Robust Gamma Ray Signature of WIMP Dark Matter

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Abstract

If dark matter consists of weakly interacting massive particles (WIMPs), annihilation of WIMPs in the galactic center may lead to an observable enhancement of high energy gamma ray fluxes. We predict the shape and normalization of the component of the flux due to final state radiation by charged particles produced in WIMP annihilation events. The prediction is made without any assumptions about the microscopic theory responsible for WIMPs, and depends only mildly on the unknown distribution of the total WIMP annihilation cross section among the possible final states. In particular, if the WIMPs annihilate into a pair of charged fermions (leptons or quarks), the photon spectrum possesses a sharp edge feature, dropping abruptly at a photon energy equal to the WIMP mass. If such a feature is observed, it would provide strong evidence for the WIMP-related nature of the flux enhancement, as well as a measurement of the WIMP mass. We discuss the prospects for observational discovery of this feature at ground-based and space-based gamma ray telescopes.
1 Introduction

While the existence of dark matter on galactic and cosmological scales has been firmly established, its microscopic nature is still unknown. According to the “WIMP hypothesis”, dark matter consists of stable, weakly interacting massive particles (WIMPs) with masses roughly within the 10 GeV – 10 TeV range. From the theoretical point of view, this hypothesis is perhaps the most attractive among the proposed candidate theories. There is as yet no direct evidence for its validity; however, it does predict several potentially observable new phenomena. In particular, pairs of WIMPs accumulated in the Milky Way and other galaxies should occasionally annihilate into lighter particles. These lighter particles (or their decay products) can then be found in cosmic rays, providing an “indirect” signature of galactic WIMPs.

The same process, pair annihilation of WIMPs into lighter particles, is also responsible for maintaining the thermal equilibrium between the WIMPs and the rest of the cosmic fluid in the early universe. As a result, the temperature at which the WIMPs decouple depends sensitively on the pair annihilation cross section. This implies that a measurement of the present dark matter density (currently known with an accuracy of about 10% [1]) provides a determination of the annihilation cross section under the conditions prevailing at the time of decoupling. Since WIMPs are non-relativistic at decoupling, it is useful to expand the total annihilation cross section as a power series in terms of the WIMP relative velocity \( v \):

\[
\sigma v = a + bv^2 + \ldots.
\]  

In a generic situation, one of the two terms in this equation dominates the cross section at decoupling \( (v^2 \sim 3T/M \sim 0.1) \): if \( s \) wave annihilation is unsuppressed, the cross section is dominated by the \( a \) term, whereas if the annihilation predominantly occurs in a \( p \) wave, the \( b \) term dominates. Therefore, a measurement of the present dark matter density determines the quantity \( \sigma_{an} \) defined in Ref. [2] as the coefficient of the dominant term (i.e. \( \sigma_{an} = a \) for \( s \)-annihilators and \( \sigma_{an} = b \) for \( p \)-annihilators). This result, shown in Fig. 1, is completely independent of the particle physics model responsible for the WIMPs; the only requirement is that the spectrum be generic, which ensures that co-annihilation processes and resonances are unimportant\(^1\). Moreover, \( \sigma_{an} \) is largely independent of the WIMP mass and spin: roughly, \( \sigma_{an}^s = 0.85 \text{ pb} \) for \( s \)-annihilators and \( \sigma_{an}^p = 7 \text{ pb} \) for \( p \)-annihilators.

In this article, we extend the model-independent approach of Ref. [2] to predict the fluxes of anomalous cosmic rays due to WIMP annihilation. Indirect WIMP searches predominantly concentrate on three signatures: anomalous high-energy gamma rays, antimatter (positrons, antiprotons, etc.), and neutrinos [4]. While the dark matter density measurement determines the total cross section of WIMP annihilation, the distribution between the various possible final states \( (e^+e^-, q\bar{q}, \gamma\gamma, W^+W^- \text{, etc.}) \) is not constrained. In order to keep the analysis as model-independent as possible, we focus on the signatures that are least sensitive to this distribution, i.e. those that appear for the maximal number of final states. High-energy neutrinos and positrons are only produced if the WIMPs annihilate directly into \( \nu\bar{\nu} \) or \( e^+e^- \)

\(^1\)The analysis can also be extended to the case of superWIMP dark matter [3].
Figure 1: Values of the quantity $\sigma_{\text{an}}$ allowed at 2$\sigma$ level as a function of WIMP mass. The lower and upper bands correspond to models where the WIMP is an $s$- and $p$-annihilator, respectively. Reproduced from Ref. [2].

pairs, respectively, or (in smaller numbers) if the primary annihilation final state contains $W/Z$ bosons. Gamma rays, on the other hand, are produced almost independently of the primary final state (with $\nu\bar{\nu}$ being the only exception among two-body final states), and we therefore concentrate on this signature. There are several ways in which gamma rays can be produced in WIMP annihilation events. Two well known processes [5, 6, 7, 8] are the direct annihilation to photon-photon or photon-$Z$ pairs ($\chi\chi \to \gamma\gamma, \gamma Z$, where $\chi$ denotes the WIMP) and fragmentation following WIMP annihilation into final states containing quarks and/or gluons. While these processes can be easily described within our approach, we will concentrate on another source of photons, the final state radiation (FSR), which has until now received far less attention in the literature\(^2\). The FSR component of the gamma ray spectrum has several important advantages. First, FSR photons are produced whenever the primary products of WIMP annihilation are charged: e.g. charged leptons, quarks or $W$ bosons. Even if the WIMPs annihilate into $ZZ$, $Zh$, or $hh$ pairs, the charged decay products of these particles will contribute to the FSR flux; only the $\nu\bar{\nu}$ channel does not contribute. In contrast, the monochromatic photons are only produced when the WIMPs annihilate into $\gamma\gamma$ or $\gamma Z$ pairs; since these processes can only occur at one-loop level [6], only a small fraction of WIMP annihilation events results in these final states. The fragmentation photons are not produced for leptonic final states. In this sense, out of the three components of the photon

\(^2\)A recent discussion of the FSR flux in the context of a specific model (universal extra dimensions) and a subset of primary final states (charged leptons) is contained in [9].
flux, the FSR component is the most robust. Second, even though the energy spectrum of the FSR photons is broad, in many cases (whenever the WIMPs annihilate directly into charged fermion pairs) the spectrum contains a sharp edge feature at an energy close to the WIMP mass [9]. This feature can be extremely useful in differentiating the WIMP signal from the astrophysical background: while no detailed theoretical understanding of the background is available, it seems very unlikely that such a feature in the relevant energy range can be produced by conventional physics. This is in sharp contrast with the fragmentation photons, whose broad and featureless spectrum makes it difficult to rule out a more conventional astrophysical explanation if an excess over the expected background is observed.

This article is organized as follows. In Section 2 we present the model-independent approximate formulas for the energy spectrum of the FSR photons produced in WIMP annihilation events. We test the accuracy of our analytical results against explicit numerical calculations in specific models. In Section 3, we use these results to predict the gamma ray fluxes from WIMP dark matter annihilation in the Milky Way. After discussing the relevant backgrounds in Section 4, we estimate the sensitivity reach of the typical space-based and ground-based gamma ray telescopes in Section 5. We reserve Section 6 for our conclusions.

2 Final State Radiation in WIMP Annihilation

If a WIMP pair can annihilate into a pair of charged particles, \(X\) and \(\bar{X}\), annihilation into a three-body final state \(X\bar{X}\gamma\) is always also possible. As long as the \(X\) particles in the final state are relativistic, the cross section of this reaction is dominated by the photons that are approximately collinear with either \(X\) or \(\bar{X}\). These are referred to as the “final state radiation” (FSR) photons. In this kinematic regime, the cross section factorizes into the short-distance part, \(\sigma(\chi\chi \rightarrow X\bar{X})\), and a universal collinear factor:

\[
\frac{d\sigma(\chi\chi \rightarrow X\bar{X}\gamma)}{dx} \approx \frac{\alpha Q_X^2}{\pi} F_X(x) \log \left( \frac{s(1-x)}{m_X^2} \right) \sigma(\chi\chi \rightarrow X\bar{X}),
\]  

(2)

where \(\alpha\) is the fine structure constant, \(Q_X\) and \(m_X\) are the electric charge and the mass of the \(X\) particle, \(s\) is the center-of-mass energy (\(s \approx 4m_X^2\) for non-relativistic WIMPs), and \(x = 2E_\gamma/\sqrt{s}\). The splitting function \(F\) is independent of the short-distance physics, depending only on the spin of the \(X\) particles. If \(X\) is a fermion, the splitting function is given by

\[
F_f(x) = \frac{1 + (1-x)^2}{x},
\]  

(3)

whereas if \(X\) is a scalar particle,

\[
F_s(x) = \frac{1-x}{x}.
\]  

(4)

If \(X\) is a \(W\) boson, the Goldstone boson equivalence theorem implies that \(F_W(x) \approx F_s(x)\). (The applicability of the Goldstone boson equivalence theorem is guaranteed whenever the collinear factorization in Eq. (2) is a good approximation, since both require \(m_X \gg m_W\).)
Does Eq. (2) provide a good approximation of the FSR photon spectrum from galactic WIMP annihilation in a realistic situation? To address this question, we compare the FSR photon spectrum obtained by a direct calculation in a specific model with the prediction of Eq. (2) with the appropriate parameters. For this comparison, we have used the minimal universal extra dimension (UED) model [10]. We computed the cross section of the process $B_1 B_1 \rightarrow e^+ e^- \gamma$ using the CompHEP package [11]. ($B_1$, the first Kaluza-Klein excitation of the hypercharge gauge boson, plays the role of the WIMP dark matter candidate in the UED model [12].) We have fixed the radius of the extra dimension to be $R = (499.07 \text{ GeV})^{-1}$, corresponding to $B_1$ mass of 500 GeV. While Eq. (2) holds for any WIMP momentum, we have chosen the colliding WIMPs to be nonrelativistic ($\sqrt{s} = 1001 \text{ GeV}$), to approximate the kinematics typical of galactic WIMP collisions. The result of the direct cross section calculation is shown by the red histogram in Fig. 2. The blue (continuous) line corresponds to the prediction of Eq. (2) with the same $\sqrt{s} = 1001 \text{ GeV}$, $X = e$, and the appropriate value of $\sigma(\chi \chi \rightarrow e^+ e^-) \approx 5.67 \text{ pb}$. The good agreement between the line and the histogram proves the validity of the collinear approximation for the total cross section. Remarkably, the spectrum has a sharp step-like edge feature at the endpoint, $E \rightarrow M_{\chi}$. The origin of the feature is obvious from Eqs. (2) and (3): ignoring the $x$ dependence of the logarithm in Eq. (2), which only has a small effect on the spectrum, it is easy to see that the differential
cross section approaches a non-zero constant value at $x \to 1$, whereas it obviously has to vanish for $x > 1$. Since it is difficult to imagine an astrophysical process providing a similarly sharp endpoint feature at the relevant energy scales, observing the step would provide a strong evidence for WIMPs [9].

If the primary product of WIMP annihilation is a lepton pair ($e^+e^-$, $\mu^+\mu^-$), the FSR mechanism discussed above is the dominant source of secondary photons. On the other hand, if the WIMPs annihilate into quark-antiquark or $\tau^+\tau^-$ pairs, an additional contribution to the secondary photon flux arises from hadronization and fragmentation. This contribution is dominated by the decays of neutral pions. While the fragmentation photons are more numerous than the FSR photons, they tend to be softer. The spectrum close to the endpoint is still dominated by the FSR component, and can be predicted using Eq. (2), with an appropriate choice of the “effective” value of $m_X$ in the logarithm. This is illustrated in Figure 3, which shows the secondary photon fluxes from a primary $u$ quark of 250 GeV energy. The upper (blue) histogram shows the total $\gamma$ spectrum, including both fragmentation and FSR components, calculated using the PYTHIA package [13]; the lower (red) histogram shows the PYTHIA prediction for the FSR flux alone. The total flux above about 225 GeV ($x = 0.9$) is dominated by the FSR component, and exhibits the expected edge feature. The FSR spectrum predicted by PYTHIA is consistent with the prediction of Eq. (2); however, to obtain a good fit, the quantity $m_u$ in the logarithm should be replaced with the “effective mass” $m_u^{\text{eff}}$, which takes into account soft gluon radiation and other effects of strong interactions. The black dashed line in Fig. 3 represents the prediction of Eq. (2) using the best-fit value

![Figure 3: Photon spectrum produced by final state radiation and fragmentation of a primary $u$ quark with an energy of 250 GeV. The histograms represent PYTHIA predictions for the total photon flux (blue) and the final state radiation flux alone (red). The black dashed line represents the prediction of Eq. (2).](image-url)
of $m_{\text{eff}} = 20 \text{ GeV}$. An excellent fit to the PYTHIA output is obtained. We conclude that the sharp endpoint with a shape given by Eqs. (2), (3) exists whenever the primary WIMP annihilation products are charged fermions: it does not matter whether they are leptons or quarks.

Based on the above discussion, we will replace the bare mass with the “effective” mass whenever we apply Eq. (2) to light quarks; this substitution will be implicit for the rest of the paper. For simplicity, we will assume $m_{u}^{\text{eff}} = m_{d}^{\text{eff}} = m_{s}^{\text{eff}} = 0.2 \text{ GeV}$, since the scale for the effective mass is set by the QCD confinement scale. In reality, the situation is more complicated, since the effective mass may depend on the energy and flavor of the primary quark. Note also that the values needed to fit the PYTHIA predictions are substantially higher than $\Lambda_{\text{QCD}}$, but the interpretation of this result is not clear due to large uncertainties inherent in the showering algorithm and the fit. However, since the dependence on the mass is logarithmic, changing $m_{\text{eff}}$ has only a moderate effect on the photon flux predictions. We have confirmed that replacing our simple assumption with an energy-dependent value of $m_{\text{eff}}$ based on a fit to PYTHIA predictions does not substantially affect any of the estimates of photon fluxes and telescope sensitivities made below.

Unfortunately, a model-independent prediction of the sharp endpoint is not valid if the primary annihilation products of the WIMP are bosons, such as $W^{+}W^{-}$ pairs or the charged Higgs bosons in the minimal supersymmetric standard model (MSSM). According to Eq. (4), \( \lim_{x \to 1} F_{s}(x) = 0 \); because of this, the flux near the endpoint is dominated by the model-dependent non-collinear contributions, and no firm model-independent prediction of the shape of the endpoint spectrum is possible.

FSR photons will also be produced when the WIMPs annihilate into neutral, unstable particles, whose decay products are charged: in the Standard Model, these could be $ZZ$, $Zh$, or $hh$ pairs. For example, consider the process $\chi \chi \rightarrow ZZ$ with the subsequent $Z$ decay into charged fermions ($\ell^{+}\ell^{-}$ or $q\bar{q}$), which in turn emit an FSR photon. The photon spectrum in the $Z$ rest frame is given by Eq. (2), with the substitutions $s \rightarrow m_{Z}^{2}$ and $\sigma(\chi \chi \rightarrow XX) \rightarrow 2\sigma(\chi \chi \rightarrow ZZ)\text{Br}(Z \rightarrow XX)$. Performing the boost to return to the laboratory frame yields

\[
\frac{d\sigma}{dx} = \frac{\alpha}{\pi} \sigma(\chi \chi \rightarrow ZZ) \Psi_{Z}(x),
\]

where

\[
\Psi_{Z} = 2\theta(m_{\chi}-m_{Z}) \frac{1}{x} \left[ 1 + \frac{1-x}{v} - \frac{2x^{2}}{v(v+1)} + \frac{2x}{v} \log \frac{2xv}{1+v} \right] \sum_{X} Q_{X}^{2} \text{Br}(Z \rightarrow XX) \log \left( \frac{m_{Z}^{2}}{m_{\chi}^{2}} \right).
\]

In this equation, $x = E_{\gamma}/m_{\chi}$, $v = \sqrt{1-m_{Z}^{2}/m_{\chi}^{2}}$ is the velocity of the $Z$ boson, and the sum runs over all the charged fermion pairs that $Z$ can decay into. We have ignored the corrections that are not enhanced by $\log(m_{Z}^{2}/m_{\chi}^{2})$. If $m_{\chi} \gg m_{Z}$, the $Z$ bosons are relativistic and the spectrum is given by

\[
\Psi_{Z} = 2 \frac{2-x+2x \log x - x^{2}}{x} \sum_{X} Q_{X}^{2} \text{Br}(Z \rightarrow XX) \log \left( \frac{m_{Z}^{2}}{m_{\chi}^{2}} \right).
\]
For the $Zh$ and $hh$ final states, we obtain expressions analogous to (5). The corresponding functions $\Psi_{Zh}$ and $\Psi_{h}$ can be easily obtained from Eq. (6) by replacing the parameters of the $Z$ boson with those of the Higgs where appropriate. In particular, in the limit $m_\chi \gg m_h$ we obtain

$$\Psi_{hZ}(x) = \frac{2 - x + 2x \log x - x^2}{x} \sum_X Q_X^2 \left[ \Br(Z \to XX) \log \left( \frac{m_Z^2}{m_X^2} \right) \right] \right. + \left. \Br(h \to XX) \log \left( \frac{m_h^2}{m_X^2} \right) \right),$$

$$\Psi_h(x) = \frac{2 - x + 2x \log x - x^2}{x} \sum_X Q_X^2 \Br(h \to XX) \log \left( \frac{m_h^2}{m_X^2} \right). \tag{8}$$

These expressions include only fermionic decays of the Higgs; we assumed that the Higgs is too light to decay into $W/Z$ pairs. The analysis can be straightforwardly generalized to include these decays. Unfortunately, it is clear from the above equations that the spectrum of FSR photons produced in $Z/h$ decays does not possess a sharp endpoint; instead, it approaches 0 gradually in the $x \to 1$ limit. This means that the non-universal, model-dependent contributions may become dominant near the endpoint.

### 3 FSR Photon Flux Estimates

In general, the differential $\gamma$ flux from WIMP annihilations observed by a telescope can generally be written as

$$\frac{d^2 \Phi}{dE d\Omega} = \left( \sum_i \left( \frac{d\sigma_i}{dE} \right) B_i \right) \frac{1}{4\pi m_\chi^2} \int \rho^2(l) dl,$$ \tag{9}

where the sum runs over all possible annihilation channels containing photons, and $\sigma_i$ and $B_i$ are the annihilation cross section and the number of photons per event in a given channel, respectively. The average is over the thermal ensemble of WIMPs in the galaxy. The integral is computed along a line of sight in the direction parametrized by $\Psi = (\theta, \phi)$, and $\rho(l)$ is the mass density of WIMP dark matter at a distance $l$ from the observer. To obtain the FSR photon flux, we substitute the differential cross section for the final states containing such photons, given in Eqs. (2) and (5), into Eq. (9), and take into account that $B_i = 1$ for these final states. We obtain

$$\frac{d^2 \Phi_{FSR}}{dE d\Omega} = \left[ \sum_X \theta(m_\chi - m_X) Q_X^2 \langle \sigma_X v \rangle \mathcal{F}_X(x) \log \left( \frac{4m_X^2(1-x)}{m_\chi^2} \right) + \langle \sigma_Z v \rangle \Psi_Z(x) 
+ \langle \sigma_{hZ} v \rangle \Psi_{hZ}(x) + \langle \sigma_h v \rangle \Psi_h(x) \right] \times \frac{\alpha}{\pi} \frac{1}{4\pi m_\chi^2} \int \rho^2 dl, \tag{10}$$

where $x = E/m_\chi$. The sum runs over all possible two-body final states with charged particles $X$ and $\bar{X}$, and $\sigma_X = \sigma(\chi\chi \to XX)$. To simplify notation, we have also defined $\sigma_Z = \sigma(\chi\chi \to ZZ)$, $\sigma_h = \sigma(\chi\chi \to hh)$, and $\sigma_{hZ} = \sigma(\chi\chi \to Z\bar{h})$. 


In the spirit of Ref. [2], we define the total WIMP annihilation cross section, \( \sigma_0 = \sigma(x\chi \rightarrow \text{anything}) \), and the “annihilation fractions” for the two-particle final states, \( \kappa_X = \langle \sigma_X v \rangle / \langle \sigma_0 v \rangle \). (Note that \( \sum_X \kappa_X = 1 \), up to a small correction due to the contribution of the processes with three or more particles in the final state.) With these definitions, the FSR flux can be written as

\[
\frac{d^2 \Phi_{\text{FSR}}}{dE d\Omega} = \frac{\alpha}{4\pi m^3_X} \langle \sigma_0 v \rangle \mathcal{G}(x) \int \rho^2 dl, \tag{11}
\]

where

\[
\mathcal{G}(x) = \sum_X \theta(m_X - m_X) Q_X^2 \kappa_X \mathcal{F}_X(x) \log \left( \frac{4m^2_X (1 - x)}{m^2_X} \right) + \kappa_Z \Psi_Z(x) + \kappa_{hZ} \Psi_{hZ}(x) + \kappa_h \Psi_h(x). \tag{12}
\]

Notice that almost all WIMP annihilation channels, with the exception of \( \nu\bar{\nu} \) and \( gg \) final states, contribute to the FSR photon flux; only the details of the flux depend on the distribution of the cross section among the channels.

The photon flux prediction is subject to large uncertainties in the distribution of dark matter in the galaxy. These uncertainties are conventionally parametrized by a dimensionless function

\[
\bar{J}(\Psi, \Delta \Omega) \equiv \frac{1}{8.5 \text{ kpc}} \left( \frac{1}{0.3 \text{ GeV/cm}^3} \right)^2 \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega \int \rho^2 dl, \tag{13}
\]

where \( \Delta \Omega \) denotes the field of view of a given experiment. The values of \( \bar{J} \) depend on the galactic halo model. The optimal line of sight for WIMP searches is towards the galactic center; in this case, the uncertainty is particularly severe due to the possibility of a sharp density enhancement at the center. For example, at \( \Delta \Omega = 10^{-3} \text{ sr} \), typical values of \( \bar{J} \) range from \( 10^3 \) for the NFW profile [14] to about \( 10^5 \) for the profile of Moore et al. [15], and can be further enhanced by a factor of up to \( 10^2 \) due to the effects of adiabatic compression [16].

Using Eq. (11) and the above definition of \( \bar{J} \) yields the FSR flux integrated over the field of view:

\[
\frac{d\Phi_{\text{FSR}}}{dE} = \Phi_0 \left( \frac{\langle \sigma_0 v \rangle}{1 \text{ pb}} \right) \left( \frac{100 \text{ GeV}}{m_X} \right)^3 \mathcal{G}(x) \bar{J}(\Psi, \Delta \Omega) \Delta \Omega, \tag{14}
\]

where \( \Phi_0 = 1.4 \times 10^{-14} \text{ cm}^{-2} \text{ sec}^{-1} \text{ GeV}^{-1} \).

While Eq. (14) provides a complete description of the FSR photon spectrum, the shape and the normalization of the flux for the most energetic photons (close to \( x = 1 \)) is of particular interest due to the possibility of the observable edge feature. In this region, the flux is dominated by the photons radiated by fermion products of WIMP annihilation. Neglecting the \( x \) dependence in the logarithm, whose only effect is to slightly smooth out the edge in the region \( 1 - x \ll 1 \), the flux is approximately given by

\[
\frac{d\Phi_{\text{FSR}}}{dE} = \Phi_0 g \left( \frac{100 \text{ GeV}}{m_X} \right)^3 \mathcal{F}(x) \bar{J}(\Psi, \Delta \Omega) \Delta \Omega. \tag{15}
\]
Here, the dimensionless parameter $g$ contains all the information about the primary WIMP annihilation processes:

$$g = \left( \frac{\langle \sigma_0 v \rangle}{1 \text{ pb}} \right) \sum_f Q_f^2 \kappa_f \log \left( \frac{4m_f^2}{m_X^2} \right),$$

where the sum runs over all kinematically accessible fermionic final states. Depending on the microscopic model giving rise to the WIMP, the parameter $g$ can vary between 0 (if, for example, the WIMPs can only annihilate into neutral states) and about 35 in the most favorable case of very heavy WIMPs annihilating into electron-positron pairs in an $s$-wave.

The normalization of the FSR photon flux is determined by the quantity $\langle \sigma_0 v \rangle$. As we argued in the Introduction, the measurement of the present cosmological abundance of dark matter determines the total WIMP annihilation cross section at decoupling ($v^2 \sim 1/10$). A typical relative velocity of galactic WIMPs is much smaller, $v \sim 10^{-3}$. In models where the $s$-wave annihilation is unsuppressed, the quantity $\sigma v$ is velocity-independent at low $v$, allowing us to make a robust model-independent prediction:

$$\langle \sigma_0 v \rangle = \sigma_s^a \approx 0.85 \text{ pb.}$$

If, on the other hand, the cross section at decoupling is dominated by the $b$ term, no firm prediction for the quantity $\langle \sigma_0 v \rangle$ is possible: even a small $a$ term, if present, may become dominant for galactic WIMPs due to the low value of $v$. If no $a$ term is present, we estimate $\langle \sigma_0 v \rangle = \sigma_p^p v^2 \sim 10^{-5} \text{ pb}$; a larger cross section is possible if an $a$ term is present, with the upper bound provided by Eq. (17). Given the uncertainty present in the $p$-annihilator case, we will use the $s$-annihilator WIMP examples to illustrate our approach in the remainder of this paper.

4 Background Fluxes

Estimating the sensitivity of WIMP searches also requires the knowledge of background fluxes. The searches for anomalous cosmic $\gamma$ rays are conducted both by space-based telescopes and ground-based atmospheric Cerenkov telescopes (ACTs). The space-based telescopes observe photons directly, and the only source of irreducible background in this case is the cosmic $\gamma$ rays of non-WIMP origin. The ACTs observe the Cerenkov showers created when a cosmic ray strikes the upper atmosphere, and are subject to the additional backgrounds of Cerenkov showers from leptonic and hadronic cosmic rays. In our estimates of the experiments’ sensitivities, we will use simple power-law extrapolations of the background fluxes measured at low energies. For the non-WIMP photon flux, we use [7]

$$\frac{d^2 \Phi_{\gamma, \text{bg}}}{dE d\Omega} = 4 \times 10^{-12} N_0(\Psi) \left( \frac{100 \text{ GeV}}{E} \right)^{2.7} \text{ cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\text{sr}^{-1},$$

where the function $N_0$ describes the angular distribution of the photons (an approximation is given in Refs. [7, 17].) In our analysis, we will replace $N_0(\Psi) \rightarrow \max N_0 \approx 89$. This
generally overestimates the background; however, the effect is small, especially for the line of sight close to the direction to the galactic center. The non-photonic background flux for the ACTs is estimated as \[7\]

\[
d\frac{2}{dE d\Omega}^{\text{lep}} = 1.73 \times 10^{-8} \left(\frac{100 \text{ GeV}}{E}\right)^{3.3} \text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\text{sr}^{-1},
\]

\[
d\frac{2}{dE d\Omega}^{\text{had}} = 4.13 \times 10^{-8} \epsilon_{\text{had}} \left(\frac{100 \text{ GeV}}{E}\right)^{2.7} \text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\text{sr}^{-1},
\]

(19)

where \(\epsilon_{\text{had}}\) is the telescope-dependent probability that a hadronic Cerenkov shower will be misidentified as a photonic shower, normalized so that it is equal to one for the Whipple telescope (see Ref. \[7\]).

It is worth emphasizing that the fluxes (18) and (19) are merely extrapolations; in both cases the background cannot be accurately predicted from theory. While we will use these fluxes in our estimates, one should keep in mind that there are large uncertainties associated with them. This is why merely observing a flux enhancement is in general not sufficient to provide convincing evidence for WIMPs; a discovery of the step-like edge feature in the spectrum would greatly strengthen the case.

5 Sensitivity Reach of Future Telescopes

To illustrate the prospects for observational discovery of the FSR edge, we will use two toy scenarios. In the first scenario, the annihilation fractions for two-body final states are taken to scale as \(Y^{4}N_{c}\), where \(Y\) is the hypercharge of the final state particles, and \(N_{c} = 3\) for quarks and \(1\) for other states\(^3\). An explicit example in which this scenario is realized is provided by the model with universal extra dimensions \[10\], and we will therefore label it as UED. In the second scenario, the WIMPs do not annihilate into bosonic final states, while the annihilation fractions \(\kappa_{i}\) for all kinematically accessible fermion final states are equal (up to a factor of \(N_{c}\)). We will refer to this scenario as “democratic”. In both scenarios, we assume that the WIMPs can only annihilate into Standard Model particles, and use a Higgs mass of 120 GeV. The values of the quantity \(g\), defined in Eq. (16), as a function of the WIMP mass \(m_{\chi}\), in the two scenarios under consideration are shown in Figure 4. In both cases, we assume that WIMPs are \(s\)-annihilators, with the total annihilation cross section given by Eq. (17).

The magnitude of the FSR photon flux in each scenario is easily estimated using Eq. (14). As an example, Fig. 5 shows the number of events per 100 GeV bin expected to be observed at an ACT with an exposure time \(T = 50\) hrs, and a field of view \(\Delta \Omega = 4 \times 10^{-3}\) sr. (These parameters are similar to those of the VERITAS \[18\] and HESS \[19\] telescope arrays.) The

\(^3\)Note that Eq. (2) can be applied to polarized final states. Therefore, accounting for the different hypercharge of left-handed and right-handed fermions is straightforward.
Figure 4: The quantity $g$, defined in Eq. (16), as a function of the WIMP mass $m_\chi$, in the UED scenario (blue line) and the "democratic" scenario (red line). In the UED scenario, the annihilation fractions for two-body final states are taken to scale as $Y^4 N_c$, where $Y$ is the hypercharge of the final state particles, and $N_c = 3$ for quarks and 1 for other states. In the second scenario, the annihilation fractions for all kinematically accessible two-fermion final states are equal (up to a factor of $N_c$).

The effective collection area of the ACTs depends on the photon energy; in our analysis, we use an analytic fit to the effective area of the VERITAS array shown in Fig. 4, Ref. [18]:

$$A(E) = 1.2 \exp \left[ -0.513 \left( \log \frac{E}{5 \text{ TeV}} \right)^2 \right] \times 10^9 \text{ cm}^2. \quad (20)$$

We assumed the UED scenario with an 800 GeV WIMP. We have further assumed $\bar{J}(\Delta \Omega) = 10^5$, which is the case in the NFW galactic profile [14] with an adiabatic compression enhancement factor of about a 100 [16], or in the profile of Moore et. al. [15] with no adiabatic compression. It is clear from the figure that the edge feature due to the FSR photon emission following WIMP annihilation should be easily discernible in this data set.

An analogous plot illustrating the observability of the edge feature at the GLAST space telescope [20] is shown in Fig. 6. We have assumed a collection area $A = 10000 \text{ cm}^2$, an exposure time $T = 2 \text{ years}$, and a field of view$^4 \Delta \Omega = 10^{-3} \text{ sr}$. We have further assumed the

$^4$The field of view at GLAST can be varied between about $5 \times 10^{-6} \text{ sr}$ (the angular resolution of the telescope) and 2.3 sr (the full field of view). While larger values of $\Delta \Omega$ are advantageous from the point of view of statistics, focusing narrowly on the galactic center can lead to improved signal/background ratio if
Figure 5: The number of signal (blue) and background (red) events at a representative atmospheric Cerenkov telescope with a collection area given in Eq. (20), an exposure time $T = 50$ hrs, and a field of view $\Delta \Omega = 4 \times 10^{-3}$ sr. The signal is computed assuming the UED scenario with an 800 GeV WIMP and a galactic model with $\bar{J}(\Delta \Omega) = 10^5$.

“democratic” scenario with a 100 GeV WIMP, and a galactic model with $\bar{J}(\Delta \Omega) = 5 \times 10^4$. Again, the edge feature would be easily discernible for these parameters.

In addition to the FSR photon flux plotted in Figs. 5 and 6, photons are also expected to be produced both by quark fragmentation and loop-induced $\chi \chi \rightarrow \gamma \gamma, \gamma Z$ annihilation processes. As we showed in Section 2, the fragmentation component is subdominant to the FSR flux near the endpoint, and therefore will not affect the edge feature. However, this component may dominate the flux at lower energies, in which case the edge feature would be accompanied by a sharp change in the slope of the spectrum. The monochromatic photon flux from $\chi \chi \rightarrow \gamma \gamma$ will contribute to the signal in the bin containing $E_{\gamma} = m_\chi$. This contribution is also generally subdominant since $\sigma(\chi \chi \rightarrow \gamma \gamma)/\sigma(\chi \chi \rightarrow X \bar{X} \gamma) \sim \alpha \sim 10^{-2}$. If present, the line contribution will make the edge feature even sharper than our predictions based on the FSR flux alone.

To observe the FSR edge feature in the photon spectrum, the experiments need to search for a large drop in the number of events between two neighboring energy bins. A statistically significant discovery requires that the drop be larger than what can be expected from a fit to the rest of the spectrum. While a detailed analysis of the reach of any particular telescope the dark matter density has a sharp peak at the center. However, reducing $\Delta \Omega$ substantially below $10^{-3}$ typically results in insufficient statistics with the assumed collection area and exposure time.
Figure 6: The number of signal (blue) and background (red) events at the GLAST space telescope (collection area $A = 10000 \text{ cm}^2$, exposure time $T = 2$ years, field of view $\Delta \Omega = 10^{-3}$). The signal is computed assuming the “democratic” scenario with a 100 GeV WIMP and a galactic model with $\bar{J}(\Delta \Omega) = 5 \times 10^4$.

is beyond the scope of this article, a simple estimate of the reach can be obtained as follows. Consider the energy bin $[m_\chi(1-\delta), m_\chi(1+\delta)]$, where $\delta$ is the fractional energy resolution of a telescope\(^5\). The number of signal events in this bin is

$$N_{\text{sig}} \approx 1.4 \times 10^{-12} g \delta \left(\frac{100 \text{ GeV}}{m_\chi}\right)^2 \bar{J}(\Delta \Omega) A_{\text{cm}^2} T_{\text{sec}} \Delta \Omega,$$

where $A_{\text{cm}^2}$ and $T_{\text{sec}}$ are the area of the telescope in cm\(^2\) and the collection time in sec, respectively. Assuming that the fit to the high energy part of the spectrum ($E > m_\chi$) produces an estimate of the background consistent with Eqs. (18) and (19), the expected number of background events $N_{\text{bg}}$ in the energy bin $[m_\chi(1-\delta), m_\chi(1+\delta)]$ can be computed. Requiring

$$N_{\text{sig}} \geq 3 \sqrt{N_{\text{bg}}}$$

for a statistically significant discovery of the step, we find that a discovery at a space-based

\(^5\)The assumption that the bin is centered at $m_\chi$ represents the worst-case scenario for the reach; the reach can be improved by up to a factor of $\sqrt{2}$ by optimizing the binning to maximize the significance. In addition, our estimates ignore the possible monochromatic photon flux from $\chi\chi \to \gamma\gamma$, which would appear in the same bin. The fragmentation photon flux, which is subdominant to the FSR component but could still enhance the signal, is also ignored. In this sense, our reach estimates are rather conservative.
telescope is possible if
\[ g\bar{J}(\Delta \Omega) \geq 6 \times 10^8 (A_{cm^2}T_{sec}\delta\Delta \Omega)^{-1/2} \left( \frac{m_\chi}{100 \text{ GeV}} \right)^{1.15}. \] (23)

This condition, together with the “minimal signal” requirement,
\[ N_{\text{sig}} \geq 10, \] (24)
can be used to determine the reach of the GLAST telescope. The reach is shown in Fig. 7, where we plot the minimal value of \( \bar{J} \) required for the discovery, as a function of the WIMP mass \( m_\chi \), in the UED and “democratic” scenarios. The reach is shown for two values of \( \Delta \Omega \): 2.3 sr, corresponding to utilizing the full field of view of the telescope, and \( 10^{-3} \) sr, corresponding to focusing narrowly on the galactic center. (We assume the collection area \( A = 10000 \text{ cm}^2 \), the exposure time \( T = 2 \text{ years} \), and the energy resolution \( \delta = 10\% \).) For \( \Delta \Omega = 2.3 \) sr, the minimal signal criterion (24) is always weaker than the 3\( \sigma \) requirement in Eq. (22), and we do not plot it. For \( \Delta \Omega = 10^{-3} \) sr, on the other hand, the minimal signal criterion (24) dominates the reach determination for large masses; the dotted lines in Fig. 5 indicate the minimal value of \( \bar{J} \) for which it is satisfied. Note that, while the reach in terms
Figure 8: The minimal value of $\bar{J}$ required for the discovery of the edge feature due to WIMP annihilation at a representative atmospheric Cerenkov telescope (collection area given in Eq. (20), exposure time $T = 50$ hrs, energy resolution $\delta = 15\%$), for the field of view $\Delta \Omega = 4 \times 10^{-3}$ sr (dash lines) and $\Delta \Omega = 5 \times 10^{-6}$ sr (solid lines show the minimum value of $\bar{J}$ for which a $3\sigma$ deviation from the background occurs, while dotted lines represent the minimum value of $\bar{J}$ for which the edge bin contains at least 10 signal events.)

of $\bar{J}$ is clearly higher for the larger $\Delta \Omega$ due to higher statistics, the values of $\bar{J}$ in most galactic halo models are substantially enhanced at low values of $\Delta \Omega$.

The discovery reach for an ACT, assuming that the background is dominated by leptonic showers\textsuperscript{6}, is given by

$$g \bar{J}(\Delta \Omega) \geq 4 \times 10^{9} (A_{\text{cm}^2} T \sec \delta \Delta \Omega)^{-1/2} \left( \frac{m_x}{100 \text{ GeV}} \right)^{0.85}.$$  \hspace{1cm} (25)

To estimate the discovery potential of the VERITAS and HESS ACT arrays, consider an ACT with the collection area given in Eq. (20), an exposure time $T = 50$ hrs, and the energy resolution $\delta = 15\%$. The discovery reach for such a telescope is shown in Fig. 8. Dashed contours correspond to an experiment utilizing the full field of view of the ACT, assumed to be $4 \times 10^{-3}$ sr. Solid contours indicate the reach of an experiment focusing narrowly on the galactic center, with the angular resolution of $0.07^\circ$ corresponding to $\Delta \Omega = 5 \times 10^{-6}$ sr. (Galactic halo model predictions for $\bar{J}$ for this value of $\Delta \Omega$ range from about $10^4$ to

\textsuperscript{6}The leptonic background is dominant over the entire range of WIMP masses of interest, provided that $\epsilon_{\text{had}} \lesssim 0.1$.\n
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a few × 10⁸.) In the latter case, the minimal signal requirement (24) dominates the reach
determination for large \( m_\chi \), and is shown in the figure using the dotted lines.

Given a model for galactic halo profile and a set of assumptions about the relevant
annihilation fractions, Figs. 7 and 8 can be used to estimate the reach of the telescopes in
terms of the highest value of the WIMP mass for which the edge feature can be observed.
The estimate indicates that the prospects for observing the feature are quite good. For
example, with a rather conservative assumption \( J(\Delta \Omega = 4 \times 10^{-3} \, \text{sr}) = 10^4 \), an ACT
with the parameters used in our study would be able to discover the feature for \( m_\chi \) up to
about 2 TeV in the UED model, covering the entire range where the model is cosmologically
consistent [12]. Comparing Figs. 7 and 8 indicates that the VERITAS and HESS arrays
have a sensitivity comparable to GLAST. The experiments are complementary in terms of
the range of WIMP masses that can be covered: the ACT will be sensitive to values of \( m_\chi \)
between about 50 GeV and 10 TeV, while GLAST can observe the FSR edge if \( m_\chi \) is in
the 10 – 250 GeV mass range. We conclude that both space based telescopes and ACTs
could provide sufficient sensitivity in the near future to discover the edge feature in the \( \gamma 
\) flux if WIMPs are \( s \)-annihilators and the galactic halo profile and annihilation fractions are
favorable.

Since the edge feature appears at \( E_\gamma = m_\chi \), an observation of this feature would provide
a direct measurement of the WIMP mass, with an accuracy determined by the energy res-
dolution of the telescope, potentially better than 10%. This is especially interesting because
this parameter would be difficult to measure in a collider experiment, since WIMPs are
pair-produced and escape the detector without interacting. Thus, observation of the edge
feature would provide information complementary to what will be obtained at the LHC. For
example, in the case of supersymmetry, the LHC can often determine the mass differences
between some of the superpartners and the lightest neutralino, but not always the overall
mass scale [21]. This ambiguity could be resolved if the edge feature in the gamma ray
spectrum is observed.

6 Conclusions

In this article, we have obtained a prediction for the flux of photons produced as final state
radiation in galactic WIMP annihilation processes. The prediction relies on the determina-
tion of the total WIMP annihilation cross section, which is provided by the measurement
of the current cosmological dark matter abundance. As emphasized in [2], this determi-
nation does not require any assumptions about the fundamental physics giving rise to the
WIMP, apart from the mild condition of a generic mass spectrum. While the distribution
of the cross section among various possible final states is not constrained by cosmological
arguments, the FSR photons are produced for almost every possible final state (with the
exception of \( \nu \bar{\nu} \) and \( gg \)), making this signature quite model-independent. Moreover, if the
final state of WIMP annihilation is a pair of charged fermions (leptons or quarks), the FSR
flux has a well-defined step-like edge feature, dropping abruptly at the energy equal to the
WIMP mass. Observing such a feature would provide strong evidence for the WIMP-related
nature of the flux distortion, and yield a measurement of the WIMP mass.

If WIMPs are s-annihilators, the predicted FSR fluxes can be quite sizable, and the edge feature can be easily discernible above the expected background. Using a rough statistical criterion, we have shown that both ground-based ACTs such as HESS and VERITAS and space-based gamma telescopes such as GLAST have a good chance of observing the edge feature. It is likely that our simplified analysis underestimates the ability of the experiments to observe a step-like feature in the photon spectrum; a more sophisticated statistical analysis is clearly needed to obtain a more realistic estimate of the reach.

In the p-annihilator WIMP case, the fluxes are expected to be lower, and it is difficult to make model-independent predictions due to the possible presence of an $a$ term in the annihilation cross section which would not affect the WIMP relic abundance, but could dominate galactic WIMP annihilation. Nevertheless, it would be interesting to analyze if observable FSR photon fluxes can be produced in models with p-annihilator WIMPs, such as the bino-like neutralino in supersymmetric models.

In summary, the flux of FSR photons emitted in the process of WIMP annihilation in the center of Milky Way could be observable. An observation of the step-like edge feature characteristic of this flux could provide the first robust signature of WIMP dark matter. We encourage the collaborations involved in the analysis of the data coming from ground-based and space-based gamma ray telescopes to perform systematic searches for this important signature in a model-independent fashion as presented here.

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