Fermi View of Gamma-ray Bursts

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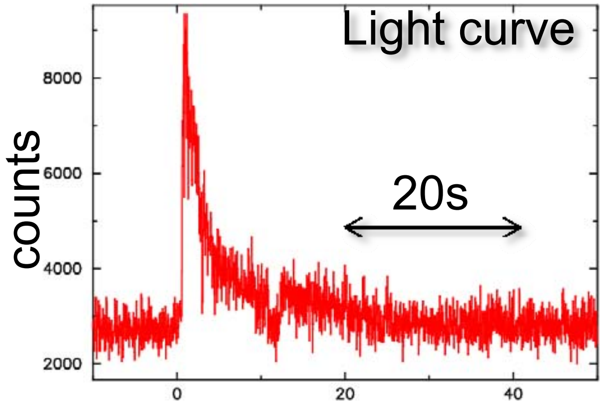
on behalf of Fermi LAT/GBM collaborations

Gamma-Ray Bursts: overview

Bright gamma-ray pulse in gamma-ray band is discovered in 1967

BATSE (1991-)

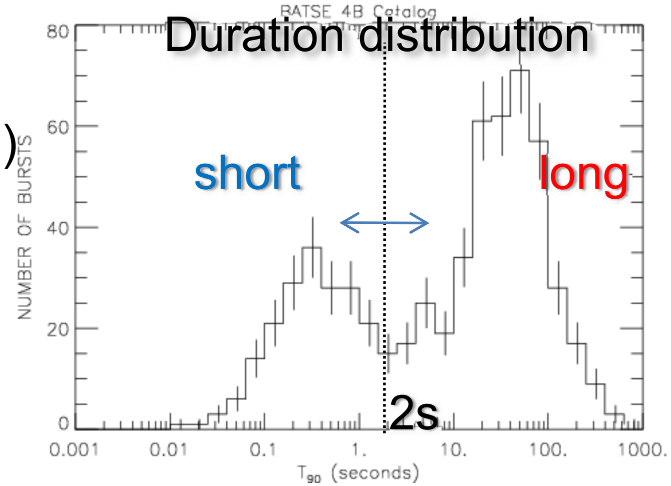
- GRBs originate from All-sky (~1GRBs/day)
- Bimodal duration distribution:
- Short (<2s) and Long (>2s) GRB



BeppoSAX(1996-)

- discovery of the X-ray afterglow

➔This leads a redshift measurement.
cosmological origin for long GRBs(z=0.1-8)
most energetic explosion in the Universe (**E_{iso}~10^{52} erg**)
relativistic jet is required (compactness problem)



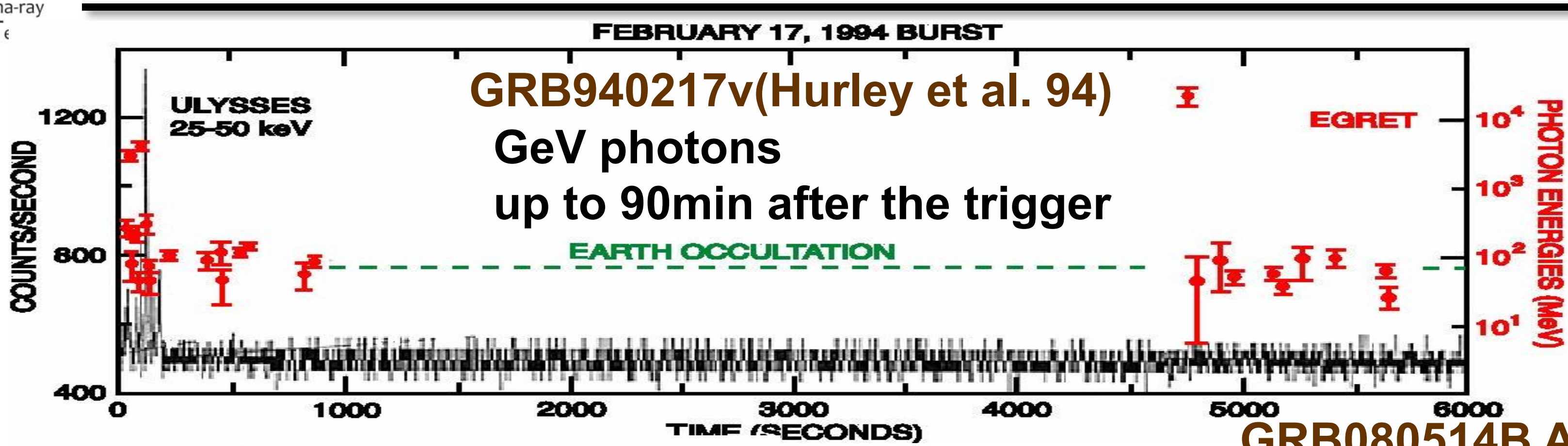
HETE-2 (2002-) Swift (2004-)

- Leads many afterglow observations
- Association with SN and long GRBs
- Discovery of afterglow from short GRBs

Still many open issues: emission mechanism, progenitor, short GRB…. etc

Little known about high energy emission from GRBs (>100 MeV)

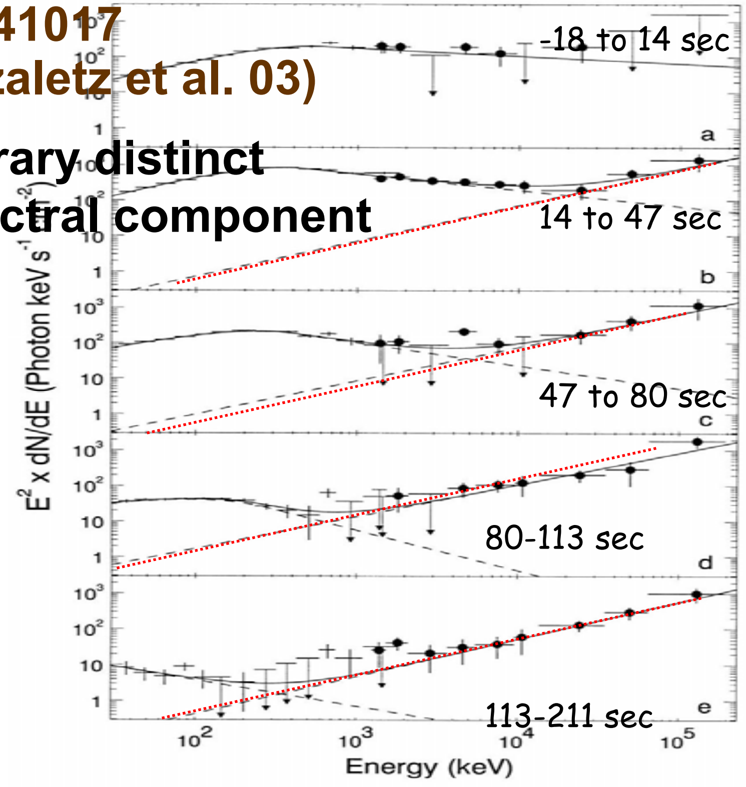
HE emission from GRBs : Pre-Fermi Era



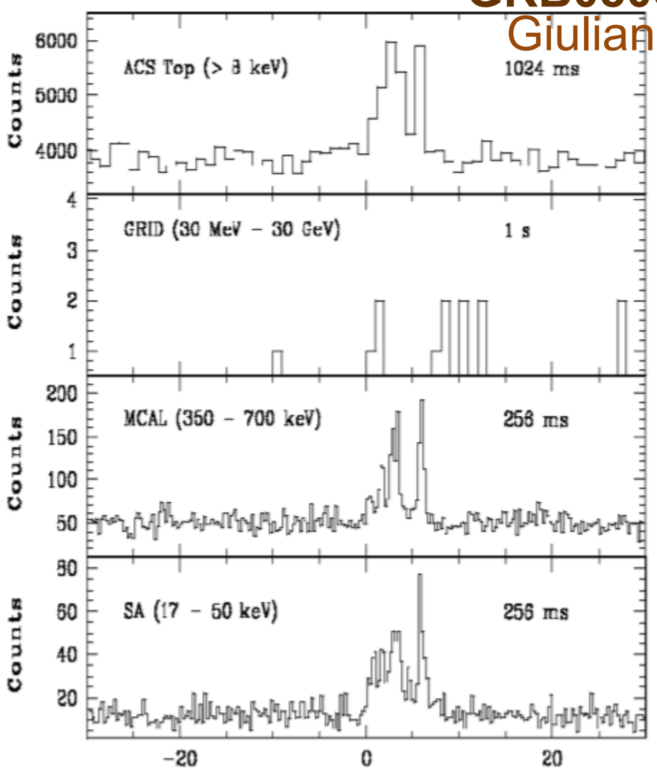
GRB940217v(Hurley et al. 94)
GeV photons
up to 90min after the trigger

GRB941017
(Gonzaletz et al. 03)

Temporary distinct
HE spectral component



GRB080514B AGILE
Giuliani et al. 08
Long-lived
HE emission



HE emission from GRBs (2)

What can we get from high energy emission of GRBs?

■Extra component of the prompt emission ?

Different emission mechanism: Synchrotron self Compton ? 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 ➔ Limit on the quantum gravity mass :M_{QG}
A few GRBs show delayed high energy emission (GRB940217, GRB080714)

Need more sensitivity and larger FoV

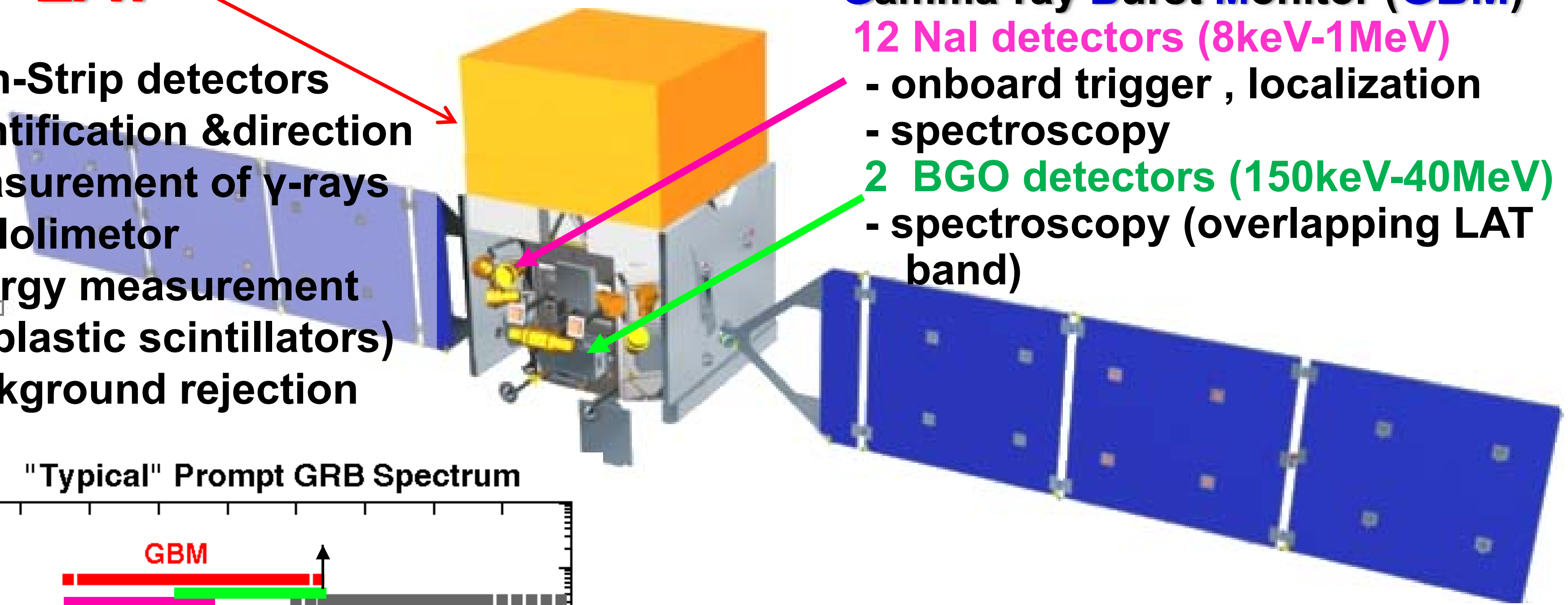
Fermi Gamma-ray Space Telescope

LAT

Silicon-Strip detectors
- **Identification &direction measurement of γ-rays**

CsI calolimetor
- **Energy measurement**

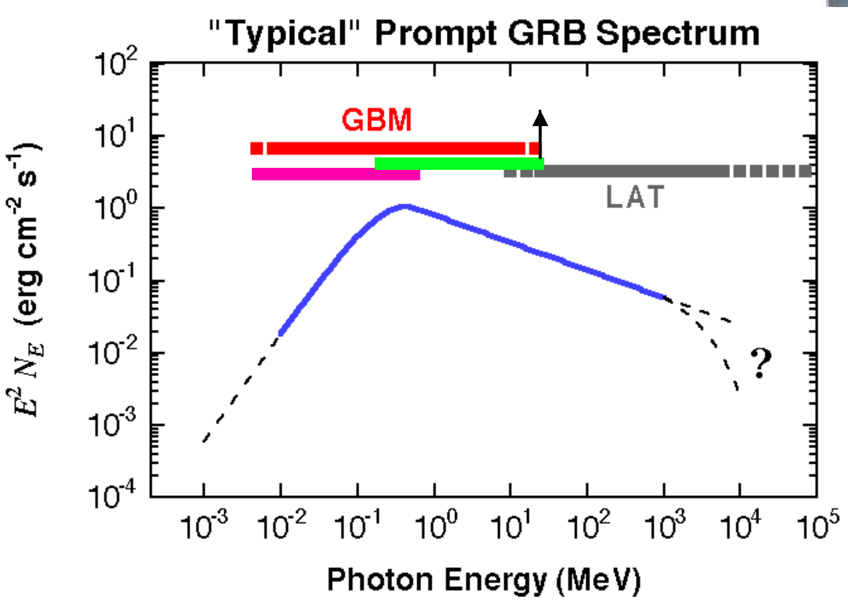
ACD (plastic scintillators)
- **background rejection**



Gamma-ray Burst Monitor (GBM)

12 NaI detectors (8keV-1MeV)
- **onboard trigger , localization**
- **spectroscopy**

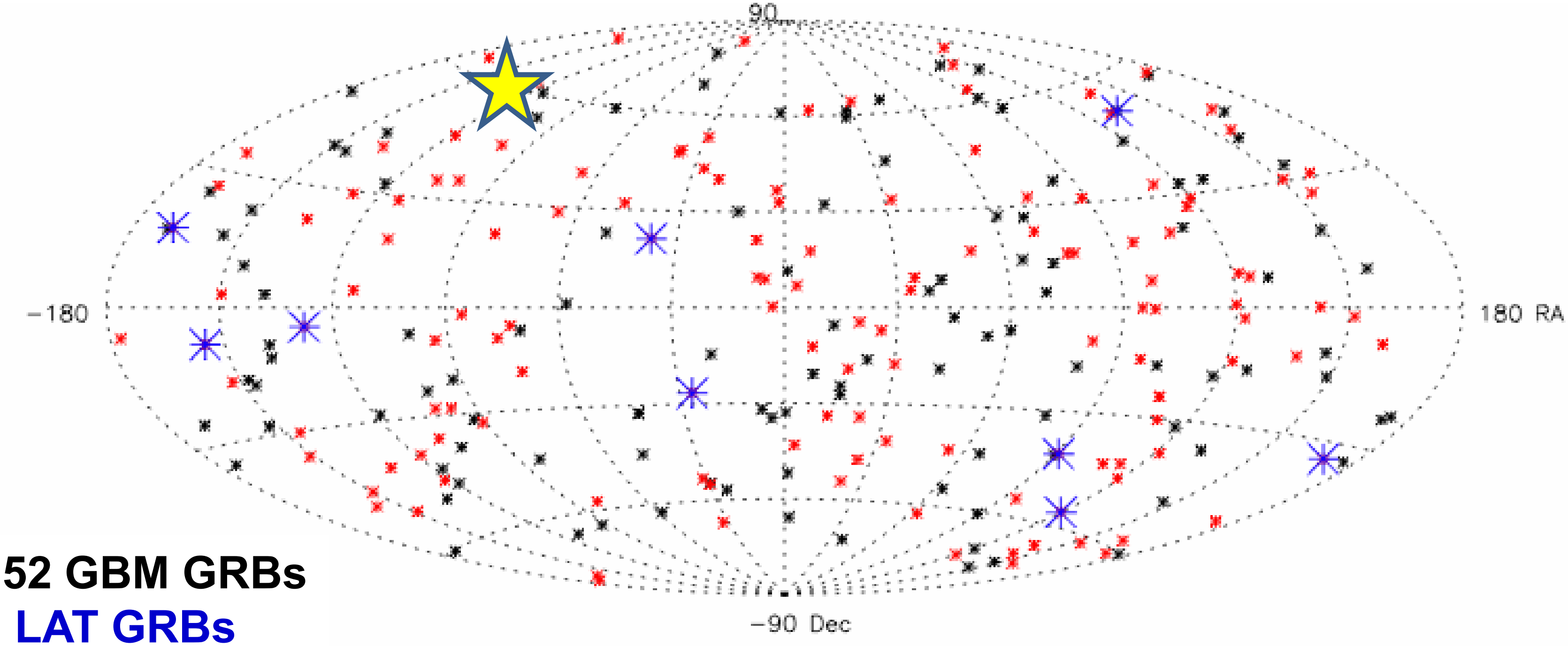
2 BGO detectors (150keV-40MeV)
- **spectroscopy (overlapping LAT band)**



-Efficient observing mode
-Wide FoV
-Low deadtime
-Large effective area
-Good angular resolution
-Energy coverage

More photons from Many GRBs

Fermi GRBs as of 090713



252 GBM GRBs

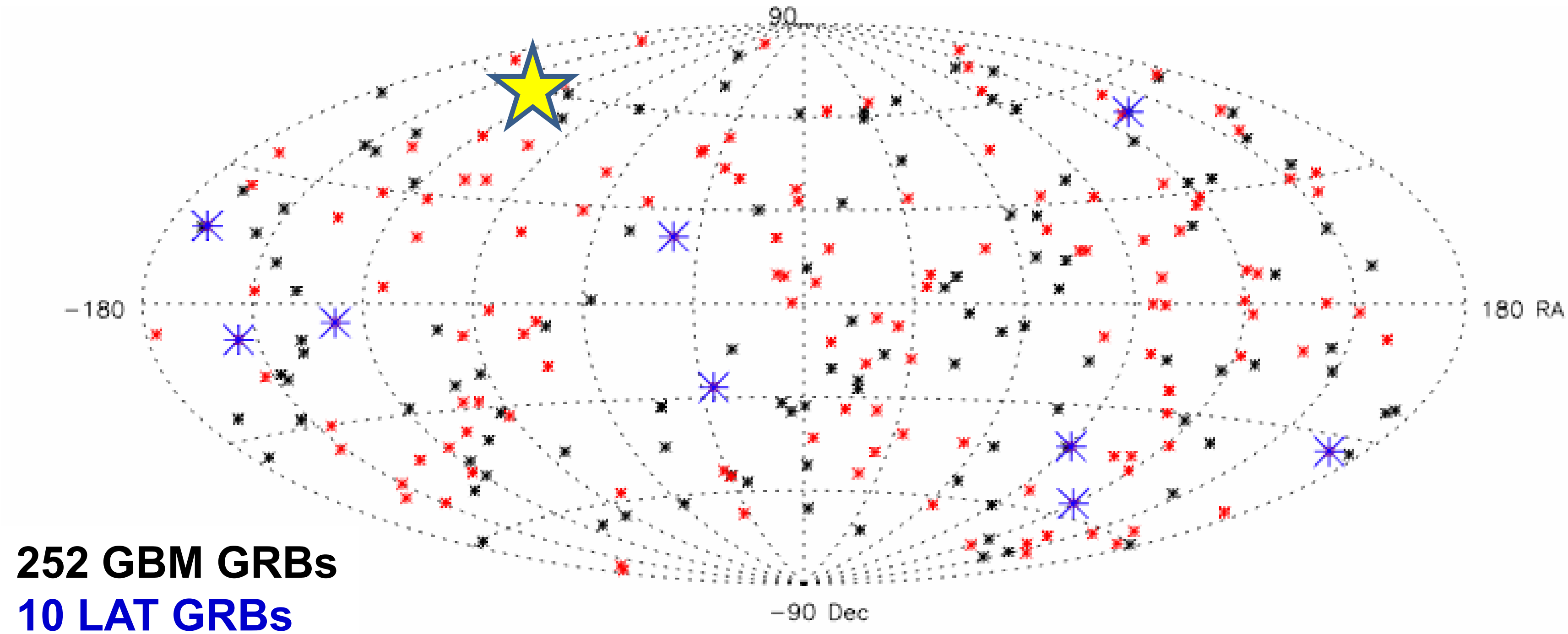
9 LAT GRBs

In Field-of-view of LAT (138)

Out of Field-of-view of LAT (114)

- **GRB 080825C**
- **GRB 080916C – very strong, z=4.35**
- **GRB 081024B – short**
- **GRB 081215A – LAT rate increase**
- **GRB090217**
- **GRB 090323 – ARR, z=3.6**
- **GRB 090328 – ARR, z=0.79**
- **GRB 090510 – short, intense, z=0.9**
- **GRB 090628**

Fermi GRBs as of 090713



252 GBM GRBs
10 LAT GRBs
In Field-of-view of LAT (138)
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- **GRB 090628**
- NEW! **GRB 090902B – ARR, intense, z=1.82**

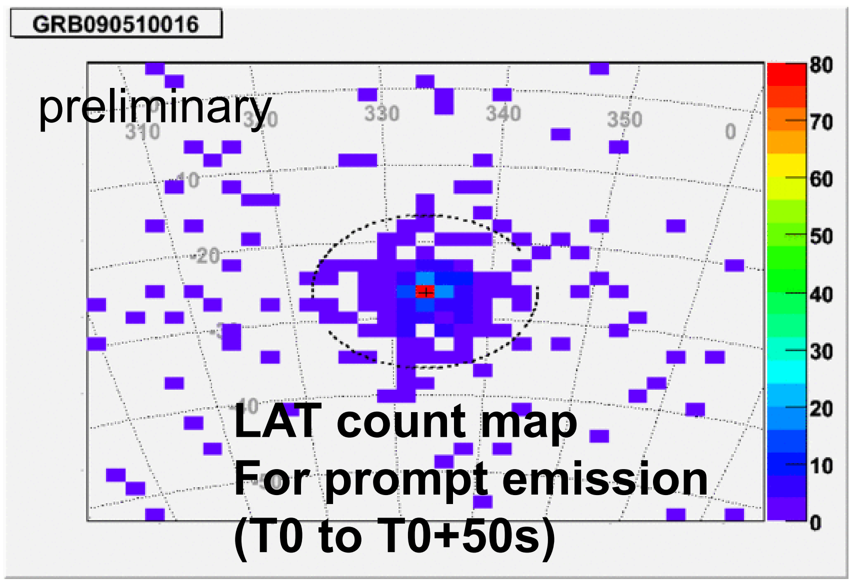
GRB 090510 very bright short GRB with redshift

(Abdo et al. Nature submitted arvix0908.1832)

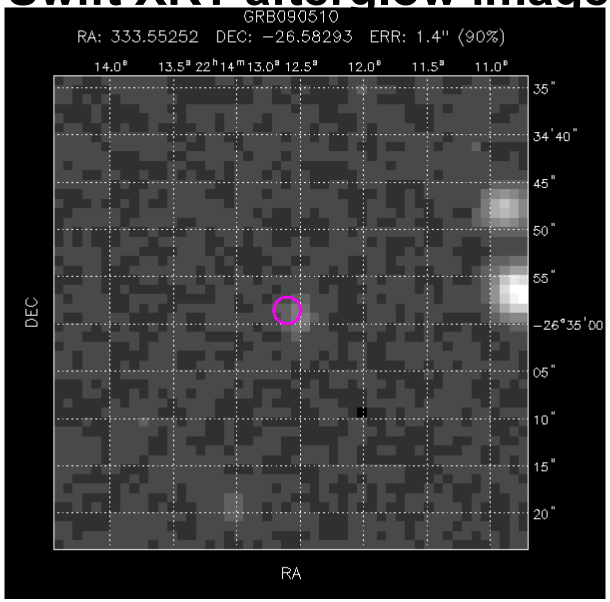
Multiwavelength detection of GRB090510

- **Bright, short GRB090510106 triggered the GBM at 00:22:59.97 UT.**
- **>5sigma detection by Fermi-LAT (Ohno et al. GCN9334)**
- **>10events above 1 GeV (Omodei et al. GCN 9350)**
- **1st LAT onboard GCN notices were issued**
- **Many other satellites and ground telescopes detected both prompt emission and afterglow**
- **Z=0.903(+/-0.003)! (VLT:Rau et al.; GCN9353)**

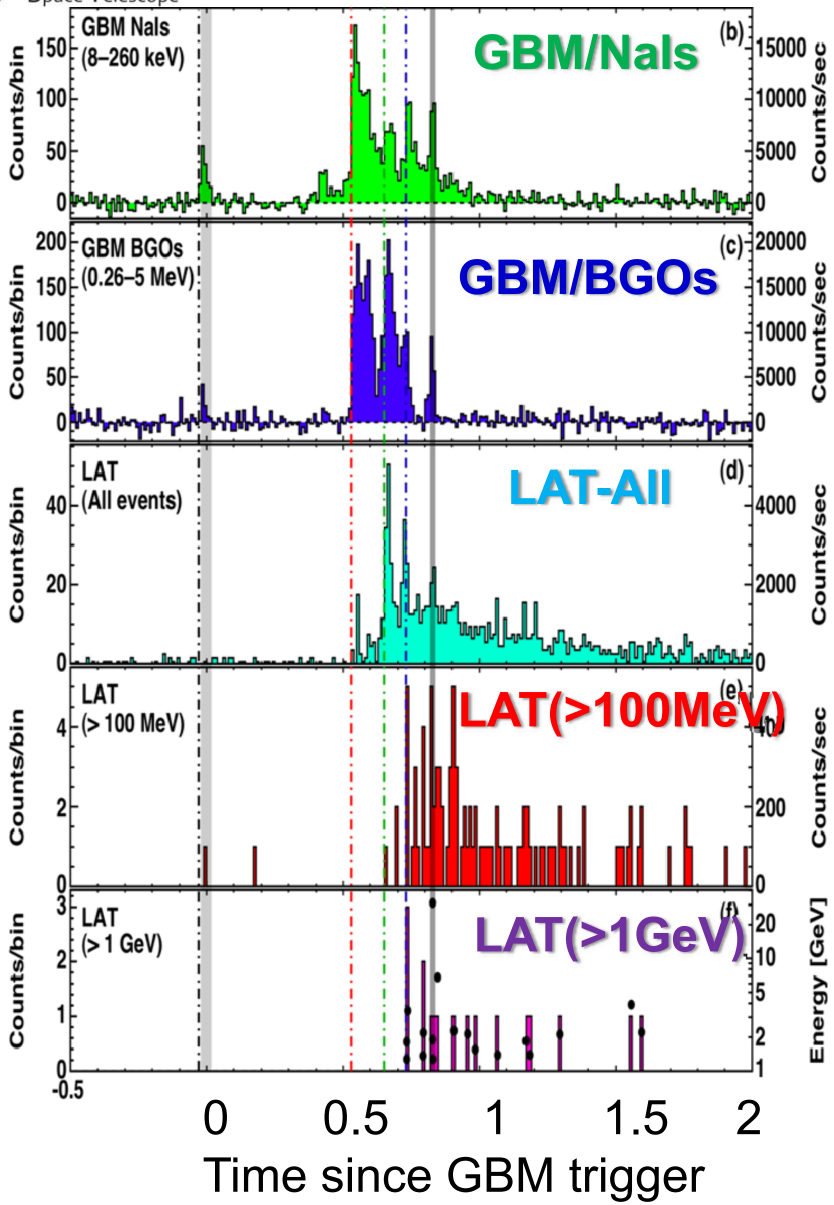
First GeV short GRB with redshift !



Swift XRT afterglow image

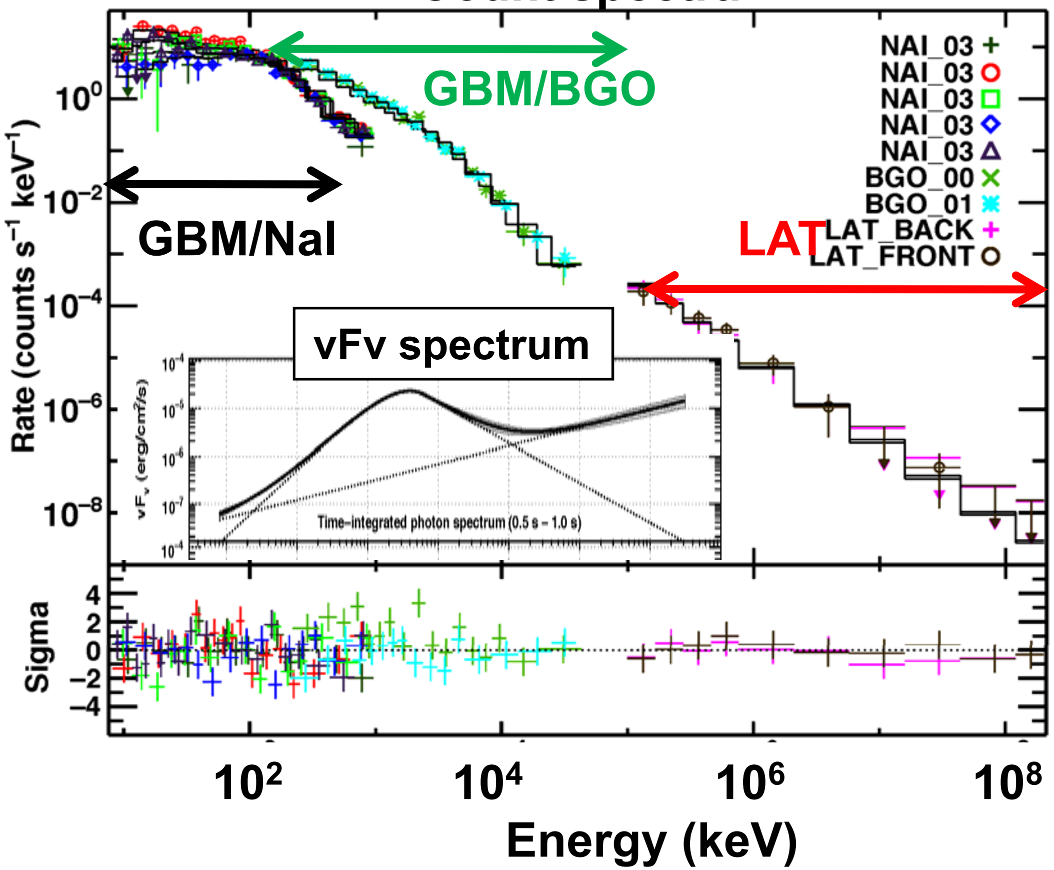


GRB090510: Fermi Lightcurve



- GBM triggered on a weak and soft pulse (T0).
- 6 main peaks in GBM (NaI+BGO) from T0+0.4s to T0+1s
- LAT emission is delayed and starts in coincidence with the brightest NaI peak (T0+0.53s)
- Emission >100MeV begins with the 4th low energy peak (T0+0.63s)
- High energy emission lasts much longer that the low energy (>0.1 GeV detected up to T0+200s)

Prompt emission spectrum:
first clear evidence of extra component

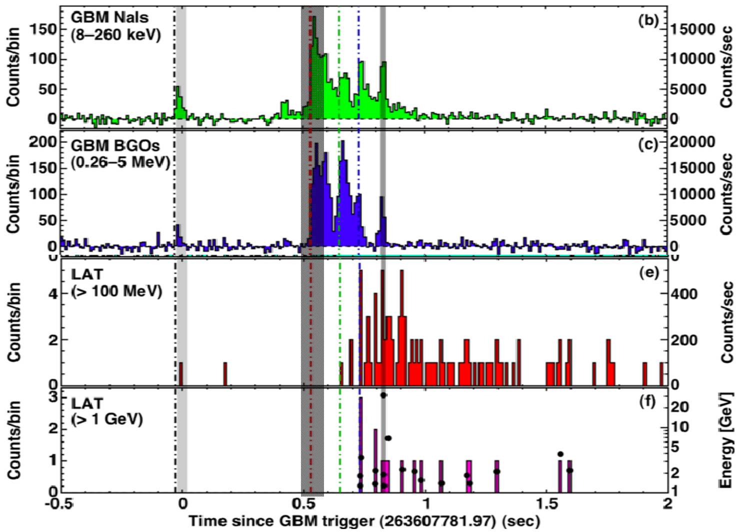


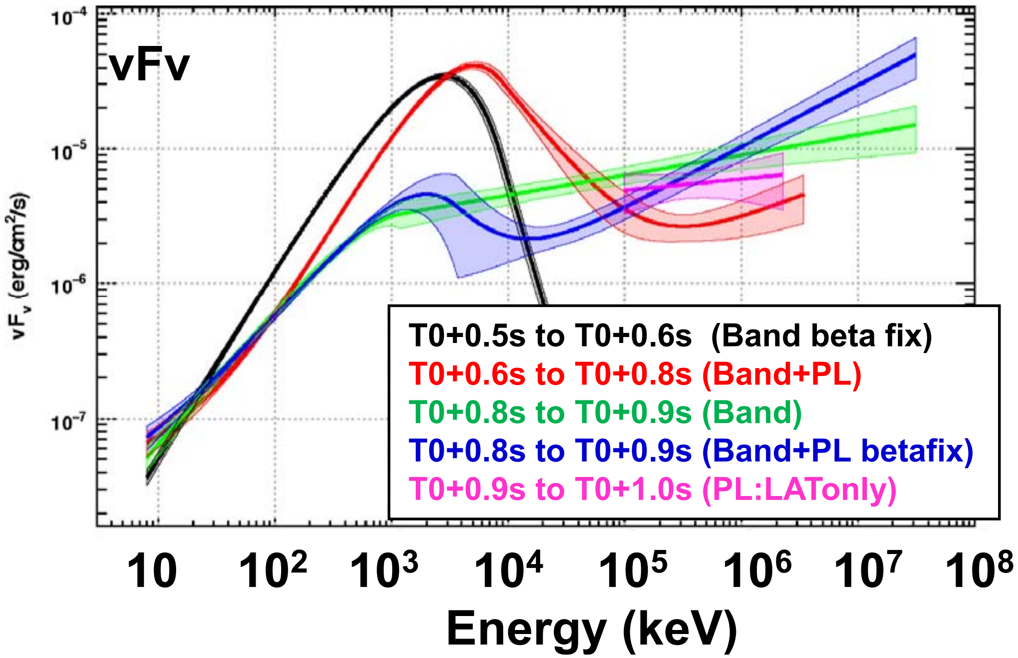
- **Significant deviation (>5σ) from the standard Band function above 10 MeV**
- **Excess adequately fit with an additional powerlaw (PL) ➔extra-component !!**
- **Lower limit on a possible second break energy: ~4 GeV**

Spectral parameters:

E_{peak} = 3.9 +/- 0.3 MeV	Fluence ($_{10keV\text{-}30GeV}$)=(5.02+/-0.26)x10^{-5}ergcm^{-2}
α = -0.58 +/- 0.06	E_{iso}=(1.08+/-0.06)x10^{53} erg
β = -2.83 +/- 0.20	⇒ ~37% of the fluence from the extra-comp.
PL Index = -1.62 +/- 0.03	⇒ EBL affects the total fluence for <1%

Time resolved spectra





(a) T0+0.5s to T0+0.6s :
Band function with steep beta (<-5.0)
No extra component

(b)T0+0.6s to T0+0.8s :
Additional component significant only in this time interval

(c) T0+0.8s to T0+0.9s :
Band only fit : harder beta
→ inconsistent with the previous bin.
Band+PL : fix beta to the value from the previous bin; extra comp. can be fit with a similar PL index.
=> Reasonable to adopt the extra component for this time bin

(d) T0+0.9s to T0+1.0s :
LAT data is fit by PL with a steeper index of ~-1.9
Extrapolation of at low energy inconsistent with GBM upper limits
→ spectral break ?

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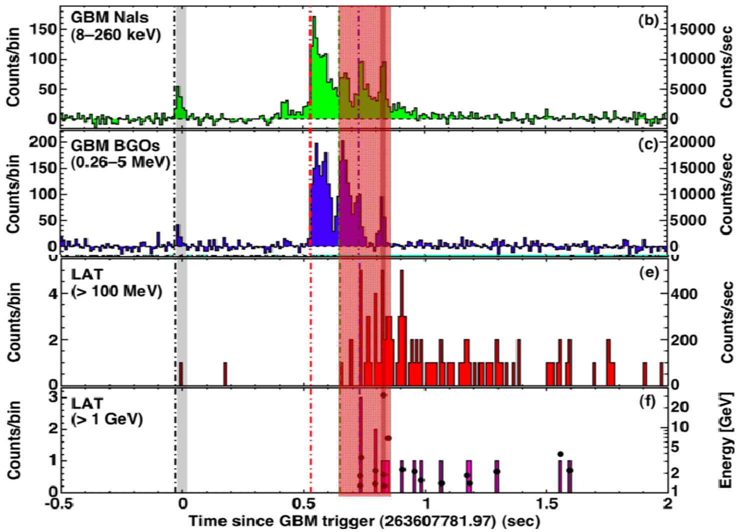

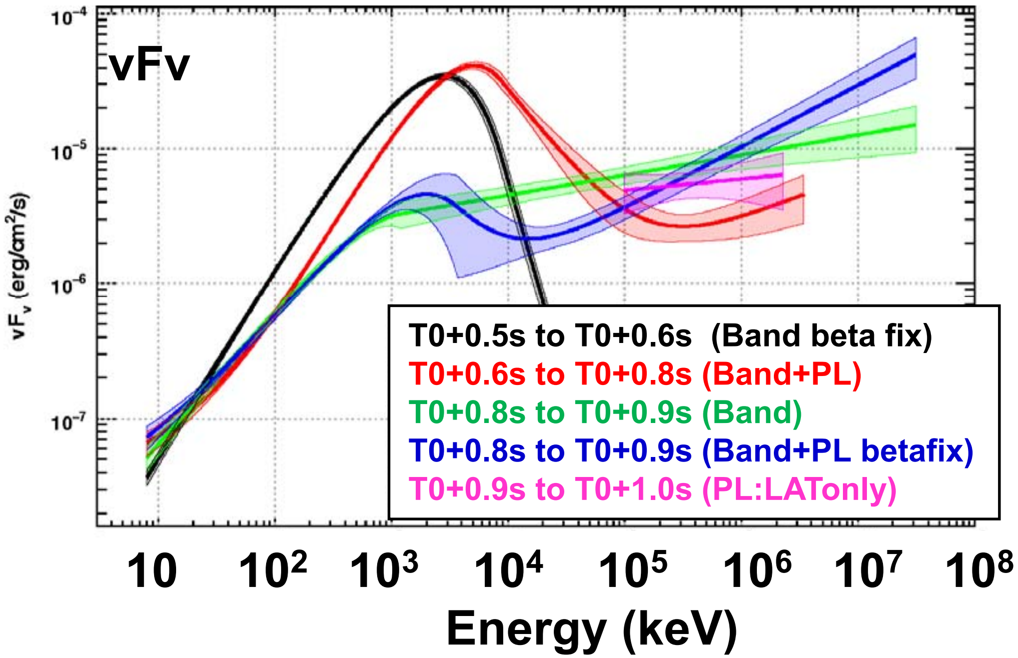

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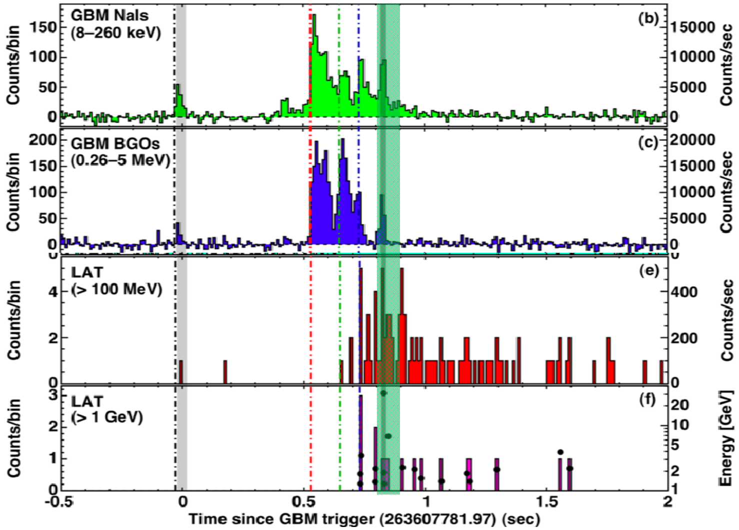

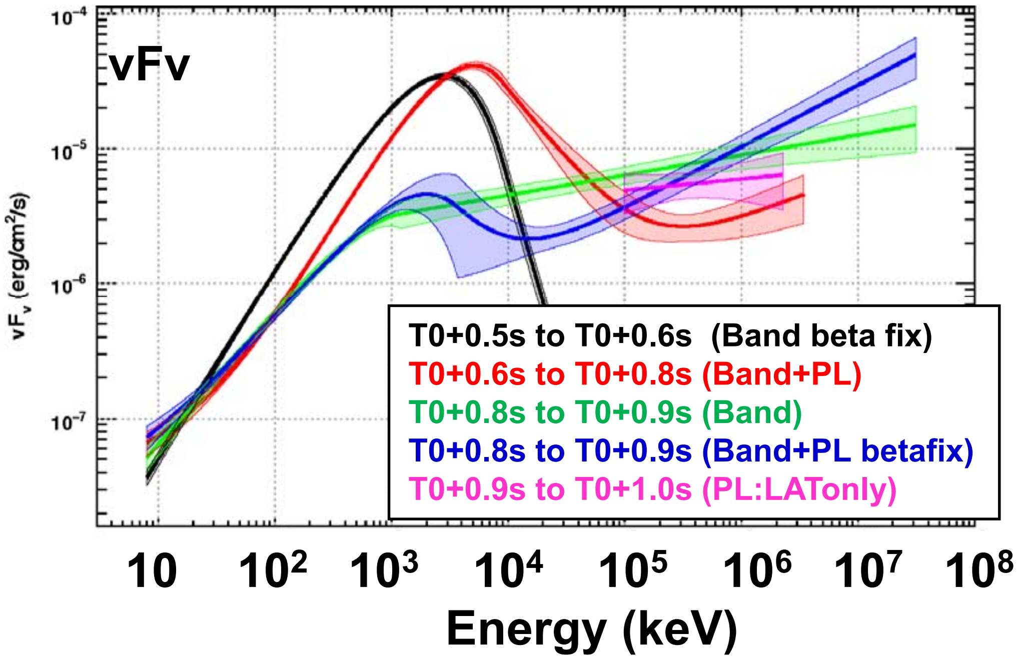

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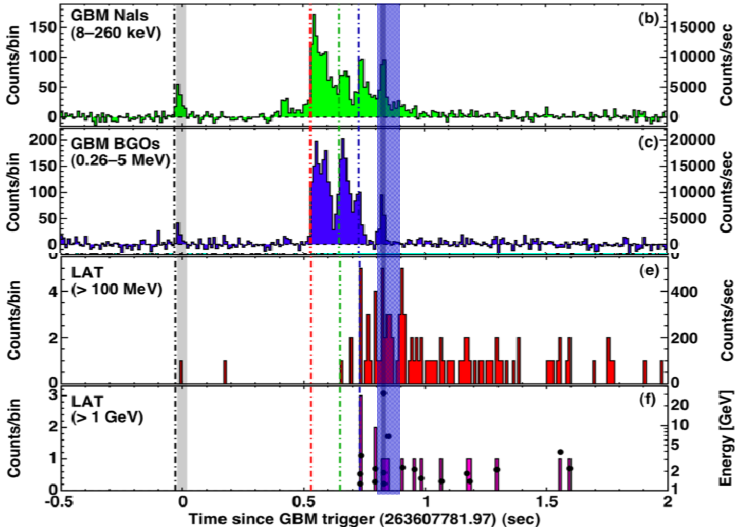

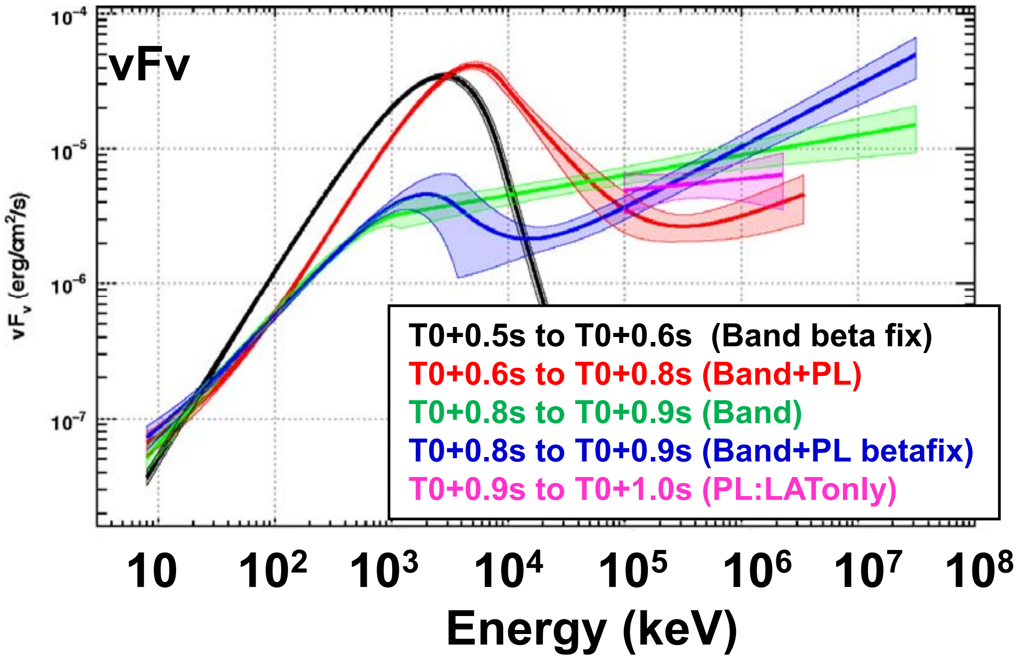

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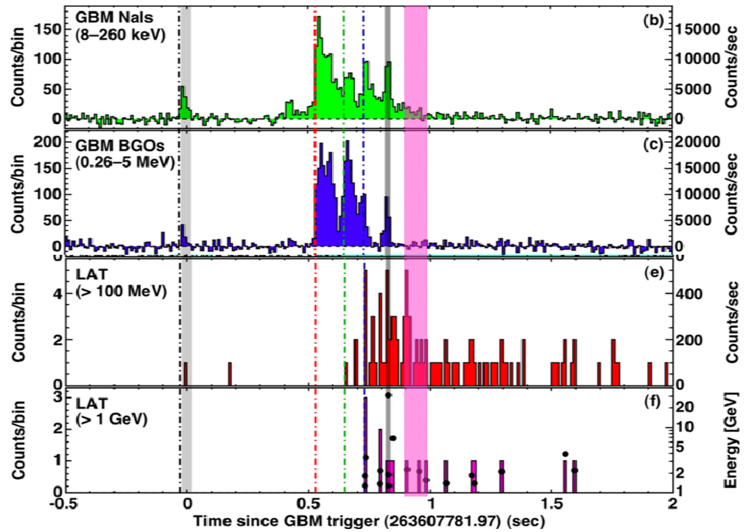

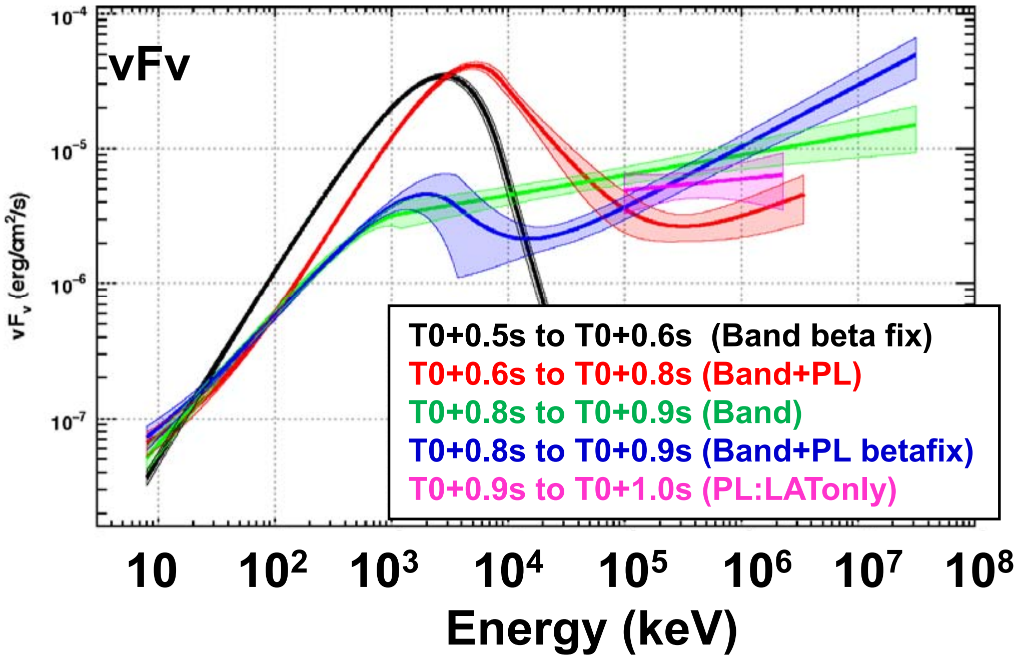

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Origin of extra component

A. Leptonic Model

Low energy component (<10MeV) : synchrotron emission from nonthermal electrons
Extra component (>10MeV) : synchrotron-self Compton

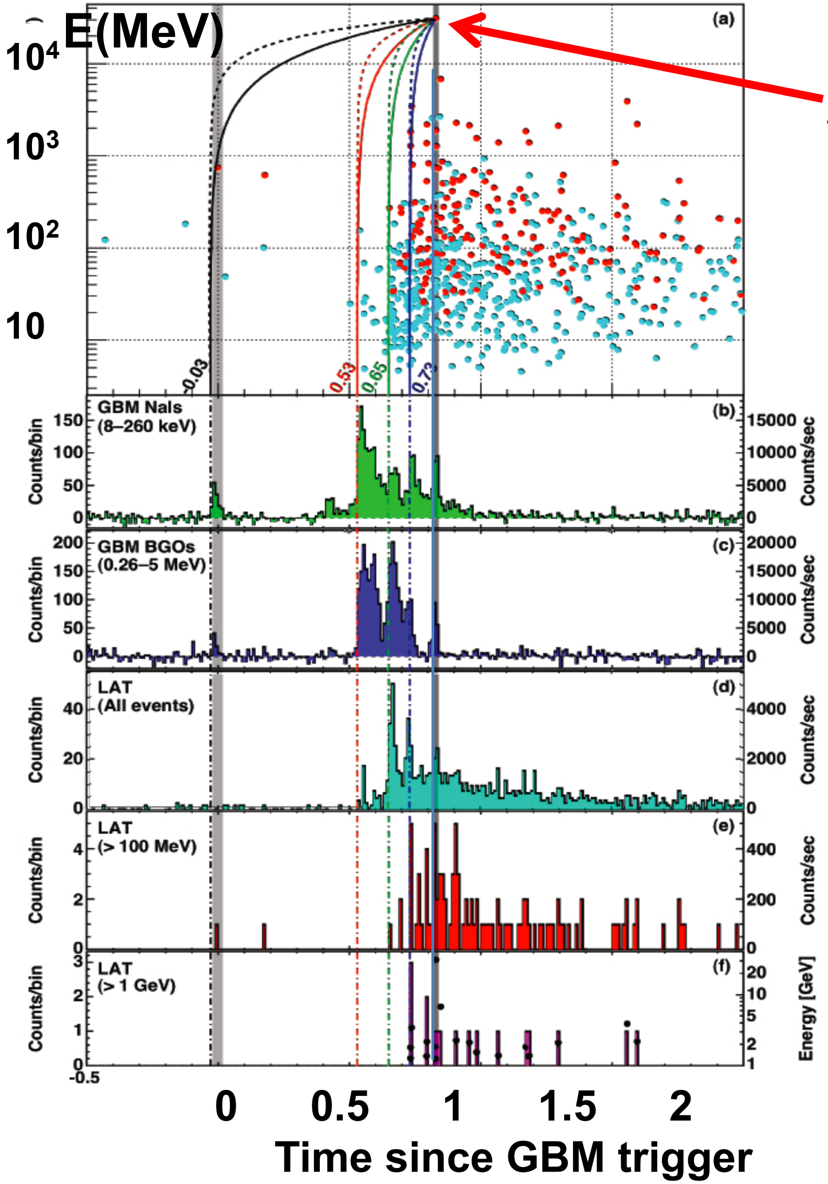
✓**Can not explan the delayed onset (0.1-0.2s) of this extra component**
✓**Rapid change of B, Γ, electron energy distribution is needed.**

B. Hadronic model

Extra component : photo-meson or synchrotron process from ultra-relativistic protons and ions

•**Short GRBs would be candidate of the origin of UHECRs**
•**Could explain the delayed onset of extra component**
✓**Much larger total energy (>100) is required..**

31 GeV photon:
highest energy photon for short GRB



31 GeV is the highest energy ever observed from short GRB

Such high energy photon can be used to constrain the bulk Lorentz factor of relativistic jet and constrain the Lorentz Invariance Violation (LIV)

Limit on bulk Lorentz factor

Due to large luminosity and small emitting region, optical depth for the γ-γ -> e+e- pair production is too large to observe the non-thermal emission from GRB → compactness problem.

Relativistic motion (Γ>>1) could avoid this compactness problem

$R \lesssim \Gamma^2 c\Delta t$

photon number for γ-γ absorption : $\Gamma^{2(1+\beta)}$

$$\tau_{\gamma\gamma}(E) = \frac{3}{4}\frac{\sigma_T d_L^2}{t_v \Gamma}\frac{m_e^4 c^6}{E^2(1+z)^3}\int_{\frac{m_e^2 c^4 \Gamma}{E(1+z)}}^{\infty}\frac{d\epsilon'}{\epsilon'^2}\, n\left(\frac{\epsilon'\Gamma}{1+z}\right)\varphi\left[\frac{\epsilon' E(1+z)}{\Gamma}\right]$$

Γ_{min} can be derived using observed highest energy photon

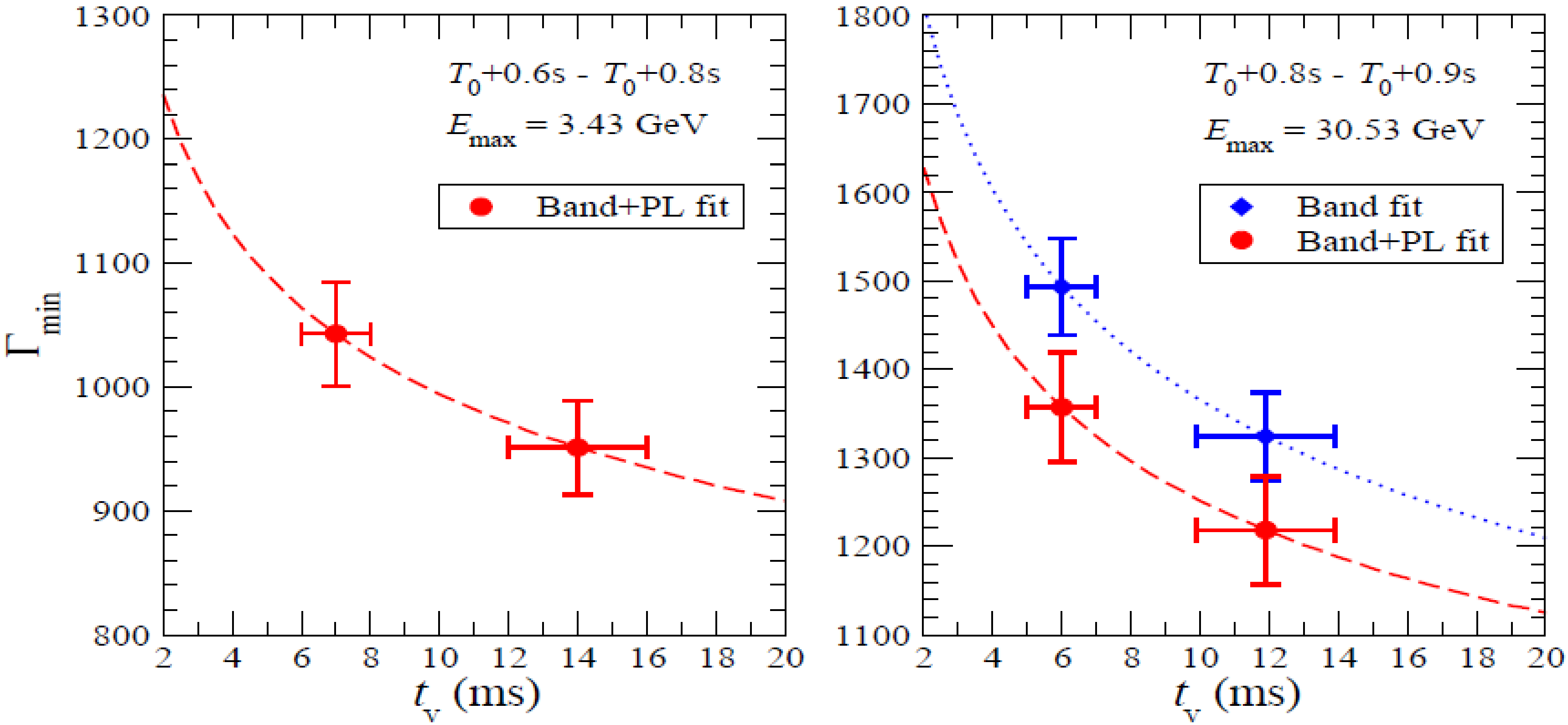
$$\begin{aligned}\Gamma_{\min}(E_{\max}) &= \left[\frac{4 d_L^2 A}{c^2 t_v}\frac{m_e^2 c^4}{(1+z)^2 E_{\max}} g\sigma_T\right]^{\frac{1}{2-2\beta}}\left[\frac{(\alpha-\beta)E_{\rm pk}}{(2+\alpha)100\ \mathrm{keV}}\right]^{\frac{\alpha-\beta}{2-2\beta}} \\ &\times \exp\left(\frac{\beta-\alpha}{2-2\beta}\right)\left[\frac{2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

$$\text{for}\quad \Gamma_{\min} > \sqrt{\frac{(1+z)^2 E_{\max} E_{\rm pk}(\alpha-\beta)}{2 m_e^2 c^4 (2+\alpha)}}\ ,$$

GRB090510:
the most powerful outflow for any GRBs

Γ_{min} (T+0.6s – T+0.8s, E_{max}=3.43 GeV, tv=14ms) : 950+/-40
Γ_{min} (T+0.8s – T+0.9s, E_{max}=31 GeV, tv=11.9ms) : 1220+/-60

First constraint on the bulk Lorentz factor for redshift known short GRB
Highest Γ_{min} for any GRB, and by far the highest for a short GRB
=> short GRBs might have similar power of outflow as long GRB



Limits on Lorentz Invariance Violation (LIV)

Some quantum gravity models allow violation of Lorentz invariance: $(v_{ph}) \neq c$

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

A high-energy photon E_h would arrive after (or possibly before in some models) a low-energy photon E_l emitted together

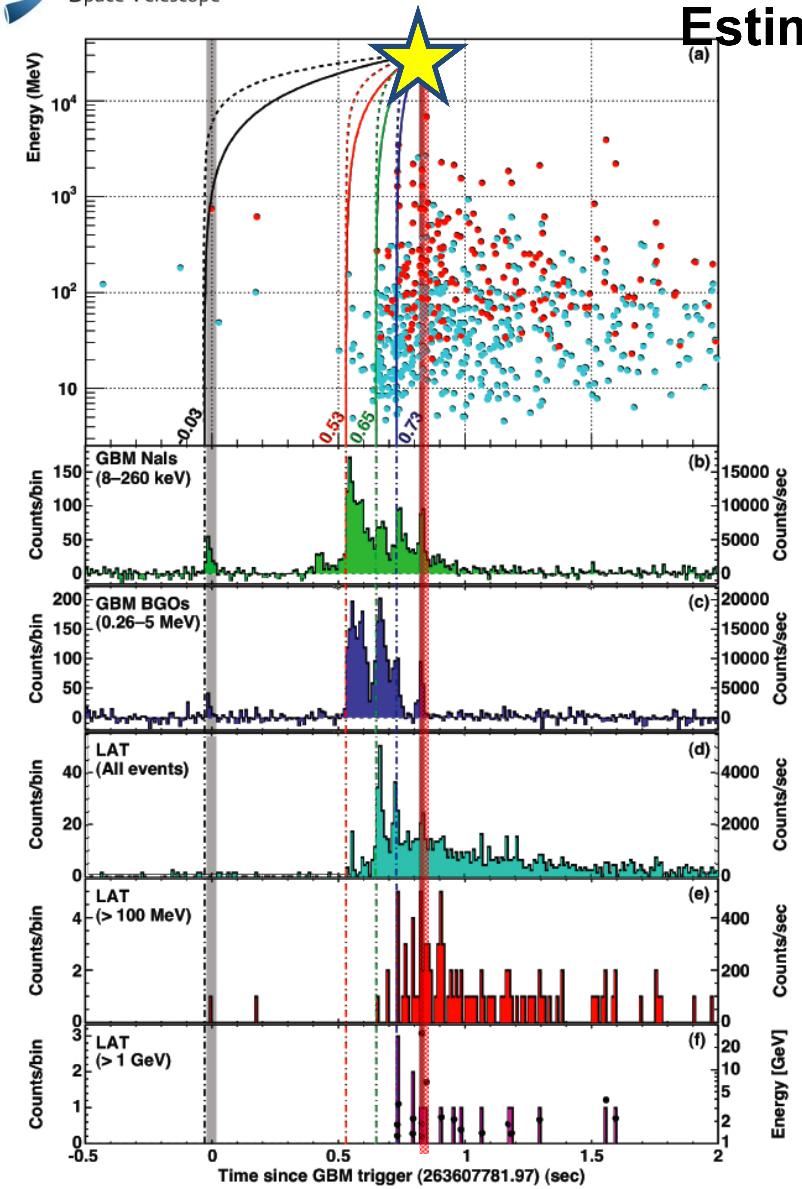
GRB 080916C : the tightest upper limit so far (Abdo et al. 09),

$$\mathrm{M}_{\rm QG,1} > (1.50 \pm 0.20) \times 10^{18}\ \mathrm{GeV/c^2}$$

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

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

LIV : first time $M_{QG} > M_{plank}$



Estimate lower limit of $M_{QG,1}$ for various ⊿t, ⊿E

◆ **Most conservative case :**

31GeV photon starts from any <1MeV emission

⊿t < 859 ms,

$M_{QG,1}/M_{plank} > 1.19$

◆ **Least conservative case:**

31 GeV photon associates with < 1 MeV spike

⊿t < 10ms,

$M_{QG,1}/M_{plank} > 102$

Our new limit : $M_{QG,1}/M_{plank}$> several is much stronger than the previous result ($M_{QG,1}/M_{plank} > 0.1$: GRB080916C ;Abdo+09)

Greatly constrain the quantum gravity model (n=1)

GRB 090510 extended emission

- I would like to add the result of extended emission if possible here

Summary for GRB 090510

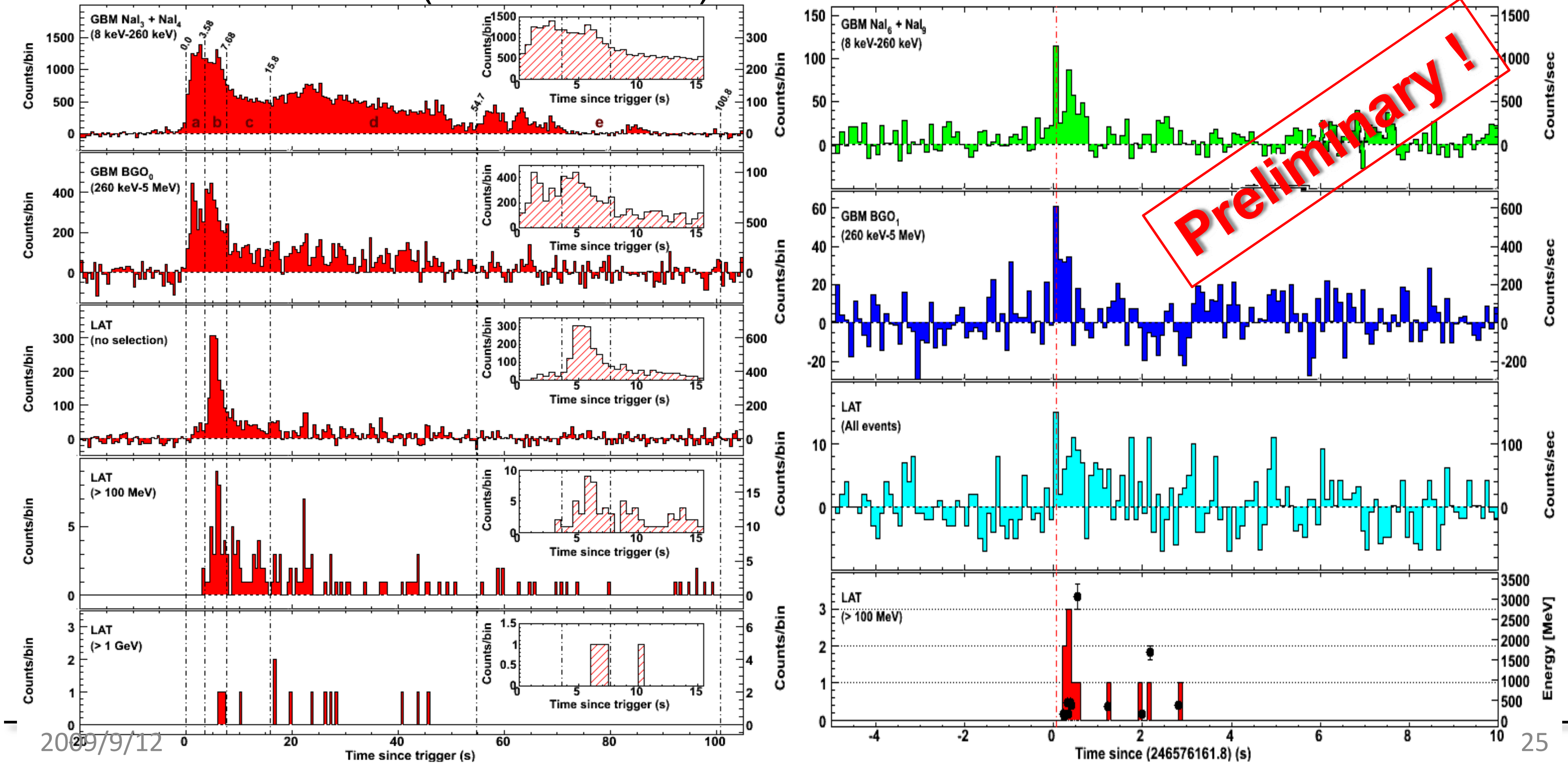
- **First GeV short GRB with known redshift (z=0.9)**
- **First clear evidence of extra component (>5σ)**
- **Highest energy photon for short GRB : 31 GeV**
- **The most powerful outflow for any GRB : Γ>1200**
- **First time, $M_{QG}>M_{plank}$ is required**
- **Long-lived emission (?)**

Common features of LAT GRBs

- **High energy LAT photons are delayed from GBM emission for many LAT GRBs**
  => different region from 1st GBM pulse ?
- **LAT high energy photons extend longer than low energy emission**

GRB 080916C (Abdo et al. 09)

GRB 081024B : short GRB



GRB090902B : the 3rd monster event

GRB090902B Fermi LAT detection

- ✓11:05:15 UT on 2 Sep 2009, Fermi-LAT detected gamma-rays from long bright GBM burst 090902B
- ✓More than 200 photons above 100 MeV and more 30 photons above 1 GeV
- ✓The highest energy photon is 33.4 GeV 82 sec after the trigger

de Palma, Bregeon & Tajima GCN Circ. 9867

GRB090902B Fermi LAT and GBM refined analysis (1st LAT/GBM joint analysis circular)

- ✓GRB 090902B is detected in the Fermi-LAT at least until 300 s after the Fermi-GBM trigger.
- ✓Spectral analyis shows a deviation from the Band function both below 50 keV and above 100 MeV
- ✓This deviation is well fitted by single power law

de Palma et al. GCN Circ. 9872

Gemini-N redshift : 1.822 (Cucchiara et al. GCN Circ. 9873)

Further analysis is ongoing

Summary

◆**Fermi detected >250 GRBs including 10 LAT GRBs**

=> 250 GRBs/year for GBM and ~1GRB/month for LAT (?)

◆**GRB 090510 : bright short LAT GRBs with many interesting results**

- The first GeV short GRBs with known redshift
- First clear (>5σ) evidence of extra component is discovered
- 31 GeV photon is detected: the highest energy photon for short GRB
- Highest bulk Lorentz factor for any GRB (Γ_{min}>1200)
  - ➔ outflow of short GRB might be as powerful as long GRB
- M_{QG}>M_{plank} is firstly required: greatly constrain many QG models
- Long lived emission (?)

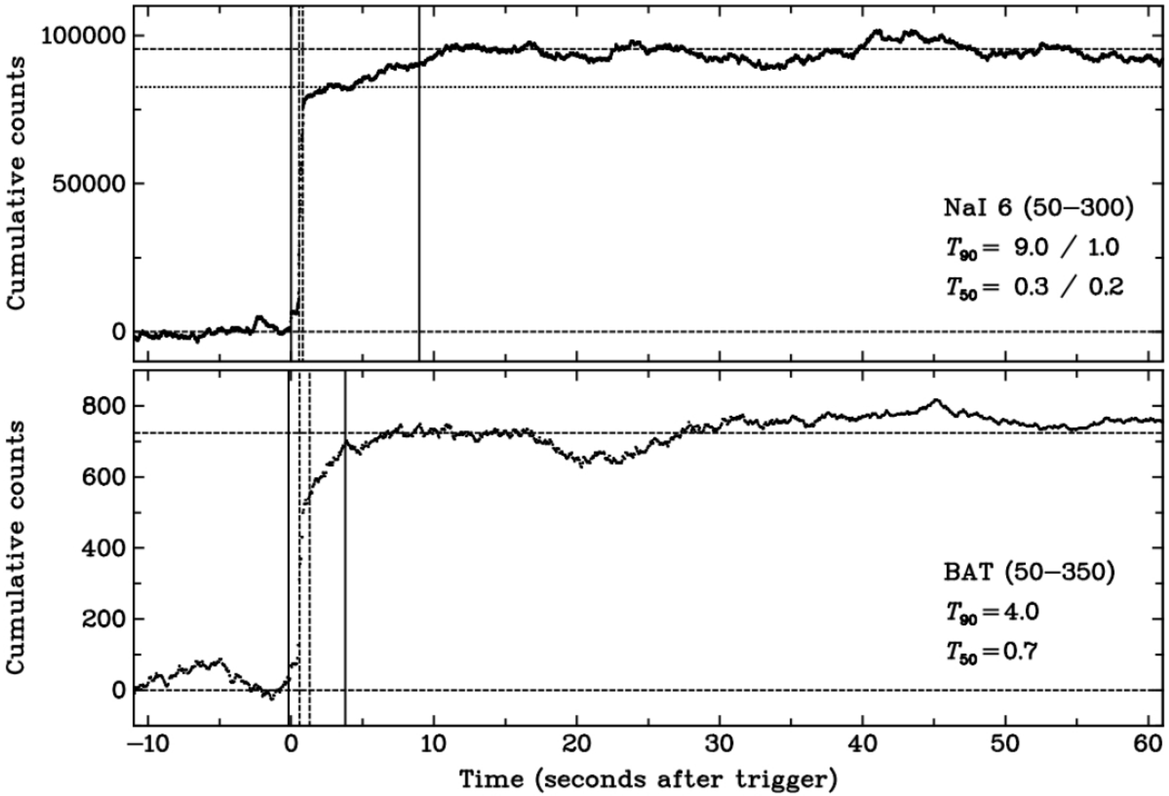
◆**Common feature of LAT GRBs**

- delayed onset of high energy photons for many LAT GRBs
- high energy emission significantly extends after the low energy emission is disappeared

LAT photon data is now already public : http://fermi.gsfc.nasa.gov/ssc/

Backup Slides

- Burst duration (T90)

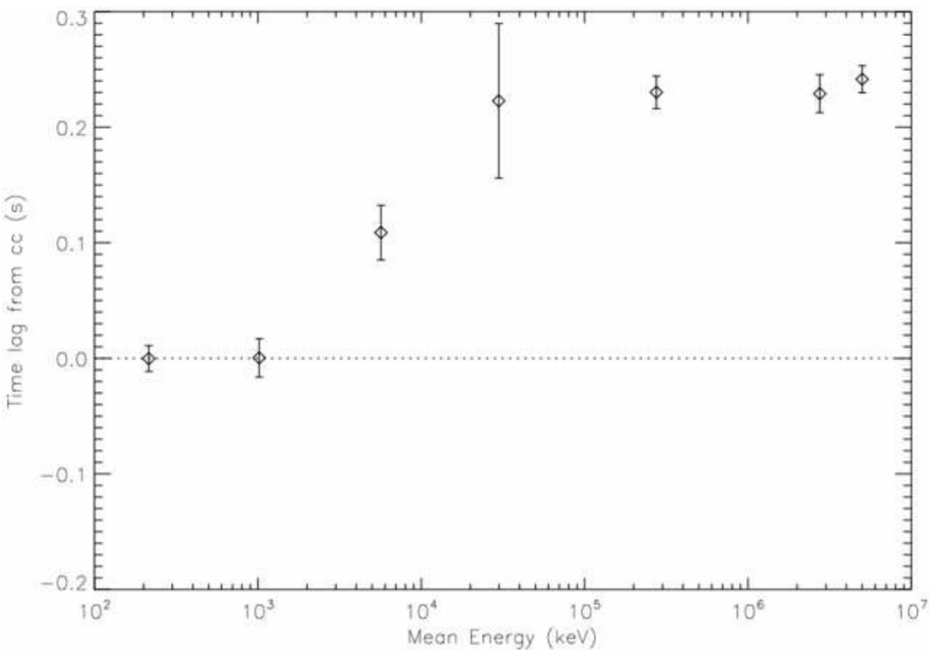


T90 (NaI3,6,7) = 2.1s
T50 (NaI3,6,7) = 0.2s

T90 (NaI6) = 9s
T50 (NaI6) = 0.3s

Short burst with a tail

Lag analysis



- Methods : Cross Correlation Function (CCF) and an baysian block based method.
- Between GBM/NaI and GBM/BGO
- Between GBM and LAT
- Time interval : T0+0.5s to T0+1.0s (with 10, 25, 100 ms time resolution for CCF)
- Energy intervals :
  - NaI : 8 log energy bins from 8 to 980 keV
  - BGO: 8 log energy bins from 0.11 to 45.5 MeV
  - LAT : 0.1-1 GeV, 1-10 GeV and >10 GeV
- Base band-width : NaI 8-40 keV
- Results:
  - Similar results with both methods
  - <1MeV: spectral lags negligible => short GRBs.
  - Progressive increase up to ~250ms then remain constant after 40 MeV.