HINTS AT AXION-LIKE PARTICLES (ALPs) FROM TeV ASTROPHYSICS

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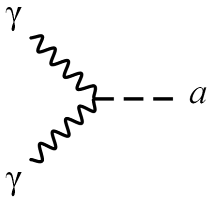
Introduction and motivation

Many extensions of the Standard Model – especially superbranes and superstrings – predict the existence of axion-like particles (ALPs): very light pseudo-scalar bosons quite similar to the axion but with mass m_a INDEPENDENT of the two-γ coupling $g_{a\gamma\gamma}$. For our subsequent discussion only such a coupling is important and its explicit form is

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma} \, \mathsf{E} \cdot \mathsf{B} \ , \tag{1}$$

where the only upper bound on $g_{a\gamma\gamma}$ is provided by the CAST experiment at CERN, which is $g_{a\gamma\gamma} < 0.66 \cdot 10^{-10} \, \mathrm{GeV}^{-1}$ for $m_a < 0.02 \, \mathrm{eV}$ at the 2σ level.

N.B. ALPs do NOT interact with SINGLE γ nor with MATTER.



In the presence of an EXTERNAL magnetic field B photon-ALP oscillations take place (**E** in Eq. (1) is then the photon electric field)

The situation is similar to the oacillations of massive neutrinos of different flavour BUT an external **B** field is COMPELLING.

FIST HINT at ALPs

We recall that according to conventional physics FLAT SPECTRUM RADIO QUASARS (FSRQs) cannot emit above $30\,\mathrm{GeV}$. This is due to the fact that the BROAD LINE REGION (BLR) at about $0.2\,\mathrm{pc}$ from the centre has a huge density of UV photon, and so the VHE along the jet γ are absorbed.

BUT FSRQs have been OBSERVED at energies as large as $E \sim 400\,\mathrm{GeV}$ 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!

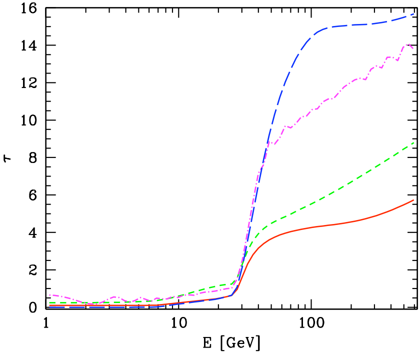
Various astrophysical solutions have been proposed, but all of them are totally AD HOC since one has to suppose that a blob with size $10^{14}\,\mathrm{cm}$ at a distance of more than 1 pc from the centre exists with the luminosity of a whole BL LAC.

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

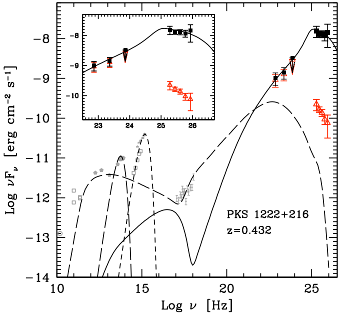
- Photons can become mostly ALPs BEFORE reaching the BLR in the jet magnetic field.
- ALPs can go UNIMPEDED through the BLR.
- Outside the BLR ALPs can reconvert into photons in the outer magnetic field.

After some playing with the parameters we find that the best choice to reduce the photon absorption by the BLR is $B = 0.2\,\mathrm{G}$, $g_{a\gamma\gamma} = 1.4 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$ e $m_a < 10^{-9}\,\mathrm{eV}$, which is represented by the RED line



A standard two-blob emission model with realistic values for the parameters yields the RIGHT RESULT shown in the next plot.

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.

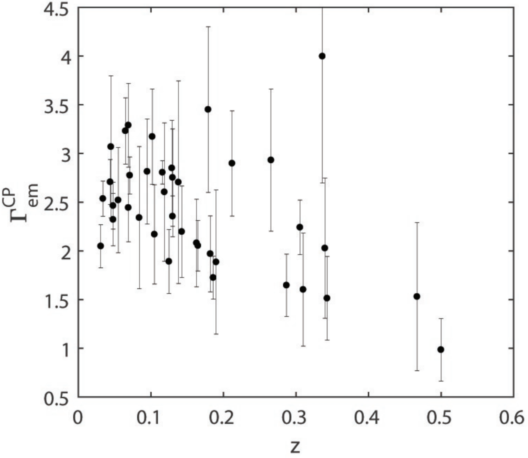


SECOND HINT at ALPs

We consider observed *flaring* BL Lacs with $E \gtrsim 100\,\mathrm{GeV}$. In order to have the most homogeneous sample and a nontrivial statistics we deal with all IBL and HBL out to $z = 0.6$ so as to avoid evolutionary effects in the sources. For each of them we need to know: z, observed spectrum with error bars, and energy range $\Delta E(z)$ wherein it is observed. Only 39 BL Lacs obey these requirements and form the sample $\mathcal{S}$.

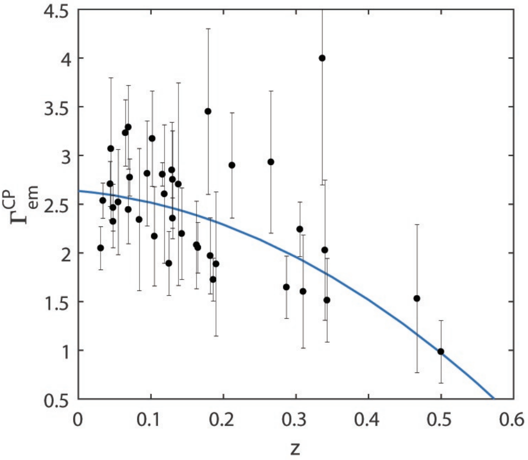
Next, we EBL-deabsorb the observed spectra, which in first approximation have simple power law spectra, since they stay on the right of the Compton peak.

Accordingly, we find the emitted slopes $\Gamma^{\mathrm{CP}}(z)$ of all 39 sources, which are shown in the next plot.



4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
z
Γ_{em}^{CP}

We proceed to carry out a statistical analysis of these data. Using the least square method we try to fit them with 1,2,3 parameters, and we evaluate the associated $\chi^2_{\rm red}$. Its smallest value $\chi^2_{\rm red} = 1.46$ and the best-fit regression line is a concave parabola shown below



This result implies a STATISTICAL CORRELATION between the $\{\Gamma^{\rm CP}(z)\}$ distribution AND z, with the farthest BL Lacs having a harder spectrum. This finding is AT ODD WITH PHYSICAL EXPECTATION, according to which NO such a correlation should exists, namely the $\{\Gamma^{\rm CP}(z)\}$ distribution should be FLAT.

NEW IDEA – Galanti, Roncadelli, De Angelis & Bignami, MNRAS **493**, 1553 (2020).

Suppose that – in addition to EBL-absorption – photon-ALP oscillations take place in extragalactic space. Accordingly, photons acquire a split personality: when they travel as true photons they undergo EBL-absorption, but when they propagate as ALPs they do *not*. So, the effective τ gets reduced, but since $P^{\rm ALP}_{\gamma \to \gamma}(E_0, z) = e^{-\tau^{\rm eff}_{\gamma}(E_0, z)}$ even a SMALL reduction of $\tau^{\rm eff}_{\gamma}(E_0, z)$ implies a GREAT enhancement of $P^{\rm ALP}_{\gamma \to \gamma}(E_0, z)$.

Assuming as usual that the extragalactic magnetic field B has a domain-like structure, we define

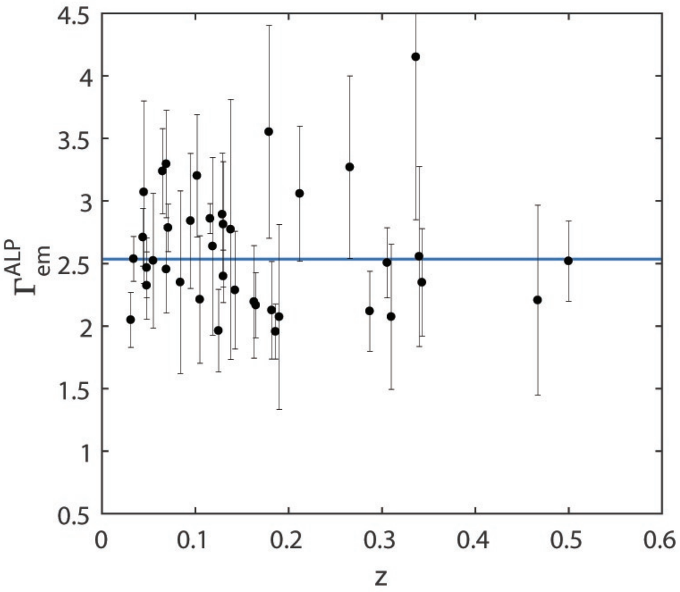
$$\xi \equiv \left(\frac{B}{\mathrm{nG}}\right)\left(g_{a\gamma\gamma}\,10^{11}\,\mathrm{GeV}\right) \ . \qquad (2)$$

As a consequence, the effective EBL-absorption gets considerably reduced.

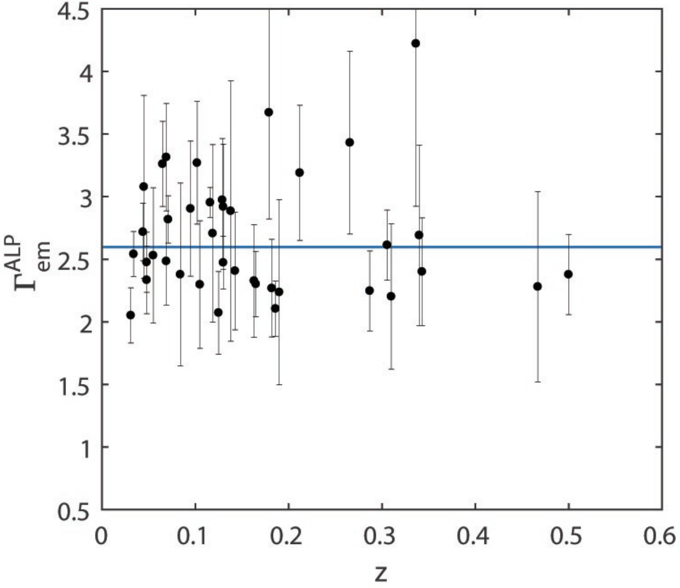
Taking the realistic benchmark values $\xi = 0.1, 0.5, 1, 5$; $L_{\rm dom} = 4\,\mathrm{Mpc}$, $10\,\mathrm{Mpc}$, for each pair of them we have performed the same best-fitting procedure and data analysis done in the case of conventional physics. For both $L_{\rm dom} = 4\,\mathrm{Mpc}$ and $L_{\rm dom} = 10\,\mathrm{Mpc}$ we find that the smallest value of $\chi^2_{\rm red}$ is for $\xi = 0.5$. specifically $\chi^2_{\rm red} = 1.29$, $\Gamma^{\rm ALP}_{\rm em} = 2.54$ and $\chi^2_{\rm red} = 1.25$, $\Gamma^{\rm ALP}_{\rm em} = 2.60$.

Our results are reported in the next 2 slides.

CASE $L_{\mathrm{dom}} = 4\,\mathrm{Mpc}$



CASE $L_{\rm dom} = 10\,{\rm Mpc}$



CONCLUSIONS

It looks astonishing that ALPs select out – among infinitely-many possibilities – just THE ONLY ONE IN AGREEMENT WITH PHYSICAL EXPECTATION. Moreover, the model parameters have the SAME values in both cases. So, we have an indirect evidence for an ALP with mass $m_a \lesssim 10^{-10}\,\mathrm{eV}$ and two-γ coupling $g_{a\gamma\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$. As a bonus, the Universe becomes considerably more transparent above energies $E \gtrsim 1\,\mathrm{TeV}$ than dictated by conventional physics.

- INDIRECT evidence can come from the new generation of observatories like CTA, HAWC, GAMMA-400, LHAASO, TAIGA-HiSCORE and HERD.
- DIRECT evidence can come from the planned laboratory experiments ALPS II (upgraded), STAX and IAXO.