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Lining up the Galactic Center gamma-ray excess

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ABSTRACT

Dark matter particles annihilating into Standard Model fermions may be able to explain the recent observation of a gamma-ray excess in the direction of the Galactic Center. Recently, a hidden photon model has been proposed to explain this signal. Supplementing this model with a dipole moment operator and a small dark sector mass splitting allows a large cross section to a photon line while avoiding direct detection and other constraints. Comparing the line and continuum cross sections, we find that the line is suppressed only by the relative scales and couplings. Given current constraints on this ratio, a line discovery in the near future could point to a new scale $\Lambda \sim \mathcal{O}(1\,\text{TeV})$, where we would expect to discover new charged particles. Moreover, such a line would also imply that dark matter can be visible in near-future direct detection experiments.
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Introduction

As the cosmological and gravitational evidence for dark matter has grown, particle physicists have continued to seek clear indications of dark matter activity on more immediate distance- and time-scales. An excess of gamma rays observed in the region of the central Milky Way, henceforth the Galactic Center gamma-ray excess (GCGE), can be interpreted as the secondary emission from dark matter annihilations, thereby providing evidence for such a local particle dark matter population [1–10]. A variety of authors have found a multitude of dark matter models that can accommodate the GCGE [11–35]. It is easily possible to build models that allow such a large indirect detection signal while still satisfying all constraints from direct detection, collider, and other searches.

Although explaining the GCGE through new particle physics is easy to do, verifying the dark matter origin of the GCGE will be one of the most urgent questions that particle physics will face in coming years. Other astrophysical explanations need to be fully explored, and all aspects of the theories of new physics that explain the signal must be thoroughly tested. Simply waiting to see the signal reproduced in other astrophysical regions with different systematics may take too long (and remain too systematically uncertain) to satisfy our curiosity, and there are no firm predictions for dark matter or mediator production at colliders; indeed, the new physics sector may be arbitrarily well secluded since it only needs to communicate to the Standard Model by a small amount of mass or kinetic mixing. Confirming that dark matter is responsible for the GCGE may therefore require new, observable predictions from our models.

Here we consider a hidden $U(1)$ dark matter model [35–48] augmented by two new operators and multiple novel observables. By adding a higher dimension operator that couples dark matter to the Standard Model photon, we generate a monochromatic photon line in dark matter annihilations. Observing such a spectral feature would, in combination with current observations, give an unambiguous and experimentally robust indication that dark matter is responsible for the GCGE. Moreover, the central energy of the line would provide a clean measurement of the dark matter mass. Intriguingly, the mass scale currently probed by the *Fermi* telescope and by direct detection experiments is exactly the TeV scale. Observing a line associated with the GCGE in this way would not only reveal the dark matter nature of the gamma-ray excess: the detection of a line could also provide a hint of new charged matter at accessible energies, plus an imminent direct detection signal.

A dipole moment

At low scales, the dark sector Lagrangian we have in mind is

$$\mathcal{L}_d = -\frac{1}{4}F_d^2 + \frac{\epsilon}{2}F_d^{\mu\nu}F_{\mu\nu} - \hat{g}_d\bar{X}\not{A}_d X - M\bar{X}X + m_d^2 A_d^{\mu}A_{d\mu} - m\left(X_L X_L + X_L^\dagger X_L^\dagger\right) + \frac{\hat{\beta}_d}{\Lambda}\bar{X}\sigma^{\mu\nu}XF_{\mu\nu}, \quad (1)$$

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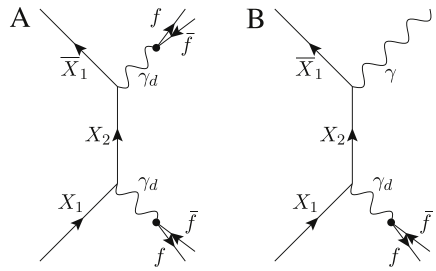

Fig. 1. Annihilation through diagram (A) sets the relic density in the early universe and accounts for the GCGE. Annihilation through diagram (B) gives a photon line (as well as a subdominant amount of continuum photons). Annihilation to two on-shell photons is suppressed relative to (B).

where the F are field strengths, ϵ is the kinetic mixing parameter, A_d^μ is the dark photon field, X is a Dirac particle with left- and right-handed components $X_{L,R}$, and Λ is a scale at which charged particles are integrated out. We define $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$. The $U(1)_d$ is explicitly broken by the gauge boson mass and by the fermion Majorana mass. The low energy spectrum has two mass-split Majorana fermions: the mass eigenstates $X_{1,2}$ have masses $m_{1,2} \simeq |M \pm m|$, where X_1 is the dark matter. Crucially, the dark matter remains exactly electrically neutral and interacts with the Standard Model photon only via a nonrenormalizable transition dipole moment operator; in particular, constraints on millicharged particles do not apply. In addition, we point out that ϵ and $\hat{\beta}_d$ arise in principle from entirely different physical mechanisms, and a large hierarchy between these two dimensionless parameters is possible. Variations on dark matter with elastic or inelastic magnetic moments have been considered in other contexts [49–51]. The Lagrangian in Eq. (1) differs from the hidden photon model of [35] only by the two final terms in Eq. (1).

These new terms are of great phenomenological interest. Without them, the model does not provide tree-level dark matter–photon vertices, and, like all other models proposed for the GCGE, can only deliver a photon line by closing the final state Standard Model fermion loop. The cross section for a photon line resulting from such loop processes is expected to be

$$\langle\sigma v\rangle_{\gamma\gamma,\,\mathrm{loop}} \sim \langle\sigma v\rangle_{f\bar{f}} \times e^4/16\pi^2 \sim 10^{-31}\ \mathrm{cm}^3/\mathrm{s}, \tag{2}$$

i.e., many orders of magnitude lower than the cross section for dark matter annihilation to fermions, and more than two orders of magnitude below the current *Fermi* bounds [52]. Such a low cross section is unlikely to be probed by near future gamma-ray telescopes. This is a typical feature of models that have no tree-level interactions between the dark matter and the photon (however, see [51] for important exceptions). In order to produce monochromatic photons in a non-negligible portion of dark matter annihilations, we must therefore add in a new operator by hand that allows the photon to couple to the dark current at tree level. As long as the dark matter remains electrically neutral, gauge invariance requires that at low energies such a coupling manifests as the final term of Eq. (1)—this is a dipole moment operator. Such a higher dimension operator can be generated by integrating out charged particles; the dimensionful suppression scale of the operator is generally the scale at which these new particles can go on shell.

In the mass eigenbasis, Eq. (1) contains a dark flavor changing neutral current,

$$\mathcal{L}_d \supset g_d \bar{X}_1 \not{A}_d X_2 + \mathrm{h.c,} \tag{3}$$

where $g_d \equiv \hat{g}_d \times m/M$. As long as $m_d \leq m_1$, this allows the annihilation $X_1\bar{X}_1 \to \gamma_d\gamma_d$, as shown in panel (A) of Fig. 1. The GCGE continuum photons and the relic density simply come about from annihilations to γ_d in exactly the same way as in the hidden sector model of [35]: pairs of dark matter particles annihilate to the slightly lighter vector γ_d, which propagates over a macroscopic distance before decaying to Standard Model fermions from the kinetic mixing of the γ_d with the Standard Model photon. In the early universe, this process remains in equilibrium until $n_X(T)\langle\sigma v\rangle_{\gamma_d\gamma_d}$ falls below the Hubble rate, leaving a relic density of X_1 and $\bar{X}_1$ particles. The annihilation cross section required to attain the cosmological abundance after this freeze out process is the same cross section as required to match the flux of photons from the GCGE.

Aside from the dark current in Eq. (3), the interaction terms of Eq. (1) also include a transition magnetic dipole moment in the mass basis,

$$\mathcal{L}_d \supset \frac{\beta_d}{\Lambda}\bar{X}_1\sigma^{\mu\nu}X_2F_{\mu\nu} + \mathrm{h.c,} \tag{4}$$

where $\beta_d \equiv \hat{\beta}_d \times m/M$. Of particular interest for this work, and in contrast to prior studies, this term allows annihilations that include monochromatic photons, as shown in panel (B) of Fig. 1. These photons will have energy $E_\gamma = (4m_1^2 - m_d^2)/4m_1 \simeq 3m_1/4$, which in addition to more refined GCGE spectra will allow a clean determination of the dark matter mass.

The annihilation cross sections shown in Fig. 1 both have *s*-wave terms. In the low-velocity limit and taking all dark sector masses to be set by the common mass $m_X \equiv m_1 \sim m_d \sim m_2$, we find

$$\langle\sigma v\rangle \underset{v\to 0}{\simeq} \begin{cases} g_d^4 p_{d,A}^3/4\pi m_X^5 & (X_1\bar{X}_1 \to \gamma_d\gamma_d) \\ 8\beta_d^2 g_d^2 p_{d,B}^3/9\pi m_X^3\Lambda^2 & (X_1\bar{X}_1 \to \gamma\gamma_d) \\ \beta_d^4 m_X^2/4\pi\Lambda^4 & (X_1\bar{X}_1 \to \gamma\gamma) \end{cases} \tag{5}$$

where $p_{d,A} = \sqrt{m_1^2 - m_d^2}$ is the momentum of the outgoing dark photons for the annihilation shown in Fig. 1(A) and $p_{d,B} = (4m_1^2 - m_d^2)/4m_1$ is the momentum of the outgoing dark photon for the annihilation shown in Fig. 1(B). For completeness, we have also calculated the cross section to two photons. The expressions in Eq. (5) are valid at the 10% level for generic mass splittings less than 20%, but we use the exact expressions in all numerical work.

From Eq. (5), we see that each on-shell photon suppresses the cross section by roughly $\beta_d^2 m_X^2/g_d^2\Lambda^2$. *Fermi* bounds on the cross section to a photon line are currently $\langle\sigma v\rangle_{\gamma\gamma} \lesssim 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$ [52],[1] compared to the normalization required for the GCGE, $\langle\sigma v\rangle_{\gamma_d\gamma_d} \sim 2 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ [10,35]. Hence, if there is no kinematic suppression, the approximations in Eq. (5) indicate

$$\frac{4\beta_d^2 m_X^2}{g_d^2\Lambda^2} \lesssim 5 \times 10^{-3} \Longrightarrow \Lambda \gtrsim \mathrm{TeV} \times \frac{\beta_d}{g_d} \times \frac{m_X}{30\ \mathrm{GeV}}. \tag{6}$$

Finding a photon line associated with the GCGE in upcoming *Fermi* data would thus point towards new charged particles at the TeV scale, unless there is a large hierarchy in β_d/g_d. We plot the ratio $\langle\sigma v\rangle_{\gamma\gamma_d}/\langle\sigma v\rangle_{\gamma_d\gamma_d}$, including the exact expressions for the annihilation cross sections, in Fig. 2. We set the masses proportionally as $m_2{:}m_1{:}m_d = 1.1{:}1{:}0.9$, and we fix $m_1 = 33.5$ GeV. This sets the dark photon mass $m_d \simeq 30$ GeV; these masses can explain the GCGE at the 1σ level [35]. The mass ratio here also gives a $X_1 - X_2$ mass splitting of a few GeV, which is relevant for the remaining bounds.

[1] *Fermi* searches constrain $\langle\sigma v\rangle_{\gamma\gamma}$, while our model produces a single photon, so the limits from [52] are weakened by a factor of two. The number quoted assumes an NFW dark matter profile and is strengthened or weakened by a factor of a few for different dark matter profiles. However, the bounds are highly sensitive to the dark matter mass, so we take a representative bound.

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