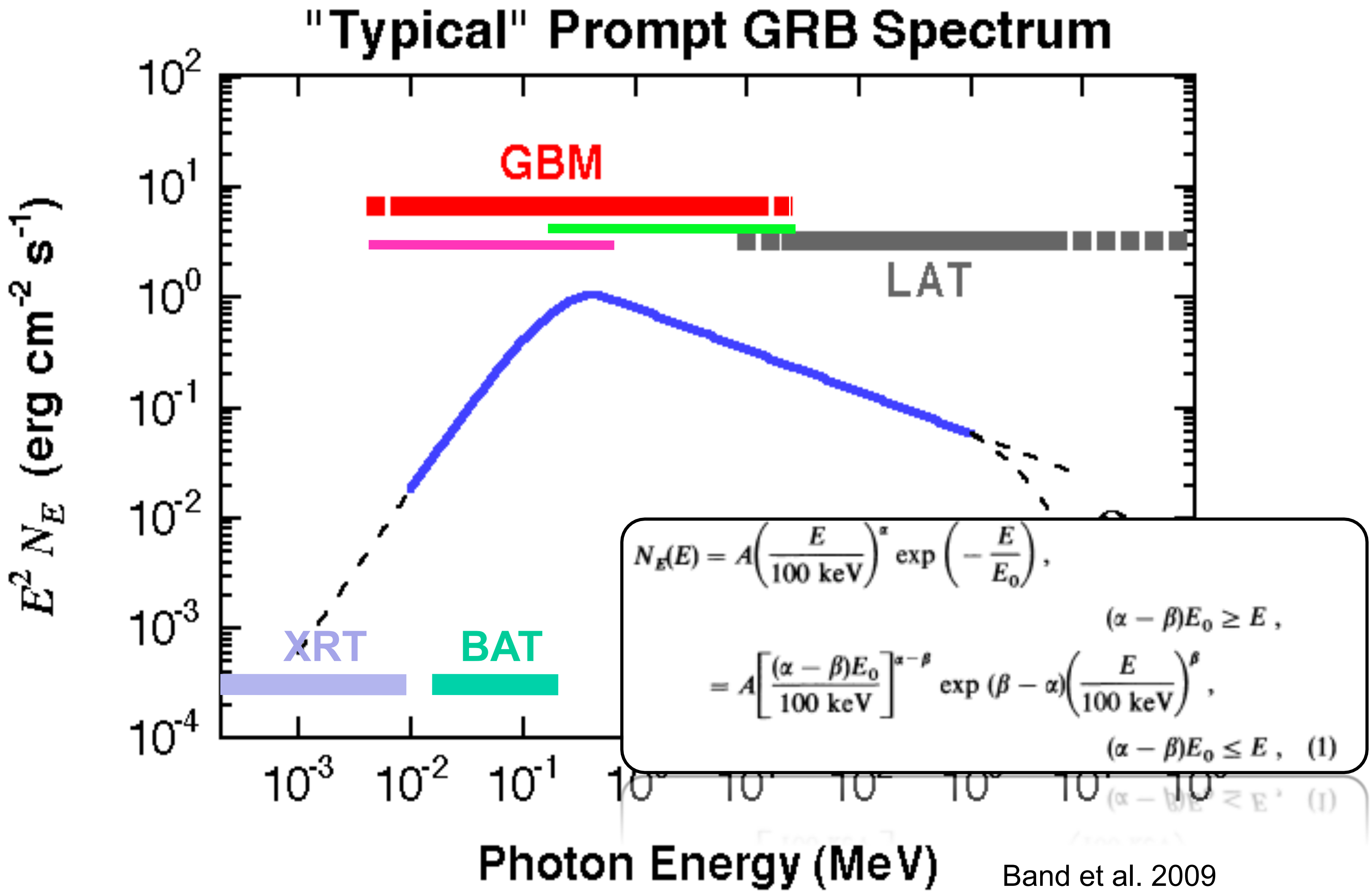
Fermi GBM and LAT Gamma-ray Burst Highlights

Judy Racusin (NASA/GSFC)
on behalf of the
Fermi GBM & LAT Teams

Fermi Summer School 2013

How does Fermi add to our understanding of GRBs?



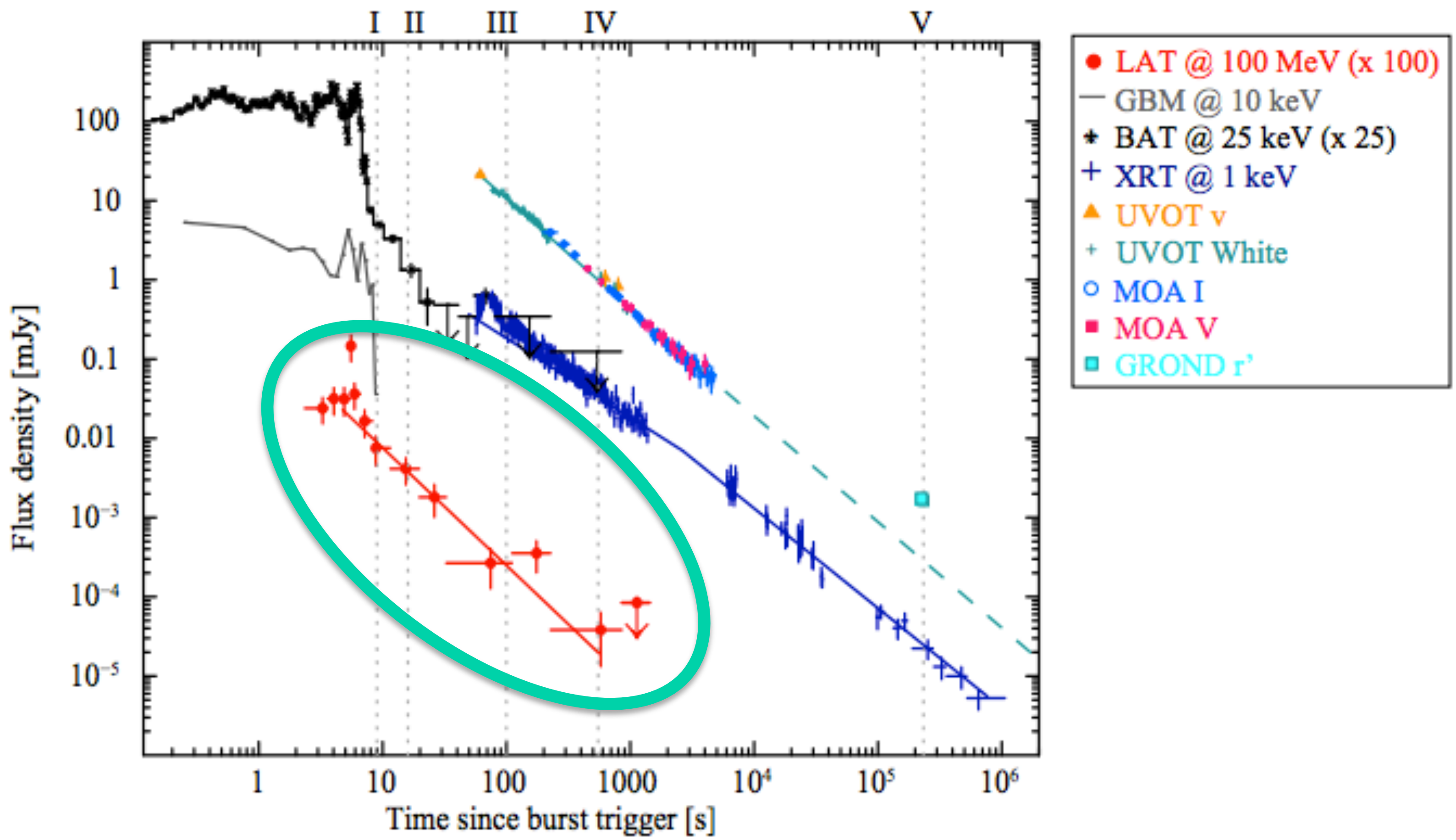
$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \quad (\alpha - \beta)E_0 \geq E,$$

$$= A\left[\frac{(\alpha - \beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta - \alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \quad (\alpha - \beta)E_0 \leq E, \quad (1)$$

Band et al. 2009

How does Fermi add to our understanding of GRBs?

GRB 110731A

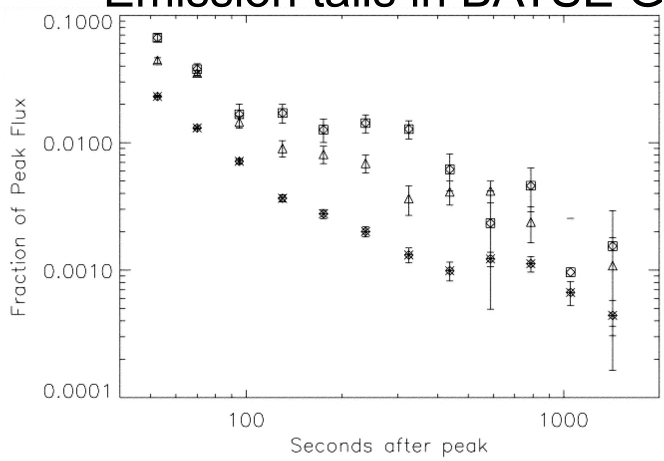


Ackermann et al 2012

What did we know about high energy GRB emission before Fermi?

- **Band Functions worked most of the time**
  - **Power laws and cutoff power laws were sometimes all that could be constrained (especially with narrower coverage – e.g. BAT)**
  - **Hints from BATSE of low energy excesses**
- **A couple of BATSE and EGRET GRBs showed some long-lasting emission**
- **One case of extra power-law component in an EGRET burst**

Emission tails in BATSE GRBs

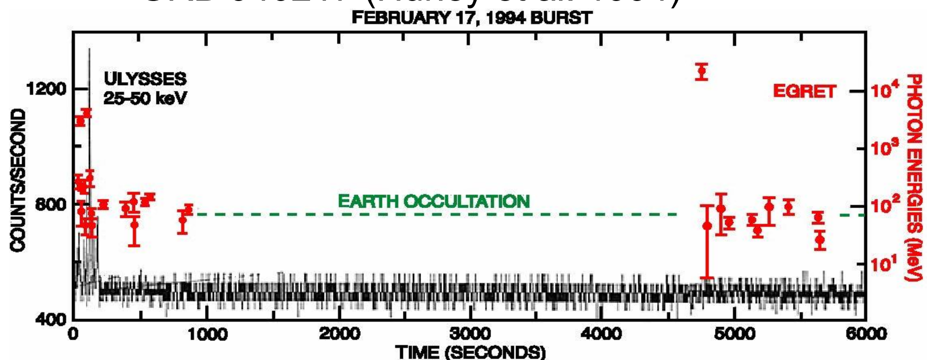


Connaughton et al. 2002

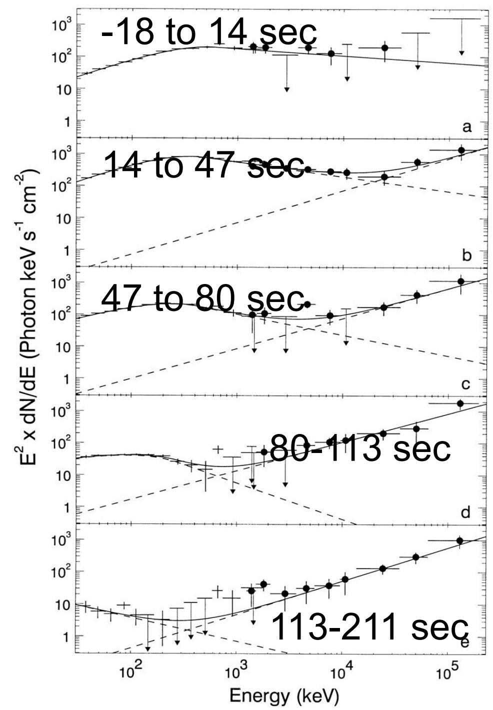
High energy emission from GRBs: Pre-Fermi era

- **Little known about GRB emission above ~100 MeV**
- **EGRET detected only 5 (long) GRBs, most notably:**
  - **GRB 940217: GeV photons were detected up to 90 minutes after the GRB trigger**
  - **GRB 941017: distinct high-energy spectral component (up to 200 MeV), with a different temporal evolution & > 3 times more energy**

GRB 940217 (Hurley et al. 1994)



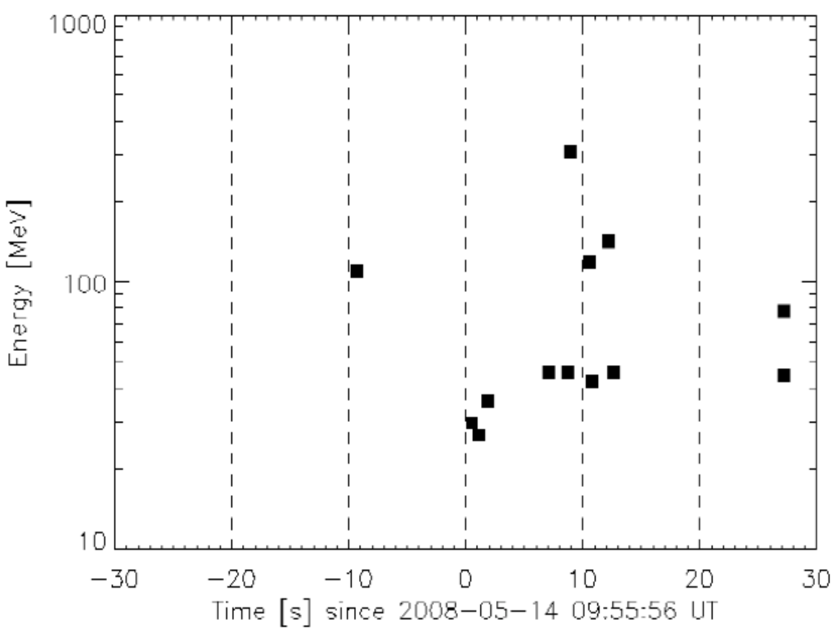
GRB 941017 (Gonzalez et al. 2003)

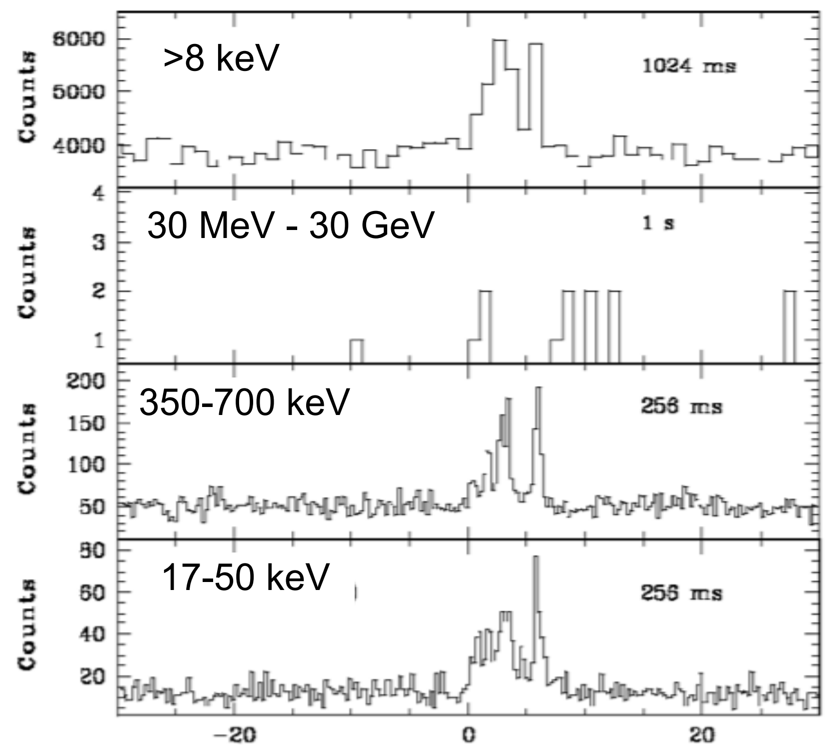


BATSE EGRET

High energy emission from GRBs: Pre-Fermi era

- **AGILE observed GRB 080514B and detected photons up to a few 100 MeV lasting somewhat longer than the soft gamma-rays**





Giuliani et al. 2008

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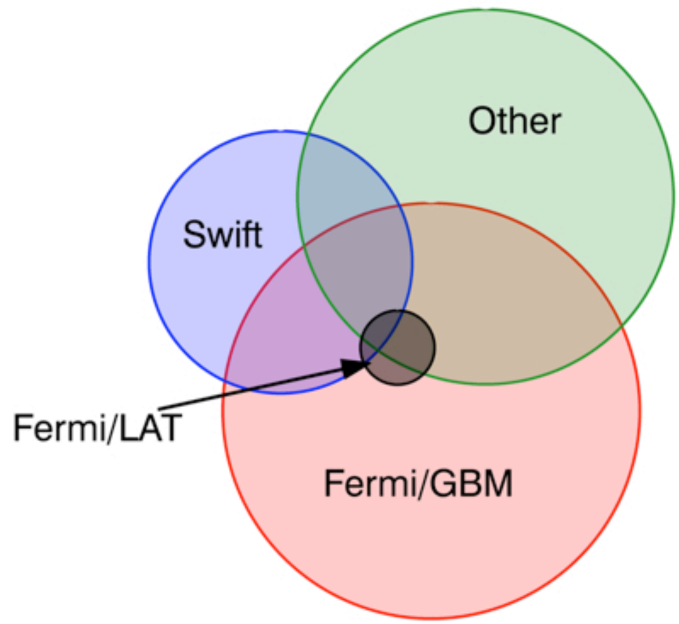
Fermi GRB Observations

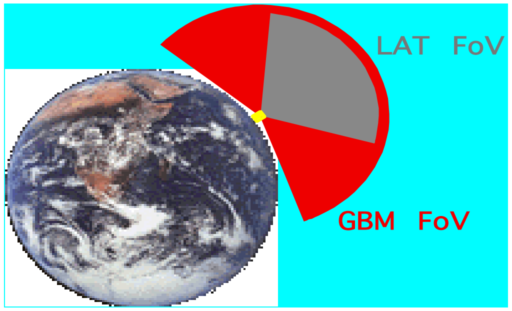
- Including bursts from Aug 2008-April 2013
  - ~450 Swift GRBs
  - ~1400 Fermi-GBM GRBs
  - ~50 Fermi-LAT GRBs
  - ~900 Other (AGILE, Suzaku, Konus, INTEGRAL, etc.)
- Limitations
  - ~200 Swift GRBs with no high energy (>150 keV) observations
  - ~1200 poorly localized GRBs without afterglow observations
- Best Observed Subset
  - Those with both high and low energy coverage



Credit: A. Goldstein

Fermi GRB Observations

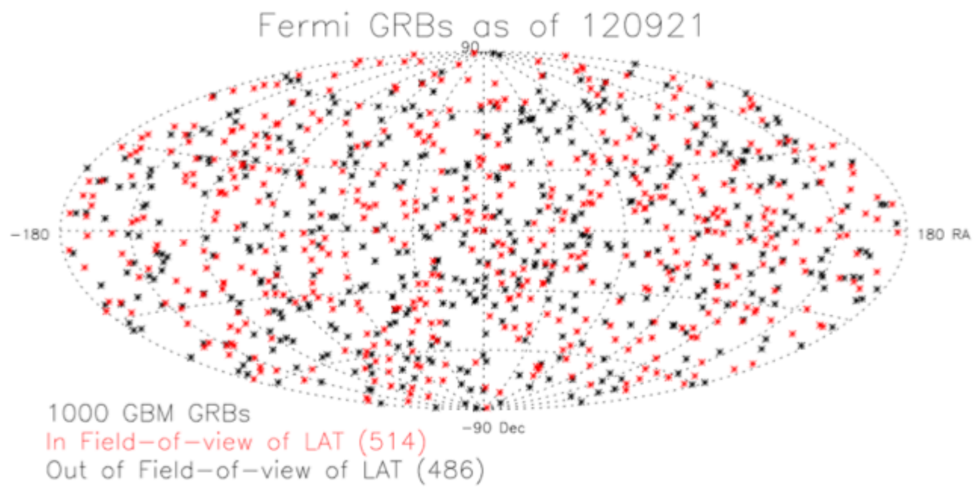
- GBM triggers
  - Onboard localization (5-10 deg radius)
    - Followed by automatic ground localization (3-5 deg radius)
    - Human in the loop position (taking into account subjective decisions like interval and energy range)
    - (Valerie will discuss more details next)



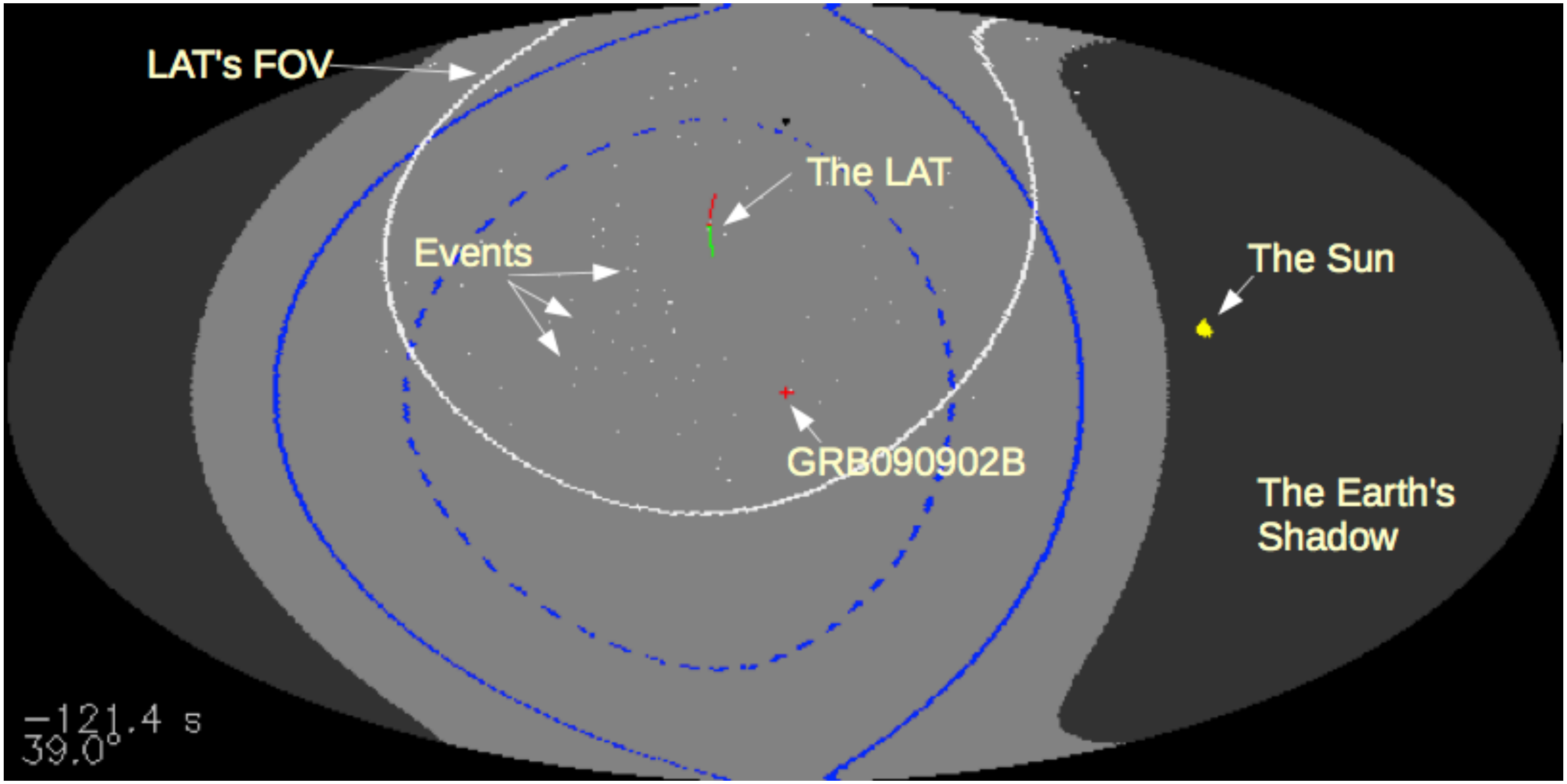
  - If high peak flux, or high fluence criteria are met -> ARR
    - triggers Autonomous Repoint Request (ARR)
    - LAT centers GRB in FoV for 2.5 hours (except when occulted)
    - Better effective area by bring burst into central area of detector
    - Improves temporal coverage for light curve to compare to broadband measurements
    - Background in GBM & LLE can be problematic due to slew

Fermi GRB Observations

- LAT observations begin
  - Onboard trigger (only happened once – GRB 090510, but we've improved algorithm and are waiting for another someday …)
  - Data comes to ground and is processed in ~8-12 hours
  - Ground analysis finds positions (automated scripts + humans)
  - LAT position disseminated to world
- Swift Follow-up (ideally)
  - Tiled or single pointing observations with XRT/UVOT
  - Arcsec position sent to world via GCN
  - Ground-based telescopes find afterglow, get spectrum and redshift

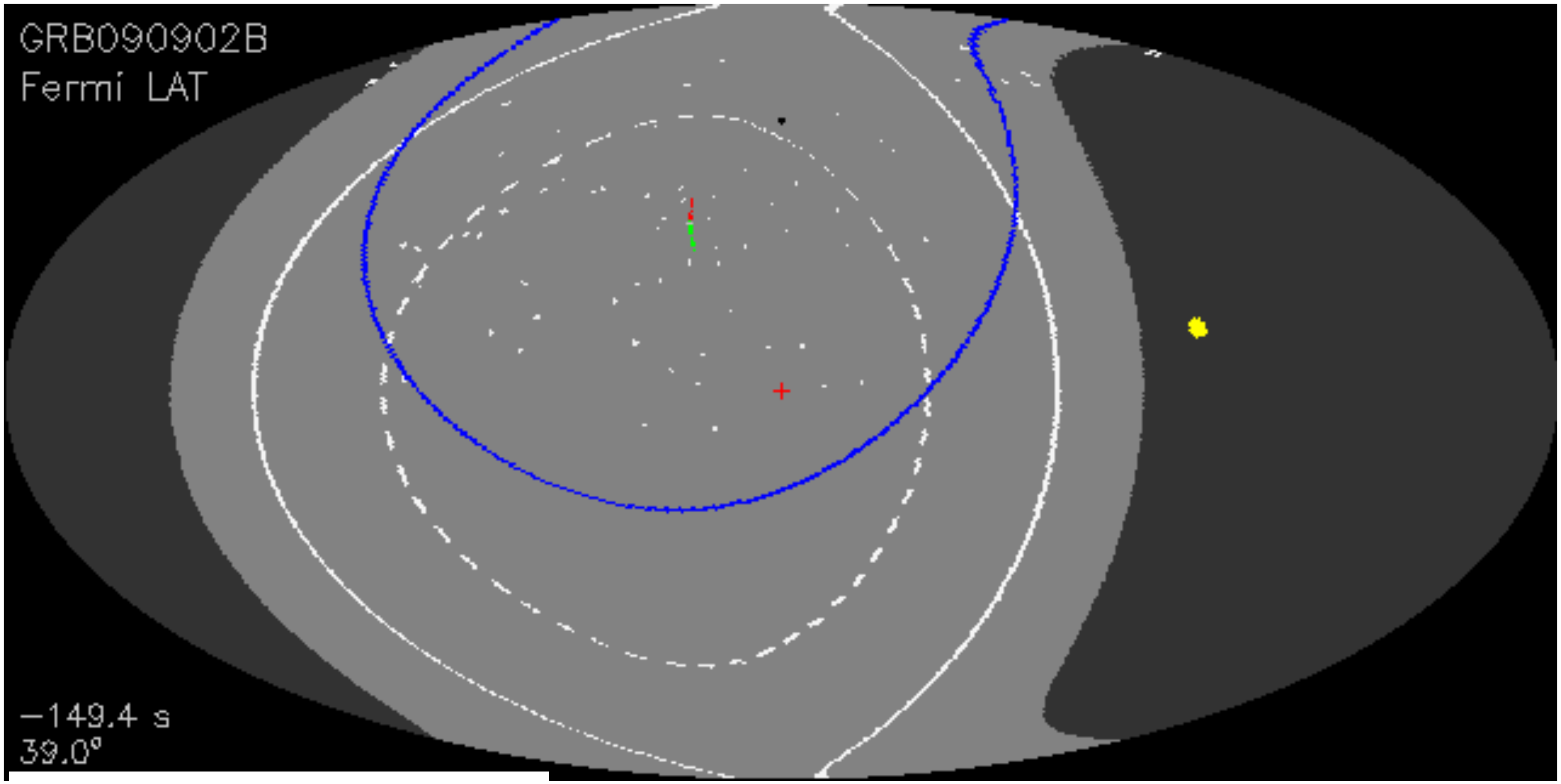


Autonomous Repoint Towards a GRB



- Red cross → GRB090902B
- Red/Green lines → The LAT
- White points → Detected events
- White circle → LAT Field of View
- Dark gray region → Earth's shadow
- Yellow dot → Sun

Autonomous Repoint Towards a GRB



- Red cross → GRB090902B
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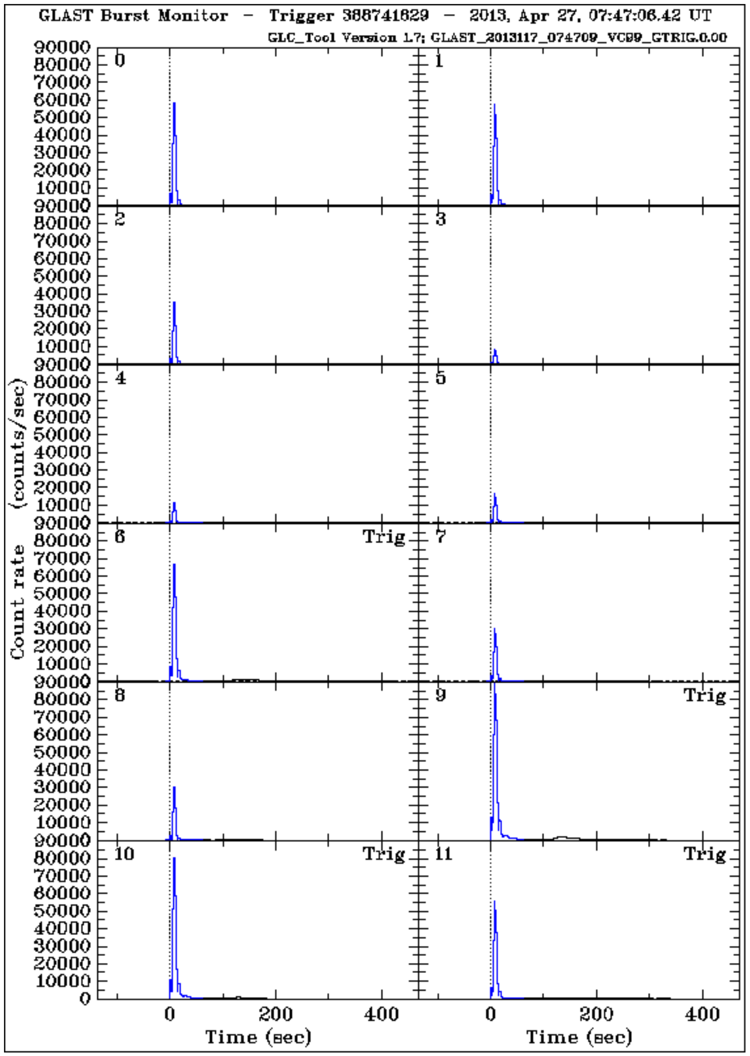
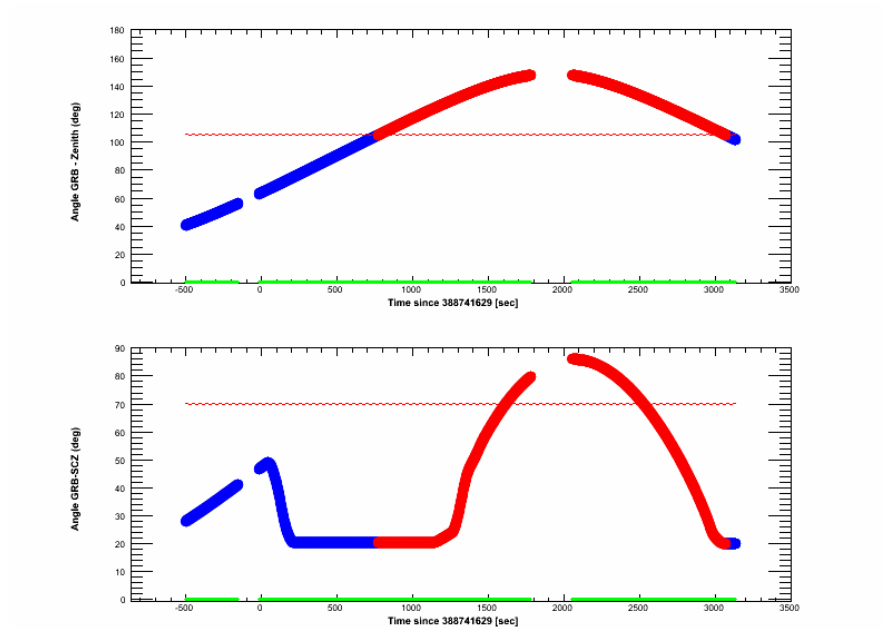
Fermi Observations of a GRB

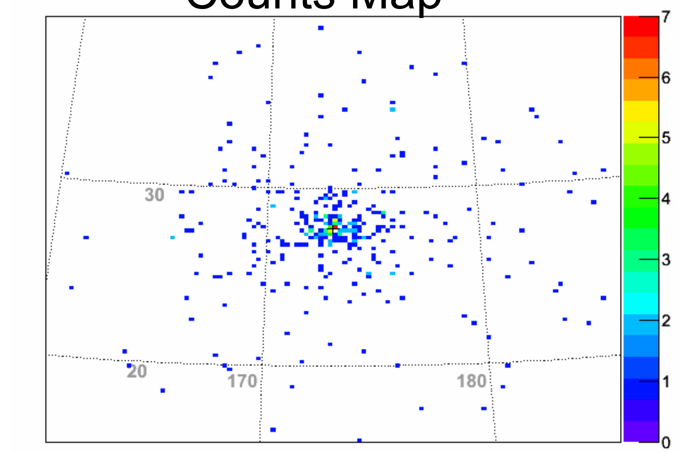
GBM quicklook light curves



GRB relative to zenith and boresight

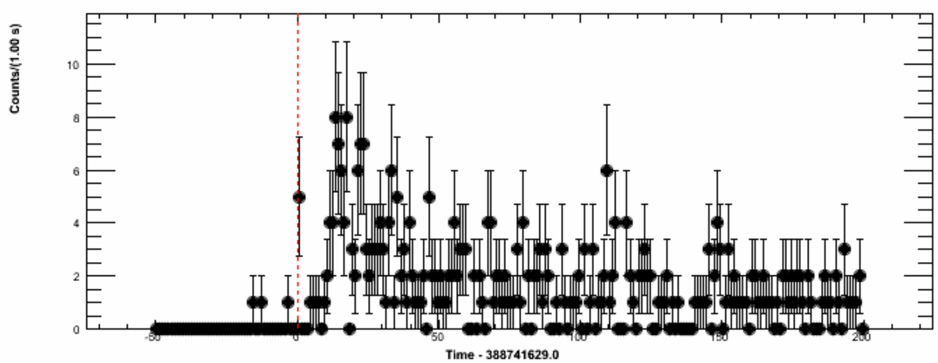


Counts Map

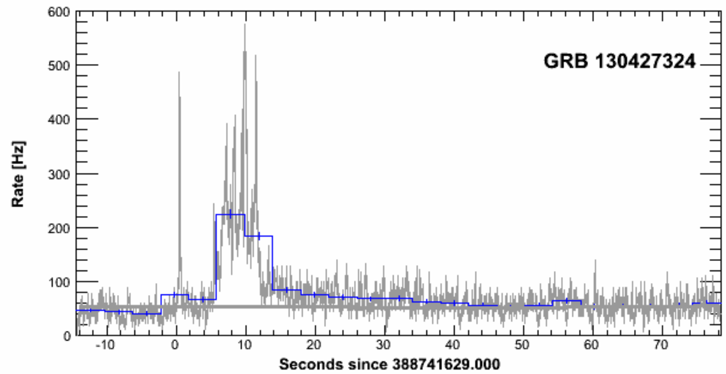


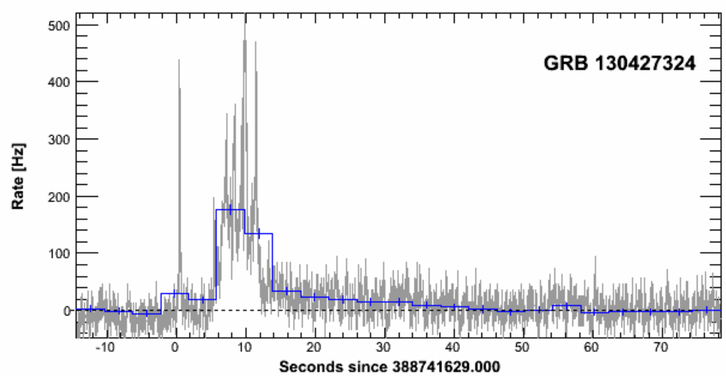
Fermi Observations of a GRB

LAT Light Curve > 100 MeV



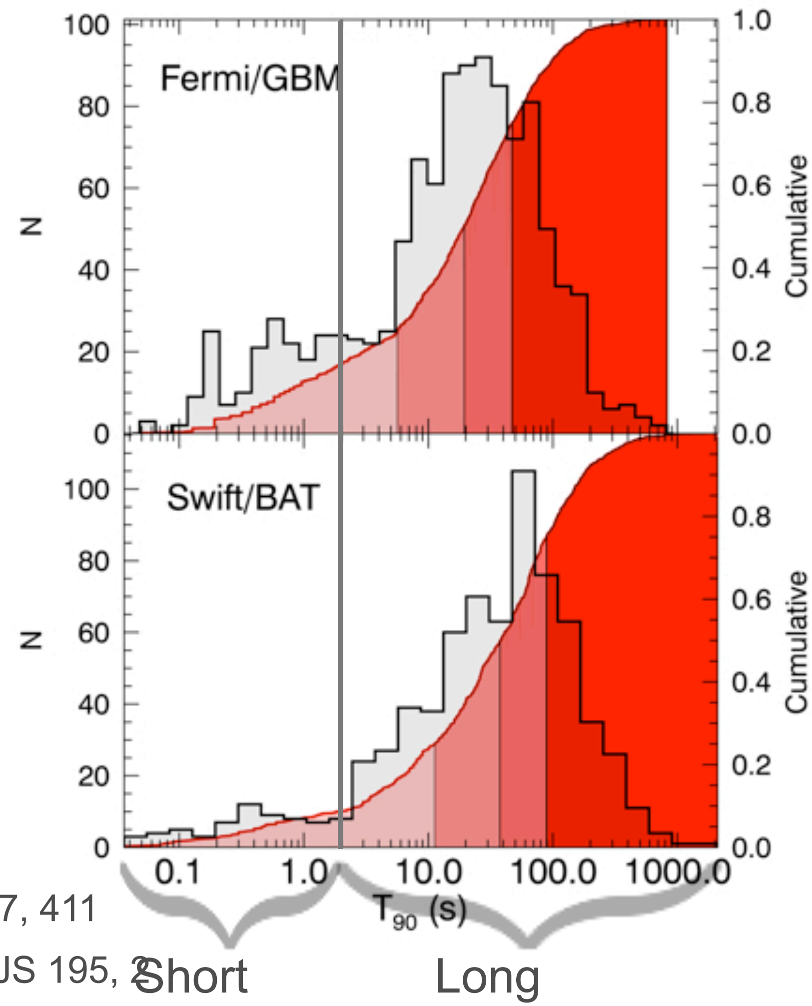
LAT Low Energy (LLE)





Properties of Fermi GRBs

- **GRB Durations**
  - **define simplistic classification scheme**
    - **Short: t< 2 s, long t>2s**
  - **GBM: ~few 10 ms to ~1000**
  - **known to depend on observed energy band and instrument sensitivity**
  - **Long soft tail on some short bursts makes them longer**
  - **Usually discussed in observed frame rather than rest from (1+z dependence)**
  - **Classification by duration is not clean**



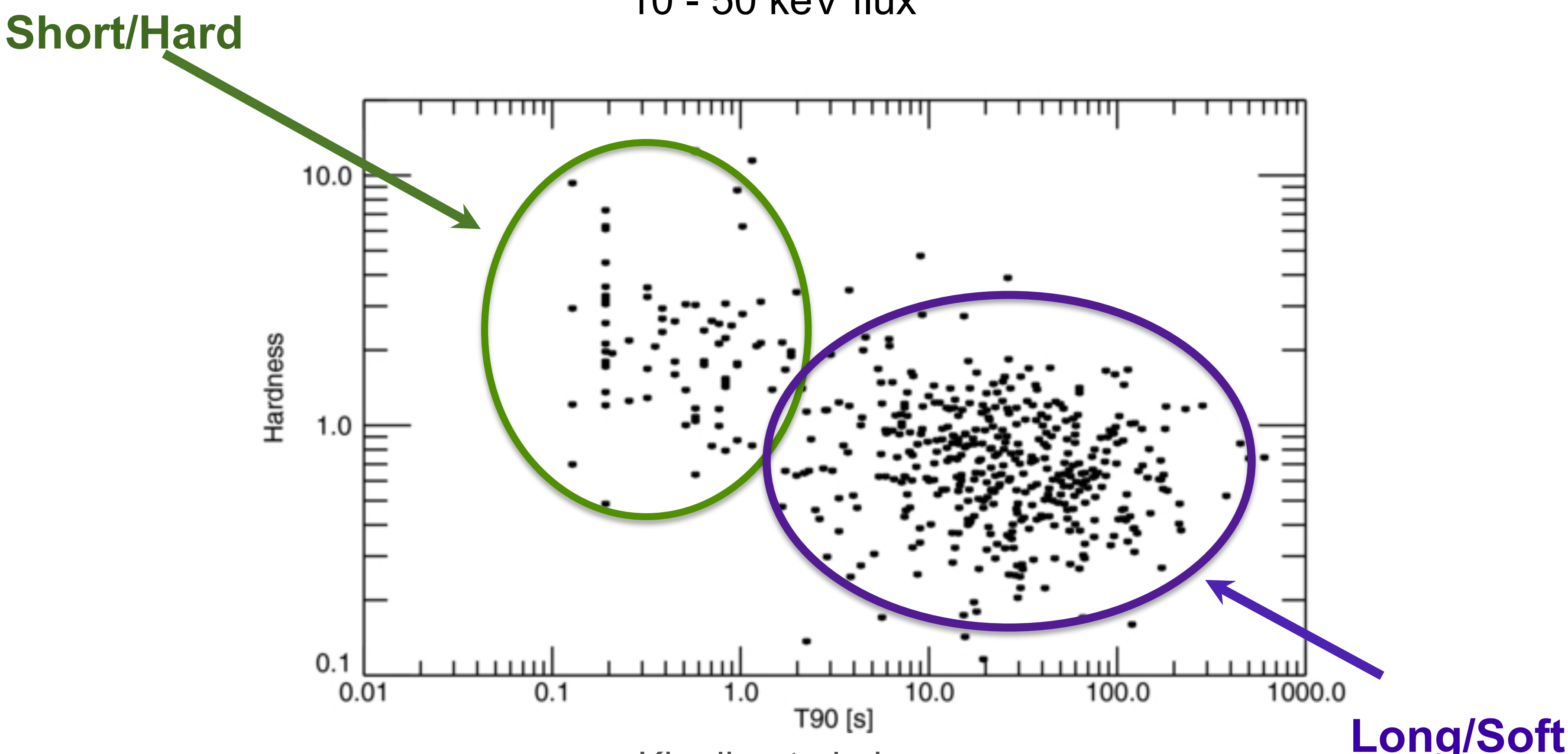
Norris et al. 2010, ApJ 717, 411

Sakamoto et al. 2011, ApJS 195, 2

Qin et al. 2013, ApJ 763, 15

Hardness-Duration Classification

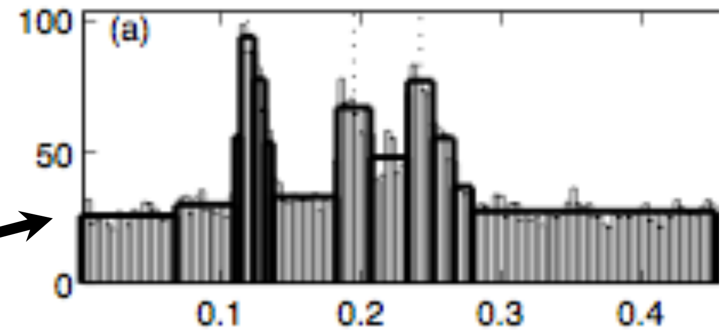
$$H = \frac{50 - 300 \text{ keV flux}}{10 - 50 \text{ keV flux}}$$



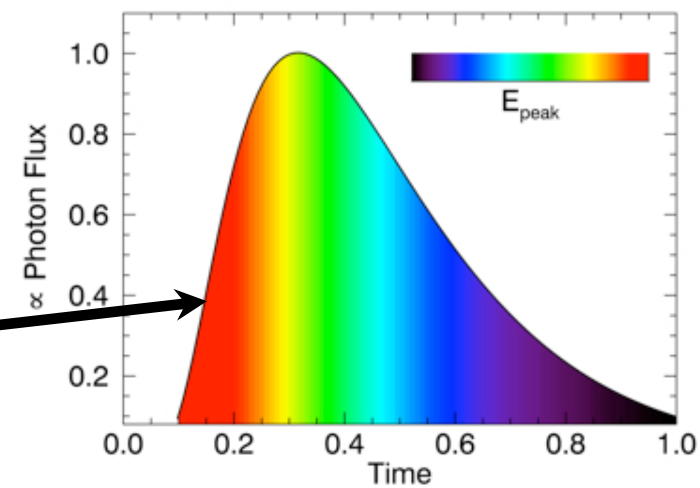
von Kienlin et al., in prep.

Pulse Spectral Evolution

- Want to employ temporal pulse-fitting techniques to separate out overlapping pulses
- Bayesian Blocks
- Several proposed functional forms for pulse-fitting
- The spectrum tends to temporally evolve from harder to softer energies through the duration of a single pulse



Scargle 1998, ApJ 504, 405



Spectral Lag

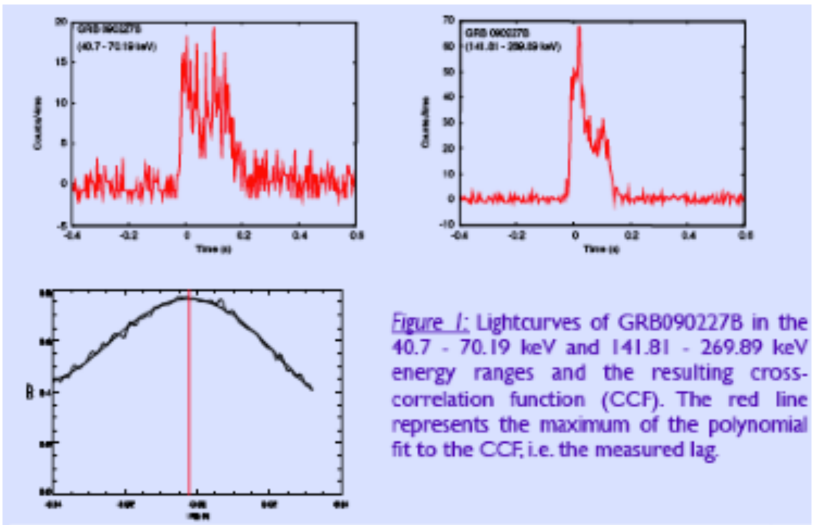
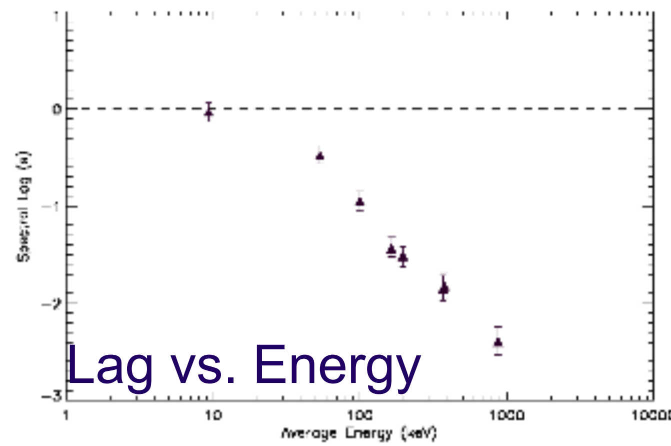
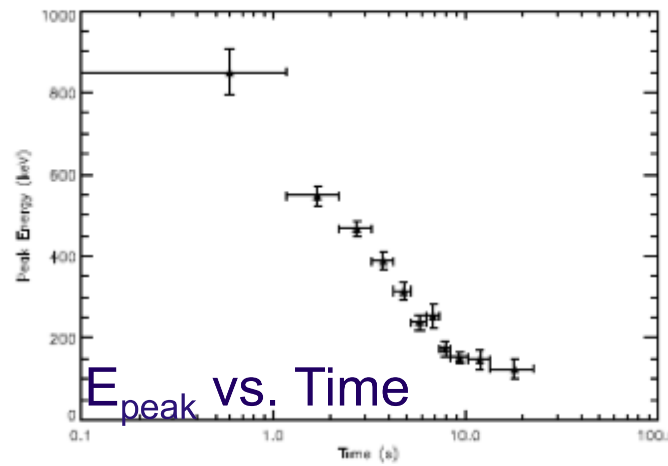


Figure 1: Lightcurves of GRB090227B in the 40.7 - 70.19 keV and 141.81 - 269.89 keV energy ranges and the resulting cross-correlation function (CCF). The red line represents the maximum of the polynomial fit to the CCF, i.e. the measured lag.

- Difference between time arrival of low- and high-energy photons
- Peak of CCF indicates spectral lag
- Spectral lag may correlate with temporal behavior of Epeak

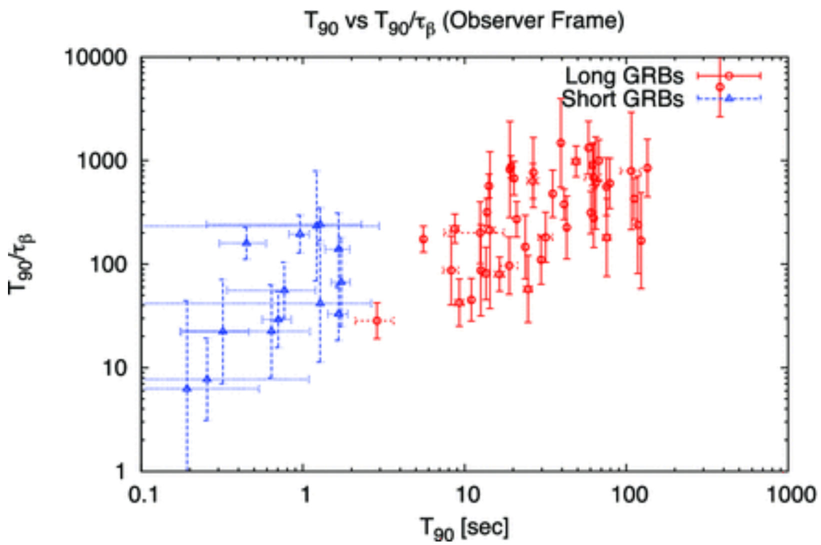
GRB 081124





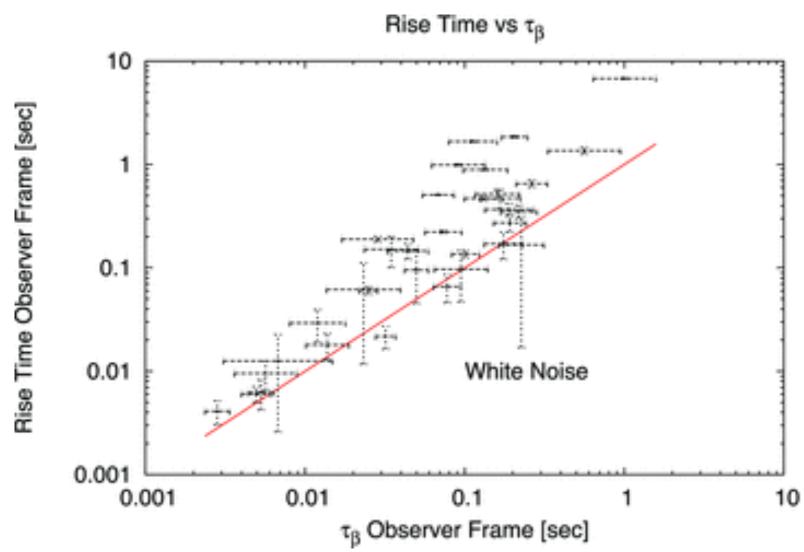
Foley et al. AIP Conf. Proc. #1358, 183, 2011

Temporal Variability



MacLachlan et al. 2013, MNRAS, 432, 857

- Minimum Variability Time Scale different for short and long GRBs
- Correlated with Minimum Rise Time



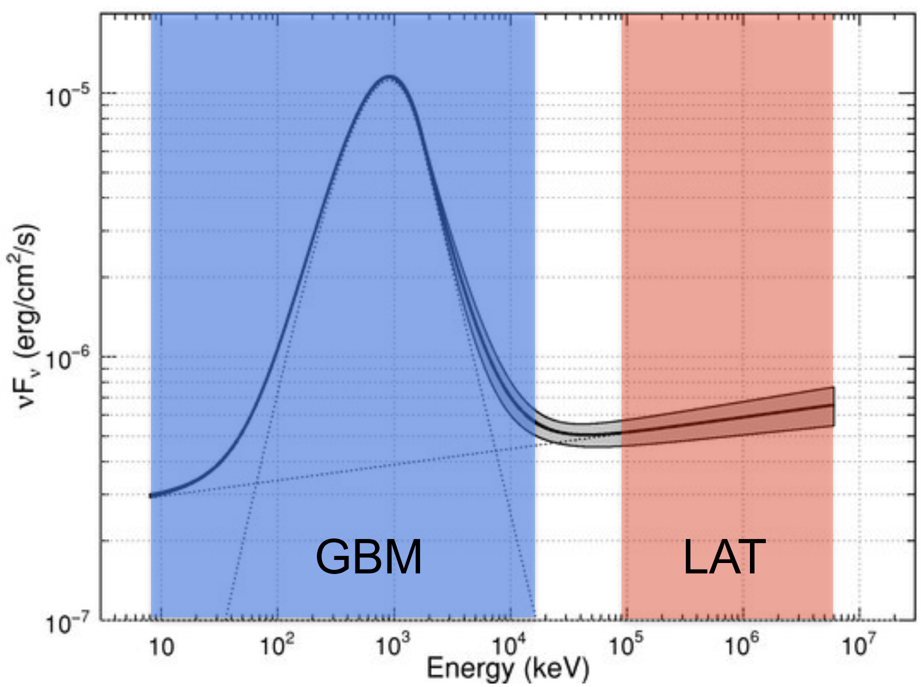
MacLachlan et al. 2012, MNRAS 425, L32

- Not caused by cosmological redshift
- Variability time scale -> minimum Lorentz factor

Common New Features in Bright Fermi GRBs

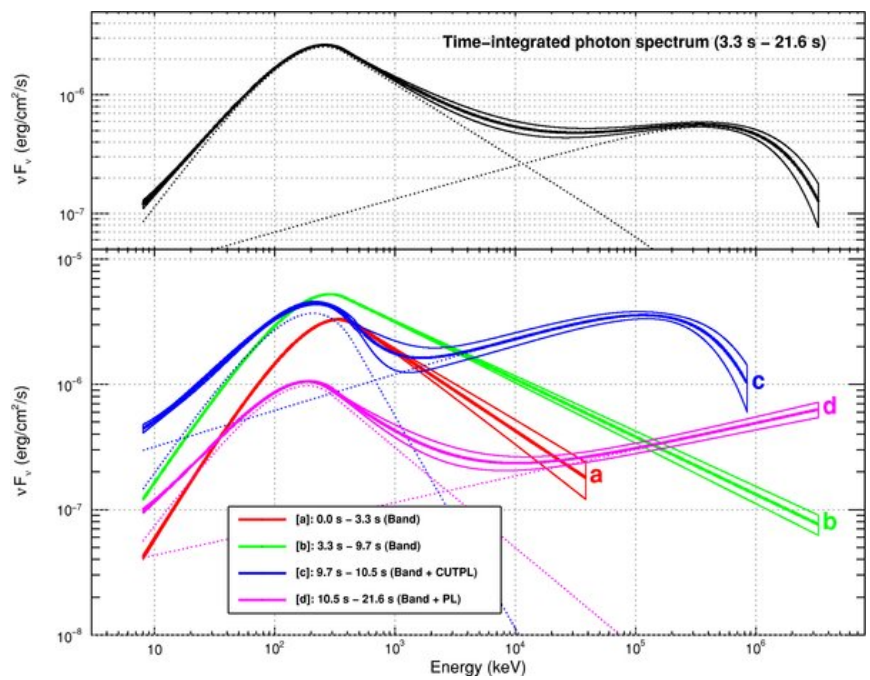
- **GRB spectra deviate from Band functions**
  - **Low energy deviation**
  - **Additional power law at high energies**
  - **High energy cut-offs is some cases**

GRB 090902B



Abdo et al. 2009, ApJ, 706L, 138A

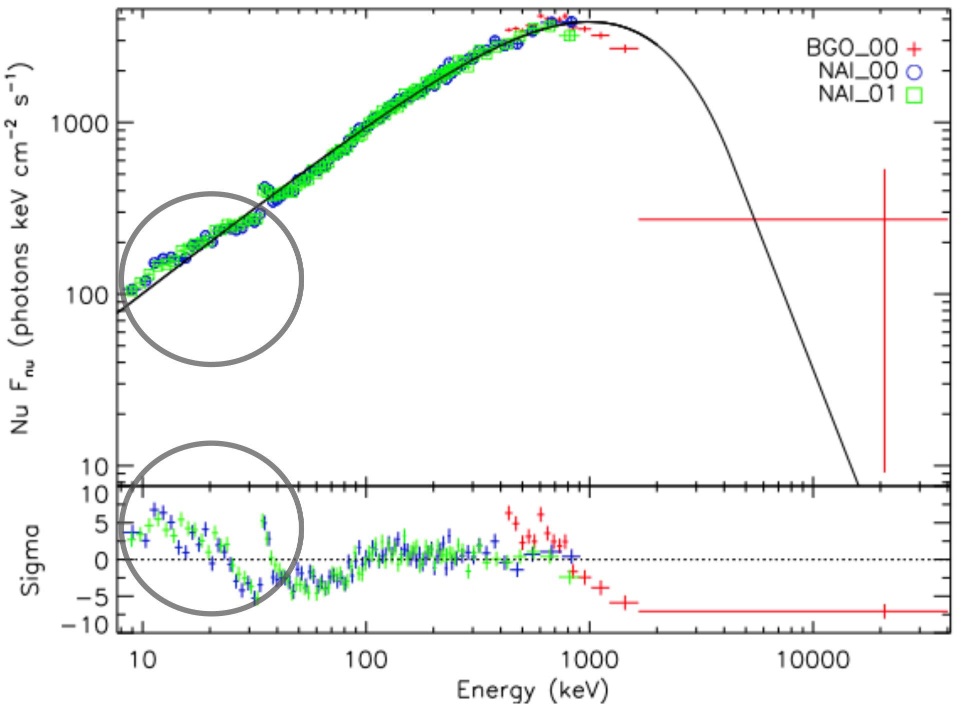
GRB 090926A



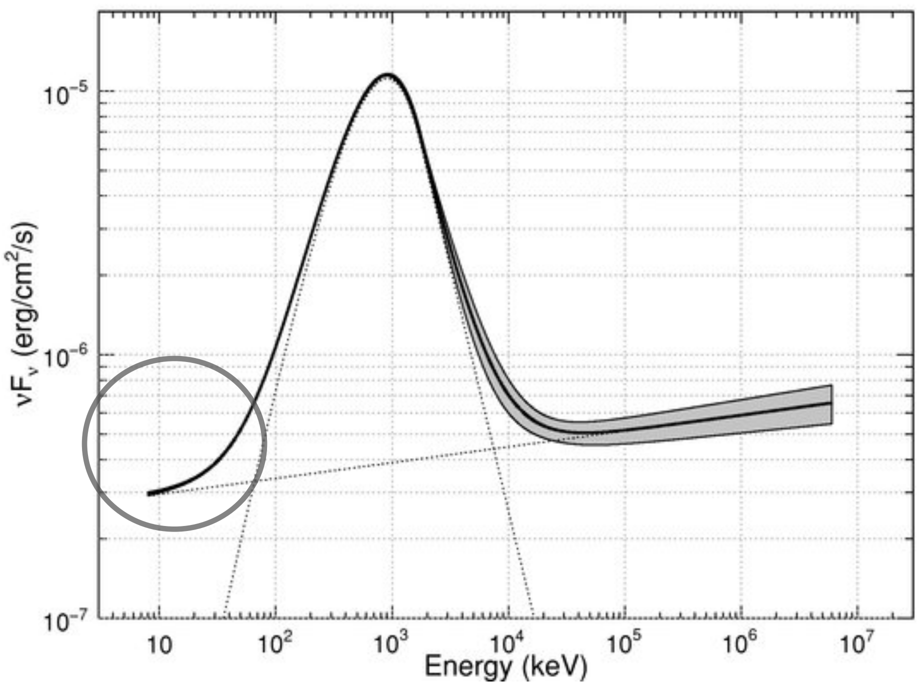
Ackermann et al. 2011, ApJ, 729, 114

Low-Energy Excess

GRB 090902B



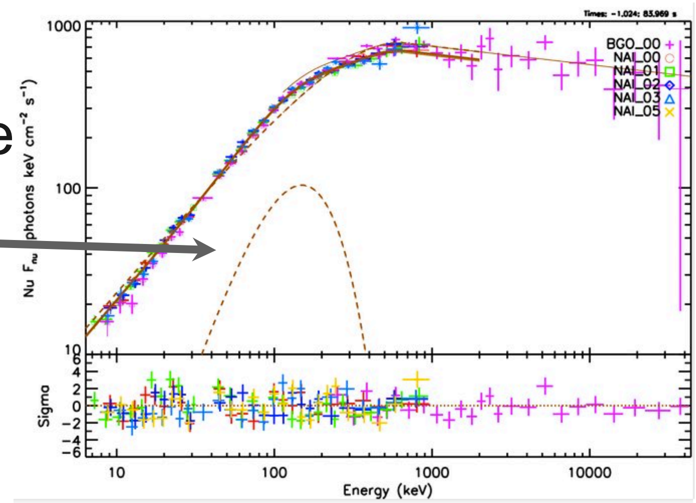
Tierney et al. 2013



Abdo et al. 2009, ApJL 706, 138

Thermal Emission - Photospheric?

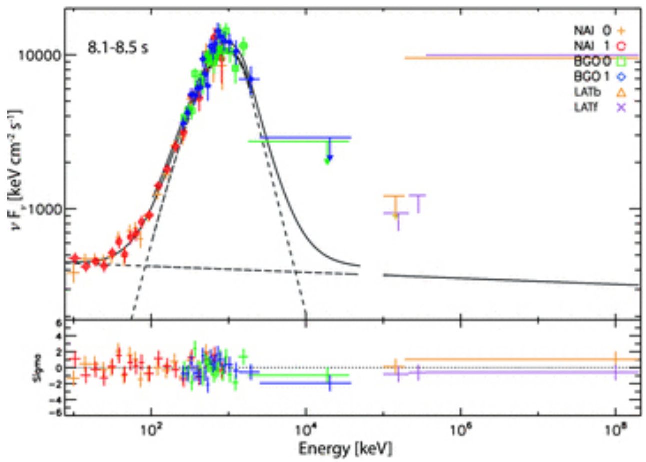
GRB 100724B

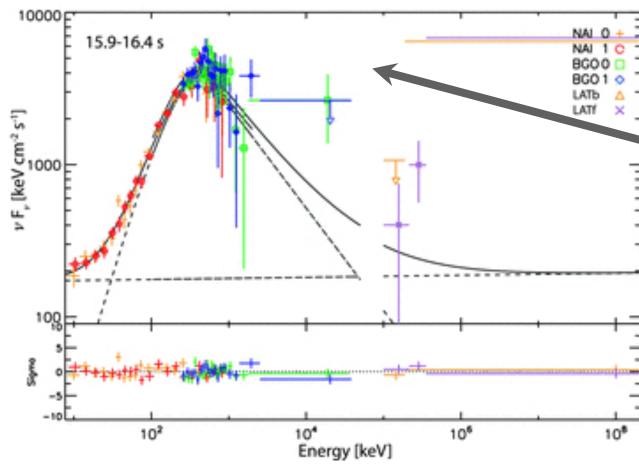


Guiriec et al. 2011, ApJL 727, L33

GRB 090902B

Sub-dominate Blackbody





Broadening not consistent with Band function

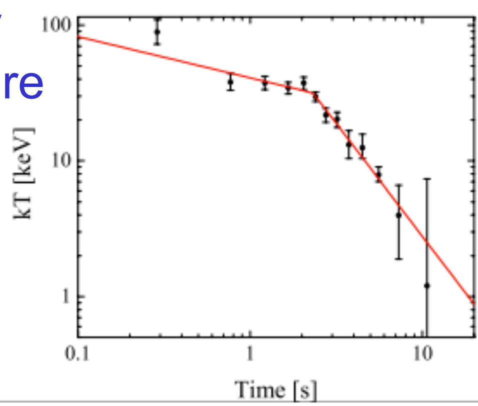
Ryde et al. 2011, MNRAS 415, 3693

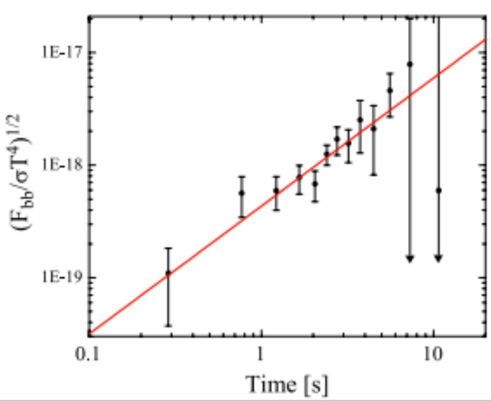
Photospheric Emission

- Blackbody emission from turbulent relativistic outflow
- Deviations from Band function
- Thermal photosphere doesn't have to emit as a blackbody – smeared by multiple temperatures, evolution, different emission regions
- However, GRB 090902B is best fit by a dominant blackbody component + power law
- Low energy excess in many other bursts fit by a sub-dominant blackbody

GRB 110721A

Evolving blackbody temperature



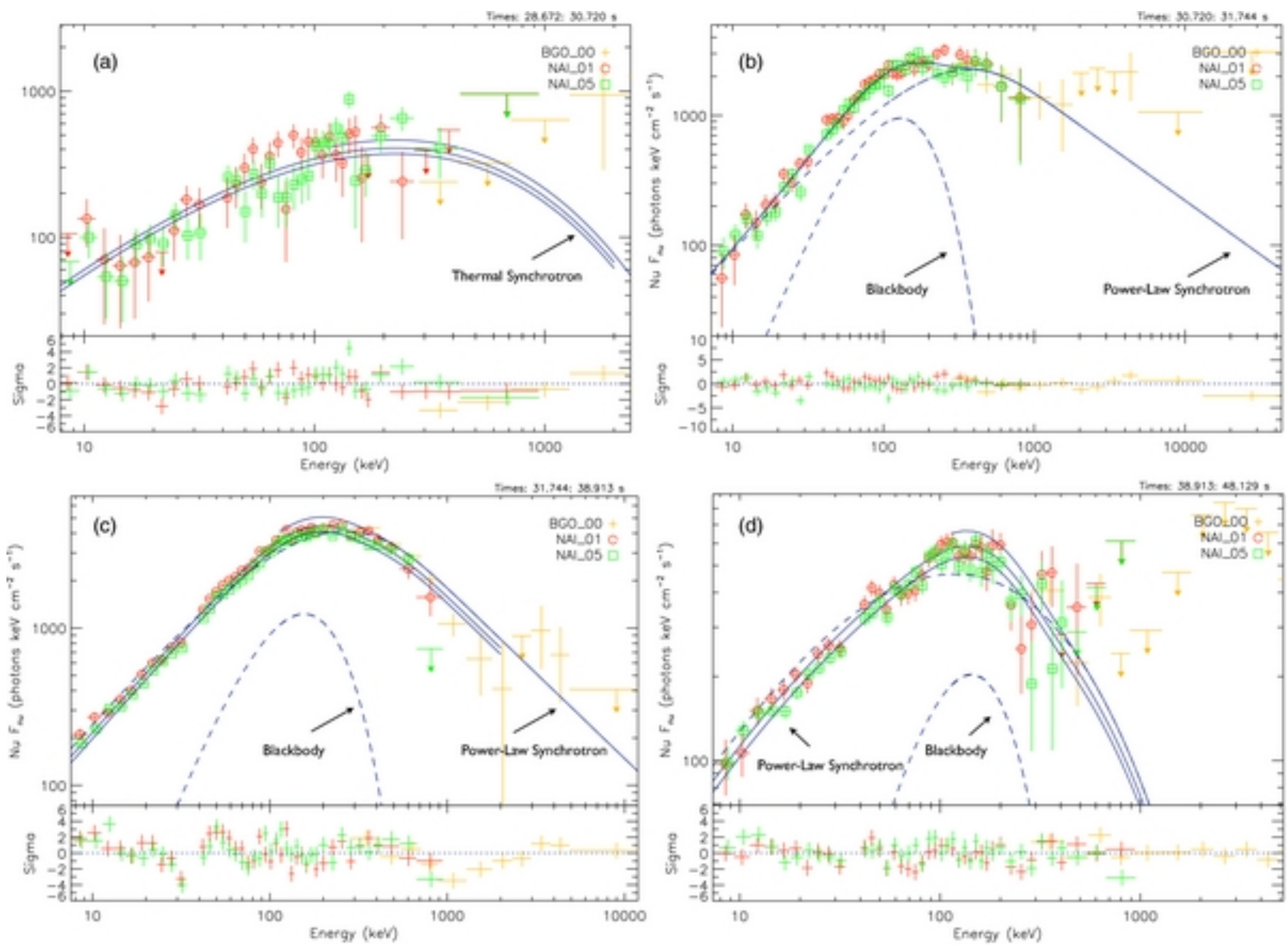


Evolving blackbody normalization

Axelsson et al. 2012

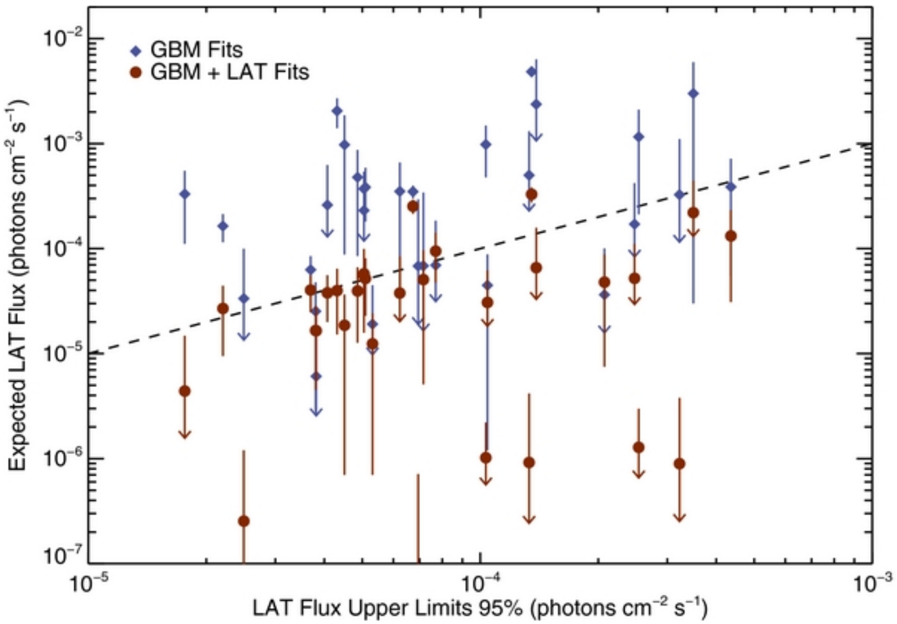
Non-Thermal Emission - Synchrotron?

GRB 090820A

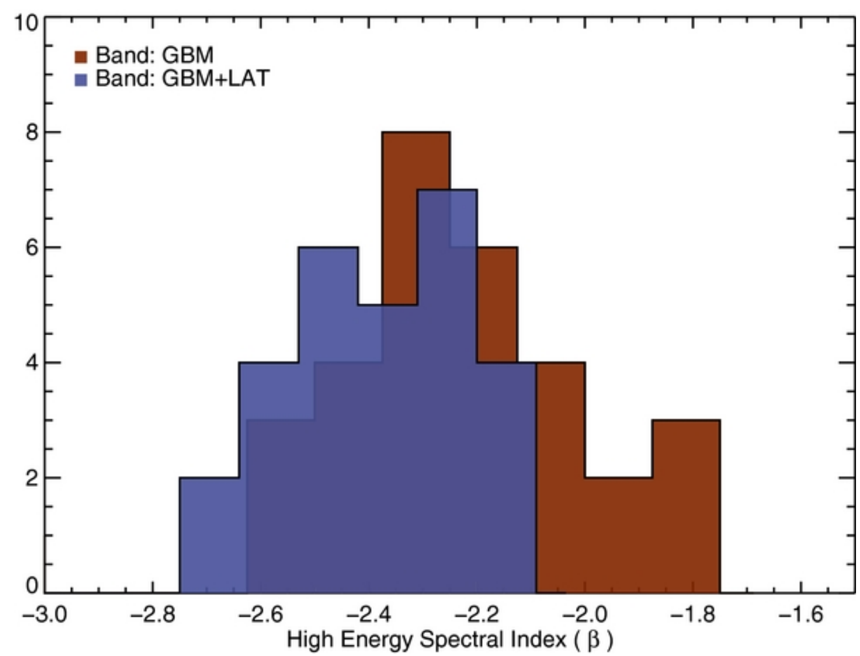


Burgess et al. 2011, ApJ 741, 24

Cutoffs in the Spectra – constraints from upper limits



- Inclusion of higher energy -> steeper beta
- Extrapolation of flux to higher energies over-predicts the actual flux



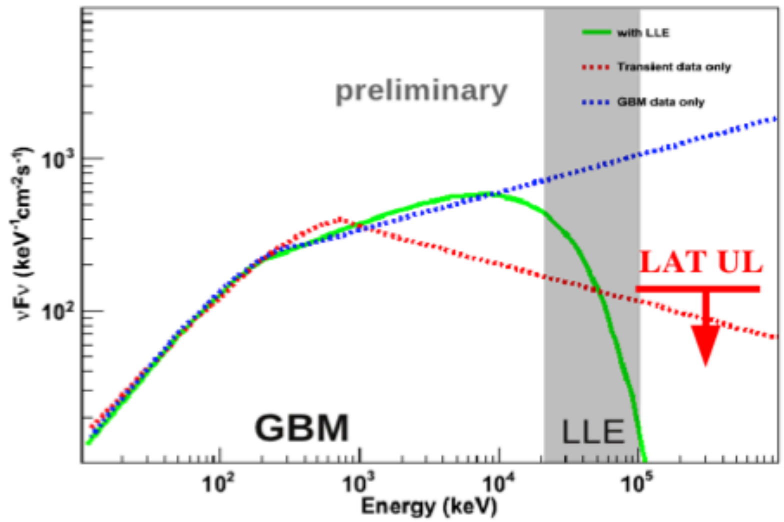
- ~50% of sample have expected fluxes > 95% CL upper limit when using low-energy data only
- Cutoffs likely between 40 & 100 MeV

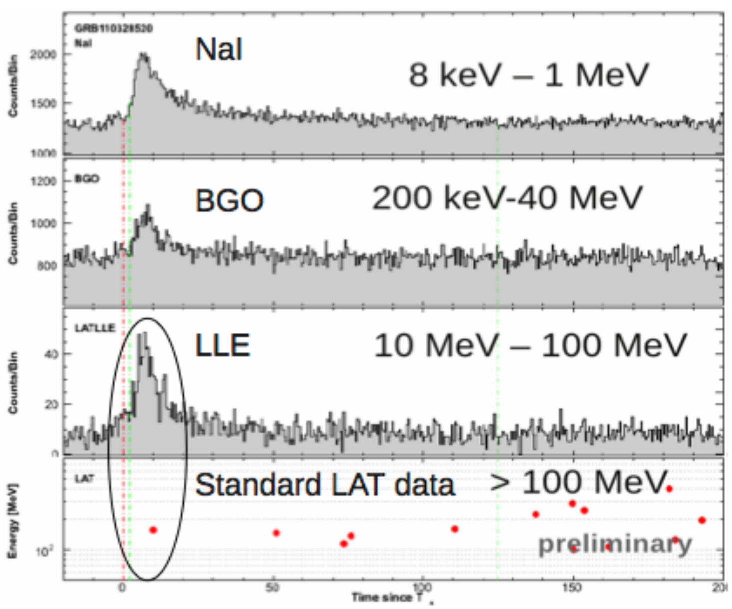
Ackermann et al., 2012, ApJ 754, 121

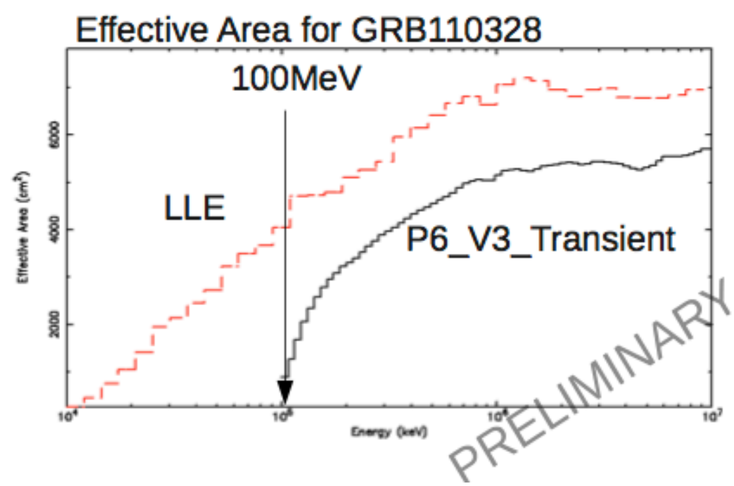
Spectral Cutoffs and the LLE Event Class

- **Standard LAT event selections ("Transient" class) run out of effective area at E<100MeV.**
- **"LAT Low Energy" (LLE) event selection → Very relaxed set of cuts → plenty of statistics in the tens-of-MeV-energy gap to probe GRB spectral cutoffs.**

To access LLE data:
http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html



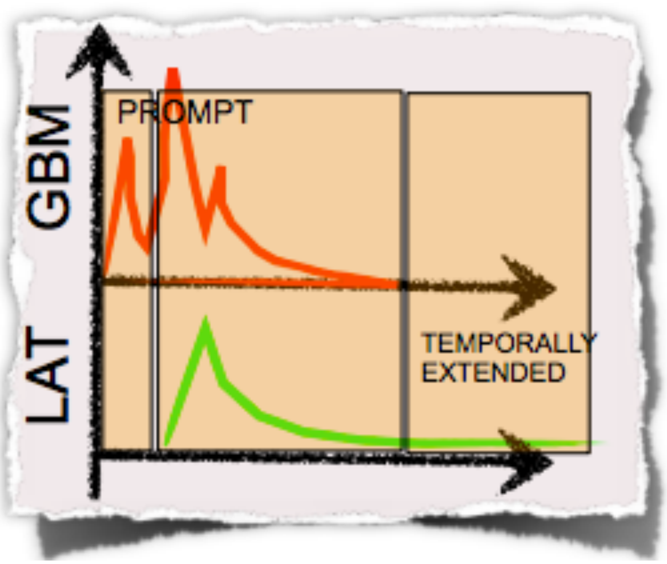




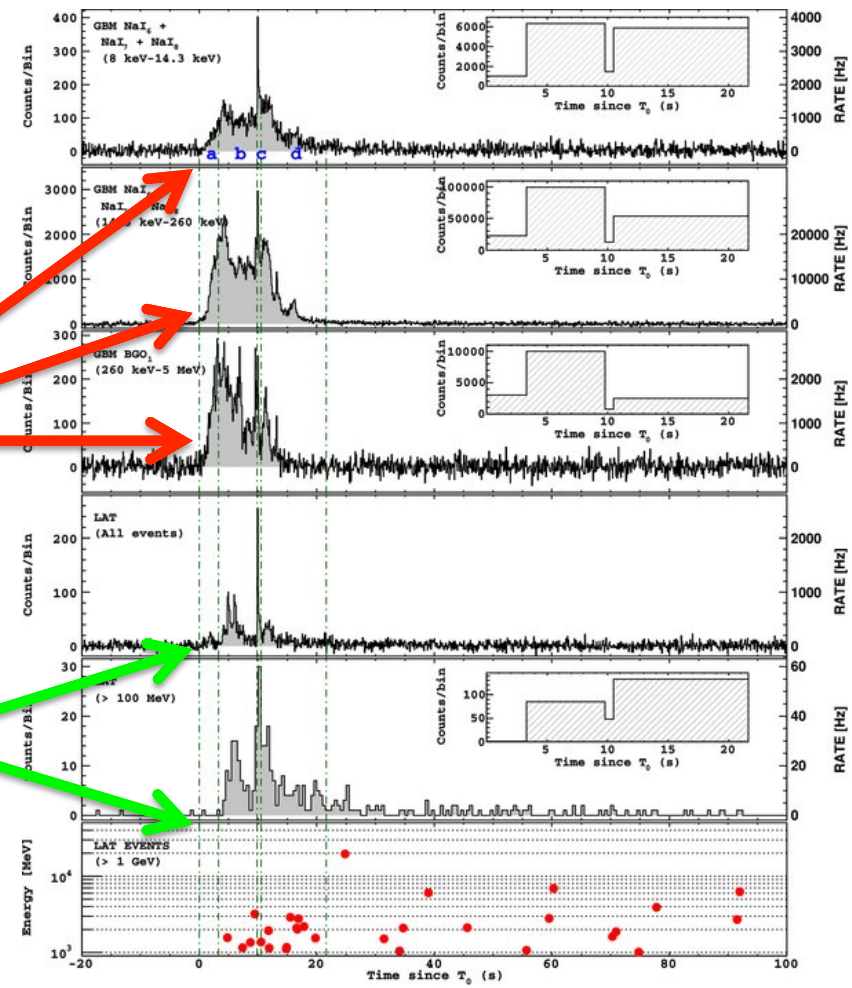
Credit: Vlasios Vasileiou

Common New Features in Fermi GRBs

- **LAT High-energy emission sometimes starts later the GBM low-energy emission**



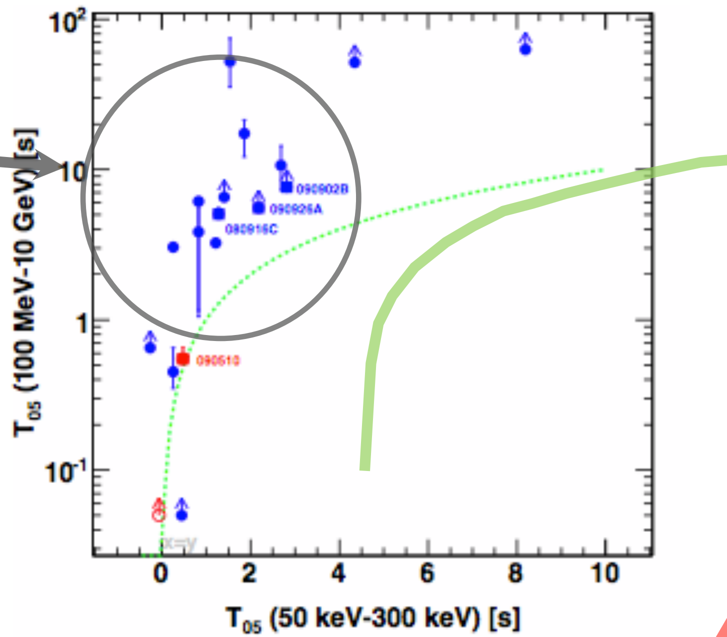
Credit: Nicola Omodei

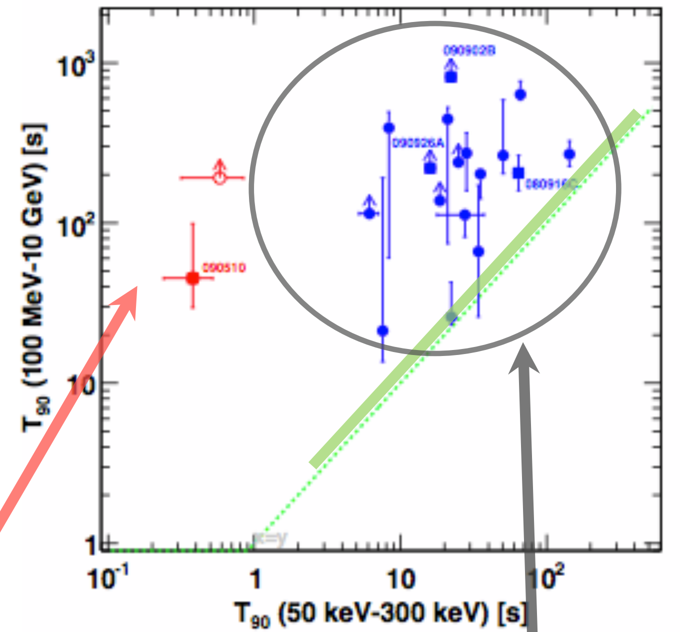


Ackermann et al. 2011, ApJ, 729, 114

Delayed High-Energy Emission

High-energy emission in the LAT is delayed from the emission in the GBM





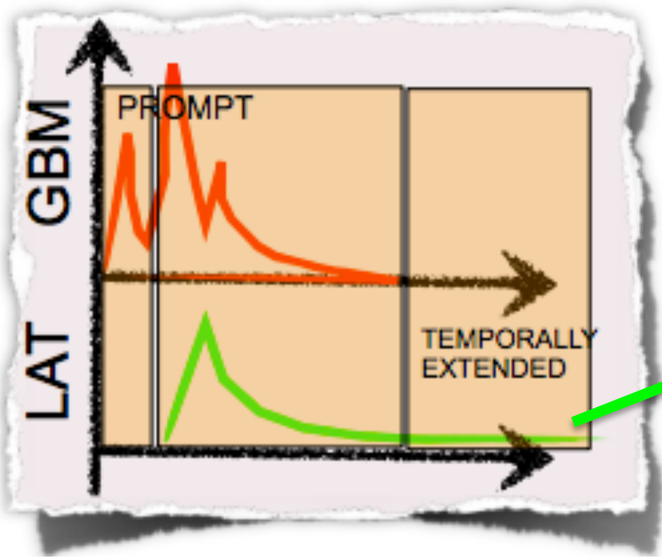
LAT Team et al., 2013, arXiv: 1303.2908

High-energy emission in the LAT also extends beyond the duration of the emission in the GBM

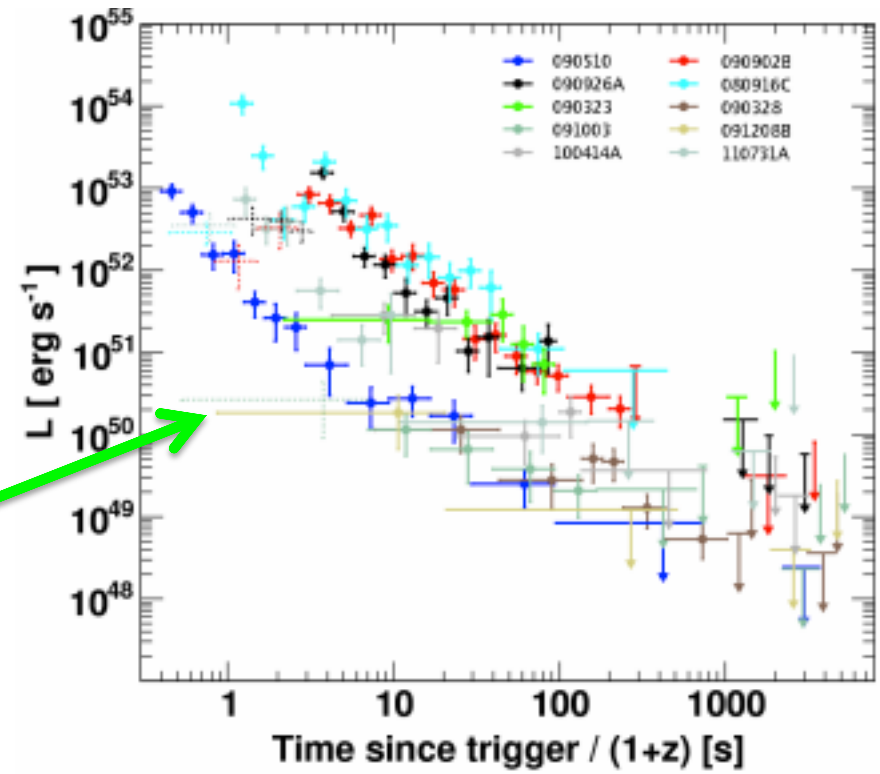
Short and Long GRBs show same extended emission behavior

Common New Features in Fermi GRBs

- **LAT High-energy emission sometimes lasts significantly longer then the GBM low-energy emission**



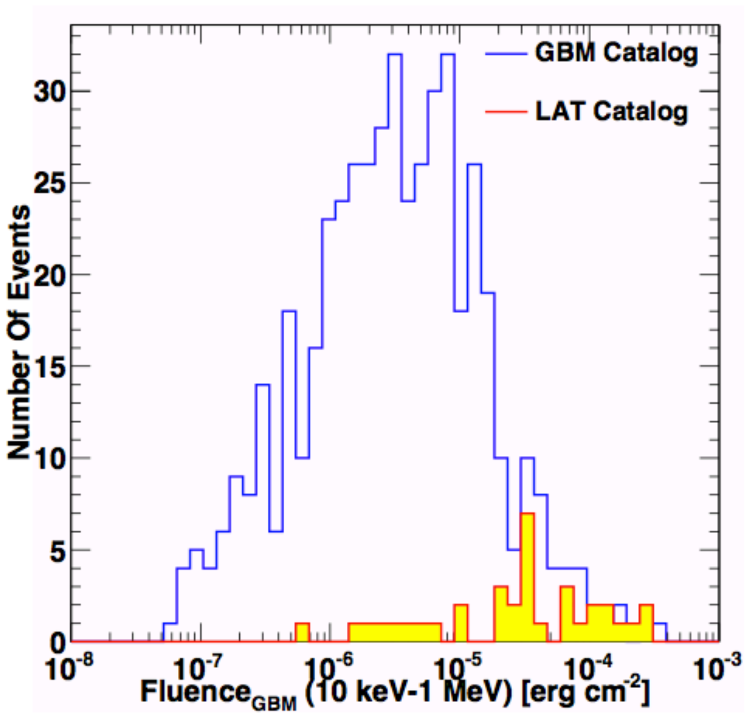
Credit: Nicola Omodei

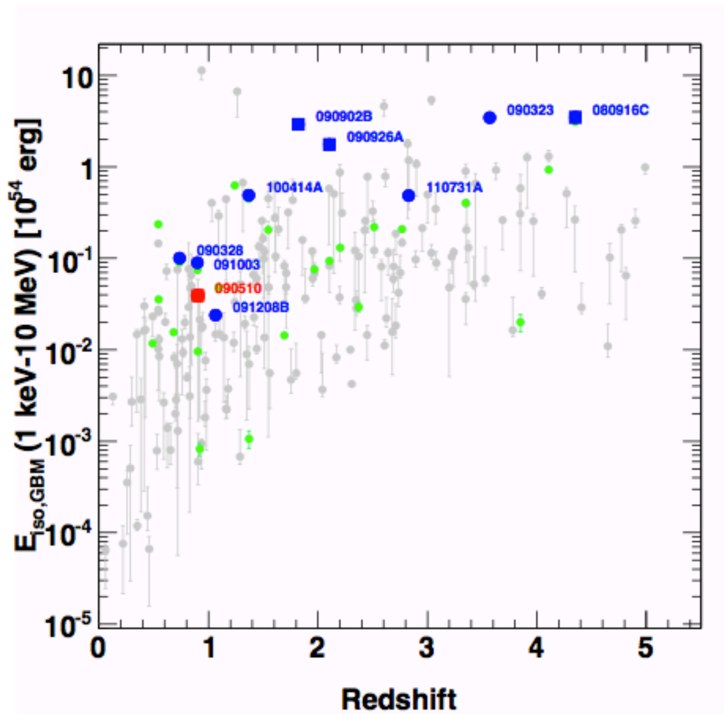


LAT Team et al., ArXiv:1303.2908

Energetics

- **LAT GRBs are among the highest fluence and highest intrinsic isotropic energy of all GRB bursts**

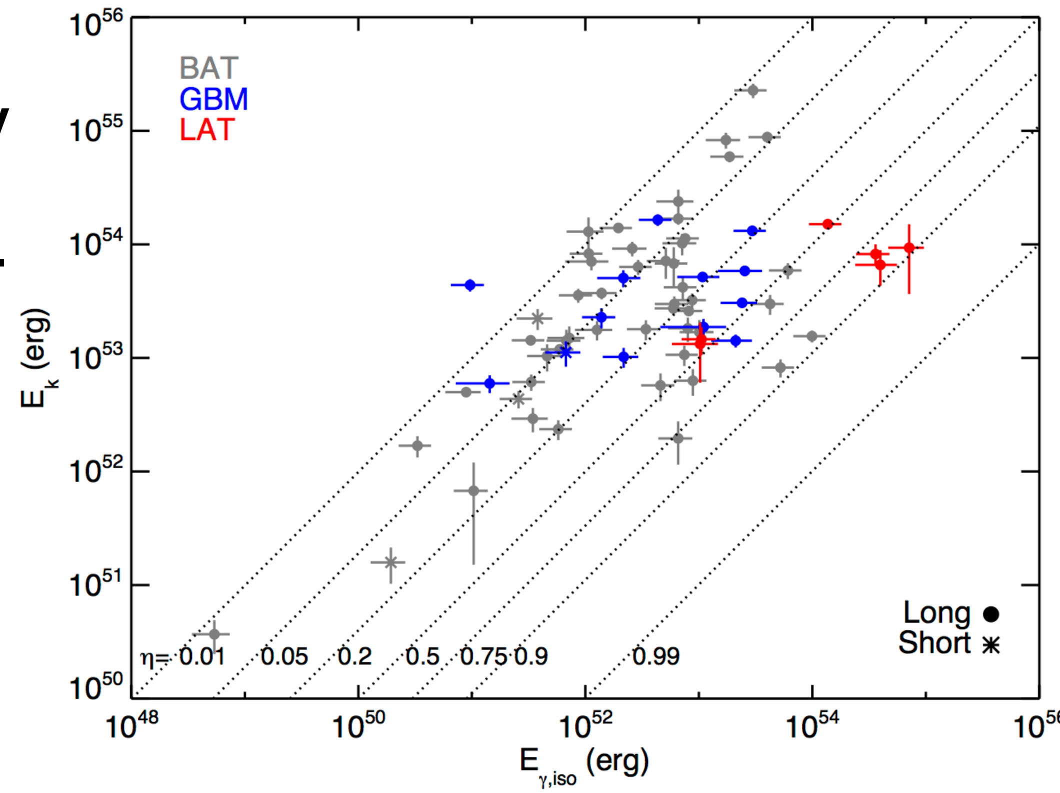




LAT Team et al., ArXiv:1303.2908

Radiative Efficency

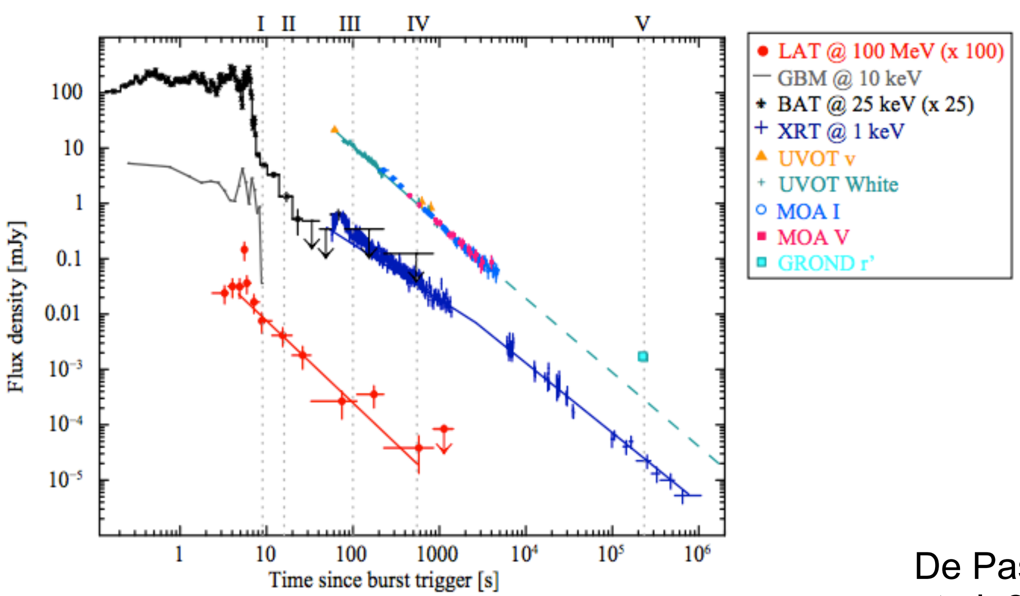
- **LAT GRBs have higher radiative efficiencies compared to those that don't produce high energy emission**
- **Derived from both gamma-ray and X-ray properties (model dependencies)**



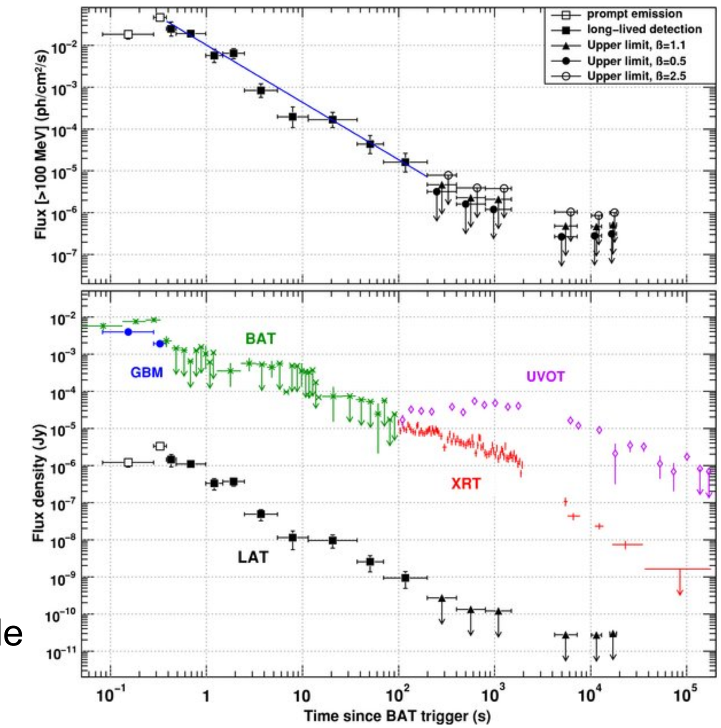
Racusin et al. 2011

Simultaneous Swift+Fermi Detections

- **At least 9 GRBs have been simultaneously detected by Swift and Fermi-LAT**
  - **GRB 090510 (de Pasquale et al 2010)**
  - **GRB100728A [Fermi Collaboration (Abdo et al ApJ 2011)]**
  - **GRB110625A [Tam, Kong and Fan, ApJ 2012]**
  - **GRB110731A [Fermi Collaboration (Ackermann et al 2013)]**
  - **GRB 120624B [GCN]**
  - **GRB 121011A, 130206A, 130305A (LLE only, GCNs)**
  - **GRB 130427A (3 papers already on arXiv and counting)**

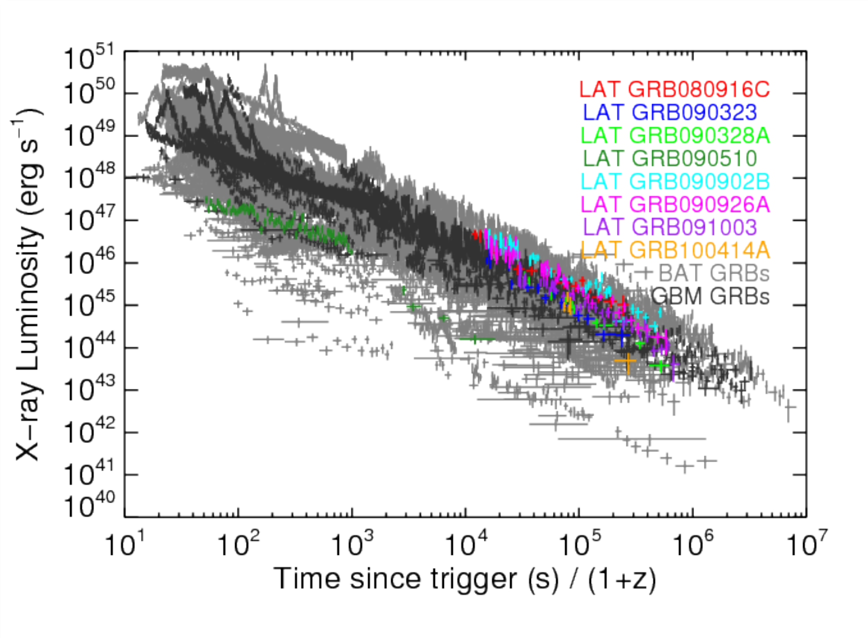


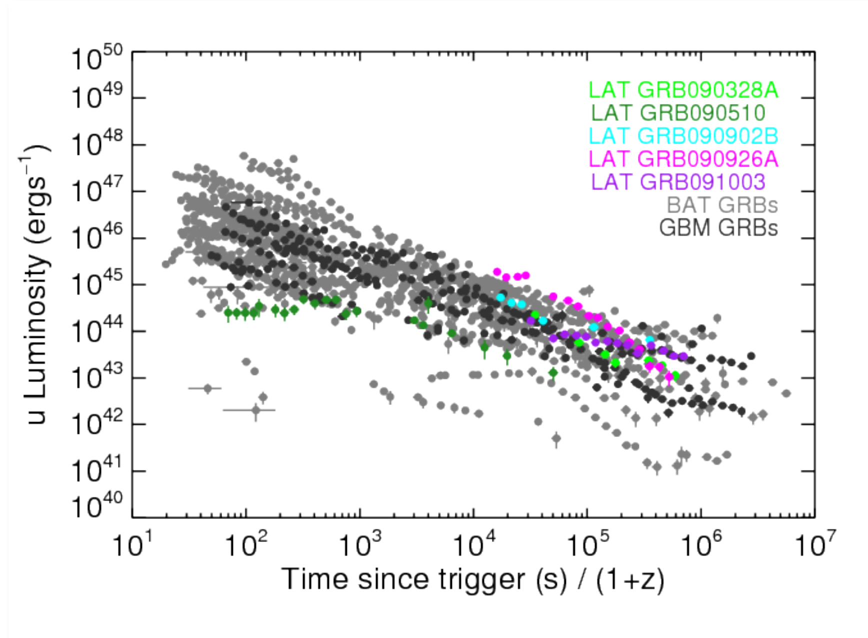
Ackermann et al 2012

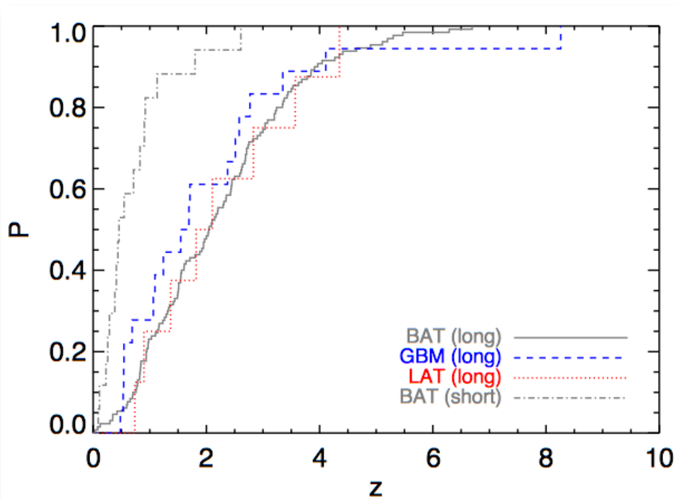


De Pasquale et al. 2010

Swift Follow-up of Fermi GRB Afterglows



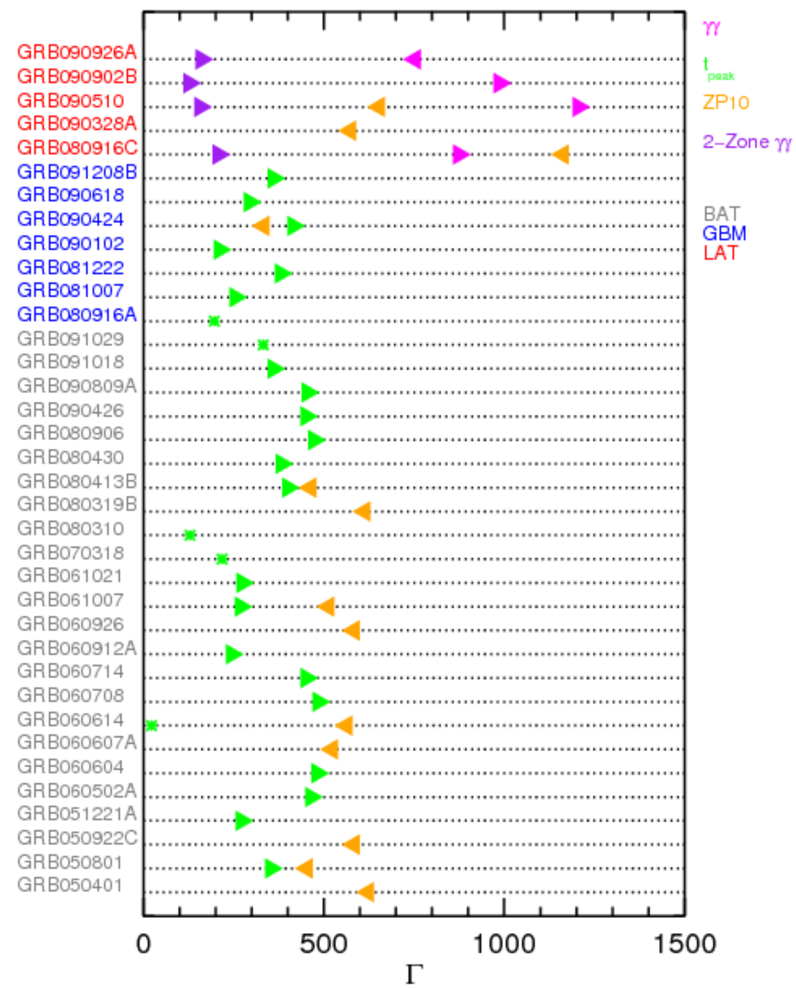




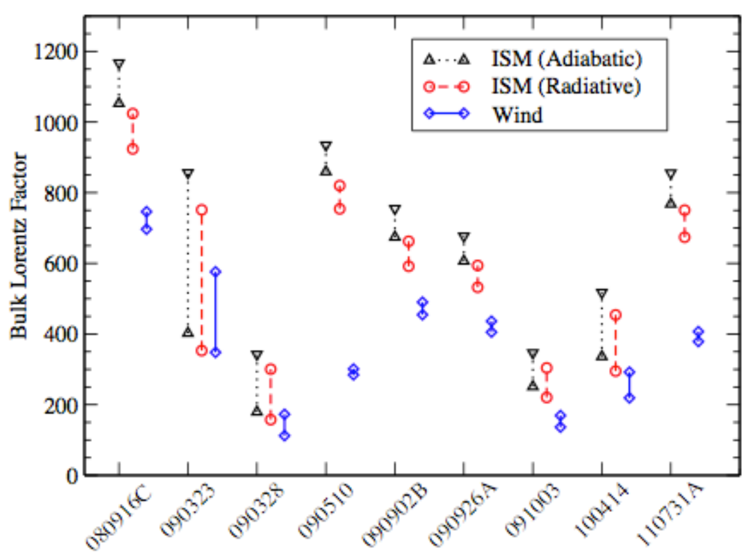
Racusin et al. 2011

Bulk Lorentz Factors

- Measure from early peak of afterglow
  - LAT?
  - Optical
- γγ pair opacity
  - Depends on multiple emission zones
  - Uses cutoffs or limits from high-E photns in LAT spectra



Racusin et al. 2011



LAT Team et al., ArXiv:1303.2908

Physical Origin of Temporally Extended 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

Fast-Cooling Adiabatic “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):
    - The flux decay in a particular energy band depends on the fast- or slow-cooling spectral models as well as on the surrounding environment (ISM or Wind) [Sari 1997, Katz & Piran 1997, Sari et al. 1998; Chevalier & Li 2000; Panaitescu & Kumar 2000, Ghisellini 2010]
    - LAT-detected >100 MeV emission is likely to be from the early afterglow phase:
      - fast-cooling part of the spectrum [Sari et al. 1998; Granot & Sari 2002]
      - $\alpha=(12\beta - 2)/7$ for radiative fireball
      - $\alpha=(3\beta - 1)/2$ for an adiabatic fireball
    - In the LAT data, $\beta = -\Gamma_{EXT} - 1 = 1.00 \pm 0.04$, and $\alpha_{radiative} = 10/7$ and $\alpha_{adiabatic}=1$
    - => Adiabatic expansion [Kumar & Barniol Duran 2009; De Pasquale et al. 2010; Razzaque 2010] (decay index ~1) rather than radiative (~1.5) [as Ghisellini et al. (2010)]

Conclusions

- Fermi gets a unique view of GRBs that is providing insight into the physics of GRBs, their environments, and as probes of the Universe
- As we collect more data, we'll see more unusual bursts, that have excellent broadband and maybe even multi-messenger observations
- We hope that both Fermi and Swift can continue operating for many years, providing broad observations, and triggers to other facilities