Photon-axion oscillations in Galaxy clusters

Daniele Montanino [1]

[1]Dipartimento di Fisica, Università del Salento and Istituto Nazionale di Fisica Nucleare sez. di Lecce, Italy

In this report we summarize the results of Ref. [1] were we address the interested reader for further details.

Axion-like particles (ALP's) with a two-photon vertex are hypothetical particles predicted in many extensions of the Standard Model. Pseudoscalar ALP's couple with photons through the following effective Lagrangian [2]

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

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.

Although there is not a direct 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 $\gamma \to a$ occurs in the magnetic field of the cluster while a reconversion $a \to \gamma$ happens in the magnetic field of the Milky Way. AGN are intense very high-energy ($\geq$TeV) gamma ray emitters. However, these gamma rays propagates over cosmological distances before reaching the Earth. These high energy photons undergo absorption due to the pair-production process off Extragalactic Backround Light (EBL) low energy photons $\gamma^{\rm VHE}\gamma^{\rm EBL} \to e^+e^-$. The energy range 100GeV $\leq E \leq$10TeV (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 int ALP's, these can evade the absorption by the EBL. 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. 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. 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.

There are several AGN's hosted in cluster of galaxies. We have focalized on two of these: 1ES 0414+009 (at $z = 0.287$) and Mkn 501 (at $z = 0.034$). For definiteness we have assumed a "cellular structure" for the intra-cluster magnetic fields, with domain size $l_c \simeq 10$kpc and a strength $B^{\rm CL} \sim 1\mu$G n the inner range (< 100kpc) of the cluster. Moreover we choose a photon-ALP coupling $g_{a\gamma} = 5 \times 10^{-11}{\rm GeV}^{-1}$ and an ALP mass $m_a = 10^{-8}$eV.

For a network of n ($n \sim 10$ in our case) magnetic domains with random magnetic field directions ψ_k, the final density matrixis given by

$$\rho_n = T(\psi_n, \ldots, \psi_1)\rho_0 \, T^\dagger(\psi_n, \ldots, \psi_1) \,, \quad (2)$$

where $\rho_0 = {\rm diag}\{1/2, 1/2, 0\}$ for an initial unpolarized photon and the evolution operator $T(\psi_n, \ldots, \psi_1)$ is the "product" of the the evolution operators for each k-th cell.

$$T(\psi_n, \ldots, \psi_1) \equiv \prod_{k=1}^{n} e^{-i\mathcal{H}(\psi_k) l_c} \,. \quad (3)$$

Since we do not know the particular configuration crossed by the beam during its propagation, in order to get an idea of the effect induced by the $\gamma \to a$ conversions it is useful to perform an ensemble average over all the possible realizations encompassing the $1, \ldots n$ domains.

Taking into account the absorption in the intergalactic medium and the back-conversion in Milky Way we obtain the observable average VHE photon flux at Earth:

$$I_\gamma^{\rm E}/I_\gamma^0 = P_{\gamma\to\gamma}^{\rm CL} e^{-\tau_\gamma} P_{\gamma\to\gamma}^{\rm MW} + P_{\gamma\to a}^{\rm CL} P_{a\to\gamma}^{\rm MW} \,, \quad (4)$$

where $P_{\gamma\to\gamma}^{\rm CL} = \langle \rho_{11} + \rho_{22} \rangle$ ($P_{\gamma\to a}^{\rm CL} = \langle \rho_{33} \rangle$) is the average photon survival (conversion) probability in the cluster, $P_{\gamma\to\gamma}^{\rm MW}$ ($P_{a\to\gamma}^{\rm MW}$) is the photon survival (conversion) probability in the Milky Way and τ_γ is the "optical depth" due to the absorption.

In Fig. 1 we show schematically the evolution of the average photon and ALP intensity (normalized to unity) as function of the distance from the 1ES 0414+009 at redshift or a representative energy $E = 8$TeV. The left panel represents the evolution inside the galaxy cluster, the central one

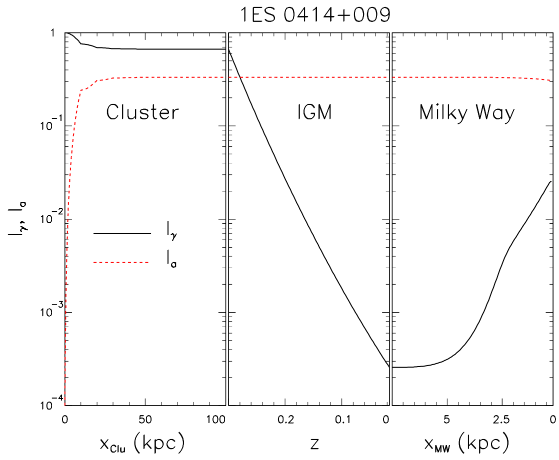

Figure 1. Evolution of the average photon (continuos line) and ALP (dashed line) intensity. See the text for details.

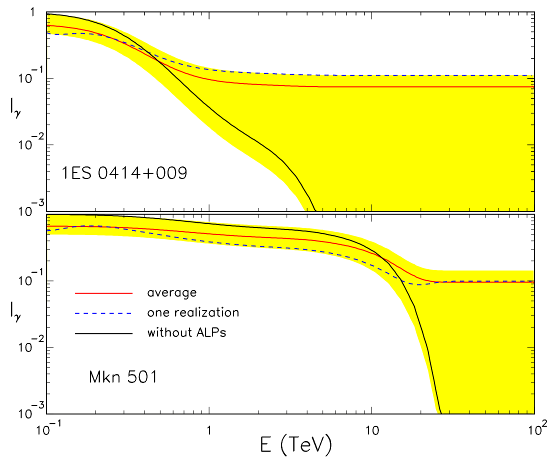

Figure 2. Spectrum of photons for two AGN. See the text for details.

the evolution in the intergalactic medium (photon absorption and ALP free propagation, with redshift on the horizontal axis), and the right one the evolution within the Milky Way. We see that only a small part of photons are converted into ALP's in the cluster. However, while the photons emerging from the cluster are strongly suppressed by absorption, the ALP's propagate unaffected till to the Milky Way. The small fraction of ALP's that are reconverted into photons in the MW magnetic field increases the photon flux by two order of magnitudes, respect to the case of no photon-ALP mixing.

In Fig. 2 it is shown the observable photon flux I_γ (normalized to 1) as a function of energy for 1ES 0414+009 and for Mkn 501 respectively. Including the effect of $\gamma \to a \to \gamma$ conversions we see that the photon flux at high energy gets strongly enhanced with respect to the expectation in the presence of conventional physics. In particular, the continuous red curves represent the photon flux in the presence of $\gamma \to a \to \gamma$ conversions, averaged over many realizations of the intra-cluster magnetic field. Indeed, the effect is striking. Since the photon-ALP conversion probability in the regime in which we are working is energy-independent, the photon flux displays a plateau – instead of a sharp drop – at which its intensity depends on the adopted Galactic magnetic field model. On average it turns out to be between 10 % and 3 % of the emitted value for 1ES 0414+009, and between 10 % and 1 % for Mkn 501. Therefore, the existence of $\gamma \to a \to \gamma$ conversions produces a considerable hardening of the spectrum at high enough energies, thereby making it possible to detect VHE photons in a range where no observable signal would be expected according to conventional physics.

However, we stress that the stochastic nature of the $\gamma \to a$ conversions in the magnetic field of a galaxy cluster implies that the final conversion probability can be considerably different from the average since the true magnetic field configuration along the line of sight is unknown. This fact entails that the photon flux observed at Earth should be better characterized in terms of probability distribution functions, obtained by considering $\gamma \to a$ conversions over different realizations of the intra-cluster magnetic field. The yellow band represents thus the range of variability of the photon flux (not equiprobable). An example of a particular realization is shown by the dashed curve. In this specific case we see that the observable photon flux at high energies can be even larger than the average one. However, if one considers many realizations of the intra-cluster magnetic fields one obtains the shaded band as envelope of the results. Therefore, depending on the particular magnetic realization crossed by the photons, it is also possible to have cases in which the suppression of the photon flux is stronger than in the presence of conventional physics.

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