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A gamma-ray perspective on the cosmological optical controversy

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Background optical and infrared photon fields can interact with very high-energy (VHE, $E >$ 100 GeV) gamma-rays propagating through the universe. Absorption patterns induced in the VHE spectra of extragalactic sources can be studied to reconstruct the sum of all optical and infrared emissions from thermal processes dating back to the cosmic dark ages, the extragalactic background light (EBL). Even though the integrated galaxy light (IGL) is expected to make up the majority of the EBL, recent measurements by the New Horizons mission outside of Pluto's orbit reveal a 4σ excess in the optical band with respect to IGL. To resolve this tension, EBL studies using VHE gamma-rays must transition from an era of discovery to an era of precision. To reduce the statistical and systematic uncertainties on the measurement of the EBL, we developed a new analysis method using a fully Bayesian framework. This choice allows us to marginalize over systematic uncertainties of instrumental origin, such as the bias on the energy scale of current-generation VHE observatories. Using STeVECat, the most comprehensive catalog of VHE spectra to date, we are further able to reduce statistical uncertainties on EBL estimates by more than 30% with respect to previous analyses of archival data. We provide preliminary constraints on the origin of the New Horizons' excess, which promise an unprecedented precision in gamma-ray cosmology.

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1. Introduction

The extragalactic background light (EBL) is the aggregate of all optical and infrared emissions from thermal processes since the cosmic dark ages [1]. The main contribution to the EBL is expected to be the integrated galactic light (IGL), the combined emission from stars, dust, and other astrophysical sources within galaxies (see e.g. [2, 3]). IGL estimations are based on the observed light from resolved galaxies and statistical modeling of the sources below the instrument sensitivity. As such, they a lower-bound estimation of the EBL. In contrast, direct measurements of the EBL involve the quantification of cumulative light emissions from diffuse and resolved sources while subtracting expected foreground emissions [4]. These measurements provide an upper-bound estimation of the EBL and complement IGL estimations, jointly constraining the intensity of the EBL. However, a recent measurement by the New Horizons probe from beyond Pluto's orbit [5], where solar-system foregrounds are expected to be negligible, reported an intensity in the optical band twice as high as IGL measurements. This corresponds to a 4σ excess with respect to the IGL.

This optical controversy can be studied within observational gamma-ray cosmology: gamma-rays at very-high energy (VHE, $E > 100$ GeV) can interact with the cosmic optical and infrared backgrounds (COB, CIB), inducing absorption patterns in the VHE spectra of extragalactic sources [6]. However, measurements of the EBL using only gamma-ray data as in [7] are currently not sufficient to confirm or infirm with high statistical power an EBL excess with respect to the IGL measurements. EBL studies using VHE gamma-rays must transition from an era of discovery to an era of precision.

To reduce the statistical and systematic uncertainties on EBL reconstructions using VHE gamma-rays, we propose a new analysis method using a fully Bayesian framework. This choice allows us to use a general model for the intrinsic spectra of extragalactic sources. We are further able to marginalize over systematic uncertainties of instrumental origin, such as the potential bias on the energy scale of current imaging atmospheric Cherenkov telescopes (IACTs: H.E.S.S., MAGIC, VERITAS). We apply this framework to STeVECat [8], the most comprehensive catalog of archival VHE spectra to date, as well as contemporaneous high-energy (HE, $E > 100$ MeV) observations by *Fermi*-LAT.

In Sec. 2, we present the data samples and the framework we developed. We discuss how we model the intrinsic spectra of sources and the EBL. In Sec. 3, we present the preliminary results we obtain by applying this new framework to the data samples. In particular, we discuss the compatibility between this new EBL measurement and both the IGL and New Horizons measurements.

2. Datasets and analysis framework

2.1 Data samples

The EBL absorption of extragalactic gamma-rays is expected to be substantial in the VHE band. We study spectra from extragalactic objects that were published in journals up to 2021. The Spectral TeV Extragalactic Catalog, STeVECat [8], is to date the largest database of VHE archival spectra from extragalactic sources. From this catalog, we select non-redundant spectra with at least four spectral points (excluding upper limits), from sources with a solid redshift measurement $z > 0.01$. We present in Fig. 1 the cumulative number of sources in our data sample as a function

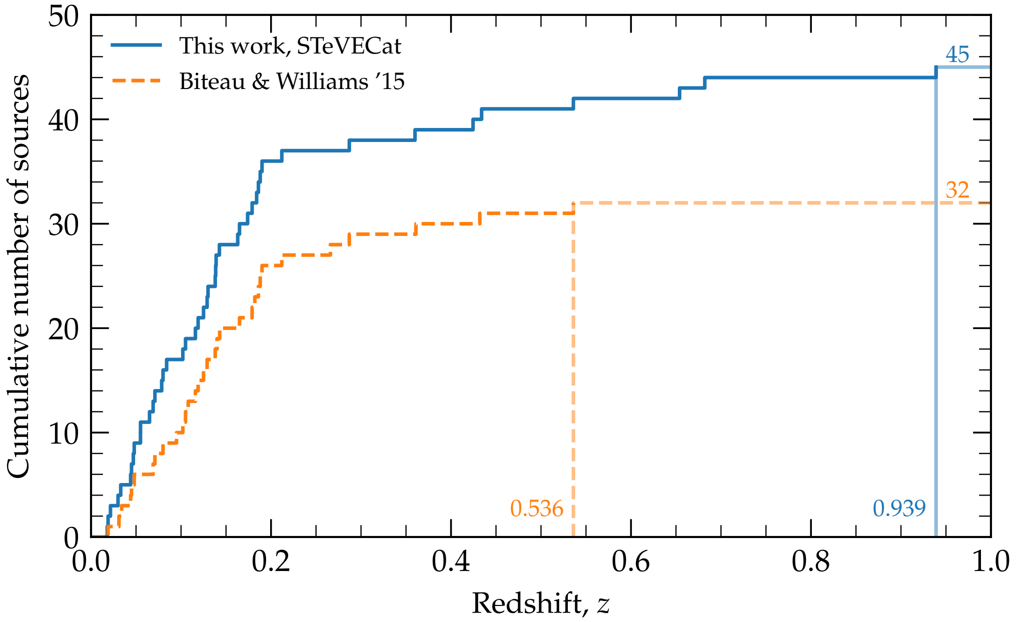

Figure 1: Cumulative number of sources as a function of source redshift. The solid blue line corresponds to the data sample used in this study, the dashed orange line corresponds to the data sample used in [7]. We note that the most distant source in our sample has a redshift almost twice as high as the most distant source from [7].

of redshift, compared to the study of [7]. Our selection amounts to 266 spectra coming from 45 distinct extragalactic sources, as opposed to 86 spectra from 32 sources in their study. Most observed sources in our data sample are AGNs, mainly from the BL Lac category (33 sources), and 3 sources are gamma-ray bursts that were observed at VHE. To date, this is the most extensive VHE spectral corpus used for an EBL study, with sources almost going up to redshift $z = 1$.

Below 100 GeV, the EBL-induced attenuation is expected to be negligible for sources with redshift $z < 1$ (e.g. [9]). Spectra observed at GeV energies can be used to constrain the non-attenuated part of the spectra emitted by the sources. When it was possible, we matched the VHE spectra to HE data, obtained by analyzing *Fermi*-LAT data during an observation period contemporaneous to the VHE observation. To ensure a reasonable exposure even for short periods, we extend the observation window for all observation periods shorter than 6h by including the 3h periods preceding and following the VHE observation. As we consider curvature in the intrinsic spectra of the sources (see Sec. 2.4), we analyzed the *Fermi*-LAT data modeling the HE spectra as log-parabolae. This analysis resulted in 95 contemporaneous observations, from which we computed the reconstructed spectral indices and curvatures that we use as priors (see Sec. 2.3).

We do not use data coming from IGL or direct measurements in this analysis. As such, our reconstruction is independent from EBL measurements coming from both of these methods.

2.2 Modeling the EBL absorption

The attenuation of the γ-ray flux at observed energy E emitted at redshift z is characterized by the EBL optical depth:

$$\tau(E,z) = \int_0^z \mathrm{d}z' \frac{\partial L}{\partial z'}(z') \int_0^\infty \mathrm{d}\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z') \int_1^{-1} \mathrm{d}\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E(1+z'), \epsilon, \mu), \tag{1}$$

where n is the number density of EBL photons, $\partial L/\partial z$ is the cosmological distance element and $\sigma_{\gamma\gamma}$ is the Breit–Wheeler cross-section. For a γ-ray source located at redshift z with an intrinsic emission spectrum Φ_{int}, the observed spectrum can be written as $\Phi_{\mathrm{obs}} = e^{-\tau(E,z)}\Phi_{\mathrm{int}}$.

In Sec. 3.1 we parameterize the EBL as a scaled version of the model from [9] with a scaling factor a. In the rest of this work, following [7], we model the EBL specific intensity at $z = 0$, $\nu I_\nu = c/4\pi \times \epsilon^2 \partial n/\partial \epsilon$, as a sum of gaussian functions with fixed means and width, leaving the amplitudes a_i free to vary:

$$\nu I_\nu(l) = \sum_i a_i \exp\left(-\frac{(l-l_i)^2}{2\sigma^2}\right), \tag{2}$$

with $l = \ln(\lambda/\lambda_{\mathrm{ref}})$. We chose the means l_i and deviation σ to match the band covered by the LORRI instrument of the New Horizons probe, which observes between 400 and 900 nm. As such, one gaussian from the model is centered around 600 nm. We model the EBL using 8 gaussian functions ranging from 200 nm to 100 μm based on the optical depth reach of our spectral corpus, and we confirm that adding other gaussians at shorter or longer wavelengths does not impact our results. We assume that the evolution and spectrum of the EBL can be locally decoupled: $\mathrm{d}\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) = \mathrm{d}\epsilon_0 \frac{\partial n}{\partial \epsilon_0} \times evol(z)$. We parameterize the EBL evolution using one parameter f_{evol}, with $evol(z) = (1+z)^{3-f_{evol}}$, choosing the value $f_{evol} = 1.2$ that best matches the evolution with redshift of the EBL model from [9].

2.3 Intrinsic spectra

The choice of intrinsic spectral model can affect the EBL reconstruction as shown by [10]. The Bayesian framework allows us to marginalize over the spectral parameters of the sources (see Sec. 2.4) to minimize this effect. We therefore chose to model the intrinsic spectra from extragalactic sources with a general model, the log-parabola with exponential cutoff (ELP):

$$\Phi_{\mathrm{ELP}}(E) = \Phi_{\mathrm{ref}} \times e^{\phi_0 - \Gamma \log{(E/E_0)} - \beta \log{(E/E_0)}^2 - \lambda \times E}, \tag{3}$$

where $E_0 = \sqrt{E_{\mathrm{min}} E_{\mathrm{max}}}$ and $\phi_{\mathrm{ref}} = \Phi(E_0)$ are fixed parameters and ϕ_0, Γ, β, λ are left free to vary.

With this framework, we can take into account systematic effects on the EBL reconstruction by considering additional nuisance parameters. In this analysis, we define an energy scale factor parameter to take into account the potential bias in the energy reconstruction of VHE observatories. Following [11], we define the energy scale factor $\varepsilon = \frac{E}{\tilde{E}} - 1$, where E is the energy reported for an event while $\tilde{E}$ is the corresponding true energy.

We therefore model the spectrum observed at Earth emitted at redshift z by

$$\Phi_{\mathrm{model}}\left(E, z\right) = e^{-\tau_{\mathrm{model}}\left(\frac{E}{1+\varepsilon}, z\right)} \times \Phi_{\mathrm{ELP}}\left(\frac{E}{1+\varepsilon}\right) \frac{1}{1+\varepsilon}. \tag{4}$$

2.4 Analysis framework

Considering some observed data $\mathcal{D}$, we search the best EBL parameters a according to the probability distribution $\mathbf{Pr}\left(a \,|\, \mathcal{D}\right) = \mathbf{Pr}\left(\mathcal{D} \,|\, a\right) \mathbf{Pr}\left(a\right) / \mathbf{Pr}\left(\mathcal{D}\right)$ where $\mathbf{Pr}\left(a\right)$ is the prior on the

EBL parameters and $\mathbf{Pr}\left(\mathcal{D}\right)$ is the *a priori* probability of the data. $\mathbf{Pr}\left(\mathcal{D} \mid a\right)$ is the likelihood used in Frequentist analysis, which quantifies the deviance between the data $\mathcal{D}$ and the values predicted by the model. We chose priors on all the parameters as uninformative priors in order to minimize the *a priori* knowledge on the expected EBL and spectral shape, with the exception of the energy-scale parameter. For this parameter, we define a gaussian prior centered around 0 and with standard deviation 0.1 following [11].

The global posterior distribution $\mathbf{Pr}\left(a \mid \mathcal{D}\right)$ can be rewritten:

$$\frac{\mathbf{Pr}\left(a \mid \mathcal{D}\right)}{\mathbf{Pr}\left(a\right)} = \prod_k \frac{\mathbf{Pr}\left(a \mid D_k\right)}{\mathbf{Pr}\left(a\right)} = \prod_k \int \mathrm{d}\theta_k \frac{\mathbf{Pr}\left(a, \theta_k \mid D_k\right)}{\mathbf{Pr}\left(a\right)}. \tag{5}$$

For each spectrum k, we independently use the Markov Chain Monte Carlo algorithm implementation `emcee` [12] to sample the posterior distribution $\mathbf{Pr}\left(a, \theta_k \mid D_k\right)$. For each pair $(a_i, a_j)_{i<j}$ of parameters from a, we marginalize over the different sets of parameters to reconstruct the bivariate distributions $\mathbf{Pr}\left(a_i, a_j \middle| D_k\right)$. We then use these distributions to compute the global bivariate distributions $\mathbf{Pr}\left(a_i, a_j \middle| \mathcal{D}\right)$, which we then use to reconstruct the posterior distribution $\mathbf{Pr}\left(a \mid \mathcal{D}\right)$. We implemented this framework using GammaPy [13, 14].

3. Preliminary results

3.1 Scaling a reference EBL model

We applied the framework developed in Sec. 2.4 to the data presented in Sec. 2.1 using a simple EBL parametrization, obtained by scaling a reference EBL model: $\tau_{\mathrm{model}}(E, z, a) = a \times \tau_{\mathrm{ref}}(E, z)$. We chose as a reference the EBL model from [9]. A factor $a = 0$ would mean that no EBL absorption is seen in the spectral corpus, while $a = 1$ would mean that the absorption is compatible with the absorption expected from the reference model. We compare three different reconstruction method. The first one is a Frequentist framework similar to the ones from [7] and [10] including a likelihood term to constrain the spectral shape with the *Fermi*-LAT best-fit index and curvature. A more complex model (e.g. with an additionnal exponential cut-off) is considered if it is favored by more than 2σ, as discussed in [10]. The other two reconstruction methods correspond to the Bayesian framework from this work, with and without the additional energy-scale factor ε.

With the Frequentist framework, we reconstruct $a_{\mathrm{Freq}} = 0.94 \pm 0.07$. With the Bayesian framework, we reconstruct $a_{\mathrm{Bayes}} = 1.00 \pm 0.06$ without the energy-scale factor, and $a_{\mathrm{Bayes},\varepsilon} = 1.09 \pm 0.07$ with it. The resulting EBL is shown in Fig. 2. The three reconstructed values are compatible with a value of one. The uncertainties on the reconstructed values are comparable to the ones obtained by [7] which, unlike this study, used IGL measurements as an additional constraining factor.

3.2 Reconstructed EBL

We applied the Bayesian framework with the energy-scale parameter ε to the data presented in Sec. 2.1, using the EBL model from Sec. 2.2. We present the resulting EBL specific intensity at $z = 0$ and the corresponding excess with respect to IGL measurements in the top and bottom part of Fig. 3, respectively.

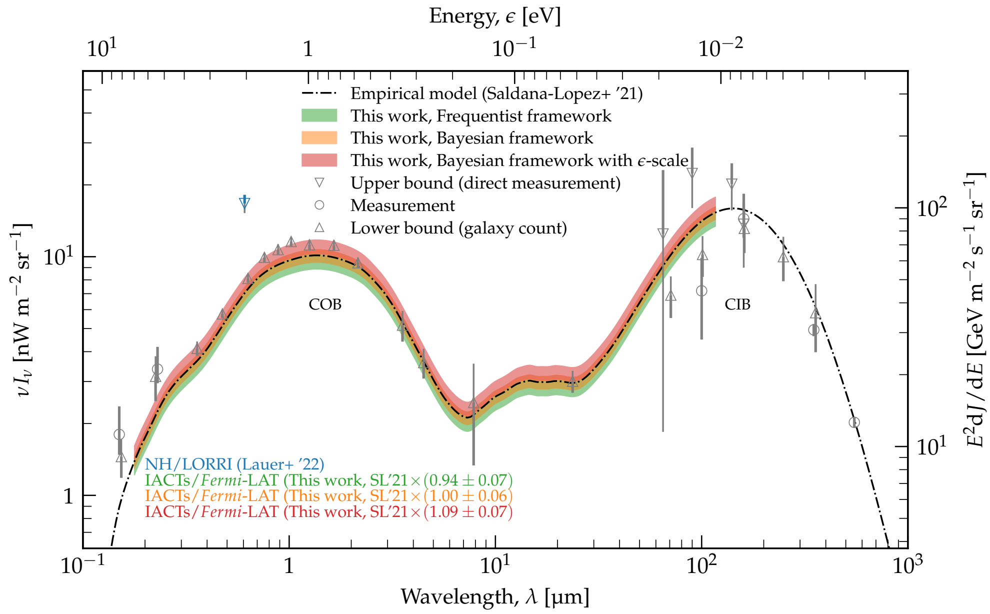

Figure 2: Reconstructed EBL specific intensity at $z = 0$ obtained by scaling the EBL model from [9], represented in black. The green, orange and red bands corresponds to the reconstructions obtained within the frequentist framework, the bayesian framework without the energy-scale factor, and the bayesian framework with this factor, respectively. The blue downward-pointing triangle corresponds to the measurement from [5]. The grey points correspond to upper bounds, measurements and lower bounds collected by [15].

For wavelengths between 1 μm and 10 μm, we obtain relative uncertainties of around 5%. The outer wavelength bins are less constrained, which is expected: at 0.3 μm, the EBL attenuation is expected to be significant for sources with redshift $z > 2$, which we do not have in the spectral corpus; at 80 μm, the EBL is expected to mainly interact with photons above 30 TeV, which corresponds to the highest energies reached by the spectral corpus. Overall, we reduce the uncertainties with respect to [7] by more than 30%, but the two reconstructions are not statistically compatible.

In the 400-900 nm band, we reconstruct an EBL intensity $\nu I_\nu = 7.4 \pm 1.2$ nW m^{-2} sr^{-1}. This value is compatible with the IGL measurements of 8.3 ± 1.2 nW m^{-2} sr^{-1}. We exclude EBL intensities larger than 9.7 nW m^{-2} sr^{-1} with 95% confidence at 600nm. An intensity of 16.4 nW m^{-2} sr^{-1} as reported by [5] is disfavored by 5.3σ. As showed in the bottom panel of Fig. 3, the analysis suggests an excess with respect to the IGL measurements at longer wavelengths. At 3 μm, this excess reaches 5.9 ± 0.8 nW m^{-2} sr^{-1}.

4. Conclusion

Measurements of the EBL from galaxy counts and from direct observations currently present a 4σ tension in the optical band. To address this cosmological controversy, we developed a new analysis method using a full Bayesian framework to reconstruct the EBL intensity from the absorption patterns it induces in the VHE spectra of extragalactic sources. Using STeVECat, the most comprehensive catalog of VHE spectra to date, we are able to reduce the statistical uncertainties

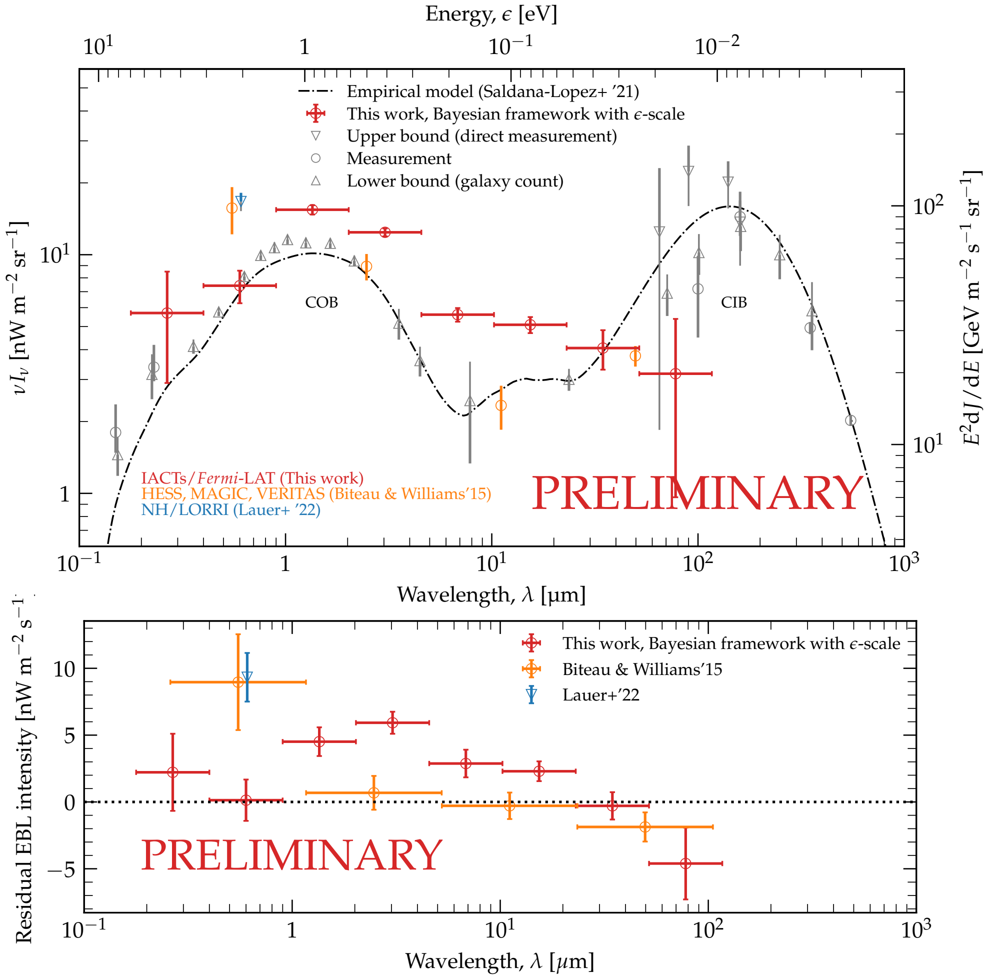

Figure 3: Reconstructed EBL specific intensity (*top*) and residual intensity with respect to IGL measurements (*bottom*) at $z = 0$ as a function of wavelength. The dashed black curve corresponds to the EBL model from [9]. The red points correspond to the best reconstructed EBL intensity using the bayesian framework with a free energy-scale factor. The orange points correspond to the intensity reconstructed by [7] independently from IGL measurements. The blue downward-pointing triangle corresponds to the New Horizons measurement from [5]. The grey points correspond to upper bounds, measurements and lower bounds collected by [15].

on EBL estimates using gamma-ray observations by more than 30%. This precision allows us to reject an intensity of 16.4 nW m^{-2} sr^{-1} at 600 nm by more than 5σ. Our analysis therefore disfavors an extragalactic origin of the excess reported by New-Horizons.

The analysis yields an excess with respect to IGL measurements between 1 and 10 μm, reaching 5.9 ± 0.8 nW m^{-2} sr^{-1} at 3 μm. This band corresponds to the wavelengths observed by the James Webb Space Telescope, which could help to confirm or infirm the inferred excess. The coming years will also mark the advent of the new generation of ground based VHE observatories, the Cherenkov Telescope Array, which promises to deepen our knowledge of the high-energy universe.

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