PROCEEDINGS OF SCIENCE

# ALPs searches on galactic sources using the HAWC Observatory

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Axion-like particles could be potential dark matter candidates, whose conversion from gamma rays could have an impact on the spectra of extremely powerful astronomical gamma-ray sources. For galactic sources, the overall result of this coupling may be reflected as an attenuation of the gamma-ray spectrum at energies above several tens of TeV. Therefore, multi-TeV observatories like the High Altitude Water Cherenkov (HAWC) Observatory would have a unique opportunity to investigate the parameters of ALPs candidates in the mass range from fractions of a neV up to tens of $\mu$eV. In this study, we present a preliminary study of the spectrum observed of the TeV gamma-ray source eHWC J1908+63, constraining the ALP coupling to better than $10^{-12}$ GeV$^{-1}$

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## 1. Introduction

The axion is a hypothetical particle proposed to solve the strong CP problem in QCD through the so-called Peccei-Quinn mechanism , which can be generalized to broader theories such as string theory, resulting in particles known as Axion-Like Particles (ALPs) [1] . Both the axion and ALPs have been proposed as candidates for dark matter, offering an intriguing possibility due to their characteristic of being in a "cold" state, meaning they would move at low velocities in accordance with mentioned ΛCDM cosmological model [2, 3] .

Unlike heavy dark matter candidates like Weakly Interacting Massive Particles (WIMPs), the ALPs are very light particles, ranging from eV to as low as $10^{-20}$ eV, making direct detection challenging. However, one distinguishing feature of ALPs is their coupling to electromagnetism, which allows for photon-ALP conversion under high-energy (TeV scale) and strong magnetic field conditions. This conversion could manifest as anomalies in the spectrum of a source emitting high-energy photons [4].

Previous studies using Fermi-LAT and H.E.S.S [5] focused on distant emission sources to ensure oscillations and examined regions with active galaxies such as PKS 2155-304 and PG 1553+113. However, this approach introduced systematic errors due to the need to consider the Extragalactic Background Light (EBL) in their analysis. Nevertheless, with increasingly sensitive instruments capable of detecting very high energies [6], the distance requirement becomes less stringent, allowing for the study of galactic sources with emission at such energies [7] (tens or hundreds of TeV), which can be found near pulsars, such as supernova remnants or objects known as TeV Halos. These sources have been reported by HAWC [8], enabling the study of possible photon-ALP conversions with galactic sources.

Studying galactic sources offers significant advantages over extragalactic sources, as there is no need to consider the effects of the EBL, and the galactic magnetic field can be modeled more accurately instead of relying on a model of the distant source's field and the intergalactic magnetic field. These advantages significantly reduce systematic errors, allowing for a better analysis of the spectrum at very-high-energies from galactic sources.

Based on the above, the objective of this study is to investigate the possible effects of ALPs on the spectrum of ultra-high-energy sources detected by the HAWC observatory emitting above tens of TeV in order to establish exclusion limits on two fundamental parameters of ALPs: their mass and coupling constant.

## 2. Source eHWC-J1908+063

In the present work we choose the source eHWC J1908+063 detected by several experiments including MILAGRO [9], H.E.S.S [10], and HAWC [11] . We use gamma-ray data from HAWC whose reported photon energy reaches above 170 TeV. The best fit spectrum reported for this source is a Log-Parabola function, and the distance reported is 3.2kpc. The Galactic magnetic field is composed of two main components: a random component with small coherence scales and a large-scale regular component. The random component, which exhibits self-cancellation in oscillation, is not considered in our analysis. Instead, we focus on the regular Galactic B-field model described in [12] where the average magnitude of the magnetic field is approximately $1\mu$G.



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## 3. Analysis

In this work we use HAWC data, using an updated reconstruction algorithm known as Pass 5. We test different models of ALPs hypothetical anomalies induced by ALPs in the specturm of the source eHWC J1909 +063.

It is assumed [7] that the observed flux by HAWC takes the form:

$$\frac{d\phi}{dE_\gamma} = \left(1 - P_{\gamma\to a}\right) \cdot f_{att} \cdot \left.\frac{d\phi}{dE_\gamma}\right|_{\text{source}}, \tag{1}$$

where $\left.\frac{d\phi}{dE_\gamma}\right|_{\text{source}}$ is the intrinsic flux of the source without considering the conversion effect, $P_{\gamma\to a}$ is the photon-ALP conversion probability, and the factor $f_{att}$ denotes the attenuation of the astrophysical flux due to gamma-ray dispersion. In the case of galactic sources, the $f_{att}$ factor can be considered $f_{att} \approx 1$ due to the proximity of the source and the high-energy of the photons. Therefore, the conversion probability is the most relevant factor in the potential distortion of the intrinsic flux. In particular, for polarized photons, the following approximation can be used [4]:

$$P_{\gamma\to a}(E_\gamma) = \left(1 + \frac{E_c^2}{E_\gamma^2}\right)^{-1} \sin^2\left(\frac{g_{a_\gamma} B_T L}{2}\sqrt{1 + \frac{E_c^2}{E_\gamma^2}}\right), \tag{2}$$

where $B_T$ is the transverse magnetic field to the photon's direction of motion, $L$ is the distance traveled within the magnetic field, $g_{a\gamma}$ the coupling constant and $E_c$ is the so-called critical energy defined as:

$$E_c = \frac{|m_a^2 - \omega_{pl}^2|}{2 g_{a\gamma} B_T}, \tag{3}$$

where $m_a$ is the ALP mass and $\omega_{pl}^2 = \frac{4\pi\alpha n_e}{m_e}$ the plasma frequency of the medium, with $n_e$ being the electron density, $m_e$ the electron mass and $\alpha$ the fine structure constant.

## 4. Results and discussion

Using the Log-Likelihood-Ratio (LLR) exclusion criterion, we obtain the Log-Likelihood (LL) using the HAWC software called ZEBRA, with which we obtain:

$$LLR = -2\left(\ln \mathcal{L}(\theta_0; m_a, g_{a\gamma} = 0) - \ln \mathcal{L}(\hat{\theta_{m_a, g_{a\gamma}}})\right), \tag{4}$$

where $\ln \mathcal{L}(\theta_0; m_a, g_{a\gamma} = 0)$ is the LL under the null hypothesis (no ALPs) and the $\ln \mathcal{L}(\hat{\theta_{m_a, g_{a\gamma}}})$ the LL under ALP hypothesis with a certain pair of $m_a$ and $g_{a\gamma}$.

The parameters on distance and magnetic field used in Figure 1 were the most *conservative* values mentioned in the literature [13],[12] in order to minimize the uncertainties. In Figure 2 different values on distance and magnetic field were used to calculate the exclusion region and also the comparison with other observatories that have set exclusion regions for ALPs[14],[15],[16], [17] .



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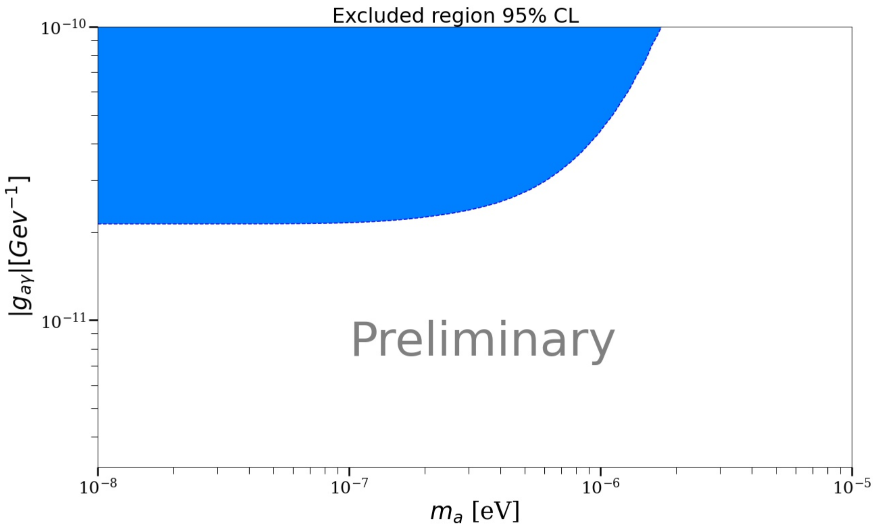


**Figure 1:** Exclusion region obtained using eHWC J1908-063 data with $L$ = 3.2kpc and $B_T$ = 1$\mu$G

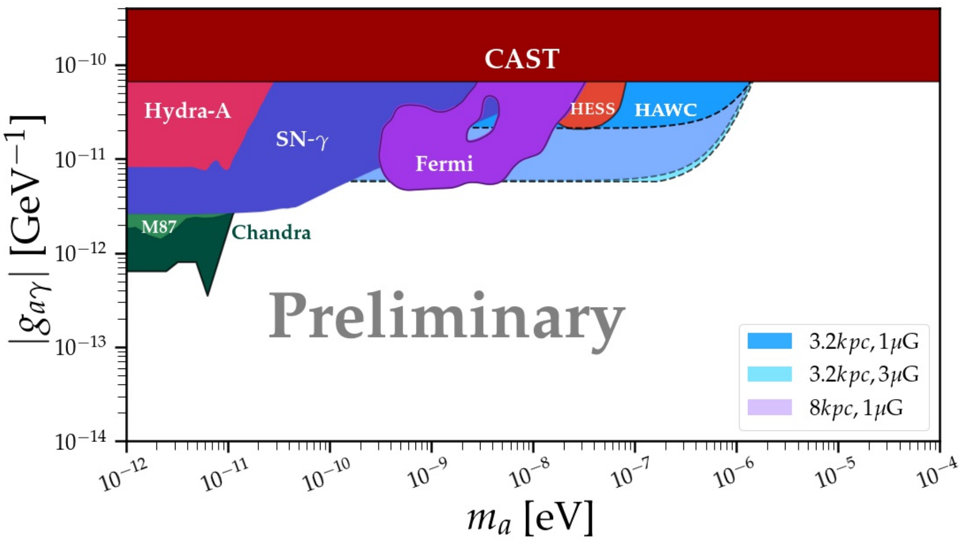


**Figure 2:** Different regions obtained varying distance and magnetic field and the regions obtained with previous studies.

In this work we show that using galactic sources emitting at very high energy it is possible to set limits on the $m_a$ and $g_{a\gamma}$ parameters for ALPs. The different sources of uncertainty that may affect the region obtained must be taken into account, such as distance and the magnetic field, however, even using the most restrictive values to minimize such uncertainties, it is possible to obtain an exclusion region that complements the regions obtained by other high-energy observatories.

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