Photon-ALP oscillations at CTA energies

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Abstract

Axions and axion-like-particles (ALPs) are well motivated beyond the standard model particles that can explain a variety of unsolved problems in physics, such as the strong CP problem and the nature of dark matter. These particles are characterised by their two-photon coupling, which leads to so-called photon-ALP oscillation as photons propagate through an external magnetic field. Such oscillations lead to characteristic signatures in the energy spectrum of high-energy photons from astrophysical sources, allowing us to probe the existence of ALPs and possibly dark matter. We review the signatures from ALPs in photon spectra and discuss a new method that can be used to directly search for the energy dependence of the oscillations. The focus is on photons at TeV-energies relevant for the upcoming Cherenkov Telescope Array (CTA).

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1 Introduction

Axion-like particles (ALPs) are pseudo-scalar particles characterised by their mass, m_a, and two-photon coupling, $g_{a\gamma}$. Despite their small mass, they can contribute to the cold dark matter relic density if they are produced e.g. via the misalignment mechanism [1–3]. The two-photon coupling leads a number of interesting physical phenomena such as photon-ALP oscillations, ALPs decaying into two photons, and mesons decaying into ALPs.

At low masses, $m_a \lesssim 10^{-6}$ eV, the best limits on the coupling, $g_{a\gamma} \lesssim 10^{-13}$–$10^{-11}$ GeV^{-1}, rely on photon-ALP oscillations in astrophysical magnetic fields. Physically, one can interpret the photon-ALP oscillation as a mixing between two mass eigenstates, similar to neutrino oscillations. Thence, the oscillation length depends on the refractive index of the photon, which in turn depends on the propagation environment (i.e. surrounding magnetic field, plasma and photon bath) and photon energy. As such, the limits on $g_{a\gamma}$ depend strongly on the modelling of the magnetic fields. Since simplified models are often used, care should be taken when interpreting any results.

In this work, we review the signatures that ALPs imprint on photon spectra, with a focus on TeV-energies. With a simple cell-like structure and a Gaussian turbulent field as examples, we discuss the important of a proper modeling of magnetic fields Furthermore, we discuss a new method that can be used to directly search for the energy dependence of the oscillations.

2 ELMAG

We simulate the propagation of photons and ALPs using ELMAG [4, 5]. ELMAG is a Monte Carlo program written in Fortran 90 that simulates electromagnetic cascades by high-energy photons, electrons and positrons interacting with the EBL. We have implemented ALPs into ELMAG [6, 7], thereby allowing for a consistent treatment of cascading and oscillations. This is however at the cost of being significantly more computationally demanding than the alternative Python packages GammaALP [8] and ALPro [9], which are based on transfer matrices.

3 Expected signatures from photon-ALP oscillations

Photon-ALP oscillations will deposit two important signatures on high energy photon spectra at $E \sim$ TeV. These are clearly shown in Fig. 1, in which we plot the observed photon spectrum on Earth with an injection spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ affected by photon-ALP oscillations with $g_{a\gamma} = 10^{-20}$ GeV, $B_{\mathrm{rms}} = 5$ nG and $L_{\mathrm{c}} = 1$ Mpc. First, photon-ALP oscillations will perturb the photon spectrum by energy dependent oscillations with $k \sim \Delta_{\mathrm{osc}} = 2\pi/L_{\mathrm{c}}$, even for a turbulent magnetic field [6] (Fig. 1; left). For concreteness, we are focusing on extragalactic magnetic fields ($B_{\mathrm{rms}} \lesssim$ nG and $L_{\mathrm{c}} \sim$ Mpc) at TeV energies, in which case the dispersion is dominated by the CMB (see Ref. [6] for a discussion of the entire parameter space). The nature of the oscilllatory features depend however on the exact magnetic field configuration, and can vary significantly between realisations of the magnetic field. We will discuss this further in the next section. Second, the photon-ALP oscillations may increase the mean free path length of photons since ALPs propagate without interacting with the CMB (Fig. 1; right). As indicated in the figure, the effect depends strongly on the modelling of the turbulent component of the magnetic field.

4 Detecting ALP wiggles using the discrete power spectrum

The photon-ALP oscillations will perturb the photon spectrum with energy dependent oscillations, $k \sim \Delta_{\mathrm{osc}}$, even for a turbulent magnetic field [6]. At energies above the strong mixing regime, the ALPs with thus lead to oscillations with $k \sim E$. Likewise, below the strong mixing regime, $k \sim E^{-1}$. In Ref. [6], we suggested that one could use the windowed discrete power spectrum,

$$G_N(k) = \left| \frac{1}{N} \sum_{\mathrm{events}} \mathrm{e}^{\mathrm{i}\eta k} \right|, \tag{1}$$

to search for these wiggles. For a turbulent magnetic field, the ALP signal is a broadened peak whose location and width is a priori unknown. While this makes a detection more challenging, it enable us to extract information about the magnetic field if these ALP wiggles are detected [6]. In this work, we expand upon this suggestion by introducing a statistical method which is independent of the modelling of a magnetic field.

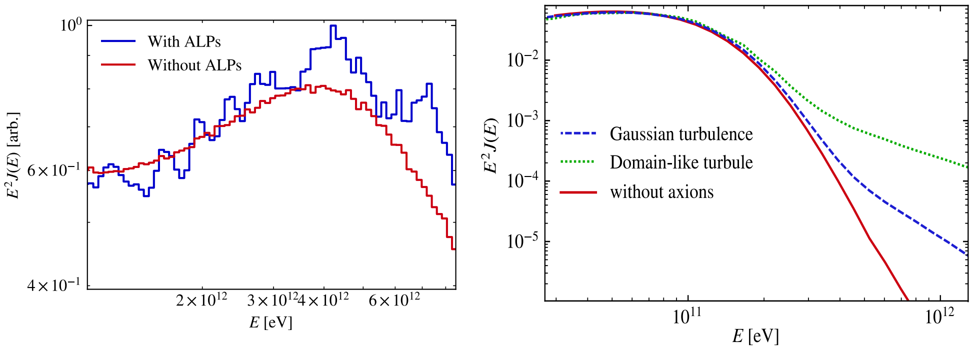

Figure 1: Using an injection spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ at $z = 0.1$ (left) and $z = 1$ (right; adapted from Ref. [6]). In the left plot, the spectrum without any ALPs (red) is compared to the spectrum with ALPs for a single realisation of the extragalactic magnetic field for a Gaussian turbulent field (blue). The ALP wiggles are easy to identify in this example. In the right plot, the average spectrum obtained using a Gaussian turbulent field (solid blue line) and a domain-like structure (dashed green line) is compared to the spectrum without any ALPs (dotted red line). The increased flux at large energies due to photon-ALP oscillations is clearly visible.

In Fig. 2, we plot the power spectrum with the background extracted obtained in 100 realisations of the magnetic field for an example source at redshift $z = 0.1$. The background is estimated in the following way. For each magnetic field realisation, we simulate N photons, which we in turn use to fit the function[1]

$$f(E) \propto E^{-b} \exp\{-\tau(E)\}, \tag{2}$$

with

$$\tau = \alpha \exp\{\beta \log(E)^3 - \gamma \log(E)^2 + \delta \log(E)\}, \tag{3}$$

to the unbinned data by minimizing the maximum likelihood estimate (MLE). The fitted function $f(E)$ represents the background estimate. The power spectrum of the background, $G_{\mathrm{B}}(k)$, is found by drawing random photon energies using $f(E)$ as the probability distribution. The statistical variance of the power spectrum, $\sigma_{\mathrm{B}}(k)^2$, can be computed by repeatably generating $G_{\mathrm{B}}(k)$ using only N photons with the same $f(E)$. The method may surprisingly be easier when applying it to real data. For example, if one uses the Fermi data, one can use existing fits to the sources and the Fermi tools to estimate the background.

In order to exemplify that this method has the ability to increase the sensitivity to ALP wiggles, we compute the test statistic given by the goodness-of-fit measure compared to the estimated background,

$$\mathrm{TS} = \frac{1}{\Delta k} \int_0^{\Delta k} \frac{[G_N(k) - G_N^B(k)]^2}{\sigma_N^B(k)^2} \mathrm{d}k\,. \tag{4}$$

We choose $\Delta k = 2\pi$ to reduce the contributions from random fluctuations at large k. The results are plotted in the left pane of Fig. 3. While Eq. (4) shares similarities with the χ^2 statistics, one should emphasise that one expects a longer tail in the test statistics since we are integrating over a range in which there statistically is expected to be random peaks. This is similar to the "look-elsewhere effect" since the probability that there is a statistically random peak at any k is larger than the probability that there is a peak at a fixed k. For visualisation and comparison, we plot the results obtained with the standard χ^2 as test statistics in the right pane of Fig. 3.

[1] The functional form of f was motivated by the shape of the optical depth of photons [10].

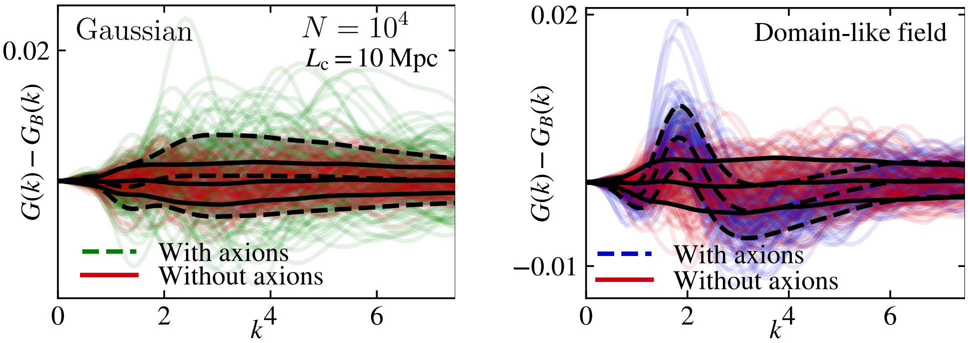

Figure 2: The power spectrum of 100 realisations of the magnetic field with the background extracted is plotted for a source at distance $z = 0.1$ with injection spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ for a Gaussian turbulent field (left; green) and a domain-like field (blue; right). The results without any ALPs is plotted in read for comparison. The averages of 1000 realisations are indicated in solid lines without ALPs and in dashed lines with ALPs.

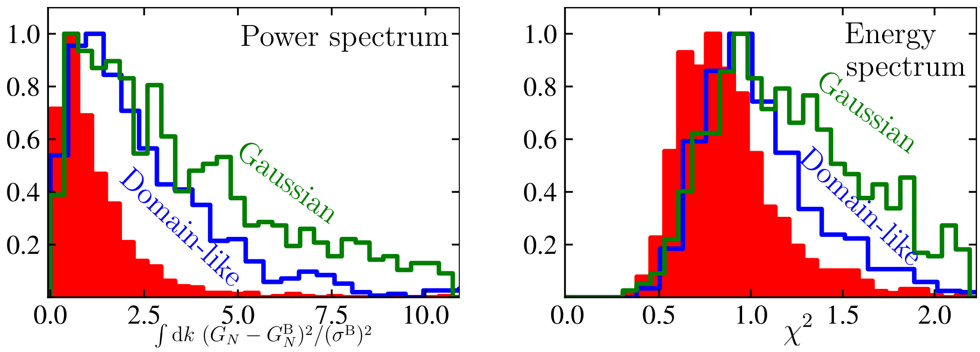

Figure 3: The test statistics, (4), are computed for the simulations in Fig. 2 (left plot) for the three considered scenarios: no ALPs (red), a Gaussian turbulent field (green) and a domain-like field (blue). For comparison, the same data is used to compute the χ^2 value of a binned energy spectrum (right).

It is interesting to note that the domain-like field in this example leads to wiggles which gives a peak around the same value of k. Meanwhile, the Gaussian turbulent field shows no indication for a signal on average. Nevertheless, the test statistics chosen in Fig. 3 shows that the large variance in the Gaussian turbulent field increases the detectability compared to the domain-like field.

5 Summary

Two important consequences of photon-ALP oscillations in extragalactic magnetic fields were discussed, with a focus on the importance of the magnetic field modelling: First, the photon-ALP oscillations makes the Universe more transparent, the amount depends strongly on the modelling of the magnetic field. For example, a cell-like field may over-predict the photon conversion probability compared to a Gaussian turbulent field. Second, the ALP wiggles in photon energy spectra depends strongly on the realisation of the magnetic field. Thus, the lack of variance in the cell-like field leads to a lack of variance in the oscillation signal compared to the Gaussian turbulence. In conclusion, care must be taken when interpreting results that depend on simplified models for the magnetic fields. In addition, we introduced a statistical model independent method that can be used to search for ALP wiggles in photon spectra from high energy sources. This method relies on using the discrete power spectrum to directly search for the expected energy dependence of the ALP wiggles.

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