IS THERE ANY NEED FOR AXIONS TO EXPLAIN THE SIGNAL FROM BLAZARS? WHERE DO WE STAND?

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1 – WHAT ARE ALPs?

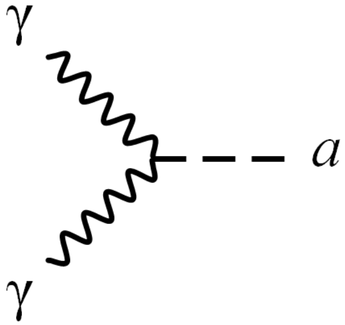
Axion-like particles (ALPs) are $s = 0$, neutral and very light pseudo-scalar particles a. They are a generic prediction of many extensions of the SM, especially of those based on superstrings. They are similar to the axion apart from 2 features.

- 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

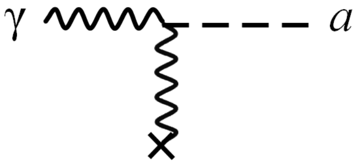
$$\mathcal{L}^0_{\rm ALP} = \frac{1}{2}\, \partial^\mu a\, \partial_\mu a - \frac{1}{2}\, m^2\, a^2 + g_{a\gamma}\, a\, \mathbf{E} \cdot \mathbf{B} \ . \qquad (1)$$

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".

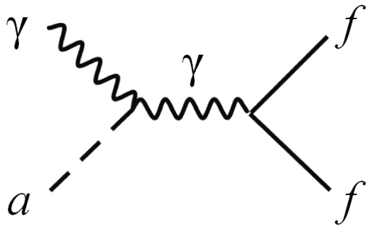
ALPs are produced in the core of MS stars (like the Sun) through the Primakoff process in the Coulomb field **E** of ionized matter



where $X = \mathbf{E}$.

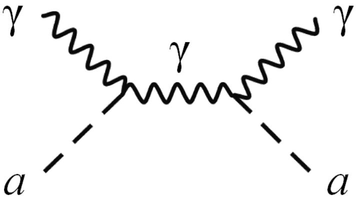
The CAST experiment at CERN was looking at the Sun and found nothing, thereby deriving $g_{a\gamma} < 0.88 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$. Recent analysis of globular clusters gives $g_{a\gamma} < 0.66 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$.

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 $\sigma < 10^{-50}\,\mathrm{cm}^2$.

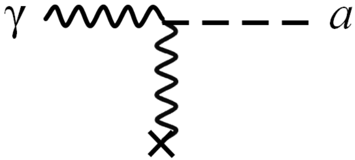
Moreover, for $a\gamma \to a\gamma$ scattering



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.

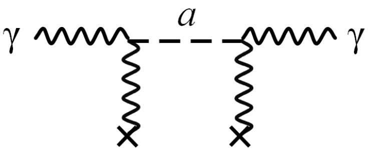
Because the $\gamma\gamma a$ vertex is $g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$, in the presence of an external magnetic field $\mathbf{B}$ we have that

- 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.

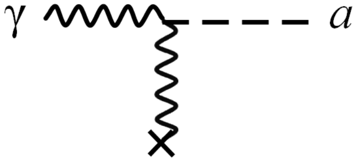
Specifically, for a beam initially linearly polarized two effects occur.

- 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.

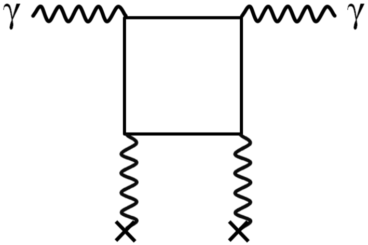


N. B. *a* REAL

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

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

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

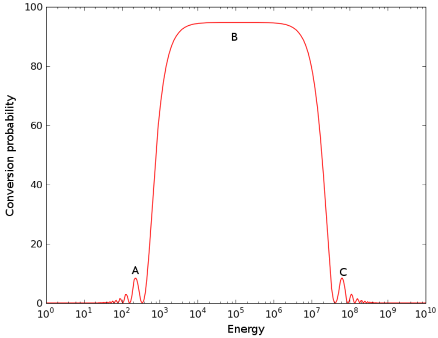
- For $E \ll E_L$ and $E \gg E_H$ then $P_{\gamma \to a}(E; 0, y) = 0$.
- For $E \sim E_L$ and $E \sim E_H$ then $P_{\gamma \to a}(E; 0, y)$ rapidly oscillates with E: WEAK-MIXING regime.
- For $E_L \ll E \ll E_H$ then $P_{\gamma \to a}(E; 0, y)$ maximal and independent of both m and E: STRONG-MIXING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

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

and

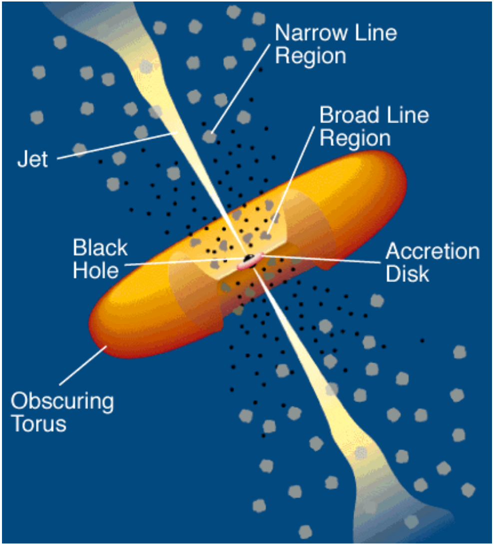
$$P_{\gamma \to a}(E; 0, y) \simeq \sin^2 \left(\frac{g_{a\gamma} \, B y}{2} \right) \; , \tag{9}$$

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 1 pc 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 (syncro-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.

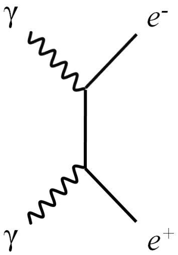
Throughout this talk we shall be interested almost ONLY in VERY-HIGH-ENERGY (VHE) blazars, namely those observed in the range $100\,\mathrm{GeV} < E < 100\,\mathrm{TeV}$.

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

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

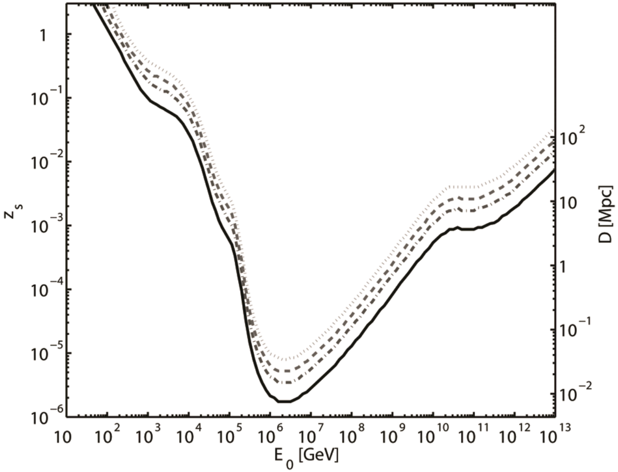
and so for $E = 70\,\mathrm{GeV} - 15\mathrm{TeV}$ we get $\epsilon = (0.06 - 13)\,\mathrm{eV}$, just where EBL dominates. So, photons emitted by a blazar at redshift z have a survival probability

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

Whence

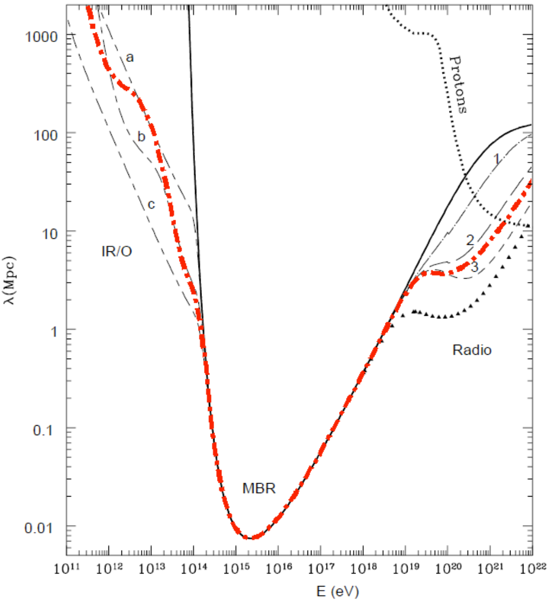
$$\Phi_{\mathrm{obs}}(E_0, z) = e^{-\tau_\gamma(E_0,z)}\,\Phi_{\mathrm{em}}\big(E_0(1+z)\big)\ . \tag{12}$$

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, MNRAS, **432**, 3245 (2013)).



z_s
E_0 [GeV]
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). 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

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

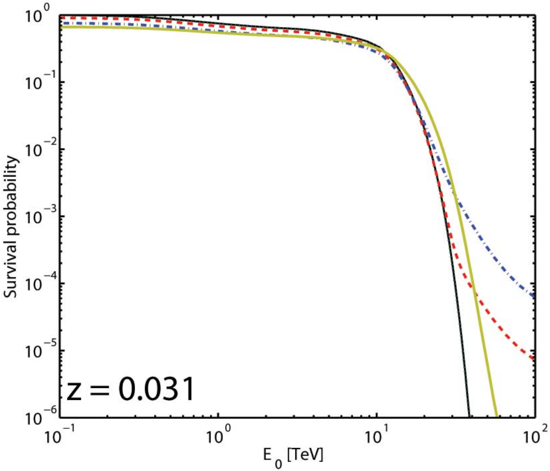
So, even a SMALL decrease of $\tau_{\rm eff}(E, z)$ produces a LARGE increases in $P^{\rm ALP}_{\gamma \to \gamma}(E, z)$. In this way EBL absorption gets considerably REDUCED.

ASSUMPTIONS

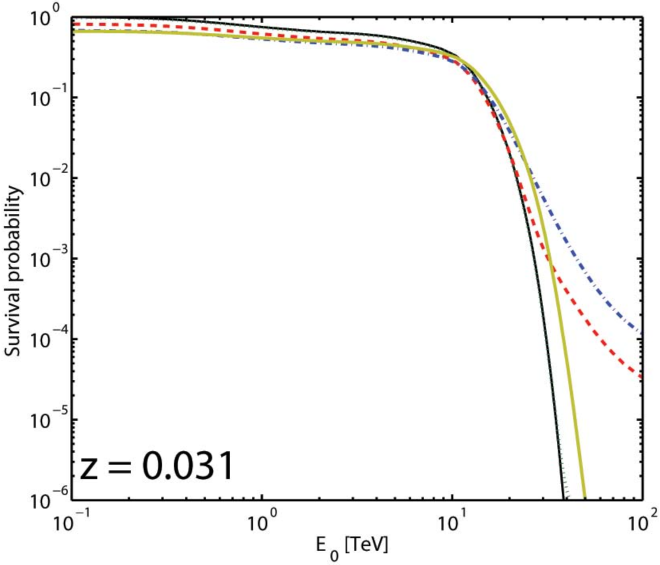
- Extragalactic magnetic field **B** modeled as a domain-like structure with $L_{\rm dom} = (1 - 10)\,{\rm Mpc}$, $B = (0.1 - 1)\,{\rm nG}$ in all domains, random direction in any domain: STRONGLY MOTIVATED by galactic outflow models.
- Since the physics depends only on $g_{a\gamma}\,B$, we work with $\xi \equiv \left(g_{a\gamma}\,10^{11}\,{\rm GeV}\right)\left(B/{\rm nG}\right)$.
- EBL described by the Franceschini, Rodighiero & Vaccari (FRV) 2008 model.
- STRONG MIXING REGIME: $m < 5 \cdot 10^{-10}\,{\rm eV}$.
- 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.



$L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$. 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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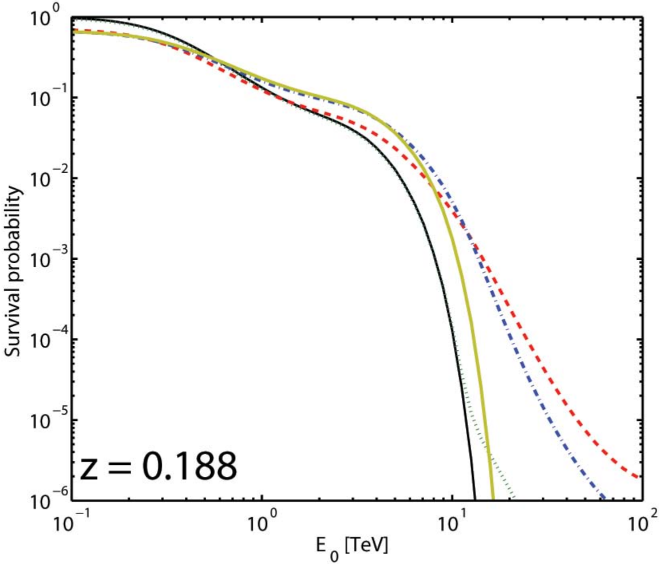

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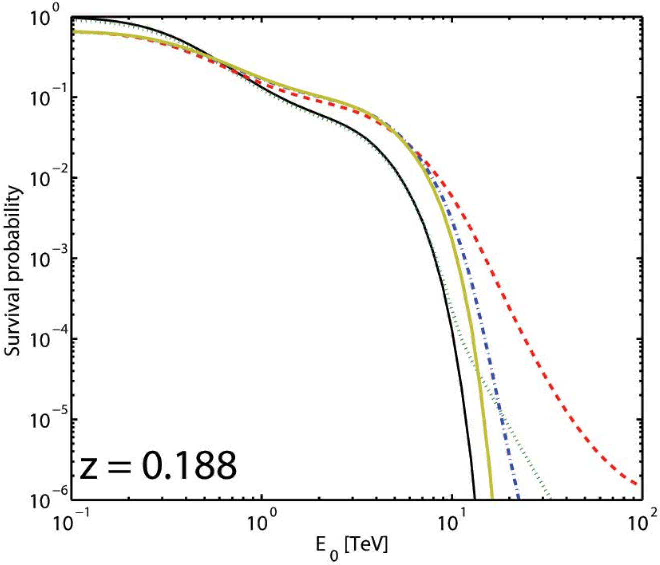

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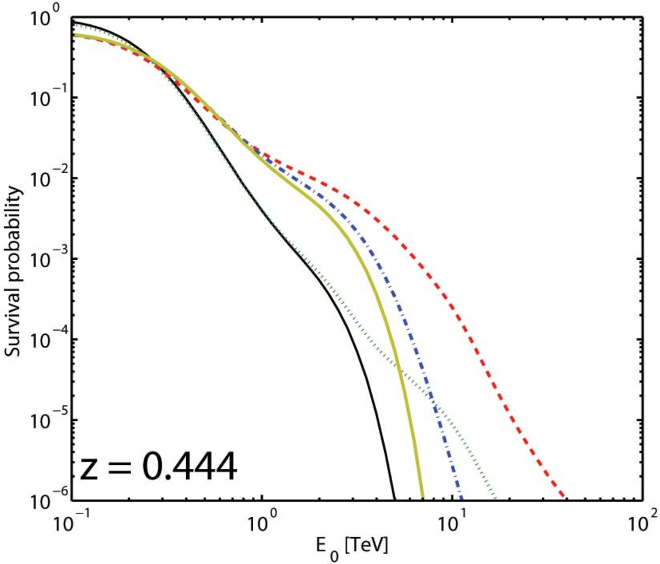

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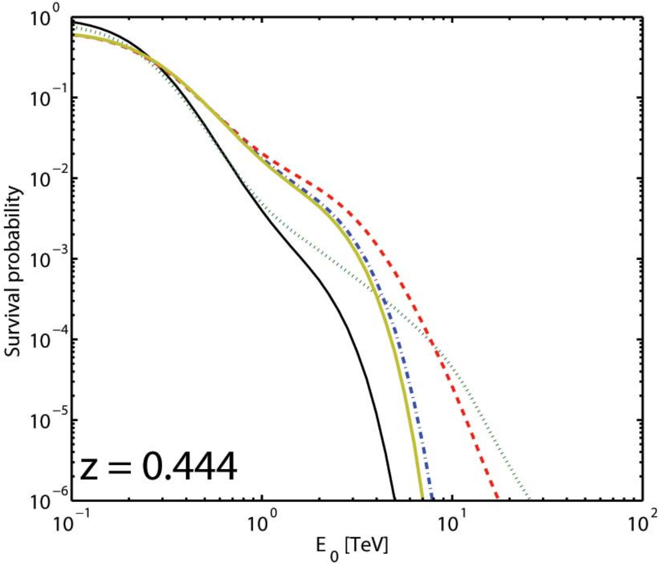

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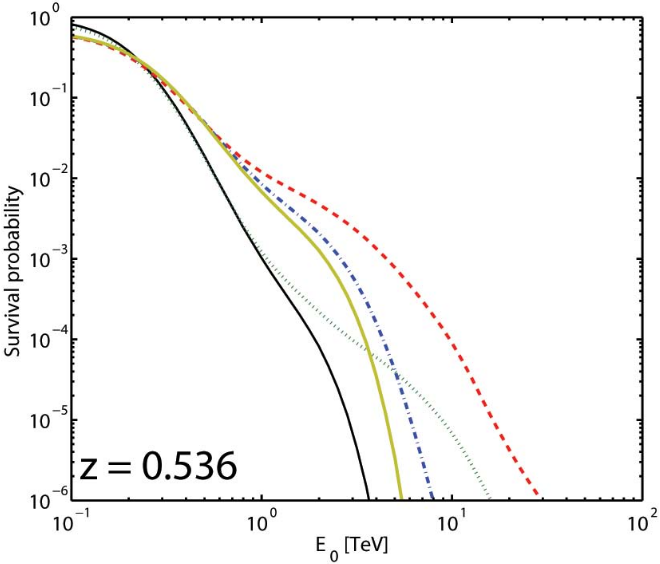

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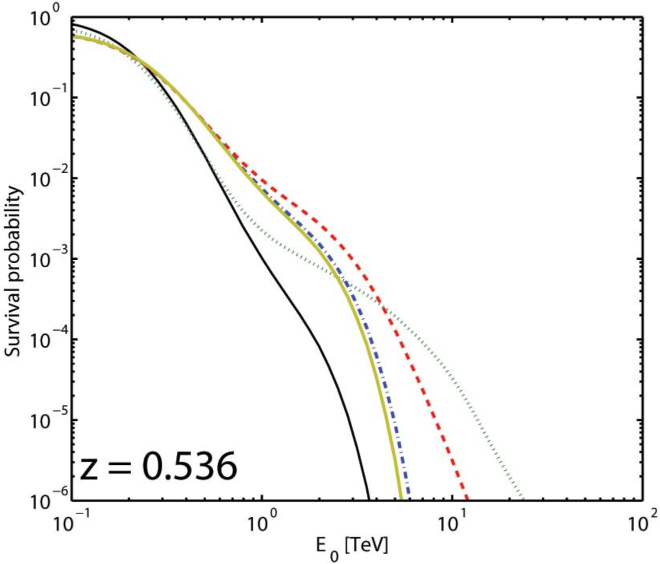


6 – ALPs EXPLAIN THE BLAZAR SPECTRAL ANOMALY

G. Galanti, M. Roncadelli, A. De Angelis & G.F. Bignami, arxiv:1503.04436

We consider a sample of VHE blazar with spectrum and z ACCURATELY known, which are FLARING and in the LOCAL Universe, namely with $z < 0.6$ and taken from the SAME catalog (Tevcat): 39 blazars. Note that the fastest source is 3C 279.
The observational quantities concerning every blazar which are relevant for the present analysis are: z, the observed flux $\Phi_{\rm obs}(E_0, z)$ and the energy range ΔE_0 where each source is observed.
All observed spectra of the considered VHE blazars are rather well fitted in first approximation by a single power-law, and so they have the form $\Phi_{\rm obs}(E_0, z) \propto K_{\rm obs,0}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$, where E_0 is the observed energy, while $K_{\rm obs,0}(z)$ and $\Gamma_{\rm obs}(z)$ are the normalization

constant and the observed slope, respectively, for a source at redshift z. To get $\Gamma_{\rm em}$ from $\Gamma_{\rm obs}(z)$, we recall

$$\Phi_{\rm obs}(E_0, z) = e^{-\tau^{\rm FRV}(E_0,z)}\,\Phi_{\rm em}\big(E_0(1+z)\big)\ . \tag{14}$$

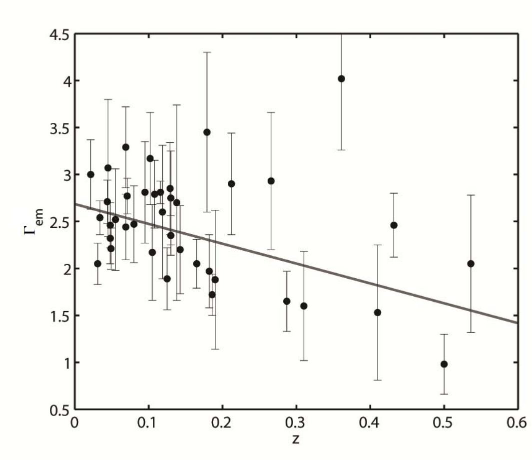
So, we first invert it, obtaining

$$\Phi_{\rm em}\big(E_0(1+z)\big) = e^{\tau^{\rm FRV}(E_0,z)}\,K_{\rm obs}(z)\,\left(\frac{E_0}{300\,{\rm GeV}}\right)^{-\Gamma_{\rm obs}(z)}\ . \tag{15}$$

The above standard photon emission mechanisms predict emitted spectra to have a single power-law behavior $\Phi_{\rm em}(E) = K_{\rm em}\,E^{-\Gamma_{\rm em}}$ for all considered VHE blazars, where $K_{\rm em}$ is the normalization constant and $\Gamma_{\rm em}$ is the emitted slope (right side of the inverse Compton peak). This is true for present observations ONLY. Therefore, we best-fit $\Phi_{\rm em}\big(E_0(1+z)\big)$ in Eq. (15) to the single power-law expression

$$\Phi^{\mathrm{BF}}_{\mathrm{em}}\big(E_0(1+z)\big) = K_{\mathrm{em}}(z)\,\left(\frac{(1+z)E_0}{300\,\mathrm{GeV}}\right)^{-\Gamma_{\mathrm{em}}(z)} \tag{16}$$

over ΔE_0. The values of the emitted slope $\Gamma_{\mathrm{em}}(z)$ are plotted in



Similarly, $K_{\rm em}(z)$ and the emitted γ-ray luminosity $F_{{\rm em},\Delta E}(z)$ can be derived.

We proceed by carrying out a statistical analysis of all values of $\Gamma_{\rm em}(z)$ as a function of z. We use the least square method and try to fit the data with one parameter (horizontal straight line), two parameters (first-order polynomial), and three parameters (second-order polynomial).

In order to test the statistical significance of the fits we compute the corresponding $\chi^2_{\rm red}$. The values of the $\chi^2_{\rm red}$ obtained for the three fits are $\chi^2_{\rm red} = 2.28$, $\chi^2_{\rm red} = 1.81$ and $\chi^2_{\rm red} = 1.83$, respectively. Therefore, data appear to be best-fitted by the first-order polynomial

$$\Gamma_{\rm em}(z) = 2.69 - 2.11\, z \ . \tag{17}$$

The best-fit straight regression line as defined by Eq. (17) is also plotted in the above Figure.

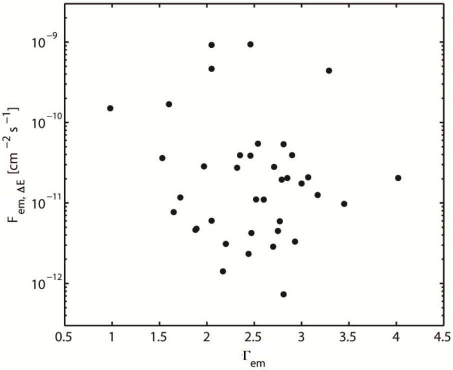
We stress that because $\Gamma_{\rm em}(z)$ is the exponent of E entering the emitted flux, according to Eq. (17) in the two extreme cases $z = 0$ and $z = 0.54$ we have for the average emitted flux

$$\left\langle \Phi_{\rm em}(E, 0) \right\rangle \propto E^{-2.69} \; , \qquad \left\langle \Phi_{\rm em}(E, 0.54) \right\rangle \propto E^{-1.55} \; , \quad (18)$$

thereby implying that the nonvanishing slope of the best-fit regression line gives rise to a LARGE VARIATION of the average emitted flux with redshift.

Actually, what is the PHYSICAL MEANING of the nonvanishing slope of such a best-fit regression line?
Since we have intentionally neglected the two blazars PKS 1441+25 and S3 0218+35 both at $z \simeq 0.94$, our set of sources extends up to $z \simeq 0.54$ (3C 279). Therefore, we are concerned with a relatively local sample, and so cosmological evolutionary effects are insignificant.

Yet, a very simple explanation emerges as a selection bias provided that $F_{\mathrm{em},\Delta E}(z)$ tightly correlates with $\Gamma_{\mathrm{em}}(z)$ so way that brighter sources have harder spectra. This seems after all very reasonable, since for the SAME normalization harder spectra give rise to larger luminosities. Actually, looking at greater distances entails that wider regions of space are probed, and so a larger number of brighter blazars should be detected. We check this possibility by plotting $F_{\mathrm{em},\Delta E}(z)$ versus $\Gamma_{\mathrm{em}}(z)$, which is reported in



Manifestly, $F_{\mathrm{em},\Delta E}$ and Γ_{em} are totally uncorrelated. As a consequence, the cheap explanation outlined above is doomed to failure. Incidentally, $F_{\mathrm{em},\Delta E}(z)$ does increase with z – as it should – but only because also $K_{\mathrm{em}}(z)$ increases as well (the assumption that all considered blazars have the same normalization is therefore wrong).

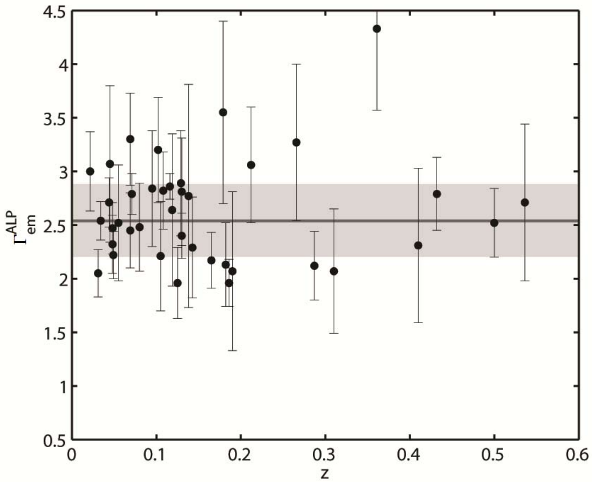
Clearly, the nonvanishing slope of such a best-fit regression line leads to a crucial question: why are blazars with harder spectra found *only* at larger redshift? Having excluded any selection bias, this must be a real fact. But then – if the blazars in question are uncorrelated objects – where does such a correlation come from? This conceptual problem has first been noted by the above authors and has been called VHE blazar spectral anomaly (VHEBSA). Evidently, according to the foregoing discussion ONLY A z-INDEPENDENT best-fit regression line – namely HORIZONTAL in the $\Gamma_{\mathrm{em}} - z$ plane – would be IN AGREEMENT WITH PHYSICAL INTUITION.

ALPs ENTER INTO PLAY

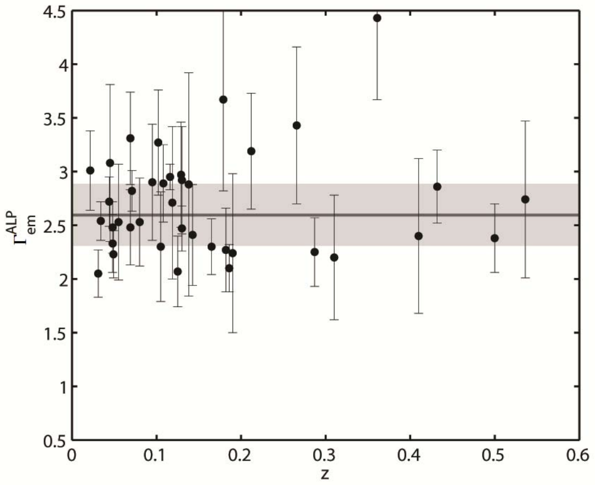
We repeat the same analysis within the framework outlined in Section 5, namely taking also photon-ALP oscillations in extragalactic magnetic field into account.
We go through the same steps as before with $e^{\tau^{\rm FRV}(E_0,z)} \to \left(P_{\gamma\to\gamma}(E_0,z)\right)^{-1}$. We recall that the last quantity is expressed in terms of ξ and $L_{\rm dom}$ for $m < 5\cdot 10^{-10}\,{\rm eV}$.
The previously-done procedure is performed for every benchmark value of ξ and $L_{\rm dom}$ mentioned in Section 5, and for each of them we carry out the same statistical analysis performed above of the values of $\Gamma_{\rm em}^{\rm ALP}(z)$ as a function of z. Our best-fitting procedure singles out two preferred situations: one for $L_{\rm dom} = 4\,{\rm Mpc}$ and the other for $L_{\rm dom} = 10\,{\rm Mpc}$. In either case, we get $\xi = 0.5$ and a straight regression line which is *EXACTLY HORIZONTAL* in the $\Gamma_{\rm em} - z$ plane, IN PERFECT AGREEMENT WITH PHYSICAL INTUITION.

Specifically, for $L_{\rm dom} = 4\,{\rm Mpc}$ we find $\Gamma_{\rm em}^{\rm ALP} = 2.54$ and $\chi^2_{\rm red,ALP} = 1.39$, while for $L_{\rm dom} = 10\,{\rm Mpc}$ we obtain $\Gamma_{\rm em}^{\rm ALP} = 2.59$ and $\chi^2_{\rm red,ALP} = 1.38$. We see that both situations are very similar. The values of $\Gamma_{\rm em}^{\rm ALP}$ are plotted versus z only for the two preferred situations together with the associated best-fit regression lines (ignore the grey strip). We remark that for any choice of $L_{\rm dom}$ the best-fitting procedure fixes the values of ξ and $\chi^2_{\rm red,ALP}$

Case $L_{\rm dom} = 4\,{\rm Mpc}$. Values of $\Gamma_{\rm em}^{\rm ALP}$ plotted source redshift z for all considered blazars with the corresponding error bars in the ALP scenario. Superimposed is the horizontal best-fit regression line $\Gamma_{\rm em}^{\rm ALP} = 2.54$ with $\chi^2_{\rm red,ALP} = 1.39$.



Case $L_{\rm dom} = 10\,{\rm Mpc}$. Values of $\Gamma_{\rm em}^{\rm ALP}$ plotted source redshift z for all considered blazars with the corresponding error bars in the ALP scenario. Superimposed is the horizontal best-fit regression line $\Gamma_{\rm em}^{\rm ALP} = 2.59$ with $\chi^2_{\rm red,ALP} = 1.38$.



Last but not least, we regard the result obtained within the ALP scenario as a sort of consistency check of the scenario itself. In spite of the fact that some issues have been treated rather crudely – like the deabsorption of the whole observed spectra – the emerging result is nonetheless the only one in agreement with physical intuition.
A final remark is in order. On the basis of the conclusion of Section IV it is obvious that the presence of photon-ALP oscillations reduces the amount of EBL absorption. As a consequence, it is equally obvious that the slope of the best-fit regression line in the $\Gamma_{\rm em} - z$ plane changes with respect to the case of conventional physics. But that – among infinitely-many possibilities – only the single one in agreement with physical intuition gets selected out looks almost like a miracle.

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 $m < 5 \cdot 10^{-10}\,\mathrm{eV}$ 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 few years this will indeed be possible with the upgrade of the ALPS II (Any Light Particle Search) experiment at DESY. In addition, if the planned experiment IAXO (International Axion Observatory) 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 missions XIPE and IXPE operating in the $(2-6)\,\mathrm{keV}$ through their induced polarization effect.