Constraints on axion-like Particles from the high-energy Universe

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The interaction of axion-like particles (ALPs) with two photons enable the oscillations between photons and ALPs in an external magnetic field. This interaction modify the energy spectrum of astrophysical sources under the form of an irregular behavior in a limited energy range. This signature is searched in the high-energy spectra of active galactic nuclei to put stringent constraints on the ALP coupling to photons.

1 Introduction and phenomenology

Axions are hypothetical new light bosons, theoretically introduced to solve the strong CP problem [1]. Axions generically couple to two photons, with their coupling strength proportional to their mass. More general light particles with the same coupling to photons but their mass and coupling unrelated are also a prediction from some string theories [2] and are considered as a possible constituent of dark matter. Such particles are called axion-like particles (ALPs). Because of the coupling between photons and ALPs, a photon can oscillate into an ALP in an external magnetic field and vice-versa, in a way similar to the neutrino flavor oscillation case. The probability of conversion of a photon into an ALP in an homogeneous magnetic field of strength B over a distance s is [3]:

$$P_{\gamma\to a} = \frac{1}{2}\frac{1}{1+E_c^2/E^2}\sin^2\frac{g_{\gamma a}Bs}{2}\sqrt{1+E_c^2/E^2}\ , \tag{1}$$

where $g_{\gamma a}$ is the coupling strength and $E_c = m^2/2g_{\gamma a}B$ is the energy threshold of the photon/ALP mixing and depends on the mass m of the ALP. For coupling strength close to the current upper limit set by the CAST experiment, $g_{\gamma a} = 5\times10^{-11}\mathrm{GeV}^{-1}$ and a magnetic field strength of 1 μG typical of galaxy clusters magnetic fields, the energy threshold is of the order of 1 TeV for ALP masses close to 1 μeV. In this study, the initial photon beam is assumed to be unpolarized, so that the conversion probability cannot be lower than 0.5.

If the magnetic field is turbulent, as it is generally the case for astrophysical magnetic fields, the conversion probability has a very complex energy behavior around the energy threshold [4]. The stochastic nature of the magnetic field translates to an irregular behavior on the conversion probability that is not predictable and depends on the specific realization of the magnetic field. An example of such modification is shown on Fig. 1 for the same ALP parameters than above and a magnetic field strength of 1 μG. The lower panel shows the same signal smeared by the energy resolution of H.E.S.S., of the order of 12%.

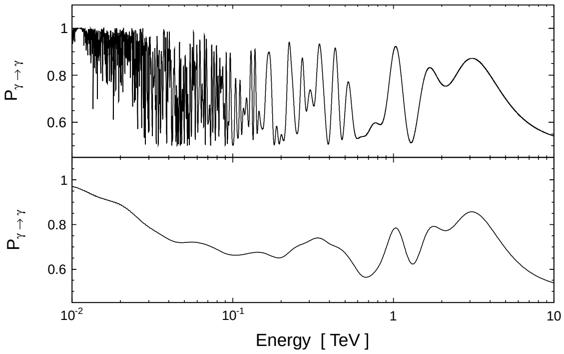

Figure 1: Typical modulation from an ALP signal with $E_c \sim 1$ TeV. Top panel : raw function. Bottom panel : Same function smeared with the energy resolution and bias of H.E.S.S.

2 Constraints from observations with H.E.S.S.

In order to identify possible anomalous deviations in the spectrum, a bright source with a large statistics is required. The brightest extragalactic source observed by H.E.S.S. is the active galactic nuclei PKS 2155-304. A strong flare has been observed in July 2006 where the flux reached levels of 7 time the flux of the Crab Nebula. Because of the high luminosity of the source during the flare the background is negligible.

A crucial point for the search of an ALP signal is a good knowledge of the magnetic field involved in the photon-ALP mixing. In the case of PKS 2155-304 a galaxy cluster of radius 370 kpc is observed. Galaxy cluster are hosts of strong magnetic fields that can be probed by Faraday rotation of the polarization axis in radio. Such measurements show that the magnetic field strength is of order of 1-10 μG [5]. The turbulence power spectrum can also be estimated with Faraday rotation [6]. Studies on the Hydra A cluster obtained a power spectrum compatible with a Kolmogorov spectrum with a maximal turbulence scale of 10 kpc. The magnetic field in the galaxy cluster of PKS 2155-304 cannot be probed via Faraday rotation since the radio lobes are aligned on the line of sight. In the following a minimal value for the magnetic field strength of 1 μG is assumed. The turbulence power spectrum is assumed to follow a Kolmogorov spectrum with a coherence length of 10 kpc. Constraints will be derived with this conservative description of the magnetic field. For the intergalactic magnetic field (IGMF), no measurements have been possible so far. The current upper limit is of 1 nG for coherence scales of order 1 Mpc. Optimistic constraints with this description of the IGMF are also derived. They are independent from the constraints derived with the cluster magnetic field because of the different values of the magnetic field strength.

The spectrum measured by H.E.S.S. during the flare, shown on the Fig. 2 of [7], does not show any evidence of an irregular behavior. Constraints on the ALP coupling are derived on a statistical basis where MC simulations of the spectrum with an ALP signal are produced. To estimate the minimal sensitivity to irregularities, an irregularity estimator is built that measure the fluctuations from bins to bins assuming that the intrinsic spectrum locally follows a power law shape on scales of three bins. The constraints derived with this method are shown on Fig. 2 for conversion in the galaxy cluster magnetic field and in the IGMF. The range of mass probed by the different conversion domains is determined by the magnetic field strength so that the energy threshold of the mixing lies in the energy range of H.E.S.S.

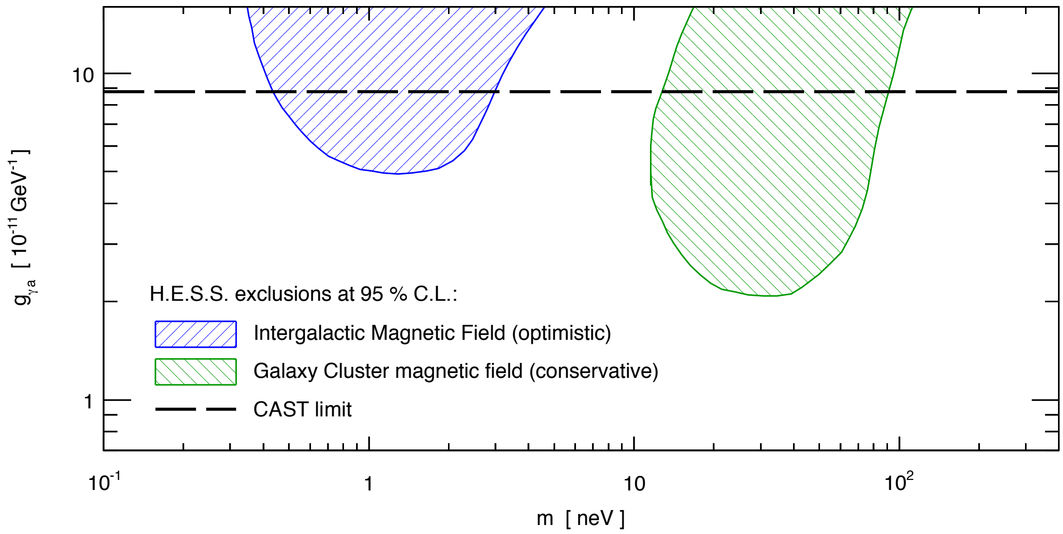

Figure 2: H.E.S.S. exclusion limits on the ALP parameters $g_{\gamma a}$ and m. The blue dashed region on the left is obtained considering γ-ALP mixing in the IGMF with in an optimistic scenario with a 1 nG strength. The green dashed region on the right is obtained considering γ-ALP mixing in the galaxy cluster of PSK 2155-304.

3 Constraints from X-ray observations

If the photon/ALP oscillations occur in an astrophysical plasma, the energy threshold of the mixing is modified: $E_c = |m_\gamma^2 - m^2|/2g_{\gamma a}B$ by taking into account the effective mass of the photon in the plasma, $m_\gamma^2 = 4\pi\alpha n_e/m_e$. Typically, the electron density of the plasma n_e in a galaxy cluster is of order of 0.01 cm^{-3}. The corresponding effective mass of the photon is $m_\gamma \sim 10^{-12}$ eV. In the case of the H.E.S.S. analysis, the range of mass probed is orders of magnitudes higher so that the effect of the plasma is negligible. For $m < m_\gamma$, the energy threshold is independent of m and is around a few keV for electron density typical of galaxy clusters. Observations in X-rays are therefore sensitive to irregularities caused by the energy threshold set by the effective mass of the photons propagating in the galaxy cluster plasma.

A good candidate source for this analysis is a bright point-like source embedded in a galaxy cluster. In order to minimize uncertainties from the lack of knowledge on the magnetic field, the magnetic field in the galaxy cluster should be measured. The magnetic field of the Hydra A galaxy cluster has been extensively measured by Faraday rotation and a good knowledge of the electron density profile and turbulence power spectrum is available. A Fanaroff-Riley I radio galaxy lies at the center of the cluster and has been observed by *Chandra* with a low angular resolution enabling the collection of a large statistics on the source. A conservative description for the magnetic field of the galaxy cluster is assumed, following the results of [6] for a jet viewing angle of 30°. In this model, the magnetic field strength at the centre of the cluster is 21 μG and the electron density is 0.056 cm^{-3}.

The spectrum of the central source observed by *Chandra* is reconstructed with observations in 1999 and 2003. Because of an important absorption system in Hydra A, the central source is only visible above 1 keV. The spectrum, shown on Fig. 1 of [8] is well fitted by a power-law moduled by the absorption system and does not show any anomalous irregularities. The exclusion is obtained by fitting simulated ALP signal on the spectrum. When the coupling strength is high enough, the spectrum with ALP signal significantly (95% C.L.) deteriorate the fit whatever the realization of the magnetic field is. The 95% C.L. exclusion is shown on Fig. 3. It extends to arbitrary small ALP masses because the energy threshold is in this case independent of the mass. When ALP masses higher than the effective photon mass are considered, the energy threshold is shifted towards higher energies and the sensitivity decreases. For ALP masses equal to the effective photon mass, the conversion is resonant and energy independent so that the sensitivity decreases.

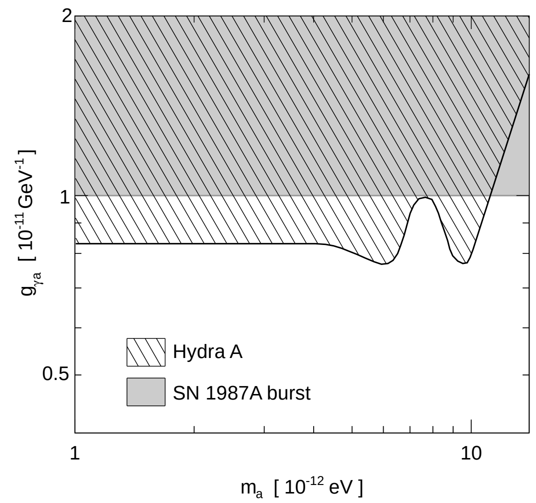

Figure 3: Exclusion limits on the ALP parameters $g_{\gamma a}$ and m from *Chandra* observations of the Hydra galaxy cluster.

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