Enhanced spectral hardening for cosmic TeV photons mixing with ALPs

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Axion-like particles (ALPs) are ultralight pseudo-scalar bosons a with a two-photon vertex $a\gamma\gamma$, predicted by several extensions of the Standard Model. In the presence of an external magnetic field, the $a\gamma\gamma$ coupling leads to the phenomenon of photon-ALP mixing [1]. This effect allows for the possibility of direct searches of ALPs in laboratory experiments.

Due to the $a\gamma\gamma$ coupling, ultra-light ALPs can also play an important role in astrophysical observations. In particular, an intriguing hint for ALPs has been recently suggested by Very High-Energy (VHE) γ-ray experiments. In this respect, recent observations of cosmologically distant γ-ray sources by ground-based γ-ray Imaging Atmospheric Cherenkov Telescopes have revealed a surprising degree of transparency of the Universe to VHE photons [2,3], where one would have expected a significant absorption of VHE photons by pair-production processes ($\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+e^-$) on the extragalactic background light (EBL).

However, the range of the parameters where ALPs would impact the cosmic transparency is constrained from other observations as shown in Fig. 1. In particular, for ALPs with masses $m_a \leq 10^{-9}$ eV, the strongest bound on $g_{a\gamma}$ is derived from the absence of γ-rays from SN 1987A (see [4] for a review).

Anyway, the distribution of the extragalactic magnetic fields has been poorly characterized in previous works on ALP conversions. In particular, a cell-like structure (hereafter the "cell" model) has been adopted with many domains of equal size ($l \sim 1$ Mpc) in which the magnetic field has (constant) random values and directions [5]. Only recently it has been pointed out that in more realistic situations, the magnetic field direction would vary continuously along the propagation path, and this would lead to sizable differences in the ALP conversions with respect to the "cell" model.

We have studied for the first time the photon conversions into ALPs using recent magneto-hydrodynamical cosmological simulations [6,7]. In this more realistic case the magnetic fields can locally fluctuate in filaments of matter up to two orders of magnitude larger that what found in the "cell" model and photon-ALP conversions are enhanced compared to previous estimates. Indeed,

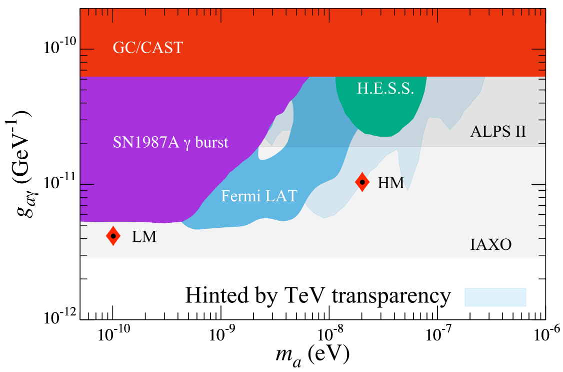

Figure 1. Limits on ALP parameter space in the plane $(m_a, g_{a\gamma})$. The parameter space where ALPs could explain the low γ-ray opacity is shown in light blue. The horizontal grey bands represent the sensitivity of future ALPS-II and IAXO experiments. The two small squares represent cases of low-mass (LM, $m_a = 10^{-10}$ eV and $g_{a\gamma} = 4 \times 10^{-12}$ GeV^{-1}) and high-mass (HM, $m_a = 2 \times 10^{-8}$ eV and $g_{a\gamma} = 10^{-11}$ GeV^{-1}) ALPs where conversions in realistic extragalactic magnetic fields would affect the TeV photon transparency.

significant conversions are found both in the low-mass region below the SN 1987A bound both in the high-mass region on the right of the recent Fermi-LAT bound. These two ranges are indicated with small squares in Fig. 1.

We have solved the propagation equation for the photon-ALP ensemble, both with a random cell model and with the realistic magnetic field. In the first case denoting $\mathbf{b}_k$ a random unit vector inside each cell, during their path with a total length L along the line of sight, the beam crosses $n = L/l_c$ domains, where l_c is the size of each domain: The set $\{\mathbf{B}_k\}_{1\leq k\leq n} = \{B_0 \cdot \mathbf{b}_k\}_{1\leq k\leq n}$ represents a given random realization of the beam propagation. We have used a fixed (comoving) value of $B_0 = 1.9$ nG which corresponds to the r.m.s. of the strength of the realistic magnetic field on all configurations and a fixed size of $l = 1.4$ Mpc per cell, which is the typical coherence length of magnetic fields in the realistic model, based on spectral analysis.

In Fig. 2 we present the photon transfer function $T_\gamma(E)$ in function of the photon energy E for a source at redshift $z = 0.3$. In the left panels we consider, the parameters corresponding to LM

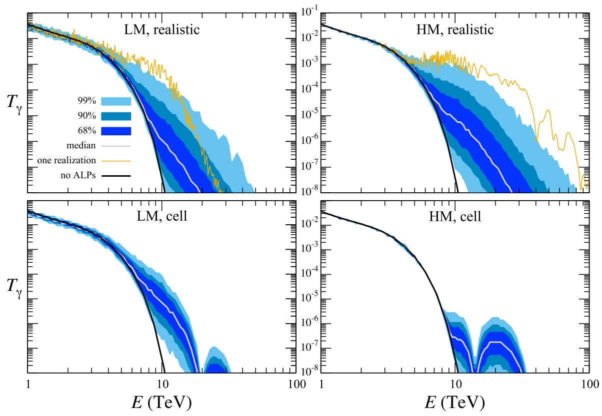

Figure 2. Photon transfer function $T_\gamma(E)$ for a source at redshift $z = 0.3$ for LM and HM cases. Upper panels refer to realistic models of extragalactic magnetic field, while lower panels are for the "cell" model. See the text for details.

parameters while in the right panels we the HM parameters marked in Fig. 1. Upper panels refer to realistic simulations for magnetic field, while lower ones are for the "cell" model. The black solid curve represents the T_γ expected in the presence of only absorption onto EBL. The solid grey curve represents the median T_γ in the presence of ALPs conversions. The orange curve corresponds to conversions for a particular realization of the extragalactic magnetic field. The shaded band is the envelope of the results on all the possible realizations of the extragalactic magnetic field at 68 % (dark blue), 90 % (blue) and 99 % (light blue) C.L., respectively by simulating 10^3 different realizations of the extragalactic magnetic field in the "cell" case, or extracting an equivalent number of 1-dimensional beams of cells randomly extracted from the outputs of the cosmological simulation at increasing redshift. According to conventional physics, it turns out that the T_γ gets dramatically suppressed at high energies ($E > 2$ TeV). As expected, including ALP conversions with cell magnetic fields, the enhancement of T_γ with respect to the standard case is modest since it is suppressed by the small coupling (left panel) or the high ALP mass (right panel). However, when we consider ALP conversions in realistic magnetic fields the enhancement of T_γ is striking.

ALP conversions in such models would produce 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 or to conversions with "cell" magnetic fields. An example of a particular realization is shown by the orange curve. In this specific case we see that the observable photon flux at high energies can be significantly larger than the average one. On this specific line of sight the enhancement of T_γ with respect to the standard case would reach 3 order of magnitudes.

Depending on the particular magnetic realization crossed by the photons, it is also possible to observe a suppression of the photon flux stronger than in the presence of conventional physics. Nevertheless, from Fig. 2 one infers that the cases in which T_γ is enhanced at high energies are much more probable. From these results it is evident that using realistic models of the extragalactic magnetic fields has a strong impact on the mechanism of photon-ALP conversions to reduce the cosmic opacity.

In conclusion, we have studied the conversions of VHE photons into ALPs proposed as a mechanism to reduce the absorption onto EBL, using for the first time realistic models of extragalatic magnetic fields, obtained from magnetohydrodynamical cosmological simulations. We find an enhancement of the magnetic field with respect to what predicted in the naive "cell" model, due to the fact that simulated magnetic fields display larger fluctuations, correlated with density fluctuations of the cosmic web. This effect would give a significant boost to photon-ALP conversions. Notably, using the "cell" model the parameter space for photon-ALP conversions at VHE energies was strongly constrained by SN 1987A and Fermi-LAT data. However, using realistic models of the magnetic field we have found significant conversions also in regions of the parameter space consistent with previous bounds. This mechanism can produce a significant hardening of the VHE photon spectrum from faraway sources and we expect such signature to emerge at energies $E \geq 1$ TeV. Therefore, this scenario is testable with the present generation of Imaging Atmospheric Cherenkov Telescope, covering energies in the range from ~ 50 GeV to ~ 50 TeV.

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