Gamma-ray spectral modulations induced by photon-ALP-dark photon oscillations

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Recently it has been noticed that the Fermi-LAT data of gamma-rays from some galactic pulsars and supernova remnants reveal spectral modulations that might be explained by the conversion of photons to ALPs (axion-like particles) induced by the conventional ALP coupling to photon in the presence of galactic magnetic fields. However the corresponding ALP mass and coupling are in a severe tension with the observational constraints from CAST, SN1987A, and other gamma-ray observations. Motivated by this, we examine an alternative possibility that those spectral modulations are explained by other type of ALP coupling involving both the ordinary photon and a massless dark photon, when nonzero background dark photon gauge fields are assumed. We find that our scheme results in oscillations among the photon, ALP, and dark photon, which can explain the gamma-ray spectral modulations of galactic pulsars or supernova remnants, while satisfying the known observational constraints.

I. INTRODUCTION

Light axion-like particles (ALPs) and hidden $U(1)$ gauge bosons have been widely discussed as well-motivated candidates for physics beyond the Standard Model of particle physics \[1\]. An appealing feature of those particles is that their lightness is protected from unknown UV physics by symmetry. They are also a good candidate for dark matter, and can result in a variety of other astrophysical and cosmological consequences. One of such phenomena associated with ALP is the photon to ALP conversions \[2\] in the presence of background magnetic fields, which may cause spectral modulations of X-rays \[3–6\] or gamma-rays, from pointlike sources, spectral distortion of CMB \[12–15\], change of the cosmic rays \[3–6\] or gamma-rays \[7–11\] from pointlike sources, ALP conversions \[2\] in the presence of background magnetic fields, which are required for many such phenomena associated with ALP is the photon to ALP conversion \[17–19\].

Recently it has been noticed that the Fermi-LAT data of gamma-rays from some galactic pulsars or supernova remnants \[8\] reveal an intriguing spectral modulation (or irregularity) which might be explained by the photon to ALP conversions caused by the coupling\[1\]

$$\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} = -g_{a\gamma\gamma}a\tilde{E} \cdot \tilde{B}$$ \quad (1)$$

in the presence of galactic magnetic fields, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the gauge field strength of the ordinary $U(1)_{\text{em}}$ gauge field $A_\mu$, and $\tilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is its dual. However the ALP mass $m_a \simeq \text{few} \times 10^{-9} \text{eV}$ and the coupling $g_{a\gamma\gamma} \simeq \text{few} \times 10^{-10} \text{GeV}^{-1}$, which are required to explain those modulations, are in a severe tension with the CAST bound $g_{a\gamma\gamma} < 6.6 \times 10^{-11} \text{GeV}^{-1}$ \[35\], as well as with the absence of gamma-ray bursts associated with SN1987A \[36\] and the Fermi-LAT data of gamma-rays from the galactic nucleus NGC 1275 in the center of the Perseus cluster \[9–10\].

Motivated by this observation, in this paper we examine an alternative scenario to explain those gamma-ray spectral modulations by means of the photon-ALP-dark photon oscillations caused by the ALP coupling \[17–18\]

$$\frac{1}{2}g_{a\gamma\gamma}aX_{\mu\nu}\tilde{F}^{\mu\nu} = -g_{a\gamma\gamma}a(\tilde{E} \cdot \tilde{B}_X + \tilde{B} \cdot \tilde{E}_X)$$ \quad (2)$$

in the presence of background $\langle B_X \rangle$ and/or $\langle E_X \rangle$, where $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu = \langle \tilde{E}_X, \tilde{B}_X \rangle$ is the gauge field strength of a massless dark photon gauge field $X_\mu$. Like the ordinary ALP coupling \[1\], the above ALP coupling involving both the ordinary photon and dark photon generically exists once a dark photon field is introduced in the theory. As we will see, this coupling induces the conversion of gamma-rays to ALPs or dark photons, which can successfully explain the gamma-ray spectral modulations noticed in \[17\] and \[8\] for certain range of ALP parameters and background dark photon gauge fields, including\[3\]

$$m_a = O(10^{-9}) \text{eV},$$

$$g_{a\gamma\gamma} = O(10^{-11} - 10^{-10}) \text{GeV}^{-1},$$

$$\langle B_X \rangle = O(1) \mu\text{G}.$$ \quad (3)$$

As we will show later, contrary to the scheme based on the ordinary ALP coupling $g_{a\gamma\gamma}$, this scenario can be compatible with all the available constraints on $g_{a\gamma\gamma}'$.

A key ingredient of this scenario is the existence of a background dark photon gauge fields $\langle B_X \rangle$ and/or $\langle E_X \rangle$ with a strength comparable to (or even bigger than) the galactic magnetic fields $\sim 1 \mu\text{G}$ and a coherent length longer than the typical galactic size $\sim 1 \text{kpc}$. If they were generated in the early universe, such background dark photon gauge fields may result in a dangerous distortion
of CMB due to the resonant conversion of CMB photons to axions, which would occur when the effective photon mass \( m_a(t) \) in the early universe crosses the ALP mass \( m_a \). To avoid this problem, we need to generate the background dark photon gauge fields at a late time with \( m_a(t) < m_a \). In this paper, we will introduce an explicit model \([16, 24]\) for such a late generation of the background dark photon gauge fields, involving an additional ultra-light ALP \( \phi \) with \( m_\phi \lesssim 10^{-27} \text{ eV} \), whose late coherent oscillations cause a tachyonic instability of the dark photon gauge fields and amplify the vacuum fluctuations to the desired background fields \( \langle B_X \rangle \sim \langle E_X \rangle \gtrsim 1 \mu \text{G} \).

This paper is organized as follows. In Sec. \( \text{I} \), we discuss the photon-ALP-dark photon oscillations induced by the coupling \( [2] \) in the presence of background \( \langle B_X \rangle \) and/or \( \langle E_X \rangle \). In Sec. \( \text{II} \), we examine if the gamma-ray spectral modulations noticed in \([7] \) and \([8] \) can be explained by the conversion of gamma-rays to ALPs or dark photons, which results from the photon-ALP-dark photon oscillations. In Sec. \( \text{IV} \), we discuss the observational constraints on the ALP coupling \( [2] \) and examine if our scenario can be compatible with those constraints. Obviously the ALP coupling \( g_{\gamma \gamma' \gamma} \) is free from the bound from helioscope axion search experiments such as CAST. Yet it should satisfy the bound from stellar evolution \([17] \), as well as another bound from the non-observation of gamma-ray bursts associated with SN1987A \([30] \). We also need to generate the background dark photon gauge fields at a late time with \( m_a(t) < m_a \) to avoid a dangerous distortion of CMB \([13, 15] \). In the later part of Sec \( \text{V} \), we present an explicit model for such a late generation of the background dark photon gauge fields. Sec. \( \text{VI} \) is the conclusion.

II. PHOTON-ALP-DARK PHOTON OSCILLATIONS

Our scheme is based on a model involving a light ALP and also a massless hidden \( U(1)_X \) gauge boson \( X_\mu \), which is dubbed the dark photon in this paper \([1] \). We assume that there is no light \( U(1)_X \)-charged matter fields. Here we are interested in the photon-ALP-dark photon oscillations induced by the ALP coupling \([37, 38] \)

\[
\frac{1}{2} g_{\gamma \gamma' \gamma} a X_{\mu \nu} F^\mu \nu = - g_{\gamma \gamma' \gamma} a \left( \vec{E} \cdot \vec{B}_X + \vec{B} \cdot \vec{E}_X \right) \quad (4)
\]

in the presence of nonzero background dark photon gauge fields, \( \langle E_X \rangle \) and/or \( \langle B_X \rangle \), as well as an ordinary background magnetic field \( \langle B \rangle \). Since there is no \( U(1)_X \)-charged matter, \( \langle E_X \rangle \) can be non-vanishing and then the equations of motion of \( X_\mu \) suggest \( \langle E_X \rangle \sim \langle B_X \rangle \) \([20] \).

Generically there can be other ALP couplings such as \( g_{\gamma \gamma' \gamma} a F \vec{F} \) and \( g_{\gamma \gamma' \gamma} a X \vec{X} \). For simplicity, here we will assume that \( g_{\gamma \gamma' \gamma} \) dominates over \( g_{\gamma \gamma' \gamma} \) and \( g_{\gamma \gamma' \gamma} \) as much as we need. Note that in many cases the ALP couplings to gauge fields are quantized as they are generated by the loops of fermions carrying quantized charges of the \( U(1)_{\text{PQ}} \), \( U(1)_{\text{em}} \) and \( U(1)_X \), where \( U(1)_{\text{PQ}} \) denotes the (spontaneously broken) global \( U(1)_{\text{PQ}} \) associated with the ALP field “a”. In those cases, one can arrange the relevant PQ and gauge charges appropriately to get the desired pattern of ALP couplings such as \( |g_{\gamma \gamma' \gamma}| \gtrsim |g_{\gamma \gamma' \gamma}| \). Alternatively, one may use the clockwork mechanism \([39, 42] \) to generate such pattern of ALP couplings as was done in \([39, 45] \) to get an axion-photon coupling much stronger than the axion-photon coupling.

To examine the oscillations among the photon, dark photon and ALP, let us choose the temporal gauge \( A_0 = 0 \). Then the equations of motion describing the propagation of small field fluctuations of \( \vec{A} \), \( \vec{X} \) and \( a \) in the background \( \langle B \rangle, \langle B_X \rangle \) and \( \langle E_X \rangle \) are given by

\[
\begin{align*}
\partial_\mu \partial^\mu \vec{A} &= g_{\gamma \gamma' \gamma} \left( \langle B_X \rangle \partial_\mu a - \langle E_X \rangle \times \nabla a \right), \\
\partial_\mu \partial^\mu \vec{X} &= g_{\gamma \gamma' \gamma} \langle \vec{B} \rangle \partial_\mu a, \\
\partial_\mu \partial^\mu a + m_a^2 a &= - g_{\gamma \gamma' \gamma} \left( \langle \vec{B} \rangle \cdot \partial_\nu \vec{X} + \langle \vec{B}_X \rangle \cdot \partial_\nu \vec{A} \right) - \langle \vec{E}_X \rangle \cdot \nabla \times \vec{A}.
\end{align*}
\quad (5)
\]

From the above wave equations, we note that the following transverse background fields induce oscillations among the photon, dark photon and ALP:

\[
\begin{align*}
\vec{B}_T &= \langle \vec{B} \rangle - \hat{k} \langle \vec{B}_X \rangle, \\
\vec{B}_{XT} &= \langle \vec{B}_X \rangle - \hat{k} \langle \vec{E}_X \rangle - \hat{k} \times \langle \vec{E}_X \rangle, \quad (6)
\end{align*}
\]

where \( \hat{k} \) is the momentum of the propagating particles and \( \hat{k} = k / |k| \). In the relativistic limit, the corresponding propagation equation is well approximated by \([2] \)

\[
\left[ w + i \partial_\mu - \mathcal{M} \right] \begin{pmatrix} A \parallel \\ X \parallel \\ a \end{pmatrix} = 0,
\quad (7)
\]

where \( \omega = |k| \) and \( z \) is the spatial coordinate along the direction \( \hat{k} \). Here \( A_\parallel \) and \( X_\parallel \) denote the polarization of \( \vec{A} \) and \( \vec{X} \) in the direction of \( \vec{B}_{XT} \) and \( \vec{B}_T \), respectively:

\[
A_\parallel = \frac{\vec{B}_{XT} \cdot \vec{A}}{B_{XT}}, \quad X_\parallel = \frac{\vec{B}_T \cdot \vec{X}}{B_T}, \quad (8)
\]

and

\[
\mathcal{M} = \begin{pmatrix}
\omega^2 z & 0 & -g_{\gamma \gamma' \gamma} B_{XT} \\
0 & 0 & g_{\gamma \gamma' \gamma} B_T \\
-g_{\gamma \gamma' \gamma} B_{XT} & -g_{\gamma \gamma' \gamma} B_T & \frac{m_a^2}{2 \omega}
\end{pmatrix}, \quad (9)
\]

where \( \omega^2 = 4 \pi n_e / m_e \) is the plasma frequency in a medium with the electron number density \( n_e \).

Here we are mostly interested in the conversion of initial unpolarized photon to ALP or dark photon in the limit when the plasma frequency is negligible:

\[
\omega_{pl}^2 \ll \min \left( m_a^2, g_{\gamma \gamma' \gamma} \omega \sqrt{B_{XT}^2 + B_T^2} \right), \quad (10)
\]
which turns out to be the case for our scenario to explain the gamma-ray spectral modulations noticed in \cite{7} and \cite{8}. To get some insights on the photon-ALP-dark photon oscillations, let us consider a simple situation that all background fields have a coherent length which is large enough to treat them as constants over the photon propagation distance \(d\). It is then straightforward to find that the conversion probabilities in such case are given by

\[
P_{\gamma\rightarrow a} = P_{a\rightarrow \gamma} = \left( \frac{B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \right) \left( \frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \frac{\Delta_{\text{osc}} d}{2},
\]

\[
P_{\gamma'\rightarrow \gamma} = P_{\gamma'\rightarrow \gamma'} = \left( \frac{2B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \right) \left( 1 - \cos \frac{\Delta d}{2} \cos \frac{\Delta_{\text{osc}} d}{2} \right)
- \frac{\omega_c}{\sqrt{\omega^2 + \omega_c^2}} \sin \frac{\Delta d}{2} \sin \frac{\Delta_{\text{osc}} d}{2}
- \frac{\omega^2}{2(\omega^2 + \omega_c^2)} \sin^2 \frac{\Delta_{\text{osc}} d}{2},
\]

(11)

where \(d\) is the propagation distance, and

\[
\omega_c = \frac{m_a^2}{2g_{\gamma\gamma} B_{\text{eff}}}, \quad \Delta_d = g_{\gamma\gamma} B_{\text{eff}} \frac{\omega_c}{\omega}, \quad \Delta_{\text{osc}} = g_{\gamma\gamma} B_{\text{eff}} \sqrt{1 + \left( \frac{\omega_c}{\omega} \right)^2}
\]

(12)

for

\[
B_{\text{eff}} \equiv \sqrt{B_{\gamma\gamma}^2 + B_{\gamma T}^2}.
\]

(13)

From the above results, we find the following photon survival probability for the photon-ALP-dark photon oscillations induced by the ALP coupling \(g_{\gamma\gamma}\):

\[
(P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'} = \left( \frac{B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \right) \left( \frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \frac{\Delta_{\text{osc}} d}{2} - \left( \frac{B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \right)^2 \left( \frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \frac{\Delta_{\text{osc}} d}{2} + 2 \left( \frac{B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \right)^2 \left( \cos \frac{\Delta d}{2} \cos \frac{\Delta_{\text{osc}} d}{2} \right) + \frac{\omega_c}{\sqrt{\omega^2 + \omega_c^2}} \sin \frac{\Delta d}{2} \sin \frac{\Delta_{\text{osc}} d}{2}.
\]

(14)

For later discussion of the possibility that the ALP coupling \(g_{\gamma\gamma}'\) explains the gamma ray modulations noticed in \cite{7} and \cite{8}, let us compare the photon depletion caused by \(g_{\gamma\gamma}\) in background \(U(1)_X\) gauge fields with the photon depletion by \(g_{\gamma\gamma}\) in ordinary magnetic fields. As is well known \cite{2}, the photon survival probability for the photon-ALP oscillations caused by \(g_{\gamma\gamma}\) in ordinary magnetic fields is given by

\[
(P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}} = 1 - \left( \frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \frac{\Delta_{\text{osc}} d}{2},
\]

(15)

where

\[
\tilde{\omega}_c = \frac{m_a^2}{2g_{\gamma\gamma} B_T}, \quad \tilde{\Delta}_{\text{osc}} = g_{\gamma\gamma} B_T \sqrt{1 + \left( \frac{\tilde{\omega}_c}{\omega} \right)^2}.
\]

(16)

There are two key spectral features of the above photon survival probability. The first is the step-down of \(P_{\gamma\rightarrow \gamma}\) at \(\omega \sim \tilde{\omega}_c\), which represents the transition from the small mixing limit \(\omega \ll \tilde{\omega}_c\) to the large mixing limit \(\omega \gg \tilde{\omega}_c\). The size of step-down is given by

\[
\Delta P \equiv P_{\gamma\rightarrow \gamma} (\omega \ll \tilde{\omega}_c) - P_{\gamma\rightarrow \gamma} (\omega \gg \tilde{\omega}_c)
= \sin^2 \left( \frac{g_{\gamma\gamma} B_T d}{2} \right),
\]

(17)

which can be significant when \(g_{\gamma\gamma} B_T d \gtrsim O(1)\). Such significant step-down of the photon survival probability may result in an observable spectral irregularity (or modulation) of the photon intensity around \(\omega \sim \tilde{\omega}_c\). An additional feature of \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}}\) is the oscillatory behavior due to \(\sin^2(\Delta_{\text{osc}} d/2)\), which has an width \(\Delta \omega = O(\pi \omega_c / g_{\gamma\gamma} B_T d)\) and becomes appreciable right before the step-down. In most cases, such oscillatory behavior is more difficult to be detected, and the spectral modulations (irregularities) noticed in \cite{7} and \cite{8} correspond to a step-down of the gamma-ray intensity around \(\omega = O(1)\) GeV.

The photon survival probability \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'}\) of (14) appears to be significantly more complicated than \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}}\) of (15). Yet, as long as \(B_{\gamma T}\) is not negligible compared to \(B_T\), it reveals a similar step-down behavior at \(\omega \sim \omega_c\), as well as a similar oscillatory feature with an width \(\Delta \omega = O(\pi \omega_c / g_{\gamma\gamma} B_T d)\). To see this, let us first consider the case \(B_{\gamma T} \gg B_T\). In such case, the dark photon is decoupled and the resulting photon-ALP oscillation yields

\[
(P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'} \approx 1 - \left( \frac{\omega^2}{\omega^2 + \omega_c^2} \right) \sin^2 \left( \frac{g_{\gamma\gamma} B_{\text{eff}} \omega}{2} \sqrt{1 + \left( \frac{\omega_c}{\omega} \right)^2} \right)
\]

(18)

for \(B_T \ll B_{\gamma T}\). Obviously the above \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}}\) mimics \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'}\) with the simple correspondence

\[
g_{\gamma\gamma} B_{\gamma T} \rightarrow g_{\gamma\gamma} B_T.
\]

(19)

Even when \(B_{\gamma T} \lesssim B_T\), if it is non-negligible, there can be a significant step-down of \((P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'}\) at \(\omega \sim \omega_c\). From (14), one finds

\[
(P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'} (\omega \ll \omega_c)
\approx 1 - \frac{4B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \sin^2 \left( \frac{g_{\gamma\gamma} B_{\text{eff}} \omega}{8} \right)
\]

(20)

and

\[
(P_{\gamma\rightarrow \gamma})_{g_{\gamma\gamma}'} (\omega \gg \omega_c)
\approx 1 - \frac{B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \sin^2 \left( \frac{g_{\gamma\gamma} B_{\text{eff}} \omega}{2} \right)
- \frac{2B_{a\gamma}^2}{B_{\gamma\gamma}^2 + B_{\gamma T}^2} \left( 1 - \cos \left( \frac{g_{\gamma\gamma} B_{\text{eff}} \omega}{2} \right) \right)
\times \cos \left( \frac{g_{\gamma\gamma} B_{\text{eff}} \omega}{2} \right).
\]

(21)
When $g_{a\gamma\gamma} B_{\text{eff}} d = \mathcal{O}(1)$, which is the case relevant for us, this results in the following step-down of the photon survival probability:

$$\Delta P = P_{\gamma \rightarrow \gamma}(\omega < \omega_c) - P_{\gamma \rightarrow \gamma}(\omega > \omega_c) \simeq \frac{4B_{XT}^2 B_T^2}{(B_{XT}^2 + B_T^2)^2} \sin^2 \left( \frac{g_{a\gamma\gamma} B_{\text{eff}} d}{4} \right) + \frac{B_{XT}^2}{(B_{XT}^2 + B_T^2)^2} \sin^2 \left( \frac{g_{a\gamma\gamma} B_{\text{eff}} d}{2} \right).$$

This step-down of the photon survival probability can be sizable enough to yield an observational consequence if $B_{XT}$ is comparable to $B_T$.

The discussions above indicate that the results of [7] and [8], which are based on the ALP coupling $g_{a\gamma\gamma}$, can be reproduced also by $g_{a\gamma\gamma'}$ for appropriate range of ALP parameters if the background dark photon gauge fields $E_X$ and/or $B_X$ are comparable to or even larger than the galactic magnetic fields $B \sim 1 \mu G$. In the next section, we examine this possibility in more detail for specific gamma-ray sources, the galactic pulsar J2021+3651 and the supernova remnant IC443.

### III. GAMMA-RAY SPECTRAL MODULATIONS

In [7] and [8], Fermi-LAT data of gamma-rays from some galactic pulsars with a distance $d \approx 5 \sim 10$ kpc and supernova remnants with $d \approx 1 \sim 5$ kpc were examined to see if there is any irregularity in the spectrum. It was then noticed that the data indicates spectral modulations at $\omega \sim 1$ GeV, which might be explained by the photon-ALP oscillations induced by an ALP coupling $g_{a\gamma\gamma} \sim \text{few} \times 10^{-10} \text{GeV}^{-1}$ in the presence of galactic magnetic fields $B \sim 1 \mu G$ for ALP mass $m_a \sim \text{few} \times 10^{-9} \text{eV}$. However these ALP parameters are in conflict with the bound from CAST [35], as well as with the non-observation of gamma-ray bursts associated with SN1987A [36]. This motivates us an alternative scenario that those spectral modulations are explained by the photon-ALP-dark photon oscillations induced by $g_{a\gamma\gamma'}$, which were discussed in the previous section.

In the previous section, the conversion probabilities for the photon-ALP-dark photon oscillations have been derived when the background gauge fields are assumed to be constant. In the following, we take a more elaborate approach taking into account the spacial variation of galactic magnetic fields along the line of sight towards the gamma-ray sources, and solve the propagation equation (7) numerically. Specifically, we adopt the latest model for galactic profile of the magnetic field, i.e. the Jansson and Farrar model [46], which was adopted also in [7] and [8]. As for the background dark photon gauge field component $B_{XT}$, we simply assume that it is homogeneous enough to be treated as constant over the galactic distance scales of $\mathcal{O}(1)$ kpc.

In Fig. 1 we depict the intensities of photon (red), dark photon (magenta), and ALP (blue) along the line of sight towards PSR J2021+3651 for the ALP parameters and background $B_{XT}$ given in (23) and the photon energy $\omega = 3$ GeV.

![Fig. 1. Photon (red), dark photon (magenta), and ALP (blue) intensity along the line of sight towards PSR J2021+3651 for the ALP parameters and background $B_{XT}$](image)

Since the distance $d \sim 1.5$ kpc from IC443 is significantly shorter than the distance $d \sim 10$ kpc from SN1987A, this result is expected to be observable from the change in the relative intensity of the photon, dark photon and ALP components.

$^1$ Indeed our mechanism to generate the background dark photon gauge fields, which will be presented in the later part of the next section, yields a coherent length $\lambda \gg$ kpc of the produced $B_{XT}$, justifying this assumption.
J2021+3651, the best model parameters \((m_a, g_{a\gamma\gamma'}, B_{XT})\) in our case) to explain the spectral irregularity of IC443 is generically different from the ones for J2021+3651. As the full \(\chi^2\)-analysis to identify the best model parameters for the full set of data involving all the available galactic pulsars and SN remnants is beyond the scope of this paper, here we take a less ambitious approach to consider the benchmark model parameters for J2021+3651 and IC443 separately. Note that the best values of \(m_a, g_{a\gamma\gamma'}\) and \(B_{XT}\) depend also on the detailed profile of the galactic magnetic fields. For instance, we have a better prospect for explaining the both modulations with the same model parameters if we use the older models for galactic magnetic fields as in [8], which would predict larger \(B_T\) than the Jansson and Farrar model [10]. On the other hand, if one keeps using the Jansson and Farrar model for galactic magnetic fields, the spectral irregularity of IC443 is better explained by different model parameters, e.g. \((m_a, g_{a\gamma\gamma'}, B_{XT})\):

\[
\begin{align*}
7.2 \text{ neV}, & 3.5 \times 10^{-10} \text{ GeV}^{-1}, 1.0 \mu \text{G}) \\
6.5 \text{ neV}, & 5.3 \times 10^{-11} \text{ GeV}^{-1}, 6.5 \mu \text{G})
\end{align*}
\]

Fig. 3 shows the resulting spectral dependence of the survival probability for gamma-rays from IC443. Again the significant step-down of the probability at \(\omega = \mathcal{O}(1) \text{ GeV}\) might be the reason for the spectral irregularity of IC443 noticed in [8].

Our results imply that the ALP parameters and background dark photon fields specified in [3] can explain the spectral modulations of galactic pulsars and supernova remnants noticed in [7] and [8] by means of the ALP coupling \(g_{a\gamma\gamma'}\). Refs. [7] and [8] have performed a \(\chi^2\)-analysis to find the statistical significance of the ALP-conversion scenario relative to the no-ALP scenario. Although such analysis is beyond the scope of this work, comparing Fig. 2 and Fig. 3 with the results of [7] and [8], we expect that our alternative explanation based on \(g_{a\gamma\gamma'}\) has a similar statistical significance as the explanations proposed in [7] and [8].

### IV. OBSERVATIONAL CONSTRAINTS AND A LATE GENERATION OF THE BACKGROUND DARK PHOTON GAUGE FIELDS

In this section, we examine if our photon-ALP-dark photon oscillation scenario discussed in the previous section can be compatible with the observational constraints available at present. Note that the major problem of the previous explanation based on the ALP coupling \(g_{a\gamma\gamma}\), which was suggested in [7] and [8], is the conflict with the bound on \(g_{a\gamma\gamma}\) from CAST [35] and also the non-observation of gamma-ray bursts from SN1987A [36].

We first note that our ALP coupling \(g_{a\gamma\gamma'}\) does not cause a conversion of ALP to photon in background magnetic field, and therefore is not constrained by helioscopic axion search experiments such as CAST. It is yet constrained by a variety of astrophysical and/or cosmological observations, including the stellar evolution, the absence of gamma-ray bursts from SN1987A, and a distortion of CMB. In the following, we examine those constraints on \(g_{a\gamma\gamma'}\) to see if the ALP parameters and the background dark photon gauge fields which would explain the gamma-ray modulations noticed in [7] and [8] can pass the observational constraints. In the later part of this section, we introduce an explicit model to generate the background dark photon gauge field \(\langle B_X \rangle\) and/or \(\langle E_X \rangle\), which is a key ingredient of our scheme.

#### A. Stellar evolutions

Let us start with the constraint from stellar evolution. If light hidden sector particles are produced and successfully emitted from the core of star, such additional energy
loss mechanism can affect the properties of the stellar object such as the core mass, luminosity, and lifetime [47]. In an ionized plasma such as the core of a star, the excitations of the electromagnetic field possess a different dispersion relation due to the coherent interaction with medium, and the photon obtains an effective mass, the plasmon mass \( \omega_{pl} = \sqrt{4\pi \alpha n_e / m_e} \). In the presence of the ALP coupling \( g_{a\gamma\gamma'} \), the massive plasmons decay into ALP and dark photon through the coupling \( g_{a\gamma\gamma'} \). The corresponding decay width is given by

\[
\Gamma_{pl} = \frac{g_{a\gamma\gamma'}^2 \omega_{pl}^4}{96\pi} \left[ \beta \left( \frac{1}{\omega_{pl}}, \frac{m_a}{\omega_{pl}} \right) \right]^{3/2}, \tag{25}
\]

where \( \beta(x, y) = x^4 + y^4 - 2x^2y^2 \). This results in the following energy loss rate per volume:

\[
Q_{pl} = \frac{2}{2\pi^2} \int_0^\infty dk k^2 \frac{\omega \Gamma_{pl}}{\epsilon / \omega - T_c - 1}, \tag{26}
\]

where \( T_c \) is the core temperature. Here only the contributions from the decays of transverse plasmon modes are considered as the longitudinal modes have a negligible number density.

The most stringent constraint associated with the above plasmon decays comes from the observationally inferred core mass at the tip of red giant. Any extra cooling during the red-giant phase causes a delay of the helium ignition until the core mass at the helion flash reaches an adequate value, i.e., an increment of the core mass [48]. On the other hand, in view of the brightness at the tip of the red-giant branch in globular clusters, the core mass at the helium flash cannot exceed its standard value by more than 5% [47]. Imposing this condition, the energy loss by plasmon decays is constrained as

\[
\frac{Q_{pl}}{\rho} \lesssim 10 \text{ erg g}^{-1} \text{ s}^{-1}, \tag{27}
\]

which results in the following upper bound:

\[
g_{a\gamma\gamma'} \lesssim 5 \times 10^{-10} \text{ GeV}^{-1} \quad \text{for } m_a, m_X \lesssim 10 \text{ keV}, \tag{28}
\]

where \( \rho \) denotes the energy density of core, and \( m_X \) denotes the dark photon mass which is assumed to be zero in our case.

B. Gamma ray bursts from SN1987A

In the presence of nonzero background dark photon fields, there can be additional constraints on \( g_{a\gamma\gamma'} \). One such example is the constraint from the gamma-ray bursts associated with SN1987A [50]. When the neutrino signals from SN1987A were observed, the Gamma-Ray Spectrometer on the Solar Maximum Mission satellite was operating to detect the \( \gamma \)-ray signals in the three energy bins, 4.1–6.4 MeV, 10–25 MeV, and 25–100 MeV, and found no appreciable gamma-ray excess [49]. This results in the following 95% confident upper bounds on the gamma ray fluence \( F_\gamma \) over the SN neutrino duration time \( t_{d\nu} \sim 10 \text{ sec} \):

\[
F_\gamma < (0.9, 0.4, 0.6) \gamma \text{ cm}^{-2} \tag{29}
\]

for (4.1 – 6.4, 10 – 25, 25 – 100) MeV.

In our case, the ALPs and dark photons are produced by the plasmon decays in SN1987A whose rate is given by [25]. Accepting the core-collapse supernovae model with the 18 \( M_\odot \) progenitor star [50], the plasma frequency in the degenerate core of SN1987A is given by \( \omega_{pl}^2 \simeq 4\alpha \mu e^2 / 3\pi \), where \( \mu_e = 5.15 \text{ keV}(Y_e \rho_e)^{1/3} \) is the electron chemical potential for the electron number per baryon \( Y_e \simeq 0.2 \) and the core density \( \rho_c \simeq 3 \times 10^{14} \) (in the unit of \( \text{g cm}^{-3} \)). The average core temperature is \( T_c \simeq 30 \text{ MeV} \) which is approximately constant within the core radius \( r_c \simeq 10 \text{ km} \) during the neutrino burst duration \( t_{d\nu} \simeq 10 \text{ sec} \). The resulting ALP and dark photon flux per unit energy over \( t_{d\nu} \) is given by

\[
\frac{d\Phi_{a\gamma'}}{d\omega} = \frac{1}{4\pi d^2} \left( \frac{2\omega}{\pi} \frac{4\omega^2 - \omega_{pl}^2}{e^{2\omega/T_c} - 1} \Gamma_{pl} \right) \frac{4\pi}{3} r_c^3 \epsilon_{d\nu}, \tag{30}
\]

where \( d \simeq 50 \text{ kpc} \) is the distance to SN1987A. For the ALP parameter range of our interest, the produced ALPs
and dark photons escape freely from the SN core as their mean free path is considerably larger than $r_c$. We then find the following total ALP and dark photon fluxes in each energy bin:

$$
\Phi_{a,\gamma'}^{4.1-6.4 \text{ MeV}} \approx 6.2 \text{ cm}^{-2} \times \left( g_{a\gamma'}/10^{-10} \text{ GeV}^{-1} \right)^2,
$$

$$
\Phi_{a,\gamma'}^{10-25 \text{ MeV}} \approx 335 \text{ cm}^{-2} \times \left( g_{a\gamma'}/10^{-10} \text{ GeV}^{-1} \right)^2, \tag{31}
$$

$$
\Phi_{a,\gamma'}^{25-100 \text{ MeV}} \approx 361 \text{ cm}^{-2} \times \left( g_{a\gamma'}/10^{-10} \text{ GeV}^{-1} \right)^2.
$$

Part of the ALPs and dark photons emitted from SN1987A can be converted into photons via the oscillations fueled by the background $B_{XT}$ and $B_T$, which would result in a gamma-ray burst whose differential flux is given by

$$
\frac{d\Phi_\gamma}{d\omega} = P_{a\rightarrow\gamma} \frac{d\Phi_a}{d\omega} + P_{\gamma'\rightarrow\gamma} \frac{d\Phi_{\gamma'}}{d\omega} = (P_{a\rightarrow\gamma} + P_{\gamma'\rightarrow\gamma}) \frac{d\Phi_{a,\gamma'}}{d\omega}. \tag{32}
$$

For the photon-ALP oscillation caused by $g_{a\gamma'}$, the galactic magnetic fields ($\lesssim \mu G$) are the dominant source of the conversion because the intergalactic magnetic fields ($< nG$) are negligibly small. On the other hand, in our case of the photon-ALP-dark photon oscillations induced by $g_{a\gamma'}$, the ALP mass $m_a = \mathcal{O}(10^{-9} - 10^{-10})$ eV, the intergalactic space between SN1987A and our Milky Way galaxy where $B_{XT} \gg B_T$ mainly contributes to the conversions. Note that in our case $B_{XT}$ is generated by a cosmological mechanism and therefore its value in intergalactic space is similar to the value inside the Milky Way galaxy. For such intergalactic conversions, the dark photon is decoupled and the conversion probability is given by

$$
P_{a\rightarrow\gamma} + P_{\gamma'\rightarrow\gamma} \approx P_{a\rightarrow\gamma} \approx \frac{\omega^2}{\omega^2 + \omega_c^2} \sin^2 \left( g_{a\gamma'} B_{XT} \frac{d}{2} \right), \tag{33}
$$

where we assumed that the coherent length of the background $B_{XT}$ is longer than the distance $d \approx 50$ kpc between SN1987A and the earth. Indeed, if $B_{XT}$ is generated by an additional ultra-light ALP $\phi$ at a late time with $m_\phi(t) < m_{a,\gamma'} = \mathcal{O}(10^{-9} - 10^{-10})$ eV, which will be presented at the end of this section, the resulting coherent length is much longer than $d \approx 50$ kpc.

Applying the upper bounds (29) to the photon flux obtained from (32), we can get an upper bound on $g_{a\gamma'}$, for given values of $m_a$ and $B_{XT}$. We depict the results in Fig. 4 for two different values of the background dark photon gauge fields, $B_{XT} = 1$ and $6.5 \mu G$, which were used in the previous section to explain the spectral irregularities of the galactic pulsar PSR J2021+3651 and the supernova remnant IC443. In Fig. 4 the red and blue colored regions are excluded by the stellar evolution constraint and the absence of gamma-ray bursts associated with SN1987A, respectively, and $\circ$ and $\otimes$ denote the ALP parameters which were chosen in the previous section as the benchmark points for PSR J2021+3651 and IC443, respectively.

**C. Other possible constraints**

In the previous subsections, we discussed the constraints on $g_{a\gamma'}$ from stellar evolution and the absence of $\gamma$-ray bursts from SN1987A. If the background dark photon gauge fields were generated early enough, e.g. in the
early universe with an effective photon mass \( m_\gamma(t) > m_\alpha \), our ALP coupling \( g_{\alpha\gamma}\gamma \) is constrained also by the absence of a significant distortion of CMB. It has been noticed that in the presence of the primordial cosmological background magnetic field \( B_0 \), the ALP coupling \( g_{\alpha\gamma}\gamma \) can induce a resonant conversion of CMB photons to ALP when \( m_\gamma(t) = m_\alpha \), which would result in a distortion of the CMB spectrum, thereby providing a bound on the combination \( g_{\alpha\gamma}\gamma B_0 \). The background dark photon field \( B_{X_T} \gtrsim 1 \mu G \) in our galaxy, which is required to explain the spectral irregularities of the galactic pulsars and supernova remnants noticed in \([7]\) and \([8]\), can not be amplified by the galactic dynamo mechanism \([51]\) and therefore should have a cosmological origin. This implies that a similar size of background dark photon gauge fields exist over the entire universe. If such cosmological \( B_{X_T} \) were generated in the early universe when \( m_\gamma(t) > m_\alpha = \mathcal{O}(10^{-9}) \) eV, so that CMB experiences a resonant conversion to ALP when \( m_\gamma(t) = m_\alpha \), the results of \([13,15]\) can be straightforwardly applied to our case, yielding a bound \( g_{\alpha\gamma}\gamma \langle B_{X_T} \rangle < 10^{-14} \text{ GeV}^{-1} \mu G \) for an ALP mass \( m_\alpha = \mathcal{O}(10^{-9}) \) eV, where \( \langle B_{X_T} \rangle \) denotes the cosmic average of \( B_{X_T} \). On the other hand, as was noticed in the previous section, we need \( g_{\alpha\gamma}\gamma \langle B_{X_T} \rangle = \mathcal{O}(10^{-10}) \text{ GeV}^{-1} \mu G \) to explain the spectral irregularities of the galactic pulsars and supernova remnants, where now \( B_{X_T} \) corresponds to the local dark photon field strength in our galaxy. As the local dark photon field strength is expected to be similar to its cosmic average, this implies that the background dark photon gauge fields should be generated at a late time when \( m_\gamma(t) < m_\alpha = \mathcal{O}(10^{-9}) \) eV, i.e. at the red-shift

\[
\Delta z_X < z_{\text{res}} \simeq \text{few} \times 10^3
\]  

where \( z_X \) denotes the red-shift factor at the time when the background dark photon gauge fields are produced, and \( z_{\text{res}} \) is the red-shift factor when \( m_\gamma(t) = m_\alpha = \mathcal{O}(10^{-9}) \) eV.

As the background dark photon gauge fields were produced over the entire universe, they constitute a dark radiation whose energy density can be parametrized in the unit of the energy density of an additional relativistic neutrino species as follows:

\[
\Delta N_{\text{eff}}(X) \simeq 0.42 \frac{\langle E_X^2 \rangle + \langle B_X^2 \rangle}{(1 \mu G)^2},
\]  

where \( \langle E_X \rangle \) and \( \langle B_X \rangle \) are the spatially averaged dark photon electric and magnetic fields today, which are expected to be comparable to the local field strengths in our galaxy. If the dark photon gauge fields were produced before the matter-radiation equality, i.e. \( z_X > z_{\text{eq}} = 3400 \), their cosmological energy density would be constrained by the CMB power spectrum as \( \Delta N_{\text{eff}}(X) \lesssim 0.3 \) \([52]\), suggesting the local \( B_{X_T} \lesssim \mathcal{O}(1) \mu G \) in our galaxy. On the other hand, if \( B_{X_T} \) were produced after the matter-radiation equality (or the recombination), which might be required to avoid a significant distortion of CMB (see \([34]\)), this bound can be relaxed and \( B_{X_T} \) significantly bigger than \( 1 \mu G \) is allowed. As we will see in the next subsection, if generated by an ultra-light ALP well after the matter-radiation equality, the produced \( B_{X_T} \) can be even as large as \( \mathcal{O}(10) \mu G \) without any conflict with the known observational constraints.

The photon-ALP-dark photon oscillations induced by \( g_{\alpha\gamma}\gamma \) can result in spectral irregularities of other gamma-ray sources, and non-observation of such irregularity may provide an upper bound on \( g_{\alpha\gamma}\gamma \). Indeed it has been noticed recently that the Fermi-LAT and MAGIC data of gamma-rays from NGC1275 in the center of the Perseus cluster suggest \( g_{\alpha\gamma}\gamma \lesssim 10^{-12} \text{ GeV}^{-1} \) for an ALP mass \( m_\alpha = \mathcal{O}(10^{-10} - 10^{-9}) \) eV \([10]\). However such consideration cannot be applied to our case because the possible spectral irregularity caused by \( g_{\alpha\gamma}\gamma \) severely depends on the detailed profile (including the directions) of the background dark photon gauge fields along the line of sight between the earth and NGC 1275, on which we don’t have any information.

### D. Generation of the background dark photon gauge fields

A key ingredient of our scenario is the background dark photon gauge fields \( E_X \) and/or \( B_X \) which are either comparable to or even stronger than the galactic magnetic fields \( B \sim 1 \mu G \). As there is no reason that the dark photon gauge fields are particularly strong in our galaxy, it is expected that a comparable size of dark photon gauge fields exist over the entire universe. An attractive mechanism to generate such cosmological background gauge fields is to amplify the vacuum fluctuations through the tachyonic instability caused by an evolving axion-like field \([16,22]\). As was noticed in the previous subsection, to avoid a resonant conversion of CMB to ALP in the early universe \([13,15]\), which would result in a dangerous distortion of CMB spectrum, those dark photon gauge fields should be generated at a late time with the corresponding red-shift factor \( z_X < z_{\text{res}} \simeq \text{few} \times 10^3 \) where \( m_\gamma(z_{\text{res}}) = m_\alpha = \mathcal{O}(10^{-9}) \) eV. If one wishes to have \( E_X \) and/or \( B_X \) significantly stronger than \( 1 \mu G \), then the background dark photon gauge fields need to be generated well after the matter-radiation equality, e.g. at \( z_X < 1000 \), to avoid the bound on the dark photon energy density from the CMB power spectrum \([52]\). In the following, we present an explicit model for such a late generation of the cosmological background dark photon gauge fields, involving an additional ultra-light ALP \( \phi \)

---

3 A previous study \([9]\) indicates that \( g_{\alpha\gamma}\gamma = \mathcal{O}(10^{-10}) \text{ GeV}^{-1} \) for \( m_\alpha = \mathcal{O}(10^{-9}) \) eV is allowed by the same Fermi-LAT data on the gamma-rays from NGC 1275, and therefore the result of \([10]\) should be taken with some caution.

4 It depends also on the profile of ordinary magnetic fields inside the Perseus cluster.
whose low energy effective Lagrangian is given by
\[ L_\phi = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{4} g_{\phi \gamma \gamma} \phi X_{\mu \nu} X^{\mu \nu}. \] (36)

In the early universe with the Hubble expansion rate \( H \gg m_\phi \), \( \phi \) is frozen at its initial value \( \phi_i \). Around the time when \( H \) becomes comparable to \( m_\phi \), more specifically at \( t = t_{\text{osc}} \) when \( 3H(t_{\text{osc}}) \gg m_\phi \), the ultra-light ALP \( \phi \) begins to oscillate, and evolves for a while as follows
\[ \phi(t) \simeq \left( R(t)/R(t_{\text{osc}}) \right)^{-3/2} \phi_i \cos \left( m_\phi (t - t_{\text{osc}}) \right), \] (37)
where \( R(t) \) is the scale factor in the spacetime metric of the expanding universe:
\[ ds^2 = dt^2 - R^2(t)d\vec{x}^2 = R^2(\tau)(d\tau^2 - d\vec{x}^2). \] (38)

Then the equation of motion for the dark photon field in the momentum space is given by
\[ X_{\mu \pm}^k + k (\mp g_{\phi \gamma \gamma} \phi^i) X_{k \pm} = 0, \] (39)
where the prime represents the derivative with respect to the conformal time \( \tau \), and the subscripts \( k \) and \( \pm \) denote the comoving momentum and the helicity, respectively. This shows that in the oscillating background \( \phi \), one of the helicity states of \( X_k \) experiences a tachyonic instability for certain range of \( k \). The vacuum fluctuations of \( X_k \) in this range of \( k \) are exponentially amplified to be a stochastic classical field [16,23].

In order for this amplification mechanism to be efficient enough in the expanding universe, the ALP coupling \( g_{\phi \gamma \gamma} \) times the ALP initial value \( \phi_i \) needs to be large enough, for instance \( g_{\phi \gamma \gamma} \equiv g_{\phi \gamma \gamma} \phi_i \gtrsim 70 \) to generate \( E_X \) and/or \( B_X \gtrsim 1 \mu G \) at a late time with \( z_X < 1000 \). If the amplification mechanism is efficient enough, the produced dark photon gauge fields can affect significantly the evolution of the ALP field \( \phi \), which should be taken into account to compute the field strength of the produced dark photon gauge field and also the residual relic energy density of \( \phi \) [18,20]. As demonstrated in the recent works [19,20], this can be achieved by a lattice calculation of the cosmological evolution of ALP and \( U(1) \) gauge field in the expanding universe. In order to see explicitly that our mechanism can yield the desired background dark photon gauge fields, following [19,21], we performed such a lattice calculation of the present values of the spatially averaged dark photon gauge field strength and the relic mass density of \( \phi \) for the parameter region
\[ m_\phi \lesssim 10^{-27} \text{eV}, \ 100 \lesssim g_{\phi \gamma \gamma} \phi_i \lesssim 200, \] (40)
and find
\[ \langle B_X \rangle \simeq \langle E_X \rangle \simeq (1.2 - 2) \left( \frac{m_\phi}{10^{-29} \text{eV}} \right)^{-1/3} \left( \frac{\phi_i}{10^{17} \text{GeV}} \right) \mu G, \] (41)
\[ \Omega_\phi h^2 \simeq 10^{-4} \left( \frac{\phi_i}{10^{17} \text{GeV}} \right)^2, \]
where the smaller (larger) field strength is obtained for \( g_{\phi \gamma \gamma} = 100 \) (200). The red-shift factor \( z_X \) at the time when the dark photon gauge fields are produced and the present coherent length \( \lambda_X \) of the produced dark photon gauge fields are given by
\[ \lambda_X \simeq 60 \left( \frac{m_\phi}{10^{-29} \text{eV}} \right)^{-1/3} \text{Mpc}, \]
\[ z_X \simeq 50 \left( \frac{m_\phi}{10^{-29} \text{eV}} \right)^{2/3}. \] (42)

To explain the gamma-ray spectral modulations noticed in [7] and [8] through the photon-ALP-dark photon oscillations, we need a background dark photon gauge field \( B_{XT} \gtrsim 1 \mu G \) in our galaxy, where \( B_{XT} = \langle B_X \rangle - \hat{k} \langle k (\hat{k} \cdot B_X) \rangle - \hat{k} \times \langle E_X \rangle \). As noticed in the previous subsection, those dark photon gauge fields should be produced at a late time with the red-shift \( z_X < 10^3 \) to avoid a dangerous distortion of CMB [13–15], as well as the constraint on dark radiation from the CMB power spectrum [52]. As for our specific mechanism to generate \( E_X \) and \( B_X \), there is an additional constraint. The relic mass density of ultra-light \( \phi \) should be small enough to be compatible with the CMB data, e.g. \( \Omega_\phi h^2 < 2.5 \times 10^{-3} \) for \( m_\phi = O(10^{-30} - 10^{-27}) \text{eV} \) [33]. Our results (41) and (42) show that our mechanism can successfully produce the desired \( B_{XT} \simeq 1 - 10 \mu G \) for \( m_\phi = O(10^{-30} - 10^{-27}) \text{eV} \) and \( \phi_i = O(10^{17}) \text{GeV} \), while satisfying all known observational constraints.

V. CONCLUSION

In this paper, we proposed a scenario that the spectral irregularities of gamma-rays from some galactic pulsars and supernova remnants, which were recently noticed in [7] and [8], are explained by means of an axionlike particle (ALP) with a mass \( m_a = O(10^{-9}) \text{eV} \) and the coupling \( g_{a \gamma \gamma} a X_{\mu \nu} F^{\mu \nu} \) in the range \( g_{a \gamma \gamma} = O(10^{-11} - 10^{-10}) \text{GeV}^{-1} \), where \( F_{\mu \nu} \) is the ordinary electromagnetic field and \( X_{\mu \nu} \) is the field strength of a massless dark photon. A key ingredient of our scenario is the presence of cosmological background dark photon gauge fields, \( E_X \sim B_X \gtrsim 1 \mu G \), which can be successfully generated by an additional ultra-light ALP \( \phi \) with \( m_\phi = O(10^{-30} - 10^{-27}) \text{eV} \) and the initial field value \( \phi_i = O(10^{17}) \text{GeV} \), whose late coherent oscillations cause a tachyonic instability of the dark photon gauge fields and amplify their vacuum fluctuations to the desired strength. Contrary to the scenario based on the conventional ALP coupling \( g_{a \gamma \gamma} a F_{\mu \nu} F^{\mu \nu} \), which was explored in [7] and [8], our scenario can be compatible with the existing observational constraints.

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