Gamma-ray lines from dark matter decay

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Abstract. No known astrophysical process can generate a monoenergetic gamma-ray with energy in the TeV range, resulting in very stringent constraints on the lifetime of dark matter particles which decay producing gamma-ray lines. We derive in this work constraints on the decay width from observations at current IACTs as well as the estimated sensitivity of the projected CTA. We also discuss the implications of these limits for two dark matter models where the dark matter particle decays at tree level producing gamma-ray lines, namely the gravitino in supersymmetric models without R-parity conservation and a vector of a hidden SU(2) gauge group. We also discuss the constraints on scenarios where the gamma-ray line is generated at the one loop level.

1. Introduction
Despite the many pieces of evidence for the existence of dark matter particles in our Universe [1], very little is known about their properties from the Particle Physics point of view. Namely, nothing is known about the spin or the parity, while the mass, the interaction cross section with nuclei or the lifetime are only very weakly constrained. In this work we aim to derive constraints on the lifetime of a dark matter particle with mass in the TeV range.

Our motivation is twofold. First, no matter particle is guaranteed to be stable and hence the lifetime of the dark matter particle should be determined from observations. This rationale is in complete analogy to the searches for proton decay. Whereas the proton stability is understood in the Standard Model as arising from an accidental baryon number conservation in the renormalizable Lagrangian, higher dimensional operators might violate baryon number inducing the proton decay. This is the case, e.g. in Grand Unified models. Similarly, the dark matter particle stability could be attributed to an approximate symmetry in the renormalizable Lagrangian which might be broken, or not, by higher dimensional operators. If the dark matter particle is a fermion which decays via a dimension 6 operator suppressed by a large mass scale $M$, the dark matter lifetime reads, for $\mathcal{O}(1)$ couplings,

$$
\tau_{DM} \sim 10^{26} \left( \frac{\text{TeV}}{m_{DM}} \right)^5 \left( \frac{M}{10^{15} \text{ GeV}} \right)^4 .
$$

This lifetime, as will argue below, can be probed in cosmic ray and gamma-ray observations if the dark matter mass is $\sim 1$ TeV and the suppression scale of the dimension six operators is $\sim 10^{15}$ GeV, which is interestingly close to the scale of Grand Unification.

Furthermore, from the experimental side, the PAMELA measurements [2] of the positron fraction and the Fermi-LAT measurements [3] of the electron+positron flux have revealed the
Decay Channel $m_{\psiDM}$ GeV $\tau_{\text{DM}} \times 10^{26}$ s
$\psiDM \rightarrow \mu^+ \mu^- \nu$ 3500 1.1
$\psiDM \rightarrow \ell^+ \ell^- \nu$ 2500 1.5
$\phiDM \rightarrow \mu^+ \mu^-$ 2500 1.8
$\phiDM \rightarrow \tau^+ \tau^-$ 5000 0.9
$\psiDM \rightarrow W^\pm \mu^\mp$ 3000 2.1

Table 1. Decay channels for fermionic and scalar dark matter, $\psiDM$ and $\phiDM$, respectively, that best fit the measurements of the electron flux and the positron fraction by Fermi and PAMELA, respectively, for the MED propagation model and the NFW halo profile (for details, see [5]). The decay mode $\psiDM \rightarrow W^\pm \mu^\mp$ is in tension with the PAMELA results on the antiproton-to-proton ratio.

existence of an excess of positrons at energies larger than 7 GeV, and a possible excess of electrons and/or positrons at energies between 600 GeV and 1 TeV. These excesses could be explained by the decay of a dark matter particle with a mass in the TeV range and lifetime of the order of $10^{26}$ s [4, 5], see Fig. 1. In this work we will also investigate whether this explanation to the electron/positron excesses could be tested in searches for gamma-ray lines.

2. Observational limits on gamma-ray lines

The decay of a dark matter particle with mass $m_{\psiDM}$ in a two-body decay involving a photon and a neutral particle $N$, $\psiDM \rightarrow \gamma N$, produces a gamma-ray with energy

$$E_\gamma = \frac{m_{\psiDM}}{2} \left( 1 - \frac{m_N^2}{m_{\psiDM}^2} \right).$$

(2)

When the neutral particle is massless, we will write $\nu$ instead of $N$ in the following.

The flux of monochromatic gamma rays from the decay of dark matter in the Milky Way halo is given by a line-of-sight integral over the dark matter distribution [6]. This component of the gamma-ray flux is explicitly given by

$$\frac{dJ_{\text{halo}}}{dE} = \frac{\Gamma(\psiDM \rightarrow \gamma N)}{4\pi m_{\psiDM}} \delta (E_\gamma - E) \int_{\text{l.o.s.}} d\vec{l} \rho_{\text{MW}}(\vec{l}),$$

(3)

where $\Gamma(\psiDM \rightarrow \gamma N)$ denotes the partial decay width of the process and $\rho_{\text{MW}}$ is the Milky Way’s dark matter halo density profile. We adopt the NFW profile here, which has the form

$$\rho_{\text{DM}}(r) = \frac{\rho_c}{r/r_c (1 + r/r_c)^2},$$

(4)

with the parameters $\rho_c = 0.35 \text{ GeV cm}^{-3}$ and $r_c = 20 \text{ kpc}$ [7], leading to a local dark matter density of 0.4 GeV/cm$^3$ [8]. The gamma-ray flux from dark matter decay inside the Galactic halo has only a mild angular dependence and can be considered as isotropic for our purposes (for details on anisotropies in the Galactic gamma-ray flux from dark matter decay, see ref. [9]). The extragalactic contribution stemming from the decay of dark matter at cosmological distances is generally fainter than the Galactic flux, and we will neglect this component here.

The Fermi LAT collaboration has conducted a negative search for Galactic gamma-ray lines in the diffuse flux in the energy range from 30 to 200 GeV [10]; the $2\sigma$ limits on the partial decay width corresponding to $\psiDM \rightarrow \gamma \nu$ are shown in Fig. 1 for the halo profile Eq. (4). This search has been recently extended in [11] for fermionic dark matter particles with masses $2 - 600 \text{ GeV}$ which decay $\psi \rightarrow \gamma \nu$. 

Figure 1. Lower limits on the inverse decay width of a dark matter particle which decays via $\psi_{\text{DM}} \rightarrow \gamma \nu$ from line searches in M31 by HEGRA, from line searches in the diffuse flux by Fermi LAT and from observations of the Perseus cluster by MAGIC. Further bounds can be derived from the $(\gamma + e^-)$ observations of H.E.S.S. Our estimates of the reach of the future CTA in measurements of the flux from M31 or spectral variations in the diffuse $\gamma + e^-$ flux are shown as red lines.

For larger dark matter masses, it is possible to derive constraints on the decay width from observations undertaken by Imaging Atmospheric Cherenkov Telescopes (IACTs). The HEGRA collaboration has published upper limits on the gamma-ray line flux from M31 [12]. Besides, the MAGIC collaboration has published upper limits on the gamma-ray flux from the Perseus galaxy cluster [13]. Lastly, the H.E.S.S. collaboration has published measurements of the electron flux at TeV energies [14, 15]. The measured electron flux may be contaminated with diffuse gamma rays by no more than $\approx 50\%$ [14], thus allowing to translate the electron flux into upper bounds on gamma-ray lines from dark matter decay in the Galactic halo. The 99\% C.L. limits on the decay width of dark matter into gamma-ray lines from all these measurements are presented Fig. 1 (for further details, see [16]). In the future, the Cherenkov Telescope Array (CTA, see ref. [17] for a recent discussion) will undertake searches of gamma-ray lines with greater sensitivity. In Fig. 1 we also show our estimation for the expected $2\sigma$ limit on the decay width from observations of M31 and the diffuse background assuming no signal is observed [16].

3. Tree level decays
The present bounds on the intensity of gamma-ray lines set very stringent constraints on models where the dark matter particle decays at tree level. We will discuss here two well motivated decaying dark matter models which can produce gamma-ray lines with a sizable rate.

3.1. Gravitino in SUSY models without R-parity conservation
Among the most interesting dark matter candidates proposed stands the gravitino [18] which is abundantly produced by thermal scatterings in the very early Universe. If the gravitino is...
the lightest supersymmetric particle (LSP), a fraction of their initial population will survive until today with a relic density which is calculable in terms of very few parameters, the result being [19]

\[ \Omega_{3/2} h^2 \simeq 0.27 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{m_{3/2}} \right) \left( \frac{m_\tilde{g}}{1 \text{ TeV}} \right)^2, \]  

where \( T_R \) is the reheating temperature of the Universe, \( m_{3/2} \) is the gravitino mass and \( m_\tilde{g} \) is the gluino mass. In predicting the relic abundance of gravitinos, the main uncertainty arises from our ignorance of the thermal history of the Universe before Big Bang nucleosynthesis (BBN) and in particular of the reheating temperature after inflation. However, we have strong indications that the Universe was very hot after inflation. Namely, the discovery of neutrino masses provided strong support to leptogenesis as the explanation for the observed baryon asymmetry of the Universe [20]. This mechanism can reproduce the observed baryon asymmetry very naturally if the reheating temperature of the Universe was above \( 10^9 \text{ GeV} \) [21]. Therefore, the abundance of gravitinos can reproduce the dark matter relic density inferred by WMAP for the \( \Lambda \)CDM model, \( \Omega_{\text{CDM}} h^2 \simeq 0.1 \) [22], for natural values of the input parameters in Eq. (5).

Being capable of reproducing the correct relic density is a necessary requirement for any dark matter candidate, but not the only one. Namely, the physical model accounting for the dark matter should not spoil the successful predictions of the standard cosmology. However, in scenarios with gravitino dark matter, when \( R \)-parity is conserved, the next-to-LSP (NLSP) is typically present during or after Big Bang nucleosynthesis, jeopardizing the successful predictions of the standard nucleosynthesis scenario [23]. A simple solution which avoids the BBN constraints altogether consists in introducing a small amount of \( R \)-parity violation, so that the NLSP decays into two Standard Model particles before the onset of Big Bang nucleosynthesis [24].

When \( R \)-parity is not exactly conserved, the gravitino LSP is no longer stable. Nevertheless, the gravitino decay rate is doubly suppressed by the Planck mass and by the small \( R \)-parity violation [25], yielding a lifetime which is typically larger than the age of the Universe. Nevertheless, gravitinos could be decaying at a rate sufficiently large to allow the detection of the decay products in experiments, thus opening the possibility of the indirect detection of the elusive gravitino dark matter [26, 27, 28, 29, 30].

We show in Fig. 2 the branching ratios of the gravitino in the interesting case of bilinear \( R \)-parity violation [29]. Especially for small masses the branching ratio into monoenergetic gamma-rays can be sizable. Hence, we expect very stringent constraints on decaying gravitinos from the negative searches of monoenergetic gamma-rays in the range \( E_\gamma = 1 - 300 \text{ GeV} \). This is illustrated in Fig. 3, right plot, where we show the expected gamma-ray flux of a gravitino with mass \( 200 \text{ GeV} \) and lifetime \( \tau = 7 \times 10^{26} \text{ s} \) [30]. The gamma-ray line is predicted to be fairly intense and is in fact in conflict with the present constraints from the Fermi-LAT.

### 3.2. Vector of a hidden SU(2) gauge group

This model considers an extension of the Standard Model where the gauge group contains a hidden non-abelian group, \( SU(2)_{HS} \), with gauge bosons \( A^\mu \). It is assumed that the hidden non-abelian symmetry is spontaneously broken via the vacuum expectation value of a complex scalar field, \( \phi \). It is also assumed that all the Standard Model particles are singlets under \( SU(2)_{HS} \), thus the Standard Model only couples to the hidden sector via the Higgs portal term \( |\phi|^2 |H|^2 \), being \( H \) the Standard Model Higgs doublet. With this assumptions, it can be shown that the Lagrangian displays a \( SO(3) \) custodial symmetry in the \( A^\mu \) component space, which prevents any decay into \( SO(3) \) singlets (such as Standard Model particles) [31]. Consequently, if the model is described just by the renormalizable Lagrangian, the three \( A^\mu \) components are degenerate in mass and are absolutely stable. Furthermore, the parameters of the model can be chosen to produce a relic density of the hidden vector dark matter in agreement with observations [31]. Nevertheless,
one expects the existence of non-renormalizable operators in the Lagrangian which break the custodial symmetry after the spontaneous symmetry breaking of $SU(2)_{HS}$ and $SU(2)_L \times U(1)_Y$, for example [32].

\[
\begin{align*}
(A) & & \frac{1}{\Lambda^2} D_\mu \phi^\dagger \phi \ D_\mu H^\dagger H , \\
(C) & & \frac{1}{\Lambda^2} D_\mu \phi^\dagger D_\nu \phi \ F^{\mu\nu Y} .
\end{align*}
\]

In turn, the breaking of the custodial symmetry leads to the decay of the dark matter hidden gauge bosons, with a decay rate and branching ratios which depend on the parameters of the model.

We show in Fig. 4, left plot, the expected gamma-ray flux from hidden vector dark matter particles which decay via the operator A in Eq. (6). The dark matter mass is 600 GeV and the various couplings have been chosen in order to reproduce the correct relic density and to be in agreement with direct detection experiments [32]. For the scenario shown in the plot the lifetime is $\tau = 1.1 \times 10^{27}$ s, which is marginally allowed by the Fermi-LAT results. On the other hand, in the right plot we show the predicted gamma ray flux in a scenario where a hidden vector dark matter particle with mass 1550 GeV decays with lifetime $1.6 \times 10^{27}$ s via the operator C, Eq. (7). In this case the dark matter particle can decay with similar branching ratios into $\gamma \eta$, the hidden sector Higgs, and $\gamma h$, the visible sector Higgs, resulting in a double gamma-ray line feature [32]. This scenario is allowed by current measurements but could be tested at the CTA.

**4. Radiative decays**

Searches for gamma-ray lines provide very stringent constraints on the width of fermionic dark matter particles which decay $\psi \rightarrow \gamma \nu$. From Fig. 1 it follows that $\Gamma^{-1}(\psi \rightarrow \gamma \nu) \gtrsim 5 \times 10^{28} - 10^{29}$ s for $m_\psi$ between 1 and 600 GeV, while in the future observations at CTA could reach this same limit for larger masses, between 600 GeV and 10 TeV. These limits are 2-3 orders of magnitude better than the limits set by observations of the cosmic electron/positron flux in that same mass range, see e.g. Fig. 1. Therefore, it is interesting to explore whether the constraints on models from one-loop induced gamma-ray lines can be competitive with the constraints from tree-level decays into leptons.
Let us first consider the decay width for the radiatively induced gamma-ray line, $\Gamma(\psi_{DM} \to \gamma \nu)$, when the dark matter decays at tree level into muons of the same chirality. The result reads [16]:

$$\Gamma(\psi_{DM} \to \gamma \nu) \approx \frac{3\alpha_{em}}{8\pi} \Gamma(\psi_{DM} \to \mu^+_L \mu^-_{L,R} \nu).$$

(8)

In the case that the dark matter decays democratically into all flavours, $\psi_{DM} \to \ell^+ \ell^- \nu$, the result is a factor of three larger. On the other hand, if the decay is mediated by a heavy vector, the corresponding decay widths must be multiplied by an additional factor of 9. In specific models, such as when the dark matter is constituted by hidden gauginos of an unbroken $U(1)$, several scalar particles circulate in the loop resulting in an enhancement of the decay rate [33].

We show in Fig. 5 the limits on the inverse decay width of the radiative process $\psi_{DM} \to \gamma \nu$ assuming that the democratic decay $\psi_{DM} \to \ell^+ \ell^- \nu$ reproduces the PAMELA positron excess (yellow regions) and the Fermi electron excess (black regions), when the decay is mediated by a heavy scalar (left plot) or by a heavy vector (right plot). It is apparent from the plot that at large masses the CTA observations of the diffuse background will provide better constraints on these models that those stemming from the electron/positron measurements. Furthermore, it is predicted that the CTA will observe a gamma-ray line if these decay channels are the explanation of the electron/positron excesses observed by PAMELA and Fermi [16].

The decay width into gamma-ray lines can be enhanced if the daughter particle $N$ in the decay $\psi \to \gamma N$ is degenerate in mass with the dark matter particle. Considering the tree level decay $\psi_{DM} \to \mu^+ \mu^- N$, the radiatively induced decay process $\psi_{DM} \to \gamma N$ has a width [16]:

$$\Gamma(\psi_{DM} \to \gamma N) \approx \frac{3\alpha_{em}}{8\pi} \left( \frac{5}{12} \frac{20}{1-m_N^2/m_{\psi_{DM}}^2} \right) \text{ for } m_N \to m_{\psi_{DM}}, \eta = +1,$$

$$\Gamma(\psi_{DM} \to \gamma N) \approx \frac{3\alpha_{em}}{8\pi} \left( \frac{5}{12} \frac{20}{1-m_N^2/m_{\psi_{DM}}^2} \right) \text{ for } m_{\psi_{DM}} \to m_N, \eta = +1,$$

(9)

with $\eta$ the relative CP parity between the dark matter particle and the daughter neutral particle. Hence, if these two particles have opposite CP parities, the branching ratio into monochromatic gamma-rays increases as their masses become more and more degenerate, as shown in Fig. 6.

In order to illustrate the enhancement of the branching ratio and the impact from the gamma-line constraints, we consider in Fig. 7 seven benchmark scenarios for which $m_{\psi_{DM}}$ and $m_N$ are of comparable size and the decay generates a gamma line at 170 GeV (benchmarks 1, 2, 3) or at 5 TeV (benchmarks 4, 5, 6, 7). All the benchmark scenarios reproduce the PAMELA positron data, and all except scenarios 1, 2 and 3 additionally reproduce the electron spectrum measured.
Figure 5. Same as fig. 1. In addition, the yellow and black shaded regions show the parts of the parameter space that are relevant for the decaying dark matter interpretation of the PAMELA/Fermi $e^\pm$ anomalies with the decay channel $\psi_{\text{DM}} \rightarrow \ell^+ \ell^- \nu$. The intermediate particle is a scalar in the left plot and a vector in the right plot, and the final fermions are assumed to have the same chirality.

by Fermi. Benchmark points 1, 3, 4 and 6 have $\eta = -1$ and $m_{\psi_{\text{DM}}}/m_N = 0.81, 0.39, 0.95$ and 0.58, while 2 and 4 have $\eta = 1$ and $m_{\psi_{\text{DM}}}/m_N = 0.57, 0.58$, respectively. It is interesting to note that present experiments are sensitive to dark matter models decaying into neutral daughter particles close in mass to the dark matter particle, when the produced leptons have the same chirality: benchmark points 1 and 4 are excluded by present gamma line constraints, while 6 and perhaps 3 and 5 could be tested in future experiments. In contrast benchmark point 2 and 7 cannot be probed with present or planned experiments (benchmark point 7 corresponds to a decay into leptons of opposite chiralities, and lies out of the figure).

5. Conclusions
We have discussed in this paper the scenario where a dark matter particle with mass in the TeV range decays producing a monoenergetic gamma-ray. We have derived upper limits on the decay width from observations at current ACTs and we have estimated the projected sensitivity of the future CTA. Lastly we have discussed the implications of these constraints on concrete models where the gamma-ray line is produced at tree level or at the one loop level.

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Figure 6. Ratio of the decay rates $\Gamma(\psi_{DM} \rightarrow \gamma N)/\sum_i \Gamma(\psi_{DM} \rightarrow f_i^+ f_i^- \bar{N})$ when the decay is mediated by a scalar. The four cases correspond to single-flavor decay (red) and democratic decay into all flavors (blue), as well as $\psi$ and $N$ having the same $CP$ parity (dashed, $\eta = +1$ ) or opposite $CP$ parity (solid, $\eta = -1$ )

Figure 7. Same as fig. 1, but with different scaling of the axes to allow for non-vanishing $m_N$. The black squares and red dots show the predictions for the different benchmark scenarios (see text). Black squares correspond to scenarios with $\eta = +1$, while red dots correspond to $\eta = -1$. 

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