Lining up the Galactic Center Gamma-Ray Excess

Samuel D. McDermott
Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510 and Michigan Center for Theoretical Physics, Ann Arbor, MI 48109

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.

**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 (see [1] for more details and references). A variety of authors have found that a multitude of dark matter models can accommodate the GCGE (see [2] for details and references). 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 physicists 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 too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically uncertain) to satisfy our curiosity, and too systematically 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where 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 \[6\]. 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 \[5\] 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 manifest 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, \[L_d \supset g_d \bar{X}_1 A_d X_2 F_{\mu\nu} + h.c.,\]

where \(g_d \equiv \tilde{g}_d \times m/M\). As long as \(m_d \leq m_1\), this allows the annihilation \(X_1 X_1 \to \gamma_d \gamma_d\), as shown in panel (A) of Fig. 1. The GCGE continuum photons and the relic dark matter annihilations, we must therefore add in the annihilation cross section to two on-shell photons. \(\langle \sigma v \rangle \approx \frac{g_d^2 p_{d,A}^2}{8\beta_d m_X^2 \Lambda^4} \left( \frac{m_X^2}{4\pi\Lambda^4} \right) \) (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 \(p_{d,B} = (m_1^2 - m_d^2)/4m_1\) 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.

From Eq. (5), we see that each on-shell photon suppresses the cross section by roughly \(\beta_d^2 m_X^2/g_d^2 \Lambda^2\). Bounds on the cross section to a photon line are currently \(\langle \sigma v \rangle_{\gamma\gamma} \lesssim 10^{-26}\) cm\(^3\)/s [6] compared to the normalization required for the GCGE, \(\langle \sigma v \rangle_{\gamma\gamma} \sim 2 \times 10^{-26}\) cm\(^3\)/s [1][2]. Hence, if there is no kinematic suppression, the approximations in Eq. (5) indicate

\[\frac{\beta_d^2 m_X^2}{g_d^2 \Lambda^2} \lesssim 5 \times 10^{-3} \implies \Lambda \gtrsim 500\text{ GeV} \times \frac{\beta_d}{g_d} \times \frac{m_X}{30\text{ GeV}}.\]

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 \(\beta_d/g_d\). We plot the ratio \(\langle \sigma v \rangle_{\gamma\gamma}/\langle \sigma v \rangle_{\gamma\gamma,d}\), 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 \(m_d \sim 30\) GeV; these masses can explain the GCGE at the 1σ level \[2\]. The mass ratio here also gives a \(X_1 - X_2\) mass splitting of a few GeV, which is relevant for the remaining bounds.

**Additional Phenomenological Implications:** We list some bounds that can constrain the model of Eq. (1).

**Collider bounds:** Because of the small couplings to Standard Model fermions (all of which are suppressed by \(\epsilon\) or \(\Lambda\)), collider searches for \(X_1\) or \(\gamma_d\) should be weak. However, \(\Lambda\) indicates a mass scale where new particles

\[\text{1}\] The Fermi bounds are based on the assumption of two monochromatic photons coming out of each annihilation event, and hence constrain \(\langle \sigma v \rangle_{\gamma\gamma}\). Since our model produces a single photon, the bounds from \[4\] are weakened by a factor of two.
FIG. 2. Contours of \( \langle \sigma v \rangle_{\gamma_d\gamma_d} / \langle \sigma v \rangle_{\gamma_d \gamma_\phi} \) as a function of the coupling \( \beta_d \) and the scale \( \Lambda \). The gray shaded region below the solid line is ruled out by \( \text{Fermi} \) line searches. The blue shaded region below the dashed line is ruled out by LUX constraints; the green region below the dot-dashed line is ruled out by electroweak measurements. We ensure a good fit to the relic density and the GCGE by taking \( \gamma_d = 0.1 \), \( m_1 = 33.5 \text{ GeV} \), and fixing \( m_2 : m_1 : m_d = 1.1 : 1 : 0.9 \).

which are charged under \( U(1)_{\text{EM}} \) can go on shell, so bounds on heavy stable charged particles provide a different test of the theory that effectively places bounds on \( \Lambda \) alone (rather than the ratio \( \beta/\Lambda \)).

As an example of the bounds on charged particles, we note that LEP requires that the chargino \( \chi^{\pm} \) of the MSSM satisfy \( m_{\chi^{\pm}} \geq 103.5 \text{ GeV} \), while ATLAS \( \gamma \) and CMS \( \gamma \) searches for charged SUSY particles are generally in the several hundred GeV range. These searches rely on model dependent final state signatures, so we do not make model independent assertions here. It suffices to say that new electromagnetically charged particles with masses around the TeV scale are both currently acceptable and potentially discoverable at the LHC. That the TeV scale falls out of the current \( \text{Fermi} \) line bounds is an exciting prediction of our model.

**Direct Detection:** The maximum energy deposition possible in terrestrial direct detection experiments is \( E_{\text{kin,max}}^{\text{DD}} \approx m_{\text{DM}} v_{\text{rel}}^2/2 \approx 50 \text{ KeV} \times m_{\text{DM}}/30 \text{ GeV} \). If the mass splitting \( 2m \) exceeds this scale, there is no tree-level scattering at direct detection experiments, neither through the higher dimension dipole operator, nor through the renormalizable scattering from \( \gamma_d - \gamma \) mixing. The scattering at direct detection experiments will only enter at loop level, for which we estimate (assuming a common dark sector mass \( m_X \))

\[
\sigma_{\text{SI}} \sim \begin{cases} \frac{g_2^4 e^4 m_d^2}{16 \pi^2 m_X^4} & \text{(via } \gamma_d \text{ exchange)} \\ \frac{\beta_d^4 e^4 m_p^2}{16 \pi^2 \Lambda^4} & \text{(via } \gamma \text{ exchange)} \end{cases}.
\]

Using the LUX \( \sigma_{\text{SI}} \) constraint\(^2\) on 33.5 GeV dark matter, \( \sigma_{\text{SI}} \lesssim 4.6 \times 10^{-45} \text{ cm}^2 \), we find \( \epsilon \lesssim 2 \times 10^{-2}/g_d \) (about two orders of magnitude weaker than found for the elastic scattering case \(^2\)) and \( \Lambda \gtrsim 1.4 \text{ TeV} \times \beta_d \), the latter of which we show in Fig. 2.

Because the direct detection constraint on the dipole moment is currently only an order of magnitude weaker than the line search bound and will rapidly strengthen, a line observation consistent with our model gives an expectation for observation at next-generation direct detection experiments. The direct detection cross section indicated by the current \( \text{Fermi} \) sensitivity is of order \( \sigma_{\text{SI}} \sim \mathcal{O} \left( 10^{-49} \text{ cm}^2 \right) \), which is just above the “neutrino floor” for \( m_1 = 33.5 \text{ GeV} \).

**Electroweak Precision:** The dipole interaction can affect the precision measurement of well-understood electroweak observables. Because these effects come in at loop level, they are insensitive to the mass splitting that suppresses the rate in direct detection experiments. The most relevant observations are the muon magnetic moment, the perturbativity of the model at the Z pole\(^4\), and the running of the fine structure constant measured by the ratio of the W mass squared to the Fermi constant\(^3\), listed in increasing order of severity. The running of \( \alpha \) requires \( \Lambda \gtrsim 440 \text{ GeV} \times \beta_d \), which confirms the intuition that new electrically charged particles must be more massive than a TeV. We show this bound in Fig. 2.

**Self-Interactions:** Analogous to direct detection, there are two channels for self-interaction in this model, and, due to the inelastic nature of the low energy Lagrangian, self-scattering that remains in the lower mass state occurs at loop level. In the limit of degenerate masses, the leading order scattering cross section may be estimated by dimensional analysis as

\[
\sigma_{\text{self}} \sim \begin{cases} \frac{g_2^6}{16 \pi^2 m_X^2} & \text{(via } \gamma_d \text{ exchange)} \\ \frac{\beta_d^6 m_X^6}{16 \pi^2 \Lambda^4} & \text{(via } \gamma \text{ exchange)} \end{cases}.
\]

Considerations of the Bullet Cluster require \( \sigma_{\text{self}}/m_X \lesssim 1 \text{ cm}^2/\text{g} \). At \( m_1 = 33.5 \text{ GeV} \) the bounds on \( g_d \) and on \( \beta_d \) are less restrictive than the requirement of perturbativity.

**Cosmology:** Since the lifetime for \( X_d \rightarrow X_\phi \) decay is very short and occurs well before BBN, the strongest

\(^2\) We have rescaled to account for the fact that scattering is only off protons and not off the entire nucleus\(^2\).

\(^3\) The mixed case gives \( \Lambda \gtrsim 1.4 \text{ TeV} \times (\beta_d g_d) \). Though this is competitive, it relies on \( \epsilon \), which may be very small.

\(^4\) This is stronger than other Z-pole observables\(^3\).
bounds from cosmology in this model are derived from requiring that the dark matter not couple too strongly to matter in the epoch of recombination. The leading bounds [12] are weakened by a loop since typical momentum transfers in the CMB epoch will fail to breach the inelastic scattering threshold, in analogy with direct detection. We find essentially nonexistent model bounds.

**Magnetic Field Interactions:** Adding a magnetic interaction to the dark sector may seem problematic because there are strong magnetic fields in the galactic center, in the form of SNe remnants, a large plane-parallel component, and turbulent eddies, with an overall magnitude on large scales of order $10 - 100 \mu G$ [13]. However, the potential energy for aligning along these field lines, $H_B \sim \beta_d B / \Lambda$, is still many orders of magnitude lower than the kinetic energy of a typical dark matter particle near the center of the galaxy, and magnetic effects should be unimportant for the gross features of the signal.

**Model Building:** Although building a UV complete model that gives rise to the Lagrangian of Eq. (1) at low scales is beyond the scope of this work, we make a few remarks here. In addition to a new charged fermion $X_\pm$ with mass $m_\pm \simeq \Lambda \gtrsim$ TeV, we need a new Higgs field whose vev spontaneously breaks the symmetries of the UV theory and provides the dark sector masses. This dark Higgs will need a charged component $H_\pm$ to couple $X$ with $X_\pm$. Because these particles must be charged under $U(1)_{EM}$, they must have electroweak quantum numbers. Finally, the neutral components of the dark sector Higgs must mix very weakly with the Higgs of the Standard Model to avoid large direct detection rates [2]. This list of model building requirements is by no means trivial, but it should be possible to satisfy.

Even in the absence of a UV-complete theory, we can estimate the coupling $\beta_d$. Since it should arise at one loop when $X$ splits into a $X_\pm$ and $H_\pm$, we estimate

$$\frac{\lambda_d^2 e_X}{16\pi^2 m_\pm^2} \sim \frac{\beta_d^2}{\Delta^2} \Rightarrow \beta_d \sim \frac{m}{M} \frac{\lambda_d^2 e_X}{4\pi} \frac{\Lambda}{m_\pm},$$

where $\lambda_d$ is the $X - X_\pm - H_\pm$ coupling, $e_X$ is the electromagnetic charge of the $X_\pm$, and $m$, $M$ are the masses in Eq. (1). If $m_\pm \simeq \Lambda \sim$ TeV (see Eq. (6)) and $m \sim M/10$, then in order for $\beta_d/\gamma_d \sim 1$ we see that $\lambda_d$ must be greater than unity, and may even have to be near strong coupling. This rough estimate indicates that it could even be interesting to consider the consequences of the low energy $X$ being a strongly coupled composite particle, where $\Lambda$ is now seen as some new QCD scale.

**Conclusions:** We have shown that a photon line induced by a transition magnetic dipole moment can be observed in Fermi line searches while retaining the phenomenological successes of the hidden photon model [2] and avoiding direct and indirect constraints. Should a line be observed with additional Fermi data, we will have unambiguous support for a dark matter explanation of the GCCE, not to mention a sharp kinematic measurement of the dark matter mass. In the event of such an observation, the TeV scale falls out “for free,” and our simple low energy model has exciting implications for LHC physics and near-future direct detection experiments.

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