γ-ray Constraints on Decaying Dark Matter and Implications for IceCube

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Utilizing the *Fermi* measurement of the γ-ray spectrum toward the Inner Galaxy, we derive some of the strongest constraints to date on the dark matter (DM) lifetime in the mass range from hundreds of MeV to above an EeV. Our profile-likelihood-based analysis relies on 413 weeks of *Fermi* Pass 8 data from 200 MeV to 2 TeV, along with up-to-date models for diffuse γ-ray emission within the Milky Way. We model Galactic and extragalactic DM decay and include contributions to the DM-induced γ-ray flux resulting from both primary emission and inverse-Compton scattering of primary electrons and positrons. For the extragalactic flux, we also calculate the spectrum associated with cascades of high-energy γ rays scattering off of the cosmic background radiation. We argue that a decaying DM interpretation for the 10 TeV–1 PeV neutrino flux observed by IceCube is disfavored by our constraints. Our results also challenge a decaying DM explanation of the AMS-02 positron flux. We interpret the results in terms of individual final states and in the context of simplified scenarios such as a hidden-sector glueball model.

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A primary goal of the particle physics program is to discover the connection between dark matter (DM) and the standard model (SM). While DM is known to be stable over cosmological timescales, rare DM decays may give rise to observable signals in the spectrum of high-energy cosmic rays. Such decays would be induced through operators involving both the dark sector and the SM. In this work, we derive some of the strongest constraints to date on decaying DM for masses from ~400 MeV to ~10^7 GeV by performing a dedicated analysis of *Fermi* γ-ray data from 200 MeV to 2 TeV.

The solid red line in Fig. 1 gives an example of our constraint on the DM (χ) lifetime, τ, as a function of its mass, m_χ, assuming the DM decays exclusively to a pair of bottom quarks. Our analysis includes three contributions to the photon spectrum: (1) prompt emission, (2) γ rays that are up-scattered by primary electrons and positrons through inverse Compton (IC) within the Galaxy, and (3) extragalactic contributions.

In addition to deriving some of the strongest limits on the DM lifetime across many DM decay channels, our results provide the first dedicated constraints on DM using the latest *Fermi* data for $m_\chi \gtrsim 10$ TeV. To emphasize this point, we provide a comparison with other limits in Fig. 1. The dashed red curve indicates our new estimate of the limits set by high-energy neutrino observations at the IceCube experiment [1–4]. Our IceCube constraint dominates in the range from $\sim 10^7$ to 10^9 GeV.

Constraints from previous studies are plotted as solid grey lines labeled from 1 to 6. Curve 6 shows that for masses above $\sim 10^9$ GeV, limits from null observations of ultrahigh-energy γ rays at air shower experiments [5], such as the Pierre Auger Observatory (PAO) [6], KASCADE [7], and CASA-MIA [8], surpass our IceCube limits. Curves 2, 5, and 3 are from previous analyses of the extragalactic [9,10] and Galactic [11] *Fermi* γ-ray flux (for related work see Refs. [12–14]). Our results are less sensitive to astrophysical modeling than Ref. [9], which makes assumptions about the

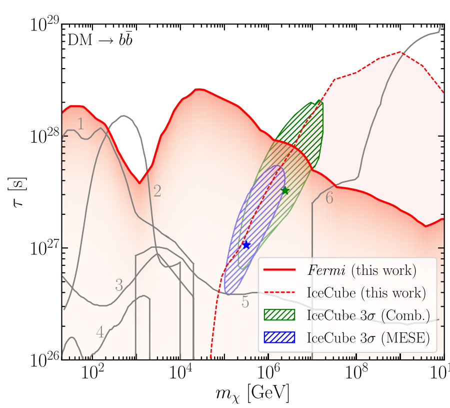

FIG. 1. Limits on DM decays to $b\bar{b}$, as compared to previously computed limits using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO, KASCADE, and CASA-MIA (6). The hashed green (blue) region suggests the parameter space where DM decay may provide a ~3σ improvement to the description of the combined maximum likelihood (MESE) IceCube neutrino flux. The best-fit points, marked as stars, are in strong tension with our γ-ray results. The red dotted line provides a limit if we assume a combination of DM decay and astrophysical sources are responsible for the spectrum.

classes of sources and their spectra that contribute to the unresolved component of the extragalactic γ-ray background. We improve and extend beyond Refs. [10,11] in a number of ways: by including state-of-the-art modeling for cosmic-ray-induced γ-ray emission in the Milky Way, a larger and cleaner data set, and a novel analysis technique that allows us to search for a combination of Galactic and extragalactic flux arising from DM decay. The limits labeled 1 and 4 in Fig. 1 are from the AMS-02 antiproton [15,16] and positron [17,18] measurements, respectively; these constraints are subject to considerable astrophysical uncertainties, due to the propagation of charged cosmic rays from their source to Earth.

An additional motivation for this work is the measurement of the so far unexplained high-energy neutrinos observed by the IceCube experiment [1–4]. If the DM has both a mass $m_\chi \sim \mathrm{PeV}$ and a long lifetime $\tau \sim 10^{28}$ seconds, its decays could contribute to the upper end of the IceCube spectrum. These DM candidates would produce correlated cosmic-ray signals, yielding a broad spectrum of γ rays with energies extending well into *Fermi*'s energy range. Taking this correlation between neutrino and photon spectra into account enables us to constrain the DM interpretation of these neutrinos using the *Fermi* data.

Figure 1 illustrates regions of parameter space where we fit a decaying DM spectrum to the high-energy neutrino flux at IceCube in hashed green. The corresponding region for the analysis of Ref. [19] using lower-energy neutrinos is shown in blue. Clearly, much of the parameter space relevant for IceCube is disfavored by the γ-ray limits; the best fit points (indicated by stars) are in strong tension with the *Fermi* observations. We conclude that models where decaying DM could account for the entire astrophysical neutrino flux observed by IceCube are disfavored. Furthermore, models where the neutrino flux results from a mix of decaying DM and astrophysical sources are strongly constrained.

The rest of this Letter is organized as follows. First, we discuss the various contributions to the γ-ray flux resulting from DM decay. Then, we give an overview of the data set and analysis techniques used in this work. Next, we provide context for these limits by interpreting them as constraints on a concrete model (glueball DM), before concluding.

The γ-ray flux.—Decaying DM contributes both a Galactic and extragalactic flux. The Galactic contribution results primarily from prompt γ-ray emission due to the decay itself, which is simulated with Pythia 8.219[20–22] including electroweak showering [23] (see, e.g., Refs. [24–34]).

These effects can be the only source of photons for channels such as $\chi \to \nu\bar{\nu}$.

In addition, the electrons and positrons from these decays IC scatter off of cosmic background radiation (CBR), producing γ rays (see, e.g., Refs. [35,36]). The prompt contribution follows the spatial morphology obtained from the line-of-sight (LOS) integral of the DM density, which we model with a Navarro-Frenk-White (NFW) profile [37,38], setting the local DM density $\rho = 0.3\ \mathrm{GeV/cm^3}$, and the scale radius $r_s = 20$ kpc (variations to the profile lead to similar results, see the Supplemental Material [39]). We only consider IC scattering off of the cosmic microwave background (CMB), as scattering from integrated stellar radiation and the infrared background is expected to be subdominant, see the Supplemental Material [39]. For scattering off of the CMB, the resulting γ-ray morphology also follows the LOS integral of the DM density. Importantly, as scattering off of the other radiation fields only increases the γ-ray flux, neglecting these effects is conservative. In the same spirit, we conservatively assume that the electrons and positrons lose energy due to synchrotron emission in a rather strong, uniform $B = 2.0\ \mu\mathrm{G}$ magnetic field (see, e.g., Refs. [60–62]) and show variations in the Supplemental Material [39].

In addition to the Galactic fluxes, there is an essentially isotropic extragalactic contribution, arising from DM decays throughout the broader Universe [63]. The extragalactic flux receives three important contributions: (1) attenuated prompt emission; (2) attenuated emission from IC of primary electrons and positrons; and (3) emission from γ-ray cascades. The cascade emission arises when an electron-positron pair is created by high-energy γ rays scattering off of the CBR, inducing IC emission along with adiabatic energy loss. We account for these effects following [10,35].

Data analysis.—We assess how well predicted Galactic (NFW-correlated) and extragalactic (isotropic) fluxes describe the data using the profile-likelihood method (see, e.g., Ref. [64]), described in more detail in the Supplemental Material [39]. To this end, we perform a template fitting analysis (using `NPTFit` [65]) with 413 weeks of *Fermi* Pass 8 data collected from August 4, 2008 to July 7, 2016. We restrict to the UltracleanVeto event class; furthermore, we only use the top quartile of events as ranked by the point-spread function (PSF). The UltracleanVeto event class is used to minimize contamination from cosmic rays, while the PSF cut is imposed to mitigate effects from mismodeling bright regions. We bin the data in 40 logarithmically spaced energy bins between 200 MeV and 2 TeV, and we apply the recommended quality cuts `DATA_QUAL==1 && LAT_CONFIG==1` and zenith angle less than 90° [66]. The data is binned spatially using a HEALPix [67] pixelation with `nside` $= 128$.

We constrain this data to a region of interest (ROI) defined by Galactic latitude $|b| \geq 20°$ within 45° of the Galactic Center (GC). The Galactic plane is masked in order to avoid issues related to mismodeling of diffuse emission in that region. Similarly, we do not extend our region out further from the GC to avoid over-subtraction issues that may arise when fitting diffuse templates over large regions of the sky (see, e.g., Refs. [68–70]). Finally, we mask all point sources (PSs) in the 3FGL PS catalog [71] at their 95% containment radius.

Using this restricted data set, we then independently fit templates in each energy bin in order to construct a likelihood profile as a function of the extragalactic and Galactic flux. We separate our model parameters into those of interest ψ and the nuisance parameters λ. The ψ include parameters for an isotropic template to account for the extragalactic emission, along with a template following a LOS-integrated NFW profile to model the Galactic emission. Note that both the prompt and IC contribute to the same template, see the Supplemental Material [39] for justification. The λ include parameters for the flux from diffuse emission within the Milky Way, flux from the *Fermi* bubbles, flux from isotropic emission that does not arise from DM decay (e.g., emission from blazars and other extragalactic sources, along with misidentified cosmic rays), and flux from PSs, both Galactic and extragalactic, in the 3FGL PS catalog. Importantly, each spatial template is given a separate, uncorrelated degree of freedom in the northern and southern hemispheres, further alleviating oversubtraction.

In our main analysis, we use the Pass 7 diffuse model gal_2 yearp7v6_v0 (p7v6) to account for diffuse emission in the Milky Way, coming from gas-correlated emission (mostly pion decay and bremsstrahlung from high-energy electrons), IC emission, and emission from large-scale structures such as the *Fermi* bubbles [72] and Loop 1 [73]. Additionally, even though the *Fermi* bubbles are included to some extent in the `p7v6` model, we add an additional degree of freedom for the bubbles, following the uniform spatial template given in Ref. [72]. We add a single template for all 3FGL PSs based on the spectra in Ref. [71], though we emphasize again that all PSs are masked at 95% containment. See the Supplemental Material [39] for variations of these choices.

Given the templates described above, we are able to construct 2D log-likelihood profiles $\log p_i(d_i|\{I^i_{\rm iso}, I^i_{\rm NFW}\})$ as functions of the isotropic and NFW-correlated DM-induced emission $I^i_{\rm iso}$ and $I^i_{\rm NFW}$, respectively, in each of the energy bins i. Here, d_i is the data in that energy bin, which simply consists of the number of counts in each pixel. The likelihood profiles are given by maximizing the Poisson likelihood functions over the λ parameters.

Any decaying DM model may be constrained from the set of likelihood profiles in each energy bin, which are provided as Supplementary Data [74]. Concretely, given a DM model $\mathcal{M}$, the total log-likelihood $\log p(d|\mathcal{M}, \{\tau, m_\chi\})$ is simply the sum of the $\log p_i$, where the intensities in each energy bin are functions of the DM mass and lifetime. The test statistics (TS) used to constrain the model is twice the difference between the log-likelihood at a given τ and the value at $\tau = \infty$, where the DM contributes no flux. The 95% limit is given by $\mathrm{TS} = -2.71$.

In order to compare our γ-ray results to potential signals from IceCube, we determine the region of parameter space where DM may contribute to the observed high-energy neutrino flux. We use the recent high-energy astrophysical neutrino spectrum measurement by the IceCube Collaboration [3]. In that work, neutrino flux measurements from a combination of muon-track and shower data are given in 9 logarithmically spaced energy bins between 10 TeV and 10 PeV, under the assumption of equal flavor ratios and an isotropic flux. (Constraints at high masses may be improved by incorporating recent results from Ref. [75], which focused on neutrino events with energies greater than 10 PeV.) We assume that DM decays are the only source of high-energy neutrino flux. In Fig. 1 (assuming the DM decays exclusively to $b\bar{b}$) we show the region where the DM model provides at least a 3σ improvement over the null hypothesis of no high-energy flux at all. The best-fit point is marked with a star. The blue region in Fig. 1 is the best-fit region [19] for explaining an apparent excess in the 2-year medium energy starting event (MESE) IceCube data, which extends down to energies $\sim$1 TeV [76].

The dashed red curve, on other hand, shows the 95% limit that we obtain on this DM channel under the assumption that astrophysical sources also contribute to the high-energy flux. We parameterize the astrophysical flux by a power law with an exponential cutoff, and we marginalize over the slope of the power law, the normalization, and the cutoff in order to obtain a likelihood profile for the DM model, as a function of τ and m_χ. We emphasize that we allow the spectral index to float, as opposed to the analysis of Ref. [19], which fixes the index equal to two.

Interpretations.—In Fig. 1, we show our total constraint on the DM lifetime for a model where $\chi \to b\bar{b}$. This result demonstrates tension in models where decaying DM explains or contributes to the astrophysical neutrino flux observed by IceCube. PeV-scale decaying DM models have received attention recently (see, e.g., Refs. [5,35,77–97]). In particular, while conventional astrophysical models such as those involving star-forming galaxies and galaxy clusters provide viable explanations for the neutrino data above 100 TeV (see Ref. [98] for a summary of recent ideas), the MESE data have been difficult to explain with conventional models [99,100]. Moreover, it is natural to expect heavy DM to slowly decay to the SM in a wide class of scenarios where, for example, the DM is stabilized through global symmetries in a hidden sector that are expected to be violated at the Planck scale or perhaps the scale of grand unification (the GUT scale).

From a purely data-driven point of view it is worthwhile to ask whether any set of SM final states may contribute significantly to or explain the IceCube data while being consistent with the γ-ray constraints. In the Supplemental Material [39] we provide limits on a variety of two-body SM final states.

It is also important to interpret the bounds as constraints on the parameter space of UV models or gauge-invariant effective field theory (EFT) realizations. If the decay is mediated by irrelevant operators, and given the long lifetimes we are probing, it is natural to assume very high cutoff scales Λ, such as the GUT scale $\sim 10^{16}$ GeV or the Planck scale $m_{\rm Pl} \simeq 2.4 \times 10^{18}$ GeV. We expect all gauge invariant operators connecting the dark sector to the SM to appear in the EFT suppressed by a scale m_{Pl} or less (assuming no accidentally small coefficients and, perhaps, discrete global symmetries).

It is also interesting to consider models that could yield signals relevant for this analysis. Many cases are explored in the Supplemental Material [39], and here we highlight one simple option: a hidden sector that consists of a confining gauge theory, at scale Λ_D [101], without additional light matter. Hidden gauge sectors that decouple from the SM at high scales appear to be generic in many string constructions (see Ref. [102] for a recent discussion). Denoting the hidden-sector field strength as $G_{D\mu\nu}$, then the lowest dimensional operator connecting the hidden sector to the SM appears at dimension 6: $\mathcal{L} \supset \lambda_D G_{D\mu\nu} G_D^{\mu\nu} |H|^2/\Lambda^2$, where λ_D is a dimensionless coupling constant, Λ is the scale where this operator is generated, and H the SM Higgs doublet. The lightest 0^{++} glueball state in the hidden gauge theory is a simple DM candidate χ, with $m_\chi \sim \Lambda_D$, though heavier, long-lived states may also play important roles (see, e.g., Ref. [103]). The lowest dimension EFT operator connecting χ to the SM is then $\sim\chi|H|^2\Lambda_D^3/\Lambda^2$. Furthermore, $\Lambda_D \gtrsim 100$ MeV in order to avoid constraints on DM self-interactions [104].

At masses comparable to and lower than the electroweak scale, the glueball decays primary to b quarks through mixing with the SM Higgs boson, while at high masses the glueball decays predominantly to $W^\pm$, Z^0, and Higgs boson pairs (see the inset of Fig. 2 for the dominant branching ratios). In the high-mass limit, the lifetime is approximately

$$\tau \simeq 5\times 10^{27}\ \mathrm{s}\left(\frac{3}{N_D}\frac{1}{4\pi\lambda_D}\right)^2\left(\frac{\Lambda}{m_{\mathrm{Pl}}}\right)^4\left(\frac{0.1\ \mathrm{PeV}}{\Lambda_D}\right)^5, \quad (1)$$

with N_D the number of colors. This is roughly the right lifetime to be relevant for the IceCube neutrino flux.

In Fig. 2, we show our constraint on this glueball model. Using Eq. (1), these results suggest that models with $\Lambda_D \gtrsim 0.1$ PeV, $\lambda_D \gtrsim 1/(4\pi)$, and $\Lambda = m_{\mathrm{Pl}}$ are excluded. As in Fig. 1, the shaded green area is the region of parameter space where the model may contribute significantly to IceCube, and the dashed red line provides the limit we obtain from IceCube allowing for an astrophysical contribution to the flux. As in the case of the $b\bar{b}$ final state, the γ-ray limits derived in this work are in tension with the decaying-DM origin of the signal.

Figure 2 also illustrates the relative contribution of prompt, IC and extragalactic emissions to the total limit. The 95% confidence interval is shown for each source, assuming background templates only, where the normalizations are fit to the data. Across almost all of the mass range, and particularly at the highest masses, the limits obtained on the real data align with the expectations from MC. In the statistics-dominated regime, we would expect the real-data limits to be consistent with those from MC,

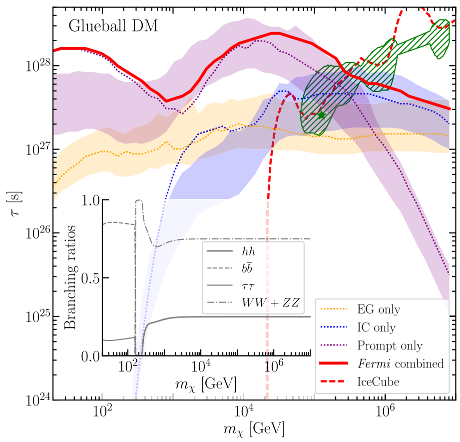

FIG. 2. Limits on decaying glueball DM (see text for details). We show limits obtained from prompt, IC, and EG emission only, along with the 95% confidence window for the expectation of each limit from MC simulations. Furthermore, the parameter space where the IceCube data may be interpreted as a $\sim 3\sigma$ hint for DM is shown in shaded green, with the best fit point represented by the star. (inset) The dominant glueball DM branching ratios.

while in the systematics dominated regime the limits on real data may differ from those obtained from MC. This is because the real data can have residuals coming from mismodeling the background templates, and the overall goodness of fit may increase with flux from the NFW-correlated template, for example, even in the absence of DM. Alternatively, the background templates may overpredict the flux at certain regions of the sky, leading to oversubtraction issues that could make the limits artificially strong.

Discussion.—In this work, we presented some of the strongest limits to date on decaying DM from a dedicated analysis of *Fermi* γ-ray data incorporating spectral and spatial information, along with up-to-date modeling of diffuse emission in the Milky Way. Our results disfavor a decaying DM explanation of the IceCube high-energy neutrino data.

There are several ways that our analysis could be expanded upon. We have not attempted to characterize the spectral composition of the astrophysical contributions to the isotropic emission, which may strengthen our limits. On the other hand, ideally, for a given, fixed decaying DM flux in the profile likelihood, we should marginalize not just over the normalization of the diffuse template but also over all of the individual components that go into making this template, such as IC emission and bremsstrahlung.

A variety of strategies beyond those described here have been used to constrain DM lifetimes (see, e.g., Ref. [105] for a review). These include γ-ray line searches, such as those performed in Refs. [106–109], which are complementary to the constraints on broader energy emission given in this Letter. Limits from direct decay into neutrinos have also been considered [110]. Less competitive limits have been set on DM decays resulting in broad energy deposition and nearby galaxies and galaxy clusters [111,112], large scale Galactic and extragalactic emission 116–11,113]], Milky Way Dwarfs [117,118], and the CMB [119]. The upcoming Cherenkov Telescope Array (CTA) experiment [120] may have similar sensitivity as our results to DM masses ~10 TeV [121]. However, more work needs to be done in order to assess the potential for CTA to constrain or detect heavier, ~PeV decaying DM. On the other hand, the High-Altitude Walter Cherenkov Observatory (HAWC) [122] and air-shower experiments such as Tibet AS + MD [123] will provide meaningful constraints on the Galactic diffuse γ-ray emission. The constraints on DM lifetimes might be as stringent as 10^{27}–10^{28} s for PeV masses and hadronic channels, assuming no astrophysical emission is seen [35,36,124].

Finally, we mention that our results also have implications for possible decaying DM interpretations (see, e.g., Ref. [125]) of the positron [17,126] and antiproton fluxes [15] measured by AMS-02. Recent measurements of the positron flux appear to exhibit a break at high masses that could indicate evidence for decaying DM to, for example, e^+e^- with $m_\chi \sim 1$ TeV and $\tau \sim 10^{27}$ s. However, our results appear to rule out the decaying DM interpretation of the positron flux for this and other final states. For example, in the e^+e^- case our limit for $m_\chi \sim 1$ TeV DM is $\tau \gtrsim 5 \times 10^{28}$ s.

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