

Gamma-ray production in cosmic ray-dark matter scattering as a probe of the axionlike particle-proton interaction

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The production of very-high-energy (VHE, $E_\gamma \gtrsim 100$ GeV) gamma rays resulting from the scattering of high-energy cosmic-ray protons off axionlike particles (ALPs) populating the dark matter halo of the Milky Way is investigated. By employing the latest instrument response functions for current and future facilities, we demonstrate that ground-based VHE gamma-ray observatories, such as H.E.S.S., CTAO, and SWGO, provide a promising and complementary avenue to probe the yet uncharted ALP-proton coupling g_{ap} . Assuming a pointlike proton, our results show that these experiments can reach sensitivity to couplings above 10^{-2} in the $1 - 10^8$ eV ALP mass range, a region that remains largely unexplored by supernova and neutron star cooling observations. Interestingly, we demonstrate that this search channel is capable of probing effective ALP-proton couplings comparable to those predicted in benchmark quantum chromodynamics (QCD) axion scenarios, such as the Kim-Shifman-Vainshtein-Zakharov (KSVZ) and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) models. These findings highlight the potential of VHE gamma-ray astronomy to provide unique constraints on the interaction between ALPs and the baryonic sector and motivate the investigation of the impact of the proton structure on the predictions.

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I. INTRODUCTION

The investigation of gamma-ray production resulting from the scattering of high-energy cosmic-ray (CR) protons off dark matter (DM) has become a well-established approach to probing the couplings and masses of particles proposed in various beyond the Standard Model (BSM) scenarios (see, e.g., Refs. [1–9]). This methodology provides a unique window into the DM sector, particularly for candidates that interact weakly with standard model baryons or leptons. Specifically, Ref. [9] focused on scenarios where the dark matter is composed of axionlike particles

(ALPs), which are pseudo-Nambu-Goldstone bosons that naturally arise in BSM theories [10–12] from the breaking of a $U(1)$ symmetry (for a review, see Ref. [13]). That work derived new constraints on the magnitude of the ALP couplings to photons and electrons considering the current and future astrophysical measurements of very-high-energy (VHE, $E \gtrsim 100$ GeV) gamma rays.

In this paper, we extend the analysis performed in Ref. [9], by exploring the potential to constrain the coupling between ALPs and protons (g_{ap}). We consider the gamma-ray production resulting from the scattering of energetic CR protons off ALPs populating the Milky Way (MW) DM halo. This process is illustrated in the Feynman diagram in Fig. 1. An incoming CR proton of energy E_i collides with an ALP a of mass m_a , loses a fraction of its energy, and yields a gamma ray of energy E_γ in the final state. The cross section for this process, $\sigma_{pa \rightarrow p\gamma}$, depends on the ALP mass and the magnitude of the ALP—proton coupling, represented by the blue vertex in Fig. 1. For a pointlike proton, as assumed in our analysis, the effective Lagrangian is well known [14] and the cross section can be calculated using perturbative theory. The associated

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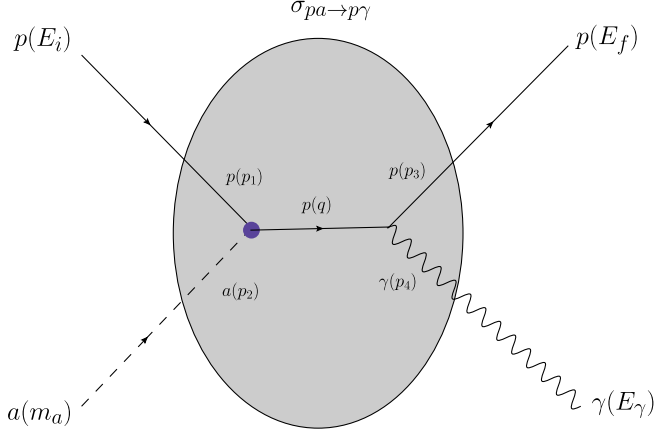


FIG. 1. Gamma-ray production via ALP-proton interaction. The blue blob represents the ALP-proton coupling.

gamma-ray flux can be calculated given the functional form of the cosmic ray flux and the MW DM distribution. Our goal is to evaluate the sensitivity of current and forthcoming VHE gamma-ray observatories, such as the Cherenkov Telescope Array Observatory (CTAO) [15] and the Southern Wide-field Gamma-ray Observatory (SWG0) [16], particularly when targeting the Galactic Center (GC). As we will demonstrate, these observatories will be able to probe the (g_{ap}, m_a) parameter space in regions currently unexplored by supernova cooling limits, neutron star observations, or neutrino water Cherenkov detectors (for recent studies, see Refs. [17–22]).

The paper is organized as follows. In Sec. II we describe gamma-ray production mechanism from CR proton-ALP scattering. In Sec. III, we establish the methodology, both for the experimental observations of this signal, and for the statistical analysis used to derive sensitivity prospects. Finally, in Sec. IV, we present our results, comparing the reach of CTAO, SWGO and a H.E.S.S.-like observatory against existing constraints in the parameter space of the CR proton-ALP interaction.

II. GAMMA RAY PRODUCTION VIA PROTON CR-ALP INTERACTIONS

Initially, we briefly review of the formalism developed to compute the expected gamma-ray flux associated with the interaction between VHE cosmic-ray proton and the ALPs populating the Milky Way DM halo. In our analysis, we focus on photophobic ALPs, i.e., processes where the ALP does not couple directly to photons, making the process represented in Fig. 1 the dominant contribution. Moreover, we assume that the proton remains intact in the final state after the interaction with the ALP, i.e., the ALP couples to the proton as a whole and the process is described in terms of the ALP-proton coupling g_{ap} . For simplicity, we treat the proton as a pointlike fermion. Such an approximation is

justified for light ALPs, with masses smaller than 1 eV, since in this case the momentum transfer is very small, which implies that the corrections associated with the proton structure are negligible. However, for heavier ALPs, such corrections can become important. As a consequence, our predictions for large masses must be considered as a benchmark projection subject to possible proton-structure corrections. For a pointlike proton, the ALP phenomenology can be determined assuming the effective interaction Lagrangian for a ALP interacting with a pointlike fermion discussed in Ref. [14], which is given by

$$\mathcal{L}_{\text{int}} \supset g_{ap} a \bar{p} i \gamma_5 p, \quad (1)$$

where a and p represent the ALP and proton, respectively. In recent literature, values of the ALP-proton coupling between 10^{-9} and 10^{-6} have been excluded for ALP masses up to ≈ 100 MeV based on observations of supernova explosions [17–20]. More recently, the authors of Ref. [22] demonstrated that the parameter space region characterized by $10^{-4} \leq m_a \leq 1.0$ MeV and $3 \times 10^{-6} \leq g_{ap} \leq 4 \times 10^{-5}$ can be explored using neutrino water Cherenkov detectors, such as Super-Kamiokande [23]. In the following, we investigate whether unexplored regions of this parameter space can be probed by the ongoing and near-future very-high-energy gamma-ray observatories.

Following Refs. [9, 14], the expected gamma-ray flux from any region of the sky within a solid angle $\Delta\Omega$ is given by

$$\frac{d\Phi_\gamma(E_\gamma)}{dE_\gamma} = \frac{1}{m_a} \times D(\Delta\Omega) \times \int_{E_p^{\min}(E_\gamma)} dE_p \frac{d\Phi_p}{dE_p}(E_p) \cdot \frac{d\sigma_{p+a \rightarrow p+\gamma}}{dE_\gamma}(E_p, E_\gamma), \quad (2)$$

where the D -factor corresponds to the integral of DM density in the MW halo along the line-of-sight (l.o.s.) s and over $\Delta\Omega$. The DM density distribution is assumed to follow the Navarro-Frenk-White (NFW) profile parametrization.¹ Moreover, $E_p^{\min}(E_\gamma)$ is the minimum CR proton energy required to produce a gamma ray with energy E_γ [9], and $d\Phi_p/dE_p$ is the energy-dependent CR proton flux in the GC region. We assume this flux follows a power-law behavior given by $d\Phi_p/dE_p(E_p) = \Phi_0 (E_p/10 \text{ TeV})^{-\Gamma}$, with $\Phi_0 = 4 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1} \text{ sr}^{-1}$ and $\Gamma = 2.4$. Following Ref. [24], the baseline value of $E_p^{\max}$ is set to 1 PeV.

Finally, the differential cross section, $d\sigma(p + a \rightarrow p + \gamma)/dE_\gamma$, is given by [14]

¹A detailed analysis of the dependence of the expected gamma-ray flux on the DM distribution has been performed in Ref. [8].

$$\begin{aligned}
\frac{d\sigma_{p+a \rightarrow p+\gamma}}{dE_\gamma} &= \frac{1}{32\pi m_a |\vec{p}|^2} \left(\frac{1}{2} \sum_{\text{spins}} |\mathcal{M}|^2 \right) \\
&= \frac{1}{32\pi m_a |\vec{p}|^2} \left\{ e^2 g_{ap}^2 \times \left[-\frac{2(m_p^4 - m_p^2(2m_a^2 + s + u) + su)}{(u - m_p^2)^2} - \frac{2(m_p^4 - m_p^2(2m_a^2 + s + u) + su)}{(s - m_p^2)^2} \right. \right. \\
&\quad \left. \left. + \frac{4(m_p^4 - 3m_a^2 m_p^2 - m_p^2(2s + t))}{(s - m_p^2)(u - m_p^2)} + \frac{4(s - m_a^2)(s + t)}{(s - m_p^2)(u - m_p^2)} \right] \right\}, \tag{3}
\end{aligned}$$

with $\mathcal{M}$ being the associated scattering amplitude, $|p|^2 = E_p^2 - m_p^2$, and the Mandelstam variables are defined as $s = m_p^2 + m_a^2 + 2E_p m_a$, $t = q^2 = m_a^2 - 2E_\gamma m_a$ and $u = 2m_p^2 + m_a^2 - s - t$. Plugging this cross section in Eq. (2) allow us to estimate the expected gamma-ray flux for a given set of (m_a, g_{ap}) values, or, conversely, to use experimental flux measurement to constrain these parameters.

III. METHODOLOGY

A. Observational strategy

This analysis focuses on computing the expected sensitivity of three ground-based observatories to the gamma-ray signature associated with the IC scattering of CR protons off ALPs in the GC region. We consider one current and two near-future gamma-ray observatories: H.E.S.S., CTAO and SWGO, utilizing publicly available instrument response functions (IRFs) for sensitivity computations.

H.E.S.S. is an array of five Imaging Atmospheric Cherenkov Telescopes (IACTs) located in the Khomas Highlands of Namibia [25], providing an ideal location for observing the GC region. The energy-dependent acceptance and residual background flux for H.E.S.S. observations of the inner halo of the MW are extracted from Ref. [7]. These data represent the most up-to-date H.E.S.S.-like observations of the GC region, obtained through the inner galaxy survey carried out since 2015. We define a region of interest (ROI) of radius 3° around the GC, further divided into 27 concentric rings of 0.1° width, assuming a homogeneous exposure time of 500 hours.

The next generation of IACTs, the Cherenkov Telescope Array Observatory (CTAO) [15], will consist of sites in both the Northern and Southern Hemispheres. CTAO is designed to detect gamma rays between 20 GeV and 300 TeV, improving flux sensitivity by up to an order of magnitude relative to current facilities, while offering angular resolution improvement by a factor of 2–3 and energy resolution as low as 5% at TeV energies. Since our target is the GC, we employ the expected performance of the Southern array in its *Alpha* configuration, comprising 14 medium-sized and 37 small-sized telescopes. The corresponding IRFs are taken from the publicly available *prod5-v0.1* dataset [26], specifically the *Performance-prod5-v0.1-South-20 deg* configuration. For CTAO we consider a ROI with a radius

of 5° around the GC and 500 hours of homogeneous observation time, divided into 47 concentric rings.

Finally, we incorporate the Southern Wide-field Gamma-ray Observatory (SWGO) [16,27], a planned wide-field water Cherenkov detector to be built in Chile. SWGO is designed to cover energies from a few hundred GeV to the PeV domain. In this work, we utilize the Strawman design and publicly available IRFs described in Ref. [28]. The exposure in this case consists of 10 years of observation time, covering a 10° circular ROI around the GC, divided into 49 concentric annuli of 0.2° width.

A crucial ingredient of any VHE gamma-ray sensitivity determination is the characterization of backgrounds. For both IACTs and wide-field water Cherenkov detectors, the dominant background arises from the misidentification of hadronic cosmic rays. While most CR-induced showers can be distinguished from gamma-ray events, a nondiscriminated fraction remains as the residual background. Since no anisotropy has been detected in the VHE CR flux to date, this background is assumed to be spatially isotropic [29]. It can be estimated using blank-field observations in extragalactic regions [6] or from detailed Monte Carlo simulations of the detector response [30]. In our analysis, the residual background is derived directly from the IRFs of each observatory. Figure 2 shows the expected background as seen by CTAO, SWGO and a H.E.S.S.-like observatory as coming from a 5° region around the GC.

In addition to instrumental backgrounds, the GC contains several astrophysical VHE gamma-ray sources and diffuse structures, including the central source HESS J1745–290 [31], the supernova remnant HESS J1745–303 [32], and a diffuse component correlated with dense molecular clouds in the central molecular zone [24], as well as other sources in the Galactic plane [33]. Modeling these emissions self-consistently is complex and beyond the scope of the present analysis. Instead, we adopt the standard and robust approach of masking bright and extended VHE gamma-ray structures [7]. Following previous GC analyses, we exclude a band of Galactic latitudes between $\pm 0.3^\circ$ to minimize contamination from these sources.

B. Statistical analysis

The expected signal counts N_{ij}^S in each energy bin i and spatial bin j are computed by integrating the

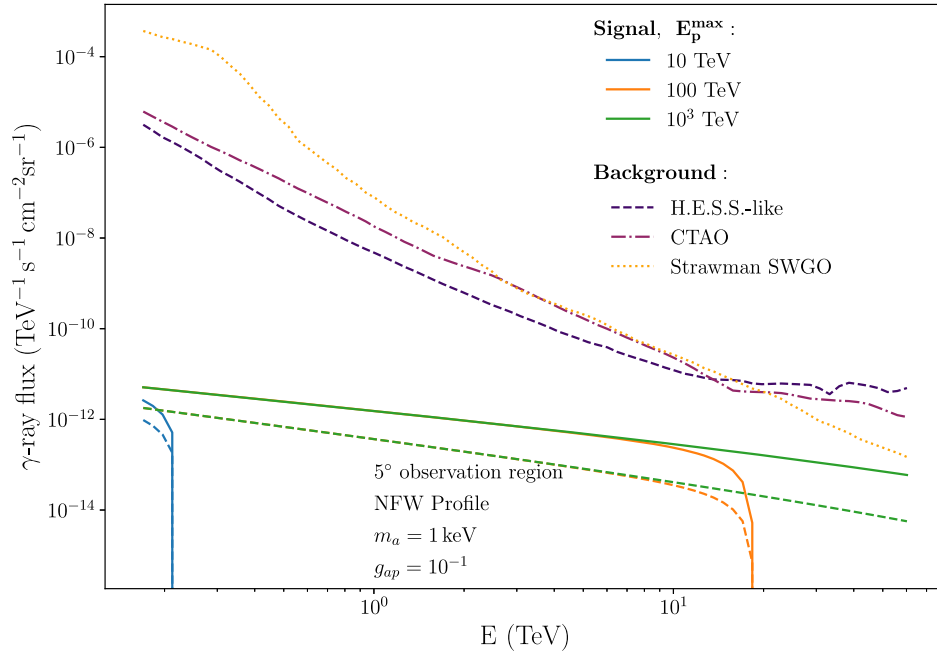


FIG. 2. Energy differential gamma-ray flux for the expected ALP-CRp IC scattering signal, as well as the expected residual background from a 5° region around the GC region. Here we assume three different observatories: a H.E.S.S.-like array, the CTAO and the SWGO strawman design [28]. The expected fluxes assume an ALP of mass $m_a = 1$ keV.

energy-differential gamma-ray flux from Eq. (2), convolved with the energy-dependent acceptance A_{eff}^γ and the energy resolution. The latter is modeled as a Gaussian $G(E - E')$, where E and E' correspond to the reconstructed and true energies, respectively. The resulting expression for N_{ij}^S is

$$N_{ij}^S = T_{\text{obs},j} \int_{E_i - \Delta E_i/2}^{E_i + \Delta E_i/2} dE \times \int_{-\infty}^{\infty} dE' \frac{d\Phi_{ij}^S}{dE'}(\Delta\Omega_j, E') A_{\text{eff}}^\gamma(E') G(E - E'), \quad (4)$$

where $T_{\text{obs},j}$ is the exposure in the spatial bin j . Expected background counts N_{ij}^B are calculated using the same expression by replacing the signal flux with the residual background flux.

The sensitivity computation for each observatory is determined using a log-likelihood ratio test statistic (TS), a widely adopted method in gamma-ray analyses [7,8,34,35]. We employ an on-off strategy in which the ROIs serve as on regions, and the off regions, with the same angular size, are used to estimate the background. The likelihood is binned in both energy and spatial dimensions, and is written as

$$\mathcal{L}_{ij} = \text{Pois}[N_{ij}^S + N_{ij}^B, N_{ij}^{\text{ON}}] \text{Pois}[\bar{N}_{ij}^S + \bar{N}_{ij}^B, N_{ij}^{\text{OFF}}], \quad (5)$$

where $\text{Pois}(k, \lambda)$ stands for the Poisson distribution and N_{ij}^{ON} and N_{ij}^{OFF} denote the observed events in the ON and

OFF regions, respectively. N_{ij}^S and $\bar{N}_{ij}^S$ represent the expected signal in these regions, while N_{ij}^B and $\bar{N}_{ij}^B$ are the corresponding background contributions. Since the residual background is derived from Monte Carlo simulations, we set $\bar{N}_{ij}^S = 0$.

The full likelihood is the product of $\mathcal{L}_{ij}$ over all bins. For a fixed ALP mass m_a and DM distribution, the signal amplitude N_{ij}^S is the only free parameter and depends solely on the coupling constant g_{ap} . The TS is defined as

$$\text{TS}(m_a) = -2 \log \frac{\mathcal{L}(g_{ap}, m_a)}{\mathcal{L}(\hat{g}_{ap}, m_a)}, \quad (6)$$

where $\hat{g}_{ap}$ maximizes the likelihood for a given mass. In the large-statistics limit, the TS follows a χ^2 distribution with one degree of freedom. One-sided 95% upper limits on g_{ap} are obtained by determining the coupling value above the best fit for which $\text{TS} = 2.71$. We derive sensitivity expressed as 95% mean expected upper limits on the (g_{ap}, m_a) parameter space following the Asimov procedure [36] widely used for sensitivity computations (see, e.g., Refs. [8,9,37]). In this approach, the expected counts in each bin are taken as the expected observation values, so that no statistical fluctuations are included. The profile likelihood ratio is then evaluated as a function of the signal strength parameter, which in our case is determined by the g_{ap} coupling. This procedure provides the median expected exclusion reach in the absence of signal

and avoids the need for computationally expensive Monte Carlo pseudoexperiments.

IV. RESULTS AND DISCUSSION

In Fig. 3, we present the 95% CL mean expected upper limits on the ALP-proton coupling g_{ap} as a function of the ALP mass m_a , derived from our analysis of H.E.S.S.-like, CTAO, and SWGO potential observations. To provide context for these results, we include current exclusion regions derived from observations of supernova SN 1987A [38], solar axion searches from the Sudbury Neutrino Observatory (SNO) [39], torsion balance experiments [40,41], and measurements of the Casimir effect [42] (for a compilation of these exclusion regions, see Ref. [43]).

Our results demonstrate that ground-based VHE gamma-ray observatories are capable of probing a vast and currently unexplored region of the (g_{ap}, m_a) parameter space. In fact, in the mass range of $\sim 10^2$ to 10^4 eV, these observatories can reach a sensitivity down to $g_{ap} \sim 5 \times 10^{-2}$. In the heavier mass range of $\sim 10^5$ – 10^8 eV the ground-based gamma-ray observatories considered in this study are able to probe effective coupling regions comparable to those predicted in benchmark QCD axion scenarios in the MeV mass range.

However, as already emphasized in the Introduction, our results for this mass range must be considered as an approximation, since the proton-structure was not taken into account. The expected sensitivity grows from the H.E.S.S.-like observatory, to CTAO and then To SWGO. This is due to the technological observatory advances, and also due to the fact that SWGO can probe a much larger field-of-view with full-day observation cycle.. The QCD axion provides a natural solution to the strong CP problem, and its coupling to nucleons is a fundamental prediction of specific models. We consider two benchmark scenarios: KSVZ model [44,45], where the axion couples to new heavy quarks, and the DFSZ model [46,47], where the axion couples to standard model quarks at the tree level.

As shown by the golden shaded region in Fig. 3, the effective couplings predicted in benchmark QCD axion scenarios within the MeV range fall within the sensitivity reach of the ground-based observatories considered here. This is significant because this specific mass-coupling window is notoriously difficult to access via traditional axion haloscopes or stellar cooling arguments. Our analysis shows that the CR-DM scattering channel provides a complementary phenomenological probe of ALP-proton interactions in this regime. In addition, such a result

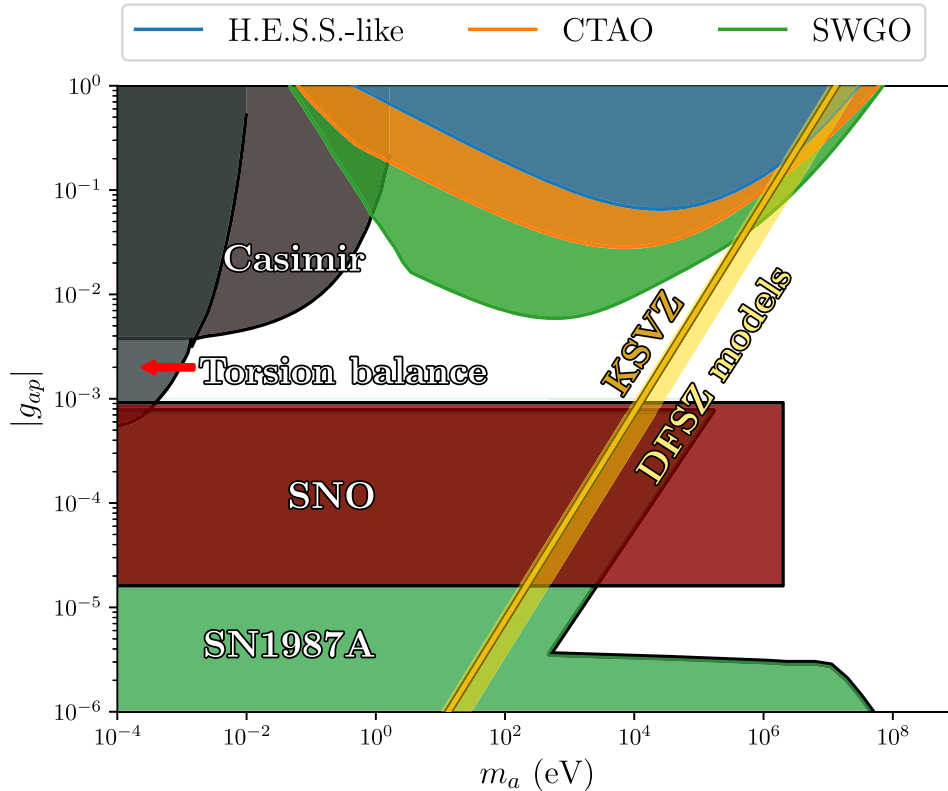


FIG. 3. Sensitivity on the ALP-proton coupling g_{ap} versus ALP mass m_a . The sensitivity is expressed as 95% CL mean expected upper limits. The sensitivity in the (m_a, g_{ap}) plane are derived assuming the IC scattering of ALPs and CRp in the GC region, as observed by a H.E.S.S.-like observatory, CTAO and SWGO. We also show exclusion regions from SN1987A observations, SNO, torsion balance and Casimir, all extracted from Ref. [43]. The golden curve and shaded region represents the portion of the parameter space corresponding to QCD axions.

motivates the investigation of the impact of proton-structure corrections in our predictions, which we intend to study in a forthcoming work.

In summary, we have investigated the sensitivity of current and future VHE gamma-ray ground-based observatories to ALP-proton interactions through the production of secondary gamma rays in the MW halo. We have demonstrated that H.E.S.S., CTAO, and SWGO are expected to reach improved sensitivities on constraints to the g_{ap} coupling relative to existing limits in the $1 - 10^8$ eV mass range. Such results indicate that astrophysical measurements in the VHE gamma-ray regime are a promising alternative to investigate the ALP-proton couplings, enabling a complementary probe of effective ALP-proton interactions relevant for dark matter phenomenology.

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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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