High Energy Astrophysics and Gamma-Ray Bursts in the \textit{Fermi} Era

Soebur Razzaque\textsuperscript{1,2}  
On behalf of the \textit{Fermi} Collaborations

\textit{Space Science Division, U.S. Naval Research Laboratory, Washington, D.C., USA}

Abstract

With the launch of the \textit{Fermi} gamma ray space telescope, high-energy astrophysics has entered a new era. Exciting new results on Galactic and extragalactic sources are leading to a better understanding of the physics and astrophysics of these objects. I will discuss results from the \textit{Fermi} gamma ray space telescope on the extragalactic background light (EBL) and gamma-ray bursts (GRBs).

1 Introduction

The \textit{Fermi} Gamma Ray Space Telescope (formerly known as \textit{GLAST}) was launched on June, 11\textsuperscript{th} 2008 to provide an unprecedented view of the γ-ray Universe. The main instrument onboard \textit{Fermi}, the Large Area Telescope (LAT), offers a broader bandpass (∼20 MeV to over 300 GeV) \cite{10} and its sensitivity exceeds by more than an order of magnitude that of its predecessor instrument EGRET onboard the \textit{Compton Gamma Ray Observatory} \cite{46}, and the Italian Space Agency satellite \textit{AGILE} \cite{45}, which was launched in 2007. The LAT observes the full sky every 3 hr in survey mode, leading to a broadly uniform exposure with less that ∼15% variation. The Gamma-ray Burst Monitor (GBM), the lower energy (∼8 keV – 40 MeV) instrument onboard \textit{Fermi}, observes the full unocculted sky at all time and provides alerts from transient sources such as GRBs.

The main science goal of \textit{Fermi} is to find answers to the questions:

- How do super-massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?
- What are the mechanisms that produce Gamma-Ray Burst explosions? What is the energy budget?
- How has the amount of starlight in the Universe changed over cosmic time?
- What are the unidentified gamma-ray sources found by EGRET?
- What is the origin of the cosmic rays that pervade the galaxy?
- What is the nature of dark matter?

While answers to many of these questions are still elusive, \textit{Fermi} is providing new insights and exciting results on the Galactic and extragalactic sources, on cosmic rays and on the total amount of starlight in the universe. GRBs and blazars (Active Galactic Nuclei with their jets pointed in our direction) constitute the primary extragalactic sources. The total amount of energy content in the form of starlight in the universe is only second to the total amount of energy content in the cosmic microwave background. Starlight photons, from infrared to ultraviolet, form a background known as the extragalactic background light (EBL) in which high-energy γ rays from extragalactic sources may be absorbed by producing an $e^+e^-$ pair. Thus it is important to understand this background.

\textsuperscript{1}Email address: srazzaque@ssd5.nrl.navy.mil
\textsuperscript{2}NRC Resident Research Associate
2 Extragalactic Background Light

The extragalactic background light is the accumulated radiation from structure formation and its cosmological evolution. The knowledge of its intensity with time probes models of galaxy and star formation. The intensity of the EBL from the near-IR to ultraviolet is thought to be dominated by direct starlight emission out to large redshifts, and by optically bright AGN. At longer wavelengths the infrared background is produced by thermal radiation from dust which is heated by starlight, and also emission from polycyclic aromatic hydrocarbons.

Direct measurement of the EBL is difficult due to contamination by foreground zodiacal and Galactic light [25], and galaxy counts result in a lower limit since the number of unresolved sources is unknown [33]. A number of EBL models (see Fig. 1) have been developed over the last two decades [19, 21, 22, 28, 29, 37, 39, 42, 44], however large scatter in available EBL data does not constrain these models strongly.

The primary extragalactic sources emitting γ-ray photons are blazars, which are galaxies with relativistic jets directed along our line of sight; and GRBs, which are thought to be caused by exploding high-mass stars (long GRBs) or possibly degenerate mergers (short GRBs) with beamed emission along our line of sight for a brief period. GRBs have not been used to constrain EBL absorption during the pre-\textit{Fermi} era mainly because of a lack of sensitivity to transient objects above a few GeV. EGRET sensitivity dropped significantly above 10 GeV while TeV instruments have a too small field-of-view to catch the prompt phase where most of the emission occurs. The new energy window (10 – 300 GeV) accessible by \textit{Fermi}, and its wide FoV, makes GRBs interesting targets to constrain EBL absorption in this energy band.

2.1 Gamma Ray Opacity of the Universe

Constraining the EBL intensity from direct measurement of γ rays is difficult because of its evolution with cosmic time (see Fig. 1) and may only be possible for nearby TeV blazars [20]. The opacity of the universe for a high-energy γ ray, emitted from redshift \( z \) with energy \( E \), to produce an \( e^+e^- \) pair by interacting with an EBL photon however can be calculated as [39]

\[
\tau_{\gamma\gamma}(E, z) = c \int_0^z \frac{dz_1}{d^2z_1} \left| \frac{dt}{dz_1} \right| \int_{\epsilon_1}^\infty d\epsilon \int_{-1}^1 d\cos \theta \frac{u_{\epsilon_1}}{2} \epsilon_1 (1 - \cos \theta) \sigma_{\gamma\gamma} \left( \frac{\epsilon}{\epsilon_1} \right) \left( 1 + \frac{z_1}{z} \right)^2 \frac{d\epsilon_1}{d\epsilon_1} \left[ \frac{u_{\epsilon_1}}{\epsilon_1} \right],
\]

(1)
Figure 2: **Left panel** – Opacity of high-energy γ rays to produce an $e^+e^-$ pair by interacting with an EBL photon at different redshift. The lines correspond to different EBL models shown in Fig. 1. **Right panel** – The $\gamma\gamma$ opacity $\tau_{\gamma\gamma} = 1$ curves for various EBL models in the $E-z$ plane. Also shown are the highest-energy γ rays detected from different blazars and GRBs along with energy ranges in which different γ-ray telescopes are sensitive. The universe is predicted to be optically thin to γ rays in the $E-z$ plane below a particular $\tau_{\gamma\gamma} = 1$ model curve. Thus high-energy data points above a model curve has potential to constrain that model. Both plots are from Ref. [19].

for an isotropic background photon field. Here $u_{\epsilon_1}$ is the specific energy density of EBL photons at redshift $z_1$ of interaction, $\sigma_{\gamma\gamma}(s)$ is the total $\gamma\gamma \rightarrow e^+e^-$ cross section and $s = E(1 + z_1)\epsilon_1/(1 - \cos \theta)/2m_e^2c^4$ is the center-of-mass energy squared. The function $\bar{\phi}[s_0]$, with $s_0 = E(1 + z_1)\epsilon_1/m_e^2c^4$, is given in Ref. [24].

The threshold energy for $e^+e^-$ pair production from the condition $s_0 = 1$ is $\epsilon_{1,th} \approx m_e^2c^4/E(1 + z_1)$. The lower limit of the energy integration $\epsilon_{1,th} \approx 1$ eV and $\sim 250/(1 + z_1)$ GeV γ-rays interact dominantly with these photons. Fig. 2 (left panel) shows the $\gamma\gamma$ opacity of the universe for different EBL models and at different redshift. The right panel of Fig. 2 shows the EBL model-dependent $\tau_{\gamma\gamma}(E,z) = 1$ curves and the highest-energy photons detected from GRBs and Blazars.

Assuming that high-energy photon absorption in EBL is the sole mechanism that affects the γ-ray flux from a source at redshift $z$, the observed and intrinsic fluxes can be related by the opacity as

$$F_{\text{obs}}(E) = e^{-\tau_{\gamma\gamma}(E,z)}F_{\text{int}}(E).$$

This expression can be used to (i) explore γ-ray flux attenuation in EBL from AGN population, assuming a fixed intrinsic spectrum for all AGNs leading to a redshift-dependent flux ratio between a low- and a high-energy band; (ii) constrain EBL models which predict $\tau_{\gamma\gamma}(E,z)$ values much higher than the opacity that would give the observed fluxes from individual blazars and GRBs; and (iii) put upper limits on γ-ray opacity calculated from observed flux of individual blazars and GRBs, and extrapolation of the intrinsic fluxes to high energies.

### 2.2 Fermi Sources Constraining EBL Models

The highest energy γ-ray emission from high redshift sources are the most effective probe of the γ-ray opacity of the universe, and consequently to contrain EBL models. In contrast to ground-based γ-ray detectors, Fermi has demonstrated the possibility of probing the EBL at high redshifts by the detection of blazars at $\geq 10$ GeV energies out to $z > 3$, and additionally by the detection of GRB 080916C at a redshift of $\sim 4.35$ [1]. GRBs are known to exist at even higher redshifts (GRB 090423 is the current record holder with $z \sim 8.2$). Therefore observations of these sources with Fermi stand as promising candidates for probing the optical-UV EBL at high redshifts which are not accessible to Cherenkov telescopes.

Fermi LAT detected 6 GRBs to-date with measured redshift. Among the detected blazars, 260 flat-spectrum radio quasars (FSRQs) and 128 BL Lacs have known redshift [7]. Highest-energy photons above

---

3Time of writing this proceedings
\section{Gamma-Ray Bursts}

To date \textit{Fermi} GBM has detected 375 GRBs (252 in the first yr). Among them 14 GRBs (9 in the first yr) have been detected with \textit{Fermi} LAT (see Fig. 4). It is worthwhile to mention a few bright GRBs detected with \textit{Fermi}.

\begin{itemize}
\item \textbf{GRB 080916C} : First bright long GRB detected with LAT (GRB 080825C is the first LAT detected GRB \cite{2}) on 16 September 2008 at a redshift $z = 4.35 \pm 0.15$. More than 3000 LAT photons were detected within first 100 sec (see Fig. 5 left plot). With a total fluence of $f \approx 2.4 \times 10^{-4}$ erg cm$^{-2}$, the total apparent-isotropic energy release from this GRB is $E_{iso} = 4\pi d_L^2 f \approx 8.8 \times 10^{54}$ erg, where $d_L$ is the luminosity distance. This is the most energetic GRB detected to-date and strongly suggests that the emission from the GRBs is jetted, covering $\gtrsim 10^{-2}$ of the total solid angle, otherwise a staggering $\sim 4.9$ times the solar rest energy would be needed to produce isotropic emission. No significant emission was detected in the LAT energy range for the first $\sim 4$ sec (see Fig. 5 left plot). The first $\gtrsim 100$ MeV and $\gtrsim 1$ GeV photons arrive $\sim 4$ sec and $\sim 6$ sec after the trigger, respectively. The highest-energy, 13.2 GeV, photon from this GRB was detected 16.54 sec after the GBM trigger. While emission in the GBM energy range lasted up to $\sim 200$ sec after the trigger, $\gtrsim 100$ MeV emission lasted up to $\sim 1400$ sec after the trigger. Details are reported in Ref. \cite{1}.

\item \textbf{GRB 090510} : This is the first short GRB detected with \textit{Fermi} LAT with a known redshift of $z = 0.903 \pm 0.003$ (GRB 081024B is the first short GRB detected with LAT \cite{5}) \cite{3, 6}. GBM triggered on a weak precursor of this burst, however the main emission starts $\sim 0.5$ sec after the trigger and extends up to $5$ sec (see Fig. 8 for a light curve). Unusually large fluence of $f \approx 5 \times 10^{-5}$ erg cm$^{-2}$ in the 10 keV - 30 GeV range from a relatively high redshift for a short burst results in $E_{iso} \approx 10^{53}$ erg, the largest for any short GRB. Note that the fluence in high-energy (100 MeV - 10 GeV) $\gamma$ rays
is larger than the fluence in low-energy (20 keV – 2 MeV) γ rays, a feature detected in the other short GRB 081024B as well (see Fig. 4, right panel). Emission at \( \gtrsim 100 \text{ MeV} \) started \( \sim 0.1 \text{ sec} \) after the start of the main GBM emission or \( \sim 0.6 \text{ sec} \) after the trigger and lasted for \( \sim 100 \text{ sec} \).

The highest-energy, 31 GeV, photon (highest for any short GRB) was detected 0.859 sec after the trigger. See Refs. [3, 6, 16] for further details.

- **GRB 090902B**: At a redshift \( z = 1.822 \), GRB 090902B is one of the most luminous long GRB detected with Fermi LAT [4]. It was detected on 2 September 2009 and the LAT repointed to its direction autonomously prompted by a GBM trigger. With a 10 keV – 10 GeV fluence of \( f \approx 4.4 \times 10^{-4} \text{ erg cm}^{-2} \) collected over the first 25 sec of the prompt emission, the apparent-isotropic energy release is \( E_{\text{iso}} \approx 3.6 \times 10^{54} \text{ erg} \) and is comparable to GRB 080916C. More than 200 photons with \( \gtrsim 100 \text{ MeV} \) (39 with \( \gtrsim 1 \text{ GeV} \)) were detected from this GRB, the first arrived \( \sim 3 \text{ sec} \) after the GBM trigger (see Fig. 5, right panel). The \( \gtrsim 100 \text{ MeV} \) emission lasted up to 1 ksec and the highest-energy, 33.4\(^{+2.7}_{-3.5}\) GeV (highest from any GRB), was detected 82 sec after the trigger.

Another bright long GRB 090926A shows similar characteristics such as delayed onset of \( \gtrsim 100 \text{ MeV} \) emission as other bright GRBs mentioned above, although details are not available yet [9]. The less-bright long GRB 080825C (\( \sim 3.4% \) chance probability) and short GRB 081024B also provide hints of such delayed onset of high-energy emission. Statistics of high-energy photon are low however from these GRBs. Their redshifts are unknown as well. On the other hand GRB 090217, again with low statistics, do not show any significant delay for the onset of \( \gtrsim 100 \text{ MeV} \) emission.

Bright LAT detected GRBs show high-energy, \( \gtrsim 100 \text{ MeV} \), temporally extended emission long after keV – MeV emission in GBM falls below detection threshold. Although previous mission, Compton Gamma Ray Observatory, detected such extended emission from GRB 940217 [26] most LAT detected GRBs display this behavior. In case of GRB 080916C high-energy emission was detected up to 1400 sec after the trigger, while GBM emission lasted for less than 200 sec High-energy emissions from short GRB 090510 and long GRB 090902B were detected up to over 200 sec and 1000 sec after trigger, respectively (see Fig. 6). However GRBs such GRB 081215A and GRB 090217, with low photon statistics and without delayed onset of high-energy emission, do not show extended emission signatures.
Figure 5: Light curves of two long GRBs 080916C (left plot) [1] and 090902B (right plot) [4]. The top 2 panels in the left plot and top 3 panels in the right plot are background subtracted light curve in the GBM energy range. The bottom panel in the right panel shows the arrival times of all photons with energies > 1 GeV. Note that the ≳ 100 MeV photons from both GRBs arrive delayed compared to the triggering GBM emission. This feature is detected in some other LAT GRBs as well.

Spectrum of GRB in the keV – MeV range is typically fitted with a Band function of the form [13]

\[
n(E) = A \left( \frac{E}{100 \text{ keV}} \right)^{\alpha} \exp \left( -\frac{E(2 + \alpha)}{E_{\text{peak}}} \right) ; \quad E < E_c
\]

\[
= A \left( \frac{E_{\text{peak}}(\alpha - \beta)}{100 \text{ keV}(2 + \alpha)} \right)^{\alpha - \beta} \exp(\beta - \alpha) \left( \frac{E}{100 \text{ keV}} \right)^{\beta} ; \quad E \geq E_c
\]

where \( E_c = (\alpha - \beta)E_{\text{peak}}/(2 + \alpha) \) and \( E_{\text{peak}} \) is the peak photon energy in the \( \nu F_\nu \) or energy spectrum and \( \alpha \) and \( \beta \) are photon number indices below and above the peak energy. While time-resolved spectra from GRB 080916C can be fitted satisfactorily by the Band function, spectra from GRB 090510 and 090902B require an additional power-law component (see Fig. 7). In case of GRB 090510 the required power-law component for the time integrated (0.5 – 1.0 sec) spectrum has an index \(-1.62\) [6]. The index remains about the same, \(-1.66\) and \(-1.54\), in time intervals 0.6 – 0.8 sec and 0.8 – 0.9 sec respectively. At later time (0.9 - 1.0 sec) the power-law index becomes slightly softer \(-1.92 \pm 0.2\) and a Band function component is not needed to fit spectrum as emission in the GBM range falls below detection threshold. In case of GRB 090902B the additional power-law component has roughly constant index, \(-1.9\), throughout the burst duration and becomes slightly harder, \(-1.6 \pm 0.2\), in the interval 19.2 – 25.0 sec after the trigger [4]. An additional power-law component is also needed to fit GRB 090926A spectra [9].

Here we summarize the main properties of the *Fermi* LAT detected bright GRBs:

- Delayed onset of ≳ 100 MeV emission with respect to keV – MeV emission detected with GBM.
- Temporally extended ≳ 100 MeV emission beyond the end of the GBM emission.
- A power-law component in addition to the typical Band function is necessary to fit spectra of a number of GRBs.
Figure 6: Extended high-energy, $\gtrsim 100$ MeV, emission from short GRB 090510 (left plot) [16] and from long GRB 090902B (right plot) [4]. The power-law decay of the flux, $\propto t^{-1.38}$ for GRB 090510 (left plot, top panel, blue line) and $\propto t^{-1.5}$ for GRB 090902B (right plot, dashed line), is a typical signature of GRB afterglow emission. Simultaneous multiwavelength data from Swift BAT, XRT and UVOT instruments are also shown for GRB 090510 (left plot, bottom panel) [16].

3.1 Modeling of Fermi LAT Detected GRBs

Gamma-ray emission detected from GRBs over six decades ($\sim 10$ keV – 10 GeV) in energy by Fermi LAT and GBM has extremely important implications for understanding GRB properties such as jetted emission, relativistic outflow speed, particle acceleration, emission region size scale, emission mechanisms, etc. Detection of high-energy $\gamma$ rays from GRBs is useful in non-GRB science as well, and can be used to probe the intensity of the extragalactic background light and quantum gravity.

**Jetted emission:** Calculation of large isotropic energy release, exceeding a few solar rest mass energy in some cases, from fluence and redshift data strongly hint that GRB emission is jetted. From observations of very high-energy photons during the prompt GRB phase, the minimum Lorentz factor of the jet bulk motion can be calculated with the constraint that the opacity for $e^\pm$ pair production with soft target photons is unity [14, 32, 38].

Given a $\gamma$-ray flux variability time-scale $t_v$, an observed broadband photon spectrum $n(\epsilon)$ and the GRB redshift $z$, a general formula can be written for the optical depth of a high-energy photons of energy $E$ to $\gamma\gamma \rightarrow e^+e^-$ pair production,

$$
\tau_{\gamma\gamma}(E) = \frac{3}{4} \frac{\sigma_T d_L^2}{t_v} \frac{m_e^2 c^6}{E^2 (1+z)^3} \int_{\epsilon/\Gamma}^{\infty} d\epsilon' \frac{\epsilon'}{c^2} \frac{n(\epsilon' (1+z)/\Gamma)}{\epsilon' (1+z)} \varphi\left[\frac{\epsilon' (1+z)}{\Gamma}\right],
$$

where $d_L$ is the luminosity distance and $\sigma_T$ is the Thomson cross-section. The function $\varphi[\epsilon' (1+z)/\Gamma]$ is defined in Ref. [24] The derivation of $\Gamma_{\text{min}}$ usually follows from the condition $\tau_{\gamma\gamma}(E_{\text{max}}) = 1$, or equivalently $\tau_{\gamma\gamma}(E < E_{\text{max}}) < 1$. In case the target photon spectrum can be fitted with the Band function in Eq. (3), $\Gamma_{\text{min}}$ can be calculated analytically with a delta-function approximation for the
Figure 7: **Left plot** — Time-resolved $\nu F_\nu$ or energy spectral fits over six decades in energy (10 keV – 10 GeV) for GRB 080916C [1]. The Band function fits spectra in all 5 time intervals (a: 0.004–3.58 sec, b: 3.58 – 7.68 sec, c: 7.68 – 15.87 sec, d: 15.87 – 54.78 sec and e: 54.78 – 100.86 sec) reasonably well, although presence of a hard spectral component as suggested by evolution of the spectra cannot be ruled-out definitely. **Center plot** — Time-integrated (top panel) and time-resolved (bottom panel) spectral fits for GRB 090510 [6]. A power-law spectral component in addition to the Band function is preferred over Band function-only fit for the time-integrated spectrum and time-resolved spectra in the intervals: 0.6 – 0.8 sec and 0.8 – 0.9 sec At later time, 0.9 – 1.0 sec a power-law alone fits spectrum. **Right plot** — Spectral fit to GRB 090902B data in the time interval 4.6 – 9.6 sec after the trigger [4]. A single power-law component in addition to a Band function is necessary to fit data above $\sim 100$ MeV and below $\sim 50$ keV. The slope of the power-law component do not change substantially at later time.

$$\gamma \gamma \rightarrow e^+ e^- \: \text{total cross-section as}$$

$$\Gamma_{\text{min}}(E_{\text{max}}) = \left[\frac{4d^2 A}{c^2 t_v} \frac{m_e^2 c^4}{(1+z)^2 E_{\text{max}} g \sigma_T} \right]^{\frac{\alpha-\beta}{2-\beta}} \left[ \frac{(\alpha-\beta) E_{\text{pk}}}{(2+\alpha)100 \: \text{keV}} \right]^{\frac{\alpha-\beta}{2-\beta}} \times \exp \left[ \frac{\beta - \alpha}{2 - 2\beta} \right] \left[ \frac{2m_e^2 c^4}{E_{\text{max}}(1+z)^2 100 \: \text{keV}} \right]^\frac{\beta}{2-\beta} ;$$

for $\Gamma_{\text{min}} > \sqrt{\frac{(1+z)^2 E_{\text{max}} E_{\text{pk}}(\alpha-\beta)}{2m_e^2 c^4 (2+\alpha)}}$, \hspace{1cm} (5)

where $A$, $E_{\text{pk}}$, $\alpha$ and $\beta$ are the Band function parameters, and $g \sigma_T$ is the total $\gamma \gamma$ cross-section. The factor $g \approx 0.23$ and it depends on the target photon spectrum. Eq. (5) agrees with the numerical solution to Eq. (4) for $\Gamma_{\text{min}}$ to within a few percent.

The minimum bulk Lorentz factor calculated from LAT detected GRBs are rather large: $\Gamma_{\text{min}} \approx 900$ for GRB 080916C [1], $\Gamma_{\text{min}} \approx 1200$ for GRB 090510 [6] and $\Gamma_{\text{min}} \approx 1000$ for GRB 090902B [4]. This implies that the $\gamma$ ray emission region is at a radius $R \approx 2\Gamma^2 c t_v/(1+z) \gtrsim 10^{16}$ cm for a typical value of $t_v \approx 100$ ms.

**Power-law spectral component:** A hard spectral component producing the observed excess at low energies in GRB 090902B is difficult to explain in the context of leptonic models by the usual synchrotron self-Compton (SSC) mechanisms [35, 36]. In the simplest versions of these models, the peak of the SSC emission is expected to have a much higher energy than the synchrotron peak at MeV energies, and the SSC component has a soft tail that is well below the synchrotron flux at lower energies and so would not produce excess emission below $\sim 50$ keV as detected in GRB 090902B [4]. Photospheric thermal emission together with power-law high-energy components may explain GRB 090902B spectra [41], although origin of the power-law component will require a separate emission mechanism. Hadronic models, either in the form of proton synchrotron radiation [40] or photohadronic interactions [12], can produce a hard component with a similar low energy excess via direct and cascade radiation (e.g., synchrotron emission by secondary pairs at low energies). However, the total energy release in hadronic models exceeds the observed gamma-ray energy significantly and may pose a challenge for the total energy budget.

**Delayed onset of high-energy emission:** The delayed onset of the $\gtrsim 100$ MeV emission from the GBM trigger has been modeled for GRB 080916C as arising from proton synchrotron radiation in
the prompt phase [40] and for GRB 090510 as arising from electron synchrotron radiation in the early afterglow phase [23, 30]. In order to produce the peak of the LAT emission 9 sec after the trigger in the early afterglow scenario for GRB 090902B from deceleration of the GRB fireball, a value of $\Gamma_0 \approx 1000$ is required [4]. This is similar to calculated $\Gamma_{\min}$ but the observed large amplitude variability on short time scales ($\approx 90$ ms) in the LAT data, which is usually attributed to prompt emission, may argue against such models. Also, the appearance of the power-law component extending down to $\approx 8$ keV within only a few seconds of the GRB trigger disfavors an afterglow interpretation for GRB 090902B. The proton synchrotron model, on the other hand, requires a rather large total energy budget, as mentioned previously.

**Temporally extended high-energy emission:** Smooth power-law decay and approximately constant spectra of the high-energy emission during the time after the end of the GBM emission (see Fig. 6) provide strong evidence that this emission arises from early afterglow phase [34, 43]. GRB 090510 provides a unique opportunity to study simultaneous emission in the optical – UV to $\gamma$ GeV energy range, the temporal behavior fails to satisfy the GRB afterglow emission model. Although GRB 090510 data can be fitted with a typical forward shock model with reasonable spectra in the UV – GeV energy range, the temporal behavior fails to satisfy the expected $F_{\nu} \propto t^{-\alpha} \nu^{-\beta}$ relations [16] from the simple forward shock model [43]. More complicated models such as a combined internal-external shock model [16] or a two-component jet model may be needed [15] to explain extended emission data.

### 3.2 Limits on Quantum Gravity Mass Scale

A number of theories leading to quantization of gravity (QG) suggest that space-time has a foamy structure that affects propagation of photons, namely their speeds become energy dependent, thus violating special relativity or Lorentz symmetry [11, 17, 18]. The dispersion relation for the photon is modified in such theories, leading to a time dispersion accumulated over cosmic length scale between photons of different energies. Cosmological distances of the GRBs make them ideal systems for such time of flight test of the Lorentz invariance violation (LIV) by detecting any arrival time difference between the high and low energy photons which were emitted simultaneously from the GRBs. The time difference is [27]

$$\Delta t = \frac{1 + n}{2H_0} \frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^2} \int_0^z \frac{(1 + z')^n}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}} dz' \quad (6)$$

where $n$ corresponds to the term in the expansion of the photon dispersion relation, $M_{QG,n}$ is the QG mass scale, $E_h^n$ and $E_l^n$ are the energies of a high and low energy photon respectively and $H_0$ is the Hubble constant.

**Fermi** LAT detected a $13.22^{+0.70}_{-0.54}$ GeV photon from GRB 080916C, at redshift $z = 4.35 \pm 0.15$ after 16.54 sec of the GRB trigger [1]. The chance probability that this highest-energy photon was from background is only $1.7 \times 10^{-5}$. This allowed to put a lower limit on the QG mass scale, for the first time using Fermi data, assuming the triggering MeV photons and the highest-energy photon were emitted simultaneously and $\Delta t = 16.54$ sec time dispersion is due to QG effect. The resulting limits, for the linear ($n = 1$) and quadratic ($n = 2$) terms are [1]

$$M_{QG,1} > 1.51 \times 10^{18} \left(\frac{E_h}{13.22 \text{ GeV}}\right) \left(\frac{\Delta t}{16.54 \text{ sec}}\right)^{-1} \text{ GeV}/c^2,$$

$$M_{QG,2} > 9.42 \times 10^9 \left(\frac{E_h}{13.22 \text{ GeV}}\right) \left(\frac{\Delta t}{16.54 \text{ sec}}\right)^{-1/2} \text{ GeV}/c^2. \quad (7)$$

Note that these limits were the most stringent of this kind at that time, and the linear limit was less than an order of magnitude below the Planck mass $M_P = \sqrt{\hbar c/G_N} = 1.22 \times 10^{19}$ GeV.

The most stringent constraint on the QG mass derived from the time of flight test however comes from the short GRB 090510 at a redshift $z = 0.9003 \pm 0.003$ [3]. The 1$\sigma$ confidence range for the highest-energy, 31 GeV, photon is $(27.97, 36.32)$ GeV which was detected 0.829 sec after the GBM trigger and 0.859 sec after an episode of weak emission or precursor (see Fig. 8). Assuming the most conservative scenario in
Figure 8: Arrival times of photons detected with Fermi LAT from GRB 090510 with two different $\gamma$-ray filters denoted with red and cyan points (top panel) [3]. The bottom five panels, (a) - (f), correspond to light curve in different energy range. The solid and dashed curves are normalized to pass through the highest energy (31 GeV) photon and represent the relation between a photon’s energy and arrival time for linear ($n = 1$) and quadratic ($n = 2$) LIV, respectively, assuming it is emitted at $t_{\text{start}} - T_0 = -30$ ms (black; first small GBM pulse onset), 530 ms (red; main < MeV emission onset), 648 ms (green; > 100 MeV emission onset), 730 ms (blue; > GeV emission onset). Photons emitted at $t_{\text{start}}$ would be located along such a line due to (a positive) LIV induced time delay. The gray shaded regions indicate the arrival time of the 31 GeV photon $\pm 10$ ms (on the right) and of a 750 MeV photon (during the first GBM pulse) $\pm 20$ ms (on the left), which can both constrain a negative time delay. See Ref. [3] for details.

which the highest-energy photon was emitted during the precursor or 0.03 sec prior to the GBM trigger and is given by

$$M_{QG,1} > 1.19 \, M_P \left(\frac{E_h}{27.97 \text{ GeV}}\right) \left(\frac{\Delta t}{0.859 \text{ sec}}\right)^{-1}. \quad (8)$$

Less conservative estimates of the emission time for the 31 GeV photon result in larger QG mass as we note below.

- The photon was emitted after the start of main MeV emission $\Delta t \leq 0.299$ sec, $M_{QG,1} \geq 3.42 \, M_P$.

- The photon was emitted after the start of $\gtrsim 100$ MeV emission $\Delta t \leq 0.199$ sec, $M_{QG,1} \geq 5.12 \, M_P$.

- The photon was emitted after the start of $\gtrsim 1$ GeV emission $\Delta t \leq 0.099$ sec, $M_{QG,1} \geq 10.0 \, M_P$. 
The photon was emitted within a 20 ms pulse, implies limit on both positive negative time dispersion
\[ \Delta t \leq \pm 0.01 \text{ sec}, \quad M_{QG,1} \geq 102 \, M_P. \]

Assuming that the 750 MeV photon, detected 0.019 sec prior to the precursor, was emitted at the same
time as the precursor emission gives another limit \( M_{QG,1} \geq 1.33 \, M_P \) from negative time delay.

Finally, an independent method called DisCan or Dispersion Cancellation was used to extract time
lag from all LAT photons in the 35 MeV – 31 GeV range. Using this method results in a QG upperlimit
of \( M_{QG,1} \geq 1.22 \, M_P \), consistent with the most conservative limit.

4 Conclusions

Fermi gamma ray space telescope is providing exciting new data in the relatively less explored \( \sim 100 \) MeV
to \( > 100 \) GeV energy range. Galactic sources such as pulsars, supernova remnants, and extragalactic
sources such as GRBs, blazars, radio galaxies and starburst galaxies are the main astrophysical objects
detected with Fermi LAT. Together with Fermi GBM, LAT is discovering new results on GRBs such as
(i) a delayed onset of \( \geq 100 \) MeV emission and (ii) a hard spectral component, as well as collecting more
data on temporally extended high-energy emission. High-energy data collected with Fermi LAT show
that the GRB jet velocity can be rather high, a jet bulk Lorentz factor of the order of 1000 or more in
a few cases. This result together with the delayed onset and hard spectral component affects emission
modeling, and no satisfactory model has been found yet to explain all these features. The highest-energy
photons from GRBs are, however, shown to constrain models of the extragalactic background light that
pervades the universe and quantum gravity models which violate Lorentz invariance.

References

(London), 393, 763
[36] Piran, T. 2005, Reviews of Modern Physics, 76, 1143