Common Origin of 3.55 keV X-Ray Line and Galactic Center Gamma Ray Excess in a Radiative Neutrino Mass Model

Debasish Borah

Department of Physics, Tezpur University, Tezpur - 784028, India

Arnab Dasgupta and Rathin Adhikari

Centre for Theoretical Physics, Jamia Millia Islamia - Central University, Jamia Nagar, New Delhi - 110025, India

Abstract

We attempt to simultaneously explain the recently observed 3.55 keV X-ray line in the analysis of XMM-Newton telescope data and the galactic center gamma ray excess observed by the Fermi gamma ray space telescope within an abelian gauge extension of standard model. We consider a two component dark matter scenario with a mass difference 3.55 keV such that the heavier one can decay into the lighter one and a photon with energy 3.55 keV. The lighter dark matter candidate is protected from decaying into the standard model particles by a remnant $Z_2$ symmetry into which the abelian gauge symmetry gets spontaneously broken. If the mass of the dark matter particle is chosen to be within $31 - 40$ GeV, then this model can also explain the galactic center gamma ray excess if the dark matter annihilation into $b\bar{b}$ pairs has a cross section of $\langle \sigma v \rangle \approx (1.4 - 2.0) \times 10^{-26}$ cm$^3$/s. We constrain the model from the requirement of producing correct dark matter relic density, 3.55 keV X-ray line flux and galactic center gamma ray excess. We also impose the bounds coming from dark matter direct detection experiments as well as collider limits on additional gauge boson mass and coupling. We also briefly discuss how this model can give rise to sub-eV neutrino masses at tree level as well as one loop level while keeping the dark matter mass at few tens of GeV. We also show the natural origin of keV mass splitting between two electroweak scale dark matter particles at one loop level in this model.

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I. INTRODUCTION

Recent analysis [1, 2] of the observations made by XMM-Newton X-ray telescope have pointed towards a monochromatic X-ray line with approximate energy 3.55 keV in the spectrum of 73 galaxy clusters (For a review of dark matter, please see [3]). The same line also appears in the Chandra observations of the Perseus cluster [1]. In the absence of any astrophysical interpretation of the line due to some atomic transitions, the origin of this X-ray line can be explained naturally by sterile neutrino dark matter with mass approximately 7.1 keV decaying into a photon and a standard model (SM) neutrino. This was pointed out by the authors in [1, 2] and subsequently studied within the framework of specific models [4]. Several other particle physics explanations of the X-ray line have also been put forward in [5, 6]. Although most of the particle physics explanations consider late time decay or annihilation of multi-keV dark matter particles as the origin of the X-ray line, there have also been a few discussions on the scenarios where the X-ray line can be generated by transitions between electroweak scale dark matter states with keV mass splittings [7]. In spite of the fact that both keV scale as well as weak scale dark matter candidates can explain the same signal, their implications in cosmology and astrophysical structure formation can be very different. As stated in [1, 2], a keV scale sterile neutrino should have mixing with the SM neutrinos of the order $\approx 10^{-11} - 10^{-10}$ to explain the X-ray line. Such a tiny mixing prevents the sterile neutrinos from entering thermal equilibrium in the early Universe, making it necessary to have some additional physics responsible for the production of sterile neutrinos. However, electroweak scale dark matter particles can be thermally populated in the early Universe due to their sizable interactions either through gauge bosons, Higgs portals or fermion portals etc. These scenarios are studied in the context of so-called weakly interacting massive particle (WIMP). The fact that the WIMP annihilation cross section turns out to be almost equal to the annihilation cross section of thermal dark matter in order to produce the correct dark matter relic abundance observed by the Planck experiment [8]

$$\Omega_{\text{DM}} h^2 = 0.1187 \pm 0.0017$$

(1)

is known as the WIMP Miracle. In the above equation (1), $\Omega$ is the density parameter and $h = (\text{Hubble Parameter})/100$ is a parameter of order unity.
Motivated by the possibility of explaining the origin of 3.55 keV X-ray line within WIMP dark matter framework \cite{7}, here we consider an abelian gauge extension of SM with two Majorana fermion dark matter candidates with a keV mass splitting. The UV complete model, originally proposed by \cite{9} and later studied in the context of dark matter and eV scale sterile neutrino in \cite{10} and \cite{11} respectively, can naturally explain dark matter and the origin of tiny neutrino masses. Sub-eV scale SM neutrino masses arise both at tree level as well as one loop level with dark matter particles running inside the loops, a framework more popularly known as ”scotogenic” model \cite{12}. Recently this model was also studied \cite{13} in the context of explaining the galactic center gamma ray excess observed by the Fermi Gamma Ray Space Telescope \cite{14}. The abelian gauge charges of the SM as well as beyond SM fields are chosen in such a way that the model is free from gauge anomalies and the abelian gauge symmetry $U(1)_X$ gets spontaneously broken to a remnant $Z_2$ symmetry so that the lightest $Z_2$-odd particle is stable and hence can be a dark matter candidate. As studied in details in \cite{10}, this model has several dark matter candidates namely, fermion singlet, fermion triplet, scalar singlet and scalar doublet. Scalar dark matter phenomenology is similar to the Higgs portal models discussed extensively in the literature. In these scenarios, the scalar dark matter annihilates into the Standard Model (SM) particles through the Higgs boson. Co-annihilations through gauge bosons can also play a role if the CP even and CP odd components of the neutral Higgs have a tiny mass difference as discussed recently in \cite{15} within the context of a different model.

Instead of pursuing Higgs portal like scalar dark matter scenarios in the model, we study the fermionic dark matter sector. This is also relevant to our discussion on the origin of 3.55 keV X-ray line. This is because, if transition between two semi-degenerate weak scale dark matter candidates with keV mass splitting is the origin of the X-ray line, then the dark matter candidates have to be fermions as one scalar decaying into another scalar and a photon does not conserve spin. As we will see in the next section, our model has two fermion singlet dark matter candidates with different gauge charges and two fermion triplet dark matter candidates with the same gauge charge. We can choose either a triplet-singlet or a singlet-singlet combination of two semi-degenerate dark matter candidates to explain dark matter abundance as well as the origin of 3.55 keV X-ray line simultaneously. However, the neutral component of fermion triplet needs to be very heavy ($2.28 - 2.42$ TeV) in order to reproduce correct dark matter relic density \cite{16}. To allow the possibility of low mass dark
matter, we therefore confine our discussion to fermion singlet dark matter in this work. That is, we explore the possibility of two fermion singlet dark matter candidates with keV mass splitting in this model which can simultaneously give rise to the 3.55 keV X-ray line and satisfy experimental bounds on dark matter relic density as well as direct detection cross section. Such fermion singlet dark matter particle will self-annihilate through the abelian vector boson $X$ into SM particles. We also incorporate the collider constraints on such additional vector boson and its gauge coupling. We find that, although the relic density and direct detection constraints allow a significant region of the parameter space, the collider constraints reduce the parameter space into the s-wave resonance region where the gauge boson mass is approximately twice that of dark matter mass. We constrain the model further by incorporating the bound from X-ray line data on the decay width of the heavier dark matter particle. We then check whether the same model can also give rise to the galactic center (GC) gamma ray excess observed by the Fermi Gamma Ray Space Telescope which has a feature similar to annihilating dark matter \cite{14}. Finally, we briefly discuss whether the chosen dark matter masses are compatible with sub-eV SM neutrino masses and also comment on the possibility of generating a keV scale mass splitting between two electroweak scale singlet fermion dark matter particles.

This letter is organized as follows: in section II we briefly discuss the model. In section III we discuss two component dark matter scenario as a source of 3.55 keV X-Ray line and GC gamma ray excess taking into account all necessary experimental constraints. In section IV we discuss the compatibility of light singlet fermion dark matter with neutrino mass and in section V we point out a natural way to generate keV mass splitting between two dark matter particles. Finally, we conclude in section VI.

II. THE MODEL

The model which we take as a starting point of our discussion was first proposed in \cite{9}. The authors in that work considered different combination of Majorana singlet fermion and Majorana triplet fermion such that the additional $U(1)_X$ gauge symmetry they introduce is anomaly free. Depending upon the combination of these additional fermions, the origin of neutrino mass is also different in these models. Here we discuss one of such models which we find the most interesting for our purposes. We however, modify the scalar sector of
that model in order to achieve the desired phenomenology. This, so called model C by the authors in [9], has fermion content shown in table I. The scalar content of the model, after modification is shown in table II.

The third column in table I shows the $U(1)_X$ quantum numbers of various fields which satisfy the anomaly matching conditions. The charges of the scalar fields in table II are
chosen according to the desired phenomenology. The Higgs content chosen above is not arbitrary and is needed, which leads to the possibility of radiative neutrino masses in a manner proposed in [12] as well as a remnant $Z_2$ symmetry. Two more singlets $S_1R, S_2R$ are required to be present to satisfy the anomaly matching conditions. In this model, the quarks couple to $\Phi_1$ and charged leptons to $\Phi_2$ whereas $(\nu, e)_L$ couples to $N_R, \Sigma_R$ through $\Phi_3$ and to $S_1R$ through $\Phi_1$. The extra five singlet scalars $\chi$ are needed to make sure that all the particles in the model acquire mass. The Lagrangian which can be constructed from the above particle content has an automatic $Z_2$ symmetry and hence provides a cold dark matter candidate in terms of the lightest odd particle under this $Z_2$ symmetry.

The scalar Lagrangian relevant for future discussion can be written as

$$V_s \supset f_3 \chi_1 \chi_3 \Phi_1^\dagger \Phi_3 + f_5 \chi^4 \Phi_3 \Phi_2 + f_6 (\Phi_1 \Phi_3^\dagger) \chi \chi_5$$  \hspace{1cm} (2)$$

Similarly, the relevant part of the Yukawa Lagrangian for the model can be written as

$$\mathcal{L}_Y \supset y \Phi_1^\dagger S_{1R} + h_N \Phi_2^\dagger N_R + h_\Sigma \Phi_3^\dagger \Sigma_R + f_N N_R \Sigma_R \chi_4 + f_S S_{1R} S_{1R} \chi_1$$

$$+ f_\Sigma \Sigma_R \Sigma \chi_4 + f_{S2} S_{2R} S_{2R} \chi_2^4 + f_{12} S_{1R} S_{2R} \chi_3^4$$ \hspace{1cm} (3)$$

Let us denote the vacuum expectation values (vev) of various Higgs fields as $\langle \phi^0_{1,2} \rangle = v_{1,2}$, $\langle \chi^0_{1,2,4,5} \rangle = u_{1,2,4,5}$. We also denote the coupling constants of $SU(2)_L, U(1)_Y, U(1)_X$ as $g_2, g_1, g_X$ respectively. The charged weak bosons acquire mass $M^2_W = \frac{g_2^2}{2}(v_1^2 + v_2^2)$. The neutral gauge boson masses in the ($W^\mu_3, Y^\mu, X^\mu$) basis is

$$M = \frac{1}{2} \begin{pmatrix} g_2^2(v_1^2 + v_2^2) & g_1 g_2 (v_1^2 + v_2^2) & M^2_{WX} \\ g_1 g_2 (v_1^2 + v_2^2) & g_1^2 (v_1^2 + v_2^2) & M^2_{YX} \\ M^2_{WX} & M^2_{YX} & M^2_{XX} \end{pmatrix}$$ \hspace{1cm} (4)$$

where

$$M^2_{WX} = -g_2 g_X \left( \frac{3}{4}(n_1 - n_4)v_1^2 + \frac{1}{4}(9n_1 - n_4)v_2^2 \right)$$

$$M^2_{YX} = -g_1 g_X \left( \frac{3}{4}(n_1 - n_4)v_1^2 + \frac{1}{4}(9n_1 - n_4)v_2^2 \right)$$

$$M^2_{XX} = g_X^2 \left( \frac{9}{4}(n_1 - n_4)v_1^2 + \frac{1}{4}(9n_1 - n_4)^2v_2^2 + \frac{1}{16}(3n_1 + n_4)^2(4u_1^2 + 25u_2^2 + 9u_3^2) + (3n_1 - n_4)^2u_5^2 \right)$$

The mixing between the electroweak gauge bosons and the additional $U(1)_X$ boson as evident from the above mass matrix should be very tiny so as to be in agreement with electroweak precision measurements. The stringent constraint on mixing can be avoided by assuming a
very simplified framework where there is no mixing between the electroweak gauge bosons and the extra $U(1)_X$ boson. Therefore $M^2_{WX} = M^2_{YX} = 0$ which gives rise to the following constraint

$$3(n_4 - n_1)v_1^2 = (9n_1 - n_4)v_2^2$$

(5)

which implies $1 < n_4/n_1 < 9$. If $U(1)_X$ boson is observed at LHC this ratio $n_4/n_1$ could be found empirically from its decay to $qar{q}, lar{l}$ and $\nu\bar{\nu}$ [9]. Here, $q, l$ and $\nu$ correspond to quarks, charged leptons and neutrinos respectively. In terms of the charged weak boson mass, we have

$$v_1^2 = \frac{M^2_W(9n_1 - n_4)}{g_Y^2(3n_1 + n_4)}, \quad v_2^2 = \frac{M^2_W(-3n_1 + 3n_4)}{g_Y^2(3n_1 + n_4)}$$

Assuming zero mixing, the neutral gauge bosons of the Standard Model have masses

$$M_B = 0, \quad M^2_Z = \frac{(g_1^2 + g_2^2)M^2_W}{g_2^2}$$

which corresponds to the photon and weak $Z$ boson respectively. The $U(1)_X$ gauge boson mass is

$$M^2_X = 2g_X^2\left(-\frac{3M^2_W}{8g_2^2}(9n_1 - n_4)(n_1 - n_4) + \frac{1}{16}(3n_1 + n_4)^2(4u_1^2 + 25u_2^2 + 9u_4^2) + (3n_1 - n_4)^2u_5^2\right)$$

(6)

III. SINGLET FERMION DARK MATTER

The relic abundance of a dark matter particle $\chi$ is given by the Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle (n_\chi^2 - (n^{\text{eqb}}_\chi)^2)$$

(7)

where $n_\chi$ is the number density of the dark matter particle $\chi$ and $n^{\text{eqb}}_\chi$ is the number density when $\chi$ was in thermal equilibrium. $H$ is the Hubble expansion rate of the Universe and $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section of the dark matter particle $\chi$. In terms of partial wave expansion $\langle \sigma v \rangle = a + bv^2$. Numerical solution of the Boltzmann equation above gives [17]

$$\Omega_\chi h^2 \approx \frac{1.04 \times 10^9 x_F}{M_{Pl}\sqrt{g_*}(a + 3b/x_F)}$$

(8)

where $x_F = m_\chi/T_F$, $T_F$ is the freeze-out temperature, $g_*$ is the number of relativistic degrees of freedom at the time of freeze-out. Dark matter particles with electroweak scale mass and
couplings freeze out at temperatures approximately in the range $x_F \approx 20 - 30$. More generally, $x_F$ can be calculated from the relation

$$x_F = \ln \left( \frac{0.038 g m_{PL} m_\chi}{g^{1/2} x_f^{1/2}} \langle \sigma v \rangle \right)$$

where $g$ is the number of internal degrees of freedom of the dark matter particle $\chi$. The thermal averaged annihilation cross section $\langle \sigma v \rangle$ is given by [18]

$$\langle \sigma v \rangle = \frac{1}{8 m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} \sigma(s - 4m^2) \sqrt{s} K_1(\sqrt{s}/T) ds$$

where $K_i$’s are modified Bessel functions of order $i$, $m$ is the mass of Dark Matter particle and $T$ is the temperature.

There are two singlet fermions $N_R, S_{2R}$ in this model which are odd under the remnant $Z_2$ symmetry and hence can be a dark matter candidate, if lightest among all the $Z_2$ odd particles. We consider a scenario where $S_{2R}$ is the lightest and $N_R$ is the next to lightest $Z_2$ odd particle of the model. If the lifetime of $N_R$ is very high, longer than the present age of the Universe, then both $S_{2R}$ and $N_R$ can contribute to the present abundance of dark matter. From the field content and their gauge charges, one can see that here is no term in the Lagrangian which involves both $S_{2R}$ and $N_R$. Also there is no scalar which couples to both $S_{2R}$ and $N_R$. Thus, there is no co-annihilating processes between $S_{2R}$ and $N_R$ which can contribute to the dark matter relic abundance. Hence, one can calculate the relic abundance of $S_{2R}$ and $N_R$ separately, keeping them decoupled. To calculate the relic density of either $S_{2R}$ or $N_R$, we need to find out its annihilation cross-section to standard model particles. For zero $Z - X$ mixing, the dominant annihilation channel is the one with $X$ boson mediation. Since the singlet fermions are of Majorana type, they have only axial coupling to the vector boson. The annihilation cross-section of Majorana singlet fermion into SM fermion anti-fermion pairs $ff$ through s-channel $X$ boson [19] can be written as

$$\sigma = \frac{n_c}{12 \pi s} \left[ \frac{(s - m_X^2)^2 + M_X^2 \Gamma_X^2}{(1 - 4m_f^2/s)^2/s} \right] \left[ 1 - \frac{4m_f^2/s}{1 - 4M_X^2/s} \right]^{1/2} \times

\left[ g_{fa}^2 g_{\chi a}^2 \left( 4m_X^2 \left[ m_f^2 \left( -6s \right) + \frac{3s^2}{M_X^2} \right] - s \right) + s \left( 4m_f^2 \right) \right]$$

$$+ g_{fe}^2 g_{\chi a}^2 \left( s + 2m_f^2 \right) \left( s - 4m_X^2 \right)$$

Expanding in powers of $v^2$ gives $\sigma v$ in the form $a + bv^2$ where $a$ and $b$ are given by
a = \frac{n_c g_f^2 m_f^2 g_{\nu_a}^2 m_{\chi}^2}{24 \pi^2 m_{\nu_a}^2 (M_{X}^2 - 4 m_{\nu_a}^2 + M_{X}^2 \Gamma_{X}^2)} \sqrt{1 - \frac{m_f^2}{m_{\nu_a}^2}} \left( -36 + 48 \frac{m_{\chi}^2}{M_{X}^2} + 96 \frac{m_{\nu_a}^2}{M_{X}^2} + 192 \frac{m_{\chi}^4}{M_{X}^4} \right)

b = a \left[ -\frac{1}{4} + \frac{2 m_{\nu_a}^2 (M_{X}^2 - 4 m_{\nu_a}^2)}{(M_{X}^2 - 4 m_{\nu_a}^2)^2 + M_{X}^2 \Gamma_{X}^2} + \frac{1}{8 (m_{\chi}^2 - m_f^2) m_f^2} \left( -16 + 2 g_{\nu_a}^2 + 28 \frac{m_{\chi}^2}{m_f^2} + 4 g_{\nu_a}^2 m_{\nu_a}^2 - 24 \frac{m_{\chi}^2}{M_{X}^2} + 96 \frac{m_{\nu_a}^2}{M_{X}^2} \right) \right] \tag{12}

The Decay width of the $X$ boson denoted by $\Gamma_X$ is given by

$$
\Gamma_{X \rightarrow \chi \chi} = \frac{n_c M_X g_{\chi}^2}{12 \pi S} \left[ 1 - \frac{4 m_{\chi}^2}{M_{X}^2} \right]^{3/2}
$$

$$
\Gamma_{X \rightarrow f \bar{f}} = \sum_f \frac{n_c M_X}{12 \pi S} \left[ 1 - \frac{4 m_f^2}{M_{X}^2} \right]^{1/2} \left[ g_{f a}^2 \left( 1 - \frac{4 m_f^2}{M_{X}^2} \right) + g_{f v}^2 \left( 1 + 2 \frac{m_f^2}{M_{X}^2} \right) \right] \tag{13}
$$

The mass of the gauge boson $X$ in the above expressions is given by equation [6]. For simplicity, we assume $u_1 = u_2 = u_4 = u$ such that the mass of $X$ boson can be written as

$$
M_{X}^2 = 2 g_{\chi}^2 \left[ -3 \frac{m_{\tau}^2}{8 g_{\chi}^2} (9 n_1 - n_4)(n_1 - n_4) + \frac{19}{8} (3 n_1 + n_4)^2 u^2 + (3 n_1 - n_4)^2 u^2 \right] \quad \tag{14}
$$

The couplings $g_{f v}, g_{f a}, g_{\nu v}, g_{\chi a}$ of fermions and dark matter to $X$ boson are tabulated in the table III.

| | $n_c$ | $g_{f v}/g_X$ | $g_{f a}/g_X$ |
|---|---|---|---|
| $l = e, \mu, \tau$ | 1 | $\frac{9}{8} (n_4 - n_1)$ | $\frac{1}{8} (n_4 - 9 n_1)$ |
| $\nu_l$ | 1 | $\frac{u_4}{2}$ | $-\frac{u_4}{2}$ |
| $U = u, c$ | 3 | $\frac{1}{8} (11 n_1 - n_4)$ | $\frac{3}{8} (n_1 - n_4)$ |
| $D = d, s, b$ | 3 | $\frac{1}{8} (5 n_1 + 3 n_4)$ | $\frac{3}{8} (n_4 - n_1)$ |
| $N_R$ | 1 | 0 | $\frac{3}{8} (3 n_1 + n_4)$ |
| $S_{2R}$ | 1 | 0 | $-\frac{5}{8} (3 n_1 + n_4)$ |

**TABLE III:** Couplings of SM particles and dark matter to the vector boson $X$

Using the couplings given in table III we calculate the dark matter relic abundance for both $N_R$ and $S_{2R}$ independently. For illustrative purposes, we fix the masses of $S_{2R}$ and
FIG. 1: Parameter space in the $g_X - M_X$ plane for $m_{S_{2R}} = 100$ GeV and $m_{N_R} - m_{S_{2R}} = 3.55$ keV. The red-hatched, green and blue dot-dashed regions correspond to the allowed region after the constraints on $M_X/g_X$ are imposed. The area to the left of the black line is ruled out by Xenon100 bounds on direct detection cross section. The solid red region corresponds to the parameter space favored by the relic density constraint.

$N_R$ to be 100 GeV and $100 + 3.55 \times 10^{-6}$ GeV. We also fix the gauge charges $n_1, n_4$ but vary the $U(1)_X$ gauge coupling $g_X$ and gauge boson mass $M_X$. Similar to our approach in \cite{10,13}, here also we choose a specific value of $n_1$ from which $n_4$ can be determined using the normalization relation $n_1^2 + n_4^2 = 1$. Using the same normalization, the 90% confidence level exclusion on $M_X/g_X$ was shown in \cite{9} where the lowest allowed value of $M_X/g_X$ was found to be approximately 2 TeV for $\phi = \tan^{-1}(n_4/n_1) = 1.5$. Using this and the normalization relation involving $n_1, n_4$ we determine both $n_1, n_4$. Since $U(1)_X$ gauge charges of all the fields are written in terms of $n_1, n_4$ it is sufficient to choose just these two values to determine all the gauge charges. After fixing dark matter mass as well as $n_{1,4}$, we vary $g_X$ and $u$ and compute the relic density of dark matter candidates $N_R$ and $S_{2R}$ independently. Instead
of assuming a particular value of $x_F$, we first numerically calculate the value of $x_F$ which satisfies the following equation

$$e^{x_F} - \ln \frac{0.038 g m_{PL} m_X}{\frac{1}{2} \frac{1}{2} g_s^{1/2} \sigma v} = 0$$

This is a simplified form of equation (9). For a fixed value of dark matter mass $m_X$, the annihilation cross section $\sigma$ depends upon $g_X, M_X$. For a particular pair of $g_X$ and $M_X$, we use this value of $x_F$ and compute the relic abundance using equation (8).

The allowed parameter space in terms of $g_X, M_X$ and $g_X, u$ satisfying dark matter relic density bound from Planck experiment for $m_{S_{2R}} = 100$ GeV and $m_{N_R} = 100 + 3.55 \times 10^{-6}$ GeV are shown in figure 1 and 2 respectively. We do this exercise by considering $N_R$ and
FIG. 3: Relative contribution of $N_R$ and $S_{2R}$ to dark matter relic abundance for $m_{S_{2R}} = 100$ GeV and $m_{N_R} - m_{S_{2R}} = 3.55$ keV.

$S_{2R}$ together to give rise to total dark matter relic abundance. After showing the region of parameter space satisfying dark matter relic density bound, we consider the bound on dark matter nucleon scattering cross section from direct detection experiments. Since both the dark matter candidates in our model are Majorana fermions, the vector current vanishes and they give rise to spin dependent scattering cross section with nuclei. The latest upper bound on this scattering cross section comes from the Xenon100 experiment \[20\]. The expression for this spin dependent scattering of dark matter particles off nuclei through t-channel mediation of X boson can be written as

$$
\sigma_{SD} = \frac{4\mu_{\chi N}^2}{\pi M_X^4} g_{\chi a} J_N (J_N + 1) \left( \frac{\langle S_p \rangle}{J_N} (2\Delta_u^{(p)} + \Delta_d^{(p)}) + \frac{\langle S_n \rangle}{J_N} (2\Delta_d^{(n)} + \Delta_u^{(n)}) \right)^2 \tag{16}
$$
where
\[ \mu_{\chi N} = \frac{m_\chi m_N}{m_\chi^2 + m_N^2} \]
and \( J_N \) is the spin of the Xenon nucleus. The standard values of the nuclear quark content
are \( \Delta_u^{(p)} = \Delta_d^{(n)} = 0.84 \) and \( \Delta_u^{(n)} = \Delta_d^{(p)} = -0.43 \) [21]. The average spins \( \langle S_p \rangle \) and \( \langle S_n \rangle \) of the Xenon nucleus are taken from [20] as given in table IV. The lowest upper bound
at 90% confidence level from Xenon100 experiment on spin dependent dark matter nuclei
cross section is \( 3.5 \times 10^{-40} \) cm\(^2\) for dark matter mass of 45 GeV. Here we take this as a
conservative upper bound on direct detection cross section and show the region of parameter
space in both \( g_X - M_X \) and \( g_X - u \) plane which gives rise to this cross section. This gives
rise to a solid exclusion line in the figure 1 and 2 so that the region of parameter space above
or towards left of this line is ruled out. Similar to the discussion in our earlier work [13],
we also incorporate the collider bounds on \( M_X \) and \( g_X \). Collider constraints on additional
gauge bosons coupling to the SM particles with generic SM like gauge couplings force them
to be heavier than approximately 2.5 TeV. However, as discussed in [22], the bounds on
the mass of additional boson \( X \) can be relaxed if it has non-negligible coupling to the dark
sector. The authors showed that for \( X \) decaying into SM particles with branching ratio 90%
and \( g_X = 0.1 \), the lowest allowed value of \( M_X/g_X \) is approximately 2.6 TeV. This limit goes
up to 4 TeV and 4.4 TeV, if \( g_X \) is increased to 0.3 and weak gauge coupling \( g \) respectively.
To apply these bounds, we calculate the branching ratios of \( X \) boson into SM and dark
sector particles and find that the maximum branching ratio of \( X \) boson into dark matter
particles is approximately 8.5%. According to the analysis of [22], this will correspond to
an approximate bound \( M_X/g_X > 2.6 \) TeV for \( g_X = 0.1 \). However, these bounds will be
weaker if \( g_X \) is lowered down into the resonance region that can be seen from figure 1 and
2. We apply moderate as well as conservative bounds on \( M_X/g_X \) between 2 TeV to 4 TeV
and show the portion of parameter space left after that in figure 1 and 2.

It can be seen from the figures 1 and 3 that the bounds on \( M_X/g_X \) necessarily rules
out most of the parameter space in $g_X - M_X$ or $g_X - u$ plane which give correct dark matter properties. Only a narrow region of parameter space near the s-channel resonance $M_X \approx 2m_{DM}$ is left. If dark matter mass is light, a few tens of GeV, then additional bounds from LEP-II experiment will apply on neutral gauge boson and its coupling. The agreement between LEP-II measurements and the standard model predictions forces the mass of additional neutral boson to be greater than 209 GeV or the couplings to be smaller than or of order $10^{-2}$ [21]. This will further reduce the parameter space to the region with $g_X \leq 10^{-2}$.

FIG. 4: Radiative decay of $N_R$ into $S_{2R}$ and a photon $\gamma$.

FIG. 5: Radiative decay of $N_R$ into $S_{2R}$ and a photon $\gamma$.

After finding the parameter space which keeps the total abundance of $N_R$ and $S_{2R}$ within the Planck limit on dark matter abundance [1], we also show the relative contribution of $N_R$ and $S_{2R}$ to dark matter relic abundance in figure 3. It can be seen from the figure that $N_R$ can give rise to $26 - 28\%$ of dark matter relic density whereas $S_{2R}$ gives rise to the rest of it. Since their relative abundance is different, their scattering probability at direct detection experiments will also be different. We have taken that factor into account while calculating
the dark matter direct detection cross section.

In order to fit our model with the 3.55 keV X-Ray line data, we apply the following constraint on the decay width of the heavier dark matter candidate \(N_R\)

\[
\Gamma(N_R \to S_{2R}\gamma) \approx 6.2 \times 10^{-47} M_{N_R} \text{ GeV} \tag{17}
\]

Where we have assumed that \(N_R\) contributes around 25% to dark matter relic abundance. The dependence of the decay width on mass \(M_{N_R}\) appears to take into account of the fact that increase in mass decreases the number density of dark matter thereby requiring a bigger decay width to get the observed X-ray flux. In our model, the heavier dark matter particle \(N_R\) can decay into the lighter dark matter particle \(S_{2R}\) and a photon \(\gamma\) only at two loop level. The corresponding Feynman diagrams can be seen in figure 4 and figure 5. Instead of calculating the two loop integrals, here we make an order of estimate of these decay diagrams which gives us a conservative bound on the couplings, assuming all the fields inside the loop to be below TeV scale. As \(N_R\) and \(S_{2R}\) are Majorana neutrinos, corresponding to all diagrams in figure 4 and 5 there will be conjugate diagrams where photon connects to opposite sign particle with respect to diagrams in figure 4 and 5. Considering those conjugate diagrams and also considering all heavy masses in the internal line of the diagrams almost degenerate and neglecting electron mass, the decay width can be approximated as

\[
\Gamma(N_R \to S_{2R}\gamma) \approx \left(\frac{m_{N_R}^2 - m_{S_{2R}}^2}{16\pi m_{N_R}^3}\right) \left(m_{N_R}^2 - m_{S_{2R}}^2\right)^2 \left[F_1^2 + F_2^2\right] \tag{18}
\]

where

\[
F_1 \simeq 2 \left(\frac{m_{N_R} - m_{S_{2R}}}{m_{\phi}^{-2}}\right) I ; F_2 \simeq 2 \left(\frac{m_{N_R} + m_{S_{2R}}}{m_{\phi}^{-2}}\right) I ; I \simeq \left(\frac{h_N f_{6f_{12}} y_u}{256\pi^4 m_{\phi}^{-}}\right) \tag{19}
\]

If there is no \(CP\) violating interactions then either \(N_R\) and \(S_{2R}\) will have same \(CP\) eigenvalues or opposite \(CP\) eigenvalues. For same \(CP\) eigenvalues \(F_2 = 0\) and for opposite \(CP\) eigenvalues \(F_1 = 0\). Taking the constraint (17) into account, we have

\[
\Gamma(N_R \to S_{2R}\gamma) \approx \left(\frac{(m_{N_R} + m_{S_{2R}})^3}{16\pi m_{N_R}^3}\right) \Delta k^3 \left[F_1^2 + F_2^2\right]
\]

\[
\sim 6.2 \times 10^{-47} M_{N_R} \text{ GeV} \tag{20}
\]

where

\[
\Delta k = m_{N_R} - m_{S_{2R}} = 3.55 \times 10^{-6} \text{ (GeV)} \tag{21}
\]
Taking $m_{N_R} \approx m_{S_{2R}} \approx 35$ GeV, $m_{\phi^-} \approx 10^2$ GeV, this constraint can be naturally satisfied if

$$h_{N} f_{6} f_{12} y \sim 10^{-3} \text{ (for same CP eigenvalues)}.$$  

$$\sim 10^{-7} \text{ (for opposite CP eigenvalues).}$$  \hspace{1cm} (22) 

As will be discussed in the next sections, to satisfy light neutrino mass constraint as well as to generate keV mass splitting between $N_R$ and $S_{2R}$ naturally, the opposite CP eigenvalues of $N_R$ and $S_{2R}$ seem to be more appropriate.

FIG. 6: Parameter space in the $g_X - M_X$ plane for $m_{S_{2R}} = 35$ GeV and $m_{N_R} - m_{S_{2R}} = 3.55$ keV. The red-hatched, green and blue dot-dashed regions correspond to the allowed region after the constraints on $M_X/g_X$ are imposed. The area to the left of the black line is ruled out by Xenon100 bounds on direct detection cross section. The solid red region corresponds to the parameter space favored by the relic density constraint.

After constraining the model parameters from dark matter, collider as well as the 3.55 keV X-ray line data, we check if the model can explain the galactic center gamma ray excess
FIG. 7: Parameter space in the $g_X - u$ plane for $m_{S_{2R}} = 35$ GeV and $m_{N_R} - m_{S_{2R}} = 3.55$ keV. The red-hatched, green and blue dot-dashed regions correspond to the allowed region after the constraints on $M_X/g_X$ are imposed. The area to the left of the black line is ruled out by Xenon100 bounds on direct detection cross section. The solid red region corresponds to the parameter space favored by the relic density constraint. for the same region of parameter space. Recent analysis [14] of the Fermi Gamma Ray Space Telescope data has shown an excess of gamma rays with a peak of $1 - 3$ GeV in the region surrounding the galactic center. Also reported by earlier analysis [23], the spectral shape of the gamma rays has a feature which resembles annihilating dark matter. As noted in [19], dark matter particle with mass either $\sim 35$ GeV annihilating mostly into $b\bar{b}$ pairs or $\sim 25$ GeV which annihilates almost democratically to SM fermions can give rise to the gamma ray excess seen in the telescope data. The same analysis also pointed out that the thermally averaged cross-sections needed to produce the required gamma ray excess are $\langle \sigma v \rangle = (0.77 - 3.23) \times 10^{-26} \text{cm}^3/\text{s}$ and $\langle \sigma v \rangle = (0.63 - 2.40) \times 10^{-26} \text{cm}^3/\text{s}$ for $m_{DM} = 35$ GeV and $m_{DM} = 25$ GeV respectively. In this work we wish to show one particular case.
FIG. 8: Relative contribution of $N_R$ and $S_{2R}$ to dark matter relic abundance for $m_{S_{2R}} = 35$ GeV and $m_{N_R} - m_{S_{2R}} = 3.55$ keV.

of 35 GeV dark matter candidate and check if the required annihilation cross section can be obtained to give rise to gamma ray excess. Since we have two dark matter candidates with a mass difference of 3.55 keV, we consider the mass of $N_R$ to be $35 + 3.55 \times 10^{-6}$ GeV and that of $S_{2R}$ to be 35 GeV. We then show in figure 6 and 7 the region of parameter space in $g_X - M_X$ and $g_X - u$ plane for which the total annihilation cross section of $N_R, S_{2R}$ into $b\bar{b}$ pairs matches the one mentioned above in order to produce gamma ray excess. We show the other relevant parameter space corresponding to dark matter relic density, direct detection exclusion line and the collider bounds similar to the 100 GeV dark matter case discussed above. We can see from figure 6 and 7 that there exist regions of parameter space that can simultaneously give rise to galactic center gamma ray excess and satisfy the dark matter relic density, direct detection as well as collider bounds. We then show the relative contribution of $N_R$ and $S_{2R}$ to dark matter relic density in figure 8 which shows a similar relative proportion as in the 100 GeV case in figure 3. We include their relative abundance
factors while calculating the annihilation cross section needed to produce galactic center gamma ray excess as well as the direct detection exclusion lines.

![Feynman diagram](image)

**FIG. 9:** Neutrino mass at one loop level

### IV. COMPATIBILITY WITH LIGHT NEUTRINO MASS

The origin of tiny neutrino masses was discussed in details in [10]. The tiny masses can arise at both tree level as well as one loop level through the Feynman diagram shown in figure 9. Since out of the three singlet neutrinos $N_R, S_1R, S_2R$, only $S_1R$ gives rise to a Dirac mass term $m_D = yv_1$ for the neutrinos through the rev of $\Phi_1$ (denoted as $v_1$), only one of the neutrinos acquire non-zero masses at tree level through type I seesaw mechanism [24]. The tree level mass for the light neutrino can be written in terms of the Dirac mass term and the mass of the heavy singlet neutrino $S_1R$ ($M_{S1R} = f_Su_1$) can be written as

$$m_\nu \approx \frac{2y^2v_1^2}{f_Su_1}$$  \hspace{1cm} (23)

From figure 2 and 7, we see that the allowed region from dark matter as well as collider constraints suggest $u_1 = u_2 = u_4 = u_5 = u \gtrsim 2 \text{ TeV}$. Since $v_1 \sim 100 \text{ GeV}$, for light neutrino masses to be at sub-eV scale, the equation (23) suggest that the Yukawa couplings $y$ have to be fine tuned to $10^{-5.5}$ which is approximately same as the electron Yukawa coupling in the SM. The other two SM neutrinos can acquire non-zero masses only when loop contributions in figure 9 are taken into account. As discussed in [10], the one-loop contribution $(M_\nu)_{ij}$ to neutrino mass is given by

$$ (M_\nu)_{ij} \approx \frac{f_3f_5v_1v_2u_1u_4}{16\pi^2} \sum_k h_{N,\Sigma ik}h_{N,\Sigma jk} \left(A_k + (B_k)_{ij}\right) $$  \hspace{1cm} (24)
Assuming all the scalar masses in the loop diagram to be almost degenerate and written as $m_{sc}$ then

$$A_k + (B_k)_{ij} \approx m_{2k} \left[ \frac{m_{sc}^2 + m_{2k}^2}{m_{sc}^2 (m_{sc}^2 - m_{2k}^2)^2} - \frac{(2 - \delta_{ij}) m_{2k}^2}{(m_{sc}^2 - m_{2k}^2)^3} \ln \left( \frac{m_{sc}^2}{m_{2k}^2} \right) \right], \quad (25)$$

where $(M_N, \Sigma)_k = m_{2k}$. For fermion singlet light dark matter, $m_{2k} \ll m_{sc}$ and hence the above expression can be approximated as

$$A_k + (B_k)_{ij} \approx \frac{m_{2k}}{m_{sc}^4}$$

The one-loop neutrino mass can be written as

$$(M_\nu)_{ij} \approx \frac{f_3 f_5 v_1 v_2 u_1 u_4}{16 \pi^2} \sum_k h_{N, \Sigma ik} h_{N, \Sigma jk} \left( \frac{m_{2k}}{m_{sc}^4} \right) \quad (26)$$

Taking $u_1, u_4, m_{sc}$ to be at few TeV’s, $v_1, v_2$ at electroweak scale and the singlet mass $m_{2k}$ at 100 GeV, the above expression can give rise to eV scale neutrino mass if

$$f_3 f_5 h_N h_N \sim 1.57 \times 10^{-8}$$

whereas for singlet mass $m_{2k}$ at 35 GeV, this constraint becomes

$$f_3 f_5 h_N h_N \sim 4.51 \times 10^{-8} \quad (27)$$

As discussed in the next section, we take $h_N \approx 10^{-1.5}, y \approx 10^{-5.5}, f_5 \approx 1$ for which the above constraint is satisfied if $f_3$ is chosen to be around $10^{-5}$. Thus, the singlet fermion dark matter masses we choose in this work are compatible with the light neutrino masses.

V. KEV MASS SPLITTING BETWEEN $N_R$ AND $S_{2R}$

For the discussion on dark matter, we assumed the masses of two dark matter candidates $N_R$ and $S_{2R}$ to be at 100 GeV and 35 GeV while keeping their mass difference 3.55 keV. From the Yukawa Lagrangian of the model in equation (3), it can be seen that $N_R$ and $S_{2R}$ receive tree level masses from the vev of $\chi_4$ and $\chi_2$ respectively. For equal vev’s of the singlet scalar fields around TeV scale as we had assumed in our previous analysis, the mass splitting of 3.55 keV will require the an unnatural fine-tuning between the two Yukawa couplings $f_N$ and $f_{S2}$ given as

$$f_N - f_{S2} \sim 10^{-9}$$
FIG. 10: Mass splitting between $N_R$ and $S_{2R}$ at one loop level.

One the other hand if we assume their tree level masses to be equal, then such a small mass splitting can arise naturally at one loop level through the Feynman diagram shown in figure 10.

The mass matrix $M_{dark}$ in the $N_R, S_{2R}$ basis can be written as

$$M_{dark} = \begin{pmatrix} f_N u_4 & M_{dark12} \\ M_{dark21} & f_{S2} u_2 \end{pmatrix}$$  \hspace{1cm} (28)$$

The one-loop contribution $M_{dark12} = M_{dark21}$ to $2 \times 2$ mass matrix is given by

$$M_{dark12} \approx \frac{2y^2 y^* h_N f_{12} f_{5}^* v_1^2 v_2 u_4}{16\pi^2} \left[I \left(m_{\phi_3 R}, m_{\chi_3 R}, m_{\nu}, m_{S_{1R}}\right) - I \left(m_{\phi_3 I}, m_{\chi_3 I}, m_{\nu}, m_{S_{1R}}\right)\right]$$  \hspace{1cm} (29)$$

in which

$$I(a, a, b, c) \approx \frac{a^2 \ln(a^2/c^2) - a^2 + c^2}{a^2(a^2 - c^2)^2}, \hspace{1cm} (30)$$

for $b << a, c$ and

$$I(a, b, c, d) \approx \frac{1}{a^2 - b^2} \left[\frac{1}{a^2 - d^2} \ln(a^2/d^2) - \frac{1}{b^2 - d^2} \ln(b^2/d^2)\right]$$  \hspace{1cm} (31)$$

for $c << a, b, d$ and these limits are useful as active neutrino mass scale $m_{\nu}$ is very small in comparison to other masses. Here, $m_{\phi_3 R}$ and $m_{\phi_3 I}$ are the masses corresponding to
Re[ϕ₀³] and Im[ϕ₀³] respectively whereas m_{χ³R} and m_{χ³I} are the masses corresponding to Re[χ₀³] and Im[χ₀³] respectively. As denoted in the previous section, v_i and u_i are the vev of electroweak scalar doublets and additional singlet scalar fields respectively. We have considered m_ν ≈ \frac{2g^2 v_1^2}{f_5 u_1} and m_{S_{1R}} ≈ f_s u_1.

Particularly if we consider m_φ₀³ ≈ m_χ³ and denote the near-equal masses of Re[m_{χ³}] and Im[m_{χ³}] as m_s where s = φ_3, χ_3, then

\[ M_{dark_{12}} \approx \frac{2y^2 g^2 h_N f_{12} f_5^* v_1^3 v_2 u_4}{16\pi^2} \left[ \frac{m_s^2 (m_s^2 - f_s^2 u_1^2)^2}{m_s^2 (m_s^2 - f_s^2 u_1^2)^2} \right] \] (32)

From tree level neutrino mass m_ν ≈ \frac{2g^2 v_1^2}{f_5 u_1}, if we keep the mass of singlet neutrino m_{S_{1R}} ≈ f_s u_1 fixed at 1 TeV or so, then the Yukawa couplings have to be tuned to 10^{-5.5} to give rise to neutrino mass of order 0.1 eV. We also assume m_{s_{φ₃}} - m_{s_{φ₄}} ≈ m_s^2 and order one dimensionless couplings f_5, f_{12} and keep h_N ≈ 10^{-1.5}. Under these simplifying assumptions and taking u_1 ≈ u_4 ≈ 20v_1 ≈ 20v_2 ≈ 2 TeV, the splitting (S) between the masses of N_R and S_{2R} is given by

\[ S = 2M_{dark_{12}} \approx \frac{10^{-7}}{(m_s^2 - f_s^2 u_1^2)^2} \{\ln (m_s^2/(f_s^2 u_1^2)) - 1\} \] (33)

This mass splitting can be few keV (10^{-6} GeV) only if m_s ≈ f_s u_1 and (m_s^2 - f_s^2 u_1^2)^2 ≈ 1 GeV^2. Thus, the desired 3.55 keV splitting between two electroweak scale dark matter candidates can be generated in our model provided the mass splitting between m_s and f_s u_1 is tuned at approximately 1 GeV. If we use y = 10^{-5.5} and h_N ≈ 10^{-1.5}, f_{12} ≈ 1, the constraint on dimensionless couplings from 3.55 keV X-ray line given in equation (22) can be satisfied if f_6 ≈ 1. Similarly the constraint coming from light neutrino mass given in equation (27) can be satisfied if f_3 ≈ 10^{-5}.

VI. RESULTS AND CONCLUSION

We have studied an abelian gauge extension of standard model which can predict tiny neutrino mass and stable dark matter candidate naturally. In particular, we have discussed the possibility of explaining the recently observed 3.55 keV X-ray line and the galactic center gamma ray excess from a common dark matter origin within the framework of this abelian
gauge model. Although the model has both scalar and fermionic dark matter candidates, we choose to study only fermionic dark matter candidates to serve our goal better. The dark matter candidate is guaranteed to be stable by a remnant $Z_2$ symmetry after the abelian gauge symmetry gets spontaneously broken. In order to explain the 3.55 keV X-ray line, we assume the dark sector to consist of two dark matter particles: the lightest $Z_2$ odd particle ($S_{2R}$) and the next to lightest $Z_2$ odd particle $N_R$, both of which are singlet fermions. The mass difference between the two dark matter particles is chosen to be 3.55 keV such that the heavier one can decay into the lighter one and a photon at loop level. We first take the lightest dark matter particle mass to be 100 GeV and then constrain the parameter space from the requirement of total dark matter relic density and the observed flux of 3.55 keV X-ray line. In order to explain the galactic center gamma ray excess, we choose the lightest dark matter mass to be 35 GeV and check whether the two dark matter particles give rise to the required annihilation cross sections into $b\bar{b}$ pairs. In both of these examples of dark matter masses, we also take into account the constraints from dark matter direct detection experiments like Xenon100 on spin dependent scattering cross section of dark matter off nuclei. These models can also face stringent limits on new gauge boson mass $M_X$ and gauge coupling $g_X$. Using the results from [22] where the authors found the lower bound on $M_X/g_X$ to be 2.6 TeV for $\text{BR}(X \to \text{SM}) = 90\%$ and $g_X = 0.1$ we also use three different cuts on $M_X/g_X$ starting from a moderate 2 TeV to a conservative 4 TeV on $M_X/g_X$. These limits will be even weaker in those region of parameter space where $g_X$ can be much lower than 0.1. We find that, even after applying a conservative lower limit on $M_X/g_X$ as 4 TeV, we still have some parameter space available near the s-wave resonance region which can satisfy all constraints related to dark matter and colliders.

After showing the allowed parameter space in terms of $g_X, M_X$ as well as $u$, the common vev of the scalar singlets, we constrain the other parameters of the model from the requirement of producing the correct 3.55 keV X-ray flux, sub-eV neutrino mass and 3.55 keV mass splitting between two dark matter candidates. From the X-ray flux constraints, we find that the product of four relevant dimensionless couplings have to be fine-tuned to around $10^{-3}$ or $10^{-7}$ for two different possibilities. Similarly, the constraints from sub-eV neutrino masses keep the product of four relevant dimensionless couplings tuned at around $10^{-8}$ for singlet fermion dark matter masses of a few tens of GeV. Finally, the 3.55 keV mass splitting between the two dark matter candidates, which naturally arises at one loop level
forces one to keep $S_{1R}$ mass around a few hundred GeV with approximately 1 GeV mass difference between $S_{1R}$ and the scalars $\phi_3, \chi_3$. Constraints from light neutrino mass and keV mass splitting between $N_R$ and $S_{2R}$ show more preference for opposite $CP$ eigenvalues of $N_R$ and $S_{2R}$ where the X-ray line constraint on the product of four dimensionless couplings is $10^{-7}$. Since the same dimensionless couplings appear in two loop decay width of heavier dark matter, light neutrino mass and mass splitting of two dark matter particles, we are not left with much freedom to adjust the parameters among themselves. Also the allowed parameter space in $g_X - M_X$ plane is very limited. This is because for light dark matter mass, in order to explain GC excess and 3.55 keV line together, the constraints from dark matter experiments as well as bound on $M_X/g_X$ allow only a limited region near the s-channel resonance $M_X \approx 2m_{DM}$. For dark matter mass around 35 GeV, the allowed mass of neutral boson becomes around 70 GeV which faces severe constraints from LEP-II data and further constrain the coupling $g_X \leq 10^{-2}$. Due to the very limited parameter space available, this model will undergo serious scrutiny at future experiments with more sensitivity.

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