130GeV gamma-ray line through axion conversion

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We apply the axion-photon conversion mechanism to the 130 GeV γ-ray line observed by Fermi satellite. Mono-energetic axions or axion-like particles (ALPs) can be produced through annihilation or decay processes of dark matter. Then the axion converts to the γ-ray in Galactic magnetic fields along its flight to the Earth, which can explain the observations. Because this mechanism suppresses the fluxes of both continuum components of γ-rays and cosmic-ray anti-protons, our model agrees with those observations. In our mechanism, the γ-ray spatial distribution depends on both the dark matter profile and the magnetic field configuration, which will be tested by future γ-ray observations, e.g., through HESS II, CTA, GAMMA-400. As an example, we discuss possible scenarios for the 130 GeV axion emissions in supersymmetric axion models.

I. INTRODUCTION

Cosmological and astrophysical measurements have been supporting the existence of dark matter (DM)1–2. Numerical simulations3–4 and the thermal relic scenario5–6 suggest that weakly interacting massive particles (WIMPs) are the most feasible candidate for the DM. Indirect detections of the DM, such as searches for an excess of anomalous cosmic rays, are promising methods to explore the nature of the DM. The indirect detection is a key method to check scenarios of the WIMP DM, since the pair-annihilation cross section is related with its thermal relic abundance.

Fermi satellite measures γ-rays with great precision, and one of the aims is to search for DM signals9. An excess of γ-rays in energy ranges 120GeV - 140GeV was reported by a group10, which is using public Fermi data11 (see also12,13). Detailed analysis focusing on the Galactic center concludes a 4.6σ evidence for this γ-ray line14, and other works also confirm the signals15–17 although there is room for instrumental errors18–20 (see also Ref.21 and references therein). Quite recently the Fermi-LAT collaboration formally reported that the line signals at around $E_\gamma = 133$ GeV have been detected at $3.3 \sigma$ (1.9 σ) for local (global) significance22.

So far there is no natural astrophysical models for a source of such γ-ray lines at around 130GeV with a narrow width $\Delta E/E < 0.15$. Some models (e.g., see Ref.23 and references therein) try to explain the sharp γ-ray line via the inverse Compton scattering of ambient photons by electrons from a neutron star in the Klein-Nishina regime, it requires that the electrons in the wind are mono-energetic with a small dispersion less than 20-30%. Hence the observed γ-ray excess has triggered building new models of an annihilating or a decaying DM at the Galactic center.24–60

It is a challenging to build particle physics models to produce the γ-ray lines without conflicting other observations. A concern is the discrepancy between a cross section expected from the thermal relic abundance and the one fitted to the γ-ray signal. Since the DM should be electrically neutral, the annihilations into monochromatic γ-ray may occur only at higher order corrections. Then, if the annihilation mode has a sufficient cross section for producing the γ-ray excess, the cross section of the tree-level annihilation into fermions or weak gauge bosons tends to become too large to account for the measured thermal-relic abundance.

Another concern is continuum γ-ray, antiproton, anti-deuteron, and positron from the annihilation or the decay at the tree level. Based on the Fermi data, lower limits on the flux ratios of the γ-ray lines to the continuum γ-rays have been found to be $\gtrsim O(10^2)$61–62. The eligible DM should therefore so weakly interact with charged particles at the tree level. Antiprotons are also produced as the secondary products, and would exceeds the bound of the flux ratio of antiproton to proton61 obtained by PAMELA satellite64. Hence the hadronic mode should be suppressed as well.

In this work, we focus on the axion-photon conversion as a source of the γ-ray lines. We propose here a scenario that mono-energetic axions are produced by annihilations or decays of DM, and changed to photons through the Primakoff effect under external Galactic magnetic fields65–66. The axion-photon

1 See also67, for discussions about morphology differences between the annihilation and the decay scenarios
2 From big-bang nucleosynthesis and cosmic-microwave background anisotropies, we can obtain milder bounds on the ratio $\gtrsim 1 \times 10^{-3}$ commonly for $W^+W^-$, $b+b$, and $e^+e^-$'s and/or γ's modes.68
conversion and their oscillating propagation in our galaxy have been studied in Refs. [62, 72] in detail. In this paper we discuss both the conventional QCD axion and very light pseudo-scalar particles which interact with photons. The latter is called axion-like particles (ALPs). The symbol $a$ in this work refers to both conventional axions and ALPs. (See also Refs. [73–75] for cosmological applications.)

This work is organized as follows. First we briefly review the axion-photon conversion and calculate its probability implementing information from Fermi satellite. Then, in order to account for the measured $\gamma$-ray lines can be fitted. Finally Sec. [IV] is devoted to summaries and discussions.

II. AXION-PHOTON CONVERSION AND ITS APPLICATION TO THE 130GEV $\gamma$

We consider scenarios that axions are produced by annihilations or decays of DM at the Galactic center. Then the axions are converted to photons under an external magnetic field $B$. The observed $\gamma$-ray signals with the axion-photon conversion, we fit the axion production cross section or the decay rate of the DM. In Sec. [III] as an example we discuss supersymmetric axion models in which the 130GeV $\gamma$-ray lines can be fitted. Finally Sec. [IV] is devoted to summaries and discussions.

A. Conversion probability

First of all, we briefly review axion-photon conversion, and then derive its probability. The conversion from an axion to a photon is described by the following Lagrangian,

$$\mathcal{L}_{a\to\gamma} = \frac{1}{2} (\partial^\mu a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}, \tag{2}$$

where $F_{\mu\nu}$ is the electromagnetic field strength, and $\tilde{F}_{\mu\nu}$ is its dual. $g_{a\gamma}$ and $m_a$ denote an effective coupling constant between photon and axion, and the mass of axion, respectively. In QCD axion models $g_{a\gamma}$ and $m_a$ are tightly connected. In this work we assume they are independent each other to include ALPs in our scenarios. So far an upper bound on $g_{a\gamma}$ has been obtained by the CAST experiment to be $g_{a\gamma} \lesssim 8.8 \times 10^{-11}\text{GeV}^{-1}$ for $m_a \lesssim 0.02\text{eV}$ [76].

The conversion probability $P_{a\gamma}$ is written by [65, 77]

$$P_{a\gamma} = |\langle A(t, x = L)|a(t = 0, x = 0)\rangle|^2 = \sin^2 2\Theta \sin^2 \left(\frac{1}{2} qL\right), \tag{3}$$

where $L$ is the distance of the propagation, and $\Theta$ is the mixing angle of the axion and the photon, which is represented by

$$\sin \Theta = i \sqrt{\frac{\lambda_+}{\lambda_+ - \lambda_-}}, \quad \cos \Theta = i \sqrt{\frac{\lambda_-}{\lambda_+ - \lambda_-}}. \tag{4}$$

Here $\lambda_{\pm}$ is the mass eigenvalue of the axion-photon mixing state, which is given by

$$\lambda_{\pm} = \frac{1}{2} \left[m_a^2 \pm \sqrt{m_a^4 + 4 g_{a\gamma}^2 B^2 E_{\gamma}^2}\right]. \tag{5}$$

The momentum transfer $q$ on the conversion is calculated to be

$$q = \sqrt{E_{\gamma}^2 - \lambda_-} - \sqrt{E_{\gamma}^2 - \lambda_+} \approx \frac{1}{2 E_{\gamma} \sqrt{m_a^2 + 4 g_{a\gamma}^2 B^2 E_{\gamma}^2}}, \tag{6}$$

in a high energy limit $E_{\gamma} \gg m_a$. Then the conversion probability is transformed into

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**FIG. 1:** Axion-photon conversion in an external magnetic field $B$. 

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\[
P_{a\gamma} = \sin^2 \left[ \frac{g_{a\gamma}BL}{2} \sqrt{1 + \left( \frac{m_a^2}{2g_{a\gamma}BE_\gamma} \right)^2} \right] \left[ 1 + \left( \frac{m_a^2}{2g_{a\gamma}BE_\gamma} \right)^2 \right]^{-1} \\
= \sin^2 \left[ 2.4 \times 10^3 \left( \frac{L}{1.794\text{kpc}} \right) \frac{130\text{GeV}}{E_\gamma} \right] \left( \frac{m_a}{10^{-7}\text{eV}} \right)^4 \left( \frac{10^{-10}\text{GeV}^{-1}}{g_{a\gamma}} \right) \left( \frac{10\mu\text{G}}{B} \right)^2 \left( \frac{130\text{GeV}}{E_\gamma} \right)^2 \right]^{-1}.
\]

In Fig. 2 we plot the conversion probability as a function of the axion mass \(m_a\). We adopt \(g_{a\gamma} = 8.8 \times 10^{-11}\text{GeV}^{-1}\) in the top panel, which is the maximal value allowed by the CAST experiments, \(g_{a\gamma} = 1 \times 10^{-11}\text{GeV}^{-1}\) in the middle panel, and \(g_{a\gamma} = 1 \times 10^{-12}\text{GeV}^{-1}\) in the bottom panel. In each panel, the magnetic field in the Galaxy is assumed to be a uniform distribution and \(B = 10\mu\text{G}\) (upper band) and \(B = 1\mu\text{G}\) (lower band)\(^3\). The width of each band represents ambiguities both of the energies of the \(\gamma\)-ray \(E_\gamma = 129.8 \pm 2.4^{+1.6}_{-1.8}\text{GeV}\) \(^{11}\) and the distance from the Galactic center to the solar system \(L = 7.94 \pm 0.42\text{kpc}\) \(^7\).

In the top panel, the probability for \(B = 10\mu\text{G}\) spans a broad range because the argument of sine of Eq. (7) becomes the order of \(\mathcal{O}(10)\) for \(g_{a\gamma} = 8.8 \times 10^{-11}\text{GeV}^{-1}\) and \(B = 10\mu\text{G}\). Thus \(P_{a\gamma}\) fluctuates even for small variations in \(E_\gamma\) and/or \(L\) within their errors.

Except for the case of \(B = 10\mu\text{G}\) and \(g_{a\gamma} = 8.8 \times 10^{-11}\text{GeV}^{-1}\), for lower mass regions, \(m_a \gtrsim \tilde{m}_a\), the probability is constant with \(m_a\) for the fixed \(B\) and \(g_{a\gamma}\) because, in Eq. (7), the term proportional to \(B^2\) in the square root in the second line becomes larger than the term proportional to \(m_a^4\), and the third line becomes unity. Here \(\tilde{m}_a\) is a connecting point between flat and damping oscillation behavior of \(P_{a\gamma}\), which depends on all parameters in Eq. (7). Each \(\tilde{m}_a\) is shown in Table 1 and is discussed later. On the other hand, for larger mass region \(m_a \gtrsim \tilde{m}_a\), the terms involving \(m_a\) become dominant both on the second and the third line in Eq. (7). Then the third line suppresses \(P_{a\gamma}\) by a factor of \(m_a^{-4}\), which gives damping oscillations shown in Fig. 2.

### B. Conditions to fit the observed \(\gamma\)-ray line

Here we introduce conditions in order to explain the observed 130 GeV \(\gamma\)-ray lines by using the axion-photon conversion. The conversion probability \(P_{a\gamma}\) is expressed by an oscillating function of \(E_\gamma\) [see Eq. (7)]. In Fig. 3 we plot \(P_{a\gamma}\) as a function of \(E_\gamma\) for some parameter sets of \((m_a, g_{a\gamma}, B)\). We find that an observed bump shape of \(\gamma\)-rays can be produced by the oscillation behavior even if the energy of axions is not tuned to be exactly 130 GeV once we choose appropriate sets of the model parameters. Therefore, there are two options to fit the observational data,

- Monochromatic axions with the energy of \(\sim 130\text{GeV}\) have to be produced. The effective coupling \(g_{a\gamma}\) can be as large as the experimental upper limit by CAST (\(< 10^{-16}\text{GeV}^{-1}\)). The axion mass should be smaller than \(\tilde{m}_a\) for each parameter sets (see Fig. 2).

- The energy spectrum of the axion is not monochromatic. There needs to be a fine tuning in the sets of parameters \((E_\gamma, m_a, B)\) with a cutoff energy \(< 200 \text{ GeV}\) so that a bump shape is produced (see Fig. 3).

In this work we consider the first option. An attractive candidate of the source for the monochromatic axion emission would be a decaying or annihilating WIMP DM. Thus searching origins of the 130 GeV \(\gamma\)-rays can be a bridge to the new physics which predicts the DM. The second option will be discussed in a separate paper.

### C. Axion production

First we consider an axion production from decays of the DM. We assume the DM is a partner of a neutral standard model (SM) field, e.g., gravitino in supergravity models, a Kaluza-Klein photon in some extra dimension models, and so on. The interactions between axions and the SM fields are only through \(g_{a\gamma}aF_{\mu\nu}F^{\mu\nu}\) or gravitational interactions. Then the lowest order process of the axion production is

\(^3\) Actual magnetic field has a complicated structure in our Galaxy, and its strength at the Galactic center may be larger. More detailed analysis needs modelings of the structures based on various observations. In particular, the detailed analysis is required for correctly handling the high frequency oscillation of \(P_{a\gamma}\).
are constrained by observations of antiprotons, anti-pair final states such as a parity +1 are assigned to the DM and the SM parity into axions as a stable massive particle (DM'), respectively. We refer to these partial cross sections as \( \sigma_v \rightarrow aZ \) and \( \sigma_v \rightarrow ah \), respectively. In a similar fashion to the decay modes, the Z boson or the Higgs boson in the final states produces antiprotons, anti-deuterons and continuum components of \( \gamma \)-rays, which are severely constrained by observations. In the next subsection, we discuss observationally-fitted decay rates and partial annihilation cross sections which agree with the \( \gamma \)-ray lines through the axion-production processes.

D. Partial cross sections or decay rates fitted by observations

A partial cross section and a decay rate to produce axions are expressed by

\[
\langle \sigma_v \rangle_{aZ,ah} = c_7 \frac{\langle \sigma_v \rangle_{\gamma\gamma} / P_{\gamma\gamma}^{\text{mean}}}{\langle \Gamma \rangle_{\gamma}} ,
\]

\[
\langle \Gamma \rangle_{a} = \langle \Gamma \rangle_{\gamma}/P_{\gamma\gamma}^{\text{mean}},
\]

where \( \langle \sigma_v \rangle_{\gamma\gamma} \) and \( \langle \Gamma \rangle_{\gamma} \) denote the cross section and the decay rate of the \( \gamma \)-ray productions, which fits the Fermi measurements. \( c_7 \) means the number of axions in the final state defined to be \( c_7 = 1 \) for \( \langle \sigma_v \rangle_{aa} \) and \( c_7 = 1/2 \) for \( \langle \sigma_v \rangle_{aZ(ah)} \). Here \( P_{\gamma\gamma}^{\text{mean}} \) is a mean value of the conversion probability averaged for deuterons and continuum components of \( \gamma \)-rays. We discuss this issue later.

Next we discuss possible annihilation processes of the DM which produce axions, e.g. through,

- \( \psi_{\text{DM}} \rightarrow a\psi_{\text{DM}}' \) (s-channel and/or t-channel)
- \( \psi_{\text{DM}} \rightarrow aZ \) (s-channel and/or t-channel)
- \( \psi_{\text{DM}} \rightarrow ah \) (s-channel and/or t-channel)

We refer to these partial cross sections as \( \langle \sigma_v \rangle_{aa} \), \( \langle \sigma_v \rangle_{aZ} \), and \( \langle \sigma_v \rangle_{ah} \), respectively. In a similar fashion to the decay modes, the Z boson or the Higgs boson in the final states produces antiprotons, anti-deuterons and continuum components of \( \gamma \)-rays, which are severely constrained by observations. In the next subsection, we discuss observationally-fitted decay rates and partial annihilation cross sections which agree with the \( \gamma \)-ray lines through the axion-production processes.

FIG. 2: Conversion probability from an axion to a photon under the magnetic field. \( B = 1 \mu \text{G}, \) and \( 10 \mu \text{G}). The width of each band represents ambiguities of the energy of an observed photon and the distance from the Galactic center to the solar system. From the top to the bottom, we have changed the coupling constant to be \( g_{\gamma\gamma} = 8.8 \times 10^{-11} \text{GeV}^{-1}, \) \( 1 \times 10^{-11} \text{GeV}^{-1}, \) and \( 1 \times 10^{-12} \text{GeV}^{-1}, \) respectively.

FIG. 3: Conversion probabilities as a function of \( E_{\gamma}(\text{GeV}) \). Numbers in the round bracket written on each line denote \( (m_a, \text{eV}), g_{\gamma\gamma}(\text{GeV}^{-1}), B(\mu \text{G})\).
TABLE I: Observationally-fitted mean values of conversion probabilities \(P^\text{mean}_{a\gamma}\).

| Coupling constant \(g_{\gamma}\) magnetic field \(B\) | \(P^\text{mean}_{a\gamma}\) for \(m_a < \tilde{m}_a\) | \(P^\text{mean}_{a\gamma}\) for \(m_a \gtrsim \tilde{m}_a\) |
|---------------------------------|-----------------|-----------------|
| \(8.8 \times 10^{-11}\) 1\(\mu\)G | \(3.71 \times 10^{-1}\) | \(3.71 \times 10^{-1}(m_a/3.70 \times 10^{-8}\text{eV})^{-4}\) |
| \(8.8 \times 10^{-11}\) 10\(\mu\)G | \(5.00 \times 10^{-1}\) | \(5.00 \times 10^{-1}(m_a/1.27 \times 10^{-7}\text{eV})^{-4}\) |
| \(1 \times 10^{-11}\) 1\(\mu\)G | \(1.72 \times 10^{-1}\) | \(1.72 \times 10^{-1}(m_a/1.73 \times 10^{-8}\text{eV})^{-4}\) |
| \(1 \times 10^{-11}\) 10\(\mu\)G | \(8.02 \times 10^{-1}\) | \(8.02 \times 10^{-1}(m_a/3.63 \times 10^{-8}\text{eV})^{-4}\) |
| \(1 \times 10^{-12}\) 1\(\mu\)G | \(1.88 \times 10^{-3}\) | \(1.88 \times 10^{-3}(m_a/1.70 \times 10^{-8}\text{eV})^{-4}\) |
| \(1 \times 10^{-12}\) 10\(\mu\)G | \(1.72 \times 10^{-1}\) | \(1.72 \times 10^{-1}(m_a/3.63 \times 10^{-8}\text{eV})^{-4}\) |

As we have shown in the previous subsection, for \(m_a < \tilde{m}_a\), \(P^\text{mean}_{a\gamma}\) is approximately constant \(P^\text{mean}_{a\gamma} = \tilde{P}^\text{mean}_{a\gamma}\). On the other hand, for \(m_a \gtrsim \tilde{m}_a\), the envelope of the oscillating \(P^\gamma\) behaves as \(\propto m_a^{-4}\). Then the probability is fitted to be

\[P^\text{mean}_{a\gamma} = \tilde{P}^\text{mean}_{a\gamma} (m_a/\tilde{m}_a)^{-4} \quad (\text{For } m_a \gtrsim \tilde{m}_a). \tag{10}\]

For \(m_a \gtrsim \tilde{m}_a\), each \(\tilde{P}^\text{mean}_{a\gamma}\) and \(\tilde{m}_a\) are chosen for numerical results with Eq. (7) to be nicely fitted by the approximate formula (Eq. (10)). Each values of \(P^\text{mean}_{a\gamma}\) and \(\tilde{m}_a\) are shown in fourth column of Table I as coefficients of \((m_a/\tilde{m}_a)^{-4}\) and the denominator in parentheses.
be of the order of $\sim \mathcal{O}(10^{-2})$ or smaller. The PAMELA satellite measurement of the antiproton to proton flux ratio puts a mild constraint on the partial modes into the $Z$ boson to be $\langle \sigma v \rangle_Z \lesssim 10^{-25}\text{cm}^3\text{s}^{-1}$ \cite{26}. Severer constraints have been also obtained by the observation of the continuum $\gamma$-rays $\langle \sigma v \rangle_Z \lesssim 10^{-25}\text{cm}^3\text{s}^{-1}$ \cite{26,27}. This may mean $\langle \sigma v \rangle_{aa} \lesssim 10^{-23}\text{cm}^3\text{s}^{-1}$, which agrees with any known limits. Furthermore a constraint on the other channel for both an axion and a $Z(h)$ emission $\psi_{\text{DM}}\psi_{\text{DM}} \rightarrow aZ(h)$ is severer, $\langle \sigma v \rangle_{aa} \lesssim 10^{-23}\text{cm}^3\text{s}^{-1}$.

Figure 5 shows fitted decay rates of the DM. Similar constraints on decay modes such as $\psi_{\text{DM}} \rightarrow a\psi_{\text{DM}} Z$, $\psi_{\text{DM}} \rightarrow a\psi_{\text{DM}} h$, or $\psi_{\text{DM}} \rightarrow a\psi_{\text{DM}} f f$ have been also obtained from the antiproton and continuum $\gamma$-ray measurements, which is $1/\langle \Gamma \rangle_{aZ(h)} \gtrsim 10^{26-27}\text{s}$ \cite{26,27,28}. Thus the obtained constraint on the partial lifetime into axions could become $1/\langle \Gamma \rangle_a \gtrsim 10^{24-25}\text{s}$.

If the DM can decay into axions through a gravitational interaction, there exist no constraint on the decay width. We will also discuss this possibility to build models in the next section.

III. MODELS

In this section, we discuss the models that can produce monochromatic axion with energy 130GeV from decay of a heavy long lived particle as the DM in our universe or annihilation of the DM.

A. Axion production from decay of the long lived DM

As we have seen in the Fig. 4, a preferred lifetime of the parent dark matter is around $10^{25}\text{sec}$ to $10^{26}\text{sec}$. In reference \cite{26} it is pointed out that such long lifetime can be achieved for the process suppressed by $1/M_{\text{GUT}}^4$, namely the process mediated by the GUT scale suppressed dimension six operators. If such a suppressed interaction can produce axions, our scenario can be realized. On the other hand, a dimension five GUT scale suppressed interaction leads the much shorter lifetime, $\mathcal{O}(1\text{sec})$.

One of the natural class of model predicting DM is supersymmetry (SUSY), and it is worth to consider the possibility to realize our scenario in the SUSY model. The LSP with conserved R parity is stable. SUSY models sometimes predict a long lived particle that can decay into LSP. Moreover, the SUSY should be extended to gravity sector. The superpartner of graviton, gravitino $\tilde{\psi}$ interacts with all particles with the interaction suppressed by $1/M_{\text{pl}}$. Here $M_{\text{pl}} = 2.44 \times 10^{18}\text{GeV}$ is the reduced Planck mass. Another suppressed coupling of this theory is axino($\tilde{a}$)-gaugino-$\gamma(Z)$ coupling, whose suppression factor is $g_{\gamma \tilde{a}}$. It should be of the order of $10^{-10}$ to $10^{-12}\text{GeV}^{-1}$ in our scenario.
Both of the interactions above are five dimensional operators and do not induce very long lived particles of our interest directly. Therefore we introduce two axion and axino pairs \((a_1, \tilde{a}_1)\) and \((a_2, \tilde{a}_2)\). The decay \(\tilde{a}_2 \to a_1 a_2\tilde{a}_1\) can be mediated by gravitino (Fig. 3). It is suppressed by \(1/M_{pl}^4\) and maybe long enough. The axino energy can be monochromatic if the mass difference between \(\tilde{a}_2\) and gravitino is small, so that \(a_2\) has low energy and hence kinematics of \(\psi_G^i\) (virtual gravitino) \(\to a_1\tilde{a}_1\) is approximately two body. In that case however, we also have to worry about \(\tilde{a}_2 \to 2\gamma\tilde{a}_1\) being mediated by a gaugino exchange, which is proportional to \((g_{\gamma a_2\gamma})^2\). The suppression of the gaugino exchange decay can be achieved if \(g_{a_2\gamma}\) is suppressed. This can be achieved if \(a_2\) belongs to a PQ sector that does not couple to SM gauge boson directly. The decay rate of \(\tilde{a}_2 \to a_1 a_2\) can be expressed as

\[
\Gamma(\tilde{a}_2 \to a_1 + a_2) \approx \left(\frac{1}{\sqrt{2}M_{pl}}\right)^4 \left(m_{\tilde{a}_2} + m_{\tilde{G}}\right)^2 \left(m_{\tilde{a}_2} - m_{\tilde{a}_1}\right)^7 \\
\simeq 3.4 \times 10^{-27} [\text{s}^{-1}] \left(\frac{1\text{MeV}}{m_{\tilde{G}} - m_{\tilde{a}_2}}\right)^2 \left(\frac{m_{\tilde{a}_2} - m_{\tilde{a}_1}}{260\text{GeV}}\right)^7,
\]

Therefore the scenario requires fine turning among the parameters.

### B. Axion production from annihilation

For the second example, we assume that a neutralino \(\tilde{\chi}^0\) is the LSP, and it is the dark matter. Under the R-parity conservation, axions are produced by the neutralino annihilation, \(\tilde{\chi}^0\tilde{\chi}^0 \to aa\) via saxion s-channel exchange. The annihilation process \(\tilde{\chi}^0\tilde{\chi}^0 \to aa\) provides the largest cross section when \(m_{\tilde{a}}^2 \simeq q^2\), i.e., \(m_a \simeq 2m_{\tilde{\chi}^0}\), and hence the width part dominates over the part of momentum transfer in the saxion propagator,

\[
\sigma v(\tilde{\chi}^0\tilde{\chi}^0 \to aa) = \left(\frac{\alpha_k C_k}{4\pi F_a}\right)^2 \left(\frac{1}{\sqrt{2}F_a}\right)^2 \times \frac{1}{(q^2 - m_{\tilde{a}}^2)^2 + \left(m_a \Gamma_a\right)^2 m_{\tilde{\chi}^0}^2} m_{\chi^0} \left(\frac{130\text{GeV}}{10^{-2}}\right)^2 \left(\frac{1}{10^{-2}}\right)^2,
\]

where \(F_a\) is the axion decay constant, \(\alpha_k = g_k^2/4\pi\) (\(g_k\) is the coupling constant for \(U(1)_Y\) or \(SU(2)_L\) gauge group). The constant \(C_k\) is the model-dependent parameter with \(O(1)\) or smaller. The interaction of neutralinos and the saxion may be modified after SUSY breaking. The constant \(C_k\) also includes this uncertainty. Here we assume that the dominant decay channel of the saxion is \(a \to ss\), and then the decay width is \(\Gamma_a \simeq m_a^2/2F_a^2 \simeq 4m_{\tilde{\chi}^0}^3/F_a^2\).

As is shown in Fig. 4 the cross section for the axion production is required to be larger than \(10^{-27}\text{cm}^3\text{s}^{-1}\). For reproducing the 130 GeV \(\gamma\)-rays, therefore, this type of SUSY models needs a boost factor of \(O(1)\) in addition to the relation \(m_a \simeq 2m_{\tilde{\chi}^0}\).

Actually we need more precise studies of decay or annihilation processes, and should include information of DM profiles of the Galaxy. Other possible decay or annihilation processes of axion productions should be also studied extensively. We will discuss these issues in a separate publication in detail [52].

### IV. SUMMARY AND DISCUSSION

We have studied a possible conversion mechanism from an axion to a photon under the Galactic magnetic field, which can fit the 130 GeV \(\gamma\)-ray line observed at the Galactic center. We have found that the observed narrow-line spectrum feature can be produced by this mechanism with the axion mass \(m_a \lesssim 10^{-6}\) eV, the magnetic field in the Milky Way Galaxy \(B \sim 1 - 10\mu\) G, and the axion-photon coupling constant \(g_{a\gamma} \lesssim 8.8 \times 10^{-11}\text{GeV}^{-1}\).

Here we have assumed that mono-energetic axions can be produced by decays or annihilations of DM particles. We have introduced the corresponding examples based on particle physics models. The former is the decaying axino, and the latter is the annihilating neutralino DM scenarios, respectively. Requiring fine turning of parameters both scenarios can explain energetic axions with their narrow-line spectra.

This mechanism has various advantages. First, it potentially reduces continuum \(\gamma\)-ray flux and the anti-proton flux without complicated gimmicks. In our scenario, axions are produced by decays or annihilations of DM at a tree-level while interactions between the DM and charged particles are invariably suppressed by higher order couplings. Second, this scenario is testable by a number of future experiments and observations. The required effective coupling between the axion and the photon is smaller by one order of magnitude than the current bound by the CAST experiment [70]. Next generation axion search experiments are planned to reach the sensitivity in the near future [53, 54]. Future \(\gamma\)-ray observations such as H.E.S.S.II, Cherenkov Telescope Array (CTA) or GAMMA-400 will also observe the 130 GeV lines with much better sensitivities and discern a model from others [55, 56]. We can discriminate models by using line shapes and the emission profile (morphology) of the spatial distribution. Third, this scenario could be sensitive not only to the nature of the DM but also to models behind the axion. These models occasionally predict an energy scale governing the axion properties to be high, beyond the energy scale of collider experiments [57, 58]. Combining the \(\gamma\)-ray line signals with the future experimental results for the axion thereby could shed...
light on the energy scale, interactions with axions and the DM, and so on. Thus the application of the axion-photon conversion potentially makes it possible to account for the observed $\gamma$-ray lines, and is worth researching and discussing its related issues.

On the other hand, several points have to be carefully considered to make a reliable analysis of the spectrum using future observations. First, we might have to include effects of reconversions from a photon to an axion, which may have simultaneously reduced photon fluxes. Second an oscillation behavior of the conversion probability should be important. In this paper we have focused on the decay or the annihilation of the DM to produce the narrow-line spectrum. However, the conversion probability depends on the axion energy. Considering this oscillation dependence, even a broader spectrum of axion could have given the appropriate excess at 130 GeV (see Fig. 3). Note that the energy resolution of $\gamma$-ray is not good, so that the observed $\gamma$-rays excess at around 130GeV can be consistent with the spectrum due to the oscillation. We will discuss these issues in detail in a separate publication [82].

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