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Gamma-Rays from Decaying Dark Matter

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Abstract. We study the prospects for detecting gamma-rays from decaying Dark Matter (DM), focusing in particular on gravitino DM in R-parity breaking vacua. Given the substantially different angular distribution of the predicted gamma-ray signal with respect to the case of annihilating DM, and the relatively poor (of order $0.1°$) angular resolution of gamma-ray detectors, the best strategy for detection is in this case to look for an exotic contribution to the gamma-ray flux at high galactic latitudes, where the decaying DM contribution would resemble an astrophysical extra-galactic component, similar to the one inferred by EGRET observations. Upcoming experiments such as GLAST and AMS-02 may identify this exotic contribution and discriminate it from astrophysical sources, or place significant constraints on the mass and lifetime of DM particles.

1. Introduction

A tremendous theoretical and experimental effort is in progress to clarify the nature of the elusive *Dark Matter* that appears to dominate the matter density of the Universe [1, 2]. The most studied DM candidates are Weakly Interacting Massive Particles, that achieve the appropriate relic density by *freezing-out* of thermal equilibrium when their self-annihilation rate becomes smaller than the expansion rate of the Universe. The characteristic mass of these particles is $\mathcal{O}(100)$ GeV, and the most representative and commonly discussed candidates in this class of models are the supersymmetric neutralino, and the $B^{(1)}$ particle, first excitation of the hypercharge gauge boson, in theories with Universal Extra Dimensions. These particle are and will be searched for via collider, direct and indirect searches. In particular, the latter are based on the very same mechanism that controls the relic density of DM, i.e., self-annihilations. In fact, although the annihilation rate in the local Universe is on average severely suppressed, it can still be extremely high at the centre of dense DM halos, since it is proportional to the square of the DM particles number density. The prospects for indirect detection of annihilating DM have been extensively discussed (see [1, 2] and references therein).

However, self-annihilating relics are not the only DM candidates, and indirect DM searches are not only relevant for self-annihilating particles. Three of us have recently studied an excellent DM candidate, the gravitino in R-parity breaking vacua, that can achieve the appropriate relic density through the thermal production in the early high-temperature phase of the Universe, and that naturally leads to a cosmological history consistent with thermal leptogenesis and primordial nucleosynthesis [3].

Since R-parity is broken, gravitinos can decay into a photon and a neutrino [4], although with a lifetime that, being suppressed both by the Planck mass and by the small R-parity breaking parameters, is naturally much longer than the age of the Universe [5]. Similarly, for sufficiently small R-parity breaking, also neutralinos [6, 7] and axinos [8] are dark matter candidates which can decay into a photon and a neutrino. These scenarios thus predict a diffuse flux of photons and neutrinos that, by comparison with existing observational data, can be used to set constraints on the mass and lifetime of the decaying particles. Interestingly, an excess in the galactic component of the diffuse gamma-ray flux measured by EGRET has been claimed in Ref. [9], at energies between 1 and 10 GeV. A more careful analysis of the Galactic foreground has led Strong *et al.* to a new estimate of the extra-galactic component [10] with a significantly different spectrum with respect to the previous analysis. More recently, Stecker *et al.* [11] pointed out a possible error in the energy calibration of EGRET above 1 GeV, a circumstance that if confirmed would make any interpretation of EGRET data in terms of exotic components, such as DM annihilation or decay, unreliable, if not meaningless.

In view of these and other systematic uncertainties [12], we will not try here to fit the EGRET data with the gamma-ray flux produced by decaying DM, although we regard this coincidence as interesting and deserving further attention. We perform instead a careful analysis of the signal that might be detected with the next generation of gamma-ray experiments. Similar analyses has previously been carried out for decaying DM candidates with masses in the keV range, such as a scalar modulus [13] or a sterile neutrino [14, 15]. More recently also the case of small mass splittings and heavy DM decaying into MeV photons has been discussed in order to explain the COMPTEL excess in the photon flux [16, 17].

Unlike the case of stable neutralinos and other WIMPs, the rate at which gravitinos produce photons is proportional to the density of DM particles, as appropriate for decaying DM particles, not to the *square* of the DM density. As a consequence, the strategies for indirect detection must keep into account the different angular distribution of the predicted signal, and the different ratio between galactic and extra-galactic contributions. Although the situation is very similar to the case of other decaying DM candidates, such as decaying sterile neutrinos, the angular resolution of experiments sensitive to photons from decaying gravitinos, typically above 5 GeV [3], are much worse than X-ray telescopes, relevant for sterile neutrinos. Here we study the best strategies to detect an exotic component in the gamma-ray diffuse flux with future experiments such as the upcoming gamma-ray satellite GLAST, scheduled for launch in the next few months, and with AMS-02. Although in our analysis we adopt gravitinos as our fiducial DM candidates, our results can be applied to any decaying DM particle in a similar range of masses into monochromatic photons.

The paper is organised as follows: in Sec. 2 we discuss our expectation for gravitino lifetime and the decay channel, while in Sec. 3 the Galactic and extra-galactic contributions to the gamma-ray flux from gravitino decays. In Sec. 4 we consider alternative targets for indirect detection such as dwarf galaxies and galaxy clusters. In Sec. 5 we discuss our results and compare the indirect detection strategies of decaying and self-annihilating DM. Finally we give our conclusions in Sec. 6.

2. Gravitino decay

As is the case for the proton, we do not know if the DM particle is absolutely stable. In the case of supersymmetric candidates, usually R-parity is invoked to make the proton sufficiently long-lived and it automatically gives that the Lightest Supersymmetric Particle (LSP) is stable. On the other hand R-parity is not the only possibility for protecting the proton from rapid decay and a small amount of R-parity violation does not rule out the possibility of having supersymmetric DM if the LSP is very weakly interacting with the R-parity violating sector or the decay is highly suppressed by phase space. As an example, in [3], we have considered a supersymmetric extension of the standard model with small R-parity and lepton number violating couplings and a gravitino LSP. The model predicts a small photino-neutrino mixing $|U_{\tilde{\gamma}\nu}| = \mathcal{O}(10^{-8})$, which leads to the decay of the gravitino into photon and neutrino [5],

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_{\rm P}{}^2} \, . \tag{1}$$

Using $M_{\rm P} = 2.4 \times 10^{18}$ GeV, one obtains for the gravitino lifetime

$$\tau_{3/2}^{2-\rm body} \simeq 3.8 \times 10^{27}{\rm s} \left(\frac{|U_{\tilde{\gamma}\nu}|}{10^{-8}}\right)^{-2} \left(\frac{m_{3/2}}{10\ {\rm GeV}}\right)^{-3} \, . \tag{2}$$

At tree level this decay channel can be suppressed if the sneutrino $v.e.v.$ responsible for the photino-neutrino mixing is very small, but even if the mixing vanishes, the decay can take place via one loop diagrams. The loop induced decay has been recently computed in [18], where it has been shown that also in this case the channel dominates over the 3-body decay into fermions [19] for small gravitino masses. For this reason we will concentrate on this particular channel and will assume in the following that our Dark Matter candidate decays into a photon and neutrino producing two monochromatic lines at energy equal to $m_{DM}/2$ with a lifetime of the order of 10^{27}s or larger. On the other hand, if the gravitino is sufficiently heavy it could decay into W or Z bosons, producing through fragmentation a continuous spectrum of photons with a characteristic shape [20]. The neutrino flux in the few GeVs energy range is unfortunately overwhelmed by the atmospheric neutrino background and so its detection seems much more difficult than that of the gamma-ray flux.

Note that the signal in gammas would be the same, only twice as strong, for the case of a scalar DM candidate decaying into two photons.

3. Gamma-Rays from DM decay

If the DM particles decay all around us, we expect two sources for a diffuse background. We have the DM decaying in the Milky Way halo nearby and in addition those decaying at cosmological distances.

Let us first consider the latter ones, which have been more intensively studied in the literature [5, 21]. The decay of DM into photon and neutrino at cosmological distances gives rise to a perfectly isotropic extragalactic diffuse gamma-ray flux with a characteristic energy spectrum, corresponding to a red–shifted monochromatic line. A photon with measured energy $E = m_{3/2}/(2(1+z))$ has been emitted at the comoving distance $\chi(z)$, with $d\chi/dz = (1+z)^{-3/2}/(a_0 H_0 \sqrt{\Omega_M(1+\kappa(1+z)^{-3})})$. Here a_0 and H_0 are the present scale factor and Hubble parameter, respectively, and $\kappa = \Omega_\Lambda/\Omega_M \simeq 3$, with $\Omega_\Lambda + \Omega_M = 1$, assuming a flat universe. Then we obtain for the photon flux

$$\frac{dJ_{eg}}{dE} = A_{eg} \frac{2}{m_{DM}} \left(1 + \kappa \left(\frac{2E}{m_{DM}}\right)^3\right)^{-1/2} \left(\frac{2E}{m_{DM}}\right)^{1/2} \Theta\left(1 - \frac{2E}{m_{DM}}\right) , \quad (3)$$

with

$$A_{eg} = \frac{\Omega_{DM}\rho_c}{4\pi\tau_{DM} m_{DM} H_0 \Omega_M^{1/2}} = 10^{-7}\,(\mathrm{cm}^2\mathrm{s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ \mathrm{s}}\right)^{-1} \left(\frac{m_{DM}}{10\ \mathrm{GeV}}\right)^{-1} ; (4)$$

here τ_{DM} is the DM particle lifetime and is given by Eq. (2) for the gravitino case. We have taken the particle density to be equal to the Cold Dark Matter density as $\Omega_{DM} h^2 = 0.1$, and the other constants as $\rho_c = 1.05\ h^2 \times 10^{-5}\mathrm{GeVcm}^{-3}$, total matter density $\Omega_M = 0.25$ and $H_0 = h\ 100\ \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$ with $h = 0.73$ [22]. We are considering here $\tau_{DM} \gg H_0^{-1}$ so that we can neglect in the above formula the depletion of the number density due to the decay.

In addition to the extragalactic signal there is an anisotropic sharp line from the halo of our galaxy with an intensity comparable to the extragalactic signal [13]. The flux from the decay of halo DM particles is given by the density profile, i.e.

$$\frac{dJ_{halo}}{dE} = A_{halo} \frac{2}{m_{DM}} \delta\left(1 - \frac{2E}{m_{DM}}\right) , \quad (5)$$

where

$$A_{halo} = \frac{1}{4\pi\tau_{DM} m_{DM}} \int_{l.o.s.} \rho_{halo}(\vec{l}) d\vec{l} . \quad (6)$$

The ratio A_{halo}/A_{eg} only depends on cosmological parameters and the halo dark matter density integrated along the line of sight ‡. Hence, the intensity and angular distribution of the halo signal is very sensitive to the distribution of the dark matter in the Milky Way. Surprisingly, for typical halo models, this ratio is of order unity [13].

Consider a Navarro-Frenk-White profile for the DM matter of our galaxy,

$$\rho_{NFW}(r) = \frac{\rho_h}{r/r_c(1 + r/r_c)^2} \quad (7)$$

‡ The coefficients A_{halo} and A_{eg} are related to the coefficients C_γ and D_γ in our previous paper [3] by a factor $2/m_{3/2}$. Let us also note that in that reference there is a typo in the definition of C_γ: it should say 10^{-7} instead of 10^{-6}.

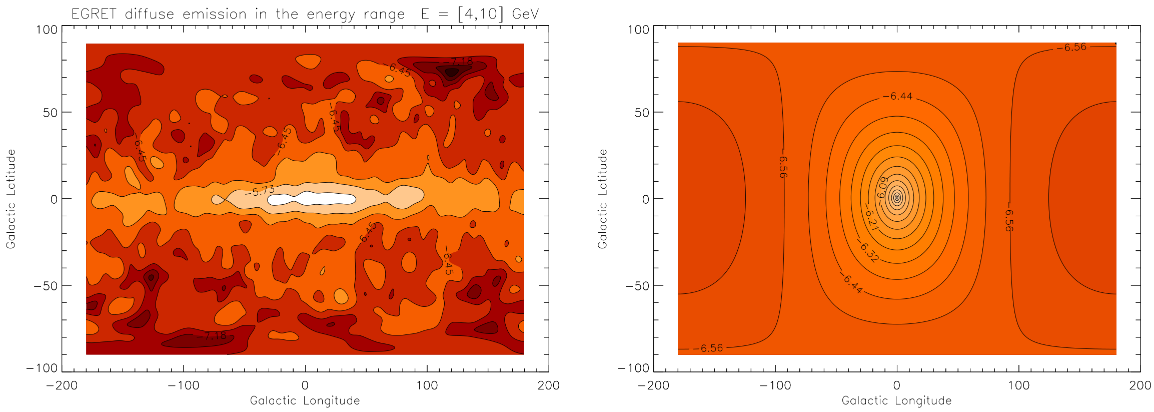

Figure 1. *Left:* EGRET diffuse emission in the energy range E=[4,10] GeV. *Right:* Sum of the Galactic plus extra-galactic contributions to the gamma-ray flux from gravitino decay, for $\tau_{DM} = 4 \times 10^{27}$ s and $m_{DM} = 10$ GeV and the NFW profile given in Eq. (7).

with $\rho_h = 0.33\ \mathrm{GeV/cm^3} = 0.6 \times 10^5 \rho_c$ giving the halo density normalisation and $r_c = 20$ kpc the critical radius where the profile slope changes. For any given point along the line of sight, the distance r from the centre of the galaxy can be expressed as function of the galactic coordinates, the longitude l and latitude b, and the distance from the Sun s in units of $R_\odot$ as

$$r^2(s,b,l) = R_\odot^2 \left[(s - \cos b \cos l)^2 + (1 - \cos^2 b \cos^2 l) \right] . \tag{8}$$

The flux factor then reads

$$A_{halo}(b,l) = \frac{R_\odot}{4\pi \tau_{DM} m_{DM}} \int_0^\infty ds\ \rho_{NFW}(r(s,b,l)) . \tag{9}$$

This expression can be used to give the flux dependence on the angle, as long as we are far away from the central cusp. In that region a more appropriate quantity is the average flux on the solid angle corresponding to the detector resolution around the direction (b,l), i.e.

$$\langle A_{halo}(b,l) \rangle_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega\ A_{halo}(b,l) , \tag{10}$$

where the infinitesimal solid angle is given by $d\Omega = dl \cos(b) db$. We consider therefore the average flux for an angular resolution of 1° as measured by EGRET. The result of the numerical integration for the halo flux plus the isotropic extragalactic component is shown in the right panel of Fig. 1, which illustrates the decrease of photon flux away from the galactic centre, both in longitude and latitude. Note that the dependence is not very strong and indeed A_{halo} changes only by a factor 20 between the galactic centre and the anti-centre, and within a factor of 8 if one cuts out the region within 10 degrees around the galactic plane. Averaging over all sky excluding the galactic plane, we obtain $\overline{A}_{halo}/A_{eg} \simeq 0.76$, so that the line is actually dominating the signal. In fact the total flux of diffuse gamma-rays for all sky directions is given by

$$\Phi_{diff} = \int d\Omega \int_0^\infty dE \left(\frac{dJ_{eg}}{dE} + \frac{dJ_{halo}}{dE}(b,l) \right) \tag{11}$$

$$= 4\pi A_{eg} \frac{2\sinh^{-1}(\sqrt{\kappa})}{3\sqrt{\kappa}} + \int_{-\pi/2}^{\pi/2} \cos(b) db \int_{-\pi}^{\pi} dl A_{halo}(b,l) \tag{12}$$

$$\simeq 4\pi A_{eg} \left(0.5 + \frac{\overline{A}_{halo}}{A_{eg}} \right) \tag{13}$$

$$\simeq 1.5 \times 10^{-6}\ (\mathrm{cm}^2\ \mathrm{s})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ \mathrm{s}} \right)^{-1} \left(\frac{m_{DM}}{10\ \mathrm{GeV}} \right)^{-1}, \tag{14}$$

where we have used $\kappa = 3$ and Eqs. (4) and (6).

The expected signal from Dark Matter decay in the halo can be compared with the diffuse gamma-ray flux observed by EGRET. Contour lines of constant flux, with photon energies between 4 GeV and 10 GeV are shown in the right panel of Fig. 1. As expected, the smallest flux is observed in the directions of the north and south poles, i.e. orthogonal to the galactic disk. According to Fig. 1, the signal in these directions is larger than in the direction opposite to the galactic centre. We therefore conclude that the signal from the MW halo could be most effectively observed looking away from the galactic disk, which generates most of the background, in direction of the poles, in contrast with the strategy usually adopted for the detection of the self-annihilating DM signal.

The photon spectrum is dominated by the sharp line coming from our local halo, while the red-shifted extragalactic signal is appreciably lower. The position of the line allows a direct measurement of the DM particle mass and the height is inversely proportional to the lifetime. In Fig. 2, we show the expected signal for decaying particle mass of 10 GeV and for a lifetime of 10^{27} s in comparison to the extragalactic EGRET data [9, 10]. We mimic the finite energy resolution of the detector by convolving the signal with a Gaussian distribution and average the halo signal over a cone of 80° around the poles. The height and width of the line depend as usual on the energy resolution of the detector; here we have taken 15% as energy resolution, as quoted by EGRET in this energy range. Note also that the DM signal peaked at 5 GeV corresponds to the expectation of the model of gravitino LSP with R-parity and B-L breaking discussed in [3]. A word of caution though is in order in the comparison between data and signal: the EGRET extragalactic background displayed here has been extracted assuming isotropy, while our halo emission is mildly anisotropic away from the galactic plane. GLAST is expected to provide much better data at these energies, allowing a much more detailed analysis of the angular and spectral properties of the diffuse gamma-ray flux.

4. Alternative targets

The Milky Way has dwarf galaxies as satellites, which have a large mass to light ratio, like Draco and Ursa Minor. One may therefore hope that the flux from decaying DM

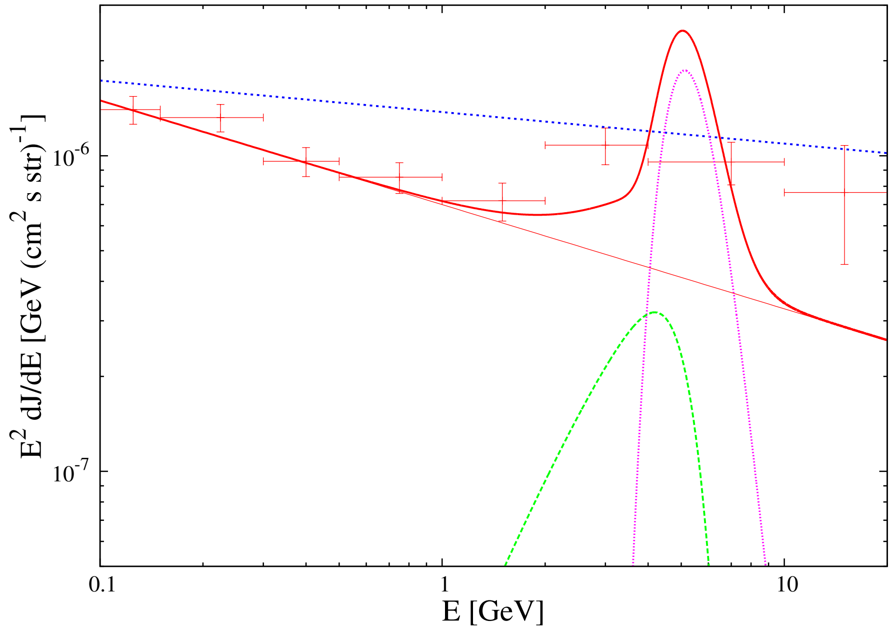

Figure 2. Energy spectrum of extragalactic and halo signal compared to the EGRET data. The data points are the EGRET extragalactic background as extracted by Strong *et al.* in [10], while the short-dashed (blue) line shows the powerlaw fit from Eq. (27) obtained previously by [9]. The extragalactic and halo signals for $\tau_{DM} = 10^{27}$ s and $m_{DM} = 10$ GeV are respectively the long-dashed (green) and dotted (magenta) lines, while the solid (thick red) line shows the sum of these contributions with a powerlaw background (thin red line), which has been obtained fitting the low energy EGRET points.

is significantly enhanced in these directions in the sky like in the case of annihilating DM [23]. In the following we shall study the dependence of the enhancement on the angular resolution of the detector and the mass of the dark matter constituents. For simplicity, we use the isothermal profile,

$$\rho_{halo}(r) = \frac{\rho_0}{1 + r^2/r_c^2} \, , \tag{15}$$

for which one can easily derive simple analytic expressions for the photon flux.

Integrating along the direction of sight and using Eqs. (5), (6) and (8), one finds for the photon flux from decaying dark matter in the Milky Way halo [13],

$$J_{halo}(b,l) = \frac{1}{4\pi}\frac{1}{\tau_{DM} m_{DM}}\frac{\rho_0 r_c^2}{R_\odot\sqrt{1-\cos^2 l\cos^2 b + r_c^2/R_\odot^2}} \times\left(\frac{\pi}{2} + \tan^{-1}\left(\frac{\cos b\cos l}{\sqrt{1-\cos^2 b\cos^2 l + r_c^2/R_\odot^2}}\right)\right) \, . \tag{16}$$

With $R_\odot \simeq 8.5$ kpc, $r_c \simeq 3.5$ kpc and $\rho_0 \simeq 1.37$ GeV cm^{-3}, this yields in the direction of Draco ($b_D = 34^\circ, l_D = 86^\circ$; $\cos l_D \cos b_D \simeq 0.06$):

$$J_{halo}(b_D, l_D) \simeq 0.8\times 10^{-7}\ (\text{cm}^2\text{s str})^{-1}\left(\frac{\tau_{DM}}{10^{27}\text{ s}}\right)^{-1}\left(\frac{m_{DM}}{10\text{ GeV}}\right)^{-1} \, . \tag{17}$$

The photon flux observed from a distant dwarf galaxy crucially depends on the angular resolution of the detector. Averaging over a cone with small opening angle δ, directed toward the centre of the dwarf galaxy, one has

$$J_{dg}(\delta) \simeq \frac{1}{2\tau_{DM} m_{DM}} \frac{1}{\Delta\Omega} \int_0^\delta \alpha d\alpha \int_{r_{min}(\alpha)}^{r_{max}(\alpha)} dr r^2 \frac{1}{r^2 + \alpha^2 r^2} \rho_{dg}(r(\alpha)) \; ; \qquad (18)$$

here $\Delta\Omega = \pi\delta^2$ is the infinitesimal solid angle, $r(\alpha) = \sqrt{(d-r)^2 + \alpha^2 r^2}$, d is the distance to the dwarf galaxy, ρ_{dg} is the isothermal profile in Eq. (15); we have also taken a finite tidal radius r_m into account, which leads to the finite integration domain given by $r(\alpha)^2 \leq r_m^2$. Performing the integrations, one obtains in the relevant case where $\delta \ll 1$ and $\delta d, r_c \ll r_m$,

$$J_{dg}(\delta) \simeq \frac{\rho_0 r_c}{4\tau_{DM} m_{DM}} \left(\frac{2r_c}{r_c + \sqrt{r_c^2 + \delta^2 d^2}} - \frac{2r_c}{\pi r_m} + \ldots \right) , \qquad (19)$$

where terms $\mathcal{O}(\delta^2)$ and $\mathcal{O}(\delta d r_c / r_m^2)$ have been neglected. Up to corrections $\mathcal{O}(r_c/d)$, the numerator of the prefactor is precisely the line of sight integral of the dark matter profile for $r_m \to \infty$,

$$\pi \rho_0 r_c = \int_{l.o.s} dr \rho_{dg}(r) , \qquad (20)$$

and for $\delta, 1/r_m \to 0$, the bracket becomes one.

Taking as an example Draco, typical parameters are $r_c = 0.1$ kpc, $\rho_0^{Dr} = 28.4$ GeV cm^{-3}, $r_m^{Dr} = 1.7$ kpc, $d^{Dr} = 80$ kpc [15]. The correction due to the finite tidal radius in Eq. (19) is then negligible, and in the line of sight approximation ($\delta = 0$) one obtains the flux

$$J_D(0) \simeq 2 \times 10^{-7} \; (\mathrm{cm^2 s \; str})^{-1} \left(\frac{\tau_{DM}}{10^{27} \; \mathrm{s}} \right)^{-1} \left(\frac{m_{DM}}{10 \; \mathrm{GeV}} \right)^{-1} , \qquad (21)$$

which is about three times larger than the flux from the halo in the same direction, as pointed out in [15]. The correction factor for finite opening angle in Eq. (19) can only be neglected for $\delta < r_c/d = 1.3 \times 10^{-3}$, which corresponds to the angular resolution of GLAST of about 0.1°. For $\delta \simeq 0.004$ the signals from Draco and the halo have equal strength, but the corresponding field of view is $\Delta\Omega \sim 5 \times 10^{-5}$, yielding the flux $\Phi_D(0.004) \sim 3.6 \times 10^{-12} (\mathrm{cm^2 s})^{-1}$, too small to be observed even by GLAST [24]. We conclude that for dark matter particles with masses in the GeV range the flux enhancement in the direction of dwarf galaxies is currently not of interest. This is different for masses in the keV range [15] where the flux is six orders of magnitude larger for the same DM density and in which case the angular resolutions of the X-rays detector is much better than for gamma rays.

Another potentially important source of gamma rays is the Andromeda Galaxy, due to its proximity, large apparent size and privileged position in the sky away from the Milky Way centre. To estimate the photon flux received from the Andromeda Galaxy, we approximate the dark matter distribution by the isothermal profile, Eq. (15), with $r_c^{\mathrm{M31}} = 1.5$ kpc, $\rho_0^{\mathrm{M31}} \simeq 15.7$ GeV cm^{-3}, $r_m^{\mathrm{M31}} = 117$ kpc [25]. The total flux received from a cone directed toward the centre of the Andromeda Galaxy with a small opening angle δ is given by Eq. (19). On the other hand, for the angular resolution of GLAST, the gamma ray flux from the Milky Way halo in the direction to the Andromeda Galaxy ($b_{\rm M31} = -22^\circ, l_{\rm M31} = 121^\circ$) is approximately

$$J_{halo}(b_{\rm M31}, l_{\rm M31}) \simeq 0.5 \times 10^{-7}\ ({\rm cm}^2{\rm s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ {\rm s}}\right)^{-1} \left(\frac{m_{DM}}{10\ {\rm GeV}}\right)^{-1} . \quad (22)$$

The opening angle at which the Milky Way signal equals the Andromeda Galaxy signal is around 5°, which corresponds to a flux $\Phi_{\rm M31}(5^\circ) \simeq 1.5 \times 10^{-9} ({\rm cm}^2{\rm s})^{-1}$. This is above the sensitivity of detection of GLAST (although below the EGRET sensitivity), hence we conclude that GLAST *might* be able to see the Andromeda Galaxy as a gamma ray source over the background from the decaying dark matter in the Milky Way halo. However, one should also note that the extraction of an extragalactic gamma ray flux at such low galactic latitudes is intricate, and the Andromeda signal from dark matter decay could be easily masked by photons from standard astrophysical processes occurring in the Milky Way disk.

Finally, let us discuss other potentially interesting sources of gamma rays, namely nearby galaxy clusters located at high galactic latitudes, like Coma or Virgo. The photon flux can be computed along the same lines as for dwarf galaxies, where the density profile Eq. (15) has to be replaced by the profile for the isothermal β-model [26, 27]

$$\rho^{cl} = \rho_0^{cl} \frac{3 + r^2/r_c^2}{(1 + r^2/r_c^2)^2} , \quad (23)$$

that approximately describes the distribution of dark matter in a galaxy cluster. The result for $\delta \ll 1$ and $\delta d, r_c \ll r_m$ can be approximated by:

$$J_{cl}(\delta) \simeq \frac{\rho_0^{cl} r_c}{2\tau_{DM} m_{DM}} \left(\frac{r_c}{\sqrt{r_c^2 + \delta^2 d^2}} - \frac{r_c}{\pi r_m} + \ldots \right) . \quad (24)$$

Nearby galaxy clusters have a large angular size and could not appear as point sources. To be precise, the core of the Coma Cluster has a size of 0.3 Mpc compared to a distance of 98 Mpc, corresponding to 0.17° of angular size, which is larger than the angular resolution of GLAST. On the other hand, the Virgo Cluster has a core radius of 10 kpc and lies at 18 Mpc, which translate into an angular size of 0.03°, slightly smaller than the angular resolution of GLAST. In consequence, for these objects the line of sight approximation $\delta = 0$ is not a good approximation and in order to obtain a reliable estimate for the photon flux the complete expression Eq. (24) has to be used. Taking $\rho_0^{cl} = 10^{-2}$ GeV cm^{-3} and $\rho_0^{cl} = 2.3$ GeV cm^{-3} for the Coma and Virgo clusters, respectively, we obtain for the angular resolution of GLAST

$$\begin{aligned} J_{\rm Coma}(0.1^\circ) &\simeq 4 \times 10^{-7}\ ({\rm cm}^2{\rm s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ {\rm s}}\right)^{-1} \left(\frac{m_{DM}}{10\ {\rm GeV}}\right)^{-1} , \\ J_{\rm Virgo}(0.1^\circ) &\simeq 10^{-6}\ ({\rm cm}^2{\rm s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ {\rm s}}\right)^{-1} \left(\frac{m_{DM}}{10\ {\rm GeV}}\right)^{-1} . \end{aligned} \quad (25)$$

which are around one order of magnitude larger than the photon flux from the Milky Way halo in the direction of the galactic pole,

$$J_{halo}(b=\pi/2) \simeq 0.7 \times 10^{-7}\ (\mathrm{cm}^2\mathrm{s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27}\ \mathrm{s}}\right)^{-1} \left(\frac{m_{DM}}{10\ \mathrm{GeV}}\right)^{-1} . \quad (26)$$

Nevertheless, the total flux received from these objects is so small that in order to distinguish a gamma ray signal from the Coma and Virgo clusters, it would be necessary a sensitivity of 7×10^{-11} photons cm^{-2} s^{-1}, which is more than one order of magnitude lower than the GLAST sensitivity [24].

5. Discussion

Should the gamma-ray line from DM decay be discovered at high galactic latitude, the problem will arise of how to discriminate it from scenarios with self-annihilating DM. The presence of a spectral line in the diffuse signal at high galactic latitude has in fact been proposed, several years ago, as a signature of annihilating DM particles [28] (see also Refs. [29, 30]). We note however that there are at least four important differences between the two scenarios:

- *the angular profile* of the predicted gamma-ray signal;
- *the comparison between galactic and extra-galactic components;*
- *the ratio between the line and the gamma-ray continuum;*
- *the angular power spectrum* of the gamma-ray background.

We stress in fact that in the case of self-annihilating DM, the gamma-ray flux from a given direction in the sky is a steeply falling function of the angle with respect to the Galactic centre, and it is in particular much steeper than the flux from decaying DM, as can be seen in Fig. 3. That is precisely why we have focused on high galactic latitudes in Sec. 2. Furthermore, the extra-galactic component of the gamma-ray flux in the case of annihilating DM is unlikely to be detected in absence of a strong signal from the Galactic centre [31]. In other words, in order for an extra-galactic component to be detected at high latitudes, the gamma-ray signal from the galactic centre should be easily detectable, despite the much stronger astrophysical background toward the innermost regions of the Galaxy. Thus, in case a line is observed at high galactic latitude, the absence of a similar line in the gamma-ray spectrum of the Galactic centre would favour an interpretation in terms of decaying DM.

It is still possible that astrophysical processes, such as the formation of spikes [32, 33, 34] and mini-spikes [35, 36, 37], i.e. large DM overdensities around Supermassive and Intermediate Mass Black Holes respectively, modify this picture, by boosting the gamma-ray signal from cosmological structures much more than the flux from the Galactic centre [38, 39]. Even in this case, however, it should be possible to discriminate between the two scenarios, by studying the spectral features of the extra-galactic background. In fact, for most self-annihilating DM candidates, such as the supersymmetric neutralino and the $B^{(1)}$ particle in theories with Universal Extra

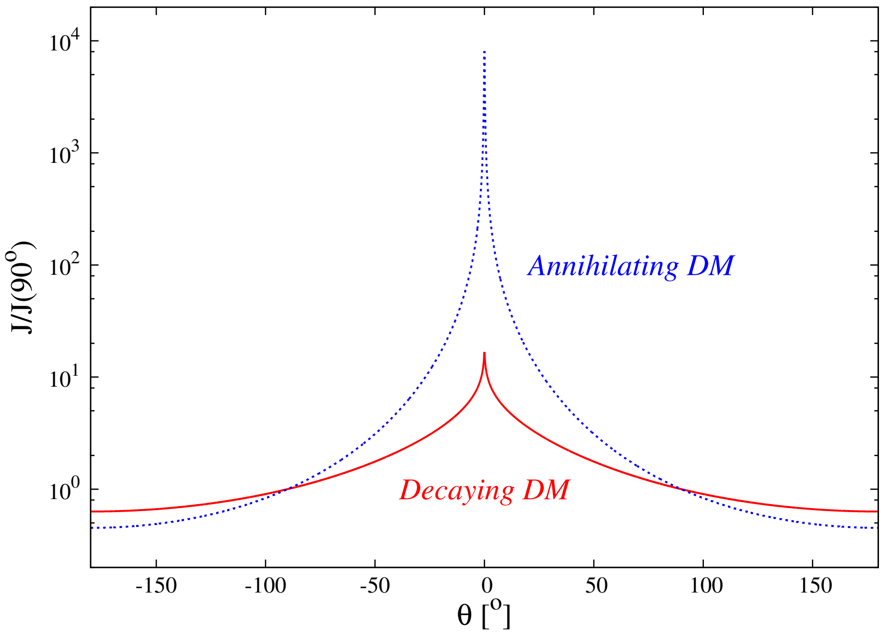

Figure 3. Angular profile of the gamma-ray signal as function of the angle θ to the centre of the galaxy for a NFW halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line. Both signals have been normalised to their values at the galactic poles, $\theta = \pm 90°$. The central cusp is regularised by assuming in both cases the GLAST angular resolution of 0.1° and integrating on the solid angle as in Eq. (10).

Dimensions, direct annihilation to photons is severely suppressed with respect to other channels such as annihilation to quarks or gauge bosons. It follows that the annihilation spectra are characterised by a continuum emission that is inevitably associated with the line signal, as shown in Fig. 4. Furthermore, masses below 50 GeV are usually considered unlikely for annihilating candidates. For instance, the current constraint in the neutralino mass is 40 GeV (assuming unification of gaugino mass parameters at the GUT scale) [22] while electroweak precision data exclude $B^{(1)}$ masses below 300 GeV [40].

Although the relative importance of the line can be in some cases particularly high, as e.g. in the case of Inert Higgs DM [41], the peculiar shape of the angular power spectrum of the gamma-ray background [42] can be used as a diagnostic tool to discriminate between annihilating and decaying DM. As for all the other strategies, this method heavily relies on the assumption that a sufficient number of photons are collected above the astrophysical background to allow a statistically meaningful analysis. In the worst case scenario, null GLAST searches can be used to exclude regions of the parameter space that lead to observable fluxes.

In Fig. 5 we show an exclusion plot in the (m_{DM}, τ_{DM}) plane, where we show the regions of the parameter space that already are ruled out by a comparison with EGRET data. In order to investigate the discovery potential of GLAST, we refer to the official

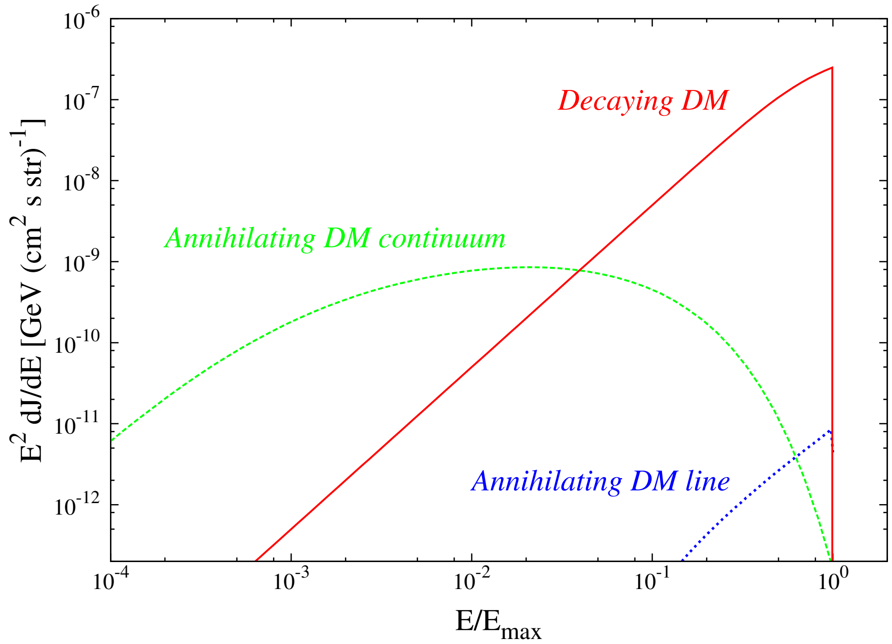

Figure 4. Spectrum of decaying DM extra-galactic component, solid (red) lines, compared with the spectrum of annihilating DM (continuum as long-dashed (green) plus line in short-dashed (blue)). For the case of decaying DM, $E_{max} = m_{DM}/2$, whereas for the case of annihilating DM, $E_{max} = m_{DM}$.

publications of the collaboration [24] where the sensitivity to astrophysical lines as a function of energy is studied for two different sky regions, namely an 'annulus' region where the signal to background ratio is maximised for annihilating DM candidates, and a 'high latitude' region, defined as the region of the sky with galactic latitude higher than 20 degrees and excluding a 35 degrees circle around the Galactic centre. In our case, there is a considerable reduction of the background, and a not-so-large decrease of the signal when going at high galactic latitude, for the reasons discussed above. So it is not a surprise that the 'high latitude' region is more favourable for constraining decaying DM. In Fig. 5 we show the reach of GLAST for the two regions along with the EGRET-excluded region. For the present bound we take conservatively the requirement that the peak in the energy spectrum with 15% energy resolution remains below the 2σ band of the EGRET spectrum obtained by Sreekumar *et al.* in [9],

$$\frac{dJ_{EGRET}}{dE} = (7.32 \pm 0.34) \times 10^{-6} (\mathrm{cm}^2\,\mathrm{s}\,\mathrm{str}\,\mathrm{GeV})^{-1} \left(\frac{E}{0.451\ \mathrm{GeV}}\right)^{-2.1\pm0.03} . \quad (27)$$

The different mass dependence of the EGRET bound is due to the fact that it is a constraint on $\frac{dJ}{dE}$ instead than on the integrated flux and on the energy dependence of the GLAST sensitivity. The limit disappears at $100 - 120$ GeV, which is the maximal energy plotted in the EGRET fit, but note that data above 10 GeV have large errors and were not used to obtain Eq. (27).

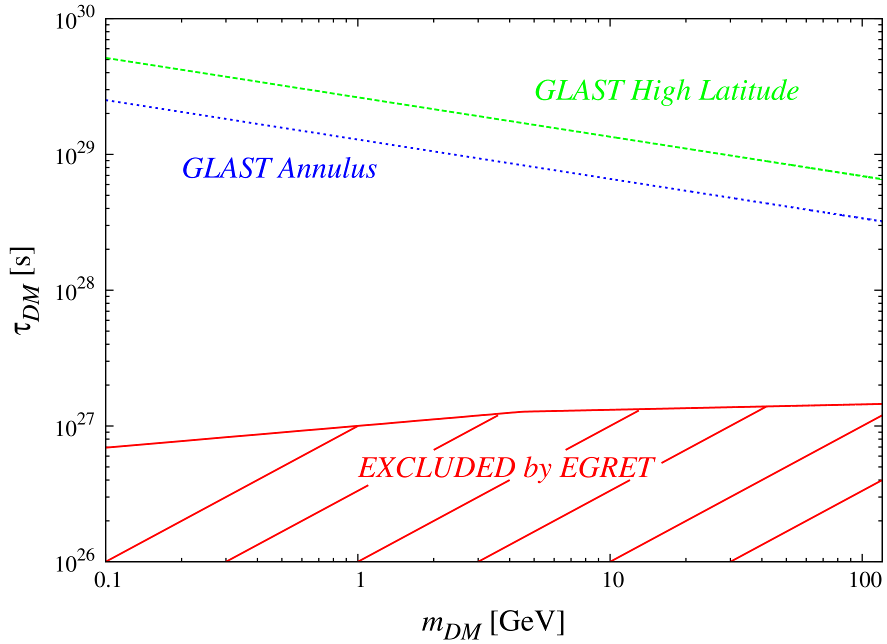

Figure 5. Exclusion plot in the (m_{DM}, τ_{DM}) plane based on EGRET data. All the region below the solid (red) line is excluded by the requirement that the halo line is below the measured flux as explained in the text. We also show the region of the parameter space where GLAST could discover the annihilation line: the short-dashed (blue) line corresponds to the GLAST sensitivity in the 'annulus' region, while the long-dashed (green) line to the 'high latitude' region.

6. Conclusions

We have discussed the prospects for indirect detection of gravitino DM in R-parity breaking vacua with upcoming experiments such as GLAST and AMS-02. The search strategy is in this case significantly different with respect to annihilating DM particles, due to different angular profile of the predicted gamma-ray signal and the different relative importance of the extra-galactic background. We found that the predicted signal from DM decays *in the galactic halo* would resemble an extra-galactic component with a shape and normalisation similar to the one inferred by EGRET data.

Without trying to fit the controversial EGRET data with our model, we have determined the regions of the (m_{DM}, τ_{DM}) plane where GLAST could discover the gamma-ray line from gravitino decay, and we discussed how to discriminate this signal from astrophysical sources and from a signal originating from annihilating DM. This discrimination is based on the fact that: the line may appear at energies below 50 GeV, which is somewhat challenging for popular annihilating DM candidates; it would exhibit no continuum flux (unless the mass of the gravitino is above the W mass); there would be a weak line signal from the galactic centre, possibly hidden in the galactic background; the angular power spectrum of the signal would be different from the case of annihilating DM, and from extra-galactic astrophysical sources.

In the worst case scenario, i.e. in case of null GLAST searches, the data can be used to set constraints in the (m_{DM}, τ_{DM}) plane and improve the bound on the DM lifetime into photons by more than one order of magnitude, actually even more than two for masses below 1 GeV.

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References

[1] G. Bertone, D. Hooper and J. Silk, Phys. Rept. **405** (2005) 279 [arXiv:hep-ph/0404175].
[2] L. Bergstrom, Rept. Prog. Phys. **63** (2000) 793 [arXiv:hep-ph/0002126].
[3] W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, JHEP **0703** (2007) 037 [arXiv:hep-ph/0702184].
[4] V. S. Berezinsky, Phys. Lett. B **261** (1991) 71.
[5] F. Takayama and M. Yamaguchi, Phys. Lett. B **485** (2000) 388 [arXiv:hep-ph/0005214].
[6] A. Bouquet and P. Salati, Nucl. Phys. B **284** (1987) 557.
[7] R. Barbieri and V. Berezinsky, Phys. Lett. B **205** (1988) 559.
[8] H. B. Kim and J. E. Kim, Phys. Lett. B **527** (2002) 18 [arXiv:hep-ph/0108101].
[9] P. Sreekumar *et al.* [EGRET Collaboration], Astrophys. J. **494** (1998) 523 [arXiv:astro-ph/9709257].
[10] A. W. Strong, I. V. Moskalenko and O. Reimer, Astrophys. J. **613** (2004) 962 [arXiv:astro-ph/0406254]; Astrophys. J. **613** (2004) 956. [arXiv:astro-ph/0405441].
[11] F. W. Stecker, S. D. Hunter and D. A. Kniffen, arXiv:0705.4311 [astro-ph].
[12] I. V. Moskalenko, S. W. Digel, T. A. Porter, O. Reimer and A. W. Strong, arXiv:astro-ph/0609768.
[13] T. Asaka, J. Hashiba, M. Kawasaki and T. Yanagida, Phys. Rev. D **58** (1998) 023507 [arXiv:hep-ph/9802271].
[14] A. De Rujula and S. L. Glashow, Phys. Rev. Lett. **45** (1980) 942.
[15] A. Boyarsky, A. Neronov, O. Ruchayskiy, M. Shaposhnikov and I. Tkachev, Phys. Rev. Lett. **97** (2006) 261302 [arXiv:astro-ph/0603660].
[16] J. A. R. Cembranos, J. L. Feng and L. E. Strigari, arXiv:0704.1658 [astro-ph].
[17] Early attempts to explain this excess can be found in: K. A. Olive and J. Silk, Phys. Rev. Lett. **55** (1985) 2362.
[18] S. Lola, P. Osland and A. R. Raklev, arXiv:0707.2510 [hep-ph].
[19] G. Moreau and M. Chemtob, Phys. Rev. D **65** (2002) 024033 [arXiv:hep-ph/0107286].
[20] A. Ibarra and D. Tran, arXiv:0709.4593 [astro-ph].
[21] J. M. Overduin and P. S. Wesson, Phys. Rept. **402** (2004) 267 [arXiv:astro-ph/0407207].
[22] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33** (2006) 1.
[23] N. W. Evans, F. Ferrer and S. Sarkar, Phys. Rev. D **69** (2004) 123501 [arXiv:astro-ph/0311145].
[24] For the GLAST performance see e.g.
http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm
http://confluence.slac.stanford.edu/download/attachments/19303/HEAD_Poster.pdf?version=1

[25] E. Tempel, A. Tamm and P. Tenjes, arXiv:0707.4374 [astro-ph].
[26] A. Cavaliere and R. Fusco-Femiano, Astron. Astrophys. **49** (1976) 137.
[27] C. L. Sarazin and J. N. Bahcall, Astrophys. J. Suppl. **34** (1977) 451.
[28] L. Bergstrom, J. Edsjo and P. Ullio, Phys. Rev. Lett. **87**, 251301 (2001) [arXiv:astro-ph/0105048].
[29] J. E. Taylor and J. Silk, "The clumpiness of cold dark matter: Implications for the annihilation Mon. Not. Roy. Astron. Soc. **339**, 505 (2003) [arXiv:astro-ph/0207299].
[30] P. Ullio, L. Bergstrom, J. Edsjo and C. G. Lacey, Phys. Rev. D **66**, 123502 (2002) [arXiv:astro-ph/0207125].
[31] S. Ando, Phys. Rev. Lett. **94**, 171303 (2005) [arXiv:astro-ph/0503006].
[32] P. Gondolo and J. Silk, Phys. Rev. Lett. **83** (1999) 1719 [arXiv:astro-ph/9906391].
[33] G. Bertone, G. Sigl and J. Silk, Mon. Not. Roy. Astron. Soc. **337** (2002) 98 [arXiv:astro-ph/0203488].
[34] G. Bertone and D. Merritt, Phys. Rev. D **72** (2005) 103502 [arXiv:astro-ph/0501555].
[35] G. Bertone, A. R. Zentner and J. Silk, Phys. Rev. D **72** (2005) 103517 [arXiv:astro-ph/0509565].
[36] G. Bertone, Phys. Rev. D **73** (2006) 103519 [arXiv:astro-ph/0603148].
[37] H. S. Zhao and J. Silk, Phys. Rev. Lett. **95** (2005) 011301 [arXiv:astro-ph/0501625].
[38] E. J. Ahn, G. Bertone and D. Merritt, arXiv:astro-ph/0703236.
[39] S. Horiuchi and S. Ando, Phys. Rev. D **74**, 103504 (2006) [arXiv:astro-ph/0607042].
[40] I. Gogoladze and C. Macesanu, Phys. Rev. D **74** (2006) 093012 [arXiv:hep-ph/0605207].
[41] M. Gustafsson, E. Lundstrom, L. Bergstrom and J. Edsjo, arXiv:astro-ph/0703512.
[42] S. Ando and E. Komatsu, Phys. Rev. D **73** (2006) 023521 [arXiv:astro-ph/0512217].