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Fermi-LAT limits on the γ-ray opacity of the Universe

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Summary. — The Fermi Large Area Telescope (LAT) has provided us with a rich sample of extragalactic sources, among which γ-ray blazars with redshift up to $z \sim 3$ and Gamma-Ray Bursts with redshift up to $z \sim 4.3$, that we have used to probe the interaction via pair production of γ-ray photons above 10 GeV with low-energy photons from the Extragalactic Background Light (EBL). The EBL from the infrared to the ultraviolet is difficult to measure directly, but can be constrained with a variety of methods. In this paper we report the method applied to evaluate the EBL attenuation of γ-ray fluxes by comparing the measured energy spectrum of the source and the unabsorbed spectrum above 10 GeV. We place upper limits on the γ-ray opacity of the Universe at various energies and redshifts, and compare this with predictions from well-known EBL models. We find that EBL intensities at optical-UV wavelengths as large as those predicted by the "baseline" and "fast evolution" models can be ruled out with high confidence. The ensuing upper limits to the EBL opacity are presented.

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1. – The Extragalactic Background Light

The Extragalactic Background Light (EBL) includes photons with wavelengths from UV through optical-IR, which constitute the main source of opacity for γ-rays from extragalactic sources, such as blazars and Gamma-Ray Bursts in the Fermi-LAT energy range. Measurement of the EBL provides a fundamental insight into galaxy and star

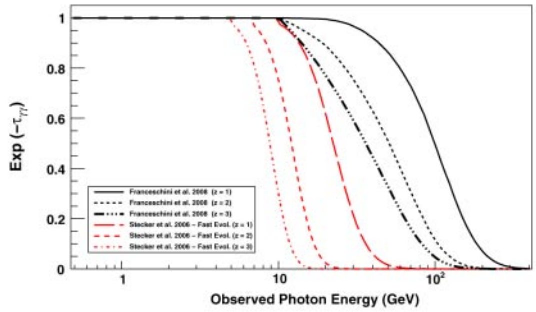

Fig. 1. – Attenuation as a function of observed γ-ray energy for the EBL models of Franceschini *et al.* [1] and Stecker *et al.* [2]. These models predict the minimum and maximum absorption of all models in the literature and thus illustrate the range of optical depths predicted in the Fermi-LAT energy range.

formation, but direct measurements of its intensity are extremely difficult, due to the bright foreground from the Milky Way and Solar system.

The effect of absorption of high-energy (HE) γ-rays is reflected in an energy and redshift-dependent softening of the observed spectrum from a distant γ-ray source. The observation, or absence, of such spectral features at HEs, for a source at redshift z can be used to constrain the $\gamma\gamma \rightarrow e^+e^-$ pair production opacity, $\tau(E, z)$. A major science goal of Fermi is to probe the opacity of the universe to HE γ-rays as they propagate from their sources to the Earth.

Figure 1 shows the optical depth as a function of observed γ-ray energy for the EBL models of [1] and [2] that predict the minimum and maximum absorption of all models in the literature, and thus illustrate the range of optical depths predicted in the Fermi-LAT energy range.

2. – Data selection and determination of opacity upper limits

The sources we have analyzed to probe the UV through optical EBL are blazars extracted from the 1st LAT AGN Catalog [3] that includes LAT events collected between 2008 August 4th and 2009 July 4th with $100\,\text{MeV} < E < 100\,\text{GeV}$. The details are explained in [4].

Assuming that HE photon absorption by the EBL is the sole mechanism that affects the γ-ray flux from a source at redshift z, the observed and unabsorbed fluxes (F_{obs} and F_{unabs}) at the observed energy E can be related by the opacity, $\tau(E, z)$, as

$$F_{obs}(E) = F_{unabs}(E) \cdot e^{-\tau(E,z)}. \tag{1}$$

This is the primary expression that we use to constrain EBL models and put upper limits on the γ-ray opacity calculated from the observed flux of individual blazars and the extrapolation of the unabsorbed flux to high energies.

This paper concentrates on one of the methods described in [4], where the evaluation of upper limits on the γ-ray optical depth is based on the comparison between the measured energy spectrum of the source and the unabsorbed spectrum above 10 GeV.

The unabsorbed spectrum, F_{unabs}, is assumed to be the extrapolation of the low-energy part, $E < 10\,\text{GeV}$, of the spectrum where the EBL attenuation is negligible, to

TABLE I. – *Upper limits (95% CL) on the γ-ray optical depth for the reported AGN.*

Source	z	E_{max} (GeV)	$\tau_{\gamma\gamma}(z, E_{max})$
J1147-3812	1.05	73.7	< 1.33
J1504+1029	1.84	48.9	< 1.82
J0808-0751	1.84	46.8	< 2.03
J1016+0513	1.71	43.3	< 0.83
J0229-3643	2.11	31.9	< 0.97
J1012+2439	1.81	27.6	< 2.41

higher energies. At high energies, if no intrinsic hardening of the spectrum is present, the measured spectrum, F_{obs}, at observed energy E, and F_{unabs}, are related by eq. (1). Since F_{unabs} is evaluated assuming no EBL attenuation, eq. (1) already gives a maximum value for $\tau(E, z)$. Consequently, an upper limit with a 95% CL (confidence level) in a constraining energy bin with mean energy $\langle E \rangle$ is calculated by propagating the parameter uncertainties in the fitted flux:

$$\tau_{\gamma\gamma UL}(95\%\,\mathrm{CL})(\langle E \rangle, z) = \tau(E, z) + 2\sigma. \tag{2}$$

We compare these opacity limits with the ones predicted by known EBL models.

3. – Results and conclusions

In order to fit the data below 10 GeV, a power law or a log-parabola was used, finally choosing the best one according to a likelihood ratio test. From the fit results of the flux below 10 GeV we have extrapolated the spectral shape to obtain the unabsorbed flux above 10 GeV, F_{unabs}.

A different method has been used to derive the measured flux F_{obs} in selected energy bins. The whole energy range from 100 MeV to 100 GeV is divided in equal logarithmically spaced bins requiring in each energy bin a TS value greater than 10(1). In each energy bin the standard gtlike tool has been applied assuming for all the point-like sources a simple power law spectrum with photon index fixed to 2.

Once both F_{unabs} and F_{obs} are determined, an upper limit on $\tau(\langle E \rangle, z)$ with 95% CL in a constraining energy bin with mean energy $\langle E \rangle$ can be estimated from eq. (2). Table I shows the ULs on the γ-ray optical depth for the analyzed AGN. The first and second column report the name of the sources and their redshift, the third column the maximum photon energy and the fourth column the optical depth upper limits evaluated at 95% CL as for eq. (2).

The two plots in fig. 2 show the derived upper limits for the optical depth of γ-rays emitted by the sources J0808-0751 and J1504+1029 at $z = 1.84$. The thin grey arrows represent upper limits at 95% CL in all energy bins used to determine the observed flux above 10 GeV. The thick grey arrow shows the upper limits at 95% CL for the highest-energy photon. Finally, the thick black arrow reports the upper limit at 99% CL for the highest-energy photon. The upper limits determined with this method are inconsistent

(1) The test statistic (TS) is defined as $\mathrm{TS} = -2\times(\log(L_0) - \log(L_1))$, with the L_0 the likelihood of the null hypothesis model as compared to the likelihood of a competitive model L_1.

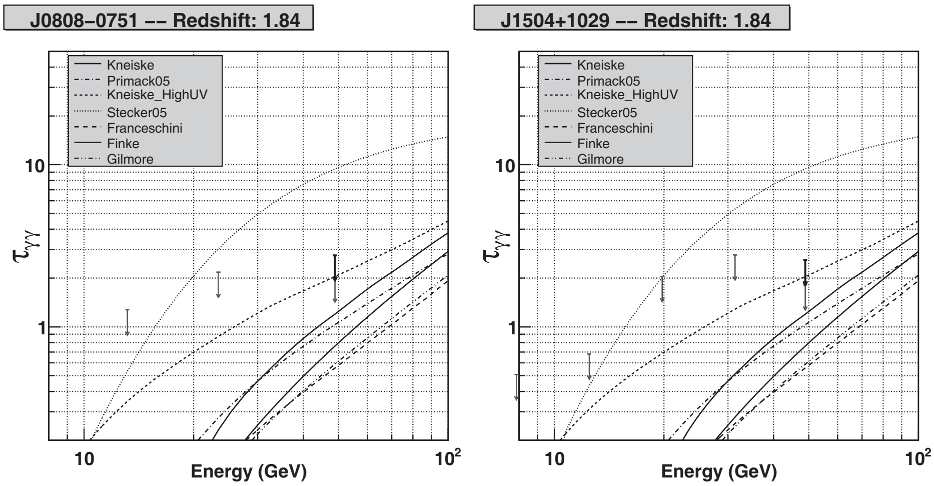

Fig. 2. – Derived upper limits for the optical depth of γ-rays emitted at $z = 1.84$. Grey thin arrow upper limits at 95% CL in all energy bins used to determine the observed flux above 10 GeV. Grey thick arrow upper limits at 95% CL for the highest-energy photon. Black thick arrow upper limit at 99% CL for the highest-energy photon [1, 2, 5-9].

with the EBL models that predict the strongest opacity. As an example consider blazar J0808-0751 at $z = 1.84$ shown in the upper left plot: a larger optical depth would require an intrinsic spectrum that at high energy lies significantly above the extrapolation obtained from the low-energy spectrum. The figure shows that the UL at 95% CL rules out those EBL models (Stecker "baseline" [2] and Kneiske "High UV" [6] models) that predict stronger attenuation. This result is consistent with all other ULs obtained with this method [4].

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