Axion-Like particles from extragalactic High Energy sources

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Abstract. Background radiation fields (such as Extragalactic Background Light, EBL, or Cosmic Microwave Background, CMB) pervade the Universe. Above a certain energy any gamma ray flux emitted by an extragalactic source should be attenuated by the process $\gamma + \gamma \rightarrow e^+ + e^-$ pair production. We have considered a scenario in which the photons are partly converted into light Axion Like Particles (ALPs) in the local magnetic field of an (extragalactic) source. Then, while the unconverted fraction of photons undergo absorption, the ALP component travel to our galaxy where is converted back to photons by the galactic magnetic field resulting in a sort of cosmic light shining through wall effect. In particular, we have considered two scenarios: 1) conversion in the turbulent magnetic field inside a galaxy cluster; and 2) conversion of photons in the coherent magnetic field at parsec scales in a Blazar jet. Afterwards, we have also analyzed mock data coming from a hypothetical Imaging Air Cherenkov Telescopes (IACT) array with characteristics similar to the Cherenkov Telescope Array (CTA) and we have investigated the dependence of the sensitivity to detect a gamma ray excess on the magnetic field parameters.

1. Introduction
Axion-like particles (ALPs) with a two-photon vertex are hypothetical particles predicted in many extensions of the Standard Model. Pseudoscalar ALPs couple with photons through the following effective Lagrangian
\[
\mathcal{L} = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu},
\]
where $a$ is the ALP field with mass $m_a$, $F^{\mu\nu}$ the electromagnetic field-strength tensor, $\tilde{F}^{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$ its dual, and $g_{a\gamma}$ the ALP-photon coupling. As a consequence of this coupling, ALPs and photons do oscillate into each other in an external magnetic field. For a photon travelling in the $x_3$ direction this phenomenon is described by a Shrödinger-like equation of the kind [1]
\[
i \partial_3 \Psi = \mathcal{H} \cdot \Psi, \quad \Psi = (A_1, A_2, a)^T
\]
and
\[
\mathcal{H} = \frac{1}{2}
\begin{bmatrix}
-i \Gamma_\gamma(E) + \omega_{pl}^2/E & 0 & g_{a\gamma}B_1 \\
0 & -i \Gamma_\gamma(E) + \omega_{pl}^2/E & g_{a\gamma}B_2 \\
g_{a\gamma}B_1 & g_{a\gamma}B_2 & -m_a^2/E
\end{bmatrix}.
\]
Here $E$ is the photon energy and $\omega_{pi}^2 = 4\pi\alpha n_e/m_e$ is the plasma frequency of the medium, being $n_e$ the electron density.

Although there is not a laboratory evidence of photon-axion conversion, we can find a proof of this mechanism from astrophysical observations. In particular we have studied Active Galactic Nuclei (AGN) hosted in clusters of galaxies, where a first conversion $\gamma \rightarrow a$ occurs in the magnetic field of the cluster while a reconversion $a \rightarrow \gamma$ happens in the magnetic field of the Milky Way. AGN are intense very high-energy ($\geq$TeV) gamma ray emitters. However, these gamma rays propagate over cosmological distances before reaching the Earth. These high energy photons undergo absorption due to the pair-production process off Extragalactic Background Light (EBL) low energy photons $\gamma + \gamma^{(bgk)} \rightarrow e^+ + e^-$. The energy range $100\text{GeV} \leq E \leq 10\text{TeV}$ (relevant for presently operating gamma-ray telescopes) absorption is dominated by the interactions with optical/infrared EBL photons.

A way to escape this absorption is the aforementioned photon-ALP oscillation. If a fraction of photons coming from the AGN is converted into ALPs, these can evade the absorption by the EBL. Some hints of anomalous absorption in the propagation of high energy photons has been recently observed [2]. Of course, we need an external magnetic field to allow the photon-ALP conversion and the ALP-photon reconversion before detection. In the past, conversion in the intergalactic magnetic field have been proposed [3]. However, the existence and the strength of this field is still a matter of question. There is a second possibility: The conversion can occur in a magnetic field surrounding the AGN and the reconversion can occur in the magnetic field of our galaxy [4]. This can be just the case of AGN hosted in cluster of galaxies. In fact, the existence of magnetic fields in galaxy clusters is well established through the observation of radio synchrotron emission as well as through the rotation measure of polarized radio sources.

Here we consider a scenario in which the photons are partly converted into ALPs in the local magnetic field of the (extragalactic) source. Then, while the unconverted fraction of photons undergo absorption, the ALP component travel to our galaxy where is converted back to photons by the galactic magnetic field. In particular, we consider two scenarios: 1) conversion of photons in the coherent magnetic field at parsec scales in a blazar jet and 2) conversion in the turbulent magnetic field inside a galaxy cluster. Afterwards we have analyzed mock data of a hypothetical IACT array with characteristics similar to the Cherenkov Telescope Array (CTA) and we have investigated the dependence of the sensitivity to detect a $\gamma$-ray excess on the magnetic-field parameters.

2. Magnetic field scenarios

BL Lac Jets: Magnetic fields in blazar jets have been deduced from measurement at different scales, ranging from ultra-compact regions at distances of $\sim 0.1\text{pc}$ from the central black hole up to $100\text{kpc}$ scale structures such as lobes, plumes, and hot spots. We focus here on BL Lac-type objects. Evidence exists that the magnetic field in these objects can be modeled with a poloidal (along the jet-axis) and a toroidal (perpendicular to the jet axis) coherent component, where the field strength for the former decreases as $B \propto r^{-2}$ and $B \propto r^{-3}$ for the latter [5]. Consequently, for large enough distances to the central black hole, the toroidal component dominates and we neglect the poloidal component. We adopt the following prescriptions for the magnetic field and the electron density of the parsec scale jet $B_{\text{jet}}(r) = B_{\text{jet}}^{bgk} \cdot r_{\text{VHE}}/r$. Typical values for $r_{\text{VHE}}$ range from $\sim 0.01\text{pc}$ to $\sim 0.1\text{pc}$, while we choose a fiducial value $B_{\text{jet}}^{bgk} = 0.1\text{G}$.

Galaxy clusters: Evidence exists that a fraction of blazars are hosted in galaxy groups or (poor) galaxy clusters. The existence of turbulent magnetic fields with strength of the order of $\mathcal{O}(\mu\text{G})$ in the intra-cluster medium (ICM) is well established through Faraday rotation measurements and non-thermal (synchrotron) emission at radio frequencies [6]. Typically the field has a turbulent structure modulated by a smooth function decreasing from the center of the cluster to a distance of $\sim 300\text{kpc}$. The simplest way to parameterize the turbulent component
Figure 1. Photon survival probability for the different inter-cluster magnetic field scenarios. See [7] for details.

is by means of cells whose dimension is usually assumed to be of the order of the size of a galaxy in the cluster, i.e. $L_{\text{coh}} \sim 10 \text{kpc}$, in which the field is constant and has random direction and random strength with gaussian distribution with zero mean and variance $B^2$, with a fiducial value $B \sim 1 \mu \text{G}$.

For a network of $N$ magnetic domains with random magnetic field directions, the photon amplitude at the exit of cluster can be calculated as the product of the evolution operators $\prod_j \exp(-i H_j l_j)$ in the $j$-th cell. However, a more physical ansatz is to suppose that the field have a Kolmogorov-like structure. Expanding each component in Fourier modes, the correlation function between modes can be written as

$$
\langle \tilde{B}_i(k) \tilde{B}_j(q) \rangle = (2\pi)^6 M(k) P_{ij}(k) \delta^3 (k - q),
$$

where the tensor $P_{ij}(k) = \delta_{ij} - k_i k_j / k^2$ assures the condition $\nabla \cdot \mathbf{B} = 0$. The spectrum $M(k)$ is assumed to be a power-law, $M(k) \propto k^q$ in an appropriate range of frequencies. Of course, in this case the transfer matrix can be obtained only by a numerical evolution of Eq. (2) for each random magnetic field realization.

The photon survival probability for jets, cells and turbulent fields is shown in figure 1 [7] for a source at $z = 0.4$ and sky coordinates coincident with the position of the blazar PG 1553+113, for $g_{11} = 2$ and $m_{\text{neV}} = 1$ ($g_{11} \equiv g_{\gamma a}/10^{11} \text{GeV}^{-1}$ and $m_{\text{neV}} \equiv m_a/10^{-9} \text{eV}$). We have assumed the minimal EBL model [8] which predicts a minimum absorption for $\sim \text{TeV} \gamma$ rays. For the random fields, 1000 realizations are simulated both for cells and for turbulent field. The green envelopes show the regions in which 68% (95%) of all realizations around the median of the gaussian turbulent $B$-field are contained.

3. Analysis

We have performed a statistical test applied to mock data to investigate the sensitivity to physical parameters for a IACT detector (similar to the Cherenkov Telescope Array, CTA). We have used a power-law spectrum of the source of the kind

$$
\phi(E) \propto E^{-\Gamma} \times \left\{ \begin{array}{ll} P_{\gamma \to \gamma}(E) & \text{w/ ALPs} \\ \exp(-\tau) & \text{w/o ALPs} \end{array} \right.,
$$

Figure 2. Simulated spectrum for a H.E.S.S: like experiment with and without ALP conversion.
where $P_{\gamma \rightarrow \gamma}(E)$ is the photon survival probability and $\tau$ is the optical depth of photons in absence of conversion. In each energy bin $i$ of width $\Delta E'_i$ the expected number of counts is, 

$$\mu_i = T_{\text{obs}} \int_{\Delta E'_i} dE' A_{\text{eff}}(E') \int dE D_E(E', E) \phi(E), \quad (5)$$

for an observational time $T_{\text{obs}}$ which we set to 20 hour where the effective area $A_{\text{eff}}(E')$ and the resolution function $D_E(E', E)$, as well the background $b$, are tabulated in [9].

In figure 2 there is an example of a simulated spectrum above $\tau = 1$ with and without an photon-ALP oscillations. The ALP contribution is shown for the fiducial turbulent ICM scenario for one random $B$-field realization and fixed mass and coupling. The extrapolated spectra (dashed and solid lines) are the results of multiplying the intrinsic best-fit spectrum with the photon survival probability. The shaded regions correspond to the fit uncertainties of the intrinsic spectrum. In case the significance in one bin is below 2$\sigma$, the horizontal dashed lines correspond to 2, 3 and 5$\sigma$ upper limits on the flux are shown. The H.E.S.S. data points are upscaled by 3.58 to emulate the $\gamma$-ray total flux of PG 1553+113 measured by MAGIC. In presence of ALPs we expect a more harder spectrum at higher energies and possibly “wiggles” at low energies (see the insert in figure 1).

The number of events from the source region (ON) and from a background (OFF) region is drawn from the corresponding Poisson distributions. From these distribution we can construct an likelihood for an expected number of source and background counts. Since we are interested in the ALP effect at high optical depth, we restrict the likelihood to only include the energy bins for which the central energy $E_i$ fulfills the condition $\tau(E_i, z) > 2$

$$L(\mu; b; \alpha | N^{\text{ON}}, N^{\text{OFF}}) = \prod_{i; \tau(E_i, z) > 2} \left[ \frac{(\mu_i + b_i)^{N_i^{\text{ON}}}}{N_i^{\text{ON}}!} e^{-(\mu_i + b_i)} \right] \cdot \left[ \frac{(b_i/\alpha)^{N_i^{\text{OFF}}}}{N_i^{\text{OFF}}!} e^{-b_i/\alpha} \right]. \quad (6)$$

($\alpha = 0.2$ is the ratio between the exposures of background and signal regions.)

We compare the no-ALP hypothesis (with expected counts $\hat{\mu}$) with the ALP hypothesis (and expected counts $\mu$) with the likelihood ratio test

$$\lambda(\hat{\mu}; b; \alpha | N^{\text{ON}}, N^{\text{OFF}}) = \frac{L(\hat{\mu}, \hat{b} | \hat{\mu} | N^{\text{ON}}, N^{\text{OFF}})}{L(\hat{\mu}, b; \alpha | N^{\text{ON}}, N^{\text{OFF}})}. \quad (7)$$

In the numerator, the likelihood is maximized by $\hat{\mu}$ for fixed $\hat{\mu}$ while in the denominator it is maximized with respect to both, $\mu$ and $b$, with $\hat{\mu}$ and $\hat{\mu}$ being the maximum-likelihood estimators.

We have constructed a “test-statistics” parameter $T^S = -2 \ln \lambda$ which converges to a $\chi^2_\nu$ distribution with $\nu = 6$ d.o.f. that can be used to calculate the significance with which the no-ALP hypothesis can be excluded. To avoid a massive Montecarlo simulation of the experimental data we applied the statistics to an Asimov data set, i.e., the number of events in each energy bin is substituted by their expectation value: $N_i^{\text{ON}} = \mu_i + b_i$ and $N_i^{\text{OFF}} = b_i/\alpha$.

In [7] we have studied the dependence of $T^S_A$ from various parameters. In particular, the sensitivity to ALP-photon coupling, as well to ALP mass is shown in figure 3. The black (red) lines correspond to a cluster with turbulent (cell) realizations of the magnetic field, while the blue line corresponds to the case of a jet. In the box are shown the astrophysical parameters chosen for the analysis (see [7] for details). The horizontal dashed lines correspond to 2, 3 and 5$\sigma$ confidence level.

For the scenarios including mixing in galaxy clusters, we have simulated 1000 random realizations of the $B$ field for each chosen parameter set and compute $T^S_A$ for each set. For each set of parameters we have considered specific realizations of the turbulent magnetic
Figure 3. Dependence of $T S_A$ on the photon-ALP coupling (left) and ALP mass (right). In the inserts the parameters used in the calculation are listed. See [7] for details.

A field that result in $T S_A$ values that correspond to different quantiles $Q$ of the Cumulative Distribution Function, $CDF(T S_A) = Q$. For instance, the realization giving the $T S_A$ value with $CDF(T S_A) = 0.5$ represents the $B$-field configuration resulting in the median of the $T S_A$ distribution. For $Q = 0.05$, 95% of all realizations give a higher test statistic and the corresponding $B$-field can be regarded as pessimistic in terms of photon-ALP mixing. In the other case, $Q = 0.95$, only 5% of the simulated turbulent $B$-fields result in a higher detection of the spectral deformations. Consequently, this configuration is the optimistic case for photon-ALP mixing.

4. Conclusions
With the suggested method, modifications of the spectra should be detectable for couplings $g_{11} \gtrsim 2$ and ALP masses $m_{\mu eV} \lesssim 100$ for a viable range of the ambient magnetic field strength given a 20 hours observation of a flaring AGN with an intrinsic spectrum that follows a power-law extrapolation up to $\sim 7.4$ TeV. These ALP parameters are also well in range of the future laboratory experiment ALPS II and the next generation Helioscope, IAXO.

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