The instability of dark matter may produce visible signals in the spectrum of cosmic gamma-rays. We consider this possibility in frameworks with additional spatial dimensions and supersymmetry. Examples of particles include superweakly-interacting massive particles such as gravitinos in supersymmetry models, the lightest Kaluza-Klein (KK) state in models with universal extra dimensions, and weakly-interacting massive particles such as branons in flexible brane-worlds.

**Introduction**

Though we know that approximately one fourth of the energy density of the Universe is made of non standard particles, the microscopic nature of such particles remains as one of the major mysteries in science. This fundamental piece of standard cosmology, known as dark matter (DM), is usually assumed to be in the form of stable, massive, collisionless and non-self-interacting particles. Weakly-interacting massive particles (WIMPs) that freeze-out with the right thermal abundance in the early Universe are well-motivated dark matter candidates with masses and interaction cross sections of the order of the weak scale. WIMPs emerge naturally from different particle physics scenarios such as the lightest supersymmetric particle (LSP) in R-parity conserving supersymmetry (SUSY) models [1], the lightest Kaluza-Klein (KK) excitation (LKP) in models with universal extra dimensions (UED) [2], or branons in flexible brane-worlds [3, 4].

Other well established candidates are superweakly-interacting massive particles (superWIMPs), which are born from unstable WIMPs with typical lifetimes $\tau \sim 1 \text{ s} - 10^8 \text{ s}$, and naturally inherit the abundance of the WIMPs from which they are produced [5, 6]. Examples of superWIMPs include non-thermally produced weak-scale gravitinos [5, 6, 7, 8, 9], axinos [10], and quintessinos [11] in supersymmetry; and Kaluza-Klein graviton and axion states in models with universal extra dimensions [12].

The experimental search for DM depends on its nature, and in general, a strong statement would need the interplay of collider experiments [14, 15] and astrophysical observations. These latter observations are typically classified as direct or indirect searches (see [13] however, for different alternatives). Additionally, elastic scattering of DM particles from nuclei should lead directly to observable nuclear recoil signatures.

In this note we point out that present DM particles can be unstable and have associated lifetimes of the order of the age of the Universe or longer. In this case, new DM signatures can be explored, such as anomalies in cosmic gamma-rays. Such DM particles can be found in the above mentioned scenarios with supersymmetry and extra dimensions, not only in form of superWIMPs, but also in form of WIMPs, for example in the case of branons.

**Gamma-ray background**

For highly degenerate particles, the decays can take place very late to soft photons. The photon spectrum is not thermalized and produces bumps in the diffuse photon spectrum that may be observable. The present differential flux of photons from a general decay is given by

$$
\frac{d\Phi}{dE_\gamma} = \frac{c n_\gamma}{4\pi} \int_0^{t_0} dt N(t) \frac{d\Gamma_\gamma}{V_0} \frac{d\varepsilon_\gamma}{dE_\gamma}.
$$

(1)
Figure 1: Contributions from extragalactic dark matter decays along with data for the cosmic gamma background observed by COMPTEL. The curves are for $B^1$ decay in mUED with lifetime $\tau = 10^3 t_0$ and $m_{B^1} = 800$ GeV (solid) and, $\tilde{B}$ decay in SUSY with lifetimes $\tau = 5 \times 10^3 t_0$ and $m_{\tilde{B}} = 80$ GeV (dashed). We have assumed that these particles make up all of non-baryonic dark matter ($\Omega_{N_{BDM}} = 0.2$) and smeared all spectra with energy resolution $\Delta E/E = 10\%$, characteristic of COMPTEL [16].

where $n_\gamma$ is the number of photons produced in a single decay. $t_0 \simeq 4.3 \times 10^{17}$ s. is the age of the universe, $N(t) = N^{in}e^{-t/\tau}$, where $N^{in}$ is the initial number of decaying particles, $V_0$ is the present volume of the universe, and the relation between the produced energy $\varepsilon_\gamma$, and observed energy $E_\gamma$, is given by the scale factor of the Universe:

$$\frac{d\varepsilon_\gamma}{dE_\gamma} = (1 + z)^{-1}.$$  

In the case of a two body decay, the produced photons have a determined energy given by the mass splitting between the decaying particle and the produced one: $\varepsilon_\gamma = \Delta M$. It means that

$$\frac{d\Phi}{dE_\gamma} = \delta \left( E_\gamma - \frac{\varepsilon_\gamma}{1+z} \right) \Gamma_\gamma$$

and

$$P(a) \equiv 2 \left( \ln \left[ \sqrt{\Omega_M a^3} + \sqrt{\Omega_\Lambda + \Omega_M a^3} \right] - \ln \left[ \sqrt{\Omega_M} \right] \right)$$

is given by the equation:

$$\frac{da}{dt} = aH \simeq H_0 \sqrt{\frac{\Omega_M}{a}} + \Omega_\Lambda a^2 \equiv Q(a),$$

The flux has a maximum at

$$E_\gamma = \varepsilon_\gamma \left[ \frac{\Omega_M}{2\Omega_\Lambda} U(H_0^2 \tau^2 \Omega_\Lambda) \right]^{1/3},$$

where $U(x) = \frac{1}{2} \exp \left( \sqrt{x^2 + 1} \right) - 1$. Here we are neglecting the radiation content, $\Omega_R \sim 0$, and the curvature: $k \sim 0$ [16]. For this calculations, we use a flat cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h = 0.7$. An interesting side

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point of this analysis is the sensitivity of the signal to cosmology. The gamma ray background may provide novel constraints on the above parameters and dark energy properties.

We can gain further insight into the spectrum shape in Fig. 1 by considering asymptotic limits. If the lifetime is much shorter than the age of the Universe, $H_0^2 \tau^2 \Omega_\Lambda << 1$, the flux grows as $d\Phi/dE_\gamma \propto E^{1/2}$ until it reaches its maximal value at:

$$E_\gamma^{\text{max}} \simeq \varepsilon_\gamma \left[ \frac{\Omega_M H_0^2 \tau^2}{4} \left( 1 - \frac{5 H_0^2 \tau^2 \Omega_\Lambda}{4} + \ldots \right)^{1/2} \right]. \quad (6)$$

From this energy, the flux is suppressed exponentially due to the decreasing number of decaying particles. On the other hand, if the lifetime is much longer than the age of the Universe, $H_0^2 \tau^2 \Omega_\Lambda >> 1$, the flux only grows as $d\Phi/dE_\gamma \propto E^{1/2}$ when the dark matter decays in the matter dominated epoch. For decays in the vacuum dominated Universe, the flux decreases as $d\Phi/dE_\gamma \propto E^{-1}$, reaching its maximum at the transition between these two regimes:

$$E_\gamma^{\text{max}} \simeq \varepsilon_\gamma \left[ \frac{\Omega_M}{2 \Omega_\Lambda} \left( 1 - \frac{\sqrt{3}}{H_0 \tau \sqrt{\Omega_\Lambda}} + \ldots \right)^{1/4} \right]. \quad (7)$$

Thus at first order the maximum does not depend on $\tau$. [10]

In figure 2 we show the generic region of parameter space $\Delta m - \tau$ that is probed by the diffuse photon background. We use the limit on the diffuse photon background from $\sim$ keV-100 GeV as determined in [17]. The solid lines label the points where the peak of the photon spectrum from decays exactly matches the observed photon background. Of course, for energy regimes where the photon background is well-resolved, these lines provide a conservative upper limit to the amount of photon flux allowed from dark matter decays. For a fixed decaying DM (DDM) mass scale, all points above these lines are roughly inconsistent with the photon background, as the peak of the decay photon spectrum lies above the observational limits. For lifetimes $\tau \gg t_0$, the peak of the energy spectrum is very similar to the mass difference. In this limit the relationship between the observed peak and the mass difference is given by Eq. (7). The turnover for lifetimes $\lesssim t_0$ reflects the fact that the photons of an emitted energy redshift to appear at different observed energies. For example, the decay of an 80 GeV particle with lifetime $\tau \approx 10^{12}$ sec. ($z \approx 4000$) and $\Delta m \approx$ MeV produces a spectrum with peak $\sim$ keV.

The shaded band in figure 2 shows the region where the energy of the detected photons fall in the unaccounted for range of 1-10 MeV. The diagonal line shows the relation for the model $B^1 \rightarrow G^1 + \gamma$, though similar relations hold for the other gravitational suppressed two-body decays. Importantly, these relations are independent of the mass scale for these high degeneracies. The region of parameter space defined by $\tau \approx 10^{21}$ sec and $\Delta m \approx$ MeV defines the preferred mUED and SUSY models that can account for the cosmic gamma-ray background in the 1-10 MeV regime.

**Gamma-ray lines from the center of the Galaxy**

If the DDM comprises the majority of the dark matter today, they will decay inside our local halo producing photons, positrons, electrons and neutrinos. The fluxes of all these particles will reach the Earth providing the possibility of a directional dependent DM signal. If this DDM produce photons directly from two-body decays, these photons will appear as line flux at energy exactly determined by the mass splitting, with no redshifting. To determine the Galactic signal, we define $\Psi$ as the angle between the direction of the Galactic center and the line of observation, and $l$ as the distance from the Sun to any point in the halo. In a line-of-sight direction determined by $\Psi$, the differential $\gamma$-ray flux from decays of dark matter is

$$\frac{d\Phi}{d\Omega dE_\gamma} = \frac{dN_\gamma}{dE_\gamma} e^{-t_0/\tau} \frac{1}{4 \pi \tau m_x} \int_0^{l_{\text{max}}(\Psi)} \rho[r(l)] dl(\Psi). \quad (8)$$

The radial distance $r$ is measured from the Galactic center, and is related to $l$ by $r^2 = l^2 + D_\odot^2 - 2 D_\odot l \cos \Psi$, where $D_\odot = 8.5$ kpc is the distance from the Sun to the center of the Galaxy. The distance from the Sun to any point on the edge

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Figure 2: The general mass difference-lifetime parameter space for decaying dark matter scenarios. The solid lines reflect the points where the peak of the spectrum from decays exactly matches the observed photon spectrum. The shaded region corresponds to a detected energy in the unaccounted for range 1-10 MeV. The diagonal line shows the relation for the $G^1$ LKP model in mUED [16].

of the halo in the direction $\theta$ is $l_{\text{max}} = D \cos \theta + \sqrt{r^2 - D^2 \sin^2 \theta}$. Each decay produces one photon with energy given by the mass difference, $\Delta m$, so the photon spectrum is $dN/\gamma/dE = \delta(E_\gamma - \Delta m)$.

The photon flux is maximized in the direction of the Galactic center, and must be averaged over the solid angle of the detector. For detectors with sensitivities to energies in the tens of MeV regime, the solid angles are typically of order $\Delta \Omega = 2\pi(1 - \cos \Psi) \approx 10^{-3}$. One can model the dark halo of the Milky Way with the results of [18]. We have found that the effects of dark matter clumps in the halo are negligible. Indeed, for realistic distributions of the clumps, the flux is only increased by $\sim 1\%$ for all lifetimes.

Positrons may also be produced in the decays. If positrons are produced with energies smaller than 3MeV, they will be effectively stopped before annihilating with electrons, losing their kinetic energy through collisional ionization or excitation in neutral Hydrogen and by interaction with plasma waves in ionized interstellar medium. In such a case, they produce a narrow photon line at $\epsilon_\gamma \approx m_e \approx 511$keV if they annihilate directly into 2 photons or through parapositronium formation. Annihilation in such a state happens 25\% of the time that positronium is formed. The other 75\% of the time, the annihilation takes place in the orthopositronium state, yielding a photon continuum with $\epsilon_\gamma < 511$ keV. Consequently, the total number of 511 keV photons produced per unit time is given by $dn_{511}/dt = 2(1 - 3p/4)\rho_{DDM}\Gamma_{e^+} = 2(1 - 3p/4)\rho_{DDM}\Gamma_{e^+}/M$, where we are supposing that annihilation takes place through positronium formation a fraction $p$ of the time.

The predicted distribution of the 511 line for any particular model of the Milky Way dark halo can be computed as the integral along the line of sight, as a function of galactic longitude $\ell$ and latitude $b$, of the emissivity $dn_{511}/dt$:

$$\frac{d\Phi_{511}(b, \ell)}{dE_\gamma d\Omega} \approx \frac{1}{4\pi} \int_0^\infty \frac{dn_{511}(r(s,b,\ell))}{dt} ds,$$

where in this case, we are parameterizing the halo radius as: $r(s,b,\ell) = D_s^2 + s^2 + 2D_s s \cos b \cos \ell$. The morphology of the emission depends on the Milky Way halo profile (in addition to the precise distribution of baryons and their chemical composition, which determine the positron propagation). Observations are just sensitive to the inner region of the halo, and demand a cuspy halo. The intensity of the emission is so low in outermost regions that it is difficult
to discriminate from the instrumental background. Interestingly, the splittings and lifetimes that can account for the cosmic gamma-ray background at MeV energies are also appropriate to explain the 511 line. An example of a DM candidate that can provide such phenomenology is the branon, due to its universal coupling with all standard model particles [19].

Conclusions

The main idea of this note is that decaying dark matter can provide indirect detection signals at scales much smaller than their masses. We have analyzed this idea for the extragalactic photon background observed by COMPTEL [20] and the photon lines coming from the Galactic center observed by INTEGRAL [21]. Below \( \sim 1 \) MeV and above \( \sim 10 \) MeV, the extragalactic photon fluxes are well-modeled by the diffuse cosmological emission of unresolved Active Galactic Nuclei [22], but in the entire regime of \( \sim 1-5 \) MeV, no population of known astrophysical sources are able to account for the observed cosmic gamma-ray background [23, 24]. An additional intriguing source of non-relativistic positrons from the center of our Galaxy has been determined recently by the INTEGRAL satellite.

We have shown that DDM provides a viable explanation that deserves further investigation. As we have seen, these late decays at MeV scales are natural for gravitationally suppressed superWIMPs, and also for TeV WIMPs such as branons in flexible brane-worlds.

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