High energy emission from Gamma Ray Bursts

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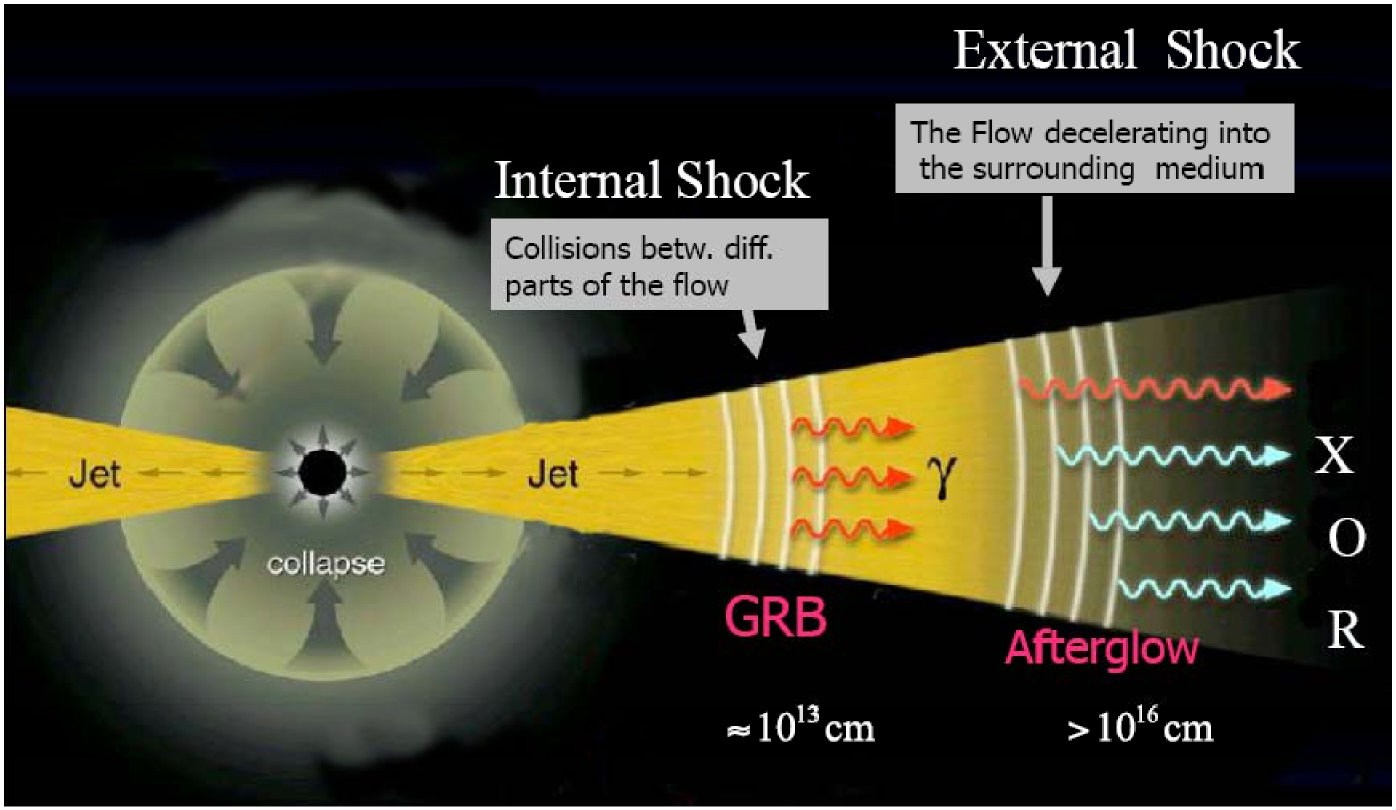
Outline

- What are GRBs
- GRB high-energy observations
- Models for GeV-TeV emission from GRBs
- Cosmic rays and neutrinos from GRBs
- Constraints on Quantum Gravity models

What are GRBs?

- Cosmological distance:Typical observed z>1
- Energy released is up to few times the rest mass of Sun (if isotropic) in a few seconds => narrow beam
- Most of the energy is emitted in γ- rays
- Relativistically expanding fireball
    - Shocks between shells of different velocity: prompt emission
    - Shocks created when fireball decelerates into external medium: afterglow
- Central Engine
    - Collapse of massive, rotating star? (long GRBs)
    - Coalescence of binary neutron stars? (short GRBs)
- Final Product is Black Hole (probably)

GRB model: Internal and External shocks



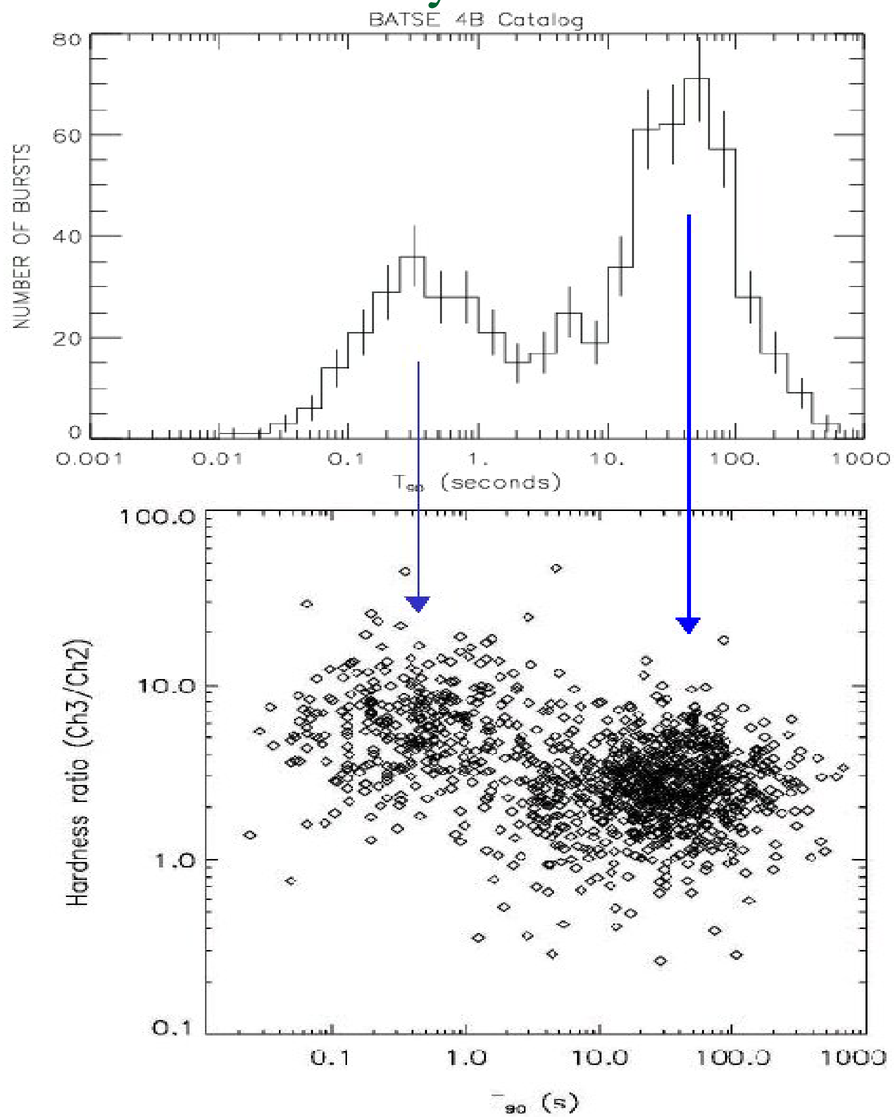
Credit P. Meszaros

Rees & Meszaros 92; Meszaros & Rees 1994

Two different classes of Gamma-Ray Bursts

- GRBs duration distribution is bimodal
  (e.g. Briggs et al. 2002)
  - 0.1-1 s -> Short bursts
  - 10-100 s -> Long bursts

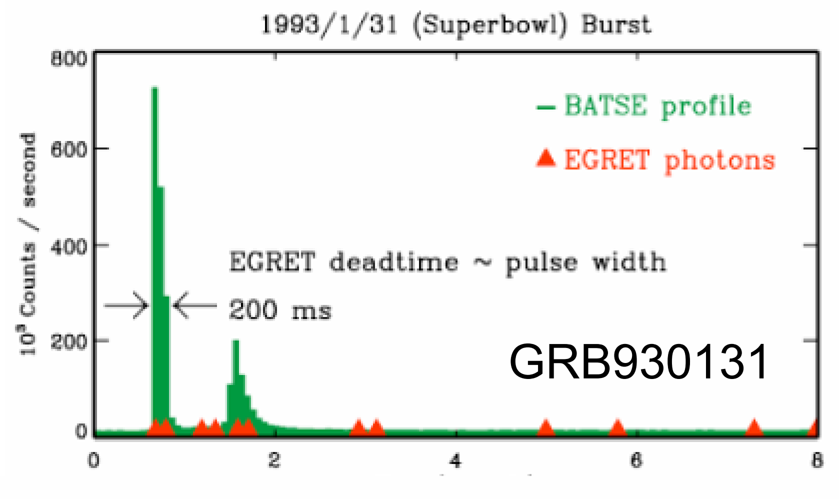
- Short GRBs are harder than long GRBs
  (e.g. Fishman & Meegan, 1995;Tavani 1996).



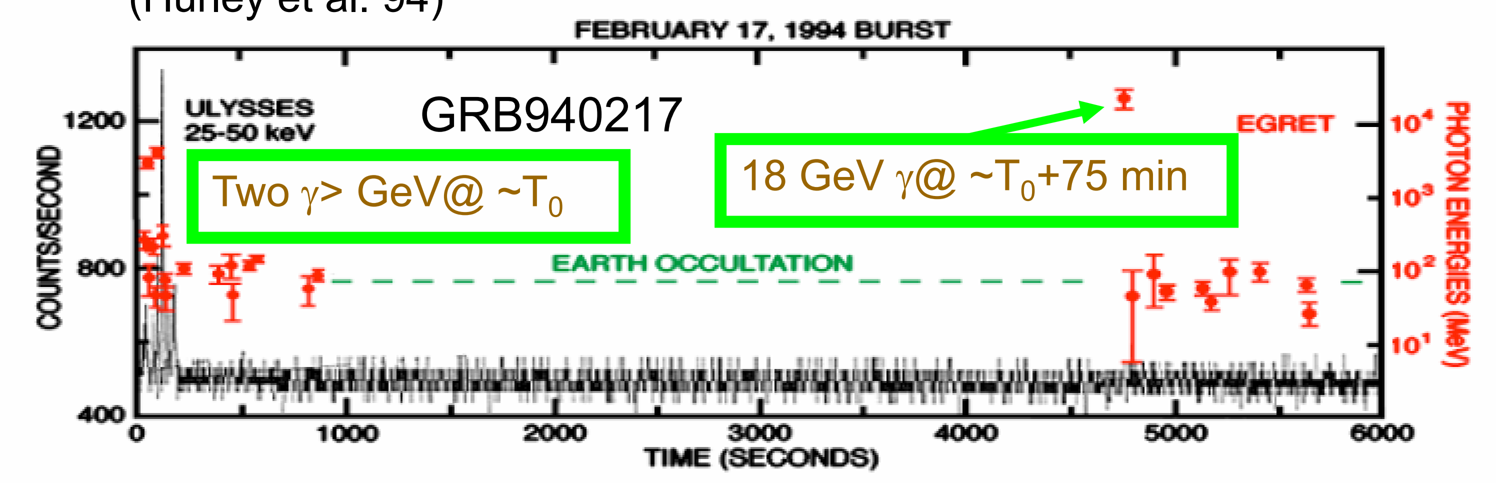
GRB high-energy observations: pre-Fermi era

EGRET on CGRO: ~ 30 MeV – 30 GeV, FoV ~ 0.6 sr

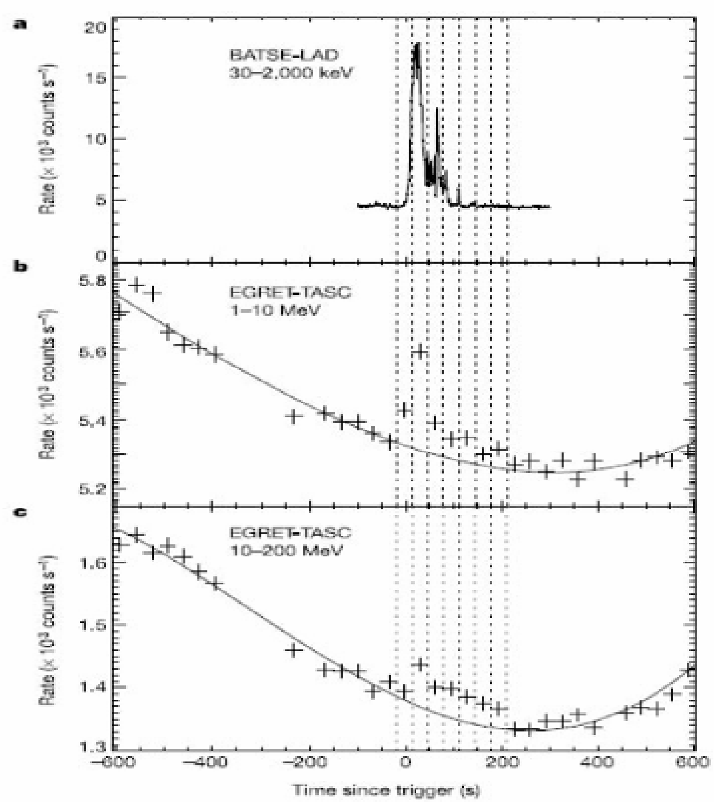
1) Prompt
2) Delayed

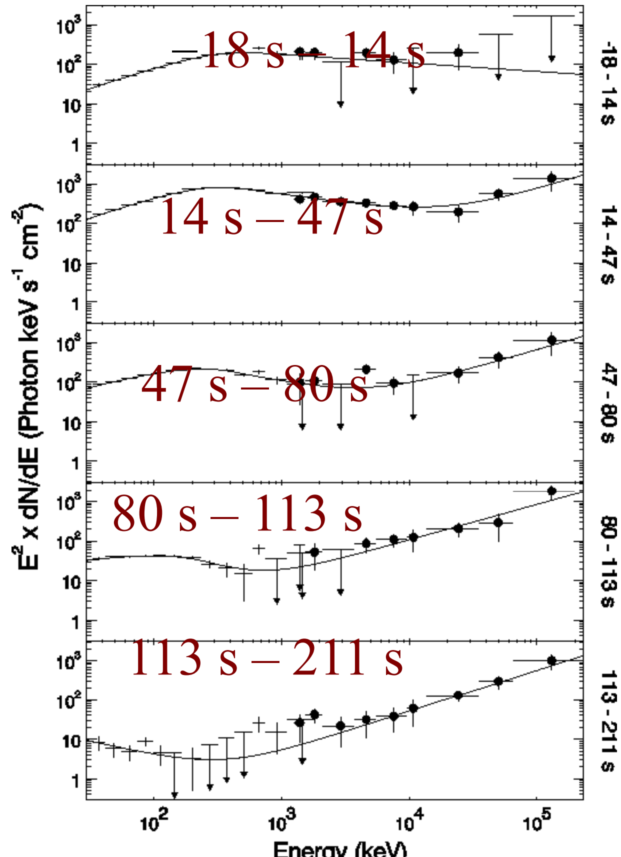


(Hurley et al. 94)



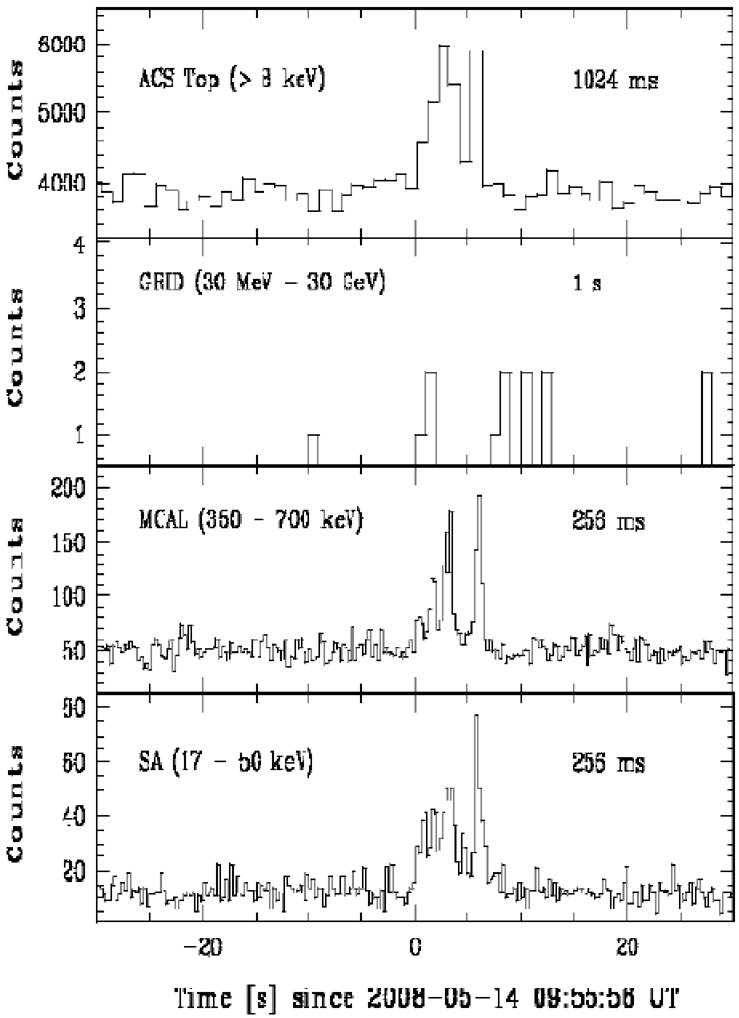
• **GRB 941017** **(Gonzalez et al. 2003): up to 200 MeV photons detected by EGRET presents a distinct multi-MeV spectral component which decays more slowly than the low energy component;**





Interpretation: Hadronic cascade *(Gonzalez et al. 2003) spectrum too soft?*, SSC in the reverse shock *(Granot & Guetta 2003)*

A burst detected by AGILE



GRB080514B

(Giuliani et al. 2008)

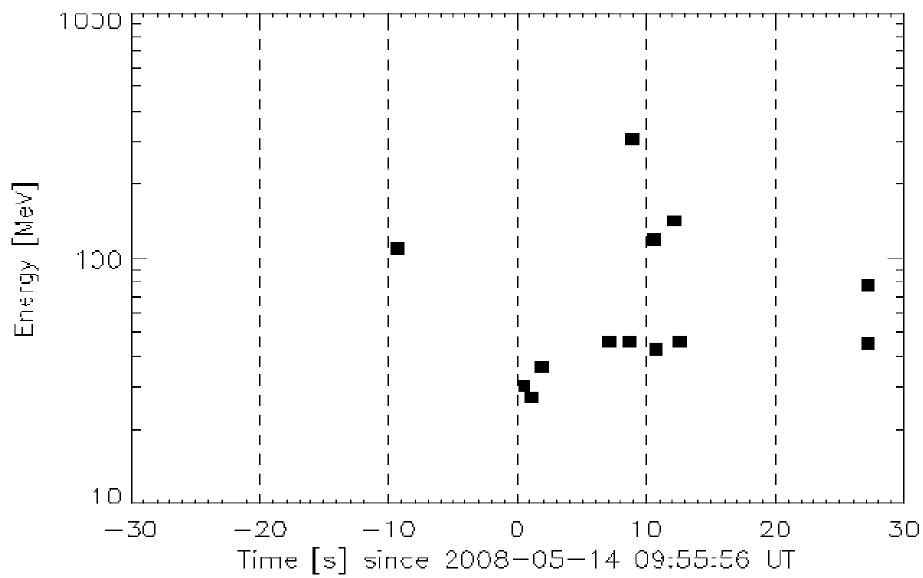


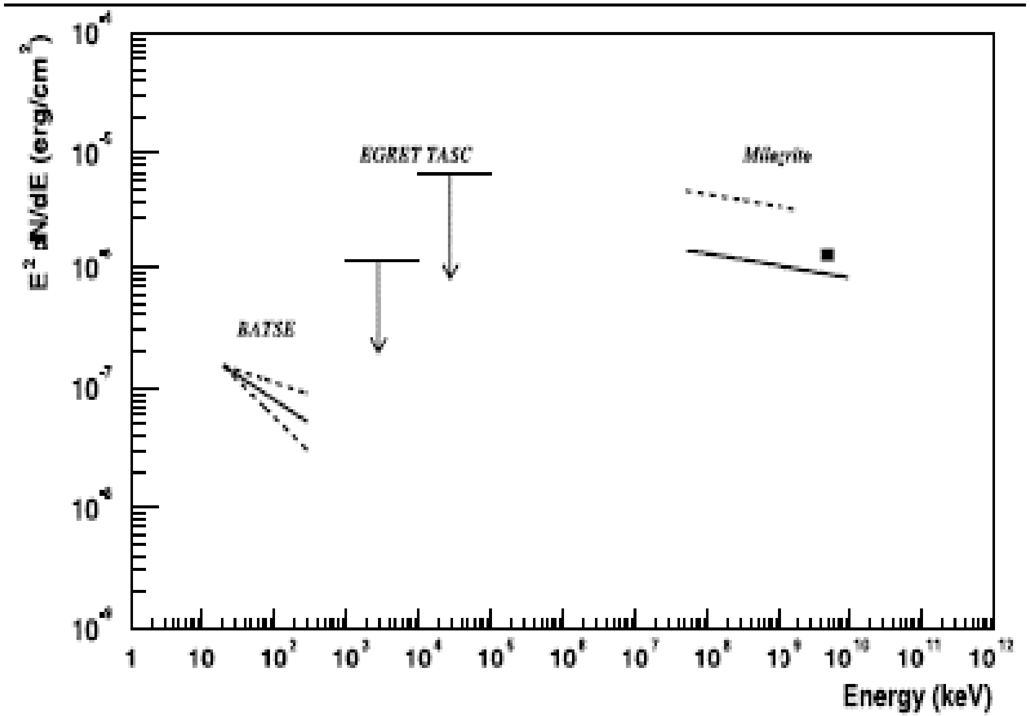
Fig. 4. Energy of the photons detected by the GRID from the direction of GRB 080514B

Similar to GRB941017, common phenomena?

Very High Energy emission in GRBs

• GRB 970417 (Atkins et al. 2000, 2003): the excess of events detected by Milagrito if true must be due to <u>photons of at least 650 GeV.</u>

VHE observation are not consistent with the extrapolation of the BATSE spectrum. The VHE fluence is at least 10 times greater than the sub-MeV fluence observed by BATSE.



HE emission from GRBs

What can we get from high energy emission of GRBs?

Extra component of the prompt emission ?

Different emission mechanisms: synchrotron radiation from relativistic electrons accelerated in the shock, which radiate in the strong magnetic field. Synchrotron self Compton: upscattering of synchrotron photons by relativstic electrons Hadronic origin Only GRB941017 shows the sign of extra component

What is the maximum energy of high energy photon?

Constrain the bulk Lorentz factor of the relativistic jet
No evidence of the cut-off so far.

Delayed or long-lived high energy emission ?

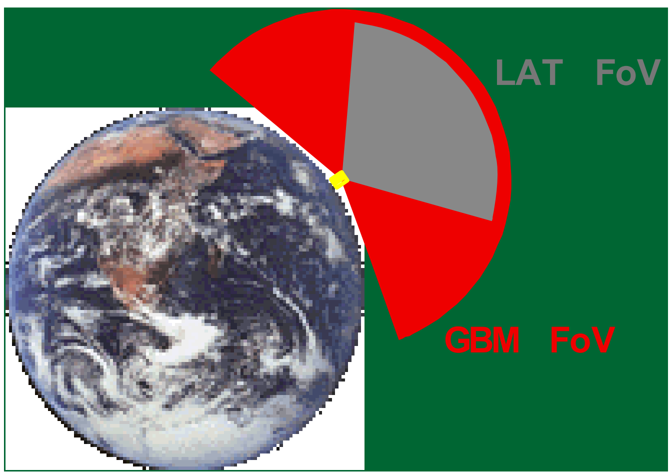
Suggests another emission mechanism
Time delay of high energy photon $\longrightarrow$ Limit on the quantum gravity mass :MQG
A few GRBs show delayed high energy emission (GRB940217, GRB080714)

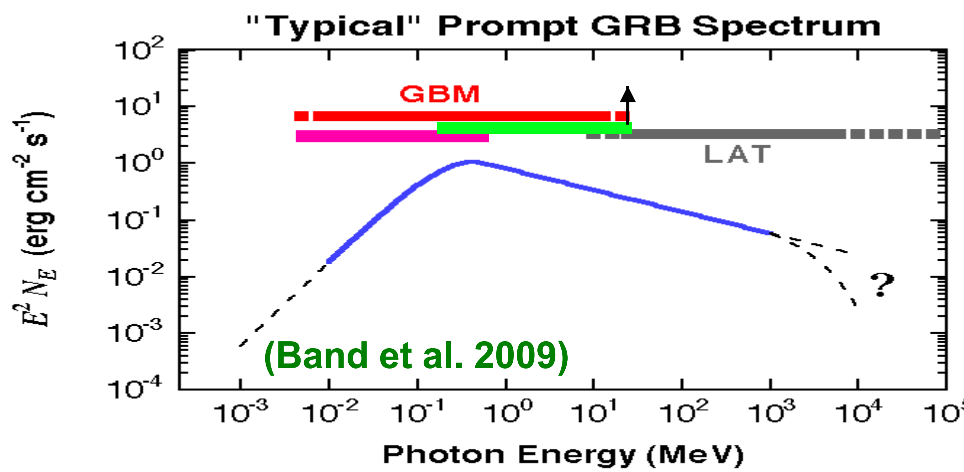
Need more sensitivity and larger FoV

Fermi Gamma-ray Space Telescope:

- Fermi GRB Monitor (GBM): 8 keV – 40 MeV full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV

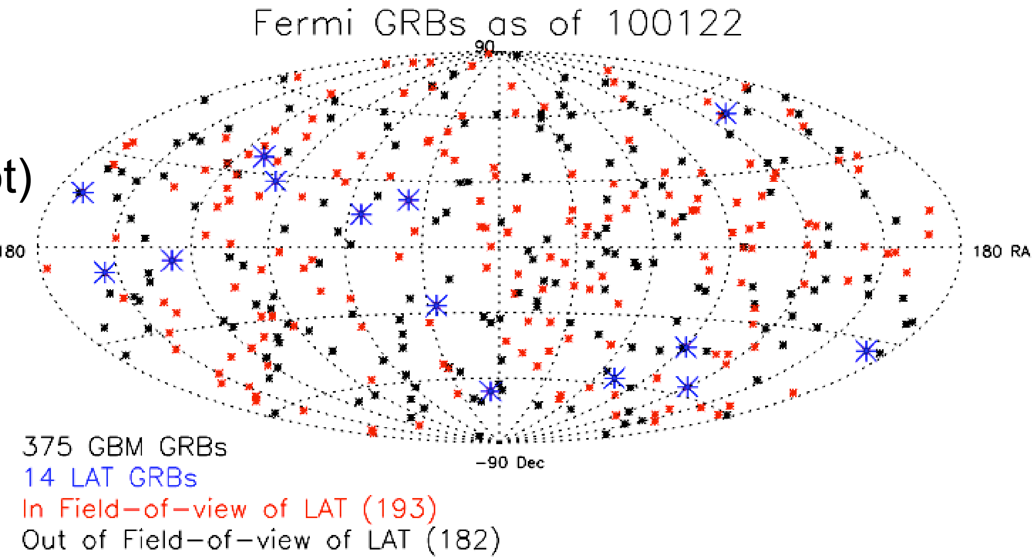
  FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime



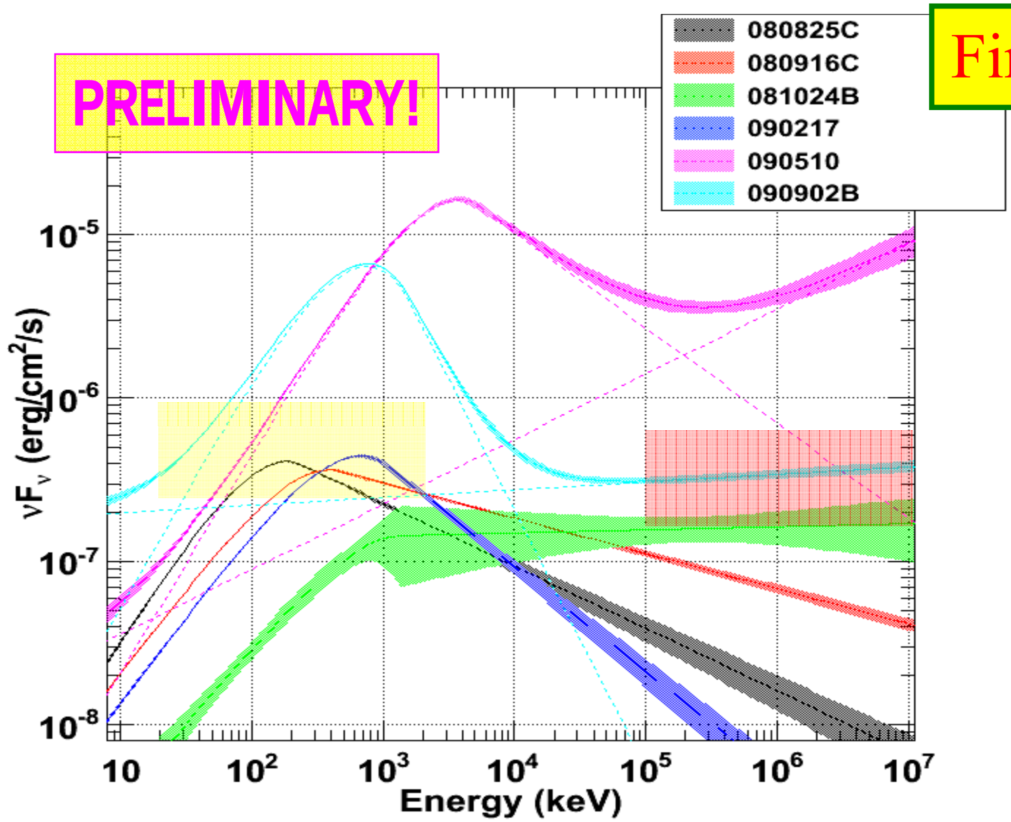


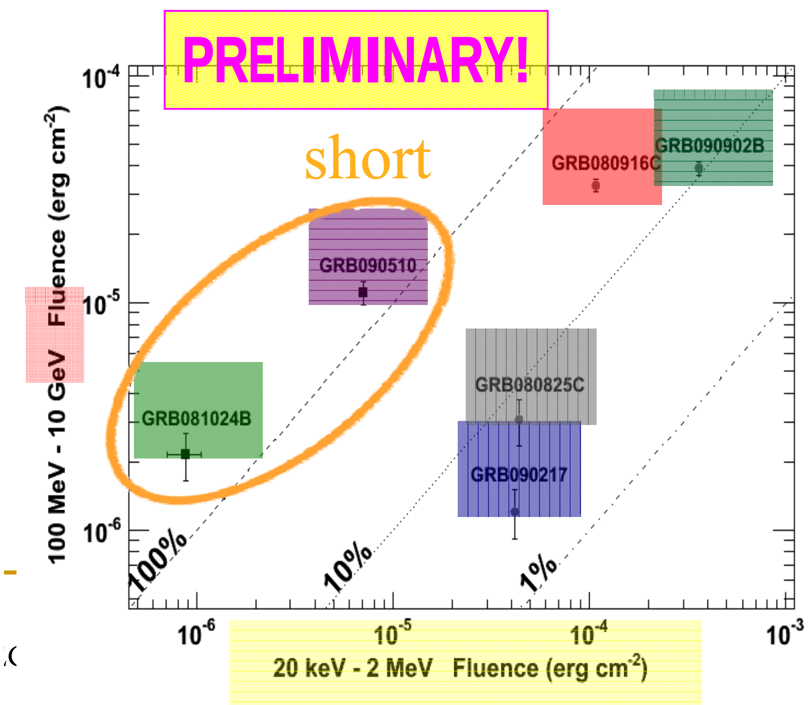
Fermi GRBs:

- **GBM:** (Courtesy Granot)
  - ~ 250 GRB/yr (~20% short)
  - **~** ½ in LAT FoV
- **LAT: 14 GRBs in ~1.5 yr**
  - 2 out of 14 are short: ~ 14%



First detections of short GRBs at HE

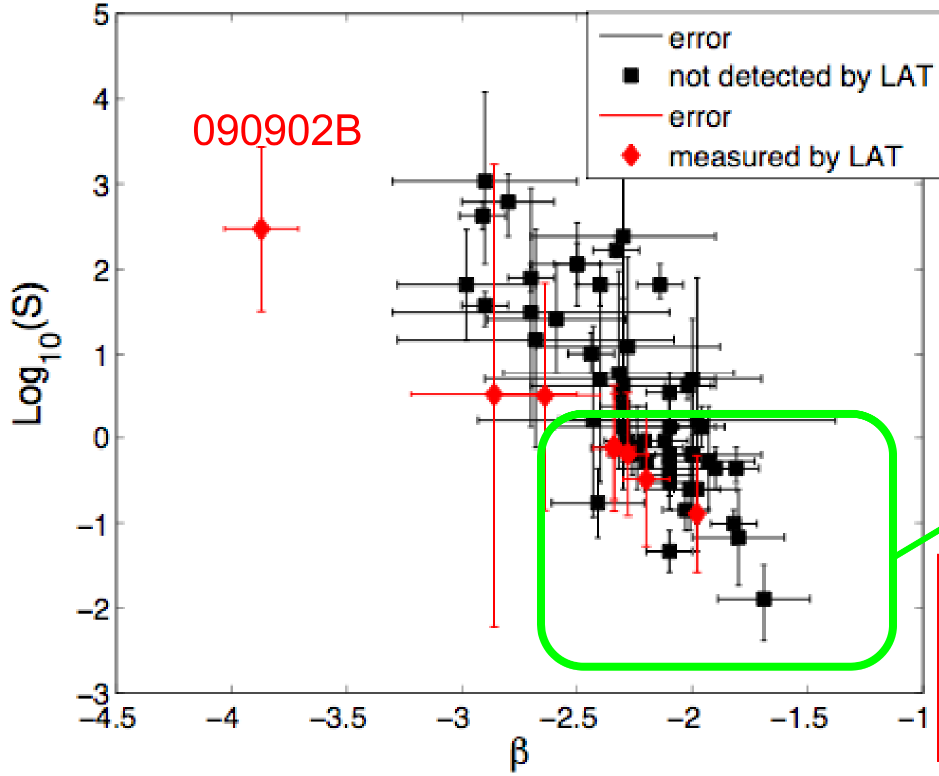




Why only 10% of GRBs detected by LAT? (1/3 expected) (Guetta, Pian &Waxman 2010)

For ~ 80 GRBs fitted by Band law, using the LAT trigger algorithm, we define s= [minimum flux for LAT detection at 100 MeV]/ [flux(100 MeV)]

Found assuming extended sync. emission

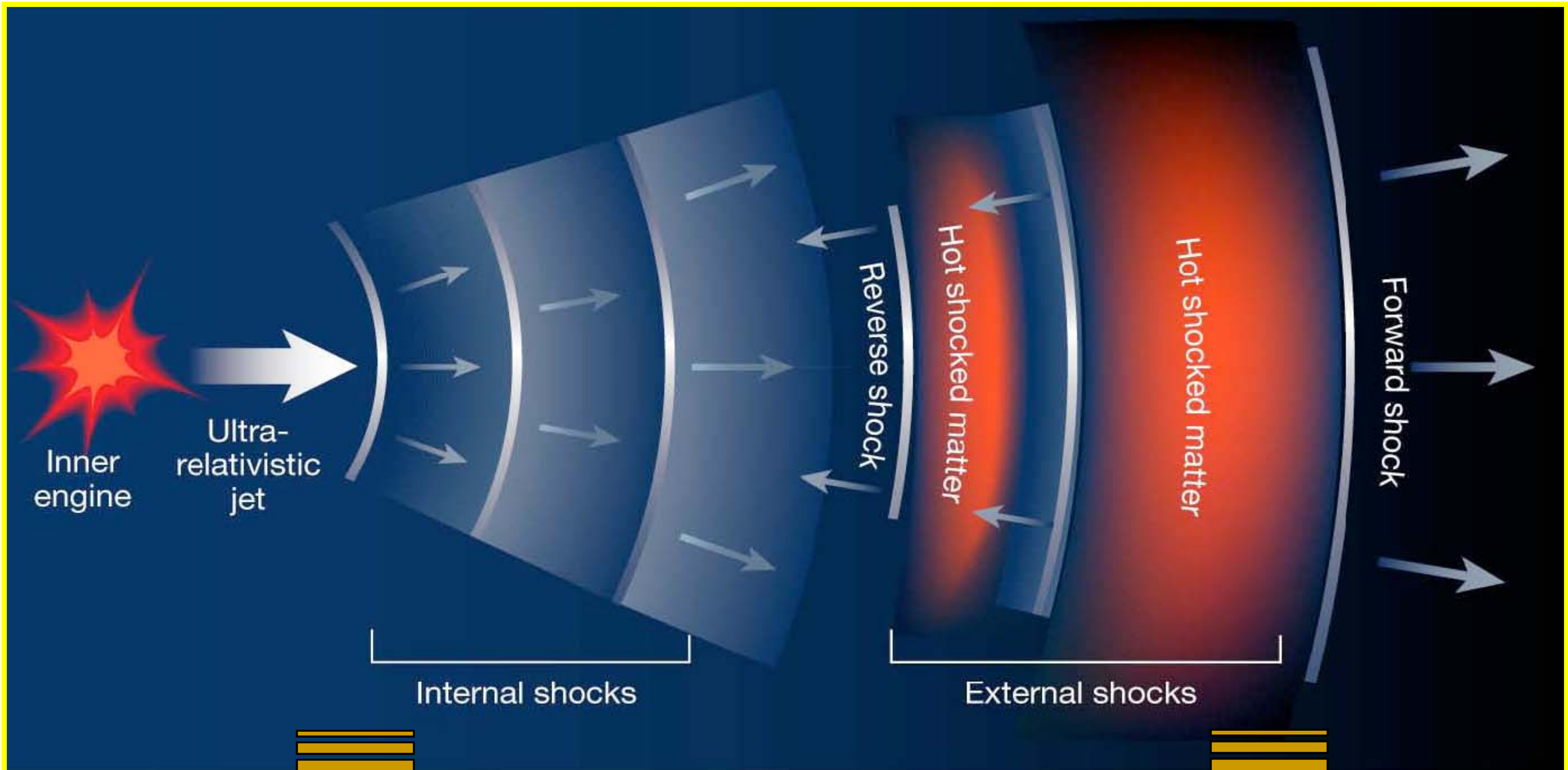


090902B: too soft to be extended synchrotron emission extra component needed!!!

LAT detectable: ~10 GRBs in the range of LAT detectability if extended synch. emission assumed not detected: **WHY??**

The emission at high energy is SUPPRESSED by some mechanism, WHAT?? Pair production, Electrons not accelerated to high energy?

If not extended synchrotron emission what else?



- SSC in internal shocks, 1 MeV-10 GeV (Guetta & Granot 2003, Meszaros et al., Galli & Guetta 2007)
- p-γ interaction, MeV – TeV (Gupta & Zhang 2007)

- SSC in RS, keV-GeV (Granot & Guetta 2003 Kobayashi et al. 2007)
- SSC in FS, MeV-TeV (Galli & Piro 2007)
- p-γ interaction in FS, GeV – TeV (Boettcher & Dermer 2003) p-sync. (Razzaque 2010)

Two basic processes for high-energy gamma-ray emission

1. Leptonic: extended synchrotron emission, inverse-Compton and Self-synchrotron Compton (electrons Inverse Compton scatter on synchrotron emission)

2. Hadronic processes: 1)proton synchrotron; 2) p-γneutral pion decay; 3)secondary electrons synchrotron & IC

- **Prompt phase**

  Internal shock, leptonic: electron synchrotron & SSC

  Internal shock, hadronic: proton synchrotron & p-γ interaction

- **Early afterglow phase**

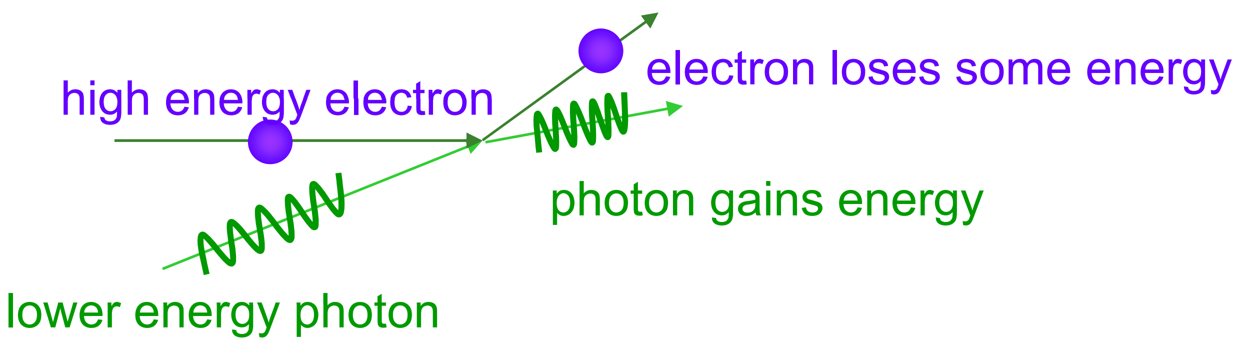
  External, leptonic: forward, reverse and cross shock SSC

  External, hadronic: proton synchrotron & p-γ interaction

Fermi may help determine the identity of the dominant emission mechanism at low and high energies

Inverse Compton scattering

- In inverse Compton scattering, a high energy electron transfers both energy and momentum to a lower energy scattering photon.



High energy cutoffs: Klein-Nishina Effect

When the energy of the seed (synchrotron) photon in the rest frame of the scattering electron exceeds the electron rest frame energy $\gamma_e h\nu_{sync} > m_e c^2$, then we move from the Thomson limit to the KN regime where there is a reduction in the scattering cross-section. The corresponding frequency where this limit is reached is:

$$\nu_{KN}^{SC} \sim \frac{\Gamma^2 m_e c^4}{h^2 \nu_m}$$

After ν_{KN}^{SC} the flux drops fast as $\nu^{-1/2-p}$ *(Guetta & Granot 2003)*

The high energy cutoff

In order for high-energy photons to escape the system and reach the observer, they must overcome several obstacles along the way

Inside the source

- $\tau_{\gamma\gamma}<1$

QuickTime™ e un
decompressore TIFF (Non compresso)
sono necessari per visualizzare quest'immagine.

- The $\tau_p<1$ due to pairs

Outside the source

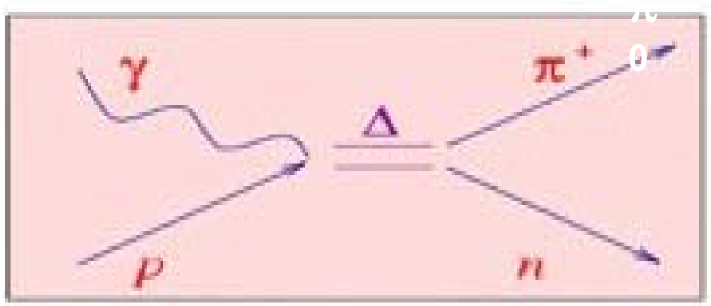
HE photons (> 500 GeV) may interact with photons from the cosmic IR to produce pairs

Typical energies of SSC emission

	Synch Energy	Electron's Lorentz Factor	SSC energy	Duration
Prompt	100 keV	1000	100GeV	Prompt
Reverse Shock	0.1 eV	1000	100MeV	Short
Forward Shock	10keV-1eV	10^5-10^3	100TeV-MeV	Long

Hadronic interactions in the prompt emission

In the region where electrons are accelerated, protons can be also accelerated to high energies $\sim 10^{20}\mathrm{eV}$ and interact with low energy photons, producing charged and neutral pions



$$\gamma + p \rightarrow n + \pi^{+}, \pi^{0}\ ; \quad \pi^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \overline{\nu}_{\mu}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

$$\left(\varepsilon_{p}/\Gamma\right)\left(\varepsilon_{\gamma}/\Gamma\right) \geq\ 0.3\ \mathrm{GeV}^{2}$$

Internal shocks ν ~ 1000 TeV, coincident with GRBs

Synchrotron radiation from p, charged π expected.

High energy photons from hadronic decay

The π^0 decay into two high energy photons that pair produce with low energy photons creating a cascade. The duration of the emission from this cascade is similar to T_{GRB} and the spectral slope is very soft $F_\nu \approx \nu^{-1}$ *(Begelman, Rudak & Sikora 1990)*

These HE photons are expected to be coincident with the prompt gamma-ray photons
and a BURST of neutrino emission is expected!!!

Particle acceleration in GRB shocks

- Electrons-

Shock acceleration: ~10 TeV

$$t_{cool} \sim t_{acc} \Rightarrow \gamma_{e,Max} \leq 10^7$$

X-ray afterglows modeling $\rightarrow \gamma_{e,Max} > 10^5$ e.g. Li & Waxman 2006

- Protons (or nuclei)-

1) Shock acceleration $\sim 10^{20}\,\mathrm{eV}$ (e.g. Waxman 1995; Vietri 1995)
Candidate source of ultra-high energy cosmic rays (UHECRs)
(Eichler, Guetta, Phool 2010 for recent estimates)

2) Neutrinos from photo-meson and pp processes
(e.g. Waxman & Bahcall 1997; Bottcher & Dermer 1998, Guetta et al. 2001,2003)

"Generic" GRB ν's

- $$\gamma + p \rightarrow n + \pi^+ \; ; \quad \pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$
  $$(\varepsilon_p / \Gamma)(\varepsilon_\gamma / \Gamma) \geq \; 0.3 \, \mathrm{GeV}^2$$
- $$\varepsilon_\gamma = 1 \, \mathrm{MeV} \, , \Gamma = 10^{2.5} \Rightarrow \quad \varepsilon_p \geq 10^{16} \, \mathrm{eV} \; , \; \varepsilon_\nu \geq 10^{14.5} \, \mathrm{eV}$$
- $$f_{p \rightarrow \pi} \approx 0.2$$
  Weak dependence on model parameters

[Waxman & Bahcall 97, 99]

[Rachen & Meszaros 98;

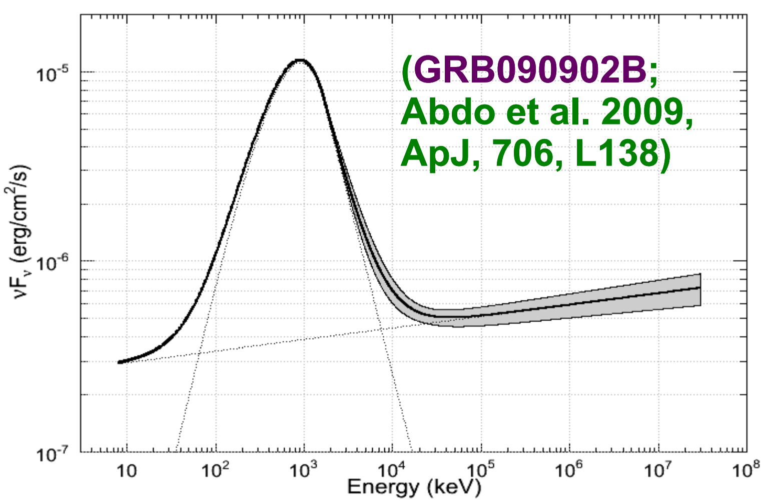
Guetta, Spada & Waxman 01]

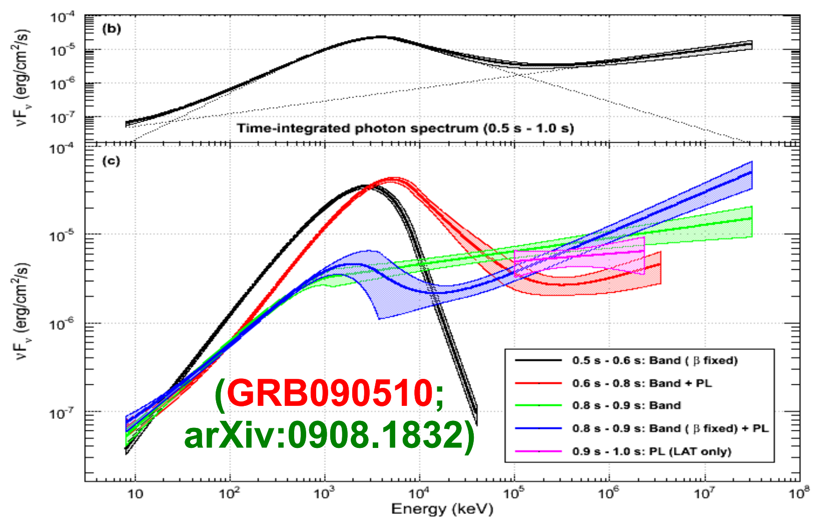
$$\Rightarrow \quad \varepsilon^2 \Phi_\nu \approx 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm^2 s \, sr}} \quad , \quad \varepsilon_\nu \geq 10^{14.5} \, \mathrm{eV}$$

$$J_{\nu \rightarrow \mu} \approx 20 / \mathrm{km^2 yr}$$

What do we learn from Fermi data?

- **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





(Courtesy J. Granot)

Highest Energy Requires Large Bulk Lorentz Factor

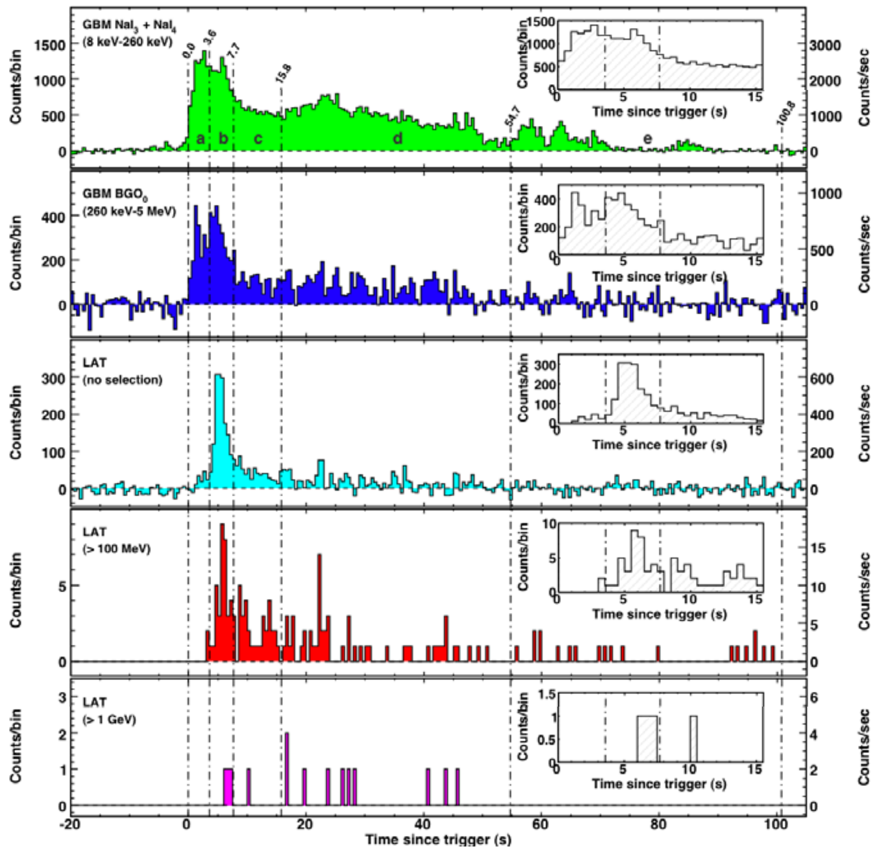
- Gamma Rays attenuated at the source by $\gamma+\gamma \rightarrow e^{+}+e^{-}$
- Density of photons is high as inferred from source distance & rapid variability
- No attenuation if emission is from fireball with large bulk Lorentz factor
  - Decrease Energy of Gamma-Rays
  - Reduce Number of Photons
  - Increase the source size

- Bulk Lorentz factor, Γ□̃ı, required to give opacity of 1 for the highest E γ-ray observed

- **$\Gamma \gtrsim 1000$** from ≥10 GeV photons detected in GRB 080916C, GRB090510, GRB090902B

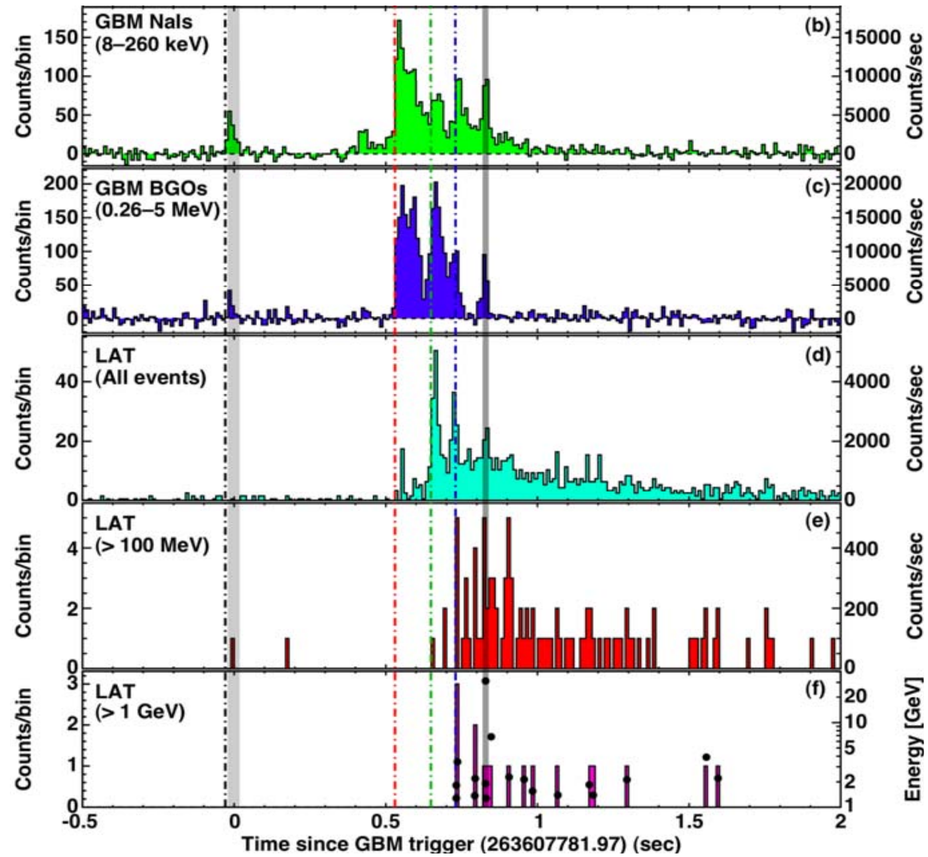
Trouble: Explain the delayed onset of HE emission seen in several GRBs

GRB080916C



Delay in HE onset: ~ 4-5 s

GRB090510



Delay in HE onset: ~ 0.1-0.2 s

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: Short & Long have similar HE properties (courtesy J. Granot)

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	✓	✓	?	~ 13.2 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
090926	~ 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	

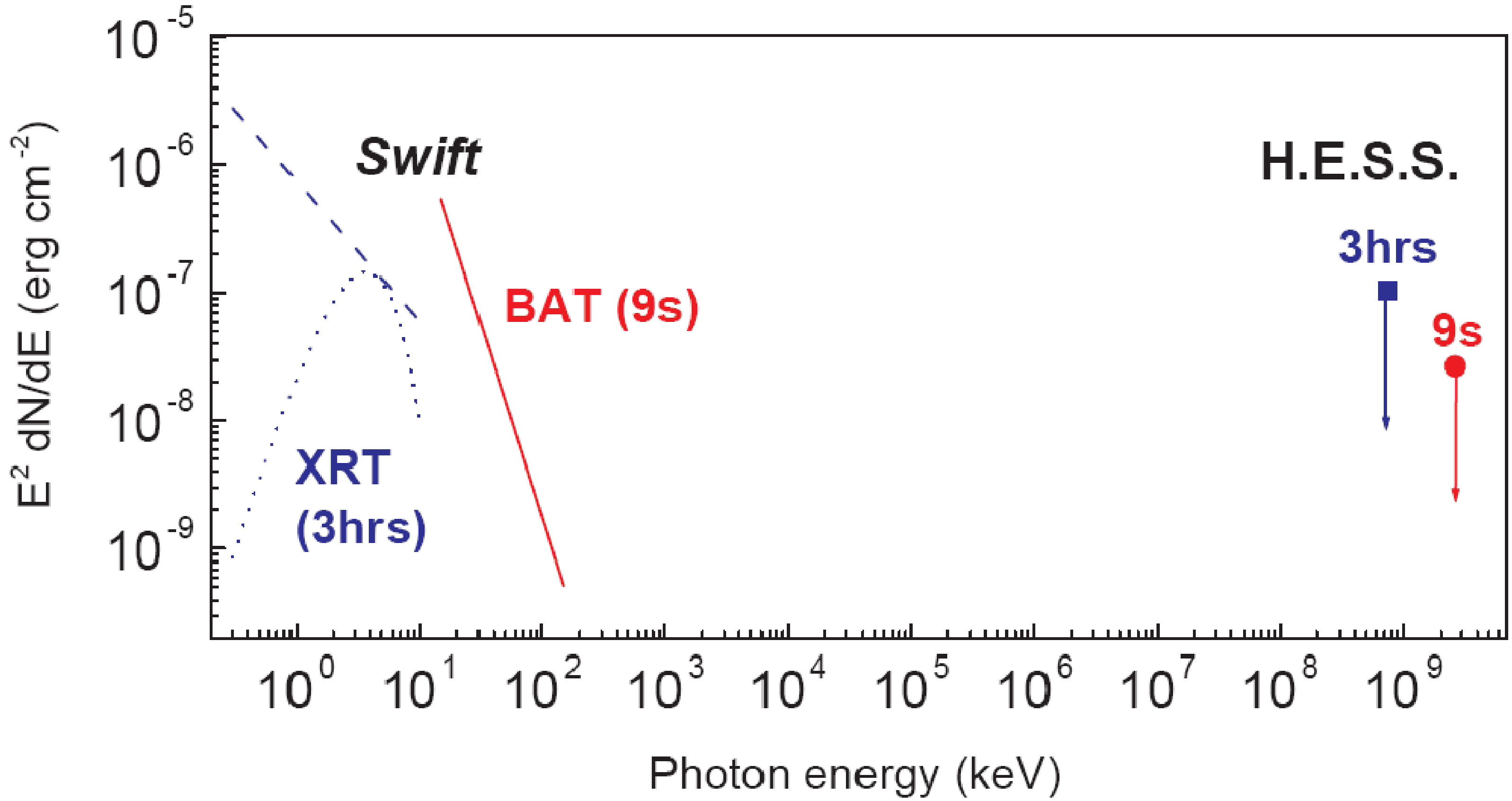
Temporally extended emission: HE afterglow?

- **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?**

E>100GeV: only upper limits

- Magic: upper limits for several Swift bursts (Albert et al., 06)
- Whipple: upper limits (Horan et al. 07)
- Milagro: upper limits fro short GRB (Abdo et al. 07)
- ARGO-YBJ array find only upper limits (Di Sciascio, et al., 06)
- HESS: upper limits of GRB060602B (Aharonian et al. 08)

Example: HESS GRB060602B



very soft BAT spectrum and proximity to the Galactic center → More likely to be a Galactic X-ray transient

Limits on Lorentz Invariance Violation

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

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

- A high-energy photon E_h would arrive after (in the sub-luminal case: $v_{ph} < c$, $s_n = 1$), or possibly before (in the super-luminal case, $v_{ph} > c$, $s_n = -1$) a low-energy photon E_l emitted together
- The time delay in the arrival of the high-energy photon is:

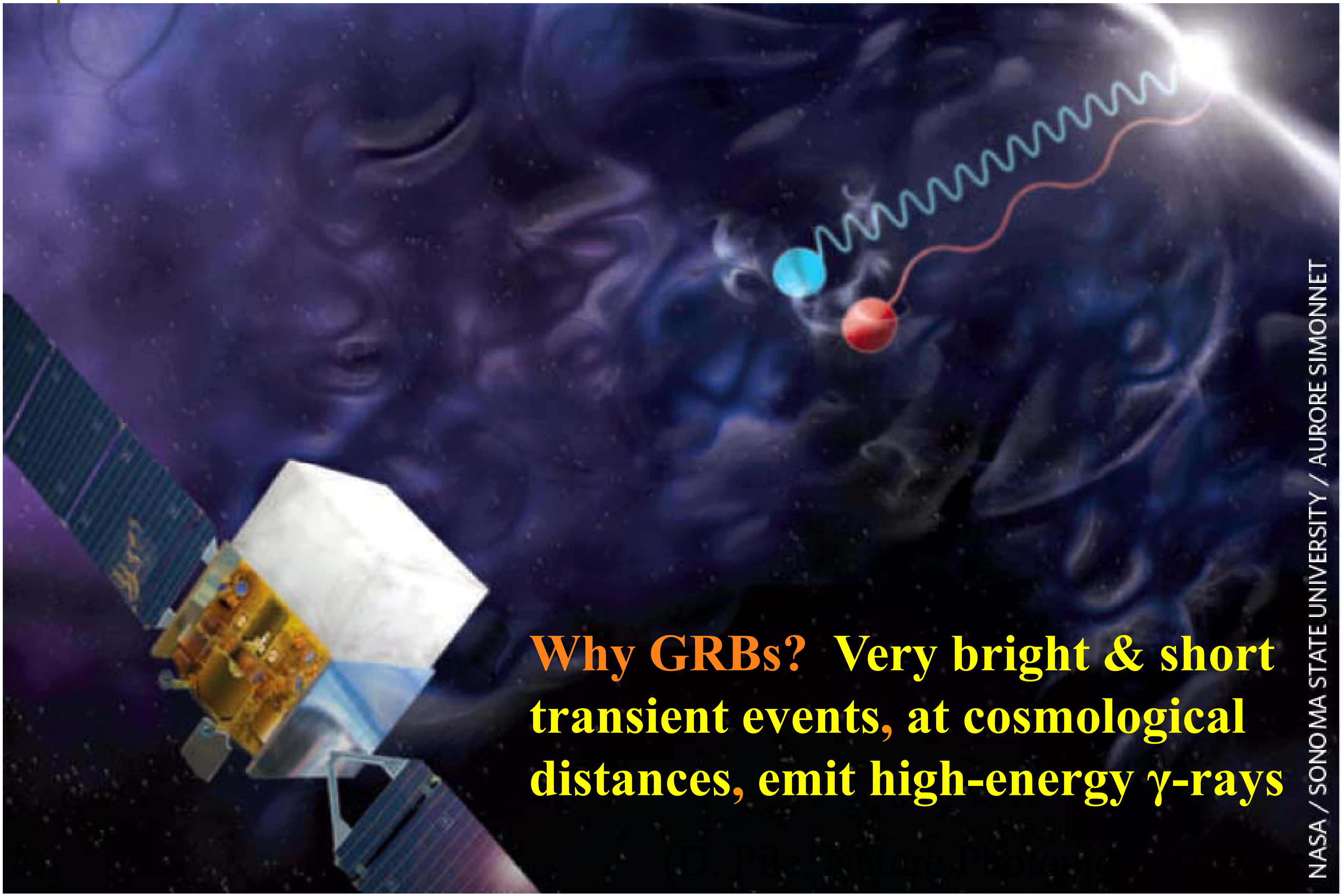
$$\Delta t = s_n \frac{(1+n)}{2H_0}\frac{E_h^n - E_l^n}{\left(\mathrm{M}_{\rm QG,n}c^2\right)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz'$$

(Jacob & Piran 2008)

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

Constraining QG Using GRBs

(first suggested by Amelino-Camelia et al. 1998)



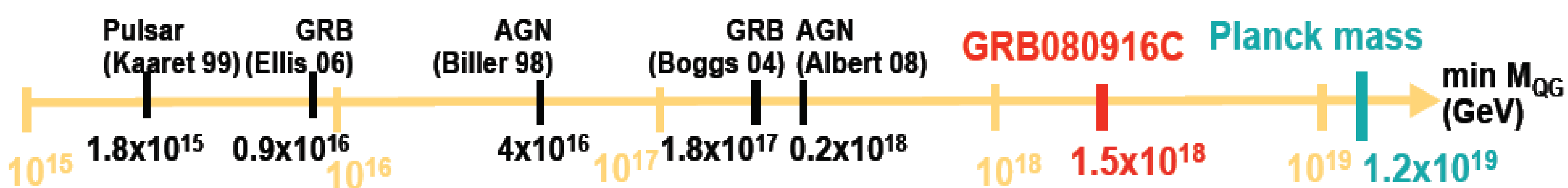
Constraints on LIV from GRB 080916C

Abdo, A. A., et al. 2009, Science, 323, 1688

- The highest-energy, 13.22 GeV, photon arrives 16.54 sec. after the GRB trigger
- High degree, 4.3σ, of association with the GRB (or not from the background)
- High redshift, z=4.35, allows large LV induced time dispersion between the 13.22 GeV and MeV photons
- 13.22 GeV photon cannot be emitted before the GRB trigger ➔ $\Delta t = 16.54$ s

Conservative lower limits on the QG mass — Abdo et al., Science, 2008

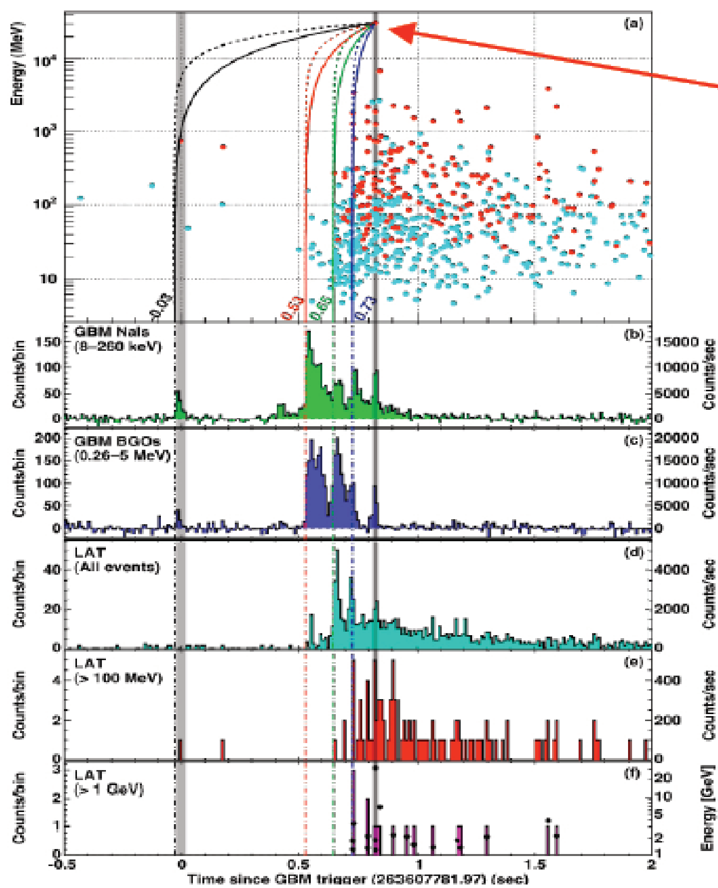
Linear, n=1 $\quad M_{\mathrm{QG},1} > (1.55 \pm 0.04) \times 10^{18} \left(\frac{E_h}{13.22\ \mathrm{GeV}}\right)\left(\frac{t}{16.54\ \mathrm{s}}\right)^{-1}\ \mathrm{GeV}/c^2,$



Stringent Constraints on Quantum Gravity Time Delay

Abdo, A.A., et al. 2009, Nature, 462, 331

GRB 090510



- Short hard GRB with many "spikes"
- High redshift, z = 0.903 +/- 0.003
- 31 GeV photon (27.97, 36.32 GeV 1s CL) 0.829 s after the GRB trigger
- Constraint on QG mass depends on Δt

The most conservative constraint comes from Δt < 0.859 s, time from precursor

$$\boxed{M_{\mathrm{QG},1} > 1.19\, M_{\mathrm{Pl}}}$$

Table 1 | Limits on Lorentz invariance violation

	Limit on $\lvert\Delta t/\Delta E\rvert$ or $\lvert\Delta t\rvert$	Limit on $M_{\mathrm{QG},1}/M_{\mathrm{Planck}}$	Valid for s_n
Limit a:	$\lvert\Delta t/\Delta E\rvert < 30\ \mathrm{ms\ GeV}^{-1}$	>1.22	±1
Limit b:	$\lvert\Delta t\rvert < 859\ \mathrm{ms}$	>1.19	1

Drawbacks of these approaches

These limits are obtained considering a SINGLE high energy photon:

- ❑ Limits are intrinsically fuzzy: not possible to know the exact time of emission of a single photon.

- ❑ Not reliable: it is difficult to assess the statistical meaning of each limit, to which confidence interval is referred to.

- ❑ Work in progress: Fiore, Guetta, Amelino Camelia suggest a method that resolve these drawbacks. Consider large sample of GRBs observed by LAT with different z to put constraint on LTT as QG effect depend on z: the effect is stronger for farther GRBs.

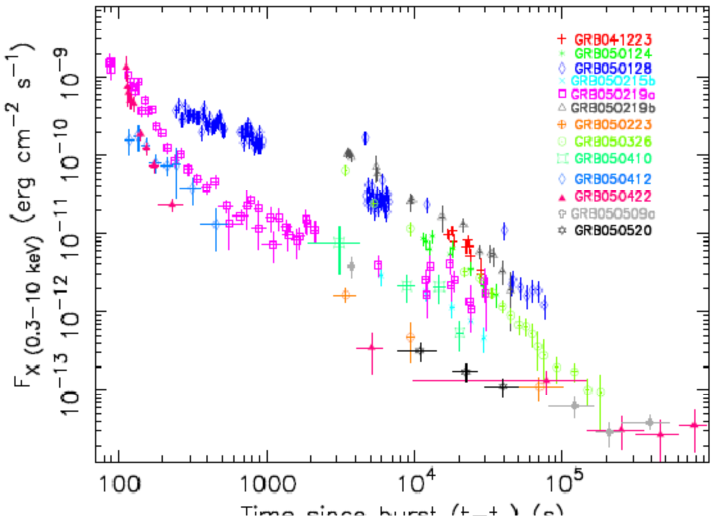
- ❑This method uses full GRB energy distribution: GRB spectrum and its temporal variations

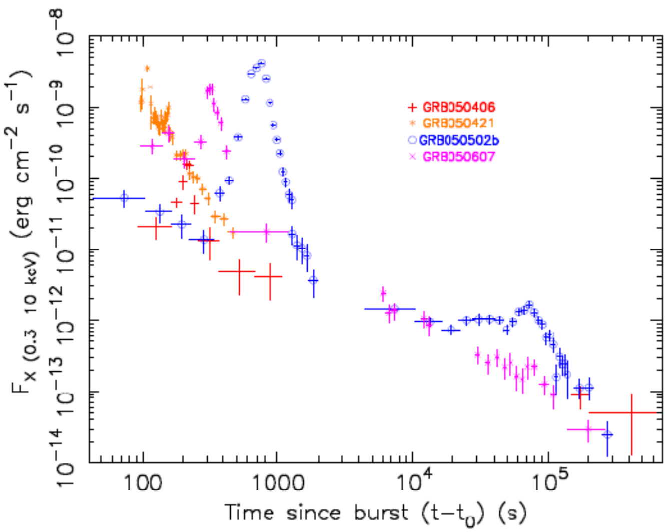
Summary

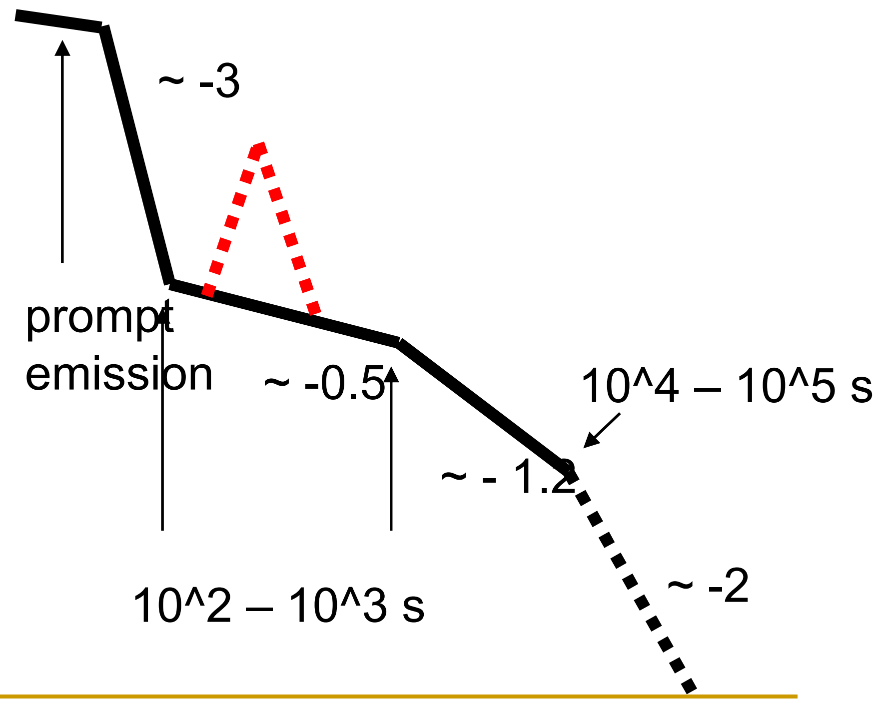
- LAT detection rate ~ 9 GRB/yr $\Rightarrow$ on average GRBs radiate only ~10-20% of their energy in the LAT range
- Prompt spectrum: the 3 brightest LAT GRBs clearly ($>5\sigma$) show a distinct high-energy spectral component
- Many LAT GRBs show **later onset** & **longer duration** of the high-energy emission, relative to low energies
- Lower limits on GRB outflow Lorentz factor $\Gamma_{min} \sim 10^3$
- 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
- GRBs as possible sources of UHECR and neutrinos
- Limit on a possible variation of the speed of light with photon energy, beyond Planck scale: $M_{QG,1} > 1.2 M_{Planck}$

Swift: A Canonical X-ray Lightcurve

(Zhang et al. 2006; Nousek et al. 2006; O'Brien et al. 2006)







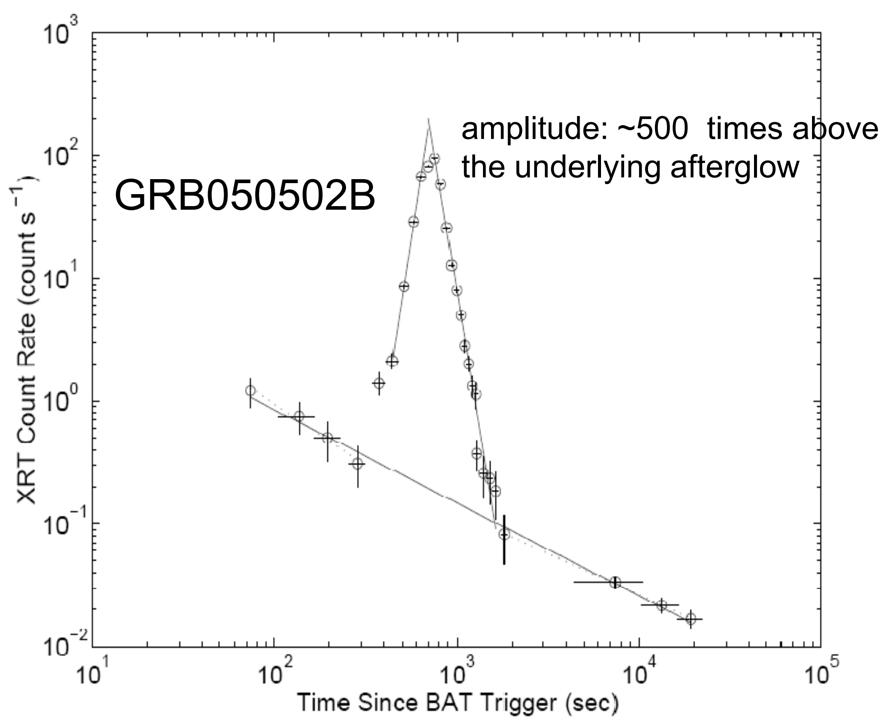
Swift-Fermi sinergy: High-energy photons from X-ray flares

X-ray flares: late-time central engine activity

- ~30%-50% early afterglow have x-ray flares, Swift discovery
- Flare light curves: rapid rise and decay

$$\delta t / t \ll 1$$

- Afterglow decay consistent with a single power-law before and after the flare



Burrows et al. 2005
Falcone et al. 2006

X-ray flares occur inside the deceleration radius of the afterglow shock HE (GeV-TeV) emission from XRF may come from SSC
(Galli & Guetta 2007)