GRB Theory in the Fermi Era

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on behalf of the Fermi LAT & GBM Collaborations

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Outline of the Talk:

- Theoretical framework & pre-Fermi observations
- Fermi LAT & GBM overview
- LAT GRB detection rate: what can it teach us?
- The Bulk Lorentz factor: lower limits & actual value
- Properties of high-energy prompt GRB emission: distinct spectral component, delayed onset & longer duration
- Pros & cons of different models
- Comparing between short & long LAT GRBs
- Limits on Lorentz Invariance Violation
- Conclusions
GRB Theoretical Framework:

- **Progenitors:**
  - Long: massive stars
  - Short: binary merger?

- **Acceleration:**
  fireball or magnetic?

- **Prompt $\gamma$-rays:**
  internal shocks? emission mechanism?

- **Deceleration:** the outflow decelerates (by a reverse shock for $\sigma \lesssim 1$) as it sweeps-up the external medium

- **Afterglow:** from the long lived forward shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray $\rightarrow$ optical $\rightarrow$ radio
Prompt GRB Observations ($\lesssim \text{MeV}$)

- Variable light curve

- Duration: $\sim 10^{-2} - 10^3$ sec

- Spectrum: non-thermal $\nu F_\nu$ peaks at $\sim 0.1-1$ MeV (well fit by a Band function)

- Rapid variability, non-thermal spectrum & $z \sim 1$  
  $\Rightarrow$ relativistic source ($\Gamma \gtrsim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;...)
High energy emission from GRBs: Pre-Fermi era

- Little known about GRB emission above ~100 MeV
- **EGRET** detected only 5 (long) GRBs, most notably:
  - **GRB940217**: GeV photons were detected up to 90 minutes after the GRB trigger
  - **GRB941017**: distinct high-energy spectral component (up to 200 MeV), with a different temporal evolution & at least 3 times more energy
- **AGILE** recently observed **GRB080514B** and detected photons up to a few 100 MeV lasting somewhat longer than the soft gamma-rays
Fermi Gamma-ray Space Telescope (Fermi Era; launched on June 11, 2008):

- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10³ keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV
  FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime

(Band et al. 2009)
Fermi GRBs:

- **GBM:**
  - ~ 250 GRB/yr (~20% short)
  - ~ ½ in LAT FoV

- **LAT:** 18 GRBs in ~ 2 yr
  - 2 out of 18 are short: ~ 11%

First detections of sort GRBs at HE
Fermi LAT GRB detection rate

- $\sim 7.3, 8.7$ GRB/yr with $\geq 1, 10$ photons above 1, 0.1 GeV
- $\sim 2.7$ GRB/yr with $\geq 1, 10, 100$ $\gamma$'s above 10, 1, 0.1 GeV
- Comparable to estimates based on Band spectrum fits to bright BATSE GRBs
- Suggests: on average GRBs don’t have much excess (HE component) or deficit (cutoff) in the LAT energy range w.r.t the extrapolated Band spectrum from $<2$ MeV ($\sim 5-10$ times less energy in the LAT range)

(Band et al. 2009)
Constraints on the Bulk Lorentz factor:

GRB080916C: \( \Gamma \gtrsim 900 \) (\( \Delta t = 2 \text{ s} \))

GRB090510: \( \Gamma \gtrsim 1200 \)

- Our \( \Gamma_{\text{min}} \) is more robust than before: it doesn’t assume the spectrum extends beyond the highest energy detected photon.
- For our conservative assumption
  \[ \Gamma_{\text{min}} \lesssim (1+z)E_{\text{ph,max}}/m_e c^2 \approx 200(1+z)(E_{\text{ph,max}}/100 \text{ MeV}) \]

so that a high \( \Gamma_{\text{min}} \) requires the observed spectrum to reach a sufficiently high energy \( E_{\text{ph,max}} \).
Constraints on the Bulk Lorentz factor:

- $\Gamma_{\text{min}}$: no high-energy cutoff due to intrinsic pair production
  $\Rightarrow$ strict lower limits on Lorentz factor of the emitting region

- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ for more realistic time-dependent self-consistent thin shell model (JG et al. 2008)

- GRB 090926A: high-energy cutoff – if due to intrinsic pair production then $\Gamma \sim 200\text{--}700$

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The diagrams show the time-integrated photon spectrum and various energy spectra with different time intervals.
Delayed Onset of High-Energy Emission

- The 1\textsuperscript{st} LAT peak coincides with the 2\textsuperscript{nd} GBM peak
- Delay in HE onset: \(\sim 4-5\) s

\begin{itemize}
  \item GRB080916C
  \item GRB090510
\end{itemize}

\begin{itemize}
  \item The first few GBM peaks are missing in LAT but later peaks coincide; the delay is \(0.1-0.2\) s
\end{itemize}

(Abdo et al. 2009, Science, 323, 1688)

(Abdo et al. 2009, Nature, 462, 331)
Temporally extended emission: HE afterglow?

Most LAT detected GRBs show significant HE emission lasting after the low-energy emission becomes (almost) undetectable (originally detected by EGRET; Hurley et al. 94)

\[ t^{-1.2\pm0.2} \]

\[ t^{-0.6} \]

\[ t^{-3.3} \]

\[ t^{-1.37\pm0.08} \]

Possible origins:

- Afterglow SSC emission (though no spectral hardening, time gap, or synchrotron/SSC valley in the spectrum are observed)
- Afterglow synchrotron: likely at \( t \gg T_{GRB} \); but: variability, \( E_{\text{syn,max}} \)
- Late X-ray flare photons IC scattered by afterglow electrons; var?
- Long lived cascade induced by ultra-relativistic ions (\( t_{\text{ad,cool}} \sim t_{\text{var}} \))
- Pair echo: TeV + EBL \( \gamma\gamma \rightarrow e^+e^- \), & the \( e^+e^- \) IC scatter the CMB
Distinct High-Energy Spectral Component

- Clearly (>5σ) appears only in 3 LAT GRBs, but these are the brightest in LAT so far
- Suggests it is very common but good photon statistics is needed for clear evidence

![Graph](image1.png)

- (GRB090502B; Abdo et al. 2009, ApJ, 706, L138)

- (GRB090510; arXiv:0908.1832)

- (GRB080816C; Abdo et al. 2009, Science, 323, 1688)

PRELIMINARY!
Late onset/HE spectral component: Possible Origin

- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index $\beta$ (determined by the electron energy dist.) is not naturally expected
  - Hard to account for the different photon index values of the HE component & the Band spectrum at low energies
  - Hard to produce a low-energy power-law (GRB090902B)

Preliminary data:

- GRB090510; arXiv:0908.1832
- GRB090902B; Abdo et al. 2009, ApJ, 706, L138
Late onset/HE spectral component: Possible Origin

- **Hadronic**: (pair cascades, proton synchrotron)?
  - Late onset: time to accelerate protons + develop cascades?
  - Does not naturally account the gradual increase in $\beta$
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)

- **GRB090510**: large energy needed: $E_{\text{total}}/E_{\gamma,\text{iso}} \sim 10^2 - 10^3$
- **GRB090902B**: synchrotron emission from secondary $e^\pm$ pairs can naturally explain the power-law at low energies

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**PRELIMINARY!**

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**GRB090902B**; Abdo et al. 2009, ApJ, 706, L138

**GRB090510**; arXiv:0908.1832
Summary of the 14 LAT GRBs so far:

| GRB     | Angle From LAT | Duration (or class) | Number of events > 100 MeV | Number of events > 1 GeV | Delayed HE onset | Long-lived HE emission | Extra spectral comp. | Highest Energy γ (GeV) | Redshift |
|---------|----------------|---------------------|-----------------------------|----------------------------|------------------|------------------------|----------------------|-------------------------|----------|
| 080825C | ~ 60°          | long                | ~ 10                        | 0                          | ?                | ✓                      | X                   | 0.57                    |          |
| 080916C | ~ 16°          | long                | 145                         | 14                         | ✓                | ✓                      | ?                   | 13                      | ~ 4.35   |
| 081006  | ~ 16°          | long                | ~10                         | 0                          | X                | X                      | X                   | 0.65                    |          |
| 081024B | 21°            | short               | ~ 10                        | 2                          | ✓                | ✓                      | ?                   | 3.1                     |          |
| 081215A | ~ 86°          | long                | —                           | —                          | —                | —                      | —                   | —                       | —        |
| 090217  | ~ 34°          | long                | ~ 10                        | 0                          | X                | X                      | X                   | 0.31                    |          |
| 090323  | ~ 55°          | long                | ~ 20                        | > 0                        | ?                | ✓                      | ?                   | 7.5                     | 3.57     |
| 090328  | ~ 64°          | long                | ~ 20                        | > 0                        | ?                | ✓                      | ?                   | 25                      | 0.7354   |
| 090510  | ~ 14°          | short               | > 150                       | > 20                       | ✓                | ✓                      | ✓                   | 31                      | 0.903    |
| 090626  | ~ 15°          | short               | > 20                        | > 0                        | ?                | ✓                      | ?                   | 2.1                     |          |
| 090902B | 51°            | long                | > 200                       | > 30                       | ✓                | ✓                      | ✓                   | 33                      | 1.822    |
| 090926  | ~ 52°          | long                | > 150                       | > 50                       | ✓                | ✓                      | ✓                   | 20                      | 2.1062   |
| 091003A | ~ 13°          | long                | ~ 30                        | > 0                        | ?                | ?                      | ?                   | 2.8                     | 0.8969   |
| 091031  | ~ 22°          | long                | ~ 20                        | > 0                        | ?                | ?                      | ?                   | 1.2                     |          |
| 100116A | ~ 29°          | long                | ~ 20                        | 3                          | ?                | ?                      | ?                   | 2.2                     |          |
| 100225A |                | long                |                             |                            |                  |                        |                     |                         |          |
| 100325A |                | long?               |                             |                            |                  |                        |                     |                         |          |
| 100414A |                | long                |                             | ~ 30                       |                  |                        |                     | 4.7                     | 1.368    |
| 100707A |                | long                |                             |                            |                  |                        |                     |                         |          |
| 100724A |                | long                |                             |                            |                  |                        |                     |                         |          |
Long vs. Short GRBs @ High-Energies:

| Property (HE: >0.1GeV) | Short GRBs | Long GRBs |
|------------------------|------------|-----------|
| Delayed HE onset       | 1 or 2 out of 2 ✓ | 3 out of 5 ✓ (+ many inconclusive cases) |
| Long-lived HE emission | 2 out of 2 ✓ | 7 out of 9 ✓ (+ some inconclusive cases) |
| Redshift               | 1 out of 2 ✓ (z = 0.903 for GRB090510) | 7 out of 16 ✓ (0.74, 0.90, 1.37, 1.82, 2.11, 3.57, 4.35) |
| Bright                 | 1 out of 2 ✓ >100 (10) events >0.1 (1) GeV | 3 out of 16 ✓ >100 (10) events >0.1 (1) GeV |
| $\Gamma_{\text{min}}$  | 1200 for GRB090510 | 900, 1000 (080916C, 090902B) |
| HE spectral component  | 1 out of 2 ✓ (GRB090510) | 2 out of 16 ✓ (GRBs 090902B, 090926) |

They show similar HE emission properties!
# Limits on LIV from Fermi GRBs

| GRB     | duration or class | # of events > 0.1 GeV | # of events > 1 GeV | method | Lower Limit on $\frac{M_{QG,1}}{M_{\text{Planck}}}$ | Valid for $S_n$ = | Highest photon Energy | redshift |
|---------|-------------------|-----------------------|---------------------|--------|-----------------------------------------------|-----------------|-----------------------|----------|
| 080916C| long              | 145                   | 14                  | 1      | 0.11                                          | +1              | ~ 13 GeV              | ~ 4.35   |
| 090510 | short             | > 150                 | > 20                | 1      | 1.2, 3.4, 5.1, 10                             | +1              | ~ 31 GeV              | 0.903    |
|         |                    |                       |                     | 2      | 102                                           | ±1              |                       |          |
|         |                    |                       |                     | 3      | 1.2                                           | ±1              |                       |          |
| 090902B| long              | > 200                 | > 30                | 1      | 0.068                                         | +1              | ~ 33 GeV              | 1.822    |
| 090926 | long              | > 150                 | > 50                | 1, 3   | 0.066, 0.082                                  | +1              | ~ 20 GeV              | 2.1062   |

- **Method 1**: assuming a high-energy photon is not emitted before the onset of the relevant low-energy emission episode
- **Method 2**: associating a high-energy photon with a spike in the low-energy light-curve that it coincides with
- **Method 3**: DisCan (dispersion cancelation; very robust) – lack of smearing of narrow spikes in high-energy light-curve
Conclusions:

- LAT detection rate $\sim 9$ GRB/yr $\Rightarrow$ on average GRBs radiate only $\sim 10$-20% of their energy in the LAT range.

- Prompt spectrum: the 3 brightest LAT GRBs clearly ($>5\sigma$) show a distinct high-energy spectral component.

- Many LAT GRBs show later onset & longer duration of the high-energy emission, relative to low energies.

- Lower limits on GRB outflow Lorentz factor are model dependent: $\Gamma_{\text{min}} \sim 10^{2.5} - 10^3$; GRB090626A: $\Gamma \sim 220$-720

- Short & long GRBs seem to have similar HE properties: delayed onset, longer duration, distinct HE spectral component & high $\Gamma_{\text{min}}$, but short GRBs may be harder.

- Limit on a possible variation of the speed of light with photon energy, beyond Planck scale: $M_{QG,1} > 1.2M_{\text{Planck}}$. 