ALPs Explain the Observed Redshift-Dependence of Blazar Spectra

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We considered a complete sample of blazars observed with the Imaging Atmospheric Cherenkov Telescopes above $E \geq 80\,\mathrm{GeV}$, out to $z = 0.54$ and described by standard photon emission models which predict simple power-law spectra to a good approximation. We first show that the best-fit regression line of the emitted slope distribution $\{\Gamma_{\rm em}(z)\}$ decreases with z, in disagreement with physical intuition. Next, we demonstrate that, by allowing for photon-ALP oscillations in intergalactic space, for a realistic values of the parameters the best-fit regression line becomes exactly horizontal in the $\Gamma_{\rm em} - z$ plane. This result is amazing, because it is the only possibility in agreement with physical expectation, and so it can be regarded as a strong hint of the existence of an ALP.

1 Introduction and background

Thanks to the observations carried out with the Imaging Atmospheric Cherenkov Telescopes (IACTs) like H.E.S.S., MAGIC and VERITAS, according to the Tevcat catalog 43 blazars with known redshift have been detected in the VHE range. We stress that 40 of them are in a flaring state, whose typical lifetime ranges from a few hours to a few days. As far as the present analysis is concerned, 3 of them 1ES 0229+200, PKS 1441+25 and S3 0218+35 will be discarded for reasons to be explained below. All observed spectra of the considered VHE blazars are well fitted by a single power-law, and so they have the form $\Phi_{\rm obs}(E_0, z) = K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$, where E_0 is the observed energy, while $K_{\rm obs}(z)$ and $\Gamma_{\rm obs}(z)$ denote the observed normalization constant and the slope, respectively, for a source at redshift z. So, we will be dealing with a sample of 40 blazars, whose $\Gamma_{\rm obs}$ values are plotted versus z in Fig. 1 with their error bars.

Unfortunately, the observational results do not provide any *direct* information about the intrinsic properties of the sources, since the VHE gamma-ray data strongly depend on the nature of photon propagation. Indeed, according to conventional physics the blazar spectra in the VHE range are strongly affected by the presence of the Extragalactic Background Light (EBL), namely the infrared/optical/ultraviolet background photons produced by stars throughout the history of the Universe [1]. This effect has been quantified in [2]. VHE photons with energy E emitted by a blazar at z get depleted by scattering off EBL photons of energy ϵ through the

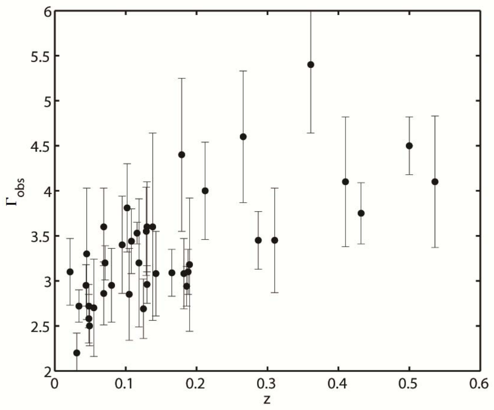

Figure 1: The values of the slope $\Gamma_{\rm obs}$ are plotted versus the source redshift z for all considered blazars.

process $\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+ + e^-$ whose Breit-Wheeler cross-section gets maximized when

$$\epsilon(E) \simeq \left(\frac{900\,{\rm GeV}}{E}\right)\ {\rm eV}\ . \tag{1}$$

So, for $100\,{\rm GeV} < E < 100\,{\rm TeV}$ $\sigma(\gamma\gamma \to e^+e^-)$ is maximal for $9 \cdot 10^{-3}\,{\rm eV} < E < 9\,{\rm eV}$, indeed in the EBL band. After a long period of uncertainty, today the spectral energy distribution (SED) of the EBL is well determined, and for definiteness we use the model of Franceschini, Rodighiero and Vaccari (FRV) which provides the optical depth $\tau_\gamma(E_0, z)$ [3].

As a rule, the blazar SED of the non-thermal radiation shows two broad humps, the first one peaking at low frequency – from IR to soft-X rays, depending on the specific source – while the second one in the gamma-ray band, often reaching multi-TeV energies. We restrict our discussion to the two standard competing models for the VHE photon emission by blazars, namely the Synchrotron-Self-Compton (SSC) mechanism and the Hadronic Pion Production (HPP) in proton-proton scattering. Both mechanisms predict emitted spectra which, to a good approximation, have a single power-law behavior $\Phi_{\rm em}(E) = K_{\rm em}(z)\,E^{-\Gamma_{\rm em}}$ for all observed VHE blazars, where $E = (1+z)E_0$ is the emitted energy, whereas $K_{\rm em}(z)$ and $\Gamma_{\rm em}$ are the emitted normalization constant and slope, respectively.

The relation between $\Phi_{\rm obs}(E_0, z)$ and $\Phi_{\rm em}(E)$ can be expressed in general terms as

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma\to\gamma}(E_0, z)\,\Phi_{\rm em}\big(E_0(1+z)\big)\ , \tag{2}$$

where $P_{\gamma\to\gamma}(E_0, z)$ is the photon survival probability from the source to us, and in conventional physics it is written in terms of the optical depth $\tau_\gamma(E_0, z)$ as

$$P_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0, z)}\ . \tag{3}$$

We should also mention that a radically different mechanism has been put forward. Basically, the idea is that *protons* are accelerated inside blazars up to energies of order 10^{11} GeV, while VHE emitted photons are neglected altogether. When the proton distance from the Galaxy is in the range $10-100\,\mathrm{Mpc}$, they scatter off EBL photons through the process $p+\gamma \to p+\pi^0$, so that the immediate decays $\pi^0 \to \gamma+\gamma$ produce an electromagnetic shower of secondary photons: it is *these photons* that replace the emitted photons in such a scenario [4]. Such a mechanism can apply only to the 3 sources detected so far which have a constant VHE luminosity [5, 6]. Actually, an analysis of the properties of the blazar 1ES 0229+200 has shown that it hardly fits within the photon emission models, and since its VHE luminosity is constant, this source is more likely explained by the proton emission model [7]. For this reason, we discard it from our discussion.

We also discard PKS 1441+25 and S3 0218+35 because they have $z \simeq 0.94$, since we want to consider only a relatively local sample with extend up to $z \simeq 0.54$ (3C 279).

Finally, we are in position to state the main goal of the work reported in this talk, namely to investigate a possible correlation between the distribution of VHE blazar *emitted spectra* and the *redshift*.

Superficially, the reader might well wonder about such a question. Why should a correlation of this kind be expected? Cosmological evolutionary effects are certainly harmless out to redshift $z \simeq 0.5$, and when observational selection biases are properly taken into account no such a correlation should show up.

As we shall see, this is *not the case*. Indeed, a statistical analysis of the $\{\Gamma_{\mathrm{em}}(z)\}$ distribution performed within conventional physics implies that the resulting best-fit regression line *decreases with increasing redshift*. So, how can the source distribution get to know the redshifts in such a way to adjust their individual $\Gamma_{\mathrm{em}}(z)$ values so as to reproduce such a statistical correlation? In particular, it implies that blazars with harder spectra are found *only* at larger redshift. While this trend might be interpreted as an observational selection effect, a deeper scrutiny based on observational information shows that this is by no means the case. Thus, we are led to the conclusion that such a behavior is at odd with physical intuition, which would instead demand the best-fit regression line to be redshift-independent.

As an attempt to achieve a physically satisfactory scenario, we put Axion-Like Particles (ALP) into the game [8]. They are spin-zero, neutral and extremely light pseudo-scalar bosons predicted by several extensions of the Standard Model of particle physics, and especially by those based on superstring theories. They are supposed to interact only with two photons. Depending on their mass and two-photon coupling, they can be quite good candidates for cold dark matter and give rise to very interesting astrophysical effects, so that nowadays ALPs are attracting growing interest. Specifically, we suppose that photon-ALP oscillations take place in extragalactic magnetic fields of strength about $0.1\,\mathrm{nG}$ – in agreement with the predictions of the galactic outflows models [9, 10] – as first proposed in [11]. Amazingly, for and ALP mass $m < 10^{-9}\,\mathrm{eV}$ and a two-photon coupling consistent with the CAST bound now the best-fit regression line of the $\{\Gamma_{\mathrm{em}}(z)\}$ distribution becomes exactly horizontal in the $\Gamma_{\mathrm{em}} - z$ plane, namely redshift-independent. This fact leads in turn to a very simple new picture of VHE blazars.

A much more thorough discussion of these matters along with a complete list of references can be found in our original paper [12].

2 Conventional propagation in extragalactic space

We start by deriving the emitted spectrum of every source, starting from the observed ones.

As a first step, we rewrite Eq. (2) as

$$\Phi_{\rm em}\big(E_0(1+z)\big) = e^{\tau_\gamma(E_0,z)}\, K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)} \ . \tag{4}$$

Next, we best-fit $\Phi_{\rm em}\big(E_0(1+z)\big)$ to a single power-law with slope $\Gamma_{\rm em}^{\rm CP}(z)$ – namely to $K_{\rm em}^{\rm CP}(z)\,\big[(1+z)E_0\big]^{-\Gamma_{\rm em}^{\rm CP}(z)}$ – over the energy range ΔE_0 where the source is observed. Finally, we plot the values of $\Gamma_{\rm em}^{\rm CP}$ versus z in the left panel of Fig. 2

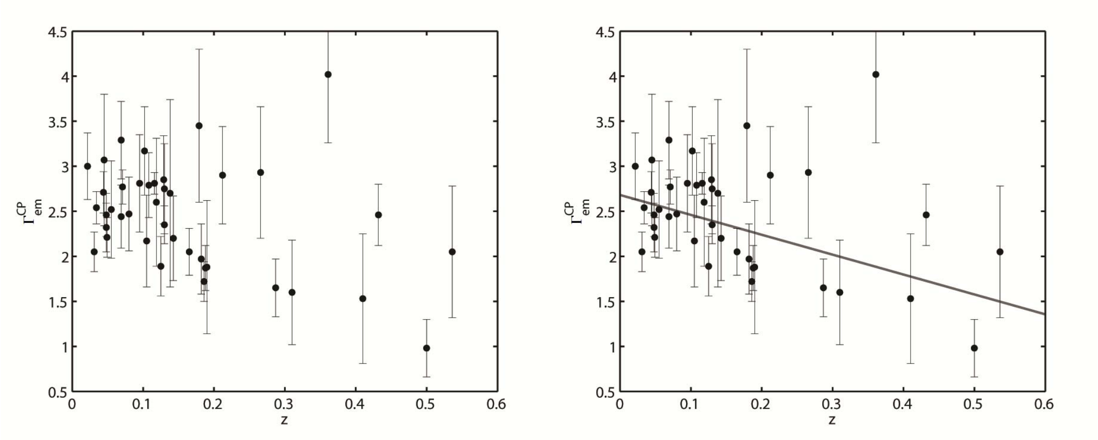

Figure 2: *Left panel:* The values of the slope $\Gamma_{\rm em}^{\rm CP}$ are plotted versus the source redshift z for all considered blazars. *Right panel:* Same as the left panel but with superimposed the best-fit straight regression line.

We proceed by performing 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 compute the corresponding $\chi^2_{\rm red}$. The values of the $\chi^2_{\rm red}$ obtained for the three fits are 2.35, 1.83 and 1.87, respectively. Thus, data appear to be best-fitted by the first-order polynomial $\Gamma_{\rm em}^{\rm CP}(z) = 2.68 - 2.21\,z$. The distribution of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z – with superimposed the best-fit straight regression line as defined by the last equation – is plotted in the right panel of Fig. 2

Manifestly, the $\{\Gamma_{\rm em}^{\rm CP}\}$ distribution shows a nontrivial redshift-dependence. What is the *physical meaning* of this fact? Note that it implies a large variation of the the emitted flux with redshift, since we have

$$\Phi_{\rm em}^{\rm CP}(E,0) \propto E^{-2.68} \ , \qquad\qquad \Phi_{\rm em}^{\rm CP}(E,0.6) \propto E^{-1.35} \ . \tag{5}$$

Because we are dealing with a relatively local sample of blazars, cosmological evolutionary effects are totally irrelevant. Moreover, we have checked that that all possible selection biases play no role. Thus, it looks mysterious how the source distribution can get to know the redshifts in such a way to adjust their individual $\Gamma_{\rm em}(z)$ values so as to reproduce such a bets-fit straight regression line.

3 Photon-ALP oscillations in extragalactic space

Let us now turn our attention to an extension of the Standar Model containing ALPs – to be denoted by a – which are supposed to interact only with two photons through a term $g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$ in the Lagrangian. We take the ALP mass $m < 10^{-9}\,\mathrm{eV}$ and $g_{a\gamma\gamma} < 0.88\cdot 10^{-10}\,\mathrm{GeV}^{-1}$ in order to be consistent with the very robust CAST bound. Here $\mathbf{E}$ is the electric field of a propagating VHE photon while $\mathbf{B}$ denotes the extragalactic magnetic fields of strength about $0.1\,\mathrm{nG}$ – in agreement with the predictions of the galactic outflows models [9, 10] – as first proposed in [11]. Moreover, $\mathbf{B}$ is supposed to have a domain-like structure with coherence length $L_{\rm dom}$ in the range $1 - 10\,\mathrm{Mpc}$, with a direction randomly changing from one domain to the next keeping however the same strength. In such a situation energy-conserving and mass-independent photon-ALP oscillations take place in extragalactic space. As a consequence, photons acquire a split personality, traveling for some time as real photons – which suffer EBL absorption – and for some time as ALPs, which are unaffected by the EBL. Therefore, $\tau_\gamma(E_0, z)$ gets replaced by the effective optical depth $\tau_\gamma^{\rm eff}(E_0, z)$, which is manifestly *smaller* than $\tau_\gamma(E_0, z)$ and is a monotonically increasing function of E_0 and z. The crux of the argument is that since the photon survival probability is now $P^{\rm ALP}_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma^{\rm eff}(E_0,z)}$, even a *small* decrease of $\tau_\gamma^{\rm eff}(E_0, z)$ with respect to $\tau_\gamma(E_0, z)$ gives rise to a *large* increase of the photon survival probability, as compared to the case of conventional physics. Hence, the main consequence of photon-ALP oscillations is to *substantially attenuate* the EBL absorption and consequently to considerably enlarging the conventional γ-ray horizon [2].

Needless to say, $P^{\rm ALP}_{\gamma\to\gamma}(E_0, z)$ can be computed exactly in term of two parameters $\xi \propto g_{a\gamma\gamma}\,B$ and $L_{\rm dom}$. Realistic values of these parameters are $\xi = 0.1, 0.5, 1, 5$ and $L_{\rm dom} = 4\,\mathrm{Mpc}, 10\,\mathrm{Mpc}$, which will be regarded as our benchmark values.

Henceforth, we proceed in parallel with the discussion in Section 2. Hence, we start by rewriting Eq. (2) as

$$\Phi^{\rm ALP}_{\rm em}\big(E_0(1+z)\big) = \Big(P^{\rm ALP}_{\gamma\to\gamma}(E_0, z)\Big)^{-1} K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)} \; . \tag{6}$$

Next, we best-fit $\Phi_{\rm em}\big(E_0(1+z)\big)$ to a single power-law with spectral index $\Gamma^{\rm ALP}_{\rm em}(z)$ – namely to $K^{\rm ALP}_{\rm em}(z)\,\big[(1+z)E_0\big]^{-\Gamma^{\rm ALP}_{\rm em}(z)}$ – over the energy range ΔE_0 where the source is observed. This procedure is performed for each benchmark value of ξ and $L_{\rm dom}$. Finally, we carry out a statistical analysis of all values of $\Gamma^{\rm ALP}_{\rm em}(z)$ as a function of z – again for all benchmark values of ξ and $L_{\rm dom}$ – along the same lines of Section 2. The best-fitting procedure selects out the two following preferred cases: $L_{\rm dom} = 4\,\mathrm{Mpc}$, $\xi = 0.5$, $\Gamma^{\rm ALP}_{\rm em} = 2.52$ and $\chi^2_{\rm red} = 1.43$ and $L_{\rm dom} = 10\,\mathrm{Mpc}$, $\xi = 0.5$, $\Gamma^{\rm ALP}_{\rm em} = 2.58$ and $\chi^2_{\rm red} = 1.39$. Manifestly, in either case the best fit straight regression line in redshift independent, in perfect agreement with physical intuition. Both situations are plotted in Fig.3.

4 Conclusions

An ALP with $m < 10^{-9}\,\mathrm{eV}$ and $g_{a\gamma\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$ remarkably achieves three important results. First, it explains the *pair-production anomaly* [13, 14]. Second, it allows flat spectrum radio quasars to emit in the VHE band [15]. Third, it provides a new view of VHE blazars, in which 95 % of them have a small spread in the values of $\Gamma^{\rm ALP}_{\rm em}(z)$ (they lie in the grey band of

Fig. 3) which gets amplified in the values of $\Gamma_{\rm obs}$ due to the last scatter in their redshift. All this taken together provides a preliminary evidence for the existence of an ALP.

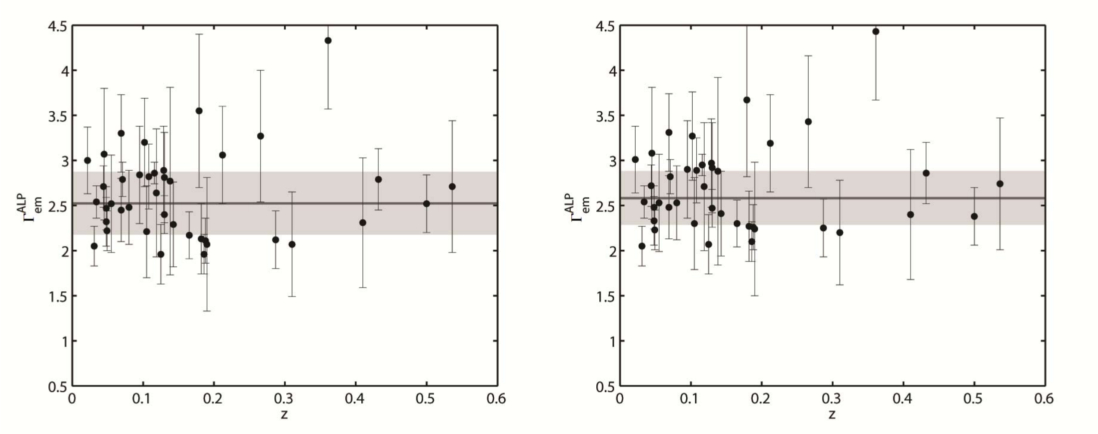

Figure 3: *Left panel:* The values of the slope $\Gamma_{\rm em}^{\rm ALP}$ are plotted versus the source redshift z for all considered blazars in the case $L_{\rm dom} = 4\,{\rm Mpc}$. Superimposed are the horizontal best-fit straight regression line and a grey band encompassing 95 % of the considered sources. *Right panel:* Same as left panel but for the case $L_{\rm dom} = 10\,{\rm Mpc}$.

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