AXIONS AND AXION-LIKE PARTICLES

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SUMMARY

1 – MOTIVATIONS

The Standard Model (SM) based on $\mathrm{SU(3)_C} \bigotimes \mathrm{SU(2)_L} \bigotimes \mathrm{U(1)_Y}$ 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, superstring theory seems 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).

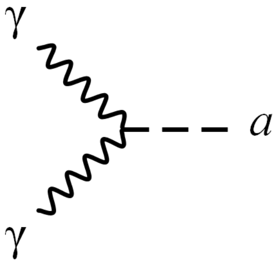
Remarkably, also other attempts to achieve the same goal like Kaluza-Klein theories with compactified large extra-dimensions point towards the same conclusion.

2 – COMMON PROPERTIES

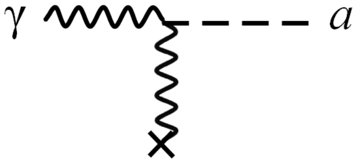
They are both described by the following Lagrangian as added to the SM Lagrangian

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

where it is always supposed that $M \gg G_F^{-1/2}$ and $m \ll G_F^{-1/2}$.
The interaction term is represented by the Feynman diagram



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.

As a consequence, in particular main-sequence stars should emit axions and ALPs from their core. As far as the Sun is concerned, the spectrum is peaked at $2.2\,\mathrm{keV}$. In order not to upset the standard solar model, the very robust bound has been derived by the CAST experiment at CERN [1]

$$M > 1.14 \cdot 10^{10}\,\mathrm{GeV} \qquad \mathrm{for} \qquad m < 0.02\,\mathrm{eV}\ . \tag{2}$$

Further, γa mixing in the presence of an EXTERNAL magnetic field gives rise to γa OSCILLATIONS [2,3]

N. B. a REAL

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

3 – AXIONS [4]

A natural solution to the *strong CP problem* was proposed in 1977 by Peccei and Quinn. They enlarged the SM by adding a global $U(1)_{PQ}$ symmetry which is spontaneously broken at the scale f_a and also slightly explicitly broken by non-perturbative QCD effects. A new pseudo-Goldstone boson called the axion is predicted with

$$\mathcal{L}_{\rm A} = \mathcal{L}_{\rm ALP} + \mathcal{L}_{\rm Af} + ..., \tag{3}$$

where

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 + \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a\ , \tag{4}$$

$$\mathcal{L}_{\rm Af} = \frac{1}{2M}\sum_i \frac{g_{ai}}{m_i}\,\overline{f}_i\,\gamma^\mu\,\gamma_5\,f_i\,\partial_\mu\,a \tag{5}$$

with $a = \text{axion field}$ and $f_i = \text{any charged lepton or quark.}$

It can be shown that

$$m \simeq 0.6 \left(\frac{10^7\,\mathrm{GeV}}{f_a} \right) \mathrm{eV} \propto \frac{1}{f_a} \;, \tag{6}$$

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

$$m = 0.7\, k \,\left(\frac{10^{10}\,\mathrm{GeV}}{M} \right) \mathrm{eV} \;, \tag{8}$$

with $k \sim 1$. Hence, mass and couplings to photons and charged fermions are tightly RELATED and both $\propto 1/f_a$.
Viable axions have $f_a \gg G_F^{-1/2}$ and $m < 1\,\mathrm{eV}$ and WEAK couplings of a to f_i, γ.
Axions are very good candidates for COLD DARK MATTER provided that $10^{-6}\,\mathrm{eV} \leq m \leq 10^{-4}\,\mathrm{eV}$. Unfortunately, NO HINT exists to date in favor of axions.

4 – AXION-LIKE PARTICLES (ALPs) [5]

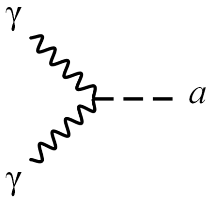
ALPs are very similar to the axion in nature, apart from the two facts that make ALPs as much as model-independent as possible.

- m and M are totally UNRELATED.
- Possible coupling of ALPs to to fermions and gluons are DISCARDED.

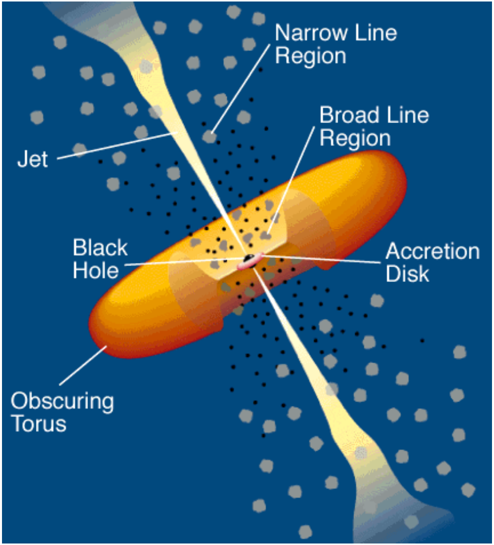
Their Lagrangian is therefore

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 + \frac{1}{M}\,\mathbf{E}\cdot\mathbf{B}\,a \tag{9}$$

with $M \gg G_F^{-1/2}$ and $m < 1\,\mathrm{eV}$.



5 – BLAZARS


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

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.

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 $20 - 30\,\mathrm{GeV}$.

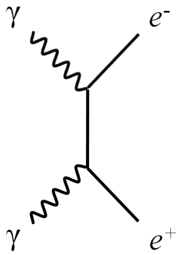
OUR INTEREST WILL HENCEFORTH BE FOCUSSED ON VHE BLAZARS WITH $E > 80\,\mathrm{GeV}$ OBSERVED WITH THE IACTs H.E.S.S., MAGIC AND VERITAS.

6 – EXTRAGALACTIC BACKGROUND LIGHT (EBL)[6]

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

$$P^{\mathrm{CP}}_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0,z)} \ , \tag{10}$$

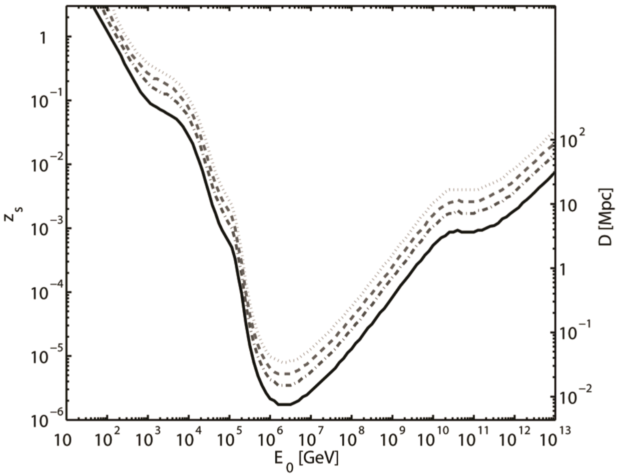
with E_0 = observed energy and $E_e = (1+z)E_0$ = emitted energy. Neglecting dust effects, hard photons with energy E get depleted by scattering off soft background photons with energy ϵ due to the $\gamma\gamma \to e^+e^-$ process



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

$$\epsilon(E) \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\ , \tag{11}$$

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 the Extragalactic Background Light, namely the light emitted by stars throughout the whole cosmic evolution.
The dimming effect of $\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \to e^+ + e^-$ is shown in the next slide taken from [7].



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

7 – PHOTON-ALP OSCILLATIONS IN EXTRAGALACTIC SPACE [8,9]

Consider a monochromatic beam from a VHE distant blazar at redshift z. In such a situation $E \gg m$, and it can be shown that the beam propagation is described by a Schrödingier-like equation with $t \to z$. So, the beam can formally be treated as a 3 LEVEL UNSTABLE NON-RELATIVISTIC QUANTUM SYSTEM.

Photon-ALP oscillations in random extragalactic magnetic field with strength $\sim 0.1\,\mathrm{nG}$ and domains size $(1 - 10)\,\mathrm{Mpc}$ – motivated by galactic outflow models [10,11] – provide the photon with a split personality: sometimes it behaves 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.

Thus, we have $\tau^{\rm ALP}(E_0, z) < \tau^{\rm CP}(E_0, z)$. But since in either case

$$P_{\gamma \to \gamma}(E_0, z) = e^{-\tau_\gamma(E_0, z)} \ , \qquad (12)$$

even a SMALL DECREASE of $\tau^{\rm ALP}(E_0, z)$ implies a LARGE INCREASE in $P_{\gamma \to \gamma}(E_0, z)$. This SUBSTANTIALLY REDUCES EBL absorption, thereby enlarging the γ-ray horizon at increasing E.

It is quite useful to define

$$\xi \equiv \left(\frac{B}{\rm nG} \right) \left(g_{a\gamma\gamma} \, 10^{11} \, {\rm GeV} \right) \ , \qquad (13)$$

and so the allowed bounds imply $\xi < 8$. Moreover, it is typically assumed $m < 10^{-9} \, {\rm eV}$.

8 – PAIR-PRODUCTION ANOMALY [12,13]

Recently it has been claimed by that VHE observations require an EBL level even lower than that predicted by the minimal EBL model normalized to the galaxy counts only. This analysis 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.
It ha been shown that the pair-production anomaly DISAPPEARS within the above model of photon-ALP oscillations in extragalactic magnetic fields.

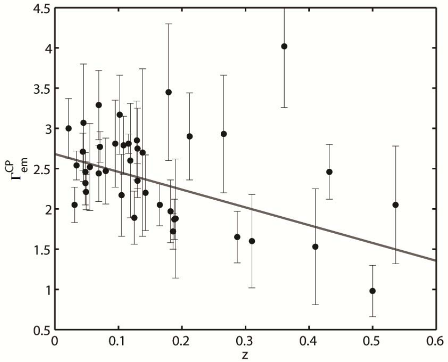
9 – ADVANTAGES OF ALPs FOR VHE BLAZAR SPECTRA [14]

We consider all blazars of TEVCAT [15] discarding 1ES 0229+200, PKS 1441+25 and S3 0218+35: the first because it is not described by photon emission models [16], and the others because they have $z \sim 0.9$. So, we are dealing with 40 sources out to $z \sim 0.6$.

According to observations and photon emission models, in the observed energy range both the emitted and the observed plectra are simple power laws: $\Phi_{\rm em}^{\rm CP}(E) \propto E^{-\Gamma_{\rm em}}$, $\Phi_{\rm obs}(E_0, z) \propto E^{-\Gamma_{\rm obs}}$.

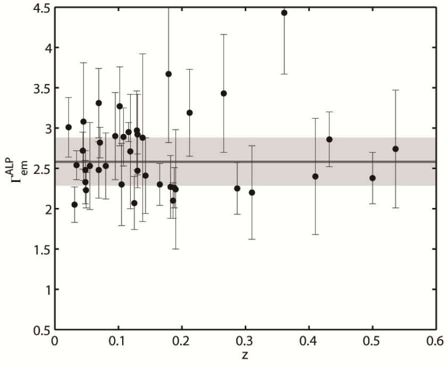
We start by de-absorbing all the 40 observed spectra using the model of Franceschini, Rodighiro and Vaccari (FRV) [17]. Next, we perform a statistical analysis of all values of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z, fitting the data with 1 ,2 and 3 parameters. The best result is a first-order polynomial $\Gamma_{\rm em}^{\rm CP}(z) = 2.68 - 2.21\, z$ with $\chi^2_{\rm red} = 1.83$. Note that this entails

$$\Phi_{\rm em}^{\rm CP}(E, 0) \propto E^{-2.68} \,, \qquad \Phi_{\rm em}^{\rm CP}(E, 0.6) \propto E^{-1.35} \,, \quad (14)$$



It is neither an evolutionary effect nor a selection bias. So, how can the source distribution get to know the redshifts in such a way to adjust their $\Gamma_{\rm em}(z)$ values so as to reproduce such a statistical correlation?

Things are quite different if we also allow for PHOTON-ALP OSCILLATIONS IN INTERGALACTIC SPACE.
By going through the same steps as before, we now find that all values of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z are best fitted by a straight horizontal line. E. g. in the case $\xi = 0.5$ we get $\chi^2_{\rm red} = 1.39$

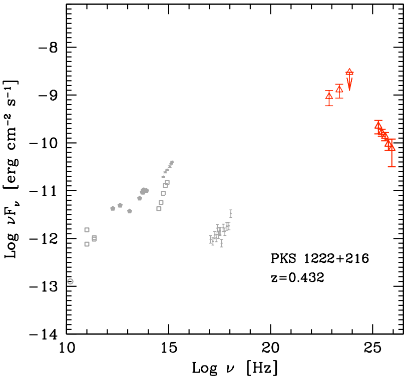


Indeed, in agreement with physical intuition.

10 – VHE EMISSION FROM FSRQs [18]

Contrary to any expectation, FSRQs have been observed up to 400 GeV with a flux similar to those of the BL LACs: this poses a great challenge to any standard emission model.
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.

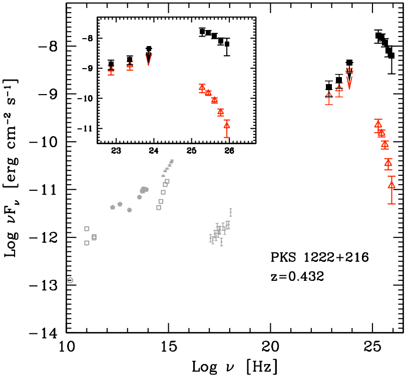


Various astrophysical solutions have been proposed, but all of them are totally ad hoc even because one has to suppose that a blob with size $10^{14}\,\mathrm{cm}$ at a distance of more than 1 pc from the centre exists with the luminosity of a whole BL LAC.
IDEA Suppose that photons are produced by a 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 $B = 0.2\,\mathrm{G}$, $M = 7 \cdot 10^{10}\,\mathrm{GeV}$ e $m < 10^{-9}\,\mathrm{eV}$. The result is shown in the next figure.

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.

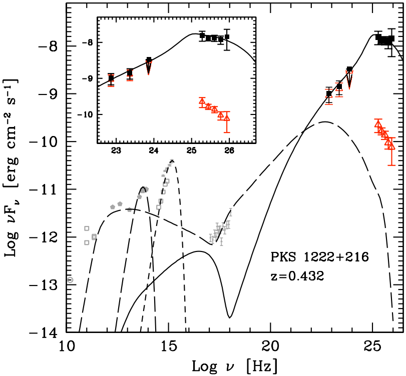


However, this is not enough. We have supposed that photons are produced by a standard emission mechanism. Moreover, PKS 1222+216 has been simultaneously observed by *Fermi*/LAT and MAGIC. So, we should pretend that the detected photons have a STANDARD SED, namely they should lie on a inverse Compton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



11 – CONCLUSIONS

AXIONS provide by now the only NATURAL solution to the strong CP problem, and for a mass range $10^{-6}\,\mathrm{eV} \leq m \leq 10^{-4}\,\mathrm{eV}$ the behave as COLD DARK MATTER, thereby giving rise to galaxy formation. Unfortunately, so far NO HINT of axion has ben reported.

PHOTON-ALP OSCILLATIONS in extragalactic fairly strong magnetic fields considerably enlarge the γ-horizon. Moreover, for the SAME VALUES OF THE PARAMETERS they explain 3 COMPLETELY DIFFERENT VHE astrophysical puzzles.

1) The pair-production anomaly.
2) The anomalous z-behaviour of VHE blazar spectra.
3) The VHE emission of FSRQs.

Taken together at the face value, this situation strongly suggests the EXISTENCE of an ALP of mass $m < 10^{-9}\,\mathrm{eV}$, which is in addition a very good candidate for COLD DARK MATTER.

Finally, not only VHE observatories like CTA, HAWC, GAMMA-400, LHAASO AND HiSCORE can provide evidence for ALPs, but also laboratory experiments like ALPSII and IAXO can detect them.

12 – BASIC REFERENCES

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