Gamma-Ray Bursts as particle accelerators
-What *Fermi* can tell us-

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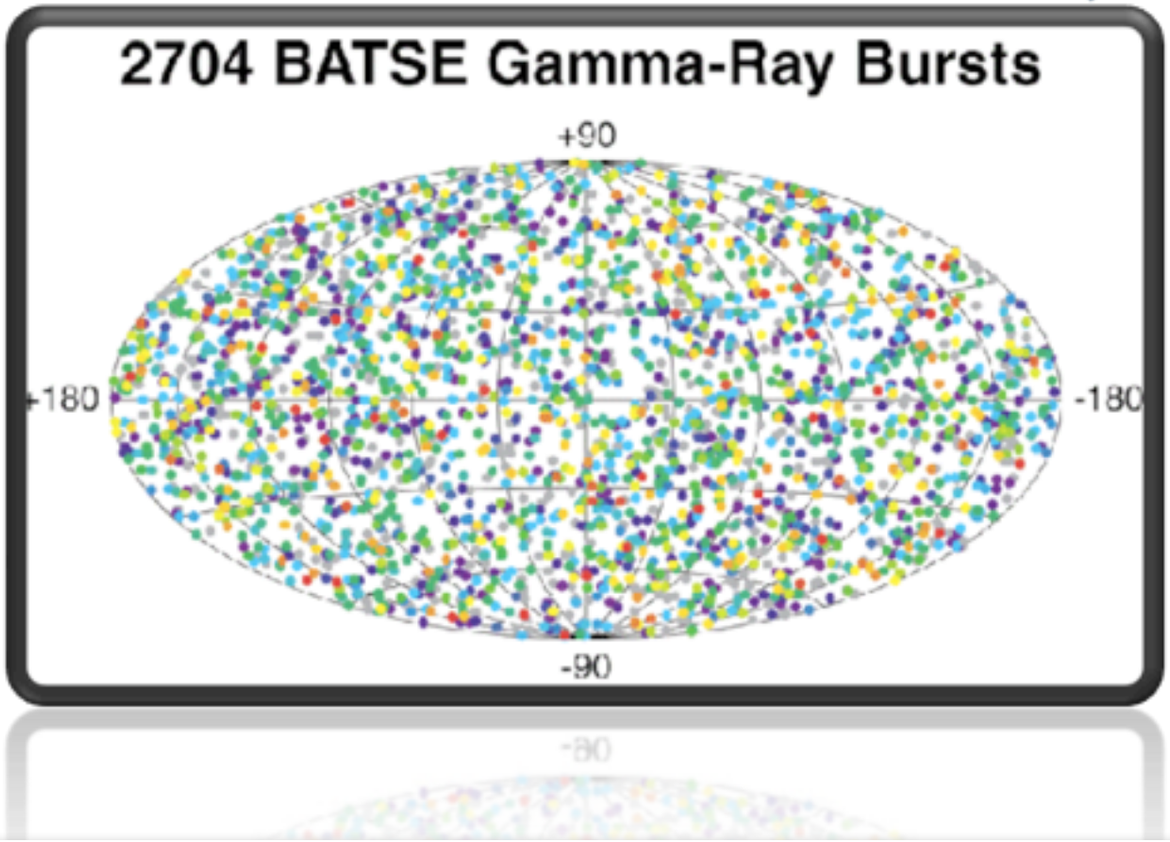
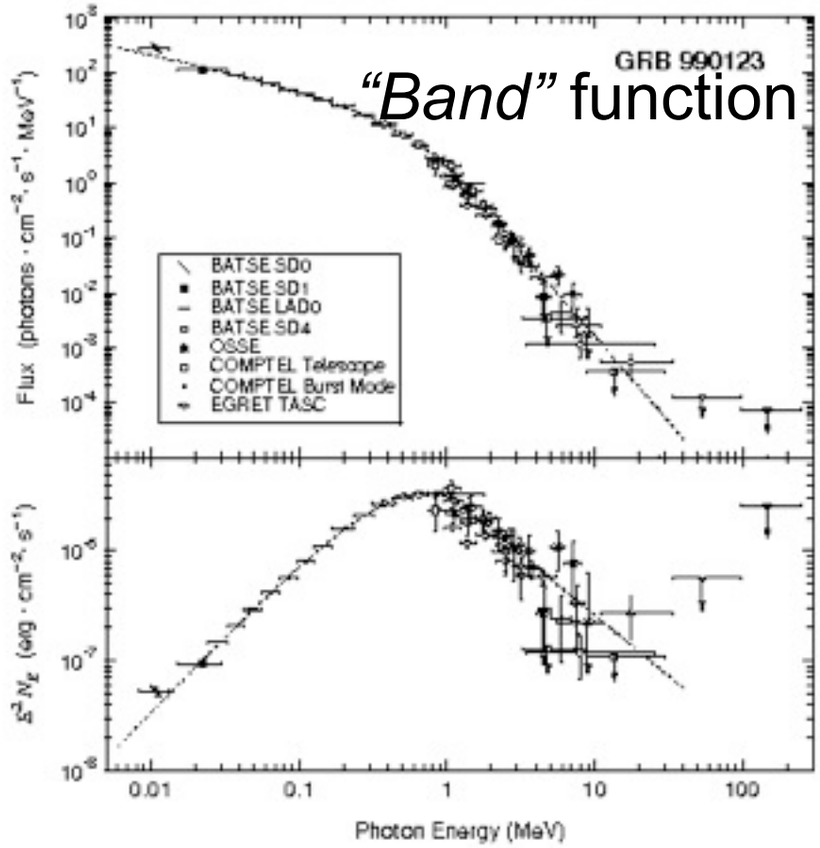
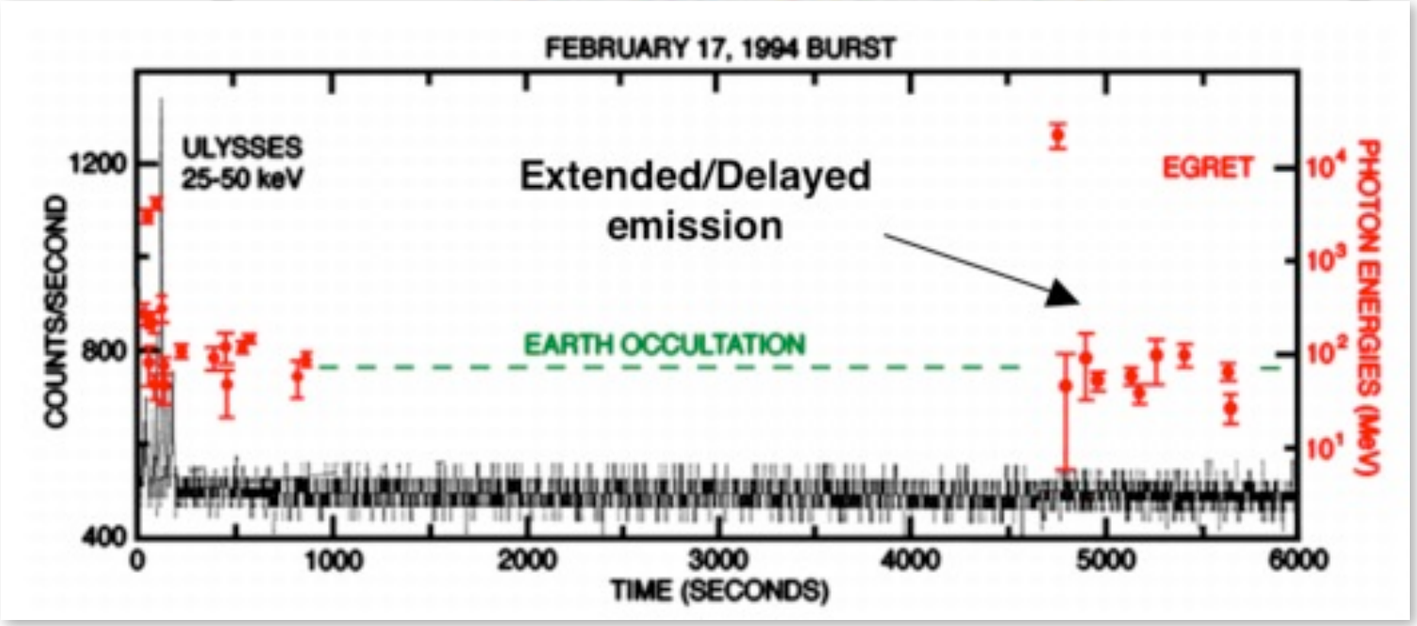
Menlo Park, CA

Gamma-Ray Bursts

- **DISCOVERY & SPECULATION: 1967 – 1991 (Vela satellites, Ginga, SMM)**
- **POPULATION STUDIES: 1991 – 1997 (CGRO/BATSE)**
  - **Isotropic distribution in the sky => cosmological origin**
  - **Distinction between Long & Short GRBs**
  - **Rapid variability => compact source**
  - **Non-thermal spectrum => Synchrotron radiation by a distribution of accelerated electrons (Tavani, 1995)**
  - **Some hint at high energy of a delayed/ temporally extended emission (EGRET)**

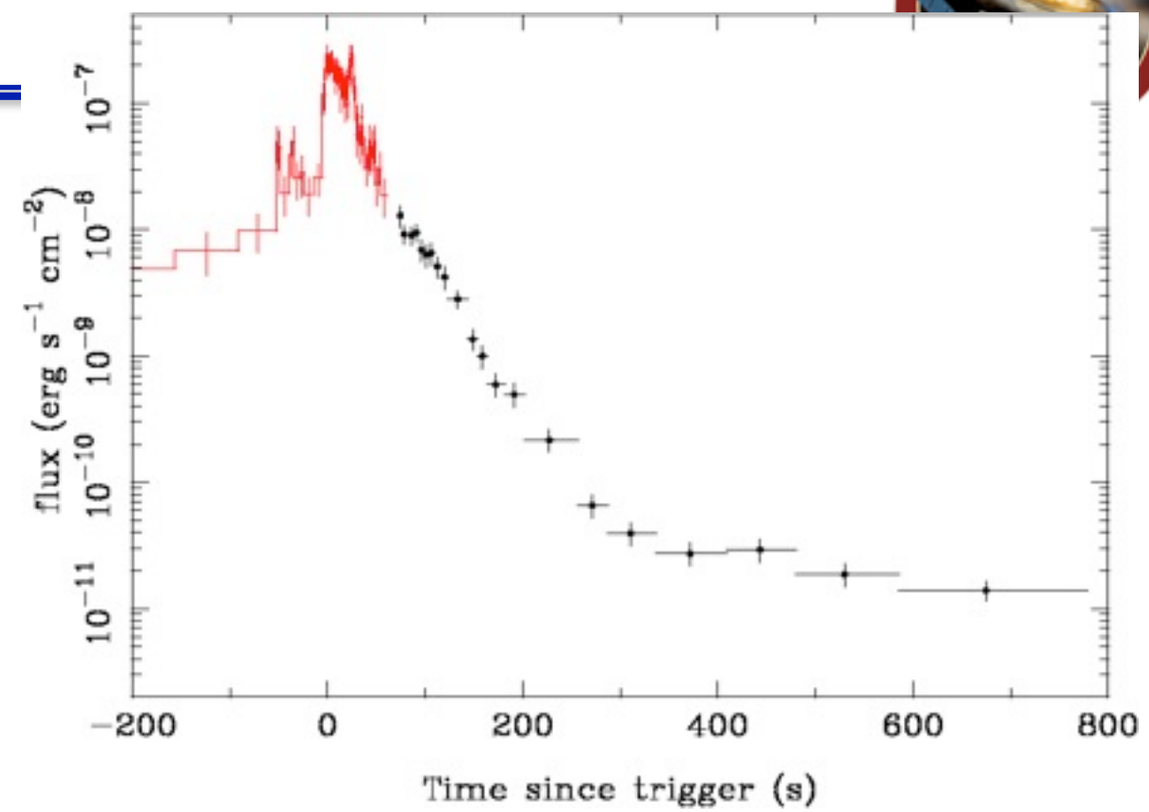


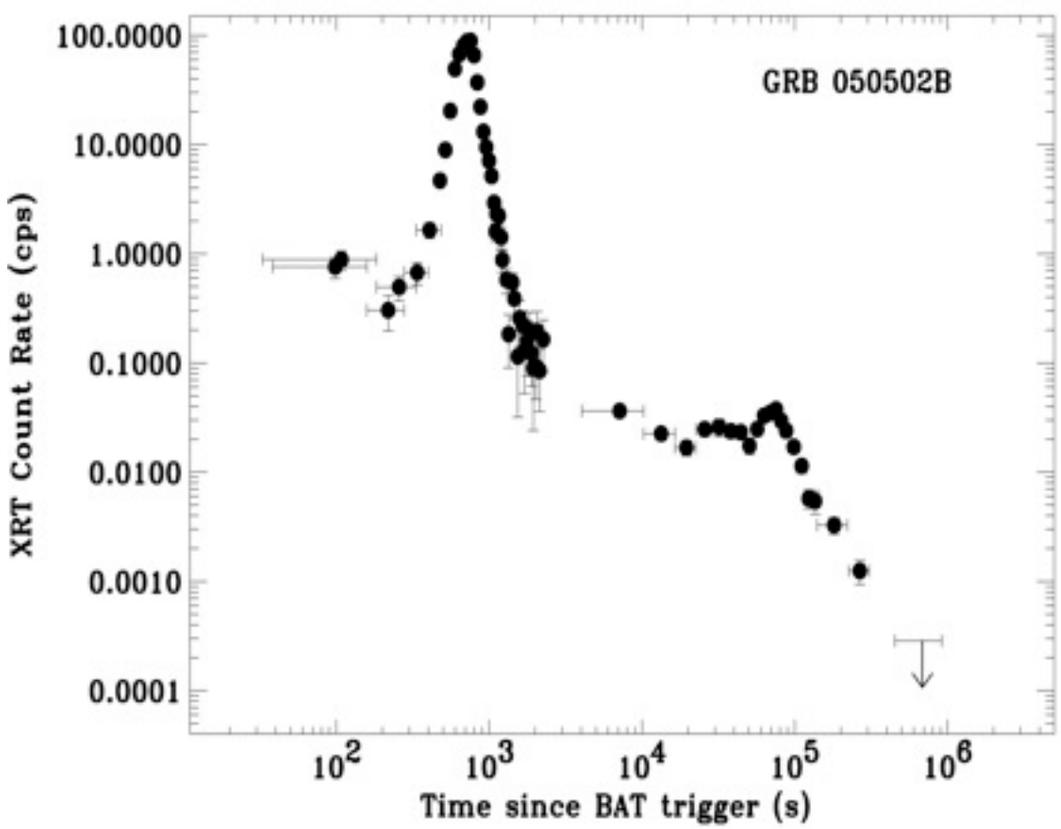


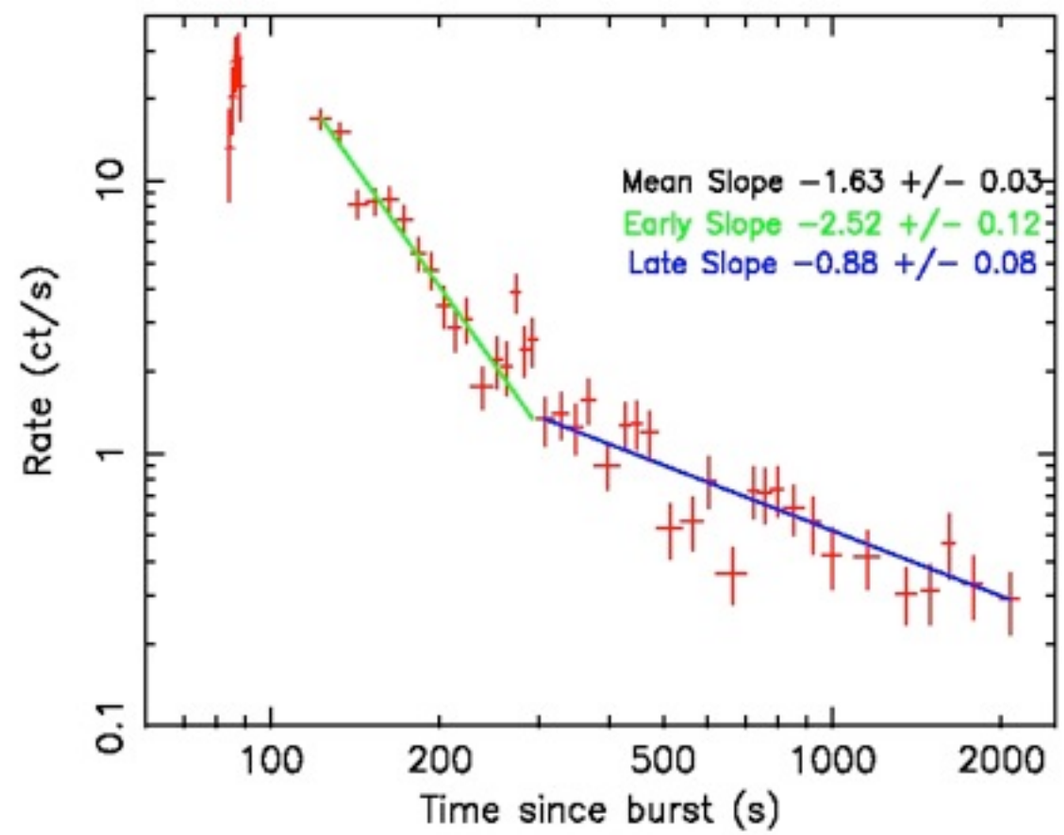


Afterglow

- **Discovered by BeppoSax ('97)**
  - **Measurements of the distance**
- **Swift (2004-*):**
  - **Connection to the "Prompt" emission**
  - **X-Ray Flashes in the afterglow**
  - **Steep-Shallow-Steep decay**
  - **Also short bursts have an afterglow!**
  - **Fading to lower frequencies**
- **Picture begun more intriguing...**



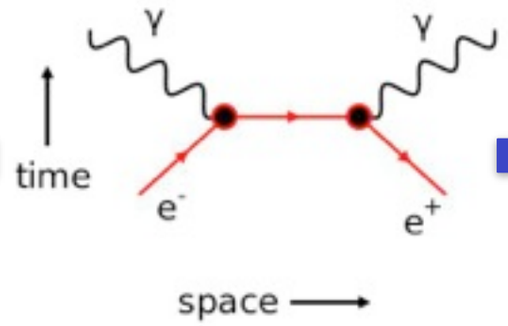




GRBs as particle accelerators

Energy source

Acceleration mechanism



Production mechanism

Absorption

E.m. radiation,
neutrinos (?),
Gravitational Waves (?)

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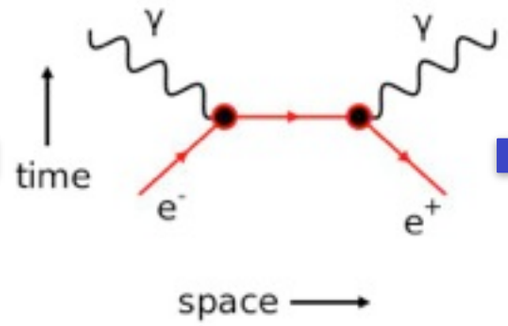

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collapse of massive stars?
coalescence of NS/BH
~10^{54} -10^{55} ergs

GRBs as particle accelerators

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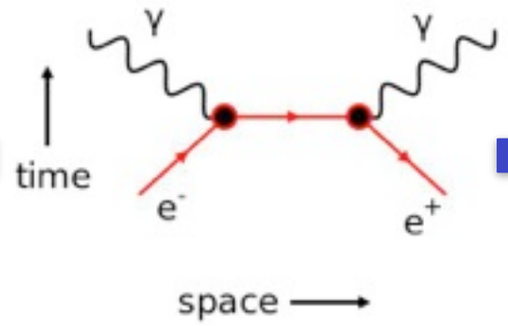

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GRBs as particle accelerators

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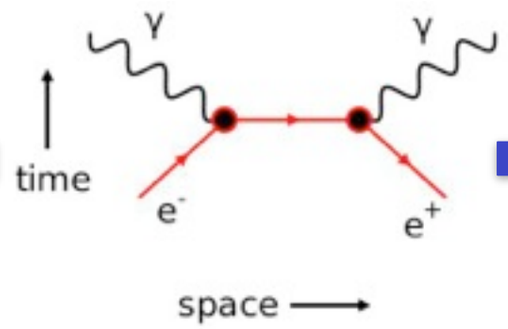

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Inverse Compton,
hadronic
cascades

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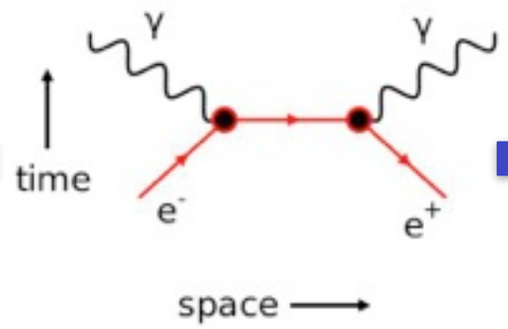

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Production mechanism

Synchrotron,
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Absorption

$\gamma-\gamma$ Intrinsic absorption,
EBL

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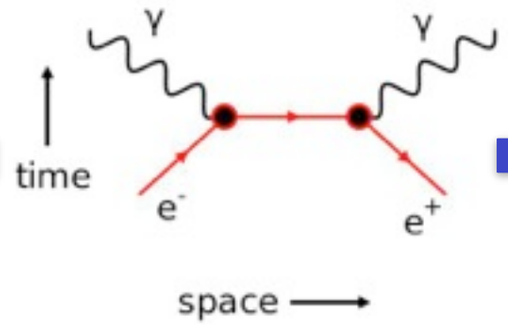
GRBs as particle accelerators

Energy source

Acceleration mechanism



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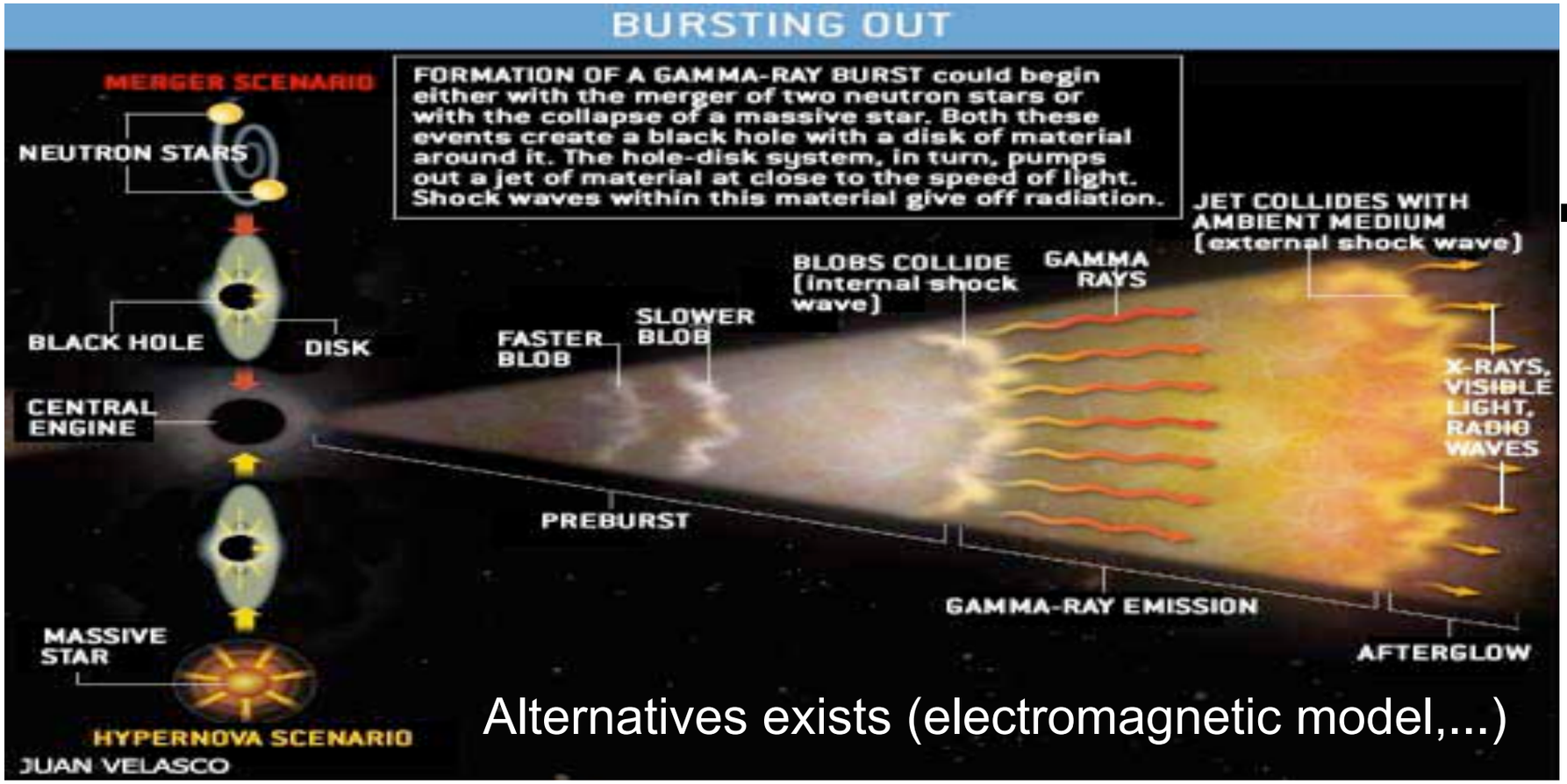

Alternatives exists (electromagnetic model,...)

➡ **High energetic gamma-rays are probe of high-energy accelerated particles!**

GRBs as particle accelerators

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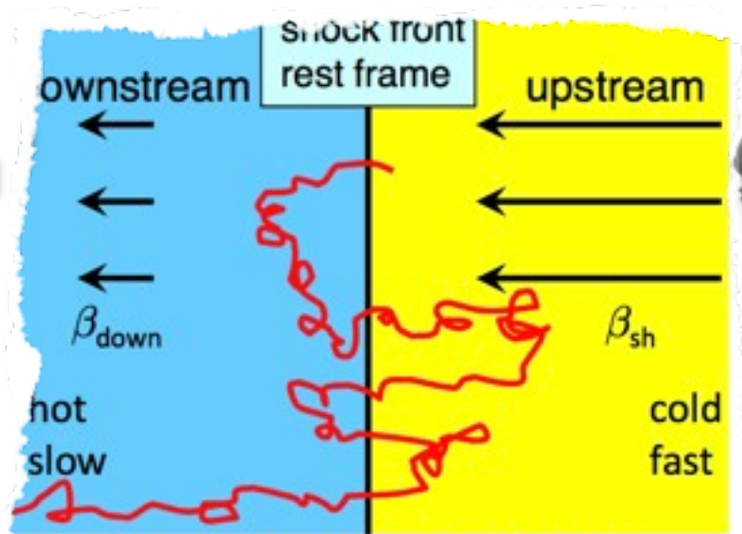
Acceleration mechanism



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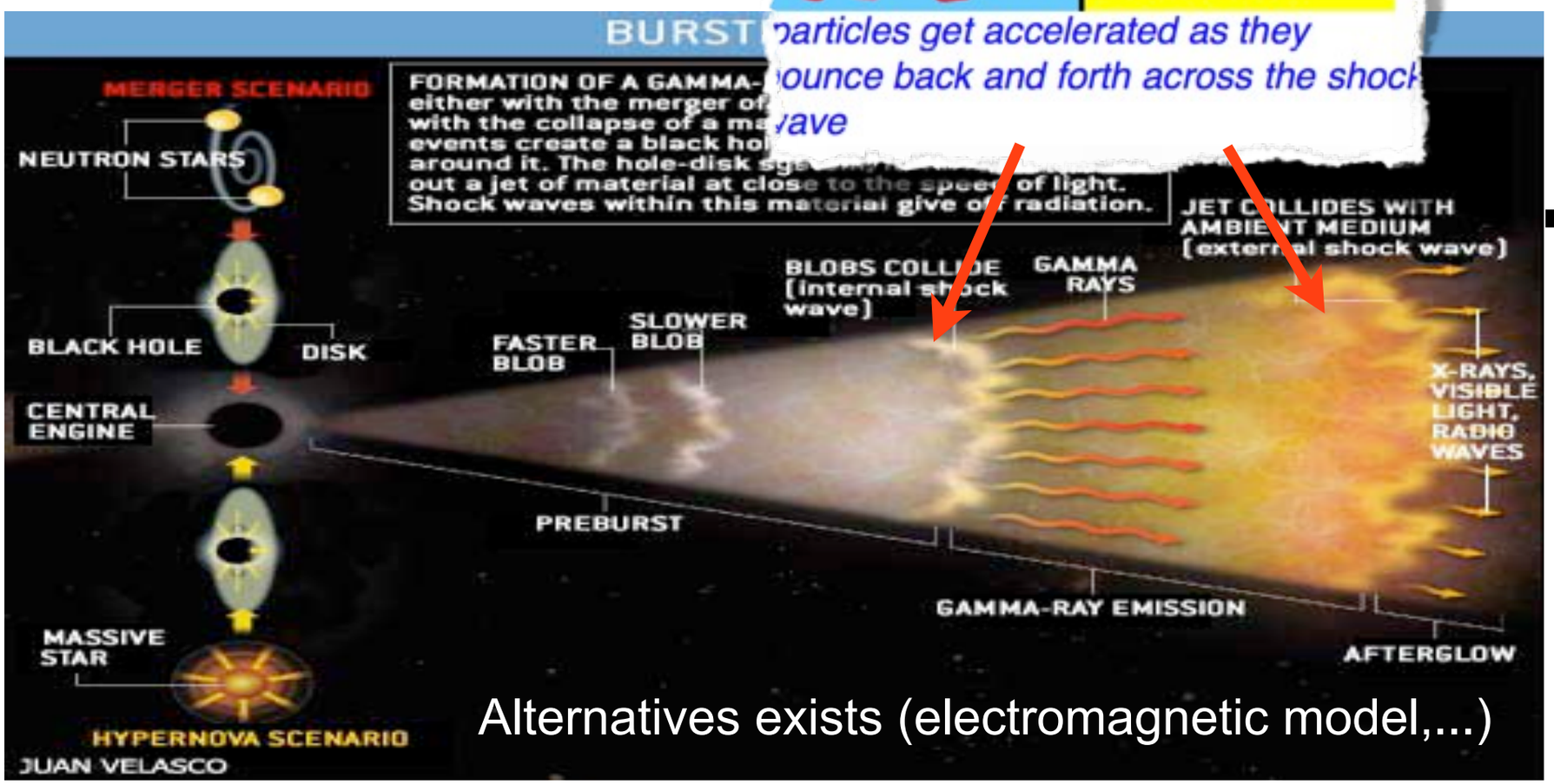

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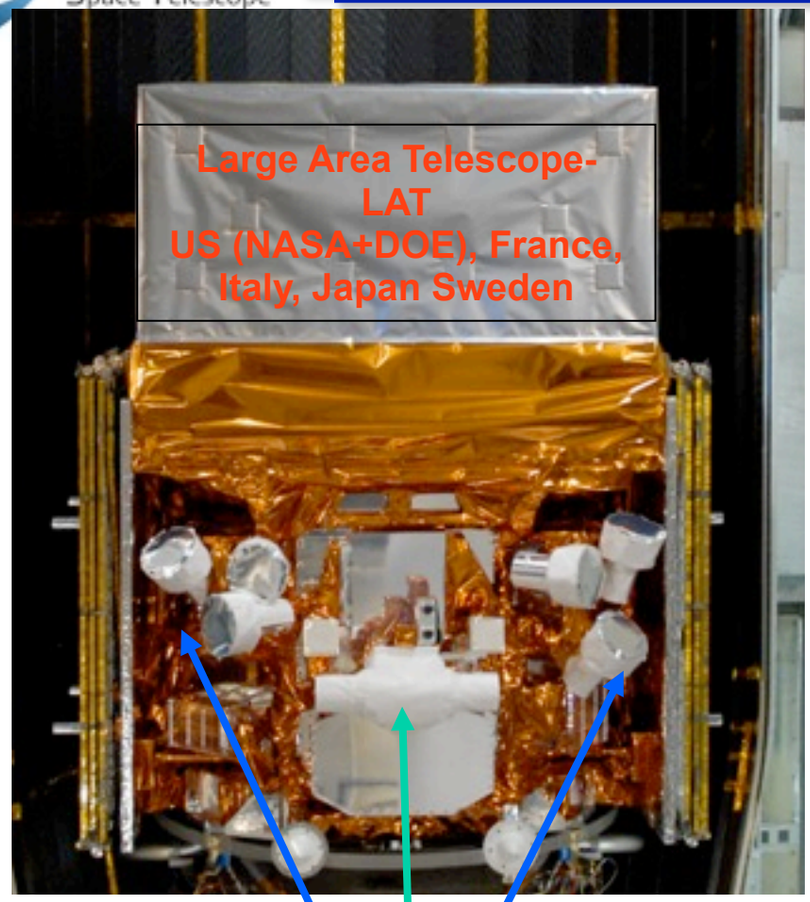
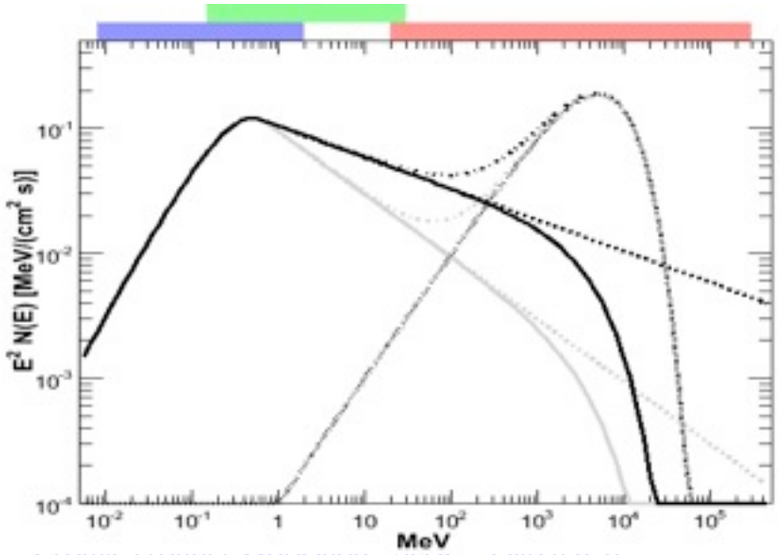
Gamma Ray Burst in the *Fermi* era



Gamma-ray Burst Monitor – GBM
Marshall SFC, UAH, MPE

NaI BGO LAT

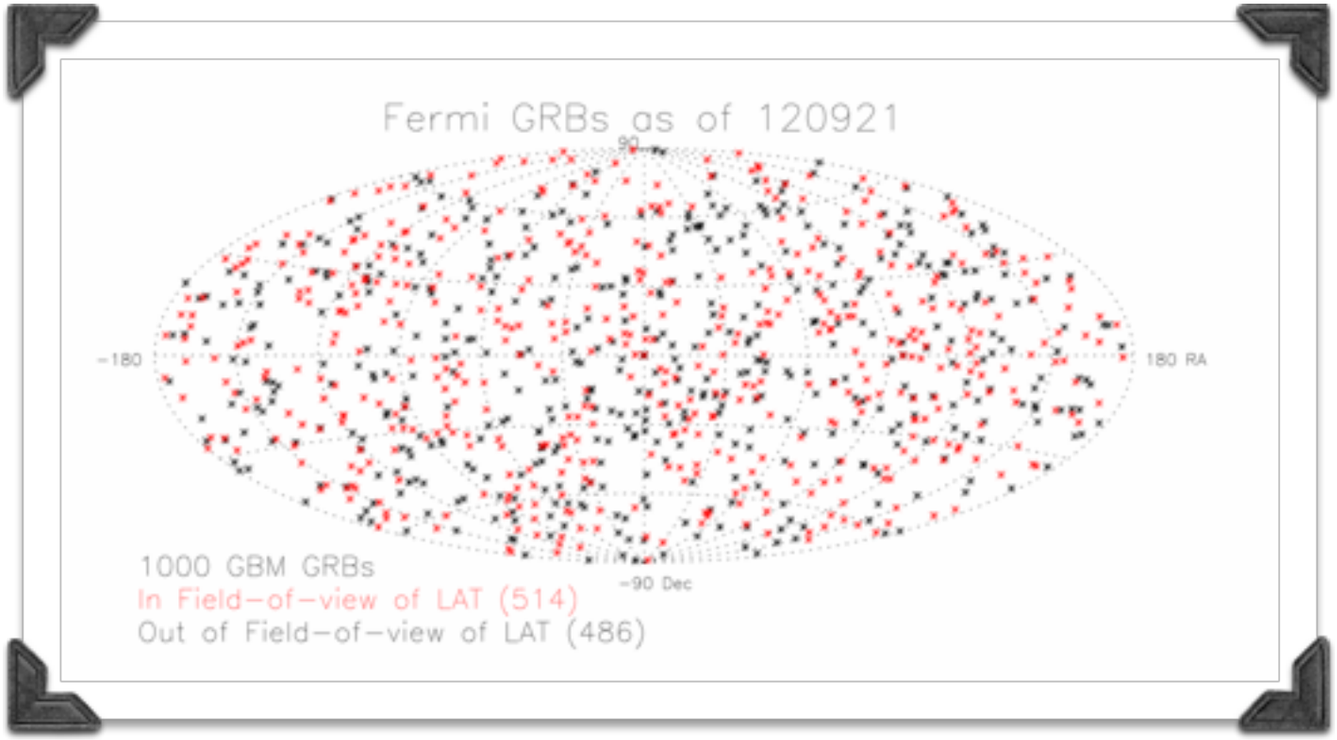


Fermi Gamma Ray Space telescope (2008-*)

GBM/NaI : 8 keV - 1 MeV

GBM/BGO: 150 keV- 40 MeV

LAT: 30 MeV - >300 GeV

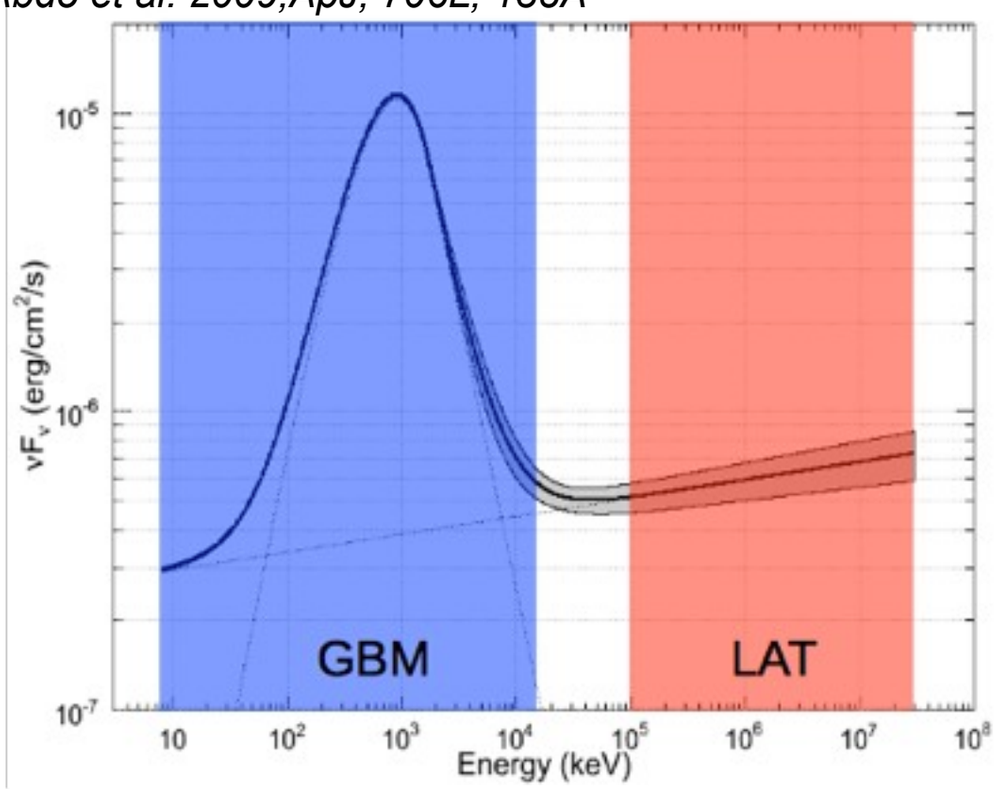


- **>1000 GRBs detected by the GBM**
- **At high energy, LAT detected ~40 GRBs in the first 4 years**
- **10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)**

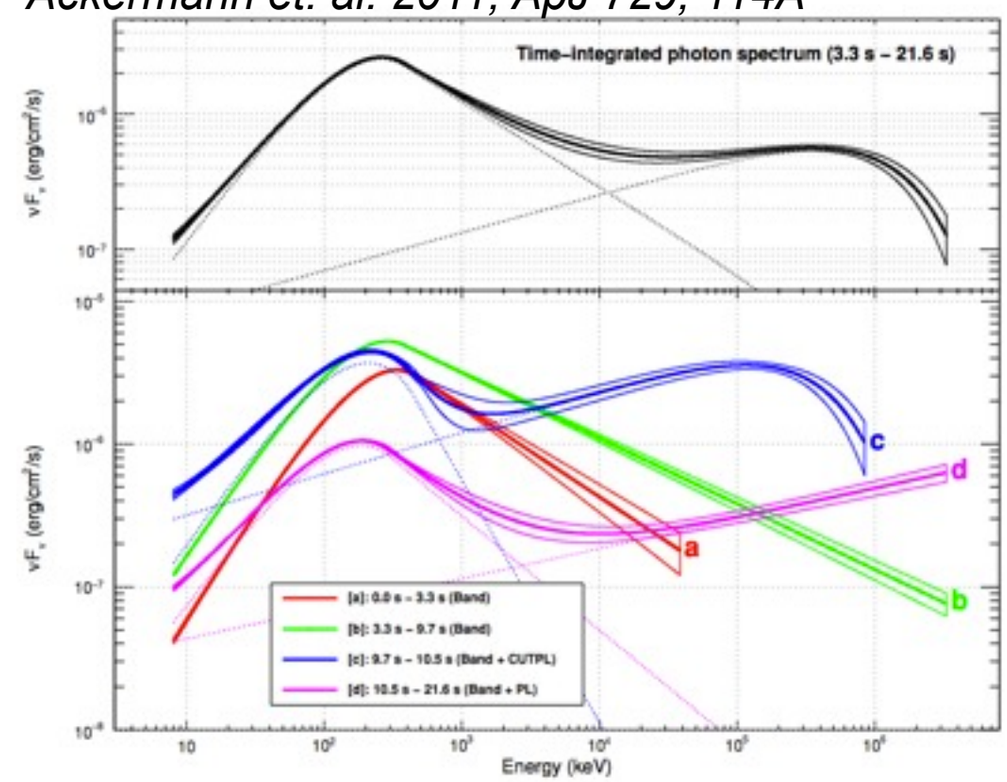
Important results from *Fermi*-LAT

- **A) GRB spectrum in several cases is NOT a simple "Band" function**
  - **Deviation from the *Band* function at low energy;**
  - **Additional power-law observed at high energy;**
  - **High energy cut-off measured in the spectrum;**
  - **Extrapolating the *Band* function from LOW to HIGH energy is really a BAD idea!**

GRB 090902B
Abdo et al. 2009,ApJ, 706L, 138A

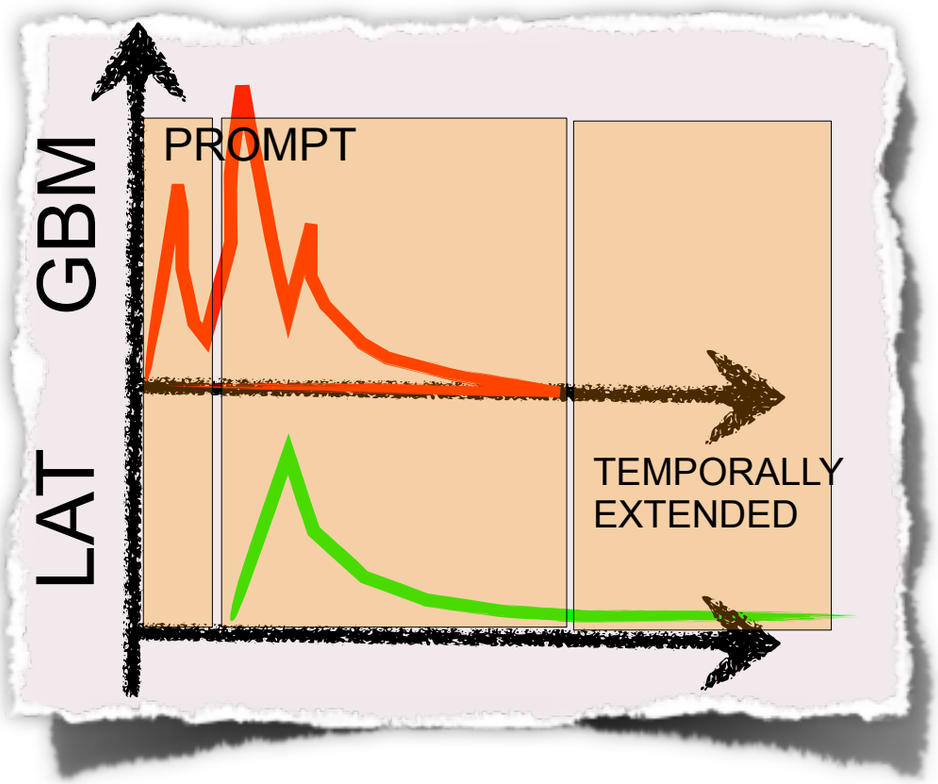


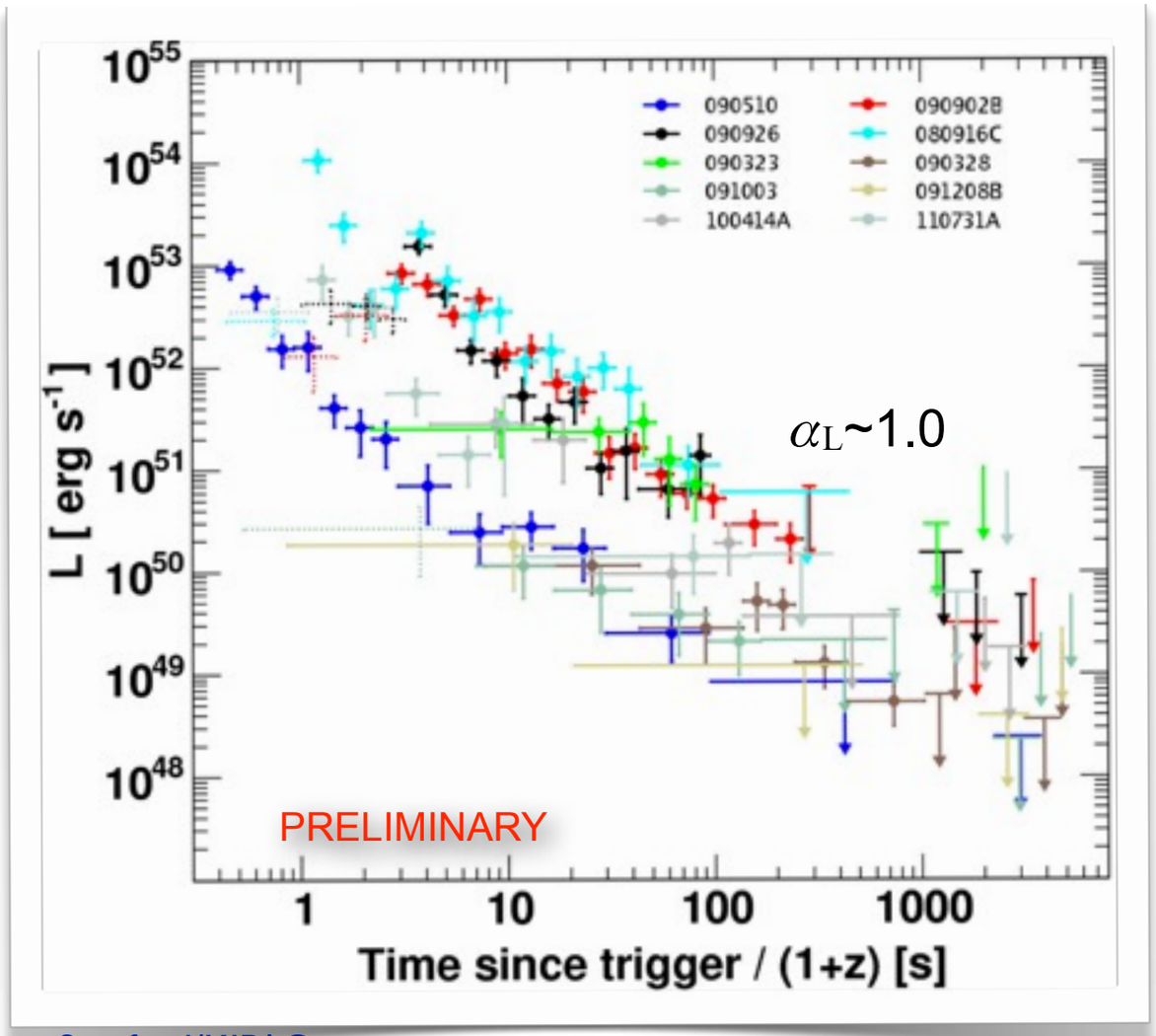
GRB 090926A
Ackermann et. al. 2011, ApJ 729, 114A



Important results from *Fermi*-LAT

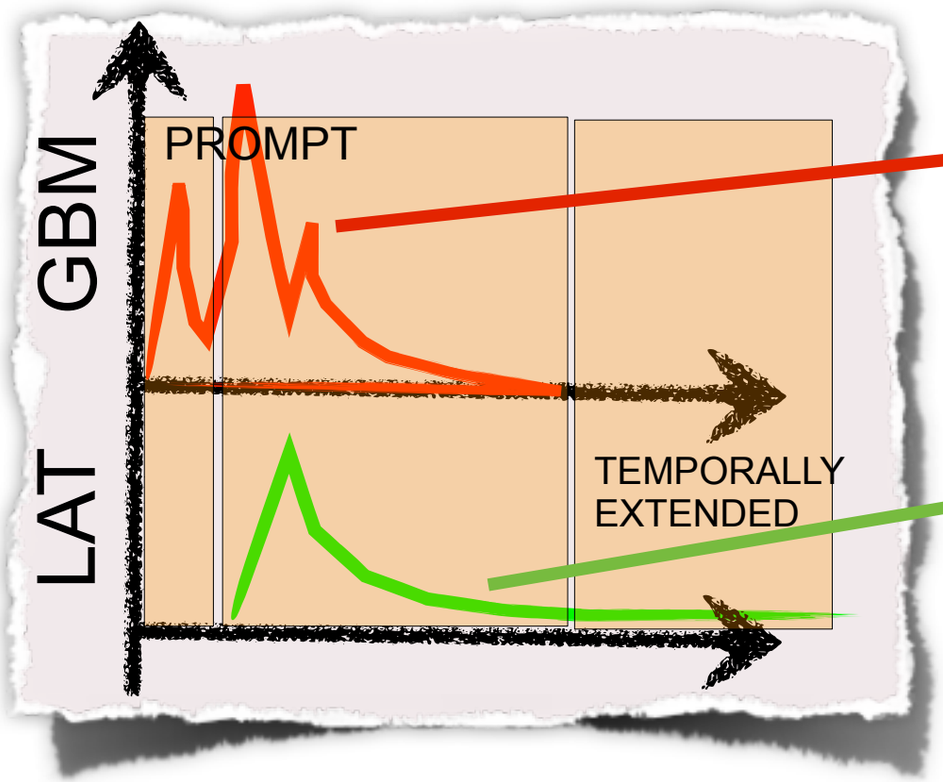
- **B) High-energy emission (observed by the LAT) starts later and lasts longer then the low-energy emission (observed by the GBM).**
  - **"Delayed onset" and "Temporally extended" emission**

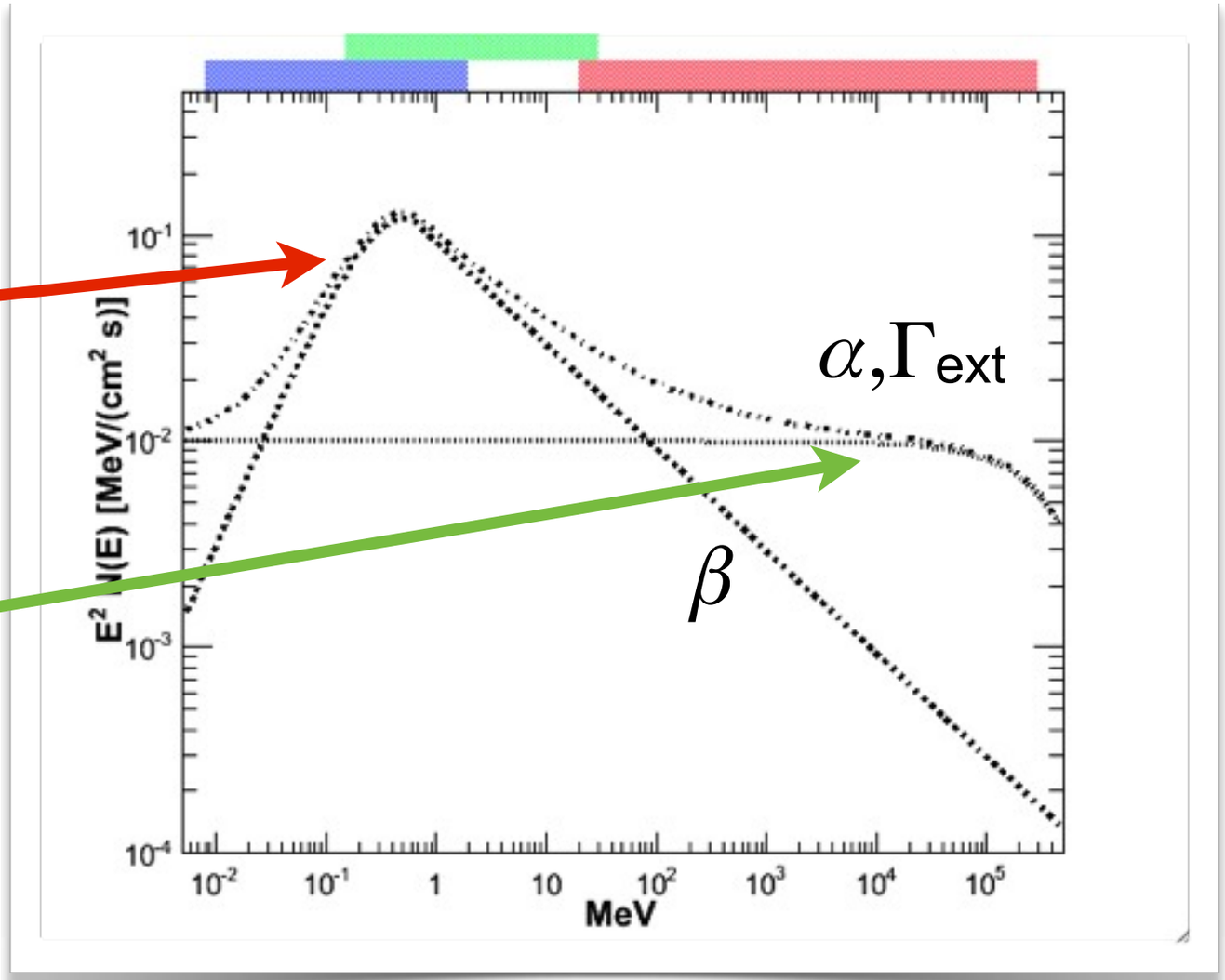




Prompt and temporally extended emission

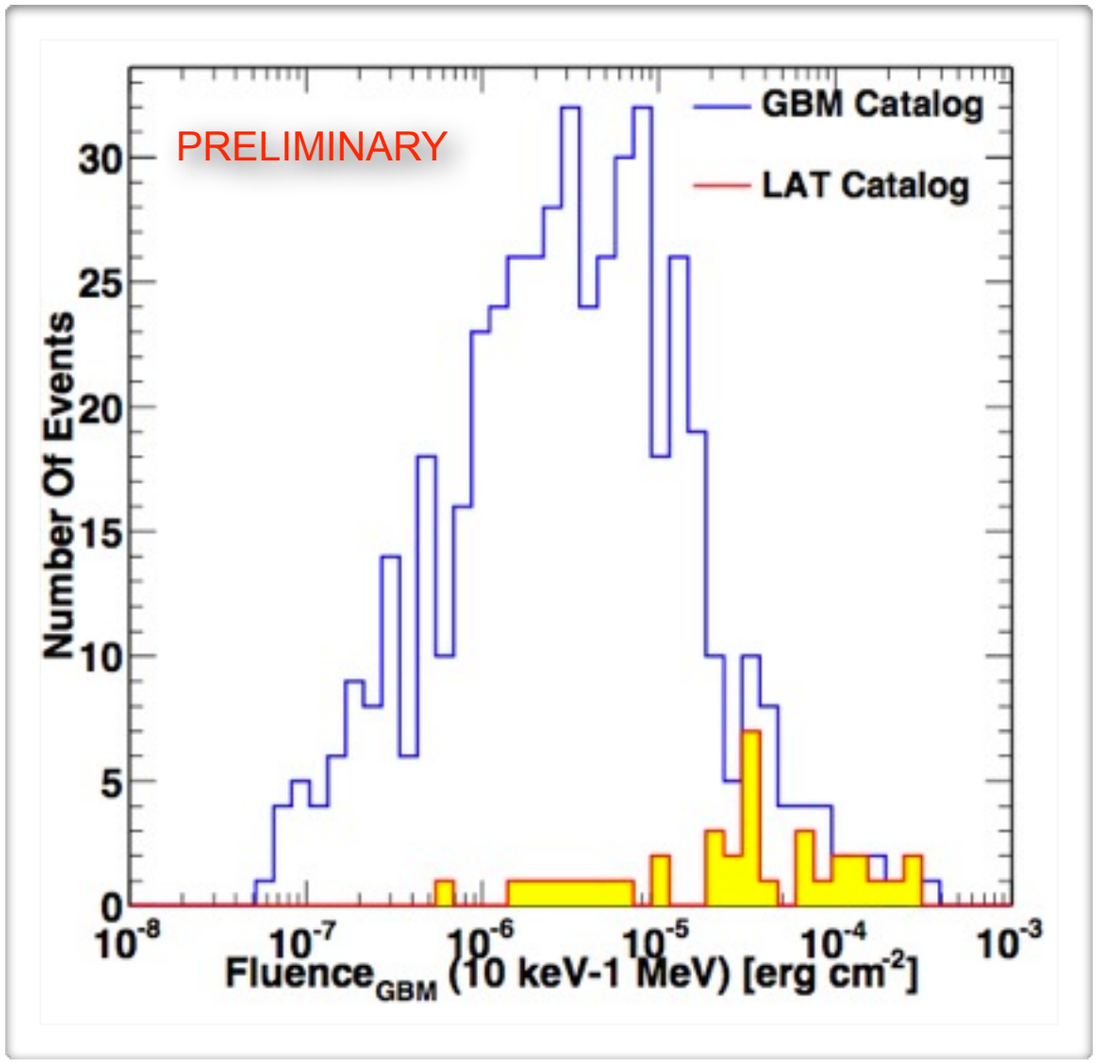
- **In the prompt phase:**
  - **larger spectral variation (-5 ÷ -2) reflecting in a larger variability of the LC**
- **In the temporal extended emission:**
  - **spectral index clustered around -2, smoother decay**

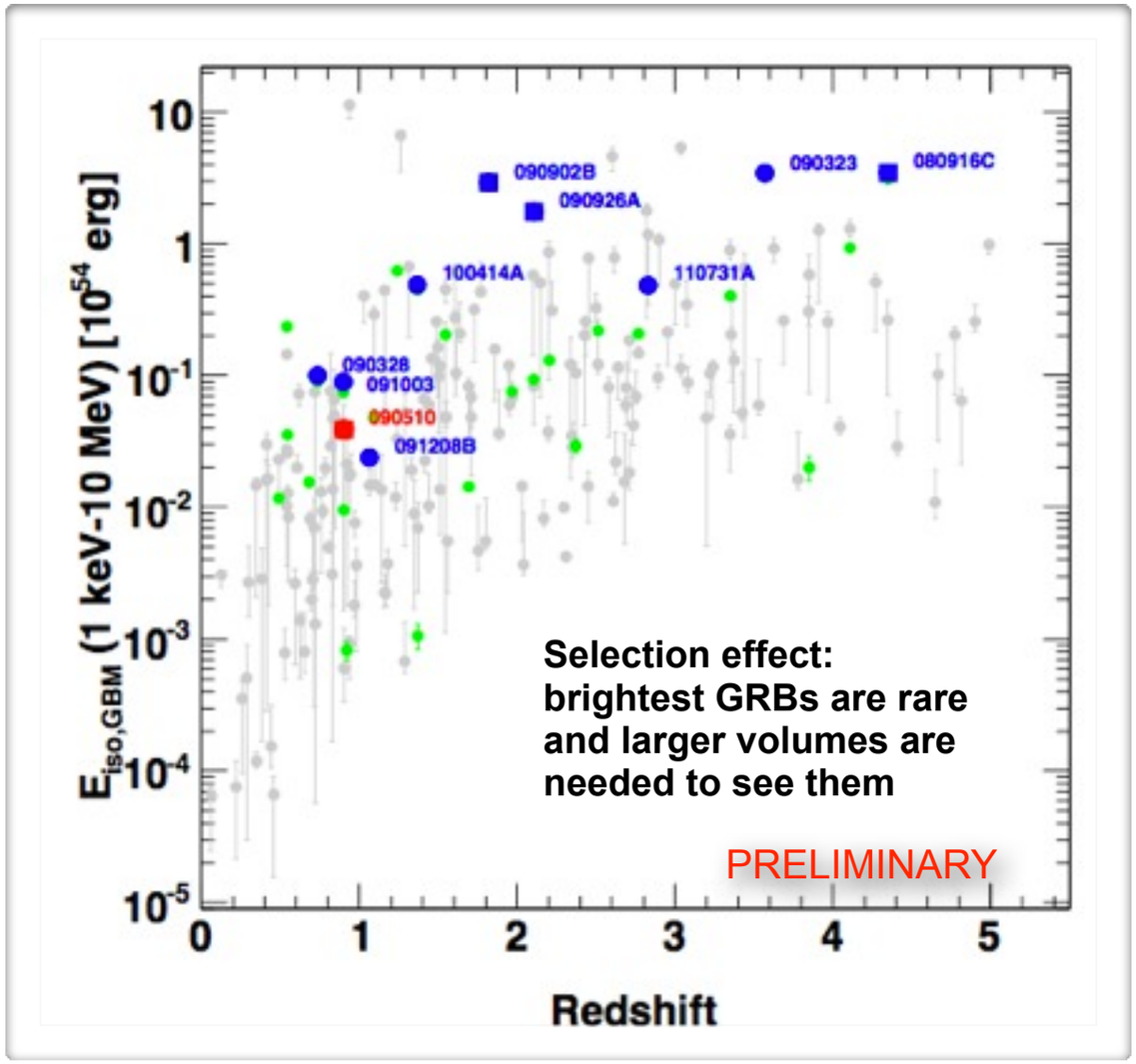




Important results from *Fermi*-LAT

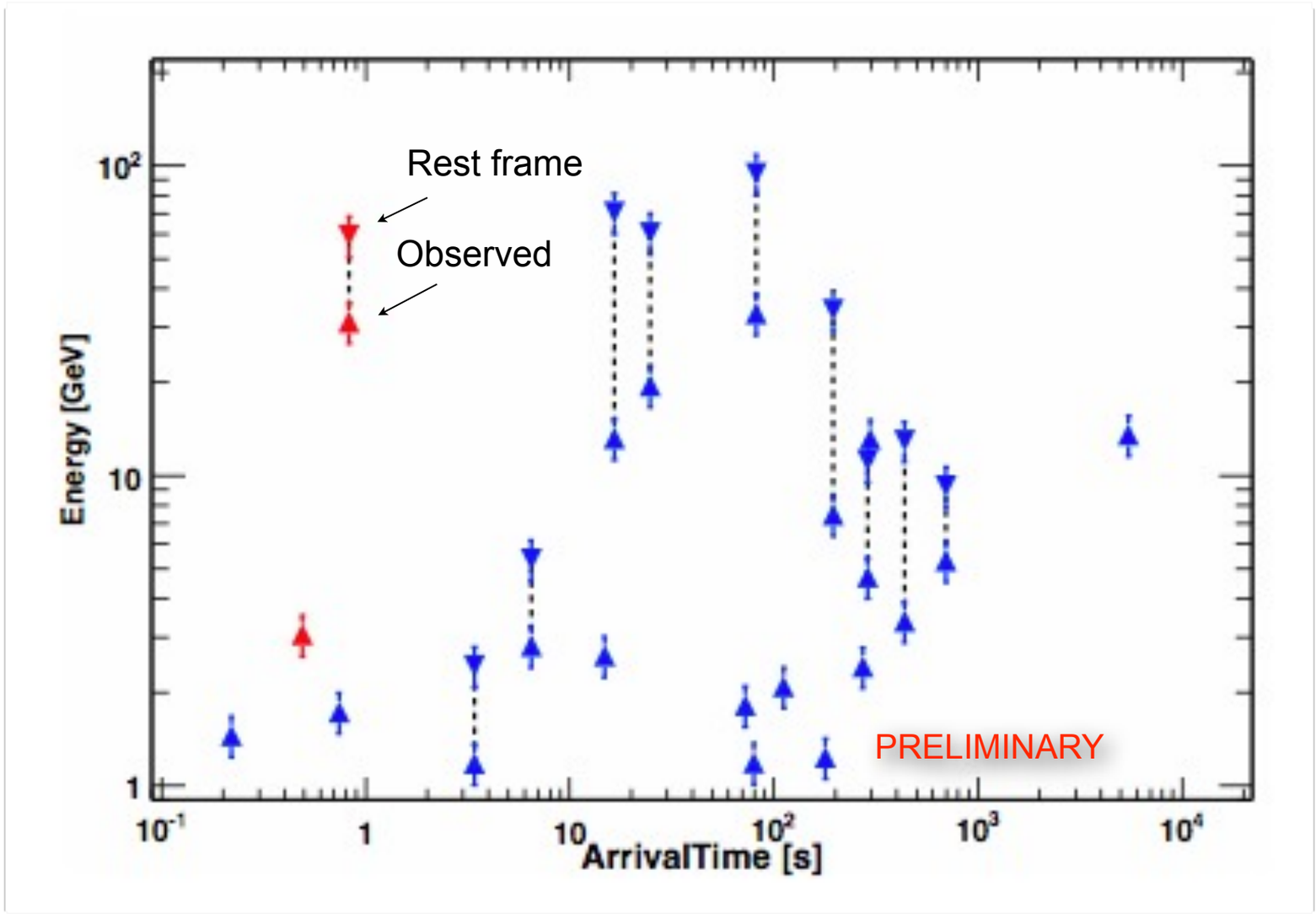
- **C) Energetics: LAT GRBs are among the brightest GRBs**
  - **4 LAT GRBs (080916C, 090510, 090902B, 090926A) exceptionally bright** [see also Cenko, et al. 2011, Racusin, et al. 2011]





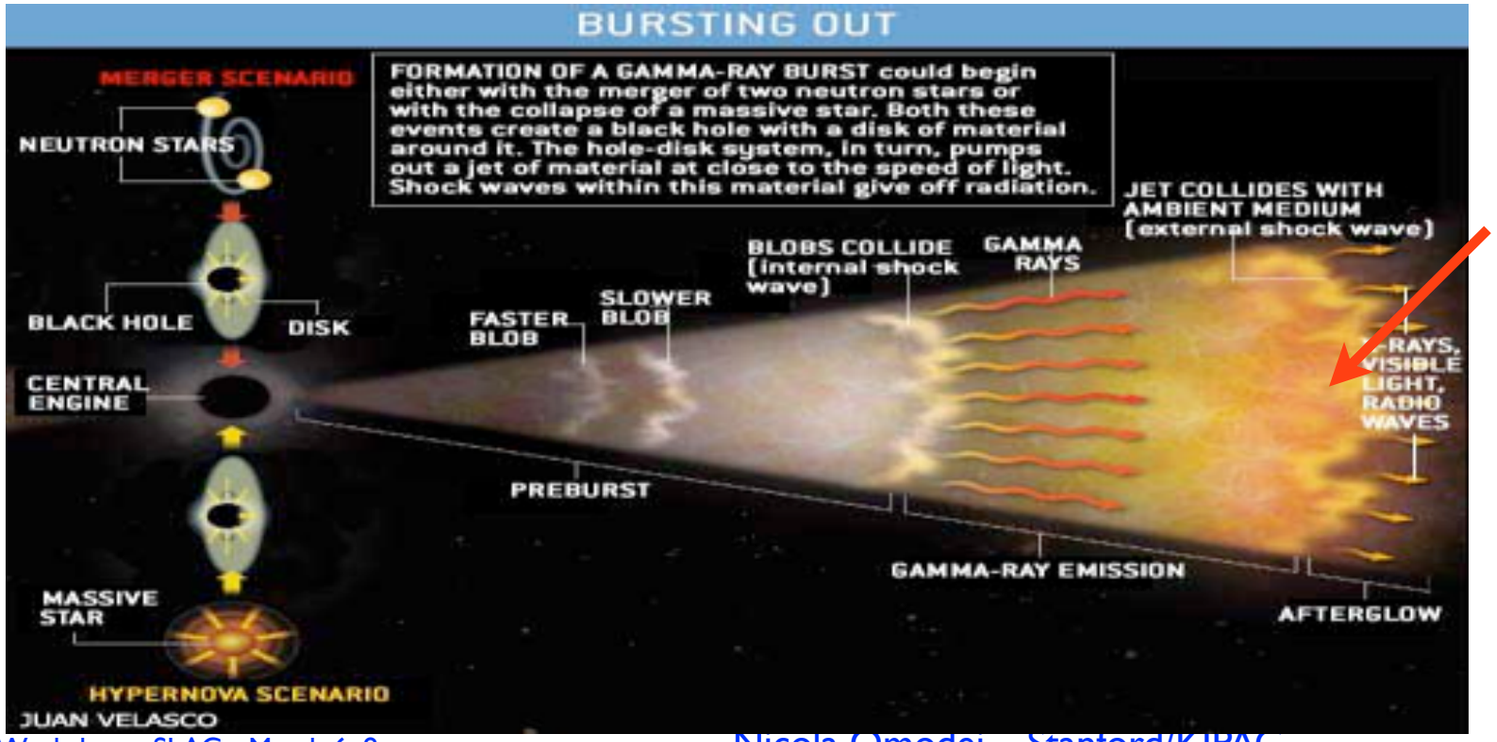
The highest energy photons

- **High-energy events arrive within ~1000 seconds in most of the cases. We have only 1 case of very late event, suggesting that very late high-energy emission (as the one observed by EGRET) is rare.**
- **High-energy events in several cases arrive after the end of the GBM emission**



Adiabatic relativistic "fireball" expansion?

- **Temporally extended emission, delayed onset, extra-power law component, no strong variability observed at high energy:**
  - **High-energy gamma-ray emission similar to X-ray or UV emission (attributed to the afterglow)** [See also Ghisellini et al. 2010, Kumar & Barniol Duran 2009; De Pasquale et al. 2010; Razzaque 2010]
  - **In the context of the fireball model (as in relativistic blast way from Blandford and McKee 1976):**
    - **Adiabatic expansion (decay index ~1) rather than radiative (~1.5)**
    - **Bulk Lorentz factor derived from the fireball energetics & deceleration time (~peak time) is Γ ~1000** [derivation in Chevalier & Li 2000, Panaitescu & Kumar 2000, see also Ghisellini et al. 2010]



...and High Energy gamma rays

Constrain the Synchrotron Emission

- **From the detection of <u>high-energy photons</u>:**
  - **What is the maximum photon energy that an electron can produce by synchrotron taking into account the acceleration time and the cooling time?**
  - **Computing the maximum energy of an electron (to complete at least 1 Larmour radius) we obtain a stringent <u>constrain on the synchrotron radiation</u> [see also Kumar et al. 2012 and Sagi & Nakar 2012]**

$$E_{\mathrm{syn,max}} \approx 29.5(1+z)^{-1}(\Gamma/1000)\ GeV$$

  - **Inverse Compton models (such as SSC) are much less constrained (depend on the "comptonization" parameters Y)**
- **Bulk Lorentz factors derived from γ-γ pair opacity (Γ ~200–700 for GRB090926A [Ackermann et al. 2011], otherwise UL;**

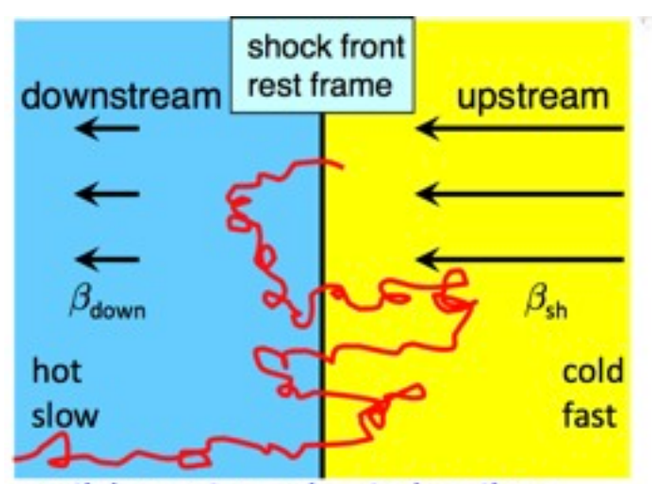


Image from M. Lemoine

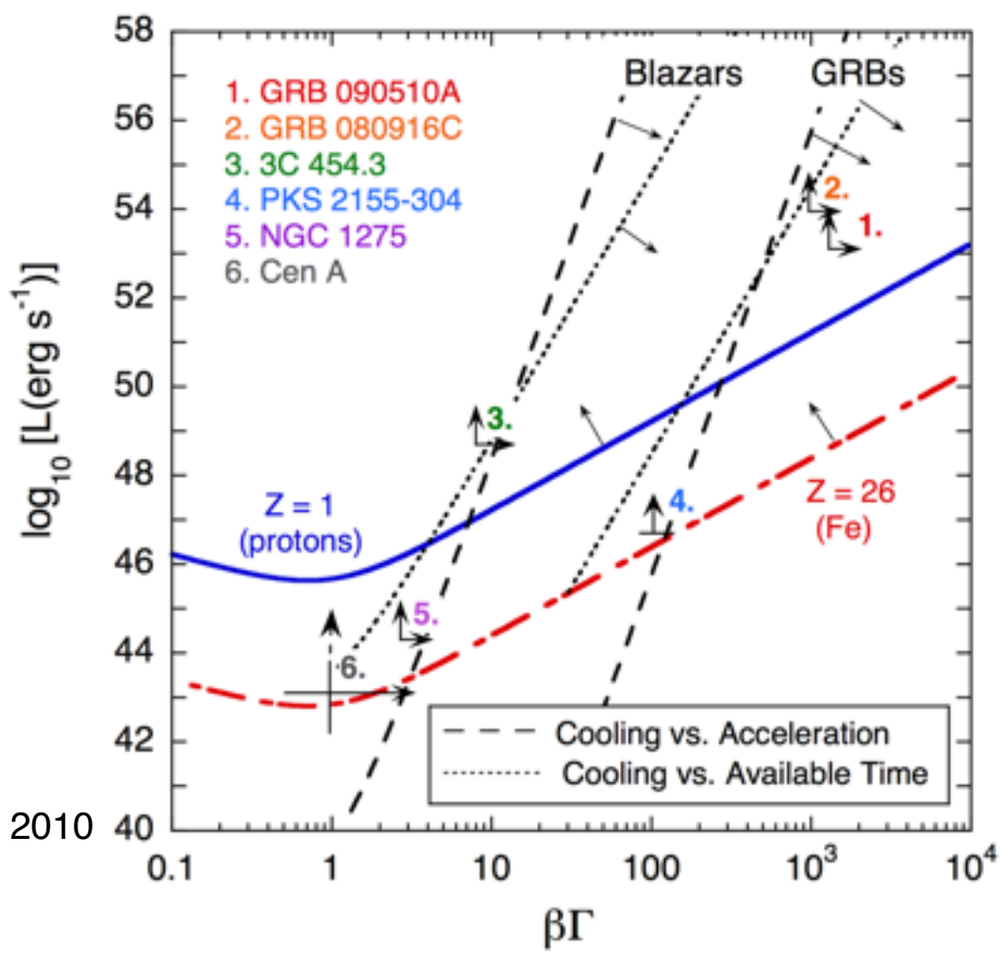
particles get accelerated as they bounce back and forth across the shock wave

GRBs as source of UHECR

- **For particles accelerated via Fermi mechanism in a magnetized plasma, there is a limitation (Hillas 1984):**

$$r_L \cong E/ZeB < R$$

- **Dermer & Razzaque (2010) derived the above condition for 2 *Fermi*-LAT GRBs (and Blazars) showing that GRB have sufficient energy to accelerate both protons and Fe to >10^{20} eV**



Dermer & Razzaque, 2010

The most serious problem seems to be the expected low rate of GRBs within the GZK radius

Some final considerations

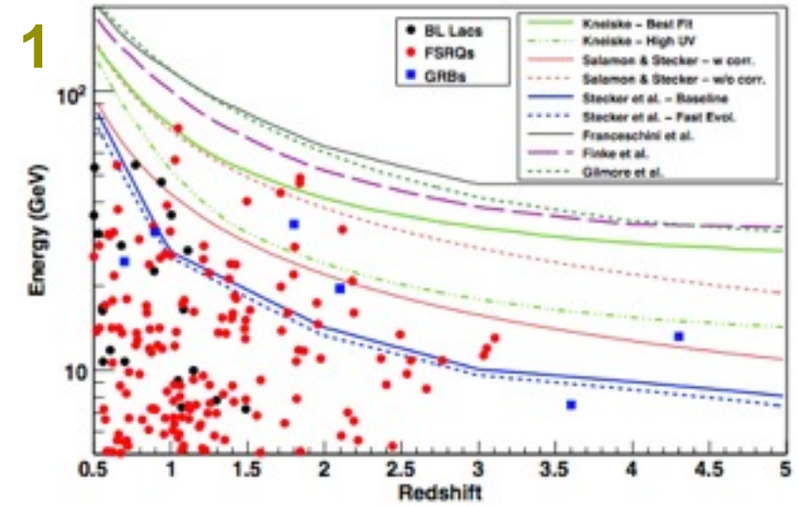
- **GRBs are powerful particle accelerators and source of high energetic gamma-rays;**
- ***Fermi*-LAT has provided additional informations on the nature of this phenomenon, especially on the temporally extended high-energy emission and the existence of the extra power-law component;**
  - **In the context of the fireball model: high-energy gamma-rays likely produced in the early afterglow phase of a relativistic adiabatic expanding fireball. Synchrotron origin still plausible;**
  - **UHECR can also be produced in GRBs, although the distance of the source might be a problem;**
- **The large effective area and the <u>large field of view</u> played an important role for the detection of high-energy GRBs with *Fermi*-LAT. For future experiments:**
  - **Ability to observe the entire (*un-occulted*) sky or to quickly repoint, + large duty cycle.**
  - **Optimization for "blind search" vs "follow up" strategy**
  - **In case of a detection, localization is also important to trigger multi-wavelength campaigns**

Backup

EBL and new physics

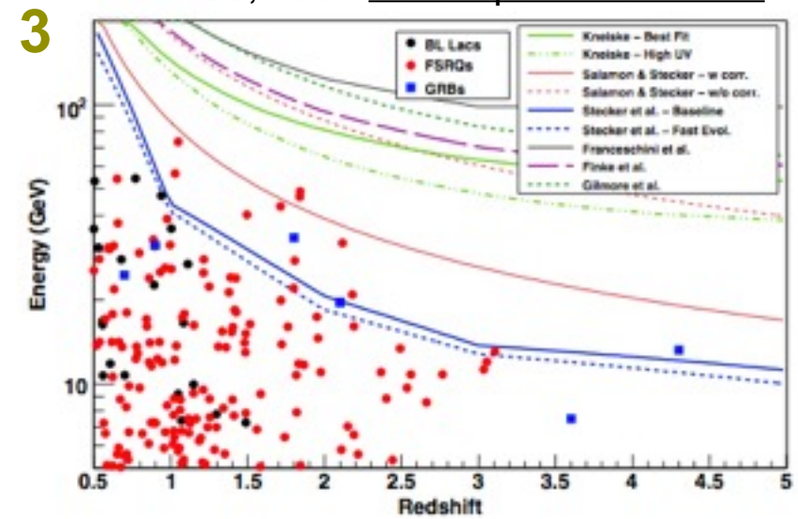
- **From the detection of <u>high energy photons</u>:**
  - **Constrain the EBL model (combined study with high energy events from AGN)**
    - **« baseline » model from Stecker et al. ruled out at ~3.6σ, using only GRBs**
  - **Testing Lorentz Invariance Violation:**
    - **Different methods can be applied, all lower limits $M_{QG,1} > M_{Planck}$**
    - **QG models with linear LIV disfavored**

$t_{\gamma\gamma} = 1$



Abdo, et al. <u>2010 ApJ...723.1082A</u>

$t_{\gamma\gamma} = 3$



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
090926A	long	> 150	> 50	1,3	0.066, 0.082	1, 1	~ 20 GeV	2.106

Is the fireball "radiative"?

Radiative

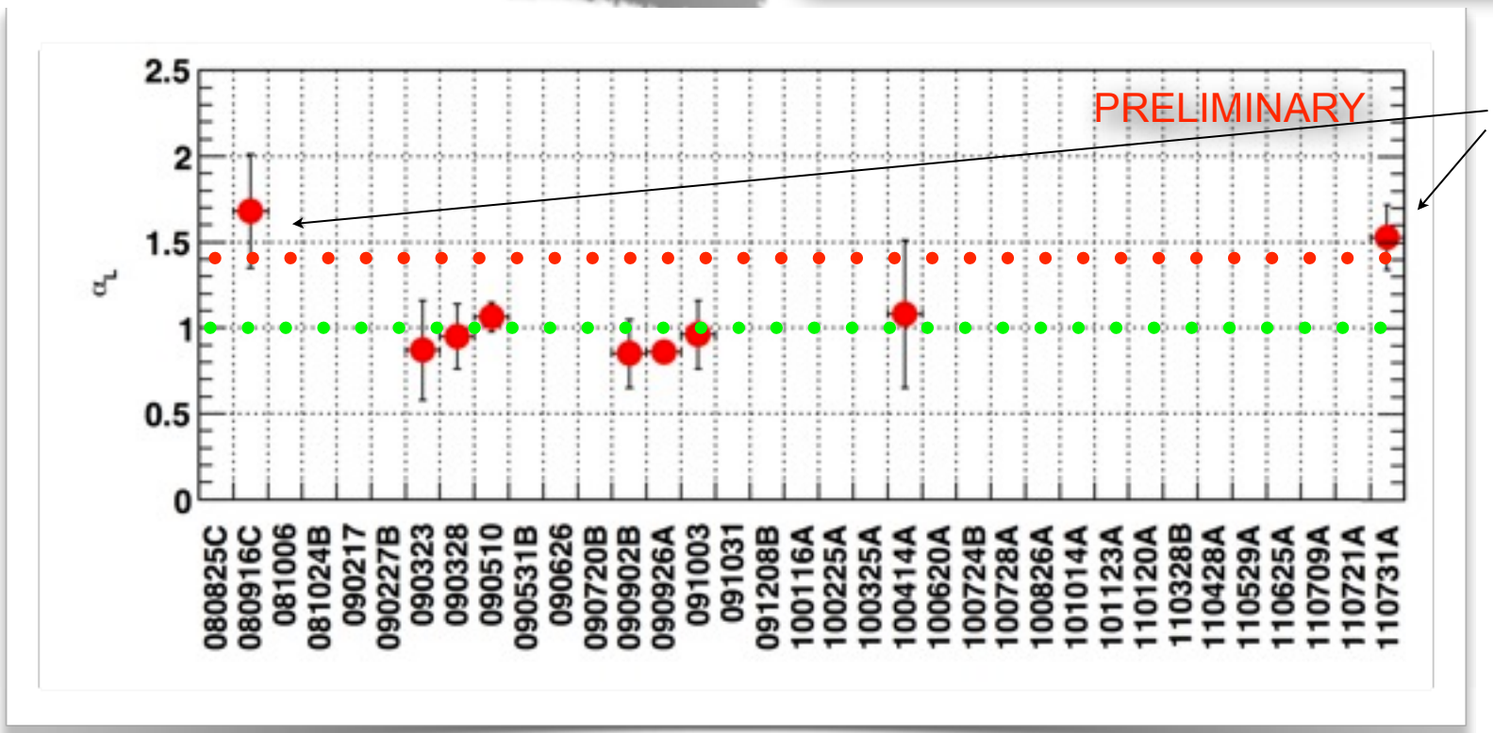
$$L_{\rm iso,r} = \frac{3\epsilon_e E_{\rm k,f}}{2a^{10/7}} t_{\rm dec}^{3/7}\, t^{-10/7} \qquad t \gg t_{\rm peak}$$

Adiabatic

$$L_{\rm iso,a} = \frac{3}{2a}\frac{\epsilon_e E_{\rm k,f}}{t}; \qquad t \gg t_{\rm peak}$$

Sari 1997, Katz & Piran 1997, Ghisellini et al. 2009

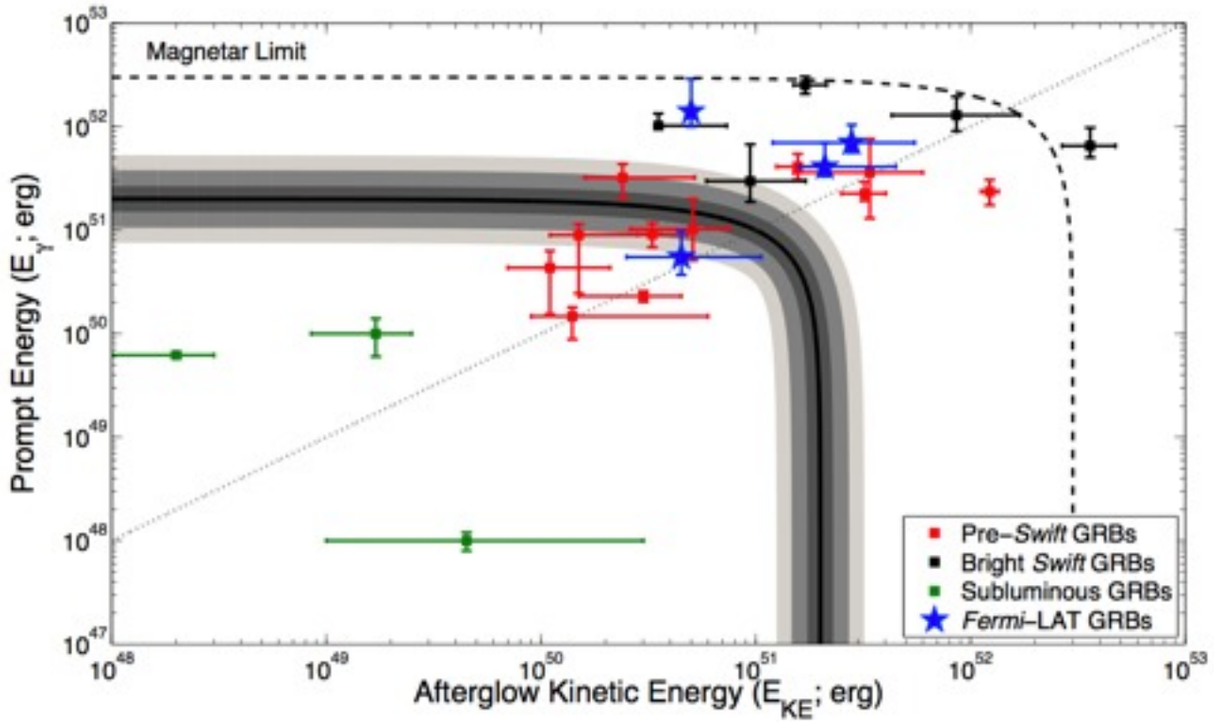
$L(e) \sim t^{-\alpha_L} e^{-\beta}$	α_L	b
Radiative	10/7	1
α_L =(12b-2)/7		
Adiabatic	1	1
α_L =(3b-1)/2		



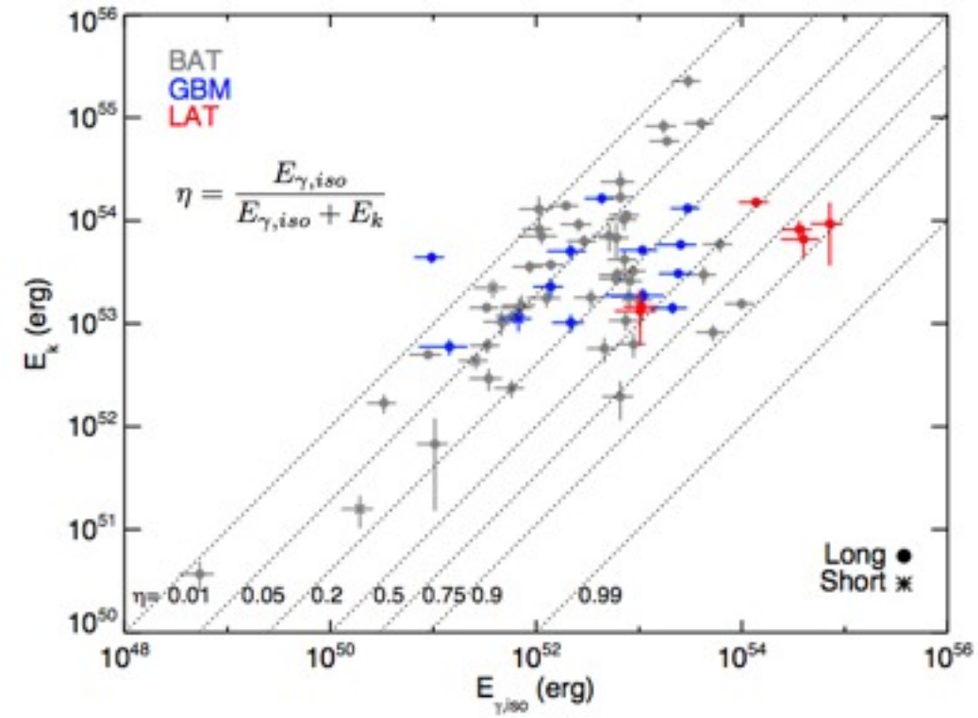
Outlier?
We probably did not see the break in the LC

– **In this framework, adiabatic expansion is preferred for most of the GRBs**

Radiative efficiency of high-energy GRBs



Cenko, S. B., et al. 2011, ApJ, 732, 29



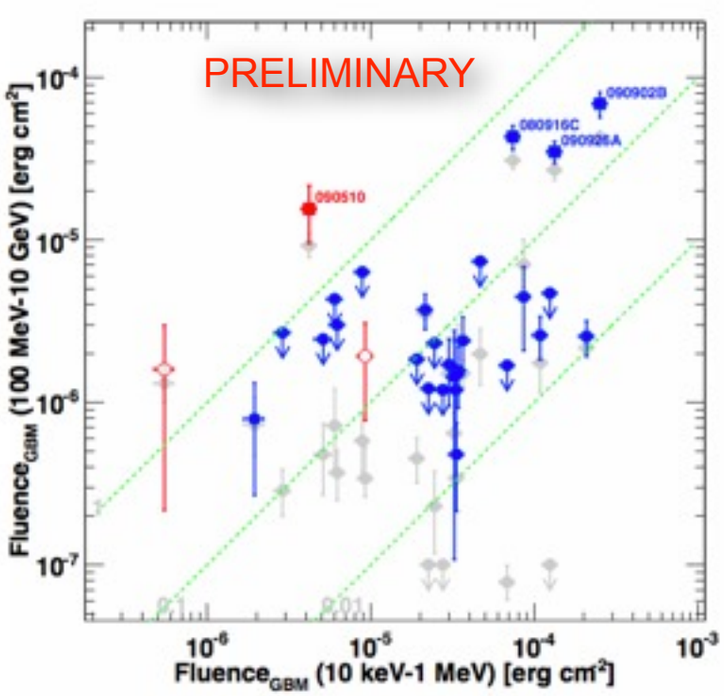
Racusin, J. L., et al. 2011, ApJ, 738, 138

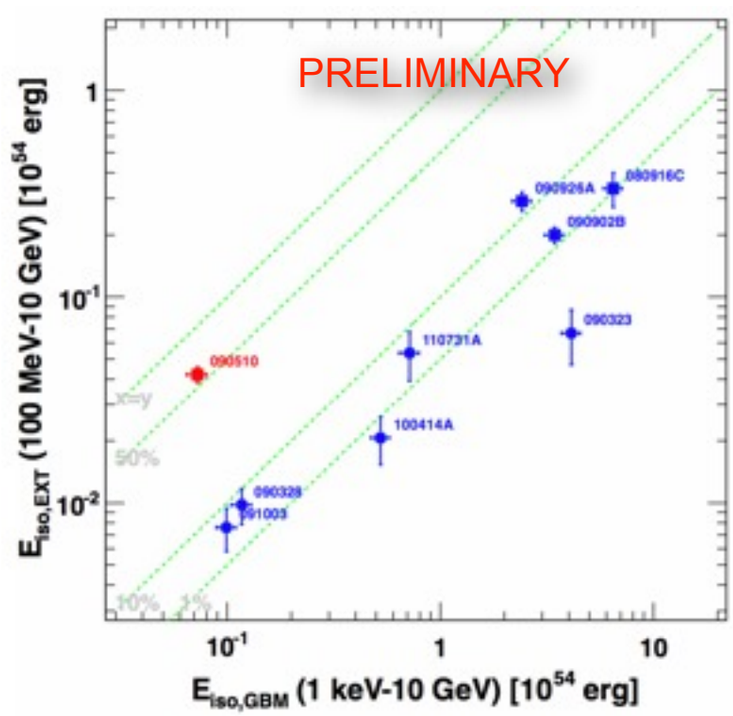
Note: From X-ray afterglow observation (Swift) one can derive the jet opening angle, and the beamed bolometric luminosity. The kinetic energy is also model-dependent

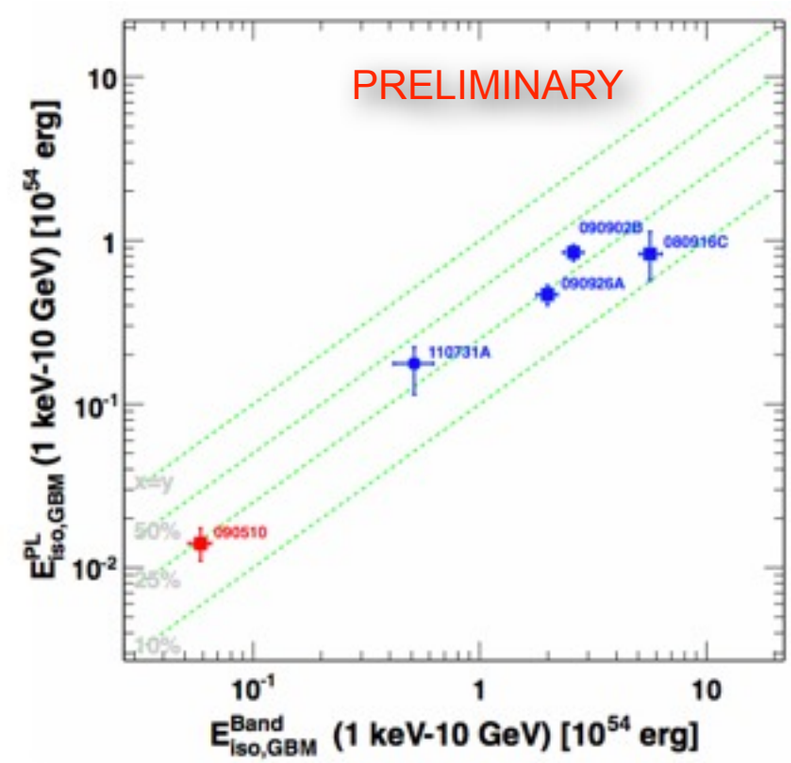
- **Hyper energetic Fermi LAT GRBs have also high radiative efficiency**

Energy Budget

- **We measure the energy budget during the different component (Prompt, temporally extended emission, Band, extra PL component)**
  - **During the prompt phase (GBM)**
    - **Fluence at high-energy similar to the Fluence released at low energy (measured by the GBM)**
    - **<10% of the total prompt energy goes in high energy late emission**
    - **The short 090510 is an exceptional bursts in several plots (typical of short GRBs?)**
  - **During the prompt phase (GBM) ,10%-30% of the total energy comes from the extra component (PL)**

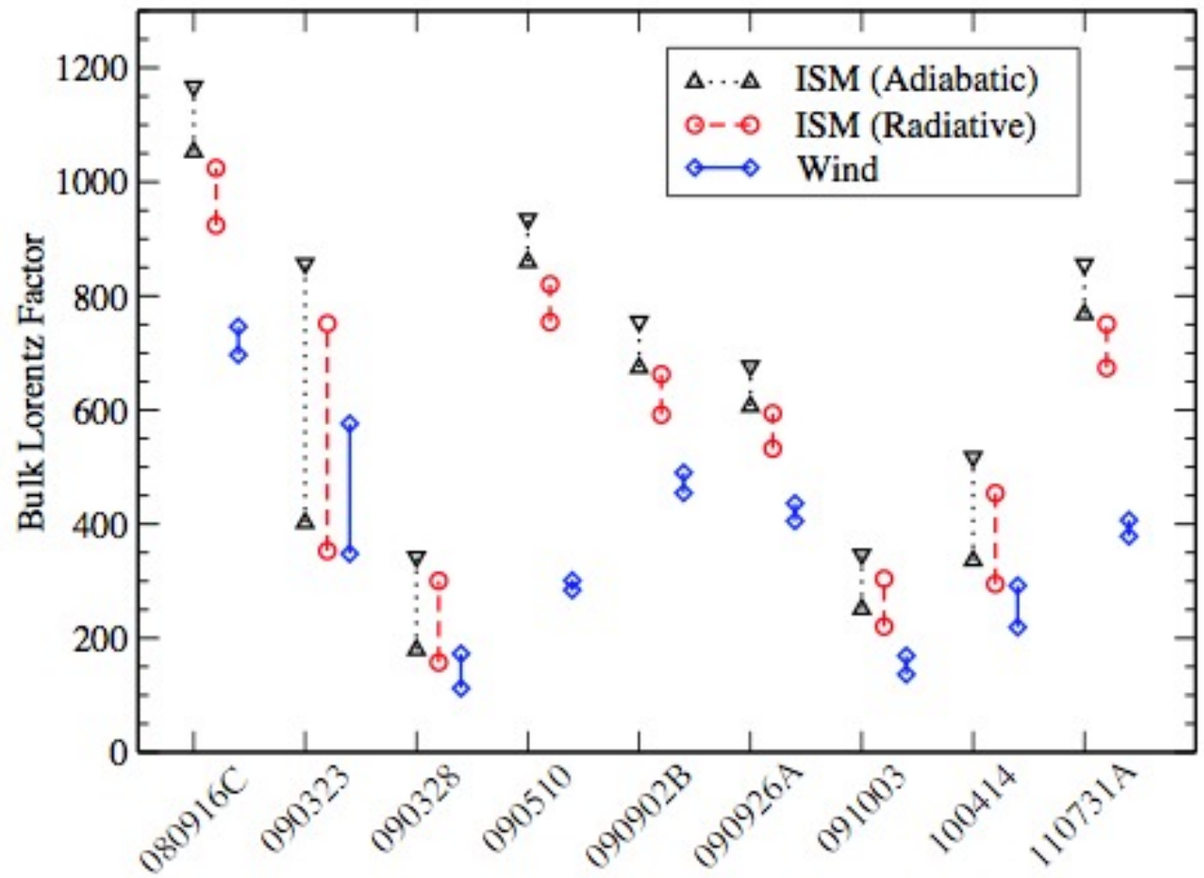






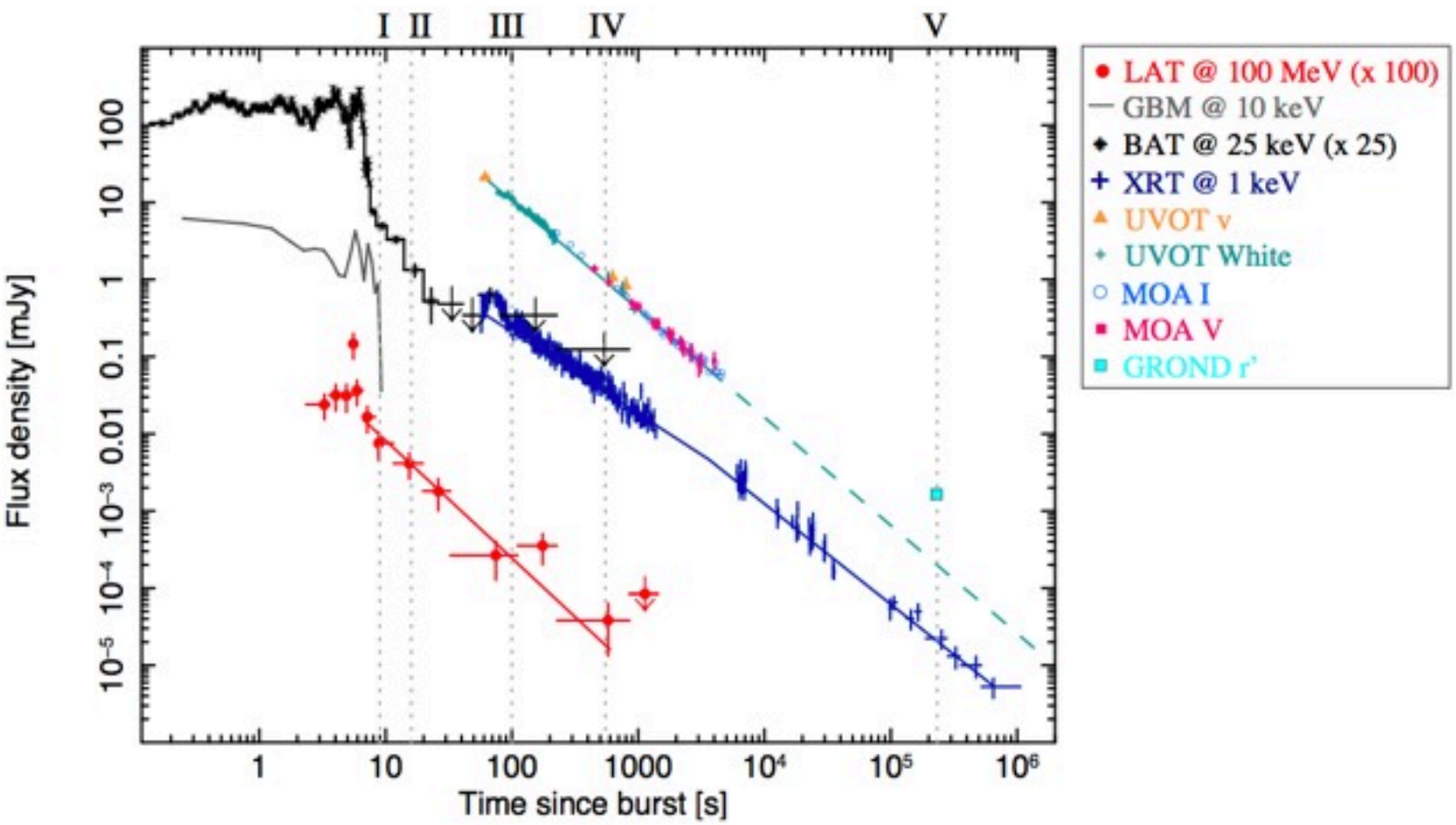
The delayed onset and the bulk Lorentz factor

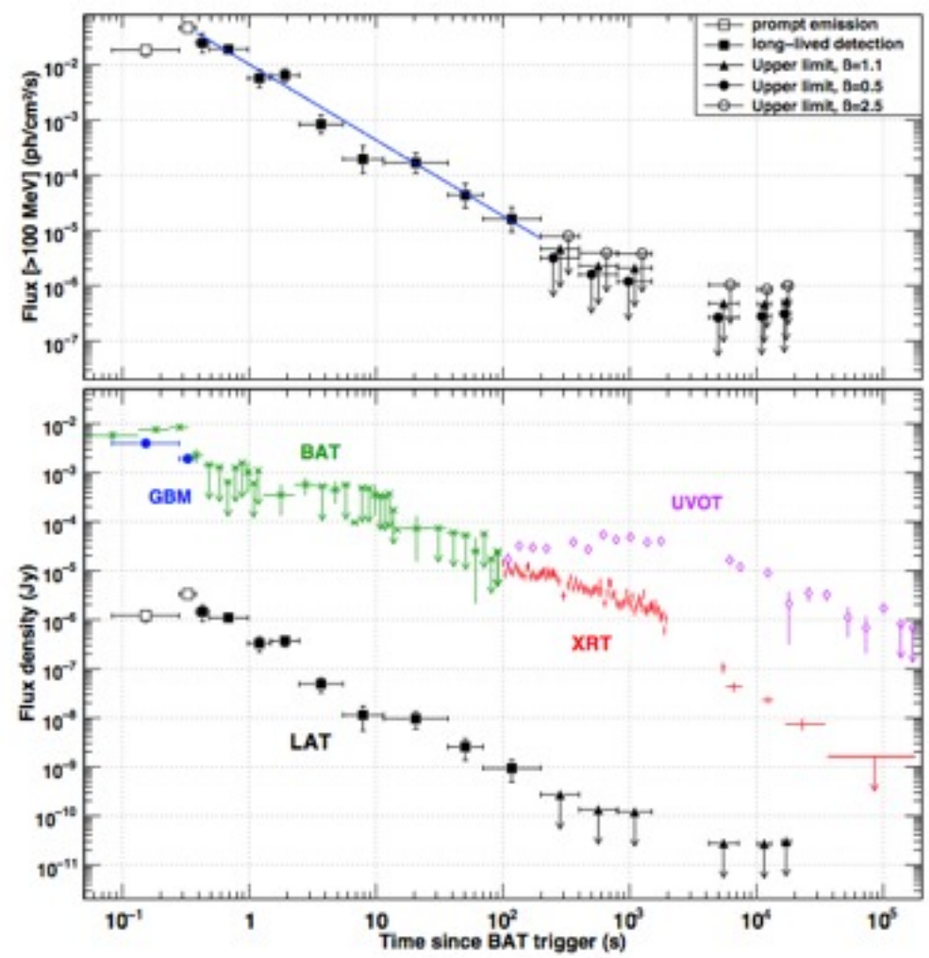
➡**The delayed onset of the LAT emission is poorly understood. In the context of early afterglow models** (Kumar & Barniol Duran 2009; Ghisellini et al. 2010; De Pasquale et al. 2010; Razzaque 2010)**, it can be related to the transition between the coasting phase (acceleration) and the self-similar phase (deceleration), and can be used to calculate the jet bulk Lorentz factor.**



Simultaneous Swift detections

- **2 GRBs have been <u>simultaneously</u> detected by LAT and Fermi**





GRB 090510 De Pasquale et al 2010