

Dark photon constraints using the ultrahigh-energy gamma-ray emission from galactic sources. A phenomenological study

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Dark photons (Dphs) appear in theories beyond the Standard Model of particles (SM). Under certain conditions, it is possible to have a mixing between SM photons and Dphs that should be observed as anomalies in the spectrum of astrophysical sources. Our aim is to either find evidence of or set constraints on the existence of Dphs with masses in the range of μeV using observations of two galactic sources observed at TeV energies. We use the flux of the Crab Nebula and MGRO J1908 + 06 at TeV energies reported by High-Altitude Water Cherenkov observatory and Large High Altitude Air Shower Observatory and assuming a model where Dphs can mix with SM photons in the vacuum; we compute the test statistic to search for evidence of Dphs in the form of variations or attenuation in the observed spectrum. We do not find statistically significant evidence of the existence of μeV Dphs. Then, we compute the 68% CL and 95% CL exclusion regions for Dphs with masses in the range from 10^{-8} to 10^{-5} eV and mixing angles with values between 0.01 and 1.0.

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I. INTRODUCTION

Cosmological measurements indicate that dark matter (DM) accounts for about 27% of the energy density of the Universe [1]. Its presence is inferred from gravitational effects on galactic and cosmological scales [2–4], yet its microscopic origin remains unknown. Assuming DM consists of new particles, their properties must be consistent with astrophysical and cosmological constraints. Cold dark matter (CDM) provides the best description of large-scale structure, and the ΛCDM model remains the standard cosmological framework. The most widely studied CDM candidates are weakly interacting massive particles with masses in the 1 GeV–100 TeV range [2,4]. However, the lack of evidence of supersymmetry has drawn attention

to bosonic particles with light masses (10^{-3} eV), such as axionlike particles [5,6] and dark photons (Dphs) [7,8]. Such particles can form condensates on galactic scales and reproduce CDM phenomenology [9,10].

Dphs are vector bosons of a hidden Abelian gauge sector with a renormalizable kinetic mixing with the Standard Model (SM) photon, characterized by a dimensionless parameter χ [7,8]. The kinetic mixing induces photon-Dph oscillations analogous to neutrino oscillations, providing a minimal portal between visible and hidden sectors [11,12]. Depending on their mass μ and mixing strength, such particles can give rise to observable phenomena in both cosmology [7,8] and high-energy astrophysics [13,14].

In particular, photon-Dphs oscillations can modify the propagation of SM photons in astrophysical environments. Such effects have been investigated at larger wavelengths using international gamma-ray astrophysics laboratory observations of x-ray emission to search for signals induced by the three-photon decay of keV Dphs [15] and the searches of oscillating signals in the time residuals of the arrival radio pulses from millisecond pulsars in the Parkes Pulsar Timing Array dataset [16]. In gamma-ray astronomy, in regions with strong magnetic fields, or over Galactic distances, the oscillation length becomes comparable to astrophysical

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scales, leading to flux distortions detectable in very-high-energy (VHE) spectra [13,14]. In an earlier study [14], Zechlin, Horns, and Redondo employed very-high-energy gamma-ray observations of the Crab Nebula to place astrophysical bounds on photon-Dphs oscillations. While pioneering, that work was constrained by the data then available: spectra limited to the sub-TeV–tens of TeV range, large statistical uncertainties at the highest energies, and the absence of PeV-scale measurements.

Current observations extend the Crab spectrum beyond 1 PeV with improved statistics [17]. Moreover, its proximity (~ 2 kpc) and high flux make it a benchmark source for testing scenarios like Dphs.

Among the currently known Galactic gamma-ray sources extending into the ultrahigh-energy regime, MGRO J1908 + 06 offers several advantages as a companion to the Crab Nebula for this analysis. It is one of the brightest and hardest-spectrum Galactic emitters above 10 TeV, with significant detections extending into the multi-100-TeV domain [18,19]. This high flux and spectral hardness yield robust statistical significance at the energies most relevant for probing photon-Dph oscillations. As a result, MGRO J1908 + 06 probes a complementary window in the (μ, χ) phase space.

In this work, we use updated gamma-ray spectra from the Crab Nebula and MGRO J1908 + 06 to test the photon-Dph hypothesis. We model the intrinsic emission of both sources and derive exclusion limits on the (μ, χ) plane by comparing predicted spectra with observational data extending to the PeV scale. The results provide astrophysical constraints complementary to laboratory and cosmological searches, demonstrating the relevance of high-energy gamma-ray astronomy in probing extensions of the SM.

The paper is organized as follows. Section II presents the conversion probability between SM photons and Dphs. In Sec. III, we describe the sources and the observational datasets employed. Section IV introduces the spectral models used for the intrinsic emission. The methodology of our statistical analysis, including joint-likelihood fits and distance-dependent effects, is presented in Sec. V. Results and discussion are given in Secs. VI and VII, respectively. Finally, we summarize our conclusions in Sec. VIII.

II. PHOTON–DARK PHOTON COUPLING

Following [7], the Lagrangian to describe the interactions of SM photons and Dphs can be expressed as

$$\mathcal{L}_0 = -\frac{1}{4}F_{(b)}^{\mu\nu}F_{(b)\mu\nu} - \frac{1}{4}F_{(a)}^{\mu\nu}F_{(a)\mu\nu} - \frac{1}{2}\chi F_{(b)}^{\mu\nu}F_{(a)\mu\nu}, \quad (1)$$

where $F_{(b)}^{\mu\nu}$ is the Faraday tensor from the gauge field A^μ associated to the SM photon and $F_{(a)}^{\mu\nu}$ is the field strength tensor of the electromagneticlike interaction $U(1)_D$ on the hidden sector from the gauge field $A^{\mu'}$ associated to

the Dph. The term χ is the mixing angle¹ that modulates the interaction between both sectors.

An additional term to the Lagrangian arises from the mass acquisition through a Stueckelberg mechanism [20] or the invocation of a “dark Higgs” mechanism after the spontaneous breaking of the $U(1)_D$ symmetry [21]. The mass term in the Lagrangian takes the form

$$\mathcal{L}_{A^{\mu'}} = \frac{1}{2}\mu^2 A^{\mu'} A_{\mu'}. \quad (2)$$

After choosing a convenient change of basis and selecting a Lorentz condition for both sectors, the equation of motion is

$$\left[(\omega^2 + \partial_z^2) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \tilde{M} \right] \begin{pmatrix} A_\mu \\ A'_\mu \end{pmatrix} = 0, \quad (3)$$

where ω is the angular frequency after a Fourier transformation of the temporal derivative [13] and $\tilde{M}$ is a matrix that includes the mixing angle (χ) and mass (μ) terms given by the following expression:

$$\tilde{M} = \begin{pmatrix} \chi^2 \mu^2 & -\chi \mu^2 \\ -\chi \mu^2 & \mu^2 \end{pmatrix}. \quad (4)$$

This means that SM photons could convert into Dphs when propagating through space. Please note that in this case we did not use any information about magnetic fields or spatial distribution of charged particles (electrons) in the medium, so this equation describes the propagation of a SM photon-Dph system in the vacuum.

Assuming that we initially have a system of pure SM photons ($A_\mu \neq 0, A'_\mu = 0$) produced at a gamma-ray source, we want to know how many Dphs exist after a time t and traveling a distance D_L . Then, comparing the propagation matrix of the initial state with the evolved state, the photon–dark photon conversion probability then follows:

$$P_{\gamma \rightarrow \gamma'}(\chi; \mu) = \sin^2(2\chi) \sin^2\left(\frac{\mu^2}{4E} D_L\right), \quad (5)$$

where D_L is the distance from the gamma-ray source to the observation point and E is the energy at which the photon is emitted. The complement of Eq. (5) ($1 - P_{\gamma \rightarrow \gamma'}$) gives us the number of SM photons after a time t and propagation distance D_L or simply the survival probability.

A. Indirect searches

As we mention at the end of the previous section, SM photons, emitted at a gamma-ray source, can undergo

¹Some authors refer to this variable as a kinetic coupling (represented with ϵ) [7]. Other authors use the term mixing angle to describe the coupling between both sectors [14]. We use the last convention.

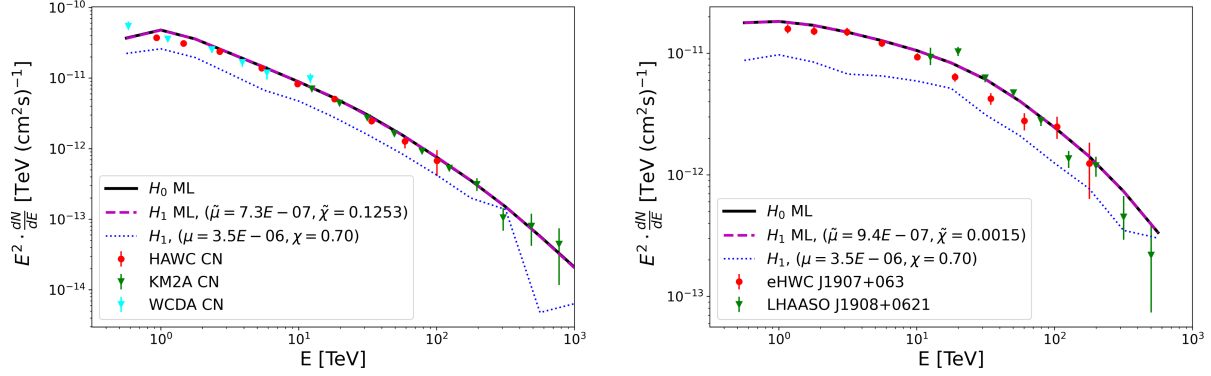


FIG. 1. Differential energy spectra. Left: Crab Nebula's differential energy spectrum. Right: MGRO J1908 + 06's differential energy spectrum. Both plots show the best H_0 fit (black solid line, log-parabola without Dphs, null hypothesis) and the best H_1 fit (magenta dashed line, log-parabola plus Dphs, alternative hypothesis) for the combined data of LHAASO KiloMeter Square Array (KM2A) + Water Cehrenkov Detector Array (WCDA) and HAWC; as well as the fit considering a variation on the dark photon parameters (μ, χ) (blue dotted line) to show the possible effect induced by the DM hypothesis on the photon spectra. All the fits consider systematic uncertainty and energy resolution of the experiments.

oscillations or conversions with Dphs during their propagation through space. Using the survival probability, we can estimate the number of photons per unit of time, per unit of area, per unit of energy (differential flux) that we would observe at Earth. The effect of SM photon-Dph conversion on the observed flux of the Crab Nebula and MGRO J1908 + 06 is shown in Fig. 1. From Eq. (5), we note that the conversion probability depends on the Dph mass μ , the energy E of the SM photon, the mixing angle χ , and the distance D_L to the source where the SM photons were emitted. If we fix the energy of the SM photon to the energy range of TeV gamma-ray observatories, we can determine the parameter space that we are able to explore by requiring that

- (1) the distance to the source is large enough to have at least one transition between SM photons and Dphs and
- (2) the conversion probability is large enough to observe an effect in the gamma-ray flux.

The first point can be estimated from the oscillation length being directly proportional to $\sim E/\mu^2$. The second point depends on the mixing angle and the oscillation length.

We also need to consider interactions of TeV photons with other radiation fields, such as the cosmic microwave background (CMB), starlight, and extragalactic background light. The total effect from those interactions is an extra attenuation to the observed flux. In the end, we need to model this secondary opacity of TeV photons related to the different radiation fields involved, according to the luminosity distance D_L of the gamma-ray source. Each radiation field will introduce additional uncertainties in the analysis, and our goal is to reduce them to the minimum. Then, we consider only galactic sources. This means that only photons with energies above hundreds of TeV suffer from attenuation induced by interactions with other radiation fields [19].

In agreement with the fixed energy of the SM photons and the distance to the sources ($\sim \text{kpc}$), the parameter space of Dphs is limited to the range of masses μ from 10^{-8} to 10^{-5} eV and mixing angles χ larger than 0.001.

III. ASTROPHYSICAL SOURCES

We chose two galactic sources with emission at TeV scales observed by current gamma-ray observatories. In this section, we present the observations for these sources and the relevant parameters to our study.

A. Crab Nebula

The Crab is a system located in the Taurus constellation at a distance of 2 kpc from Earth, resulting from a supernova event. It consists of the Crab pulsar, a neutron star with strong magnetic fields and high-velocity rotation; the Crab Nebula, a pulsar wind nebula result of the interaction of the electrons ejected from the pulsar (pulsar wind) with the medium; and the remnant of the explosion [22].

The Crab Nebula's nearly constant emission has been observed throughout the whole range of the electromagnetic spectrum, widely contributing to a deeper understanding of the processes involved in the emission of high-energy photons that reach the PeV energy scale. The main processes involved in the nebula's VHE ($E \sim 10$ TeV) emission above 60 GeV are synchrotron and inverse Compton, as well as synchrotron self-Compton [23]. The two latter are mainly associated with its ultrahigh-energy (UHE) ($E \sim 100$ TeV–1 PeV) radiation.

These unique characteristics have earned it the title of standard candle for the calibration and design of all telescopes and cosmic ray observatories currently operating. Both the Crab Pulsar and the Crab Nebula have been subject to a great number of studies in the cosmic rays and high-energy astrophysics field, in general, ever since its first observation in AD 1054.

For this source, we are using the latest observations from High-Altitude Water Cherenkov (HAWC) [24] and Large High Altitude Air Shower Observatory (LHAASO) KM2A and WCDA [25,26] of the spectral energy distribution to obtain a dataset consisting of energies from 500 GeV and including LHAASO's PeV photon. The Crab Nebula's spectral dataset is usually described by a log-parabola model, with the observatories' individual estimated parameters $\phi_0 = (2.35 \pm 0.04) \times 10^{-12} \text{ cm}^{-2} \text{ TeV}^{-1} \text{ s}^{-1}$, $\alpha = 2.79 \pm 0.02$, and $\beta = 0.10 \pm 0.01$ found by HAWC [24] and with LHAASO's estimated parameters $\phi_0 = (8.72 \pm 0.10) \times 10^{-12} \text{ cm}^{-2} \text{ TeV}^{-1} \text{ s}^{-1}$, $\alpha = 2.92 \pm 0.04$, and $\beta = 0.18 \pm 0.04$ for the KM2A array [26] and $\phi_0 = (2.32 \pm 0.19) \times 10^{-12} \text{ cm}^{-2} \text{ TeV}^{-1} \text{ s}^{-1}$, $\alpha = 2.57 \pm 0.06$, and $\beta = 0.02 \pm 0.05$ for the WCDA array [25].

B. MGRO J1908 + 06

Another interesting extended UHE gamma-ray source, that would offer a complementary study due to its specific characteristics, is MGRO J1908 + 06. This is a source seen both by LHAASO and by HAWC, reported as LHAASO J1908 + 0621 in [19] and eHWC J1908 + 063 in [27]. It was first seen by Milagro, but its emission has also been detected by other gamma-ray observatories like HESS [28], ARGO-YBJ [29], VERITAS [30], HAWC [27], and LHAASO [19]. Its emission extends past the PeV scale. However, there is not a clear association to this source. Several distances (from Earth to source) have been proposed according to possible counterparts such as 2.37 kpc [31] linked to radio-faint pulsar PSR J1907 + 0602 and a composite scenario where the observed gamma-ray emission is originated by two sources: PSR J1907 + 0602 at a distance of 3.2 kpc and the interacting SNR G40.5-0.5 at 8.7 kpc [32]. The pulsar PSR J1907 + 0637, located at a distance of 7.9 kpc and associated with SNR G40.5-0.5, was also proposed as a counterpart of MGRO J1908 + 06; however, its offset with the gamma-ray emission peak disfavors this scenario [33]. The distance to SNR G40.5-0.5 has larger uncertainties with a lower value of 3.4 kpc [34].

While the nature of the source remains unknown, for this study, we decided to use the lower value of the distance to SNR G40.5-0.5 as a benchmark model. In addition, we explore the impact of the change in the distance to the source on the final Dph constraints. We also assume that the TeV emission from MGRO J1908 + 06 could be explained by only one source. Then, we consider the values of 2.7, 3.4, and 8.7 kpc to study the impact of the distance on the final Dph constraints. From Sec. II A, we see that, once the number of oscillations is fixed, a change in distance impacts the range of Dph masses we can test. However, there is no change in the range of mixing angles. Then, by testing the Dph hypothesis with the different distances associated to MGRO J1908 + 06, we expect that larger distances shift the final exclusion region to lower masses.

In this study, we consider MGRO J1908 + 06 spectral energy distribution observations reported by both HAWC [27] and LHAASO (only KM2A) [19], to build a second dataset with the data's energy range going from 1 up to 500 TeV. This source's spectra are usually described by a log-parabola model as well, with HAWC's estimated parameters $\phi_0 = (0.95 \pm 0.05) \times 10^{-13} \text{ cm}^{-2} \text{ TeV}^{-1} \text{ s}^{-1}$, $\alpha = 2.46 \pm 0.03$, and $\beta = 0.11 \pm 0.02$ and LHAASO's $\alpha = 2.27$ and $\beta = 0.46$ estimated parameters.

IV. SPECTRAL MODELS

For the analysis, we use two spectral models to describe the data and search for evidence of the existence of dark photons. Each spectral model corresponds to a different hypothesis to test: a null hypothesis H_0 , where we do not assume existence of Dph, and an alternative hypothesis H_1 , where we consider SM photon-Dph oscillations. In the following, we describe the parameters of each model.

A. Null hypothesis H_0

For the null hypothesis, we refer to the case where the gamma-ray flux is well described by the standard astrophysical processes occurring at the position of the source (acceleration, diffusion, and others). We can refer to this model as the intrinsic spectrum. Moreover, we should consider other propagation effects, as $\gamma - \gamma$ interactions, that can lead to attenuation of the TeV photons emitted at the source. However, we do not know all the processes in order to extensively explain the observed gamma-ray flux. In order to avoid a model-dependent description of the observed flux, we use a phenomenological approach, where the observed flux is described according to the best model obtained after fitting the observations. In particular, the spectra of the Crab Nebula and MGRO J1908 + 06 are well described by a log-parabola model (see Sec. III) for energies above $\sim \text{GeV}$ as it properly matches the VHE and UHE gamma-ray emissions. The log-parabola follows the equation

$$\frac{dN}{dE} = \phi_0 \left(\frac{E}{E'} \right)^{-\alpha - \beta \ln(\frac{E}{E'})}, \quad (6)$$

where ϕ_0 is the normalization of the spectra, E' is the pivot energy, E is the energy of the gamma-ray, α is the spectral index, and β is the curvature index.

To consider the attenuation effects due to the propagation of TeV gamma rays in our Galaxy, we consider the attenuation, as a function of the energy, used in the analysis by the LHAASO Collaboration of the Crab Nebula and MGRO J1908 + 06 [19].

Furthermore, to calculate the expected flux on Earth, we consider the energy dispersion σ_{eng} and the energy binning of each observatory. For HAWC, the energy resolution is taken from [24], while for LHAASO-WCDA and

LHAASO-KM2A values of the energy resolution are taken from [25,35], respectively. The complete model expectation for the flux $\lambda_{\text{exp}}^{\text{H}_0}$ used for the null hypothesis is

$$\lambda_{\text{exp}}^{\text{H}_0} = \frac{f_{\text{att}}(E_{\text{mean}})}{\sqrt{2\pi}\sigma_{\text{eng}}} \int_{E_{\text{min}}}^{E_{\text{max}}} d\bar{E} \Phi_0 \left(\frac{\bar{E}}{E'} \right)^{-\alpha-\beta \ln(\frac{\bar{E}}{E'})} \times \exp \left(-\frac{(\bar{E} - E_{\text{mean}})^2}{2\sigma_{\text{eng}}^2} \right), \quad (7)$$

with $f_{\text{att}}(E_{\text{mean}})$ encoding the attenuation of TeV gamma rays induced by $\gamma - \gamma$ interactions, E_{mean} the energy at the center of the reported flux points, and $(E_{\text{min}}, E_{\text{max}})$ the energy bin bounds.

B. Alternative hypothesis H_1

Additional to the log-parabola and the $\gamma - \gamma$ interaction considered for the null hypothesis, the alternative hypothesis includes the survival probability of TeV gamma rays obtained from the conversions between Dphs and SM photons when propagating toward Earth. In this case, the expectation $\lambda_{\text{exp}}^{\text{H}_1}$ is described by

$$\lambda_{\text{exp}}^{\text{H}_1} = \frac{f_{\text{att}}(E_{\text{mean}})}{\sqrt{2\pi}\sigma_{\text{eng}}} \int_{E_{\text{min}}}^{E_{\text{max}}} dE (1 - P_{\gamma \rightarrow \gamma'}(\chi; \mu)) \times \Phi_0 \left(\frac{E}{E'} \right)^{-\alpha-\beta \ln(\frac{E}{E'})} \exp \left(-\frac{(E - E_{\text{mean}})^2}{2\sigma_{\text{eng}}^2} \right), \quad (8)$$

where $P_{\gamma \rightarrow \gamma'}$ follows from Eq. (5).

Following a parallel approach to the H_0 expected flux calculation [Eq. (7)], we include the energy dispersion and attenuation factors as well as the averaging of the survival probability and LP component over the widths of the energy bins to obtain the H_1 expected flux model.

V. MODEL FITTING METHODOLOGY

In this section, we describe the different steps to find the best-fit parameters for the null and alternative hypotheses and to obtain the exclusion upper limits (UL).

A. Maximum-likelihood estimates

The maximum-likelihood (ML) method allows us to estimate the value of unknown parameters $\vec{\theta}$ of the probability distribution function, associated to a model of interest λ that represents the hypothesis to test, given a finite experimental dataset with values x_i [36]. The likelihood function $\mathcal{L}$ is the product of the normalized probability density function at the given measurements x_i with uncertainties σ_i :

$$\mathcal{L}(\vec{\theta}; \{x_i, \sigma_i\}) = \prod_{i=1}^n p(x_i; \vec{\theta}, \sigma_i^2). \quad (9)$$

Optimization of $\mathcal{L}(\vec{\theta}; \{x_i, \sigma_i\})$ provides the estimates of the model parameters at which the observed data are the most likely to have come from our model, so that $\lambda(\hat{\vec{\theta}})$ is the value of the model evaluated with the best-fit parameters values [37].

We consider the fluxes and their statistical uncertainties reported by the HAWC and LHAASO Collaborations for the Crab Nebula and MGRO J1908 + 06. Then, we use a Gaussian distribution to estimate the likelihood given the observed fluxes. The log-likelihood for one dataset is

$$\ln(\mathcal{L}(\vec{\theta}; \{x_i, \sigma_i\})) = -\frac{1}{2} \sum_{i=1}^n \left(\frac{(x_i - \lambda(\vec{\theta}))^2}{\sigma_i^2} + \ln(2\pi\sigma_i^2) \right), \quad (10)$$

where $\lambda(\vec{\theta})$ is the model expectation of the flux for the null or alternative hypotheses defined in Eqs. (7) and (8). x_i and σ_i are the observed fluxes and (statistical + systematic) uncertainties, respectively. The log-likelihood is summed over the n energy intervals.

As the observations from different experiments are assumed to be independent between each other, the joint-likelihood (JL) function takes the product of the individual likelihood functions. Using the logarithmic of the functions, this translates into a sum over the different datasets:

$$\ln(\mathcal{L}_{\text{joint}}) = \sum_{\text{exp}} \ln \mathcal{L}_{\text{exp}}(\vec{\theta}). \quad (11)$$

For the same source, we assume the model λ to explain both the reported flux by HAWC and LHAASO. Then, both datasets share the same model parameters $\vec{\theta}$.

B. Test statistic

We use the likelihood ratio test and the test statistic (TS) to perform a comparison between our null and alternative hypotheses and decide which model provides a better description of the data. The TS as a function of the mixing angle χ and Dph mass μ is

$$TS(\chi, \mu) = -2 \ln \left(\frac{\mathcal{L}_0(\alpha, \beta, \phi_0)}{\mathcal{L}_1(\alpha', \beta', \phi'_0, \chi; \mu)} \right). \quad (12)$$

The parameters α, β, ϕ_0 are the best-fit parameters for the null hypothesis, while the parameters α', β', ϕ'_0 are the best-fit parameters obtained for the alternative hypothesis as a function of the mixing angle χ and μ .

C. Data selection and JL fit for the null hypothesis

When performing a joint analysis with observed data from different observatories, we must keep in mind that each observatory has different characteristics and sensitivities.

In the preparation state of the datasets, we take into account the reported systematic uncertainties and energy resolutions for each observatory as we do not have direct access to the counts maps. Both systematic uncertainties and energy resolution are incorporated during the calculation of $\lambda(\vec{\theta})$ in Eq. (10). For HAWC, we consider a global systematic uncertainty of 10% [38], while the energy resolution is taken from [24]. For LHAASO, we consider systematic uncertainties of 8% and 7% for LHAASO-WCDA and LHAASO-KM2A, respectively, as reported in [39]. Values of the energy resolution for LHAASO-WCDA and LHAASO-KM2A are taken from [25,35], respectively. In particular, for KM2A, we assume that the Crab Nebula is observed at zenith angles close to zero and MGRO J1908 + 06 is observed at angles between 20 and 40 deg.

We consider only the flux reported by the HAWC and LHAASO Collaborations, because we want to reduce the systematic uncertainties and the correlation between the different parameters of the null hypothesis.²

After selecting an adequate dataset, we repeat the fit for the null hypothesis over a list of 100 different fixed values for the pivot energy E' , in the energy range from 1 to 100 TeV, to find the value that minimizes the correlation between the spectral index α and the normalization ϕ_0 . Once we have the best pivot energy E' , we repeat the JL fit to find the best-fit parameters for the null hypothesis.

D. JL fit for the alternative hypothesis

For the alternative hypothesis, we consider a mesh in the Dph parameter space in the range from 10^{-8} to 10^{-5} eV in Dph mass μ and from 0.001 to 1.0 in mixing angles χ . First, we find the best-fit value for (χ, μ) simultaneously. Then, we construct the likelihood and TS profiles in the ranges specified previously.

In the case where we do not find any evidence of the existence of Dphs ($TS < 3$) and assuming that likelihood profiles are well behaved, we can define ΔTS as

$$\Delta TS = TS_{\max} - TS(\chi, \mu), \quad (13)$$

with $TS_{\max}$ the value of the test statistic evaluated at the best-fit parameters of the null and alternative hypotheses. For the range of parameters we explore whether the ΔTS profile follows a χ^2 distribution with 2 degrees of freedom. We use the ΔTS criteria to find the exclusion region

²We also considered reported fluxes from HESS, MAGIC, Tibet- γ AS, and VERITAS. However, the uncertainties of the parameters for the null hypothesis and the correlation between normalization ϕ_0 and spectral index α were minimal in the case of considering only HAWC and LHAASO measurements.

TABLE I. The spectral fit values for the Crab Nebula and for MGRO J1908 + 06, obtained from the log-parabola maximum-likelihood estimate, are presented. Additionally, the right ascension (RA), declination (Dec), and distance to the source information for each source are provided, although they are not used as fitting parameters.

Source	Crab Nebula	MGRO J1908 + 06
Distance [kpc]	~ 2.0	From 2.37 to 8.7
RA [°]	83.61 ± 0.02	286.91 ± 0.10
Dec [°]	22.00 ± 0.03	6.32 ± 0.09
E' [TeV]	6.55	15.51
$\log \phi_0$ [(TeV cm ² s) ⁻¹]	-12.456 ± 0.013	-13.390 ± 0.015
α	2.905 ± 0.024	2.556 ± 0.025
β	0.074 ± 0.012	0.093 ± 0.015

($\Delta TS = 5.99$ for 95% CL and $\Delta TS = 2.28$ for 68% CL) on the mass μ and mixing angle χ parameter space.

E. Expected limits

To estimate the impact on the exclusion region induced by systematic uncertainties in the photon spectrum (related to characteristics of the observatories, misclassification of cosmic ray events, etc.); we generate a sample of 200 simulated spectra of the Crab Nebula. We fluctuate the reported fluxes assuming a Gaussian distribution for each bin with mean equal to the measured flux and variance equal to the (statistical + systematic) uncertainty and apply the same fit methodology reported in this section: joint likelihood for null and alternative hypotheses, calculation of TS , and get the exclusion regions (95% CL and 68% CL) on the dark-photon mixing angle χ . For the resultant distribution of the expected UL, we estimate the mean value, 1σ and 2σ confidence intervals (CI).

VI. RESULTS

In this section, we present the different results for the null and alternative hypotheses. The underlying fits were performed using the iMinuit 2.25.2 minimizer [40]³.

A. Null hypothesis fits

For each source, the estimated parameters of the joint differential energy distribution, without considering a photon-dark photon conversion, are reported in Table I. The position parameters of the source are those reported by the observatories, and the pivot energies (E') are those found from minimizing the correlation between normalization and the spectral index α . For the normalization ϕ , the spectral index α , and the curvature index β , the central values and their statistical uncertainties (1σ) are those from the best fit.

³<https://github.com/iminuit/iminuit>

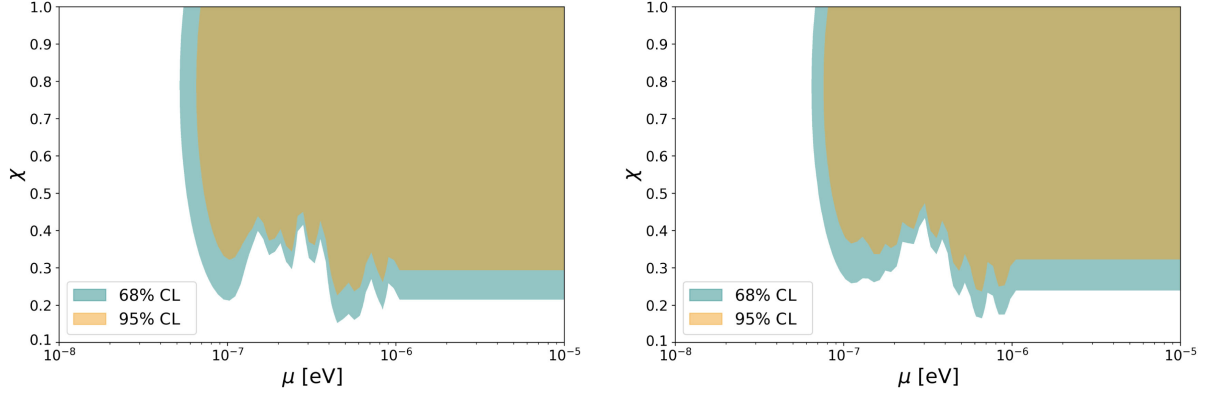


FIG. 2. Exclusion region of the parameter space of dark photons at a 95% CL (gold) and 68% CL (green teal) using the VHE gamma-ray emission of the Crab Nebula (left) and MGRO J1908 + 06 (right).

B. Alternative hypothesis: Exclusion regions

Figure 1 illustrate the spectra obtained after fitting the alternative hypothesis (dashed magenta line) and its comparison to the null hypothesis (solid black line). We also show, as an example, the expected spectrum for a specific mass ($\mu = 3.5 \times 10^{-6}$ eV) and mixing angle ($\chi = 0.70$) (dotted blue line). For the expected spectrum of the alternative hypothesis, we would expect quantitatively significant oscillations, even at PeV energies. After considering the energy resolution of HAWC and LHAASO, the expected effect induced by the mixing with Dphs is an attenuation in the spectrum that is not seen by the observatories. As a reference, the expected spectra shown in Fig. 1 are 9.9σ and 8.8σ away from the best fit for the Crab Nebula and MGRO J1908 + 06, respectively. However, for the H_1 best-fit parameters, these oscillations are not evident and are actually indistinguishable of the H_0 best fit.

From Fig. 2, the exclusion regions of both sources do not provide any information on the mixing angle values for masses below $\sim 6 \times 10^{-8}$ eV, and oscillating UL values throughout the entire range of the exclusion region are observed.

In the same way that the analysis was done for each source and for a fixed luminosity distance, an analysis on MGRO J1908 + 06 for three different luminosity distances was replicated. Figure 3 illustrates how variations in the distance to the source can alter the final constraints of the Dph parameters. In particular, for the case of $D_L = 8.7$ kpc, we see that the exclusion region extends to lower masses (4.02×10^{-8} eV).

In Fig. 4, we present the resulting expected regions. The expected region for a 2σ CI fully contains the 1σ CI region and is consistent with the UL from the observations. In addition, the mean value of the simulated spectra UL mixing angles do not differ significantly from the observed UL.

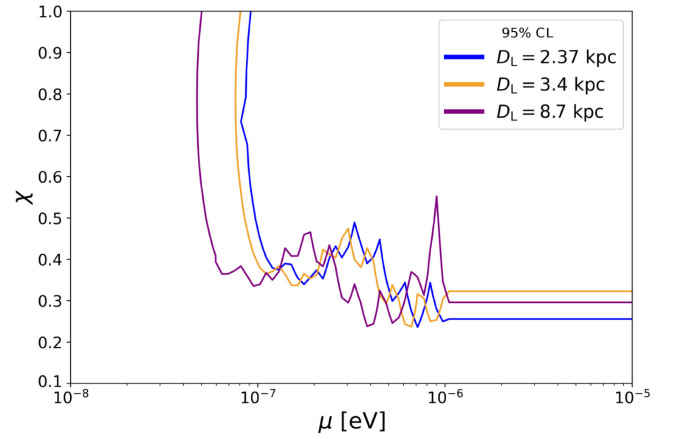


FIG. 3. Exclusion region of the parameter space of dark photons at a 95% CL for different luminosity distance values associated with MGRO J1908 + 06.

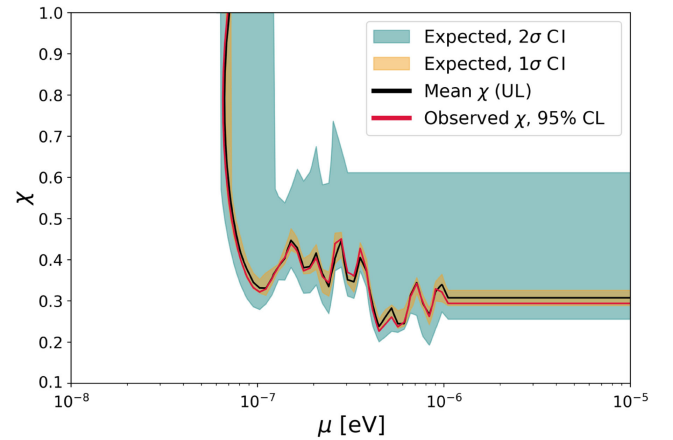


FIG. 4. Crab Nebula's expected region for the excluded mixing angle and Dph mass paired values.

VII. DISCUSSION

A. Null hypothesis

The H_0 fit performed using ML uses the same spectral hypothesis with a change in the pivot energy from those used by the observatories. In result, we get mismatched normalizations. Regardless of using mismatched pivot energies between the ML fit and the fits performed by the observatories, resulting in unlike normalization values, the spectral hypothesis used in both cases remains the same and the spectral and curvature indices stay consistent with HAWC's and LHAASO's measurements.

In [19], the LHAASO Collaboration estimated the magnitude of the attenuation due to CMB and interstellar radiation field. For example, in the direction of the Crab Nebula, 400 TeV photons have a 90% probability of reaching Earth. This attenuation factor is similar to the one expected from the average effect induced by Dphs; see the left panel in Fig. 1. However, in this study we have found that, after including the corresponding attenuation factor $f_{\text{att}}(E)$ in the spectral model from Eq. (8), there was no significant difference from the final estimated values previously found for both H_0 and H_1 spectral fit parameters.

B. Alternative hypothesis and expected limits

The obtained exclusion regions (at 68% CL), for both Crab Nebula and MGRO J1908 + 06, have a similar morphology to the constraints reported by [14], with a notable difference in the extension of the regions. In [14], it appears to report a more restrictive result. However, for this study we are actually considering an updated dataset with energies over 10 TeV. This means that the model fitted has to be adequate for VHE emissions, changing from a simple power-law to a log-parabola spectral hypothesis. As a result, the exclusion regions in this article have a shift in the range that we are able to explore to larger mixing angles and larger masses.

The excluded regions we found from the analysis for the Crab Nebula and MGRO J1908 + 06 correspond to a region of the parameter space where the Dph does not explain all the DM in the Universe. However, models where the Dph does not explain the DM relic density are still viable, corresponding to multicomponent scenarios. Examples are models with a massive fermion DM particle, where Dphs can be produced through annihilation [41].

Dph parameter space constraints have been obtained from several studies throughout a mass range going from 10^{-17} up to 10^5 eV [42,43]. However, while cosmological and experimental studies have previously probed the mass range from 10^{-8} to 10^{-5} eV and constrained χ to be smaller than 10^{-7} (Coulomb tests [43]) or $\sim 10^{-12}$ (CMB observations [8]), our results establish the first astrophysical constraints for this mass range using the most up-to-date observational data available. The robustness of the

astrophysical approach of this work lies in the reproducibility of the methodology for other galactic and extragalactic sources, which may offer an extension of the probed parameter space, as well as in the adaptability of the general framework to more complex spectral models (model-dependent studies) and multicomponent scenario considerations.

What the expected regions (1σ and 2σ CI) depict is that the observed constraints are in agreement with changes within the statistical uncertainties of the observed spectra in a way that we would not be able to distinguish effects induced by the mixing between gamma rays and Dph candidates inside the expected exclusion region.

VIII. CONCLUSIONS

Using the gamma-ray emission at TeV and up to PeV energies of two different sources, we were able to establish bounds to the Dph parameters. We used the ML method to estimate the best-fit parameters of two different spectral hypotheses: a model-independent depiction of the emitted photons and a model including the effect induced by Dphs. By comparing both hypotheses and replicating the analysis for simulated spectra, we obtained exclusion regions that rule out Dph candidates on the mass range from 10^{-8} to 10^{-5} eV and mixing angle between 0.01 and 1.0.

This allows us to consider Dph searches in sources with similar characteristics and/or doing a joint analysis with data from the counts maps of multiple experiments. Another interesting approach to studying the effects of photon-Dph conversions would be to focus on a model-dependent analysis that provides a physical description of the intrinsic spectra instead of assuming a log-parabola hypothesis to explain the spectral energy distribution of the Crab Nebula, as proposed by [44]. Additionally, other model-independent searches based on irregularity tests of the gamma-ray spectral energy distribution [45] should also offer complementary results to methods based on model-comparison tests, as the one we have used on this work.

For this study, we assume that gamma rays travel in an empty space, without the presence of magnetic fields and charged particles in the interstellar medium. While the approximation for null magnetic field seems to be valid for TeV photons, the conversion probability obtained in [11] for nonzero magnetic field may not be valid at TeV energies. More studies are needed to properly estimate the conversions between TeV gamma rays and Dphs in the interstellar medium.

In addition to the previous considerations, we should be able to improve the constraints on the mixing angle χ by using the observations of extragalactic sources (active galactic nuclei or gamma-ray burst). Additional to the expected attenuation of the gamma-ray flux, conversions between SM photons and Dphs would also induce an increase in the observed flux, as some of the Dphs will reconvert to TeV gamma rays when reaching Earth.

However, this requires us to do a proper modeling of the different magnetic fields and environments during the propagation of gamma rays and compute the correct conversion probability valid at TeV energies. Combination of the two previous considerations should allow us to reach the region where the Dphs could account for all the DM in the Universe, without requiring unreal precision measurements of the flux at TeV energies as should be the case if we use only the conversion probability expressed in Eq. (8). This is similar to the existing framework dedicated to search for evidence of axionlike particles, and we may adapt or integrate those methods to search for Dphs at TeV scales.

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A. M. G.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing original draft, and writing review and editing. S. H. C.: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, writing original draft, and writing review and editing. R. A. M.: conceptualization, methodology, funding acquisition, and supervision.

DATA AVAILABILITY

The data that support the findings of this article are openly available [19,24–27].

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- [1] N. Aghanim, Y. Akrami, Ashdown *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020).
 - [2] G. Bertone, D. Hooper, and J. Silk, Particle dark matter: Evidence, candidates and constraints, *Phys. Rep.* **405**, 279 (2004).
 - [3] A. Arbey and F. Mahmoudi, Dark matter and the early Universe: A review, *Prog. Part. Nucl. Phys.* **119**, 103865 (2021).
 - [4] Jonathan L. Feng, Dark matter candidates from particle physics and methods of detection, *Annu. Rev. Astron. Astrophys.* **48**, 495 (2010).
 - [5] L. D. Duffy and K. v. Bibber, Axions as dark matter particles, *New J. Phys.* **11**, 105008 (2009).
 - [6] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner, and K. A. van Bibber, Experimental searches for the axion and axion-like particles, *Annu. Rev. Nucl. Part. Sci.* **65**, 485 (2015).
 - [7] Marco Fabbrichesi, Emidio Gabrielli, and Gaia Lanfranchi, *The Physics of the Dark Photon* (Springer International Publishing, Cham, 2021), 10.1007/978-3-030-62519-1.
 - [8] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, WISPy cold dark matter, *J. Cosmol. Astropart. Phys.* **06** (2012) 013.
 - [9] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Ultralight scalars as cosmological dark matter, *Phys. Rev. D* **95**, 043541 (2017).
 - [10] W. Hu, R. Barkana, and A. Gruzinov, Fuzzy cold dark matter: The wave properties of ultralight particles, *Phys. Rev. Lett.* **85**, 1158 (2000).
 - [11] M. Ahlers, H. Gies, J. Jaeckel, J. Redondo, and A. Ringwald, Light from the hidden sector: Experimental signatures of paraphotons, *Phys. Rev. D* **76**, 115005 (2007).
 - [12] A. Berlin, R. T. D’Agnolo, S. A. R. Ellis, and J. I. Radkovski, Signals of millicharged dark matter in light-shining-through-wall experiments, *J. High Energy Phys.* **08** (2023) 017.
 - [13] J.-F. Fortin and K. Sinha, Photon-dark photon conversions in extreme background electromagnetic fields, *J. Cosmol. Astropart. Phys.* **11** (2019) 020.
 - [14] H.-S. Zechlin, D. Horns, and J. Redondo, New constraints on hidden photons using very high energy gamma-rays from the Crab Nebula, *AIP Conf. Proc.* **1085**, 727 (2009).
 - [15] T. Linden, T. T. Q. Nguyen, and T. M. P. Tait, X-ray constraints on dark photon tridents, *Phys. Rev. D* **112**, 023026 (2025).
 - [16] X. Xue, Z.-Q. Xia, X. Zhu *et al.* (PPTA Collaboration), High-precision search for dark photon dark matter with the Parkes Pulsar Timing Array, *Phys. Rev. Res.* **4**, L012022 (2022).
 - [17] Z. Cao, F. Aharonian, Q. An, L. X. Bai *et al.* (LHAASO Collaboration), Peta-electron volt gamma-ray emission from the Crab Nebula, *Science* **373**, 425 (2021).
 - [18] A. Albert, R. Alfaro, C. Alvarez *et al.*, HAWC study of the ultra-high-energy spectrum of MGRO J1908 + 06, *Astrophys. J.* **928**, 116 (2022).
 - [19] Z. Cao, F. A. Aharonian, An *et al.*, Ultrahigh-energy photons up to 1.4 PeV from 12 γ -ray Galactic sources, *Nature (London)* **594**, 33 (2021).
 - [20] B. K rs and P. Nath, How Stueckelberg extends the standard model and the MSSM, in *PASCOS 2004* (World Scientific Publishing Company, Singapore, 2005), 10.1142/9789812701756_0056.

- [21] C. Mondino, M. Pospelov, J. T. Ruderman, and O. Slone, Dark Higgs dark matter, *Phys. Rev. D* **103**, 035027 (2021).
- [22] E. Amato and B. Olmi, The Crab Pulsar and Nebula as seen in gamma-rays, *Universe* **7**, 448 (2021).
- [23] I. Mochol and J. Petri, Very high energy emission as a probe of relativistic magnetic reconnection in pulsar winds, *Mon. Not. R. Astron. Soc.* **449**, L51 (2015).
- [24] A. U. Abeysekara, A. Albert, R. Alfaro *et al.*, Measurement of the Crab Nebula spectrum past 100 TeV with HAWC, *Astrophys. J.* **881**, 134 (2019).
- [25] F. Aharonian, Q. An, Axikegu, L. X. Bai *et al.*, Performance of LHAASO-WCDA and observation of the Crab Nebula as a standard candle, *Chin. Phys. C* **45**, 085002 (2021).
- [26] Z. Cao, F. Aharonian, Q. An *et al.*, Optimization of performance of the KM2A full array using the Crab Nebula, *Chin. Phys. C* **48**, 065001 (2024).
- [27] HAWC Collaboration, Multiple galactic sources with emission above 56 TeV detected by HAWC, *Phys. Rev. Lett.* **124**, 021102 (2020).
- [28] H. Abdalla, A. Abramowski, F. Aharonian, F. Ait Benkhali, E. O. Angüner *et al.* (H. E. S. S. Collaboration), The H.E.S.S. Galactic plane survey, *Astron. Astrophys.* **612**, A1 (2018).
- [29] B. Bartoli, P. Bernardini, X. J. Bi, C. Bleve, I. Bolognino, P. Branchini *et al.*, Observation of the TeV gamma-ray source MGRO J1908 + 06 with ARGO-YBJ, *Astrophys. J.* **760**, 110 (2012).
- [30] E. Aliu, S. Archambault, T. Aune, B. Behera, M. Beilicke, W. Benbow *et al.*, Investigating the TeV morphology of MGRO J1908 + 06 with VERITAS, *Astrophys. J.* **787**, 166 (2014).
- [31] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs, The Australia Telescope National Facility Pulsar catalogue, *Astron. J.* **129**, 1993 (2005).
- [32] L. Duvidovich, A. Petriella, and E. Giacani, Radio study of the extended TeV source VER J1907 + 062, *Mon. Not. R. Astron. Soc.* **491**, 5732 (2019).
- [33] S. Crestan, A. Giuliani, S. Mereghetti, L. Sidoli, F. Pintore, and N. La Palombara, Multiwavelength investigation of the candidate Galactic PeVatron MGRO J1908 + 06, *Mon. Not. R. Astron. Soc.* **505**, 2309 (2021).
- [34] Ji Yang, Jie-Long Zhang, Zhi-Yong Cai, Deng-Rong Lu, and You-Heng Tan, Molecular gas distribution around the supernova remnant G40.5 0.5, *Chin. J. Astron. Astrophys.* **6**, 210 (2006).
- [35] F. Aharonian, Q. An, Axikegu, L. Bai *et al.*, Observation of the Crab Nebula with LHAASO-KM2A—a performance study, *Chin. Phys. C* **45**, 025002 (2021).
- [36] G. Cowan, *Statistical Data Analysis* (Oxford University Press, New York, 1998).
- [37] C. A. Pruneau, *Data Analysis Techniques for Physical Scientists* (Cambridge University Press, Cambridge, England, 2017).
- [38] A. Albert, R. Alfaro, C. Alvarez *et al.*, Performance of the HAWC observatory and TeV gamma-ray measurements of the Crab Nebula with improved extensive air shower reconstruction algorithms, *Astrophys. J.* **972**, 144 (2024).
- [39] Z. Cao, F. Aharonian, Q. An, Axikegu, L. Bai *et al.*, The first LHAASO catalog of gamma-ray sources, *Astrophys. J. Suppl. Ser.* **271**, 25 (2024).
- [40] F. James and M. Roos, Minuit: A system for function minimization and analysis of the parameter errors and correlations, *Comput. Phys. Commun.* **10**, 343 (1975).
- [41] Michael L. Graesser, R. Andrew Gustafson, Kate Hildebrandt, Varun Mathur, and Ian M. Shoemaker, Detecting boosted dark photons with gaseous detectors, *Phys. Rev. D* **109**, 095015 (2024).
- [42] A. Caputo, A. J. Millar, C. A. J. O’Hare, and E. Vitagliano, Dark photon limits: A handbook, *Phys. Rev. D* **104**, 095029 (2021).
- [43] M. Ahlers, J. Jaeckel, J. Redondo, and A. Ringwald, Probing hidden sector photons through the Higgs window, *Phys. Rev. D* **78**, 075005 (2008).
- [44] L. Dirson and D. Horns, Phenomenological modelling of the Crab Nebula’s broadband energy spectrum and its apparent extension, *Astron. Astrophys.* **671**, A67 (2023).
- [45] H. E. S. S. Collaboration, Constraints on axionlike particles with H. E. S. S. from the irregularity of the PKS 2155 – 304 energy spectrum, *Phys. Rev. D* **88**, 102003 (2013).