Confronting the 511 keV Galactic emission with the féeton dark matter

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ABSTRACT

The féeton is the gauge boson of the $B-L$ gauge symmetry motivated from the successful generation of the seasaw mechanism and leptogenesis. We show that if the féeton constitutes a small fraction of the dark matter (DM) it can originate the Galactic 511 keV emission. For the first time among all the proposed DM sources, the féeton DM predicts the injection energy of positrons to be $\lesssim 3$ MeV. This prediction is verified by current observations. The model suggests the $B-L$ breaking scale is in a relatively narrow range, i.e., $V_{B-L} \sim 10^{15} - 10^{16}$ GeV, which is consistent with a Grand Unification (GUT) scale seasaw mechanism and has important impacts on the early-universe phenomenology. A further investigation on the emission morphology is warranted for a robust test of this féeton scenario.

1. INTRODUCTION

Since the discovery of the 511 keV emission (presumably) from position ($e^+$) annihilation in the Galaxy, (Johnson et al. 1972; Haymes et al. 1975; Leventhal et al. 1978), its origin has remained a mystery for about half a century; for a review, see (Prantzos et al. 2011). Its large intensity and morphology are difficult to explain with astrophysical origins, which has motivated a number of DM explanations such as the light DM annihilation (Boehm et al. 2004; Gunion et al. 2006) and decay (Hooper & Wang 2004; Picciotto & Pospelov 2005; Takahashi & Yanagida 2006). However, light DM candidates often suffer from other astrophysical or experimental constraints (Fayet et al. 2006; Lees et al. 2017; Knapen et al. 2017; Aguilar-Arevalo et al. 2019). Besides, none of these attempts are 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 féeton—the gauge boson associated with the $B-L$ gauge symmetry (Choi et al. 2020; Okada et al. 2020; Lin et al. 2022). The $U(1)_{B-L}$ gauge symmetry is a well-motivated minimum extension to the Standard Model of particle physics (SM). It is anomaly free naturally with the presence of 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 (Yanagida 1979a,b; Gell-Mann et al. 1979; Minkowski 1977; Wilczek 1979) and the cosmological baryon asymmetry via leptogenesis (Fukugita & Yanagida 1986; Buchmuller et al. 2005). When the gauge coupling constant is $g_{B-L} \lesssim 10^{-18}$, the féeton can be a dark matter candidate (Lin et al. 2022; Choi et al. 2021). It predominantly decays into active neutrinos, which provides a unique way to test the $B-L$ extension to SM that is otherwise difficult to probe with high-energy colliders (Lin et al. 2022). The decay to three photons is extremely suppressed (Choi et al. 2020; Okada et al. 2020), so that it safely satisfies the constraints from the precise $\gamma$-ray and X-ray observations. The small gauge coupling and light mass also allow it to avoid the constraints from the current DM direct searches. The next leading decay channel of the féeton is that into an electron-positron pair if the féeton mass is larger than the threshold for such a pair production.

Given the important role of the féeton played in testing the $B-L$ symmetry and the unresolved nature of the Galactic 511 keV emission, it is timely to investigate whether féeton DM can explain such an astrophysical anomaly and study the implications on the physics of $B-L$ symmetry. In this work we show that accounting for such a Galactic emission requires the féeton...
to constitute only a small fraction of the DM amount. In the scenario consistent with cosmological constraints and the motivation from the seesaw mechanism, we successfully predict a féeton mass upper bound of $\sim 6$ MeV and hence an upper bound of the positron injection energy of $\sim 3$ MeV, which is verified by current observations. Profoundly, the model also implies that the breaking scale is $V_{B-L} = 7 \times 10^{14} - 10^{16}$ GeV, which is consistent with a GUT-scale seesaw mechanism (Buchmuller & Yanagida 1999; Buchmuller et al. 2005) and with the energy scales required for other phenomenological considerations as we shall discuss.

2. POSITRON PRODUCTION FROM THE FÉETON DECAY

When the féeton mass ($m_f$) is larger than $2 m_e$, it decays into an electron-positron pair with a rate given by (Fabbrichesi et al. 2020)

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

(1)

where $g_{B-L}$ is the gauge coupling constant, $m_e$ is the electron mass. We define $\Delta m = m_f - 2m_e$, 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 (NFW) DM density profile Navarro et al. (1996),

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

(2)

with the characteristic density $\rho_s = 1.4 \times 10^7 M_\odot \text{kpc}^{-3}$ and scale radius $r_s = 16 \text{kpc}$ given in Nesti & Salucci (2013). We parameterize today’s féeton fraction in the DM amount as $f_1 \equiv \rho_f / \rho_{DM}$, where $\rho_f$ ($\rho_{DM}$) is the cosmic average density of the féeton DM (total DM) today. We assume this fraction holds universally for the entire universe. The positron production rate is then

$$\dot{n}_{e^+} = \Gamma_{f \to e^- e^+} f_1 \rho_{DM} / m_f.$$

After the positrons are produced, they can annihilate with electrons either directly or via Ps formations. The Ps fraction $f_{Ps}$—the ratio of the number of positron forming positronium to the total number—is measured to be close to unity (Harris et al. 1998; Siegert et al. 2016; Jean et al. 2006). Here, we take $f_{Ps} = 1$ for simplicity.\(^2\) For all the Ps, 1/4 of them are in the para-positronium (p-Ps) state that annihilates into two photons with 511 keV. We assume the positrons annihilate closely to their production sites and we equal the positron annihilation rate 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 ($s$),

$$\frac{d\Phi_{511}}{d\Omega} = \frac{1}{4\pi} \frac{d\Gamma}{d\Omega} = 4 \times 10^3 f_1 \left(\frac{g_{B-L}}{10^{-26}}\right)^2 \sqrt{1 - \frac{4m_e^2}{m_f^2}} \left(1 + \frac{2m_e^2}{m_f^2}\right) \times \tilde{D}_N(\cos \theta) \text{[cm}^{-2}\text{s}^{-1}\text{sr}^{-1}],$$

(3)

where $\tilde{D}_N(\cos \theta)$ is a function of the angle ($\theta$) from the Galactic Center (GC) representing the morphology of the flux and is normalized so that $\int \tilde{D}_N(\cos \theta) d\Omega = 4\pi$. There are then three model parameters ($f_1$, $g_{B-L}$, $m_f$). Note that $\cos \theta = \cos \ell \cos b$, where $\ell$ and $b$ are Galactic longitude and latitude.

3. COMPARISON TO THE GALACTIC 511 KEV EMISSION

The Galactic 511 keV emission has a rather diffuse morphology but is more concentrated towards GC than radiation in other wavelengths (Bouchet et al. 2010; Siegert et al. 2016); also see Sec. 3.3. Analyses of the associated Bremsstrahlung and in-flight annihilation radiations indicate that the injection energy of the positron is $\lesssim 3$ MeV (Beacom & Yuksel 2006; Sizun et al. 2006). Table 1 summarizes some important parameters about the Galactic 511 keV emission given in Siegert et al. (2016) and Beacom & Yuksel (2006).

| Field | Value |
|-------|-------|
| Total intensity | $2.74 \pm 0.25 \times 10^{-3} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ |
| Bulge intensity | $0.96 \pm 0.07 \times 10^{-3} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ |
| Disk intensity | $1.66 \pm 0.35 \times 10^{-3} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ |
| Bulge/disk ratio | $0.58 \pm 0.13$ |
| Bulge extent $(\sigma_f, \sigma_b)$ | $(8.7, 8.7)$ [degrees] |
| Disk extent $(\sigma_f, \sigma_b)$ | $(60^{+10}_{-5}, 10.5^{+2}_{-1.5})$ [degrees] |
| Ps fraction $f_{Ps}$ (bulge) | $1.080 \pm 0.029$ |
| Injection energy of $e^+$ | $\lesssim 3$ MeV |

### Notes:

\(^2\) We keep in mind that a somewhat lower $f_{Ps} = 0.76 \pm 0.12$ is reported recently in Kierans et al. (2020). Adopting this different $f_1$ does not qualitatively change our conclusions.

### Table 1. Parameters of the Galactic 511 keV emission adopted from Siegert et al. (2016). The last row is from Beacom & Yuksel (2006).

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The bulge flux and féeton model parameters

We first focus on the bulge flux and will discuss the flux morphology in Sec. 3.3. In Siegert et al. (2016), the (broad) bulge region is modeled as a two-dimensional Gaussian function with a width $\sigma_\ell =$
$\sigma_b = 8.7$ degrees, or a Full-Width-at-Half-Magnitude (FWHM) of 20.55 degrees in either dimension. Using Eq. (3), we calculate the integrated flux for a region that is within $\theta < 10.28$ degrees from GC and equal it to half of the measured bulge flux. This gives us the following constraint on the model parameters,

$$f_f \left( \frac{g_{B-L}}{10^{-20}} \right)^2 \sqrt{1 - \frac{4m_e^2}{m_f^2}} \left( 1 + \frac{2m_e^2}{m_f^2} \right) \approx 2.3 \times 10^{-7}. \quad (4)$$

In Figure 1, the dashed lines show this constraint in the $(f_f, g_{B-L})$ plane for different $\Delta m$'s. The value of $f_f$ for a fixed $g_{B-L}$ is smaller as $\Delta m$ (or equivalently, $m_f$) becomes larger, but it becomes insensitive to $\Delta m$ when $\Delta m \gtrsim m_e$. This is because, when $\Delta m \ll m_e$, the predicted flux increases rapidly with $\Delta m$ [see Eq. (3)] and $f_f$ 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 the fêton mass. We find that $f_f$ is typically very small, so the fêton only constitutes a small fraction of the DM amount.

Secondly, we require the fêton to satisfy cosmological observations. Given the small fraction of fêton in the DM amount today, to estimate such a cosmological constraint we require that the fêton has never been the dominant DM component in the past, i.e., the comoving density $\rho_f(t) = \rho_f^0 \exp(\mu_0^f t) > \rho_c^{CDM}$ at all times

$$f_f \exp(\mu_0^f t) < 1. \quad (5)$$

We note that the above estimate of the cosmological constraint is rather conservative. Given the consistency between the DM density measured at the early times and that measured at the late times (Lin et al. 2021; Aghanim et al. 2020; Scolnic et al. 2018), we expect the detailed cosmological constraint is stronger than our estimate. But, our estimate suffices for the goal of this work. This is because, as we shall see, the allowed $f_f$ 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 fêtons predominantly decay into the three active neutrinos with a rate given by (Lin et al. 2022)

$$\Gamma_f \rightarrow \nu \bar{\nu} = \frac{g_{B-L}^2}{8\pi} m_f. \quad (6)$$

The fêton lifetime is then $\frac{1}{\Gamma_f} = \Gamma_f \rightarrow \nu \bar{\nu} + \Gamma_f \rightarrow e^- e^+$. The light blue regions in Figure 1 show the cosmologically viable parameter space for cases with different $m_f$'s. This region shrinks as $m_f$ increases, which can be seen from the left to the right panels.

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 the leptogenesis. Since $m_f = 2g_{B-L}V_{B-L}$, the range of $g_{B-L}$ corresponding to $V_{B-L} = 10^{12} - 10^{16}$ GeV changes with $m_f$. For each panel in Figure 1 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 that to the right.

Combining the above three constraints, the viable parameters are shown by the thick portions of the dashed
lines in Figure 1. In the left panel, we show some examples for $\Delta m \ll m_e$. In this case, as already discussed, $f_I$ decreases as $m_I$ 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. The f´eeton fraction is found to be $f_I \sim 10^{-9} - 10^{-5}$.

In the middle and the right panels of Figure 1, we show two examples of $\Delta m \gtrsim m_e$ where the effects from an increasing $m_I$ are opposite to the case when $\Delta m \ll m_e$. The value of $f_I$ is now insensitive to $m_I$ because the predicted flux becomes insensitive to $m_I$. So, the dashed lines in these two panels are essentially the same. However, the range of $g_{B-L}$ shrinks as $m_I$ increases. As a consequence, there is no more viable parameter space for $m_I \gtrsim 6$ MeV; see the right panel.

Interestingly, releasing the f´eeton fraction $f_I$ as a free parameter does not drastically change the upper limit of the f´eeton mass compared to that found in Lin et al. (2022). In fact, the bound on $m_I$ is very robust against the value of $f_I$ as long as the f´eeton contributes some amount of DM today. For example, even if $f_I$ is as low as $10^{-20}$, the upper limit of $m_I$ is only slightly changed to $m_I \lesssim 7$ MeV.

3.2. The upper limit of the positron injection energy and the $B-L$ breaking scale

From the above analyses, we derive two important implications if the f´eeton DM is the source of the Galactic 511 keV emission anomaly.

1. Given the upper limit of the f´eeton mass $m_I \lesssim 6$ MeV, the model predicts the positron injection energy to be $\lesssim 3$ MeV. This is consistent with observations (Beacom & Yuksel 2006; Sizun et al. 2006). 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 (Prantzos et al. 2011).

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 Figure 1. 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 (Buchmuller & Yanagida 1999; Buchmuller et al. 2005). We further remark on the significance of such a range of $V_{B-L}$ below.

Such a high energy scale of $V_{B-L}$ is difficult to reach with the current and near-future particle colliders. It is then important to investigate tests with other indirect astrophysical phenomenology. It is pointed out in Lin et al. (2022) that the detection of neutrinos from f´eeton decays would be a smoking gun for the f´eeton DM as well as the $B-L$ symmetry extension to SM. For the scenario considered in this work, however, the f´eeton fraction in DM is so small that it is not realistic in the near future to detect such a neutrino signal.

Alternatively, one can study the f´eeton 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 some energy scales under other phenomenological considerations in the early universe.

First, if the $B-L$ symmetry is broken during inflation, the f´eeton DM as a vector boson can be produced during inflation without violating the constraint from the non-detection of isocurvature perturbations (Graham et al. 2016). The viable parameter space here permits a self consistency for such an inflationary production: if produced during inflation, the f´eeton fraction $f_I$ is related to the f´eeton mass $m_I$ and the inflation scale $H_{\text{inf}}$ by $f_I = \left( \frac{m_I}{6 \times 10^{-9} \text{keV}} \right)^{1/2} \left( \frac{H_{\text{inf}}}{10^{14} \text{GeV}} \right)^2$ (Graham et al. 2016). Taking $f_I \lesssim 10^{-3}$ and $m_I \simeq 1$ MeV, we obtain an inflation scale of $H_{\text{inf}} \lesssim 5 \times 10^6$ GeV. This is in turn consistent with the condition that the $B-L$ symmetry is broken during inflation, because $H_{\text{inf}} < V_{B-L}$. In addition, the string axion DM can be accommodated as the major DM component, since the inferred inflation scale satisfies the constraint from the non-detection of the isocurvature perturbation; see Eq. (6) in Kawasaki et al. (2016).

Further, on top of the above inflationary production, if the quartic coefficient ($\lambda$) of the scalar field ($\phi$) 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 restore after reheating and be broken again as the temperature cools down. Cosmic string loops can form due to such a phase transition after reheating (Kibble 1976). Those cosmic strings emit GWs as they shrink and lose energy (Vachaspati & Vilenkin 1985), which may explain the recently reported detection of a stochastic GW background by NANOGrav (Blasi et al. 2021; Ellis & Lewicki 2021). 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 Blasi et al. (2021). This scenario can be further tested with future GW experiments such as SKA (Janssen et al. 2015) and LISA (Bartolo et al. 2016).

\textsuperscript{5} In the left panel, we only show the $m_I = 1$ MeV case for the light blue region and the vertical line, but the effect of $\Delta m$ can be seen by the slightly shrinking thick dashed lines as $\Delta m$ increases.
We leave the full exploration of the féeton DM production mechanism(s) along with the early-universe phenomenology in a future work.

3.3. Remarks on the flux morphology

The morphology of the Galactic 511 keV emission has been difficult to explain with all astrophysical or DM sources (Prantzos et al. 2011). Such an emission is concentrated towards GC, which can be roughly presented by a high value of bulge-to-disk flux ratio B/D. Based on the earlier data from INTEGRAL/SPI with B/D ≈ 1.5 (Knodlseder et al. 2005), it was found that decaying DM scenarios are disfavored unless the inner DM density increases towards the center very sharply (Ascasibar et al. 2006). A similar conclusion was obtained in Skinner et al. (2015) where it was found that the positron production rate is proportional to the DM density squared. This morphology problem to decaying dark matter scenarios (and to the traditional astrophysical explanations in general) is alleviated with the new data as the B/D has reduced to 0.58 ± 0.13 (Siegert et al. 2016). The flux morphology in the decaying DM scenarios is solely described by the function $\bar{D}_N(\cos \theta)$. We estimate the B/D for decaying DM scenarios by taking (the mean values of) the extents of the bulge and the disk derived in Siegert et al. (2016), which is summarized in Table 1. We obtain B/D ≈ 0.31, which is still about a factor of 2 (and $\sim 2$-$\sigma$) smaller than the derived value from observations (Siegert et al. 2016). Therefore, decaying DM scenarios is still in mild tension with the new data.

It is however too early to exclude decaying DM scenarios based on the currently measured morphology of the flux for two reasons. (1) Given some uncertainties of the positron transportation in the interstellar median (Prantzos et al. 2011), the assumption that positrons annihilate closely to their production sites may not be satisfied in the disk area. Some positrons may have escaped from the disk, reducing the annihilation flux from there 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 Skinner et al. (2015); Siegert et al. (2016); Kierans et al. (2020). 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 féeton model parameters as we did in Sec. 3.1.

4. CONCLUSION

The unresolved nature of the Galactic 511 keV emission could point to new physics beyond SM. In this work, we have explored a scenario that the decay of the féeton DM into electron-positron pairs sources such an emission. We consistently consider the model parameter space that is theoretically motivated from the seesaw mechanism, viable with cosmology and accounting for the Galactic 511 keV bulge emission. We find that the resultant model successfully accounts for the positron injection energy and has an important prediction on the physics of the $B - L$ symmetry.

We find that, while the féton fraction is released as a free parameter, its mass is bounded to $\lesssim 6$ MeV by the cosmological constraint and the scale of the $B - L$ symmetry breaking. This bound is very robust against the féton fraction in the DM amounts. The féton if found to constitute only a small fraction of the DM amount ($f_{\ell} \sim 10^{-9} - 10^{-5}$).

As a result, the injection energy of the positrons from the féton decay is bounded to $\lesssim 3$ MeV, which coincides with the current observational constraint. So far, no other DM sources but the féton DM is able to predict such a limit of the injection energy.

The model has a nontrivial implication on the $B - L$ 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 the GUT-scale seesaw mechanism. The range of $V_{B-L}$ permits a self-consistent inflationary production of the féton DM and accommodates the possibility that the cosmic strings generated by the gauge $U(1)_{B-L}$ breaking after reheating explain the stochastic GW background detected by NANOGrav.

One caveat is that we assume 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 argue that the tension may be alleviated or even eliminated with further studies of the transportation of positrons in the interstellar median 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 (Okada et al. 2020). However, as long as the féton decay into neutrinos is not suppressed, our conclusions are not significantly changed.

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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.
REFERENCES

Aghanim, N., et al. 2020, Astron. Astrophys., 641, A6, doi: 10.1051/0004-6361/201833910

Aguilar-Arevalo, A., et al. 2019, Phys. Rev. Lett., 123, 181802, doi: 10.1103/PhysRevLett.123.181802

Ascasibar, Y., Jean, P., Boehm, C., & Knödlseder, J. 2006, Monthly Notices of the Royal Astronomical Society, 368, 1695, doi: 10.1111/j.1365-2966.2006.10226.x

Bartolo, N., et al. 2016, JCAP, 12, 026, doi: 10.1088/1475-7516/2016/12/026

Beacom, J. F., & Yuksel, H. 2006, Phys. Rev. Lett., 97, 071102, doi: 10.1103/PhysRevLett.97.071102

Blasi, S., Brdar, V., & Schmitz, K. 2021, Phys. Rev. Lett., 126, 041305, doi: 10.1103/PhysRevLett.126.041305

Boehm, C., Hooper, D., Silk, J., Casse, M., & Paul, J. 2004, Phys. Rev. Lett., 92, 101301, doi: 10.1103/PhysRevLett.92.101301

Bouchet, L., Roques, J. P., & Jourdain, E. 2010, ApJ, 720, 1772, doi: 10.1088/0004-637X/720/2/1772

Buchmuller, W., Peccei, R. D., & Yanagida, T. 2005, Ann. Rev. Nucl. Part. Sci., 55, 311, doi: 10.1146/annurev.nucl.55.090704.151558

Buchmuller, W., & Yanagida, T. 1999, Phys. Lett. B, 445, 399, doi: 10.1016/S0370-2693(98)01480-4

Choi, G., Yanagida, T. T., & Yokozaki, N. 2020, Phys. Lett. B, 810, 135836, doi: 10.1016/j.physletb.2020.135836 — 2021, JHEP, 01, 057, doi: 10.1007/JHEP01(2021)057

Ellis, J., & Lewicki, M. 2021, Phys. Rev. Lett., 126, 041304, doi: 10.1103/PhysRevLett.126.041304

Fabbrichesi, M., Gabrielli, E., & Lanfranchi, G. 2020, The Physics of the Dark Photon: A primer (Cham, Switzerland: Springer), doi: 10.1007/978-3-030-62519-1

Fayet, P., Hooper, D., & Sigl, G. 2006, Phys. Rev. Lett., 96, 211302, doi: 10.1103/PhysRevLett.96.211302

Fukugita, M., & Yanagida, T. 1986, Phys. Lett. B, 174, 45, doi: 10.1016/0370-2693(86)91126-3

Gell-Mann, M., Ramond, P., & Slansky, R. 1979, Conf. Proc., C7900927, 315, https://arxiv.org/abs/1306.4669

Graham, P. W., Mardon, J., & Rajendran, S. 2016, Phys. Rev. D, 93, 103520, doi: 10.1103/PhysRevD.93.103520

Gunion, J. F., Hooper, D., & McElrath, B. 2006, Phys. Rev. D, 73, 015011, doi: 10.1103/PhysRevD.73.015011

Hall, L. J., & Nomura, Y. 2003, Annals Phys., 306, 132, doi: 10.1016/S0003-4916(03)00077-0

Harris, M. J., Teegarden, B. J., Cline, T. L., et al. 1998, Astrophys. J. Lett., 501, L55, doi: 10.1086/311429

Haymes, R. C., Walraven, G. D., Meegan, C. A., et al. 1975, ApJ, 201, 593, doi: 10.1086/153925

Hooper, D., & Wang, L.-T. 2004, Phys. Rev. D, 70, 063506, doi: 10.1103/PhysRevD.70.063506

Janssen, G., et al. 2015, PoS, AASKA14, 037, doi: 10.22323/1.215.0037

Jean, P., Knödlseder, J., Gillard, W., et al. 2006, Astron. Astrophys., 445, 579, doi: 10.1051/0004-6361:20053765

Johnson, W. N., I., Harnden, F. R., J., & Haymes, R. C. 1972, ApJL, 172, L1, doi: 10.1086/180878

Kawasaki, M., Yanagida, T. T., & Yokozaki, N. 2016, Phys. Lett. B, 753, 389, doi: 10.1016/j.physletb.2015.12.043

Kibble, T. W. B. 1976, J. Phys. A, 9, 1387, doi: 10.1088/0305-4470/9/8/029

Kierans, C. A., et al. 2020, Astrophys. J., 895, 44, doi: 10.3847/1538-4357/ab89a9

Knapen, S., Lin, T., & Zurek, K. M. 2017, Phys. Rev. D, 96, 115021, doi: 10.1103/PhysRevD.96.115021

Knödlseder, J., et al. 2005, Astron. Astrophys., 441, 513, doi: 10.1051/0004-6361:20042063

Lees, J. P., et al. 2017, Phys. Rev. Lett., 119, 131804, doi: 10.1103/PhysRevLett.119.131804

Leventhal, M., MacCallum, C. J., & Stang, P. D. 1978, ApJL, 225, L11, doi: 10.1086/182782

Lin, W., Chen, X., & Mack, K. J. 2021, Astrophys. J., 920, 159, doi: 10.3847/1538-4357/ac12cf

Lin, W., Visinelli, L., Xu, D., & Yanagida, T. T. 2022. https://arxiv.org/abs/2202.04496

Minkowski, P. 1977, Phys. Lett., 67B, 421, doi: 10.1016/0370-2693(77)90435-X

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, Astrophys. J., 462, 563, doi: 10.1086/171713

Nesti, F., & Salucci, P. 2013, JCAP, 07, 016, doi: 10.1088/1475-7516/2013/07/016

Okada, N., Okada, S., Raut, D., & Shafi, Q. 2020, Phys. Lett. B, 810, 135785, doi: 10.1016/j.physletb.2020.135785
Picciotto, C., & Pospelov, M. 2005, Phys. Lett. B, 605, 15, doi: 10.1016/j.physletb.2004.11.025
Prantzos, N., et al. 2011, Rev. Mod. Phys., 83, 1001, doi: 10.1103/RevModPhys.83.1001
Scolnic, D. M., et al. 2018, Astrophys. J., 859, 101, doi: 10.3847/1538-4357/aab9bb
Siegert, T., Diehl, R., Khachatryan, G., et al. 2016, Astron. Astrophys., 586, A84, doi: 10.1051/0004-6361/201527510
Sizun, P., Casse, M., & Schanne, S. 2006, Phys. Rev. D, 74, 063514, doi: 10.1103/PhysRevD.74.063514
Skinner, G., Diehl, R., Zhang, X.-L., Bouchet, L., & Jean, P. 2015, in Proceedings of 10th INTEGRAL Workshop: A Synergistic View of the High-Energy Sky — PoS(Integral2014), Vol. 228, 054, doi: 10.22323/1.228.0054
Takahashi, F., & Yanagida, T. T. 2006, Phys. Lett. B, 635, 57, doi: 10.1016/j.physletb.2006.02.026
Vachaspati, T., & Vilenkin, A. 1985, Phys. Rev. D, 31, 3052, doi: 10.1103/PhysRevD.31.3052
Wilczek, F. 1979, Proceedings: Lepton-Photon Conference (Fermilab, Aug 1979) Conf. Proc., C790885
Yanagida, T. 1979a, Proceedings: Workshop on the Unified Theories and the Baryon Number in the Universe: KEK, Japan, February 13-14, 1979, Conf. Proc., C7902131, 95 —. 1979b, Phys. Rev. D, 20, 2986, doi: 10.1103/PhysRevD.20.2986