High-energy observations of Gamma-Ray Bursts with *Fermi*

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For the Fermi GBM and LAT collaborations

Ioffe Workshop on GRBs & other transient sources:
20 Years of Konus-Wind Experiment

Outline

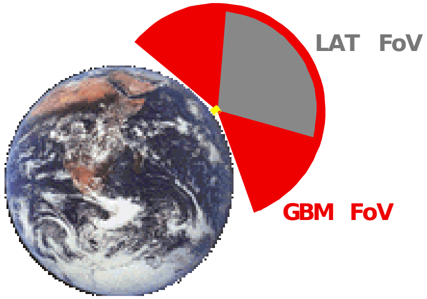
- **The Fermi observatory**
- **GRB properties from keV to GeV**
  - Population studies
  - Characteristics of some individual bursts, including GRB 130427A
- **Physical implications and open questions**
  - GRB jet physics
  - Lorentz Invariance Violation

The instruments onboard *Fermi*

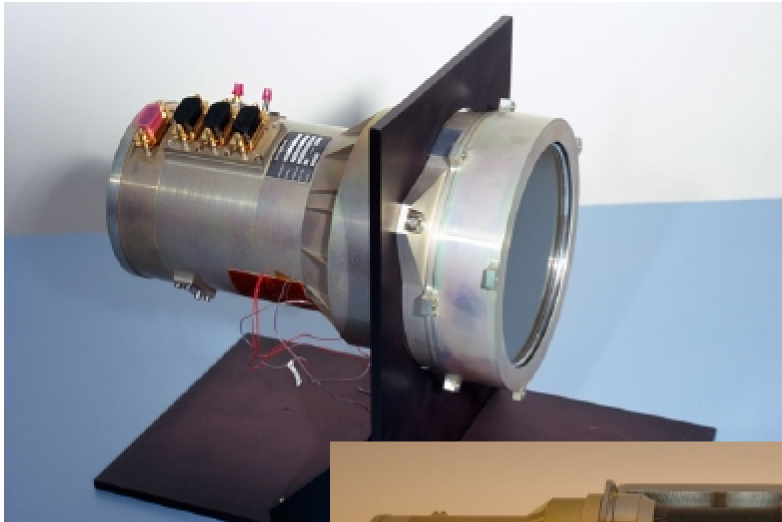
Atwood et al. 2009, ApJ 697, 1071
Meegan et al. 2009, ApJ 702, 791

- **Large Area Telescope (LAT)**
  - Large field of view (2.4 sr @ 1 GeV)
  - Sees the entire sky every 3 hours
  - 20 MeV to >300 GeV
  - Onboard and ground burst triggers
  - Localization, spectroscopy
- **Gamma-ray Burst Monitor (GBM)**
  - Sees the entire unocculted sky (>9.5 sr)
  - 8 keV to 40 MeV
  - 12 NaI detectors (8 keV to 1 MeV)
    - Onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 40 MeV)
    - Spectroscopy

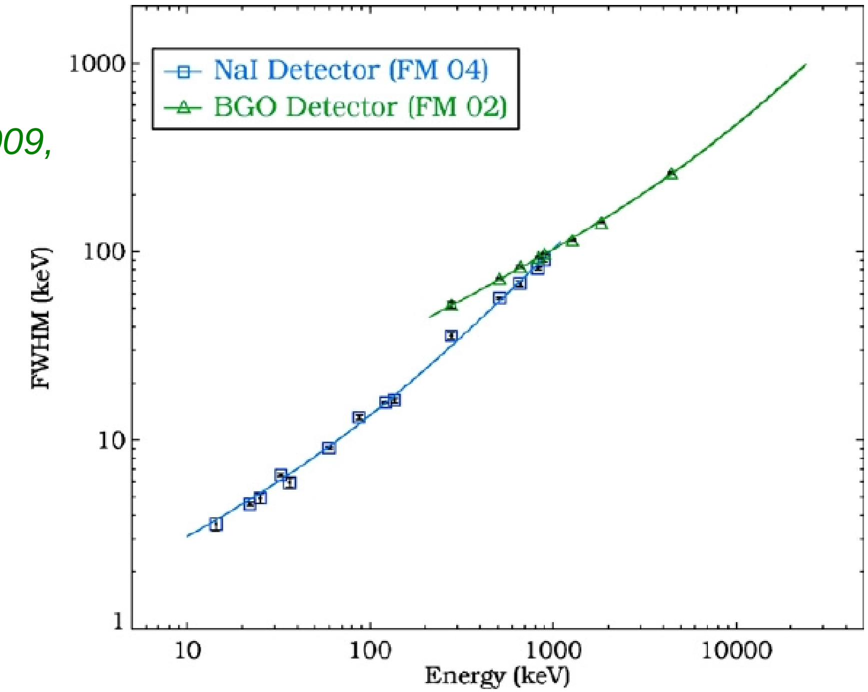
A broad energy range and sky coverage to study GRBs

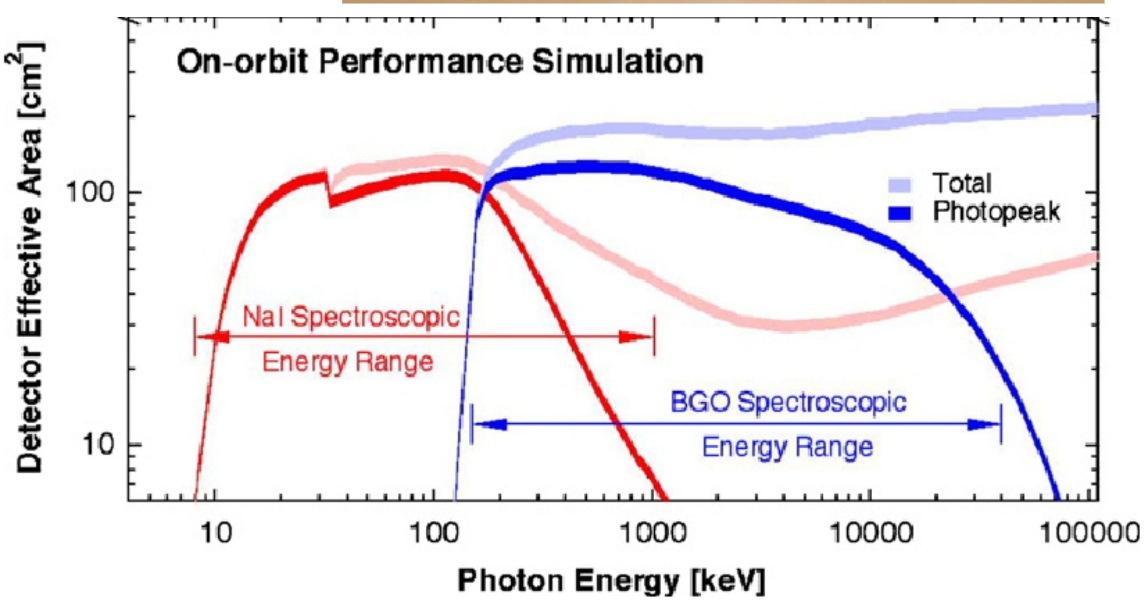


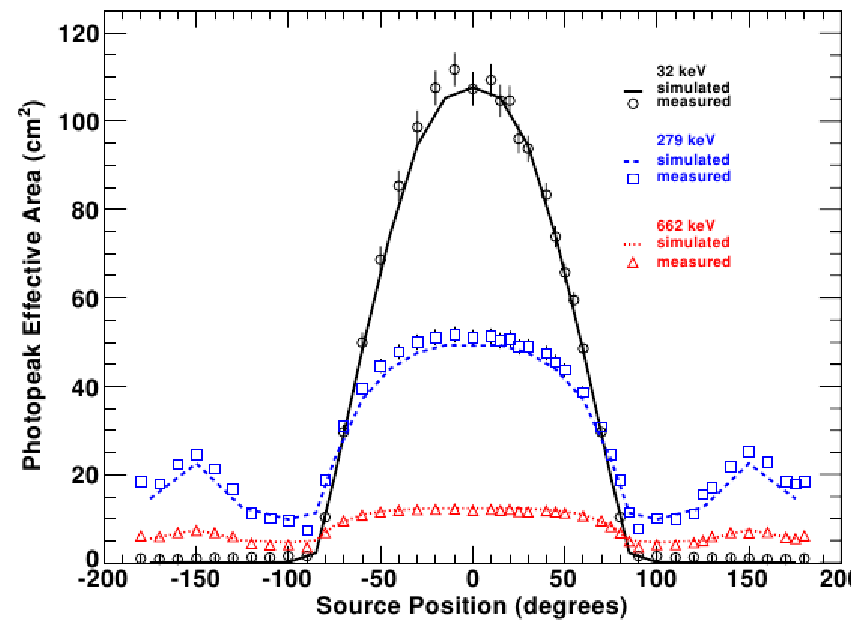
Response of GBM detectors



Meegan et al. 2009, ApJ 702, 791

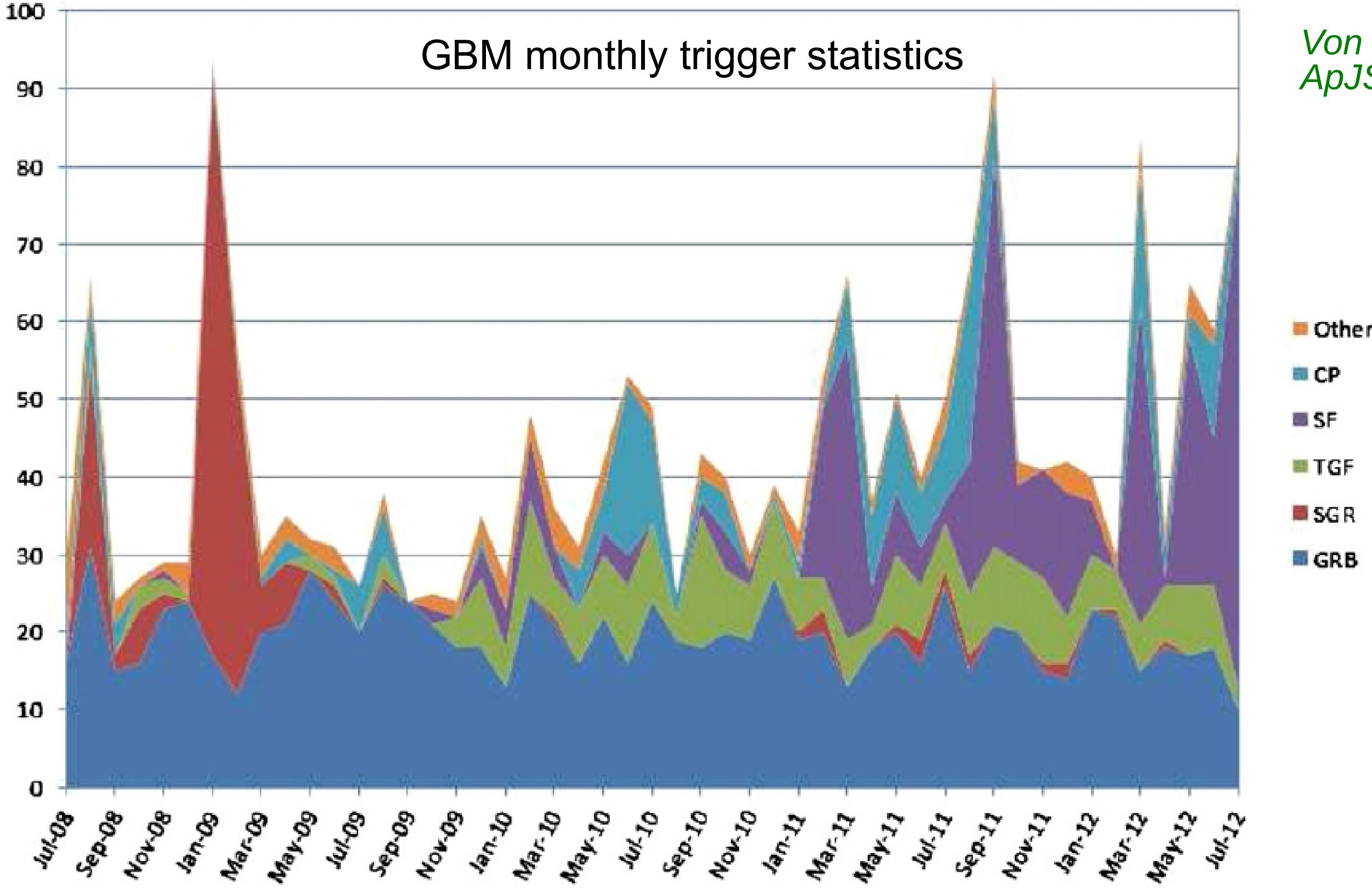






GBM triggers

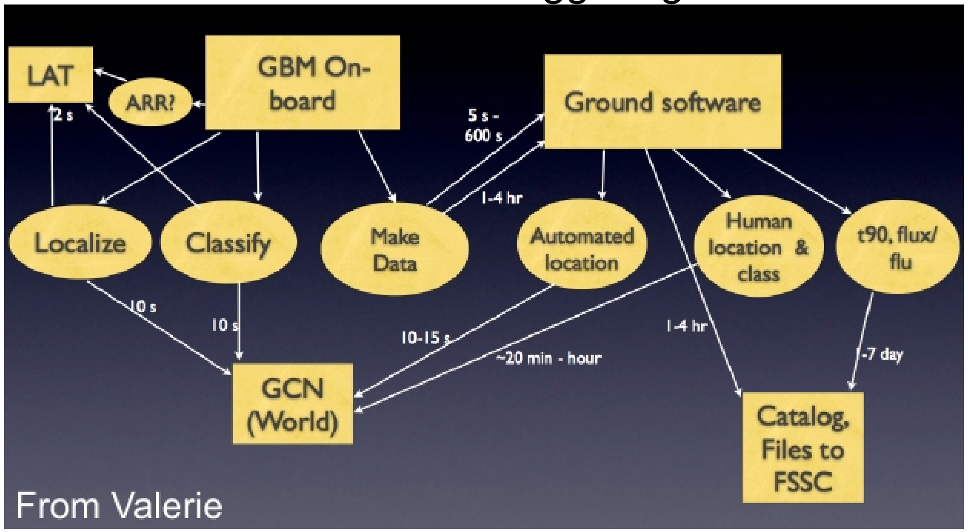
Von Kienlin et al. 2014, ApJS 211, 13

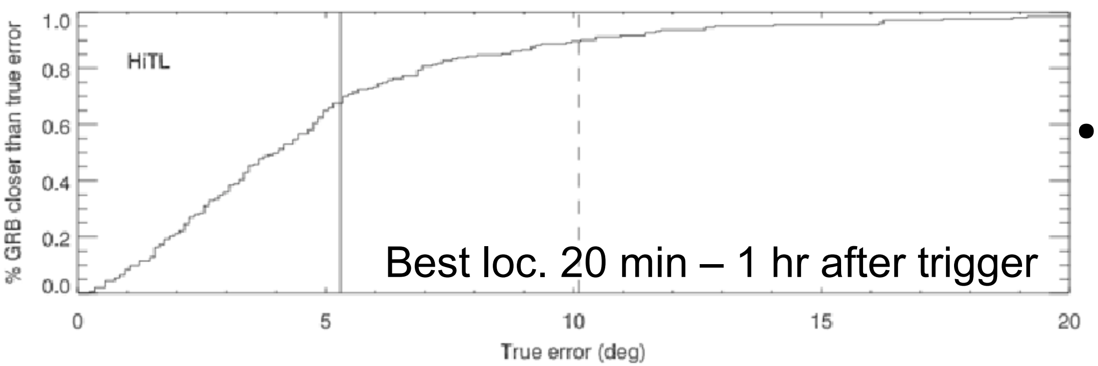


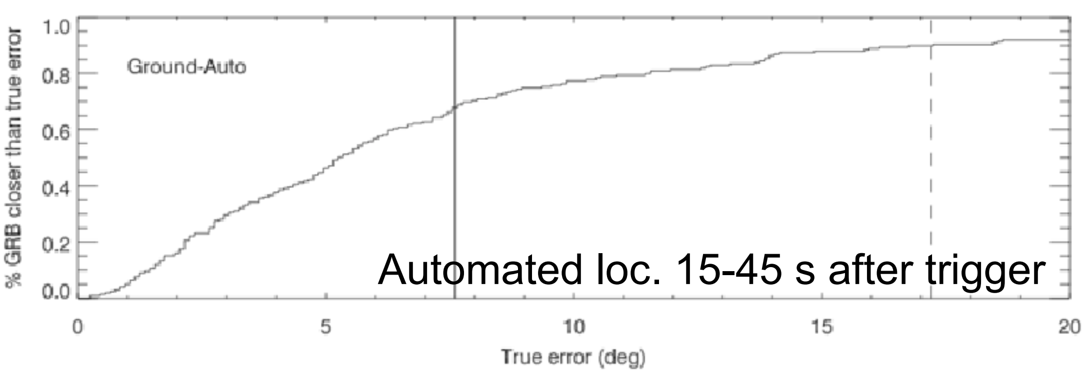
- **Increase of the solar cycle over the mission**
- **New TGF algorithm on Nov. 2009**
- **Onboard GRB trigger**
  - Two or more detectors over threshold
  - More flexible algorithm than with BATSE → better sensitivity to very short GRBs and long soft GRBs
  - Onboard trigger classifications (solar flare, particle event, GRB, etc)

GBM localization of GRBs

GBM actions on triggering



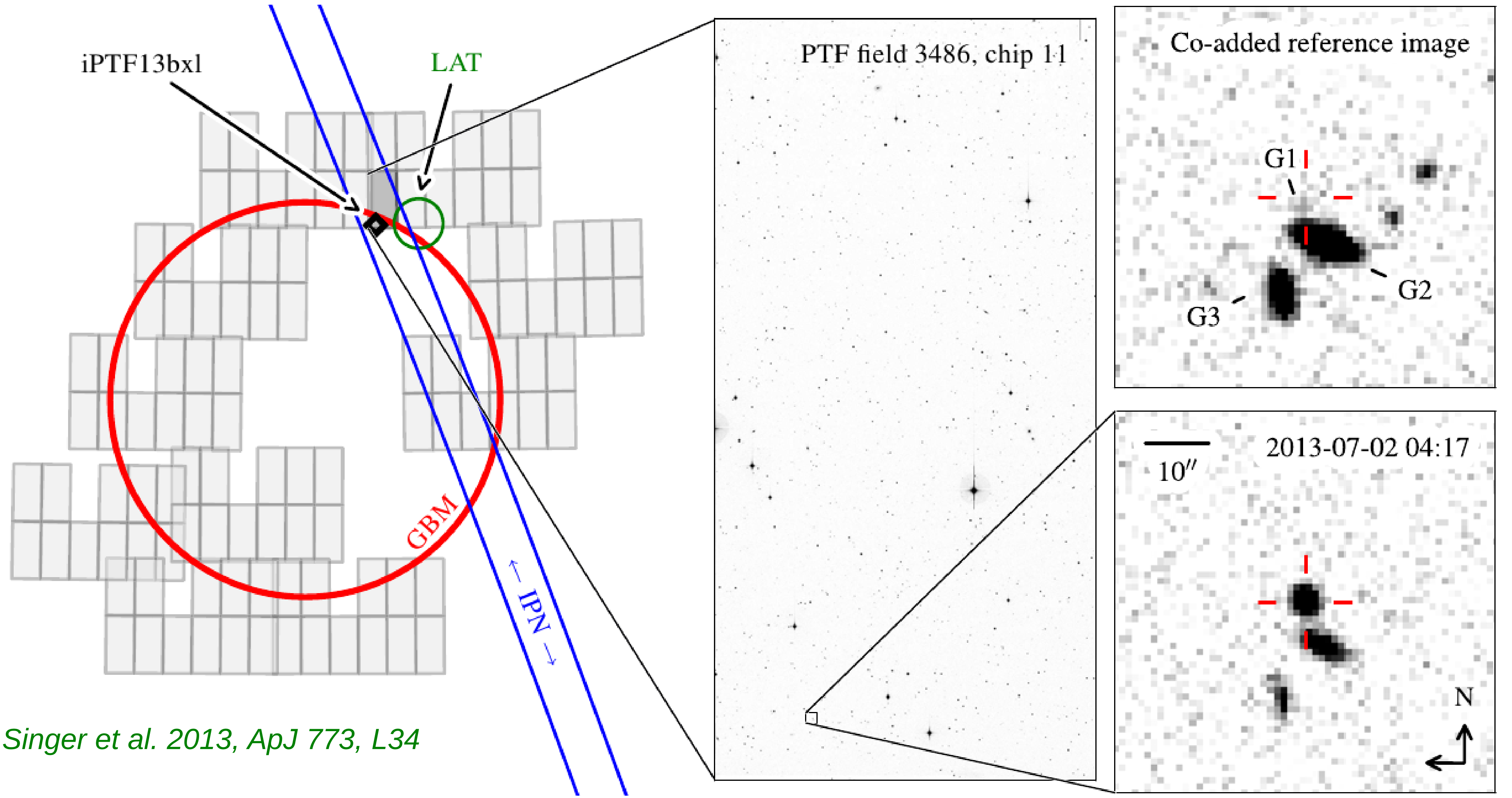




- **Onboard and on-ground**
  - GRB locations computed onboard (<2 s) to allow re-orienting the s/c in view of LAT afterglow observations
  - On-board locations transmitted to the ground and distributed (GCN notices), with a typical latency of ~10 s
  - On-ground automated locations: more accurate, typical latency of few 10's s
  - Somewhat longer latency using human intervention
- **68% GBM localizations are within 5 (8) deg of true location**
  - Using ~200 reference locations
- **Localization contains both statistical and systematic uncertainties**
  - Since January 2014 contours reflecting total uncertainty have been distributed and used by follow-up observers to tile uncertainty regions

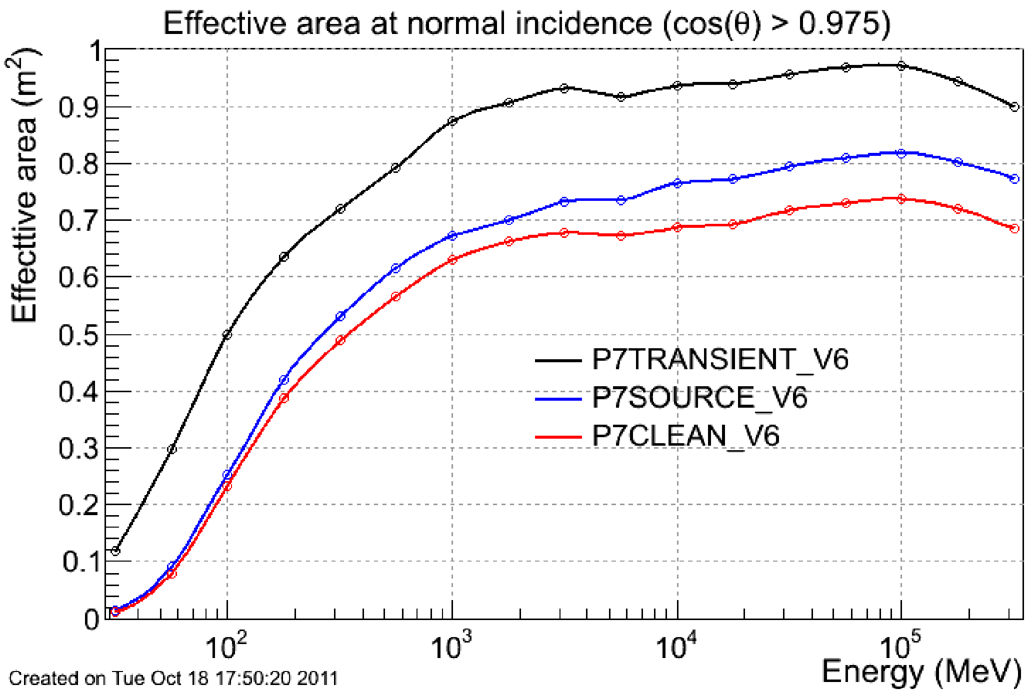
First iPTF detection (GRB 130702A)

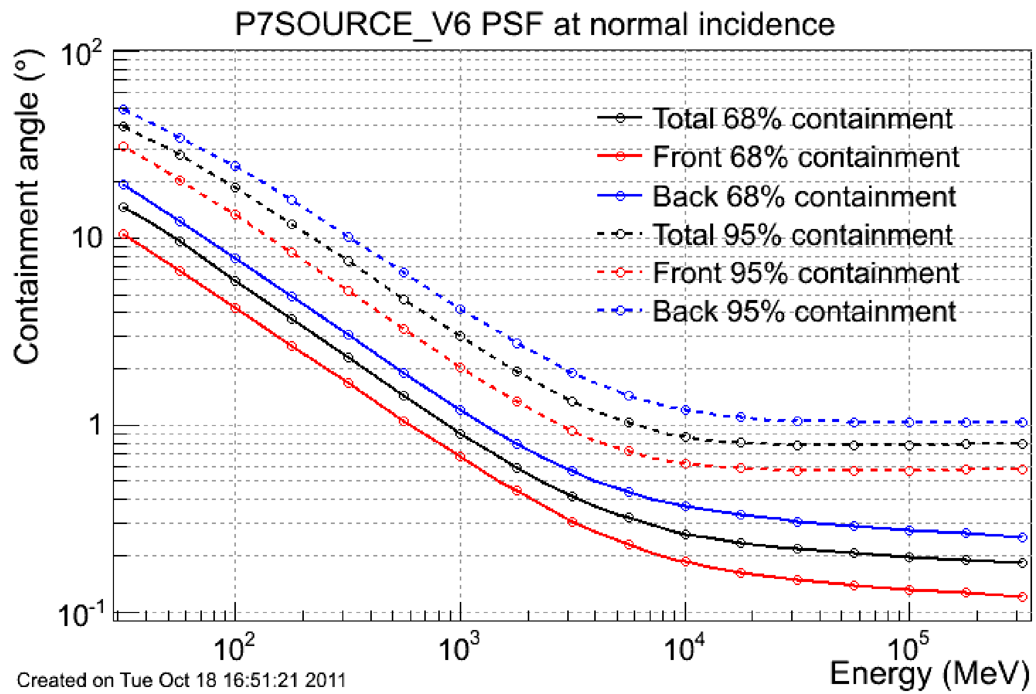
- **The intermediate Palomar Transient Factory (iPTF) has been scanning the GBM localization error boxes**
- **First detection (iPTF13bxl) based on GBM position, later confirmed by LAT and IPN**
- **First observational proof-of-principle for ~10 *Fermi*-iPTF localizations / year**

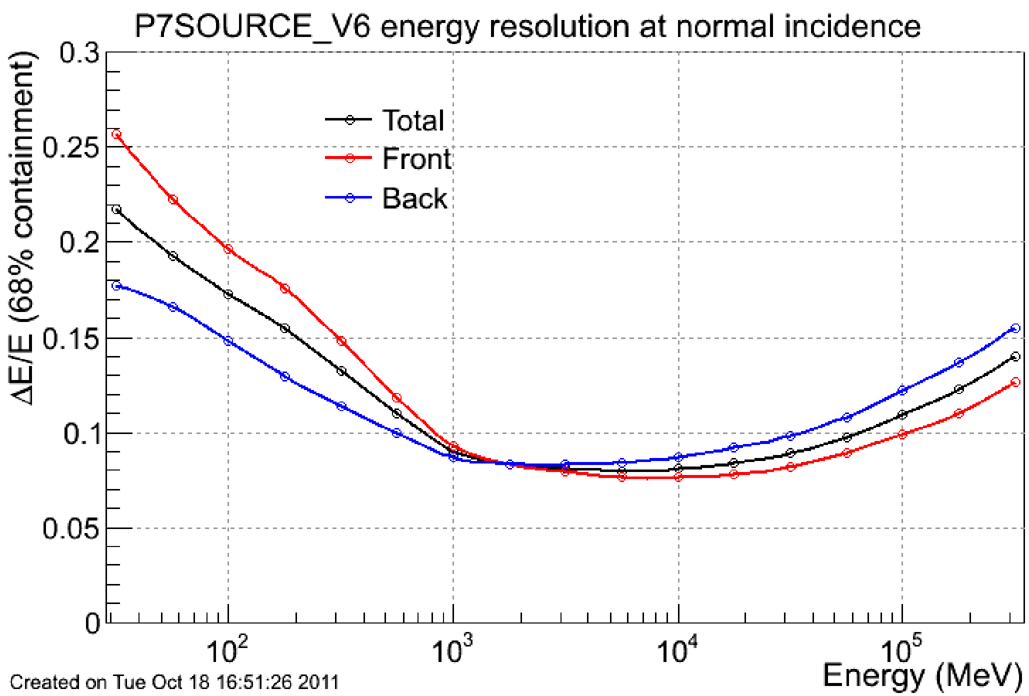


Singer et al. 2013, ApJ 773, L34

LAT Instrument Response Functions



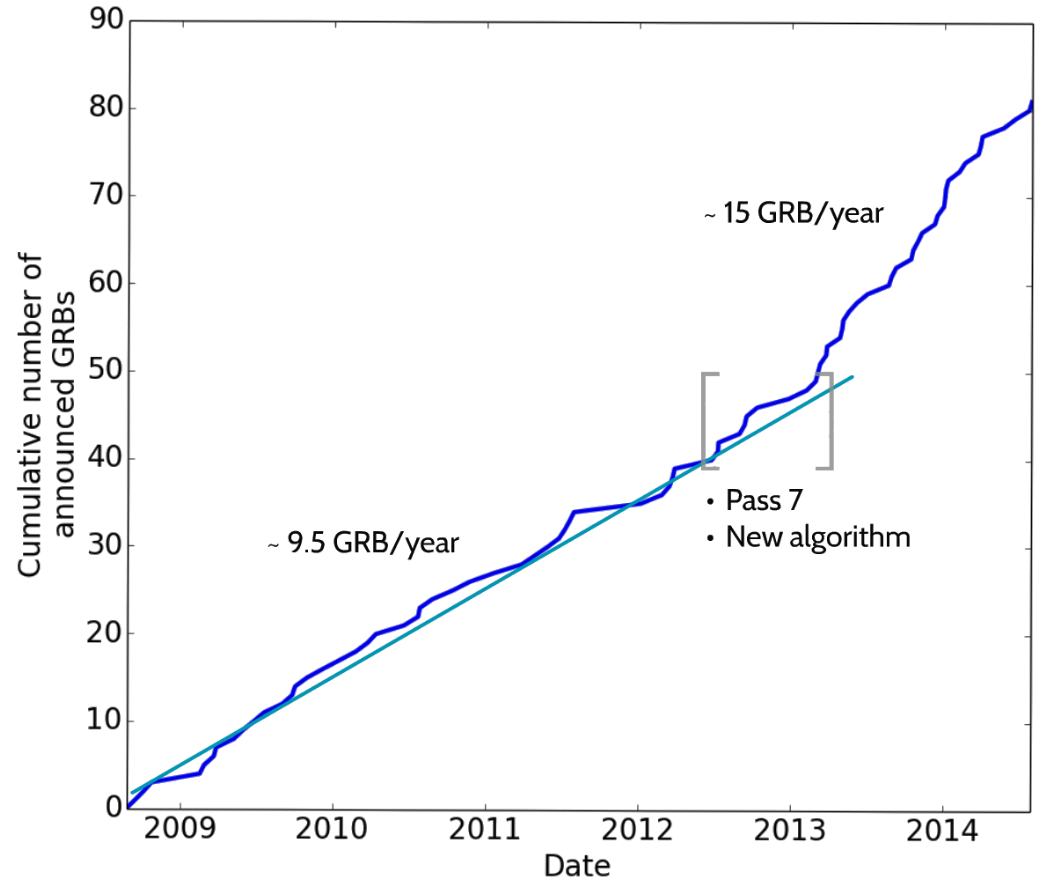


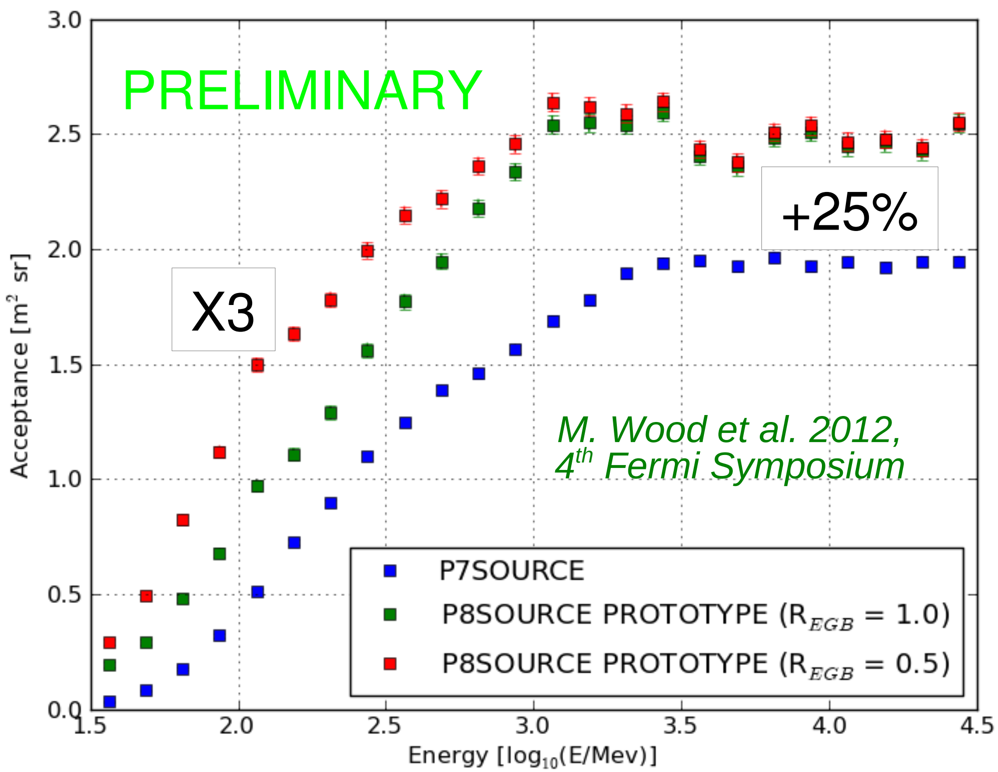


	LAT	EGRET
Energy range	20 MeV to >300 GeV	20 MeV – 30 GeV
Energy resolution (on axis, 0.1-10 GeV)	<18%	10%
Peak effective area	~ 9000 cm²	1500 cm²
Angular resolution (single photon, 10 GeV)	0.25°	0.54°
Field of view	~2.4 sr (@ 1 GeV)	0.4 sr
Deadtime per event	27 us	100 ms

Pass 8: a radical revision of LAT event-level analysis

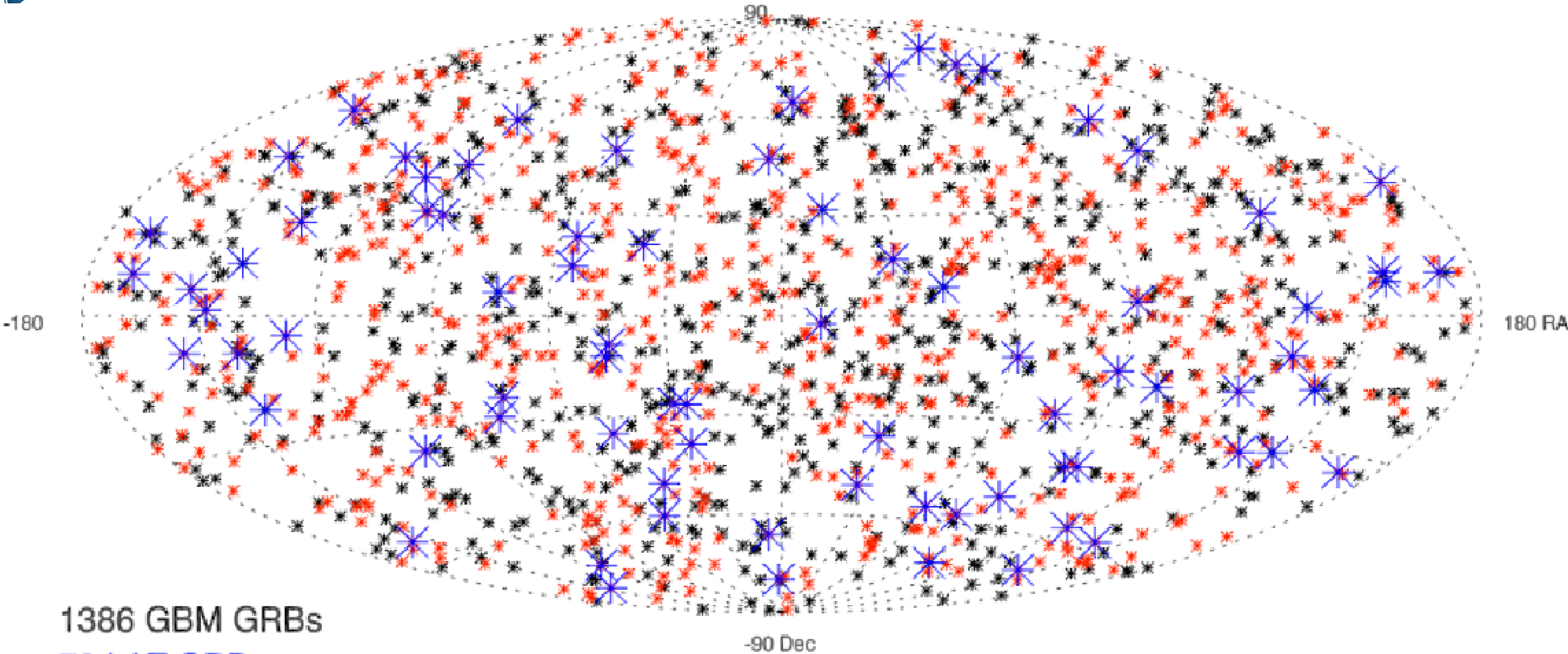
- **Pass 6 data:** release in August 2009
  - Pre-flight
- **Pass 7 data:** release in August 2011
  - Fix for so-called "ghosts"





- **Pass 8 data:** release in 2015
  - Includes virtually every aspect of the data-reduction process
- **More GRBs expected with Pass 8**
  - Larger effective area, better PSF, lower energy threshold for spectral analysis

Fermi GRBs as of 140620



1386 GBM GRBs
79 LAT GRBs
In Field-of-view of LAT (716)
Out of Field-of-view of LAT (670)

- **The GBM detects ~240 GRBs / year, ~45 of them are short GRBs**
- **The LAT sees ~10% of GBM GRBs in its field-of-view above 100 MeV**
  - 7 short GRBs among the 79 LAT GRBs
  - Bright LAT bursts with good localizations are all followed-up by Swift

Fermi GRB catalogs

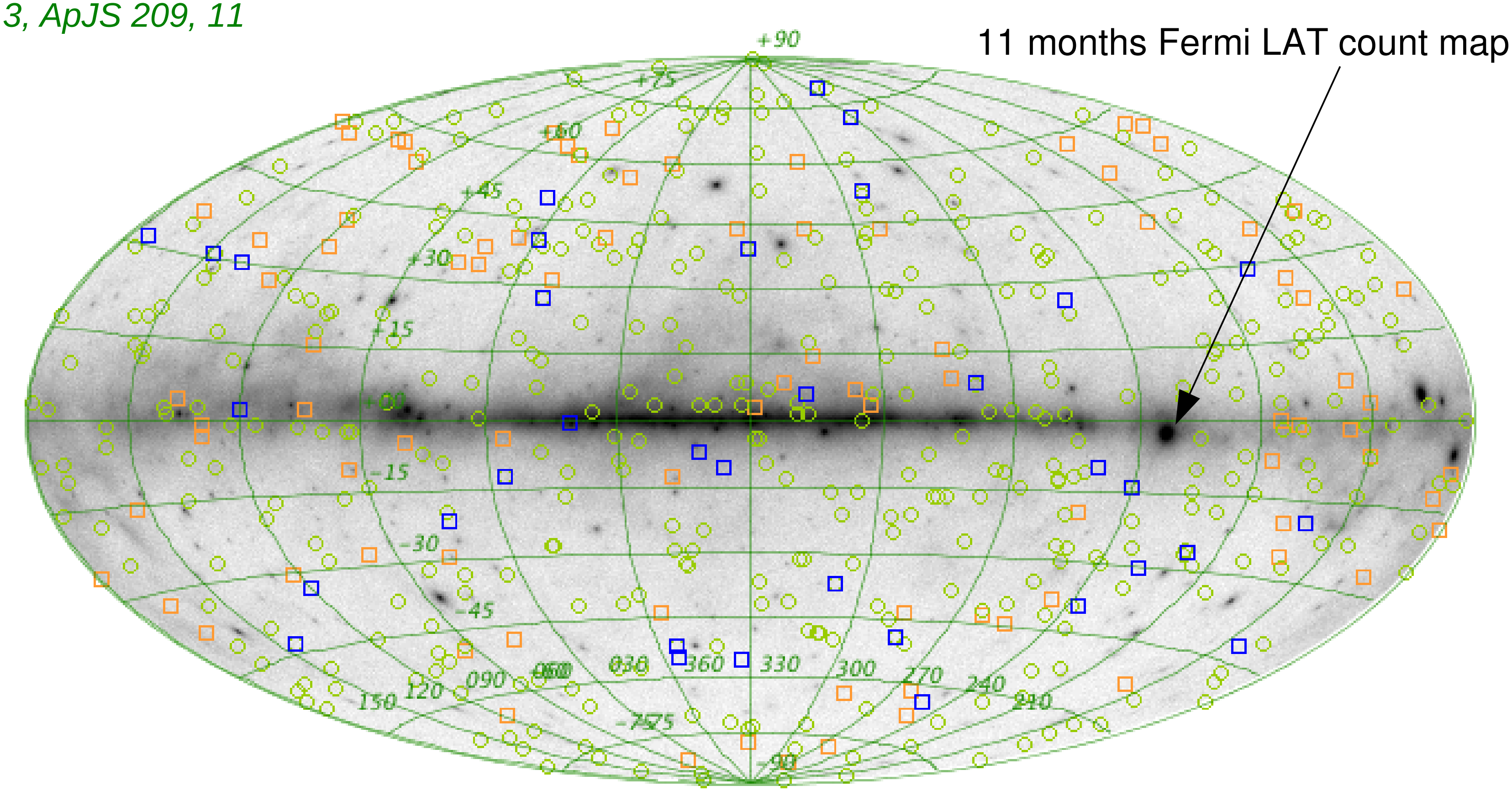
- **GBM: 2-yr and 4-yr trigger & spectral catalogs**
  - 491 (953) triggered GRBs in 2 (4) years

Paciesas et al. 2012, ApJS 199, 18
Goldstein et al. 2012, ApJS 199, 19
Von Kienlin et al. 2014, ApJS 211, 13
Gruber et al. 2014, ApJS 211, 12

- **LAT: first GRB catalog covers 3 years and contains 35 GRBs** (30 long, 5 short)
  - 10 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)

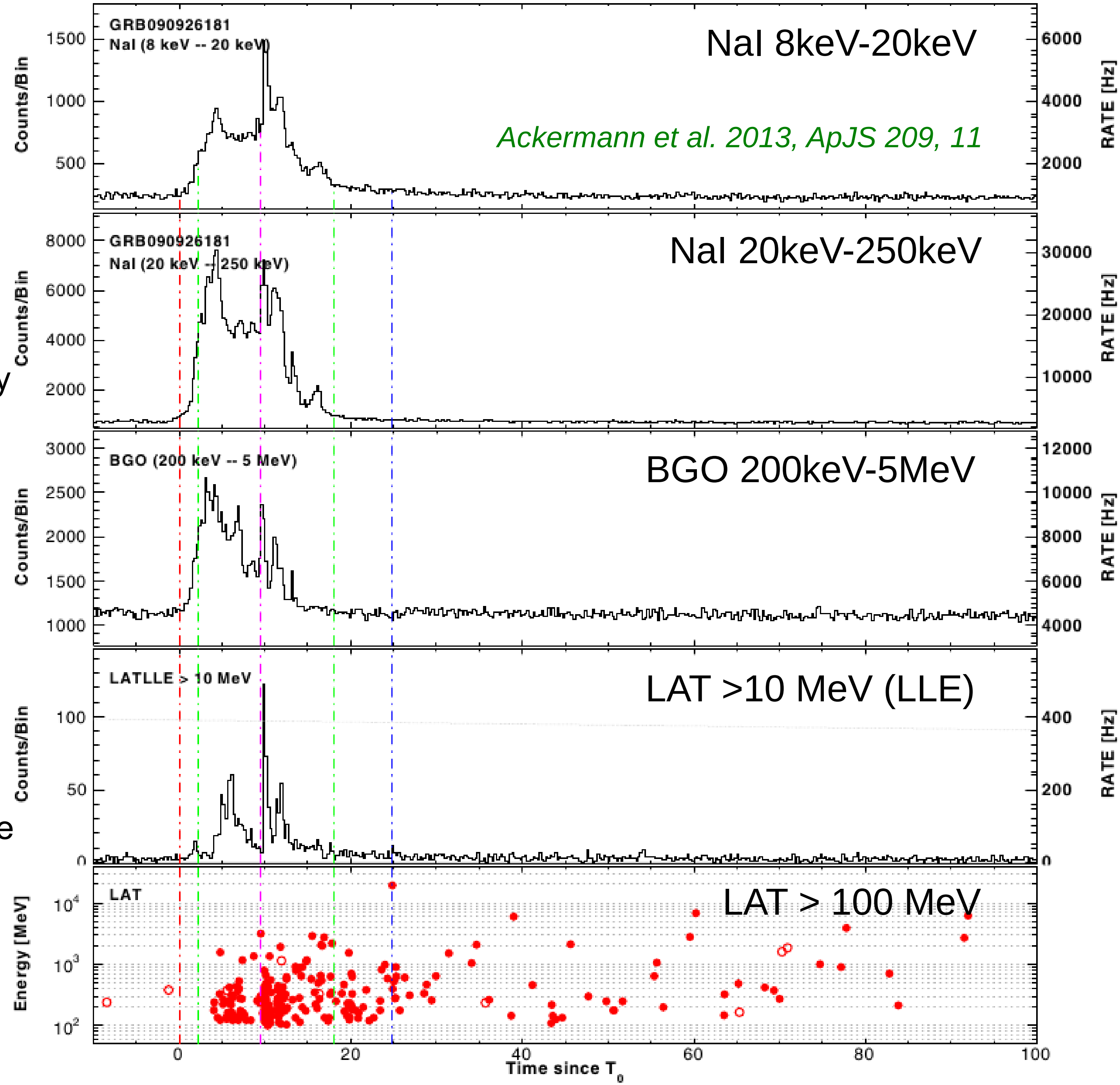
Ackermann et al. 2013, ApJS 209, 11

GBM 2-year catalog
(LGRB, SGRB)
LAT 3-year catalog



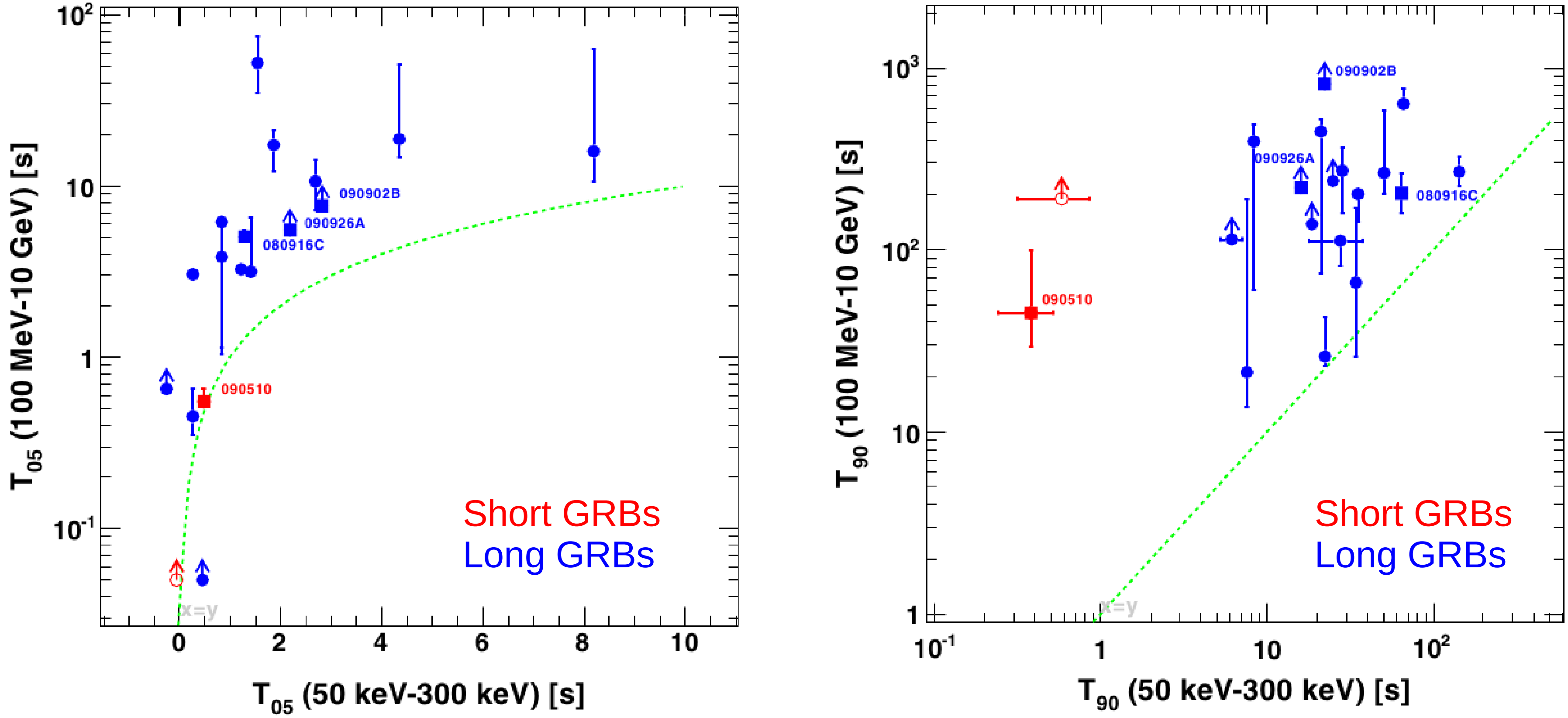
GRB 090926A multi-detector light curve

- **Correlated variability in various bands with a sharp spike at T_0+10 s**
  - All energy ranges synchronized (<50 ms)
  - Low and high energies are co-located or even causally correlated
- **LAT >100 MeV emission is delayed (~4 s)**
  - Delay > spike widths
- **LAT >100 MeV emission is temporally extended**
  - Well after the prompt phase
  - 19.6 GeV photon detected at T_0+24.8 s



Broad-band temporal properties

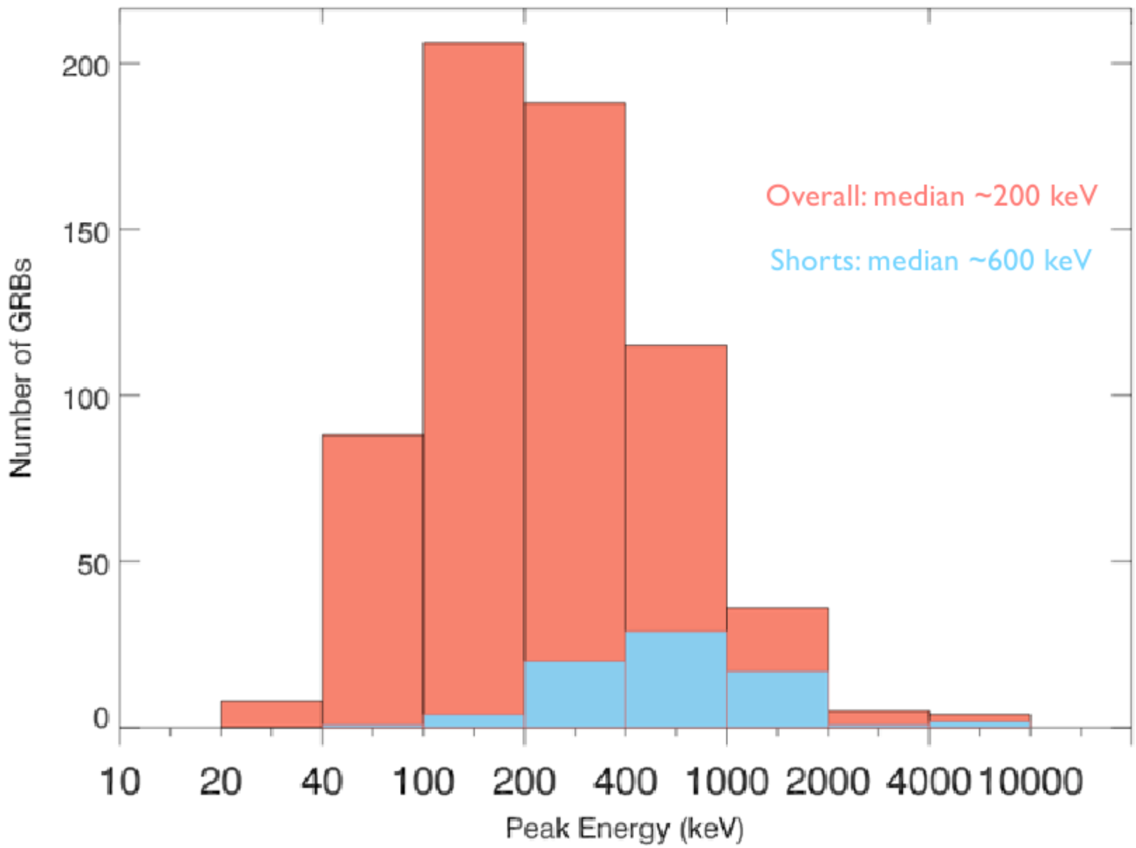
Ackermann et al. 2013, ApJS 209, 11

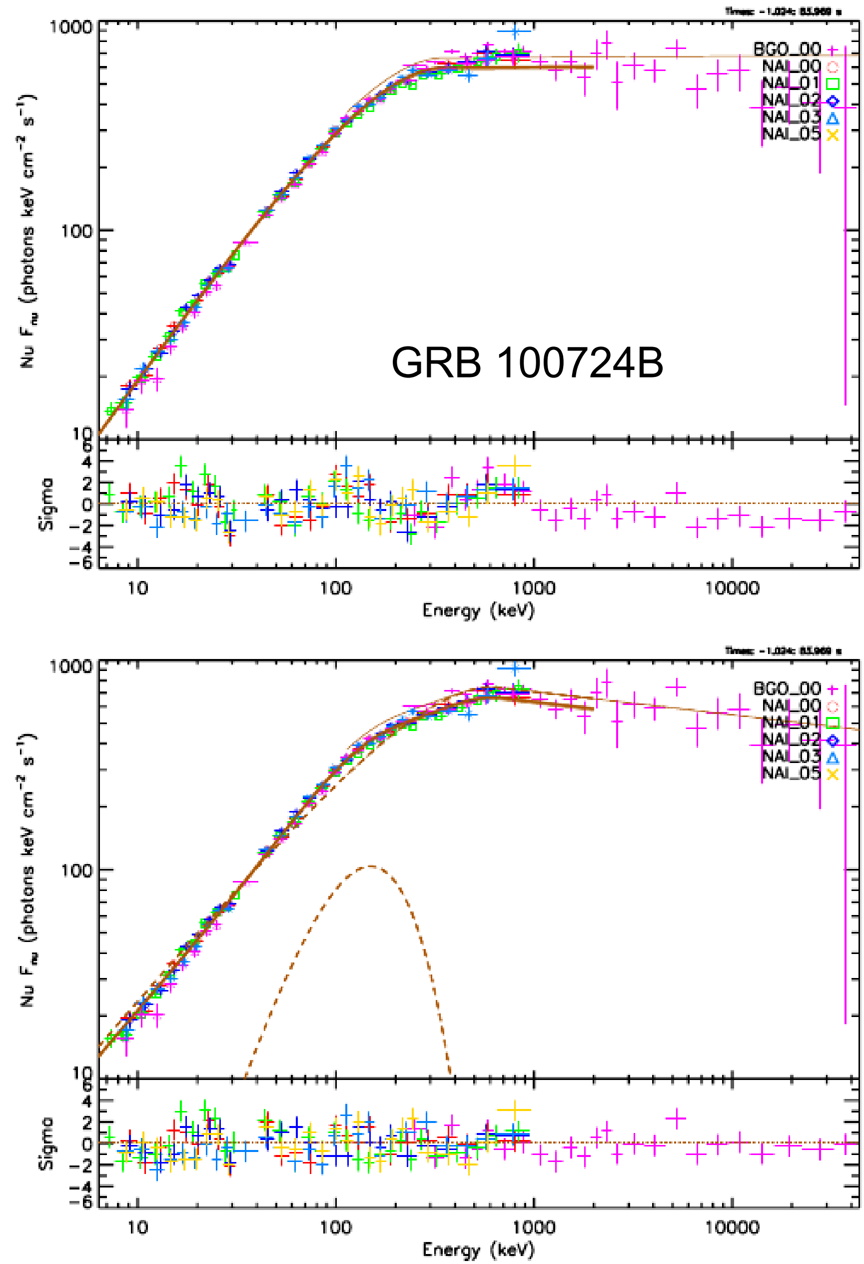


- **GeV emission onset is delayed and temporally extended**
  - Most (but not all) of this emission likely comes from early afterglow: external shock → synchrotron emission from accelerated electrons
  - Confirmed by individual broad-band (visible to GeV domains) analyses (GRBs 090510, 110731A)
  - Late internal shocks (inverse Compton scattering) or hadronic emission (proton synchrotron and/or photopion-induced cascades) still possible

GBM GRB spectra

- **GBM shows how short GRB spectra are different from long**
  - E.g., higher peak energies in time-integrated spectra
- **Extra component sometimes seen above Band function**
  - Consistent with BB photosphere emission



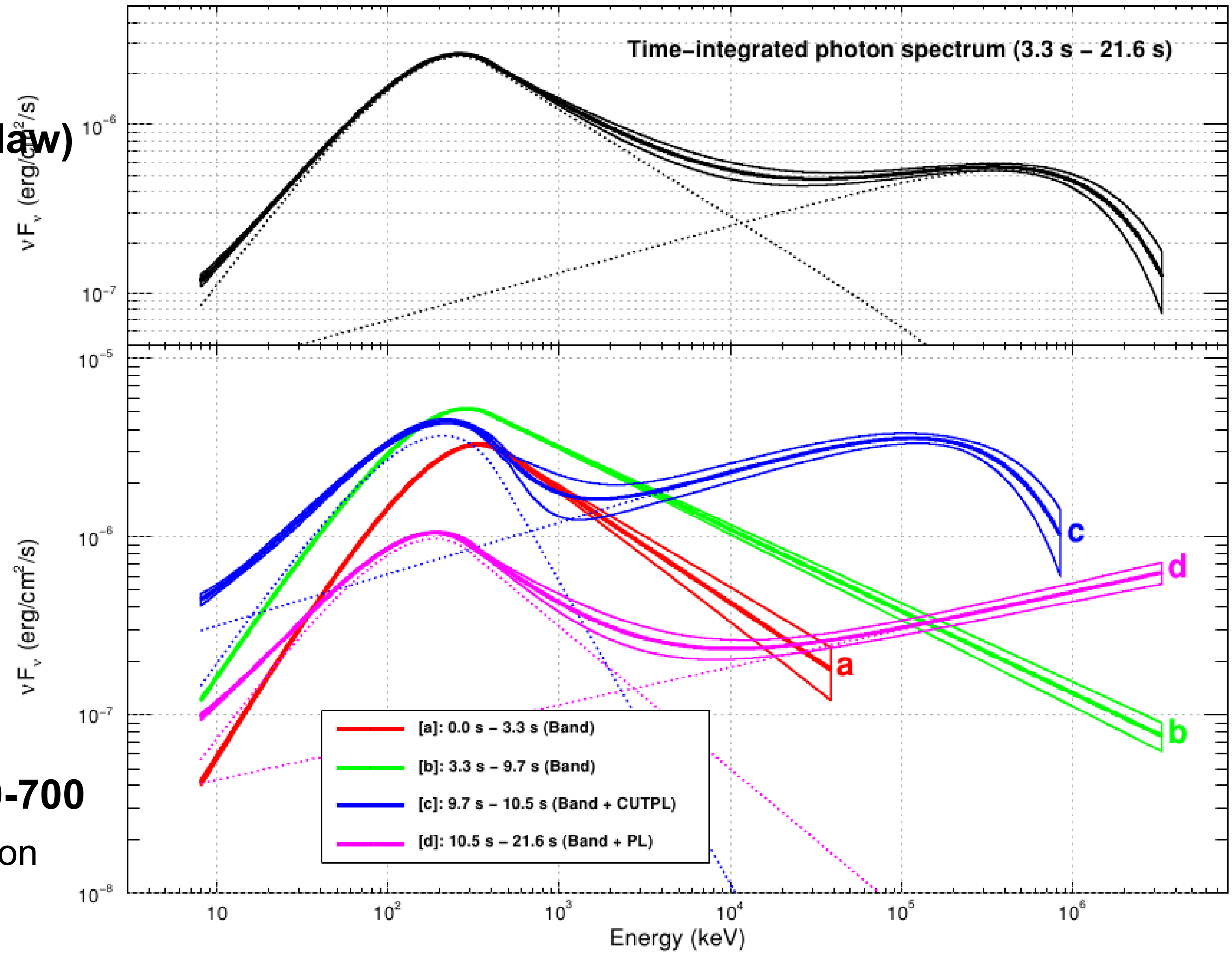


Guiriec et al. 2011, ApJ 727, L33
(See also Guiriec et al. 2013, ApJ 770, 32)

GRB 090926A broad-band spectrum

Ackermann et al. 2011, ApJ 729, 114

- E_{iso} = 2.2 x 10^{54} erg
- **Extra component (power law)**
  - Starts delayed (~9 s)
  - Persists at longer times
  - Dominates > 10 MeV
- **Spectral cutoff**
  - Significant in bin c, marginally in bin d
  - Shape not constrained
- **First measurement of the jet Lorentz factor: Γ ~ 200-700**
  - If cutoff due to $\gamma\gamma$ absorption
  - Model dependent

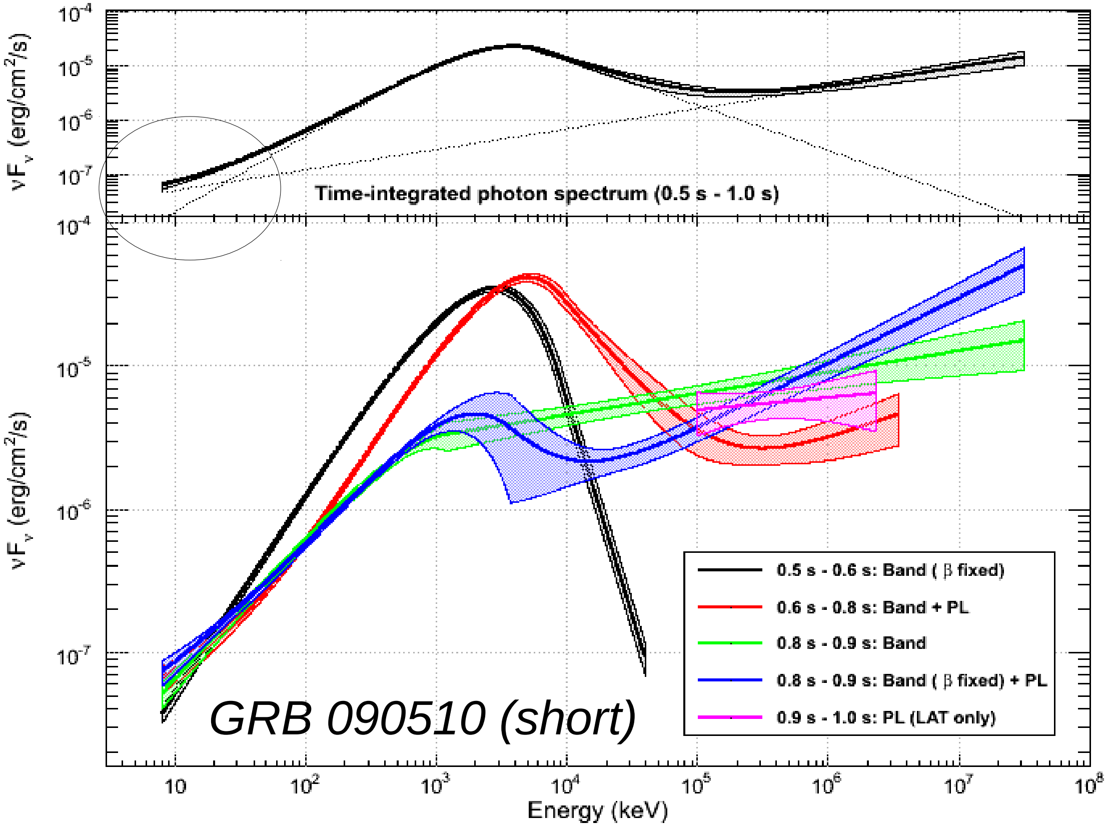


Broad-band spectral properties

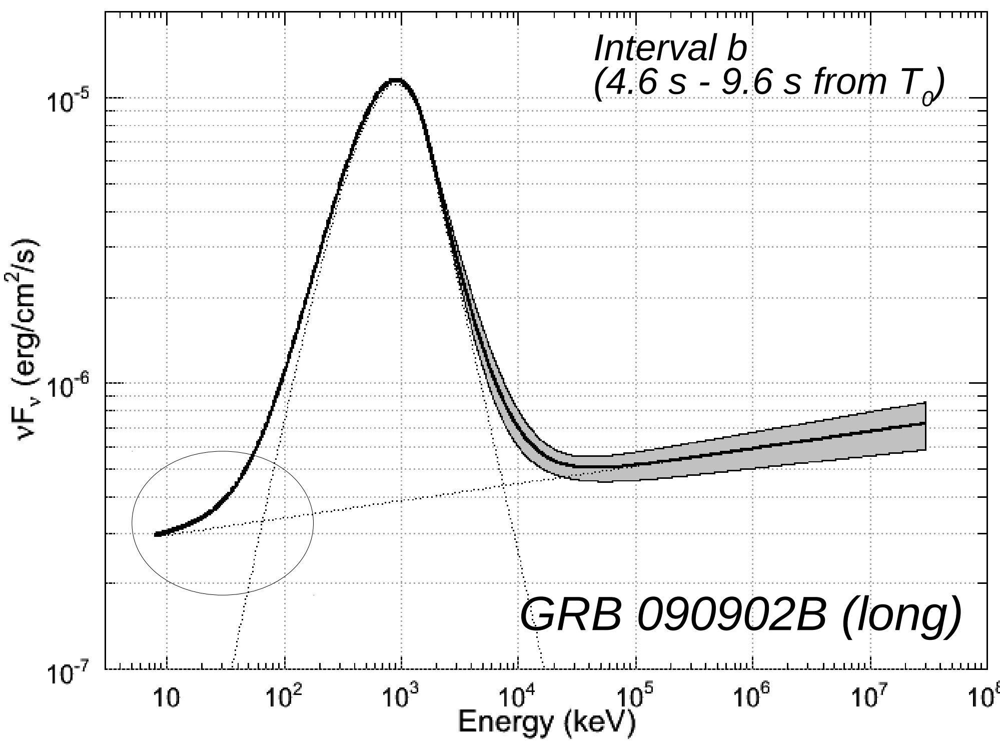
- **The Band function is no longer the best phenomenological model**
  - Deviation from the Band function at low energy
  - Additional power law component at high energy
  - High-energy cutoff measured in the spectrum

→ **Broad-band physical models are needed** (Cf talks on emission mechanisms later this week)

Ackermann et al. 2010, ApJ 716, 1178



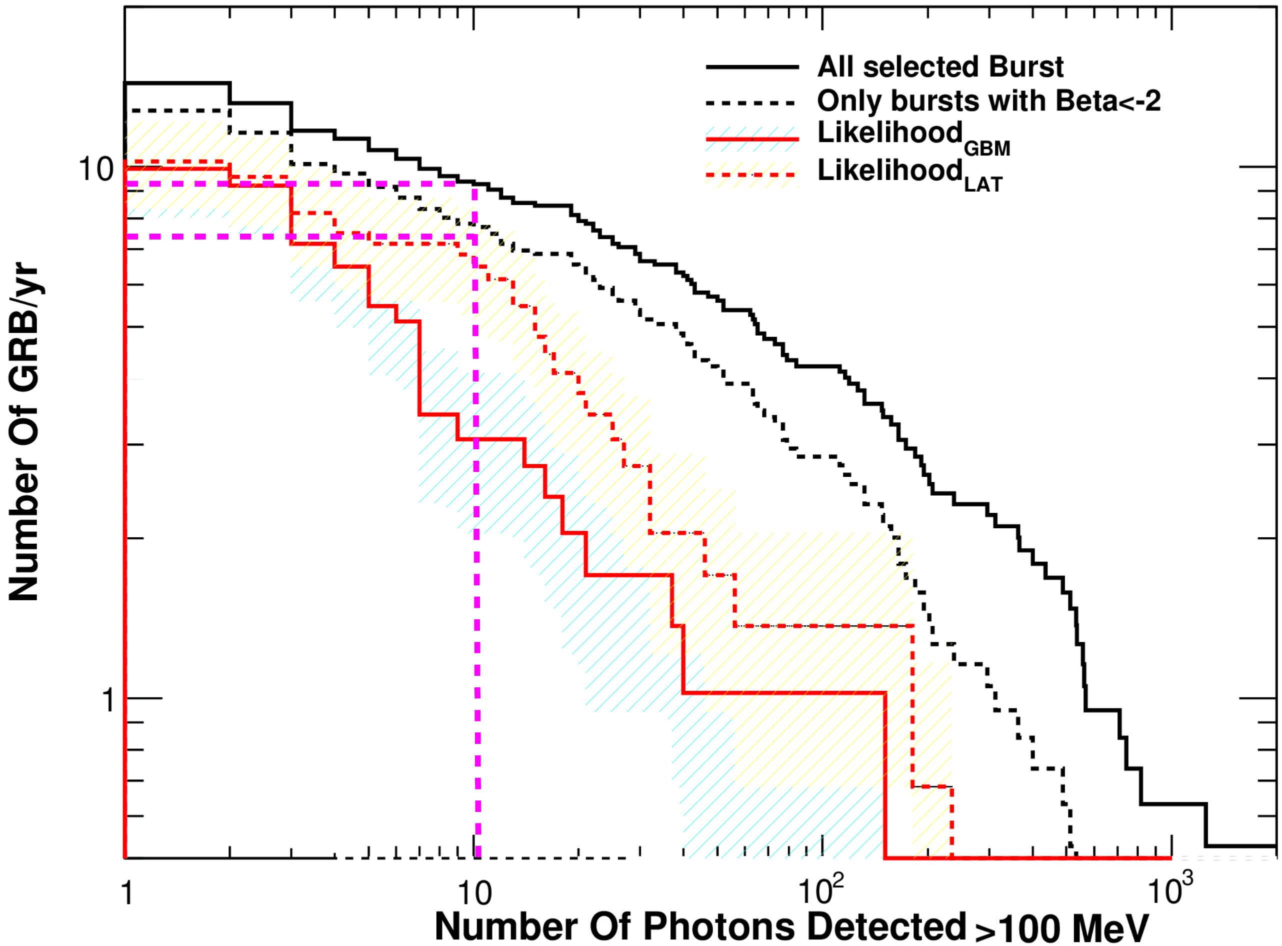
Abdo et al. 2009, ApJL 706, 138
(See also Ryde et al. 2010, ApJ 709, L172)



LAT burst rate

- **9.3 GRBs expected / year >100 MeV with >10 photons**
  - Pre-launch estimates, extrapolating BATSE spectra
- **6.3 GRBs observed / year >100 MeV with >10 photons**
  - Number of photons predicted by the likelihood fit

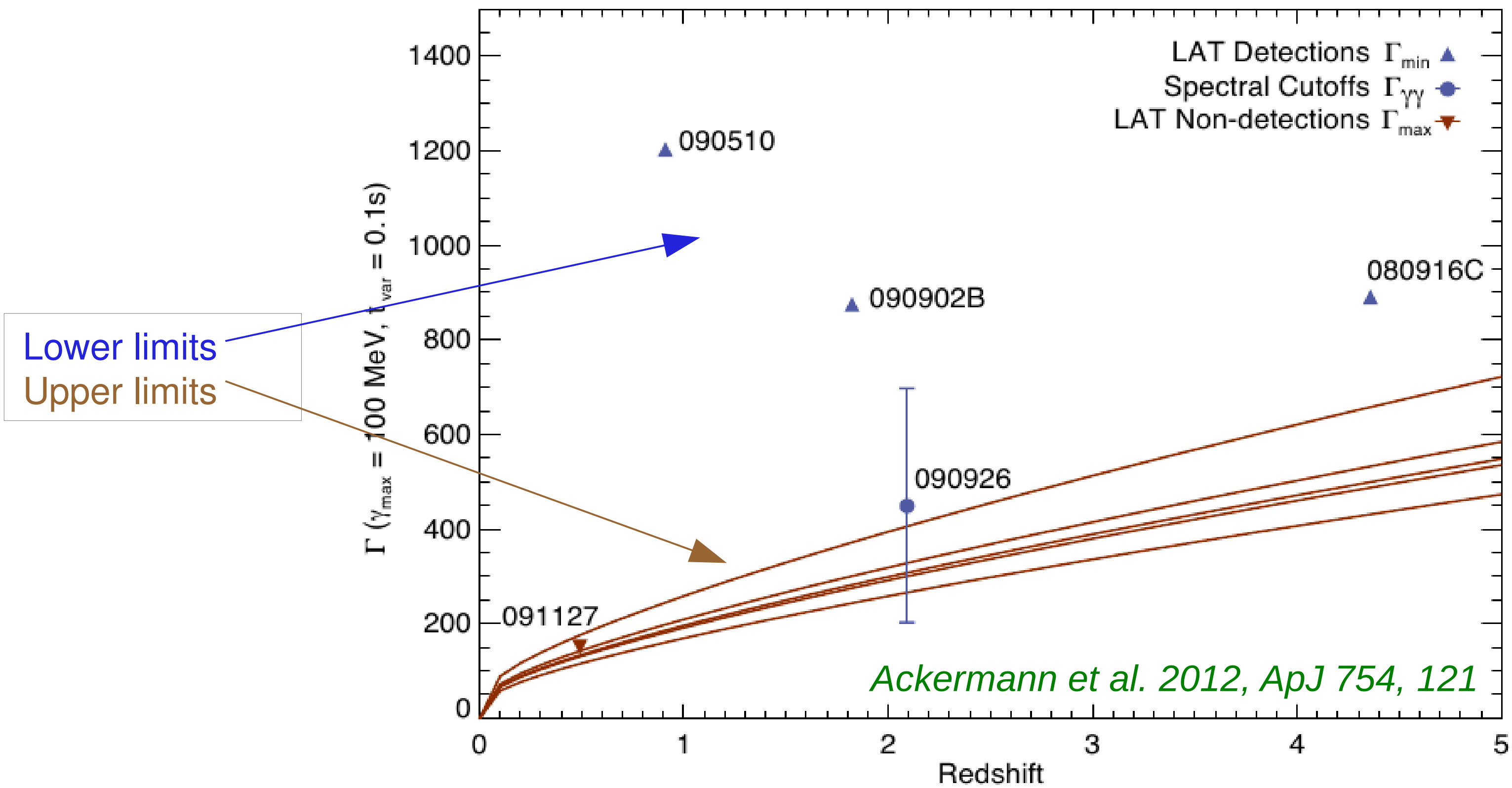
Band et al. 2009, ApJ 701, 1673
Ackermann et al. 2013, ApJS 209, 11



- **Fewer GRBs than anticipated**
  - Are extra power-law components rare?
- **Is the high-energy emission suppressed?**
  - Like for GRB 090926A

Constraints on the jet Lorentz factor

- **3 of the 4 brightest LAT bursts** show an extra PL component with no attenuation → **high Γ_{min}~1000**
- **6 GBM bright bursts not detected by the LAT** show some form spectral softening at tens of MeV → **Γ_{max}~150-650** assuming 100 ms variability and 1<z<5 (we only know the redshift for GRB 091127)



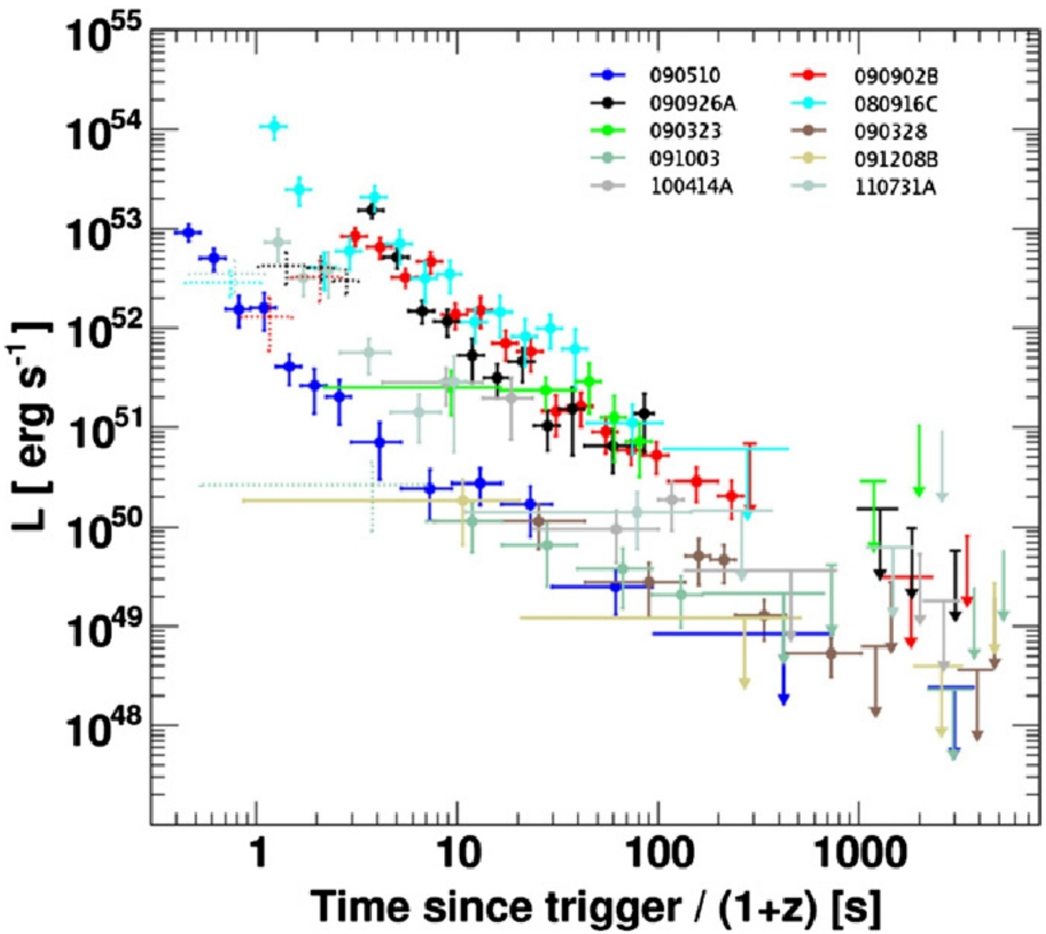
- **Target photon field for γγ absorption assumed uniform, isotropic and time-independent**
  - Granot et al. 2008, Hascoët et al. 2012 give significantly (~3 times) lower Γ values
  - Error bar for GRB 090926A accounts for different models

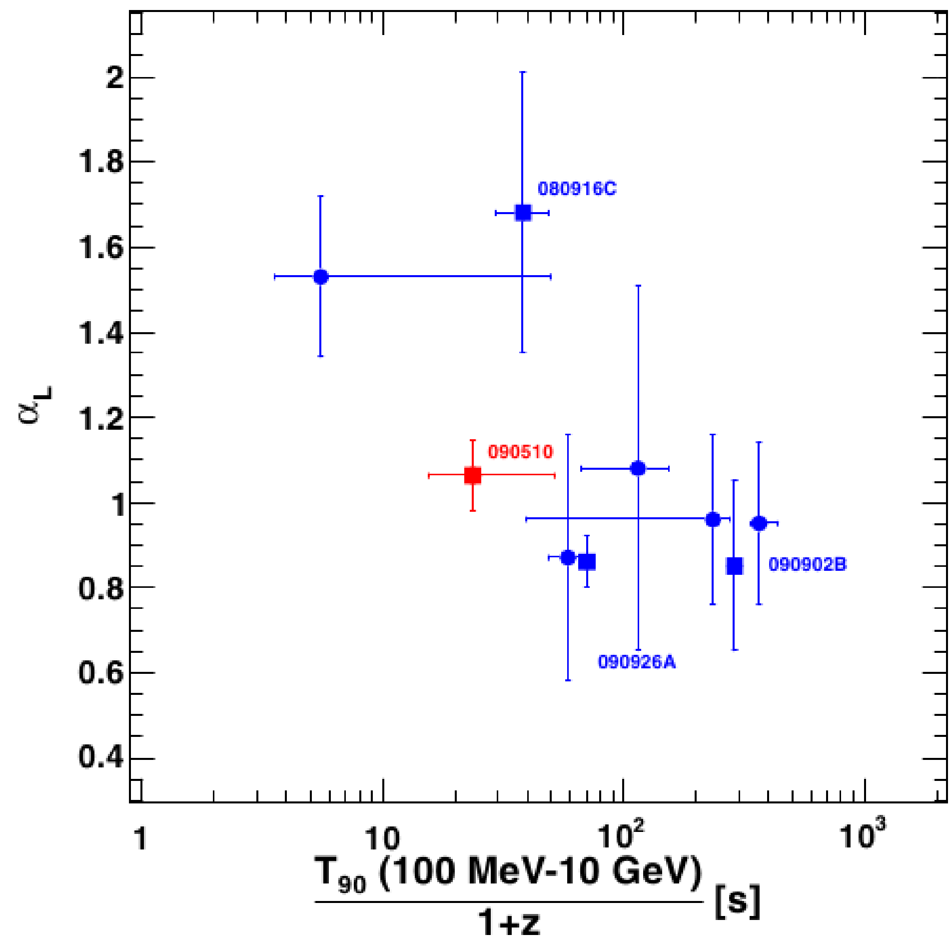
Long-lasting GeV emission

- **Consistent with afterglow models**
  - No strong spectro-temporal variability
  - Break in 2 long and 1 short bursts: prompt-contaminated to pure afterglow phase?
  - Emission decays as t^{-1} with a photon spectral index Γ_{EXT}=-2 at late times

- **$L(E,t) \sim t^{-\alpha}E^{-\beta}$**
- $\beta = -\Gamma_{EXT} - 1 = 1$
- α=1 (10/7) for an adiabatic (radiative) fireball in a constant density environment

  → Adiabatic expansion is favored
- (See also Nava et al. 2014, MNRAS 443, 3578)





Ackermann et al. 2013, ApJS 209, 11

New constraints on the jet Lorentz factor

- **Temporally extended emission, delayed onset, extra power-law component, no strong variability observed above ~1 GeV**
  - GeV emission similar to UV or X-ray emission, attributed to the afterglow

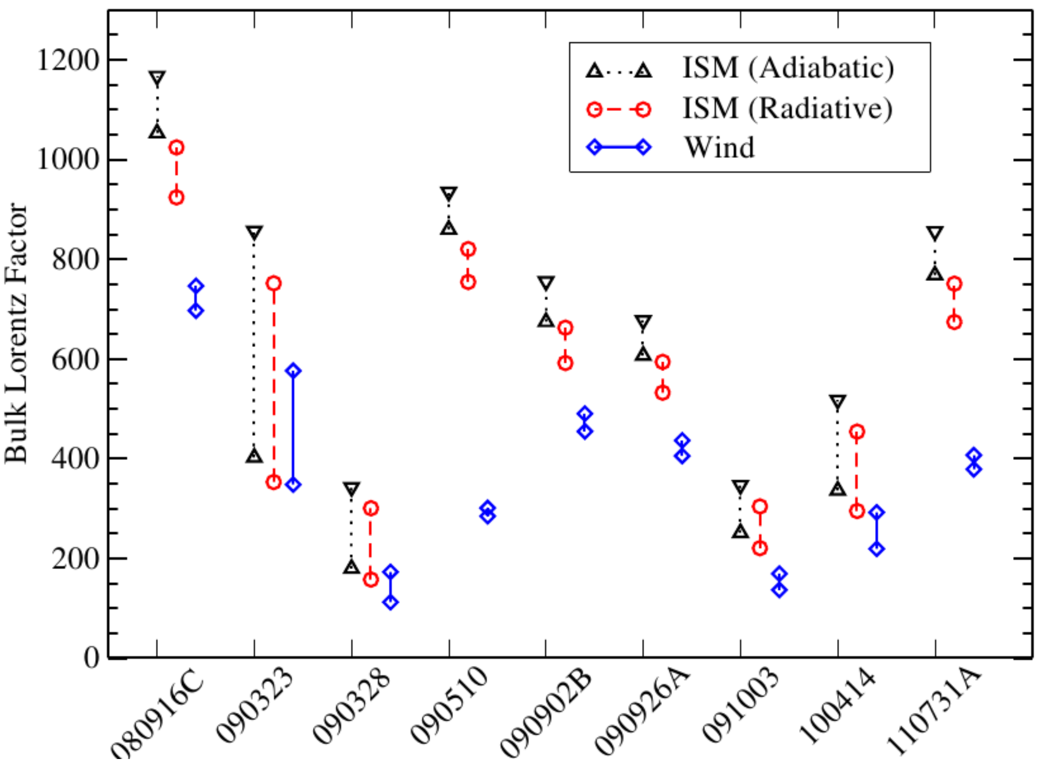
- **The bulk Lorentz factor can be derived from the fireball energetics and from its deceleration time (taken as the peak flux time in the LAT light curve)**
  - ISM of constant density *(Blandford & McKee 1976, Sari et al. 1998, Ghisellini et al. 2010)*

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

  - Wind environment *(Chevalier & Li 2000, Panaitescu & Kumar 2000)*

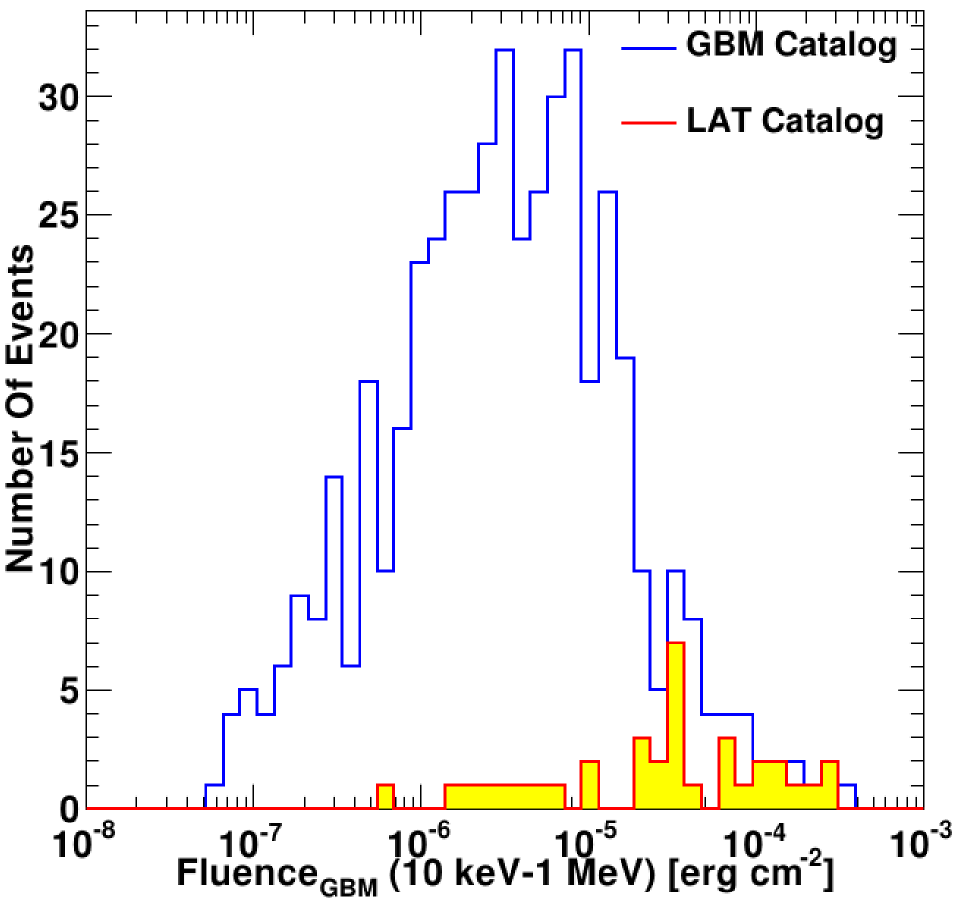
$$\Gamma_0 = \left[\frac{E_{k,\mathrm{iso}}(1+z)}{16\pi A m_p c^3 t_{\mathrm{dec}}}\right]^{1/4}$$

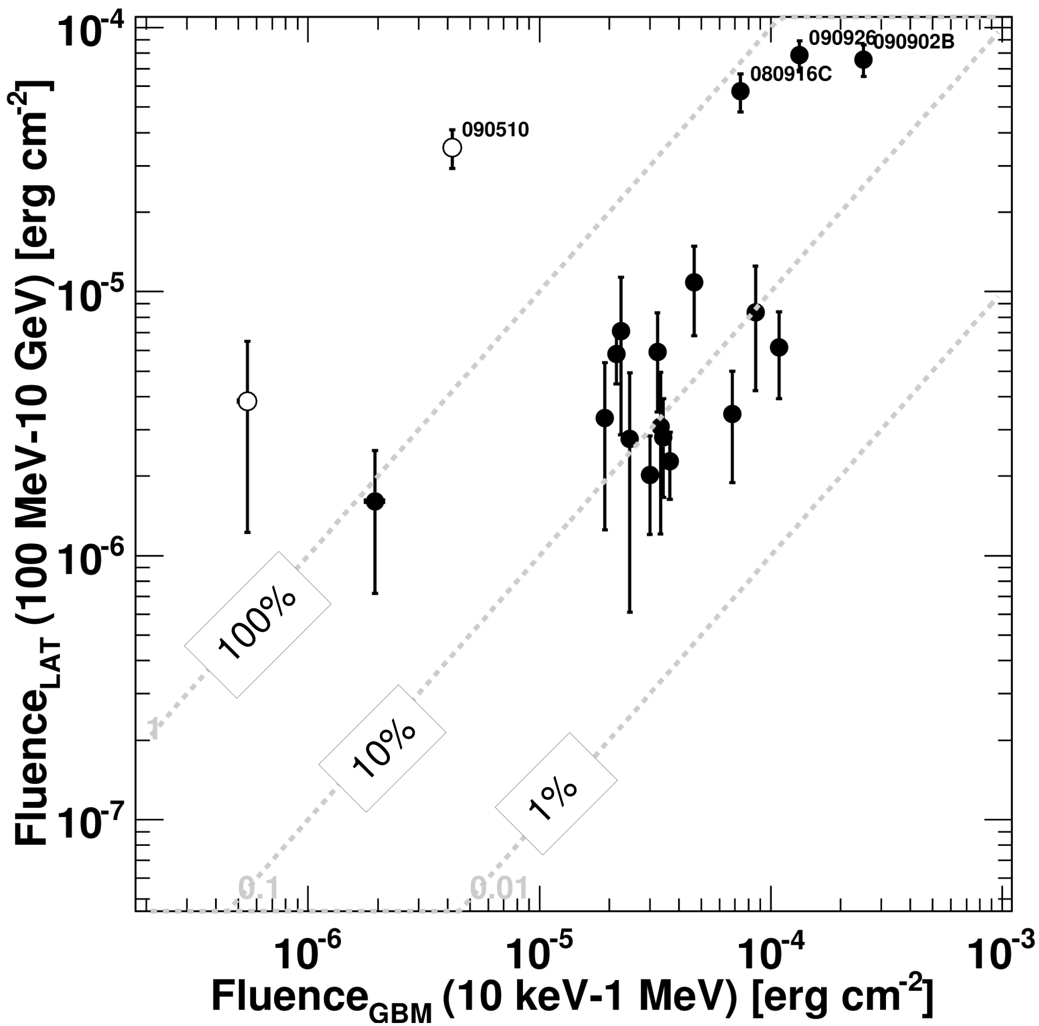
Ackermann et al. 2013, ApJS 209, 11



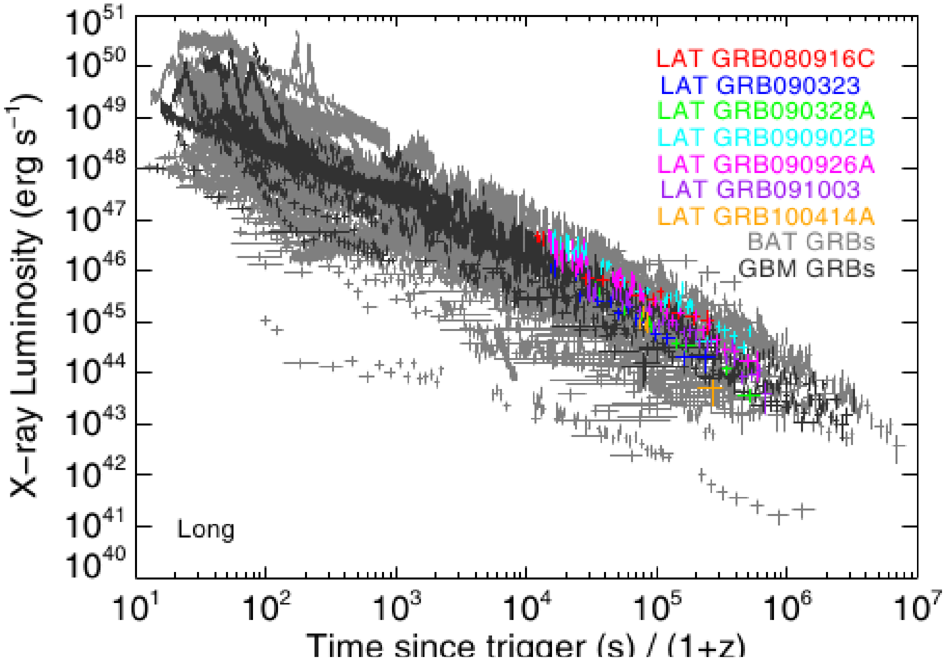
GBM & LAT fluences

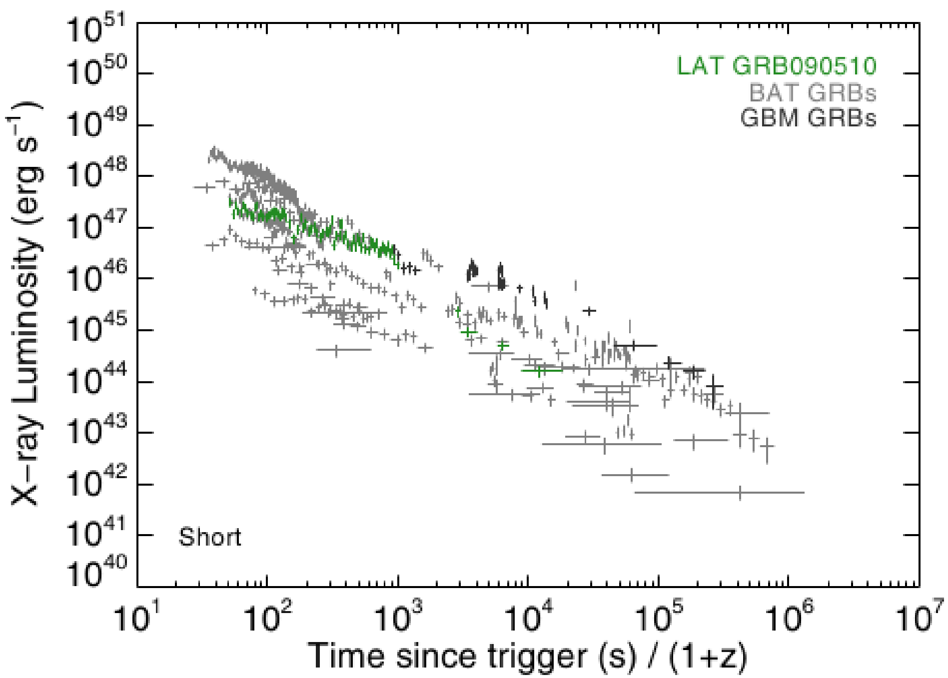
- **Not surprisingly, LAT GRBs are among the most fluent GBM GRBs**
- **Short GRBs (LAT fluence > GBM fluence) are harder than long GRBs (LAT/GBM fluence ~10%)**



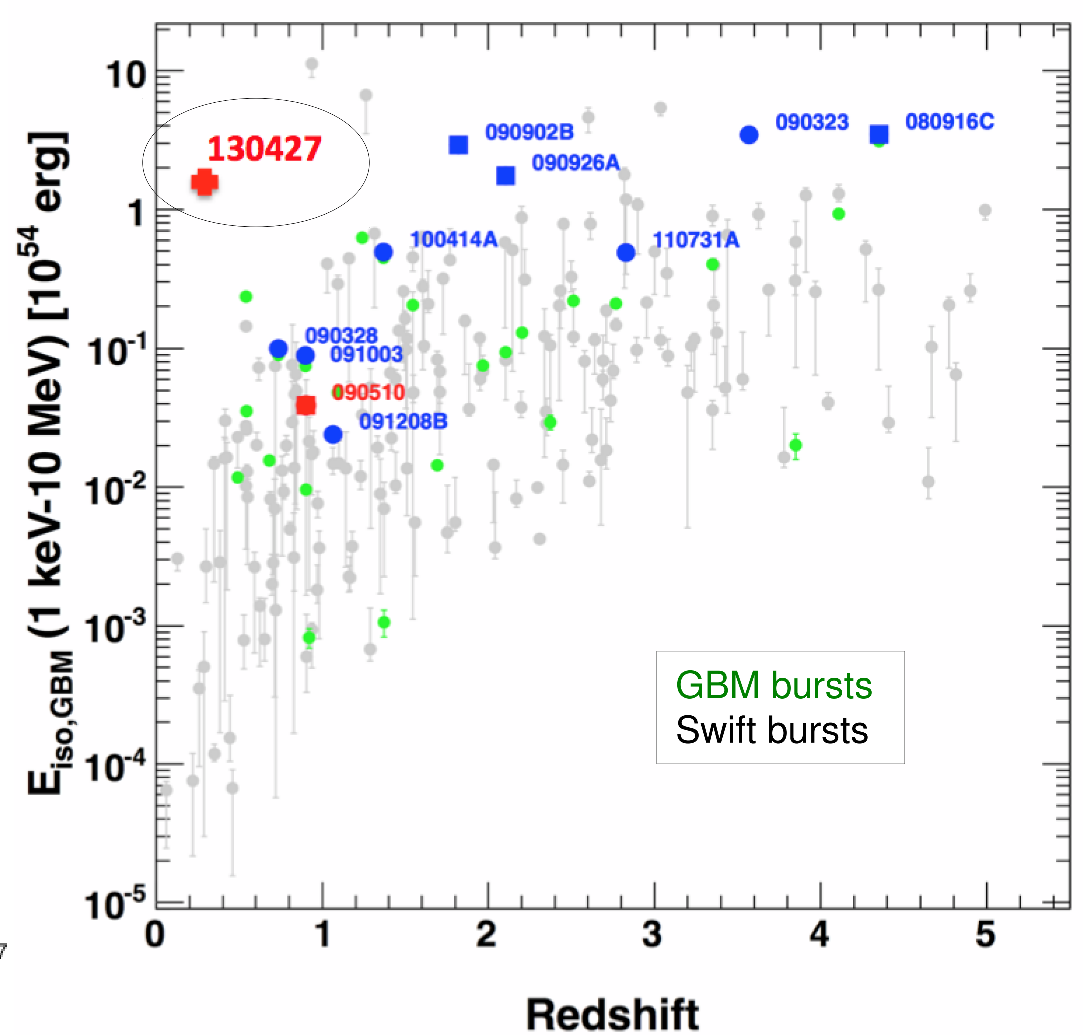


LAT bursts: bright, fluent and energetic



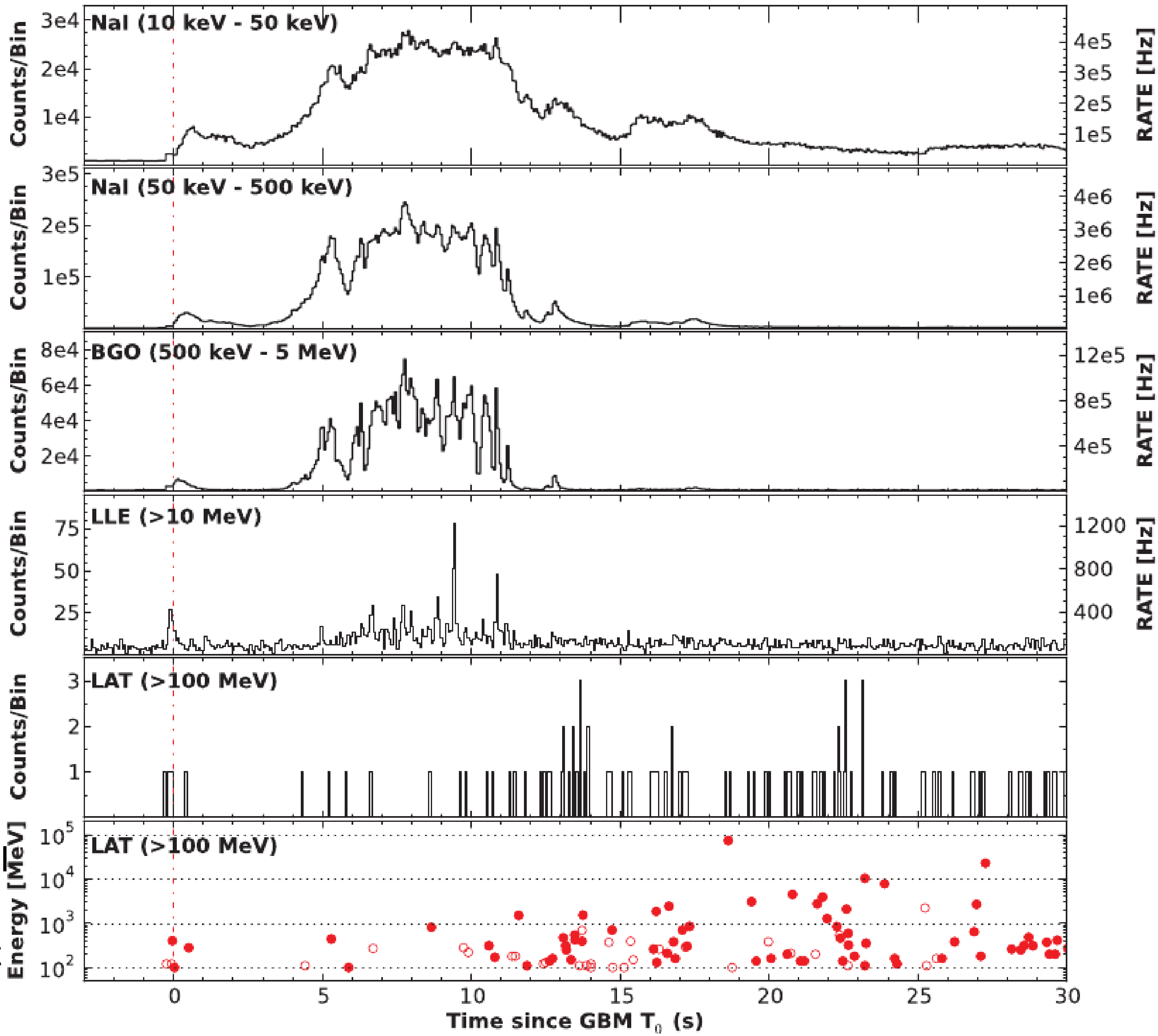


- **Comparing *Swift* and *Fermi* GRB samples:**
  - *Butler et al. 2007, ApJ 671, 656 (see also Sakamoto et al. 2011, ApJS 195, 2)*
  - *Racusin et al. 2011, ApJ 738, 138*
  - *Goldstein et al. 2012, ApJS 199, 19*
  - *Ackermann et al. 2013, ApJS 209, 11*



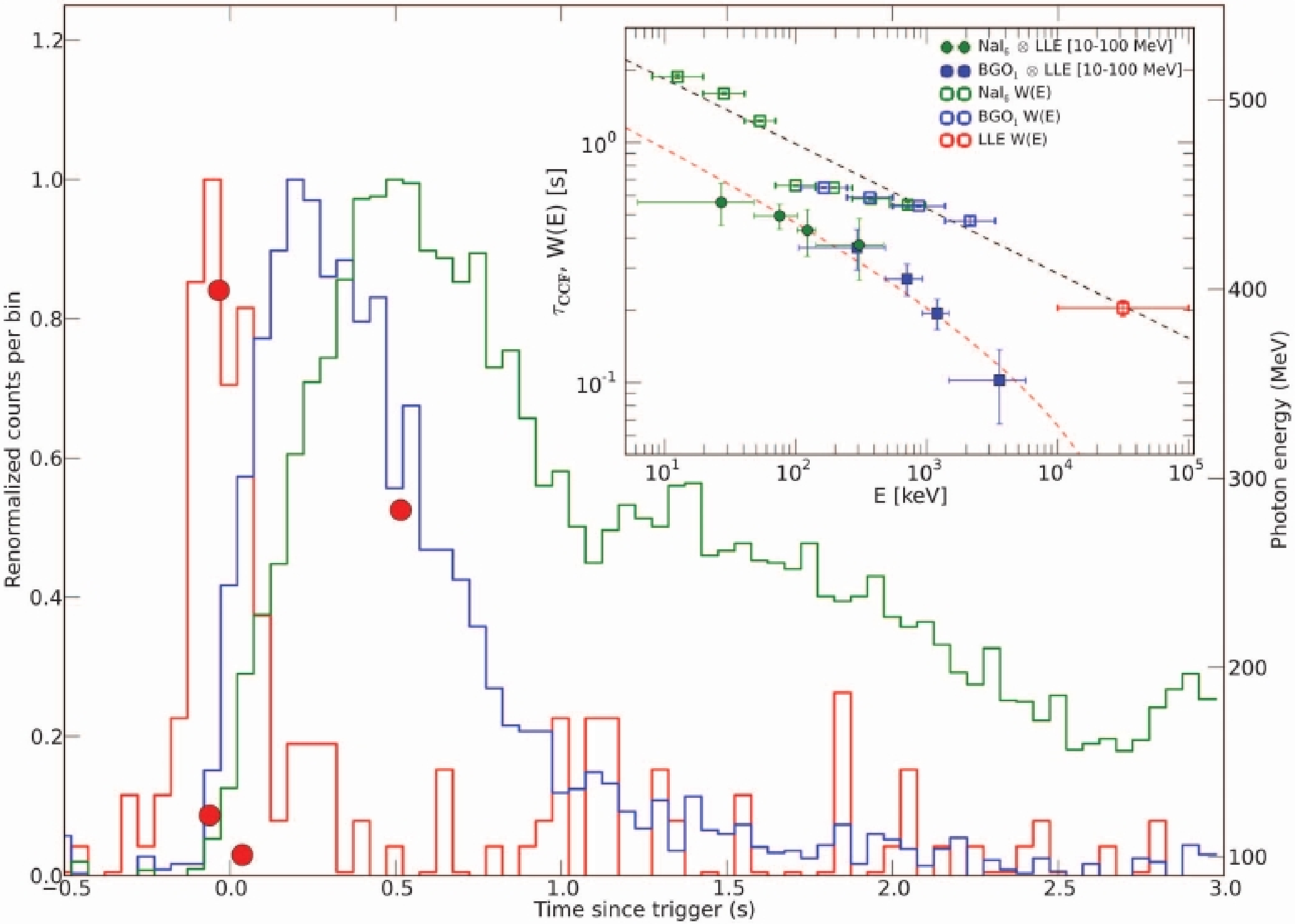
GRB 130427A composite light curve

- E_{iso} = 1.4 10^{54} erg
- **Brightest LAT GRB**
  - >500 photons >100 MeV
  - 15 photons >10 GeV
- **Unlike other bright LAT GRBs, the LAT >100 MeV emission is temporally distinct from the GBM emission**
- **LAT >100 MeV emission is delayed and temporally extended**
  - Delay ~10 s, continues well after the prompt phase
  - 73 GeV photon detected at T_0+19 s



Ackermann et al. 2014, Science 343, 42

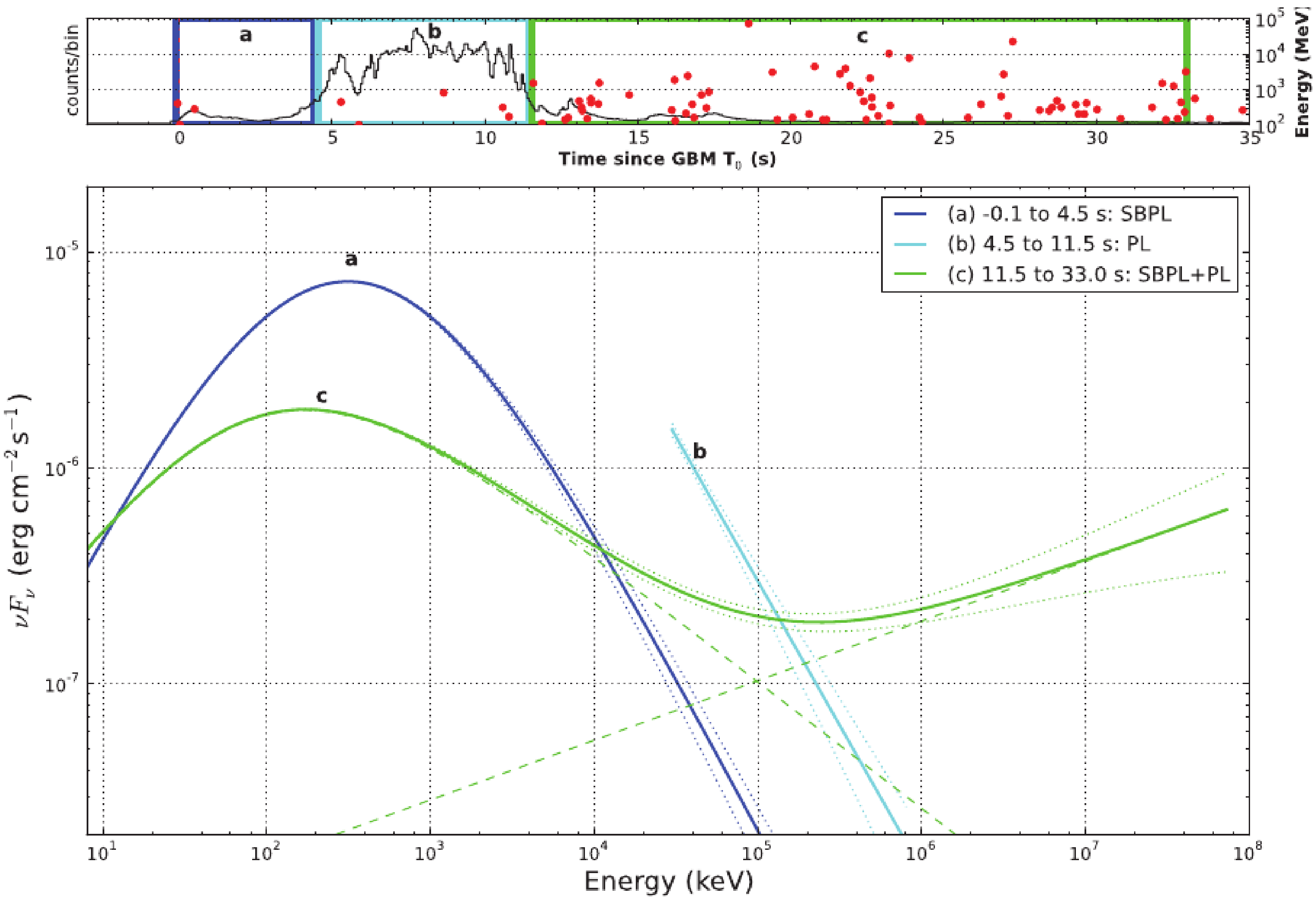
The first 3 seconds of GRB 130427A



Preece et al. 2014, Science 343, 51

- **A test lab for synchrotron shocks**
  - Spectral lag and pulse width in good agreement
  - Epeak evolves as t^{-1} as expected
  - But: photospheric radius too large, Lorentz factor decreases with time

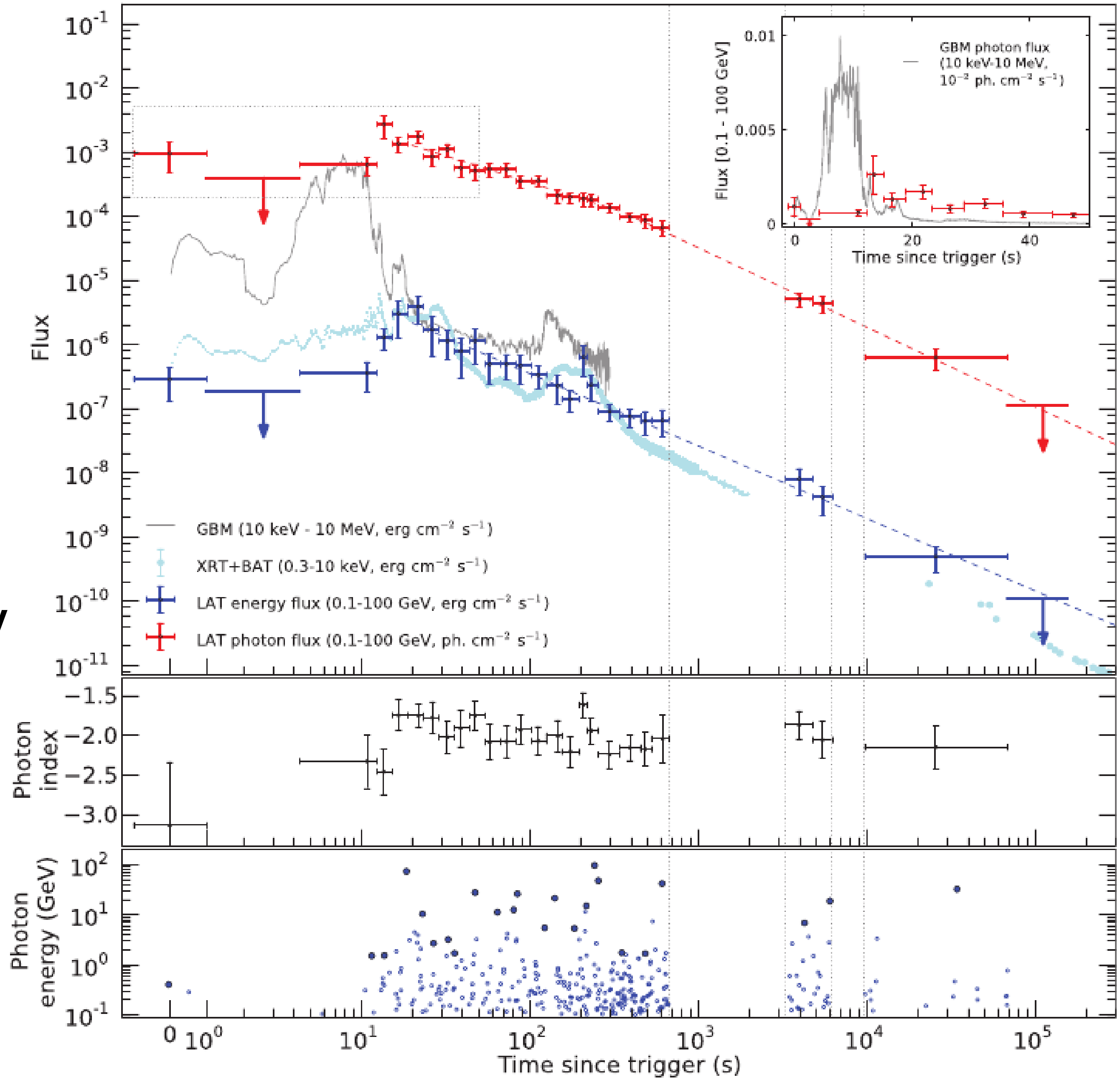
Spectral Energy Distributions



- **Unlike other bright LAT-detected GRBs, the extral PL component becomes significant only after the GBM-detected emission has faded. This suggests that:**
  - The GBM-detected emission is prompt emission (produced by internal shocks)
  - The LAT-detected emission is afterglow emission (produced by external shock)

GRB 130427A afterglow in X-rays and γ-rays (1/2)

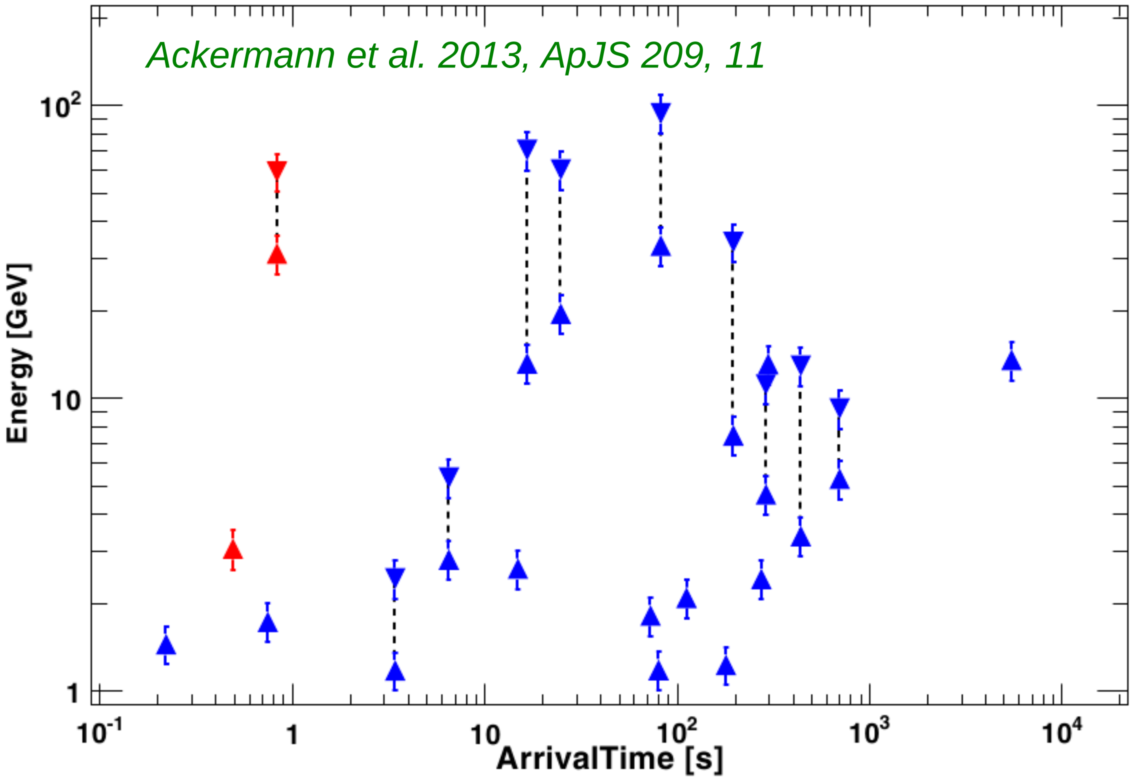
- **Brightest X-ray afterglow ever detected**
- **Longest-lived gamma-ray emission: LAT emission detected for 19 hours**
- **LAT light curve is ~smooth**
  - Photon flux: t_{break} ~ 300s
  - Energy flux temporal index: -1.17 +- 0.06
- **LAT spectrum described by a power law at all times**
  - Late spectral index ~ -2
- **Some common features between LAT and lower energy light curves**
- **Record breaking 95 GeV photon at T_0+244 s**



Ackermann et al. 2014, Science 343, 42

Highest-energy detected photons

- **First LAT GRB catalog**



- **GRB 090902B: 33.4 GeV photon at T_0+81.8 s**
- **GRB 080916C: 27.5 GeV photon at T_0+40.5 s** (~150 GeV rest frame, z=4.35) in Pass 8 data

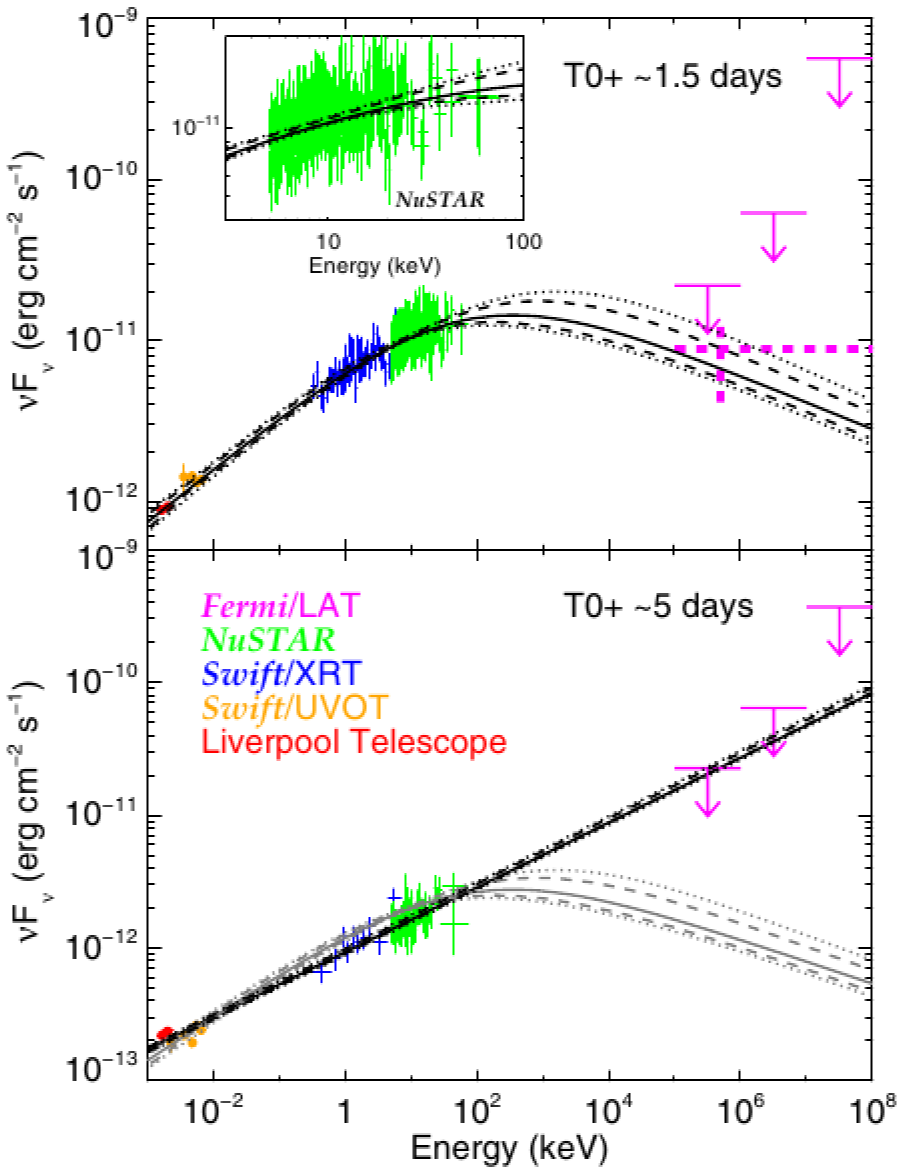
- **GRB 130427A**

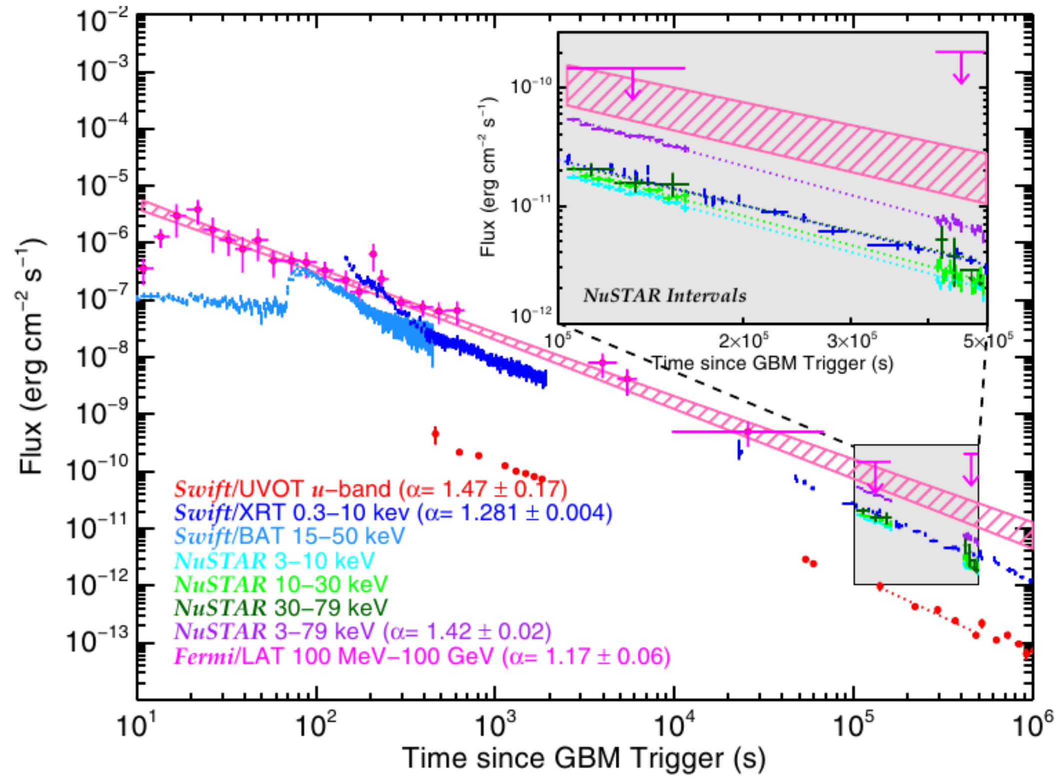
E	E_{rf}	$T - T_0$
95	128	243.55
73	97	19.06
47	63	256.70
41	55	611.01
39	52	3410.26
32	43	34366.58
28	37	48.01
26	35	85.16
21	21	141.53
15	20	217.89

Ackermann et al. 2014, Science 343, 42

GRB 130427A afterglow in X-rays and γ-rays (2/2)

Kouveliotou et al. 2013, ApJ 779, L1

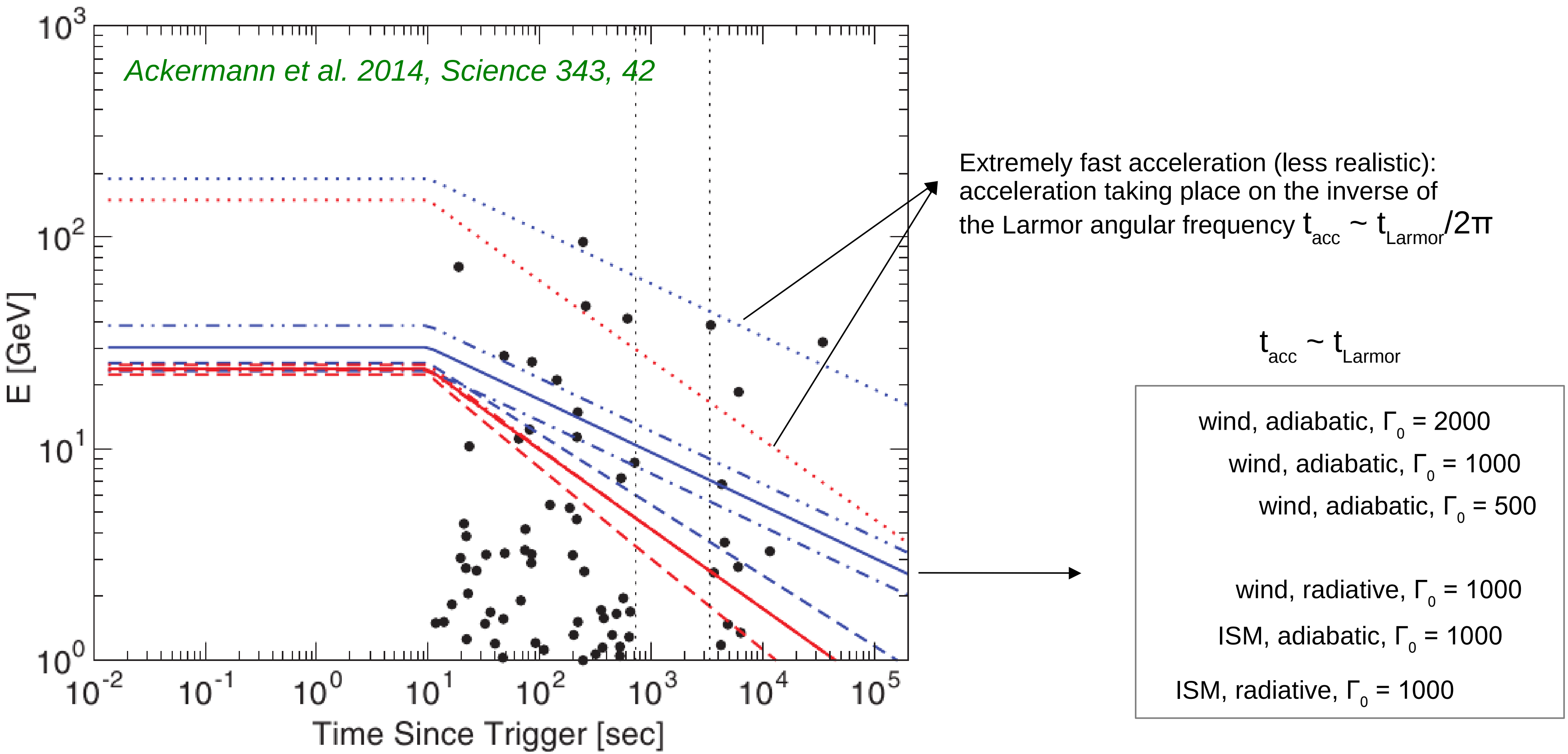




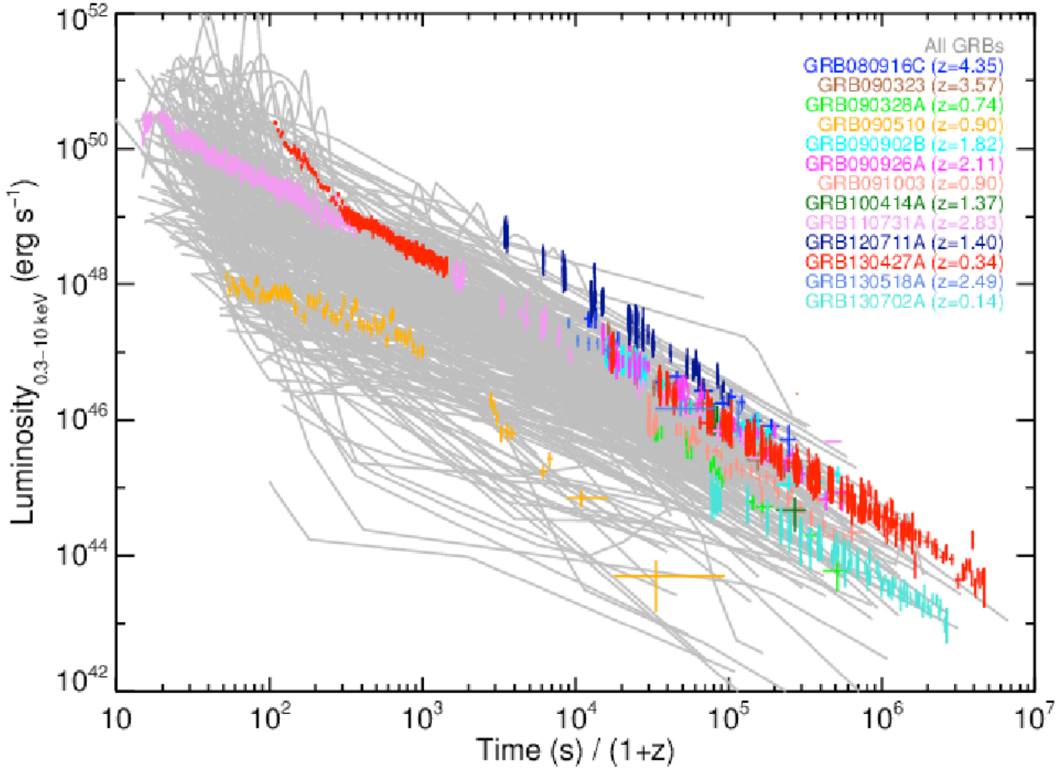
- **The broad-band optical to GeV spectrum at ~1 day implies a single synchrotron spectral component**
- **The consistency of a single component has important implications for the ability of the standard synchrotron model to produce these observations**

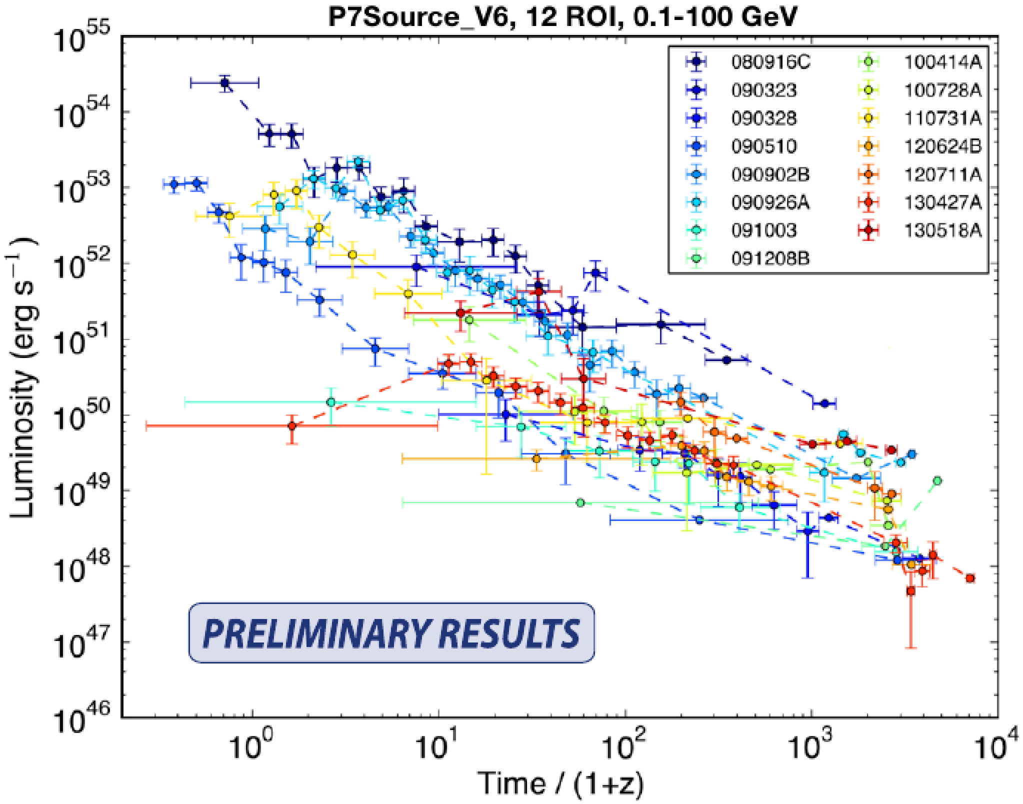
GRB 130427A: a challenge for synchrotron models

- **Synchrotron radiation models predict a maximum synchrotron energy, derived by equating the electron acceleration and synchrotron radiative cooling timescales**
  - Assuming a single acceleration and emission region
  - $E_{max} \sim 79\Gamma(t)$ MeV, with $\Gamma(t)$ given by Blandford & McKee (1976) in the adiabatic limit
- **The LAT highest energy photons are incompatible with having a synchrotron origin**



GRB 130427A in the source frame





- **Source frame X-ray and GeV light curves are not extraordinary**
  - Fainter than GRBs 080916C, 090902B, & 090926A at early times
  - Apart from that, GRB 130427A is similar to other LAT detected bursts
  - Would not have been detected by the LAT beyond z=2 (and not by the GBM beyond z ~ 4.5-5)

Constraining LIV with LAT GRB photons

- Quantum Gravity (QG) effects at Planck scale (E_{Planck}=1.2 x 10^{19} GeV) may induce an energy-dependent speed of light (Lorentz Invariance Violation):

$$v_{\rm ph}(E) \simeq c \times \left[1 \mp \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^n\right]$$

with n=1 or 2

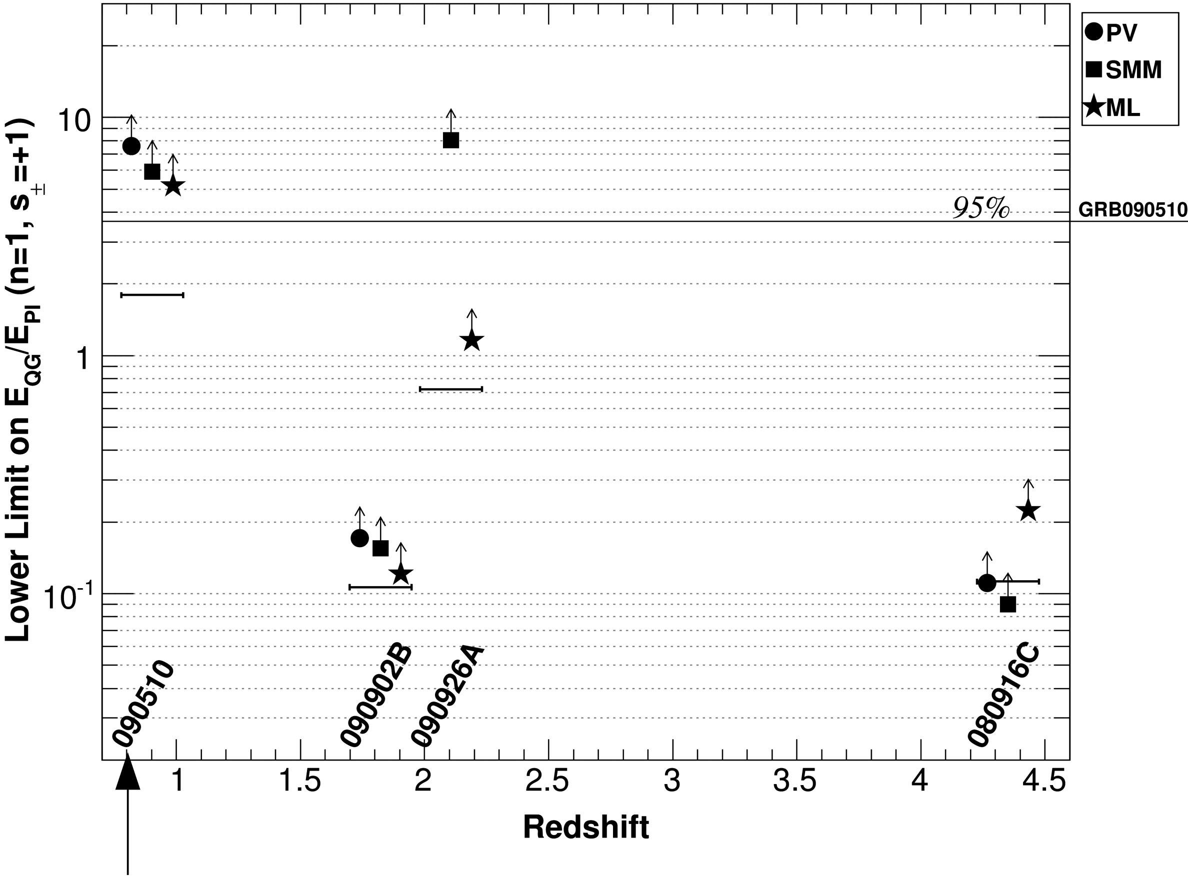
- Time-of-flight technique: 3 methods applied on *Fermi*-LAT bright GRBs

$$\frac{\Delta t}{10\ \rm ms} \approx \left(\frac{\Delta E}{1\ \rm GeV}\right)\left(\frac{E_{\rm Planck}}{E_{\rm QG}}\right)\left(\frac{L}{1\ \rm Gpc}\right)$$

- Robust and well tested analysis, including GRB-intrinsic effects
→ the most stringent limits ever

- Results in the linear case (*n=1*):
  - $E_{QG} > 7.6 \times E_{Planck}$ (95%)
  - Theoretical models predicting $E_{QG} \lesssim E_{Planck}$ are excluded

Abdo et al. 2009, Nature 462, 331
Vasileiou et al. 2013, PRD 87, 122001



- Our best constraints from GRB 090510 (z=0.93)
  - 31 GeV photon coincident with a narrow (~0.4 s) pulse
  - Dispersion ≲ ms/GeV

Summary and conclusions

- **GRB population studies at high energy are now possible with *Fermi***
  - LAT bursts are bright, fluent & energetic
  - GRB >100 MeV emission is delayed & temporally extended w.r.t. the emission in the MeV range
  - Short and long GRBs seem to have similar high-energy properties
  - The distribution of GRB jet Lorentz factors might be broad

- **Prompt emission phase observed over a wide energy range**
  - Complex spectral shapes are needed to reproduce the spectrum
  - Origin of the delayed onset of the LAT >100 MeV emission?
  - Transition from prompt emission phase to early afterglow phase?
- **Long-lived GeV emission is consistent with the canonical afterglow model**

- **GRB 130427A was exceptionally unique in the observer frame (z=0.34)**
  - The γ-ray records broken
    - Highest γ-ray fluence (>10^{-3} erg/cm^2)
    - γ-ray photon w/ the highest observed energy (95 GeV)
    - Longest-lasting GeV emission (19 hours)
  - GBM and LAT emissions arise from different emission mechanisms and/or regions
  - LAT observations put severe constraints on the FS synchrotron model