Very high energy optical depth of the universe

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Abstract. The propagation of very energetic gamma-rays at GeV–TeV energies over cosmological distances is mainly affected by pair-production on the soft background photon field. The resulting energy dependent absorption is sensitive to the level of background photon field present along the line of sight as well as to possible modifications of the pair-production process. In this study, we focus on the latter aspect by fixing the absorption to the guaranteed level by invoking a minimum model for the background photon field. The result of the study suggests (at the level of 4.2 standard deviations) that the intrinsic spectra (after correction for absorption) show a significant upturn at the transition from optically thin to optically thick. The observation is not explained by known systematic effects related to the instrument (e.g. energy scale, spectral bias). By construction, neither the intrinsic source spectra nor the background photon field can be responsible for the observed effect unless either an un-realistic fine-tuning of the sources or a substantially lower level of the background light below the guaranteed level is realized in nature. We conclude, that the origin of the observed effect is most likely related to an anomaly of the pair-production process similar to the effect predicted in the case of a pseudo-scalar (axion-like) field.

1. Introduction
The pair-production of energetic gamma-rays with low-energy background photons of the extra-galactic background light (EBL) and the expected absorption have been investigated already 50 years ago [1, 2]. Despite on-going efforts to measure the absolute level of background-light, uncertainties are large and therefore, the predicted optical depth $\tau$ is of similar uncertainty. The absolute level of background light is difficult to determine from observations given the overwhelmingly strong foreground emission (see e.g. [3] for a review). With increasing accuracy of observational data on star-formation rates as well as understanding of spectral modelling of galactic emission, predictions of the EBL have been continuously refined (for recent calculations see e.g. [4, 5, 6, 7, 8]). On the other hand, the observation and spectroscopy of extra-galactic objects at TeV energies have become a powerful tool to constrain the level of the EBL indirectly [9]: under various assumptions or measurements on the shape of the emitted spectrum, the level [10, 11] as well as shape [12, 13, 14, 15] of the EBL spectrum has been constrained in a competitive way. With the detection of sources at increasing redshifts, the latest upper limits on the EBL [16] are uncomfortably close to the EBL level predicted by the resolved sources of light.
A number of phenomenological considerations have been put forward to explain the apparent transparency of the Universe. The approaches fall roughly in three categories: (i) source-intrinsic [17, 18, 19, 20, 21], (ii) production of gamma-rays en route (cascading) [22, 23, 24], and (iii)
non-standard propagation of photons [25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. In this proceedings article, the main results of [35] are summarized with an extended discussion.

2. Summary of the observations used
The data sample is based upon an extensive collection of published energy spectra taken with the HEGRA, Whipple, CAT, HESS, MAGIC, and VERITAS air Cherenkov telescopes. In total, 50 spectra of 25 different sources have been considered after discarding sources without confirmed spectral measurements of the redshift. The 389 individual spectral points $\phi_i(E_i, z_j)$ are indicated in the plane of energy vs. redshift in Fig. 1.

3. Analysis method and result
For each data point $\phi_i(E_i, z_j)$, a corresponding lower limit on the optical depth $\tau(E_i, z_j)$ is calculated using the minimum EBL model of [7]. The flux measurements are corrected for the effect of absorption $\Phi_i(E_i, z_j) = \exp(\tau) \phi_i$. We employ two different statistical (KS and RES) tests to compare the data points observed at large optical depth (search sample $S = \{\Phi_i|\tau > 2\}$) with the data points observed at smaller optical depth (base sample $B = \{\Phi_i|1 < \tau \leq 2\}$). A very robust test for this task is the Kolmogorov-Smirnov (KS) test which does not rely on any knowledge of the underlying distributions. In order to construct a test which is sensitive to spectral changes, we fit a power law or whenever required ($p(\chi^2) < 0.05$) a curved power law to the data points which are observed at small optical depth $\tau \leq 1$. This fitting function $f_{id}$ is obtained for every source spectrum (labelled id) with at least 2 data points at $\tau \leq 1$ and then extrapolated for the two samples $S$ and $B$ such that the ratio is calculated $R = (\Phi_i - f_{id}(E_i))/ (\Phi_i + f_{id})$ and a KS-test is carried out between $B$ and $S$. The resulting probability that the samples are drawn from the same underlying distribution is $p = 1.7 \times 10^{-5}$ ($S = 4.2 \sigma$). For the RES test, the distributions of residuals normalized to the measurement uncertainty $\chi_i = (\Phi_i - f_{id}(E_i))/\sigma(\Phi_i)$ is compared between the two samples (note, the fit is now derived from the entire spectrum id). Again, a similarly small $p$-value is obtained, confirming the result.

A systematic and significant shift of the measurements with respect to the extrapolation/expectation is observed indicating that the applied correction for minimum absorption is too large.

4. Discussion
Before addressing the possible explanations related to physical processes, it is necessary to verify that the effect is not related to systematic effects of the instruments like calibration of the

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1 Nearby sources like M 87 and Cen A have not been considered
absolute energy scale [36], bias in the spectral reconstruction (spill-over effects, selection effects), or by the method. As demonstrated in [35], the systematic effects in the worst-case scenario (maximum down-ward shift of the energy-scale, unreliable measurements at the end-point of the spectra) do not suffice as a remedy. We therefore conclude that the observed effect is not explainable with known instrumental issues.

Finally, the observations can in principle be explained (as outlined in the introduction) through (i) source-intrinsic effects, (ii) secondary radiation from cascades, or (iii) modifications of photon-propagation. Even though the observed spectral hardening takes place for all sources at widely different energies (0.4–21 TeV), it takes place at the onset of large optical depth. Generally, the required fine-tuning excludes source-intrinsic effects to explain all of the observations. The proposal (ii) of secondary radiation from cascading of ultra-high energy protons/nuclei to be responsible for the bulk of the observed emission is a possibility to circumvent the optical depth problem. However the nature of the cascade evolution would wash out source intrinsic variability. Even though a number of large redshift blazars are suspiciously steady in flux, observations of broad-band ($E > 1$ TeV) variability of sources like 1ES1218+304 ($z = 0.184$) [37], 1ES0229+200 ($z = 0.140$) [38], and $H1426 + 428$ ($z = 0.129$) [39] is not supporting the proposed cascade mechanism.

Finally, modifications of the standard picture of photon-propagation have been proposed including formation of Bose-Einstein condensates [34] (BEC), violation of Lorentz invariance [25, 26, 27] (LIV), and effective mixing of photons with pseudo-scalars (axion-like particles: ALPS, for reviews see [40, 29]). The predicted phenomenology is largely different between these scenarios and is testable through observations. The formation of BEC has been tested observationally, excluding that a large fraction of the photons detected from Mkn 501 are condensates [41]. Based upon a simple coherence argument [42], this possibility appears also from a theoretical point of view unlikely. In the case of LIV in the neutral (photon) sector, the energy threshold for pair-production is shifted which affects essentially a fixed energy scale and is therefore not consistent with the observations.

Finally, an intriguing possibility is the presence of ALPS which could modify the generation of gamma-rays in the source [43, 44], during the propagation in the inter-galactic medium [45, 30, 33], as well as in the interstellar medium in the Galaxy [46]. Through the Primakoff-process, gamma-rays mix with light ALPS depending on the strength of the magnetic field $B$ and the coupling $g_{a\gamma}$ [47]. In general, the expected behaviour in an ALPS-related scenario resembles the effect reported here: At a sufficiently large optical depth, the (in the strong mixing regime energy-independent) conversion and re-conversion probability is larger than the survival probability $\exp(-\tau)$. For the case of conversion/re-conversion taking place in inter-galactic space, such a large probability requires roughly $g_{a\gamma} \cdot B > 5 \cdot 10^{-12}$ GeV$^{-1}$ nG and a mass $m_{\text{ALPS}} < 10^{-9}$ eV which is formally not excluded (and can be probed with next-generation light shining through the wall experiments). This region is still consistent with the scenario that ALPS form dark matter with $N > 1$ [48] and explain the anomalous cooling of white dwarfs [49].

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