

Gamma Ray Constraints on Flavor Violating Asymmetric Dark Matter

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Abstract

We show how cosmic gamma rays can be used to constrain models of asymmetric Dark Matter decaying into lepton pairs by violating flavor. First of all we require the models to explain the anomalies in the charged cosmic rays measured by PAMELA, Fermi and H.E.S.S.; performing combined fits we determine the allowed values of the Dark Matter mass and lifetime. For these models, we then determine the constraints coming from the measurement of the isotropic γ -ray background by Fermi for a complete set of lepton flavor violating primary modes and over a range of DM masses from 100 GeV to 10 TeV. We find that the Fermi constraints rule out the flavor violating asymmetric Dark Matter interpretation of the charged cosmic ray anomalies.

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1 Introduction

It is interesting to explore as model independent as possible all the relevant properties of Dark Matter (DM). In practice, due to the different experimental setups, we can only explore a limited set of DM properties. For example, for indirect DM searches, till recently one could explore whether DM is decaying or purely annihilating; and on the basis of its standard model couplings, hope to determine its mass and decay rate and/or annihilation cross section.

Another interesting general property of DM deals with the possibility for it to violate flavor. The consequences of flavor violating DM in the quark sector have been investigated in [1–3] considering specific signatures at colliders. In this paper we study the impact of such models in indirect DM searches focussing on the lepton sector which is less constrained. In particular, we have recently shown that the charged cosmic ray experiments are not yet enough sensitive to measure a possible charge asymmetry in the electron and positron fluxes [4–6]. If the ratio of the electron to positron fluxes will be found to differ from unity and this were to be attributed to a primary decaying DM component, one would learn that such DM component should necessarily be asymmetric and lepton flavor violating [5]. We will refer to this possibility as A(symmetric) F(lavor) V(iolating) dark matter (AFVdm). The aim of this work is to consider the impact of gamma ray measurements on AFVdm models.

It is useful therefore to summarize the experimental landscape which sets the scene for our phenomenological investigation. The data collected by PAMELA [7, 8] and recently by Fermi [9] indicate that there is a positron excess with a rising behavior in the cosmic ray (CR) energy spectrum above 10 GeV. On the other hand PAMELA’s data show no unexpected features in the protons nor the anti-protons fluxes [10, 11]. Fermi [12] and H.E.S.S. [13, 14] reported a slight additional harder component, in the total ($e^+ + e^-$) spectrum, on the top of a smooth astrophysical spectrum with eventually a steepening at energies of a few TeV. Fermi has also recently presented updated measurements of the total flux of ($e^+ + e^-$) [15] and of the separate e^+ and e^- contributions [9] confirming the notorious rise exposed by PAMELA in 2008. Recent data of the PAMELA collaboration [16] on the e^- flux and of the MAGIC collaboration [17] on the total ($e^+ + e^-$) flux have also been released.

These interesting features in charged CR have drawn much attention, and many explanations have been proposed: For example, these excesses could be due to an inadequate account of the cosmic ray astrophysical background in previous modeling; They could be due to the presence of new astrophysical sources; They could also originate from annihilations and/or decays of leptophilic dark matter particle. The interpretation in terms of dark matter annihilations often leads to an unobserved excess of neutral messenger probes (essentially gamma rays, but also neutrinos) originating from dense DM concentrations. The interpretation instead in terms of dark matter decays [18–25] is less constrained, coming from the fact that in this case, the signal is linear in the DM number density. On the other hand, both Fermi [26] and H.E.S.S. telescopes are making huge progress in the study of the gamma ray map constructed by observing more targets in different regions of the sky, including those of interest for decaying DM.

In this work, we first reconsider the interpretation of the charged CR data anomalies as due to AFVdm decaying in lepton pairs, finding the allowed values for the DM mass and lifetime. Then we investigate the impact that the recent Fermi isotropic gamma ray flux measurement [26] has on constraining our AFVdm models. It is known that this measurement is a powerful probe for any model involving decaying DM (see e.g. [27–29]). In our analysis,

we use the most advanced semi-analytic tools for DM indirect searches which include the electroweak corrections for the primary fluxes and a refinement of the propagation scheme for the e^\pm . As happens for models respecting flavour symmetry, we find that also models of AFVdm decaying into lepton pairs are not compatible with photon observations.

2 Flavor Violating Dark Matter Observables

It is useful to define the flux of charged particles at the Earth location, coming from a general primary decay mode $\text{DM} \rightarrow ij$, as follows:

$$\Phi_{ij}^{\text{tot}}(E) = \Phi^{e^+}(E) + \Phi^{e^-}(E) = \Phi_i^{e^+}(E) + \Phi_j^{e^-}(E) + \Phi_{ij}^{e_s}(E), \quad (1)$$

$$\Phi_{ij}^{e_s}(E) = \Phi_i^{e_s^+}(E) + \Phi_j^{e_s^-}(E) + \Phi_j^{e_s^+}(E) + \Phi_i^{e_s^-}(E), \quad (2)$$

where i and j refer to primary charged lepton (e, μ, τ) with the first index positively charged and the second one negatively charged. e_s stands for the soft part of the spectrum which arises from secondary hadronic decays as can be deduced by comparing PYTHIA against HERWIG for the version not including $\ell \rightarrow \ell\gamma$ and $\gamma \rightarrow f\bar{f}$ with f generic SM fermions and ℓ are the charged leptons. In the bottom-left panel of Fig. 2 in [38] one can see the emergence of the secondary electron and positrons when comparing the two MonteCarlos for the same process. We also note that within the standard model the following is an excellent approximation:

$$\Phi_{ij}^{e_s}(E) = 2\Phi_i^{e_s}(E) + 2\Phi_j^{e_s}(E), \quad (3)$$

with $\Phi_i^{e_s^+}(E) = \Phi_i^{e_s^-}(E) \equiv \Phi_i^{e_s}(E)$ for any i .

In the case where the AFVdm model violates lepton flavor maximally i is always different from j . Following [5] it is convenient to define the following ratio:

$$r_{ij}(E) = \frac{\Phi_j^{e^-}(E) + \Phi_j^{e_s^-}(E) + \Phi_i^{e_s^-}(E)}{\Phi_i^{e^+}(E) + \Phi_i^{e_s^+}(E) + \Phi_j^{e_s^+}(E)} = \frac{2\Phi_j^{e^-}(E) + \Phi_{ij}^{e_s}(E)}{2\Phi_i^{e^+}(E) + \Phi_{ij}^{e_s}(E)}. \quad (4)$$

We are assuming for the analysis a given i and j to be the dominant decay mode. It is, however, straightforward to generalize the result to include different branching ratios in different channels.

The case of lepton-flavor preserving primary channels (i.e. $i = j$) has been studied in [30–37]. An improved analysis appeared recently in [31] making use of the electroweak corrections for the primary fluxes of the relevant stable standard model particles determined in [38, 40] and a refinement of the propagation scheme for the e^\pm (see [38] for further details). In [39] it was already pointed out that the electroweak corrections were relevant. In the case of flavor preserving DM there is the obvious simplification that $\Phi_i^{e^+} = \Phi_i^{e^-}$ and therefore $\Phi_{ii}^{\text{tot}}(E) = 2\Phi_i^{e^+}(E) + \Phi_{ii}^{e_s}(E)$.

In our case we should determine $\Phi_i^{e^+}$ and $\Phi_j^{e^-}$ independently since the observables useful to identify AFVdm are sensitive to these independent fluxes. In general it is not possible to use directly the tools provided in [38] for AFVdm since in the latter the direct and secondary contributions are not separated. However, as we shall explain, for the decay modes relevant here we can still capitalize on Ref. [38] while for a more general flavor violation involving also the quarks this is not obvious and should be implemented in the numerical codes. For

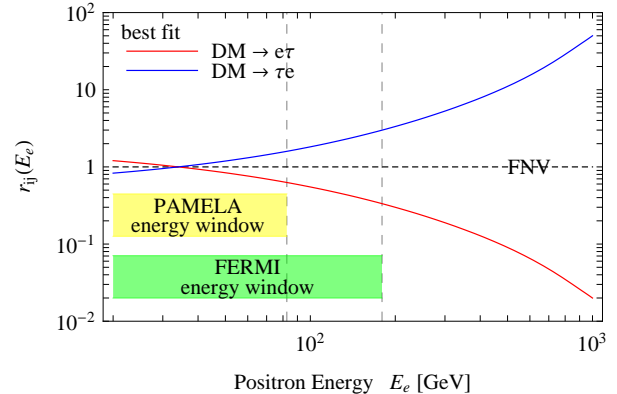
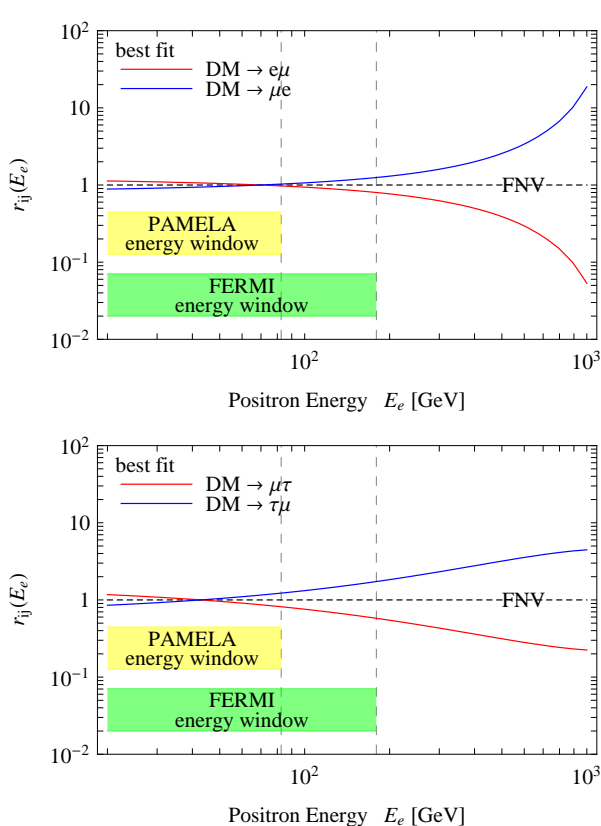


Figure 1: The ratio $r_{ij}(E)$ as a function of the positron energy. In each plots the blue/red lines are performed by using the best fit DM mass for the primary channels $DM \rightarrow ij/DM \rightarrow ji$. The yellow and green bands represent the energy ranges of the positron fraction data of PAMELA and Fermi respectively. The horizontal dashed lines refer to flavor non-violating models for which $r_{ij}(E) \equiv 1$.

the total flux of positron and electrons coming from a two-body decays one can always use the identity:

$$\Phi_{ij}^{\text{tot}}(E) = \frac{\Phi_{ii}^{\text{tot}}(E) + \Phi_{jj}^{\text{tot}}(E)}{2}. \quad (5)$$

For the ratio $r_{ij}(E)$ the situation instead is trickier and we make the following phenomenologically excellent approximation valid for scalar DM decaying into two-body lepton-violating processes:

$$r_{ij}(E) = \frac{\Phi_{jj}^{\text{tot}}(E) + 2(\Phi_i^{e_s^-}(E) - \Phi_j^{e_s^-}(E))}{\Phi_{ii}^{\text{tot}}(E) + 2(\Phi_j^{e_s^+}(E) - \Phi_i^{e_s^+}(E))} \approx \frac{\Phi_{jj}^{\text{tot}}(E)}{\Phi_{ii}^{\text{tot}}(E)}, \quad (6)$$

where we neglected the differences which are numerically very small. This quantity can be directly related to the measured positron fraction (see [5]) representing the relevant observable for AFVdm.

2.1 DM interpretations of the charged CR anomalies

As already mentioned in Sec. 1, the anomalous PAMELA, Fermi and H.E.S.S. data have been already interpreted in terms of decaying DM models. Here we present a careful analysis of the charged CR anomalies in the context of lepton flavor-violating asymmetric DM.

We use the following set of data: The PAMELA [7, 8] and Fermi [9] positron fraction selecting points with $E > 20$ GeV; The total fluxes ($e^+ + e^-$) of Fermi [15], H.E.S.S. [13, 14] and MAGIC [17]; Finally the PAMELA \bar{p} flux [11]. We select the data from 20 GeV and above for PAMELA in order to: *i*) have a more consistent overlap with the Fermi positron fraction data points, *ii*) to avoid the low-energy region affected by the uncertainty coming

from the solar modulation. The total fluxes and positron fraction used to compare with data have been determined using the tools in [38], which correspond to the flavor-preserving fluxes $\Phi_{ii}^{\text{tot}}(E)$. To determine the best fit parameters for the DM mass (M_{DM}) and flavor-violating decay half-life (τ_{dec}) we also varied within the allowed uncertainties: The slope and the normalization of the energy dependent parametrization of the astrophysical background; The propagation parameter of charged cosmic rays. We follow the analysis for the flavor non violating processes presented in [41] and [30] where the reader can find more details. We have checked that the allowed regions of the parameters are not significantly modified even if we consider the recent determination of the e^+ astrophysical background given in [42] rather than the standard one [43, 44]).

We have found that it is possible to obtain a reasonable combined fit of the whole datasets of charged CR for all the leptonic flavor-violating primary modes ($\text{DM} \rightarrow ij$) as well as their charge conjugate ($\text{DM} \rightarrow ji$). This can be appreciated in Fig. 3, where we show the allowed regions in the plane ($M_{\text{DM}}, \tau_{\text{dec}}$) for all the channels we consider. In particular the red/blue and orange/magenta blobs refer to the 95.45% and 99.999% C.L. regions for the channels $\text{DM} \rightarrow ij/\text{DM} \rightarrow ji$ respectively. We have also checked that the resulting flux of antiprotons remains within the experimental bounds even when taking into account the final state radiation of electroweak gauge bosons. The quality of the fit to the CR data for flavor-violating processes from asymmetric DM is as good as the ones for flavor-preserving processes.

However, only for flavor-violating process coming from the asymmetric DM sector the ratio $r_{ij}(E)$ can be, and will be, different from unity [5]. Therefore it is important to show the resulting ratio using the best fit value of the DM mass recalling that by construction $r_{ij}(E)$ does not depend on the decay rate. The resulting $r_{ij}(E)$ for the different processes are shown in Fig. 1. A ratio larger than unity is associated to an electron flux at Earth bigger, at a given energy, than the positron one. Within the energy ranges investigated by PAMELA (yellow band) and Fermi (green band) for the positron fraction data, whose maximum extent has been marked in the figures by two vertical lines, one can appreciate a sizable deviation from unity only for the $e\tau$ primary mode and its charged conjugate. This last result is in agreement with the preliminary analysis performed in [5]. An interesting result from the investigation of the combined allowed region of the parameter space is that for sufficiently large values of $r_{ij}(E)$ one can resolve the degeneracy between ij and ji . As one can see from Fig. 3, with the current precision of the positron excess data points, the discrimination among red/orange and blue/magenta regions turns out to be experimentally appreciable only for the $e\tau$ primary mode.

As a final comment, it is perhaps worth stressing that in order to be coherent with the Fermi positron energy range data, and to be absolutely sure that we were not affected by the solar modulation we only considered data starting from 20 GeV. If we were to add also the lower energy data of PAMELA (between 10 and 20 GeV) the two blobs would be even more separated.

2.2 Isotropic Gamma Ray Constraints

The isotropic residual gamma ray flux measured by Fermi [26] extends from about 200 MeV up to 580 GeV. This flux is due to a variety of physical phenomena such as unresolved sources as well as genuine diffuse processes (see [26]).

If DM is present in the sky and it decays it will, in general, also contribute to this isotropic

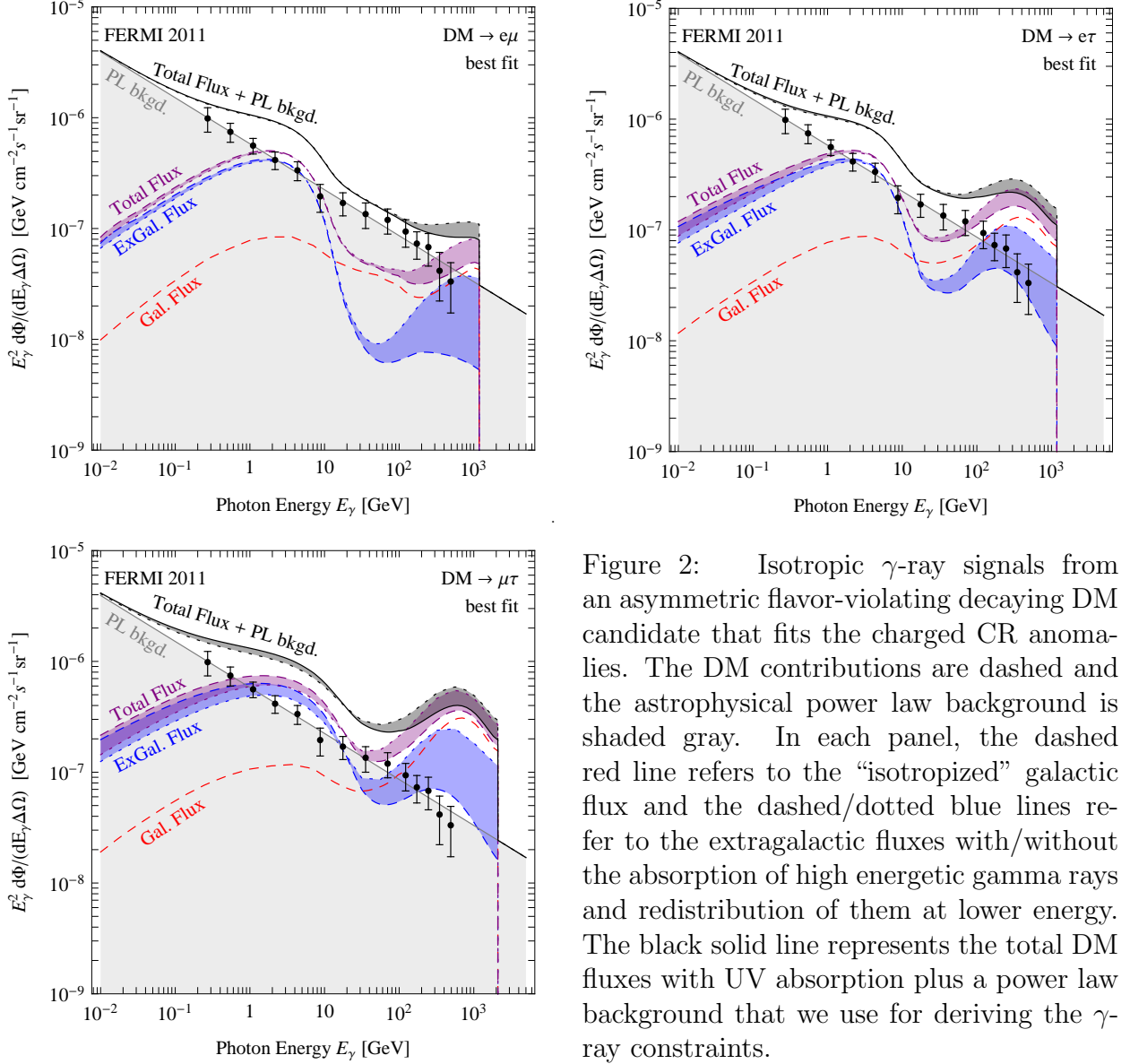


Figure 2: Isotropic γ -ray signals from an asymmetric flavor-violating decaying DM candidate that fits the charged CR anomalies. The DM contributions are dashed and the astrophysical power law background is shaded gray. In each panel, the dashed red line refers to the “isotropized” galactic flux and the dashed/dotted blue lines refer to the extragalactic fluxes with/without the absorption of high energetic gamma rays and redistribution of them at lower energy. The black solid line represents the total DM fluxes with UV absorption plus a power law background that we use for deriving the γ -ray constraints.

flux:

$$\frac{d\Phi_{\text{isotropic}}}{dE_\gamma} = \frac{d\Phi_{\text{ExGal}}}{dE_\gamma} + 4\pi \left. \frac{d\Phi_{\text{Gal}}}{dE_\gamma d\Omega} \right|_{\text{minimum}} \quad (7)$$

where the former term is the extragalactic cosmological flux and it is truly isotropic. The latter, which describes the residual emission from the DM halo of our Galaxy it is not, but its minimum constitutes an irreducible contribution to the isotropic flux. Typically the two contributions are comparable. We followed the approach established in [30, 31] where the reader can find further details.

Here we need to generalize the situation to the case of ij primary modes for i different from j and write:

$$\frac{d\Phi_{\text{ExGal}}^{ij}}{dE_\gamma} = \Gamma_{\text{dec}} \frac{\Omega_{\text{DM}} \rho_{c,0}}{M_{\text{DM}}} \int_0^\infty dz \frac{e^{-\tau(E_\gamma(z), z)}}{H(z)} \frac{1}{2} \left[\frac{dN^{ii}}{dE_\gamma}(E_\gamma(z), z) + \frac{dN^{jj}}{dE_\gamma}(E_\gamma(z), z) \right], \quad (8)$$

where $\frac{dN^{ii}}{dE_\gamma}(E_\gamma(z), z)$ are taken from the non flavor violating processes and photon energy is E_γ . The formula above makes use of the fact that the gamma flux for the case studied here corresponds to a DM decaying without violating flavor into 50% ii and jj modes. It is therefore clear that the photon signal as well as the total flux of positron and electron alone cannot discriminate between AFVdm and flavor symmetric DM. Here $\Gamma_{\text{dec}} = (\tau_{\text{dec}})^{-1}$ is the decay rate and $H(z) = H_0 \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$ is the Hubble function where H_0 is the present Hubble expansion rate. The DM, matter and cosmological constant energy density are Ω_{DM} , Ω_M and Ω_Λ and are expressed in units of the critical density, $\rho_{c,0}$. At any redshift z , the spectrum of gamma ray dN/dE_γ is given by: a) the prompt γ -ray emission from DM decays and b) the Inverse Compton Scatterings (ICS) on CMB photons of the e^+ and e^- from the same decays. Using now Eq. (8), we can compute the extragalactic flux in terms of known quantities for any specified DM mass M_{DM} and flavor-violating decay channel. The resulting fluxes are taken from [38] with an improved treatment of the optical depth (the factor $e^{-\tau(E_\gamma(z), z)}$ in Eq. (8)) in which the absorption of high energy gamma rays due to scattering with the extragalactic UV background light is fully taken into account. As recently pointed out in [31], this effect is important at energies $E_\gamma \gtrsim 100$ GeV and can decrease the flux at high energy by about one order of magnitude. In Fig. 2 we show the fluxes obtained neglecting absorption (dotted blue lines) and the one including it (dashed blue lines). As one can see the effect is sizable for all the channels we consider. In particular for the processes which involved a τ in the primary modes one can even appreciate the redistribution of high energy γ -ray towards the lower part of the spectrum. This will affect the γ -ray constraints especially for channels which feature a large prompt contribution. In deriving the γ -ray constraints we will take into account the full UV absorption.

In our case, the galactic differential flux coming from a given direction of the sky $d\Omega$ is:

$$\frac{d\Phi_{\text{Gal}}^{ij}}{dE_\gamma d\Omega} = \frac{1}{4\pi} \frac{\Gamma_{\text{dec}}}{M_{\text{DM}}} \int_{\text{los}} ds \rho_{\text{halo}}[r(s, \psi)] \frac{1}{2} \left[\frac{dN^{ii}}{dE_\gamma} + \frac{dN^{jj}}{dE_\gamma} \right], \quad (9)$$

where the coordinate s parameterizes the distance from the Sun along the line-of-sight (los). Here ρ_{halo} is the Milky Way DM distribution, for which we take the standard Navarro-Frenk-White [45] profile. One can consider in principle other choices of DM profiles, however, for decaying DM these choices lead to comparable results. The coordinate r , centered on the galactic center (GC), reads $r(s, \psi) = (r_\odot^2 + s^2 - 2r_\odot s \cos \psi)^{1/2}$, where $r_\odot = 8.33$ kpc is the most likely distance of the Sun from the GC and ψ is the angle between the direction of observation in the sky and the GC. dN/dE_γ is again the sum of two components: the prompt one and the ICS one. They are then determined by using the tools in [38]. In particular, for the ICS flux we use the full spatial dependence of the energy losses, which can be taken into account by a generalized halo functions for the IC radiative process provided there. In finding the minimum of the galactic flux we make the reasonable approximation that it corresponds to the value at the anti galactic center [31]. In formulæ

$$\left. \frac{d\Phi_{\text{Gal}}}{dE_\gamma d\Omega} \right|_{\text{minimum}} \rightarrow \left. \frac{d\Phi_{\text{Gal}}}{dE_\gamma d\Omega} \right|_{\text{anti-GC}}. \quad (10)$$

In Fig. 2 we show the ‘‘isotropized’’ galactic flux for all the channels we consider (dashed red lines). For all the panels one observes the low energy contribution due to ICS on CMB photons, and the high energy one coming from prompt emission. The junction between the

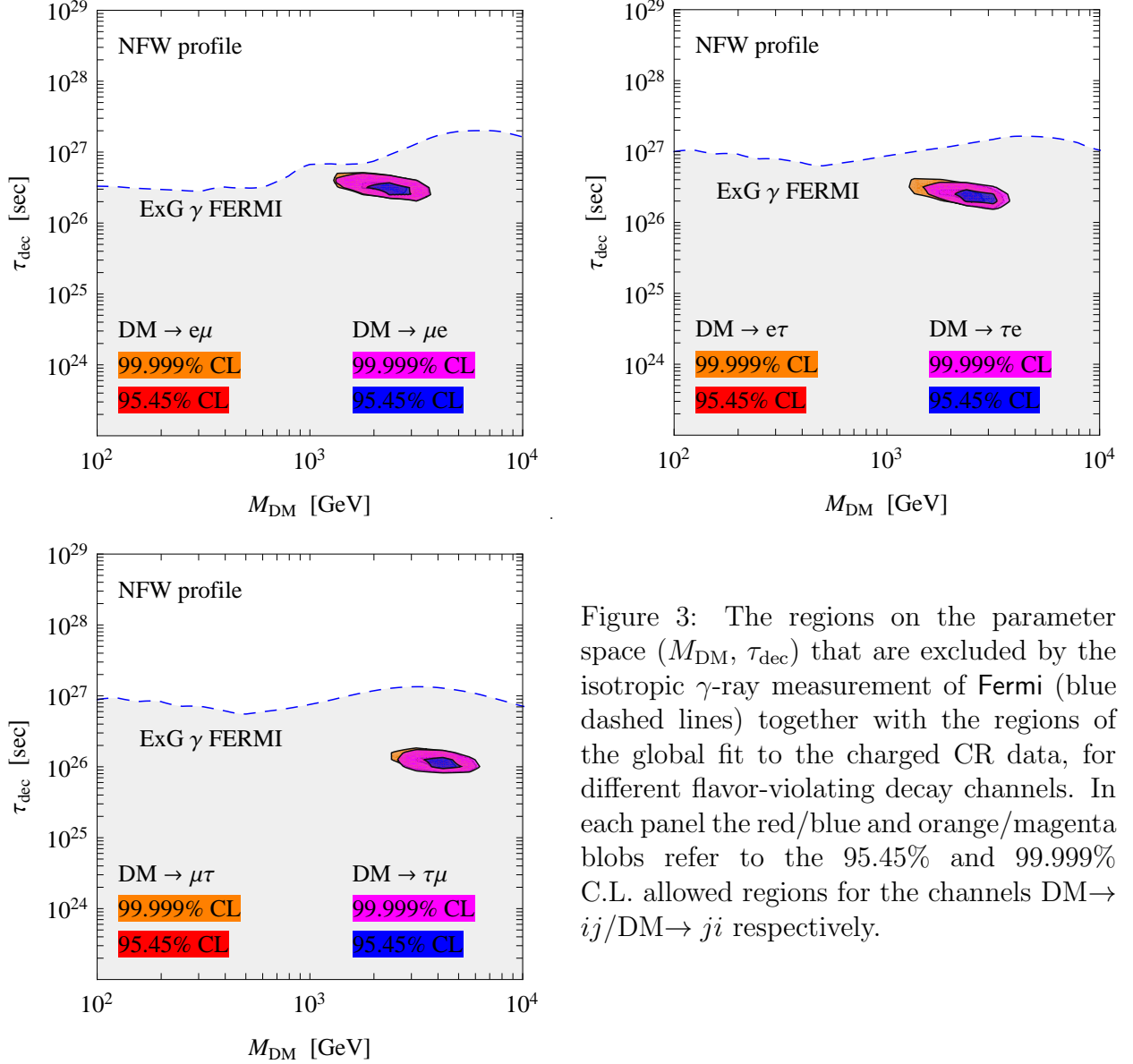


Figure 3: The regions on the parameter space ($M_{\text{DM}}, \tau_{\text{dec}}$) that are excluded by the isotropic γ -ray measurement of **Fermi** (blue dashed lines) together with the regions of the global fit to the charged CR data, for different flavor-violating decay channels. In each panel the red/blue and orange/magenta blobs refer to the 95.45% and 99.999% C.L. allowed regions for the channels $\text{DM} \rightarrow ij/\text{DM} \rightarrow ji$ respectively.

two parts of the spectrum originates from the ICS on the residual starlight and infrared light present along the los towards the anti galactic center.

We are now able to compare the isotropic gamma ray flux coming from AFVdm with the one measured by **Fermi**. In Fig. 2 we show an example for the candidates which fit the charged CR anomalies. It is clear that the signal overshoots the data and even provides local, in energy, features which are clearly not present in the data. In fact, the data are in good agreement with an astrophysical power-law background. To determine the actual constraints we demand that the sum of the DM signal and power-law background (solid black lines in Fig. 2) does not exceed a given significance. There are several potential sources that may produce such background, like unresolved blazars, star-forming galaxies or electromagnetic cascades from ultrahigh-energy cosmic ray losses. In general, a combination of them is not expected to produce an exact power law, which could be also inaccurate for some of the different contributions taken alone. However, within the actual precision of the detector, we find that the data alone (without DM contribution) are well fitted by a power-law index

-2.41 and normalization $1.02 \times 10^{-5}/(\text{GeV cm}^2 \text{ sr})$. In view of that and since the bumpy shape of the DM signal is so different from the featureless observations, it is reasonable to consider a power-law astrophysical background for the computations of the constraints on DM properties. On the top of this power-law, for a given M_{DM} we add the DM signal, whose normalization is controlled by Γ_{dec} , letting the normalization and the index of the DM free power-law vary¹ and marginalizing over them. We then compute the χ^2 and impose 95% C.L. limits on Γ_{dec} .

The exclusion plots can be found in Fig. 3 where we summarize our results for AFVdm. As one can see the isotropic γ -ray data measured by the *Fermi* satellite exclude DM lifetimes of the order of 10^{26} to few 10^{27} seconds. This therefore rules out the interpretation of the charged CR excesses in terms of AFVdm. In this study we have focussed on two-body lepton flavor-violation decay modes of scalar asymmetric DM. For vector asymmetric DM, the decay channels differ only in polarization with respect to the ones coming from scalar DM. Therefore, since this differences are not large, it is reasonable to expect that the allowed regions and constraints showed in Fig. 3 apply also for these cases.

3 Conclusions

Flavor violating decaying asymmetric DM models allow for a new type of DM phenomenology and can feature heavy or/and light DM candidates. Here we showed that it is possible to explain the anomalies in the charged CR measured by *PAMELA*, *Fermi* and *H.E.S.S.* in the context of AFVdm. Because of the nature of AFVdm the ratio of the electron over positron DM induced flux is, in general, different from unity while it must be unity for any other type of DM. We therefore determined the associated energy and flavor dependent ratio $r_{ij}(E)$ from the combined fits to the CR anomalies and found that the current data allow for flavor-violation for asymmetric DM for all the decay processes. An interesting result from the investigation of the combined allowed region of the parameter space is that for sufficiently large values of $r_{ij}(E)$ one could resolve the degeneracy between ij and ji .

We then discussed the constraints coming from the measurement of the isotropic γ -ray background by *Fermi* for a complete set of lepton flavor-violating primary modes and over a range of DM masses from 100 GeV to 10 TeV. We used updated computational tools which are the most refined semi-analytical computations present in the literature.

We found that *Fermi* constraints rule out the AFVdm interpretation of the charged CR anomalies. This analysis complements the constraints for flavor preserving DM for which similar constraints have been derived.

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¹When we compute the bounds, we let the normalization of the power-law background to vary within a factor of 2 from the central value specified above, and its index within 0 and -1. These choices are astro-physically plausible, although varying the parameters in a broader range would not change the results.

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