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XENON1T anomaly and its implication for decaying warm dark matter

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ABSTRACT

An excess in the electronic recoil data was observed in the XENON1T detector. One of plausible explanations for the excess is absorption of a vector bosonic particle with the mass of $2-3$ keV. For this, the kinetic mixing $\kappa \sim 10^{-15}$ of the dark photon with the photon is required if the dark photon explains the current DM abundance. We recently proposed a model where the main component DM today is a decaying warm dark matter (WDM) with the life time comparable to the age of the current universe. The WDM decays to a massless fermion and a massive dark photon. This model was originally designed for addressing both the small scale problems which ΛCDM suffers from and the H_0 tension. In this letter, we show that the massive dark photon produced by the WDM decay can be identified with the vector boson inducing the anomalous excess in the XENON1T experiment. Depending on a lifetime of the parent decaying WDM, the dark photon could be either the main component or the sub-component of DM population today.

1. Introduction

Recently, an incomprehensible excess in the electronic recoil data was observed in the XENON1T experiment [1]. The energy regime where the excess over the known background appears ranges from 1 keV to 7 keV with the events near $2-3$ keV particularly prominent. In an effort to interpret the excess as a hint for a new physics beyond the Standard Model (SM), several possible new physics including solar axions, an anomalous neutrino magnetic moment,[1] and bosonic dark matter were discussed and constraints on the relevant physical quantities were reported as well [1]. (See also the follow-up works about the use of the axion-like particle [5] and the dark photon for interpretation [6] and an explanation using an elastic scattering between a particle with the velocity $\sim \mathcal{O}(10^{-2}c)$ and the electron [7,8] and explanation introducing new interactions between neutrino and electron [9].) Among these, in this letter, we pay our special attention to the possibility where the excess is triggered by absorption of a vector bosonic particle [10] in the XENON1T detector via the dark photon version of photoelectric effect.

As a resolution to the small scale problems (e.g. core/cusp problem [11], missing satellite problem [12,13], too-big-to-fail problem [14]), the fermionic warm dark matter (WDM) is an interesting possibility. By suppressing the growth of matter fluctuations at scales below its free-streaming length, it may help us understand the observed mass deficit of inner halos in galaxies and galaxy clusters [15–17]. Especially when its mass lies in sub-keV regime and its temperature is low enough, Fermi degeneracy pressure may form to prohibit the core collapse of halos. Aside from the warm nature, this quantum mechanical property is another advantage of the fermionic WDM in regard to the core-cusp problem [18–22].[2] Along this line of reasoning, we recently proposed a consistent model for WDM with a non-thermal origin in Ref. [25]. (See also Ref. [26].) The possibility of decaying WDM was discussed there in which case a fermionic WDM decays to a massless fermion and a massive hidden gauge boson. The model was originally designed for not only the small scale problems but also the Hubble tension.[3]

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[1] The excess can be explained by a large magnetic moment of neutrinos $\sim 7\times 10^{-11}\mu_B$ [1] which can be theoretically explained by an extension of the SM [2–4].

[2] The sub-keV mass regime seems to be in severe tension with thermal WDM mass constraint from Lyman-α forest [23,24]. However, for the case where the WDM has a non-thermal origin, the mass constraint can be relaxed to make the non-thermal sub-keV WDM scenario still viable.

[3] Recently it was figured out that decaying DM solution to the Hubble tension is severely constrained by the cosmic microwave background (CMB) power spectrum [27]. To enable the late time accelerated evolution of the Hubble expansion rate, the shorter life time and the larger energy transfer from the decaying particle to the radiation decay product are required, which causes inconsistency with the observed CMB power spectrum by increasing the low multipole regime and enhancing oscillations at the high multipole regime. Nonetheless, it might be still probable to avoid this side effects provided a scale dependent spectral index ($n_s(k)$) is invoked, which could be still possible depending on an inflation model.

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Extending the framework of Ref. [25], in this letter, we consider a decaying WDM with the lifetime comparable to or greater than the current age of the Universe. We shall identify the decay product gauge boson with the vector bosonic particle causing the excess in the electronic recoil data recorded by the XENON1T detector. To explain the anomaly, we set the mass of the gauge boson to be $2-3$ keV and attribute a significant fraction of the current DM density to the gauge boson. Intriguingly, we found that this set-up motivated by the experimental anomaly provides us with an implication for non-thermal origin of the WDM in the model. This implication is derived from the requirement that effects the decaying WDM has on the CMB anisotropy be minimal for consistency.

2. A model

Having a vector bosonic particle in mind as a source of the anomaly, we introduce an Abelian gauge symmetry $U(1)_X$ as an addition to the SM gauge group. The gauge boson A'_μ of $U(1)_X$ is to be identified with the vector bosonic particle. For having a fermionic decaying WDM producing A'_μ, we introduce chiral fermions charged under $U(1)_X$, but neutral to the SM gauge group. Since we are interested in low energy physics (keV regime), we avoid to introduce any vector-like fermion of which a natural mass scale is a UV-cutoff of the theory. Because of the neutrality of dark chiral fermions under the SM gauge group, their $U(1)_X$ charges are subject to only two following anomaly conditions

$$\sum_{i=1}^{N_X} Q_i^3 = 0 \quad , \quad \sum_{i=1}^{N_X} Q_i = 0 \,, \tag{1}$$

which are demanding cancellation of $U(1)_X^3$ anomaly and gravitational $U(1)_X \times [\text{gravity}]^2$ anomaly respectively. By referring to [28,29], it is realized that the minimum value for N_X is five and thus we introduce five chiral fermions with the following exemplary $U(1)_X$ charge (Q_X) assignment

$$\psi_{-9}, \quad \psi_{-5}, \quad \psi_{-1}, \quad \psi_7, \quad \psi_8 \,. \tag{2}$$

Here the subscripts are denoting $U(1)_X$ charges. To make both A'_μ and chiral fermions massive, we introduce two scalars Φ_1 and Φ_6 with $V_1 > V_6$ where V_{Q_X} is the vacuum expectation value (VEV) of Φ_{Q_X}. Note that even if we introduced two scalars with non-zero VEVs, there is no domain wall problem due to $V_1 \gg V_6$ as we see below. We assume the quartic coupling (λ_{Q_X}) of Φ_{Q_X} to be $\mathcal{O}(1)$ so that scalar masses satisfy $m_{Q_X} \simeq \sqrt{\lambda_{Q_X}} V_{Q_X}$.

Thanks to the charge assignment, the scalars and chiral fermions couple to each other via

$$\mathcal{L}_{\rm Yuk} = y_1 \Phi_1 \psi_{-9}\psi_8 + y_2 \Phi_6 \psi_{-5}\psi_{-1} + y_3 \Phi_6^\dagger \psi_{-1}\psi_7 + \text{h.c.} \tag{3}$$

Without loss of generality, we can take $y_i\,(i = 1-3)$ to be real by the field redefinition of chiral fermions. Diagonalizing the mass matrix for ψ_{-5}, ψ_{-1} and ψ_7 yields the following mass eigenstate

$$\chi \equiv \left(\frac{y_2}{\sqrt{y_2^2+y_3^2}}\right)\psi_{-5} + \left(\frac{y_3}{\sqrt{y_2^2+y_3^2}}\right)\psi_7 \,, \tag{4}$$

which forms a Dirac fermion $\Psi_{\rm wdm} = (\psi_{-1}, \chi^*)^T$ together with ψ_{-1}. Its mass is given by $m_{\rm wdm} \equiv \sqrt{y_2^2+y_3^2}\,V_6$. We identify $\Psi_{\rm wdm}$ with our WDM candidate hereafter. The remaining orthogonal direction to χ becomes a massless Weyl field ξ

$$\xi \equiv \left(\frac{y_3}{\sqrt{y_2^2+y_3^2}}\right)\psi_{-5} - \left(\frac{y_2}{\sqrt{y_2^2+y_3^2}}\right)\psi_7 \,. \tag{5}$$

This massless ξ would become one of the decay products of $\Psi_{\rm wdm}$. For simplicity, we assume y_2 and y_3 to be of a similar order, i.e. $y_2 \simeq y_3 \equiv y^*$.

With this basic set-up arranged, we imagine a thermal history of the dark sector which is very similar to the case discussed in our companion paper [25]. To make a long story short, we first introduce a gauge singlet inflaton (Φ_I) which couple to scalars in the dark sector at renormalizable level. We assume that the inflaton mainly decays to the SM sector. With the choice of a large enough V_1 rendering $y_1 V_1$ and $\sqrt{\lambda_1} V_1$ (ψ_{-9}, ψ_8 and Φ_1 masses) larger than the inflaton mass, at the reheating era the inflaton decay produces only ϕ_6 particles which form a dark thermal bath purely made up of ϕ_6.[4] Here λ_1 is the quartic coupling of Φ_1 and ϕ_6 is the radial direction of Φ_6. Since then, the temperature of the dark sector ($T_{\rm DS}$) continues to decrease and Φ_6 becomes non-relativistic when $T_{\rm DS} \simeq m_6$ is reached. Here m_6 is the mass of Φ_6. With the comoving number density of ϕ_6 preserved, ϕ_6 behaves as a matter until the time comes when $\Gamma(\phi_6 \to {\rm DM}+{\rm DM}) \simeq H$ holds and ϕ_6 starts to decay to a pair of DMs ($\Psi_{\rm wdm}$) then. With the decay of ϕ_6, the free-streaming of DM candidates $\Psi_{\rm wdm}$ commences. As we shall see, due to $m_6 > m_{\rm wdm}$, DMs are highly relativistic when it is produced from ϕ_6 and starts free-streaming and thus it is classified as a WDM. We set a life time of $\Psi_{\rm wdm}$ to be comparable to or greater than the age of the present universe so that a significant fraction of $\Psi_{\rm wdm}$ population today is indeed converted into the massless ξ and the $U(1)_X$ gauge boson, A'_μ. Note that we have made an implicit assumption that scalars in the dark sector have a negligible coupling to the SM Higgs. Also assumed is that kinetic mixing between dark $U(1)$ gauge boson and the SM $U(1)$ is sufficiently suppressed so that dark sector thermal bath has never chance to be in thermal equilibrium with the SM thermal bath. For more details about the thermal history in the dark sector, we refer the readers to Ref. [25].

3. XENON1T anomaly and dark photon

In the model and the concrete scenario we presented in the previous section, we have the Dirac fermion parent DM, $\Psi_{\rm DM} = (\psi_{-1}, \ \chi^*)^T$, with the mass $m_{\rm wdm} \simeq y^* V_6$. It decays to the massless ξ and the massive A'_μ with mass $m_{A'} = g V_1$. With the hypothesis that the observed excess in the electronic recoil data in XENON1T stems from absorption of A'_μ via the mechanism analogous to the photoelectric effect, we set $m_{A'} = g V_1 \simeq 2-3$ keV. Note that since a large enough value of V_1 is assumed to integrate out ψ_{-9}, ψ_8 and Φ_1, the $U(1)_X$ gauge theory comes to be featured by a very weak gauge interaction, i.e. a small g value. This structural attribute of the model, in turn, guarantees a large enough life time of A'_μ so that the decay of A'_μ to two massless ξs is suppressed and the produced A'_μ from the decay of $\Psi_{\rm wdm}$ can trigger XENON1T anomaly nowadays.

We introduce a kinematic parameter ϵ to quantify a fraction of $m_{\rm wdm}$ transferred to the energy of massless ξ. Thus, the massless ξ and the massive A'_μ have the four momenta $p_\mu = (\epsilon m_{\rm wdm}, \overrightarrow{p})$ and $p'_\mu = ((1-\epsilon)m_{\rm wdm}, -\overrightarrow{p})$ respectively at the rest of frame of $\Psi_{\rm wdm}$. Now the dispersion relation of A'_μ results in

$$\frac{m_{A'}}{m_{\rm wdm}} = \sqrt{1-2\epsilon} \,. \tag{6}$$

[4] Unless a reheating temperature $T_{\rm RH}$ is close to Planck mass, the quartic coupling induced scattering among Φ_6 easily forms a thermal bath. As we shall see later, particles other than ϕ_6 cannot join the dark thermal bath due to the smallness of the gauge coupling g_X of $U(1)_X$ and Yukawa couplings, y_2 and y_3.

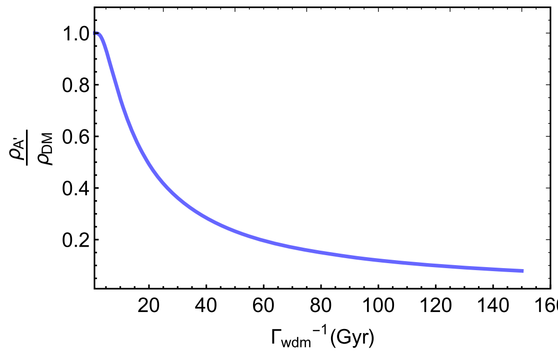

Fig. 1. The plot of fraction of DM density contributed by A'_μ, i.e. $f_{A'}/(1+f_{A'})$ as a function of a life time of decaying WDM. We used $\epsilon \approx 0.002(\Gamma_{wdm}/\text{Gyr}^{-1})^{-0.8}$ which we referred to from Ref. [27].

Note that masses of the parent WDM and the decay product A'_μ are almost degenerate in the small ϵ limit. In terms of ϵ, we can write down Ψ_{wdm}'s decay rate, $\Gamma(\Psi_{wdm} \to A' + \xi) \equiv \Gamma_{wdm}$, as

$$\Gamma_{wdm} = \frac{9}{4\pi}\epsilon g_X^2 m_{A'}\left[\left(\frac{m_{wdm}}{m_{A'}}\right)^3 - 2\frac{m_{A'}}{m_{wdm}} + \frac{m_{wdm}}{m_{A'}}\right] = \frac{9g_X^2 m_{A'}}{2\pi} \times \frac{\epsilon^2(3-4\epsilon)}{(1-2\epsilon)^{3/2}}\,, \quad (7)$$

where g_X is the gauge coupling of $U(1)_X$. By solving the time evolution equation for the energy density of A'_μ and Ψ_{wdm}, we find the below expression as the estimate of the energy density ratio $f_{A'} \equiv \rho_{A'}/\rho_{wdm}$ evaluated at today.[5]

$$f_{A'} \simeq e^{\Gamma_{wdm}t_0}(1-\epsilon)\left[e^{-\Gamma_{wdm}t_{rec}} - e^{-\Gamma_{wdm}t_0}\right]\,, \quad (8)$$

where t_{rec} and t_0 are the age of the universe at recombination and today respectively. From Eq. (8), it can be inferred that a set of $(\epsilon,\ \Gamma_{wdm})$ determines an abundance of A'_μ today.

Given XENON1T anomaly, we focus on a value of Γ_{wdm}^{-1} which is close to the current age of the universe, i.e. ~ 13.6 Gyr. With this, we need to avoid inconsistency with the observed CMB anisotropy power spectrum, which could be potentially caused by the decaying dark matter scenario [27,31]. The larger Γ_{wdm} and ϵ we take, the larger amplitude of CMB power spectrum on the low multipole regime and the larger magnitude of oscillations at the high multipole regime would be brought about. Therefore, values of $(\epsilon,\ \Gamma_{wdm})$ should be chosen with care so as not to distort CMB power spectrum more than allowed. To this end, we refer to Ref. [27] to borrow the expression of the upper-bound $\epsilon \approx 0.002(\Gamma_{wdm}/\text{Gyr}^{-1})^{-0.8}$ (95% C.L.). Considering the exemplary range of $150^{-1} \lesssim (\Gamma_{wdm}/\text{Gyr}^{-1}) \lesssim 1^{-1}$, we obtain the expected fraction of DM population contributed by A'_μ today as shown in Fig. 1. For the exemplary Γ_{wdm}, we see that A'_μ is responsible for about $\sim \mathcal{O}(10)$% of DM energy density today.

Since we are dealing with the spontaneously broken $U(1)_X$ (A'_μ is massive), the symmetry of the theory allows for the coupling $U(1)_X$ gauge field to the SM through the kinetic mixing with the hypercharge gauge field via

$$\mathcal{L}_{kin} = -\frac{\kappa}{2}F^{\mu\nu}F'_{\mu\nu}\,, \quad (9)$$

where $F'_{\mu\nu}$ and $F^{\mu\nu}$ are the field strength for $U(1)_X$ gauge field and the hypercharge gauge field respectively. Hereafter we use κ to denote the kinetic mixing between the dark photon and the SM photon by absorbing $\cos\theta_w$ into the κ in Eq. (9) with θ_w the Weinberg angle. The upper limit for the kinetic mixing between the photon and the dark photon for the mass range $2-3$ keV of A'_μ reads $\kappa \lesssim 10^{-15}$ [1] when the dark photon causing the electronic recoil excess forms the whole DM population today. Now for the case where the lifetime of Ψ_{wdm} is as long as $1-150$ Gyr, as the decay product of Ψ_{wdm}, about $10-99$% of the DM population is attributed to A'_μ as can be seen in Fig. 1. Thus the different upper bound on $10^{-15}/\sqrt{0.99} \lesssim \kappa \lesssim 10^{-15}/\sqrt{0.1} \simeq (1-3)\times 10^{-15}$ applies for our case, depending on a Γ_{wdm} value.[6] Note that this is still sufficiently small so that the thermal history of the dark sector we envisioned from the outset remains valid and intact. Note that the choice $150^{-1} \lesssim (\Gamma_{wdm}/\text{Gyr}^{-1}) \lesssim 1^{-1}$ was made so that the lifetime of Ψ_{wdm} is not too large to be left with no A'_μ today.

As for the Hubble tension, the larger Γ_{wdm} and ϵ are favored [27,33] to make the decaying DM solution to the Hubble tension more viable. However, these parameters cannot be chosen arbitrarily large for consistency with the observed CMB power spectrum [27]. Put in another way, the set of values $(\Gamma_{wdm},\ \epsilon) = (1\text{Gyr}^{-1},\ 0.002)$ being consistent with the observed CMB power spectrum at 95% C.L., it cannot solve the Hubble tension since ϵ is too small to produce H_0 as large as 74 km/sec/Mpc. For this point, we speculate that it might be still justified to have ϵ larger than reported in Ref. [27] if a scale dependent spectral index ($n_s(k)$) is considered. A reasonable inflation model may be able to achieve a well-designed $n_s(k)$ to compensate the problematic change in CMB power spectrum caused by a large ϵ. This may enable a large ϵ to be still viable to make CMB power spectrum remain consistent with the observed one. If this were to be case, much larger mass of Ψ_{wdm} would be allowed and H_0 inferred from CMB power spectrum based on the decaying DM scenario [33] might be able to be close to a local measurement of H_0 [34–37]

4. XENON1T anomaly and decaying WDM

Following the discussion of Sec. 3, for $150^{-1} \lesssim (\Gamma_{wdm}/\text{Gyr}^{-1}) \lesssim 1^{-1}$, ϵ parameter is constrained to be at most $\sim 10^{-1}$. A'_μ being responsible for the XENON1T anomaly, we can infer the almost equal, but slightly greater mass of the parent WDM Ψ_{wdm} than $m_{A'} \simeq 2-3$ keV from Eq. (6). We note that this mass regime of Ψ_{wdm} (m_Ψ) is consistent with the mass constraint inferred from the Lyman-α forest observation and redshifted 21 cm signals in EDGES observations because Ψ_{wdm} has the non-thermal origin as discussed in Sec. 2.[7]

As such, we notice that Ψ_{wdm} has potential to address the small scale problems such as the missing satellite problem and too-big-to-fail problem by traveling a long enough free-streaming length (λ_{FS}) after produced from ϕ_6-decay.[8] This is because growth of the matter fluctuation for scales below λ_{FS} is suppressed, giving

[5] For a more exact estimation, see, e.g. Ref. [30].

[6] Note that for the sub-interval of $m_{A'} \in$ (2keV, 2.6keV), the scenario with $\mathcal{O}(10)$% dark photon DM is in tension with the constraint on κ from the anomalous energy loss in the horizontal branch stars [32].

[7] The current constraint on the mass of the thermal WDM obtained based on Lyman-α forest observation [38] and redshifted 21 cm signals in EDGES observations [24,39] are given by $m_{wdm}^{thermal} > 5.3$ keV and $m_{wdm}^{thermal} > 6.1$ keV. After mapping these to the mass constraint for a non-thermal WDM originating from the decay of a non-relativistic scalar particle in accordance with Ref. [26,40], we obtain $m_{wdm} \gtrsim 1$ keV.

[8] Since the mass of Ψ_{wdm} lies in $2-3$keV range, the rough estimate for a size (R) of the self-gravitating degenerate Fermi (Ψ_{wdm}) gas with the mass of order $\mathcal{O}(10^8)M_\odot$ is expected to be $\mathcal{O}(10)$pc based on $R \sim h^2/m_\Psi^{8/3}G_N M$ where h, G_N and M are the Planck constant, the Newton constant and the total mass [18]. Therefore, $2-3$ keV Ψ_{wdm} WDM at least cannot fully address the core-cusp problem due to the rather small $R \sim \mathcal{O}(10)$pc. Nevertheless, the problem can be mildly alleviated in comparison with CDM case since the finite phase space density prohibit formation of the DM density cusps [41].

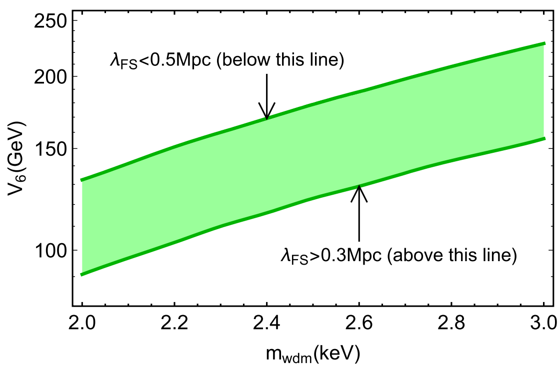

Fig. 2. The parameter space of $(m_{\rm wdm}, V_6)$ which yields the free-streaming length of interest, i.e. $0.3{\rm Mpc} < \lambda_{\rm FS} < 0.5{\rm Mpc}$.

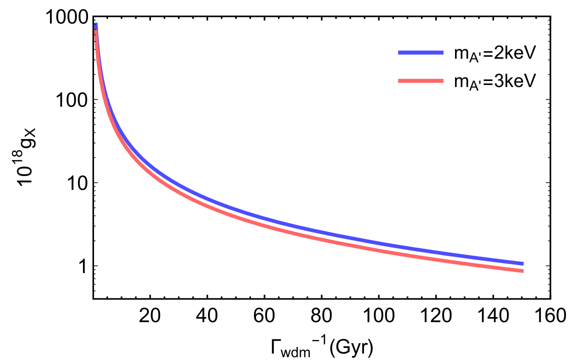

Fig. 3. The plot of the gauge coupling g_X of $U(1)_X$ as a function of a life time of decaying WDM.

rise to suppression of formation the low-mass halos (or sub-halos) as compared to ΛCDM case. Particularly for $0.3{\rm Mpc} \lesssim \lambda_{\rm FS}$, it becomes easier for sub-halos to be destroyed by dynamical friction and tidal disruption so that the predicted number of satellites shows the better agreement with the number of observed ones in our own galaxy (Milky way) [16,42]. On the other hand, $\lambda_{\rm FS}$ should avoid being too large to cause deviation of WDM matter power spectrum from the observed matter power spectrum. This sets the upper bound $\lambda_{\rm FS} \lesssim 0.5{\rm Mpc}$ [43]. Putting together, we take $0.3\,{\rm Mpc} < \lambda_{\rm FS} < 0.5\,{\rm Mpc}$ as the free-streaming length of $\Psi_{\rm wdm}$ to ameliorate the small scale problems and keep the consistency with observation [18,44].

Since $\Psi_{\rm wdm}$ is produced from the decay of the non-relativistic ϕ_6, with the assumption of $m_6 \simeq V_6$, we see that $\Psi_{\rm wdm}$ starts free-streaming with the initial velocity amounting to $\sim V_6/2$. $\lambda_{\rm FS}$ of $\Psi_{\rm wdm}$ can be estimated via[9]

$$\lambda_{\rm FS} = \int_{t_{\rm FS}}^{t_0} \frac{<v_\Psi(t)>}{a} {\rm d}t = \int_{a_{\rm FS}}^{1} \frac{{\rm d}a}{H_0 F(a)} \frac{<p_\Psi(a_{\rm FS})> a_{\rm FS}}{\sqrt{(<p_\Psi(a_{\rm FS})> a_{\rm FS})^2 + m_\Psi^2 a^2}}, \quad (10)$$

where $F(a) \equiv \sqrt{\Omega_{\rm rad,0} + a\Omega_{\rm m,0} + a^4\Omega_{\Lambda,0}}$, $<p_\Psi(a_{\rm FS})>$ is the average initial momentum of $\Psi_{\rm wdm}$ at the starting time of the free-streaming $(a = a_{\rm FS})$ and H_0 is the expansion rate of the universe today. For the mass regime $2\,{\rm keV} \lesssim m_{\rm wdm} \lesssim 3\,{\rm keV}$, following the logic in Ref. [25], we present in Fig. 2 the space of V_6 that can lead to the desired free-streaming length. We also checked that $\Delta N_{\rm eff}$ contributed by $\Psi_{\rm wdm}$ during the BBN era is consistent with $\Delta N_{\rm eff}^{\rm BBN} \lesssim 0.114$ (95% C.L.) [45].

Given values of $(\epsilon,\ \Gamma_{\rm wdm},\ m_{A'})$ of interest, we discuss how the gauge coupling of g_X is constrained via Eq. (7). As discussed in Sec. 3, ϵ parameter's maximum allowed value is a function of $\Gamma_{\rm wdm}$. Thus, for a fixed $m_{A'}$, Eq. (7) constrains the gauge coupling g_X for the range of $\Gamma_{\rm wdm}$ of our interest. In Fig. 3, we show g_X as a function of the lifetime of the parent WDM. For $1{\rm Gyr} \lesssim \Gamma_{\rm wdm}^{-1} \lesssim 150{\rm Gyr}$, we find that g_X is as small as $10^{-18} - 10^{-15}$. Note that in company with the small Yukawa coupling $y^* \sim \mathcal{O}(10^{-8})$ corresponding to values of $(m_{\rm wdm}, V_6)$ shown in Fig. 2, this smallness of the gauge coupling is the underlying reason that guarantees the purity of the dark thermal bath made up of ϕ_6. Also critical is that for y_2 close to $\sqrt{5/7}y_3$, the possible decay process $A'_\mu \to \xi + \xi$ can be sufficiently suppressed thanks to the cancellation in the effective gauge coupling of ξ and the smallness of g_X. Before concluding this section, we note that the gauge coupling constant $g_X \sim 10^{-15}$ is allowed as shown in Fig. 3. With this gauge coupling we do not need the mixing with the photon to explain the recoil electron excess if the $U(1)_X$ is nothing but the $U(1)_{\rm B-L}$ [46,47].

5. Discussion

In this letter, we addressed the problem of explaining a potential source of anomalous excess observed in electronic recoil data taken by XENON1T detector. Attending to the possibility where the excess was caused by absorption of a vector boson, we reduce the problem to pointing out a reasonable candidate of such a vector boson. We previously proposed a decaying fermionic WDM model to deal with the small scale problems and the Hubble tension. Extending the model, we could explain the presence of the desired vector boson by identifying it with the dark photon that naturally arises as one of the decay products of the parent WDM. Hence, the model was shown to be appealing in that it can potentially explain the XENON1T anomaly as well as be invoked for dealing with the small scale problems and the Hubble tension.

In order to have the vector boson today for explaining XENON1T anomaly, we set the lifetime of the decaying WDM to be comparable to or greater than the age of the present universe. The anomaly-inferred mass $(2-3\,{\rm keV})$ of the dark photon, when combined with the consistency with CMB power spectrum, pinned down the similar mass range as the WDM mass, which is consistent with the Lyman-α forest observation and redshifted 21 cm signals in EDGES observations due to the non-thermal origin of the parent WDM. As a consequence, the model predicts that a significant fraction of the current DM abundance is attributed to the dark photon. For the free-streaming length range $0.3\,{\rm Mpc} < \lambda_{\rm FS} < 0.5\,{\rm Mpc}$ of interest and WDM lifetime similar to the age of the universe, couplings (y^*, g_X) in the model were shown to be sufficiently small to ensure the thermal history of the dark sector as desired.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[9] Since matter fluctuations start to grow monotonically after matter-radiation equality, sometimes $\lambda_{\rm FS}$ is defined to be expression in Eq. (10) with the upper limit of the integral replaced with the time of the matter-radiation $(t_{\rm eq})$. Let us call this free-streaming length $\lambda'_{\rm FS}$. Since the integral contributed by the times between $t_{\rm eq}$ and t_0 is negligible, our definition of $\lambda_{\rm FS}$ given in Eq. (10) is almost the same as $\lambda'_{\rm FS}$.

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