Fermi observations of GRB prompt emission

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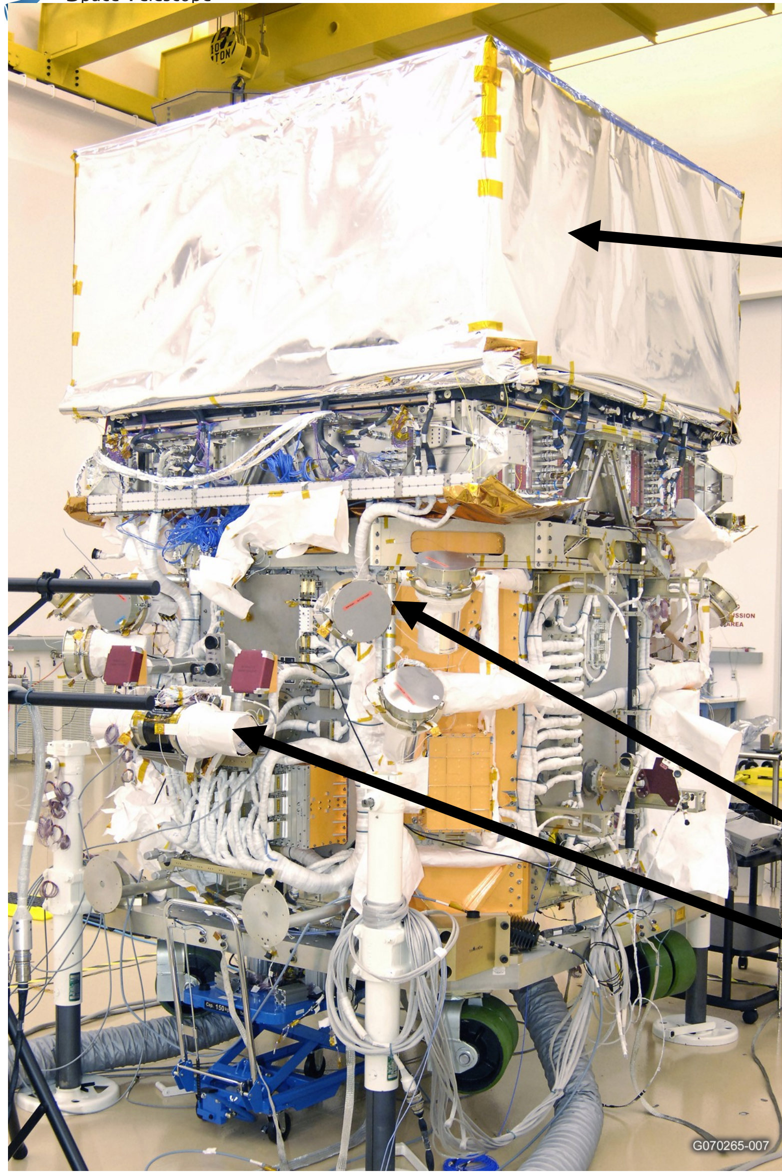
on behalf of the *Fermi* LAT and GBM collaborations

Outline

- Instruments; the *Fermi* bursts
- Common properties in GRB prompt emission at high energies: delayed onset, spectral evolution, extra spectral component
- Constraints from gamma-ray opacities
- Implications for models
- LAT burst rate
- Summary

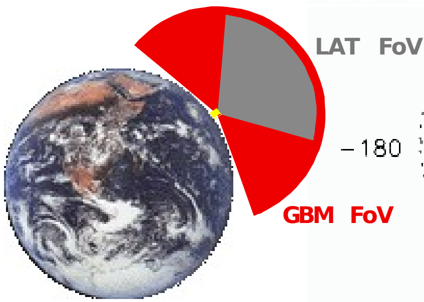
The *Fermi* observatory

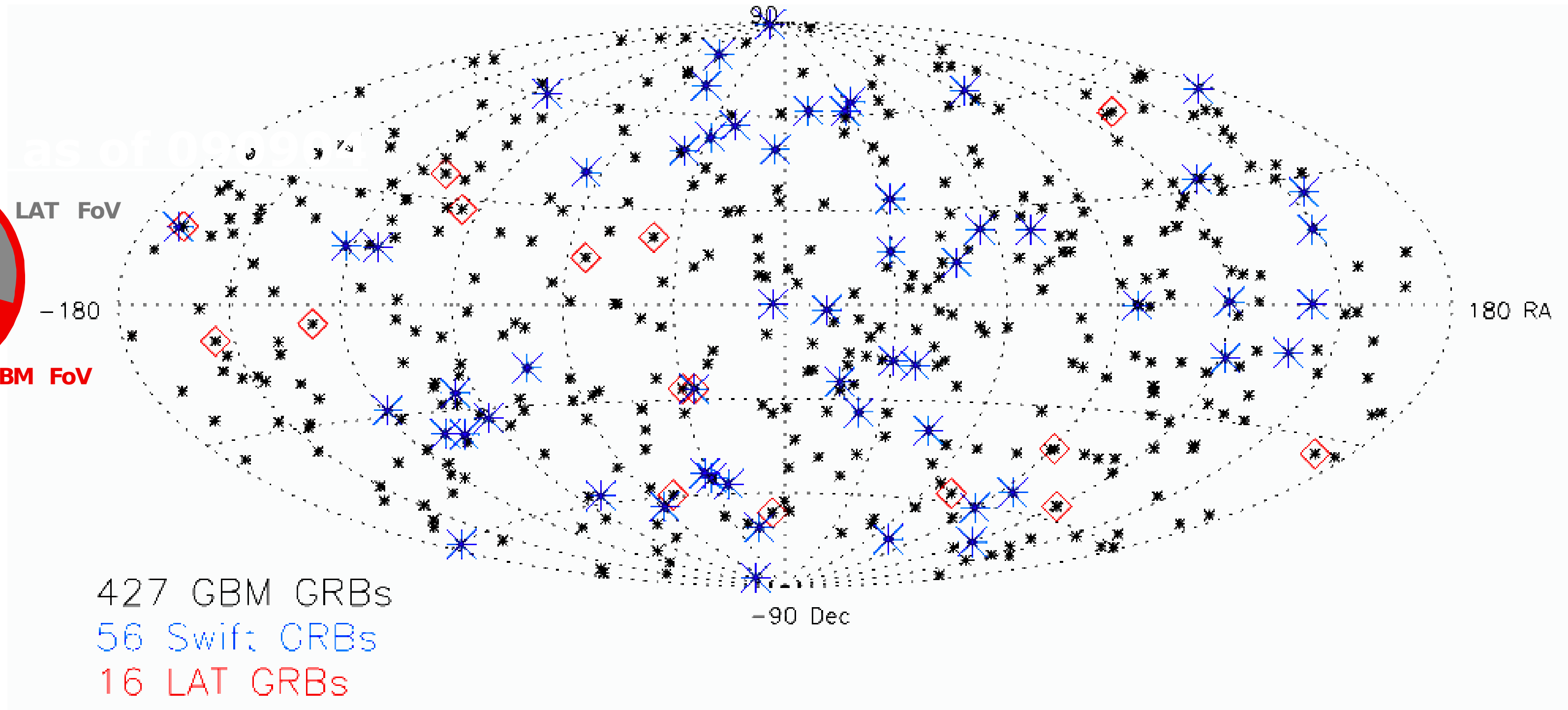


- Large Area Telescope (LAT)
  - Large FoV (~2.4 sr @ 1 GeV)
  - Sees the entire sky every 3 hr
  - 20 MeV to >300 GeV
  - onboard and ground burst triggers, localization, spectroscopy

- Gamma-ray Burst Monitor (GBM)
  - Sees the entire unocculted sky (>9.5 sr)
  - 8 keV to 40 MeV
  - 12 NaI detectors (8 keV to 1 MeV)
    - onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - spectroscopy

The *Fermi* bursts as of April 6, 2010



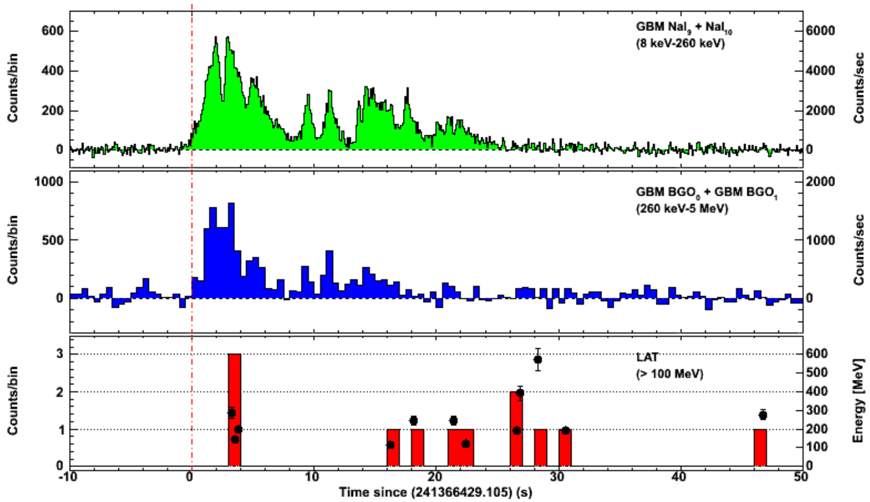


- The GBM detects ~250 GRBs/year
  - ~18% short
  - ~50% in the LAT FoV
- The LAT detects ~10 GRBs/year (16 total)
  - 10% of GBM GRB observed
- Excellent synergy with Swift
  - ~19 Swift GRBs/year in LAT FoV
  - 7 LAT GRBs detected in XRT follow-up (9 observed in >12 hours)
  - All afterglows detected by XRT have led to ground-based redshift measurement
  - Only one BAT/GBM/LAT common trigger to date (GRB 090510)

The first long and the first short LAT GRBs

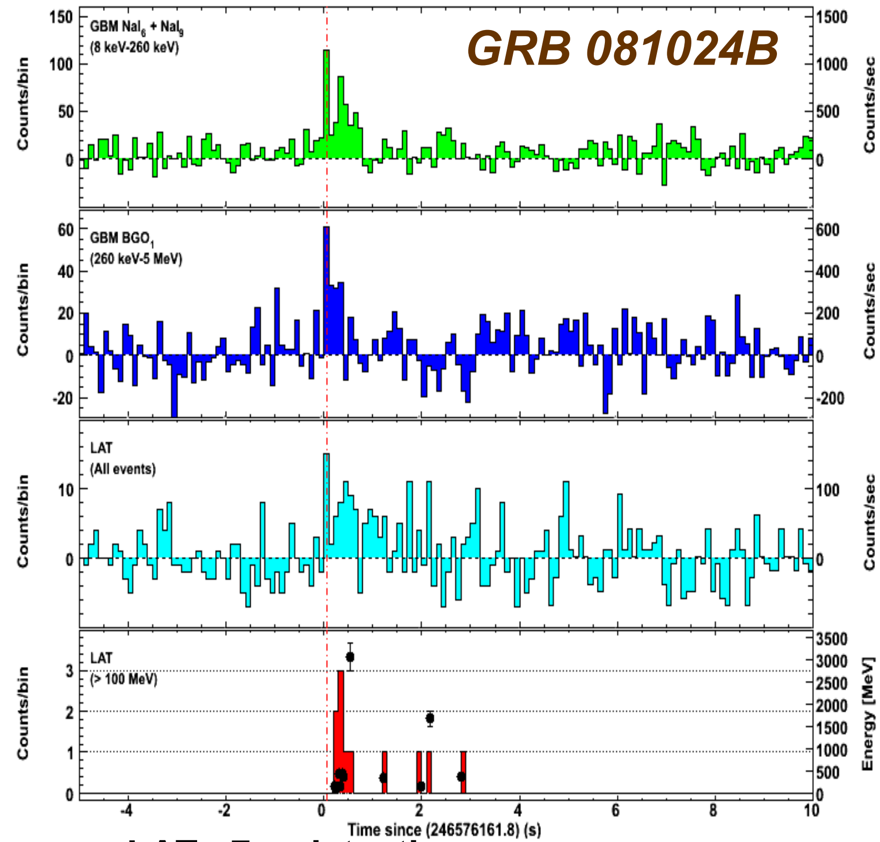
GRB 080825C

Abdo et al. 2009, ApJ 707, 580



- LAT ~6 σ detection
- GBM signal shows multiple peaks (with 2 brightest in ~5 s) and lasts ~35 s
- First LAT events coincident with the second GBM peak
- Evidence for long-lasting >100 MeV emission
- Highest energy event is detected when GBM emission is very weak

Abdo et al. 2010, ApJ 712, 558

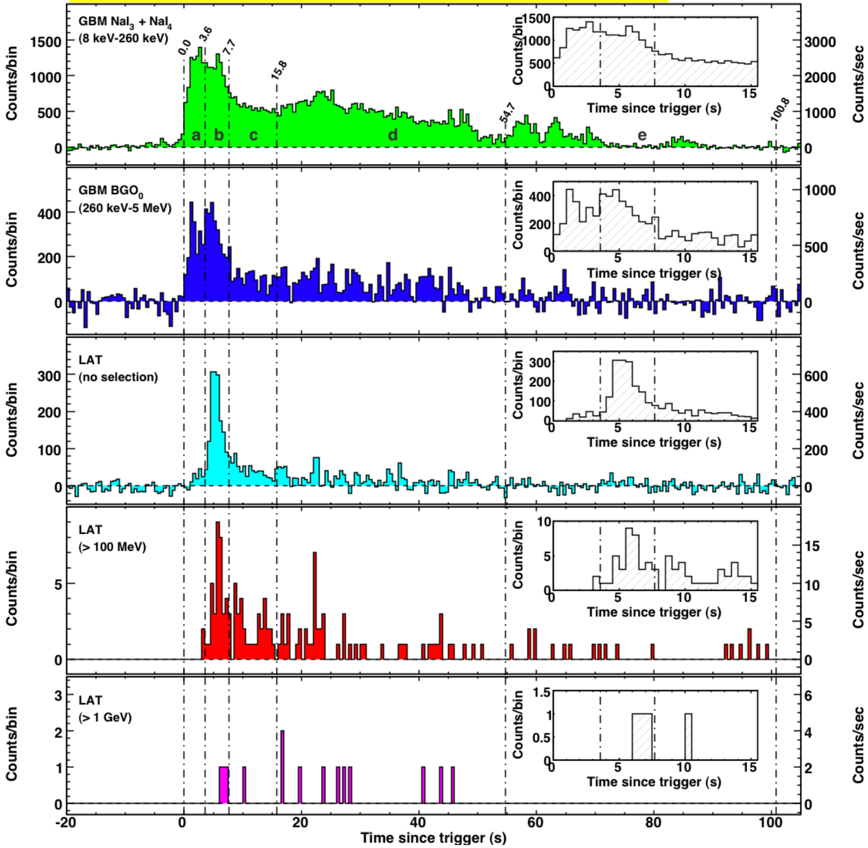


- LAT ~7 σ detection
- First short GRB >1GeV
- First GBM peak seen in raw counts (<100 MeV)
- HE (>100 MeV) LAT emission possibly delayed w.r.t. GBM onset
- Coincident with second GBM pulse and extends beyond keV-MeV emission (~0.8 s)

HE delayed onset in long and short GRBs

GRB 080916C

Abdo et al. 2009, Science 323, 1688

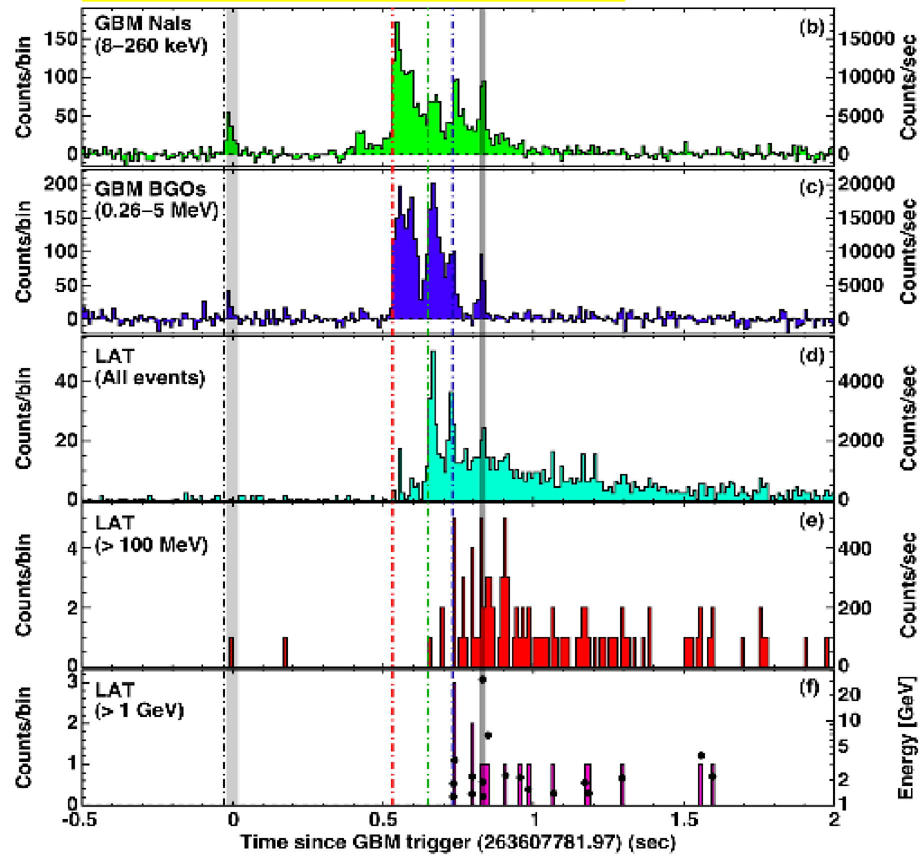


The first LAT peak coincides with the second GBM peak

Delay in HE onset: ~4-5 s

GRB 090510

Abdo et al. 2009, Nature 462, 331



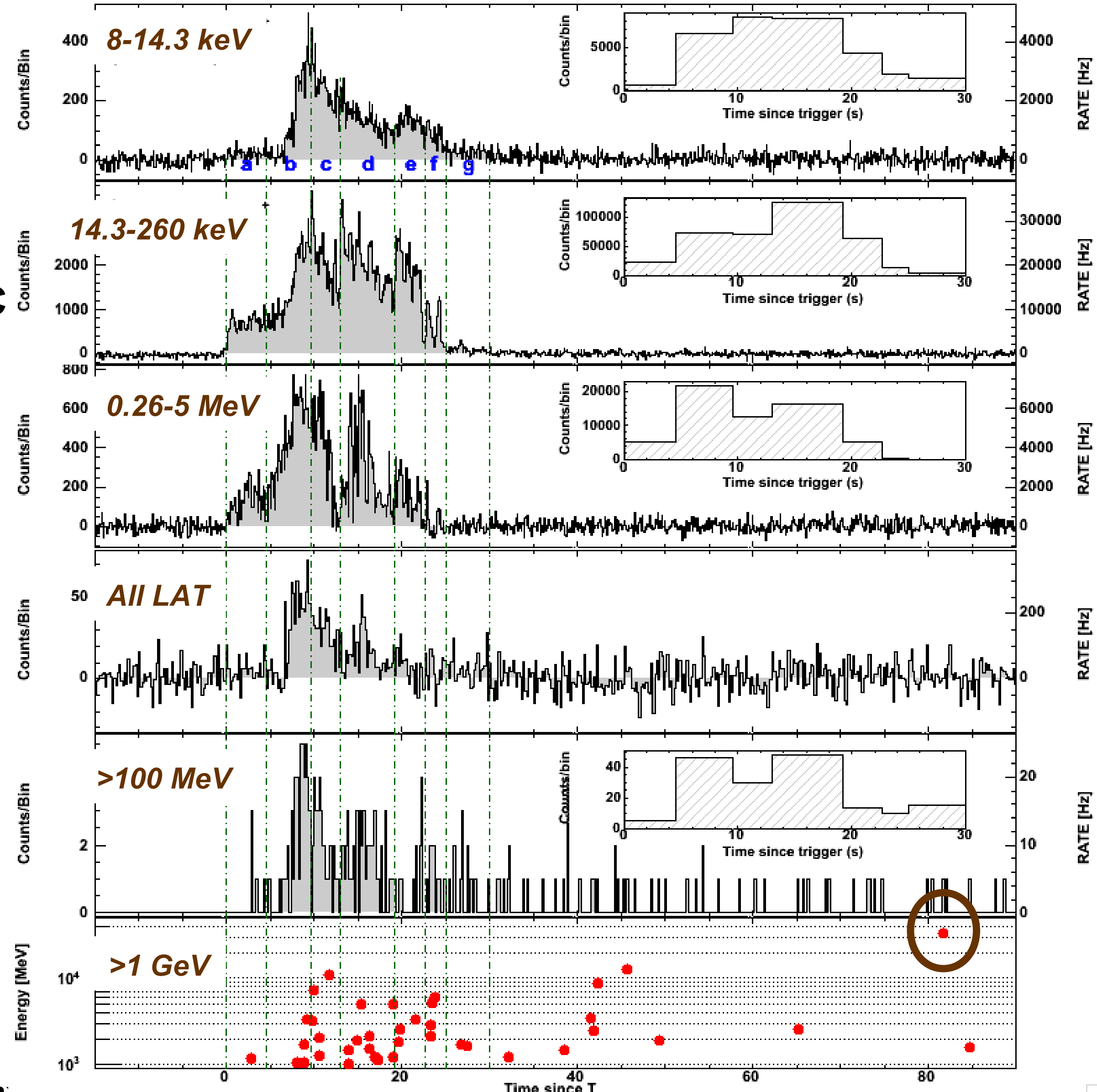
The first few GBM peaks are missing in the LAT but later peaks coincide

Delay in HE onset: 0.1-0.2 s

GRB 090902B multi-detector light curve

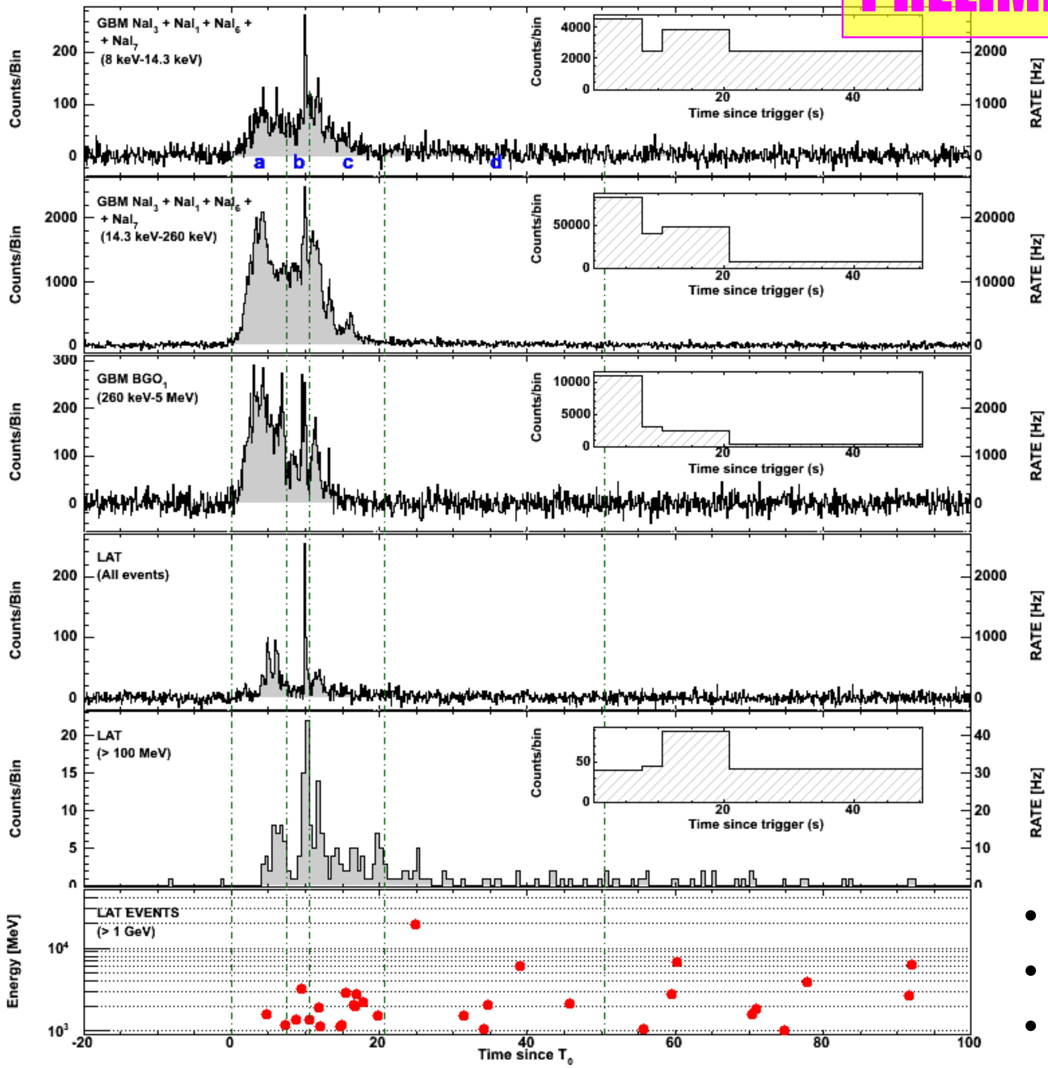
Abdo et al. 2009, ApJL 706, 138

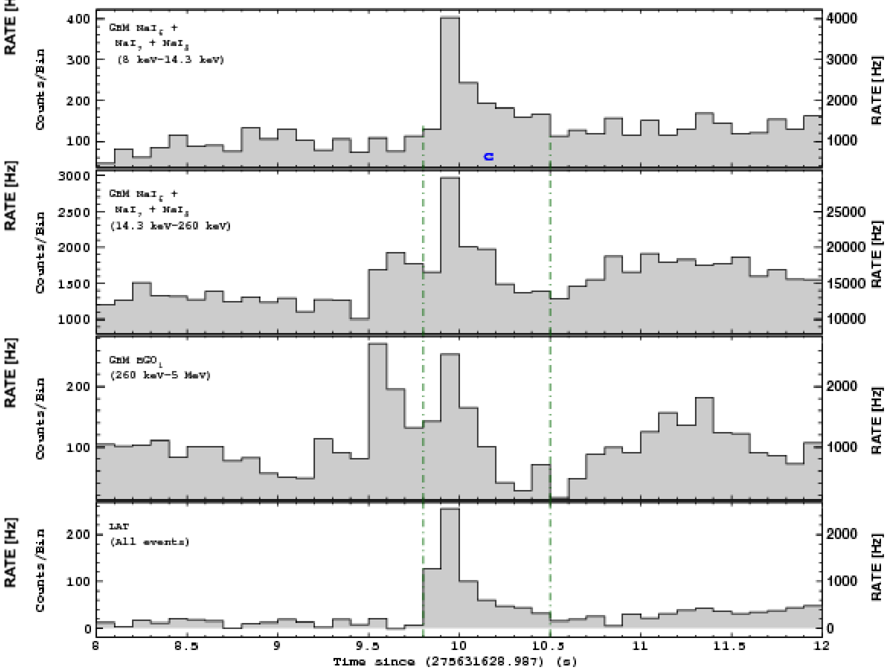
- T90 = 21.9 s, 50-300 keV
- Fluence = 4.4× 10^{-4} erg cm^{-2} (10 keV – 10 GeV)
- Eiso = 3.6× 10^{54} erg (~9× 10^{54} erg for GRB 080916C
- Delayed onset of >100 MeV emission (~9 s) (~4.5 s for GRB 080916C)
- LAT extended emission, well beyond GBM prompt phase
- Highest energy photon measured from a burst: 33.4 GeV at T0 + 82 s
- Study correlated variability in various bands



GRB 090926A multi-detector light curve

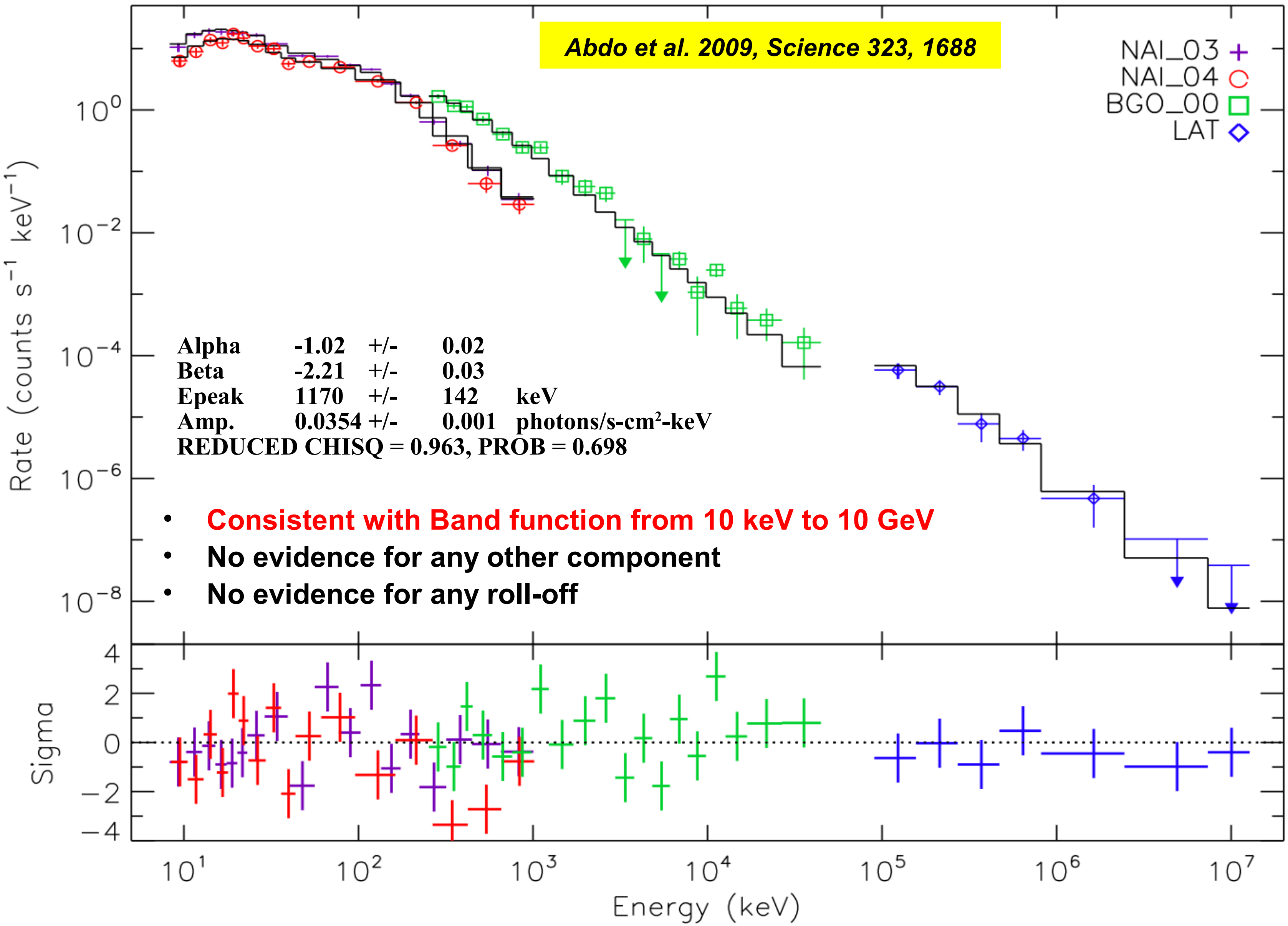
PRELIMINARY!





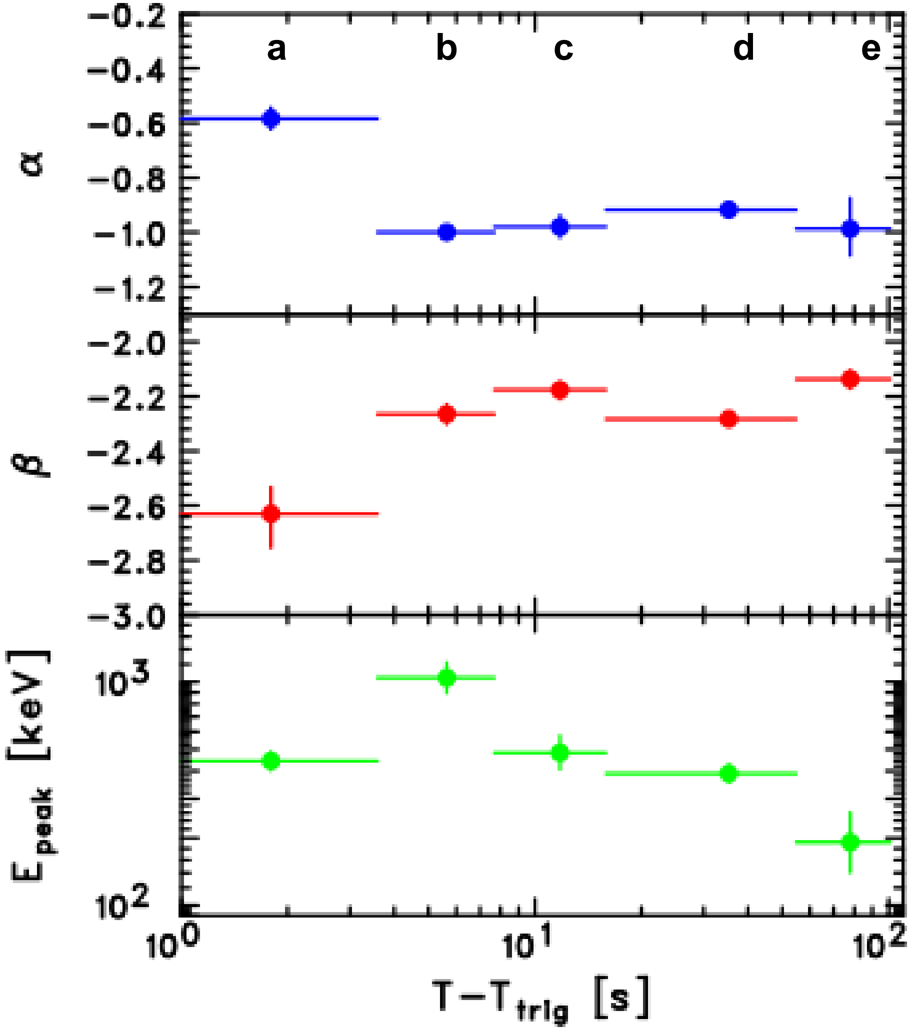
- Delay in HE onset: ~3 s
- Many sub-structures
- Very narrow spike of ~0.1 s at ~10 s from ~10 keV to >100 MeV

GRB 080916C: spectroscopy of main LAT peak

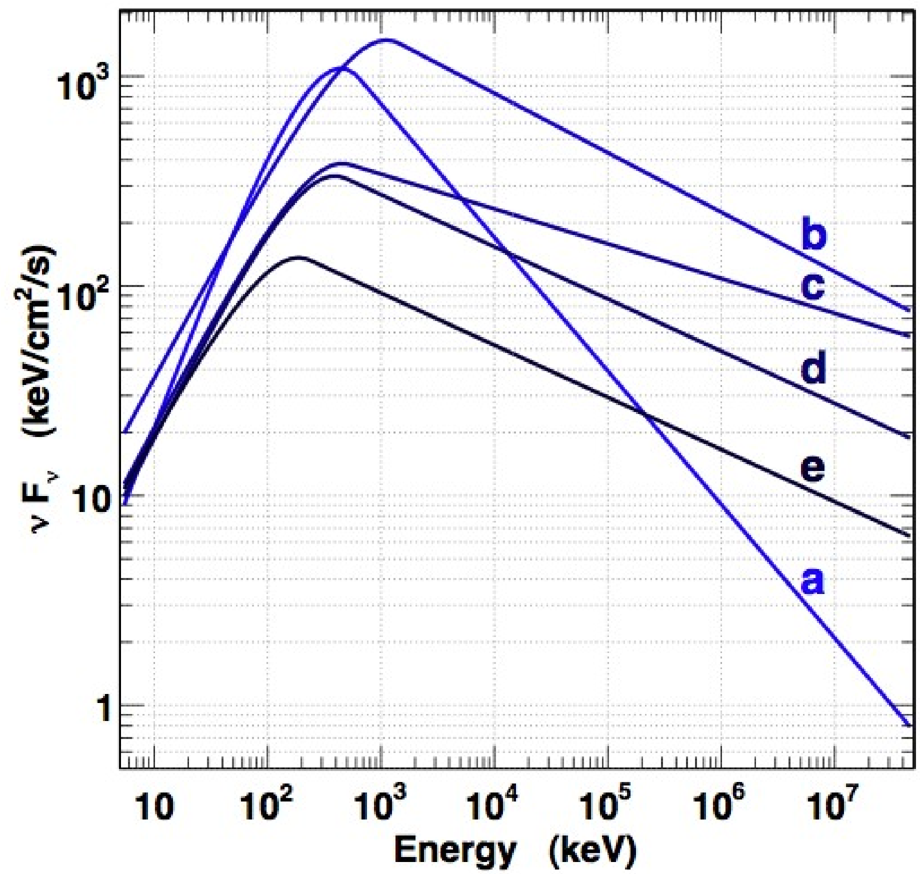


Spectral evolution of GRB 080916C

Soft-to-hard, then hard-to-soft evolution of E_{peak}



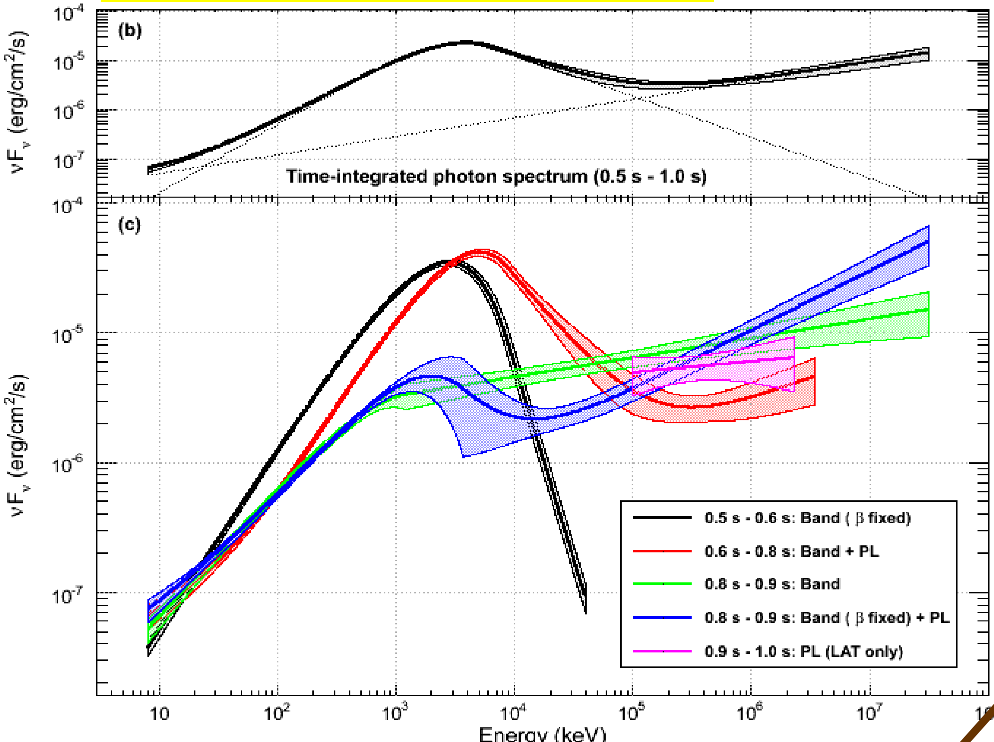
Abdo et al. 2009, Science 323, 1688



Extra PL component in short and long GRBs

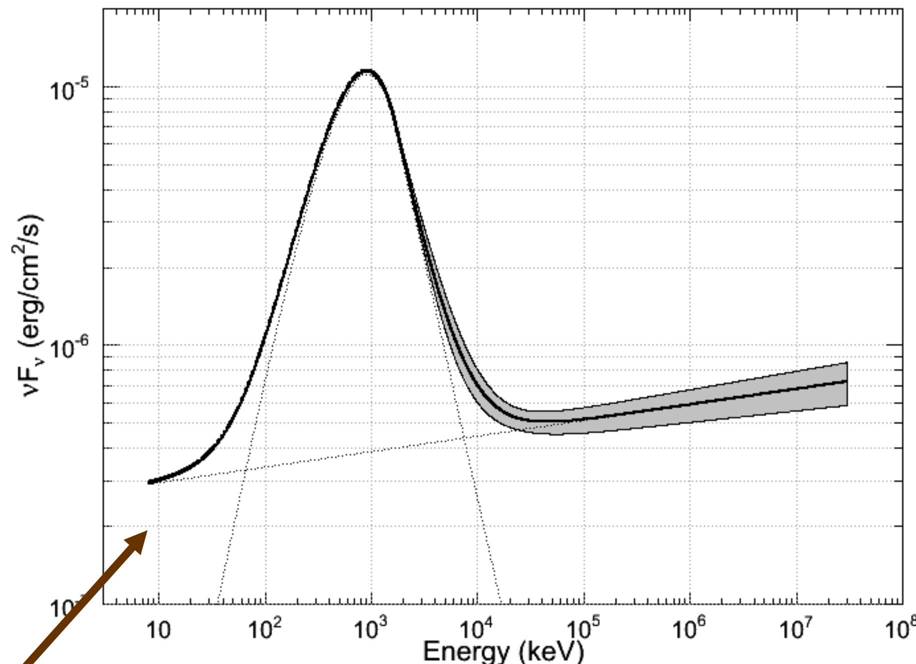
GRB 090510

Ackermann et al. 2010, ApJ 716, 1178



GRB 090902B

Abdo et al. 2009, ApJL 706, 138



Band function + Power-Law Fit Parameters for the Time-Resolved Spectral Fits

Interval	Time Range (s)	E_{peak} (kev)	α	β	Γ	CSTAT/DOF	ΔCSTAT
...	0.0–30.0	726 (±8)	−0.61 (±0.01)	$-3.8\ (^{+0.2}_{-0.3})$	$-1.93(^{+0.01}_{-0.01})$	2562/963	2005
a	0.0–4.6	526 (±12)	−0.09 (±0.04)	$-3.7\ (^{+0.3}_{-0.6})$	$-1.87(^{+0.04}_{-0.05})$	901/963	43
b	4.6–9.6	$908\ (^{+15}_{-14})$	0.07 (±0.03)	$-3.9\ (^{+0.2}_{-0.3})$	−1.94 (±0.02)	1250/963	3165
c	9.6–13.0	821 (±16)	−0.26 (±0.03)	$-5.0(^{+0.8}_{-2.8})$	−1.98 (±0.02)	1310/963	2109
d	13.0–19.2	529 (±9)	−0.65 (±−0.02)	$-3.2\ (^{+0.1}_{-0.2})$	−1.86 (± 0.02)	1418/963	199
e	19.2–22.7	317 (±8)	−0.78 (±−0.02)	−2.4 (±0.1)	...	1117/965	...
f	22.7–25.0	$236\ (^{+25}_{-33})$	$-1.30\ (^{+0.04}_{-0.03})$	−2.2 (±0.1)	...	1077/965	...
e+f	19.2–25.0	327 (±8)	−0.91 (±0.02)	−2.6 (±0.1)	−1.59 (±0.20)	1219/963	16
g	25.0–30.0	...	...	...	$-1.93\ (^{+0.25}_{-0.26})$	1209/967	...

- **Soft-hard-soft evolution in E_{peak}**
  - **GRB 090510: highest E_{peak} ever**
- **Extra-PL can emerge right after the onset of the Band emission in the LAT**
- **GRB 090902B, time interval b**
  - **ΔCSTAT=3165 (>1000 GBM only)**
  - **Low-energy extension (<50 keV) of the extra PL**
  - **Weak evidence (3 σ) for a spectral cutoff at ~1 GeV**

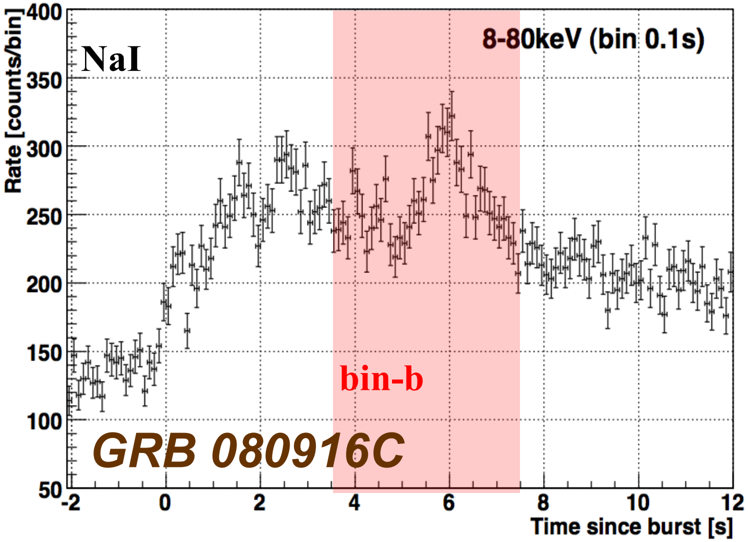
Constraints from gamma-ray opacities – Γ

- **The compactness problem**
  - **Large luminosity $L_{iso} \sim 10^{50}$-10^{53} erg/s**
  - **For a source at rest, a fast variability t_V gives a limit on the size of the emitting region $R < ct_V$ which is small enough for photons of energy $\varepsilon = E_{ph} / m_e c^2 \sim 1$ to annihilate in pairs ($\gamma\gamma \rightarrow e^+e^-$):**
    - **The density of the target photons $n_{ph}(1/\varepsilon) \sim L_{1/\varepsilon}/(4\pi R^2 m_e c^3)$ leads to the following opacity: $\tau_{\gamma\gamma}(\varepsilon) \sim \sigma_T n_{ph}(1/\varepsilon) R = \sigma_T L_{1/\varepsilon}/(4\pi m_e c^3 R) > 10^{14} L_{1/\varepsilon,51} (t_V/1\text{ ms})^{-1}$**
    - **Such an opacity would produce a thermal spectrum, which is not observed at high energies**
  - **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)**
    - **For a Band spectrum of the target photon field (e.g. GRB 080916C):**

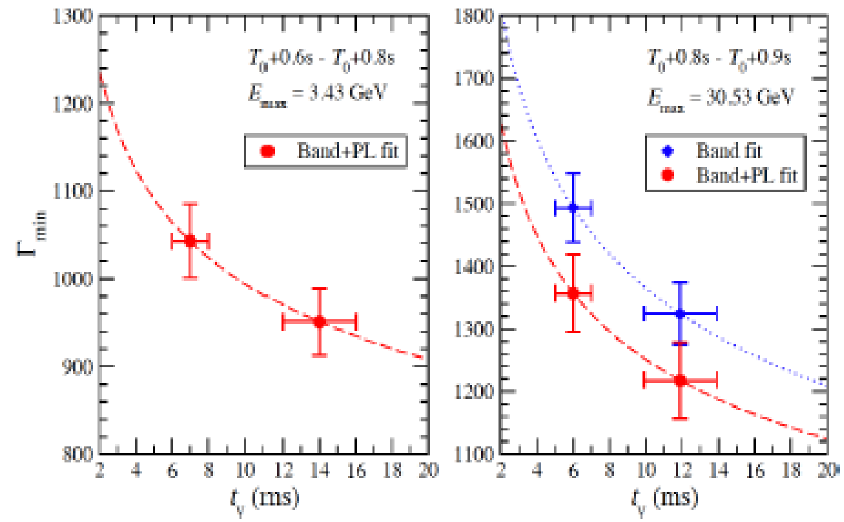
$$\Gamma_{\min}(E_{\max}) = \left[\frac{4\,d_L^2\,A}{c^2\,t_v}\;\frac{m_e^2\,c^4}{(1+z)^2\,E_{\max}}\;g\,\sigma_T\right]^{\frac{1}{2-2\beta}}\left[\frac{(\alpha-\beta)\,E_{\rm pk}}{(2+\alpha)\,100\,{\rm keV}}\right]^{\frac{\alpha-\beta}{2-2\beta}}\exp\left(\frac{\beta-\alpha}{2-2\beta}\right)\left[\frac{2\,m_e^2\,c^4}{E_{\max}\,(1+z)^2\,100\,{\rm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

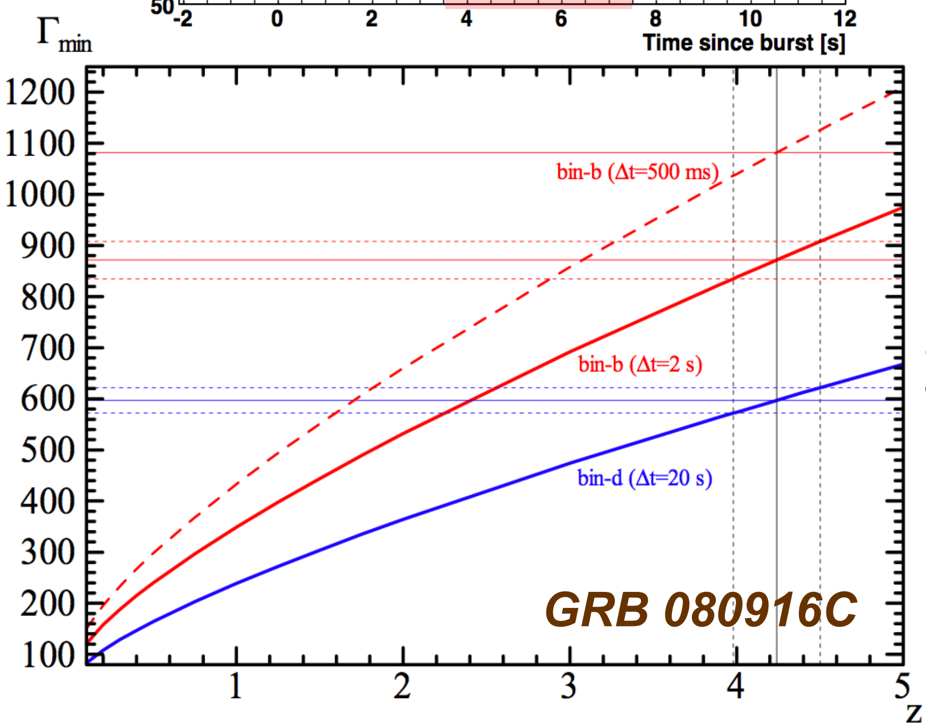
- **More robust estimates than before**
  - **Does not assume that the spectrum extends beyond the highest energy detected photon**
  - **E.g. GRB 090902B: E_{max}=11.16 GeV, t_V=53 ms (from BGO)**
- **This computation assumes a uniform, isotropic and time-independent target photon field**
  - **More realistic models (e.g. Granot 2008) give significantly (~3 times) lower values**

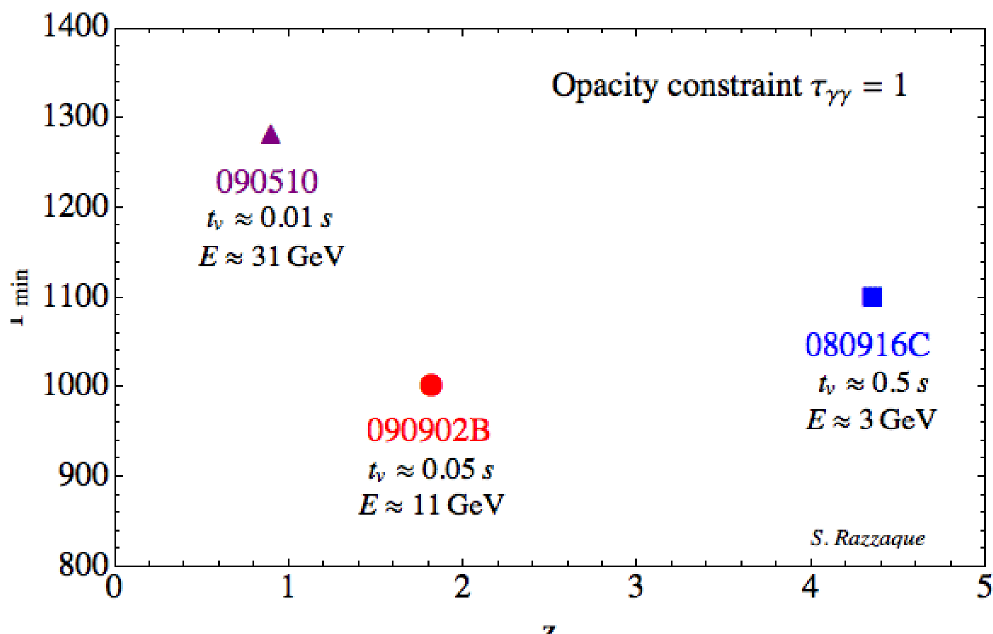
Constraints from gamma-ray opacities – Γ



GRB 090510

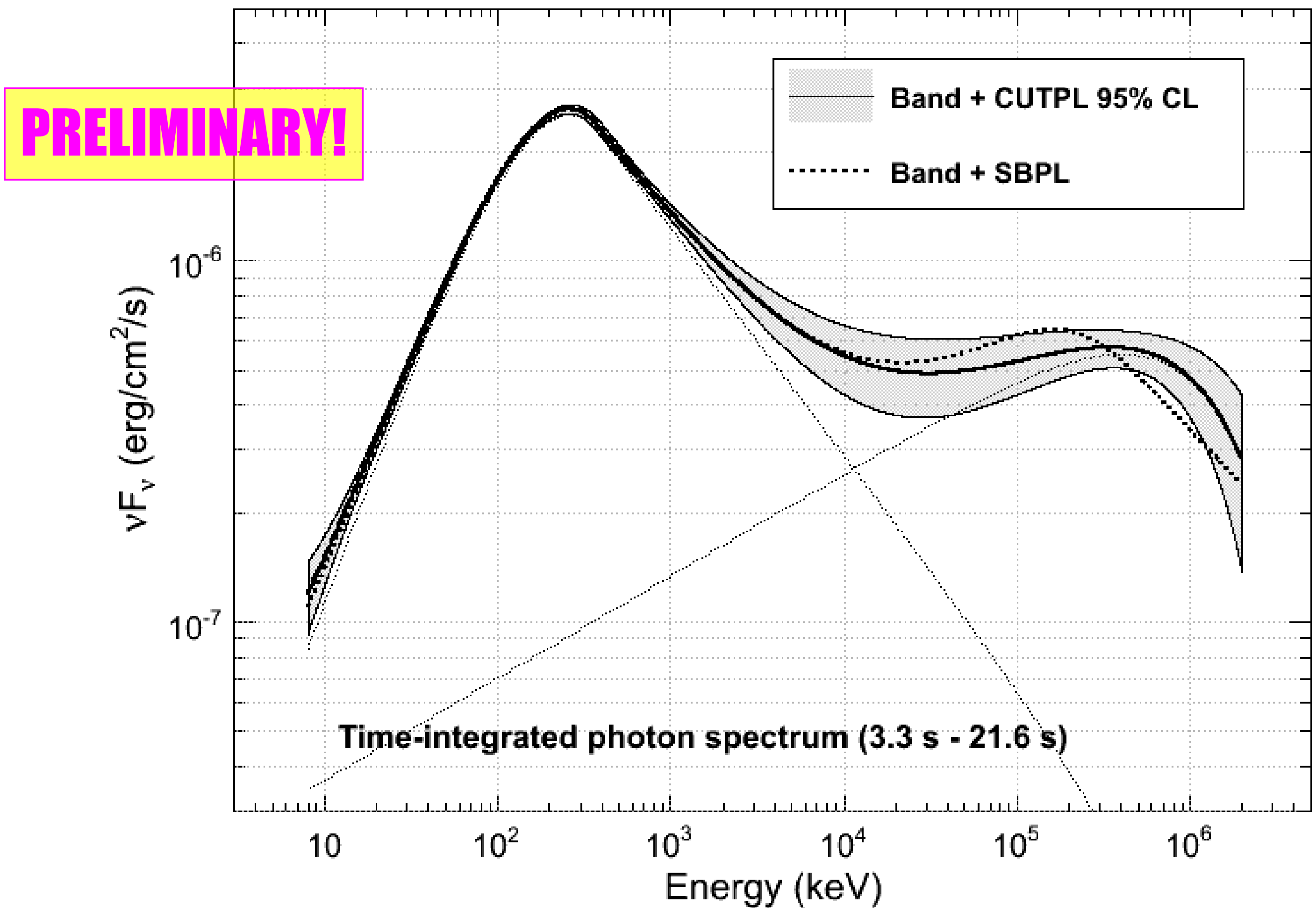






GRB 090926A and the first HE spectral cutoff

- The extra component shows a >5 σ **spectral break at ~1.4 GeV**
- The shape of the spectral break is not constrained
- **First direct measurement of the bulk Lorentz factor: Γ ~ 200-700 (model dependent) if cutoff due to gamma-gamma absorption**



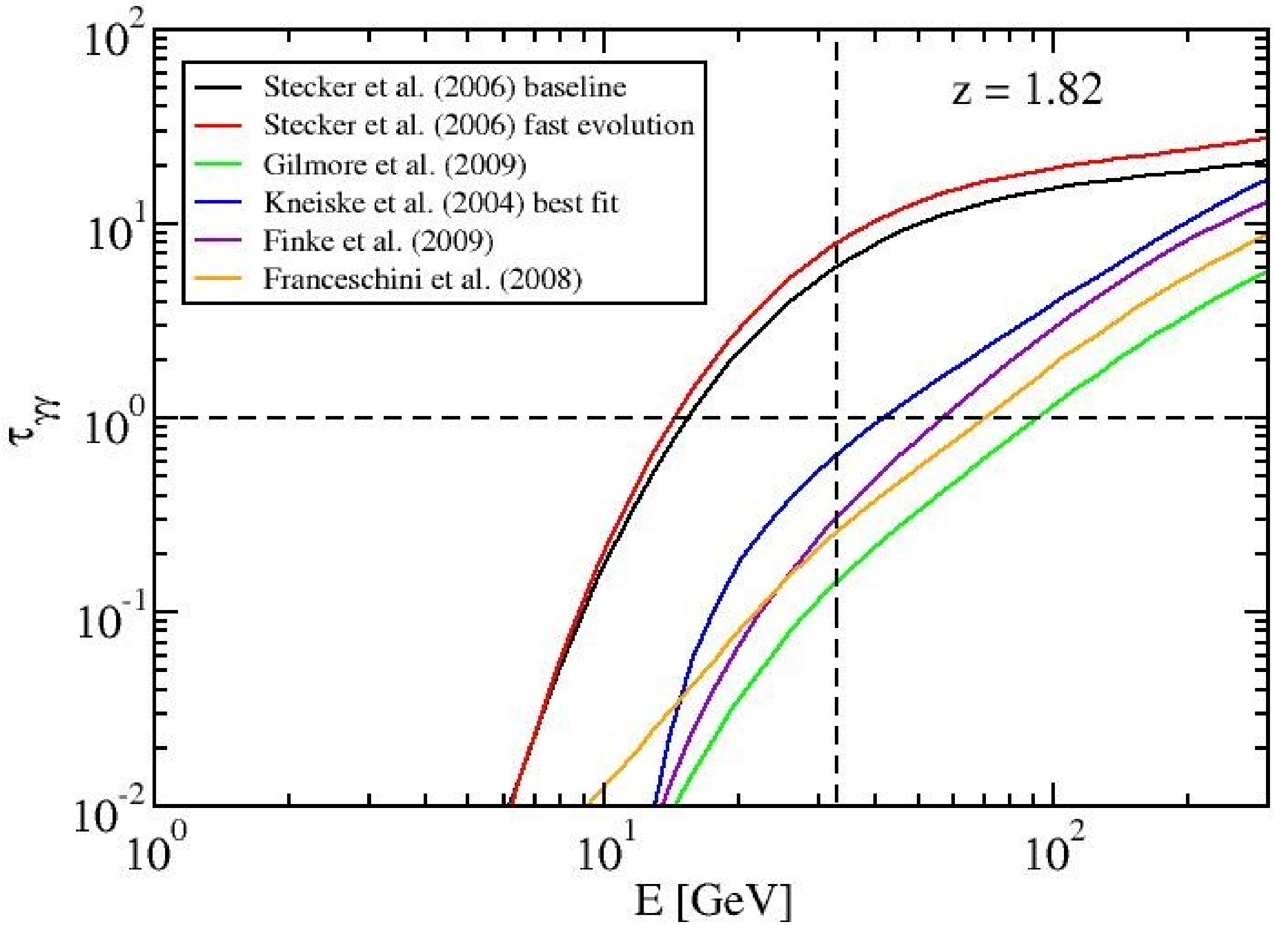
Models for HE delayed onset and PL component

- 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
  - Hard to account for the different photon index values of the HE component and the Band spectrum at low energies
  - But photospheric emission models could explain these properties (Ryde 2010, Toma 2010)
- Hadronic models (pair cascades, proton synchrotron) – Asano 2009, Razzaque 2009
  - GRBs as possible sources of Ultra-High Energy Cosmic Rays
  - Late onset: time to accelerate protons & develop cascades?
  - 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
  - Both scenarios require substantially more energy (1-3 orders of magnitude) than observed
    - GRB 090510: Etotal / Eiso ~ 100-1000
  - Hard to produce correlated variability at low- and high-energies (e.g. spikes of GRB 090926A)?
- Early Afterglow (e+e- synchrotron from external shock) – Kumar 2009, Ghirlanda 2010
  - Can account for the delayed onset of the PL – difficult in the case of GRB 090902B
  - Short variability time scales in LAT data (e.g. GRB 090902B, GRB 090926A) argues against external shock (requires highly clumpy external medium)
  - Requires larger Γ than measured for GRB 090926A, or large external medium density

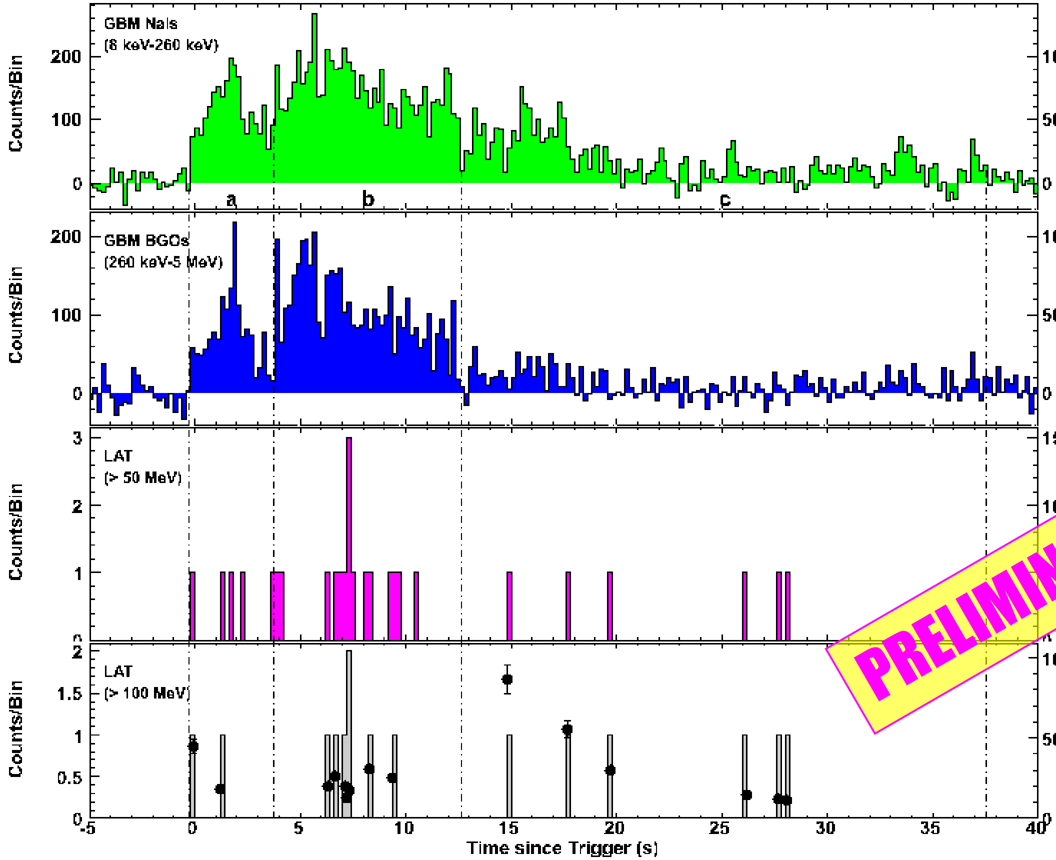
Constraints from gamma-ray opacities – EBL

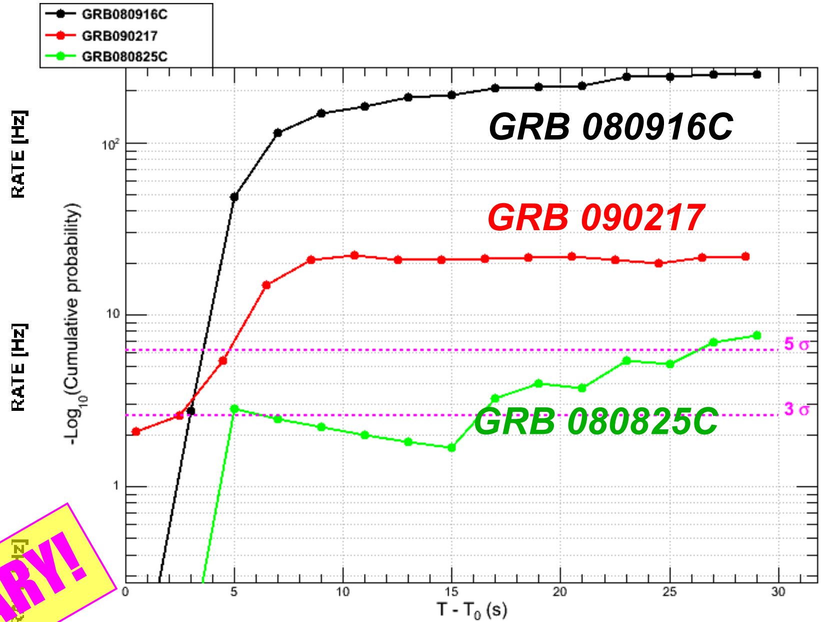
- **Extrinsic absorption by the Extragalactic Background Light**
  - **Most models are optically thin for the 33 GeV photon from GRB 090902B**
  - **“Baseline” and “fast-evolution” models rejected at 3.6 σ**

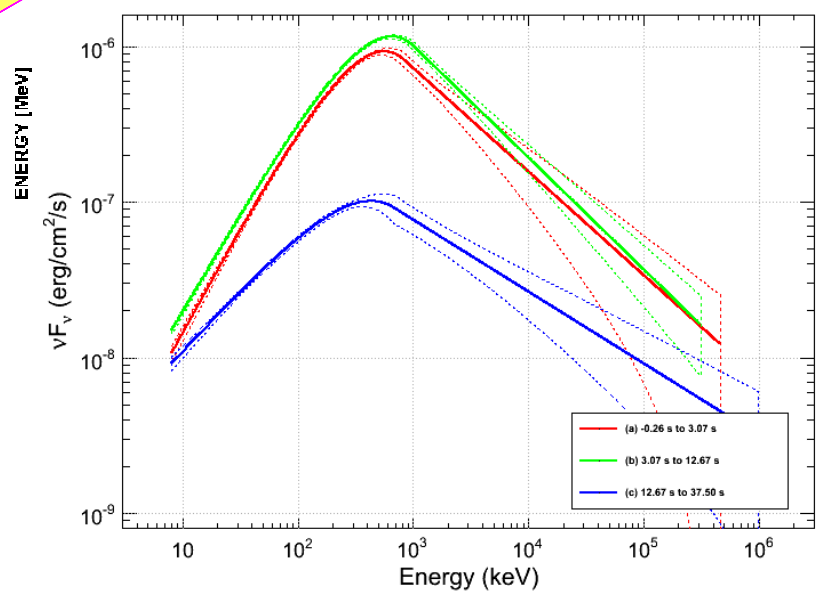
GRB 090902B



The featureless GRB 090217





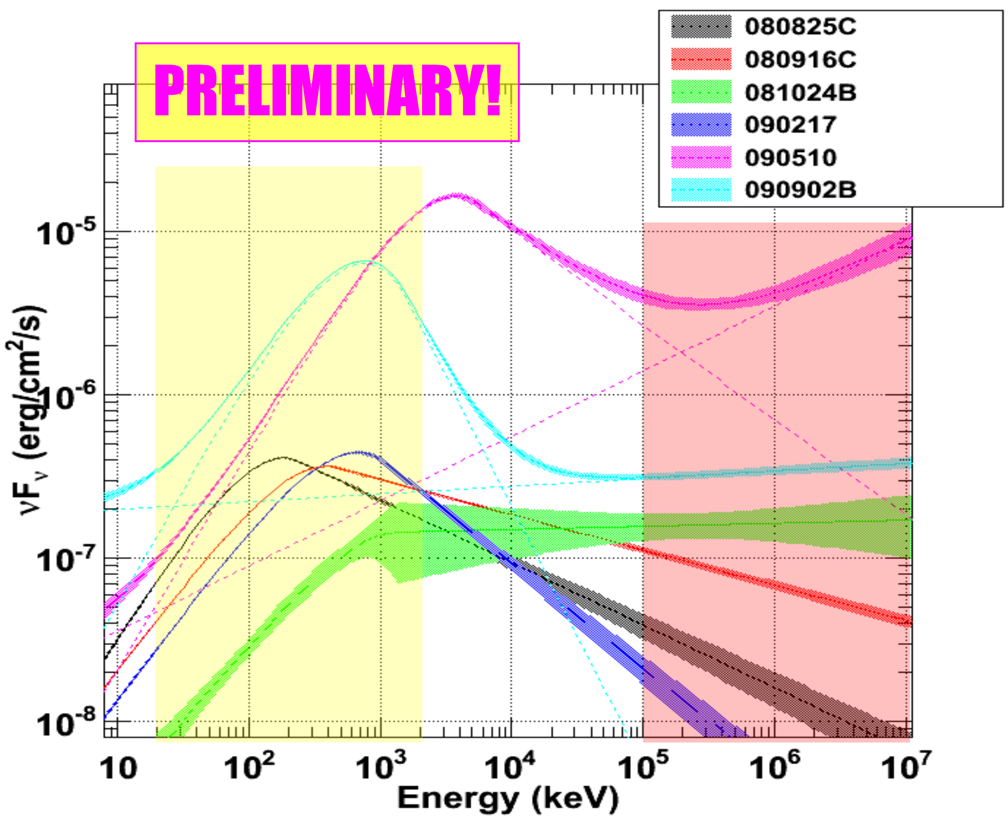


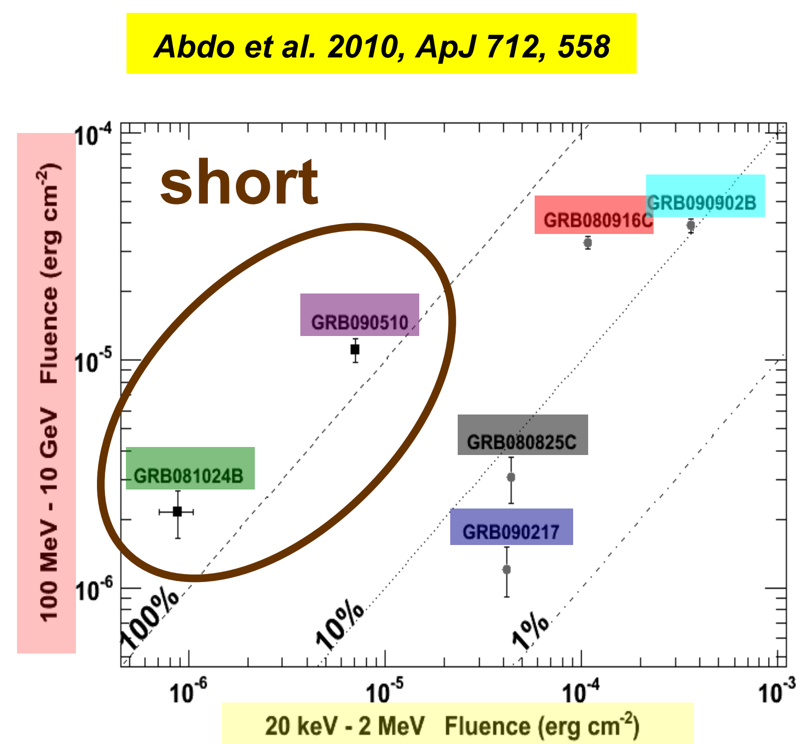
- HE onset not much delayed
- No temporally extended HE emission
- All spectra well fit by a Band function
- No spectral evolution
- Suggests a unique mechanism (synchrotron, jitter radiation)
- How many such GRBs?

Summary of LAT GRBs as of Jan. 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	

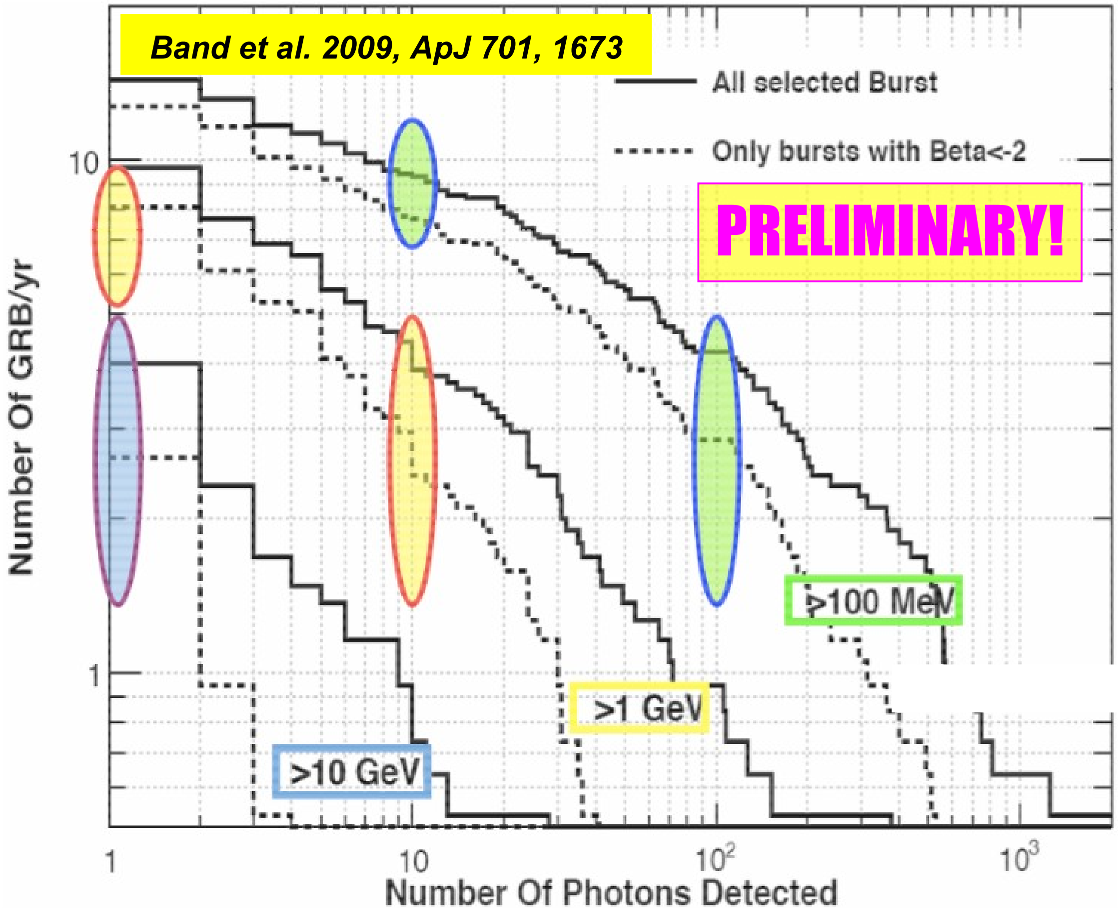
LAT fluence vs. GBM fluence





- **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**

LAT GRB detection rate



- ~9.3 GRBs/year with >10 photons >100 MeV
- ~2.7 GRBs/year with >10 (100) photons >1 (0.1) GeV
- Comparable to estimates based on Band spectrum fits to bright BATSE GRBs
- Suggests that on average, GRBs 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

(But remember: ~5-20 times less energy in the LAT for long GRBs than for short GRBs)

Summary

- GBM ~250 GRBs/year, LAT ~10 GRBs/year (close to pre-launch estimates)
  – Excellent synergy with Swift (7 redshifts, 1 Swift/LAT common trigger)

- Many LAT GRBs show later onset & longer duration of the HE emission
- The 3 brightest LAT GRBs clearly show a distinct HE spectral component
- High GRB outflow Lorentz factors: $\Gamma_{min} \sim 1000$ for the simple one-zone steady-state model
  – First direct measurement $\Gamma \sim 200\text{-}700$ for GRB 090926A (if cutoff from internal absorption)
- On average GRBs radiate only ~10%-20% of their energy in the LAT range
- Short and long GRBs seem to have similar HE properties, but short GRBs may be harder
- Leptonic or hadronic emission at high energies?
- Highest energy photons constrain EBL models
- Best lower limits on LIV (see J. Granot's talk)

- Long-lived GeV emission (not discussed in this talk) is a common property of GRBs

Fermi (GBM and LAT) data and analysis software are public: http://fermi.gsfc.nasa.gov/ssc