Two Lines or Not Two Lines? That is the Question of Gamma Ray Spectra

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Lines in the spectrum of cosmic gamma rays are considered one of the more robust signatures of dark matter annihilation. We consider such processes from an effective field theory vantage, and find that generically, two or more lines are expected, providing an interesting feature that can be exploited for searches and reveal details about the underlying theory of dark matter. Using the 130 GeV feature recently reported in the Fermi-LAT data as an example, we analyze the energy spectrum in the multi-line context and find the data to be consistent with a single $\gamma\gamma$ line, a single $\gamma Z$ line or both a $\gamma\gamma$ and a $\gamma Z$ line.

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\section*{INTRODUCTION}

Nonbaryonic dark matter is now a crucial element in the picture of the cosmology of the early Universe. And yet, its role in the framework of particle physics has remained elusive. Discovery of any kind of non-gravitational interactions of dark matter, through observation of its production at high energy accelerators, its direct scattering with heavy nuclei, or its annihilation is an area of major experimental activity. Any of these observations would establish dark matter as an exotic particle, and would give insights into its nature.

In the search for WIMP annihilation, gamma rays provide a promising window. Gamma rays produced in the galaxy do not typically scatter on their way to the Earth, providing a handle from the morphology of their origin. If dark matter annihilates into quarks (or any particle with large decay branching ratios into quarks, such as $W$, $Z$, and Higgs bosons), the resulting spectrum of gamma rays tends to be rather soft, arising from the eventual decays of particles produced in the hadronic showers, and with a cutoff at the mass of the WIMP. These continuum signals are difficult to extract from the (often unknown) astrophysical backgrounds, and so to date searches have been most efficient when observing regions of the sky which are largely background free, such as dwarf spheroidal galaxies \cite{ref1}.

If dark matter annihilates into charged particles, it must also be able to annihilate directly into two-body final states including a photon. Such processes are mediated by loops, and thus are suppressed compared to the continuum annihilation. Their power comes from the feature that they produce a photon with a well-defined energy given (for the process $\chi\chi \rightarrow \gamma Y\gamma$) by

\begin{equation}
E_\gamma = m_\chi \left(1 - \frac{M_Y^2}{4m_\chi^2}\right)
\end{equation}

where $M_Y$ is the mass of the second annihilation product. For the case where $Y = \gamma$, the line occurs at an energy equal to the mass of the WIMP itself, $E_\gamma = m_\chi$.

Given this striking feature, the search for gamma ray lines has become a standard item on the menu of searches for WIMP annihilation using Fermi-LAT data \cite{ref2,ref3}.

While it is possible for instrumental effects or more prosaic astrophysical processes \cite{ref4} to mimic a bump in the gamma ray spectrum, a line remains one of the most compelling prospects for the indirect detection of dark matter annihilation. Motivated by the recent tentative indication that there may be such a feature at an energy around 130 GeV \cite{ref5,ref6} with a relatively large (rough 1/10 of the thermal expectation) cross section, and consistent with originating close to the galactic center \cite{ref7,ref8}, we explore the generic properties that one might expect in a theory which can produce strong line signals. We use the Fermi-LAT data as analyzed in Ref. \cite{ref9} to illustrate how one may dissect a putative line signal both to lend strength to its origin from dark matter annihilations, as well as to learn something about the details of the theory of dark matter.

\section*{THE THEORY SPACE OF $\gamma$ RAY LINES}

Boiled down to its essence, the process $\chi\chi \rightarrow \gamma Y$ results from an amplitude involving a loop of charged particles which also couple to $Y$. The charged particles in the loop could be either exotic states, or part of the Standard Model, or (as is typical) a mixture of the two. For the current discussion, rather than wed ourselves to any specific UV-complete theory, we work in an effective theory framework and discuss operators in the effective action allowing WIMPs to annihilate into two particle final states, one of which is a $\gamma$-ray.

The operator description is only appropriate to describe theories for which the momentum transfer is smaller than the masses of any of the mediators which have been integrated out. For annihilation, the momentum transfer is $\sim m_\chi$, so this restriction boils down to the requirement that all of the charged loop particles are much heavier than the WIMP itself (but one can enlarge
the effective theory to capture cases where some of the loop particles are heavier than the WIMP, and some are SM particles, see Ref. [3] for an example and Ref. [9] for some related discussion).

In constructing the operators in the EFT language, we consider both scalar and fermionic WIMPs. We identify the leading operators of each type, and ignore higher mass dimension operators which are presumably further suppressed by the heavy mediator masses. We work in a description where the SU(2)_L × U(1)_Y gauge symmetry is realized manifestly. In counting the dimension of operators, this choice is equivalent to the assumption that the charged particles which have been integrated out have masses largely independent of electroweak symmetry-breaking.

The natural ingredients from which operators are built are the field strengths of the hypercharge and SU(2) gauge fields, B_μν and W^a_μν, the Higgs doublet Φ, and the dark matter field χ (which we take to be either a scalar or spin-1/2 fermion). We will build operators up to dimension-7 out of these ingredients, focusing on operators which produce at least one photon. We classify each operator according to what type(s) of process(es) it mediates, including γγ, γZ [10, 13, and/or γh [14, 15] (where h is the SM Higgs boson)\(^1\). We further distinguish operators leading to velocity-suppressed or -unsuppressed rates into gamma ray lines depending on whether the leading term in the expansion of ⟨σv⟩ for small relative WIMP velocity v is a constant or is proportional to v^2. Since v ∼ 10^{-3} in the Milky way halo, velocity-suppressed operators need much larger couplings in order to produce a visible signal to compensate their v^2 suppression.

At dimension-4, for either a scalar or fermionic WIMP, the unique choice leading to coupling to the photon requires that the dark matter particles themselves are charged under U(1)_Y and/or SU(2)_L leading after EWSB to couplings to γ and Z. The cosmological bounds on such “milli-charged” WIMPs are very strong [17], leaving this possibility unlikely to produce a line feature that could be observable by any near future experiment.

At dimension-5, there are two operators for a Dirac fermion

\[ \bar{\chi} \gamma^{\mu \nu} \chi B_{\mu \nu} \quad \text{and} \quad \bar{\chi} \gamma^{\mu \nu} \chi \tilde{B}_{\mu \nu} \quad (2) \]

where γ^{\mu \nu} ≡ 1/2[γ^\mu, γ^\nu]. These operators correspond to a weak magnetic (electric) dipole moment for the WIMP and leads to unsuppressed annihilation into both γγ and γZ.

At dimension-6, there is a family of operators built out of the set of dimension-4 factors,

\[ \left\{ B_{\mu \nu} B^{\mu \nu}, \ W^a_{\mu \nu} W^{a \mu \nu}, \ B_{\mu \nu} \tilde{B}^{\mu \nu}, \ W^a_{\mu \nu} \tilde{W}^{a \mu \nu} \right\} \quad (3) \]

multiplied by \( \chi^2 \) (or |χ|^2 if χ is a complex scalar). These operators also lead to unsuppressed annihilation into both γγ and γZ.

Similarly, at dimension-7, there is another family of operators built out of the same set [3] of dimension-4 factors, multiplied by

\[ \bar{\chi} \chi \quad \text{or} \quad \bar{\chi} \gamma_5 \chi. \quad (4) \]

for either a Majorana or Dirac fermion. These operators generate both γγ and γZ annihilations which are unsuppressed (suppressed) for \( \bar{\chi} \chi \) (\( \bar{\chi} \chi \)).

Finally, for a Dirac fermion, we can also have the dimension-7 terms involving tensor operators formed from \( \bar{\chi} \gamma^{\mu \nu} \chi \) multiplied by a factor from either the set,

\[ \left\{ B_{\mu \alpha} \tilde{B}^{\alpha \nu}, \ W^a_{\mu \alpha} \tilde{W}^{a \alpha \nu} \right\}, \quad (5) \]

or

\[ \left\{ B_{\mu \nu} |\Phi|^2, \ B_{\mu \nu} |\Phi|^2, \ \Phi^\dagger W^a_{\mu \nu} T^a \Phi, \ \Phi^\dagger \tilde{W}^{a \mu \nu} T^a \Phi \right\}, \quad (6) \]

the set contained in (5) leads again to both γγ and γZ lines (unsuppressed), whereas the set contained in (6) leads to a single unsuppressed γ line.

At dimension-8, there is a very large number of operators, which we will not catalogue exhaustively. We note, however, that at dimension-8, there are operators built out of the vector currents, \( J_\mu = (\chi \partial_\mu \chi^* - \chi^* \partial_\mu \chi) \) (for a complex scalar WIMP), \( S_\mu = \chi \gamma_\mu \chi \) for a Dirac fermion WIMP, and \( S^5 = \chi \gamma_\mu \gamma_5 \chi \) for either a Dirac or Majorana fermion WIMP. Any of them may be combined with a factor from the set,

\[ \left\{ B_{\mu \alpha} \Phi^\dagger D_\alpha \Phi, \ \tilde{B}_{\mu \alpha} \Phi^\dagger D_\alpha \Phi, \ \Phi^\dagger W^a_{\mu \alpha} T^a D_\alpha \Phi, \ \Phi^\dagger \tilde{W}^{a \mu \alpha} T^a D_\alpha \Phi \right\}. \quad (7) \]

All operators in this set lead to both γZ and γh lines. Those constructed from \( J_\mu \) and \( S^5 \) are v-suppressed, whereas \( S_\mu \) is unsuppressed. These operators are naturally generated in models where the dark matter dominant communication with the SM particles is through exchange of a Z’ boson (for examples of models where this is the case, see [15, 18, 20]). The absence of a γγ line is naturally explained by the Landau-Yang theorem [21], which forbids a neutral vector state from decaying into two photons.

The simple exercise of cataloguing operators in the effective field theory already reveals very interesting features. Every operator considered leads to two lines (γγ and γZ) or γZ and γh), with a simple prediction for

\(^1\) We necessarily will miss annihilation into a photon together with a dark sector particle [10], which would require extension of the effective theory to contain the second decay product.
their relative intensities. The sole exception is the set of operators contained in \( \mathcal{O} \) which exist only for a Dirac WIMP and lead to a single \( \gamma h \) line.

In terms of the underlying picture in which line processes are mediated by charged particles running in a loop, the fact that there are multiple lines corresponds to the fact that such particles must be charged under \( SU(2)_L \) and/or \( U(1)_Y \) and thus must couple to both the photon and the Z boson. Similarly, coupling to a Higgs boson often is accompanied by coupling to a longitudinal \( Z \) photon and the always two longitudinal \( W \) bosons. Presumably any realistic UV complete theory will generate more than one operator, allowing for the possibility of interference. Interference will adjust the relative sizes of the two or three lines, but in the absence of fine tuning will not cancel one of them completely.

Our results suggest interesting variations in the experimental analyses of gamma ray lines. First, one may search for two (or three) lines whose energies are consistent with Eq. (1) for a single WIMP mass. Such an observation would be highly suggestive of dark matter annihilation, and less likely to be produced by astrophysical or instrumental effects. Of course, the ability to resolve two lines is very challenging for WIMP masses larger than \( \sim 150 \text{ GeV} \), because of the finite energy resolution of the detector (\( \Delta E/E \sim 10\% \) at \( E \sim 100 \text{ GeV} \) for the Fermi-LAT). Second, if there is a concrete observation of a single line, will be highly suggestive of a Dirac fermion WIMP annihilating through one of a definite set of effective interactions, providing clues to the nature of the UV theory.

**THE FERMI 130 GEV FEATURE AS A CASE STUDY**

In order to explore how multiple lines could manifest themselves in realistic data, we analyze the observed \( \gamma \)-ray spectrum of Fermi-LAT, including the feature at \( E_\gamma = 130 \text{ GeV} \) [6], in the context of the multi-line theory. While it is premature to interpret this feature as dark matter annihilation, it provides an interesting case study which could even turn out to ultimately tell us something about dark matter. We use the regions of interest found to have largest significance, Reg3 and Reg4 [6] and the ULTRACLEAN photon selection. While not presented here, we have also performed the analysis for the looser photon selection (SOURCE class), which yields very similar results. We will focus our analysis on the \( \gamma \gamma \) plus \( \gamma Z \) case; the extrapolation for \( \gamma Z \) plus \( \gamma h \) is straightforward.

We follow the standard Fermi analysis procedure, evaluating the relative likelihood of the background-only hypothesis (null) and the background-plus-signal (best) hypothesis using the test statistic (TS):

\[
TS = -2 \ln \frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{best}}} \tag{8}
\]

but with a likelihood \( \mathcal{L} \) which includes both a power-law background model as well as terms for potential \( \gamma \gamma \) and \( \gamma Z \) lines:

\[
\mathcal{L}(E_\gamma | N_{\gamma\gamma}, N_{\gamma Z}, \beta, \alpha) = \\
\beta \left( \frac{E_\gamma}{E_0} \right)^{-\alpha} + N_{\gamma\gamma} f_{DM}(E_\gamma | m_\chi) + N_{\gamma Z} f_{DM}(E_\gamma | m_\chi) \left( 1 - \frac{M_\phi^2}{4 m_\chi^2} \right) \tag{9}
\]

The function \( f_{DM}(E_\gamma | E_{\text{line}}) \) is a normalized double Gaussian function fit to the expected line shape for \( E_{\text{line}} = 130 \text{ GeV} \) as provided in Ref [6]. For other values of the expected peak location \( E_{\text{line}} \), the values of the Gaussian widths and means are treated as linearly dependent on the position of the expected peak. The parameters \( N_{\gamma\gamma} \) and \( N_{\gamma Z} \) control the total yield from the \( \gamma \gamma \) and \( \gamma Z \) processes, respectively. The two terms describe the correlated \( \gamma \gamma \) and \( \gamma Z \) contributions.

For \( \mathcal{L}_{\text{best}} \), the parameters \( (N_{\gamma\gamma}, N_{\gamma Z}, \beta, \alpha) \) are floated to find the maximum likelihood value. For \( \mathcal{L}_{\text{null}} \), the yields \( (N_{\gamma\gamma}, N_{\gamma Z}) \) are fixed to zero and the background model parameters \( (\beta, \alpha) \) are floated to their best fit values. The local statistical significance may be interpreted in the asymptotic regime [22], as \( \sigma = \sqrt{TS} \).

Example fits are shown in Fig 1. If the WIMP is assumed to have mass of 145 GeV, a \( \gamma Z \) process would produce a line at \( E_\gamma = 130 \text{ GeV} \). In this case, the feature at \( E_\gamma = 130 \text{ GeV} \) can be interpreted as pure \( \gamma Z \); any contribution from \( \gamma \gamma \) would appear at larger \( E_\gamma \), where no such feature appears. If, on the other hand, the WIMP is assumed to have a mass of 130 GeV, then a \( \gamma \gamma \) process would produce a line at \( E_\gamma = 130 \text{ GeV} \), explaining the feature\(^2\). In this case, however, there is room at lower values of \( E_\gamma \) for contributions from a \( \gamma Z \) process. The two fits have approximately equal significance.

Figure 2 shows a scan of WIMP masses and total yields \( (N_{\gamma\gamma} + N_{\gamma Z}) \), revealing the two regions of maximal significance, near \( m_\chi = 130 \) and 145 GeV. At each point, the contribution from \( \gamma \gamma \) is also shown. If \( m_{WIMP} = 130 \text{ GeV} \), then the interpretation is consistent with a large \( \gamma \gamma \) contribution, but cannot rule out some contribution from \( \gamma Z \). If, however, \( m_\chi = 145 \text{ GeV} \), then a pure \( \gamma Z \) interpretation is preferred. Figure 3 shows the same scan for Reg4, which has largely the same features.

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2 In Ref [6] it is claimed that in order to produce a peak at \( E_\gamma = 130 \text{ GeV} \) after electromagnetic showering of the parent photon, a WIMP mass of \( \sim 145 \text{ GeV} \) is required. We disagree with this statement.
In Figures 4 and 5 the scans are performed as a function of WIMP mass and the ratio of $\gamma Z$ to $\gamma \gamma$ yields for Reg3 and Reg4. Note that while the region of maximum significance is near $m_\chi = 130$ GeV, it prefers $N_{\gamma Z}/N_{\gamma \gamma} > 0$. Also shown in each figure is the value of $N_{\gamma \gamma}$ corresponding to the best fit for each point in $(m_\chi, N_{\gamma Z}/N_{\gamma \gamma})$.

The two regions show consistent features. The maximum significance is consistent with either a pure $\gamma Z$ or pure $\gamma \gamma$ scenario; the interpretation of the $E_\gamma = 130$ GeV line in the $\gamma \gamma$ scenario also allows for $\gamma Z$ contributions at lower $E_\gamma$. In fact, the best fits have a non-zero fraction of $\gamma Z$ (less than one), but this preference is not very significant. Clearly more data would be very helpful in terms of sharpening this analysis in order to draw more firm conclusions from it.

From Ref. [6], the best fit value of the cross section (assuming a $\gamma \gamma$ interpretation) is about $10^{-27}$ cm$^3$/s $\sim 10^{-4}$ TeV$^{-2}$ for dark matter distributed according to an NFW profile. From here one could compare with detailed calculations based on the operators in the effective field theory catalogue to determine a consistent parameter space, but we leave such detailed comparisons for future work, and instead interpret such a target cross section schematically.

Focusing as an example on any one of the dimension-6 operators for scalar WIMPs, we normalize the operator as $\alpha_\chi/M^2$, where $\alpha \equiv e^2/(4\pi)$ is the electromagnetic coupling and $\alpha_\chi \equiv g^2/(4\pi)$ represent (unknown) couplings in the dark sector. This choice of normalization is
consistent with the operator being generated at one loop, with $M$ playing the role of the mass(es) of the particles in the loop. Obviously, this implementation is subject to unknown numerical factors such as the number of species contributing inside the loop, as well as factors associated with their spins, etc. The idea is to get a very rough sense for the mass scale $M$ of the loop particles, given the target cross section of the Fermi feature.

Our simple estimate indicates that provided there is no velocity-suppression,

$$M \sim \sqrt{\alpha} \times 150 \text{ GeV}. \quad (10)$$

This is an interesting result. If the dark sector is strongly coupled ($\alpha_\chi \sim 1$), the loop particles should have masses in the range of 150 GeV, safely above the LEP bound of about 100 GeV, but low enough that the LHC has an opportunity to observe them through electroweak production. For weaker $\alpha_\chi$, the mass must be lower to compensate, rapidly coming into conflict with the LEP bound for $\alpha_\chi \lesssim 0.5$.

For a velocity-suppressed operator, the target mass is of the order $M \sim \sqrt{\alpha} \times 5 \text{ GeV}$, far enough below the LEP bound that not even a strongly coupled dark sector would be able to reconcile the two. However, it is worth mentioning a few provisos to this statement. For example, one way in which the EFT could spectacularly break down would be when there is an additional dark sector state which appears in the $s$-channel for annihilation. Very large enhancements are possible in this case, depending how close to on-shell the resonance is for WIMP
annihilation. In addition, if a large multiplicity of species contribute to the line annihilation, the amplitude will grow with the number. For a rather extreme multiplicity of $\sim 500$, a $v^2$-suppressed annihilation would be consistent with the LEP bound for $\alpha_X \sim 1$.

**OUTLOOK**

Annihilation of dark matter into a two body final state containing a photon provides a striking signature, and is one of the most promising prospects for an indirect detection of dark matter. In this article, we have explored some generic features of gamma ray lines using an effective theory framework.

The effective theory illustrates a fascinating feature – the operators which give rise to one gamma ray line, typically also give rise to two. For a scalar or Majorana WIMP, every operator considered produces either $\gamma\gamma$ and $\gamma Z$, or $\gamma Z$ and $\gamma h$, and the intensities of each line are correlated for a given operator. Multiple lines are a generic feature, and one that can be used to improve searches in data from gamma ray observatories, or help match to specific UV complete theories once a discovery is made. For a Dirac WIMP, one class of operators provides an exception to the multiple-line rule, producing a single $\gamma h$ line. Nonetheless, observation of a single line provides very specific information about the nature of the theory of dark matter.

Using the recent observation of a feature at 130 GeV in the Fermi-LAT data, we analyze the data in a multilinear context, and find that there is a very mild preference for contribution from two lines, though uncertainties are large. Should this feature persist and not ultimately prove to be instrumental or astrophysical in nature, more data should help sharpen this analysis and make more concrete statements.

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[1] M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. 107, 241302 (2011) [arXiv:1108.3546 [astro-ph.HE]];
[2] A. A. Abdo et al. [The Fermi-LAT Collaboration], Phys. Rev. Lett. 104, 091302 (2010) [arXiv:1001.4836 [astro-ph.HE]];
[3] M. Ackermann et al. [Fermi-LAT Collaboration], arXiv:1205.2739 [astro-ph.HE].
[4] S. Profumo and T. Linden, arXiv:1204.6047 [astro-ph.HE].
[5] T. Bringmann, X. Huang, A. Ibarra, S. Vogl and C. Weniger, arXiv:1203.1312 [hep-ph].
[6] C. Weniger, arXiv:1204.2797 [hep-ph].
[7] E. Tempel, A. Hektor and M. Raidal, arXiv:1205.1045 [hep-ph].
[8] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. -B. Yu, Nucl. Phys. B 844, 55 (2011) [arXiv:1009.0008 [hep-ph]].
[9] K. N. Abazajian, P. Agrawal, Z. Chacko and C. Kilic, arXiv:1111.2835 [hep-ph].
[10] L. Bergstrom and P. Ullio, Nucl. Phys. B 504, 27 (1997) [arXiv:hep-ph/9706232]; Z. Bern, P. Gondolo and M. Perelstein, Phys. Lett. B 411, 86 (1997) [arXiv:hep-ph/9706538]; P. Ullio and L. Bergstrom,
