Feebly interacting $U(1)_{B-L}$ gauge boson warm dark matter and XENON1T anomaly

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ABSTRACT

The recent observation of an excess in the electronic recoil data by the XENON1T detector has drawn many attentions as a potential hint for an extension of the Standard Model (SM). Absorption of a vector boson with the mass of $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$ is one of the feasible explanations to the excess. In the case where the vector boson explains the dark matter (DM) population today, it is highly probable that the vector boson belongs to a class of the warm dark matter (WDM) due to its suspected mass regime. In such a scenario, providing a good fit for the excess, the kinetic mixing $\kappa \sim 10^{-15}$ asks for a non-thermal origin of the vector DM. In this letter, we consider a scenario where the gauge boson is nothing but the $U(1)_{B-L}$ gauge boson and its non-thermal origin is attributed to the decay of the coherently oscillating scalar of which condensation induces the spontaneous breaking of $U(1)_{B-L}$. We discuss implications for the early universe physics when the warm nature of the vector DM serves as a resolution to both the small scale problems that ΛCDM model encounters and the XENON1T anomaly.

1. Introduction

Recently, the XENON1T collaboration reported an excess in the electronic recoil data for the energy regime ranging from 1 keV to 7 keV [1]. Especially, the prominence of the excess for $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$ aroused many interesting interpretations based on various extensions of the SM. Absorption of a vector boson is one of the plausible possibilities for the excess in which case its suspected mass and kinetic mixing read $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$ and $\kappa \sim 10^{-15}$ respectively [2–5]. Provided this vector boson serves as a dominant component of DM today, its suspected mass regime could be of interest in regard to the small scale problems (e.g. core/cusp problem [6], missing satellite problem [7,8], too-big-to-fail problem [9]); keV scale WDM can alleviate some of the small scale problems if the free-streaming length traveled by the WDM amounts to $\mathcal{O}(0.1)$ Mpc [10–12].

Note that, however, the dark photon (A'_μ) mass $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$ is actually outside of the allowed thermal WDM mass regimes inferred from Lyman-α forest observation $m_{\mathrm{wdm}}^{\mathrm{thermal}} > 5.3\,\mathrm{keV}$ [13] and redshifted 21 cm signals in EDGES observations

$m_{\mathrm{wdm}}^{\mathrm{thermal}} > 6.1\,\mathrm{keV}$ [14,15]. Therefore in order for the dark photon to be a candidate for WDM to address the small scale problems, it should be a non-thermally originated one. Very interestingly, this line of reasoning to have a non-thermal dark photon DM (DPDM) gathers momentum when it is taken into account that a fit of good quality for the excess can be accomplished for the kinetic mixing $\kappa \sim 10^{-15}$ [1–4]. Being the most direct and dangerous coupling to thermalize A'_μ with the SM thermal bath, the observed kinetic mixing $\kappa \sim 10^{-15}$ ensures that A'_μ can avoid to join the SM thermal bath unless there is another significant indirect coupling to the SM sector. Now there arises an interesting question: what could be a non-thermal production mechanism that allows the mass regime $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$ consistent with the Lyman-α forest observation? Different non-thermal production mechanisms will be characterized by different momentum spaces for A'_μ. And we will invoke the decay of a scalar in the coherent oscillation to answer this question.

In this letter, we study the scenario where the keV-scale DPDM with the suppressed kinetic mixing arises with a non-thermal origin. Especially for $m_{A'} \in (2\,\mathrm{keV}, 3\,\mathrm{keV})$, the DPDM can induce the XENON1T anomaly through absorption analogous to the photoelectric effect. We identify A'_μ with the massive gauge boson of the broken $U(1)_{B-L}$ gauge theory which is the most well-motivated

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minimal extension of the SM.[1] When incorporated with a scalar and three heavy right handed neutrinos, $U(1)_{B-L}$ gauge theory provides us with the most elegant explanation for the origin of the smallness of the active neutrino masses based on the seesaw mechanism [18–20] and the leptogenesis [21,22]. In spite of this concreteness of the model, our mechanism and result can be easily generalized to a hidden broken $U(1)$ gauge theory, emphasizing its usefulness in the study of the DPDM. To enable the observed mass regime $m_{A'} \in (2 \text{ keV}, 3 \text{ keV})$ to be consistent with the Lyman-α forest observation, we consider the production mechanism where the non-relativistic scalar charged under $U(1)_{B-L}$ produces A'_μ via its decay after $U(1)_{B-L}$ gets spontaneously broken.[2] The parent scalar is assumed to obtain a positive Hubble induced mass squared greater than the scalar's mass squared during the inflation and later decays to A'_μ while going through the coherent oscillation. To ensure the consistency with the Lyman-α flux power spectrum, we compute the free-streaming length of A'_μ based on its history given in the model. We show presence of the parameter space in which A'_μ becomes the WDM candidate resolving some of the small scale problems. For defining the WDM, we take $\lambda_{\text{FS}} \lesssim 1 \text{ Mpc}$ as the criterion. Especially $\lambda_{\text{FS}} \simeq 0.3 - 0.5 \text{ Mpc}$ is of our interest since it is consistent with non-vanishing matter power spectrum at large scales (0.5 Mpc) and helps WDM candidate resolve the missing satellite problem (0.3 Mpc) [10–12].

2. Model

We consider the broken $U(1)_{B-L}$ gauge theory of which the massive gauge boson A'_μ is taken to be the DM candidate in the model. On top of the SM particle contents, we introduce a complex scalar Φ (-2) and three right-handed neutrino Weyl fields $\overline{N}_{i=1,2,3}$ (+1) where the numbers in the parenthesis denote $U(1)_{B-L}$ charges assigned to each field. These additional fields form the following Yukawa coupling

$$\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{3} \frac{1}{2} y_{N,ij} \Phi \overline{N}^{(i)} \overline{N}^{(j)} + \text{h.c.} \quad , \tag{1}$$

by which the right handed neutrinos acquire masses when the condensation of Φ induces the spontaneous breaking of $U(1)_{B-L}$. Stemming from the large vacuum expectation value (VEV) of Φ, the heaviness of these right handed neutrino fields can explain the tiny active neutrino masses via the seesaw mechanism [18–20]. Moreover, the out-of-equilibrium decay of the heavy right-handed neutrinos creates the lepton asymmetry of the universe which is converted into the baryon asymmetry later with the help of the sphaleron transition [21].

Since A'_μ in the model is identified with the hypothetical vector boson triggering the XENON1T excess, we set $m_{A'} = 2 g_{B-L} V_{B-L} \simeq 2 - 3 \text{ keV}$ where g_{B-L} is the gauge coupling of $U(1)_{B-L}$ and $<\Phi> \equiv V_{B-L}/\sqrt{2}$ is defined. As will be shown in the coming sections, the model is to be featured by a high breaking scale $V_{B-L} \gtrsim 10^{16} \text{ GeV}$. From $m_{A'} \in (2 \text{ keV}, 3 \text{ keV})$, we obtain $g_{B-L} \lesssim \mathcal{O}(10^{-22})$. Along with these tiny g_{B-L} and κ, A'_μ's interaction with other particles in the model is extremely feeble and thus A'_μ is totally isolated entity in the model. As the DM candidate, the lifetime of A'_μ is required to be greater than at least the current age of the universe. Indeed,

we can see that the requirement $\tau_{A'} > 13.8 \text{ Gyr}$ is easily satisfied since the above g_{B-L}, V_{B-L} and $m_{A'}$ are easily satisfying either of $m_{A'}^3 < 10^{-40} V_{B-L}^2 \text{ GeV}$ or $g_{B-L} < 5 \times 10^{-18} \times (m_{A'}/1 \text{ keV})^{-1/2}$.[3]

On the other hand, the scalar sector of the model is described by the following potential

$$V_{\text{scalar}} = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4$$
$$+ \lambda_{H\Phi} H^\dagger H |\Phi|^2 + V(H), \tag{2}$$

where H denotes the SM SU(2) Higgs doublet and $V(H)$ is the Higgs potential in the SM. We see that there appear two new dimensionless couplings λ and $\lambda_{H\Phi}$, and one dimensionful coupling m_Φ as compared to the SM scalar sector. If $\lambda_{H\Phi}$ is significant, our purpose of producing the non-thermal DPDM might be challenged: after $U(1)_{B-L}$ is broken, the longitudinal component (θ) of A'_μ could have couplings to the radial component (ϕ) of Φ which is independent of g_{B-L}. Thus, once ϕ is produced from the SM thermal bath, θ becomes easily thermalized as well. To avoid this danger, we assume a sufficiently suppressed $\lambda_{H\Phi}$ in Eq. (2) in this work. On the other hand, differing from $\lambda_{H\Phi}$, there is no any a priori assumption for m_Φ and λ. In the coming next sections, we study how these new couplings (λ, m_Φ) are constrained in the light of the purpose to have A'_μ non-thermally produced from Φ decay and become WDM which can resolve the small scale problems and explain the XENON1T anomaly.

3. Production of the dark photon

As a scalar field present during the inflation era, Φ may obtain the Hubble induced mass much greater than its original mass. For our model, we assume Φ acquires a positive Hubble induced mass squared during inflation so that the effective potential of Φ during inflation becomes

$$V(\Phi)|_{a<a_{\text{end}}} = (c_I \mathcal{H}_I^2 - m_\Phi^2)|\Phi|^2 + \lambda |\Phi|^4$$
$$\simeq c_I \mathcal{H}_I^2 |\Phi|^2 + \lambda |\Phi|^4, \tag{3}$$

where a_{end} is the scale factor at which the inflation ends, c_I is assumed to be a positive dimensionless coupling and $\mathcal{H}_I$ is the Hubble expansion rate during the inflation. $V(\Phi)$ reduces to the second line form due to the assumption of $\mathcal{H}_I \gg m_\Phi^2$. Thus, it can be seen from Eq. (3) that Φ sits on the origin in the field space during inflation.

After the inflation ends ($a > a_{\text{end}}$), $V(\Phi)$ returns to the form given in the first line of Eq. (2), i.e. $V(\Phi) = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4$. Then the global minima of the potential become located at $|\Phi| = V_{B-L}/\sqrt{2} = m_\Phi/\sqrt{2\lambda}$ where $V_{B-L} = m_\Phi/\sqrt{\lambda}$. This makes the displacement of Φ from the global minima at the end of inflation amount to $\Phi_{\text{ini}} = V_{B-L}/\sqrt{2}$. Until the time when the Hubble expansion rate ($\mathcal{H}$) becomes comparable to the mass of Φ is reached, Φ field stays at the origin in the field space with its energy density $\rho_\Phi \simeq (m_\Phi^2 \Phi_{\text{ini}}^2)/2$. From $\mathcal{H} \simeq m_\Phi$, we read the temperature of the SM plasma when Φ field starts its coherent oscillation at $a = a_{\text{osc}}$

$$T(a_{\text{osc}}) \simeq \left(\frac{90}{\pi^2}\right)^{1/4} g_*(a_{\text{osc}})^{-1/4} \sqrt{M_P m_\Phi}$$

$$\simeq (0.85 \times 10^9) \left(\frac{g_*(a_{\text{osc}})}{100}\right)^{-1/4} \left(\frac{m_\Phi}{1 \text{ GeV}}\right)^{1/2} \text{ GeV}, \tag{4}$$

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[1] Other examples of the use of $U(1)_{B-L}$ gauge symmetry for addressing the XENON1T anomaly can be found in Refs. [16,17].

[2] A variety of other ways to produce the vector DM non-thermally has been suggested: resonant decays from an axion-like scalar via a tachyonic instability [23–26], production from a dark Higgs via a parametric resonance [27], decays from a network of the cosmic strings [28], vector coherent oscillation [29–32], and the gravitational production [33–35].

[3] The last inequalities are obtained from $\Gamma(A'_\mu \to f + \bar{f}) \lesssim (13.8 \text{ Gyr})^{-1}$ where f is a SM fermion with its mass satisfying $m_{A'} \gtrsim 2 m_f$.

where $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass and g_* is the effective degrees of freedom for the radiation. As the coherent oscillation starts out, $U(1)_{B-L}$ gets spontaneously broken and the heavy right-handed neutrinos acquire masses via the Yukawa coupling given in Eq. (1). In this work, we focus on the case where a reheating temperature T_{RH} is greater than $T(a_{osc})$.[4]

Since $a = a_{osc}$, the coherent oscillation of Φ continues in the expanding background and eventually when the Hubble expansion rate becomes comparable to the rate of the decay of Φ to a pair of longitudinal modes of A'_μ, the decay of Φ produces A'_μ.[5] Note that this A'_μ production time coincides with the onset of the free-streaming of A'_μ thanks to the feeble interaction of A'_μ with other particles. By equating the decay rate $\Gamma_{\phi \to A' + A'}$ to the Hubble expansion rate during radiation dominated era, we obtain the time ($a = a_{FS}$) of A'_μ-production

$$\Gamma_{\phi \to A' + A'} \simeq \frac{Q_\Phi^4 g_{B-L}^4 V_{B-L}^2 m_\phi^3}{32\pi m_{A'}^4} \simeq \frac{T^2(a_{FS})}{M_P}$$

$$\Longleftrightarrow T(a_{FS}) \simeq 2.2 \times 10^8 \times \sqrt{\lambda} \times \left(\frac{m_\Phi}{1\,\text{GeV}}\right)^{1/2} \text{GeV},$$

(5)

where we used $m_\phi = \sqrt{2\lambda} V_{B-L}$, Q_Φ is the $U(1)_{B-L}$ charge of Φ, and a_{FS} is the scale factor for the onset of the free-streaming of A'_μ.[6] For the second line in Eq. (5), we used $Q_\Phi = -2$. Using the temperature $T(a_{EW}) \simeq 100$ GeV and scale factor $a_{EW} \simeq 10^{-15}$ at which the electroweak symmetry breaking takes place, we can estimate a_{FS}

$$a_{FS} \simeq 4.5 \times 10^{-22} \times \lambda^{-1/2} \times \left(\frac{m_\phi}{1\,\text{GeV}}\right)^{-1/2},$$

(6)

based on the entropy conservation, i.e. $a_{EW} T(a_{EW}) \simeq a_{FS} T(a_{FS})$ and Eq. (5).

In this section, we studied one possible mechanism of the non-thermal production of A'_μ. The feeble interaction between A'_μ and other particles in the model deprives A'_μ of any chance to be produced from the thermal plasma. Nevertheless, the presence of Φ in the model enables unexpected intriguing way of A'_μ-production: the coherently oscillating homogeneous Φ field decays to produce the longitudinal mode of A'_μ.[7] In the next section, we constrain the parameter space (λ, m_Φ) by attributing the current DM population to A'_μ as well as by requiring A'_μ to travel the distance $\lambda_{FS} \lesssim 1$ Mpc with a special interest in $\lambda_{FS} \simeq 0.3 - 0.5$ Mpc since production.

4. Dark photon as the WDM

Here we study physical quantities that characterize the dark photon A'_μ as the WDM. These quantities include the relic density, ΔN_{eff} contributed by A'_μ and the free-streaming length λ_{FS} of A'_μ.

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[4] For the other case with $T_{RH} < T(a_{osc})$, we confirmed that presence of a viable parameter space requires very high reheating temperature greater than 10^{17} GeV. This may make it difficult to find a consistent inflation model. Thus we restrict ourselves to the case with $T_{RH} > T(a_{osc})$.

[5] For another way of non-thermal DM production mechanism, see, for example, Refs. [3,36,37].

[6] For the decay rate formula, we used the mass of the radial component of Φ which is $m_\phi = \sqrt{2}m_\Phi$ because it is $|\Phi|$ that decays to the longitudinal mode of A'_μ.

[7] The other non-thermal production of A'_μ was considered in Ref. [38]. There, the radial component of Φ is non-thermally produced from the scattering among the right-handed neutrinos via $\overline{N} + \overline{N} \to \phi + \phi$. These ϕ particles either form the dark thermal bath or just free-stream and then A'_μ can be generated from the decay of ϕ. However, for this scenario, it is figured out that DPDM with mass $2 - 3$ keV cannot be consistent with the Lyman-α forest observation.

4.1. Relic density

We assume that A'_μ explains the whole of DM population today. The fraction of the energy density of the universe today attributed to the DM reads

$$\Omega_{DM,0} = \frac{\rho_{DM,0}}{\rho_{cr,0}} = \frac{s_0}{\rho_{cr,0}} \times m_{DM} \times Y_{DM} \simeq 0.27,$$

(7)

where the comoving number density of DM, $Y_{DM} \equiv n_{DM}/s$, is the conserved quantity since the production of the DM. From the values of $s_0 = 2.21 \times 10^{-11}$ eV^3 and $\rho_{cr,0} = 8.02764 \times 10^{-11} \times h^2$ eV^4, one obtains

$$Y_{DM} = 9.8 \times 10^{-4} \times \left(\frac{m_{DM}}{1\,\text{keV}}\right)^{-1} \times h^{-2},$$

(8)

where h is defined to be $\mathcal{H}_0 = 100h$ km/sec/Mpc. On the other hand, having the decay process $\phi \to A'_\mu + A'_\mu$ as the origin of DM in the model, we have the relation $n_{A'} = 2n_\phi (= 2n_\Phi)$. Φ's number density can be estimated by $n_\Phi = \rho_\Phi/m_\Phi$. Using these relations, for the case where $T_{RH} > T(a_{osc})$, we can estimate the DPDM comoving number density as what follows

$$Y_{DM} \equiv \frac{n_{A'}}{s} = \left. \frac{2n_\Phi}{s} \right|_{a=a_{osc}}$$

$$= \frac{m_\Phi \Phi_{ini}^2}{\frac{2\pi^2}{45} g_{*,s}(a_{osc}) T(a_{osc})^3},$$

(9)

where s is the entropy density of the universe and $\Phi_{ini} = V_{B-L}/\sqrt{2}$ is assumed. We used the fact that the comoving number density of ϕ remains conserved since ϕ field begins the oscillation. Thus, using $h = 0.68$, equating Eq. (8) and Eq. (9) yield

$$\left(\frac{g_*(a_{osc})}{100}\right)^{1/4} \left(\frac{m_\Phi}{1\,\text{GeV}}\right)^{1/2} \left(\frac{m_{A'}}{1\,\text{keV}}\right)^{-1} \left(\frac{V_{B-L}}{10^{13}\,\text{GeV}}\right)^{-2} \simeq 0.875,$$

(10)

where we used $g_*(a_{osc}) = g_{*,s}(a_{osc})$. In Fig. 1, the set of points on (λ, m_Φ) plane obeying Eq. (10) is shown as the red solid line.

4.2. ΔN_{eff} contributed by the dark photon

As the keV-scale DM candidate, A'_μ is the relativistic particle during the BBN era, behaving as the radiation. Therefore, its energy density contributes to the background expansion during the radiation dominated era, which is parametrized by its contribution to the extra effective number of neutrinos, ΔN_{eff}^{BBN}. The momentum of A'_μ when produced is well defined to be $p_{A'}(a_{FS}) = m_\phi/2$ because the mother scalar field is homogeneous and behaves like a motionless matter. The amount of energy density of A'_μ at BBN time is given by

$$\rho_{DM}(a_{BBN}) = \sqrt{m_{DM}^2 + \left(\frac{m_\phi a_{FS}}{2a_{BBN}}\right)^2} \times Y_{DM}$$

$$\times \frac{2\pi^2}{45} g_s(a_{BBN}) T(a_{BBN})^3,$$

(11)

where Y_{DM} is given in Eq. (8) and g_s is the effective number of relativistic degrees of freedom for the entropy density. In terms of $\rho_{DM}(a_{BBN})$, ΔN_{eff}^{BBN} is defined to be

$$\Delta N_{eff}^{BBN} \simeq \frac{\rho_{DM}(a_{BBN})}{\rho_\gamma(a_{BBN})} \times \frac{8}{7} \left(\frac{11}{4}\right)^{4/3}.$$
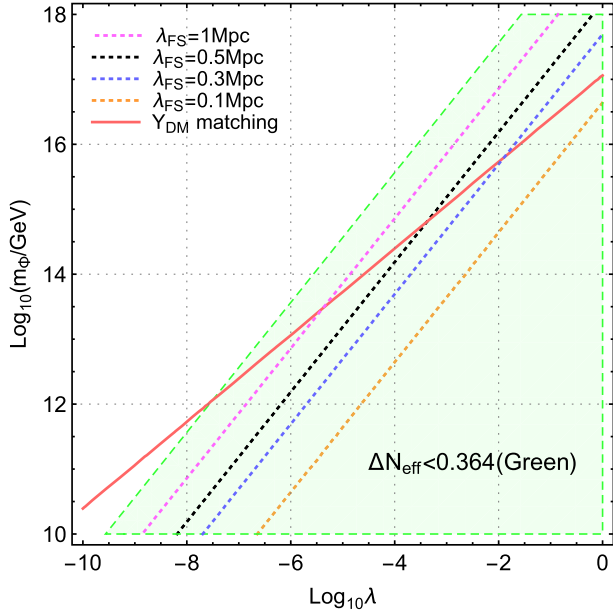
(12)

Fig. 1. The red solid line is the set of points on (λ, m_Φ) plane producing A'_μ which can explain the current DM relic density. Each dotted line of different color is the set of points (λ, m_Φ) making DPDM travel the specified free-streaming length. For the points within the green shaded region, DPDM's contribution to the radiation energy density at BBN era satisfies $\Delta N_{\rm eff}^{\rm BBN} < 0.364$. Here the relation $m_\phi = \sqrt{2} m_\Phi$ for converting the constraint on m_ϕ to that on m_Φ is used.

From the constraint on $\Delta N_{\rm fluid}^{\rm BBN} \lesssim 0.364$ [39] (95% C.L.), Eq. (11) and Eq. (12), we obtain

$$m_\phi \lesssim (2.3 - 5.2) \times 10^{19} \lambda \; {\rm GeV}, \tag{13}$$

for $m_{A'} \in (2\,{\rm keV}, 3\,{\rm keV})$. The green shaded region in Fig. 1 satisfies Eq. (13).

4.3. Free-streaming length of the dark photon

As the WDM candidate, A'_μ can alleviate the small scale problems provided its free-streaming length amounts to $\lambda_{\rm FS} \simeq \mathcal{O}(0.1)\,{\rm Mpc}$. As mentioned in the introduction, we focus on the parameter space which can produce $\lambda_{\rm FS} \lesssim 1\,{\rm Mpc}$ with a special interest in $\lambda_{\rm FS} = 0.3 - 0.5\,{\rm Mpc}$ to make A'_μ DPDM WDM candidate addressing the small scale problems, still consistent with the non-vanishing matter power spectrum at the large scales [10–12].

The free-streaming length is computed by

$$\lambda_{\rm FS} = \int_{t_{\rm FS}}^{t_0} \frac{<v_{A'}(t)>}{a} {\rm d}t$$

$$= \int_{a_{\rm FS}}^{1} \frac{{\rm d}a}{\mathcal{H}_0 F(a)} \frac{<p_{A'}(a_{\rm FS})> a_{\rm FS}}{\sqrt{(<p_{A'}(a_{\rm FS})> a_{\rm FS})^2 + m_{\rm DM}^2 a^2}}, \tag{14}$$

where $F(a) \equiv \sqrt{\Omega_{\rm rad,0} + a \Omega_{\rm m,0} + a^4 \Omega_{\Lambda,0}}$, $a_{\rm FS}$ is given in Eq. (6) and $<p_{A'}(a_{\rm FS})> \simeq m_\phi/2$. Importantly, for the case where A' is produced from the coherently oscillating scalar's decay, the momentum space of A' is expected to be almost close to the delta function centered around $m_\phi/2$ since the mother scalar field has almost zero momentum. This makes the estimation of $\lambda_{\rm FS}$ of A'_μ in our model much more reliable than that for A'_μ with a significant width of the momentum space distribution. Because $a_{\rm FS}$ is a function of (λ, m_Φ), so is $\lambda_{\rm FS}$ in our model. In Fig. 1, we show the

set of points producing $\lambda_{\rm FS} = 0.1, 0.3, 0.5$ and $1\,{\rm Mpc}$ as the dotted yellow, blue, black and magenta lines respectively.

4.4. Combined constraints on $V(\Phi)$

In Fig. 1, for the exemplary value of $m_{A'} = 3\,{\rm keV}$, we show the resultant parameter space of (m_Φ, λ) obtained by applying the constraints on $\Delta N_{\rm eff}^{\rm BBN}$ and the free-streaming criterion. The green shaded area shows the region where $\Delta N_{\rm eff}^{\rm BBN} \lesssim 0.364$ is satisfied. Each of dotted lines of different colors is a set of points on (m_Φ, λ) plane producing each specified free-streaming length of A'_μ based on Eq. (14). The red line shows the set of points which makes the abundance of A'_μ explain the current DM relic density.

It can be seen from Fig. 1 that those DPDMs arising from the decay of the mother scalar with the mass $m_\Phi \gtrsim 10^{13}\,{\rm GeV}$ and the quartic coupling $\lambda \gtrsim 5 \times 10^{-6}$ can not only explain the current DM relic density but also resolve the small scale problems as the WDM by traveling the distance $\lambda_{\rm FS} \lesssim 1\,{\rm Mpc}$ since production. As such, A'_μ in the model is really shown to be a non-thermally originated WDM causing XENON1T anomaly, consistent with the various existing cosmological constraints.

From $T_{\rm RH} > T(a_{\rm osc}) \simeq \sqrt{m_\Phi M_P}$ and the viable scalar mass regime $m_\Phi \gtrsim 10^{13}\,{\rm GeV}$, we can infer that the model is consistent with a reheating temperature as high as $T_{\rm RH} \simeq 10^{15}\,{\rm GeV}$. If one focuses on the regime $\lambda_{\rm FS} \simeq 0.3 - 0.5\,{\rm Mpc}$, then consistent $T_{\rm RH}$ becomes required to be as high as $T_{\rm RH} \simeq 10^{16}\,{\rm GeV}$.

Finally, the obtained viable range of m_Φ and λ indicates the breaking scale $V_{\rm B-L} \simeq \mathcal{O}(10^{16})\,{\rm GeV}$. Given this scale, we found that the right-handed neutrino mass satisfying $m_{\bar{N}} \lesssim 10^{12}\,{\rm GeV}$ can be consistent with our DM production scenario without thermalizing ϕ particle. This result, combined with the $T_{\rm RH}$ constraint above, indicates that the leptogenesis is realized in the model in the thermal manner (thermal leptogenesis).

5. Discussion

In this letter, motivated by the recently reported XENON1T excess, we propose a minimal model where the massive gauge boson of $U(1)_{\rm B-L}$ gauge theory with the kinetic mixing $\simeq 10^{-15}$ can play the role of the dark photon dark matter with its mass $m_{A'} \in (2\,{\rm keV}, 3\,{\rm keV})$ inducing XENON1T anomaly. As the DM candidate with the free-streaming length of order $\sim \mathcal{O}(0.1)\,{\rm Mpc}$, A'_μ is classified as the WDM which can address the small scale problems that ΛCDM is suffering from.

Relying on $U(1)_{\rm B-L}$ gauge theory which is the well motivated extension of the SM, we introduced a scalar and three heavy right-handed neutrinos charged under $U(1)_{\rm B-L}$ in addition to the SM particle content, which is the minimal set-up for ensuring the successful operation of the seesaw mechanism and leptogenesis. Imposing masses to the three-right handed neutrinos, the scalar was shown to be able to serve as the parent particle for the dark photon warm dark matter. Due to the non-thermal production mechanism we assumed in the model, the gauge boson mass of $m_{A'} \in (2\,{\rm keV}, 3\,{\rm keV})$ can be consistent with the Lyman-α forest observation. Intriguingly, we figured out that for the self-quartic interaction $\lambda \gtrsim 5 \times 10^{-6}$ and the scalar mass $m_\Phi \gtrsim 10^{13}\,{\rm GeV}$, the model can produce the non-thermally originated dark photon warm dark matter without running a foul of existing cosmological and astrophysical constraints as a source of XENON1T anomaly. Due to the inferred heavy mass of Φ, the model is found to demand a high scale inflation with $\mathcal{H}_I \gtrsim \mathcal{O}(10^{13})\,{\rm GeV}$ for consistency. Although we focus on $U(1)_{\rm B-L}$ gauge theory, our DPDM production mechanism based on the decay of the scalar going through the coherent oscillation can be easily applied to a hidden Abelian gauge theory. Finally we conclude this work by leaving a comment on the potential relevance to the pulsar timing data recently

reported by the NANOGrav collaboration [41]. There has been a trial to interpret the NANOGrav results based on a stochastic gravitational wave background arising from metastable cosmic strings formed on breaking of $U(1)_{B-L}$ [42]. The inferred $B-L$ breaking scale there reads $\sim \mathcal{O}(10^{15})$ GeV. We note that this inferred breaking scale, interestingly enough, coincides with that required by our scenario.

Note added in proof

After we finished this paper, we became aware of arXiv: 2007.02898 [hep-ph] [40]. However, the mechanism to make the $U(1)_{B-L}$ gauge boson DM there is different from ours. See also references in their paper for proposals related to XENON1T anomaly.

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.

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