Gamma-Ray Bursts in the *Fermi* era

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on behalf of the *Fermi*
GBM and LAT teams

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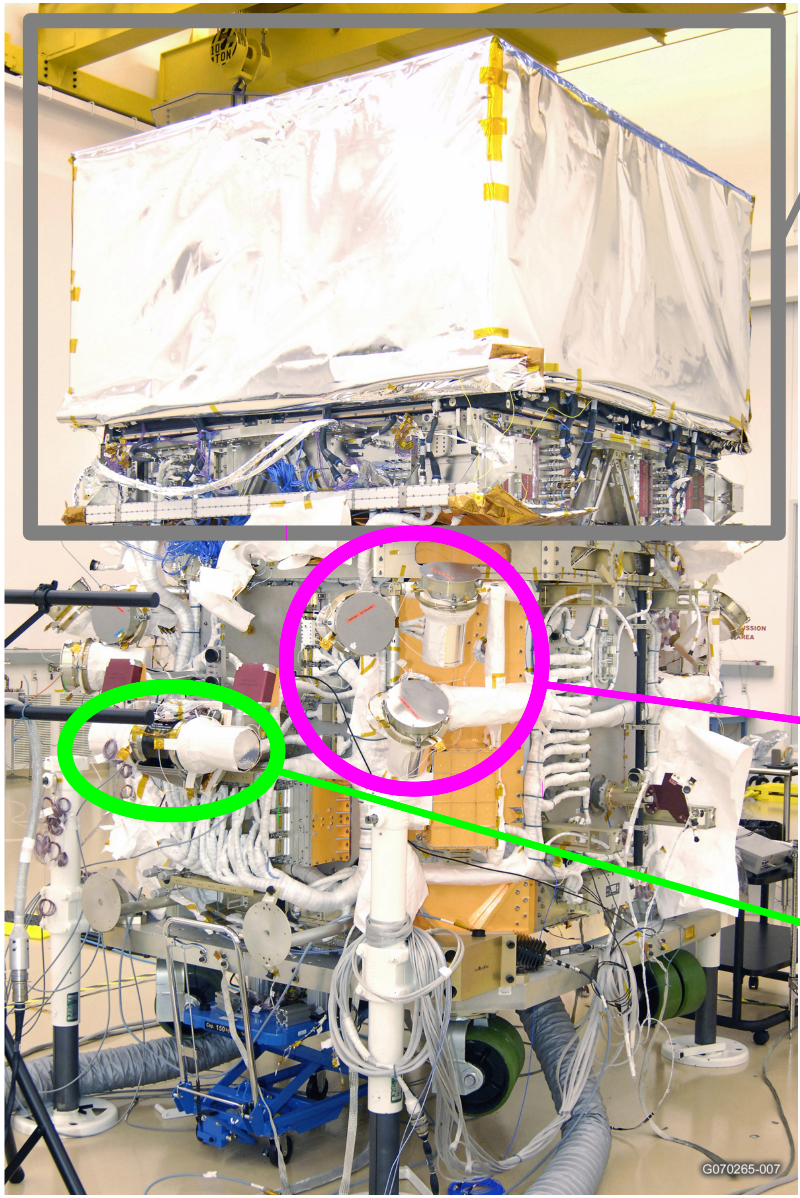
Vulcano Workshop : Frontiers objects in astrophysics and particle physics

UAHuntsville
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

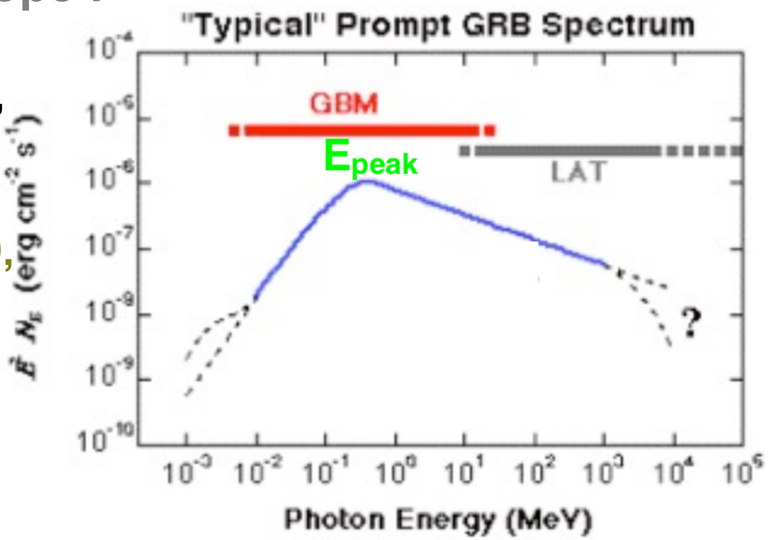
Outline

The Fermi observatory
Summary of detections
Prompt emission specta and light curves
High-energy long-lived emission
GRB as tools
Fermi and future GRB observations

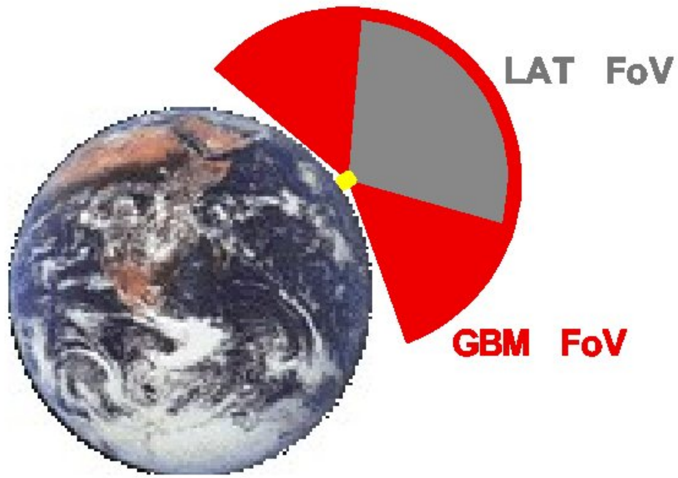
Fermi instruments



Large Area Telescope :
Pair conversion
Trigger, localization, spectroscopy
20 MeV – 300 GeV
W. Atwood et al 2009, ApJ 697, 1071



Gamma-ray Burst Monitor :
14 PMT
12 NaI
Trigger, localization, spectroscopy
8 keV – 1 MeV
2 BGO
Spectroscopy
200 keV – 40 MeV
C. Meegan et al 2009, ApJ 702, 791



GRB trigger and observation

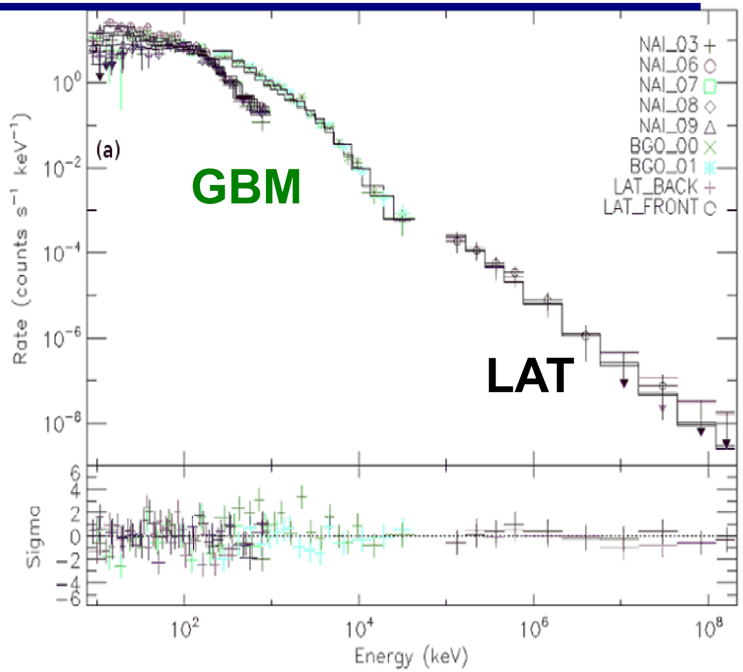
GBM :
Continuous data are binned in energy and time.
Data of higher temporal resolution and tagged time events for triggered events.
Trigger: 4 energy ranges (50 – 300keV for GRB), timescales 16ms, 32ms... 4.096s
On board localization : ~5° (up to 15°) within a few s (→ GCN notice)
Trigger data available for localization in ~15min, science data within a few hours.
On ground human-in-the-loop localization : 2-3° (1° to 10°) within 2h (→ GCN notice)

GBM is part of the InterPlanetary Network : triangulation by several γ-ray detectors and satellites, box #dimensions depends on #satellites... (→ GCN circular ~2-3d)

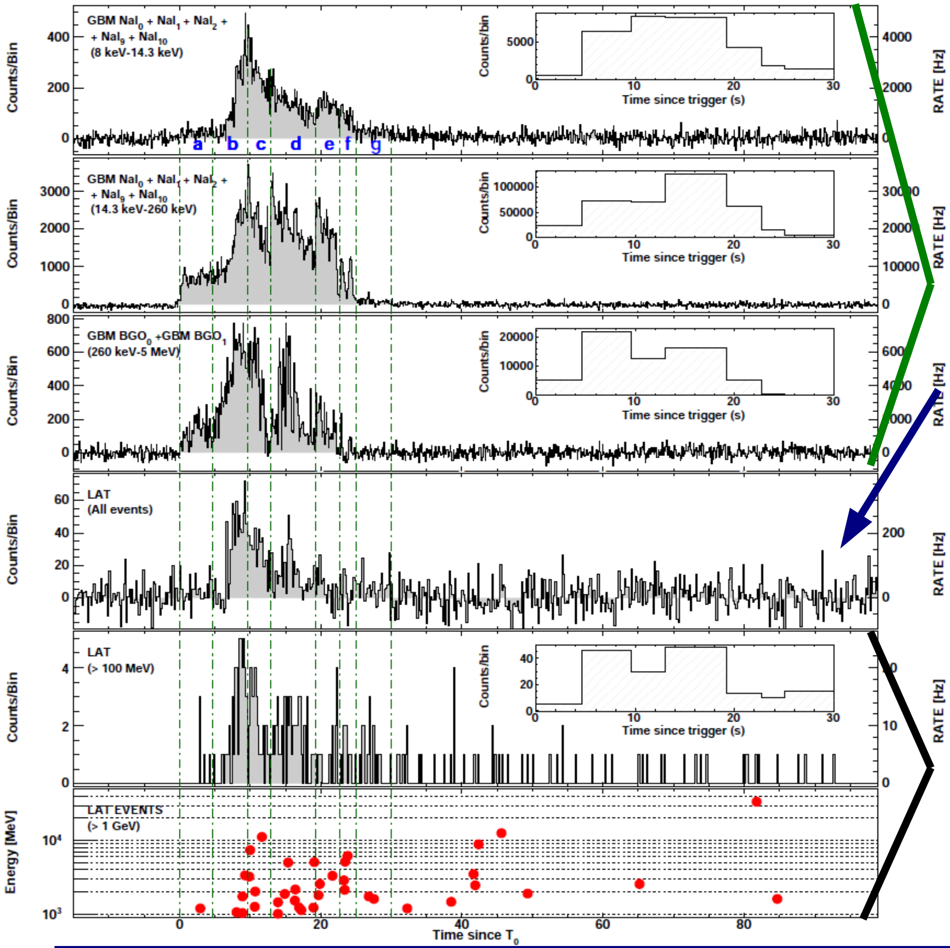
LAT :
Tagged time events from continuous survey, energy and direction reconstructed.
On-board trigger : 2 modes (blind or GBM-seeded), searching for clustered tracks.
Localization : 0.1° to 0.5° within a few seconds (→ GCN notice)
Autonomous repoint for bright GRB (~1/week in FoV, ~1/month out of FoV) : 2.5hr follow-up with source 10° off-axis (while 20° above horizon).
Data for a specific trigger available >8h for localization and further analyses.
On-ground localization : 0.1° to 1° (→ GCN circular)

Prompt emission as seen by Fermi

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



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

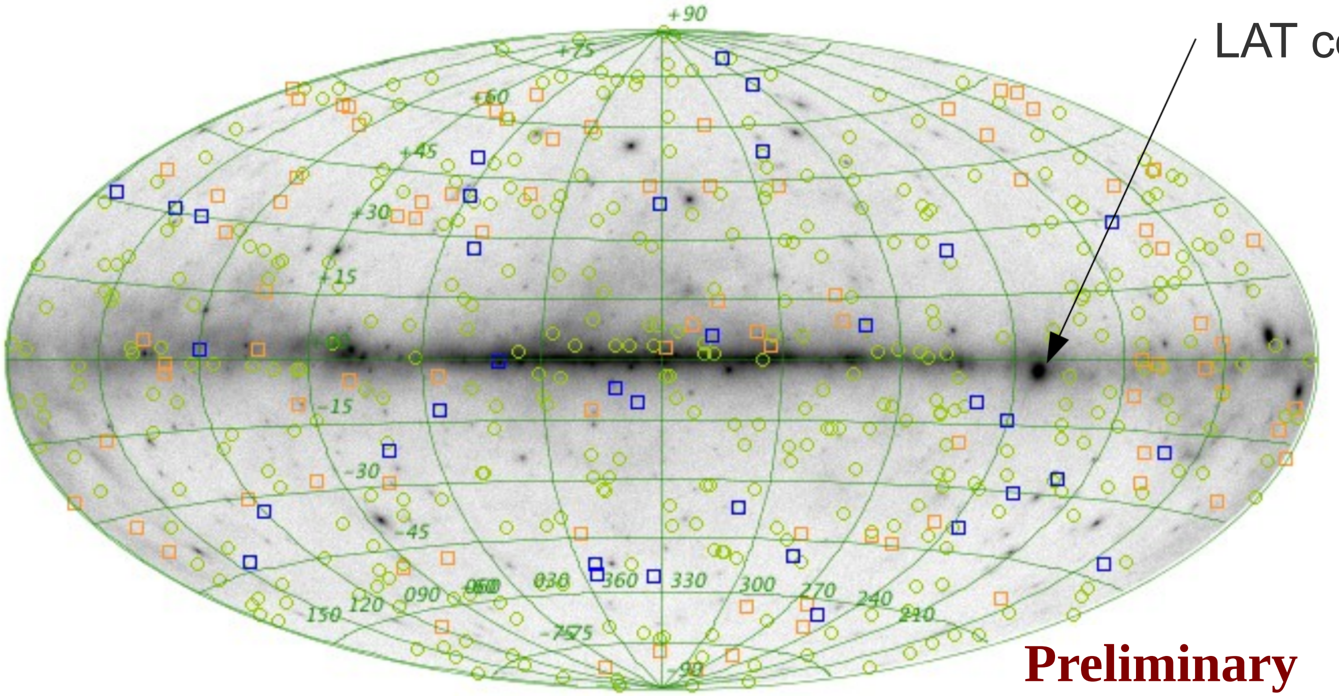


GBM (bkg-limited)

LLE = "LAT Low Energy" (bkg limited)
On-board photon selection + 1 track
In our first catalog : detection & duration
Starting/ongoing : Light curve analyses (>10MeV)
Spectral analyses (>30MeV)
Data to be released soon for GRB and solar flares

LAT standard data
Tight quality cuts > 100MeV in ROI : very low bkg.
Event by event likelihood analyses :
spectra, localization

First Fermi GRB catalogs



Preliminary

LAT count map : first 11 months

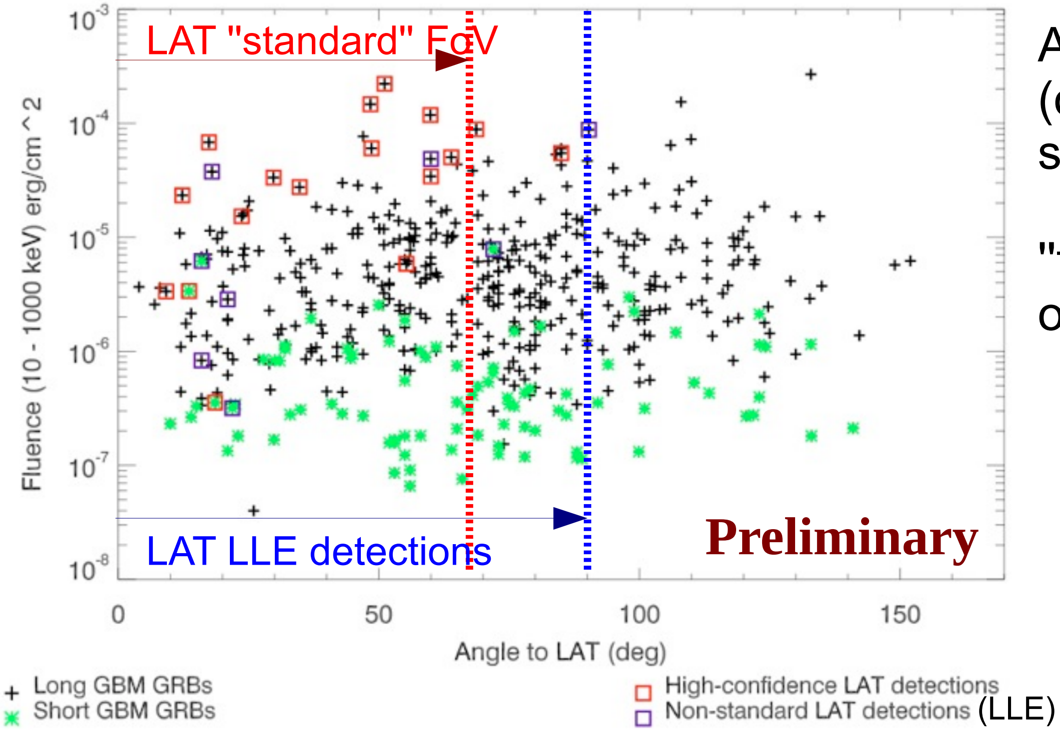
Green circles : long GBM GRB
Orange squares : short GBM GRB
From catalog (07/08 –07/10)
trigger cat : Paciesas et al. 2012
spec cat : Goldstein et al. 2012
(ApJS 199, articles 18 & 19)
http://fermi.gsfc.nasa.gov/ssc/
(soon also at ASDC)

Blue squares : LAT GRB from in prep. catalog (08/08 – 07/11)

GBM : ~250 GRB/yr, ~45/yr are short. 931 triggered GRB as of today.
~1/2 GRB occur within the LAT FoV

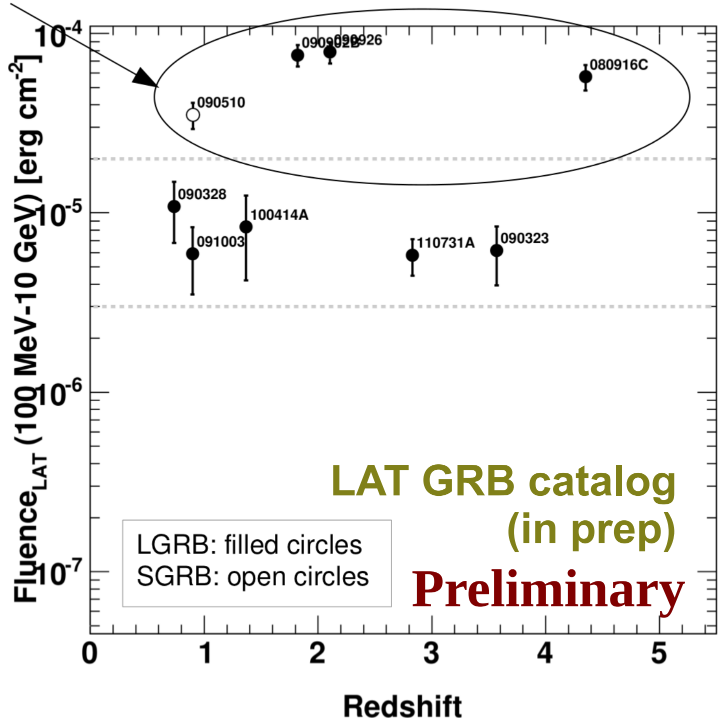
LAT : ~10 GRB/yr. 5 short GRB detected so far.
~1/2 follow-up by Swift & ground-based telescopes (GROND, Gemini-S, Gemini-N, VLT)
9 redshift measurements
→ Detection rate lower than expectation, but systematics in extrapolation from BATSE/EGRET are not negligible. We see ~8% of GBM GRB located in the LAT FoV.

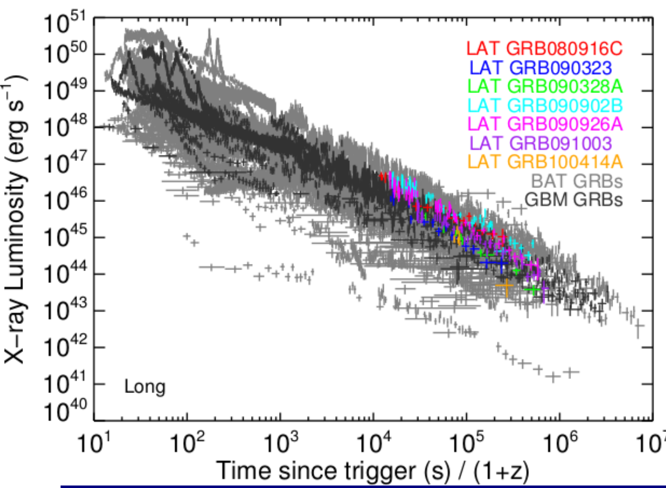
LAT detections: bright bursts

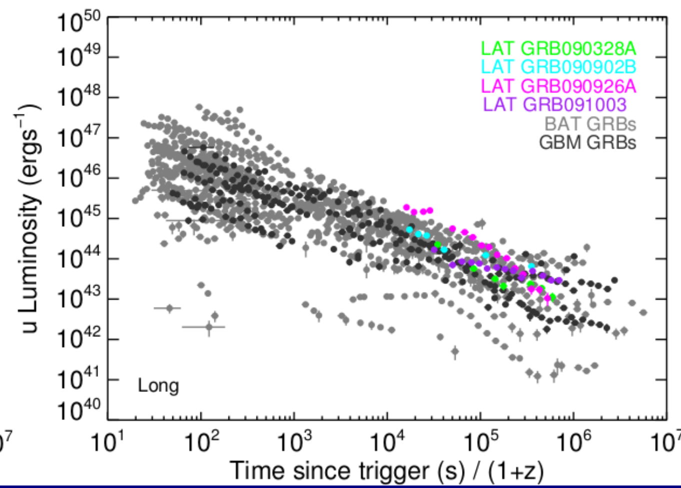


A subsample of high fluence GBM bursts (or well enough within the LAT FoV), not systematically closer to us

"the Fantastic 4" : a sub-sub-sample of very energetic bursts !





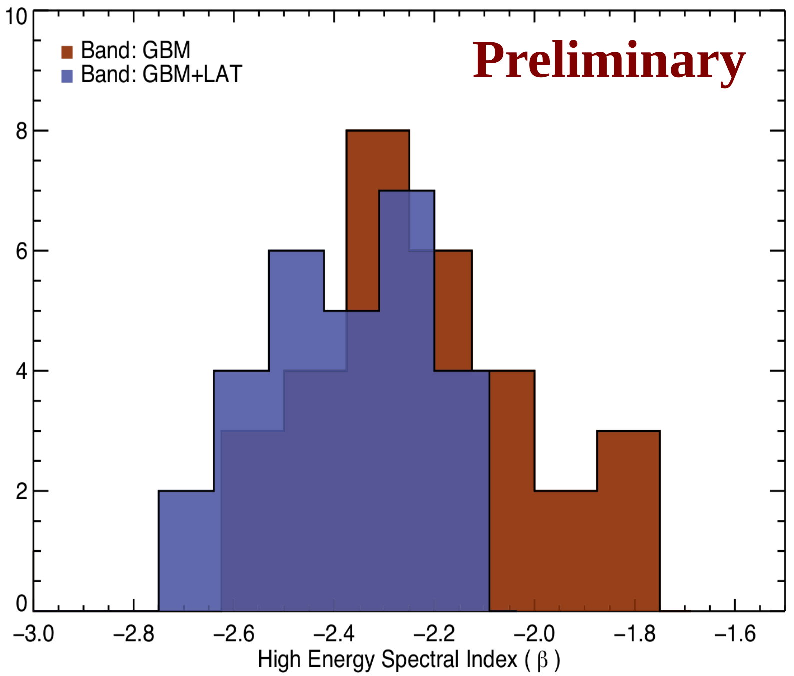


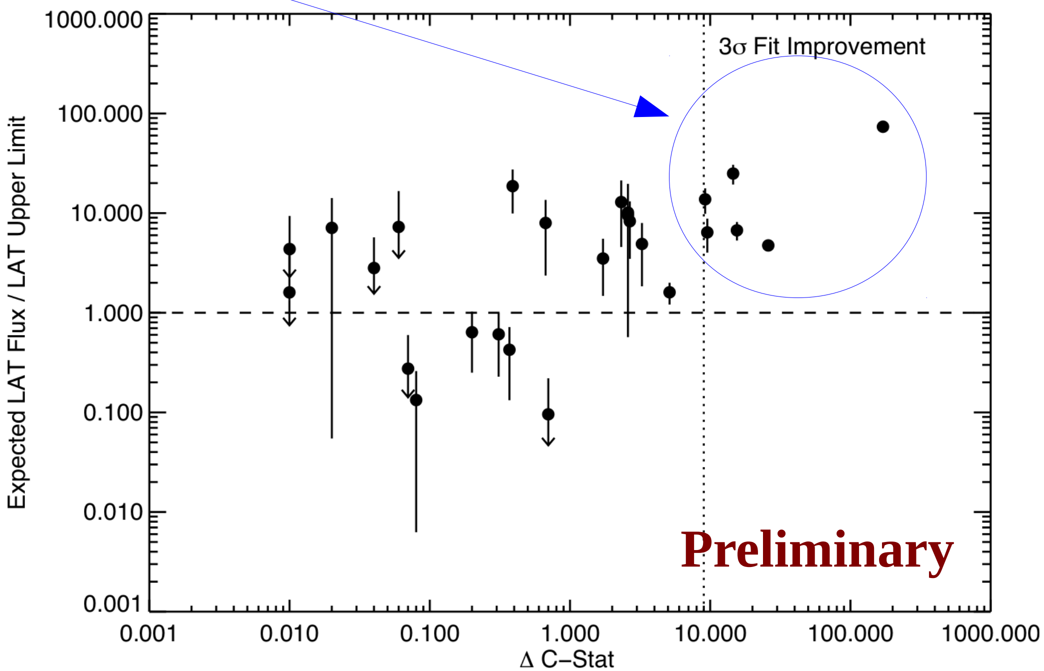
Xray and UV afterglows of LAT GRB
J.Racusin et al. 2011, ApJ 738, 138

LAT non-detections

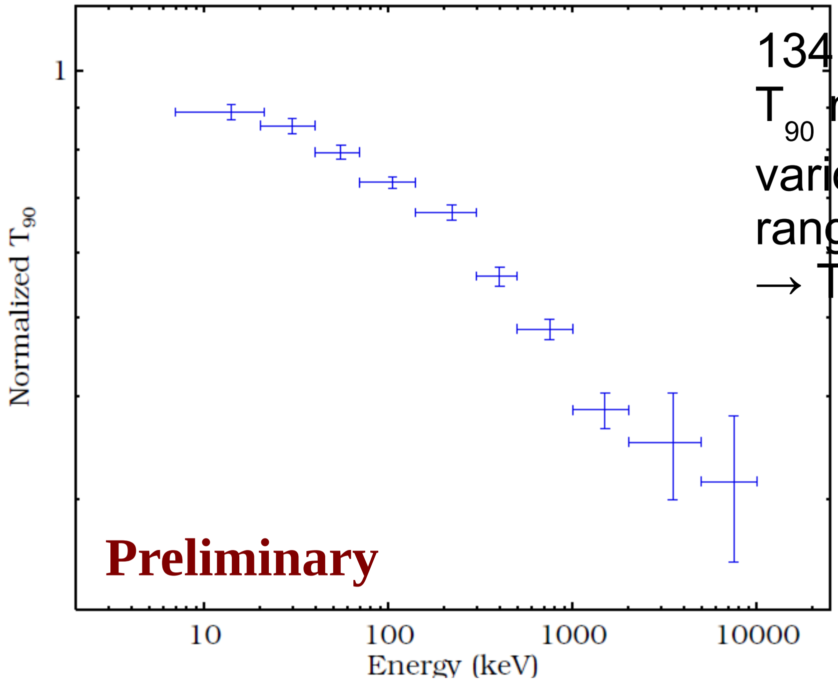
"Constraining the high-energy emission from GRB with *Fermi*"
(Abdo et al, submitted to ApJ, astro-ph/1201.3948)

Sample of 30 bright undetected bursts within LAT FoV
→ 1/2 have predicted LAT flux (GBM fit) > measured LAT UL
→ HE index from GBM+LAT fit softer than in GBM fit : 80%
(extrapolated LAT flux lowered, consistent with UL)
→ 6 GRB require a spectral attenuation : 20%

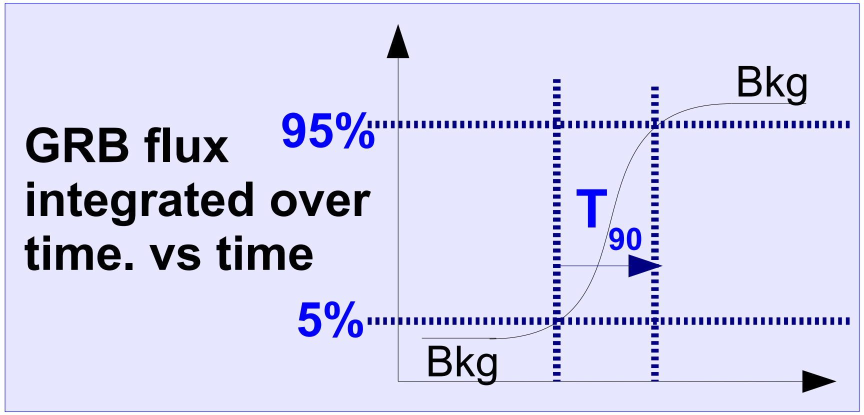


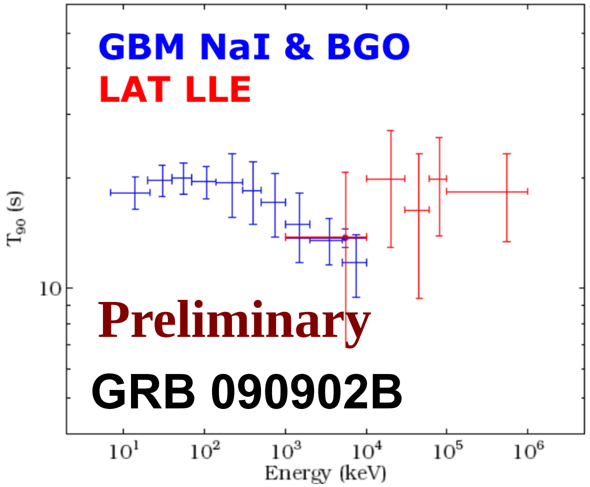


Prompt emission: duration vs E



134 bright BGO bursts T_{90} measurements in various GBM energy ranges up to 10MeV → T_{90}(E) decreases

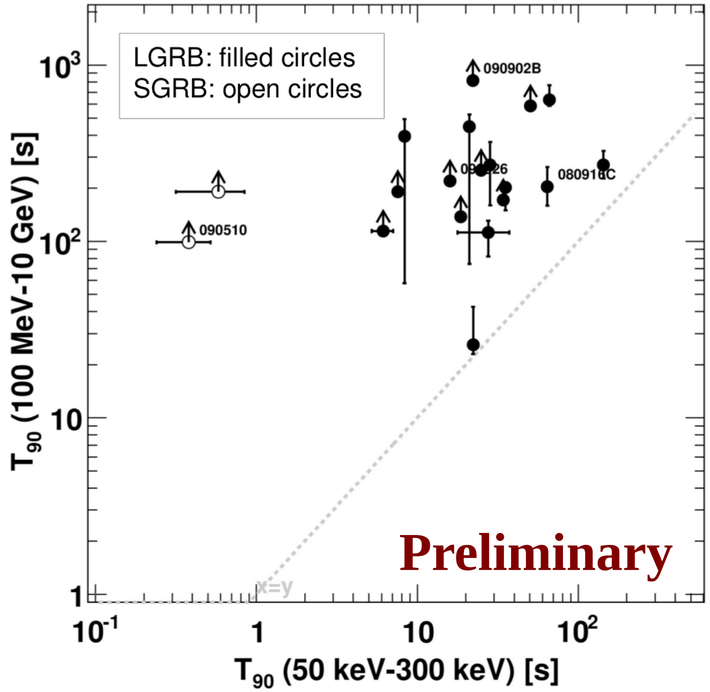




E. Bissaldi et al

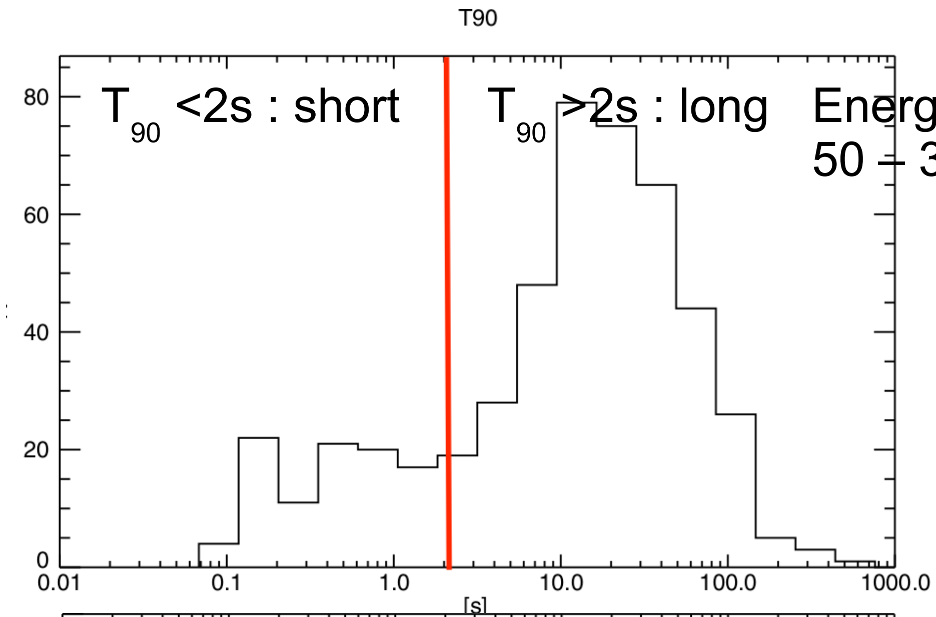
T_{90} above 10MeV consistent with GBM, does not decrease further

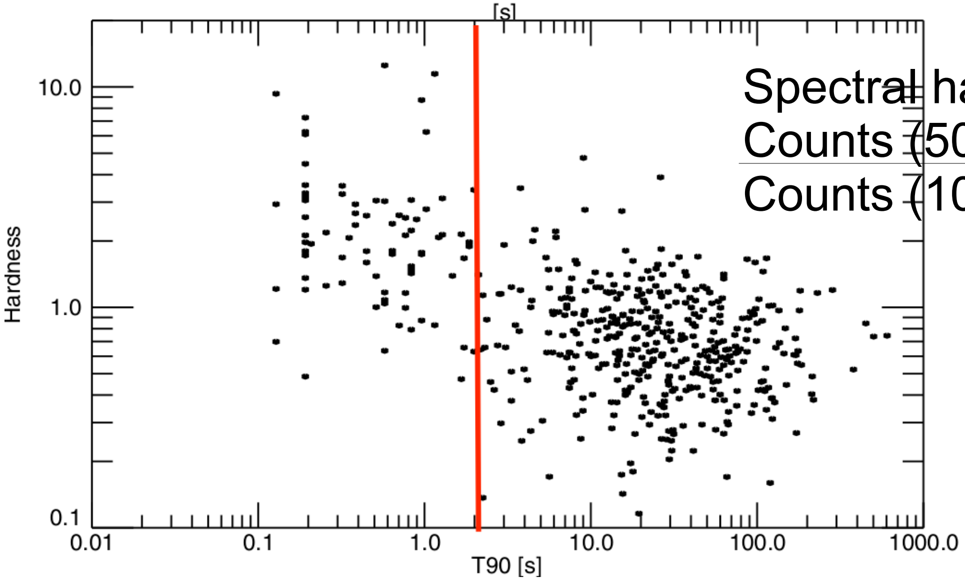
T_{90} >100MeV systematically longer than in the GBM range



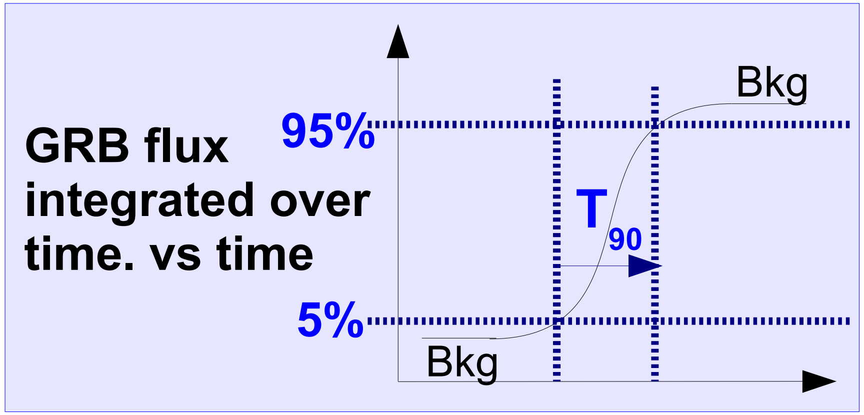
LAT GRB catalog, in prep

Short (hard) and long (soft) GRB

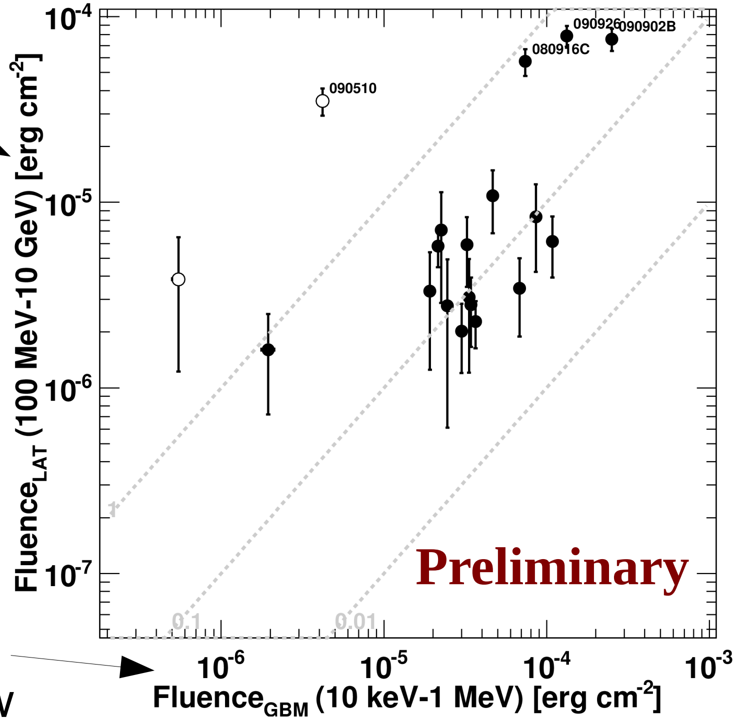




GBM catalog



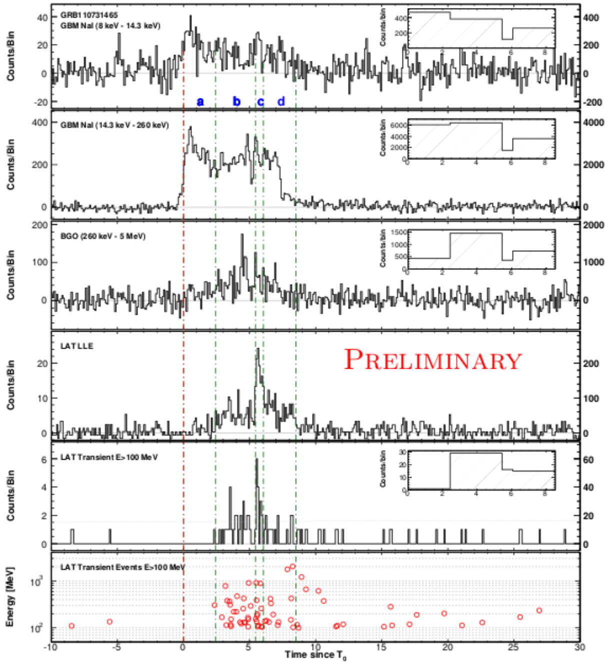
LAT fluence in LAT T_{90} window

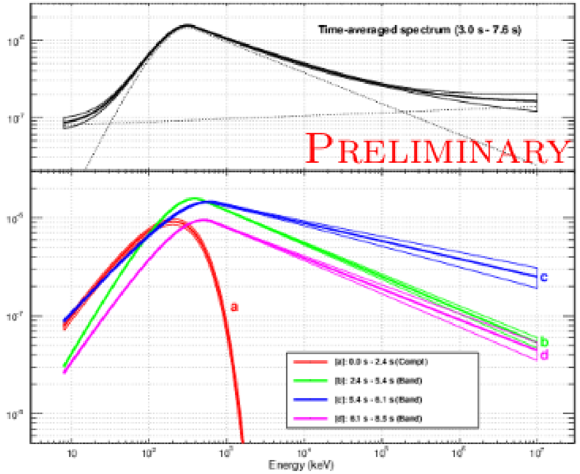


GBM fluence in GBM T_{90} window

LAT GRB catalog, in prep

HE emission delayed onset

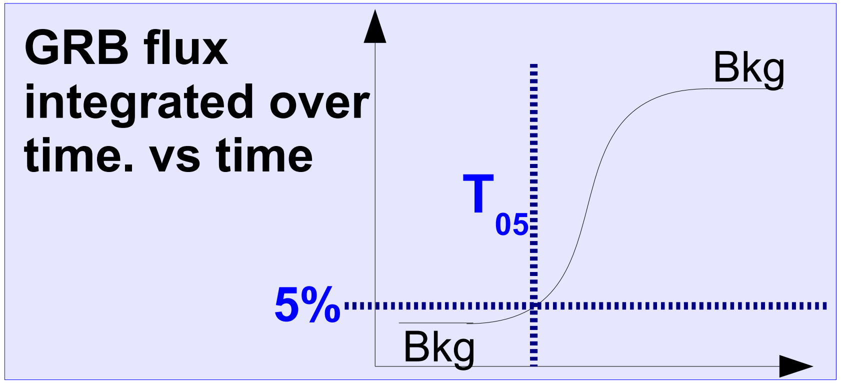


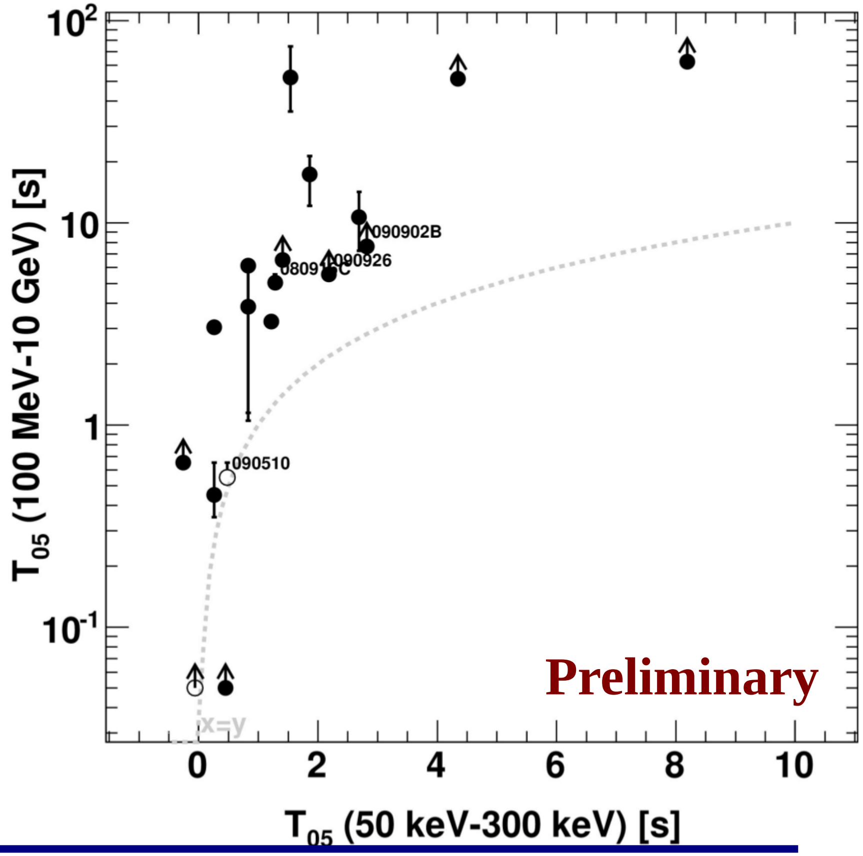


GRB 110731A
in prep paper by *Fermi* LAT&GBM, Swift, GROND, MOA

HE emission onset delayed wrt GBM light curve onset
Correlated variabilities at all energies
Spectral evolution : soft-hard-soft

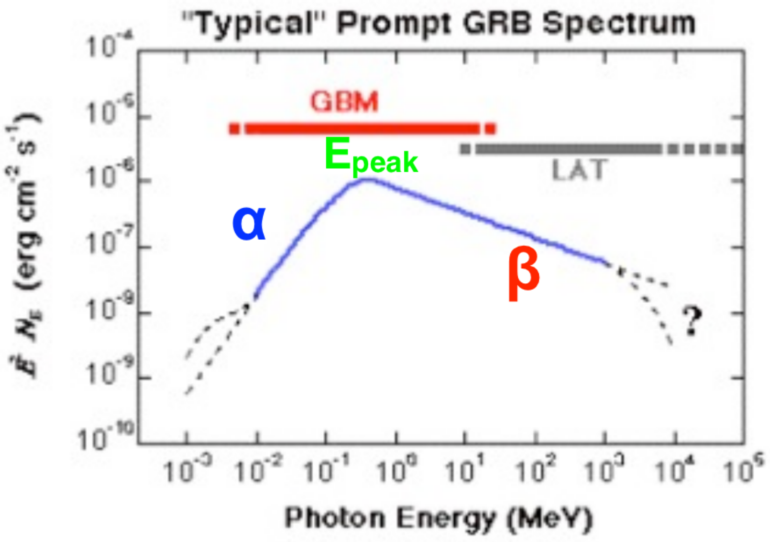
Systematic characteristic of LAT GRB





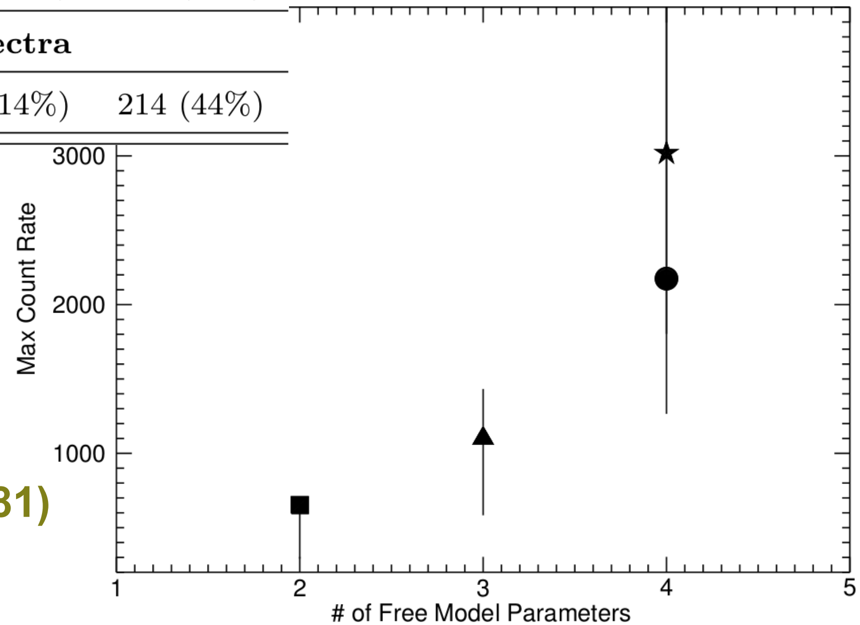
LAT GRB catalog, in prep

Empirical fits of GBM spectra



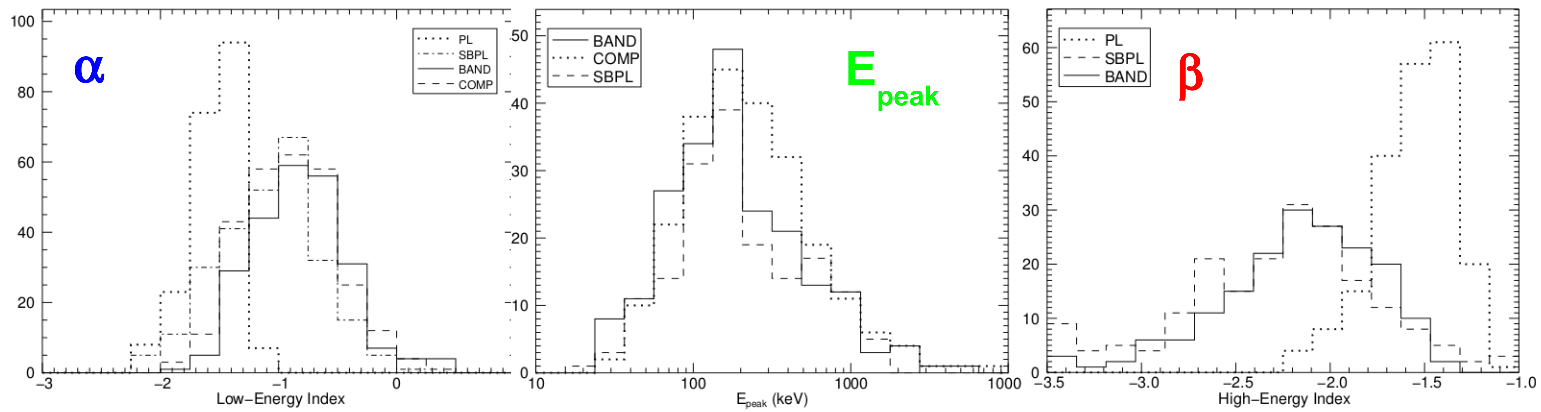
PL *square*	SBPL *circle*	BAND *star*	COMP *triangle*
Fluence Spectra			
113 (23%)	67 (14%)	75 (15%)	231 (48%)
Peak Flux Spectra			
152 (31%)	48 (10%)	69 (14%)	214 (44%)

GBM spectroscopic catalog

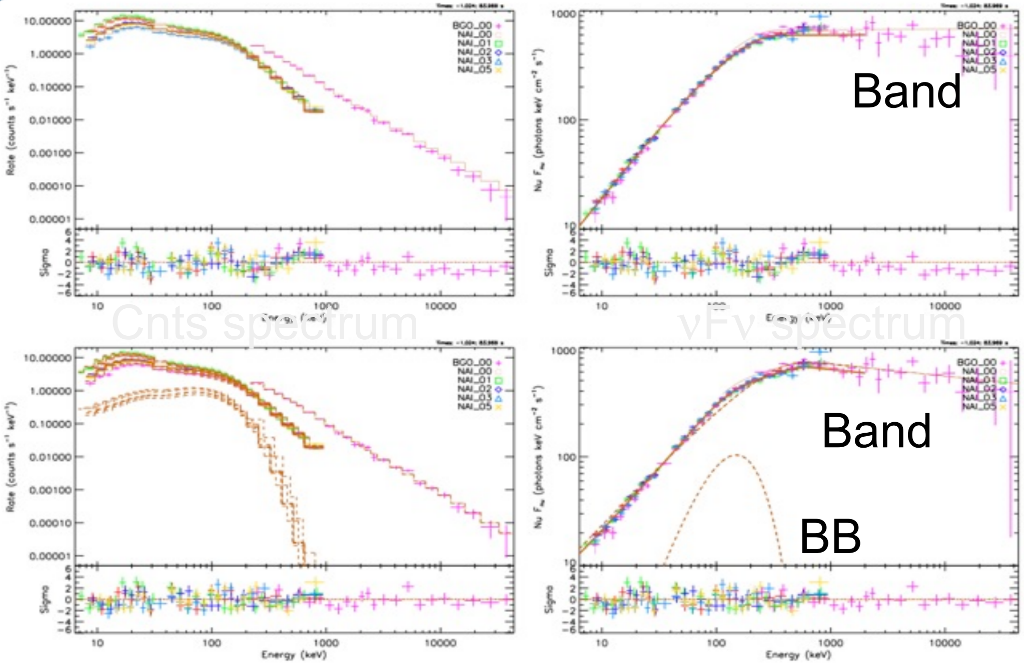


The Band function fits well the spectra when enough counts are available. Since 1993 **(D.Band et al, ApJ 413, 281)**

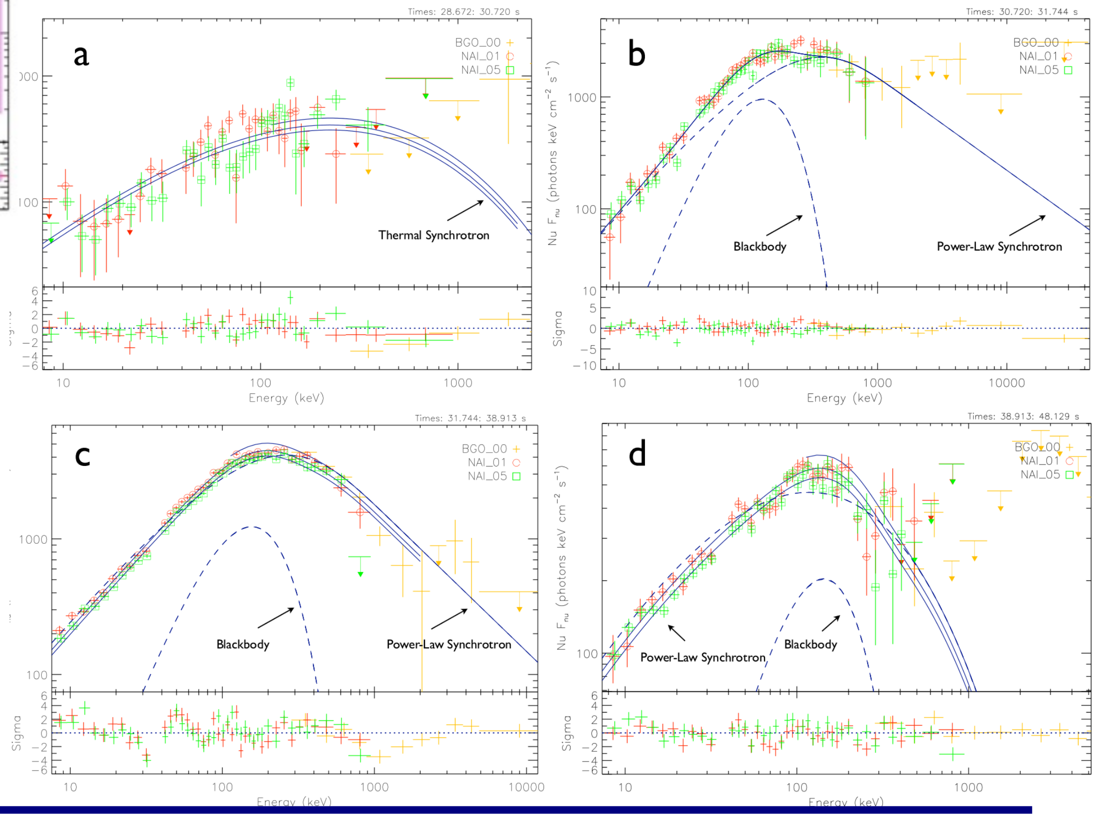
Alternatively : the "Smoothly Broken Power Law" (SBPL, "a hyperbolic cosine in log scale") allows to fit a broader/smoother peak.



Nature of the MeV spectrum ?



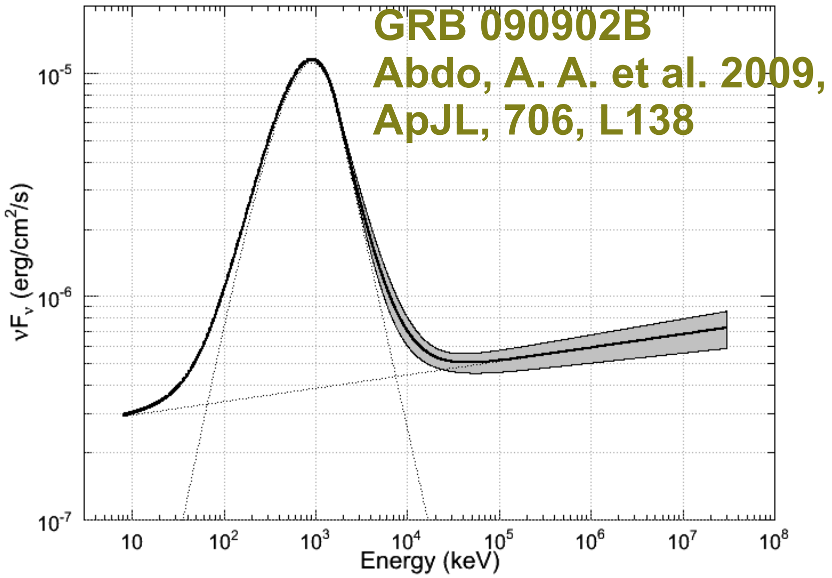
GRB 110724B
S. Guiriec et al, 2011, ApJ 727, L33
Spectral fit improved (look at the residuals) by adding a non-dominant Black Body component in several bursts.
While a dominant multicolour BB component can be found in e.g. 090902B **(F. Ryde et al, 2009)**

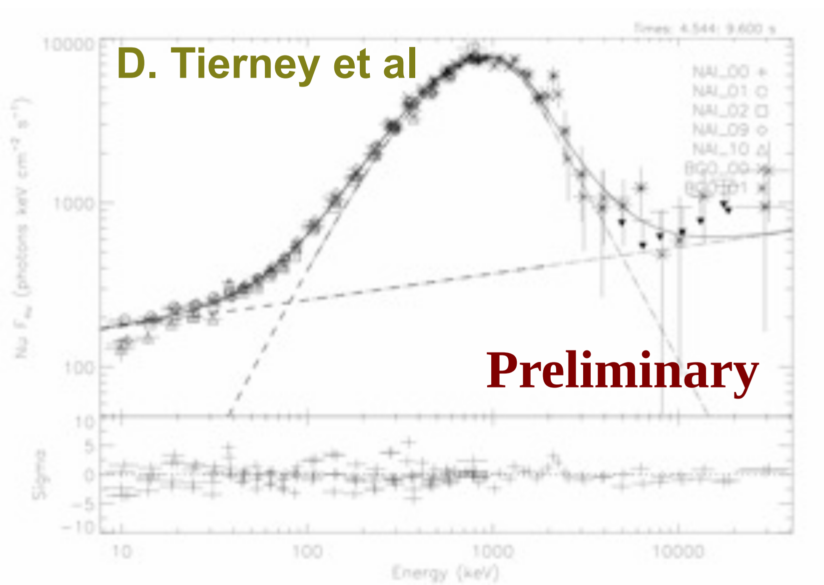


GRB 090820A
J. Burgess et al 2011, ApJ 741, 24

Modelling different epochs of this GRB :
Thermal or non-thermal synchrotron
+ Black body component

The additional powerlaw component...





…that dominates emission at LE and HE in several GRB

Leptonic models : Inverse Compton, SSC

✗ Low-energy excess and delay>variability ??

➢ 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, say, 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

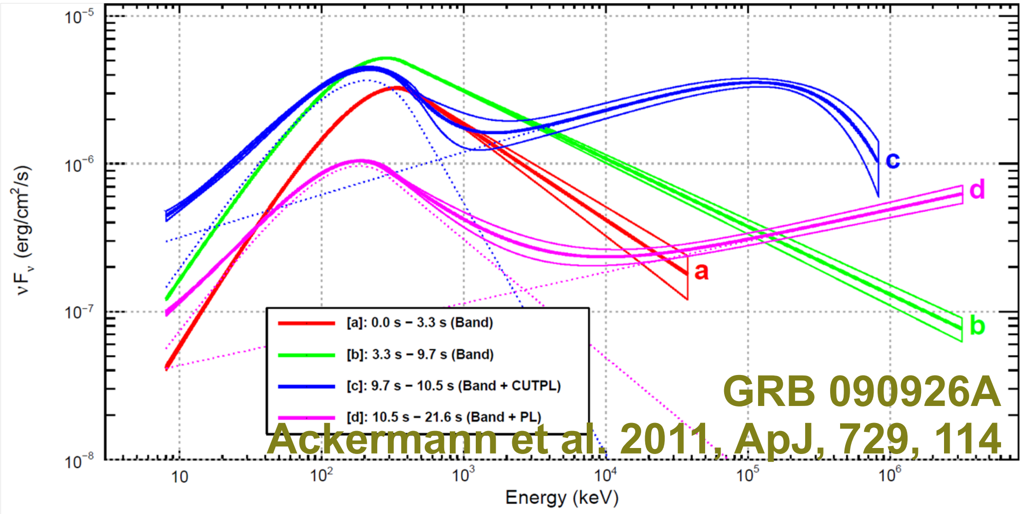
✗ Requires high Lorentz factor

γγ opacity and jet 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

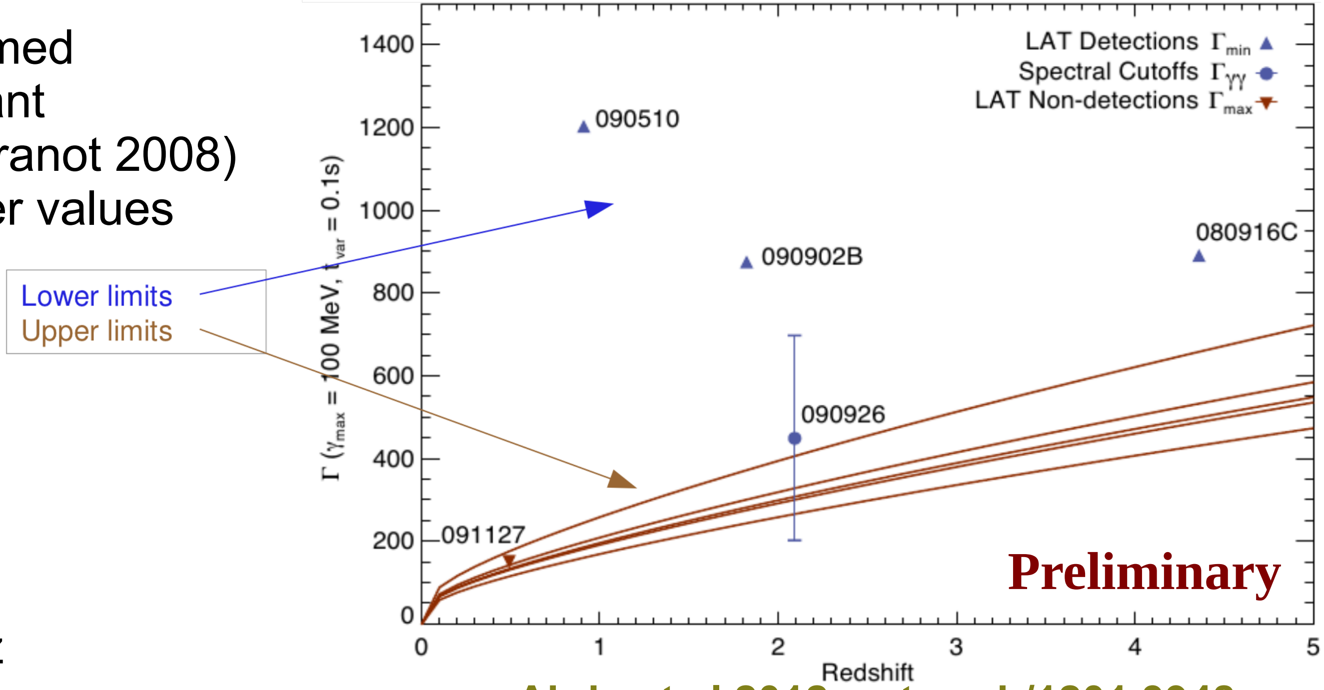
Variability timescale from GBM light curve (more statistics)

➢ Robust (modulo caveat) constraints for most GRB

Cutoff energy for GRB 090926A

➢ Measurement Γ~ 200-700

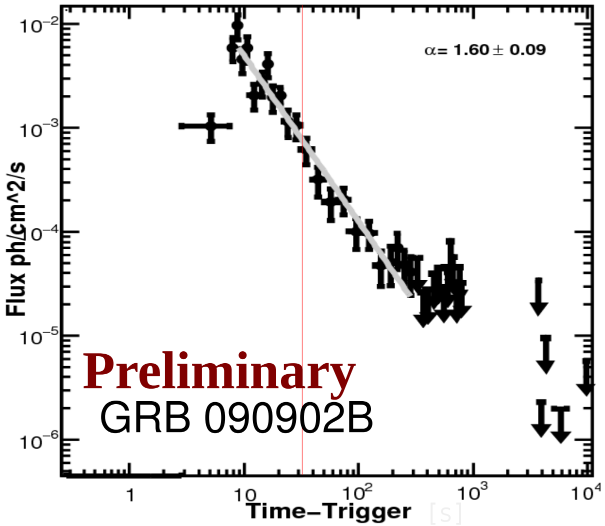
LAT non-detections : 5 unknown z

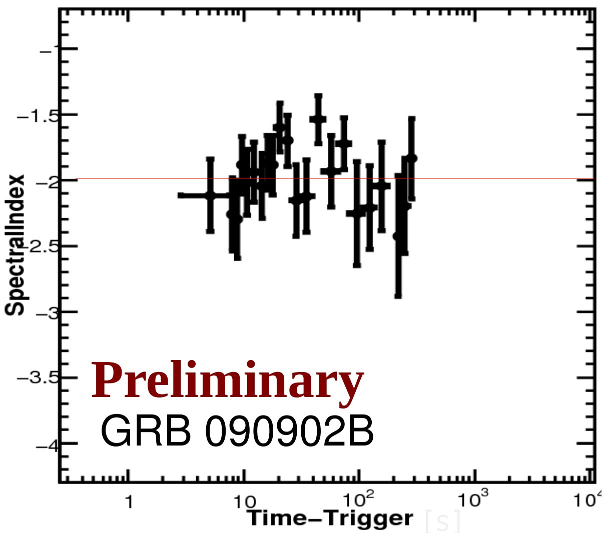


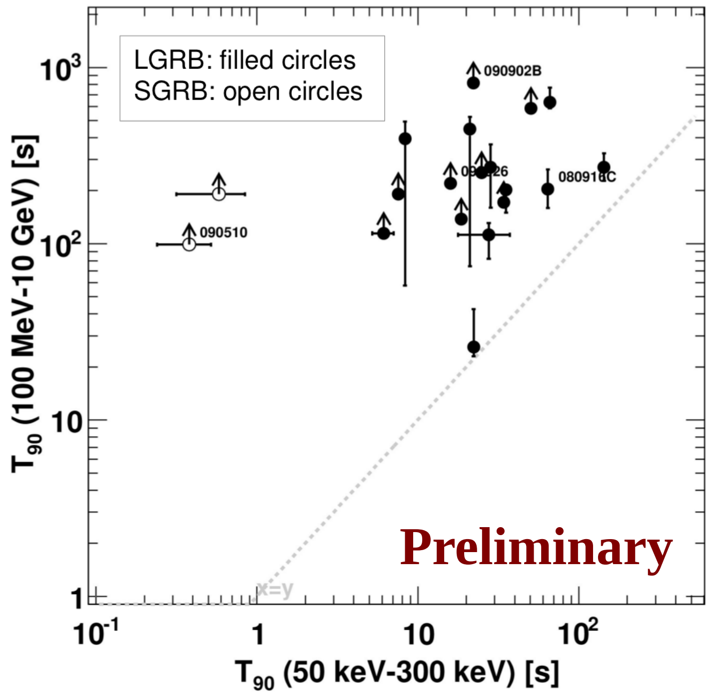
Abdo et al 2012, astro-ph/1201.3948

Long-lived HE emission

LAT GRB catalog, in prep



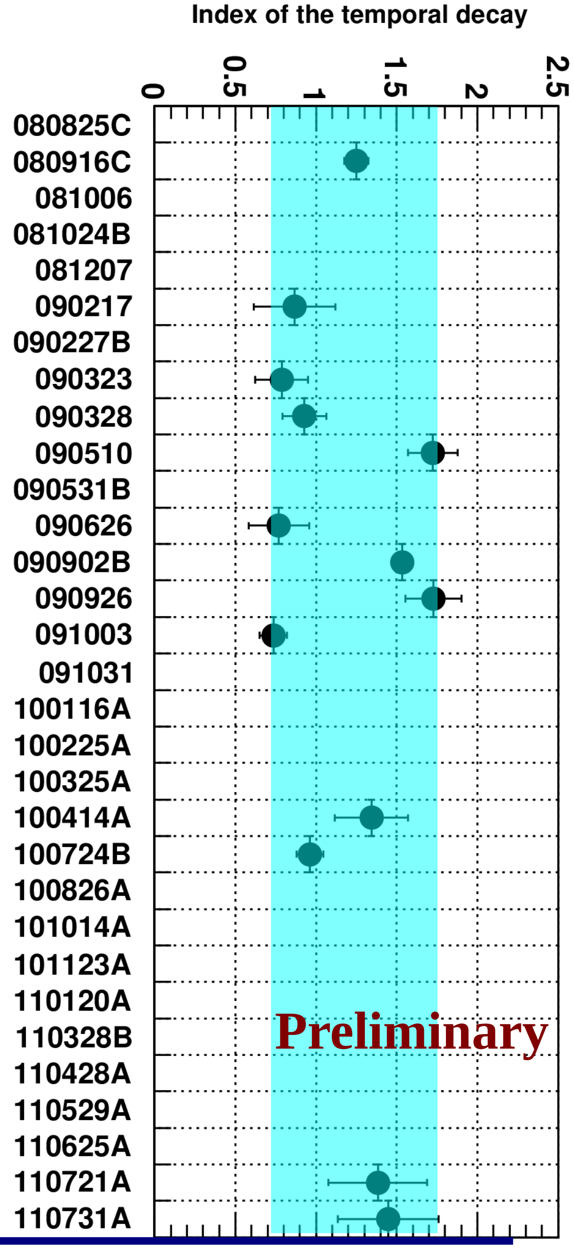




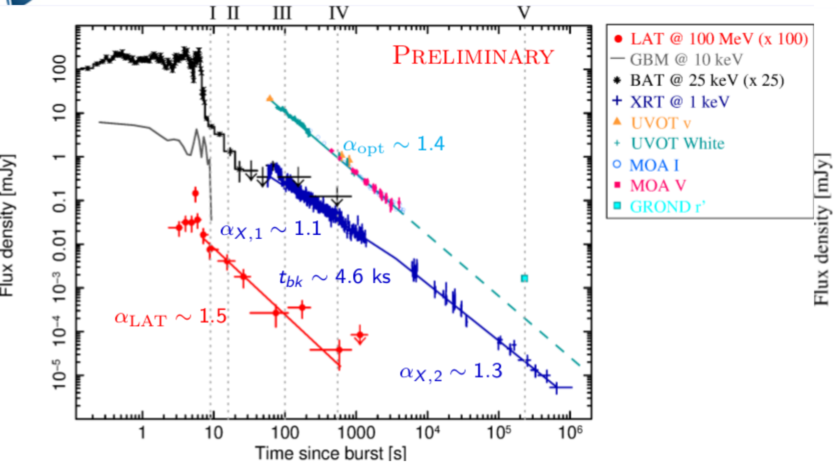
>100 MeV flux in time bins of approx constant significance → T_{90} (>100MeV)

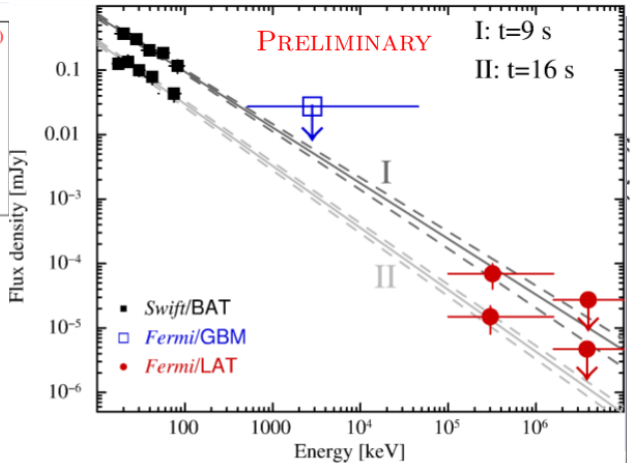
Flux decays as a PL over time
Index between -1.8 and -0.8
Consistent with AG interpretation

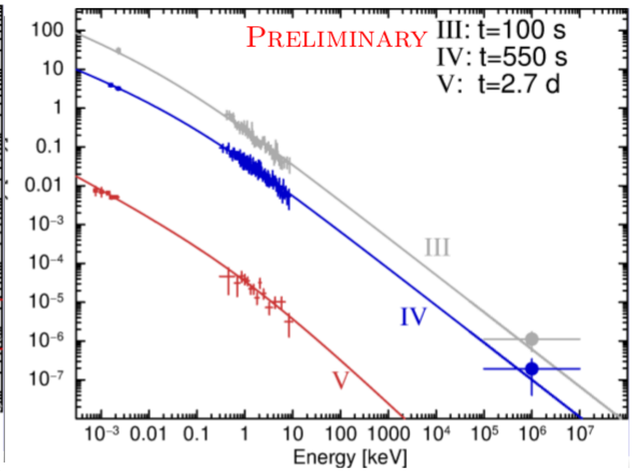
Photon spectral index averages ~-2, with no obvious spectral evolution



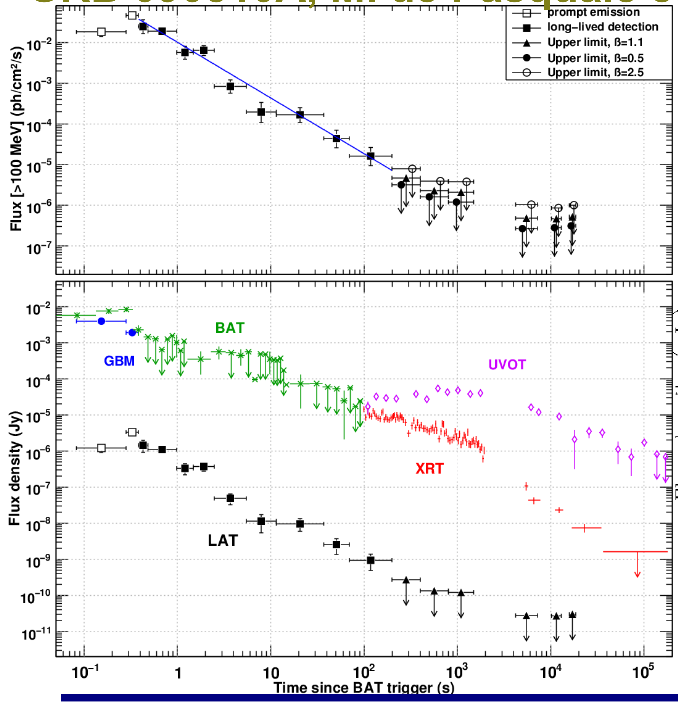
Multicolour afterglows



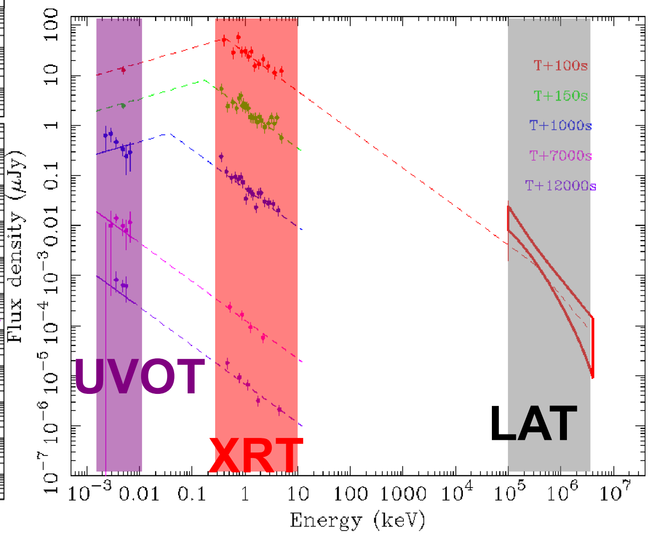




GRB 110731A, in prep paper by *Fermi* LAT&GBM, Swift, GROND, MOA
GRB 090510A, M. de Pasquale et al (*Swift*+*Fermi* LAT) 2009, ApJL 709 146



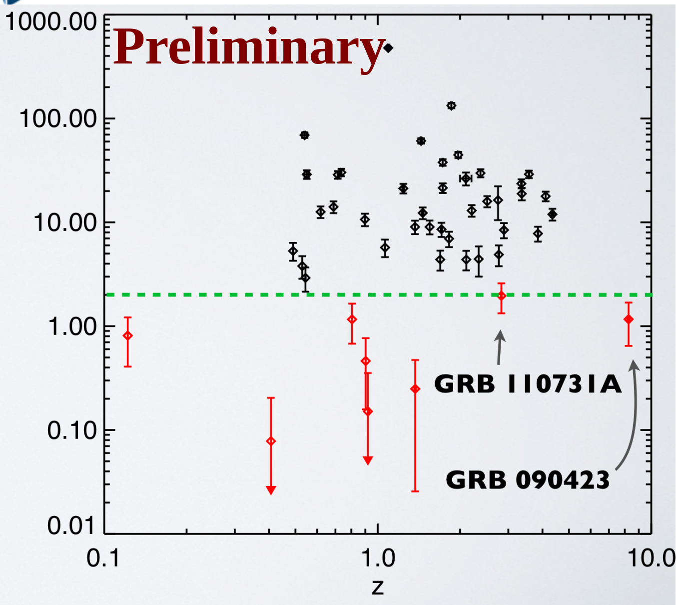
2 common *Fermi*/GBM + *Swift*/BAT triggers
with overlapping gamma-ray, Xray and optical observations



Support an afterglow model
of e- synchrotron emission
at the forward shock

110731A : transition from prompt
emission to afterglow
090510A : significant break → ν_c

Gamma-Ray Bursts for cosmology



Rest-frame properties :

$T_{90,rest}$ and $E_{peak,rest}$

Correlations found :

$E_{peak,rest}$ – z : possibly

$E_{peak,rest}$ – E_{iso} **(Amati 2006)** : LGRB

$E_{peak,rest}$ – L_p **(Yonetoku 2004)** : yes

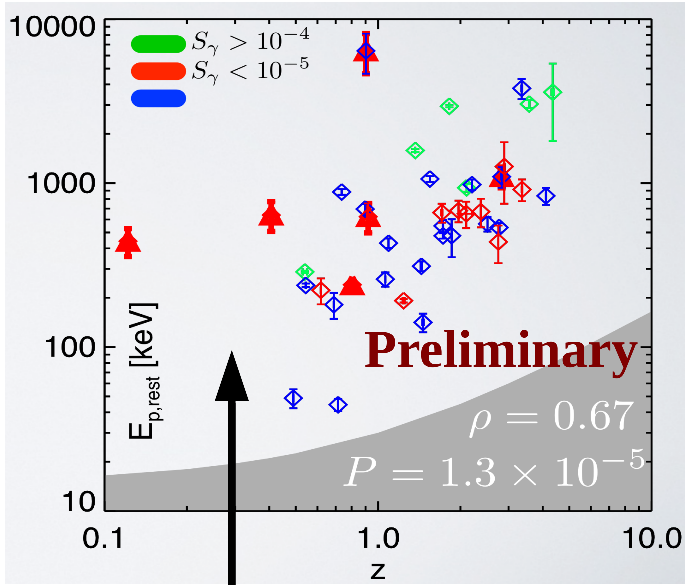
Caveats :

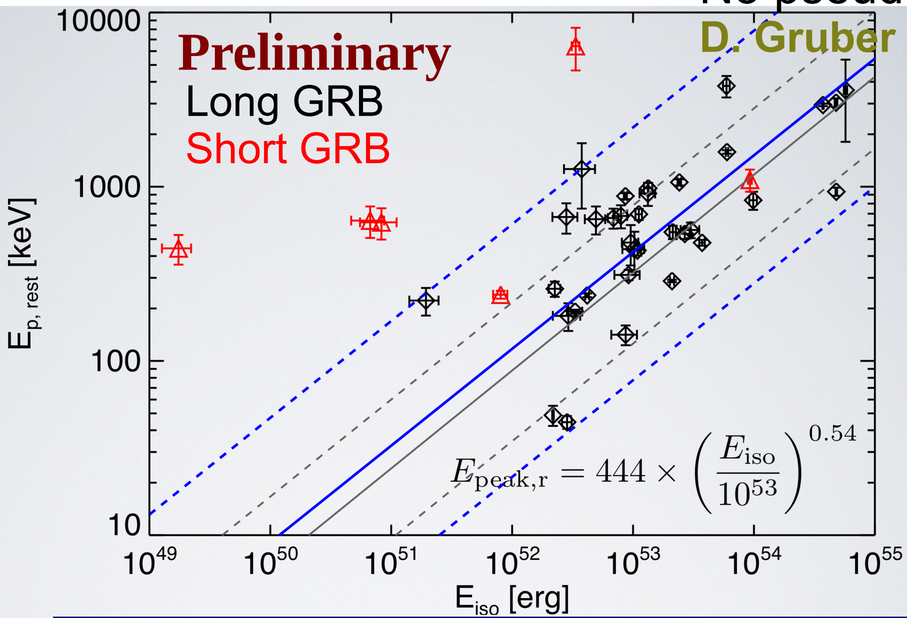
selection effects

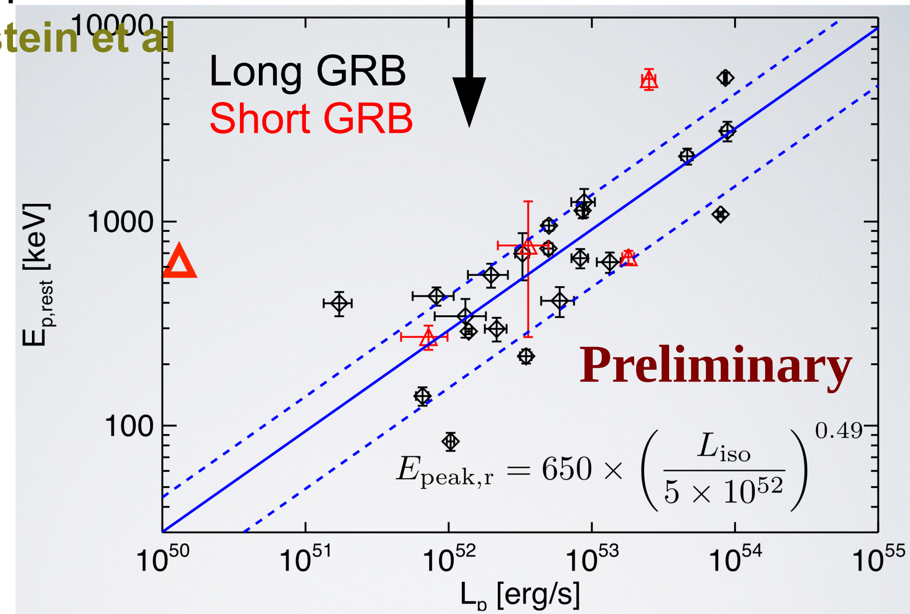
T_{90} & energetics : lower limits

No pseudo-z estimation

D. Gruber et al, A. Goldstein et al







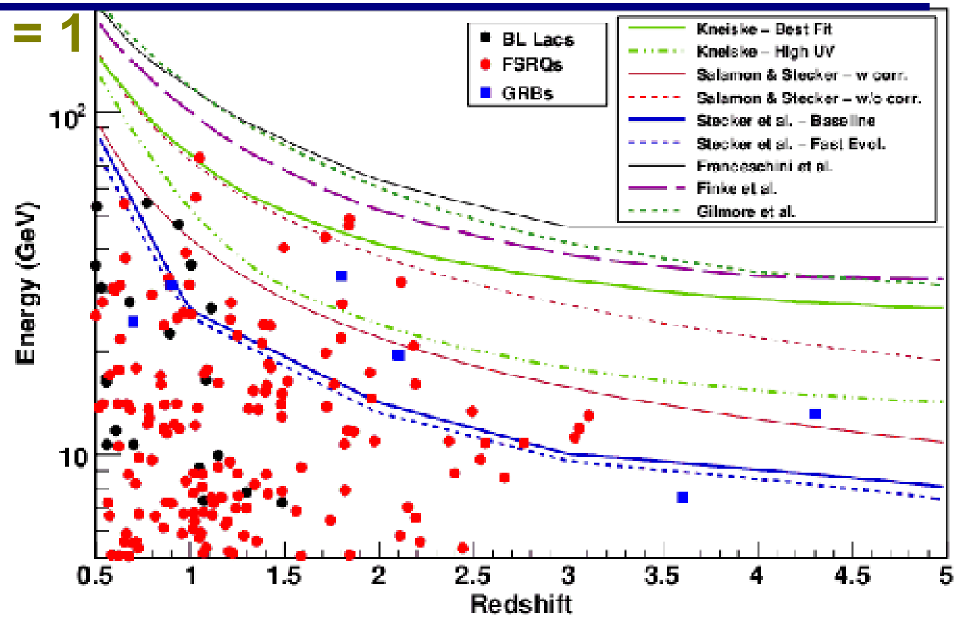
Extragalactic Background Light

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

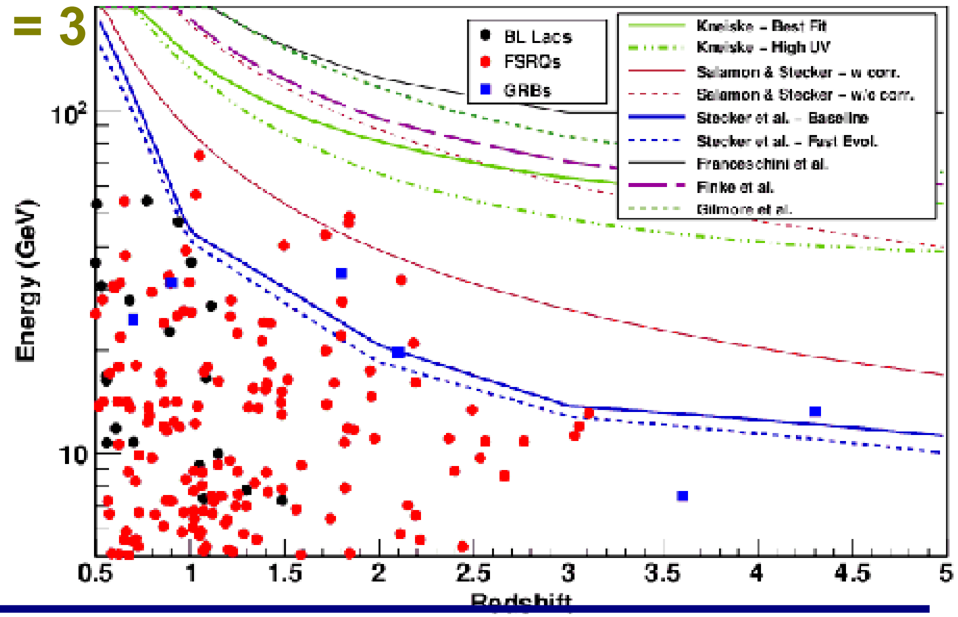
Highest photon energies
consistent w/ sources

➢ « 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

Lorentz Invariance Violation (I)

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

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

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 (II)

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

Some perspectives...

Fermi & advanced LIGO – Virgo :

NS-NS and NS-BH mergers are expected sources of gravitational waves and plausible origins of short GRB (T90<2s)

→ complementary : GW → inspiral characteristics ; EM → jet properties, environment

→ *Fermi* GBM is a good detector of short GRB : 45/yr (on-board triggers)

→ finding EM emission coincident with GW triggers enhances merger detections.

→ *Fermi* localization can reduce the search box for a GW trigger's OT

→ ~2/yr coincidental triggers within NS-NS horizon (z<0.11 in Abadie et al. 2010, Class. Quant. Grav. 27: 17300), ~8/yr within NS-BH horizon (z<0.22)

Hope for TeV observations :

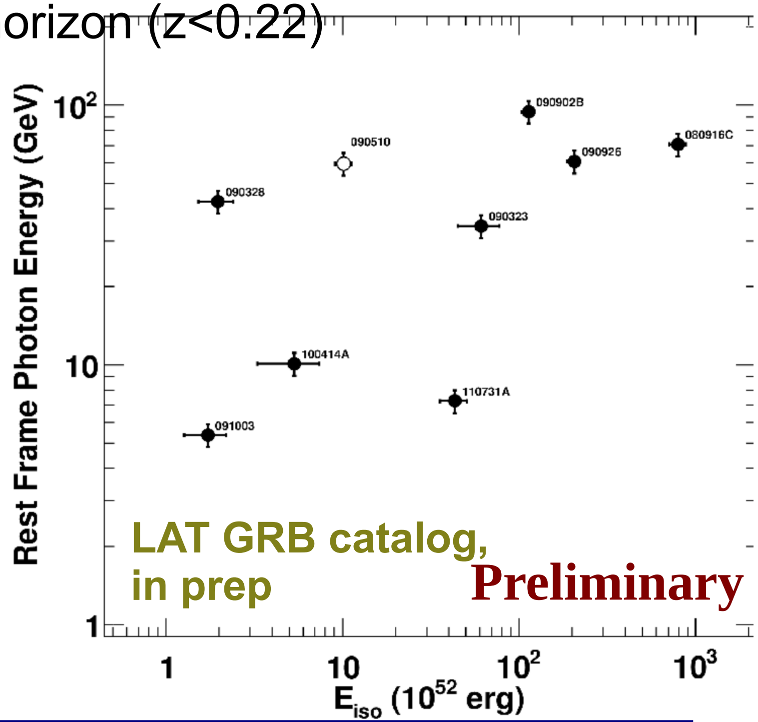
High energy photons from LAT GRB

New generation detectors with improved sensitivity :

→ CTA (few "own" triggers, repoint on external triggers)

→ HAWC (large FoV => "own" triggers, survey => search for external triggers' counterparts)

Caveat : EBL and intrinsic spectral attenuation



Summary

***Fermi* is a powerful tool for GRB studies :**
The GBM is a prolific detector, the LAT reveals the GeV features of energetic bursts, in good synergy (cooperation) with other instruments(teams) (Swift, IPN, optical telescopes...).

Deeper studies of BATSE & EGRET findings, new findings :
Long-lived high-energy emission... consistent with afterglow models.
"The Additional Powerlaw" component... at low and high energies, challenging the models.
Richness of the "MeV component" : synchrotron, photosphere, ...
Systematically delayed onset of the HE emission ↔ soft → hard (→ soft) spectral evolution.

Constraints to : Cosmology ? Not yet. But :
The jet's properties : intial Γ ~ few hundreds
Lorentz Invariance Violation models : linear models from QG strongly disfavored
Extragalactic Backgound Light attenuation models : the most "opaque" scenarii are disfavored

***Fermi* has an important role in future multi – wavelengths/messengers observations :**
provide triggers and localizations (GBM) and/or info on (V)HE observation likelihood (LAT)

THANK YOU !!

Data (GBM, LAT, soon also LLE), GRB catalogs, software : http://fermi.gsfc.nasa.gov/ssc/
Work by (non)*Fermi* and (non)*Swift* people : http://www.mpe.mpg.de/events/GRB2012/