We study a light dark matter in a radiative neutrino model to explain the X-ray line signal at about 3.5 keV recently reported by XMN-Newton X-ray observatory using data of various galaxy clusters and Andromeda galaxy. The signal requires very tiny mixing between the dark matter and an active neutrino; $\sin^2 2\theta \approx 10^{-10}$. It could suggest that such a light dark matter cannot contribute to the observed neutrino masses if we use the seesaw mechanism. In other words, neutrino masses might come a structure different from the dark matter. We propose a model in which Dirac type active neutrino masses are induced at one-loop level. On the other hand the mixing between active neutrino and dark matter are generated at two-loop level. As a result we can explain both the observed neutrino masses and the X-ray line signal from the dark matter decay with rather mild hierarchy of parameters in TeV scale.
I. INTRODUCTION

The energy density of dark matter (DM) occupies about 27% of the universe. However, its nature is not known yet clearly. Recently two groups independently reported anomalous X-ray line signal at about 3.5 keV from the analysis of XMM-Newton X-ray observatory data of various galaxy clusters and Andromeda galaxy \[1, 2\]. In this sense, the X-ray line signal at 3.5 keV can be explained by a 7 keV dark matter mixing with the active neutrino by angle given by \(\sin^2 2\theta \approx 10^{-10}\). This could provide a lot of implications on the nature of DM. Already several works have appeared in various models \[3–11\]. Due to its too small mixing, the DM cannot contribute to the neutrino masses directly.

In this letter, we propose a Dirac type neutrino scenario at one-loop level, introducing continuous \(U(1)'\) symmetry \[12–14\]. On the other hand the mixing between active neutrino and dark matter are generated at two-loop level. As a result, such a tiny mixing can be naturally explained within TeV scale.

This paper is organized as follows. In Sec. II, we show our model for neutrino sector and DM sector, and analyze these properties. In Sec. III, we summarize and conclude.

II. THE MODEL

A. Model setup

| Particle | \(L_L\) | \(e_R\) | \(S_L\) | \(S_R\) | \(N_R\) | \(X\) |
|----------|--------|--------|--------|--------|--------|--------|
| \((SU(2)_L, U(1)_Y)\) | \((2, -1/2)\) | \((1, -1)\) | \((1, 0)\) | \((1, 0)\) | \((1, 0)\) | \((1, 0)\) |
| \(U(1)'\) | \(- (3\Sigma + \Sigma')/4\) | \(- (3\Sigma + \Sigma')/4\) | \((3\Sigma - \Sigma')/4\) | \((3\Sigma - \Sigma')/4\) | \((5\Sigma - \Sigma')/4\) | \((3\Sigma - \Sigma')/4\) |

TABLE I: The particle contents and the charges for fermions.

| Particle | \(\eta\) | \(\Phi\) | \(\chi_1\) | \(\chi_2\) | \(\chi_3\) | \(\Sigma\) | \(\Sigma'\) |
|----------|--------|--------|--------|--------|--------|--------|--------|
| \((SU(2)_L, U(1)_Y)\) | \((2, 1/2)\) | \((2, 1/2)\) | \((1, 0)\) | \((1, 0)\) | \((1, 0)\) | \((1, 0)\) | \((1, 0)\) |
| \(U(1)'\) | \(3\Sigma/2\) | \(0\) | \(-\Sigma/2\) | \(-\Sigma'/2\) | \(- (3\Sigma - \Sigma')/2\) | \(\Sigma\) | \(\Sigma'\) |

TABLE II: The particle contents and the charges for bosons.
We discuss a one-loop induced radiative neutrino model. The particle contents are shown in Tab. I and Tab. II. Here one finds that all the terms are written in terms of the charges of $\Sigma$ and $\Sigma'$, as can be seen in those tables. We add three $SU(2)_L$ singlet vector like neutral fermions $S_L$ and $S_R$, three singlet Dirac fermions $N_R$, and gauge singlet Majorana fermion $X$, which is expected to be DM. For new bosons, we introduce $SU(2)_L$ doublet scalar $\eta$ and singlet scalars $\chi_1$, $\chi_2$, $\chi_3$, $\Sigma$, and $\Sigma'$ to the standard model (SM). We suppose that only the SM-like Higgs $\Phi$, $\Sigma$, and $\Sigma'$ have vacuum expectation values (VEVs), $v/\sqrt{2}$, $v_\Sigma/\sqrt{2}$, and $v_{\Sigma'}/\sqrt{2}$, respectively, where $v = 246$ GeV and $\mathcal{O}(10)$ keV $= v_{\Sigma'} < v_\Sigma \ll v$ is assumed.

The continuous $U(1)'$ symmetry is imposed so as to restrict their interaction adequately. Here notice that $\Sigma + \Sigma' \neq 0$ to forbid the mass term of $N_RX$ that provides too large enhancement of the mixing between active neutrinos and $X$.

Moreover, we impose to generate mass term of $X$ through VEV of $\Sigma'$ for our convenience. From this $\Sigma = 5\Sigma'/3$ is derived.

The renormalizable Lagrangian for Yukawa sector and relevant scalar potential under these assignments are given by

$$ -\mathcal{L}_Y = y_\ell \bar{L}\ell \Phi e_R + y_\eta \bar{L}\eta^* S_R + y_{\chi_1} \bar{S}_L N_R \chi_1 + y_{\chi_2} \bar{S}_R^c X \chi_2 + y_{\chi_3} \bar{S}_R^c S_R \chi_3 + \text{h.c.} \quad (\text{II.1}) $$

$$ + \mu_1 (\chi_1)^2 + \mu_2 (\chi_2)^2 + a (\Phi^\dagger \eta) \chi_1 \Sigma^* + b (\Phi^\dagger \eta) \chi_2 \chi_3 + M_S \bar{S}_L S_R + \lambda \Sigma' X X + \text{h.c.} \quad (\text{II.2}) $$

where the first term of $\mathcal{L}_Y$ can generates the charged-lepton masses, and all the couplings are assumed to be real. Moreover there is a mixing between $\eta$ and $\chi_1$, but $\chi_2$ and $\chi_3$ are mass eigenstate from the beginning. The $\chi_2$ has a mass splitting between real part and imaginary part as follows: $m_{\chi_{2R}} = \sqrt{m_{\chi_{2I}}^2 + 2\sqrt{2}\mu_2 v_{\Sigma'}}$, that plays an crucial role in generating non vanishing neutrino mass as well as mixing active neutrino and DM as discussed later.

After the scalar fields get vev’s, (II.2) suggests there is a remnant $Z_2$ symmetry. The odd particles under this discrete symmetry is $L_L, e_R, N_R, X, \eta, \chi_1, \chi_2$. The lightest $Z_2$-odd particle is the lightest neutrino and $X$ can decay into it without breaking $Z_2$ symmetry.

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1 We used the same notation, $\Sigma, \Sigma'$, both for the fields and their $U(1)'$ charges for simplicity.
The Dirac neutrino mass matrix at one-loop level as depicted in the left hand side of Fig. II is given by [15]

\[
(m_\nu)_{ab} = \sum_{\alpha=1}^{3} \left\{ \frac{M_{S\alpha}}{64\pi^2} (y_\eta)_{ao}(y_{\chi_1})_{ba} \sin 2\theta_R I \left( \frac{m_{H_{\chi_1}}^2}{M_{S\alpha}^2}, \frac{m_{H_\eta}^2}{M_{S\alpha}^2} \right) - \left[ (H_{\chi_1}, H_\eta, \theta_R) \rightarrow (A_{\chi_1}, A_\eta, \theta_I) \right] \right\},
\]

(II.3)

where

\[
I(x, y) = -x \ln x + y \ln y + xy \ln \frac{y}{x} - \frac{(1-x)(1-y)}{x}, \quad \sin 2\theta_R = -\frac{\alpha v v_\Sigma}{m_{H_\eta}^2 - m_{H_\chi_1}^2}, \quad \sin 2\theta_I = -\frac{\alpha v v_\Sigma}{m_{A_\eta}^2 - m_{A_{\chi_1}}^2}.
\]

(II.4)

Here \( H_i \) and \( A_i \) represents real part and imaginary part of mass eigenstates. We show a benchmark point to satisfy the data of neutrino masses reported by Planck data [16]: \( \sum m_\nu < 0.933 \text{ eV} \), as follows:

\[
a \approx y_\eta y_{\chi_1} \approx 1, \quad m_{H_\eta} \approx 300 \text{ GeV}, \quad m_{H_{\chi_1}} \approx 150 \text{ GeV}, \quad M_S \approx 100 \text{ GeV}, \quad v_\Sigma \approx \mathcal{O}(1) \text{ MeV},
\]

\[
(m_{H_\eta}^2 - m_{A_\eta}^2) \approx (m_{H_{\chi_1}}^2 - m_{A_{\chi_1}}^2) \approx \mu_1 v_\Sigma, \quad \sin 2\theta_R \approx \sin 2\theta_I \approx 0.1(\ll 1).
\]

(II.5)

Then we can obtain the neutrino mass as

\[
(m_\nu)_{ab} \approx 0.1 \text{ eV}.
\]

(II.6)

C. Mixing between \( X \) and \( \nu \)

The mixing mass term between \( X \) and \( \nu \) are obtained at two-loop level as depicted in the left hand side of Fig. II and its form is given by

\[
(m_{\nu-X})_{ab} \approx \sum_{c=1}^{3} \sum_{d=1}^{3} \left[ \frac{v(y_\eta)_a c(M_S)_c (y_{\chi_3})_{cd}(M_S)_d (y_{\chi_2})_{db}}{8\sqrt{2}(4\pi)^4(M_{S\alpha})^2} \right]
\times \left[ F \left( \frac{m_{H_{\chi_2}}^2}{M_{S\alpha}^2}, \frac{m_{\chi_3}^2}{M_{S\alpha}^2}, \frac{m_{\chi_2}^2}{M_{S\alpha}^2} \right) - F \left( \frac{m_{H_{\chi_2}}^2}{M_{S\alpha}^2}, \frac{m_{\chi_3}^2}{M_{S\alpha}^2}, \frac{m_{\chi_2}^2}{M_{S\alpha}^2} \right) \right],
\]

(II.7)

where we assume \( \theta_R I \ll 1 \), and the loop function \( F \) is computed by

\[
F (X_1, X_2, X_3) = \int_0^1 dx \int_0^1 dy \int_0^1 dz \delta(x + y + z - 1) \int_0^1 d\alpha \int_0^1 d\beta \int_0^1 d\gamma \delta(\alpha + \beta + \gamma - 1)
\times \frac{1}{(z^2 - z)(\alpha + \beta X_1 - \gamma X_1)}, \quad \Delta = \frac{x M_{S\alpha}^2 + y X_2 + z X_3}{(z^2 - z)}.
\]

(II.8)
The mixing between active neutrino and DM is given as

$$\theta \equiv \frac{m_{\nu} - m_X}{m_X} \approx 5 \times 10^{-6},$$

where $m_X = \lambda v_{\Sigma}/\sqrt{2}(\approx 7.5$ keV) is the mass of DM, and $5 \times 10^{-6}$ is an expected mixing angle from the X-ray experiment [1, 2]. In Fig. 2 we show the mixing $\theta$ as a function of the imaginary mass of $\chi_2$, $m_{\chi_2}$. The figure shows that we can get the required mixing angle near $m_{\chi_2} = 200$ GeV. We fixed $\theta_R \approx \theta_I << 1$, $b(y_0y_3^{*}y_{\chi_2}) \approx 1.0$, $M_S = 100$ GeV, $m_{H\eta} = 300$ GeV, $m_{\chi_3} = 200$ GeV, $\mu_2 = 1$ TeV, and $v_{\Sigma} = 10$ keV for the figure.

III. SUMMARY AND CONCLUSION

We have shown that a light DM in a radiative model can explain the X-ray line signal from the XMN-Newton X-ray observatory data of various galaxy clusters and Andromeda
FIG. 2: Order estimation for the mixing angle $\theta$ between active neutrino and DM as a function of the $\chi_{2I}$ mass. Here we fixed $\theta_R \approx \theta_I \ll 1$, $b(y_\eta y_{\chi_3}^* y_{\chi_2}) \approx 1.0$, $M_S = 100$ GeV, $m_{H_\eta} = 300$ GeV, $m_{\chi_3} = 200$ GeV, $\mu_2 = 1$ TeV, and $v_{\Sigma'} = 10$ keV. The black line represents $\theta$ given in Eq (II.9). The blue line, $\theta \approx 5 \times 10^{-6}$, is the expected mixing angle to explain X-ray line signal reported by [16].

galaxy. We can accommodate both the observed neutrino masses and the DM ($m_X = 7$ keV) mixing weakly with active neutrino ($\sin^2 2\theta \approx 10^{-10}$) for the signal by a benchmark point with a rather mild hierarchy at TeV scale;

\begin{align}
& a \approx y_\eta y_{\chi_1} \approx 1, \quad m_{H_\eta} \approx 300 \text{ GeV}, \quad m_{H_{\chi_1}} \approx 150 \text{ GeV}, \quad M_S \approx 100 \text{ GeV}, \quad v_\Sigma \approx \mathcal{O}(1) \text{ MeV}, \\
& (m_{H_\eta}^2 - m_{A_\eta}^2) \approx (m_{H_{\chi_1}}^2 - m_{A_{\chi_1}}^2) \approx \mu_1 v_\Sigma, \quad \sin 2\theta_R \approx \sin 2\theta_I \approx 0.087(<1), \quad v_{\Sigma'} = 10 \text{ keV}, \\
& m_{\chi_{2I}} \approx 200 \text{ GeV}, \quad b(y_\eta y_{\chi_3}^* y_{\chi_2}) \approx 1.0, \quad m_{H_\eta} = 300 \text{ GeV}, m_{\chi_3} = 200 \text{ GeV}, \quad \mu_2 = 1 \text{ TeV}. 
\end{align}

The relic density of DM can be thermally obtained through an additional gauged boson, if our $U(1)'$ is localized [17–19], or it can be also obtained non-thermally [20].

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