Radiatively decaying scalar dark matter through U(1) mixings and the Fermi 130 GeV gamma-ray line

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Abstract

In light of the recent observation of the Fermi-LAT 130 GeV gamma-ray line, we suggest a model of scalar dark matter in a hidden sector, which can decay into two (hidden) photons. The process is radiatively induced by a GUT scale fermion in the loop, which is charged under a hidden sector U(1), and the kinetic mixing ($\sim \epsilon F_{\mu\nu} F'_{\mu\nu}$) enables us to fit the required decay width for the Fermi-LAT peak. The model does not allow any dangerous decay channels into light standard model particles.

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I. INTRODUCTION

Although the major constituent of matter content of the Universe is dark matter (DM), we only know little about its nature so far \[1\]. Having no DM candidate in its particle contents, the standard model (SM) is strongly required to be extended. One intriguing possibility is that a hidden sector attached to the standard model sector includes a dark matter candidate. The singlet DM candidate could be a scalar \[2\], a fermion \[3–5\] or a vector boson \[6, 7\].

The recent claim of the Fermi Large Area Telescope (Fermi-LAT) \[8\] 130 GeV $\gamma$-ray line \[9, 10\] shed light on further details of the dark matter property since no known astrophysical source would produce such a peak. The claim was further strengthened by \[11\] (and also \[12, 13\]) even though the Fermi-LAT collaboration only has provided sensitivity limits on dark matter models based on a part of the acquired data set on different region of interest \[14\] (also see \[15\]). There are explanations of this $\gamma$-ray line based on spectral and spatial variations of diffuse $\gamma$-ray \[16\] and new background with ‘Fermi-bubble’ \[17\], but the most interesting interpretation might be that the $\gamma$-ray line could be originated from the DM annihilation, $\chi\chi \rightarrow \gamma\gamma$ [or $\gamma X$] with $E_{\gamma} \simeq m_{\chi}$ [or $m_{\chi}(1 - m_{X}^{2}/4m_{\chi}^{2})] \simeq 130$ GeV \[18–30\] or the DM decay, $\chi \rightarrow \gamma\gamma$ [or $\gamma X$] with $2E_{\gamma} \simeq m_{\chi}[or m_{\chi}(1 - m_{X}^{2}/m_{\chi}^{2})] \simeq 260$ GeV \[28, 31\].

For the DM annihilation interpretation of the 130 GeV $\gamma$-ray peak, the required values for annihilation cross section is found to be $\langle \sigma v \rangle_{\chi\chi \rightarrow \gamma\gamma} \sim \text{a few} \times 10^{-27}$ cm$^{3}$/s,\(^2\) which is approximately one order of magnitude smaller than the total annihilation cross section for the thermal production of DM, $\langle \sigma v \rangle_{\chi\chi \rightarrow \text{SM}} \simeq 3 \times 10^{-26}$ cm$^{3}$/s \[1\]. As the dark matter is likely to be electrically neutral (or milli-charged \[4, 5, 37\]), the annihilation process for $\gamma\gamma$ production may be radiatively induced by massive charged particles in the loop. If some of the charged particles are lighter than the DM particle, there could appear tree-level annihilation channels to these charged particles, which may dominantly determine the relic abundance of dark matter. However, the loop factor is too small as $g^{2}/16\pi^{2} \lesssim 10^{-2}$ and thus does not correctly account the discrepancy between the cross sections. A variety of

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1 If the Fermi-LAT peak is from the “box-shaped” spectrum as was discussed in \[18\], the energy of gamma-ray $E_{\gamma}$ would not be $m_{\chi}$ or $m_{\chi}/2$. In Refs. \[32, 34\], it has been studied to constrain the DM models accompanied by continuum photons correlated to the 130 GeV gamma-ray line.

2 More precisely, $\langle \sigma v \rangle_{\chi\chi \rightarrow \gamma\gamma} \simeq (1.27 \pm 0.32^{+0.18}_{-0.29}) \times 10^{-27}$ cm$^{3}$/s \((2.27 \pm 0.57^{+0.32}_{-0.51}) \times 10^{-27}$ cm$^{3}$/s\) for the Einasto \[35\] (NFW \[36\]) DM profile \[10\].
annihilating DM models have been suggested to overcome this issue \[18–30\].

Decaying DM can be an alternative explanation. Indeed, decaying dark matter models have been recently proposed to account for the excessive observation of positron in the PAMELA and ATIC where the dark matter is a vector boson in a hidden sector \[7\]. The vector boson of the hidden sector Abelian gauge group \(U(1)'\) can decay to the standard model photon through the kinematical mixing term \(\epsilon F_{\mu\nu} F'^{\mu\nu}\), where \(F_{\mu\nu}(F'^{\mu\nu})\) is the field strength tensor of \(U(1)/(U(1)'\) gauge boson, respectively. As the mixing parameter could be small \((\epsilon \sim 10^{-26})\) \[7\], the decay width could be suppressed. However, the decay of a vector boson to a pair of photons is forbidden by the Landau-Yang theorem \[38\] so that we need another model. In Refs. \[28, 31\], a scalar dark matter, \(\phi\), was considered with an effective operator allowing the decay to two photons: \(c_6 \phi \Lambda^2 F_{\mu\nu} F_{\mu\nu}\), which is dimension six. It is pointed out in Ref. \[31\] that a dimension five operator, \(c_5 \phi \Lambda F_{\mu\nu} F_{\mu\nu}\), cannot fit the data without introducing Trans-Planckian cutoff \((\Lambda \gg M_{Pl})\) or equivalently a largely suppressed coefficient \(c_6 \ll 1\) as the required partial decay width of the dark matter to photons is extremely small, \(\Gamma(\phi \to \gamma \gamma) \sim 10^{-29} \text{s}^{-1}\).

In this paper, we try to combine the advantages of above two cases:

- A scalar dark matter can decay into \(\gamma \gamma\) differently from the massive vector dark matter,
- A small kinetic mixing \(\epsilon\) can make the effective couplings of the dark matter particle with the standard model particles small.

Combining these two advantages, we suggest a dark matter model, which has an effective dimension five operators of the form:

\[
\mathcal{O} = c_5 \frac{\phi}{\Lambda} \left( F'_{\mu\nu} F'^{\mu\nu}, + \epsilon F_{\mu\nu} F'^{\mu\nu} + \epsilon^2 F_{\mu\nu} F^{\mu\nu} \right),
\]

from which we can learn that the decay amplitudes to \(\gamma \gamma'\) and \(\gamma \gamma\) are relatively suppressed by a factor of \(\epsilon\) and \(\epsilon^2\) with respect to the one for \(\gamma' \gamma'\) channel due to the mixing.

In the next section (Sec. \[II\]), we further explain the model in detail and present the partial decay widths of the dark matter to (hidden) photons then clarify the model parameter space providing a good fit to the 130 GeV gamma-ray line. Discussions on possible experimental bounds on the same parameter space follow. In Sec. \[IV\] we further discuss the theoretical

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3 For radiative DM decays to \(\gamma \gamma\) or \(\gamma X\), see e.g. \[39\].
issues concerning the consistency of the model and also other cosmological observations
then conclude in Sec. V. Finally, in Appendix, we present some details of the U(1) mixing
Lagrangian for an extra unbroken U(1) symmetry.

II. THE MODEL AND EXPERIMENTAL BOUNDS

Postulating extra U(1) gauge symmetries is one of the simplest extensions of the standard
model. As the kinetic mixing term $\epsilon F^{\mu\nu} F'^{\mu\nu}$ is compatible with Lorentz as well as gauge
symmetry, the term should be included in view of effective field theory. The term can be
generated through one-loop diagrams with a bi-charged fermion [40]. If the extra U(1) is
broken by a hidden sector Higgs mechanism, the gauge boson ($Z'$) gets mass and mixes
with the standard model $Z$ boson [41]. A general analysis for a hidden sector DM, which
is charged under a broken U(1)$_H$ was done in Ref. [42]. On the other hand, if the extra
U(1) is exact, the massless gauge boson (hidden photon or exphoton, $\gamma_H$) can mix with the
usual photon ($\gamma$) and the corresponding phenomenology becomes quite different from the
case with $Z'$. It is worth noticing that a light DM explanation with the hidden photon for
the anomalous 511 keV $\gamma$-ray signature from the Galactic Center was considered in Ref. [5],
where a milli-charged fermion dark matter was introduced.

For the Fermi-LAT $\gamma$-ray peak, a scalar DM is more profitable. The minimal setup only
introduces a heavy vector-like fermion $\psi$, which is only charged under the U(1)$_H$, and a
scalar dark matter candidate $\phi$. The hidden sector can interact with the SM sector through
a kinetic mixing between U(1)$_{EM}$ and U(1)$_H$. The model Lagrangian is given by

$$
\mathcal{L} \supset \mathcal{L}_{SM} - \frac{1}{4} \tilde{F}_{H\mu\nu} \tilde{F}_{H}^{\mu\nu} - \frac{\sin \epsilon}{2} \tilde{F}_{\mu\nu} \tilde{F}_{H}^{\mu\nu} - \lambda \phi \bar{\psi} \psi + i \bar{\psi} \gamma^\mu (\partial_\mu - i g_H A^H_\mu) \psi - m_\psi \bar{\psi} \psi,
$$

where $\tilde{F}_{\mu\nu}$ and $\tilde{F}_{H\mu\nu}$ are respectively field strength tensors for U(1)$_{EM}$ and U(1)$_H$. The
detailed derivation of the kinetic mixing between U(1)$_{EM}$ and massless U(1)$_H$ can be found
in Appendix A. Current bounds on hidden U(1) gauge bosons and milli-charged particles
(MCPs) are well summarized in Ref. [43]. Indeed, when $m_{\gamma_H} = 0$, the only change for the
SM photon interactions is the modification of the coupling constant, $\hat{e} \to \hat{e} / \cos \epsilon$, which can
be simply refined by a field redefinition.

4 Here the ‘Higgs-portal’ interaction, $\phi^2 |H|^2$, is assumed to be negligible as we do not allow the DM decay
via mixing with the Higgs boson. Further discussion is given in Sec. IV.
FIG. 1: (a) Scalar dark matter decaying to two hidden photons. (b) Scalar dark matter decaying to one hidden photon and one SM photon. (c) Scalar dark matter decaying to two SM photons.

The scalar DM candidate $\phi$ can radiatively decay to the hidden photon ($A_H = \gamma_H$) as well as the conventional photon ($\gamma$) of the EM interaction through the triangle diagrams with the virtual hidden sector fermion $\psi$ as can be seen from Fig. 1. From the couplings in Eq. (2), one can easily calculate the decay width of $\phi$:

$$\Gamma(\phi \rightarrow \gamma_H\gamma_H) = \frac{(\alpha_H \lambda)^2 m_\phi^3}{256\pi^3 m_\psi^2} |F(\tau)|^2,$$

where $\alpha_H = g_H^2/4\pi$ and $F(\tau = 4m_\psi^2/m_\phi^2) = -2\tau \left[ 1 + (1 - \tau) \arcsin^2(1/\sqrt{\tau}) \right]$ which is well approximated by $-4/3$ at a large $\tau$ limit. To make $\phi$ stable enough, we would require the longevity of $\phi$:

$$\Gamma(\phi \rightarrow \gamma_H\gamma_H)^{-1} \gg \tau_{\text{Universe}} \approx 4.34 \times 10^{17} \text{ sec}.$$  

Thus, we can obtain a constraint on the combination $\alpha_H \lambda$:

$$\alpha_H \lambda \ll 1.96 \times 10^{-7} \left( \frac{m_\phi}{10^{16} \text{ GeV}} \right) \quad \text{for} \quad m_\phi = 260\text{GeV}. \quad (5)$$

The DM candidate $\phi$ predominantly decays to two hidden photons, $\phi \rightarrow \gamma_H\gamma_H$ [Fig. 1-(a)], which thus determines the life time of $\phi$ but a hidden photon can be converted into a SM photon through the kinetic mixing. Consequently, one can detect the DM decay signals through the decay modes $\phi \rightarrow \gamma\gamma_H/\gamma\gamma$ [Fig. 1-(b)/(c)], which are respectively suppressed by $\epsilon^2$ and $\epsilon^4$ compared with the dominant decay mode:

$$\Gamma(\phi \rightarrow \gamma_H\gamma_H) : \Gamma(\phi \rightarrow \gamma\gamma_H) : \Gamma(\phi \rightarrow \gamma\gamma) \simeq 1 : \epsilon^2 : \epsilon^4.$$  

This helps as the effective dimension five operators, $\phi F_{\mu\nu}F^{\mu\nu}$ and $\phi F_{\mu\nu}X^{\mu\nu}$, are all suppressed by powers of $\epsilon$ and provides the required decay rate $\Gamma^{-1} \approx C \times 10^{29} \text{ sec}$.
FIG. 2: Contour plot for the kinetic mixing parameter $\epsilon$ in the $m_\psi - \alpha_H \lambda$ plane. The colored region above the thick line is excluded since the life time of $\phi$ is shorter than the age of the Universe. The partial life time of $\phi$ to $\gamma \gamma_H$ is fixed to be in $(10^{28}, 10^{29})$ sec, which is required to fit the Fermi-LAT data, with $\epsilon = 10^{-4} - 10^{-2}$ in the colored bands from the top to the bottom on the right lower side of the graph. The larger $\alpha_H \lambda$ is required for the smaller $\epsilon$.

or

$$\Gamma(\phi \to \gamma \gamma_H)^{-1} \approx 1.52C \times 10^{53} \text{ GeV}^{-1},$$

where a convenient parameter $C \in (0.1, 1)$ is introduced. Then, the parameter range for the mixing parameter $\epsilon$ can be read:

$$\epsilon \approx \frac{4.1 \times 10^{-13}}{\alpha_H \lambda \sqrt{C}} \left( \frac{m_\psi}{10^{16} \text{ GeV}} \right) \quad \text{for} \quad m_\phi = 260 \text{ GeV}.$$  

(8)

Having a small value for $\alpha_H \lambda \ll 10^{-7}$, a relatively sizable kinetic mixing parameter $\epsilon$ is required.

In Fig. 2 we plotted the parameter space in the $m_\psi - \alpha_H \lambda$ plane. The upper left region in shade (grey) is excluded by the longevity of the dark matter. The three colored bands are for fitting the required decay width $(\Gamma^{-1} = 10^{28} - 10^{29} \text{ sec})$ with $\epsilon = 10^{-4}, 10^{-3}$ and $10^{-2}$, respectively. The charged fermion $\psi$ is assumed to be heavy ($\sim 10^{16} \text{ GeV}$).
III. MORPHOLOGY OF THE 130 GEV $\gamma$-RAYS: DECAY VS ANNIHILATION

Based on the information about the spatial distribution of the 130 GeV gamma-ray line, we can compare decaying dark matter with annihilating dark matter. As the observed gamma-ray flux would depend linearly on the dark matter density for decaying dark matter ($\propto n_{DM}$), the characteristic morphology of the expected gamma-ray from decaying dark matter is flatter than the one from the annihilating dark matter, which is quadratically sensitive to the density ($\propto n_{DM}^2$). Taking the spatial distribution of the Fermi-LAT excess at 130 GeV into account, which is relatively peaky in the Galactic Center, indeed the decaying dark matter would require an enhancement of the density near the Galactic Center, in comparison with conventional profiles e.g., NFW and Einasto profiles [32]. However, there still exists large uncertainty of the dark matter density close to the Galactic Center and large systematic and statistical uncertainties at present. Thus, the decaying dark matter could remain as a possible solution to the Fermi-LAT excess as the similar conclusion was made in Ref. [32].

In Fig. 3, we plotted the best fit distributions of gamma-rays for the decaying (Top) and annihilating (Bottom) DM within the allowed range of $\Gamma_{DM}$ and $\langle \sigma v \rangle$ in Galactic longitude, $\ell \leq |10|^{\circ}$. The estimated background is depicted by green line, which is roughly $\ell$ independent. For fitting we used a useful parametrization of the DM profiles with $(\alpha, \beta) = (1, 3)$:

$$
\rho(r) = \rho_0 \left( \frac{r_s}{r} \right)^\gamma \left( \frac{1 + (r_0/r_s)^\alpha}{1 + (r/r_s)^\alpha} \right)^{\frac{\beta - \gamma}{\alpha}},
$$

(9)

where the local density $\rho_0 \approx 0.4$ GeV/cm$^3$ is given at $r_0 \approx 8.5$ kpc. The scale radius is set to be $r_s = 20$ kpc for numerical analysis. The popular Navarro-Frenk-White (NFW) profile is obtained with $(\alpha, \beta, \gamma) = (1, 3, 1)$ but we allow a rather broad parameter range $\gamma \in [1.0, 1.7]$. With the bigger $\gamma$, the profile becomes sharper in the center. Einasto profile is also commonly used but provides less sharp distribution thus is less favored for the decaying DM scenario. As it is expected, the sharper profile provides the better fit for the decaying DM. When $\gamma = 1.7$ (1.5, 1.0), the best fits are found with the decay widths $\Gamma^{-1} = 2.8$ (2.1, 1.3) $\times 10^{28}$ sec, respectively.

The overall quality of fit is parametrized with $\chi^2/d.o.f.$ value as shown in Table 1. Taking the background effect into account, we found that the best fit is found with a rather small $\gamma$ for the annihilating DM but the larger $\gamma$ for the decaying DM. It is worth noticing that
FIG. 3: The profiles of decaying (top) and annihilating (bottom) dark matter fitting the 130 GeV gamma-ray line along the Galactic plane ($\Delta l = 0.5^\circ, |b| < 5^\circ$). Compared to the rather flat NFW profile ($\gamma = 1.0$: the red dotted line), the steeper profile ($\gamma = 1.7$: the blue dashed) provides the better fit for the decaying DM. For comparison, we plotted the fits for the annihilating DM with $\gamma = 1.0$ (red dotted) and $\gamma = 1.3$ (blue dashed). The green line is for the background. Fermi-LAT excess data is taken from Ref. [11]. See Table I for $\chi^2/d.o.f.$ values for each fit.

the decaying DM provides acceptable fits with $\chi^2/d.o.f < 1.80$ for all values of $\gamma \in [1.0, 1.7]$ even though the annihilating DM provides better fit when $\gamma \leq 1.5$. When the profile is extremely peaky with a larger value $\gamma > 1.5$, the decaying DM provides better fit than the
annihilating DM. The reason is simple: as it is seen in Fig. 3, the gamma-rays are found not only within $|\ell| \leq 5^\circ$ but also in rather broad range of $5^\circ - 10^\circ$, which can not be properly explained by the background (green line in Fig. 3). Due to those signals from the outside of $5^\circ$, a peaky profile does not necessarily help but actually makes the fitting worse in the annihilating DM case.

In conclusion, currently both of decaying and annihilating dark matter models are acceptable with $\chi^2/d.o.f. < 1.8$ provided that the profile could be enhanced at the center with $\gamma > 1.0$ for the decaying DM model. Future improvement in observation is highly required to judge the fate of each model.

| NFW $\gamma$ | 1.0 | 1.3 | 1.5 | 1.7 |
|---------------|-----|-----|-----|-----|
| Ann.          | 1.05| 1.03| 1.17| 1.40|
| Dec.          | 1.80| 1.60| 1.44| 1.28|

TABLE I: The $\chi^2/d.o.f$ values for Annihilating and decaying dark matter for various dark matter profiles with $\gamma \in [1.0, 1.7]$.

### IV. OTHER ISSUES

In this section, we discuss possible difficulty of the ‘Higgs-portal’ type interaction and its way out. Then, we propose some scenarios for producing the singlet dark matter from the inflaton or other heavy particle decays in the early universe.

#### A. $\sigma \phi^2|H|^2$ or $\mu \phi|H|^2$ type interactions

The gauge invariant renormalizable interactions between the dark matter and the Higgs boson of the form $\sim \sigma \phi^2|H|^2$ (“Higgs portal”) and $\mu \phi|H|^2$ are generically allowed. If $m_\phi \geq 2m_h$, $\phi$ can therefore decay into two Higgs bosons with the decay rate:

$$\Gamma(\phi \to hh) \propto \frac{1}{16\pi} \frac{(\sigma \langle \phi \rangle + \mu)^2}{m_\phi} \sqrt{1 - \left(\frac{2m_h}{m_\phi}\right)^2},$$ (10)
which can be significantly larger than the required decay width in Eq. (4). This difficulty can be avoided when an additional spatial dimension exists and all the hidden sector particles \((\phi, \psi, \gamma_H)\) are localized on the ‘hidden-brane’ which is spatially distant from the ‘visible-brane’ on which all the SM particles \((\supset \{H, \gamma, \text{leptons, quarks}\})\) reside. A mediator fermion \(\psi_M\), which is charged under the both of the Abelian gauge groups \(U(1)_{\text{EM}} \times U(1)_H\), could provide a sizable \(\gamma - \gamma_H\) mixing. Then, the operator \(\hat{O} \sim \phi^2 HH^\dagger\) is suppressed by many loop factors (two one-loops of the \(\phi\phi - \gamma_H\gamma_H\) and \(HH - \gamma\gamma\) vertices, and two additional one-loops of the \(\gamma - \gamma_H\) mixings) and also by possible suppressed wave function overlaps \(\sim \psi(y_{\text{hidden}})^* \psi(y_{\text{visible}})\). Similarly, the other operator \(\hat{O} \sim \phi HH^\dagger\) is also suppressed.

**B. The production of \(\phi\)**

1. **Model-1**

A simple mechanism for the production of \(\psi\) and \(\phi\) is the inflaton decay after reheating: \(\Phi \to \psi\overline{\psi}\) and \(\Phi \to \phi\phi\), where \(\Phi\) is the inflaton field. As the mass of \(\psi\) is around the GUT scale, we do not expect any sizable number of remaining \(\psi\) in our patch universe, but still \(\phi\) could remain to be a good DM candidate. Here the only requirement is

\[
m_\psi > T_{\text{reheating}} > m_\phi,
\]

where a large space of reheating temperature in TeV to GUT-scale could be allowed, in principle. With this condition, \(\phi\) can be produced but \(\psi\) cannot. In this paper, we simply assume that the reheating temperature is low enough compared with the GUT-scale to make the number of \(\psi\) small enough.

2. **Model-2**

If \(m_\psi \ll T_{\text{reheating}}\), large number of \(\psi\) can be produced through the reheating process. In the presence of an additional hidden sector fermion field \(\psi'\), we can consider the decay of \(\psi, \psi \to \psi'\phi\). Then, a simple \(U(1)_H\) interaction of the form \(\overline{\psi'}\psi'\gamma_H\) can induce the pair annihilation of \(\psi', \psi'\psi' \to \gamma_H\gamma_H\), so that the relic abundance of \(\psi'\) could be small enough.
provided that
\[ \langle \sigma v \rangle_{\psi' \rightarrow \gamma H \gamma H} \sim \frac{\pi \alpha_H^2}{m_{\psi'}^2} \gg 2 \times 10^{-9} \text{GeV}^{-2}, \tag{12} \]
for which we assume that the mass of $\psi'$ is relatively light. For instance, if $\alpha_H \sim 10^{-4}$, $m_{\psi'} \ll 4$ GeV insures that the number of relic $\psi'$ is too small to affect the present universe. The least constrained mass range for the hidden sector milli-charged particle is $0.1$ GeV $\lesssim m_{\psi'} \lesssim 500$ GeV \[43\]. Thus, we can easily find experimentally allowed masses for $\psi'$ satisfying Eq. (12).

V. CONCLUSION

The recently reported gamma-ray excesses around 130 GeV based on the Fermi-LAT data is difficult to explain with well known dark matter models. Inspired by the Fermi-LAT 130 GeV line, we suggest a model with a decaying scalar dark matter $\phi$ and a heavy hidden fermion $\psi$ charged under a hidden gauge symmetry $U(1)_H$ allowing a Yukawa interaction, $\lambda \phi \bar{\psi} \psi$. In this model, the hidden sector can communicate with the SM sector through the kinetic mixing ($\epsilon F^{\mu\nu} F'_{\mu\nu}$) and the unwanted fast decay to $\gamma \gamma$ is well suppressed by the small mixing $\epsilon^2$ after ensuring the longevity of $\phi$ by a doubly suppressed loop factor, $\Gamma_{\phi}/m_{\phi} \sim (\alpha_H \lambda)^2 (m_{\phi}^2/m_{\psi}^2)/(256 \pi^3)$. Assuming $\alpha_H \lambda \sim 10^{-7}$ and $\epsilon \sim 10^{-2} - 10^{-4}$, we found that the required decay rate $\Gamma(\phi \rightarrow \gamma_H \gamma) \sim 10^{-28} \text{sec}^{-1}$ for the observed $\sim 130$ GeV gamma-ray flux is obtained with a GUT scale mass for the fermion $m_{\psi} \sim 10^{16}$ GeV.

From the morphology of the observed gamma-ray, the dark matter profile is suggested to be relatively enhanced in the Galactic Center for the decaying dark matter. It is found that the decaying dark matter could provide a good fit producing less additional gamma-rays outside of the Galactic Center when $\gamma > 1$, which is still compatible with microlensing and stellar rotation curve observations \[44\]. The model is free from possible other observational bounds especially from the continuum gamma-ray flux and also antiprotons. We also discussed possible production mechanisms for the dark matter from the inflation or a heavy particle decay but other possibilities are still open for studies in the future.

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Appendix A: Kinetic mixing between U(1)\textsubscript{EM} and massless U(1)\textsubscript{H}

Consider two Abelian gauge groups U(1)\textsubscript{EM} and U(1)\textsubscript{H}.\textsuperscript{5} The kinetic mixing between U(1)\textsubscript{EM} and U(1)\textsubscript{H} is parameterized as

\[ L = -\frac{1}{4} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} - \frac{1}{4} \hat{F}_{H\mu\nu} \hat{F}^{\mu\nu}_H - \frac{\xi}{2} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu}_H , \]  

(A1)

where \( \hat{A}_\mu(\hat{A}_H^\mu) \) is the U(1)\textsubscript{EM}(U(1)\textsubscript{H}) gauge boson and its field strength tensor is \( \hat{F}^{\mu\nu}(\hat{F}^{\mu\nu}_H) \). The kinetic mixing is parameterized by \( \xi \), which is generically allowed by the gauge invariance and the Lorentz symmetry. In the low energy effective theory, the kinetic mixing parameter \( \xi \) is considered to be an arbitrary parameter. An ultraviolet theory is expected to generate the kinetic mixing parameter \( \xi \)\textsuperscript{[40]}. We are only interested in a small kinetic mixing, \( \xi < 1 \). Thus, for convenience we can set \( \xi \equiv \sin \epsilon \). The kinetic terms for the photon and hidden photon are diagonalized by the following transformation:

\[ \begin{pmatrix} A'_\mu \\ A'^H_\mu \end{pmatrix} = \begin{pmatrix} \cos \frac{\epsilon}{2} & \sin \frac{\epsilon}{2} \\ \sin \frac{\epsilon}{2} & \cos \frac{\epsilon}{2} \end{pmatrix} \begin{pmatrix} \hat{A}_\mu \\ \hat{A}^H_\mu \end{pmatrix}. \]  

(A2)

In this transformed basis, the Lagrangian is given by

\[ L = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F'^{H}_{\mu\nu} F'^{H\mu\nu} , \]  

(A3)

where \( F'_{\mu\nu} \) and \( F'^{H}_{\mu\nu} \) are the field strength tensors corresponding to \( A'_\mu \) and \( A'^H_\mu \), respectively. Since two gauge bosons are massless, we still have an SO(2) symmetry:

\[ \begin{pmatrix} A_\mu \\ A^H_\mu \end{pmatrix} = \begin{pmatrix} \cos \eta & \sin \eta \\ -\sin \eta & \cos \eta \end{pmatrix} \begin{pmatrix} A'_\mu \\ A'^H_\mu \end{pmatrix}. \]  

(A4)

If we choose the mixing angle as \( \eta = -\epsilon/2 \), the final relation between the bases \( (A_\mu, A^H_\mu) \) and \( (\hat{A}_\mu, \hat{A}^H_\mu) \) is

\[ \begin{pmatrix} A_\mu \\ A^H_\mu \end{pmatrix} = \begin{pmatrix} \cos \epsilon & 0 \\ \sin \epsilon & 1 \end{pmatrix} \begin{pmatrix} \hat{A}_\mu \\ \hat{A}^H_\mu \end{pmatrix}. \]  

(A5)

\textsuperscript{5} For the case of massive U(1)\textsubscript{H}, see Ref. [42].
By this diagonalization procedure of the kinetic terms, we finally obtain

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F_{\mu\nu}^H F^{H\mu\nu}, \quad (A6)$$

where the new field strength tensors are $F_{\mu\nu}$ and $F_{\mu\nu}^H$. The SM photon corresponds to $A_\mu$ and the hidden photon to $A_\mu^H$.

Let us take the following simple interaction Lagrangian of a SM fermion $f$ with the photon in the original basis as

$$L_f = \bar{f} \left( \hat{e} Q_f \gamma^\mu \right) f A_\mu. \quad (A7)$$

Note that in this basis no direct interaction exists between the SM fermion and the hidden sector gauge boson $\hat{A}_H$. If there exists a hidden sector fermion $\psi$ with the U(1)$_H$ charge $Q_H$, its interaction with the hidden sector gauge boson is simply represented by

$$L_\psi = \bar{\psi} \left( \hat{g}_H Q_H \gamma^\mu \right) \psi A_H^\mu. \quad (A8)$$

In this case, there is also no direct interaction between the hidden fermion and the SM photon $\hat{A}$.

We can recast the Lagrangian (A7) in the transformed basis $(A_\mu, A_\mu^H)$,

$$L_f = \bar{f} \left( \hat{e} \cos \epsilon Q_f \gamma^\mu \right) \psi A_\mu. \quad (A9)$$

Here, one notices that the SM fermion has a coupling only to the visible sector gauge boson $A$ even after changing the basis of the gauge bosons. However, the coupling constant $\hat{e}$ is modified to $\hat{e} / \cos \epsilon$, and so the physical visible sector coupling $e$ is just defined as $e \equiv \hat{e} / \cos \epsilon$. Similarly, we can derive the following interactions for $\chi$,

$$L_\psi = \bar{\psi} \gamma^\mu \left( \hat{g}_H Q_H A_\mu^H - \hat{g}_H \tan \epsilon Q_\psi A_\mu \right) \psi. \quad (A10)$$

In this basis, the hidden sector matter field $\psi$ now can couple to the SM photon $A$ with the coupling $-\hat{g}_H Q_\psi \tan \epsilon$. Consequently, we can interpret the hidden particle $\psi$ as a particle with a EM charge $Q_\psi \equiv (-\hat{g}_H Q_\psi \tan \epsilon) / e$. In addition, we can set the physical hidden sector coupling $g_H$ as $g_H \equiv \hat{g}_H$.

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