# A new test of the transparency of the Universe

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We present a brand new quantitative test of the degree of transparency of the Universe to gamma rays, confronting existing models of pair production on the extragalactic background light with observational data. We discuss this result in the context of various scenarios of photon mixing with axion-like particles.

In this note, written along the lines of a poster presented at the Patras workshop and based on Ref. [1], we give a proof that the so-called "infrared-TeV crisis" is back: gamma-ray observations of distant blazars indicate that the Universe is much more transparent for energetic photons than suggested by the lowest-absorbtion models. Indeed, energetic gamma rays scatter on soft background radiation when propagating through the Universe, producing electron-positron pairs [2]. Gamma rays with energies between 100 GeV and a few TeV interact mostly with infrared background photons whose amount is poorly known experimentally but safely constrained from below by account of the contribution of observed light from known galaxies [3]. The expected opacity of the intergalactic space limits the mean free path of TeV gamma rays to dozens of Megaparsecs. However, TeV photons from numerous more distant sources have been detected [4]. One does not know what flux was emitted in the source, so the observation of photons may be made consistent with strong absorbtion if the emitted spectrum breaks upwards at high energies. This interpretation works in every particular case, though it requires presently unknown mechanisms to work in the sources [5]. Here we show that this interpretation is not supported by the analysis of the ensemble of all observed sources. In the frameworks of an infrared-background model with the lowest opacity [6], we reconstruct the emitted spectra of distant blazars and find that upward spectral breaks appear precisely at those energies where absorption effects are essential. Since these energies are very different for similar sources located at various distances, we conclude that the breaks are nothing but artefacts of the incorrect account of absorption and, therefore, the opacity of the Universe for gamma rays is overestimated even in the most conservative model. This implies that some novel physical or astrophysical phenomena should affect long-distance propagation of gamma rays.

All observed distant sources are blazars, that is belong to a certain class of active galactic nuclei whose relativistic jets point to the observer. While the mechanism of high-energy emission of blazars is disputable, the bulk of their spectral energy distribution is well studied. The overall shape of the distribution is to a large extent determined by the energy scale of the electron population. One often distinguishes two large classes of blazars, namely flat-spectrum radio quasars (FSRQs) with the synchrotron peak in the radio to infrared and BL Lac type objects (BLLs) with the peak in optical to X-ray bands. However, deabsorbed spectra of distant blazars often exhibit high-energy hardening which is not seen in nearby objects. Even a visual inspection of the deabsorbed blazar spectra leads to a conclusion that both the position and

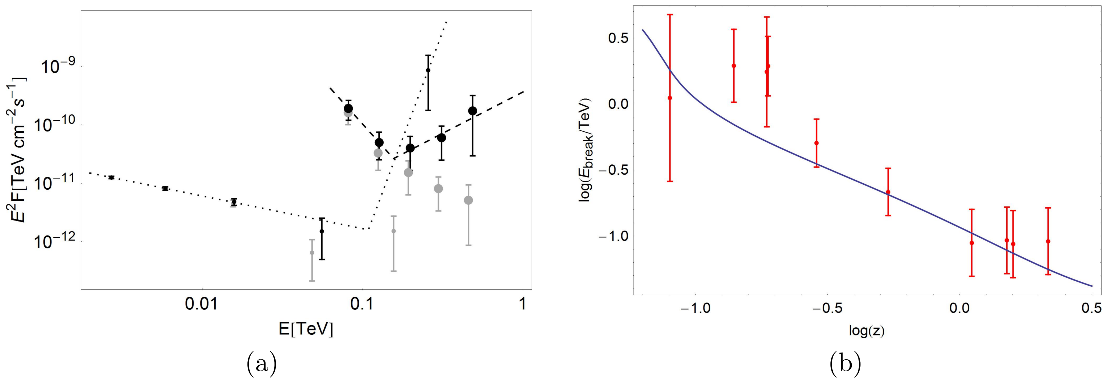


Figure 1: (a). Example of two spectra with breaks: 3C 279 (redshift $z = 0.536$, large points) and PKS J0730-1141 (redshift $z = 1.591$, small points). Grey points represent the observed spectrum, dark points are corrected for the EBL absorption with the most conservative model. (b). Positions of individual significant upward breaks versus redshift $z$. The line represents the energy $E_0(z)$ at which the optical depth with respect to the pair production $\tau = 1$.

the strength of the spectral hardening differ for similar blazars located at different distances, see Fig. 1(a) for an example.

We consider a sample of blazars, located at various distances but with fluxes measured beyond the energies where absorption on EBL is significant, compiled from published data of atmospheric Cerenkov telescopes by making use of the TeVCat catalog [4] and supplemented with a set of more distant objects observed by Fermi. For each of the objects in the sample, we construct a deabsorbed spectrum.

First, we fit each spectrum with a power law and, independently, with two power laws with a break, keeping the break position arbitrary. We select these (few) objects for which the fit with a break is better than without it and the break corresponds to a spectral hardening (it is not so for a few nearby sources). Then we compare the break positions with the values of energy at which the absorption is expected to be significant (namely, with the energy $E_0$ for which the optical depth due to pair production $\tau = 1$). The results are shown in Fig. 1(b), where we plot the positions of these significant upward breaks versus the redshift $z$. The break positions are statistically consistent with $E = E_0$. A further test of this relation constitutes the main part of our study and results in our principal conclusion.

We assume that the position of the break is fixed at $E = E_0$ and study how the strength of the break, determined as the difference $\Delta\Gamma$ between power-law indices below and above the break, depends on $z$. In this approach, we use the information from all sources, even if their individual breaks are not statistically significant. The results are presented in Fig. 2, together with the best-fit approximation. The absence of distance-dependent spectral hardening is excluded at the 12.4 standard deviations ($12.4\sigma$) level. This gives a serious argument in favour of the hypothesis that the upward breaks in deabsorbed blazar spectra are unphysical and are caused by incorrect account of absorbtion. Potential systematic errors and statistical biases are discussed in Ref. [1]; it is unlikely that they might affect our result.

Among previous studies of gamma-ray blazars in the context of the EBL opacity, two groups went beyond the discussion of individual objects and used a sample, like we do here. The first

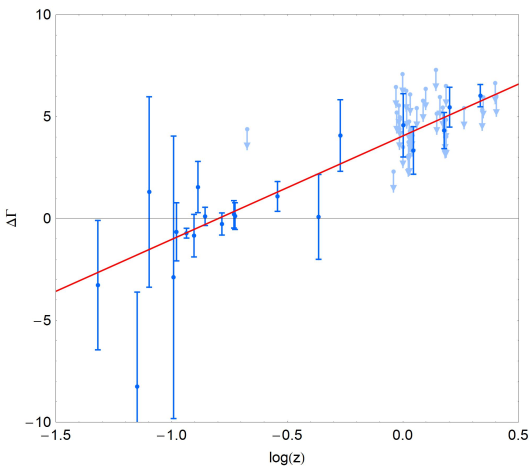


Figure 2: Value $\Delta\Gamma$ of the break in the spectrum deabsorbed with the most conservative model, assumed to happen at $E = E_0$, versus redshift $z$. The line gives the best fit; its slope is non-zero at the $12\sigma$ significance.

one is the Fermi LAT collaboration [9] which discovered a spectrum suppression by comparison of stacked BLL spectra grouped in large redshift bins, interpreted as the effect of the EBL absorption. This result does not exclude the opacity below the lowest model and even favours it for high energies, cf. Fig. 1 of Ref. [9]. Horns and Meyer [10] concentrated on the sample of blazars detected at very large optical depths, $\tau \geq 2$, and found a 4-sigma evidence for the pair-production anomaly which lead them to conclusions similar to ours. The differences of our approach from Ref. [10] are in the choice of the sample, in the use of simultaneous data only and in the method of the analyzis. They also did not take into account the shift of the mean energy in the bin in the deabsorbed versus observed spectrum, important at large opacities.

How to explain the fact that the most conservative EBL model is likely to overestimate the absorption? The probability of the pair-production process cannot be questioned: it is calculated in quantum electrodynamics at the center-of-mass energies where no unknown effects are expected to contribute, and has been measured experimentally. The downward change in the amount of target photons is hardly acceptable because the EBL model we use is already saturated by lower limits of Ref. [3]. One should consider new processes which affect the observed photon flux and are not accounted for in the absorption model which takes into account pair production only. Several models of this kind have been suggested; they invoke either new physical processes or very unusual astrophysical assumptions.

Two quite different scenarios invoke similar extensions of the particle-physics Standard model, the so-called axion-like particles (ALPs; see Ref. [11] for a review and a list of references). In external magnetic fields, these particles may convert to photons and vice versae. Applied to our problem, this conversion may happen [12] in intergalactic magnetic fields provided they are sufficiently strong ($> 10^{-9}$ G). In this regime, VHE photons convert to ALPs and back during propagation in a way similar to neutrino oscillations. In a rough approximation and for the maximal possible photon/ALP mixing, the path becomes longer by a factor of $\sim 3/2$. Assuming this in our analysis, we obtain the reduction in significance of the distance dependence of breaks from $\sim 12\sigma$ to $\sim 6\sigma$ which suggests that this scenario may not explain the entire observed effect, though a detailed analyzis is required for a firm conclusion.

In the second scenario, intergalactic magnetic fields are assumed to be weaker, $\lesssim 10^{-10}$ G, and therefore insufficient for the photon/ALP transitions which may happen instead in the regions of stronger field around both the source and the observer. The conversion may happen on magnetic fields of galaxies [13], galaxy clusters or superclusters [14]. A rough account of this mechanism in our study reduces the effect to $\sim 2\sigma$ thus making it insignificant. We conclude that our result may be explained in this scenario.

The third option [15] does not require new physics beyond the Standard Model; however, it invokes some non-conventional astrophysical assumptions. In this approach, a competitive source of VHE photon *production* along the path from the source to the observer feeds the photon flux which is, in parallel, absorbed in the usual way. These additional photons may be created in interactions of ultra-high-energy cosmic protons, which are assumed, in this model, to be produced in the very same source, with the background radiation. It is not possible to perform a simple rough test of this model in our study because this scenario is necessarily based on rather arbitrary parameters of the hypothetical proton flux. This scenario requires very low values of the intergalactic magnetic fields, $\lesssim 10^{-14}$ G, otherwise charged particles would be deflected and secondary photons would not point back to the source.

While detailed tests of these scenarios versus our results will be presented elsewhere, our preliminary considerations thus favour the ALP convertion/reconvertion scenario [13, 14] for the explanation of the effect we observe.

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