ASTROPHYSICAL GAMMA-RAY PROBES OF AXION-LIKE PARTICLES (ALPs)

Marco Roncadelli

INFN – Pavia, Italy

SUMMARY

1 – MOTIVATIONS

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 20 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.

Among the candidates for a more Fundamental Theory (FT), superstring theory and its variations seem to have the best chance to be successful. Not only seem superstrings to offer a solution to all the above problems, but in addition – depending on the compactification pattern – they predict the existence of the axion and one or more axion-like particles (ALPs).
Remarkably, also other attempts to achieve the same goal like Kaluza-Klein theories with compactified large extra-dimensions point towards the same conclusion.
As a consequence, the SM is viewed as the part of the Low-Energy Effective Theory (LEET) of the FT characterized by a very large energy scale $\Lambda \gg G_F^{-1/2}$ after compactification, so that it is a 4-dimensional field theory containing both light ϕ and heavy Φ particles and defined by the Lagrangian $\mathcal{L}_{\rm FT}(\phi, \Phi)$.

Denoting by

$$Z_{\rm FT}[J,K] \propto \int \mathcal{D}\phi \int \mathcal{D}\Phi \exp\left(i \int d^4x \left[\mathcal{L}_{\rm FT}(\phi,\Phi) + \phi J + \Phi K \right] \right) \tag{1}$$

the generating functional of the FT, the resulting LEET emerges by integrating out the heavy particles and so its lagrangian $\mathcal{L}_{\rm eff}(\phi)$ is defined by

$$\exp\left(i \int d^4x \, \mathcal{L}_{\rm eff}(\phi) \right) \equiv \int \mathcal{D}\Phi \exp\left(i \int d^4x \, \mathcal{L}_{\rm FT}(\phi,\Phi) \right) \ . \tag{2}$$

Actually, $\mathcal{L}_{\rm eff}(\phi)$ not only contains $\mathcal{L}_{\rm SM}(\phi)$ but also includes nonrenormalizable terms involving ϕ that are suppressed by inverse powers of M. So the SM is embedded in the LEET whose generating functional reads

$$Z_{\rm eff}[J,K] \propto \int \mathcal{D}\phi \, \exp\left(i \int d^4x \left[\mathcal{L}_{\rm eff}(\phi) + \phi J \right] \right) \ . \tag{3}$$

Any sufficiently rich gauge structure such as the FT contains some GLOBAL symmetry $\mathcal{G}$ which is an accidental consequence of gauge invariance. As a rule, when gauge invariance gets spontaneously broken $\mathcal{G}$ gets SPONTANEOUSLY broken as well. Therefore some massless Goldstone bosons show up in the physical spectrum. Yet, typically $\mathcal{G}$ is also slightly EXPLICITLY broken, e.g. this happens when Planck-scale effects are included since black holes do not carry definite global quantum numbers. So, Goldstone bosons $\rightarrow$ pseudo-Goldstone bosons with mass $\ll G_F^{-1/2}$, which must be present in the LEET even though they arise from physics at energies $\gg G_F^{-1/2}$. Hence, denoting by a the pseudo-Goldstone bosons and splitting up $\phi \rightarrow \{\phi_{\rm SM}, a\}$ we have

$$\begin{aligned} \mathcal{L}_{\rm eff}(\phi_{\rm SM}, a) = \mathcal{L}_{\rm SM}(\phi_{\rm SM}) + \mathcal{L}_{\rm nonren}(\phi_{\rm SM}) + \\ + \mathcal{L}_{\rm ren}(a) + \mathcal{L}_{\rm nonren}(\phi_{\rm SM}, a) \qquad , \end{aligned} \tag{4}$$

2 – AXIONS

An important example of this strategy is provided by the global Peccei-Quinn $U(1)_{\rm PQ}$ symmetry which was proposed as a natural solution to the strong CP problem. Because $U(1)_{\rm PQ}$ is spontaneously broken at a very high scale $f_a \propto \Lambda$ and explicitly by non-perturbative QCD effects, a pseudo-Goldstone boson of mass m named AXION comes into play. Accordingly, we have

$$\mathcal{L}_{\rm ren}(a) = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2\ , \tag{5}$$

$$\mathcal{L}_{\rm nonren}(\phi_{\rm SM}, a) = \mathcal{L}_{a\gamma\gamma} + \mathcal{L}_{\rm af}\ , \tag{6}$$

with

$$\mathcal{L}_{a\gamma\gamma} = -\,\frac{1}{4M}\,F^{\mu\nu}\,\tilde{F}_{\mu\nu}\,a = \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a\ , \tag{7}$$

where $M \propto \Lambda$, $F^{\mu\nu} \equiv (\mathbf{E}, \mathbf{B}) \equiv \partial^\mu A^\nu - \partial^\nu A^\mu$ is the usual electromagnetic field strength and $\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$, and

$$\mathcal{L}_{\mathrm{af}} = \frac{1}{2M} \sum_i \frac{g_{ai}}{m_i} \overline{f}_i \, \gamma^\mu \, \gamma_5 \, f_i \, \partial_\mu \, a \tag{8}$$

with $a = \text{axion field}$ and $f_i = \text{any charged lepton or quark}$. Finally, we have a STRICT RELATIONSHIP exists between m and M

$$m \simeq 0.6 \left(\frac{10^7 \, \mathrm{GeV}}{f_a} \right) \, \mathrm{eV} \propto \frac{1}{f_a} \ , \tag{9}$$

$$M = 1.2 \cdot 10^{10} \, k \, \left(\frac{f_a}{10^7 \, \mathrm{GeV}} \right) \, \mathrm{GeV} \propto f_a \ , \tag{10}$$

$$m = 0.7 \, k \, \left(\frac{10^{10} \, \mathrm{GeV}}{M} \right) \, \mathrm{eV} \ , \tag{11}$$

with $k \sim 1$. Hence, mass and couplings to photons and charged fermions are tightly RELATED and both $\propto 1/f_a$.

Actually, axions are terribly unstable against a tiny explicit breaking of $\mathrm{U}(1)_{\mathrm{PQ}}$ – even at the Plank scale – and so $\mathrm{U}(1)_{\mathrm{PQ}}$ MUST be embedded into a larger theory containing e.g. discrete gauge symmetries.

Therefore, if the axion exists it is a signal that even MORE NEW PHYSICS must exist as well.

3 – AXION-LIKE PARTICLES (ALPs)

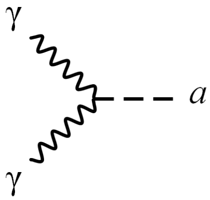
ALPs are similar to the axion in nature, apart from two facts, in order to make them as much as model-independent as possible.

- m and M are totally UNRELATED.
- ALPs couple ONLY to two photons (any other possible coupling is discarded).

Their Lagrangian is therefore

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^{\mu} a\,\partial_{\mu} a - \frac{1}{2}\,m^2\,a^2 + \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a \tag{12}$$

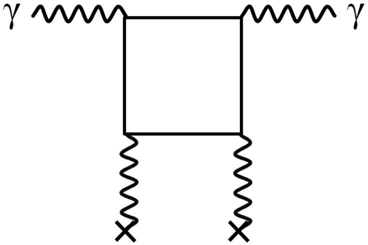
with $M \gg G_F^{-1/2}$ and $m \ll G_F^{-1/2}$. So, for ALPs the ONLY NEW THING is



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

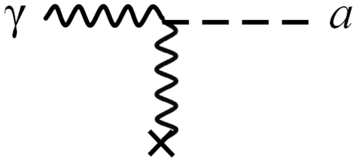
$$\mathcal{L}'_{\mathrm{ALP}} = \mathcal{L}_{\mathrm{ALP}} + \frac{2\alpha^2}{45 m_e^4} \left[\left(\mathbf{E}^2 - \mathbf{B}^2 \right)^2 + 7 \left(\mathbf{E} \cdot \mathbf{B} \right)^2 \right] , \qquad (13)$$

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



4 – 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.

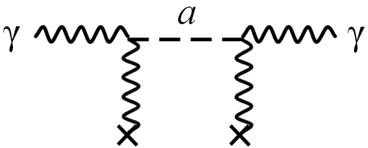
However here there is an additional effect.
Since the $\gamma\gamma a$ vertex goes like $\mathbf{E} \cdot \mathbf{B}$, in the presence of an EXTERNAL magnetic field $\mathbf{B}$.

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

Hence we have a CHANGE of the photon POLARIZATION state.

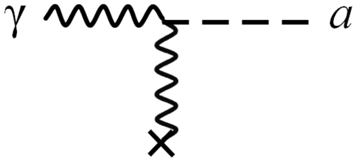
Specifically, for a beam initially LINEARLY polarized two effects occur.

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



N. B. *a* REAL

5 – 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 $\mathbf{B}$ is homogeneous. Taking the z-axis along $\mathbf{B}$, we have

$$P_{\gamma \to a}(E; 0, y) = \left(\frac{B}{M \, \Delta_{\rm osc}} \right)^2 \sin^2 \left(\frac{\Delta_{\rm osc} \, y}{2} \right) \, , \qquad (14)$$

with

$$\Delta_{\rm osc} \equiv \left\{ \left[\frac{m^2 - \omega_{\rm pl}^2}{2E} + \frac{3.5\alpha}{45\pi} \left(\frac{B}{B_{\rm cr}} \right)^2 E \right]^2 + \left(\frac{B}{M} \right)^2 \right\}^{1/2} , \quad (15)$$

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

$$E_L \equiv \frac{|m^2 - \omega_{\rm pl}^2| M}{2B} , \quad (16)$$

and

$$E_H \equiv \frac{90\pi}{7\alpha} \frac{B_{\rm cr}^2}{BM} . \quad (17)$$

Accordingly

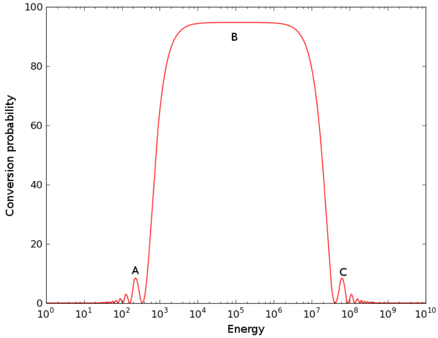
- For $E \ll E_L$ and $E \gg E_H$ the effect disappears.
- For $E \sim E_L$ and $E \sim E_H$ $P_{\gamma \to a}(E; 0, y)$ rapidly oscillates with E: WEAK-MIXING regime.
- For $E_L \ll E \ll E_H$ $\;P_{\gamma \to a}(E; 0, y)$ maximal and independent of both m and E: STRONG-MIXING regime, where

$$\Delta_{\rm osc} \simeq \frac{B}{M} \tag{18}$$

and

$$P_{\gamma \to a}(E; 0, y) \simeq \sin^2 \left(\frac{By}{2M} \right) \;, \tag{19}$$

which is MAXIMAL.



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

6 – RELEVANCE OF AXIONS AND ALPs FOR STARS

Owing to their couplings, axions and ALPs can be a new and dangerous energy-loss mechanism for stars of various kinds.

AXIONS

- The red-giant branch in globular clusters is extended to larger brightness if the degenerate helium core loses too much energy. Agreement with contemporary stellar evolution theory requires both $g_{ae} < 4.3 \cdot 10^{-13}$ for axion Bremsstrahlung and $M > 1.52 \cdot 10^{10}\,\mathrm{GeV}$ for the Primakoff effect.
- According to Isern and collaborators, the white dwarf luminosity function is better fitted if an additional cooling provided by Bremsstrahlung of axions with a mass of a few meV is included in the calculations.

- As far as the Sun is concerned the most efficient channel is axion Bremsstrahlung from electrons. The CAST experiment at CERN was looking for several years towards the Sun in order to detect the emitted axions. No detection has provided the bound $g_{ae}/M < 8.1 \cdot 10^{-23}\,\mathrm{GeV}^{-1}$ for $m < 10^{-2}\,\mathrm{eV}$.

ALPs
The only experimental bound is set by CAST through the Primakoff process and yields $M > 1.14 \cdot 10^{10}\,\mathrm{GeV}$, apart from red giant stars, which give $M > 1.52 \cdot 10^{10}\,\mathrm{GeV}$ for the Primakoff effect.

7 – COSMOLOGICAL RELEVANCE OF AXIONS

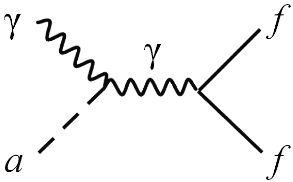
Cosmological constraint of ALPs depends on m and M. We shall come back to this point later.
This is not the case for axions.

- NON-THERMAL PRODUCTION: $\Omega < 1$ implies $m > 10^{-6}\,\mathrm{eV}$. Moreover axions are COLD DARK MATTER with $f_a \simeq (6 \cdot 10^{11} - 6 \cdot 10^{12})\,\mathrm{GeV}$, therefore $m \simeq (10^{-6} - 10^{-5})\,\mathrm{eV}$ & $M \simeq (7 \cdot 10^{14} - 7 \cdot 10^{15})\,k\,\mathrm{GeV}$.
- THERMAL PRODUCTION: Axions are HOT DARK MATTER with $m \simeq (10^{-1} - 1)\,\mathrm{eV}$.

Because galaxy formation requires dark matter to be COLD we need $m \simeq (10^{-6} - 10^{-5})\,\mathrm{eV}$ if axions are to be the leading component.

BOTTOM LINE

- For ALPs the only constraint is $M > 1.52 \cdot 10^{10}\,\mathrm{GeV}$. 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.

- For axions we must have $M \simeq (7 \cdot 10^{14} - 7 \cdot 10^{15})\,k\,\mathrm{GeV}$ if they are to be the bulk of cold dark matter.

8 – IS THE AXION FOUND?

In 2014 Fraser et al., MNRAS **445**, 2146 (2014) with the XMM-Newton observatory claimed positive evidence for detection of axions emitted from the Sun, with mass $m \simeq 2.6 \cdot 10^{-6}$. So, not only axions would be found, but they would be COLD dark matter particles.

But a re-analysis by Tavecchio & Roncadelli, MNRAS **450**, L26 (2015) has shown that such a claim is COMPLETELY WRONG.

9 – ALPs X-RAY POLARIMETRIC EFFECTS

Given a random distribution of viewing angles, a STATISTICAL study of the polarization properties of a large sample of GRBs is expected to allow to discriminate among different emission models.

Specifically, the ratio N_m/N_d of the number N_m of GRBs for which the degree of polarization can be measured to the number N_d of GRBs that are detected, and the distribution of the degree of LINEAR polarization Π_L, can be used as criteria. Actually

- If $N_m/N_d > 30\%$ and Π_L clusters between 0.2 and 0.7, then the SYNCHROTRON EMISSION MODEL WITH ORDERED MAGNETIC FIELDS will be favored.
- If instead $N_m/N_d < 15\%$, then both the SYNCHROTRON EMISSION MODEL WITH RANDOM MAGNETIC FIELDS and the COMPTON-DRAG MODEL will be preferred.
- If several events with $\Pi_L > 0.8$ are observed, then the COMPTON-DRAG MODEL will instead be singled out.

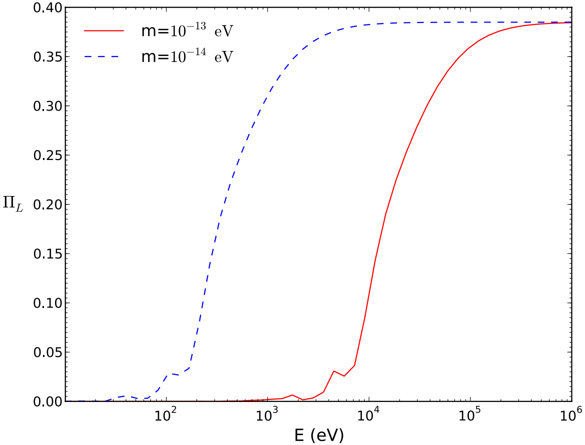
We show that the presence of ALPs mixing with photons in COSMIC magnetic fields can DRASTICALLY AFFECT such expected statistical distributions for the linear polarization of GRBs.

Our procedure is as follows. We start with a given polarization density matrix $\rho_{\rm in}$ and we ITERATE it over all magnetic domains WHITOUT taking any average, thereby getting $\rho_{\rm fin}$. Standard STOKES parameters are defined as

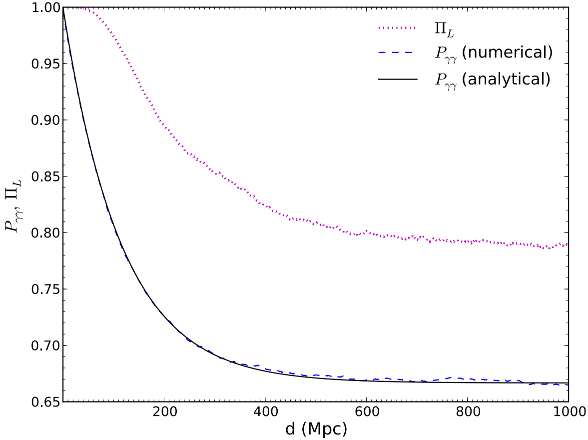
$$\rho_\gamma = \frac{1}{2}\begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix} \tag{20}$$

where ρ_γ is the 2×2 PHOTON polarizaton density matrix. Then the degree of *linear polarization* Π_L is defined as

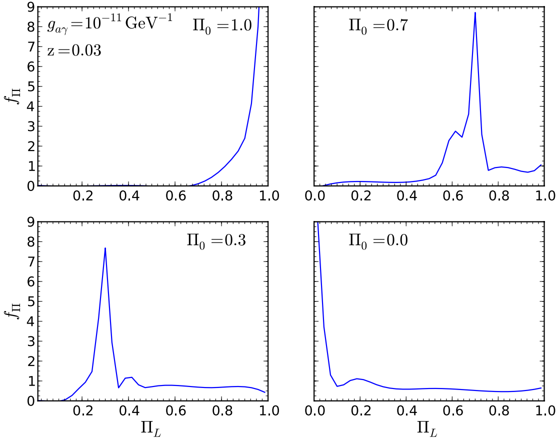
$$\Pi_L \equiv \frac{(Q^2 + U^2)^{1/2}}{I} = \frac{\left[(\rho_{11} - \rho_{22})^2 + (\rho_{12} - \rho_{21})^2\right]^{1/2}}{\rho_{11} + \rho_{22}} \ . \tag{21}$$



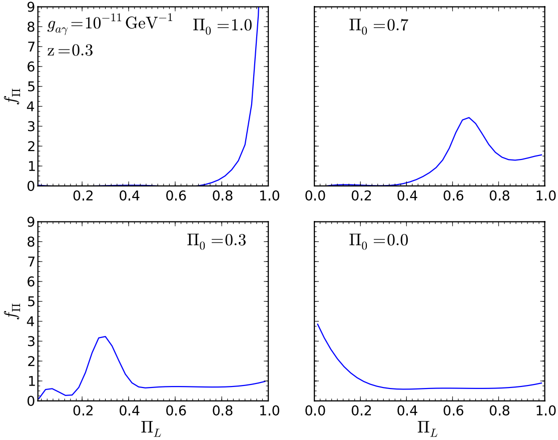
Average final linear polarization Π_L as a function of the photon energy E after propagation in the extragalactic magnetic field for ALP masses $m = 10^{-13}$ eV (solid line) and $m = 10^{-14}$ eV (dashed line), respectively. The emitting GRB is assumed to be completely unpolarized and at distance $d = 100$ Mpc.



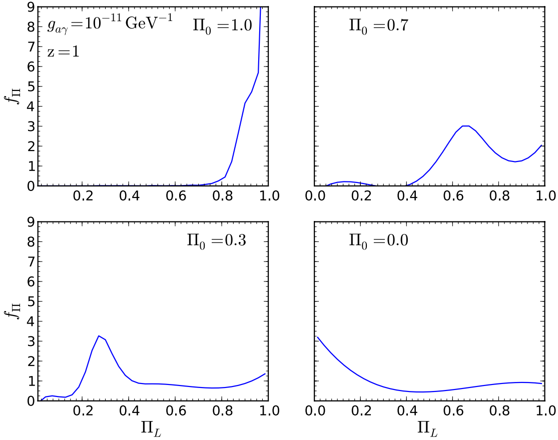
Average linear polarization Π_L (dotted line) and photon survival probability $P_{\gamma\gamma}$ evaluated numerically (dashed line) and analytically (solid line), as a function of the source distance d for photon-ALP mixing in the extragalactic magnetic field. The source is assumed to be fully polarized along the x direction.



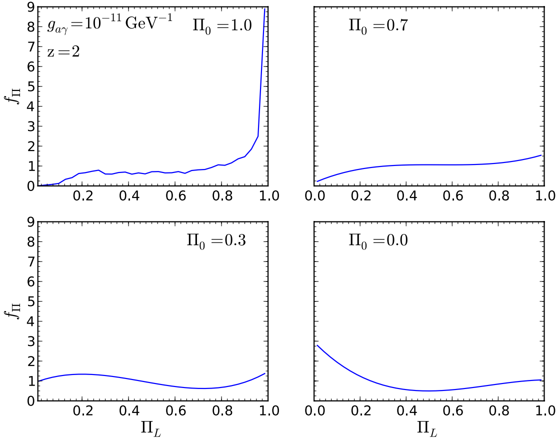
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 0.03$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.



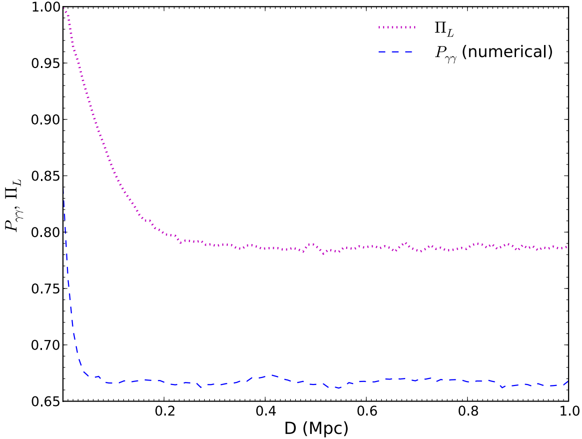
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 0.3$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.



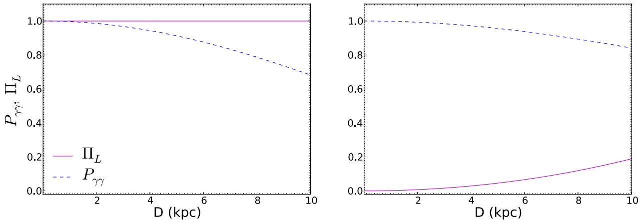
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 1$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.



Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 2$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.

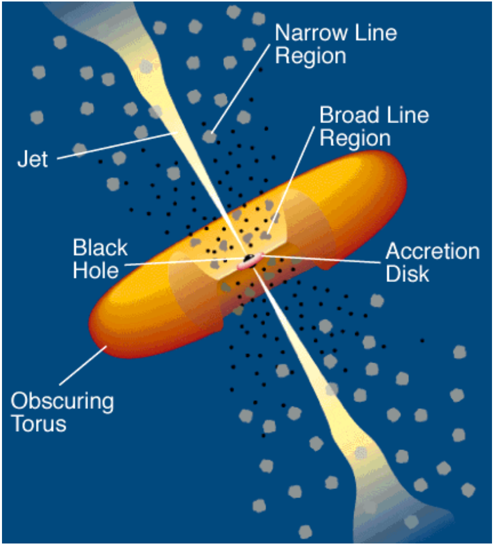


Average linear polarization Π_L (dotted line) and photon survival probability $P_{\gamma\gamma}$ (dashed line) as a function of the distance D traveld inside the intracluster region. The source is assumed to be fully polarized along the z direction.



Linear polarization Π_L (solid line) and photon probability $P_{\gamma\gamma}$ (dashed line) for the photon-ALP mixing in the regular component of the Galactic magnetic field as a function of the photon path D in the Galaxy. We have assumed photons to be fully polarized along the x direction (left panel) or completely unpolarized (right panel) before entering the Galaxy. We have taken as Galactic magnetic field $B \simeq 4 \cdot 10^{-6}\,\mathrm{G}$ oriented along the x axis.

10 – BLAZARS


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

Two standard non-thermal photon emission mechanisms.

- LEPTONIC mechanism (syncro-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, 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 $20\,\mathrm{GeV}$.

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.

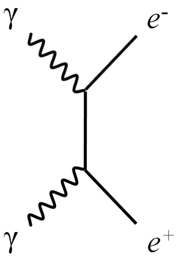
Other planned VHE photon detectors are HAWC (High-Altitude Water Cherenkov Observatory), GAMMA-400 (Gamma Astronomical Multifunctional Modular Apparatus), LHAASO (Large High Altitude Air Shower Observatory) and HiSCORE (Hundred Square km Cosmic Origin Explorer).

11 – EXTRAGALACTIC BACKGROUND LIGHT (EBL)

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

$$P^{\mathrm{CP}}_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0,z)} \; , \tag{22}$$

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

$$\epsilon(E) \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\ , \tag{23}$$

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

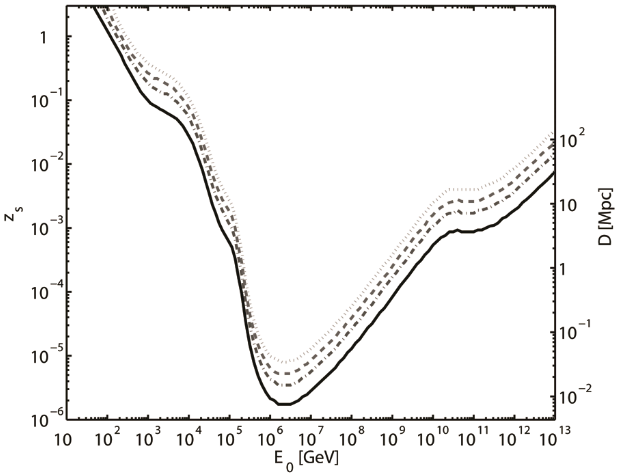
$$\tau_\gamma(E_0, z_s) = \int_0^{z_s} \mathrm{d}z\ \frac{\mathrm{d}l(z)}{\mathrm{d}z}\ \int_{-1}^{1} \mathrm{d}(\cos\varphi)\ \frac{1-\cos\varphi}{2}\ \times \tag{24}$$

$$\times \int_{\epsilon_{\mathrm{thr}}(E(z),\varphi)}^{\infty} \mathrm{d}\epsilon(z)\, n_\gamma(\epsilon(z), z)\, \sigma_{\gamma\gamma}\big(E(z), \epsilon(z), \varphi\big)\ ,$$

where

$$\frac{dl(z)}{dz} = \frac{c}{H_0}\frac{1}{(1+z)\left[\Omega_\Lambda + \Omega_M\,(1+z)^3\right]^{1/2}}\ . \tag{25}$$

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)).

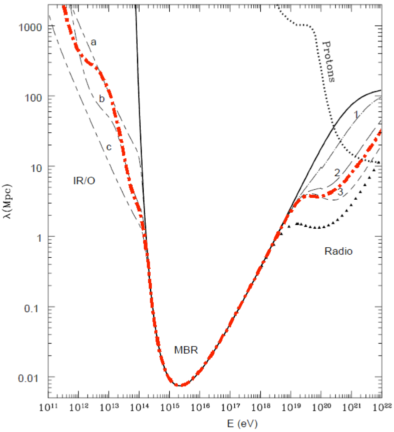


z_s
E_0 [GeV]
D [Mpc]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^2
10
1
10^{-1}
10^{-2}

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

$$P^{\mathrm{CP}}_{\gamma\to\gamma}(E, D) = e^{-D/\lambda_\gamma(E)} \ , \tag{26}$$

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



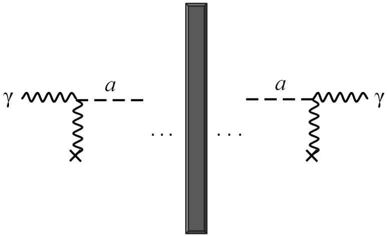
12 – ALPs AGAINST EBL

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

$$P^{\rm DARMA}_{\gamma \to \gamma}(E,z) = e^{-\tau_{\rm eff}(E,z)} \ . \tag{27}$$

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.

Schematically



where the vertical bar is the EBL.

13 – IMPLEMENTATIONS

Various scenarios have been developed to implement the above idea.

- DARMA SCENARIO – Photon-ALP oscillations in intergalactic 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)).

14 – 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 $\mathbf{B}$ changes randomly from a domain to the next. Motivated by the galactic outflows 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

$$\xi \equiv \left(\frac{B}{\mathrm{nG}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{M}\right) , \qquad (28)$$

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.

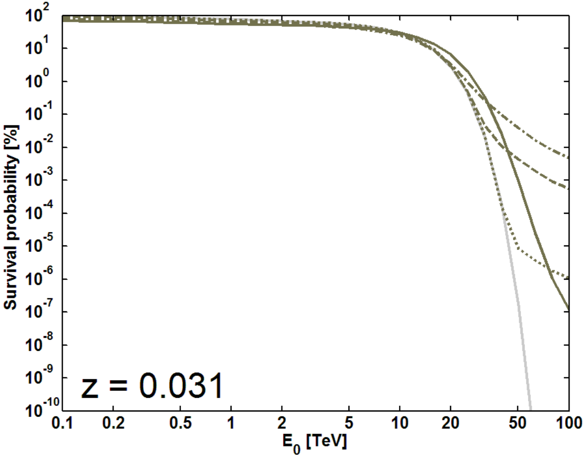
Using the formalism of non-relativistic quantum mechanics for unstable systems and assuming the beam to be unpolarized, It can be shown that the photon survival probability in the presence of EBL absorption and photon-ALP oscillations is

$$P^{\rm DARMA}_{\gamma \to \gamma}\left(E_0, z\right) = \Big\langle P_{\rho_{\rm unpol} \to \rho_x}\left(E_0, z; \psi_1, ..., \psi_{N_d}\right) \Big\rangle_{\psi_1, ..., \psi_{N_d}} + \quad (29)$$

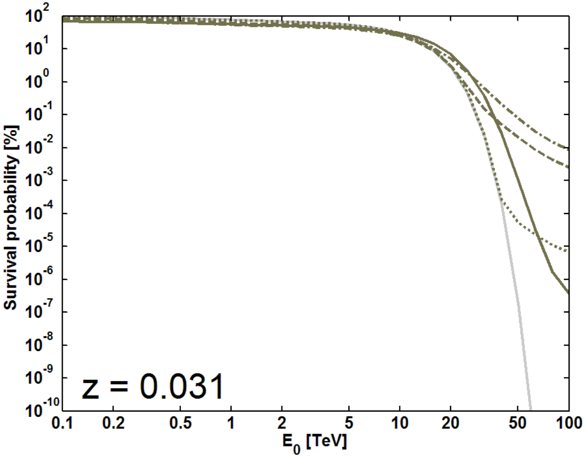
$$+ \Big\langle P_{\rho_{\rm unpol} \to \rho_z}\left(E_0, z; \psi_1, ..., \psi_{N_d}\right) \Big\rangle_{\psi_1, ..., \psi_{N_d}} \; .$$

14.1 – DARMA PREDICTIONS FOR THE CTA

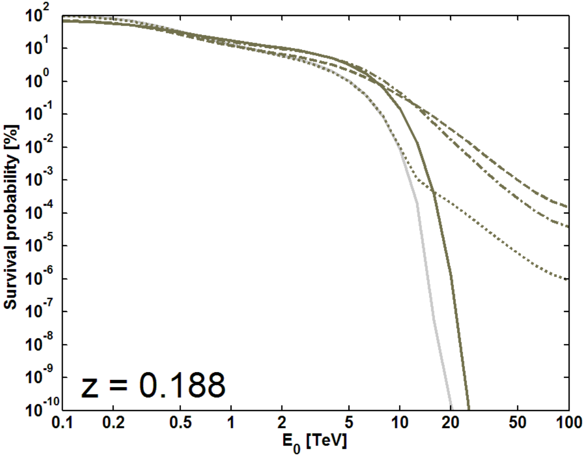
Solid black line = $\xi = 5.0$, dotted-dashed line = $\xi = 1.0$, dashed line = $\xi = 0.5$, dotted line = $\xi = 0.1$ and solid grey line = conventional physics. $L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$



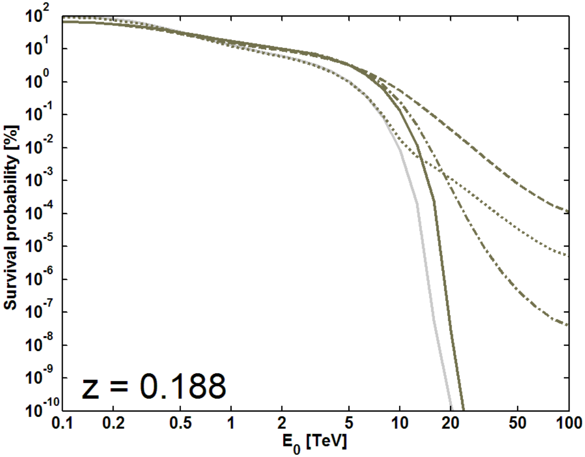
Solid black line $= \xi = 5.0$, dotted-dashed line $= \xi = 1.0$, dashed line $= \xi = 0.5$, dotted line $= \xi = 0.1$ and solid grey line $=$ conventional physics. $L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$



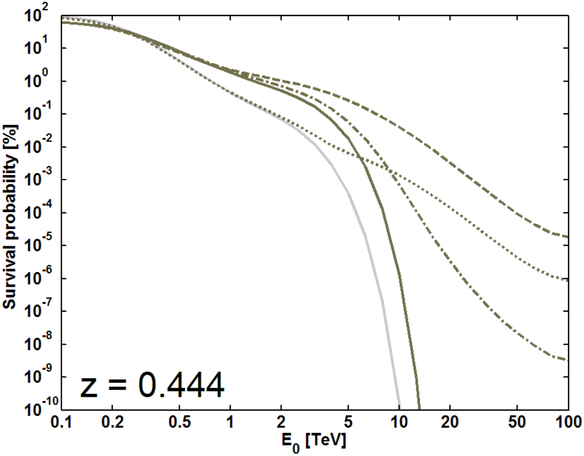
Solid black line = $\xi = 5.0$, dotted-dashed line = $\xi = 1.0$, dashed line = $\xi = 0.5$, dotted line = $\xi = 0.1$ and solid grey line = conventional physics. $L_{\rm dom} = 4\,{\rm Mpc}$



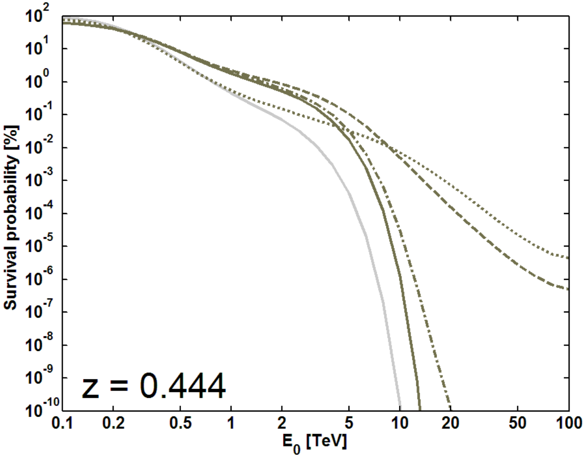
Solid black line = $\xi = 5.0$, dotted-dashed line = $\xi = 1.0$, dashed line = $\xi = 0.5$, dotted line = $\xi = 0.1$ and solid grey line = conventional physics. $L_{\rm dom} = 10\,{\rm Mpc}$



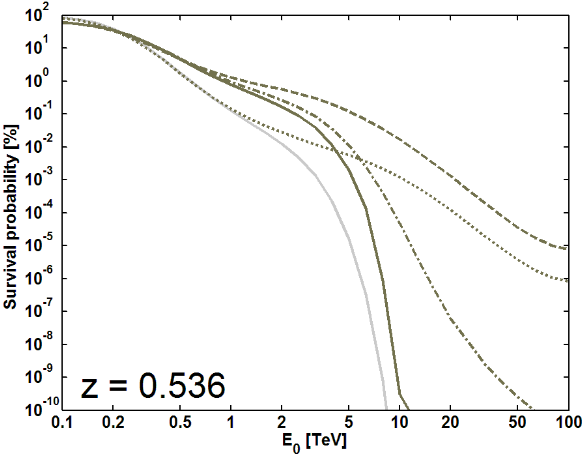
Solid black line = $\xi = 5.0$, dotted-dashed line = $\xi = 1.0$, dashed line = $\xi = 0.5$, dotted line = $\xi = 0.1$ and solid grey line = conventional physics. $L_{\rm dom} = 4\,{\rm Mpc}$.



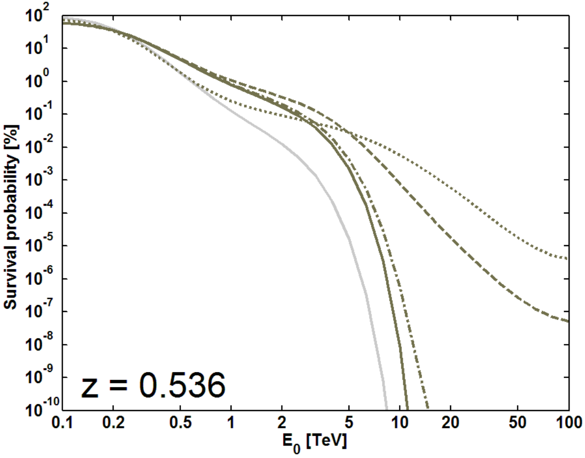
Solid black line $= \xi = 5.0$, dotted-dashed line $= \xi = 1.0$, dashed line $= \xi = 0.5$, dotted line $= \xi = 0.1$ and solid grey line $=$ conventional physics. $L_{\mathrm{dom}} = 10\,\mathrm{Mpc}$.



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



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



15 – DARMA EXPLAINS THE PAIR-PRODUCTION ANOMALY

it has recently been claimed that VHE observations require an EBL level EVEN LOWER than that predicted by the minimal EBL model normalized to the galaxy counts only – D. Horns & M. Meyer, JCAP **02**, 033 (2012); Meyer, Horns & Raue, PR D **87**, 035027 (2013).

This is the so-called PAIR-PRODUCTION ANOMALY, which is based on the Kolmogorov test and so does not rely upon the estimated errors. It has thoroughly been quantified by a global statistical analysis of a large sample of observed blazars, showing that measurements in the regime of large optical depth deviate by 4.2 σ from measurements in the optically thin regime. Systematic effects have been shown to be insufficient to account for such the pair-production anomaly, which looks therefore real.

Actually, the discovery of new blazars at large redshift like the observation of PKS 1424+240 have strengthened the case for the pair-production anomaly – Meyer and Horns, arxiv:1310.2058.

Quite recently, the existence of the pair-production anomaly has been questioned by using a new EBL model and a χ^2 test, in which errors play instead an important role – Biteau and Williams, arxiv:1502.04166.
Because the Kolmogorov test looks more robust in that it avoids taking errors into account, we tend to believe that the pair-production anomaly is indeed at the level of 4.2 σ.

16 – 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).

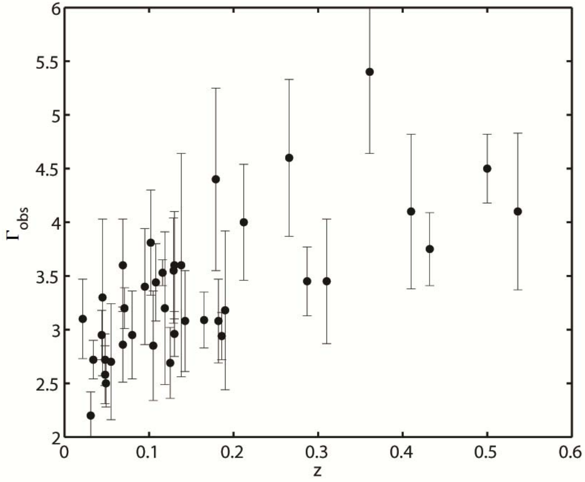
Moreover, all observed spectra of the considered VHE blazars are well fitted by a single power-law, and so they have the form $\Phi_{\rm obs}(E_0, z) \propto K_{\rm obs,0}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$, where E_0 is the observed energy, while $K_{\rm obs,0}(z)$ and $\Gamma_{\rm obs}(z)$ denote the 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

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big) \ , \qquad (30)$$

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.

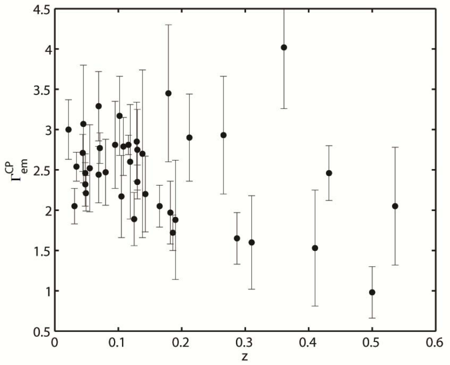
OBSERVED spectra: slope $\Gamma_{\rm obs}$ plotted versus source redshift z.



16.1 – 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.

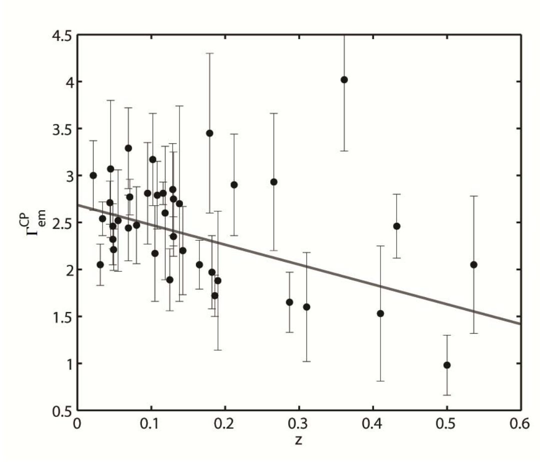


We perform a statistical analysis of all values of $\Gamma_{\mathrm{em}}^{\mathrm{CP}}(z)$ as a function of z. We use the least square method and try to fit the data with one parameter (horizontal straight line), two parameters (first-order polynomial), and three parameters (second-order polynomial). In order to test the statistical significance of the fits we evaluate the corresponding χ^2_{red}. The values of the χ^2_{red} obtained for the three fits are $\chi^2_{\mathrm{red}} = 2.28$, $\chi^2_{\mathrm{red}} = 1.81$ and $\chi^2_{\mathrm{red}} = 1.83$, respectively. Thus, data appear to be best-fitted by the first-order polynomial

$$\Gamma_{\mathrm{em}}^{\mathrm{CP}}(z) = 2.69 - 2.11\, z \; . \tag{31}$$

The of $\{\Gamma_{\mathrm{em}}^{\mathrm{CP}}\}$ 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

$$\Phi_{\rm em}^{\rm CP}(E, 0) \propto E^{-2.69} \; , \qquad \Phi_{\rm em}^{\rm CP}(E, 0.6) \propto E^{-1.42} \; , \tag{32}$$

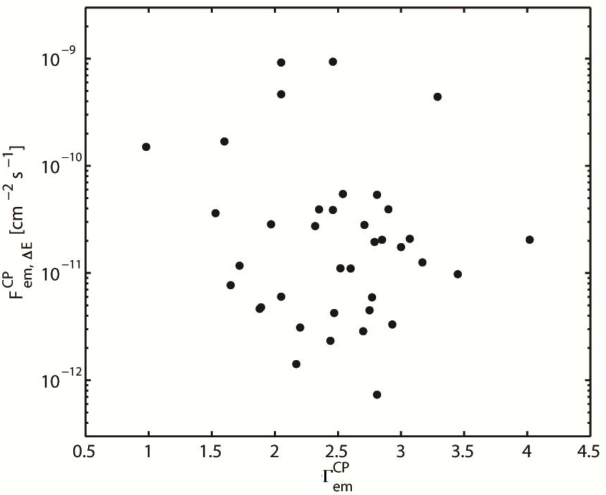
thereby implying that its nonvanishing slope gives rise to a LARGE VARIATION of the emitted flux with redshift.

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.

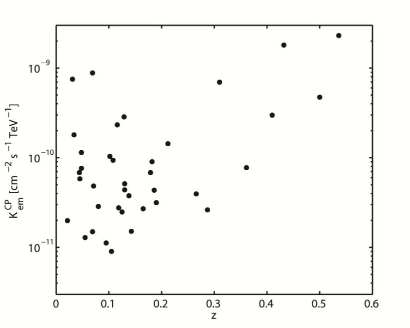
- As we look at larger distances only the brighter sources are observed while the fainter ones progressively disappear.
- Looking at greater distances entails that larger regions of space are probed, and so – under the assumption of an uniform source distribution – a larger number of brighter blazars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

Now, PROVIDED that $\Gamma_{\rm em}^{\rm CP}(z)$ STRONGLY CORRELATES with the observed luminosity $\Gamma_{\rm em}^{\rm CP}(z)$ 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}
0.5
1
1.5
2
2.5
3
3.5
4
4.5
$F^{CP}_{em,\Delta E}$ [cm $^{-2}$ s $^{-1}$]
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.

16.2 – 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

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big)~, \tag{33}$$

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

$$\xi \equiv \left(\frac{B}{\rm nG}\right) \left(\frac{10^{11}\,{\rm GeV}}{M}\right) = 0.1,\, 0.5,\, 1,\, 5~, \tag{34}$$

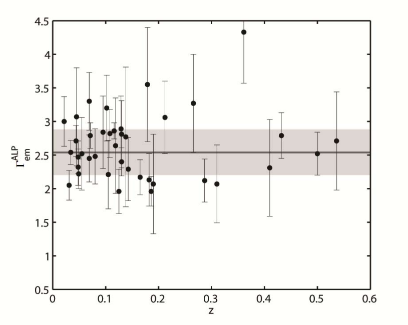
and $L_{\rm dom} = 4\,{\rm Mpc}$, $10\,{\rm Mpc}$. We take $m < 10^{-9}\,{\rm eV}$ in order to be in the strong-mixing regime.

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.

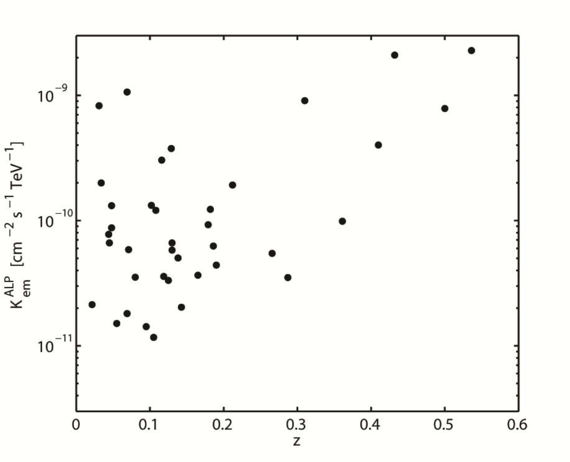
So, we have got the ONLY possible result CONSISTENT WITH PHYSICAL INTUITION.

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

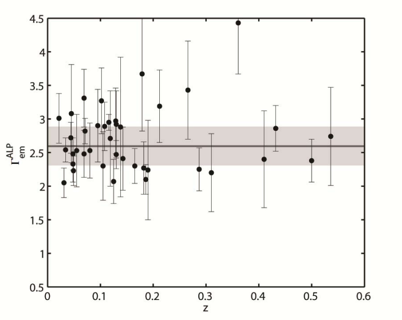


HSRL with equation $\Gamma_{\rm em}^{\rm ALP} = 2.54$. The grey band encompasses 95 % of the considered sources.

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

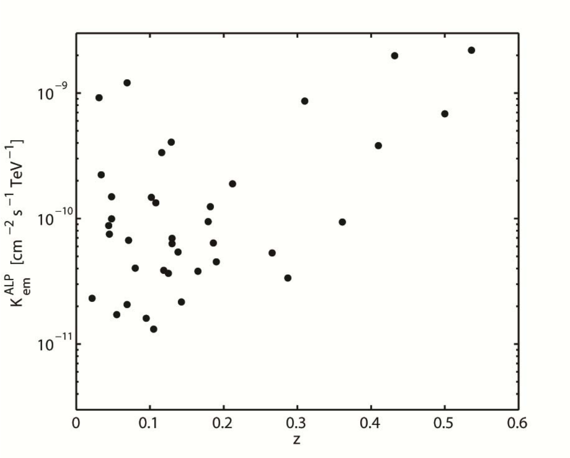


Plot of $\Gamma_{\rm em}^{\rm DARMA}$ for $L_{\rm dom} = 10\,{\rm Mpc}$.



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

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



16.3 – NEW PICTURE OF VHE BLAZARS

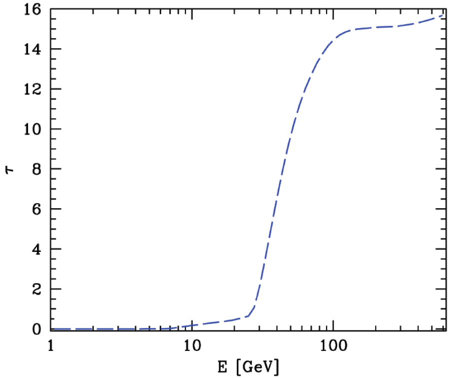
The previous result implies that 95 % of the sources have a *small spread* in the values of $\Gamma_{\rm em}^{\rm ALP}(z)$. Specifically, $\Gamma_{\rm em}^{\rm ALP}(z)$ departs from the value of the best-fit straight regression line by AT MOST 13 % for $\xi = 0.5$ and $L_{\rm dom} = 4\,{\rm Mpc}$, and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

17 – ALPs ALLOW FSRQs TO EMIT ABOVE 20 GeV

We recall that in the BLR the UV photon density is huge, and so

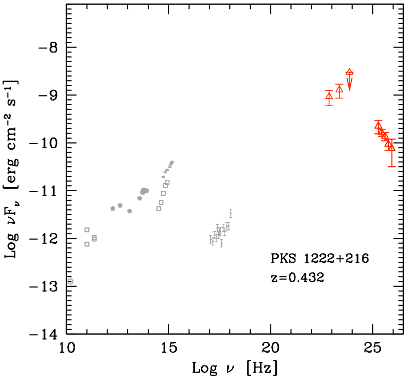


thereby implying $P_{\gamma \to \gamma}(E) = \exp[-\tau(E)] \simeq 0$.

Instead the FSRQs have been OBSERVED at energies as large as $E \sim 500\,\mathrm{GeV}$ and their fluxes are similar to those of the BL LACs!

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 $70 - 400\,\mathrm{GeV}$. Moreover, 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.



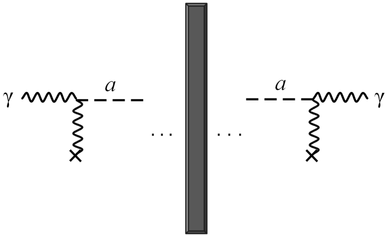
Various astrophysical solutions have been proposed, but all of them are totally $\mathrm{ad\ hoc}$ even because one has to suppose that a blob with size $10^{14}\,\mathrm{cm}$ at a distance of more than 1 pc from the centre exists with the luminosity of a whole BL LAC.

NEW IDEA – Tavecchio, Roncadelli, Galanti & Bonnoli, PR D **86**, 085036 (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

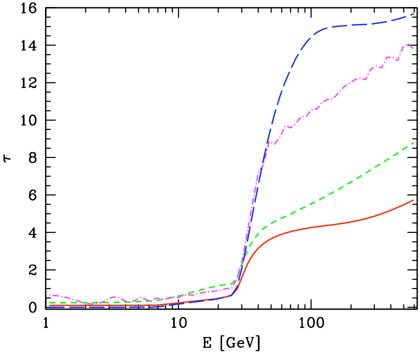
- Photons can become mostly ALPs BEFORE reaching the BLR in the jet magnetic field.
- ALPs can go UNIMPEDED through the BLR.
- Outside the BLR ALPs can reconvert into photons in the outer magnetic field.

Schematically

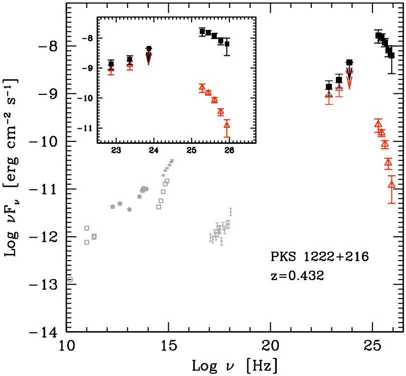


where the vertical bar is the BLR.

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.

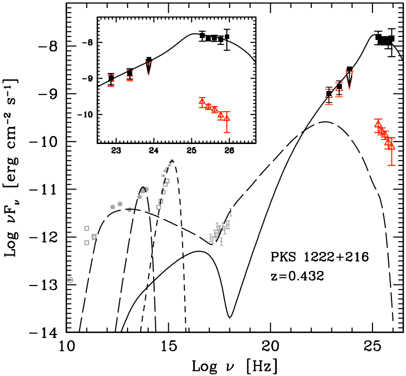


However, this is not enough. We have supposed that photons are produced by a standard emission mechanism. Moreover, PKS 1222+216 has been simultaneously observed by *Fermi*/LAT and MAGIC. So, we should pretend that the detected photons have a STANDARD SED, namely they should lie on a inverse Compton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



18 – ALPs AS COLD DARK MATTER PARTICLES?

"HIC SUNT LEONES"

Too many uncertainties to make predictions and sharp statements.

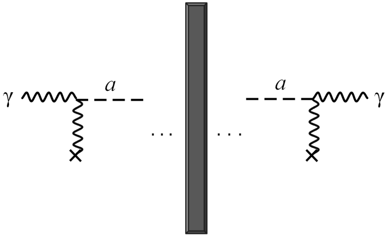
- The lightness of ALPs strongly suggests that they are pseudo-Goldstone bosons associated with some broken global global symmetry $\mathcal{G}$ of the FT. In this case, the following relation is expected

$$\frac{1}{M} = \frac{\alpha}{2\pi} \frac{\mathcal{N}}{f_{\rm ALP}} , \tag{35}$$

  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?

19 – LABORATORY CHECK

A clear-cut check for the existence of ALPs is provided by the SHINING THROUGH A WALL experiment.



where the vertical bar is a normal wall.

This will be done by the ALPS II experiment at DESY, which will reach the astrophysical important region for M in the near future.

20 – 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.
- The pair-production anomaly is explained.
- 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.