フェルミ衛星で見たガンマ線バーストからの高エネルギー放射

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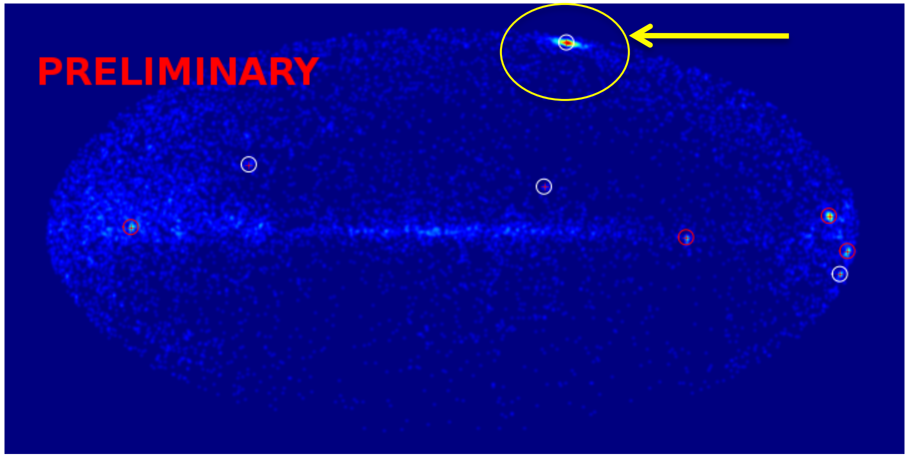
On behalf of the Fermi LAT/GBM collaboration

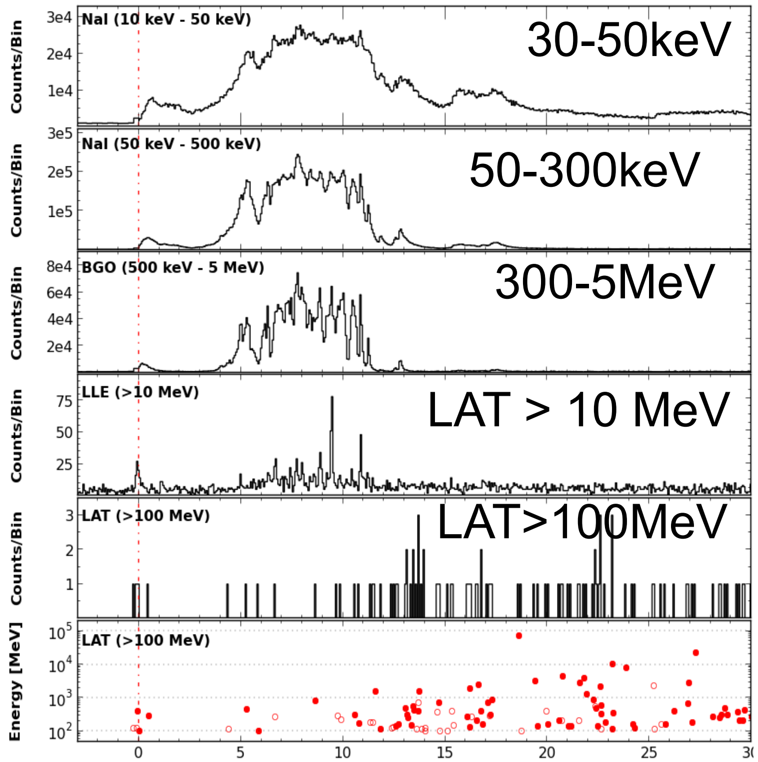
Long-awaited “Monster” event : GRB 130427A

- Highest gamma-ray fluence (>10^{-3} erg cm^{-2})
- Highest observed gamma-ray energy (95 GeV)
- Longest lived gamma-ray emission (19 hours)
- Within the closest 5% of GRBs (z = 0.34)



6 hours LAT all-sky map

PRELIMINARY



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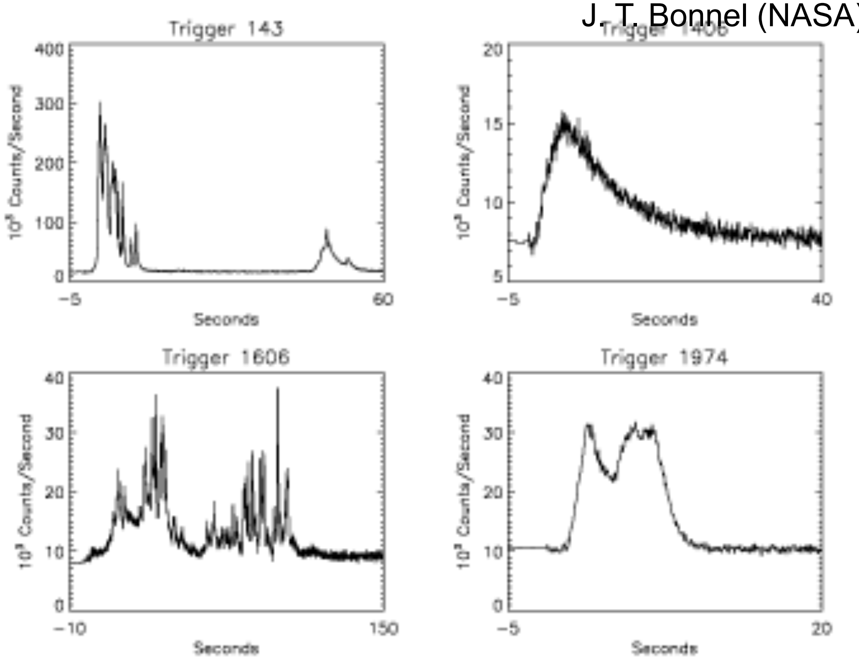
  - delayed onset of high energy emission
  - bulk Lorentz factor of GRB jet
  - Limit on EBL model & Lorentz invariance violation (LIV)
- **Prospect for CTA**
- **Summary**

Gamma-ray Bursts: prompt emission

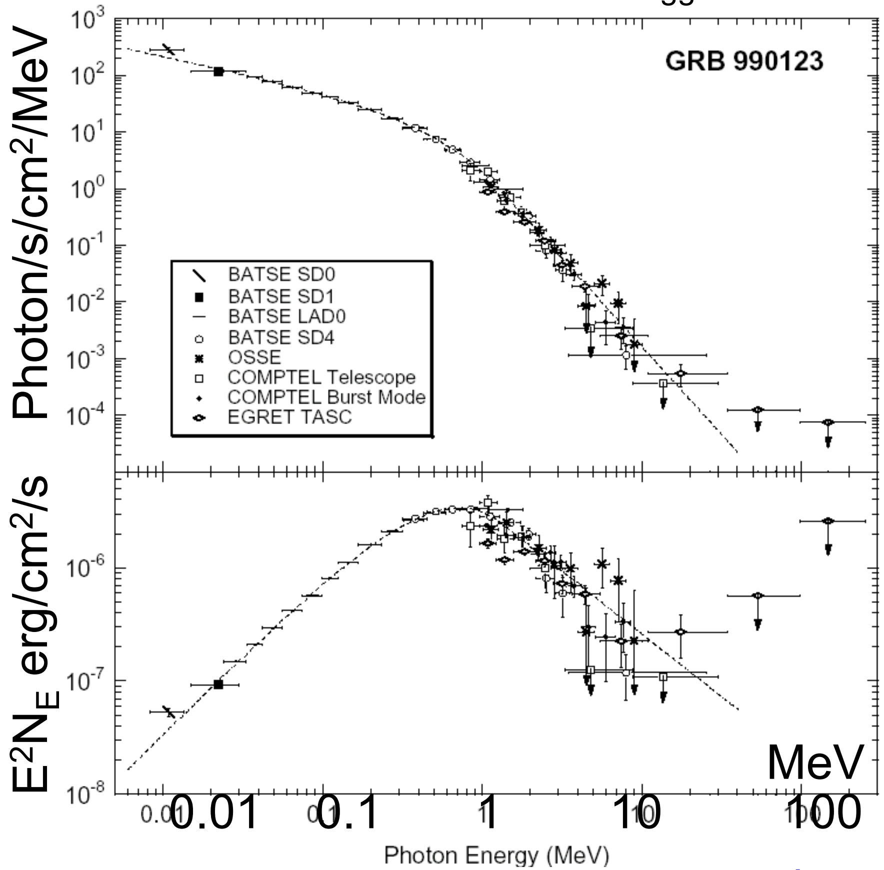
Intense hard X-ray to gamma-ray emission discovered at the 60's

- Event rate : 1-2 per day
- Wide diversity in light curve (0.1-1000s duration)
- Cosmological distance (z~0.1-9)
- Bimodal duration distribution
  (short/long GRB)
- Non-thermal spectrum

J. T. Bonnel (NASA)

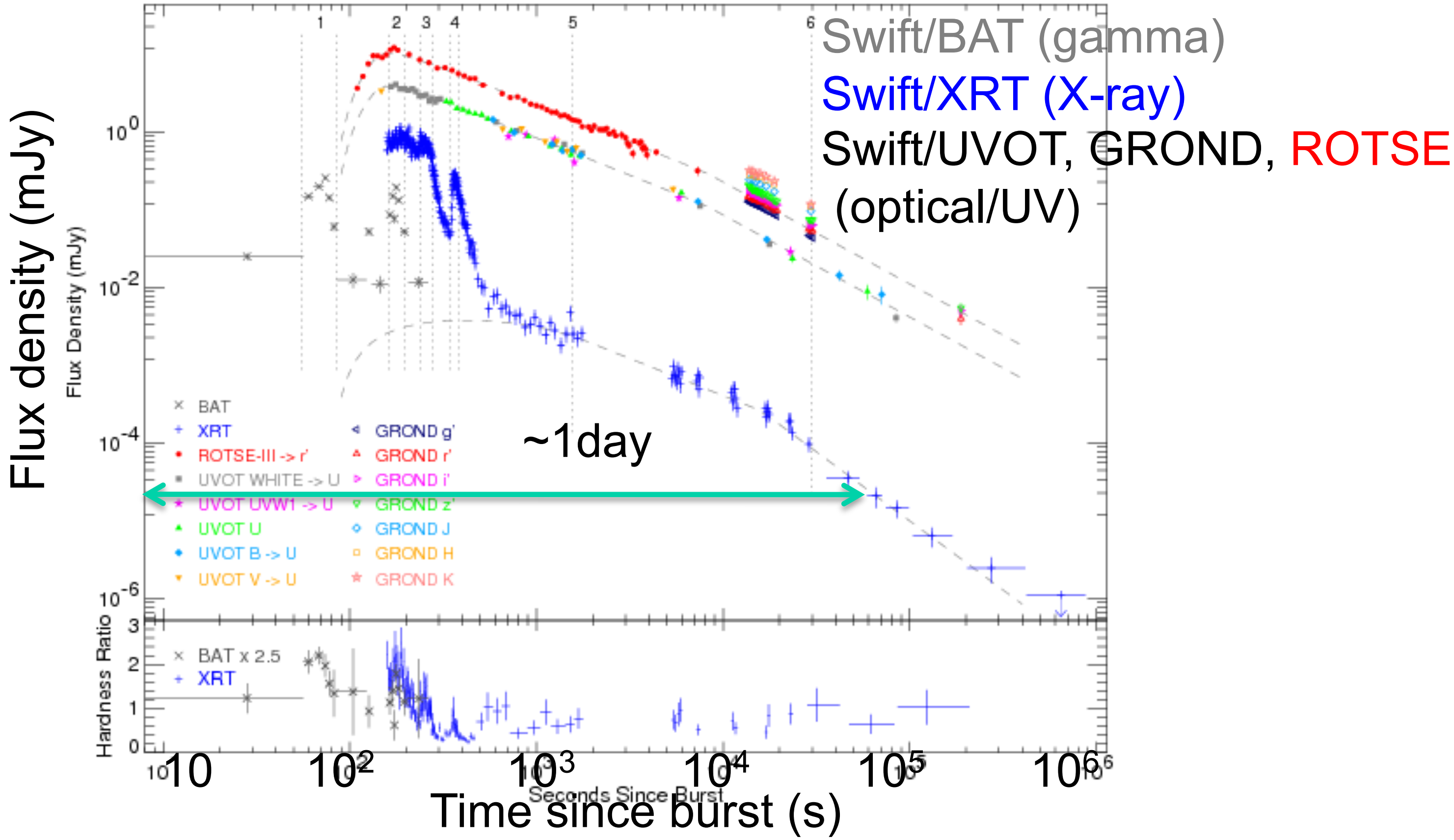


Briggs et al. 1999

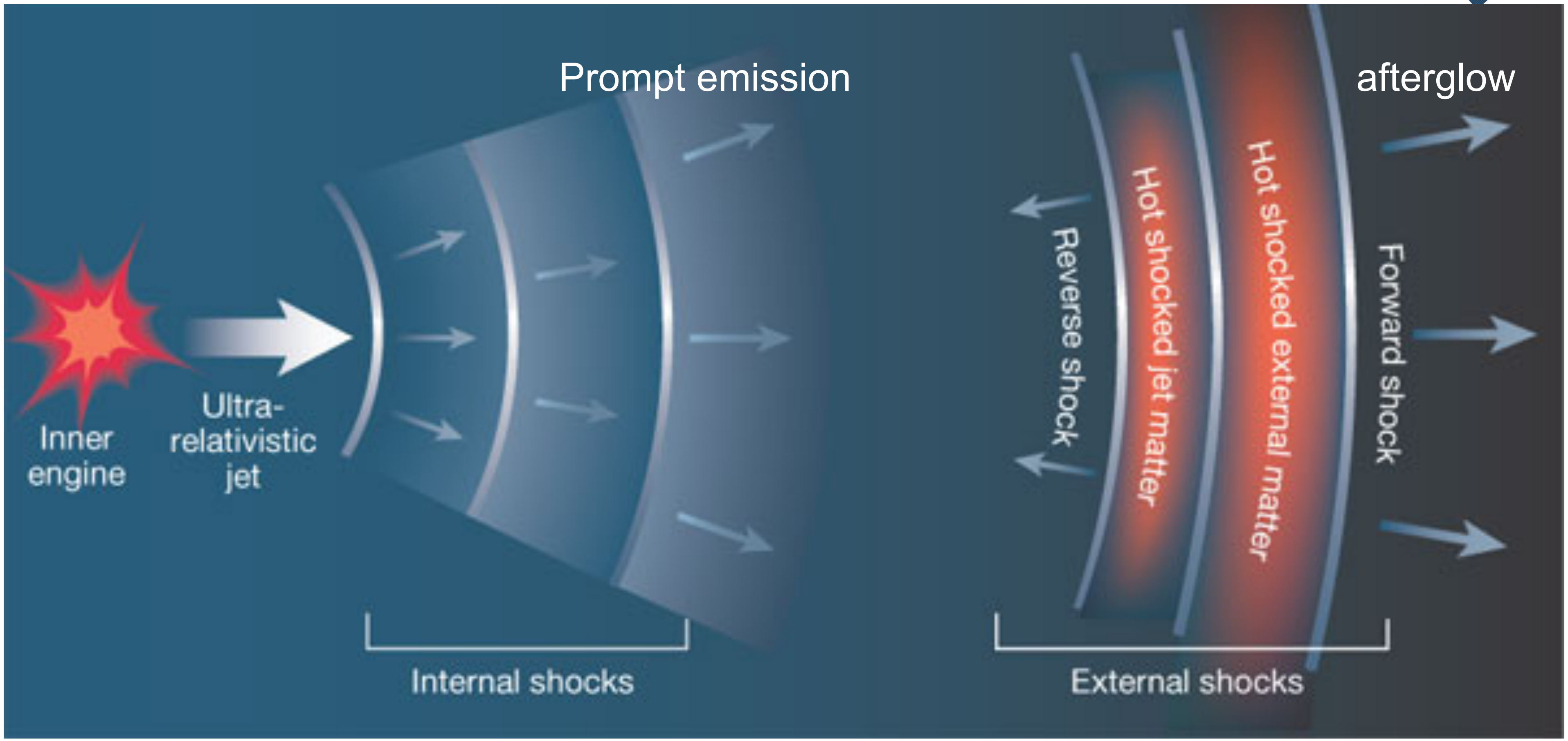


Gamma-ray bursts : afterglow

- After the spiky prompt emission, there is long-lived (~day) afterglow from radio to X-rays
- Late phase afterglow shows smooth light curve



Standard model



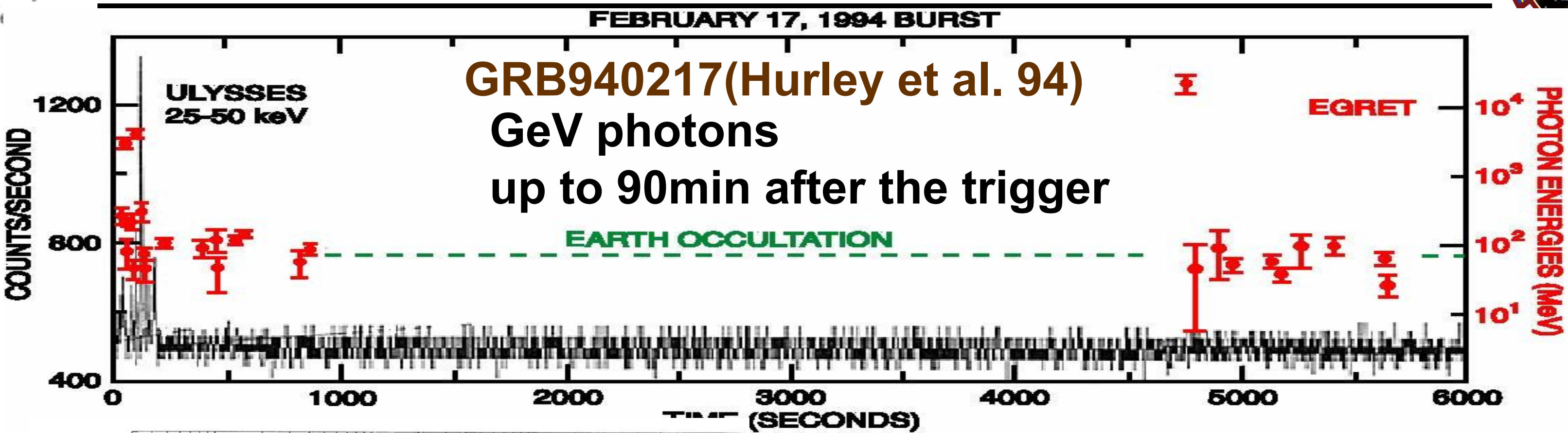
Piran 2003

- **Still many unknown, unclear…**

  emission mechanism of gamma-ray, jet formation, .. Etc

  key observation: high-energy gamma-ray emission

High energy emission from GRB : Pre Fermi Era

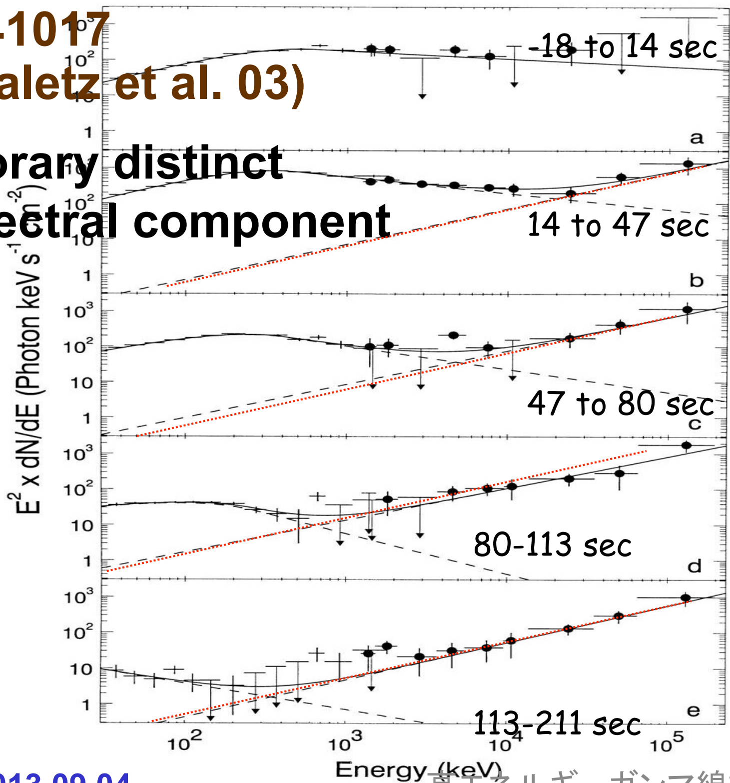


GRB940217(Hurley et al. 94)

GeV photons
up to 90min after the trigger

GRB941017 (Gonzaletz et al. 03)

Temporary distinct
HE spectral component



EGRET detected > 100 MeV photons from a few GRBs
Different behavior from <100 MeV photons

- ✓Long-lived emission
- ✓Extra spectral component
  - ➔ constrain on emission mechanism
- ✓Highest energy photon
  - ➔ bulk Lorentz factor of jet
- ✓Cosmology, fundamental physics
  - Extra galactic background light
  - Lorentz invariance violation

Need large FoV, high sensitivity

Fermi Gamma-ray Space Telescope

LAT

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

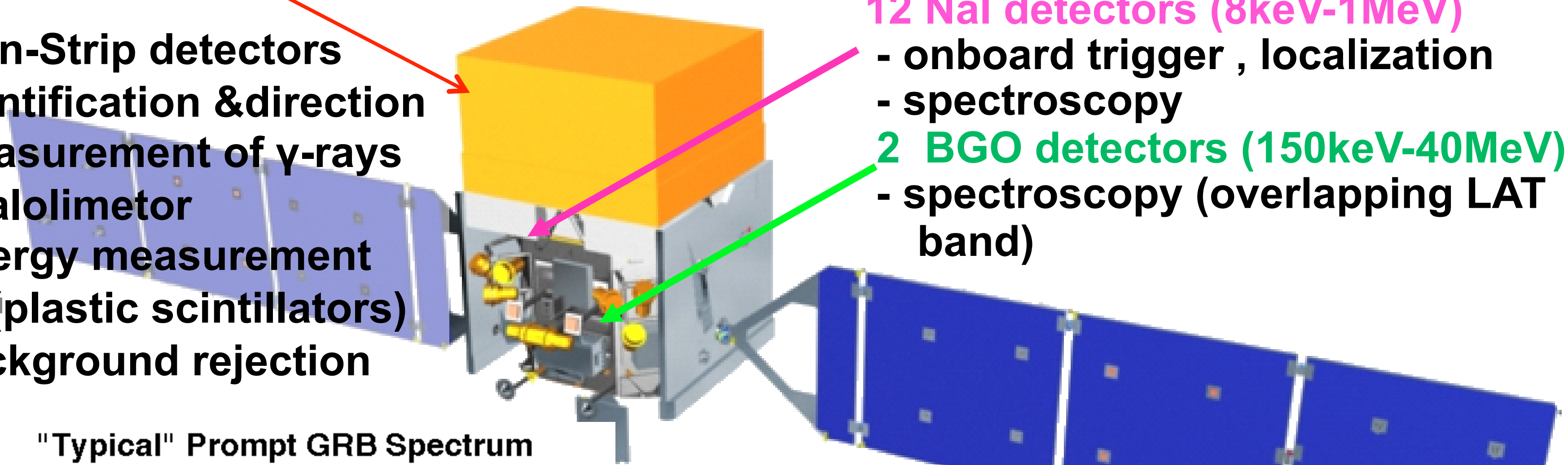
CsI calolimetor
- Energy measurement

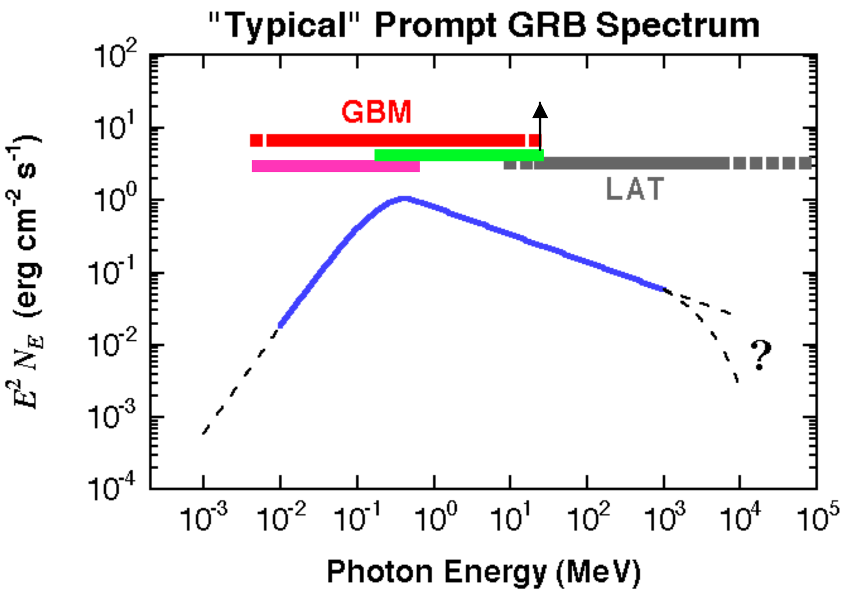
ACD (plastic scintillators)
- background rejection

Gamma-ray Burst Monitor (GBM)

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

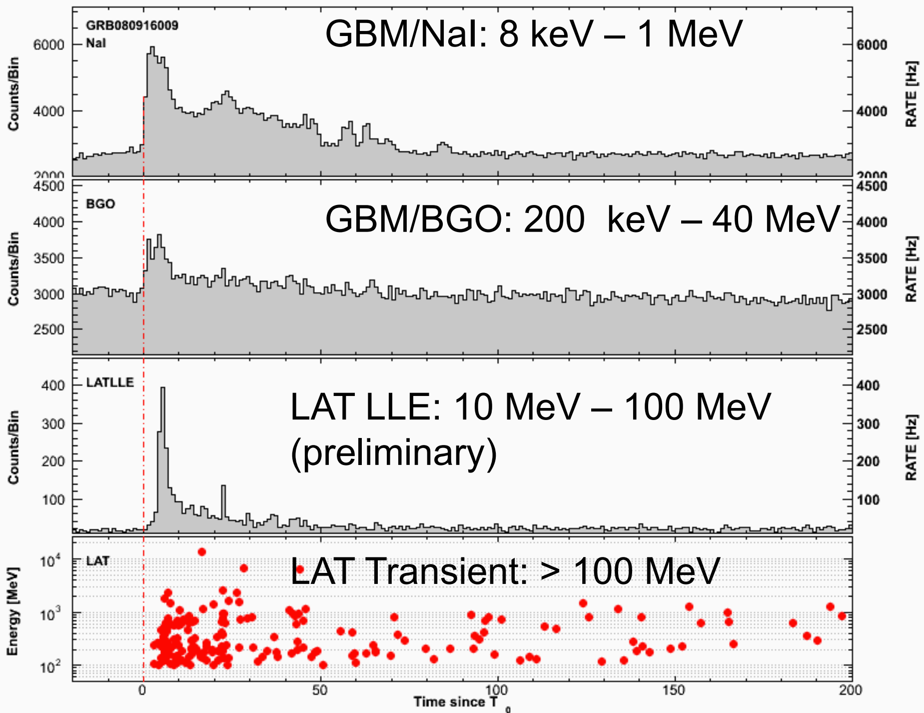
2 BGO detectors (150keV-40MeV)
- spectroscopy (overlapping LAT band)

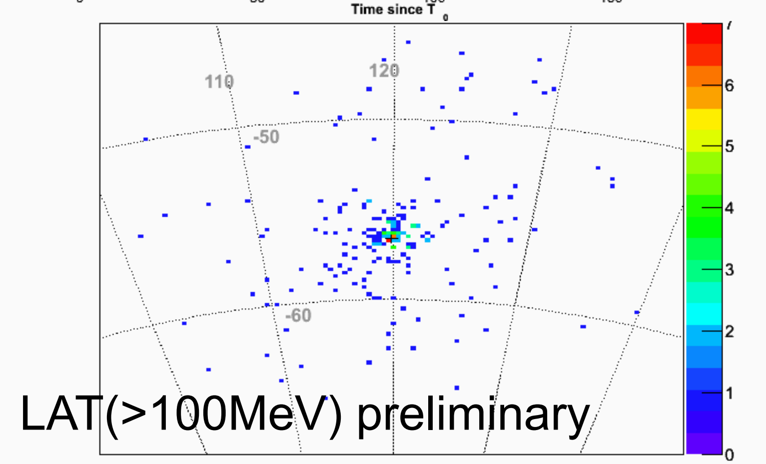




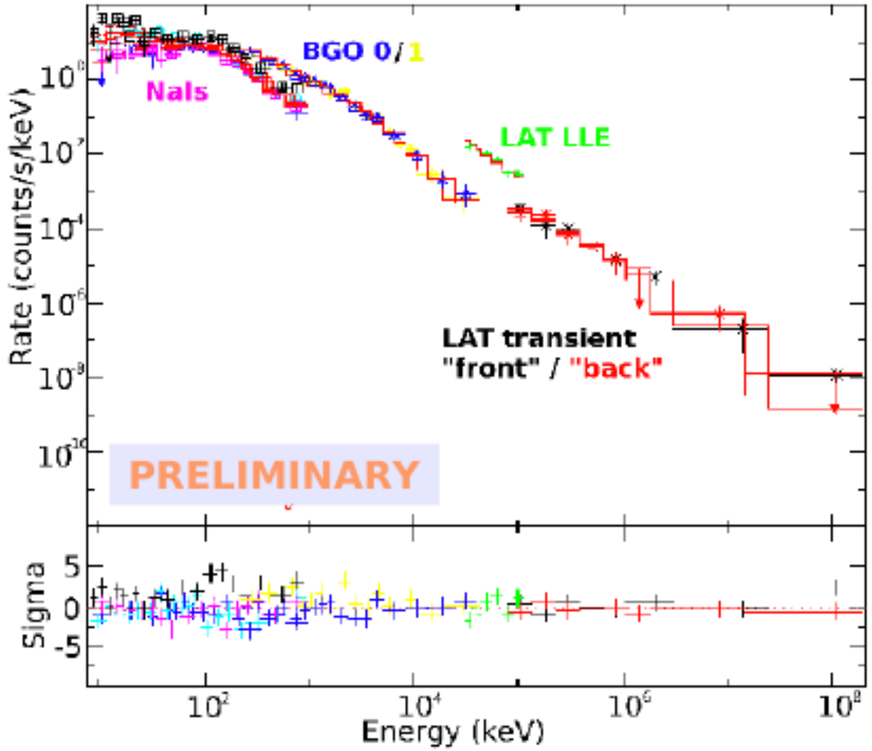
- Efficient observing mode
- Wide FoV
- Low deadtime
- Large effective area
- Good angular resolution
- Energy coverage

GRB observation by Fermi

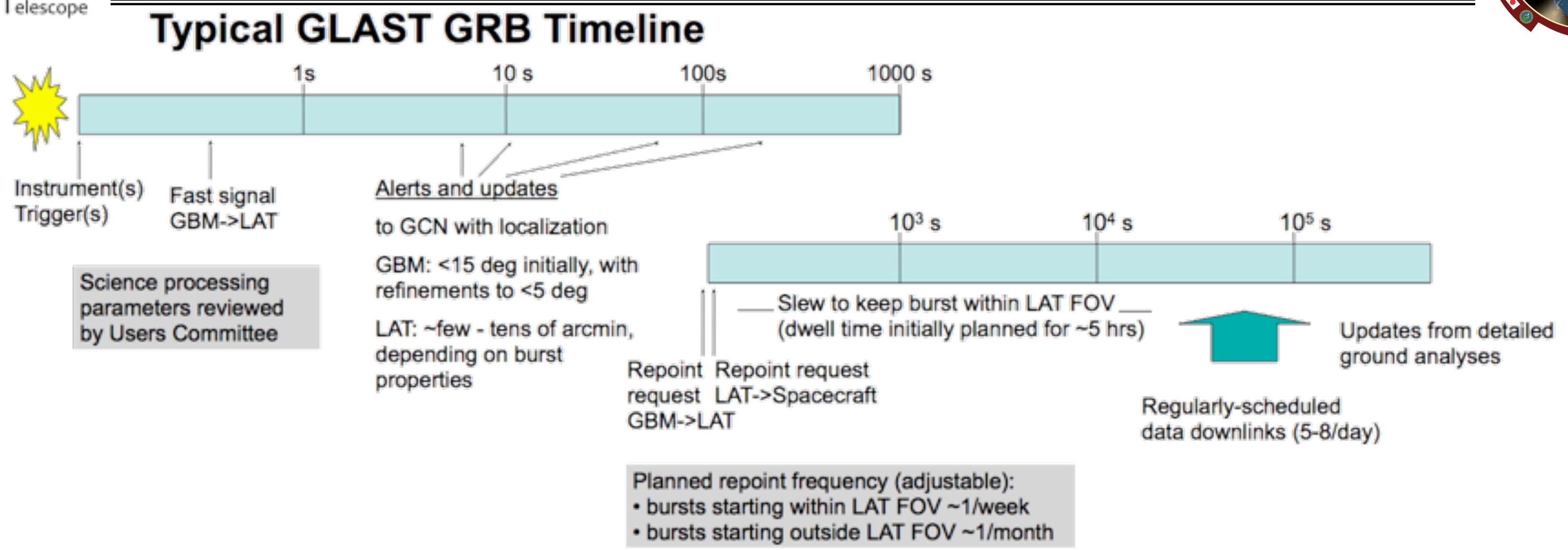




- •> 7 decades of energy range
- •Large FoV(GBM:~4π,
  LAT: ~65deg(90deg for LLE))
- • > 10 times sensitivity of EGRET



Onboard alert and ground analysis



- GBM/LAT on-board processing (10—15 s):

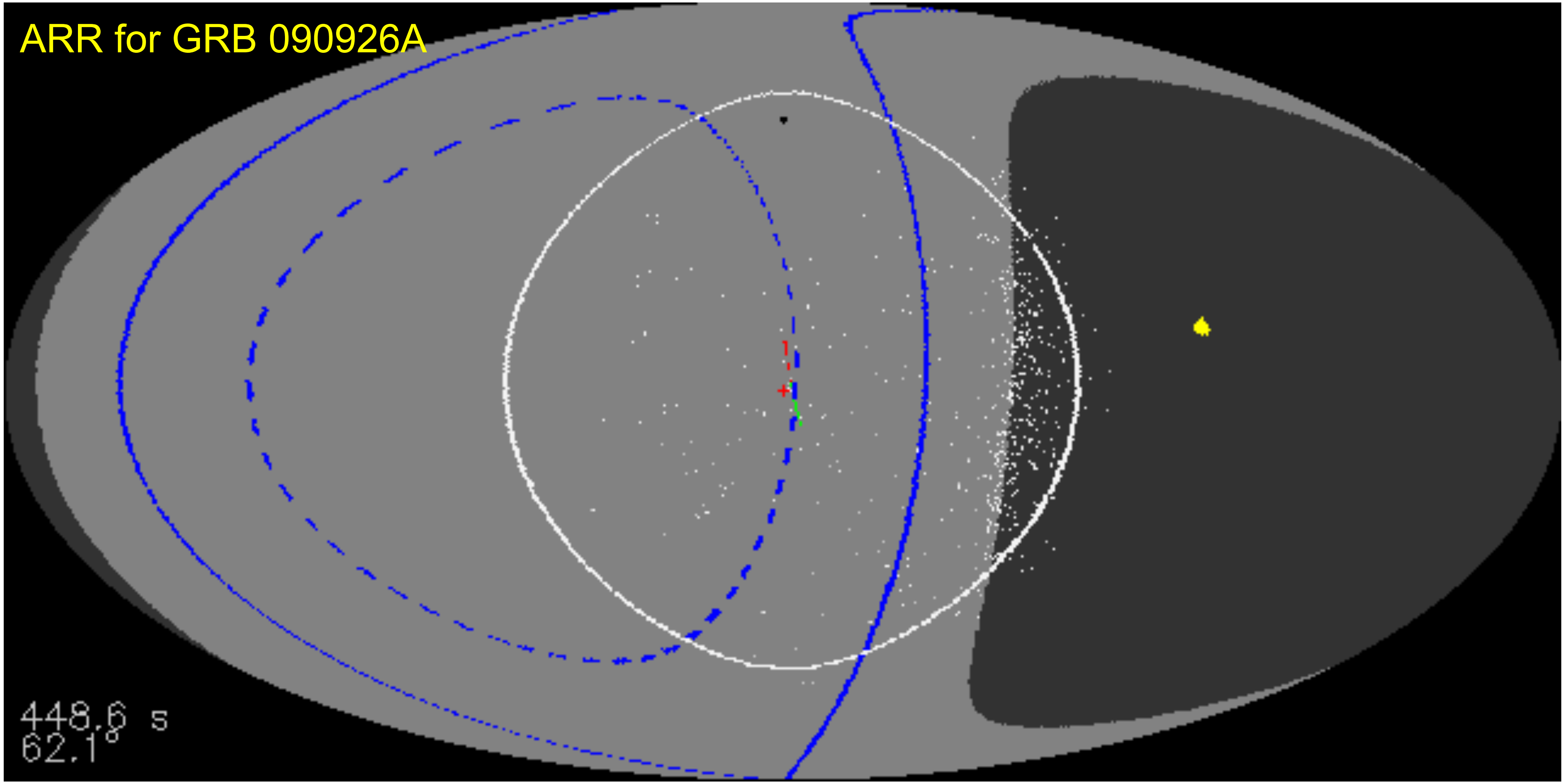
  GCN alert within 10—15 s from the trigger time through TDRSS (alert, location).
  Now 2 s~ 150s windows are also used for on-board search
  We have only one trigger for GRB 090510

- LAT ground processing (a few hours after data downlink)

  Final location, spectrum (1st circular).
  Final location, high-energy flux and spectrum, afterglow search results (2nd circular).
  Data downlink may take > a half of day once ARR is triggered

Autonomous Repoint Request (ARR)

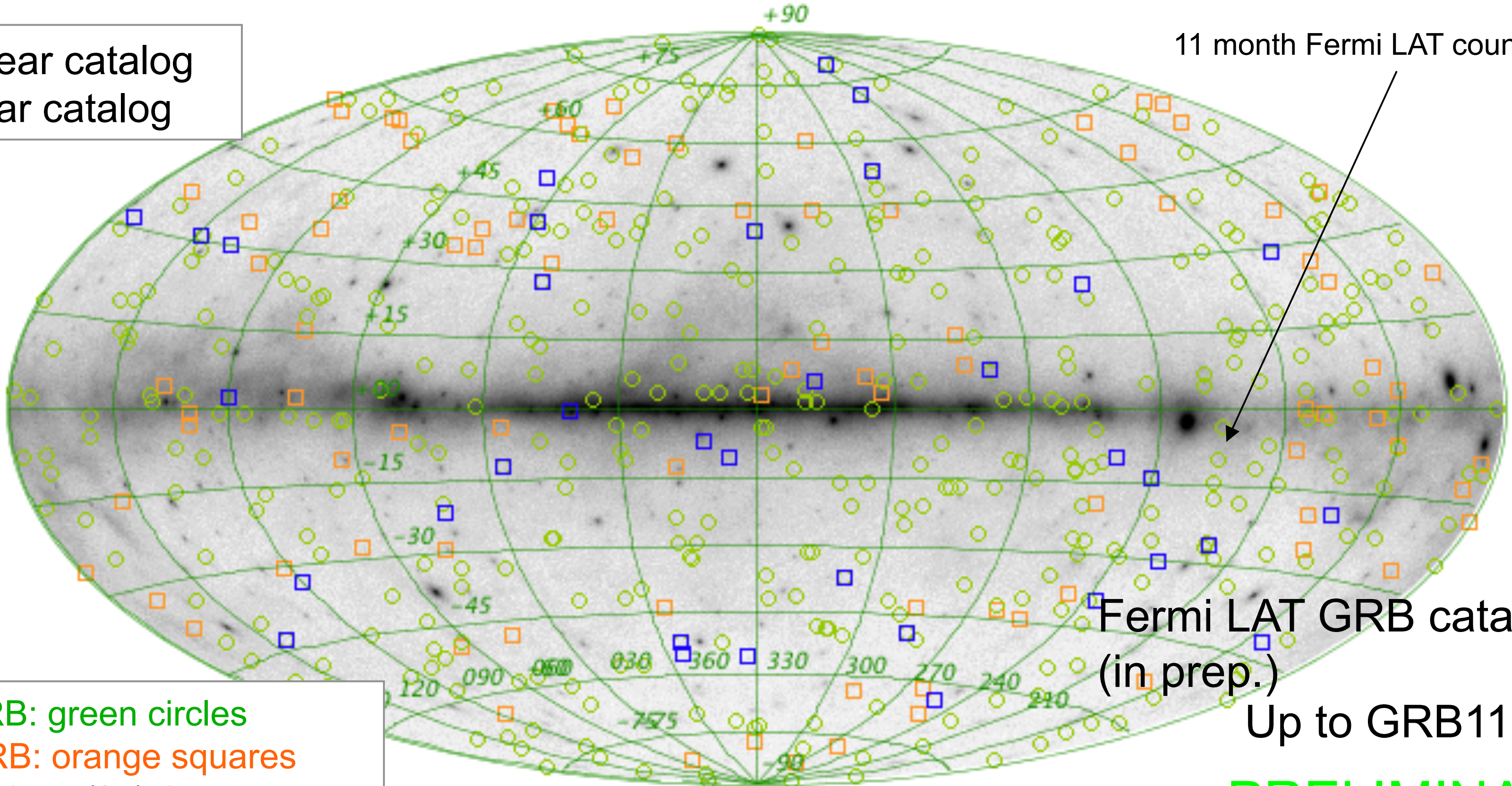
GBM FSW triggers Autonomous Repoint Request (ARR)
S/C slew to the GBM position up to 2.5 hours subject to earth-limb constraint



ARR triggered for almost a half of LAT events ➔ helpful for extended emission search

Fermi GRB statistics

GBM 2-year catalog
LAT 3-year catalog



GBM LGRB: green circles
GBM SGRB: orange squares
LAT detections (35): blue squares

- The GBM detects ~250 GRBs / year, ~half in the LAT FoV
- The LAT detected 62 GRBs up to 2013/09
  - ~Half with more accurate follow-up localisations by Swift and ground-based observatories (GROND, Gemini-S, Gemini-N, VLT)
  - 13 redshift measurements, from z=0.34 (GRB 130427A) to z=4.35 (GRB 080916C)

Highlight of Fermi result

1. Temporally extended high energy emission
   -- emission mechanism GRB (mainly in afterglow phase)

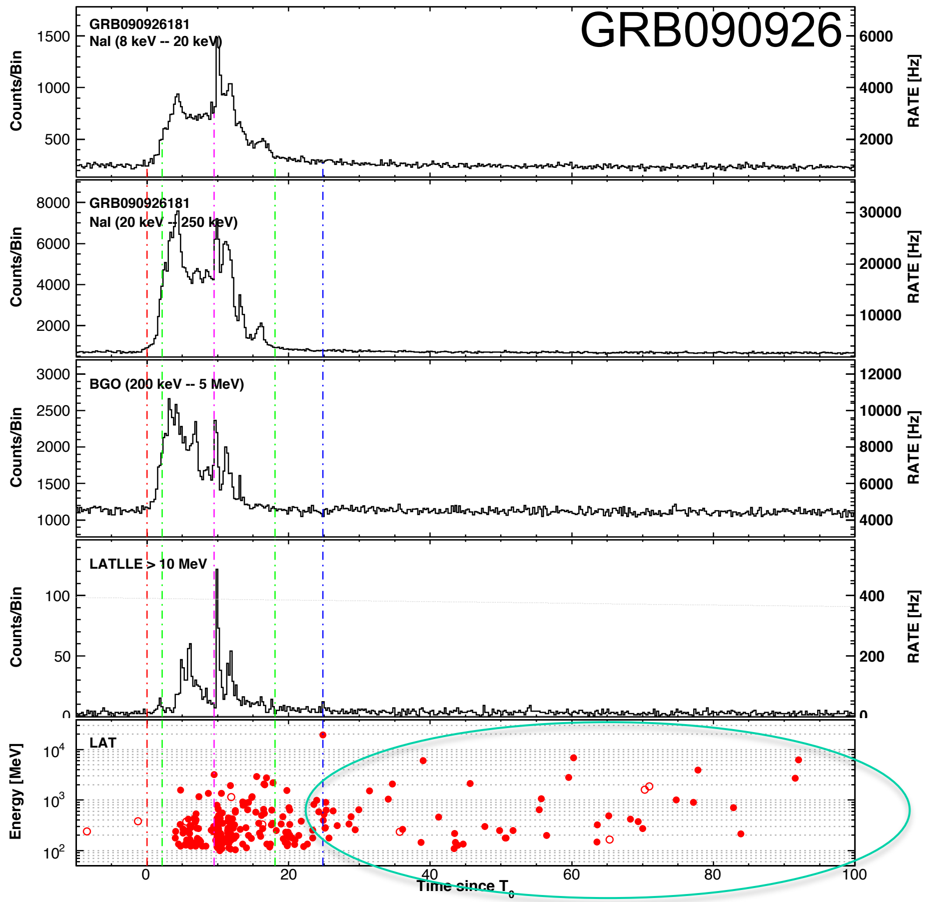
2. Delayed onset of high energy photons
   -- onset time of afterglow ?
   -- prompt emission origin? leptonic/hadronic ?

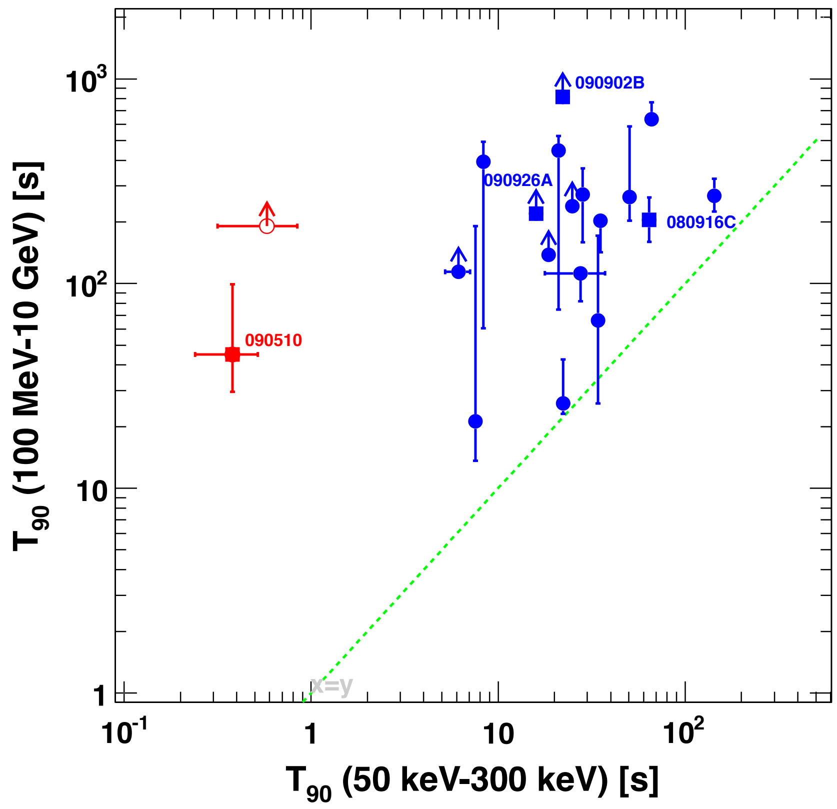
3. Extra component in the prompt emission spectrum
   -- Band model crisis

4. Highest energy photon
   -- constraint on bulk Lorentz factor, EBL, and LIV
   -- new high energy photons from new analysis method

1. Temporally extended high energy emission

LAT (>100 MeV) emission lasts systematically longer than GBM emission

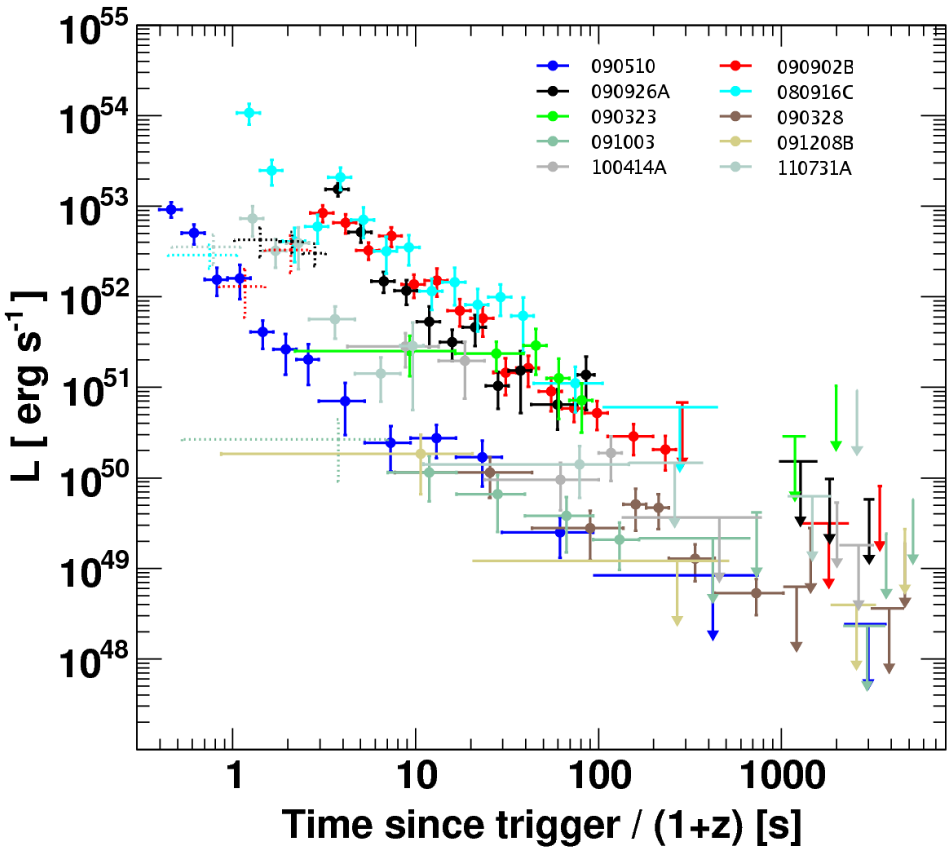




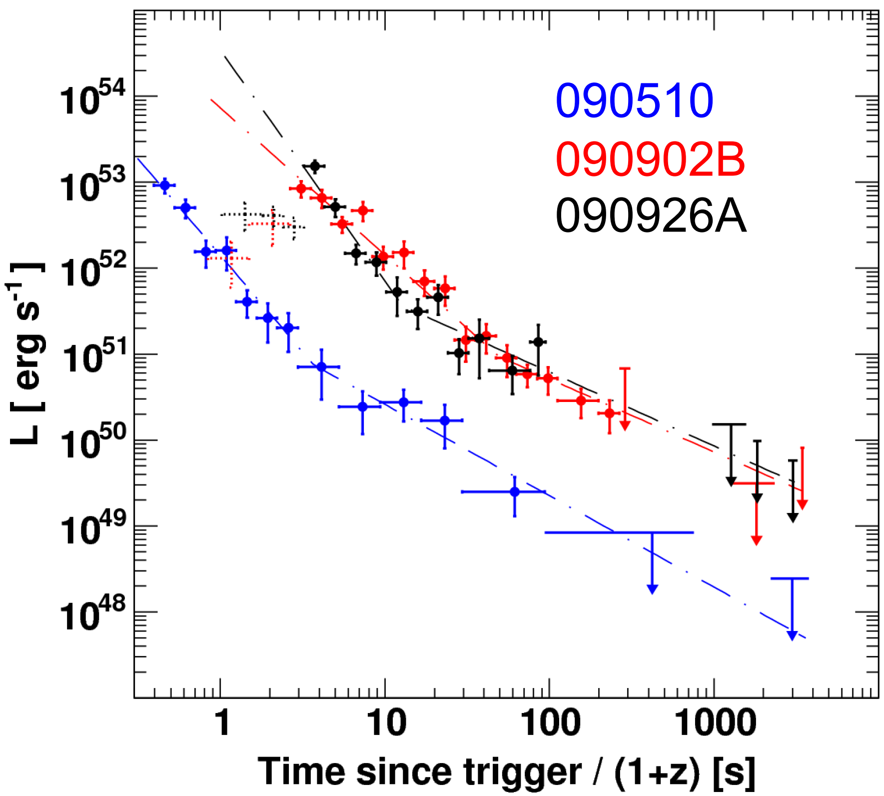
Fermi LAT 1st GRB catalog
(Fermi LAT Collab. 2013 in press arXiv1303.2908)

1. Temporally extended high energy emission

Luminosity of extended emission
Smoothly decreases with temporal
Index of about 1



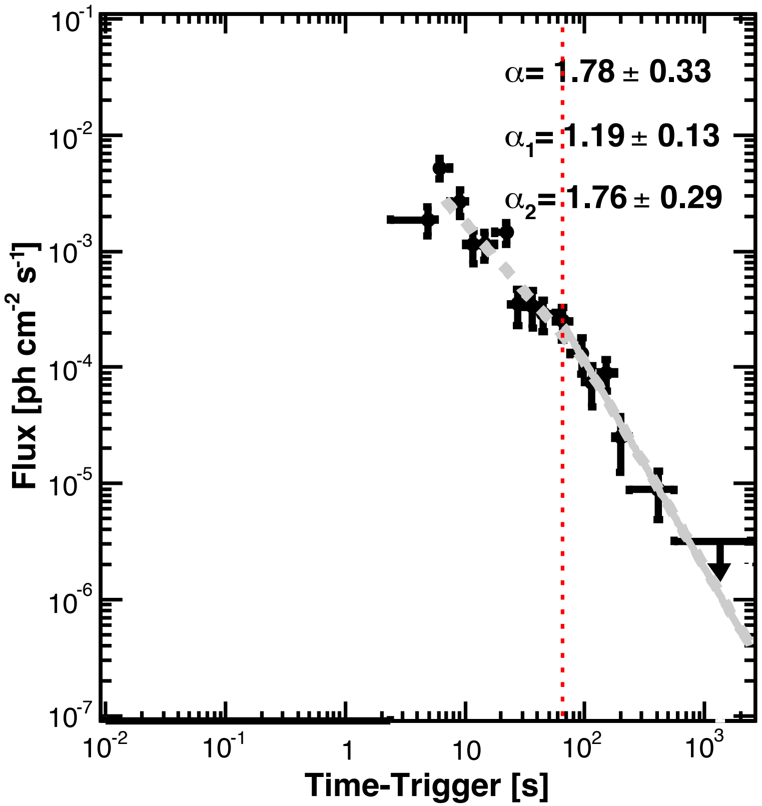
Detection of break from 3 events
(090510, 090902B, 090926)
Transition from prompt-dominate
Phase (?)



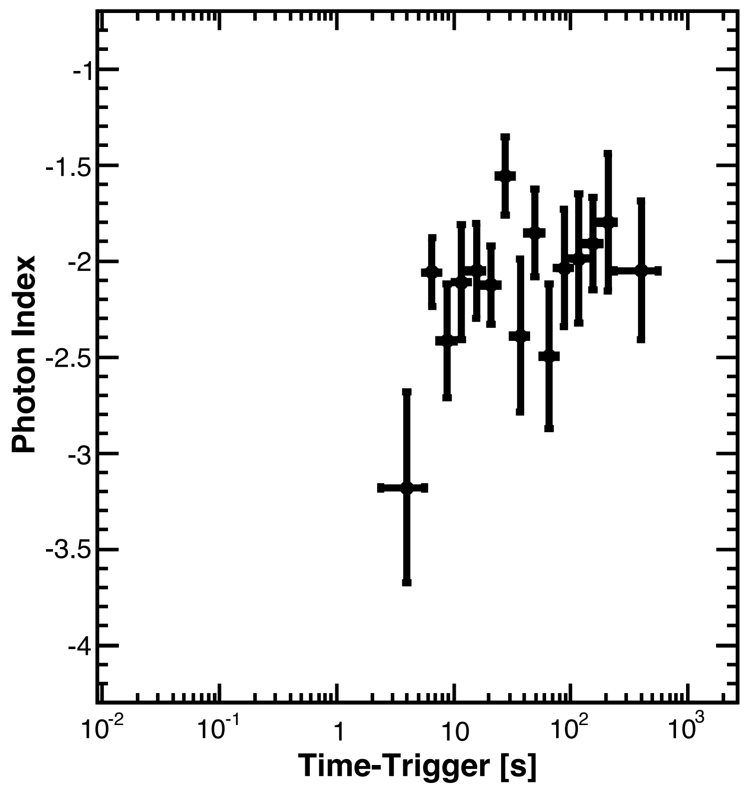
Fermi LAT 1st GRB catalog
(Fermi LAT Collab. 2013 in press arXiv1303.2908)

1. Temporally extended high energy emission

GRB 080916C flux curve



GRB 080916C photon index

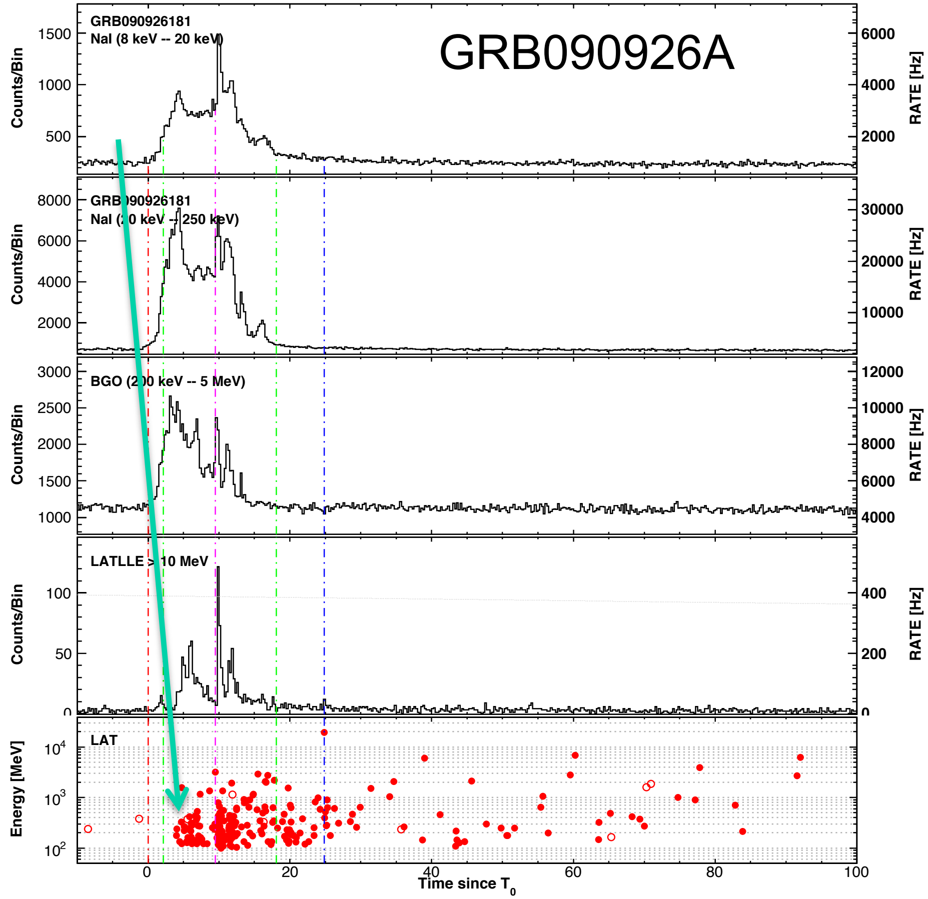


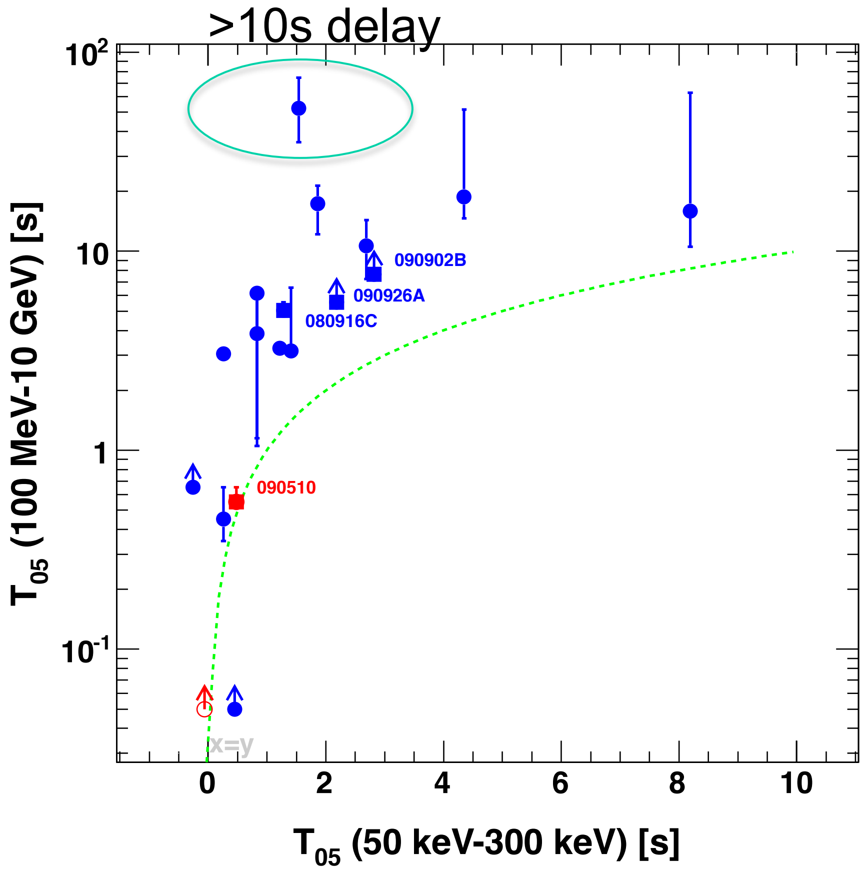
Stable spectrum of extended emission with photon index of around -2.0

Fermi LAT 1st GRB catalog
(Fermi LAT Collab. 2013 in press arXiv1303.2908)

2. Delayed onset of high energy photons

LAT(>100MeV) emission is systematically "delayed" from GBM emission



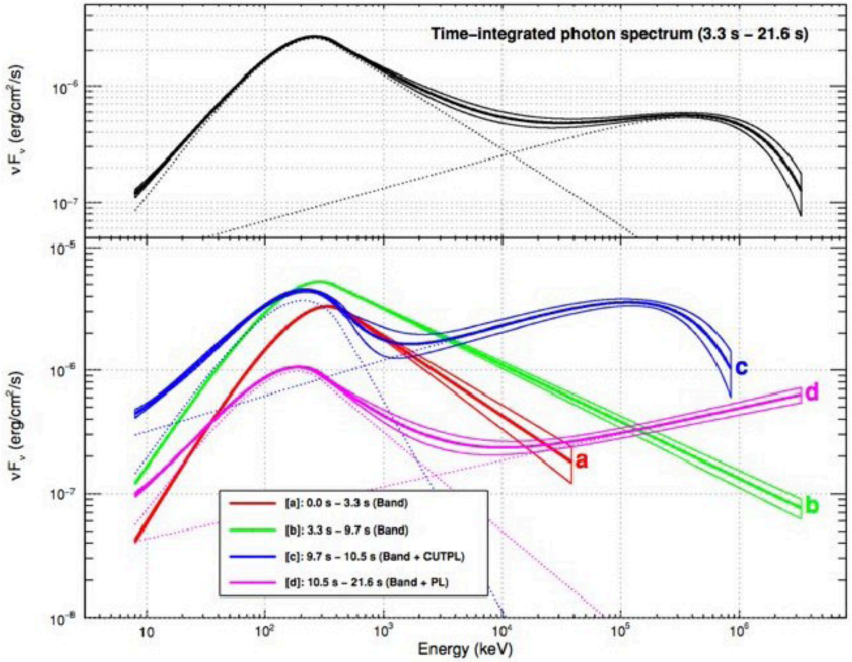


Fermi LAT 1st GRB catalog
(Fermi LAT Collab. 2013 in press arXiv1303.2908)

3. Extra spectral component

Extra power-law (or cut-off) component is required significantly for 6 LAT events with high S/N

GRB090926A (Ackermann et al. 2011)



High fluence

	Fluence 10 keV - 10 GeV (10^{-7} erg/cm^2)	Best model
GRB100724B	4665^{-76}_{+78}	Band with exponential cutoff
GRB090902B	4058^{-24}_{+25}	Comptonized + Power law
GRB090926A	2225^{-48}_{+50}	Band + Power law with exponential cutoff
GRB080916C	1795^{-39}_{+41}	Band + Power law
GRB090323	1528^{-44}_{+44}	Band
GRB100728A	1293^{-27}_{+28}	Comptonized
GRB100414A	1098^{-27}_{+35}	Comptonized + Power law
GRB090626	927^{-16}_{+17}	Logarithmic parabola
GRB110721A	876^{-28}_{+28}	Logarithmic parabola
GRB090328	817^{-33}_{+34}	Band
GRB100116A	638^{-25}_{+26}	Band
GRB110709A	518^{-27}_{+28}	Band
GRB080825C	517^{-20}_{+21}	Band
GRB0902[illegible]	512^{-15}_{+16}	Band
GRB091003	461^{-14}_{+15}	Band
[illegible]	422^{-22}_{+23}	Band
GRB110328B	417^{-37}_{+47}	Comptonized
GRB110731A	379^{-21}_{+20}	Band + Power law
GRB090510	360^{-16}_{+18}	Band + Power law
GRB091031	288^{-10}_{+10}	Band
GRB110428A	255^{-9}_{+10}	Band
GRB090720B	185^{-11}_{+13}	Band
GRB100225A	101^{-7}_{+7}	Band
GRB091208B	93^{-11}_{+13}	Band
GRB100620A	84^{-9}_{+9}	Band
GRB081006	56^{-9}_{+10}	Band
GRB110529A	$49^{-6}_{+[illegible]}$	Band
GRB100325A	46^{-4}_{+4}	Band
GRB0905[illegible]B	[illegible] $_{+5}$	Comptonized
GRB081024B	30^{-5}_{+6}	Band

Normal fluence/ on-axis angle

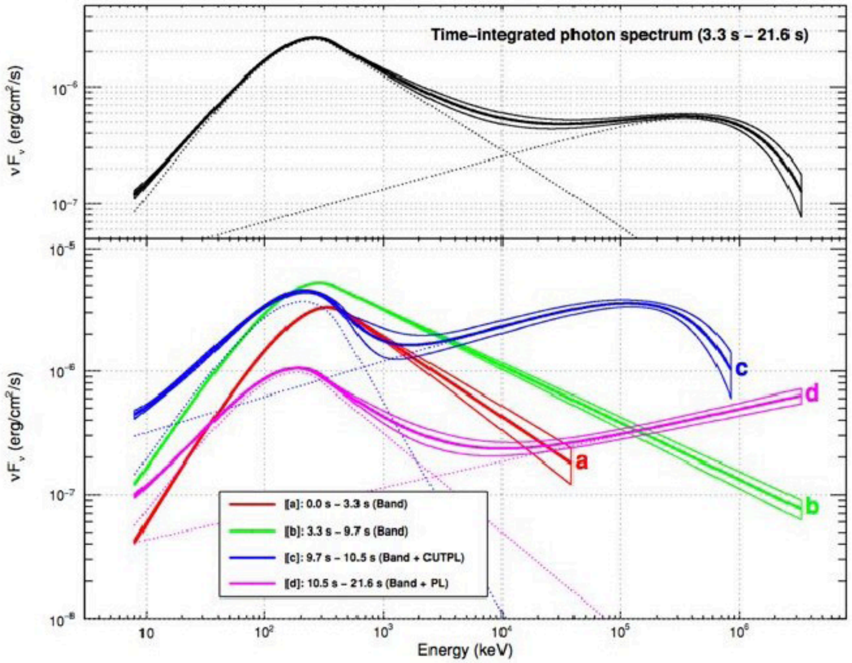
fluence

Fermi LAT 1st GRB catalog (Fermi LAT Collab. 2013 in press arXiv1303.2908)

3. Extra spectral component

- ✓**Simple Band model does not represent spectral features for high S/N LAT event**
- ✓**Band model crisis. Further spectral modeling are investigating**

GRB090926A (Ackermann et al. 2011)



High fluence

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GRB100620A	84^{+9}_{-9}	Band
GRB081006	56^{+10}_{-9}	Band
GRB110529A	49 −6 [illegible]	Band
GRB100325A	46 [illegible] +4	Band
GRB0905[illegible]B	[illegible] +5	Comptonized
GRB081024B	3[illegible] −5 +6	Band

Normal fluence/ on-axis angle

fluence

Fermi LAT 1st GRB catalog
(Fermi LAT Collab. 2013 in press arXiv1303.2908)

Origin on the temporally extended, delayed-onset emission

✦ Is related to the prompt emission? Reprocessing by inverse-Compton or SSC

➡Hard to produce a delayed onset time longer than spike widths

➡Hard to produce a low-energy (<50 keV) power-law excess (as in GRBs 090510, 090902B)

➡Photospheric emission models could help to solve the last two issues

➡Difficult to explain the long lasting emission with only internal shocks

✦Hadronic models (pair cascades, proton synchrotron)

➡HE onset time = time to accelerate protons & develop cascades?

➡Synchrotron emission from secondary e± pairs produced via photo-hadron interactions can naturally explain the power-law at low energies but Proton synchrotron radiation requires large B-fields

➡Both scenarios require substantially more energy (1-3 orders of magnitude) than observed (much less stringent

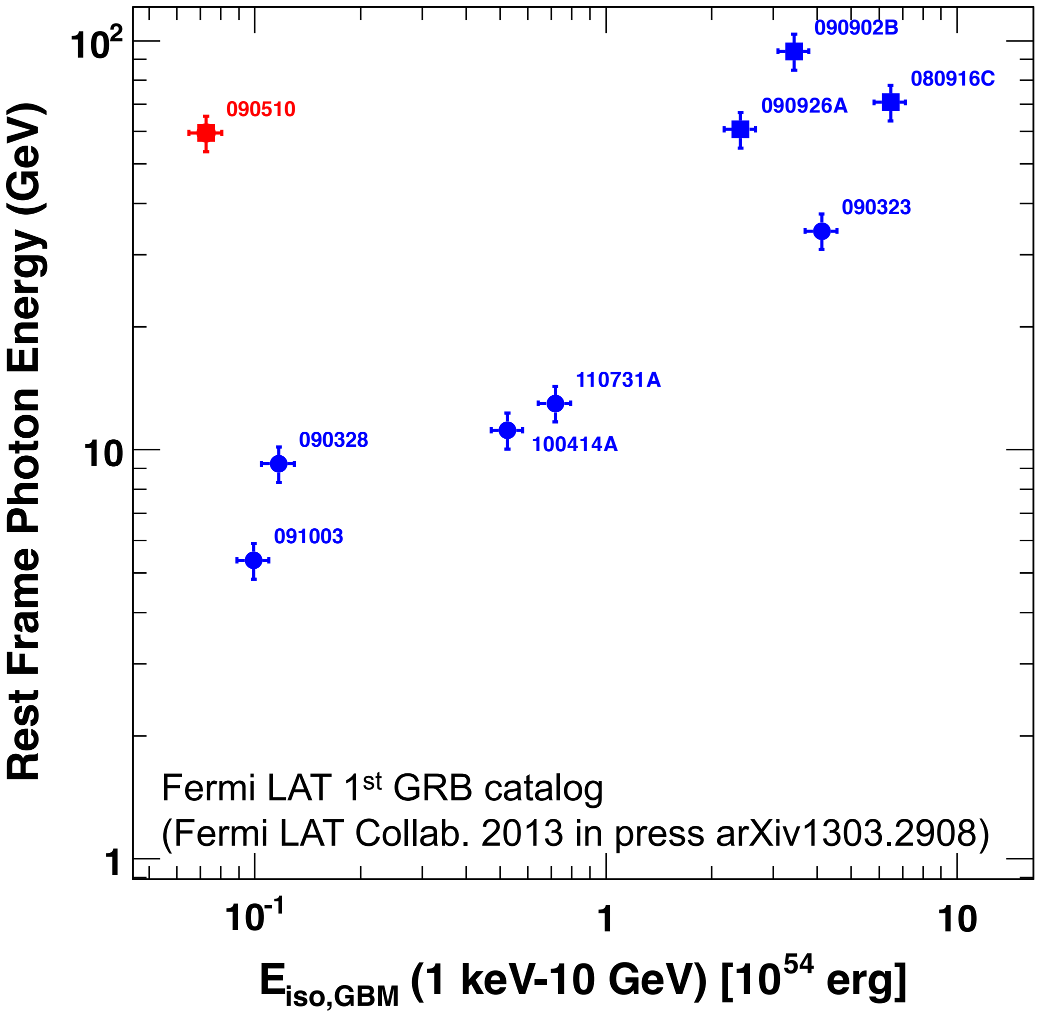
✦Early afterglow: e^+e^- synchrotron from the forward shock (FS) / decelerating blast wave

➡HE onset time = time required for FS to sweep up enough material and brighten

➡Temporally extended emission explained by the radiating phase of the fireball

➡Synchrotron can not explain correlated light curves (e.g., spike of GRB 090926A) but IC of Band photons by HE electrons at the FS? → possible & can explain correlated light curves

4. Highest energy photon



Several-tens-of-GeV photons
In GRB frame

Possible correlation between
E_{iso} and highest photon energy

Short GRB is outlier ?
Need more sample !

Highest photon energy is useful for
- Limit on bulk Lorentz factor
- Constraint on synchrotron model
- EBL model
- Lorentz invariance violation (LIV)

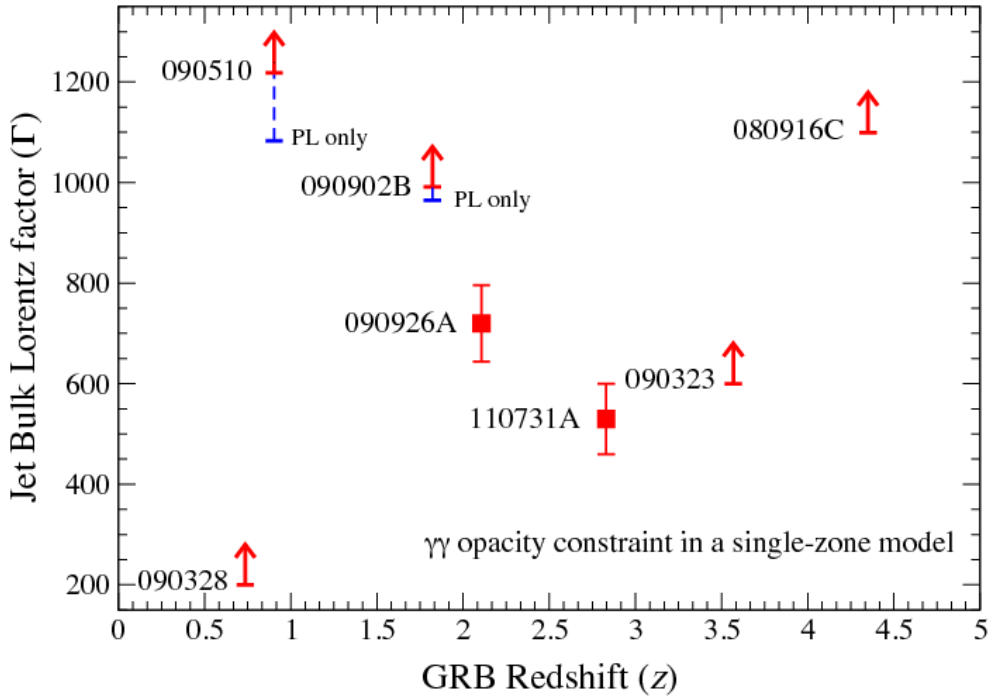
4. Highest energy photon
-- Limit on bulk Lorentz factor

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

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

Gehrels et al. arXiv1301.0841



4. Highest energy photon
-- Limit on bulk Lorentz factor

- **In the context of the early afterglow model, the delayed LAT onset is due to the transition between the coasting fireball and the self similar phase (Blandford & McKee 1976, Rees & Meszaros 1994)**
- **Peak-flux time of the LAT is of the order of the fireball deceleration time**

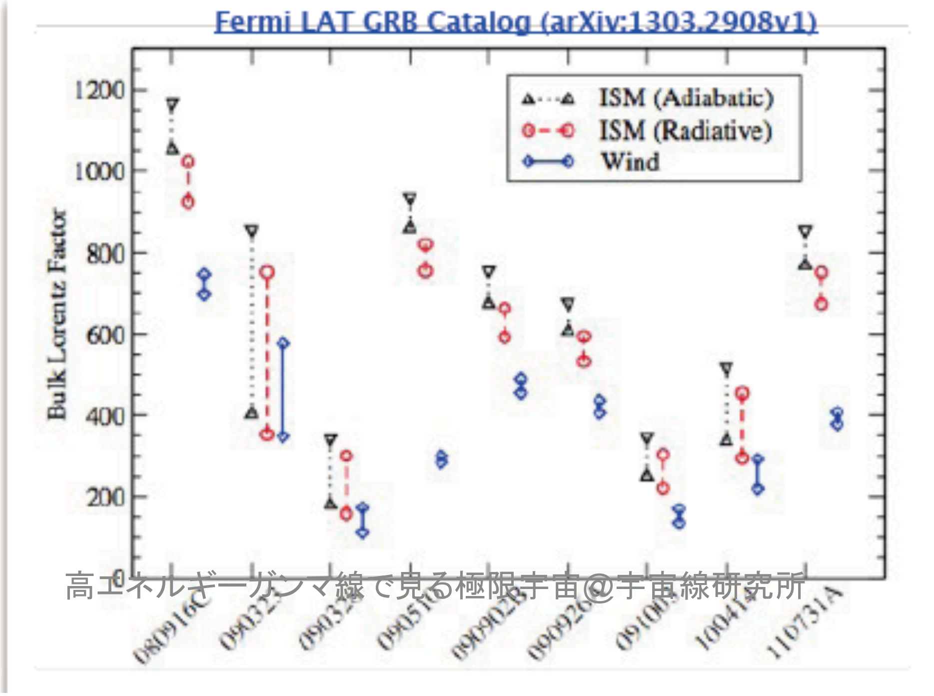
ISM [Blandford & McKee 1976; Sari et al. 1998; Ghisellini et al. 2010)]

$$\Gamma_0 = \left[\frac{3E_{k,\mathrm{iso}}(1+z)^3}{32\pi n m_p c^5 t_{\mathrm{peak}}^3}\right]^{1/8} \times \begin{cases} a^{-1/8}; \ a=4 & (adiabatic) \\ a^{-5/32}; \ a=7 & (radiative), \end{cases}$$

Wind environment [10^{-5} M⊙ yr^{-1} mass-loss rate, 10^3 km s^{-1} [Chevalier & Li 2000; Panaitescu & Kumar 2000]

$$\Gamma_0 = \left[\frac{E_{k,\mathrm{iso}}(1+z)}{16\pi A m_p c^3 t_{\mathrm{dec}}}\right]^{1/4}$$

Similar result to γ-γ opacity limit



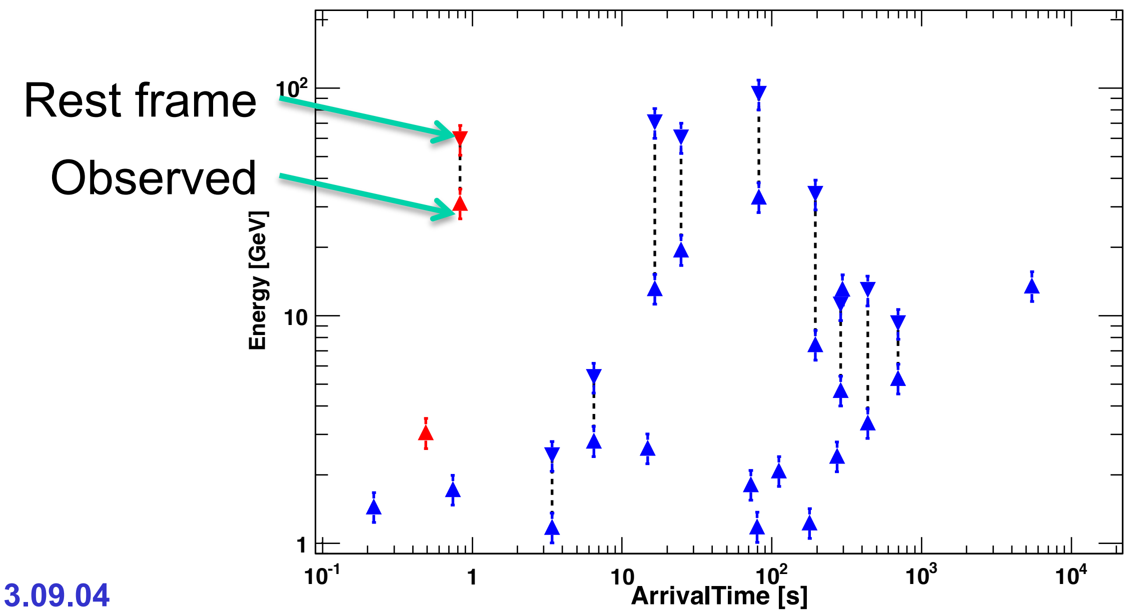
4. Highest energy photon
Constrain the Synchrotron Emission

- **From the detection of high-energy photons:**

-- maximum photon energy that an electron can produce by synchrotron taking into account the acceleration/cooling time

-- computing maximum energy of an electron (to complete at least 1 Lamor radius) ➔ constraint on maximum photon energy by synchrotron (Kumar et al. 2012, Sari & Nakar 2012)

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



New high energy photon from new Fermi event reconstruction

- Pass-8 : new revision of event-level analysis data by Fermi collaboration
- Improvement event reconstruction at each stage

-- TKR: (before) pattern recognition seeded by CAL

(Pass8) New pattern recognition decoupled from CAL

-- CAL: (before) All crystals hits grouped together

(Pass8) introduce new clustering algorithm to reduce miss-reconstruction due to background ghost event

-- ACD: (before) use absolute distance between ACD and TKR

(Pass8) propagate covariance matrix and measure distance

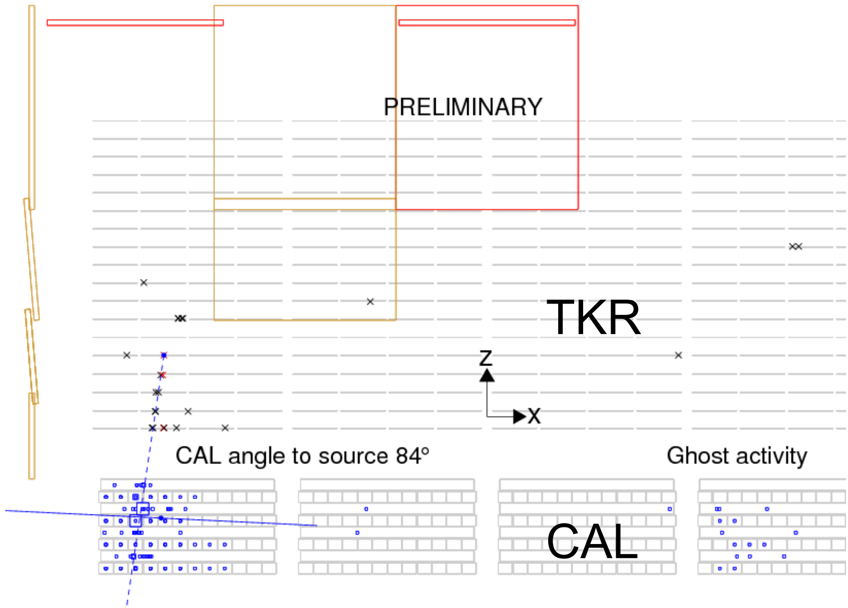
- Will be published by Fermi team
- Test analysis to show improvement the data analysis

Atwood et al. 2013 ApJ, 774, 76

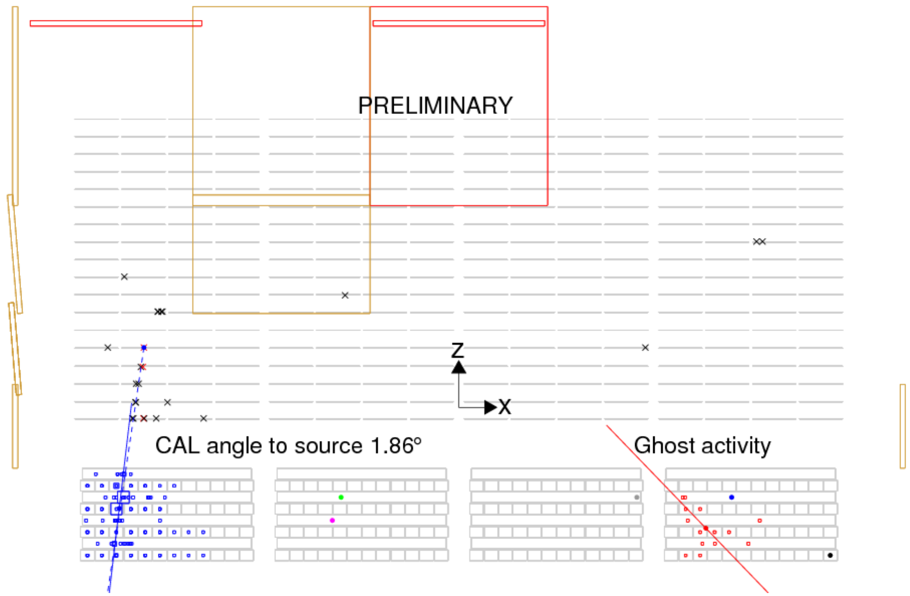
New high energy photon from new Fermi event reconstruction

- **Example for CAL new reconstruction**

Previous event reconstruction



Pass8 reconstruction

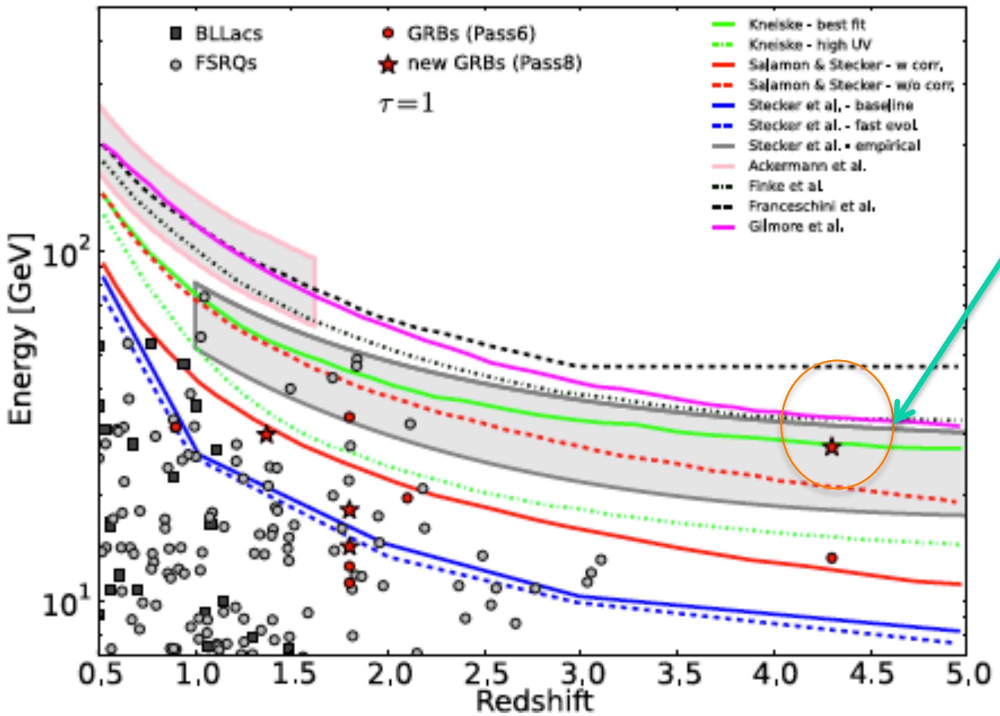


We will loss such miss-reconstructed event

New high energy photon from new Fermi event reconstruction

- Find 4 new photons which were miss-reconstructed in previous event class
- 27.4 GeV photon from GRB 080916C at T0+40.5s (z=4.35),

  147 GeV in GRB frame !
- If synchrotron origin, Γ>5000 is required (unrealistic?)
- More useful to constrain EBL model



27.4 GeV photon
(147 GeV in GRB frame)
From GRB 080916C

The most constraining gamma-ray
So far from GRBs
(similar constrain from AGN)

4. Highest energy photon Lorentz Invariance Violation

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

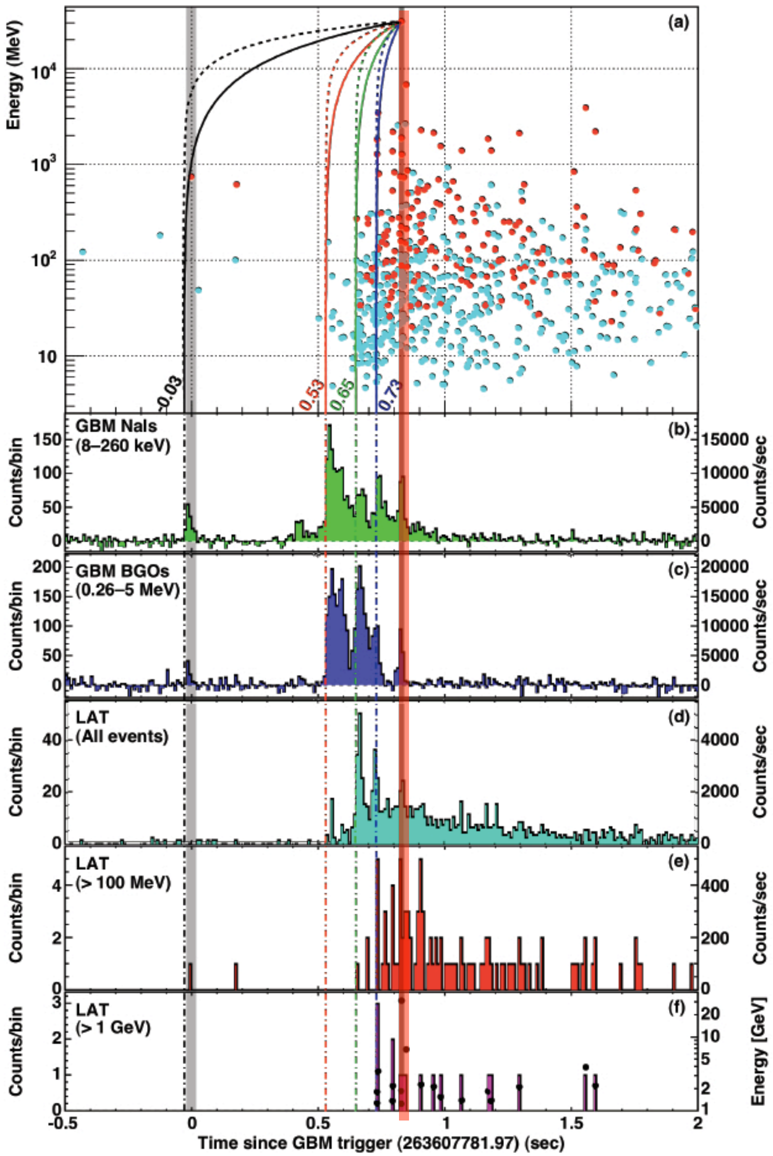
$$c^2 p_{ph}^2 = E_{\rm ph}^2 \left[1 + \frac{E_{\rm ph}}{M_{\rm QG,1} c^2} + \left(\frac{E_{\rm ph}}{M_{\rm QG,2} c^2} \right)^2 + \ldots \right] \quad , \quad v_{\rm ph} = \frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c \left[1 - \frac{1+n}{2} \left(\frac{E_{\rm ph}}{M_{\rm QG,n} c^2} \right)^n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

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

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

High-z, large ΔE (not so high E for EBL) is preferable ➔ GRB is a good target !

4. Highest energy photon LIV for GRB 090510



- Estimate lower limit of $M_{QG,1}$ for various Δt, ΔE
- Highest energy photon from GRB 090510 is 31 GeV at 0.83 s after trigger
- Most conservative case: 31 GeV photon starts from any <1MeV emission
- Δt < 859 ms, $M_{QG,1}/M_{plank}$ > 1.19

- This new limit MQG,1/Mplank > several

is much stronger than the previous result

➔ Greatly constrain the QG model (n=1)

(Abdo et al. 2010)

Summary for highlight of LAT GRB observation

- Delayed-onset and temporally extended high energy emission

 - common in LAT observed GRBs

 - several models to explain such temporal feature (leptonic/ hadronic/early afterglow)

- Extra spectral component

 - extra spectral component in prompt emission phase can be seen for LAT GRBs with good S/N (so far, 6 GRBs)

 - GRB090926A and GRB100728A shows high-E spectral cut-off

 - need further spectral model

- Observation of highest energy photon

 - minimum bulk Lorentz factor of jet could be $\Gamma \sim 1000$

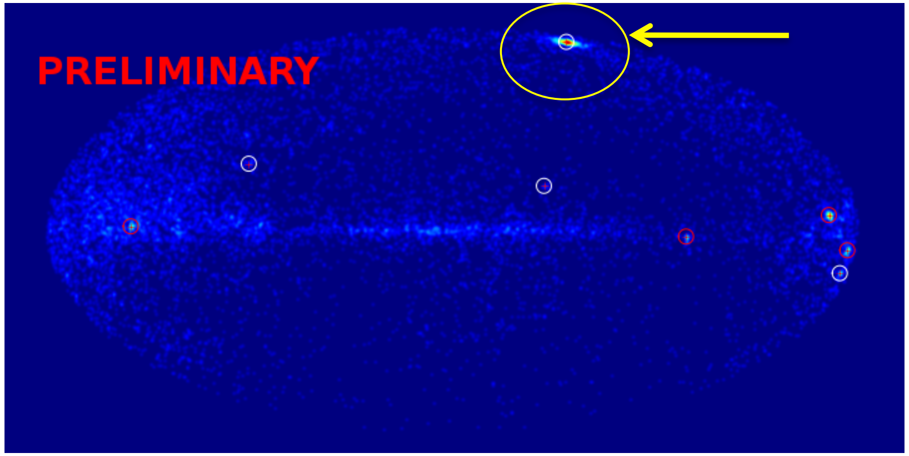
 - maximum energy for synchrotron

 - Fermi LAT new event reconstruction algorithm found new high energy photons (147 GeV in GRB frame)

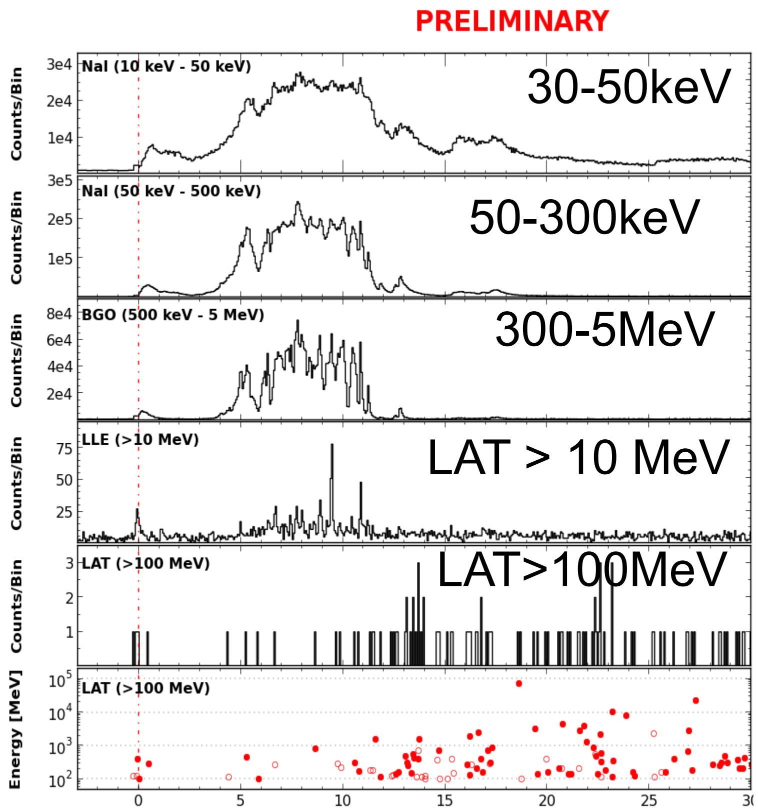
- Useful for EBL and LIV constraint

Long-awaited “Monster” event : GRB 130427A

– **Highest gamma-ray fluence (>10^{-3} erg cm^{-2})**
– **Highest observed gamma-ray energy (95 GeV)**
– **Longest lived gamma-ray emission (19 hours)**
– **Within the closest 5% of GRBs (z = 0.34)**



6 hours LAT all-sky map



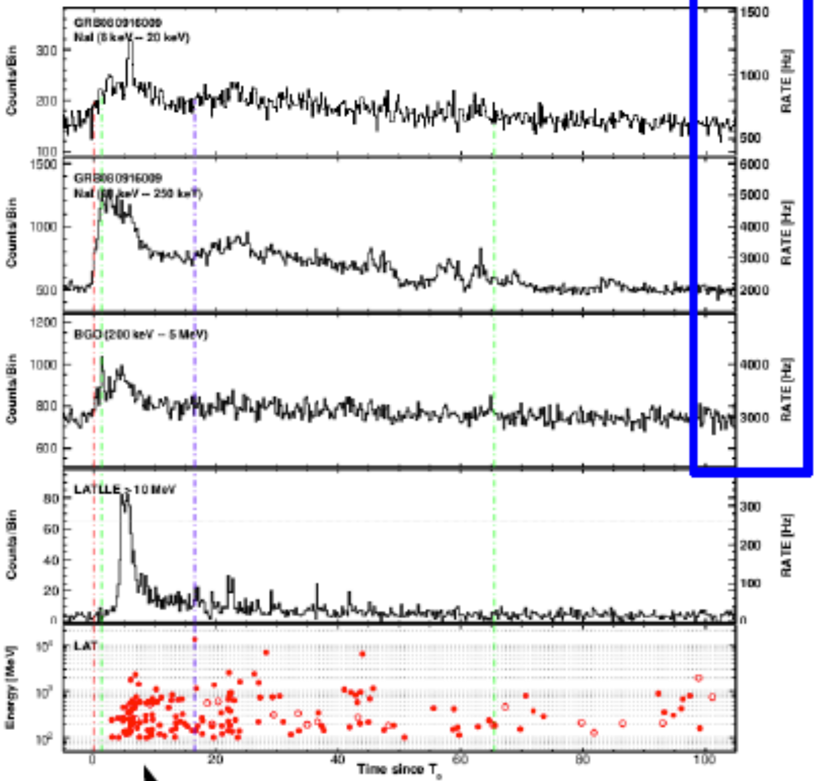
GRB 130427A challenges the model that
Temporally extended emission is nonthermal
Synchrotron emission

Compare with other bright LAT GRB

Fermi LAT collab. Science submitted

GRB 080916C

10^3



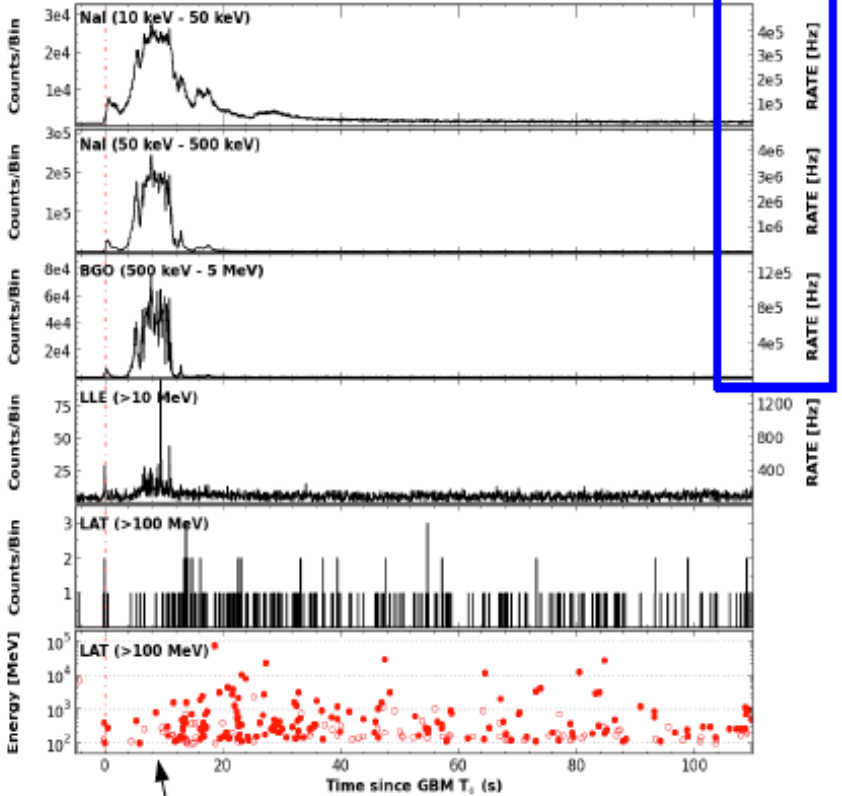
LAT emission dying down

LAT and GBM are bright at the same time

GRB 130427A

PRELIMINARY

10^5, 10^6



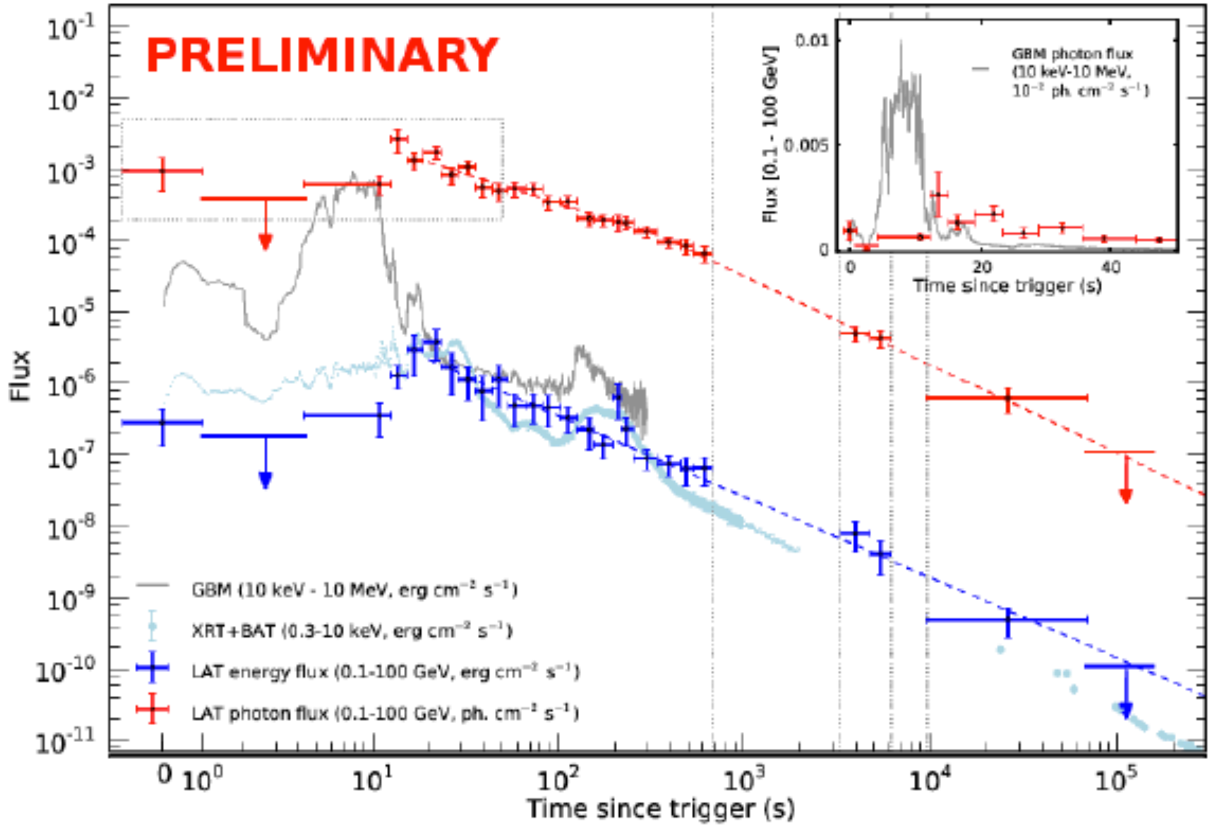
LAT emission still going

Very little LAT emission when GBM emission is bright

Temporally extended high-energy emission

Fermi LAT collab. Science submitted

LAT photon flux
LAT energy flux



LAT light curves are ~smooth

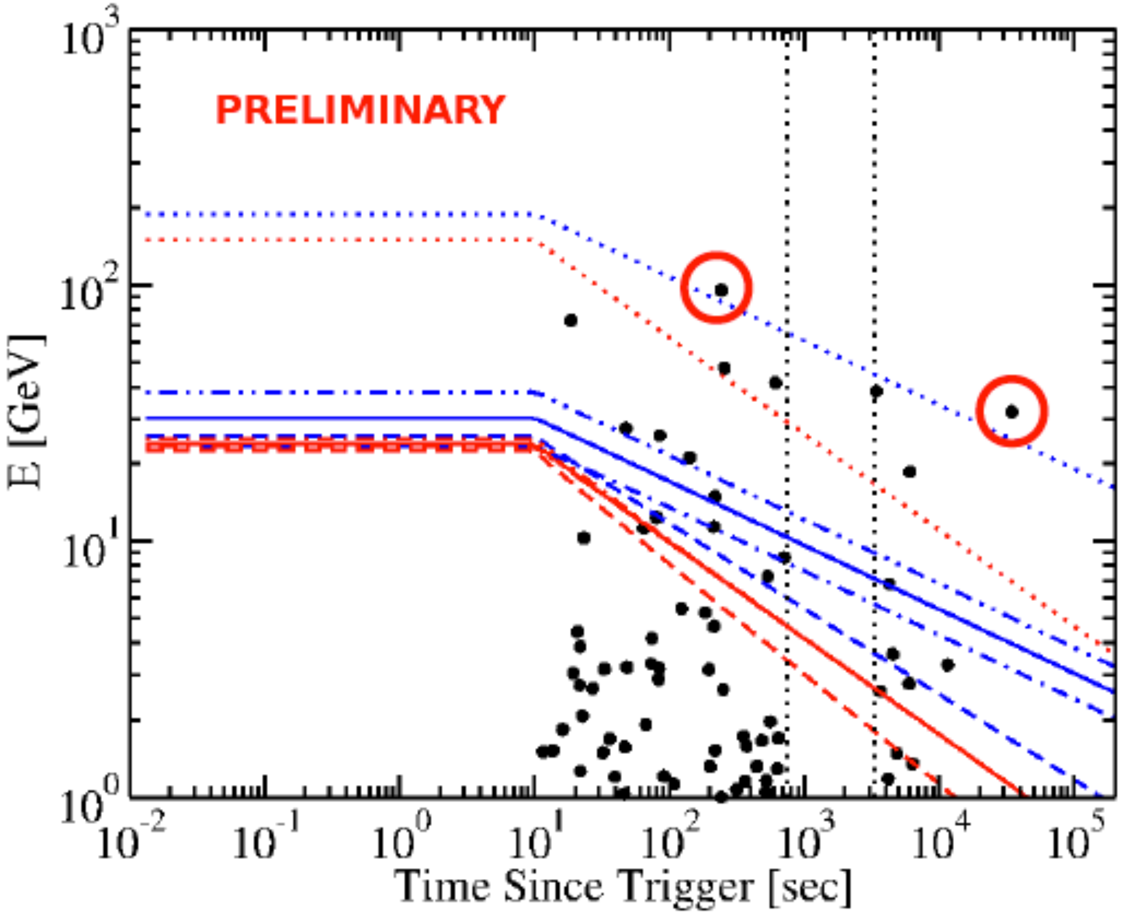
- Photon flux: broken power law (t_{break} ~ 300 +/- 100 s)
- Energy flux: single power law

Some common features between LAT and lower energy light curves

LAT emission is detected for ~20 hours total (previous record ~1.5 hr)

Synchrotron emission model

Fermi LAT collab. Science submitted



Curves of maximum synchrotron photon energy from external shocks

Black dot: LAT photons

Red → constant density
Blue → density ~ r^{-2}
(Dotted: “extreme”, unrealistic cases)

Assume fast acceleration on a time scale shorter than Lamor timescale

95 GeV, and 32 GeV photons cannot originate from leptonic standard synchrotron radiation.

Short comments on prospect for CTA

Mostly taken from Inoue et al. 2013 paper (arXiv 1301.3014)

- **Origin of delayed, temporally extended emission**

  - Time variability of high energy photon is an important key

  - A number of GeV photon is still poor for Fermi-LAT

  - CTA light curve with good statistics can be compared to prompt gamma-ray light curve

- **Constraint on EBL**

  - high energy photon (>100GeV) could come >100s after trigger

  - EBL cut-off can be observed by CTA

- **Constraint on LIV**

  - to improve on LIV constraint for GRB 090510, need < 30s observation for 1 TeV photon

  - wide-field mode would be useful (? Event rate: 2-3 GRB/year)

  - other statistical approach, use X-ray flare in afterglow..

Conclusion

- **Fermi satellite is now observing GRBs normally**
- **Delayed-onset and temporally extended high energy emission**

- common in LAT observed GRBs, but origin is still discussing

- **Extra spectral component**

- can be seen from some of high S/N events, need further spectral model

- **Observation of highest energy photon**

- highest energy photon from GRBs is very useful for various GRB science (i.e., constrain on bulk Lorentz factor, synchrotron model, EBL, LIV.. etc)

- **Monster GRB 130427A challenges synchrotron emission model for high energy emission**
- **Need much more GeV photons for more study. ➔ CTA !**