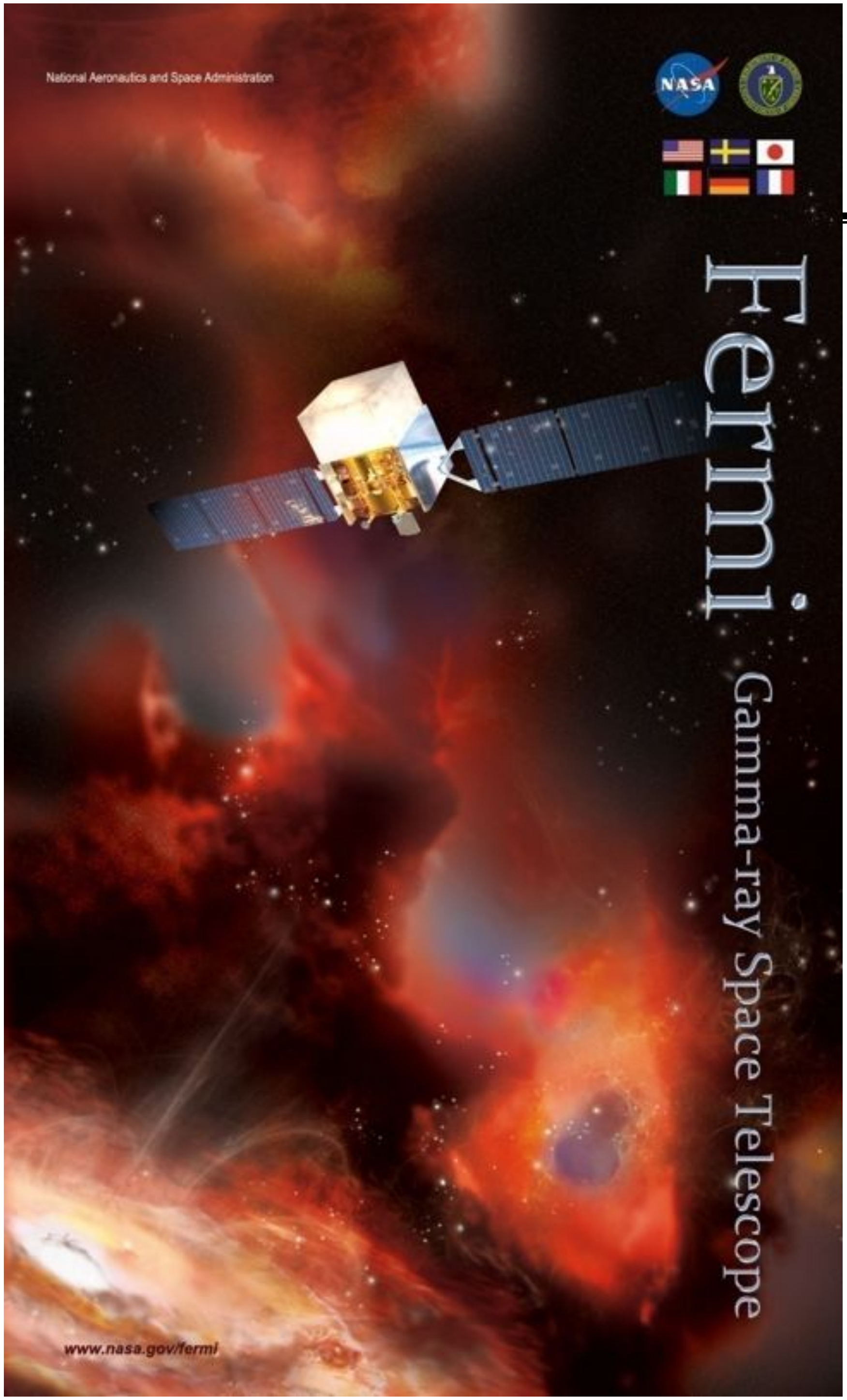


Fermi

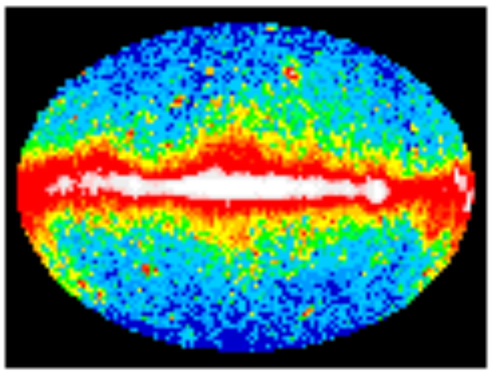
Gamma-ray Space Telescope

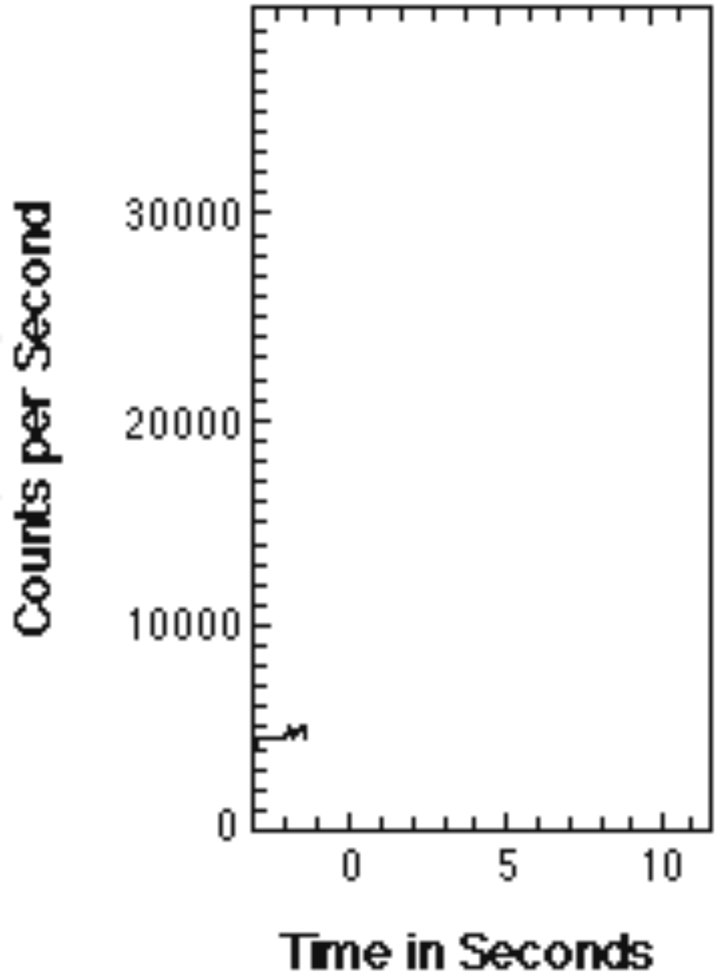
LAT Observations of Gamma-ray Bursts

Julie McEnery
NASA/GSFC and University of Maryland

On behalf of the Fermi-LAT and Fermi-GBM collaborations

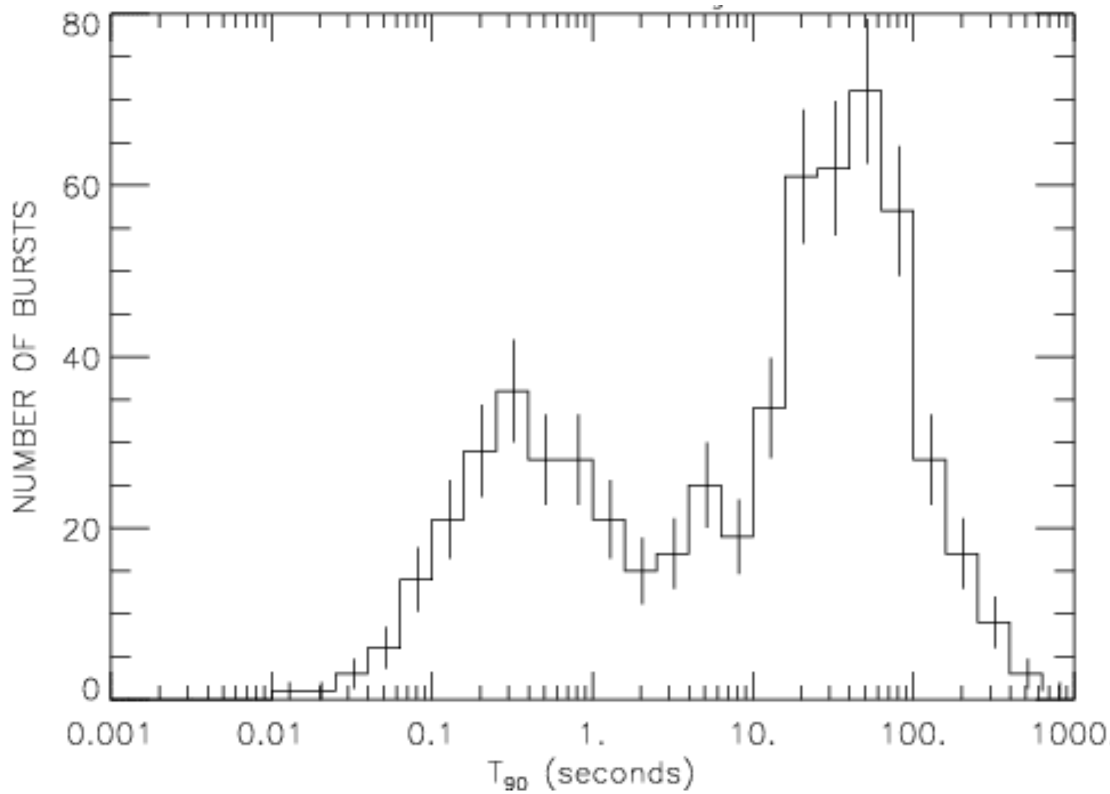
Briefly the brightest gamma-ray source in the sky





After the burst itself, afterglow emission in radio, optical and X-ray is observed for days (and sometimes months and years) which decays with time.

Duration distributions - two classes?



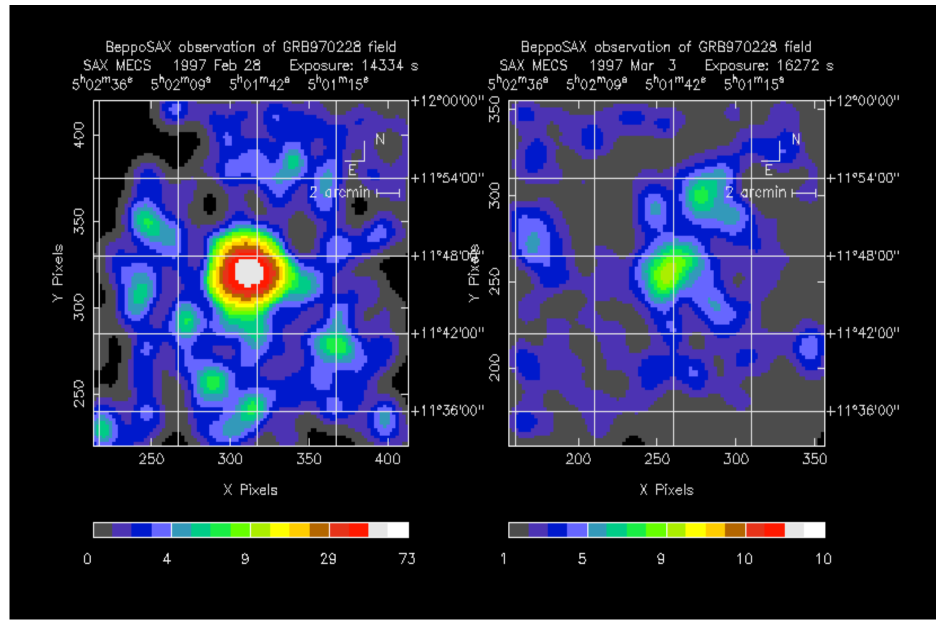
- **Two distinct populations**
  - **Short <~2s**
  - **Long >2 s**

GRB Afterglows

GRB leave behind a faint declining echo at lower wavelengths. Important as it allows us to better measure the location of the source

- **Faint, fading X-ray, optical or radio afterglows.**

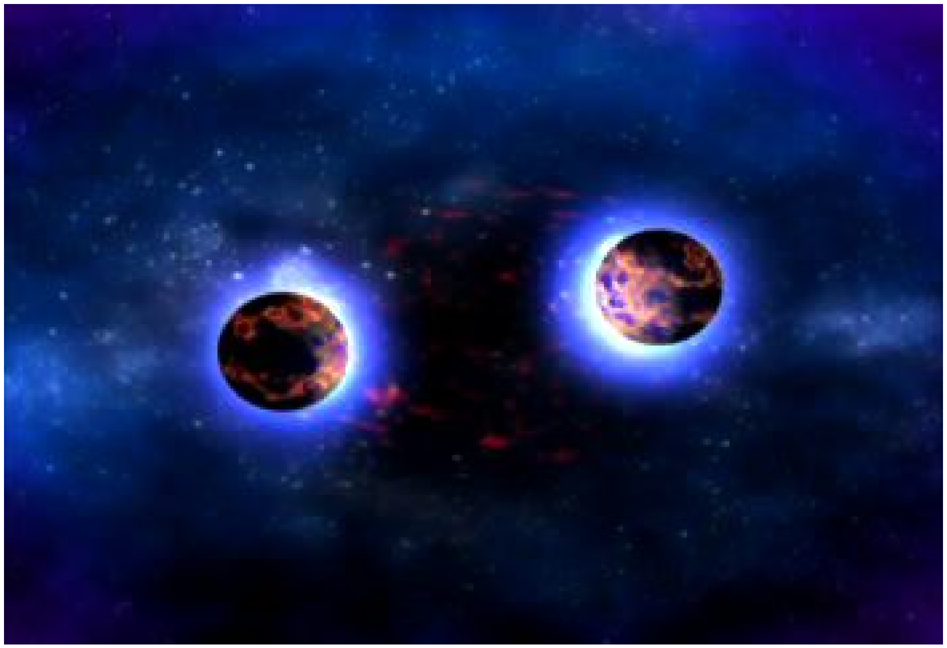
- **Identification of absorption or emission lines in afterglow or host galaxy allows determination of distance.**

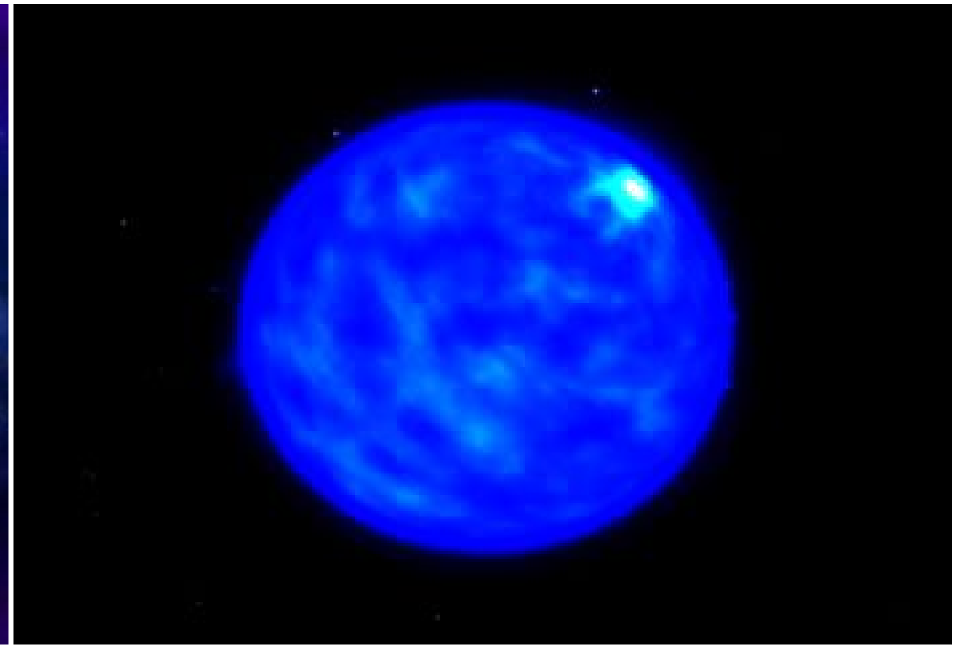


Implies that GRB are enormously energetic: 10^{48} -10^{54} ergs. (c.f. Solar rest mass = ~2 x 10^{54} ergs)

Gamma-ray bursts

Huge flux of gamma-rays lasting from 0.1-1000's seconds

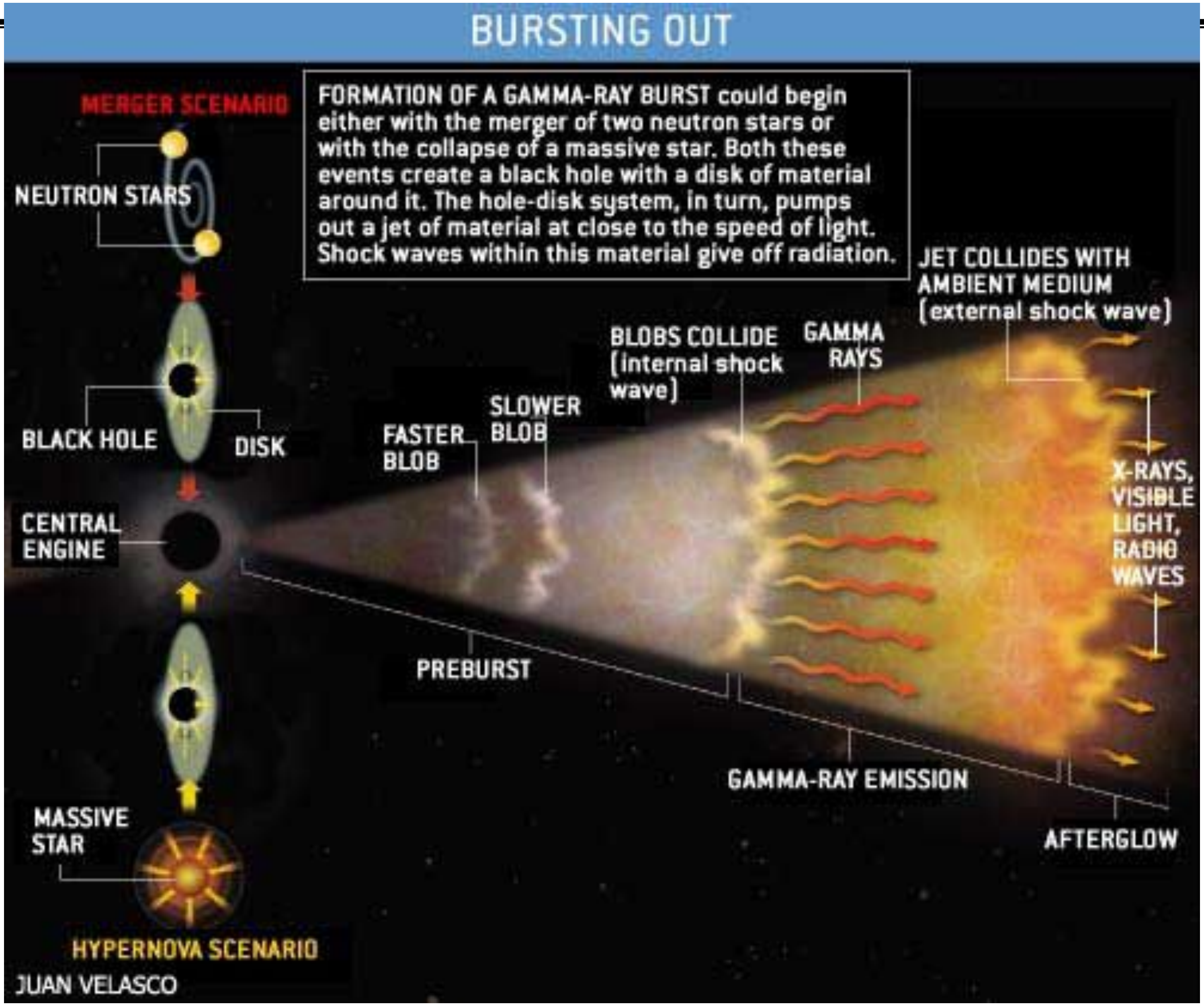




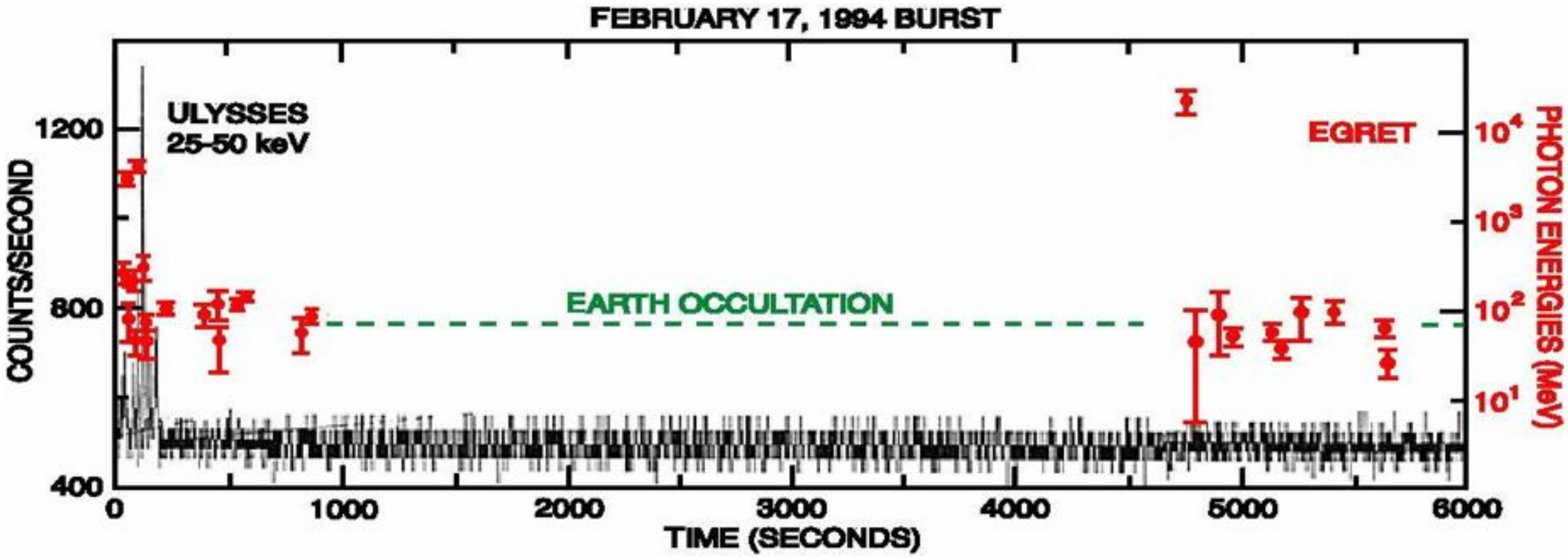
Compact Mergers: Two neutron stars, or a neutron star and a black hole, collide and merge, producing a jet.

Collapsars: A rapidly spinning stellar core collapses and produces a supernova, along with relativistic jets.

Fireball model



Some History



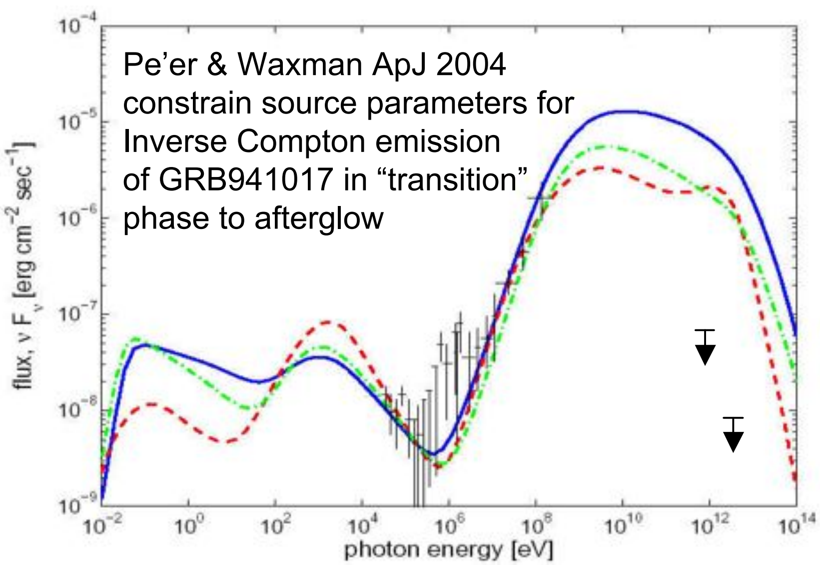
- EGRET detected 4 GRB in its pair conversion telescope.
- In one GRB, EGRET observed emission above 30 MeV for more than an hour after the prompt emission.
- 18 GeV photon was observed (the highest ever seen by EGRET from a GRB).
- Due to Earth occultation/telemetry gap, it is unknown for how long the high energy emission lasted.

Unlike optical/X-ray afterglows, gamma-ray luminosity did not decrease with time -> additional processes contributing to high energy emission?

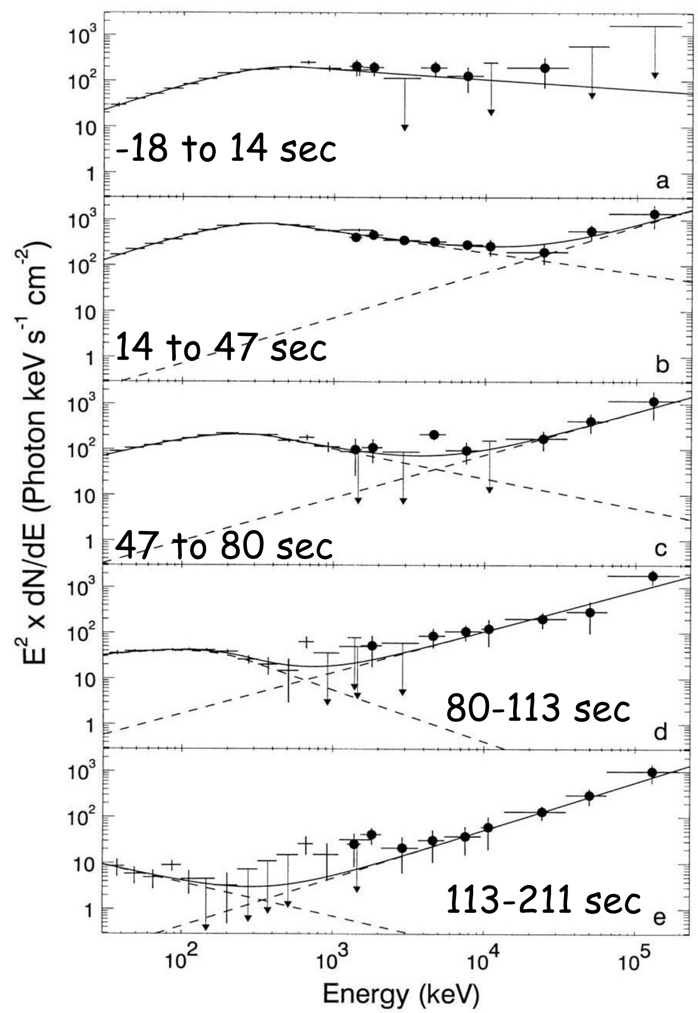
Joint EGRET-BATSE observations

Analysis using EGRET TASC data

- **Classic sub-MeV component observed in BATSE data which decays by factor of 1000 and Epeak moves to lower energies**
- **Higher Energy component observed within 14-47 seconds by EGRET and at later times by both BATSE and EGRET detectors**
- **Higher Energy Component has**
  - **$dN_\gamma/dE = kE^{-1}$**
  - **lasts ~200 seconds**
  - **Increases total energy flux by factor of 3**



GRB941017



(See also Granot and Guetta, 2003)

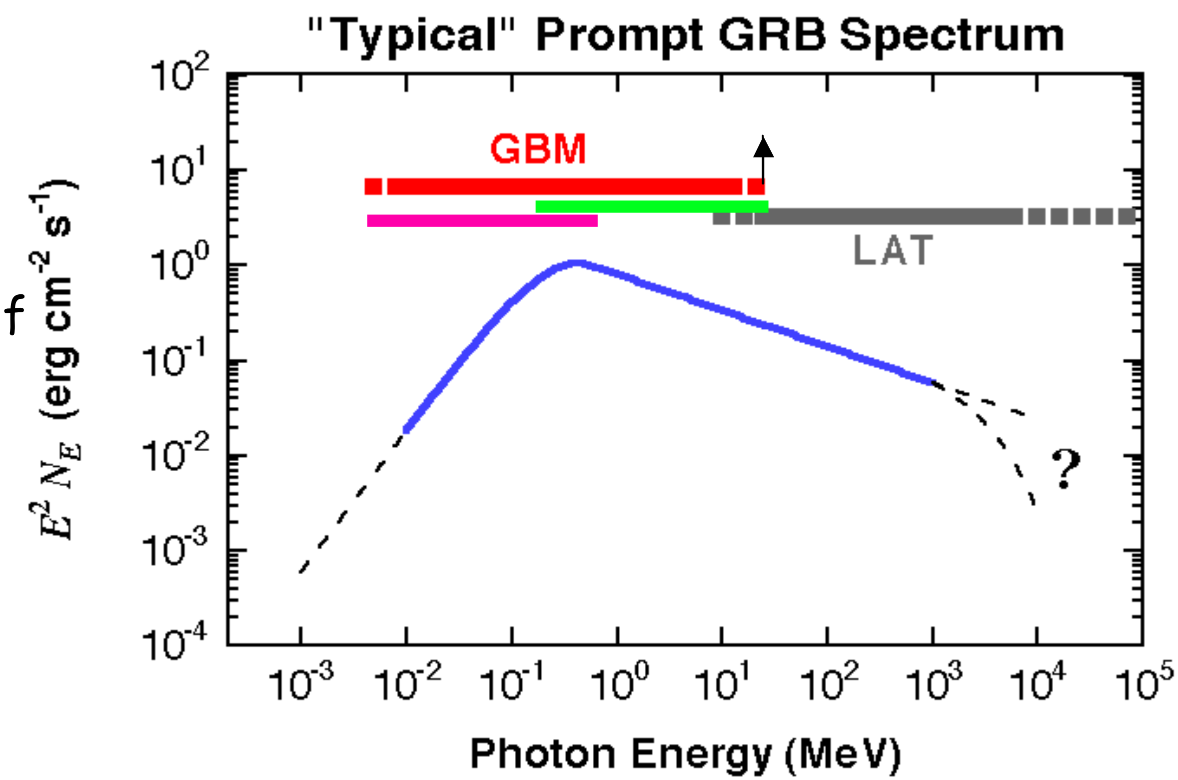
Some open questions

- How high in energy does the prompt GRB emission extend?
  - Measurements of high energy cutoffs in GRB provide information on:
    - particle acceleration
    - Bulk Lorentz factors for each pulse
- Is there a second emission component? What is its nature?
- How common are high energy afterglows such as that seen in EGRET?
- What is the density and spectrum of UV/optical intergalactic radiation fields?
  - Look for high energy cutoffs/spectral breaks as a function of redshift
- Test of Lorentz invariance at high energies (quantum gravity...)
  - Set a limit on the constant speed of light

Fermi and GRB

- **LAT:** <20 MeV to >300 GeV. With both onboard and ground burst triggers.
- **GBM: 12 NaI detectors—** 8 keV to 1 MeV. Used for onboard trigger, onboard and ground localization, spectroscopy: **2 BGO detectors—** 150 keV to 40 MeV. Used for spectroscopy.
- Total of >7 energy decades!

Good spectral observations of the prompt phase of lots of GRB



Large Area Telescope (LAT)

- **Efficient observing mode (don't look at Earth)**
- **Wide FoV (useful GRB observations out to 65 half angle, 3.6 sr)**
- **Low deadtime (27μs c.f. 100ms for EGRET)**
- **Large effective area**
- **Good angular resolution**
- **Increased energy coverage (to few hundred GeV)**

Many GRB

More photons detected from each GRB

Good GRB locations

Very major improvements in capabilities for GRB observations compared to previous missions in this energy range.

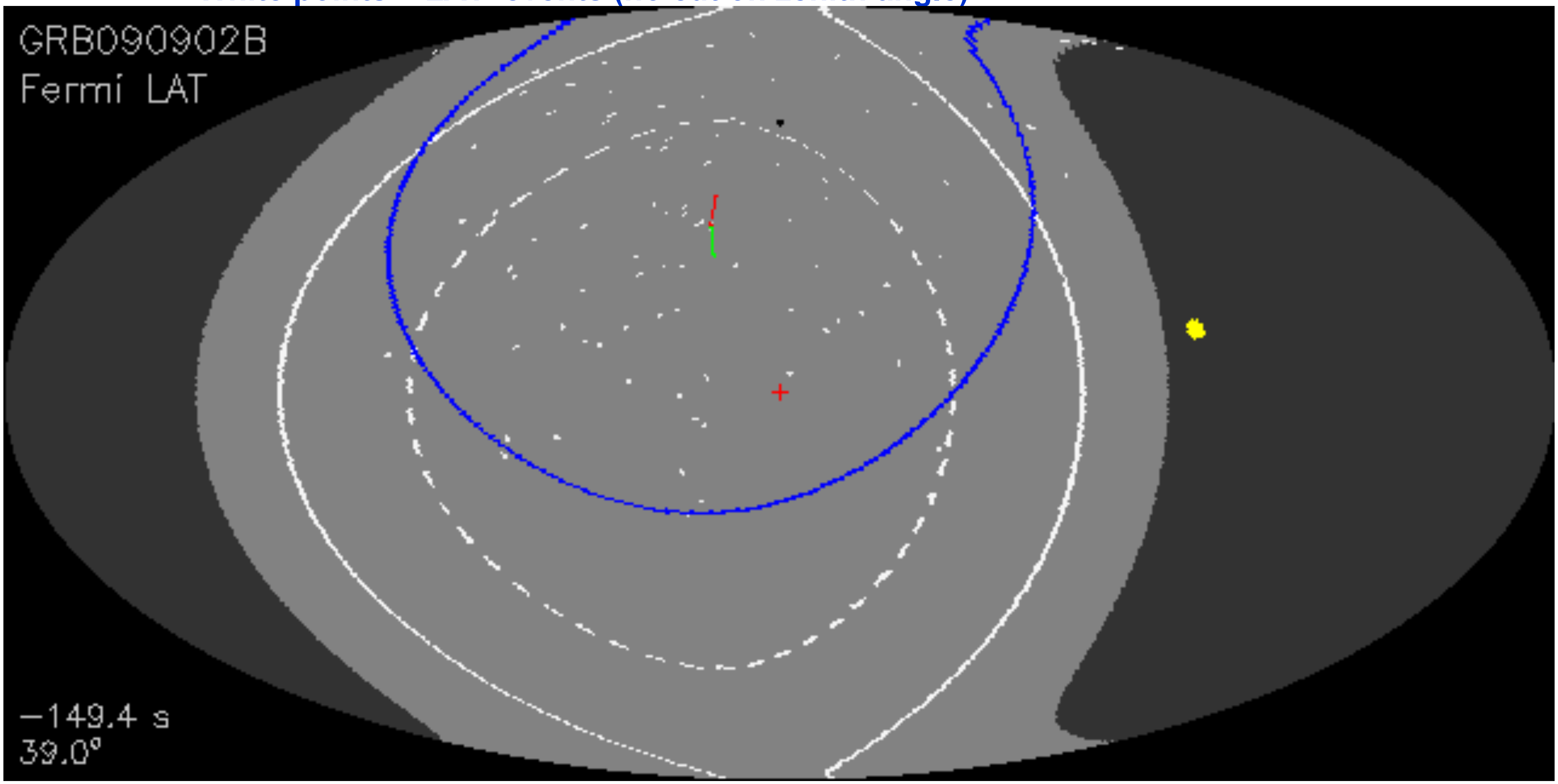
More photons - study high energy lightcurves, good detection sensitivity

Study the *population* of MeV-GeV bright bursts

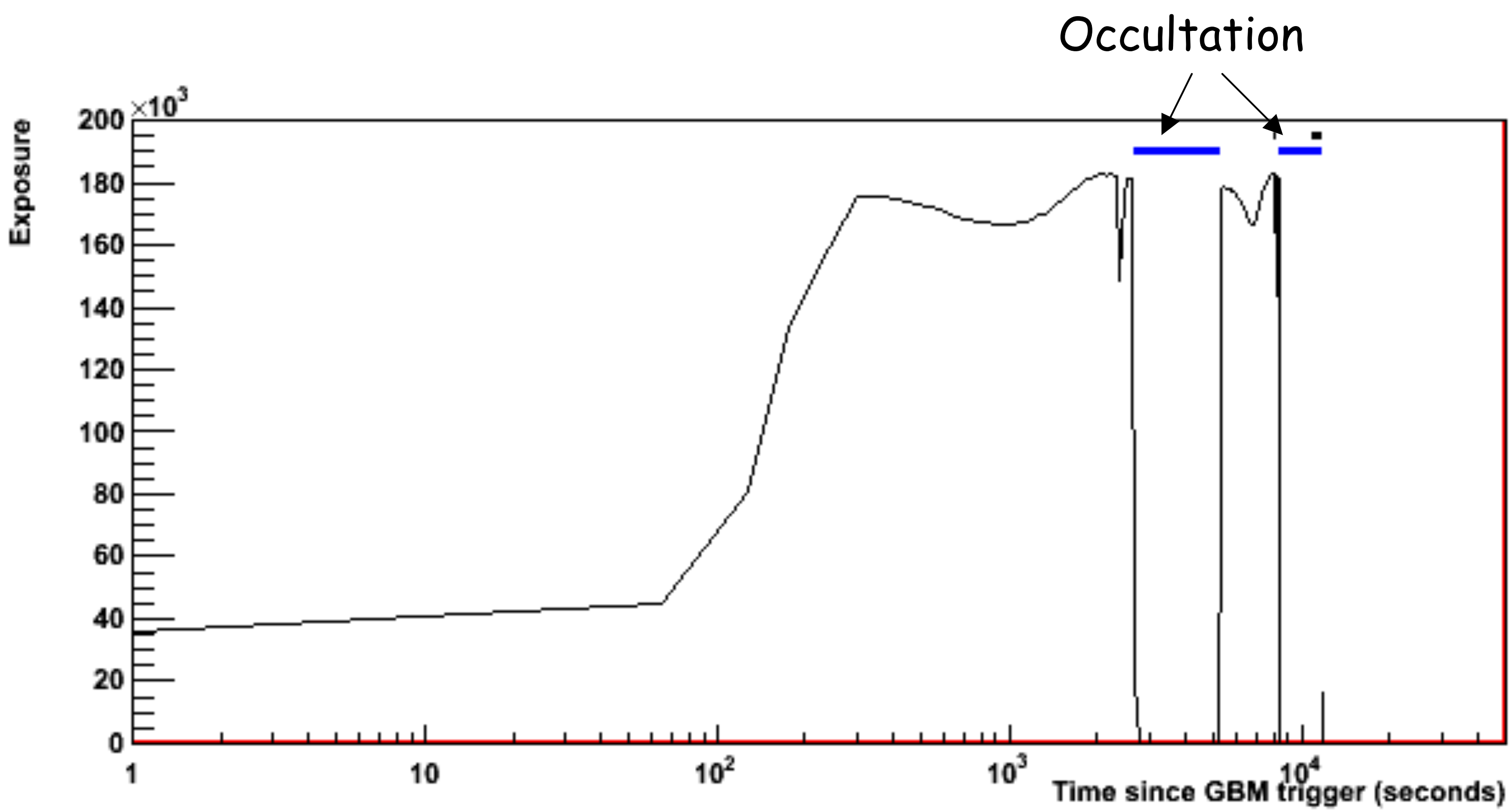
Measure spectra out to hundreds of GeV - how common are the high energy components such as that seen in GRB 941017?

GRB090902B - Autonomous repoint

- LAT pointing in celestial coordinates from -120 s to 2000 s
  - Red cross = GRB 090902B
  - Dark region = occulted by Earth (qz>113°)
  - Blue line = LAT FoV (±66°)
  - White lines = 20° (Earth avoidance angle) / 50° above horizon
  - White points = LAT events (no cut on zenith angle)



Exposure vs time for GRB090328



Rapid increase in exposure as GRB location comes to the center of the FoV

~Constant exposure for 5 hours, with gaps for occultation and SAA passage

Fermi GRB detections

>600 GBM GRB

27 LAT GRB

20 (>100 MeV, TS > 16)

7 LAT LLE-only GRB

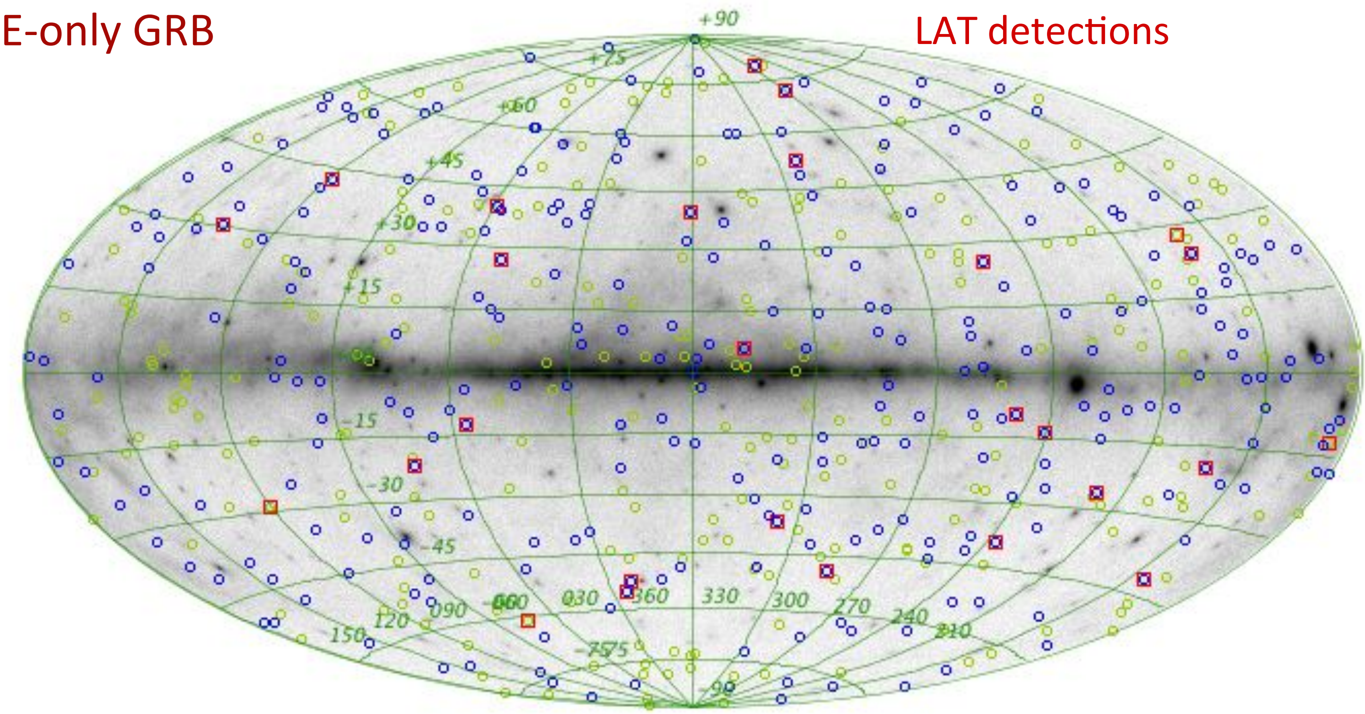
Circles:

In Field-of-view of LAT (<70˚): 275

Out of the FOV

Squares:

LAT detections



11 months Fermi LAT count map

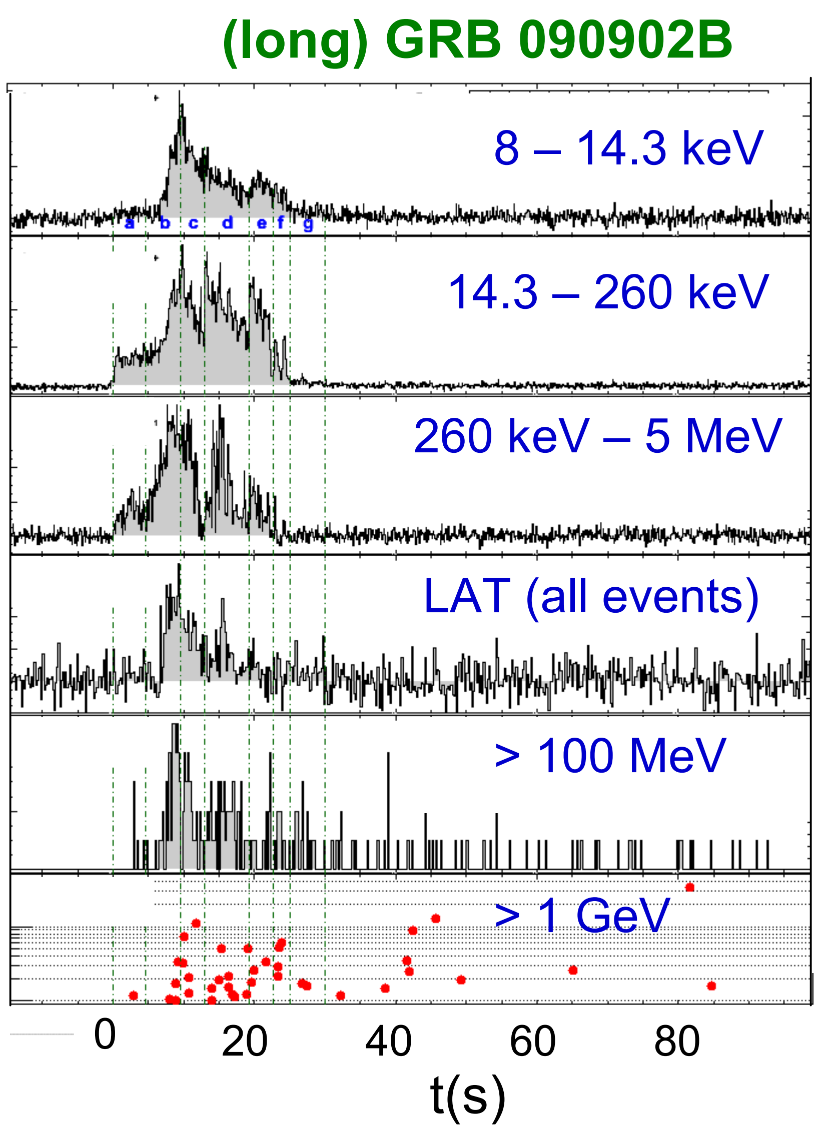
PRELIMINARY

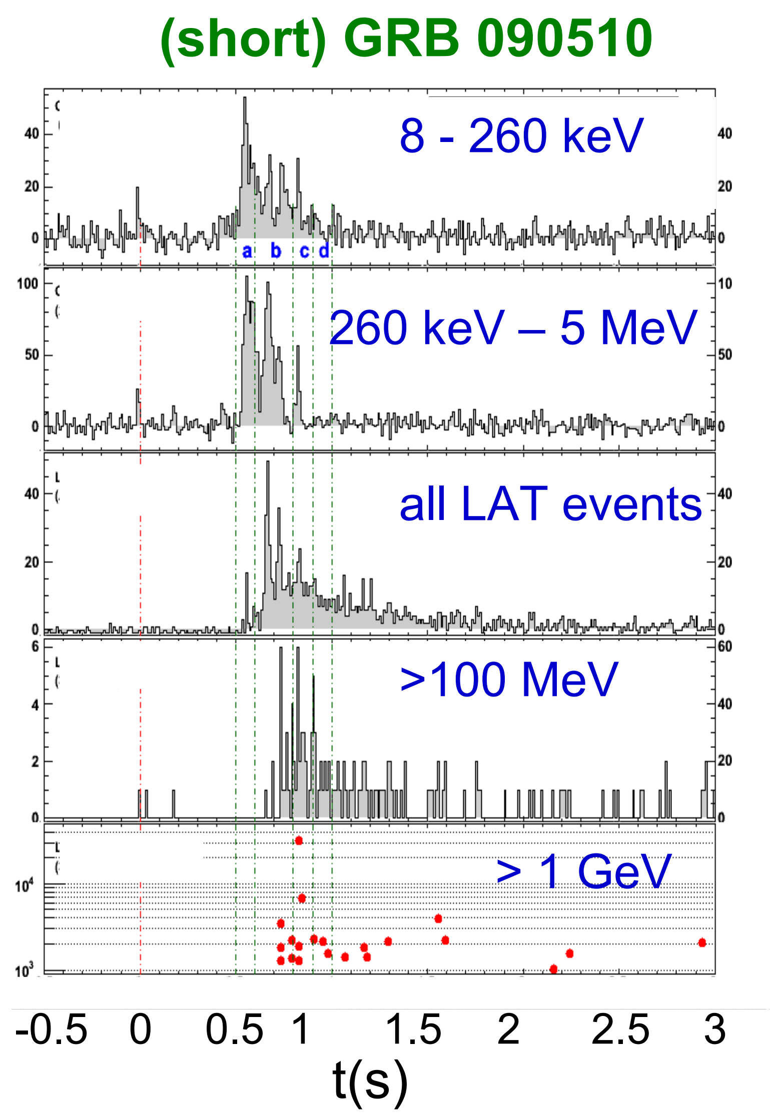
Swift observations of bright well-localized LAT bursts have been extremely successful in detecting X-ray afterglows. Follow-up optical obs provide redshift

Fermi-LAT Observations of GRB

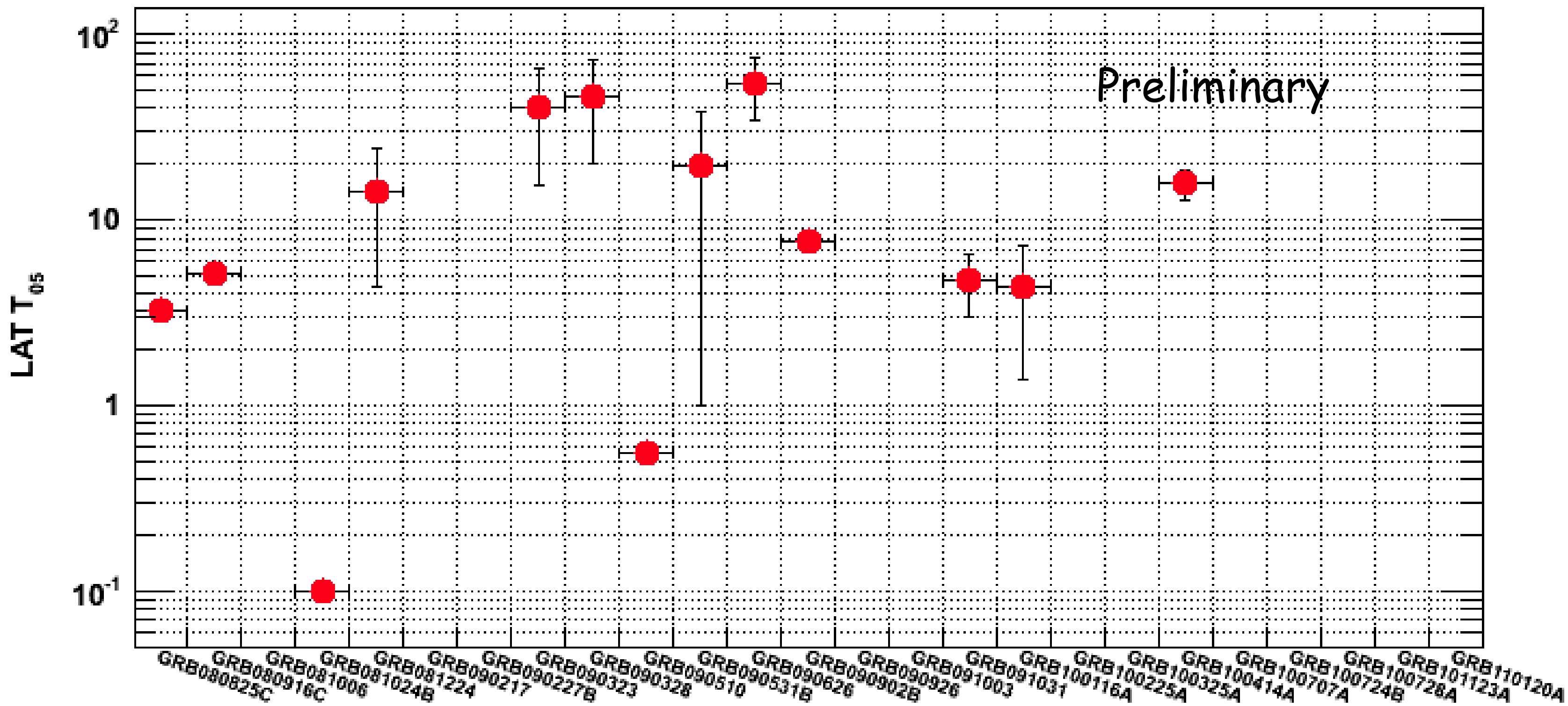
- **Prompt emission phase**
  - **Onset of >100 MeV delayed w.r.t. keV flux**
  - **Durations of high energy emission longer than keV emission**
  - **Hard power-law components seen in bright LAT GRB**
  - **Cutoffs -> fewer detected GRB than hoped**
- **Afterglows**
  - **Properties of MeV-GeV afterglows and connection to prompt phase**
  - **MeV-GeV counterparts to x-ray flares**

Delayed Onset and Extended GeV Radiation of Fermi LAT GRBs



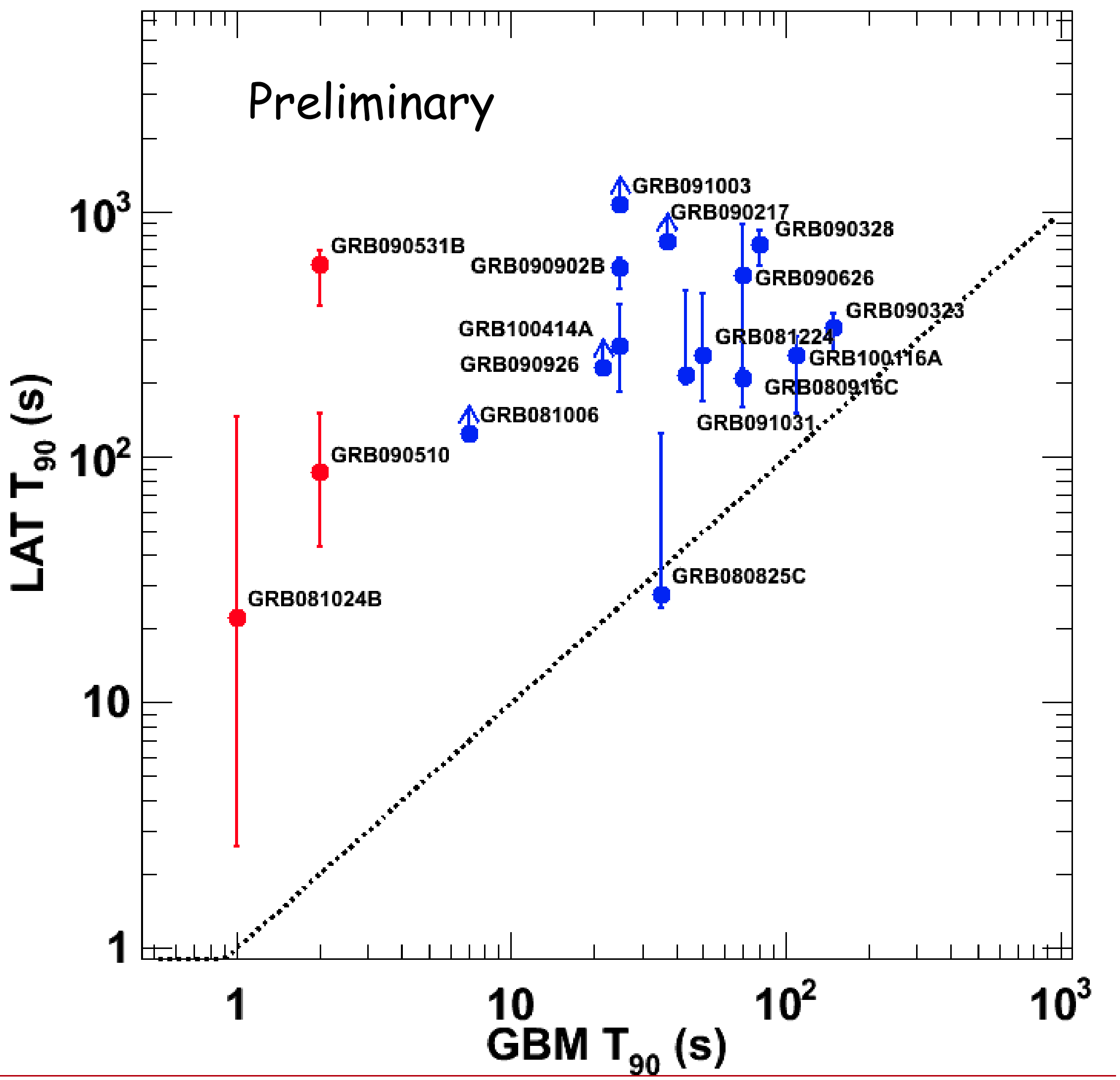


Delayed onset of >100 MeV



- **The LAT >100 MeV emission starts after the keV emission, sometimes by up to 80 seconds.**

Duration Distributions

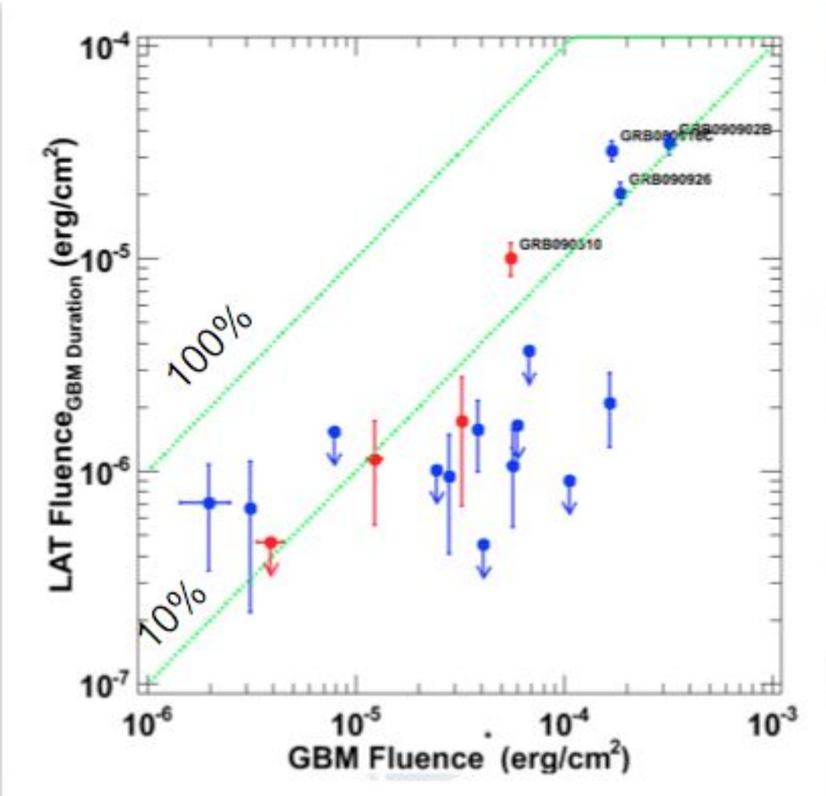


We measure a systematically longer duration in the LAT

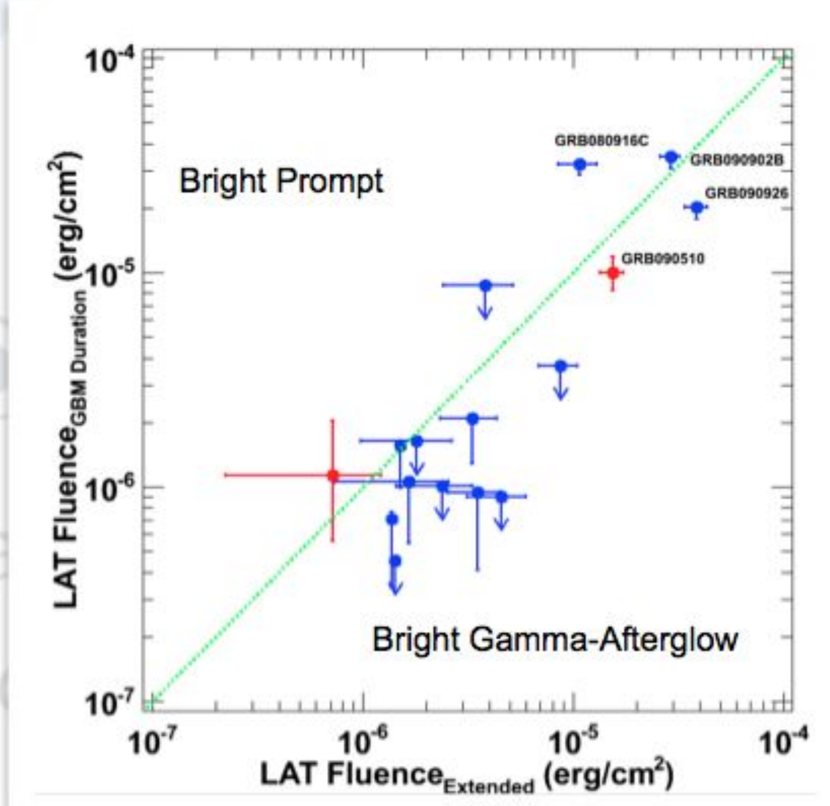
- Emission at GeV energy lasts longer than the emission at MeV energy
  - Different component?
- OR, better sensitivity of the LAT detector (low background) than the GBM detector (background dominated)

Fluence Distributions

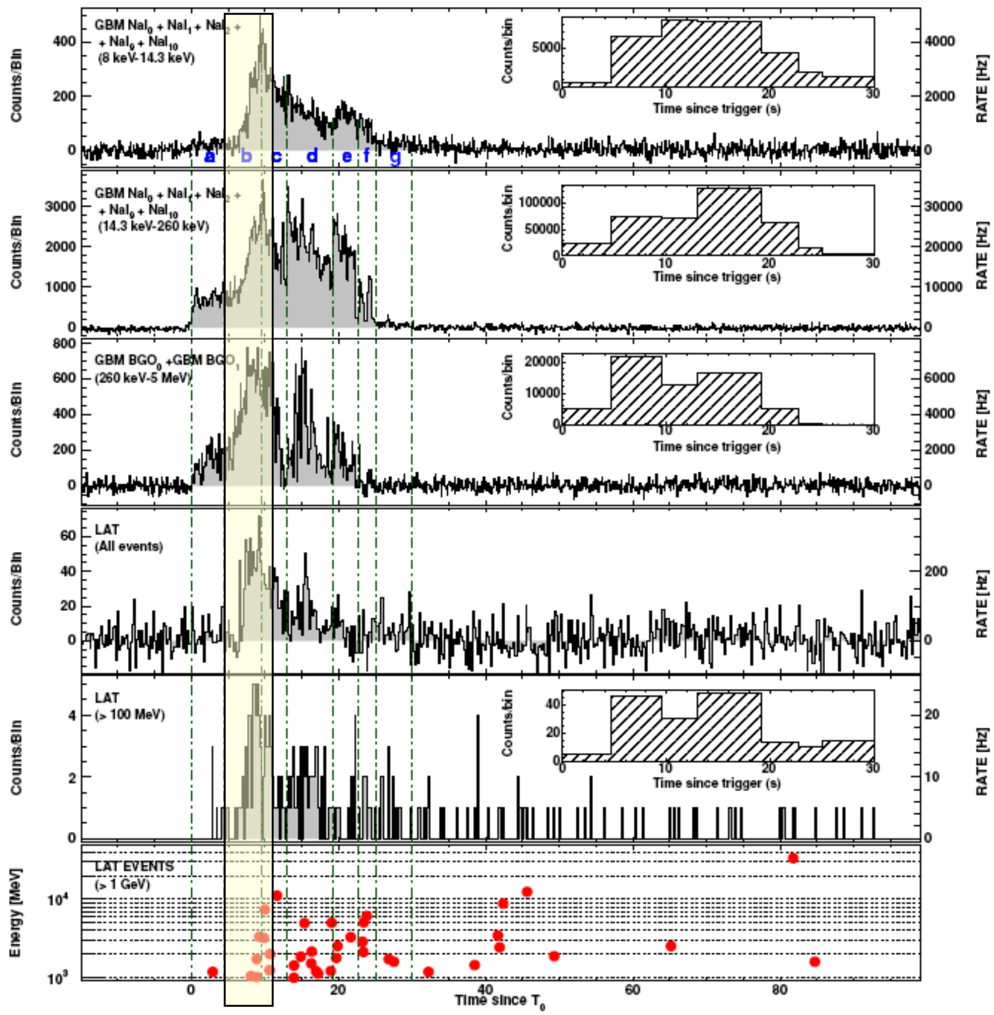
PRELIMINARY



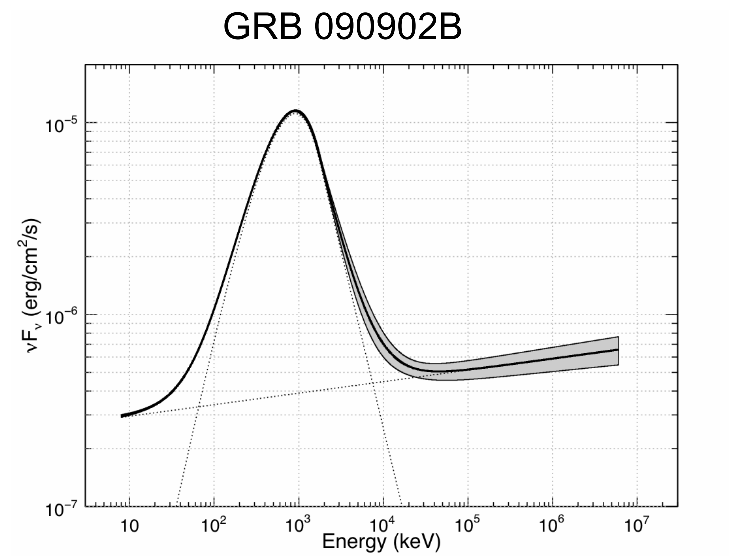
GBM Fluences from 8 keV to 35 MeV
(Nava et al.2011)



GRB 090902B: A Hard Component in Long GRB



Abdo, A. A., et al. 2009, ApJ, 706, L138

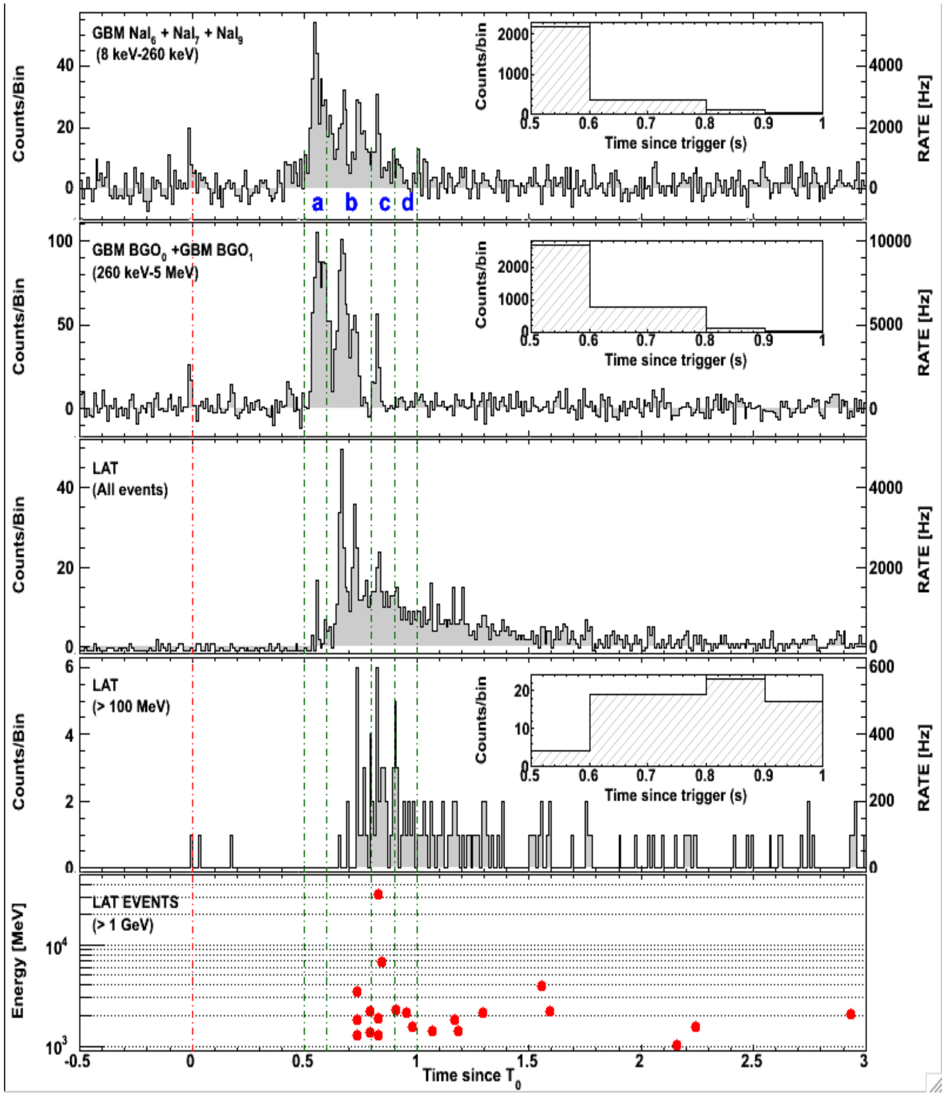


Best fit spectrum to interval b (T_0+4.6 s to T_0 + 9.6 s) is a band function (smoothly broken power-law) + power-law component.

Hadronic model providing additional hard component with excess at low and high energies?

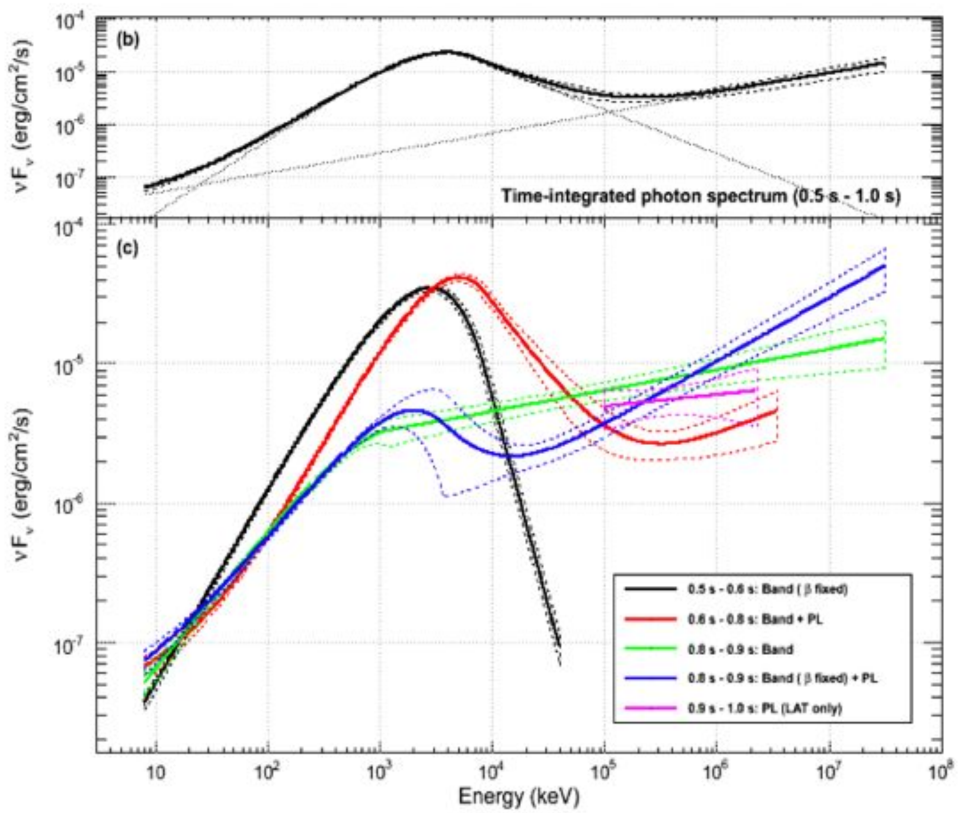
Two non-thermal power-law + thermal component?

GRB 090510: A Short Hard GRB with an extra component



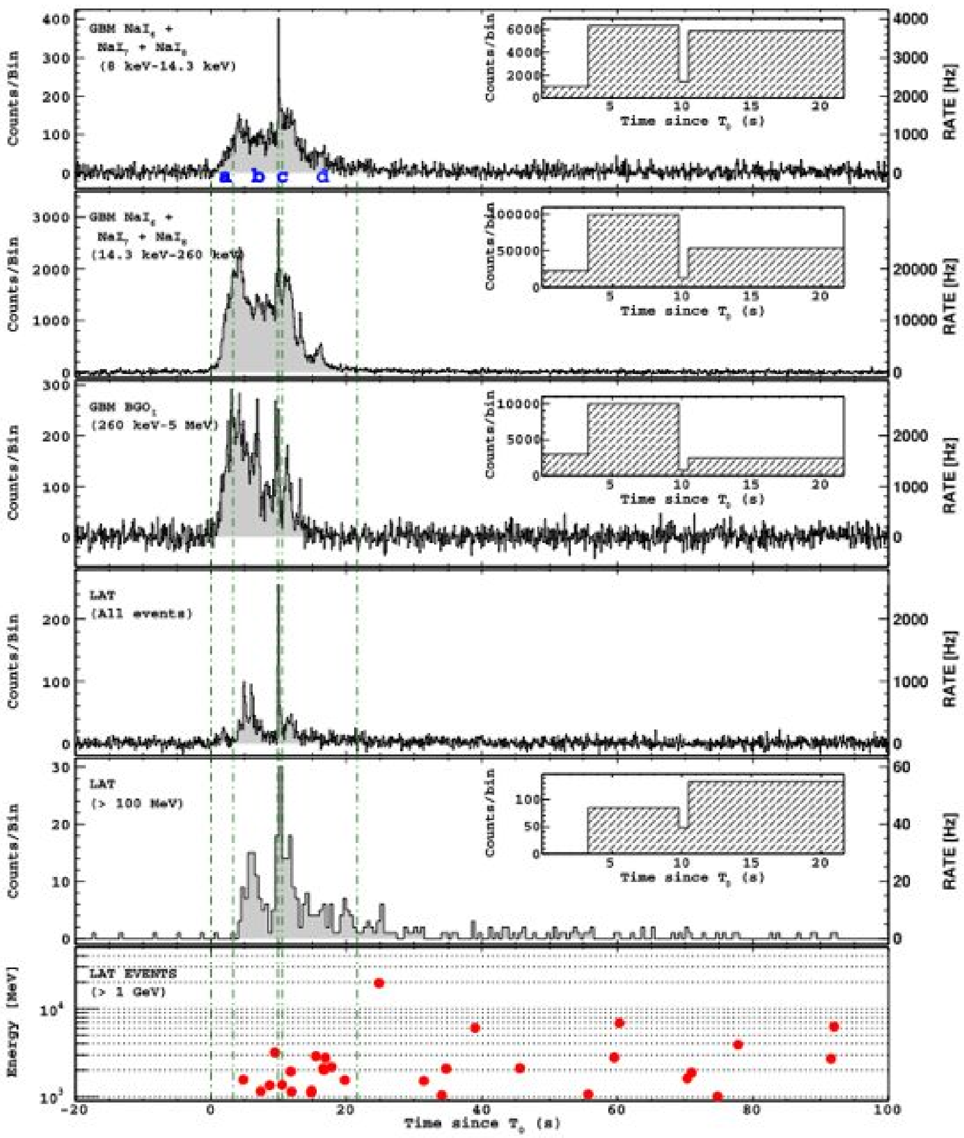
GRB090510. First bright short GRB
Clear detection of an extra component, inconsistent with the Band function.

Ackermann et al., ApJ



Early onset of afterglow?

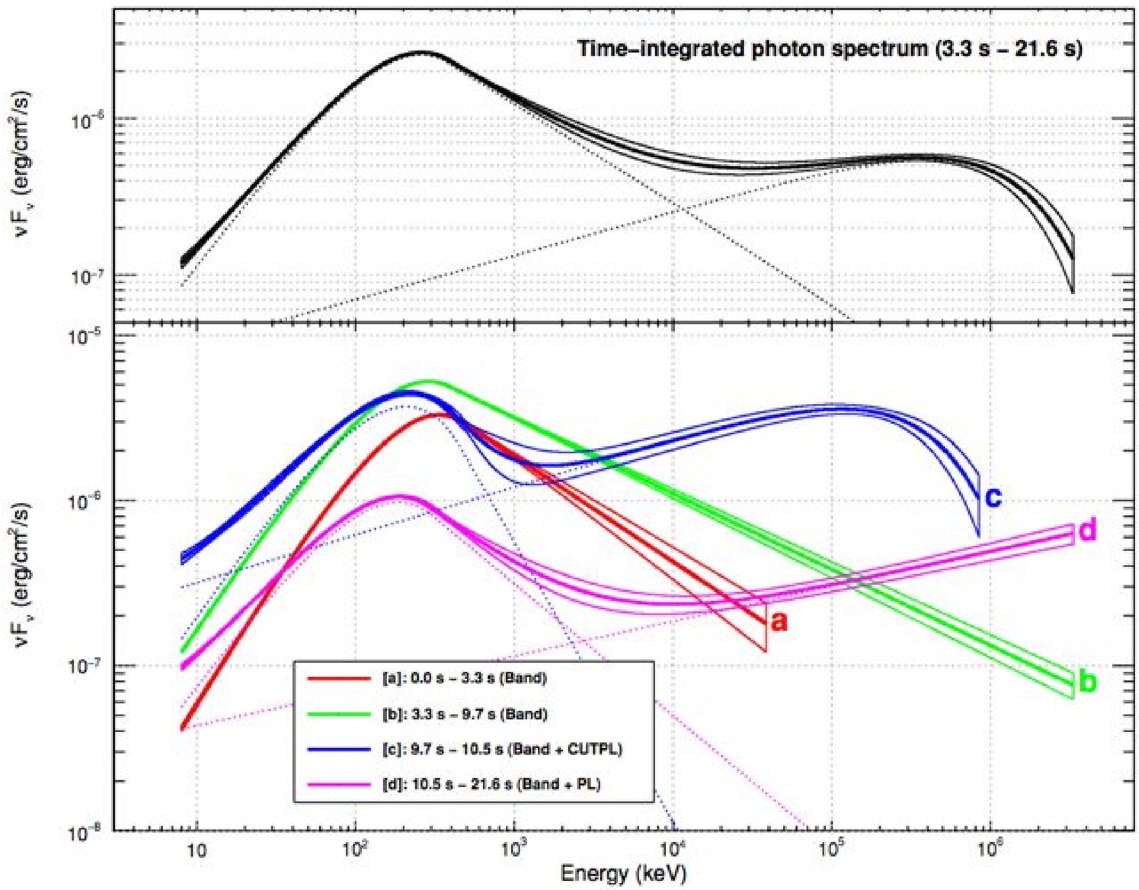
GRB090926B



- **Sharp spike seen at all measured gamma-ray energies**
  - **Strongest below 15 keV and above 10 MeV**
  - **Clear correlation between keV and MeV/GeV lightcurves**

Ackermann et al, 2011

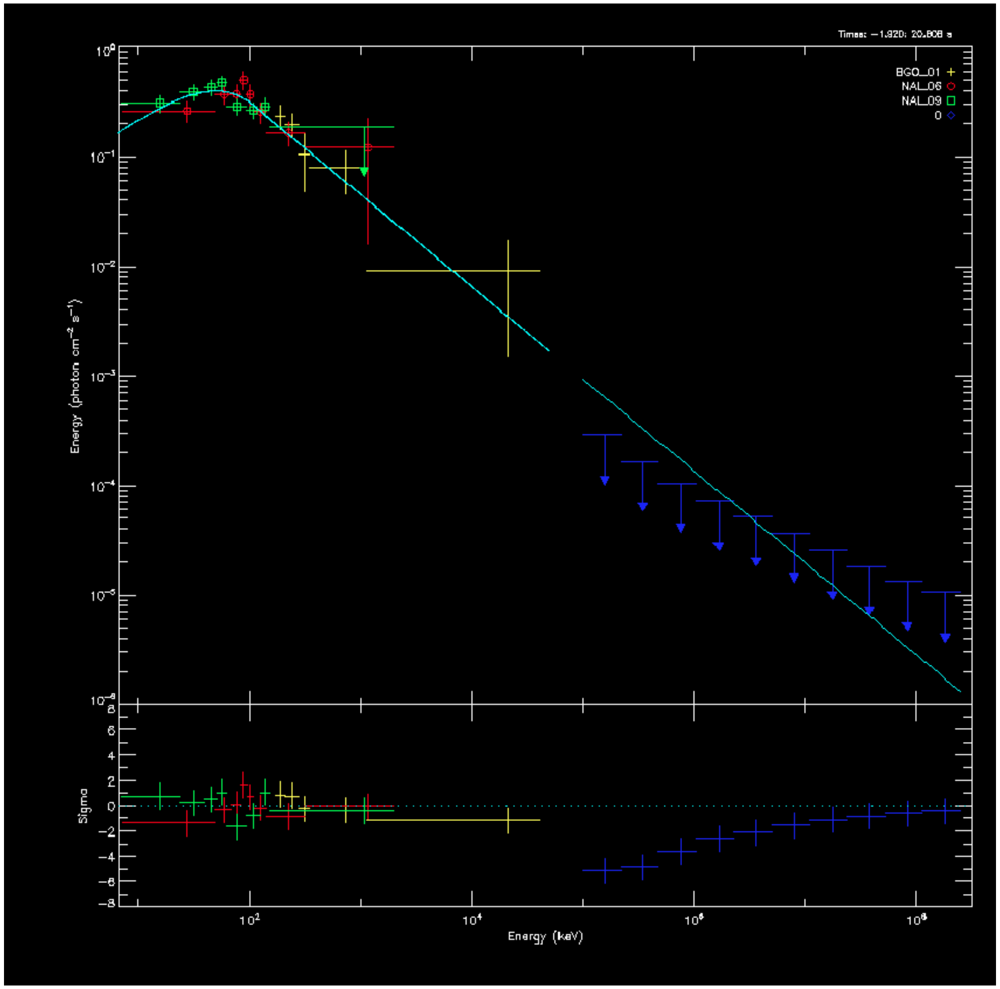
GRB090926 - extra spectral component



- **Hard power-law component emerges during the bright spike, with cutoff at 1.4 GeV**
- **Power-law index remains constant through the afterglow (~5000 seconds)**

More on cutoffs and spectral breaks

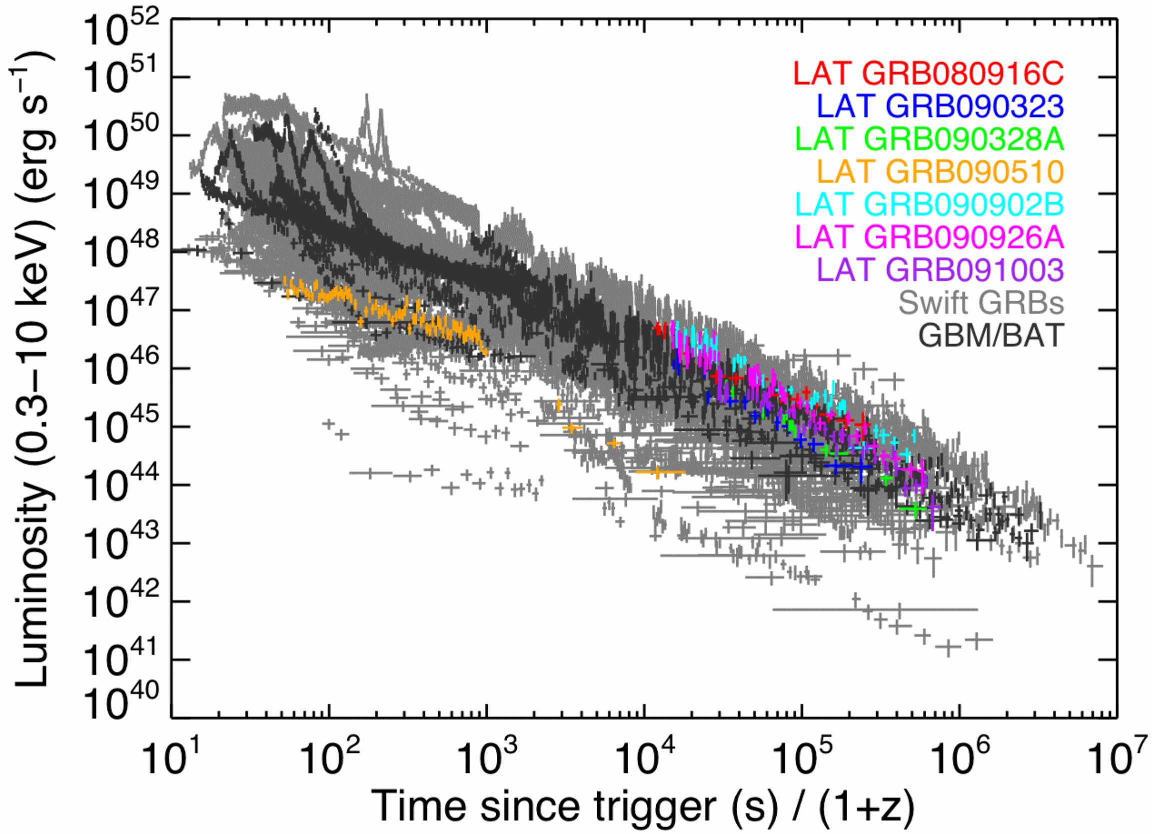
- **Sample of 36 bright BGO detected bursts**
  - **Extrapolate GBM spectrum to the LAT range**
  - **Compare LAT upper limit with that "expected" from extrapolation**
  - **Test that the data cannot be adequately fit by a softer spectrum when fitting LAT and GBM data together.**
- **Significant evidence for a spectral break in ~10% of the sample.**
  - **Intrinsic break**
  - **Or, incorrectly measured spectral parameters**



See also Beniamini et al 2011, Guetta et al, 2011

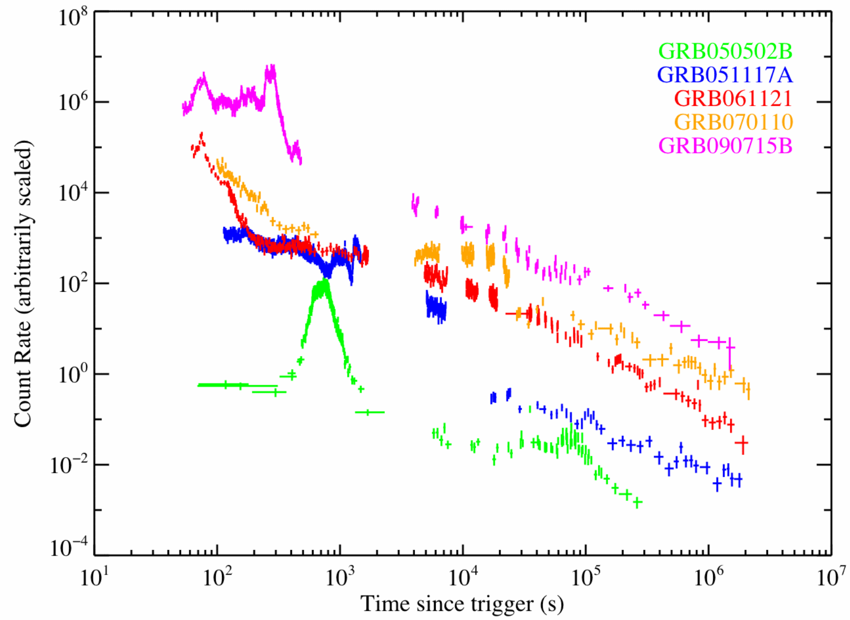
Afterglows

Swift XRT observations of GRB afterglows

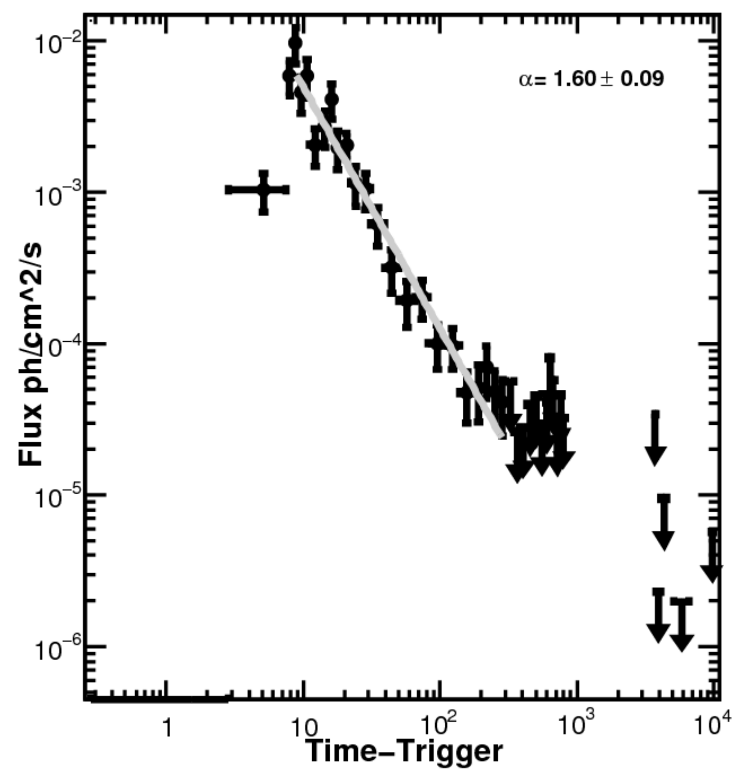


- **Fermi-LAT bursts are bright!**
- **X-ray observations typically start ~12 hours after the prompt emission.**

Early Afterglows

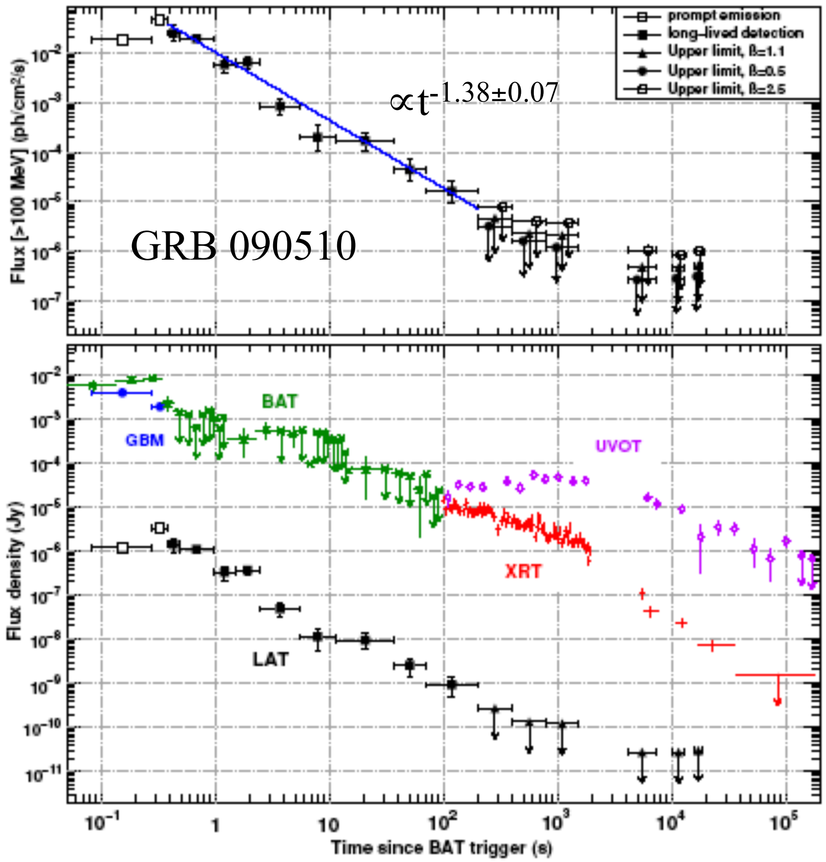


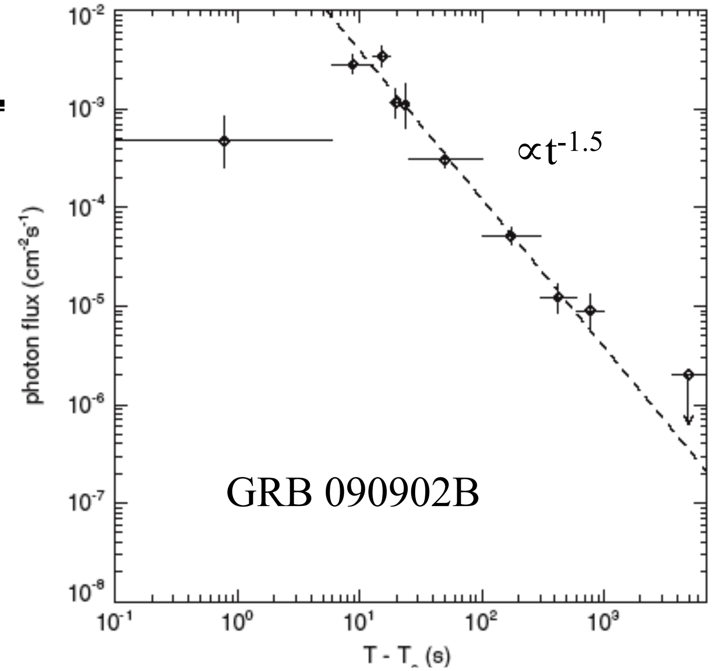
Large flares/rebrightening often seen during the early afterglow (within an hour or so)

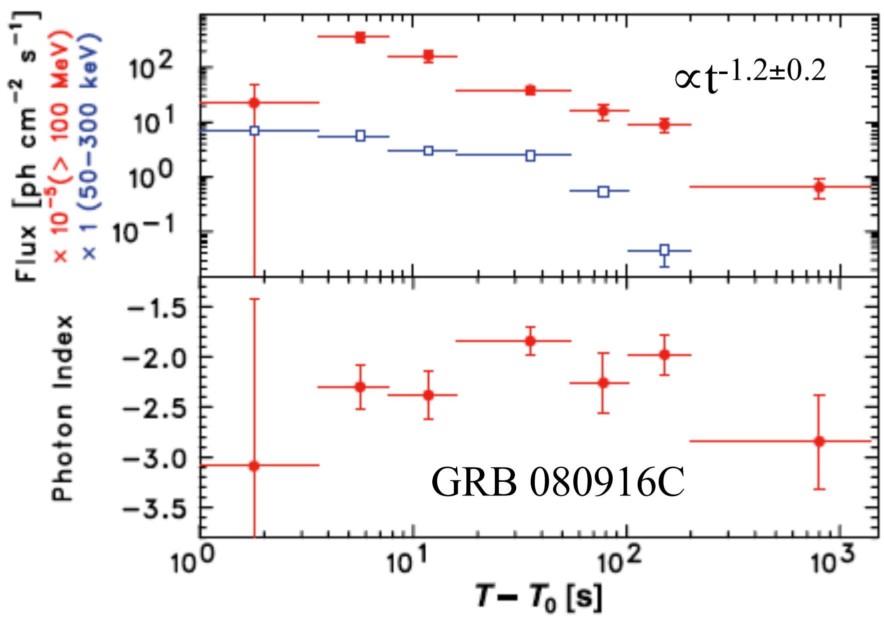


LAT afterglows seen for several GRB with durations lasting up to an hour or so

Long-lived Emission with power-law temporal decays



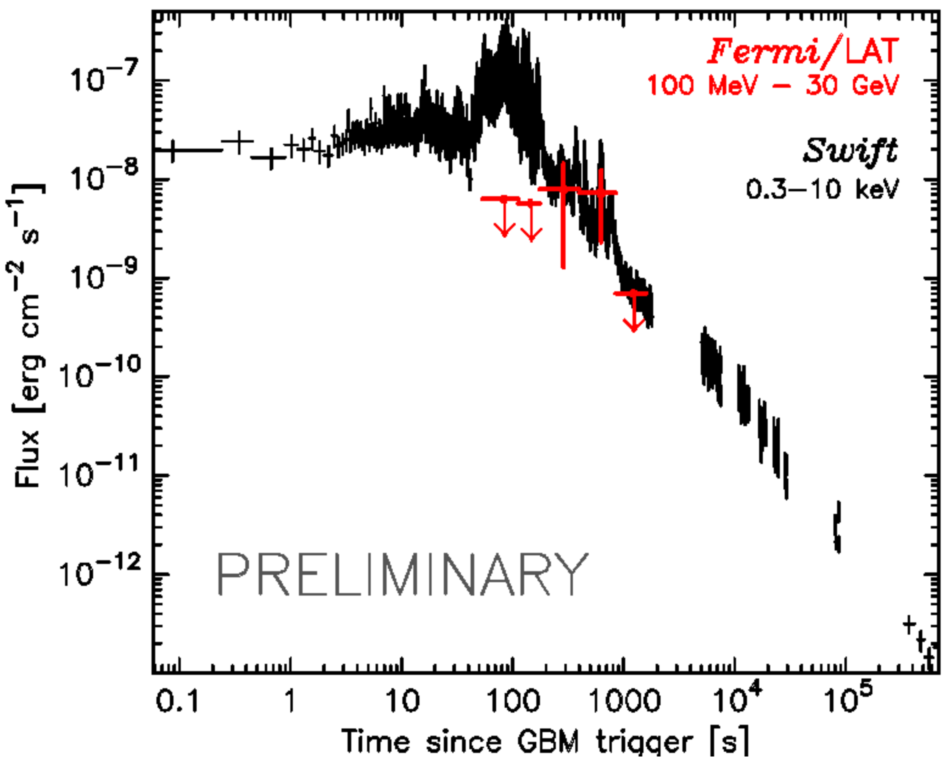




De Pasquale, M., et al. 2010, ApJ, 709, L146

LAT Detection during X-ray Flare Activity

- **GRB100728A**
  - Bright GBM burst->ARR
  - No prompt LAT detection (but was at edge of FoV, 58 deg)
  - Hard spectrum (1.4+-0.2)
  - Gamma-ray fluence consistent with extrapolation of the X-ray flare spectrum
  - Unable to distinguish between afterglow or flare emission due to weak LAT detection

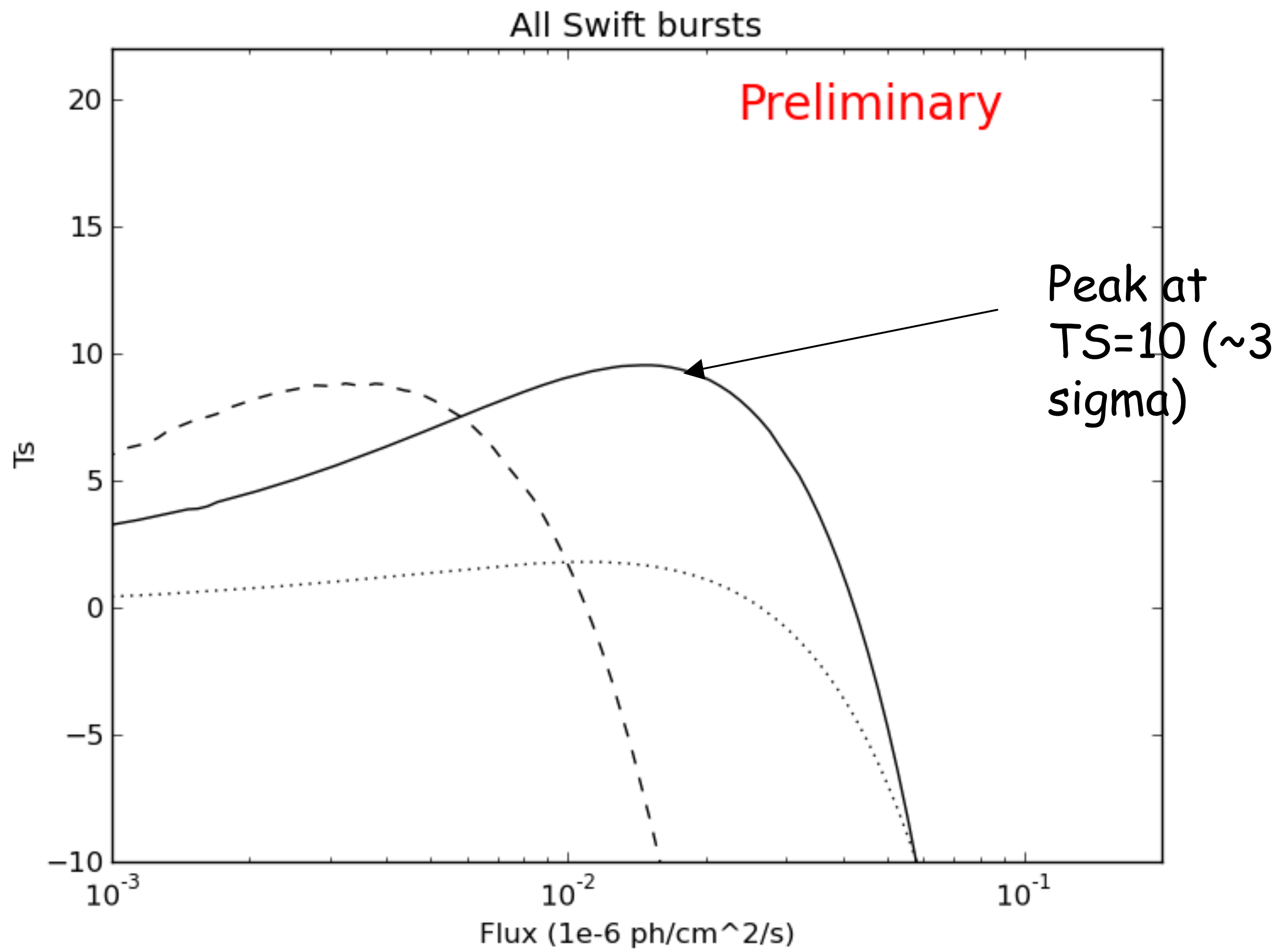


- **Sample of 140 Swift GRB**
  - 49 (35%) show flares at early times
  - 12 with good LAT observations (in FoV and away from Earth limb)
  - 29 flares with simultaneous Fermi/Swift observations, 1 detection!

Afterglow in bulk

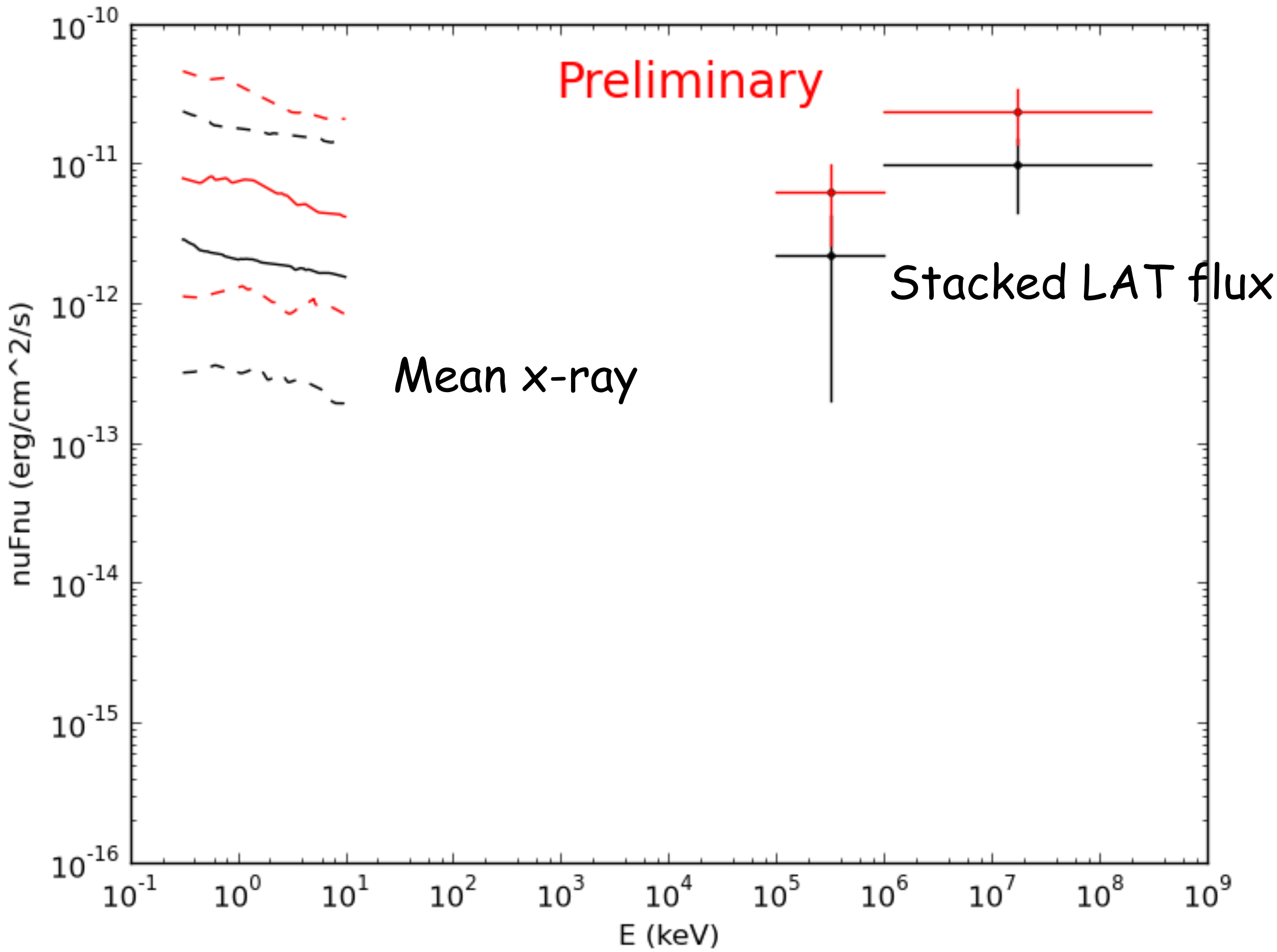
- We have only one joint Swift/LAT trigger
- Swift routinely observes x-ray and optical afterglows
- LAT observes the entire sky every two hours
  – Guaranteed to have LAT observations for every Swift afterglow.
  – Remove the two known detections (GRB090510 and GRB0100728A) and combine the rest of the GRB to seach for a weak signal
- 155 BAT GRBs from Aug 2008 - Dec 2010 with XRT detections
- For each burst, perform likelihood analysis between 0.1-300 GeV, 0.1-1 GeV and 1-300 GeV
  – Calculate test statistic (TS) as a function of flux (peak indicates best fit value for each GRB
  – Sum the TS curves for all GRB, the peak in the summed curve is the most probable value for the population

Combining to get a marginally significant detection



- **Signal becomes more significant if we select UVOT detected bursts, or select bursts with high fluence in prompt phase**

Comparing X-ray and Gamma-ray SED



- **Evidence for an SSC component?**

Summary Table & Highest Energy Events compatible with the GRB position

GRB Name	Likelihood Detection >100 MeV	LLE Detection	LAT off axis angle at T_0 (degrees)	GBM T_{90}	N Pred. Events (>100MeV, Trans.)	HE Delayed Onset?	Long Lived HE Emission?	Maximum Energy (GeV) meas. during the LAT detection	Arrival time of the highest events (seconds since trigger)	Redshift
GRB080825C	√	√	60.3	21	10	√	√	0.6	28.3	-
GRB080916C	√	√	48.8	63	211	√	√	13.2	16.5	4.35
GRB081006	√	x	10.7	6.4	13	-	√	0.6	1.8	-
GRB081024B	√	√	18.6	0.6	11	√	√	3.1	0.6	-
GRB081215	x	√	97.1	5.6	-	-	-	-	-	-
GRB081224	x	√	17	16.4	-	√	√	-	-	-
GRB090217	√	√	34.5	33.3	17	√	√	0.9	14.8	-
GRB090227B	√	√	70.1	1.3	3	-	-	-	-	-
GRB090323	√	√	57.2	135.2	39	√	√	7.5	195.4	3.57
GRB090328	√	√	64.6	61.7	58	√	√	5.3	698.3	0.736
GRB090510	√	√	13.6	1	183	√	√	31.3	0.8	0.903
GRB090531B	x	√	21.9	0.8	-	-	-	-	-	-
GRB090626	√	√	18.2	48.9	30	√	√	2.1	111.6	-
GRB090902B	√	√	50.8	19.3	323	√	√	33.4	81.7	1.822
GRB090926	√	√	48.1	13.8	252	√	√	19.6	24.8	2.106
GRB091003	√	√	12.3	20.2	33	√	√	2.8	6.5	0.897
GRB091031	√	√	23.8	33.9	16	√	√	1.2	79.7	-
GRB100116A	√	√	26.6	102.5	21	-	√	2.2	105.7	-
GRB100225A	x	√	54.9	13	-	-	-	-	-	-
GRB100325A	√	x	7.4	7.1	5	-	√	0.8	0.4	-
GRB100414A	√	√	69	26.5	28	√	√	4.3	39.3	1.368
GRB100707A	x	√	90.3	81.8	-	-	-	-	-	-
GRB100724B	√	√	48.8	87	24	-	-	0.1	15.4	-
GRB100728A	√	x	59.9	162.9	17	-	√	1.7	709	-
GRB101014A	x	√	54.1	450.9	-	-	-	-	-	-
GRB101123A	x	√	84.2	~160	-	-	-	-	-	-
GRB110120A	√	x	13.7	~20	9	-	√	1.8	72.5	-

PRELIMINARY

Some comments on the extra spectral component

- Leptonic models : Inverse Compton, SSC
  - Low-energy excess and delay -> variability not explained
  - Couple internal shocks to photospheric emission ? (Ryde 2010, Toma 2010)
- Hadronic models : p synchrotron, hadronic cascades (Asano 2009, Razzaque 2009)
  - Low-energy excess (from secondary pairs)
  - Late onset (p acceleration and cascade development)
  - Require large B field and larger energy than observed
  - What about GRB 090926A spike? (variability at all energies)
- External shock synchrotron models (Early afterglow) (Ghisellini 2010, Kumar & Barniol Duran 2009), but also Piran 2010
  - Delayed onset, smooth afterglow
  - High variability of prompt emission not reproduced

Lorentz Invariance Violation

- **There is a fundamental scale (Planck scale $\lambda_{Pl} \approx 10^{-35}$ m) at which quantum gravity (QG) effects are expected to strongly affect the nature of space-time.**
- **Lorentz symmetry implies a scale-free space-time**
- **QG effects might cause violations of Lorentz Invariance (LIV) → $\upsilon_\gamma(E_\gamma) \neq c$:**
- **LIV terms are typically described using a Taylor series:**

$$c^2 p_\gamma^2 = E_\gamma^2 \left[1 + \sum_{k=1}^{\infty} s_k \left(\frac{E_\gamma}{M_{QG,k} c^2} \right)^k \right]$$

$$M_{QG} \lesssim M_{Planck} \equiv \sqrt{\hbar c / G} \simeq 1.22 \times 10^{19} GeV/c^2$$

Lorentz Invariance Violation

- QG effects might cause violations of Lorentz Invariance (LIV) → $\upsilon_\gamma(E_\gamma) \neq c$
- The now energy-dependent speed of light can be expressed as:

Usually n=1 or 2 (linear and quadratic LIV respectively).

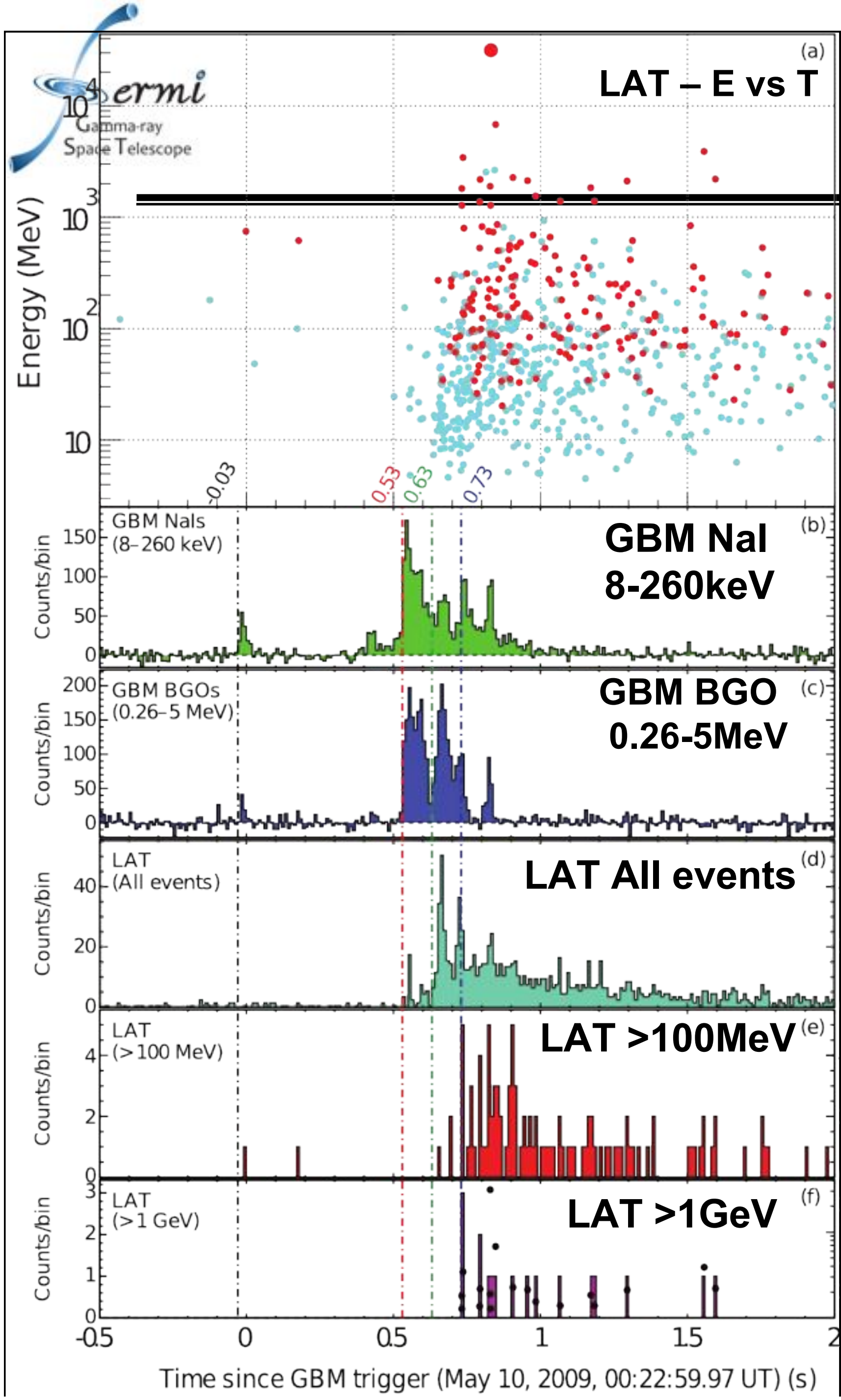
$$\upsilon_\gamma = \frac{\partial E_\gamma}{\partial p_\gamma} \simeq c \left[1 - s_n \frac{1+n}{2} \left(\frac{E_\gamma}{M_{QG,n} c^2} \right)^n \right]$$

s_n=+1 or -1 for speed retardation or acceleration with an increasing photon energy.

LIV perturbation term we would like to constrain

- There are many models that *allow* such Lorentz-Invariance violations, and some others that *actually predict* them (e.g. stringy-foam model J. Ellis et al. 2008).
- If the speed of light depends on its energy → then two photons of different energies emitted together will arrive at different times.

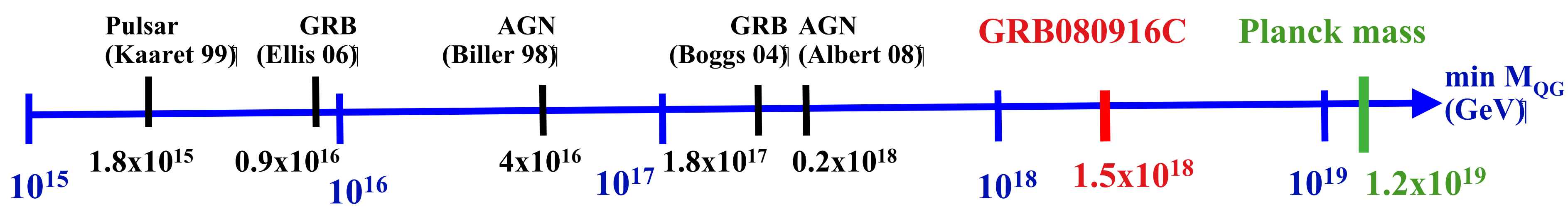
GRB090510 as seen by Fermi



- **Top**: Energy versus Time plot for the events detected by the LAT.
- **Light curves**: GRB's emission at different energies.
- The GRB started with a precursor event, that caused the GBM trigger.
- After about half a second the bulk of the main emission started.
- How was this GRB used to constrain LV?
  - Using the 31GeV photon and an assumption for its maximum time delay.
  - Based on its tens-of-ms narrow pulses and searching for spectral lags

Fermi-LAT Constraints from GRB090510

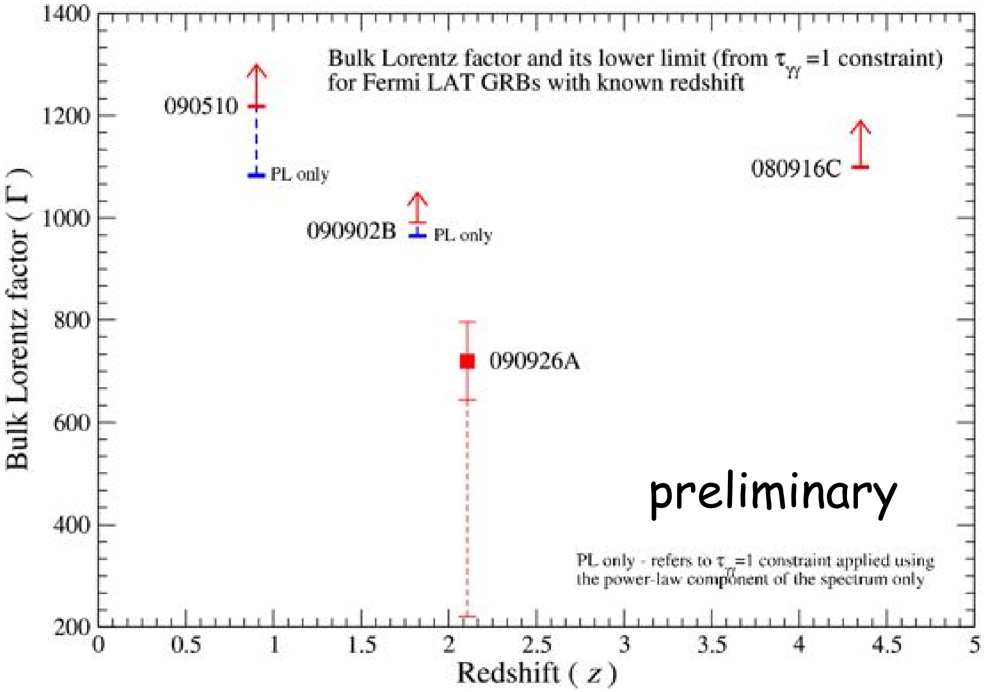
- **Extract dispersion information from all the detected LAT photons (detected energy range 35MeV – 31GeV).**
  - **Performed multiple trials, in which it moved each photon time according to a *trial spectral lag coefficient* (in ms/GeV), find the lag that maximises the sharpness of the lightcurve.**
  - **The spectral lag coefficient *was found to be consistent with zero*.**
- **Perform a bootstrap analysis to gauge the statistical errors of that measurement, which produced our final result:**
  - **a symmetric upper limit on the spectral lag coefficient**
- **$|\Delta t/\Delta E| < 30 ms/GeV \leftrightarrow M_{QG,1} > 1.22 M_{Pl}$**
- **(99% CL) on possible linear (n=1) dispersion of either sign ($s_n = \pm 1$).**



How fast is the emission region moving?

- **Relativistic motion of the emitting shell:**
  - **A relativistic motion of the shell allows higher energy events in dense region to escape.**
  - **Observing high-energy events correlated with the fast variability allows us to constrain to the speed (Γ_{min}) of the emitting shell.**

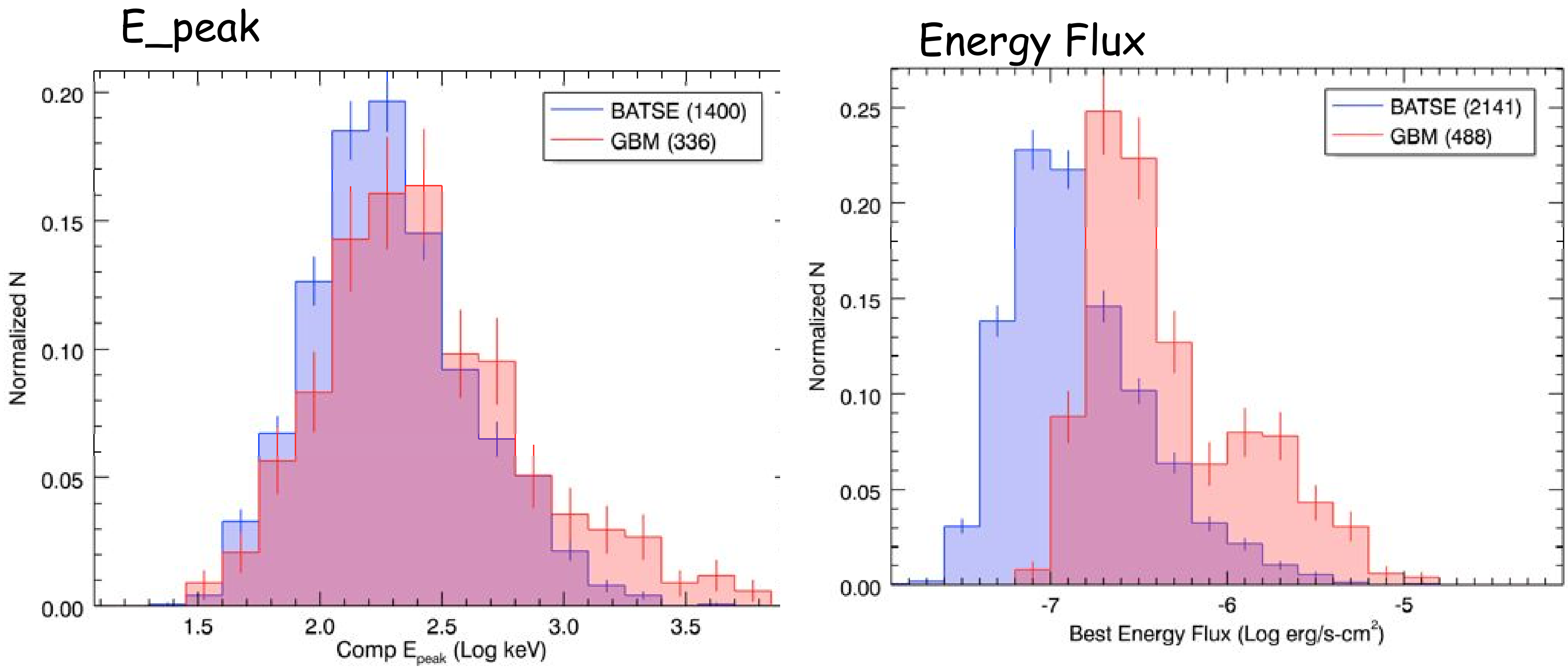
- **For target photon spectrum assume band function, or power-law.**
- **Caveat : target photon field assumed uniform, isotropic, time-independent**
  - **More realistic modeling yields significantly (~3 times) lower values**



Summary

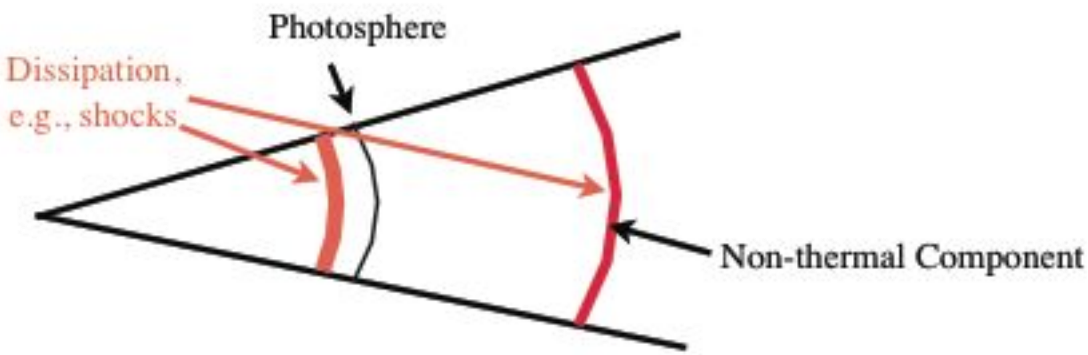
- 250 GRB/year detected by GBM
- 27 GRBs detected at high energy by the Fermi LAT
- Common properties at high energies
  - Temporal extended emission
    - Flux decreases as a power-law with time, with no breaks
  - Time onset between the LAT and GBM
  - Existence of an extra spectral component
- Measured a cut-off in the spectrum
  - This could explain why we are seeing fewer bursts than we expected
- New techniques to extend the energy range to the LAT at lower energy (<100 MeV)
  - Study of the cut-offs
  - Filling the gap with the GBM
- Waiting for more MW early afterglow observations (joint Lat-BAT trigger, or LAT onboard trigger + rapid TOO)

GBM Observations of GRB



- **GBM detects ~250 GRB/year (c.f. 100 with Swift)**
  - **Exceed pre-launch expectations of ~200/year due to flexible trigger algorithm**
- **Broad spectral coverage, relatively poor localization**

GBM Spectra - Thermal Components?

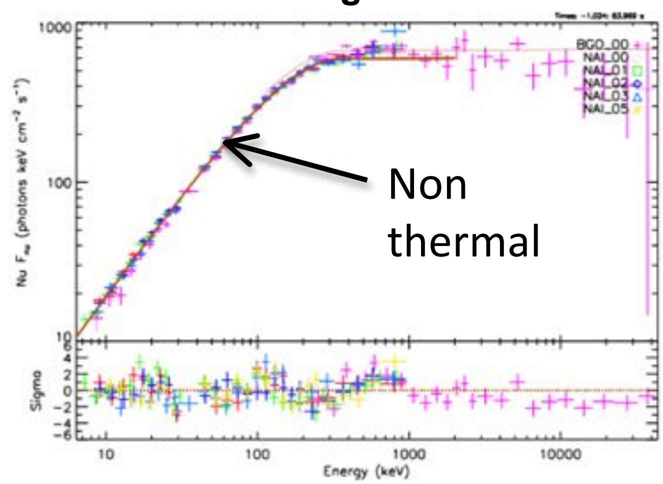


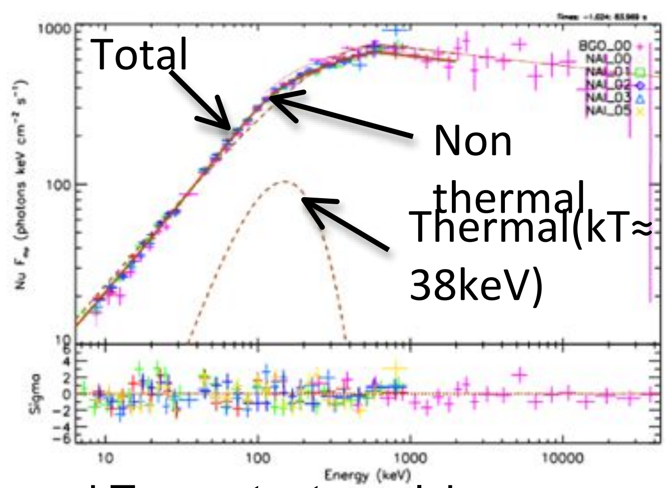
Expect thermal/blackbody component from photosphere

- **Black body components have been fit in several GRB - GRB080916C, GRB090902, GRB100724B…**

Guiriec et al, 2011, Ryde et al 2011

GRB100724B - brightest GBM burst

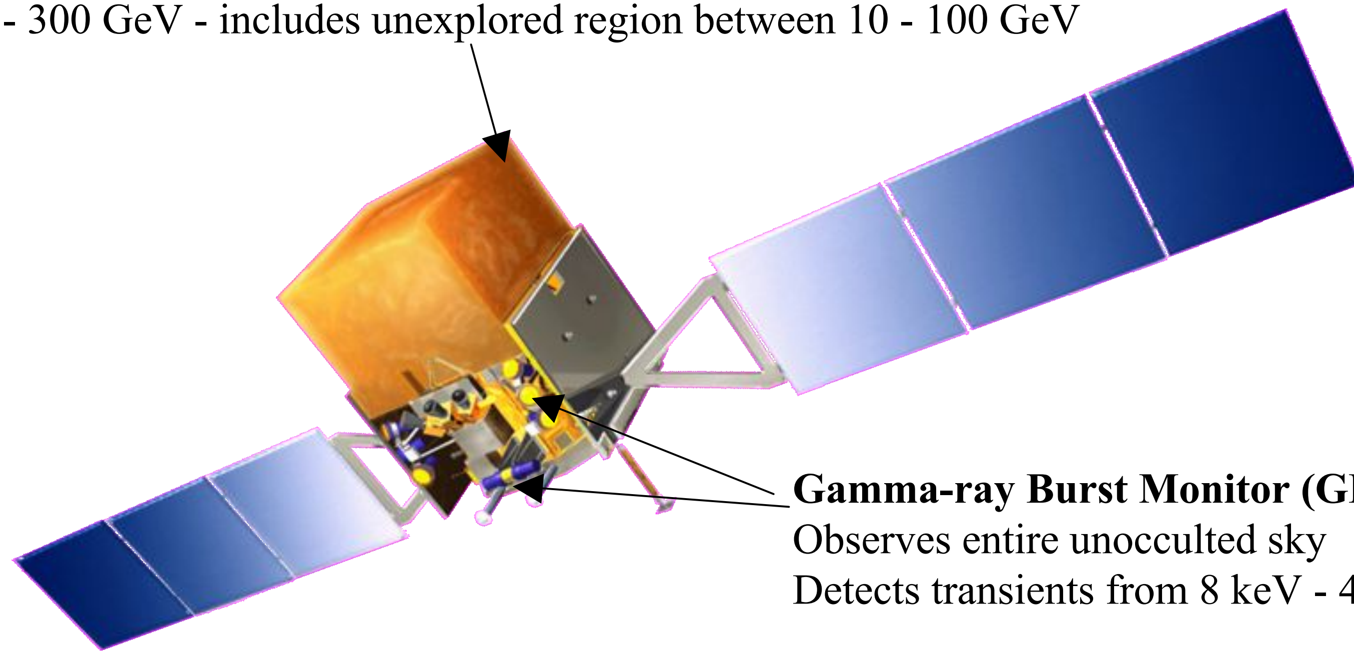




kT~constant, evolving non-thermal component

The Fermi Observatory

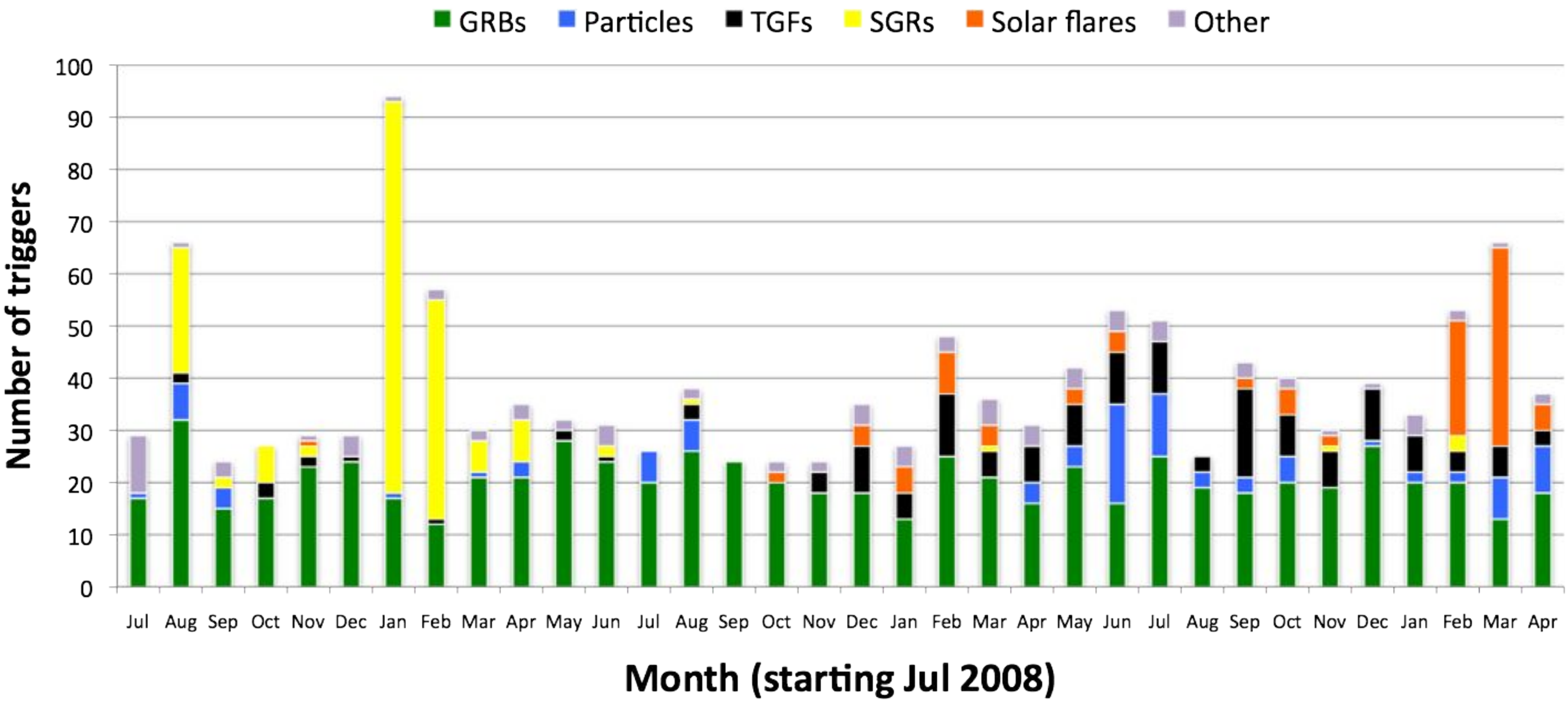
Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

- **Huge improvement over previous missions in this waveband**
  - **Increased effective area**
  - **Improved angular resolution**
  - **Broader energy range**
  - **Wide field of view**

GBM Triggers/Month

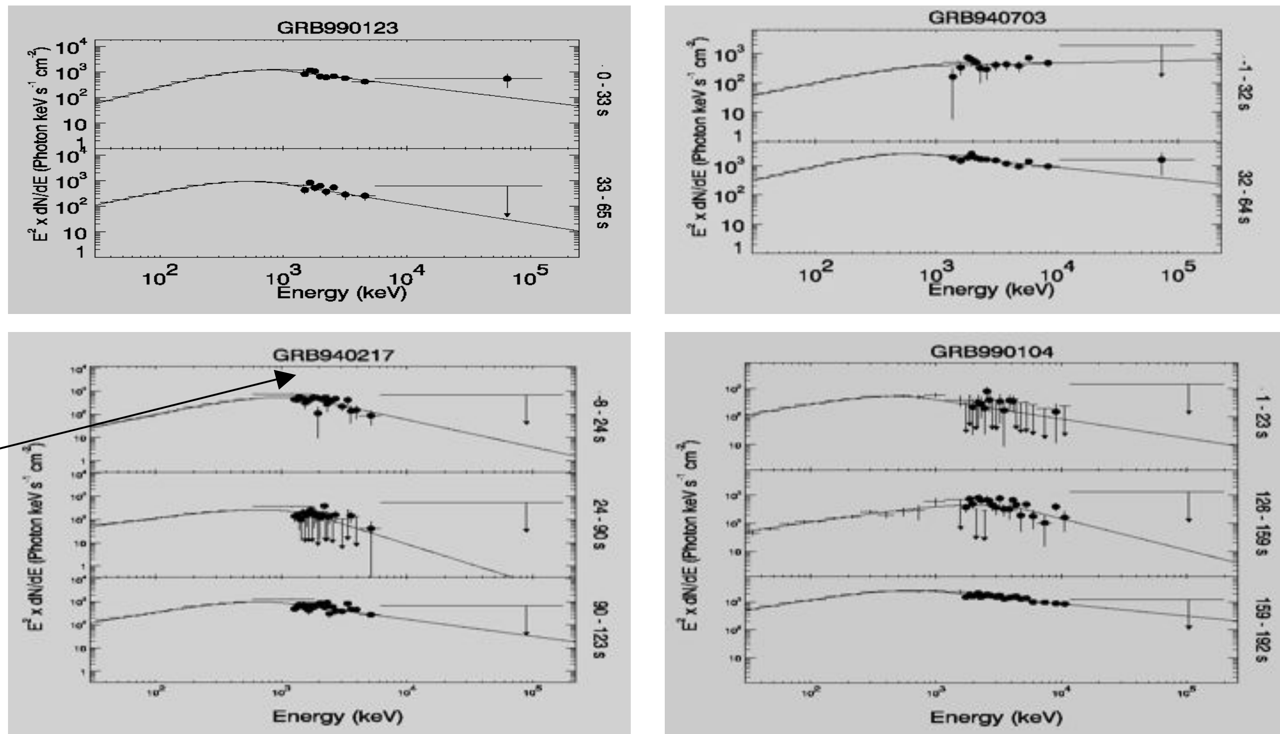


- **Nov 9, 2009 - add new TGF trigger**
  - **TGF trigger rate increased by factor of ~10 to 1 per 3.7 days**
- **Feb/March 2011, solar activity**

Joint EGRET-BATSE observations

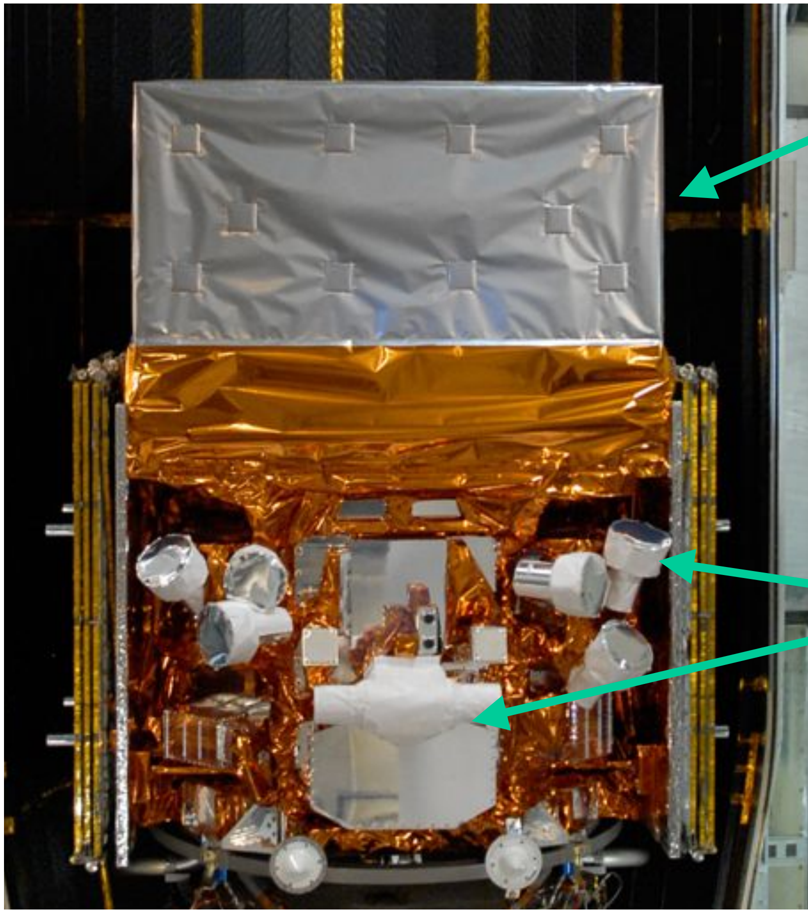
- **High energy component not always present in EGRET TASC observations.**

Note this GRB



- **Above 100 MeV, spark chamber observations were much more sensitive than TASC observations (albeit with smaller FoV)**

Fermi Observatory



Large Area Telescope (LAT):

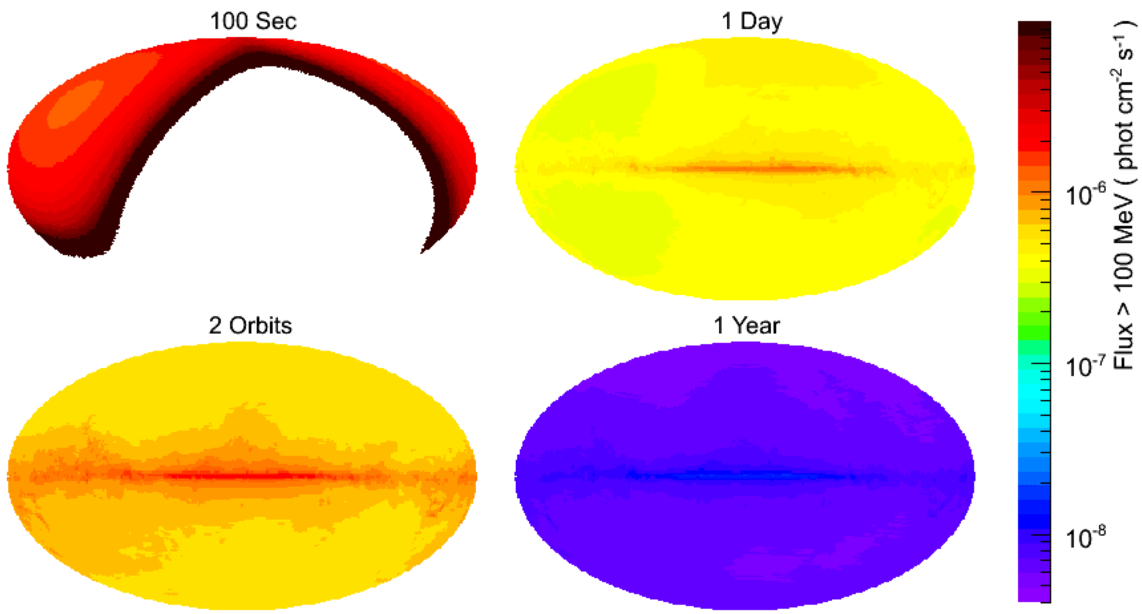
- 20 MeV - >300 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

Gamma-ray Burst Monitor (GBM)

- 8 keV - 40 MeV
- views entire unocculted sky

Launched on June 11, 2008

All Sky Coverage



LAT sensitivity on 4 different timescales: 100 s, 1 orbit (96 mins), 1 day and 1 year

- **In survey mode, the LAT observes the entire sky every two orbits (~3 hours).**
- **Multiwavelength observations in coordination with the LAT are limited only by the ability to coordinate to other observations in other wavebands.**
- **Can also perform pointed observations of particularly interesting regions of the sky.**