

# Dark Matter Decay and Cosmic Rays

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The decay of dark matter is predicted by many theoretical models and can produce observable contributions to the cosmic-ray fluxes. I shortly discuss the interpretation of the positron and electron excess as observed by PAMELA and Fermi LAT in terms of decaying dark matter, and I point out the implications for the Fermi LAT observations of the  $\gamma$ -ray flux with emphasis on its dipole-like anisotropy.

## 1 Introduction

The most popular type of dark matter (DM) candidate, the weakly interacting massive particle (WIMP), can naturally reproduce the observed DM abundance due to effective self-annihilation in the early Universe, and today this same annihilation process could produce an observable contribution to the measured cosmic-ray fluxes on Earth. Such an indirect detection of DM is also possible if DM *decays* with a sufficiently large rate. There exist a number of interesting DM models (see *e.g.* [1] and references therein) that predict the decay of DM on cosmological time scales, namely with lifetimes around and above  $\tau_{\text{DM}} \simeq \mathcal{O}(10^{26} \text{ s})$ , which are typically required to be not in conflict with current observational limits. Among these models is the gravitino with a small violation of  $R$ -parity, motivated by requiring a consistent thermal history of the Universe, and the sterile neutrinos, whose long lifetime is due to tiny Yukawa couplings. The typical masses for these DM candidates lie in the 100 GeV and the 10 keV regime, respectively. Another interesting model with kinetically mixed hidden gauginos was also recently studied [2]. Even in models where DM is stable in the first place, the consideration of higher-dimensional operators often renders the DM particle unstable with cosmological lifetimes. Since the indirect detection signals from decay differ in general from the ones of annihilation, a dedicated study of decaying DM signals is mandatory. Below I will shortly review the  $\gamma$ -ray and  $e^\pm$ -signals that can come from DM decay, and I will discuss them in light of recent observations.

## 2 Cosmic rays from dark matter decay

Provided the decays occur at a sufficiently large rate, their products could be observable as an exotic contribution to the high energy cosmic ray fluxes of  $\gamma$ -rays, electrons, positrons, antiprotons, neutrinos or antideuteron. Among the different cosmic-ray species,  $\gamma$ -rays play a distinct role, due to their sensitivity to far-distant sources and their potential to discriminate between astrophysical and DM signals. The *gamma-ray* signal from DM decay consists of several components. The most important one is related to the prompt radiation (*e.g.* final state radiation) produced in the decay of DM particles inside the Milky Way halo. It depends on the

halo density profile, and although the halo profile is expected to be approximately isotropic, the corresponding flux at Earth exhibits a strong dipole-like anisotropy due to the offset between sun and galactic center. In contrast, the extragalactic prompt component of the  $\gamma$ -ray signal, which stems from the decay of DM particles at cosmological distances, is largely isotropic. At energies around 10 GeV or below, the magnitude of the halo and extragalactic fluxes are of the same order, whereas at much higher energies around 1 TeV the inelastic scattering between  $\gamma$ -rays and the intergalactic background light renders the extragalactic component negligible. Decaying DM in general also produces electrons and positrons, which give rise to another contribution of the  $\gamma$ -ray signal, coming from the inverse Compton scattering (ICS) between the electrons and positrons and the interstellar radiation field (ISRF). This component is highly anisotropic and usually lower in energy than the component from prompt radiation. The main background in the  $\gamma$ -ray channel is the diffuse emission of our Galaxy, which is mainly due to interactions of cosmic rays with the galactic gas and the ISRF. This component is by far strongest in the galactic disk region, and it turns out that exotic fluxes from DM decay would dominantly show up at higher latitudes, away from the disk. This is in contrast to annihilation signals, which are often expected to be best seen very near to the galactic center.

The *electrons and positrons* produced in the Milky Way halo by DM decay scatter on irregularities of the Galactic magnetic field, which results in a wash-out of directional information before they reach the Earth. Their propagation is commonly described by a diffusion model, whose free parameters are tuned to reproduce the observed cosmic-ray nuclei fluxes. The astrophysical background in this channel is mainly due to primary electrons, which are presumably produced in supernova remnants, and due to secondary positrons, produced in the interaction of cosmic-rays with the galactic gas.

Recently it has become apparent that state-of-the-art propagation models fail to reproduce the PAMELA measurements of the *positron fraction* at energies larger than 10 GeV [3]. Together with the more recent Fermi LAT and HESS data [4] for the total  $e^\pm$ -flux the experiments suggest an excess of electrons and positrons up to energies around a few 1 TeV. The most common astrophysical explanation of this excesses is the electron-positron pair production by the interactions of high-energy photons in the strong magnetic field of nearby pulsars, such as Geminga or Monogem (see *e.g.* [5] and references therein). However, an arguably more exciting explanation of the cosmic-ray electron/positron excesses is the possibility that the electrons and positrons are produced in the annihilation or the decay of DM particles.

### 3 Positron excess and gamma-ray prospects

If the observed excess of positrons and electrons is entirely due to DM decay, one obtains clear predictions for the  $\gamma$ -ray signal that should be observable at Fermi LAT. In Ref. [6] we analyzed the predictions for the positron fraction and the total electron plus positron flux including a possible contribution from DM decay in order to account for the anomalies observed by PAMELA and Fermi. We considered several scenarios of de-

Decay Channel	$M_{\text{DM}}$ [GeV]	$\tau_{\text{DM}}$ [ $10^{26}$ s]
$\psi_{\text{DM}} \rightarrow \mu^+ \mu^- \nu$	3500	1.1
$\psi_{\text{DM}} \rightarrow \ell^+ \ell^- \nu$	2500	1.5
$\phi_{\text{DM}} \rightarrow \mu^+ \mu^-$	2500	1.8
$\phi_{\text{DM}} \rightarrow \tau^+ \tau^-$	5000	0.9
$\psi_{\text{DM}} \rightarrow W^\pm \mu^\mp$	3000	2.1

Table 1: DM decay channels that we found to best fit the Fermi LAT and PAMELA data [6].

caying DM, being it either a fermionic or a bosonic particle, which decays into various channels with a branching ratio of 100%. Our results are summarized in Tab. 1, an example is shown in Fig. 1. From the data leptonic, and in particular muonic, modes are favored. Note that the decay into  $W^\pm \mu^\mp$  is in some tension with the anti-proton/proton ratio observed by PAMELA.

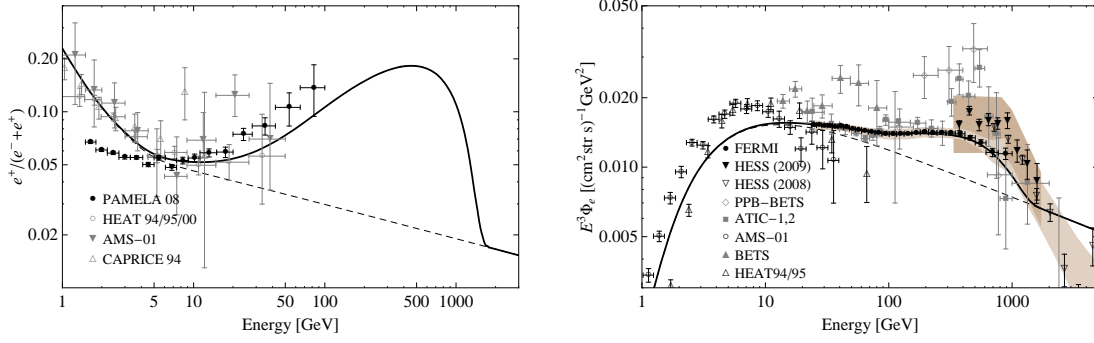


Figure 1: Positron fraction (*left panel*) and electron+positron flux (*right panel*) for DM decay  $\psi_{\text{dm}} \rightarrow \mu^+ \mu^- \nu$  (see Tab. 1). The dashed line shows the astrophysical background. Details are given in Ref. [6].

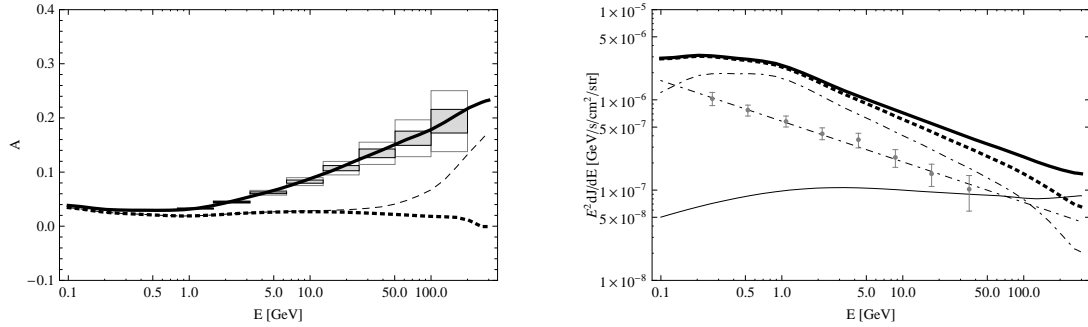


Figure 2: *Left panel*: Anisotropy of  $\gamma$ -ray signal for the decay mode  $\psi_{\text{dm}} \rightarrow \mu^+ \mu^- \nu$  [7]. The *solid* line shows the anisotropy of the total signal, including the galactic foreground, the *dotted* line shows the anisotropy of the foreground alone. The *thin dashed* line is the anisotropy of the total signal when neglecting ICS radiation of electrons and positrons from DM decay. *Right panel*: Averaged fluxes of the different  $\gamma$ -ray components. Line coding as in left panel, in addition the *thin solid* line shows the pure DM signal and the *dot-dashed* lines show the adopted extragalactic background flux and the galactic foreground. Data points correspond to the preliminary Fermi LAT results for the extragalactic  $\gamma$ -ray background [8].

The production of electrons and positrons in the DM decay inevitably produces also contributions to the cosmic  $\gamma$ -rays. In particular the  $\gamma$ -ray signal of the decay modes shown in Tab. 1 should give rise to a clear signal in the Fermi LAT observations at higher latitudes. Furthermore this signal is expected to be anisotropic, which can be used to discriminate it from the galactic foreground and the extragalactic  $\gamma$ -ray background. To illustrate this we define

the anisotropy parameter  $A = (\bar{J}_{\text{GC}} - \bar{J}_{\text{GAC}})/(\bar{J}_{\text{GC}} + \bar{J}_{\text{GAC}})$ , where  $\bar{J}_{\text{GC}}$  and  $\bar{J}_{\text{GAC}}$  denote the diffuse  $\gamma$ -ray flux averaged over the hemisphere in direction of the Galactic center (GC) and anticenter (GAC), respectively. The galactic disk, with latitudes  $|b| < 10^\circ$ , is excluded from the average. The left panel of Fig. 2 shows our results for the anisotropy parameter which is expected to be observed by the Fermi LAT if the DM particle decays into  $\mu^+\mu^-\nu$  (see Ref. [7] for details). Although the decay channel is marginally consistent with preliminary data (right panel), a sizeable anisotropy, around  $A \simeq 0.2-0.3$ , is predicted at energies  $E_\gamma \simeq 100$  GeV. This can be significantly different from the anisotropy of the astrophysical foreground (we adopt the conventional model 44\_500180 from `galprop.stanford.edu`). As indicated by our estimates of the statistical error bars for one-year and five-year Fermi LAT observation, this deviation should be clearly visible in the upcoming results for the diffuse  $\gamma$ -ray sky.

## 4 Conclusions

Many theoretical models predict the decay of DM on cosmological timescales, giving rise to an anomalous contribution to the observed cosmic-ray fluxes. The corresponding  $\gamma$ -ray signals could show up as broad features over large angular distance in the  $\gamma$ -ray sky. If decaying DM is the right explanation of the positron and electron excess observed by PAMELA and Fermi LAT, a corresponding  $\gamma$ -ray signal with a large dipole-like anisotropy should be observed in the very near future with Fermi LAT. This anisotropy would be due to prompt radiation at high latitudes, and due to ICS radiation at lower latitudes, most prominent in a region of a few kpc around the galactic center. It is tempting to speculate that such an ICS signal already showed up in the Fermi LAT data, see Ref. [9].

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## References

- [1] W. Buchmüller, L. Covi, K. Hamaguchi, A. Ibarra and T. Yanagida, *JHEP* **0703** (2007) 037 [arXiv:hep-ph/0702184]; A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, arXiv:0901.0011 [hep-ph]; A. Arvanitaki, S. Dimopoulos, S. Dubovsky, P. W. Graham, R. Harnik and S. Rajendran, *Phys. Rev. D* **79** (2009) 105022 [arXiv:0812.2075 [hep-ph]].
- [2] A. Ibarra, A. Ringwald, D. Tran and C. Weniger, *JCAP* **0908** (2009) 017 [arXiv:0903.3625 [hep-ph]]. A. Ibarra, A. Ringwald and C. Weniger, *JCAP* **0901** (2009) 003 [arXiv:0809.3196 [hep-ph]].
- [3] O. Adriani *et al.* [PAMELA Collaboration], *Nature* **458** (2009) 607 [arXiv:0810.4995 [astro-ph]].
- [4] A. A. Abdo *et al.* [The Fermi LAT Collaboration], *Phys. Rev. Lett.* **102**, 181101 (2009) [arXiv:0905.0025 [astro-ph.HE]]; F. Aharonian *et al.* [H. E. S. S. Collaboration], arXiv:0905.0105 [astro-ph.HE].
- [5] D. Grasso *et al.* [FERMI-LAT Collaboration], *Astropart. Phys.* **32** (2009) 140 [arXiv:0905.0636 [astro-ph.HE]].
- [6] A. Ibarra, D. Tran and C. Weniger, arXiv:0906.1571 [hep-ph] (2009).
- [7] A. Ibarra, D. Tran and C. Weniger, arXiv:0909.3514 [hep-ph] (2009).
- [8] M. Ackermann, Talk given at TeV Particle Astrophysics 2009.
- [9] G. Dobler, D. P. Finkbeiner, I. Cholis, T. R. Slatyer and N. Weiner, arXiv:0910.4583 [astro-ph.HE].