ALPs AND HIGH-ENERGY ASTROPHYSICS: WHERE DO WE STAND?

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1 – WHAT ARE ALPs?

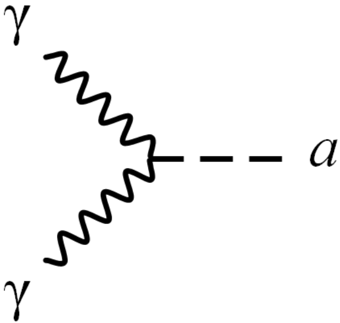
Axion-like particles (ALPs) are $s = 0$, neutral and very light pseudo-scalar particles a. They are a generic prediction of many extensions of the SM, especially of those based on superstrings. They are similar to the axion apart from 2 features.

- ALPs couple almost only to two photons through $g_{a\gamma}\, a\, \mathbf{B} \cdot \mathbf{E}$ (very small couplings to fermions are allowed but here they are discarded because they do not give rise to any interesting effect).
- The two-photon coupling $g_{a\gamma}$ is totally unrelated to the ALP mass m.

Hence ALPs are described by the Lagrangian

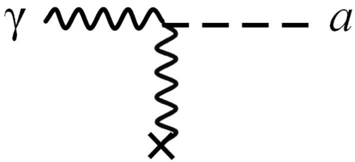
$$\mathcal{L}^0_{\mathrm{ALP}} = \frac{1}{2}\, \partial^\mu a\, \partial_\mu a - \frac{1}{2}\, m^2\, a^2 + g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}\ . \tag{1}$$

So, for ALPs the only new thing with respect to the Standard Model is shown in



which – at this stage – should be regarded as “God given”.

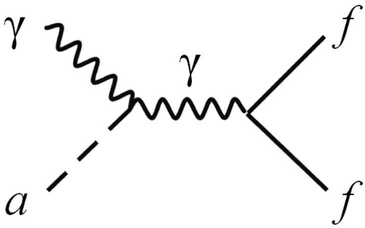
ALPs are produced in the core of MS stars (like the Sun) through the Primakoff process in the Coulomb field **E** of ionized matter



where $X = \mathbf{E}$.

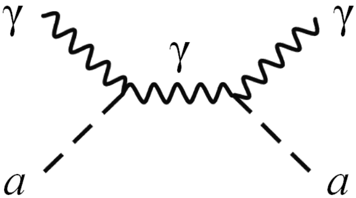
The CAST experiment at CERN was looking at the Sun and found nothing, thereby deriving $g_{a\gamma} < 0.88 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$. Recent analysis of globular clusters gives $g_{a\gamma} < 0.66 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$.

ALPs interact with nothing. Denote by f a generic fermion and consider the diagram for the scattering $a\gamma \to f\bar{f}$ with f a generic fermion



In the s-channel it describes the $a\gamma \to f\bar{f}$ scattering, while in the t-channel the $af \to af$ scattering. The cross-section is $\sigma \sim \alpha\, g_{a\gamma}^2$. So the previous bound yields $\sigma < 10^{-50}\,\mathrm{cm}^2$.

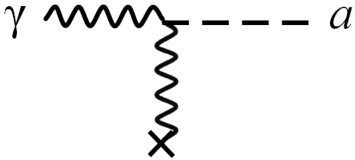
Moreover, for $a\gamma \to a\gamma$ scattering



the cross-section is $\sigma \sim s\, g_{a\gamma}^4$, and so we get

$$\sigma < 7 \cdot 10^{-69} \left(\frac{s}{\mathrm{GeV}^2} \right) \mathrm{cm}^2 \ . \qquad (2)$$

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 of a beam photon while $\mathbf{B}$ is the external magnetic field. So $\gamma \to a$ conversions can occur



where now and in the following $X = \mathbf{B}$.

Needless to say, also the inverse process $a \to \gamma$ can equally well take place. As a consequence, as the beam propagates we can have photon-ALP oscillations

This is quite similar to what happens for massive neutrinos of different flavor apart from the need of the external field to compensate the spin mismatch.

N. B. a REAL

However here there is an additional effect.

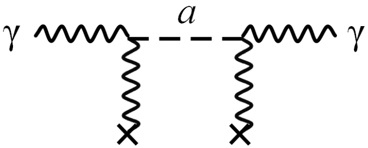
Because the $\gamma\gamma a$ vertex is $g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$, in the presence of an external magnetic field $\mathbf{B}$ we have that

- only the component $\mathbf{B}_T$ orthogonal to the photon momentum $\mathbf{k}$ matters,
- photons $\gamma_\perp$ with linear polarization orthogonal to the plane defined by $\mathbf{k}$ and $\mathbf{B}$ do NOT mix with a, and so only photons $\gamma_{||}$ with linear polarization parallel to that plane DO mix with a.

Hence the term $g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$ act as a POLARIZER.

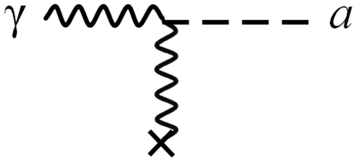
Specifically, for a beam initially linearly polarized two effects occur.

- BIREFRINGENCE i. e. linear polarization becomes ELLIPTICAL with its major axis PARALLEL to the initial polarization.



N.B. a VIRTUAL

- DICHROISM i. e. selective photon CONVERSION, which causes the ellipse's major axis to be MISALIGNED with respect to the initial polarization.

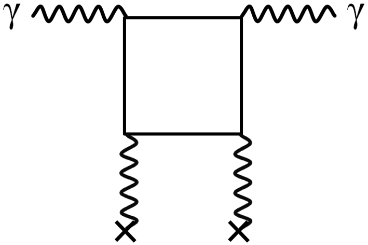


N. B. *a* REAL

Sometimes in the presence of an an external magnetic field also QED one-loop vacuum polarization effects have to be taken into account. They are described by

$$\mathcal{L}'_{\mathrm{ALP}} = \mathcal{L}_{\mathrm{ALP}} + \frac{2\alpha^2}{45 m_e^4} \left[\left(\mathbf{E}^2 - \mathbf{B}^2 \right)^2 + 7 \left(\mathbf{E} \cdot \mathbf{B} \right)^2 \right] \,, \qquad (3)$$

which gives an additional diagonal contribution to the γa mass matrix.



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 $E \gg m$ 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.

Consider the simplest possible case, where no photon absorption takes place and **B** is homogeneous. Taking the z-axis along **B**, we have

$$P_{\gamma \to a}(E; 0, y) = \left(\frac{g_{a\gamma} \, B}{\Delta_{\rm osc}} \right)^2 \sin^2 \left(\frac{\Delta_{\rm osc} \, y}{2} \right) \; , \qquad (4)$$

with

$$\Delta_{\rm osc} \equiv \left\{ \left[\frac{m^2 - \omega_{\rm pl}^2}{2E} + \frac{3.5\,\alpha}{45\pi} \left(\frac{B}{B_{\rm cr}} \right)^2 E \right]^2 + \left(g_{a\gamma}\, B \right)^2 \right\}^{1/2} , \quad (5)$$

where $B_{\rm cr} \simeq 4.41 \cdot 10^{13}\,\rm G$ is the critical magnetic field and $\omega_{\rm pl}$ is the plasma frequency of the medium.

Define

$$E_L \equiv \frac{|m^2 - \omega_{\rm pl}^2|}{2\, g_{a\gamma}\, B} , \quad (6)$$

and

$$E_H \equiv \frac{90\pi}{7\alpha} \frac{B_{\rm cr}^2\, g_{a\gamma}}{B} . \quad (7)$$

Accordingly

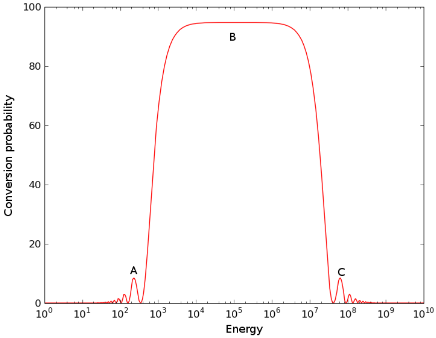
- For $E \ll E_L$ and $E \gg E_H$ then $P_{\gamma \to a}(E; 0, y) = 0$.
- For $E \sim E_L$ and $E \sim E_H$ then $P_{\gamma \to a}(E; 0, y)$ rapidly oscillates with E: WEAK-MIXING regime.
- For $E_L \ll E \ll E_H$ then $P_{\gamma \to a}(E; 0, y)$ maximal and independent of both m and E: STRONG-MIXING regime, where

$$\Delta_{\rm osc} \simeq g_{a\gamma}\, B \tag{8}$$

and

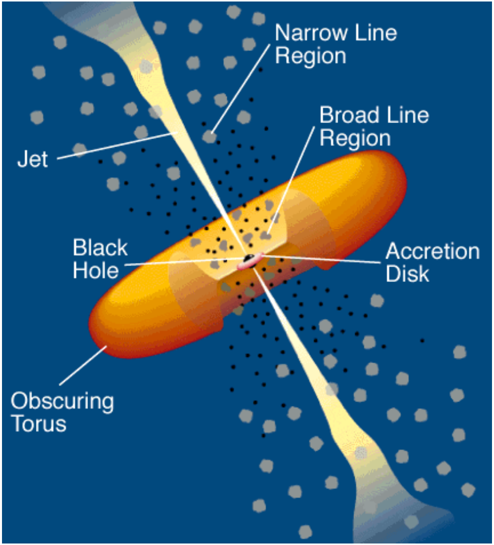
$$P_{\gamma \to a}(E; 0, y) \simeq \sin^2\left(\frac{g_{a\gamma}\, By}{2}\right) , \tag{9}$$

which is MAXIMAL.



We always work throughout in the STRONG-MIXING REGIME whenever possible.

3 – BLAZARS



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

When the jet is oriented towards us the AGN is called BLAZAR.

There are 2 kinds of blazars:

- BL LACs: they lack broad optical lines which entails that the BLR is lacking.
- FLAT SPECTRUM RADIO QUASARs (FSRQs): they show broad optical lines which result from the existence of the BROAD LINE REGION (BLR) al about $10^{18}\,\mathrm{cm}$ from the centre. They also possess magnetized RADIO LOBES at the end of the jet.

In the BLR there is a high density of ultraviolet photons, so that the very-high-energy (VHE) photons ($E > 50\,\mathrm{GeV}$) produced at the jet base undergo the process $\gamma\gamma \to e^+e^-$. As a result, the FSRQs should be INVISIBLE in the gamma-ray band above $30\,\mathrm{GeV}$.

Two non-thermal photon emission mechanisms of BL Lacs.

- LEPTONIC mechanism (syncrotron-self Compton): in the presence of the magnetic field relativistic electrons emit synchrotron radiation and some emitted photons acquire much larger energies by inverse Compton scattering off the parent electrons (external electrons). The resulting SED (spectral energy distribution) $\nu F_\nu \propto E^2\, dN/dE$ has two peaks: the synchrotron one somewhere from the IR to the X-ray band, while the inverse Compton one lies in the γ-ray band around $50\,\mathrm{GeV}$.

- HADRONIC mechanism: same as before for synchrotron emission, but the gamma peak is produced by hadronic collisions so that also neutrinos are emitted.

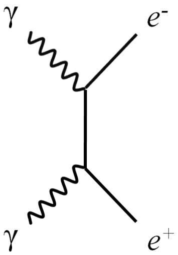
Throughout this talk we shall be interested almost ONLY in VERY-HIGH-ENERGY (VHE) blazars, namely those observed in the range $100\,\mathrm{GeV} < E < 100\,\mathrm{TeV}$.

Nowadays these observations are performed by the Imaging Atmospheric Cherenkov Telescopes (IACTs) H.E.S.S., MAGIC and VERITAS, which reach an E of several Tev. But in the future they will be carried out by the CTA (Cherenkov Telescope Array) which will explore the whole VHE band with more greater sensitivity.

Other new generation VHE photon detectors are HAWC (High-Altitude Water Cherenkov Observatory), GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus), LHAASO (Large High Altitude Air Shower Observatory) and HiSCORE (Hundred Square km Cosmic Origin Explorer).

4 – EXTRAGALACTIC BACKGROUND LIGHT (EBL)

In the infrared/optical/ultraviolet the Universe is dominated by the EBL. Accordingly hard beam photons with energy E scatter off soft EBL photons through $\gamma\gamma \to e^+e^-$



and this depletes the beam: BIG PROBLEM for VHE observations, since $\sigma(\gamma\gamma \to e^+e^-)$ gets maximized for

$$\epsilon(E) \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\ , \tag{10}$$

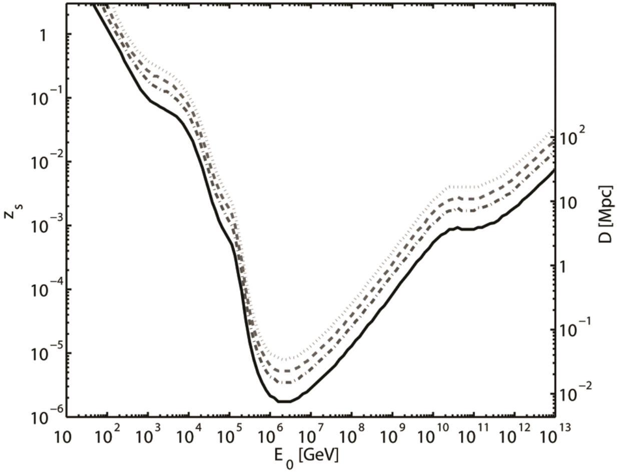
and so for $E = 70\,\mathrm{GeV} - 15\mathrm{TeV}$ we get $\epsilon = (0.06 - 13)\,\mathrm{eV}$, just where EBL dominates. So, photons emitted by a blazar at redshift z have a survival probability

$$P_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0,z)}\ . \tag{11}$$

Whence

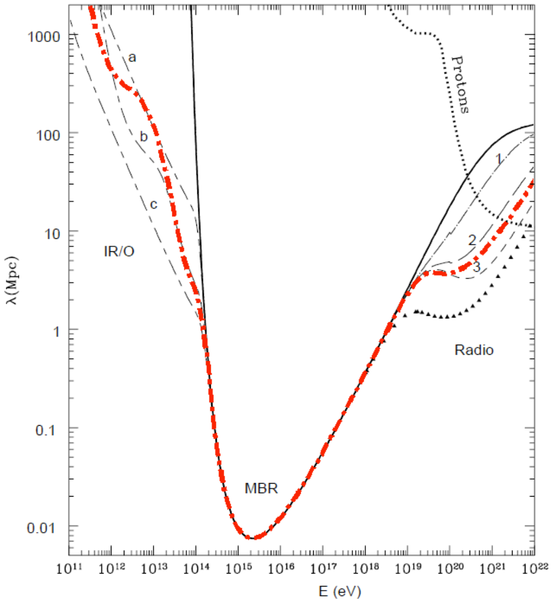
$$\Phi_{\mathrm{obs}}(E_0, z) = e^{-\tau_\gamma(E_0,z)}\,\Phi_{\mathrm{em}}\big(E_0(1+z)\big)\ . \tag{12}$$

Below, the source redshifts z_s is shown at which the optical depth takes fixed values as a function of the observed hard photon energy E_0. The curves from bottom to top correspond to a photon survival probability of $e^{-1} \simeq 0.37$ (the horizon), $e^{-2} \simeq 0.14$, $e^{-3} \simeq 0.05$ and $e^{-4.6} \simeq 0.01$. For $z_s < 10^{-6}$ the photon survival probability is larger than 0.37 for any value of E_0 (De Angelis, Galanti & Roncadelli, 2013).



z_s
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
E_0 [GeV]
10^2
10
1
10^{-1}
10^{-2}
D [Mpc]

Discarding cosmic expansion $P_{\gamma\to\gamma}(E, D) = e^{-D/\lambda_\gamma(E)}$



5 – REDUCED OPACITY OF THE VHE UNIVERSE

The key-idea is as follows (De Angelis, Roncadelli & Mansutti, 2007; De Angelis, Galanti & Roncadelli, 2011). 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 photon it undergoes EBL absorption, but when it propagates as an ALP in does NOT. Therefore, the EFFECTIVE optical depth $\tau_{\rm eff}(E,z)$ in extragalactic space is SMALLER than $\tau(E,z)$ as computed according to conventional physics. Hence

$$P_{\gamma \to \gamma}^{\rm ALP}(E,z) = e^{-\tau_{\rm eff}(E,z)} \ . \tag{13}$$

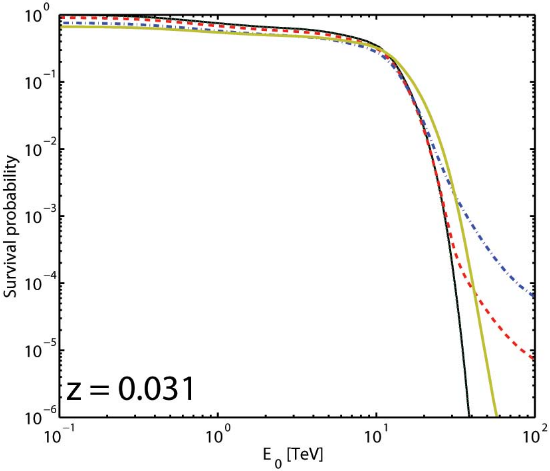
So, even a SMALL decrease of $\tau_{\rm eff}(E,z)$ produces a LARGE increases in $P_{\gamma \to \gamma}^{\rm ALP}(E,z)$. In this way EBL absorption gets considerably REDUCED.

ASSUMPTIONS

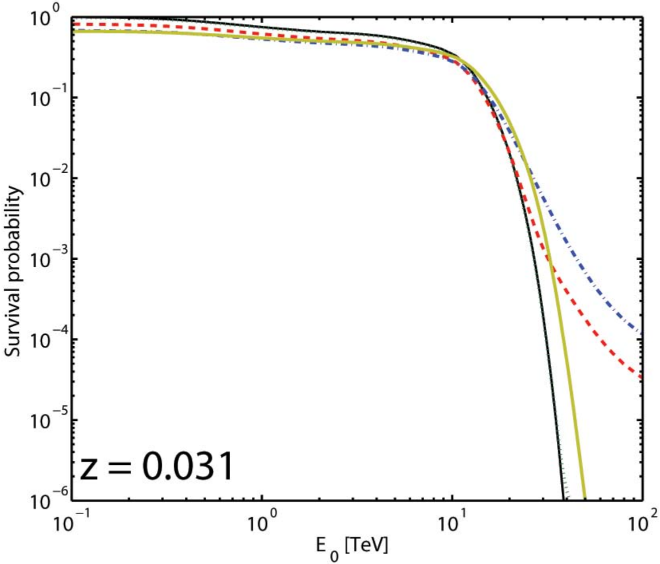
- Extragalactic magnetic field **B** modeled as a domain-like structure with $L_{\rm dom} = (1-10)\,{\rm Mpc}$, $B = (0.1-1)\,{\rm nG}$ in all domains, random direction in any domain: STRONGLY MOTIVATED by galactic outflow models.
- Since the physics depends only on $g_{a\gamma}\,B$, we work with $\xi \equiv \left(g_{a\gamma}\,10^{11}\,{\rm GeV}\right)\left(B/{\rm nG}\right)$.
- EBL described by the Franceschini, Rodighiero & Vaccari (FRV) 2008 model.
- STRONG MIXING REGIME: $m < 10^{-9}\,{\rm eV}$.
- Benchmark values: $\xi = 0.1, 0.5, 1, 5$; $L_{\rm dom} = 4\,{\rm Mpc}, 10\,{\rm Mpc}$.
- Beam is FORMALLY described as a 3-LEVEL UNSTABLE NON-RELATIVISTIC QUANTUM SYSTEM.
- Polarization UNKNOWN: we have to deal with the POLARIZATION DENSITY MATRIX.

PRELIMINARY RESULTS FOR MOCK BLAZARS

$L_{\rm dom} = 4\,{\rm Mpc}$. Solid black line: $\xi = 5.0$, dotted-dashed line: $\xi = 1.0$, dashed line: $\xi = 0.5$, dotted line: $\xi = 0.1$, solid grey line: conventional physics.



$L_{\rm dom} = 10\,{\rm Mpc}$. Solid black line: $\xi = 5.0$, dotted-dashed line: $\xi = 1.0$, dashed line: $\xi = 0.5$, dotted line: $\xi = 0.1$, solid grey line: conventional physics.



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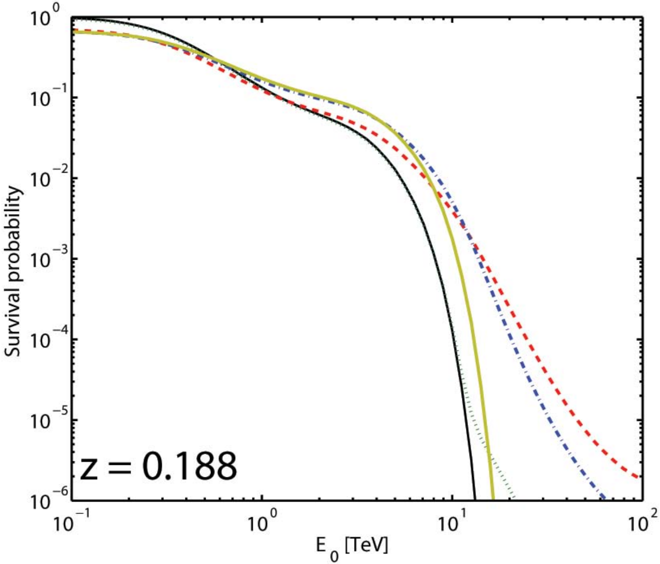
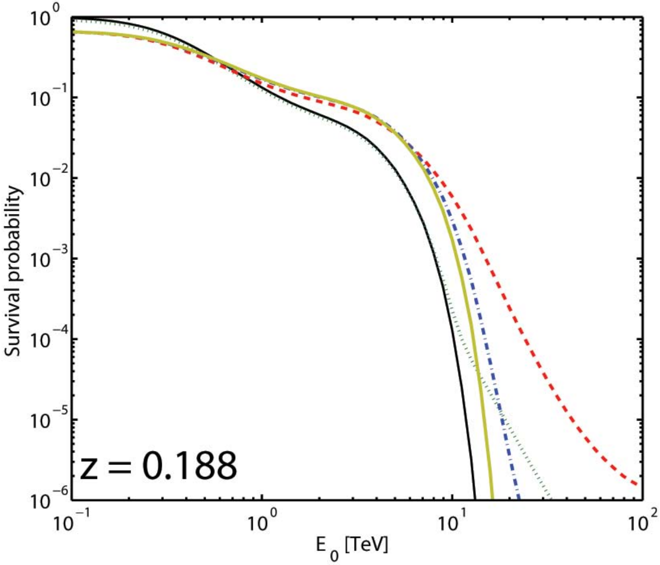


$L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$. Solid black line: $\xi = 5.0$, dotted-dashed line: $\xi = 1.0$, dashed line: $\xi = 0.5$, dotted line: $\xi = 0.1$, solid grey line: conventional physics.



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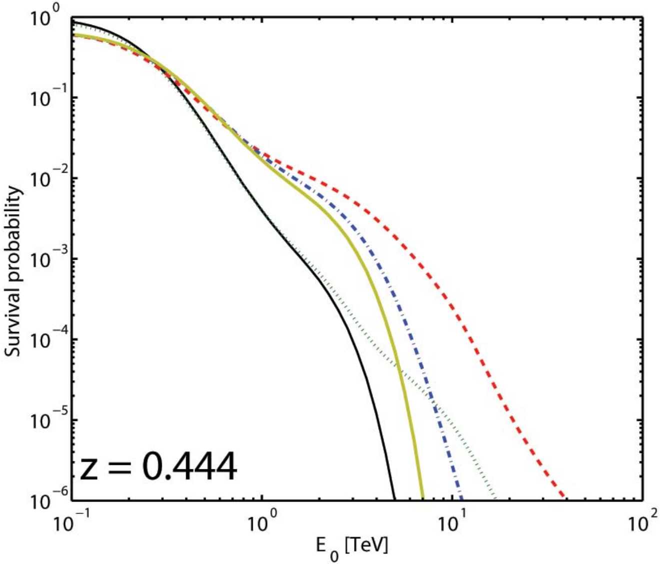

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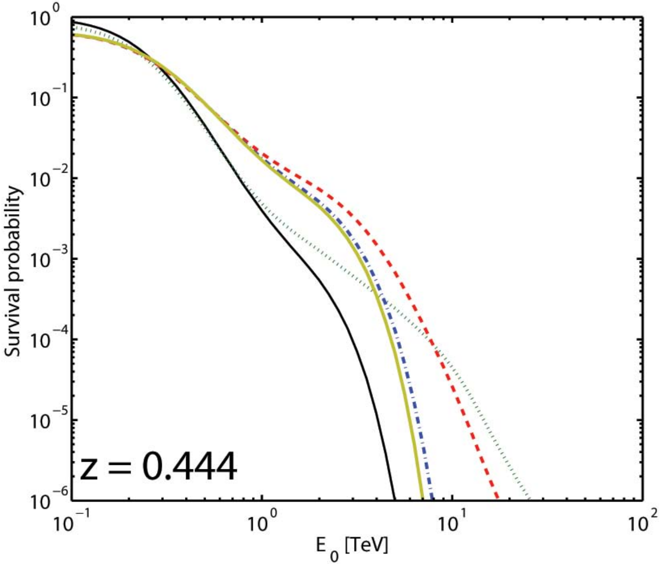

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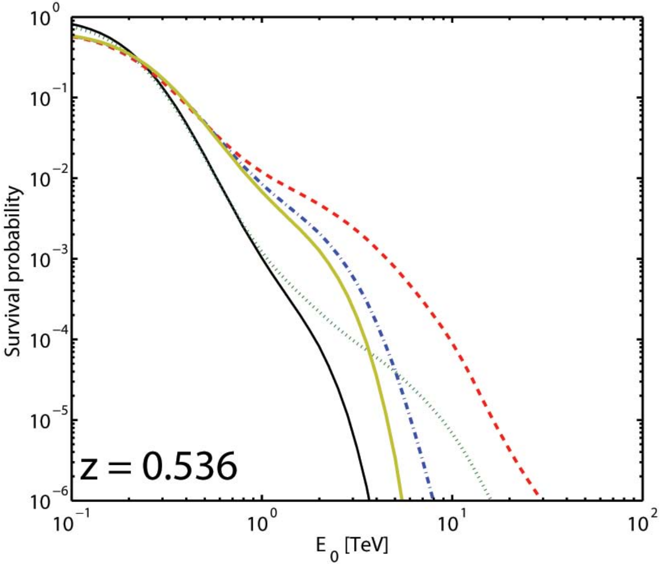

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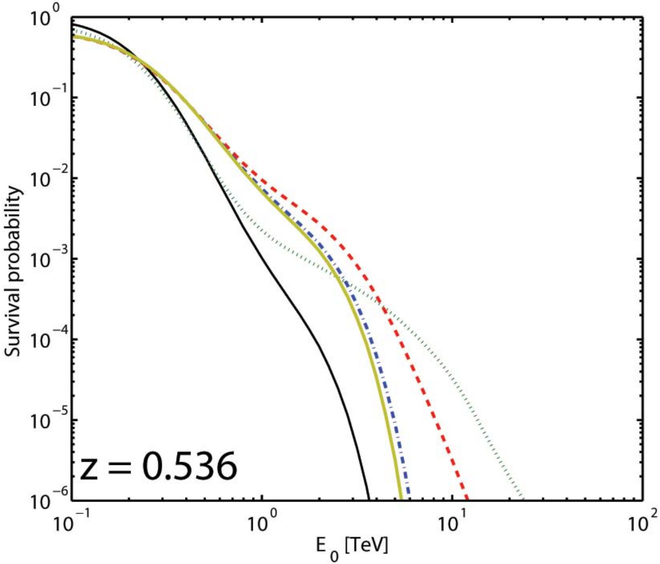
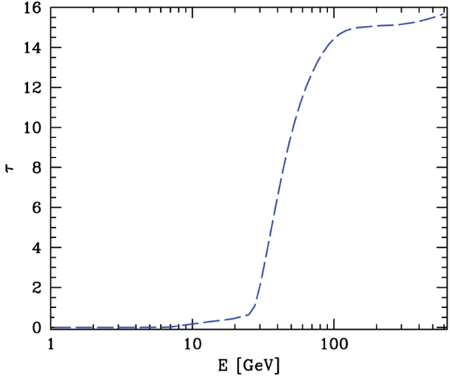


6 – ALPs EXPLAIN THE VHE FSRQ EMISSION

In the BLR there is a high density of ultraviolet photons, so that the very-high-energy (VHE) photons ($E > 50\,\mathrm{GeV}$) produced at the jet base undergo the process $\gamma\gamma \rightarrow e^+e^-$. As a result, the FSRQs should be INVISIBLE in the gamma-ray band above $20 - 30\,\mathrm{GeV}$.

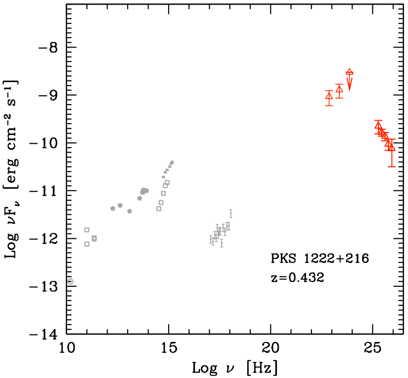


However OBSERVATIONS show that this is NOT TRUE.
At least 5 FSRQs have been observed by Imaging Atmospheric Cherenkov Telescopes (IACTs) in the energy range $100\,\mathrm{GeV} - 1\,\mathrm{TeV}$, and their fluxes are similar to those of the BL LACs!

What is going on?

The most striking case is that of PKS 1222+216 which has been observed SIMULTANEOUSLY by *Fermi*/LAT in the band $0.3 - 3\,\mathrm{GeV}$ and by MAGIC in the band $70 - 400\,\mathrm{GeV}$.
In addition, MAGIC has detected a flux doubling in about 10 minutes which entails that the emitting region has size of about $10^{14}\,\mathrm{cm}$, but the observed flux is similar to that of a BL LAC. So, 2 problems at once!

Red open triangles at high and VHE are the spectrum of PKS 1222+216 recorded by *Fermi*/LAT and the one detected by MAGIC but EBL-deabsorbed according to conventional physics.



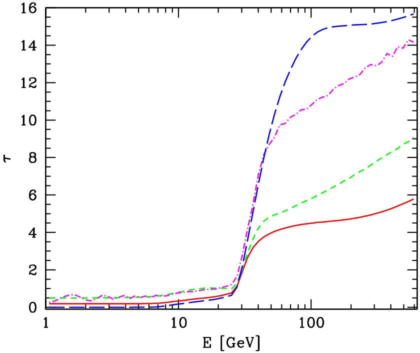
Various astrophysical solutions have been proposed, but all of them are totally AD HOC even because one has to suppose that a blob with size $10^{14}\,\mathrm{cm}$ at a distance of more than $10^{18}\,\mathrm{cm}$ from the centre exists with the luminosity of a whole BL LAC.

IDEA (Tavecchio, Roncadelli, Galanti & Bonnoli, 2012)

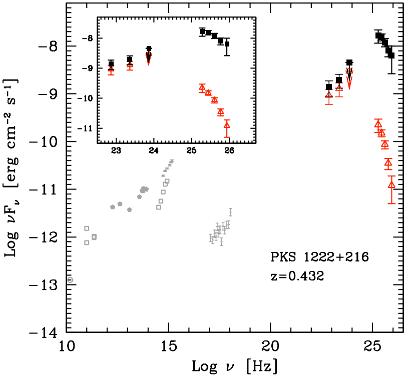
Suppose that photons are produced by a standard emission model like SSC at the jet base like in BL LACs, but that ALPs exist. Then

- Photons can become mostly ALPs BEFORE reaching the BLR in the jet magnetic field.
- ALPs can go UNIMPEDED through the BLR.
- Outside the BLR ALPs can reconvert into photons in the outer magnetic field.

After some playing with the parameters we find that the best choice to reduce the photon absorption by the BLR is $B = 0.2\,\mathrm{G}$, $M = 7 \cdot 10^{10}\,\mathrm{GeV}$ e $m < 10^{-9}\,\mathrm{eV}$, which is represented by the RED line



Red open triangles at high energy and VHE are the spectrum of PKS 1222+216 recorded by Fermi/LAT and the one detected by MAGIC but EBL-deabsorbed according to conventional physics. Black filled squares represent the same data once FURTHER corrected for the photon-ALP oscillation effect.

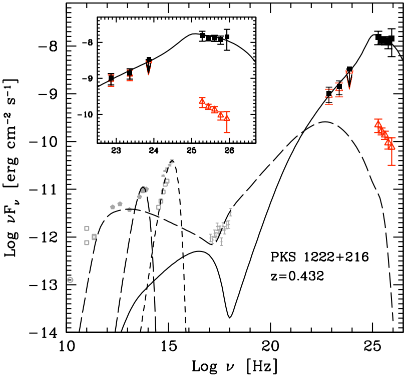


However, this is not enough. We have supposed that photons are produced by a standard emission mechanism. Moreover, PKS 1222+216 has been SIMULTANEOUSLY observed by *Fermi*/LAT and MAGIC. So, we should pretend that the detected photons have a STANDARD SED, namely they should lie on a inverse Compton peak.

This is by far NOT guaranteed, since in the presence of absorption and one-loop QED effects the photon-ALP conversion probability is E-DEPENDENT.

Nevertheless, a standard two-blob emission model with realistic values for the parameters yields

Red points at high energy and VHE are the spectrum of PKS 1222+216 recorded by Fermi/LAT and the one detected by MAGIC but EBL-deabsorbed according to conventional physics. Black points represent the same data once FURTHER corrected for the photon-ALP oscillation effect. Solid black line is the resulting SED.



7 – CONCLUSIONS

The most significant achievement is that – for the SAME CHOICE OF THE PARAMETERS – photon-ALP oscillations solve two open problems: the spectral anomaly of VHE FLARING blazars and why flat spectrum radio quasars (FSRQs) emit up to $400\,\mathrm{GeV}$. The combination of these two results – one occurring in extragalactic space while the other inside a FSRQ – provides a strong hint of the existence of an ALP with $m < 10^{-9}\,\mathrm{eV}$ and $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$. What we get for free is that the cosmic opacity in the VHE band get CONSIDERABLY REDUCED.

Our prediction of such an ALP can not only checked with the new generation of gamma-ray detectors, but also in the laboratory.

Withins a few years this will indeed be possible with the upgrade of the ALPS II experiment at DESY. Moreover, the same goal can be achieved by the STAX experiment. Finally, 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, ALPs with still lower mass can be detected by the planned XIPE, IXPE missions operating in the $(2-6)\,\mathrm{keV}$ through their induced polarization effect. A combined γ-ray and polarization measurement in the $0.3\,\mathrm{MeV} - 3\,\mathrm{GeV}$ can be performed by the planned e-ASTROGAM and AMEGO missions.