

# Pair-production opacity at high and very-high gamma-ray energies

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The propagation of high energy (HE,  $E_\gamma > 100$  MeV) and very high-energy gamma-rays (VHE,  $E_\gamma > 100$  GeV) in the extra-galactic photon field leads to pair-production and consequently energy- and distance-dependent attenuation of the primary intensity. The spectroscopy of an increasing number of extra-galactic objects at HE and VHE energies has demonstrated indeed the presence of such an attenuation which in turn has been used to constrain the photon density in the medium. At large optical depth ( $\tau \gtrsim 2$ ) potential modifications of pair-production due to competing but rare processes (as, e.g., the presence of sub-neV axion-like particle) may be found. Indications for a pair-production anomaly have previously been found with VHE-spectra. Here, we present further indications (at the level of  $3.68 \sigma$ ) for a reduced optical depth at high energies from an analysis of Fermi-*LAT* data.

## 1 Introduction

The extra-galactic photon field in the optical/ultraviolet and infra-red is the stellar and dust-reprocessed light (see [7] for a review) accumulated during the cosmological evolution following the era of re-ionization. For sufficiently energetic ( $E > 10$  GeV) photons from distant sources, pair-production processes with this background photon field lead to an energy- and distance dependent exponential attenuation,  $\exp(-\tau)$ , where  $\tau$  is the optical depth. This effect has recently been detected in the observed HE gamma-ray spectra of 50 Blazars in the redshift range 0.5 to 1.6 [3] as well as independently in the observed VHE gamma-ray spectra of mainly 2 BL Lac type objects at redshifts of 0.116 and 0.186 [1]. Given the measurement uncertainties, the spectral shape of the extra-galactic background light (EBL) has been fixed to a choice of models with normalizations left to vary. The two independent measurements of the redshift dependent EBL level for one particular model [11] is shown in Fig. 1. Given the large uncertainties, variations of the normalization by a factor of two are consistent with the data. Particularly, the VHE data favor a drop of the EBL normalization towards larger redshifts, broadly consistent with the HE measurement.

At large optical depth ( $\tau > 2$ ), modifications of the transparency by non-standard propagation effects may lead to noticeable effects in the attenuation. Even though in principle the residuals (Fig. 4 of [1] and Fig. 2 of [3]) do not show obvious deviations from the best-fit, it is difficult to interpret this result given that the normalization of the EBL (and therefore of the optical depth) was varied by more than a factor of two between the different redshift bins.

Several studies of the VHE measurements provided indications for deviations from the expected transparency [4, 5, 9, 12]. The proposed interpretations have either focussed on the assumption that Blazars are powerful accelerators of ultra-high energy protons [8] or additional processes including light pseudo-scalars (a la axion-like particles, for a review see, e.g., [13]) have been invoked [6, 16]. In this contribution, we extend our previous work in the HE energy regime (see also [15] for an update of the original analyses of VHE data [12]) using Fermi-*LAT* observations of distant AGN [14].<sup>1</sup>

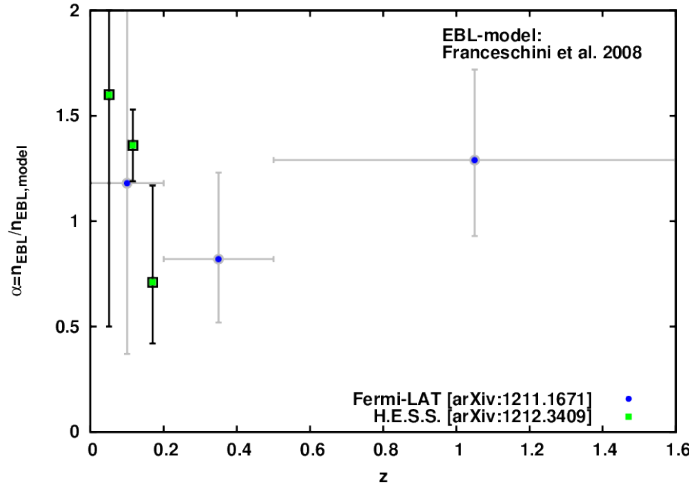


Figure 1: Comparison of the high-energy ( $E_\gamma > 100$  MeV) and VHE ( $E_\gamma > 100$  GeV) measurements of the normalization factor of the extra-galactic background light (EBL) for different ranges of redshift.

## 2 Fermi-*LAT* observations

The data-set from the first 4.3 years of operation (until Nov. 29, 2012)<sup>2</sup> of Fermi-*LAT* are searched for the most energetic photons which can be associated with known gamma-ray emitting AGN from the second Fermi-*LAT* catalog [18] as well as from [17]. Each photon-like event detected at energies  $E_\gamma > 10$  GeV at high Galactic latitude  $|b| > 10^\circ$  of event class **ULTRACLEAN** and zenith angle  $Z < 100^\circ$  is matched against the list of AGN with known redshift. An event is considered to be associated with a source, if its angular uncertainty ( $r_{68}$  at 68 % c.l. derived from the instrumental response function P7V6\_ULTRACLEAN from the in-flight calibration) is larger than the angular distance to the location of the AGN. The resulting list of photons (see Fig. 2) contains 23(9) photons with optical depth  $\tau > 1(2)$ . Similar to the study carried out with VHE-spectra, we focus on the photons detected from sources at an optical depth  $\tau > 2$  (assuming the best-fit level of the extra-galactic background [3]). The two highest-energy photons exceeding the well-calibrated energy range of 500 GeV are excluded from the sample as well as four photons where the probability of association with the source is less than 90 % even in the case of no absorption present<sup>3</sup>. The final sample comprises three photons from GB6J1001+2911

<sup>1</sup>Note, the search for anomalous transparency effects as discussed here is complementary to searches for additional noise induced by photon-axion coupling in AGN spectra as originally proposed for optical QSO spectra [19] and recently extended to a VHE and X-ray spectra [20].

<sup>2</sup>using time-intervals passing the standard cuts

<sup>3</sup>The probability is calculated using the `gtsrcprob` tool.

$(\tau(E = 308 \text{ GeV}, z = 0.558) = 2.18)$ , S4 0218+35  $(\tau(E = 179 \text{ GeV}, z = 0.944) = 2.46)$ , Ton 599  $(\tau(E = 301 \text{ GeV}, z = 0.725) = 3.1)$ . For each photon and source, the number of photons predicted from the source for a nominal absorption is calculated ( $= \mathcal{O}(10^{-3})$ ) as well as the number of background events ( $= \mathcal{O}(10^{-4})$ ). The predicted number of source photons is based upon a power-law extrapolation of the energy spectrum fit in the range from 1 GeV to the energy where absorption diminishes the expected flux by 1 %. A power-law was chosen even in the case of significant curvature of the energy spectrum. Given this choice, the predicted number of source photons is an upper limit to the real value.

The resulting probability for detecting the three photons is combined using Fisher's method [10] to be  $P_{\text{pre-trial}} = 6.57 \times 10^{-6} (4.36 \sigma)$  and correcting for trials  $P_{\text{post-trial}} = 1.17 \times 10^{-4} (3.68 \sigma)$ , consistent with the result obtained from the VHE data. Systematic effects include changing of the energy within the estimated 68 % c.l. uncertainty ( $P_{\text{pre-trial}} = 3.34 \times 10^{-5}$ ) and assuming a harder intrinsic spectrum ( $P_{\text{pre-trial}} = 1.85 \times 10^{-5}$ ). In both cases, the probabilities increase, but the significance remains larger than  $3 \sigma$ .

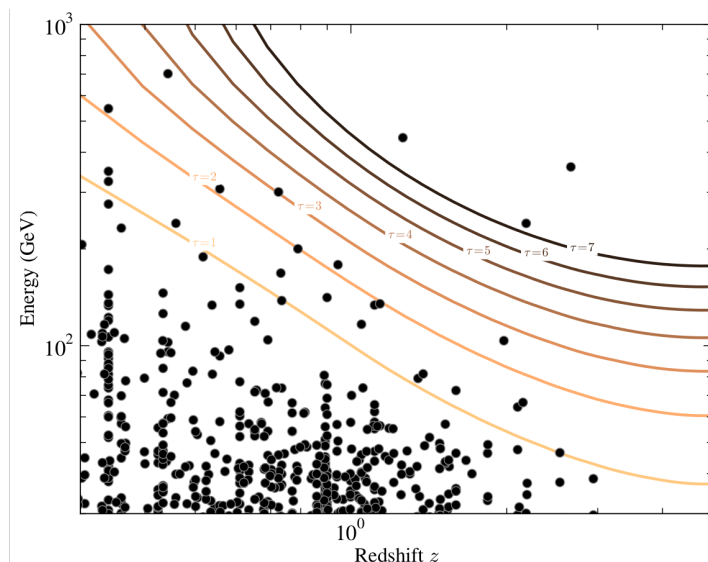


Figure 2: Photons detected at energies  $E > 10 \text{ GeV}$  associated with  $\gamma$ -ray emitting AGN with known redshift.

### 3 Summary and discussion

We have extended our previous work to search for anomalous transparency of the Universe to very-high energy (VHE)  $\gamma$ -rays to the low-energy regime covered with the Fermi-*LAT* instrument. We find three photons from three sources with optical depth  $\tau > 2$ . The combined probability to detect these photons is (post-trial)  $1.17 \times 10^{-4}$  corresponding to  $(3.68 \sigma)$ . The on-going observation as well as improvements of data-analysis will increase the sensitivity to search for deviations from the expected (astrophysical) transparency for gamma-rays. Future observations carried out with the next generation of ground-based air Cherenkov telescopes (Cherenkov telescope array: CTA [2]) will bridge the energy gap between the energy range covered with today's ground based installation and space-based telescopes and therefore will be sensitive to confirm the indications for anomalous transparency.

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