GRB Theory in the Fermi Era

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(Royal Society Wolfson Research Merit Award Holder)

on behalf of the Fermi LAT & GBM Collaborations

"Accretion and Outflow in Black Hole Systems"

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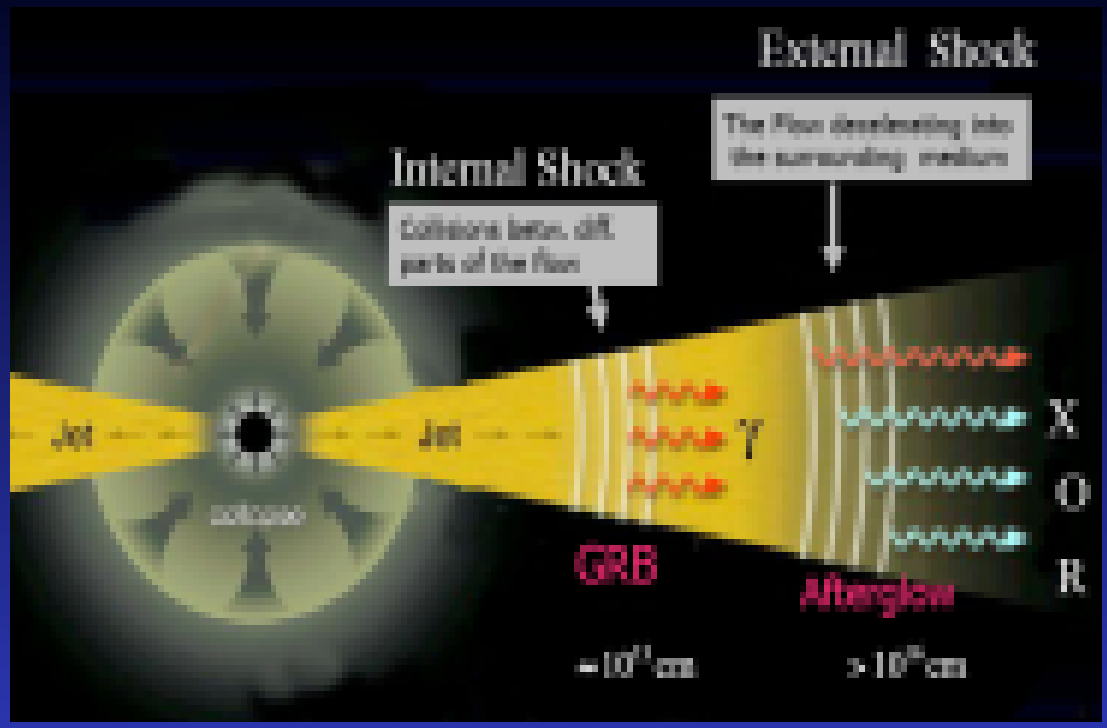
Outline of the Talk:

- Theoretical framework & pre-Fermi observations
- Fermi LAT & GBM overview
- LAT GRB detection rate: what can it teach us?
- The Bulk Lorentz factor: lower limits & actual value
- Properties of high-energy prompt GRB emission:
  distinct spectral component, delayed onset & longer duration
- Pros & cons of different models
- Comparing between short & long LAT GRBs
- Limits on Lorentz Invariance Violation
- **Conclusions**

GRB Theoretical Framework:

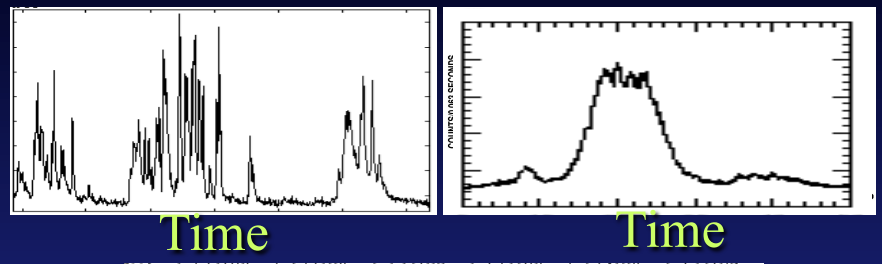
- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: internal shocks? emission mechanism?



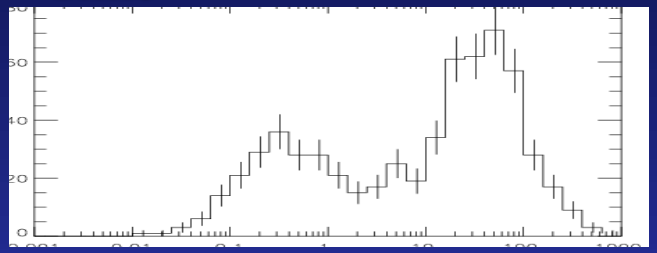
- **Deceleration**: the outflow decelerates (by a **reverse** shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

Prompt GRB Observations ($\lesssim$ MeV)

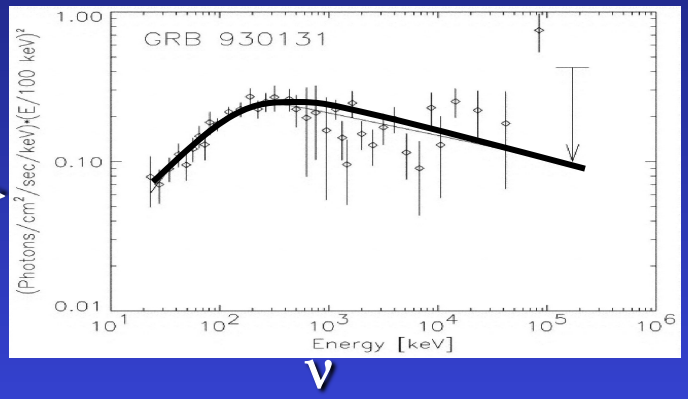
- Variable light curve



- Duration: $\sim 10^{-2} - 10^{3}$ sec

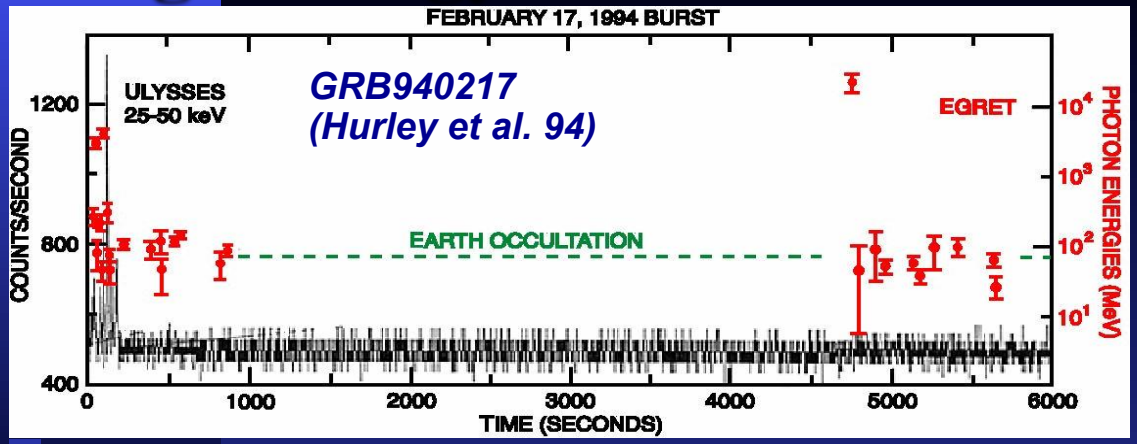


- Spectrum: non-thermal
  νF_ν peaks at $\sim$ 0.1-1 MeV
  (well fit by a Band function)



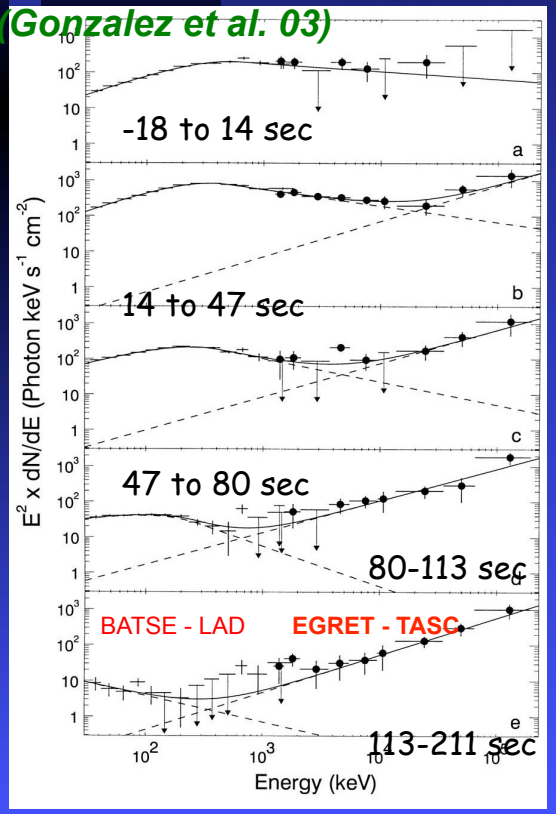
- Rapid variability, non thermal spectrum & $z \sim 1$
  $\Rightarrow$ relativistic source ($\Gamma \gtrsim 100$) (compactness problem:
  Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

High energy emission from GRBs: Pre-Fermi era

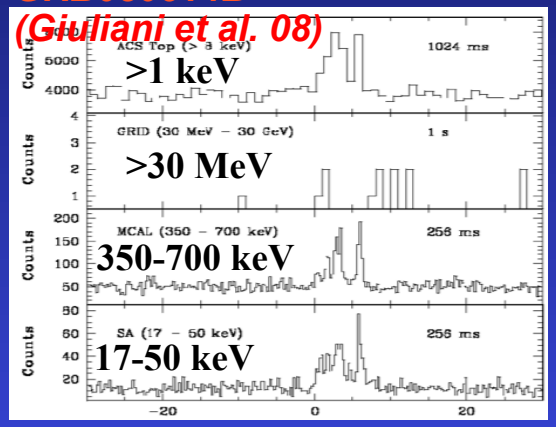


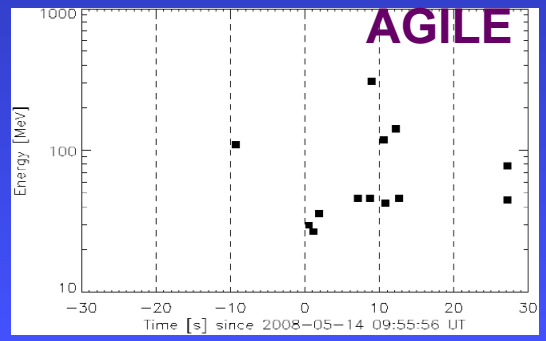
EGRET

GRB941017
(Gonzalez et al. 03)



GRB080514B
(Giuliani et al. 08)

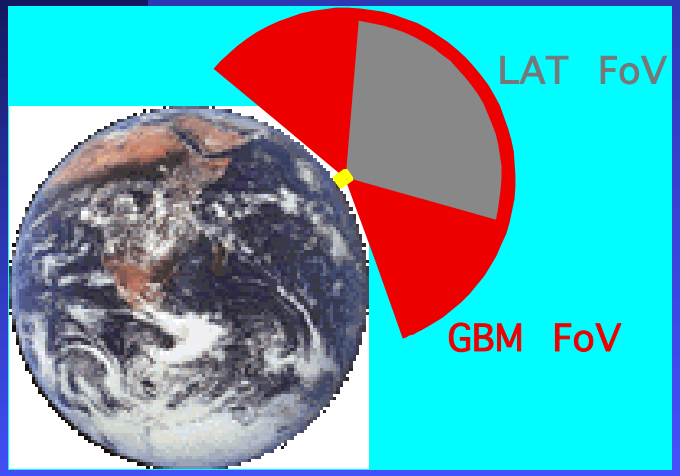


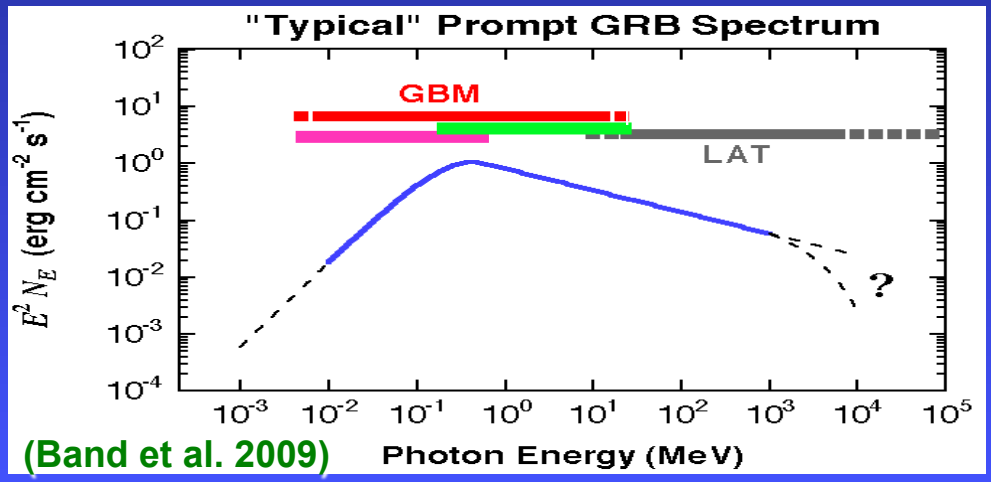


- Little known about GRB emission above ~100 MeV
- **EGRET** detected only 5 (long) GRBs, most notably:
  - **GRB940217: GeV photons were detected up to 90 minutes after the GRB trigger**
  - **GRB941017: distinct high-energy spectral component (up to 200 MeV), with a different temporal evolution & at 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 Gamma-ray Space Telescope (Fermi Era; launched on June 11, 2008):

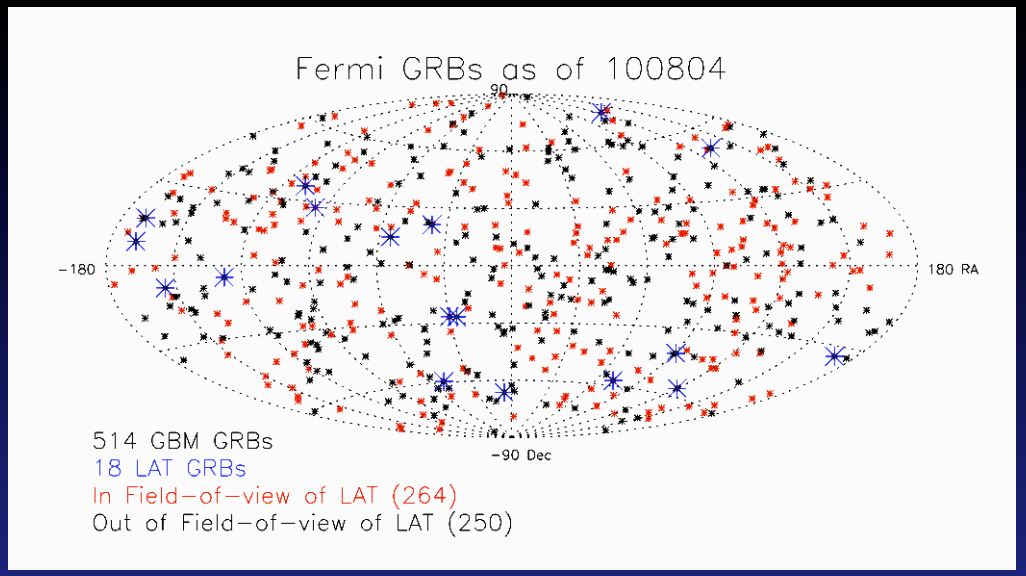
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime

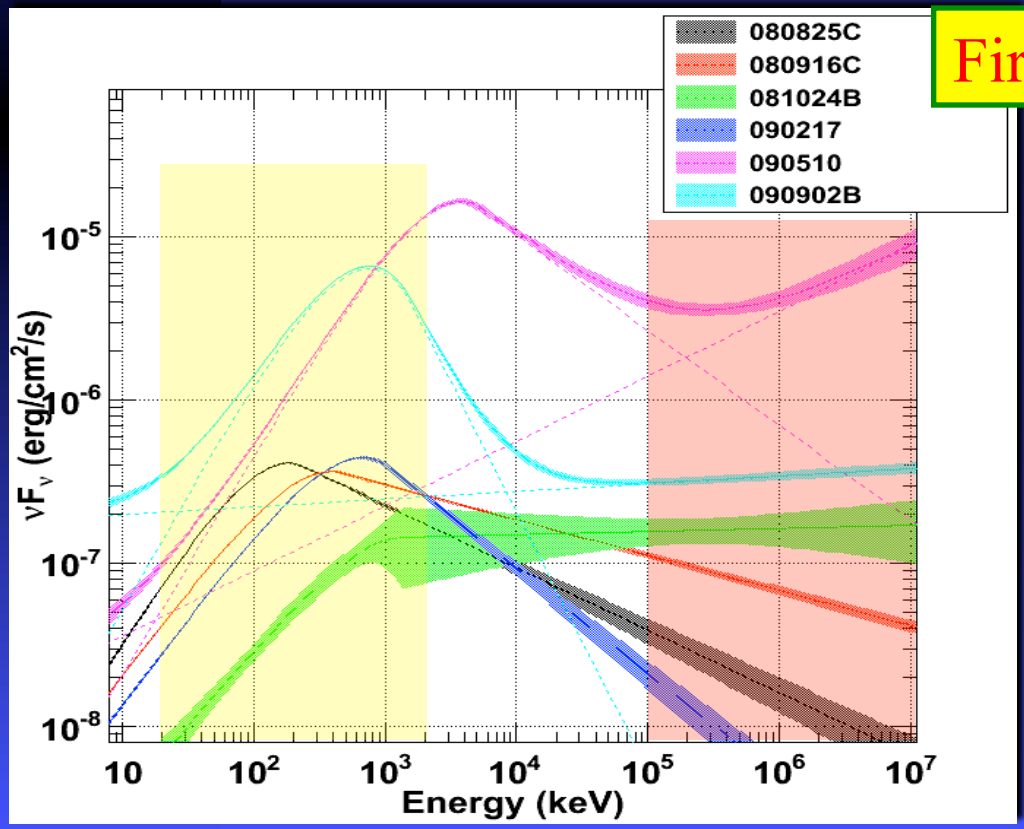




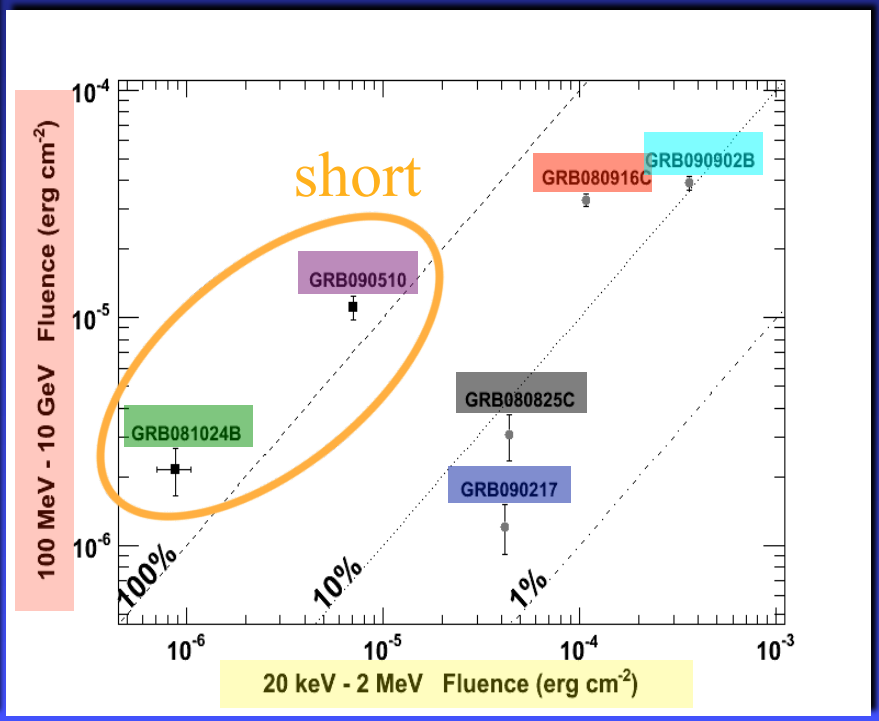
Fermi GRBs:

- **GBM:**
  - ~ 250 GRB/yr (~20% short)
  - ~ ½ in LAT FoV
- **LAT: 18 GRBs in ~ 2 yr**
  - 2 out of 18 are short: ~ 11%



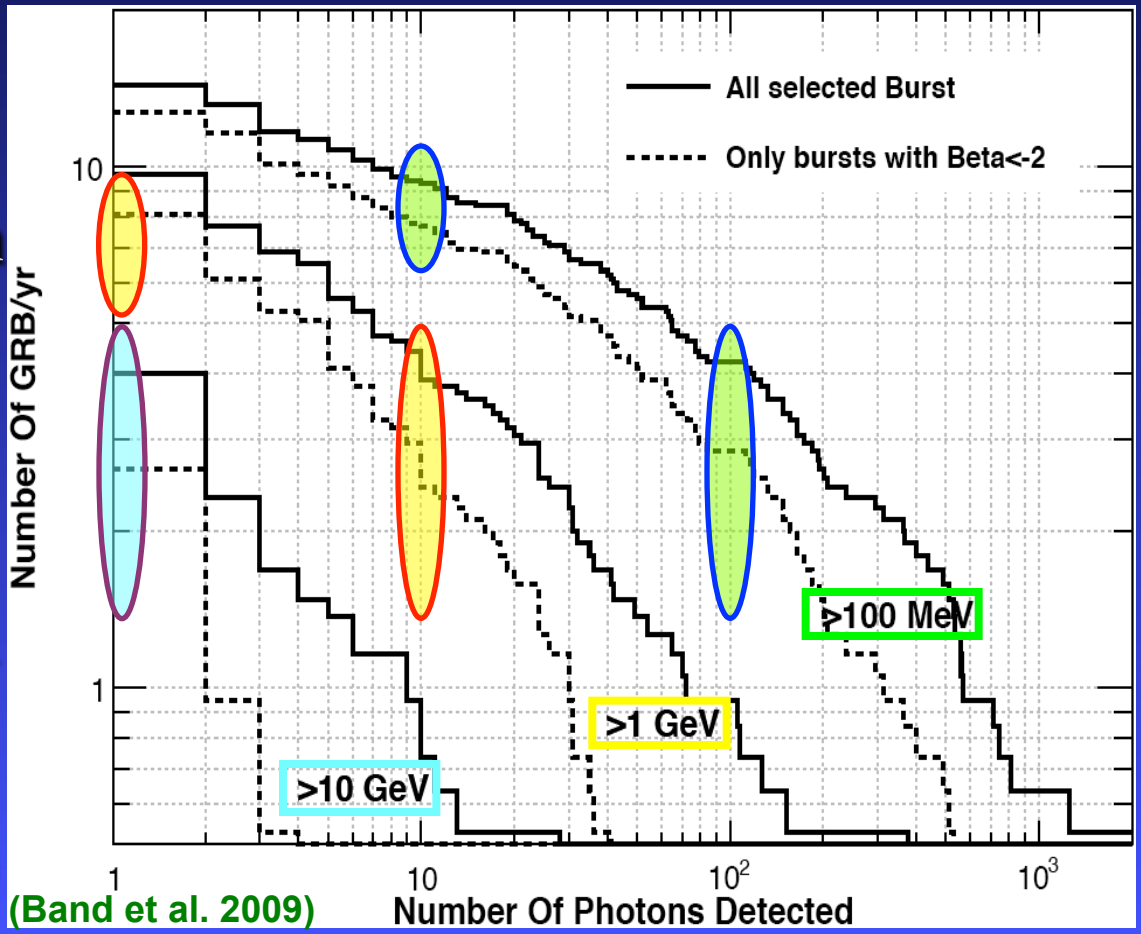


First detections of sort GRBs at HE



Fermi LAT GRB detection rate

- ~ 7.3, 8.7 GRB/yr with ≥ 1, 10 photons above 1, 0.1 GeV
- ~ 2.7 GRB/yr with ≥ 1, 10, 100 γ's above 10, 1, 0.1 GeV
- Comparable to estimates based on Band spectrum fits to bright BATSE GRBs
- Suggests: 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 (~5-10 times less energy in the LAT range)

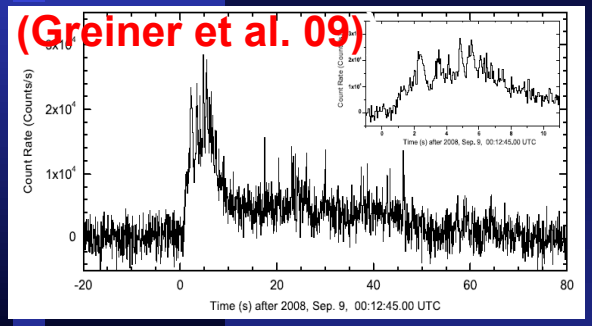


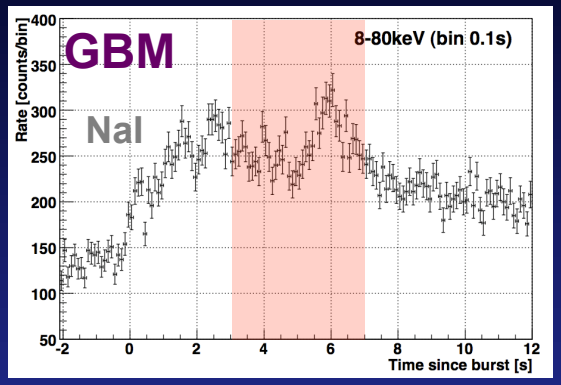
(Band et al. 2009)

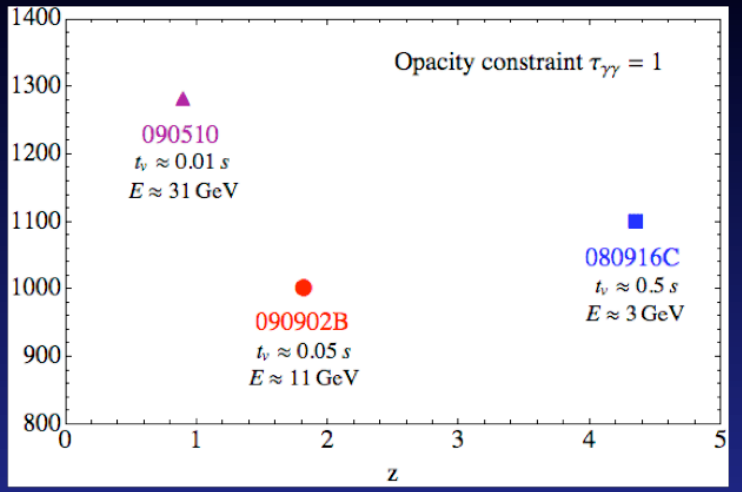
Constraints on the Bulk Lorentz factor:

GRB080916C: $\Gamma \gtrsim 900$ ($\Delta t = 2$ s)

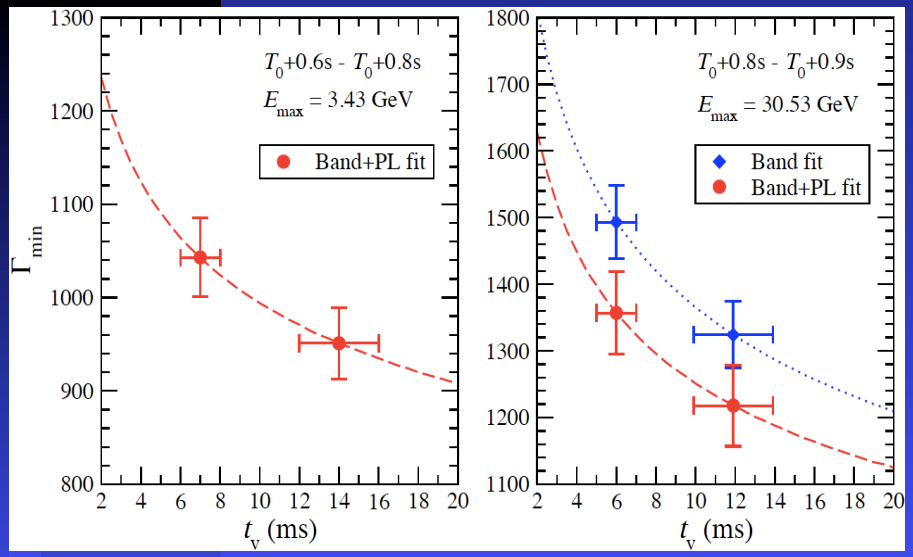
INTEGRAL light curve (Greiner et al. 09)







GRB090510: $\Gamma \gtrsim 1200$

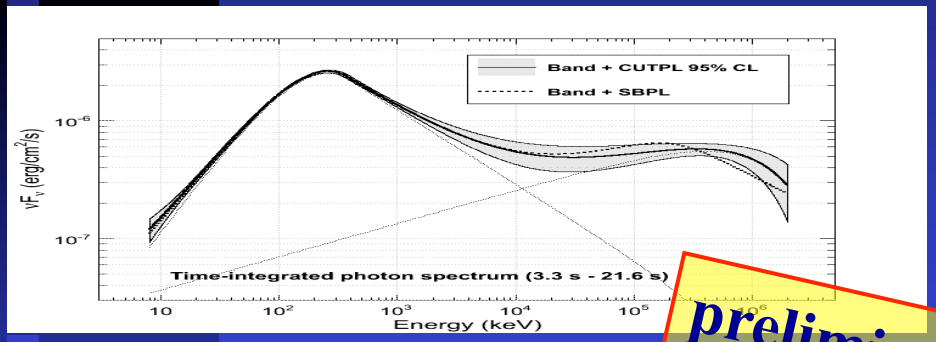


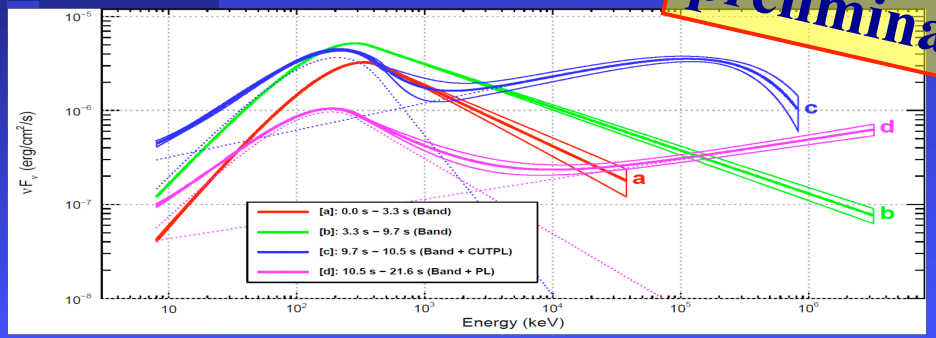
GRB090902B: $\Gamma \gtrsim 1000$

- Our Γ_{min} is more robust than before: it doesn't assume the spectrum extends beyond the highest energy detected photon
- For our conservative assumption $\Gamma_{min} \lesssim (1+z)E_{ph,max}/m_e c^2 \approx 200(1+z)(E_{ph,max}/100\,\mathrm{MeV})$ so that a high Γ_{min} requires the observed spectrum to reach a sufficiently high energy $E_{ph,max}$

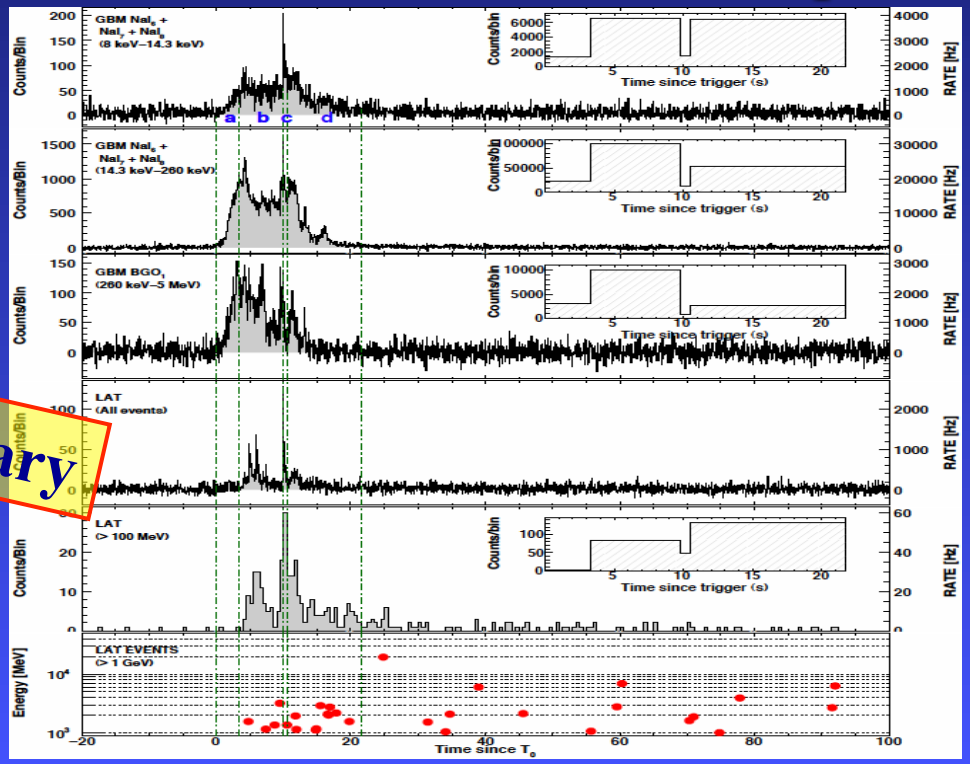
Constraints on the Bulk Lorentz factor:

- Γ_{min}: no high-energy cutoff due to intrinsic pair production
  ⇒ strict lower limits on Lorentz factor of the emitting region
- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ for more realistic time-dependent self-consistent thin shell model (**JG et al. 2008**)
- **GRB 090926A**: high-energy cutoff – if due to intrinsic pair production then $\Gamma \sim 200\text{-}700$



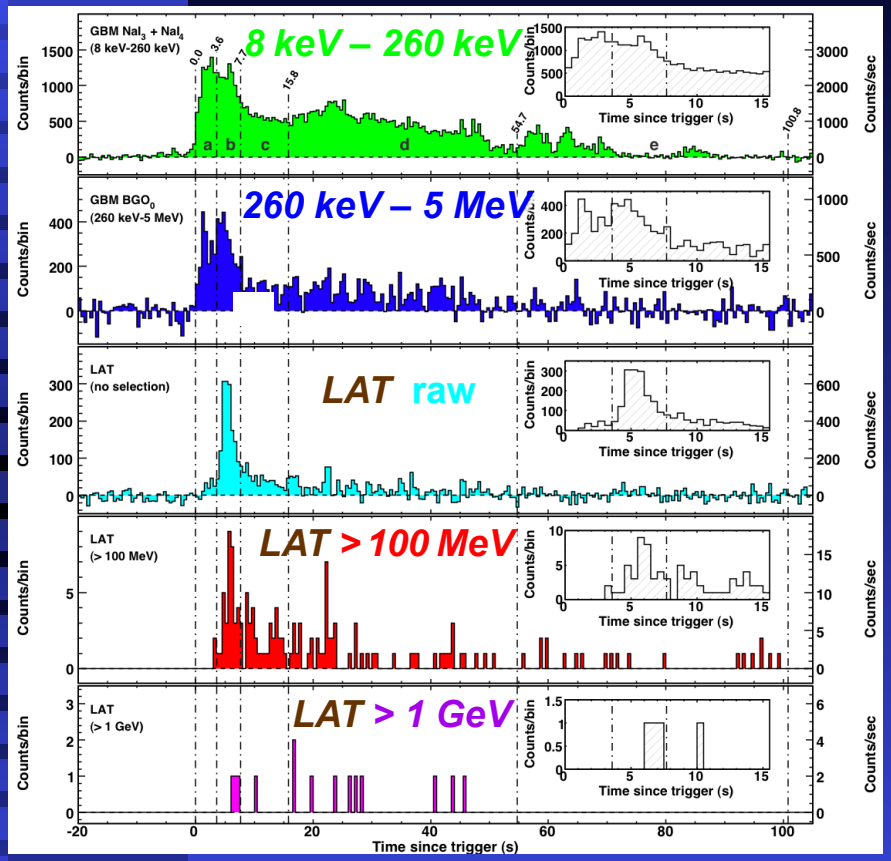


Preliminary



Delayed Onset of High-Energy Emission

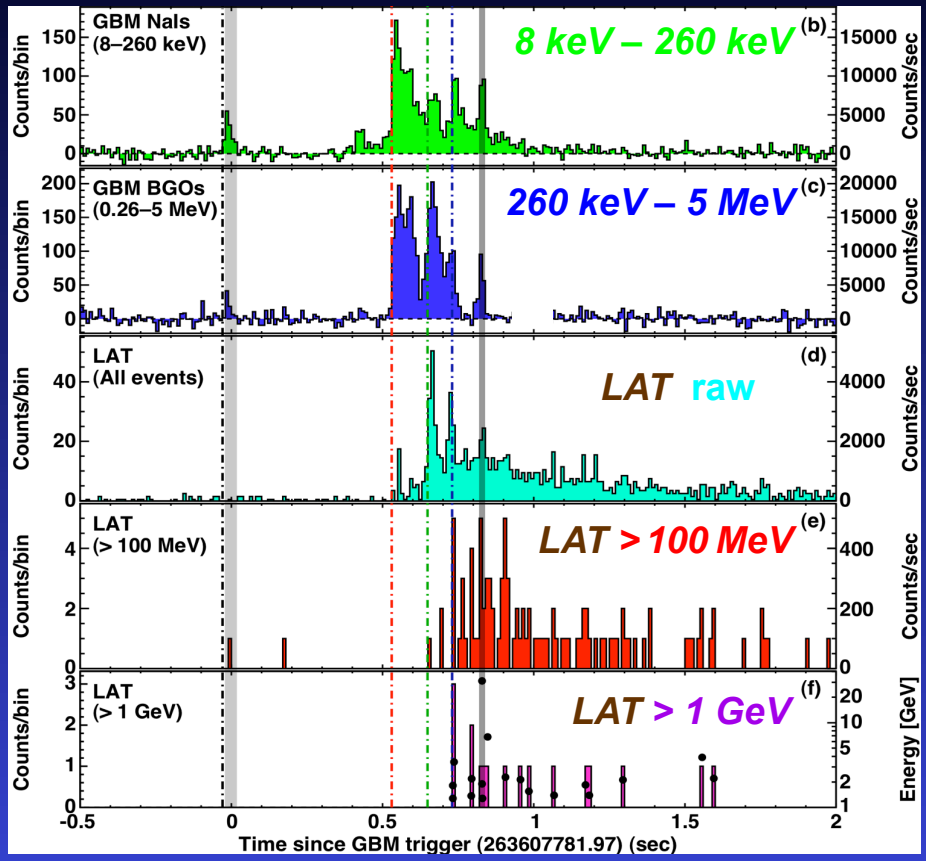
GRB080916C



(Abdo et al. 2009, Science, 323, 1688)

- The 1st LAT peak coincides with the 2nd GBM peak
- Delay in HE onset: ~ 4-5 s

GRB090510

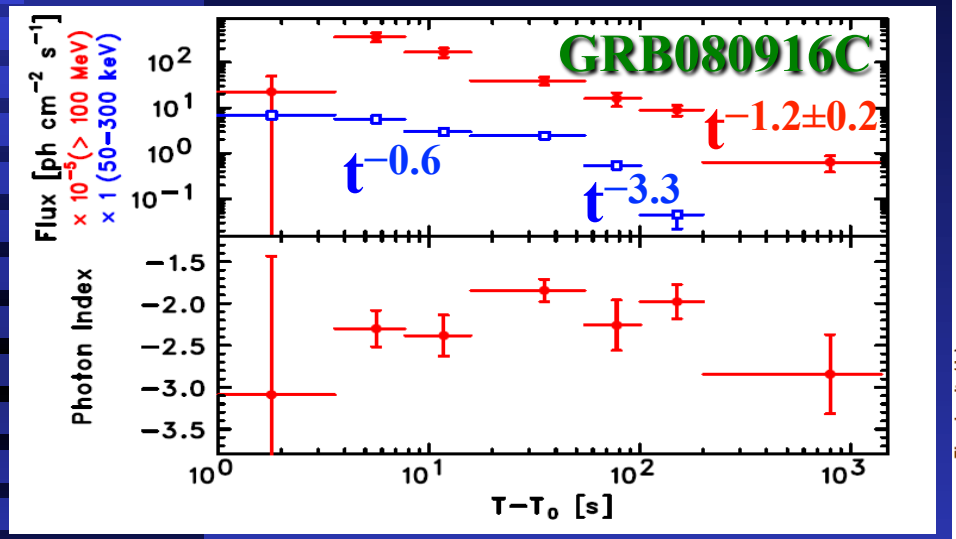


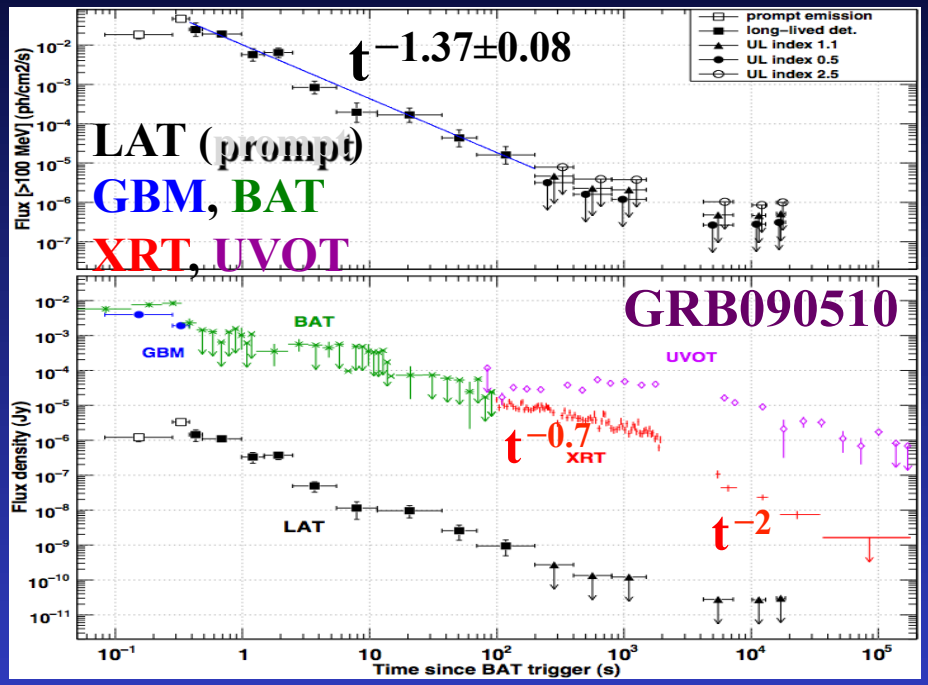
(Abdo et al. 2009, Nature, 462, 331)

- The first few GBM peaks are missing in LAT but later peaks coincide; the delay is 0.1-0.2 s

Temporally extended emission: HE afterglow?

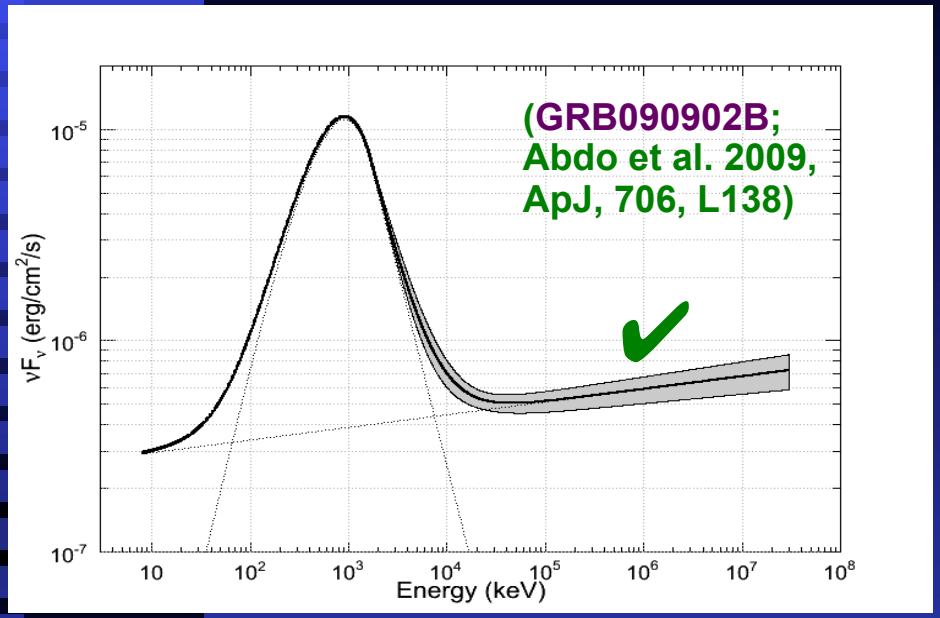
- Most LAT detected GRBs show significant HE emission lasting after the low-energy emission becomes (almost) undetectable
  (originally detected by EGRET; Hurley et al. 94)



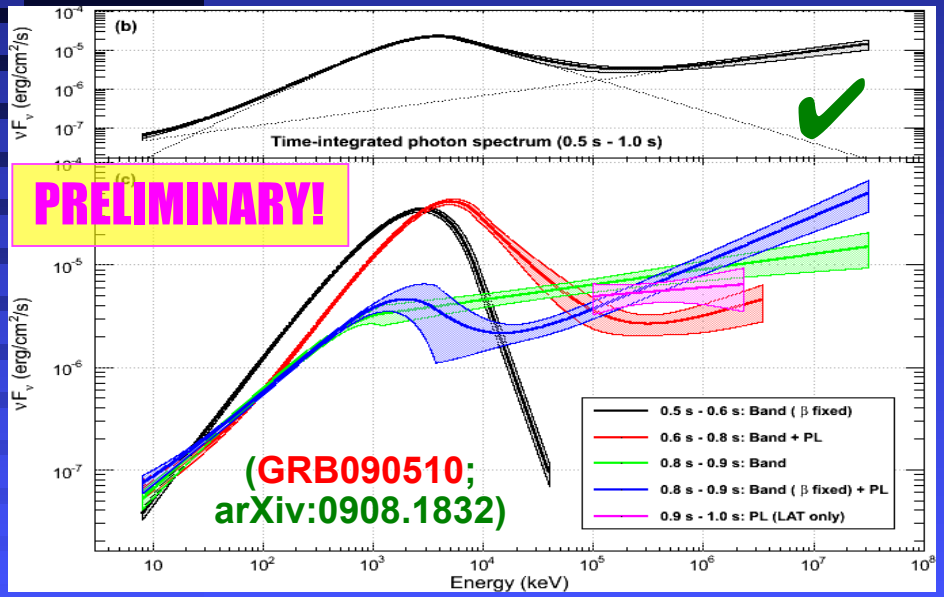


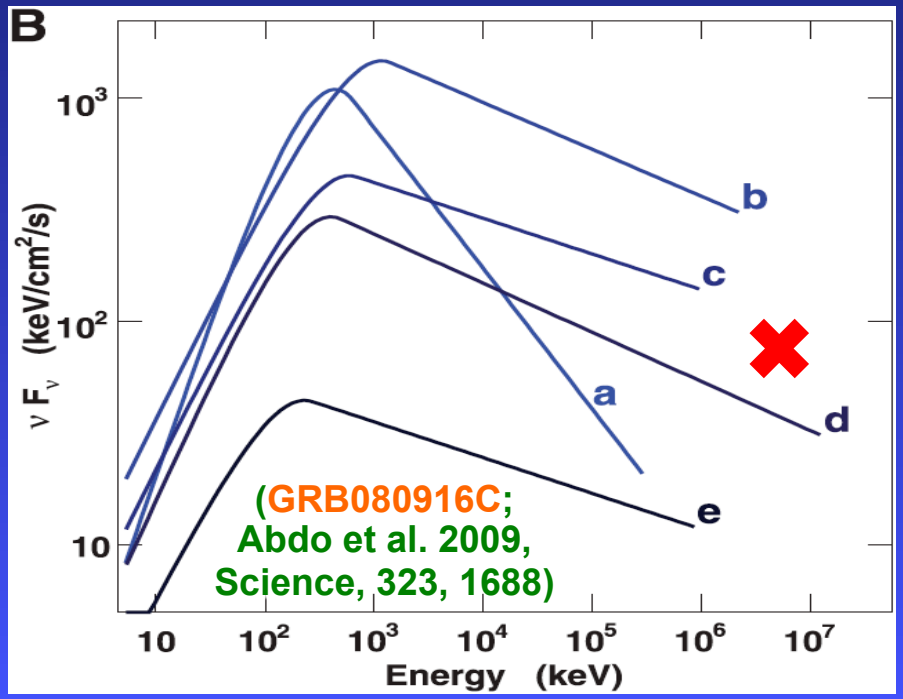
- Possible origins:
  - Afterglow SSC emission (though no spectral hardening, time gap, or synchrotron/SSC valley in the spectrum are observed)
  - Afterglow synchrotron: likely at $t \gg T_{GRB}$; but: variability, $E_{syn,max}$
  - Late X-ray flare photons IC scattered by afterglow electrons; var?
  - Long lived cascade induced by ultra-relativistic ions ($t_{ad,cool} \sim t_{var}$)
  - Pair echo: TeV + EBL $\gamma\gamma \rightarrow e^+e^-$, & the e^+e^- IC scatter the CMB

Distinct High-Energy Spectral Component



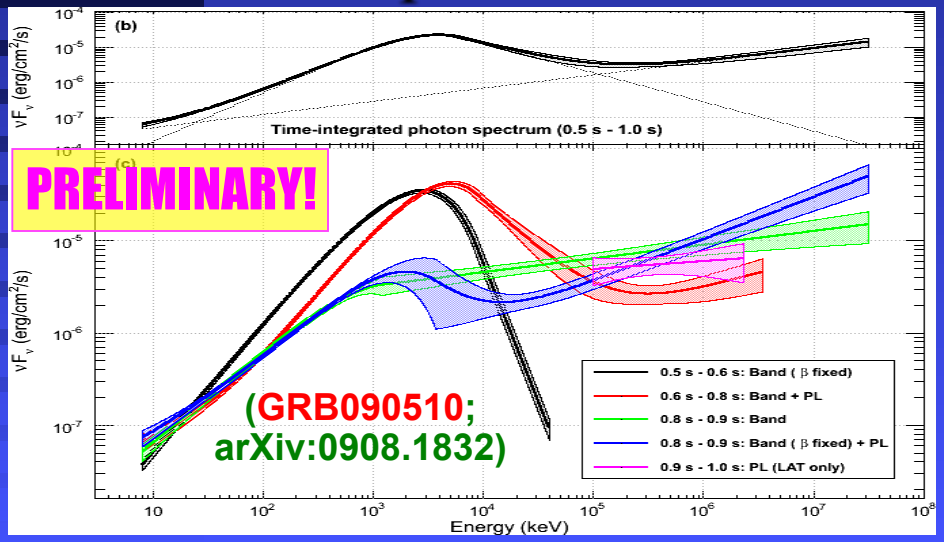
- Clearly (>5σ) appears only in 3 LAT GRBs, but these are the brightest in LAT so far
- Suggests it is very common but good photon statistics is needed for clear evidence

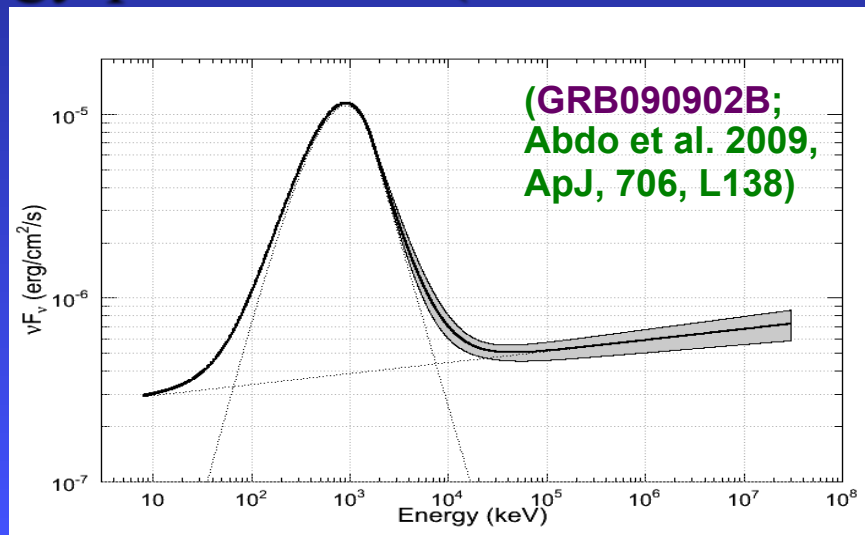




Late onset/HE spectral component: Possible Origin

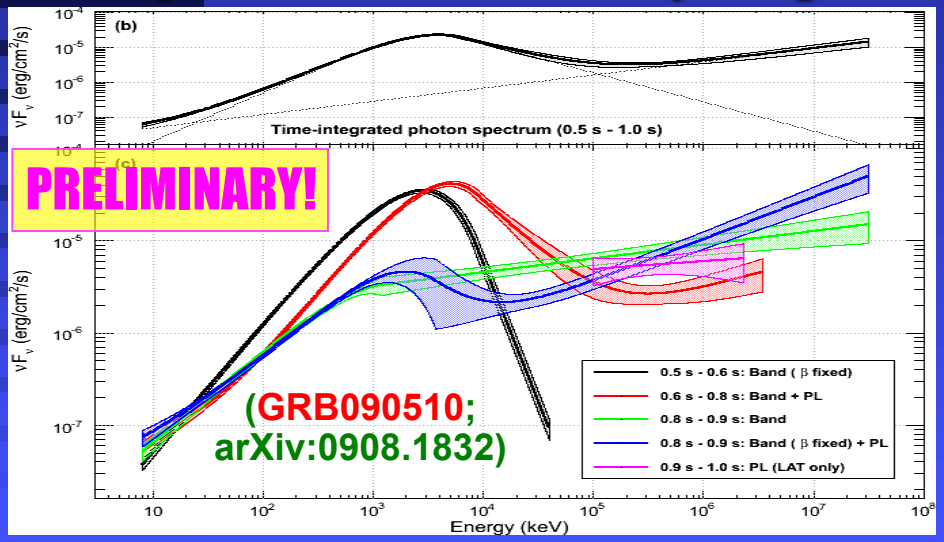
- **Leptonic**: inverse-Compton (or synchrotron self-Compton)?
  - Hard to produce a delayed onset longer than spike widths (the seed photon field builds-up on the dynamical time)
  - A gradual increase in the HE photon index **β** (determined by the electron energy dist.) is not naturally expected
  - Hard to account for the different photon index values of the HE component & the Band spectrum at low energies
  - Hard to produce a low-energy power-law (GRB090902B)

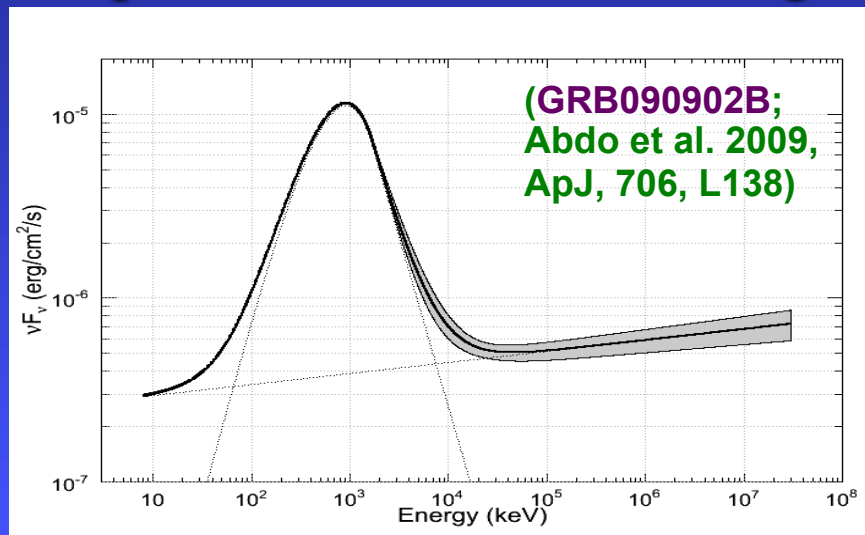




Late onset/HE spectral component: Possible Origin

- **Hadronic**: (pair cascades, proton synchrotron) ?
  - Late onset: time to accelerate protons+develop cascades?
  - Does not naturally account the gradual increase in **β**
  - Hard to produce the observed sharp spikes that coincide with those at low energies (+ a longer delay in the onset)
  - GRB090510: large energy needed: $E_{total}/E_{\gamma,iso} \sim 10^2 - 10^3$
  - GRB090902B: synchrotron emission from secondary $e^{\pm}$ pairs can naturally explain the power-law at low energies





Summary of the 14 LAT GRBs so far:

GRB	Angle From LAT	Duration (or class)	Number of events > 100 MeV	Number of events > 1 GeV	Delayed HE onset	Long-lived HE emission	Extra spectral comp.	Highest Energy γ (GeV)	Redshift
080825C	~ 60°	long	~ 10	0	?	✔	X	0.57	
080916C	49°	long	145	14	✔	✔	?	13	~ 4.35
081006	~ 16°	long	~10	0	X	X	X	0.65	
081024B	21°	short	~ 10	2	✔	✔	?	3.1	
081215A	~ 86°	long	—	—	—	—	--	—	
090217	~ 34°	long	~ 10	0	X	X	X	0.31	
090323	~ 55°	long	~ 20	> 0	?	✔	?	7.5	3.57
090328	~ 64°	long	~ 20	> 0	?	✔	?	25	0.7354
090510	~ 14°	short	> 150	> 20	✔	✔	✔	31	0.903
090626	~ 15°	long	~ 20	> 0	?	✔	?	2.1	
090902B	51°	long	> 200	> 30	✔	✔	✔	33	1.822
090926	~ 52°	long	> 150	> 50	✔	✔	✔	20	2.1062
091003A	~ 13°	long	~ 30	> 0	?	?	?	2.8	0.8969
091031	~ 22°	long	~ 20	> 0	?	?	?	1.2	
100116A	~ 29°	long	~ 20	3	?	?	?	2.2	
100225A		long							
100325A		long?							
100414A		long	~ 30					4.7	1.368
100707A		long							
100724A		long							

Long vs. Short GRBs @ High-Energies:

Property (HE: >0.1GeV)	Short GRBs	Long GRBs
Delayed HE onset	1 or 2 out of 2 ✔	3 out of 5 ✔ (+ many inconclusive cases)
Long-lived HE emission	2 out of 2 ✔	7 out of 9 ✔ (+ some inconclusive cases)
Redshift	1 out of 2 ✔ (z = 0.903 for GRB090510)	7 out of 16 ✔ (0.74, 0.90, 1.37, 1.82, 2.11, 3.57, 4.35)
Bright	1 out of 2 ✔ >100 (10) events >0.1 (1) GeV	3 out of 16 ✔ >100 (10) events >0.1 (1) GeV
Γ_{min}	**1200** for GRB090510	**900, 1000** (080916C, 090902B)
HE spectral component	1 out of 2 ✔ (GRB090510)	2 out of 16 ✔ (GRBs 090902B, 090926)

They show similar HE emission properties!

Limits on LIV from Fermi GRBs

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
090926	long	> 150	> 50	1 , 3	0.066, 0.082	+1	~ 20 GeV	2.1062

- 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

Conclusions:

- LAT detection rate ~9 GRB/yr ⇒ on average GRBs radiate only ~10-20% of their energy in the LAT range
- Prompt spectrum: the 3 brightest LAT GRBs clearly (>5σ) show a distinct high-energy spectral component
- Many LAT GRBs show **later onset & longer duration** of the high-energy emission, relative to low energies
- Lower limits on GRB outflow Lorentz factor are model dependent: $\Gamma_{min} \sim 10^{2.5}$-$10^{3}$; GRB090626A: $\Gamma \sim$ 220-720
- short & long GRBs seem to have similar HE properties: delayed onset, longer duration, distinct HE spectral component & high Γ_{min}, but short GRBs may be harder
- Limit on a possible variation of the speed of light with photon energy, beyond Planck scale: $M_{QG,1} > 1.2 M_{Planck}$