



## New Limits on the Density of the Extragalactic Background Light from TeV Blazars

DANIEL MAZIN<sup>1</sup> AND MARTIN RAUE<sup>2</sup>.

<sup>1</sup>Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München

<sup>2</sup>Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg  
martin.raue@desy.de

**Abstract:** The star and galaxy formation history has left an imprint on the diffuse extragalactic radiation field in the ultraviolet to infrared wavelength regime. In the spectral energy distribution two distinct bumps are expected: A first bump in the optical to near-infrared coming from direct starlight redshifted over time and a second bump in the infrared from dust-reemission. Direct measurements of this extragalactic background light (EBL) have proven to be difficult, especially in the mid-infrared where foregrounds dominate (zodiacal light). The observation of distant sources of VHE  $\gamma$ -rays via Imaging Cherenkov Telescopes can provide an indirect measurement of the EBL: The VHE  $\gamma$ -rays are attenuated via pair production and the observed spectra therefore carry an imprint of the EBL. With assumptions about the source spectrum limits on the EBL can be derived. Since the detection of the first extragalactic VHE  $\gamma$ -rays source this technique has been applied in various forms to many of the available spectra. In this paper we describe a generic way to derive limits on the EBL by using a scan on a grid in wavelength vs EBL density and using only minimal assumptions about the source spectrum. These technique allows to explore a wide range of EBL-shapes and to treat all available spectra of extragalactic TeV-sources in a consistent way. We utilize the spectra of all TeV blazars with published spectra, making this the most complete study of this type to date. We present strong limits on the EBL in a wide wavelength range from the optical to the far-infrared.

### Introduction

The present EBL consists of the integrated electromagnetic radiation from all epochs, which is redshifted, corresponding to its formation epoch. In the energy density distribution a two peak structure is commonly expected: a first peak around  $1 \mu\text{m}$  produced by starlight and a second peak at  $\sim 100 \mu\text{m}$  resulting from starlight that has been absorbed and reemitted by dust in galaxies. However, the shape of the EBL is not yet well known and is a matter of debate.

Direct measurements of the EBL are very difficult because of strong foreground emissions, but measurements of very high energy (VHE)  $\gamma$ -rays from distant sources can provide an indirect measurement of the EBL. These VHE  $\gamma$ -rays are attenuated via pair production with low energy photons from the EBL [1]. If the intrinsic  $\gamma$ -ray spectra of distant sources would be known precisely, the EBL could be reconstructed from the attenuation imprint on

the measured spectra. Unfortunately, the intrinsic VHE spectra of distant sources are not yet fully understood. Nevertheless, with reasonable assumptions about the intrinsic spectrum emitted at the source, upper limits on the EBL density can be inferred [2, 3, 4].

We developed a novel technique of describing the EBL number density by spline functions, which allows to test a large number of hypothetical EBL shapes. We use spectra from all TeV blazars detected so far to derive upper limits on the EBL density in a wide wavelength range from the optical to far-infrared. The aims of this work are:

1. Provide limits on the EBL density, which do not rely on a predefined shape or model.
2. Treat all TeV blazar spectra in a consistent way, using simple and generic assumptions about the intrinsic VHE  $\gamma$ -ray spectra and statistical methods to find exclusion criteria.

3. Use spectral data from all detected TeV blazars to (a) derive upper limits on the EBL density from the individual spectra and (b) combine these results into a single limit on the EBL density for a wide wavelength range.

## Technique

**Grid Scan of the EBL with Splines:** A spline parameterization is used to construct a set of EBL shapes using a grid in EBL energy density vs. wavelength. The x-positions of the grid points (wavelength) are used as positions for the supporting points of the spline. The y-positions of the grid points (energy density of the EBL) are used as weights. For the scan a subset of grid points is selected (Fig. 1, top) such that all resulting shapes are within the limits given by the galaxy counts on the lower end and the limits from the direct measurements and the fluctuation analyses on the upper end. The highest and the lowest tested EBL shapes are shown in comparison with the existing direct EBL measurements in Fig. 1 (bottom). By iterating over all grid points we obtain 8 064 000 different EBL shapes, which will be examined. Noteworthy, extremely sharp and strong cut-offs or bumps can only be described in an approximate way. Such features are generally not expected since they would be smoothed out by redshift.

**TeV Blazar Sample:** In this study we utilize spectral data obtained during the last seven years by four different experimental groups operating ground-based imaging atmospheric Cherenkov telescopes: WHIPPLE, HEGRA, H.E.S.S. and MAGIC. We select at least one spectrum for every extragalactic source with known redshift. If there is more than one measurement with a comparable energy range, we take the spectrum with the better statistics and the harder spectrum. If different measurements of one source cover different energy ranges, we include both spectra as independent tests. The selected spectra are shown in Fig. 2.

**Exclusion Criteria for the EBL shapes:** In order to construct an upper limit on the EBL, we examine every EBL shape, whether the intrinsic TeV blazar spectra, which result from correcting the measured spectra for the corresponding optical depths, are

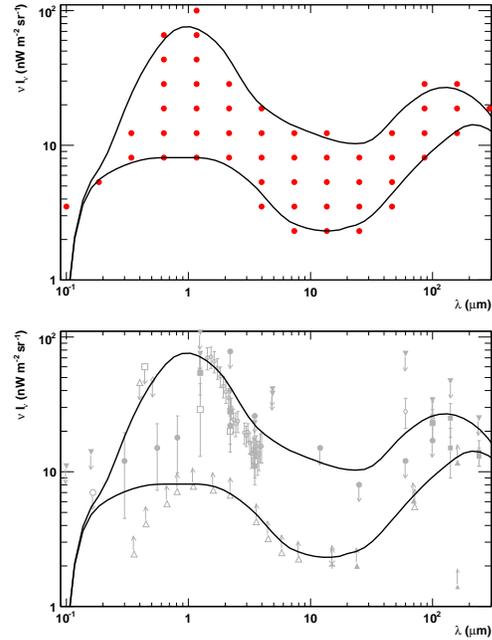


Figure 1: *Top:* Chosen grid points (red filled circles) and minimum and maximum shape of the scan. *Bottom:* Minimum and maximum shape overlaid on different EBL measurements and limits [5].

physically feasible. EBL shapes are considered to be allowed if the intrinsic spectra of all tested TeV blazars are not excluded. As upper limit we define the upper envelope of all allowed shapes. It is constraining in the wavelength range where it lies below the maximum shape of the scan. Otherwise no upper limit is quoted.

The exclusion criteria are defined as follows: for each intrinsic spectrum an analytical description giving a satisfactory probability is found. The parameters of the analytical function are examined for: (1) hardness of the spectrum and its parts and (2) significant pile-up at high energies. The theoretical expectations on the smallest possible photon index  $\Gamma^{\text{limit}}$  have a certain spread. Thus, two scans are performed, one with a limit of  $\Gamma^{\text{limit}} = 1.5$ <sup>1</sup> on the hardness of the spectrum (we call it *realistic* scan) and another scan with a limit of  $\Gamma^{\text{limit}} = 2/3$  (labeled *extreme* due to extreme physics scenario

<sup>1</sup> hardness  $\Gamma$  defined for the photon spectrum  $dN/dE \propto E^{-\Gamma}$

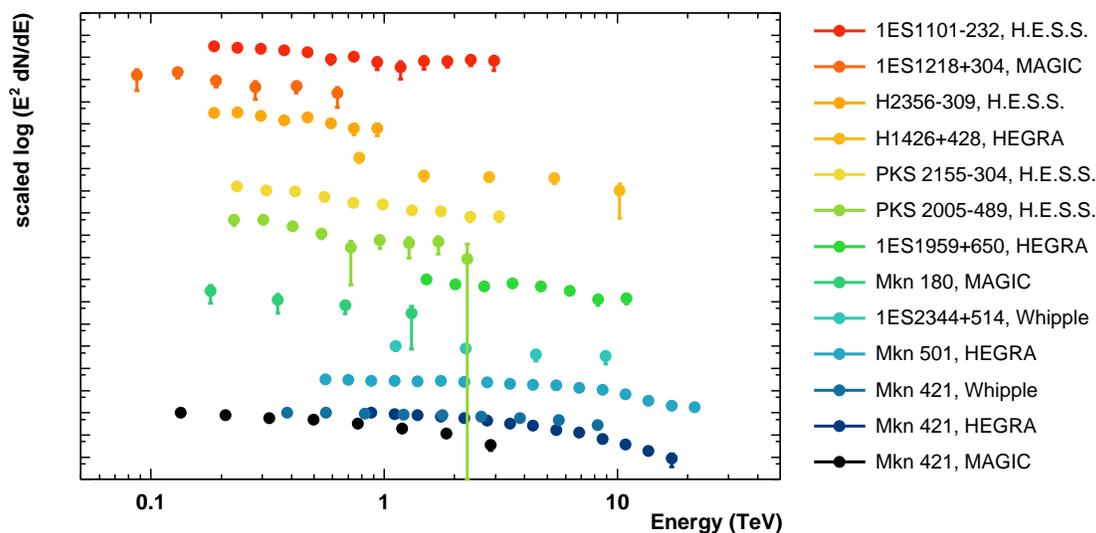


Figure 2: TeV blazar sample utilized in this study. The spectra are multiplied by  $E^2$  to emphasize spectral differences and are spread out along the Y-axis and ordered in redshift to avoid cluttering of the plot. The redshifts range from 0.03 (Mkn 421) to 0.186 (1ES 1101-232).

required for such a hard photon spectrum). A detailed description of the method and the obtained results can be found in [5].

## Results and Conclusions

While examining EBL limits derived from individual TeV spectra, we find that there are three spectra giving the strongest constraints in different wavelength ranges: (1) The spectrum of 1ES 1101-232 with its large redshift of  $z=0.186$  gives the strongest constraints in the NIR (dashed-dotted red line in Fig. 3, top). (2) The spectrum of H 1426+428 gives the strongest constraints in mid IR (short dashed yellow line in the Fig. 3, top)). (3) The Mkn 501 gives the strongest constraints in the far IR (long dashed blue line in the Fig. 3, top). Combining the individual results, i.e. allowing a certain EBL shape only if it gives a feasible intrinsic spectrum for all tested TeV blazars, we obtain an even stronger upper limit (black line in the Fig. 3, top). This envelope is our final result for the *realistic* scan. The derived upper limit for the *extreme* results in a looser upper limit (dashed line in Fig. 3, bottom). However, we conclude that even

in case of the *extreme* scan several claimed direct detections of the EBL in the NIR regime can be excluded. Moreover, the derived upper limits for the *realistic* scan are just a factor of 2 to 2.5 above the absolute lower limits from source counts. Alternatively, the assumptions made about the physics of TeV blazars could be wrong, which would require a substantial modification to the current standard model.

The strong constraints derived in this paper only allow for a rather low level of the EBL in the optical to the far-infrared, suggesting that the universe is more transparent to VHE  $\gamma$ -rays as previously thought. Hence, we expect detections of many new extragalactic VHE sources in the next few years. Further multi-wavelength studies of TeV blazars will improve the understanding of the underlying physics, which will help to refine the exclusion criteria for the VHE spectra in this kind of studies. The upcoming GLAST satellite experiment, operating in an energy range from 0.1 up to  $\sim 100$  GeV, will allow to extend such studies of the EBL to the ultraviolet to optical wavelength region.

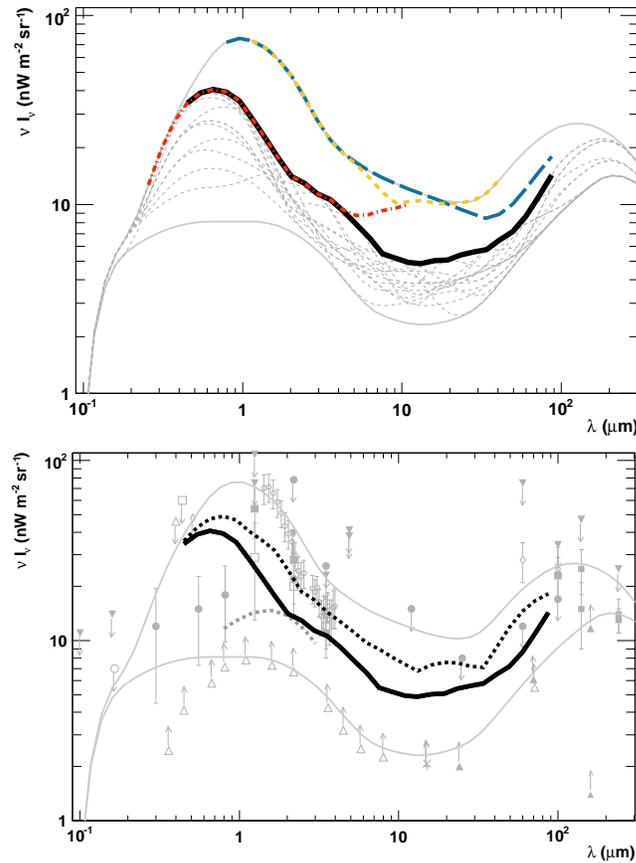


Figure 3: *Top*: Combined results for the *realistic* scan. Maximum allowed shapes of the combined scan (thin dashed grey lines) and the corresponding envelope shape (thick black line) in comparison to the limits for individual spectra: Mkn 501 (long dashed blue line), H 1426+428 (short dashed yellow line) and 1ES 1101-232 (dashed-dotted red line). *Bottom*: The combined limit from the *realistic* (solid black line) and the *extreme* (dashed black line) scans in comparison to direct measurements and limits (grey marker). The grey dashed curve around  $2 \mu\text{m}$  is the limit derived by [4].

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