LAT observations of Gamma-Ray Bursts

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on behalf of the *Fermi* GBM and LAT collaborations

GRB2010 conference
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Outline

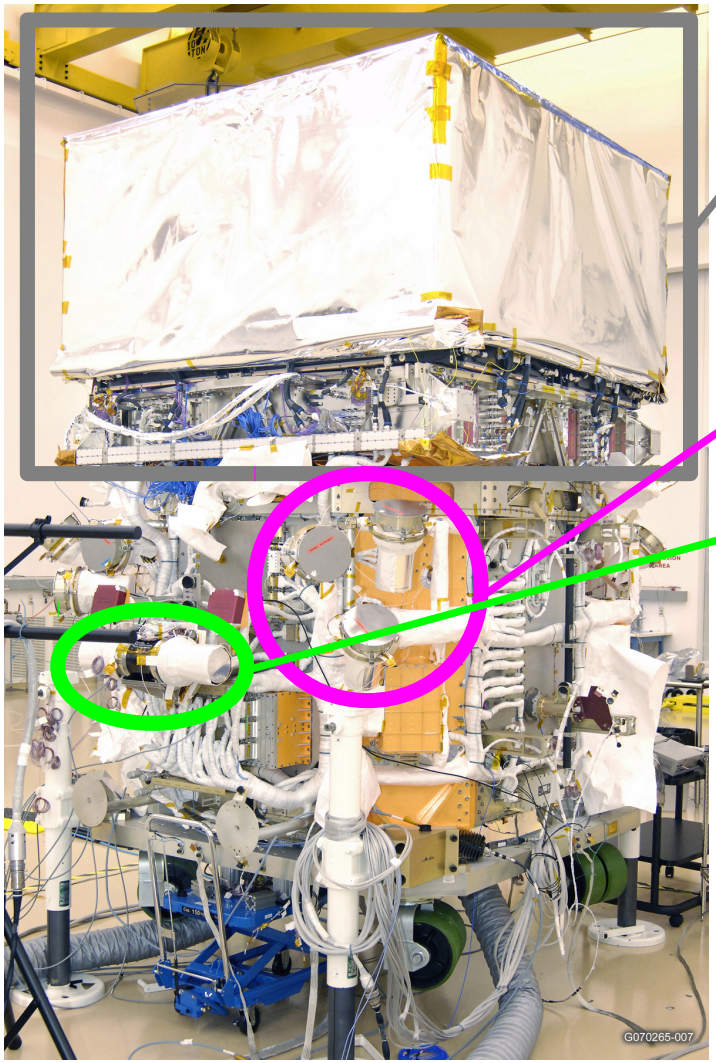
GRB observation
- The observatory
- Detection and localization
- Follow-up
- Data

GRB detections
- Summary of detections
- Sensitivity

GRB analysis
- LAT + GBM : spectral properties
- LAT + GBM : temporal properties
- LAT + *Swift*
- Summary of observations

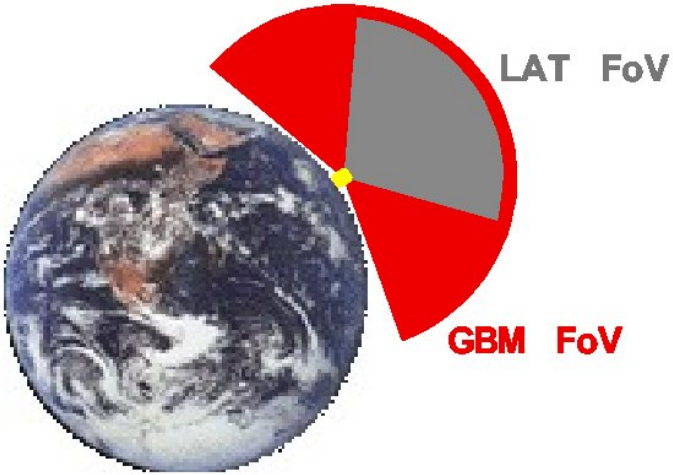
Implications
- Energetics
- Jet's bulk Lorentz factor
- Limits on Lorentz invariance violation
- Extragalactic Background Light
- Possible interpretations of HE emission

The *Fermi* observatory



LAT : Pair conversion telescope
Trigger, localization, spectroscopy
20 MeV – 300 GeV

GBM 14 PMT
12 NaI
Trigger, localization, spectroscopy
8 keV – 1 MeV
2 BGO
Spectroscopy
150 keV – 40 MeV



GRB detection and localization

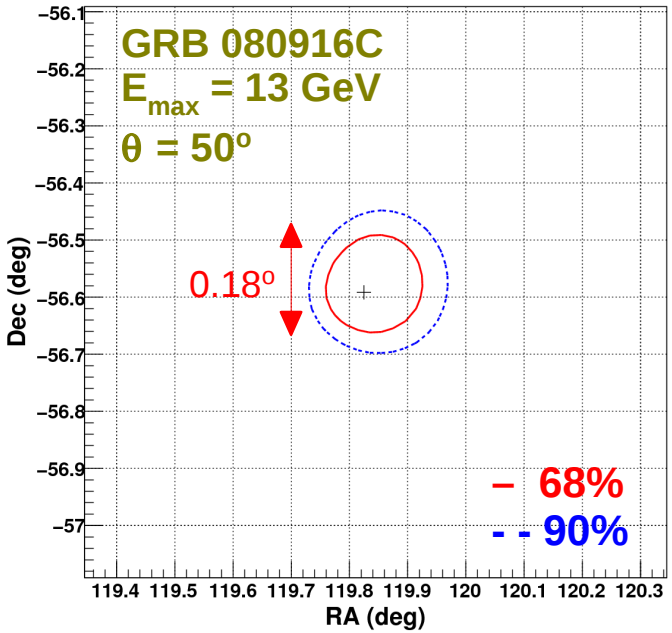
On-board LAT detection :
On-board track reconstruction
Search for clustered tracks
Modes : seeded by GBM trigger or blind
1 LAT-only detection so far : GRB 090510

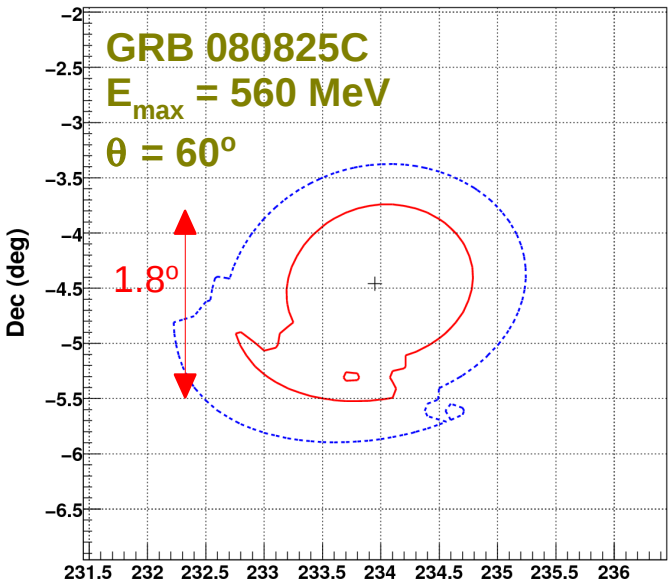
On-board LAT localization :
0.1° to 0.5° few seconds after trigger
→ GCN notice
(see GCN circular 10777)

On-ground (>8 hours after trigger) :
Automatic search, simultaneous to data processing
Modes : seeded with GBM and *Swift* GCN notices or blind
→ significance, localization

Burst Advocate performs likelihood analysis
→ detection significance, localization

Better accuracy if GeV events available (PSF smaller)
Small systematic error at large inclination angles





Abdo, A. A. et al. 2009, ApJ, 707, 580

GRB follow-up

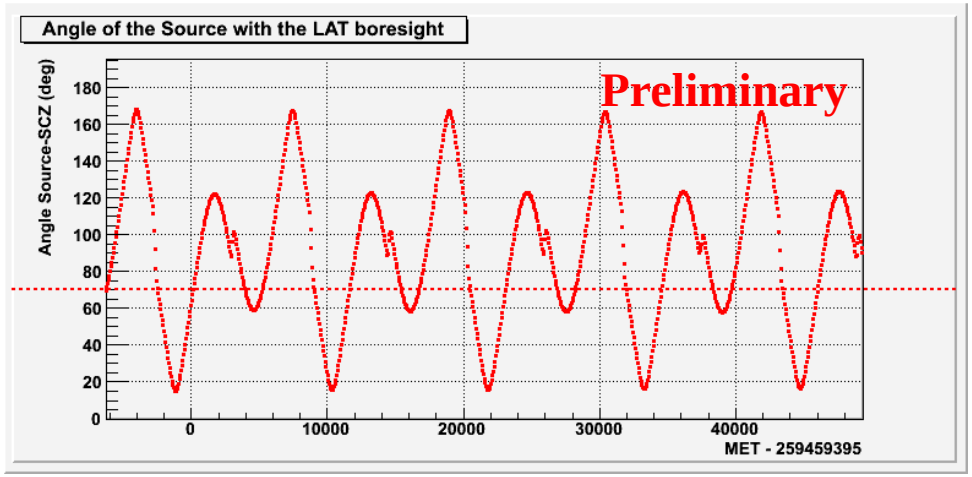
- GBM detection
  Two thresholds : in and out LAT FoV
- <10s : repoint request sent to S/C
- <100s : slew (if accepted and observable)
- Up to 18ks follow-up

Target 10° off-axis (best acceptance)
while 20° above horizon

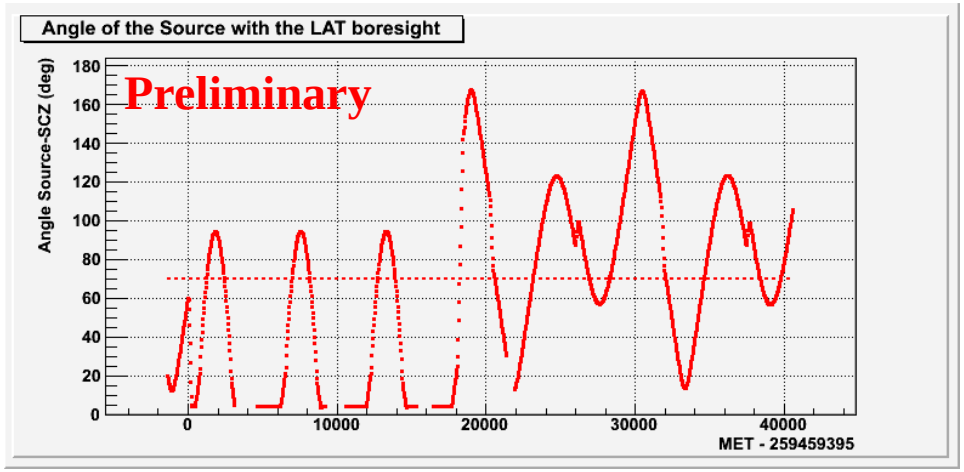
- ✔ Long-lived high-energy emissions
- ✔ Increased statistics
- ✔ Better significance and localization
- ✗ Varying backgrounds in GBM and LAT
- ✗ Higher contamination by Earth limb

(see F. Piron's presentation)

GRB 090323
planned orbit

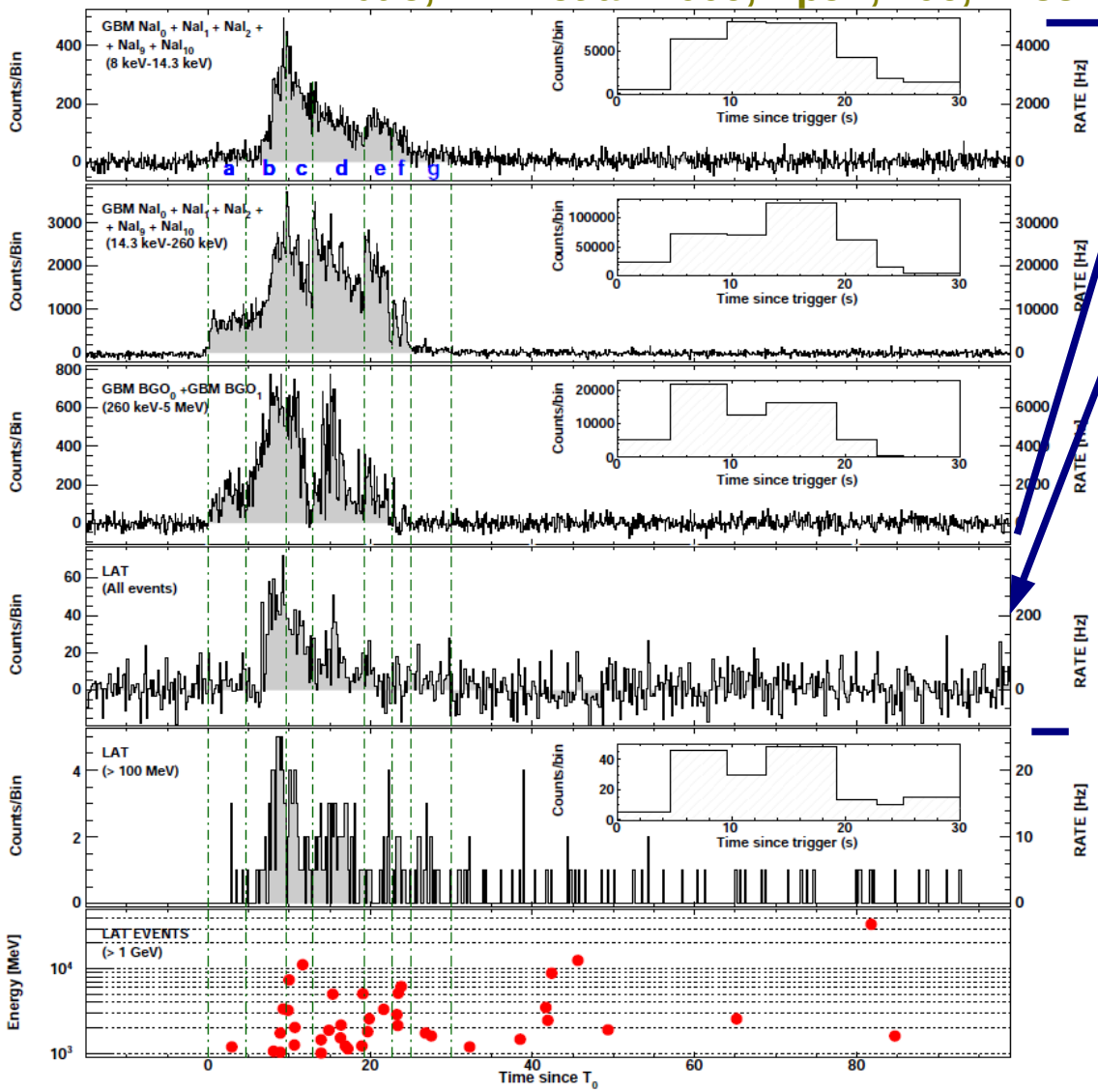


GRB 090323
actual orbit with repoint



GRB data

GRB 090902B
Abdo, A. A. et al. 2009, ApJL, 706, L138



GBM data

LAT « LLE » data

On-board photon selection
One track required

✔ High statistics
➢ Timing and spectral analyses (yet unpublished)
✗ High background rates
➢ (energetically) binned analyses of bkg-subtracted data

LAT standard data

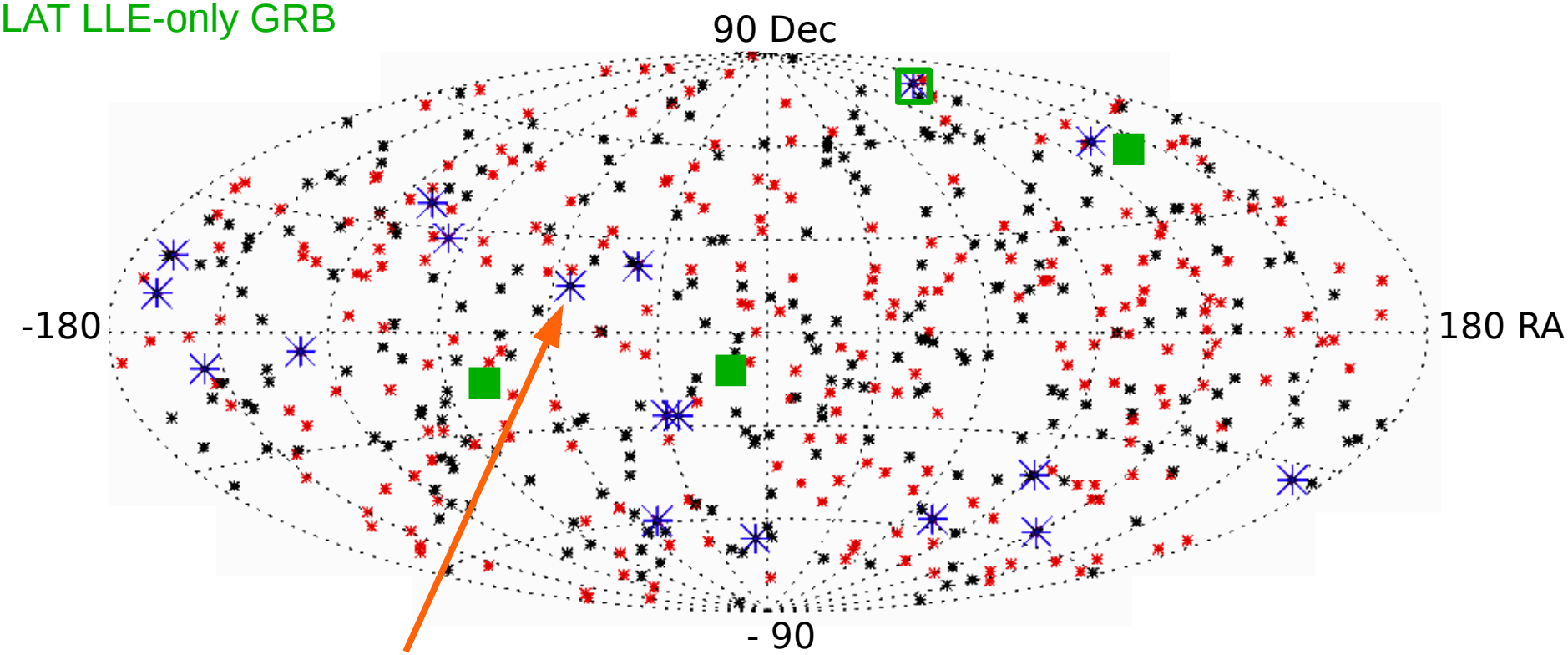
Tight quality cuts > 100MeV in ROI
➢ (very) low background
➢ (published) likelihood analyses :
spectra, localization

Even tighter cuts used for long-lived emissions (faint)

Fermi detections as of 100804

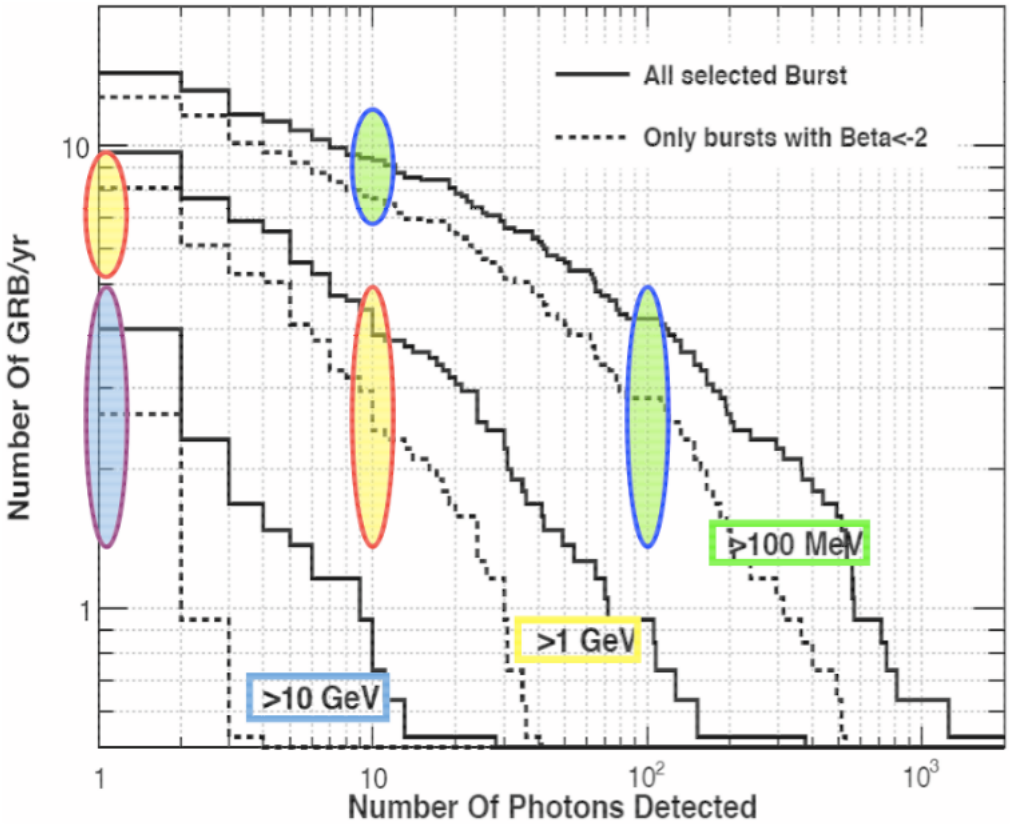
514 GBM GRB
18 LAT GRB (>100 MeV)
3 LAT LLE-only GRB

In Field-of-view of LAT (264)
Out of Field-of-view of LAT (250)



(see S. Zhu's poster P4.05 about peculiar GRB 100116A)

Detection rate / Sensitivity



Band, D> et.al. 2009, ApJ 701, 1673

Pre-launch estimates :

Band function fits to bright BATSE GRB

- ~9.3 GRB/y w/ >10 photons >100 MeV
- ~2.7 GRB/y w/ >100 photons >100 MeV
- ~2.7 GRB/y w/ >10 photons >1 GeV

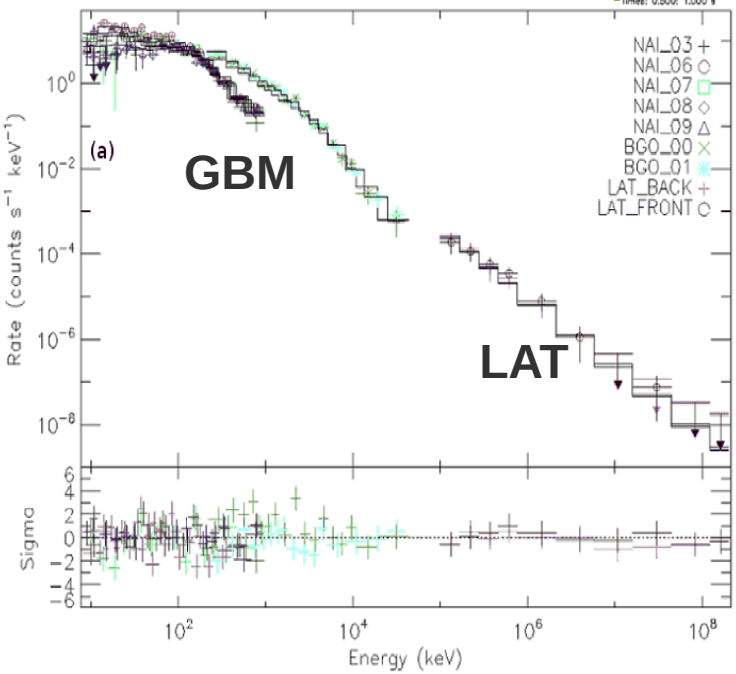
✔ Consistent with actual observations

Suggests that on average, GRB don't have much excess (HE component) or deficit (cutoff) in the LAT energy range w.r.t. the extrapolated Band spectrum from <2 MeV

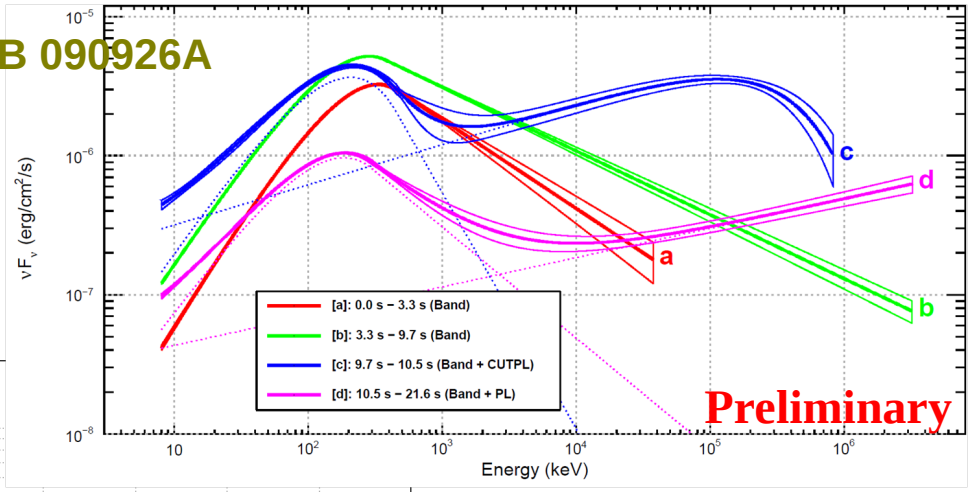
What about non-detected GRB in FoV?
Systematic study ongoing
(see D. Kocevski's presentation)

LAT and GBM : spectra

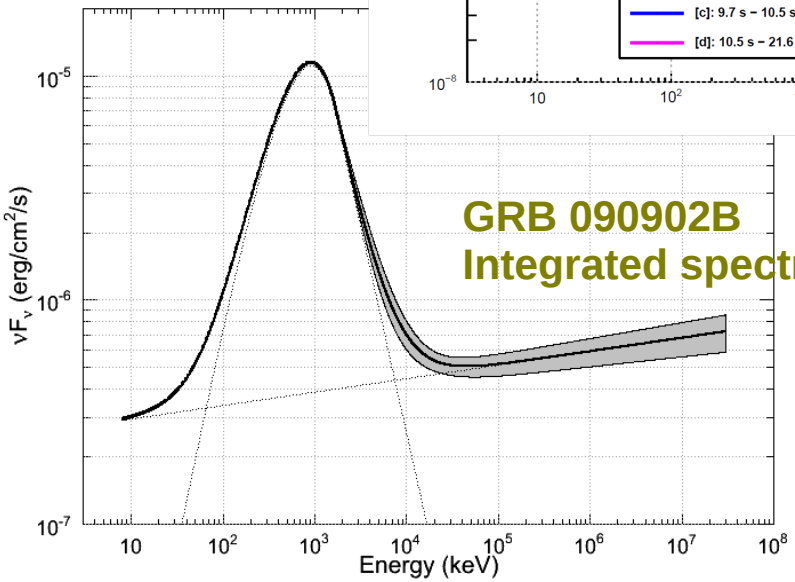
GRB 090510
integrated counts spectrum
Ackermann, M. et al. 2010, ApJ, 716, 1178



GRB 090926A



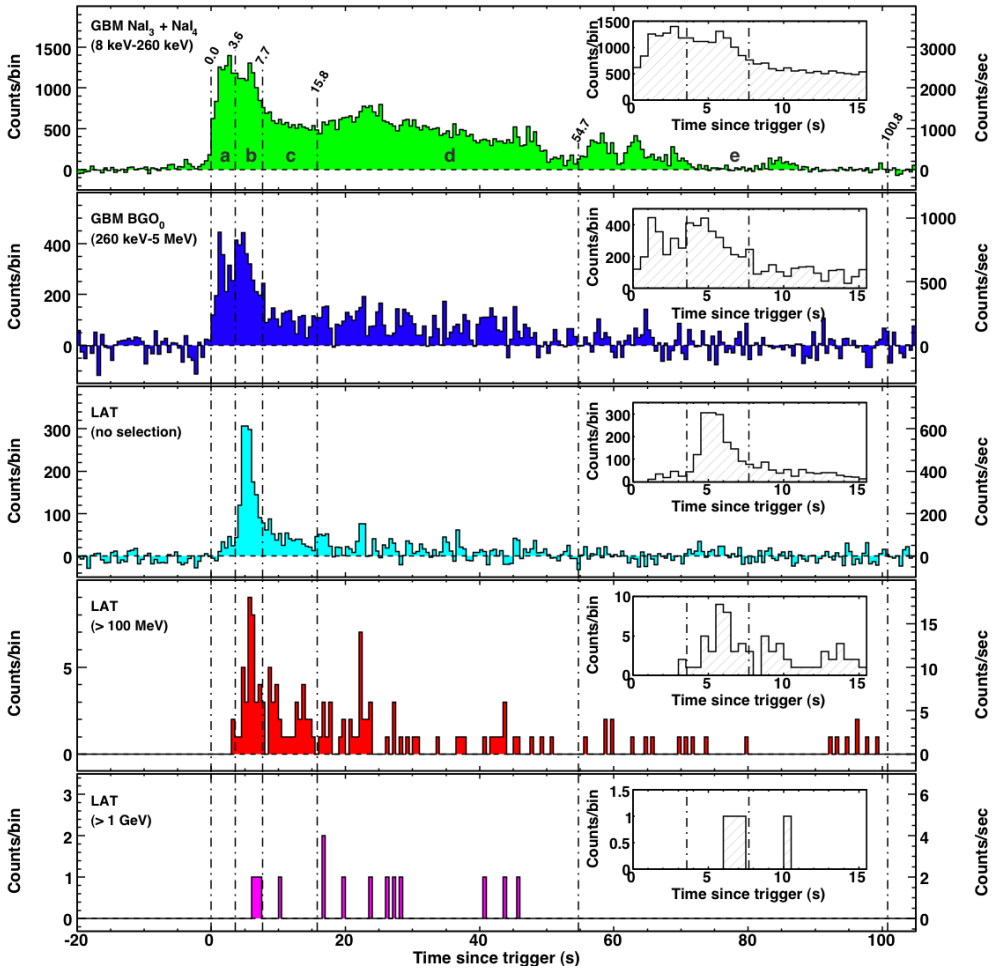
GRB 090902B
Integrated spectrum fit



Joint spectral fit (of binned data) :
GBM<40MeV
standard LAT data>100MeV
Fill the Gap : use LLE data

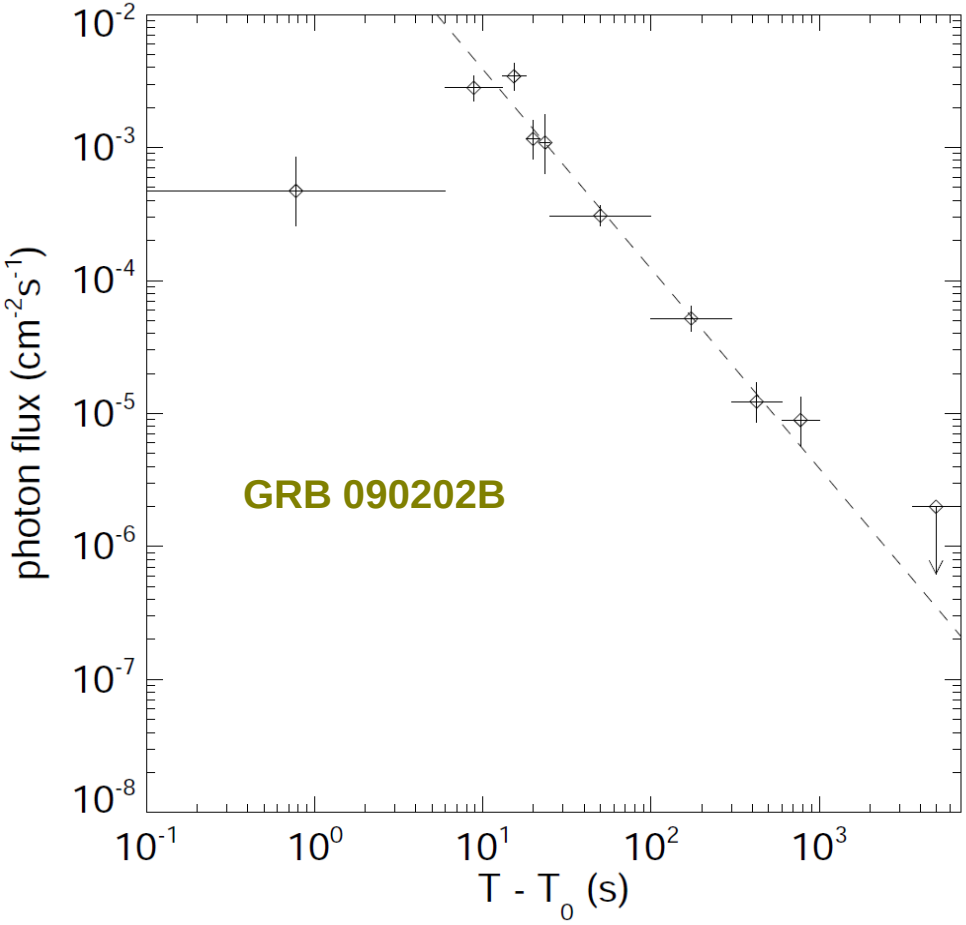
- Constrains main keV-MeV component
- Spectral evolution during prompt phase
- Additional PL component seen at high and low energies
- High energy cutoff (GRB 090926A)

LAT and GBM : temporal properties



GRB 080916C multi-detector light curve
Abdo, A. A. et al. 2009, Science 323, 1688

GeV emission delayed wrt keV – MeV



Long-lived high-energy emissions in most bursts ~ 10^2 – 10^3 s

(see presentations by F. Piron, V. Vasileiou and S. Razzaque)

LAT and *Swift*

Overlapping fields of view of *Fermi*/GBM and *Swift*/BAT

~40 common detections /yr

1 common GBM/LAT/BAT detection so far : GRB 090510

→ Joint analysis of long-lived emission from UV to GeV

(see M. DePasquale's presentation)

***Swift* follow-up of *Fermi* bursts**

Good LAT localizations (error <0.4°)

→ 9 ToO observations

8 X-ray, 7 UV detections

→ afterglows and accurate localizations

(see J. Racusin's poster P9.09 about these afterglows)

Follow-ups by ground observatories

→ 8 redshifts measurements

LAT counterparts to *Swift* bursts

Systematic searches ongoing

(see presentations by J. Chiang and E. Troja)

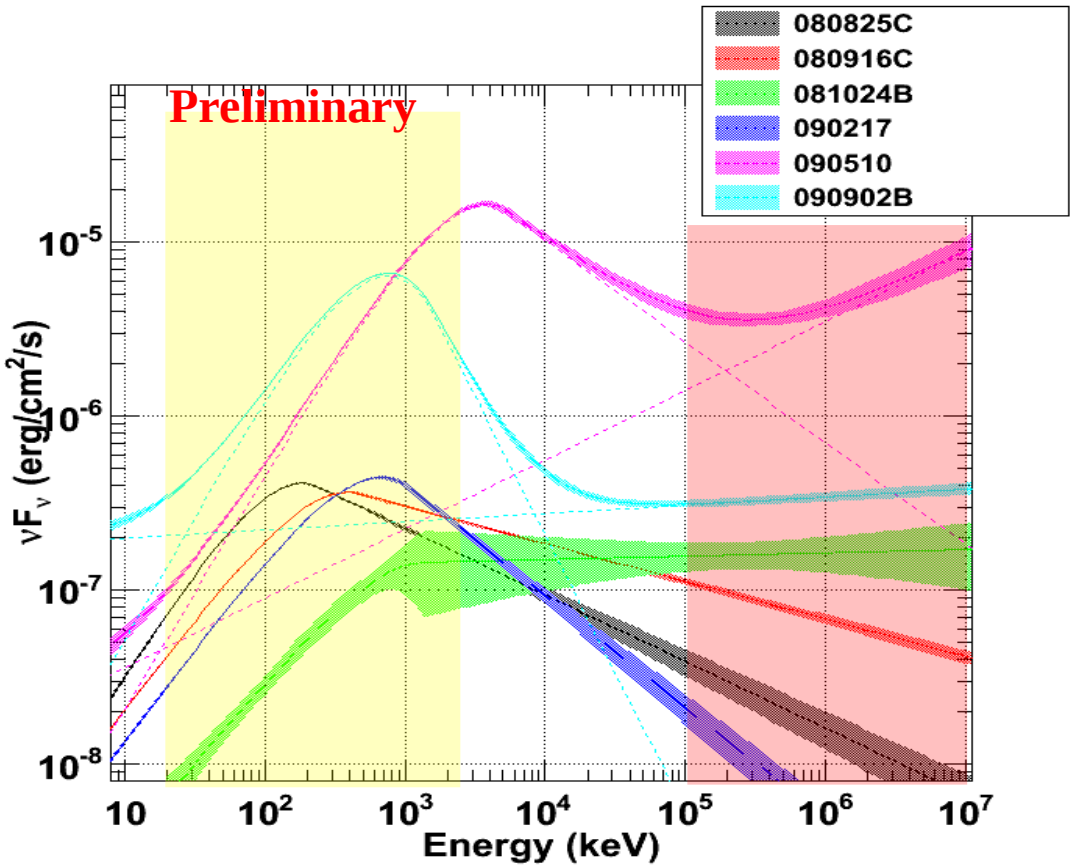
Summary of observations (to sept. 2009)

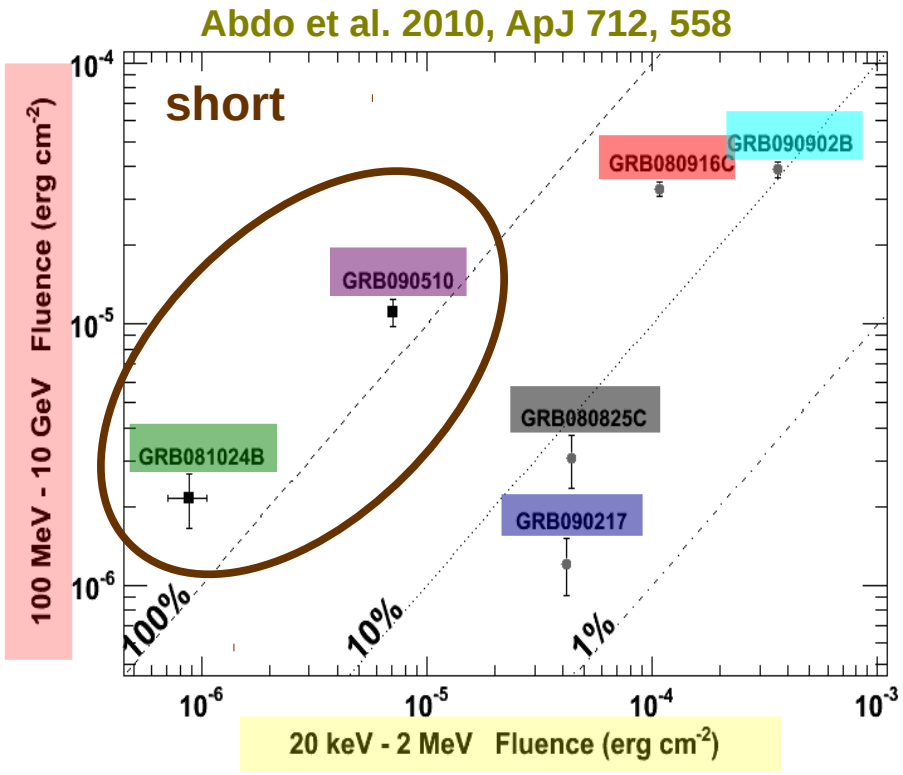
GRB	Angle from LAT	Duration (or class)	# of events >100 MeV	# of events >1 GeV	Delayed HE onset	Long-lived HE emission	Additional spectral component	Highest photon energy	Redshift
080825C	~ 60°	long	~ 10	0	✓	✓	X	~ 560 MeV	
080916C	49°	long	145	14	✓	✓	?	~ 13 GeV	4,35
081024B	21°	short	~ 10	2	✓	✓	?	~ 3 GeV	
081215A	~ 86°	long	-	-	-	-	-	-	
090217	~ 34°	long	~ 10	0	X	X	X	~ 1GeV	
090323	~ 55°	long	~ 20	> 0	?	✓	?	?	3,57
090328	~ 64°	long	~ 20	> 0	?	✓	?	?	0,736
090510	~ 14°	short	> 150	> 20	✓	✓	✓	~ 31 GeV	0,903
090626	~ 15°	long	~ 20	> 0	?	?	?	?	
090902B	51°	long	> 200	> 30	✓	✓	✓	~ 33 GeV	1,822
090926A	~ 52°	long	> 150	> 50	✓	✓	✓	~ 20 GeV	2,106

(etc.)

Systematic study of all LAT bursts characteristics underway :
upcoming LAT GRB catalog ***(see V. Vasileiou's presentation)***

Energetics





Comparable LE and HE gamma-ray outputs for short GRBs

Long GRBs seem to emit ~5-20 times less at HE than at LE w.r.t. short GRBs

Jet's bulk Lorentz factor

γ–γ opacity constraint

Maximum photon energy from relativistically moving source is related to its:

- Size: variability timescale
- Bulk Lorentz factor: limit energy higher than for source at rest
- Target photon field spectrum: Band, PL or Band+PL depending on cases

Caveat : target photon field assumed uniform, isotropic, time-independant

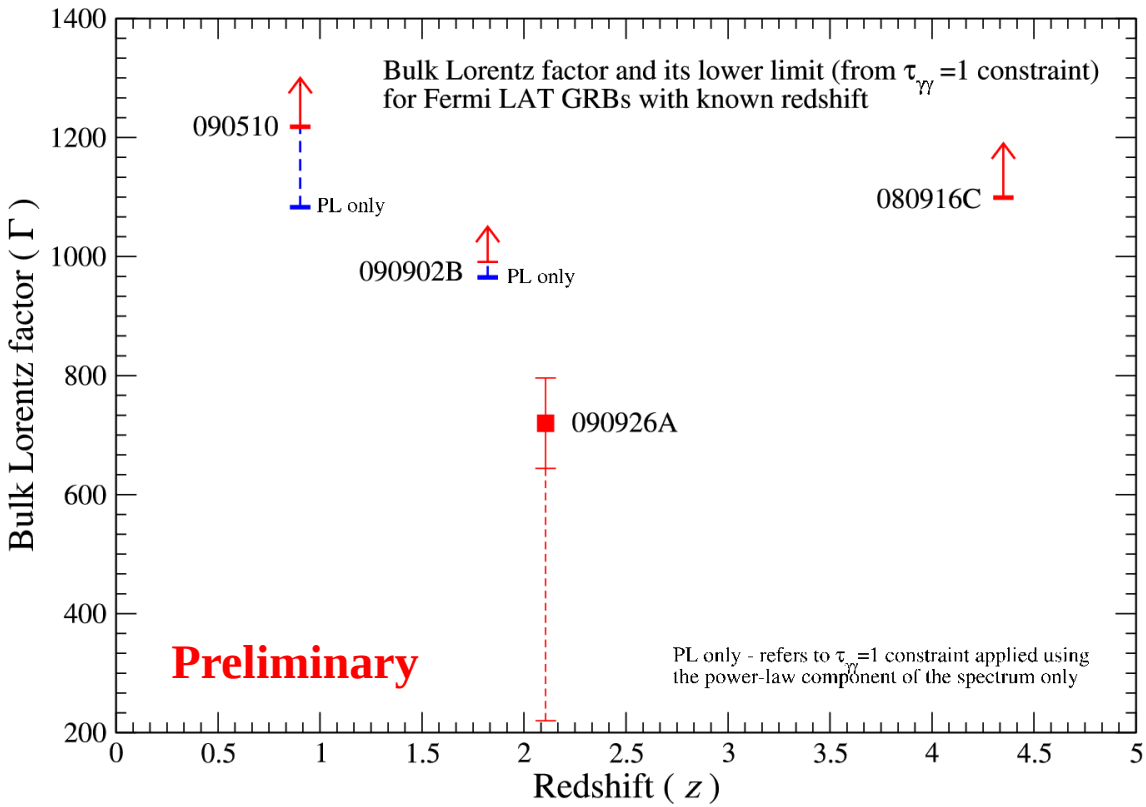
➢ More realistic modelling (e.g. Granot 2008) yields significantly (~3 times) lower values

Maximum photon energy in LAT Variability timescale from GBM light curve (more statistics)

➢ Robust (modulo caveat) constraints for most GRB

Cutoff energy for GRB 090926A

➢ Measurement Γ~ 200-700



Lorentz invariance violation (1/2)

Some QG models are consistent with Lorentz invariance voliation: $v_{ph}(E_{ph}) \neq c$

$$c^2 p_{ph}^2 = E_{ph}^2 \left[1 + \frac{E_{ph}}{M_{QG,1} c^2} + \left(\frac{E_{ph}}{M_{QG,2} c^2} \right)^2 + \ldots \right] \quad , \quad v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} c \left[1 - \frac{1+n}{2} \left(\frac{E_{ph}}{M_{QG,n} c^2} \right)^n \right]$$

A high-energy photon E_h would arrive after (in the sub-luminal case: $v_{ph} < c$, $s_n = 1$), or possibly before (in the super-luminal case, $v_{ph} > c$, $s_n = -1$) a low-energy photon E_l emitted together :

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

LAT is more sensitive to linear term n=1

Lorentz invariance violation (2/2)

Method 1: assuming a high-energy photon is not emitted before the onset of the relevant low-energy emission episode

Method 2: associating a high-energy photon with a spike in the low-energy light curve that it coincides with

Method 3: DisCan (dispersion cancelation; very robust) – lack of smearing of narrow spikes in high-energy light curve

GRB	Duration (or class)	# of events > 0.1 GeV	# of events > 1 GeV	Method	Lower Limit on $M_{QG,1}/M_{Planck}$	Valid for s_n =	Highest photon energy	Redshift
080916C	long	145	14	1	0.11	1	~ 13 GeV	~ 4.35
090510	short	> 150	> 20	1 2 3	1.2, 3.4, 5.1, 10 102 1.2	1 ±1 ±1	~ 31 GeV	0.903
090902B	long	> 200	> 30	1	0.068	1	~ 33 GeV	1.822
090926A	long	> 150	> 50	1,3	0.066, 0.082	1, 1	~ 20 GeV	2.106

All lower limits $M_{QG,1} > M_{Planck}$

QG models with linear LIV disfavored

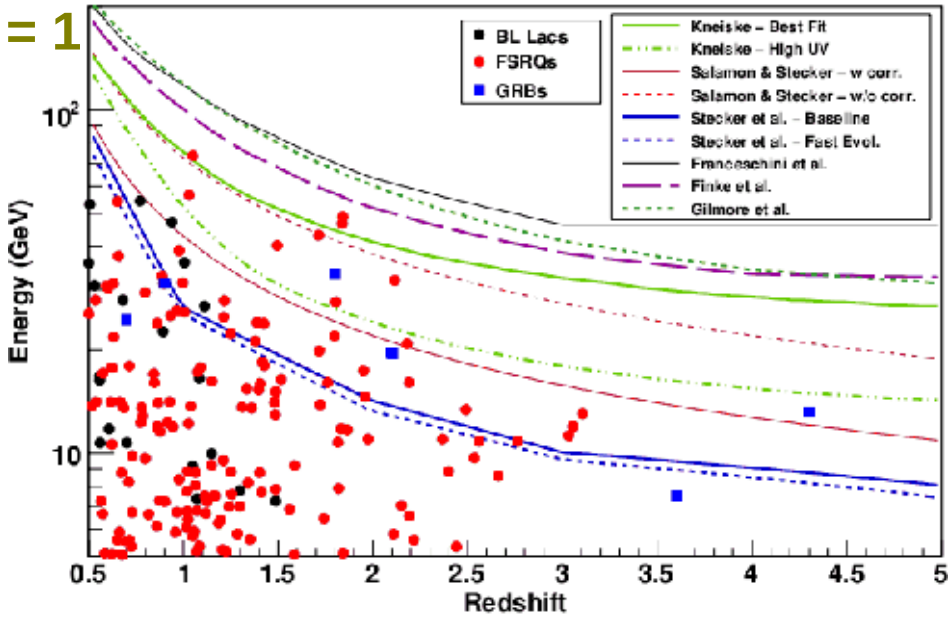
Extragalactic Background Light

Extrinsic γ–γ absorption by UV background light
Combined study of
AGN and GRB of known redshift

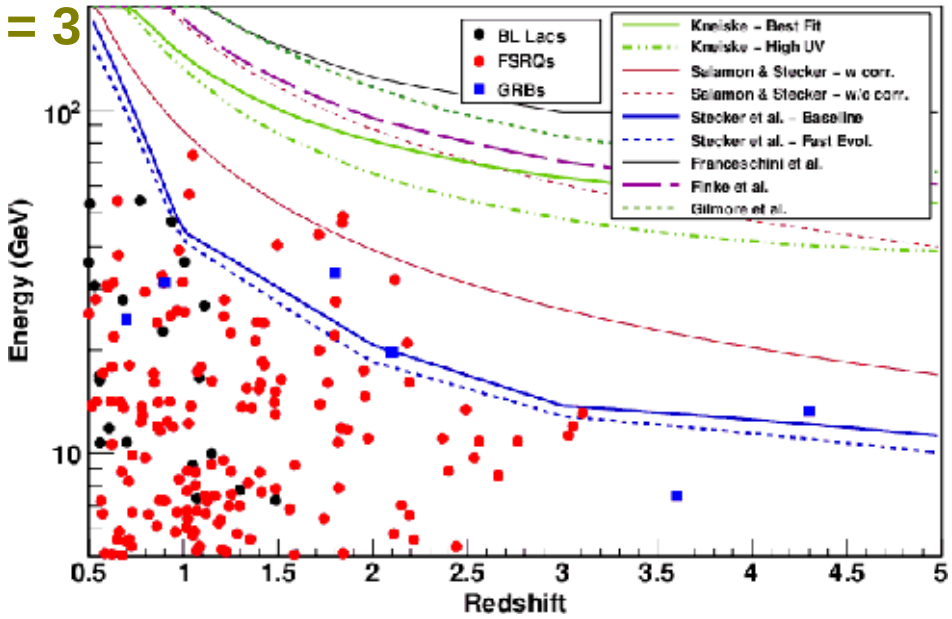
Highest photon energies consistent w/ sources

➢ « baseline » model from Stecker et al. ruled out at ~3.6σ

$\tau_{\gamma\gamma} = 1$



$\tau_{\gamma\gamma} = 3$



Abdo, A. A. et al. 2010, ApJ, 723, 1082

Origin of the additional component ?

Leptonic models : Inverse Compton, SSC

✗ Low-energy excess and delay>variability not explained

➢ Couple internal shocks to photospheric emission ? **(Ryde 2010, Toma 2010)**

(see K. Toma's presentation)

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? (correlated variability at all energies)

Early Afterglow : forward shock pairs' synchrotron (Ghisellini 2010, Kumar 2009)

✔ Delayed onset

✗ High variability of prompt emission not reproduced

✗ Requires high Lorentz factor

Summary

21 LAT GRB so far :
~10 GRB/y : close to pre-launch estimates
7 redshifts thanks to *Swift* and ground-based follow-ups
1 common *Swift*/GBM/LAT detection and multi-wavelength study

Prompt emission features and implications :
Additional PL component visible at high and low energies
Delayed onset and longer duration of high energy emission

- **Lower limits on jet's bulk Lorentz factor : $\Gamma_{min} \sim 1000$ (for simple model)**
- **Direct measurement for GRB 090926A : $\Gamma \sim 200\text{-}700$**
- **Stringent and robust constraints on linear LIV models : $M_{QG,1} > M_{Planck}$**
- **Constraints on EBL absorption models**

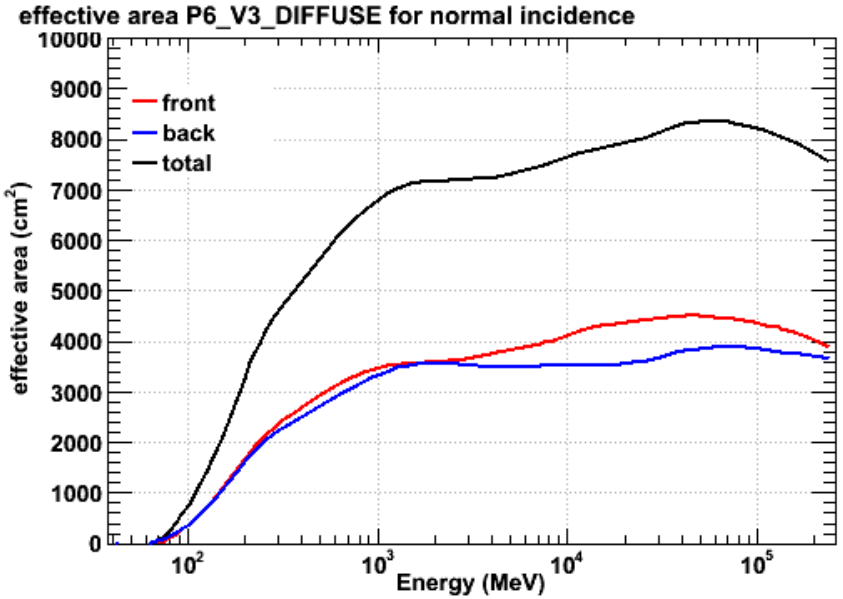
Origin of additional PL component yet unclear : leptonic ? hadronic ? other ?

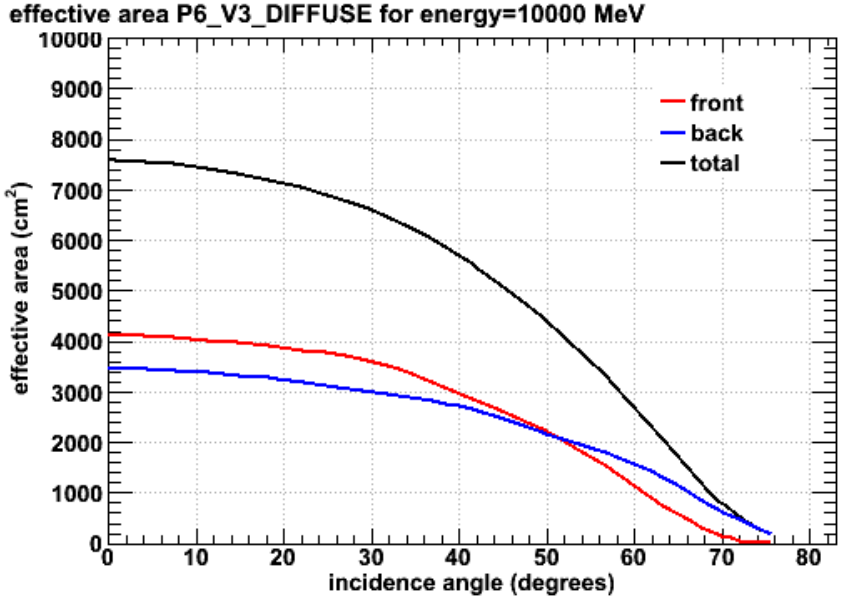
Long-lived high-energy emission seen in most LAT GRB :
Several 100's or 1000's seconds with similar properties among GRB
How does this emission relate to the prompt emission spectrum ?

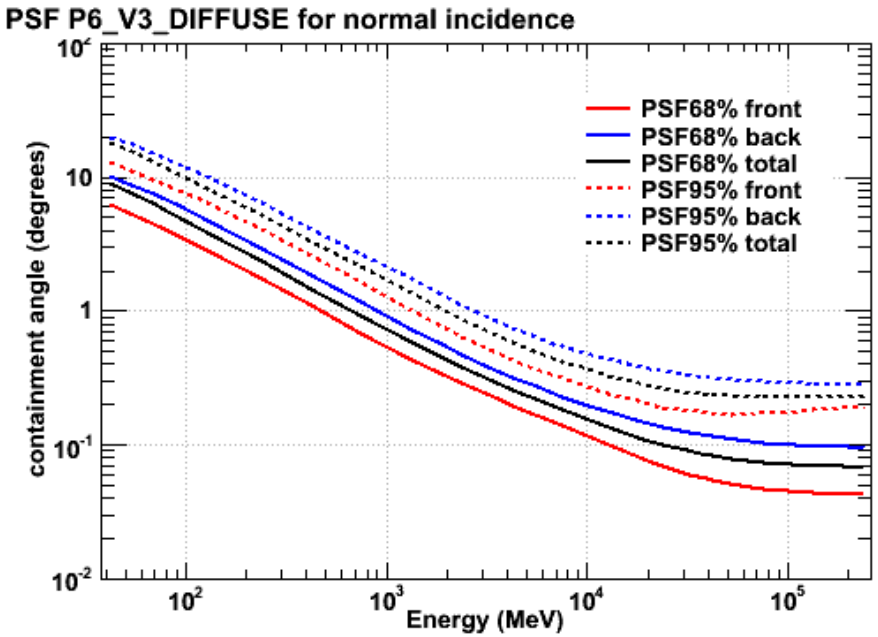
THANK YOU !! … STAY TUNED ...

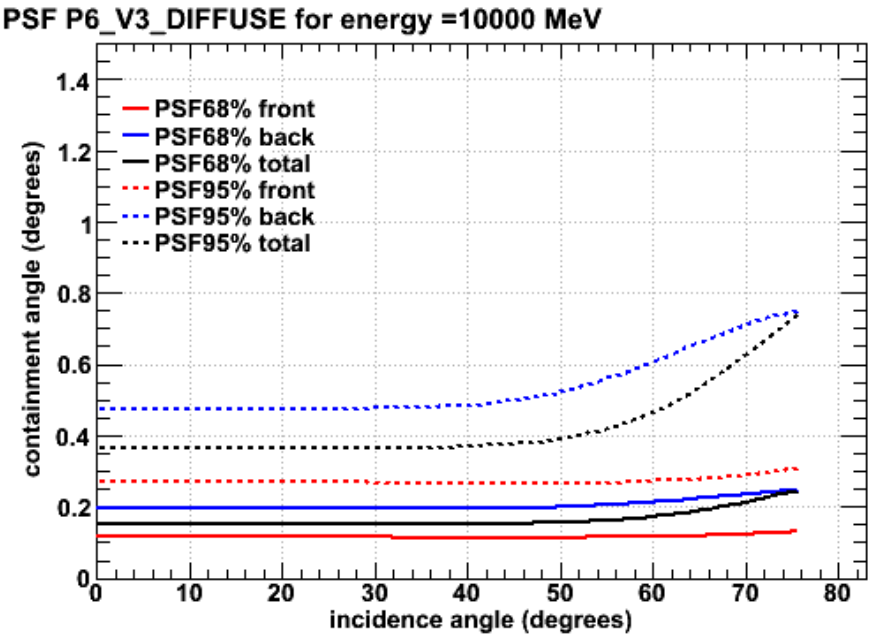
Backup slides

LAT performance

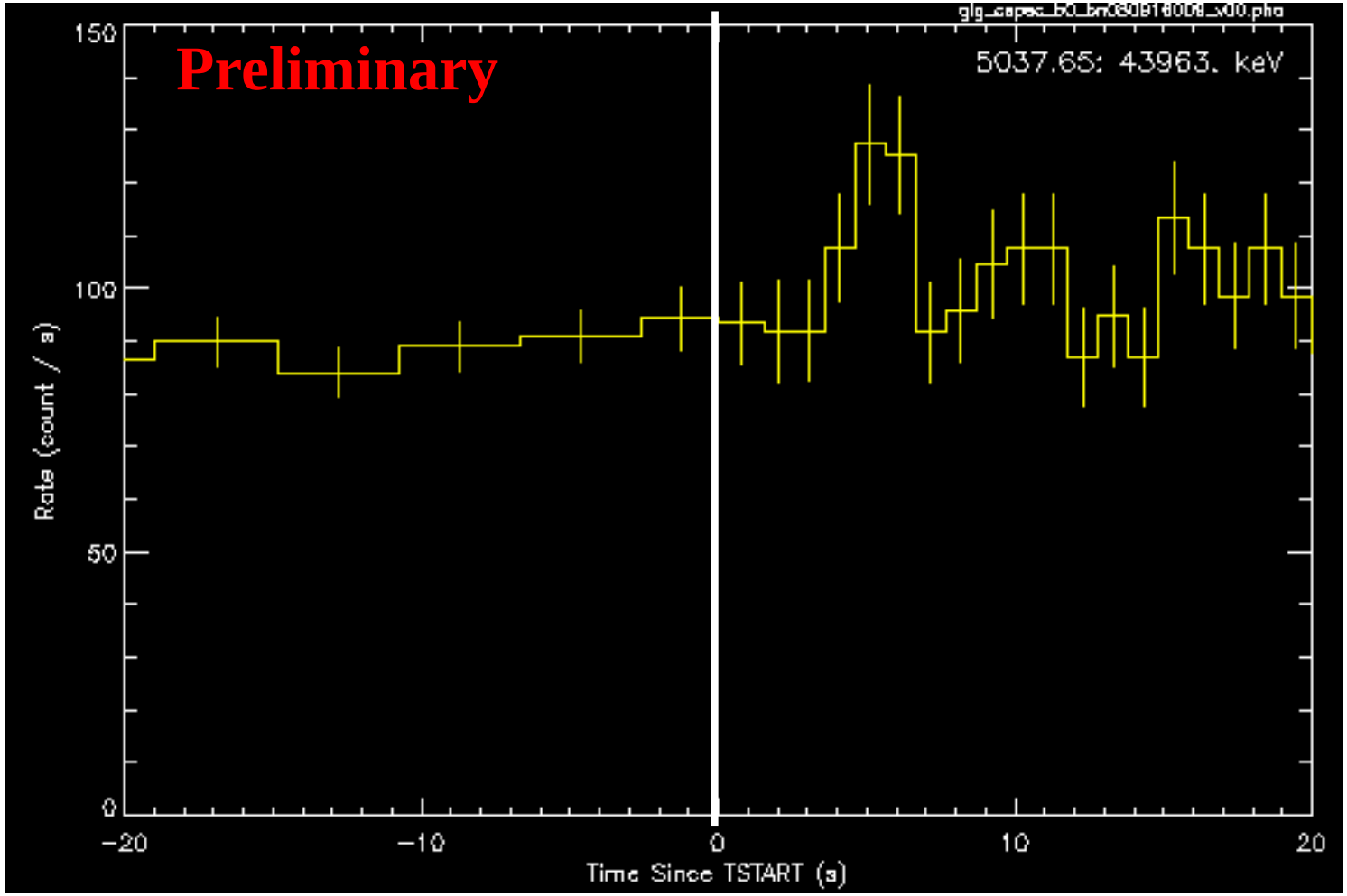








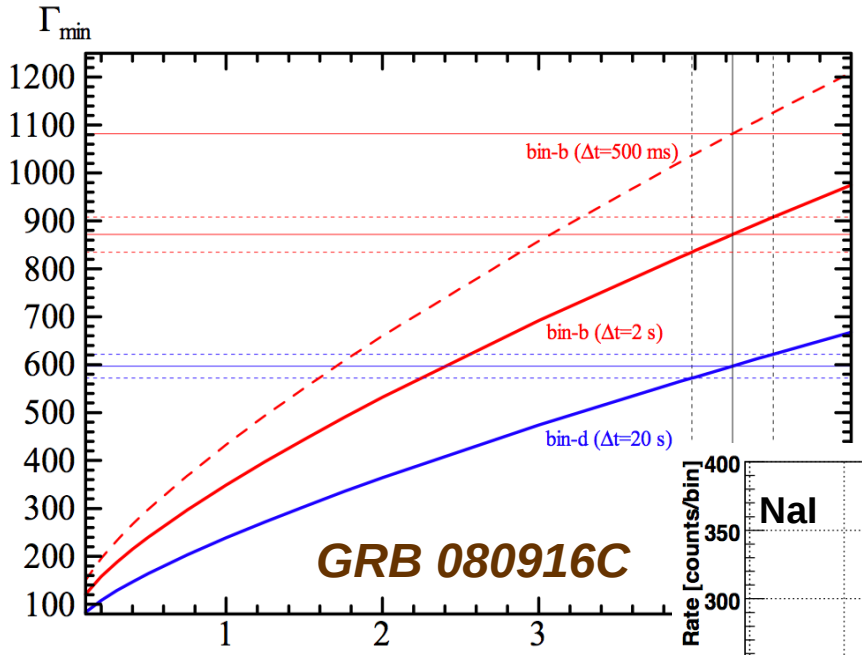
GRB 080916C light curve BGO>5MeV

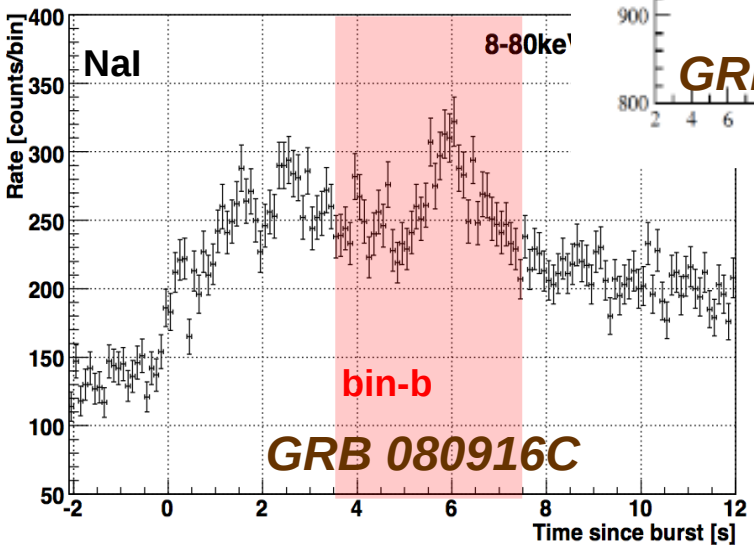


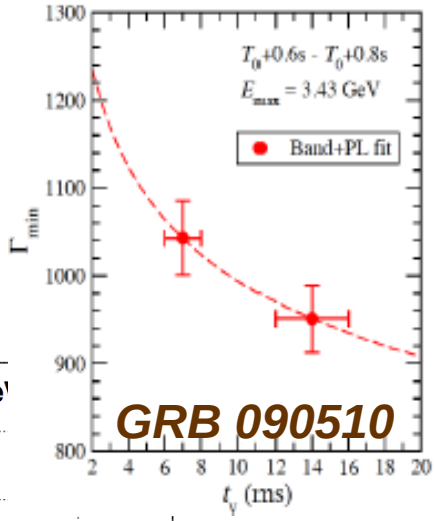
Bulk Lorentz factor computation

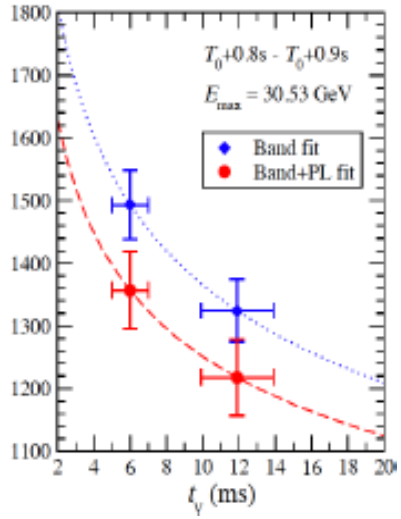
For a Band spectrum target photon field (simple modelling) :

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









DisCan analysis (1/2)

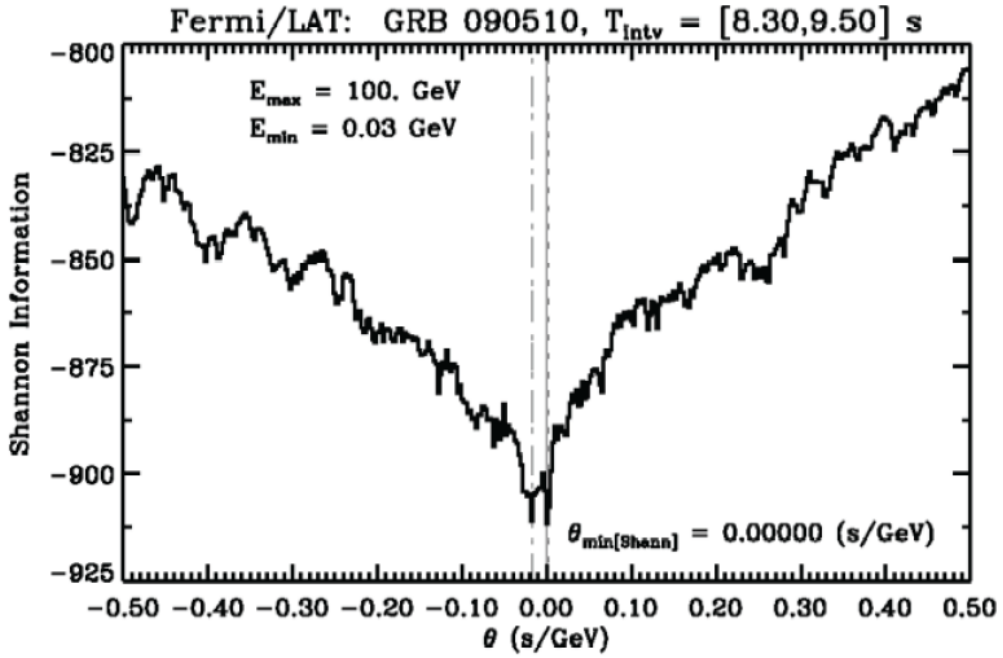


Figure S2. Shannon Information versus trial values of θ for the interval $T = 0.50 - 1.45$ s. The best value of θ is annotated, and shown as a vertical solid line. The two dashed vertical lines left and right of the best value represent the θ values which are 100 times less probable than the best θ value, *for the given data set*. Thus the contained interval between the two dashed lines is an approximate error region, but *does not reflect statistical uncertainties*.

$$t'_{\rm i} = t^{\rm obs} - \theta E_{\rm i}^{\rm obs}$$

DisCan analysis (2/2)

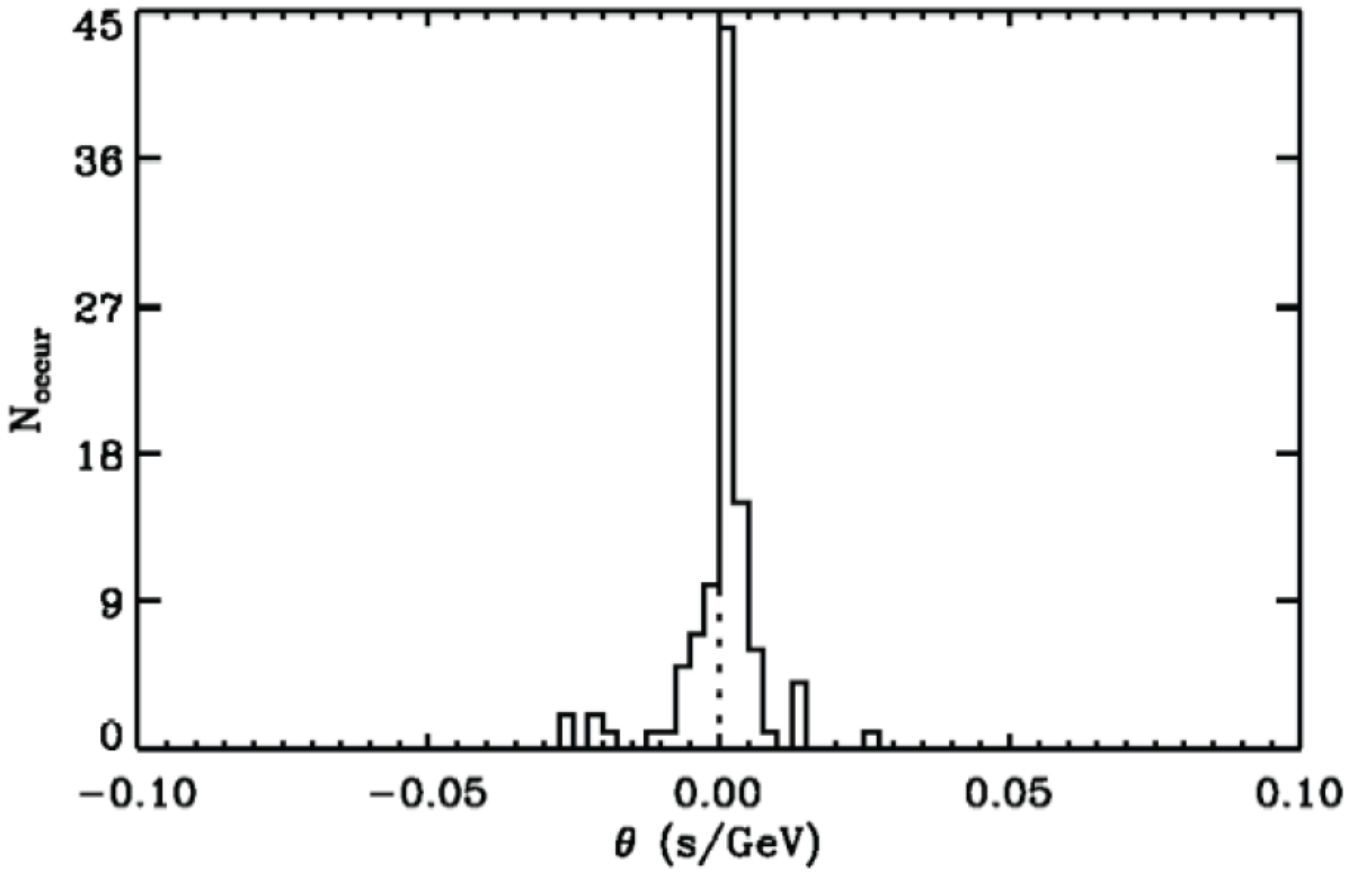
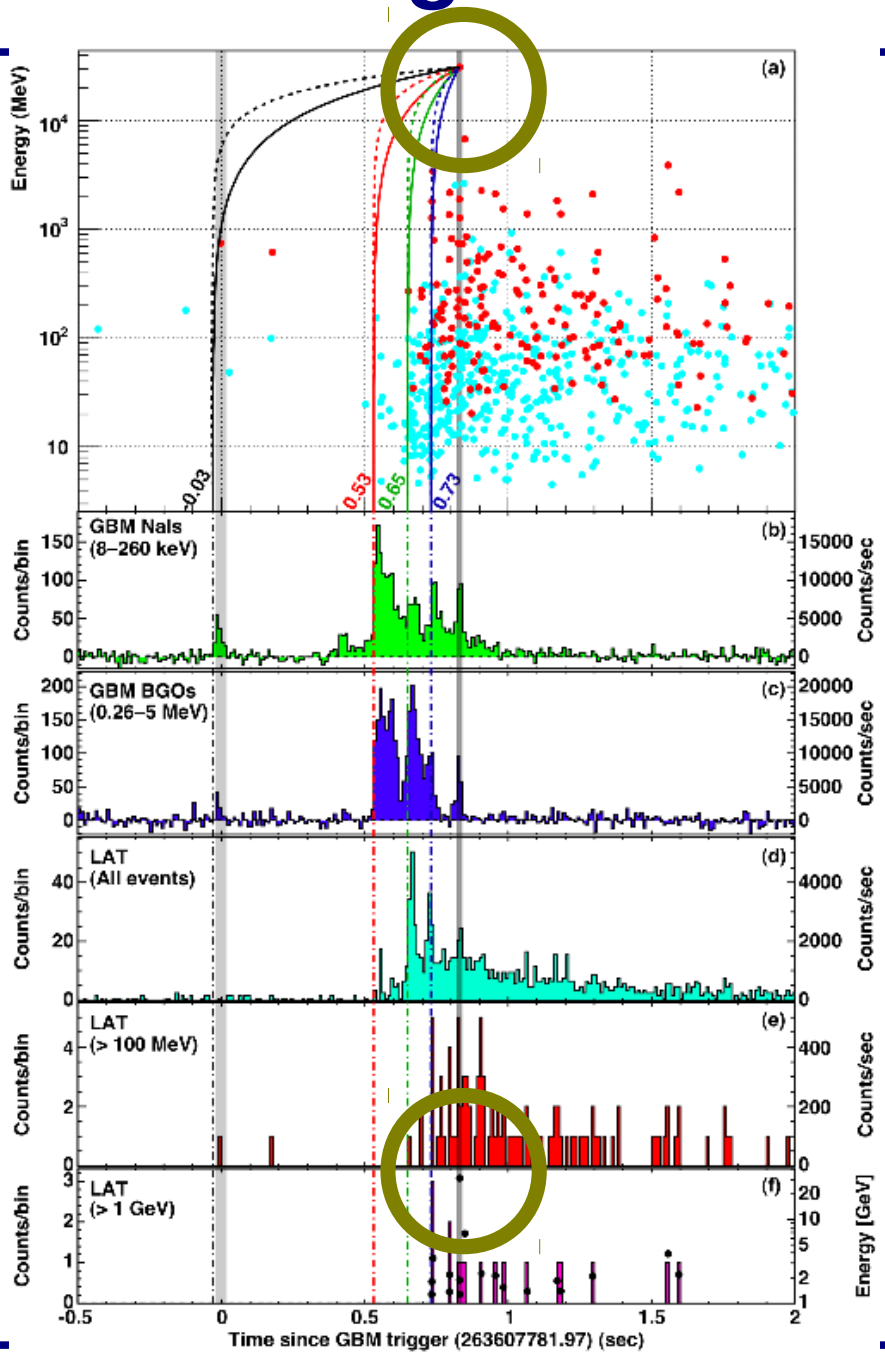


Figure S3. For the interval analyzed in Figure S2, to gauge uncertainty due to statistical variations we generated 100 realizations with the photon times randomized. $\theta_{\rm min}$ for these 100 realizations is within the range ± 0.03 s/GeV.

$$t'_{\rm i} = t^{\rm obs} - \theta E_{\rm i}^{\rm obs}$$

GRB 090510 light curve



Abdo et al. 2009, Nature 462, 331

GRB 090926A light curve