Gamma-Ray Burst Observations with the Fermi Gamma-Ray Space Telescope

by

Sylvain Guiriec

NASA Marshall Space Flight Center

National Space Science and Technology Center

University of Alabama in Huntsville

On behalf of the Fermi Collaboration

fermi
Gamma-ray
Space Telescope

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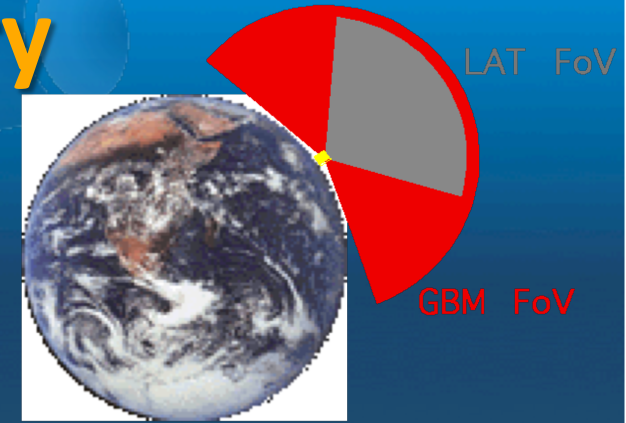
Outline

- Fermi LAT and GBM, two different instruments and technics to detect and observe GRBs
- Overview of GRB detections with Fermi
- Main Fermi results for the physics of GRBs
  - → Delayed high energy emission onset (>100 MeV)
  - → Long lived GeV emission
  - → Spectral evolution
  - → Extra spectral component
- Derived results using Fermi GRB observations
  - → Constraints on the jet Lorentz factor
  - → Constraints on the Lorentz invariance
  - → Constraints on the Extra galactic Background Light models
- Summary of the LAT observations

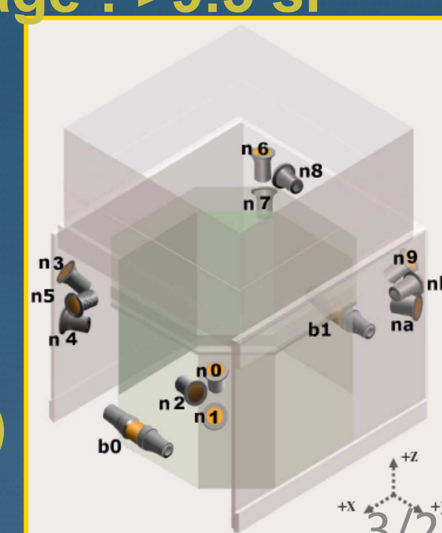
The Fermi Observatory



- **Spacecraft :**

  Low-Earth Circular Orbit (altitude 550 km) with 28.5° inclination

- **Large Area Telescope (LAT) :**
  - **Energy range : 20 MeV to >300 GeV**
  - **Large field of view : ~2.4 sr at 1 GeV**
  - **Full sky coverage every 3 hours**
  - **Localization, spectroscopy and GRB trigger capabilities (on board and ground)**
- **Gamma-ray Burst Monitor (GBM):**
  - **Full unocculted sky coverage : >9.5 sr**
  - **On board triggers**
  - **8 keV to 40 MeV**
  - **12 NaI (8 keV to 1 MeV)**
    - Localization (on board & ground)
    - Spectroscopy
  - **2 BGO (200 keV to 40 MeV)**
    - Spectroscopy



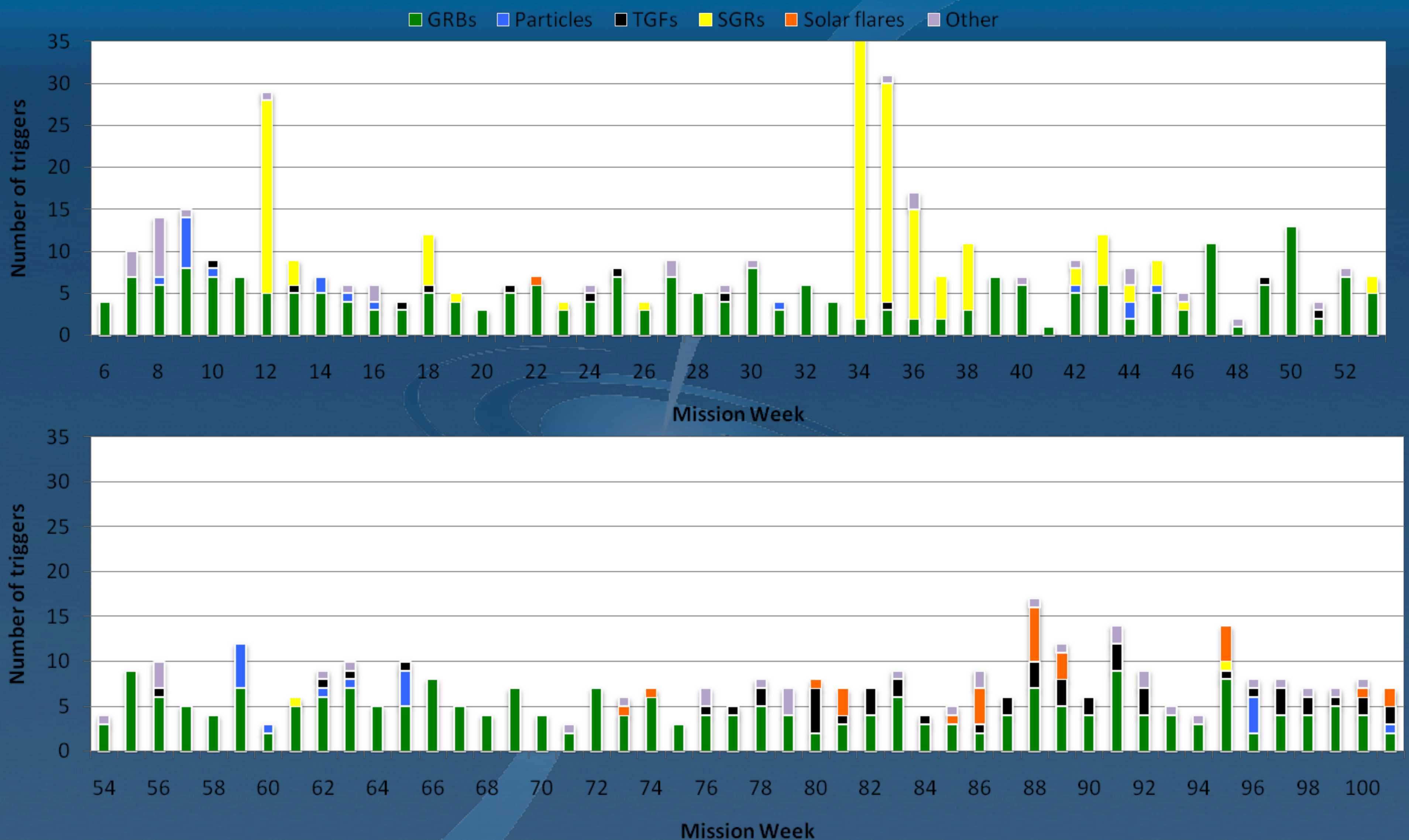
GBM and LAT, 2 different techniques

- **LAT is based on the event by event identification and reconstruction technique**
  - → Good for transient and steady sources
  - → Low background
  - → Good localization capabilities
  - → Good Energy resolution (ΔE/E = 10% at 1 GeV)
  - → Low effective area bellow 100 MeV

- **GBM based on the temporal on-source/off-source subtraction**
  - → For transient sources only
  - → High background rate
  - → energy dispersion (NaI: ~0% low energy, 10% ~300 keV ; BGO: 8-12%)

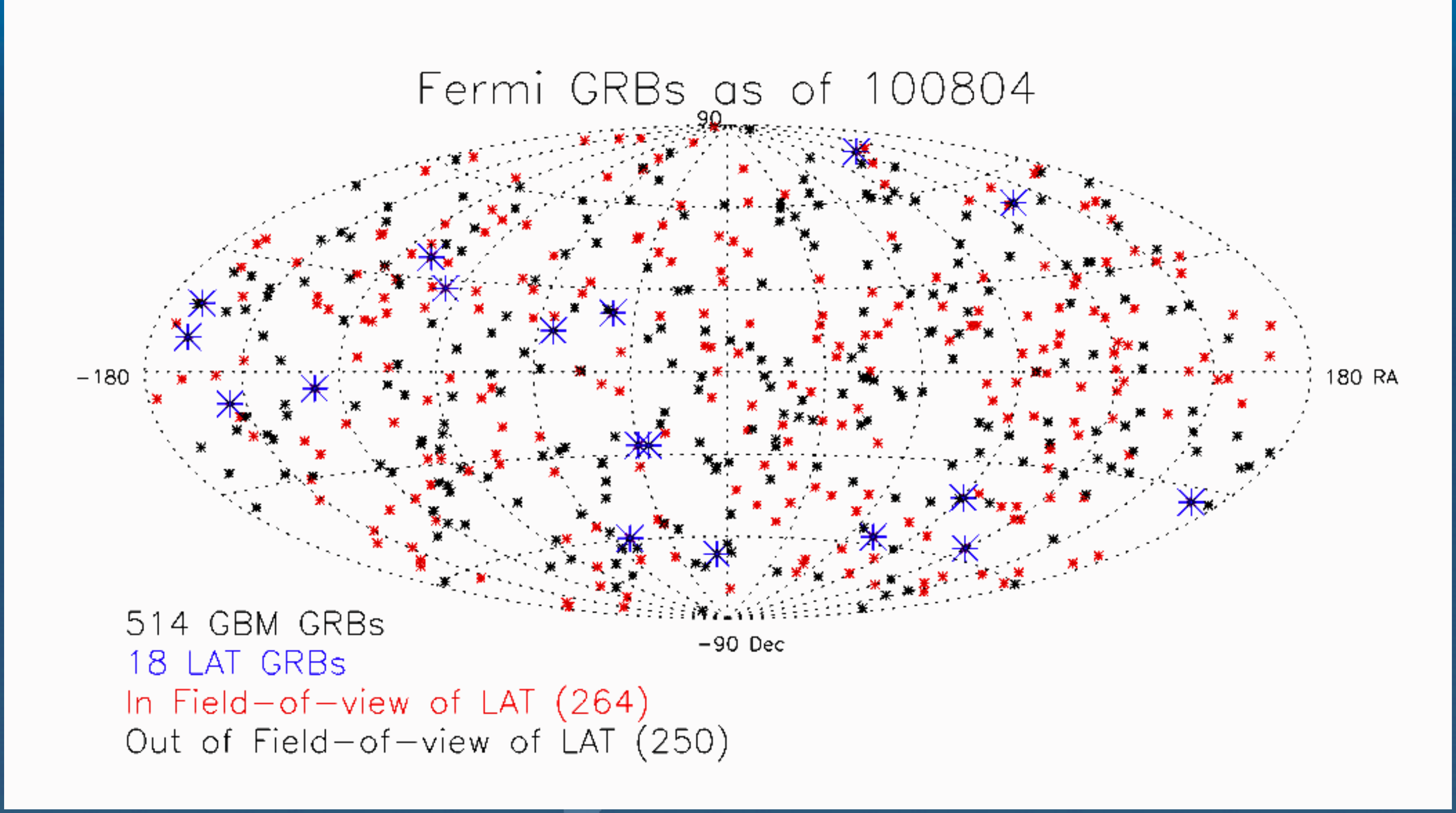
- **New LAT analysis technique based on GBM to increase the sensitivity between 30 MeV and 100 MeV : LAT Low Energy (LLE)** see Veronique Pelassa's Presentation

GBM triggers



- **From the start of the mission, GBM triggered on ~947 events**
- **549 of the GBM triggers are GRBs**

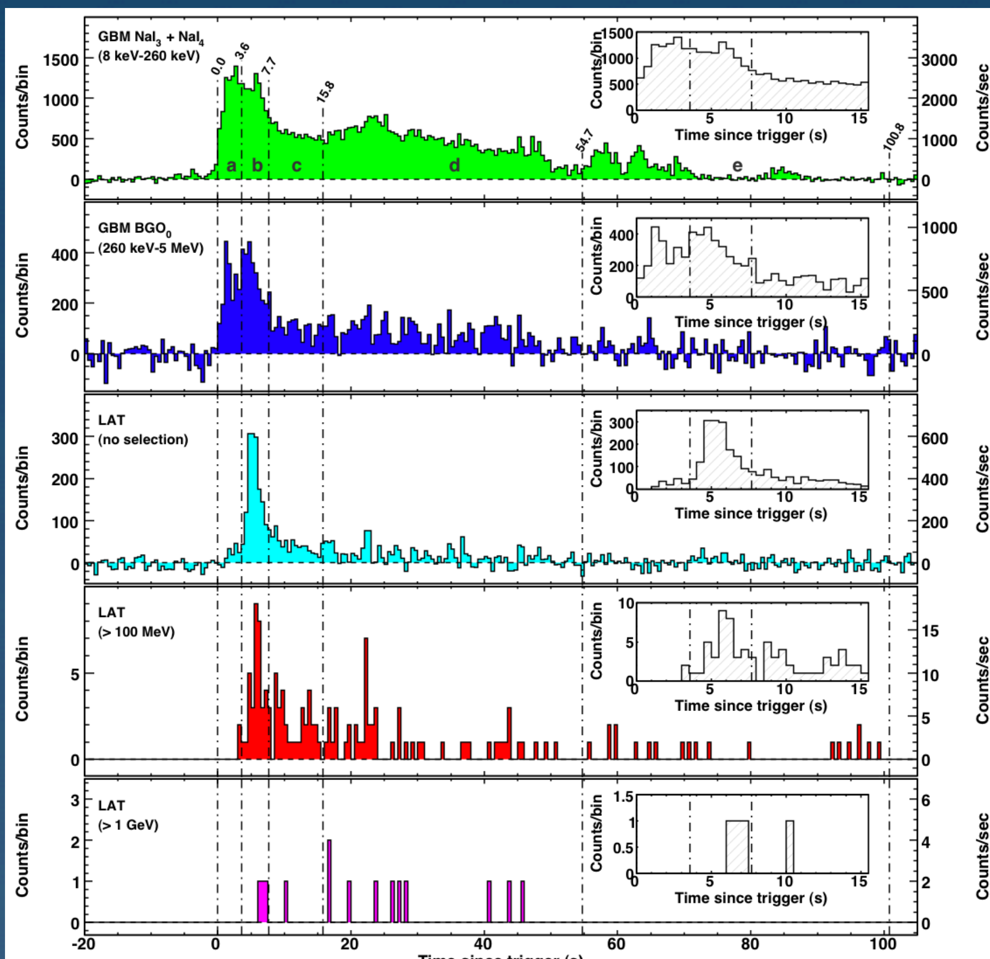
GRBs detected with Fermi



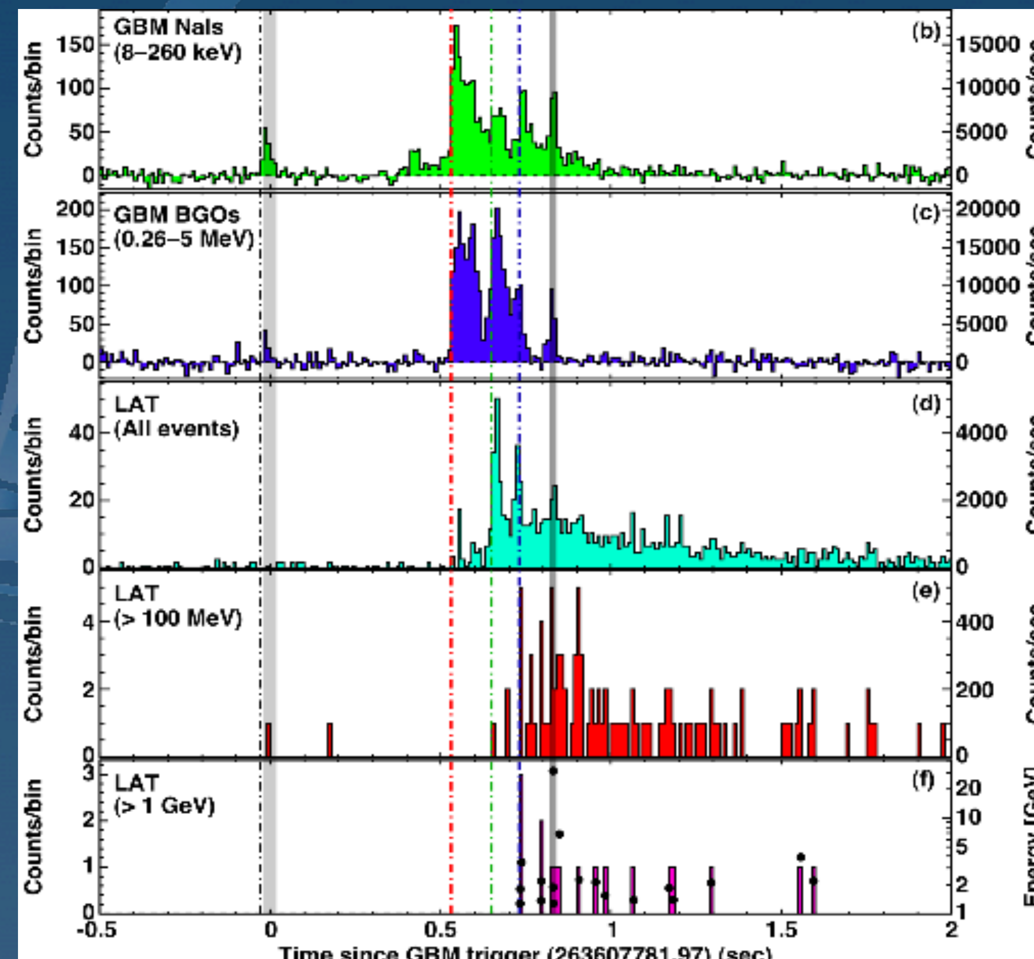
- **18/549 GBM GRBs are clear LAT detections (>5σ) above 100 MeV**
- **11% of GBM GRBs were also observed with Swift**
- **10/18 LAT GRBs were followed up with Swift/XRT and 8 were detected => optical counter part +redshift**

Delay High-Energy Emission onset (>100 MeV)

Case of the long GRB 080916C
Abdo et al. 2009, Science 323, 1688



Case of the short GRB 090510
Abdo et al. 2009, Nature 462, 331

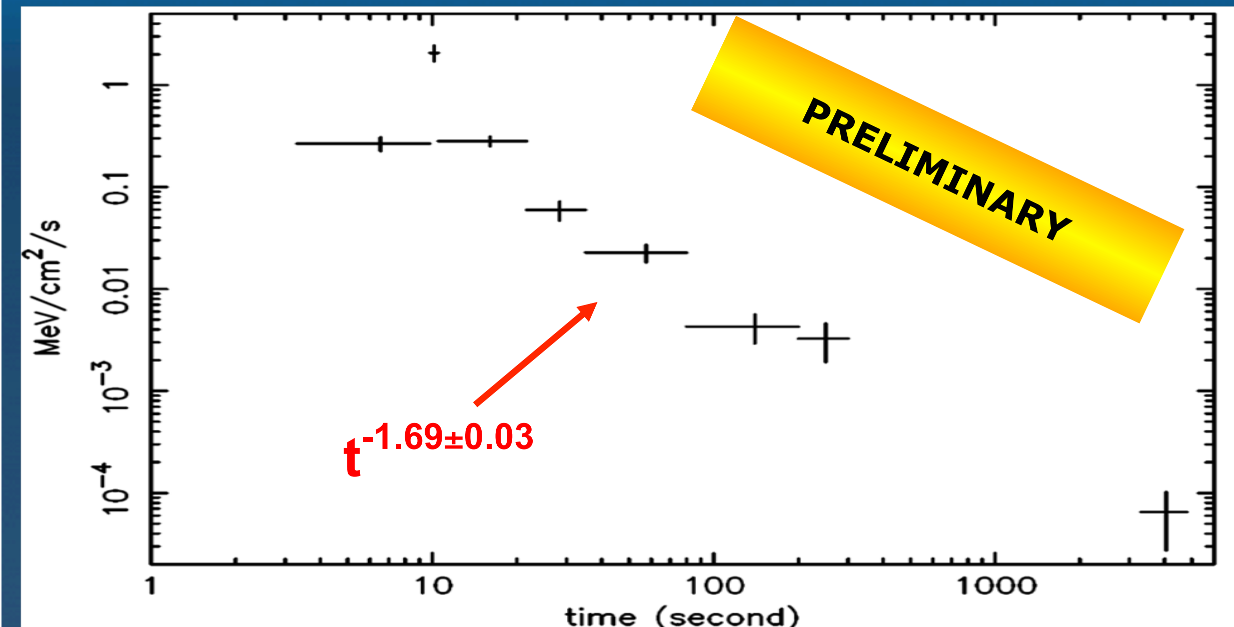


- **The first LAT peak coincides with the second GBM peak**
- **Delay in HE onset: ~4-5 s**

- **The first few GBM peaks are missing but later peaks coincide**
- **Delay in HE onset: ~0.1-0.2 s**

Long Lived GeV Emission

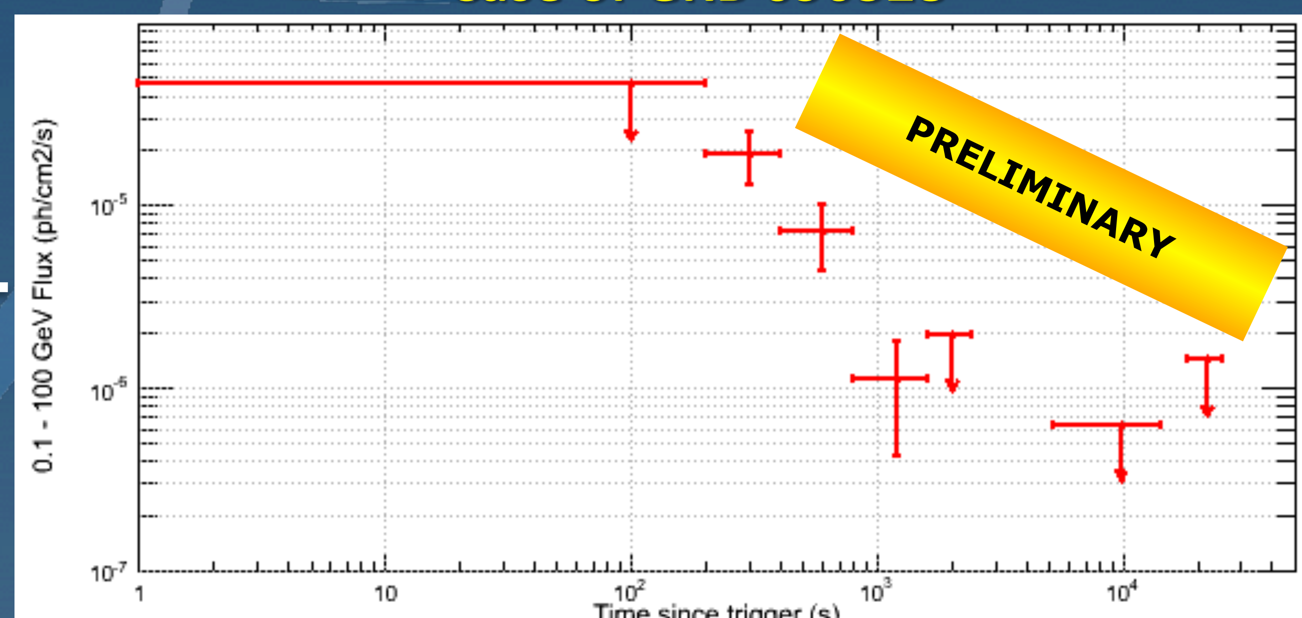
Case of GRB 090926A



→ 5σ Detection up to 4800s

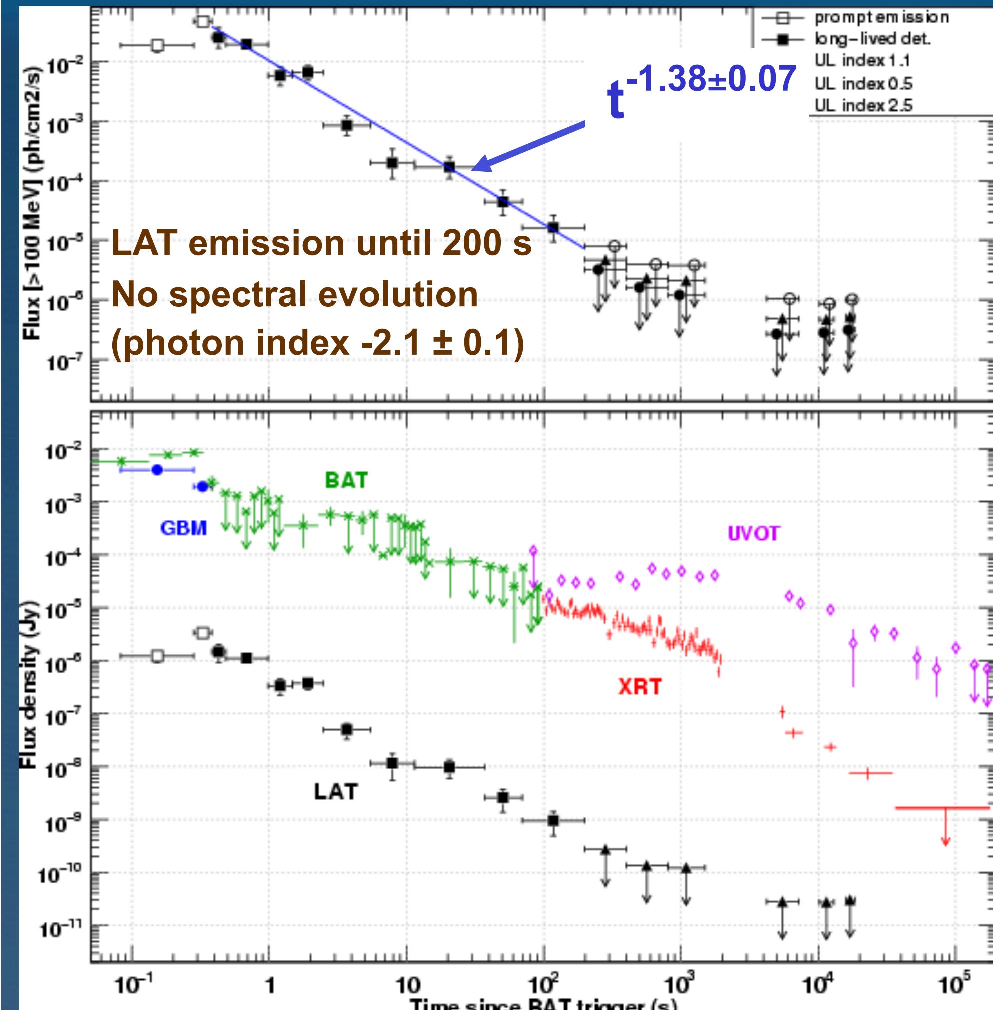
Case of GRB 090328

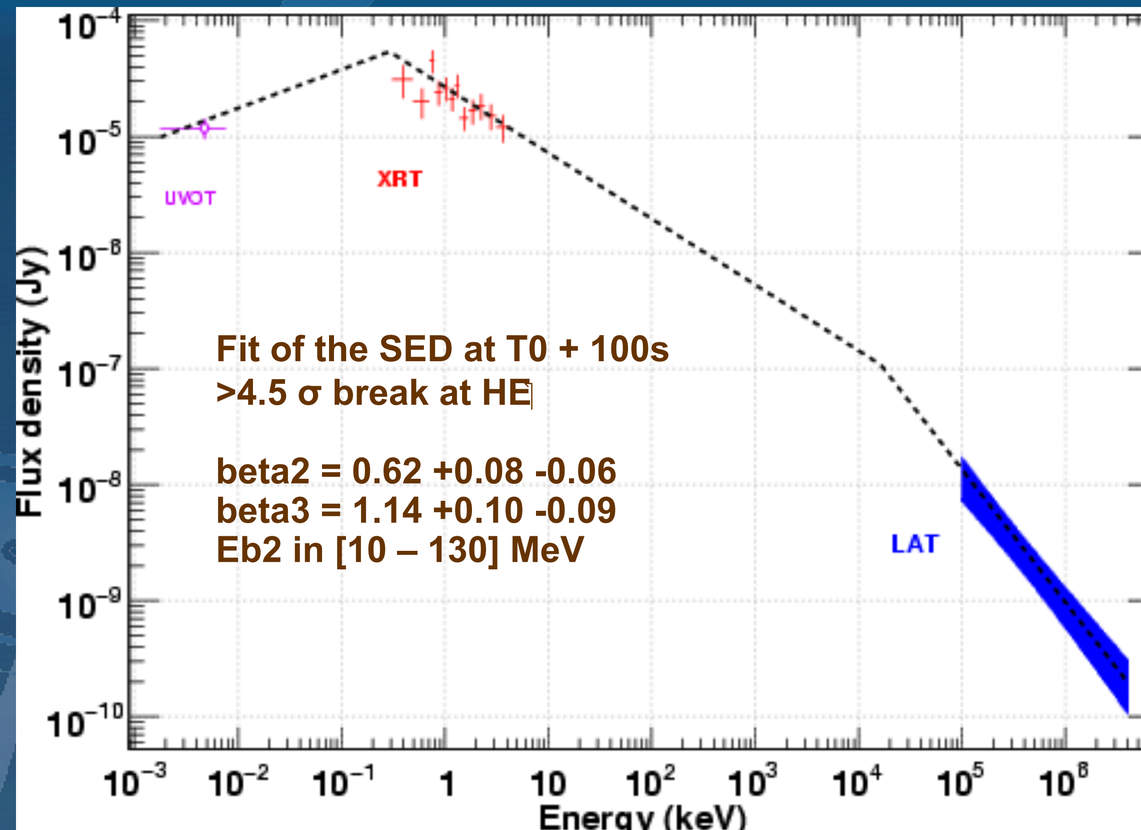
5σ Detection up to 1600s ←



Long Lived GeV Emission

Case of GRB 090510 (De Pasquale et al 2010, ApJL 709, 146)

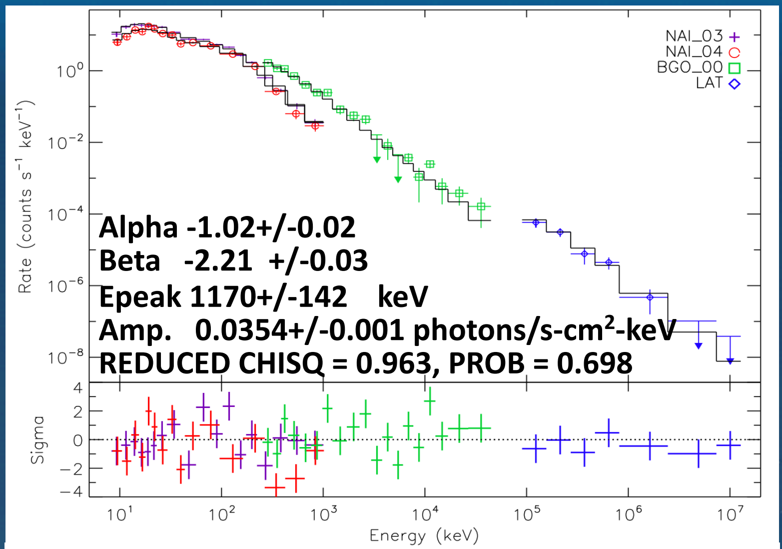


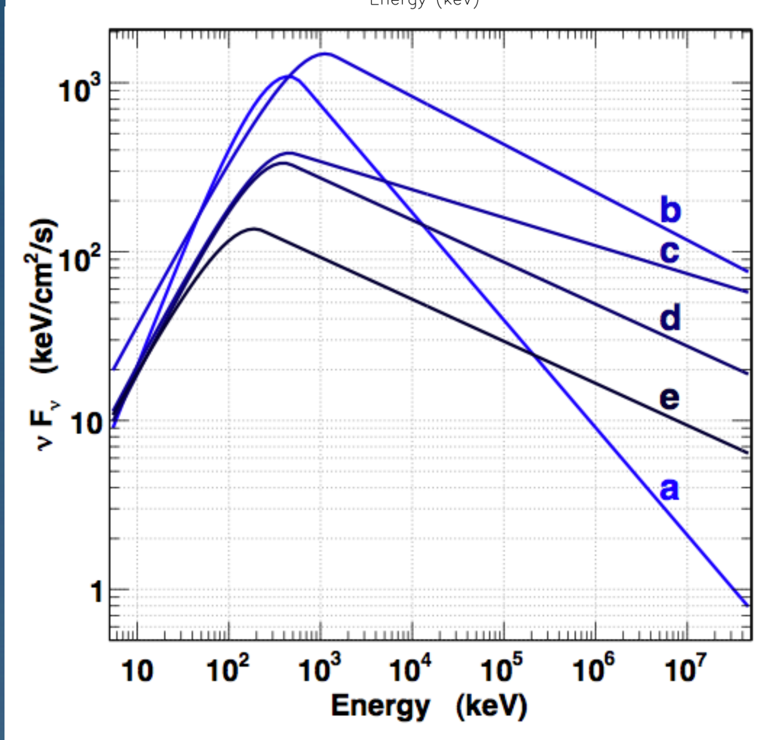


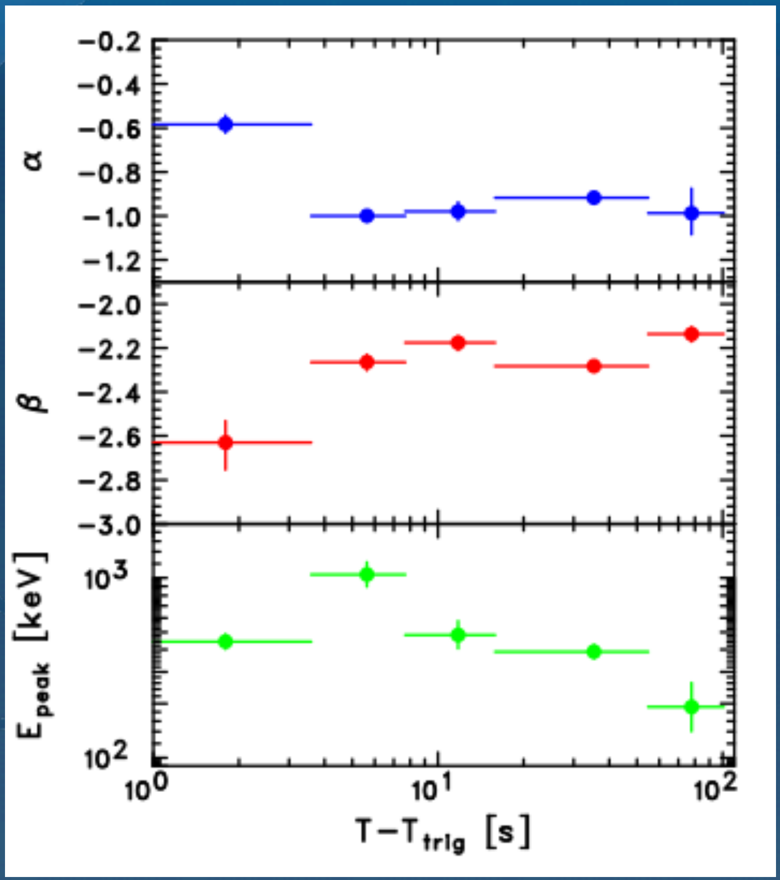
Forward shock model can reproduce the spectrum from the optical up to GeV energies! (non thermal synchrotron emission from the decelerating blast wave)

Spectral Evolution

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



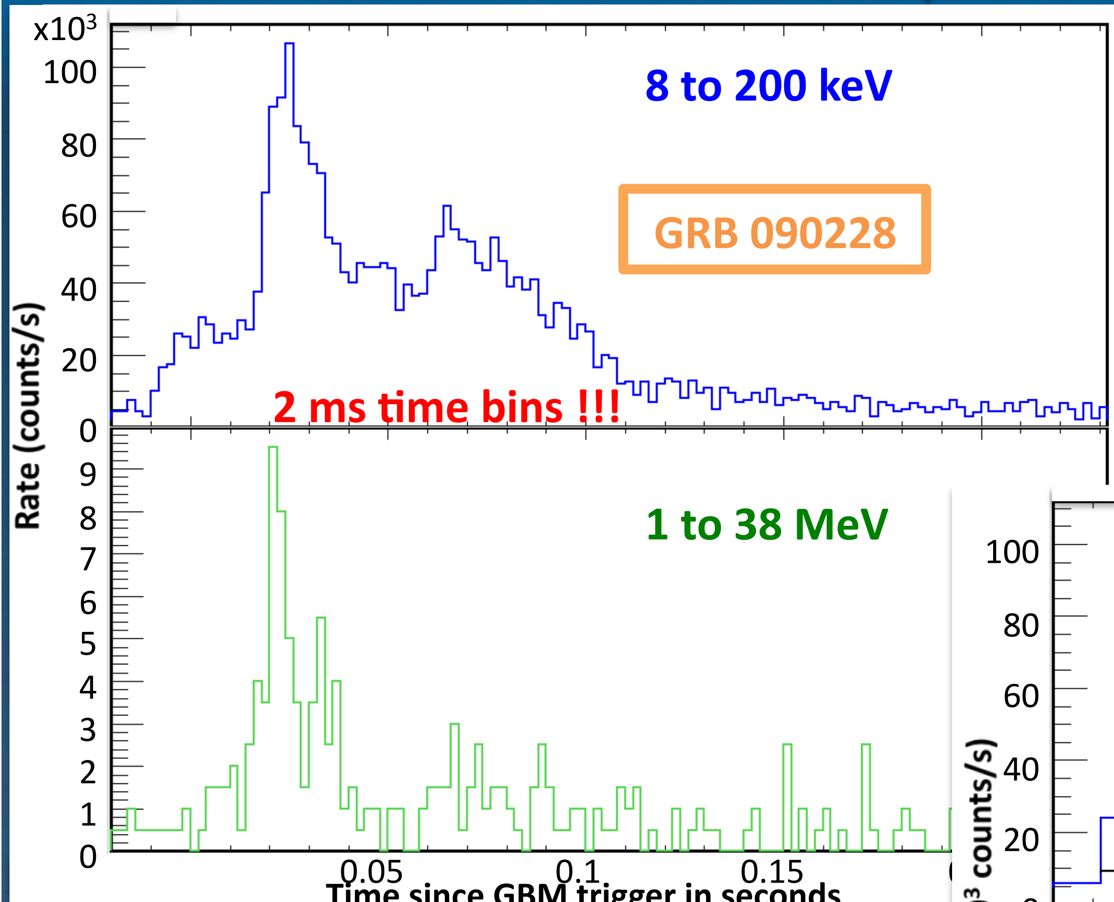


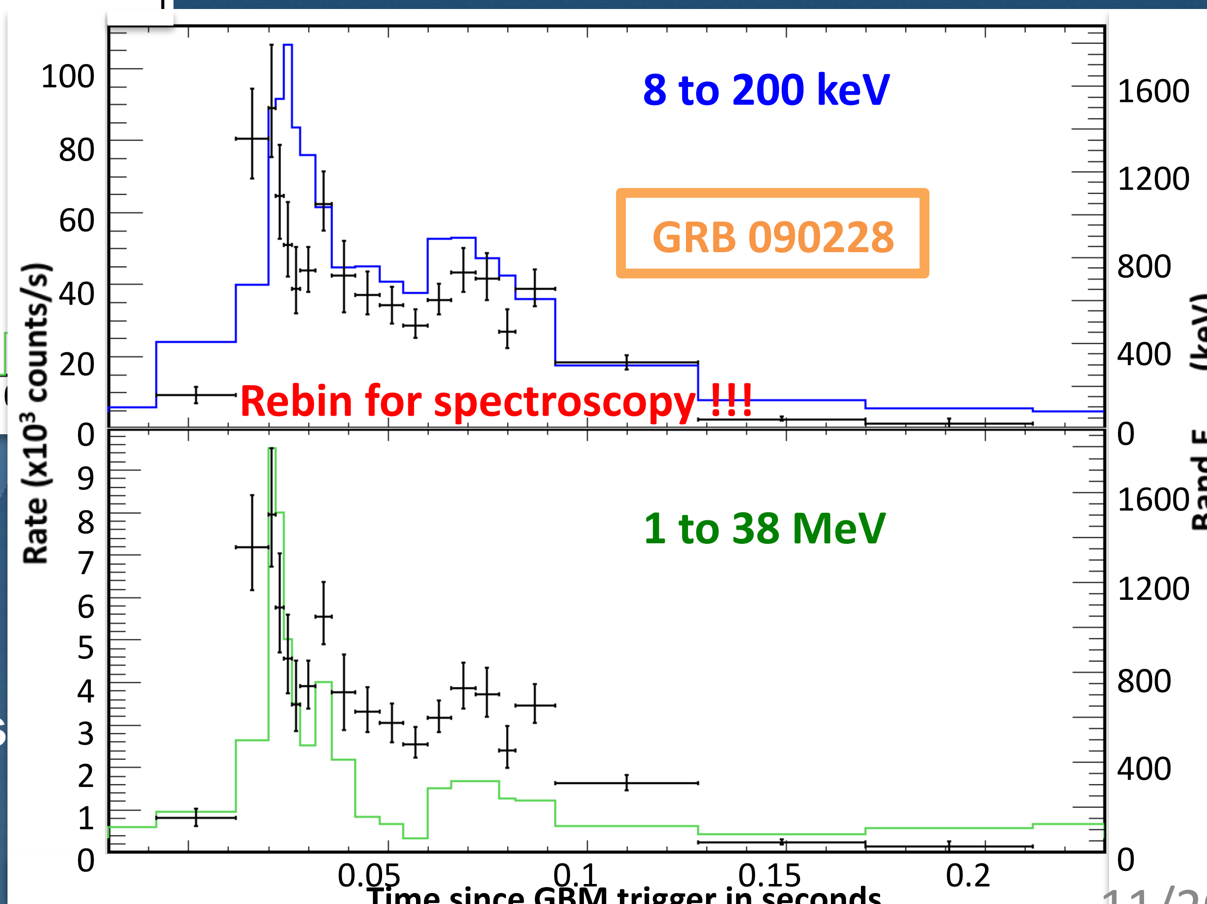


- **Consistent with a single Band function from 10 keV to 10 GeV.**
- **Global soft-hard-soft evolution.**

Fine-Time Resolved Spectroscopy of Short GRBs

Case of GRB 090228 (Guiriec et al, submitted to ApJ)

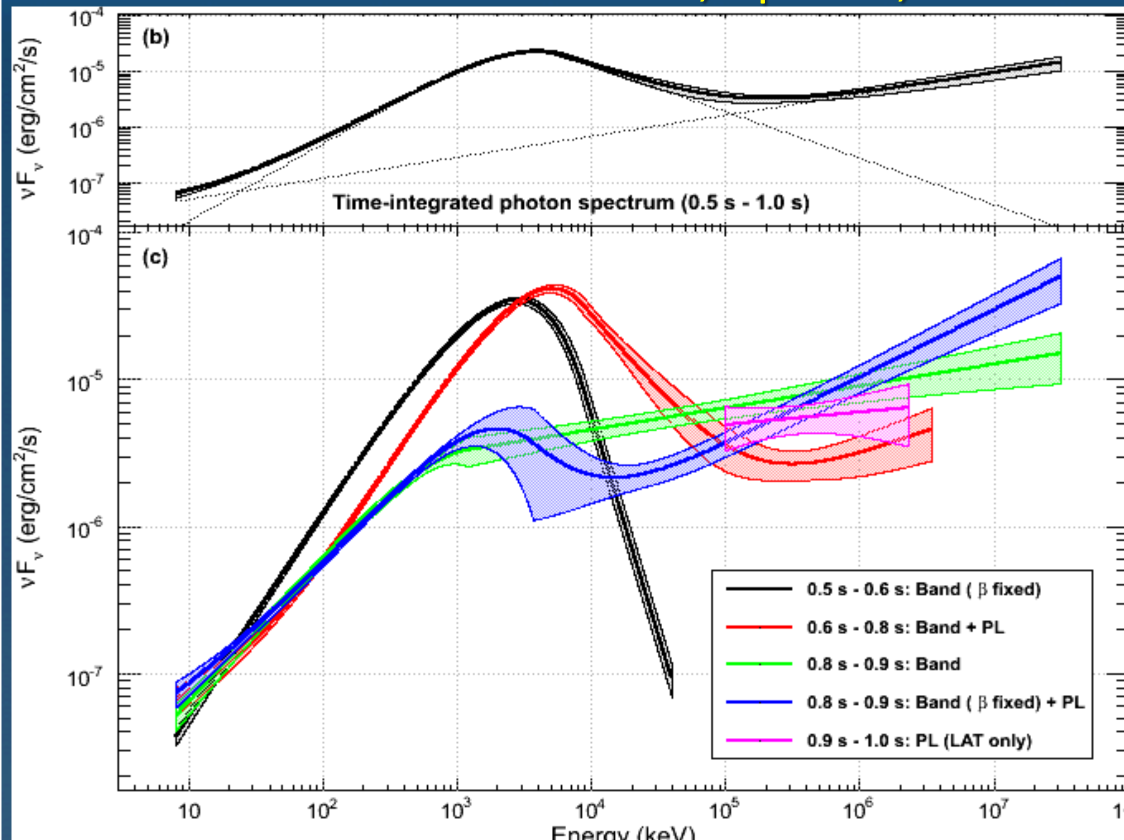




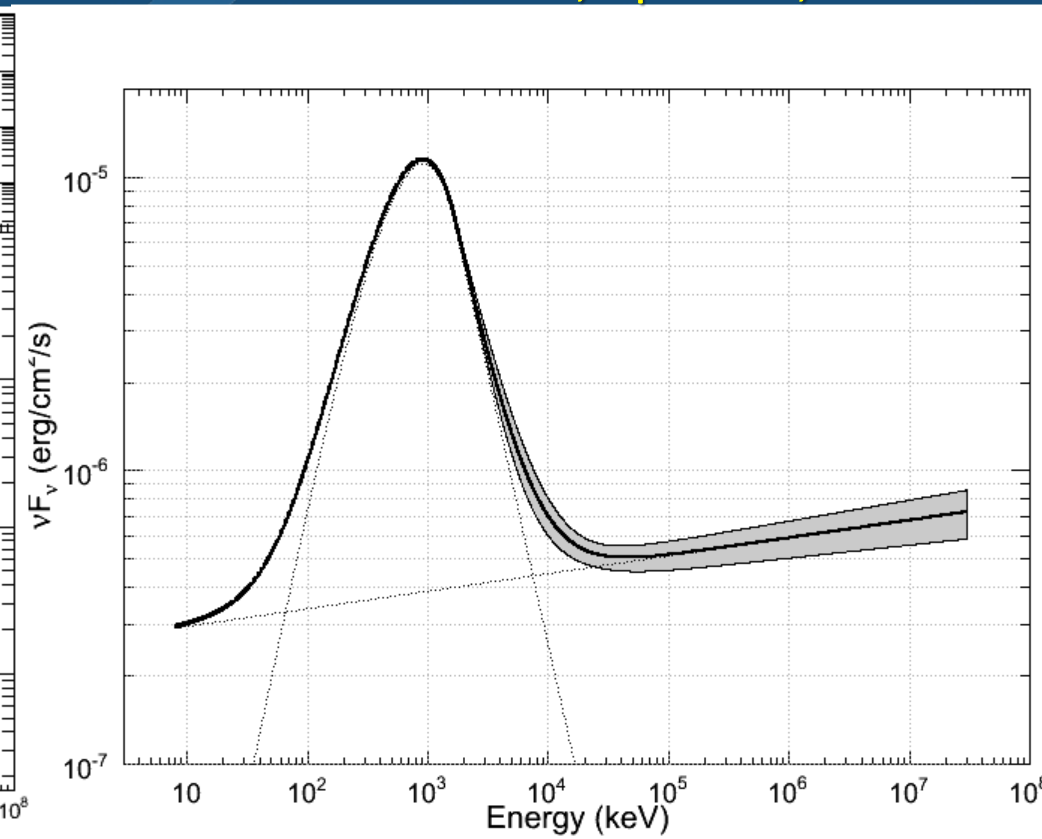
- Light curves of short GRBs similar to the light curves of long GRBs but contracted in time and stretched toward the highest energies.
- Band E_{peak} tracks the LC structures
- Soft-hard-soft evolution.

Additional Spectral Component

Case of the short GRB 090510
Ackermann et al. 2010, ApJ 716, 1178



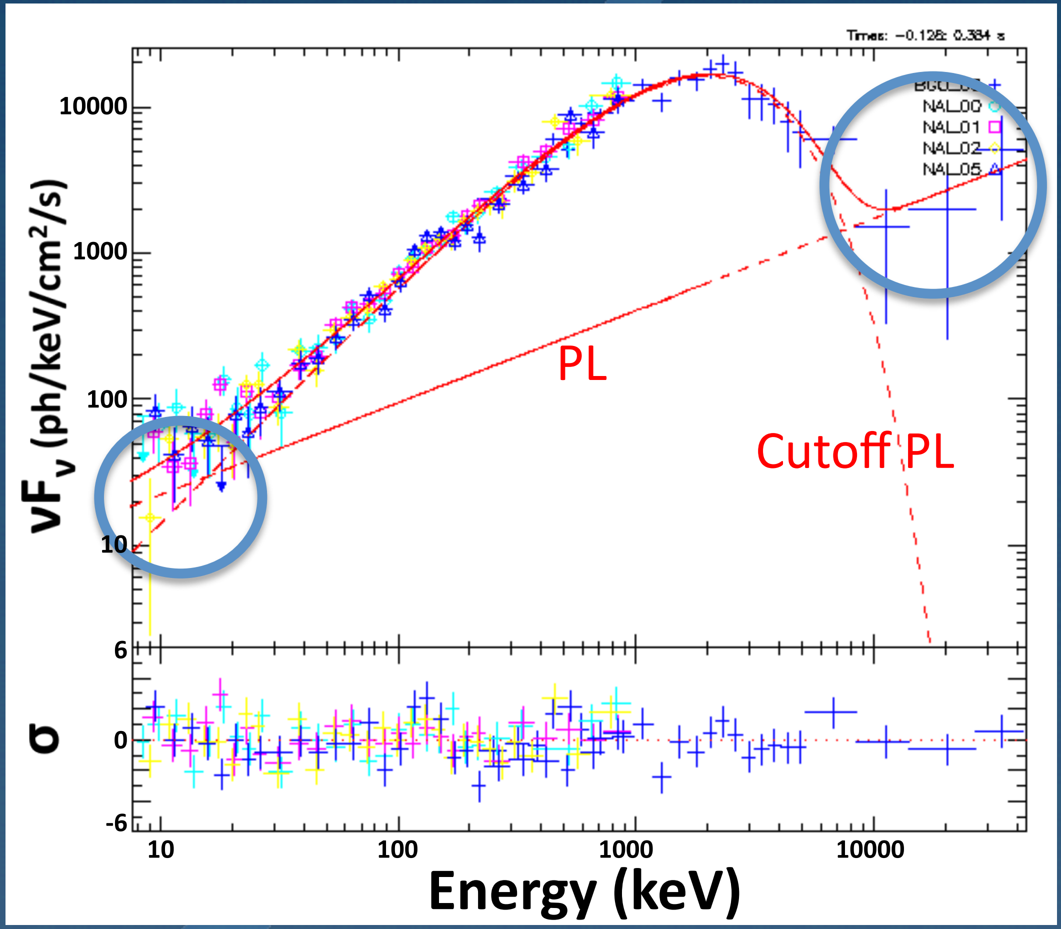
Case of the long GRB 090902B
Abdo et al. 2009, ApJL 706, 138



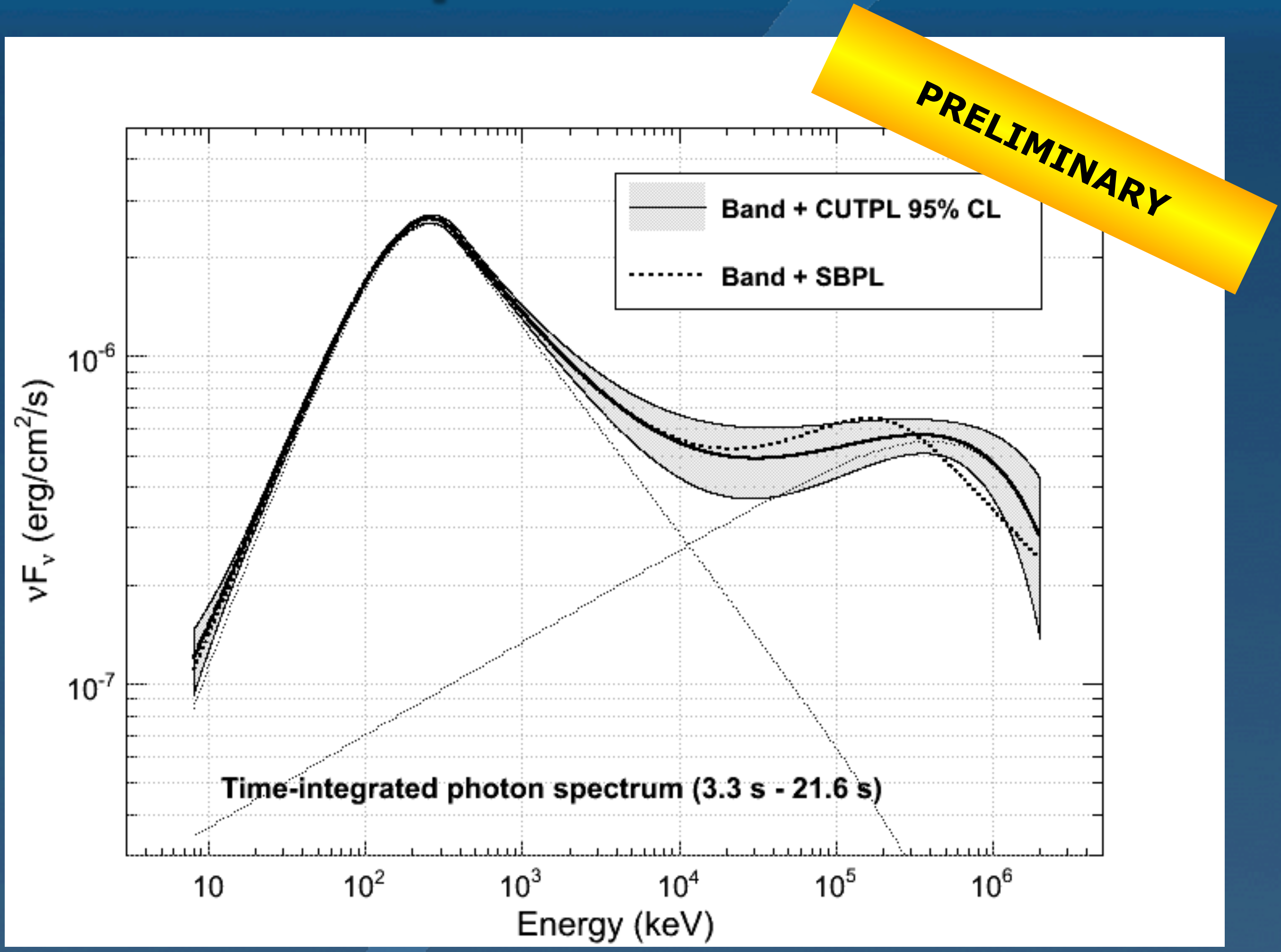
- Spectral deviation from the standard Band function adequately fit with an additional power law in long and short GRBs.
- The Extra-PL is usually not present during the all burst duration.
- Usually, the extra-PL over-power the Band function at low (< ~tens of keV) and high (> ~tens of MeV) energy.
- Possible PL break in a time resolved spectrum of GRB 090902B.

Additional Spectral Component in GBM Data Only

Case of GRB 090227B (Guiriec et al, submitted to ApJ)



High-Energy spctral cuttoff in the extra-PL component of GRB 090926A



- The extra-PL overpower the standard Band function above ~10 MeV.
- Existence of a 6σ spectral cutoff at ~1.4 GeV in the extra-PL.
- Break shape not constraint.

Interpretation of the HE Delayed Onset and of the Extra Power-law Spectral Component

- **Leptonic models (inverse-Compton or SSC)**
  - Hard to produce a delayed onset longer than spike widths
  - Hard to produce a low-energy (<50 keV) power-law excess

- **Hadronic models (pair cascades, proton synchrotron) – Asano 2009, Razzaque 2009**
  - Late onset: time to accelerate protons & develop cascades?
  - Hard to produce correlated variability at low- and high-energies (e.g. spikes of GRB 090926A)?
  - Proton synchrotron radiation requires large B-fields
  - Synchrotron emission from secondary e± pairs produced via photo-hadron interactions can naturally explain the power-law at low energies

- **Early Afterglow (e+e- synchrotron from external shock) – Kumar 2009, Ghirlanda 2010**
  - Can account for the delayed onset of the PL
  - Short variability time scales in LAT data argues against external shock

Lower Limit on the Jet Lorentz-Factor : Γ_{min}

- **Compactness problem :**

→ Non thermal gamma-ray emission should be blocked due to the γ−γ pair production opacity.

→ A relativistic jet reduces the photon seed population above the pair production threshold (compatible with the observations)

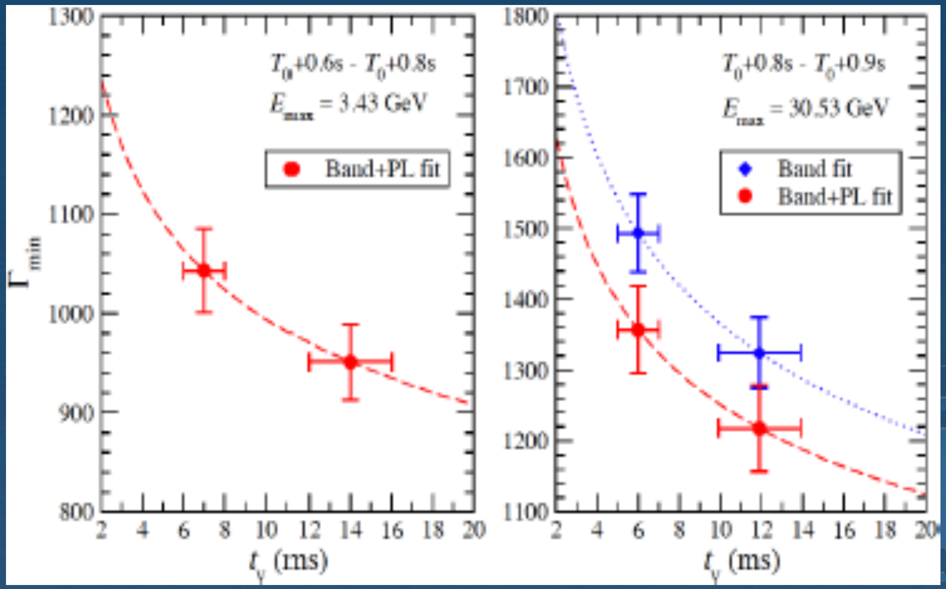
- **Estimation of the jet Lorentz-Factor lower-limit :**
  - Based on a seed photon field, the highest energy photon detected, and the LC variability

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

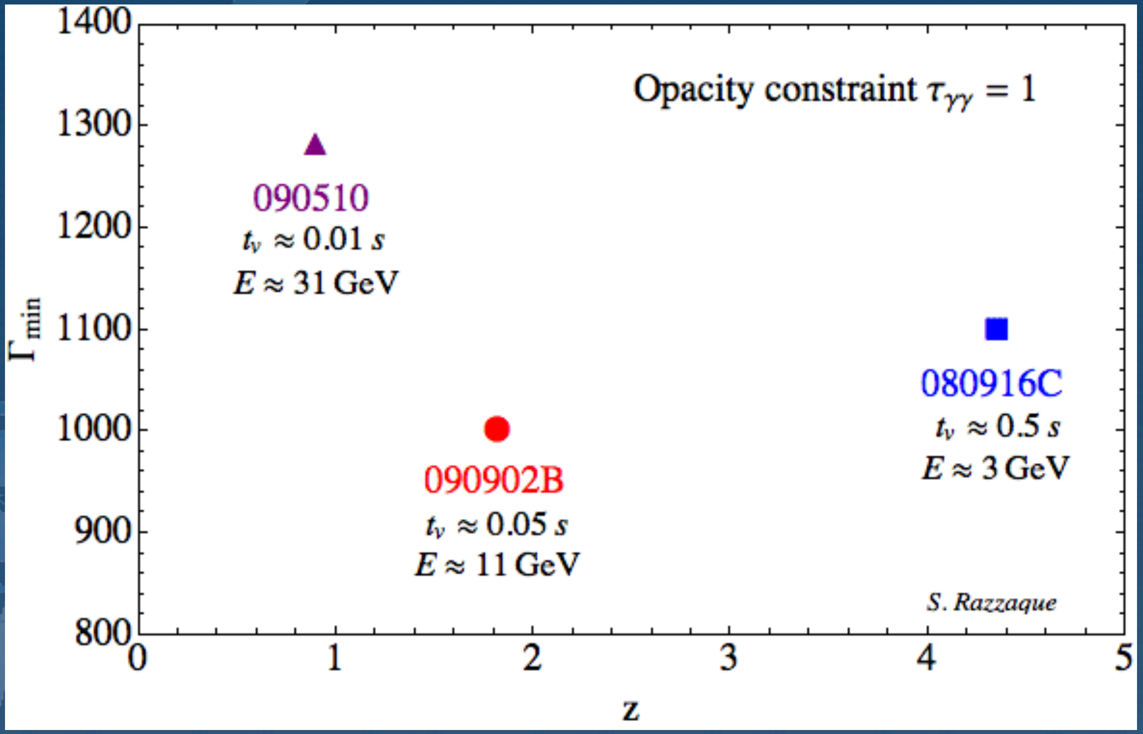
  - Hypothesis : uniform, isotropic and time-independent seed photon field.
  - More realistic models (i.e. Granot, 2008) give significantly lower values (~3 times).

Lower Limit on the Jet Lorentz-Factor : Γ_{min}

Case of the short GRB 090510



Result Summary



- Lower limit of the bulk Lorentz factor >900.

- GRB 090926A : it is the first direct measurement of the bulk Lorentz factor if the high-energy power-law cutoff is due to the γ-γ pair production opacity => Γ ~ 200-700 (model dependent).

Contraints on the Lorentz Invariance

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

- **Some QG models predict a violation of the Lorentz invariance ($V_{ph}(E) \neq c$)**

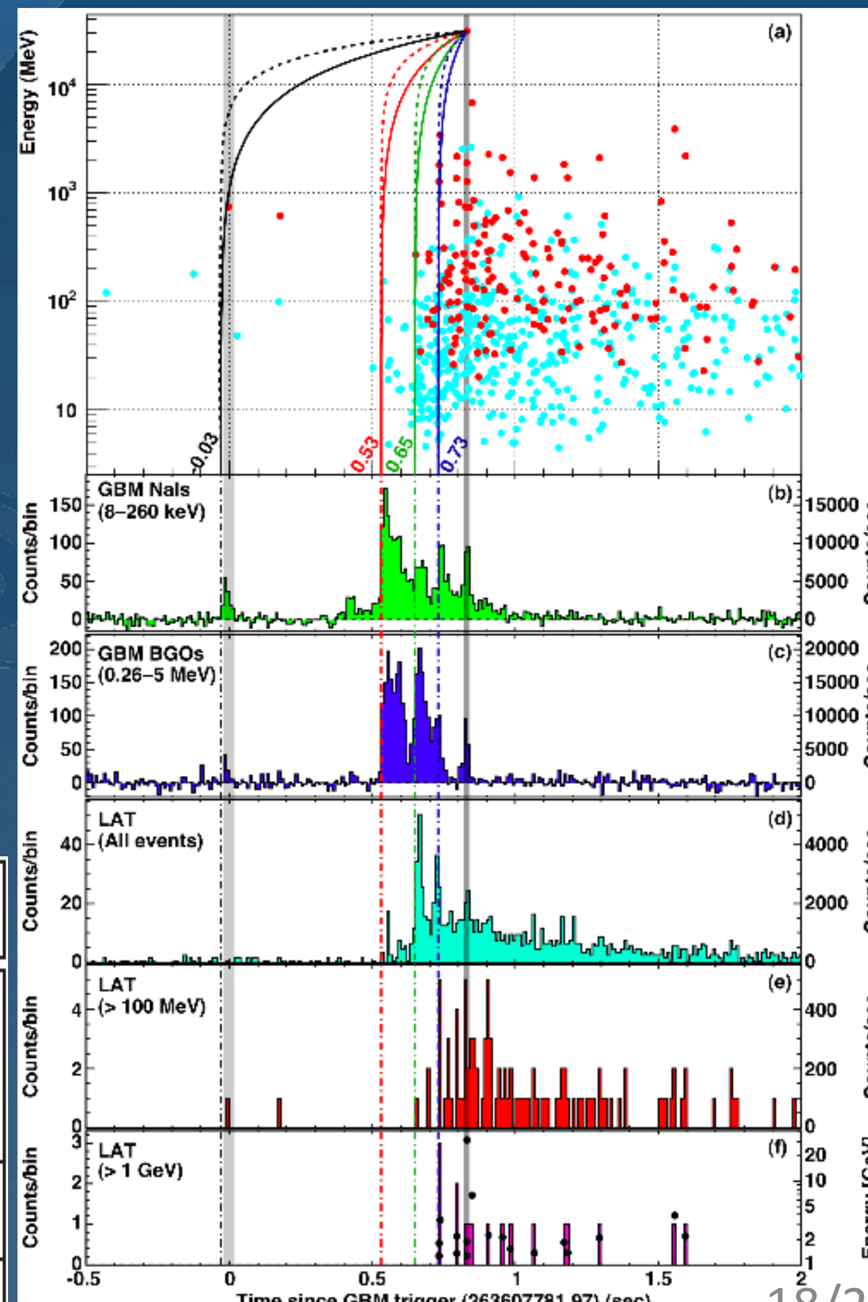
$$c^2 p_{ph}^2 = \frac{E_{ph}{}^2}{\sqrt{1 - \frac{E_{ph}}{M_{QG}c^2}}} = E_{ph}^2 \left[1 + \frac{E_{\mathrm{ph}}}{M_{\mathrm{QG,1}}c^2} + \left(\frac{E_{\mathrm{ph}}}{M_{\mathrm{QG,2}}c^2} \right)^2 + \ldots \right] \text{ with } \frac{\mathrm{E_{ph}}}{\mathrm{c}^2} << \mathrm{M_{QG}}$$

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

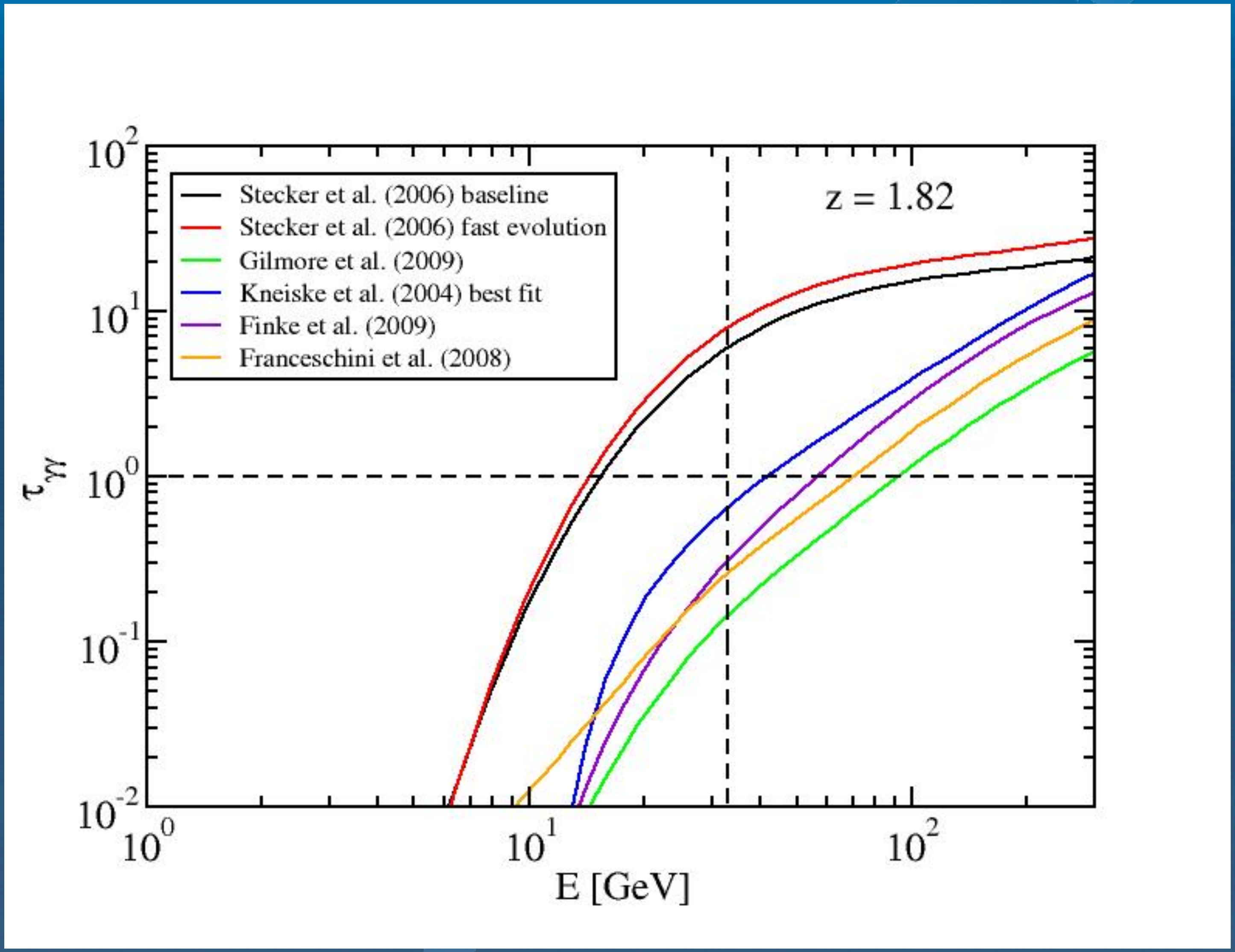
$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'$$

- **The LAT is mostly sensitive to linear variation (n=1) and maybe quadratic variations (n=2)**

$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$	limit on $M_{\rm QG,2}$ in 10^{10} GeV/c^2
-30	< 859	start of any observed emission	0.1	1	> 1.19	> 2.99
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42	> 5.06
630	< 199	start of > 100 MeV emission	100	1	> 5.12	> 6.20
730	< 99	start of > 1 GeV emission	1000	1	> 10.0	> 8.79
—	< 10	association with < 1 MeV spike	0.1	± 1	> 102	> 27.7
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	-1	> 1.33	> 0.54
$\lvert\Delta t/\Delta E\rvert < 30$ ms/GeV		lag analysis of all LAT events	—	± 1	> 1.22	—



Contraints on the EBL models



- Most models are optically thin for the 33 GeV photon from GRB 090902B.
- "Baseline" and "fast evolution" models rejected at 3.6 σ.

Conclusion

- GBM : ~250 GRBs/year, LAT : ~10 GRBs/year

- Excellent synergy with Swift : ~11% GBM GRBs, 8 redshifts LAT, 1 Swift/LAT common trigger

- Prompt emission
  - Time-resolved spectroscopy favors internal shock scenario
  - Short and long GRBs seem to have similar HE properties, but short GRBs are harder

  - Many LAT GRBs show later onset & longer duration of the HE emission
  - Spectral deviation adequately fit with additional PL (Leptonic or hadronic emission)

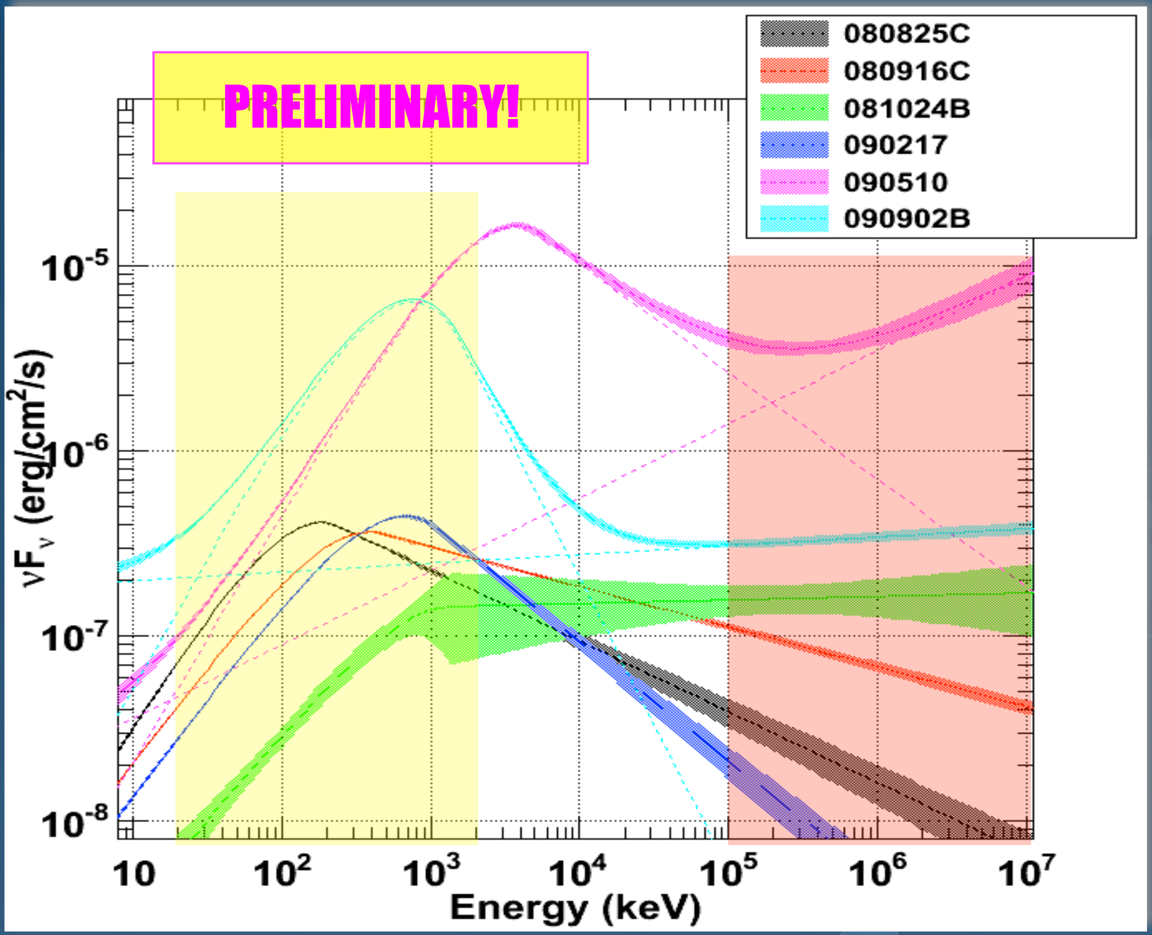
  - High GRB outflow Lorentz factors: $\Gamma_{min} \sim 1000$
  - Highest energy photons constrain EBL models
  - Best lower limits on LIV (n=1 disfavored)

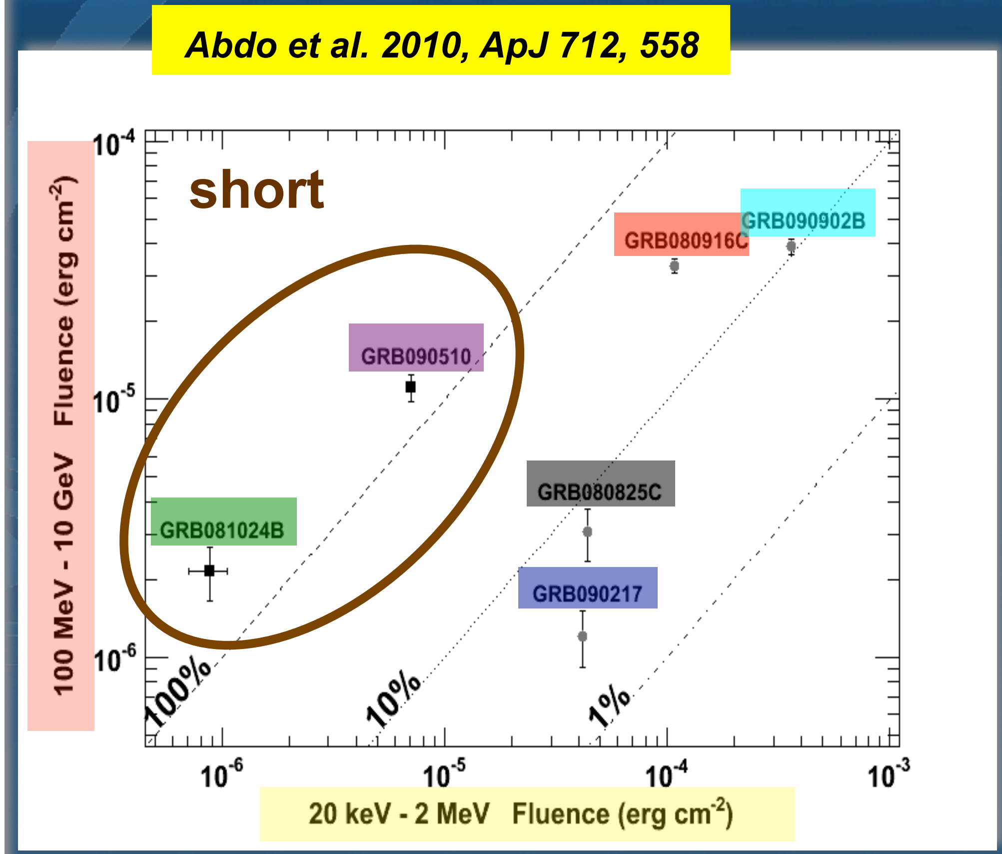
- Long-lived GeV emission is a ubiquitous property of GRBs
  - Extending up to a few 100's or 1000's seconds (~5 ks for GRB 090926A)
  - PL temporal decay with index ~ -1.5, and PL spectrum with index ~ -2.1
  - GRB 090510 afterglow well reproduced by the FS model from the optical up to GeV energies!

Summary of LAT GRBs as of January 2010

GRB	Angle from LAT	Duration (or class)	# of events > 100 MeV	# of events > 1 GeV	Delayed HE onset	Long-lived HE emission	Extra spectral comp.	Highest photon Energy	Redshift
080825C	~ 60°	long	~ 10	0	✔ / ?	✔	X	~ 600 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	~ 1 GeV	
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	2.1062
091003A	~ 13°	long	~ 20	> 0	?	?	?		0.8969
091031	~ 22°	long	~ 20	> 0	?	?	?	~ 1.2 GeV	
100116A	~ 29°	long	~ 10	3	?	?	?	~ 2.2 GeV	

LAT Fluence vs GBM Fluence





- 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