Non-abelian dark matter solutions for Galactic gamma-ray excess and Perseus 3.5 keV X-ray line

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Abstract. We attempt to explain simultaneously the Galactic center gamma-ray excess and the 3.5 keV X-ray line from the Perseus cluster based on a class of non-abelian SU(2) DM models, in which the dark matter and an excited state comprise a “dark” SU(2) doublet. The non-abelian group kinetically mixes with the standard model gauge group via dimensions-5 operators. The dark matter particles annihilate into standard model fermions, followed by fragmentation and bremsstrahlung, and thus producing a continuous spectrum of gamma-rays. On the other hand, the dark matter particles can annihilate into a pair of excited states, each of which decays back into the dark matter particle and an X-ray photon, which has an energy equal to the mass difference between the dark matter and the excited state, which is set to be 3.5 keV. The large hierarchy between the required X-ray and γ-ray annihilation cross-sections can be achieved by a very small kinetic mixing between the SM and dark sector, which effectively suppresses the annihilation into the standard model fermions but not into the excited state.

Keywords: dark matter theory, X-rays, cosmic ray theory

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1 Introduction

A gamma-ray excess around a few GeV near the Galactic center (GC) region, seen by the Fermi-LAT collaboration (see, for instance, the recent analysis by the collaboration [1]), has been widely discussed based on dark matter (DM) annihilations into standard model (SM) fermions [2–15], which hadronize into neutral pions followed by $\pi^0 \rightarrow \gamma\gamma$, or electromagnetic bremsstrahlung. On the other hand, recent reports of the 3.5 keV X-ray line [16, 17] from the XMM-Newton data have triggered many studies in the context of DM, for example, refs. [18–65]. Roughly speaking, they can be classified into two categories: (i) DM undergoes upscattering into an excited stated followed by the decay back into DM and an X-ray photon; and (ii) decaying DM matter, such as a 7 keV sterile neutrino decaying into an active neutrino and the X-ray photon. The excited DM, however, has an advantage of explaining some null results on X-ray line searches due to a low local DM velocity as shown in ref. [66].

There is a very interesting connection between the $\gamma$-ray excess and X-ray line as follows. The GC $\gamma$-ray excess can be explained by annihilating DM with a mass from 10 to 60 GeV [2, 5–8, 10–12], depending on the final state of the annihilation. On the other hand, due to the fact that the current DM velocity is around $10^{-3} c$ in the Perseus cluster, where the X-ray line is observed, the DM with a mass of 10 to 60 GeV coincidentally has a kinetic energy of a few keV. It implies if there exists an excited state with a 3.5 keV mass splitting from the DM particle, then the DM particles can annihilate into the excited state, followed by the decay back into the DM particle with a photon accounting for the observed X-ray line.
In this work, we employ a class of non-abelian SU(2) \( X \) DM models proposed in refs. [18, 67], where the DM particle and the excited state form an SU(2) \( X \) doublet with a 3.5 keV mass splitting. The SU(2) \( X \) kinetically mixes with the SM gauge group via dimension-5 operators, through which the SM particles can couple to the SU(2) \( X \) currents and the DM (and the excited state) couples to the SM currents. As mentioned above, the GC \( \gamma \)-ray excess comes from the DM annihilation into SM fermions accompanied by photon emission while the X-ray line is realized from the DM annihilation into the excited state followed by the subsequent decay. Besides, the annihilation into SM fermions, induced by the kinetic mixing, is suppressed compared to that into the excited state if the kinetic mixing is small. This suppression naturally explains the hierarchy between the required annihilation cross-sections for the \( \gamma \)-ray excess \( (10^{-26} \text{ cm}^3\text{sec}^{-1}) \) and the X-ray line emission \( (10^{-19} \text{ cm}^3\text{sec}^{-1}) \) as shown below. Note that similar ideas connecting the \( \gamma \)-ray and X-ray excess have been suggested in refs. [18, 39] with intermediate states (instead of the SM fermion final state) while an effort connecting the 511 keV line [68] and the GC \( \gamma \)-ray excess turns out to be negative [69].

This paper is organized as follows. In section 2, we specify the model and divide into the Majorana and Dirac DM cases. In section 3, we calculate the relevant cross-sections. In section 4, we discuss the calculations of \( \gamma \)-ray and X-ray flux as well as the DM relic abundance. In section 5, we present our numerical analysis with separation into the Majorana and Dirac cases. Finally, we conclude in section 6.

2 Non-abelian dark matter models

For the nonabelian DM model, we employ a “dark” SU(2) \( X \) gauge group with kinetic mixing with the SM gauge groups proposed in refs. [18, 67]. We start with a SU(2) \( X \) doublet, which is comprised of the fields for the DM particle and an excited state. In the following we will discuss two cases: (i) Majorana DM (\( \chi_1 \)) with the Dirac excited state (\( \psi_2 \)) and (ii) Dirac DM (\( \psi_1 \)) with the Dirac excited state (\( \psi_2 \)).\(^1\) As we shall see later, we have to make use of the resonance enhancement in order to achieve large annihilation cross-sections, especially for explaining the X-ray line. The resonance enhancement does not occur if both DM and the excited state are Majorana with nearly degenerate masses, as shown in appendix A. On the other hand, the Dirac DM with the Majorana excited state will lead to a large \( \gamma \)-ray flux but a small X-ray one, in contradiction to the \( \gamma \)-ray and X-ray data Therefore, we will not discuss these two scenarios in this work. The Lagrangian of the model reads,

\[
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM_1} + \mathcal{L}_{DM_2} + \mathcal{L}_{mix},
\]

where \( \mathcal{L}_{SM} \) is the SM Lagrangian. \( \mathcal{L}_{DM_1,2} \) correspond to the DM sector, including the DM doublet and the dark SU(2) gauge bosons, \( X^a \) (\( a = (1, 2, 3) \)), and dark Higgs triplets/doublets, which are used to provide masses to \( \chi \)s and \( X \)s:

\[
\mathcal{L}_{DM_i} = -\frac{1}{4} X^\mu{}^a X^a_{\mu\nu} + (D^X_\mu \Delta_1)^\dagger (D^X_\mu \Delta_1) + (D^X_\mu \Delta_2)^\dagger (D^X_\mu \Delta_2),
\]

where \( D^X_\mu \) is the covariant derivative of SU(2) \( X \) and \( \Delta_{1,2} \) are SU(2) triplets, whose vacuum expectation values (VEVs) provide masses to dark gauge bosons. Note that one can play with the structure of \( \langle \Delta_i \rangle \) to give different masses to \( X^a \). For example, with \( \langle \Delta_2 \rangle = (0, v, 0)^T \) in the isospin basis (the first component has the highest isospin 1, the second with \( I^X_3 = 0 \), and so on) \( X^{1,2} \) are massive but \( X^3 \) remains massless.

\(^1\)In this work, we denote Majorana particles by \( \chi \) and Dirac particles with \( \psi \) for particles in the dark sector.
\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Field} & \Delta_{1,2} & h_D & \chi & \tilde{\chi}_2 & X^{1,2,3} \\
\hline
\text{SU}(2)_X & 3 & 2 & 2 & 1 & 3 \\
\text{spin} & 0 & 0 & 1/2 & 1/2 & 1 \\
\hline
\end{array}
\]

Table 1. The particle content and quantum numbers in the dark sector for the Majorana case.

2.1 Majorana DM

In the case of Majorana DM, the \( \mathcal{L}_{DM_2} \) takes the form

\[
\mathcal{L}_{DM_2} = i\chi^\dagger D^X_{\mu} \sigma^\mu \chi + i\tilde{\chi}_2^\dagger \partial_\mu \tilde{\sigma}^\mu \tilde{\chi}_2 + \left( \frac{i}{2} \lambda_\Delta (\chi \cdot \Delta_1 \cdot \chi) + \lambda_{h_2} (\chi \cdot h_D) \tilde{\chi}_2 + h.c. \right),
\]

where the two-component Weyl spinor notation is employed. Here "\( \cdot \)" refers to the SU(2)-invariant multiplication. \( \chi \) is an SU(2)\( _X \) doublet, consisting of two Weyl spinors, \( \chi_1 \) and \( \chi_2 \):

\[
\begin{align*}
\chi_1 & = \begin{pmatrix} h_1 \\ \chi \end{pmatrix}, \\
\chi_2 & = \begin{pmatrix} \chi \\
\chi_2 \end{pmatrix}.
\end{align*}
\]

The corresponding \( X^3 \)-current in the Weyl and Dirac-spinor notation is given by

\[
\mathcal{L} \supset g_X X^3 J_{\chi}^\mu = -\frac{g_X}{2} X^3_{\mu} \chi_1^\dagger \tilde{\sigma}^\mu \chi_1 + \frac{g_X}{2} X^3_{\mu} \chi_2^\dagger \tilde{\sigma}^\mu \chi_2
\]

\[
= -\frac{g_X}{2} X^3_{\mu} \tilde{\psi}_1 \gamma^\mu \left( -\frac{\gamma^5}{2} \right) \psi_1 + \frac{g_X}{2} X^3_{\mu} \tilde{\psi}_2 \gamma^\mu \left( 1 - \frac{\gamma^5}{2} \right) \psi_2,
\]

where the pre-factors \( \pm 1/2 \) come from the fact that \( \chi_{2(1)} \) has SU(2)\( _X \) isospin 1/2 (−1/2).

In order to give a Majorana mass to \( \chi_1 \), one can make use of the lowest isospin \( (I_3^X = -1) \) component of \( \langle \Delta_1 \rangle \), leaving VEVs of other components vanishing, i.e., \( \langle \Delta_1 \rangle = (0, 0, v_{-1})^T \) in the isospin basis. The \( \chi_1 \) mass becomes \( \lambda_\Delta v_{-1} \). Similarly, with the lower isospin \( (I_3 = -1/2) \) of \( \langle h_D \rangle \), the Dirac mass of \( \chi_2 \) and \( \tilde{\chi}_2 \) becomes \( \lambda_{h_2} v_{-1/2} \), where \( v_{-1/2} \) is the VEV of the component of \( I_3^X = -1/2 \). Moreover, \( X^\mu \)'s masses, at phenomenological level, are considered independent since as mentioned above one can always use \( \langle \Delta_2 \rangle \) to give a mass to specific gauge boson(s).

The particle content in the dark sector and the relevant quantum numbers in this model are summarized in table 1.

We would like to point out that the VEVs of \( \Delta_{1,2} \) and \( h_D \) are used to give a mass to the particles of interest and induce the kinetic mixing between the SM and the dark sector. We simply assume that they are very heavy and play no roles in the context of GC gamma ray excess and the 3.5 keV X-ray line.

2.2 Dirac DM

In the case of Dirac DM, the \( \mathcal{L}_{DM_2} \) takes the form

\[
\mathcal{L}_{DM_2} = i\chi^\dagger D^X_{\mu} \sigma^\mu \chi + \sum_{i=1}^2 i\chi_i^\dagger \partial_\mu \tilde{\sigma}^\mu \chi_i + (\lambda_{h_1} (\chi \cdot h_{D_1}) \tilde{\chi}_1 + \lambda_{h_2} (\chi \cdot h_{D_2}) \tilde{\chi}_2 + h.c.),
\]

-3
where $\langle h_{D_1} \rangle = (v_1, 0)^T$ ($\langle h_{D_2} \rangle = (0, v_2)^T$) gives a Dirac mass to $\chi_1$ and $\tilde{\chi}_1$ ($\chi_2$ and $\tilde{\chi}_2$). We list the particle content and quantum numbers in Table 2. The conversion between Dirac- and Weyl-spinors for $\chi_1$, $\chi_2$ and $\tilde{\chi}_2$ is:

$$
\psi_1 = \left( \begin{array} {c} \chi_1 \\ \tilde{\chi}_1 \end{array} \right),
$$

$$
\psi_2 = \left( \begin{array} {c} \chi_2 \\ \tilde{\chi}_2 \end{array} \right),
$$

(2.7)

and the corresponding $X^3$-current in the Weyl and Dirac-spinor notation is

$$
\mathcal{L} \supset g_X X_\mu^3 \bar{\psi}_1 \gamma^\mu \left( \frac{1 - \gamma^5}{2} \right) \psi_1 + \frac{g_X}{2} X_\mu^3 \bar{\psi}_2 \gamma^\mu \left( \frac{1 - \gamma^5}{2} \right) \psi_2.
$$

(2.8)

### 2.3 Kinetic mixing

Finally, $\mathcal{L}_{mix}$ describes the mixing between the SU(2)$_X$ and SM gauge groups [18, 67] via dimension-5 (dim-5) operators:

$$
\mathcal{L}_{mix} = \sum_{i=1}^{2} \frac{1}{\Lambda_i} \Delta_a X_a^\mu \gamma_\mu Y_{\nu},
$$

(2.9)

where the corresponding $X_a$ mixes with the SM $\gamma$ and $Z$ once $\Delta_a$ obtains a VEV. In this work, we choose $\mathcal{L}_{mix}$ to be

$$
\mathcal{L}_{mix} = -\frac{\sin \chi}{2} X_3^\mu \gamma_\mu Y_{\nu} - \frac{\sin \chi'}{2} X_1^\mu \gamma_\mu Y_{\nu},
$$

(2.10)

which implies $X^1$ and $X^3$ mixes with SM neutral gauge bosons at tree level. The reason why we include $X^1$ in the mixing is to enable the excited state $\psi_2$ to decay into the DM and a photon to explain the 3.5 keV X-ray line. Moreover, we assume $\sin \chi' \ll \sin \chi$ for simplicity and neglect the effect of $\sin \chi'$ in diagonalizing the gauge boson mass matrix.\(^2\) The relevant Lagrangian, with Lorentz indices suppressed, before and after diagonalizing the mass matrix of $\gamma$, $Z$ and $X^3$ reads

$$
\mathcal{L} \supset \left( \begin{array} {c} A_f \ Z_f \ X_f^3 \end{array} \right) \begin{pmatrix} e J_{EM} \\ g J_Z \\ g X J_X \end{pmatrix} = \begin{pmatrix} A_m \ Z_m \ X_m^3 \end{pmatrix} R \begin{pmatrix} e J_{EM} \\ g J_Z \\ g X J_X \end{pmatrix},
$$

(2.11)

\(^2\)It is a legitimate assumption as long as the lifetime of the excited state $\psi_2$ is less than 1 sec, thus having no influence on Big-Bang nucleosynthesis.
where $e$, $g$ and $g_X$ are U(1)$_{EM}$, SU(2)$_L$ and SU(2)$_X$ gauge couplings, respectively. The subscript $f$ refers to the flavor states, $m$ denotes the mass and kinetic eigenstates, and $J$s are currents. $R$ is the rotation matrix connecting the flavor and mass basis of the gauge bosons [70]:

$$R = \begin{pmatrix}
1 & 0 & 0 \\
-\cos\theta_w \tan\chi \sin\zeta & \cos\theta_w \tan\chi \cos\zeta + \cos\sec\chi \sin\zeta & 0 \\
-\cos\theta_w \tan\chi \cos\zeta & \sin\theta_w \tan\chi \cos\zeta - \sin\zeta \sec\chi \cos\zeta & 0
\end{pmatrix}, \quad (2.12)$$

where

$$\tan(2\zeta) = \frac{2\delta_X \left( m_{X3}^2 - m_W^2 \sec^2\theta_w \right)}{(m_{X3}^2 - m_W^2 \sec^2\theta_w)^2 - \delta_X^2},$$

$$\delta_X = -\frac{m_W^2 \sin\theta_w \tan\chi}{\cos^2\theta_w}. \quad (2.13)$$

It is clear that $R = 1_{3 \times 3}$ if $\sin\chi = 0$. Note that the photon does not couple to $J_X$ at tree-level but the interaction will be induced at loop-level. From now on, we will suppress the subscript $m$ in the gauge bosons: $A$, $Z$ and $X_3$ refer to the mass and kinetic eigenstates, unless otherwise stated.

3 Relevant annihilation cross-sections

In this section, we calculate the DM annihilation cross-sections into SM fermions and the excited state $\psi_2$. The first process will give rise to $\gamma$-rays via fragmentation of quarks and final state radiation from leptons, while the second one will yield X-rays when $\psi_2$ decays back into the DM and a photon via $\sin\chi' X_{1 \mu} Y_{\mu \nu}$ as shown in figure 1.

In this work, we focus on the regime, where $m_{X^a} > m_{DM}$, such that the GC gamma-ray excess and 3.5 keV X-ray line can be realized through DM annihilations into SM particles and excited $\chi_2$, respectively. As we shall see below, we need a large resonance enhancement in the annihilation cross-section coming from the $X^3$ narrow width; therefore, to a very good approximation, we only include $X^3$-exchange processes in the computation.

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3 To be more precise, $J_{EM}^{f \gamma \mu f} = Q f \gamma^{\mu} f$, while $J_Z = \frac{1}{\sin^2\theta_w} \bar{f} \gamma^{\mu} (\{I_3 - \sin^2\theta_w Q_I\} P_L + \{\sin^2\theta_w Q_I\} P_R) f$ for a fermion $f$. $P_{L(R)}$ is the left- (right-)handed projection operator. $J_X$ are defined in eq. (2.5) and (2.8) for the Majorana and Dirac DM, respectively.
$\chi_1 \chi_1$ annihilate into SM particles that fragment into photons, which are responsible for GC gamma rays.

### 3.1 Majorana DM

For Majorana DM, we have the following relevant annihilation cross-sections: $\chi_1 \chi_1 \rightarrow f \bar{f}$ ($P$-wave) for $\gamma$-ray and the DM density, $\chi_1 \chi_1 \rightarrow \bar{\psi}_2 \psi_2$ ($P$-wave), $\bar{\psi}_2 \psi_2 \rightarrow f \bar{f}$ ($S$-wave) for the DM density. In order to account for the X-ray line, the mass splitting between $m_{\chi_1}$ and $m_{\psi_2}$ is set to be 3.5 keV, which in turn implies that the $S$-wave $\bar{\psi}_2 \psi_2 \rightarrow f \bar{f}$ is the dominant contribution to the DM abundance computation as opposed to the $\gamma$-ray excess and X-ray line, which arise from $P$-wave processes due to axial-vector interactions of $\chi_1$.

For $\chi_1$ annihilating into SM fermions $f$ of mass $m_f$ via $X_3$, as shown in figure 2, the relevant interactions are

$$\mathcal{L}_{\chi_1 \chi_1 \rightarrow f \bar{f}} \supset -\frac{1}{2} (g_X \sec \chi \cos \zeta) X_3^\dagger \sigma^\mu \chi_1 X_3^\dagger \gamma^\mu (g_L P_L + g_R P_R) f,$$

(3.1)

where

$$g_L = -e Q_f \cos \theta_w \tan \chi \cos \zeta + (\sin \theta_w \tan \chi \cos \zeta - \sin \zeta) \frac{g}{\cos \theta_w} (I_3 - \sin^2 \theta_w Q_f),$$

$$g_R = -e Q_f \cos \theta_w \tan \chi \cos \zeta + (\sin \theta_w \tan \chi \cos \zeta - \sin \zeta) \frac{g}{\cos \theta_w} (-\sin^2 \theta_w Q_f),$$

(3.2)

in which $Q_f$ is the fermion electric charge and $I_3$ is the isospin, associated with left-handed field. The annihilation cross-section times the relative velocity $v$ is,

$$\langle \sigma v \rangle_{\chi_1 \chi_1 \rightarrow f \bar{f}} = \sum_f \frac{(g_X \sec \chi \cos \zeta)^2 \sqrt{s - 4m_f^2}}{48 \pi m_{\chi_1}^4 s^{3/2} \left( (s - m_{X_3}^2 + \Gamma_{X_3}^2 m_{X_3}^2) \right)} (\lambda_{\sigma_1} + \lambda_{\sigma_2} - \lambda_{\sigma_3}),$$

(3.3)

where

$$s = \frac{4m_{\chi_1}^2}{1 - v^2/4},$$

$$\lambda_{\sigma_1} = s^2 \left( m_{X_3}^2 (g_L^2 + g_R^2) + 6m_{\chi_1}^2 m_f^2 (g_L - g_R)^2 \right),$$

$$\lambda_{\sigma_2} = 2m_{X_3}^2 m_{\chi_1} m_f^2 (5g_L^2 - 18g_L g_R + 5g_R^2),$$

$$\lambda_{\sigma_3} = s^2 m_{X_3}^2 \left( 4m_{\chi_1}^2 (g_L^2 + g_R^2) + 3m_f^2 (g_L - g_R)^2 \right) + m_{X_3}^2 m_f^2 (g_L^2 - 6g_L g_R + g_R^2).$$

Note that one has to sum over all different final states as denoted by $\sum_f$. To simplify the expression, we employ the resonant limit of $m_{\chi_1} = \frac{1}{2} m_{X_3}$ on the matrix element while keeping

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4 Again, we use the Weyl spinor notation for Majorana $\chi_1$. 
the kinetic part intact.\(^5\) The annihilation cross-section reads, up to the second order in \(v^2\),

\[
(\sigma v)_{\chi_1 \chi_1 \to ff} \simeq \sum_f \frac{(g_X \sec \chi \cos \zeta)^2 \sqrt{s - 4m_f^2}}{96\pi \left( (s - m_{\chi_3}^2)^2 + \Gamma_{\chi_3}^2 m_{\chi_3}^2 \right)} m_{\chi_1} (g_1 v^2 + g_2 v^4),
\]

(3.4)

where

\[
g_1 = \left( g_L^2 + g_R^2 \right) - \frac{m_f^2 (g_L^2 - 6g_{LR} + g_R^2)}{4m_{\chi_1}^2},
\]

\[
g_2 = \frac{1}{8} \left( \left( g_L^2 + g_R^2 \right) + \frac{m_f^2 (g_L^2 - 3g_{LR} + g_R^2)}{m_{\chi_1}^2} \right).
\]

Similarly, for \(\bar{\psi}_2 \psi_2 \to \bar{f} f\), which is relevant for the relic abundance computation, we have, up to the first order in \(v^2\),

\[
(\sigma v)_{\bar{\psi}_2 \psi_2 \to ff} \simeq \sum_f \frac{(g_X \sec \chi \cos \zeta)^2 \sqrt{s - 4m_f^2}}{64\pi \left( (s - m_{\chi_3}^2)^2 + \Gamma_{\chi_3}^2 m_{\chi_3}^2 \right)} m_{\psi_2} (h_1 + h_2 v^2),
\]

(3.5)

with

\[
s = \frac{4m_{\psi_2}^2}{1 - v^2/4},
\]

\[
h_1 = \left( g_L^2 + g_R^2 \right) - \frac{m_f^2 (g_L^2 - 6g_{LR} + g_R^2)}{4m_{\psi_2}^2},
\]

\[
h_2 = \frac{5}{24} \left( g_L^2 + g_R^2 \right) + \frac{m_f^2 (g_L^2 - 6g_{LR} + g_R^2)}{96m_{\psi_2}^2}.
\]

In addition, the \(X^3\) decay width \(\Gamma_{X^3}\) is given by, including the channels into \(\chi_1\), \(\psi_2\) and SM fermions,

\[
\Gamma_{X^3} = \Gamma_{X^3 \to \chi_1 \chi_1} + \Gamma_{X^3 \to \bar{\psi}_2 \psi_2} + \sum_f \Gamma_{X^3 \to ff},
\]

(3.6)

where

\[
\Gamma_{X^3 \to \chi_1 \chi_1} = \Theta \left( m_{X^3} - 2m_{\chi_1} \right) (g_X \sec \chi \cos \zeta)^2 \frac{(m_{X^3}^2 - 4m_{\chi_1}^2)^{3/2}}{96\pi m_{X^3}^2},
\]

\[
\Gamma_{X^3 \to \bar{\psi}_2 \psi_2} = \Theta \left( m_{X^3} - 2m_{\psi_2} \right) (g_X \sec \chi \cos \zeta)^2 \frac{(m_{X^3}^2 - m_{\psi_2}^2)^{1/2}}{96\pi m_{X^3}^2},
\]

\[
\Gamma_{X^3 \to ff} = \Theta \left( m_{X^3} - 2m_f \right) \sqrt{m_{X^3}^2 - 4m_f^2} \frac{m_{X^3}^2 (g_L^2 + g_R^2) - m_f^2 (g_L^2 - 6g_{LR} + g_R^2)}{24\pi m_{X^3}^2}.
\]

(3.7)

\(^5\) We apply this simplification to annihilation cross-sections below as well.
processes are.

For Dirac DM, the distinctive feature compared to the Majorana case is that all relevant

\[ \sigma v = \frac{(g_X \sec \chi \cos \zeta)^4 \sqrt{s - 4m_{\psi_2}^2}}{192\pi m_{X^3}^4 s^{3/2} \left( (s - m_{X^3}^2)^2 + \Gamma_{X^3 m_{X^3}}^2 \right)} (\kappa_{\sigma_1} + \kappa_{\sigma_2}), \]  

where

\[ \kappa_{\sigma_1} = 6s^2 m_{X_1}^2 m_{\psi_2}^2 - 12s m_{X_3}^2 m_{X_1}^2 m_{\psi_2}^2, \]
\[ \kappa_{\sigma_2} = m_{X_3}^4 (2m_{X_1}^2 (5m_{\psi_2}^2 - 2s) + s (s - m_{\psi_2}^2)). \]

For \( m_{X_1} \approx m_{\psi_2} \), we have to a very good approximation, up to the second order in \( v^2 \):

\[ \sigma v \approx \frac{(g_X \sec \chi \cos \zeta)^4 \sqrt{s - 4m_{\psi_2}^2}}{1536\pi \left( (s - m_{X_3}^2)^2 + \Gamma_{X_3 m_{X_3}}^2 \right)} m_{X_1} (v^2 (3 + v^2)) \]  

### 3.2 Dirac DM

For Dirac DM, the distinctive feature compared to the Majorana case is that all relevant processes are \( S \)-wave dominated due to the vector interactions of \( \psi_1 \). The annihilation cross-section of \( \tilde{\psi}_1 \tilde{\psi}_1 \rightarrow f \bar{f} \) is, up to the first order in \( v^2 \),

\[ \sigma v \approx \sum_f \frac{(g_X \sec \chi \cos \zeta)^2 \sqrt{s - 4m_f^2}}{64\pi \left( (s - m_{X_3}^2)^2 + \Gamma_{X_3 m_{X_3}}^2 \right)} m_{\psi_1} (\omega_1 + \omega_2 v^2), \]  

with

\[ s = \frac{4m_{\psi_1}^2}{1 - v^2/4}, \]
\[ \omega_1 = \left( g_L^2 + g_R^2 \right) - \frac{m_f^2 \left( g_L^2 - 6g_L g_R + g_R^2 \right)}{4m_{\psi_1}^2}, \]
\[ \omega_2 = \frac{5}{24} \left( g_L^2 + g_R^2 \right) + \frac{m_f^2 \left( g_L^2 - 6g_L g_R + g_R^2 \right)}{96m_{\psi_1}^2}. \]

and for \( \tilde{\psi}_1 \tilde{\psi}_1 \rightarrow \tilde{\psi}_2 \tilde{\psi}_2 \) we have

\[ \sigma v \approx \frac{(g_X \sec \chi \cos \zeta)^4 \sqrt{s - 4m_{\psi_2}^2}}{393216\pi \left( (s - m_{X_3}^2)^2 + \Gamma_{X_3 m_{X_3}}^2 \right)} m_{\psi_1} (1152 + 336v^2 + 83v^4). \]  

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**Figure 3.** \( \chi_1 \chi_1 \) annihilation into \( \tilde{\psi}_2 \tilde{\psi}_2 \) responsible for the X-ray line.
Note that the $X^3$ partial decay width into $\bar{\psi}_1\psi_1$ becomes

$$\Gamma_{X^3 \to \bar{\psi}_1\psi_1} = \Theta \left( m_{X^3} - 2m_{\psi_1} \right) \left( g_X \sec \chi \cos \zeta \right)^2 \frac{\left( m_{X^3}^2 - m_{\psi_1}^2 \right) \left( m_{X^3}^2 - 4m_{\psi_1}^2 \right)}{96\pi m_{X^3}^2} \left( m_{X^3}^2 - 2m_{\psi_1}^2 \right)^{1/2} \left( m_{X^3}^2 - 4m_{\psi_1}^2 \right)^{1/2} \frac{1}{96\pi m_{X^3}^2} \left( 3.13 \right)$$

Furthermore, the Dirac DM $\psi_1$ will have sizable DM-nucleon interactions in the context of direct detections. The effective DM-quark interaction reads,

$$L \supset -\frac{(g_X \sec \chi \cos \zeta) (g_L + g_R)}{8m_{X^3}^2} \bar{\psi}_1 \gamma^\mu \psi_1 \bar{f} \gamma_\mu f, \quad (3.14)$$

where $g_L$ and $g_R$ are defined in eq. (3.2).

### 4 Observables

Based on the DM annihilation cross-sections into the excited state and SM fermions, we now describe how to compute the flux of $X$-rays and $\gamma$-rays, and will comment on the DM relic density computation.

#### 4.1 X-ray

Recently, a potential signal of a monochromatic photon line from the Perseus cluster at energy around $3.56$ keV has been identified from the XMM-Newton data [16, 17]. The flux of such a monochromatic photon line at the X-ray energy $E_\gamma = 3.56$ keV is measured to be $\Phi_{\gamma\gamma} = 5.2^{+3.70}_{-2.13} \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ [17]. Although the source of this X-ray line signal is still unclear, the DM annihilation (or decay) into photons is a well motivated possibility [18–36, 38–65]. Considering the Perseus Mass $\simeq 1.49 \times 10^{14} M_\odot$ and the distance between the Perseus cluster and the solar system $\simeq 78$ Mpc, the photon-line flux from DM annihilation can be written as

$$\Phi_{\gamma\gamma} \text{cm}^{-2}\text{s}^{-1} = 2.08 \times 10^{-3} \times \left[ \frac{1 \text{ GeV}}{m_{DM}} \right]^2 \times \frac{D \langle \sigma v \rangle_{\gamma\gamma}}{10^{-19} \text{cm}^3\text{s}^{-1}}, \quad (4.1)$$

where $D$ is 1 for Majorana DM and 1/2 for Dirac DM. The monochromatic annihilation cross section $\langle \sigma v \rangle_{\gamma\gamma}$ is the relative velocity averaged with all the DM inside the Perseus cluster. Here, we adopt the relative velocity $v_{rel.}$ described by the Maxwell-Boltzmann distribution [71],

$$f(v_{rel.}) = \frac{v_{rel.}^2}{2\sqrt{\pi}v_0^2} \exp \left[ -\frac{v_{rel.}^2}{4v_0^2} \right], \quad (4.2)$$

where we take the mean value of the velocity dispersion $v_0 \sim 10^{-3} c$ [71]. One can see that a DM mass $m_{DM} \sim 10$ GeV requires $\langle \sigma v \rangle_{\gamma\gamma} \sim 2.5 \times 10^{-19} \text{cm}^3\text{s}^{-1}$ in order to explain the X-ray signal from the Perseus cluster.

It is worthy to mention that the information of Perseus mass, which is constrained by the velocity dispersion, can substantially reduce the uncertainties arising from halo inner slope. In ref. [39], an overall uncertainty about a factor of 5 was obtained for the DM flux predicted in eq. (4.1).
4.2 GC γ-ray

A gamma-ray excess in the GC region, found in the Fermi-LAT data, has been widely studied in the context of DM annihilation [2–7, 10–12]. Assuming spherical symmetry, the spatial distribution of such an excess can be explained by DM annihilation in the generalized Navarro-Frenk-White (gNFW, [72, 73]) profile,

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}. \quad (4.3)$$

To explain the gamma-ray excess, the inner slope $\gamma$ parameter requires $\gamma = 1.2$ [11, 74]. In this work, we adopt this value together with the local density $\rho(8.5\text{ kpc}) = 0.4\text{ GeV/cm}^3$ and $r_s = 20\text{ kpc}$.

The differential diffuse gamma-ray flux along a line-of-sight (l.o.s.) at an open angle relative to the direction of the GC is given by

$$\frac{dN}{dE} = \frac{(\sigma v)_\gamma}{D \pi m^2_\chi} \frac{dN}{dE} \int_{\text{l.o.s.}} ds \rho^2(r(s,\psi)), \quad (4.4)$$

where $D$ is 8 for Majorana DM but 16 for Dirac one. The $\langle \sigma v \rangle_\gamma$ is the velocity averaged annihilation cross section at the GC. However, the mean value of the velocity dispersion $v_0$ in eq. (4.2) is $\sim 10^{-4}\text{ c}$ at the GC region [71, 75].

The $\frac{dN}{dE}$ is the photon energy distribution per annihilation. All possible annihilation channels are included. The branching ratio of all the possible annihilation channels can be obtained by using eq. (3.4) and (3.11). For each annihilation channel, the corresponding $\frac{dN}{dE}$ is taken from the numerical PPC4 table [76].

One has to bear in mind that the background uncertainties for the GC gamma ray excess can significantly change the DM parameter space. Therefore, in order to include the background uncertainties, we use the central values and error bars in figure 17 from ref. [77], where the systematic uncertainties coming from the Galactic diffuse emission have been properly included. Following ref. [77], the inner Galactic central region described by the Galactic longitude $\ell$ and latitude $b$ is

$$|\ell| \leq 20^\circ \quad \text{and} \quad 2^\circ \leq |b| \leq 20^\circ. \quad (4.5)$$

We conclude this section with figure 4 where the data on γ-ray spectrum is taken from ref. [77] and the photon spectra are calculated using our best-fit points in both the Majorana (solid red line) and Dirac cases (dashed blue line), for which we include the γ-ray and X-ray data into fitting. One can see the GC γ-ray excess, a distinctive bump around a few GeV, can be well explained by DM annihilations into the SM fermions, which then fragment into photons. The continuous photon spectrum mainly comes from the decay of neutral pions, which are originated from the fragmentation of the quarks in the annihilation of the dark matter. In addition, the quarks can also fragment into charged pions, which subsequently decay into muons and eventually electrons. The dark matter can also directly annihilate into taus, muons, and electrons. The taus and muons will eventually decay into electrons. Although all these electrons undergo the inverse Compton scattering and bremsstrahlung, which can only give rise to photons at the lower photon energy, it does not effect the region of $E_\gamma > 1\text{ GeV}$ [78]. As a result, we do not consider inverse Compton scattering and bremsstrahlung in this study.
Figure 4. GC γ-ray excess spectrum taken from ref. [77]. We also show the corresponding photon spectra obtained for the Majorana (solid red line) and Dirac (dashed blue line) case.

4.3 DM relic abundance

The DM relic density can be obtained by solving the Boltzmann equation for the DM density evolution with the thermally-averaged annihilation cross-section into SM fermions. In this work, we assume that the thermal relic scenario such that the current relic density is determined by the DM annihilation and coannihilation of the excited state, and the number densities of these particles follow the Boltzmann distribution before freeze-out. Note that, in the context of the relic density calculation, one cannot simply assume \( v \ll 1 \), that is only valid in the X-ray and γ-ray flux computation. Instead, one has to properly take into account the thermal average effect. Following ref. [79], we compute the thermal relic density from the thermally averaged annihilation cross-section based on eqs. (3.3), (3.5) and (3.11). However, the effective relativistic degrees of freedom are taken from the default numerical table of DarkSUSY [80]. Also, we use the PLANCK result of \( \Omega h^2 = 0.120 \) [81] together with the 10% theoretical error to constrain the relic density.

A comment on the DM density computation is in order here. Due to a small mass splitting of 3.5 keV between the DM particle and excited state to account for the X-ray line, coannihilation processes involving the excited state have to be taken into account. As mentioned above, we focus on the scenario with the resonance enhancement via the \( X^3 \) exchange. As a result, the only relevant interactions are the DM annihilation and excited state annihilation into SM fermions. For the Majorana DM case, the dominant contribution to relic abundance comes from the excited state annihilation, \( \psi_2 \bar{\psi}_2 \rightarrow \bar{f}f \), which is dominated by \( S \)-wave due to the Dirac nature of \( \psi_2 \), while \( \chi_1 \chi_1 \rightarrow \bar{f}f \) is \( P \)-wave suppressed because of \( \chi_1 \) being Majorana. Furthermore, the large resonance enhancement in the process \( \chi_1 \chi_1 \rightarrow \bar{f}f \) required to explain the X-ray line at current time \( (v \sim 10^{-5}c) \) is no longer the case at...
the time of freeze-out, because during the freeze-out the relative velocity is much larger of order $\sim \frac{1}{4}c$ such that the annihilation deviates considerably away from the resonance region. Therefore, $\langle \sigma v \rangle_{1\chi_1 \rightarrow \bar{f} f}$ at freeze-out is much smaller than the current annihilation cross-section $10^{-26}\text{ cm}^3\text{sec}^{-1}$, which is the right size to accommodate the GC $\gamma$-ray excess.\footnote{One might think that $S$-wave dominated interactions will have the same cross-section at freeze-out as the current one while $P$-wave dominated ones have the larger cross-section at freeze-out due to the larger DM velocity ($\sim \frac{1}{4}c$) compared to the current velocity ($\sim 10^{-3}c$). However, it is not always true, especially when the resonance enhancement takes place as we shall see later.} Hence, $\chi_1\chi_1 \rightarrow \bar{f} f$ alone cannot give rise to the correct relic density, which roughly requires an annihilation cross section of $3 \times 10^{-26}\text{ cm}^3\text{sec}^{-1}$. For the Majorana DM case, this problem can be circumvented by the $S$-wave process $\psi_2\bar{\psi}_2 \rightarrow \bar{f} f$, which can give an annihilation cross section of order $10^{-26}\text{ cm}^3\text{sec}^{-1}$ to explain the relic abundance.

In the Dirac DM case, however, both $\psi_1$ and $\psi_2$ are Dirac particles and all processes are $S$-wave dominated. In the context of the DM density, annihilations of $\psi_1$ and those of $\psi_2$ contribute almost equally due to the nearly degenerate mass spectrum. However, the annihilation cross sections of both processes are much smaller than $10^{-26}\text{ cm}^3\text{sec}^{-1}$ at freeze-out due to the deviation from the resonance region as explained above. Therefore, one has to involve an additional DM annihilation mechanism to reduce the relic abundance. A possible solution, for instance, is to embed $(\chi_2, \chi_1)^T$ into a larger multiplet such as $(\chi_4, \chi_2, \chi_1, \chi_3)^T$ such that annihilations between $\chi_1$ and $\chi_3$ via $X^{1,2}$ is possible to bring down the relic density. As long as the mass difference between $m_{\chi_3}$ and $m_{\chi_1}$ is much larger than 3.5 keV, $\chi_3$ cannot be generated currently and thus the existence of $\chi_3$ is irrelevant to the X-ray line and $\gamma$-ray excess.

We summarize the discussion here with table 3, where we show the cross-sections in orders of magnitude in units of cm$^{-3}$sec$^{-1}$ at the freeze-out and at the current time. $\langle \sigma v \rangle_{\chi_1\chi_1 \rightarrow \bar{\psi}_2\psi_2}$ and $\langle \sigma v \rangle_{\bar{\psi}_1\psi_1 \rightarrow \bar{\psi}_2\psi_2}$ at freeze-out are not relevant for DM relic density computation.

| DM Type   | $\langle \sigma v \rangle_{\chi_1\chi_1 \rightarrow \bar{f} f}$ | $\langle \sigma v \rangle_{\bar{\psi}_2\psi_2 \rightarrow \bar{f} f}$ | $\langle \sigma v \rangle_{\chi_1\chi_1 \rightarrow \bar{\psi}_2\psi_2}$ |
|------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| Majorana   | $10^{-26}$ (GC $\gamma$-ray)                                   | $10^{-26}$ (X-ray)                                             | $10^{-26}$ (X-ray)                                             |
| Dirac      | $0$                                                            | $10^{-26}$ (GC $\gamma$-ray)                                   | $10^{-26}$ (X-ray)                                             |

Table 3. Relevant cross-sections in orders of magnitude in units of cm$^{-3}$sec$^{-1}$ at the freeze-out and at the current time. $\langle \sigma v \rangle_{\chi_1\chi_1 \rightarrow \bar{\psi}_2\psi_2}$ and $\langle \sigma v \rangle_{\bar{\psi}_1\psi_1 \rightarrow \bar{\psi}_2\psi_2}$ at freeze-out are not relevant for DM relic density computation.

5 Results

In order to employ the resonance enhancement, we rewrite $m_{\chi_3} = (2 - \delta)m_{DM}$ with $m_{DM} = m_{\chi_1}$ ($m_{\psi_1}$) in the Majorana (Dirac) DM case. Therefore, at phenomenological level we choose $m_{\chi_1}$, $g_X$, $\delta$ and $\sin \chi$ as 4 independent input parameters to investigate if the proposed non-abelian DM models can simultaneously account for the GC $\gamma$-ray excess and the 3.5 keV X-ray line, and thermally reproduce the correct relic abundance.
Before moving into the numerical analysis, we would like to comment on the region of interest for $\sin \chi$. For illustration, we choose the Majorana DM case but the Dirac DM case exhibits the same feature. As mentioned above, we aim for $\langle \sigma v \rangle_{\chi_1 \chi_1 \to \bar{\psi}_2 \psi_2} \sim 10^{-19} \text{ cm}^3 \text{ sec}^{-1}$ to explain the 3.5 keV X-ray line and $\langle \sigma v \rangle_{\chi_1 \chi_1 \to ff} \sim 10^{-26} \text{ cm}^3 \text{ sec}^{-1}$ to realize the GC $\gamma$-ray excess. On the other hand, we have from eq. (3.4) and (3.10) in the limit of $m_{\chi_1}^2 \gg v^2$ and $m_f \simeq 0$,

$$
\langle \sigma v \rangle_{\chi_1 \chi_1 \to ff} \sim \frac{\sqrt{s}}{(s - m_{\chi_1}^2/2 + \Gamma_{\chi_1}^2 m_{\chi_1}^2)} \left( g_L^2 + g_R^2 \right) v^2 \sim \frac{\sqrt{s}}{m_{\chi_1}^4 v_{\text{rel}}^4 + 4 m_{\chi_1}^2 \Gamma_{\chi_1}^2} \sin^2 \chi v^2,
$$

$$
\langle \sigma v \rangle_{\chi_1 \chi_1 \to \bar{\psi}_2 \psi_2} \sim \frac{\sqrt{s - 4m_{\psi_2}^2}}{(s - m_{\chi_1}^2/2 + \Gamma_{\chi_1}^2 m_{\chi_1}^2)} v^2 \sim \frac{\sqrt{s - 4m_{\psi_2}^2}}{m_{\chi_1}^4 v_{\text{rel}}^4 + 4 m_{\chi_1}^2 \Gamma_{\chi_1}^2} v^2,
$$

(5.1)

where we have suppressed the kinematics factors and the coupling constant $g_X$, which do not affect the argument. It is clear that in order to achieve $\langle \sigma v \rangle_{\chi_{\text{DM}}}/\langle \sigma v \rangle_{\gamma} \sim 10^7$, one must have $\sin^2 \chi$ smaller than $10^{-7}$. It implies that in the denominator of the cross-section, $\Gamma_{\chi_1}^2 m_{\chi_1}^2 \sim \left( \frac{1}{16\pi} \right)^2 m_{\chi_1}^4 \sin^4 \chi$ becomes negligible compared to $m_{\chi_1}^4 v^4$ with $v \sim 10^{-3} c$. In other words, we saturate the resonance enhancement since the DM velocity becomes dominant in the denominator and any further decrease in $\sin \chi$ will not affect the cross-section. In figure 5, we can clearly see that for both the Majorana and Dirac case, $\sin \chi$ is located in the saturated area, i.e., $\sin \chi \ll v$. Furthermore, the reasons why the required mixing is so small, $\sin^2 \chi \ll 10^{-7}$, are because first, $\langle \sigma v \rangle_{\chi_1 \chi_1 \to \bar{\psi}_2 \psi_2}$ has a large kinematical suppression factor, compared to $\langle \sigma v \rangle_{\chi_1 \chi_1 \to ff}$ and second, the $v$ for X-rays in the Perseus cluster is larger than the $v$ for $\gamma$-rays in the GC. Subsequently, $\langle \sigma v \rangle_{\chi_1 \chi_1 \to \bar{\psi}_2 \psi_2}$ is much smaller than $\langle \sigma v \rangle_{\chi_1 \chi_1 \to ff}$ with $\sin \chi \sim 1$. It indicates that one actually needs $\sin^2 \chi \ll 10^{-7}$ in order to fulfill $\langle \sigma v \rangle_{\chi_{\text{DM}}}/\langle \sigma v \rangle_{\gamma} \sim 10^7$.

For the fitting procedure, we make use of the minimum chi-squared method. Since the likelihoods for the relic density, X-ray line, and GC $\gamma$-rays data are well Gaussian-distributed, and the 95% and 99.73% confidence limits in two-dimensional contour plots correspond to $\delta \chi^2 = 5.99$ and $\delta \chi^2 = 11.83$, respectively.

### 5.1 Majorana case

In this section, we present the results in the Majorana DM case with the Majorana DM $\chi_1$ and the Dirac excited state $\psi_2$. Throughout this (and also next) section, the way we present the results is to project confidence regions into planes of parameters or observables. In the figures, inside the legend: “GC+Perseus” means that the confidence regions are obtained from the fit with only the GC $\gamma$-ray and X-ray data, while “GC+Perseus+$\Omega h^2$” indicates that the DM relic density is also included in the fit in addition to the $\gamma$- and X-ray data.

In figure 6, we show the confidence regions in terms of the DM annihilation cross-section for the X-ray and $\gamma$-ray versus the DM mass. In the upper panels, we include the GC $\gamma$-ray excess and X-ray line only while the DM density is also included in the lower panels. The green (blue) area corresponds to the 95% (99.73%) confidence region while the red star represents the best-fit point. Furthermore, the unitarity bound [82] denoted by the red line.

In figure 6, for instance, we project the confidence region into the $\langle \sigma v \rangle_{X\gamma m_{\chi_1}}$ (left panels) and $\langle \sigma v \rangle_{\gamma m_{\chi_1}}$ (right panels) plane.
Figure 5. Left panel: the Majorana case. Right panel: the Dirac case. The grey band represents the 95% confidence region for the γ-rays and X-rays data.

comes from

$$\langle \sigma v \rangle \lesssim \frac{3 \times 10^{-22} \text{ cm}^3/\text{sec}}{m_{\chi_1}/(1 \text{ TeV})}.$$  \hfill (5.2)

We would like to make the following comments.

- The corresponding X-ray cross-section (left panels) is centered around $10^{-18} \text{ cm}^3/\text{sec}$ consistent with eq. (4.1) while for γ-rays (right panels), one needs $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3/\text{sec}$ complying with ref. [77].

- The γ-ray spectrum coming from $\chi_1\chi_1 \rightarrow ff$ certainly depends on the final states. In this model, the final states include both quarks and leptons, and the final state composition is fixed according to eq. (3.1) and (3.2). In general, a quark final state demands a higher DM mass due to soft photon spectra compared to a leptonic one. Therefore, $m_{\chi_1}$ will lie between that of the purely $b$-quark case and that of purely $\tau$ case.

- For X-ray plots (left panels), there exists a sharp cut-off close to the best-fit point on the top of the confidence regions. It is due to the perturbative limit: $g_X \leq 4\pi$ as we shall see later the best-fit point has $g_X$ quite close to $4\pi$. In contrast, the best-fit points for γ-ray plots (right panels) are located near the central area of the confidence region, which comes from the fact the $\langle \sigma v \rangle_\gamma$ can be enlarged by increasing the mixing $\sin \chi$ between the SM and dark sector without varying $g_X$ as shown in figure 5 while $\langle \sigma v \rangle_{\text{X-ray}}$ is insensitive to $\sin \chi$ in the saturated area.

- All plots exhibit a sharp cut-off on 2σ regions especially on the left-hand side. It is due to the fact that GC γ-ray bump shown in figure 4 has a sharp drop around 0.5 GeV compared to the milder change on the right hand side around 20 GeV. Consequently, the bump of the predicted photon spectrum will not coincide with that of the GC excess, leading to a surge in chi-square, once $m_{\chi_1}$ becomes much smaller than the best-fit value.
Figure 6. The 95% and 99.73% confidence-level regions in the plane of annihilation cross sections versus the DM mass obtained in the fits with (i) GC gamma-ray and Perseus X-ray data (upper panels) and (ii) also the DM relic density (lower panels) for the Majorana DM case. We show on the left panels: \(\langle \sigma v \rangle_{X}\) versus \(m_{\chi_1}\) for X-rays, and on the right panels: \(\langle \sigma v \rangle_{\gamma}\) versus \(m_{\chi_1}\) for \(\gamma\)-rays.

- As explained in section 4.3, the Majorana DM case can accommodate the correct DM density with the \(S\)-wave process \(\psi_2 \psi_2 \rightarrow \bar{f} f\) being the main contribution. Including the DM relic constraint reduces the confidence region significantly; only in the region of \(25 \lesssim m_{\chi_1} \lesssim 40\) GeV can the model yield the correct DM density.

In figure 7, we show \(g_X\) versus \(m_{\chi_1}\) in the upper panels and \(\sin \chi\) versus \(m_{\chi_1}\) in the lower panels. For the left panels, only the \(\gamma\)-ray and X-ray data are included in the fits while the DM density is also included in the right panels. Note that both \(\chi_1 \chi_1 \rightarrow \bar{f} f\) responsible for the GC \(\gamma\)-ray excess and \(\chi_1 \chi_1 \rightarrow \bar{\psi}_2 \psi_2\) for the X-ray line are \(P\)-wave suppressed by the small DM velocity in the current Universe. To compensate for the velocity suppression, one needs large \(g_X\) in addition to the resonance enhancement to realize the very large \(\langle \sigma v \rangle\), which
is proportional to $g_X^4$, for the X-ray line. It turns out that $g_X$ is close to the perturbativity limit $4\pi$ for the best-fit point. In contrast, as we shall see later, the Dirac case features $S$-wave dominated cross-sections, i.e., without the velocity suppression, where $g_X$ can be much smaller ($\sim 1$). The mixing between the SM and the dark sector is roughly of order $10^{-7}$ but with a dip for $m_{\chi_1} = \frac{1}{2}m_Z$. It comes from large $\zeta$ defined in eq. (2.13) for $m_{X^3}$ ($= 2m_{\chi_1}$) $\simeq m_Z$, leading to large $g_{L,R}$ ($\sim \sin \zeta$) defined in eq. (3.2) and large $\langle \sigma v \rangle_\gamma$. On the other hand, $\langle \sigma v \rangle_{X,\text{ray}}$ ($\sim \cos \zeta$) does not change dramatically for $m_{\chi_1} = \frac{1}{2}m_Z$. So as to maintain $\langle \sigma v \rangle_{X,\text{ray}}/\langle \sigma v \rangle_\gamma \sim 10^7$, smaller $\sin \chi$ is needed to suppress the $\gamma$-ray flux with respect to the X-ray one. Note that when $m_{X^3} \sim m_Z$, the electroweak precision data put a stringent bound on the SM-dark sector mixing, $\sin \chi \lesssim 5 \times 10^{-3}$ [83], which is however too weak to constrain any relevant parameter space of the model under consideration.
We conclude this section with figure 8, in which we project the confidence regions, including the X-ray and γ-ray data only, into the DM relic density and $m_{\chi_1}$ plane. It is clear that only for $25 \leq m_{\chi_1} \leq 40$ GeV, the correct DM density can be reproduced. Furthermore, the best-fit point corresponds to the slightly lower relic density, which results in a minor shift in the best-fit point when the DM relic density is included into the fit, as can be seen from figure 6 and 7.

5.2 Dirac case

Here we show the results of the Dirac DM case. As argued in section 4.3, all relevant processes responsible for the X-ray line, GC γ-ray excess and DM relic density are S-wave dominated. Moreover, the large cross-section needed to account for the X-ray line requires the large resonance enhancement with the help of the very small $X^3$ decay width. The large DM velocity ($\sim \frac{1}{3} c$) at freeze-out implies a considerable deviation from the resonance when DM decouples from the thermal universe. In order to achieve $\langle \sigma v \rangle_\gamma \sim 10^{-26}$ cm$^3$sec$^{-1}$ at current time, the cross-section of $\bar{\psi}_1 \psi_1 \rightarrow f\bar{f}$ at freeze-out will be much smaller than $3 \times 10^{-26}$ cm$^3$sec$^{-1}$, the size required to reproduce the DM density. Therefore, we do not include the DM relic density constraint into the fits here. Notice that we have to take into account the stringent bounds on the spin-independent DM-nucleon cross-section [84] due to vector-current interactions, but it hardly has any impact on the analysis since $\sin \chi$ of interest is extremely small, leading to a large suppression on the DM-nucleon cross-section.

In figure 9, we show $\langle \sigma v \rangle$ versus $m_{\psi_1}$ for X-rays (left panel) and γ-rays (right panel). Unlike the Majorana case in figure 6, the best-fit point in $\langle \sigma v \rangle_{\gamma-ray}$ is near the central area...
Figure 9. The 95% and 99.73% confidence-level regions in the plane of annihilation cross sections versus the DM mass obtained in the fits with GC gamma-ray and Perseus X-ray data only for the Dirac DM case. Left panel: $\langle \sigma v \rangle_{\text{X-ray}}$ versus $m_{\psi_1}$ for X-rays; right panel: $\langle \sigma v \rangle_{\gamma}$ versus $m_{\psi_1}$ for $\gamma$-rays.

Figure 10. The 95% and 99.73% confidence-level regions in the planes of $(m_{\chi_1}, g_X)$ (left panel), $(m_{\chi_1}, \sin \chi)$ (middle), and $(m_{\chi_1}, \delta)$ (right) obtained in the fits with GC gamma-ray and Perseus X-ray data only in the Dirac DM case.

of the confidence region since $g_X$ is much smaller than that of the Majorana case. The steep shrink on the $2\sigma$ confidence region, which is observed at the Majorana case as well, around $m_{\psi_1} \approx 29$ GeV is again due to the sharp change on the GC $\gamma$-ray spectrum around 0.5 GeV shown in figure 4.

In figure 10, we show $g_X$, $\sin \chi$ and $\delta$ versus $m_{\psi_1}$, respectively. All processes of interest are $S$-wave dominated without the DM velocity suppression. It implies that the resonance enhancement from the narrow $X^3$ decay width alone is sufficient to achieve the large $\langle \sigma v \rangle_{\text{X-ray}}$ without resorting to large $g_X$. Therefore, $g_X$ is of $\mathcal{O}(0.6)$ in this case, compared to $g_X \sim 10$ for Majorana $\chi_1$. Similar to the Majorana DM case explained above, around $m_{\psi_1}$ ($\simeq m_{X^3}$) $\approx \frac{1}{2}m_Z$, $\zeta$ defined in eq. (2.13) becomes large, resulting in large $g_{L,R}$ ($\sim \sin \zeta$) and $\langle \sigma v \rangle_{\gamma}$. It is then offset by the decrease in $\sin \chi$ as shown in the left panel of figure 10. At the same time,
from eq. (3.11), large \( \zeta \) implies that \( \langle \sigma v \rangle_{\text{X-ray}} \sim (g_X \cos \zeta) \) becomes smaller. So \( g_X \) has to increase to achieve \( \langle \sigma v \rangle_{\text{X-ray}} \sim 10^{-19} \) \( \text{cm}^{3}\text{sec}^{-1} \) for the X-ray line, as seen from the middle panel. In addition, larger \( g_X \) implies larger \( \langle \sigma v \rangle_{\gamma} \), which can be reduced by larger \( \delta \) (and a larger deviation away from the resonance region) as in the right-panel.\(^8\) Note that for the Majorana case, we do not spot this behavior for \( g_X \) and \( \delta \) since \( g_X \) is constrained to be less than \( 4\pi \).

To summarize, we present in table 4 the chi-squares (\( \chi^2 \)) and \( p \)-values for the best-fit points, and also the \( 3\sigma \) confidence regions for both the Majorana and Dirac DM cases. We would like to emphasize again that first, both cases can explain the \( \gamma \)-ray and X-ray data but only the Majorana DM can reproduce the correct DM density. Second, the best-fit point shifts toward the lower \( m_{\chi_1} \) region when including the DM relic density into the fits. Finally, \( g_X \) is close to \( 4\pi \) in the Majorana case because of \( P \)-wave velocity suppression as opposed to the Dirac case where \( g_X \) is of \( \mathcal{O}(0.6) \).

6 Conclusions

In this work, we have attempted to explain simultaneously the GC \( \gamma \)-ray excess and the 3.5 keV X-ray line, as well as fulfilling the DM relic abundance in the context of non-abelian DM models, and we have success in the case of Majorana DM with a Dirac excited state. We employed a “dark” SU(2)\(_X\) gauge group with a SU(2)\(_X\) doublet consisting of the DM particle and the excited state with a mass-splitting of 3.5 keV. The SU(2)\(_X\) sector talks to the SM gauge groups via kinetic mixing, characterized by \( \sin \chi \). We have studied two cases: Majorana DM (\( \chi_1 \)) and Dirac DM (\( \psi_1 \)), and both with the Dirac excited state \( \psi_2 \). The X-ray line results from \( \chi_1 \chi_1 \rightarrow \psi_1 \psi_2 \rightarrow \psi_2 \psi_2 \), followed by the decay of \( \psi_2 \) back to the DM and a photon. On the other hand, DM annihilations into SM fermions, which then emit photons, can explain the GC \( \gamma \)-ray excess but this process is suppressed by the aforementioned SU(2)\(_X\)-SM kinetic mixing. In order to account for the \( \gamma \-) and X-ray data, one would need \( \langle \sigma v \rangle_{\text{X-ray}} \sim 10^{-19} \) and \( \langle \sigma v \rangle_{\gamma} \sim 10^{-26} \) \( \text{cm}^{3}\text{sec}^{-1} \). We employ the resonance enhancement to fulfill the large \( \langle \sigma v \rangle_{\text{X-ray}} \). Additionally, the large hierarchy between two cross-sections \( \langle \sigma v \rangle_{\text{X-ray}}/\langle \sigma v \rangle_{\gamma} \) (\( \sim 10^7 \)) can be realized if the kinetic mixing is very small (\( \sin \chi \lesssim 10^{-7} \)).

\(^8\) Again, \( \langle \sigma v \rangle_{\text{X-ray}} \) is insensitive to the \( \delta \) change in the saturated area as shown in figure 5.
For the Majorana DM case, both the $\gamma$-ray and X-ray excess can be accommodated really well. However, all $\chi_1$-involved processes are $P$-wave suppressed due to the Majorana nature. As a result, the SU(2)$_X$ gauge coupling $g_X$ is driven close to the perturbativity limit $4\pi$ to counterbalance the velocity suppression. Regarding the DM relic density, the relatively large DM velocity ($\sim 1/3c$) at freeze-out compared to the current one ($\sim 10^{-3}c$) implies a large deviation from the resonance region. Therefore, the cross-section of $\chi_1\chi_1 \to \bar{f}f$ at freeze-out is much smaller than the current value $10^{-26}$ cm$^3$sec$^{-1}$ demanded to explain the GC $\gamma$-ray excess, as well as much smaller than $3 \times 10^{-26}$ cm$^3$sec$^{-1}$, the size of the cross section to achieve the correct relic density. The solution comes from the $S$-wave dominated process $\bar{\psi}_2\psi_2 \to \bar{f}f$, which should be included as a coannihilation process at the freeze-out in light of the tiny mass splitting between $\chi_1$ and $\psi_2$. The coannihilation can reach a level of $3 \times 10^{-26}$ cm$^3$sec$^{-1}$ for certain $m_{\psi_2}$ to reproduce the correct relic density. The allowed $m_{\chi_1}$ (also $m_{\psi_2}$) ranges from 25 to 40 GeV. This coannihilation cross section is much larger than the cross section of the $P$-wave process $\chi_1\chi_1 \to \bar{f}f$.

In the Dirac DM case, the model can explain both $\gamma$- and X-ray data for $16 \lesssim m_{\psi_1} \lesssim 56$ GeV, with much smaller $g_X$ ($\sim 0.6$) compared to the Majorana DM case, since all processes involved are $S$-wave dominated without the velocity suppression. Nevertheless, it cannot yield the proper DM relic density because both $\psi_1$ and $\psi_2$ annihilations into SM fermions are of the same order at freeze-out and both annihilations are away from the resonance region due to the large DM velocity. As a consequence, they are much smaller than $10^{-26}$ cm$^3$sec$^{-1}$, the current value for $\bar{\psi}_1\psi_1 \to \bar{f}f$, associated with the GC $\gamma$-ray. An additional mechanism has to be introduced to increase the annihilation cross-section and lower the relic density. In addition, the direct search bounds hardly constrain our model since the SU(2)$_X$-SM mixing $\sin \chi$ is very small such that the DM-nucleon cross-section is negligible.

It is worthwhile to mention that recent studies [85–87], based on the AMS-02 electron and positron data [88, 89], infer stringent bounds on low-mass DM annihilation into leptons and also quarks. In these works, the background with broken power-laws in energy fits the data very well, leading to strong constraints on the DM component. It might be arguable that the broken power-law background is driven by the AMS02 data and somehow different from the conventional background. Hence, we take a more conservative point of view that as long as predicted DM signals do not exceed the AMS-02 data. In this sense, such approach is not able to constrain our model.

Finally, we would like to comment that we have taken a phenomenological approach, without justifying the smallness of the mass splitting between the DM and the excited state, as well as and the tiny kinetic mixing. Both are basically determined based on the $\gamma$- and X-ray data. Besides, as shown in table 4 for the 99.73% confidence region, the resonance condition of $m_{X^3} \simeq 2m_{\chi_1}$ has to be precisely satisfied up to one part in $10^9$ or $10^6$ for the Majorana or Dirac case respectively, where $\delta$ is driven to $10^{-9}$ for the strong enhancement on the (co-)annihilation cross-section of the excited state to achieve the correct density in the Majorana case. This fine-tuning results from the hierarchical annihilations required to explain the X-ray line and GC $\gamma$-ray excess and it could arise from an underlying flavor symmetry, aligned with the gauge symmetry such that the resonance is not perturbed by large gauge couplings. The concrete model building is, however, beyond the scope of this work.
Figure 11. The cross-section for the purely Majorana case (blue) and Dirac case (red). We assume a 3.5 keV mass splitting between DM and the excited state, $\Gamma_X = \frac{m_X}{10} = 10$ GeV and $v \sim 3 \times 10^{-3} c$.

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A Resonance enhancement and cancellation

We here show that if both the DM and the excited state are Majorana particles and degenerate in mass, one cannot obtain the resonance enhancement but the “resonance cancellation” instead. So it is not capable of achieving the required large cross-section for the X-ray line. For demonstration, we use the following two types of interactions, the vector current and axial-vector current, for purely Dirac and Majorana DM:

\[
\mathcal{L}_M \supset \sum_{i=1}^{2} g_X \chi_i \bar{\sigma}^\mu \chi_i X_\mu, \\
\mathcal{L}_D \supset \sum_{i=1}^{2} g_X \bar{\psi}_i \gamma^\mu \psi_i X_\mu, \tag{A.1}
\]

where $i = 1$ (2) corresponds to DM (excited state) with $\chi$ ($\psi$) referring to a Majorana (Dirac) particle.

In the vicinity of the resonance ($2m_{\chi(\psi)} \sim m_X$) and the low DM velocity $v \ll c$, the resulting cross-sections for $\chi_1 \chi_1 \rightarrow \chi_2 \chi_2$ and $\bar{\psi}_1 \psi_1 \rightarrow \bar{\psi}_2 \psi_2$ through the current interac-
tions read

\[
(\sigma v)_{\chi_1 \chi_1 \to \chi_2 \chi_2} \sim \frac{(m_{\chi_1}^8 - m_{\chi_1}^6 m_{\chi_2}^2) v^2 + 12 m_{\chi_1}^4 m_{\chi_2}^2 (m_X - 2 m_{\chi_1})^2}{m_X^4 \left( (s - m_X^2)^2 + \Gamma_X^2 m_X^2 \right)},
\]

\[
(\sigma v)_{\tilde{\psi}_1 \psi_1 \to \tilde{\psi}_2 \psi_2} \sim \frac{2 m_{\psi_1}^4 + m_{\psi_1}^2 m_{\psi_2}^2}{(s - m_X^2)^2 + \Gamma_X^2 m_X^2},
\]

where we have suppressed coupling constants and coefficients from the phase space integral and kinematics. For the Majorana case, the first term in the numerator is double suppressed because of \( v \ll 1 \) and \( m_{\chi_1} \simeq m_{\psi_2} \) and the second term becomes small in the vicinity of the resonance. In contrast, in the Dirac case the numerator is unsuppressed, which is characteristic of \( S \)-wave. In figure 11, we show the comparison between the two cases, in which we assume a 3.5 keV mass splitting between the DM and the excited state, \( \Gamma_X = \frac{m_X}{10} = 10 \) GeV, and \( v \sim 3 \times 10^{-3} c \). It is clear that the pure Majorana case has the resonance “cancellation” instead of enhancement while the \( S \)-wave Dirac case features the resonance behavior as expected.

References

[1] Fermi-LAT collaboration, M. Ackermann et al., The Spectrum and Morphology of the Fermi Bubbles, Astrophys. J. (2014) [arXiv:1407.7905] [SPIRE].

[2] 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 [SPIRE].

[3] D. Hooper and L. Goodenough, Dark Matter Annihilation in The Galactic Center As Seen by the Fermi Gamma Ray Space Telescope, Phys. Lett. B 697 (2011) 412 [arXiv:1010.2752] [SPIRE].

[4] A. Boyarsky, D. Malyshev and O. Ruchayskiy, A comment on the emission from the Galactic Center as seen by the Fermi telescope, Phys. Lett. B 705 (2011) 165 [arXiv:1012.5839] [SPIRE].

[5] 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. D 86 (2012) 083511 [arXiv:1207.6047] [SPIRE].

[6] C. Gordon and O. Macias, Dark Matter and Pulsar Model Constraints from Galactic Center Fermi-LAT Gamma Ray Observations, Phys. Rev. D 88 (2013) 083521 [arXiv:1306.5725] [SPIRE].

[7] W.-C. Huang, A. Urbano and W. Xue, Fermi Bubbles under Dark Matter Scrutiny Part II: Particle Physics Analysis, JCAP 04 (2014) 020 [arXiv:1310.7609] [SPIRE].

[8] N. Okada and O. Seto, Gamma ray emission in Fermi bubbles and Higgs portal dark matter, Phys. Rev. D 89 (2014) 043525 [arXiv:1310.5991] [SPIRE].

[9] K.P. Modak, D. Majumdar and S. Rakshit, A possible explanation of low energy \( \gamma \)-ray excess from galactic centre and Fermi bubble by a Dark Matter model with two real scalars, JCAP 03 (2015) 011 [arXiv:1312.7488] [SPIRE].

[10] K.N. Abazajian, N. Canac, S. Horiiuchi and M. Kaplinghat, Astrophysical and Dark Matter Interpretations of Extended Gamma-Ray Emission from the Galactic Center, Phys. Rev. D 90 (2014) 023526 [arXiv:1402.4090] [SPIRE].
[11] T. Daylan et al., The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter, arXiv:1402.6703 [INSPIRE].

[12] T. Lacroix, C. Boehm and J. Silk, Fitting the Fermi-LAT GeV excess: On the importance of including the propagation of electrons from dark matter, Phys. Rev. D 90 (2014) 043508 [arXiv:1403.1987] [INSPIRE].

[13] N. Okada and O. Seto, Galactic Center gamma-ray excess from two-Higgs-doublet-portal dark matter, Phys. Rev. D 90 (2014) 083523 [arXiv:1408.2583] [INSPIRE].

[14] B. Zhou et al., GeV excess in the Milky Way: Depending on Diffuse Galactic gamma ray Emission template?, arXiv:1406.6948 [INSPIRE].

[15] L. Wang and X.-F. Han, A simplified 2HDM with a scalar dark matter and the galactic center gamma-ray excess, Phys. Rev. D 90 (2014) 083523 [arXiv:1408.2583] [INSPIRE].

[16] E. Bulbul et al., Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters, Astrophys. J. 789 (2014) 13 [arXiv:1402.2301] [INSPIRE].

[17] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, Unidentified Line in X-Ray Spectra of the Andromeda Galactic and Perseus Galaxy Cluster, Phys. Rev. Lett. 113 (2014) 251301 [arXiv:1402.4119] [INSPIRE].

[18] J.M. Cline and A.R. Frey, Nonabelian dark matter models for 3.5 keV X-rays, JCAP 10 (2014) 013 [arXiv:1408.0233] [INSPIRE].

[19] K.N. Abazajian, Resonantly Produced 7 keV Sterile Neutrino Dark Matter Models and the Properties of Milky Way Satellites, Phys. Rev. Lett. 112 (2014) 161303 [arXiv:1403.0954] [INSPIRE].

[20] A. Adulpravitchai and M.A. Schmidt, A Fresh Look at keV Sterile Neutrino Dark Matter from Frozen-In Scalars, JHEP 01 (2015) 006 [arXiv:1409.4330] [INSPIRE].

[21] K.S. Babu and R.N. Mohapatra, 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model, arXiv:1405.3730 [INSPIRE].

[22] S. Baek and H. Okada, 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model, arXiv:1403.1710 [INSPIRE].

[23] K.S. Babu and R.N. Mohapatra, 7 keV Scalar Dark Matter and the Anomalous Galactic X-ray Spectrum, Phys. Rev. D 89 (2014) 115011 [arXiv:1404.2220] [INSPIRE].

[24] F. Bezrukov and D. Gorbunov, Relic Gravity Waves and 7 keV Dark Matter from a GeV scale inflaton, Phys. Lett. B 736 (2014) 494 [arXiv:1403.4638] [INSPIRE].

[25] K.K. Boddy, J.L. Feng, M. Kaplinghat, Y. Shadmi and T.M.P. Tait, Strongly interacting dark matter: Self-interactions and keV lines, Phys. Rev. D 90 (2014) 095016 [arXiv:1408.6532] [INSPIRE].

[26] N.E. Bomark and L. Roszkowski, 3.5 keV x-ray line from decaying gravitino dark matter, Phys. Rev. D 90 (2014) 011701 [arXiv:1403.6503] [INSPIRE].

[27] S. Chakraborty, D.K. Ghosh and S. Roy, 7 keV Sterile neutrino dark matter in U(1)R− lepton number model, JHEP 10 (2014) 146 [arXiv:1405.6967] [INSPIRE].

[28] N. Chen, Z. Liu and P. Nath, 3.5 keV galactic emission line as a signal from the hidden sector, Phys. Rev. D 90 (2014) 035009 [arXiv:1406.0687] [INSPIRE].

[29] C.-W. Chiang and T. Yamada, 3.5 keV X-ray line from nearly-degenerate WIMP dark matter decays, JHEP 09 (2014) 006 [arXiv:1407.0460] [INSPIRE].

[30] K.-Y. Choi and O. Seto, X-ray line signal from decaying axino warm dark matter, Phys. Lett. B 735 (2014) 92 [arXiv:1403.1782] [INSPIRE].
[31] M. Cicoli, J.P. Conlon, M.C.D. Marsh and M. Rummel, 3.55 keV photon line and its morphology from a 3.55 keV axionlike particle line, Phys. Rev. D 90 (2014) 023540 [arXiv:1403.2370] [nSPIRE].

[32] J.M. Cline, Y. Farzan, Z. Liu, G.D. Moore and W. Xue, 3.5 keV x rays as the “21 cm line” of dark atoms and a link to light sterile neutrinos, Phys. Rev. D 89 (2014) 121302 [arXiv:1404.3729] [nSPIRE].

[33] J.P. Conlon and F.V. Day, 3.55 keV photon lines from axion to photon conversion in the Milky Way and M31, JCAP 11 (2014) 033 [arXiv:1404.7741] [nSPIRE].

[34] J.P. Conlon and A.J. Powell, A 3.55 keV line from DM → a → γ: predictions for cool-core and non-cool-core clusters, JCAP 01 (2015) 019 [arXiv:1406.5518] [nSPIRE].

[35] V.K. Dubrovich, Identification of the 3.55 keV line within the framework of standard physics, Astron. Lett. 40 (2014) 749 [arXiv:1407.4629] [nSPIRE].

[36] E. Dudas, L. Heurtier and Y. Mambrini, Generating X-ray lines from annihilating dark matter, Phys. Rev. D 90 (2014) 035002 [arXiv:1404.1927] [nSPIRE].

[37] R. Allahverdi, B. Dutta and Y. Gao, keV Photon Emission from Light Nonthermal Dark Matter, Phys. Rev. D 89 (2014) 127305 [arXiv:1403.5717] [nSPIRE].

[38] B. Dutta, I. Gogoladze, R. Khalid and Q. Shafi, 3.5 keV X-ray line and R-Parity Conserving Supersymmetry, JHEP 11 (2014) 018 [arXiv:1407.0863] [nSPIRE].

[39] D.P. Finkbeiner and N. Weiner, An X-Ray Line from eXciting Dark Matter, arXiv:1402.6671 [nSPIRE].

[40] M.T. Frandsen, F. Sannino, I.M. Shoemaker and O. Svendsen, X-ray Lines from Dark Matter: The Good, The Bad and The Unlikely, JCAP 05 (2014) 033 [arXiv:1403.1570] [nSPIRE].

[41] M. Frigerio and C.E. Yaguna, Sterile Neutrino Dark Matter and Low Scale Leptogenesis from a Charged Scalar, Eur. Phys. J. C 75 (2015) 31 [arXiv:1409.0659] [nSPIRE].

[42] Y. Farzan and A.R. Akbarieh, Decaying Vector Dark Matter as an Explanation for the 3.5 keV Line from Galaxy Clusters, JCAP 11 (2014) 015 [arXiv:1408.2950] [nSPIRE].

[43] G. Faisel, S.-Y. Ho and J. Tandean, Exploring X-Ray Lines as Scotogenic Signals, Phys. Lett. B 738 (2014) 380 [arXiv:1405.5887] [nSPIRE].

[44] C.-Q. Geng, D. Huang and L.-H. Tsai, X-ray Line from the Dark Transition Electric Dipole, JHEP 08 (2014) 086 [arXiv:1406.6481] [nSPIRE].

[45] N. Haba, H. Ishida and R. Tsai, νR dark matter-phobic Higgs for 3.5 keV X-ray signal, Phys. Lett. B 743 (2015) 35 [arXiv:1407.6827] [nSPIRE].

[46] T. Higaki, K.S. Jeong and F. Takahashi, The 7 keV axion dark matter and the X-ray line signal, Phys. Lett. B 733 (2014) 25 [arXiv:1402.6996] [nSPIRE].

[47] T. Higaki, N. Kitajima and F. Takahashi, Hidden axion dark matter decaying through mixing with QCD axion and the 3.5 keV X-ray line, JCAP 12 (2014) 004 [arXiv:1408.3936] [nSPIRE].

[48] H. Ishida, K.S. Jeong and F. Takahashi, 7 keV sterile neutrino dark matter from split flavor mechanism, Phys. Lett. B 732 (2014) 196 [arXiv:1402.5837] [nSPIRE].

[49] H. Ishida and H. Okada, 3.55 keV X-ray Line Interpretation in Radiative Neutrino Model, arXiv:1406.5808 [nSPIRE].

[50] J. Jaeckel, J. Redondo and A. Ringwald, 3.55 keV hint for decaying axionlike particle dark matter, Phys. Rev. D 89 (2014) 103511 [arXiv:1402.7335] [nSPIRE].

[51] J.-C. Park, S.C. Park and K. Kong, X-ray line signal from 7 keV axino dark matter decay, Phys. Lett. B 733 (2014) 217 [arXiv:1403.1536] [nSPIRE].
C. Kolda and J. Unwin, X-ray lines from R-parity violating decays of keV sparticles, Phys. Rev. D 90 (2014) 023535 [arXiv:1403.5580] [SPIRE].

Z. Kang, P. Ko, T. Li and Y. Liu, Natural X-ray Lines from the Low Scale Supersymmetry Breaking, Phys. Lett. B 742 (2015) 249 [arXiv:1403.7742] [SPIRE].

H.M. Lee, Magnetic dark matter for the X-ray line at 3.55 keV, Phys. Lett. B 738 (2014) 118 [arXiv:1404.5446] [SPIRE].

S.P. Liew, Axino dark matter in light of an anomalous X-ray line, JCAP 05 (2014) 044 [arXiv:1403.6621] [SPIRE].

K.P. Modak, 3.5 keV X-ray Line Signal from Decay of Right-Handed Neutrino due to Transition Magnetic Moment, JHEP 03 (2015) 064 [arXiv:1404.3676] [SPIRE].

K. Nakayama, F. Takahashi and T.T. Yanagida, The 3.5 keV X-ray line signal from decaying moduli with low cutoff scale, Phys. Lett. B 735 (2014) 338 [arXiv:1403.1733] [SPIRE].

K. Nakayama, F. Takahashi and T.T. Yanagida, Anomaly-free flavor models for Nambu-Goldstone bosons and the 3.5keV X-ray line signal, Phys. Lett. B 734 (2014) 178 [arXiv:1403.7390] [SPIRE].

K. Nakayama, F. Takahashi and T.T. Yanagida, Extra light fermions in $E_6$-inspired models and the 3.5 keV X-ray line signal, Phys. Lett. B 737 (2014) 162 [arXiv:1404.4795] [SPIRE].

S. Patra and P. Pritimita, 7 keV sterile neutrino Dark Matter in extended seesaw framework, arXiv:1409.3656 [SPIRE].

F.S. Queiroz and K. Sinha, The Poker Face of the Majoron Dark Matter Model: LUX to keV Line, Phys. Lett. B 735 (2014) 69 [arXiv:1404.1400] [SPIRE].

D.J. Robinson and Y. Tsai, Dynamical framework for KeV Dirac neutrino warm dark matter, Phys. Rev. D 90 (2014) 045030 [arXiv:1404.7118] [SPIRE].

W. Rodejohann and H. Zhang, Signatures of Extra Dimensional Sterile Neutrinos, Phys. Lett. B 737 (2014) 81 [arXiv:1407.2739] [SPIRE].

J.M. Cline and A.R. Frey, Consistency of dark matter interpretations of the 3.5keV x-ray line, Phys. Rev. D 90 (2014) 123537 [arXiv:1410.7766] [SPIRE].

F. Chen, J.M. Cline and A.R. Frey, Nonabelian dark matter: Models and constraints, Phys. Rev. D 80 (2009) 083516 [arXiv:0907.4746] [SPIRE].

J. Knodlseder et al., The All-sky distribution of 511 keV electron-positron annihilation emission, Astron. Astrophys. 441 (2005) 513 [astro-ph/0506026] [SPIRE].

C. Boehm et al., A possible link between the GeV excess and the 511 keV emission line in the Galactic Centre, arXiv:1406.4683 [SPIRE].

S. Cassel, D.M. Ghilencea and G.G. Ross, Electroweak and Dark Matter Constraints on a Z-prime in Models with a Hidden Valley, Nucl. Phys. B 827 (2010) 256 [arXiv:0903.1118] [SPIRE].

J.F. Navarro, C.S. Frenk and S.D.M. White, A Universal density profile from hierarchical clustering, Astrophys. J. 490 (1997) 493 [astro-ph/9611107] [SPIRE].
[73] H. Zhao, Analytical models for galactic nuclei, Mon. Not. Roy. Astron. Soc. 278 (1996) 488 [astro-ph/9509122] [inSPIRE].

[74] 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 [arXiv:1302.6589] [inSPIRE].

[75] M. Fornasa and A.M. Green, Self-consistent phase-space distribution function for the anisotropic dark matter halo of the Milky Way, Phys. Rev. D 89 (2014) 063531 [arXiv:1311.5477] [inSPIRE].

[76] M. Cirelli et al., PPCP 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection, JCAP 03 (2011) 051 [arXiv:1012.4515] [inSPIRE].

[77] F. Calore, I. Cholis and C. Weniger, Background model systematics for the Fermi GeV excess, JCAP 03 (2015) 038 [arXiv:1409.0042] [inSPIRE].

[78] D.T. Cumberbatch, Y.-L.S. Tsai and L. Roszkowski, The impact of propagation uncertainties on the potential Dark Matter contribution to the Fermi LAT mid-latitude gamma-ray data, Phys. Rev. D 82 (2010) 103521 [arXiv:1003.2808] [inSPIRE].

[79] K. Griest and D. Seckel, Three exceptions in the calculation of relic abundances, Phys. Rev. D 43 (1991) 3191 [inSPIRE].

[80] P. Gondolo et al., DarkSUSY: Computing supersymmetric dark matter properties numerically, JCAP 07 (2004) 008 [astro-ph/0406204] [inSPIRE].

[81] Planck collaboration, P.A.R. Ade et al., Planck 2013 results. XVI. Cosmological parameters, Astron. Astrophys. 571 (2014) A16 [arXiv:1303.5076] [inSPIRE].

[82] K. Griest and M. Kamionkowski, Unitarity Limits on the Mass and Radius of Dark Matter Particles, Phys. Rev. Lett. 64 (1990) 615 [inSPIRE].

[83] A. Hook, E. Izaguirre and J.G. Wacker, Model Independent Bounds on Kinetic Mixing, Adv. High Energy Phys. 2011 (2011) 859762 [arXiv:1006.0973] [inSPIRE].

[84] LUX collaboration, D.S. Akerib et al., First results from the LUX dark matter experiment at the Sanford Underground Research Facility, Phys. Rev. Lett. 112 (2014) 091303 [arXiv:1310.8214] [inSPIRE].

[85] L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper and C. Weniger, New limits on dark matter annihilation from AMS cosmic ray positron data, Phys. Rev. Lett. 111 (2013) 171101 [arXiv:1306.3983] [inSPIRE].

[86] A. Ibarra, A.S. Lamperstorfer and J. Silk, Dark matter annihilations and decays after the AMS-02 positron measurements, Phys. Rev. D 89 (2014) 063539 [arXiv:1309.2570] [inSPIRE].

[87] K. Kong and J.-C. Park, Bounds on dark matter interpretation of Fermi-LAT GeV parameters, Nucl. Phys. B 888 (2014) 154 [arXiv:1404.3741] [inSPIRE].

[88] AMS collaboration, M. Aguilar et al., First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV, Phys. Rev. Lett. 110 (2013) 141102 [inSPIRE].

[89] AMS collaboration, L. Accardo et al., High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV with the Alpha Magnetic Spectrometer on the International Space Station, Phys. Rev. Lett. 113 (2014) 121101 [inSPIRE].