Photon-axion oscillations and the transparency of the universe

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Axion-like particles (ALP's) with a two-photon vertex are predicted in many extensions of the Standard Model. Pseudoscalar ALP's couple with photons through the following effective Lagrangian [1]

$$\mathcal{L}_{a\gamma} = -\frac{1}{8} g_{a\gamma} \epsilon_{ijkl} F^{ij} F^{kl} a \,, \tag{1}$$

where a is the ALP field with mass m_a, F^{ij} the electromagnetic field-strength tensor, and $g_{a\gamma}$ the ALP-photon coupling. As a consequence of this coupling, ALP's and photons do oscillate into each other in an external magnetic field.

ALP's play an intriguing role in astrophysics. Indeed, photons emitted by distant sources and propagating through cosmic magnetic fields can oscillate into ALP's. In particular, in the last recent years photon-ALP conversions have been proposed as a mechanism to avoid the opacity of the extragalactic sky to high-energy radiation due to pair production on the Extragalactic Background Light (EBL). (For simple estimations, the background photon spectrum can be approximated with a power–law.) At this regard, recent observations of cosmologically distant gamma-ray sources by ground-based gamma-ray telescopes have revealed a surprising degree of transparency of the universe to very high-energy (VHE) photons ($E > 100$ GeV). Oscillations between very high-energy photons and ALP's could represent an intriguing possibility to explain this puzzle. In fact, if VHE photons are converted into ALP's and then regenerated, they should not suffer absorption effects while they propagate as ALP's.

Since we have to perform averages on the random configurations of the intergalactic magnetic field, it is convenient to stick in the formalism of the density matrix. The evolution equation for photon moving in the x_3 direction can be written as [2]

$$\frac{\partial}{\partial x_3} \rho = -i[\mathcal{H}, \rho] \,, \tag{2}$$

where ρ is the density matrix of the photon–axion system, i.e.

$$\rho = \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \otimes \begin{pmatrix} A_1 & A_2 & a \end{pmatrix}^* . \tag{3}$$

In the high energy limit ($E \geq 100$ GeV) the hamiltonian $\mathcal{H}$ can be written as

$$\mathcal{H} = \begin{bmatrix} -i\frac{\Gamma_\gamma(E)}{2} & 0 & \frac{g_{a\gamma} B_T}{2} c_\phi \\ 0 & -i\frac{\Gamma_\gamma(E)}{2} & \frac{g_{a\gamma} B_T}{2} s_\phi \\ \frac{g_{a\gamma} B_T}{2} c_\phi & \frac{g_{a\gamma} B_T}{2} s_\phi & 0 \end{bmatrix} . \tag{4}$$

Here $\mathbf{B}_T = \mathbf{B} - B_3 \mathbf{e}_3$ is the transverse component of the external magnetic field, $c_\phi \equiv \cos\phi = \mathbf{B}_T \cdot \mathbf{e}_1 / B_T$, and Γ_γ is the absorption rate for the pair production process $\gamma^{\rm VHE}\gamma^{\rm bkg} \to e^+ e^-$, where $\gamma^{\rm bkg}$ is a background (EBL) photon.

Very high-energy gamma-rays propagate in the extragalactic magnetic fields during their route to the Earth which presumably have a turbulent structure. Let us now consider the propagation of photons in many domains of equal size l ($\simeq 1$ Mpc in our case) in which the magnetic field has (constant) random values and directions. Along a given line of sight, the angles ϕ are randomly distributed in $[0, 2\pi)$. During their path with a total length L, photons cross $k = 1, \dots n$ domains ($n = L/l$) representing a given random realization of B_k and ϕ_k. Since we cannot know this particular configuration, we perform an ensemble average over all the possible realizations on the $1, \dots n$ domains. Defining this ensemble average as $\bar\rho_n = \langle \rho_n \rangle_{1 \dots n}$, we have

$$\bar\rho_n = \langle e^{-i\mathcal{H}_n l} \cdot \bar\rho_{n-1} \cdot e^{i\mathcal{H}_n^\dagger l} \rangle_n \,. \tag{5}$$

Performing then the ensemble average, using that $\bar\rho_n - \bar\rho_{n-1} \simeq l \partial_{x_3} \bar\rho(x_3)$, and summing over the two indistinguishable photon polarization states, we finally arrive at a system of two coupled differential equations ($dy = P_{a\gamma} dx_3 / l$)

$$\frac{d}{dy} \begin{pmatrix} T_\gamma \\ T_a \end{pmatrix} = \begin{bmatrix} -\alpha - \frac{1}{2} & 1 \\ \frac{1}{2} & -1 \end{bmatrix} \begin{pmatrix} T_\gamma \\ T_a \end{pmatrix} , \tag{6}$$

where $T_\gamma \equiv I_\gamma(y)/I_\gamma(0) = \bar\rho_{11} + \bar\rho_{22}$ and $T_a = \bar\rho_{aa}$ are the mean transfer functions for the photon and for the ALP respectively; $P_{a\gamma} = g_{a\gamma}^2 |\mathbf{B}|^2 l^2 / 6$

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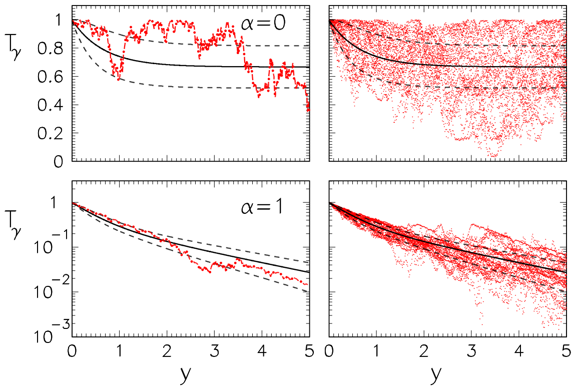

Figure 1. Photon transfer function $T_\gamma(y)$ for $\alpha = 0$ (the upper panels) and $\alpha = 1$ (lower panels) for a given random realization of the magnetic field (left) and for 20 realizations (right).

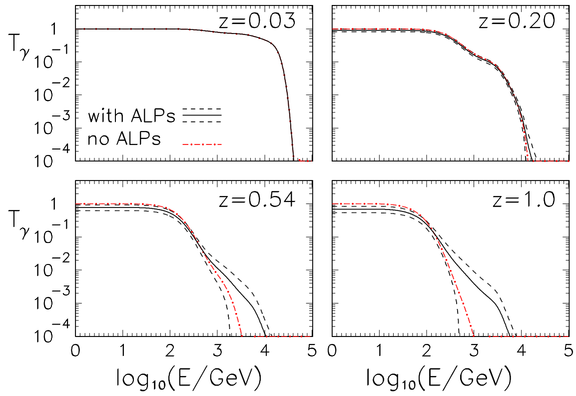

Figure 2. VHE photons transfer function T_γ in function of the observed photon energy E, for different values of the redshift z.

is the average photon-ALP conversion probability in each domain (in absence of absorption) and finally $\alpha = \Gamma_\gamma l/P_{a\gamma}$ is the ratio between the absorption probability and the conversion probability. In realistic astrophysical situations both $P_{a\gamma}$ and α are functions of the distance, due to the redshift dependence of the extragalactic magnetic field and of the EBL.

In particular, in the case of strong absorption ($\alpha \gg 1$) from Eq. (6) we obtain $T_\gamma \propto (\Gamma_\gamma)^{-2}$. Using the approximate power–law spectrum for the EBL we observe that the transfer function would drop as a power of the energy (rather than exponentially as expected without ALP mixing). Moreover, also the attenuation of the transfer function with the distance is less than in the case of absence of conversions. In fact, in this case we have $T_\gamma \propto e^{-\Gamma_\gamma x/\alpha}$, in which the argument of the exponential is suppressed by a factor α with respect to the no-conversion case. Thus this effect would explain the high transparency of the universe.

In [2] we have also calculated the root mean square δT_γ for the distribution of the transfer function in different random realizations of the magnetic field. This result is useful to estimate the uncertainty associated with the averaging procedure. In Fig. 1 we compare the transfer function $T_\gamma(y)$ (continuous lines) calculated from Eq. (6) with those calculated for a given random realization of the magnetic field along the photon line of sight, with and without absorption (left panels) and for 20 realizations (right panels). For comparison we have also shown the dispersion around the mean $T_\gamma \pm \delta T_\gamma$ (dashed lines).

In Fig. 2 we show the photon transfer function as function of the energy for four different values of the redshift of the emitting source. We have used a realistic EBL model [3] which provides a strict lower-limit flux for the extragalactic background light which gives us the maximal possible transparency compatible with the standard expectations, so that an evidence of a greater transparency would have to be attributed to nonstandard effects in the photon propagation. We see that in absence of ALP conversions the photon transfer function would be strongly suppressed at energies above $E \geq 100$ GeV, the stronger the suppression the larger the redshift. We also realize that the spread in the possible values of T_γ would make difficult to infer strong conclusions about ALP mixing observing only few sources. To test this effect we would need to collect data from sources along different directions in the sky in order to perform a study of the photon energy distributions, from which we could hope to infer possible hints of ALP's. A further signature of these stochastic conversions would be the detection of peculiar direction-dependent dimming effects in the diffuse photon radiation observable in GeV range, testable with the FERMI (previously called GLAST) experiment.

As further developments, we plan to use our calculation to perform a systematic study of ALP signatures in very high-energy gamma-rays, analyzing in details the spectral deformations expected for observed sources at different redshifts and for different models of the extragalactic background light. Thanks to our calculation, this task now appears more doable than before. After that, it will remain to see if elusive ALP's will show up from the sky.

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