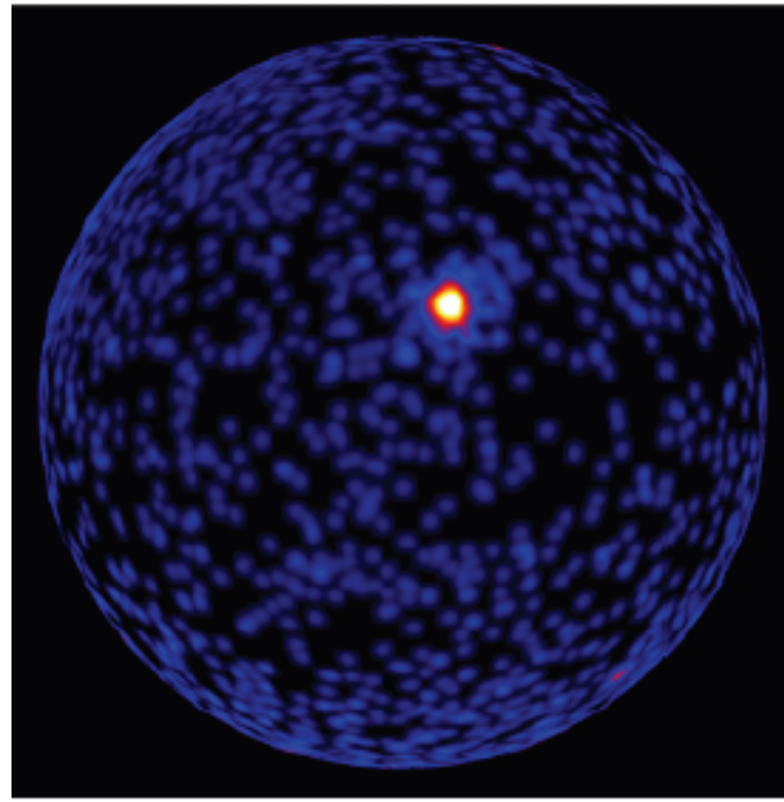
High energy GRB observations with the Fermi Large Area Telescope

F.Longo
University of Trieste and INFN
On behalf of the Fermi/LAT collaboration

Outline

- **Gamma-ray Bursts**
  - **Brief introduction**
- **High energy emission from GRBs**
  - **The EGRET heritage**
  - **AGILE observations**
- **Fermi LAT and GRBs**
  - **The LAT**
  - **The first LAT GRB catalog**
  - **GRB 130427A**
  - **Towards the 2nd GRB catalog**



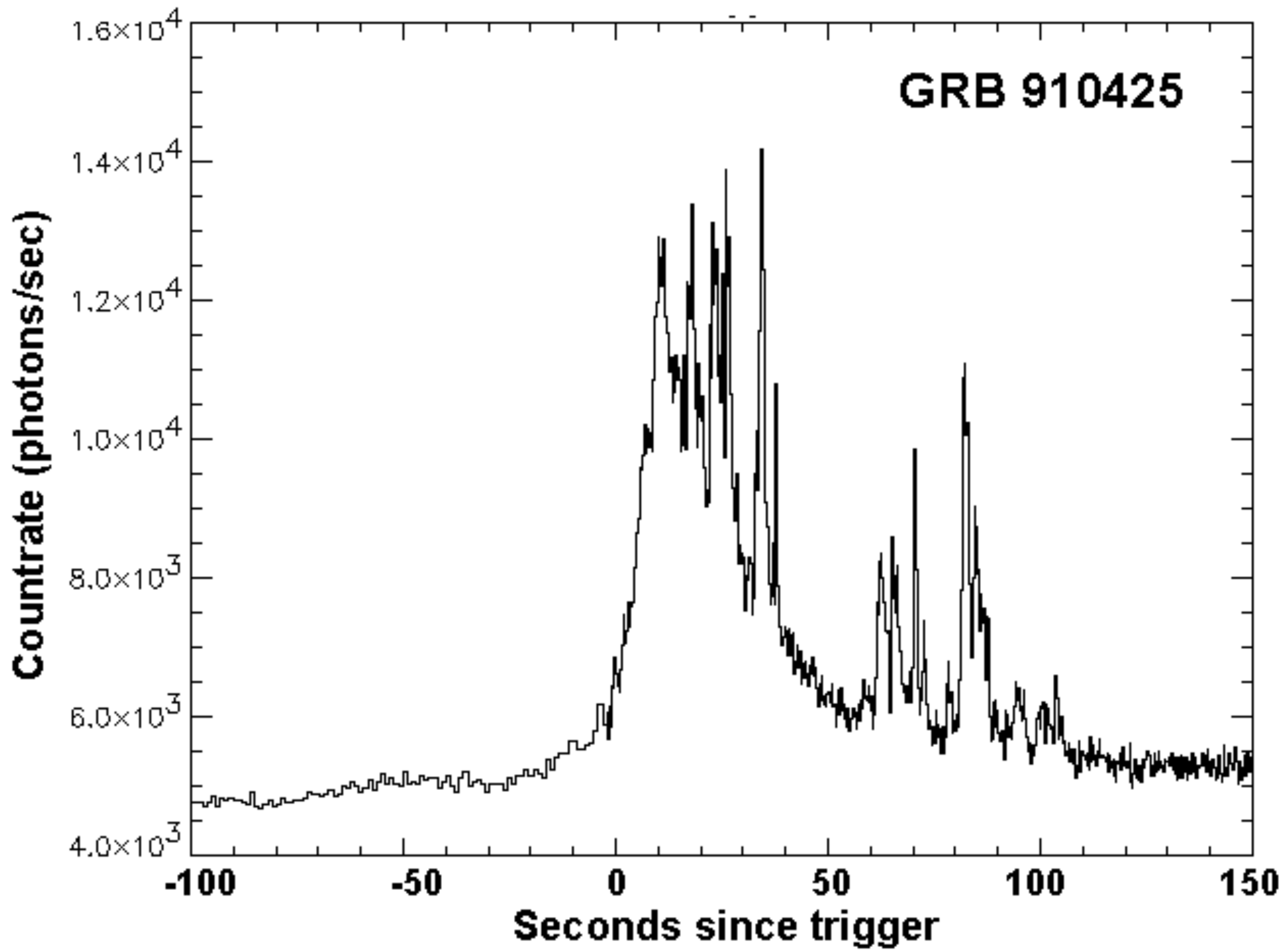
Mostly based on the papers:

Ackermann, M. et al. 2013, ApJS, 209, 11
Contact authors: N.Omodei, F.Piron, S.Razzaque, G.Vianello, V.Vasileiou

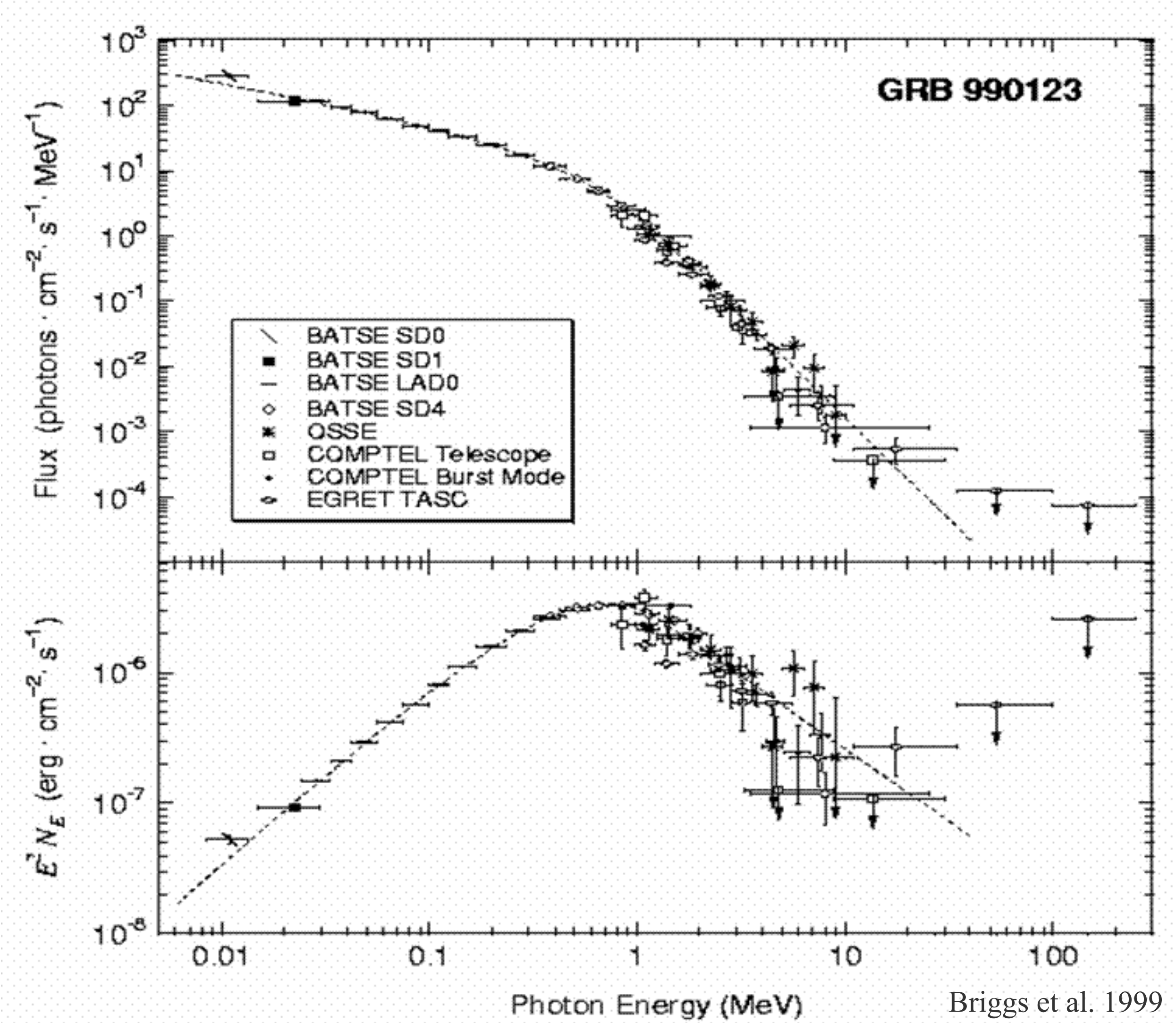
Ackermann, M. et al. 2014, Science, 343, 42
Contact authors: J.Chiang, C.Dermer, N.Omodei, G.Vianello, S.Xiong, S.Zhu

Gamma-ray Bursts

GRB – a very brief introduction



GRB – a very brief introduction



Briggs et al. 1999

GRB – a very brief introduction

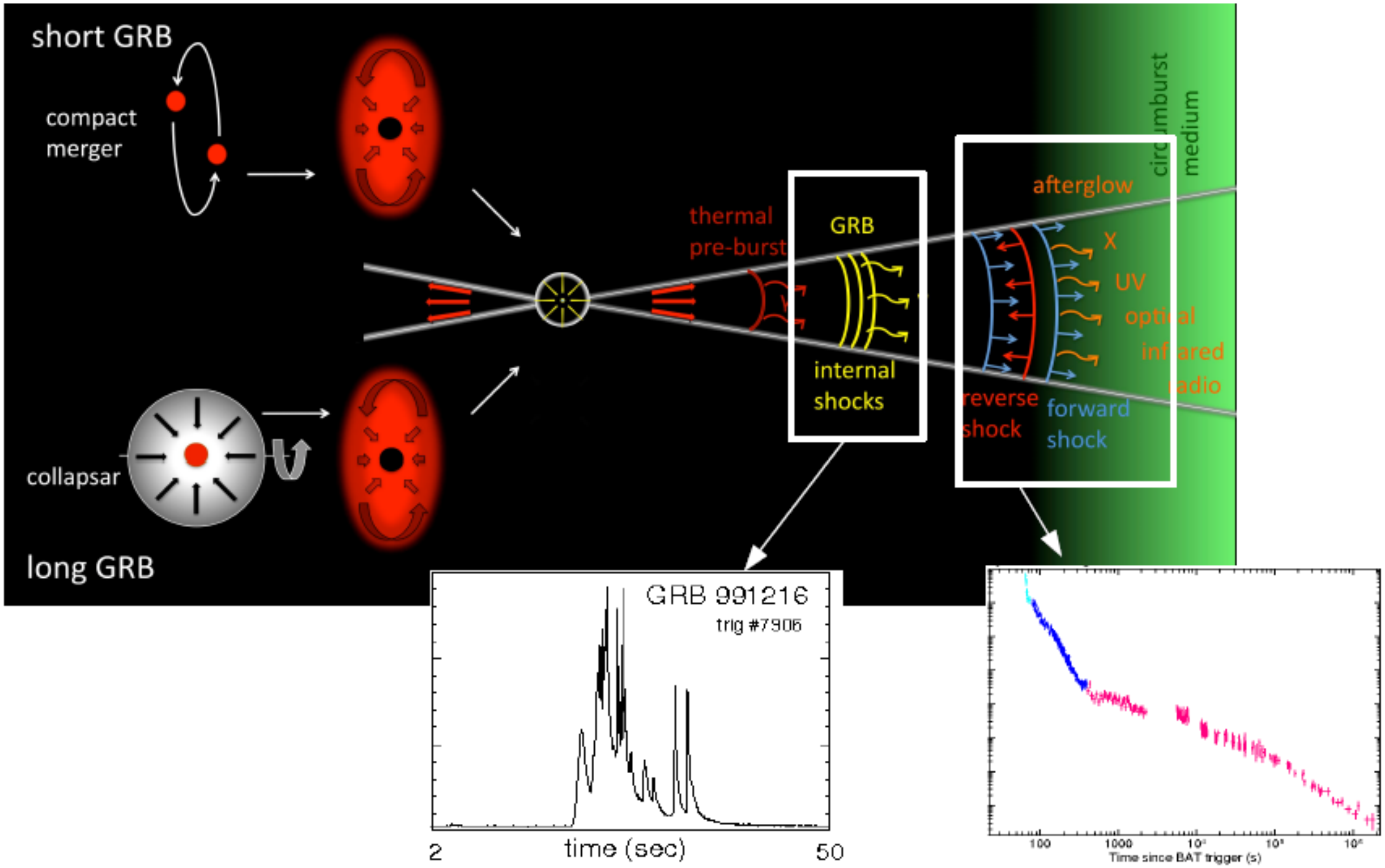


Diagram: arXiv:1206.3127 [astro-ph.HE]
BATSE light curve, GRB 991216
Swift light curve, GRB 100621A

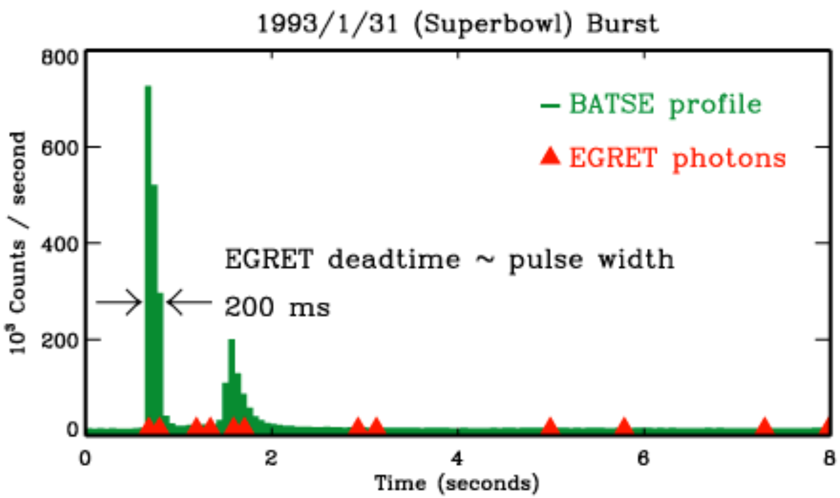
7

High Energy Emission from GRBs

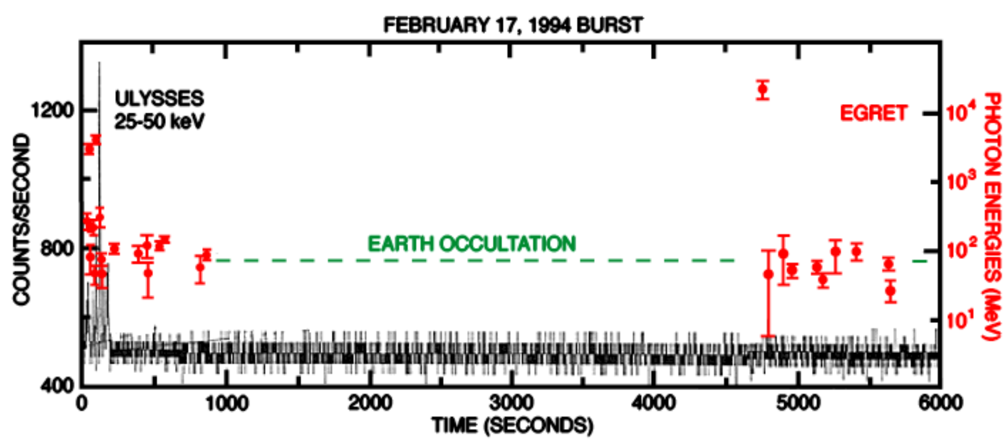
The EGRET heritage on GRBs

- **Need fast timing for gamma-ray detection (improving EGRET deadtime, 100 msec → 100 microsec or less).**

Prompt Emission (GRB 930131)

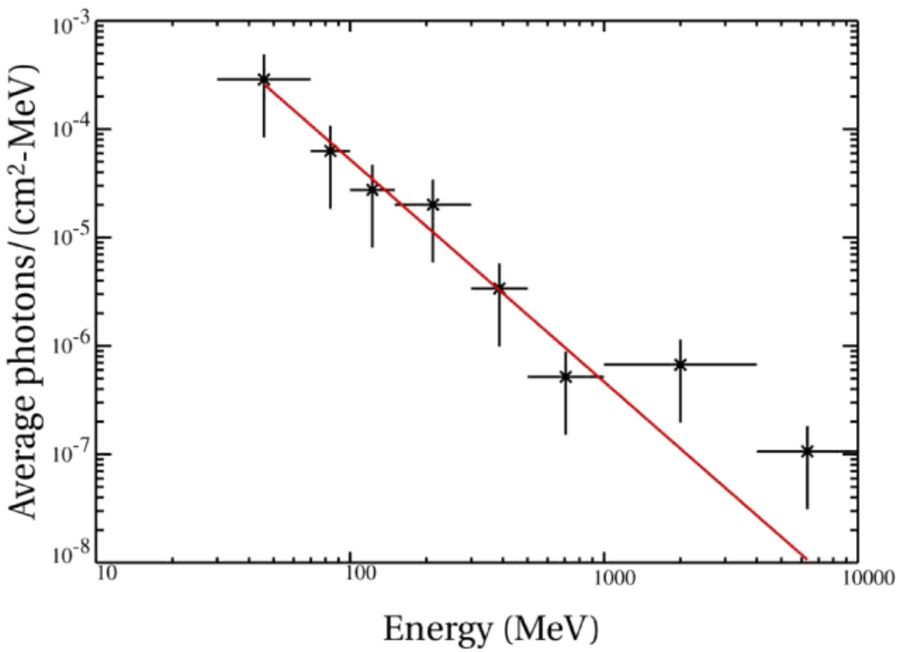


Delayed Emission (GRB 940217)

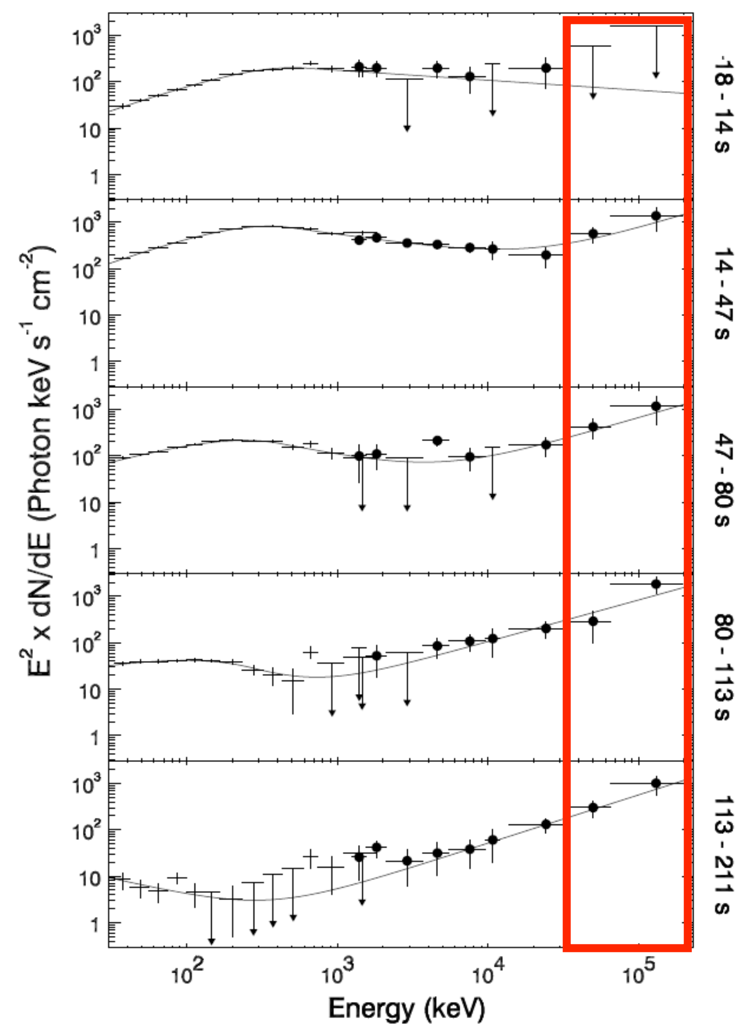


The EGRET heritage on GRBs

Sepctral extra components (GRB 941017)



Dingus et al. (1998)



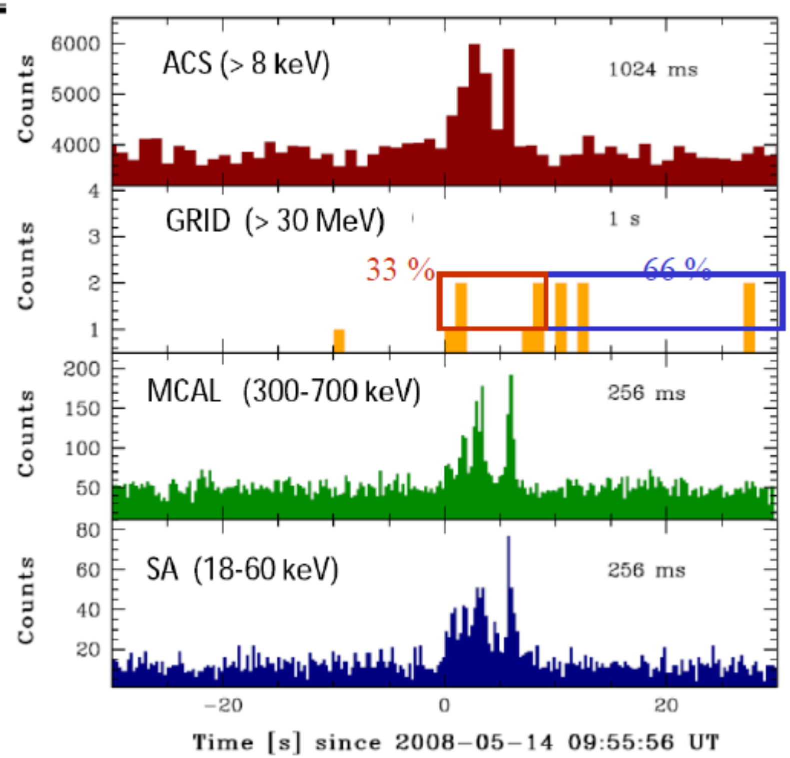
(Gonzalez et al 2004)

High Energy emission from EGRET

- **Extended emission?**
- **Prompt emission?**
- **Spectral Components?**
- **Ubiquity of HE emission?**

The AGILE telescope and GRBs

Gamma-ray extended emission in GRB 080514B

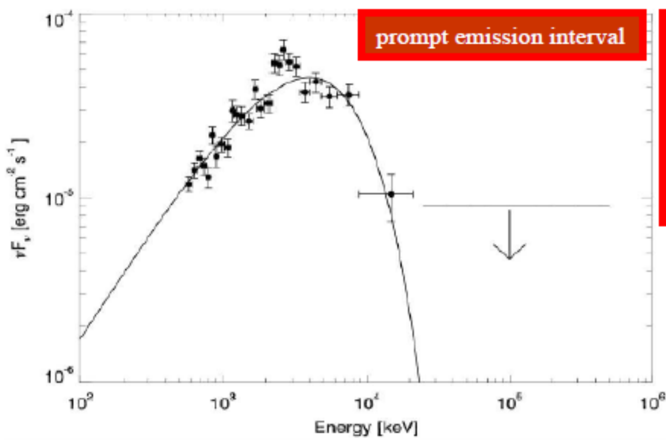


Giuliani et al., 2009, A&A, 491, L25 – L28

GRB 080514B is the first GeV-bright GRB after EGRET and it is also associated to an afterglow and a photometric redshift measure of 1.8 (A. Rossi et al., 2009, A&A).

The AGILE telescope and GRBs

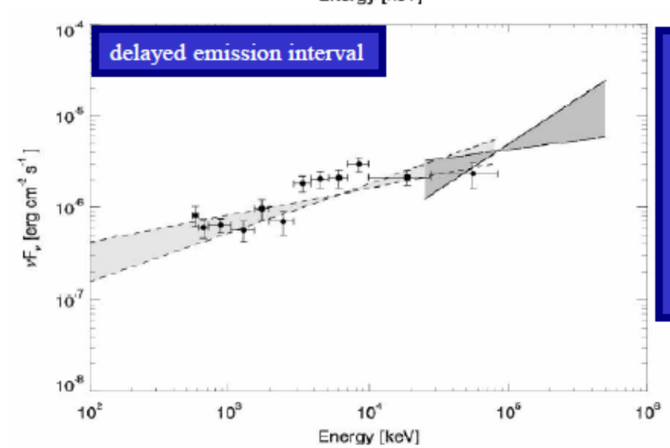
GRB 090510: spectral evolution in a short GRB



Powerlaw with cutoff

$\alpha_1 = 0.6 \pm 0.3$
Ec = 2.8 ± 0.9 MeV
1.8×10^{-5} erg/cm^2 (0.5 – 10 MeV)

Giuliani et al. 2010, ApJ, 708, L84 – L88



Powerlaw without cutoff

$\alpha_2 = 1.6 \pm 0.1$
3.1×10^{-6} erg/cm^2 (0.5 – 10 MeV)

$\alpha_3 = 1.4 \pm 0.4$
2.9×10^{-5} erg/cm^2 (25 – 500 MeV)

GRB with Fermi LAT

The Fermi Observatory

- Large Area Telescope (LAT)
  - Large field of view (2.4 sr @ 1 GeV)
  - Sees the entire sky every 3 hours
  - 20 MeV to >300 GeV
  - Onboard and ground burst triggers
  - Localization, spectroscopy

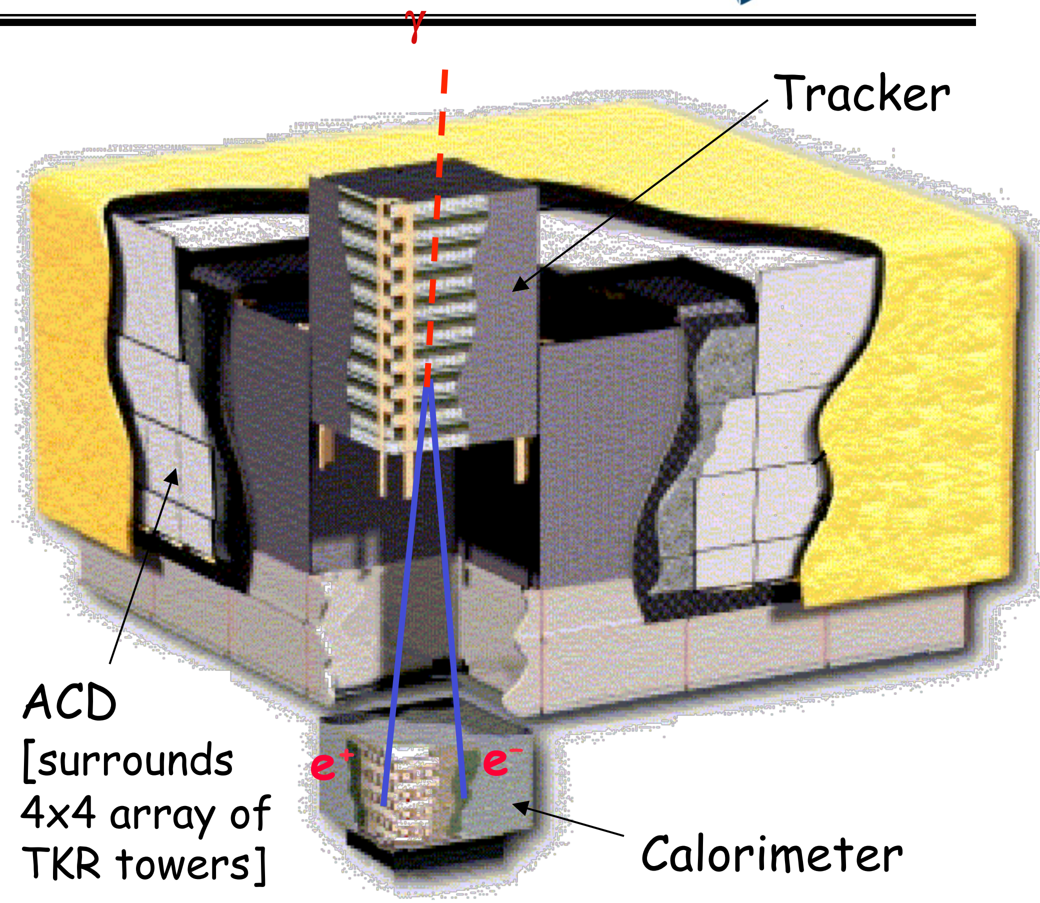
Atwood et al. 2009, ApJ 697, 1071

- Gamma-ray Burst Monitor (GBM)
  - Sees the entire unocculted sky (>9.5 sr)
  - 8 keV to 40 MeV
  - 12 NaI detectors (8 keV to 1 MeV)
    - Onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - Spectroscopy

Meegan et al. 2009, ApJ 702, 791

Overview of LAT

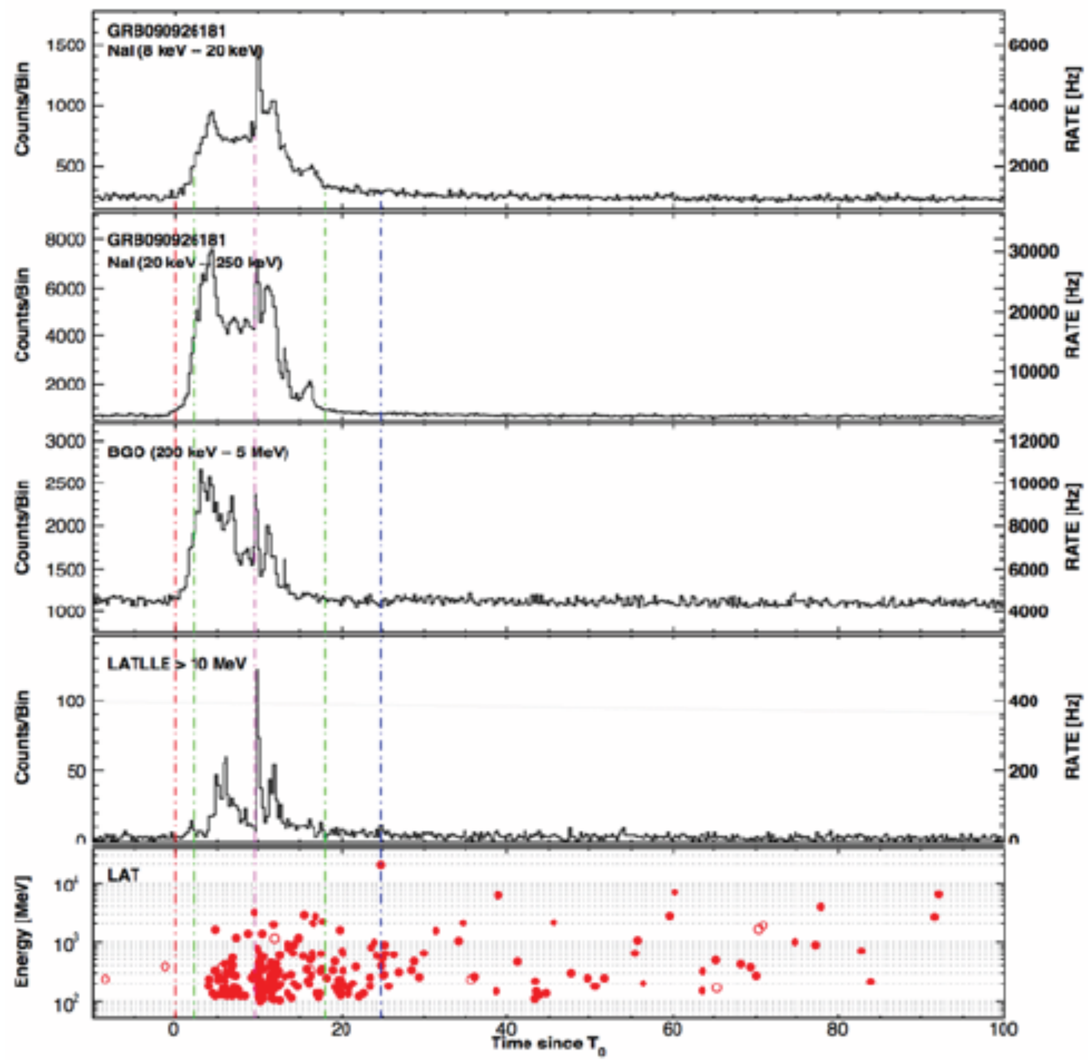
- **Precision Si-strip Tracker (TKR)**
  18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- **Hodoscopic CsI Calorimeter(CAL)**
  Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- **Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.**
- **Electronics System Includes flexible, robust hardware trigger and software filters.**



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

A “typical” bright GRB in Fermi

- Ackerman+11: correlated variability in various bands, with a sharp spike at T_0+10 s
  - All energy ranges synchronized (<50 ms)
  - Low and high energies are co-located or even causally correlated
- LAT >100 MeV emission is delayed (~4 s)
  - Delay > spike widths
- LAT >100 MeV emission is temporally extended, well after the GBM prompt phase
  - 19.6 GeV photon detected at T_0+24.8 s

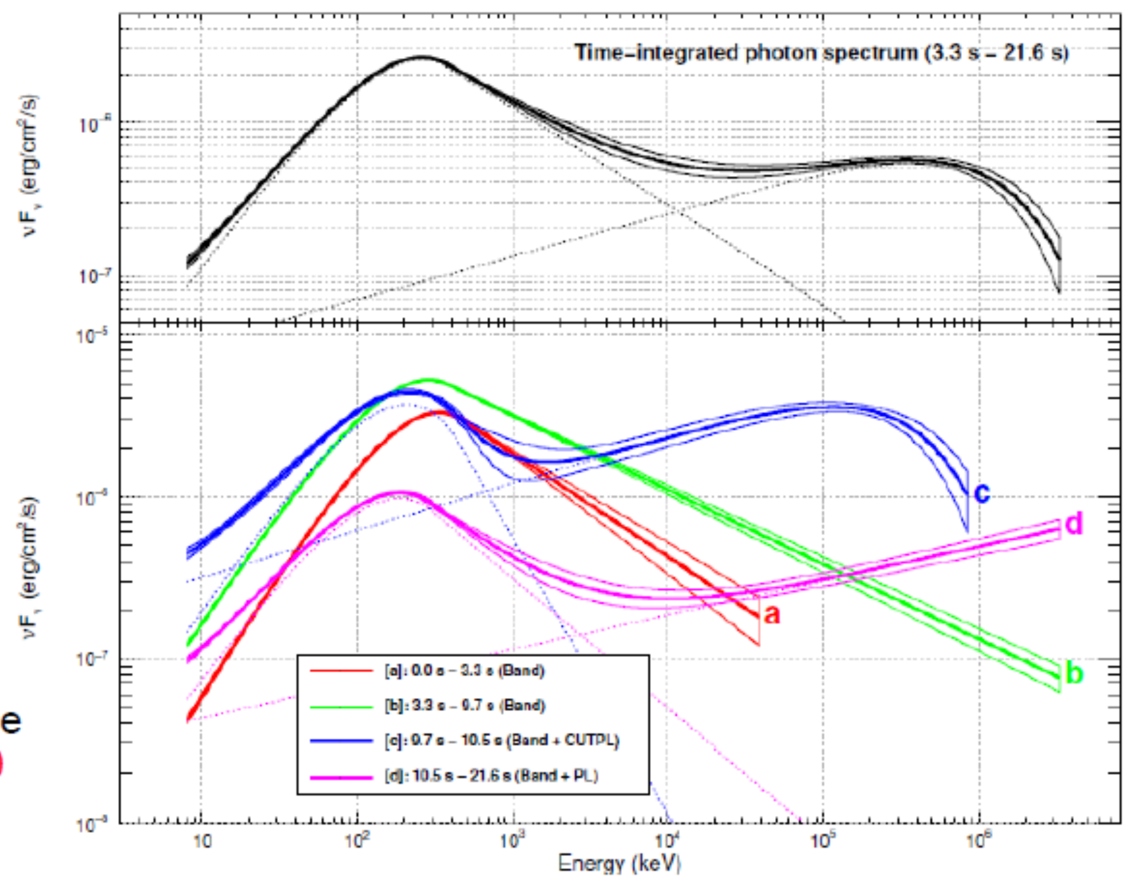


6

A “typical” bright GRB in Fermi

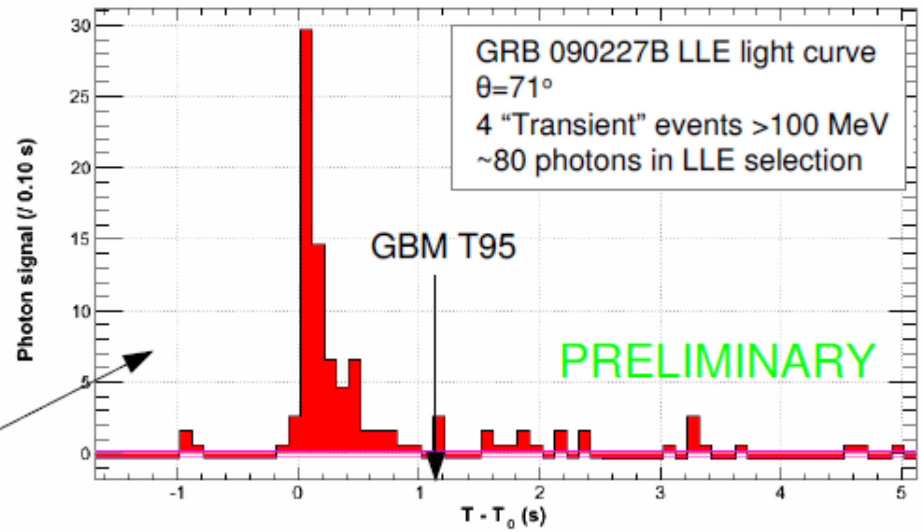
- Fluence = 2.2 x 10^{4} erg cm^{2} (10 keV - 10 GeV)
- E_{iso} = 2.2 x 10^{54} erg
- Extra component (power law)
  - Starts delayed (~9 s)
  - Persists at longer times
  - Dominates > 10 MeV
- Spectral cutoff
  - Significant in bin c, marginally in bin d
  - Shape not constrained
- First direct measurement of the jet Lorentz factor: Γ ~ 200-700
  - If cutoff due to γγ absorption
  - Model dependent

Ackermann et al. 2011, ApJ 729, 114

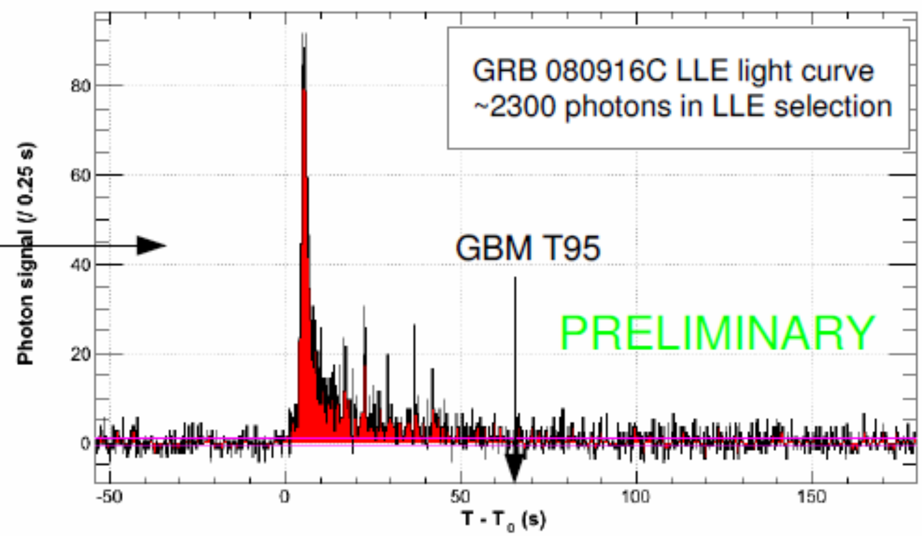


The LAT Low Energy (LLE) event class

- Most GRBs are detected using the standard event selection (Pass6_V3 "Transient") and analysis technique (unbinned maximum likelihood >100 MeV)
  - **Current "default" is Pass7REP. "Transient" selection for < 100 s. "Source" selection for > 100 s**
- Some other bursts are too weak, too soft, or at a too high off-axis angle to be significantly detected



- We introduced the LLE event class
  - Relaxed selection criteria → higher background, significantly higher effective area in the 10-100 MeV range and at larger off-axis angles
  - Worse PSF than transient class (no localization possible)



Fermi LLE

FERMILLE - Fermi LAT Low-Energy Events Catalog

Browse this table...

HEASARC Archive

Overview

LAT Low-Energy events (LLE) are automatically produced for each GBM GRB in the GBM Trigger Catalog if the GBM GRB has a position within 90 degrees of the LAT boresight. LLE data are generated for a given position in the sky (RA, DEC) and for a given interval of time (T0, T1) corresponding to the GBM Burst.

The standard LLE selection applied to the downloaded events is the following:

(FswGamState==0 && TkrNumTracks>0 && (GltEngine==6 || GltEngine==7) && EvtEnergyCorr > 0) && (FT1ZenithTheta<90.0) && (FT1Theta<=90.0) && (((cos(FT1Dec*0.0174533)*(FT1Ra - (RA)))^2 + (FT1Dec - (DEC))^2) < PSF(EvtEnergyCorr, Theta)

where

- FswGamState is the status of the Flight Sofware Gamma filter. We require that the event is a gamma-ray (FswGamState==0).
- TkrNumTracks is the number of tracks in the tracker. We require that there is at least one track. This requires the event to have a reconstructed direction.
- GltEngine is the status of the Global LAT Trigger. We require that GltEngine equals 6 or 7, which corresponds to taking all the events that trigger in the tracker TKR but did not have a region of interest (ROI) associated (GltEngine 7) or all the events that pass the CalHI (at least 1 GeV in one crystal).
- EvtEnergyCorr is the best estimation of the reconstructed energy, especially at low energy.
- Theta is the reconstructed source direction (Theta) with respect the LAT boresight.
- PSF(EvtEnergyCorr, Theta) represents the functional form of the containment radius of the Point Spread Function (PSF) of the LAT.

The exact cut used to select the events is saved in the keyword LLECUT in the primary header of each LLE file. If the GBM catalog position of the burst is updated (due to a refined localization from LAT or Swift or from subsequent on ground analysis), the LLE data are automatically updated and new versions of the LLE files are produced. In some cases, LLE data are manually generated (using a better localization which may or may not have been used in the GBM Trigger Catalog). For each updated position, the version of the corresponding LLE files increases by one.

There are six FITS files provided for each entry: the LLE event file, the time-binned spectrum (CSPEC) file, the CSPEC response (RSP) file, and the extracted burst spectrum (the PHA-I file) for the entire duration of the burst, an LLE event file with same time cut as the RSP and PHA-I files, and a LAT pointing and livetime history file.

There are six FITS files provided for each entry: the LLE event file (gll_lle_bnNNNNNNNNN_vMM.fit), the time-binned spectrum (CSPEC) file (gll_cspec_bnNNNNNNNNN_vMM.pha), the CSPEC response (RSP) file (gll_cspec _bnNNNNNNNNN_vMM.rsp), and the extracted burst spectrum (the PHA-I file) for the entire duration of the burst (gll_pha_bnNNNNNNNNN_vMM.fit), an LLE event file with same time cut as the RSP and PHA-I files (gll_selected_bnNNNNNNNNN_vMM.fit), and a LAT pointing and livetime history file (gll_pt_bnNNNNNNNNN_vMM.fit).

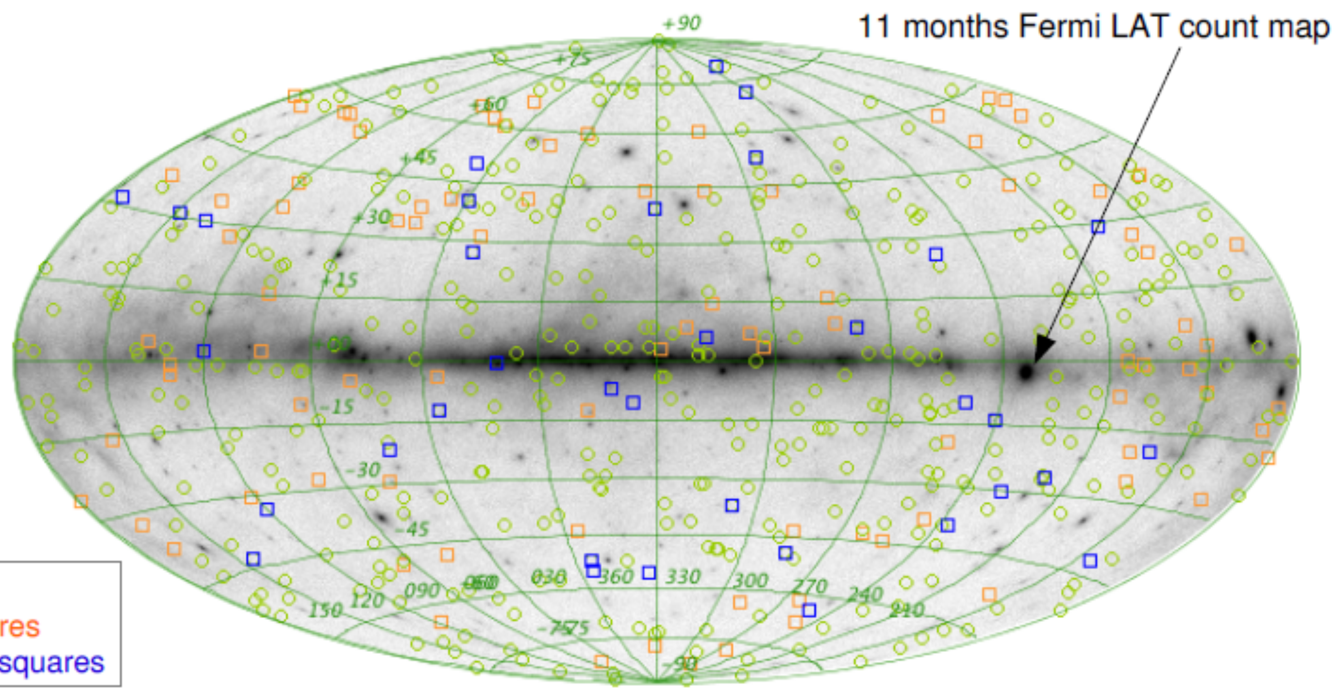
http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html

The Fermi/LAT GRB catalog

- Systematic study of GRB properties at high energies (>10 MeV)
- Covers a 3-year period starting from August 2008, including:
  - Tabulated GRB parameters
    - Start / end times, duration, fluence, energetics, average and peak fluxes, time of the peak flux, temporal decay slope, spectral evolution
    - Spectral analysis results (from GBM+LAT joint fits)
  - Discussions on the unique properties of individual bursts (presence of extra spectral components and of high-energy spectral cutoffs)
  - Details on the analysis: methodology, tools, methods and caveats
- Ackermann, M. et al. 2013, ApJS, 209, 11

The GRB catalog

GBM 2-year catalog
LAT 3-year catalog

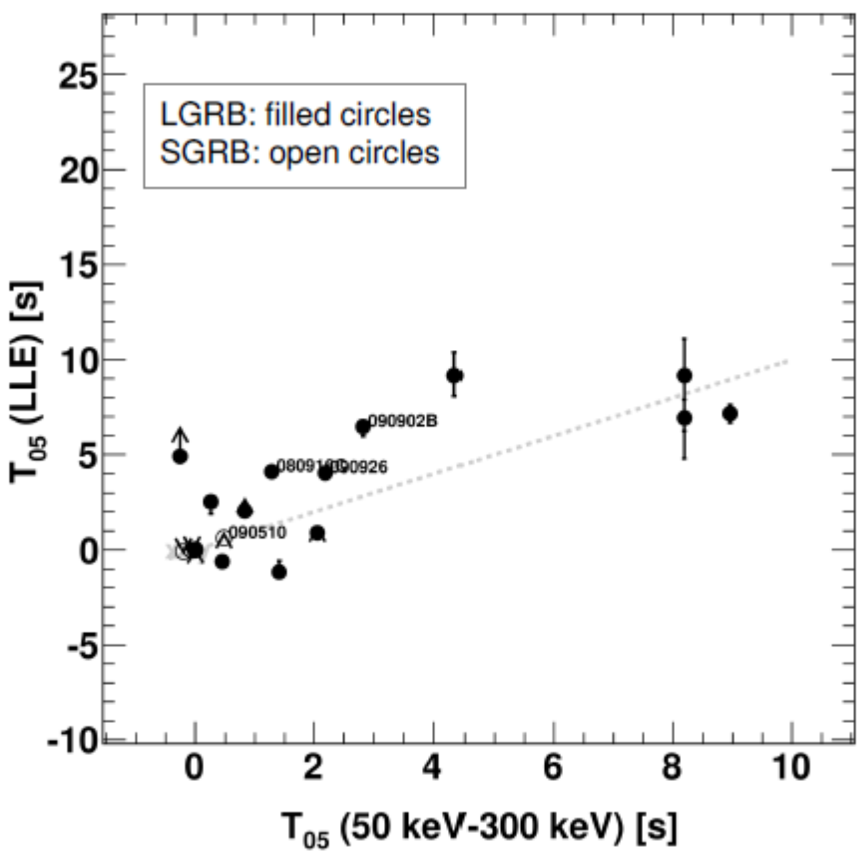


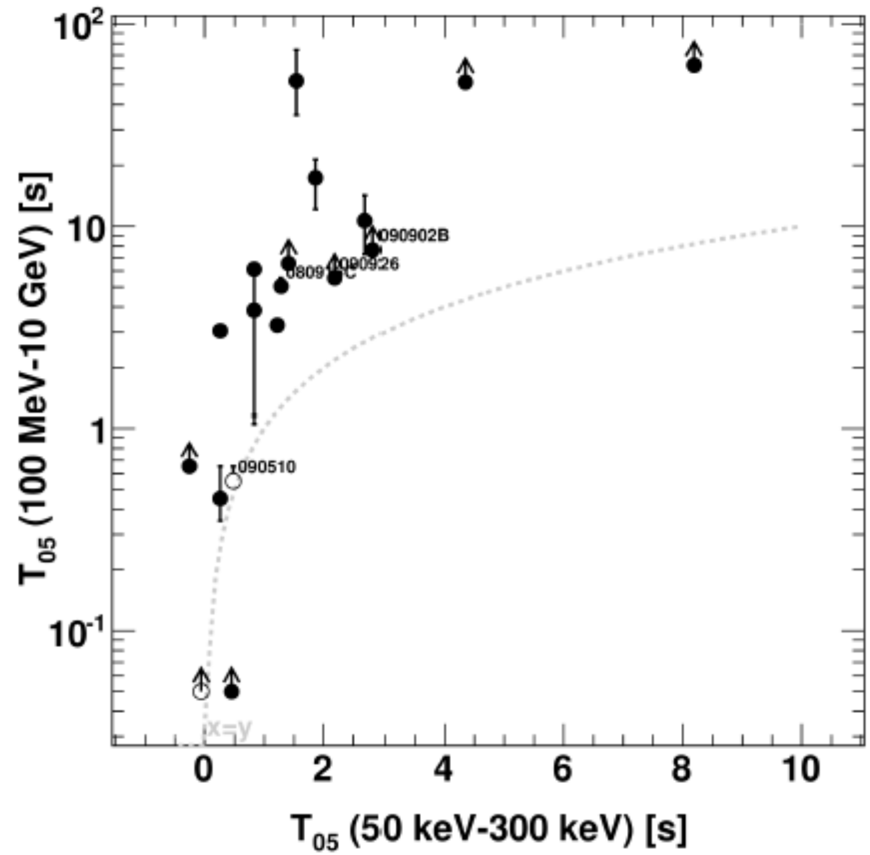
GBM LGRB: green circles
GBM SGRB: orange squares
LAT detections (35): blue squares

- The GBM detects ~250 GRBs / year, ~half in the LAT FoV
  Paciesas et al. 2012, ApJS 199, 18; Goldstein et al. 2012, ApJS 199, 19
- The LAT detected 35 GRBs in 3 years (30 long, 5 short), including 7 “LLE-only” GRBs
  - Bright LAT bursts with good localizations are all followed-up by Swift
  - 10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)
  - 4 joint BAT-GBM-LAT detections: GRBs 090510, 100728A, 110625A, 110731A

Delayed onset of >100 MeV photons

- GBM T_{05} vs. LLE T_{05}: onset of LLE emission is compatible with GBM
- GBM T_{05} vs. LAT T_{05}: LAT >100 MeV emission is systematically delayed

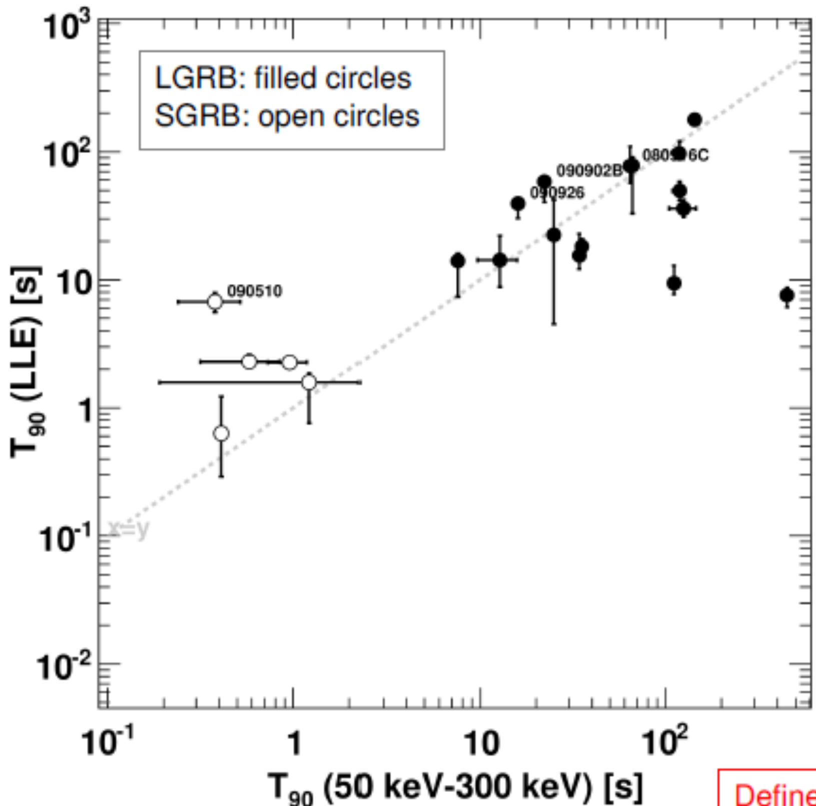


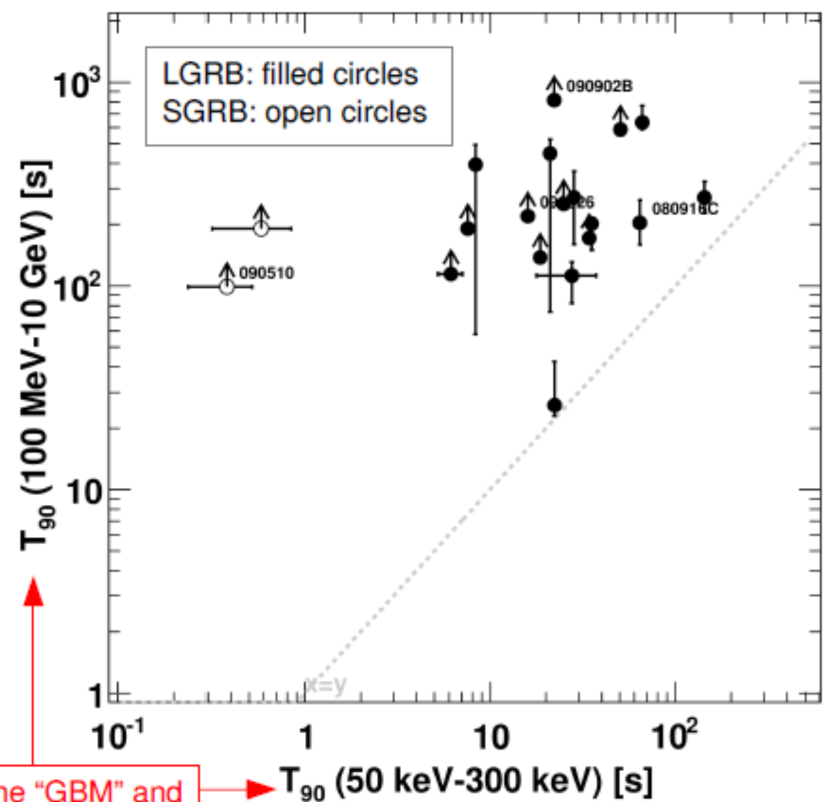


Temporally extended emission of > 100 MeV component

- GBM T_{90} vs. LLE T_{90}: duration of LLE emission is compatible with GBM
- GBM T_{90} vs. LAT T_{90}: LAT >100 MeV emission lasts systematically longer

Different components? Caveat: different sensitivities and S/N ratios between GBM, LLE and LAT >100 MeV





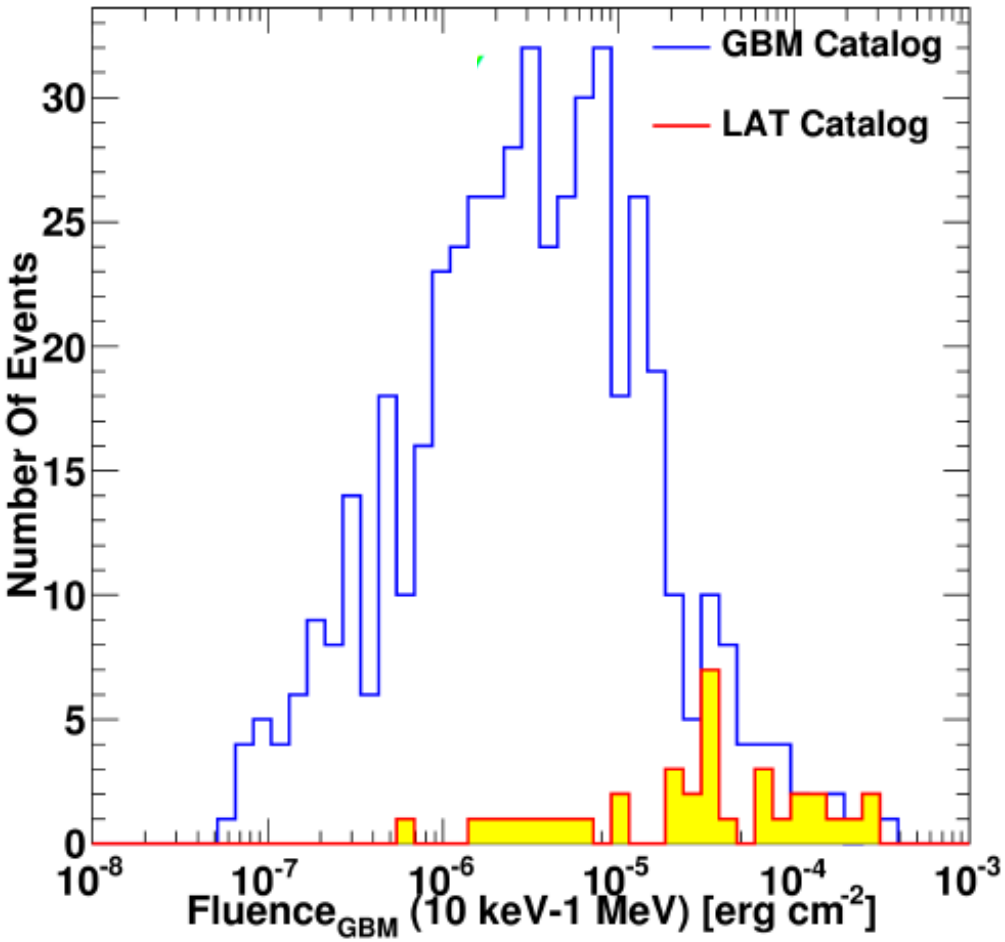
Define the "GBM" and "LAT" time windows

Band model "crisis"

- GBM+LAT joint spectral fits during "GBM" time window
  - Photospheric emission component (seen in a couple of *Fermi* bursts so far) not included in the catalog spectral fits
- The (phenomenological) Band function does not capture all features in the data
  - Note: extra PL detected in GRB 080916C spectrum (better bkg estimation and response matrices than in the 1st paper)
- Broad-band physical models are needed

Fluence 10 keV - 10 GeV (10^{-7} erg/cm^2)	Best model
4665^{-76}_{+78}	Band with exponential cutoff
4058^{-24}_{+25}	Comptonized + Power law
2225^{-48}_{+50}	Band + Power law with exponential cutoff
1795^{-39}_{+41}	Band + Power law
1528^{-44}_{+44}	Band
1293^{-27}_{+28}	Comptonized
1098^{-27}_{+35}	Comptonized + Power law
927^{-16}_{+17}	Logarithmic parabola
876^{-28}_{+28}	Logarithmic parabola
817^{-33}_{+34}	Band
638^{-25}_{+26}	Band
518^{-27}_{+28}	Band
517^{-20}_{+21}	Band
512^{-15}_{+16}	Band
461^{-14}_{+15}	Band
422^{-22}_{+23}	Band
417^{-37}_{+47}	Comptonized
379^{-21}_{+20}	Band + Power law
360^{-16}_{+18}	Band + Power law

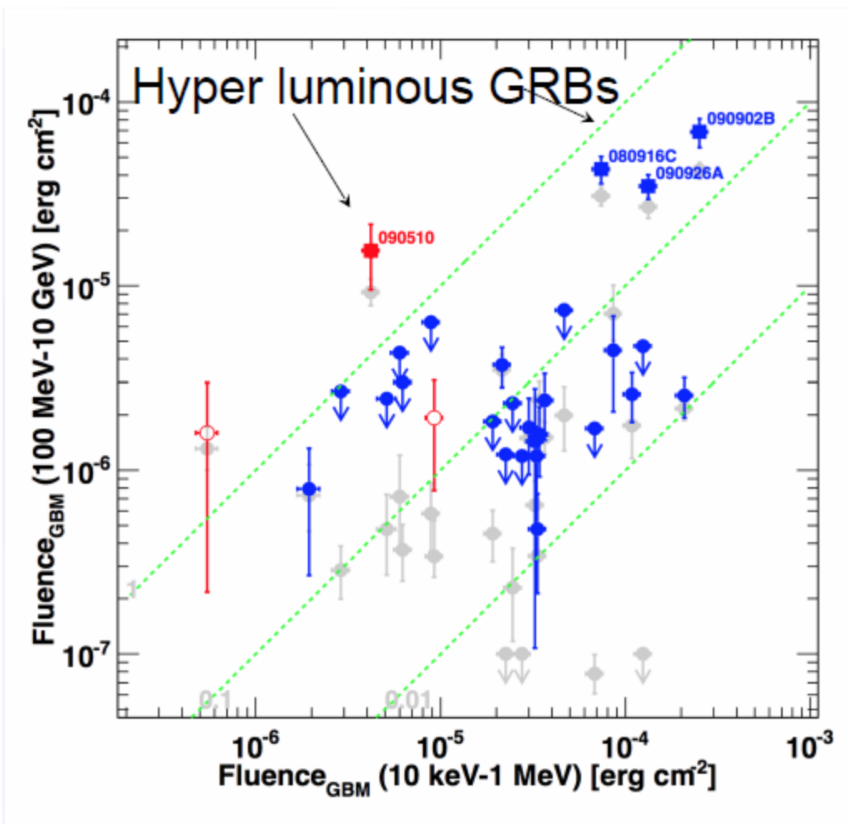
< 1 MeV of LAT GRB

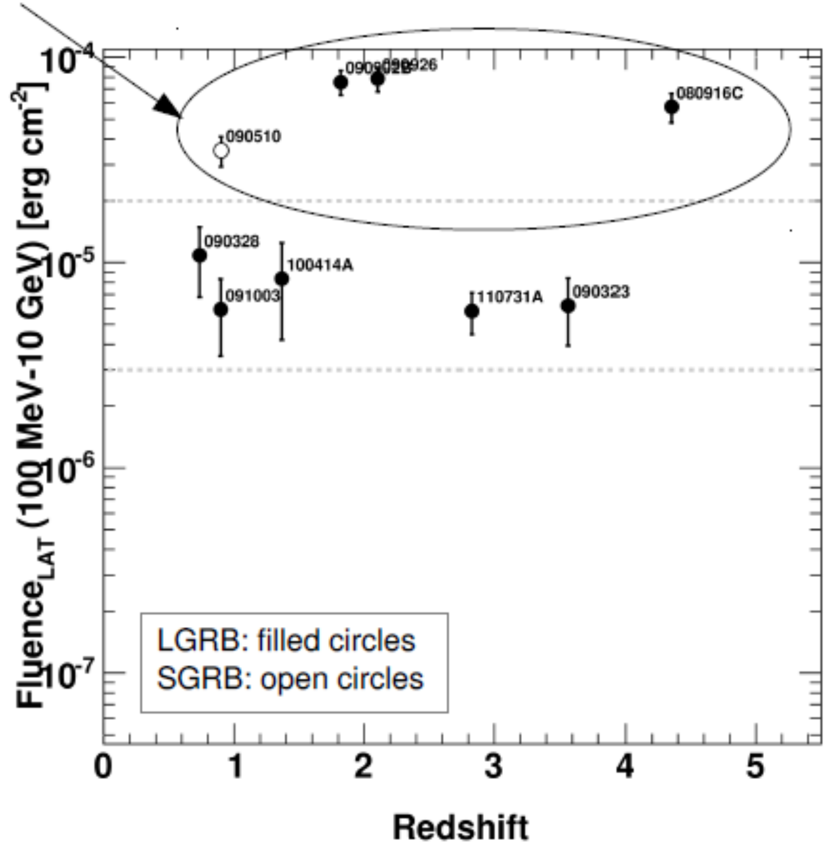


- Fluence in GBM energy range and "GBM" time window
  - LAT bursts vs. entire sample in GBM spectral catalog (Goldstein et al. 2012)
- Not surprisingly, LAT bursts are among the brightest GBM bursts
  - Selection effects (autonomous repointings) are possible though

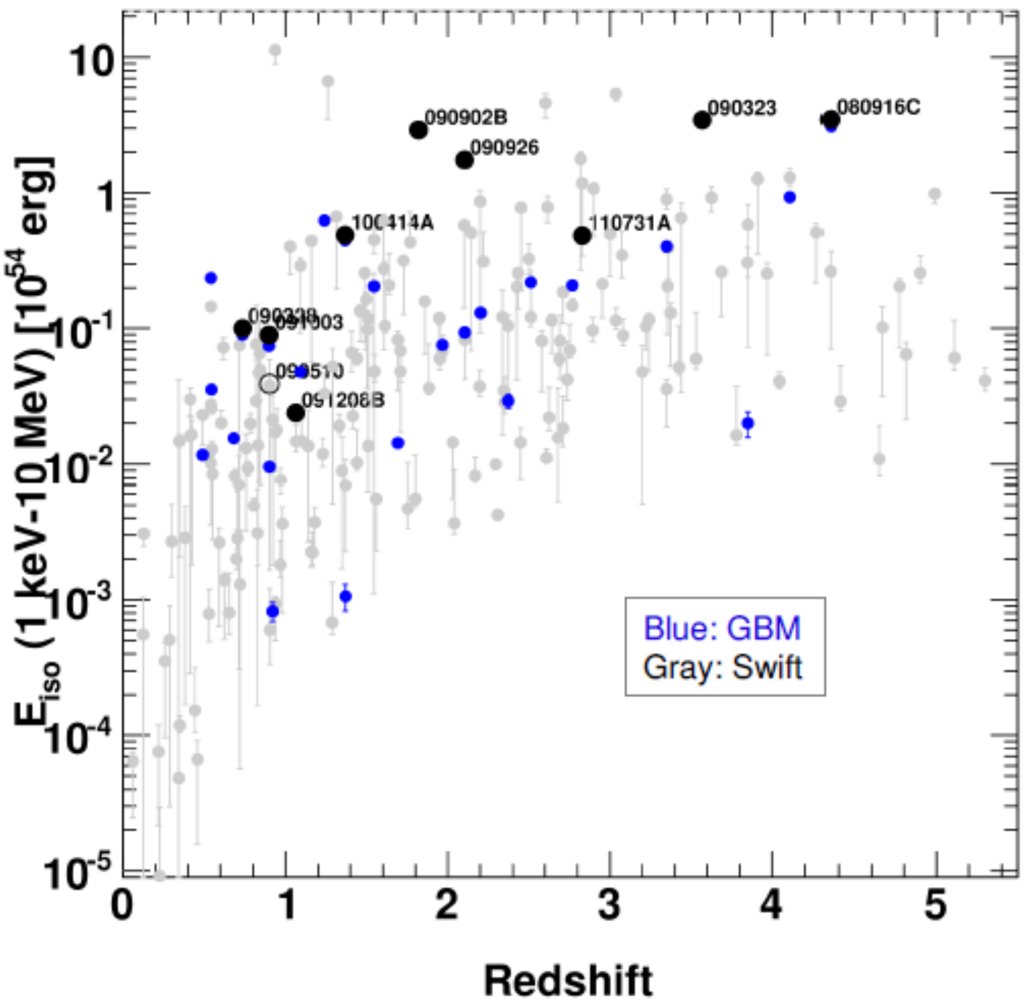
GBM and LAT fluence

- GBM and LAT fluences computed in “GBM” and “LAT” time windows, respectively
  - Short GRBs (LAT fluence > GBM fluence) are harder than long GRBs (LAT/GBM fluence ~10%)
- A hyper-energetic class of long bursts? GRBs 080916C, 090902B, 090926A are exceptionally bright
  - They do <u>not</u> appear bright because they are systematically closer to us





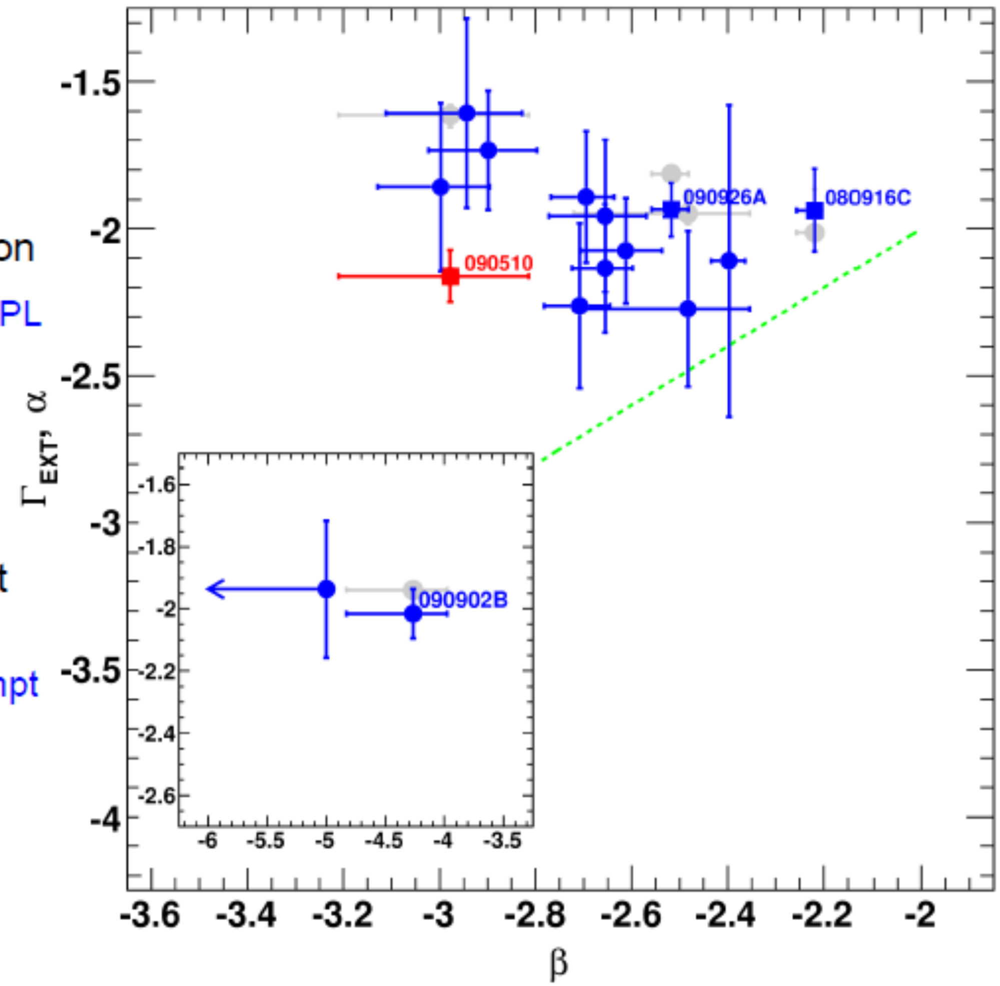
Energetics



- E_{iso} (1 keV - 10 MeV) in "GBM" time window vs. redshift
  - LAT bursts vs. GBM (Goldstein et al. 2012) and Swift (Butler et al. 2007) samples
- LAT bursts are among the most energetic bursts
  - Intrinsically and observationally
- GRB 090510 is also one of the most energetic short bursts
- No particular trend in redshift (small sample)

Extended and Prompt Spectra

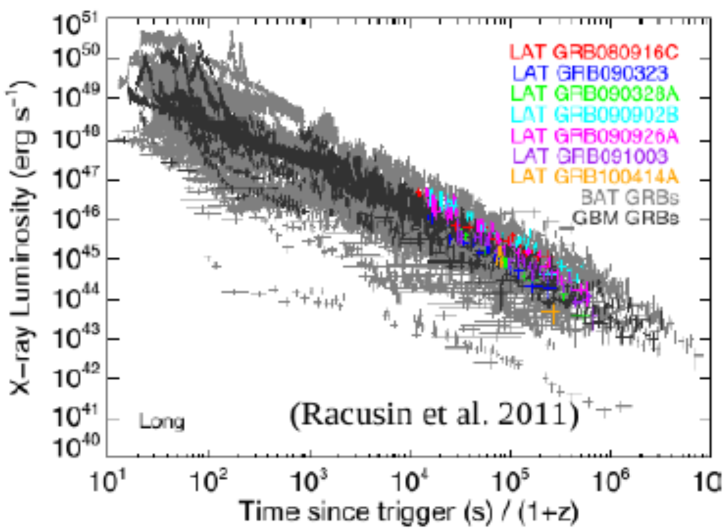
- $\beta=\beta_{BAND}$ here: spectral index of Band function in the prompt phase
- Γ_{EXT} : spectral index of extended emission
  - α (grey points): spectral index of extra PL from GBM-LAT joint fit in the prompt phase
- Prompt and extended phase spectra not correlated
  - Stronger spectral variability in the prompt phase

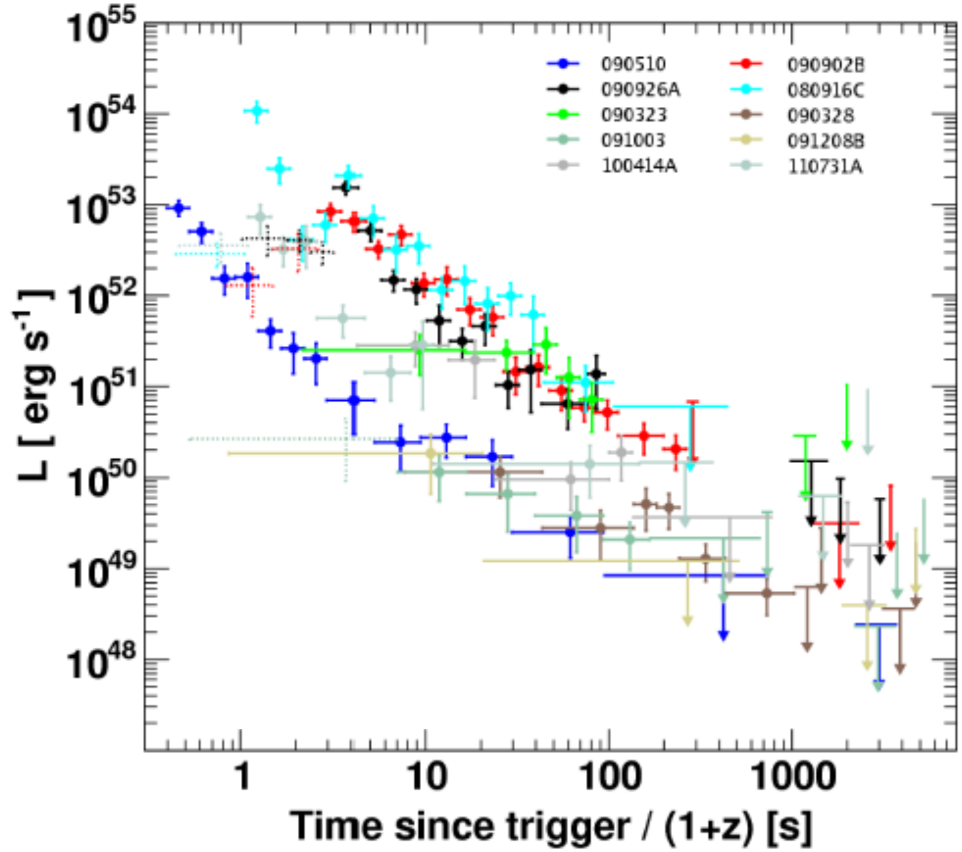


Afterglow of LAT GRB

- Photon spectral index is constant and typically averages around $\Gamma_{EXT} \sim -2$ (previous slide)
- Rest-frame luminosity (100 MeV – 10 GeV) in the afterglow phase: $L(E,t) \sim t^{-\alpha}E^{-\beta}$

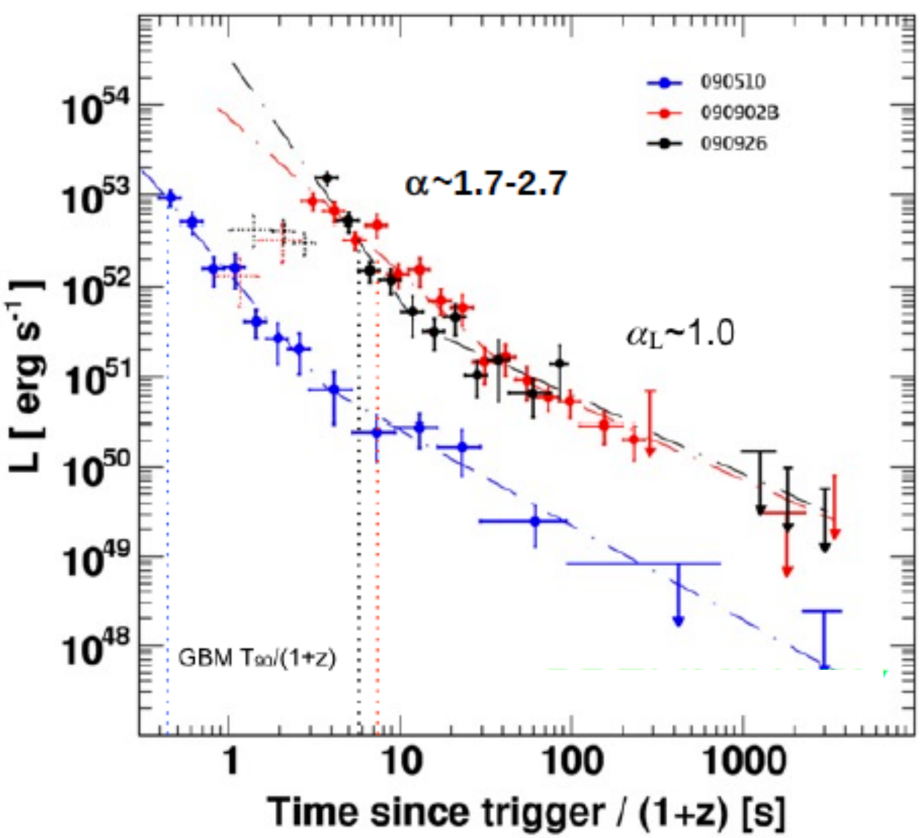
  $\beta=-\Gamma_{EXT}-1=1$, $\alpha=1$ for an adiabatic fireball in a constant density environment (10/7 if radiative)

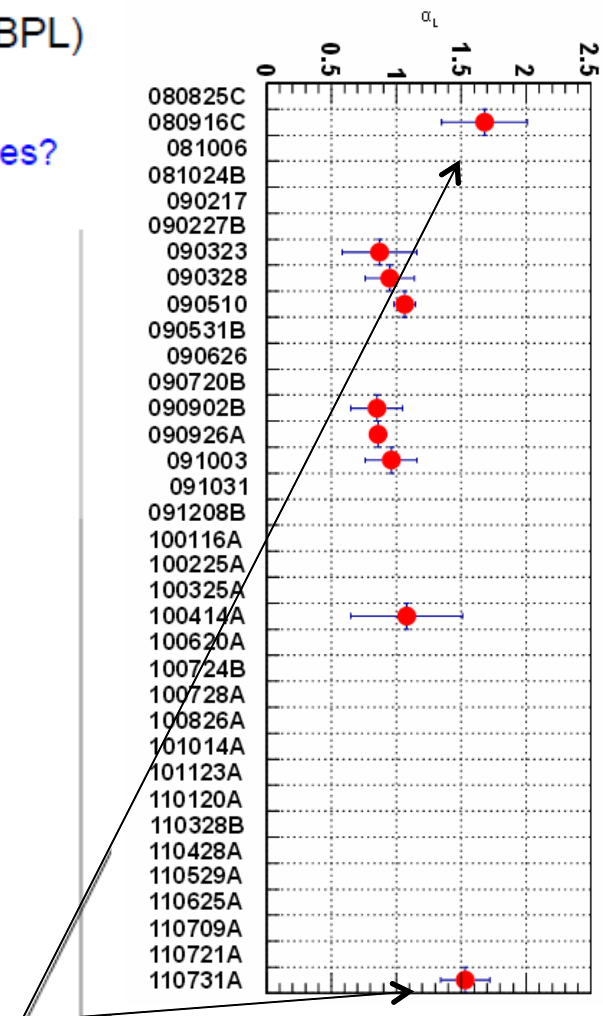




Decay of High energy flux

- Light curves fitted with a simple or a broken power law (BPL)
- BPL significant in 3 cases (chance probability < 10^{-3})
  - Transition between prompt- and afterglow-dominated phases?
- α_L ~ 1 at late times → adiabatic fireball

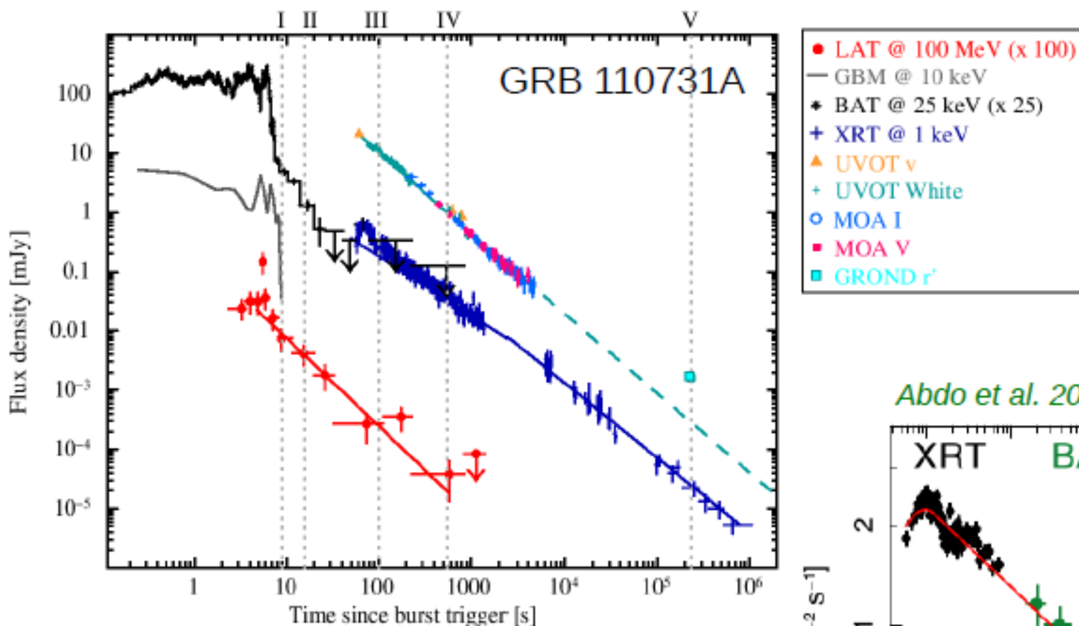




- 2 outliers: break not detected? (Both have the shortest detected emission in the rest frame)

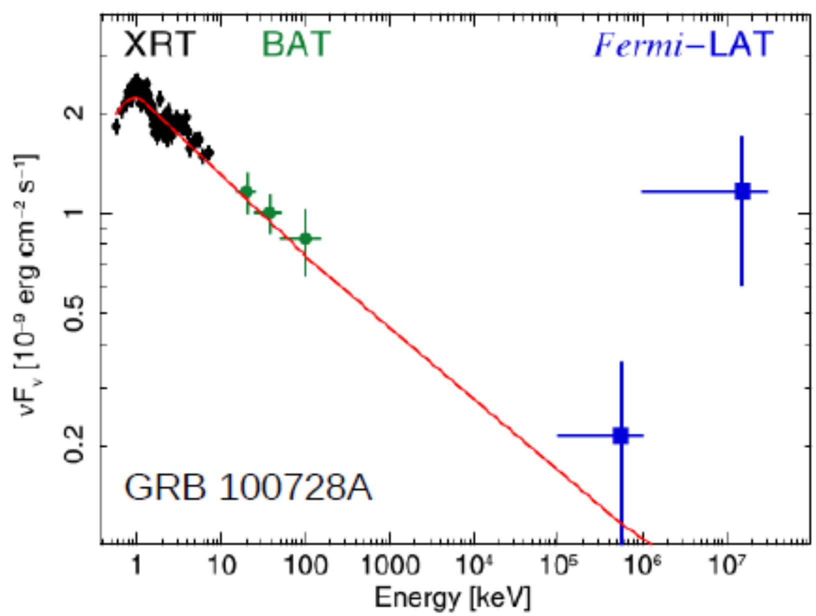
Swift and Fermi GRB

Ackermann et al. 2013, ApJ 763, 71



- GRB 110731A long-lived GeV emission from forward shock
  - Onset time <T_0+8 s (possible contamination from IS)
  - Γ~500 compatible with the value derived from the cutoff seen in the prompt emission spectrum (P~3x10^{-4})

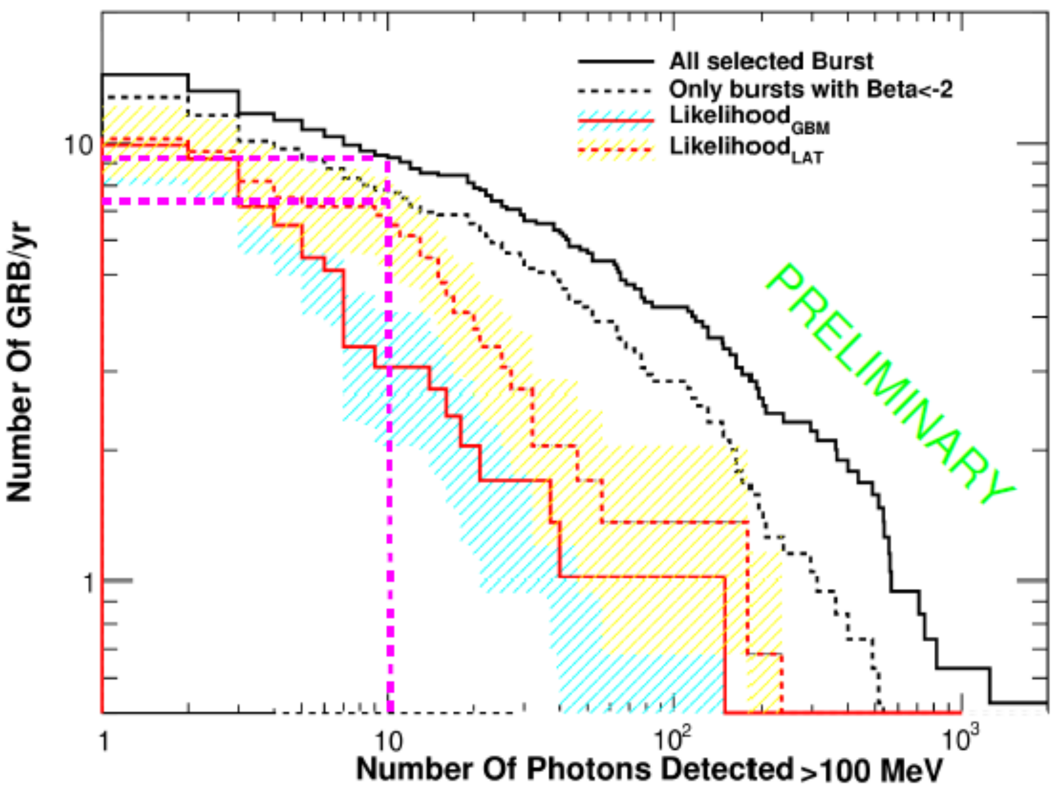
Abdo et al. 2011, ApJ 734, L27



- GRB 100728A was detected during X-ray flaring activity only
  - Spectrum compatible with same PL from X rays to gamma rays, modeled with internal shocks

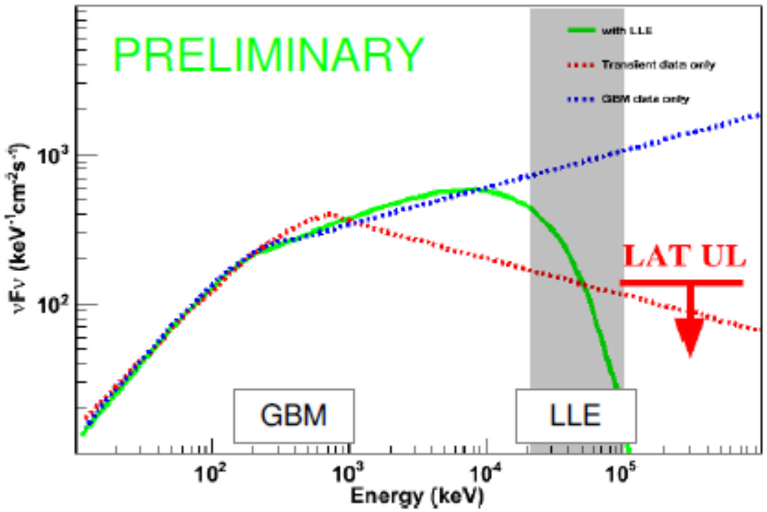
GRB rate at High Energy

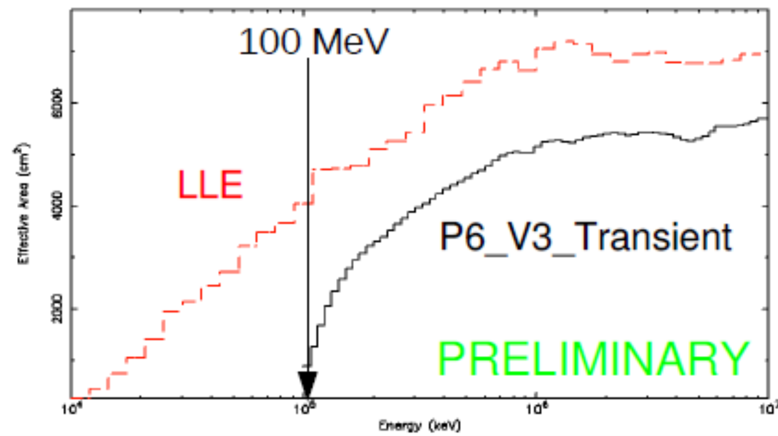
- Pre-launch estimates (Band et al. 2009):
  - 9.3 GRBs expected / year >100 MeV with >10 photons
- Number of “predicted” photons from likelihood fit (“GBM” and “LAT” time windows)
  - 6.3 GRBs observed / year >100 MeV with >10 photons

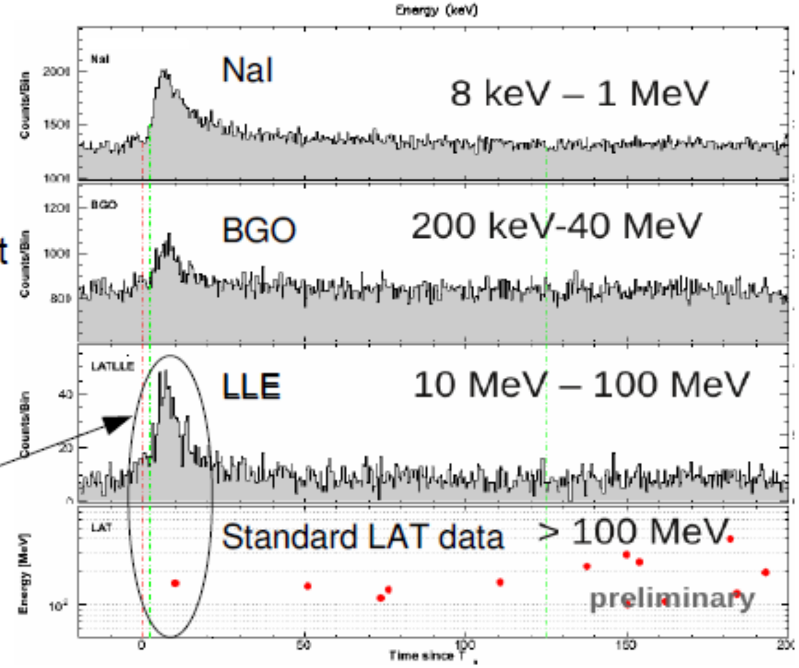


- Fewer GRBs than anticipated
  - Although both analyses have their own systematic uncertainties
- Extra PL components must be rare
- Is the high-energy emission suppressed?
  - Like for GRB 090926A

Spectral cutoffs at LE?





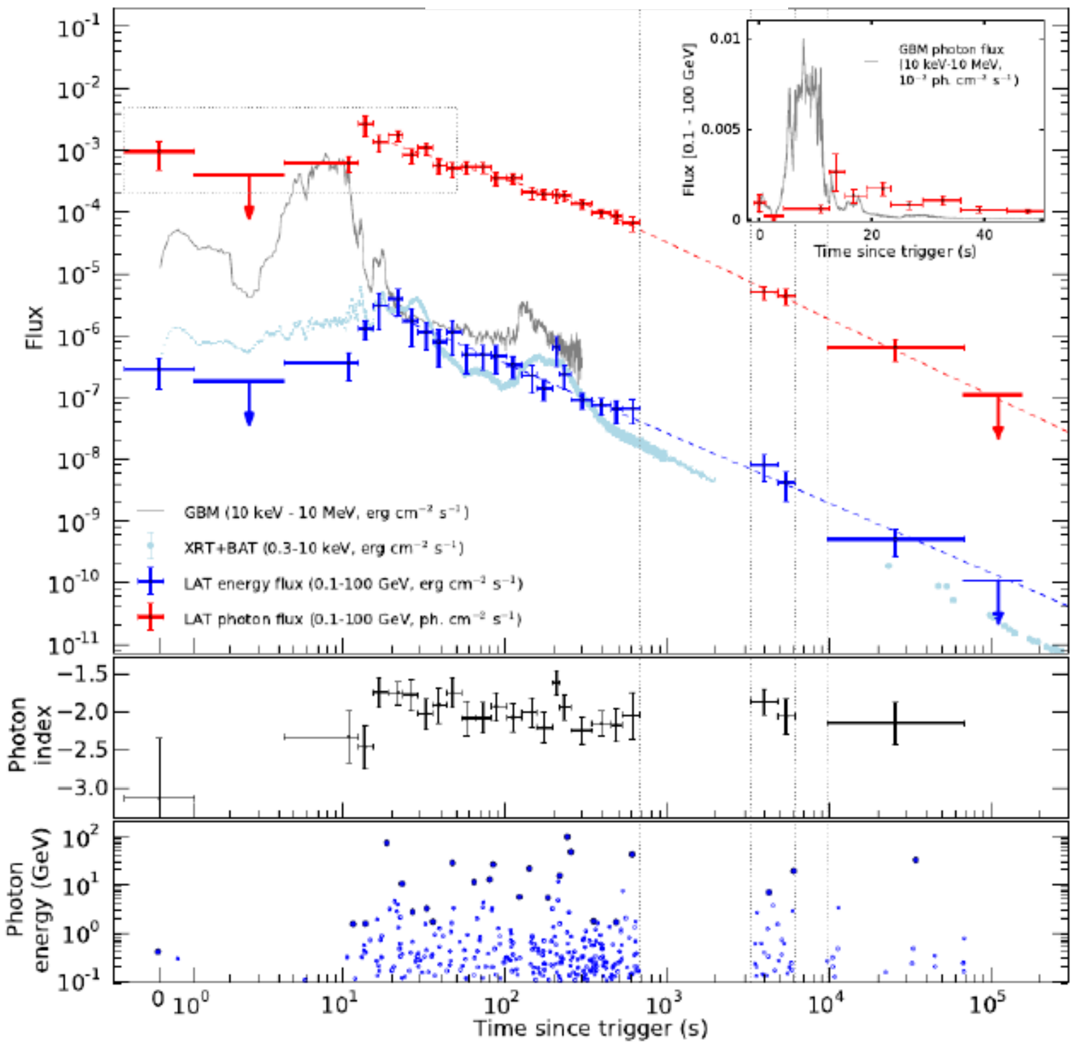


- Standard LAT "Transient" selection runs out of effective area below 100 MeV
- The LLE event selection provides plenty of statistics to probe GRB spectral cutoffs in the 10-100 MeV energy range

http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html

GRB 130427A

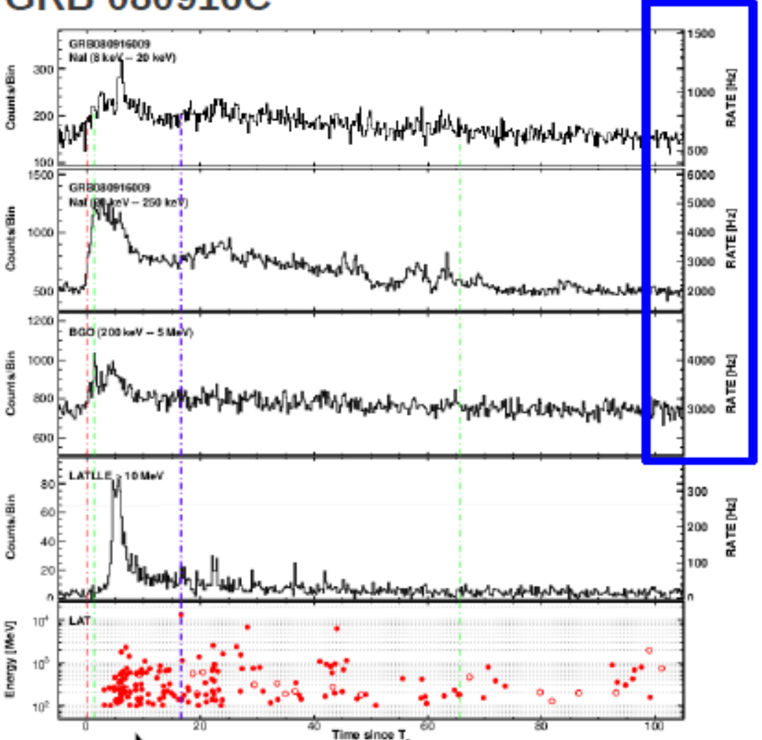
GRB 130427A



(Ackermann et al., Science, Vol. 343 no. 6166 pp. 42-47)

GRB 130427A

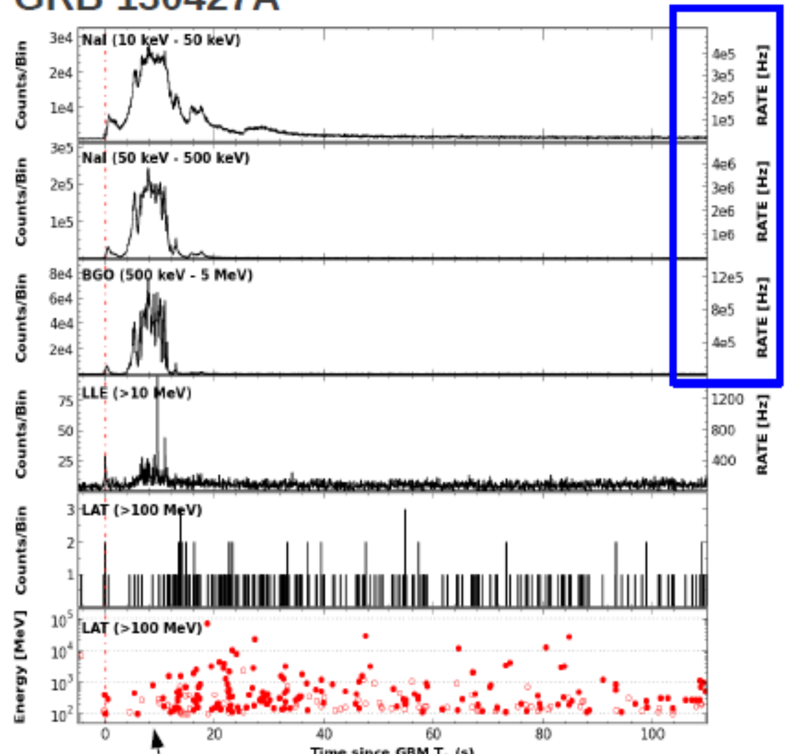
GRB 080916C



LAT emission dying down

LAT and GBM are bright at the same time

GRB 130427A

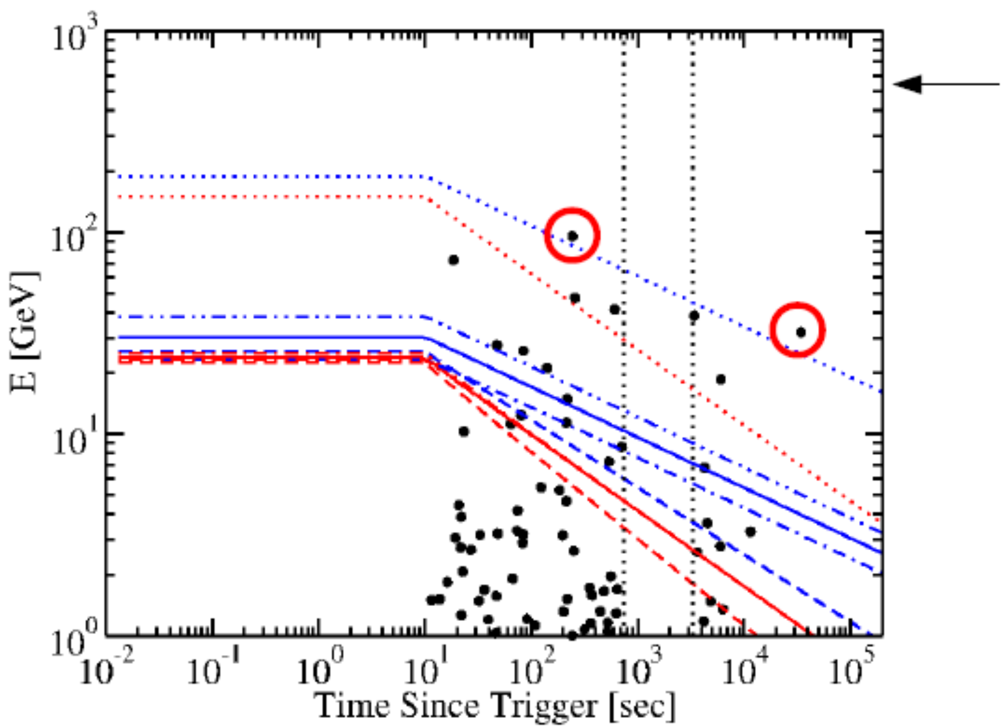


LAT emission still going

Very little LAT emission when GBM emission is bright

GRB 130427A

- **Jet interacts with circumburst medium.**
  - **Charged particles are accelerated.**
  - **These particles then emit photons via synchrotron emission.**
- **This prescribes a maximum synchrotron photon energy.**



Curves of **maximum** synchrotron photon energy from external shocks, for various conditions

Black dots: LAT photons

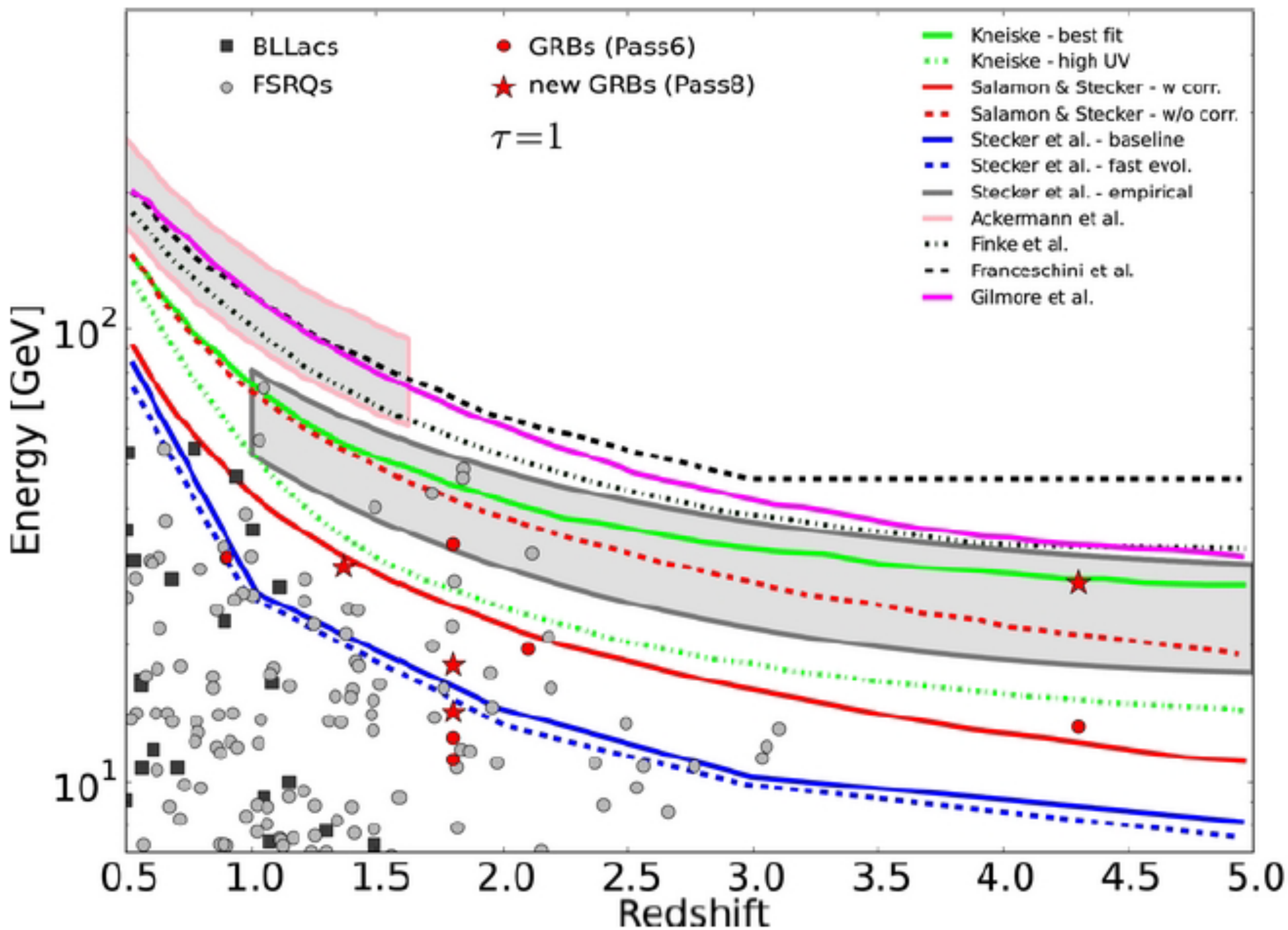
Circumburst medium:
Red → constant density
Blue → density ~ r^{-2}

Dotted lines: more "extreme" (i.e., unrealistic) scenarios
→ LAT photons *still* lie above these lines

Conclusions

- Interesting patterns and emergent groups
  - LAT >100 MeV emission is delayed & temporally extended w.r.t. the emission seen in the GBM
  - Short & long GRBs seem to have similar HE properties – short GRBs may be harder
  - LAT bursts are fluent, bright & energetic
  - Hint for a class of hyper-energetic GRBs → needs more observations
  - The distribution of GRB jet Lorentz factors might be broad → needs better spectral coverage in the 10-100 MeV range (LLE, Pass 8)
- Prompt emission phase
  - Band model crisis → need detailed physical models
  - Origin of the delayed onset of the LAT >100 MeV emission?
  - Origin of the high-energy emission? From internal and/or external shocks? Leptonic and/or hadronic?
  - Transition from prompt emission phase to early afterglow: how does the extra PL component relate to the long-lived GeV emission?
- Long-lived GeV emission
  - Decays as t^{-1} at late times, consistent with the canonical afterglow model (adiabatic fireball)

Towards the 2nd Catalog

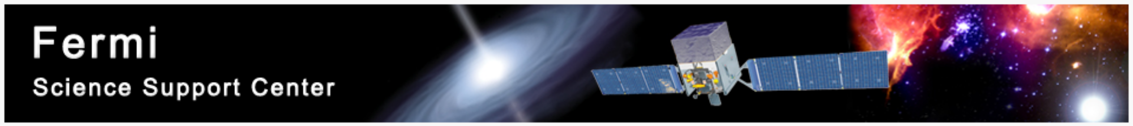


Atwood at al. 2013

Towards the 2nd GRB Catalog

FSSC • HEASARC • Sciences and Exploration

National Aeronautics and Space Administration
Goddard Space Flight Center



Fermi LAT GRBs

Important Table Information:

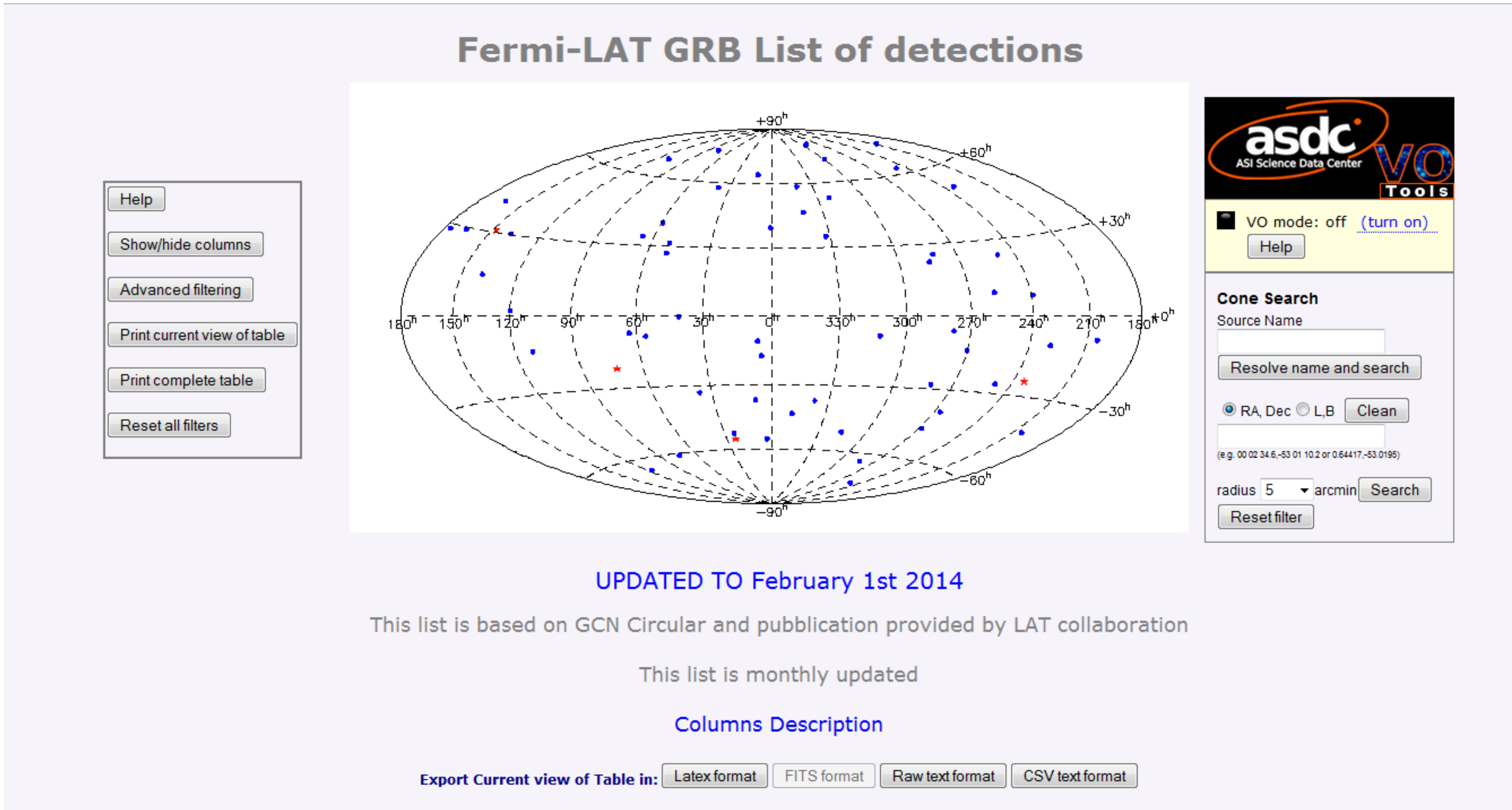
All analysis results presented here are preliminary and are not intended as an official catalog of Fermi-LAT detected GRBs. Please consult the table's caveat page for analysis details and other important information.

Fermi SSC Home » LAT GRBs

GRB	GCN Name	MET	Date (UTC)	Time (UT)	RA (Degrees)	Dec (Degrees)	Error (Degrees)	Source	Theta (Degrees)	Zenith (Degrees)	LLE Detection	Likelihood Detection	LLE Significance	Likelihood TS	Analysis Start	Analysis Stop	Analysis RA (Degrees)	Analysis Dec (Degrees)
140402007	140402A	418090210.0	2014-04-02	00:10:07	207.46	5.87	0.14	Fermi-LAT	13.470	47.296	NO	YES	3.66	45.25	0.0	800.0	207.46	5.87
140329295	140329A	417769481.33	2014-03-29	07:04:38.33	145.698	-32.229	0.2	Fermi-LAT	115.05	99.128	NO	YES	--	45.43	0.0	10000.0	145.698	-32.229
140323433	140323A	417262994.9	2014-03-23	10:23:11.90	356.95962	-79.90455	4.44e-4	Swift-XRT	31.229	69.168	NO	YES	0.92	29.61	0.0	1000.0	356.46	-79.87
140219824	140219A	414531995.0	2014-02-19	19:46:32	156.44	7.46	5.0	IPN	95.386	111.26	NO	YES	--	25	500	2300	158.2	7.2
140206275	140206B	413361375.0	2014-02-06	06:36:12	315.26	-8.51	0.23	Fermi-LAT	46.313	85.431	YES	YES	58.0	198.9	0.0	10000.0	314.6	-6.6
140110263	140110A	411027520.94	2014-01-10	06:18:37.94	28.90	-36.26	0.50	Fermi-LAT	30.00	68.981	YES	YES	9.47	49	0.0	1300.0	33.75	-39.73
140104731	140104B	410549526.15	2014-01-04	17:32:03.15	218.81	-8.90	0.22	Fermi-LAT	17.959	36.431	NO	YES	1.32	42.70	0.0	1510.0	216.99	-8.32
140102887	140102A	410390260.64	2014-01-02	21:17:37.64	211.91939	1.33329	1.4e-4	Swift-UVOT	47.190	45.135	YES	YES	7.93	92.7	0.0	1000.0	211.919	1.333
131231198	131231A	410157919.08	2013-12-31	04:45:16.08	10.590271	-1.6529472	8.3e-5	NOT	38.068	42.058	YES	YES	13.81	110	0.0	1000.0	10.11	-2.42
131216081	131216A	408851795.06	2013-12-16	01:56:32.06	91.59	-35.5	2.7	Fermi-GBM	44.127	76.714	YES	NO	4.31	13.1	0.0	100.0	94.71	-35.11
GRB	GCN Name	MET	Date (UTC)	Time (UT)	RA (Degrees)	Dec (Degrees)	Error (Degrees)	Source	Theta (Degrees)	Zenith (Degrees)	LLE Detection	Likelihood Detection	LLE Significance	Likelihood TS	Analysis Start	Analysis Stop	Analysis RA (Degrees)	Analysis Dec (Degrees)
131209547	131209A	408287279.97	2013-12-09	13:07:56.97	136.5	-33.2	0.9	Fermi-LAT	20.961	53.581	NO	YES	1.35	25	0.0	200.0	136.5	-33.2
131108862	131108A	405636118.0	2013-11-08	20:41:55	156.50179	9.6624722	4.44e-4	Swift-XRT	23.779	23.388	YES	YES	60.5	870	0	1355	156.662	9.774
131029973	131029A	404781651	2013-10-29	23:20:48.58	200.785	48.298	0.26	Fermi-LAT	59.420	93.693	NO	YES	0.66	73	0	800	200.785	48.298

http://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/table.php

Towards the 2nd GRB catalog



http://www.asdc.asi.it/grblat/