

Observing dark matter decays to gravitons via graviton-photon conversion

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Since dark matter is only known to have gravitational interactions, it may plausibly decay to gravitons on cosmological timescales. Although such a scenario can be easily realized, there are currently no known limits on this possibility based on indirect-detection methods. We propose a new search strategy that exploits the Gertsenshtein effect, whereby the gravitons produced in dark matter decays can convert to photons in large-scale magnetic fields along the line of sight to an observer. These conversions primarily occur within cosmological filaments which occupy a large (order unity) volume fraction and contain $\sim 10\text{--}100$ nG fields with $\sim \text{Mpc}$ coherence lengths. Thus, dark matter decays to gravitons predict an irreducible population of extragalactic *photons*, which we constrain using the extragalactic gamma-ray background measured by the *Fermi*-LAT telescope. Using this method, we derive the first-ever constraints on the dark matter lifetime in the $0.1 \text{ GeV} - 10^8 \text{ GeV}$ mass range, contingent on the assumed filament magnetic field strength. We also make projections for the Advanced Particle-astrophysics Telescope, which can improve sensitivity to this dark matter decay channel by an order of magnitude beyond those we set using *Fermi*-LAT data.

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I. INTRODUCTION

The evidence for dark matter (DM) is overwhelming, but its only known interaction with the Standard Model (SM) is through gravity. If there is no symmetry to stabilize the DM, it is possible it can decay to *gravitons*. Since graviton couplings to the SM are suppressed by powers of the Planck mass, such a scenario is exceedingly difficult to probe using established techniques. Although there are indirect detection limits on DM decays to all other SM particles (including neutrinos), to date, there are no observational limits on the graviton channel.¹

However, gravitons are not completely dark. As they traverse spatial regions with nonzero magnetic fields, they can convert to photons through a SM process known as the Gertsenshtein effect [2,3]. Furthermore, our Universe provides ample opportunities for such conversion events in a variety of astrophysical and cosmological settings. Since the length scale for graviton-photon conversion typically exceeds the Hubble radius, the most promising sources for realizing this effect are cosmological filaments, which feature ~ 100 nG magnetic fields on long $\sim \text{Mpc}$ coherence lengths [4], and fill an order unity fraction of our Universe's volume [5].

In this work, we introduce a new search strategy for dark matter decays to gravitons, which leverages the Gertsenshtein effect in magnetized cosmological filaments. If DM particles decay to gravitons in the early Universe, the latter traverse many filament patches and have a small, but appreciable probability of converting to *photons* along the line of sight to an observer. For a given choice of dark matter mass and lifetime, these Gertsenshtein photons add an irreducible contribution to the isotropic gamma-ray background (IGRB), and this observable flux offers a new discovery channel for DM decays, as shown schematically in Fig. 1.

Over a wide range of DM masses, we use existing data to derive constraints on the DM lifetime if the graviton decay

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¹However, there are generic bounds on DM decays to invisible radiation from probes of large scale structure, which require that the DM comoving mass density be constant to within $\sim 4\%$ over the age of the Universe [1].

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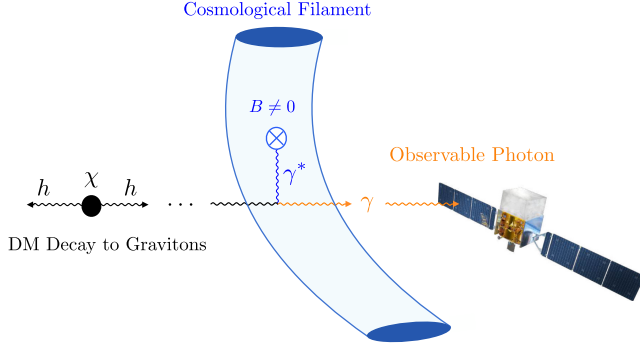


FIG. 1. Schematic cartoon of our search strategy: a DM particle χ decays to gravitons at early times. The gravitons propagate through magnetized cosmological filaments and can oscillate into photons along the line-of-sight toward an observer. This flux is an irreducible prediction of any DM model that allows for decays to gravitons.

channel predominates, with sensitivity depending on the assumed filament magnetic field strength. As future telescopes improve sensitivity to the IGRB and as the magnetic fields of cosmological filaments become better understood through observations and simulations, our strategy has the potential to achieve world-leading sensitivity to this decay channel.

II. GRAVITON DECAYS

The lowest dimension operators that allow a spin-0 field χ to decay to gravitons h have nonminimal² [6–8] quadratic couplings to the Riemann tensor $R_{\mu\nu\alpha\beta}$ and its dual $\tilde{R}_{\mu\nu\alpha\beta}$,

$$\mathcal{L}_{\chi hh} = \sqrt{|g|} \left(\frac{\chi}{\Lambda} R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta} + \frac{\chi}{\tilde{\Lambda}} R^{\mu\nu\alpha\beta} \tilde{R}_{\mu\nu\alpha\beta} \right), \quad (1)$$

where Λ and $\tilde{\Lambda}$ are scales associated with integrating out heavy particles and $|g|$ is the metric determinant. The χ lifetime arising from either operator is [7]

$$\tau_\chi = \frac{4\pi\Lambda^2 M_{\text{Pl}}^4}{m_\chi^7} \approx 2 \times 10^{20} \text{ s} \left(\frac{10^6 \text{ GeV}}{m_\chi} \right)^5 \left(\frac{\Lambda}{m_\chi} \right)^2, \quad (2)$$

where M_{Pl} is the reduced Planck mass. Alternatively, χ may decay to a single graviton and another light dark state, in which case the lifetime can scale as only $\propto M_{\text{Pl}}^2$ and may be much shorter than the estimate in Eq. (2).

In our treatment, we thus remain agnostic about the origin of the operators contributing to DM decays to gravitons. For our purposes, it suffices to specify the lifetime for χ , which is equivalent to freely choosing a

²Naïvely there are several simpler operators that might induce $\chi \rightarrow hh$ decays—for example, $\sqrt{g}\chi R$, $\sqrt{g}\chi R^2$, or $\sqrt{g}\chi R^{\mu\nu} R_{\mu\nu}$. However, these bilinear interactions with gravitons vanish either in flat space or in the true vacuum of the theory [6,7].

set of coefficients for these operators; throughout this analysis, we assume that a suitable choice can always be made to realize any χ lifetime, subject only to observational bounds.

Although we are agnostic about the mechanism that populates χ in the early Universe, there are many viable possibilities that are consistent with our scenario. Over a wide range of χ masses, the abundance can arise through gravitational interactions during inflation [9–11], reheating [12], radiation domination [8,13], or primordial black hole evaporation [14,15]. More generally, the abundance can arise through any production mechanism compatible with the existence of the operators in Eq. (1), as long as $\chi \rightarrow hh$ remains the dominant decay channel.

Ensuring that decays to gravitons dominate the total decay rate of χ can easily be achieved. For example, nonrenormalizable operators between χ and the SM can be suppressed by the Planck scale or even exponentially suppressed in scenarios like Randall-Sundrum models [16,17]. Additionally, if dark matter is composite, decay rates can be further suppressed by form factors or compositeness scales, like baryon number.

III. GERTSENSHTEIN EFFECT

In this Section we review the Gertsenshtein effect whereby a graviton converts to a photon in the presence of a uniform magnetic field. Following the formalism in Ref. [18], the $h \rightarrow \gamma$ conversion probability over some distance ℓ can be written as

$$P_{h \rightarrow \gamma} = |K_{\text{osc}}|^2 \ell_{\text{osc}}^2 \sin^2 \left(\frac{\ell}{\ell_{\text{osc}}} \right), \quad (3)$$

with the characteristic oscillation length

$$\ell_{\text{osc}} = 2[\omega^2(1 - \mu)^2 + \kappa^2 B^2]^{-1/2}, \quad (4)$$

where ω is the incident graviton/photon energy, $\kappa^2 = 16\pi G$, and B is the angle-averaged transverse magnetic field strength. We have also defined an oscillation amplitude K_{osc} and refractive index μ , which, respectively, satisfy

$$|K_{\text{osc}}| = \frac{\sqrt{\mu\kappa B}}{1 + \mu}, \quad \mu = \sqrt{1 - (\omega_{\text{pl}}^2 - \omega_{\text{EH}}^2)/\omega^2}, \quad (5)$$

where the characteristic plasma frequency is

$$\omega_{\text{pl}} = \sqrt{\frac{4\pi\alpha n_e}{m_e}} \sim 10^{-14} \text{ eV} \left(\frac{n_e}{10^{-6} \text{ cm}^{-3}} \right)^{1/2}, \quad (6)$$

and the Euler-Heisenberg frequency is

$$\omega_{\text{EH}} \approx \sqrt{\frac{7\alpha}{45\pi}} \left(\frac{B}{B_c} \right) \omega \sim 10^{-14} \text{ eV} \left(\frac{B}{60 \text{ nG}} \right) \left(\frac{\omega}{\text{GeV}} \right), \quad (7)$$

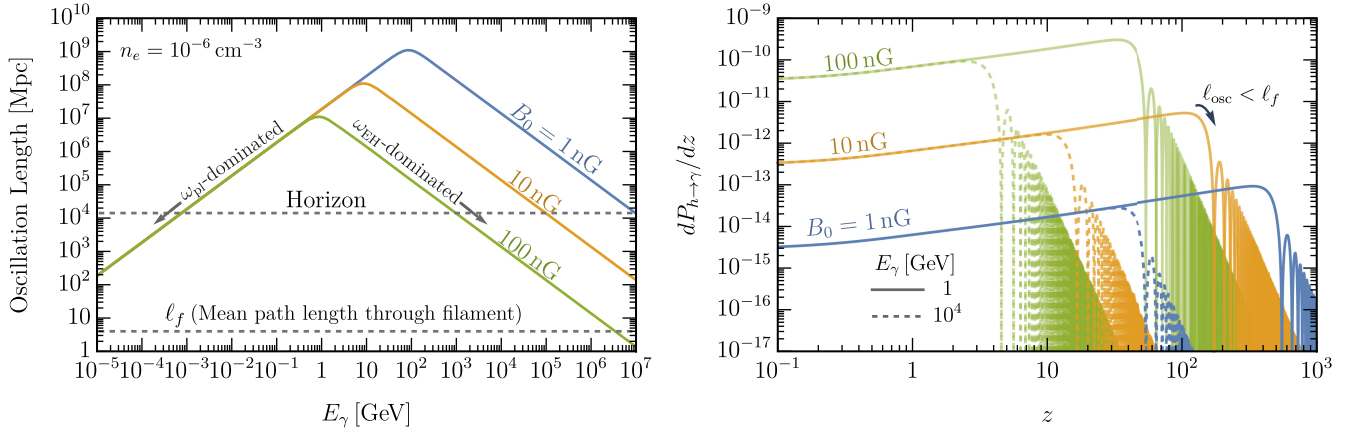


FIG. 2. Left: Present-day oscillation length for graviton-photon conversion from Eq. (4) for various choices of B_0 . Note that for most graviton energies of interest in this paper (10 GeV – TeV), $\omega_{EH} \gg \omega_{pl}$ which is to the right of the peak. The upper horizontal black curve is the proper distance of the present-day cosmological horizon $\sim 3.3H_0^{-1} \approx 14.4$ Gpc. The lower horizontal curve is the typical path length traveled by a graviton through a single filament today, ≈ 4 Mpc. Right: The differential graviton-photon oscillation probability as a function of cosmological redshift from Eq. (16) for two different energies using the same B_0 values as the left panel.

where α is the fine structure constant, $B_c = m_e^2/e \approx 4.4 \times 10^{13}$ G [19], and n_e the ambient electron number density.

IV. COSMOLOGICAL FILAMENTS

Cosmological filaments provide an irreducible source of magnetic fields that can be modeled as [20]

$$B(z) = B_0(1+z)^2, \quad (8)$$

where z is the cosmological redshift and B_0 is the average present day field value, which ranges from 1–600 nG [4,5,20–29] with coherence lengths that range from 1–10 Mpc [4,24,26]. It is estimated that 10%–30% of our present Hubble volume consists of such filaments [30,31].

Assuming characteristic present-day filament parameters $B_0 = 60$ nG and $n_e = 10^{-6} \text{ cm}^{-3}$ in Eqs. (6) and (7), the plasma and Euler-Heisenberg frequencies are comparable for $\omega \sim \text{GeV}$ in the gamma-ray band. For these reference values, the ω dependence in Eq. (4) is negligible, so the present-day oscillation length for $h \rightarrow \gamma$ conversion is simply

$$\ell_{\text{osc}} \approx 2 \times 10^4 \text{ Gpc}, \quad (9)$$

which vastly exceeds the present day Hubble radius of $H_0^{-1} \approx 4$ Gpc. Indeed, Fig. 2 shows that ℓ_{osc} is much larger than the horizon or typical filament coherence length for a wide range of photon energies.³ Thus, we

³In contrast, the oscillation length of gravitational waves from astrophysical or primordial sources is typically in the extreme subhorizon since the graviton energies are much smaller than those we consider in this work.

treat the conversion probability in each filament as an independent trial and a typical graviton will encounter many such patches while propagating over $\sim \text{Gpc}$ distance scales.

Within a single filament, a graviton has a photon conversion probability of

$$P_{h \rightarrow \gamma}^{(1)}(z) = |K_{\text{osc}}(z)|^2 \ell_{\text{osc}}(z)^2 \sin^2 \left[\frac{\ell_f(z)}{\ell_{\text{osc}}(z)} \right] \quad (10)$$

$$\approx 4\pi G B(z)^2 \ell_f(z)^2, \quad (11)$$

where $\ell_f(z)$ is the length traversed by a graviton within a single filament at redshift z . In the second line, we write the approximate form of $P_{h \rightarrow \gamma}^{(1)}$ when $\ell_f \ll \ell_{\text{osc}}$ and $\mu \simeq 1$, which is often the case. Dirac showed [32,33] that the isotropically averaged chord length of a convex shape of volume V and area A is $4V/A$, implying that for filaments, roughly cylinders of radius r and height $h > r$,

$$\langle \ell_f(z) \rangle \approx \frac{2r(z)}{1 + r(z)/h(z)} \approx \frac{2r_0}{1 + z}, \quad (12)$$

and the average squared chord length [34]

$$\langle \ell_f(z)^2 \rangle \approx \frac{16r(z)^2}{3} \simeq [2.3r(z)]^2. \quad (13)$$

Simulations indicate that the typical filament radius today is $r_0 \approx 1\text{--}3$ Mpc [35,36]. In Eq. (12), we assume the filament radius scales with redshift as $(1+z)^{-1}$, though the exact redshift scaling is not crucial since most of the converted photon flux is generated at low redshifts. For the

remainder of this work, we adopt the fiducial value $r_0 = 2$ Mpc.

In a small physical distance dr , the graviton traverses a number of filaments

$$dN_f = \frac{f_{\text{vol}}(z)}{\ell_f(z)} dr = \frac{f_{\text{vol}}(z)}{\ell_f(z)} \frac{dz}{H(z)(1+z)}, \quad (14)$$

where $f_{\text{vol}}(z) \approx 0.15$ is the volume-filling fraction of cosmological filaments at redshift z [30,31]. Thus, the cumulative probability for graviton-photon conversion between two arbitrary redshifts is

$$P_{h \rightarrow \gamma} = \int_{z_1}^{z_2} dN_f(z) P_{h \rightarrow \gamma}^{(1)}(z), \quad (15)$$

and we can write the differential conversion probability per unit redshift

$$\frac{dP_{h \rightarrow \gamma}}{dz} = \frac{dN_f}{dz} \frac{dP_{h \rightarrow \gamma}}{dN_f} = \frac{f_{\text{vol}}(z)}{\ell_f(z)} \frac{P_{h \rightarrow \gamma}(z)}{H(z)(1+z)}, \quad (16)$$

where we have used Eq. (14). In principle, $f_{\text{vol}}(z)$ may depend on redshift, but here we assume this quantity to be a constant, given that the converted photon flux mainly arises at low redshift. In our treatment, we also conservatively assume that graviton propagation outside of filaments does not contribute to the conversion probability.

Nevertheless, gravitons from DM decays can also convert to photons inside the magnetic fields found in galaxy clusters, and voids. Since the graviton energies we consider are large ($\omega \gg 1$ GeV), the graviton-photon oscillation length is typically far larger than the coherence sizes of these systems (see Fig. 2). As a result, Eqs. (10) and (14) indicate that to optimize the total probability of $h \rightarrow \gamma$ conversion, the product of $B^2 \ell f_{\text{vol}}$ should be maximized, where B , ℓ , and f_{vol} are the typical magnetic fields, scale sizes, and Universe filling fraction of these systems, as shown in Table I.

In this analysis, we conservatively focus on filaments as the most promising regions for studying the contribution of our DM model to diffuse emission. Including contributions from clusters and voids would further strengthen our results (see also Galactic probes [40]). Targeted observations⁴ will also be promising for this kind of study. In particular, for targeted observations, the total probability of conversion is

⁴Here, “target searches” refer to observations where the telescope points at a single target, while “diffuse emission searches” refer to cases in which the cumulative emission from objects contributes to the IGRB or other types of diffuse emission.

TABLE I. Comparison of cosmological domains where graviton to photon conversion can occur. Filaments [4,5,30], galaxy clusters [30,37], and voids [30,38,39] possess different typical magnetic fields B , coherence lengths ℓ , and volume filling fractions f_{vol} . The contribution to the diffuse gamma-ray background from DM decays to gravitons scales with $B^2 \ell f_{\text{vol}}$, which is largest for cosmic filaments.

Domain	B (nG)	ℓ (Mpc)	f_{vol}	$B^2 \ell f_{\text{vol}}$
Filaments	~ 10 – 100	~ 1	$\sim 10^{-1}$	$10 - 10^3$
Clusters	$\sim 10^3$	$\sim 10^{-2}$	$\sim 10^{-2}$	$\sim 10^2$
Voids	10^{-7} – 10^{-4}	~ 1	~ 1	10^{-14} – 10^{-8}

of the form of Eq. (16), but with $f_{\text{vol}} \rightarrow 1$ and the integration only over the physical extent of the target. An additional advantage is that the point-source sensitivity of telescopes is typically orders of magnitude better than their sensitivity to diffuse emission, particularly for gamma-ray telescopes. This analysis focuses on contributions to diffuse emission, while a systematic study of targeted observations is deferred to future work.

V. PHOTON FLUX

The flux of gravitons from DM decays before the redshift of graviton-photon conversion z_c can be written

$$\frac{d\Phi_h}{dE}(z_c) = \frac{\Omega_\chi \rho_c}{\tau_\chi m_\chi} \int_{z_c}^{\infty} \frac{dz}{H(z)} \frac{dN_h}{dE}(z) e^{-t(z)/\tau_\chi}, \quad (17)$$

where τ_χ is the DM lifetime, $t(z)$ the age of the Universe at redshift z , $\Omega_\chi = 0.24$ is the DM energy fraction, ρ_c is the critical density, and

$$\frac{dN_h}{dE}(z) = 2\delta \left[E(1+z) - \frac{m_\chi}{2} \right], \quad (18)$$

is the present-day graviton energy spectrum due to decays at redshift z , where $E(1+z)$ is the graviton energy at the time of decay, and E is the present-day graviton (or photon) energy. In the late Universe, the Hubble rate in Eq. (20) can be written

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}, \quad (19)$$

where $H_0 = 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is the Hubble constant, $\Omega_\Lambda = 0.69$ is the present-day dark energy fraction, and $\Omega_m = 0.31$ is the present-day matter fraction [41].

To derive the total photon flux at redshift z from all prior conversion events in cosmological filaments, we convolve Eq. (17) with Eq. (16) to obtain

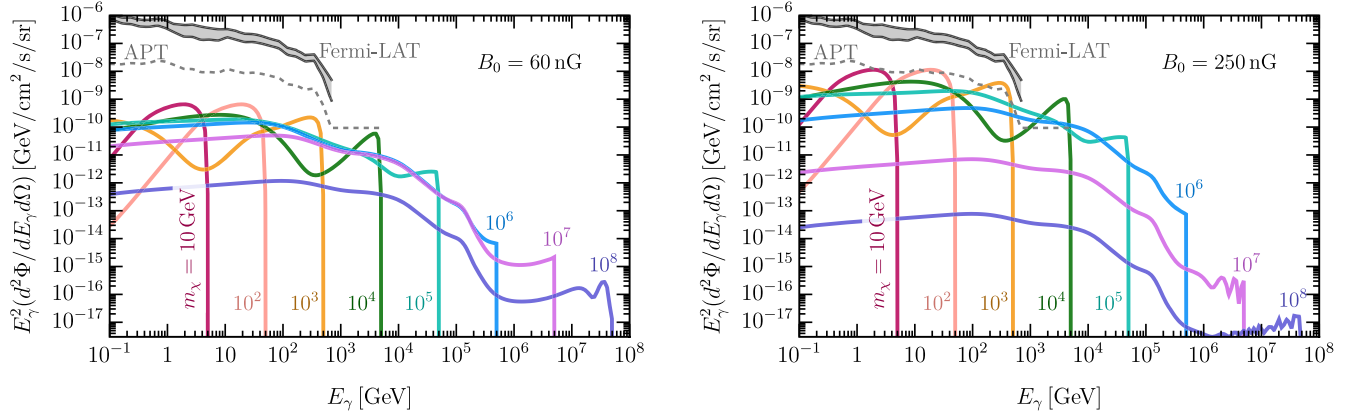


FIG. 3. Left: Differential photon fluxes from $\chi \rightarrow hh$ decays followed by graviton-photon conversion in cosmological filaments. Each curve represents a different choice of DM mass in GeV assuming the same values of $B_0 = 100$ nG, $\tau_\chi = 10^{19}$ s, $\ell_f = 4$ Mpc, and $f_{\text{vol}} = 0.15$. Right: Same as left, but with $B = 250$ nG.

$$\frac{d\Phi_\gamma}{dE}(z) = \int_z^\infty dz_c \frac{dP_{h \rightarrow \gamma}(z_c)}{dz_c} \frac{d\Phi_h}{dE}(z_c), \quad (20)$$

which is shown in Fig. 3. Using the delta function from Eq. (18) to eliminate the integral in Eq. (17), the photon flux from Eq. (20) can be written as

$$\frac{d\Phi_\gamma}{dE}(z) = \frac{2\Omega_\chi \rho_c e^{-t(z_*)/\tau_\chi}}{\tau_\chi m_\chi E H(z_*)} \int_z^{z_*} dz_c \frac{dP_{h \rightarrow \gamma}(z_c)}{dz_c}, \quad (21)$$

where we have defined $z_* \equiv (m_\chi - 2E)/(2E)$ as the redshift of χ decay and $z_* > z$.

The spectrum in Eq. (21) represents the photon flux at redshift z before accounting for the electromagnetic cascades that result from photon interactions with their surroundings. As they traverse cosmological distances, these photons scatter cosmic microwave background and extragalactic background photons to undergo pair production via $\gamma\gamma \rightarrow e^+e^-$ reactions, which attenuate photons above ~ 100 GeV energies. The e^+e^- pairs produced in these reactions inject softer secondary photons via $e^+e^- \rightarrow \gamma\gamma$ annihilation, $e\gamma \rightarrow e\gamma$ inverse-Compton scattering, and synchrotron radiation. Collectively, these cascades redistribute photon energies and asymptote to a nearly universal secondary spectrum for input energies above the TeV scale [42]. To model this secondary photon population, we use the injected flux from Eq. (21) as an input for the γ -Cascade v4 code package [43], which generates the present-day photon flux.

Finally, note that the photon spectrum of Eq. (21) is indistinguishable from the scenario when only a fraction, f , of DM decays to gravitons with lifetime $\tau_\chi \rightarrow \tau_{\text{eff}} = f\tau_\chi$ when τ_{eff} is greater than the age of the Universe. This is because both scenarios yield approximately the same energy injection into gravitons at low redshifts where the signal dominates. Large scale structure and CMB observations require that not more than $\sim 4\%$ of

DM can decay to invisibles by today, demanding $\tau_{\text{eff}} \gtrsim 10^{19}$ s [1].⁵

VI. RESULTS

Figure 3 shows representative photon fluxes from DM decays to gravitons followed by graviton-photon conversion in filaments, with each colored contour corresponding to a different DM mass. For $E_\gamma \gtrsim 1$ TeV, cascades are important and DM masses between $10^4 \lesssim m_\chi \lesssim 10^6$ GeV possess a near universal spectrum at sub-100 GeV energies. For $m_\chi \gtrsim 10^6$ GeV, the Euler-Heisenberg contribution to the photon mass is sufficiently large to drop ℓ_{osc} below ℓ_f (see Fig. 2), and the probability of conversion is suppressed due to the $\sin^2(\ell_f/\ell_{\text{osc}})$ term in Eq. (10) becoming important. This oscillation in the $P_{h \rightarrow \gamma}$ leads to an imprinted oscillatory pattern at the highest photon energies in the spectrum and the reduction in amplitude relative to the universal spectrum for low-energy photons.

The gray band of Fig. 3 represents the observed IGRB flux from Fermi-LAT telescope data [44]. In the future, the Advanced Particle-physics Telescope (APT) will be able to probe the γ -ray sky with an order of magnitude improvement in γ -ray sensitivity and effective area compared to Fermi-LAT [45]. The APT will be able to resolve many of the currently unresolved point sources that contribute to the IGRB observed by Fermi-LAT.

In terms of the acceptance ξ , which is provided in Fig. 3 of Ref. [45], the APT sensitivity to the IGRB flux is expected to increase between a factor of $\sqrt{\xi_{\text{APT}}/\xi_{\text{Fermi}}}$ and $\xi_{\text{APT}}/\xi_{\text{Fermi}}$ if the measurement is background or signal dominated, respectively; these ratios are approximately

⁵This limit assumes the Λ CDM cosmological model and the precise bound on the lifetime can vary in alternative cosmological scenarios.

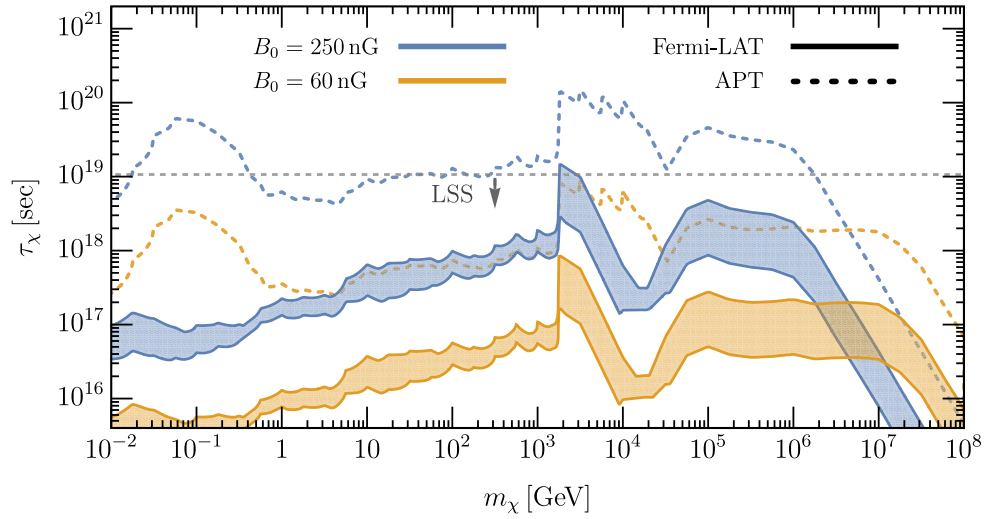


FIG. 4. Limits on the DM lifetime assuming $\chi \rightarrow hh$ decays, where h is a graviton, followed by $h \rightarrow \gamma$ conversion in cosmic filaments. Each panel assumes filaments with coherence length $\ell_f = 4$ Mpc and volume fraction $f_{\text{vol}} = 0.15$. The horizontal dotted line is the constraint on DM decaying to dark radiation from CMB and large scale structure observations, which allow for $\sim 4\%$ of DM to have decayed invisibly on cosmological timescales at 95% confidence [1].⁵ We note that our bounds are conditional on the value of B_0 , which represents the typical magnetic field in cosmological filaments; this value is currently constrained to be between one and a few hundred nG [4]. As observations and simulations improve, this uncertainty will become narrower and these limits may change to reflect that. Our limits and projections are competitive with large-scale structure bounds for $B_0 \gtrsim 100$ nG.

$\sqrt{10}$ (10) for photon energies above 100 GeV and $\sqrt{500}$ (500) for photon energies around 10 MeV. Although the acceptance in Ref. [45] is only plotted out to TeV energies, the APT team anticipates that the telescope will be able to measure photons up to energies of 5 TeV, so we extrapolate the APT acceptance out to this higher value⁶ as shown by the dashed gray APT line of Fig. 3.

To constrain the DM lifetime, we compare candidate photon spectra from $\chi \rightarrow hh$ decays and place limits on parameter values for which this graviton-induced photon flux exceeds IGRB observations by Fermi-LAT, which constitutes a well-defined procedure for deriving DM constraints [42,46–49]. In Fig. 4, we present our main result: the limit on the DM lifetime assuming $\chi \rightarrow hh$ decays with 100% branching fraction over a wide range of masses. The thickness of this band reflects the uncertainty of the Fermi-LAT IGRB measurement, as shown in the gray band of Fig. 3. For DM masses near the TeV scale, our analysis sets stringent limits for $B_0 \gtrsim 100$ nG. The sharp rise in the bounds around $m_\chi \approx 2$ TeV is due to the steep drop in the IGRB near $E_\gamma \approx 1$ TeV coinciding with the sharp cutoff of the photon spectrum at $E_\gamma = m_\chi/2$. Figure 4 also shows generic bounds on DM decays to invisible final states from Ref. [1] (gray dashed curve) and APT sensitivity projections assuming an acceptance enhancement factor of $\xi_{\text{APT}}/\xi_{\text{Fermi}}$ to reduce the IGRB flux from point sources. If the signal is instead noise dominated, the

APT projections on τ_χ are reduced by a factor of $\sqrt{\xi_{\text{APT}}/\xi_{\text{Fermi}}} \sim 4$ for most photon energies of interest.

VII. DISCUSSION

In this work, we have introduced a novel technique for observing dark matter decays to gravitons, a channel that is completely unconstrained by indirect detection methods. Our method exploits the Gertsenshtein effect to calculate the flux of extragalactic gamma rays from graviton conversion in cosmological filaments. We emphasize that this effect is a SM process and that the only new physics considered here is the hypothesis that dark matter can decay to gravitons. We derive the first constraints on the DM lifetime across a wide range of masses, assuming 100% branching fraction to graviton pairs. We note that the strength of these constraints depends significantly on the assumed filament magnetic field B_0 , which currently carries substantial observational uncertainty. We show our results assuming $B_0 = 100$ nG as benchmark and $B_0 = 250$ nG as optimistic. The results of our paper are based on the state-of-the-art knowledge regarding the average filament length, number density, volume-filling fraction, and magnetic field strengths within these cosmic bridges. With future improvements in characterizing both the IGRB and the properties of cosmological filaments, our strategy has the potential to either discover DM decaying to gravitons or place world-leading limits on its lifetime.

Approximately half of the Universe’s baryons are believed to reside in cosmic filaments in the form of a warm-hot diffuse gas, known as the warm-hot intergalactic

⁶Private communication with Jim Buckley.

medium (WHIM). The thermal emission and synchrotron radiation from the WHIM in the filaments result in x-rays and radio waves. Therefore, future observations in the x-ray band with AXIS [50], Athena [51] and XRISM [52], as well as through radio observations with ngVLA [53], SKA [54], and its pathfinders, will make it possible to further constrain the properties of filaments.

While waiting for new observations, hydrodynamical simulations such as EAGLE [55–57], BAHAMAS [58], Illustris-TNG [59,60], MillenniumTNG [61], and FLAMINGO [62,63] are particularly well suited for studying these structures due to their large box sizes (100 Mpc for EAGLE and BAHAMAS, 205 Mpc for TNG300, 500 Mpc for MillenniumTNG, 1–2.8 Gpc for FLAMINGO), which enable the analysis of extensive intercluster filaments—ideal environments for this type of dark matter search.

Intriguingly, given the cosmologically long distances required for appreciable graviton-photon conversion in filaments, this signal arises predominantly from extragalactic sources, not from the Galactic center, as one typically finds for DM decays to all other SM particle species. Thus, a smoking gun for this scenario is a statistically significant excess in the extragalactic gamma-ray flux, with negligible flux from the Galactic Center. Another powerful technique to disentangle DM-produced gamma-rays from the astrophysical background is to cross-correlate these gamma rays with a tracer of the large-scale structure like galaxy clusters and filaments, given their $B^2\ell f_{\text{vol}}$ is much larger compared to other large-scale structures tracers.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] V. Poulin, P. D. Serpico, and J. Lesgourgues, A fresh look at linear cosmological constraints on a decaying dark matter component, *J. Cosmol. Astropart. Phys.* **08** (2016) 036.
 - [2] M. Gertsenshtein, Wave resonance of light and gravitational waves, *Sov. Phys. JETP* **14**, 84 (1962).
 - [3] D. Boccaletti, V. De Sabbata, P. Fortini, and C. Gualdi, Conversion of photons into gravitons and vice versa in a static electromagnetic field, *Nuovo Cimento B* **70**, 129 (1970).
 - [4] A. D. Amaral, T. Vernstrom, and B. M. Gaensler, Constraints on large-scale magnetic fields in the intergalactic medium using cross-correlation methods, *Mon. Not. R. Astron. Soc.* **503**, 2913 (2021).
 - [5] T. Vernstrom, G. Heald, F. Vazza, T. J. Galvin, J. West, N. Locatelli, N. Fornengo, and E. Pinetti, Discovery of magnetic fields along stacked cosmic filaments as revealed by radio and X-ray emission, *Mon. Not. R. Astron. Soc.* **505**, 4178 (2021).
 - [6] A. Alonzo-Artiles, A. Avilez-López, J. L. Díaz-Cruz, and B. O. Larios-López, The Higgs-graviton couplings: From amplitudes to the action, [arXiv:2105.11684](https://arxiv.org/abs/2105.11684).
 - [7] Y. Ema, K. Mukaida, and K. Nakayama, Scalar field couplings to quadratic curvature and decay into gravitons, *J. High Energy Phys.* **05** (2022) 087.
 - [8] G. Landini and A. Strumia, Optical gravitational waves as signals of gravitationally-decaying particles, *J. High Energy Phys.* **04** (2025) 068.
 - [9] T. Markkanen and S. Nurmi, Dark matter from gravitational particle production at reheating, *J. Cosmol. Astropart. Phys.* **02** (2017) 008.
 - [10] Y. Ema, R. Jinno, K. Mukaida, and K. Nakayama, Gravitational effects on inflaton decay, *J. Cosmol. Astropart. Phys.* **05** (2015) 038.
 - [11] L. H. Ford, Gravitational particle creation and inflation, *Phys. Rev. D* **35**, 2955 (1987).
 - [12] D. J. H. Chung, E. W. Kolb, and A. Riotto, Superheavy dark matter, *Phys. Rev. D* **59**, 023501 (1998).
 - [13] M. Garny, M. Sandora, and M. S. Sloth, Planckian interacting massive particles as dark matter, *Phys. Rev. Lett.* **116**, 101302 (2016).
 - [14] G. E. A. Matsas, J. C. Montero, V. Pleitez, and D. A. T. Vanzella, Dark matter: The Top of the iceberg?, in *Conference on Topics in Theoretical Physics II: Festschrift for A.H. Zimerman* (IFT, Sao Paulo, 1998).
 - [15] T. Fujita, M. Kawasaki, K. Harigaya, and R. Matsuda, Baryon asymmetry, dark matter, and density perturbation

- from primordial black holes, *Phys. Rev. D* **89** (2014) 103501.
- [16] L. Randall and R. Sundrum, A large mass hierarchy from a small extra dimension, *Phys. Rev. Lett.* **83**, 3370 (1999).
- [17] L. Randall and R. Sundrum, An alternative to compactification, *Phys. Rev. Lett.* **83**, 4690 (1999).
- [18] V. Domcke and C. Garcia-Cely, Potential of radio telescopes as high-frequency gravitational wave detectors, *Phys. Rev. Lett.* **126**, 021104 (2021).
- [19] G. Raffelt and L. Stodolsky, Mixing of the photon with low mass particles, *Phys. Rev. D* **37**, 1237 (1988).
- [20] E. Carretti, F. Vazza, S. P. O'Sullivan, V. Vacca, A. Bonafede, G. Heald, C. Horellou, S. Mchedlidze, and T. Vernstrom, The nature of LOFAR rotation measures and new constraints on magnetic fields in cosmic filaments and on magnetogenesis scenarios, *Astron. Astrophys.* **693**, A208 (2025).
- [21] S. Brown, T. Vernstrom, E. Carretti, K. Dolag, B. M. Gaensler, L. Staveley-Smith, G. Bernardi, M. Haverkorn, M. Kesteven, and S. Poppi, Limiting magnetic fields in the cosmic web with diffuse radio emission, *Mon. Not. R. Astron. Soc.* **468**, 4246 (2017).
- [22] V. Vacca *et al.*, Observations of a nearby filament of galaxy clusters with the Sardinia Radio Telescope, *Mon. Not. R. Astron. Soc.* **479**, 776 (2018).
- [23] S. P. O'Sullivan *et al.*, The intergalactic magnetic field probed by a giant radio galaxy, *Astron. Astrophys.* **622** (2019) A16.
- [24] T. Vernstrom, B. Gaensler, L. Rudnick, and H. Andernach, Differences in faraday rotation between adjacent extragalactic radio sources as a probe of cosmic magnetic fields, *Astrophys. J.* **878**, 92 (2019).
- [25] S. P. O'Sullivan *et al.*, New constraints on the magnetization of the cosmic web using LOFAR faraday rotation observations, *Mon. Not. R. Astron. Soc.* **495**, 2607 (2020).
- [26] N. Locatelli, F. Vazza, A. Bonafede, S. Banfi, G. Bernardi, C. Gheller, A. Botteon, and T. Shimwell, New constraints on the magnetic field in cosmic web filaments, *Astron. Astrophys.* **652**, A80 (2021).
- [27] E. Carretti *et al.*, Magnetic field strength in cosmic web filaments, *Mon. Not. R. Astron. Soc.* **512**, 945 (2022).
- [28] D. N. Hoang *et al.*, A search for intercluster filaments with LOFAR and eROSITA, *Mon. Not. R. Astron. Soc.* **523**, 6320 (2023).
- [29] C. S. Anderson *et al.*, Probing the magnetized gas distribution in galaxy groups and the cosmic web with POSSUM Faraday rotation measures, *Mon. Not. R. Astron. Soc.* **533**, 4068 (2024).
- [30] N. I. Libeskind *et al.*, Tracing the cosmic web, *Mon. Not. R. Astron. Soc.* **473**, 1195 (2018).
- [31] T. Dome, A. Fialkov, N. Sartorio, and P. Mocz, Cosmic web dissection in fuzzy dark matter cosmologies, *Mon. Not. R. Astron. Soc.* **525**, 348 (2023).
- [32] P. Dirac, Approximate rate of neutron multiplication for a solid of arbitrary shape and uniform density, declassified british report ms-d-5, part i, Second World War Atomic Energy Research in Britain (1943).
- [33] R. Sanchez, On the use of the average chord length, *Ann. Nucl. Energy* **31**, 2211 (2004).
- [34] K. M. Case, *Introduction to the Theory of Neutron Diffusion* (Los Alamos Scientific Laboratory, Los Alamos, New Mexico (USA), 1953), Vol. 1.
- [35] J. M. Colberg, K. S. Krughoff, and A. J. Connolly, Intercluster filaments in a λ cdm universe, *Mon. Not. R. Astron. Soc.* **359**, 272 (2005).
- [36] W. Wang *et al.*, The boundary of cosmic filaments, *Mon. Not. R. Astron. Soc.* **532**, 4604 (2024).
- [37] C. Pfrommer and L. J. Dursi, Detecting the orientation of magnetic fields in galaxy clusters, *Nat. Phys.* **6**, 520 (2010).
- [38] A. M. Taylor, I. Vovk, and A. Neronov, Extragalactic magnetic fields constraints from simultaneous GeV-TeV observations of blazars, *Astron. Astrophys.* **529**, A144 (2011).
- [39] A. M. Rodríguez-Medrano, F. A. Stasyszyn, D. J. Paz, and V. Springel, Magnetic fields in cosmic voids, *arXiv*: 2305.01765.
- [40] S. Ramazanov, R. Samanta, G. Trenkler, and F. R. Urban, Shimmering gravitons in the gamma-ray sky, *J. Cosmol. Astropart. Phys.* **06** (2023) 019.
- [41] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020).
- [42] C. Blanco and D. Hooper, Constraints on decaying dark matter from the isotropic gamma-ray background, *J. Cosmol. Astropart. Phys.* **03** (2019) 019.
- [43] A. Capanema and C. Blanco, γ -Cascade v4: A semi-analytical code for modeling cosmological gamma-ray propagation, *Comput. Phys. Commun.* **307**, 109408 (2025).
- [44] M. Di Mauro (Fermi-LAT Collaboration), The origin of the Fermi-LAT γ -ray background, in *14th Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories* (World Scientific, Rome, Italy, 2017), Vol. 3, pp. 3098–3104.
- [45] S. Alnussirat *et al.*, The advanced particle-physics telescope: Simulation of the instrument performance for gamma-ray detection, *Proc. Sci., ICRC2021* (2021) 590.
- [46] A. A. Abdo *et al.* (Fermi-LAT Collaboration), Constraints on cosmological dark matter annihilation from the Fermi-LAT isotropic diffuse gamma-ray measurement, *J. Cosmol. Astropart. Phys.* **04** (2010) 014.
- [47] T. Bringmann, F. Calore, M. Di Mauro, and F. Donato, Constraining dark matter annihilation with the isotropic γ -ray background: Updated limits and future potential, *Phys. Rev. D* **89** (2014) 023012.
- [48] Fermi LAT Collaboration, Limits on dark matter annihilation signals from the fermi lat 4-year measurement of the isotropic gamma-ray background, *J. Cosmol. Astropart. Phys.* **09** (2015) 008.
- [49] A. Arbey, J. Auffinger, and J. Silk, Constraining primordial black hole masses with the isotropic gamma ray background, *Phys. Rev. D* **101** (2020) 023010.
- [50] C. S. Reynolds *et al.*, Overview of the advanced x-ray imaging satellite (AXIS), *Proc. SPIE Int. Soc. Opt. Eng.* **12678**, 126781E (2023).
- [51] D. Barret, A. Decourchelle, A. Fabian, M. Guainazzi, K. Nandra, R. Smith, and J.-W. d. Herder, The Athena space X-ray Observatory and the astrophysics of hot plasma, *Astron. Nachr.* **341**, 224 (2020).

- [52] XRISM Science Team, Science with the X-ray Imaging and Spectroscopy Mission (XRISM), [arXiv:2003.04962](https://arxiv.org/abs/2003.04962).
- [53] J. Di Francesco, D. Chalmers *et al.*, The next generation very large array, <https://zenodo.org/record/3765763>.
- [54] A. Weltman *et al.*, Fundamental physics with the Square Kilometre Array, *Pub. Astron. Soc. Aust.* **37**, e002 (2020).
- [55] J. Schaye *et al.*, The EAGLE project: Simulating the evolution and assembly of galaxies and their environments, *Mon. Not. R. Astron. Soc.* **446**, 521 (2015).
- [56] R. A. Crain *et al.*, The EAGLE simulations of galaxy formation: Calibration of subgrid physics and model variations, *Mon. Not. R. Astron. Soc.* **450**, 1937 (2015).
- [57] The EAGLE team, The EAGLE simulations of galaxy formation: Public release of particle data, [arXiv:1706.09899](https://arxiv.org/abs/1706.09899).
- [58] I. G. McCarthy, J. Schaye, S. Bird, and A. M. C. Le Brun, The bahamas project: Calibrated hydrodynamical simulations for large-scale structure cosmology, *Mon. Not. R. Astron. Soc.* **465**, 2936 (2016).
- [59] A. Pillepich *et al.*, Simulating galaxy formation with the illustrisTNG model, *Mon. Not. R. Astron. Soc.* **473**, 4077 (2018).
- [60] V. Springel *et al.*, First results from the IllustrisTNG simulations: Matter and galaxy clustering, *Mon. Not. R. Astron. Soc.* **475**, 676 (2018).
- [61] R. Pakmor *et al.*, The MillenniumTNG Project: The hydrodynamical full physics simulation and a first look at its galaxy clusters, *Mon. Not. R. Astron. Soc.* **524**, 2539 (2023).
- [62] J. Schaye *et al.*, The FLAMINGO project: Cosmological hydrodynamical simulations for large-scale structure and galaxy cluster surveys, *Mon. Not. R. Astron. Soc.* **526**, 4978 (2023).
- [63] R. Kugel *et al.*, FLAMINGO: Calibrating large cosmological hydrodynamical simulations with machine learning, *Mon. Not. R. Astron. Soc.* **526**, 6103 (2023).