Confronting the Galactic 511 keV emission with $B-L$ gauge boson dark matter

Weikang Lin[1,*] and Tsutomu T. Yanagida[1,2,†]

[1]Tsung-Dao Lee Institute (TDLI) & School of Physics and Astronomy, Shanghai Jiao Tong University, Shengrong Road 520, 201210 Shanghai, P. R. China

[2]Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

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$B-L$ gauge symmetry is motivated by the successful generation of the seesaw mechanism and leptogenesis. We show that if the $B-L$ gauge boson constitutes a small fraction of dark matter (DM) it can explain the Galactic 511 keV emission via decay into an electron-positron pair. We find the model parameter space that is consistent with the seesaw mechanism, is cosmologically viable, and accounts for the amplitude of the Galactic positron line. From this parameter space, we derive an upper bound on the gauge boson mass and a bound on the positron injection energy $\lesssim$3 MeV. This derived energy bound is consistent with the observational upper limit of the injection energy. The resultant model predicts the $B-L$ breaking scale to be in a relatively narrow range, i.e., $V_{B-L} \sim 10^{15}$–10^{16} GeV, which is consistent with a grand unification scale seesaw mechanism. The model is consistent in several phenomenologies, suggesting that they have a common origin in $B-L$ symmetry breaking.

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I. INTRODUCTION

The origin of the 511 keV emission (presumably) from positron (e^+) annihilation in the Galaxy [1–3] has remained a mystery for about half a century; for a review, see Ref. [4]. Its intensity and morphology are difficult to explain with astrophysical origins, which has motivated a number of dark matter (DM) explanations such as light DM annihilation [5,6] and decay [7–9]. However, light DM candidates often suffer from other astrophysical or experimental constraints [10–13]. Besides, none of these attempts have been able to predict the spectral features of the Galactic 511 keV emission line, such as the injection positron energy.

A recently proposed light DM candidate is the $B-L$ gauge boson $(A^{\mathfrak{f}}_\mu)$ associated with the $B-L$ gauge symmetry [14–16].[1] The $U(1)_{B-L}$ gauge symmetry is a well-motivated minimum extension to the Standard Model of particle physics (SM). It is naturally anomaly free and contains three right-handed neutrinos. The large Majorana masses of the right-handed neutrinos are generated when such a gauge symmetry is spontaneously broken, which can simultaneously solve the problems of the small active-neutrino masses via the seesaw mechanism [17–20] and the cosmological baryon asymmetry via leptogenesis [21,22]. When the gauge coupling constant is $g_{B-L} \lesssim 10^{-18}$, $A^{\mathfrak{f}}_\mu$ can be a dark matter candidate [16,23]. It predominantly decays into active neutrinos, which provides a unique way to test the $B-L$ extension of the SM that is otherwise difficult to probe with high-energy colliders [16]. Decay to three photons is extremely suppressed [14,15], and thus it safely satisfies the constraints from precise γ-ray and x-ray observations. The small gauge coupling and light mass also allow it to avoid constraints from current DM direct-detection searches. The next leading decay channel of $A^{\mathfrak{f}}_\mu$ is into an electron-positron pair if the mass of $A^{\mathfrak{f}}_\mu$ $(m_{\mathfrak{f}})$ is larger than the threshold for such pair production.

Given the important role that the $B-L$ gauge boson plays in testing the $B-L$ symmetry and the unresolved nature of the Galactic 511 keV emission, it is timely to investigate whether it can explain such an astrophysical anomaly and study the implications on the physics of $B-L$ symmetry. In this work, we show that the $B-L$ gauge boson with a seesaw-motivated and cosmologically viable model parameter space can explain the amplitude of the Galactic positron line. $A^{\mathfrak{f}}_\mu$ DM can only constitute a small fraction of the total DM abundance. From the resultant

[*]weikanglin@sjtu.edu.cn

[†]tsutomu.tyanagida@sjtu.edu.cn

[1]The superscript "$\mathfrak{f}$" stands for "féeton." Such a small-mass and feebly coupled gauge boson provides a unique test of the well-motivated $B-L$ gauge symmetry, as is pointed out in Ref. [16]. Given this important role, we have called this $B-L$ gauge boson the "féeton" in Ref. [16].

model, we derive an upper bound of $m_{\mathfrak{f}} \simeq 6$ MeV and hence an upper bound of the positron injection energy of ~ 3 MeV. This derived upper bound of the positron injection energy coincides with the observational bound on the positron injection energy [24]. Most profoundly, the model also implies that the $B-L$-breaking scale is $V_{B-L} = 7 \times 10^{14}$–$10^{16}$ GeV, which is consistent with a grand unified theory (GUT) scale seesaw mechanism [22,25] and with the energy scales required for other phenomenological considerations, as we will discuss.

II. POSITRON PRODUCTION FROM THE DECAY OF $A_\mu^{\mathfrak{f}}$

When $m_{\mathfrak{f}}$ is larger than twice the electron mass $2m_e$, it decays into an electron-positron pair with a rate given by [26]

$$\Gamma_{\mathfrak{f}\to e^- e^+} = \frac{g_{B-L}^2 m_{\mathfrak{f}}}{12\pi}\sqrt{1-\frac{4m_e^2}{m_{\mathfrak{f}}^2}}\left(1+\frac{2m_e^2}{m_{\mathfrak{f}}^2}\right), \qquad (1)$$

where g_{B-L} is the gauge coupling constant and m_e is the electron mass. We define $\Delta m \equiv m_{\mathfrak{f}} - 2m_e$, and require $\Delta m > 13.6$ eV to allow positronium (Ps) formation via the charge exchange of positrons with hydrogen atoms. For the Galactic DM density distribution we assume a Navarro-Frenk-White DM density profile [27],

$$\rho_{\rm DM}^{\rm Gal} = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}, \qquad (2)$$

where the characteristic density $\rho_s = 1.4 \times 10^7\ M_\odot\,{\rm kpc}^{-3}$ and scale radius $r_s = 16$ kpc were given in Ref. [28]. We parametrize the current fraction of $A_\mu^{\mathfrak{f}}$ to the total DM abundance as $f_{\mathfrak{f}} \equiv \rho_{\mathfrak{f}}^0/\rho_{\rm DM}^0$, where $\rho_{\mathfrak{f}}^0$ and $\rho_{\rm DM}^0$ are the current cosmic average densities of $A_\mu^{\mathfrak{f}}$ DM and total DM. We assume that this fraction holds for the entire Universe. The positron production rate is then $\dot{n}_{e^+} = \Gamma_{\mathfrak{f}\to e^- e^+} f_{\mathfrak{f}} \rho_{\rm DM}^{\rm Gal}/m_{\mathfrak{f}}$.

After the positrons are produced, they can annihilate with electrons either directly or via Ps formation. The Ps fraction f_{Ps}—the ratio of the number of positrons in positronium to the total positrons produced is measured to be close to unity [29–31]. Here, we take $f_{Ps} = 1$ for simplicity.[2] One quarter of the positronium is in the para-positronium (p-Ps) state, which annihilates into two 511-keV photons. We assume that the positrons annihilate close to their production sites, and we set the positron annihilation rate equal to the production rate. The production rate of the 511 keV photons is then $\dot{n}_\gamma = 2\dot{n}_{e^+}/4$, and the angular differential flux is given by the following integral along the line of sight (s):

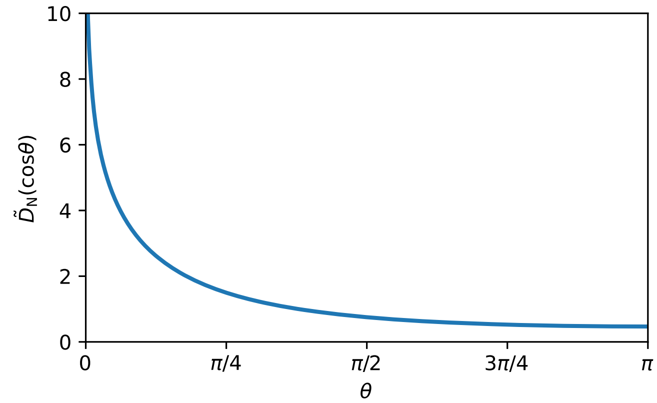

FIG. 1. Angular dependence of the function $\tilde{D}_{\rm N}(\cos\theta)$ defined in Eq. (3).

$$\frac{{\rm d}\Phi_{511}}{{\rm d}\Omega} = \frac{1}{4\pi}\int \dot{n}_\gamma {\rm d}s = 4\times 10^3 f_{\mathfrak{f}}\left(\frac{g_{B-L}}{10^{-20}}\right)^2\sqrt{1-\frac{4m_e^2}{m_{\mathfrak{f}}^2}}\left(1+\frac{2m_e^2}{m_{\mathfrak{f}}^2}\right) \times \tilde{D}_{\rm N}(\cos\theta)\ [{\rm cm^{-2}\,s^{-1}\,sr^{-1}}], \qquad (3)$$

where $\tilde{D}_{\rm N}(\cos\theta)$ is a function of the angle (θ) from the Galactic center (GC) representing the morphology of the flux and is normalized so that $\int \tilde{D}_{\rm N}(\cos\theta){\rm d}\Omega = 4\pi$, with $\cos\theta = \cos\ell\cos b$, where ℓ and b are Galactic longitude and latitude. The function $\tilde{D}_{\rm N}(\cos\theta)$ is plotted in Fig. 1. Thus, there are three model parameters: ($f_{\mathfrak{f}}$, g_{B-L}, $m_{\mathfrak{f}}$).

III. COMPARISON TO THE GALACTIC 511 keV EMISSION

The Galactic 511 keV emission has a rather diffuse morphology but is more concentrated towards the GC than radiation with other wavelengths [30,33]. Analyses of the associated Bremsstrahlung and in-flight annihilation radiation indicate that the injection energy of positrons is $\lesssim 3$ MeV [24,34]. Table I summarizes some important parameters of the Galactic 511 keV emission given in Refs. [24,30].

A. Bulge flux and constraints on model parameters

We first focus on the bulge flux and will discuss the flux morphology later. In Ref. [30], the (broad) bulge region was modeled as a two-dimensional Gaussian function with a width $\sigma_\ell = \sigma_b = 8.7$ degrees, or a FWHM of 20.55 degrees in either dimension.[3] Using Eq. (3), we calculate the integrated flux for a region that is within $\theta < 10.28$ degrees

[2] We keep in mind that a somewhat lower $f_{Ps} = 0.76 \pm 0.12$ was reported recently in Ref. [32]. Adopting this different $f_{\mathfrak{f}}$ does not qualitatively change our conclusions.

[3] We are aware that the bulge region is modeled with a narrow bulge and a broad bulge [30]. To calculate the bulge flux, we only refer to the broad-bulge region for the bulge area and we compare the predicted bulge flux to the total measured bulge intensity.

TABLE I. Parameters of the Galactic 511 keV emission adopted from Ref. [30]. The last row is from Ref. [24].

Field	Value
Total intensity	$2.74 \pm 0.25 \times 10^{-3}$ cm^{-1} s^{-1}
Bulge intensity	$0.96 \pm 0.07 \times 10^{-3}$ cm^{-1} s^{-1}
Disk intensity	$1.66 \pm 0.35 \times 10^{-3}$ cm^{-1} s^{-1}
Bulge/disk ratio	0.58 ± 0.13
Bulge extent (σ_ℓ, σ_b)	(8.7, 8.7) [degrees]
Disk extent (σ_ℓ, σ_b)	$(60^{+10}_{-5}, 10.5^{+2.5}_{-1.5})$ [degrees]
Ps fraction f_{Ps} (bulge)	1.080 ± 0.029
Injection energy of e^+	$\lesssim$3 MeV

of the GC and set it equal to half of the measured bulge flux. With $\int_{\theta<10.28^\circ} \tilde{D}_{\rm N}(\cos\theta) {\rm d}\Omega = 0.52$ and the bulge intensity given in Table I, the above procedure gives us the following constraint on the model parameters:

$$f_{\mathfrak{f}} \left(\frac{g_{B-L}}{10^{-20}}\right)^2 \sqrt{1 - \frac{4m_e^2}{m_{\mathfrak{f}}^2}} \left(1 + \frac{2m_e^2}{m_{\mathfrak{f}}^2}\right) \simeq 2.3 \times 10^{-7}. \quad (4)$$

In Fig. 2, the dashed lines show this constraint in the $(f_{\mathfrak{f}}, g_{B-L})$ plane for different Δm's. The value of $f_{\mathfrak{f}}$ for a fixed g_{B-L} becomes smaller as Δm (or, equivalently, $m_{\mathfrak{f}}$) becomes larger, but it becomes insensitive to Δm when $\Delta m \gtrsim m_e$. This is because, when $\Delta m \ll m_e$, the predicted flux increases rapidly with Δm [see Eq. (3)] and $f_{\mathfrak{f}}$ needs to decrease to match the observed value of the flux. On the other hand, when $\Delta m \gtrsim m_e$, the predicted flux becomes insensitive to $m_{\mathfrak{f}}$. We find that $f_{\mathfrak{f}}$ is typically very small, so $A^{\mathfrak{f}}_\mu$ only constitutes a small fraction of the DM abundance.

Second, we require that $A^{\mathfrak{f}}_\mu$ DM satisfies cosmological observations. Given the small fraction of $A^{\mathfrak{f}}_\mu$ to the total DM today, in order to estimate such a cosmological constraint we require that $A^{\mathfrak{f}}_\mu$ has never been the dominant DM component in the past, i.e., the comoving density $\rho_{\mathfrak{f}}(t) = \rho^0_{\mathfrak{f}} \exp[(t_{\rm U} - t)/\tau] < \rho^0_{\rm CDM}$ at all times[4] (t), where τ is the lifetime of $A^{\mathfrak{f}}_\mu$, $t_{\rm U}$ is the age of the Universe, and "CDM" denotes the dominant DM component. Since $\rho^0_{\mathfrak{f}} \ll \rho^0_{\rm CDM}$, the estimated cosmological constraint translates into

$$f_{\mathfrak{f}} \exp(t_{\rm U}/\tau) < 1. \quad (5)$$

We note that the above estimate of the cosmological constraint is rather conservative. Given the consistency between the DM density measured at early times and that measured at late times [35–37], we expect that a detailed cosmological constraint would be stronger than our estimate. However, our estimate suffices for the goal of this work. This is because, as we shall see, the allowed $f_{\mathfrak{f}}$ value drops very quickly as g_{B-L} increases and it is the range of g_{B-L} that is relevant for the inference of V_{B-L}.

Recall that $A^{\mathfrak{f}}_\mu$ predominantly decays into the three active neutrinos with a rate given by [16]

$$\Gamma_{\mathfrak{f}\to\nu\bar{\nu}} = \frac{g^2_{B-L}}{8\pi} m_{\mathfrak{f}}. \quad (6)$$

The lifetime of $A^{\mathfrak{f}}_\mu$ is then $\frac{1}{\tau} = \Gamma_{\mathfrak{f}\to\nu\bar{\nu}} + \Gamma_{\mathfrak{f}\to e^- e^+}$. The light blue regions in Fig. 2 show the cosmologically viable parameter space for cases with different $m_{\mathfrak{f}}$'s. This region shrinks as $m_{\mathfrak{f}}$ increases, which can be seen in the panels from left to right.

Finally, the $B-L$-breaking scale V_{B-L} is of the order of $V_{B-L} = 10^{12} - 10^{16}$ GeV for the successful generation of the seesaw mechanism and leptogenesis. Since $m_{\mathfrak{f}} = 2g_{B-L}V_{B-L}$, the range of g_{B-L} corresponding to $V_{B-L} = 10^{12} - 10^{16}$ GeV changes with $m_{\mathfrak{f}}$. For each panel in Fig. 2 we show the g_{B-L} value corresponding to $V_{B-L} = 10^{16}$ GeV with a vertical line, and the theoretically motivated parameter space is to the right of this line.

Combining the above three constraints, the viable parameters are shown by the thick portions of the dashed lines in Fig. 2. In the left panel, we show some examples for $\Delta m \ll m_e$. In this case, as already discussed, $f_{\mathfrak{f}}$ decreases as $m_{\mathfrak{f}}$ increases. On the other hand, the range of g_{B-L} that is cosmologically viable (light blue) and corresponds to $V_{B-L} < 10^{16}$ GeV (right to the vertical line) is only slightly affected.[5] The fraction of $A^{\mathfrak{f}}_\mu$ in DM is found to be $f_{\mathfrak{f}} \sim 10^{-9} - 10^{-5}$.

In the middle and right panels of Fig. 2, we show two examples of $\Delta m \gtrsim m_e$ where the effects from an increasing $m_{\mathfrak{f}}$ are opposite to the case when $\Delta m \ll m_e$. The value of $f_{\mathfrak{f}}$ is now insensitive to $m_{\mathfrak{f}}$ because the predicted flux becomes insensitive to $m_{\mathfrak{f}}$. So, the dashed lines in these two panels are essentially the same. However, the range of g_{B-L} shrinks as $m_{\mathfrak{f}}$ increases. As a consequence, there is no viable parameter space for $m_{\mathfrak{f}} \gtrsim 6$ MeV; see the right panel.

Interestingly, allowing $f_{\mathfrak{f}}$ to be a free parameter does not drastically change the upper limit of $m_{\mathfrak{f}}$ compared to that found in Ref. [16]. In fact, the bound on $m_{\mathfrak{f}}$ is very robust against the value of $f_{\mathfrak{f}}$ as long as $A^{\mathfrak{f}}_\mu$ contributes some amount of DM today. For example, even if $f_{\mathfrak{f}}$ is as low as 10^{-20}, the upper limit of $m_{\mathfrak{f}}$ is only slightly changed to $m_{\mathfrak{f}} \lesssim 7$ MeV.

[4] $A^{\mathfrak{f}}_\mu$ DM can be the dominant DM component well before the epoch of matter-radiation equality, but substituting such a small initial time instead of $t = 0$ does not affect our estimation.

[5] In the left panel, we only show the $m_{\mathfrak{f}} = 1$ MeV case for the light blue region and the vertical line, but the effect of Δm can be seen by the slightly shrinking thick dashed lines as Δm increases.

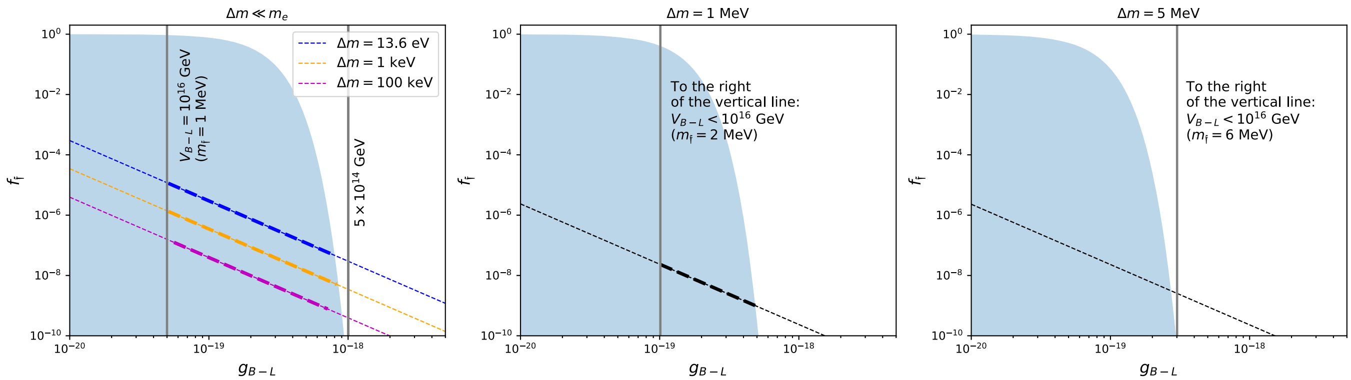

FIG. 2. Parameter space in cases with different $m_{\mathfrak{f}}$ (and $\Delta m \equiv m_{\mathfrak{f}} - 2m_e$). Left: $\Delta m \ll m_e$. The light blue region is the cosmologically viable parameter space. The vertical line indicates the value of $g_{B-L} = m_{\mathfrak{f}}/(2V_{B-L})$ for some specific values of V_{B-L}. The dashed lines are parameters that can account for the bulge positron annihilation flux, while the thicker portions also satisfy the cosmological constraints and the motivation from the seesaw mechanism. Middle: $m_{\mathfrak{f}} = 2$ MeV. Right: $m_{\mathfrak{f}} = 6$ MeV. There is no viable parameter space when $m_{\mathfrak{f}} \gtrsim 6$ MeV.

B. Upper limit of the positron injection energy and the $B-L$-breaking scale

From the above analyses, we derive two important implications if the $B-L$ gauge boson DM is the source of the Galactic 511 keV emission anomaly.

(1) Given the upper limit of $m_{\mathfrak{f}} \lesssim 6$ MeV, the model predicts the positron injection energy to be $\lesssim$3 MeV. This is consistent with observations [24,34]. We note that none of the other current DM scenarios are able to predict this feature of the Galactic positron annihilation emission, which is also difficult to reproduce with some (but not all) astrophysical sources [4].

(2) The inferred $B-L$-breaking scale is rather narrow, i.e., $V_{B-L} = 7 \times 10^{14}$–$10^{16}$ GeV, which can be read from the left panel of Fig. 2. This is much improved and more informative than the naive estimation from the seesaw mechanism alone (10^{12}–10^{16} GeV). The inferred range of V_{B-L} is consistent with a GUT-scale seesaw [22,25]. We further remark on the significance of such a V_{B-L} range below.

Such a high energy scale of V_{B-L} is difficult to reach with current and near-future particle colliders. It is then important to investigate tests with other indirect astrophysical phenomenology. It was pointed out in Ref. [16] that the detection of neutrinos from decays of $A_\mu^{\mathfrak{f}}$ would be a smoking gun for the $B-L$ symmetry extension of the SM. For the scenario considered in this work, however, the fraction of $A_\mu^{\mathfrak{f}}$ in DM is so small that it is not realistic to expect to detect such a neutrino signal in the near future.

Alternatively, one can study the $A_\mu^{\mathfrak{f}}$ DM production mechanism and the early-Universe phenomenology. Remarkably, besides being consistent with a GUT-scale seesaw, the inferred range of V_{B-L} is consistent with the energy scale that allows self-consistent inflationary production as explained below.

First, if the $B-L$ symmetry is broken during inflation, the $B-L$ gauge boson DM can be produced as a vector boson during inflation without violating the constraint from the nondetection of isocurvature perturbations [38]. The viable parameter space here permits a self-consistency for such a production mechanism for the $B-L$ gauge boson DM: if it is produced during inflation, $f_{\mathfrak{f}}$ is related to $m_{\mathfrak{f}}$ and the inflation scale $H_{\rm inf}$ by $f_{\mathfrak{f}} = \left(\frac{m_{\mathfrak{f}}}{6\times10^{-9}\ \mathrm{keV}}\right)^{1/2}\left(\frac{H_{\rm inf}}{10^{14}\ \mathrm{GeV}}\right)^2$ [38]. Taking $f_{\mathfrak{f}} \lesssim 10^{-5}$ and $m_{\mathfrak{f}} \simeq 1$ MeV, we obtain an inflation scale of $H_{\rm inf} \lesssim 5 \times 10^8$ GeV. This is in turn consistent with the condition that the $B-L$ symmetry is broken during inflation, because $H_{\rm inf} < V_{B-L}$. In addition, the string axion DM can be accommodated as the major DM component, since the inferred inflation scale satisfies the constraint from the nondetection of the isocurvature perturbation; see Eq. (6) in Ref. [39].

Further, on top of the above inflationary production, if the quartic coefficient (λ) of the scalar field (ϕ) responsible for the spontaneous symmetry breaking is $\lambda \lesssim 10^{-4}$, the reheating temperature can be higher than the mass of the scalar field. In that case, the $B-L$ symmetry may be restored after reheating and be broken again as the temperature decreases. Cosmic string loops can form due to such a phase transition after reheating [40]. These cosmic strings emit gravitational waves (GWs) as they shrink and lose energy [41], which may explain the recently reported detection of a stochastic GW background by NANOGrav [42,43]. Interestingly, the inferred range of V_{B-L} required to source the Galactic 511 keV emission coincides with that required to explain the NANOGrav detection; see Eq. (10) in Ref. [42]. This scenario can be further tested with future GW experiments such as SKA [44] and LISA [45]. We leave a full exploration of the early-Universe phenomenology to a future work.

C. Remarks on the flux morphology

The morphology of the Galactic 511 keV emission has been difficult to explain with all astrophysical or DM sources [4]. Such an emission is concentrated towards the GC, which can be roughly represented by a high value of the bulge-to-disk flux ratio (B/D). Based on earlier data from INTEGRAL/SPI with $\mathrm{B/D} \sim 1.5$ [46], it was found that decaying DM scenarios are disfavored unless the inner DM density increases towards the center very sharply [47]. A similar conclusion was obtained in Ref. [48] where it was found that the positron production rate is proportional to the DM density squared. This morphology problem in decaying dark matter scenarios (and in traditional astrophysical explanations in general) is alleviated with new data, as B/D has decreased to 0.58 ± 0.13 [30]. The flux morphology in the decaying DM scenarios is solely described by the function $\tilde{D}_{\mathrm{N}}(\cos\theta)$. We estimate the B/D for decaying DM scenarios by taking (the mean values of) the sizes of the bulge and the disk derived in Ref. [30], which are summarized in Table I. We obtain $\mathrm{B/D} \simeq 0.3$, which is still about a factor of 2 (and $\sim 2\sigma$) smaller than the value derived from observations [30].[6] Therefore, decaying DM scenarios are still in mild tension with the new data.

However, it is too early to exclude decaying DM scenarios based on the currently measured morphology of the flux for two reasons. 1) Given some uncertainties regarding positron transportation in the interstellar medium [4], the assumption that positrons annihilate close to their production sites may not be satisfied in the disk area. Some positrons may escape the disk, reducing its annihilation flux and giving a larger predicted B/D. 2) Due to the low surface luminosity of the flux from the disk, its detection has proven to be difficult [30,32,48]. It is possible that the detection of the flux from the disk is still incomplete and the actual disk flux is larger, and hence the current observed B/D might be biased to be larger than the true value. Thus, it is still possible that DM decays can explain the morphology of the Galactic 511 emission, which we assume in this work. Since the detected bulge flux is more reliable, we only use it to infer the model parameters as we did in the previous sections.

IV. CONCLUSION

The unresolved nature of the Galactic 511 keV emission could point to new physics beyond the SM. In this work, we have explored a scenario where the decay of $B-L$ gauge boson DM into electron-positron pairs sources such an emission. We consistently considered a model parameter space that is theoretically motivated by the seesaw mechanism, cosmologically viable, and accounts for the Galactic 511 keV bulge emission. We found that the resultant model successfully accounts for the positron injection energy and makes important predictions for the physics of the $B-L$ symmetry.

We found that, while the fraction of $A_\mu^{\mathfrak{f}}$ in the DM abundance is treated as a free parameter, its mass is bounded to be $\lesssim 6$ MeV by the cosmological constraint and the scale of the $B-L$ symmetry breaking. This bound is very robust against the value of $f_{\mathfrak{f}}$. $A_\mu^{\mathfrak{f}}$ DM was found to constitute only a small fraction of the DM abundance ($f_{\mathfrak{f}} \sim 10^{-9}$–$10^{-5}$).

As a result of the constraint on $m_{\mathfrak{f}}$, the positron injection energy from the decay of $A_\mu^{\mathfrak{f}}$ is bounded to be $\lesssim 3$ MeV, which coincides with the current observational limit of the injection energy. This is different from other DM scenarios in the literature so far; in our case, we derived an upper bound on $m_{\mathfrak{f}}$ and hence an upper bound on the positron injection energy from the consideration of cosmological observations, the seesaw mechanism, and the amplitude of the Galactic positron line. This derived energy bound turned out to be consistent with the observational limit of the positron injection energy. On the contrary, other DM scenarios need to use the upper bound of the positron injection energy to set a constraint on the DM mass range.

The model has a nontrivial implication for $B-L$ physics: the $B-L$ symmetry breaking scale is predicted to be $V_{B-L} = 7 \times 10^{14}$–$10^{16}$ GeV, which is consistent with a GUT-scale seesaw mechanism. The range of V_{B-L} permits self-consistent inflationary production of $A_\mu^{\mathfrak{f}}$ DM and accommodates the possibility that cosmic strings generated by the $U(1)_{B-L}$ gauge breaking after reheating explain the stochastic GW background reported by NANOGrav. The resultant model is consistent for several phenomenologies, including small neutrino masses, cosmic baryon asymmetry, the Galactic 511 keV emission, and the tentative stochastic GW background reported by NANOGrav, which suggests a common origin from $B-L$ symmetry breaking.

One caveat is that we assumed that the morphology of the Galactic 511 keV can be explained by DM decays. There is still some mild tension between the flux bulge-to-disk ratio predicted in decaying DM scenarios and that derived from current observations. However, we argued that the tension may be alleviated or even eliminated with further studies of the transportation of positrons in the interstellar medium and more complete surveys in the disk area.

We note that our definition of $U(1)_{B-L}$ is not to be confused with the generalization that includes the SM hypercharge [15]. However, as long as the decay of $A_\mu^{\mathfrak{f}}$ into neutrinos is not suppressed, our conclusions are not significantly changed.

Finally, we commented on the small gauge coupling constant, which is another caveat of our work. However,

[6]For a more robust conclusion, one should compare the predicted flux profile with the observed flux profile, which is beyond the goal of this work.

while the $B-L$ gauge symmetry is well motivated by the seesaw mechanism and leptogenesis, the gauge coupling constant is completely undetermined by theory and needs to be determined by experiments. Here, g_{B-L} is bounded by assuming that the $B-L$ gauge boson is a long-lived DM component. Second, the small gauge coupling is not a result of an extreme fine-tuning. Since $U(1)_{B-L}$ is an asymptotic non-free theory, $g_{B-L}=0$ is the infrared stable point and thus, although some tuning is needed to fit observations (just like any other parameter in a model), a small g_{B-L} is natural. This may be different from $U(1)_Y$, since the hypercharge $U(1)_Y$ might be embedded into the GUT group $SU(5)$. In that case, $U(1)_Y$ is a part of the asymptotic free gauge theory.

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