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Is there any need for axion-like particles to explain the signal from blazars?

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Summary. — We briefly outline the main effects due to axion-like particles (ALPs) in high-energy astrophysics. Chiefly among them is a substantial reduction of the cosmic opacity in the very-high-energy (VHE) range, a simple explanation of the VHE emission of flat spectrum radio quasars, a straightforward solution of the spectral anomaly for VHE flaring blazars and polarization effects. Amazingly, all this is achieved for the *same* realistic choice of the model parameters, a fact that provides a strong hint of the existence of an extremely light ALP. Remarkably, its existence can be checked not only by astrophysical observations but also in laboratory experiments.

1. – What are axion-like particles (ALPs)?

Axion-like particles (ALPs) are neutral and very light pseudo-scalar particles a. They are a generic prediction of many extensions of the Standard Model, especially of those based on superstrings (in a broad sense). They are similar to the axion apart from two features. First, ALPs couple almost only to two photons (very small couplings to fermions are allowed but here they are discarded because they do not give rise to any interesting effect). Second, the two-photon coupling is totally unrelated to the ALP mass m (for a review, see [1, 2]). Hence, ALPs are described by the Lagrangian

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 + g_{a\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}, \tag{1}$$

where $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic components of the field strength $F^{\mu\nu}$.

We will henceforth consider a monochromatic photon beam and assume that an external magnetic field $\mathbf{B}$ is present. Hence in $g_{a\gamma}\,a\,\mathbf{E}\cdot\mathbf{B}$ the term $\mathbf{E}$ is the electric field

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(*) E-mail: `marco.roncadelli@pv.infn.it` of a beam photon while $\mathbf{B}$ is the external magnetic field. So the mass matrix in the photon-ALP sector is non-diagonal, which implies that $\gamma \to a$ conversions occur. Moreover, also the inverse process $a \to \gamma$ takes place, and so as the beam propagates we have photon-ALP oscillations [3]. These are quite similar to what happens for massive neutrinos of different flavors, apart from the need of the external field to compensate the spin mismatch. Still, because of the structure of the $\gamma\gamma a$ vertex in eq. (1) in the presence of an external magnetic field $\mathbf{B}$ only the component $\mathbf{B}_T$ orthogonal to the photon momentum $\mathbf{k}$ matters, and photons $\gamma_\perp$ with linear polarization orthogonal to the plane defined by $\mathbf{k}$ and $\mathbf{B}$ do not mix with a, and only photons $\gamma_\parallel$ with linear polarization parallel to that plane do mix with a. Hence the $\gamma\gamma a$ vertex act as a *polarizer*. Specifically, two distinct phenomena come about: *birefringence*, namely the change of a linearly polarized beam into an elliptically polarized one with the major axis parallel to the initial polarization, and *dichroism*, namely a selective conversion $\gamma \to a$ which implies that the ellipse's major axis becomes misaligned with respect to the initial polarization [4]. These facts are of paramount importance in view of the satellite missions XIPE, IXPE, e-ASTROGAM and AMEGO.

2. – Properties of photon-ALP mixing

We suppose that our monochromatic γ/a beam of energy E is in the X-ray or γ-ray band and propagates along the y direction from a far-away astronomical source reaching us. In the approximation $E \gg m$ —which is presently valid (see below)— the beam propagation equation becomes a Schrödinger-like equation in y, hence the beam is *formally* described as a *3-level non-relativistic quantum system* [5]. Consider now the simplest possible case, where no photon absorption takes place and $\mathbf{B}$ is homogeneous. Choosing the z-axis along $\mathbf{B}$, we have

$$(2) \quad P_{\gamma\to a}(E;0,y) = \left(\frac{g_{a\gamma}\,B}{\Delta_{\rm osc}}\right)^2 \sin^2\left(\frac{\Delta_{\rm osc}\,y}{2}\right), \quad \Delta^2_{\rm osc} \equiv \left(\frac{m^2-\omega^2_{\rm pl}}{2E}\right)^2 + \left(g_{a\gamma}\,B\right)^2\,,$$

where $\omega_{\rm pl}$ is the plasma frequency of the medium. Defining next $E_* \equiv |m^2-\omega^2_{\rm pl}|/(2\,g_{a\gamma}\,B)$ it turns out that $P_{\gamma\to a}(E;0,y) = 0$ for $E \ll E_*$, $P_{\gamma\to a}(E;0,y)$ rapidly oscillates with E for $E \sim E_*$ —this is the *weak-mixing regime*— while $P_{\gamma\to a}(E;0,y)$ is maximal and independent of m and E for $E \gg E_*$, which is the *strong-mixing regime*. Below, we will work in this regime.

3. – Signal from blazars

Nowadays, blazar observations in the very-high-energy (VHE) range ($100\,{\rm GeV} < E < 100\,{\rm TeV}$) are performed by the Imaging Atmospheric Cherenkov Telescopes (IACTs) H.E.S.S., MAGIC and VERITAS, which reach an E of several TeV.

Unfortunately, the *extragalactic background light* (EBL) —which is the light emitted by all galaxies during the cosmic history— dominates the present Universe in the infrared/optical/ultraviolet band (for a review, see [6]). As a consequence, hard beam photons with energy E scatter off soft EBL photons with energy ϵ through the $\gamma\gamma \to e^+e^-$ process, thereby depleting the beam. Because the corresponding cross-section is maximized for $\epsilon \simeq (900\,{\rm GeV}/E)\,{\rm eV}$, we see that for $E = 70\,{\rm GeV} - 15\,{\rm TeV}$ we get $\epsilon = (0.06–13)\,{\rm eV}$, just where EBL dominates: this circumstance causes a big problem for VHE observations. Indeed, recalling that the average survival probability for photons emitted at redshift z is given by

$$P_{\gamma \to \gamma}(E_0, z) = e^{-\tau(E_0, z)}, \tag{3}$$

the resulting plot of the optical depth τ is reported in [7] using the EBL model of Franceschini, Rodighiero and Vaccari (FRV) [8]: for instance, the γ-ray horizon ($P_{\gamma \to \gamma}(E_0, z) = e^{-1} \simeq 0.37$) shrinks to about $2\,\mathrm{Mpc}$ for $E_0 = 100\,\mathrm{TeV}$, thereby preventing observations at this energy of sources outside the Local Group!

4. – Reduced opacity of the Universe

The key-idea is as follows [9]. Imagine that photon-ALP oscillations take place in the extragalactic magnetic field. Then they provide a photon with a *split personality*: sometimes it travels as a true photon and sometimes as an ALP. When it propagates as a true photon it undergoes EBL absorption, but when it propagates as an ALP it does not. Therefore, the effective optical depth $\tau_{\mathrm{eff}}(E, z)$ in extragalactic space is *smaller* than $\tau(E, z)$ as computed according to conventional physics (as above). Hence, eq. (3) gets presently replaced by

$$P^{\mathrm{ALP}}_{\gamma \to \gamma}(E, z) = e^{-\tau_{\mathrm{eff}}(E, z)} \ . \tag{4}$$

So, even a *small* decrease of $\tau_{\mathrm{eff}}(E, z)$ produces a *very large* increases in $P^{\mathrm{ALP}}_{\gamma \to \gamma}(E, z)$. In this way EBL absorption gets considerably reduced.

Let us next explicitly state our assumptions. 1) The extragalactic magnetic field $\mathbf{B}$ is modeled as a domain-like structure with $L_{\mathrm{dom}} = (1 - 10)\,\mathrm{Mpc}$, $B = (0.1 - 1)\,\mathrm{nG}$ in all domains, but with the $\mathbf{B}$ direction changing randomly in any domain: this $\mathbf{B}$ structure is strongly motivated by galactic outflow models. 2) Since the physics depends only on the combination $g_{a\gamma}\, B$, we shall deal with $\xi \equiv (g_{a\gamma}\, 10^{11}\,\mathrm{GeV})(B/\mathrm{nG})$. 3) The EBL is still described by the FRV model. 4) The request to stay within the strong mixing regime implies $m < 5 \cdot 10^{-10}\,\mathrm{eV}$. 5) Our benchmark values of the parameters are: $\xi = 0.1, 0.5, 1, 5$; $L_{\mathrm{dom}} = 4\,\mathrm{Mpc}, 10\,\mathrm{Mpc}$. 6) Because the beam polarization is unknown we have to use the polarization density matrix. 7) All relevant constraints on the model parameters are taken into account. Observe that now the beam is formally described as a *3-level unstable non-relativistic quantum system* (because of EBL absorption).

We refer to [10] for the computation of the average photon survival probability $P^{\mathrm{ALP}}_{\gamma \to \gamma}(E, z)$ for a sample of mock blazars at different redshifts z (an alternative strategy has been developed in [11]). In fig. 1, we exhibit the energy behavior of $P^{\mathrm{ALP}}_{\gamma \to \gamma}(E, z)$ for different values of z as well as of L_{dom} and ξ. We see that for a suitable realistic choice of the model parameters the EBL absorption gets indeed substantially reduced, thereby considerably increasing the γ-ray horizon. While these results are quite correct for the blazars observed so far, an extrapolation to $E > 20\,\mathrm{GeV}$ requires CMB-induced vacuum polarization effects to be taken into account [12].

5. – Conclusions and outlooks

The existence of ALPs give rise to intriguing effects in high-energy astrophysics. As shown elsewhere, flat spectrum radio quasars (FSRQs) should not emit above about

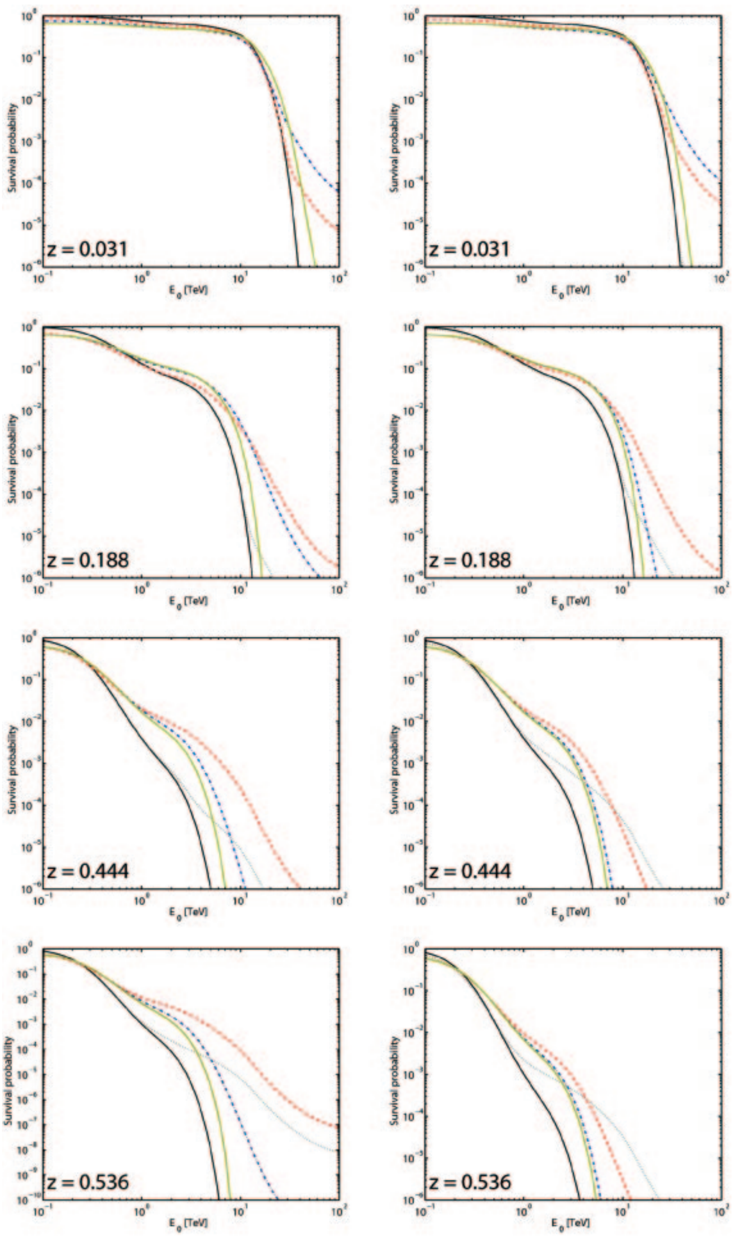

Fig. 1. – Energy behavior of the average photon survival probability for different values of z as well as of $L_{\rm dom}$ and ξ. The left panels correspond to $L_{\rm dom} = 4\,{\rm Mpc}$ while the right ones to $L_{\rm dom} = 10\,{\rm Mpc}$. Moreover, the solid black line corresponds to $\xi = 5.0$, the dotted-dashed line to $\xi = 1.0$, dashed line to $\xi = 0.5$, dotted line to $\xi = 0.1$ and the solid grey line to conventional physics.

20 GeV, in blatant contradiction with the observation of a few FSRQs up to 400 GeV: a remarkably simple solution is provided by ALPs [13]. Moreover, it has been shown that VHE flaring blazars suffer from the *spectral anomaly*, namely they become *intrinsically harder* as their redshift increases: also in this case ALPs straightforwardly solve the

problem, in the sense that all observed VHE blazars become on average equally hard regardless of their redshift [14,15]. Finally, as shown above, ALPs considerably reduce the EBL absorption. What is really amazing is that all these effects take place for the *same* choice of the model parameters. This fact provides a strong hint of the existence of an ALP with $m < 10^{-9}\,\mathrm{eV}$ and $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$. Moreover, if the ALP mass falls into the range $10^{-15}\,\mathrm{eV}$–$10^{-11}\,\mathrm{eV}$, in addition they give rise to observable polarimetric effects. Finally, they can be good candidates for cold dark matter [16].

Our predictions can be checked with the new generation of gamma-ray detectors like CTA, HAWC, GAMMA-400, LHAASO and TAIGA-HiSCORE, and for an ALP mass in the range $10^{-15}\,\mathrm{eV} - 10^{-11}\,\mathrm{eV}$ also by the satellite missions XIPE, IXPE, e-ASTROGAM and AMEGO.

Last but not least, our predictions can be tested also in the laboratory. Within a few years this will indeed be possible with the upgrade of the ALPS II experiment at DESY and by the STAX experiment. In addition, if the planned experiment IAXO will be built —which in a sense is the “analytic continuation” of CAST— also couplings down to $g_{a\gamma} \simeq 10^{-12}\,\mathrm{GeV}^{-1}$ will be probed. Finally, experiments based on the proposals of Avignone and collaborators will be very helpful to look for ALPs [17,18].

Coming back to the question asked in the title, our answer is: probably yes!

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