Evidence for an axion-like particle from blazar spectra?

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SUMMARY

1 – AXION-LIKE PARTICLES (ALPs)

Aesthetic reasons and conceptual problems lead to regard the Standard Model (SM) as an EFFECTIVE LOW-ENERGY THEORY (ELET) of some more fundamental theory (FT) characterized by a very large energy scale $M \gg G_F^{-1/2}$ and containing both light ϕ and heavy Φ particles.

Actually, this view is made compelling by the observational evidence of NONBARYONIC DARK MATTER responsible for the formation of cosmic structures and of DARK ENERGY presumably triggering the present accelerated cosmic expansion.

Denoting by

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

the generating functional of the FT, the resulting ELET emerges

by integrating out the heavy particles and so its lagrangian $\mathcal{L}_{\mathrm{eff}}(\phi)$ is defined by

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

As a consequence, $\mathcal{L}_{\mathrm{eff}}(\phi)$ not only contains $\mathcal{L}_{\mathrm{SM}}(\phi)$ but also includes nonrenormalizable terms involving ϕ that are suppressed by inverse powers of M. So the SM is embedded in the ELET defined by

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

Spontaneously broken global symmetries that are also slightly explicitly broken give rise to very light pseudo-Goldstone bosons a in the ELET, whose lagrangian therefore has the structure

$$\mathcal{L}_{\mathrm{eff}}(\phi_{\mathrm{SM}},a) = \mathcal{L}_{\mathrm{SM}}(\phi_{\mathrm{SM}}) + \mathcal{L}_{\mathrm{ren}}(a) + \mathcal{L}_{\mathrm{nonren}}(\phi_{\mathrm{SM}},a) \ . \quad (4)$$

A remarkable example of this strategy is provided by the Peccei-Quinn $U(1)$ symmetry – giving rise to the AXION as a pseudo-Goldstone boson – which was proposed as a natural solution to the strong CP problem. Accordingly, we have

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

where m is the axion mass and

$$\mathcal{L}_{\rm nonren}(\phi_{\rm SM}, a) = -\frac{1}{4M} \, F_{\mu\nu} \tilde{F}^{\mu\nu} a = \frac{1}{M} \, \mathbf{E} \cdot \mathbf{B} \, a \, , \qquad (6)$$

where $F_{\mu\nu} \equiv (\mathbf{E}, \mathbf{B})$ is the electromagnetic field tensor, $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$ is its dual, α is the fine-structure constant and m_e is the electron mass. Natural Lorentz-Heaviside units with with $\hbar = c = k_{\rm B} = 1$ are employed throughout. Finally, the scale at which the Peccei-Quinn symmetry is spontaneously broken is proportional to M and a STRICT RELATIONSHIP exists between m and M.

AXION-LIKE PARTICLES (ALPs) have just the same properties of the axion apart from the fact that m and M are UNRELATED. Moreover, it is always assumed $M \gg G_F^{-1/2}$ and $m \ll G_F^{-1/2}$.

Depending on the values of m and M, ALPs can be good candidates for either NONBARYONIC DARK MATTER or QUINTESSENTIAL DARK ENERGY.

Remarkably enough, attempts to extend the SM – as mentioned above – along very different directions such as four-dimensional models, Kaluza-Klein theories and superstring theories all converge in generically predicting the existence of ALPs.

2 – 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 photon-ALP system shows up. Therefore, the interaction eigenstates differ from the propagation eigenstates and photon-ALP MIXING occurs.

The situation is analogous to what happens in the case of massive neutrinos with different flavours, apart from an important difference. All neutrinos have equal spin, and so neutrino oscillations can freely occur. Instead, ALPs are supposed to have spin zero whereas the photon has spin one, and so one of them can transform into the other only if the spin mismatch is compensated for by an external field.

Observe that since the vertex $\gamma\gamma a$ 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. In addition,

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 $\gamma_\parallel$ with linear polarization parallel to that plane DO mix.

Thus, photon-ALP mixing in the presence of an EXTERNAL magnetic field produces two different effects:

- ▶ photon-ALP OSCILLATIONS;
- ▶ CHANGE of the photon POLARIZATION state.

We consider throughout a monochromatic photon/ALP beam of energy E propagates along the z direction in a cold medium with the following properties:

- ▶ a HOMOGENEOUS magnetic field $\mathbf{B}$ is present;
- ▶ matter is IONIZED, and denoting by n_e the electron density the associated plasma frequency is $\omega_{\mathrm{pl}}^2 = 4\pi\alpha n_e/m_e$;
- ▶ photons CAN be ABSORBED - so that they have a FINITE mean free path $\lambda_\gamma(E)$ - but ALPs CANNOT.

Because we are interested in the regime $E \gg m$, the short-wavelength approximation (WKB) can be meaningfully applied, and so the beam propagation equation - which would be SECOND-ORDER coupled generalized Klein-Gordon and Maxwell equations - become FIRST-ORDER equations of the form

$$\left(i \frac{d}{dz} + E + \mathcal{M} \right) \begin{pmatrix} A_x(z) \\ A_y(z) \\ a(z) \end{pmatrix} = 0 \ , \tag{7}$$

where $A_x(z)$ and $A_y(z)$ are the two photon linear polarization amplitudes along the x and y axis, respectively, $a(z)$ denotes the ALP amplitude and $\mathcal{M}$ represents the photon-ALP mixing matrix which fails to be self-adjoint when photon absorption occurs. Observe that this is a Schrödinger-like equation, which entails that the beam is in general formally described as a NONRELATIVISTIC 3-LEVEL UNSTABLE QUANTUM SYSTEM.

We will employ the generalized polarization density matrix

$$\rho(z) = \begin{pmatrix} A_x(z) \\ A_y(z) \\ a(z) \end{pmatrix} \otimes \begin{pmatrix} A_x(z) & A_y(z) & a(z) \end{pmatrix}^* \qquad (8)$$

which obeys the Liouville-Von Neumann equation

$$i\frac{d\rho}{dz} = \rho \, \mathcal{M}^\dagger - \mathcal{M}\rho \qquad (9)$$

associated with Eq. (7), whose solution is

$$\rho(z) = T(z, z_0) \, \rho(z_0) \, T^\dagger(z, z_0) \qquad (10)$$

in terms of the transfer function $T(z, z_0)$, namely the solution of Eq. (7) with initial condition $T(z_0, z_0) = 1$. Then the probability that a photon/ALP beam initially in the state ρ_1 will be found in the state ρ_2 after a distance z is

$$P^{(0)}_{\rho_1 \to \rho_2}(z) = \frac{\mathrm{Tr}\left(\rho_2 \, T(z, 0) \, \rho_1 \, T^\dagger(z, 0)\right)}{\mathrm{Tr}\left(\rho_1 \, T^\dagger(z, 0) \, T(z, 0)\right)} \; . \qquad (11)$$

Choosing the y-axis along $\mathbf{B}_T$, B_x vanishes. Correspondingly, M can be written as

$$
\mathcal{M} = \begin{pmatrix} -\omega_{\rm pl}^2/2E + i/2\lambda_\gamma(E) & 0 & 0 \\ 0 & -\omega_{\rm pl}^2/2E + i/2\lambda_\gamma(E) & B_T/2M \\ 0 & B_T/2M & -m^2/2E \end{pmatrix} ,
$$
(12)

where 1-loop QED vacuum polarization effects have been discarded since we shall deal with very weak magnetic fields. Also Faraday rotation is neglected because we are concerned with high-energy photons.

Photon-ALP mixing is MAXIMAL and ENERGY-INDEPENDENT in the STRONG-MIXING REGIME, occurring for $E \gg E_*$, with

$$
E_* \equiv \frac{|m^2 - \omega_{\rm pl}^2|M}{2B_T} \simeq
$$
(13)

$$
0.26 \left(\frac{G}{B_T} \right) \left(\frac{M}{10^{10}\,\mathrm{GeV}} \right) \left| \left(\frac{m}{10^{-6}\,\mathrm{eV}} \right)^2 - \left(\frac{\omega_{\rm pl}}{10^{-6}\,\mathrm{eV}} \right)^2 \right|^{1/2} \mathrm{GeV} .
$$

3 – ASTROPHYSICAL IMPLICATIONS

ALPs turn out to be extremely elusive in high-energy experiments and the only way to look for them in the laboratory requires very careful polarimetric measurements to be carried out on a laser beam or alternatively to perform a *shining-through-a-wall* experiment. Unfortunately, successful detection of ALPs requires in either case a fairly large $a\gamma\gamma$ coupling.

Astrophysical manifestations of ALPs appear the best way to discover their existence, since they can give rise to observable effects even for much smaller values of the $a\gamma\gamma$ coupling. In fact, it has been noticed since a long time that for an $a\gamma\gamma$ coupling that looks hopelessly small to be probed in the laboratory stellar evolution would be dramatically altered and this fact sets a strong upper bound on the coupling in question.

Specifically, the negative result of the CAST experiment designed to detect ALPs emitted by the Sun yields the bound $M > 0.86 \cdot 10^{10} \, \mathrm{GeV}$ for $m < 0.02 \, \mathrm{eV}$. Moreover, theoretical considerations concerning star cooling via ALP emission provide the generic bound $M > 10^{10} \, \mathrm{GeV}$, which for $m < 10^{-10} \, \mathrm{eV}$ gets replaced by the stronger one $M > 10^{11} \, \mathrm{GeV}$ even if with a very large uncertainty.

In the last few years it has been realized that photon-ALP oscillations triggered by intervening COSMIC magnetic fields along the line of sight can produce DETECTABLE effects in observations of very-high-energy (VHE) gamma-ray sources.

4 – INTERGALACTIC MEDIUM (IGM)

We shall be concerned throughout with the following scenario.

Gamma-ray photons are emitted by a distant astronomical source - typically a BLAZAR or a GAMMA-RAY BURST (GRB) - and are detected on Earth. On their way to us they propagate in the INTERGALACTIC MEDIUM (IGM).

We do NOT assume that the Universe is dominated by an ALP background.

Still, we ASSUME that INTERGALACTIC MAGNETIC FIELDS (IMFs) exist. Then inside the IGM photon-ALP OSCILLATIONS take place along with a change of the photon POLARIZATION.

We assume that the IGM consists of the following components:

1 - MAGNETIC FIELD. Owing to the notorious lack of information about their morphology, one usually supposes that they have a DOMAIN-LIKE structure. That is, **B** ought to be constant over a domain of size L equal to its coherence length, with **B** RANDOMLY changing its direction from one domain to another but keeping approximately the SAME strength. Plausible ranges are $0.3\,\mathrm{nG} < B < 10\,\mathrm{nG}$ and $1\,\mathrm{Mpc} < L < 10\,\mathrm{Mpc}$.

2 - IONIZED MATTER. Absence of the Gunn-Peterson effect entails that the IGM is ionized. The mean diffuse intergalactic plasma density is bounded by $n_e \lesssim 2.7 \times 10^{-7}$ cm^{-3}, corresponding to the WMAP measurement of the baryon density

3 - EXTRAGALACTIC BACKGROUND LIGHT (EBL). This is the light produced by galaxies during the whole cosmic evolution. Based on synthetic models of the evolving stellar populations in galaxies as well as on deep galaxy counts the spectral energy distribution of the EBL can be estimated. We employ the result of Franceschini et al. 2008, which is displayed below
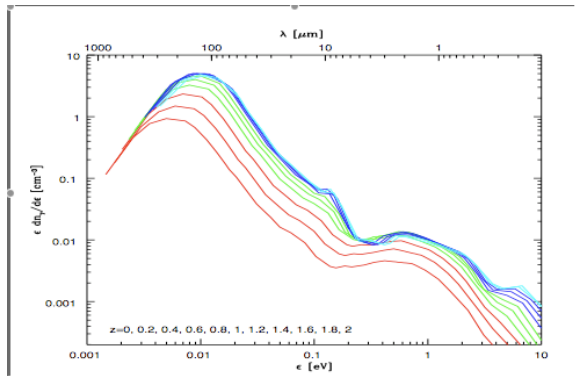
Very-high-energy photons from distant sources scatter off the EBL, thereby disappearing into e^+e^- pairs. This effect becomes IMPORTANT for energies larger than $10 - 100\,\mathrm{GeV}$. As a consequence, the horizon of the observable Universe ought to rapidly SHRINK above $10 - 100\,\mathrm{GeV}$ as the energy increases. The cross-section for $\gamma\gamma \to e^+e^-$ peaks at

$$\epsilon(E) \simeq \left(\frac{500\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\,, \tag{14}$$

where ϵ is the EBL energy. Observations of blazars performed so far by Imaging Atmospheric Cherenkov Telescopes (IACTs) extend over the energy range $200\,\mathrm{GeV} < E < 2\,\mathrm{TeV}$, and so the

COSMIC OPACITY is dominated by the interaction with EBL photons with $0.005 \, \mathrm{eV} < \epsilon < 5 \, \mathrm{eV}$ (corresponding to $1.2 \cdot 10^3 \, \mathrm{GHz} < \nu < 1.2 \cdot 10^6 \, \mathrm{GHz}$ and $0.25 \, \mu\mathrm{m} < \lambda < 250 \, \mu\mathrm{m}$). Over this range, the spectral energy distribution of Franceschini et al. 2008 can be approximated by

$$n_\gamma(\epsilon_0, 0) \simeq 10^{-3} \, \alpha \left(\frac{\epsilon_0}{\mathrm{eV}} \right)^{-2.55} \mathrm{cm}^{-3} \, \mathrm{eV}^{-1} \, , \qquad (15)$$

with $0.5 < \alpha < 3$. Both the exact spectral energy distribution of Franceschini et al. 2008 and the power-law approximation in Eq. (15) are exhibited in the Figure below
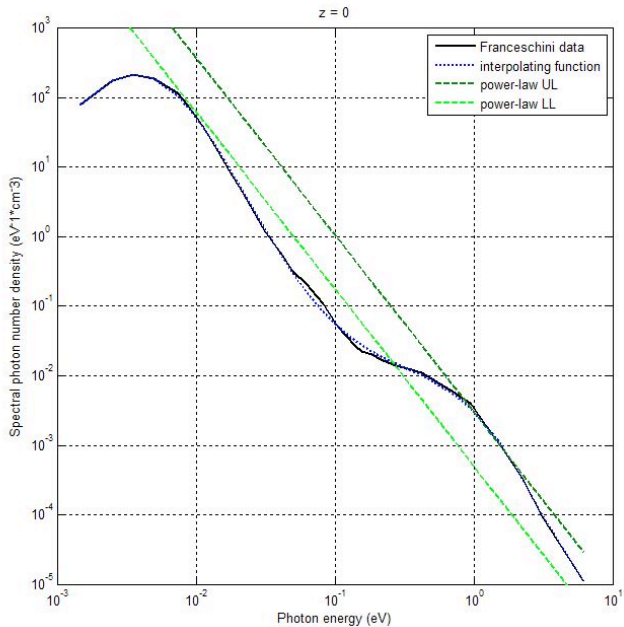
5 – BEAM PROPAGATION INSIDE THE IGM

Manifestly, the WHOLE propagation process of the beam in question can be recovered by ITERATING the propagation over a SINGLE domain as many times as the number of domains crossed by the beam, taking each time a RANDOM value for the angle θ between **B** and a FIXED fiducial direction. In this way, we are effectively led to the much easier problem of photon-ALP oscillation in a HOMOGENEOUS magnetic field, which can be solved exactly also in the presence of photon absorption.

Eventually, such a procedure can be repeated very many times and finally we AVERAGE all these realizations of the propagation process over the random angles. In this way we obtain the PHOTON SURVIVAL PROBABILITY for a source at redshift z $P_{\gamma\to\gamma}(E, z)$.

We work within the STRONG-MIXING REGIME, which requires $m < 10^{-10}\,\mathrm{eV}$.

6 – POLARIZATION 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 ρ_{in} and we ITERATE it over all magnetic domains WHITOUT taking any average, thereby getting ρ_{fin}. Standard STOKES parameters are defined as

$$\rho_\gamma = \frac{1}{2} \begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix} \qquad (16)$$

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

$$\Pi_L \equiv \frac{(Q^2 + U^2)^{1/2}}{I} = \frac{\left[(\rho_{11} - \rho_{22})^2 + (\rho_{12} - \rho_{21})^2\right]^{1/2}}{\rho_{11} + \rho_{22}} \ . \qquad (17)$$
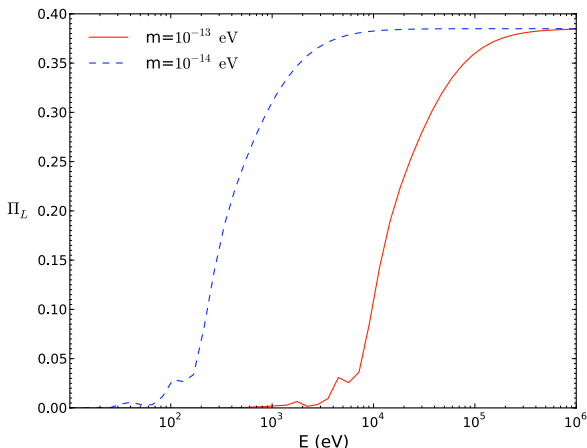
Average final linear polarization Π_L as a function of the photon energy E after propagation in the extragalactic magnetic field for ALP masses $m = 10^{-13}$ eV (solid line) and $m = 10^{-14}$ eV (dashed line), respectively. The emitting GRB is assumed to be completely unpolarized and at distance $d = 100$ Mpc.
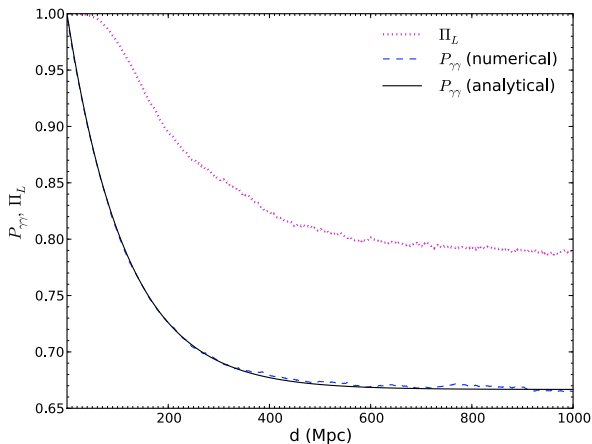
Average linear polarization Π_L (dotted line) and photon survival probability $P_{\gamma\gamma}$ evaluated numerically (dashed line) and analytically (solid line), as a function of the source distance d for photon-ALP mixing in the extragalactic magnetic field. The source is assumed to be fully polarized along the x direction.
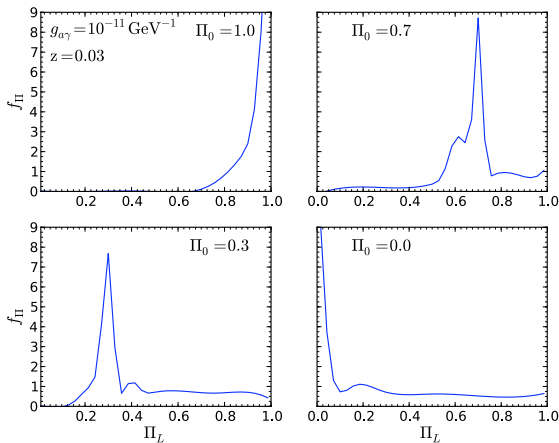
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 0.03$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.
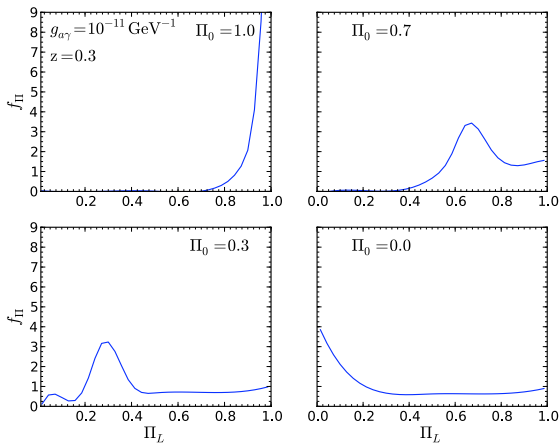
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 0.3$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.
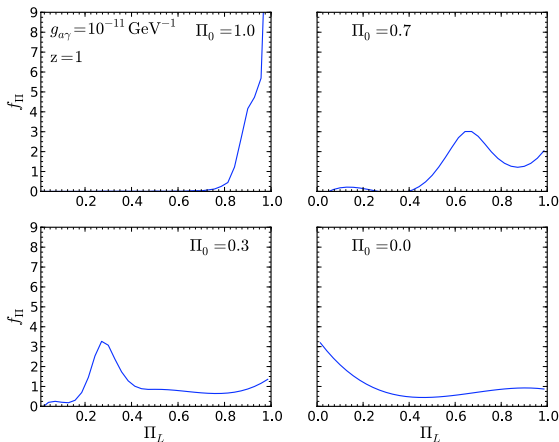
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 1$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.
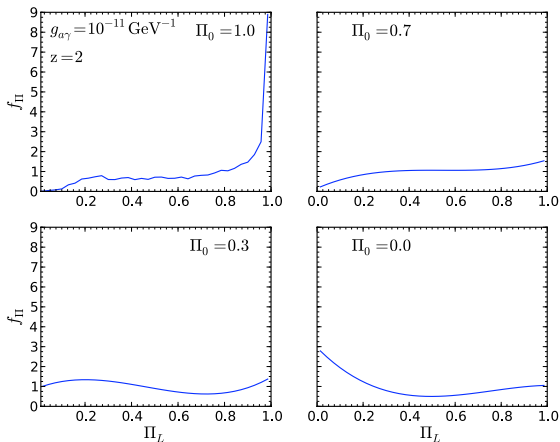
Probability density function f_Π for the final linear polarization Π_L after propagation in the extragalactic magnetic field, considering 10^4 GRBs at redshift $z = 2$, with initial linear polarization $\Pi_0 = 0.0, 0.3, 0.7, 1.0$.

7 – DIMMING EFFECTS

Owing to photon-ALP oscillations, some photons become ALPs along to way to us, thereby causing a DIMMING of the source.

Since the intensity of the source is UNKNOWN, the effect can be detected ONLY by performing observations ABOVE AND BELOW E_* and detecting a SPECTRAL DISTORTION of the source. So, we have to enter the WEAK-MIXING regime as well. The effect is shown in the Figure below.
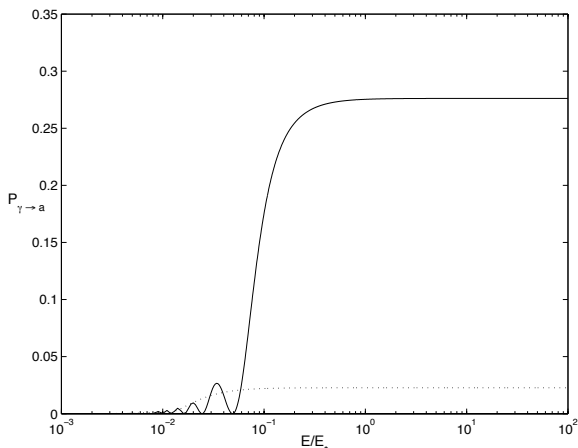
Conversion probability versus photon energy in units of E_* in the intergalactic magnetic field. The plot arises for $M = 1 \cdot 10^{11}$ GeV. Dotted and solid lines correspond to $B = 1 \cdot 10^{-9}$ G and $B = 5 \cdot 10^{-9}$ G, respectively.

8 – DARMA EFFECT

We consider all blazars observed so far by IACTs above $100\,\mathrm{GeV}$. Because of EBL absorption, the OBSERVED flux of a source at distance D is related to the EMITTED one by

$$\Phi_{\mathrm{obs}}(E, D) = e^{-D/\lambda_\gamma(E)}\,\Phi_{\mathrm{em}}(E)\;. \qquad (18)$$

The photon mean free path $\lambda_\gamma(E)$ decreases like a power law from the Hubble radius $4.3\,\mathrm{Gpc}$ around $100\,\mathrm{GeV}$ to nearly $1\,\mathrm{Mpc}$ around $100\,\mathrm{TeV}$. Therefore, Eq. (18) leads to two conceptually distinct expectations concerning the observed photon flux $\Phi_{\mathrm{obs}}(E, D)$ in the very high energy range.

- $\Phi_{\mathrm{obs}}(E, D)$ is *exponentially* suppressed at *large distances*, so that sufficiently far-away sources become *hardly visible*.

- $\Phi_{\mathrm{obs}}(E, D)$ decreases *exponentially* at *high energies*, thereby entailing that it gets *much steeper* than the emitted one $\Phi_{\mathrm{em}}(E)$.

Given the fact that all blazars observed so far by IACTs lie in the energy band $0.2\,\mathrm{TeV} < E < 2\,\mathrm{TeV}$, we restrict our attention to this energy range from now on, in which blazar data are fitted by $\Phi_{\mathrm{obs}} \propto E^{-\Gamma_{\mathrm{obs}}}$. It is generally assumed that $\Phi_{\mathrm{em}} \propto E^{-\Gamma_{\mathrm{em}}}$ for $E > 100\,\mathrm{GeV}$, and so it follows from Eq. (18) that $\Phi_{\mathrm{obs}}(E, z)$ indeed decreases exponentially with z. In addition, Eq. (18) yields

$$\Gamma_{\mathrm{obs}}(z) \propto \Gamma_{\mathrm{em}} + \tau_\gamma(E, z) \ , \qquad (19)$$

with $D \simeq 4.3\,z\,\mathrm{Gpc}$ for $z < 1$.

We expect the EBL photon absorption to be negligible for nearby blazars ($z < 0.03$), and so we suppose that observations of these sources do yield $\Phi_{\mathrm{em}}(E)$. We find $\Gamma_{\mathrm{em}} \simeq 2.4$ on average. We remark that in the widely used Synchro-Self-Compton (SSC) emission model $\Gamma_{\mathrm{em}} \simeq 2.4$ suggests a Compton peak at around or below $100\,\mathrm{GeV}$.

We further assume that ALL observed blazars have an emission spectrum with basically the SAME slope $\Gamma_{\rm em} \simeq 2.4$. As a consequence – in the absence of any new physics – the predicted observed spectral index $\Gamma_{\rm obs}^{\rm CP}(z)$ for a generic blazar at redshift z is expected to be given by

$$\Gamma_{\rm obs}^{\rm CP}(z) \propto 2.4 + 0.50\,\alpha \left(\frac{E}{500\,{\rm GeV}}\right)^{1.55} \left[(1+z)^{4.4} - 1\right] \quad (20)$$

and it is represented by the LIGHT gray area in the Figure as α varies in the range $0.5 < \alpha < 3$ in the power-law approximation to the Franceschini et al. 2008 spectrum of the EBL.
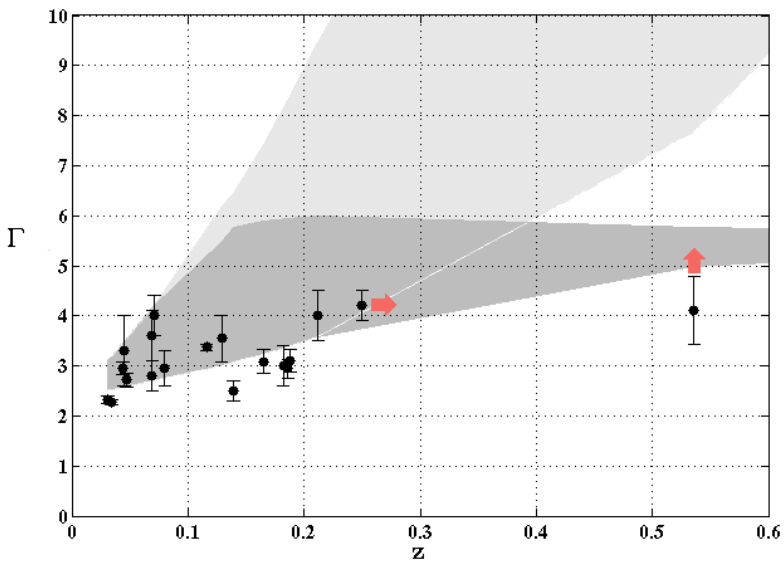
As it is clear from the Figure, the actually observed spectral index $\Gamma_{\rm obs}(z)$ increases MORE SLOWLY than $\Gamma_{\rm obs}^{\rm CP}(z)$ for redshifts $z > 0.2$. Moreover, the observed values cannot be explained for $z > 0.3$ by the EBL model of Franceschini et al. 2008 even for α as low as 0.5. Being $\tau_\gamma(E, z)$ a monotonically increasing function of z, we interpret the conflict between $\Gamma_{\rm obs}(z)$ and $\Gamma_{\rm obs}^{\rm CP}(z)$ shown by the Figure as calling for a DEPARTURE from the conventional view.

PHOTON-ALP OSCILLATIONS PARTIALLY UNDO EBL ABSORPTION. Suppose that a sizeable fraction of the emitted photons convert into ALPs close enough to the source and that a nonnegligible fraction of the ALPs in question are in turn converted back into photons close enough to the Earth. Because ALPs propagate UNIMPEDED, in such a situation the photon mean free path $\lambda_\gamma(E)$ has to be replaced by the LARGER effective mean free path $\lambda_{\gamma,{\rm eff}}(E)$.

As a consequence, the observed photon flux is NOW given by

$$\Phi_{\rm obs}(E, D) = e^{-D/\lambda_{\gamma,\rm eff}(E)} \; \Phi_{\rm em}(E) \qquad (21)$$

and – owing to its exponential dependence on $\lambda_{\gamma,\rm eff}(E)$ – even a SLIGHT increase of $\lambda_{\gamma,\rm eff}(E)$ produces a LARGELY ENHANCED flux.

NOW we have

$$\Gamma_{\rm obs}^{\rm DARMA}(z) \propto 2.4 - \ln P_{\gamma\to\gamma}(E, z) \qquad (22)$$

and it is represented by the HEAVY gray area in the above Figure as α varies in the range $0.5 < \alpha < 3$ in the power-law approximation to the Franceschini et al. 2008 spectrum of the EBL. We have taken $M = 4 \cdot 10^{11} \, {\rm GeV}$, $L = 7 \, {\rm Mpc}$ and $B = 0.5 \, nG$. This result was derived two years ago.

An update is shown in the next Figure for the same values of the parameters.
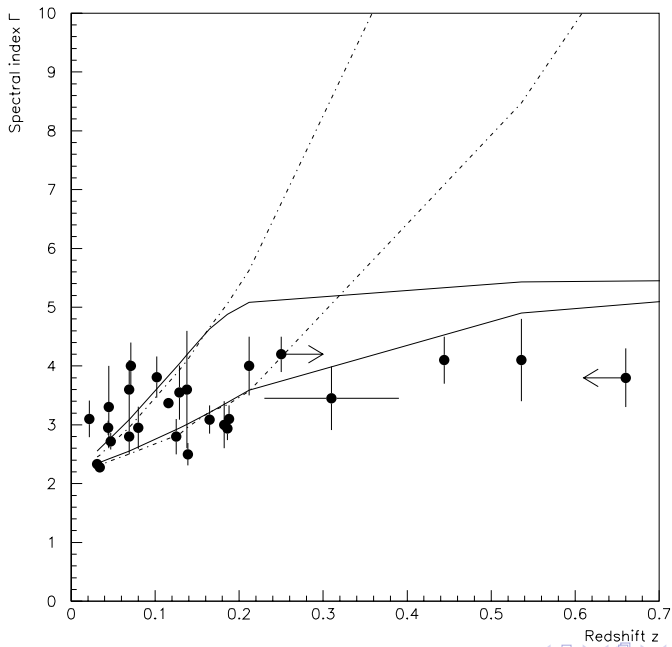
We have quite recently repeated this analysis for the EXACT spectrum of the EBL as given by Franceschini et al. 2008. The results for the four most distant sources – those which are AT ODD WITH CONVENTIONAL PHYSICS – are displayed in the following Figures, for different values of the parameters.

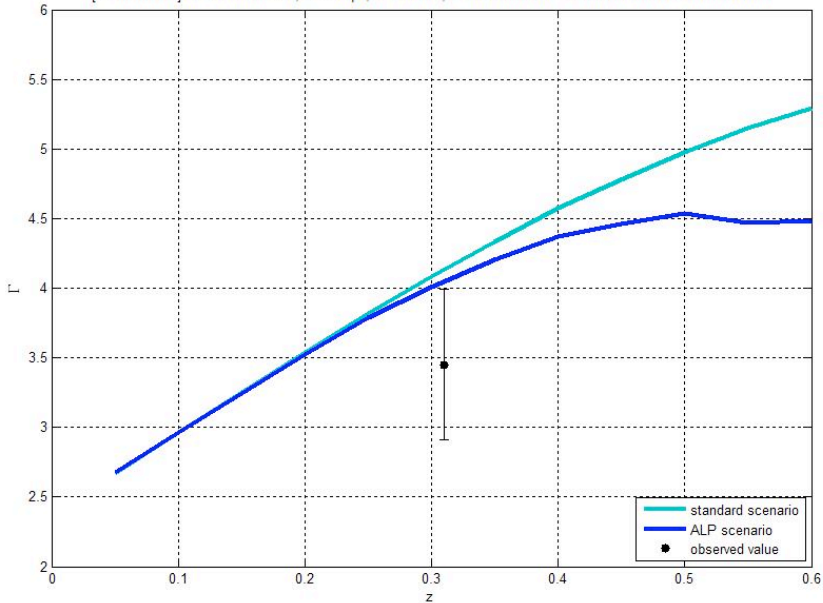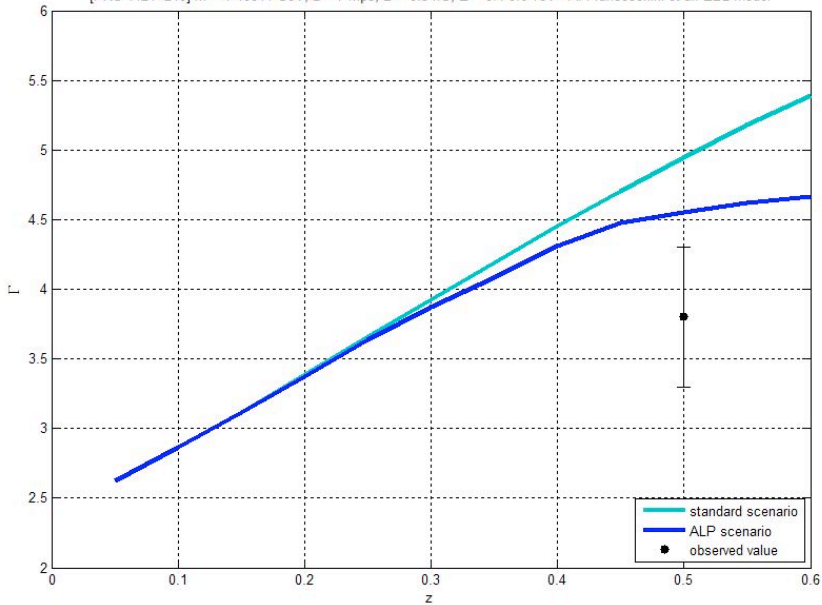[3C 279] M = 4*10e11 GeV, L = 7 Mpc, B = 0.5 nG, E = 0.2-0.6 TeV - A. Franceschini et al. EBL model

3C279

[3C 66A] M = 4*10e11 GeV, L = 7 Mpc, B = 0.5 nG, E = 0.2-0.5 TeV - A. Franceschini et al. EBL model
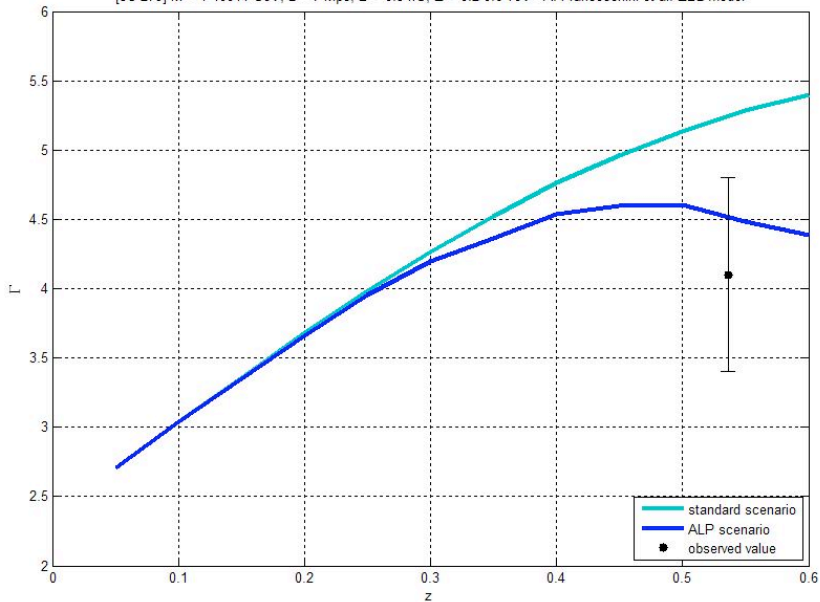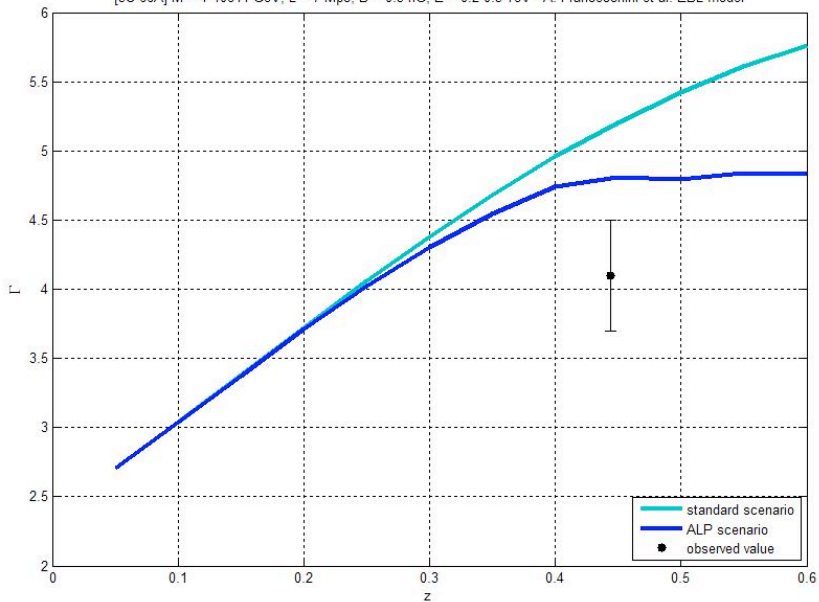
3C66A

[S5 0716+714] M = 4*10e11 GeV, L = 7 Mpc, B = 0.5 nG, E = 0.15-0.7 TeV - A. Franceschini et al. EBL model

S50716+714

[PKS 1424+240] M = 4*10e11 GeV, L = 7 Mpc, B = 0.5 nG, E = 0.1-0.6 TeV - A. Franceschini et al. EBL model

standard scenario
ALP scenario
observed value

PKS1424+240

[3C 279] M = 1*10e11 GeV, L = 1 Mpc, B = 1 nG, E = 0.2-0.6 TeV - A. Franceschini et al. EBL model
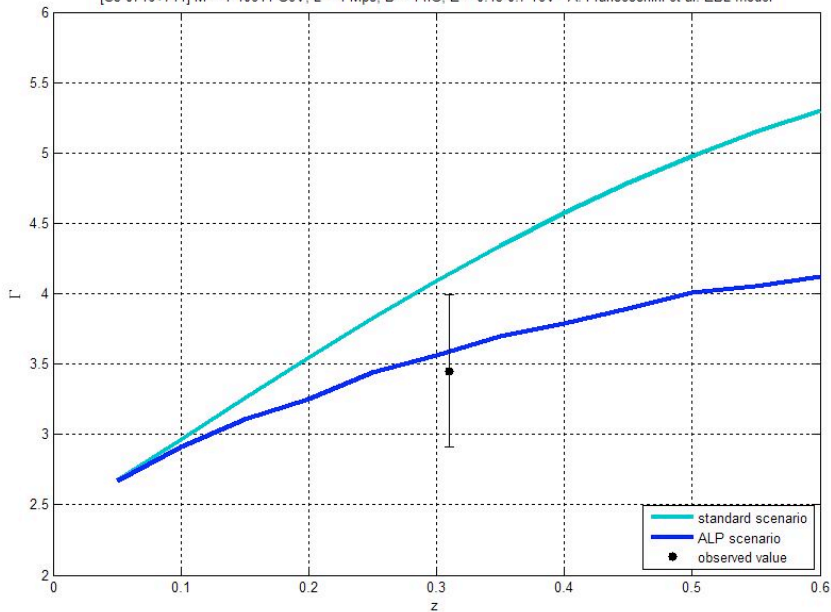
3C279

[3C 66A] M = 1*10e11 GeV, L = 1 Mpc, B = 1 nG, E = 0.2-0.5 TeV - A. Franceschini et al. EBL model

3C66A

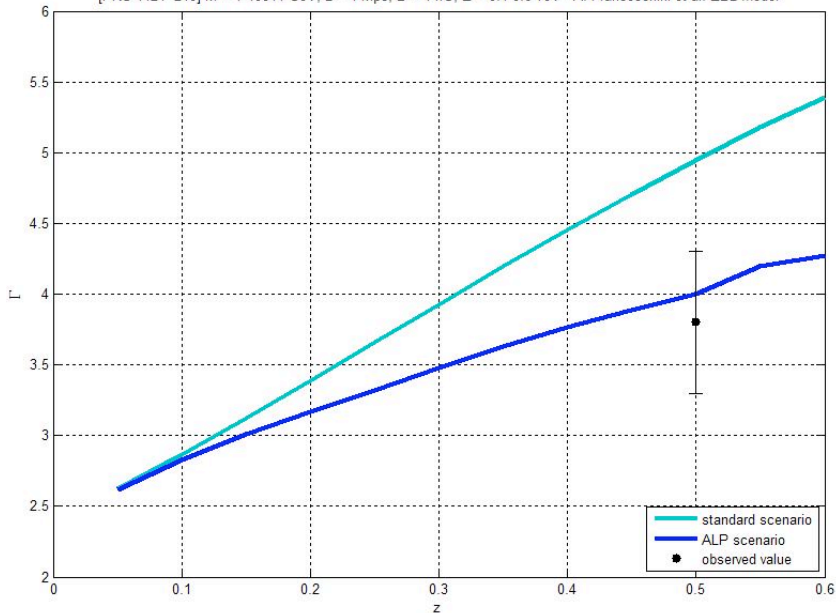[S5 0716+714] M = 1*10e11 GeV, L = 1 Mpc, B = 1 nG, E = 0.15-0.7 TeV - A. Franceschini et al. EBL model
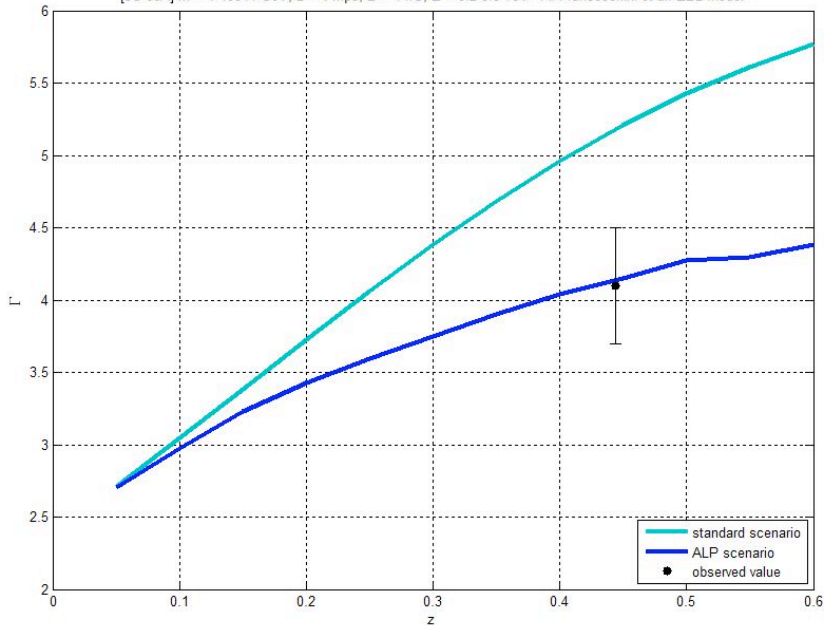
S50716+714

[PKS 1424+240] M = 1*10e11 GeV, L = 1 Mpc, B = 1 nG, E = 0.1-0.6 TeV - A. Franceschini et al. EBL model

PKS1424+240