Blazars as beamlights to probe the Extragalactic Background Light in the Fermi and Cherenkov telescopes era

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The Extragalactic Background Light (EBL) is the integrated light from all the stars that have ever formed, and spans the IR-UV range. The interaction of very-high-energy (VHE: $E > 100\text{GeV}$) $\gamma$-rays, emitted by sources located at cosmological distances, with the intervening EBL results in $e^-e^+$ pair production that leads to energy-dependent attenuation of the observed VHE flux. This introduces a fundamental ambiguity in the interpretation of the measured VHE blazar spectra: neither the intrinsic spectra, nor the EBL, are separately known – only their combination is. In this paper we propose a method to measure the EBL photon number density. It relies on using simultaneous observations of blazars in the optical, X-ray, high-energy (HE: $E > 100\text{MeV}$) $\gamma$-ray (from the Fermi telescope), and VHE $\gamma$-ray (from Cherenkov telescopes) bands. For each source, the method involves best-fitting the spectral energy distribution (SED) from optical through HE $\gamma$-rays (the latter being largely unaffected by EBL attenuation as long as $z \lesssim 1$) with a Synchrotron Self-Compton (SSC) model. We extrapolate such best-fitting models into the VHE regime, and assume they represent the blazars’ intrinsic emission. Contrasting measured versus intrinsic emission leads to a determination of the $\gamma\gamma$ opacity to VHE photons – hence, upon assuming a specific cosmology, we derive the EBL photon number density. Using, for each given source, different states of emission will only improve the accuracy of the proposed method. We demonstrate this method using recent simultaneous multi-frequency observations of the blazar PKS 2155-304 and discuss how similar observations can more accurately probe the EBL.

I. INTRODUCTION

The Extragalactic Background Light (EBL), in both its level and degree of cosmic evolution, reflects the time integrated history of light production and re-processing in the Universe, hence the history of cosmological star-formation. Roughly speaking, its shape must reflect the two humps that characterize the spectral energy distributions (SEDs) of galaxies: one arising from starlight and peaking at $\lambda \sim 1\text{µm}$ (optical background), and one arising from warm dust emission and peaking at $\lambda \sim 100\text{µm}$ (infrared background).

Direct measurements of the EBL are hampered by the dominance of foreground emission (interplanetary dust and Galactic emission), hence the level of EBL emission is uncertain by a factor of several.

One approach has been modeling the EBL arising from an evolving population of galactic stellar populations: however, uncertainties in the assumed galaxy formation and evolution scenarios, stellar initial mass function, and star formation rate have led to significant discrepancy among models (e.g., [13, 14, 21, 23, 25]). These models have been used to correct observed VHE spectra and deduce (EBL model dependent) ‘intrinsic’ VHE $\gamma$-ray emissions.

The opposite approach, of a more phenomenological kind, deduces upper limits on the level of EBL attenuation making basic assumptions on the intrinsic VHE $\gamma$-ray shape of AGN spectra: assuming, specifically, that the VHE photon index must be $\Gamma \geq 1.5$; e.g., ([3, 16, 18]); but see ([26]), or that the same-slope extrapolation of the observed Fermi/LAT HE spectrum into the VHE domain exceeds the intrinsic VHE spectrum there ([9]). The only unquestionable constraints on the EBL are model-independent lower limits based on galaxy counts ([6, 8]). It should be noted, however, that the EBL upper limits in the 2–80µm obtained by [18] combining results from all known TeV blazar spectra (based on the assumption that the intrinsic $\Gamma \geq 1.5$) are only a factor $\approx 2$–2.5 above the absolute lower limits from source counts. So it would appear that there is little room for additional components like Pop III stars, unless we miss some fundamental aspects of blazar emission theory (which we never observed in local sources, however).

An attempt to measure the EBL used the relatively faraway blazar 3C 279 as a background light source ([24]), assumed that the intrinsic VHE spectrum was known from modeling and extrapolating the (historical) average broad-band data. However, blazars are highly variable sources, so it’s almost impossible to determine with confidence the intrinsic TeV spectrum – which itself can be variable.

In this paper we propose a method to mea-
sure the EBL that improves on [24] by making a more realistic assumption on the intrinsic TeV spectrum. Simultaneous optical/X-ray/HE/VHE (i.e., eV/keV/GeV/TeV) data are crucial to this method, considering the strong and rapid variability displayed by most blazars. After reviewing features of EBL at large redshift, in sect. 4 we describe our technique, in sect. 5 we apply it to recent multifrequency observations of PKS 2155-304 and determine the photon-photon optical depth out to that source’s redshift. In sect. 6 we discuss our results.

II. EBL ABSORPTION

The cross section for the reaction $\gamma\gamma \rightarrow e^+e^-$ is ([22]),

$$
\sigma_{\gamma\gamma}(E, \epsilon) = \frac{3}{16} \sigma_T(1 - \beta^2) \times \left[ 2 \beta (\beta^2 - 2) + (3 - \beta^2) \ln \frac{1 + \beta}{1 - \beta} \right],
$$

(1)

where $\sigma_T$ is the Thompson cross section and $\beta \equiv \sqrt{1 - (m_e c^2)^2/E^2}$. For demonstration purposes let us assume, following [24], that $n(\epsilon)$ is the local number density of EBL photons having energy equal to $\epsilon$ (no redshift evolution – as befits the relatively low redshifts accessible to IACTs), $z_e$ is the source redshift, and $\Omega_0 = 1$: the corresponding optical depth due to pair creation attenuation between the source and the Earth, is (see [24])

$$
\tau_{\gamma\gamma}(E, z_e) = \frac{c}{H_0} \int_0^{z_e} \sqrt{1 + z} \, dz \int_0^z \frac{x}{2} \, dx \times 
\int_{\frac{2m_e c^2}{E(1+z)^2}}^{\infty} n(\epsilon) \, \sigma_{\gamma\gamma}(2x\epsilon(1+z)^2) \, d\epsilon,
$$

(2)

where $x \equiv (1 - \cos \theta)$, $\theta$ being the angle between the photons, and $H_0$ is the Hubble constant. We further assume, again following [24], that the local EBL spectrum has a power-law form, $n(\epsilon) \propto \epsilon^{-2.55}$. Then Eq.(1) yields $\tau(E, z) \propto E^{1.55} z_e^{1.5}$ with $\eta \sim 1.5$.

This calculation, although it refers to an idealized and somewhat simplified situation, highlights an important property of the VHE flux attenuation by the $\gamma\text{VHE} \rightarrow \text{EBL} \rightarrow e^+e^-$ interaction: $\tau_{\gamma\gamma}$ depends both on the distance traveled by the VHE photon (hence on $z$) and on its (measured) energy $E$. So the spectrum measured at Earth is distorted with respect to the emitted spectrum. In detail, the expected VHE $\gamma$-ray flux at Earth will be: $F(E) = (dI/dE) \, e^{-\tau_{\gamma\gamma}(E)}$ (differential) and $F(\gtrsim E) = \int_{E}^{\infty} (dI/dE') \, e^{-\tau_{\gamma\gamma}(E')} \, dE'$ (integral).

III. BLAZAR SSC EMISSION

In order to reduce the degrees of freedom, we use a simple one-zone SSC model (for details see [28, 29]). This has been shown to adequately describe broadband SEDs of most blazars ([10, 29]) and, for a given blazar, both its ground and excited states ([27]). The reason for the one-zone model to work is that in most blazars the temporal variability is clearly dominated by one characteristic timescale, which implies one dominant characteristic size of the emitting region ([4]).

The emission zone is supposed to be spherical with radius $R$, in motion with bulk Lorentz factor $\Gamma$ at an angle $\theta$ with respect to the line of sight. Special relativistic effects are described by the relativistic Doppler factor, $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$. The energy spectrum of the relativistic electrons is described by a smooth broken power-law function of the electron Lorentz factor $\gamma$, with limits $\gamma_1$ and $\gamma_2$ and break at $\gamma_b$. In calculating the SSC emission we use the full Klein-Nishina cross section.

As detailed in [29], this simple model can be fully constrained by using simultaneous multifrequency observations. Indeed, the total number of free parameter of the model is reduced to 9: the 6 parameter specifying the electron energy distribution, plus the Doppler factor $\delta$, the size of the emission region $R$, and the magnetic field $B$. On the other hand, from observations ideally one can derive 9 observational quantities: the slopes of the synchrotron bump after and above the peak $\alpha_{1,2}$ (uniquely connected to $n_{1,2}$), the synchrotron and SSC peak frequencies ($\nu_{s,c}$) and luminosities $L_{s,c}$, and the minimum variability timescale $t_{\text{var}}$ which provides an estimate of the size of the sources through $R < ct_{\text{var}}/\delta$.

Therefore, once the relevant observational quantities are known, one can uniquely derive the set of SSC parameters.

IV. THE METHOD

The method we are proposing stems from the consideration that both the EBL and the intrinsic VHE $\gamma$-ray spectra of background sources are fundamentally unknown. In order to measure the EBL at different $z$, one should single out a class of sources that is homogeneous, i.e., it can be described by one same emission model at all redshifts. This approach is meant to minimize biases that may possibly arise from systematically different SED modelings adopted for different classes of sources at different distances. So we choose the class of source that both has the simplest emission model and has the potentiality of being seen from large distances: blazars, i.e. the AGN whose relativistic jets point toward the observer so their luminosities...
are boosted by a large factor and dominate the source flux with their SSC emission. Within blazars, we propose to use the sub-class of "high-frequency peaked BL Lacs" (HBL), because their Compton peak can be more readily detected by IACTs than other types of blazar, and because their HE spectrum can be described as a single (unbroken) power law in photon energy, unlikely other types of blazar [1, 15].

For a given blazar, our method relies on using, a simultaneous broad-band SED that samples the optical, X-ray, high-energy (HE; E > 100 MeV) γ-ray (from the Fermi telescope), and VHE γ-ray (from Cherenkov telescopes) bands. A given SED will be best-fitted, from optical through HE γ-rays, with a Synchrotron Self-Compton (SSC) model. [Photons with E ≤ 100 GeV are largely unaffected by EBL attenuation (for reasonable EBL models) as long as z ≤ 1.] Extrapolating such best-fitting SED model into the VHE regime, we shall assume it represents the blazar’s intrinsic emission. Contrasting measured versus intrinsic emission yields a determination of e^{−τ_γ(E,z)}, the energy-dependent absorption of the VHE emission coming from a source located at redshift z due to pair production with intervening EBL photons. Upon assumption of a specific cosmology, the final step is deriving the EBL photon number density.

Using, for each blazar, SEDs from different states of emission will improve the accuracy of the method by increasing the number of EBL measurements at that redshift.

### A. Best-fit procedure: χ² minimization

In order to fit the observed optical, X-ray and HE γ-ray flux with the SSC model, a χ² minimization is used. We vary the SSC model’s 9 parameters by small logarithmic steps. If the variability timescale of the flux, t_{var}, is known, one can set R ≈ c_{var}δ, so the free parameters are reduced to 8. We assume here γ_{min}=1: for a plasma with n_e=O(10) cm⁻³ and B=O(0.1) G (as generally appropriate for TeV blazar jets: e.g., 3, 7, 10), this approximately corresponds to the energy below which Coulomb losses exceed the synchrotron losses (e.g., 20, 22) and hence the electron spectrum bends over and no longer is power-law. However, in general γ_{min} should be left to vary – e.g., cases of a "narrow" Compton component require γ_{min}>1 (30). In order to reduce the run time of the code, the steps are adjusted in each run such that, a larger χ² is followed by larger steps.

### V. RESULTS: APPLICATION TO PKS 2155-304

We apply the procedure described in Sect. 4 to the simultaneous SED data set of PKS 2155-304 described in [2]. The data and resulting best-fit SSC model (from optical through HE γ-rays) are shown in Fig. 1. The extrapolation of the model into the VHE γ-ray range clearly lies below the observational H.E.S.S. data, progressively so with increasing energy. We attribute this effect to EBL attenuation, F_{obs}(E;z)≈F_{cm}(E;z)e^{−τ_γ(E;z)}. The corresponding values of τ_γ(E;z) for E=0.23, 0.44, 0.88, 1.70 TeV and z=0.12 are, respectively, τ_γ = 0.12, 0.48, 0.80, and 0.87.

We note that the SED analysis of [2] was based on a slightly different SSC model, that involved a three-slope (as opposed to our two-slope) electron spectrum. This difference may lead to a somewhat different decreasing wing of the modeled Compton hump, and hence to a systematic difference in the derived τ_γ(E;z). That said, it’s however interesting to note that the main parameters describing the plasma blob (B, δ, n_e) take on similar values in our best-fit analysis and in [2].

In Fig. 2 we compare our determination of τ_γ with some recent results [3] or upper limits [11, 14, 19]. Whereas our values are generally compatible with previously published constraints, we note that our values closely agree with the corresponding values of [3], which are derived from galaxy number counts and hence represent the light contributed by the stellar populations of galaxies prior to the epoch corresponding to source redshift z_s – i.e., the minimum amount (i.e., the guaranteed level) of EBL.

### VI. DISCUSSION

The method for measuring the EBL we have proposed in this paper is admittedly model-dependent. However, its only requirement is that all the sources used as background beamlights should have one same emission model. In the application proposed here, we have used a one-zone SSC model where the electron spectrum was a (smoothed) double power law applied to the SED of the HBL blazar PKS 2155-304. While this choice was encouraged by the current observational evidence fact that seem to HBLs have, with no exception, single-slope Fermi-LAT spectra [15], we could have as well adopted the choice [2] of a triple power law electron spectrum in our search for the best-fit SSC model of PKS 2155-304’s SED. Should the latter electron distribution be shown to provide a better fit to HBL Fermi-LAT spectra, then it would become our choice. In general, what matters to the application of this method, is that all source SEDs be fit with one same SSC model.
FIG. 1: Data (symbols: from [see 2]) and best-fit SSC model (solid curve) of the SED of PKS 2155-304. The best-fit SSC parameters are: \( n_e = 150 \text{ cm}^{-3} \), \( \gamma_{br} = 2.9 \times 10^7 \), \( \gamma_{max} = 8 \times 10^7 \), \( \alpha_1 = 1.8 \), \( \alpha_2 = 3.8 \), \( R = 3.87 \times 10^{16} \text{ cm} \), \( \delta = 29.2 \), \( B = 0.056 \text{ G} \). The obtained values of \( R \) and \( \delta \) imply a variability timescale \( t_{\text{var}} \sim R/(c\delta) \), which is compatible with the observed value of \( \approx 12 \text{ hr} \).

This work will be the subject of a forthcoming paper ([17]).

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FIG. 2: Measured values of $\tau_{\gamma\gamma}(E; z)$ for $E=0.23$, 0.44, 0.88, 1.70 TeV derived from comparing, for simultaneous observations of the HBL blazar PKS 2155-304 ($z=0.12$), the (EBL-affected) VHE $\gamma$-ray data with the eV-through-GeV best-fitting SSC model extrapolated into the TeV domain. The curves represent, for redshifts $z = 0.05$, 0.1, 0.2, 0.3, 0.4, and 0.5, the optical depth $\tau_{\gamma\gamma}(E)$ according to [8] (top left), and upper limits to it according to [11] (top right), [14] (bottom left), [19] (bottom right).

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