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Anomalous X-ray galactic signal from 7.1 keV spin-3/2 dark matter decay

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Abstract. In order to explain the recently reported peak at 3.55 keV in the galactic X-ray spectrum, we propose a simple model. In this model, the Standard Model is extended by including a neutral spin-3/2 vector-like fermion that transforms like a singlet under SM gauge group. This 7.1 keV spin-3/2 fermion is considered to comprise a portion of the observed dark matter. Its decay into a neutrino and a photon with decay life commensurate with the observed data, fits the relic dark matter density and obeys the astrophysical constraints from the supernova cooling.

Keywords: dark matter theory, supernova type Ia - standard candles

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1 Introduction

Recently X-ray emission at ~ 3.55 keV has been observed in the XMM-Newton X-ray observatory [1, 2] in many Galaxy clusters and in the Andromeda Galaxy spectra. The observed flux and any X-ray line energy measured in the MOS spectra is given by

$$\begin{aligned}\Phi_{\gamma}^{\text{MOS}} &= 4.0_{-0.8}^{+0.8} \times 10^{-6} \text{ photons cm}^{-2} \text{ sec}^{-1} \\ E_{\gamma}^{\text{MOS}} &= 3.54 \pm 0.02 \text{ keV} .\end{aligned}\tag{1.1}$$

The source of this line is yet to be identified. An attractive possibility, considered in the literature to explain the observed flux and energy, is to attribute it to the decay/ annihilation of some dark matter particle which is stable over cosmological time scale and can account for at least a significant fraction of dark matter relic density with mass and decay life time commensurate with the observed data. Sterile Neutrino of mass 7.1 keV capable of producing warm Dark Matter (WDM) density through resonant or non-resonant production with parameters required to produce the observed signal is an attractive proposition discussed in the literature [3–7]. R-parity violating decays of the lightest super-symmetric particle (LSP), the decay of gravitons and axions, into neutrino photon pair and the decay of scalar field ϕ or axion-like pseudoscalar fields a into photon pairs as possible explanation of the signals have been considered in the literature [7–16] with varying success. The scalar case is of particular interest because the scale of the new physics may involve super-symmetry (SUSY) which conforms to the expectations from the physics of moduli.

Several new physics models beyond the standard model (SM) predict the existence of spin-3/2 particles. In models of super-gravity, the graviton is accompanied by spin-3/2 gravitino super partner. In models of composites [17, 18], the top quark has an associated spin-3/2 resonance. New physics models may include exotic fermions and gauge bosons which are not present in the SM. Spin-3/2 fermions also exist as Kaluza -Klein modes in string theory [19–22] if one or more of compactification radii are of the scale lower than the Planck scale.

The prediction of spin-3/2 particle as a cold dark matter has been made by several authors in SUSY models [23, 24]. Gravitinos with mass in the keV range have been studied

as the probable WDM candidate in various SUSY models [25–28] even before the observation of 3.55 keV X ray emission. Recently, authors of the reference [29, 30] have studied the implication of the effective four fermion interactions involving the DM spin-3/2 particle on relic density, the antiproton to proton flux ratio in cosmic rays, and the elastic scattering off nuclei (direct detection) in the effective field theory approach. Constraints from direct detection of dark matter exist in literature on spin-3/2 WIMP candidates [31].

A recent comprehensive analysis by the authors of reference [32] demonstrated that the measured flux of the 3.55 keV line can be accounted for, by the conventionally known plasma lines without invoking the dark matter decay as its origin. This explanation, however, requires the fixing of the abundances of different elements which are still uncertain to a certain degree. We, thus, feel that it is worthwhile to investigate alternative interpretations that are consistent with the other astrophysical and cosmological data.

In this paper, we consider a new neutral spin-3/2 fermion assumed to be a vector-like SM singlet. We will consider the decay of this 7.1 keV DM particles into a neutrino-photon pair ($\chi \rightarrow \nu\gamma$) with decay life commensurate with the observed galactic X-ray spectrum. This spin-3/2 particle could exist as fundamental particle or could be a bound state of SM neutrino and U(1) gauge bosons. We will explore the possibility of such an exotic spin-3/2 particle to constitute the relic dark matter for a reasonable choice of parameters and confront the model from cosmological and astrophysical constraints.

In section 2, we describe the spin-3/2 fermion model. In section 3, we discuss the implication of the model to explain the observed galactic X Ray spectrum data. In section 4, we obtain the relic abundance and the resulting constraints on the model parameters. In section 5, we discuss the bounds obtained from supernova energy loss. Section 6 is devoted to results and discussion.

2 The spin-3/2 model

The standard model is extended by including a spin-3/2, vector like particle χ , whose right-handed (RH) as well as left-handed (LH) projections transform the same way under $SU(2) \times SU(1)$. We further let χ to be a SM singlet. Spin-3/2 free Lagrangian is given by

$$\begin{aligned} \mathcal{L} &= \bar{\chi}_\mu(p_{\bar{\chi}}) \Lambda^{\mu\nu} \chi_\nu(p_\chi) \quad \text{where} \\ \Lambda^{\mu\nu} &= (i\not{\partial} - m_\chi) g^{\mu\nu} - i(\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu) + i\gamma^\mu\not{\partial}\gamma^\nu + m_\chi\gamma^\mu\gamma^\nu. \end{aligned} \quad (2.1)$$

Here χ_μ satisfies $\Lambda^{\mu\nu}\chi_\nu = 0$. For on mass-shell χ , we have

$$\gamma^\mu\chi_\mu(p_\chi) = 0 = \partial^\mu\chi_\mu(p_\chi) = (\not{p} - m_\chi)\chi_\mu(p_\chi). \quad (2.2)$$

The spin-sum for spin-3/2 fermions

$$\mathcal{S}^+_{\mu\nu}(p) = \sum_{i=-3/2}^{3/2} u_\mu^i(p) \bar{u}_\nu^i(p) \quad \text{and} \quad \mathcal{S}^-_{\mu\nu}(p) = \sum_{i=-3/2}^{3/2} v_\mu^i(p) \bar{v}_\nu^i(p) \quad (2.3)$$

are given by

$$\mathcal{S}^\pm_{\mu\nu}(p) = -(\not{p} \pm m_\chi) \left[g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3m_\chi^2}p_\mu p_\nu \mp \frac{1}{3m_\chi}(\gamma_\mu p_\nu - \gamma_\nu p_\mu) \right], \quad (2.4)$$

respectively.

The most general leading order standard model gauge invariant interaction between the spin-3/2 SM singlet χ and SM spin-1/2 fermions is given by the effective dimension six operators:

$$\begin{aligned}\mathcal{L}_{\text{Int.}}^{\text{Eff.}} &= \sum_{i=1}^3 \frac{C_i}{\Lambda^2} \mathcal{O}_i \\ &= \frac{C_1}{\Lambda^2} \bar{l}_L^k \gamma^\alpha [\gamma^\mu, \gamma^\nu] \chi_\alpha \tilde{\phi} B_{\mu\nu} + \frac{C_2}{\Lambda^2} \bar{l}_L^k \gamma^\alpha D_\mu \chi_\alpha D^\mu \tilde{\phi} + \frac{C_3}{\Lambda^2} \bar{l}_L^k \gamma^\mu \chi^\nu \tilde{\phi} B_{\mu\nu},\end{aligned}\quad (2.5)$$

where $D_\mu \equiv i \partial_\mu - i(g_s/2) \lambda^a G_\mu^a - i(g/2) \tau^I W_\mu^I - i g' Y B_\mu$, $B_{\mu\nu} = (\cos \theta F_{\mu\nu} - \sin \theta Z_{\mu\nu})$, $\tilde{\phi} = i\tau_2 \phi$ and l_L^k is the SM lepton doublet. The weak U(1) hyper-charge Y for ϕ and χ are 1/2 and 0, respectively.

In view of the on-mass shell conditions as given in eq. (2.2), the second operator \mathcal{O}_2 vanishes and the third operator \mathcal{O}_3 becomes identical to the first operator \mathcal{O}_1 . Therefore we are left with only one coupling constant C , which can be simplified to give after symmetry breaking:

$$\mathcal{L}_I = \frac{C v_0}{\Lambda^2} \bar{\nu}_{kL} (p_{\nu_e}) \gamma_\mu \chi_\rho (p_\chi) (\cos \theta F^{\mu\rho} - \sin \theta Z^{\mu\rho}).\quad (2.6)$$

Here v_0 is the SM Higgs vacuum expectation value and Λ is the new cut-off scale.

3 Galactic X-ray spectrum

The decay width for $\chi \rightarrow \nu_e \gamma$ is given by

$$\begin{aligned}\Gamma_{\chi \rightarrow \nu_e \gamma} &= \left(\frac{C v_0 \cos \theta}{\Lambda^2} \right)^2 \frac{1}{16\pi} m_\chi^3 \\ &= 4.73 \times 10^{-27} \left[\frac{C}{10^{-9}} \right]^2 \left[\frac{\Lambda}{100 \text{ TeV}} \right]^{-4} \left[\frac{m_\chi}{7 \text{ keV}} \right]^3 \text{ sec}^{-1}.\end{aligned}\quad (3.1)$$

Here we have taken the coupling of spin-3/2 particle with only one generation (say for the first generation only) of SM neutrino.

The expected X-ray flux is proportional to the density of the decaying dark matter χ . The WDM which in the case considered here constitutes of spin-3/2 SM singlet, is believed to comprise a portion of the observed DM relic abundance with CDM as the dominant component [33, 34]. If the X-ray galactic signal is interpreted as coming from the spin-3/2 WDM χ decaying into a neutrino and a photon pair, the required value of the life time of χ should be given by $\tau_\chi \sim 1.4 f \times 10^{28}$ seconds, where f ($0 < f \leq 1$) is the fraction of the relic dark matter density contributed by the WDM χ . At $f = 1.0$ the WDM χ would account for the entire dark matter relic density with a choice of new physics scale Λ of the order of $\simeq 100$ TeV along with the coupling constant $C \simeq 10^{-9}$. The small value of C should not be surprising as it can be considered to be a measure of trilinear lepton number violating coupling and hence naturally small. Similar situation occurs in super-symmetric models of R-parity violating interactions considered in the literature [9–16] as possible explanation of the observed galactic X-ray flux. In realistic model, the mixing between photino and neutrino for example, is suppressed by a small parameter $\sim 10^{-10}$ characterising lepton number violation [14, 35–37].

If, the 7.1 keV signal, on the other hand, is interpreted as coming from pair annihilation of 3.55 keV spin-3/2 DM into two photons, the annihilation cross-section $\langle\sigma v\rangle_{\text{ann.}}$ has to match with the best-fit decay-width of 7.1 keV DM i.e.

$$\langle\sigma v\rangle_{\text{ann.}} \approx 2 \frac{\Gamma_{\chi\bar{\chi}\rightarrow\nu_e\gamma}}{n_\chi}, \quad (3.2)$$

where $n_\chi = \rho_\chi/m_\chi \approx (10^4 - 10^5) \text{ cm}^{-3}$ is the number density of spin-3/2 DM. This translates into $\langle\sigma v\rangle_{\text{ann.fit}} \simeq 2 \times 10^{-16} \text{ GeV}^{-2}$.

The spin-3/2 particles can couple to two photons through U(1) gauge invariant dimension seven effective Lagrangian

$$\mathcal{L}_{\text{int.}} = \frac{C_{\gamma\gamma}}{\Lambda^3} \bar{\chi}_\mu g^{\mu\nu} \chi_\nu F^{\alpha\beta} F_{\alpha\beta}. \quad (3.3)$$

This gives an annihilation cross-section $\sigma(\chi\bar{\chi} \rightarrow \gamma\gamma) \approx C_{\gamma\gamma}^2 m_\chi^4 / (\pi\Lambda^6)$ and the desired annihilation rate is achieved for $\Lambda \lesssim O(100) \text{ MeV}$ (for $C_{\gamma\gamma} \lesssim 1$), which is clearly unphysical. Thus, it is unlikely that the observed galactic X-ray signal can be explained by DM χ 's annihilation into photons.

4 Relic abundance of spin-3/2

Since the χ 's couple weakly to the SM particles and are nearly stable with a lifetime comparable to the age of the Universe if they have to account for the observed X-ray flux, they will decouple early when they are relativistic. They will, therefore, contribute to the present mass density of the Universe as DM. Their abundance at decoupling is nearly equal to the photon density at that time. During the adiabatic expansion of the Universe, their number densities remain comparable. A rough estimate of the bound on χ mass can be obtained just like the bound on the neutrino mass [38] by requiring that the ratio of DM χ density to the critical density remain less than one. This gives $m_\chi \leq 12.8g^*(T_D)/g_{\text{eff}} \text{ eV}$.

The effective number of degrees of freedom $g^*(T_D)$ at decoupling time of electroweak symmetry breaking transition is found to be about 113.75. In the computation of $g^*(T_D)$, we have included the effective degrees of freedom from all SM particles and $\chi, \bar{\chi}$ spin-3/2 DM particles. However, in the MSSM, $g^*(T_D)$ is much larger ~ 228.75 and thus it is not reasonable for the spin-3/2 DM particle χ to have a mass of the order of about 7.1 keV. The relic abundance of dark matter χ depends on the sources of production of χ in the early Universe. The leading order processes (shown in figure 1) that maintain the DM χ in equilibrium with the rest of the

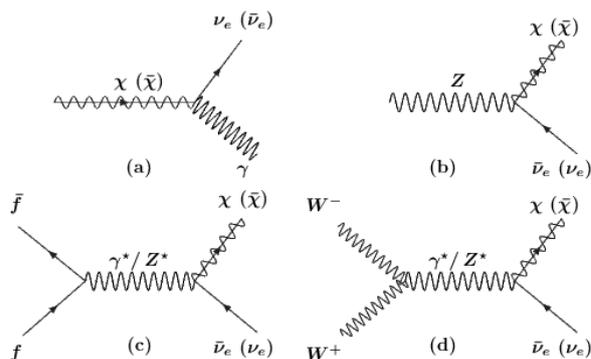


Figure 1. Relevant diagrams for decay and production of the DM candidate χ .

SM plasma are the decay rate of $Z \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e$ and the 2 \rightarrow 2 pair annihilation rates, namely, $\Gamma(Z \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e)$, $\Sigma_{f_i} \sigma(f_i \bar{f}_i \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e)$ and $\sigma(W^+W^- \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e)$ where Σ_{f_i} means summation over all SM fermions (quarks and leptons). Using the interaction Lagrangian given in eq. (2.6), the decay and spin averaged annihilation cross-sections can be

computed in a straightforward manner. We obtain:

$$\Gamma(Z \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e) \approx \frac{C^2 v_0^2 \sin^2 \theta}{\Lambda^4} \frac{1}{72\pi} \frac{m_Z^2}{m_\chi^2} m_Z^3, \quad (4.1)$$

$$\begin{aligned} \sigma\left(\sum_i f_i \bar{f}_i \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e\right) &\approx \frac{4\pi\alpha C^2 v_0^2}{\Lambda^4} \frac{1}{128\pi} \frac{8}{9} \sum_i \frac{1}{\sqrt{1 - \frac{4m_i^2}{s}}} \left(\frac{s}{m_\chi^2}\right) s^2 \\ &\times \left[\cos^2 \theta \frac{Q_{f_i}^2}{s^2} \left(1 + 2\frac{m_i^2}{s}\right) + \frac{1}{\cos^2 \theta} \frac{1}{(s - m_Z^2)^2 + \Gamma^2 m_Z^2} \left\{ (g_V^i)^2 + g_A^i \right\} \left(1 + \frac{3}{4} \frac{s}{m_Z^2}\right) \right. \\ &\left. + 2\frac{m_i^2}{s} \left\{ (g_V^i)^2 - g_A^i \right\} + \left\{ \frac{3}{4} \left(\frac{s}{m_Z^2}\right)^2 - \frac{3}{8} \frac{s}{m_Z^2} \right\} (g_V^i + g_A^i) \right\} + \frac{Q_{f_i}(s - m_Z^2)}{s\{(s - m_Z^2)^2 + \Gamma^2 m_Z^2\}} \\ &\times \left. \left\{ g_V^i \left(\frac{3}{8} + \frac{m_Z^2}{s} + 2\frac{m_Z^2 m_i^2}{s^2}\right) + \frac{3}{8} (g_V^i + g_A^i) \frac{m_i^2}{s} \left(\frac{2m_i^2}{s} - 1\right) \right\} \right], \quad (4.2) \end{aligned}$$

and

$$\begin{aligned} \sigma(W^+ W^- \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e) &\approx \frac{4\pi\alpha C^2 v_0^2}{\Lambda^4} \frac{1}{288\pi} \left(1 - \frac{4m_f^2}{s}\right)^{-\frac{1}{2}} \frac{1}{18} \frac{s}{m_\chi^2} \left(\frac{s}{m_W^2}\right)^2 s^2 \\ &\left[\frac{m_Z^2}{s} \frac{1}{(s - m_Z^2)^2 + \Gamma^2 m_Z^2} \left(1 - \frac{4m_W^2}{s}\right) \left(1 + 20\frac{m_W^2}{s} + 12\frac{m_W^4}{s^2}\right) \right. \\ &\left. + \frac{1}{s^2} \left(1 + 16\frac{m_W^2}{s} - 68\frac{m_W^4}{s^4} - 48\frac{m_W^6}{s^3}\right) \right], \quad (4.3) \end{aligned}$$

where g_V^i and g_A^i are the vector and axial vector couplings of respective fermions in SM.

If the decay and annihilation rates are much smaller than the Hubble expansion rate at the temperature of the order of Electro-Weak (EW) symmetry-breaking scale, the spin-3/2 DM particle χ will never be in thermal equilibrium. The Hubble expansion rate at a temperature T is given by $H(t) \approx 1.66g^* T^2/m_{\text{Pl}}$ where g^* is the effective number of relativistic degrees of freedom at the temperature T . The decay $Z \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e$ comes into play only below EW symmetry breaking phase transition temperature $T_{\text{EW}} \sim 150$ GeV. The Z bosons go out of the equilibrium below roughly 5 GeV, the other SM fermions remain in equilibrium much below this temperature.

The decay and annihilation rates can be estimated from eqs. (4.1)–(4.3). The Z decay rate is given by

$$\Gamma(Z \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e) \approx 7.7 \times 10^{21} C^2 \left[\frac{\Lambda}{1 \text{ GeV}}\right]^{-4} \text{ GeV}. \quad (4.4)$$

The leading terms in the cross-section corresponding to χ production through $f\bar{f}$ annihilation and W fusion processes are given by

$$\sum_i \sigma(f_i \bar{f}_i \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e) \approx 2.3 \times 10^{13} C^2 \left[\frac{s}{1 \text{ GeV}^2}\right] \left[\frac{\Lambda}{1 \text{ GeV}}\right]^{-4} \text{ GeV}^{-2} \quad (4.5)$$

and

$$\sigma(W^+ W^- \rightarrow \chi \bar{\nu}_e + \bar{\chi} \nu_e) \approx 6.96 \times 10^3 C^2 \left[\frac{s}{1 \text{ GeV}^2}\right]^3 \left[\frac{\Lambda}{1 \text{ GeV}}\right]^{-4} \text{ GeV}^{-2}, \quad (4.6)$$

respectively. One can obtain the constraint on the effective coupling C/Λ^2 by demanding the thermal average $\Gamma(Z \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e)$, $\langle \sigma(\sum_f f\bar{f} \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e) |nv\rangle$ and $\langle \sigma(W^+W^- \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e) |nv\rangle$ to be less than the $H(T)$ for $T \sim 150$ GeV (i.e. at the EW phase transition temperature). Therefore, using $g^* = 113.45$, we obtain

$$C \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-2} \leq 0.9 \times 10^{-17} \quad \text{from } Z \text{ decay}, \quad (4.7)$$

$$C \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-2} \leq 1.0 \times 10^{-19} \quad \text{from } (\Sigma_f f\bar{f} \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e), \quad (4.8)$$

and

$$C \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-2} \leq 2.4 \times 10^{-19} \quad \text{from } W^+W^- \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e. \quad (4.9)$$

The thermal averaged cross-sections $\langle \sigma |nv\rangle$ are estimated using the relation $s = 4 \langle E \rangle^2$ where $\langle E \rangle = 3.15$ T and 2.7 T, and $n = \frac{3}{4} \frac{\zeta(3)}{\pi^2} gT^3$ and $\frac{\zeta(3)}{\pi^2} gT^3$ for Fermi-Dirac and Bose-Einstein particles, respectively.

The relic density of the spin-3/2 DM χ can be evaluated by solving the Boltzmann equation for the evolution of the number density n_χ of DM χ and is given by

$$\begin{aligned} \dot{n}_\chi + 3Hn_\chi = & -\langle \Gamma(Z \rightarrow \chi\bar{\nu}_e) \rangle (n_\chi^2 - n_0^2) - \Sigma_f \left\langle \sigma \left(\sum_f f\bar{f} \rightarrow \chi\bar{\nu}_e \right) |v\rangle (n_\chi n_{\nu_e}^0 - n_0^{f^2}) \right. \\ & \left. - \langle \sigma(W^+W^- \rightarrow \chi\bar{\nu}_e) |v\rangle (n_\chi n_{\nu_e}^0 - n_0^{W^2}). \end{aligned} \quad (4.10)$$

Here, n_0^i is the equilibrium number density of species i . The region of validity of the equation is when all the SM particles are in thermal equilibrium unlike the DM candidate χ which is realized for $T \lesssim (15 - 20) m_i$. We can then put $n_\chi = 0$ in the r.h.s. of this equation. Changing the variable from time to temperature, the equation can be put in the form:

$$\frac{df_\chi}{dz} = \frac{\Gamma(Z \rightarrow \chi\bar{\nu}_e)}{K m_Z^2} z f_0^Z + \sum_i \frac{\langle \sigma(f_i\bar{f}_i \rightarrow \chi\bar{\nu}_e) |v\rangle}{K Z^2} (f_0^i)^2, \quad (4.11)$$

where $z = m_Z/T$, $f_\chi = n_\chi/T^3$, $f_0^i = n_0^i/T^3$, and $K = 1.66\sqrt{g^*}/m_{\text{Pl}}$. We use Boltzmann distribution functions for both the fermions and bosons, i.e.

$$f_0^i(m_i/T) = f_0^i \left(\frac{m_i}{m_Z} \frac{m_Z}{T} \right) = f_0^i(x_i z) = \frac{g_i}{2\pi^2} \int_0^\infty p^2 e^{-\sqrt{p^2 + x_i^2 z^2}} dp. \quad (4.12)$$

The thermal averaged decay rate and annihilation cross-sections can be expressed, following refs. [39, 40], as

$$\langle \Gamma(Z \rightarrow \chi\bar{\nu}_e) \rangle = \Gamma(Z \rightarrow \chi\bar{\nu}_e) \frac{K_1(z)}{K_2(z)} \quad (4.13)$$

and

$$\langle \sigma(f_i\bar{f}_i \rightarrow \chi\bar{\nu}_e) \rangle = \frac{1}{8m_i^4 T K_2^2 \left(\frac{m_i}{T} \right)} \int_{4m_i^2}^\infty \sigma(f_i\bar{f}_i \rightarrow \chi\bar{\nu}_e) (s - 4m_i^2) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right) ds. \quad (4.14)$$

Here, $K_{1,2}(x)$ are the modified Bessel functions. In terms of scaled number density defined as $N_\chi = f_\chi K m_Z$ and by using the expressions for thermal averaged decay width and the annihilation cross-sections given in eqs. (4.13) and (4.14), the Boltzmann equation can be written as

$$\begin{aligned} \frac{dN_\chi}{dz} = & \Gamma(Z \rightarrow \chi \bar{\nu}_e) \frac{K_1(z)}{K_2(z)} \frac{1}{m_Z} z f_0^z(z) \\ & + \sum_i \frac{1}{8} \frac{z}{x_i^4} \frac{m_Z^2}{K_2^2(x_i z)} \int_{4x_i^2}^{\infty} (y - 4x_i^2) \sqrt{y} K_1(\sqrt{y} z) \sigma(f_i \bar{f}_i \rightarrow \chi \bar{\nu}_e) \frac{1}{z^2} (f_0^i(x_i z))^2 dy. \end{aligned} \quad (4.15)$$

We solve the above Boltzmann equation for the scaled number density N_χ of spin-3/2 dark matter particle χ for $0.6 < z < 18$ corresponding to $5 \text{ GeV} < T < 150 \text{ GeV}$.

The contribution of the proposed 7.1 keV spin-3/2 fermion χ to the relic dark matter density is obtained by numerically solving the Boltzmann eq. (4.15) from the electroweak phase transition temperature to the freeze-out temperature of W 's and Z 's. The scaled number density N_χ 's for the leading processes that maintain the dark matter χ in equilibrium with the rest of SM plasma are obtained to be

$$\begin{aligned} N_\chi(\Gamma(Z)) & \simeq C^2 \times 10^{19} \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-4}; & N_\chi \left(\sum_f \sigma(f \bar{f}) \right) & \simeq C^2 \times 10^{20} \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-4}; \\ \text{and } N_\chi(\sigma(W^+ W^-)) & \simeq C^2 \times 10^{23} \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-4}; \end{aligned} \quad (4.16)$$

for the Z -decay, fermion-antifermion annihilation and W^\pm fusion processes, respectively.

We find that the contribution of spin-3/2 DM fermion to the relic density from W^\pm boson fusion process is about three order of magnitudes greater than the contribution from the rest of the processes. For our estimate of the dark matter density, we use the $N_\chi \approx C^2 \times 10^{23} [\Lambda/1 \text{ GeV}]^{-4}$. Thus, the number density of χ at the electroweak phase transition temperature is given by $n_\chi/T^3|_{T=T_{\text{EW}}} \approx N_\chi/(K M_z) \sim 10^{23}/(K M_z)$. The number density of χ 's as the Universe cools to the present day is estimated to be $n_\chi|_{T_0} \sim T_0^3/(\zeta K m_Z)$ where T_0 is the present day temperature ($T_0 = 2.73 \text{ K}$) and $\zeta = g^*(T_{\text{EW}})/g^*(T_0) \sim 33.85$. The present day dark matter relic density $\rho_\chi|_{T_0} \approx C^2 \times 10^{-5} [\Lambda/1 \text{ GeV}]^{-4} \text{ GeV}^4$ is then obtained by multiplying the number density n_χ with its mass m_χ . Since, the critical dark matter density $\rho_{\chi_c} \sim 8.1 h^2 10^{-47} \text{ GeV}^4$, the $\Omega_\chi = \rho_\chi/\rho_{\chi_c}$ is computed as

$$\Omega_\chi h^2 \approx 0.11 \times 10^{42} C^2 \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-4}. \quad (4.17)$$

However, the desired value of $\Omega_\chi h^2 \sim \Omega_{\text{DM}} = 0.11$ will be obtained for $C[\Lambda/1 \text{ GeV}]^{-2} \approx 10^{-21}$.

5 Supernova energy loss

The 7.1 keV spin-3/2 dark matter χ can be a source of significant energy loss in the supernova core. The emission rates for SN 1987 A have been extensively studied for weakly interacting DM candidate particles like axions, gravitinos, right handed neutrinos, majorons, low mass

neutralinos, Goldstone bosons etc. in new physics models. Constraints have been put on the properties and interactions of these particles [41–48]. The SN bound on neutrino magnetic dipole moment have been one of the tightest [49]. In our estimate of the constraints on the parameters of our model, we would use the Raffelt criterion [50] that new source of cooling should not exceed the emissivity $\dot{\epsilon}/\rho = 10^{19}$ ergs per gm per section. The main source of χ pair production in the core of SN is through the $\chi\bar{\nu}_e$ and/ or $\bar{\chi}\nu_e$ production processes. The emissivity i.e. the energy emitted per unit time and volume, is

$$\dot{\epsilon} = \int \prod_{i=1}^4 \frac{d^3 p_i}{(2\pi)^3} \frac{1}{2E_i} (2\pi)^4 \delta^4(p_{e^+} + p_{e^-} - p_{\bar{\nu}_e} - p_{\chi}) f_1 f_2 (1 - f_3) (1 - f_4) E_{\chi} \overline{|M|^2}, \quad (5.1)$$

where $\overline{|M|^2}$ is the matrix element squared, summed over the initial and final states and $f_i \equiv [\exp(E_i - \mu_i)/T + 1]^{-1}$ is the Fermi-Dirac distribution for the i th particle.

In the supernova core immediately after the collapse, the temperature is high being of the order of tens of MeV. Even though the nucleons are nearly non-degenerate, the electrons are degenerate and the neutrinos are trapped. The core has a fixed value of the lepton number. Thus, there also exists a sub-dominant energy loss process via the neutrino pair annihilation $\nu\bar{\nu} \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e$. Since, the coupling of the dark matter particle χ to SM fermions is extremely weak, the χ 's once produced freely stream out of the SN core, their mean free path being greater than the core radius. We thus have $\mu_{\chi} \approx 0$. Carrying out the phase space integrals and making a change in variables from E_1, E_2, θ to $E_+ = E_1 + E_2, E_- = E_1 - E_2$ and $s = 2m_e^2 + 2E_1 E_2 - 2|\vec{p}_1||\vec{p}_2|\cos\theta$, we get

$$\dot{\epsilon} = \frac{1}{2\pi^3} \int_{4m_e^2}^{\infty} ds \int_{\sqrt{s}}^{\infty} dE_+ \int_{-\sqrt{E_+^2 - s}}^{\sqrt{E_+^2 - s}} dE_- s \frac{E_+ + E_-}{2} f_1 f_2 \sigma(e^+ e^- \rightarrow \chi\bar{\nu}_e). \quad (5.2)$$

In deriving the above expression, we have neglected the Pauli blocking terms for the final state particles χ and ν_e which is an excellent approximation for $\bar{\nu}_e, \chi$ and $\bar{\chi}$. We have similar expression for the process $\nu_e \bar{\nu}_e \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e$. The cross-section for these processes has been evaluated in eq. (4.2).

The core density lies anywhere between 3×10^{13} to 3×10^{14} gm/cc. At a core temperature of about 40 MeV, the electron chemical potential is $\mu_e \approx 200$ MeV and $\mu_e - \mu_{\nu_e} \approx 50$ MeV. In our estimate of the energy loss, we consider the core density to be 3×10^{14} GeV with a core temperatures 30 (50) MeV and electron and neutrino chemical potentials 200 (150) MeV and 150 (100) MeV, respectively, and evaluate the energy loss integral numerically.

Constraints from supernova cooling are obtained by numerical integration of the emissivity expression (5.2) for the process $e^+ e^- \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e$ at $T = 30$ MeV and electron chemical potential $\mu_e = 200$ MeV, we obtain

$$\frac{\dot{\epsilon}(e^+ e^- \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e)}{\rho_{\text{core}}} = 2.2 \times 10^{53} C^2 \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-4} \text{ ergs/gm/s} \quad (5.3)$$

where we have taken the core density ρ_{core} to be about 3×10^{14} gm/cc. Requirement of $\frac{\dot{\epsilon}}{\rho_{\text{core}}} < 10^{19}$ ergs/gm/cc constrains

$$C \left[\frac{\Lambda}{1 \text{ GeV}} \right]^{-2} \leq 6.7 \times 10^{-18}. \quad (5.4)$$

Core temperature of 50 MeV and $\mu_e = 250$ MeV results in a somewhat tighter constraint $C [\Lambda/1 \text{ GeV}]^{-2} \leq 10^{-18}$. The contribution from the process $\nu_e \bar{\nu}_e \rightarrow \chi\bar{\nu}_e + \bar{\chi}\nu_e$ is totally negligible being roughly 10 orders of magnitude smaller compared to the annihilation process.

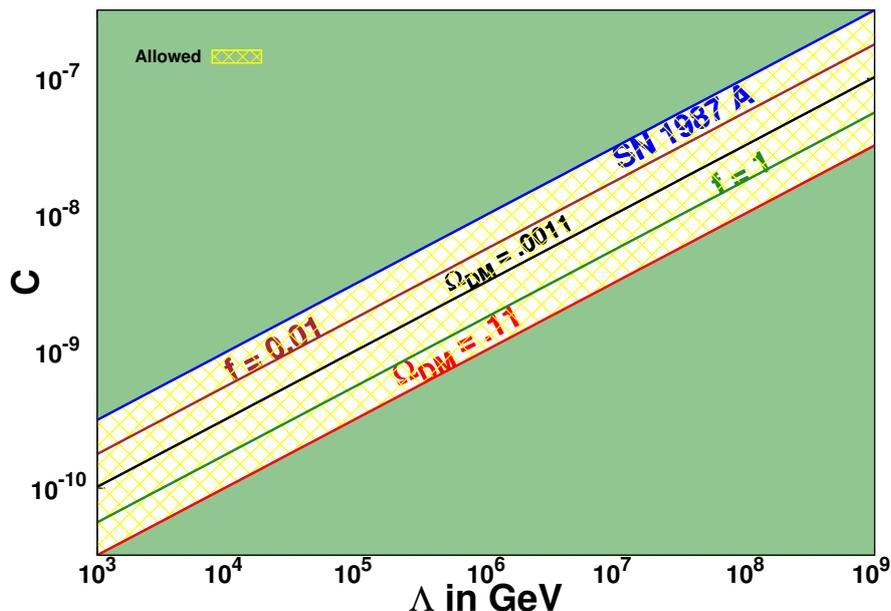


Figure 2. Combined constraints on the coupling C and cut-off scale Λ from contribution to the relic density as WDM, the rapid cooling of supernova SN 1987 A and decay of the spin-3/2 particle. Allowed region (with yellow lines) of the parameter space is bounded by the maximum DM relic density constraint $\Omega_{\text{DM}} = 0.11$ and from supernova cooling of SN 1987 A. The region in green is forbidden.

6 Results and discussion

6.1 Summary

We summarize the constraints on the parameters of our 7.1 keV spin-3/2 dark matter particle χ from cosmological and astrophysical observations. We observe that the ratio of the coupling and the square of the cut-off scale C/Λ^2 associated with spin-3/2 particle χ of mass 7.1 keV can be constrained as

- $C \left[\frac{\Lambda}{1\text{GeV}} \right]^{-2} \lesssim 10^{-21}$ from the consideration of χ as a WDM candidate accounting for the entire observed relic dark matter density $\Omega_\chi h^2 = \Omega_{\text{DM}} = 0.11$,
- $C \left[\frac{\Lambda}{1\text{GeV}} \right]^{-2} \lesssim 6.7 \times 10^{-18}$ from the the rapid cooling of the supernova through the emission of χ and,
- $C \left[\frac{\Lambda}{1\text{GeV}} \right]^{-2} \approx 2.4 \times 10^{-20}$ from the lifetime of χ through its decay $\chi \rightarrow \nu_e \gamma$.

These combined constraints on the parameter space of coupling C and the cut-off scale Λ arising from its appropriate lifetime, contribution to relic density and supernova cooling are shown in figure 2. The curves marked $f = 0.01$ and $f = 1$ correspond to the life time τ_χ required for the observed X-ray flux for WDM χ contribution $\Omega_\chi h^2 = 0.01 \times \Omega_{\text{DM}}$ and $\Omega_\chi h^2 = \Omega_{\text{DM}}$ respectively. We find that the constraints from the cooling of supernova 1987A and the DM relic density $\Omega_\chi h^2 = 0.11$ enclose an allowed band (shaded with yellow lines in the figure) in the parameter space spanned by C and Λ . The parameter space shaded in green is forbidden.

We thus see that a minimal extension of the SM by adding a spin-3/2 SM singlet with mass 7.1 keV can account for the dark matter in the Universe, while at the same time explaining the 3.55 keV X-ray line in the galactic X-ray spectrum through its decay $\chi \rightarrow \nu\gamma$.

6.2 Outlook

Recently, superconducting detectors are proposed for direct detection of light DM particles of mass as low as 1 keV through electron recoil from DM-electron scattering in superconductors [51]. It will be worthwhile to study the DM model discussed in this article to compute the DM scattering rates with electrons in a superconducting environment where electrons are highly degenerate and the scattering is inhibited by the Pauli blocking and to explore the feasibility of detecting the proposed DM particle. We leave this for the future work.

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