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Potential of the next generation VHE instruments to probe the EBL (I): the low- and mid-VHE

Daniel Mazin
Institut de Fisica d'Altes Energies (IFAE)
Edifici Cn. Universitat Autonoma de Barcelona
ES-08193 Bellaterra (Barcelona), Spain
E-mail: mazin@ifae.es

Martin Raue
University of Hamburg, Institute for Experimental Physics
Luruper Chaussee 149
D-22761 Hamburg, Germany
E-mail: martin.raue@desy.de

The diffuse meta-galactic radiation field at ultraviolet to infrared wavelengths - commonly labeled extragalactic background light (EBL) - contains the integrated emission history of the universe. Difficult to access via direct observations, indirect constraints on its density can be derived through observations of very-high energy (VHE; E>100 GeV) γ-rays from distant sources: the VHE photons are attenuated via pair-production with the low energy photons from the EBL, leaving a distinct imprint in the VHE spectra measured on earth. Discoveries made with current generation VHE observatories like H.E.S.S. and MAGIC enabled strong constraints on the density of the EBL, especially in the near-infrared. In this article the prospect of future VHE observatories to derive new constraints on the EBL density are discussed. To this end, results from current generation instruments will be extrapolated to the future experiment's sensitivity and investigated for their power to enable new methods and improved constraints on the EBL density.

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1. Introduction

The observation of very-high energy γ-rays (VHE; $E > 100\,\mathrm{GeV}$) from distant sources offers the unique possibility to probe the density of the meta-galactic radiation field at ultraviolet (UV) to infrared (IR) wavelengths, which is commonly labeled the extragalactic background light (EBL; typically 0.1-100 μm). The VHE γ-rays interact with the low energy EBL photons via the pair production process ($\gamma_{\mathrm{VHE}}\gamma_{\mathrm{EBL}} \rightarrow e^{+}e^{-}$) and the flux is attenuated [1, 2]. This attenuation can leave distinct signatures in the measured VHE spectra. With assumptions about the source physics and the spectrum emitted at the source location (intrinsic spectrum), constraints on the density of the EBL can be derived [3, 4].

The current generation of VHE instruments (H.E.S.S., MAGIC, VERITAS) significantly increased the number of known extragalactic VHE sources from 4 in the year 2003 to more than 25 today. These discoveries, combined with the advanced spectral resolution of these instruments and the wide energy range they cover, led to new strong constraints on the EBL density, in particular at optical to near-IR (NIR) wavelengths [5, 6, 7]. Since these limits depend on assumptions about the source physics, the strong constraints also sparked intense discussions on the validity of the assumptions and possible caveats [8, 9]. This discussion has not yet converged and there are interesting arguments for both sides.

Current generation systems have recently been upgraded (MAGIC II) or the upgrades are under construction (H.E.S.S. II). These upgrades are mainly aimed to improve the overall sensitivity by a factor two to three and extend the energy range toward the lower energy regime of 20 to 100 GeV. This will lead to some improvements, but a quantitative difference or a breakthrough compared to the performance of the existing facilities will only be achieved with an order of magnitude improvement in sensitivity. The Next Generation Cherenkov Telescope Systems (NGCTS) are in the advanced planing phase aiming to achieve this order of magnitude improvement: the Cherenkov Telescope Array (CTA[1]) [10] and the Advanced Gamma-ray Imaging System (AGIS[2]) [11]. Whereas CTA envisions to improve the sensitivity over a wide energy range from the few tens of GeV to the multi TeV regime, AGIS mainly concentrates on energies above 100 GeV, an extended field of view and an improvement of the angular resolution. The integral sensitivities of the current and invisioned instruments are shown in Fig. 1.

The potential of these upcoming experiments to probe the EBL is the topic of this article. While an order of magnitude improvement in sensitivity for an astronomical instrument will always lead to new and unexpected results, this article will - as a first step - focus on known results and their extrapolation according to the sensitivities of the next generation instruments. Emphasis will be on new techniques enabled by the performance features (extended sensitivity and energy range) of the upcoming instruments.

For the calculations in the paper a standard ΛCDM cosmology with $h = \Omega_{\Lambda} = 0.7$ and $\Omega_{M} = 0.3$ is adopted. More dertails on the analysis and the results can be found in [12].

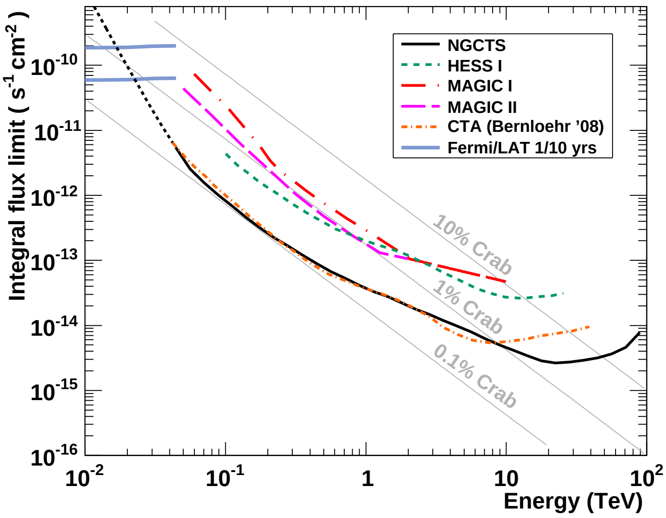

Figure 1: Integral flux sensitivity (5σ in 50 h) of the NGCTS used in this study in comparison to the sensitivity of existing observatories (H.E.S.S.: [13]; MAGIC: [14]; *Fermi*/LAT: `http://www-glast.slac.stanford.edu/software/IS/glast_lat_Performance.htm`).

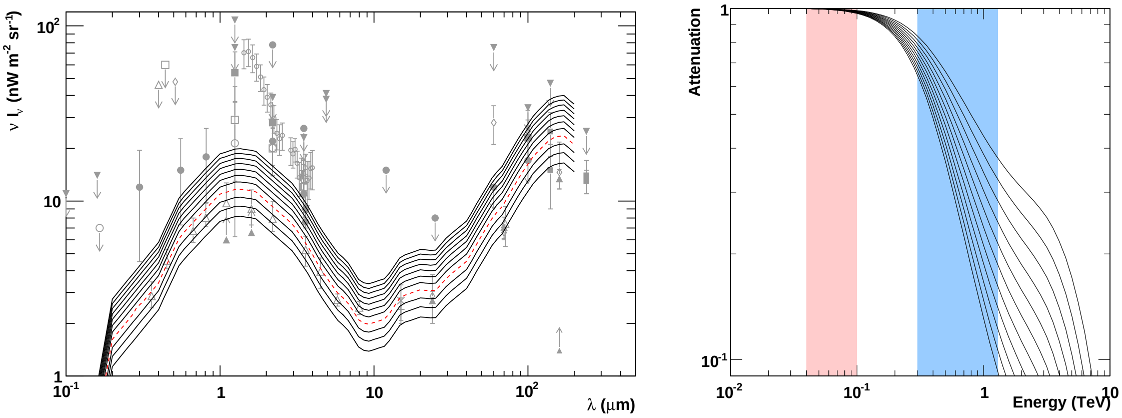

Figure 2: *Left:* EBL measurements (grey points) and the EBL models for z=0. The Fra08 model is shown by the red dotted line whereas the scaling of the model is shown by the grey solid lines. *Right:* Resulting attenuations for VHE γ-rays for a source at z=0.116 (PKS 2155-304). Each line corresponds to one EBL scaling from the left figure. The higher is the EBL density the stronger absorption is expected. The energy marked in red corresponds to the fit range for the unabsorbed part of the spectrum, whereas the energy range marked blue to the absorbed one.

2. Basic assumptions and simulation details

The precise level of the EBL density is not well known. To account for the uncertainty in the EBL density, scaling of the EBL density presented in [15] and the model of [16] (Fran08 in the following) is adopted. The scaled EBL densities of Fran08 together with direct and indirect EBL

[1]http://www.cta-observatory.org/
[2]http://www.agis-observatory.org/

measurements are shown in Fig. 2, left plot. The resulting attenuations for γ-rays for a source at a distance z=0.116 (like PKS 2155-304) are shown in Fig. 2, right plot.

In this paper two different methods to derive limits on the EBL density will be explored: (i) utilizing the unabsorbed part of the VHE spectrum and (ii) searching for attenuation modulation signatures. While not completely new, it will be shown that with the NGCTS's extended energy range paired with its vastly improved sensitivity it will be possible to utilize these methods effectively for the first time. Method (i) holds the potential to derive limits on the EBL density with a minimal set of assumptions, while method (ii) enables to not only derive upper limits on the EBL density but to probe the absolute level.

To simulate the VHE spectra of distant sources, which will be detected by the NGCTS, assumptions about the sensitivity of the instrument have to be made. As baseline sensitivity, the sensitivity of the "4 large + 85" CTA array presented in [13] is taken and the sensitivity is derived assuming an effective detector area (effective area) and a background rate. For the effective area the post cut MAGIC effective area at 20 deg zenith angle ([17]) scaled up by a factor 20 is adopted to reach an effective area exceeding $10^6 \mathrm{m}^2$ at energies above a few hundred GeV. In addition, the MAGIC effective area is shifted by a factor of 2 to lower energies to reflect the improved sensitivity at low energies.

3. Utilizing the unabsorbed part of the spectrum

Simulation & analysis chain The following simulation and analysis chain is utilized:

1. Calculate EBL attenuation for a specific EBL density and source distance.
2. De-attenuate a measured spectrum and fit with power law ($dN/dE = \Phi_0 \cdot E^{-\Gamma}$). The fit results serve as input flux function for the simulated spectrum.
3. Simulate spectrum as measured by an NGCTS with calculated input flux function.
4. Fit simulated spectrum in a low energy regime (intrinsic spectrum) and high energy regime (absorbed spectrum). Again, a simple power law function is used in each energy regime.
5. 200 spectra are simulated and mean values are used.

An example for this procedure is shown in Fig. 3 (left panel) for the quiescence spectrum of PKS 2155-304 ($z = 0.116$). An observation time of 20 h has been assumed, which could easily be extended given that this is a steady flux state. As EBL model the Fran08 model is used, scaled in steps of 0.1 from 0.7 to 1.7 (Fig. 2).

EBL attenuation spectral break Fig. 3 right panel shows the spectral index resulting from the power law fit for the two energy bands for the different scalings of the EBL model. The markers show the mean spectral index of the fits, with the error given as the RMS of the mean spectral index distribution (shaded bands). The black crosses mark the spectral index utilized for the input source spectrum. It can be seen that the fit in the low energy band reproduces very well the assumed intrinsic spectral indices. For the highest scaled EBL densities the effect of attenuation becomes relevant in the low energy band and the spectral index from the fit is steeper (larger) than the

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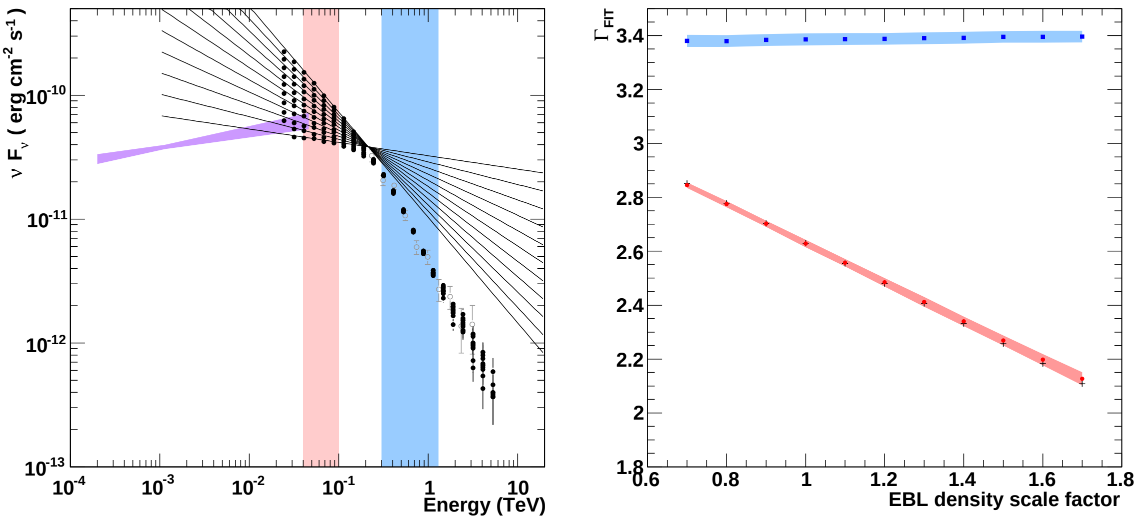

Figure 3: *Left:* Example of simulated spectra of of PKS 2155-304 in the quiescent state (20 h observation time). for different EBL densities, EBL model is from Fran08. Shown are: the measured spectrum (grey markers), the simulated spectra for different level of the EBL density (black markers) and the corresponding assumed intrinsic spectra (black lines), the source spectrum in the GeV energy range as measured by *Fermi*/LAT [18] (purple butterfly), and the energy ranges which are used to determine the slope of the simulated spectrum at low (blue) and high (red) energies. *Right:* Results from the power law fit to the simulated spectrum as a function of the EBL scaling. The spectral index in the unabsorbed (absorbed) part is shown by blue (red) points together with the corresponding error bar. The dependence of the spectral break (difference between the two indexes) as a function of the EBL scaling is clearly seen.

one from the input spectrum. The difference between the fitted spectral index in the unabsorbed spectral part and the spectral index in the absorbed part represents the derived spectral break due to the EBL. An EBL density scale factor of 0.1 corresponds to one to two standard deviations difference in the strength of the break. This means if the Fran08 EBL model is correct and the intrinsic spectrum follows a power law in the energy range considered a 1.3 scaling of the model could be excluded with 3 standard deviations. Note that a scaling of 0.1 corresponds to an EBL density of $\sim$1 nW m^{-2}sr^{-1} at 2 μm which is of the same order as the error on the lower limits from integrated source counts at this wavelength. The detection of a break with certain strength can be converted into an upper limit of the EBL density.

4. Attenuation modulation at mid-energies

Smoothness of AGN spectra The measured energy spectra of AGNs in the energy range between 100 GeV and few TeV follow usually a smooth shape. For most of the measured sources, a simple power law fit is sufficient to describe the available data well, whereas for sources in a flare state (like the flare of PKS 2155-304 in 2006) or with a generally high emission state (like Mkn 421), either a curved power law or a power law with a cut-off are successfully used. The curved power law (also known in the literature as the double-log parabola) is expected to describe the spectra well at energies close to the position of the Inverse-Compton peak. The power law with a cut-off instead

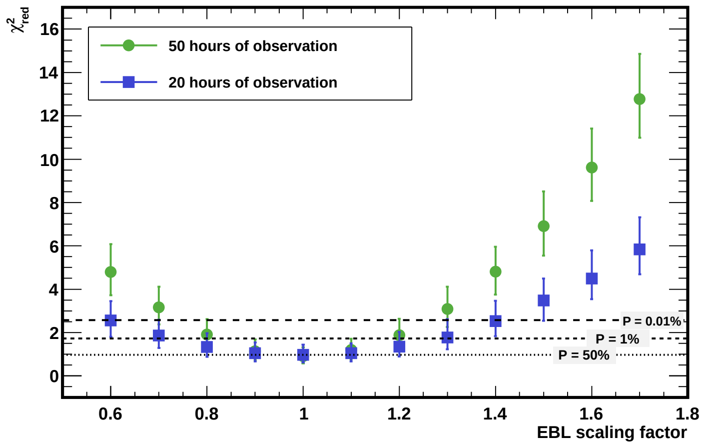

Figure 4: Quantitative results from the search for EBL signatures in the mid-VHE using the energy spectrum of Mkn 501. Shown are the reduced χ^2 values from the fits to the reconstructed spectra of Mkn 501 as a function of EBL scaling factor. Blue filled squares and green filled circles show the expected result for 20 and 50 hours of NGTCS observations, respectively. The black horizontal lines correspond to fit probabilities as labeled.

is the expected behavior of a source which does not provide necessary conditions for acceleration of charged particles to sufficiently high energies. All scenarios do have one common feature: the measured spectra can be described by smooth functions,i.e., no features, wiggles or pile-ups are expected, especially after de-convolving the spectra for the effect of the EBL absorption. This property can, therefore, be used to distinguish between different overall EBL levels in the optical to infrared regime: whereas the "correct" EBL model and level will produce a smooth intrinsic AGN spectrum, an "incorrect" EBL level would result in a signature (in form of well defined wiggles) in the reconstructed intrinsic spectrum.

Th strength to measure wiggles due to a "incorrect" EBL in the reconstructed spectrum is shown in Fig. 4 on the example of a strong flare of Mkn 501 (z=0.034). An EBL scaling is considered to be excluded when the mean reduced χ^2 value including its 68% error exceeds the χ^2 value for P=0.01%. For the case constructed here this means that in case of 50 hours observation, the EBL scalings below 0.65 and above 1.35 are excluded. In the case of 20 hours observation, the EBL scalings above 1.50 are excluded. As one can see, the method is not only sensitive in constraining the EBL density but it is also a first attempt to resolve the actual EBL level.

5. Conclusions

In this paper the potential of a Next Generation Cherenkov Telescope System (NGCTS) to study the EBL through observations of VHE spectra from distant sources is explored. In the focus of the study lies the energy range between 40 GeV and 10 TeV, where a factor 10 improvement in sensitivity over current generation experiments is expected. Two different methods are investigated: (i) utilizing the unabsorbed part of the VHE spectrum in the energy range 40-100 GeV and (ii) searching for attenuation modulation signatures at energies between 100 GeV to 7 TeV. While some caveats, like e.g. the exact shape of the intrinsic spectra, do exist, overall the two methods show promising results, clearly go beyond what is possible with current generation instruments.

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