Les sursauts gamma vus par *Fermi*

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Atelier OCEVU

"The physics of relativistic outflows"

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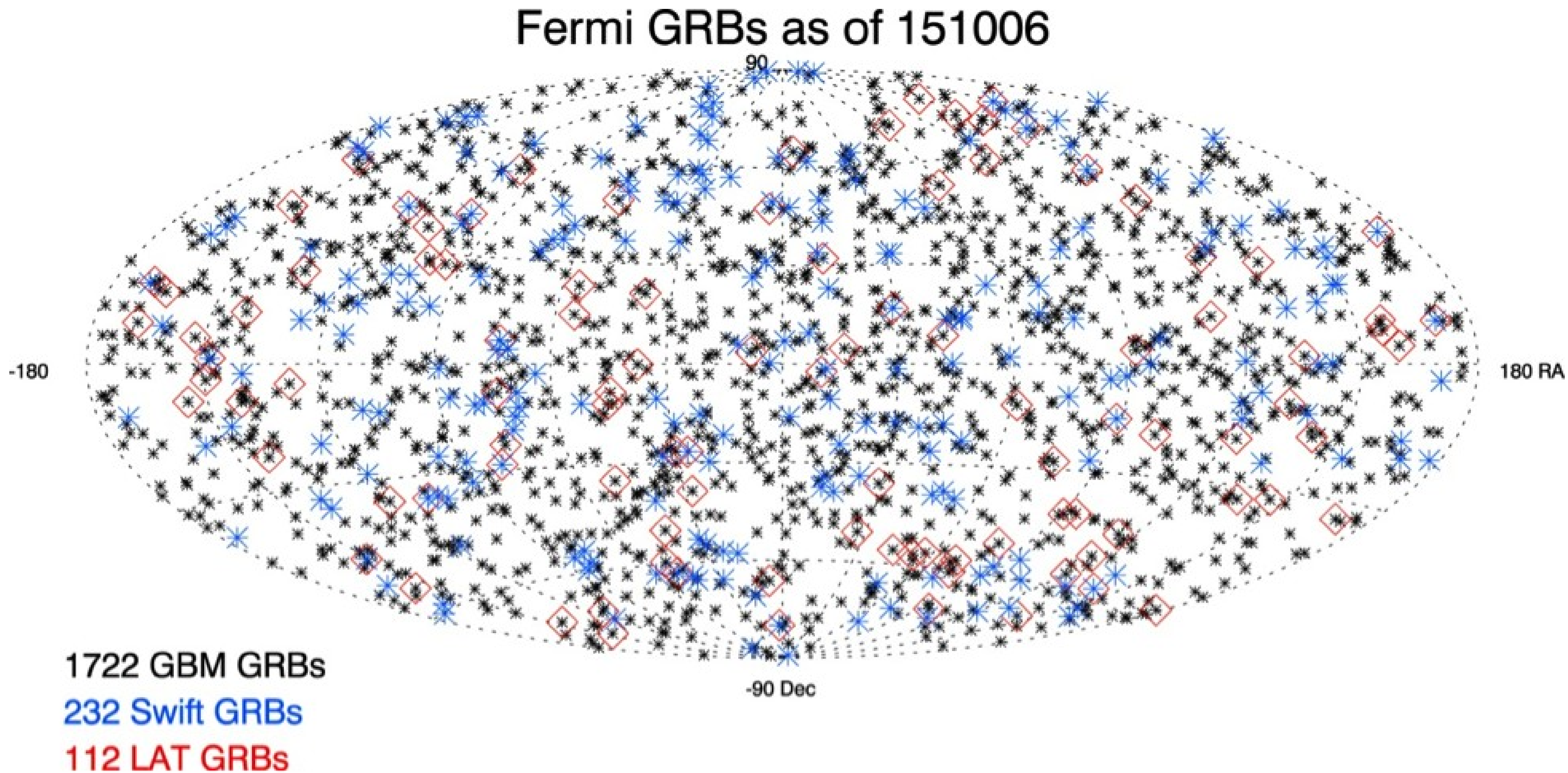
Outline

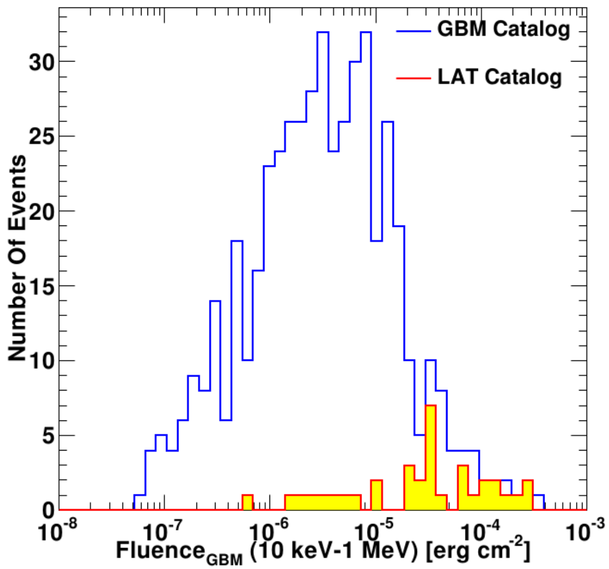
- **Detection statistics**
- **GRB observations with *Fermi***
  - Common properties at high energies
  - Focus on GRBs 090926A and 130427A
  - Physical implications and open questions
- **Summary and outlook**

Fermi GRB statistics



- **The GBM detects ~240 GRBs / year, ~45 of them are short**
- **The LAT detects ~10% of GBM GRBs in its field-of-view above 100 MeV**
  - LAT bright GRBs with good localizations are all followed-up by Swift
  - From z=0.145 (GRB 130702A) to z=4.35 (GRB 080916C)

LAT bursts: bright, fluent and energetic

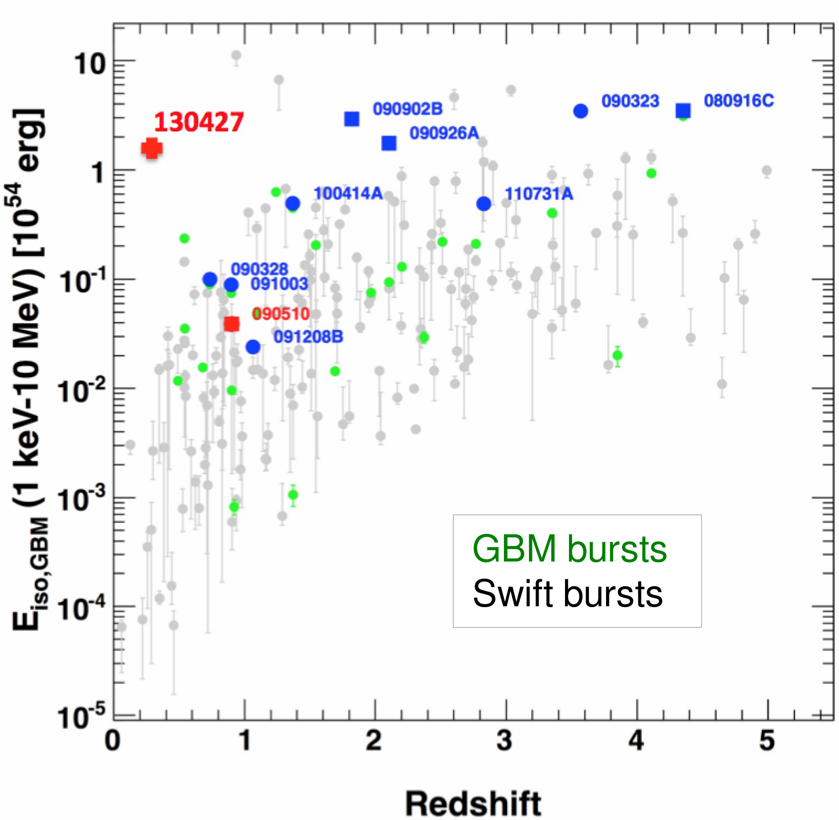


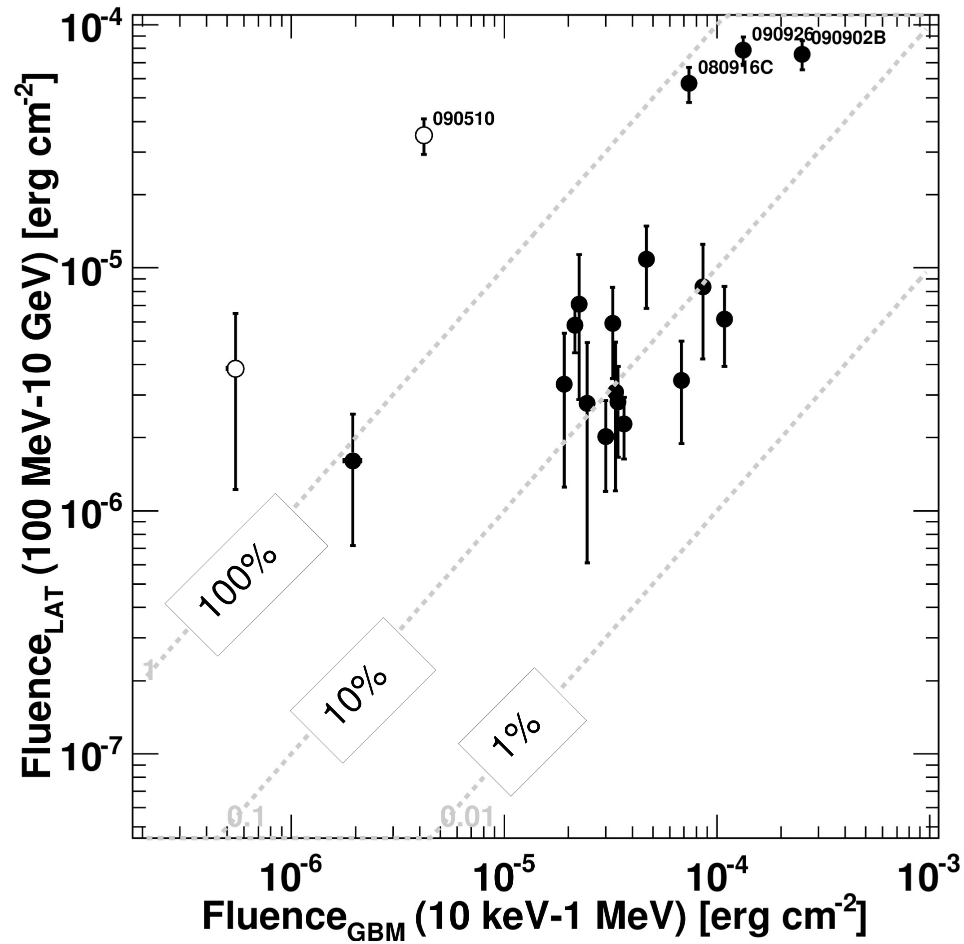
Butler et al. 2007, ApJ 671, 656 (see also Sakamoto et al. 2011, ApJS 195, 2)

Goldstein et al. 2012, ApJS 199, 19

Ackermann et al. 2013, ApJS 209, 11

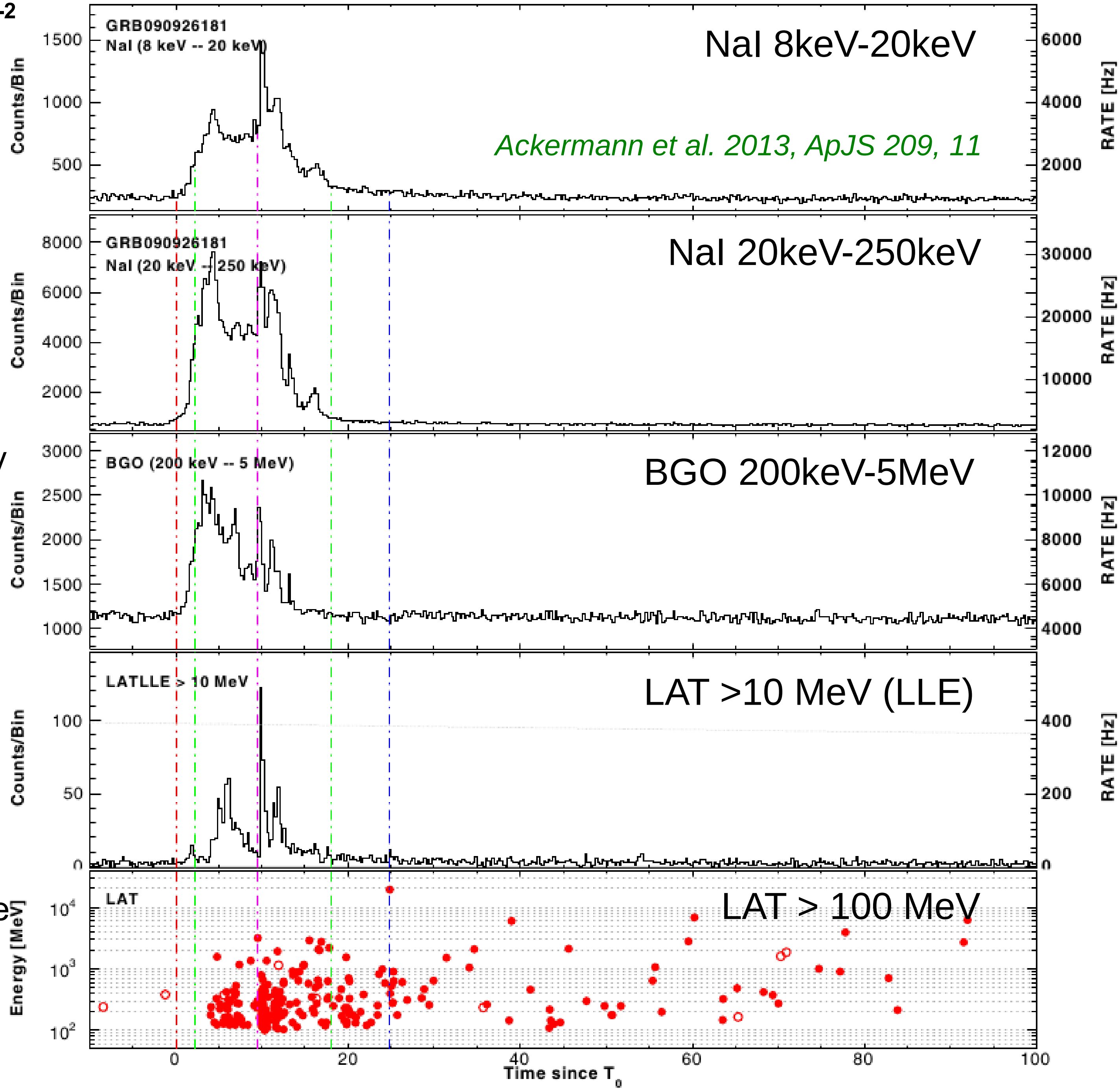
- **Among the brightest and most fluent GBM GRBs**
- **Among the most energetic GRBs**
- **Short GRBs have larger LAT/GBM fluence ratios (>1) than long GRBs (~10%)**





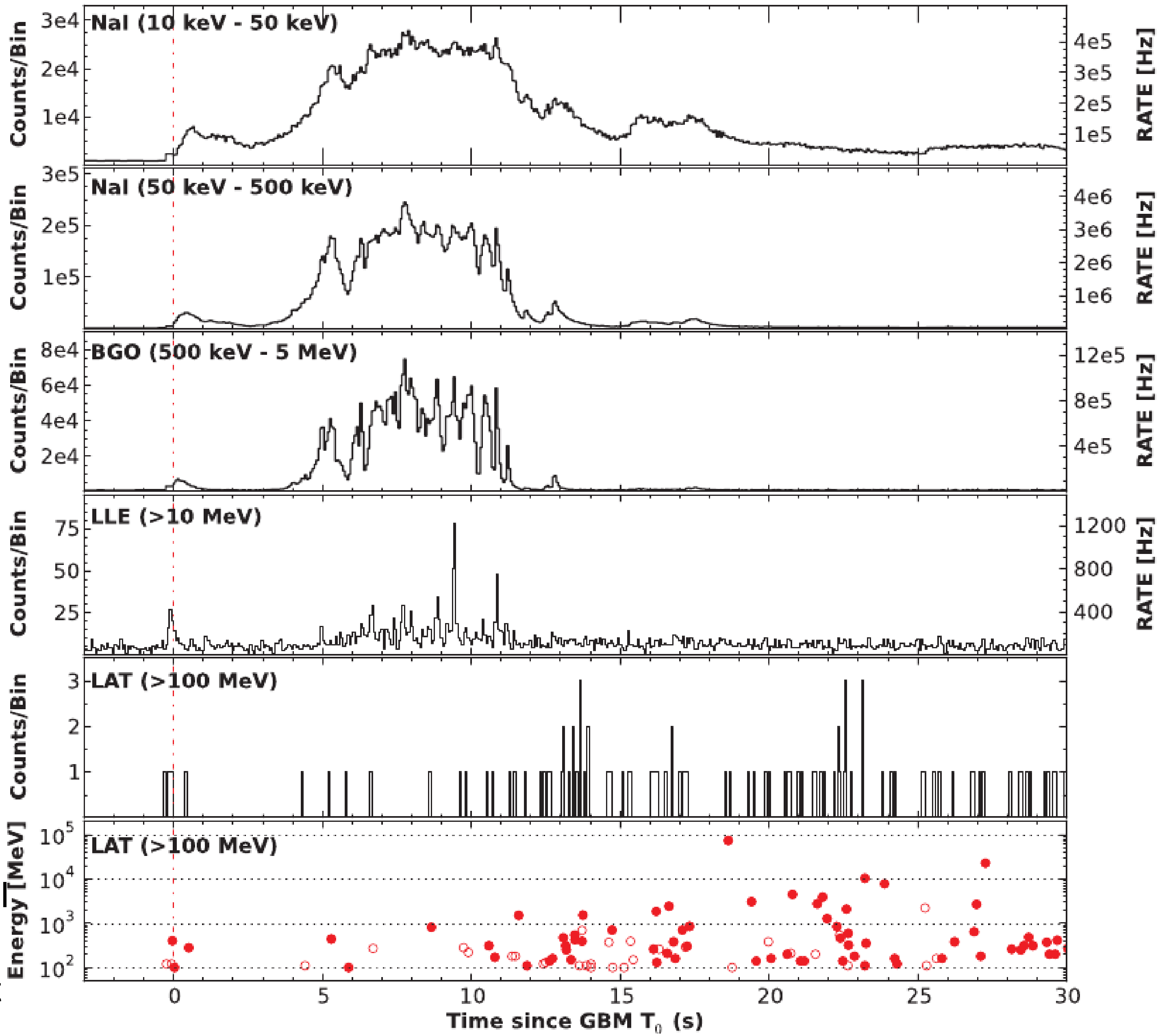
GRB 090926A multi-detector light curve

- **Fluence = 2.2 x 10^{-4} erg cm^{-2}**
- **E_{iso} = 2.2 x 10^{54} erg**
- **Correlated variability in various bands with a sharp spike at T_0+10 s**
  - All energy ranges synchronized (<50 ms)
  - Low and high energies are co-located or even causally correlated
- **LAT >100 MeV emission is delayed (~4 s)**
  - Delay > spike widths
- **LAT >100 MeV emission is temporally extended**
  - Well after the prompt phase
  - 19.6 GeV photon detected at T_0+24.8 s



GRB 130427A multi-detector light curve

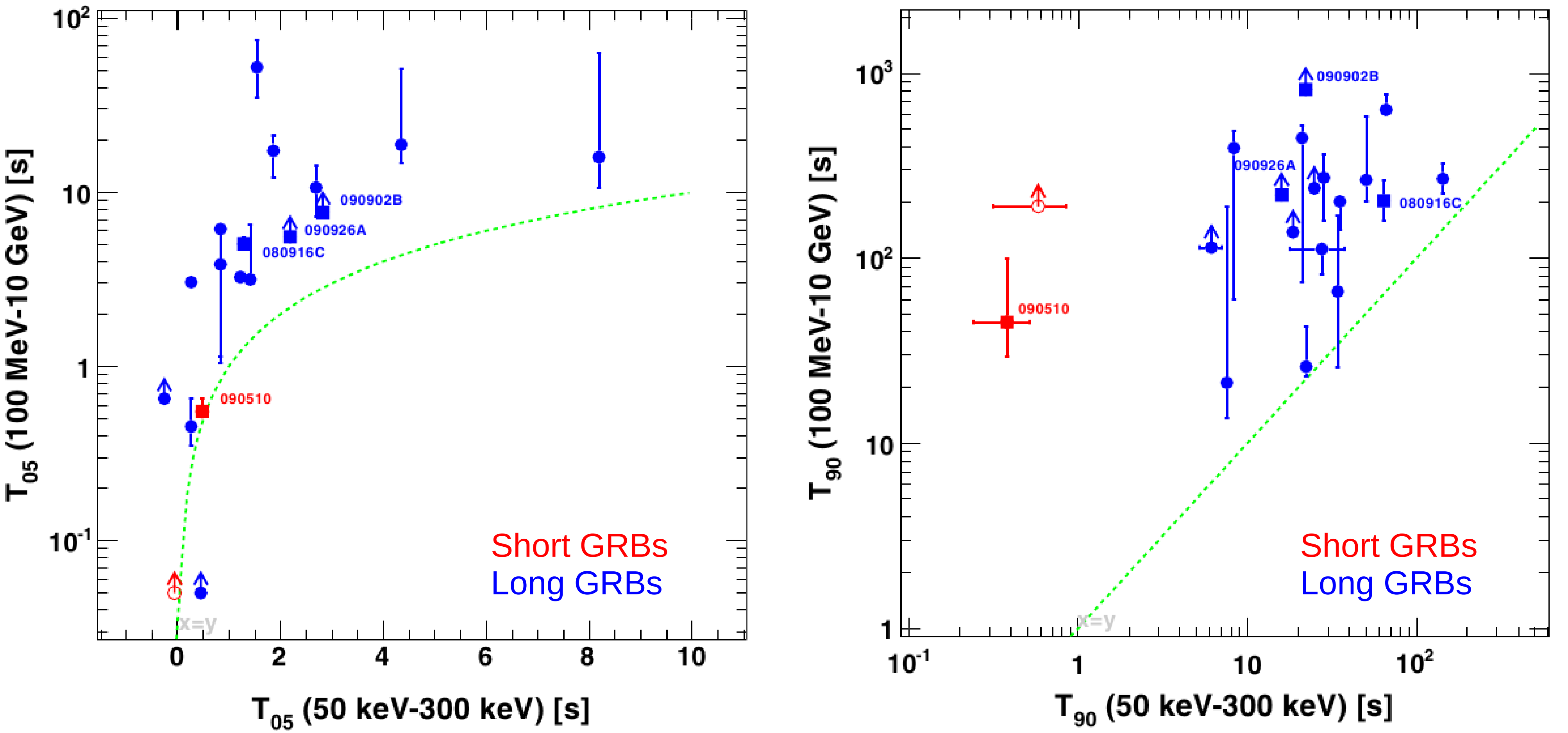
- **Highest γ-ray fluence ever ($> 10^{-3}$ erg cm^{-2})**
- **$E_{iso} = 1.4 \times 10^{54}$ erg**
- **Brightest LAT GRB**
  - >500 photons >100 MeV
  - 15 photons >10 GeV
- **Unlike other bright LAT GRBs, the LAT >100 MeV emission is temporally distinct from the GBM emission**
- **LAT >100 MeV emission is delayed and temporally extended**
  - Delay ~10 s, continues well after the prompt phase
  - 73 GeV photon detected at T_0+19 s



Ackermann et al. 2014, Science 343, 42

Temporal properties

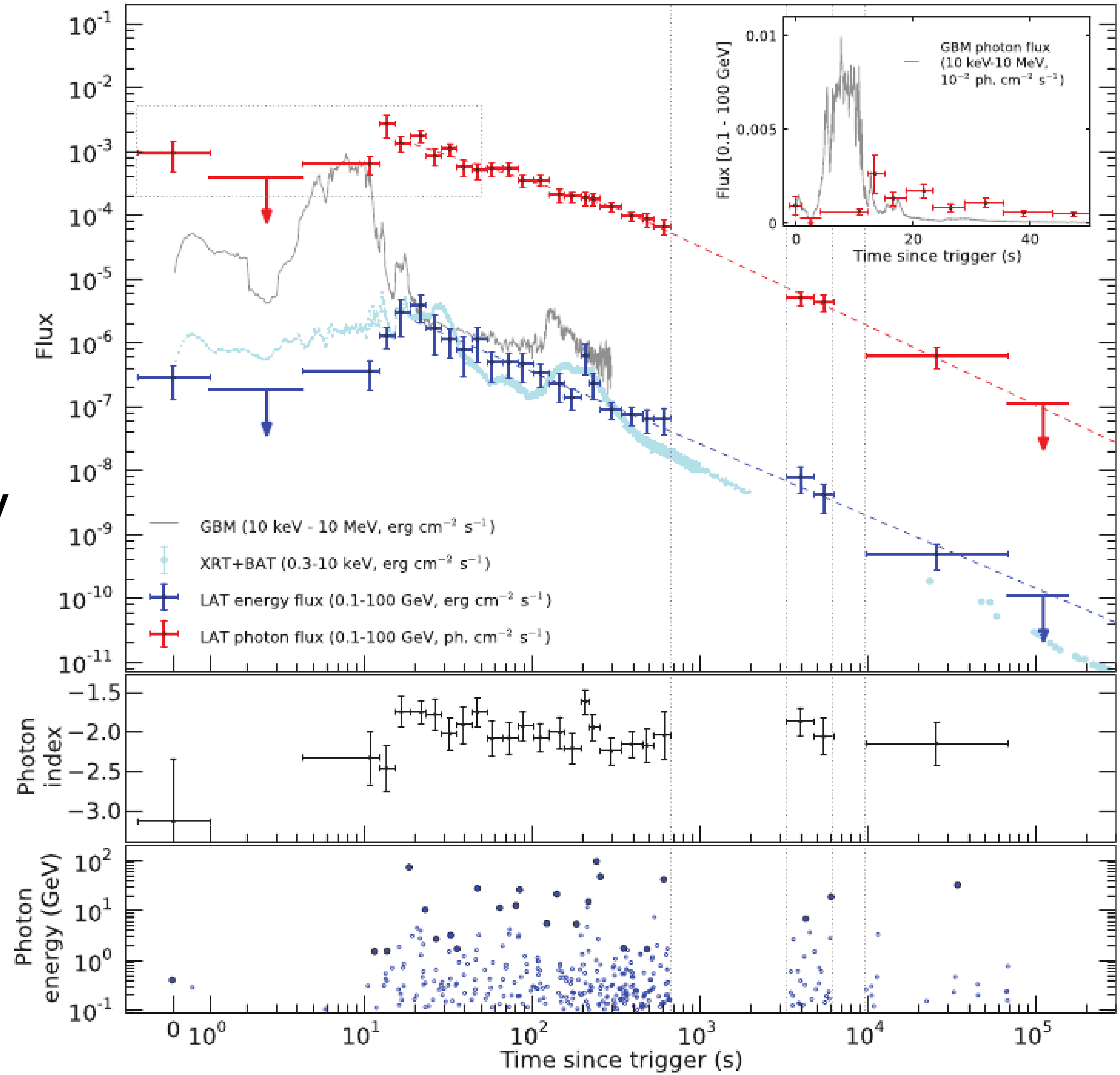
Ackermann et al. 2013, ApJS 209, 11



- **The delay in the onset of the >100 MeV emission and its temporal extension are common to the vast majority of LAT-detected GRBs**
- **Suggests independent emission processes at keV-MeV and >100 MeV energies**

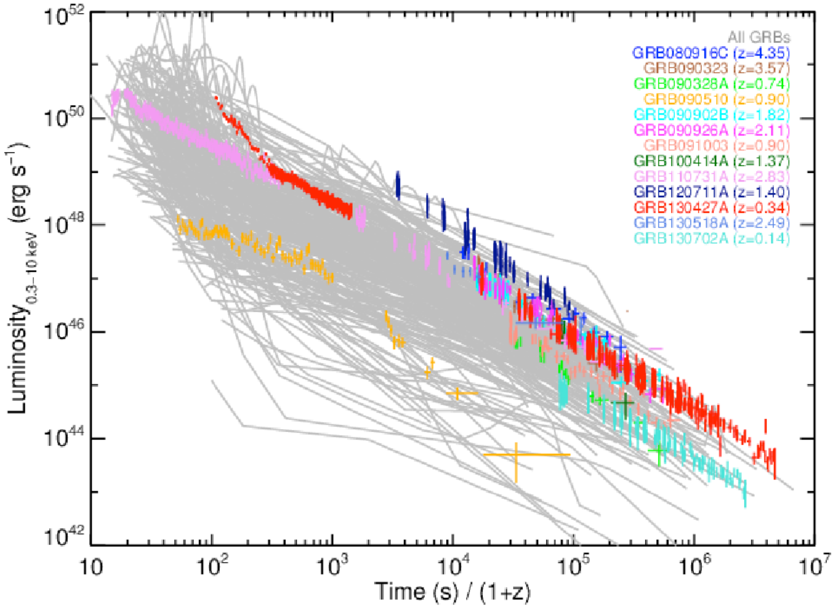
GRB 130427A afterglow in X-rays and γ-rays

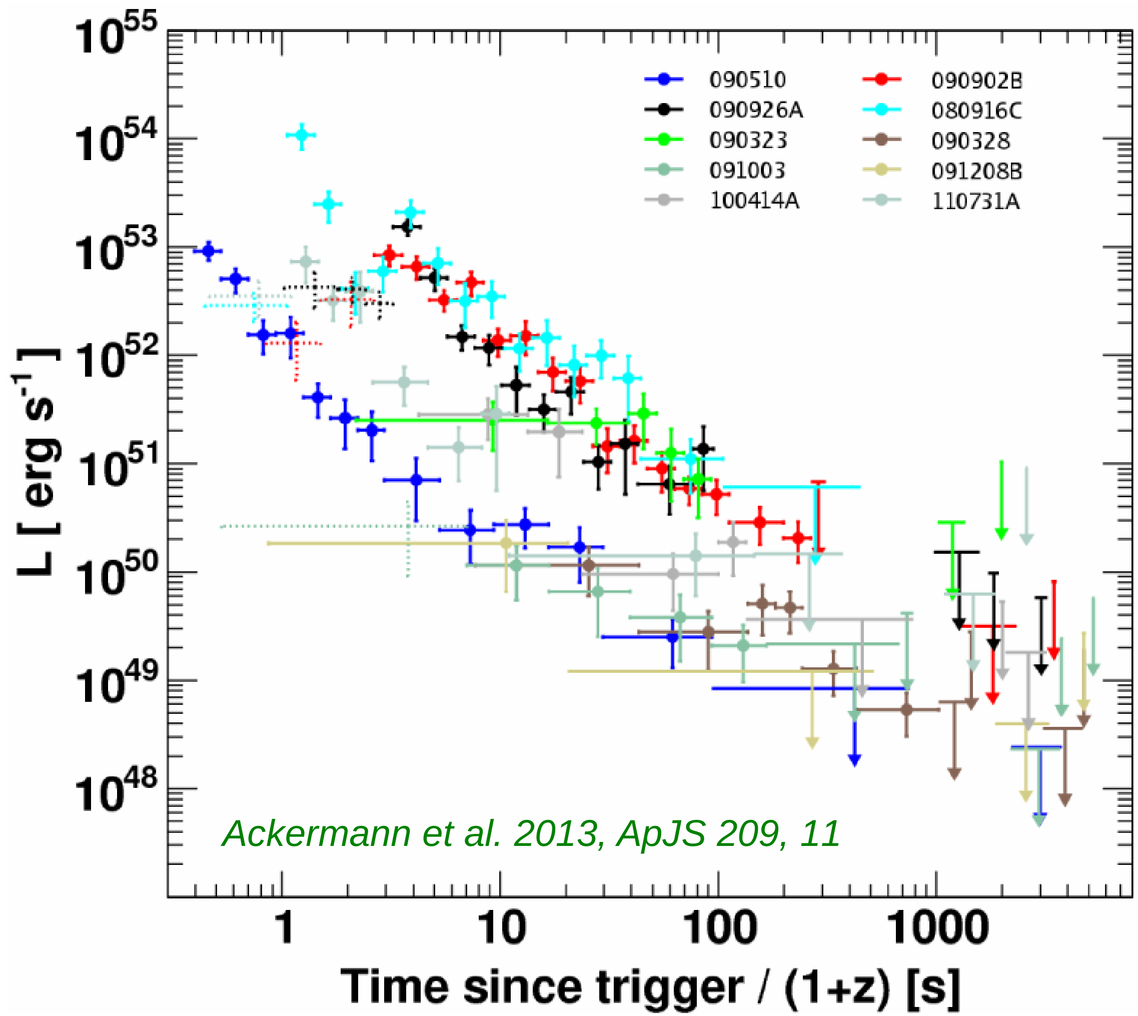
- **Brightest X-ray afterglow ever detected**
- **Longest-lived gamma-ray emission: LAT emission detected for 19 hours**
- **LAT light curve is ~smooth**
- **LAT spectrum described by a power law at all times**
  - Spectral index $\alpha_{EX} \sim -2$
- **Common features between LAT and lower energy light curves**
- **Record breaking 95 GeV photon at T_0+244 s**



Ackermann et al. 2014, Science 343, 42

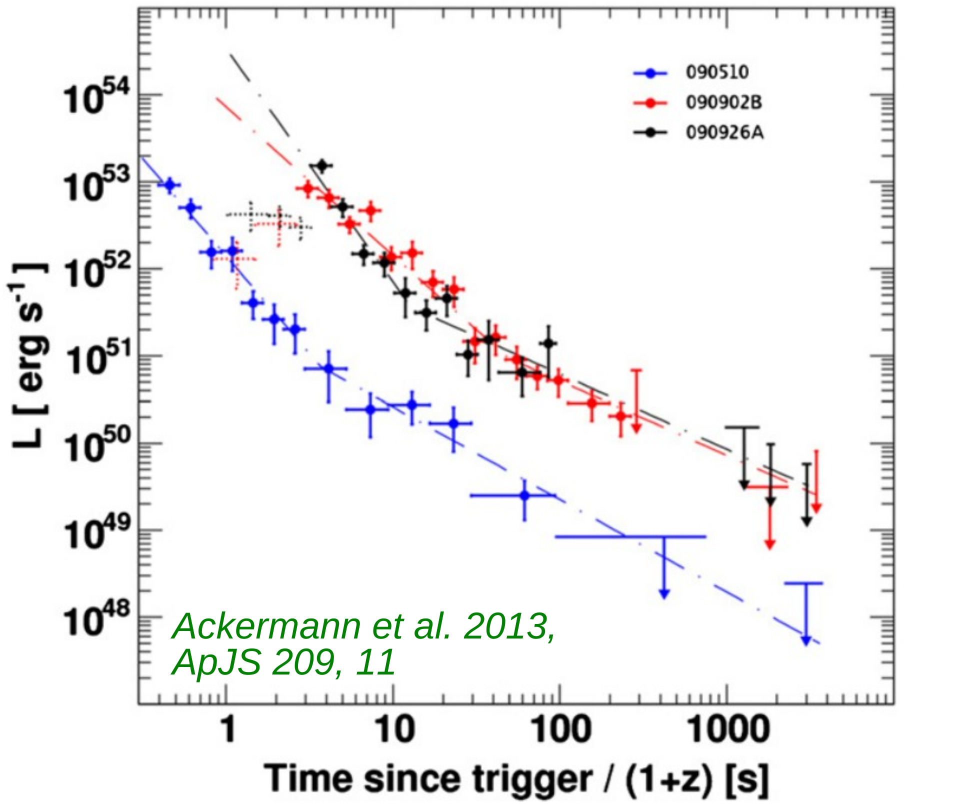
Long-lived GeV emission (1/2)

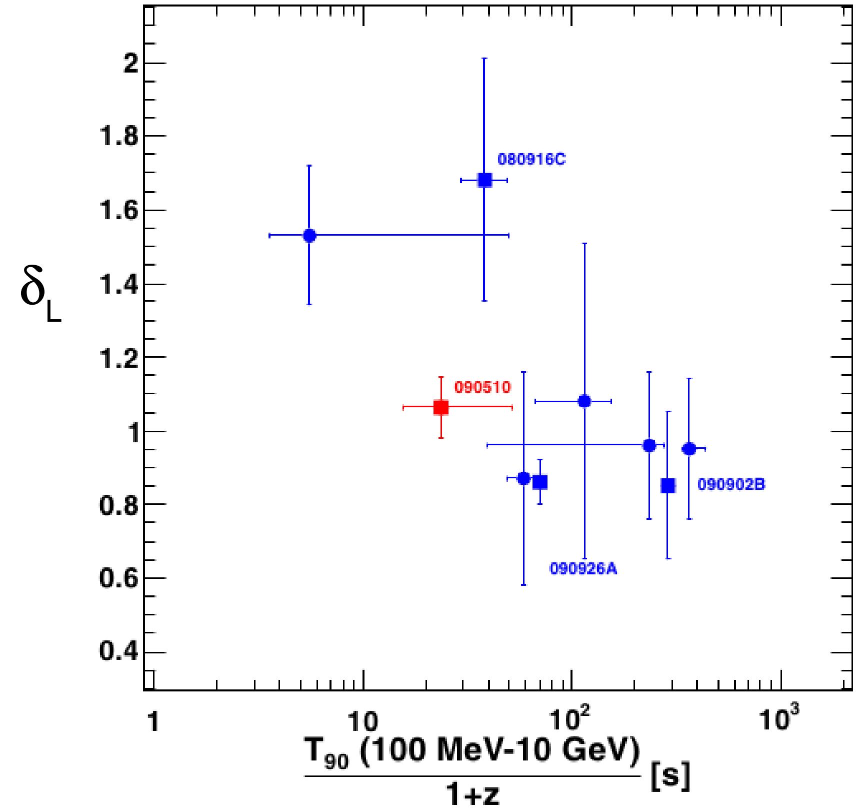




- **At late times, GRB >100 MeV emission is compatible with an afterglow origin**
  - Smooth decay of the luminosity $L(t) \sim t^{-\delta}$ similar to the visible / UV / X-ray afterglow
  - No noticeable spectral evolution (see previous slide)

Long-lived GeV emission (2/2)

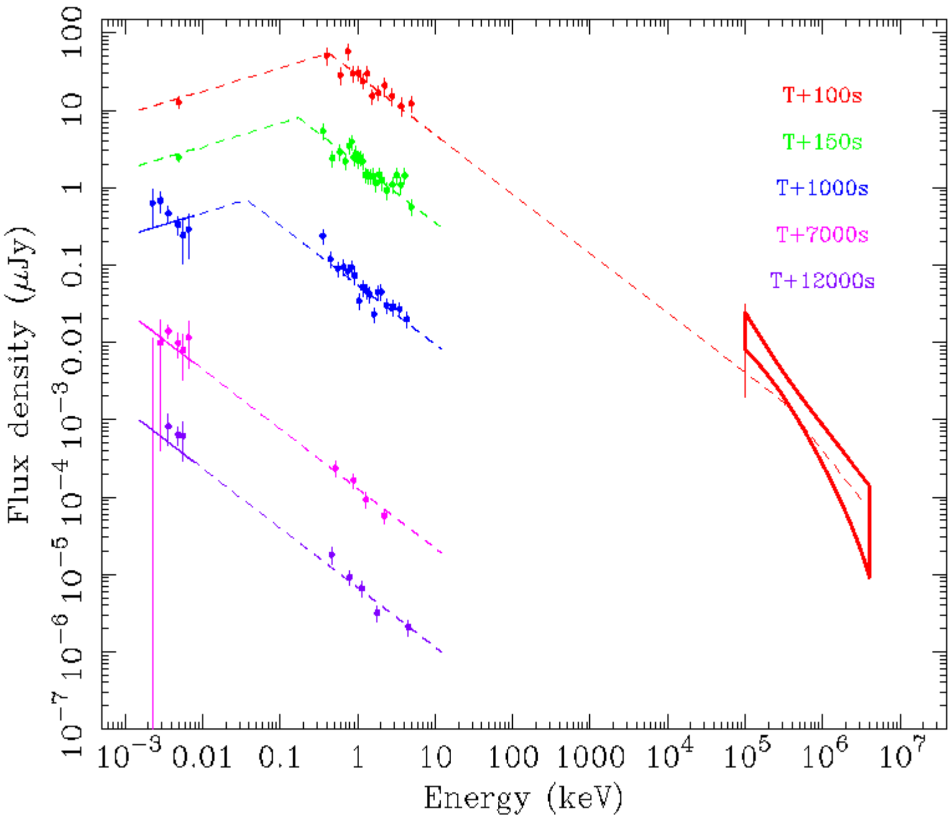




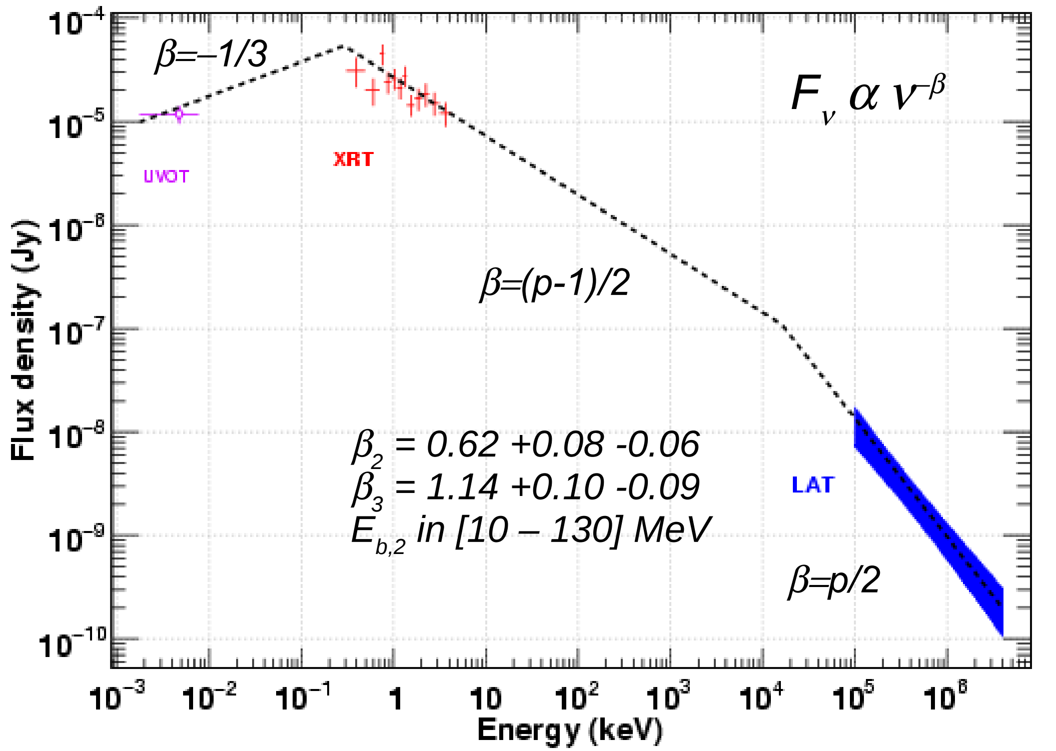
- **Broken power-law decay in 3 cases**
  - Decay index δ decreases from ~2 to ~1 after the time of the break (> GBM T_{95})
  - Transition between prompt- and afterglow-dominated phases?
- **At very late times: $\delta \rightarrow \delta_L$~1 for all bursts**
  - Except for the long GRBs 080916C and 110731A, which have the shortest intrinsic durations → break still possible at later times
- **α_{EX} ~ -2 and δ~1 → synchrotron emission from a blast wave in adiabatic expansion**

Swift and *Fermi* view of the short GRB 090510

- Fit of the afterglow SED at 5 different times simultaneously



- Fit of the SED at T_0+100 s
- >4.5 σ cooling break at ~20 MeV



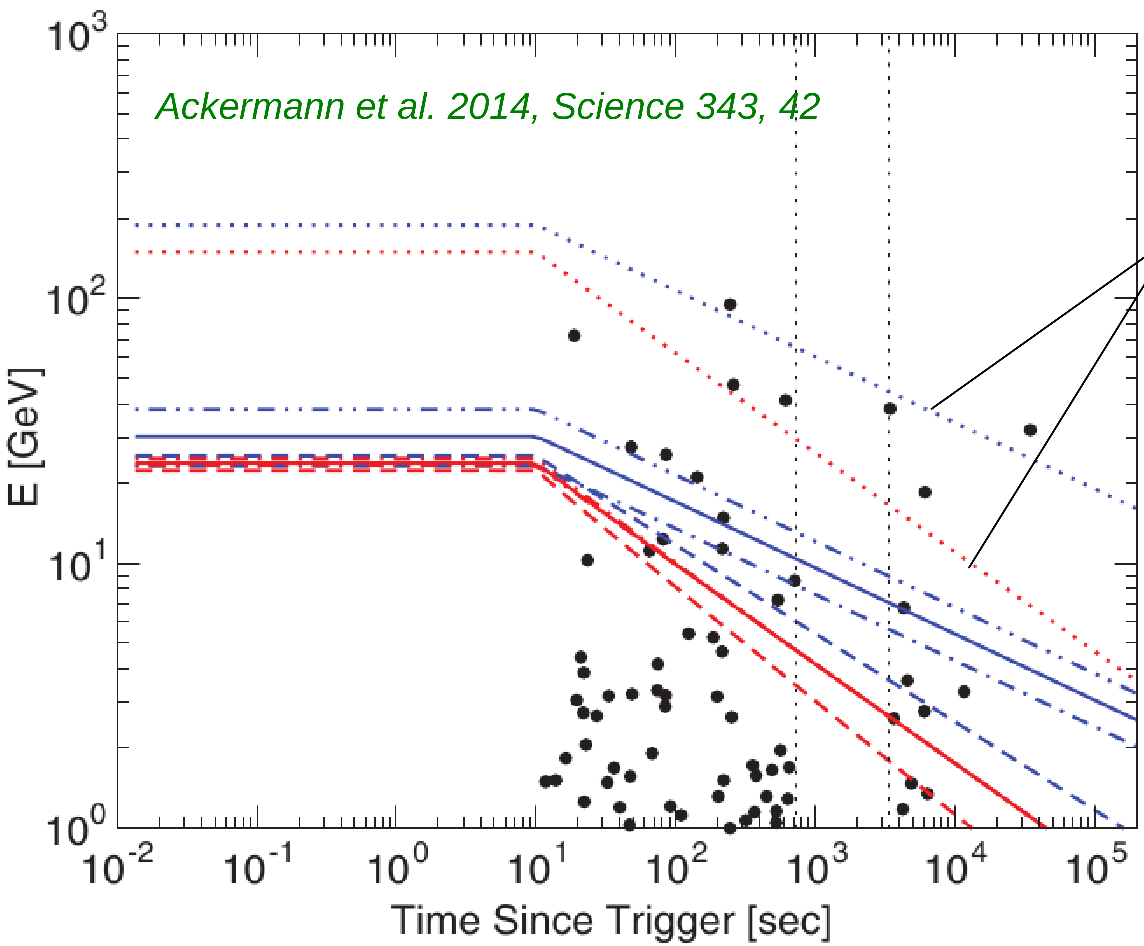
De Pasquale et al. 2010, ApJL 709, 146

- **Forward shock synchrotron emission model** can reproduce the spectrum from the visible domain up to GeV energies

GRB 130427A: a challenge for synchrotron models

- **Synchrotron radiation models predict a maximum synchrotron energy, derived by equating the electron acceleration and synchrotron radiative cooling timescales**
  - Assuming a single acceleration and emission region
  - $E_{max} \sim 79\Gamma(t)$ MeV, with $\Gamma(t)$ given by Blandford & McKee (1976) in the adiabatic limit

- **The LAT highest energy photons are incompatible with having a synchrotron origin**



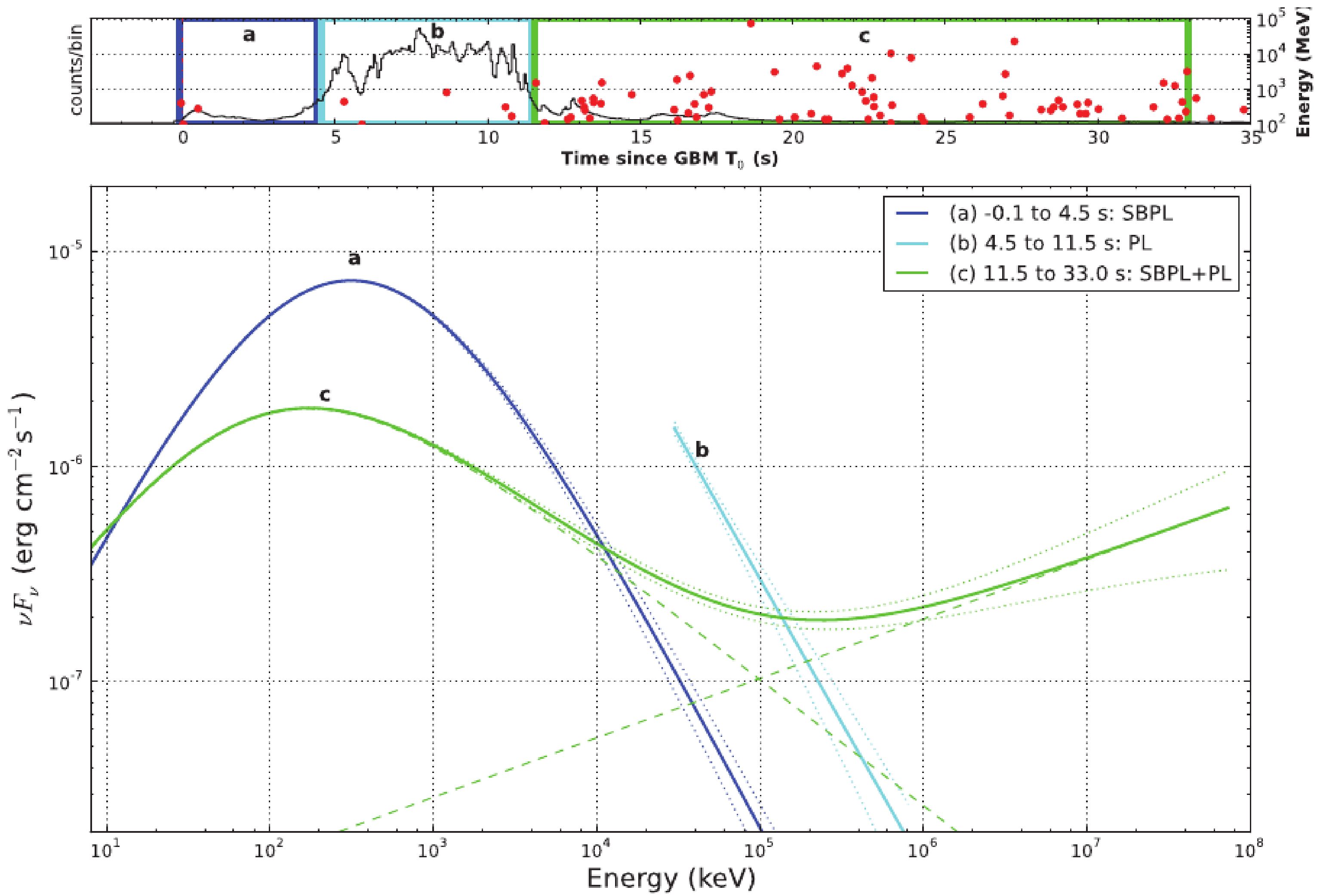
Extremely fast acceleration (less realistic): acceleration taking place on the inverse of the Larmor angular frequency $t_{acc} \sim t_{Larmor}/2\pi$

$t_{acc} \sim t_{Larmor}$

wind, adiabatic, $\Gamma_0 = 2000$
wind, adiabatic, $\Gamma_0 = 1000$
wind, adiabatic, $\Gamma_0 = 500$

wind, radiative, $\Gamma_0 = 1000$
ISM, adiabatic, $\Gamma_0 = 1000$
ISM, radiative, $\Gamma_0 = 1000$

GRB 130427A prompt emission spectrum

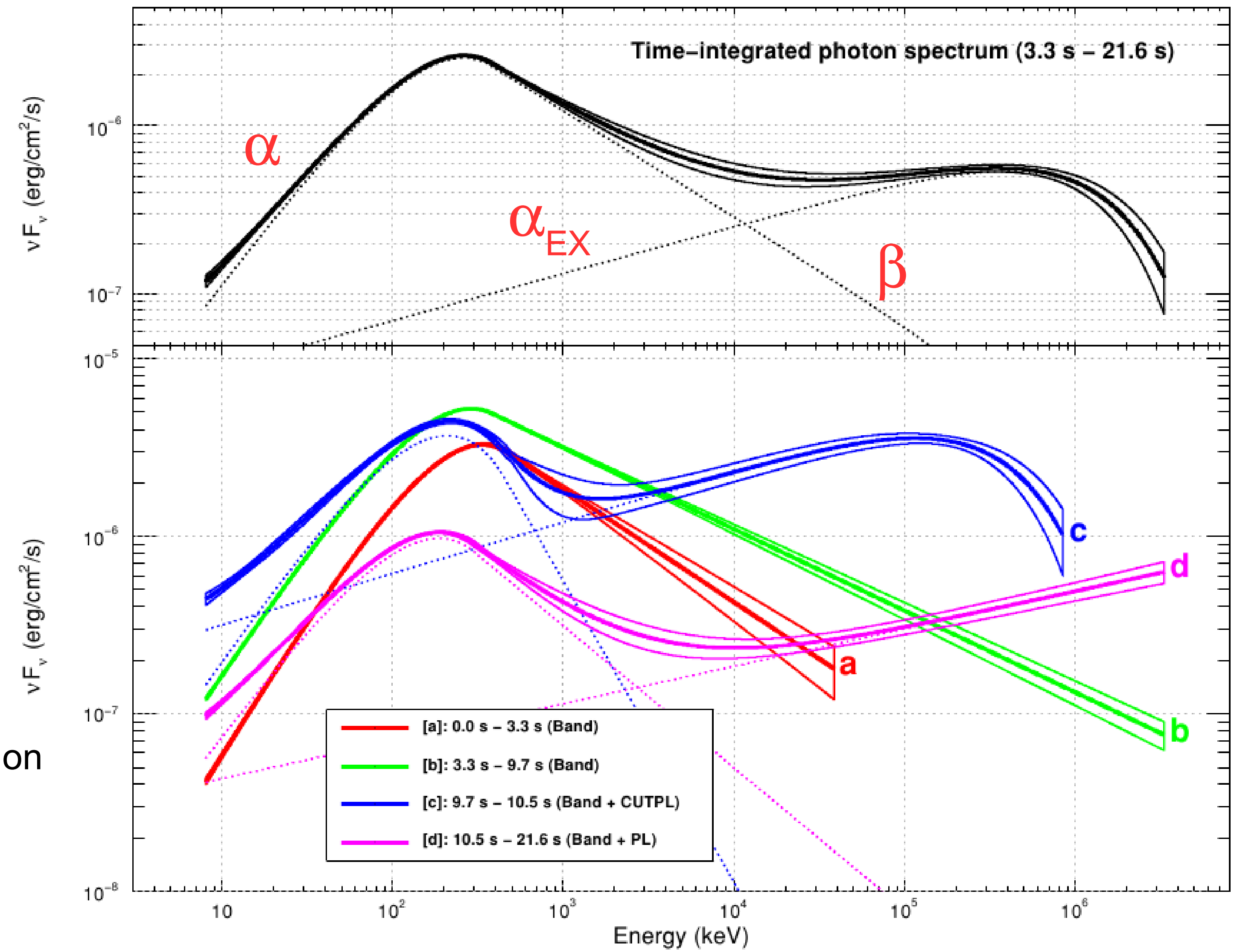


- **Unlike other bright LAT-detected GRBs, the extral PL component becomes significant only after the GBM-detected emission has faded**

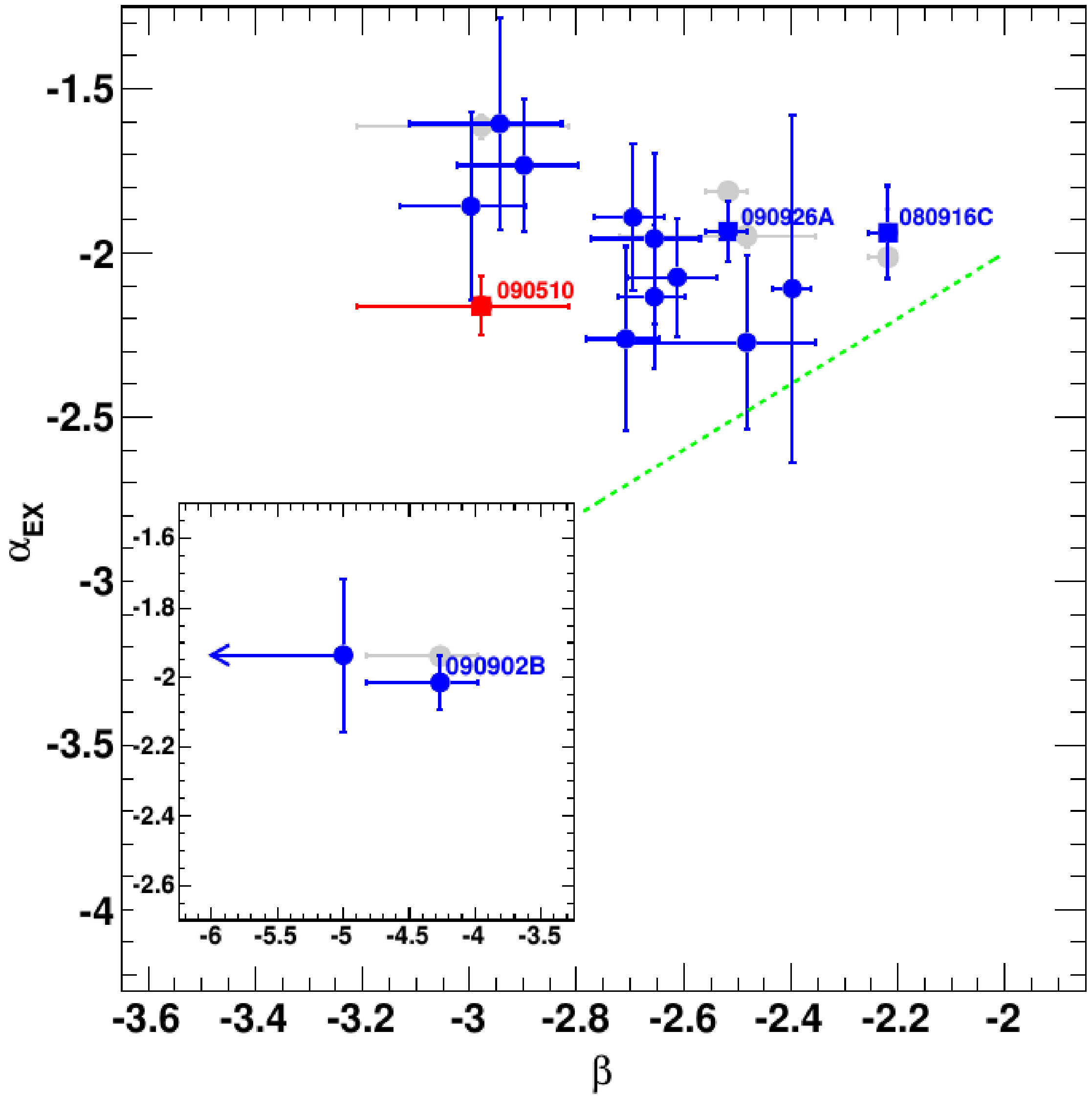
GRB 090926A prompt emission spectrum

- **Extra PL component**
  - Starts delayed (~9 s)
  - Persists at longer times
  - Dominates > 10 MeV
- **Spectral cutoff**
  - Significant in bin c, marginally in bin d
  - Shape not constrained
- **First measurement of the jet Lorentz factor**
  - **Γ ~ 200-700**
  - If cutoff due to $\gamma\gamma$ absorption
  - Model dependent

Ackermann et al. 2011, ApJ 729, 114



Extra PL component vs. keV-MeV spectrum

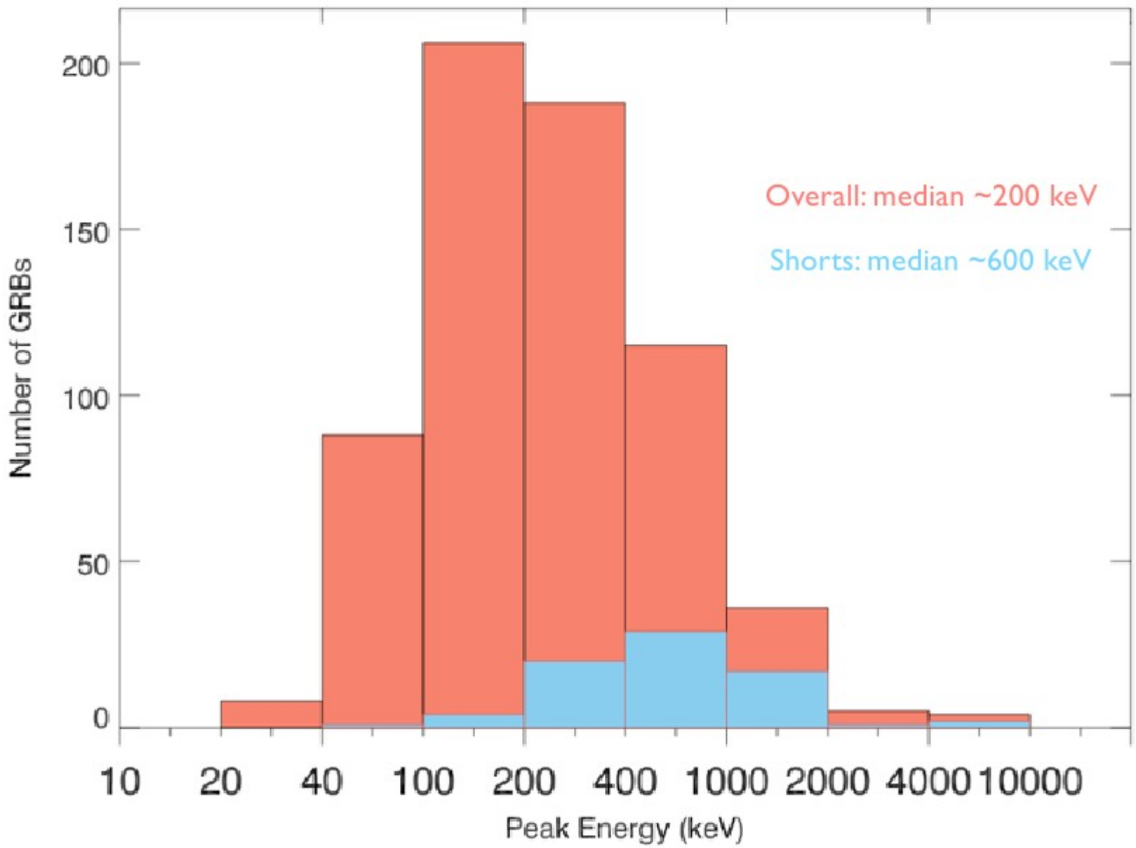


Ackermann et al. 2013, ApJS 209, 11

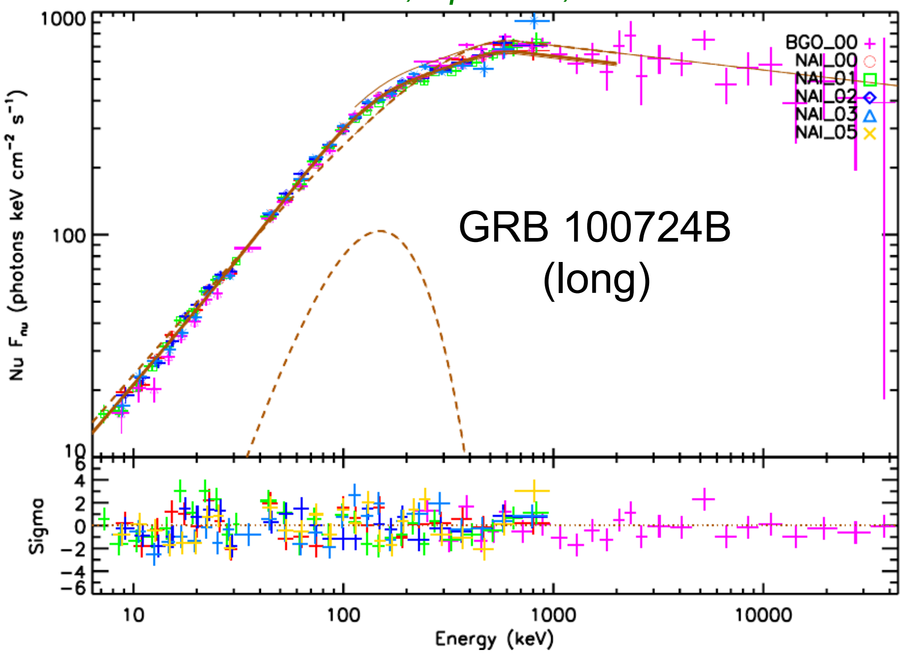
- **Band function index β (from a joint GBM+LAT fit during the GBM T_{90}) vs. PL index α_{EX} (from a LAT fit after the GBM T_{95})**
- **α_{EX} very stable, not correlated with β**
  → afterglow origin of the high-energy emission is reinforced
- **Gray points: joint fits which require an extra PL during the GBM T_{90}**
  → the FS synchrotron emission can be dominant during the early afterglow phase, while the prompt keV-MeV emission remains detectable
  → GeV emission from internal shocks still required for highly variable episodes
- **Disentangling both contributions <u>needs time-resolved spectra AND variability study</u> (pulse width, lags...)**

GBM GRB spectra

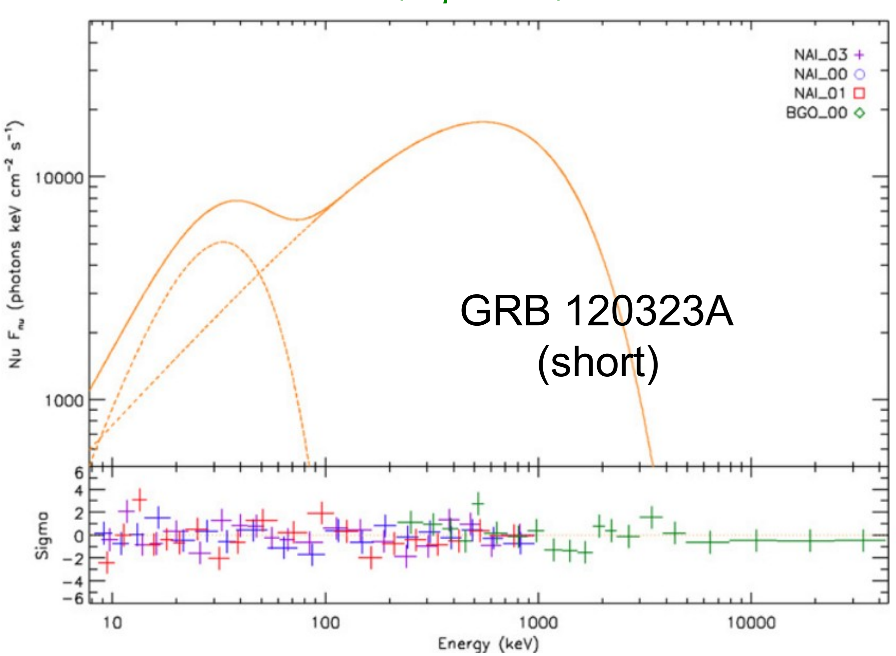
- **Short GRB spectra have higher peak energies in time-integrated spectra**
- **Extra component sometimes seen above Band function**
  - Consistent with BB photosphere emission



Guiriec et al. 2011, ApJ 727, L33



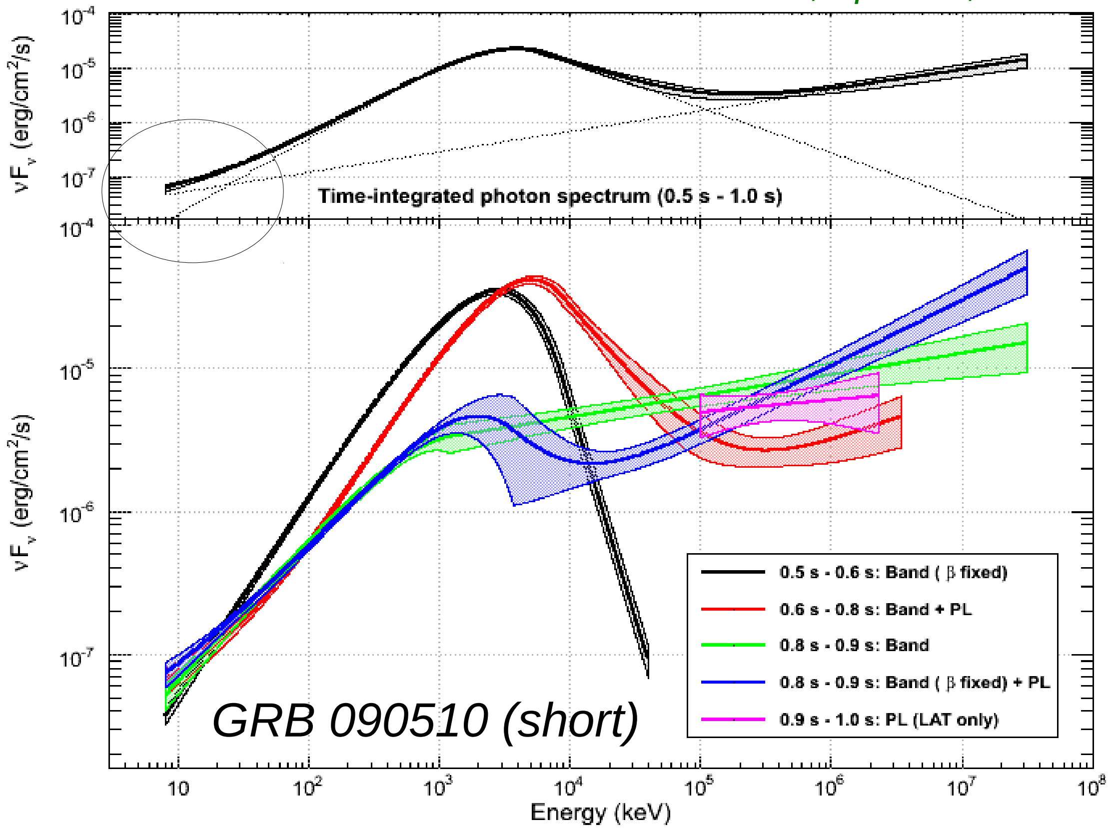
Guiriec et al. 2013, ApJ 770, 32



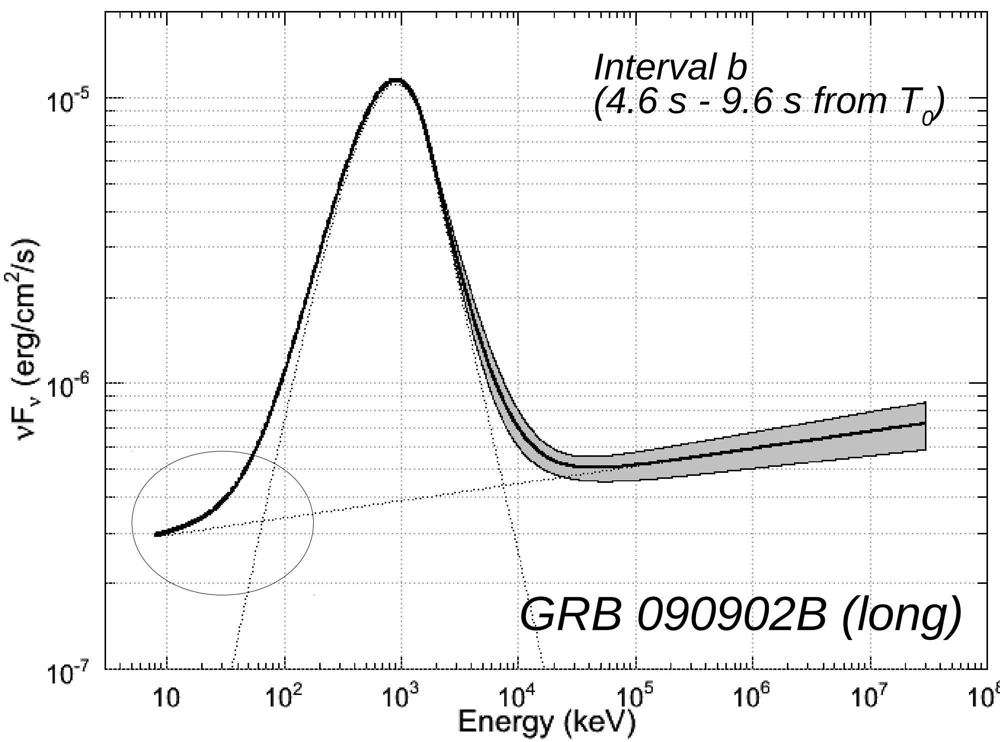
Broad-band spectra

- **The Band function is no longer the best phenomenological model**
- **Several deviations from the Band function**
  - At low energies: BB component, low-energy flux excess
  - At high energies: extra PL component, sometimes attenuated (cutoff)

Ackermann et al. 2010, ApJ 716, 1178



Abdo et al. 2009, ApJL 706, 138
(See also Ryde et al. 2010, ApJ 709, L172)



Possible origins of the “prompt” high-energy emission

- **Leptonic models (e.g., internal shocks and inverse-Compton or SSC processes)**
  - HE onset time: hard to produce a delay longer than spike widths
  - Hard to produce a low-energy (<50 keV) flux excess (e.g., GRBs 090510, 090902B)
  - Hard to account for the Band α (line of death problem)
  - Better agreement with observations in some cases including a photospheric emission component

- **Hadronic models (internal shocks and proton synchrotron or cascades)**
  - HE onset time = time to accelerate protons & develop cascades?
  - Synchrotron emission from secondary e± pairs can naturally explain the low-energy flux excess
  - Proton synchrotron radiation requires large B-fields
  - Both scenarios require substantially more energy (1-3 orders of magnitude) than observed (much less stringent constraint with lower values of Γ)
  - Hard to produce correlated variability (e.g., spike of GRB 090926A)

- **Early afterglow (forward shock and electron synchrotron)**
  - HE onset time = time required for FS to sweep up enough material and brighten
  - Hard to explain rapid high-energy variability observed in some bursts (e.g., GRBs 090902B, 090926A)
  - Hard to produce correlated variability (e.g., spike of GRB 090926A)

Constraints on the jet Lorentz factor (1/3)

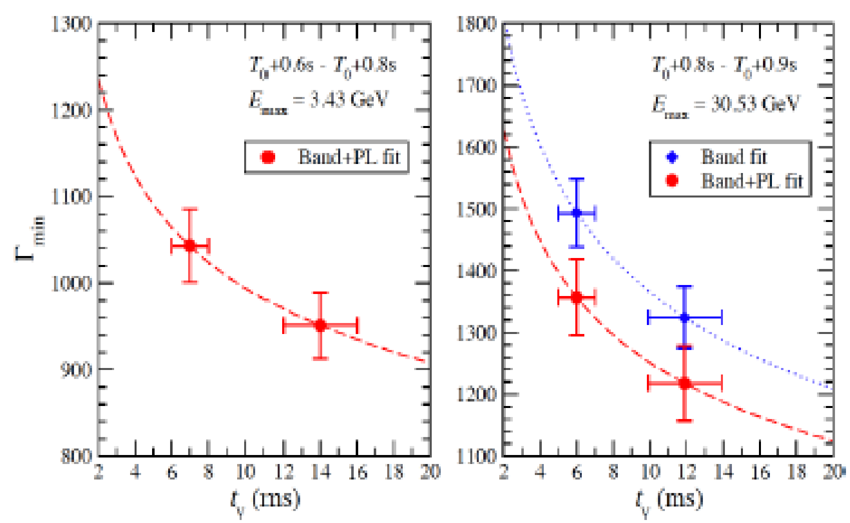
- **>GeV photons + fast variability (t_v) + large luminosities ($L_{iso} \sim 10^{50}$-10^{53} erg/s)**

- **For a source at rest**
  - The size of the emitting region is small enough ($R < ct_V$) for photons of energy $\varepsilon = E_{ph} / m_e c^2 \sim 1$ to annihilate in pairs ($\gamma\gamma \rightarrow e^+e^-$)
  - Opacity $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T n_{ph}(1/\varepsilon)R = \sigma_T L_{1/\varepsilon} /(4\pi m_e c^3 R) > 10^{13} L_{1/\varepsilon,51}(t_V/10\text{ ms})^{-1}$
    $\rightarrow$ a thermal spectrum, not observed $\rightarrow$ **compactness problem**

- **For a source with relativistic motion, $\tau_{\gamma\gamma}$ is reduced by a factor $\Gamma^{2(1-\beta)}$**
  - $-\beta \sim 2$-3 and $\tau_{\gamma\gamma} < 1 \Rightarrow$ **$\Gamma > \Gamma_{min} \sim 100$** (increases with $1/t_V$, E_{max}, z and flux)
  - The attenuation in the spectrum is shifted to an energy E / 1 MeV ~ Γ

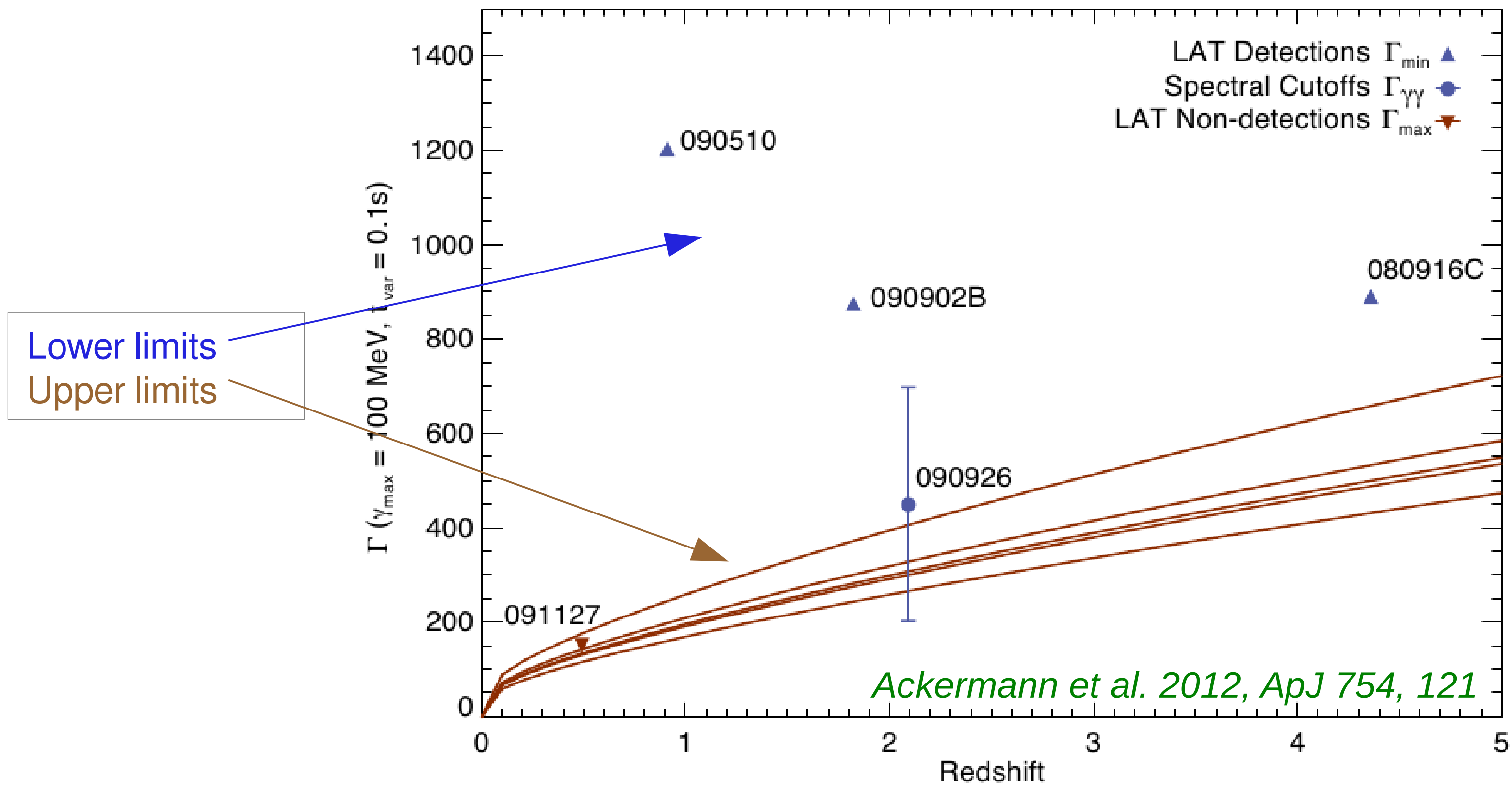
- **The spectrum of the target photons needs to be measured during the short variability time scales of the high-energy emission**

GRB 090510



Constraints on the jet Lorentz factor (2/3)

- Γ_{min}**~1000 for 3 of the 4 brightest LAT bursts** showing an extra PL component with no attenuation
- Γ_{max}**~150-650 for 6 GBM bright bursts not detected by the LAT** (spectral softening at tens of MeV)
  - Assuming 100 ms variability and 1<z<5 (except GRB 091127, with known redshift)



- **Target photon field for γγ absorption assumed uniform, isotropic and time-independent**
  - Granot et al. 2008, Hascoët et al. 2012 give significantly (~3 times) lower Γ values
  - Error bar for GRB 090926A accounts for different models

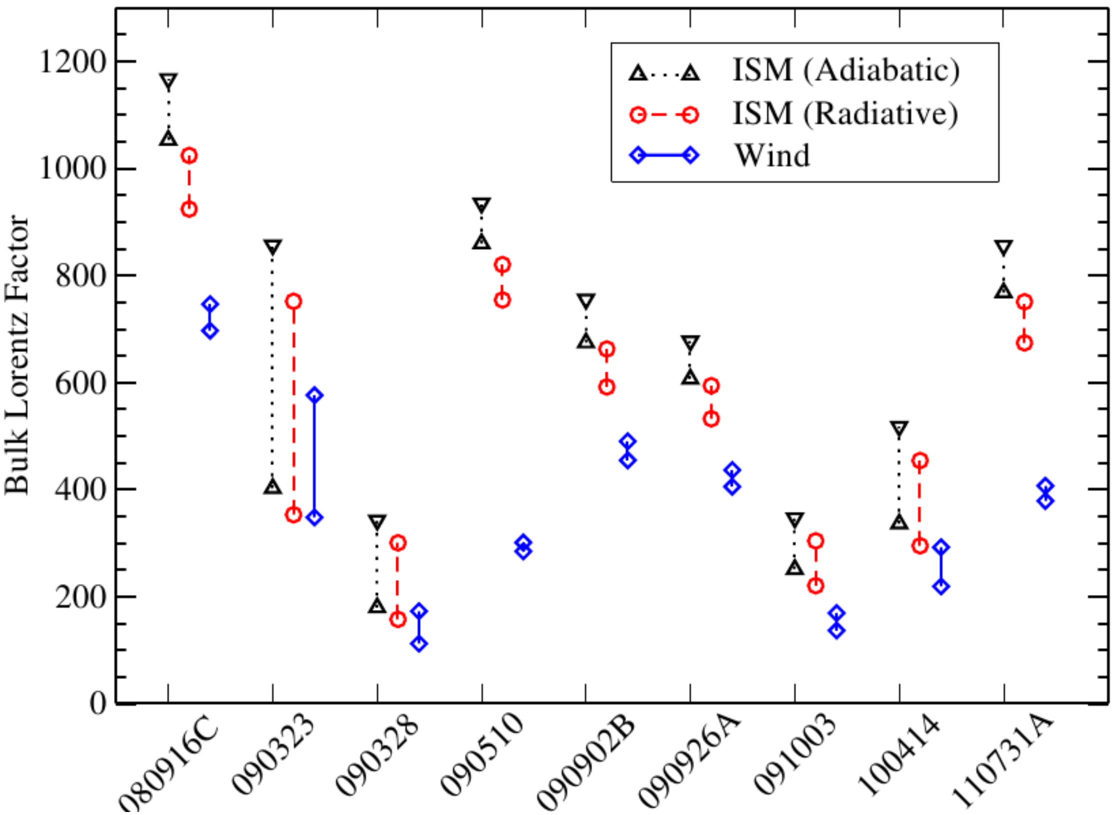
Constraints on the jet Lorentz factor (3/3)

- **Independent constraints from early afterglow models**

- **The jet Lorentz factor can be derived from the fireball energetics and from its deceleration time (taken as the peak flux time in the LAT light curve)**
  - ISM of constant density *(Blandford & McKee 1976, Sari et al. 1998, Ghisellini et al. 2010)*

$$\Gamma_0 = \left[\frac{3E_{k,\mathrm{iso}}(1+z)^3}{32\pi n m_p c^5 t_{\mathrm{peak}}^3}\right]^{1/8} \times \begin{cases} a^{-1/8};\ a=4 & \text{(adiabatic)} \\ a^{-5/32};\ a=7 & \text{(radiative)}, \end{cases}$$

Ackermann et al. 2013, ApJS 209, 11



  - Wind environment *(Chevalier & Li 2000, Panaitescu & Kumar 2000)*

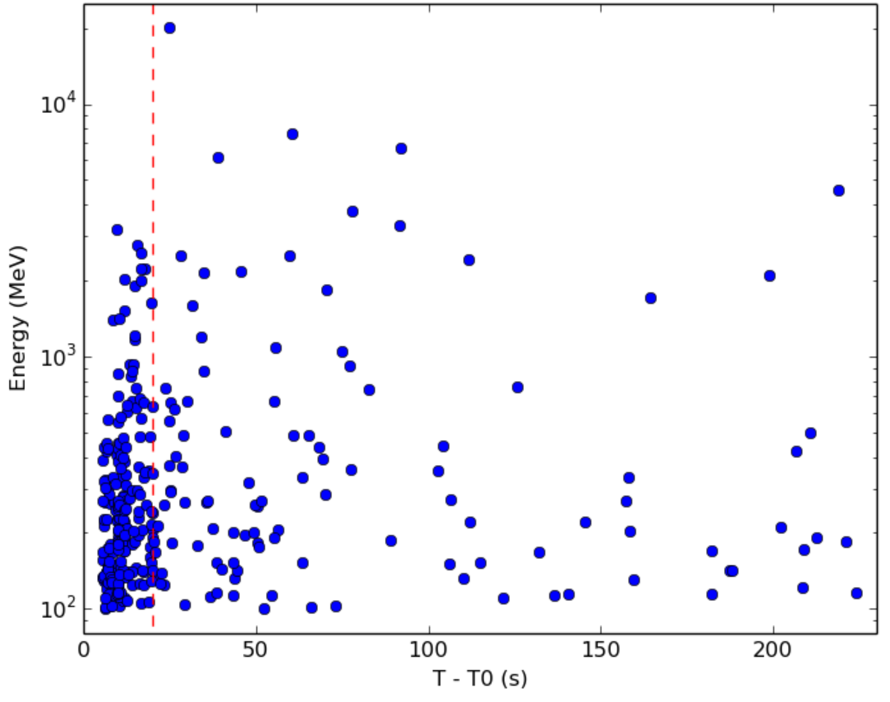
$$\Gamma_0 = \left[\frac{E_{k,\mathrm{iso}}(1+z)}{16\pi A m_p c^3 t_{\mathrm{dec}}}\right]^{1/4}$$

- **Confim that both short and long GRBs have relativistic outflow**

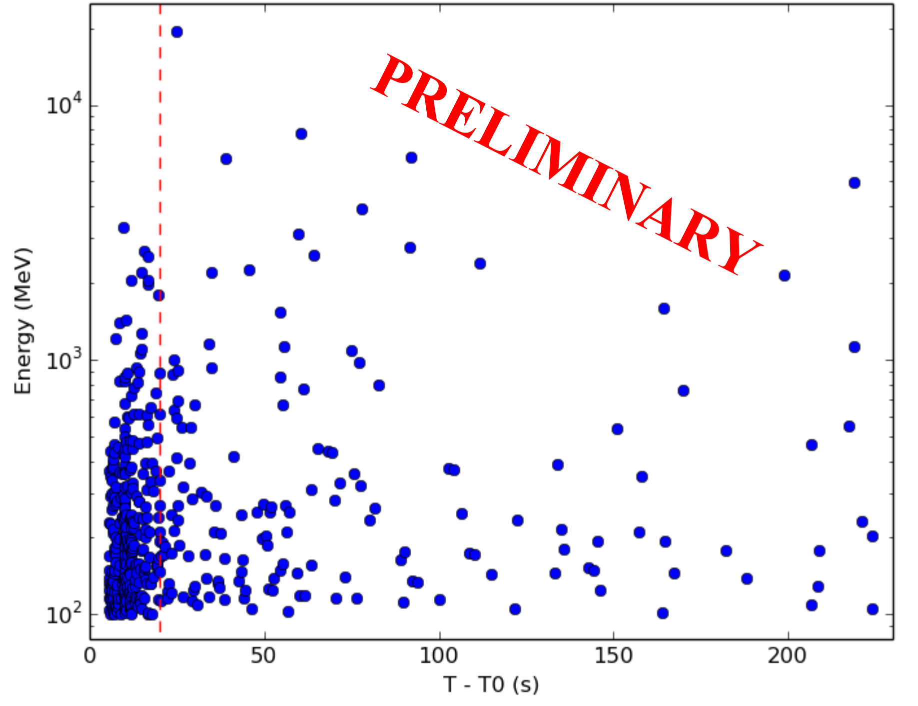
GRB 090926A revisited: event statistics

LAT T90 [5 s-209.8 s]	Pass 7	Pass 8	Pass 8/Pass 7
Number of events	447	1088	2.4
[30 MeV-50 MeV]	33	243	7.4
[50 MeV-100 MeV]	95	381	4.0
[100 MeV-0.5 GeV]	257	391	1.5
[0.5 GeV-1 GeV]	29	40	1.4
[1 GeV-10 GeV]	32	32	1
> 10 GeV	1	1	1

Pass 7

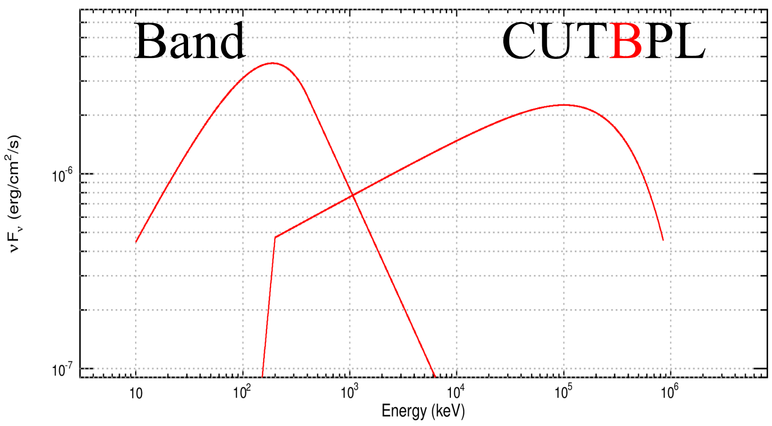


Pass 8



M. Yassine et al., Fermi Symposium (Nov. 2015)

GRB 090926A revisited: best fit model (1/2)

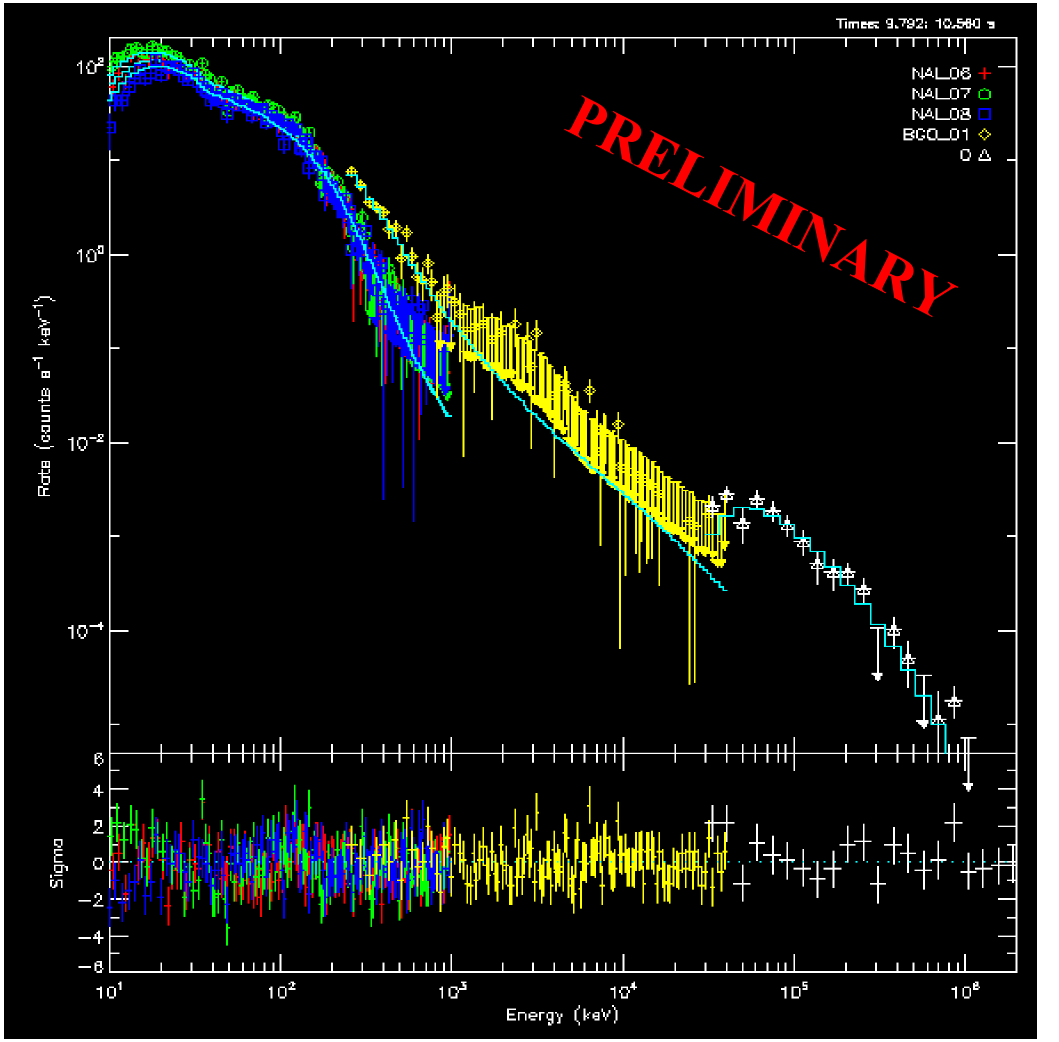


An extra high-energy power law (CUTPL) extending down to ~10 keV is not physically motivated (not expected from an IC component)

Use a power law with a break at low energy (Band + CUTBPL)

Time bin c

Parameters	Band+CUTBPL
Band α β Epeak (keV)	-0.94 – 0.02 + 0.03 -3.20 – 0.89 + 0.24 190 - 9 + 9
CUTBPL Photon index E folding (MeV)	-1.48 - 0.08 + 0.09 335 - 45 + 65
C-stat / DOF	604.7 / 518
ΔC-stat w.r.t Band+CUTPL	15



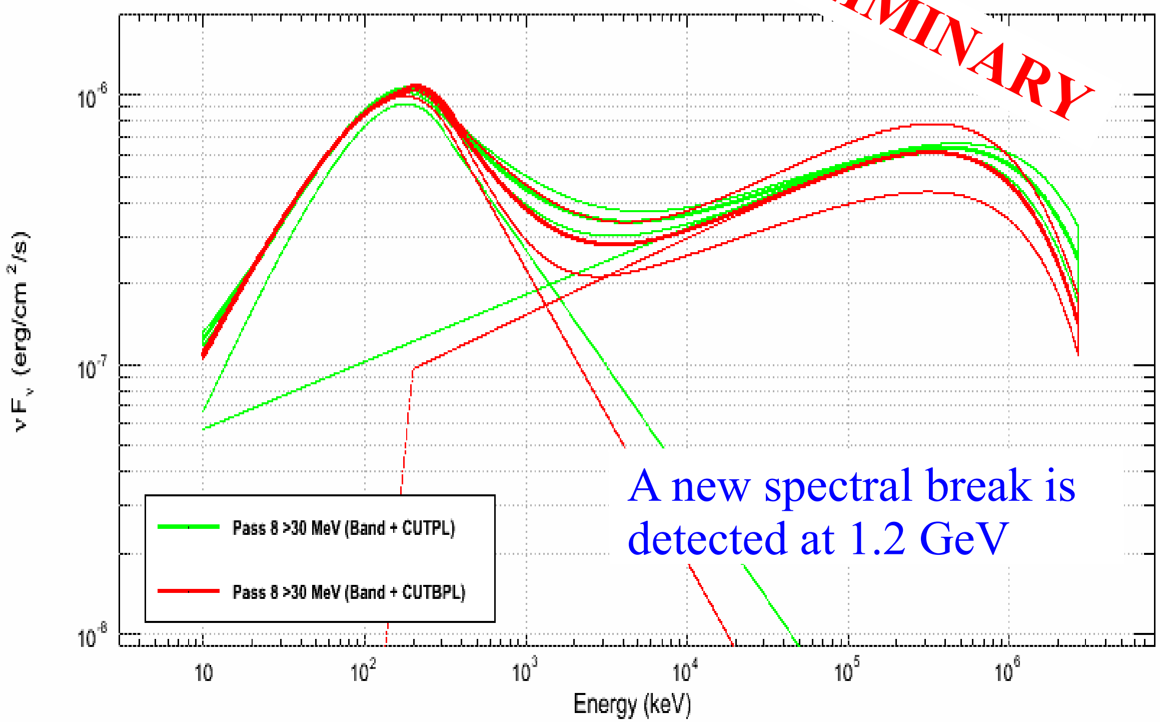
M. Yassine et al., Fermi Symposium (Nov. 2015)

GRB 090926A revisited: best fit model (2/2)

Use a power law with a break at low energy (Band + CUTBPL)

Time bin d

Parameters	Band+CUTBPL
Band α β Epeak (keV)	$-0.86_{-0.03}^{+0.01}$ $-3.1_{-0.5}^{+0.2}$ 177_{-3}^{+7}
CUTBPL Photon index E folding (GeV)	$-1.71_{-0.05}^{+0.05}$ $1.20_{-0.18}^{+0.22}$
C-stat / DOF	652.7 / 518
ΔC-stat w.r.t Band+CUTPL	12



The Band + CUTBPL model fits well the data in the time bins c and d

M. Yassine et al., Fermi Symposium (Nov. 2015)

GRB 090926A revisited: HE break temporal evolution

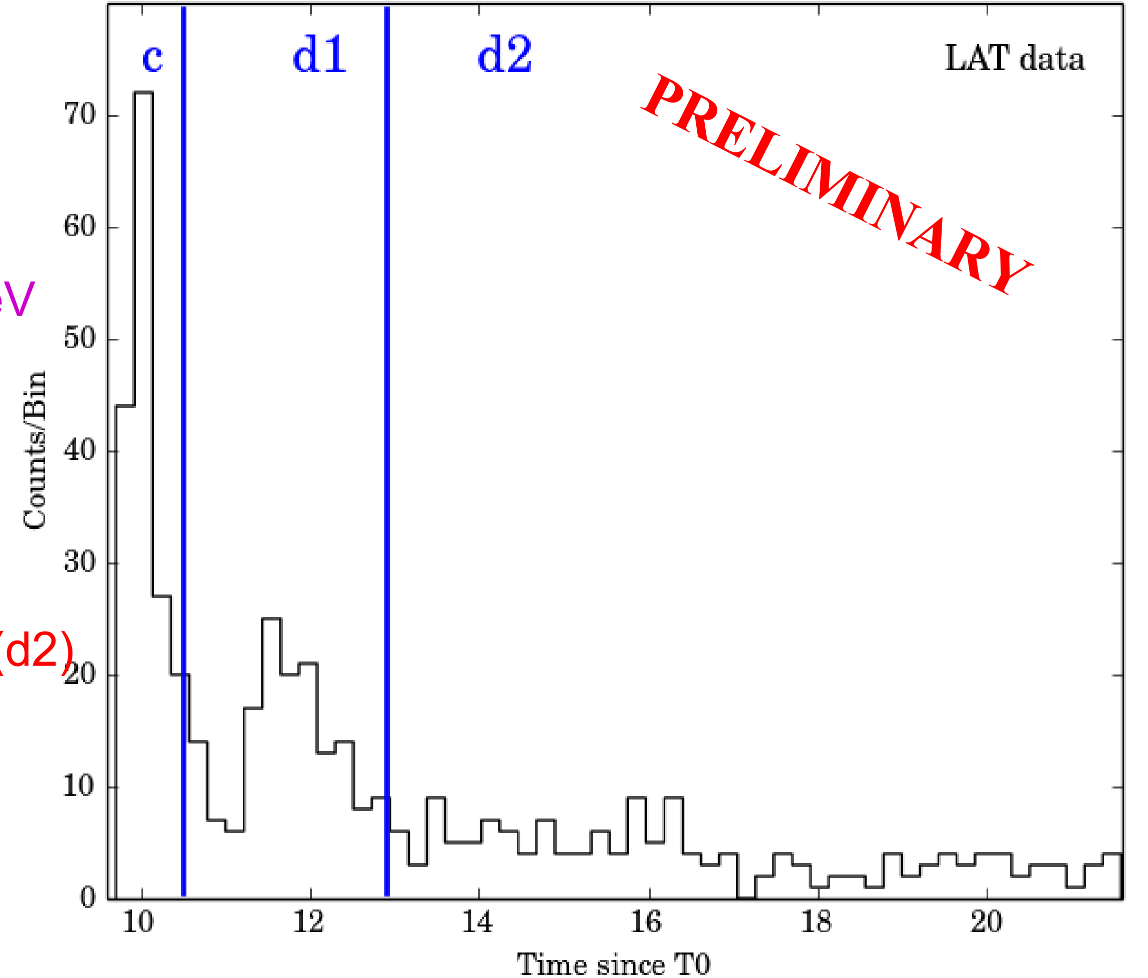
Time bins	c [9.8 s, 10.5 s]	d [10.5 s, 21.6 s]	d1 [10.5 s, 12.9 s]	d2 [12.9 s, 21.6 s]
Efolding (MeV)	335_{-45}^{+65}	$(1.20_{-0.18}^{+0.22})\times10^3$	550_{-100}^{+130}	$(1.44_{-0.25}^{+0.49})\times10^3$
Significance (nb. sigma)	7.6	6.1	4.3	5.1

Significance of the cutoff

Time bin c :
better constrained
Time bin d :
new spectral break is detected at 1.2 GeV

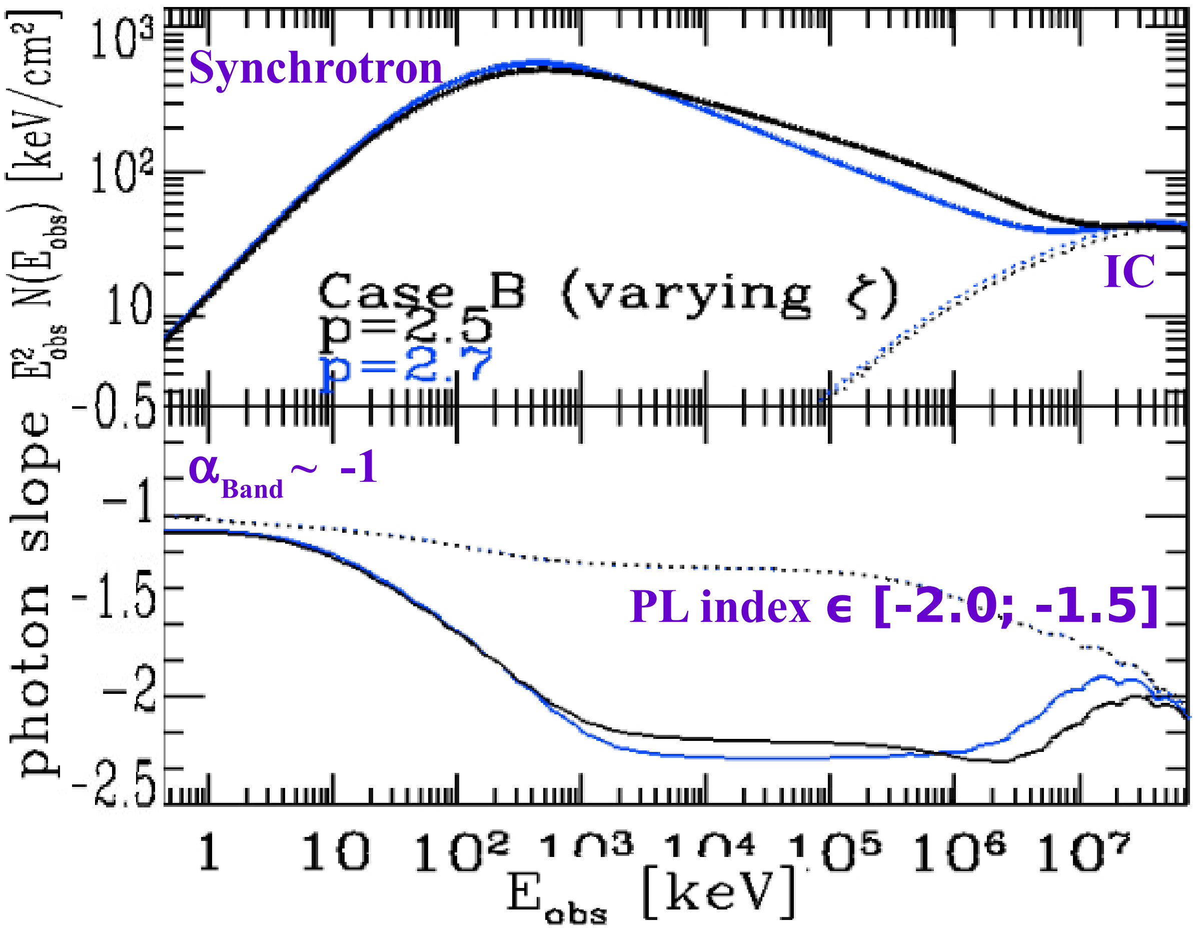
Temporal evolution

Time bin c :
no evolution was found
Time bin d :
Increase from 550 MeV (d1) to 1.4 GeV (d2)



M. Yassine et al., Fermi Symposium (Nov. 2015)

GRB 090926A HE break = IC curvature (interpretation 1)



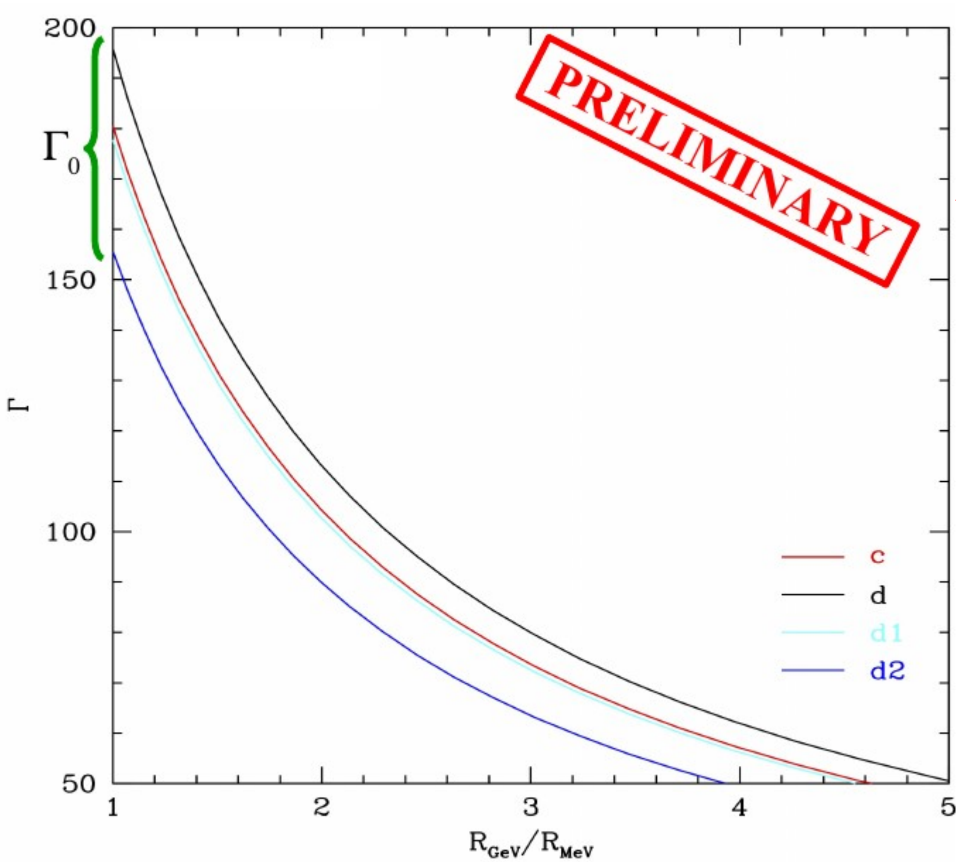
Comparison to the internal shock model
Bosnjak & Daigne 2014, A&A 568, 45

- MeV component (Band): fast cooling synchrotron radiation, modified by IC in KN regime: $\alpha_{Band} \rightarrow -1$
- High-energy component (CUTBPL) :
  - IC with a high-energy shape affected by KN + $\gamma\gamma$ attenuation
  - Extra PL photon index: -2.0 → -1.5

- Example of a single pulse synthetic burst (not adjusted to reproduce GRB 090926A)
- Observed spectral evolution, Ebreak(CUTBPL): KN → Thomson when Epeak(Band)?
- The comparison with the observed slopes is promising
- The detailed shape (peaks, fluence ratio) is not reproduced yet : a better comparison needs a dedicated simulation of GRB 090926A (ongoing work)

M. Yassine et al., Fermi Symposium (Nov. 2015)

GRB 090926A HE break = γγ attenuation (interpretation 2)



- Following
  Hascoet et al. 2012, MNRAS 421, 525

$$\Gamma = \Gamma_0(E_{cutoff}, \Delta t_{var}) \left[\frac{1}{2}\left(1 + \frac{R_{GeV}}{R_{MeV}}\right)\left(\frac{R_{GeV}}{R_{MeV}}\right)\right]^{-1/2}$$

- $150 < \Gamma_0 < 200$ (similar to Ackermann 2011)
- Γ decreases with increasing ratio between the GeV and MeV emission radii
- Similar Γ values in the 4 time bins

Time bins (duration)	c (0.7s)	d (11.1s)	d1 (2.4s)	d2 (8.7s)
Ecutoff (MeV)	335	1.2×10^3	550	1.4×10^3
Δt_{var} (s)	0.15	1	0.5	1

M. Yassine et al., Fermi Symposium (Nov. 2015)

Summary and outlook

- **GRB population studies at high energies are now possible with *Fermi***
  - Short and long GRBs seem to share similar properties
  - Both have relativistic outflows, but the distribution of jet Lorentz factors might be broad
  - GRB >100 MeV emission is delayed & temporally extended w.r.t. the emission in the keV--MeV range

- **Prompt emission phase observed over a wide energy range**
  - Complex spectral shapes are needed to reproduce the spectrum
  - Broad-band physical models are a pre-requisite to understanding GRB high-energy emission
  - Origin of the delayed onset of the LAT >100 MeV emission?
  - Understanding the transition from the prompt emission phase to the early phase is of great importance

- **Long-lived GeV emission is consistent with the canonical afterglow model**
  - But LAT observations of GRB 130427A put severe constraints on the FS synchrotron emission model

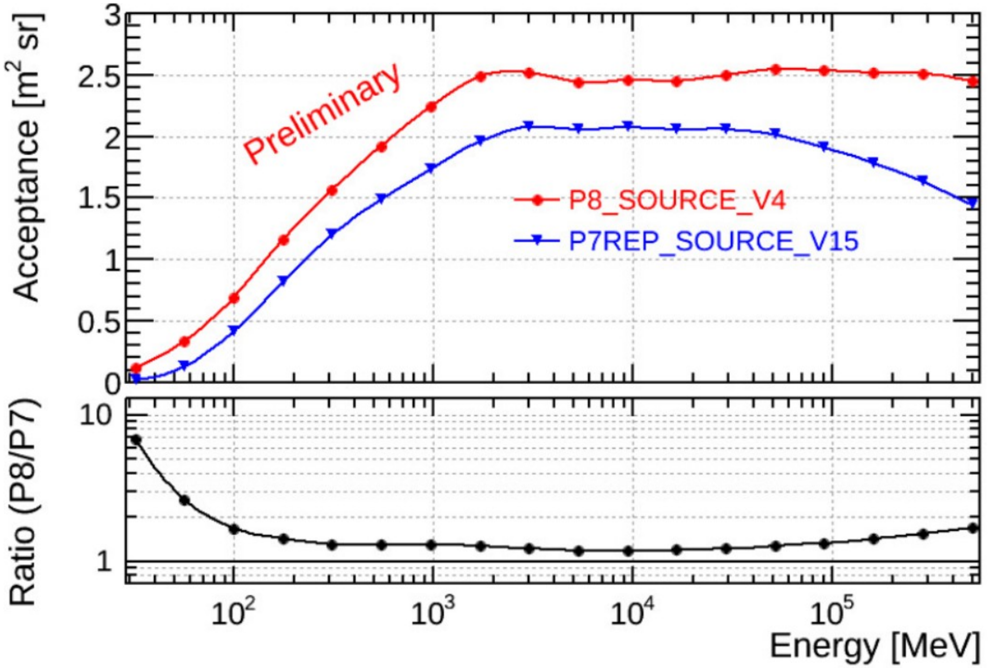
- **Future prospects**
  - SVOM will bring new spectro-temporal diagnosis covering the entire activity of each GRB
  - New constraints on GRB physics at the highest energies are expected from VHE detections in a few but invaluable cases in the coming years

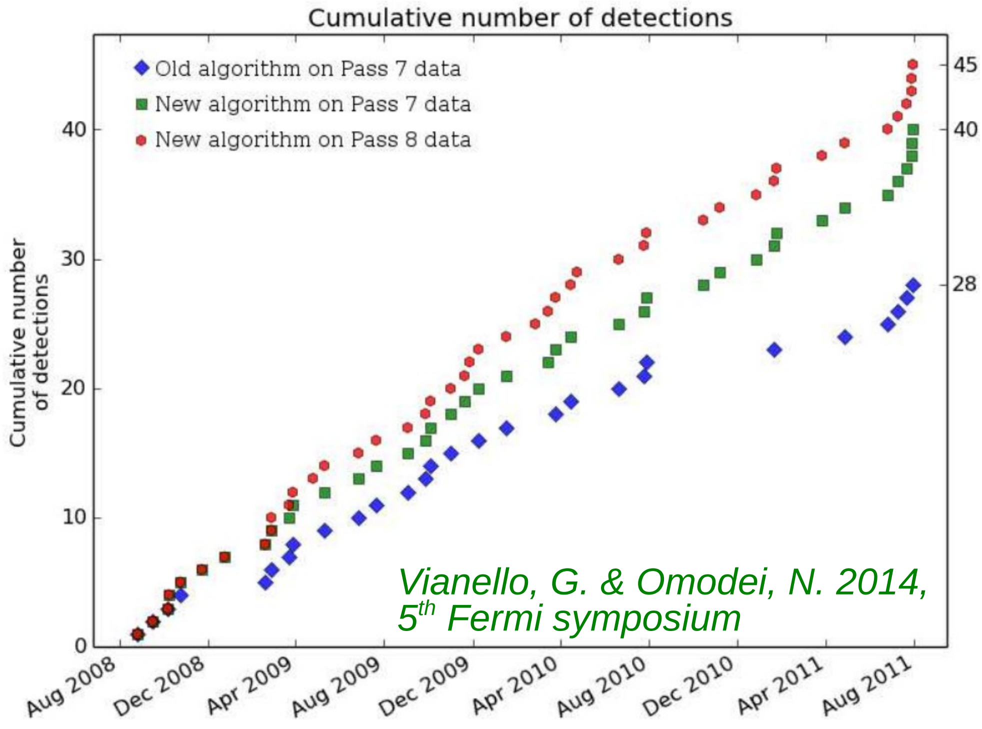
F. Piron, "Gamma-Ray Bursts at high and very high energies", http://arxiv.org/abs/1512.04241

Backup

Improved GRB studies with LAT Pass 8 data

- **Pass 6 data:** release in August 2009
  - Pre-flight
- **Pass 7 data:** release in August 2011
  - Fix for so-called “ghosts”
- **Pass 8 data:** release in 2015
  - Includes virtually every aspect of the data-reduction process
- **More GRB detections**
  - Pass 8: larger effective area, better PSF, lower energy threshold for spectral analysis
  - New GRB detection algorithm

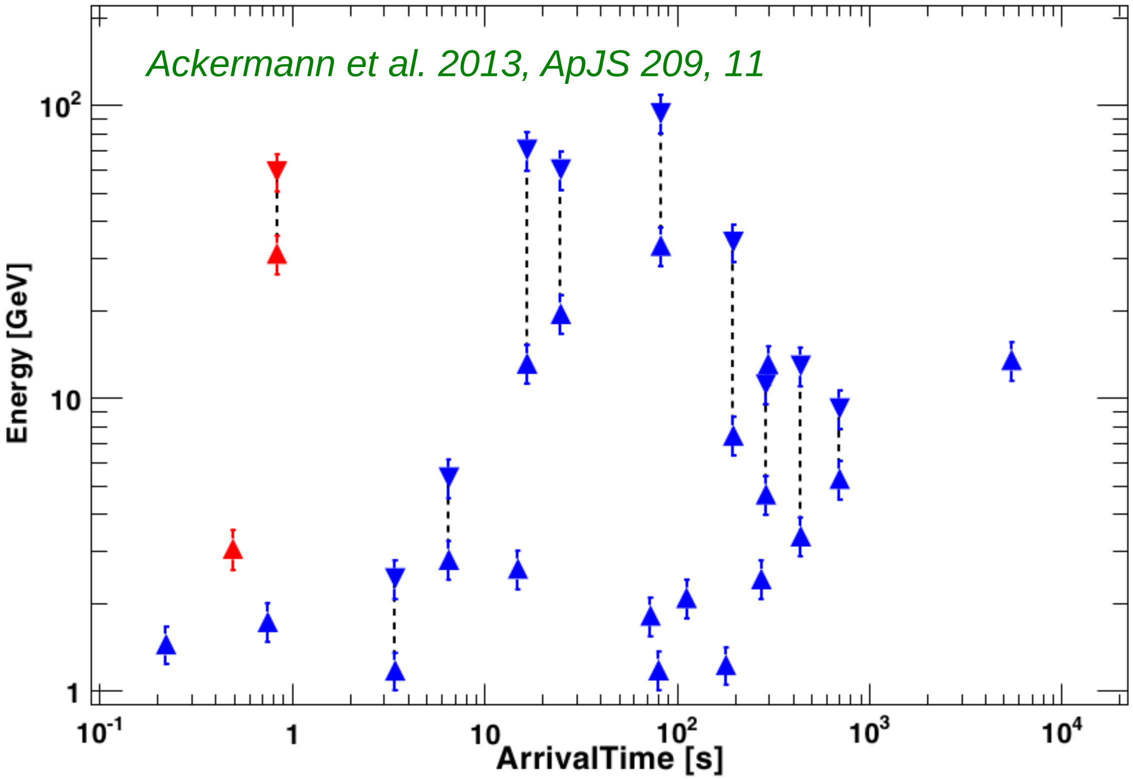




Vianello, G. & Omodei, N. 2014, 5th Fermi symposium

LAT highest-energy detected photons

- **First LAT GRB catalog**



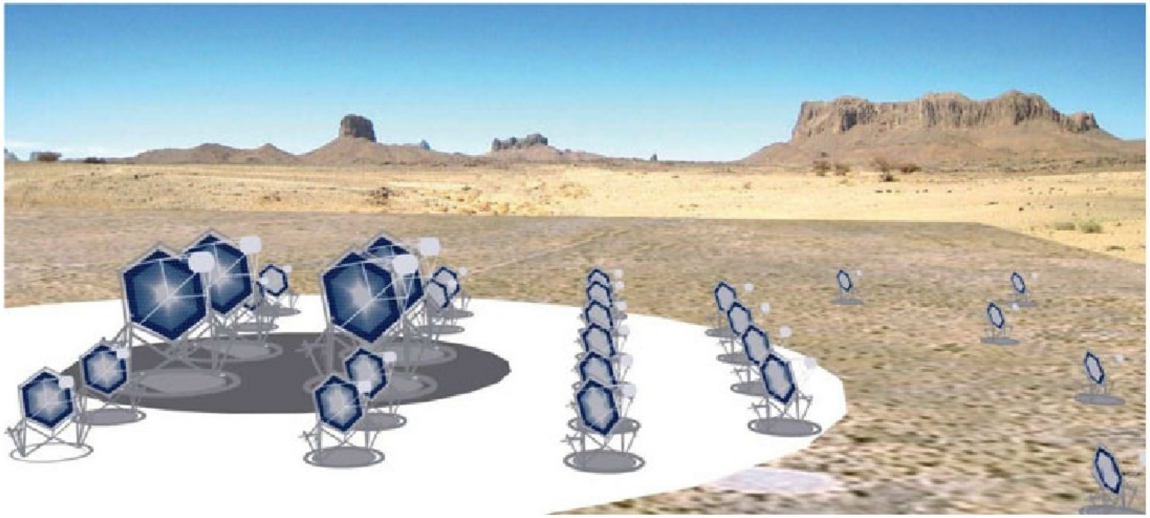
- **GRB 130427A**

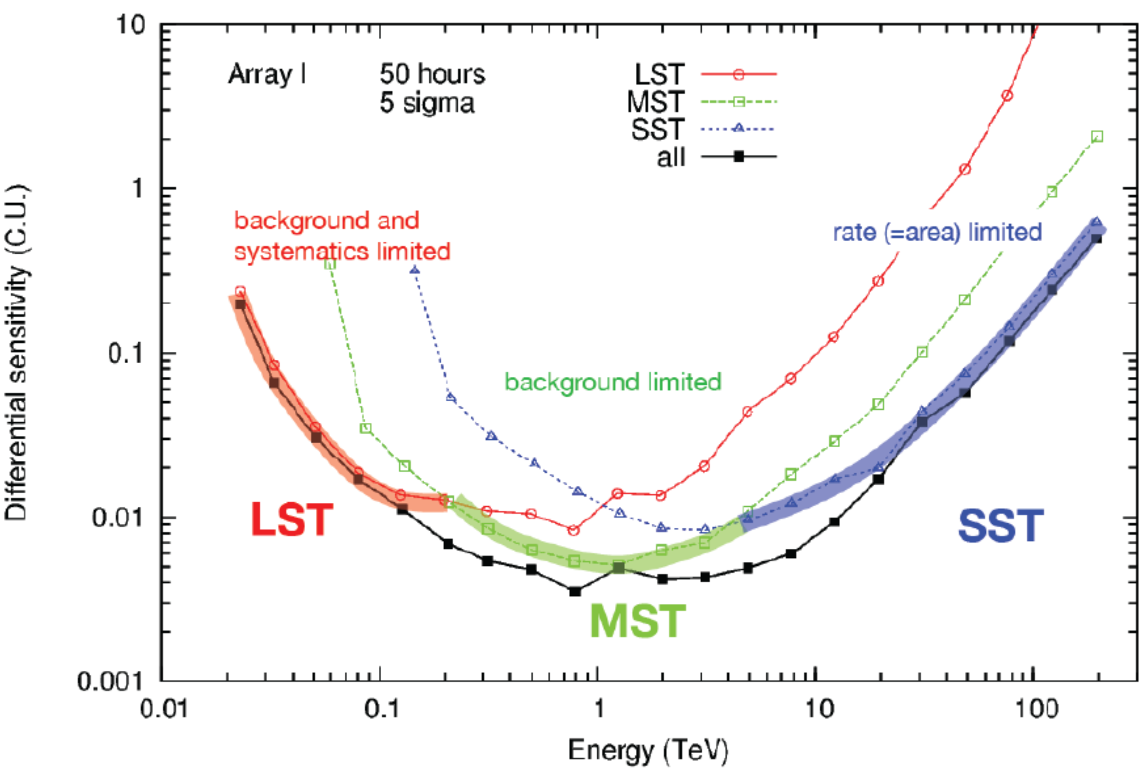
E	E_{rf}	$T - T_0$
95	128	243.55
73	97	19.06
47	63	256.70
41	55	611.01
39	52	3410.26
32	43	34366.58
28	37	48.01
26	35	85.16
21	21	141.53
15	20	217.89

Ackermann et al. 2014, Science 343, 42

- **GRB 090902B: 33.4 GeV photon at T_0+81.8 s**
- **GRB 080916C: 27.5 GeV photon at T_0+40.5 s** (~150 GeV rest frame, z=4.35) in Pass 8 data

The Cherenkov Telescope Array

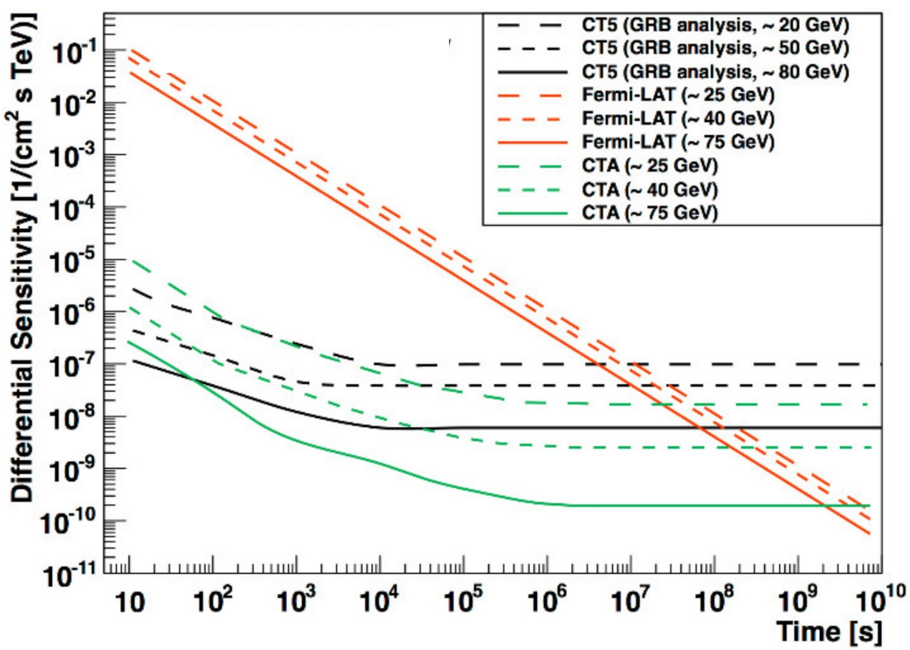


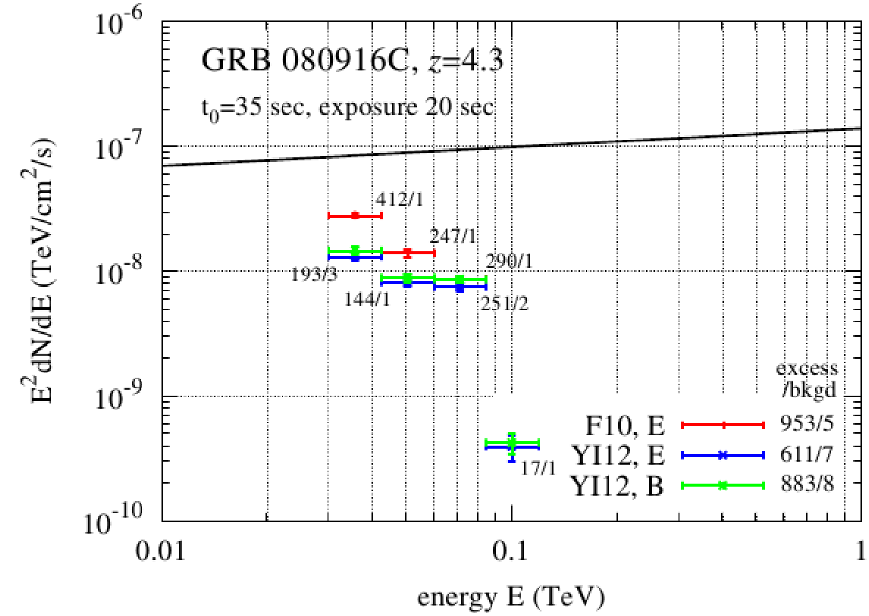


- **Two arrays (North & South) of Imaging Atmospheric Cherenkov Telescopes (IACTs)**
  - Limited fields of view (few deg) → pointing instruments
  - Low duty cycle (~10%)
- **Large Size Telescopes (LSTs)**
  - A few 23-m diameter telescopes
  - ~20 GeV to 1 TeV
- **Medium Size Telescopes (MSTs)**
  - Core array: ~40 12-m telescopes
  - ~1 km^2 array, 100 GeV to 10 TeV
  - Sensitivity of ~1 mCrab at 1 TeV
- **Small Size Telescopes (SSTs)**
  - ~40 6-m telescopes on a ~10 km^2 area
  - Energies > 10 TeV

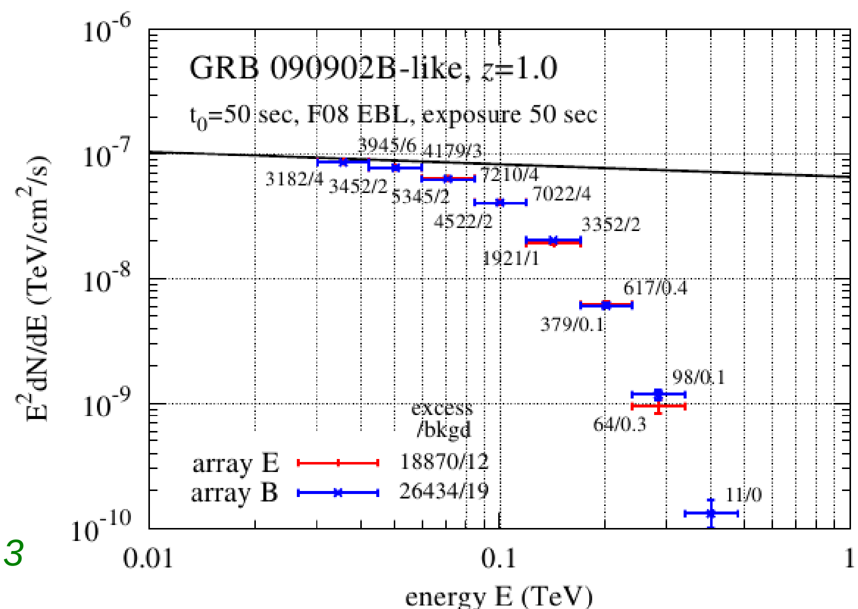
GRB observations with CTA

Adapted from Funk & Hinton 2013, APh 43, 348





- Intrinsic spectrum extrapolated from *Fermi*/LAT
- Spectrum determination between 50 GeV and 100 GeV (if no spectral break <100 GeV)

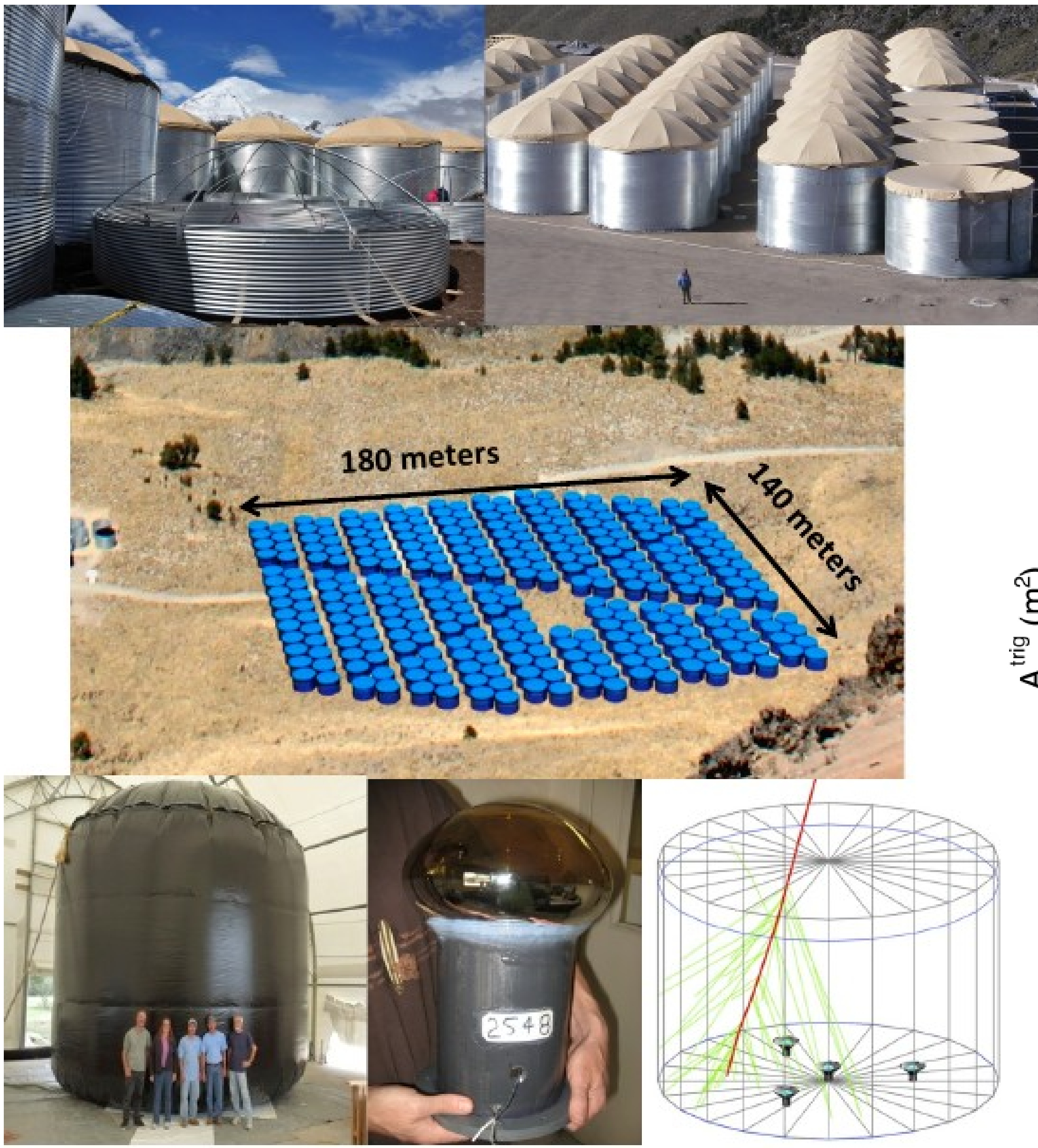


- **The *Fermi*/LAT signal is limited above 10 GeV**
- **GRB observations at very high energies need**
  - **Low-energy threshold** to fight the EBL → strongly depends on the LST performance (few 10's GeV threshold)
  - **Fast repointing**: 180° in 20 s (LSTs)
    - Scanning mode possible
- **CTA GRB rate: estimates range from 1 GRB every 20-30 months to 1-2 GRBs/yr**

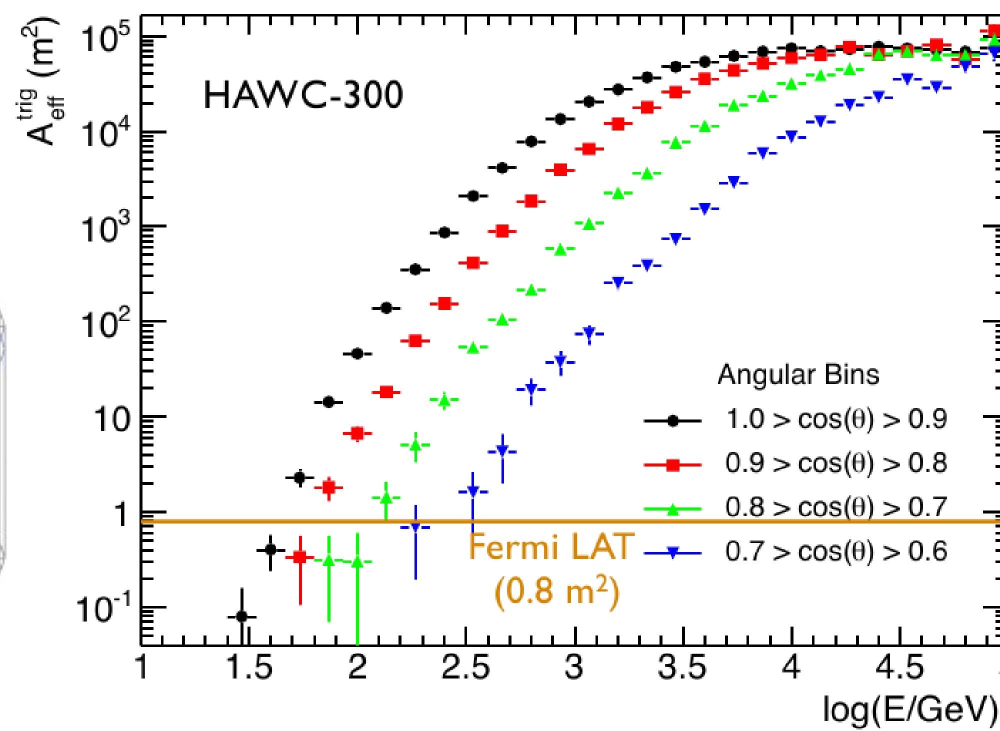
Inoue et al. 2013, APh 43, 252
Gilmore et al. 2013, Exp Astron 35, 413

The HAWC experiment

Abeysekara et al. 2012, APh 35, 641

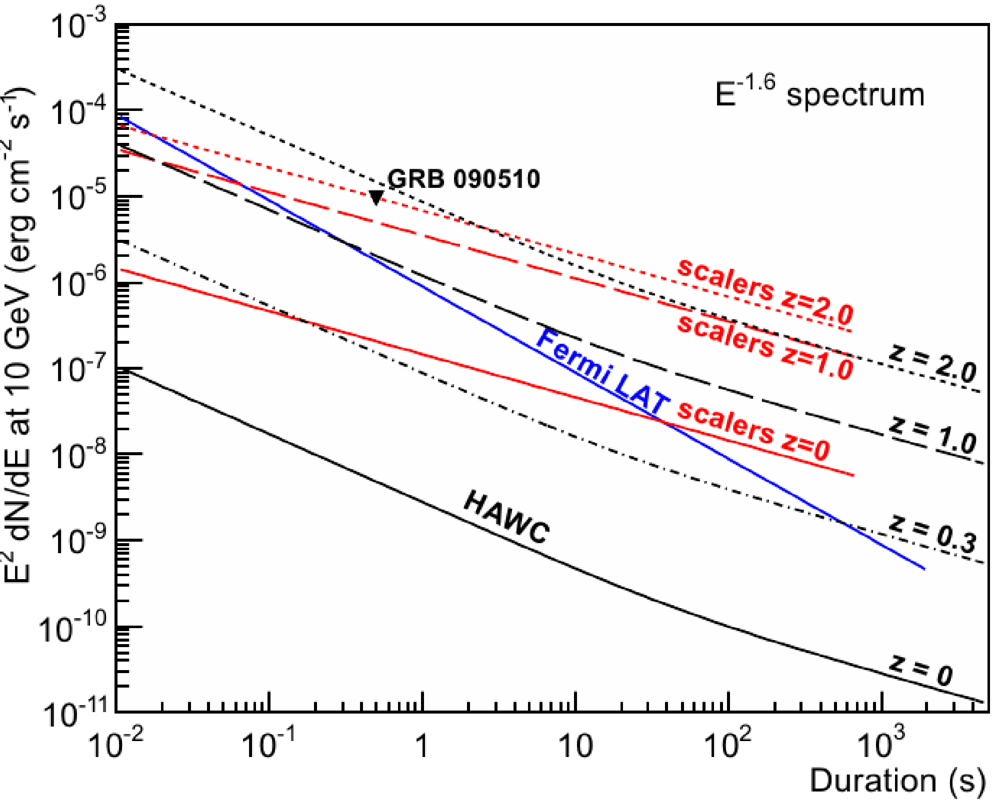


- **High-Altitude Water Cerenkov detector**
  - 4100 m a.s.l., 249 km East of Mexico city
  - Synoptic detector (~1 sr FoV)
  - High duty cycle (~100%)
  - Higher energy threshold and lower sensitivity than IACTs
- **300 water tanks, 4 PMTs each**
  - 7.3 m diameter x 4.5 m deep
  - Covering 22 500 m² area
- **Depth and spacing of PMTs optimized for γ-ray sensitivity from 100 GeV to 100 TeV**

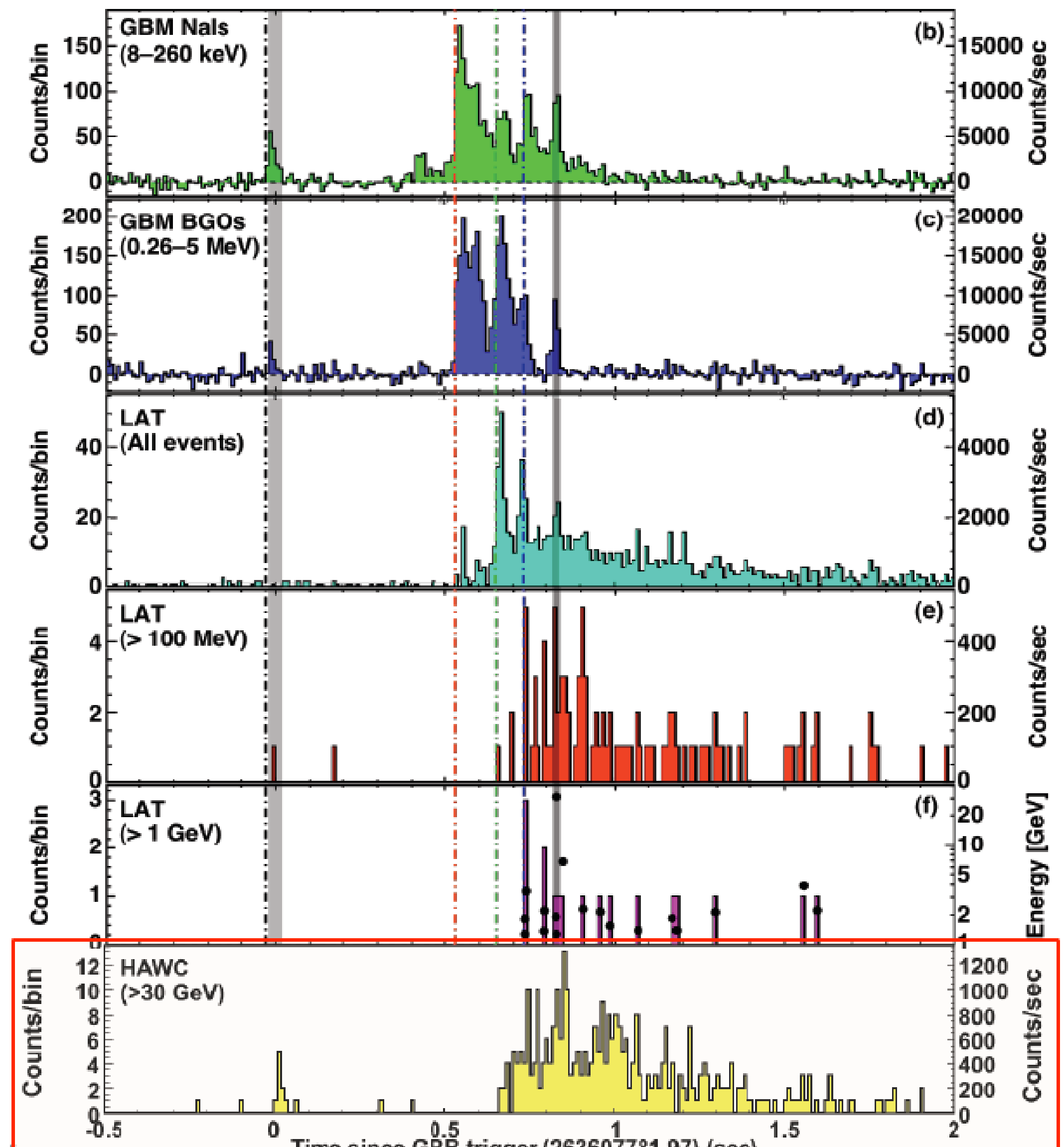


GRB observations with HAWC

- **Main DAQ**
  - Trigger rate ~8 kHz
  - Gives direction, species, and energy of primary particle
- **Scalers**
  - Measure PMT counting rates
  - Energy threshold of a few GeV



GRB 090510

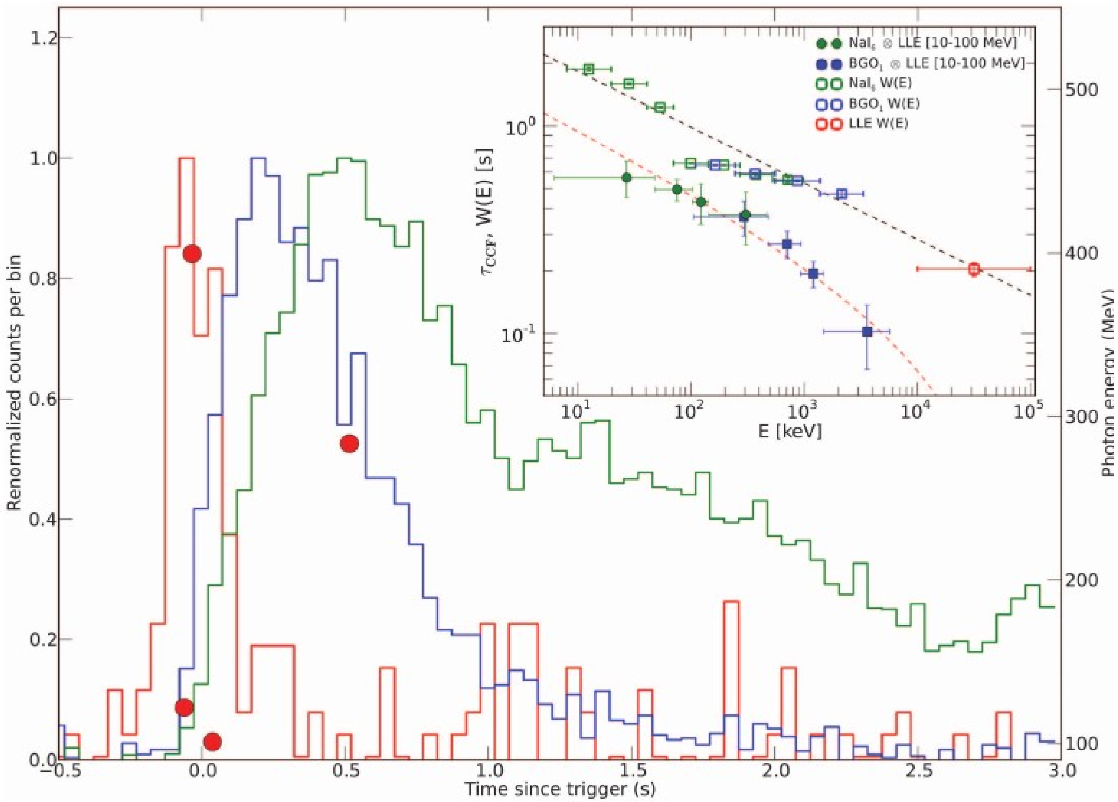


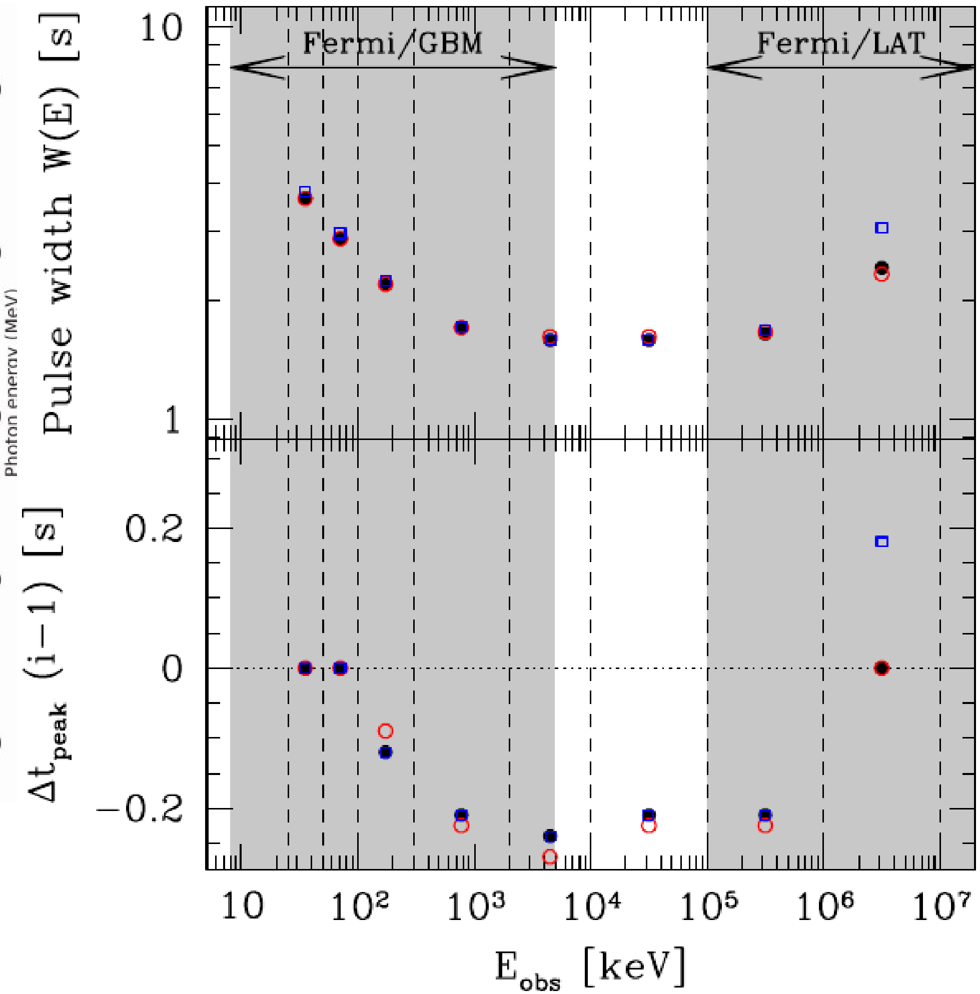
- Main DAQ and scalers, 20° zenith angle
- Various z, EBL absorption included

Time lags

Preece et al. 2014, Science 343, 51

Bosnjak Z. & Daigne 2014, astro-ph/1404.4577





- **The first 3 seconds of GRB 130427A, a test lab for synchrotron shocks**
  - Spectral lag and pulse width in good agreement
  - Epeak evolves as t^{-1} as expected