Photons into axion-like particles conversion in Active Galactic Nuclei

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The idea that photons can convert into axion-like particles (ALPs) $\gamma \rightarrow a$ in or around an AGN and reconvert back into photons $a \rightarrow \gamma$ in the Milky Way magnetic field has been put forward in 2008 and has recently attracted growing interest. Yet, so far nobody has estimated the conversion probability $\gamma \rightarrow a$ as carefully as allowed by present-day knowledge. Our aim is to fill this gap. We first remark that AGN that can be detected above 100 GeV are blazars, namely AGN with jets, with one of them pointing towards us. Moreover, blazars fall into two well defined classes: BL Lac objects (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs), with drastically different properties. In this Letter we evaluate the $\gamma \rightarrow a$ conversion probability inside these two classes of blazars, taking also the host elliptical galaxy into account. Our findings are surprising. For, while in the case of BL Lacs the conversion probability turns out to be totally unpredictable due to the strong dependence on the values of the somewhat uncertain position of the emission region along the jet and strength of the magnetic field therein, for FSRQs we are able to make a clear-cut prediction. Our results are of paramount importance in view of the planned very-high-energy detectors like the CTA, HAWK and HISCORE, as well as for laboratory experiments like ALPS II at DESY and IAXO.

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Introduction – Many extensions of the Standard Model of particle physics – and chiefly among them superstring theories – generically predict the existence of axion-like particles (ALPs), which are spin-zero, neutral and extremely light bosons closely resembling the axion [1] apart from two facts that makes them as much as model-independent as possible: (1) possible couplings to fermions and gluons are discarded and only their two-photon coupling $a \gamma \gamma$ is taken into account, (2) the ALP mass $m$ is totally unrelated to their $a \gamma$ coupling constant $1/M$ [2]. As a consequence, they are described by the Lagrangian

$$\mathcal{L}_{\text{ALP}}^0 = \frac{1}{2} \partial^{\mu} a \partial_{\mu} a - \frac{1}{2} m^2 a^2 + \frac{1}{M} E \cdot B a , \quad (1)$$

where $E$ and $B$ denote the electric and magnetic components of the field strength $F^{\mu\nu}$. Throughout this Letter, $E$ is the electric field of a propagating photon while $B$ is an external magnetic field. Actually, because $E$ is perpendicular to the $\gamma$ momentum, the structure of the last term in Eq. (1) implies that only the transverse component $B_T$ couples to $a$. Accordingly, the mass matrix of the $a \gamma$ system is off-diagonal, thereby implying that the propagation eigenstates differ from the interaction eigenstates. Therefore $\gamma \leftrightarrow a$ oscillations take place much in the same way that occurs for massive neutrinos of different flavor (apart from the need of $B$ in order to compensate for the spin mismatch) [3]. However, in the situations to be addressed below also the one-loop QED vacuum polarization in the presence of $B$ has to be taken into account and is described by the effective Lagrangian [4]

$$\mathcal{L}_{\text{HEW}} = \frac{2\alpha^2}{45m_e^2} \left[ (E^2 - B^2)^2 + 7(E \cdot B)^2 \right] , \quad (2)$$

where $\alpha$ is the fine-structure constant and $m_e$ is the electron mass. So, the considered ALP Lagrangian is

$$\mathcal{L}_{\text{ALP}} = \mathcal{L}_{\text{ALP}}^0 + \mathcal{L}_{\text{HEW}}.$$
ity of extragalactic sources detected in the VHE band – and flat spectrum radio quasars (FSRQs) [5]. As a rule, the blazar spectral energy distribution (SED) shows two broad humps, the first one peaking at low frequency – from IR to soft-X rays, depending on the specific source – while the second one in the γ-ray band. In BL Lacs the latter component extends to VHE, often reaching multi-TeV energies. In the widely assumed leptonic models, the VHE γ-ray emission is the result of the inverse Compton (IC) scattering of soft photons by relativistic electrons in the jet. Moreover, it is widely accepted that the dominant soft photon population derives – through the synchrotron mechanism – by the same electrons that scatter them into the VHE band. This is the scheme which lies at the basis of the so-called synchrotron self Compton (SSC) model [6].

Yet, the VHE band is plagued by the existence of the extragalactic background light (EBL) which is the light emitted by galaxies during the whole cosmic history and extends from the far-infrared to the near-ultraviolet [7]. What happens is that when a VHE γ emitted by a distant blazar scatters off an EBL γ it has a good chance to disappear into an e+e− pair [8]. Indeed, according to conventional physics this effect becomes dramatic even for E above a few TeV (see the Figure in Ref. [9]), a fact that drastically reduces the γ-ray horizon at increasing E.

A breakthrough came in 2007 when it was first realized [10] [11] that γ → a → γ oscillations taking place in intergalactic space can greatly decrease the EBL dimming for sufficiently far-away blazars and high enough E provided that a large-scale magnetic field in the 0.1 – 1 nG range exists with a domain-like structure, which is consistent with all presently available upper bounds [12]. Why this happens can be understood in an intuitive fashion. Photon-ALP oscillations give a photon a split personality: as it propagates from the blazar to us, it behaves sometimes as a true photon and sometimes as an ALP. When it propagates as a photon it undergoes EBL absorption, but when it propagates as an ALP it does not. Therefore the effective photon mean free path in extragalactic space λγ,eff(E) is larger than λγ(E) as predicted by conventional physics. Correspondingly, the photon survival probability becomes Pγ→γ(E) = exp(−Ds/λγ,eff(E)), where Ds is the blazar distance. So, because of the exponential dependence on the mean free path even a small increase of λγ,eff(E) with respect to λγ(E) produces a large enhancement of Pγ→γ(E), thereby giving rise to a drastic reduction of the EBL dimming. A tantalizing fact is that for a suitable choice of the free parameters it has been shown that this mechanism provides a solution to the pair-production anomaly at the 3.68 σ level [13]: a statistical analysis of all blazars observed so far at VHE has shown that the EBL level needed to best-fit observations is lower than even the minimal EBL level [14].

As a follow-up of the previous proposals that γ → a conversions occur in AGN [15], a complementary scenario was put forward in 2008 [16]. Schematically, VHE photons are simply assumed to substantially or even maximally convert into ALPs inside a blazar, so that the emitted flux can consist in up to 1/3 of ALPs and in 2/3 of photons. Once ALPs reach the Milky Way (MW), they can be converted back into photons in the MW magnetic field. Clearly, the amount of back-conversion strongly depends on the galactic coordinates of the blazar, since the morphology of the MW magnetic field is quite complicated and by no means isotropic, and also in this case the EBL dimming is drastically reduced. Basically the same idea has been taken up subsequently [17]. Unfortunately, either the blazar has not been modelled at all [15] [16] or incorrectly [17], assuming a domain-like structure for the jet magnetic field.

The aim of this Letter is to report on the evaluation of the γ → a conversion probability Pγ→a(E) inside these two classes of blazars taking also the host elliptical galaxy into account as carefully as possible consistently with the presently available knowledge.

**BL Lacs** – They are the simplest blazars, and so we better start from them. Denoting by y the coordinate along the jet axis, in order to achieve our goal two quantities are needed where the photon/ALP beam propagates: the transverse magnetic field Bγ(y) and the electron density n_e(y) profiles. Because the electrons are accelerated in shocks produced in the flow, the VHE photons are produced in a well-localized region RVHE pretty far from the central engine. So, four crucial parameters are the distance dVHE of RVHE from the centre, its size, and the values of Bγ,VHE and n_e,VHE inside it. The SSC diagnostics applied to the SED of BL Lacs [18] provides the main physical quantities concerning RVHE. They are Bγ,VHE = 0.1 – 1 G and n_e,VHE ≃ 5 · 10^4 cm^{-3}, leading to a plasma frequency of 8.25 · 10^{-9} eV. The quantity dVHE is difficult to determine directly, because the current instrumental spatial resolution is still too poor. A common indirect way consists in inferring dVHE from the size RVHE of RVHE, assumed to be a measure of the jet cross-section, derived in turn from spectral models and the observed variability timescale. Typical values lie in the range 10^{15} – 10^{16} cm. Whenever the jet aperture angle θ_{jet} is measurable – which is certainly the case for BL Lacs at a relatively large distance – it is generally found θ_{jet} ≃ 0.1 rad, so that under the assumption of a simple conical geometry for the jet it follows that RVHE = Bγ,VHE/θ_{jet} ≃ 10^{16} – 10^{17} cm. Beyond RVHE VHE photons travel outwards unimpeded until they leave the jet with a typical length of 1 kpc and propagate into the host galaxy. Given the fact that dVHE is a fairly large quantity, the component of B relevant for us is the toroidal part which is transverse to the jet axis and goes like y^{-1} [19]. The same conclusion follows from the conservation of the
FIG. 1: Plot of $P_{\gamma \rightarrow a}(E)$ for a BL Lac including the host galaxy contribute. The different curves correspond to $B = 0.1 \text{ G}$ (solid blue), $0.2 \text{ G}$ (dashed cyan), $0.5 \text{ G}$ (long dashed, green) and $1 \text{ G}$ (dot-dashed, red). The three panels correspond to three values of the distance of the emitting region, namely $d_{\text{VHE}} = 10^{16} \text{ cm}$ (bottom), $3 \cdot 10^{16} \text{ cm}$ (middle), $10^{17} \text{ cm}$ (upper).

FIG. 2: Plot of $P_{\gamma \rightarrow a}(E)$ for a FSRQ including the conversion in the host galaxy and in the radio lobe. The different curves correspond to $B = 1 \text{ G}$ (solid blue), $3 \text{ G}$ (dashed cyan), $5 \text{ G}$ (long dashed, red). The three panels correspond to three values of the distance of the emitting region, namely $d_{\text{VHE}} = 3 \cdot 10^{16} \text{ cm}$ (bottom), $10^{17} \text{ cm}$ (middle), $3 \cdot 10^{17} \text{ cm}$ (upper).

magnetic luminosity if the jet conserves its speed [20]. Moreover, recent work has succeeded to observationally characterize the $B$ structure over distances in the range $0.1 - 100 \text{ pc}$ in several jets of BL Lacs through polarimetric studies, showing unambiguously that in BL Lacs $B$ is indeed substantially ordered and predominantly traverse to the jet [21]. We stress that in particular these results are inconsistent with a domain-like structure of $B$ in the jet as assumed e.g. in [17].

Turning next to the electron density, under the usual assumption that the jet has a conical shape we expect that it goes like $y^{-2}$. Whence

$$B_T(y) = \frac{B_{T,\text{VHE}} d_{\text{VHE}}}{y}, \quad n_e(y) = \frac{n_{\text{VHE}} d_{\text{VHE}}^2}{y^2},$$  

(3)

for $y > d_{\text{VHE}}$. Observe that Eq. (3) holds true in a frame co-moving with the jet, so that the transformation to a fixed frame is effected by $E \to \gamma E$ [22]. Here $\gamma = 15$.

FSRQs – These are the most powerful blazars and are in a sense a more complicated version of BL Lacs. The additional components are: (1) the broad line region (BLR) consisting in a spherical shell of many clouds photo-ionized by the radiation from the matter accreting onto the SMBH, located at about $d_{\text{BLR}} \simeq 10^{18} \text{ cm}$ from the centre and rapidly rotating about it; (2) a dusty torus reprocessing part of the above radiation in the infrared band; (3) the radio lobes consisting in a hot non-thermal plasma inflated where the jets collide with the extragalactic gas. Because both the BLR and the dusty torus lie beyond $R_{\text{VHE}}$ and are quite rich of ultraviolet and infrared photons, respectively, they give rise to a huge absorption of $\gamma$ rays with $E_{\gamma} > 10 - 20 \text{ GeV}$ through the same $\gamma \gamma \rightarrow e^+e^-$ process considered above. On the other hand, the lobes – being magnetized – represents a further conversion region. The jets in FSRQs are longer and less prone to instabilities than those of the weaker BL Lacs. Presently, concerning the VHE $\gamma$-ray emission region $R_{\text{VHE}}$ we take $d_{\text{VHE}}$ larger by a factor of 3 as compared to the BL Lac case, based on the larger variability time scales [23]. The modeling of the SED with state-of-the-art emission models provides $B_{T,\text{VHE}} = 1 - 5 \text{ G}$ and $n_{\text{VHE}} \simeq 10^4 \text{ cm}^{-3}$ [24]. The geometry and the intensity of $B$ in the jet beyond $R_{\text{VHE}}$ are far less clear than in the case of BL Lacs. In fact, there are indications that $B$ has a globally ordered structure, but its inclination angle $\varphi$ with respect to the jet axis does not have a unique value for all sources, actually covering the whole interval $0 - 90^\circ$. For definiteness, we assume the same profiles of $B_T(y)$ and $n_e(y)$ as in Eq. (3), taking $\varphi = 45^\circ$ and $\gamma = 10$. Radio polarimetric observations yield a good amount of information about the structure and the intensity of $B$ in the radio lobes. Specifically, one gets a turbulent $B$ which can be modelled as a domain-like structure with homogenous strength $B = 10 \mu \text{G}$, coherence length $10 \text{ kpc}$ and random orientation in each domain.
Host Galaxy – Blazars are hosted by optically bright, massive ellipticals, which belong to poor galaxy groups in the case of BL Lacs [24] whereas they can well lie in rich clusters when they host a FSRQ. In this kind of galaxies a sizable amount of ionized gas at temperature $T_{\text{gas}} \sim 10^7$ K can be present [25]. Even in those cases in which the gas is in hydrostatic equilibrium subsonic turbulence can exist, which has been shown to typically produce a random magnetic field, which average strength $5 \mu G$, coherence length 150 pc and extension close to 15 kpc from the center [26].

Results – Because of lack of space, we cannot report the explicit calculation of the $\gamma \rightarrow a$ conversion probability $P_{\gamma \rightarrow a}(E)$ which is anyway a straightforward application of the technique discussed in great detail in [11]. We assume as benchmark values the most often adopted ones: $M = 10^{11}$ GeV and $m = 10^{-9}$ eV. Basically, our results can be summarized as follows. Owing to the leading role played by the QED term, in the case of BL Lacs $P_{\gamma \rightarrow a}(E)$ shows a rather complex behaviour and a strong dependence on $B_{\gamma,\text{VHE}}$ and $d_{\gamma,\text{VHE}}$, as shown in Fig. 1. As a consequence, $P_{\gamma \rightarrow a}(E)$ turns out to be intrinsically unpredictable. On the contrary, for FSRQs due to the efficient $\gamma \leftrightarrow a$ oscillations in the radio lobes – which actually leads to the equipartition among the three degrees of freedom – the above peculiar features get smoothed out and below 20 GeV we get $P_{\gamma \rightarrow a}(E) = 1/3$. Above 20 GeV instead the above-mentioned absorption leads to a drastic reduction of the emitted ALP flux. Altogether, in the case of FSRQs we make a clear-cut prediction which is exhibited in Fig. 2.

Our results are of great importance for the planned very-high-energy detectors like the CTA, HAWK and HISCORE, for laboratory experiments like ALPS II at DESY and IAXO, and for those based on the techniques discussed in [27]. In particular, the analyses carried out in [14, 25] should be properly revised according to the present conclusions.

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