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AXION-LIKE PARTICLES AND γ-RAY SOURCE SPECTRA

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Abstract. Oscillations from high energy photons into Axion Like Particles (ALPs) in an external magnetic field are expected to leave an imprint on the spectra of astrophysical γ-ray sources. We show that the usual observables, that are a drop in the energy spectra and a boost of fluxes at very-high energies in case of propagation through the intergalactic medium, are only valid when averaging observations over a multitude of sources. A new signature of ALPs in the case of observations of single sources is outlined, that could be used as an efficient method to tag photon-ALP oscillations.

1 Introduction

Axion-like particles (ALPs) are a class of hypothetical light pseudoscalar particles that only to Standard Model components through a two-photon vertex. This coupling allows for photon-ALP oscillations in an external magnetic field. Such process has recently gained interest in astrophysics as being a possible explanation for various phenomena; these phenomena includes the anomalous cooling of white dwarves (Isern et al. 2008), the scatter in the luminosity relations of sources (Burrage et al. 2009) or possibly the dimming of type Ia supernovae (Csáki et al. 2002). In very-high energy (VHE, E > 100 GeV) astrophysics, ALPs were introduced as an exotic explanation to the problem of the lack of opacity of the universe to TeV γ-ray, opacity due to the absorption of γ-rays on the the extragalactic background light (EBL) through pair creation (De Angelis et al. 2007; Simet et al. 2008; Horns & Meyer 2012). Back in 2006 when the Cherenkov telescope array H.E.S.S. observations of two blazars implied a low level of EBL compared to semi-empirical models (Aharonian et al. 2006), it has been proposed that γ-ALPs oscillations in the Inter-Galactic Magnetic Field (IGMF) could reduce the observed opacity as photons travel shielded to EBL when they are in the ALP state. The same effect has been proposed to explain the VHE emission from dense regions in blazars (Tavecchio et al. 2012). A second signature of γ-ALPs oscillations in γ-ray spectra is a dimming of the fluxes above the energy threshold at which the mixing starts to be efficient, the composition of the beam being on average 2/3 of photons and 1/3 of ALPs (Mirizzi et al. 2007; Hooper & Serpico 2007; Hochmuth & Sigl 2007).

In astrophysical environments relevant to this study, be it a galaxy cluster or the intergalactic medium, magnetic fields are turbulent so that the exact structure of the magnetic field crossed by the beam is not predictable. This results in a consequential randomness of the observable effects. For instance, Mirizzi & Montanino (2009) have shown that there exist realizations of the IGMF leading to a decrease of the γ-ray flux through γ-ALPs oscillations and EBL absorption, stronger than what is predicted from the EBL absorption only. The two expected signatures of ALPs in γ-ray source spectra, a more transparent universe and a drop in energy spectra at the threshold of coupling are in fact based on an average structure of the turbulent magnetic field. Such observables are thus useless to look for ALPs through the observation of a single source leaving only the possibility of a population study to average the effects over a collection of sources. A signature outlined in Wouters & Brun (2012) that applies to observations of only one source is studied here.

2 γ-ALPs mixing for a single-source spectrum

Magnetic fields involved in a possible coupling between ALPs and photons from astrophysical TeV sources are usually turbulent. To model the evolution of the γ-ALPs system when propagating through a turbulent magnetic field, the simplest way is to divide the path between domains of constant size typical of the coherence length

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of the magnetic field. In each domain, the strength of the magnetic field is considered as constant and only the orientation is randomly varying. In this picture, one realization of the magnetic field is a set of randomly chosen orientation of the magnetic field for each domain, corresponding to the structure of the magnetic field crossed by a photon beam from a source randomly picked on the sky. This is a crude description of the turbulent magnetic field but it proves useful to understand the simple basics of the behavior of the coupling. The validity of such a description when considering other turbulence models is latter addressed in section 3 and in particular that it is conservative compared to more accurate descriptions.

The structure of the turbulence model is such that in each domain, the magnetic field is coherent. γ-ALPs mixing in a coherent magnetic field has long been studied. It turns out that only the magnetic field component transverse to the propagation is involved in the coupling (Raffelt & Stodolsky 1988). Moreover, only one polarization state of the photon parallel to the field couples, such that the problem depends in fact on two geometrical angles, encoding the orientation of the magnetic field. The mixing is efficient above en energy threshold given as function of the mass of the ALPs, m_a, the coupling strength, g, and the projection of the magnetic field on the polarization plane of the photon B_T:

$$E_{\rm thr} = \frac{m_a^2}{2gB_T} \ .$$

The conversion probability of the photon crossing the coherent magnetic domain of size s has the following dependence: For $E \ll E_{\rm thr}$ no conversion occurs, for $E \sim E_{\rm thr}$, spectral oscillations happen and for $E \gg E_{\rm thr}$, the conversion is no longer energy dependent and takes the value $\sin^2 \delta/2$ where $\delta = gB_T s/2$. Therefore, the condition required for a significant conversion is $\delta \gtrsim 1$, similar to the Hillas criterion for the acceleration of ultra-high energy cosmic rays (Hooper & Serpico 2007), suggesting that the two processes could take place in the same astrophysical environments. As an example, the photon survival probability as a function of the energy for an allowed large IGMF value of 1 nG, an ALP mass of 2 neV and a coupling $g = 8 \times 10^{-11}\,\mathrm{GeV}^{-1}$ at the limit of current experimental constraints (Arik et al. 2011) is shown for different values of δ (increasing s) on fig. 1. For the parameters chosen, $E_{\rm thr}$ is fixed at 1 TeV.

For each domain of the turbulent magnetic field, a transfer function of the system giving the conversion probability can be constructed. The total transfer function corresponding to one random realization of the magnetic field is given by the product of all individual transfer functions. For each single domain transfer functions, the spectral oscillations around $E_{\rm thr}$ such as those displayed on fig. 1 have a different structure, depending on the orientation of the magnetic field (giving different values for B_T). The global survival probability is therefore the result of interferences of all these oscillation patterns, yielding a very complex energy dependence around $E_{\rm thr}$. An example is shown on fig. 2, for a source at redshift 0.1 whose photons travel trough the IGMF assuming a coherence length $s_0 = 1$ Mpc, and for the same set of ALP parameters. The figure is displayed using the EBL model from Kneiske & Dole (2010). One can see that the prediction of a model with ALPs is the presence of a significant level of noise over one decade or so around $E_{\rm thr}$. At VHE, a smooth behavior of the spectrum is retrieved, as the interferences weaken. Although the exact shape of the spectrum is not predictable, as it depends on one single random realization of the magnetic field, the noise level can be predicted as shown in the next section.

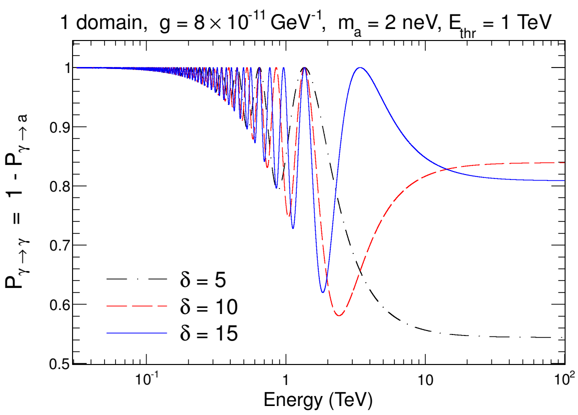

Fig. 1. Survival probability of an unpolarized photon as function of the energy for three values of δ

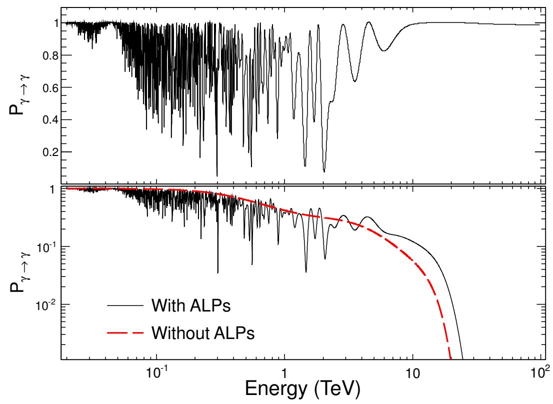

Fig. 2. Survival probability as function of the energy for a source at z = 0.1 using $B = 1$ nG, $s_0 = 1$ Mpc, $g = 8 \times 10^{-11}\,\mathrm{GeV}^{-1}$ and $m_\mathrm{a} = 2$ neV without absorption (upper panel) and with EBL absorption (lower panel)

3 Observational effects

The spectrum obtained in sec. 2. from the simulation of the propagation through the IGMF is the theoretical continuous spectrum that will be observed. In practice, astrophysical sources spectra at TeV energies are observed with a given energy resolution, that is approximately 15% for the latest generation of atmospheric Cherenkov telescopes, HESS, MAGIC or VERITAS. This finite energy resolution tends to smooth the alternation of peaks and drops that form the noisy behavior around E_thr, so that it could remain unobservable.

To study the experimental relevance of the proposed signature, a simulation is performed considering 50 h of observations of a source at redshift 0.1 emitting at the Crab level. To match current generation of instruments, an effective area of $10^5\,\mathrm{m}^2$ is assumed in addition to the 15% energy resolution. The source spectrum is the product of the intrinsic spectrum, here for example following a log-parabola shape, and a survival probability pattern generated for a random realization of the IGMF convolved with EBL absorption. This spectrum is then binned in bins of size corresponding to the energy resolution to obtain the observed binned spectrum. For each bin, the number of detected photons is redistributed with a Poisson distribution, to account for statistical errors. An example of such simulation is shown on the left panel of fig. 3, together with a fit of the binned spectrum with a log-parabola shape moduled by EBL absorption. The relative residuals of that fit are displayed on the right panel of fig. 3. As compared to the case without ALPs for which the residuals evenly spread around 0, the noisy behavior of the underlying unbinned spectrum in the ALPs model clearly impacts the binned measured spectrum, the relative fit residuals displaying anomalous strong and chaotic deviations from 0.

To further quantify this noise, the variance of these relative fit residuals is computed. An average of this variance over 5000 simulations of different realizations of the IGMF is shown on tab. 1 for different scenarios. From this table, the variance, which is a prediction of given ALP parameters, instrumental response functions and chosen source, scales with the coupling strength g. For the coupling strengths tested, the effect turns out to be significant compared to the conventional expectation. Observations of a Crab-level source for 50 h has been chosen as an illustration, but for the same redshift and energy range, a hint of effect would still be visible but with less significance by observing only 5 h.

The turbulence as it has been described so far is the simplest model one could think of. A more realistic description is to use a Kolmogorov-like turbulence, that accounts for the power distribution of a large range

Table 1. Values of the RMS of the fit residuals to mock data with different assumptions for g and m (in units of GeV^{-1} and neV resp.), for constant size magnetic field domains and Kolmogorov turbulent magnetic field.

Model	Variance of the fit residuals Constant size domains	Variance of the fit residuals Kolmogorov turbulence
No ALP	0.04 ± 0.01	*idem*
$g = 10^{-11}$, $m = 0.7$	0.11 ± 0.04	0.18 ± 0.05
$g = 8 \times 10^{-11}$, $m = 2$	0.20 ± 0.05	0.42 ± 0.14

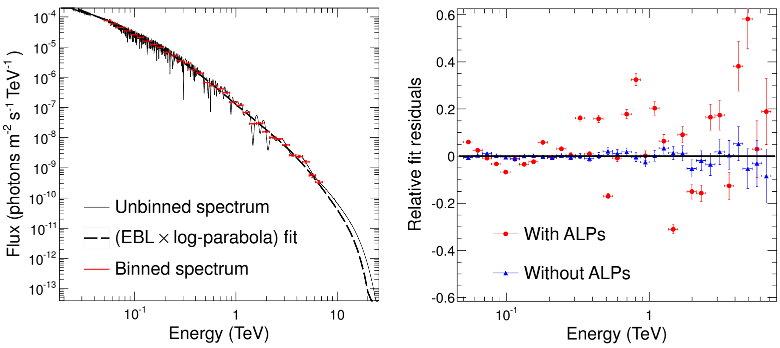

Fig. 3. Simulation of the observation of one γ-ray source at z=0.1, with the effect of γ-ALP mixing (left), and distribution of the residuals of fits to a conventional model and a model with ALPs (right).

of modes $k = 2\pi/s$ where the power in each mode scales as $k^{-5/3}$. In this framework, magnetic fields that are coherent on small scales should have contributions that become rapidly negligible due to two effects: first, because of the Kolmogorov power-law, the magnetic field involved is weaker. Second, for small coupling, the averaged conversion probability is proportional to B^2L/s so that even for a magnetic field uniform over all scales, the mixing is less and less efficient at small scales. Finally, given the two mentioned effects, the conversion probability for a scale $s/10$ is only 2.5‰ of the probability at scale s ($P \propto s^{-8/3}$), so that one can safely consider that only the largest scales contribute. The results of the variance of the fit residuals assuming a Kolmogorov-like turbulence over scales between 0.1 and 100 Mpc and a rms intensity of B of 1 nG at 100 Mpc are also reported on table 1. The variance of the fit residuals is still significantly larger in the ALP model.

4 Conclusion

In this study, the effects of γ-ALP oscillations on γ-ray source spectra have been discussed, making the difference between average observables, valid for a large collection of sources, and single source observables. For the first time, a signature of ALPs for observations of a single has been outlined with an explicit example given in the case of mixing in the IGMF. It has been checked that this signature is experimentally detectable given current generation of instruments. Such effect could be used to constrain ALP models in the range of very small masses ($m_a \sim 10^{-10} - 10^{-7}$ eV).

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