

Searches for Axionlike Particles Using γ -Ray Observations

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Axionlike particles (ALPs) are a common prediction of theories beyond the Standard Model of particle physics that could explain the entirety of the cold dark matter. These particles could be detected through their mixing with photons in external electromagnetic fields. Here, we provide a short review over ALP searches that utilize astrophysical γ -ray observations. We summarize current bounds as well as future sensitivities and discuss the possibility that ALPs alter the γ -ray opacity of the Universe.

1 Introduction

Astrophysical observations with space-borne and ground based γ -ray experiments have proven to be a powerful tool to search for physics beyond the Standard Model. The currently operating *Fermi* Large Area Telescope (LAT), sensitive to γ rays between 20 MeV and above 300 GeV [1], and imaging air Cherenkov telescopes (IACTs), such as H.E.S.S., MAGIC, and VERITAS (sensitive to γ rays above ~ 50 GeV [2, 3, 4]) have provided strong constraints on, e.g., Lorentz invariance violation [5, 6], as well as on the annihilation cross section of weakly interacting massive particles, which are prime cold dark matter candidates [7, 8, 9].

Observations at γ -ray energies can also be used to search for traces of axionlike particles (ALPs). ALPs are closely related to the axion, which plays an essential role in the solution of the strong CP problem in QCD [10, 11, 12, 13]. Just as the axion, ALPs are well motivated cold dark-matter candidates [14, 15, 16, 17, 18] that could be detected through their coupling to photons in external magnetic fields [19, 20]. They arise in several extensions of the Standard Model [21, 22, 23].

Here, we review advancements in astrophysical γ -ray searches for ALPs that have, for certain ALP masses (m_a) below μeV , reached a sensitivity comparable to that of current or future dedicated laboratory experiments. We give a short overview of the relevant astrophysical magnetic fields (Sec. 2),¹ and review the status of evidence found for a reduced γ -ray opacity that might be caused by photon-ALP oscillations (Sec. 2.1). We review searches for ALP-induced spectral irregularities (Sec. 2.2) before closing with an outlook on future observations (Sec. 3).

¹This review focuses on photon-ALP mixing in external magnetic fields, however, searches for γ -ray signals from axion and ALP decays have also been carried out [24, 25].

2 Photon-ALP mixing at γ -ray energies

Solving the full equations of motion for the photon-ALP system, one realizes that the conversion probability becomes maximal and independent of energy above a critical energy $E_{\text{crit}} = |m_a^2 - \omega_{\text{pl}}^2|/2g_{a\gamma}B$, where B denotes the field strength transversal to the photon propagation direction, $g_{a\gamma}$ the photon-ALP coupling, and ω_{pl} the plasma frequency of the medium. This strong mixing regime persists as long as $E < E_{\text{max}} = 90\pi g_{a\gamma} B_{\text{cr}}^2/7\alpha B$, with α the fine structure constant and the critical magnetic field $B_{\text{cr}} \sim 4.4 \times 10^{13}$ G. For photons around PeV energies, background photon fields such as the cosmic microwave background cause an additional photon dispersion leading to a modification of E_{max} [26]. Reviews on solving the equations of motion and deriving the photon-ALP mixing matrices in a number of magnetic fields are provided in, e.g., Refs. [27, 28, 29, 30, 31, 32].

One abundantly studied source class to search for traces of ALPs are blazars, active galactic nuclei (AGNs) with their relativistic jets closely aligned to the line of sight [33]. Blazars make up the majority of extragalactic sources detected at γ -ray energies [34]. Their intrinsic brightness, especially during flaring episodes, and the numerous magnetic-field environments traversed by the photon beam along the line of sight make them excellent targets to search for ALP signatures. The photon-ALP oscillations may lead to two observables in the energy spectra of these objects (discussed in the following subsections): a) the γ -ray source flux can be attenuated due to pair production with low energy photons originating from background radiation fields [35, 36, 37]. ALPs produced in the vicinity of the source would circumvent this attenuation, and, if they reconvert to γ rays, could lead to a significant boost of the observed photon flux, and b) oscillations of the flux should be imprinted in the spectra around E_{crit} and E_{max} that depend on the morphology of the traversed B fields.

To accurately model the effect of ALPs on γ -ray spectra, a thorough understanding of the intervening B fields is necessary. Several different B -field environments have been studied in connection to photon-ALP conversions at γ -ray energies. They cover both coherent and turbulent magnetic fields, where the turbulent fields are often modeled with a simplified cell-like structure: each cell has a length equal to the coherence length λ and the magnetic-field orientation changes randomly from one cell to the next. Starting from the blazar, the considered B fields include: the B -field in the AGN jet, [38, 39, 40, 41, 32], the turbulent magnetic fields of the host galaxies (usually found to be elliptical galaxies) that, because of the short coherence length of $\lambda \sim 0.1$ kpc should not contribute significantly to photon-ALP mixing [39, 32], the B field of the lobes of AGN jets [41, 42], the turbulent B fields of galaxy clusters that might host the blazar [43, 44, 32], the intergalactic magnetic field (IGMF) [45, 46, 47, 48, 38, 30, 31] (for which only upper limits exist, $B \leq 1.7$ nG for λ equal to the Jeans' length [49]), and eventually the Galactic magnetic field (GMF) of the Milky Way [47, 43], which consists of both a turbulent and coherent component. Several models for the GMF have been put forward in the literature [50, 51], with the best-fit values for the model of Ref. [51] recently updated with measurements of the Planck satellite [52].

2.1 Evidence for a reduced γ -ray opacity?

One predominant radiation field responsible for the attenuation of γ rays originating from blazars with energies $10 \text{ GeV} \lesssim E \lesssim 50 \text{ TeV}$ is the extragalactic background light (EBL), which stretches from UV to far infrared wavelengths [53]. The isotropic EBL photon density is difficult to measure directly due to strong foreground contamination with zodiacal light [54]. The EBL

is composed of the emitted starlight integrated over the history of the Universe and the starlight that has been absorbed and re-emitted by dust in galaxies [55, 56]. The exponential attenuation scales with the optical depth $\tau(E, z)$, a monotonically increasing function with γ -ray energy E , source redshift z , and EBL photon density (see Refs. [57, 58, 59, 60, 61, 62] for a selection of EBL models).

Using published IACT spectral data points, several authors have indeed found indications that state-of-the-art EBL models over-predict the observed γ -ray attenuation. Once the observed spectrum has been corrected for the absorption utilizing an EBL model, such an over-prediction would manifest itself by a spectral hardening at energies corresponding to a high optical depth. Accordingly, one way to search for such a feature is to fit power laws, $\phi(E) = dN/dE \sim E^{-\Gamma}$, with spectral indices Γ_{low} and Γ_{high} separately to the low and high energy part of the de-absorbed spectra. If the opacity is over-predicted, the difference between the spectral indices $\Delta\Gamma = \Gamma_{\text{low}} - \Gamma_{\text{high}}$ should increase with redshift as the predicted attenuation increases (this should also hold if the sources get dimmer at higher energies). The above effect has been found and ALPs have been suggested as a possible solution [45, 47, 63, 38, 64, 31, 65, 66, 67]. Alternatively, it is possible to search for the spectral hardening by examining fit residuals $\chi = (\phi_{\text{obs}} - \phi(E)e^{-\tau(E)})/\sigma_\phi$ of fits of smooth concave, i.e. non-hardening, functions $\phi(E)$ multiplied with EBL absorption to the observed spectra ϕ_{obs} with flux uncertainties σ_ϕ . Again, if τ is overestimated, the fit residuals should display a positive correlation with optical depth. A 4σ indication for such an effect was found [68, 69] that could be reduced significantly when photon-ALP oscillations are taken into account [70]. Intrinsic source effects leading to a spectral hardening can fake such a signal (see e.g. Ref. [71] for one possibility), however, it would be highly contrived if such a hardening occurred in several sources at exactly the energy where $\tau > 1$.

So far we have summarized observations of spectral hardening at high optical depths that might hint at photon-ALP oscillations. However, recent analyses could not confirm these results. Using the largest IACT data set to date, the authors of Ref. [72] repeated the analysis of Ref. [68] and found no deviation from EBL-only expectations. Furthermore, when including uncertainties on the IACT energy resolution, and further systematic uncertainties, no spectral upturn can be observed when comparing *Fermi*-LAT and IACT spectra (spectra measured with the *Fermi*-LAT should be less affected by EBL absorption at low redshift due to the lower energy range accessible with the satellite) [73]. Using a sample of *Fermi*-LAT detected blazars above 50 GeV and up to redshifts of $z \sim 2$, again, no evidence for a spectral hardening was found in *Fermi*-LAT data [74]. It should be noted that the *Fermi*-LAT has only detected γ rays up to $\tau \sim 3$ [75], whereas the ALP effect should become particularly pronounced for $\tau \gtrsim 4$ [42].

Future dedicated analyses that search for spectral hardening carried out by the IACT collaborations (who have access to the full instrumental response functions and raw data) would be extremely valuable. This would enable a full likelihood analysis that could provide important insights not only into ALPs but also into other processes that might alter the γ -ray opacity such as electromagnetic cascades induced by ultra-high energy cosmic rays [76] or the propagation of photons through cosmic voids [77].

2.2 ALP-induced spectral irregularities

In case no spectral hardening is observed, it is difficult to constrain the photon-ALP coupling. The reason is that the non-observation might not be due to the absence of ALPs but due to

a high-energy cutoff of the intrinsic spectrum. This problem is alleviated when searching for spectral irregularities around E_{crit} and E_{max} as these features should be detectable as long as the energy resolution is sufficient to resolve the features and that signal-to-noise ratio is high enough to distinguish the features from Poisson noise.²

Such analyses have been carried out at X-ray [79, 80] and γ -ray energies [44, 81] with observations of central AGNs in galaxy clusters and groups. The authors employed more sophisticated B -field models in which the turbulent fields are described with suitable power spectra instead of cell-like morphologies. The non-observation of such features at X-rays leads to the exclusion of ALP masses $m_a < 10^{-11}$ eV [79], and $m_a < 10^{-12}$ eV [80] for $g_{a\gamma} \gtrsim 6 \times 10^{-12} \text{ GeV}^{-1}$. These bounds also apply for lower masses since $\omega_{\text{pl}} \gg m_a$, leading to irregularities independent of m_a .³ At γ -ray energies, the strongest bounds on $g_{a\gamma}$ come from *Fermi*-LAT observations of NGC 1275 that are the most constraining limits between $0.5 \text{ neV} \lesssim m_a \lesssim 20 \text{ neV}$ to date [81]. Taken at face value, together with the bounds from the non-observation of irregularities in H.E.S.S. data of PKS 2155-304 [44] and the absence of a γ -ray burst signal from SN 1987A [84], the possibility that ALPs alter the EBL γ -ray opacity is already seriously constrained (see Fig. 1).

3 Conclusion and outlook

Blazar observations at γ -ray energies pose a complementary approach to search for ALPs, that could reveal themselves either through spectral irregularities or a boost of the γ -ray flux that would otherwise be attenuated through pair production. Current limits, future experimental sensitivities, and theoretically preferred regions for low mass ALPs are summarized in Fig. 1.

Future observations with CTA [85], HAWC [86], and HiSCORE [87] with their good point source sensitivities also at energies beyond 1 TeV have the potential to search for ALPs at masses above 10 neV. Especially CTA will be able to probe the entire parameters space where ALPs could explain the hints for a low γ -ray opacity [42]. The planned full-sky extragalactic CTA survey could also be used to search for a spectral hardening correlated with the photon-ALP conversion probability in Galactic magnetic fields [88].

ALPs could also be searched for with γ -ray observations using sources other than blazars. Other possible sources to look for traces of ALPs include spectra of pulsars and observations of pulsar binary systems [89]. Another alternative is to search for a short γ -ray burst from the next Galactic core-collapse supernova. ALPs would be produced in such an event via the Primakoff process and subsequently convert into γ rays in the Galactic magnetic field. These γ rays would arrive simultaneously with the neutrinos produced in the supernova. If such an event occurs during the lifetime of the *Fermi* mission and while the supernova is in the field of view of the satellite (the *Fermi* LAT surveys $\sim 20\%$ of the sky at any given moment), it would be possible to probe couplings down to $2 \times 10^{-13} \text{ GeV}^{-1}$ for masses below 1 neV [90]. Future γ -ray missions such as e-ASTROGAM [91], ComPair [92], or PANGU [93] should even be more sensitive to such a signal given their accessible energy range and improved point spread function in comparison to the *Fermi* LAT.

²Even for magnetic-field configurations in cell-like models that lead to no mixing in the strong mixing regime, the irregularities would still occur [78].

³Interestingly, the conversions of ALPs from a cosmic ALP background could explain excess diffuse X-ray emission observed in several galaxy clusters [82, 83].

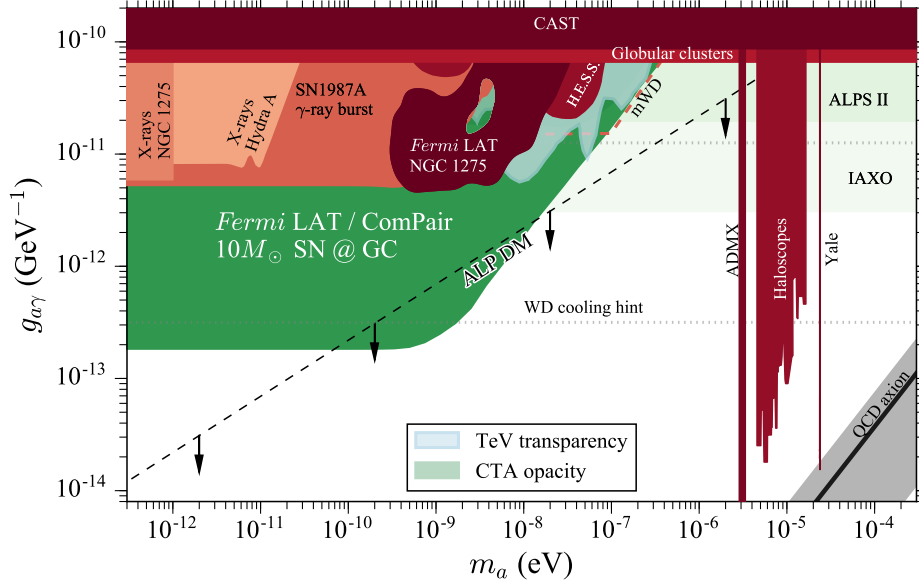


Figure 1: The low-mass ALP parameter space. Current bounds are shown in red and include the non-observations of spectral irregularities at X-ray energies from Hydra A [79] and NGC 1275 [80], at γ -ray energies using the same source with the *Fermi* LAT [81] and PKS 2155-304 with H.E.S.S. [44]. Also shown are bounds from the CAST helioscope [94], and haloscope microwave cavities looking for dark-matter axions and ALPs [95, 96, 97, 98, 99], as well as limits inferred from globular cluster observations [100], and the non-detection of a γ -ray burst from SN 1987A [84]. Limits derived from optical polarization measurements (that could also be interpreted as a preferred region to explain such a polarization) of magnetic white dwarfs (mWD) are shown as a red dashed line [101]. ALP parameters that could explain a low opacity of the Universe to γ rays are shown in blue [70] while those that would cause an additional white dwarf (WD) cooling lie between grey dashed lines [102]. Predicted parameters for one particular QCD axion model (the “KVSZ” axion [103, 104]) are shown together with an order of magnitude uncertainties (grey band). Sensitivities of future experiments such as ALPS II [105], IAXO [106] and future observations with CTA [42] are shown in green along with the parameter space that could be probed with the *Fermi* LAT in case of a core-collapse ($10 M_{\odot}$) supernova (SN) in the Galactic center (GC) [90]. ALPs with parameters below the black dashed line could account for the entirety of the cold dark matter [18].

Acknowledgments

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