HIGH-ENERGY ASTROPHYSICS AND AXION-LIKE PARTICLES (ALPs) – 1

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SUMMARY

1 – MOTIVATION

The Standard Model (SM) based on $\mathrm{SU}(3)_\mathrm{C} \bigotimes \mathrm{SU}(2)_\mathrm{L} \bigotimes \mathrm{U}(1)_\mathrm{Y}$ has turned out to be extremely successful in explaining ALL available data concerning elementary particles, and the recent discovery of the Higgs boson has FULLY established its validity.

Yet, going beyond the SM looks COMPELLING for various reasons.

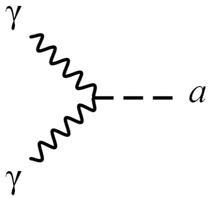
- More than 30 arbitrary parameters have to be fine-tuned in order to explain observations.
- No natural solution of the *strong CP problem* exists.
- No unification of strong and electroweak interactions is accomplished. Moreover gravity is ignored.
- The SM has no room for *non-baryonic cold dark matter* required by galaxy formation and for *dark energy* needed to explain the accelerated cosmic expansion.

2 – WHAT ARE ALPs?

A generic prediction of many extensions of the SM – and especially those based on superstring theory and its variations – is the existence of ALPs. They are quite similar to the Axion, but differ in 2 respects in order to make them as much as model-independent as possible.

- ALPs couple ONLY to 2 photons (any other possible coupling is discarded).
- The ALP mass m and the 2 photon coupling $1/M$ are fully UNRELATED.

So, the only new thing with respect to the SM is



Their Lagrangian is therefore

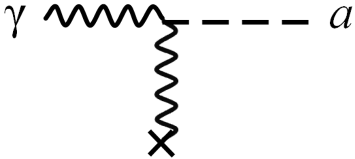
$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^{\mu} a\,\partial_{\mu} a - \frac{1}{2}\,m^2\,a^2 + \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a \tag{1}$$

with $1/M \equiv g_{a\gamma\gamma}$. The most robust bound on M is provided by CAST at CERN: $M > 1.1.4 \cdot 10^{10}\,\mathrm{GeV}$ for $m < 0.02\,\mathrm{eV}$. Other astrophysical bounds exists but they exclude only very small regions of the parameter plane $M - m$ at most at 2 σ level and are irrelevant for the subsequent discussion. As we shall see, sizable astrophysical effects demand $m < 10^{-9}\,\mathrm{eV}$: this fact strongly suggests that ALPs are pseudo-Goldstone bosons associated with some global symmetry beyond the SM that is both spontaneously and slightly explicitly broken.

N.B. WE SHALL WORK ALL THE TIME IN THE PRESENCE OF AN EXTERNAL MAGNETIC B FIELD.

3 – PHOTON-ALP MIXING

Because of the $\gamma\gamma a$ vertex, in the presence of an EXTERNAL electromagnetic field an off-diagonal element in the mass matrix for the γa system shows up.



Therefore, the interaction eigenstates DIFFER from the propagation (mass) eigenstates and γa mixing occurs.

Thus, γa mixing in the presence of an EXTERNAL magnetic field gives rise to γa OSCILLATIONS

N. B. a REAL

Analogy with neutrino oscillations but **B** is needed to compensate for the spin mismatch.

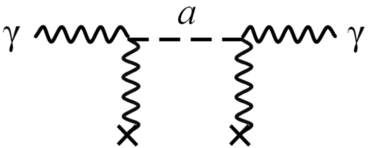
However here there is an additional effect.
Since the $\gamma\gamma a$ vertex goes like $\mathbf{E} \cdot \mathbf{B}$, in the presence of an EXTERNAL magnetic field $\mathbf{B}$.

- 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 an ALP, and so ONLY photons $\gamma_{||}$ with linear polarization parallel to that plane DO mix.

Hence we have a CHANGE of the photon POLARIZATION state.

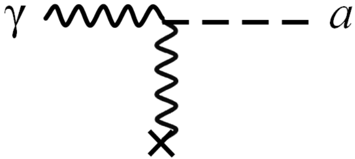
Specifically, for a beam initially LINEARLY polarized two effects occur.

- 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-ALP CONVERSION, which causes the ellipse's major axis to be MISALIGNED with respect to the initial polarization.

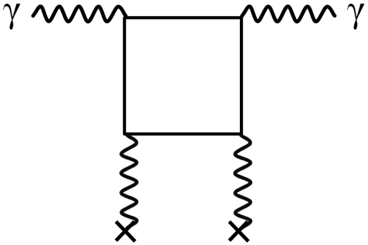


N. B. a REAL

However, sometimes in the presence of an an EXTERNAL electromagnetic field also QED one-loop vacuum polarization effects have to be taken into account. They are described by

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

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



4 – PROPERTIES OF PHOTON-ALP MIXING

We consider throughout this talk a monochromatic γ/a beam of energy E in the X-ray or γ-ray band that 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 an **B** is homogeneous. Taking the z-axis along **B**, we have

$$P_{\gamma \to a}(E; 0, y) = \left(\frac{B}{M \, \Delta_{\rm osc}} \right)^2 \sin^2 \left(\frac{\Delta_{\rm osc} \, y}{2} \right) \; , \qquad (3)$$

with

$$\Delta_{\rm osc} \equiv \left\{ \left[\frac{m^2 - \omega_{\rm pl}^2}{2E} + \frac{3.5\alpha}{45\pi} \left(\frac{B}{B_{\rm cr}} \right)^2 E \right]^2 + \left(\frac{B}{M} \right)^2 \right\}^{1/2} , \quad (4)$$

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

$$E_L \equiv \frac{|m^2 - \omega_{\rm pl}^2| M}{2B} , \quad (5)$$

and

$$E_H \equiv \frac{90\pi}{7\alpha} \frac{B_{\rm cr}^2}{BM} . \quad (6)$$

Accordingly

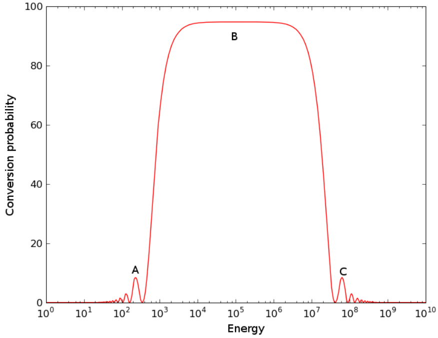
- For $E \ll E_L$ and $E \gg E_H$ the effect disappears.
- For $E \sim E_L$ and $E \sim E_H$ $P_{\gamma \to a}(E; 0, y)$ rapidly oscillates with E: WEAK-MIXING regime.
- For $E_L \ll E \ll E_H$ $P_{\gamma \to a}(E; 0, y)$ maximal and independent of both m and E: STRONG-MIXING regime, where

$$\Delta_{\rm osc} \simeq \frac{B}{M} \tag{7}$$

and

$$P_{\gamma \to a}(E; 0, y) \simeq \sin^2 \left(\frac{By}{2M} \right) \ , \tag{8}$$

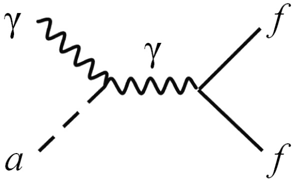
which is MAXIMAL.



We always work in the STRONG-MIXING REGIME.

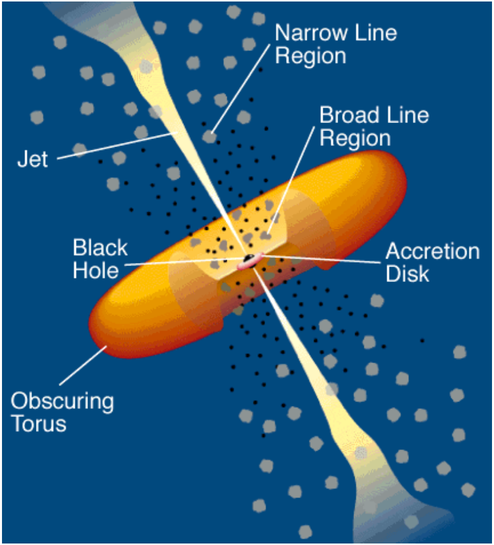
BOTTOM LINE

- For ALPs the only constraint is $M > 1.14 \cdot 10^{10}\,\mathrm{GeV}$. The interaction of ALPs with matter and radiation is represented by



where f is a generic fermion. Since the cross-section is $\sigma \sim \alpha/M^2$ we get $\sigma < 10^{-52}\,\mathrm{cm}^2$. So, ALPs interact NEITHER with matter NOR with radiation.

5 – BLAZARS



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

Basically they are AGN with 2 opposite jets. Two standard non-thermal photon emission mechanisms in the jet.

- LEPTONIC mechanism (syncrotron-self Compton): in the presence of the magnetic field relativistic elections emit synchrotron radiation and the 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.

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, hence the very-high-energy (VHE) photons ($E > 50\,\mathrm{GeV}$) produced at the jet base undergo the process $\gamma\gamma \to e^+e^-$. So, the FSRQs should be INVISIBLE in the gamma-ray band above $20\,\mathrm{GeV}$.

Throughout this talk we shall be interested 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.

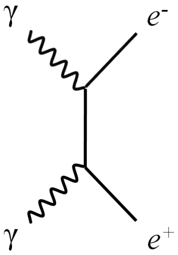
Other planned VHE photon detectors are HAWC (High-Altitude Water Cherenkov Observatory), GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus), LHAASO (Large High Altitude Air Shower Observatory) and TAIGA-HiSCORE (Hundred Square km Cosmic Origin Explorer).

6 – EXTRAGALACTIC BACKGROUND LIGHT (EBL)

According to conventional physics, photons emitted by an extra-galactic source at redshift z have a survival probability

$$P^{\mathrm{CP}}_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0,z)} \ , \tag{9}$$

with E_0 = observed energy and $E_e = (1+z)E_0$ = emitted energy. Neglecting dust effects, hard photons with energy E get depleted by scattering off soft background photons with energy ϵ due to the $\gamma\gamma \to e^+e^-$ process



The corresponding Breit-Wheeler cross-section $\sigma(\gamma\gamma \to e^+e^-)$ gets maximized for

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

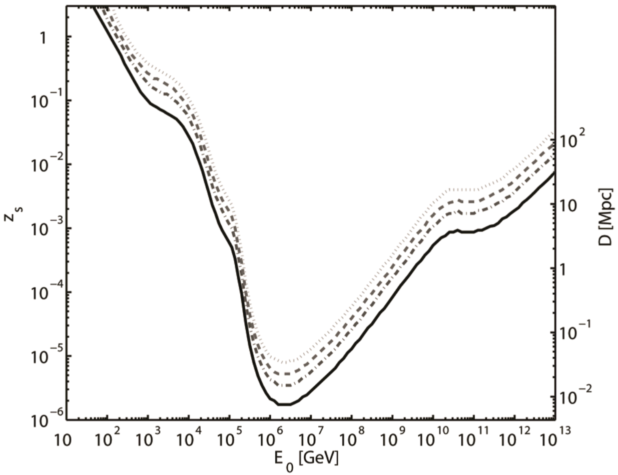
where E and ϵ correspond to the same redshift. Therefore for $100\,\mathrm{GeV} < E < 100\,\mathrm{TeV}$ photon depletion is MAXIMAL for $9 \cdot 10^{-3}\,\mathrm{eV} < E < 9\,\mathrm{eV}$, and so the relevant photon background is just the EBL. The resulting optical depth is

$$\tau_\gamma(E_0, z_s) = \int_0^{z_s} \mathrm{d}z\;\frac{\mathrm{d}l(z)}{\mathrm{d}z}\int_{-1}^{1}\mathrm{d}(\cos\varphi)\;\frac{1-\cos\varphi}{2}\;\times \tag{11}$$
$$\times\int_{\epsilon_{\rm thr}(E(z),\varphi)}^{\infty}\mathrm{d}\epsilon(z)\,n_\gamma(\epsilon(z),z)\,\sigma_{\gamma\gamma}\big(E(z),\epsilon(z),\varphi\big)\;,$$

where

$$\frac{dl(z)}{dz} = \frac{c}{H_0}\frac{1}{(1+z)\left[\Omega_\Lambda + \Omega_M\,(1+z)^3\right]^{1/2}}\;. \tag{12}$$

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)).

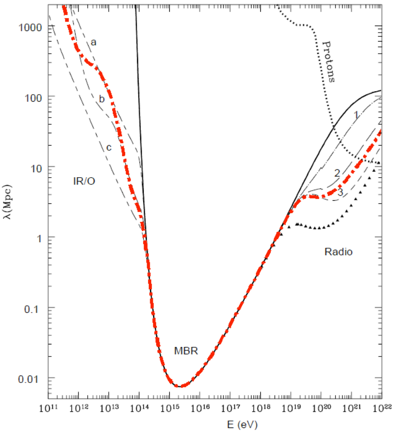


z_s
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
E_0 [GeV]
D [Mpc]
10^2
10
1
10^{-1}
10^{-2}

Discarding cosmic expansion, $D = cz/H_0$ and

$$P^{\rm CP}_{\gamma\to\gamma}(E,D) = e^{-D/\lambda_\gamma(E)} \ , \tag{13}$$

with $\lambda_\gamma(E)$ = mfp for $\gamma\gamma \to e^+e^-$.



7 – ALPs AGAINST EBL

The key-idea is as follows (De Angelis, Roncadelli & Mansutti, 2007). Imagine that photon-ALP oscillations take place in extragalactic space. 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. Whence

$$P^{\rm DARMA}_{\gamma \to \gamma}(E,z) = e^{-\tau_{\rm eff}(E,z)}~. \tag{14}$$

So, even a SMALL decrease of $\tau_{\rm eff}(E,z)$ produces a LARGE enhancement in $P^{\rm DARMA}_{\gamma \to \gamma}(E,z)$. In this way EBL absorption gets DRASTICALLY REDUCED and the γ-ray horizon gets widened.

8 – IMPLEMENTATIONS

Various scenarios have been developed to implement the above idea.

- DARMA SCENARIO – Photon-ALP oscillations in extragalactic space. Large scale magnetic fields in the $0.1 - 1\,\mathrm{nG}$ range are needed (De Angelis, Roncadelli & Mansutti PR D **76**, 121301 (2007), De Angelis, Mansutti, Persic & Roncadelli, MNR **394**, L21 (2009). Mirizzi & Montanino, JCAP **12**, 004 (2009). De Angelis, Galanti & Roncadelli, PR D **84**, 105030 (2011); PR D **87**, 109903(E) (2013)).

- CONVERSION-RECONVERSION SCENARIO – Photon-to-ALP conversion inside the blazar and ALP-to-photon reconversion in the Milky Way magnetic field. Not clear whether the first step works and strong dependence on galactic latitude (Simet, Hooper and Serpico, PR D **77**, 063001 (2008)).
- COMBINED SCENARIO – Of course, the two possibilities can be combined together (Sancez-Conde, Paneque, Bloom, Prada and Dominguez, PR D **79**, 123511 (2009)).
- CLUSTER SCENARIO – For a blazar located in a cluster of galaxies (PKS 0548-322, PKS 2005-489, PKS 2155-304, 1ES 1101-232, 1ES 0414+009, etc.) photon-to-ALP conversion in the cluster magnetic field and ALP-to-photon reconversion in the Milky Way magnetic field. Strong dependence on galactic latitude (Horns, Maccione, Meyer, Mirizzi, Montanino and Roncadelli, PR D **86**, 075024 (2012)).

9 – DARMA SCENARIO

It is just the implementation of the original idea.
In the present situation – $E \gg m$ and EBL photon absorption – the monochromatic photon/ALP beam of energy $E > 100\,\mathrm{GeV}$ can formally be described as a 3-LEVEL UNSTABLE NON-RELATIVISTIC QUANTUM SYSTEM.

Following a standard attitude we assume that the large-scale magnetic field has a domain-like structure with size $L_{\rm dom}$ and the same strength B, but the direction of **B** changes randomly from a domain to the next. Motivated by the GALACTIC OUTFLOW MODELS, we take for definiteness $L_{\rm dom} = 4\,\mathrm{Mpc}$ and $L_{\rm dom} = 10\,\mathrm{Mpc}$. Correspondingly, the bound $B < 6\,\mathrm{nG}$ has been derived. Since the physics depends only on B/M, we work with

$$\xi \equiv \left(\frac{B}{\mathrm{nG}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{M}\right) , \qquad (15)$$

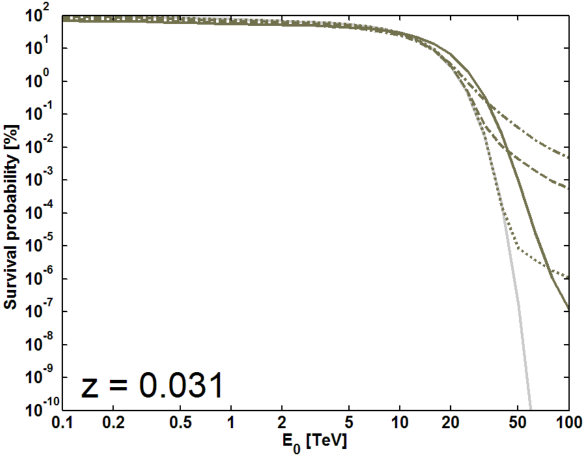
and so the above bounds translate into $\xi < 6$. Consistency with the observational bounds plus requirement to be in the strong-mixing regime requires $m < 10^{-9}\,\mathrm{eV}$.
Incidentally, for $L_{\rm dom} = (1-10)\,\mathrm{Mpc}$ the first AUGER results entail $B = (0.3-0.9)\,\mathrm{nG}$ (De Angelis, Persic & Roncadelli, MPL A **23**, 315 (2008)). They are consistent with our choice.

Using the formalism of non-relativistic quantum mechanics for unstable systems and assuming the beam to be unpolarized, It can be shown that the photon survival probability in the presence of EBL absorption and photon-ALP oscillations is

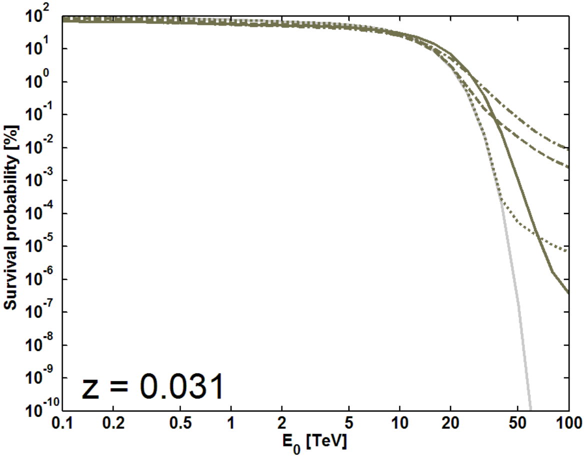
$$P^{\rm DARMA}_{\gamma \to \gamma}(E_0, z) = \Big\langle P_{\rho_{\rm unpol} \to \rho_x}(E_0, z; \psi_1, ..., \psi_{N_d}) \Big\rangle_{\psi_1, ..., \psi_{N_d}} + \Big\langle P_{\rho_{\rm unpol} \to \rho_z}(E_0, z; \psi_1, ..., \psi_{N_d}) \Big\rangle_{\psi_1, ..., \psi_{N_d}} . \tag{16}$$

9.1 – DARMA PREDICTIONS FOR THE CTA (PRELIMINARY)

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



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



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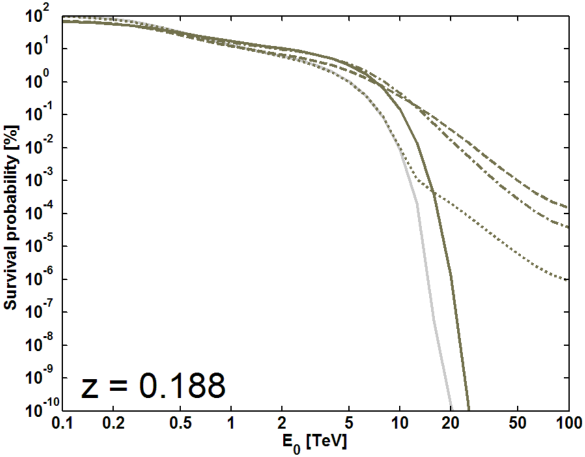

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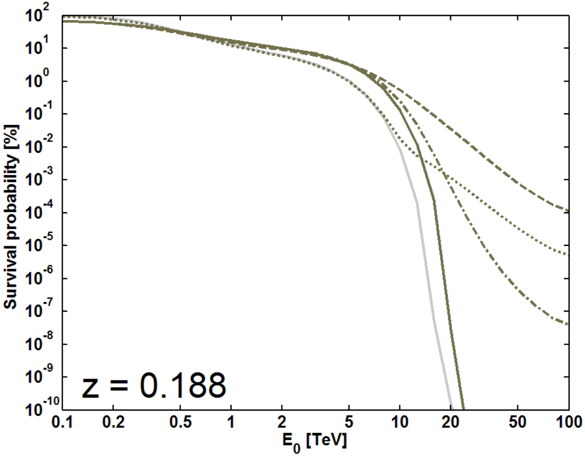

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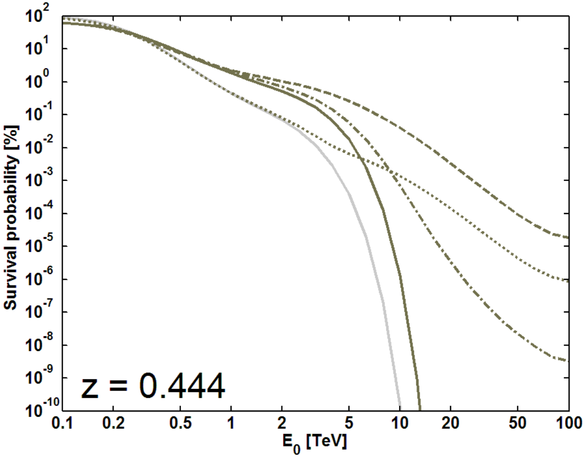

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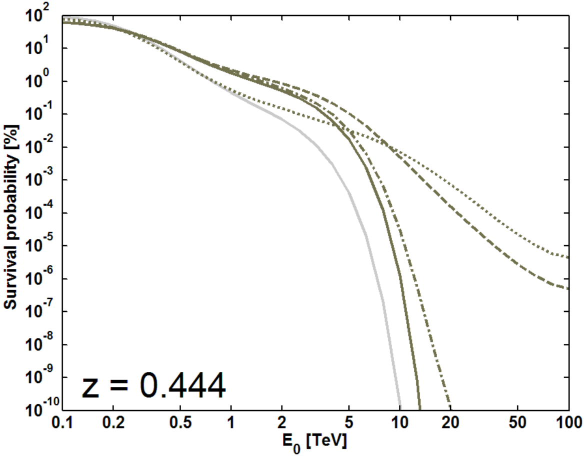

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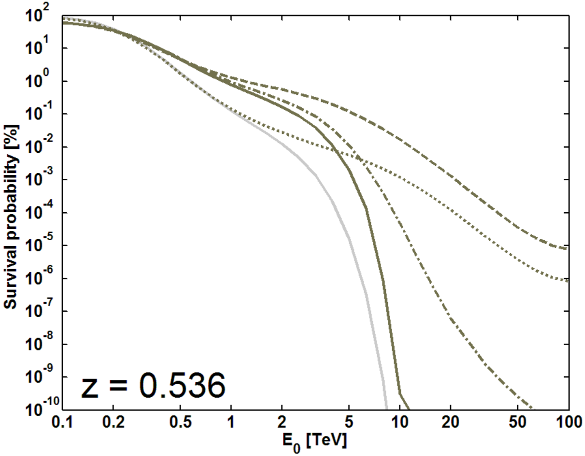

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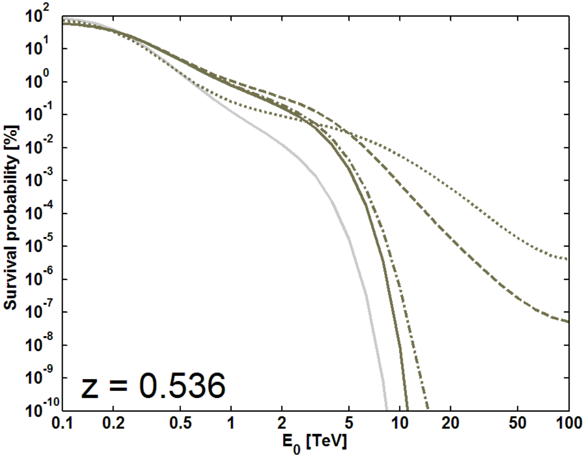


10 – DARMA EXPLAINS ANOMALOUS z-DEPENDENCE OF BLAZAR SPECTRA

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

According to the Tevcat catalog, 43 blazars with known redshift have been detected in the VHE so far, and 39 of them are in the flaring state, whose typical lifetime ranges from a few hours to a few days. We discard 1ES 0229+200 and 1ES 0347-121 from our discussion, since an analysis of their properties has shown that they can hardly fit within the above standard photon emission mechanisms, which predict – in first approximation – 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. We also discard PKS 1441+25 and S3 0218+35 both at $z \simeq 0.94$, so that cosmological evolutionary effects are harmless out to redshift $z \simeq 0.5$ (3C 279).

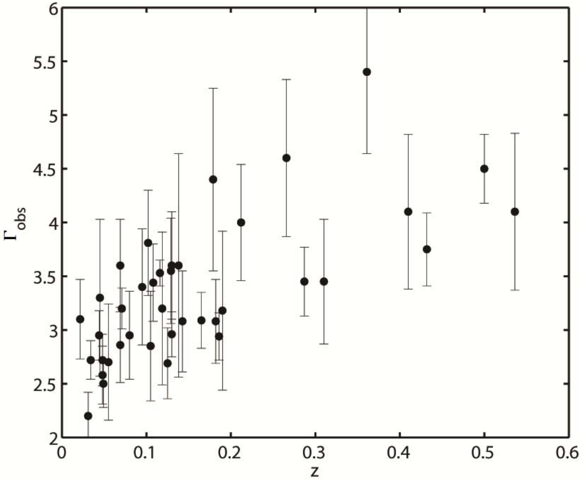
Moreover, all observed spectra of the considered VHE blazars are well fitted by a single power-law, and so they have the form $\Phi_{\rm obs}(E_0, z) \propto K_{{\rm obs},0}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$, where E_0 is the observed energy, while $K_{{\rm obs},0}(z)$ and $\Gamma_{\rm obs}(z)$ denote the normalization constant and the observed slope, respectively, for a source at redshift z.
The relation between $\Phi_{\rm obs}(E_0, z)$ and $\Phi_{\rm em}(E)$ is the usual one

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1 + z)\big) \ , \qquad (17)$$

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

The observational quantities concerning every blazar which are relevant for the present analysis are: the redshift z, the observed flux $\Phi_{\rm obs}(E_0, z)$ and the energy range ΔE_0 where each source is observed.

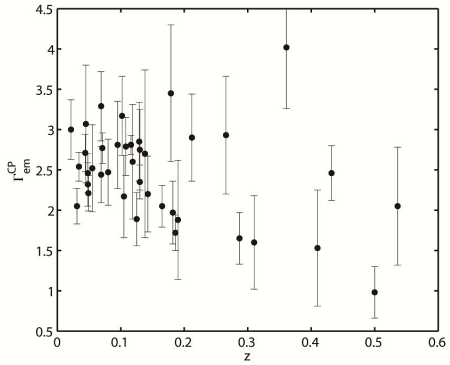
OBSERVED spectra: slope $\Gamma_{\rm obs}$ plotted versus source redshift z.



10.1 – WORKING WITHIN CONVENTIONAL PHYSICS

We start to deabsorb the observed spectra using the EBL model of Franceschini, Rodighiero & Vaccaro (FRV) A & A **487**, 837 (2008).

EMITTED spectra: slope $\Gamma_{\rm obs}$ plotted versus source redshift z.

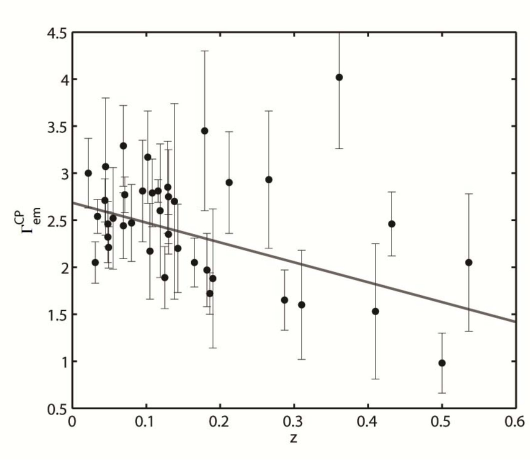


We perform a statistical analysis of all values of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z. We use the least square method and try to fit the data with one parameter (horizontal straight line), two parameters (first-order polynomial), and three parameters (second-order polynomial). In order to test the statistical significance of the fits we evaluate 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. Thus, data appear to be best-fitted by the first-order polynomial

$$\Gamma_{\rm em}^{\rm CP}(z) = 2.69 - 2.11\, z \ . \tag{18}$$

The of $\{\Gamma_{\rm em}^{\rm CP}\}$ distribution as a function of z and the associated best-fit straight regression line as defined by the last equation are plotted in the next Figure.

Same as previous Figure but with superimposed BEST-FIT STRAIGHT REGRESSION LINE



In order to appreciate the physical meaning of this result we recall that $\Gamma_{\rm em}^{\rm CP}(z)$ is the *exponent* of the emitted energy entering $\Phi_{\rm em}^{\rm CP}(E)$. Hence, in the two extreme cases we have

$$\Phi_{\rm em}^{\rm CP}(E,0) \propto E^{-2.69} \;, \qquad \Phi_{\rm em}^{\rm CP}(E,0.54) \propto E^{-1.55} \;, \tag{19}$$

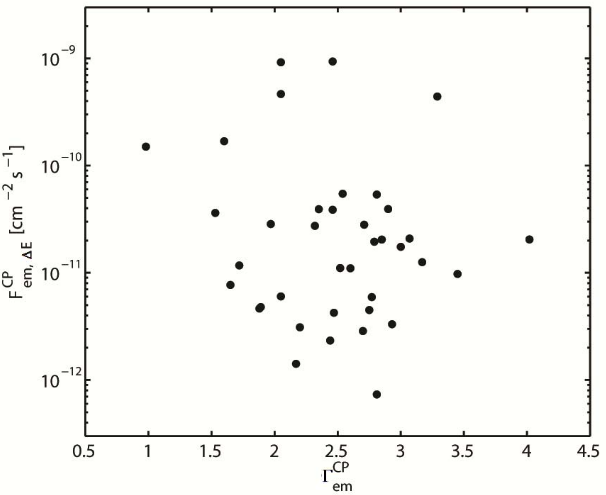
thereby implying that its nonvanishing slope gives rise to a LARGE VARIATION of the emitted flux with redshift.

Actually, one of the implications of such a best-fit straight regression line is that blazars with HARDER spectra are found ONLY at larger redshift. What is its PHYSICAL MEANING?

The simplest explanation would be a SELECTION BIAS, since evolutionary effects are irrelevant.

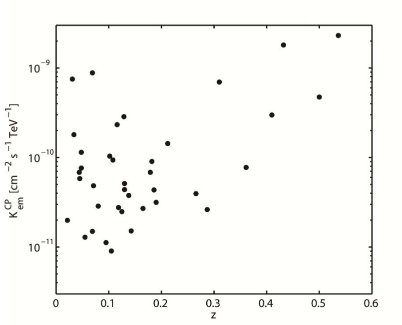
- As we look at larger distances only the brighter sources are observed while the fainter ones progressively disappear.
- Looking at greater distances entails that larger regions of space are probed, and so – under the assumption of an uniform source distribution – a larger number of brighter blazars should be detected.

Now, PROVIDED that $\Gamma_{\rm em}^{\rm CP}(z)$ STRONGLY CORRELATES with the observed luminosity $F_{\rm em}^{\rm CP}(z)$ it follows that BRIGHTER SOURCES HAVE HARDER SPECTRA, which would nicely explain our finding. But this is NOT the case: see next figure.



10^{-9}
10^{-10}
10^{-11}
10^{-12}
$F^{CP}_{em,\Delta E}$ [cm $^{-2}$ s $^{-1}$]
0.5 1 1.5 2 2.5 3 3.5 4 4.5
Γ^{CP}_{em}

The reason is that the luminosity increases with z NOT because the spectrum gets harder but because the normalization constant increases with z, as shown below



MORAL – CONVENTIONAL PHYSICS does NOT explain the z-dependence of the straight best-fit straight regression line.

So, we have 2 problems at once.

- Why blazars with HARDER spectra are found ONLY at larger redshift?
- How can a source get to know its redshift z in such a way that the $\{\Gamma_{\rm em}^{\rm CP}\}$ distribution has the RIGHT z-dependence?

Manifestly, NEW PHYSICS is needed.

10.2 – WORKING WITHIN DARMA

We choose to work within the DARMA scenario.
So, we go through the same steps as before. Namely, we first de-absorb the observed spectra by taking into account BOTH the EBL (same FRW model) + PHOTON-ALP oscillations. Recalling that

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big)~, \tag{20}$$

all we need to do is to evaluate the photon survival probability $P_{\gamma \to \gamma}^{\rm DARMA}(E, z)$ for the same benchmark values used above, namely

$$\xi \equiv \left(\frac{B}{\rm nG}\right)\left(\frac{10^{11}\,{\rm GeV}}{M}\right) = 0.1,\, 0.5,\, 1,\, 5~, \tag{21}$$

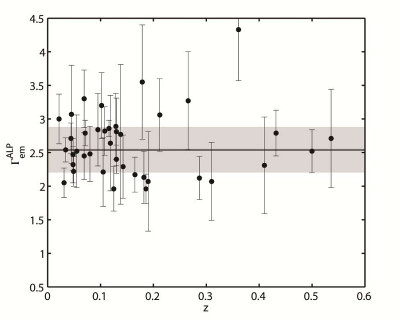
and $L_{\rm dom} = 4\,{\rm Mpc},\, 10\,{\rm Mpc}$. We take $m < 10^{-9}\,{\rm eV}$ in order to be in the strong-mixing regime.

Next, we carry out the same statistical analysis as above of the values of $\Gamma_{\rm em}^{\rm DARMA}$ as a function of z for any benchmark value of ξ and $L_{\rm dom}$. We still use the least square method and we try to fit the data with one parameter (horizontal line), two parameters (first-order polynomial) and three parameters (second-order polynomial). Finally, we compute the $\chi^2_{\rm red}$.

Our result is that in either case the best-fit regression line is STRAIGHT and HORIZONTAL in the $\Gamma_{\rm em}^{\rm DARMA} - z$ plane, and we get $\chi^2_{\rm red,DARMA} = 1.39\,1.38$ for $L_{\rm dom} = 4\,{\rm Mpc}$, $10\,{\rm Mpc}$, respectively, corresponding to $\xi = 0.5$ in either case.

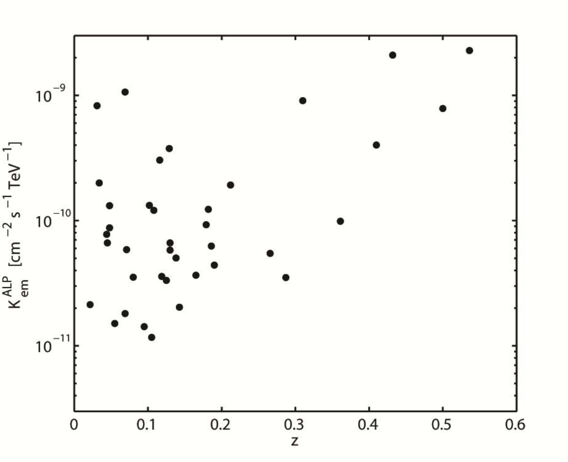
So, we have got the ONLY possible result CONSISTENT WITH PHYSICAL INTUITION.

Plot of $\Gamma_{\rm em}^{\rm DARMA}$ for $L_{\rm dom} = 4\,{\rm Mpc}$.

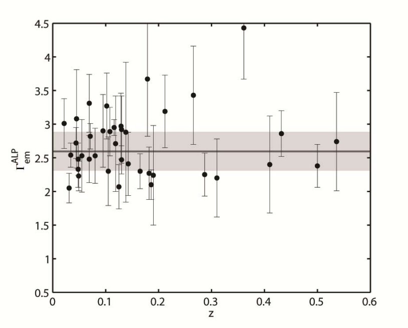


HSRL with equation $\Gamma_{\rm em}^{\rm ALP} = 2.54$. The grey band encompasses 95 % of the considered sources.

Plot of the flux normalization constant $K_{\mathrm{em}}^{\mathrm{DARMA}}$ for $L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$.

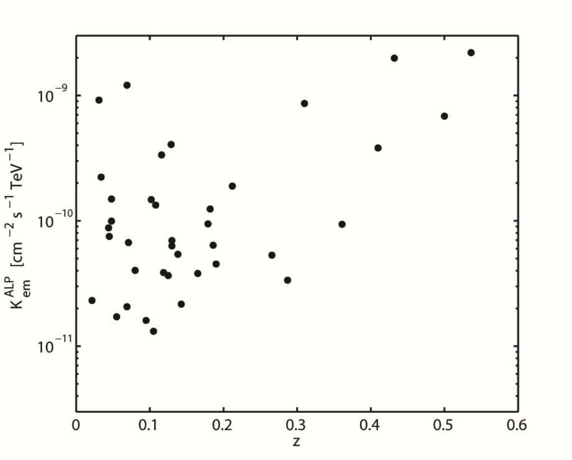


Plot of $\Gamma_{\mathrm{em}}^{\mathrm{DARMA}}$ for $L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$.



HSRL with equation $\Gamma_{\mathrm{em}}^{\mathrm{ALP}} = 2.59$. The grey band encompasses 95 % of the considered sources.

Plot of the flux normalization constant $K_{\rm em}^{\rm DARMA}$ for $L_{\rm dom} = 10\,{\rm Mpc}$.



10.3 – NEW PICTURE OF VHE BLAZARS

The previous result implies that 95 % of the sources have a *small spread* in the values of $\Gamma_{\rm em}^{\rm ALP}(z)$. Specifically, $\Gamma_{\rm em}^{\rm ALP}(z)$ departs from the value of the best-fit straight regression line by AT MOST 13 % for $\xi = 0.5$ and $L_{\rm dom} = 4\,{\rm Mpc}$, and by 11 % for $\xi = 0.5$ and $L_{\rm dom} = 10\,{\rm Mpc}$.

Actually, the small scatter in the values of $\Gamma_{\rm em}^{\rm ALP}(z)$ strongly suggests that the PHYSICS of all sources is NEARLY THE SAME, with the LARGE DIFFERENCE in the flux normalization – presumably unaffected by photon-ALP oscillations when error bars are taken into account – is due to quite different BOUNDARY CONDITIONS.

So, a new question arises: where the large spread in the $\{\Gamma_{\rm obs}(z)\}$ distribution comes from? The answer is very simple: from the large scatter in the source redshift.

11 – ALPs AS COLD DARK MATTER PARTICLES?

"HIC SUNT LEONES"

Too many uncertainties to make predictions and sharp statements.

- The lightness of ALPs strongly suggests that they are pseudo-Goldstone bosons associated with some broken global global symmetry $\mathcal{G}$ of the FT. In this case, the following relation is expected

$$\frac{1}{M} = \frac{\alpha}{2\pi} \frac{\mathcal{N}}{f_{\rm ALP}} \ , \tag{22}$$

  where $f_{\rm ALP}$ is the scale of the spontaneous breakdown of $\mathcal{G}$.
- It depends on whether $\mathcal{G}$ is broken BEFORE or AFTER inflation.
- But they can also come from the compactification pattern.
- Are ALP mainly produced by the vacuum misalignment mechanism – and so they are COLD – or mainly thermally, in which case they would be HOT?

12 – CONCLUSIONS

We have shown that photon-ALP oscillations for the $a\gamma\gamma$ inverse coupling in the range $5 \cdot 10^{10}\,\mathrm{GeV} < M < 5 \cdot 10^{11}\,\mathrm{GeV}$ and $m < 10^{-9}\,\mathrm{eV}$ give rise to the following effects.

- EBL absorption in extragalactic space is offset to a considerable extent. The trend is that a boost factor of 10 in the photon survival probability occurs at an energy E_{10} which decreases as the source distance increases, and becomes e.g. as low as $E_{10} = 2\,\mathrm{TeV}$ at $z = 0.536$ (3C 279). So, the gamma-ray horizon gets considerably enlarged.
- Anomalous z-dependence of blazar spectra is explained.
- The FSRQ emission at energies $E > 20\,\mathrm{GeV}$ is explained.
- ALPs can be cold dark matter particles.
- The considered range for M will be probed in the laboratory.

Exciting predictions for CTA are not missing!