GRB observations with *Fermi*

Frédéric Piron

(LPTA/IN2P3/CNRS -- Montpellier)

on behalf of the
LAT and GBM collaborations

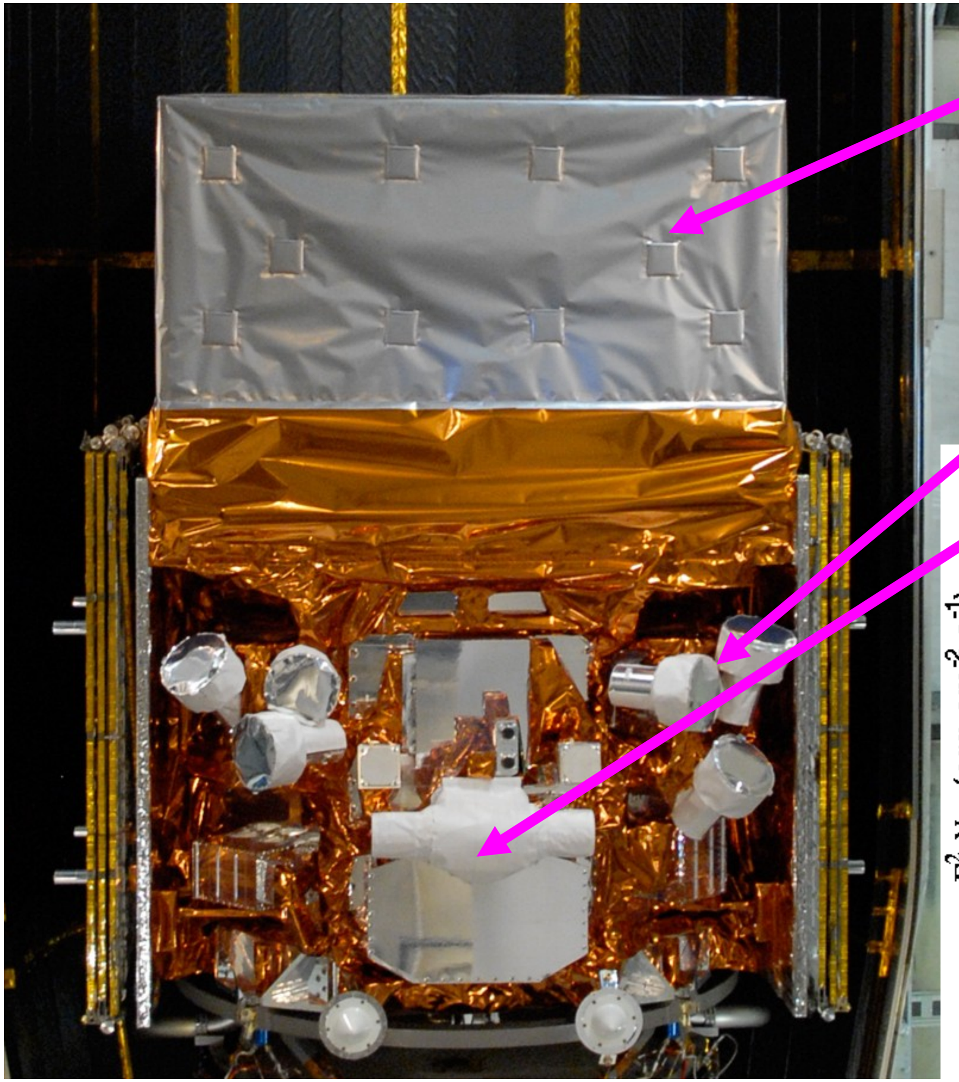
Outline

- **Mission, instruments and performance**

- **First observations and common trends in GRB high-energy properties**

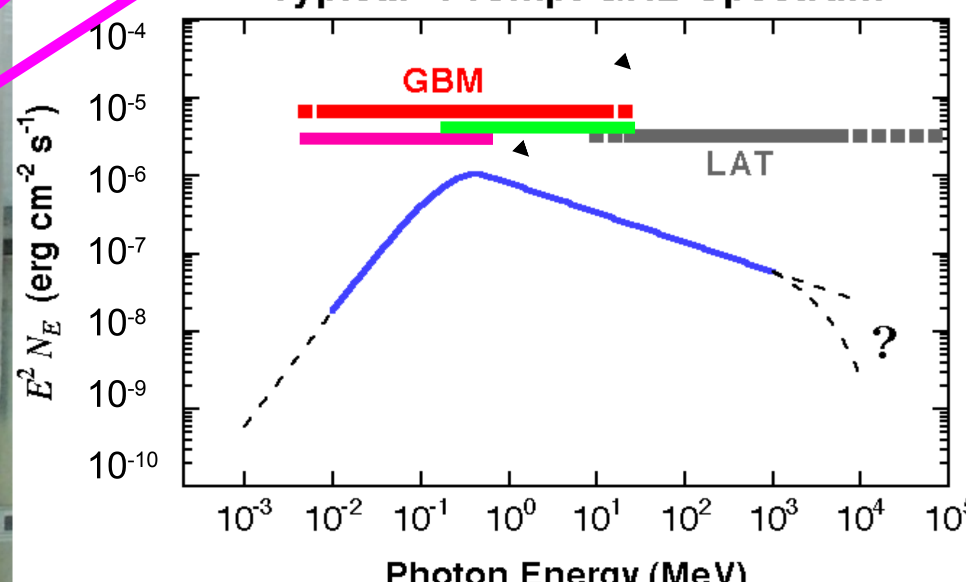
The Observatory (prior to fairing installation)

The instruments onboard *Fermi*



- Large Area Telescope (LAT)
  - 20% of the sky at any instant
  - 20 MeV to >300 GeV
  - onboard and ground burst triggers, localization, spectroscopy
- Gamma-ray Burst Monitor (GBM)
  - Whole unocculted sky at any time
  - 12 NaI detectors (8 keV to 1 MeV)
    - onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - spectroscopy

"Typical" Prompt GRB Spectrum



Exceptionally good spectral observations of the prompt phase of lots of GRBs

LAT Collaboration

- France
  - CNRS/IN2P3 (LLR, CENBG, LPTA)
  - CEA/Saclay
- Italy
  - INFN, ASI, INAF
- Japan
  - Hiroshima University
  - ISAS/JAXA
  - RIKEN
  - Tokyo Institute of Technology
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University
- United States
  - Stanford University (SLAC and HEPL/Physics)
  - University of California, Santa Cruz - Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - The Ohio State University
  - University of Washington

PI: Peter Michelson
(Stanford)

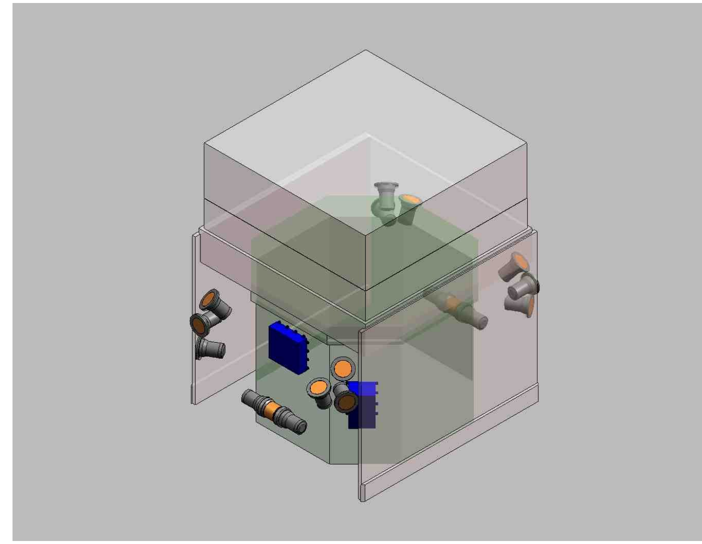
~390 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at SLAC.

GBM Collaboration

PI: William Paciesas
Co-PI: Jochen Greiner



National Space Science & Technology Center

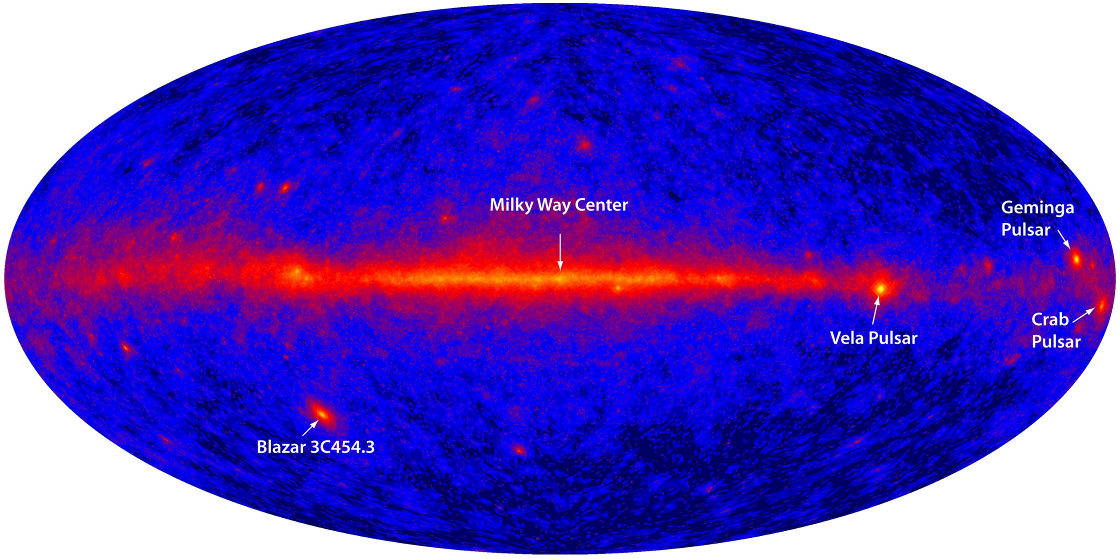
University of Alabama
in Huntsville

NASA
Marshall Space Flight Center

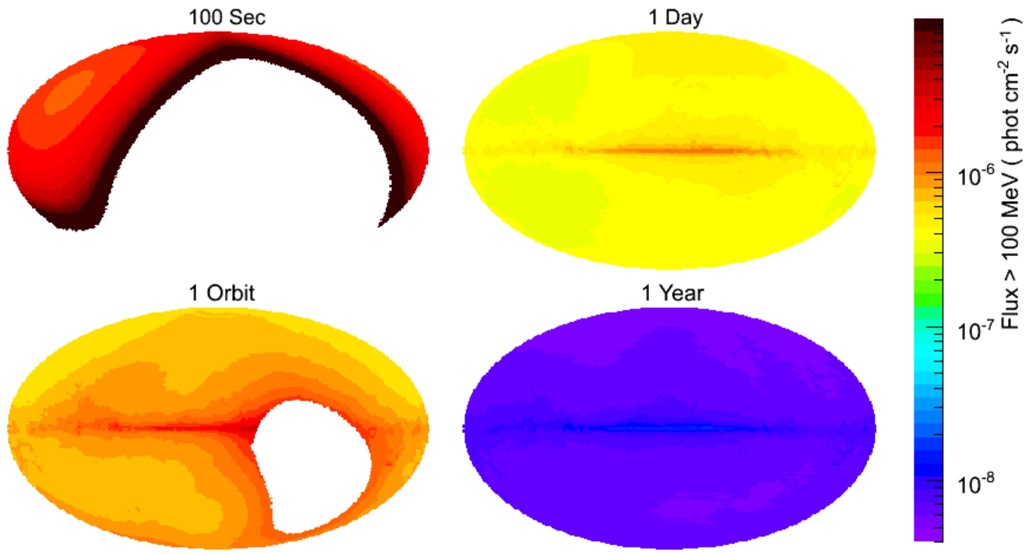
Max-Planck-Institut für
extraterrestrische Physik

Launch and first light

- Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination
- Launch & Early Operations (2 months up to 11 August 2008)
- First light on 4 days of engineering data



Operating modes



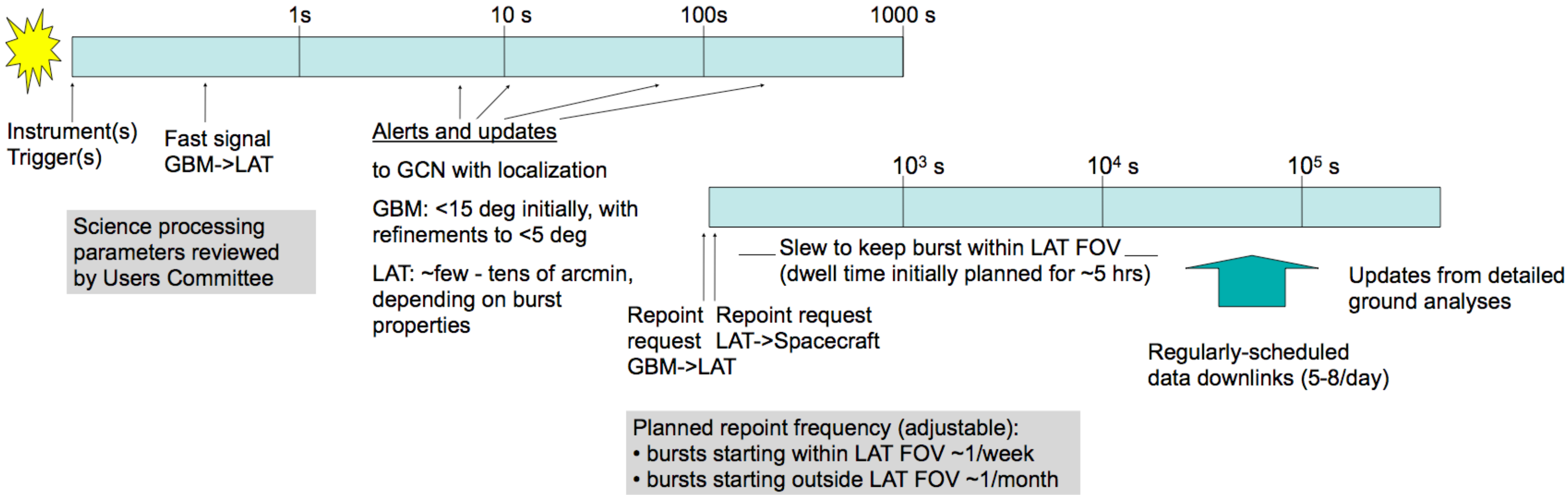
- Primary observing mode is Sky Survey
  - Full sky every 2 orbits (3 hours)
  - Uniform exposure: each region viewed for ~30 minutes every 2 orbits
  - Best serves majority of science, facilitates multiwavelength observation planning
  - EGRET sensitivity reached in days
- Pointed observations when appropriate (selected by peer review in later years) with automatic earth avoidance selectable
- Target of Opportunity pointing
- The observatory can be repointed (ARR) to obtain LAT observations of afterglow from strong bursts

Fermi GRB response scenario: alerts and data flow

- **Using TDRSS (*) from burst trigger to GCN: ~10-15 s**

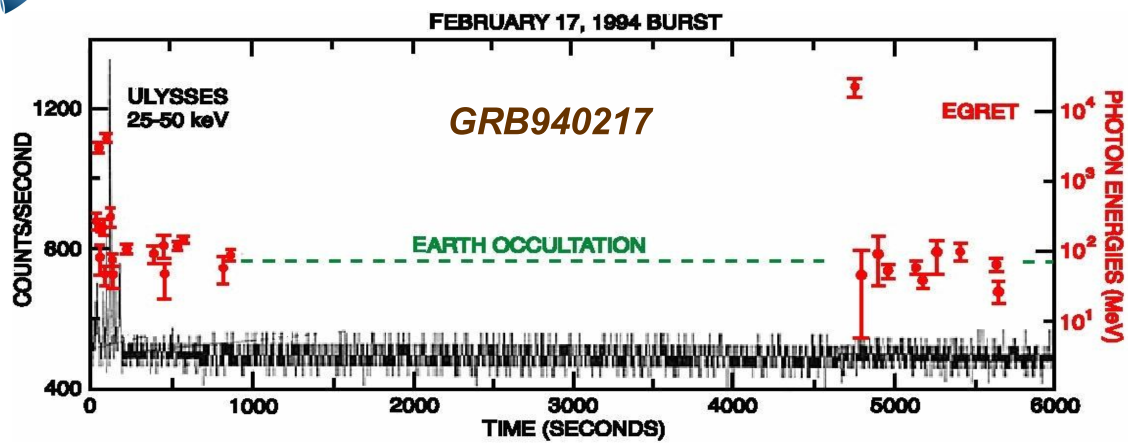
(*) Tracking and Data Relay Satellite System

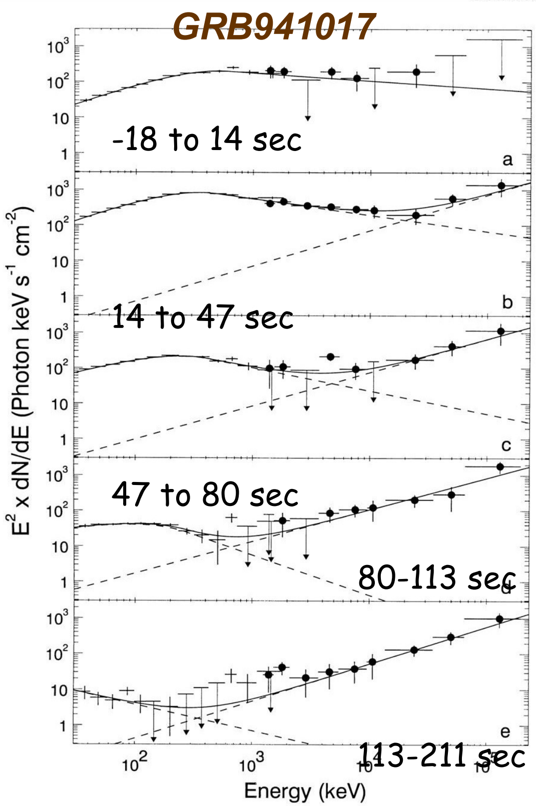
Typical GLAST GRB Timeline

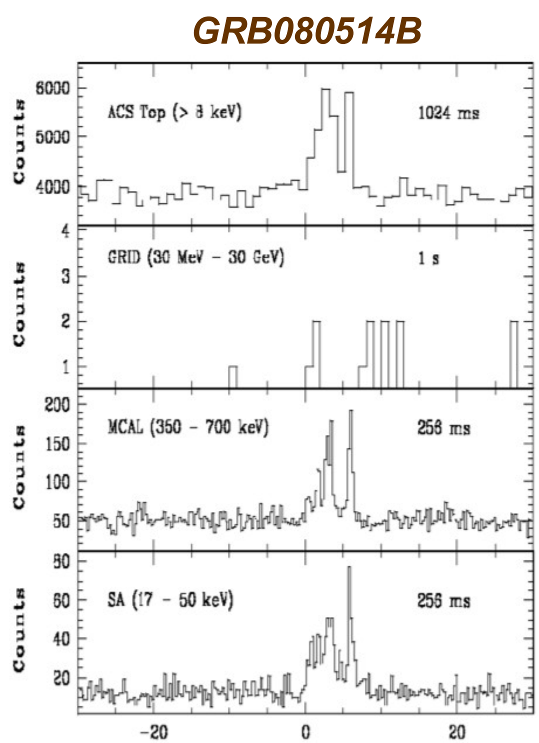


- **Onboard processing - GCN alerts:**
  - **GBM location (<15º initially, within 2 s), intensity (counts), hardness ratio, trigger classification, LAT location**
- **Ground processing of prompt data (~15 mins):**
  - **Updated GBM location (<5º), preliminary GBM light-curve**
- **LAT ground processing (5-12 hours):**
  - **Updated location, HE flux & spectrum (or UL), afterglow search results**
- **Final ground processing (24-72 hours):**
  - **GBM model fit (spectral parameters, flux, fluence), joint GBM-LAT model fit, raw GBM data available**

GRBs at high energies before *Fermi*



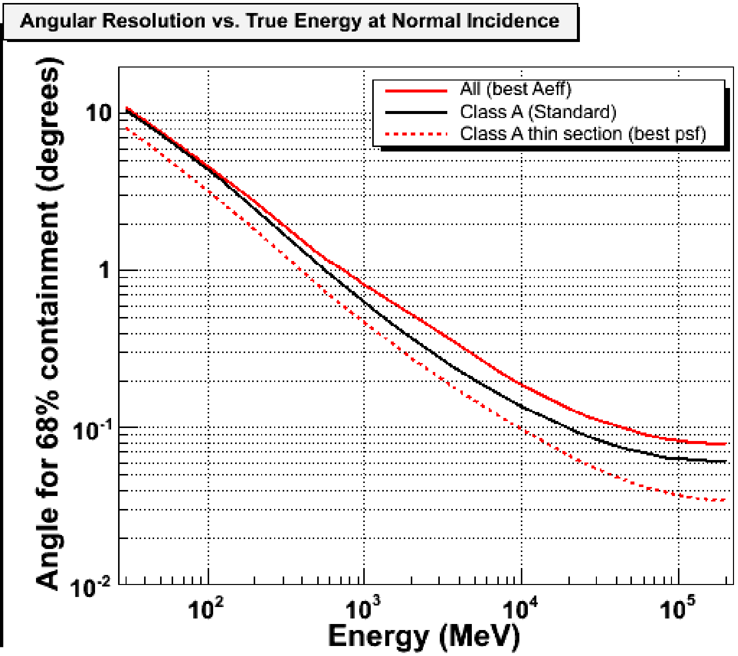




- Little is known about GRB emission above ~100 MeV
- Prompt HE gamma emission
  - Prompt GeV emission with no HE cutoff (combined with rapid variability) implies highly relativistic bulk motion
  - EGRET detections from a few GRBs, e.g. GRB940217
  - New HE extra component, with “independent” temporal evolution (GRB 941017)
    Inconsistent with the synchrotron model! (Gonzalez ’03)
- Extended or delayed HE emission
  - It may require more than one emission mechanism, and remains one of the unsolved problems
  - GRB 940217 (EGRET)
  - GRB 080514B (AGILE)
- HE emission clearly has different time dependence
  - What is its spectral shape?
  - Need more sensitivity and larger FOV

LAT performance

	LAT	EGRET
Energy range	20 MeV to >300 GeV	20 MeV – 30 GeV
Energy resolution (on axis, 100 MeV – 10 GeV)	<10%	10%
Peak effective area	9000 cm^2	1500 cm^2
Angular resolution (single photon, 10 GeV)	0.15°	0.54°
Field of view	>2.2 sr	0.4 sr
Deadtime per event	27 us	100 ms



- **Major improvements in capabilities for GRB observation**
  - **Efficient observing mode (don't look at Earth)**
  - **Wide FoV**
  - **Low deadtime (exploring dt's down to μsec)**
    - **Studies of short bursts possible**
  - **Large effective area**
  - **Good angular resolution**
  - **Increased energy coverage (to hundreds of GeV)**

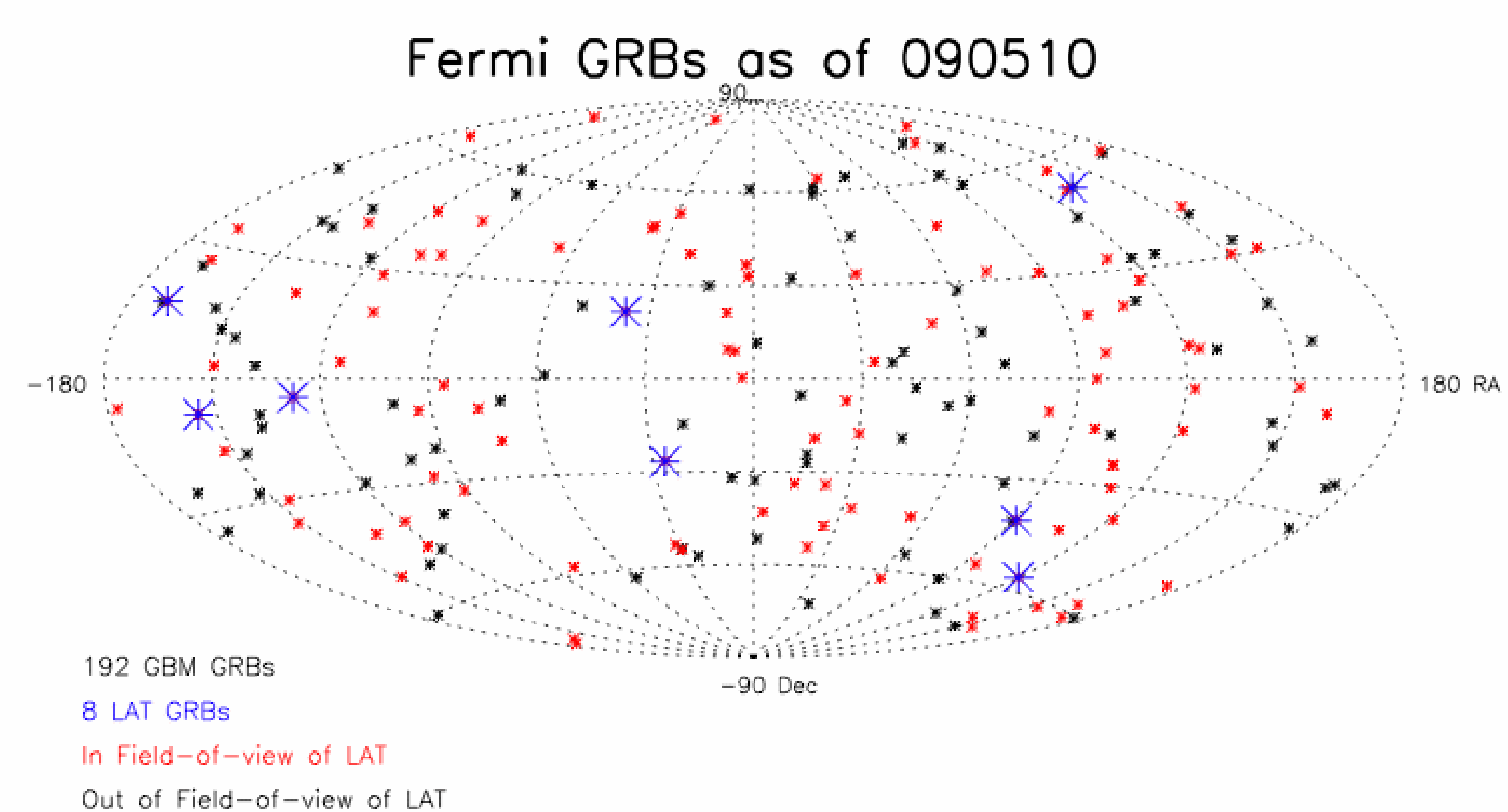
Many GRBs

More photons detected from each GRB

Good GRB locations

Fermi GRBs as of 090510

- GRB 080825C
- GRB 080916C – very strong, z=4.35
- GRB 081024B – short
- GRB 081215A – LAT rate increase
- GRB 090217
- GRB 090323 – ARR, z=3.6
- GRB 090328 – ARR, z=0.736
- GRB 090510 – short, intense, 1st LAT GCN notice, z=0.9



First 4 *Fermi*-LAT detected GRBs

GRB080916C

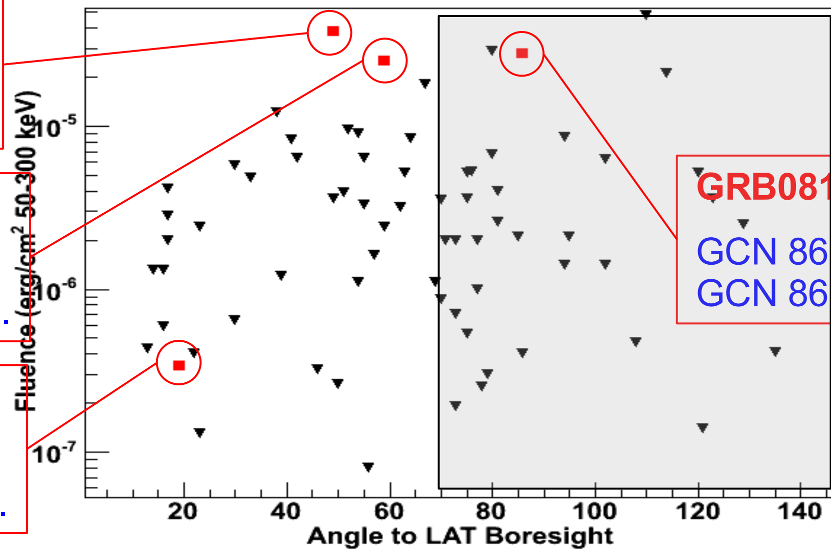
GCN 8246, Tajima, H. et al.;
GCN 8245, 8278, Goldstein A. et al.

GRB080825C

GCN 8183, Bouvier, A. et al.;
GCN 8141, 8184, van der Horst, A. et al.

GRB081024B

GCN 8407, Omodei N. et al.;
GCN 8408, Connaughton, V. et al.



GRB081215A

GCN 8684, McEnery, J. et al.;
GCN 8678, Preece, R. et al.

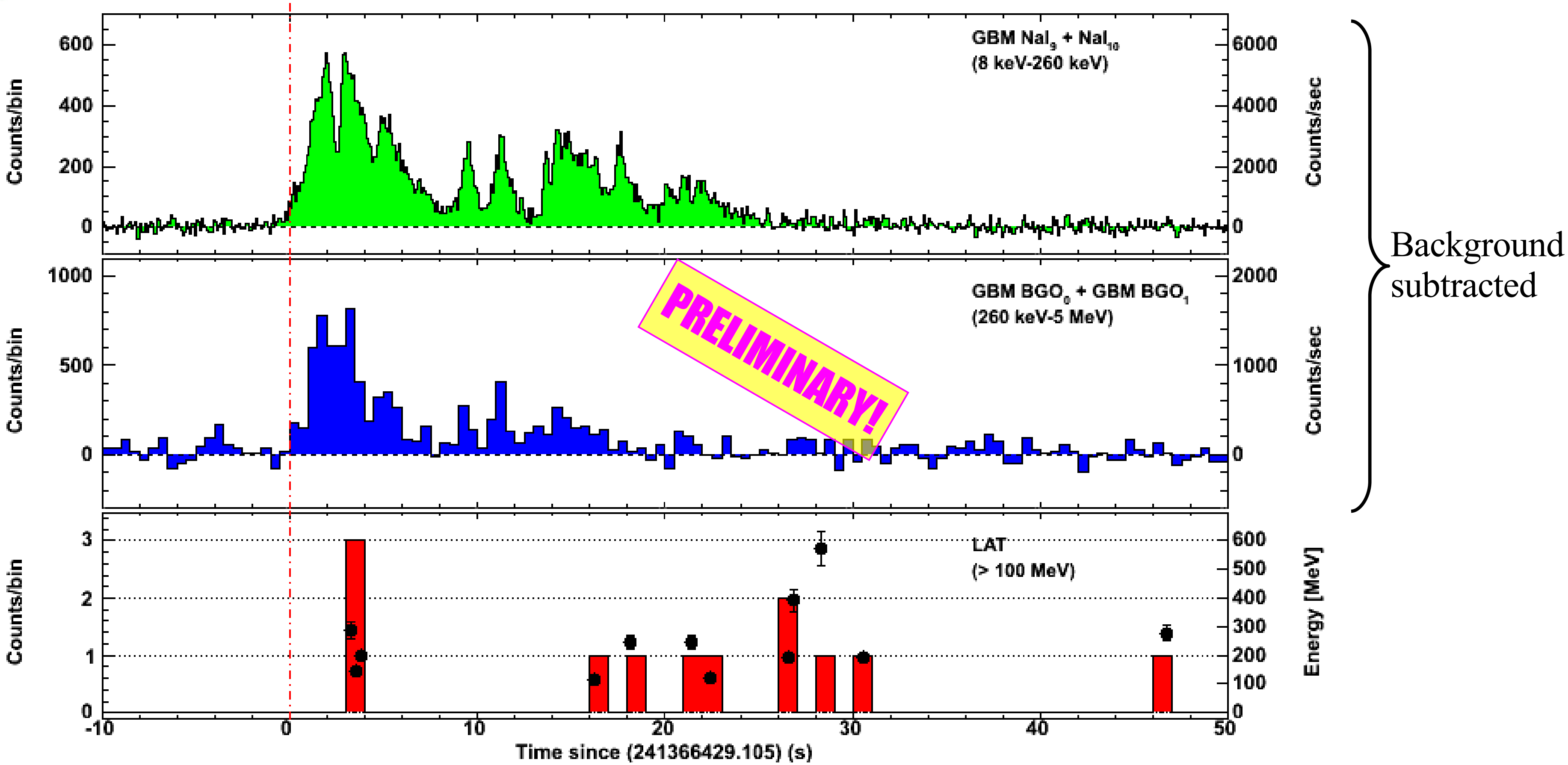
GRB080825C - the first one : **> 10 events above 100 MeV**

GRB080916C - the bright one : **> 10 events above 1 GeV and > 140 events above 100 MeV (used for spectral analysis) ; measured z = 4.35**

GRB081024B - the short one : **first short GRB with >1 GeV emission**

GRB081215A - the transverse one : **86 deg to LAT boresight, excess in raw count rates**

GRB 080825C



LAT detection : 6.4 σ (Li&Ma '83, likelihood ratio)

GBM signal shows multiple peaks with 2 brightest in 5s and lasts ~35s

First LAT events coincident with the 2nd GBM peak

Evidence for long-lasting >100 MeV emission

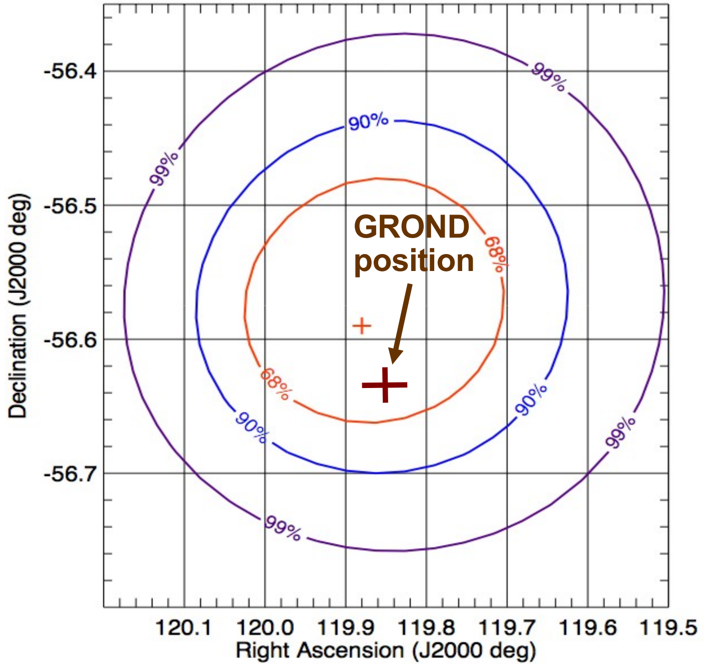
Highest energy event is detected when GBM low energy emission is very weak

GRB 080916C

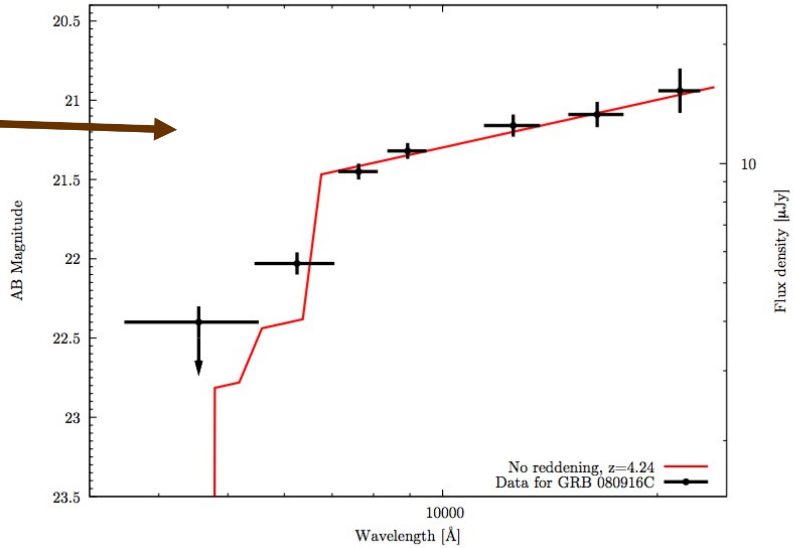
At 00:12:45 UT (T_0) on 16 September 2008:
The GBM flight software triggered on a count rate increase in NaI detectors 3 and 4 caused by GRB 080916C
Large signal recorded in 9 NaI and 1 BGO detectors
LAT onboard GRB search not enabled

GBM on-ground position [GCN 8245 – A. Goldstein]
RA = 121.8˚, Dec= -61.3˚ (± 1˚ or at 68% C.L., syst. 2˚-3˚)
T_{90}=66 s (50-300 keV), several peaks

LAT on-ground position [GCN 8246 – H. Tajima]
On-ground Automated Science Processing triggered
ROI of 20 deg around GBM location, more than 10 photons > 1 GeV
RA = 119.88˚, Dec = −56.59˚
Statistical error = 0.09˚ (0.13˚) at 68% (90%) C.L.
Systematic error < 0.1˚
Consistent with GBM location



GROND optical follow up [GCN 8257, 8272]
Faint (21.7 mag at T_0+32h) and fading (T_0+3.3d) source
RA = 119.8472˚, Dec = −56.6383˚ (±0.5” at 68% C.L.)
Photometric redshift of z=4.35 +/- 0.15



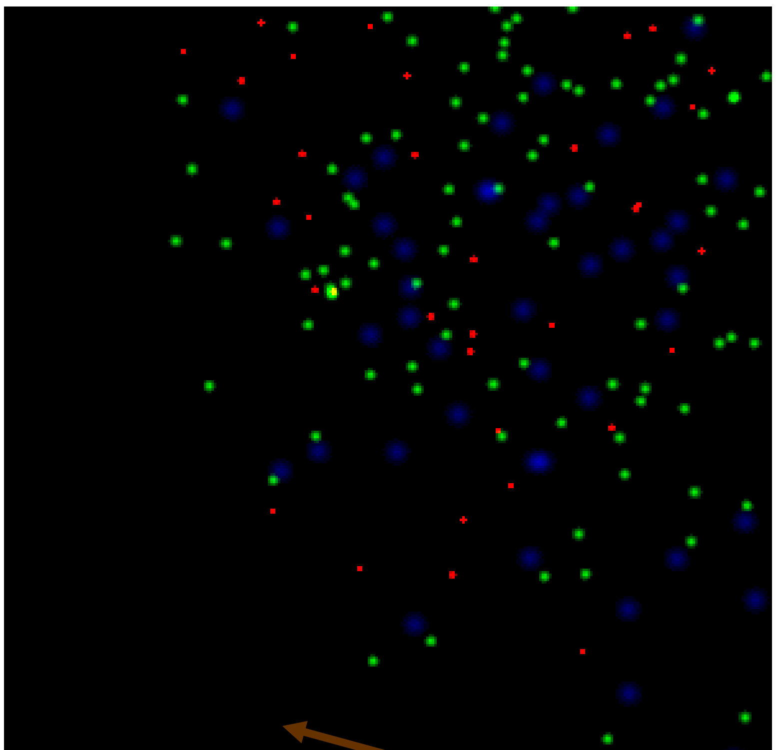
Swift/XRT follow up after T_0+17h [GCN 8261, Report 166.1]
RA = 119.8468˚, Dec = −56.6380˚ (±1.9” at 90% C.L.)

IPN triangulation [GCN 8251]

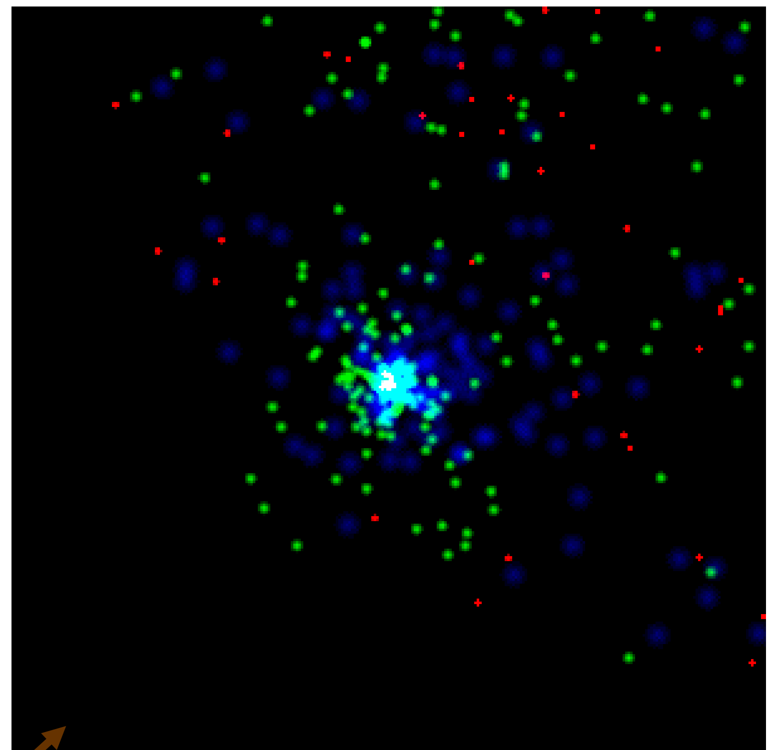
LAT skymap

- ±30 deg region around GRB 080916C
  - GRB at 48˚ from the LAT boresight at T_0
- RGB= <100 MeV, 100 MeV - 1 GeV, >1 GeV

Before the burst (T_0-100 s to T_0)

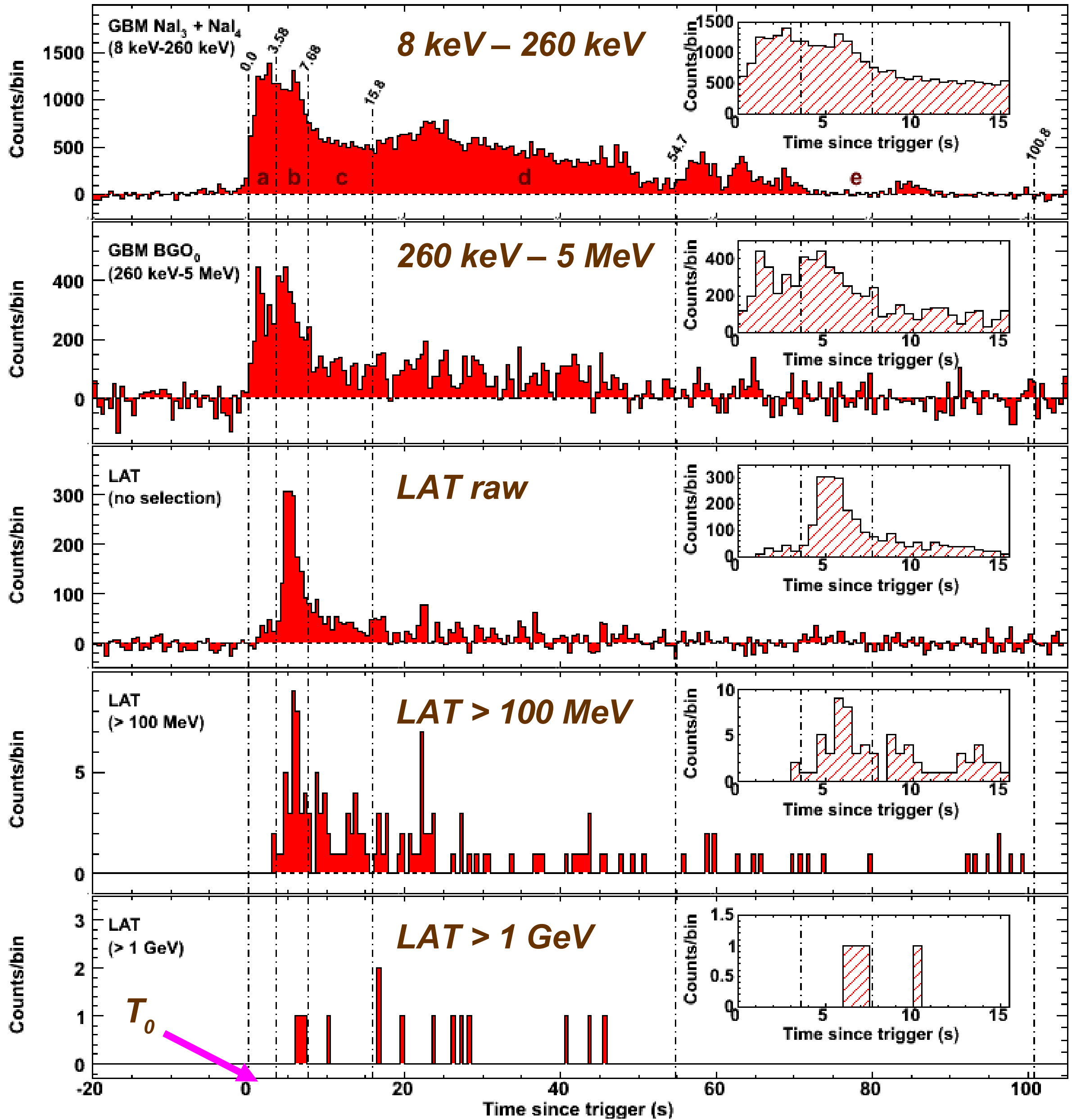


During the burst (T_0 to T_0+100 s)



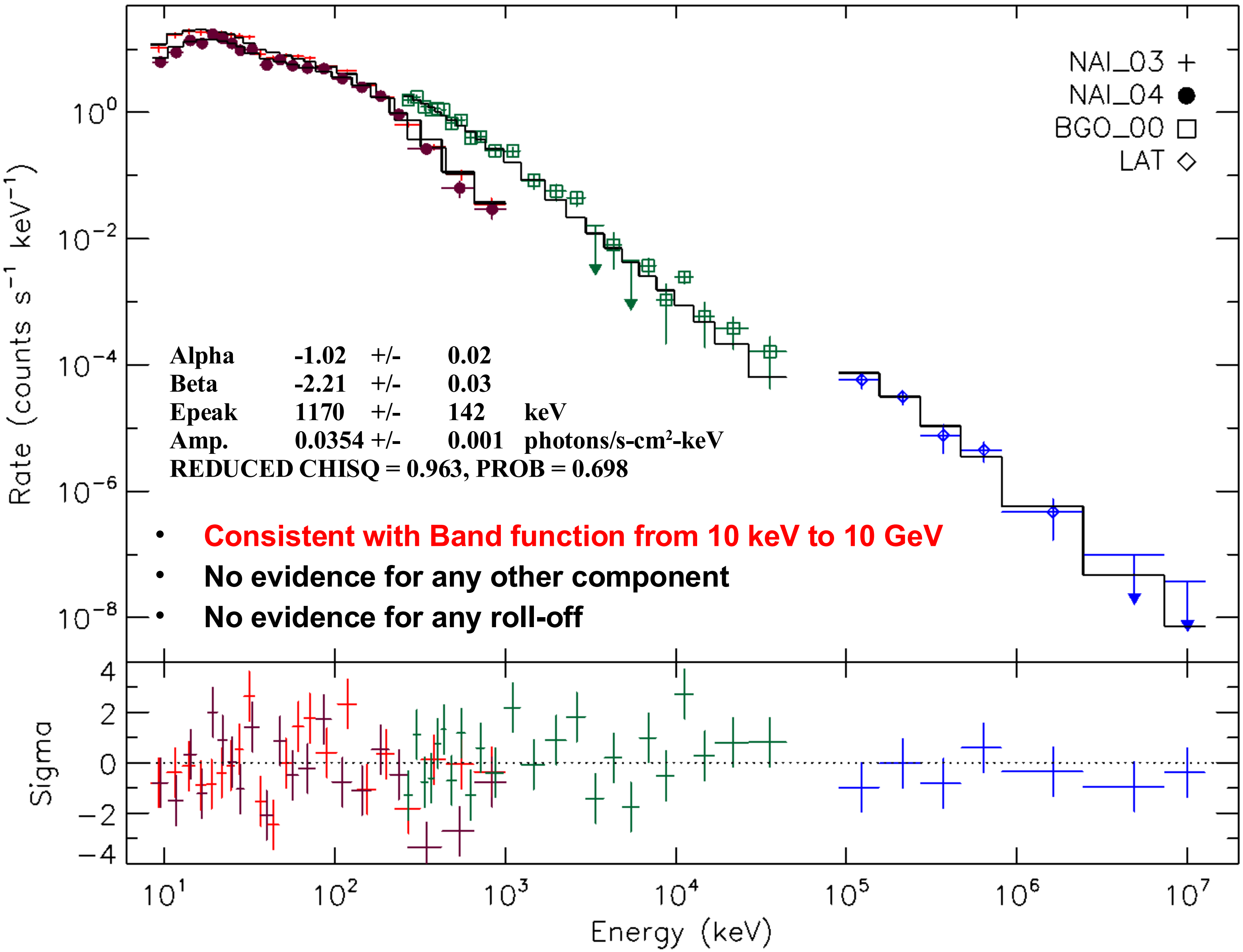
Black region = out of FoV

Multi-detector light-curve of GRB 080916C



- First high-energy GRB (>100 MeV) with known redshift
- The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV
  - ~4.5 s delay between >100 MeV and 100 keV radiations
- Spectroscopy needs LAT event selection (>100 MeV)
  - Apparent isotropic energy release is 8.8×10^{54} ergs, ~5 $M_{\odot}$ (jet / collapsar paradigm)
  - Largest sample >100 MeV
  - 14 events >1 GeV
  - Highest energy photon (E = 13.2 GeV after 16.5 s) from GRB with z

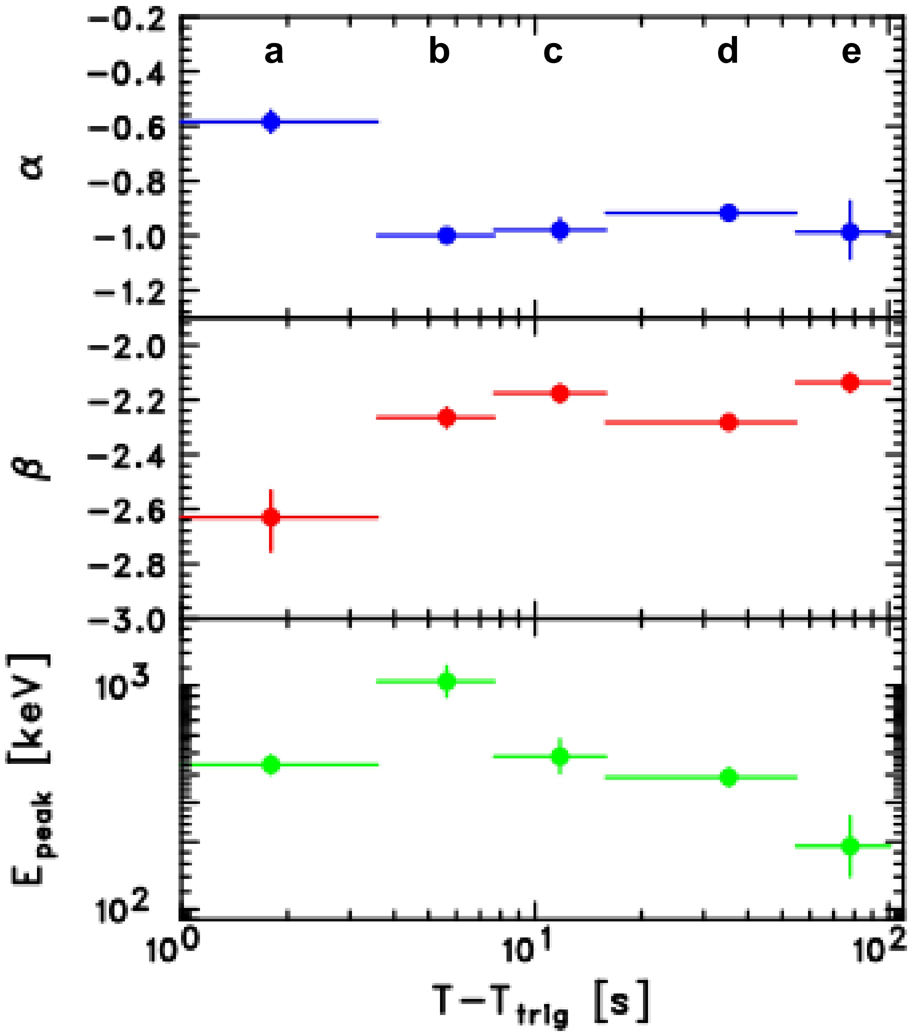
Spectroscopy of main LAT peak (bin 'b')

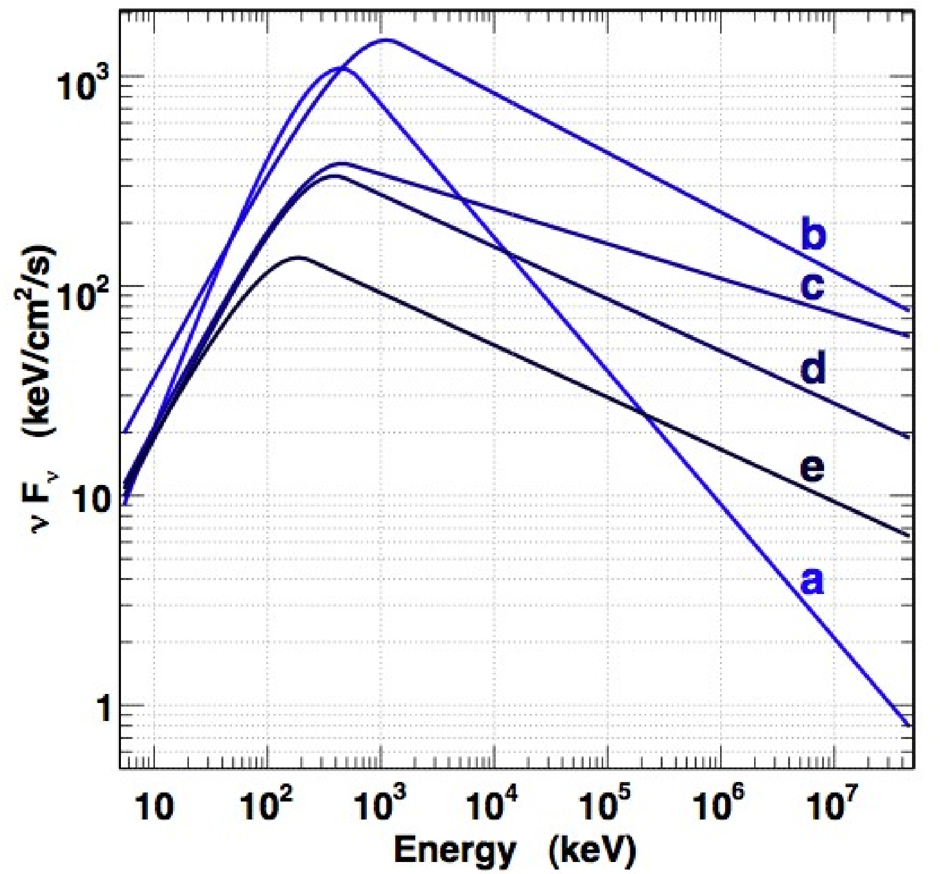


- Consistent with Band function from 10 keV to 10 GeV
- No evidence for any other component
- No evidence for any roll-off

Spectral evolution of GRB 080916C

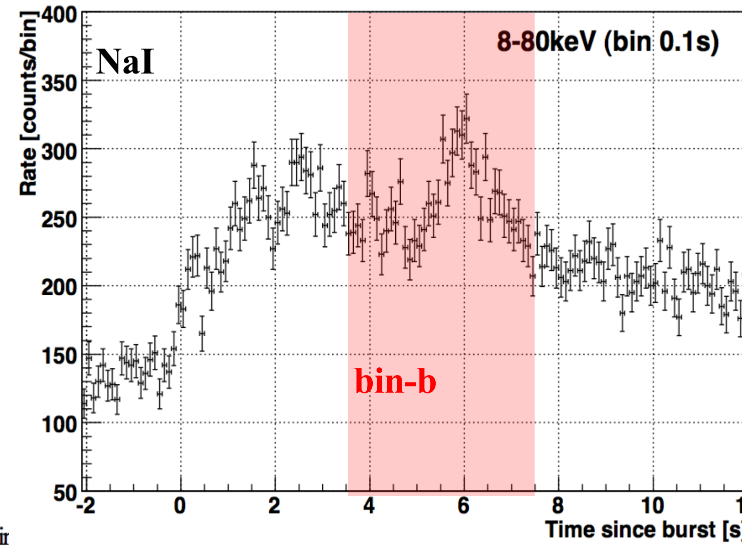
Soft-to-hard, then hard-to-soft evolution



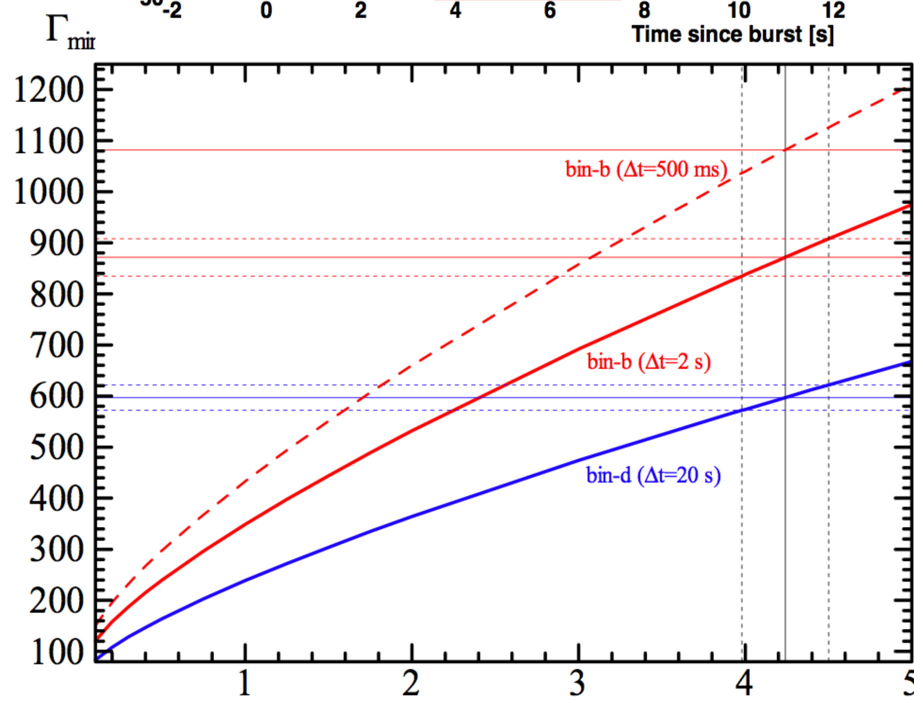


Time delay from opacity effects?

- **Compactity effect**
  - Compact cloud expands and becomes optically thin to gg->e+e- and begins to shine in GeV g-rays
  - Predicts spectral softening break evolving to higher energies – not observed



- **Constraint on minimum bulk Lorentz factor (from opacity argument)**
  - Using conservative assumptions on variability timescales
  - Γ > 887 +/- 21 (bin b)
  - Γ > 608 +/- 15 (bin d)

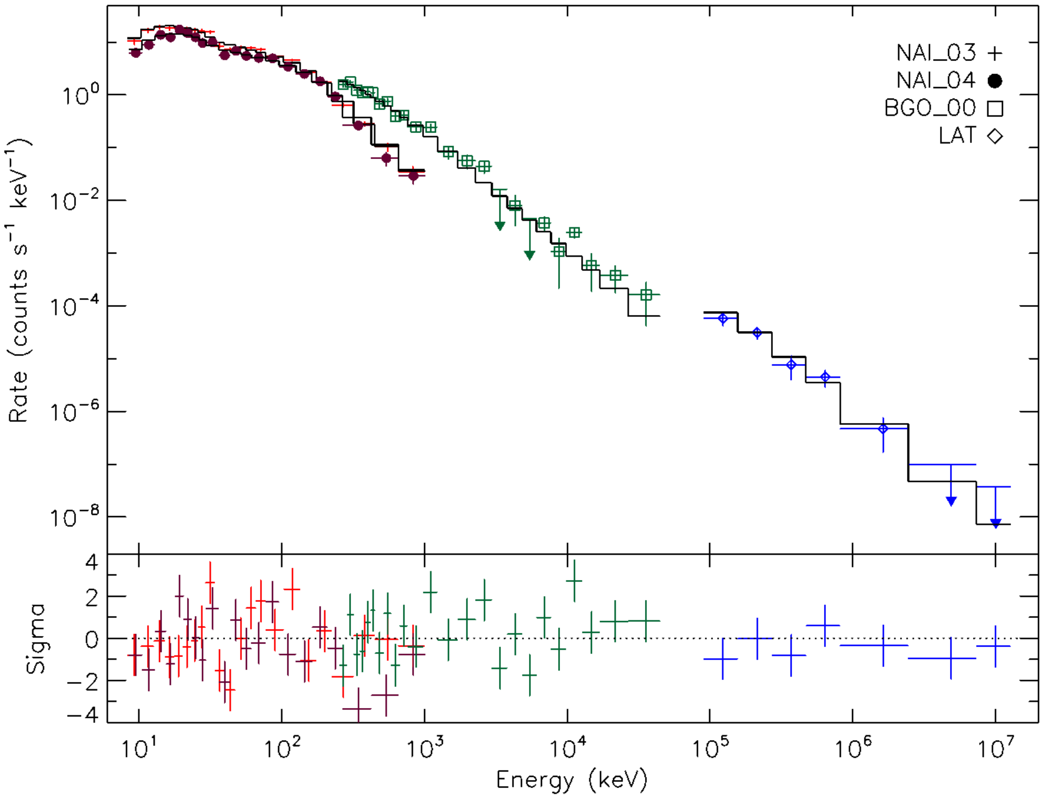


Spectral implications of GRB 080916C

- **<u>No strong evidence for an additional HE component</u>:**
  - Spectra are well fitted by a single Band function

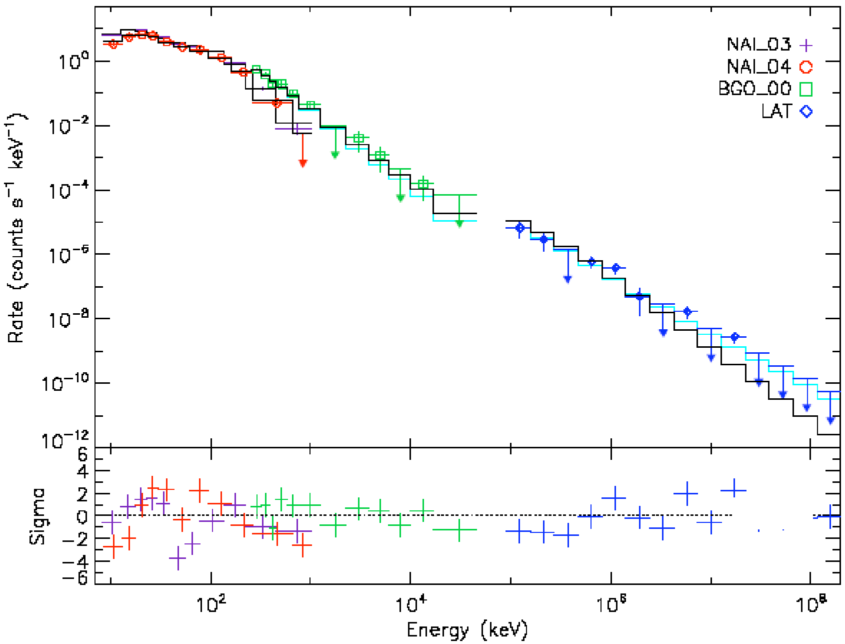
- Single emission mechanism (e.g., nonthermal synchrotron) dominates

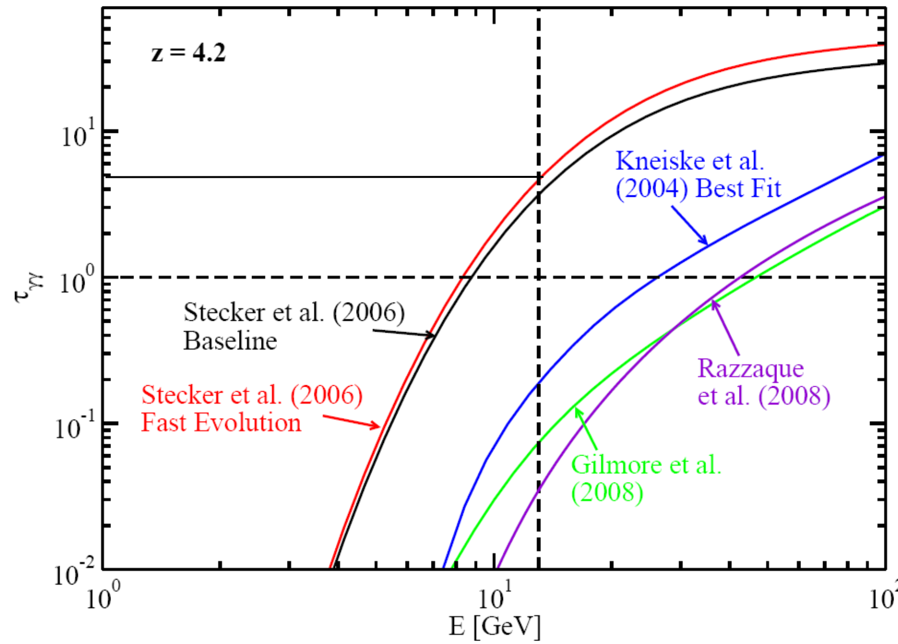
- SSC not observed
  - peaks at higher energy
  - mostly suppressed if $\varepsilon_B > \varepsilon_e$



Spectral implications of GRB 080916C

- **<u>No strong evidence for an additional HE component, but…</u>**
  - **Only 1% probability in time bin d for no extra (hard) component**



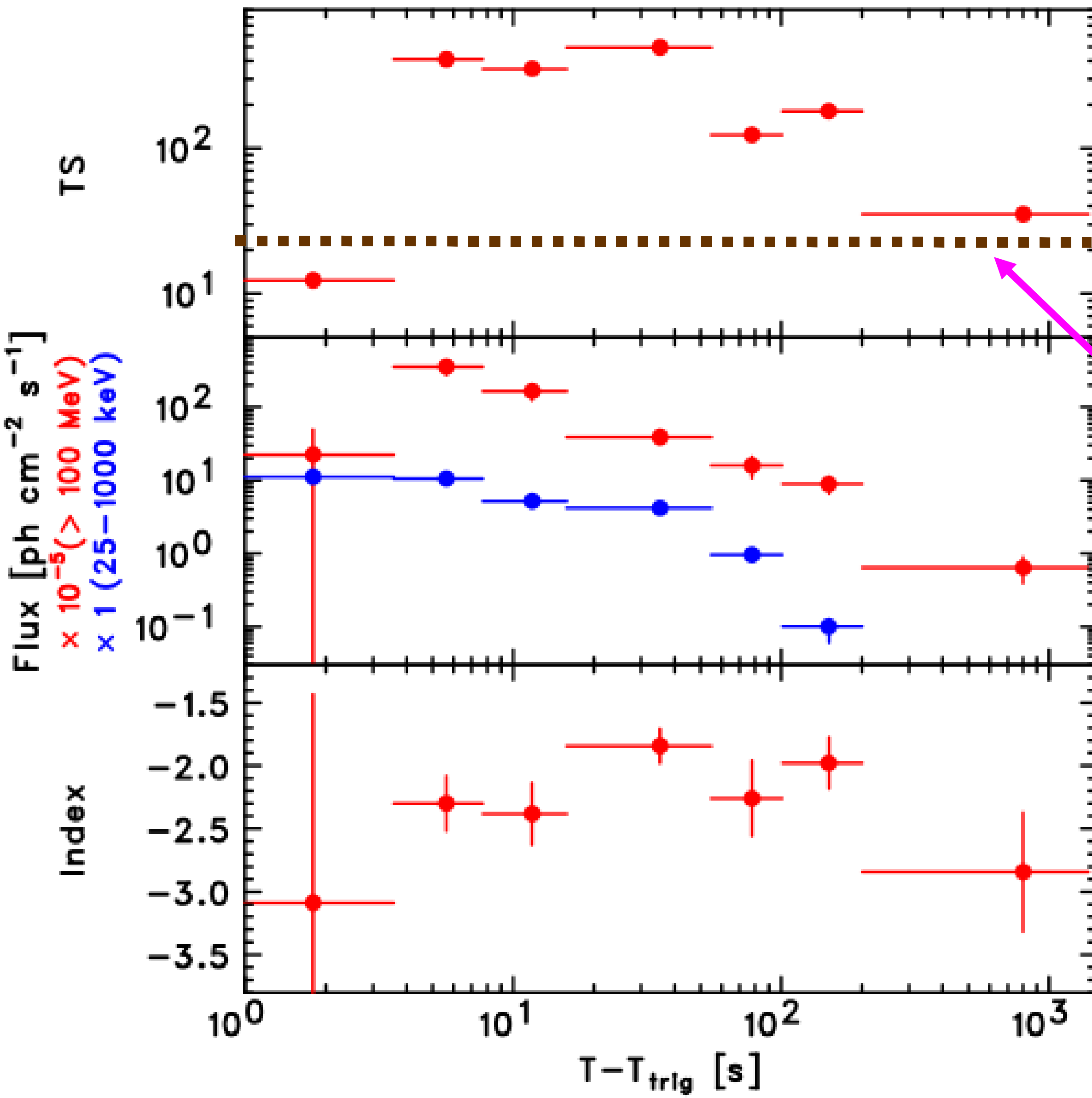


GRB absolute energy release depends on EBL intensity for 13.2 GeV photon

Stecker et al. (2006) fast-evolution EBL provide >3σ evidence for hard spectral component in GRB 080916C, implying significant energy carried by high-energy radiation

Low EBLs consistent with Band function, no extra component

GRB 080916C extended emission

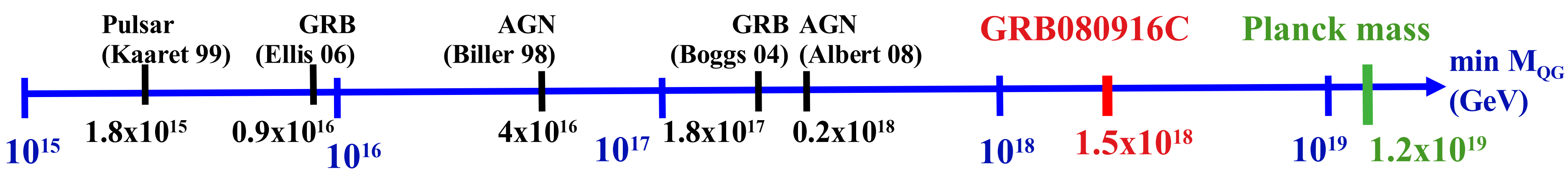


- GBM emission drop-off ~55 seconds after T_0
- Significant LAT emission from T_0+3.6 s to T_0+1400 s
  - Tighter event selection cuts, optimized for weak sources
  - Test Statistics with position fixed at GROND location: TS > 25 (square of significance)
  - Still significant (5.9σ) between T_0+200 s and T_0+1400 s, and consistent with the trend from the prompt emission
- Could be due to:
  - Delayed arrival of SSC emission (though no spectral hardening or sync/SSC valley observed)
  - Cascades induced by ultra-relativistic ions

Quantum Gravity mass limits

- **Quantum gravity:**
  - Highest energy, ≅ 13.2 GeV photon, detected 16.5 sec after GBM trigger
  - Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger): $M_{QG} > (1.50 \pm 0.20) \times 10^{18}$ GeV/c^2

    (1 order of magnitude higher than the previous best estimate, 1 order of magnitude below the Planck mass)

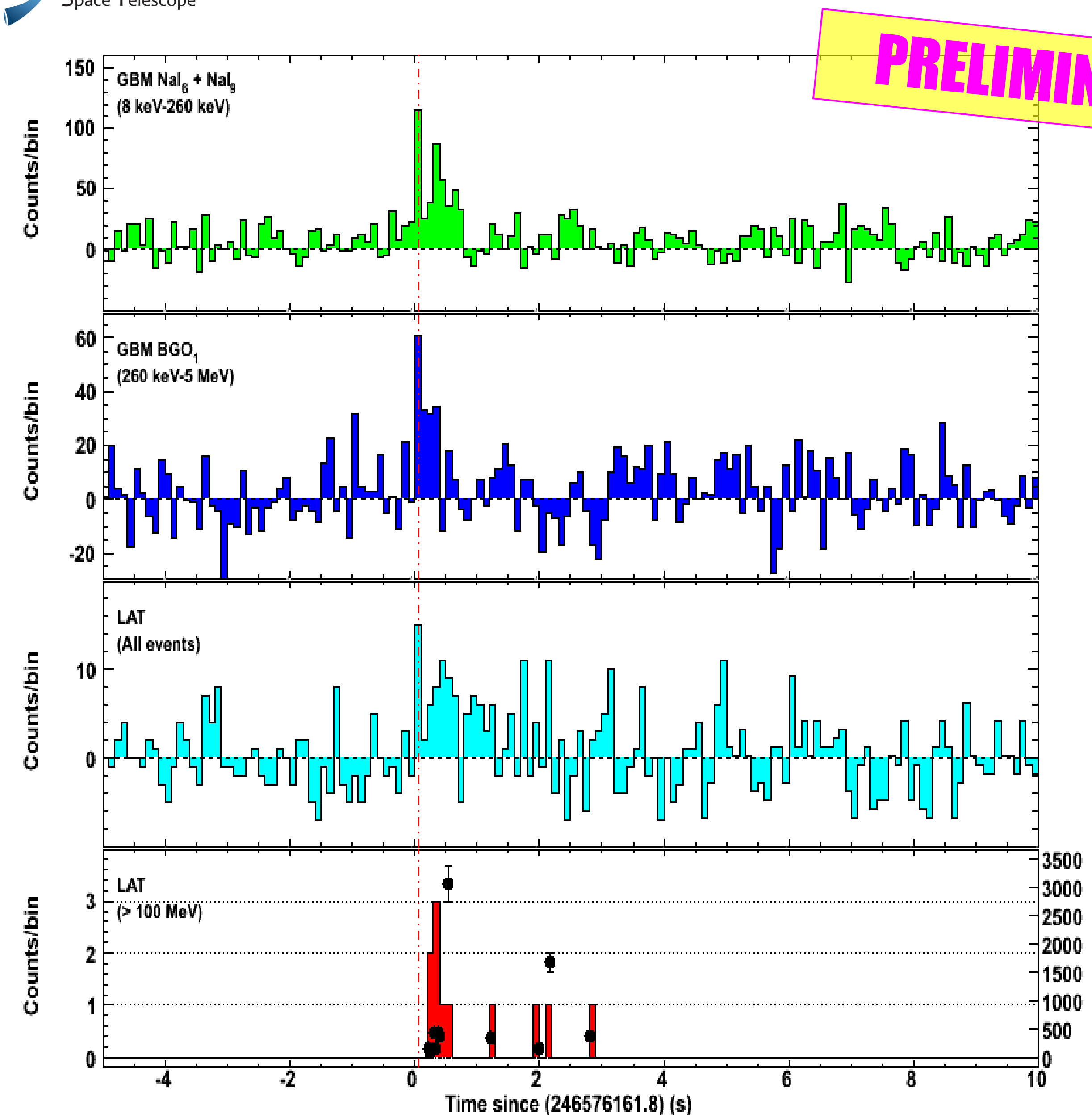


$$\Delta t = \frac{(1+n)}{2H_0}\frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz'$$

Ellis et al. (2003); Jacob and Piran (2008)

n=1,2 for linear and quadratic Lorentz invariance violation, respectively

GRB 081024B



LAT detection : 8.4 σ (Li&Ma '83, likelihood ratio)

First short GRB >1GeV

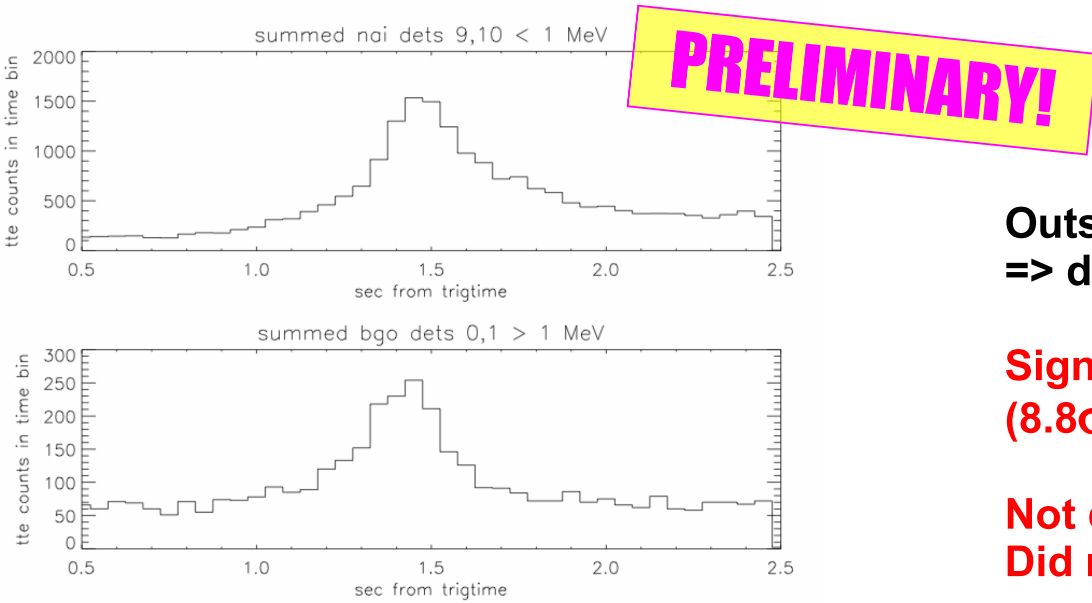
First GBM peak seen in raw counts (probably <100MeV)

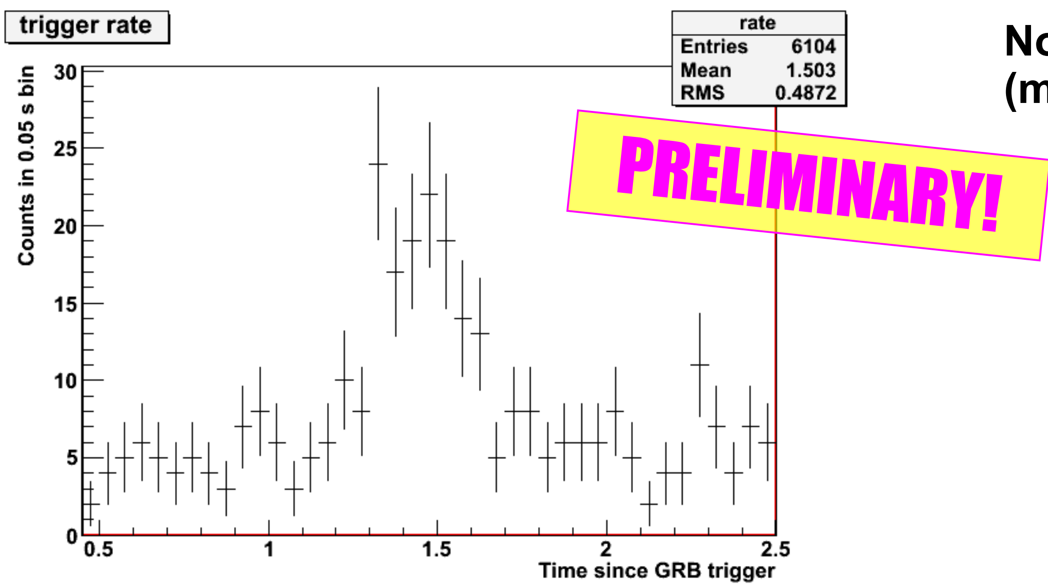
HE (>100MeV) LAT emission possibly delayed wrt GBM onset

Coincident with 2nd GBM pulse and extends beyond keV-MeV emission (~0.8 sec)

Fermi Gamma-ray Space Telescope

GRB 081215A





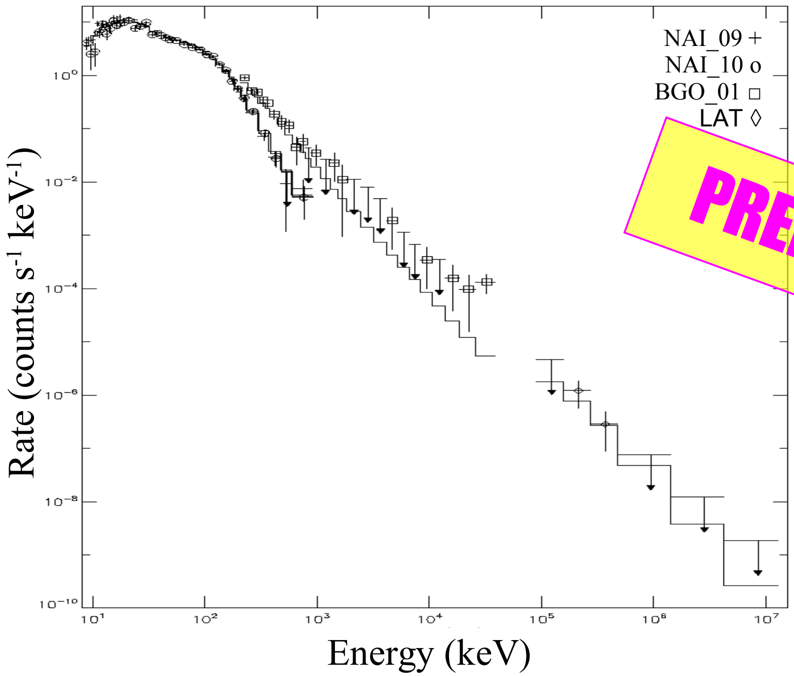
Outside LAT FoV (86 deg to boresight)
=> difficult study

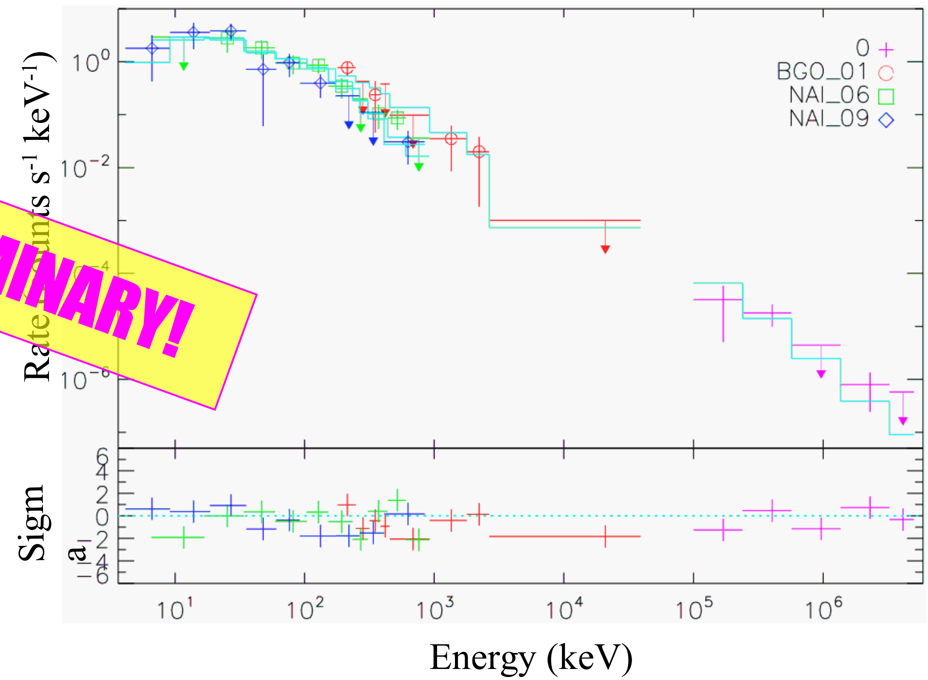
Significant increase of raw TKR rates (8.8σ) coincident with GBM trigger

Not delayed wrt GBM pulse
Did not last longer than GBM pulse

No accurate energy information (mostly <150MeV)

GRB 080825C & GRB 081024B





GRB 080825C
GBM + LAT : Band function

GRB 081024B
2nd GBM pulse + LAT data : Band function

Consistent with a Band function from 10keV to ~1GeV

Conclusions

- ~200 bursts detected by the GBM, including 8 LAT detections
  - LAT and GBM working well together
- High-energy GRB observations
  - Evidence (though not significant in all cases) for a delay between keV-MeV and >100MeV emissions
  - Band function provide good fits over wide energy range with no need for additional components so far
  - All LAT detected GRBs show significant HE emission extending after the low energy emission has (almost) disappeared below detectability
- Consequences
  - Narrow collimated relativistic jet
  - keV-GeV spectrum and variability: unique mechanism, same emission region (leptonic or hadronic origin?)
  - Best constraints ever on Bulk Lorentz factor (> 600 to 900) and M_{QG} >0.1 M_{planck}
  - Opening high-energy window has great promise for emission mechanisms and tests for Lorentz invariance
- Data available through FSSC
  - GBM data and s/w already public
  - LAT Science Tools already public
  - LAT data public release mid-August 2009