High-Energy Emission from GRBs: First Year Highlights from the Fermi Gamma-ray Space Telescope

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on behalf of the Fermi LAT & GMB Collaborations

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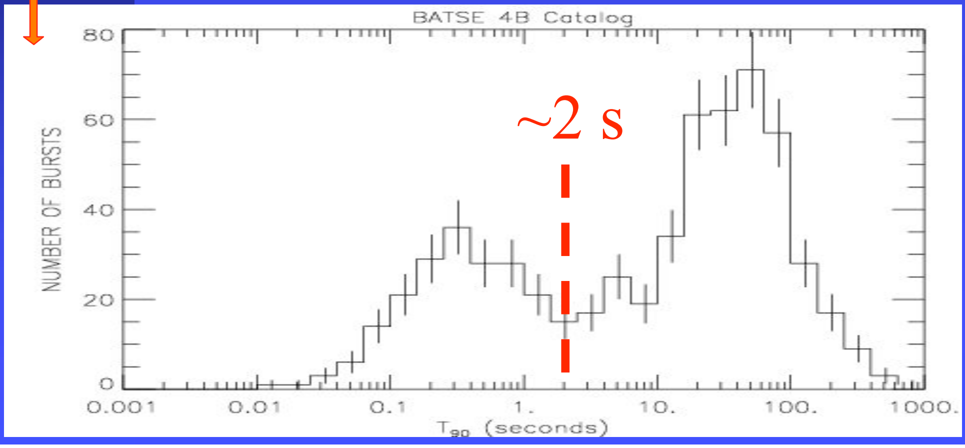
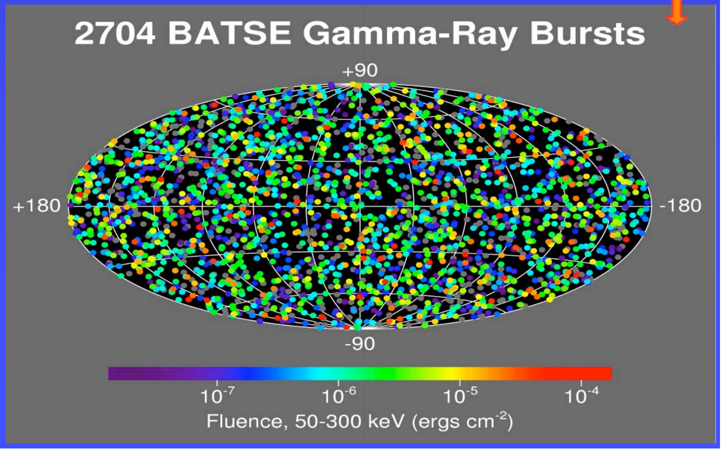
Outline of the Talk:

- New Space missions help drive progress in GRBs
- High-energy emission processes & pre-Fermi obs.
- **Fermi: highlights from 1st year results**
  - **GRB081024B**: 1st clearly short GRB above 1 GeV
  - **GRB080916C**: very bright, long & redshift - interesting
  - **GRB090510**: bright, short & redshift – truly amazing
    - Delayed onset & longer duration at high energies
    - Lower limits on the Bulk Lorentz factor
    - Distinct high-energy spectral component
    - Limits on Lorentz invariance violation
- **Conclusions**

GRBs: Brief Historical Overview

- 1967: 1st detection of a GRB (published in 1973)
- In the early years there were many theories, most of which invoked a Galactic (neutron star) origin
- 1991: the launch of CGRO with BATSE lead to significant progress in our understanding of GRBs
  - **BATSE**: ~ 30 keV – 2 MeV, full sky (~½ Earth occ.)
  - **Isotropic dist. on sky**: favors a cosmological origin
  - **Bimodal duration** distribution: **short** vs. **long** GRBs
  - **EGRET**: ~ 30 MeV – 30 GeV, FoV ~ 0.6 sr

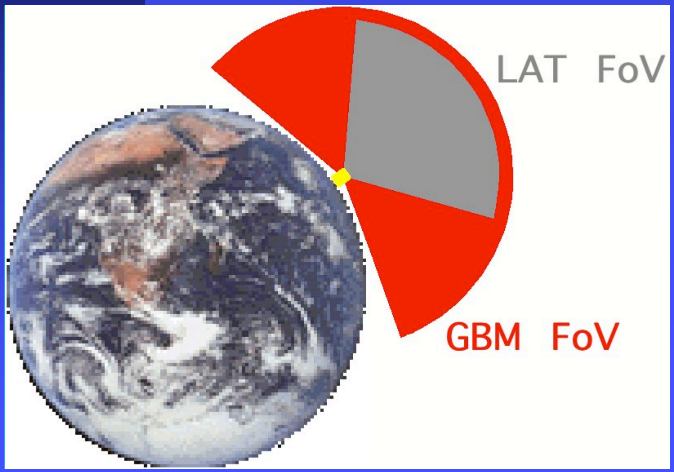


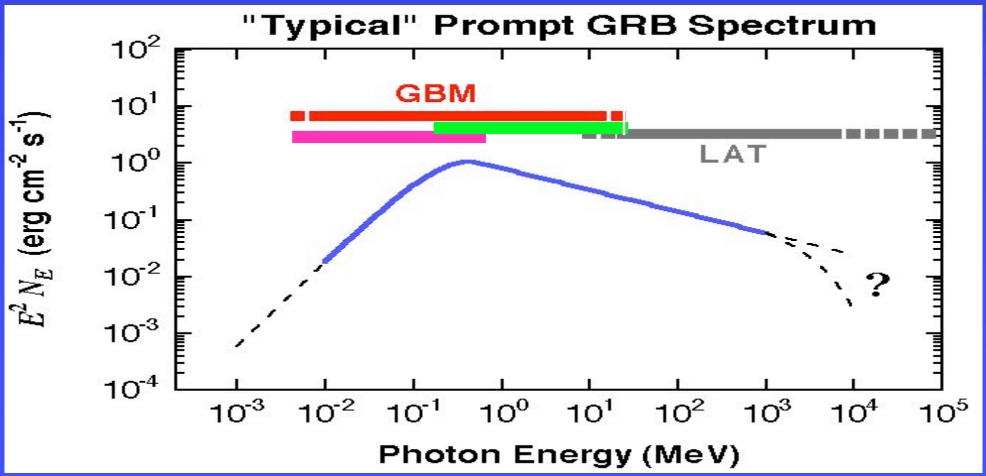


- **BeppoSAX** (1996-2002): lead to **discovery** of **afterglow** (1997) in X-rays, optical, radio (for long GRBs)
  - This led to **redshift** measurements: clear cut determination of the **distance/energy** (long GRBs) $E_{\gamma,iso} \sim 10^{52}$ -10^{54} erg
  - Afterglow observations provided information on beaming (narrow jets: $E_{\gamma} \sim 10^{51}$ erg), event rate, external density, supernova connection (⇒ long GRB progenitors)
- **Swift** (2004-?): autonomously localizes GRBs slews in ~1-2 min) and observed in X-ray + optical/UV
  - Discovered unexpected behavior of early afterglow
  - Led to the discovery of **afterglow** from **short** GRBs ➔ host galaxies, redshifts, energy, rate, clues for progenitors
- **Fermi** (2008-?): may also lead to significant progress in

Fermi Gamma-ray Space Telescope (Fermi Era; launched on June 11, 2008):

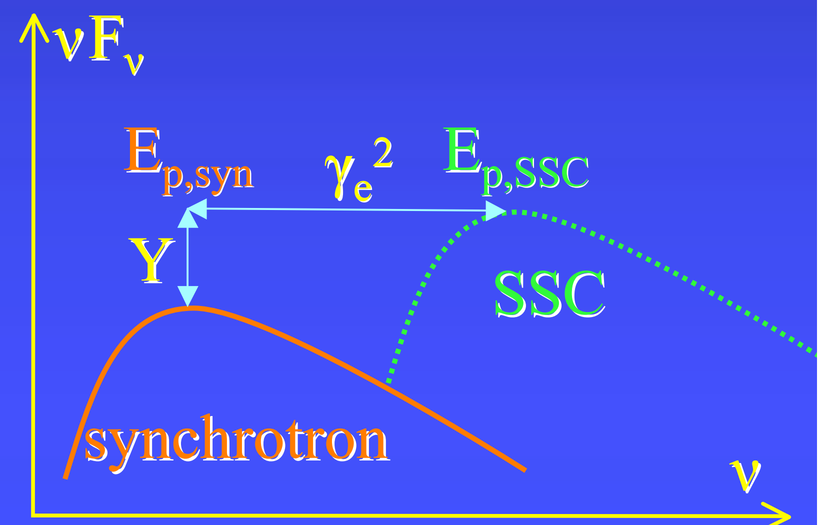
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15-40 MeV), full sky
- Slightly less sensitive than BATSE: expected to detect ~ 200 GRB/yr (≳ 60 in the LAT FoV)
- Large Area Telescope (LAT): 20 MeV – 300 GeV FoV ~ 2.4 sr ; up to 40 times the EGRET sensitivity



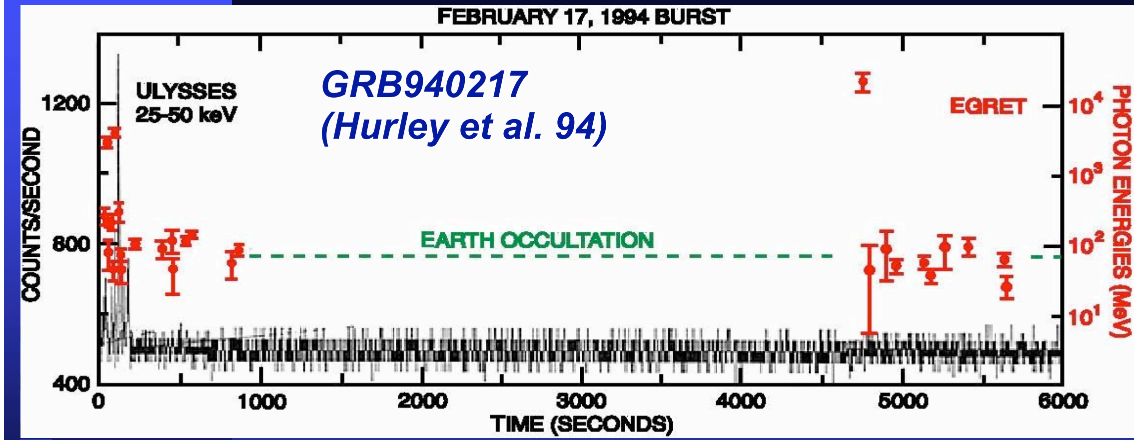


GRB: High Energy Emission Processes

- **Leptonic**: Inverse-Compton or Synchrotron-Self Compton: $E_{p,SSC}/E_{p,syn} \sim \gamma_e^2$, $L_{SSC}/L_{syn} = Y$, $Y(1+Y) \sim \varepsilon_{rad}\varepsilon_e/\varepsilon_B$
- **Hadronic** processes: photopair production ($p+\gamma \rightarrow p+e^+e^-$), proton synchrotron, pion production via $p-\gamma$ (photopion) interaction or p-p collisions
- The neutral pions decay into high energy photons $\pi^0 \rightarrow \gamma\gamma$ that can pair produce with lower energy photons $\gamma\gamma \rightarrow e^+e^-$, producing a pair cascade
- **Fermi** may help determine the identity of the dominant **emission mechanism** at high & low energies
- Most of the radiated energy can be in the LAT range (**energetics**)

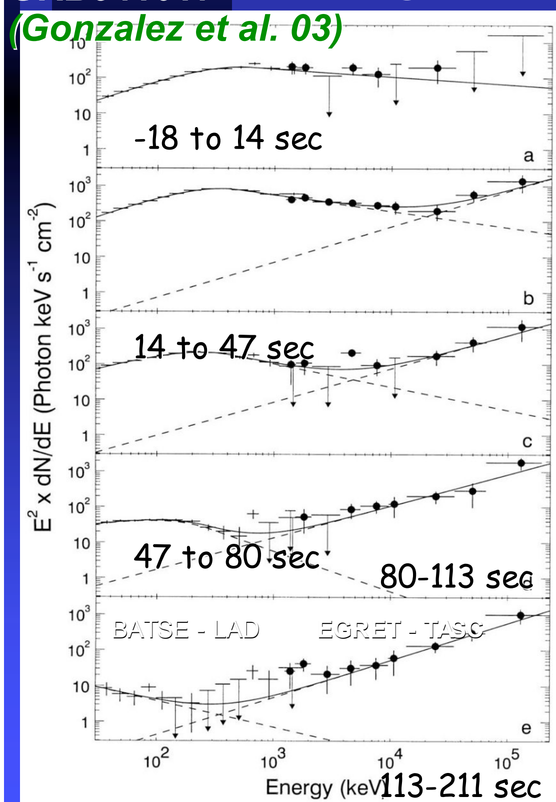


High energy emission from GRBs: Pre-Fermi era

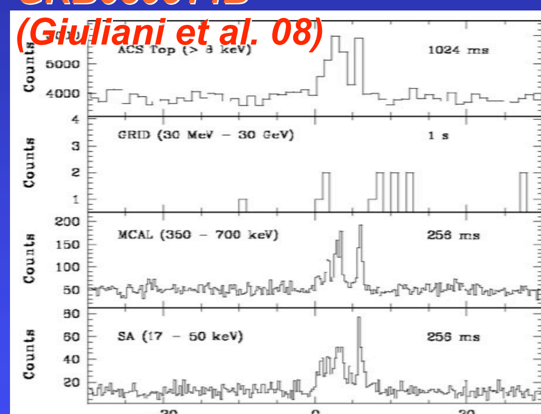


EGRET

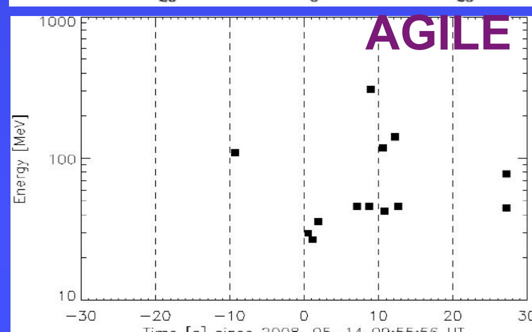
GRB941017
(Gonzalez et al. 03)



GRB080514B
(Giuliani et al. 08)



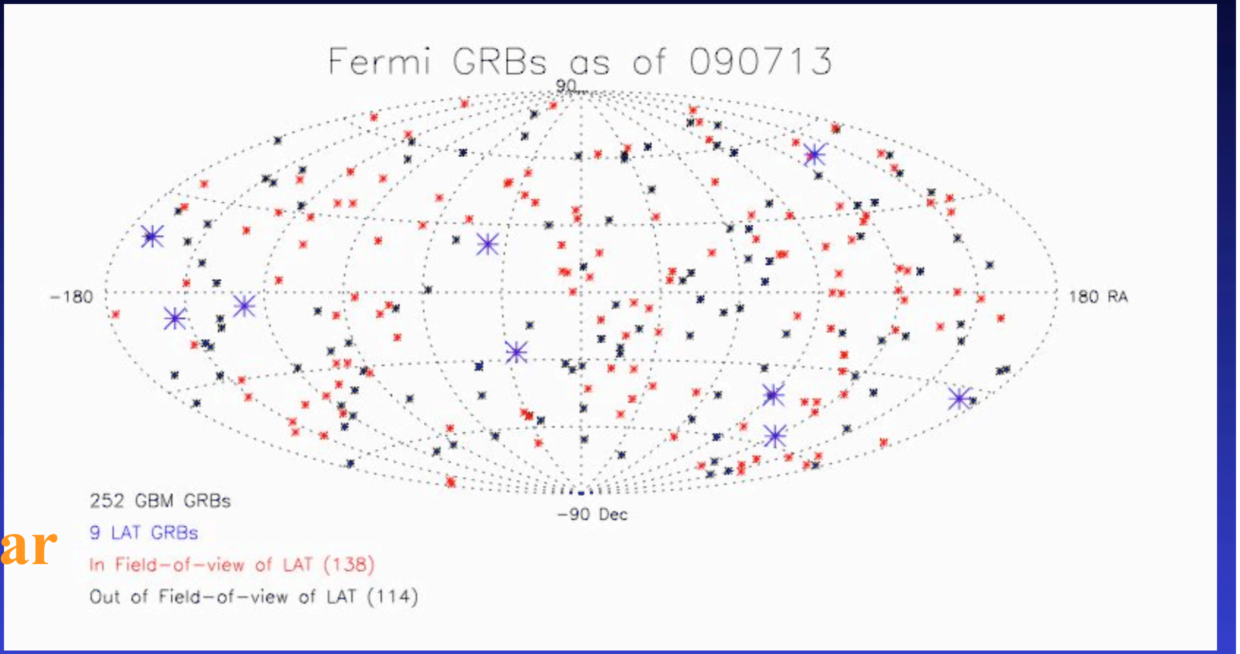
AGILE

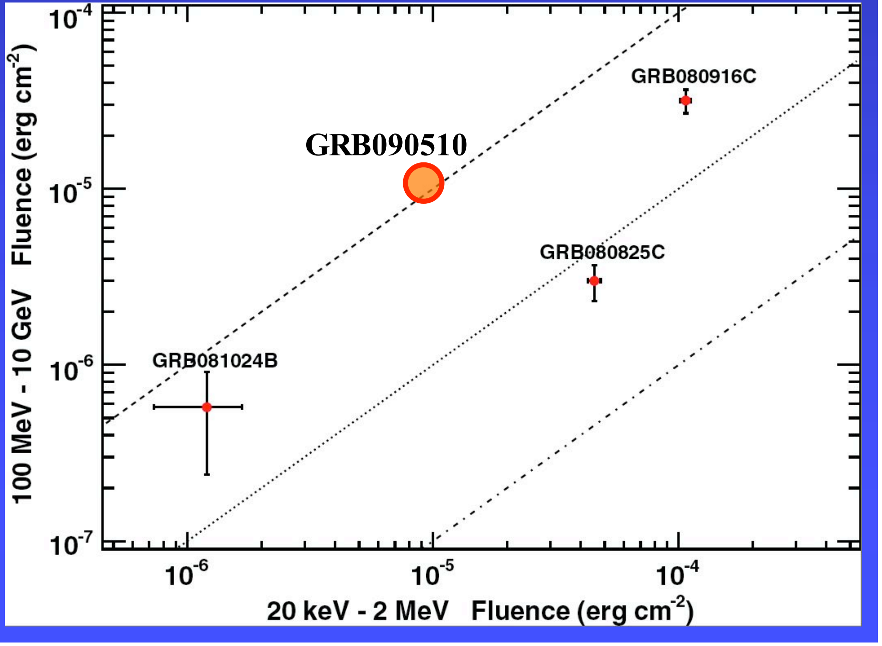


- Little known about GRB emission above ~100 MeV
- EGRET detected only a few GRBs, most notably:
  - GRB940217: GeV photons were detected up to 90 minutes after the GRB trigger
  - GRB941017: distinct high-energy spectral component (up to 200 MeV), with a different temporal evolution & at least 3 times more energy
- AGILE recently observed GRB080514B and detected photons up to a few 100 MeV lasting somewhat longer than the soft gamma-rays

Fermi GRB detections:

- GBM:
  - ~ 230 GRB/yr (~ 18% are short)
  - ≳ ½ in LAT FoV
  - Automated repoint
- LAT: 9 GRBs in 1st year
  - GRB080825C: relatively dim, long (1st LAT GRB)
  - GRB080916C: bright, long GRB (Abdo et al. 2009, Science, 323, 1688)
  - GRB081024B: first short GRB with >1 GeV emission
  - GRB090510: bright, short GRB (submitted to Nature; arXiv:0908.1832)



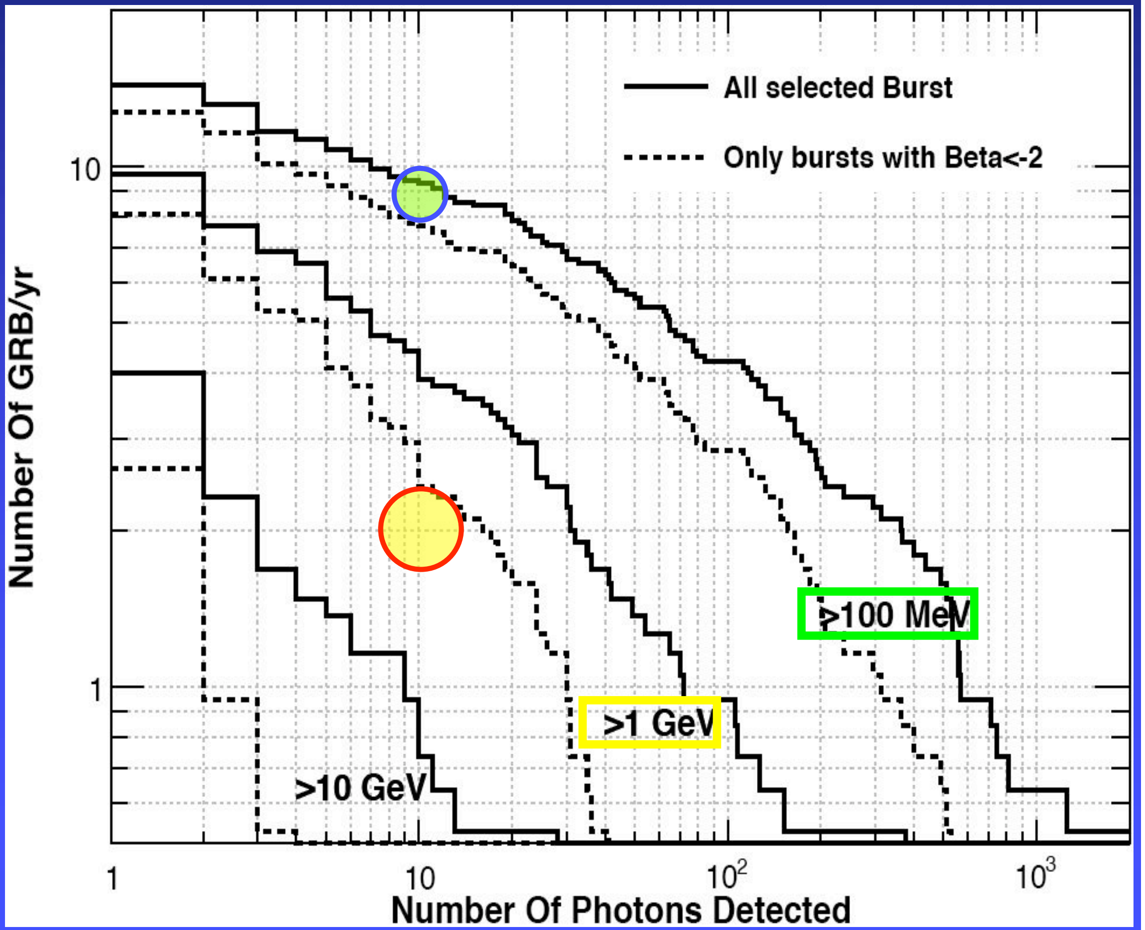


Fermi LAT GRB detection rate

- ~ 9 GRB/yr with >10 photons above 100 MeV
- ~ 2 GRB/yr with >10 photons above above 1 GeV
- Somewhat below estimates based on a Band spectrum for a bright GRB

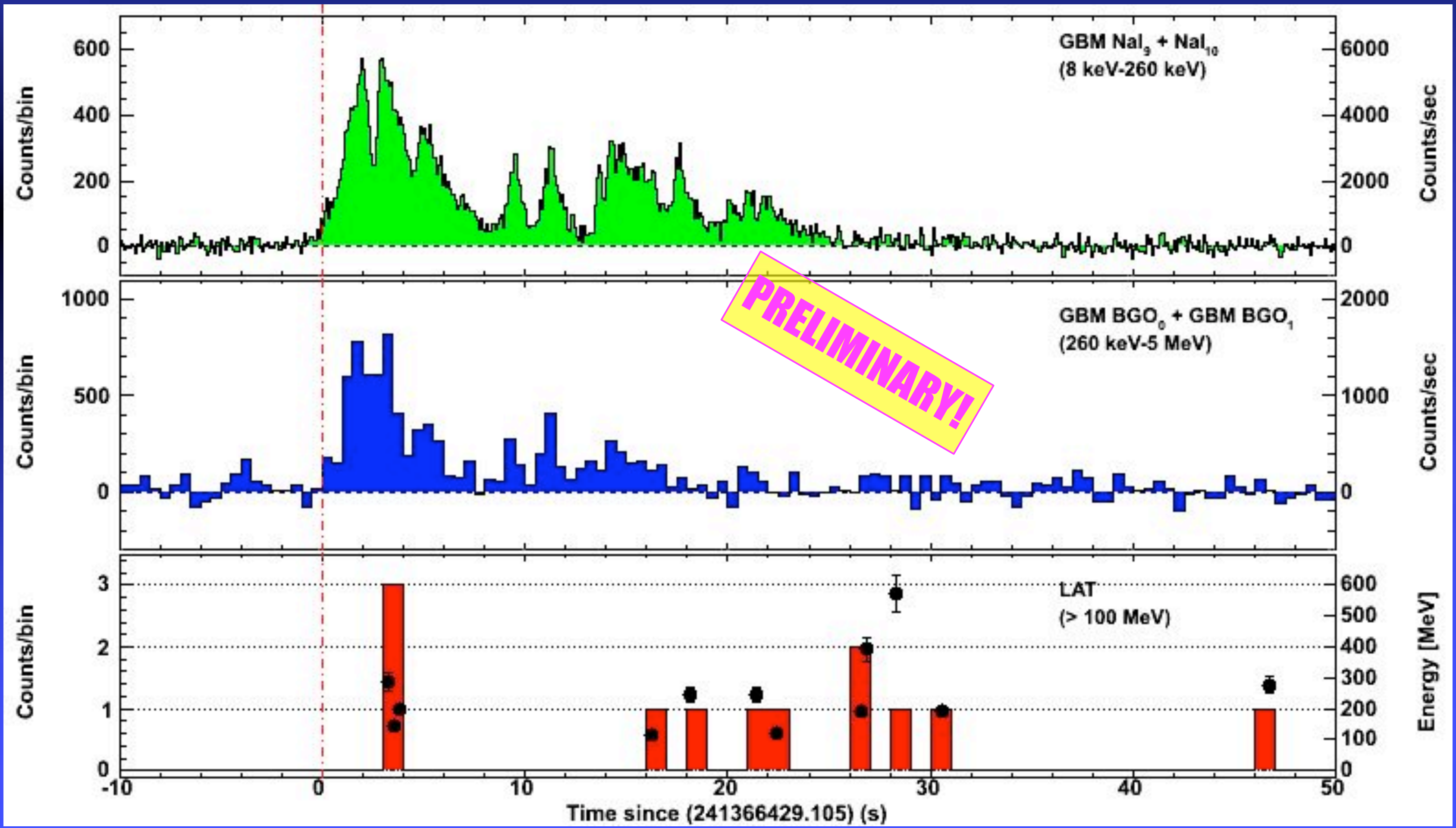
BATSE sample

- Suggests: most GRBs don't have significant excess (HE component) or deficit (cutoff) in the LAT energy range w.r.t the extrapolation of a Band spectrum from lower energies

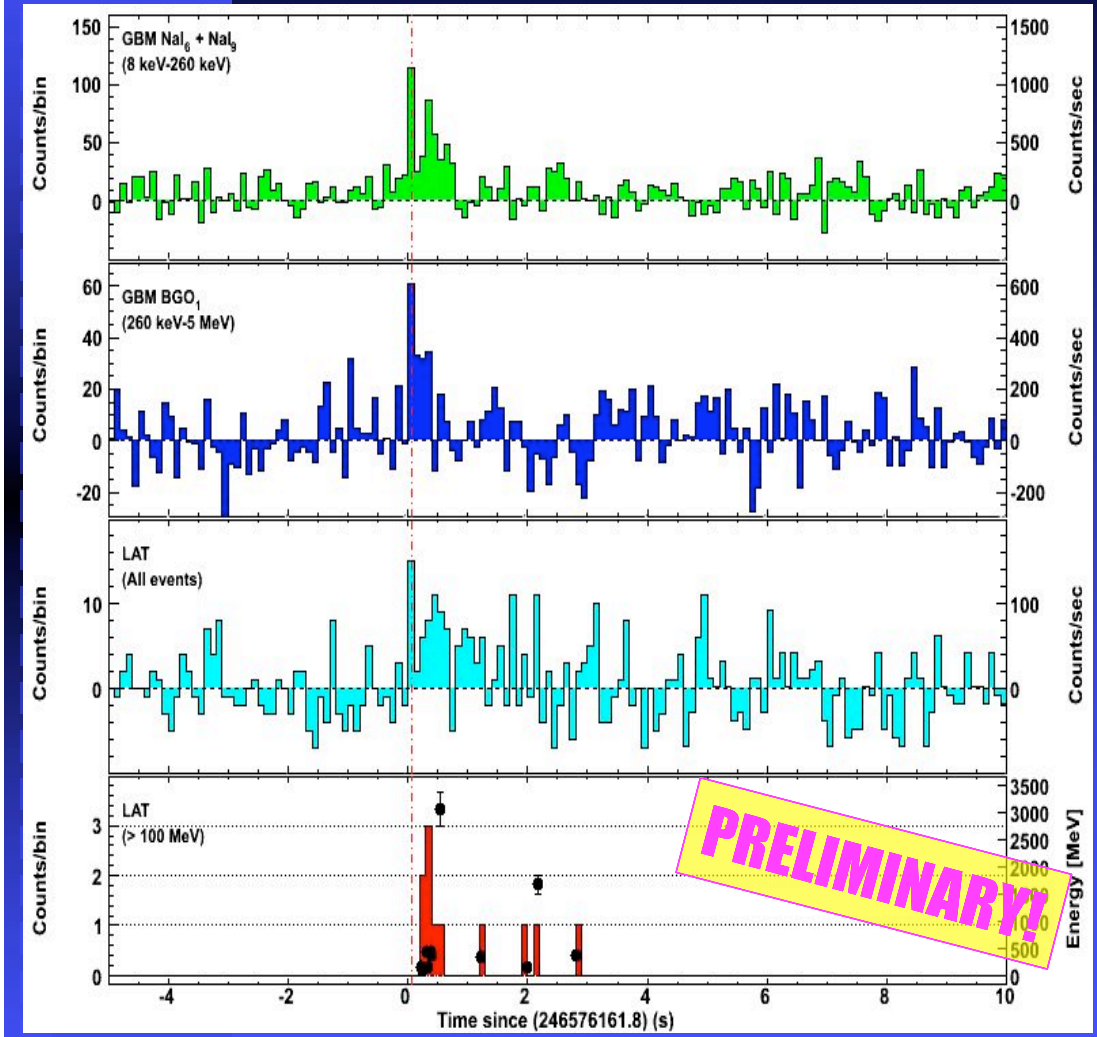


GRB080825C: the 1st LAT GRB

- The 1st LAT events coincide with the 2nd GBM peak
- The high-energy emission lasts longer: highest energy photon arrives when the GBM emission is very weak



GRB081024B: 1st short GRB >1 GeV



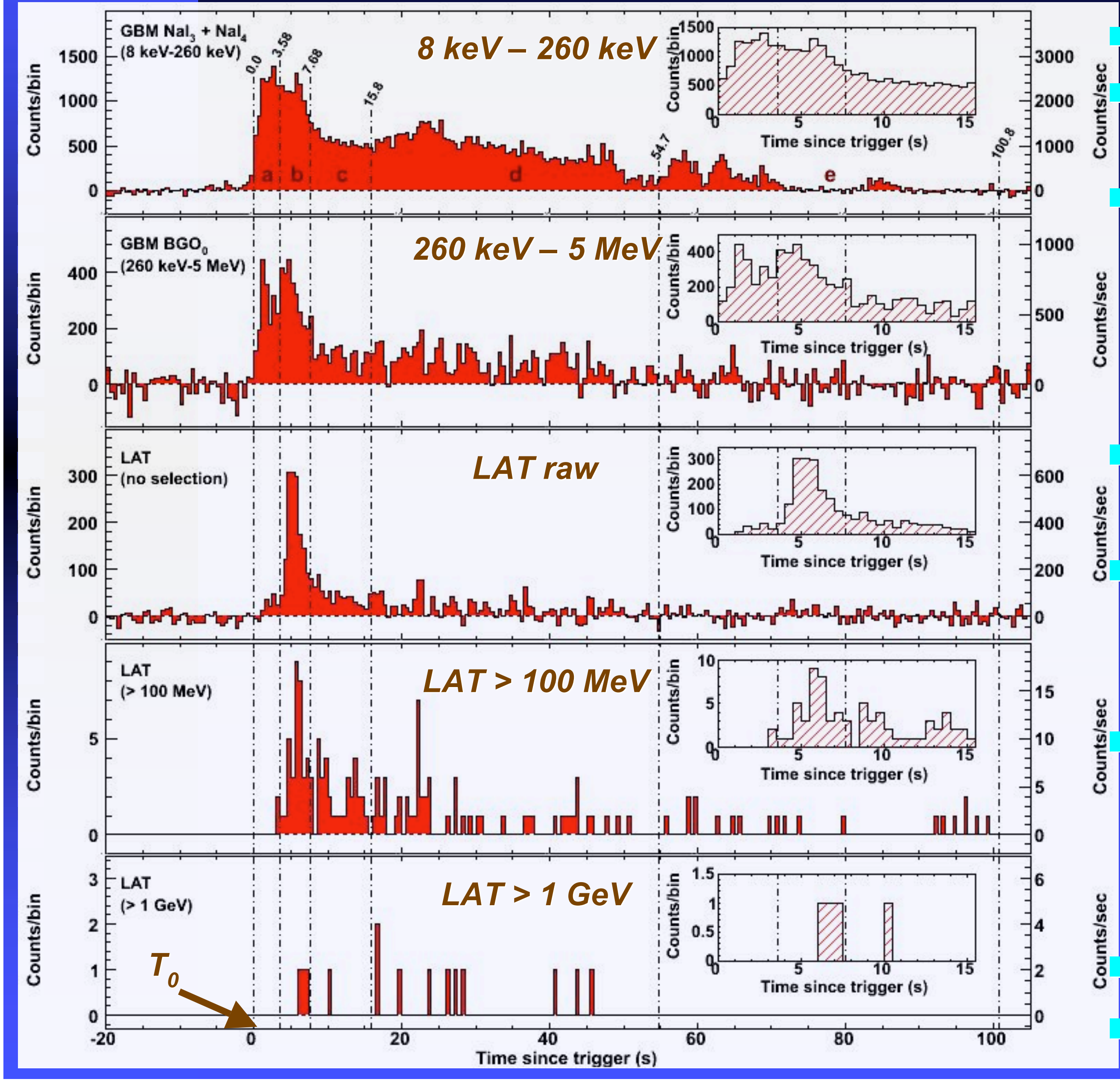
- 1st LAT events coincide with 2nd GBM peak (**delayed** HE **onset**)
- The HE emission **lasts longer** than low-energies
- One spectral component that hardens with time
- Lower limit on Γ from pair opacity constraints:

  $\Gamma_{min}(z=0.1) \approx 150$

  $\Gamma_{min}(z=3.0) \approx 900$

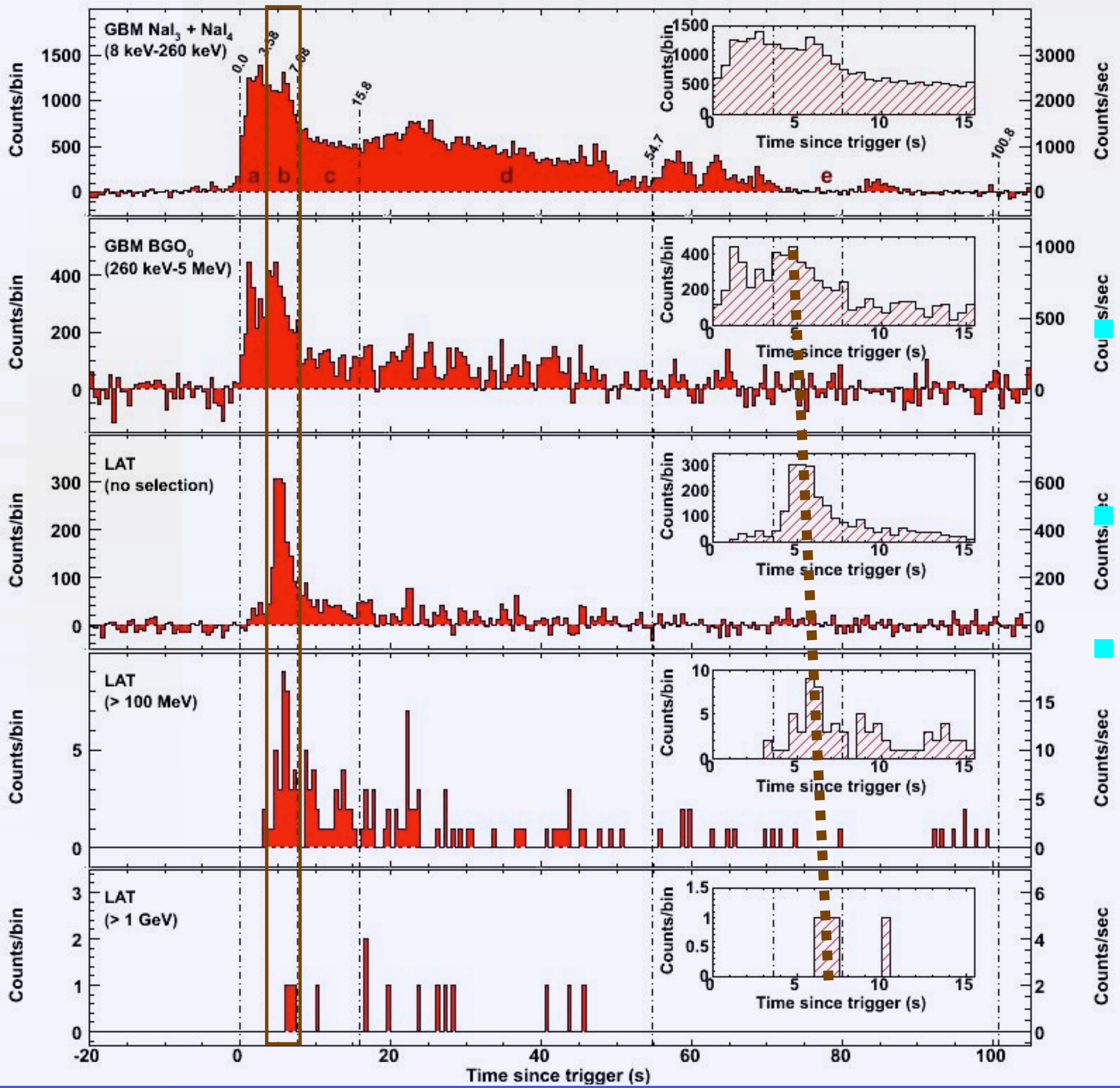
  (highest then for a short GRB, but z is uncertain)

GRB080916C: multi-detector light curve



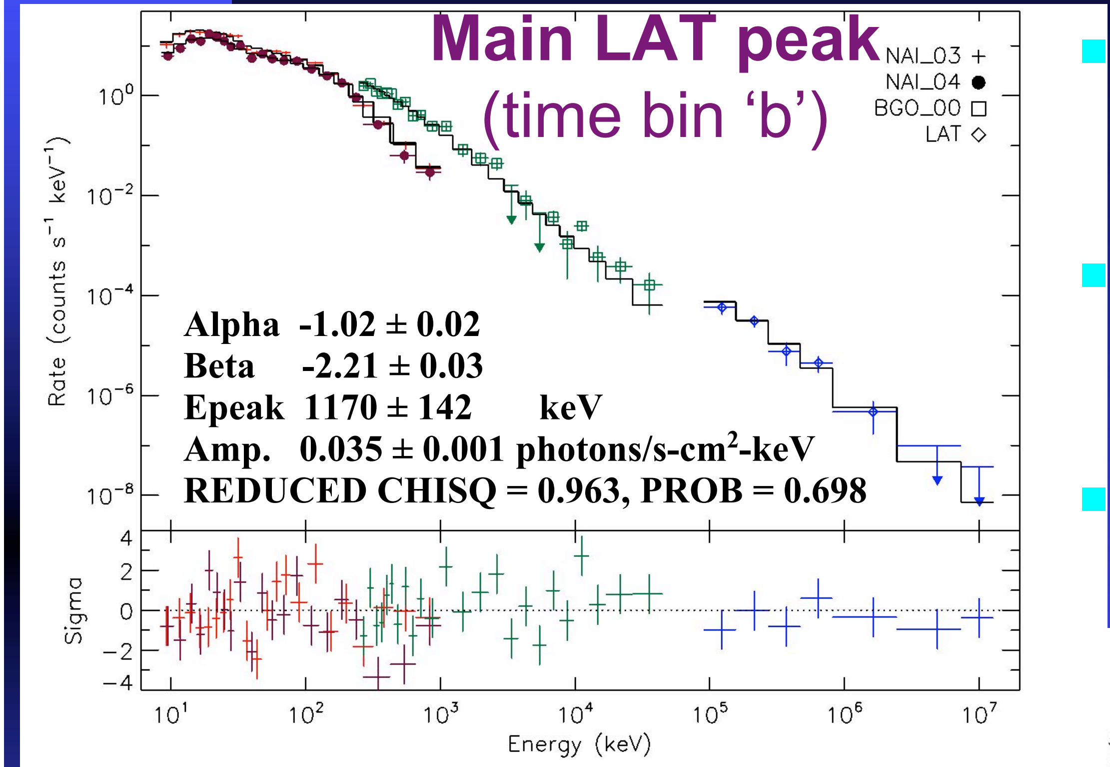
- **z = 4.35±0.15** (photometric)
- First 3 lightcurves are background subtracted
- The LAT can be used as a **counter** to maximize the rate and to study time structures **> tens of MeV**
- **>3000** LAT photons in the 1st **100 seconds**
- The first low-energy peak is not observed at LAT energies
- **Spectroscopy**: LAT event selection **>100 MeV** ⇒ **145** events made it
- **5** time bins (**a** to **e**)
- **14 events > 1 GeV**

GRB080916C: multi-detector light curve

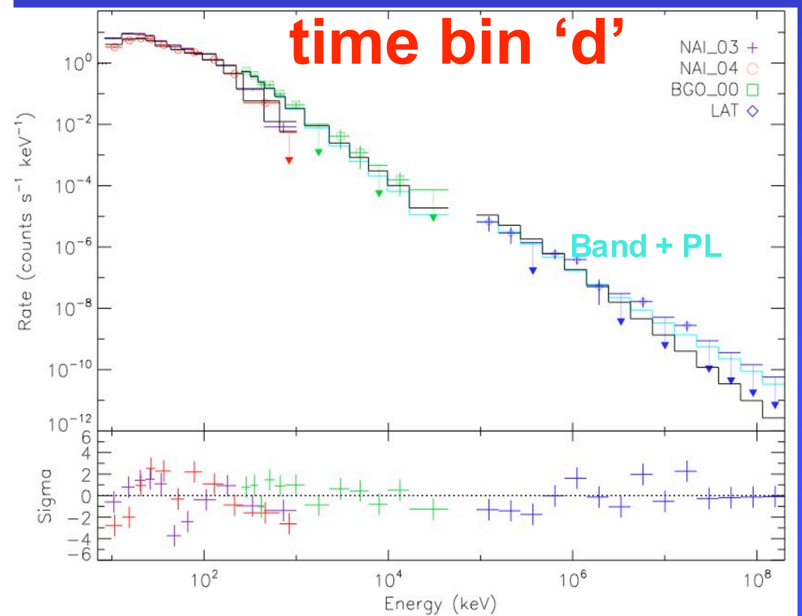


- Most of the emission in the 2nd peak occurs later at higher energies
- This is clear evidence of spectral evolution
- The **delay** of the **HE emission** seems to be a **common feature** of the GRBs observed by the LAT so far.

GRB080916C: time resolved spectroscopy

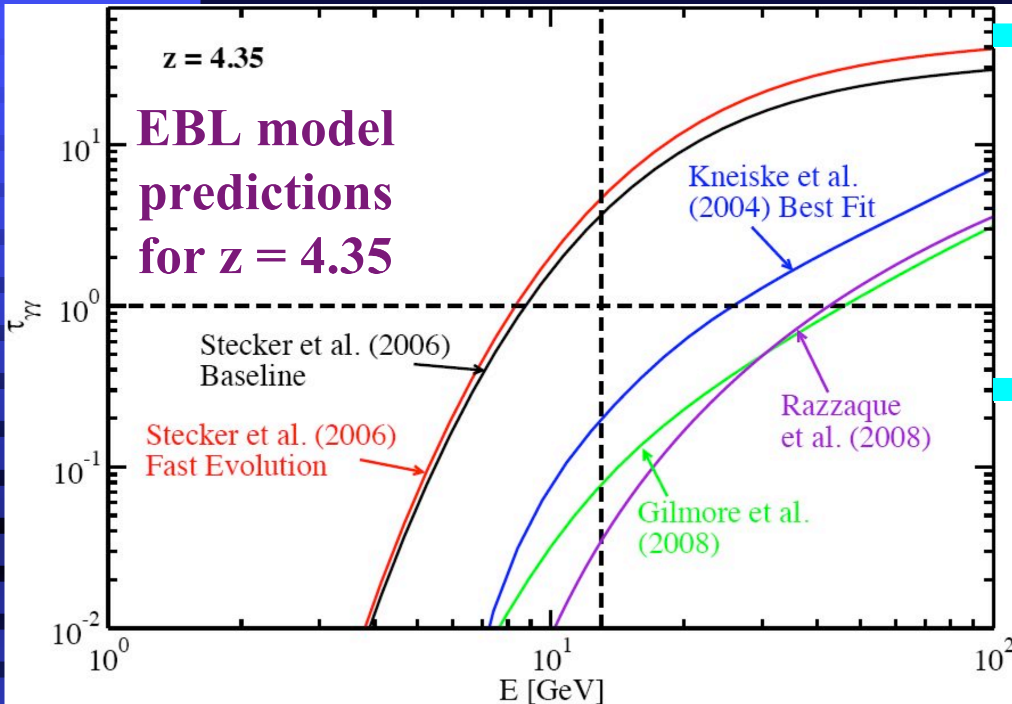


- Time resolved spectroscopy over 6 decades in energy!!! (10 keV – 10 GeV)
- Consistent with a Band function: a single dominant spectral component
- No strong evidence for an additional spectral component

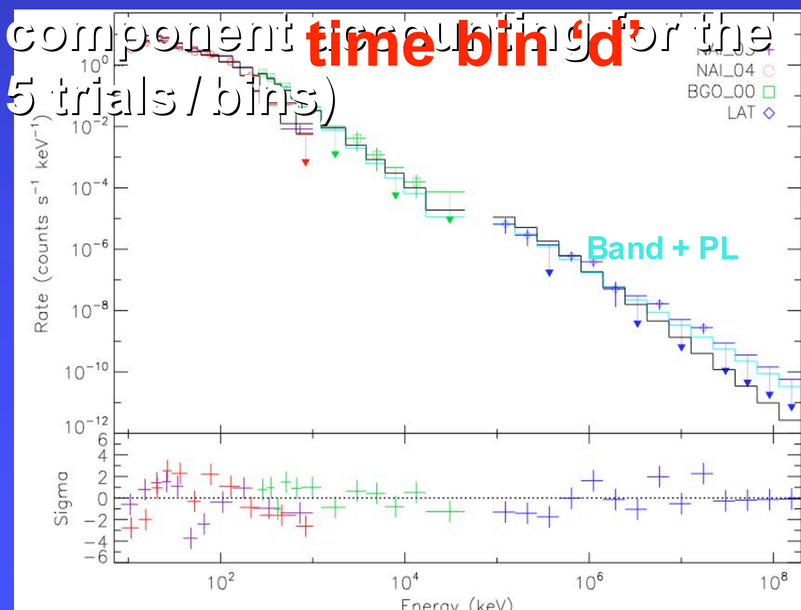


- A likelihood ratio test in bin 'd': the probability of having no additional HE spectral component is 1% (5 bins/trials)
- Possible pair production ($\gamma\gamma \rightarrow e^+e^-$) of HE photons with the EBL leaves this probability from unchanged to 0.03% depending on the model chosen.

GRB080916C: time resolved spectroscopy



- The Stecker et al. model/s would imply $\tau_{\gamma\gamma}$ ~ 3-4 $\Rightarrow > 3\sigma$ for distinct HE spectral component that carries significant energy
- For other EBL models $\tau_{\gamma\gamma} \ll 1$: weak evidence for an extra HE spectral component (5% chance probability for no HE-component accounting for the 5 trials / bins)



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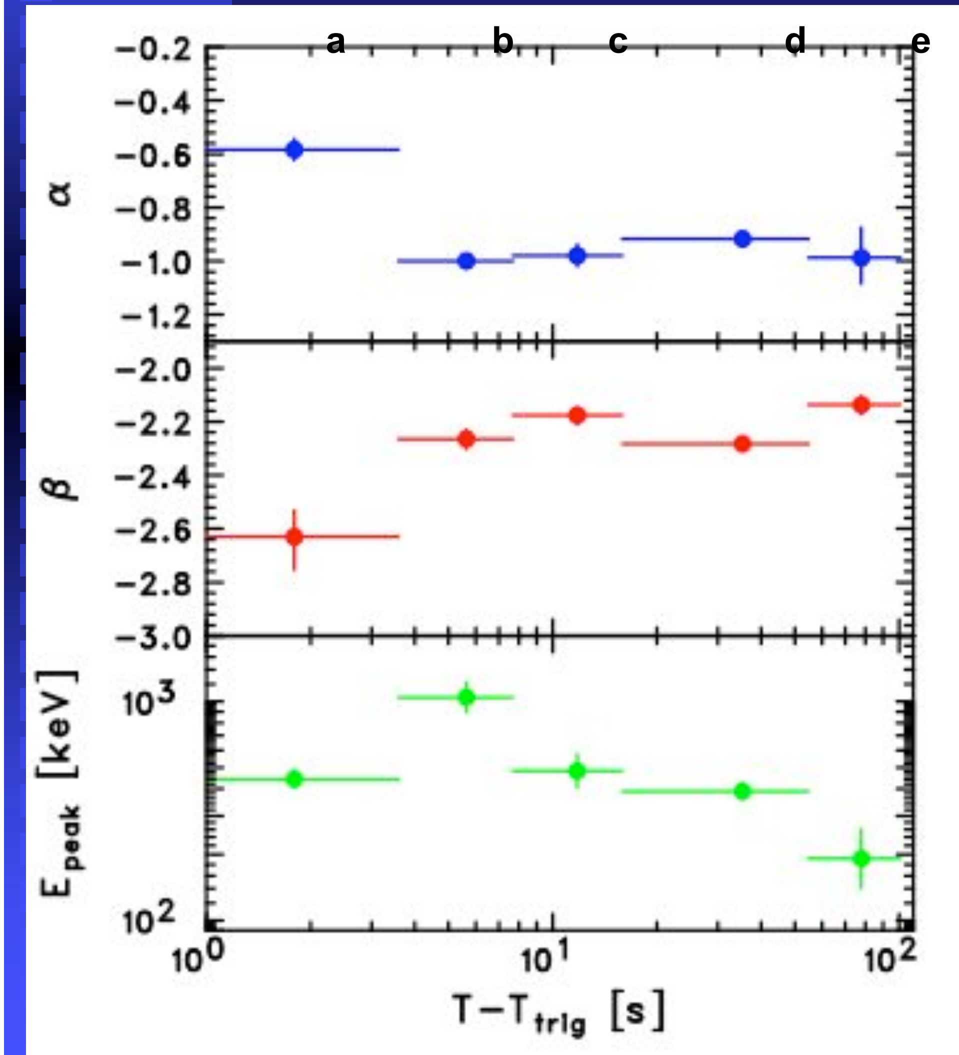
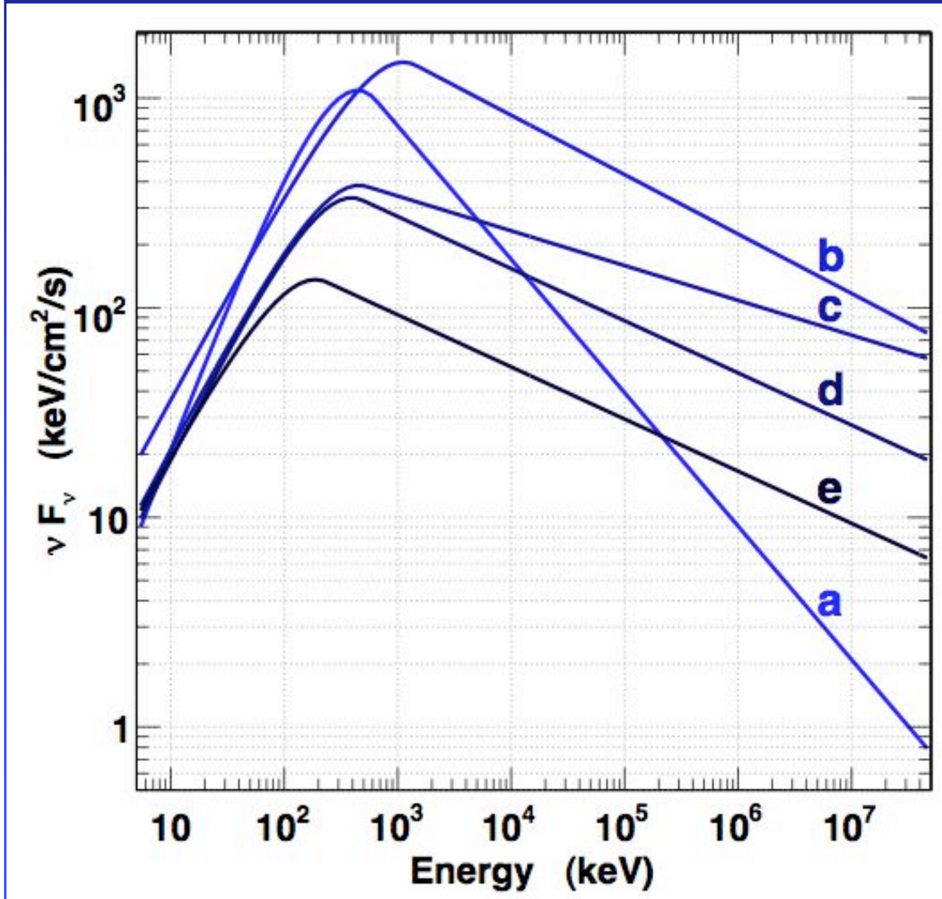
GRB080916C: Spectral Evolution

- Band function fits
- Soft → hard → soft E_{peak} evolution



- Low (α) & high (β) energy photon indexes change significantly only between time bins 'a' and 'b'

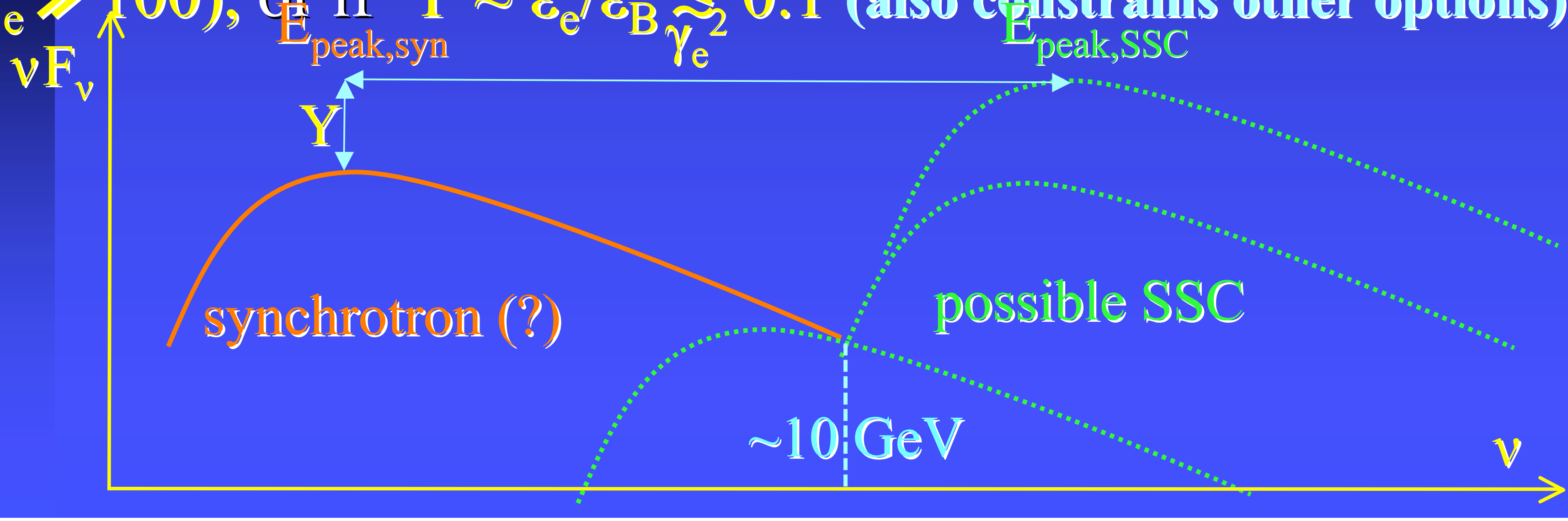


Delayed onset of HE emission: Possible Causes

- 1. The 1st and 2nd peaks are emitted from distinct physical regions (e.g. different colliding shell in the internal shocks model)
  - Unclear why a similar behaviour occurs in most LAT GRBs (if it is random then some GRBs should have a reverse order)
- 2. opacity effects don't work well as there is no cutoff or steepening of the spectrum at high-energies
- 3. Hadronic origin: time to accelerate protons & develop pair cascade, if the high-energy emission is of hadronic origin
  - Two distinct spectral components (leptonic at low-energies & hadronic at high-energies) expected but not seen; requires a total energy $\gg E_{\gamma,iso}$ (energy crisis); hard to explain sharpness of 1st LAT peak + coincidence with 2nd GBM peak

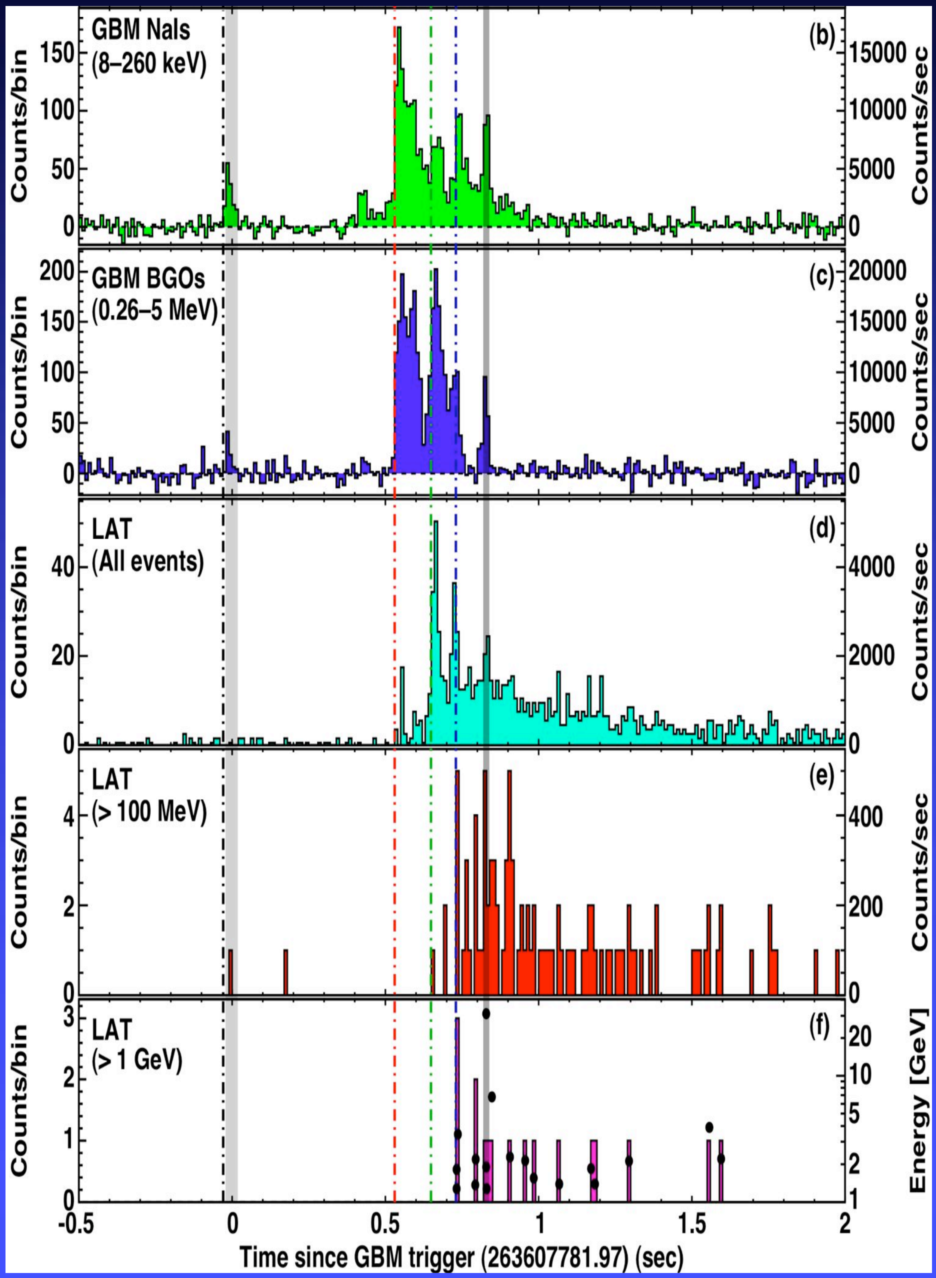
Other Interesting Results for GRB080916C:

- Large fluence (2.4×10^{-4} erg/cm^2) & redshift ($z = 4.35 \pm 0.15$) $\Rightarrow$ record breaking apparent isotropic energy release $E_{\gamma,\rm iso} \approx 8.8\times10^{54}$ erg $\approx 4.9\ M_\odot c^2$ $\Rightarrow$ suggests strong beaming (jet)
- The HE (>100 MeV) emission is detected for >1000 s
- Single dominant emission mechanism: if synchrotron, SSC is expected, and can avoid detection if $E_{\rm peak,SSC} \gg 10$ GeV ($\gamma_e \gg 100$), or if $Y \approx \epsilon_e/\epsilon_B \lesssim 0.1$ **(also constrains other options)**



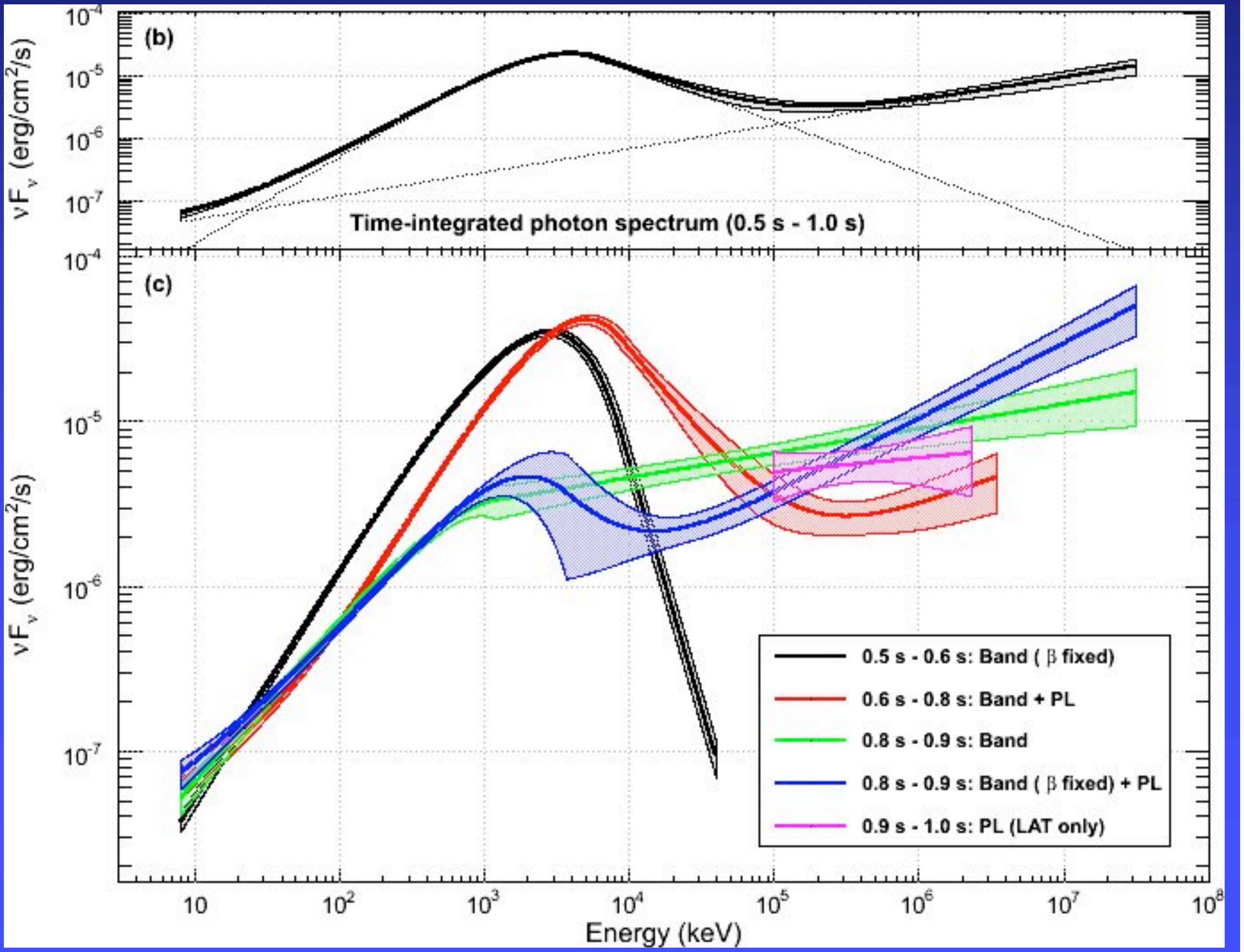
GRB090510: short, hard & bright

- $z = 0.903 \pm 0.003$
- $E_{\gamma,iso} \approx 1.1\times10^{53}$ erg
- 31 GeV photon at 0.83 s
- Onset of main emission episode occurs later at higher photon energies
- HE emission lasts longer (>0.1 GeV det. up to 200 s)
- Triggered on a precursor
- Low-energy spikes at



GRB090510: Spectral Evolution

- The high-energy photon index β hardens during main emission episode
- A significant excess above a single Band spectrum at high-energies: distinct high-energy spectral component (> 5 σ significance); power-law
- Required at 0.6-0.8 s
- Carries 37% of fluence
- HE & LE components are correlated in time: same emission region (1st GRB to show this)
- 0.8-0.9 s not required but likely still there
- 0.9-1.0 s single softer power-law; a break is needed at ~ a few MeV



High-energy spectral component: Possible Origin

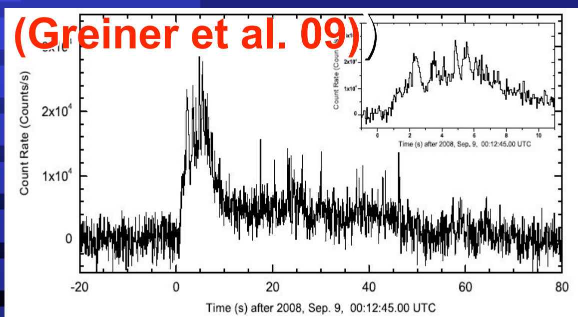
- Leptonic: inverse-Compton (SSC)?
  - The gradual increase in **β** is not naturally expected
  - Hard to reconcile the relative values of the photon index of the HE component Band spectrum at low energies
- Hadronic: (pair cascades, proton synchrotron) ?
  - May account for a delayed HE onset (time to accelerate protons & develop cascades), but not necessarily for the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies
  - Requires a very large total energy: $E_{total} / E_{\gamma,iso} \sim 10^2 - 10^3$

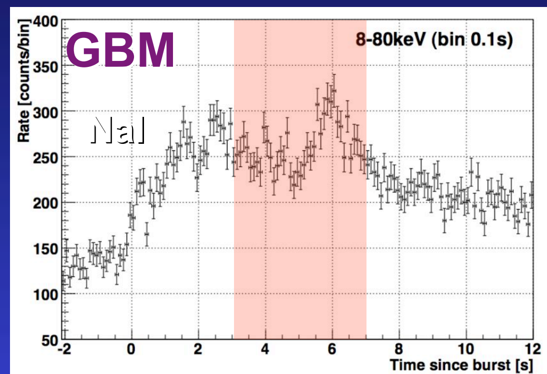
GRB080916C: Bulk Lorentz factor $\Gamma \gtrsim 900$

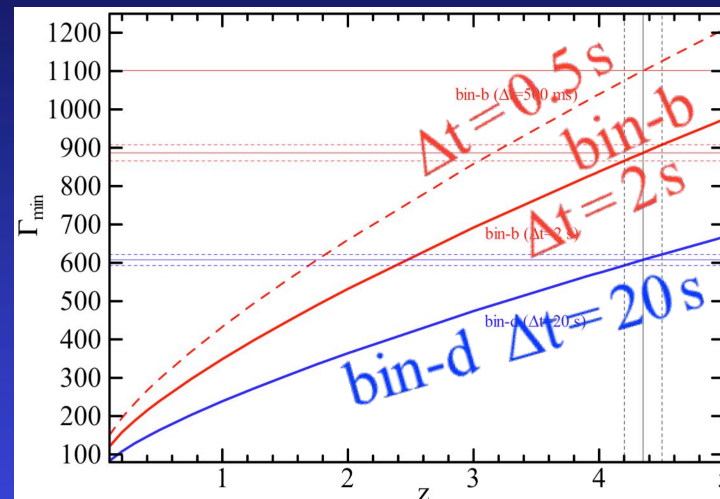
- Robust + highest lower limits on Γ from opacity constraints: $\Gamma_{min} \approx 890 \pm 20$ (bin 'b', for $\Delta t = 2$ s) & $\Gamma_{min} \approx 600$ (bin 'd')

INTEGRAL light curve

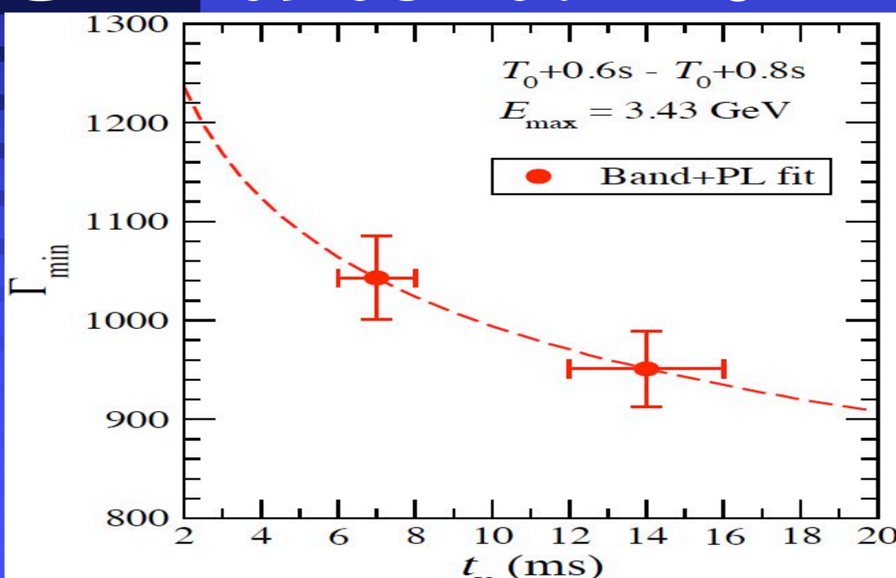
(Greiner et al. 09)

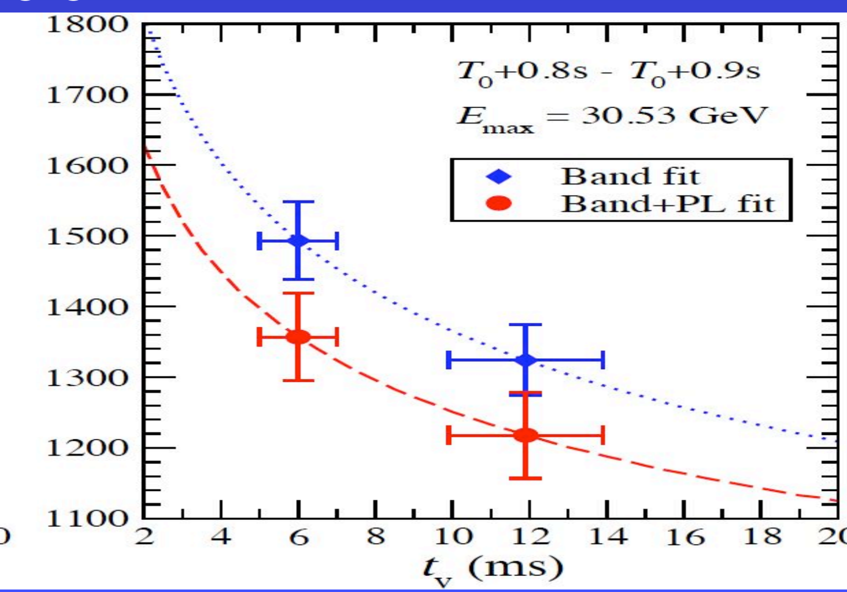






GRB090510: $\Gamma \gtrsim 1200$



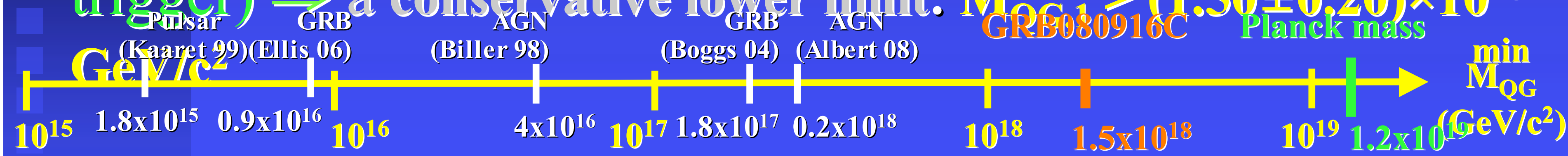


Limits on Lorentz Invariance Violation

- Some QG models violate Lorentz invariance: $v_{ph}(E_{ph}) \neq c$

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

- A high-energy photon E_h would arrive after (or possibly before in some models) a low-energy photon E_l emitted together
- GRB080916C: highest energy photon (13 GeV) arrived 16.5 s after low-energy photons started arriving (=the GRB trigger) ⇒ a conservative lower limit: $M_{QG,1} > (1.50 \pm 0.20) \times 10^{18}$ GeV/c^2



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

(Jacob & Piran 2008)

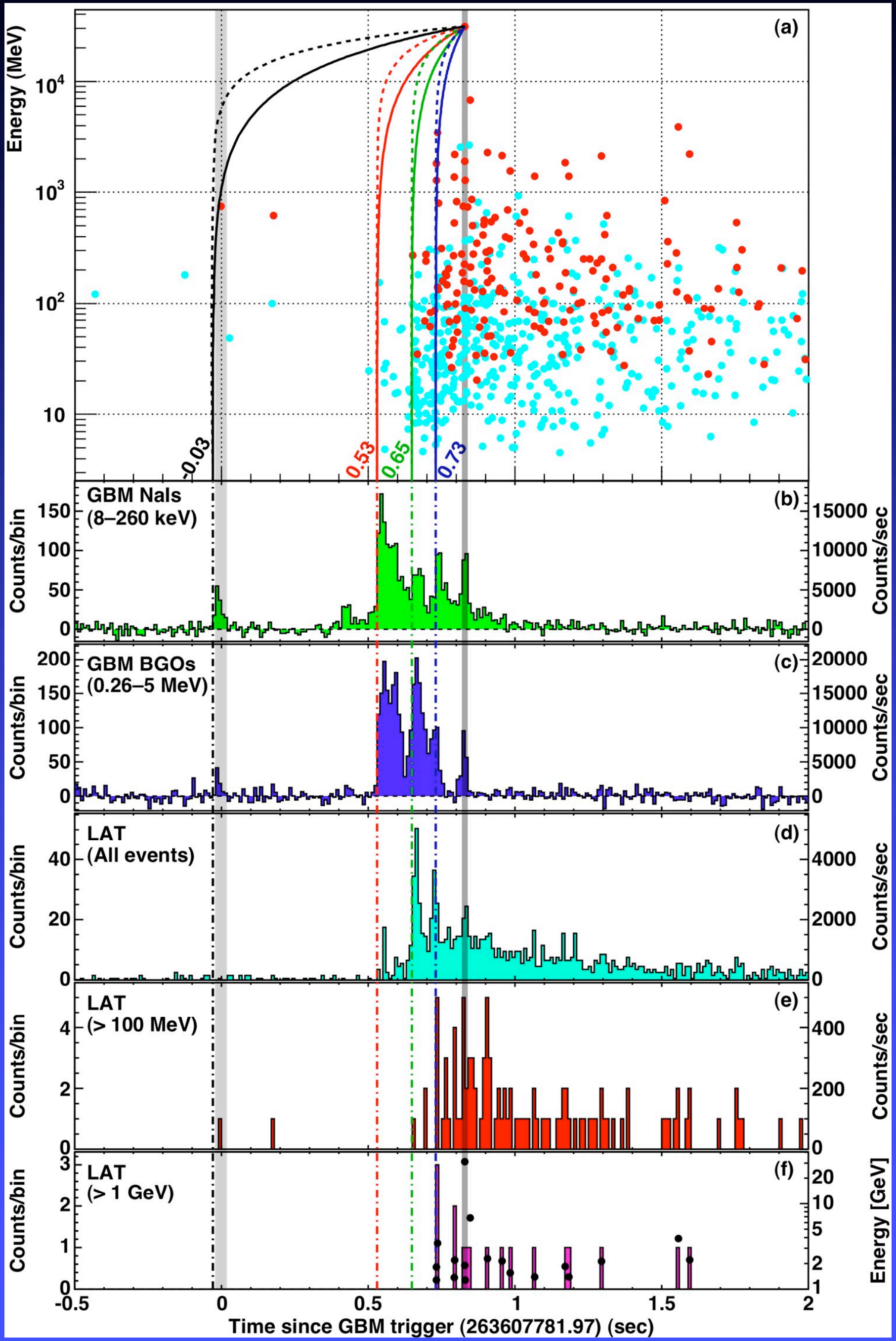
n = 1,2 for linear and quadratic Lorentz invariance violation, respectively

GRB090510: L.I.V

Table 2 | Limits on Lorentz Invariance Violation

#	$t_{start} - T_0$ (ms)	Limit on $\lvert\Delta t\rvert$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\lvert\Delta t/\Delta E\rvert$	E_l† (MeV)	Valid for s_n*	Lower limit on $M_{QG,1}/M_{Planck}$
(a)✻	−30	< 859	start of any < 1 MeV emission	0.1	1	> 1.19
(b)✻	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
(c)✻	*648*	< 181	start of main > 0.1 GeV emission	100	1	> 5.63
(d)✻	730	< 99	start of > 1 GeV emission	1000	1	> 10.0
(e)♦	—	< 10	association with < 1 MeV spike	0.1	±1	> 102
(f)♦	—	< 19	If 0.75 GeV‡ γ-ray from 1st spike	0.1	−1	> 1.33
(g)♠	$\lvert\Delta t/\Delta E\rvert$ < 30 ms/GeV		lag analysis of > 1 GeV spikes	—	±1	> 1.22

- All of our lower limits on $M_{QG,1}$ are above M_{Planck}
- a-e based on 31 GeV γ-ray
- a-d assume that $t_{em} \geq t_{strat}$ t_{strat} = emission onset time
- e,f association with a specific low-energy spike



Conclusions:

- ~ 9 LAT GRBs/yr suggest that most GRBs do not strongly deviate from a Band spectrum in LAT range
- Spectra: most LAT GRBs are consistent with a single dominant component; 090510 has a distinct HE spectral component (temporally correlated with low energy comp.)
- Many LAT GRBs show **later onset & longer duration** of the high-energy emission, relative to low energies
- short & long GRBs seem to have similar HE properties: HE delayed onset & longer duration, high Γ_{min}
- GRB080916C: **$\Gamma \gtrsim 900$, $M_{QG,1}/M_{Planck} > 0.1$**