Gamma-Ray Bursts in the AGILE / Fermi era

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The Third Birthday

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Outline

a) The puzzle of GRB emission physics

b) The impact of high energy observations by AGILE and Fermi

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a) The puzzle of GRB emission physics

b) The impact of high energy observations by AGILE and Fermi

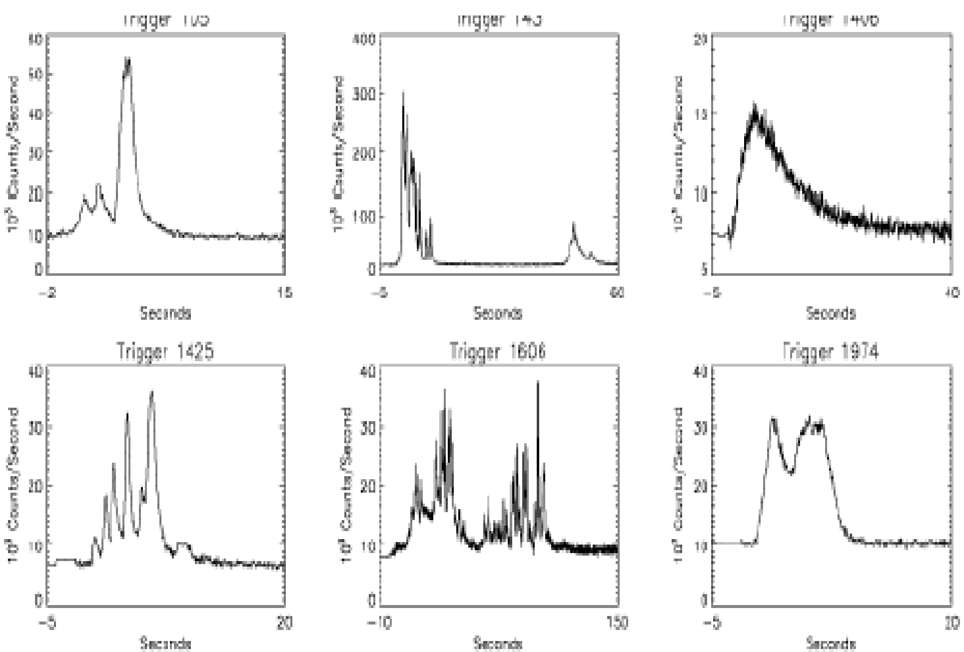
Talk by Del Monte

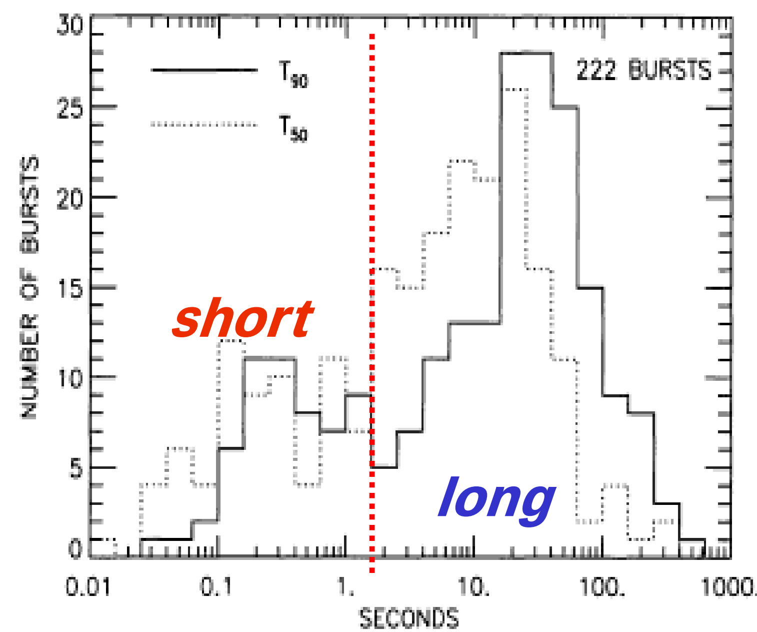
This talk

The puzzle of GRB emission physics

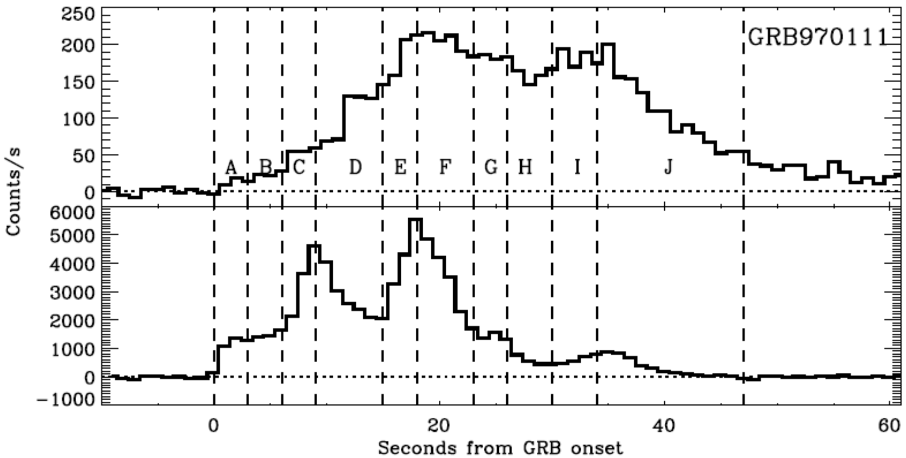
➢ *Gamma-Ray Bursts: a complex phenomenon*

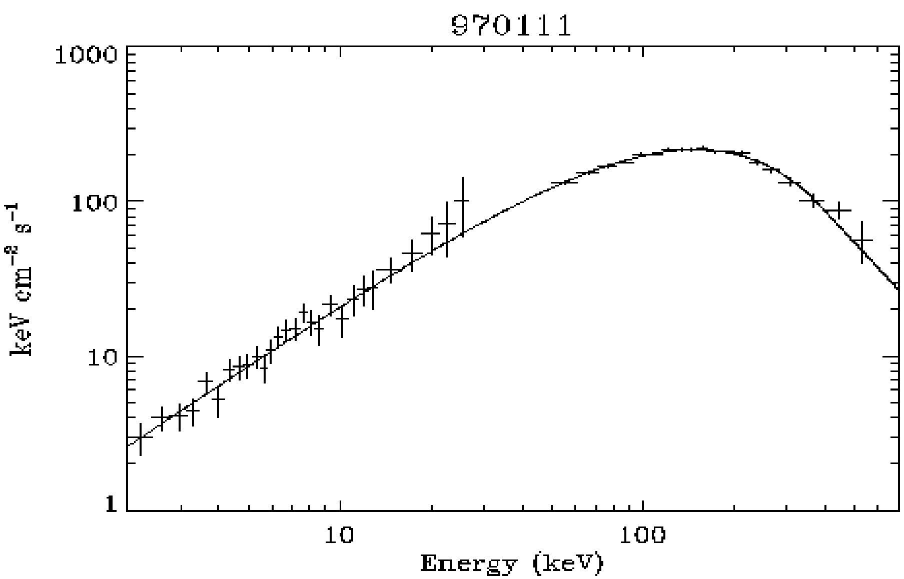
❑ “prompt” emission: complex and unclassifiable light curves, variability down to a few ms

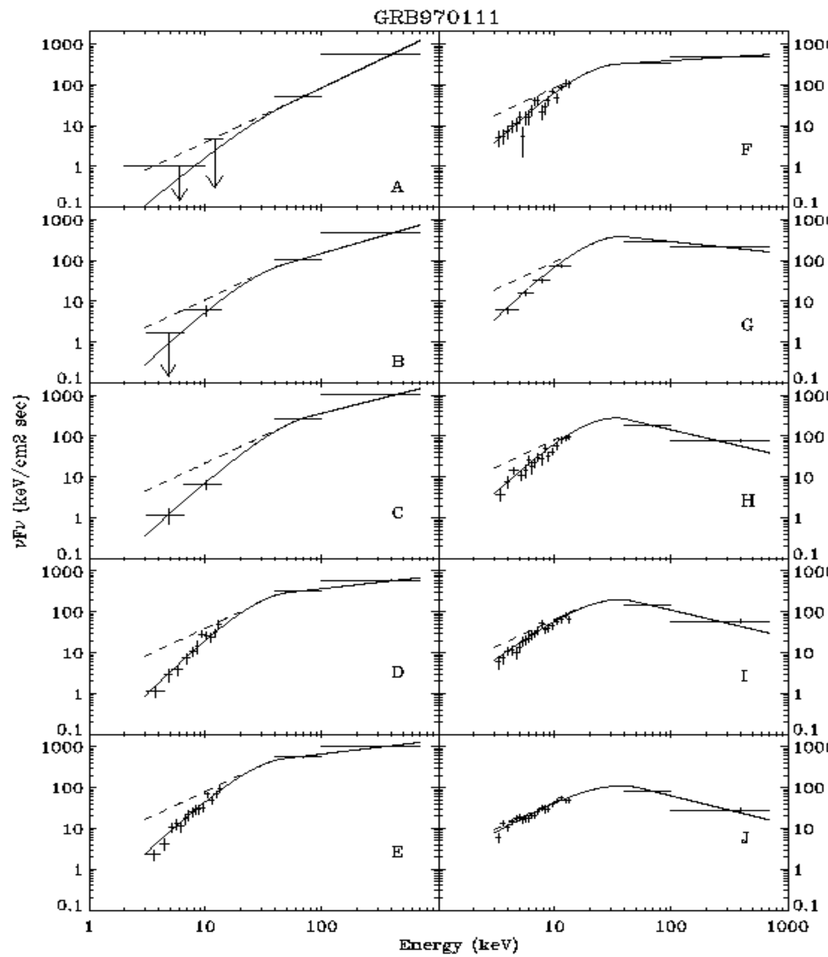




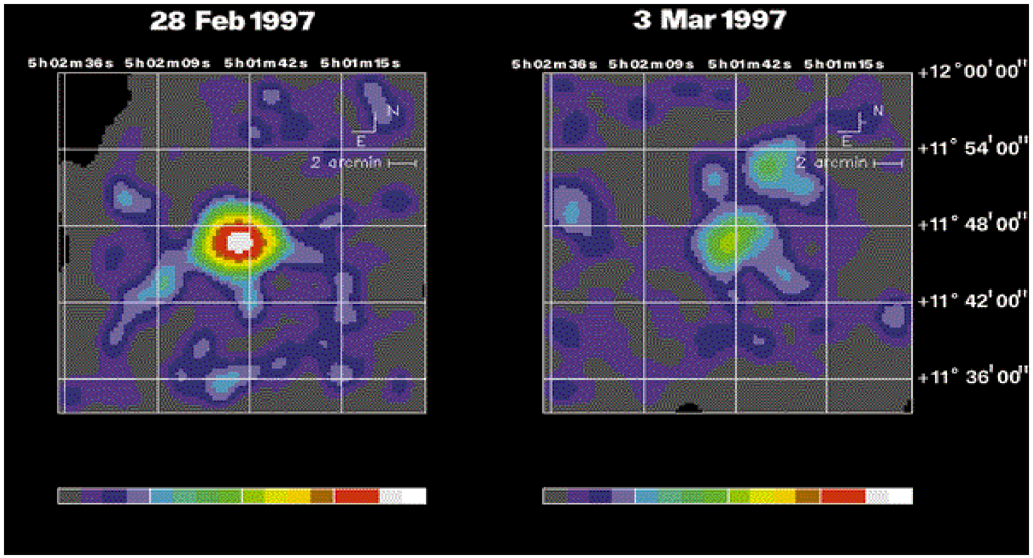
❑ prompt emission: fastly evolving non thermal spectra

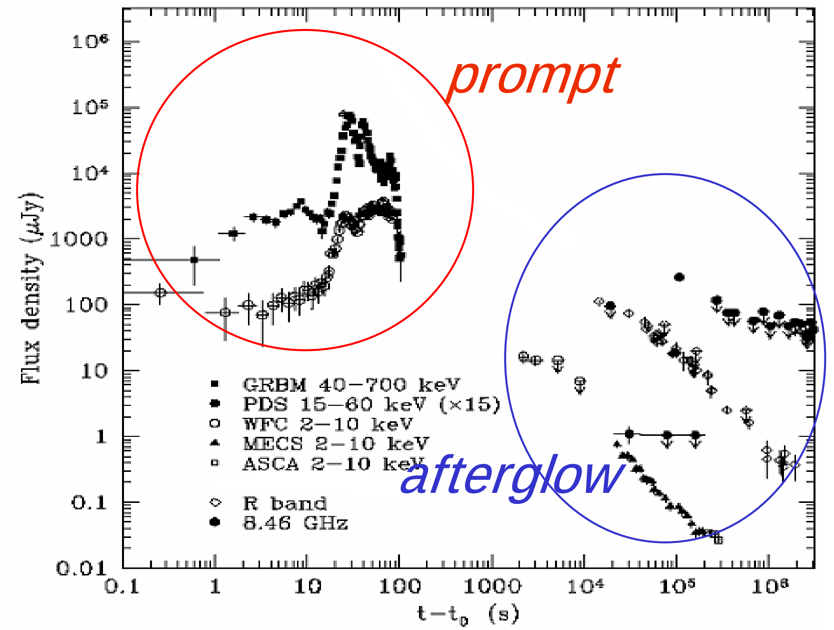


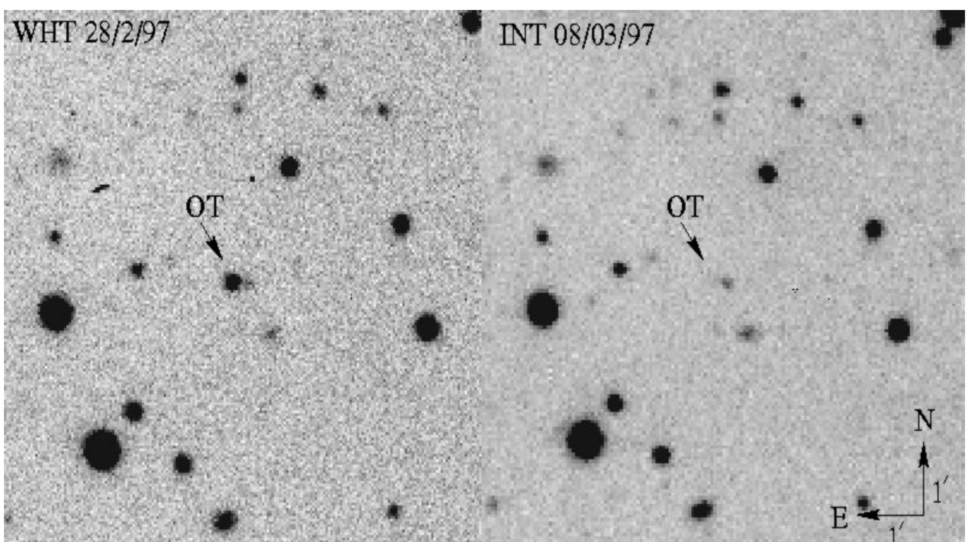


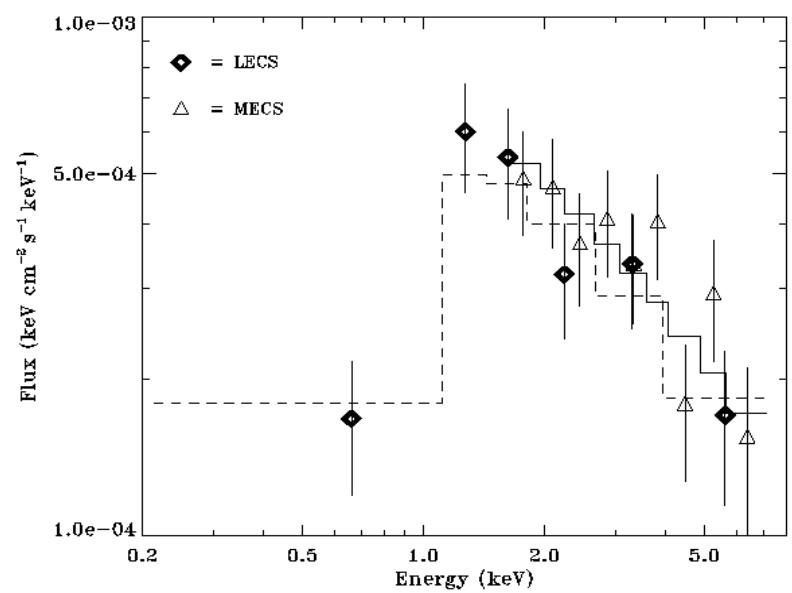


❑ afterglow emission: ~power-law light curves and spectra

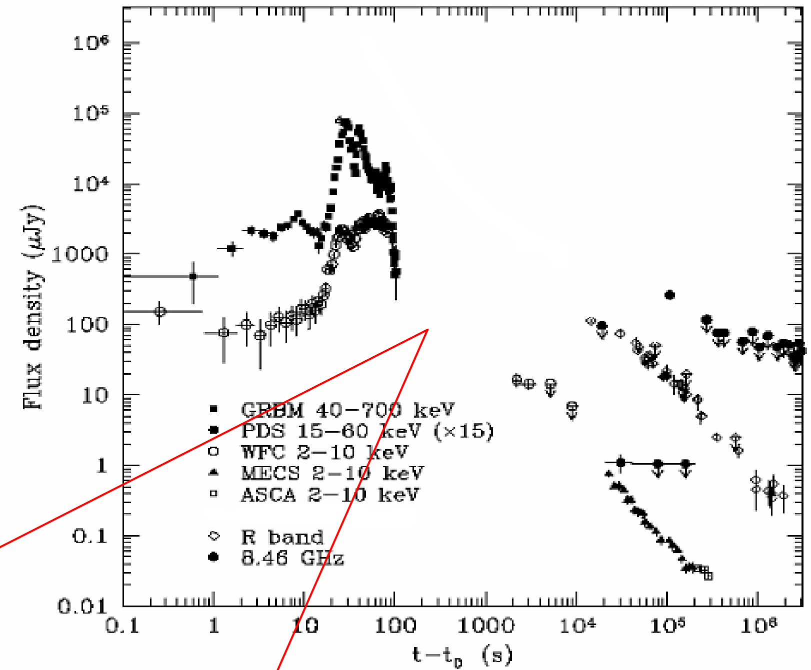


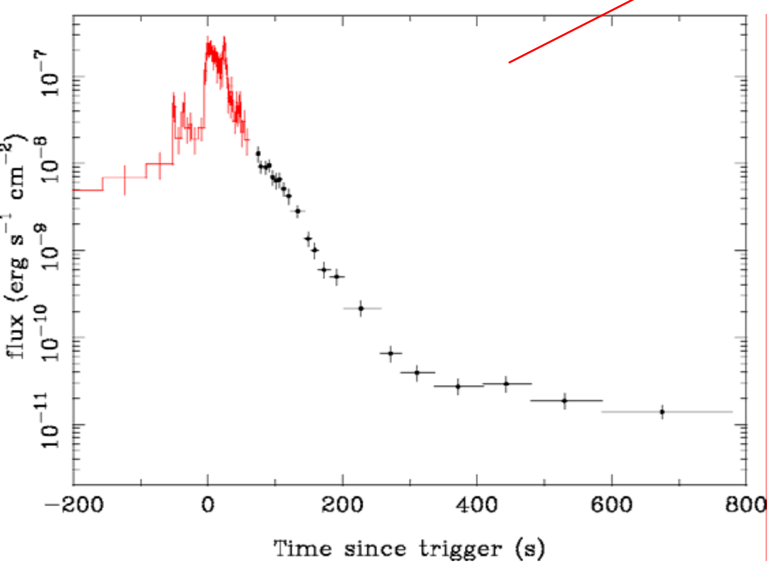




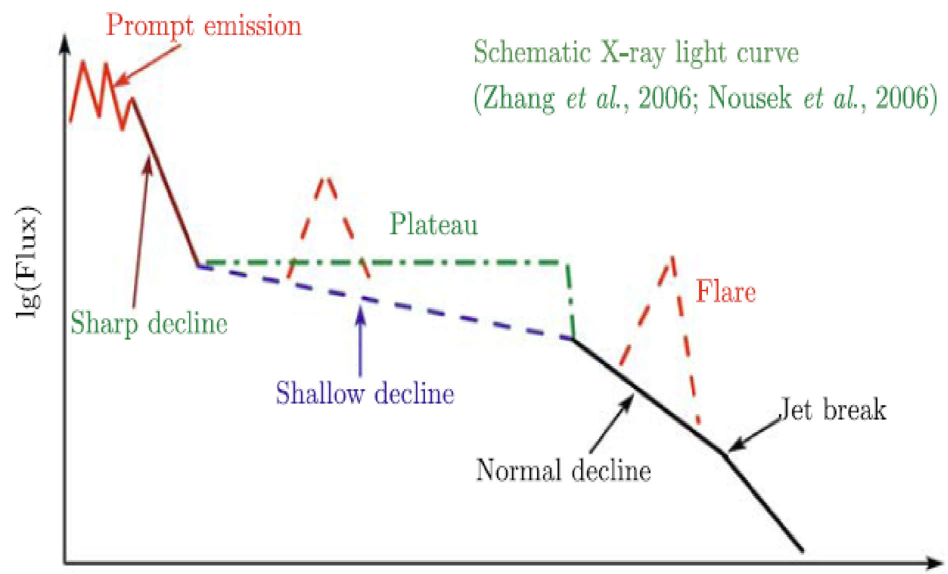


❑ early afterglow emission: steep decay, flat decay, flares

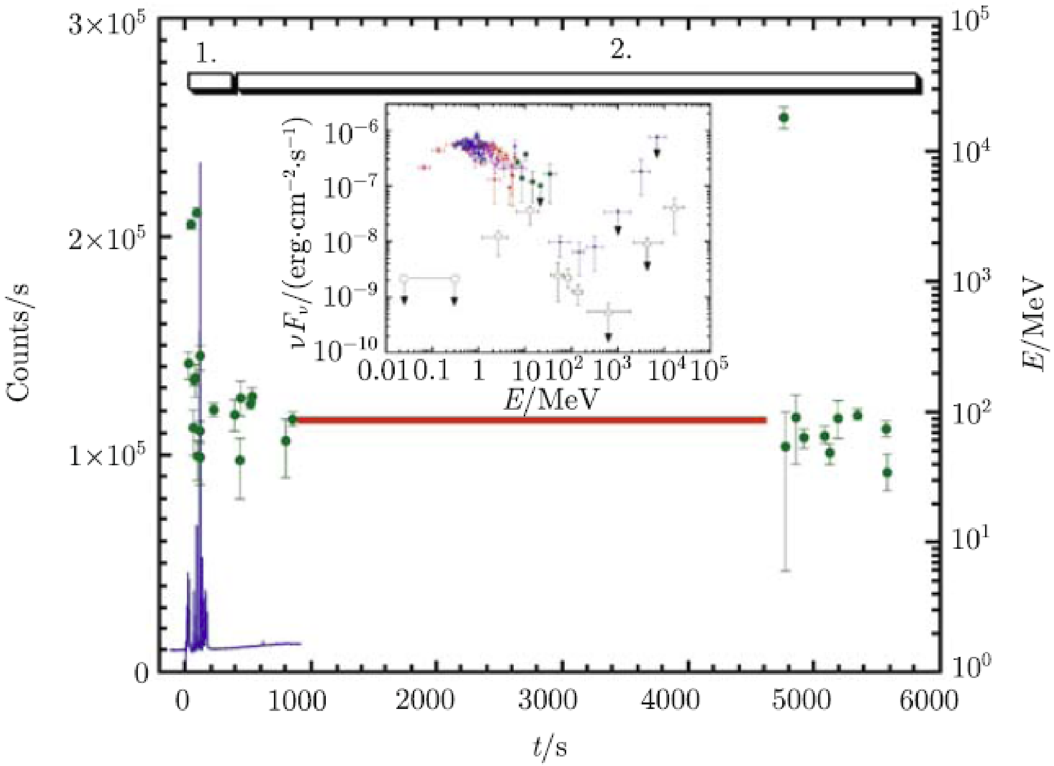


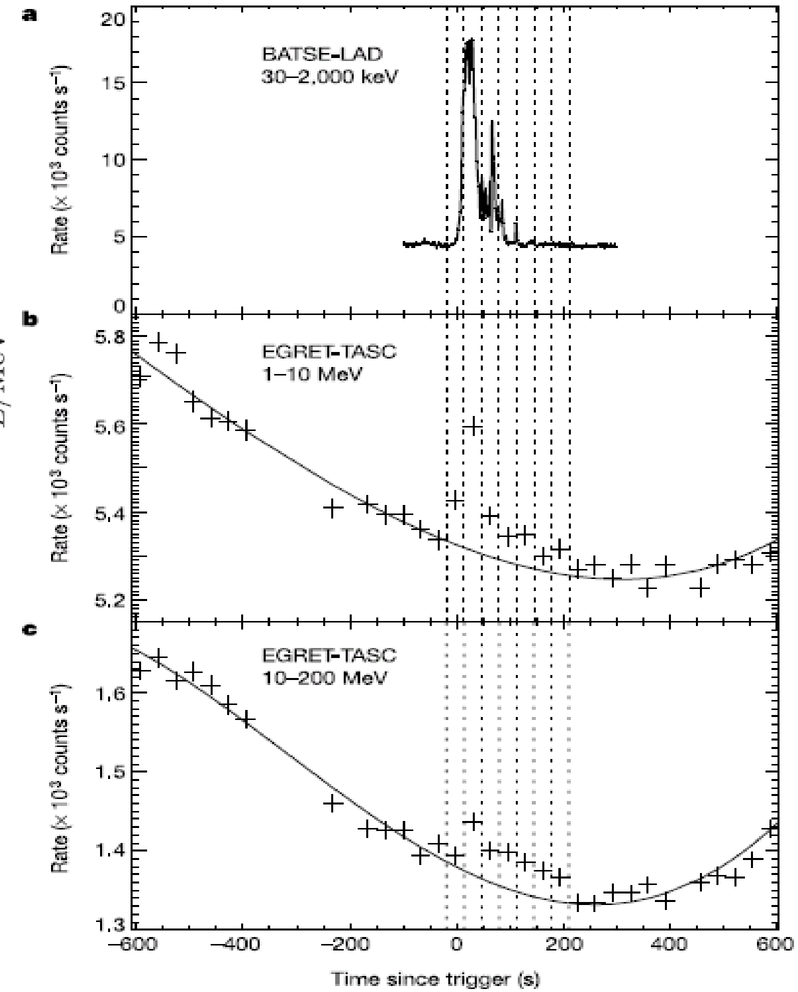


Swift team

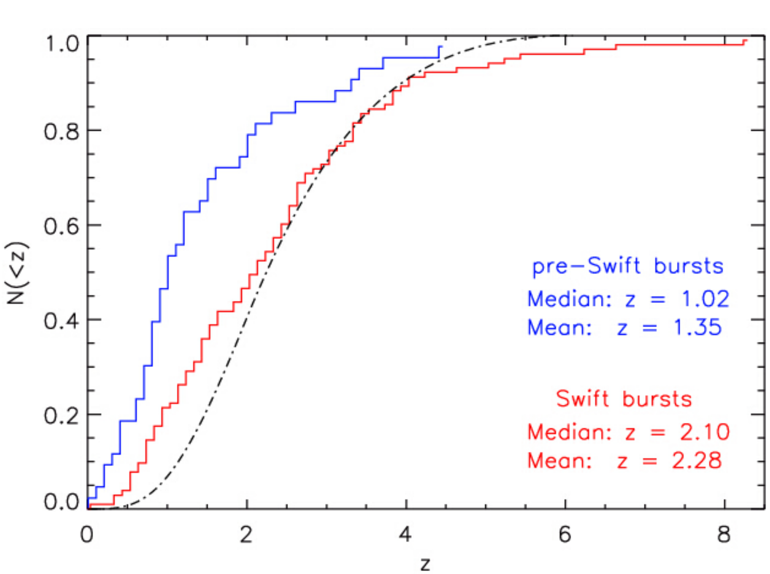


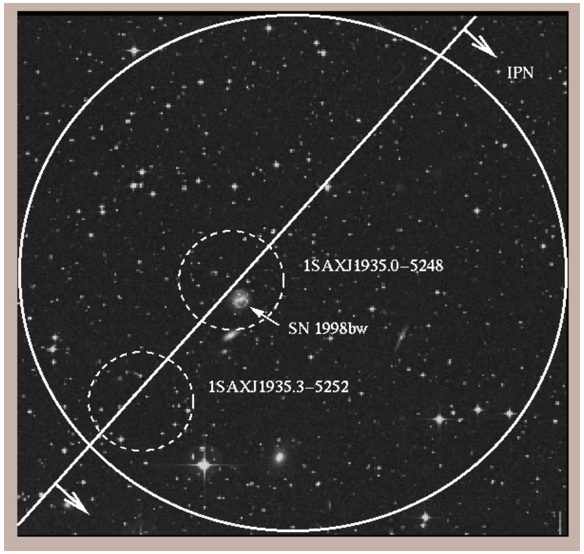
❑ GeV emission detected (in the '90s) by CGRO/EGRET for a few GRBs

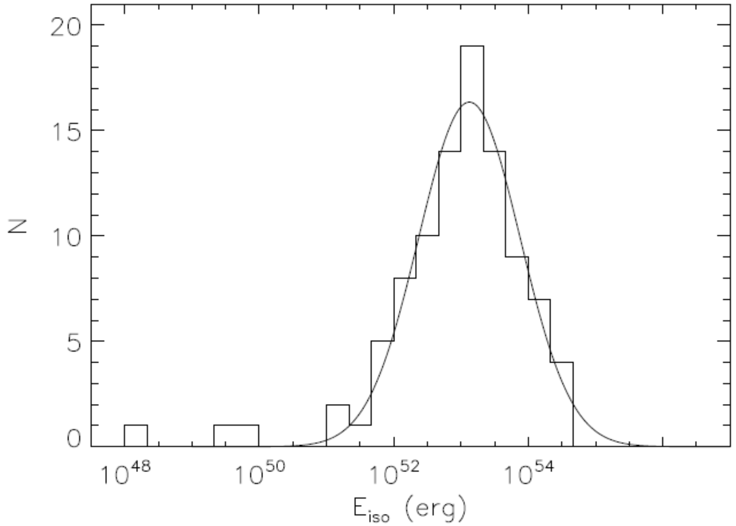


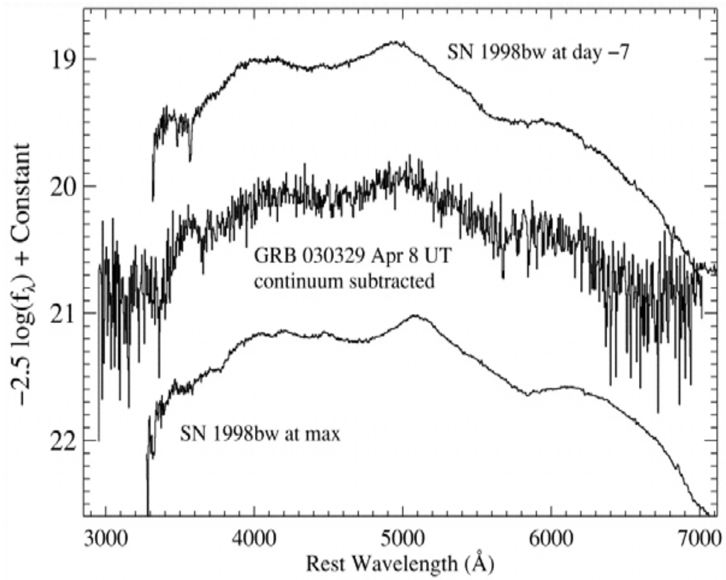


- cosmological redshifts, huge radiated energies
- evidence of association of a few long GRBs with peculiar type Ib/c SNe

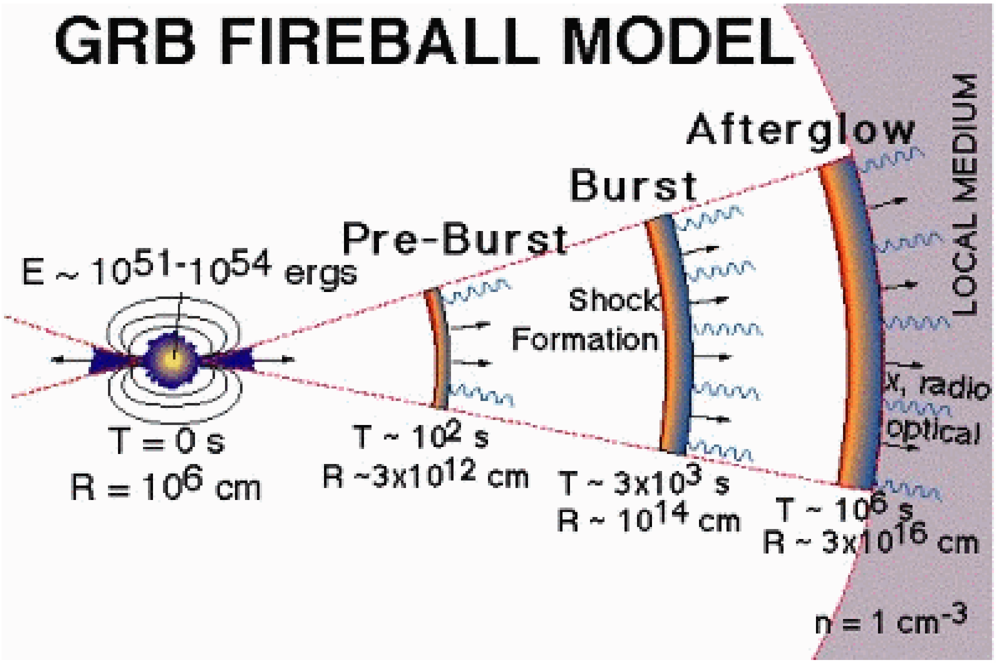


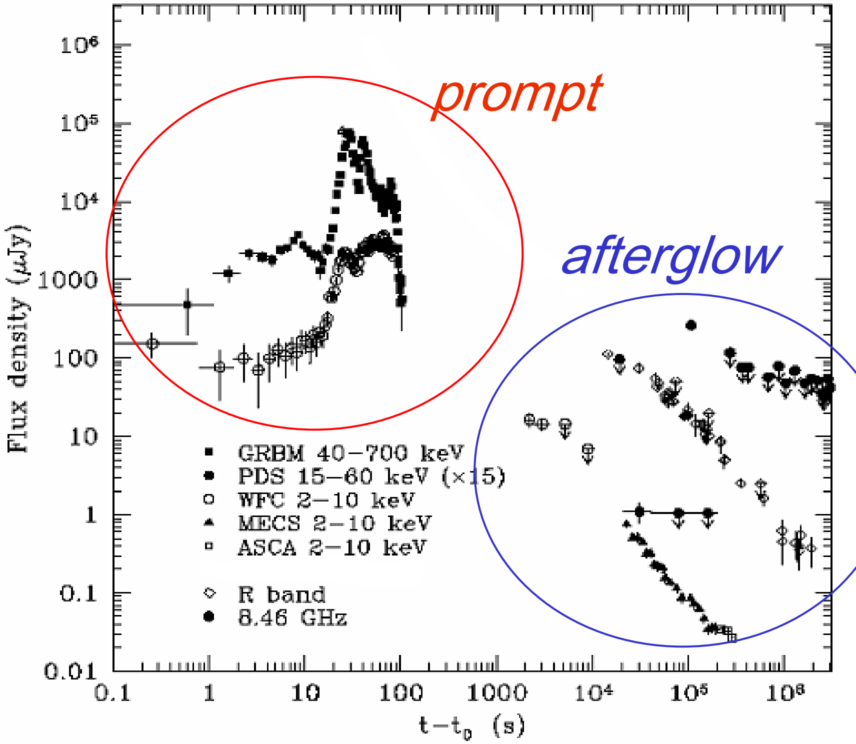






➢ *Standard scenario for GRB emission and progenitors*





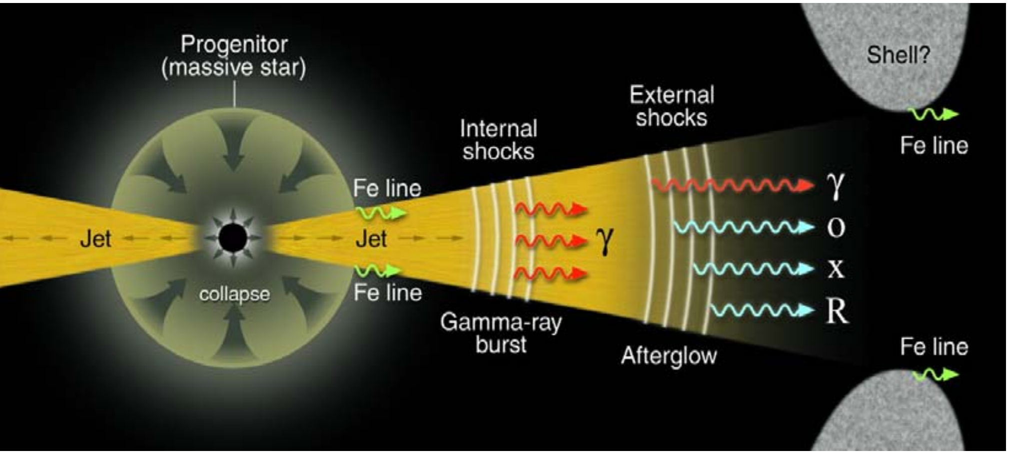
❑ ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic ($\Gamma > 100$) expansion (fireball or firejet)

❑ non thermal spectra -> shocks synchrotron emission (SSM)

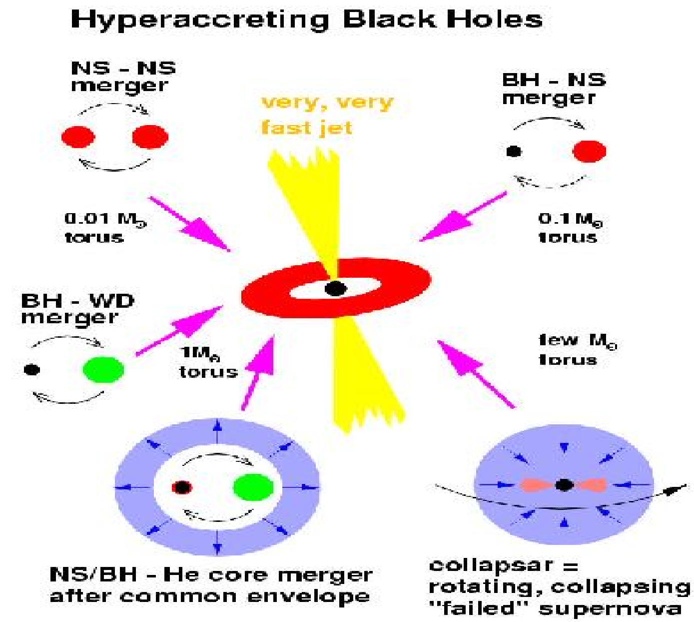
❑ fireball internal shocks -> prompt emission

❑ fireball external shock with ISM -> afterglow emission

LONG



SHORT

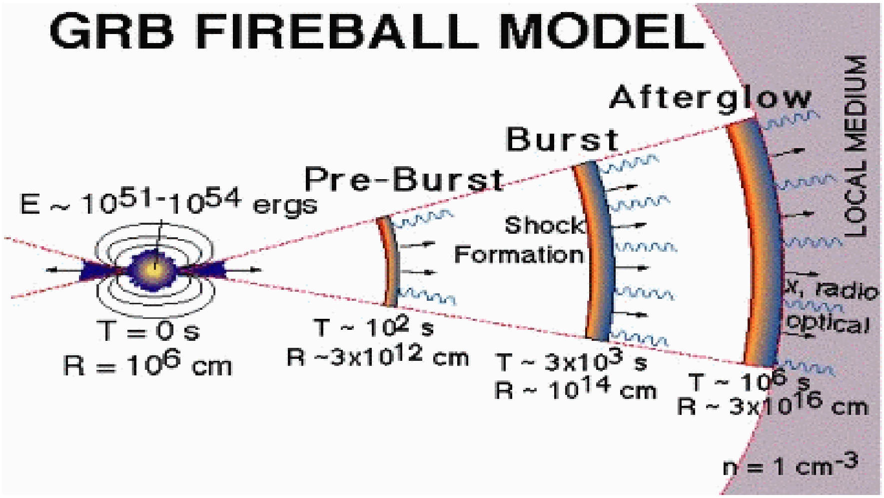


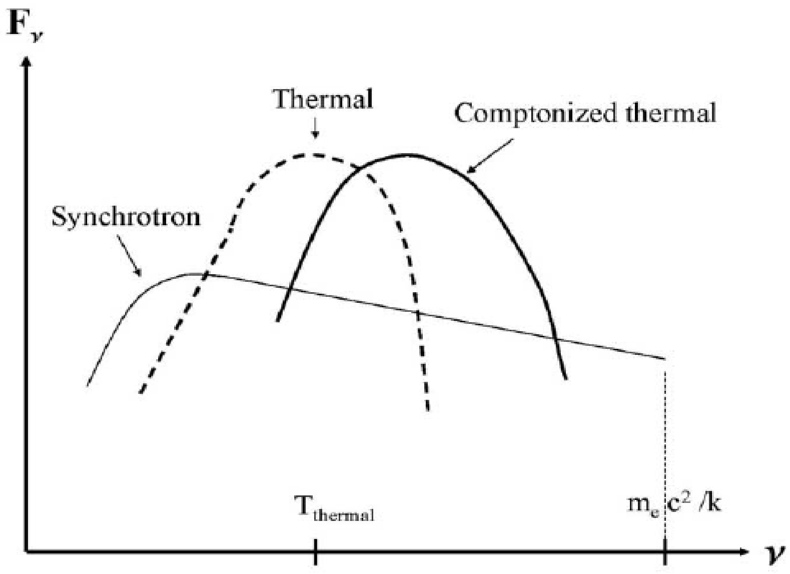
- energy budget up to >10^{54} erg
- long duration
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

➢ *… a rather "simple" picture, but there are several complications and still open issues, e.g.:*

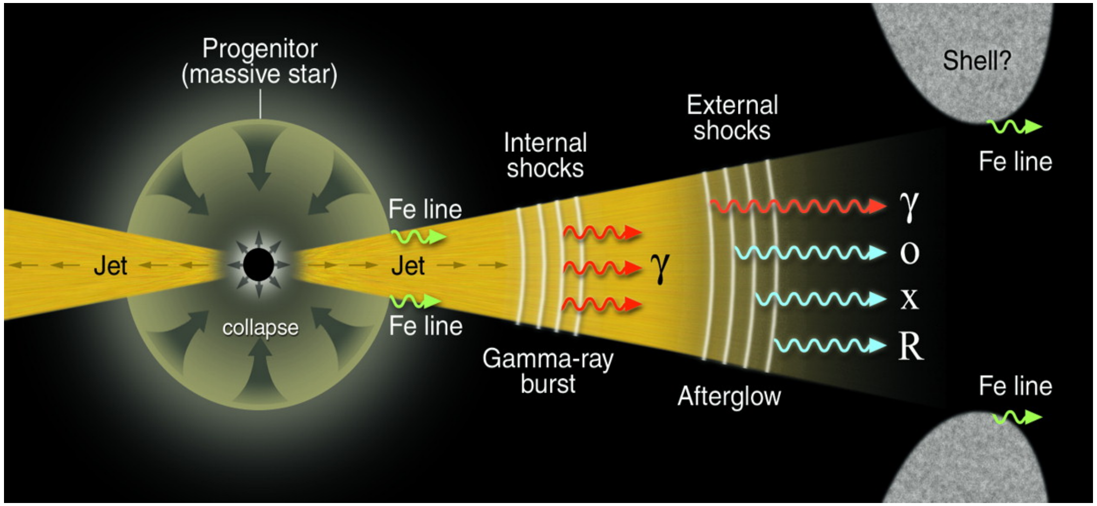
❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, …)

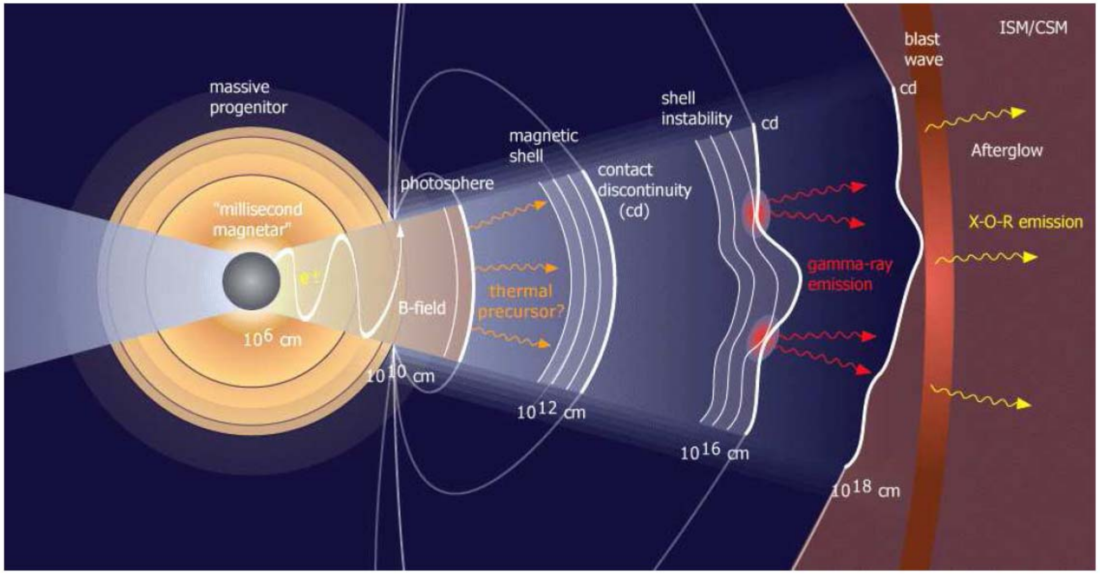




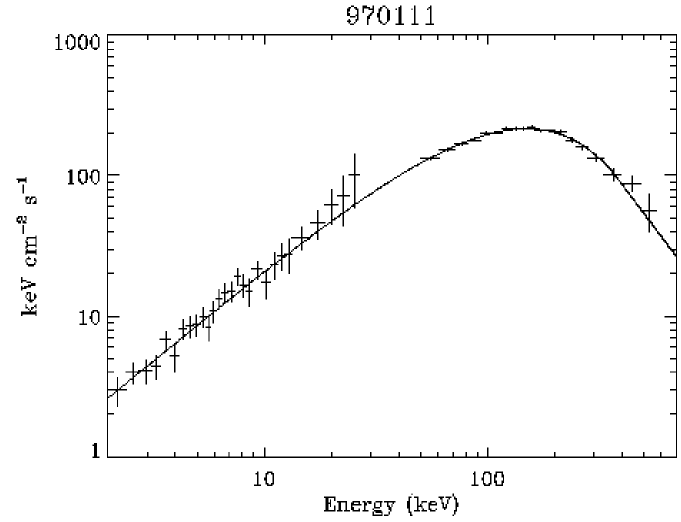
α $N(E)$	$\alpha+1$ $F(E)$	$\alpha+2$ EF_E	model/spectrum
-3/2	-1/2	1/2	Synchrotron emission with cooling
-1	0	1	Quasi–saturated Comptonization
-2/3	1/3	4/3	Instantaneous synchrotron
0	1	2	Small pitch angle/jitter
			inverse Compton by single e^-
1	2	3	Black Body
2	3	4	Wien

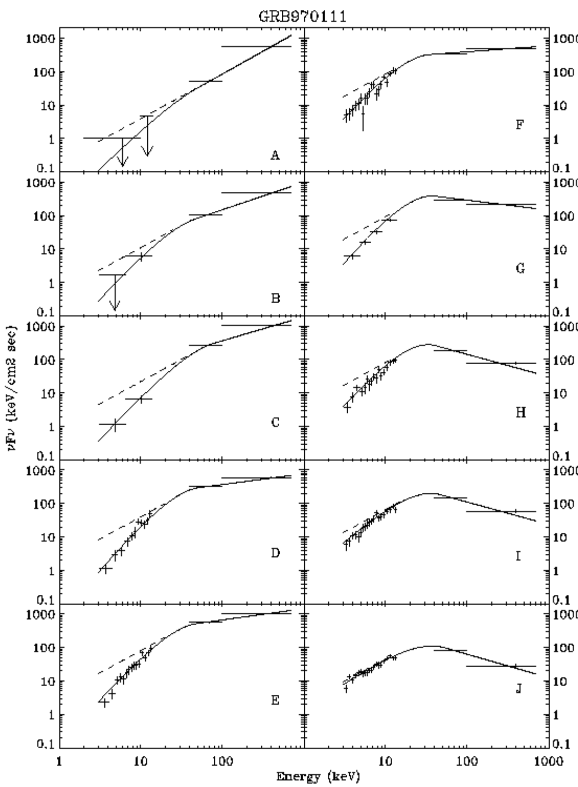
❑ fireball nature (baryon kinetic energy or Poynting flux dominated) and bulk Lorentz factor Γ are still to be firmly established

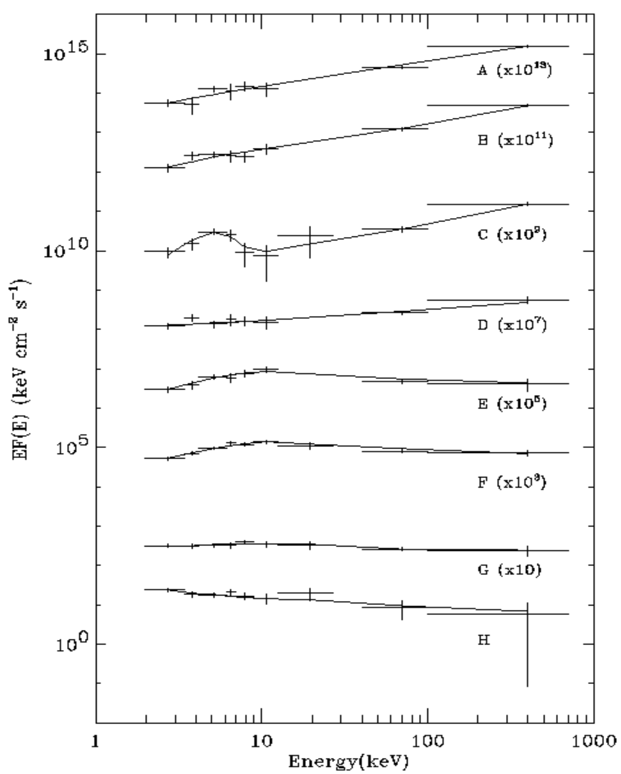


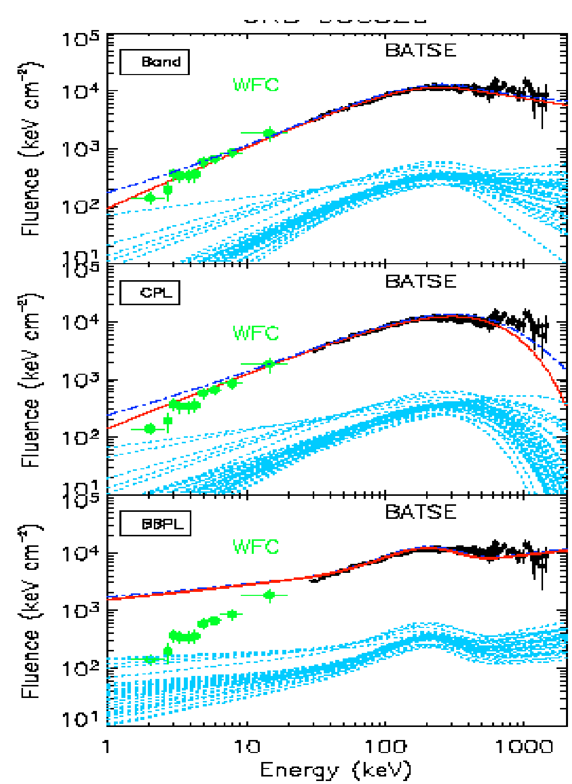


- a good fraction of time averaged spectra of GRBs are well fit by synchrotron shock models
- at early times, some spectra inconsistent with optically thin synchrotron: possible contribution of IC component and/or thermal emission from the fireball photosphere
- thermal models challenged by X-ray spectra



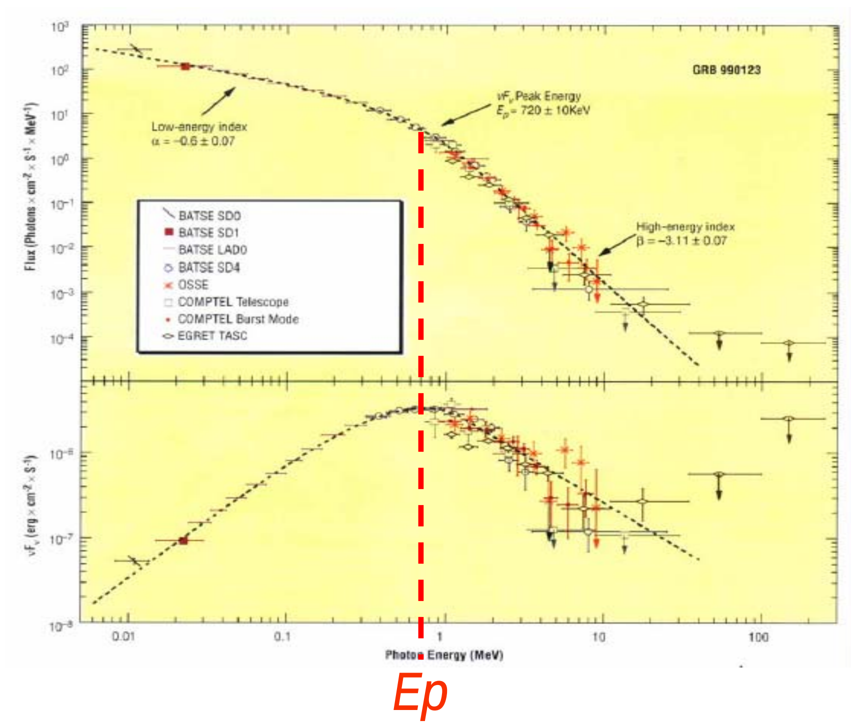


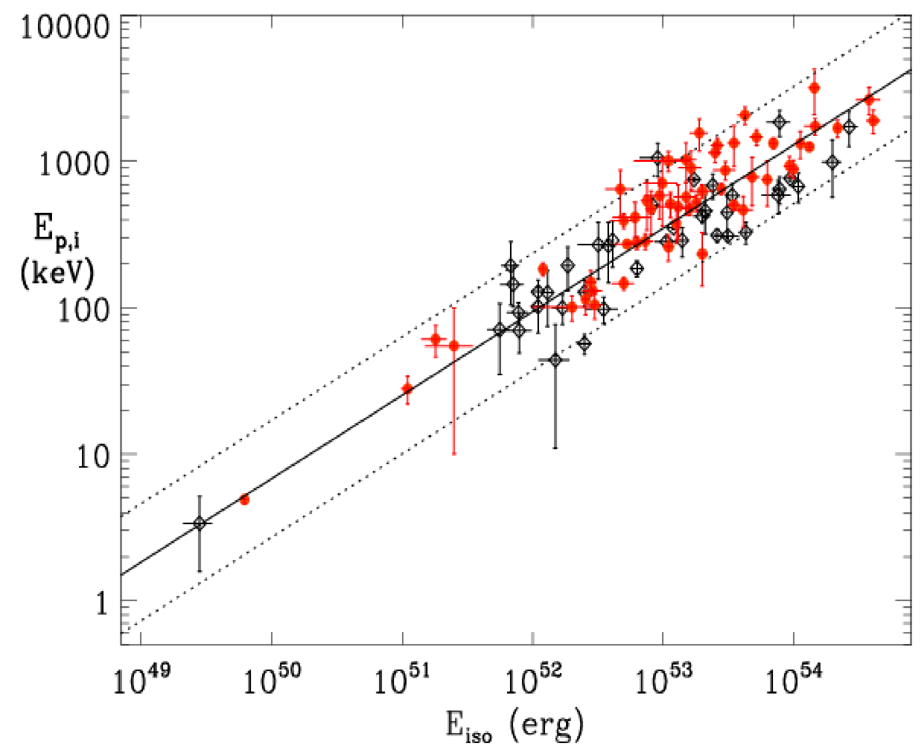




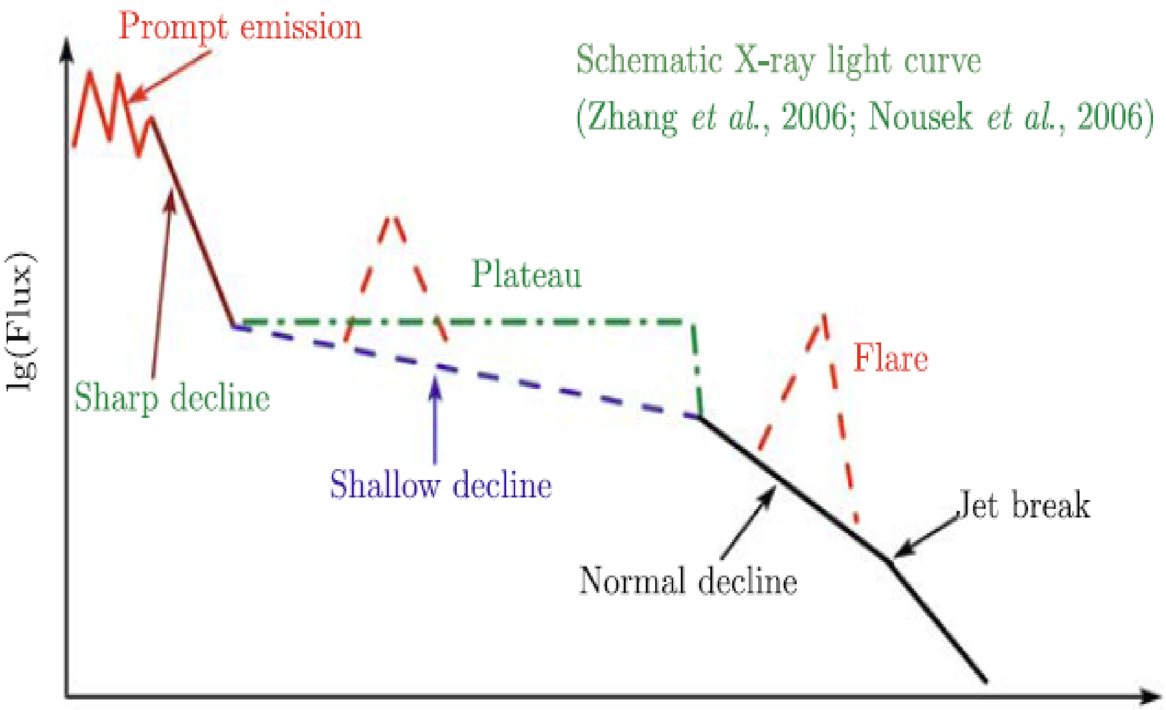
- Strong correlation between spectral peak photon energy, Ep,i, and isotropic-equivalent radiated energy Eiso for long GRBs: test for prompt emission models (physics, geometry, GRB/XRF unification models), identification and understanding of sub-classes of GRBs, GRB cosmology

- open issues: physical explanation, peculiar events, instrumental effects

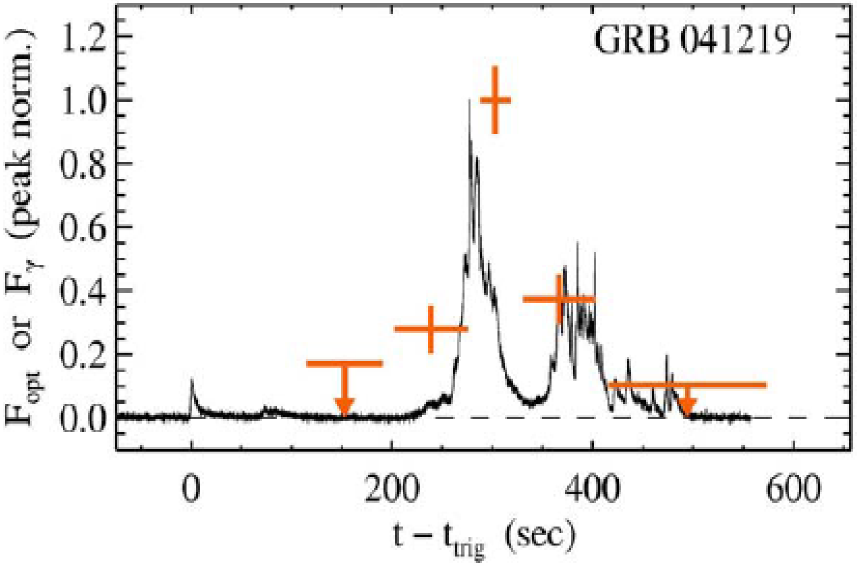


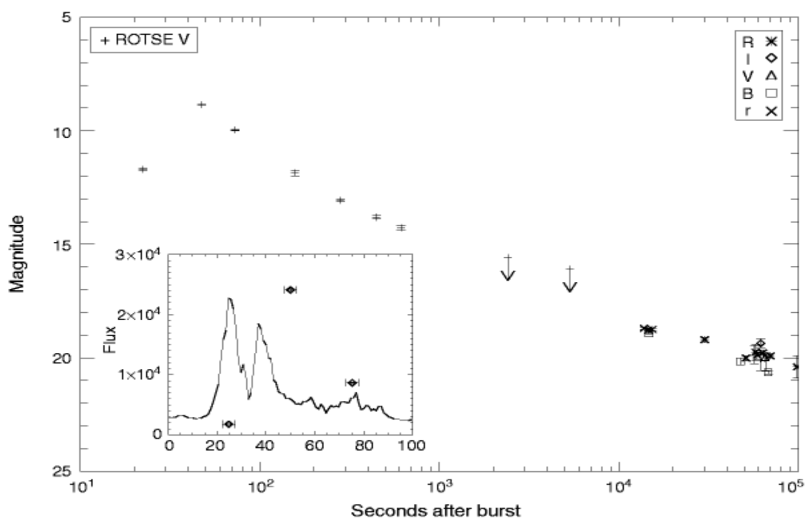


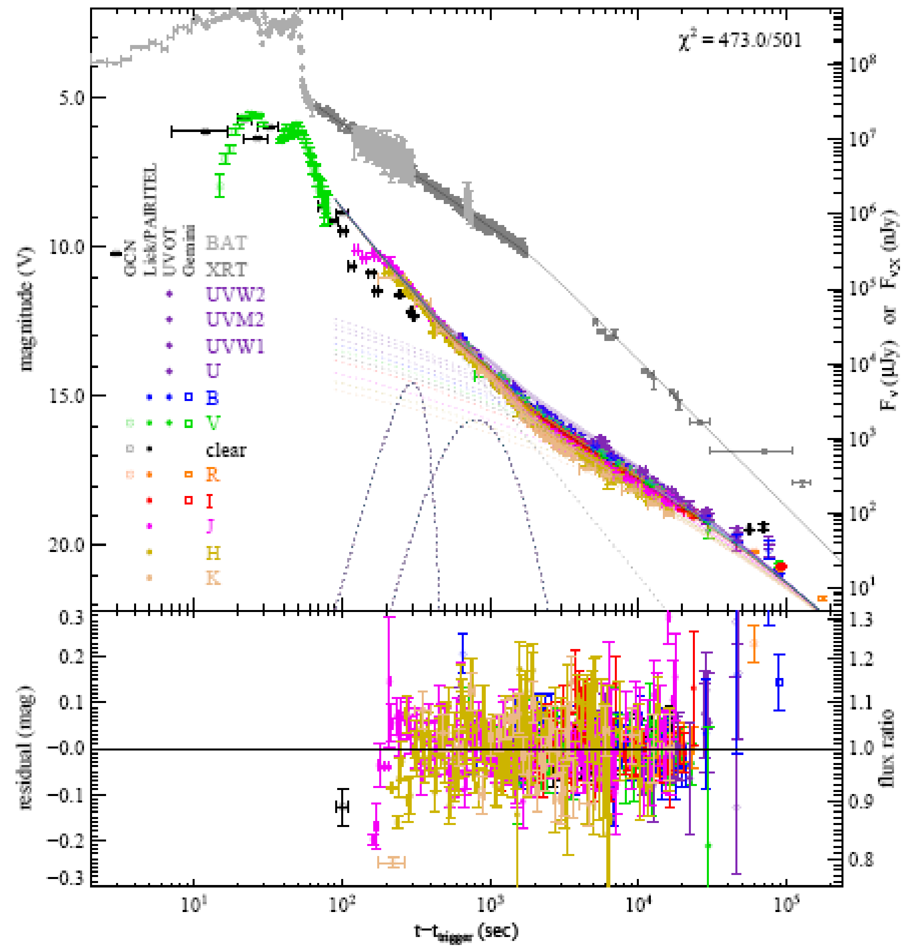
- features seen by Swift in X-ray early afterglow light curves (initial very steep decay, early breaks, flares) mostly unpredicted and unexplained
- initial steep decay: continuation of prompt emission, high latitude emission, IC up-scatter of the reverse shock sinchrotron emission ?
- flat decay: probably "refreshed shocks" (due either to long duration ejection or short ejection but with wide range of Γ) ?
- flares: could be due to: refreshed shocks, IC from reverse shock, external density bumps, continued central engine activity, late internal shocks…



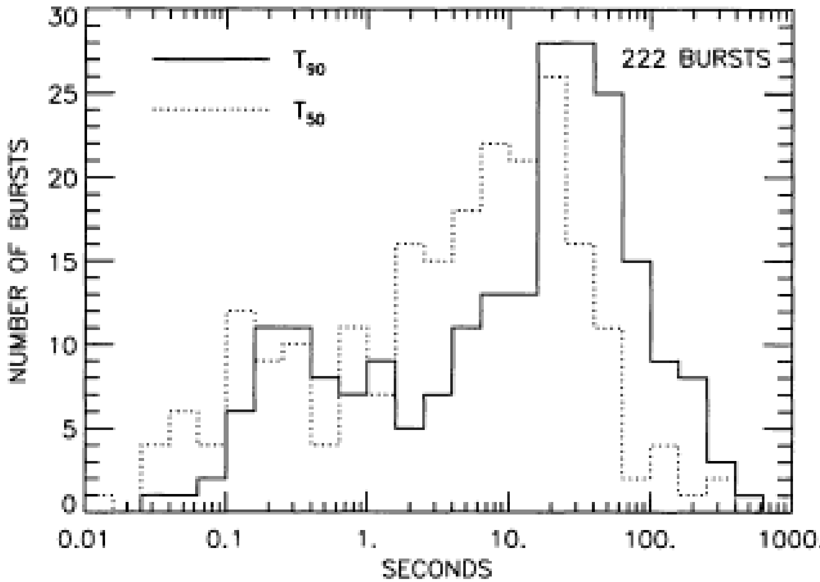
❑ prompt and afterglow optical emission: usually significantly different behaviours (optical from reverse shock ? optical from synchrotron and gamma from SSC ?)

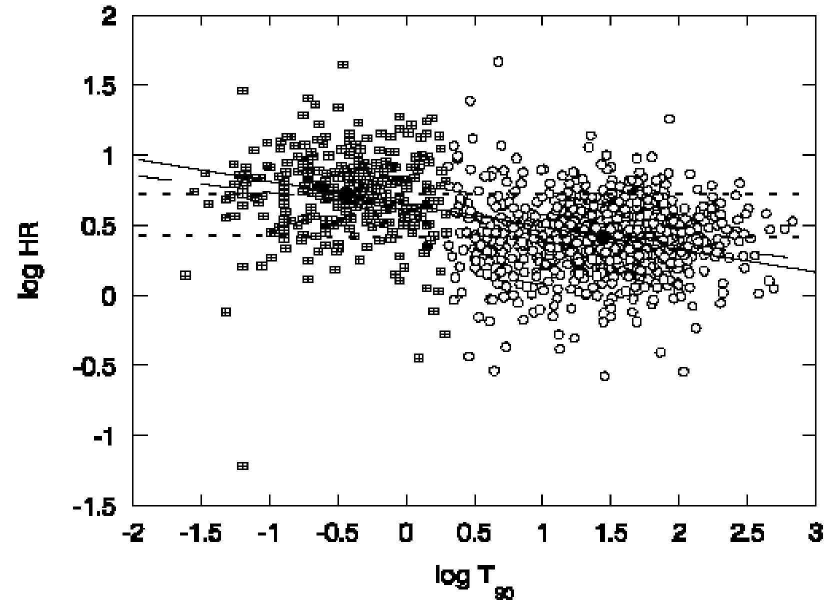


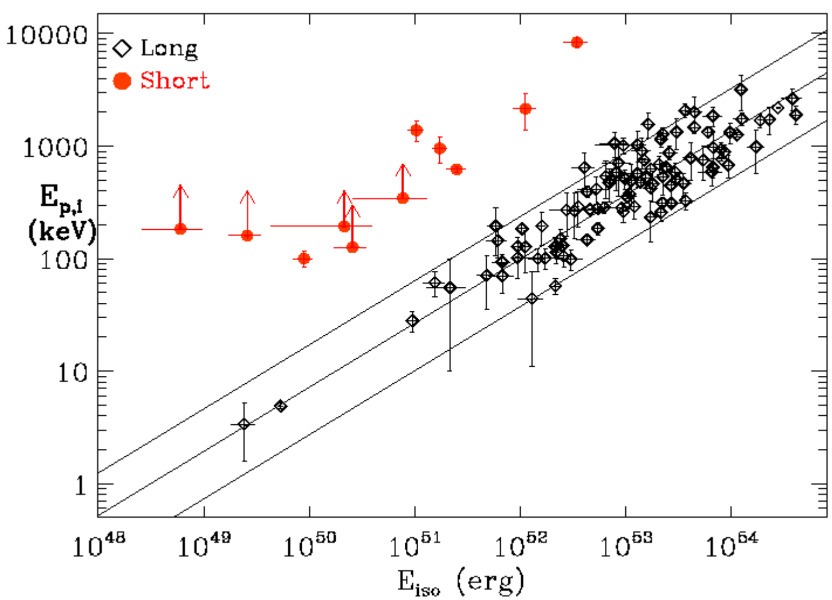


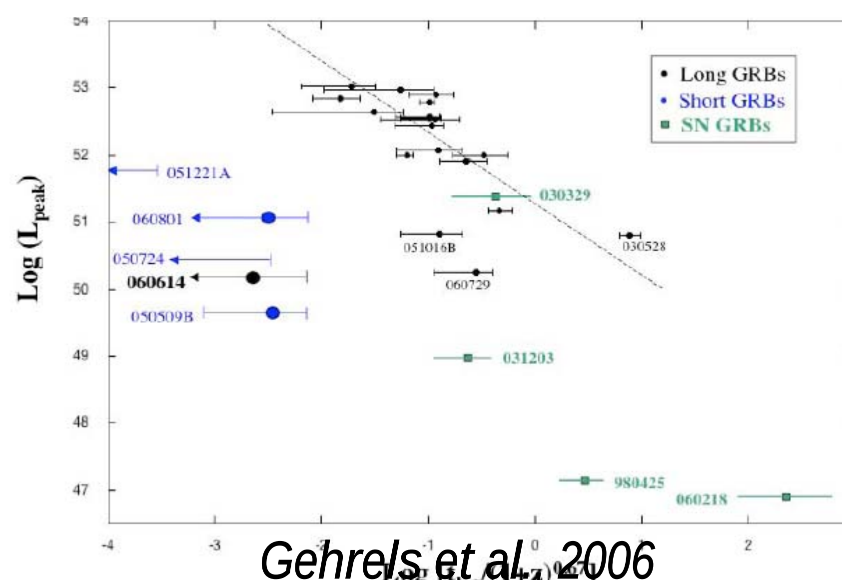


- evidences of different main emission mechanism in short and long GRBs, still to be understood





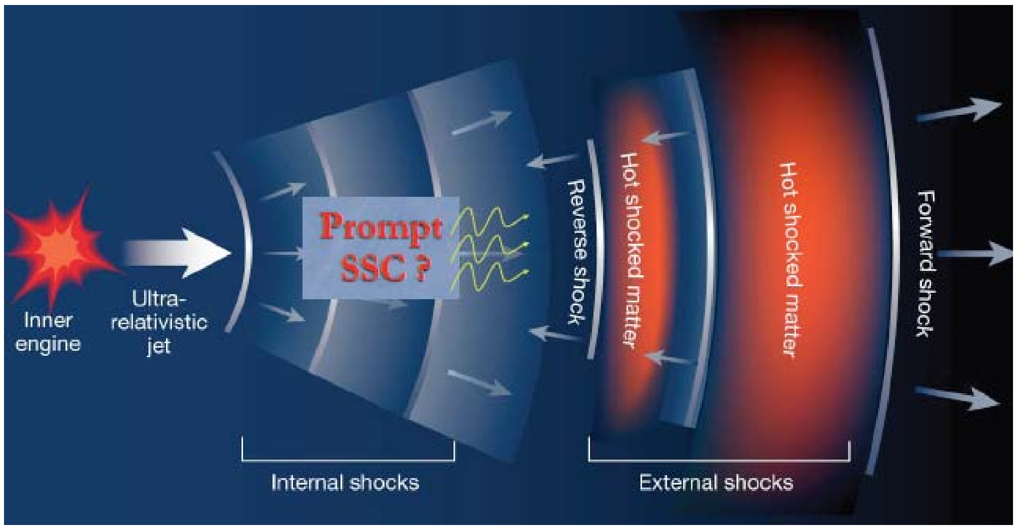


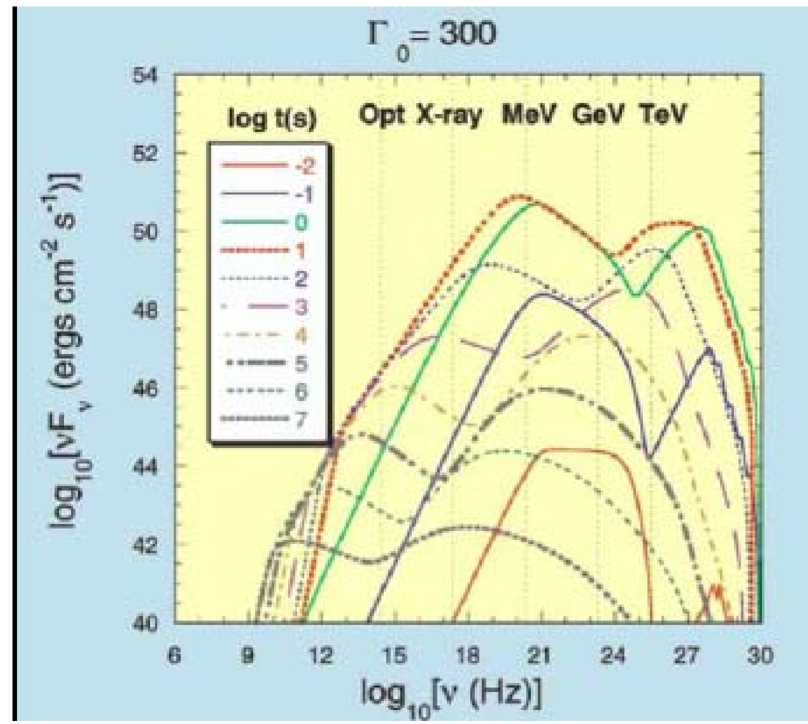


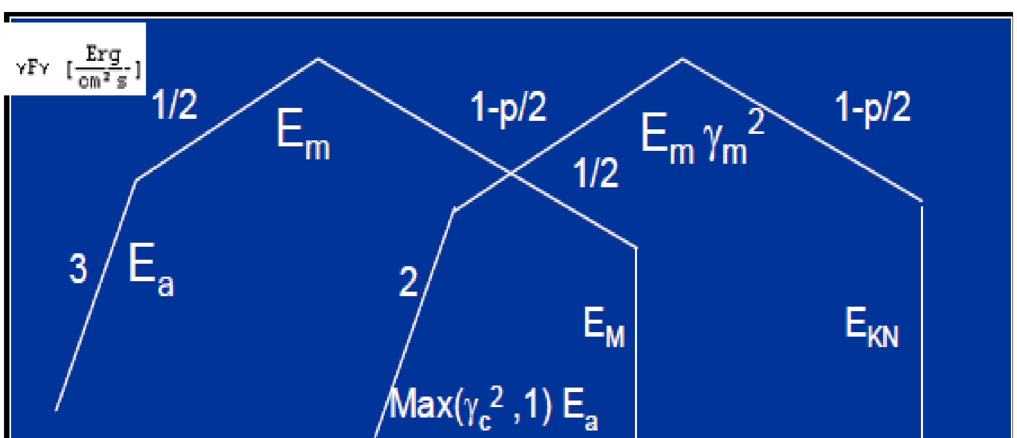
Gehrels et al., 2006

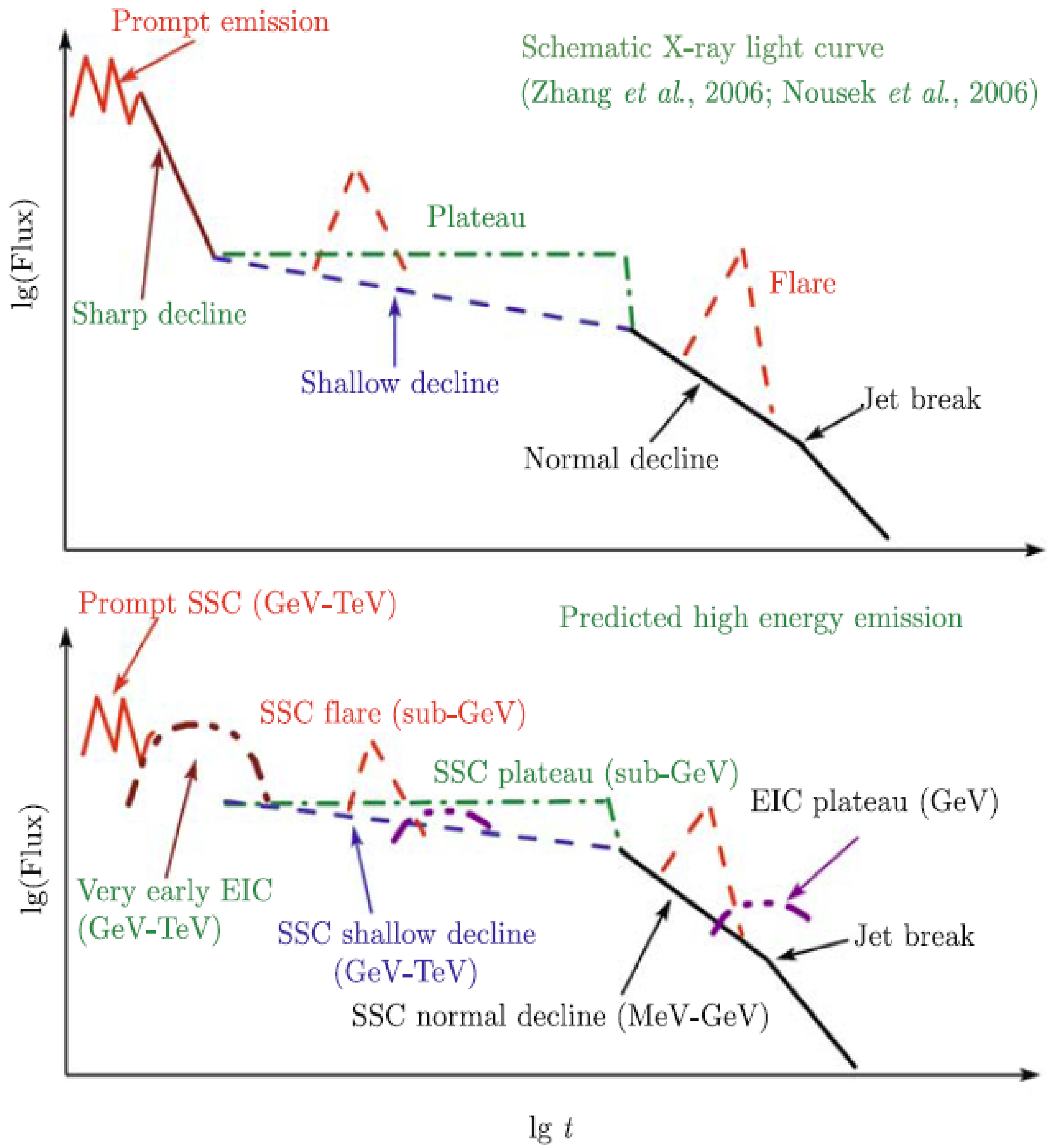
The impact of observations in the GeV range

- GeV emission of GRB predicted and explained in several scenarios / emission mechanisms: synchrotron self-compton in internal shocks, IC in external shocks, proton synchrotron emission in external shocks, …









Prompt emission
Schematic X-ray light curve
(Zhang et al., 2006; Nousek et al., 2006)
lg(Flux)
Plateau
Flare
Sharp decline
Shallow decline
Jet break
Normal decline
Prompt SSC (GeV-TeV)
Predicted high energy emission
SSC flare (sub-GeV)
SSC plateau (sub-GeV)
EIC plateau (GeV)
lg(Flux)
Very early EIC
(GeV-TeV)
SSC shallow decline
(GeV-TeV)
Jet break
SSC normal decline (MeV-GeV)
lg t

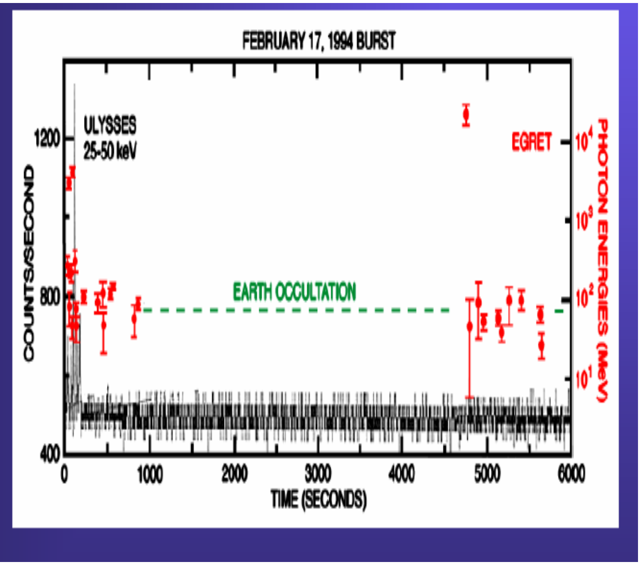
➢ *Early measurements by CGRO/EGRET*

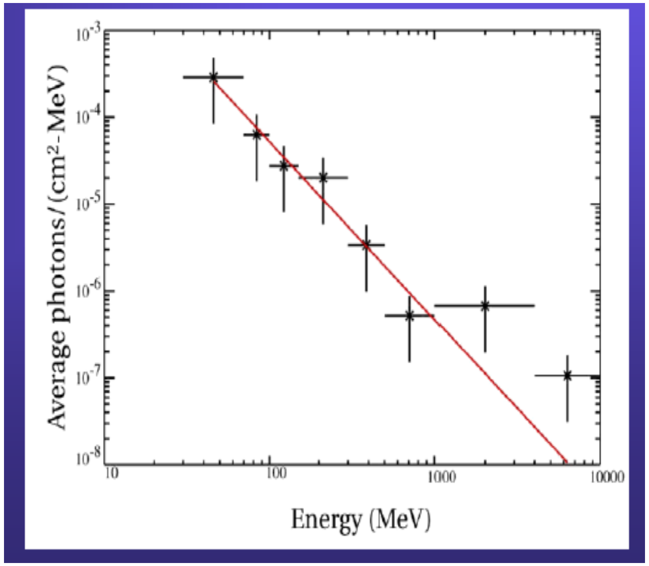
❑ CGRO/EGRET detected VHE (from 30 MeV up to 18 GeV) photons for a few GRBs

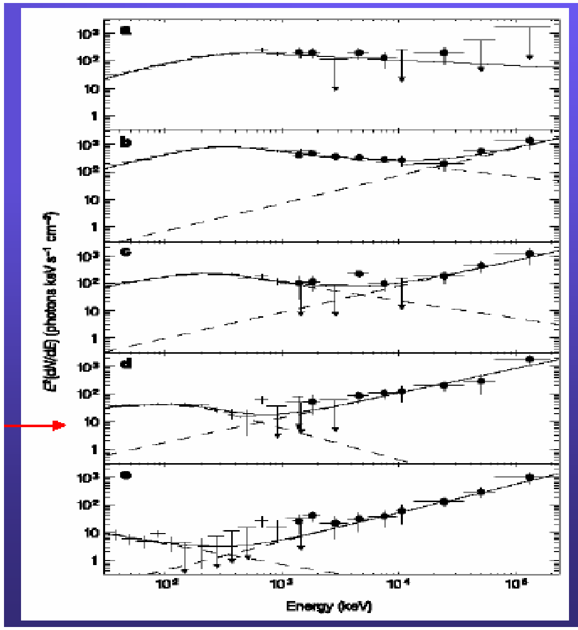
❑ HE emission can last up to thousends of s after GRB onset

❑ average spectrum of 4 events well described by a simple power-law with index ~2 , consistent with extension of low energy spectra

❑ GRB 941017,measured by EGRET-TASC shows a high energy component inconsistent with synchrotron shock model





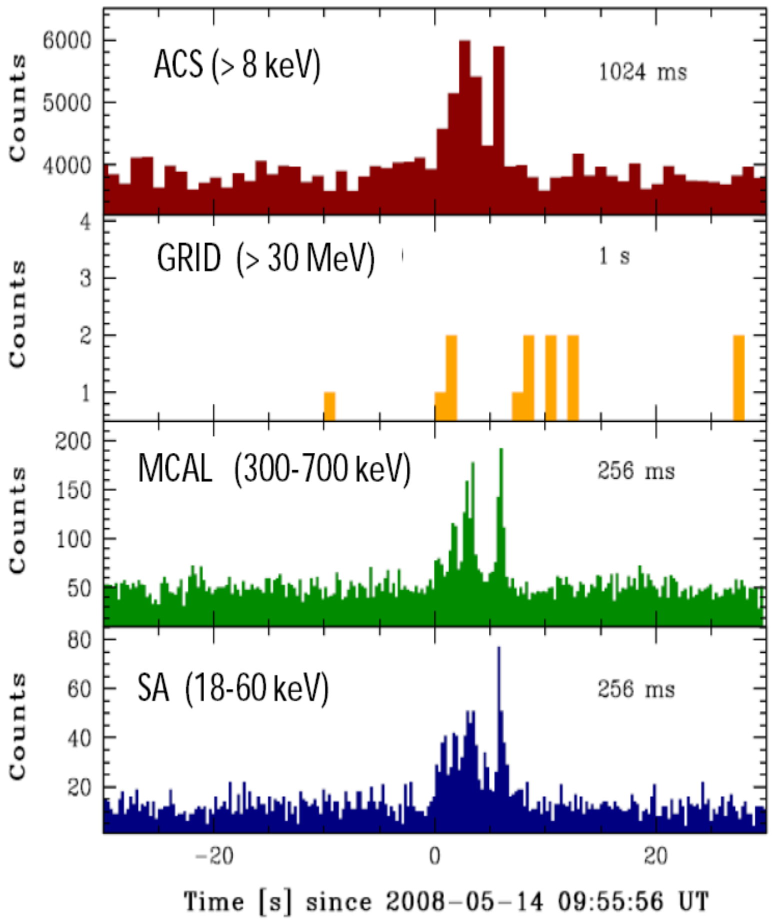


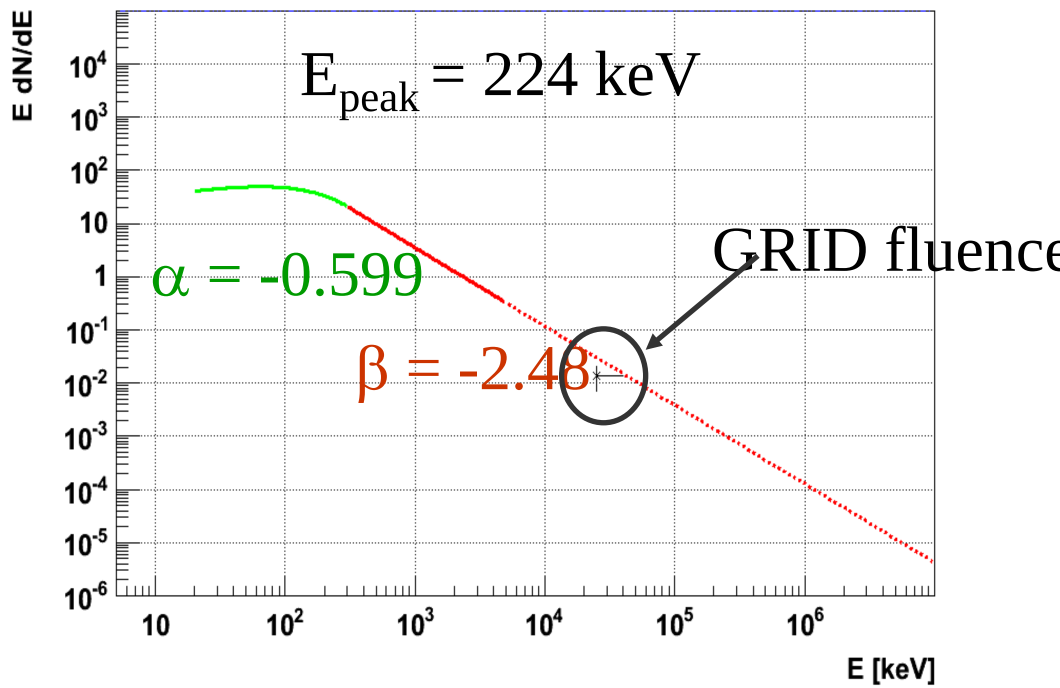
BATSE/EGRET team

➢ *GRBs HE detections with AGILE (highlights from Del Monte)*

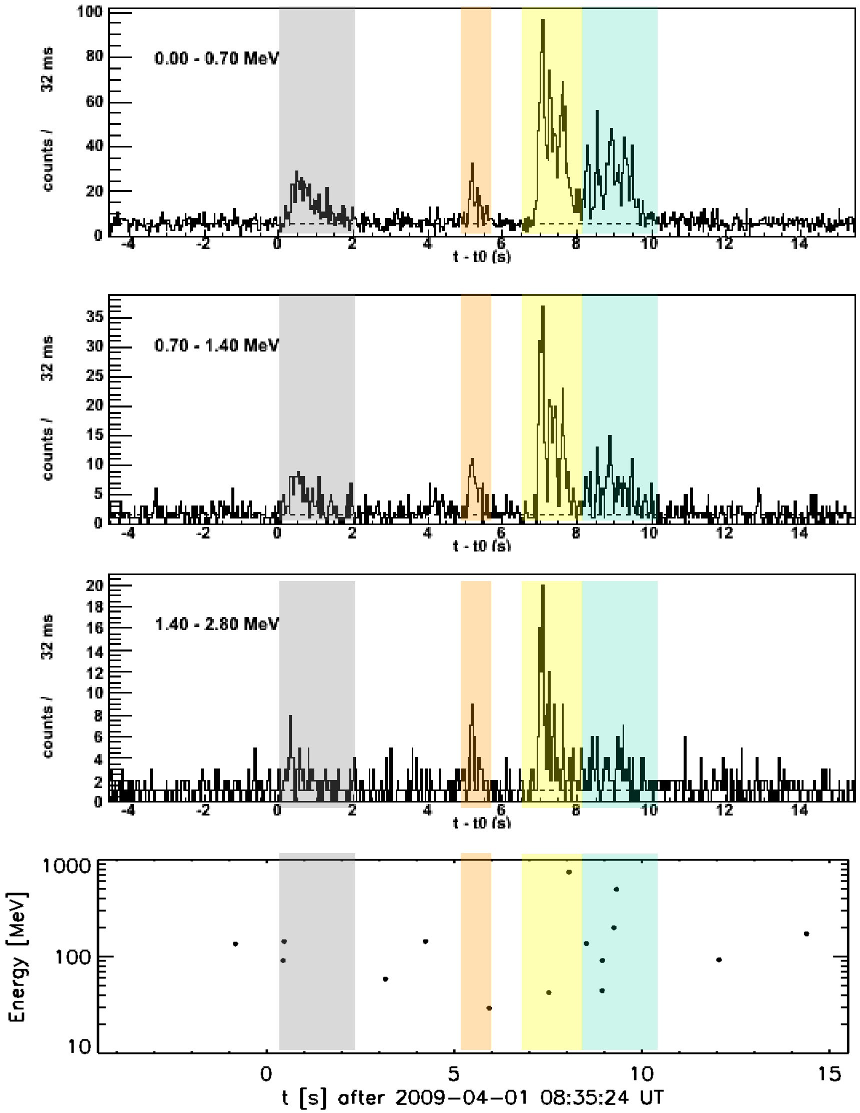
❑ GRID (>30 MeV) : 3 detections (GRB 080514B, GRB 090401B and short GRB 090510) + 2 less significant detections (GRB 080721 and GRB 081001)

❑ GRB 080514B: no spectral cut-off or excess up to 50 MeV





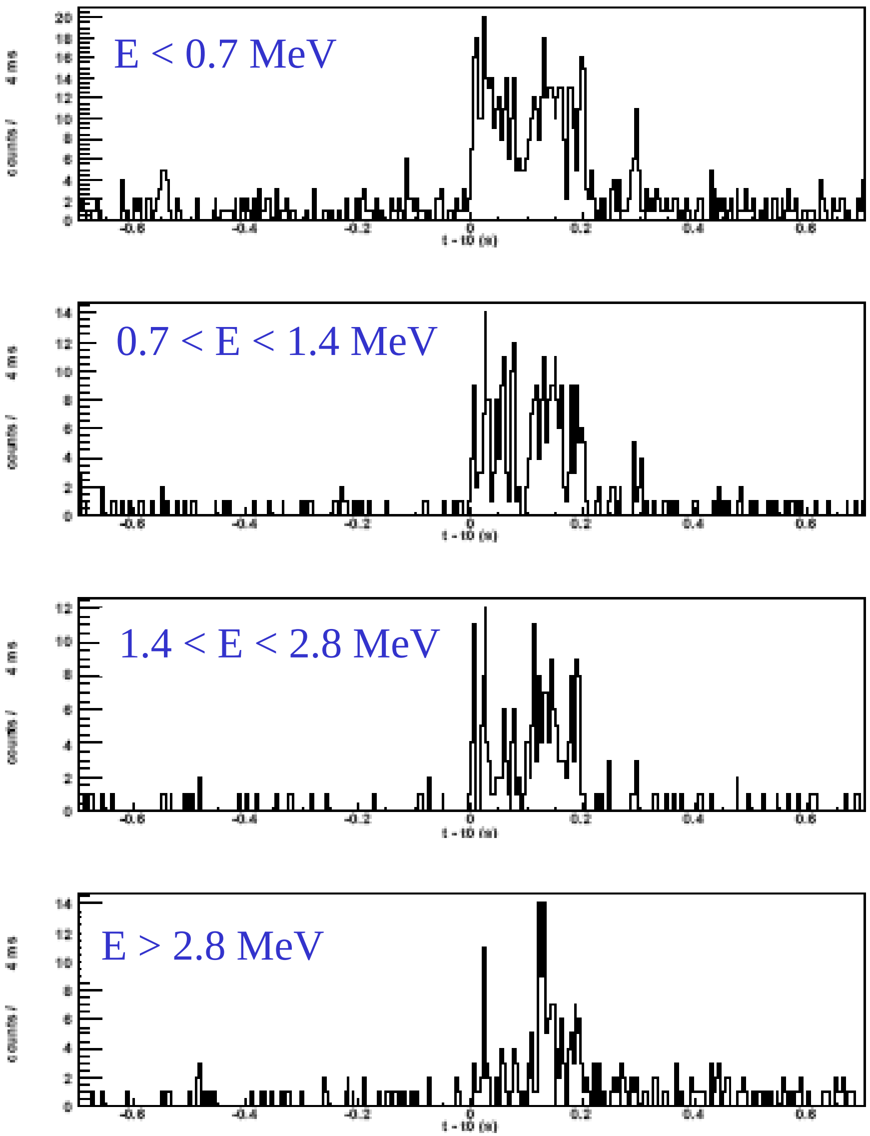
❑ GRB 090401B: prompt and extended HE emission

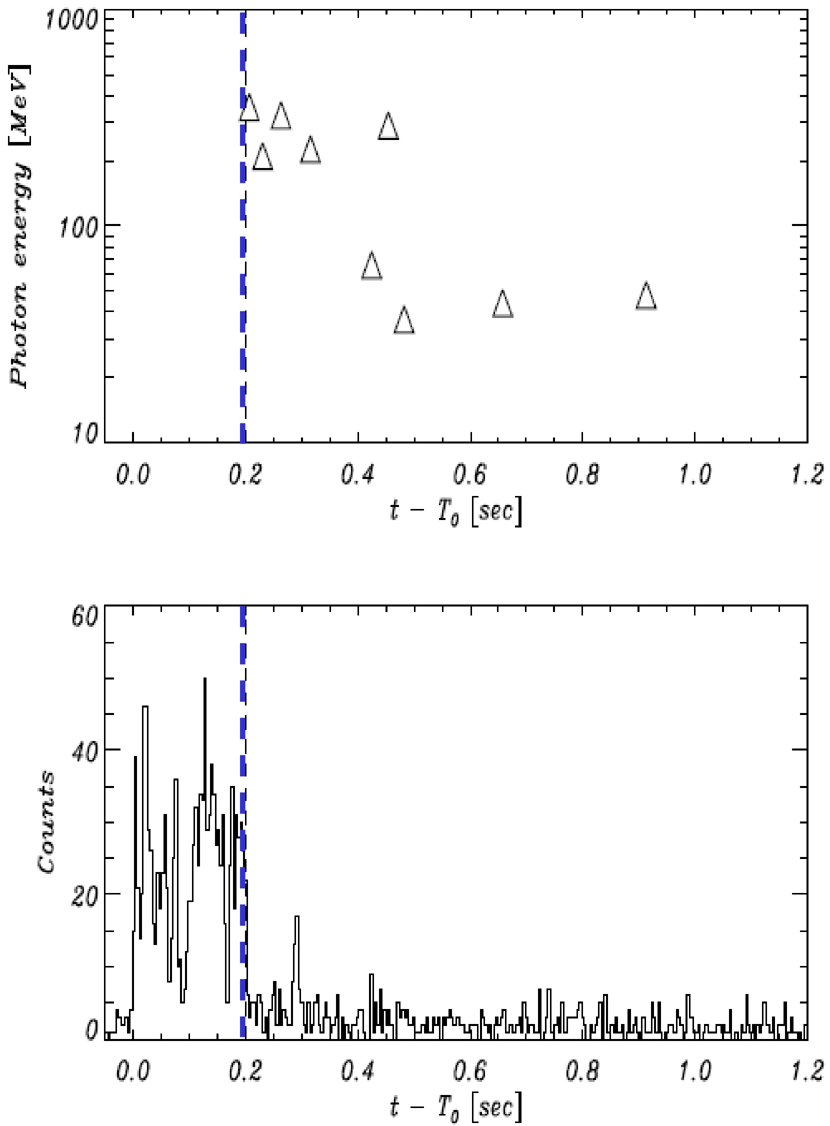


68 % of the gamma ray photons are emitted during prompt;

32 % of the gamma ray photons are in the extended emission

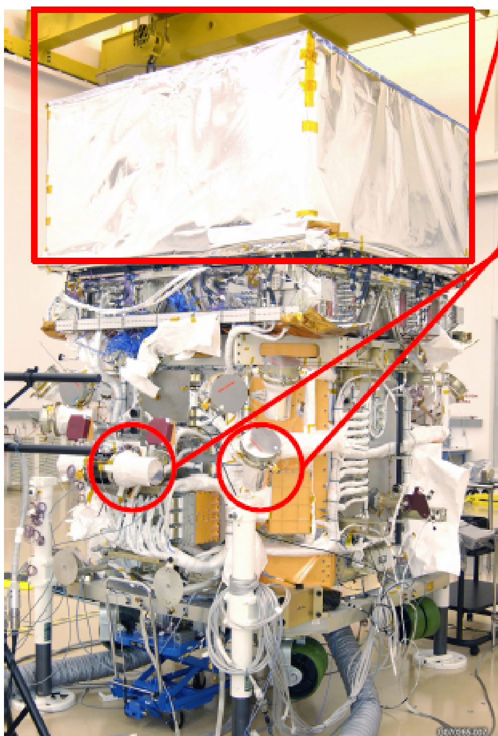
❑ GRB 090510: first detection of prompt and delayed HE photons from a short GRB



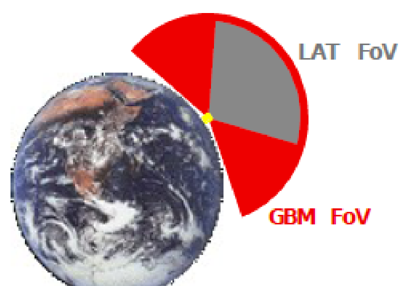


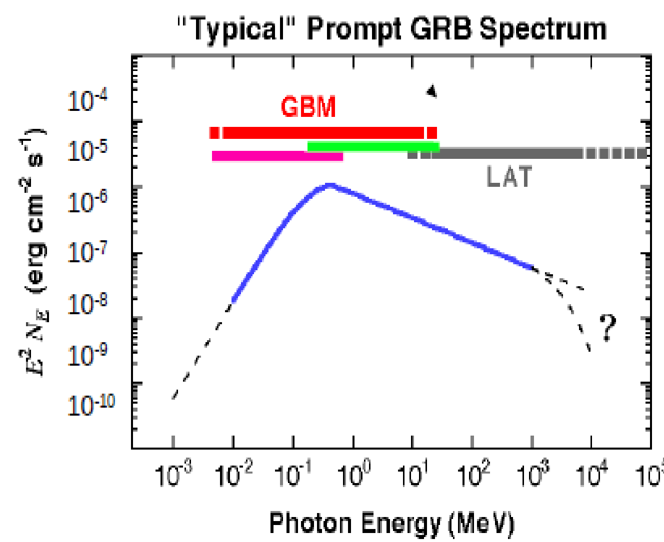
key features of Fermi for the study of GRBs

- Detection, arcmin localization and study of GRBs in the GeV energy range through the LAT instrument, with dramatic improvement w/r CGRO/EGRET
- Detection, rough localization (a few degrees) and accurate determination of the shape of the spectral continuum of the prompt emission of GRBs from 8 keV up to 30 MeV through the GBM instrument

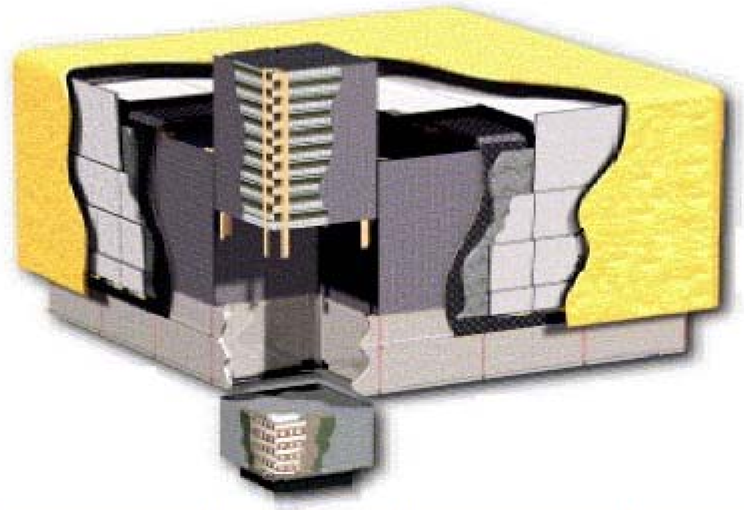


- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.





❑ substantial improvement of Fermi/LAT w/r CGRO/EGRET



- Precision Si-strip Tracker/Converter
- Hodoscopic CsI Calorimeter.
- Segmented Anti-Coincidence Detector

	Field of view (sr)	Effective area (cm^2)	PSF @ 100 MeV (deg)	PSF @ 10 GeV (deg)	Dead time	Energy range
EGRET	0.4	1500	4.7	0.2	100 ms	30 MeV—10 GeV
Fermi LAT	2.5	9000	3.5	0.1	25.6 μs	20 MeV--300 GeV

Many GRBs

Localization

Unexplored time and energy scales

➢ *Main Fermi results on GRBs HE emission*

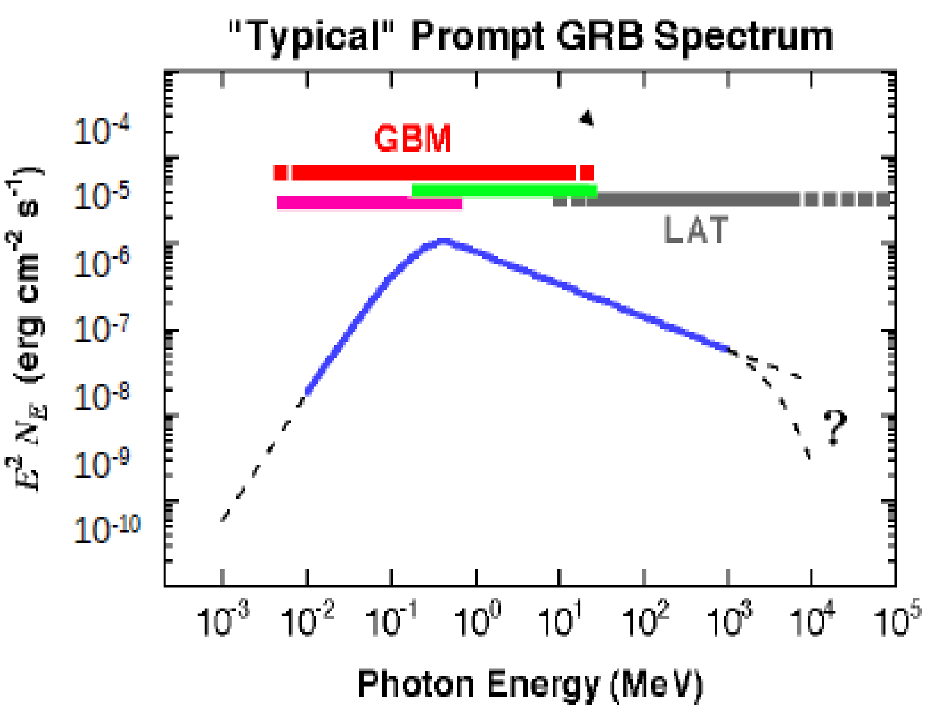
- Up to now, 17 GRB detections by the LAT
- The sample includes also 2 short GRBs and 8 GRBs with redshift

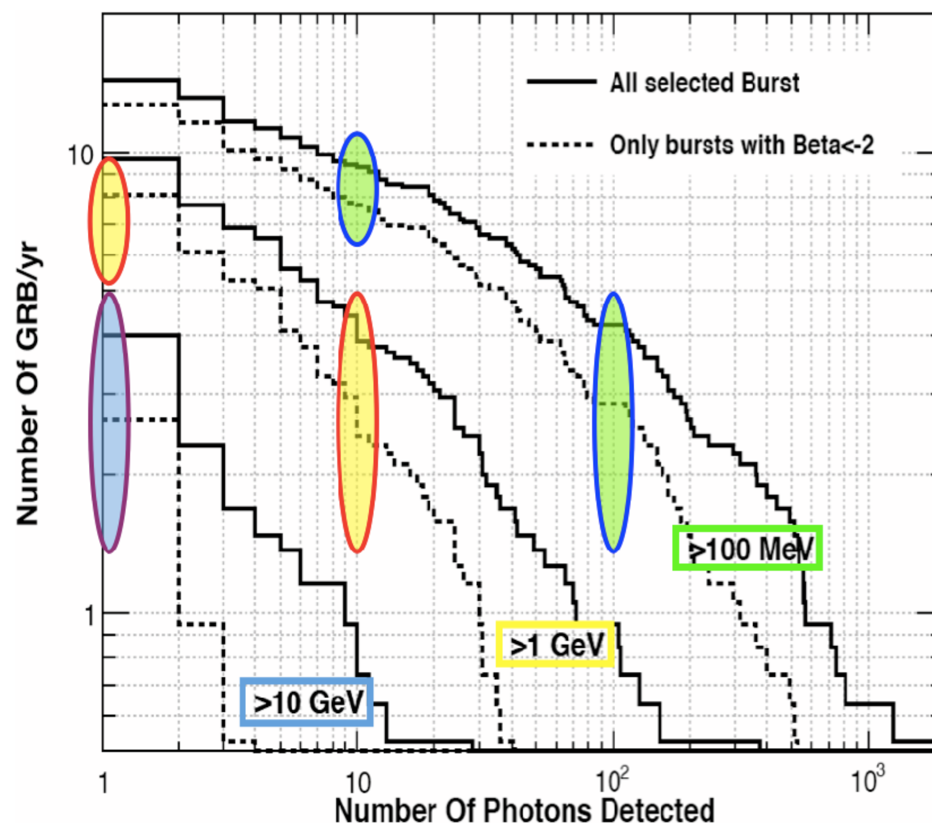
GRB	θ_{LAT}	long or short	number of events above		HE emission		extra spec. comp.	highest energy (GeV)	z
			0.1 GeV	1 GeV	starts later	lasts longer			
080825C	$\sim 60°$	long	~ 10	0	?	yes	no	~ 0.6	—
080916C	49°	long	145	14	yes	yes	?	~ 13	~ 4.35
081024B	21°	short	~ 10	2	yes	yes	?	~ 3	—
081215A	$\sim 86°$	long	—	—	?	?	—	—	—
090217	$\sim 34°$	long	~ 10	0	no	no	no	~ 1	—
090323	$\sim 55°$	long	~ 20	> 0	?	yes	?	?	3.57
090328	$\sim 64°$	long	~ 20	> 0	?	yes	?	?	0.736
090510	$\sim 14°$	short	> 150	> 20	yes	yes	yes	~ 31	0.903
090626	$\sim 15°$	long	~ 20	> 0	?	yes	?	?	—
090902B	51°	long	> 200	> 30	yes	yes	yes	~ 33	1.822
090926	$\sim 52°$	long	> 150	> 50	yes	yes	yes	~ 20	2.1062
091003A	$\sim 13°$	long	~ 20	> 0	?	?	?	?	0.8969
091031	$\sim 22°$	long	~ 20	> 0	?	?	?	~ 1.2	—
100116A	$\sim 29°$	long	~ 10	3	?	?	?	~ 2.2	—

❑ During its first 1.5 yr of routine operation, from Aug. 2008 to Jan. 2010, the LAT has detected 14 GRBs, corresponding to a detection rate of ~9.3 yr^{-1}

❑ the detection rate of bright LAT GRBs (i.e., with 1 photon above 10 GeV, 10 photons above 1 GeV, and 100 photons above 100 MeV) is ~ 2.7 GRB/yr

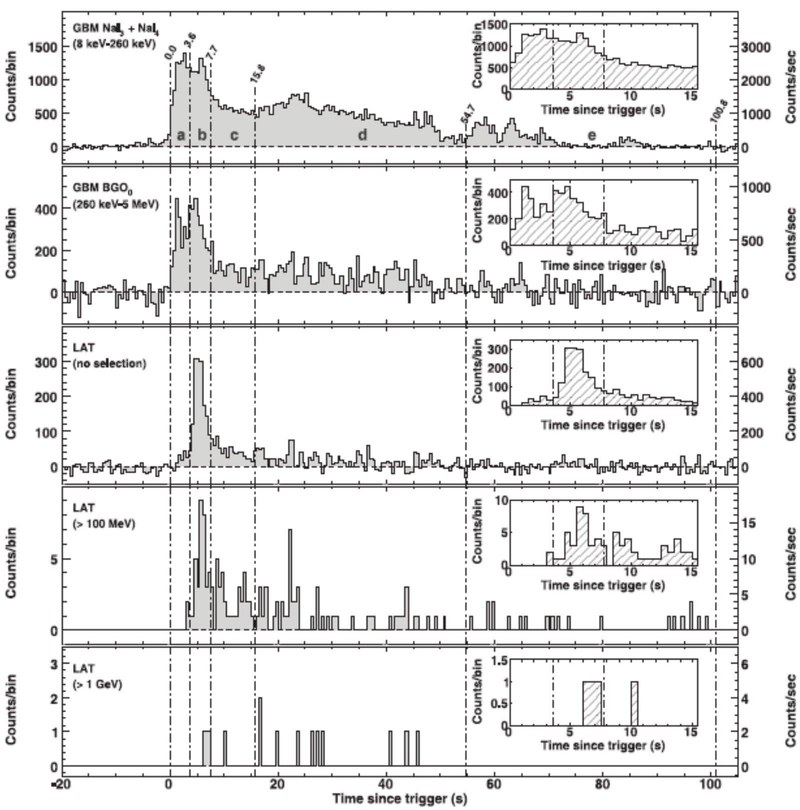
❑ these rates are fully consistent with pre-launch estimates based on the assumption of no GeV excess w/r to the extrapolation of the lower energy (Band) spectrum

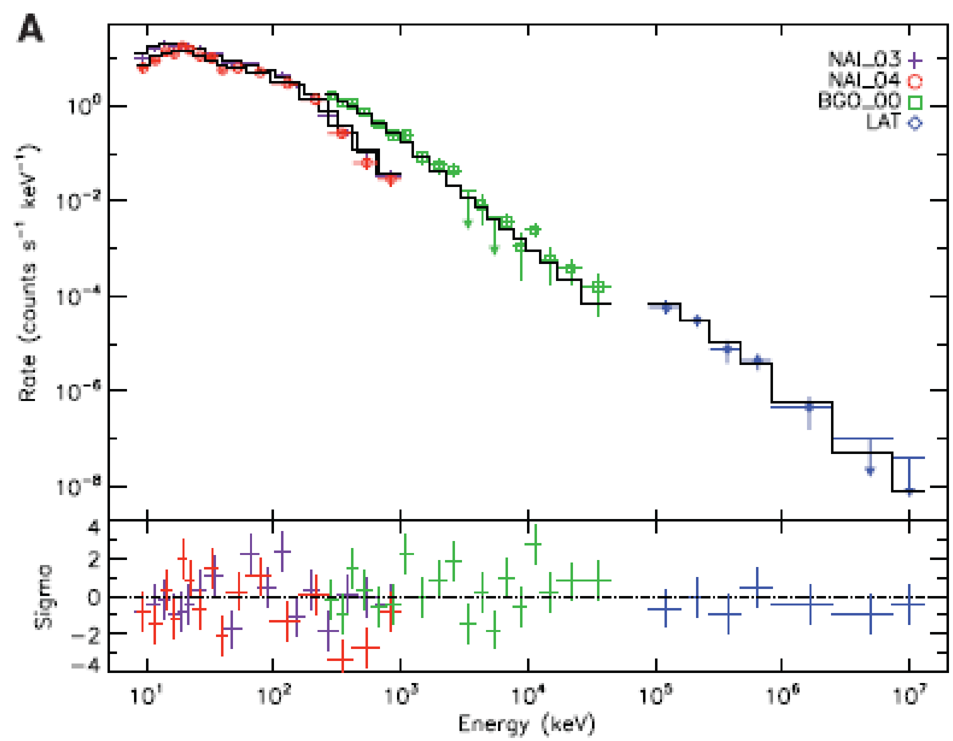




- ❑ this rates imply that, on average, there is no significant excess or deficit of high-energy emission in the LAT energy range relative to such an extrapolation from lower energies

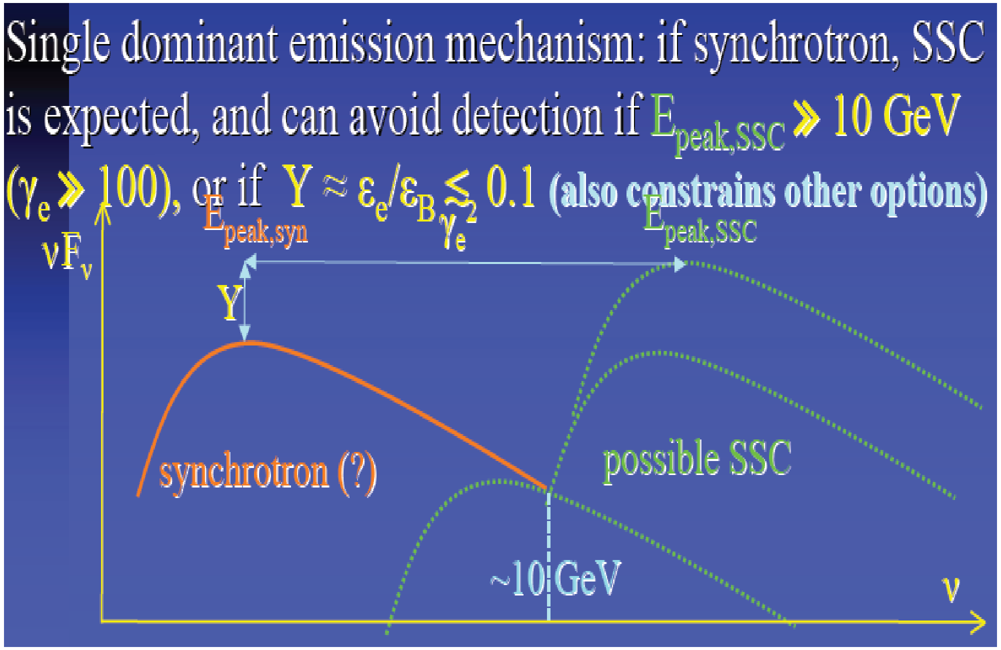
- ❑ this evidence was also supported by the early measurements of GRB 080514B by AGILE and the Fermi/GBM + LAT spectrum of GRB 080916C, the most energetic GRB ever detected (Eiso ~ 9×10^{54} erg)

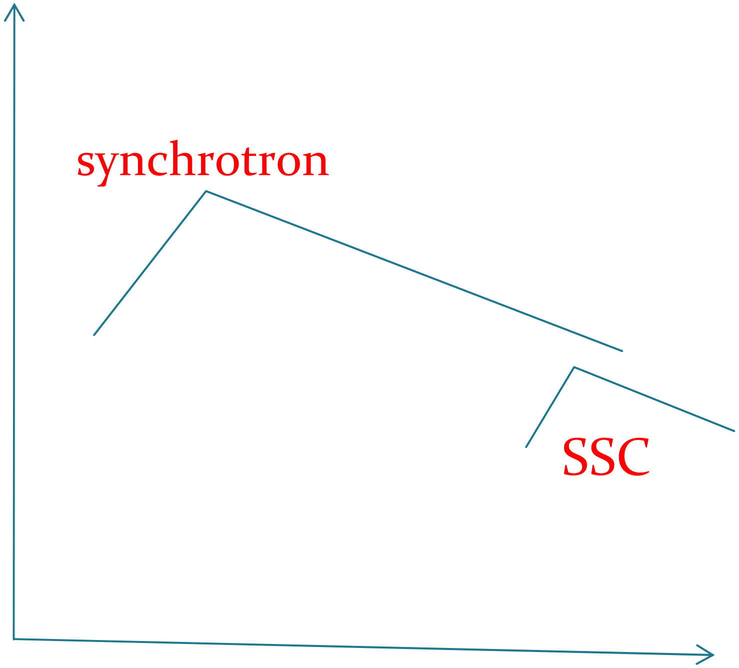




❑ the extension of the spectrum up to > GeV without any excess or cut-off for most GRBs is a challenging evidences for emission models

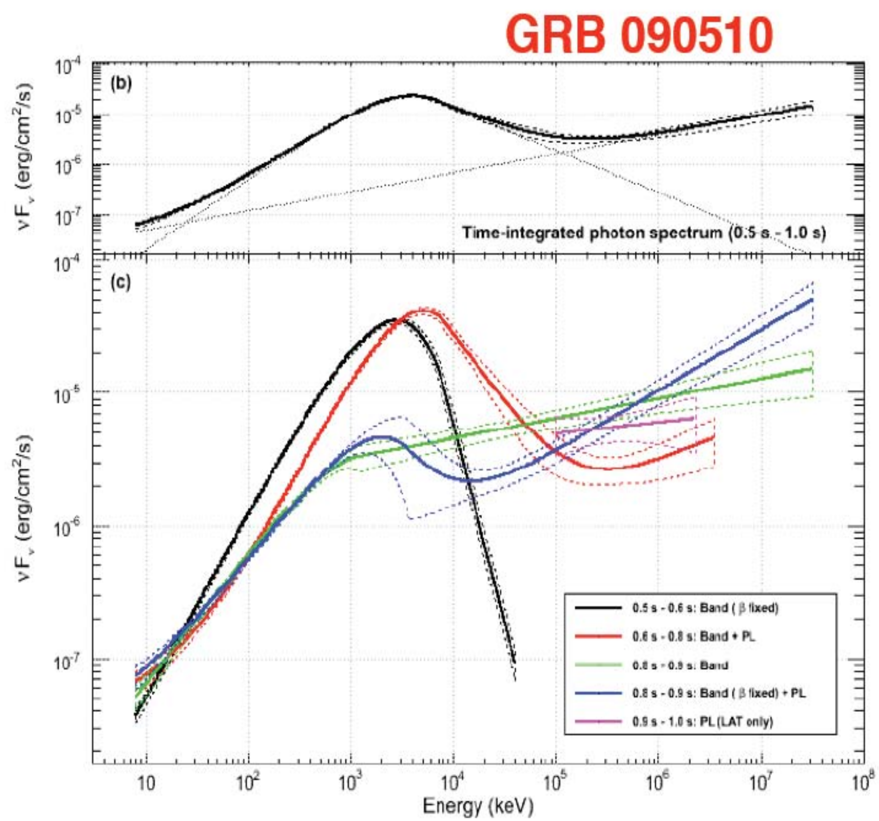
❑ possible expanations in standard baryonic fireball scenario: SSC of the internal shocks is within the extreme Klein-Nishina regime and is thus very inefficient; mildly magnetized internal shocks; Poynting flux dominated fireballs: strong magnetic field in the emitting region can suppress the inverse Compton radiation of electrons accelerated in the magnetic dissipation process

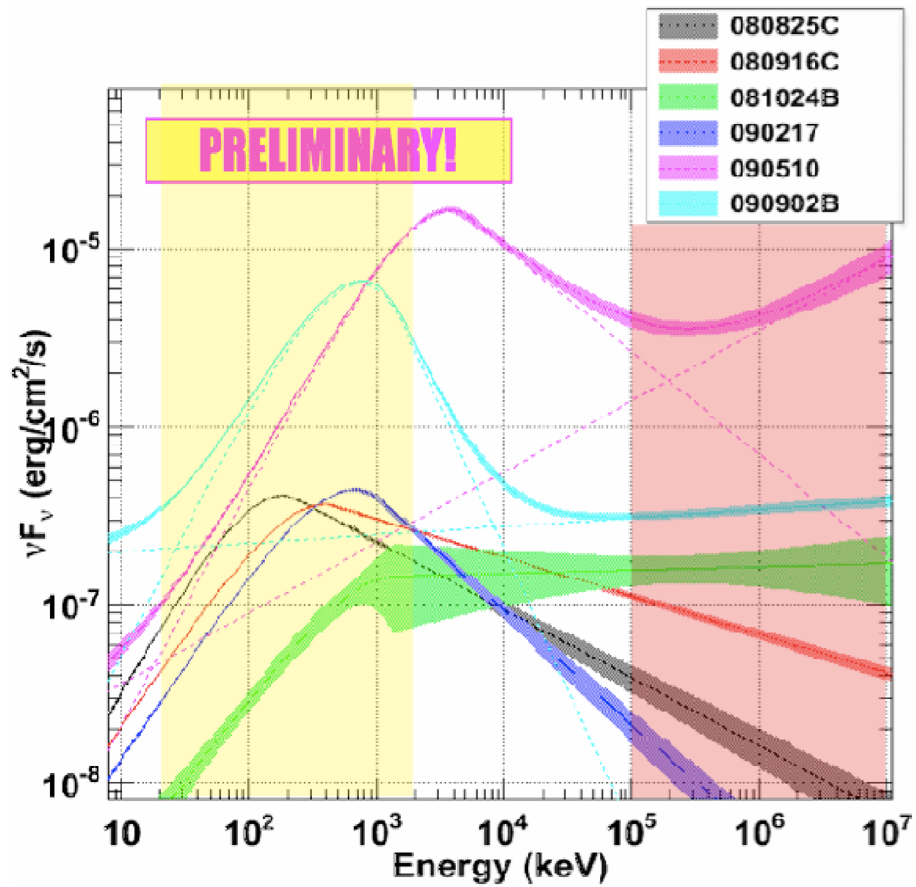




(magnetized fireball)

- nevertheless, an excess at E > 100 MeV, modeled with an additional power-law component, is detected in some GRBs (e.g., GRB 090902B, GRB090510)
- possible explanations: SSC of lower energy sinchrotron emission, IC of photospheric emission, hadronic processes

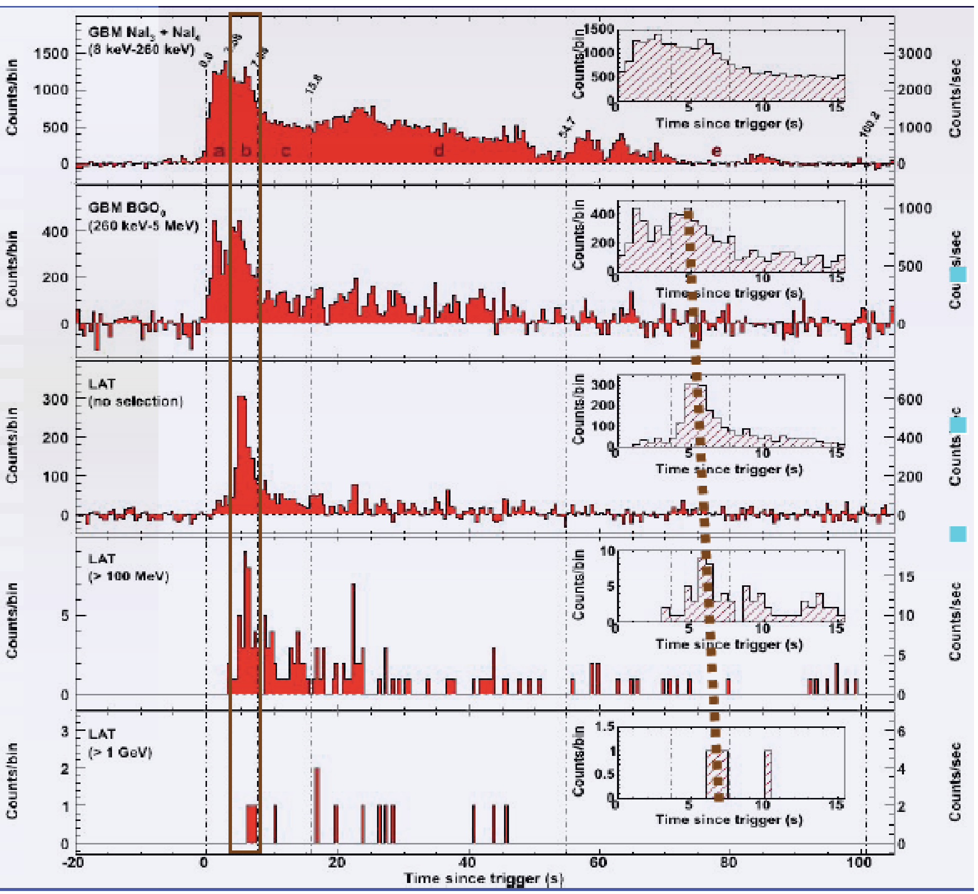


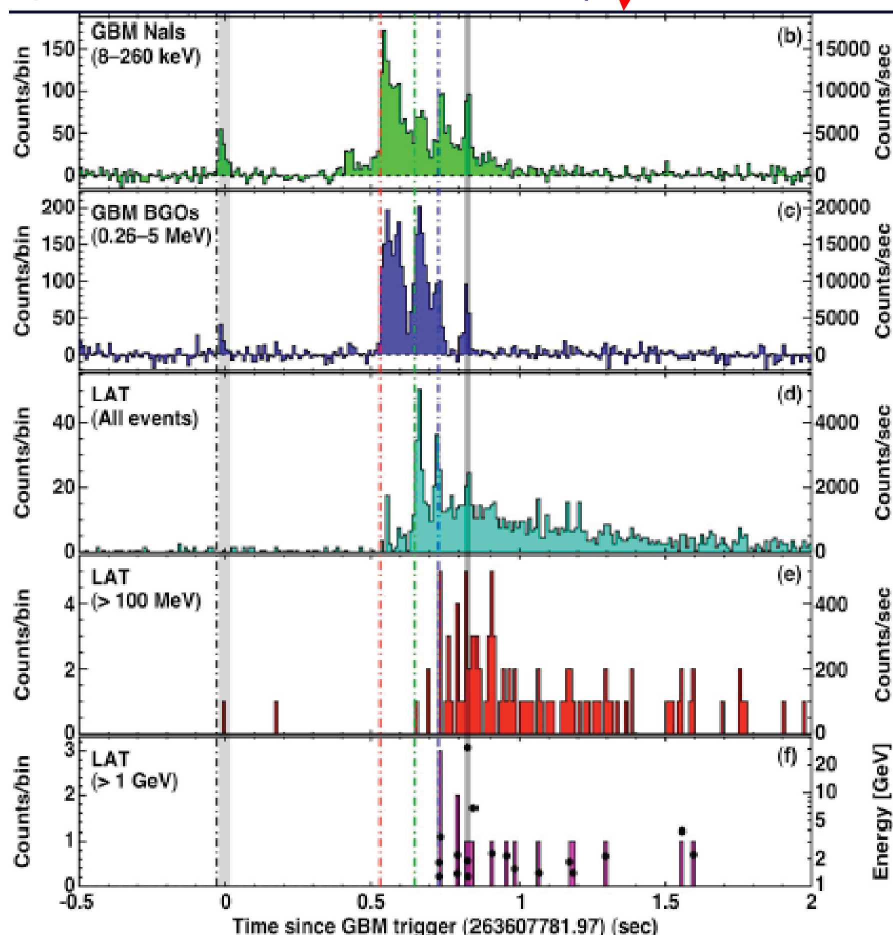


- significant evidence (at least for the brightest GRBs) of a delayed onset of HE emission with respect to soft gamma rays;

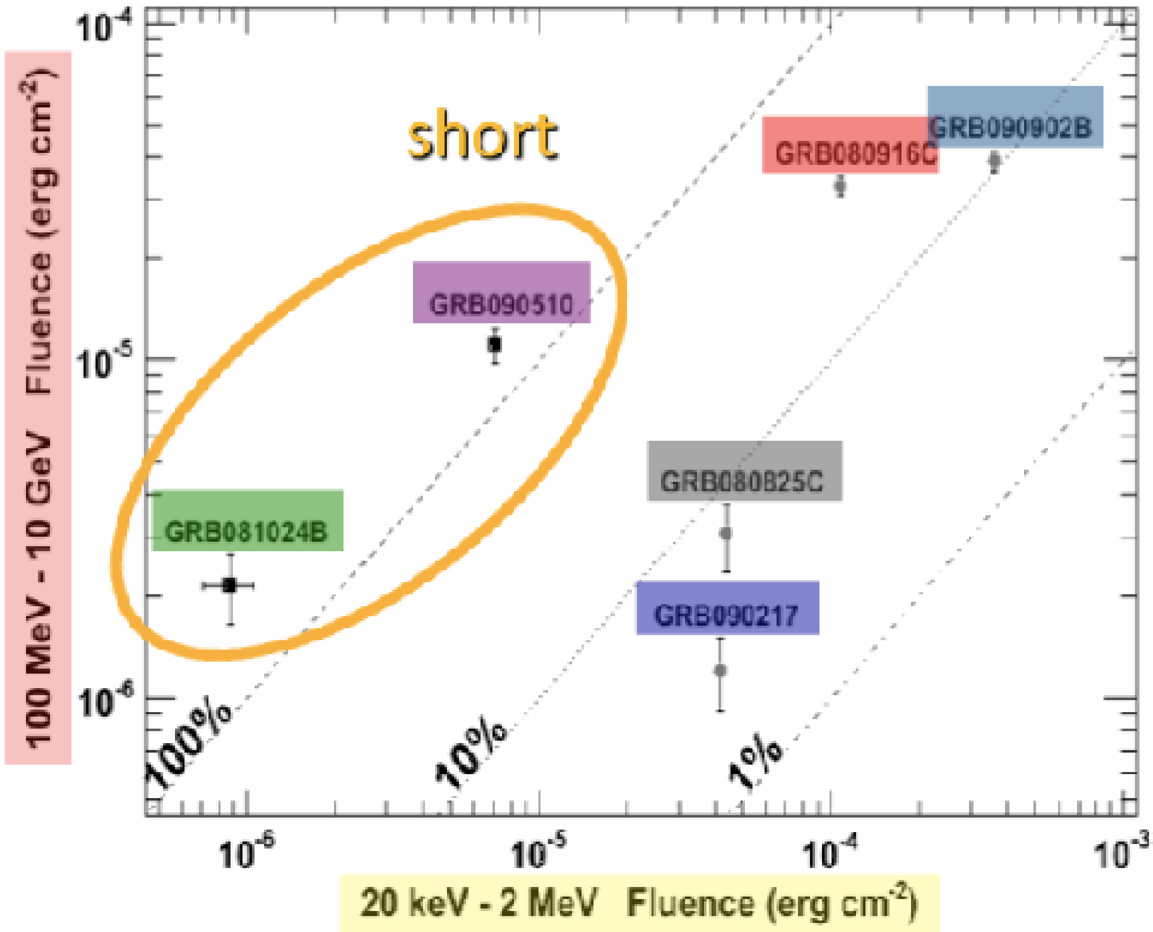
- the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)

- again, challenging for models (hadronic: e.g., proton acceleration time ?)



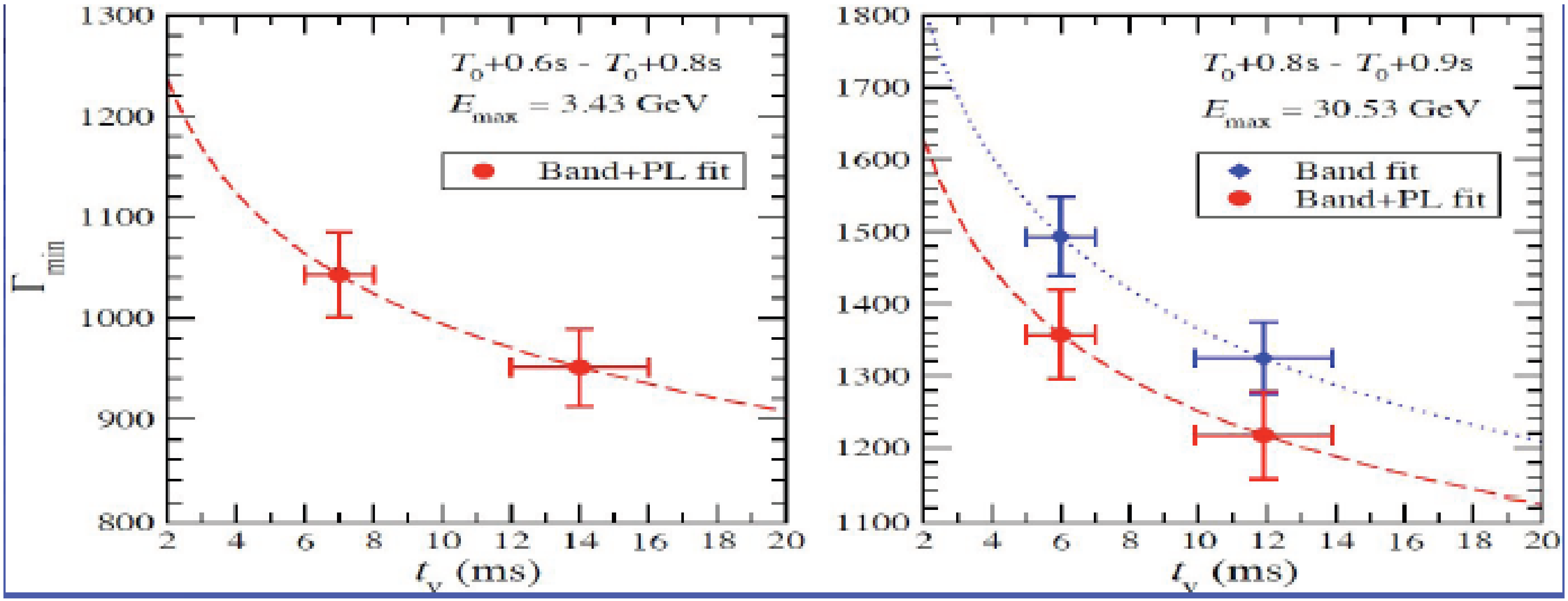


- short GRBs seem to show HE energy emission as long GRBs (the detection fraction in the LAT is about 15%, as for the GBM)
- however, short GRBs appear to have a comparable energy output at high and low photon energies, while long GRBs tend to radiate a smaller fraction of their energy output at high photon energies

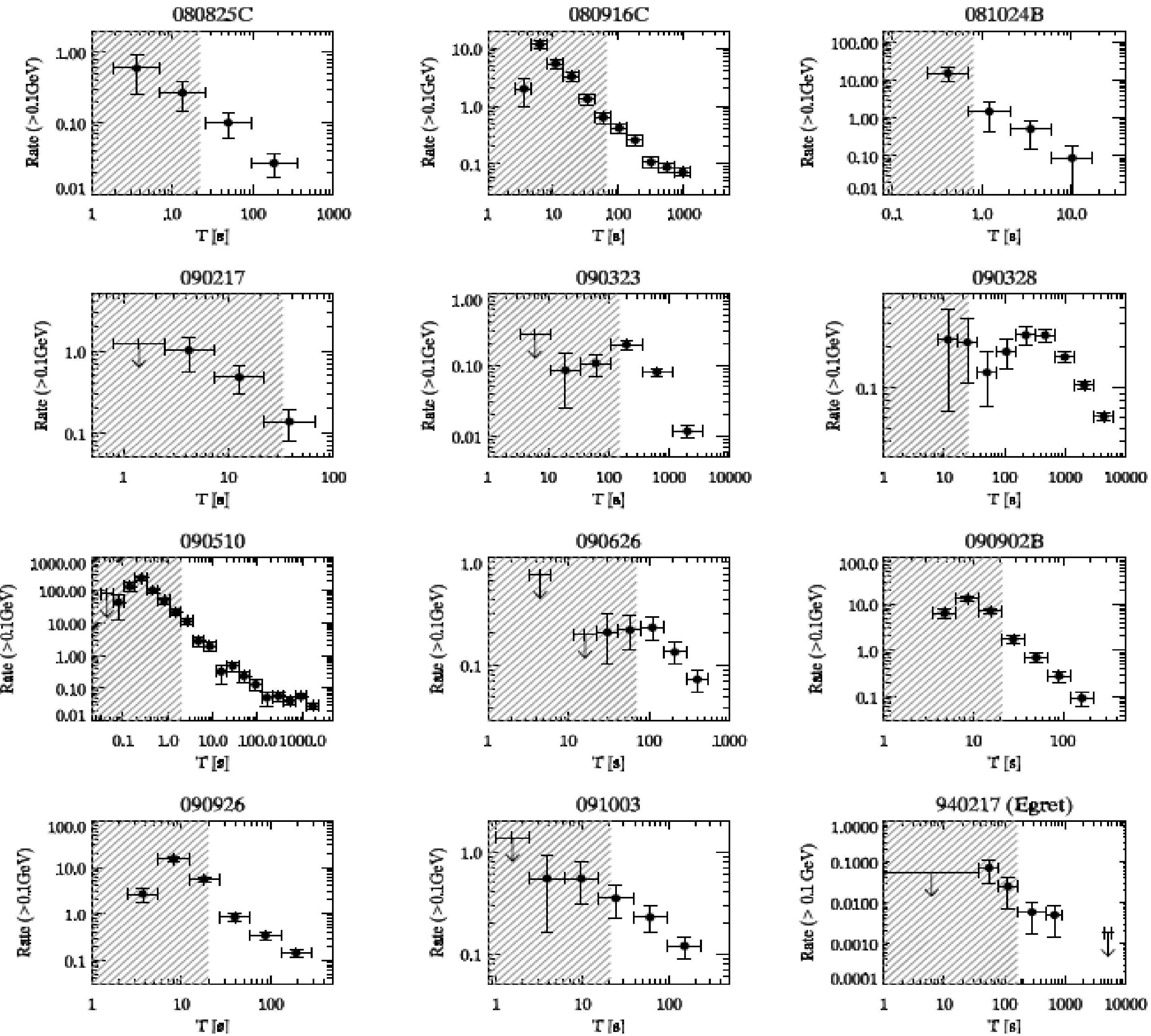


❑ using highest energy photons to infer lower limits to the fireball bulk Lorentz factor Γ (combined with time variability and spectral model; based on opacity constraints): 900 for GRB 080916C, 1200 for GRB 090510, and 1000 for GRB 090902B

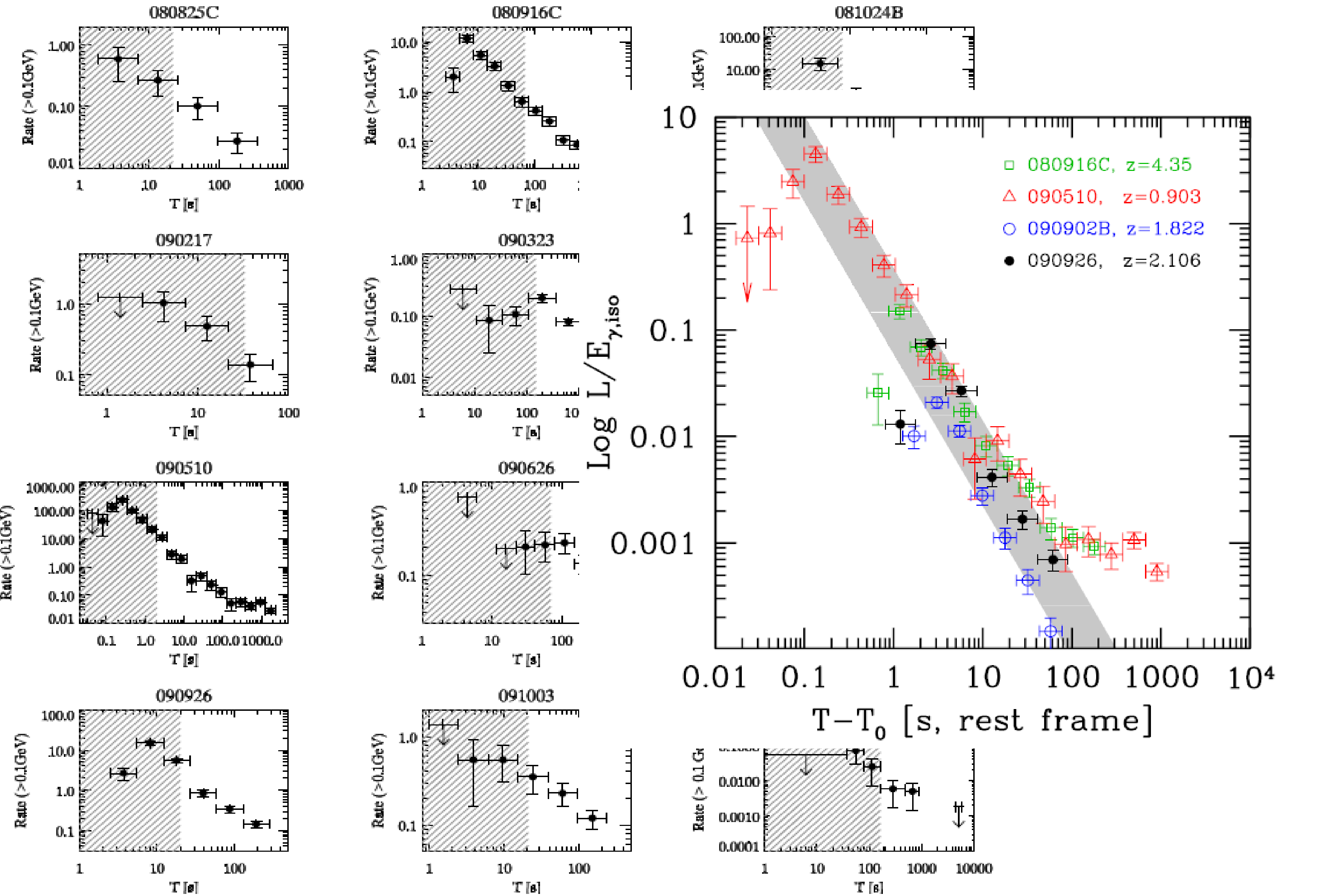
GRB 990510



❑ prolonged HE emission: afterglow ?



❑ prolonged HE emission: afterglow ?



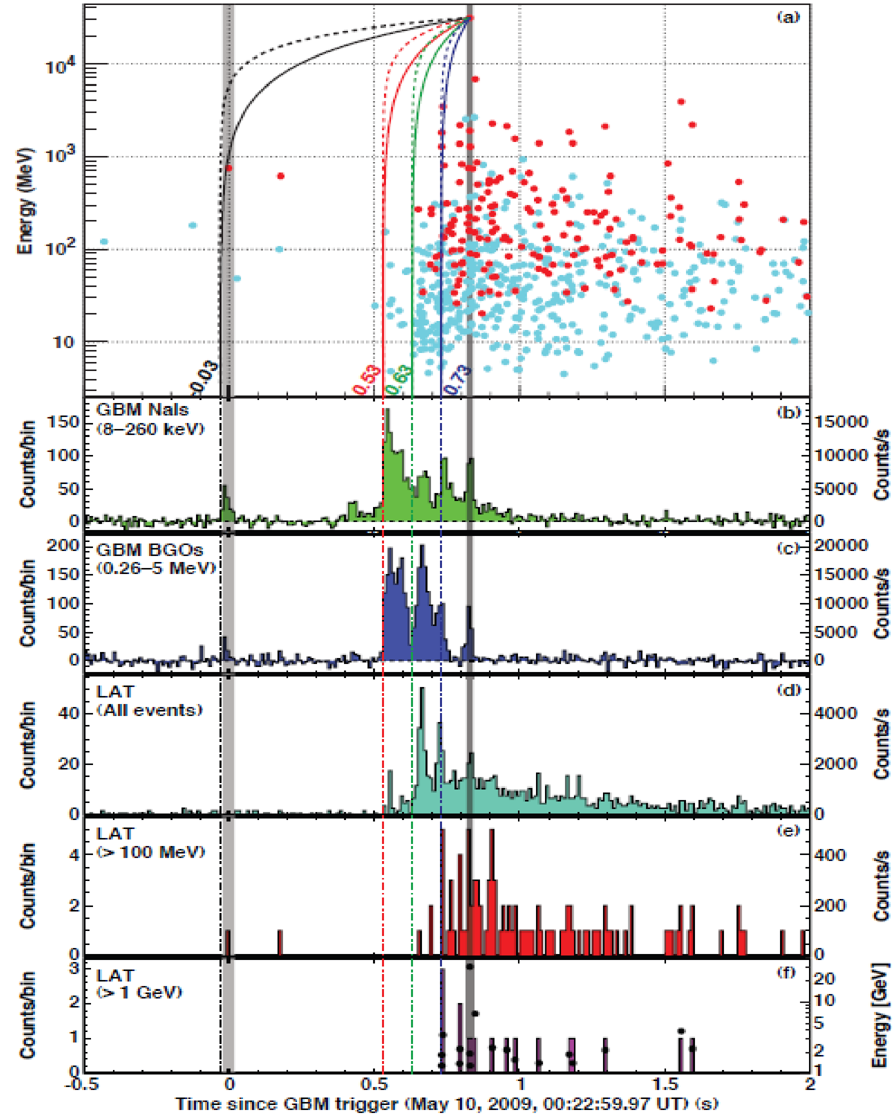
❑ Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

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

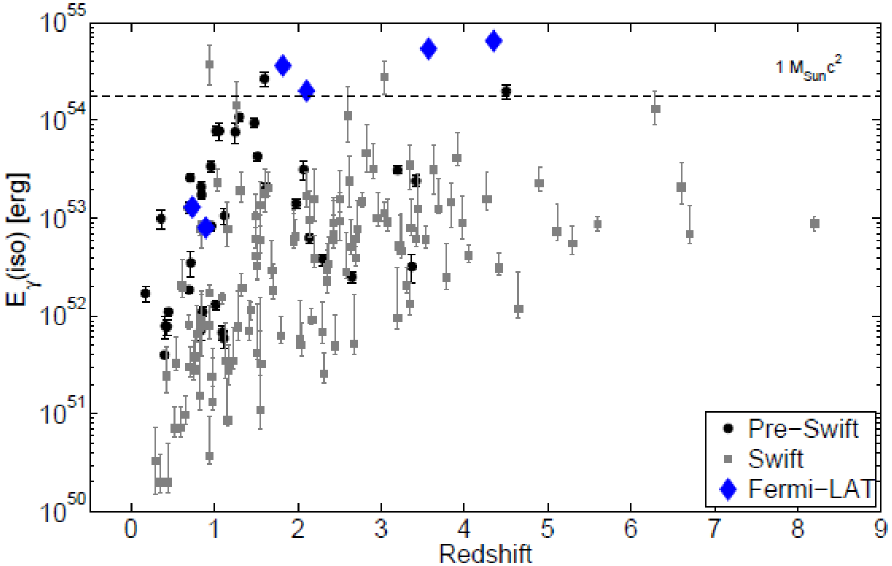
$$\Delta t = s_n \frac{(1+n)}{2H_0}\frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

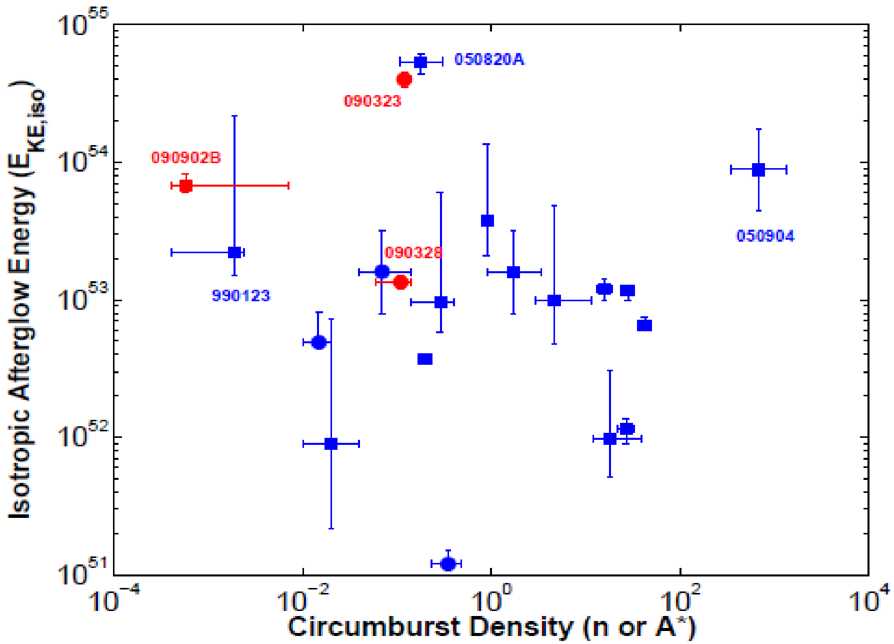
GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

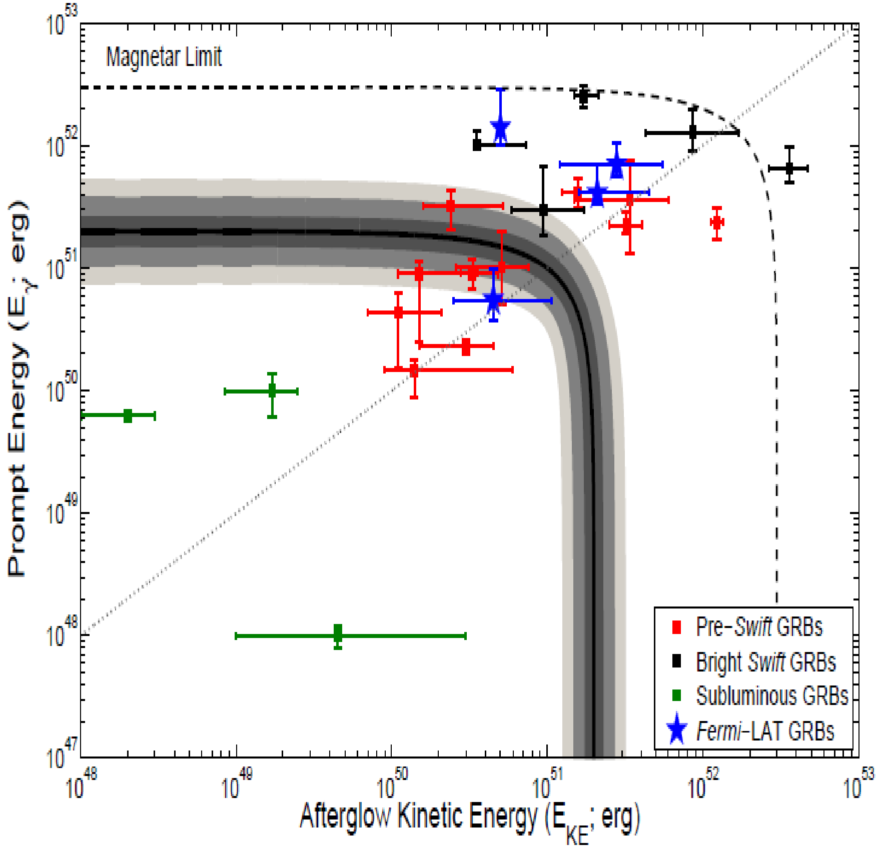
$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
−30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start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



❑ Emerging class of hyper-energetic events ?



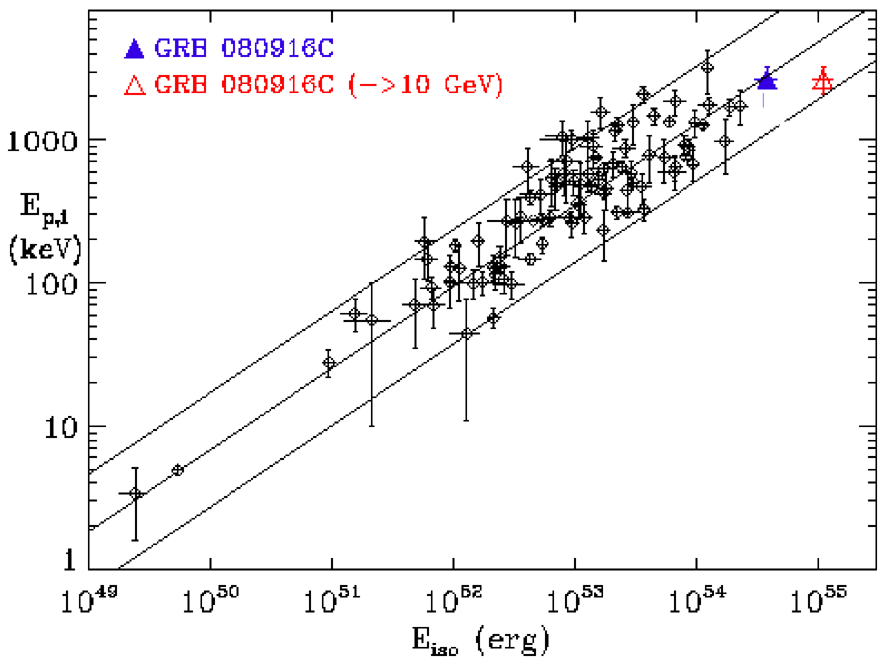


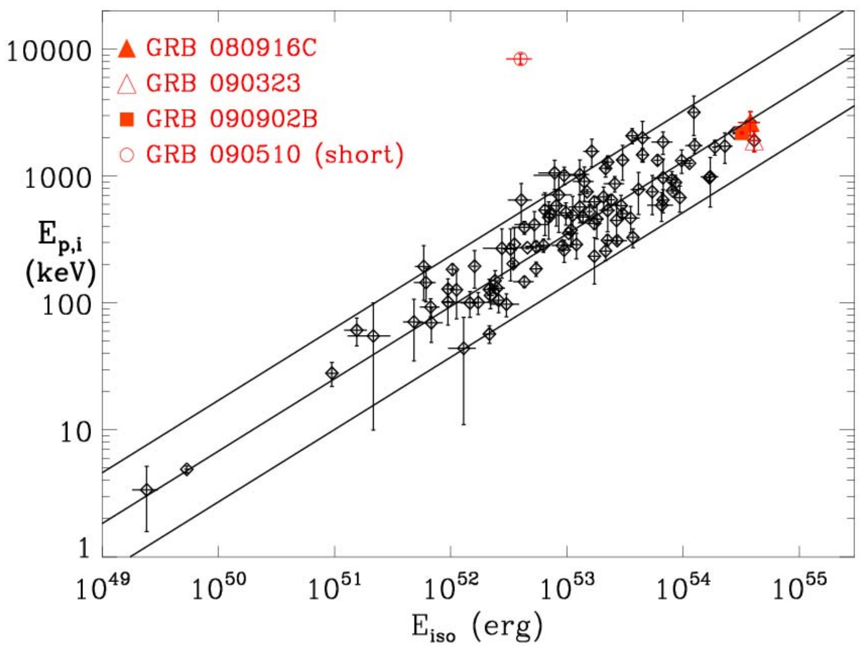


❑ GRB 080916C, the most energetic GRB ever (Eiso~10^{55} erg in 1 keV – 10 GeV), and the other hyper-energetic GRBs 090323 and 090902B are fully consistent with the Ep,i – Eiso correlation

❑ -> further extension of the correlation and further evidence that the main physics behind the X-ray – soft gamma-ray emission of extremely energetic events with GeV emission is similar to "normal" ones

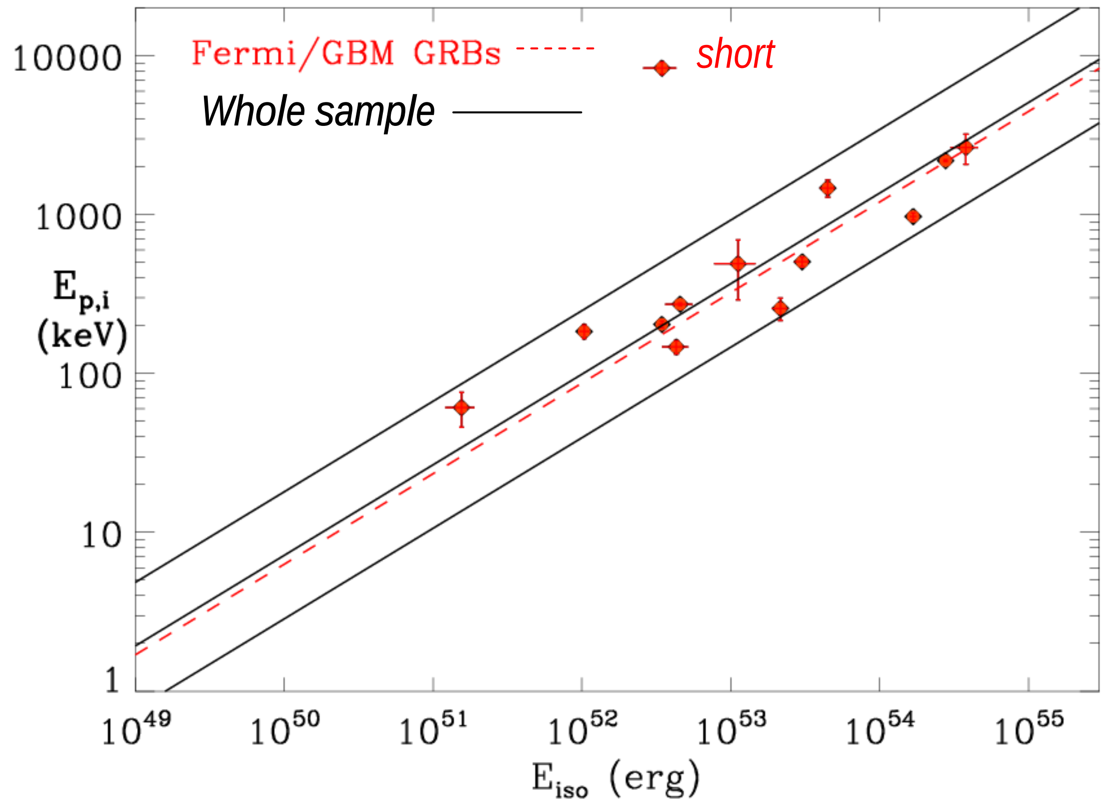
❑ GRB 990510: further evidence that short GRBs do not follow the correlation





❑ Thanks to its unprecedented energy band (8 keV – 30 MeV), Fermi/GBM is providing most accurate estimates of spectral peakk energy Ep

❑ *All Fermi/*GBM long GRBs with known z are fully consistent with Ep,i – Eiso correlation as determined with previous / other experiments: further confirmation of non relevant instrumental effects



Conclusions

- Despite the huge observational progress, the physics behind GRB prompt and early afterglow emission is still far to be fully understood (e.g., main prompt emission mechanism, short vs vs. long GRBs, steep + flat decay and flares, correlations)
- High energy observations by AGILE and Fermi are adding new pieces to the puzzle (lower limits to Γ, HE tail in the spectra of some GRBs, HE emission from short GRBs, HE afterglow)
- … but also new issues (lack of GeV excess in most GRBs, onset delay of HE emission, different balance between low and high energy output in short / long GRBs)
- Measurements of GRB emission from hard X-rays to GeV allows fundamental physics studies (e.g., test of Lorentz invariance)
- Last (but not least), Fermi results confirm and extend the Ep,i – Eiso (“Amati”) relation for long GRBs