

Constraining gravitational dark matter with LHAASO and Fermi-LAT

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We use diffuse Galactic high energy gamma ray data from LHAASO and Fermi-LAT to constrain gravitationally produced decaying dark matter (DM). Focusing on four benchmark candidates: a dark photon, a heavy right-handed neutrino (RHN), a pseudo-Nambu-Goldstone boson (pNGB), and a nonminimally coupled scalar we derive bounds on the DM mass and its couplings to the visible sector. For dark photons, RHNs, and pNGBs, the combined data constrain the effective interaction strength to $\lesssim \mathcal{O}(10^{-30})$ for DM masses $\gtrsim \mathcal{O}(\text{TeV})$. For the nonminimally coupled scalar, this interaction strength is limited to $\lesssim \mathcal{O}(10^{-10})$, for the same DM mass range. Moreover, photon-dark photon oscillations yield strong constraints for massive dark photon beyond 10 GeV, closing a region of parameter space previously left unconstrained.

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I. INTRODUCTION

Among the four fundamental forces, gravity is by far the weakest. Yet it possesses a unique universality: it couples indiscriminately to all forms of energy and matter known to exist. This makes gravity the most natural mediator between dark matter (DM), which accounts for roughly 24% of the total matter-energy content of the Universe [1], and the visible sector described by the Standard Model (SM). Although gravitational interactions are Planck-suppressed, DM can still be efficiently produced at very high temperatures, most notably during reheating, realizing the UV freeze-in mechanism [2,3]. If no exact symmetry enforces cosmological stability, such DM may decay into SM final states demanded by the underlying particle physics model, which may also address open questions such as neutrino mass generation. A particularly intriguing aspect, relevant for the present work, is that the DM mass range naturally associated with gravitational production

may contribute to the diffuse Galactic gamma (γ)-ray flux observed by telescopes such as LHAASO [4,5] and Fermi-LAT [6,7]. For high-energy diffuse Galactic γ -ray observations, LHAASO, through its SKA and WCDA arrays, has provided unprecedented measurements from the TeV to PeV range [5], while Fermi-LAT has mapped the corresponding GeV to TeV emission [6], covering both the inner ($15^\circ < l < 125^\circ$, $|b| < 5^\circ$) and outer ($125^\circ < l < 235^\circ$, $|b| < 5^\circ$) Galactic plane regions [4,6].

In this paper, we explore several well-motivated scenarios, rooted in particle physics, gravity, and cosmology, in which DM is produced through minimal or nonminimal gravitational interactions in the light of observed high energy Galactic γ -rays by LHAASO [4] and Fermi-LAT [6]. Specifically, we have four horsemen of DM candidates: the dark photon, the right-handed neutrino (RHN), a massive pseudo-Nambu-Goldstone boson (pNGB), and a nonminimally coupled scalar singlet, respectively. Following their gravitational production, these DM species can decay into visible particles, with the decay channels determined by the structure of their interactions with the visible sector. The decay of these DM candidates into photons contributes to the Galactic diffuse γ -ray emission. Using LHAASO and Fermi-LAT data, we constrain the resulting γ -ray fluxes, which in turn provides bound on the corresponding DM decay rates or their interaction strengths with the SM. Remarkably, the combined constraints from LHAASO and Fermi-LAT probe regions of parameter space characterized by extremely

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feeble couplings $\lesssim \mathcal{O}(10^{-30})$, depending on the underlying particle physics model and very heavy DM [8,9], domains those have hitherto remained largely unexplored within these theoretical frameworks. We also derive limits on photon-dark photon oscillations induced by kinetic mixing, that surpass existing bounds for dark photon masses above ~ 10 GeV.

II. FRAMEWORKS

We now turn to scenarios in which particle DM is produced gravitationally—either through massless-graviton mediation or via a nonminimal gravity portal. Once produced, such DM can subsequently decay into photons, either directly or through intermediate states, depending on the underlying particle-physics model manifesting the DM metastable. This leads to a key constraint on its lifetime, namely $\tau_{\text{DM}} > \tau_U \simeq 10^{17}$ s, where τ_U denotes the age of the Universe. In the following, we discuss each scenario in detail.

- (1) *Gravity portal to decaying DM*: Minimal gravity-mediated production of DM from the radiation bath in the early Universe is an unavoidable irreducible process. Such gravitational production of frozen in DM has been studied in, e.g., Refs. [10–17]. The relevant Lagrangian in this case,

$$\mathcal{L} \supset -\frac{1}{M_P} h_{\mu\nu} T^{\mu\nu}, \quad (1)$$

where $h_{\mu\nu}$ is the massless spin-2 graviton and $T^{\mu\nu}$ is the energy-momentum tensor, that depends on the spin of the DM. The interaction rate density for a 2-to-2 DM production process reads $\gamma(T) = kT^8/M_P^4$ [11,18], where $k \simeq 2.9 \times 10^{-3}$ (spin-0), $k \simeq 3.4 \times 10^{-2}$ (spin-1/2 Majorana) or $k \simeq 7.3 \times 10^{-2}$ (spin-1), considering $T \gg m_{\text{dm}}$ [19–21]. In order to follow the evolution of the DM number density n_{DM} , we express the Boltzmann equation in terms of the DM yield $Y_{\text{DM}} \equiv n_{\text{DM}}/\mathfrak{s}$ as,

$$x\mathcal{H}\mathfrak{s} \frac{dY_{\text{DM}}}{dx} = \gamma(T), \quad (2)$$

where $x \equiv m_{\text{DM}}/T$ is a dimensionless variable with T the bath temperature. For a radiation-dominated Universe, the entropy density $\mathfrak{s}(T)$ and the Hubble rate $H(T)$ are given by

$$\mathfrak{s}(T) = \frac{2\pi^2}{45} g_{\star s}(T) T^3, \quad \mathcal{H}(T) = \frac{\pi}{3} \sqrt{\frac{g_{\star}(T)}{10}} \frac{T^2}{M_P}, \quad (3)$$

where $g_{\star s}(T)$ and $g_{\star}(T)$ denote the effective relativistic degrees of freedom associated with entropy and energy densities, respectively and M_P is the reduced Planck mass. To account for the observed relic abundance, the present-day DM yield must

satisfy $Y_0 m_{\text{DM}} = \Omega h^2 \frac{1}{\mathfrak{s}_0 h^2} \simeq 4.3 \times 10^{-10}$ GeV where $Y_0 \equiv Y_{\text{DM}}(T_0)$ is DM yield at present epoch, $\rho_c \simeq 1.05 \times 10^{-5} h^2$ GeV/cm³ is the critical energy density, $\mathfrak{s}_0 \simeq 2.69 \times 10^3$ cm⁻³ the present entropy density [1] and $\Omega h^2 \simeq 0.12$ the measured DM relic density [1]. Solving Eq. (2), one can analytically obtain the asymptotic yield,

$$Y_0 \simeq \frac{45k}{2\pi^3 g_{\star s}} \sqrt{\frac{10}{g_{\star}}} \left(\frac{T_{\text{rh}}}{M_P} \right)^3, \quad (4)$$

leading to reheating temperature

$$T_{\text{rh}} \simeq \left(\frac{1 \text{ PeV}}{m_{\text{dm}}} \right)^{1/3} \begin{cases} 9.4 \times 10^{14} \text{ GeV} & \text{spin-0,} \\ 5.3 \times 10^{14} \text{ GeV} & \text{spin-1/2,} \\ 3.2 \times 10^{14} \text{ GeV} & \text{spin-1,} \end{cases} \quad (5)$$

in order to satisfy the right DM abundance. These DM, once produced, could undergo decay into photonic final states, depending on the following well-known benchmark scenarios:

- (a) *Decaying dark photon via kinetic mixing*: An extended gauge sector containing two $U(1)$ symmetries, one associated with the visible sector and the other with a dark sector composed of SM gauge singlets. These two sectors can interact via a kinetic mixing portal [22], which gives rise to the interaction Lagrangian

$$\mathcal{L} \supset -\frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} F^{\mu\nu} X_{\mu\nu} - \frac{1}{2} m_X^2 X_\mu X^\mu, \quad (6)$$

where, $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ and $X^{\mu\nu} = \partial^\mu X^\nu - \partial^\nu X^\mu$ are the field-strength tensors of the SM and dark $U(1)$ gauge fields, A^μ and X^μ , respectively. Diagonalizing Eq. (6) one arrives at an interaction Lagrangian,

$$\mathcal{L} \supset -\frac{e\epsilon}{\sqrt{1-\epsilon^2}} J_\mu X^\mu + e J_\mu A^\mu. \quad (7)$$

The dark photon then can decay into the visible sector with decay rates [23]

$$\Gamma_X = \begin{cases} \frac{N_c Q_f^2 \alpha_{\text{EM}} \epsilon^2}{3} m_X \sqrt{1 - \frac{4m_\ell^2}{m_X^2}} \left(1 + \frac{2m_\ell^2}{m_X^2} \right), & f\bar{f} \\ \frac{\mathbb{R} \alpha_{\text{EM}} \epsilon^2}{3} m_X \sqrt{1 - \frac{4m_\mu^2}{m_X^2}} \left(1 + \frac{2m_\mu^2}{m_X^2} \right), & \text{hadron,} \end{cases} \quad (8)$$

where $N_c = 1(3)$ for leptons (quarks), Q_f is the corresponding fermionic electromagnetic (EM) charge and $\mathbb{R} \equiv \frac{\sigma(e^+e^- \rightarrow \text{had})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ is the EM spectral function ratio.

- (b) *Photon-dark photon oscillation*: Dark photons can oscillate into SM photons through kinetic mixing, presented in Eq. (6).¹ A fraction of dark photon can get converted into photons with flux,

$$\Phi_\gamma(\omega) = \Phi_X(\omega) \cdot P_{X \rightarrow \gamma}, \quad (9)$$

where the conversion probability $P_{X \rightarrow \gamma} \propto \varepsilon^2$ (see Appendix A for details), for GeV-PeV scale dark photons and Φ_X is the integrated dark photon flux.

- (c) *Decaying Majorana DM*: The minimal $U(1)_X$ extension framework, that addresses both neutrino masses and DM. The three SM gauge singlet right-handed neutrinos (RHN), responsible for light neutrino masses via the seesaw mechanism after $U(1)_X$ and electroweak symmetry breaking (EWSB), also ensures complete cancellation of the gauge anomaly. Details of the anomaly-free $U(1)_X$ construction and neutrino-mass generation can be found in [25,26]. Partial decay widths of the heavy RHNs are given by,

$$\Gamma_{N_\beta} \simeq \begin{cases} \frac{|Y_{\nu\alpha\beta}^{\text{NH(IH)}}|^2}{32\pi} M_{N_\beta}, & W\ell_\alpha \\ \frac{|Y_{\nu\alpha\beta}^{\text{NH(IH)}}|^2}{64\pi} M_{N_\beta}, & Z\nu_\alpha, \end{cases} \quad (10)$$

while its radiative decay rate for $M_N \gg m_W$ reads,

$$\Gamma_{N_\beta \rightarrow \nu_\alpha \gamma} \simeq M_{N_\beta} \frac{\alpha_{\text{EM}} |Y_{\nu\alpha\beta}^{\text{NH(IH)}}|^2}{256\pi^6} \left(\frac{m_\mu}{v}\right)^2, \quad (11)$$

where $m_{W(\mu)}$ is the W boson (muon) mass in SM.

Depending on the normal hierarchy (NH) or inverted hierarchy (IH) scenario, it is possible to consider N_1 or N_3 to be the viable DM candidate.

- (2) *Massive pNGB DM*: We consider an effective field theory describing the interactions of a gauge-singlet pseudoscalar resonance φ with the electroweak (EW) gauge bosons of the SM. Using the interactions described in the Appendix B, the partial decay rates are computed as,

$$\Gamma_\varphi = \begin{cases} \frac{1}{2} \left(\frac{C_{\gamma\gamma}}{f_\varphi}\right)^2 \frac{\alpha^2 m_\varphi^3}{32\pi^3}, & \gamma\gamma \\ \left(\frac{C_{\gamma Z}}{f_\varphi}\right)^2 \frac{\alpha^2 m_\varphi^3}{32\pi^3} \left[1 - \left(\frac{m_Z}{m_\varphi}\right)^2\right]^3, & Z\gamma \\ \frac{1}{2} \left(\frac{C_{ZZ}}{f_\varphi}\right)^2 \frac{\alpha^2 m_\varphi^3}{32\pi^3} \left[1 - \left(\frac{2m_Z}{m_\varphi}\right)^2\right]^{3/2}, & ZZ \\ \left(\frac{C_{WW}}{f_\varphi}\right)^2 \frac{\alpha^2 m_\varphi^3}{32s_W^4\pi^3} \left[1 - \left(\frac{2m_W}{m_\varphi}\right)^2\right]^{3/2}, & WW \end{cases} \quad (12)$$

where $m_{Z,W}$ denotes the $Z(W)$ boson mass.

¹In [24], LHAASO bounds has been utilized to constrain graviton energy via graviton-to-photon conversion.

- (3) *Gravity induced DM decay*: We consider a SM gauge singlet scalar DM S nonminimally coupled to the Ricci scalar $\mathcal{R}$ via a linear coupling of the form $\xi M_P S \mathcal{R}$, where ξ is the strength of the nonminimal interaction. The relevant action in the Jordan frame in this case reads,

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[-\frac{1}{4} g^{\mu\nu} g^{\lambda\rho} \mathcal{V}_{\mu\lambda}^{(a)} \mathcal{V}_{\nu\rho}^{(a)} + \frac{1}{\omega^2} (\mathcal{L}_Y - V(H)) + \frac{1}{\omega} |D_\mu H|^2 + \frac{i}{\omega^{3/2}} \bar{f} \not{\partial} f + \frac{3i}{\omega^2} \bar{f} (\not{\partial} \omega) f \right], \quad (13)$$

using the conformal transformation $\tilde{g}_{\mu\nu} = \omega^{-1} g_{\mu\nu}$ where $\omega \simeq 1 + (\xi/M_P) \tilde{S}$, with $\tilde{S} = S(1 + \frac{\xi}{4} \frac{S}{M_P})$. Clearly, the DM S can decay into all possible SM final states following Eq. (13). These decay channels are purely gravity induced for $\xi \rightarrow 0$ ensuring the absolute stability of the DM. Hence we obtain the following Planck-suppressed two-body decay rates for the DM,

$$\Gamma_S = \frac{\xi^2 m_S^3}{32\pi M_P^2} \begin{cases} \left[1 - 4\left(\frac{m_h}{m_S}\right)^2\right]^{1/2}, & hh \\ N_c \left(\frac{m_f}{m_S}\right)^2 \left[1 - 4\left(\frac{m_f}{m_S}\right)^2\right]^{3/2}, & ff \\ \frac{1}{4} \sqrt{1 - 4\left(\frac{m_V}{m_S}\right)^2} \times F(m_V, m_S), & \mathcal{V}\mathcal{V}, \end{cases} \quad (14)$$

where, $F(m_V, m_S) = 1 - 4(m_V/m_S)^2 + 12(m_V/m_S)^4$ and $\mathcal{V} \in Z, W^\pm$. Due to nonminimal interaction, the DM can be produced from the bath with a reaction rate that we parametrize as, $\gamma_S \equiv \xi^4 T^8 / M_P^4$. Using Eq. (4) we obtain the upper bound

$$|\xi| \lesssim 1.3 (1 \text{ TeV}/m_{\text{DM}})^{1/4} (10^{15} \text{ GeV}/T_{\text{th}})^{3/4}, \quad (15)$$

to avoid DM overabundance.

III. RESULTS AND DISCUSSIONS

To compute the γ -ray flux in our scenarios, we adopt the Navarro-Frenk-White (NFW) density profile for the Milky Way halo [27–31],

$$\rho_{\text{DM}}(R_{\text{GC}}) = \frac{\rho_{\text{C}}}{(R_{\text{GC}}/R_{\text{C}})(1 + R_{\text{GC}}/R_{\text{C}})^2}, \quad (16)$$

with $R_{\text{C}} = 11 \text{ kpc}$ and ρ_{C} is fixed by the local density $\rho_\odot = 0.43 \text{ GeV cm}^{-3}$. The differential flux from DM decay is

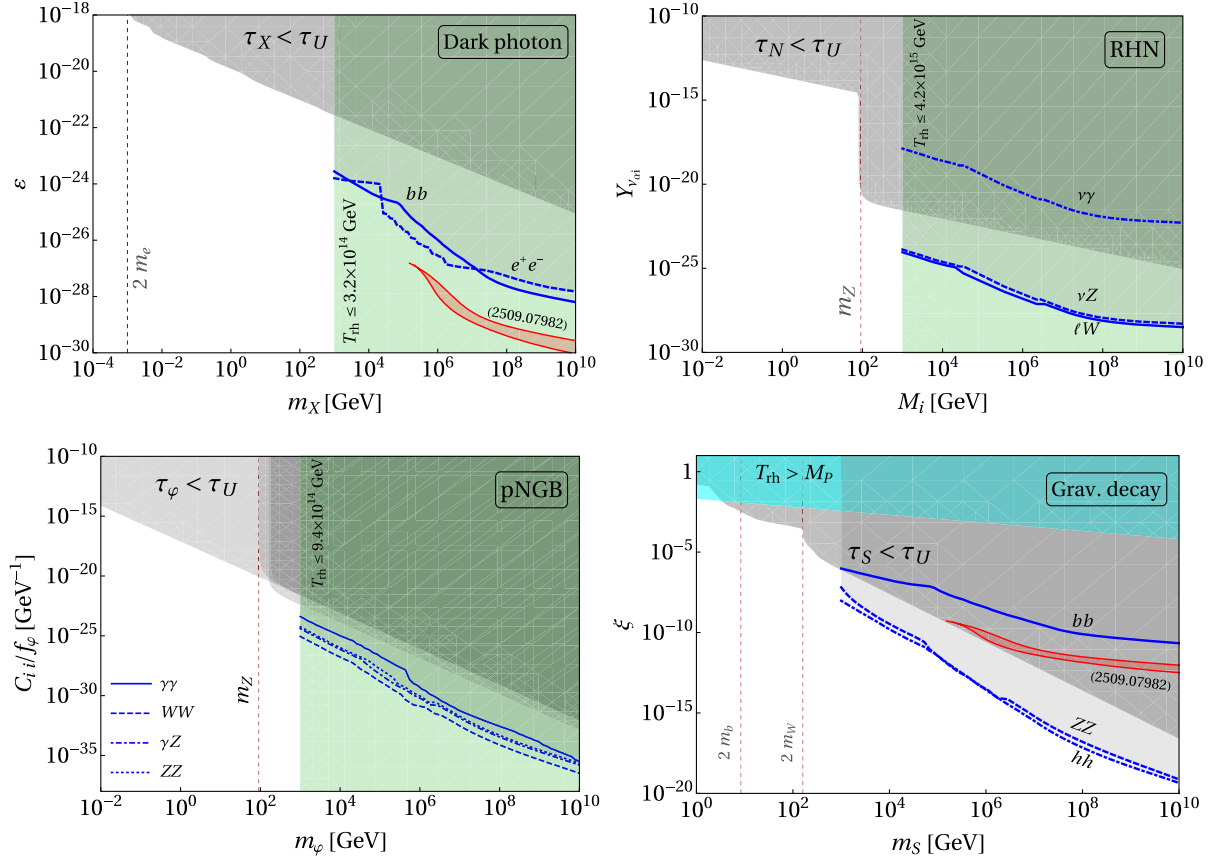


FIG. 1. Bounds on DM coupling and mass, depending on different benchmark scenarios. Within the gray shaded region the lifetime of the relevant DM species is below the lifetime of the Universe. The blue curves are obtained utilizing combined data from LHAASO and Fermi-LAT. Within the green shaded region right relic abundance is obtained. The cyan shaded region in the bottom right panel is forbidden from $T_{\text{rh}} > M_P$ [cf. Eq. (15)]. The red filled bands in the top left and bottom right panels are bounds extracted from Fig. 4 of Ref. [8], corresponding to 2-body decay of DM into $b\bar{b}$ final states (see text for details).

$$\phi_\gamma(E_\gamma) = \frac{\mathcal{D}}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN}{dE_\gamma}, \quad (17)$$

where

$$\mathcal{D} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_0^{s_{\text{max}}} ds \rho_{\text{DM}}(s, b, l), \quad (18)$$

where, $r = \sqrt{s^2 + R_\odot^2 + 2sR_\odot \cos b \cos l}$ with $R_\odot = 8.3$ kpc. For the inner Galactic plane, we obtain $\mathcal{D} \approx 3 \times 10^{19}$ GeV cm $^{-2}$. The photon spectrum dN/dE_γ is evaluated using HDMSpectra [32]. For dark photon-photon oscillations in Eq. (9), corresponding flux is, $\Phi_X = \mathcal{D}/(4\pi m_X \tau_U)$.

Constraints derived from the combined LHAASO and Fermi-LAT observations are presented in Fig. 1, shown via the blue curves in the coupling-mass plane for different DM decay channels. These bounds apply to feebly interacting DM with masses $\gtrsim 1$ TeV. In each case, we indicate the region of parameter space where $\tau_{\text{DM}} < \tau_U$. The vertical dashed lines mark the kinematic thresholds for decay into different final states in each case. For dark photon, RHN

and pNGB, we additionally highlight (in light green) the values of T_{rh} that yield the correct relic abundance for $m_{\text{dm}} \geq 1$ TeV. Achieving the correct abundance for heavier DM requires a lower reheating temperature [cf. Eq. (4)]. Consequently, the LHAASO + Fermi-LAT constraints are relevant for couplings corresponding to $T_{\text{rh}} \lesssim \{9.5 \times 10^{15}, 4.2 \times 10^{15}, 3.2 \times 10^{15}\}$ GeV for the dark photon, RHN and pNGB, respectively. Both the kinetic mixing parameter and the RHN Yukawa coupling are pushed down to values as small as $\mathcal{O}(10^{-26})$, for masses $\mathcal{O}(1$ PeV), depending on the decay channel. For the same DM mass, bounds on massive pNGB scenario requires $C_{ii}/f_\phi \lesssim 10^{-31}$ (GeV $^{-1}$) [i stands for different final states, following Eq. (12)] for ZZ final state. For the nonminimally coupled scenario, we obtain $\xi \lesssim \mathcal{O}(10^{-14})$ for DM mass $\gtrsim 1$ PeV, considering ZZ, hh final states. The cyan shaded region in the bottom right panel, derived from Eq. (15), is disallowed because of super-Planckian T_{rh} . For oscillation-driven photon-dark photon conversion we show bounds in Fig. 2, where LHAASO + Fermi-LAT data provide stringent limit, yielding $\epsilon \lesssim 10^{-3}$ for $m_X \gtrsim 10$ GeV

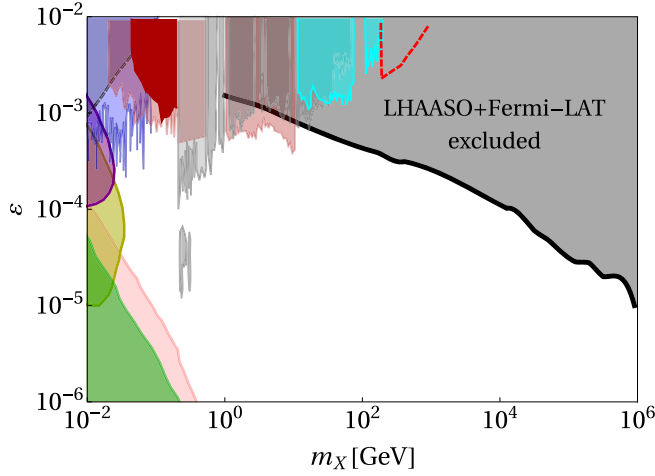


FIG. 2. Bounds on kinetic mixing parameter (ϵ) with respect to dark photon mass (m_X) from oscillation conversion. Combined bounds from LHAASO and Fermi-LAT are shown by the thick black solid line. We show existing limits from dilepton searches at low energy scattering, high energy collider and fixed target experiments: A1 [35] (darker red), LHCb [36] (gray), CMS [37] (cyan), BABAR [38] (lighter red), NA48/2 [39] (blue), as well as beam-dump experiments: E141 [40] (yellow), ν -Cal [41,42] (pink), CHARM [43] (green), and projected limit from HL-LHC [34] (red, dashed). Additional limits arises from the electron anomalous magnetic moment $(g-2)_e$ [44] (gray diagonal dashed line).

compared to those obtained from low energy scattering, high energy collider and fixed-target experiments [23,33]. Interestingly, high luminosity LHC (HL-LHC) [34] can potentially test part of this parameter space, as shown by the red dashed curve.

We compare our bounds with the latest constraints on DM lifetime derived in [8] using LHAASO data in a model-independent framework, assuming DM decays into two-body SM final states. These are shown in the top left and bottom right panel, corresponding to DM decay into $b\bar{b}$ final states. Note that, these constraints appear stronger than those obtained in our work. This is primarily due to the subtraction of the gamma-ray background arising from cosmic ray interactions. Although such background subtraction can lead to tighter constraints, it also introduces significant systematic uncertainties (as shown by the red band) associated with the modeling of cosmic ray interactions and diffuse gamma-ray emission. Since our primary objective is to place conservative bounds on the DM model parameters, we do not incorporate the effects of the cosmic ray induced gamma-ray background.

Before concluding this section, let us see whether the same interactions responsible for DM decay can also generate the observed DM abundance in the present framework. For the case of dark photon DM decaying through the kinetic-mixing portal, the corresponding inverse decay processes, e.g., $f\bar{f} \rightarrow X_\mu$, can populate the dark photon abundance in the early Universe. However,

requiring the correct relic abundance constrains the kinetic-mixing parameter to be extremely small, typically $\epsilon \lesssim \mathcal{O}(10^{-12})$, for dark photon masses in the range $m_X \in [10^{-2}, 10^2]$ GeV. As evident from the top-left panel of Fig. 1, such values of ϵ are incompatible with the lifetime bounds required for viable DM. A qualitatively similar conclusion also applies to the singlet Majorana DM scenario. On the other hand, dark photons and ALPs can naturally obtain the observed relic abundance through the misalignment mechanism [45–47]. In particular, for dark photons this mechanism can successfully account for the entire dark matter abundance over a wide mass range $m_X \in [10^{-17}, 10^{-5}]$ eV, while simultaneously remaining consistent with the DM lifetime constraints (see, e.g., [48,49]).

IV. CONCLUSIONS

We have shown that diffuse Galactic high-energy γ -ray observations from LHAASO, together with Fermi-LAT, can place meaningful constraints on the mass and couplings of decaying DM produced purely through gravitational interactions. We specifically focused on the diffuse emission from the inner Galactic plane. Additionally, we also looked into the constraints from the outer Galaxy and found to be similar to those from the inner Galaxy. It is worth noting that the constraints derived here depend mainly on the DM decay channels, while their (irreducible) gravitational origin provides insight into the maximum temperature at which the DM abundance was set, offering a window into early Universe cosmology. For the nonminimal coupling scenario, however, both the production as well as the decay rates are fixed by the gravitational interaction. Finally, it is worth mentioning that, for computing the constraints, we have ignored the contribution of conventional astrophysical sources such as supernova remnants and pulsars to the Galactic diffuse γ -ray flux. Including these conventional sources will result in lower γ -ray flux from DM decay, thereby leading to even stronger constraints than those presented in this work.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms

of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: PHOTON ↔ DARK PHOTON CONVERSION PROBABILITY

To compute the oscillation probability, we first perform a field redefinition that brings the kinetic terms into canonical form

$$\mathcal{A}^\mu \equiv \begin{pmatrix} A_a^\mu \\ A_s^\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\varepsilon & 1 \end{pmatrix} \begin{pmatrix} A^\mu \\ X^\mu \end{pmatrix}, \quad (\text{A1})$$

where A_a^μ and A_s^μ denote the active (photon) and sterile (dark photon) states, respectively. In the canonical basis, the Lagrangian becomes

$$\mathcal{L} \supset -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{s\mu\nu}F_s^{\mu\nu} + \frac{1}{2}\mathcal{A}_\mu^T \mathbb{M}^2 \mathcal{A}^\mu + \mathcal{O}(\varepsilon^2), \quad (\text{A2})$$

with the mass-squared matrix

$$\mathbb{M}^2 = \begin{pmatrix} m_{\text{eff}}^2 & \varepsilon m_X^2 \\ \varepsilon m_X^2 & m_X^2 \end{pmatrix}. \quad (\text{A3})$$

Here, the (1, 1) entry represents the effective mass of the photon induced by the medium, which vanishes for propagation in vacuum. To evaluate active-sterile oscillations, we follow the time evolution of the system by solving the corresponding Klein-Gordon equation

$$(\omega^2 - k^2 - \mathbb{M}^2)\tilde{\mathcal{A}}^\mu(\omega, k) = 0, \quad (\text{A4})$$

where $\tilde{\mathcal{A}}^\mu(\omega, k)$ denotes the field in Fourier space. In the relativistic limit, $\omega \simeq k \gg m_X, m_{\text{eff}}$, the system reduces to a linearized Schrödinger-like equation [50],

$$i\partial_z \mathcal{A}^\mu = \mathcal{H} \mathcal{A}^\mu, \quad (\text{A5})$$

with the Hamiltonian

$$\mathcal{H} = \begin{pmatrix} \omega + \Delta_{\text{pl}} & \varepsilon \Delta_X \\ \varepsilon \Delta_X & \omega + \varepsilon \Delta_X \end{pmatrix}, \quad (\text{A6})$$

where

$$\Delta_{\text{pl}} \equiv -\frac{m_{\text{eff}}^2}{2\omega}, \quad \Delta_X \equiv -\frac{m_X^2}{2\omega}. \quad (\text{A7})$$

To diagonalize the Hamiltonian, we introduce the rotation matrix

$$\mathcal{U} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}, \quad (\text{A8})$$

such that $\mathcal{H}_{\text{diag}} = \mathcal{U}^\dagger \mathcal{H} \mathcal{U}$, with the mixing angle: $\theta = \frac{1}{2} \arctan[\frac{2\varepsilon \Delta_X}{\Delta_{\text{pl}} - \Delta_X}]$. In this basis, the solution takes the form,

$$A_k^{\text{diag}}(z) = \exp \left[-i \int_{z_0}^z dz' \Theta_k(z') \right] A_k(z_0), \quad (\text{A9})$$

where the eigenvalues of $\mathcal{H}$ are

$$\lambda_k = \frac{1}{2} \left(2\omega + \Delta_{\text{pl}} + \Delta_X \pm \sqrt{4\varepsilon^2 \Delta_X^2 + (\Delta_{\text{pl}} - \Delta_X)^2} \right). \quad (\text{A10})$$

The z -dependence in these quantities arises from m_{eff} , which may be treated as approximately constant whenever it varies on scales much larger than k^{-1} [51,52]. Assuming the initial state at $z_0 = 0$ is a pure dark photon, the probability of detecting a SM photon after traveling a distance z is

$$P_{X \rightarrow \gamma} = |\langle A_a(z) | A_s(0) \rangle|^2 = \sin^2(2\theta) \sin^2 \left(\frac{z \Delta \lambda}{2} \right) \simeq \frac{4\varepsilon^2 \Delta_X^2}{(\Delta_X - \Delta_{\text{pl}})^2} \sin^2 \left[\frac{z}{2} (\Delta_X - \Delta_{\text{pl}}) \right] + \mathcal{O}(\varepsilon^3), \quad (\text{A11})$$

where,

$$\Delta \lambda = \sqrt{4\varepsilon^2 \Delta_X^2 + (\Delta_{\text{pl}} - \Delta_X)^2}. \quad (\text{A12})$$

At resonance, where $\Delta_{\text{pl}} = \Delta_X$, the conversion becomes maximal: $P_{X \rightarrow \gamma}^{\text{res}} = \sin^2(\frac{z \varepsilon m_X^2}{2\omega})$. In the interstellar medium the plasma frequency is $\omega_{\text{pl}} \sim 10^{-12}$ eV, implying an effective photon mass $m_{\text{eff}} = \omega_{\text{pl}} \ll m_X$. Under this condition, Eq. (A11) reduces to $P_{X \rightarrow \gamma} = 4\varepsilon^2 \sin^2(\frac{z m_X^2}{4\omega})$. For Galactic propagation distances, the oscillatory term averages to 1/2, yielding a constant conversion probability: $P_{X \rightarrow \gamma} = 2\varepsilon^2$.

APPENDIX B: PNGB EFT

Above the electroweak symmetry breaking (EWSB) scale, the pNGB Lagrangian reads,

$$\begin{aligned} \mathcal{L}_\phi \supset & \frac{1}{2} [(\partial\phi)^2 - m_\phi^2 \phi^2] + \left(\frac{g_1}{4\pi} \right)^2 C_{BB} \frac{\phi}{f_\phi} B_{\mu\nu} \tilde{B}^{\mu\nu} \\ & + \left(\frac{g_2}{4\pi} \right)^2 C_{WW} \frac{\phi}{f_\phi} W_{\mu\nu}^i \tilde{W}_i^{\mu\nu} + C_{GG} \frac{\alpha_s}{4\pi} \frac{\phi}{f_\phi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} \\ & + \left(\frac{g_1}{4\pi} \right) \left(\frac{g_2}{4\pi} \right) C_{BW} \frac{\phi}{f_\phi} B_{\mu\nu} \tilde{W}^{3\mu\nu}, \end{aligned} \quad (\text{B1})$$

where $W_{\mu\nu}^i$ and $B_{\mu\nu}$ denote the field-strength tensors of the $\text{SU}(2)_W$ and $\text{U}(1)_Y$ gauge groups before EWSB, and the corresponding dual field strengths are defined by $\tilde{W}^{i\mu\nu} = \epsilon^{\mu\nu\rho\sigma} W_{\rho\sigma}^i/2$ and $\tilde{B}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} B_{\rho\sigma}/2$. We point out that

pNGB couples with all of the SM fermions as well as with the SM Higgs [53–55]. Here f_φ is the pNGB decay constant that is related to the relevant new-physics scale by $\Lambda = 4\pi f_\varphi$ and C_{ii} 's are the Wilson coefficients. For simplicity, we are considering interactions only with the gauge bosons. These effective interactions may arise from integrating out heavy fermions charged under the electroweak group at one loop. Consequently, the coefficients are suppressed by loop factors of order $1/(4\pi)^2$. A commonly used choice rescales the parameters

$$\{C_{WW}, C_{BB}, C_{BW}\} \rightarrow \left\{ \left(\frac{g_2}{4\pi} \right)^2 C_{WW}, \left(\frac{g_1}{4\pi} \right)^2 C_{BB}, \frac{g_1 g_2}{(4\pi)^2} C_{BW} \right\}, \quad (\text{B2})$$

absorbing both gauge couplings and loop factors into the definitions of the Wilson coefficients. We adopt the normalization in Eq. (B1) throughout our analysis. Below the EWSB scale, interactions with the gauge boson mass eigenstates take the form

$$\mathcal{L}_\varphi \supset \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m_\varphi^2\varphi^2 + \frac{\alpha}{4\pi}\frac{\varphi}{f_\varphi} \left(C_{\gamma\gamma}F\tilde{F} + 2C_{\gamma Z}F\tilde{Z} + C_{ZZ}Z\tilde{Z} + \frac{2}{s_W^2}C_{WW}W^+\tilde{W}^- \right), \quad (\text{B3})$$

where the electroweak field strengths satisfy $F\tilde{Z} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}Z_{\rho\sigma}$ and $s(c)_W \equiv \sin(\cos)\theta_W \simeq 0.48(0.87)$ being the measures of weak mixing angle in the $\overline{\text{MS}}$ scheme [56]. The coefficient C_{WW} remains unchanged, while the remaining three couplings are,

$$C_{\gamma\gamma} \equiv C_{BB} + C_{WW} + C_{BW}, \quad (\text{B4})$$

$$C_{\gamma Z} \equiv C_{WW}\frac{c_W}{s_W} - C_{BB}\frac{s_W}{c_W} + \frac{1}{2}C_{BW}\left(\frac{c_W}{s_W} - \frac{s_W}{c_W}\right), \quad (\text{B5})$$

$$C_{ZZ} \equiv C_{WW}\frac{c_W^2}{s_W^2} + C_{BB}\frac{s_W^2}{c_W^2} - C_{BW}. \quad (\text{B6})$$

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- [1] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
 - [2] F. Elahi, C. Kolda, and J. Unwin, UltraViolet freeze-in, *J. High Energy Phys.* **03** (2015) 048.
 - [3] N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen, and V. Vaskonen, The dawn of FIMP dark matter: A review of models and constraints, *Int. J. Mod. Phys. A* **32**, 1730023 (2017).
 - [4] Z. Cao *et al.* (LHAASO Collaboration), Measurement of ultra-high-energy diffuse gamma-ray emission of the galactic plane from 10 TeV to 1 PeV with LHAASO-KM2A, *Phys. Rev. Lett.* **131**, 151001 (2023).
 - [5] Z. Cao *et al.* (LHAASO Collaboration), Measurement of very-high-energy diffuse gamma-ray emissions from the galactic plane with LHAASO-WCDA, *Phys. Rev. Lett.* **134**, 081002 (2025).
 - [6] R. Zhang, X. Huang, Z.-H. Xu, S. Zhao, and Q. Yuan, Galactic diffuse γ -ray emission from GeV to PeV energies in light of up-to-date cosmic-ray measurements, *Astrophys. J.* **957**, 43 (2023).
 - [7] W. B. Atwood *et al.* (Fermi-LAT Collaboration), The Large Area Telescope on the Fermi Gamma-ray space telescope mission, *Astrophys. J.* **697**, 1071 (2009).
 - [8] C. Boehm, R. Laha, and T. N. Maity, LHAASO galactic plane γ -rays strongly constrain heavy dark matter, *arXiv:2509.07982*.
 - [9] A. Dubey and A. K. Saha, Breaking dark: Hunting heavy decaying dark matter with Tibet AS $_\gamma$ and LHAASO-KM2A, *arXiv:2509.08039*.
 - [10] Y. Ema, R. Jinno, K. Mukaida, and K. Nakayama, Gravitational effects on inflaton decay, *J. Cosmol. Astropart. Phys.* **05** (2015) 038.
 - [11] M. Garny, M. Sandora, and M. S. Sloth, Planckian interacting massive particles as dark matter, *Phys. Rev. Lett.* **116**, 101302 (2016).
 - [12] Y. Tang and Y.-L. Wu, Pure gravitational dark matter, its mass and signatures, *Phys. Lett. B* **758**, 402 (2016).
 - [13] Y. Ema, R. Jinno, K. Mukaida, and K. Nakayama, Gravitational particle production in oscillating backgrounds and its cosmological implications, *Phys. Rev. D* **94**, 063517 (2016).
 - [14] M. Garny, A. Palessandro, M. Sandora, and M. S. Sloth, Theory and phenomenology of Planckian interacting massive particles as dark matter, *J. Cosmol. Astropart. Phys.* **02** (2018) 027.
 - [15] Y. Tang and Y.-L. Wu, On thermal gravitational contribution to particle production and dark matter, *Phys. Lett. B* **774**, 676 (2017).
 - [16] N. Bernal, M. Dutra, Y. Mambrini, K. Olive, M. Peloso, and M. Pierre, Spin-2 portal dark matter, *Phys. Rev. D* **97**, 115020 (2018).
 - [17] S. Clery, Y. Mambrini, K. A. Olive, and S. Verner, Gravitational portals in the early universe, *Phys. Rev. D* **105**, 075005 (2022).
 - [18] B. Barman and N. Bernal, Gravitational SIMPs, *J. Cosmol. Astropart. Phys.* **06** (2021) 011.
 - [19] S. Clery, Y. Mambrini, K. A. Olive, A. Shkerin, and S. Verner, Gravitational portals with nonminimal couplings, *Phys. Rev. D* **105**, 095042 (2022).

- [20] B. Barman, S. Cléry, R. T. Co, Y. Mambrini, and K. A. Olive, Gravity as a portal to reheating, leptogenesis and dark matter, *J. High Energy Phys.* **12** (2022) 072.
- [21] M. A. G. Garcia, K. Kaneta, W. Ke, Y. Mambrini, K. A. Olive, and S. Verner, The role of vectors in reheating, *J. Cosmol. Astropart. Phys.* **06** (2024) 014.
- [22] B. Holdom, Two U(1)'s and epsilon charge shifts, *Phys. Lett.* **166B**, 196 (1986).
- [23] M. Fabbrichesi, E. Gabrielli, and G. Lanfranchi, *The Physics of the Dark Photon* (Springer, Cham, 2021).
- [24] S. Ramazanov, R. Samanta, G. Trenkler, and F. R. Urban, Shimmering gravitons in the gamma-ray sky, *J. Cosmol. Astropart. Phys.* **06** (2023) 019.
- [25] B. Barman, A. Das, S. Jyoti Das, and M. Merchand, Hunting for heavy Z' with IceCube neutrinos and gravitational waves, *Phys. Rev. D* **112**, 035035 (2025).
- [26] B. Barman, A. Das, and P. Sarmah, What KM3-230213A event may tell us about the neutrino mass and dark matter, *Phys. Rev. D* **112**, 075014 (2025).
- [27] J. F. Navarro, C. S. Frenk, and S. D. M. White, A universal density profile from hierarchical clustering, *Astrophys. J.* **490**, 493 (1997).
- [28] J. F. Navarro, E. Hayashi, C. Power, A. Jenkins, C. S. Frenk, S. D. M. White, V. Springel, J. Stadel, and T. R. Quinn, The inner structure of Lambda-CDM halos 3: Universality and asymptotic slopes, *Mon. Not. R. Astron. Soc.* **349**, 1039 (2004).
- [29] J. Einasto and U. Haud, Galactic models with massive corona. I-method. II-galaxy, *Astron. Astrophys.* **223**, 89 (1989).
- [30] A. W. Graham, D. Merritt, B. Moore, J. Diemand, and B. Terzic, Empirical models for dark matter halos. I. Nonparametric construction of density profiles and comparison with parametric models, *Astron. J.* **132**, 2685 (2006).
- [31] A. Burkert, The structure of dark matter halos in dwarf galaxies, *Astrophys. J. Lett.* **447**, L25 (1995).
- [32] C. W. Bauer, N. L. Rodd, and B. R. Webber, Dark matter spectra from the electroweak to the Planck scale, *J. High Energy Phys.* **06** (2021) 121.
- [33] G. Lanfranchi, M. Pospelov, and P. Schuster, The search for feebly interacting particles, *Annu. Rev. Nucl. Part. Sci.* **71**, 279 (2021).
- [34] D. Curtin, R. Essig, S. Gori, and J. Shelton, Illuminating dark photons with high-energy colliders, *J. High Energy Phys.* **02** (2015) 157.
- [35] H. Merkel *et al.*, Search at the Mainz microtron for light gauge bosons decaying into e^+e^- pairs, *Phys. Rev. Lett.* **112**, 221802 (2014).
- [36] R. Aaij *et al.* (LHCb Collaboration), Search for dark photons produced in 13 TeV pp collisions, *Phys. Rev. Lett.* **120**, 061801 (2018).
- [37] CMS Collaboration, Search for a narrow resonance decaying to a pair of muons in proton-proton collisions at 13 TeV, *Phys. Lett. B* **796**, 131 (2019).
- [38] J. P. Lees *et al.* (BABAR Collaboration), Search for a dark photon in e^+e^- collisions at BABAR, *Phys. Rev. Lett.* **113**, 201801 (2014).
- [39] J. R. Batley *et al.* (NA48/2 Collaboration), Search for the dark photon in π^0 decays, *Phys. Lett. B* **746**, 178 (2015).
- [40] E. M. Riordan *et al.*, A search for short-lived axions in an electron-beam-dump experiment, *Phys. Rev. Lett.* **59**, 755 (1987).
- [41] J. Blümlein and F. Brunner, New exclusion limits for dark gauge forces from beam-dump data, *Phys. Lett. B* **701**, 155 (2011).
- [42] J. Blümlein and F. Brunner, New bounds on dark gauge forces from proton bremsstrahlung data, *Phys. Lett. B* **731**, 320 (2014).
- [43] S. N. Gninenko, Constraints on dark photons from CHARM, *Phys. Lett. B* **713**, 244 (2012).
- [44] M. Pospelov, Secluded U(1) below the weak scale, *Phys. Rev. D* **80**, 095002 (2009).
- [45] J. Preskill, M. B. Wise, and F. Wilczek, Cosmology of the invisible axion, *Phys. Lett.* **120B**, 127 (1983).
- [46] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, *Phys. Lett.* **120B**, 133 (1983).
- [47] A. E. Nelson and J. Scholtz, Dark light, dark matter and the misalignment mechanism, *Phys. Rev. D* **84**, 103501 (2011).
- [48] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, WISPy cold dark matter, *J. Cosmol. Astropart. Phys.* **06** (2012) 013.
- [49] A. Caputo, A. J. Millar, C. A. J. O'Hare, and E. Vitagliano, Dark photon limits: A cookbook, *Phys. Rev. D* **104**, 095029 (2021).
- [50] G. Raffelt and L. Stodolsky, Mixing of the photon with low-mass particles, *Phys. Rev. D* **37**, 1237 (1988).
- [51] N. Brahma, A. Berlin, and K. Schutz, Photon-dark photon conversion with multiple level crossings, *Phys. Rev. D* **108**, 095045 (2023).
- [52] M. A. Ismail, C. S. Nugroho, and Q. M. B. Soesanto, Dark photon-photon resonance conversion of GRB221009A through extra dimension, *Phys. Lett. B* **866**, 139531 (2025).
- [53] I. Brivio, M. B. Gavela, L. Merlo, K. Mimasu, J. M. No, R. del Rey, and V. Sanz, ALPs effective field theory and collider signatures, *Eur. Phys. J. C* **77**, 572 (2017).
- [54] M. Bauer, M. Neubert, and A. Thamm, Collider probes of axion-like particles, *J. High Energy Phys.* **12** (2017) 044.
- [55] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, The low-energy effective theory of axions and ALPs, *J. High Energy Phys.* **04** (2021) 063.
- [56] R. L. Workman *et al.* (Particle Data Group Collaboration), Review of particle physics, *Prog. Theor. Exp. Phys.* **2024**, 083C01 (2024).