PROCEEDINGS OF SCIENCE

Propagation of Ultra High-Energy Cosmic Rays in light of the latest EBL constraints

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Recent progress in measurements and modeling of the Extragalactic Background Light (EBL) has placed considerable constraints on its spectral density. These constraints are particularly relevant for the propagation of Ultra-High Energy Cosmic Rays (UHECRs), as in the past the EBL uncertainties have significantly impacted the result of simulations that aim at inferring source properties from the observed UHECR spectral and composition data. In this contribution, we show that the reduction in EBL uncertainties recently achieved makes their impact on the propagation of UHECRs subdominant.

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1. Introduction

The extragalactic origin of Ultra-High Energy Cosmic Rays (UHECRs) is strongly supported by theoretical arguments and experimental evidence [1]. Experimental limits on the galactic magnetic field constrain the possibilities of confinement of cosmic rays beyond ∼10 EeV, while directional studies with the Pierre Auger Observatory have found an increasing anistropy for energies above ∼8 EeV [2]. These highly significant measurements underline the importance of understanding the relevant interactions of UHECRs in intergalactic space, which have been identified since more than half a century [3]: photopair production, photopion production, and in the case of nuclei photodisintegration.

The Cosmic Microwave Background (CMB) is the dominant target for UHECR protons that exceed the GZK threshold at ∼50 EeV [4] while the Extragalactic Background Light (EBL) at shorter wavelenths is of more importance at lower UHECR energies. While the CMB spectrum has been well constrained since the launch of COBE in the late '80s, the spectrum of the EBL is still a matter of ongoing refinements (see, e.g., [5]).

The EBL is composed of the Cosmic Infrared Background (CIB), peaking at 10 meV, and the Cosmic Optical Background (COB), peaking at around 1 eV, as illustrated in Figure 1. The two broad humps have comparable energy densities ($\propto \int \nu I_\nu \, \mathrm{d}\ln\nu$, the integral below the curve in Figure 1). Due to the lower energy of the infrared photons, the photon number density at the CIB peak is about 100 times larger than that of the COB, and thus it is the most likely target photon field for UHECRs below the GZK energy range.

Previous studies found that differences between EBL models had non-negligible impact in UHECR propagation [6]. Using state-of-the art models from a decade ago [7, 8], the authors of [6] showed that a homogeneous injection of iron nuclei out to $z = 1$ would result in spectra differing by up to 30% depending on energy. Figure 1 illustrates the spectral energy density of the EBL at $z = 0$ from up-to-date models of three different types [see 9, for a discussion]: (i) the semi-analytic model from [7], still representative of the state-of-the-art of a-priori approaches, (ii) the phenomenological model of [10], which is constrained with the latest galaxy counts from [11], and (iii) the empirical model of [12], which is an updated version of the work of [8] that accounts for the latest compilations of galaxies observed in the five fields of CANDELS[13] out to $z = 6$ with the Hubble Space Telescope. The increasing precision of measurements and the corresponding convergence of the models, particularly at far-infrared wavelengths, reduces the range permissible for models considerably compared to a decade ago.

In this context, we set out to estimate the impact of remaining EBL uncertainties on UHECR propagation.

2. Impact on UHECR propagation

We select as reference the EBL model of Ref. [7] (*Gilmore '12* in what follows), which has been widely used in UHECR propagation studies. Two other state-of-the-art models in agreement with present uncertainties, *Andrews '19* [10] and *Saldana-Lopez '21* [12] thereon, are used for comparison. The lines labeled as "Other models" represent the models published in Refs. [8, 14–

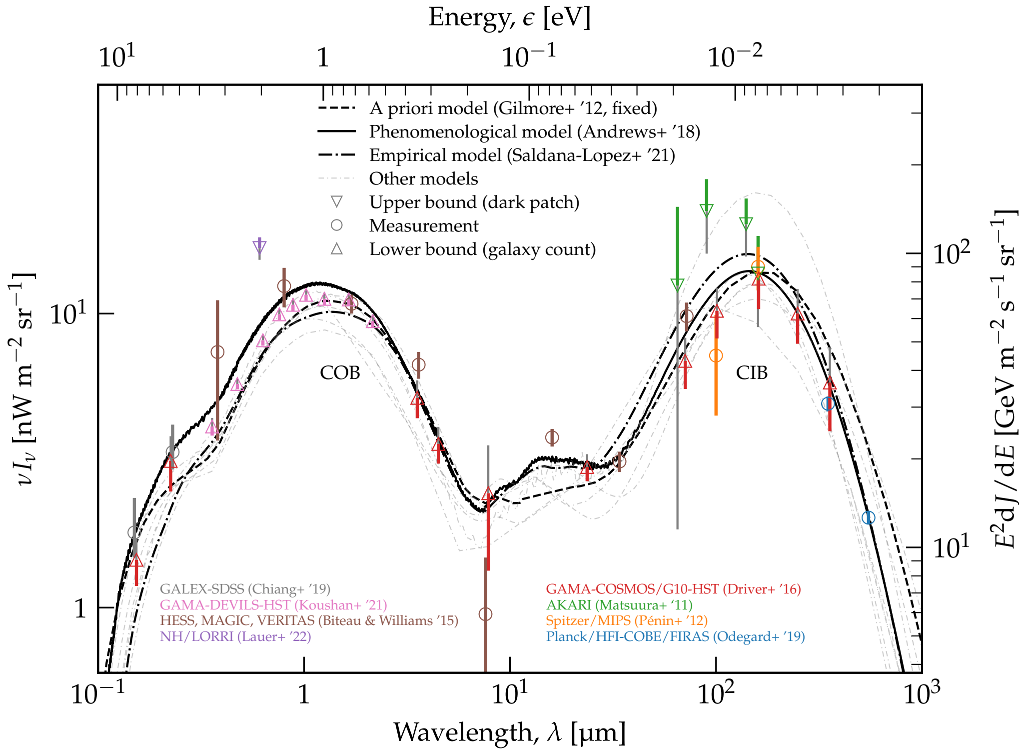

Figure 1: EBL models selected for this work [7, 10, 12] compared to other models [8, 14–18] in tension with observations [11, 18–24]. Code and data available in [25].

18] that are currently disfavoured by observational constraints, some of which were previously employed in UHECR propagation studies.

The interaction rates of UHECRs with EBL photons are obtained through integrating over the range of EBL energies [26]:

$$\lambda(\gamma, z) = \frac{1}{2\gamma^2} \int_0^\infty \frac{n(\epsilon, z)}{\epsilon^2} d\epsilon \int_0^{2\epsilon\gamma} \varepsilon\sigma(\varepsilon) d\varepsilon, \tag{1}$$

with $\varepsilon = \gamma\epsilon(1 - \cos\theta)$, $n(\epsilon, z)$ being the EBL photon density, and $\sigma(\varepsilon)$ the cross section for the corresponding interaction. Figure 2 shows as representative examples the energy loss lengths for nitrogen and iron nuclei for the three EBL models *Gilmore '12*, *Andrews '19*, and *Saldana-Lopez '21*. The interactions with the CMB (dotted grey line) are prevalent at all energies but photodisintegration interactions with the EBL are comparable at few tens of EeV. The models *Andrews '19* and *Saldana-Lopez '21* are very close to each other because their spectral number densities are very close around the peak value (~ 10 meV), whereas interaction lengths for *Gilmore '12* are shorter given the larger values at that energy.

3. Impact on UHECR spectra at Earth

Figure 3 provides a comparison of UHECR spectra observed at Earth for the three EBL models. The spectra are computed with CRPropa 3.2 [27] by injecting one nuclear species (nitrogen or iron)

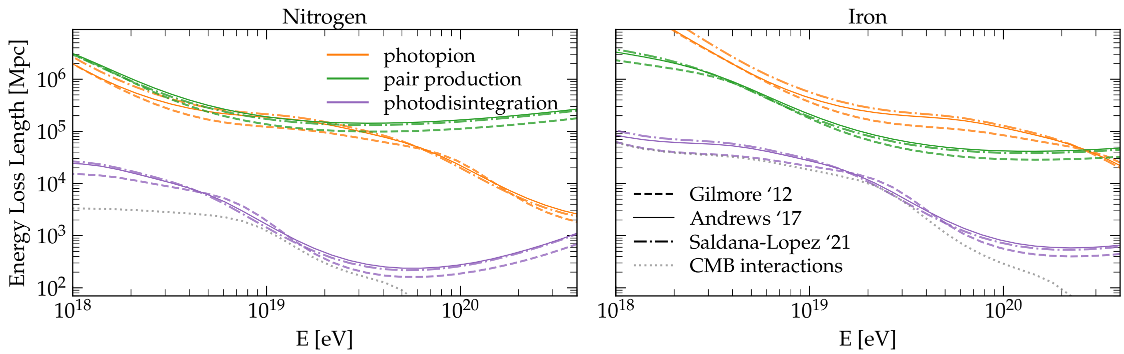

Figure 2: Energy loss lengths of nitrogen (*left*) and iron (*right*) for different EBL models. Differences in flux are expected to matter near the propagation cut-off, if source acceleration reaches such energies.

with a power-law of spectral index $\alpha = 2$ covering energies in the range $1 - 100$ EeV. A continuous and homogeneous source distribution is considered, with constant density spanning distances from 1 Mpc to 3 Gpc. The model of *Gilmore '12* used here is part of CRPropa 3.2, as introduced in earlier versions of the code; the more recent models of *Andrews '19* and *Saldana-Lopez '21* have been implemented in CRPropa 3.2 using the existing tools to include custom photon fields which have been introduced in [27].

The differences between the overall spectra obtained for different EBL models (black lines) are of the order of a few percent, although reaching almost 10% when comparing to the older model *Gilmore '12* . These small differences are slighltly higher when comparing the spectral distributions of individual mass groups. These larger differences appreciable in the subdominant mass groups are a consequence of statistical fluctuations due to the considerably lower probabilities for producing those nuclei. Overall, the differences between the models of *Andrews '19* and *Saldana-Lopez '21* are smaller than their respective differences to *Gilmore '12* , as expected from the differences in

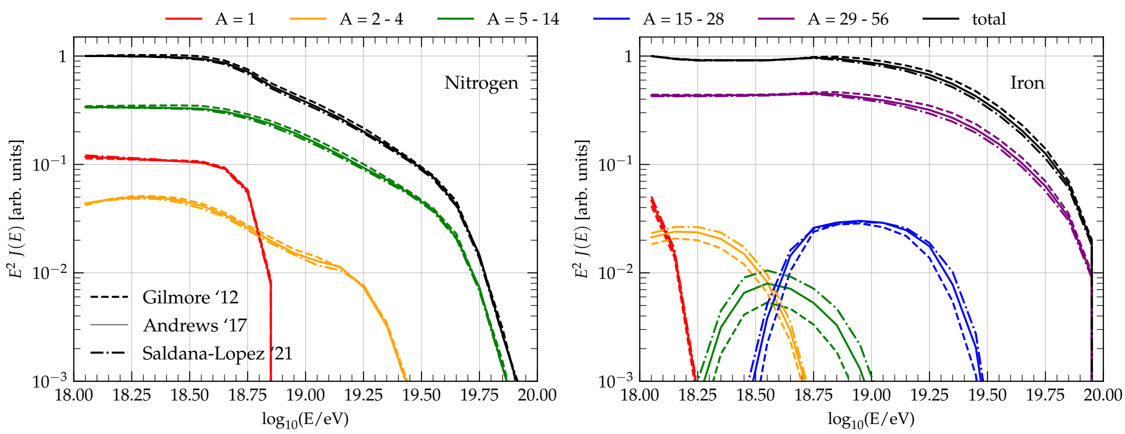

Figure 3: Full-sky differential spectra at Earth, scaled to third power of energy, for an homogeneous injection of nitrogen (*left*) and iron (*right*) from 1 Mpc to 1 Gpc. The total spectrum and contributions from sub-species grouped by mass are shown as black and colored lines, respectively, as labeled in the right-hand side panel. The three tested EBL models are displayed with different linestyles, as displayed in the left-had side panel.

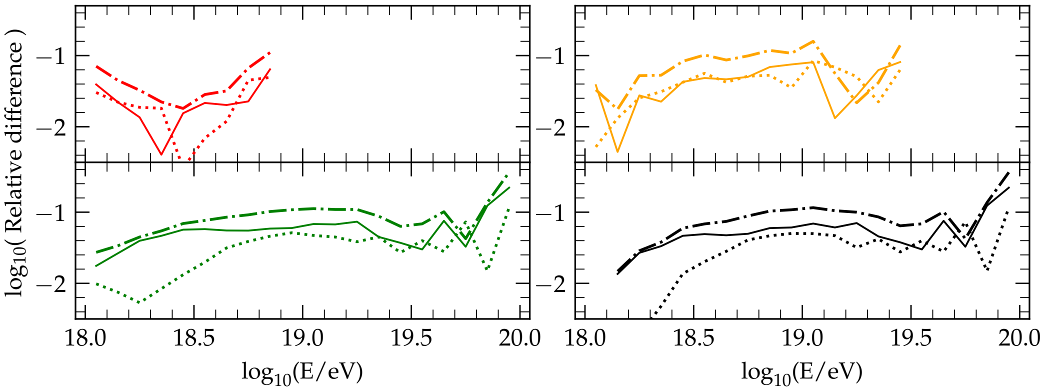

Figure 4: Relative differences of spectral fluxes for nitrogen injection. The line colors represent the mass groups (see Figure 3) and the solid lines show the comparison of *Andrews '19* to *Gilmore '12*, the dash-dotted the comparison of *Saldana-Lopez '21* to *Gilmore '12* , and the dotted the comparison of *Andrews '19* to *Saldana-Lopez '21* .

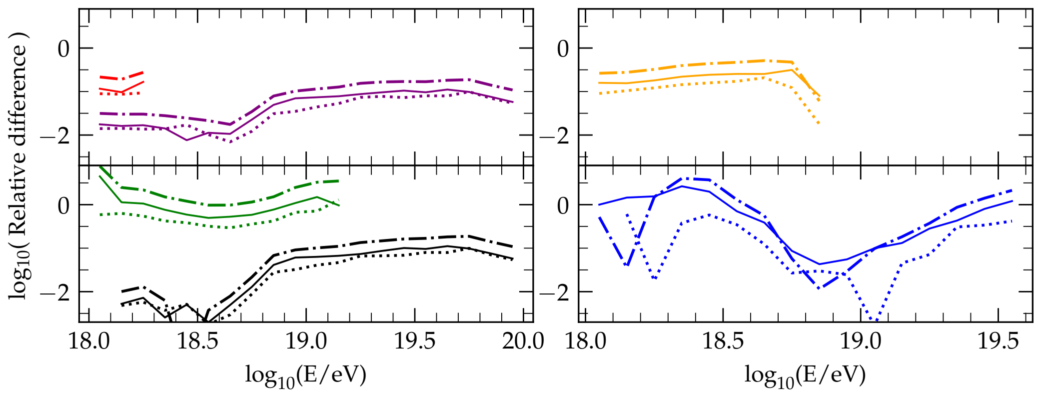

Figure 5: Relative differences of spectral fluxes for iron injection. The line colors represent the mass groups (see Figure 3) and the solid lines show the comparison of *Andrews '19* to *Gilmore '12*, the dash-dotted the comparison of *Saldana-Lopez '21* to *Gilmore '12*, and the dotted the comparison of *Andrews '19* to *Saldana-Lopez '21* .

their EBL spectra shown in Figure 2.

The relative differences of the spectra obtained with the models of *Andrews '19* and *Saldana-Lopez '21* with respect to the spectra obtained with the model of *Gilmore '12* are shown in Figures 4 and 5. As in Figure 3, the differences between spectra based on the EBL models of *Saldana-Lopez '21* and *Andrews '19* are smaller (dotted lines) than their differences with the spectra based on the model of *Gilmore '12* . The largest deviations appear in the spectra of mass groups with the lowest yields: they are dominated by the statistical fluctuations between simulations, as evidenced by the deviation between the *Andrews '19* and *Saldana-Lopez '21* models. The total flux relative differences are at most 50% when comparing to *Gilmore '12* , while the comparison between *Saldana-Lopez '21* and *Andrews '19* is constrained to less than 10%. The magnitude of the differences expected in the combined fits of UHECR spectral distributions and mass compositions (see e.g. Ref. [28]) will be quantified in an upcoming work.

4. Summary

We have initiated a systematic comparison of the state-of-the-art EBL models to determine the remaining uncertainties induced on the propagation of UHECRs on cosmic scales. We select three EBL models of different types that are consistent with the latest compilations of measurements: an earlier model still in agreement with measurements [7] as reference, and two more recent models [10, 12] for comparison. The propagation of UHECRs in a benchmark scenario is performed with CRPropa 3.2 employing the aforementioned models. The spectra of the primary and secondary nuclei from nitrogen and iron show differences smaller than 50% at all relevant UHECR energies, while the differences between the most recent models *Andrews '19* and *Saldana-Lopez '21* are smaller than 10%. Upcoming efforts will be aimed at quantifying the uncertainties induced on the combined fit of spectral and composition data at ultra-high energies, which we expect to be significantly reduced.

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