Astrophysical High-Energy γ's oscillations into ALPs: perspectives

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Background radiation fields (such as Extragalactic Background Light, EBL, or Cosmic Microwave Background, CMB) pervade the Universe. Above a certain energy any γ-ray flux emitted by an extragalactic source should be attenuated due to the process $\gamma\gamma^{\rm bgk}\to e^+e^-$ pair production. The opacity could be alleviated if photons oscillated into hypothetical axion-like particles (ALPs) in ambient magnetic fields, leading to a γ-ray excess especially at high optical depths that could be detected with Imaging Air Cherenkov Telescopes (IACTs).

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 [1]

$$\mathcal{L}=\frac{1}{2}\partial_\mu a\partial^\mu a-\frac{1}{2}m_a^2a^2-\frac{1}{4}g_{a\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}a\,, \qquad (1)$$

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 $i\partial_3\Psi=\mathcal{H}\cdot\Psi$, where $\Psi=(A_1,A_2,a)^T$ and

$$\mathcal{H}=\frac{1}{2}\left[\begin{array}{ccc}-i\Gamma_\gamma(\omega) & 0 & g_{a\gamma}B_\perp c_\phi\\ 0 & -i\Gamma_\gamma(\omega) & g_{a\gamma}B_\perp s_\phi\\ g_{a\gamma}B_\perp c_\phi & g_{a\gamma}B_\perp s_\phi & -m_a^2/\omega\end{array}\right]. \qquad (2)$$

Here ω is the photon energy, $\mathbf{B}_\perp=\mathbf{B}-B_3\mathbf{e}_3$ is the transverse component of the external magnetic field, $c_\phi\equiv\cos\phi=\mathbf{B}_\perp\cdot\mathbf{e}_1/B_\perp$, and Γ_γ is the absorption rate for the pair production process $\gamma\gamma^{\rm bkg}\to e^+e^-$. Index of refraction due to background plasma is negligible for the energy of our interest (>100 GeV)

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 γ-ray excess on the magnetic-field parameters.

1. BL Lac Jets

Magnetic fields in blazar jets have been deduced from measurement at different scales, ranging from ultra-compact regions at distances of ~ 0.1pc from the central black hole up to 100 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 $B\propto r^{-1}$ for the latter. 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 $B^{\rm jet}(r)=B_0^{\rm jet}\cdot r_{\rm VHE}/r$. Typical values for $r_{\rm VHE}$ range from ~ 0.01 pc to ~ 0.1 pc, while we choose a fiducial value $B_0^{\rm jet}=0.1$ G.

2. 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 $\mathcal{O}(\mu{\rm G})$ in the intracluster medium (ICM) is well established through Faraday rotation measurements and non-thermal (synchrotron) emission at radio frequencies. Typically the field has a turbulent structure modulated by a smooth function decreasing from the center of the cluster to a distance of ~ 300 kpc. The simplest way to parameterize the turbulent component 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. $L_{\rm coh}\sim 10$ kpc, in which the field is constant and has random direction and random strength with gaussian distribution with zero mean and variance $\mathcal{B}^2$, with a fiducial value

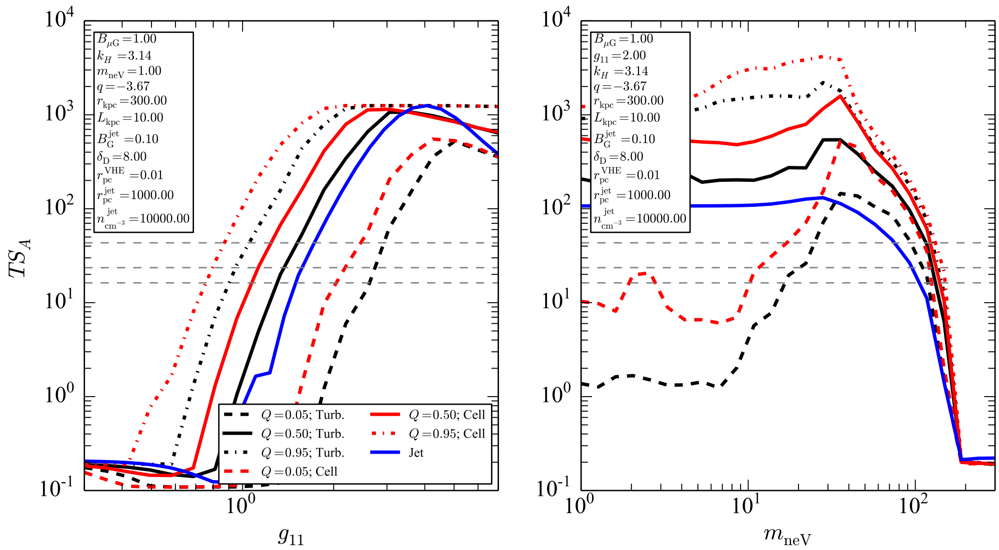

Figure 1. Dependence of TS_A on the photon-ALP coupling (*left*) and ALP mass (*right*). See [2] for details.

$\mathcal{B} = 1\,\mu$G.

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

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

were the tensor $P_{ij}(\mathbf{k}) = \delta_{ij} - k_i k_j/k^2$ 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.

In both cases it is possible to simulate many realizations of the transverse field $\mathbf{B}_\perp$ on the line of sight of the photon [2].

3. Analysis

We have performed a sophisticated 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 address the reader to [2] for the details of the analysis. We have constructed a "test-statistics" parameter TS_A which is essentially the logarithm of a likelihood ratio between the cases of ALP and no-ALP conversion. 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 (this is the meaning of the subscript A). It is shown that the parameter TS_A has a specific Distribution Fucntion (a χ^2 with 6 d.o.f.).

In [2] we have studied the dependence of TS_A from various parameters. In particular, the sensitivity to ALP-photon coupling, as well to ALP mass is shown in Fig. 1, where $g_{11} = g_{\gamma a}/10^{11}\,\mathrm{GeV}^{-1}$ and $m_{neV} = m_a/10^{-9}\,\mathrm{eV}$. 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 [2] for details). The horizontal dashed lines correspond to 2, 3 and 5σ 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 TS_A for each set. For each set of parameters we have considered specific realizations of the turbulent magnetic field that result in TS_A values that correspond to different quantiles Q of the Cumulative Distribution Function, $\mathrm{CDF}(TS_A) = Q$. For instance, the realization giving the TS_A value with $\mathrm{CDF}(TS_A) = 0.5$ represents the B-field configuration resulting in the median of the TS_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.

With the suggested method, modifications of the spectra should be detectable for couplings $g_{11} > 2$ and ALP masses $m_{neV} < 100$ 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 ~ 7.4 TeV. These ALP parameters are also well in range of the future laboratory experiment ALPS II and the next generation Helioscope, IAXO.

REFERENCES

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