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Resolving Cosmic Gamma Ray Anomalies with Dark Matter Decaying Now

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Dark matter particles need not be completely stable, and in fact they may be decaying now. We consider this possibility in the frameworks of universal extra dimensions and supersymmetry with very late decays of weakly interacting massive particles to Kaluza-Klein gravitons and gravitinos. The diffuse photon background is a sensitive probe, even for lifetimes far greater than the age of the Universe. Remarkably, both the energy spectrum and flux of the observed MeV γ -ray excess may be simultaneously explained by decaying dark matter with MeV mass splittings. Future observations of continuum and line photon fluxes will test this explanation and may provide novel constraints on cosmological parameters.

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The abundance of dark matter is now well known from observations of supernovae, galaxies and galactic clusters, and the cosmic microwave background (CMB) [1], but its identity remains elusive. Weakly interacting massive particles (WIMPs) with weak-scale masses ~ 0.1 –1 TeV are attractive dark matter candidates. The number of WIMPs in the Universe is fixed at freeze-out when they decouple from the known particles about 1 ns after the Big Bang. Assuming they are absolutely stable, these WIMPs survive to the present day, and their number density is naturally in the right range to be dark matter. The standard signatures of WIMPs include, for example, elastic scattering off nucleons in underground laboratories, products from WIMP annihilation in the galaxy, and missing energy signals at colliders [2].

The stability of WIMPs is, however, not required to preserve the key virtues of the WIMP scenario. In fact, in supersymmetry (SUSY) and other widely studied scenarios, it is just as natural for WIMPs to decay after freeze-out to other stable particles with similar masses, which automatically inherit the right relic density to be dark matter [3]. If the resulting dark matter interacts only gravitationally, the WIMP decay is very late, in some cases leading to interesting effects in structure formation [4] and other cosmological observables. Of course, the WIMP lifetime depends on Δm , the mass splitting between the WIMP, and its decay product. For high degeneracies, the WIMP lifetime may be of the order of or greater than the age of the Universe $t_0 \approx 4.3 \times 10^{17}$ s, leading to the tantalizing possibility that dark matter is decaying now.

For very long WIMP lifetimes, the diffuse photon background is a promising probe [3,5]. Particularly interesting is the (extragalactic) cosmic gamma ray background (CGB) shown in Fig. 1. Although smooth, the CGB must be explained by multiple sources. For $E_\gamma \lesssim 1$ MeV and $E_\gamma \gtrsim 10$ MeV, the CGB is reasonably well modeled by thermal emission from obscured active galactic nuclei (AGN) [6] and beamed AGN, or blazars [7], respectively. However, in the range $1 \text{ MeV} \lesssim E_\gamma \lesssim 5 \text{ MeV}$, no astrophysical source can account for the observed CGB. Blazars

are observed to have a spectral cutoff ~ 10 MeV, and also only a few objects have been detected below this energy [8,9]; a maximal upper limit [10] on the blazar contribution for $E_\gamma \lesssim 10$ MeV is shown in Fig. 1. Diffuse γ rays from Type Ia supernovae (SNIa) contribute below ~ 5 MeV, but the most recent astronomical data show that they also cannot account for the entire spectrum [11,12]; previous calculations suggested that SNIa are the dominant source of γ rays at MeV energies [13].

In this Letter, we study the contribution to the CGB from dark matter decaying now. We consider simple models with extra dimensions or SUSY in which WIMP decays are highly suppressed by both the weakness of gravity and small mass splittings and are dependent on a single parameter, Δm . We find that the CGB is an extremely sensitive probe, even for lifetimes $\tau \gg t_0$. Intriguingly, we also find that both the energy spectrum and the flux of the gamma ray excess described above are naturally explained in these scenarios with $\Delta m \sim \text{MeV}$.

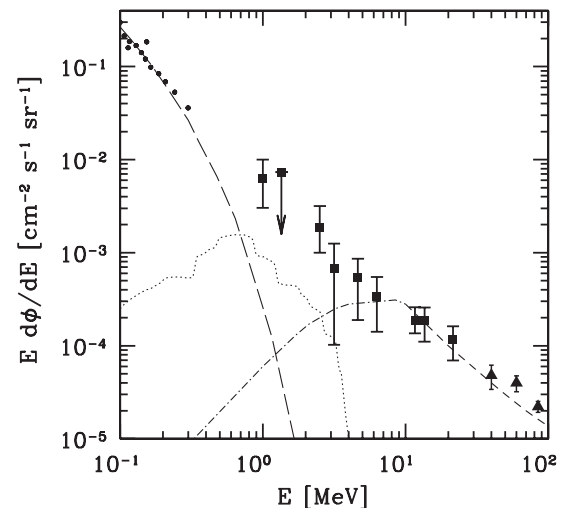


FIG. 1. The CGB measured by HEAO-1 [19] (●), COMPTEL [26] (■), and EGRET [27] (▲), along with the known astrophysical sources: AGN (long dashed line), SNIa (dotted line), and blazars (short dash line and dot-dashed line extrapolation).

As our primary example we consider minimal universal extra dimensions (mUED) [14], one of the simplest imaginable models with extra dimensions. In mUED all particles propagate in one extra dimension compactified on a circle, and the theory is completely specified by m_h , the Higgs boson mass, and R , the compactification radius. (In detail, there is also a weak, logarithmic dependence on the cutoff scale Λ [15]. We present results for $\Lambda R = 20$.) Every particle has a Kaluza-Klein (KK) partner at every mass level $\sim m/R$, $m = 1, 2, \dots$, and the lightest KK particle (LKP) is a dark matter candidate, with its stability guaranteed by a discrete parity.

Astrophysical and particle physics constraints limit mUED parameters to regions of (R^{-1}, m_h) parameter space where the two lightest KK particles are the KK hypercharge gauge boson B^1 , and the KK graviton G^1 , with mass splitting $\Delta m \lesssim \mathcal{O}(\text{GeV})$ [16]. This extreme degeneracy, along with the fact that KK gravitons interact only gravitationally, leads to long NLKP lifetimes

$$\tau \simeq \frac{3\pi}{b \cos^2 \theta_W} \frac{M_P^2}{(\Delta m)^3} \simeq \frac{4.7 \times 10^{22} \text{ s}}{b} \left[\frac{\text{MeV}}{\Delta m} \right]^3, \quad (1)$$

where $M_P \simeq 2.4 \times 10^{18} \text{ GeV}$ is the reduced Planck scale, θ_W is the weak mixing angle, $b = 10/3$ for $B^1 \rightarrow G^1 \gamma$, and $b = 2$ for $G^1 \rightarrow B^1 \gamma$ [17]. Note that τ depends only on the single parameter Δm . For $795 \text{ GeV} \lesssim R^{-1} \lesssim 809 \text{ GeV}$ and $180 \text{ GeV} \lesssim m_h \lesssim 215 \text{ GeV}$, the model is not only viable, but the B^1 thermal relic abundance is consistent with that required for dark matter [18] and $\Delta m \lesssim 30 \text{ MeV}$, leading to lifetimes $\tau(B^1 \rightarrow G^1 \gamma) \gtrsim t_0$.

We will also consider supersymmetric models, where small mass splittings are also possible, since the gravitino mass is a completely free parameter. If the two lightest supersymmetric particles are a B -ino-like neutralino \tilde{B} and the gravitino \tilde{G} , the heavier particle's decay width is again given by Eq. (1), but with $b = 2$ for $\tilde{B} \rightarrow \tilde{G} \gamma$, and $b = 1$ for $\tilde{G} \rightarrow \tilde{B} \gamma$. As in mUED, τ depends only on Δm , and $\Delta m \lesssim 30 \text{ MeV}$ yields lifetimes greater than t_0 .

The present photon flux from two-body decays is

$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi} \int_0^{t_0} \frac{dt}{\tau} \frac{N(t)}{V_0} \delta(E_\gamma - a\varepsilon_\gamma), \quad (2)$$

where $N(t) = N^{\text{in}} e^{-t/\tau}$ and N^{in} is the number of WIMPs at freeze-out, V_0 is the present volume of the Universe, a is the cosmological scale factor with $a(t_0) \equiv 1$, and $\varepsilon_\gamma = \Delta m$ is the energy of the produced photons. Photons from two-body decays are observable in the diffuse photon background only if the decay takes place in the late Universe, when matter or vacuum energy dominates. In this case, Eq. (2) may be written as

$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi} \frac{N^{\text{in}} e^{-P(E_\gamma/\varepsilon_\gamma)/\tau}}{V_0 \tau E_\gamma H(E_\gamma/\varepsilon_\gamma)} \Theta(\varepsilon_\gamma - E_\gamma), \quad (3)$$

where $P(a) = t$ is the solution to $(da/dt)/a = H(a) =$

$H_0 \sqrt{\Omega_M a^{-3} + \Omega_{\text{DE}} a^{-3(1+w)}}$ with $P(0) = 0$, and Ω_M and Ω_{DE} are the matter and dark energy densities. If dark energy is a cosmological constant Λ with $w = -1$,

$$P(a) \equiv \frac{2 \ln[(\sqrt{\Omega_\Lambda a^3} + \sqrt{\Omega_M + \Omega_\Lambda a^3})/\sqrt{\Omega_M}]}{3H_0 \sqrt{\Omega_\Lambda}}. \quad (4)$$

The flux has a maximum at $E_\gamma = \varepsilon_\gamma [\frac{\Omega_M}{2\Omega_\Lambda} U(H_0^2 \tau^2 \Omega_\Lambda)]^{1/3}$, where $U(x) \equiv (x + 1 - \sqrt{3x + 1})/(x - 1)$.

The energy spectrum is easy to understand for very long and very short decay times. For $\tau \ll t_0$, $H_0^2 \tau^2 \Omega_{\text{DE}} \ll 1$, and the flux grows due to the decelerated expansion of the Universe as $d\Phi/dE_\gamma \propto E^{1/2}$ until it reaches its maximum at $E_\gamma^{\text{max}} \simeq \varepsilon_\gamma (\Omega_M H_0^2 \tau^2 / 4)^{1/3}$. Above this energy, the flux is suppressed exponentially by the decreasing number of decaying particles [3].

On the other hand, if $\tau \gg t_0$, $H_0^2 \tau^2 \Omega_{\text{DE}} \gg 1$, and the flux grows as $d\Phi/dE_\gamma \propto E^{1/2}$ only for photons that originated in the matter-dominated epoch. For decays in the vacuum-dominated Universe, the flux decreases asymptotically as $d\Phi/dE_\gamma \propto E^{(1+3w)/2}$ due to the accelerated expansion. The flux reaches its maximal value at $E_\gamma^{\text{max}} \simeq \varepsilon_\gamma [-\Omega_M / ((1 + 3w)\Omega_{\text{DE}})]^{-1/(3w)}$ where photons were produced at matter-vacuum equality. Note that this value and the spectrum shape depend on the properties of the dark energy. Assuming $\Omega_M = 0.25$, $\Omega_{\text{DE}} = 0.75$, $w = -1$, and $h = 0.7$, and that these particles make up all of nonbarionic dark matter, so that

$$\frac{N^{\text{in}}}{V_0} = 1.0 \times 10^{-9} \text{ cm}^{-3} \left[\frac{\text{TeV}}{m} \right] \left[\frac{\Omega_{\text{NBDM}}}{0.2} \right], \quad (5)$$

we find that the maximal flux is

$$\begin{aligned} \frac{d\Phi}{dE_\gamma}(E_\gamma^{\text{max}}) &= 1.33 \times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} \left[\frac{\text{TeV}}{m} \right] \\ &\times \left[\frac{\text{MeV}}{\Delta m} \right] \left[\frac{10^{21} \text{ s}}{\tau} \right]^{2/3} \left[\frac{\Omega_{\text{NBDM}}}{0.2} \right]. \end{aligned} \quad (6)$$

Figure 2 shows example contributions to the CGB from decaying dark matter in mUED and SUSY. The mass splittings have been chosen to produce maximal fluxes at $E_\gamma \sim \text{MeV}$. These frameworks are, however, highly constrained: once Δm is chosen, τ and the flux are essentially fixed. It is thus remarkable that the predicted flux is in the observable, but not excluded, range and may explain the current excess above known sources.

To explore this intriguing fact further, we relax model-dependent constraints and consider τ and Δm to be independent parameters in Fig. 3. The labeled curves give the points in $(\tau, \Delta m)$ parameter space where, for the WIMP masses indicated and assuming Eq. (5), the maximal flux from decaying dark matter matches the flux of the observed photon background in the keV to 100 GeV range [19]. For

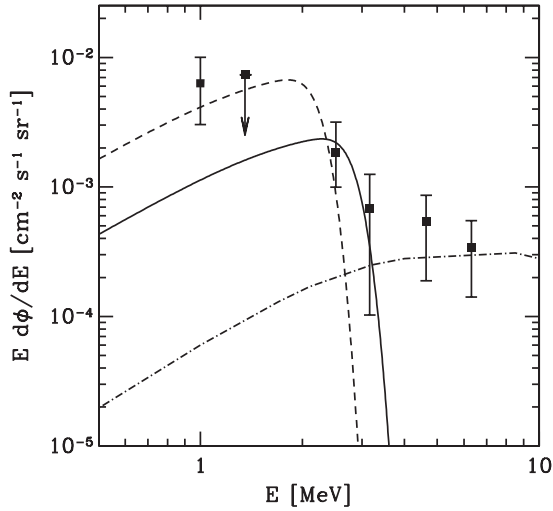


FIG. 2. Data for the CGB in the range of the MeV excess, along with predicted contributions from extragalactic dark matter decay. The curves are for $B^1 \rightarrow G^1 \gamma$ in mUED with lifetime $\tau = 10^3 t_0$ and $m_{B^1} = 800$ GeV (solid line) and $\tilde{B} \rightarrow \tilde{G} \gamma$ in SUSY with lifetime $\tau = 5 \times 10^3 t_0$ and $m_{\tilde{B}} = 80$ GeV (dashed line). We have assumed $\Omega_{\text{NBDM}} = 0.2$ and smeared all spectra with energy resolution $\Delta E/E = 10\%$, characteristic of experiments such as COMPTEL. The dot-dashed curve is the upper limit to the blazar spectrum, as in Fig. 1.

a given WIMP mass, all points above the corresponding curve predict peak fluxes above the observed photon background and so are excluded.

The shaded band in Fig. 3 is the region where the maximal flux falls in the unaccounted for range of 1–5 MeV. For $\tau \geq t_0$, $E_\gamma^{\text{max}} \approx 0.55 \Delta m$. However, for $\tau \leq t_0$, E_γ^{max} does not track Δm , as the peak energy is significantly redshifted. For example, for a WIMP with mass 80 GeV, $\tau \sim 10^{12}$ s and $\Delta m \sim \text{MeV}$, $E_\gamma^{\text{max}} \sim \text{keV}$. The overlap of this band with the labeled contours is where the observed excess may be explained through WIMP decays. We see that it requires $10^{20} \text{ s} \leq \tau \leq 10^{22} \text{ s}$ and $1 \text{ MeV} \leq \Delta m \leq 10 \text{ MeV}$. These two properties may be simultaneously realized by two-body gravitational decays: the diagonal line shows the relation between τ and Δm given in Eq. (1) for $B^1 \rightarrow G^1 \gamma$, and we see that this line passes through the overlap region. Similar conclusions apply for all other decay models discussed above.

These considerations of the diffuse photon background also have implications for the underlying models. For mUED, $\Delta m = 2.7\text{--}3.2$ MeV and $\tau = 4\text{--}7 \times 10^{20}$ s can explain the MeV excess in the CGB. This preferred region is realized for the decay $B^1 \rightarrow G^1 \gamma$ for $R^{-1} \approx 808$ GeV. (See Fig. 4.) Lower R^{-1} predicts larger Δm and shorter lifetimes and is excluded. The MeV excess may also be realized for $G^1 \rightarrow B^1 \gamma$ for $R^{-1} \approx 810.5$ GeV, though in this case the G^1 must be produced nonthermally to have the required dark matter abundance [17,20].

So far we have concentrated on the cosmic, or extragalactic, photon flux, which is dependent only on cosmo-

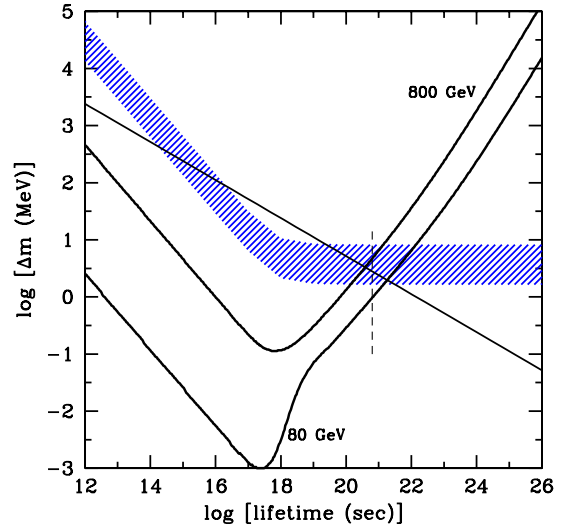


FIG. 3 (color online). Model-independent analysis of decaying dark matter in the $(\tau, \Delta m)$ plane. In the shaded region, the resulting extragalactic photon flux peaks in the MeV excess range $1 \text{ MeV} \leq E_\gamma^{\text{max}} \leq 5 \text{ MeV}$. On the contours labeled with WIMP masses, the maximal extragalactic flux matches the extragalactic flux observed by COMPTEL; points above these contours are excluded. The diagonal line is the predicted relation between τ and Δm in mUED. On the dashed line, the predicted galactic flux matches INTEGRAL's sensitivity of $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$ for monoenergetic photons with $E_\gamma \sim \text{MeV}$.

logical parameters. The galactic photon flux depends on halo parameters and so is less robust, but it has the potential to be a striking signature, since these photons are not redshifted and so will appear as lines with $E_\gamma = \Delta m$. INTEGRAL has searched for photon lines within 13° from the galactic center [21]. For lines with energy $E \sim \text{MeV}$ and width $\Delta E \sim 10$ keV, INTEGRAL's energy resolution at these energies, INTEGRAL's sensitivity is $\Phi \sim 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$. The galactic flux from decaying dark matter saturates this limit along the vertical line in Fig. 3, assuming $m_\chi = 800$ GeV. This flux is subject to halo uncertainties; we have assumed the halo density profiles of Ref. [22], which give a conservative upper limit on the flux within the field of view. Remarkably, however, we see that the vertical line also passes through the overlap region discussed above. If the MeV CGB anomaly is explained by decaying dark matter, then the galactic flux is also observable, and future searches for photon lines will stringently test this scenario.

In conclusion, well-motivated frameworks support the possibility that dark matter may be decaying now. We have shown that the diffuse photon spectrum is a sensitive probe of this possibility, even for lifetimes $\tau \gg t_0$. This is the leading probe of these scenarios. Current bounds from the CMB [23] and reionization [24] do not exclude this scenario, but they may also provide complementary probes in the future. We have also shown that dark matter with mass splittings $\Delta m \sim \text{MeV}$ and lifetimes $\tau \sim 10^3\text{--}10^4$ Gyr can explain the current excess of observations above astrophys-

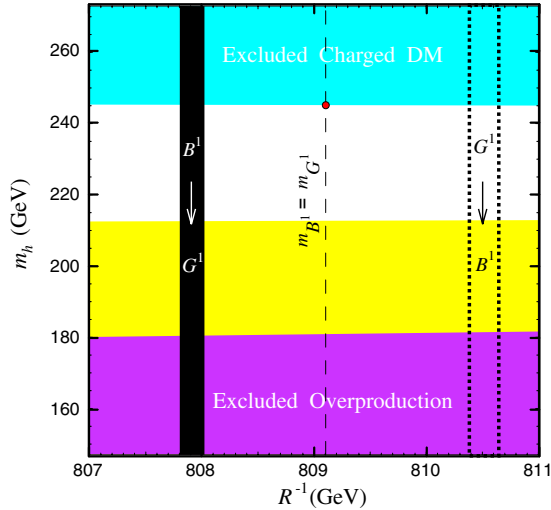


FIG. 4 (color online). Phase diagram of mUED. The top and bottom shaded regions are excluded for the reasons indicated [16]. In the yellow (light) shaded region, the B^1 thermal relic density is in the 2σ preferred region for nonbaryonic dark matter [18]. In the vertical band on the left (right) the decay $B^1 \rightarrow G^1 \gamma$ ($G^1 \rightarrow B^1 \gamma$) can explain the MeV diffuse photon excess.

ical sources at $E_\gamma \sim \text{MeV}$. Such lifetimes are unusually long, but it is remarkable that these lifetimes and mass splittings are simultaneously realized in simple models with extra dimensional or supersymmetric WIMPs decaying to KK gravitons and gravitinos. Future experiments, such as ACT [25], with large apertures and expected energy resolutions of $\Delta E/E = 1\%$, may exclude or confirm this explanation of the MeV excess through both continuum and line signals. Finally, we note that if dark matter is in fact decaying now, the diffuse photon signal is also sensitive to the recent expansion history of the Universe. For example, as we have seen, the location of the spectrum peak is a function of Ω_M/Ω_{DE} and w . The CGB may therefore, in principle, provide novel constraints on dark energy properties and other cosmological parameters.

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