

Article

Photon-photon Interactions and the Opacity of the Universe in Gamma-Rays

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Abstract: We discuss the topic of the transparency of the Universe in gamma-rays due to the Extragalactic Background Light, and its cosmological and physical implications. Rather than a review, this is a personal account on the development of 30 years of this branch of physical science. Extensive analysis of the currently available information appears to us as revealing a global coherence among the astrophysical, cosmological, and fundamental physics data, or, at least, no evident need so far of substantial modification of our present understanding. Deeper data from future experiments will verify to what extent and in which directions this conclusion should be modified.

Keywords: High energy astrophysics – Background radiation – Photon-photon interaction – Pair production

1. Introduction

Photons are by far the fundamental channel of information that we have for investigating the Universe, its structure, its origin. Fortunately, after the optically thick phase ending at the recombination time 380.000 years from Big Bang and thanks to the disappearance of free electrons from the cosmic fluid, photons over a large range of frequencies have been allowed to travel almost freely across the Universe.

However, Thomson scattering, that was so effective before recombination, is not the only process limiting the photon path. Once the first cosmic sources - either stellar populations, galaxies, or gravitationally accreting Active Galactic Nuclei - started to shine at about redshift $z \sim 10$, a large flow of low-energy photons went progressively filling up homogeneously the entire Universe. This low-energy photon field, covering a wide frequency range from the far-UV to the millimeter ($0.1 < \lambda < 1000 \mu\text{m}$) and growing with time down to the present epoch, is indicated as the Extragalactic Background Light (EBL). It adds to the already present and much more numerous relic of the Big Bang, the Cosmic Microwave Background (CMB).

As a consequence of the presence of such high-density diffuse background radiation, high-energy particles - both cosmic rays and photons - have a high chance of interaction. Gamma-ray photons, in particular, have a significant probability, increasing with energy, to collide with background photons and decay into an electron-positron pair [1,2],

$$\gamma + \gamma \rightarrow e^- + e^+,$$

hence essentially disappearing from view. Quantum electrodynamics makes precise predictions [3] about such a probability, that peaks when the product of the two photon energies equals on average the square of the rest-mass energy ($m_e c^2$)² of each one. As a consequence, Very High Energy (VHE) spectra of extragalactic sources show high-energy exponential cutoffs $\propto e^{-\tau_{\gamma\gamma}}$, where $\tau_{\gamma\gamma}$ is the optical depth to photon-photon interaction. Once the source distance is known, a spectral analysis of the gamma-ray

source, complemented with some assumptions about the intrinsic spectrum, allows us a measure of $\tau_{\gamma\gamma}$, hence an inference of the background photon density.

In conclusion, on one side the $\gamma\gamma$ interaction analysis is required to infer the intrinsic source spectrum for physical investigations of its properties. But on the other side, this opacity effect offers the potential to constrain an observable, the EBL background, of great cosmological and astrophysical interest. The EBL collects in an integrated fashion all radiation processes by cosmic sources during the whole lifetime of the Universe, and then sets a fundamental constraint on its evolutionary history.

Because direct measurements of such radiations are very difficult or even impossible, the possibility to constrain them via the gamma-ray photon opacity analyses is highly valuable, and makes an interesting bridge between the high-energy physics and the low-energy astrophysics and cosmological domains.

Photon-photon interactions and opacity effects are also of relevance for other questions of cosmology and fundamental physics. One is related with the existence of tiny magnetic fields on large cosmic scales. The latter might originate during the earliest inflationary phases, or alternatively in dynamo effects during the large-scale structure's growth. Such low intensity fields are not directly measurable, e.g. with Faraday rotation, while a potential probe is offered by magnetic deflections of electron-positron pairs produced by gamma-gamma interactions and Inverse Compton (IC) scattering of background photons. This effect produces both extended halos from the reprocessed gamma-rays and spectral bumps and holes, potentially measurable with *Fermi* and IACT telescopes [4,5].

Opacity measurements have also been considered for constraining cosmological parameters, like the Hubble constant H_0 , by pushing the argument to the extreme [6,25, among others]. In our view, however, the degeneracy in the solutions due to the large number of parameters involved is such to make this application of very limited value compared to the many alternative observational approaches. This at least until a new generation of IACTs will appear with significantly better spectral resolution to identify sharp absorption features e.g. due to the integrated PAH emissions in the IR EBL. Similar problems limit the possibility to measure the redshifts of distant blazars lacking the spectroscopic measurement [7].

Processes involving VHE photons and opacity measurements in distant gamma-ray sources allow us important tests for possible deviations from the Standard Model predictions, and for new physics, well beyond the reach of the most powerful terrestrial accelerators (LHC).

In particular, possible violations of a fundamental physical law such as the special-relativistic Lorentz Invariance are testable in principle. Such violations may arise in the framework of alternative theories of gravity and quantum gravity [8,9].

While quantum gravity effects are expected to manifest themselves in the proximity of the extreme Planck's energy $E_{QG} = \sqrt{\hbar c^5/2\pi G} \simeq 10^{19} \text{ GeV}$, it turns out that the effects may be testable even at much lower energies. In particular, the quantization of space-time may affect the propagation of particles and a modification of the dispersion relation for photons in the vacuum would appear at an energy given by E_{QG} , bringing for example to a relation

$$c^2 p^2 = E^2 (1 + \lambda E/E_{QG} + 0(E/E_{QG}))^2 \quad (1)$$

E the photon energy and λ a dimensionless parameter, that, if different from zero, would violate the Lorentz invariance [10]. Such a dispersion relation leads to an energy-dependent propagation velocity of photons: $v = dE/dp = c(1 - \lambda(E/E_{QG}))$, with a consequent time of arrival also depending on energy that is testable with VHE observations of fast transient sources like variable blazars or even Gamma Ray Bursts (GRB) [11].

The interesting point here is that an anomalous dispersion as above would also affect the interactions of high energy particles, like the photon-photon collisions. The

threshold condition for pair creation, given one photon of energy and momentum E_1 and P_1 and a second with E_2 and P_2 given by $(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2 \geq 4m_e^2c^4$, would be modified by the anomalous dispersion as $2(E_1E_2)(1 - \cos\theta) - \lambda E_1^3/E_{QG} \geq 4m_e^2c^4$, assuming E_1 is the gamma photon energy and E_2 that of the low-energy background. Deviations from Lorentz Invariance, with $\lambda \neq 0$, would then be testable, assuming the characteristic EBL energy of $E_2 \simeq 1 \text{ eV}$, with gamma-ray energies in the range $E_1 \sim 10$ to 100 TeV , that is well below the Planck energy scale [12]. An observational consequence would be the suppression or the reduction of the photon-photon interaction and absorption in the spectra of distant blazars, potentially testable above 10 TeV (see Sect. 5.3 below).

Similarly, quantum gravitational effects would also influence hadronic and mesonic processes, like for example the pion decay $\pi^0 \rightarrow \gamma + \gamma$ for energies in the PeV range, as well as many other processes involving high energy particles [13].

Among the various attempts to achieve a *theory of everything* of all four fundamental interactions, including gravity, super-symmetric models and particularly *super-string* theories have been considered. A common prediction of these is the existence of spin-zero, neutral, very light bosons, that are the generalization of the *axion* particle. Axion-like particles (ALP) are predicted to interact with two photons or with a photon and a static electromagnetic E and B field. So, in the presence of a magnetic field, high energy photons and ALPs would oscillate, like it is the case for solar neutrinos: a VHE photon emitted by a gamma-ray source, by interacting with an intergalactic B field, would transform into an ALP, and the latter be reconverted in a photon after a subsequent interaction with another B field. Since during the ALP phase there is no interaction with background photons and pair production, this would overall reduce the photon-photon opacity. Observations of VHE distant sources can then offer a potential to constrain the existence of ALPs, by the analysis of their gamma-ray spectra.

The paper is structured as follows. A brief historical account on the photon-photon interaction process in the astrophysical context is reported in Sect. 2. The Extragalactic Background Light as the low-energy photon field responsible for the high-energy cosmic opacity is discussed in Sect. 3. Its cosmological significance, the issues related with its measurements and modelling the known-source contributions to the EBL are all discussed in the relative subsections. The high-energy opacity of the Universe to photon-photon interaction is reported in Sect. 4, while specific problems concerning the ultraviolet and optical EBL, the near-IR and the far-IR EBL are specifically addressed in the Subsects. 4.2, 4.3, 4.4. Various aspects and consequences, including current constraints on the ALPs and Lorentz Invariance Violations (LIV) are discussed in Sect. 5, together with a mention of the relevant prospects for improvement expected by forthcoming and future instrumentation. Conclusions appear in Sect. 6.

2. Photon-photon Interaction in the Astrophysical Context: Brief Historical Account

The discovery of the CMB radiation in 1965, in addition to being a game-changer in our understanding of the Universe, prompted a number of reflections about its physical and astrophysical implications. People immediately realised that the propagation of high-energy particles across it might be impeded to some extent [e.g. 14,15]. This was found to apply to cosmic ray particles, but also to photons [2,16,17], still in relation to the CMB cosmological background, and it was found that gamma rays from the cosmos with energies $> 100 \text{ TeV}$ cannot reach the Earth.

With the early development of the radio and IR astronomy [see for a review 18], it became clear that not only the Universe hosts the dense CMB photon field, but also a rich variety of other diffuse extragalactic radiations. If the radio background is of no relevance for gamma-ray astronomy, the IR one at shorter wavelengths than the CMB was indicated by [19,20] to make an important component. Based on the scanty data of the pre-IRAS era, Puget, Stecker, & Bredekamp [19] have predicted quite realistic

radiation intensities in the far- and mid-IR, results that have been largely confirmed by the first all-sky investigation by the IRAS satellite in 1984 [see for a review 21].

However, it was only with the launch of the first gamma-ray observatory in space, the Compton GRO in 1991, that the first ideas of a profound relationship between low-energy astrophysics and high-energy physics have started to be considered. In particular, soon after the launch, a large flare by the distant blazar 3C279 at $z=0.54$ was detected by the Compton GRO at energies between 70 MeV and 5 GeV, showing a perfect power-law spectrum. Stecker, de Jager, & Salamon [22] argued that, assuming such a HE spectrum continues at higher energies and a far-IR (FIR) background intensity consistent with the IRAS data of the epoch, an exponential cutoff due to photon-photon interaction would be measured in the VHE spectra between 0.1 and 1 TeV by the new generation of air Cherenkov detectors. They also argued, for the first time, that this would provide an opportunity to obtain a measurement of, or at least a severe constraint on, the extragalactic IR background radiation field.

Indeed, a year later, the detection of the low- z ($z=0.03$) blazar MKN421 by the Whipple Cherenkov observatory [23], showing a pure power-law spectrum up to 3 TeV, prompted Stecker & de Jager [24] to set an upper limit to the near-IR (NIR) EBL intensity of $\nu I(\nu) < 10^{-8} \text{ Watt/m}^2/\text{sr}$ in the wavelength interval from 1 to 5 μm : this remarkable constraint on the NIR EBL was essentially confirmed by many later analyses.

In the meantime, progresses have been made on both the theoretical side about the EBL intensity [26], and the Cherenkov instrumental facilities. The combination of Compton-GRO, HEGRA and Whipple observations produced a remarkably extended and well-sampled HE and VHE spectrum of MKN421, showing a significant cutoff above 1 TeV that was interpreted by Stecker & de Jager [27] as a preliminary evidence in favour of photon-photon absorption. Two EBL model solutions by [26] appeared to be consistent with the observations.

At the same time in 1997, a huge flare characterizing the other local ($z=0.03$) blazar MKN501 was observed with HEGRA by Aharonian et al. [28] up to an energy of 10 TeV, thanks to the extreme luminosity of the source. Stanev & Franceschini [29] inferred from this a significant upper limit on the IR EBL between $\lambda = 3$ and 20 μm ($\nu I(\nu) < 5 \cdot 10^{-9} \text{ Watt/m}^2/\text{sr}$, very close to the lower limits set by deep extragalactic counts in the same wavelength interval by the Infrared Space Observatory's [30] deep mid-IR surveys. This was first evidence of very little room left to the IR EBL for a truly diffuse background in addition the contribution of known sources. These results were confirmed with similar analyses by Stecker & de Jager [31], Renault et al. [32], Malkan & Stecker [33]. Instead, Konopelko et al. [34], de Jager & Stecker [35], using a high normalization of the IR EBL from a model by [31], found an indication for a very large absorption correction ($\times 20-40$) in the HEGRA spectrum of MKN501 at the energy of 20 TeV.

Mazin & Raue [36] attempted to infer constraints on the spectral shape of the EBL over a large wavelength interval, 0.4 to 80 μm , by a joint analysis of 14 blazar TeV spectra and using EBL educated guesses by [37], however with limited success because of the strong degeneracy in the solutions.

The start of the operations of the HESS large Cherenkov array led to the discovery in 2006 of two very distant blazars, H 2356-309 and 1ES 1101-232 at $z=0.165$ and $z=0.186$ that allowed Aharonian et al. [38] to set an important constraint on the EBL around 1 μm , essentially ruling out large excesses in the EBL indicated by IR space telescope observations [39]. For the first time, photon-photon opacity measurements led to a rather fundamental achievement for cosmology. This issue will be further discussed below.

More recently, thanks to important developments allowed by new relevant observational facilities and much better knowledge of the cosmic source populations by astronomical telescopes, during the last decade the field has achieved a maturity. Major imaging Cherenkov telescope arrays (HESS, VERITAS, MAGIC) operating at VHE have been implemented, while the multi-epoch all-sky surveys by the *Fermi* space observatory

has extensively monitored the sky at the HE energies in an extremely complementary and synergistic fashion.

The operation of a plethora of astrophysical observatories in space (HST, ISO, Spitzer, Herschel) and from ground offered deep understanding of cosmic low-energy source populations over a substantial fraction of the Hubble time, hence setting hard lower limits to the EBL over 4 photon-frequency decades from 0.1 to 1000 μm . All this will be subject to our later discussion in Sect. 3.3.

3. The Low-Energy Extragalactic Background Radiation (EBL)

3.1. Origin and cosmological significance of the EBL

The Extragalactic Background Light in the wavelength interval between 0.1 and 1000 μm is an important constituent of the Universe, permeating it quite uniformly (e.g. Longair [40]). The EBL is the collection of all photon emission processes at these wavelengths from Big Bang till today, and offers an integrated information on all of them. For this reason it makes a fundamental constraint on our past history.

A likely dominant source of energy is thermonuclear burning in stars, whose past integral peaks in the EBL at around $\lambda \simeq 1 \mu\text{m}$, as a consequence of surface temperature of stars from few thousands to about 100,000 degrees. However, stellar activity often takes place in dust-opaque media, as is particularly the case for young massive and luminous stars, that form inside dusty molecular clouds. As a consequence, a quite significant fraction of the short wavelength UV-optical stellar photons is absorbed by dust grains and re-emitted by them in the IR via a quasi-thermal process at the equilibrium temperature of few to several tens of degrees.

The EBL then has two fairly well characterized maxima at $\lambda \simeq 1 \mu\text{m}$ and 100 μm corresponding to the integrated stellar photospheric and dust-reprocessed emissions, with a minimum between the two at $\lambda \simeq 10 \mu\text{m}$.

Another important energy-generation process originates from gas accretion onto massive collapsed objects, like it typically happens onto super-massive black-holes (SMBH) in Active Galactic Nuclei and quasars. Similarly to stellar emission, gravitational accretion also emits fluently in the UV and the optical from the hot accreting plasmas, but again significant part of this radiation is absorbed by dust in the accreting matter and emerges in the IR. In spite of the higher mass-to-energy transformation efficiency η of the latter process compared to stellar nucleosynthesis, because only about one part of a thousand of the processed baryon material goes to accrete onto the SMBH, AGN accretion is deemed to contribute a minor fraction to the EBL compared to stars [41,42]. Assuming a stellar efficiency of $\eta \sim 0.001$ and the AGN one $\eta \sim 0.1$ and similar evolutionary histories for the two [41], the average observed ratio of stellar mass to that of SMBH's in galaxies of about 1000 [43] implies that only about 10% of the EBL intensity can be ascribed to AGN activity.

Astrophysical processes in individual sources so far described are easily detectable with current imaging telescopes above the map's background. A question however remains how much these imagers can detect of more diffuse emissions, like could take place from low-density regions in the outskirts of galaxies or even from stellar populations distributed in the intergalactic medium: all these would easily sink onto the background, and possibly remain completely undetectable. Extreme occurrences of this kind might be a diffuse medium of decaying particles emerging from the Big Bang or early populations of stars, like the so-called Population III stars often invoked to explain the early metal enrichment in the Universe [44–46].

These cosmological signals are in any case all registered in the EBL spectral intensity. Therefore, any attempts to retrieve the history of energy production events in the past history of the Universe has to be confronted with available EBL constraints, like not exceeding in any case the total figure. For example, the history of star-formation (SF), which is a major responsible for EBL, receives important constraints from that observable.

3.2. Observational issues related with the background radiations

Unfortunately, direct measurements of EBL all-over its wavelength definition range are very difficult, and even largely impossible. Excellent reviews of the subject can be found in [47] for the IR part and in [48] for the optical-UV one. The situation is well illustrated in Figure 1, showing how the Earth is immersed, more than within the EBL photon field, inside a variety of radiations of local origin. The major component is the Zodiacal light, including both Sun scattered light by Inter-Planetary Dust (IPD) particles, and their quasi-thermal emission peaking at $10 \mu\text{m}$. Contributions by the integrated emission of faint stars and by high-galactic latitude dust (*cirrus*) are also indicated.

As shown by the figure, even outside the terrestrial atmosphere, these emissions are so bright compared to the expected level of the EBL (that is around $10^{-8} \text{ W/m}^2/\text{sr}$) that any attempts of a direct measure is prone to huge uncertainties.

One possible exception is the spectral window from $\lambda \sim 200$ to $1000 \mu\text{m}$ that is at the minimum of all such radiations. It is exactly there that credible claims of an extragalactic background radiation signal has been reported by Puget et al. [50], Lagache et al. [51]. While in this case too the total intensity is still dominated by *cirrus* and CMB emissions, the EBL can be safely extracted thanks to the *a-priori* knowledge of the CMB spectral intensity and the clear dependence of the *cirrus* on Galactic coordinates.

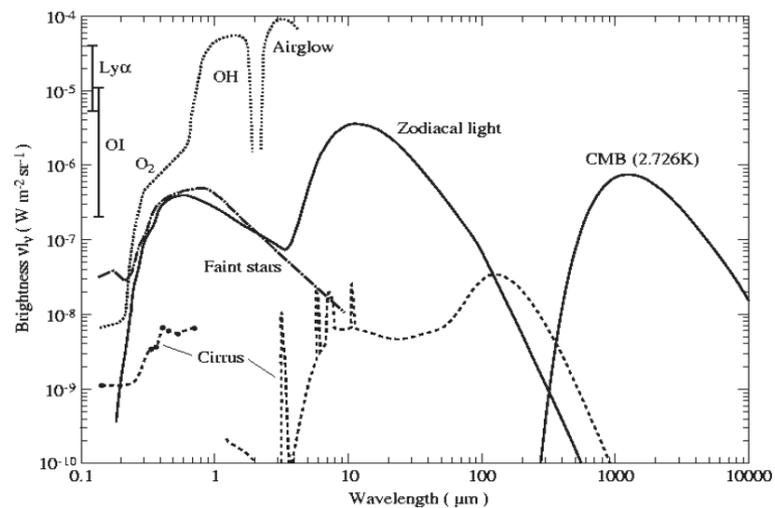


Figure 1. Overview of the various components of the total night sky background at high galactic and ecliptic latitudes. The Zodiacal Inter-Planetary Dust emission, Zodiacal scattered light, and starlight (bright stars excluded) are indicated. The interstellar (*cirrus*) emission is normalized to the minimum column density observed at high Galactic latitudes ($N_H = 10^{20} \text{ H atoms/cm}^2$). Atmospheric O2 air glow and OH emissions in the near-IR, as well as the CMB, are also indicated. [Figure taken from Leinert et al. [49].]

At all other wavelengths, foregrounds are so much dominating to prevent reliable EBL determinations. This is particularly the case from 5 to $100 \mu\text{m}$ because of the IPD brightness and its weak dependence on the ecliptic coordinates (about a factor 2 from pole to equator) preventing it to be reliably subtracted from the total sky maps.

A particularly interesting situation has emerged in the range from about 1 to $5 \mu\text{m}$ (the near-IR EBL, NIR EBL), where completely different experiments (DIRBE on COBE, [52]); Spitzer [53]; AKARI [54]; IRTS [55]; CIBER [59], among others) indicated high levels of the NIR EBL intensity (but see also [56]). Such an intense isotropic radiation would have a spectrum like the RJ tail of a thermal radiation (as also shared by the Zodiacal scattered light) and a sharp cutoff at about $\lambda \sim 1 \mu\text{m}$, consistent with processes taking place at high redshift ($z \sim 10$), whose light is redshifted to that peak wavelength. Primeval (Population III) stars have been considered as a possible origin [39,57,58].

These estimates of the EBL are based on detailed modeling of the measured total intensity and the subtraction of the local Zodiacal and stellar contributions. These results show quite high values of the NIR EBL, of the order of $\nu I(\nu) \simeq 40 - 60 \text{ nW/m}^2/\text{sr}$ [see e.g. the review by 60]. Unfortunately, they are possibly compromised particularly by uncertainties in the precise level of the Zodiacal foreground.

A way to circumvent this difficulty was identified in the study of the background fluctuations $\delta I_\nu / I_\nu$ instead of the total intensity I_ν , under the well-supported hypothesis that the Zodiacal light is completely uniform [see for a general review 61]. Various authors report excess fluctuations in the deep maps in various near-IR and optical bands, typically showing wavelength dependencies consistent with the Rayleigh-Jeans law [among others 53,54,59,62–64]. These results have been alternatively interpreted with sources present during re-ionization at redshift $z > 8$, or primordial black holes, and with stellar emission from tidally stripped intergalactic stars residing in dark matter halos, or extended stellar halos at low z .

Mitchell-Wynne et al. [64] have expanded this search to emissions specifically at redshifts $z > 8$, where primeval sources responsible for the cosmological re-ionization are expected to be found, via an ultra-deep multi-wavelength investigation with HST. They find faint excess fluctuation signals above the current constraints based on Lyman-dropout galaxy surveys and low- z galaxies, but with low significance. Their conclusions appear to disfavour the very high values for the EBL found by the analyses of the foreground-subtracted total light intensity (see above), and rather consistent with lower EBL values of $\nu I(\nu) \sim 10 \text{ nW/m}^2/\text{sr}$. Another relevant outcome of the multiwavelength analysis by [64] was that good part of the large near-IR intensity fluctuations found by other teams [e.g. by CIBER, 59] is likely to be attributed to diffuse light from our Galaxy, with the consequence to lower also the inferred EBL flux.

Fluctuation studies, in any case, are all but free of significant uncertainties. Apart from the problem of the residual local foreground contribution, these measurements are sensitive to the details of the instrumental PSF of the imager. One further difficulty comes from the determination of the level of spatial clustering of the various source populations contributing to the total fluctuation signal. For example, Helgason & Komatsu [65] have suggested that some of the claimed excess fluctuations may be entirely explained by the clustering of ordinary galaxies.

Not at all easier is the direct measurement of the optical-UV EBL, not only because of faint stars and the Sun-scattered light, but also due to the diffuse high-Galactic latitude dust reflecting starlight. Important data have been recently obtained from the photometric camera onboard the *New Horizon* spacecraft observing at >40 AU from the Sun, so as to get rid of the Zodiacal light. The data analysis by Lauer et al. [66] (see also [67]) has derived a total EBL intensity at the band-center of $\lambda = 0.6 \mu\text{m}$ of $17.4 \pm 5 \text{ nW/m}^2/\text{sr}$, about half of which due to the integrated emission of galaxies and half to a diffuse unresolved component of unknown origin. It will be interesting to check later if such high background can be reconciled with the constraints set by the photon-photon opacity determinations.

In summary, while being a fundamental cosmological component of great significance, and in spite of the enormous effort dedicated to its determination, the EBL is escaping any reliable direct measurement over most of its waveband range of definition. The next Sections will be dedicated to infer entirely independent constraints of its value.

3.3. Modelling the known-source contributions to the EBL

Thanks to the variety of astronomical facilities, both from ground and from space, operative over the full wavelength range of 0.1 to 1000 μm , we can at least set a reliable minimum boundary to the extragalactic radiation field from known sources, that in turn will set a minimal threshold to the cosmic photon-photon opacity.

Many attempts have been published to model the known source contributions to the EBL based on the statistics of the multi-wavelength populations of galaxies and AGNs.

The present-time EBL intensity can be obtained by the relation with the differential source number counts $N(S)$ [sources/unit flux-density interval], $S(\nu)$ being the source flux density [erg/s/Hz]:

$$I(\nu) = \int_{S_{min}}^{S_{max}} N(S) S dS \quad [erg/s/cm^2/sr] \quad (2)$$

or in the equivalent time-honoured units of $Watt/m^2/sr$. $N(S)$ is the immediate observable that can be obtained from a sky survey at frequency ν . If instead we are interested in the evolution of the intensity with cosmic time, which is needed to estimate the opacity for a distant gamma-ray source, then the approach is complicated to account for the progressive production of photons by sources and their redshift effects. In this case, the background intensity at redshift z^* reads:

$$I_{\nu_0}(z^*) = \frac{1}{4\pi} \frac{c}{H_0} \int_{z^*}^{z_{max}} dz j[\nu_0(1+z)] \{ (1+z)^2 [(1+z)^2 (1 + \Omega_m z) - z(2+z)\Omega_\Lambda] \}^{-1/2}, \quad (3)$$

for a flat universe with $\Omega_m + \Omega_\Lambda = 1$, with $j[\nu_0]$ being the galaxy comoving volume emissivity:

$$j[\nu_0] = \int_{L_{min}}^{L_{max}} d \log L \cdot n_c(L, z) \cdot K(L, z) \cdot L_{\nu_0}, \quad (4)$$

with $K(L, z)$ the K-correction, $K(L, z) = (1+z)L_{\nu_0(1+z)}/L_{\nu_0}$ and n_c the comoving luminosity function at the redshift z expressed in number of galaxies per Mpc^3 per unit logarithmic interval of luminosity L at frequency ν_0 , L the luminosity in [erg/s/Hz]. The local background intensity as in eq. (2) coincides with eq. (3) for $z^* = 0$.

From eq. (3), the photon differential proper number density [$photons/cm^3/Hz$] at the redshift z^* is given by:

$$\frac{dn_\gamma(\epsilon_0, z^*)}{d\epsilon} = \frac{4\pi}{c} \cdot I_{\nu_0}(z^*) \frac{1}{\epsilon}, \quad (5)$$

where $\epsilon_0 = h\nu_0$ is the photon energy.

Two main strategies have been followed to model the source contributions to the EBL.

3.3.1. Empirical models

One approach to model the EBL was to be as adherent as possible to the multi-wavelength observational data, including the source number counts, redshift distributions, and the redshift-dependent luminosity functions. The models here have to identify the main population components, like star-forming and quiescent galaxies, and Active Galactic Nuclei of various categories, each one with its own statistical properties and its - somehow physically motivated - redshift evolution. The latter are fitted with simple parametric functions, that are needed to interpolate binned and discretized data (like the redshift dependencies), and to extrapolate them to regions of the parameter space where they are not directly measured (like the luminosity functions at the lowest - immeasurable - L).

An important aspect about this approach and supporting it has been emphasized by Madau & Pozzetti [68]: the observational number counts of extragalactic sources are so deep from the UV to the IR and cover such a large fraction of the flux-density range at the various λ in eq. (2) that the undetected sources below the flux detection limits give completely negligible contributions to EBL.

The quality of these empirical models of the EBL then rests on their ability to offer precise fine-grade description of the data and the ability to account for all the available observational constraints. Models of this sort are discussed in particular in [26,33,37,42,69–71,73–76].

The proper photon density and redshift variation, as well as the modelled local EBL spectral intensity, based on [75], are reported in Fig. 2.

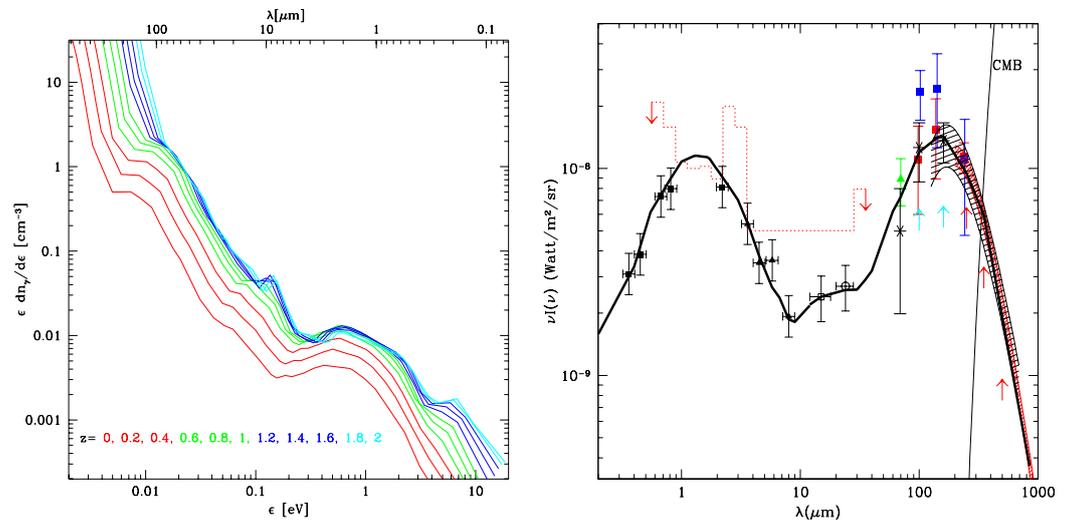


Figure 2. *Left:* the energy-weighted proper number density of EBL photons as a function of the energy ϵ . The various curves correspond to different redshifts, as indicated. The contributions of CMB photons appear in the fast rise below 0.01 eV. *Right:* the corresponding EBL spectral intensity (thick line). The data-points correspond to the integration of the known-source number counts as in eq. (2) [From 75].

3.3.2. Physical models

In a somewhat complementary fashion, models have been devised that predict the emissivity of cosmic sources based on *a-priori* treatment of their origin and cosmic evolution based on physical prescriptions. In particular, an approach of this kind was pioneered by Gilmore et al. [77], based on semi-analytic Λ CDM modelling of galaxy formation [78].

An advantage of this is that the effects of different assumptions about the values of the cosmological parameters can be investigated, and that interpolations and, particularly, extrapolations outside the observationally-constrained parameter space are physically motivated. A serious draw-back is that it is almost impossible by these means to achieve full compliance with the observational statistics and the model suffers rigidity to reproduce them.

3.3.3. Other approaches

Of some historical interest, EBL models have been published less directly related to the data and rather built on some parametrization of the history of the star-formation rate in galaxies. The latter is complemented with prescriptions about the source spectral energy distributions, dust extinction, and their evolution. An advantage here is that it is possible to discuss the model uncertainties by simple variations of the model parameters, which is definitely not the case for the previously mentioned more elaborated ones.

Mazin & Raue [36] have adopted a new approach to constrain a kind of free-form representation of the EBL spectrum and its redshift dependence directly from observations of the photon-photon opacity based on the VHE spectra of 14 extragalactic sources. Useful limits on the EBL have been inferred in this way. As an interesting development of this kind of thought, Biteau & Williams [6] have analysed a very large sample of 106 blazars producing some 300,000 detected photons: by assuming an EBL spectral shape as in [69,77] and a simplified treatment for the redshift-dependence of the EBL intensity, they have found a remarkable agreement among all these data with an EBL local spectrum as reported in Fig. 3.

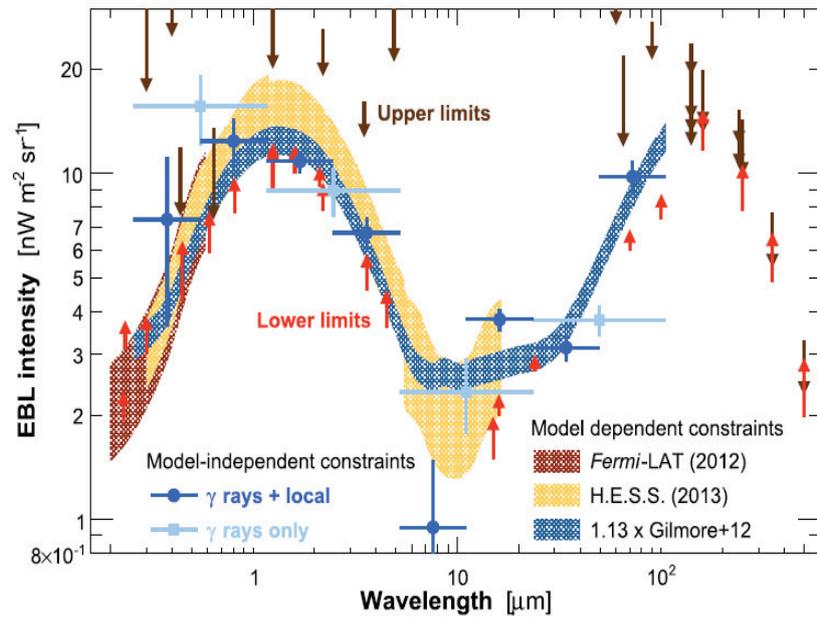


Figure 3. EBL intensity at $z = 0$ from the analysis of Biteau & Williams [6]. The best-fit spectra derived there are shown with light blue (gamma-rays only, four point spectrum) and blue points (gamma rays + direct constraints, eight-point spectrum) based on best-fit scaled-up models by [69,77], 1σ confidence. Lower and upper limits are shown with orange upward-going and dark-brown downward-going arrows, respectively. The results by [79] and the H.E.S.S. Collaboration (2013) are shown for comparison. [Kind permission by Biteau & Williams [6]].

4. EBL and the Cosmological Photon-Photon Opacity

One clearly established fact about the EBL is the existence of a minimum intensity threshold imposed by the existence of numerous sources populating the sky, and the condition of general homogeneity and isotropy of the Universe. This is an unavoidable condition, on top of which other radiations of more diffuse origin can add. The latter are mostly impossible to measure, given the previously mentioned foreground problem, and the lack of absolute photometric measurement capabilities of the typical astronomical facility. Our approach will then be to calculate photon-photon opacities for this minimal EBL and test against gamma-ray source spectra such predictions.

This can be immediately performed assumed an EBL spectral intensity and its cosmic evolution (see Fig. 2), complemented with Standard Model treatment of the photon-photon interaction and pair creation process [3].

4.1. Cosmic opacity due to known sources

The optical depth as a function of the gamma-ray source distance and photon energy is given, for an EBL density $dn_\gamma(\epsilon, z)/d\epsilon$ as in Fig. 2, by

$$\tau(E, z_e) = c \int_0^{z_e} dz \frac{dt}{dz} \int_0^2 dx \frac{x}{2} \int_0^\infty d\epsilon \frac{dn_\gamma(\epsilon, z)}{d\epsilon} \sigma_{\gamma\gamma}(\beta) \quad (6)$$

where $\sigma_{\gamma\gamma}$ is the pair-creation cross section and the argument β is computed as: $\beta \equiv (1 - 4m_e^2 c^4/s)^{1/2}$; $s \equiv 2E\epsilon x(1+z)^2$; $x \equiv (1 - \cos\theta)$, θ being the angle between the colliding photon directions, and, for a flat universe,

$$dt/dz = H_0^{-1}(1+z)^{-1} \left[(1+z)^2(1 + \Omega_m z) - z(z+2)\Omega_\Lambda \right]^{-1/2}.$$

The intrinsic spectrum S_{int} of a gamma-ray source at redshift z_e is then absorbed as a function of energy as: $S_{abs} = S_{int} \exp -\tau(E, z_e)$.

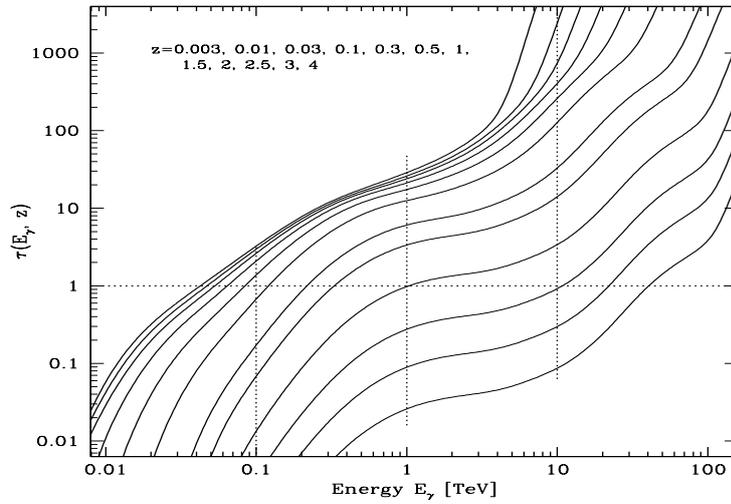


Figure 4. The optical depth by photon-photon collision as a function of the photon energy for sources located at $z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4$, from bottom to top. The fast rise at the high τ and E_γ values is due to the large volume density of CMB photons.

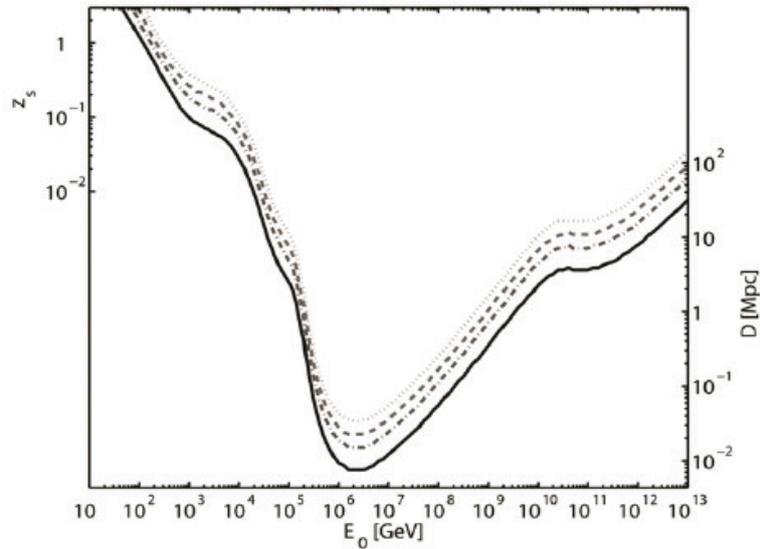


Figure 5. Graphical representation of the global photon-photon opacity. The graph shows the source redshifts z_s at which the optical depth takes fixed values as a function of the observed hard photon energy E_0 ; the y-scale on the right side shows the distance in Mpc for nearby sources. The curves from bottom to top correspond to a photon survival probability of $e^{-1}=0.37$ (the horizon), $e^{-2}=0.14$, $e^{-3}=0.05$ and $e^{-4.6}=0.01$. For $D > 8$ kpc the photon survival probability is larger than 0.37 for any value of E_0 . [Kind permission by [72].]

This $\sigma_{\gamma\gamma}$ cross-section implies that the absorption is maximum for photon energies

$$\epsilon_{max} \simeq 2(m_e c^2)^2 / E_\gamma \simeq 0.5 \left(\frac{1 \text{ TeV}}{E_\gamma} \right),$$

or in terms of wavelength

$$\lambda_{max} \simeq 1.24(E_\gamma [\text{TeV}]) \mu\text{m}. \quad (7)$$

The plot in Fig. 4 shows the optical depth as a function of the gamma-ray energy for a range of values of the redshift of the source. In addition to our modelled EBL we include here also the contribution to the opacity coming from the high density of CMB photons, assuming a temperature of $T = 2.738$ K. This shows up as a fast increase of τ at high values of E_γ .

The effects of the CMB and radio-backgrounds are further reported in Fig. 5, showing the redshifts at which the photon-photon optical depth assumes the values of $\tau = 1, 2, 3$, and 4.6 , as a function of the gamma-ray energy.

4.2. Constraining the Near-IR EBL (NIR-EBL)

As mentioned in Sect. 3.2, background radiations at near-IR wavebands have been intensively investigated by several independent experiments, with claims of intensities largely in excess of the baseline EBL from known sources, as shown in Fig. 2 right. Such excesses would amount to several tens of $nW/m^2/sr$ in the figure. Thanks to the very sensitive instrumentation (HST and Spitzer from space, very large telescopes from ground), the baseline EBL is very well constrained and understood at these wavelengths. At the same time, from eq. (7) these background photons produce opacity effects in the VHE spectra of sources at gamma energies of ~ 1 TeV, where IACT's are maximally efficient. This combination then offers a good chance to test the excess NIR-EBL hypothesis via the pair-production effect.

The analysis of the two distant blazars by Aharonian et al. [38] offered the first important test exploiting pair production effects, that ruled out the reality of the excess at the levels previously indicated and the possibility that such a large signal might originate from the first light sources at $z \sim 10$. All subsequent analyses have fully confirmed this result, leaving little room for any truly diffuse background at such wavelengths [e.g. 69]. Eventually, this EBL level turned out to be consistent with recent developments about the background signals as in [64,65].

4.3. Constraining the UV-optical EBL (UV-EBL)

The *Fermi* space observatory offered, during the last decade and counting, the first major facility promoting gamma-ray to a fully-fledged and mature field of astronomy. Its *LAT* instrument detected several thousands of extragalactic sources between 20 MeV and 300 GeV, including many high- z ones. Since the cutoff energy due to pair production scales with redshift approximately as

$$E_{\gamma,cutoff}(z) \sim 800(1+z)^{-2.4} \text{ GeV},$$

the observatory turned out to be in the ideal position to investigate how this cutoff evolves with z , hence, from eq. (7), how the UV-EBL intensity evolves with time. This analysis was performed by Ackermann et al. [79], who found excellent agreement with the predictions by [69]. This analysis was further expanded by [80] to include the spectra of as many as 739 active galaxies and one GRB up to a redshift $z \simeq 4.35$. The inferred constraints on the UV-EBL are so precise and detailed that, assuming recipes for the dust-extinction from literature, these data were used to estimate the evolutionary UV-emissivity and the history of star-formation in the Universe per average comoving volume, given the tight relation of UV light and the rate of SF.

These results appear remarkably consistent, over the full range of EBL wavelengths of $0.1 < \lambda < 5 \mu\text{m}$, with the mere integrated emissions of know galaxies. Instead, they are not entirely consistent with the latest direct evaluation of the local EBL at $\lambda = 0.608 \mu\text{m}$ by the *New Horizon* interplanetary explorer of $\nu I(\nu) \simeq 17.5 \pm 4.2 \text{ nW}/\text{m}^2/\text{sr}$ (see Sect. 3.2), against the intensity of $\nu I(\nu) \simeq 6.2_{-1}^{+2} \text{ nW}/\text{m}^2/\text{sr}$ allowed by the pair-production constraint. This is a significant inconsistency that has to be resolved in some way and may indicate some improper calibration of the *Horizon* photometers.

4.4. Constraining the Far-IR EBL (FIR-EBL)

The wide wavelength interval from 5 to 300 μm hosts a large portion of the integrated radiant energy by cosmic sources (Fig. 2). This is radiation by dust extinguishing short-wavelength emission by galaxies and AGNs, and re-processing it as quasi-thermal radiation. Indeed, major episodes in the formation of galaxies, of their stellar populations, and of AGN gravitational accretion happen inside dust-opaque media, where extinction of energetic radiation favours the coalescence and collapse of the primordial gas [41,42,85].

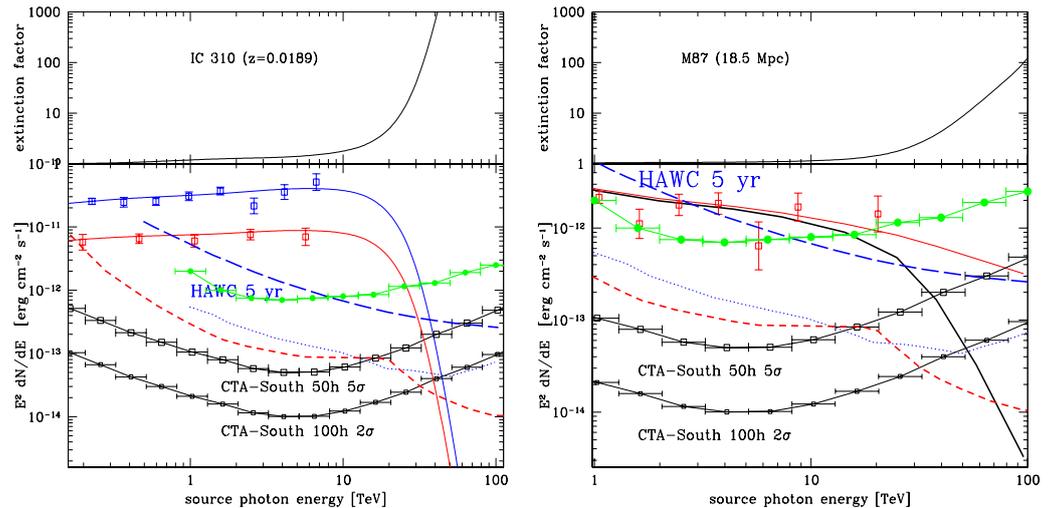


Figure 6. *Left panel:* *Top:* The photon-photon absorption correction ($\exp[\tau_{\gamma\gamma}]$) for the source IC 310 at $z = 0.0189$, based on the EBL model by [75]. *Bottom:* The blue data-points and continuous line were taken during an outburst phase, the red data and continuous line during a prolonged high-state. The 50-hour 5σ and 100 hours 2σ sensitivity limits for CTA, and the HAWC 5 years limits are shown. The blue dotted line and the red dashed one indicate the SWGO and LHAASO 5 years 5σ limits, respectively. The 50-hour limit for the forthcoming ASTRI mini-array is shown in green. *Right panel:* Photon-photon absorption for the source M 87 at 18.5 Mpc. The observed (open red and continuous line) and absorption-corrected (black line) spectral data are reported. Same as in the left panel.

We have seen in Sect. 3.2 that over that wavelength interval direct observations of the Infrared EBL are precluded by the dominance of the Inter-Planetary Dust and Galactic dust emissions [47, and Fig. 1]. Infrared telescopes from space can detect point sources, but are blind to diffuse emission, like extended halos of dust emission or truly diffuse processes, because of the huge background noise. Also, the source confusion problem due to the limited angular resolution at such long wavelengths prevents the detection of faint sources.

Clearly pair-production opacity effects detectable in the spectra of distant gamma-ray sources offer an interesting tool to indirectly measure the IR-EBL [86]. From eq. (7) the FIR-EBL can be constrained by VHE observations at energies above several TeV. With the current IACT instrumentation, the highest energy photons so far detected by extragalactic sources came from the two lowest- z prototypical blazars MKN421 and MKN501. Aharonian et al. [28], Stanev & Franceschini [29], Stecker & de Jager [31], Aharonian et al. [82,83,84] took advantage of exceptional flaring events of the two sources in 1999-2001 and 1997, to constrain their spectra up to 10-20 TeV.

Eq. 7 tells, however, that to constrain EBL over a larger portion of the dust-reprocessing region in Fig. 2 requires probing VHE spectra well above 10 and possibly up to 50-70 TeV. Now from Fig. (4) it is evident that such high energy photons are detectable (with $\tau[E_{\gamma,z}] < 20$) only from very low redshift sources, say $z < 0.03$, meaning

that even MKN421 and MKN501 are too far away to be suitable, while better chances are offered by long VHE observations of local radio-loud AGNs, like IC310 and M87 [86]. Fig. 6 illustrates simulated observations with various future VHE observatories of these two local radio sources during high-states and an outburst. With sufficiently long integrations (particularly promising observations with CTA and LHAASO), the spectra could be measured up to several tens of TeV and the FIR-EBL be constrained almost up to $100 \mu\text{m}$.

5. Discussion

An important cautionary note is in order. The analyses based on the photon-photon interaction suffer a limitation in the degeneracy between the source gamma-ray spectra and the EBL spectral intensity. For example, any attempts dedicated to constraining the EBL intensity should include some prior knowledge and assumptions about the extrapolations of the source spectra to the highest energies, where pair-production cutoffs show up. Therefore, these analyses offer significant model constraints and consistency checks more than precise measurements and parameter estimation.

We discuss in this Sect. some of such investigations. We can outline our discussion by splitting it into two sections: one considering constraints on astrophysics and cosmology, the other concerning themes relevant for fundamental physics. The former will assume Standard Model physical prescriptions for the photon-photon interaction, while the latter will instead adopt standard assumptions for astrophysics and look for consistencies, or inconsistencies, that would require modifications to the Standard Model.

5.1. Some (resolved?) controversy

Let us first of all anticipate a brief mention to a controversy that has originated from analyses of the cosmological gamma-ray horizon and pair production process. Using IACT spectral data published during the last decade, some groups have found indications that EBL model corrections for pair production opacity over-predict the observed gamma-ray attenuation [87–92]. This would manifest itself by a spectral hardening after EBL absorption correction at photon energies corresponding to a high optical depths.

Thanks to the joint efforts from space (Fermi) and the IACTs from ground looking at blazars over a range of redshifts, the analysis was performed by comparing the gamma-ray spectral slopes at HE and at VHE and searching for spectral hardening with the photon energy. Horns [92] in particular reports some indications for anomalous cosmic transparency by plotting the spectral slopes α as a function of the $\gamma - \gamma$ optical depth $\tau_{\gamma\gamma}$: he finds that while α naturally steepens for small values of optical depth up to $\tau_{\gamma\gamma} \sim 1$, for $\tau_{\gamma\gamma} > 1.5$ it seems to show an upturn, that he attributes to anomalous transparency, considering that it would be contrived if such a hardening occurred in sources at exactly the energy where $\tau_{\gamma\gamma} > 1$, instead of depending on the source distance.

Various other teams have argued against such an evidence [6,69,76,79–81]. A particularly extensive analysis is reported by Biteau & Williams [6]: based on their large VHE database of 106 gamma-ray spectra they report finding "no significant evidence for anomalies".

One aspect that seems to have been largely overlooked in the analyses of the VHE pair-production spectral cutoffs at the VHE energies is the statistical effect known as Eddington bias. This applies when trying to measure a quantity for a statistical set, subject to errors, in the presence of gradients in the probability distribution of that quantity. In our case, in the presence of significant uncertainties in the photon energy measurements, there is a finite probability that photons counted at the highest energies – where the exponential drop-off for pair-production opacity applies – include a number of truly lower energy photons scattered high, not compensated by the much fewer entering

from the higher-energy bin. Corrections for this effect are proposed in many papers, starting from the original [93], see e.g. [94, among others].

In conclusion, it is perhaps fair to say that such controversy has recently somewhat weakened. Supporters of the anomaly seem to agree that the effect may not be so significant and anyhow requiring confirmation by future more sensitive experiments [95]. With the currently available data set, mostly from existing IACT and Fermi observations, our analyses did not so far appear having revealed significant inconsistencies with the present physical and astrophysical understanding so as to require fundamental revision.

Certainly this is not to say that everything is clear and settled - further discussion will be reported in later subsections. And, in any case, forthcoming and future instrumentation will go to investigate regions of the parameter space that are so far uncovered.

5.2. The present understanding: constraints on astrophysics and cosmology

5.2.1. The history of star-formation

We have summarized in Sect. 4 a number of studies reporting constraints on EBL from gamma-ray observations. The bottom line appears to be that no major evidence has so far emerged for excess radiation components of EBL in addition to what is contributed by known source populations. Some remaining open questions that might require further inspection concern the large claimed excess at near-IR wavelengths from space IR observatories and the factor ~ 2 excess background at $\lambda = 0.6 \mu\text{m}$ reported by the *New Horizon* spacecraft, two results however uncertain for various reasons, especially because of the foreground contamination, and also not very statistically significant.

Not unexpected, but not even entirely obvious *a-priori*, data on the photon-photon opacity did not require EBL levels lower than the minimal baseline set by the integrated emission of source, as inferred from cosmological deep surveys and based on eq. (2).

Now, let us reverse the argument, i.e. having in mind that the gamma-ray data appear so far largely consistent with the mere EBL from known sources, a question might arise if there would be indications from astrophysics and cosmology of processes and events implying larger background fluxes at some wavelengths. One such instance would be the source population responsible for the early metal enrichment of the primordial gas and for the re-ionization of the Universe at $z \geq 9$, the Population III stars, that are the products of zero-metallicity star-formation [45,96]. Such faint sources would be undetectable individually by astronomical telescopes, but their integrated emission might be substantial, and indeed these were mentioned as the possible origin of the putative large NIR-EBL excess in Sect. 3.2.

The general question about such past excess activity can be addressed by consideration of the local relics of the past history, like the stellar mass and black-hole mass functions, and the metal abundances observed in cosmic plasma's, all remnant products of high- z stars and AGNs.

Madau & Silk [97] dedicated a detailed analysis of the consequences of trying to explain the NIR-EBL excess. While not excluding that a small portion of that excess - say of order of few $nW/m^2/sr$ - might still be present, they conclude that attempt to explaining the whole claimed excess faces a number of inconsistencies making this a very unlikely possibility. These are related to the uncomfortably large amount of metals produced and, alternatively, the excess amount of intermediate-mass black holes (by a factor 50 more mass than hosted in galactic nuclei), creating problems with the data on the X-ray background.

Similar constraints apply to populations of normal galaxies and AGNs in excess of those already categorized. A question might arise of how much our current understanding of galaxy and AGN formation and evolution offers a consistent picture, or if inconsistencies of any kind would call for major revisions, with impact on their EBL contributions. Once more radiations from remote sources can be compared with the various local relics.

Madau & Dickinson [41] have performed an extensive review to map the cosmic history of star formation, and heavy element production. Under the assumption of a universal initial stellar mass function (that proposed by Chabrier [98] in particular), the average stellar mass density in galaxies observed as a function of z matches well the integral of all the previous star-formation activity. The comoving rates of star formation and central black hole accretion, all consistent with a huge amount of published observational data, follow a similar redshift evolution. The corresponding predicted rise of the mean metallicity of the Universe is also consistent with the observations of the abundance of metals in various cosmic sites and also, though a bit marginally, with the energy requirements by the cosmological re-ionization from the cosmic “dark ages” to the present. Many published reports agree with the results of this analysis [75,99–102].

Driver et al. [99] operate an equally extensive analysis, including as many as 600,000 galaxies over the whole Hubble time, reaching similar conclusions. However with the important addition that all these data not only offer a consistent picture of galaxy activity, as discussed above, but also strongly limit the fraction of stellar mass being stripped or ejected by the individual galaxies to not exceed the 13%.

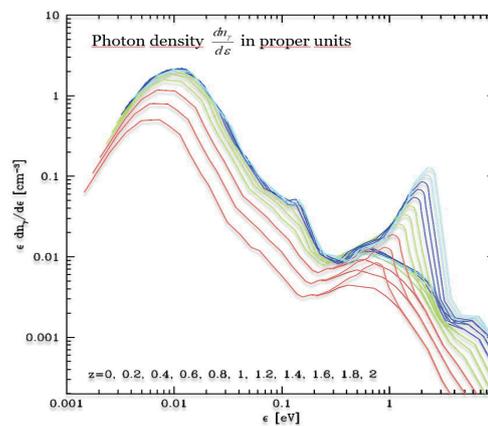


Figure 7. Energy-weighted proper number density of EBL photons as a function of the energy ϵ and for various redshifts. The standard EBL evolution, as in Fig. 2, is compared to the densities when including photons from primeval objects: an excess local background by less than a factor 2 at $1.4 \mu\text{m}$ becomes a factor 50 by $z = 2$ due to the $(1+z)^3$ increase in the proper photon density.

and their proper density vanishes at higher z , those from primeval sources strongly increase proportionally to $(1+z)^3$ because of the simple cosmological expansion. An example is reported in Fig. 7, where a modest excess EBL flux at $z = 0$ from very high-redshift sources becomes a factor 50 in photon density already by $z = 2$, making a significant and possibly measurable contribution to the opacity in $z > 1$ blazars.

5.3. Constraints on new physics: Lorentz Invariance Violations and photon to axion-like particle mixing

Playing with such high-energy photons as those observable at HE and VHE with Cherenkov observatories offers also invaluable tests of fundamental physics.

A major frontier for today’s physics is the attempt to describe the gravitational interaction with the language of quantum mechanics, trying to achieve a coherent picture. In this context, modifications to the relativistic Lorentz transformation are expected at VHE energies by many proposed theories [103–105]. Indeed tests of the

All this is entirely consistent with the EBL modelling as in Sects. 3.3 and 4, with little room for optical Intra-Cluster Light and Intra-Halo Light, and consistent with data on the photon-photon opacity.

5.2.2. Potential constraints on primeval re-ionization sources

Certainly, the new generation of large IACT telescope arrays, like CTA, will offer such a large sensitivity gain over current instrumentation, including the *Fermi* space observatory, to extend the observational horizon at tens to hundreds GeV up to substantial redshifts, $z \sim 1$ to several. In relation to the mentioned Population III and cosmic re-ionization sources, some new tests would then become feasible to detect such emissions from the pre-galactic era in the form of excess $\gamma\gamma$ absorption. This is based on the fact that, while major part of the EBL photons by galaxies are produced at $z < 1$ (e.g. Fig. 2) and

Lorentz Invariance with VHE gamma rays allow us probing it at the highest observable energies.

A predicted effect of LIV may be an energy-dependent variation of the speed of light with respect to the standard value in the vacuum, as previously mentioned. This however would make a negligible effect (10^{-15} in relative velocity units) even at the highest detectable photon energies.

A better testable potential effect concerns anomalies in the kinematics of particle collisions and scattering, particularly in the pair-production processes, with consequences for the photon absorption effect. Kifune [105], among others, based on eq. (1), for $\lambda = \pm 1$ and assuming the emergence of quantum-gravity effects at the Planck energy, predicts that significant anomalies, like spectral upturns or strong convergences would be observable at blazar photon energies larger than ~ 10 TeV. While this is at the edge of the capabilities of current-day gamma-ray observatories, the new generation of instruments, both IACT's (CTA [106] and ASTRI [107], in particular) and water-Cherenkov arrays (LHAASO [108] in particular, and HAWC [109]) will be perfectly suited to cover with sufficient sensitivity this extreme spectral range up to and above 100 TeV.

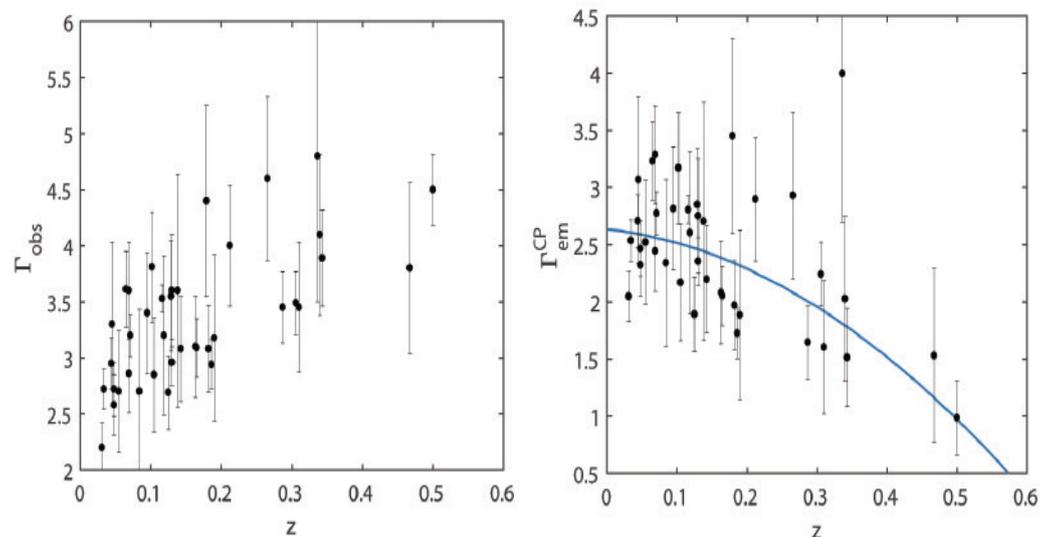


Figure 8. *Left panel:* Values of the observed spectral indices Γ_{obs} for the flaring blazar sample by [110], versus redshift. *Right panel:* Same as on the left panel, but corrected for EBL absorption following [75,76] (Γ_{cor}). The blue curve superimposed on the data is the best-fit regression line based on a reduced-absorption model with photon-ALP mixing elaborated by [110], producing a reduced $\chi^2_v = 1.46$. Eliminating the ALP effect would degrade the fit to $\chi^2_v = 2.37$, corresponding to fit an horizontal line. The improvement has a 3σ significance. [Kind permission by [110].]

Another potential source of anomalous $\gamma\gamma$ opacity might be the existence of axions or axion-like particles, mentioned in Sect. 1, these being one of the considered candidates for the long-sought non-baryonic dark matter. Their expected behavior of mixing with two photons or a gamma-ray and a virtual photon associated with environmental magnetic fields would have potentially important observational consequences in terms of a reduced photon-photon opacity, as during the ALP phase no interaction with the EBL photons is expected to occur.

Waiting for direct laboratory detection of such extremely elusive particles, some indirect evidence can be achieved from detailed analyses of the associated anomalous photon-photon absorption effects on distant blazar spectra. This is what de Angelis, Galanti, & Roncadelli [72] and Galanti et al. [110], among others, have attempted, by comparing the spectral properties for samples of BL Lac blazars at various redshifts and VHE energies. They have paid particular care in the sample selection (using only blazars in flaring states) and corrections for bias. Their results are summarized in Fig. 8: on the

left panel the power-law fit to the observed VHE spectra at around 1 TeV are reported, where the increase is caused by the stronger spectral softening at larger redshifts due to the larger cosmic opacity. The authors argue that, after standard [75] EBL corrections, the spectral indices of their sources show a correlation with redshift that has no physical justification, hinting for a lower average opacity as allowed by the photon-ALP mixing. While formally indicative of a few σ effect calling for new physics, their result mostly weights on just a couple of objects around $z = 0.5$ with inferred low $\Gamma_{cor} \simeq 1 - 1.5$ values. It should also be cautiously considered that the observed trend might also reflect a bias introduced by the Malmquist effect, emphasizing higher luminosity sources at larger redshifts, with possibly different spectral properties.

In conclusion, gamma-ray astronomy has an enormous potential to probe physics at extreme energies. However, at the sensitivity limits of current instrumentation no evident discrepancy has been revealed that would call for modifications to the Standard Model. In particular, testing Lorentz Invariance requires extending the IACT's or water Cherenkov to energies > 10 TeV, that will be feasible only with very large arrays, while tests of ALP mixing will need better sensitivities to expand the observational parameter space and strengthen the statistics. Both requirements will be fulfilled by CTA.

5.4. Other open questions and prospects

Gamma-ray astronomy also offers invaluable tests of astrophysics of extreme environments. Astrophysical jets from galactic and extragalactic sources are certainly among these, while the detected highest energy cosmic rays can hardly be classified differently than their most extreme manifestation. A possible link between the two has been recently suggested by the detection of a PeV neutrino from the direction of a blazar, with concomitant flaring gamma-ray emission from the object [111]. Blazars and blazar jets are therefore suggested to be considered as the sources of cosmic rays, particularly those of the highest energies. The clear consequence would be that jets not only include leptonic particles and processes (electrons, positrons, SSC, etc.), but also collimated beams of hadrons.

Hadron beams have been studied by various authors [e.g. 112,113]. Emitted protons and heavier nuclei would produce VHE photons via interactions and cascades along their trajectory, at some distance from Earth, whose paths then are shorter than the source distance, with an overall reduced photon-photon opacity. Within this scenario, we would expect the emergence of spectral components at energies well above the TeV. However, while hadronic components in jets cannot be ruled out, the present phenomenology of blazar properties appear still overall consistent with standard leptonic processes like the synchrotron self-Compton model [e.g. 114, among others].

6. Conclusions

Gamma-ray astronomy, particularly after the successful space mission *Fermi* and the implementation of the first IACT arrays, is becoming a clearly mature science. Its current main limitation rests on the VHE domain, above 100 GeV: because of the rarity of photonic events, the number of such energetic photons is decreasing very sharply with energy ($S_\nu \propto \nu^{-2,-3}$ at least). Fortunately, major progress is expected by the forthcoming implementation of very large arrays of IACT's (CTA) and water-Cherenkov (LHAASO) arrays, that will compensate such extremely low rate of arrival with the expansion of the photon collectors.

Major progress is expected in many fields from these developments. For astrophysics, fundamental topics like the origin of the high-energy cosmic rays and the structure of astrophysical jets will largely benefit. Furthermore, the technique based on the photon-photon opacity analysis also offers interesting tests and constraints in the field of observational cosmology, for the topic of the history of stellar formation and AGN accretion, hence uniquely embracing high-energy physics with low-energy astrophysics and cosmology.

As for fundamental physics, laboratory experiments and large particle accelerators have likely reached their current technological frontier, while the next steps forward will require lot of effort, resources, and time. An excellent complement at much lower price, however, is offered by gamma-ray astronomy at its VHE limits, with opportunities to test the validity of fundamental laws in regimes - e.g. close to the Planck energy - where they have never been tested, to set the stage for higher level theories beyond the Standard Model.

If we have to summarize our present understanding, it seems to us that current investigation concerning the highest energy photons from cosmic sources has not found clear and significant evidence for deviations and need for new physics, neither in the field of astrophysics and cosmology, nor that of fundamental physics.

No doubt, however, that improved instrumentation, refined observational techniques, and new ideas will call for the next steps in our understanding of the universe and its fundamental laws.

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