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Photon-ALP oscillations at TeV energies

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Axion and axion-like-paricles (ALPs) are well motivated cold dark matter candidates. Nevertheless, an astoundingly huge parameter space remains unexplored despite much effort, ranging from fuzzy dark matter at $m_a \sim 10^{-22}$ eV to light dark matter at $m_a \sim$ keV. Most experimental ALP searches rely on the characteristic two-photon–ALP coupling. This coupling has a number of interesting observational consequences, such as a mixing between photon and ALPs when the photon propagates through an external magnetic field. Here, we discuss the signatures that ALPs imprint on high-energy photon spectra from astrophysical sources due to photon-ALP oscillations. In particular, we present a model-independent statistical test designed to search for these signatures that may improve current experimental sensitivities significantly. The focus is on photon energies relevant for the upcoming Cherenkov Telescope Array (CTA) and on oscillations in extragalactic magnetic fields.

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[*] Speaker

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1. Motivation

Axions and axion-like particles (ALPs) can be used by a creative physicist to explain many of the unsolved mysteries in physics, including e.g. the nature of dark matter, the strong CP problem, the $g - 2$ anomaly, inflation and dark energy. Due to the characteristic two-photon–ALP coupling, photons will mix with ALPs when they propagate through external magnetic fields. Thus, one can search for axions and ALPs by searching for the charactersitc imprints that the photon-ALP oscillation leaves on high-energy photon spectra.

2. The photon propagation program `ELMAG`

`ELMAG` [1] is a standard tool for modelling the propagation of gamma-rays in the Universe in a Monte Carlo framework. The tool was made to simulate the electromagnetic cascade that arises when high-energy gamma-rays undergo pair production upon interacting with the extragalactic backround light (EBL), $\gamma + \gamma_{\rm EBL} \to e^+ + e^-$. We have now also implemented ALPs into `ELMAG` [2, 3], allowing us to include properly the interplay of cascading and oscillations.

3. Parameter space of photon-ALP oscillation

Photon-ALP oscillations can physically be described as a mixing between two mass-eigenstates, similar to neutrino oscillations. An energy dependence of the oscillation length is thus induced by the variation of the refractive index of the photon. The photon-ALP oscillations at high energies can described by the equation of motion

$$(E + \mathcal{M} - \mathrm{i}\partial_z)\,\phi(z) = 0, \qquad \mathcal{M} = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & g_{a\gamma}B_\perp/2 \\ 0 & g_{a\gamma}B_\perp/2 & -2m_a/E \end{pmatrix}, \tag{1}$$

where $\Delta_{\perp/\parallel} = (n_{\perp/\parallel} - 1)E = \Delta_{\rm QED} + \Delta_{\rm CMB} + \Delta_{\rm plasma}$. The entire parameter space of the photon-ALP oscillation is visualised in Fig. 1. As indicated in the figure, the oscillation length at high energies is $L_{\rm osc} = 2\pi/\Delta \propto E^{-1}$, while at low energies it is $L_{\rm osc} \propto E$. The oscillations will be strongest close to the strong mixing regime. The same qualitative behaviour is present even in turbulent magnetic fields [2].

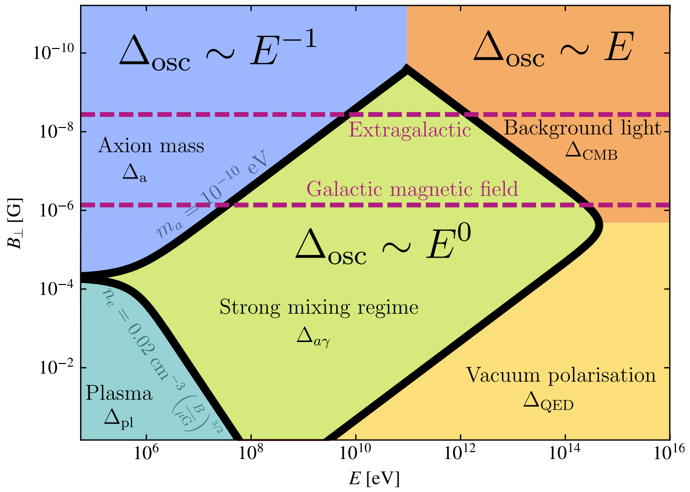

Figure 1: Representation of the parameter space of photon-ALP oscillations: The different coloured regions indicate which term dominates the photon-ALP dispersion; see Ref. [2] for a detailed discussion.

4. The importance of an accurate description of the magnetic field

The signature from photon-ALP oscillations depend strongly on the modelling for the magnetic field; this will be clear in the examples that follows. Thus, care should be taken when interpreting results that depend on simplified magnetic field models. We simulate the extragalactic magnetic field as a Gaussian turbulent field with a Kolmogorov spectrum and $B_{\rm rms} = 5 \times 10^{-9}$ G. It is usually assumed that its coherence length is $L_{\rm c} \sim 1$ Mpc, but it is practically unconstrained from above [4]. For comparison, we consider also a simple domain-like field in which the magnetic field is split into patches of size L_c of homogeneous magnetic field with a random direction. While the latter is an unphysical field, it is commonly used in the literature due to its simplicity.

5. Detecting axions with CTA

The Cherenkov Telescope Array (CTA) [5] is expected to have a great sensitivity for photons with energies between 10^{11} and 10^{14} eV, which means that it will be sensitive to ALP wiggles induced by a magnetic field of strength $10^{-11}\ {\rm G} \lesssim Bg_{a\gamma}/10^{-20}\ {\rm eV} \lesssim 10^{-8}$ G, cf. Fig. 1. At the same time, the attenuation of photons due to interactions with the extragalactic background light becomes significant above TeV energies. Thus, the CTA is ideal to look for photon-ALP oscillations in the extragalactic magnetic field and in the increased mean free path length of photons.

5.1 Increased mean free path length

At energies $E_\gamma \gtrsim$ TeV, photons will undergo pair production upon interacting with the extragalactic background light (EBL), strongly attenuating the photon spectrum. Since ALPs do not interact with the EBL, photon-ALP oscillations will lead to an increased mean free path length of the photon. As an example, Fig. 2 shows how a production spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ at redshift $z = 0.1$ is affected by the attenuation and photon-ALP oscillations. Interestingely, the effect depends strongly on the considered magnetic field configuration. If one considers a more distant source, or take into account conversions in galactic magnetic fields, the effect is larger.

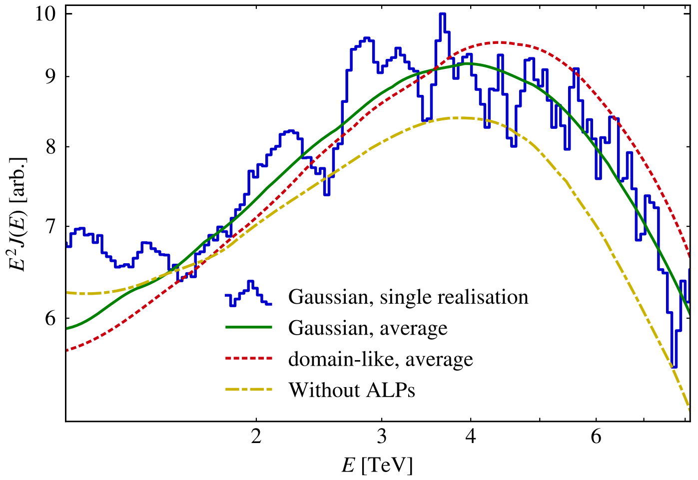

Figure 2: The observed spectrum at Earth from an source $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ at redshift $z = 0.1$ as simulated using `ELMAG` with (green and red lines) and without (yellow dashed dotted line) photon-ALP oscillation in the extragalactic magnetic field. The result from a single realisation of the Gaussian turbulent field is shown for visualisation (blue).

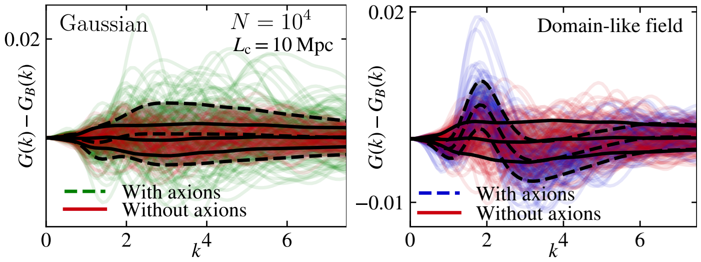

Figure 3: The power spectrum for 100 realisations of the magnetic field with the background extracted is plotted for a source with injection spectrum $\propto E^{-1.2}$ at a distance $z = 0$. A Gaussian turbulent field (left; green) and a domain-like field (blue; right) with coherence length 10 Mpc have been used. The no-ALP case is plotted in red.

5.2 ALP Wiggles

Since the photon-ALP oscillations lead to wiggles in the photon spectra with a characteristic energy dependence (Fig. 2), one can extract the information using the discrete power spectrum

$$G_N(k) = \left| \int_{\eta_{\min}}^{\eta_{\max}} \mathrm{d}\eta\, q(\eta) \mathrm{e}^{\mathrm{i}\eta k} \right|^2 = \left| \frac{1}{N} \sum_{\text{events}} \mathrm{e}^{\mathrm{i}\eta k} \right|^2, \tag{2}$$

where the sum goes over detected photons [2]. The energy parameter must be chosen such that it describes the correct energy dependence, $\eta \sim \Delta_{\text{osc}}$. That is, $\eta \sim E^{-1}$ at low energies and $\eta \sim E$ at high energies. In the examples in Fig. 3, the power spectrum with extracted background for 10^4 photons with a production spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ at $z = 0.1$ has been used; see Ref. [6] for details. Since the domain-like field does not describe the cosmic variance of the magnetic field, the power spectrum obtains a clear peak even on average. Meanwhile, the Gaussian turbulent field shows no clear signal on average. However, for a specific source, only a single realisation of the magnetic field is relevant. Thus, the detectability of photon-ALP oscillations in a Gaussian turbulent field may be larger due to the large variance between the realisations.

6. Summary

At TeV energies, photon-ALP oscillation will lead to two features in photon spectra: (1) an apparent decrease in the opacity of the Universe and (2) characteristic wiggles. The signatures depend strongly in the modelling of the magnetic fields, and results obtained using a simplified models should therefore be interpreted with care. Since we know the energy dependence of the wiggles, we can directly search for them by using the discrete power spectrum. Such a search will be independent of the magnetic field modelling.

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