

New constraints on axions with gamma-ray observations of the Crab Nebula

Kazunori Kohri^{1,2,3,4,5,6} and Haruki Takahashi^{3,5}

¹*Division of Science, National Astronomical Observatory of Japan (NAOJ),
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*

²*School of Physical Sciences, Graduate University for Advanced Studies (SOKENDAI),
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*

³*Theory Center, IPNS, High Energy Accelerator Research Organization (KEK),
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

⁴*Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

⁵*School of High Energy Accelerator Science, Graduate University for Advanced Studies (SOKENDAI),
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

⁶*Department of Astronomy, The University of Tokyo, Bunkyo-ku, Hongo, Tokyo 113-0033, Japan*



(Received 4 December 2025; accepted 3 June 2026; published 6 August 2026)

In this paper, we derive the upper bounds on the coupling of axionlike particles (ALPs) with photon as a function of the mass by considering axion-photon conversion in the Crab Nebula. Previous studies have not considered the influence of the magnetic field within the Crab Nebula. The magnetic field plays a crucial role through the synchrotron self-Compton process, in which high-energy electrons produce synchrotron radiation that is subsequently upscattered by the same electrons via inverse Compton scattering to generate γ rays. Therefore, neglecting the magnetic field in modeling leads to theoretical inconsistencies. In this work, we investigate the significance of the magnetic field effect and demonstrate that even differences in magnetic field modeling can substantially alter the conversion probability. We thus, for the first time, point out that proper consideration of the magnetic field is essential in ALP searches using γ rays from the Crab Nebula. The resulting constraints reach up to a coupling of $g_{a\gamma\gamma} \lesssim 1 \times 10^{-11} \text{ GeV}^{-1}$ for ALP masses in the range $10^{-10} \text{ eV} \lesssim m_a \lesssim 10^{-6} \text{ eV}$.

DOI: [10.1103/xskn-kdn7](https://doi.org/10.1103/xskn-kdn7)

I. INTRODUCTION

Dark matter is a massive and invisible piece in the Universe. A lot of dark matter candidates have been proposed beyond the Standard Model, such as weakly interacting massive particles, primordial black holes, axions, and so on (see, e.g., Ref. [1] for a lecture note). Axions are pseudo-Nambu-Goldstone bosons appearing after an additional $U(1)_{\text{PQ}}$ symmetry is spontaneously broken. It is a dynamical solution to the strong CP problem in QCD [2,3] and called QCD axions. QCD axions were soon found to work as dark matter in the Universe [4–8], and models were developed such as Kim-Shifman-Vainshtein-Zakharov (KSVZ) model [9,10] and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) model [11,12] (see, e.g., Refs. [13–15] for reviews). Axionlike particles (ALPs) are a kind of generalization of the QCD axions and can be a candidate of dark matter. ALPs mass m_a and its coupling to photons $g_{a\gamma\gamma}$ do not have relations with

each other as opposed to the QCD axion, whose mass is proportional to the coupling. ALPs appear in models beyond the Standard Model, such as grand unified theories, higher-dimensional theories, and string theories [16–26] (see, e.g., Refs. [27–30] for reviews and lectures).

For the axion searches (see, e.g., Refs. [31,32] for reviews), photons are an important probe and couple to the axions through the Chern-Simons coupling $-\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$, where a is the axion field, $F_{\mu\nu}$ is the strength tensor of electromagnetic fields, and $\tilde{F}^{\mu\nu}$ is its dual. This coupling allows the axions to convert into photons and vice versa. As proposed by Sikivie [33], helioscopes and haloscopes are experiments to look for the axions from the Sun and the axion dark matter in the halo, respectively [34–46]. The CERN Axion Solar Telescope (CAST) [34–38] is one of the helioscopes to detect the solar axions produced in the core of the Sun through the Primakoff process. CAST has given upper bounds on the axion-photon coupling $g_{a\gamma\gamma} < 6.5 \times 10^{-11} \text{ GeV}^{-1}$ [38]. The Axion Dark Matter eXperiment [44,45] is a halo-scope to look for the dark matter axions in the mass range 2.66 to 3.1 μeV . Light shining through a wall experiments [47–49] such as Any Light Particle Search have also

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constrained the axion parameters as well as the helioscopes and the haloscopes.

In addition to these experiments, observations of celestial objects also give us a hint for axions [50–84] (see Ref. [85] for a recent review). For example, γ -ray observations are ways to get information about axions [54,86–141] (see for recent reviews Refs. [142–144]), as follows: high-energy γ -rays emitted from a source are absorbed by low-energy background photons, and can be converted to ALPs and vice versa under magnetic fields in the Universe. The γ -ray absorption and the ALP-photon conversion can alter the γ -ray spectra and give constraints on the ALP mass m_a and the ALP-photon coupling $g_{a\gamma\gamma}$. While extragalactic objects such as blazars and radio galaxies have been used for the ALPs search and given constraints on the ALPs parameters, Galactic sources have also been recently used in a similar way (e.g., Refs. [121,145–148]), such as the Crab Nebula [121,148]. The Crab Nebula is the brightest pulsar wind nebula in the Milky Way (MW) and powered by relativistic electron-positron wind from the Crab Pulsar at the center. Electromagnetic waves from the Crab Nebula have been observed in a broad energy range from radio to γ rays [149–158]. These datasets allowed for developing emission models for the Crab Nebula (e.g., Refs. [159–161]).

When we use observations of the γ rays from some astrophysical sources for the ALPs search, it is important to consider astrophysical models of magnetic fields precisely as far as possible. This is because magnetic fields affect the ALP-photon conversion and the constraints with the γ -ray observations. In this paper, we investigate how the magnetic fields in the Crab Nebula affect the ALP-photon conversion. This effect has not been taken into account in the ALPs search with γ -rays from the Crab Nebula so far. As explained in Sec. III, we consider a model for the magnetic field discussed in Ref. [161]. The magnetic field is important not only in the ALP-photon conversion but also in photon emission process in the Crab Nebula, called the synchrotron self-Compton (SSC) process, which will also be explained in Sec. III. We find that this consideration significantly affects the ALP-photon conversion and alters the resulting constraint on the ALP parameters m_a and $g_{a\gamma\gamma}$. Finally, we obtain new constraints reaching down to $g_{a\gamma\gamma} \lesssim 1 \times 10^{-11} \text{ GeV}^{-1}$ at $m_a \simeq 10^{-8} \text{ eV}$ and exceeding the constraints by CAST in the ALP mass range $10^{-10} \text{ eV} \lesssim m_a \lesssim 10^{-6} \text{ eV}$.

This paper is organized as follows: in Sec. II, we show how we can characterize the effects of the γ -ray absorption and axion-photon conversion. Section III introduces emission models of electromagnetic waves from the Crab Nebula, including the model for magnetic fields around the source, which is important not only for the intrinsic γ -ray emission but also for the ALP-photon conversions. We next perform statistical analyses based on the developed model and constrain the ALP mass m_a and the ALP-photon coupling $g_{a\gamma\gamma}$, and show that magnetic fields in the Crab

Nebula also contribute to the ALP-photon conversions and give new constraints on the ALP parameters.

II. AXION-PHOTON CONVERSION

In this section, we use natural units where $c = \hbar = 1$. The system of ALPs a and photons A_μ is described by the following Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (1)$$

where a is the ALP field, m_a denotes the ALP mass, and $g_{a\gamma}$ is the ALP-photon coupling. $F_{\mu\nu}$ and $\tilde{F}_{\mu\nu}$ are the electromagnetic field strength tensor and its dual, respectively. ALPs and photons are mixing with each other through the ALP-photon coupling, which can be written as $g_{a\gamma}a\mathbf{E} \cdot \mathbf{B}$ in terms of the electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$. ALP-photon beams with a monochromatic energy E are propagating along x_3 -direction under magnetic fields.

The propagation can be described by the equation [162]

$$\left(i\frac{d}{dx_3} + E + \mathcal{M}\right)\Psi(x_3) = 0, \quad (2)$$

where $\mathcal{M}$ is the mixing matrix and $\Psi(x_3) = (A_1(x_3), A_2(x_3), a(x_3))^T$. Neglecting Faraday rotation effects, the mixing matrix $\mathcal{M}$, as follows:

$$\mathcal{M} = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}, \quad (3)$$

has several components, such as $\Delta_\perp = \Delta_{\text{pl}} + 2\Delta_{\text{QED}} - i\Gamma/2$, $\Delta_\parallel = \Delta_{\text{pl}} + 7/2\Delta_{\text{QED}} - i\Gamma/2$, and $\Delta_a = -m_a^2/(2E)$ corresponding to the kinetic term of ALPs, and $\Delta_{a\gamma} = g_{a\gamma}B/2$ resulting in the ALP-photon conversions. The plasma term $\Delta_{\text{pl}} = -\omega_{\text{pl}}^2/(2E)$ arises from the effective photon mass in plasma of astrophysical environments where $\omega_{\text{pl}} = \sqrt{4\pi n_e e^2/m_e}$, with the electron density n_e , electric charge e , and electron mass m_e . QED vacuum polarization effects appear in $\Delta_{\text{QED}} = \alpha E/(45\pi)(B/B_{\text{cr}})^2$, where α is the fine structure constant and $B_{\text{cr}} = m_e^2/|e| \sim 4.4 \times 10^{13} \text{ G}$. Γ characterizes an absorption effect of high-energy γ rays as explained below.

High-energy γ rays are absorbed through the pair production process, where they interact with low-energy background photons and annihilate into electrons and positrons. Cosmic microwave background (CMB) and interstellar radiational fields including starlight emission and its dust reemission [163–165] act as the low-energy background photons. This process occurs when γ -ray energy exceeds its threshold value,

$$E_{\text{th}} \sim \frac{4m_e^2}{\epsilon} \sim 0.5 \text{ TeV} \left(\frac{\epsilon}{1 \text{ eV}} \right)^{-1}, \quad (4)$$

with the energy of background photons ϵ . The absorption effect is characterized by

$$\Gamma = \int d\epsilon \frac{dn_{\text{bg}}}{d\epsilon} \int_{-1}^1 d\cos\theta \frac{1 - \cos\theta}{2} \sigma_{\gamma\gamma}, \quad (5)$$

where $dn_{\text{bg}}/d\epsilon$ is the spectrum of the background photons and θ is the collision angle between high-energy γ rays and background photons. The cross section $\sigma_{\gamma\gamma}$ is written as

$$\sigma_{\gamma\gamma} = \frac{3}{16} \sigma_T (1 - \beta^2) \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left(\frac{1 + \beta}{1 - \beta} \right) \right], \quad (6)$$

where σ_T is the Thomson cross section and $\beta = 1 - 4m_e^2/s$ with the Mandelstam variable $s = 2E\epsilon(1 - \cos\theta)$.

The ALP-photon conversion and γ -ray absorption affect the γ -ray spectrum. We can numerically calculate these effects with the public code `gammaALPs` [166] based on equation of transfer matrices as follows: we first rewrite Eq. (2) as

$$i \frac{d\rho}{dx_3} = [\rho, \mathcal{M}], \quad (7)$$

in terms of the density matrix $\rho(x_3) = \Psi(x_3)\Psi(x_3)^\dagger$. Its solution,

$$\rho(z) = \mathcal{T}(x_3, 0; E) \rho(0) \mathcal{T}^\dagger(x_3, 0; E), \quad (8)$$

can be obtained with the transfer matrix $\mathcal{T}$, which is the solution of Eq. (2) under initial condition $\mathcal{T}(0, 0; E) = 1$. Transfer matrices can be calculated for each environment corresponding to the Crab Nebula $\mathcal{T}_1$ and the MW $\mathcal{T}_2$. For the environment in the MW, we use the Jansson and Farrar model [167]. Models for the Crab Nebula are taken from Ref. [161] and explained in Sec. III.

In each environment, we assume that the propagation path can be divided into N_i ($i = 1, 2$) domains where astrophysical quantities such as the magnetic field and electron density are constant [166]. The transfer matrix in the total path of ALP-photon beams is given by

$$\mathcal{T}_{\text{total}} = \prod_{i=1}^2 \prod_{n=1}^{N_i} \mathcal{T}_i(x_{3,[N_i-n+1]}, x_{3,[N_i-n]}; E), \quad (9)$$

where $x_{3,0}$ is the x_3 coordinate closest to the Crab Nebula. We then obtain an expression for the photon survival probability, as follows:

$$P_{\gamma\gamma} = \text{Tr}((\rho_{11} + \rho_{22}) \mathcal{T}_{\text{total}} \rho(0) \mathcal{T}_{\text{total}}^\dagger), \quad (10)$$

where $\rho_{11} = \text{diag}(1, 0, 0)$, $\rho_{22} = \text{diag}(0, 1, 0)$, and $\rho(0) = \text{diag}(1/2, 1/2, 0)$ for unpolarized γ rays.

III. MODELING OF THE CRAB NEBULA

A. Electrons and magnetic fields in the Crab Nebula

We explain the model for the broadband emission of the Crab Nebula [161]. Electrons and positrons are distributed around the Crab Nebula. These spectra are characterized with a power law by the first-order Fermi acceleration. We refer to both electrons and positrons as electrons below. The accelerated electron distribution in Crab Nebula is radially symmetric and steady in this model, and assumed to have two components: radio electrons and wind electrons. Radio electrons are contributing as synchrotron emission from radio to optical regime. At higher energy, synchrotron emission from wind electrons is dominant. The total electron spectrum $n_e(\gamma, r)$ is characterized as

$$n_e(\gamma, r) = n_{\text{radio}}(\gamma, r) + n_{\text{wind}}(\gamma, r), \quad (11)$$

with the electron's Lorentz factor γ and distance from the center of the Crab Nebula r .

For the radio electrons, the authors of Ref. [161] assumed that their spectrum $n_{\text{radio}}(\gamma, r)$ follows a power law from $\gamma_{r,\text{min}}$ and has a super-exponential cutoff around $\gamma_{r,\text{max}}$, as follows:

$$n_{\text{radio}}(\gamma, r) = \frac{n_{r,0}}{\rho_r^3} \gamma^{-s_r} \exp \left[- \left(\frac{\gamma}{\gamma_{r,\text{max}}} \right)^{\beta_{\text{min}}} \right] \Theta(\gamma - \gamma_{r,\text{min}}) F_{\text{radio}}(r), \quad (12)$$

$$F_{\text{radio}}(r) = \exp \left(- \frac{r^2}{2\rho_r^2} \right) \Theta(r - r_s), \quad (13)$$

where $n_{r,0}$ is the normalization, s_r is the index, β_{min} is responsible for the super-exponential cutoff, and $\Theta(x)$ is the Heaviside step function. $F_{\text{radio}}(r)$ shows the radial dependence of the electron spectrum and follows a Gaussian function with constant width ρ_r .

The wind electron spectrum $n_{\text{wind}}(\gamma, r)$ is modeled as

$$n_{\text{wind}}(\gamma, r) = \frac{n_{w,0}}{\rho_w(\gamma)^3} G(\gamma) \exp \left[- \left(\frac{\gamma_{w,\text{min}}}{\gamma} \right)^{\beta_{\text{min}}} \right] \times \exp \left[- \left(\frac{\gamma}{\gamma_{w,\text{max}}} \right)^{\beta_{\text{max}}} \right] F_{\text{wind}}(\gamma, r), \quad (14)$$

$$G(\gamma) = \left(\frac{\gamma}{\gamma_{w,1}} \right)^{-s_{w,1}} \left(\frac{\gamma_{w,1}}{\gamma_{w,2}} \right)^{-s_{w,2}} (1 - \Theta(\gamma - \gamma_{w,1})) \quad (15)$$

$$+ \left(\frac{\gamma}{\gamma_{w,2}} \right)^{-s_{w,2}} (\Theta(\gamma - \gamma_{w,1}) - \Theta(\gamma - \gamma_{w,2})) \quad (16)$$

$$+ \left(\frac{\gamma}{\gamma_{w,2}} \right)^{-s_{w,3}} \Theta(\gamma - \gamma_{w,2}), \quad (17)$$

$$F_{\text{wind}}(\gamma, r) = \exp\left(-\frac{r^2}{2\rho_w(\gamma)^2}\right)\Theta(r - r_s). \quad (18)$$

The spectrum has super-exponential cutoffs at $\gamma_{w,\min}$ and $\gamma_{w,\max}$. $G(\gamma)$ denotes a double broken power law of the spectrum with the indexes $s_{w,1}$; $s_{w,2}$; and $s_{w,3}$. The spatial distribution $F_{\text{wind}}(\gamma, r)$ is assumed to follow a Gaussian function and also to depend on the energy of the wind electrons. Its dependence is given by

$$\rho_w(\gamma) = \rho_{w,0} \left[\left(\frac{\gamma}{9 \times 10^5} \right)^2 \right]^{-\alpha_w}. \quad (19)$$

The radio and wind electrons radiate low-energy photons through the synchrotron process under magnetic fields around the Crab Nebula. For a model of magnetic fields near the Crab Nebula, we consider a variable B -field model developed in Refs. [160,161]. In the variable B -field model, the magnetic field has a power-law profile with respect to r , as follows:

$$B(r) = B_0 \left(\frac{r}{r_s} \right)^{-\alpha_b}, \quad (20)$$

where $\alpha_b (\geq 0)$ is the index, r_s is a shock radius, and B_0 is the magnetic field strength at r_s .

B. Emission mechanism of the Crab Nebula

Using the expressions for the distribution of electrons $n_e(\gamma, r)$ [Eq. (11)] and magnetic fields $B(r)$ [Eq. (20)], we can write down the spectral volume emissivity $j_\nu(\nu, r) \equiv dE/dtdVd\nu d\Omega$. For the synchrotron process, its spectral volume emissivity is expressed as

$$j_\nu^{\text{sync}}(\nu, r) = \frac{1}{4\pi} \frac{\sqrt{3}e^3 B(r)}{m_e c^2} \int_1^\infty d\gamma n_e(\gamma, r) f_{\text{sync}}\left(\frac{\nu}{\nu_c}\right), \quad (21)$$

where c is the speed of light and $\nu_c = 3eB\gamma^2/(4\pi m_e c)$ is the critical frequency. Note that we do not use the natural unit in this section. The function $f_{\text{sync}}(x)$ is given by

$$\begin{aligned} f_{\text{sync}}(x) = & \frac{x}{20} [(8 + 3x^2)(K_{1/3}(x/2))^2 \\ & + xK_{2/3}(x/2)(2K_{1/3}(x/2) \\ & - 3xK_{2/3}(x/2))], \end{aligned} \quad (22)$$

where K_ξ is the modified Bessel function of the kind ξ .

Low-energy photons radiated through the synchrotron process can be kicked up by high-energy electrons and become high-energy γ rays by inverse Compton (IC) scattering. This is called a synchrotron self-Compton process. The emissivity of the IC scattering

$$\begin{aligned} j_\nu^{\text{IC}}(\nu, r) = & \frac{3\sigma_T hc}{4} \frac{h\nu}{4\pi} \int_1^\infty d\gamma \frac{n_{\text{el}}(\gamma, r)}{\gamma^2} \\ & \times \int_0^\infty d\epsilon f_{\text{IC}}(\nu, \epsilon, \gamma) \frac{n_{\text{seed}}(\epsilon, r)}{\epsilon} \end{aligned} \quad (23)$$

can be calculated with the IC kernel function

$$f_{\text{IC}}(x) = 2q \ln q + (1 + 2q)(1 - q) + \frac{1}{2} \frac{(\Gamma_\epsilon q)^2}{1 + \Gamma_\epsilon q} (1 - q), \quad (24)$$

where σ_T is the Thomson cross section, h is the Planck constant, $\Gamma_\epsilon = 4\epsilon\gamma/(m_e c^2)$, and $q = h\nu/(\Gamma_\epsilon \gamma m_e c^2 - h\nu)$. $n_{\text{seed}}(\epsilon, r)$ denotes the seed photon's density where ϵ is the energy of seed photons.

While synchrotron photons are important as seed photons of the SSC process, CMB and dust emissions are also components of seed photons. CMB photons act as not only one of seed photons but also prevent especially PeV γ rays from propagating for long distances in the Universe [168], as explained in Sec. II, and their density is

$$n_{\text{seed}}^{\text{CMB}} = \frac{4\pi B_\nu(T_{\text{CMB}})}{hc} \frac{1}{h\nu}, \quad (25)$$

where $B_\nu(T)$ is the intensity of the black body at temperature T . Dust emissions were introduced to explain the observational data in the radio and optical ranges (e.g., Ref. [150]). The authors of Ref. [161] used a model where the dust emission originated from a mixture of two populations consisting of amorphous carbon dust grains with different temperatures T_i ($i = 1, 2$) and their masses M_i ($i = 1, 2$). The dust populations are within a shell whose inner and outer radii are r_{in} and r_{out} , respectively. The emissivity of the dust is given by

$$j_\nu^{\text{dust}}(\nu, r) = \frac{3\kappa[\Theta(r - r_{\text{in}}) - \Theta(r - r_{\text{out}})]}{4\pi(r_{\text{out}}^3 - r_{\text{in}}^3)} \sum_{i=1,2} M_i B_\nu(T_i), \quad (26)$$

where κ is the absorption coefficient dependent on the wavelength λ , as follows:

$$\kappa = 2.15 \times 10^{-4} \text{ cm}^2 \text{ g}^{-1} \left(\frac{\lambda}{\mu\text{m}} \right)^{-1.3}. \quad (27)$$

We can calculate the density of synchrotron and dust emissions as seed photons of the SSC process, as follows:

$$\begin{aligned} n_{\text{seed}}^j(\epsilon, r) = & \frac{r_0}{2hc} \frac{4\pi}{\epsilon} \int_{r_s/r_0}^1 dy \frac{y}{x} \ln \frac{x+y}{|x-y|} \\ & \times j_\nu^i(\nu, r_0 y), \quad (j = \text{sync, dust}), \end{aligned} \quad (28)$$

where $r_0 = 2.0$ pc is the radius of the Crab Nebula. The total density of seed photons is expressed by

$$n_{\text{seed}}(\epsilon, r) = \sum_k n_{\text{seed}}^k(\epsilon, r), \quad (k = \text{sync, dust, CMB}), \quad (29)$$

and used to calculate the IC emissivity in Eq. (23). The total luminosity L_ν can be calculated by integrating the emissivity in the SSC process over volume dV and solid angle $d\Omega$ as

$$L_\nu = \oint d\Omega \int dV j_\nu(\nu, r) = (4\pi)^2 \int_{r_s}^{r_0} dr r^2 [j_\nu^{\text{sync}}(\nu, r) + j_\nu^{\text{IC}}(\nu, r)], \quad (30)$$

using Eqs. (21) and (23).

C. Axion-photon conversion in the Crab Nebula

This model [161] enables us to numerically calculate the flux of high-energy γ rays. We can obtain parameters for magnetic fields based on this model shown in Table I. In the model of the variable magnetic field, we adopt the best-fit value $\alpha_b = 0.4691$ to fit the full multiwavelength spectrum without the ALPs, which gives the conservative upper bound on the model parameters of the ALPs. However, the numerical calculations are consuming a lot of time and computer resources to fit the broad emission from radio to γ rays. Since we would like to see how ALPs affect the spectrum of high-energy γ rays only, we focus on the γ -ray spectrum in the GeV $\sim$ PeV energy range. A similar approach was taken in the case of ALP search using γ rays from a blazar [127]. The Fermi-Large Area Telescope (Fermi-LAT) has observed the γ rays consisting of synchrotron and IC emissions around GeV scale [169,170], and Large High Altitude Air Shower Observatory (LHAASO) reported TeV and PeV γ rays in the IC part [158]. It is known that the γ -ray spectrum in the energy scale can be well described by the following function [158,170]:

$$\Phi_{\text{int}} = N_{\text{sync}}^0 \left(\frac{E}{100 \text{ MeV}} \right)^{-\Gamma_{\text{sync}}} + N_{\text{IC}}^0 \left(\frac{E}{1 \text{ GeV}} \right)^{-\alpha - \beta \ln(E/1 \text{ GeV})}, \quad (31)$$

where $E = h\nu$ is the energy of γ rays. Equation (31) will be used in the following analysis. A power-law spectrum with the index Γ_{sync} was used for the synchrotron part [170], while IC emission was explained by using a log-parabola spectrum whose shape is characterized by α and β [158,170]. N_{sync}^0 and N_{IC}^0 are the normalization constants for synchrotron and IC emissions, respectively. Here, Γ_{sync} , α , β , N_{sync}^0 and N_{IC}^0 are free parameters to be fitted. If we denote the

TABLE I. Parameters of magnetic fields in the variable B -field model taken from Ref. [161].

Parameter	Variable B -field model
$B_0 [\mu\text{G}]$	256.4
α_b	0.4691
$r_s [\text{pc}]$	0.13

spectrum of the primary electron number density as $dn_e/dE \propto E^{-p_e}$, the spectrum of the synchrotron emission is represented by $E^2 dN/dE \propto E^{-(p_e-3)/2}$. The spectrum of the standard IC is also the same: $E^2 dN/dE \propto E^{-(p_e-3)/2}$ at low energies. However, in the case of the SSC, there also exists a higher-energy range where the spectrum becomes flatter, e.g., $E^2 dN/dE \propto E^{-(p_e-2)/2}$ [168,171]. With the parameters used in this paper, therefore, we have $\Gamma_{\text{sync}} \sim \alpha \sim (p_e - 3)/2$ in most of the energy regions. On the other hand, there surely exists an energy region where $\alpha \sim (p_e - 2)/2$ at a higher energy. This serves as evidence for the SSC. In fact, this feature of the spectrum for the SSC has been confirmed in the Crab Nebula (e.g., see Ref. [168]) and can be used to constrain the parameters of the ALPs.

As explained in Sec. II, the intrinsic spectrum of γ rays Φ_{int} emitted from the source undergoes the ALP-photon conversion and γ -ray absorption during its propagation to Earth. We can numerically calculate the model flux Φ_{model} as

$$\Phi_{\text{model}} = P_{\gamma\gamma} \Phi_{\text{int}}. \quad (32)$$

The photon survival probability $P_{\gamma\gamma}$ determines how the γ -ray spectrum can be distorted by the effects of the ALP-photon conversion and γ -ray absorption. Note that we took into account the effects of magnetic fields of the Crab Nebula on ALP-photon conversions. Since we have considered the model for magnetic fields in the Crab Nebula, this can alter constraints on the ALP mass m_a and coupling to photons $g_{a\gamma\gamma}$ as discussed in Sec. IV.

IV. ANALYSIS AND RESULTS

We minimize the χ^2 function

$$\chi^2 = \sum_i \frac{(\Phi_{\text{model}}^i - \Phi_{\text{data}}^i)^2}{\sigma_i^2} \quad (33)$$

to get the best-fit spectrum where Φ_{model}^i , Φ_{data}^i , and σ_i are the predicted flux, observed one, and its error bar, respectively. Each i corresponds to a data point from experiments. The test statistic (TS) is defined as $\text{TS} = \chi_{\text{w/ALP}}^2 - \chi_{\text{w/o ALP}}^2$. We cannot apply the Wilks' theorem [172] because of nonlinear effects on the γ -ray spectrum in the ALP-photon system [153], and should get a TS distribution with Monte Carlo simulations as performed in Refs. [118,120,122,126]. Five hundred mock datasets of the photon flux are randomly

produced with Gaussian sampling. Each data point has the mean value and error bar which are set to be the predicted flux based on the best-fit spectrum and the experimental error, respectively. Optimizing the model flux to these mock datasets reproduces the TS distribution under the null hypothesis. This distribution is considered to be the approximation of the TS distribution under the ALP hypothesis [153], and it turns out to follow a noncentral χ^2 distribution. Its noncentrality and effective degrees of freedom (d.o.f.) are found to be 0.82 and 4.06, respectively. The 95% quantile value is $\Delta\text{TS}_{95\%} = 11.41$. We can exclude the parameter region where the best-fit χ^2 under the ALP hypothesis $\hat{\chi}_{\text{ALP}}^2$ exceeds $\hat{\chi}_{\text{min}}^2 + \Delta\text{TS}_{95\%}$ at 95% confidence level (CL). Here, $\hat{\chi}_{\text{min}}^2$ is the global best-fit χ^2 for the observational data in the scanned parameter space spanning $m_a \in [10^{-11}, 10^{-5}]$ eV, $g_{a\gamma} \in [10^{-12}, 5 \times 10^{-10}]$ GeV $^{-1}$.

Following the statistical analysis described above, we use the observational data of the Crab Nebula with Fermi-LAT [169] and LHAASO [158] to get constraints on ALP parameters m_a and $g_{a\gamma}$. In Figs. 1 and 2, we show these observational datasets and the best-fit spectrum with and without ALPs in some parameter sets, for instance. Figure 3 represents the excluded region (95% CL) with high-energy γ rays from the Crab Nebula in blue. The red region is excluded by CAST experiments [38]. As shown in Fig. 3,

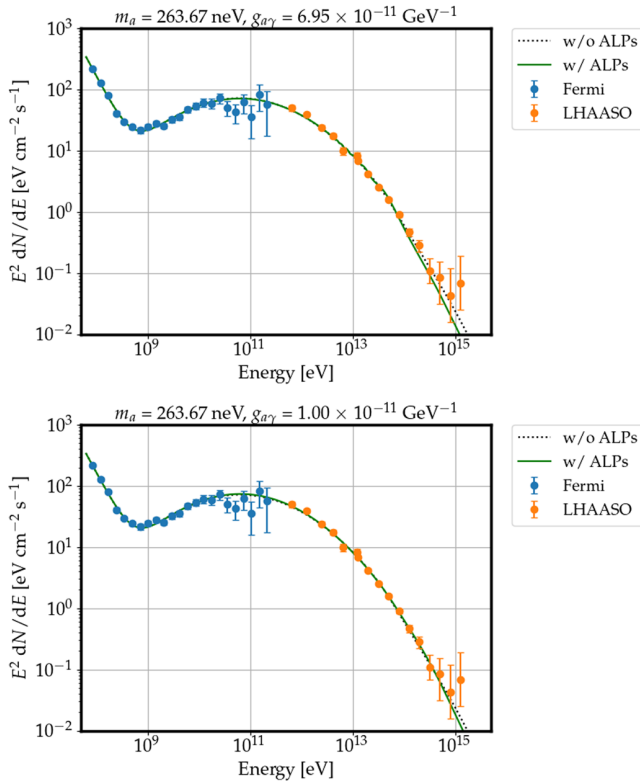


FIG. 1. Spectral energy distribution without and with ALPs in some parameter sets. While the parameter set for the top panel is excluded in Fig. 3, the bottom one is allowed with decreasing the axion-photon coupling $g_{a\gamma}$.

the parameter sets for the top panels in Figs. 1 and 2 are excluded, while ones for the bottom panels are allowed with decreasing the axion-photon coupling $g_{a\gamma}$ in Fig. 1 or the axion mass m_a in Fig. 2. Taking into account the effects of the magnetic field in the Crab Nebula, the resulting constraint reaches up to $g_{a\gamma} \lesssim 1 \times 10^{-11}$ GeV $^{-1}$ at $m_a \simeq 10^{-8}$ eV, and is exceeding the constraints by CAST in the mass range 10^{-10} eV $\lesssim m_a \lesssim 10^{-6}$ eV. The shown parameter space which is excluded by the Crab Nebula in this work might be milder than other γ -ray observations (e.g., NGC 1275 in the Perseus galaxy cluster [139,153], Mrk 421 [118,120,122,127], quasars [136], and other constraints in Ref. [173] and references therein.). However, a reliable constraint on the parameters from observations should be the one derived under the most conservative assumptions. One should avoid obtaining overly stringent constraints under intentionally strong assumptions. Our constraints arise from the fact that the magnetic-field effect appears twice in the SSC process: once in synchrotron radiation and again in the scattering of that radiation via the inverse Compton process. This aspect was overlooked in the previous works. Consequently, even with the most conservative treatment, we obtained unavoidably more stringent constraints. Then, our limit can be regarded to be newly complement to those other limits.

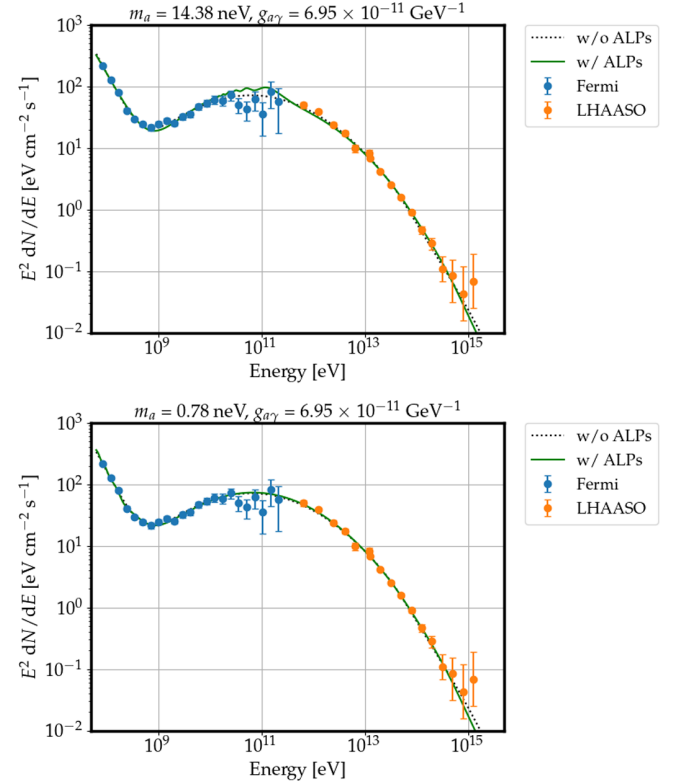


FIG. 2. Same as Fig. 1 but in different parameter sets. The parameter set corresponding to the top panel is excluded in Fig. 3. With decreasing the axion mass m_a , the parameter set for the bottom panel is allowed.

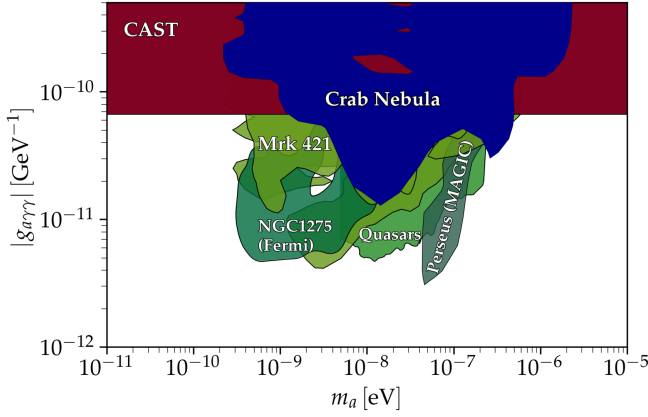


FIG. 3. Excluded region at 95% CL is shown in blue, based on the observations of γ rays from the Crab Nebula. The red region is excluded by CAST experiments [38]. The green region corresponds to existing constraints (e.g., NGC 1275 in the Perseus galaxy cluster [139,153], Mrk 421 [118,120,122,127], quasars [136], and other constraints in Ref. [173] and references therein.). This figure was produced with AxionLimits [173].

We can roughly understand the shape of the excluded region as follows: for sizable conversions from ALPs to photons, the γ -ray energy E and propagation distance L should satisfy

$$E \gtrsim E^* = \frac{m_a^2}{2g_{a\gamma\gamma}B}, \quad (34)$$

$$L \gtrsim L^* = \frac{2}{g_{a\gamma\gamma}B}. \quad (35)$$

E^* and L^* can be written in a suitable unit as [107]

$$E^* \sim \frac{10 \text{ GeV} m_{a,\text{neV}}^2}{g_{11} B_{10 \mu\text{G}}}, \quad (36)$$

$$L^* \sim \frac{10 \text{ kpc}}{g_{11} B_{10 \mu\text{G}}}, \quad (37)$$

with the following notation: $m_{a,\text{neV}} \equiv m_a/\text{neV}$, $g_{11} \equiv g_{a\gamma\gamma}/10^{-11} \text{ GeV}^{-1}$, and $B_{10 \mu\text{G}} \equiv B/10 \mu\text{G}$. The region below the green area in Fig. 3 is allowed since Eq. (35) is not satisfied for Galactic sources in the MW, corresponding to the upper bounds $g_{a\gamma\gamma} \lesssim 1 \times 10^{-11} \text{ GeV}^{-1}$. The right region around $m_{a,\text{neV}} \sim 1000$ is not excluded by the condition in Eq. (34), meaning that this condition [Eq. (34)] necessitates ultra high-energy γ rays with energy above the PeV scale. We could not conservatively exclude the left region for the following reason. E^* becomes smaller than 1 GeV in the parameter space $m_{a,\text{neV}} \lesssim 0.1$ and $1 \lesssim g_{11} \lesssim 50$ and then the ALP-photon conversion is efficient for the energy range observed by Fermi-LAT [169] and LHAASO [158]. However, this effect is compensated by the parameters for the intrinsic spectrum, and we cannot distinguish the case with and without ALPs. These imply

that, roughly speaking, the observed γ -ray energy corresponds to the mass range excluded in this analysis ($0.1 \lesssim m_{a,\text{neV}} \lesssim 1000$).

Here, let us put a comment on statistical analyses. We did not use the so-called Confidence Levels (CL_s) method, which was used in the ALP search with γ -ray observations (e.g., Refs. [121,126,127,140]) as well as high-energy experiments [174–176]. It is known that this method allows us to get less optimistic constraints on considering parameters than the traditional frequentist approach when it is difficult to distinguish the null and alternative hypothesis with experiments. However, the CL_s method requires high computational resources because one needs to optimize the model flux with mock datasets for each point in the broad parameter space. The authors of Ref. [126] compared the CL_s method with the one used in Refs. [118,120,122,153], and concluded that the latter is consistent with the former. This is why we took the latter approach to reduce time for numerical calculations.

V. CONCLUSION

In this paper, we have investigated the importance of magnetic fields in the Crab Nebula for the ALP search with γ rays. The ALP-photon beams experience the γ -ray absorption and the ALP-photon conversion in their journey from the source. For the models of magnetic fields around the Crab Nebula, we considered the variable B -field model [161]. It turns out that the magnetic fields in the Crab Nebula affect how the γ -ray spectrum is distorted by the ALP-photon conversion (Figs. 1 and 2). This effect has not previously been taken into account in the ALP search with γ rays from the Crab Nebula. By considering the magnetic fields of the Crab Nebula, we obtain new constraints reaching down to $g_{a\gamma\gamma} \lesssim 1 \times 10^{-11} \text{ GeV}^{-1}$ at $m_a \simeq 10^{-8} \text{ eV}$ and exceeding the constraints by CAST in the ALP mass range $10^{-10} \text{ eV} \lesssim m_a \lesssim 10^{-6} \text{ eV}$. This consideration can be applicable to other Galactic sources. The analysis in this paper will be a step forward to more precise constraints on the ALP parameters, as briefly mentioned below.

Let us give a comment on the statistical analysis and other model uncertainties. As explained in Sec. IV, we have not used the CL_s method for saving time for numerical calculations. It was shown in Ref. [126] that the statistical analysis used in Refs. [118,120,122,153] and this paper gave consistent results compared to the CL_s method. However, we may have a possibility to obtain more conservative results based on the CL_s method after increasing computer resources. We have also a comment on model uncertainties of the Crab Nebula. Although the Crab Nebula has been observed for long time and in broad energy ranges allowing for developing SSC emission models, there still is a little room for adding other contributions to the spectrum of the Crab Nebula. For example, the authors of Ref. [177] considered a hadronic contribution such as neutral pion decay in addition to the leptonic component in order to fit the γ -ray spectrum

with LHAASO data [158] at PeV scale. If we take this possibility into account, we could extend our analysis performed in this paper. These remain as future works.

ACKNOWLEDGMENTS

This work was in part supported by JSPS KAKENHI Grants No. JP23KF0289, No. JP24K07027 (K. K.), and

No. JP24KJ1153 (H. T.), and MEXT KAKENHI Grant No. JP24H01825 (K. K.).

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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