ALPs EXPLAIN THE UNPHYSICAL REDSHIFT-DEPENDENCE OF BLAZAR SPECTRA

Marco Roncadelli

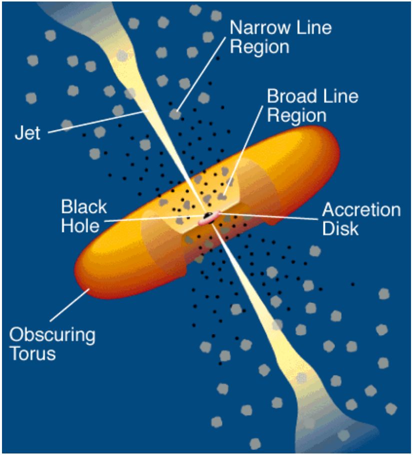
INFN – Pavia, Italy

SUMMARY

Work done in collaboration with G: GALANTI, A. DE ANGELIS & G. F. BIGNAMI. See: arxiv:1503.04436

1 – PRELIMINARIES

BLAZARS:



AGN possess two possible non-thermal 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.

Both mechanisms predict emitted spectra with a single power-law behavior

$$\Phi_{\rm em}(E) = K_{\rm em}\, E^{-\Gamma_{\rm em}} \ , \qquad 100\,{\rm GeV} < E < 20\,{\rm TeV} \ . \tag{1}$$

When the jet is oriented towards us the AGN is called BLAZAR.

I will be interested ONLY in the VERY-HIGH-ENERGY (VHE) blazars i. e. within $100\,{\rm GeV} < E < 100\,{\rm TeV}$.

So far, IACTs have detected 43 VHE blazars with $E < 11\,{\rm TeV}$, whose spectra are well fitted by a simple power-law

$$\Phi_{\rm obs}(E_0, z) = K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)} \ . \tag{2}$$

Emitted and observed fluxed are related by

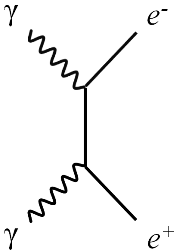
$$\Phi_{\rm obs}(E_0, z) = P_{\gamma\to\gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big) \ , \qquad (3)$$

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

$$P_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0, z)} \ . \qquad (4)$$

EXTRAGALACTIC BACKGROUND LIGHT (EBL):

Infrared/optical/ultraviolet light emitted by stars throughout the history of the Universe. VHE photons with energy E emitted by a blazar at z get depleted by scattering off EBL photons of energy ϵ through the process $\gamma_{\rm VHE} + \gamma_{\rm EBL} \to e^+ + e^-$



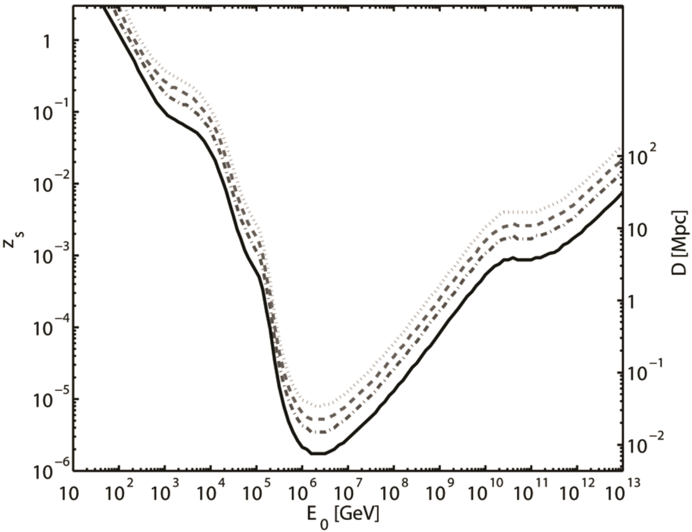
whose Breit-Wheeler cross-section gets maximized when

$$\epsilon(E) \simeq \left(\frac{900\,\mathrm{GeV}}{E}\right)\,\mathrm{eV}\ . \tag{5}$$

So, for $100\,\mathrm{GeV} < E < 100\,\mathrm{TeV}$ $\sigma(\gamma\gamma \to e^+e^-)$ is MAXIMAL for $9 \cdot 10^{-3}\,\mathrm{eV} < E < 9\,\mathrm{eV}$, indeed in the EBL band.

After a long period of uncertainty, today the SED of the EBL is well determined. I use the model of Franceschini, Rodighiero & Vaccari (FRV) (Astron. Astrophys. **487**, 837 (2008)).

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
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
E_0 [GeV]
10^2
10
1
10^−1
10^−2
D [Mpc]

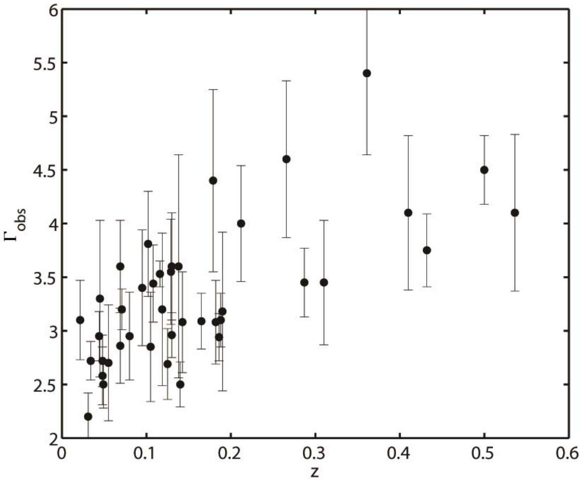
2 – OBSERVATIONAL INFORMATION

I consider the 41 VHE blazars detected at the time of writing. Observational quantities concerning every blazar relevant for the present analysis:

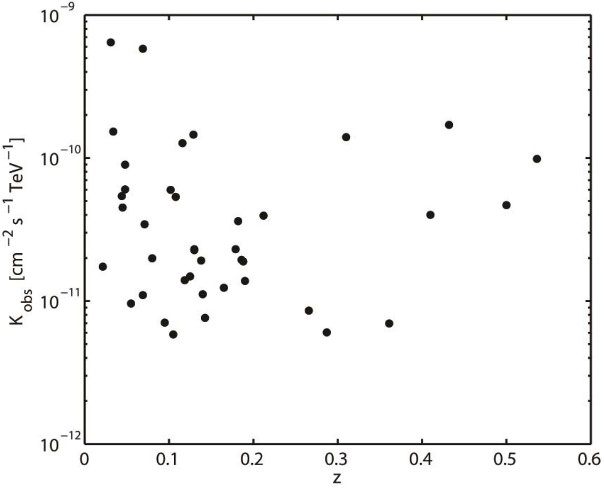
- Source redshift z.
- Observed spectral index $\Gamma_{\rm obs}(z)$ with error bar.
- Observed flux normalization constant $K_{\rm obs}(z)$ without error bar.
- Energy range ΔE_0 where the source is observed.

I express $K_{\rm obs}(z)$ for all sources in units of $E_* = 300\,{\rm GeV}$. Recalling $\Phi_{\rm obs}(E_0, z) = K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)}$ I find the observed flux $F_{{\rm obs},\Delta E_0}(z)$ inside ΔE_0.

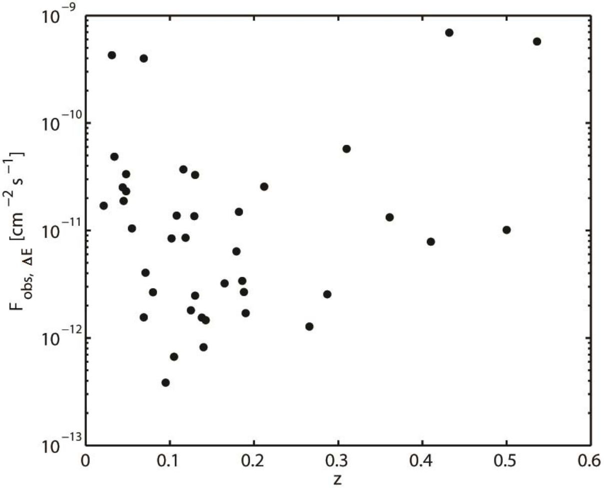
Observed values of $\Gamma_{\rm obs}(z)$ plotted vs. the source redshift z for all VHE blazars detected at the time of writing:



Observed values of $K_{\rm obs}(z)$ plotted vs. the source redshift z for all VHE blazars detected at the time of writing:



Values of $F_{\mathrm{obs},\Delta E_0}(z)$ plotted vs. the source redshift z for all VHE considered blazars:



3 – CONVENTIONAL PROPAGATION

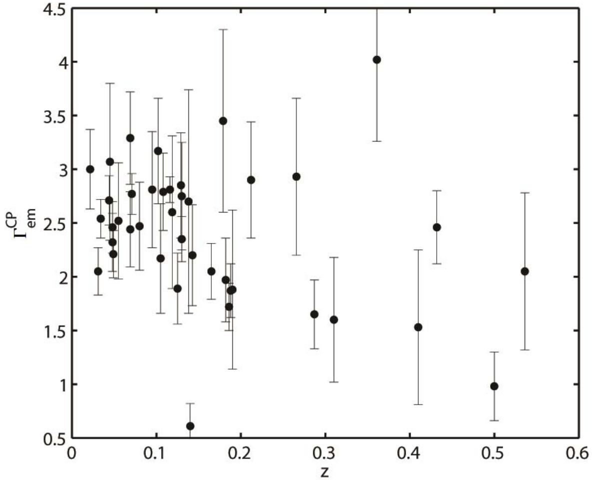
I start by deriving the EMITTED spectrum of every source, starting from the observed ones.
As a first step, I rewrite Eq. (3) as

$$\Phi_{\rm em}\big(E_0(1+z)\big) = e^{\tau_\gamma^{\rm FRV}(E_0,z)}\, K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)}~. \qquad (6)$$

Next, I best-fit $\Phi_{\rm em}\big(E_0(1+z)\big)$ to a single power-law with spectral index $\Gamma_{\rm em}^{\rm CP}(z)$ – 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.

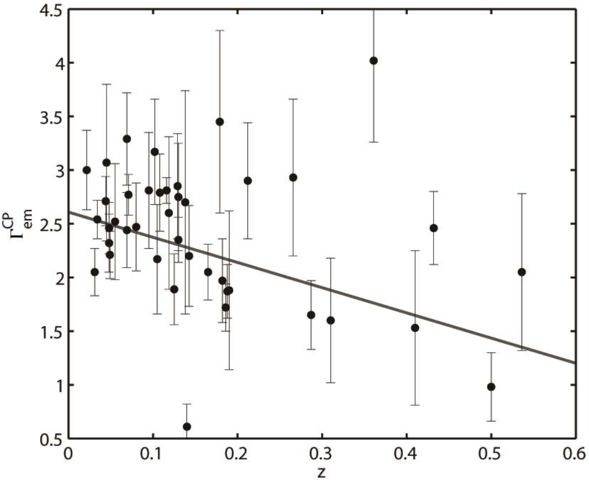
Finally, I plot the values of $\Gamma_{\rm em}^{\rm CP}$ vs. z in the next Figure.

Plot of the values of $\Gamma_{\mathrm{em}}^{\mathrm{CP}}$ vs. z:



I proceed by performing a statistical analysis of all values of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z. I 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 I compute the corresponding $\chi^2_{\rm red}$. The values of the $\chi^2_{\rm red}$ obtained for the three fits are 4.03, 3.49 and 3.56, respectively. Thus, data appear to be best-fitted by the first-order polynomial $\Gamma_{\rm em}^{\rm CP}(z) = 2.61 - 2.35\, z$. The distribution of $\Gamma_{\rm em}^{\rm CP}(z)$ as a function of z with the best-fit straight regression line as defined by the last equation is plotted in the next Figure.

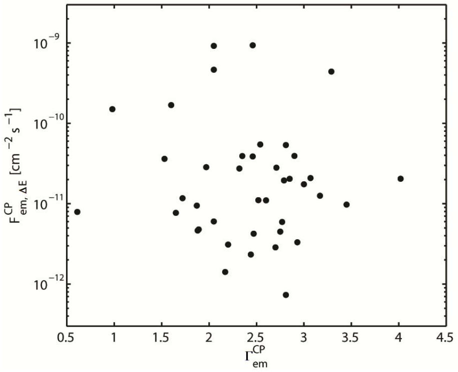
Best-fit straight regression line with $\chi^2_{\rm red} = 3.49$



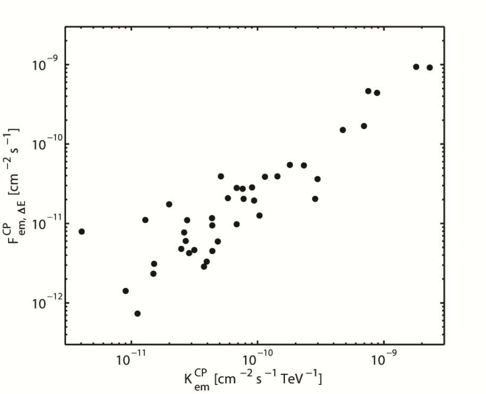
The best-fit straight regression line implies that blazars with HARDER spectra are found ONLY at LARGER redshift. WHY???

- Relatively LOCAL sample $\Rightarrow$ cosmological evolutionary effects are INSIGNIFICANT.
- Selection bias ONLY if brighter sources have harder spectra $\Rightarrow F^{\rm CP}_{{\rm em},\Delta E}(z)$ TIGHTLY CORRELATES with $\Gamma^{\rm CP}_{\rm em}(z)$.

Yet the OPPOSITE is TRUE



$\Rightarrow$ NOT a selection bias. Nevertheless, $F^{\rm CP}_{{\rm em},\Delta E}(z)$ TIGHTLY CORRELATES with $K^{\rm CP}_{\rm em}(z)$, es it is evident from the Figure below



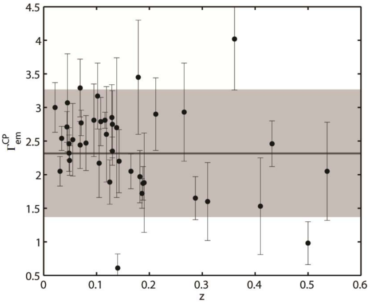
4 – A PHYSICALLY SATISFACTORY SCENARIO

Let me ask what should happen in order to avoid the above problem. I argue as follows. Obviously $F^{\rm CP}_{{\rm em},\Delta E}(z)$ depends just by definition on both $K_{\rm em}(z)$ and $\Gamma_{\rm em}(z) \Rightarrow$ $F_{{\rm em},\Delta E}(z) = \mathcal{F}\big(K_{\rm em}(z), \Gamma_{\rm em}(z)\big)$. Still, in order for a tight correlation between $F_{{\rm em},\Delta E}(z)$ and $K_{\rm em}(z)$ to shows up $\Gamma_{\rm em}(z)$ should be NEARLY INDEPENDENT of z. Thus, 2 conditions should be met.

- Assuming that the tight correlation between $F_{{\rm em},\Delta E}(z)$ and $K_{\rm em}(z)$ found above in conventional physics persists in the present scenario, then the best-fit regression line of the distribution of the values of $\Gamma_{\rm em}(z)$ vs. the source redshifts should be VERY CLOSE TO STRAIGHT AND HORIZONTAL.
- Almost all the values of $\Gamma_{\rm em}(z)$ – say, 95 % of them – should lie inside a RATHER THIN STRIP about the nearly horizontal best-fit straight regression line.

5 – ATTEMPT WITHIN CONVENTIONAL PHYSICS

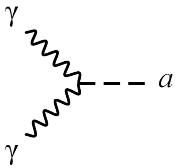
I FORCE a best-fitting with a HORIZONTAL line, which is $\Gamma^{CP}_{\rm em} = 2.32$. It has $\chi^2_{\rm red} = 4.03$: unduly LARGE. Further, to encompass 95 % of observed sources within a strip about that line I need its width to be 82 % of 2.32 $\Rightarrow$ LARGE SPREAD in $\Gamma^{CP}_{\rm em}$ which DESTROYS the tight correlation between $F^{\rm CP}_{{\rm em},\Delta E}(z)$ and $K^{\rm CP}_{\rm em}(z)$. $\Rightarrow$ IT DOES NOT WORK.



6 – DARMA SCENARIO (ALPs)

STANDARD MODEL + ALPS (A. De Angelis, M. Roncadelli & O. Mansutti, Phys. Rev. D **76**, 121301 (2007)). .

I assume that ALPs interact with 2 γs ONLY $\Rightarrow$ new ingredient



Here one photon line is the extragalactic magnetic field **B** $\Rightarrow$ oscillations between VHE γs and ALPs take place in extragalactic space $\Rightarrow$ γs acquire a split personality, travelling for some time as real γs – suffering EBL absorption – and for some time as ALPs, unaffected by the EBL $\Rightarrow$ $\tau_\gamma^{\rm CP}(E_0, z) \to \tau_\gamma^{\rm ALP}(E_0, z) < \tau_\gamma^{\rm CP}(E_0, z)$.

Recalling

$$P_{\gamma\to\gamma}(E_0, z) = e^{-\tau_\gamma(E_0,z)} \; , \tag{7}$$

$\Rightarrow$

$$P^{ALP}_{\gamma\to\gamma}(E_0, z) \gg P^{CP}_{\gamma\to\gamma}(E_0, z) \; . \tag{8}$$

MORAL: EBL absorption STRONGLY REDUCED $\Rightarrow$ γ-ray horizon GREATLY enlarged.

Only 2 FREE parameters.

- $$\xi \equiv \left(\frac{B}{\rm nG}\right) \left(g_{a\gamma\gamma}\, 10^{11}\, {\rm GeV}\right) \ , \tag{9}$$

  where $\mathbf{B}$ = extragalactic magnetic field with a domain-like structure, i.e. $\mathbf{B}$ is homogeneous over a domain of size $L_{\rm dom}$ and has nearly the same strength B in all domains, but its direction changes RANDOMLY from one domain to another
- $L_{\rm dom}$ = coherence length of $\mathbf{B}$

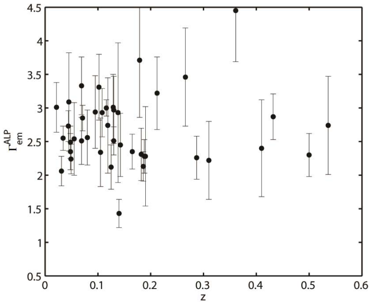
As an orientation, I take $L_{\rm dom} > 1\,{\rm Mpc}$ & $B = 0.1 - 1\,{\rm nG} \Rightarrow$ AGREEMENT will ALL BOUNDS + GALACTIC OUTFLOWS MODELS. CAST $\Rightarrow g_{a\gamma\gamma} < 8.8 \cdot 10^{-11}\,{\rm GeV}$ for $m < 0.02\,{\rm eV}$. So $\xi < 8$. BENCHMARK VALUES: $\xi = 0.1, 0.5, 1, 5$ & $L_{\rm dom} = 4\,{\rm Mpc}, 10\,{\rm Mpc}$.
A third free parameter is the ALP mass m, but we assume $m < 10^{-9}\,{\rm eV} \Rightarrow P^{\rm ALP}_{\gamma \to \gamma}(E_0, z)$ INDEPENDENT of m.

7 – ATTEMPT WITHIN DARMA SCENARIO

Now $P_{\gamma\to\gamma}^{\rm ALP}(E_0, z)$ can be computed EXACTLY, and so I can proceed just as above. I first write the emitted flux of every source as

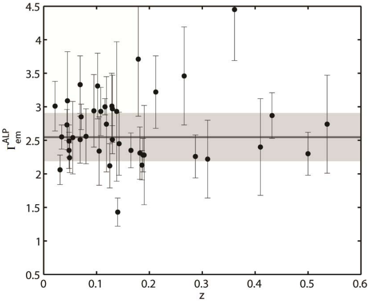
$$\Phi_{\rm em}\big(E_0(1+z)\big) = \Big(P_{\gamma\to\gamma}^{\rm ALP}(E_0, z)\Big)^{-1} K_{\rm obs}(z)\, E_0^{-\Gamma_{\rm obs}(z)} \;, \qquad (10)$$

and next I best-fit this function to the single power-law $K_{\rm em}^{\rm ALP}(z)\,\big[(1+z)E_0\big]^{-\Gamma_{\rm em}^{\rm ALP}(z)}$ over the energy range ΔE_0 where the source is observed. This procedure is performed for each benchmark value of ξ and $L_{\rm dom}$. Just to be specific, I consider the case $\xi = 1$, $L_{\rm dom} = 4\,{\rm Mpc}$ in the Figure below.



Next, I carry out a statistical analysis of the values of $\Gamma_{\rm em}^{\rm ALP}(z)$ as a function of z, again for any benchmark value of ξ and $L_{\rm dom}$. I still use the least square method and I try to fit the data with one parameter (horizontal line), two parameters (first-order polynomial) and three parameters (second-order polynomial).

Finally, in order to quantify the statistical significance of each fit I compute the corresponding $\chi^2_{\rm red}$. Again, to be specific I consider the same case as before. Accordingly, values of the $\chi^2_{\rm red}$ obtained for the three fits are 2.16, 2.21 and 2.26, respectively. Hence, data are best-fitted by an HORIZONTAL straight regression line $\Gamma^{CP}_{\rm em} = 2.52$.



So, even on a pure STATISTICAL LEVEL the present situation is MUCH BETTER than that of conventional physics: $\chi^2_{\rm red} = 3.49$ with 2 parameters or $\chi^2_{\rm red} = 4.03$ with 1 parameter $\Rightarrow \chi^2_{\rm red} = 2.16$ with 1 parameter.
Moreover, to encompass 95 % of observed sources within a strip about the best-fit regression line I need its width to be 28 % of 2.16 $\Rightarrow$ SMALL SPREAD in $\Gamma^{ALP}_{\rm em}$ which PRESERVES the tight correlation between $F^{\rm CP}_{{\rm em},\Delta E}(z)$ and $K^{\rm CP}_{\rm em}(z)$.

8 – CONCLUSIONS

Obviously, by changing the effective level of EBL absorption we expect the z- dependence of the $\Gamma_{\rm em}^{\rm ALP}(z)$ distribution to differ from that of the $\Gamma_{\rm em}^{\rm CP}(z)$ distribution. But getting EXACTLY HORIZONTAL best-fit regression lines looks like a MIRACLE.

So, this picture perfectly fits our PHYSICALLY SATISFACTORY SCENARIO.

Moreover, a natural physical situation arises. The LARGE spread in the values of $\Gamma_{\rm obs}(z)$ arises from the SMALL spread of $\Gamma_{\rm em}^{\rm ALP}(z)$ because of the LARGE spread in the z values of the sources.

9 – OUTLOOKS

AMAZINGLY the existence of an ALP with the SAME values of the parameters explains 3 COMPLETELY DIFFERENT effects AT ONCE.

- PAIR-PRODUCTION ANOMALY (D. Horns and M. Meyer, JCAP **02**, 033 (2012); M. Meyer, D. Horns and M. Raue, Phys. Rev. D **87**, 035027 (2013)).
- Observed VHE emission from FLAT SPECTRM RADIO QUASARS (F. Tavecchio, M. Roncadelli, G. Galanti and G. Bonnoli, Phys. Rev. D **86**, 085036 (2012)).
- Effect discussed above.

All this poses a WONDERFUL CHALLANGE both to the planned LABORATOTY experiments like ALPS II & IAXO and to the upcoming ASTROPHYSICAL DETECTORS like the CTA, HAWC, γ 400 and HISCORE.