Probing the evolution of the EBL photon density out to $z \sim 1$ via $\gamma$-ray propagation measurements with Fermi

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Abstract The redshift ($z$) evolution of the Extragalactic Background Light (EBL) photon density is very important to understand the history of cosmological structure formation of galaxies and stars since the epoch of recombination. The EBL photons with the characteristic spectral energy distribution ranging from ultraviolet/optical to far-infrared provide a major source of opacity of the Universe to the GeV-TeV $\gamma$-rays travelling over cosmological distances. The effect of the EBL is very significant through $\gamma\gamma \rightarrow e^-e^+$ absorption process on the propagation of the $\gamma$-ray photons with energy $E > 50$ GeV emitted from the sources at $z \sim 1$. This effect is characterized by the optical depth ($\tau$) which strongly depends on $E$, $z$ and density of the EBL photons. The proper density of the EBL photons increases with $z$ due to expansion of the Universe whereas evolution of radiation sources contributing to the EBL leads to a decrease in the density with increasing $z$. Therefore, the resultant volumetric evolution of the EBL photon density is approximated by a modified redshift dependence. In this work, we probe evolution of the EBL photon density predicted by two prominent models using cosmic gamma-ray horizon ($\tau(E, z) = 1$) determined by the measurements from the Fermi-Large Area Telescope (LAT) observations. The modified redshift dependence of the EBL photon density is optimized for a given EBL model by estimating the same gamma-ray horizon as predicted by the Fermi-LAT observations. We further compare the optical depth estimates in the energy range $E = 4$ GeV-1 TeV and redshift range $z = 0.01 - 1$ from the Fermi-LAT observations with the values derived from the two EBL models to further constrain the evolution of the EBL photon density in the $z \sim 1$ Universe.

Keywords cosmology: diffuse radiation, extragalactic background light: evolution, gamma-rays: general

1 Introduction

The extragalactic background light (EBL) is the diffuse background radiation at ultraviolet (UV), optical, and infrared (IR) wavelengths. It is also described as the present epoch ($z = 0$) metagalactic radiation field associated with the star and galaxy formation (Kneiske et al. 2002). The dominant contributors to the EBL are direct starlight in the UV/optical wavelength band and reprocessed emission by dust in the host galaxies and interstellar medium in the IR waveband since the epoch of reionization (Hauser & Dwek 2001; Dwek & Krennrich 2013). The spectral energy distribution (SED) of the EBL is observed to exhibit two distinct humps peaking at the optical and IR wavelengths and a valley between these two humps. Other radiation sources such as extremely faint galaxies, accretion on to the compact objects, active galactic nuclei, and decay of the elementary particles can also contribute to the SED of the EBL (Mattila & Väisänen 2019). The peak at IR wavelength may originate due to re-radiation from the significantly hotter dust in the torus of the active galactic nuclei. Therefore, intensity and spectrum of the EBL could provide important information about the nature of star formation, galaxy evolution, stellar and interstellar contents of the galaxies through the history of the Universe. The observed spectra of high redshift quasistellar sources suggest reionization of the intergalactic gas between the epoch of cosmic recombination ($z \approx 1100$) and $10^9$ years later ($z \approx 6$) (Fan et al. 2006). The UV component of the EBL emitted by first stars galaxies is considered as the primary suspect for this process through photoionization (Gilmore et al. 2009).
Thus, information about the UV radiation is very important to probe the phenomena of reionization in the early Universe (Raue & Meyer 2012; Khaire & Srianand 2019; Cowley et al. 2019). In general, understanding the properties of the broadband SED of the EBL photons is one of the attractive goals of the modern cosmology.

Strict constraints on the intensity and SED of the EBL come mainly in three flavors: direct measurements, indirect measurements through the high energy γ-ray observations, and estimations from the integrated galaxy counts from the resolved source populations. Direct measurements of the EBL intensity are subject to very large uncertainties due to strong foreground emissions from the solar system, interplanetary dust (zodiacal light) and Milky-Way (diffuse galactic light) in the same wavelength band (Hauser & Dwek 2001; Hauser et al. 1998). Recent attempts for direct measurement of the EBL intensity as a function of wavelength are found to be very challenging and limited by the systematic uncertainties (Matsuura et al. 2017; Zemcov et al. 2017). An alternative method for indirect measurement of the EBL intensity involves the effect of γ−γ absorption via pair production during propagation of the high energy γ-ray photons emitted from the sources at the cosmological distances (Gould & Schröder 1966; Stecker et al. 1992). This method is also challenged by the set of uncertainties related to the measurement and determination of the spectra of distant γ-ray emitters. However, several stringent upper limits have been derived on the intensity of the EBL by γ-ray observations of distant blazars and assuming different spectral forms for their intrinsic spectra (Aharonian et al. 2006; Mazin & Raue 2007; Meyer et al. 2012; Singh et al. 2014, 2019; Sinha & Menter 2020). Integral of the light emitted by all resolved galaxies provides a strict lower limit to the EBL intensity (Madau & Pozzetti 2000; Dole et al. 2006; Keenan et al. 2010; Driver et al. 2016). Several promising models for the SED of the EBL at z = 0 have been proposed using different distinct approaches based on the above constraints (Kneiske & Dole 2010; Finke et al. 2010; Domínguez et al. 2011; Gilmore et al. 2012; Stecker et al. 2016; Franceschini & Rodighiero 2017). Most of these EBL models are found to be in good agreement with the lower limits from the resolved galaxy counts and scaling of a few of them combined with the high energy γ-ray observations provide well defined measurements of the EBL intensity at the present epoch (Ackermann et al. 2012; Abramowski et al. 2013; Biteau & Williams 2015; Ahnen et al. 2016a; Desai et al. 2019; Abeysekara et al. 2019). Recently, analysis of the high energy γ-ray photons emitted from the active galaxies and detected by the Fermi-Large Area Telescope (LAT) has been used to determine the intensity of the EBL up to redshift z ~ 6, i.e. light emission over 90% of the cosmic time (Abdollahi et al. 2018). The EBL spectrum determined by the Fermi-LAT at the present epoch (z = 0) is consistent with the predictions from the method of the resolving individual galaxies.

The EBL intensity has also been constrained from the measurements of the γ-ray attenuation effects on the GeV-TeV spectra of the blazars observed with the current generation ground-based atmospheric Cherenkov telescopes like VERITAS, H.E.S.S. and MAGIC up to redshifts z ~ 1. Observation of the γ-ray emission up to ≈ 200 GeV from the blazar PKS 1441+25 at z = 0.939 with the VERITAS telescopes has set a stringent upper limit on the EBL intensity broadly consistent with the resolved galaxies surveys (Abeysekara et al. 2015). This has provided an excellent baseline with the redshifted UV emission from the primordial stars. Recent model-independent measurement of the EBL from the γ-ray spectra of 14 VERITAS-detected blazars at z = 0.044 − 0.604 also shows good agreement with the lower limits derived from the resolved galaxies counts (Abeysekara et al. 2019). The H.E.S.S. collaboration also derived a model-independent SED of the EBL using the γ-ray observations of a sample of blazars in the redshift range z = 0.031 − 0.287 (Abdalla et al. 2017). The EBL intensity levels extracted in the different spectral bands are found to be in line with the results obtained from the Fermi-LAT measurements close to the lower limits in the optical range (Ackermann et al. 2012) and are also consistent with the upper limits derived from the VERITAS observations (Abeysekara et al. 2015). The MAGIC collaboration presented EBL constraints based on a joint likelihood analysis of 32 γ-ray spectra for 12 blazars in the redshift range z = 0.031 − 0.944 obtained by the MAGIC telescopes and the Fermi-LAT (Acciari et al. 2019). A wavelength-resolved determination of the EBL indicated an excess in the UV/optical component of the SED relative to other models. However, this is compatible with the existing EBL models within statistical uncertainties. At high redshifts, the γ-ray bursts offer a significant advantage over the blazars for constraining the EBL intensity. Analysis of a sample of 22 γ-ray bursts detected by the Fermi-LAT in the energy range of 65 MeV-500 GeV has been used to place first constraint on the UV component of the EBL at an effective redshift z ~ 1.8 (Desai et al. 2017).

In the present work, we study the redshift evolution of the proper density of the EBL photons in the local Universe z ≤ 1 using predictions from the γ-ray observations with the Fermi-LAT. We have used two most promising and widely used SEDs of the EBL at z = 0 proposed by Finke et al. (2010) and Domínguez et al. (2011) to probe the EBL evolution at lower redshifts. We first discuss the cosmological evolution of the EBL in Section 2. Propagation of the γ-rays in the Universe and recent predictions from the Fermi-LAT observations are described in Section 3. In Section 4, we present and discuss the results followed by the conclusion of this study in Section 5.
2 EBL Evolution

Accelerated expansion of the Universe has been confirmed and very well understood by the observations of type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1999). The dynamics of expanding Universe is described by a free function of time called the scale factor \( a(t) \), which is expressed as

\[
a(t) = a_0 (1 + z)^{-1}
\]  

(1)

where \( a_0 \) is the scale factor at the present epoch corresponding to \( z = 0 \). The comoving radial distance is proportional to \( a(t) \) and therefore the density of the EBL photons (number of photons per unit volume) evolves as

\[
n(z) \propto (1 + z)^3
\]  

(2)

This implies that the photon proper density increases with redshift due to the expansion of the Universe. This is generally referred to as the volumetric evolution of the background photons. An observer in a galaxy at redshift \( z > 0 \) would observe a Universe which is smaller than the present day Universe by a factor \((1 + z)^3\). Since, the EBL represents integrated cosmic activities involving star and galaxy formation and models of dust or matter distribution in the galaxies, it is very important to consider the evolution of radiation sources contributing to the EBL intensity. Thus, at any given epoch, the proper number density of the EBL photons consists of accumulated radiation emitted at the previous epochs and their sources in the rest frame. During most of the cosmic time to the present epoch, the stars and galaxies progressively emit photons contributing to the EBL. Sources contributing to the optical regime of the EBL are at lower redshift \((z \leq 0.6)\) whereas IR photons originate at higher redshifts \((z > 0.6)\). This implies that increase in the proper photon density with redshift is larger for the IR and smaller for the optical photons. The enhancement in the proper photon density of the optical photons due to the volumetric evolution (Equation 2) can be quickly compensated by the decrease in the population of available photons with the increasing redshift. Therefore, the effective comoving density of photons decreases at larger redshifts. To account for this, an evolutionary parameter \( k \) is introduced to scale the proper number density of the EBL photons as

\[
n(z) \propto (1 + z)^{3-k}
\]  

(3)

The value of \( k \) can vary with redshift as it quantifies the effect of radiation sources contribution to the EBL. It plays a very important role in the propagation of the high energy \( \gamma \)-ray photons over cosmological distances. There is no uniquely determined value of \( k \) and multiple values are proposed in the literature (Madau & Phinney 1996; Aharonian et al. 2007; Raue & Mazzin 2008). In case of no radiation source, \( k = 0 \) indicates strong evolution of the optical emission of the galaxies with no absorption or reprocessing and photons are already present at the given redshift. A significant amount of the UV photons emitted at the early epochs are redshifted to the optical due to expansion of the Universe. In the case of the static Universe, the photon number density is higher than that integrated over redshift. Therefore, evolution of the galaxies should be properly considered while estimating the cosmological dependence of the number density of the EBL photons. The comoving number density of the EBL photons in the energy range \( \epsilon \) and \( \epsilon + d\epsilon \) at redshift \( z \) is given by

\[
n(\epsilon, z) = n(\epsilon_0, 0)(1 + z)^{3-k}
\]  

(4)

where \( \epsilon_0 = \epsilon(1 + z)^{-1} \) is the observed energy of the EBL photon at \( z = 0 \). The comoving number density at the present epoch can be estimated from the intensity \( \nu I_\nu \) of the EBL using the relation (Dwek & Krennrich 2013)

\[
n(\epsilon_0, 0) \left[ \text{ph cm}^{-3} \text{eV}^{-1} \right] = \frac{4\pi \nu I_\nu(\nu_0, 0) [\text{mW m}^{-2} \text{sr}^{-1}]}{c e_0^2 [\text{eV}]} \nu_0^3
\]  

(5)

where \( \nu \) and \( \nu_0 \) are the frequencies corresponding to \( \epsilon \) and \( \epsilon_0 \) respectively. The broadband SED of the EBL is represented by \( \nu I_\nu \) vs \( \lambda \) (wavelength) on log-log scale as shown in Figure 1 for the two widely used models described in (Finke et al. 2010; Domínguez et al. 2011). The model proposed by Finke et al. (2010) assumes main-sequence stars as blackbodies which re-emit the star light absorbed by the dust after taking into account the star formation rate, initial mass function and dust extinction. It also includes emission from the post-main-sequence stars to model the broadband SED of the EBL photons which is very close
to the lower limits from the galaxy counts at $z = 0$. The second model by Dominguez et al. (2011) is based on the multi-wavelength data of about 6000 galaxies from different surveys and the rest frame K-band galaxy luminosity function which provides an accurate measurement of the galaxy evolution. Recently, a new determination of the evolving SED of the EBL up to $z \sim 6$ purely based on the deepest multi-wavelength observations from the UV to the far-IR of more than 150,000 galaxies has been reported by Saldana-Lopez et al. (2020). The UV/optical peak of the SED derived in this new model for $z \leq 1$ is compatible with the Finke et al. (2010) and Dominguez et al. (2011) models. However, there is a large disagreement between these models at all redshifts in the IR range. In this work, we adopt the broadband SED of the EBL at $z = 0$ predicted by above two models (shown in Figure 1) to probe the evolution of the EBL photon density in the local Universe ($z \leq 1$) using the propagation of high energy $\gamma$ rays emitted at different redshifts.

### 3 $\gamma$-ray Propagation in Fermi-Era

The radiation field of the EBL behaves as a dominant source of the opacity for the high energy $\gamma$-ray photons travelling over the cosmological distances from the source towards the Earth. Photons in a $\gamma$-ray beam emitted from a distant source are attenuated by the EBL photon field via photon-photon pair production. The underlying interaction can be expressed through the Breit-Wheeler process as Gould & Schröder (1966, 1967)

$$\gamma + \gamma_{EBL} \rightarrow e^- + e^+ \quad (6)$$

From the theory of quantum electrodynamics, the above interaction is kinematically allowed if the following condition is satisfied by the energies of two photons in the center of mass frame:

$$E_0 \epsilon_0 = \frac{2E^2_\gamma}{(1+z)^2(1-\cos\theta)} \quad (7)$$

where $E_0$ is the observed energy of the $\gamma$-ray photon emitted from a source at redshift $z$, $\theta$ is the angle between the momenta of the $\gamma$-ray and the EBL photons, and $E_\gamma$ is the total energy of electron (also the positron) produced in the pair creation (Equation 6). The total scattering cross-section for the Breit-Wheeler process is given by (Breit & Wheeler 1934)

$$\sigma(\beta) = \frac{3\sigma_T}{16}(1-\beta^2) \left[ (3-\beta^4) \ln \left( \frac{1+\beta}{1-\beta} \right) - 2\beta(2-\beta^2) \right]$$

(8)

where $\sigma_T$ is the Thomson cross section and $\beta$ is a parameter defined as

$$\beta(E_0, \epsilon_0, \theta, z) = \sqrt{1 - \frac{2m^2e^4}{E_0\epsilon_0(1+z)^2(1-\cos\theta)}} \quad (9)$$

with $m_e c^2 (= 0.511 MeV)$ being the rest mass energy of the electron. The pair production cross section given by Equation 8 has a peak value of $1.7 \times 10^{-25} \text{ cm}^2$ at $\beta = 0.70$ (Gould & Schrédèr 1967). This corresponds to the relation (from Equation 9)

$$\epsilon_0 = \frac{4(m_e c^2)^2}{E_0(1+z)^2(1-\cos\theta)} \quad (10)$$

This is the observed energy of the EBL photons which are most likely responsible for the pair production in the $\gamma - \gamma$
interaction. Attenuation of the \( \gamma \)-ray photons due to the interaction with the low energy background photons via pair creation is characterized by the optical depth (\( \tau \)) which strongly depends on the energy of the \( \gamma \)-ray photon (\( E_0 \)), redshift of the \( \gamma \)-ray source (\( z_s \)) and the proper number density of the EBL photons (\( n(\epsilon, z) \)). The EBL optical depth to the \( \gamma \)-ray photons is computed as

\[
\tau(E_0, z_s) = \int_0^z \left( \frac{dl}{dz} \right) dz \int_0^\pi \left( \frac{1 - \cos\theta}{2} \right) \sin\theta d\theta \int_{\epsilon_{th}}^\infty n(\epsilon, 0)(1 - \exp(-\epsilon / \epsilon_{th})) d\epsilon
\]

(11)

where \( \epsilon_{th} \) is the threshold energy of the EBL photon for the pair production, \( \frac{dl}{dz} \) is the cosmological line element, and \( \epsilon_0 \) and \( \epsilon \) are the EBL photon energies as defined under Equation 7. From Equation 7, we can write

\[
\epsilon_{th} = \frac{2(m_e c^2)^2}{E_0(1 + z)(1 - \cos\theta)}
\]

(12)

From Equations 10 and 12, it is evident that the EBL photons in the energy range \( \approx 10^{-3} - 10^2 \) eV play leading role in the absorption of the high energy \( \gamma \)-ray photons travelling over the cosmological distances with energies above 10 GeV. Attenuation due to the EBL strongly limits the propagation of the high energy \( \gamma \)-ray photons in the intergalactic space. The distance travelled by a \( \gamma \)-ray photon of energy \( E_0 \) corresponding to the redshift \( z \) for which \( \tau(E_0, z) = 1 \), is referred to as the Gamma Ray Horizon [Fazio & Stecker 1970]. In the observational cosmology, the gamma ray horizon provides an estimate of the transparency of the Universe to the high energy photons. From radiative transfer theory, the gamma ray horizon predicts a redshift \( z_{th} \) of a source for which the emitted \( \gamma \)-ray flux is attenuated by a factor \( 1/e \) for each observed energy \( E_0 \). Therefore, the sources beyond the gamma ray horizon will become progressively invisible. For head on encounter (\( \theta = \pi \)) between the \( \gamma \)-ray and the EBL photons, the interaction cross section for the pair production maximizes at redshift \( z_{max} \) along the line of propagation, which is given by (rearranging Equation 7 for \( E_c = m_e c^2 \))

\[
z_{max} = 2.0 \left( \frac{2 \text{ eV}}{\epsilon_0} \right)^{1/2} \left( \frac{30 \text{ GeV}}{E_0} \right)^{1/2} - 1
\]

(13)

The EBL absorption feature has been observed in the \( \gamma \)-ray spectra of a sample of blazars in the energy range \( E_0 = 1 - 500 \) GeV out to a redshift of \( z \approx 1.6 \) detected by the Fermi-LAT [Ackermann et al. 2012]. This has also allowed to estimate the EBL intensity in the optical and UV wavebands by extracting the collective absorption effects on the \( \gamma \)-ray spectra of the blazars at different redshifts. Further, detection of the EBL attenuation in the spectra of a large sample of the active galaxies up to a redshift of \( z \approx 3.1 \) and one gamma-ray burst by the Fermi-LAT observations in the energy range \( E_0 = 10 - 1000 \) GeV, has allowed to determine the star formation history of the Universe up to \( z \approx 6 \) [Abdollahi et al. 2018]. The Fermi-LAT provides an excellent coverage of the whole \( \gamma \)-ray sky in wide energy range above 100 MeV. Recent measurements of the gamma ray horizon and highest energy of photons observed from a large sample of the blazars up to a redshift \( z \leq 1 \) are depicted in Figure 2 from the Fermi-LAT observations [Abdollahi et al. 2018]. We observe that the local Universe (\( z \leq 1 \)) is transparent to the high energy \( \gamma \)-ray photons with energies up to 500 GeV. Interestingly, the MAGIC telescopes have detected the significant \( \gamma \)-ray emissions in the energy bands 40-250 GeV and 65-175 GeV from the two most distant blazars at \( z = 0.939 \) [Ahnen et al. 2013] and \( z = 0.944 \) [Ahnen et al. 2016b] respectively. The VERITAS telescopes also reported the \( \gamma \)-ray emission up to 200 GeV from the blazar detected by the MAGIC telescopes at \( z = 0.939 \) [Abeysekara et al. 2015]. These observations represent the most distant blazars detected to date and have significantly expanded the gamma ray horizon for the ground-based \( \gamma \)-ray telescopes. The highest energy of photons (\( \sim 200 \) GeV) detected from these sources place stronger constraints on the gamma ray horizon from the Fermi-LAT observations as shown in Figure 2. It is obvious from Figure 2 that the Universe is transparent to the \( \gamma \)-ray photons with energy above 200 GeV emitted from a source at \( z \approx 0.9 \). Therefore, the \( \gamma \)-ray observations in the GeV energy band can be used as a powerful tool to probe the EBL in the local Universe.

In the present work, we have assumed a flat \( \Lambda \)CDM cosmology with \( \Omega_L = 0.7 \), \( \Omega_m = 0.3 \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). The cosmological line element for the propagation of the \( \gamma \)-ray photons in the flat \( \Lambda \)CDM cosmology is expressed as

\[
\frac{dl}{dz} = \frac{c}{H_0 (1 + z)^2} \left( \frac{1}{\sqrt{\Omega_L + \Omega_m(1 + z)^3}} \right)
\]

(14)

4 Results and Discussion

We aim to probe the cosmological evolution of the EBL photons in the local Universe (\( z \leq 1 \)) using the gamma ray horizon (Figure 2) obtained from the Fermi-LAT observations [Abdollahi et al. 2018]. By definition, the gamma ray horizon represents a combination of \( E_0 \) and \( z \) corresponding to \( \tau(E_0, z) = 1 \). We have selected such \( E_0 \) and \( z \) combinations from Figure 2 (orange curve) and estimated \( \tau(E_0, z) = 1 \) using Equation 11 by varying the evolution coefficient \( k \) and assuming that the density of the EBL photons at the present epoch is described by the two models shown in Figure 3. The variation of \( k \) as a function of \( z \) in the local Universe for the two EBL models is presented in
Figure 3: We observe that $k$ strongly depends on the $z$ values for the observed $\gamma$-ray energies $E_0$ in the range 100-500 GeV over the redshift range of $z=0.2-1$. For the Finke et al. (2010) model, $k$ increases from 3.0 to 3.5 corresponding to $z=0.2$ and 0.3 respectively and subsequently decreases to a minimum value of $\sim 2.0$ at $z=1.0$ for the gamma ray horizon of photons in the energy range 100-500 GeV. Similarly, the value of $k$ first increases from 2.5 (at $z=0.2$) to 3.0 (at $z=0.3$) followed by a rapid decrease to a value $\sim 2.0$ at $z=1.0$ in case of the Domínguez et al. (2011) model. This implies that the gamma ray horizon from the Fermi-LAT observations for photons in the energy range $\approx 100-500$ GeV suggests nearly similar evolution of the EBL photon density for the two EBL models employed in this study and predicts a value of $k$ between $\sim 2.0$ and $\sim 3.0$ in the local Universe $z \leq 1$.

We further estimate the optical depth values for the high energy $\gamma$-ray photons in the energy range 4 GeV to 1 TeV at a given source redshift ($z_s=0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$) for different values of $k$ ranging between 0.0-3.0 using Equation (11) corresponding to the two EBL models. A comparison of the optical depth values derived using the EBL model reported by Abdollahi et al. (2018) from the Fermi-LAT observations, with the corresponding estimates for the Finke et al. (2010) and Domínguez et al. (2011) EBL models is shown in Figure 4 and Figure 5 respectively. It is obvious from both the figures 4 & 5 that a close matching between the two opacity values is observed for different values of $k$ at various redshifts in the different energy range of the $\gamma$-ray photons. The variation of $k$ with $z$ for a close matching between the computed and measured opacity of the Universe to the high energy $\gamma$-ray photons in the two energy bands 4-100 GeV and above 100 GeV (up to 1 TeV) is reported in Figure 6. For $E_0 \leq 100$ GeV, the optical depth values are consistent with each other for $k = 3$ up to $z < 0.2$ (low redshift) for the two EBL models. Beyond redshift $z > 0.2$, the value of $k$ decreases from 3.0 to 1.7 and 2.0 corresponding to the Finke et al. (2010) and Domínguez et al. (2011) models respectively at $z = 1.0$ in the local Universe (Figure 6). This suggests that the evolution coefficient shows completely different behaviour in the local Universe for the two EBL models and the values of $k$ can be inferred in the range 3.0-1.7 and 3.0-2.0 for the Finke et al. (2010) and Domínguez et al. (2011) models respectively. Above 100 GeV, the agreement between the derived optical depth values for the two EBL models and the Fermi-LAT estimates is obtained for $k = 3.0$ up to $z < 0.1$. Beyond this redshift, the value of $k$ is observed to decrease very rapidly with increasing $z$ and attains a common value of $\sim 0.75$ at $z = 1.0$ (Figure 6) for both the EBL models. This indicates that the variations in the value of $k$ derived from the gamma ray horizon are broadly consistent with the inferences from the comparison of the optical depth estimates. For both the EBL models, $k = 3$ suggests no cosmological evolution of the EBL photon density at redshifts below 0.1. The value of $k$ decreases with increasing $z$ at higher redshifts beyond $z \geq 0.1$ for the $\gamma$-ray energies up to 1 TeV.

The gamma ray horizon of the Universe to the TeV $\gamma$ rays is limited to $z < 1$. Recent observations of the most distant blazars at $z = 0.9$ with the MAGIC and VERITAS telescopes are limited to highest energies up to $\sim 200$ GeV (Abevsekara et al. 2015; Ahnen et al. 2015, 2016b). The observed $\gamma$-ray spectra of these sources are very steep with power law spectral indices $> 3.5$. However, after corrections for the expected EBL absorption, their intrinsic spectra are found to be very hard with the power law spectral indices $< 1.5$. From the standard scenario for high energy $\gamma$-ray emission from blazars, the intrinsic spectra cannot be harder than 1.5 (Aharonian et al. 2006). However, the current statistics of the $\gamma$-ray observations of the blazars with the ground-based telescopes do not allow any robust conclusion regarding the intrinsic $\gamma$-ray spectra above 1 TeV for sources at $z \sim 1$. The gamma ray horizon predicted by a model-independent EBL measurement with the H.E.S.S. array is compatible with the predictions from the Finke et al. (2010) and Domínguez et al. (2011) models, but the sensitivity of this approach is limited due to the consideration of systematic uncertainties in the horizon envelope up to $z \sim 0.3$ and energy less than 1 TeV (Abdalla et al. 2017).

From the literature, the evolution proposed by Raue & Mazin (2008), $k = 1.2$, leads to a significant agreement for redshift up to $z \sim 0.7$ provided the EBL photon density at $z = 0$ is described by a generic model which is in compliance with the lower and upper EBL limits. The present epoch EBL density predicted by this generic model is just above the lower limits derived from the galaxy source counts and the SED of the EBL simply represents a fit to the existing limits and not a complete theoretical model (Raue & Mazin 2008). A template evolution with $k = 1.7$ for another EBL model in (Gilmore et al. 2012) is found to be in good agreement with the $\gamma$-ray observations up to redshift $z = 0.6$ (Biteau & Williams 2015). However, optical depths are underestimated by the template evolution with $k = 2.2$ at higher redshifts. This model is based on the semi-analytical approach for simulating the galaxy formation and evolution involving complex physical processes in the EBL emission (Gilmore et al. 2012). These values are broadly consistent with the $k$ values obtained in the present work for the two EBL models. The EBL models employed in this study do not require any complex stellar structure code or semi-analytical models of the galaxy formation. The star formation history determined by the Fermi-LAT observations out to a redshift of $z \sim 5$ is in agreement with the independent measurements of the galaxy counts with a peak at $z \sim 2$ (Abdollahi et al. 2018).
5 Conclusions

The cosmological evolution of the EBL photon number density suggests that the EBL does not represent instantaneously produced background photons. The UV/optical and IR photons contributing to the broadband SED of the EBL are built up slowly over the history of the Universe from the epoch of recombination to the present epoch. Therefore, the number density of the EBL photons at the present epoch \((z = 0)\) is scaled by a factor \((1 + z)^{3-k}\), where value of the evolution coefficient \(k\) can be tuned as summarized below:

- Cosmological evolution of the EBL photon density in the local Universe cannot be described by a unique value of the evolution coefficient \(k\). The value of \(k\) varies between \(k = 3\) and \(k = 0.75\) corresponding to the low \((z \leq 0.1)\) and high redshifts \((z \sim 1)\) respectively.
- \(k = 3\) suggests no evolution of the EBL photon density at low redshifts and is compatible with the transparency of the Universe to the \(\gamma\)-rays with energy below 100 GeV.
- \(k = 0\) represents a simple cosmological dilution of the EBL photon field due to expansion of the Universe. However, the present study suggests \(k \geq 0.75\) in the local Universe \((z \sim 1)\) for the high energy \(\gamma\)-ray photons with energy above 100 GeV (up to 1 TeV).
- For the EBL photon density described by Finke et al. (2010) and Domínguez et al. (2011) at the present epoch, the cosmological evolution can be broadly described by a mean value of \(k\) in the range 0.75 - 3 for the observed \(\gamma\)-ray energies in the range 4 GeV-1 TeV.
- The value of \(k = 1.7\) widely used in the literature is consistent with the results derived in the present study at \(z \sim 0.6-0.7\) for the gamma ray horizon predicted by the Domínguez et al. (2011) model in the GeV energy regime.

The complex behaviour of evolution coefficient \(k\) as a function of redshift can be further addressed significantly by the new-generation ground-based Cherenkov Telescope Array (CTA) observatory (Acharyya et al. 2019). The CTA observations over a wide energy range are expected to explore the effect of the EBL on the \(\gamma\)-ray propagation up to a redshift beyond \(z = 1\).

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Fig. 4 Comparison of the optical depth values calculated using the Finke et al. (2010) model for different values of \(k\) at various redshifts with the corresponding opacity estimates derived using the EBL model proposed by Abdollahi et al. (2018) from the Fermi-LAT observations.
Fig. 5 Same as Figure 4 for the Domínguez et al. (2011) EBL model

Fig. 6 Evolution coefficient $k$ as a function of $z$ for a good agreement between the optical depth values computed using the two EBL models and estimates from the Fermi-LAT observations in two energy bands: 4-100 GeV and above 100 GeV (up to 1 TeV)
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