Variations of $\gamma$–ray flux obtain from the annihilation of $S$ in the Galactic Centre as a function of the photon energy ($E_\gamma$) for three different values of $M_\psi$. 

\begin{align*}
\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle &= 1.56 \times 10^{-26} \text{ cm}^3/\text{s} \\
\langle \sigma v_{SS^\dagger \rightarrow f\bar{f}} \rangle &= 1.45 \times 10^{-26} \text{ cm}^3/\text{s} \\
\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle &= 1.53 \times 10^{-26} \text{ cm}^3/\text{s} \\
\langle \sigma v_{SS^\dagger \rightarrow f\bar{f}} \rangle &= 1.59 \times 10^{-26} \text{ cm}^3/\text{s}
\end{align*}
surrounding the Galactic Centre due to the self annihilation of the dark matter candidate $S$ of mass 35 GeV in the $b\bar{b}$ final state for three different values of $M_\psi = 100, 80$ and 60 GeV respectively. In each of the plots (a-c) of Fig. 9 the red and green solid lines represent the $\gamma$-ray fluxes obtained by using maximum and minimum allowed values of the “effective annihilation cross section” $\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle'$ for a particular value of the mass of heavier dark matter component $\psi$. These quantities are represented by $\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle'_{\text{max}}$ and $\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle'_{\text{min}}$ respectively. The range of allowed values of $\langle \sigma v_{SS^\dagger \rightarrow b\bar{b}} \rangle'$ with the mass of $S$ for three different values of $M_\psi$ ($M_\psi = 60, 80$ and 100 GeV) are given in plots of Fig. 8. The black vertical lines in each of the plots of Fig. 9 represent the Fermi-LAT data and corresponding error bars. Since the allowed ranges of the “effective annihilation cross section” of the dark matter particle $S$ for the channel $SS^\dagger \rightarrow b\bar{b}$ decrease with the increase of $M_\psi$ (see plots (a-c) of Fig. 8 and the related discussions), therefore the corresponding $\gamma$-ray fluxes (Eq. (41)) shown in Fig. 9 also decrease with $M_\psi$. It appears from all the plots (a-c) of Fig. 9 that the $\gamma$-ray flux obtained for the heavier dark matter mass $M_\psi = 60$ GeV fits well with the available Fermi-LAT data.

6 Summary

In the present work, we propose a dark matter model which is an extension of the Standard Model of particles physics in all three sectors namely gauge, fermionic as well as scalar and contains two different types of dark matter candidates. Therefore, in this two component dark matter model the role of two dark matter candidates are played by a complex scalar field $S$ and a Dirac fermion $\psi$ respectively. Although, both of these dark sector particles ($S, \phi$) are singlet under SM gauge group (SU(2)$_L \times$ U(1)$_Y$) but possess a non zero U(1)$_X$ charge which ensures their stability. Thus, in addition to SM gauge group (SU(2)$_L \times$ U(1)$_Y$) we have an additional local U(1)$_X$ gauge symmetry under which all the SM particles (including the Higgs boson) behave like singlet. Besides the dark matter component $S$, the scalar sector of the present model is composed of another complex singlet $\Phi_s$ and a scalar doublet ($\Phi$) under SU(2)$_L$ (the usual Higgs doublet). Both $\Phi$ and $\Phi_s$ possess non zero VEVs namely, $v$ and $v_s$ respectively which break the SU(2)$_L \times$ U(1)$_Y \times$ U(1)$_X$ symmetry spontaneously. The spontaneous breaking of this symmetry is manifested by the presence of five gauge bosons in the model such as $W^\pm, Z, Z'$ and $A$. Among these five gauge bosons only $W^\pm$ has non zero electrical charge and $A$ remains massless which is identified as the “photon” (mediator of the electromagnetic interaction). Considering $S$ and $\psi$ as the two candidates for the dark matter particles in the Universe, their viability is examined by computing the total relic abundance at the present epoch and the scattering cross sections off the detector nuclei. In order to find the total relic abundance which is the sum of
the individual relic abundances of both the dark matter components, we have solved two coupled Boltzmann’s equations for $\psi$ and $S$ at the present epoch. We find that for a wide range of values of the model parameters the total relic density of the two dark matter candidates falls within the range specified by the PLANCK experiment. We have compared the spin independent “effective scattering cross sections” for both the dark matter candidates off the nuclei with the latest results of LUX experiment. We find that although, some portion of this present two component dark matter model has already been excluded by the results of LUX experiment but still their exist enough region in the $\sigma_{\text{SI}} - M_{\text{DM}}$ plane which can be tested by the “ton-scale” direct detection experiments in near future. Finally, we have computed the $\gamma$–ray flux originated from the self annihilation of the dark matter candidate $S$ into $b \bar{b}$ final state at the Galactic Centre region. We find that our two component dark matter model also shows an excess in the $\gamma$–ray spectrum obtained from the GC region at an energy range $1 \sim 3$ GeV from the annihilation of dark matter candidate $S$, having mass in the range $30 \sim 40$ GeV. The resulting $\gamma$–ray flux becomes lower as the mass splitting between the two dark matter components increases. We have shown that the $\gamma$–ray spectrum resulting from the self annihilation of a 35 GeV $S$ particles at the GC with an annihilation cross section in the range $1.59 \times 10^{-26}$ cm$^3$/s $\sim 1.71 \times 10^{-26}$ cm$^3$/s for the mass of heavier dark matter $M_\psi = 60$ GeV, fits well with the available Fermi-LAT data.

7 Acknowledgement

Author would like to thank D. Adak, A. Dutta Banik and D. Majumdar for many useful suggestions and discussions. Author would also like to acknowledge Department of Atomic Energy (DAE), Govt. of India for their financial assistance.

References

[1] G. Jungman, M. Kamionkowski, and K. Griest, *Supersymmetric dark matter*, Phys.Rept. 267 (1996) 195–373, [hep-ph/9506380].

[2] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: Evidence, candidates and constraints*, Phys.Rept. 405 (2005) 279–390, [hep-ph/0404175].

[3] L. Goodenough and D. Hooper, *Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope*, arXiv:0910.2998.
[4] D. Hooper and L. Goodenough, *Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope*, Phys.Lett. B697 (2011) 412–428, [arXiv:1010.2752].

[5] A. Boyarsky, D. Malyshev, and O. Ruchayskiy, *A comment on the emission from the Galactic Center as seen by the Fermi telescope*, Phys.Lett. B705 (2011) 165–169, [arXiv:1012.5839].

[6] D. Hooper and T. Linden, *On The Origin Of The Gamma Rays From The Galactic Center*, Phys.Rev. D84 (2011) 123005, [arXiv:1110.0006].

[7] K. N. Abazajian and M. Kaplinghat, *Detection of a Gamma-Ray Source in the Galactic Center Consistent with Extended Emission from Dark Matter Annihilation and Concentrated Astrophysical Emission*, Phys.Rev. D86 (2012) 083511, [arXiv:1207.6047].

[8] D. Hooper and T. R. Slatyer, *Two Emission Mechanisms in the Fermi Bubbles: A Possible Signal of Annihilating Dark Matter*, Phys.Dark Univ. 2 (2013) 118–138, [arXiv:1302.6589].

[9] K. N. Abazajian, N. Canac, S. Horiuchi, and M. Kaplinghat, *Astrophysical and Dark Matter Interpretations of Extended Gamma-Ray Emission from the Galactic Center*, Phys.Rev. D90 (2014) 023526, [arXiv:1402.4090].

[10] T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, et al., *The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter*, [arXiv:1402.6703].

[11] A. Alves, S. Profumo, F. S. Queiroz, and W. Shepherd, *The Effective Hooperon*, [arXiv:1403.5027].

[12] A. Berlin, D. Hooper, and S. D. McDermott, *Simplified Dark Matter Models for the Galactic Center Gamma-Ray Excess*, Phys.Rev. D89 (2014) 115022, [arXiv:1404.0022].

[13] P. Agrawal, B. Batell, D. Hooper, and T. Lin, *Flavored Dark Matter and the Galactic Center Gamma-Ray Excess*, Phys.Rev. D90 (2014) 063512, [arXiv:1404.1373].

[14] E. Izaguirre, G. Krnjaic, and B. Shuve, *The Galactic Center Excess from the Bottom Up*, Phys.Rev. D90 (2014) 055002, [arXiv:1404.2018].
[15] D. Cerdeño, M. Peiró, and S. Robles, Low-mass right-handed sneutrino dark matter: SuperCDMS and LUX constraints and the Galactic Centre gamma-ray excess, JCAP 1408 (2014) 005, [arXiv:1404.2572].

[16] S. Ipek, D. McKeen, and A. E. Nelson, A Renormalizable Model for the Galactic Center Gamma Ray Excess from Dark Matter Annihilation, Phys.Rev. D90 (2014) 055021, [arXiv:1404.3716].

[17] C. Boehm, M. J. Dolan, and C. McCabe, A weighty interpretation of the Galactic Centre excess, Phys.Rev. D90 (2014) 023531, [arXiv:1404.4977].

[18] P. Ko, W.-I. Park, and Y. Tang, Higgs portal vector dark matter for GeV scale γ-ray excess from galactic center, JCAP 1409 (2014) 013, [arXiv:1404.5257].

[19] M. Abdullah, A. DiFranzo, A. Rajaraman, T. M. Tait, P. Tanedo, et al., Hidden On-Shell Mediators for the Galactic Center Gamma-Ray Excess, Phys.Rev. D90 (2014) 035004, [arXiv:1404.6528].

[20] D. K. Ghosh, S. Mondal, and I. Saha, Confronting the Galactic Center Gamma Ray Excess With a Light Scalar Dark Matter, [arXiv:1405.0206].

[21] A. Martin, J. Shelton, and J. Unwin, Fitting the Galactic Center Gamma-Ray Excess with Cascade Annihilations, Phys.Rev. D90 (2014), no. 10 103513, [arXiv:1405.0272].

[22] N. Okada and O. Seto, Galactic center gamma ray excess from two Higgs doublet portal dark matter, Phys.Rev. D90 (2014), no. 8 083523, [arXiv:1408.2583].

[23] A. D. Banik and D. Majumdar, Low Energy Gamma Ray Excess Confronting a Singlet Scalar Extended Inert Doublet Dark Matter Model, [arXiv:1408.5795].

[24] P. Agrawal, B. Batell, P. J. Fox, and R. Harnik, WIMPs at the Galactic Center, [arXiv:1411.2592].

[25] F. Calore, I. Cholis, C. McCabe, and C. Weniger, A Tale of Tails: Dark Matter Interpretations of the Fermi GeV Excess in Light of Background Model Systematics, [arXiv:1411.4647].

[26] S. Gopalakrishna, S. Jung, and J. D. Wells, Higgs boson decays to four fermions through an abelian hidden sector, Phys.Rev. D78 (2008) 055002, [arXiv:0801.3456].
[27] H. Davoudiasl, H.-S. Lee, and W. J. Marciano, 'Dark' Z implications for Parity Violation, Rare Meson Decays, and Higgs Physics, Phys.Rev. D85 (2012) 115019, [arXiv:1203.2947].

[28] H.-S. Lee and M. Sher, Dark Two Higgs Doublet Model, Phys.Rev. D87 (2013), no. 11 115009, [arXiv:1303.6653].

[29] ATLAS Collaboration, G. Aad et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys.Lett. B716 (2012) 1–29, [arXiv:1207.7214].

[30] CMS Collaboration, S. Chatrchyan et al., Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys.Lett. B716 (2012) 30–61, [arXiv:1207.7235].

[31] Planck Collaboration, P. Ade et al., Planck 2013 results. XVI. Cosmological parameters, Astron.Astrophys. 571 (2014) A16, [arXiv:1303.5076].

[32] L.-B. Jia and X.-Q. Li, Study of a WIMP dark matter model with the updated results of CDMS II, Phys.Rev. D89 (2014) 035006, [arXiv:1309.6029].

[33] Y. Mambrini, Higgs searches and singlet scalar dark matter: Combined constraints from XENON 100 and the LHC, Phys.Rev. D84 (2011) 115017, [arXiv:1108.0671].

[34] J. Giedt, A. W. Thomas, and R. D. Young, Dark matter, the CMSSM and lattice QCD, Phys.Rev.Lett. 103 (2009) 201802, [arXiv:0907.4177].

[35] R. Barbieri, L. J. Hall, and V. S. Rychkov, Improved naturalness with a heavy Higgs: An Alternative road to LHC physics, Phys.Rev. D74 (2006) 015007, [hep-ph/0603188].

[36] LUX Collaboration, D. Akerib et al., First results from the LUX dark matter experiment at the Sanford Underground Research Facility, Phys.Rev.Lett. 112 (2014), no. 9 091303, [arXiv:1310.8214].

[37] XENON100 Collaboration, E. Aprile et al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys.Rev.Lett. 109 (2012) 181301, [arXiv:1207.5988].

[38] G. Belanger, B. Dumont, U. Ellwanger, J. Gunion, and S. Kraml, Status of invisible Higgs decays, Phys.Lett. B723 (2013) 340–347, [arXiv:1302.5694].
[39] CMS Collaboration, *Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV*, CMS-PAS-HIG-13-005 (2013).

[40] A. Biswas, D. Majumdar, A. Sil, and P. Bhattacharjee, *Two Component Dark Matter: A Possible Explanation of 130 GeV γ− Ray Line from the Galactic Centre*, JCAP 1312 (2013) 049, [arXiv:1301.3668](https://arxiv.org/abs/1301.3668).

[41] G. Belanger and J.-C. Park, *Assisted freeze-out*, JCAP 1203 (2012) 038, [arXiv:1112.4491](https://arxiv.org/abs/1112.4491).

[42] P. Gondolo and G. Gelmini, *Cosmic abundances of stable particles: Improved analysis*, Nucl.Phys. B360 (1991) 145–179.

[43] M. Srednicki, R. Watkins, and K. A. Olive, *Calculations of Relic Densities in the Early Universe*, Nucl.Phys. B310 (1988) 693.

[44] Particle Data Group Collaboration, J. Beringer et al., *Review of Particle Physics (RPP)*, Phys.Rev. D86 (2012) 010001.

[45] J. Edsjo and P. Gondolo, *Neutralino relic density including coannihilations*, Phys.Rev. D56 (1997) 1879–1894, [hep-ph/9704361](https://arxiv.org/abs/hep-ph/9704361).

[46] A. Biswas and D. Majumdar, *The Real Gauge Singlet Scalar Extension of Standard Model: A Possible Candidate of Cold Dark Matter*, Pramana 80 (2013) 539–557, [arXiv:1102.3024](https://arxiv.org/abs/1102.3024).

[47] M. Cirelli, G. Corcella, A. Hektor, G. Hutsi, M. Kadastik, et al., *PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection*, JCAP 1103 (2011) 051, [arXiv:1012.4515](https://arxiv.org/abs/1012.4515).

[48] J. F. Navarro, C. S. Frenk, and S. D. White, *A Universal density profile from hierarchical clustering*, Astrophys.J. 490 (1997) 493–508, [astro-ph/9611107](https://arxiv.org/abs/astro-ph/9611107).