The high energy GRBs: lessons learned from Fermi

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On behalf of the Fermi GBM and LAT teams

Photospheric emission in BATSE bursts

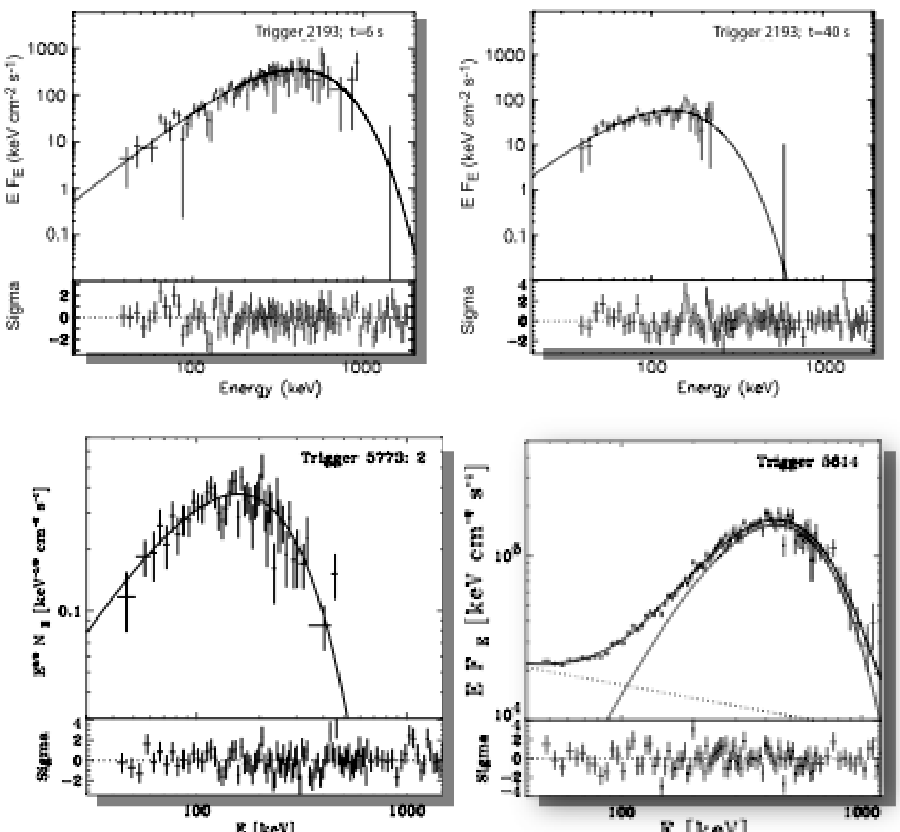
CGRO BATSE ERA (1994-2000)

Spectra from temporally resolved pulses observed by BATSE over the energy range 20-2000 keV.

Spectral fit: Black body combined with a power law:

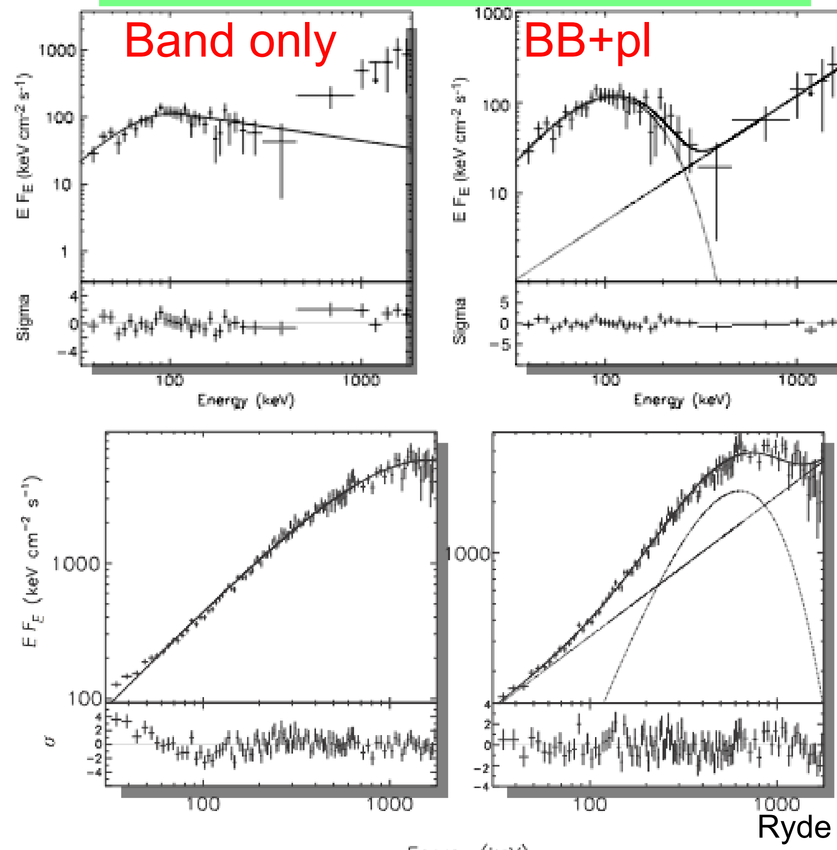
$$N_{\rm E}(E,t) = A(t)\,\frac{E^2}{exp[E/kT(t)]-1} + B(t)\;E^s$$

Photosphere (Planck function)



Ryde 2004 (see also Ghirlanda et al. 2003)

Additional non-thermal emission



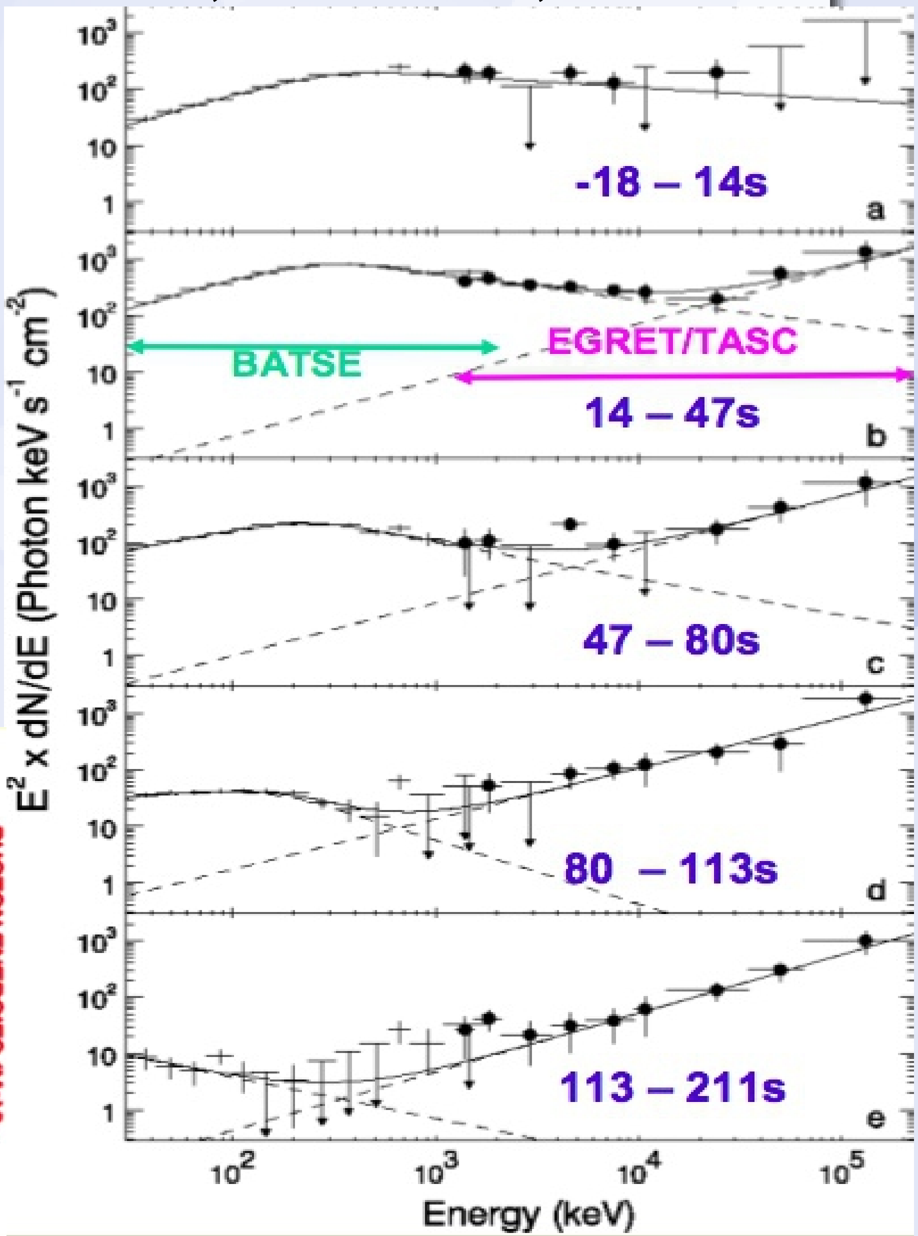
Ryde 2005

EGRET TASC peak at E_p = 1600 keV

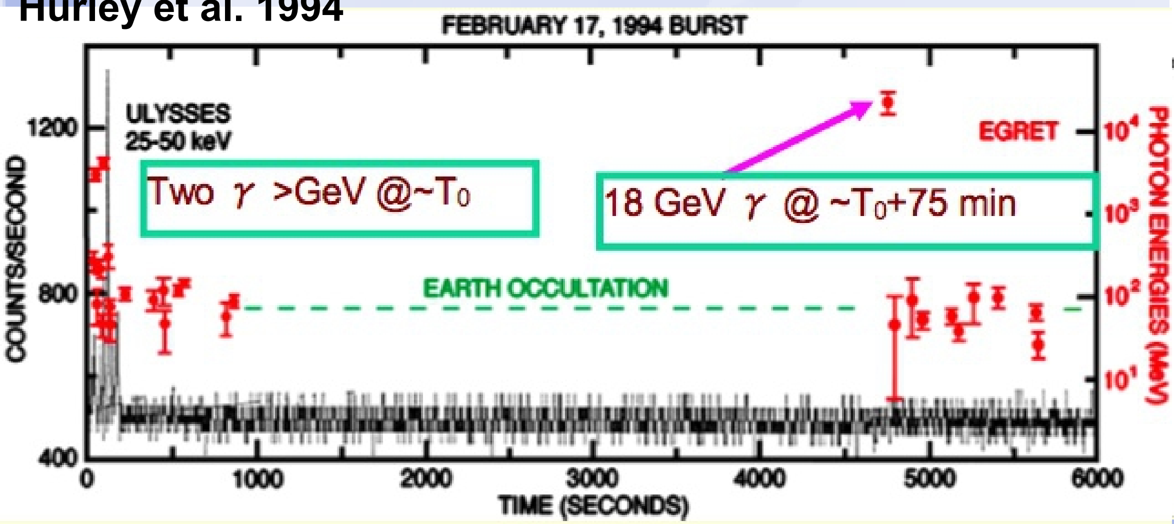
High-Energy Emissions from GRB (Past)

- 5 EGRET bursts with >50 MeV observations in 7 years
- EGRET observed:
  - delayed HE gamma-ray emissions;
  - spectral extra component;

Gonzalez, Nature 2003 424, 749

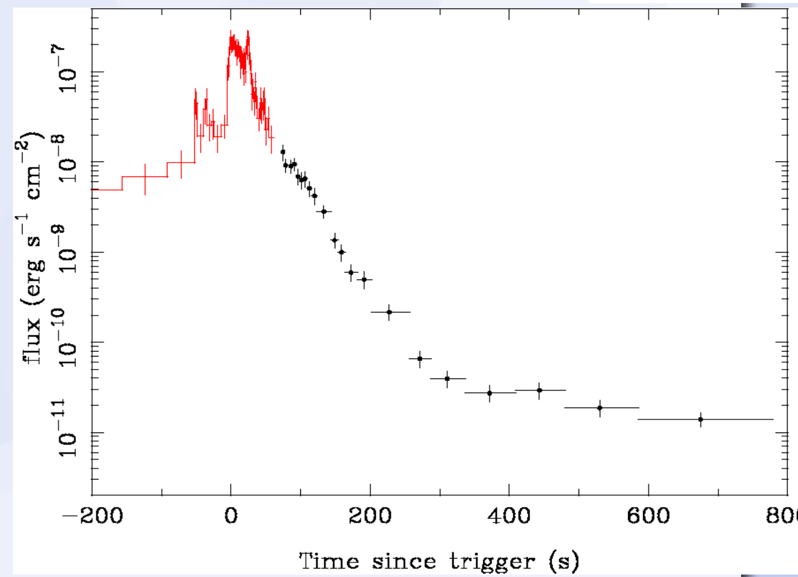


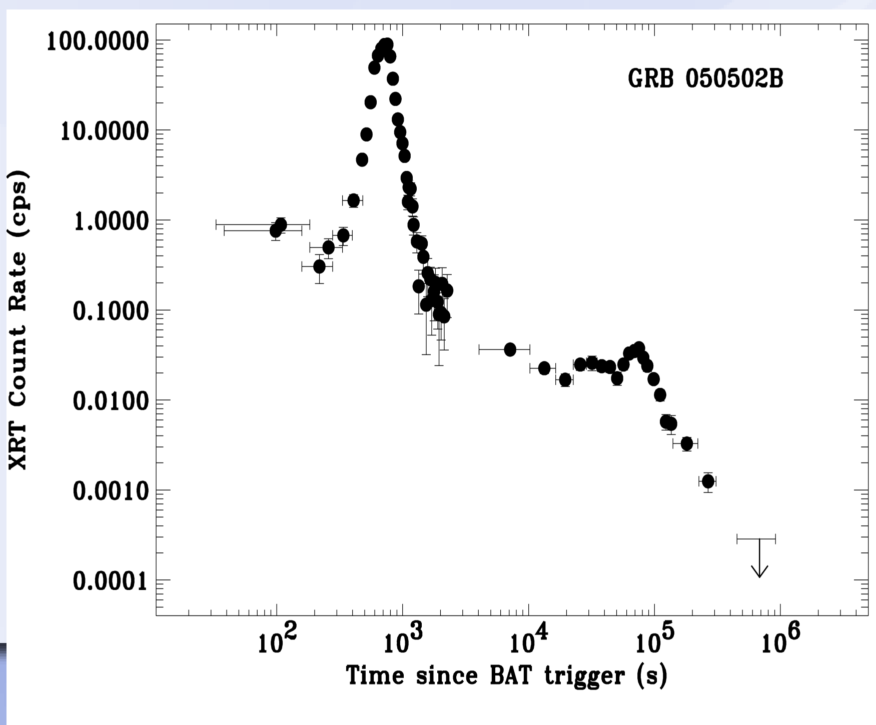
Hurley et al. 1994

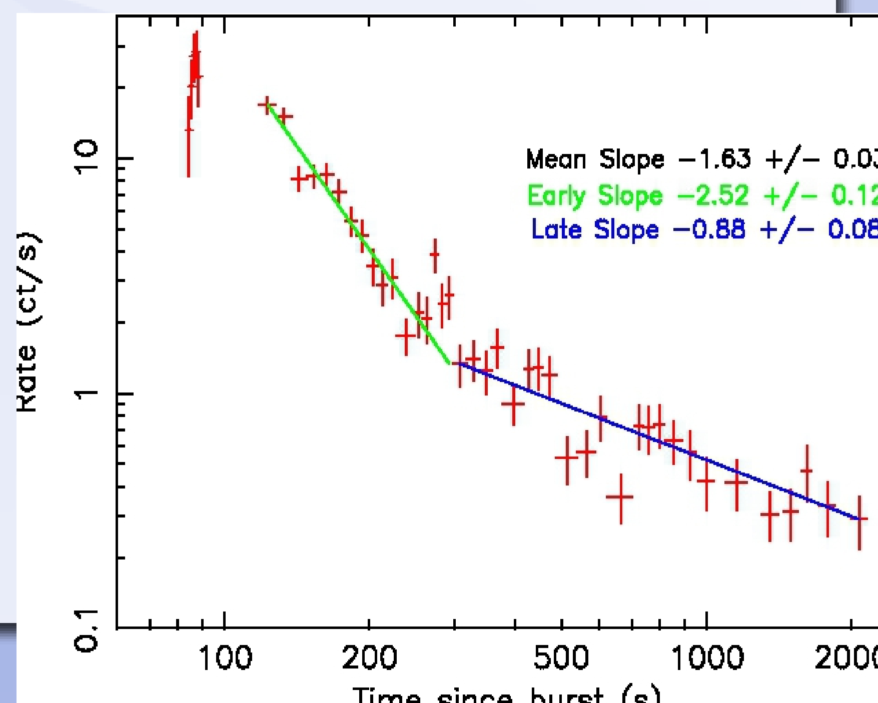


... and the X-ray Afterglow

- Discovered by BeppoSax ('97)
  - Measurements of the distance
- Swift (2004-*):
  - Connection to the "Prompt" emission
  - X-Ray Flashes in the afterglow
  - Steep-Shallow-Steep decay
  - Also short bursts have an afterglow!
  - Fading to lower frequencies







The LAT and GBM on Fermi

The GBM detects ~250 GRBs/year

~18% short

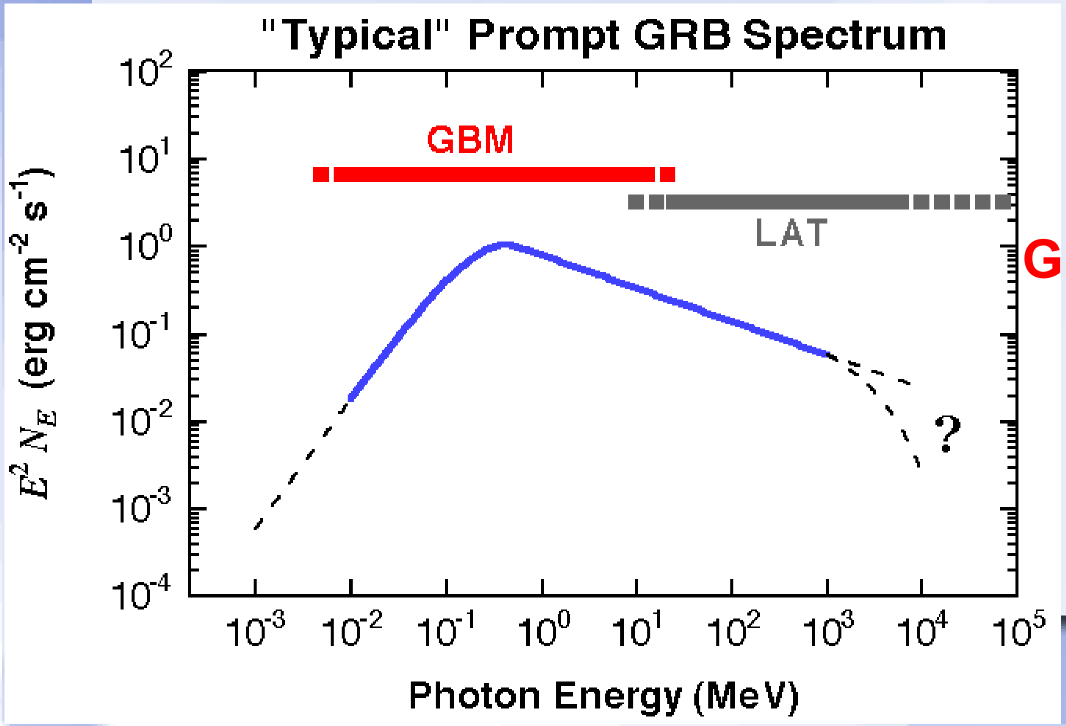
~50% in the LAT FoV

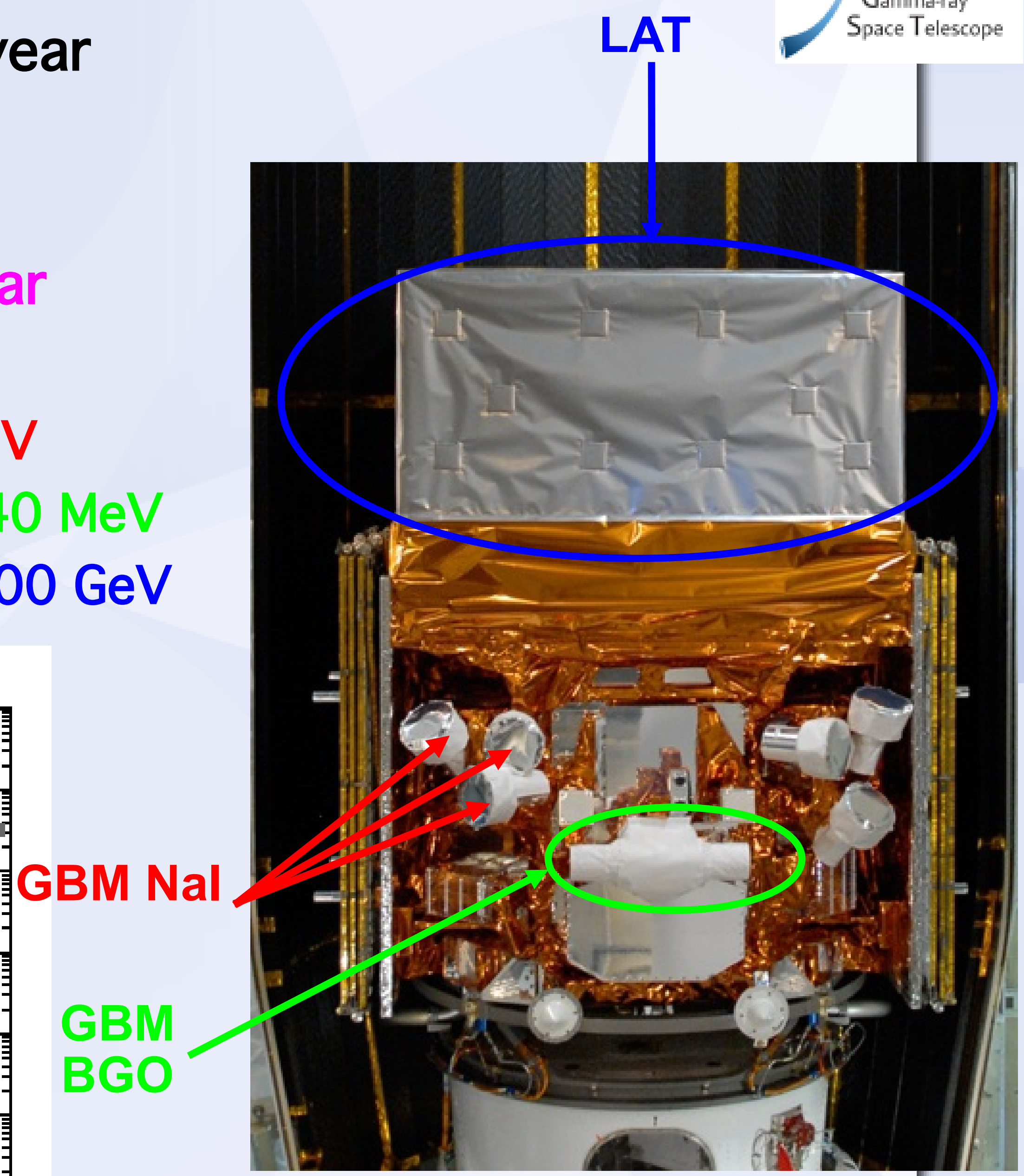
The LAT detects ~10 GRBs/year

NaI: 8 keV - 1 MeV

BGO: 200 keV - 40 MeV

LAT: 30 MeV – 300 GeV





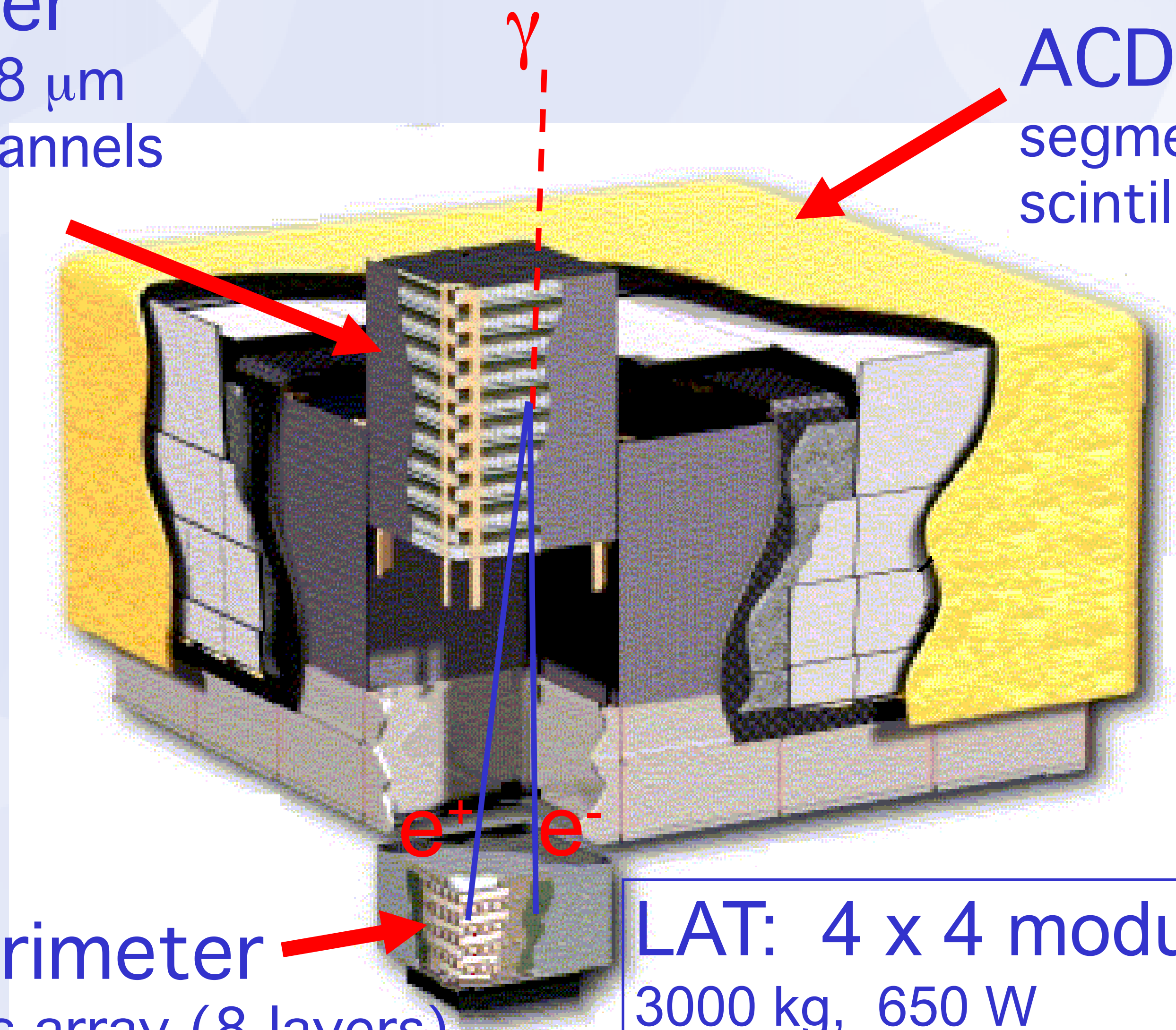
The Large Area Telescope

Si Tracker

pitch = 228 μm
$8.8\ 10^5$ channels
18 planes

ACD

segmented
scintillator tiles



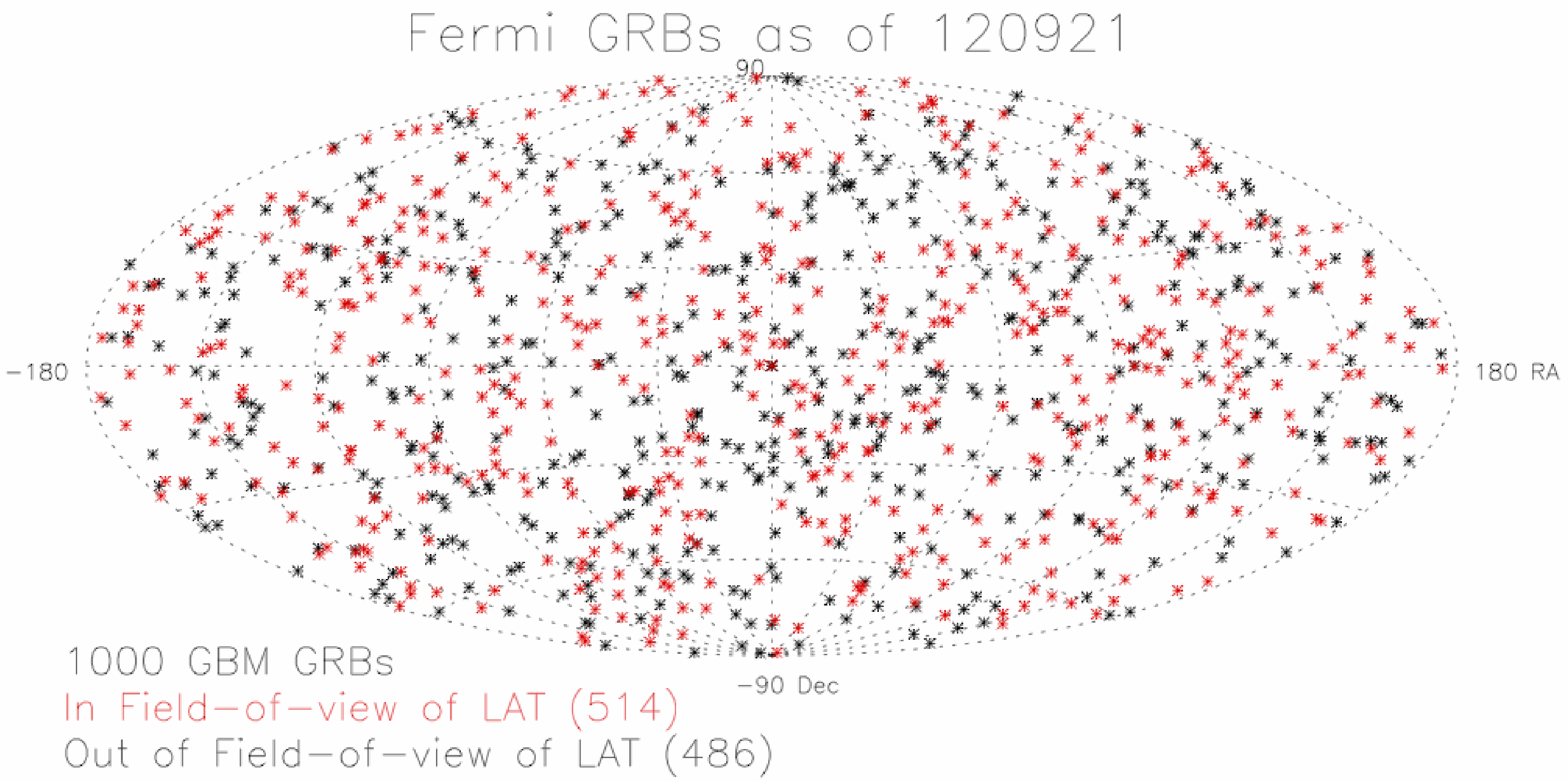
CsI Calorimeter

hodoscopic array (8 layers)
$6.1\ 10^3$ channels

LAT: 4 x 4 modular array

3000 kg, 650 W
20 MeV – 300 GeV

GBM GRBs



Fermi GRBs as of 120921
90
-180
180 RA
-90 Dec
1000 GBM GRBs
In Field-of-view of LAT (514)
Out of Field-of-view of LAT (486)

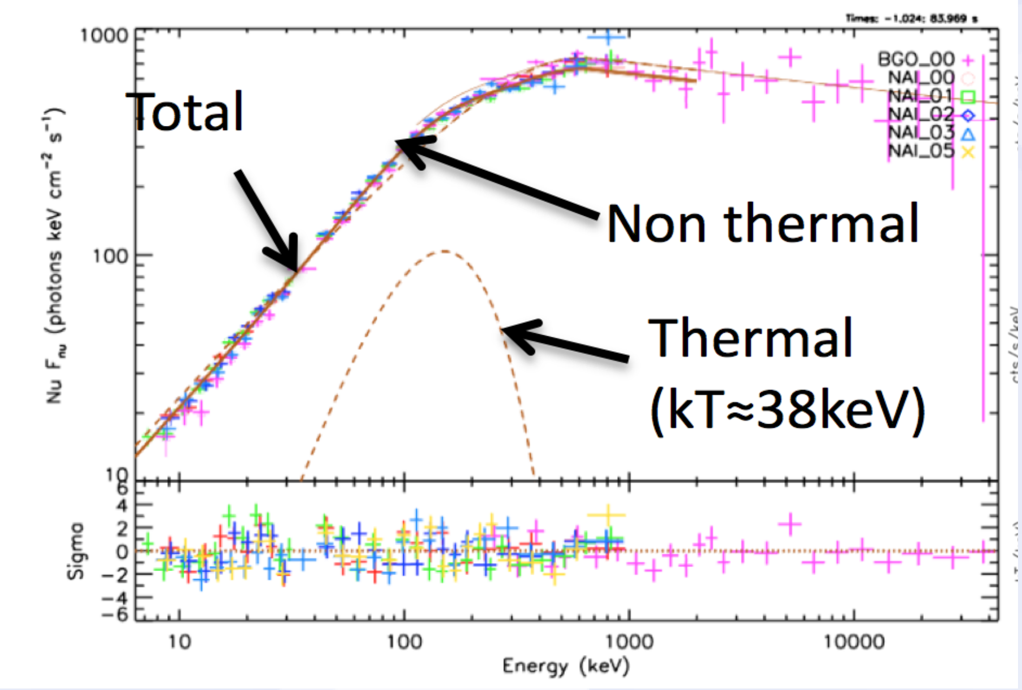
The prompt spectrum

- Band model is favorite only for a subset of bursts, while COMPT and PL are the most favorite;

Table 1
BEST GRB Models

PL	SBPL	BAND	COMP
Fluence spectra			
112 (23%)	68 (14%)	75 (15%)	232 (48%)
Peak flux spectra			
213 (44%)	51 (10%)	69 (14%)	154 (32%)

Goldstein et al, 2012



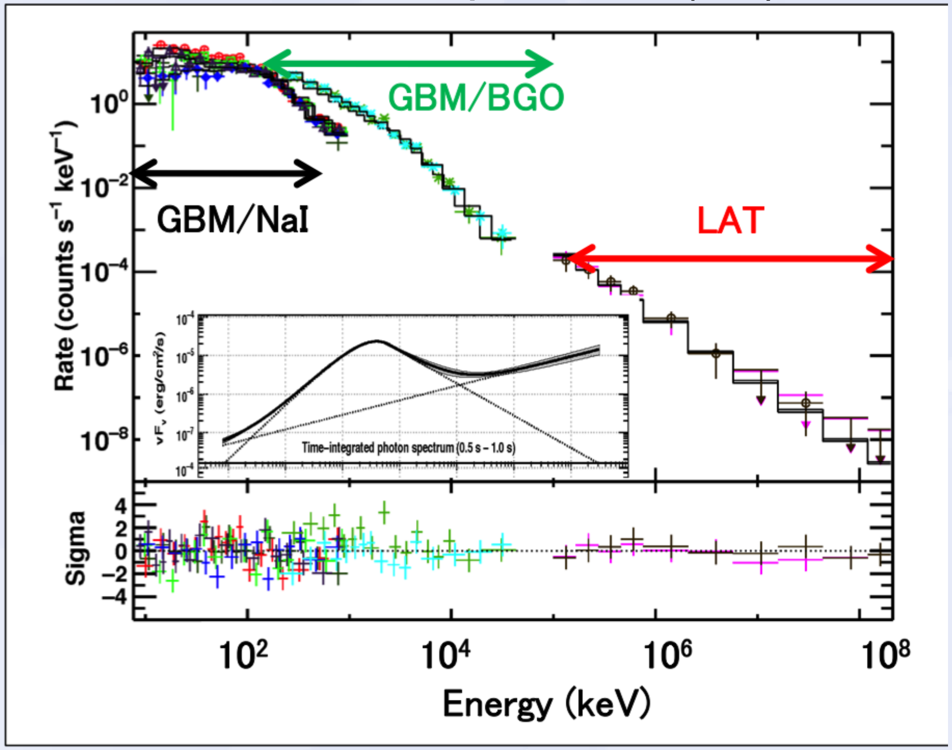
Guiriec et al 2011, ApJL 727,L33

Additional "Black Body" component over a Band function improves the residuals of the fit.

Extra HE spectral component

GRB 090510 (short)

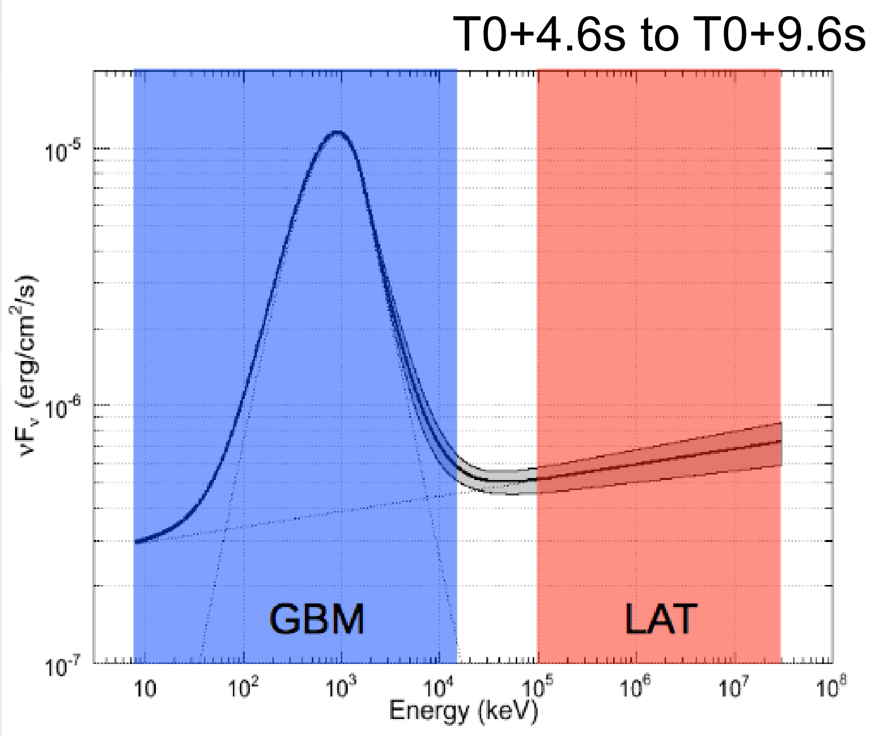
Abdo, A. A. et al., ApJ 716, 1178A (2010)



First extra component by Fermi
At > 5 sigma level

GRB 090902B (long)

Abdo, A. A. et al., ApJL 706, 138 (2009)



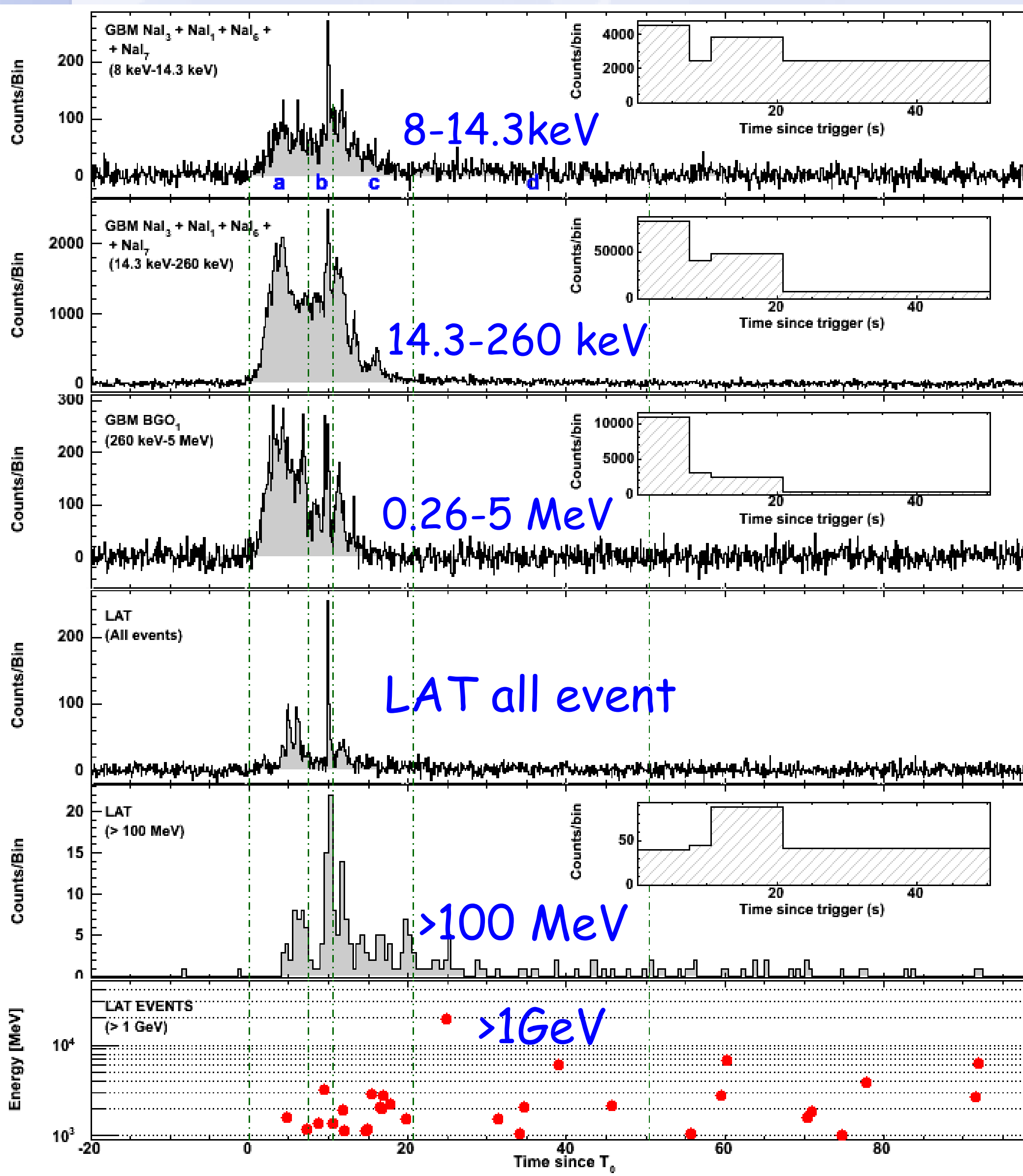
First time a low-energy extension of the PL component has been seen

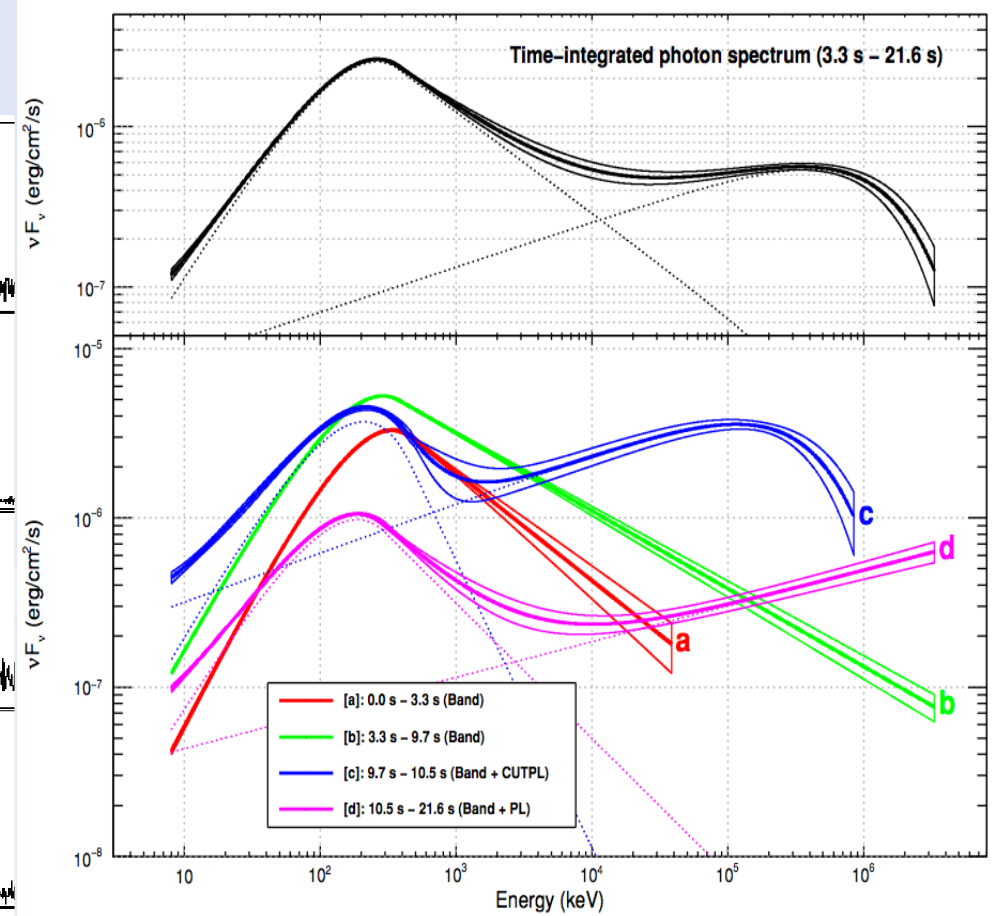
6 LAT GRBs show clear extra PL component

Cut-off on HE spectral component

GRB 090926A (long)

Ackermann et. al. 2011, ApJ 729, 114A





- Extra component shows at >5 σ
- spectral break at ~1.4 GeV
- First direct measurement of Γ ~ 630 (if cutoff due to γ-γ absorption)

Joint LAT GBM spectral analysis

Ackermann et. al. 2013, ApJS 209, 11A

- GRB spectrum in several cases is NOT a simple "Band" function
- Deviation from the Band function at low energy;
- Additional power-law observed at high energy;
- High energy cut-off measured in the spectrum;

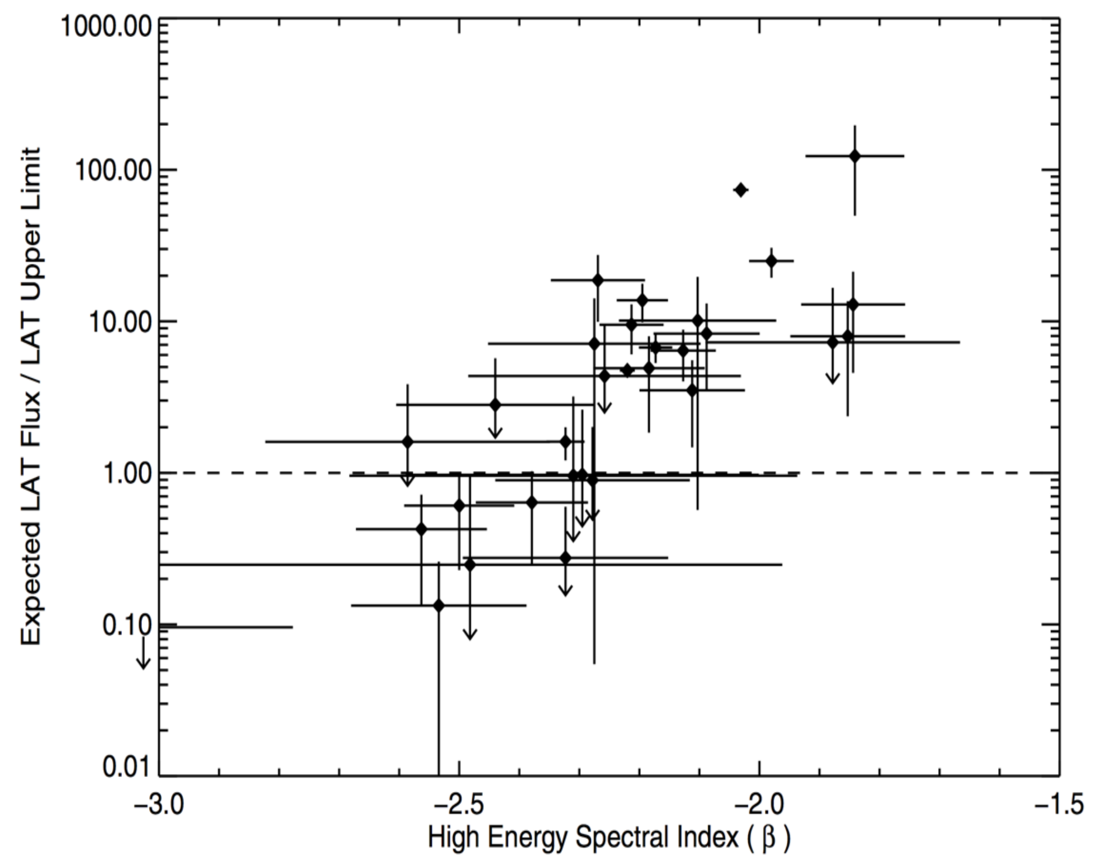
	Fluence 10 keV - 10 GeV (10^{-7} erg/cm^2)	Best model	θ deg
100724B	4665^{-76}_{+78}	Band with exponential cutoff	48.9
090902B	4058^{-24}_{+25}	Comptonized + Power law	50.8
090926A	2225^{-48}_{+50}	Band + Power law with exponential cutoff	48.1
080916C	1795^{-39}_{+41}	Band + Power law	48.8
090323	1528^{-44}_{+44}	Band	57.2
100728A	1293^{-27}_{+28}	Comptonized	59.9
100414A	1098^{-27}_{+35}	Comptonized + Power law	69.0
090626	927^{-16}_{+17}	Logarithmic parabola	18.3
110721A	876^{-28}_{+28}	Logarithmic parabola	40.3
090328	817^{-33}_{+34}	Band	64.6
100116A	638^{-25}_{+26}	Band	26.6
110709A	518^{-27}_{+28}	Band	53.4
080825C	517^{-20}_{+21}	Band	60.3
090217	512^{-15}_{+16}	Band	34.5
091003	461^{-14}_{+15}	Band	21.3
110120A	422^{-22}_{+23}	Band	13.6
110328B	417^{-37}_{+47}	Comptonized	31.7
110731A	379^{-21}_{+20}	Band + Power law	3.4
090510	360^{-16}_{+18}	Band + Power law	13.6
091031	288^{-10}_{+10}	Band	23.9
110428A	255^{-9}_{+10}	Band	34.6
090720B	185^{-11}_{+13}	Band	56.1
100225A	101^{-7}_{+7}	Band	55.5
091208B	93^{-11}_{+13}	Band	55.6
100620A	84^{-9}_{+9}	Band	24.3
081006	56^{-9}_{+10}	Band	11
110529A	49^{-6}_{+6}	Band	30
100325A	46^{-4}_{+4}	Band	7.1
090531B	38^{-5}_{+5}	Comptonized	21.9
081024B	30^{-5}_{+6}	Band	18.7

NOTE.—We exclude from this table all GRBs outside the nominal LAT FOV (with $\theta > 70^\circ$) and GRB 101014A, which was detected too close to the Earth limb.

Non-detected LAT GRB

Bright GBM/BGO GRBs, non detected in the LAT:

➔ the flux “expected” (extrapolated) exeedes the LAT flux UL;

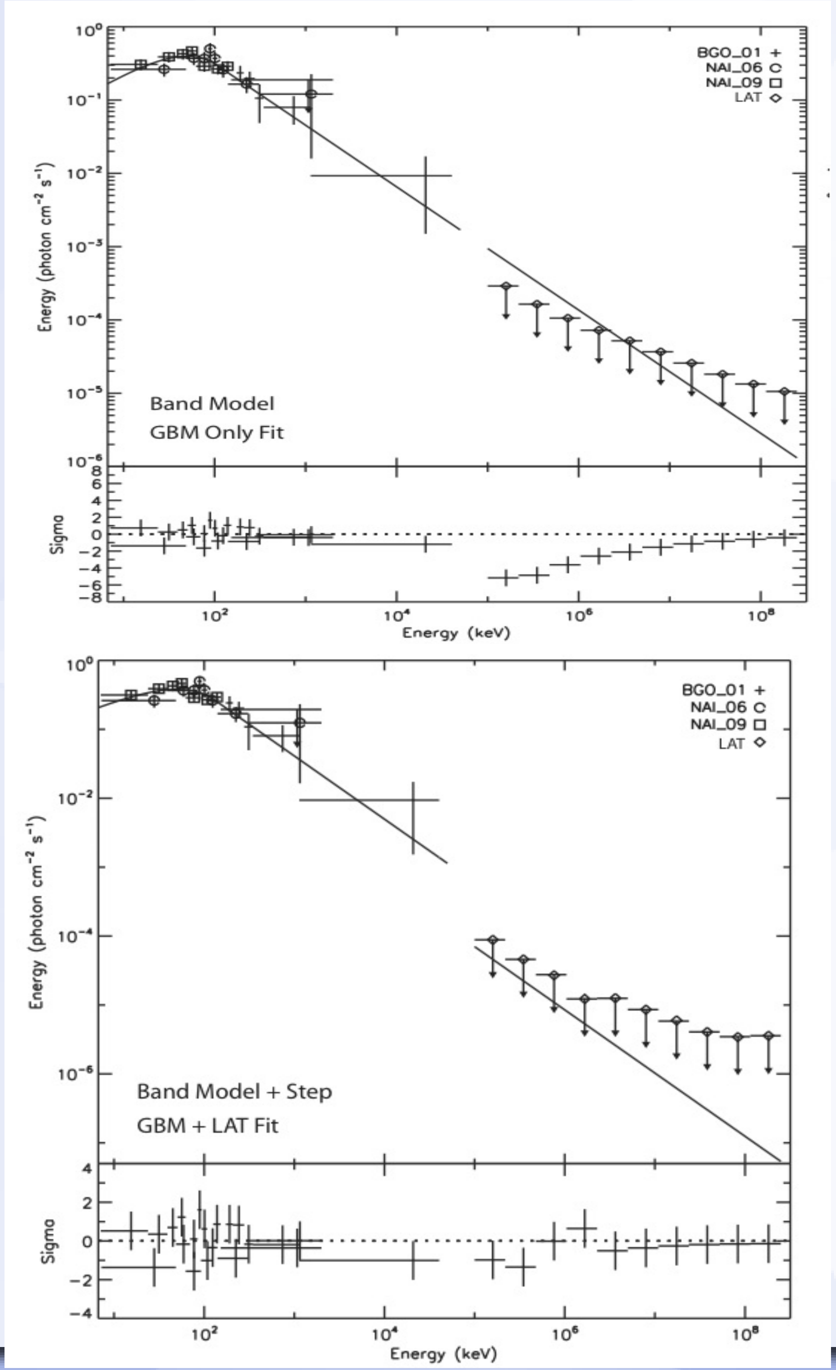


Ackermann et. al. 2012, ApJ 754, 121F

Non-detected LAT GRB

Bright GBM/BGO GRBs, non detected in the LAT:

- ➔ the flux “expected” (extrapolated) exeedes the LAT flux UL;
- ➔ an intrinsic spectral cut off is required to reconcile the GBM and LAT data.



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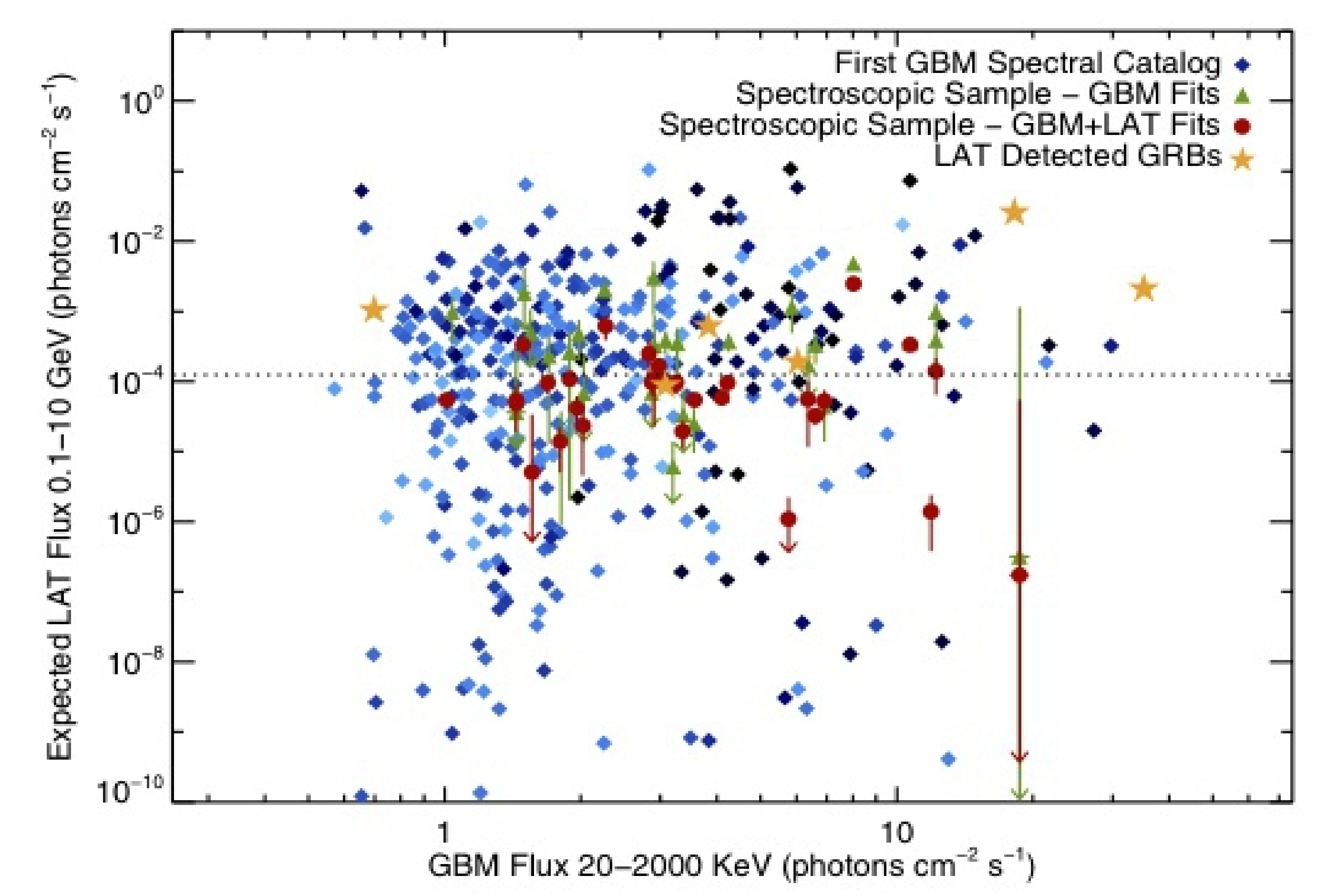
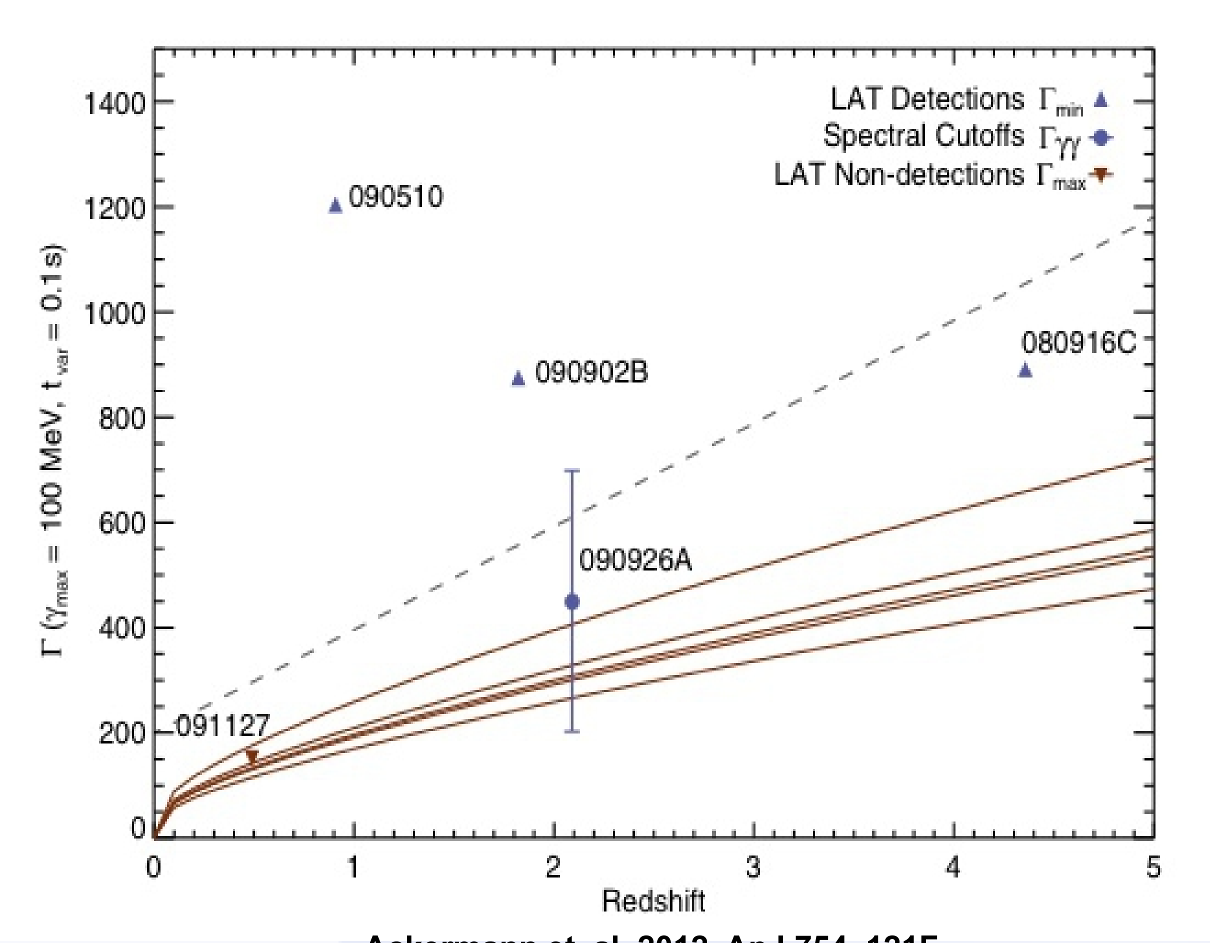


Ackermann et. al. 2012, ApJ 754, 121F

Non-detected LAT GRB

Bright GBM/BGO GRBs, non detected in the LAT:

➔ It is possible to estimate the bulk Lorentz factor if the cut off is due to γγ absorption.

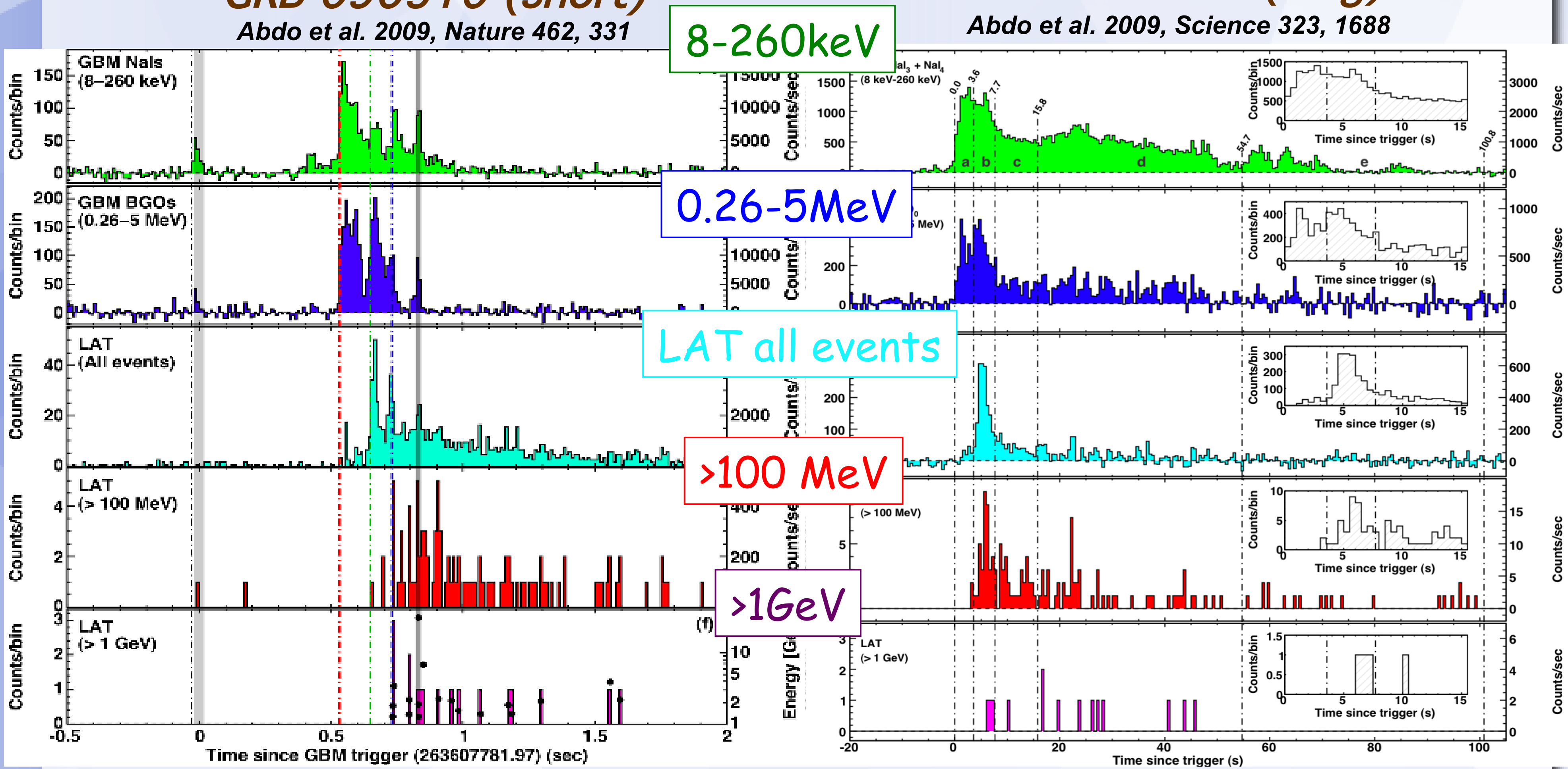


Ackermann et. al. 2012, ApJ 754, 121F

Delayed Onset

GRB 090510 (short)
Abdo et al. 2009, Nature 462, 331

GRB 080916C (long)
Abdo et al. 2009, Science 323, 1688



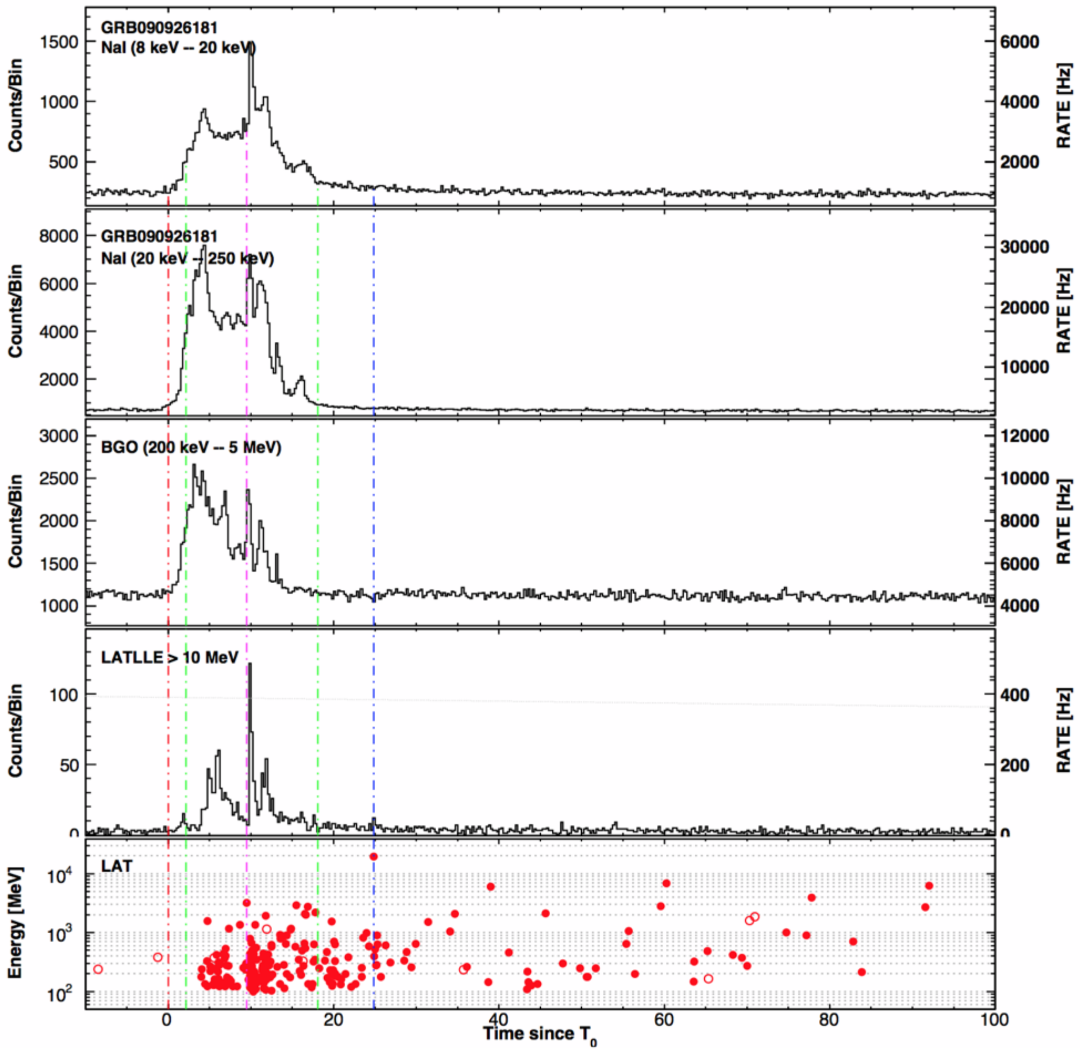
Delay: ~0.5s

Delay: ~5s

Almost all GRBs show a delayed onset of the HE component!!!

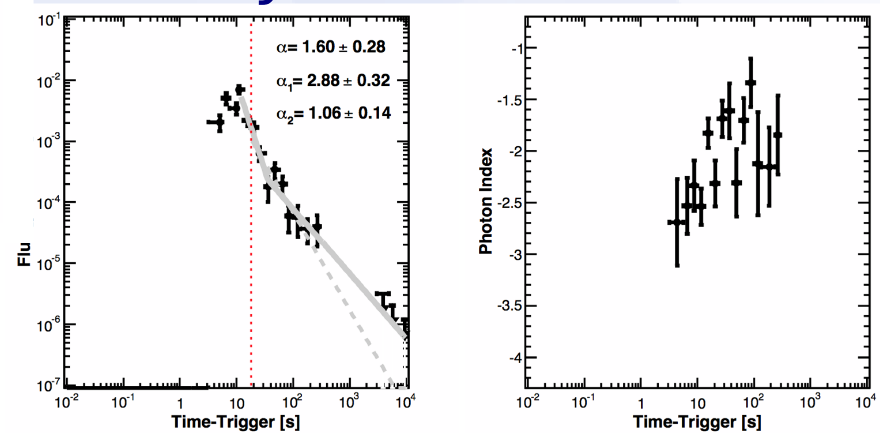
Prompt and temporally extended emission

GRB 090926A (long)



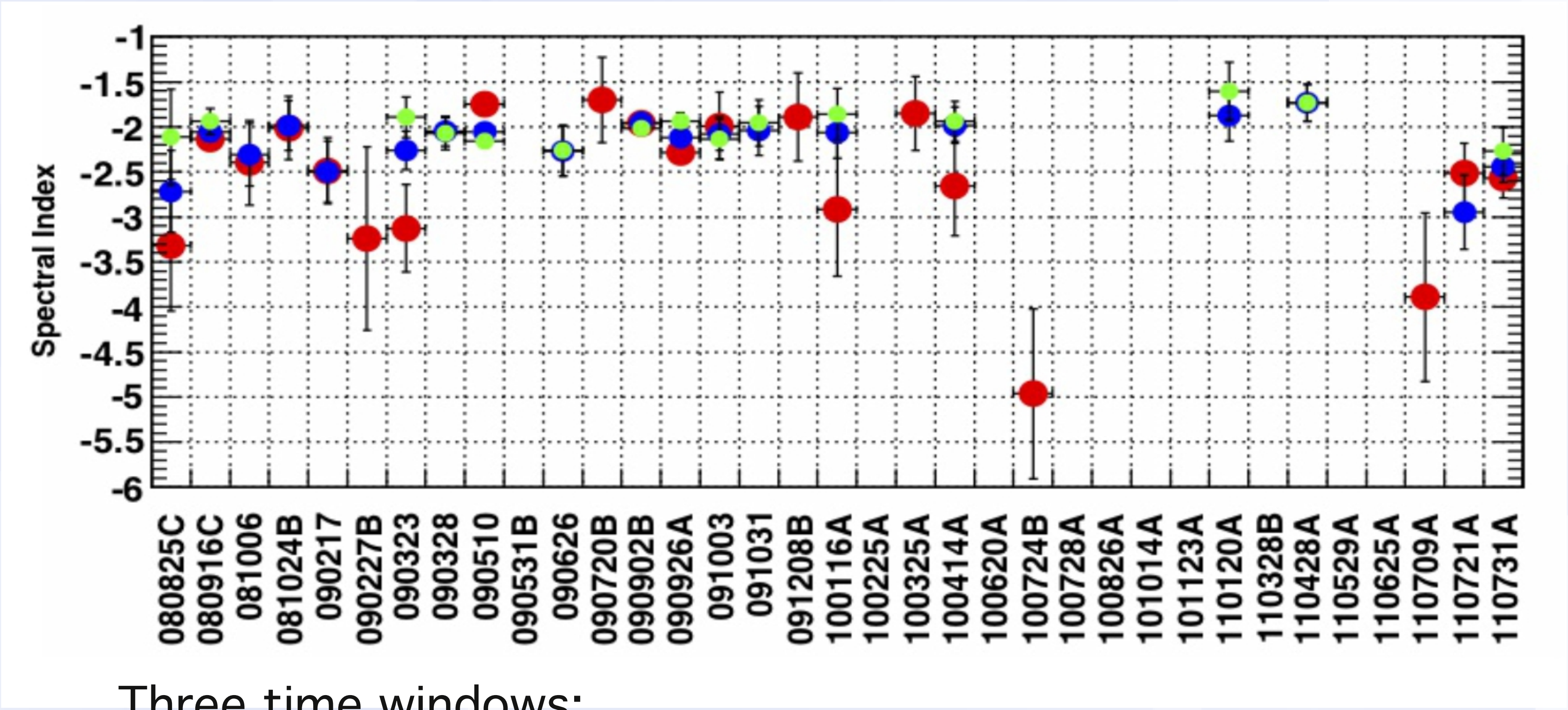
Ackermann et. al. 2013, ApJS 209, 11A

- Clear onset of the high energy
- Spectral evolution in the prompt phase
  - Spectral index stable at later times
- Highest event not coincident with lower energy pulses
- Time extended emission clearly visible



Prompt and temporally extended emission

- The Spectral index is stable at later times and has very similar value in many GRBs of ~ -2.

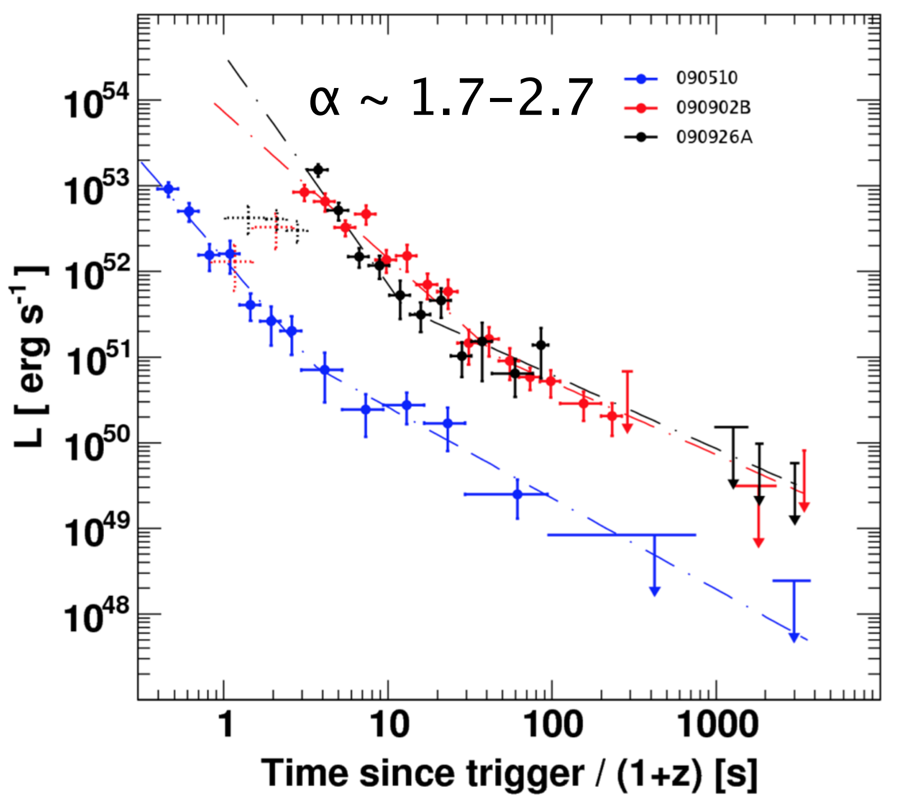


Three time windows:
- GBM;
- LAT;
- EXT;

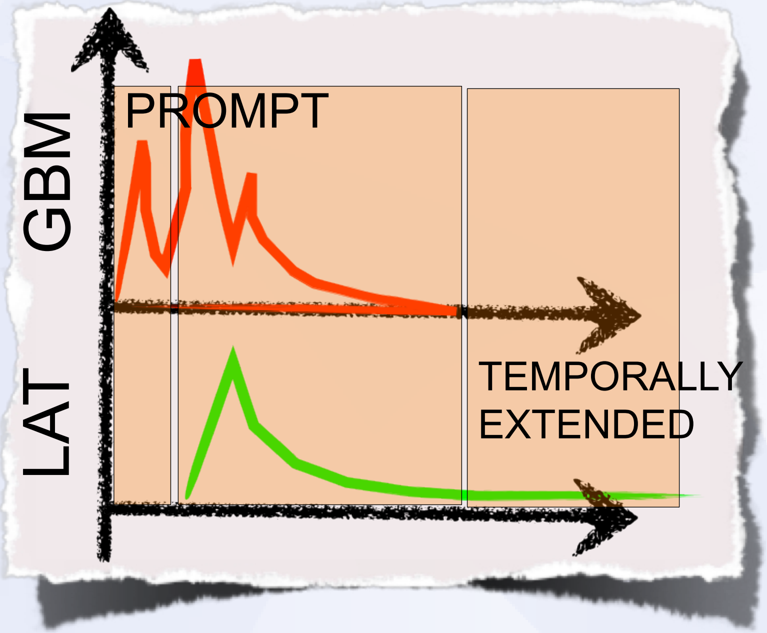
Ackermann et. al. 2013, ApJS 209, 11A

Temporally extended emission

- High-energy emission (observed by the LAT) starts later and lasts longer then the low-energy emission (observed by the GBM).
  - "Delayed onset" and "Temporally extended" emission
  - In three cases a significant (3σ) break is measured in the Light curve



Ackermann et. al. 2013, ApJS 209, 11A



Ground telescope possible catches

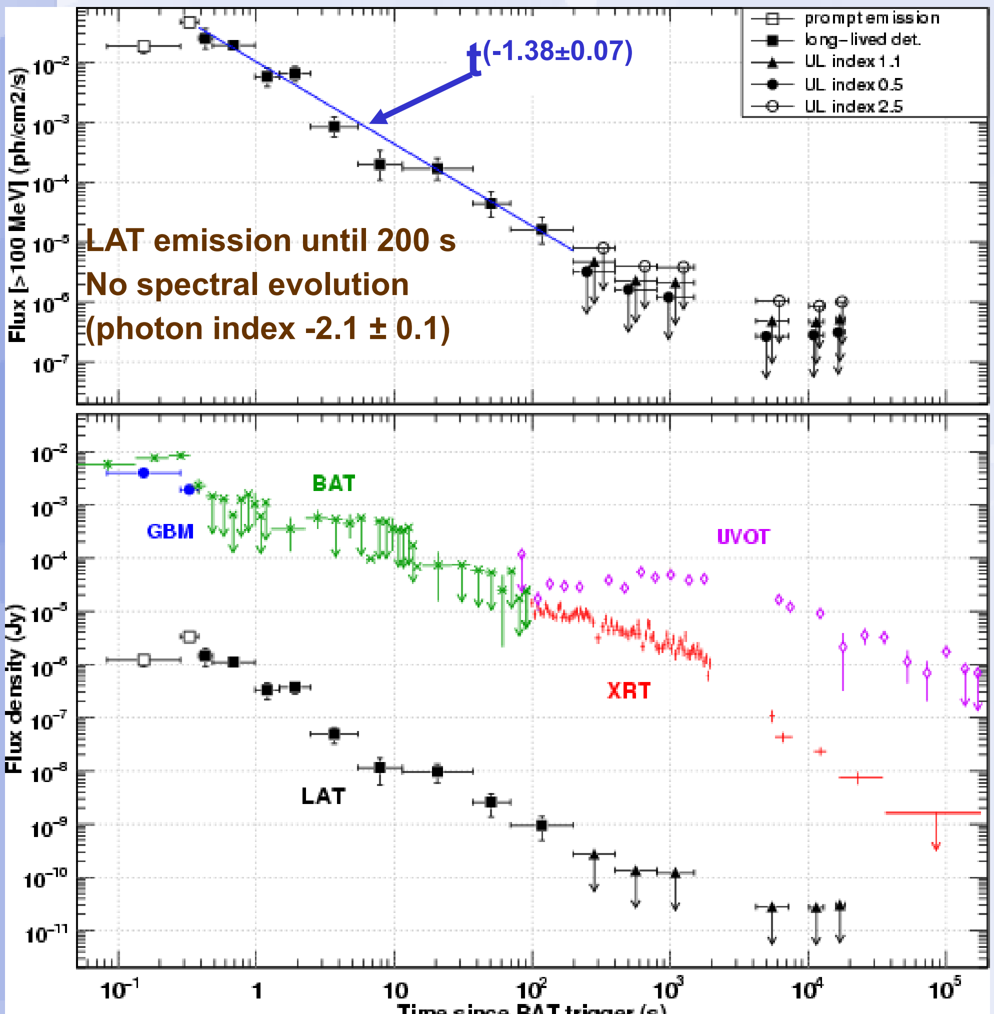
GRB NAME	Number of events (P>0.9)	Energy GeV	Arrival time s	Probability
GRB080825C	10	0.57	28.29	0.997
GRB080916C	181	13.22	16.54	1.000
GRB081006	10	0.79	12.08	0.955
GRB081024B	11	3.07	0.49	1.000
GRB090217	16	1.23	179.08	0.907
GRB090323	28	7.50	195.42	1.000
GRB090328	23	5.32	697.80	0.926
GRB090510	186	31.31	0.83	1.000
GRB090626	15	2.09	111.63	0.999
GRB090720B	2	1.45	0.22	0.997
GRB090902B	276	33.39	81.75	0.949
GRB090926A	239	19.56	24.83	1.000
GRB091003	20	2.83	6.47	1.000
GRB091031	7	1.19	79.75	0.999
GRB091208B	4	1.18	3.41	0.956
GRB100116A	14	13.12	296.43	0.993
GRB100325A	5	0.84	0.35	0.990
GRB100414A	19	4.72	288.26	1.000
GRB100620A	6	0.27	3.77	0.994
GRB100724B	16	0.22	61.75	0.988
GRB100728A	5	13.54	5461.08	0.987
GRB110120A	6	1.82	72.46	0.999
GRB110428A	6	2.62	14.79	1.000
GRB110625A	6	2.42	272.44	0.986
GRB110709A	5	0.42	41.75	0.921
GRB110721A	22	1.73	0.74	0.998
GRB110731A	64	3.39	435.96	0.998

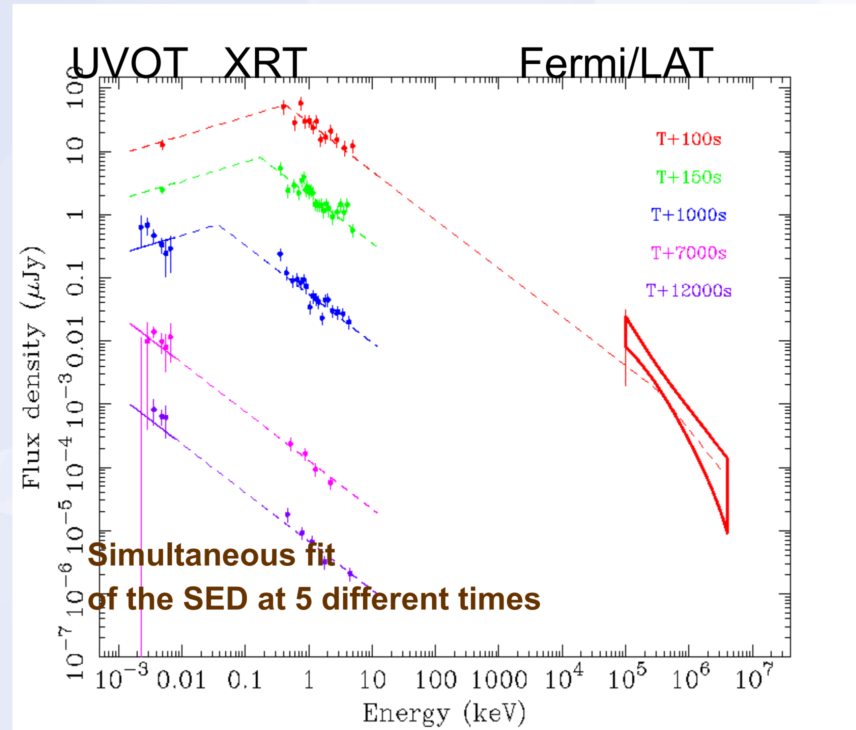
Ackermann et. al. 2013, ApJS 209, 11A

Long lived HE component

GRB 090510 (short GRB)

De Pasquale et al., ApJL 709, 146 (2010)

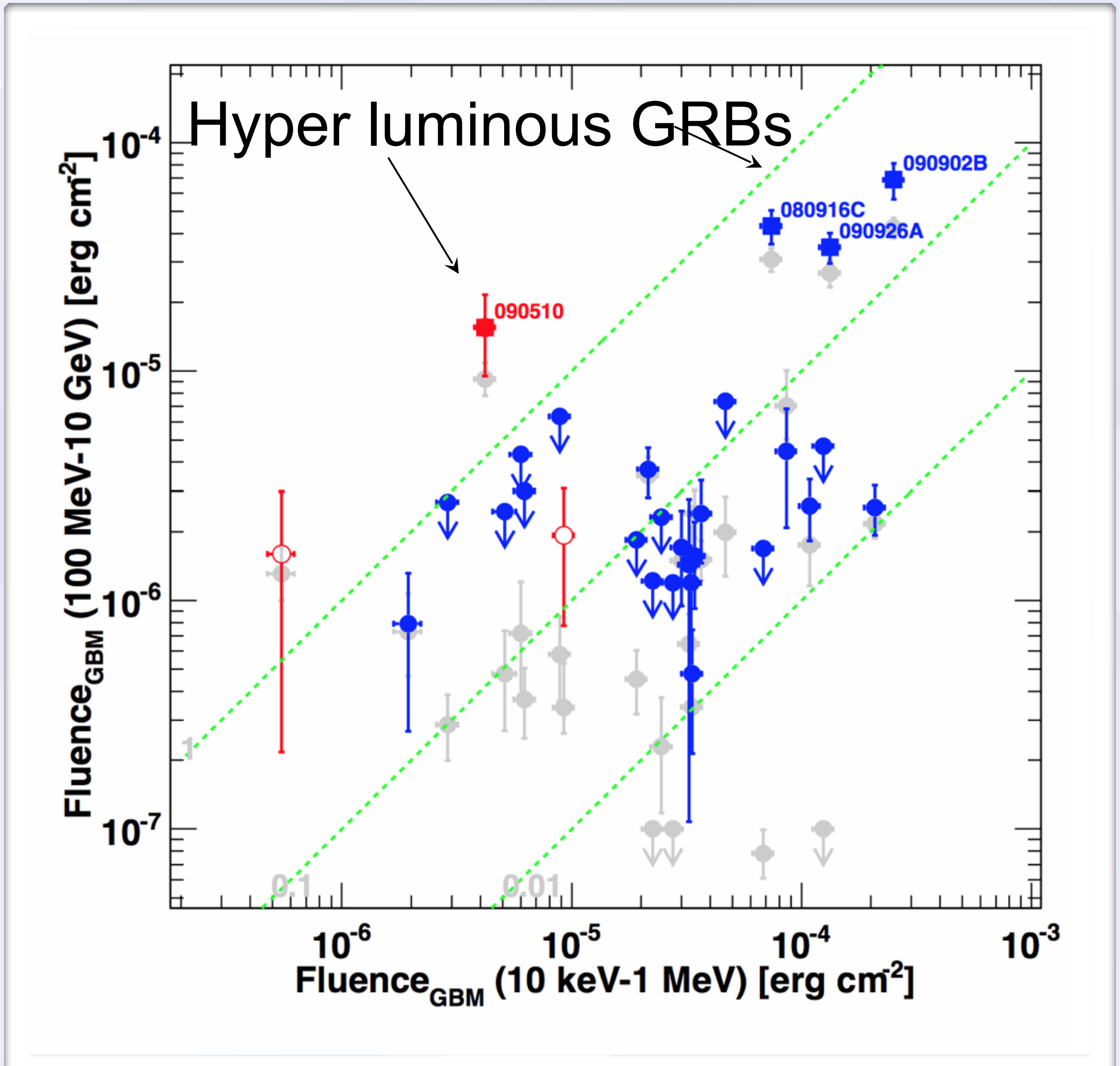




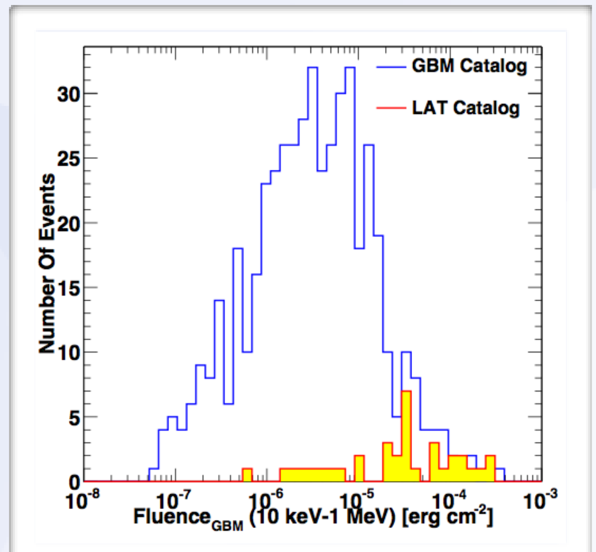
- **Forward shock model can reproduce the spectrum from the optical up to GeV energies**
- **Extensions needed to arrange the temporal properties**

Several GRBs have been detected simultaneusly from Fermi and Swift

HE fluence

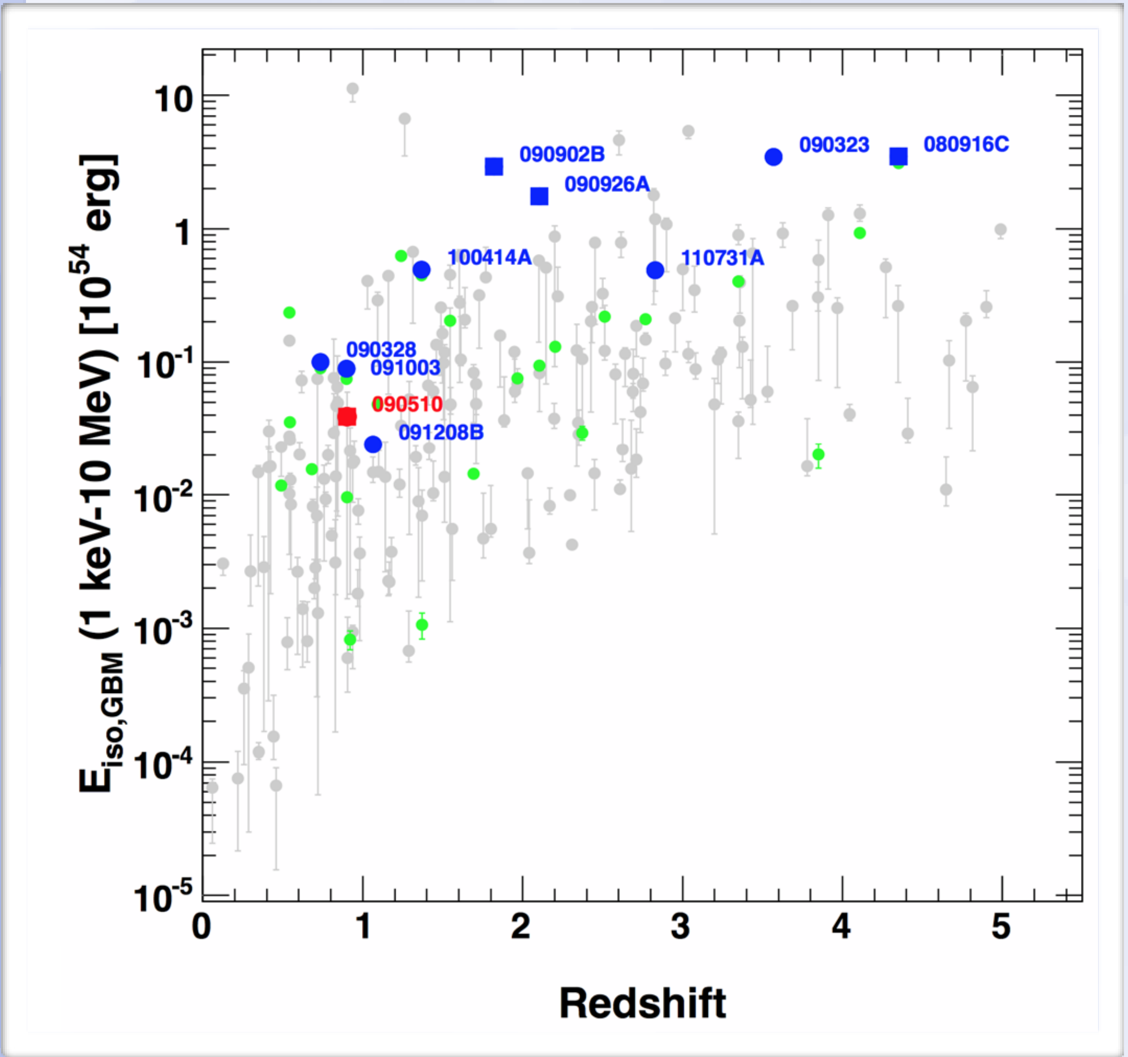


- Brightest GBM bursts, are also the Brightest LAT bursts
- Large dispersion Class of hyper luminous bursts
- statistical fluctuation?



Fermi LAT GRB Catalog (arXiv:1303.2908v1)

Intrinsic energetic



Ackermann et. al. 2013, ApJS 209, 11A

- The brightest GRBs are also the most energetic GRBs (not the closest)
- In the tail of the E_{iso} distribution

Conclusions

- Fermi has made new interesting observations on GRB:
  - Prompt emission observed over a wider energy range:
    - Band model is no longer the best phenomenological model.
    - More complex spectral shapes are needed to reproduce the spectrum
  - High-energy emission not common in GRBs
  - Long lasting-delayed high-energy emission common in LAT detected GRB

Thank you!

LAT detection during X-ray flare activity

GRB100728A:

★Fermi/GBM: Very bright burst:

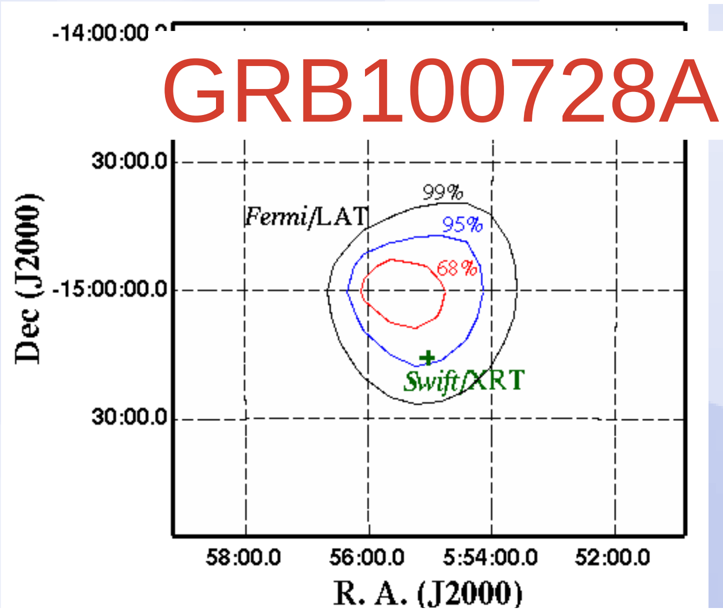
- ✳ S (10-1000 keV) ~ 1.3 x 10^{-4} erg/cm2/s → Fermi ARR

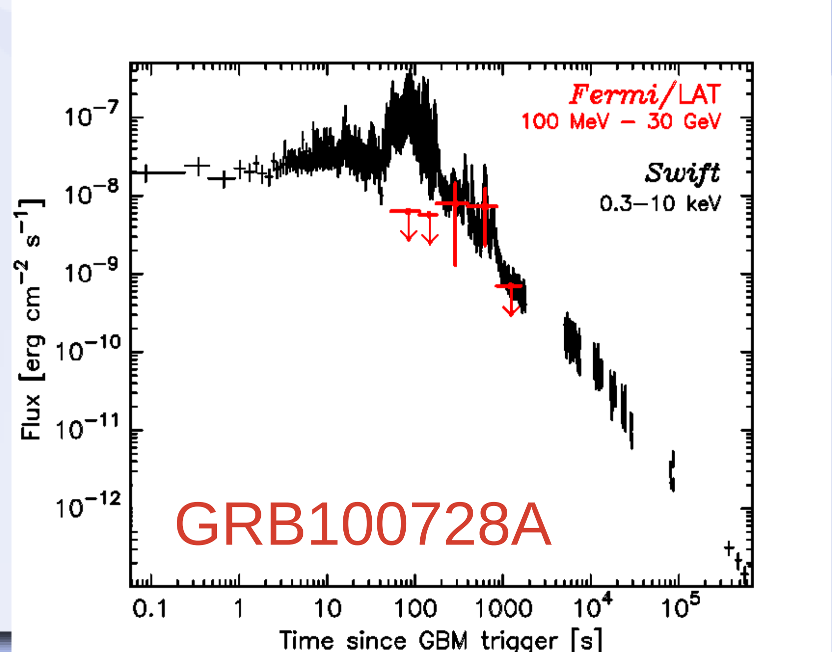
★Swift/BAT: T90~200 s, faint emission seen up to ~750 s

★Swift/XRT: 8 bright flares (from ~150 s to ~850 s)

★Fermi LAT:

- ✳ No detection during the prompt phase (large incident angle ~ 58°)
- ✳ Significant detection during the flaring activity (TS=32)
- ✳ No significant temporal correlation (which does not mean significant non correlation!)



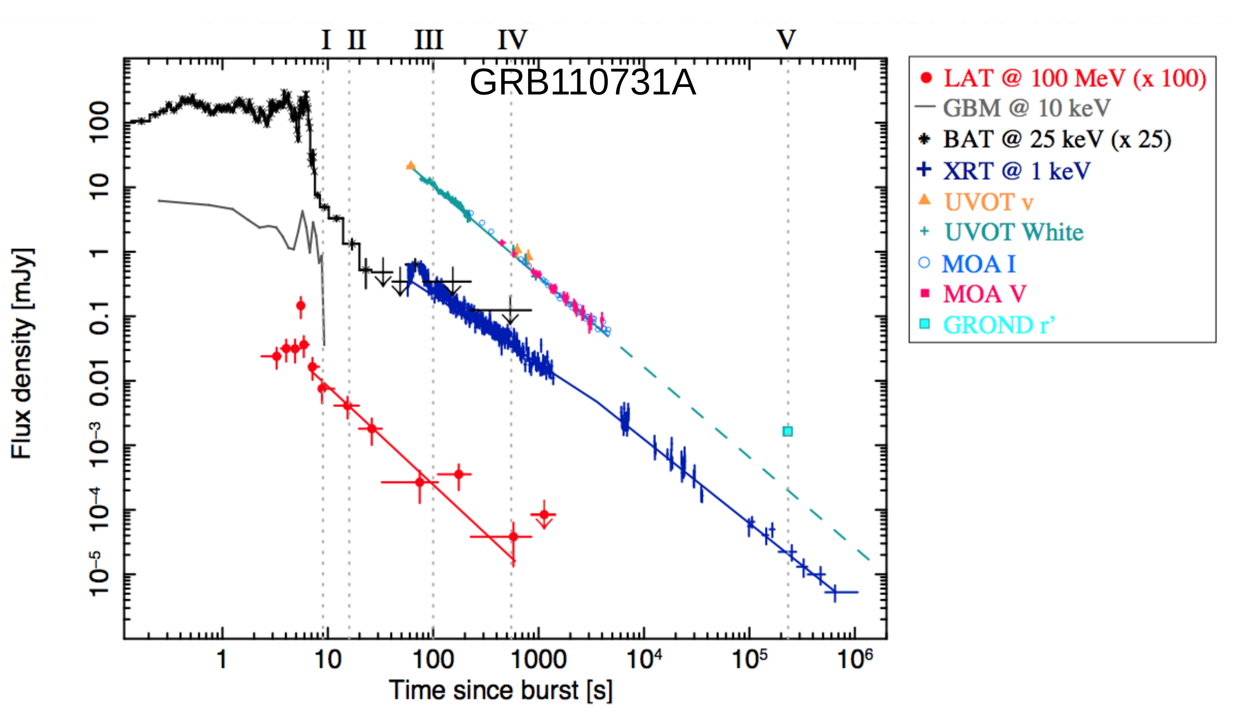


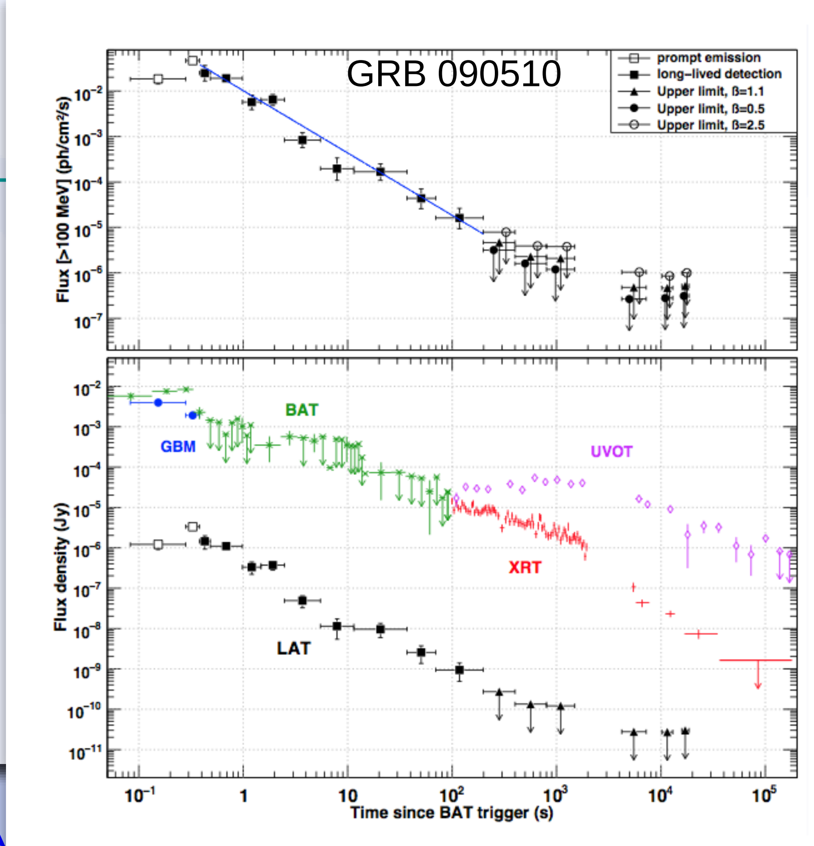
A. A. Abdo et al. 2011 ApJ 734 L27

Simultaneous Swift detections

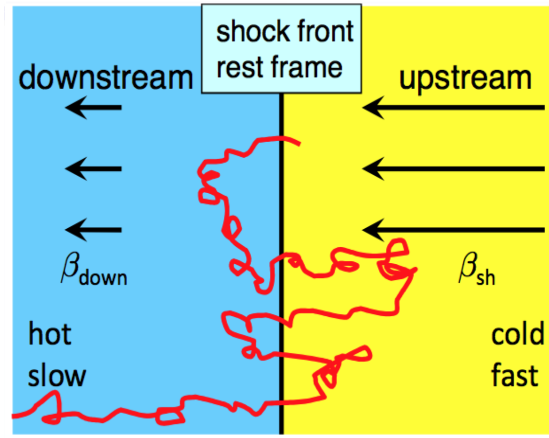
Fermi Gamma-ray Space Telescope

- 6 GRBs have been simultaneously detected by LAT and Fermi
  - GRB090510 [de Pasquale et al 2010 +...]
  - GRB100728A [Fermi Collaboration (Abdo et al ApJ 2011)]
  - GRB110625A [Tam, Kong and Fan, ApJ 2012]
  - GRB110731A [Fermi Collaboration (Ackermann et al 2013)]
  - GRB 120624B [GCN]

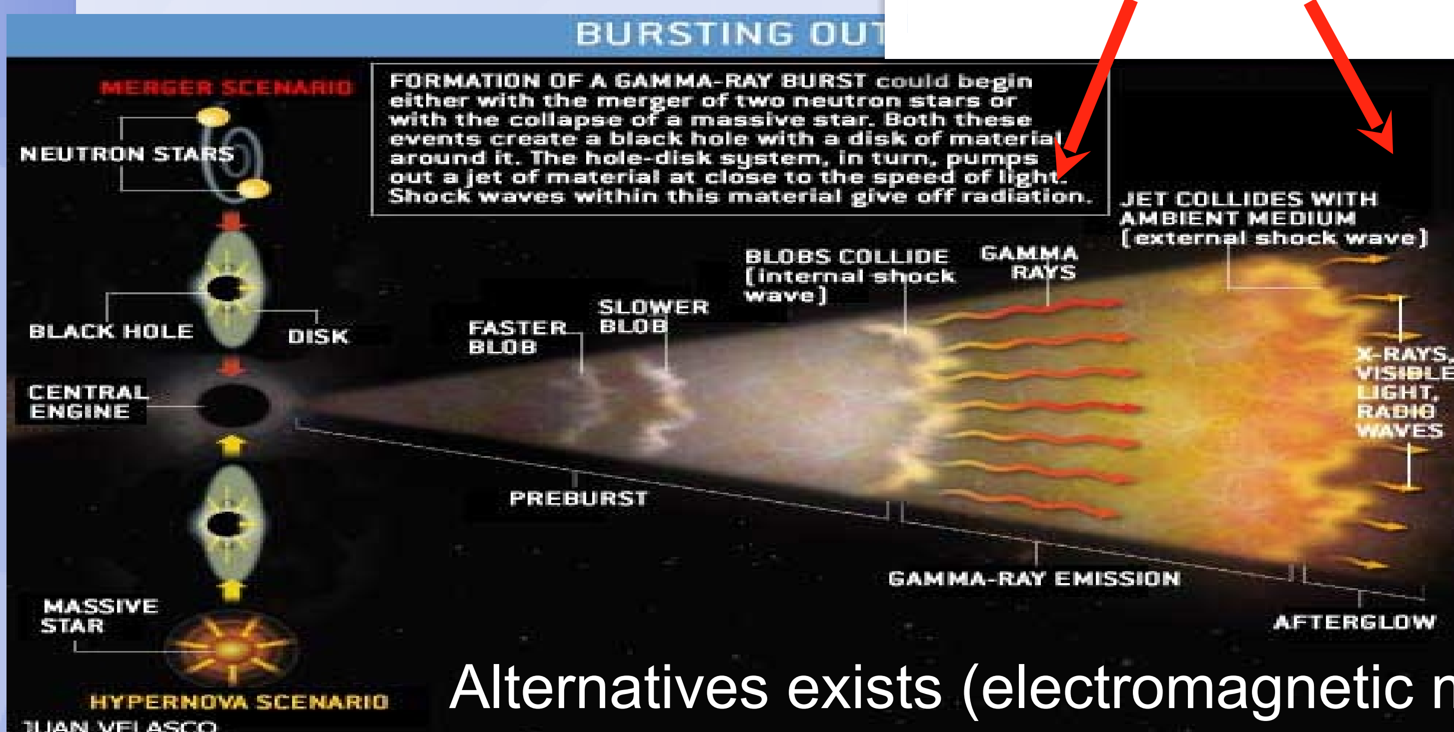




The "fireball" model



particles get accelerated as they bounce back and forth across the shock wave



Alternatives exists (electromagnetic model,…)

Properties: Γ_{min} calculation

compactness problem: large luminosity + small emitting region = large optical depth (γ-γ -> e+e- large)

Possible solution: relativistic motion ($\Gamma >> 1$)

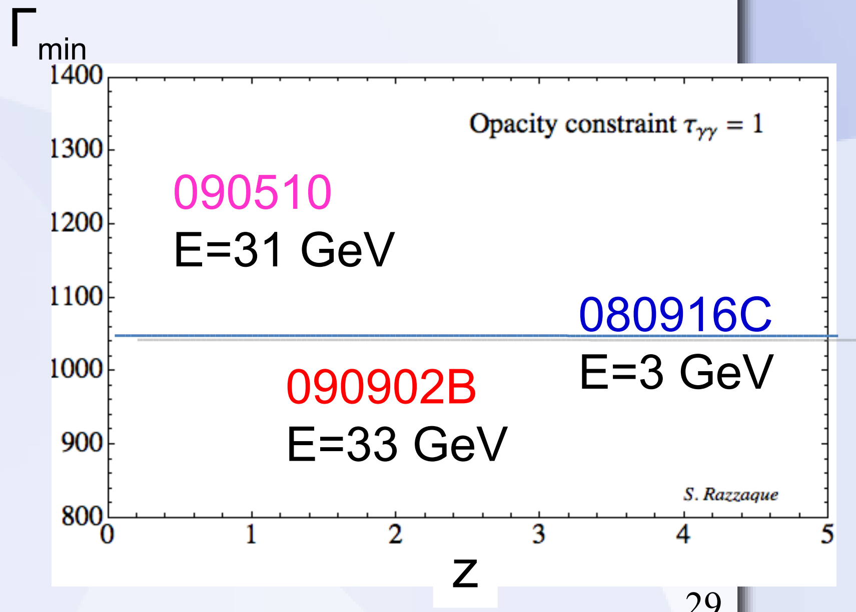
$$\tau_{\gamma\gamma}(E) = \frac{3}{4}\frac{\sigma_T d_L^2}{t_v \Gamma}\frac{m_e^4 c^6}{E^2(1+z)^3}\int_{\frac{m_e^2 c^4 \Gamma}{E(1+z)}}^{\infty} \frac{d\epsilon'}{\epsilon'^2}\, n\left(\frac{\epsilon' \Gamma}{1+z}\right) \varphi\left[\frac{\epsilon' E(1+z)}{\Gamma}\right]$$

Γ_{min} calculation from highest energy photon

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

$$\times \exp\left(\frac{\beta-\alpha}{2-2\beta}\right)\left[\frac{2m_e^2c^4}{E_{\rm max}(1+z)^2 100\ {\rm keV}}\right]^{\frac{\beta}{2-2\beta}} ;$$

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



Γ_{min}~1000 for short and long GRBs

Quantum gravity mass constrain

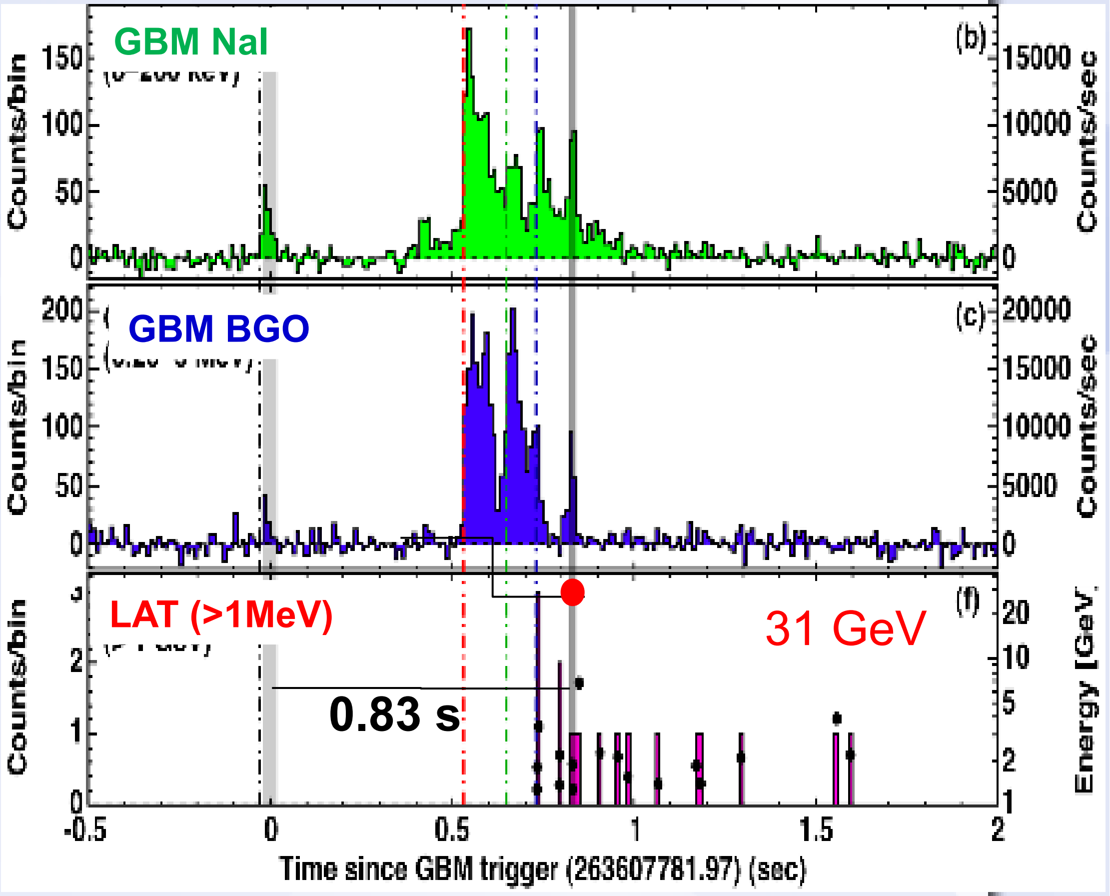
A Constraint on the quantum gravity mass (M_{QG}) can be derived by direct measurement of photon arrival time (assuming the emitted time is the same for all photons):

$$M_{QG,1}/M_{plank} > 1.19$$

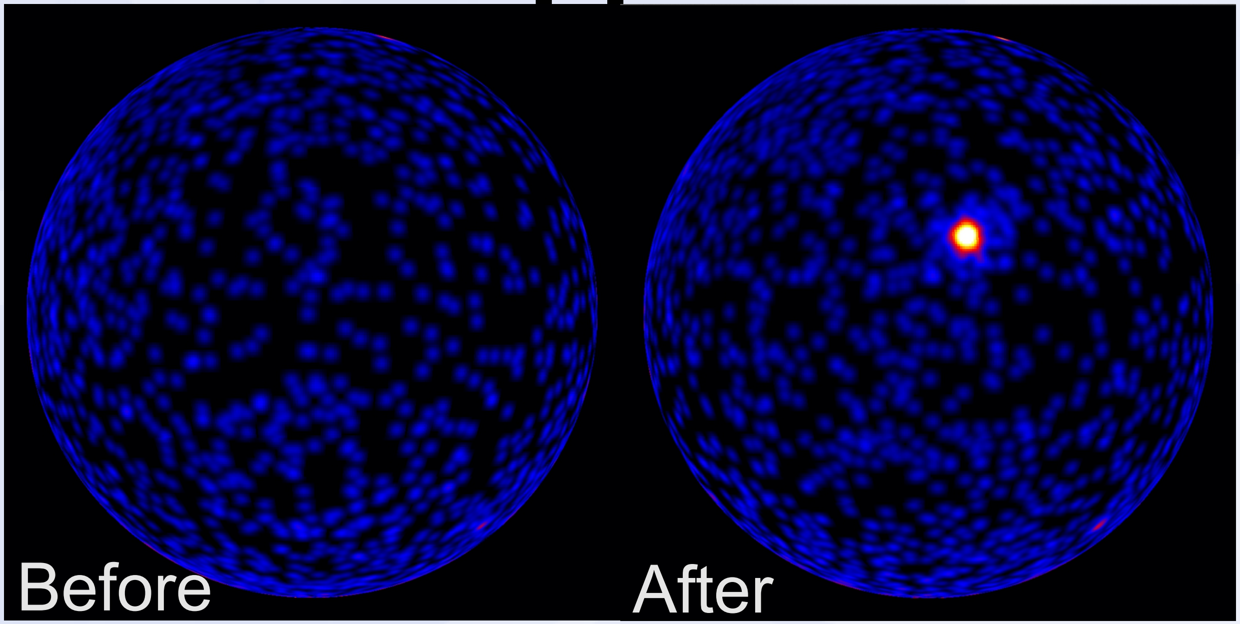
This value disfavors quantum gravity models which linearly alters the speed of light (n=1)

GRB 090510

Abdo et al. 2009, Nature 462, 331

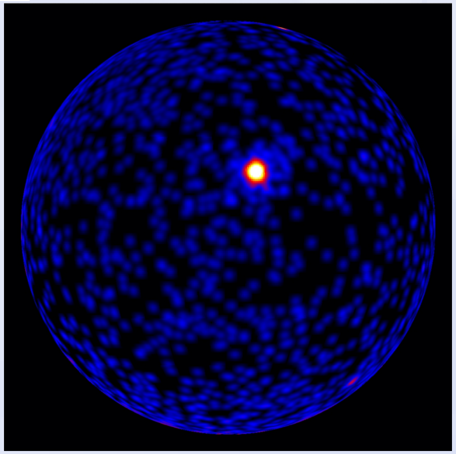


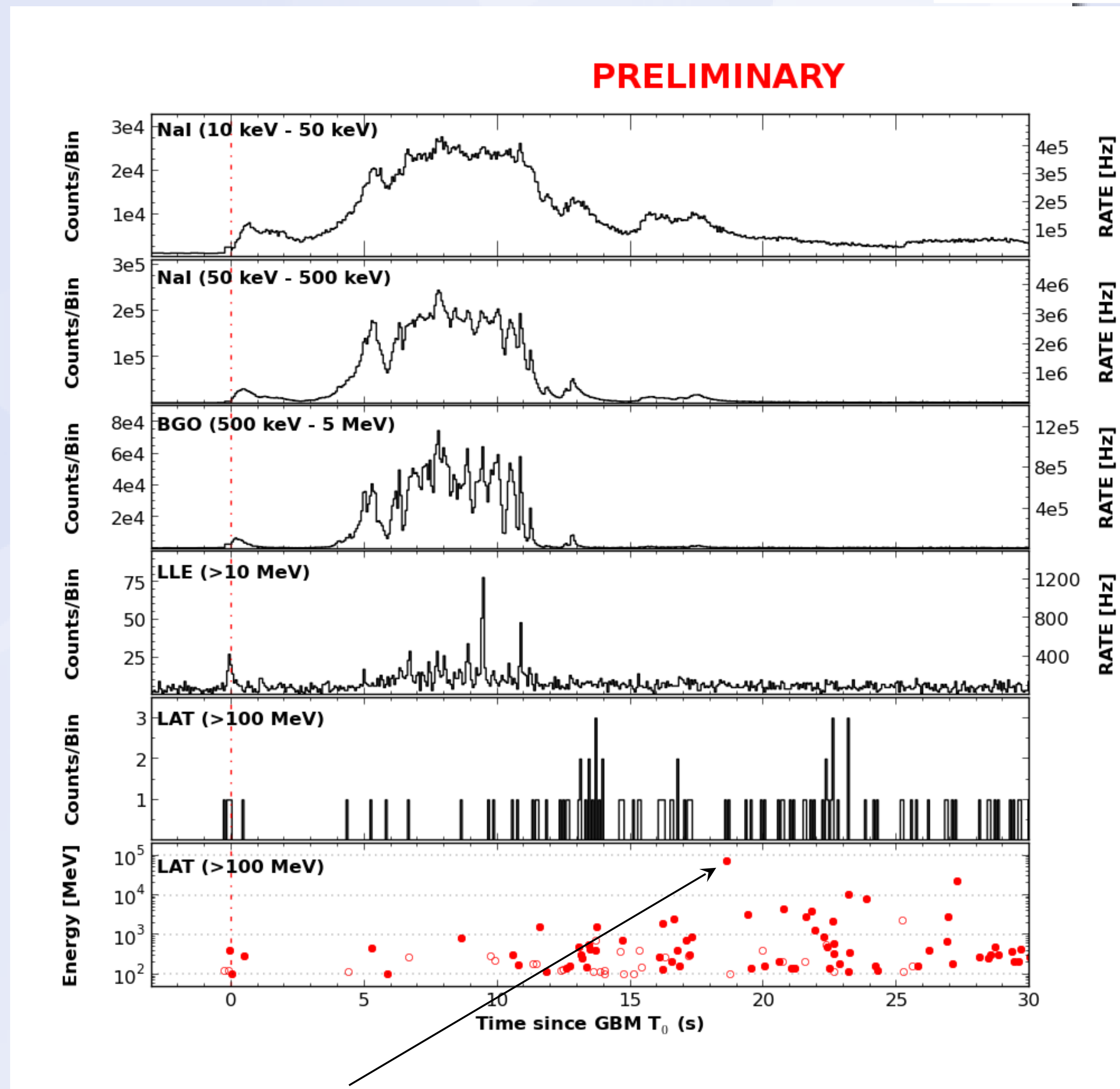
And then GRB130427A happen…



- The brightest GRB in the LAT ever detected;
- More than 80 circulars delivered to the archive from several observatories:
  - GCN from the "usual suspects" + HAWC + IceCube
- Concept proven! Discoveries rely on the fast delivery of informations (GCN) quick look analysis and possible data sharing.

Extremely bright GRB (close)





95 GeV

- One of the brightest GRBs in gamma rays ever detected!
  - Redshift: z = 0.34, Energy released in gamma rays ~ 10^{54} erg
  - The emission saturated GBM detectors!
  - The brightest burst ever detected by the LAT
- LAT detected emission for ~20 hours!