Observations de sursauts gamma avec *Fermi*

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du labex OCEVU
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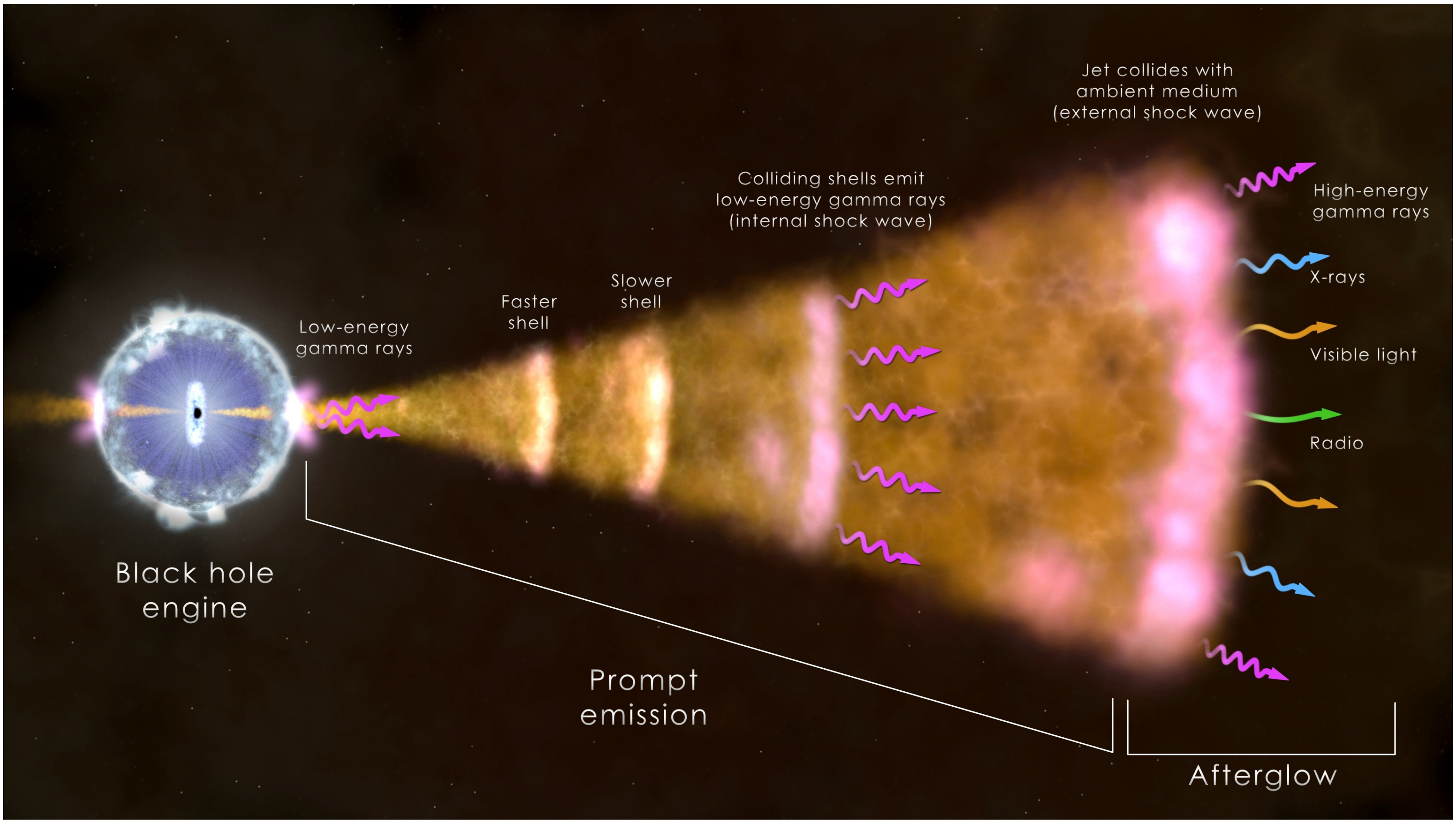
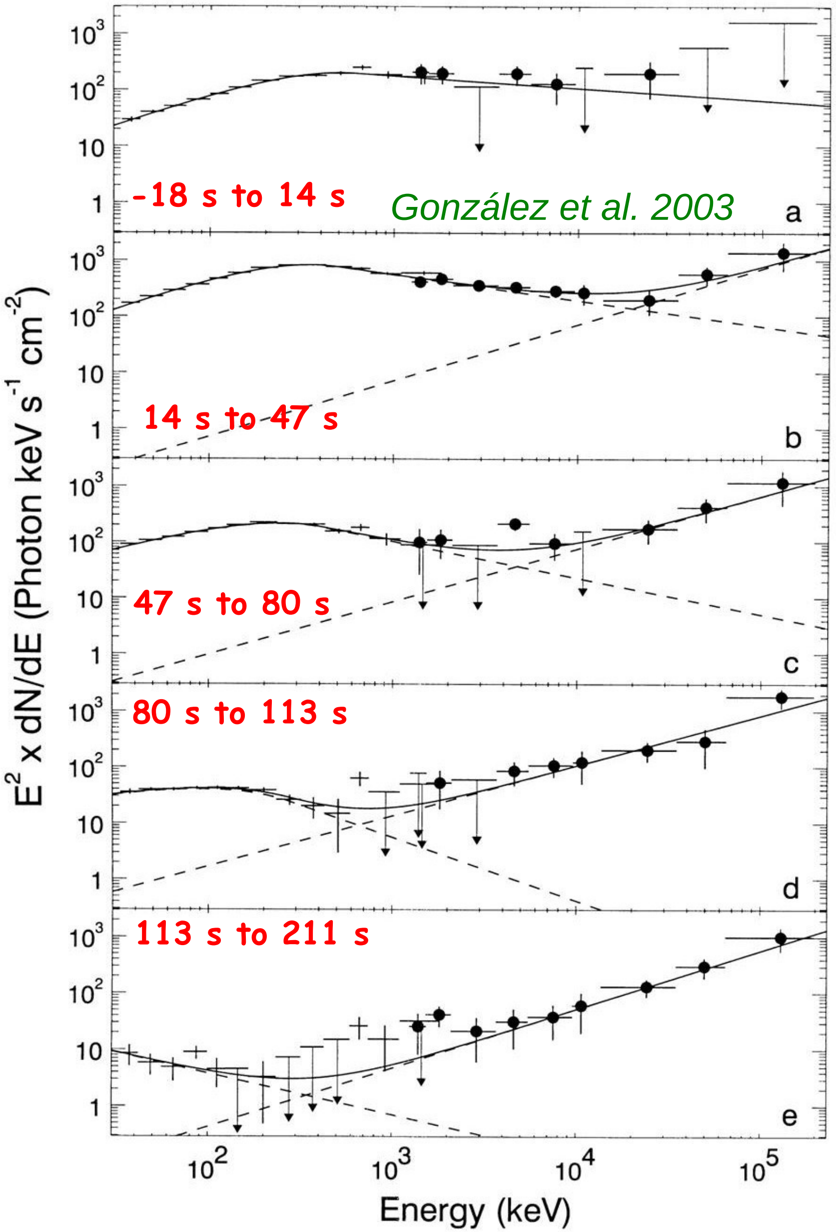
The standard picture

- Formation of a stellar black hole (core collapse of a massive star, or NS/BH coalescence)
- Collimated jet at relativistic speed (Γ>100); photospheric radius R~10^{11-12} cm
- Internal shocks accelerate particles → non thermal gamma-ray emission (prompt phase, R~10^{14-15} cm)
- External shock between the jet and the circumburst medium (afterglow phase, R~10^{16-17} cm)



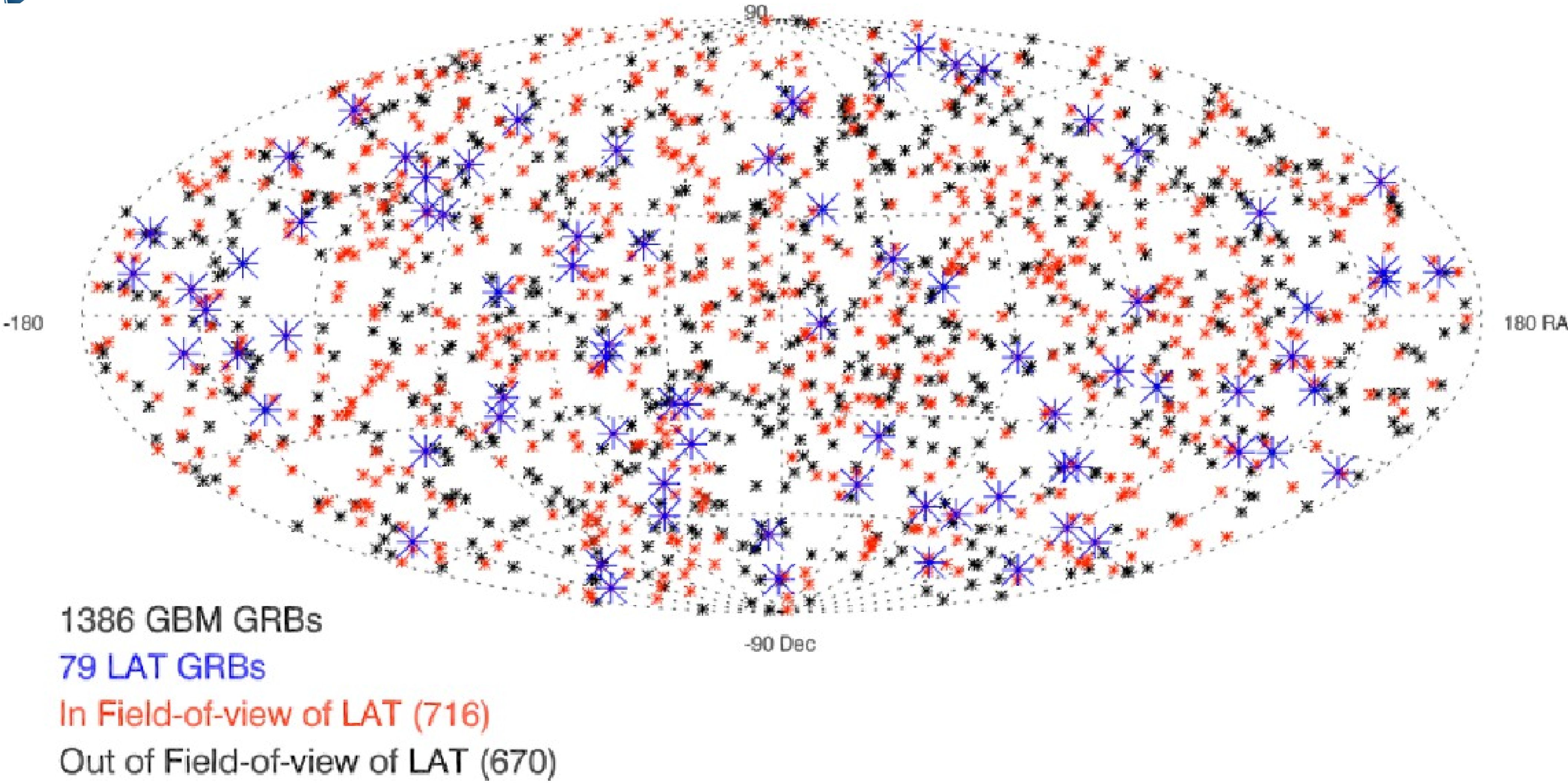
GRBs at high energy

GRB 941017 (EGRET)



- **GRB 941017: >MeV emission has a different time dependence and spectral shape**
- **Nature of accelerated particles (electrons, ions)?**
- **Where / how are they accelerated? Internal shocks or external shock? Particle spectrum?**
- **When do internal shocks (prompt phase) end? When does the external shock (afterglow) start?**
- **Which emission mechanisms prevail at high energy? What are the non-thermal emission radii?**
- **Is the extra HE component ubiquitous in GRB spectra?**
- **Maximum energy? Spectral cutoff at the highest energies? Opacity effects?**

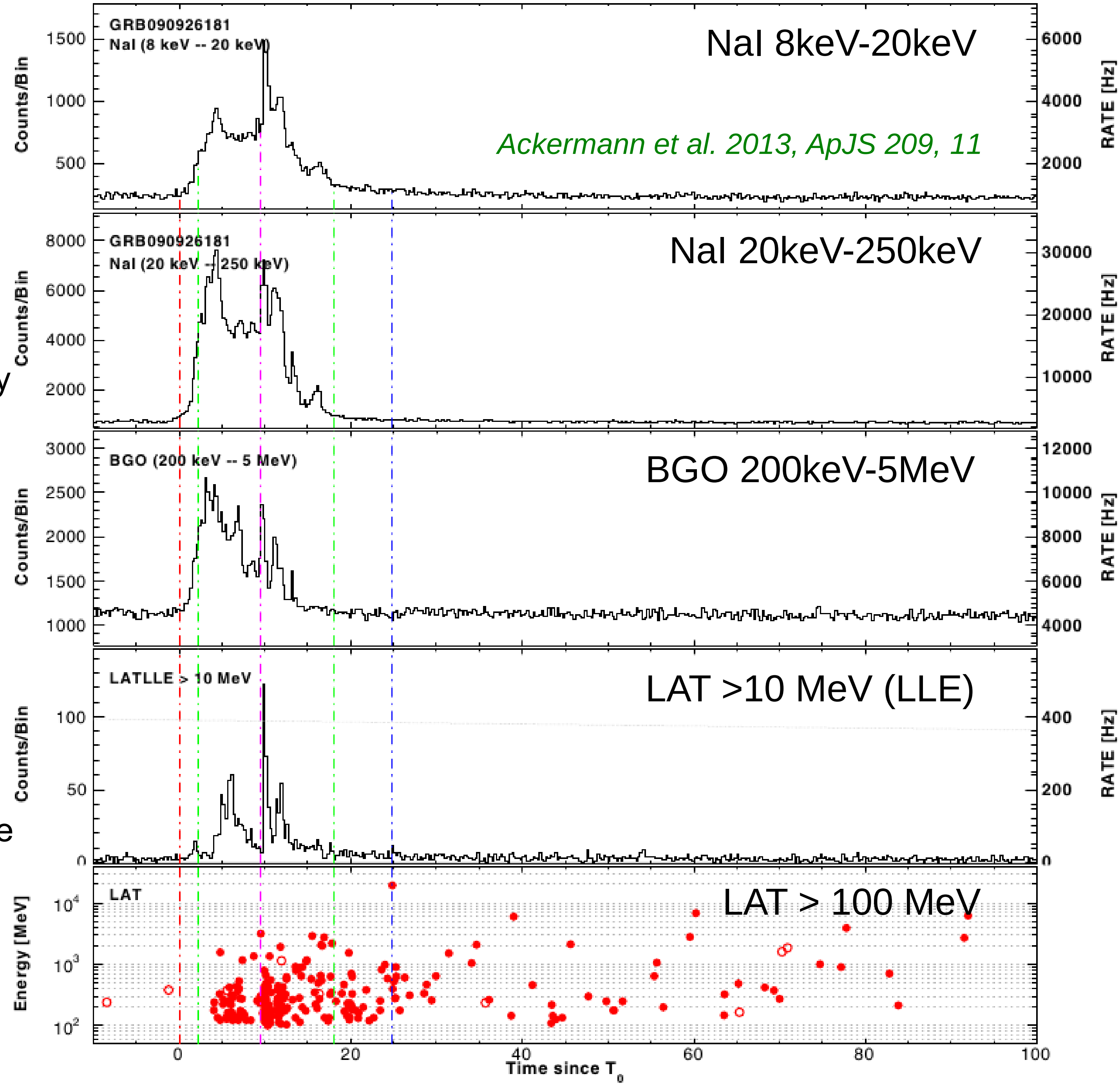
Fermi GRBs as of 140620



- **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

GRB 090926A multi-detector light curve

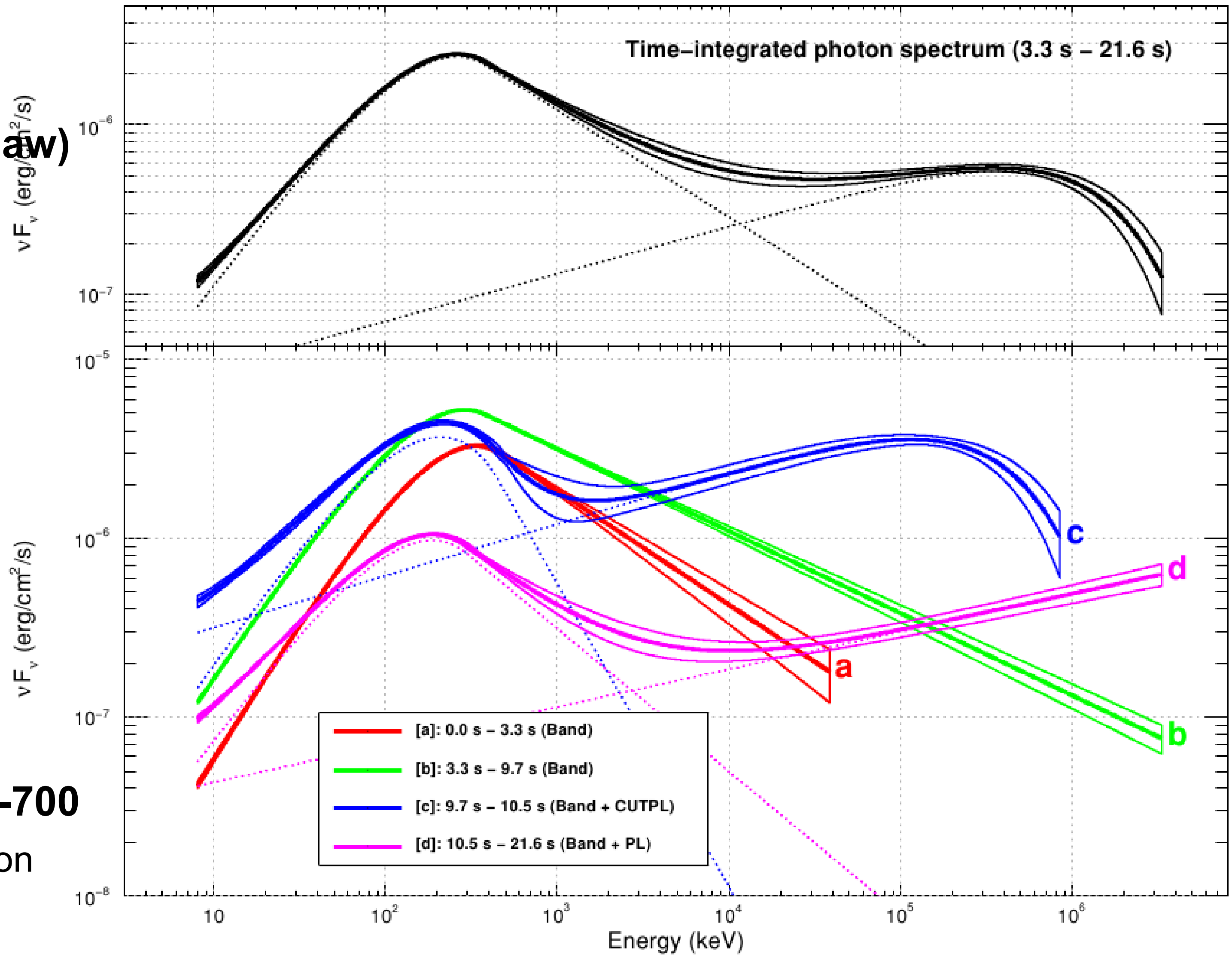
- **Correlated variability in various bands with a sharp spike at T_0+10 s**
  - All energy ranges synchronized (<50 ms)
  - Low and high energies are co-located or even causally correlated
- **LAT >100 MeV emission is delayed (~4 s)**
  - Delay > spike widths
- **LAT >100 MeV emission is temporally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



GRB 090926A broad-band spectrum

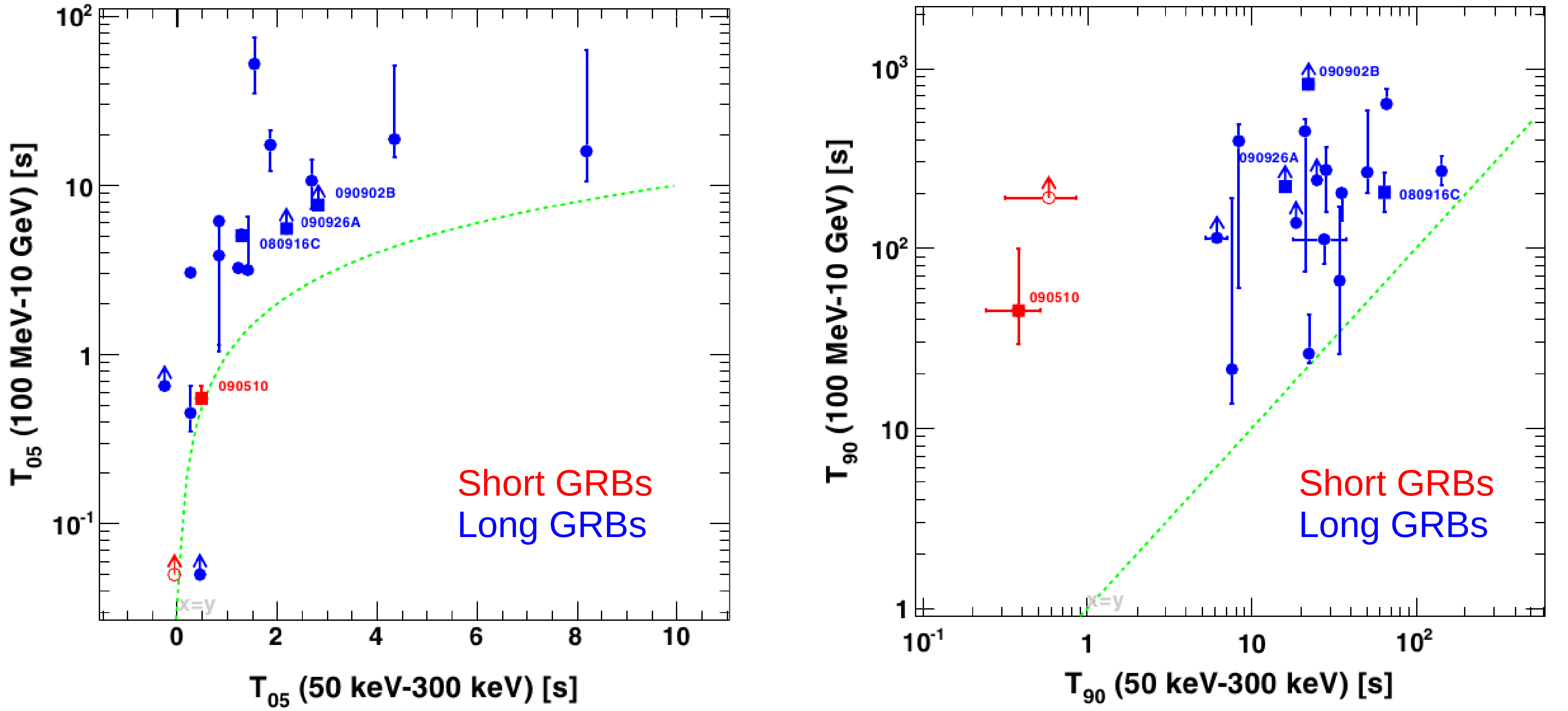
Ackermann et al. 2011, ApJ 729, 114

- **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 temporal properties

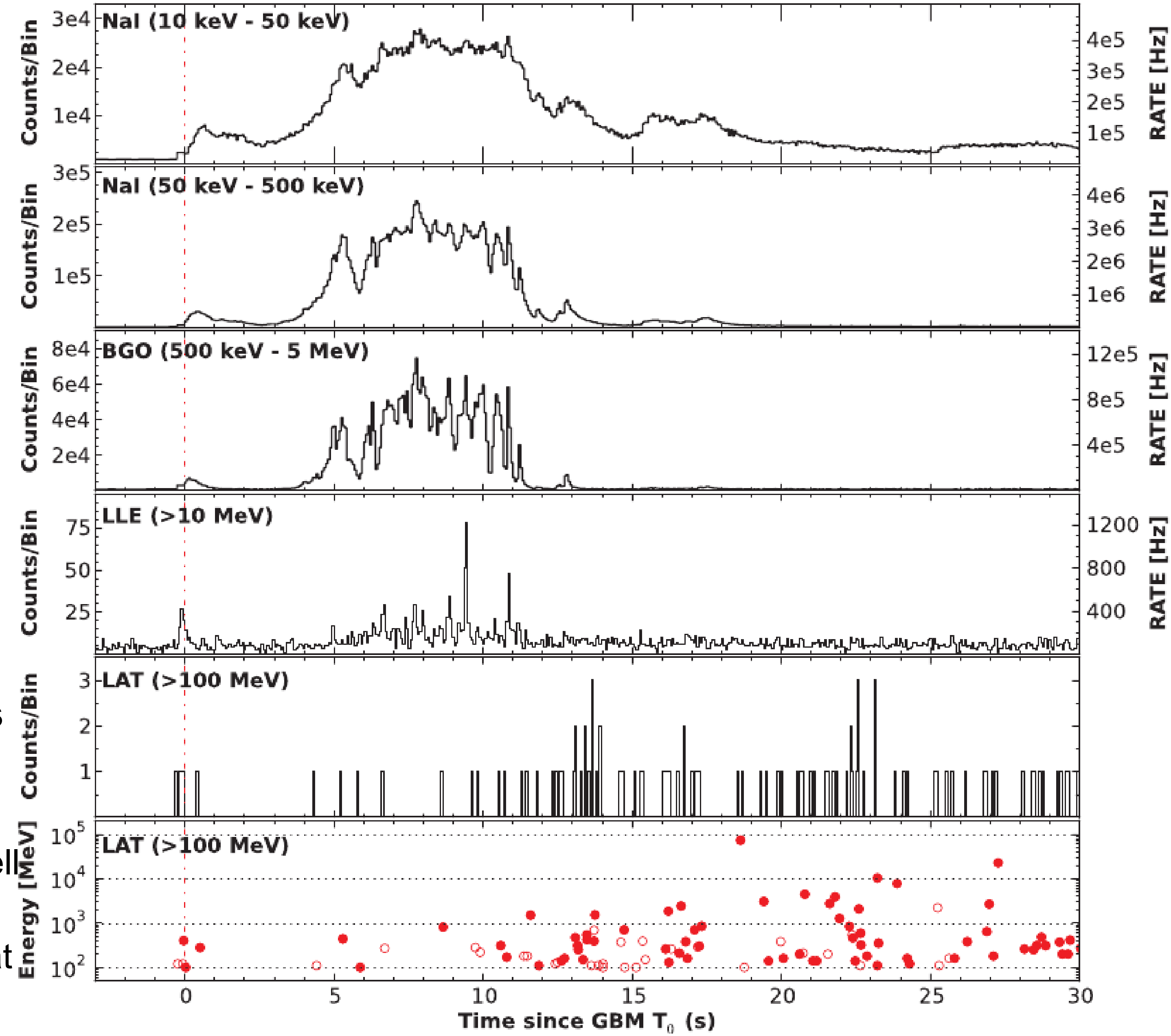
Ackermann et al. 2013, ApJS 209, 11



- **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)

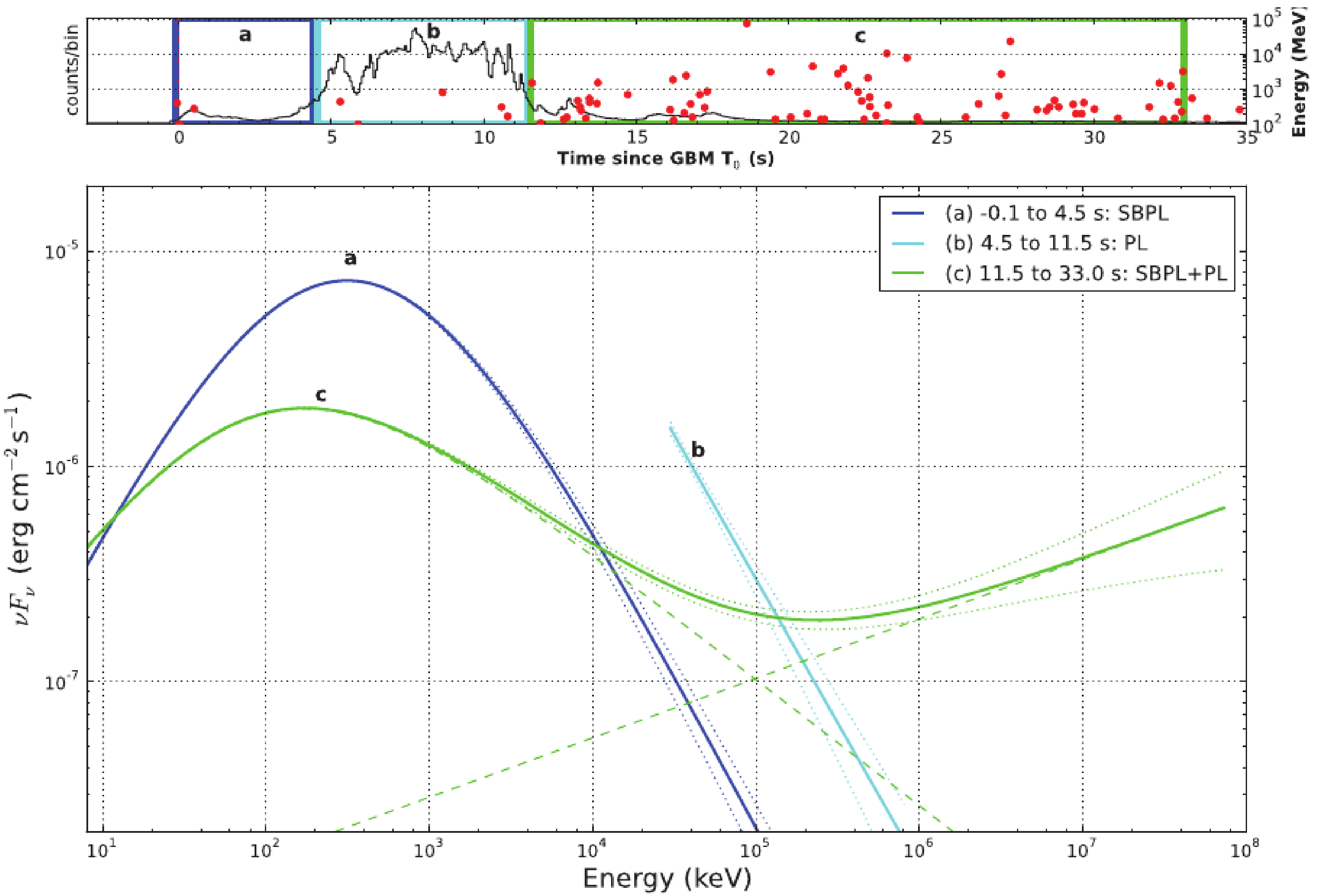
GRB 130427A composite light curve

- 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

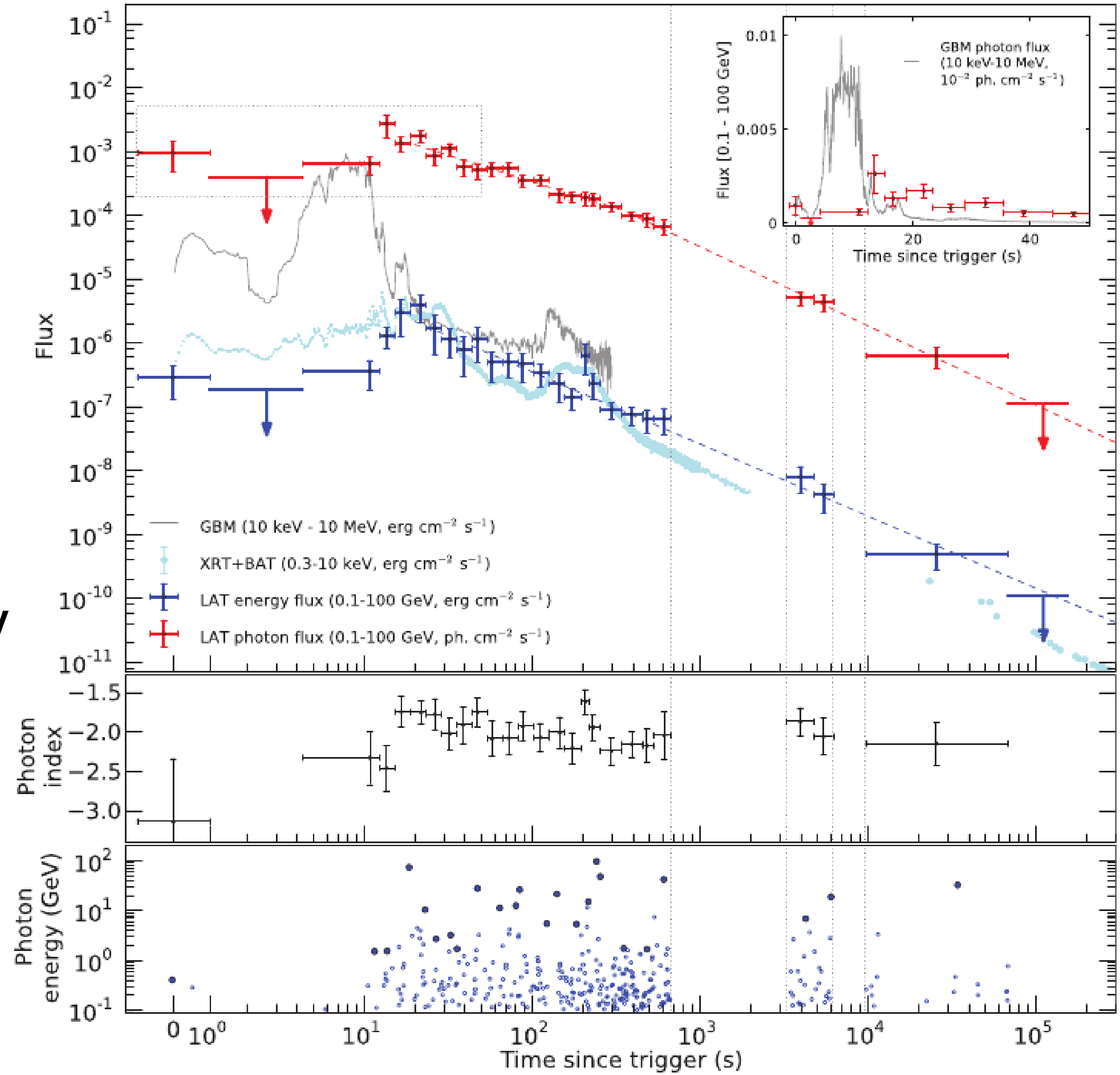
Spectral Energy Distributions



- **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

- **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**

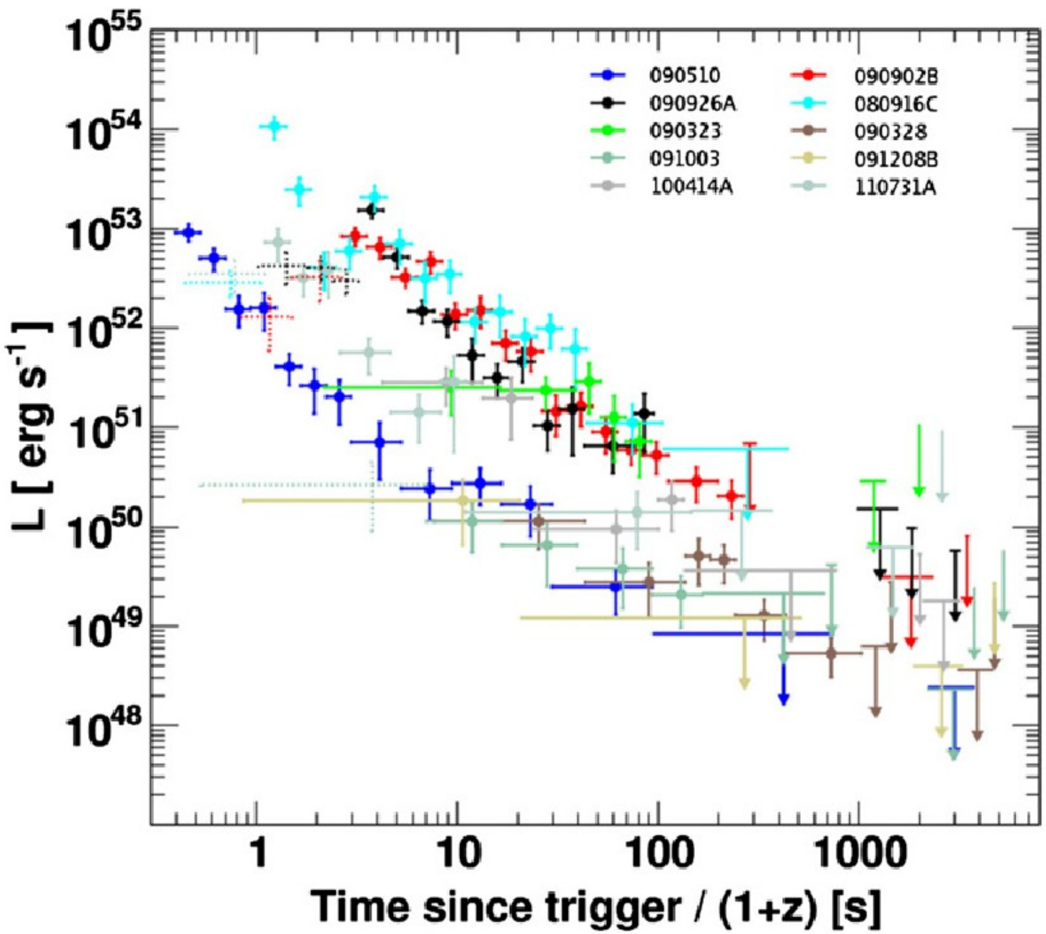


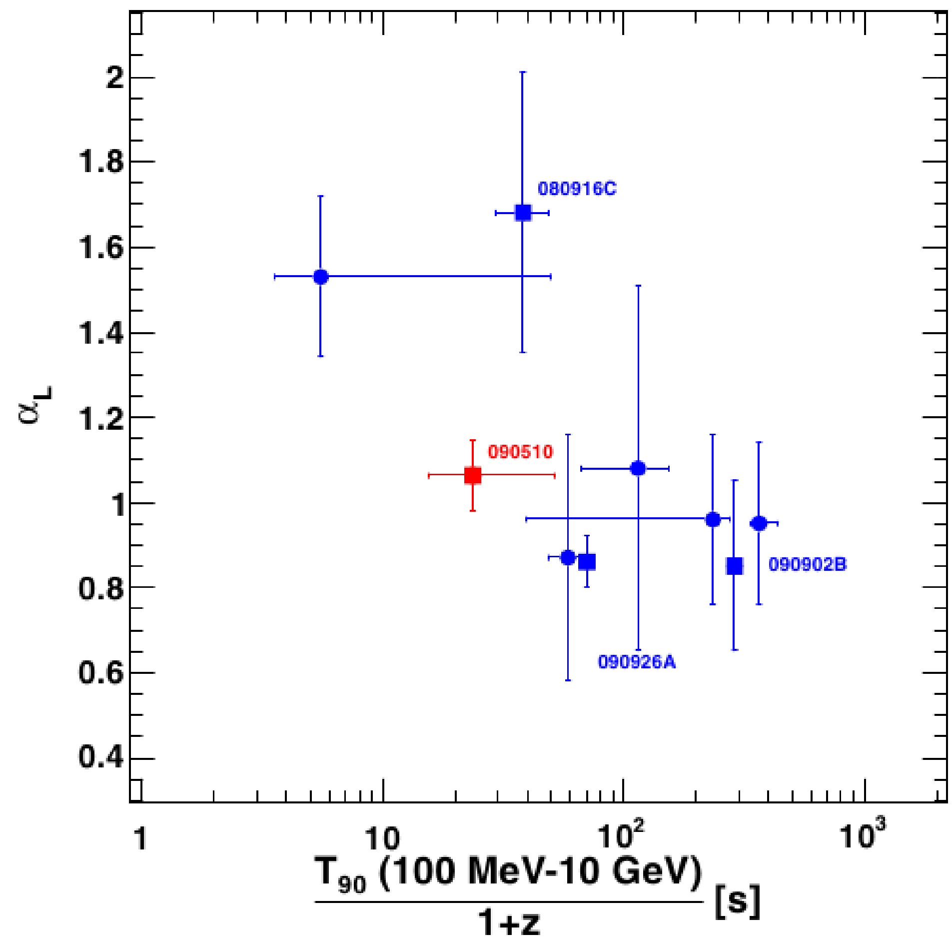
Ackermann et al. 2014, Science 343, 42

Long-lasting GeV emission

- **Consistent with afterglow models**
  - No strong spectro-temporal variability
  - 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)

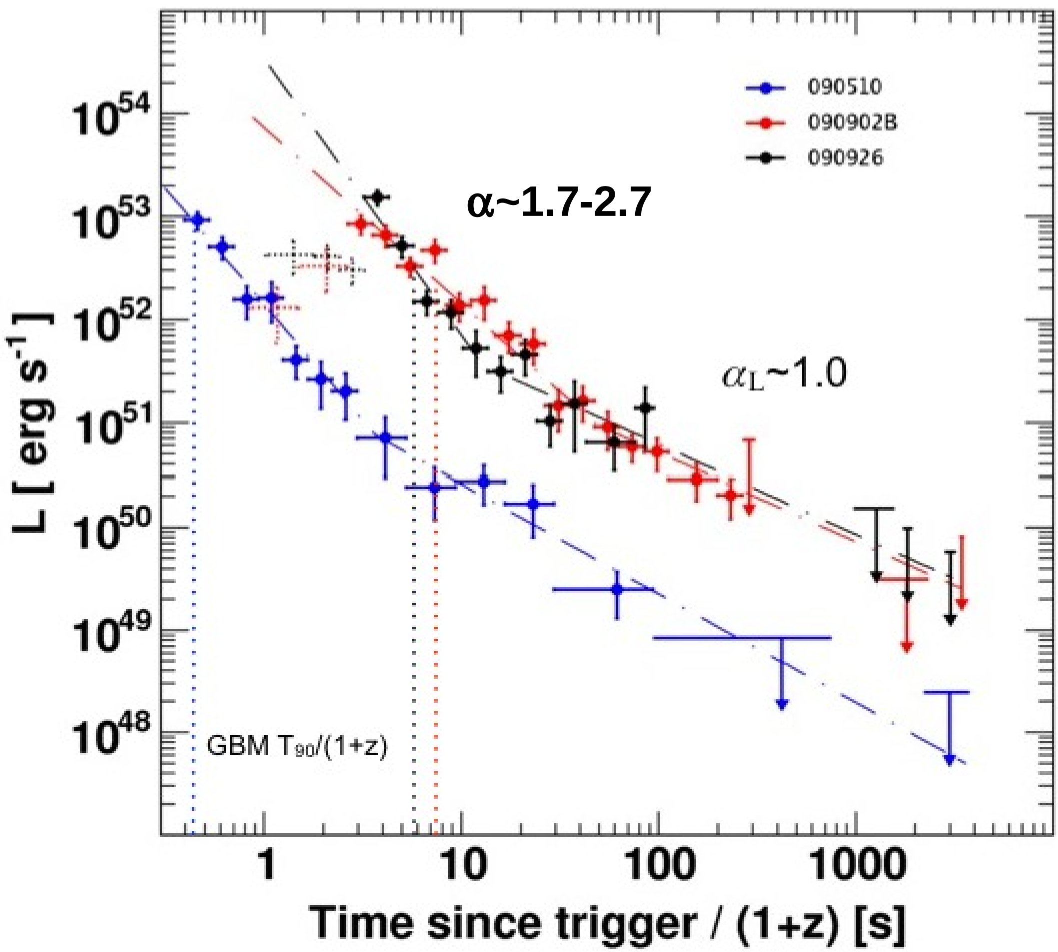


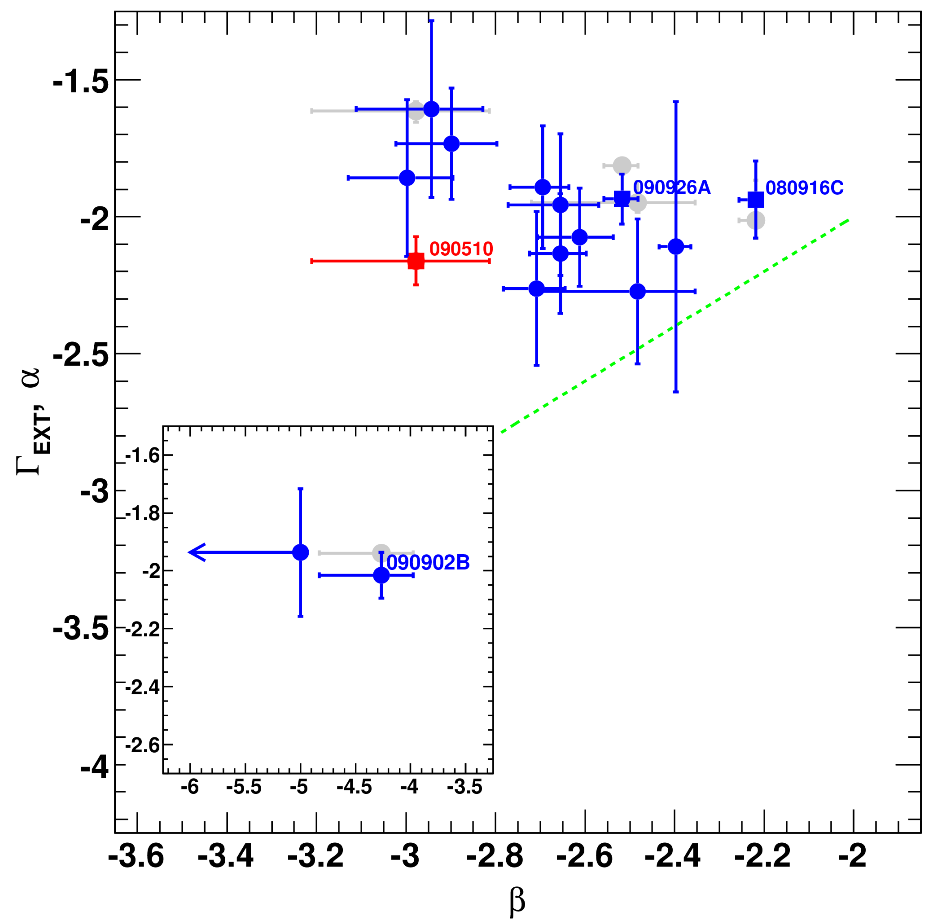


Ackermann et al. 2013, ApJS 209, 11

Prompt vs. afterglow phases

- **Temporal break in 2 long and 1 short bursts**
  - Prompt-contaminated to pure afterglow phase?
- **Photon spectral index is constant ($\Gamma_{EXT} \sim -2$)**
  - Not correlated with the high-energy spectral slope β_{Band} in the prompt emission



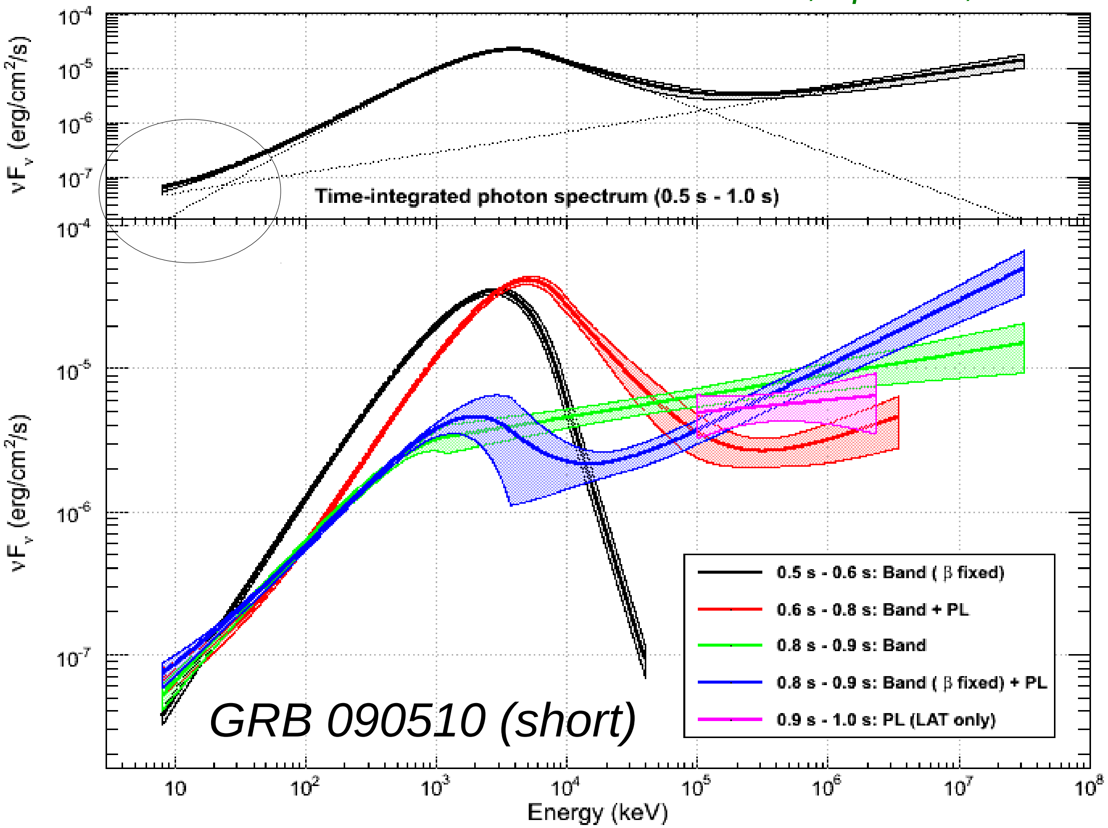


Ackermann et al. 2013, ApJS 209, 11

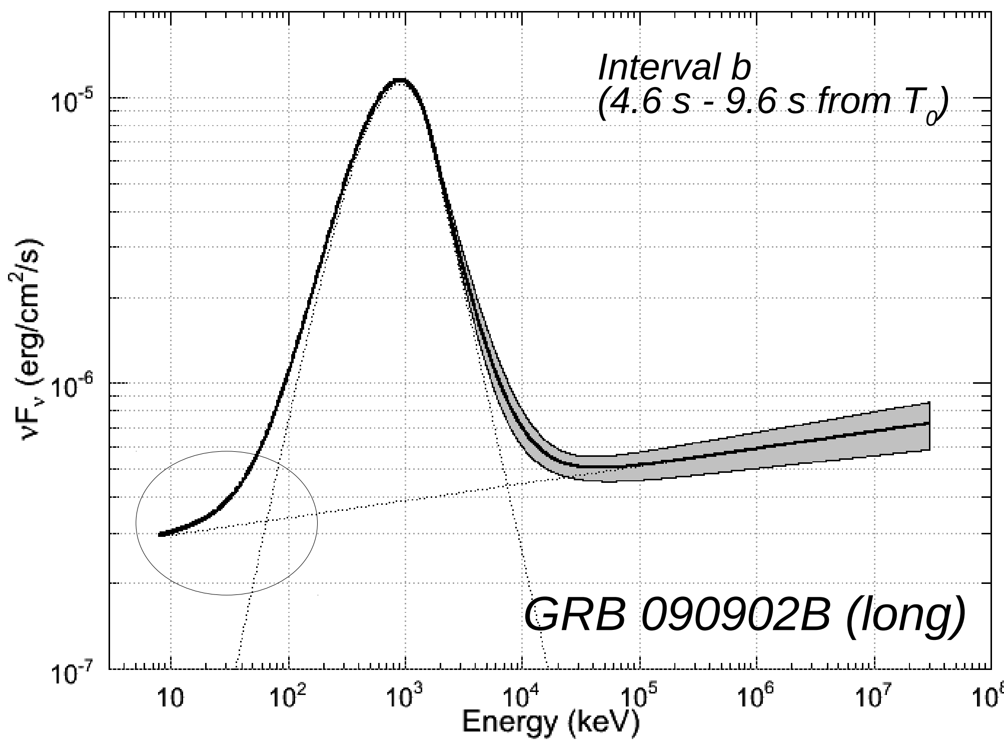
Broad-band spectral properties

- **The Band function is no longer the best phenomenological model**
  - Additional power law component at high energy
  - High-energy cutoff measured in the spectrum
  - Deviation from the Band function at low energy
  - → **Broad-band physical models are needed**

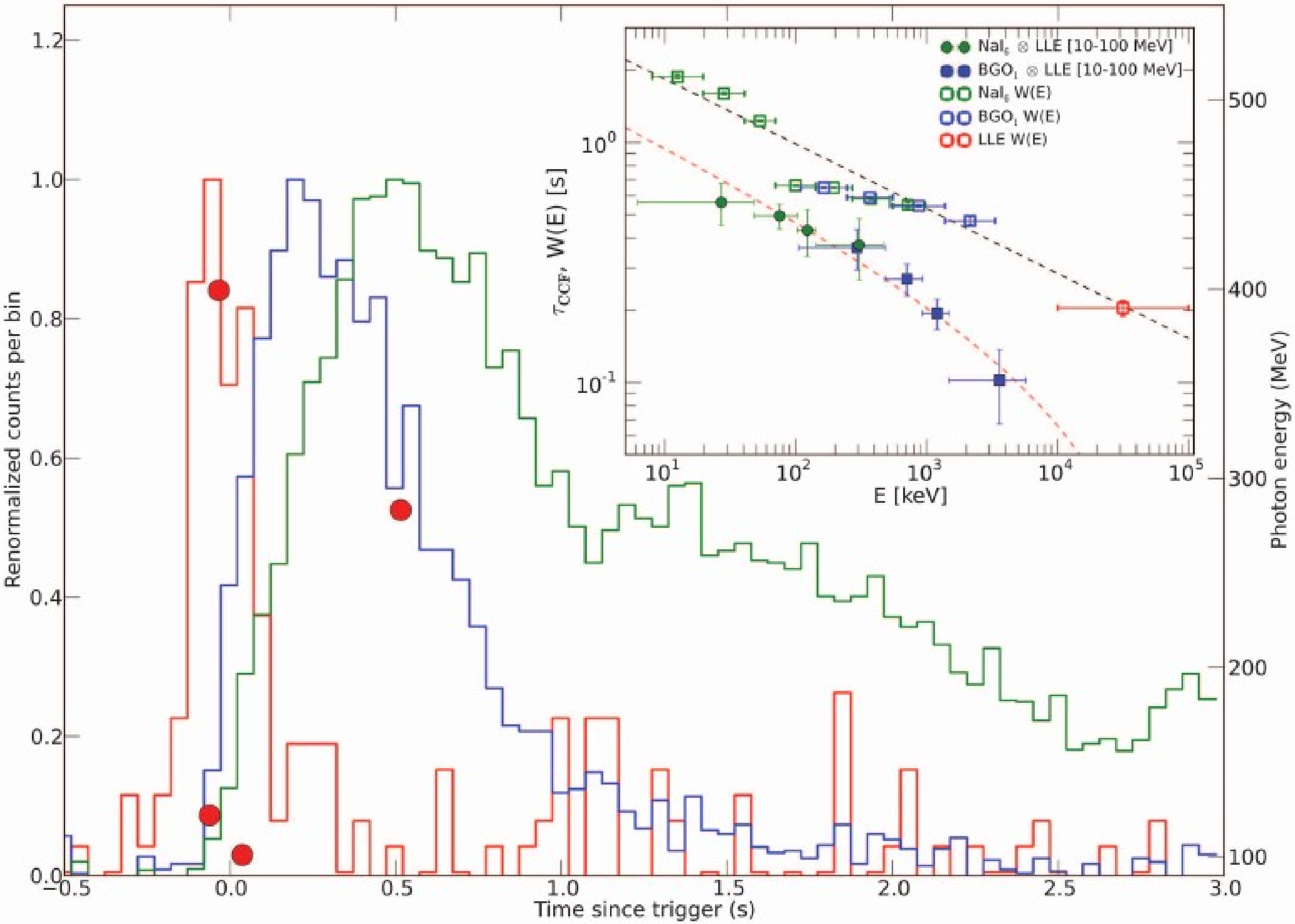
Ackermann et al. 2010, ApJ 716, 1178



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



The first 3 seconds of GRB 130427A

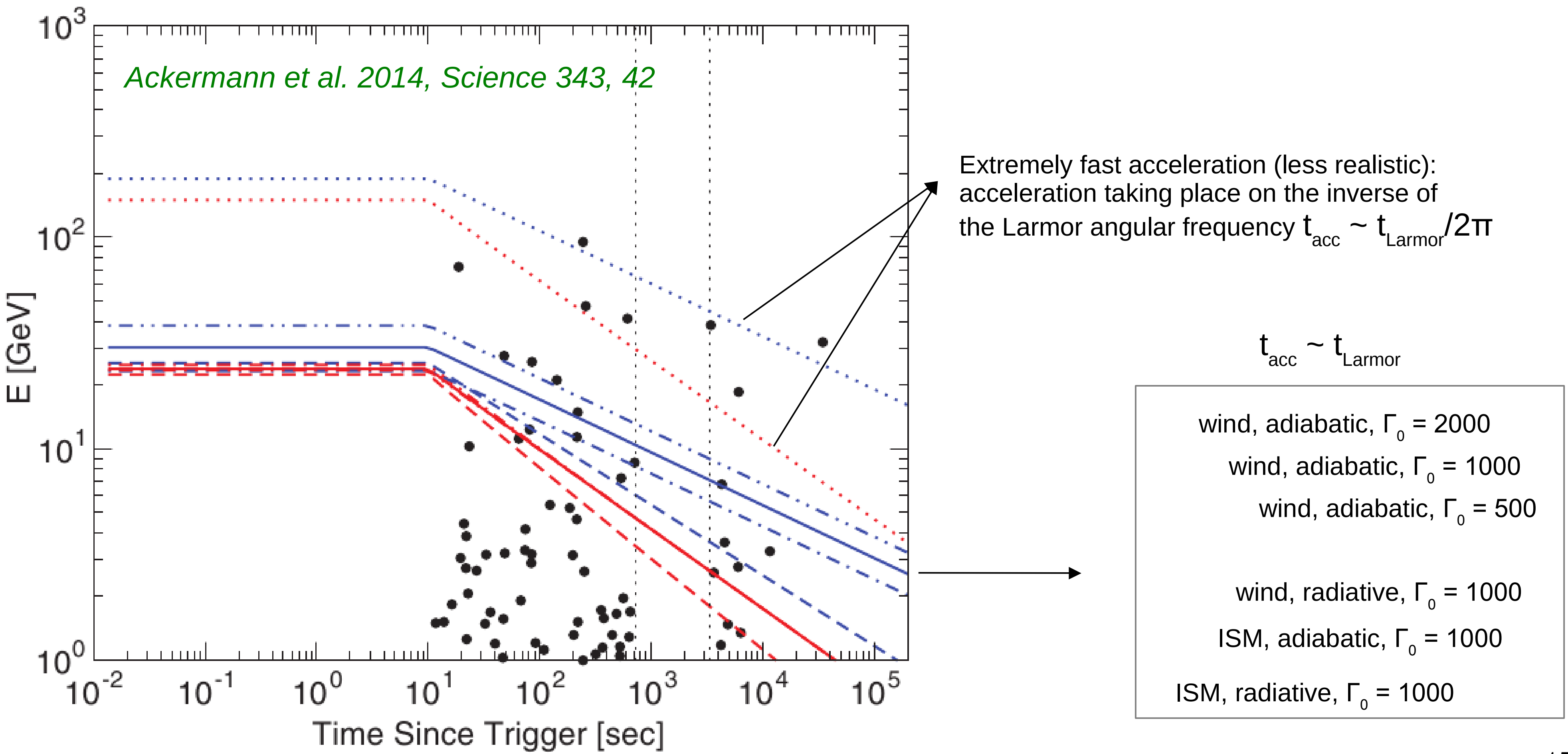


- **A test lab for synchrotron shocks**
  - Spectral lag and pulse width in good agreement
  - Epeak evolves as t^{-1} as expected

Preece et al. 2014, Science 343, 51

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**



Jet Lorentz factor

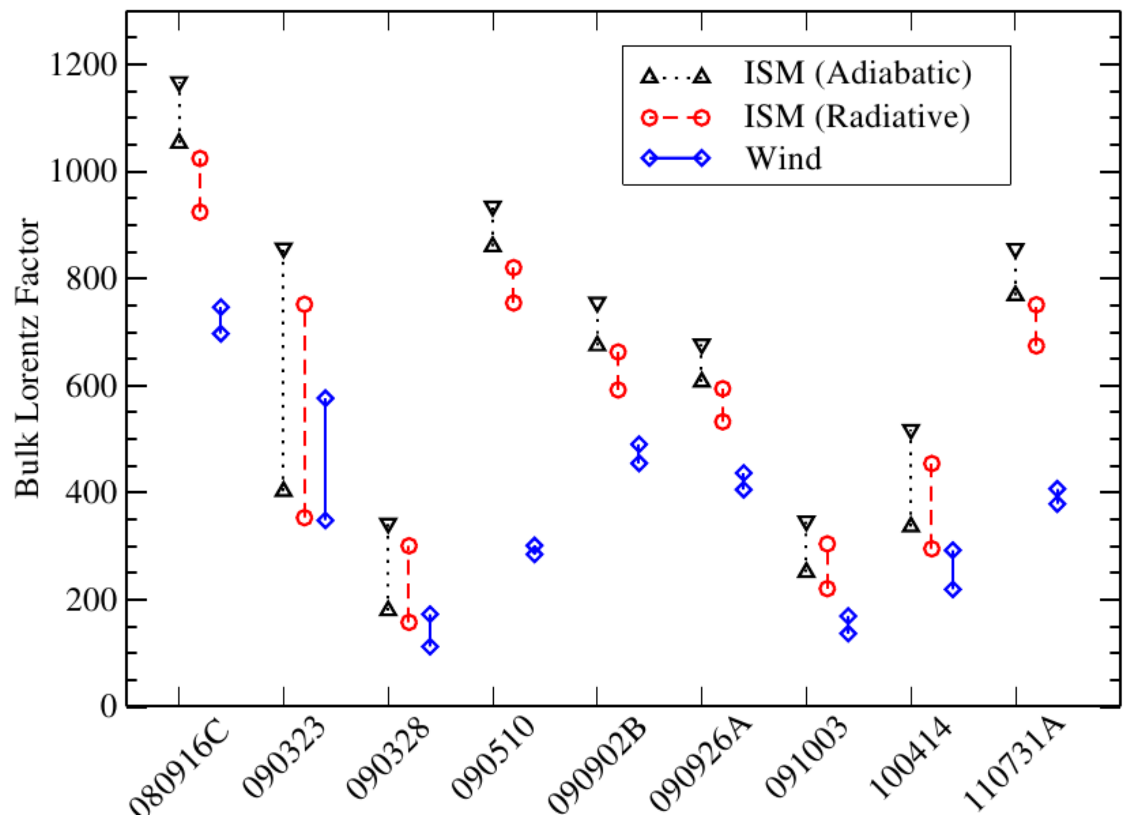
- **The bulk Lorentz factor can be derived from the fireball energetics and from its deceleration time (taken as the peak flux time in the LAT light curve)**
  - ISM of constant density *(Blandford & McKee 1976, Sari et al. 1998, Ghisellini et al. 2010)*

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

Ackermann et al. 2013, ApJS 209, 11

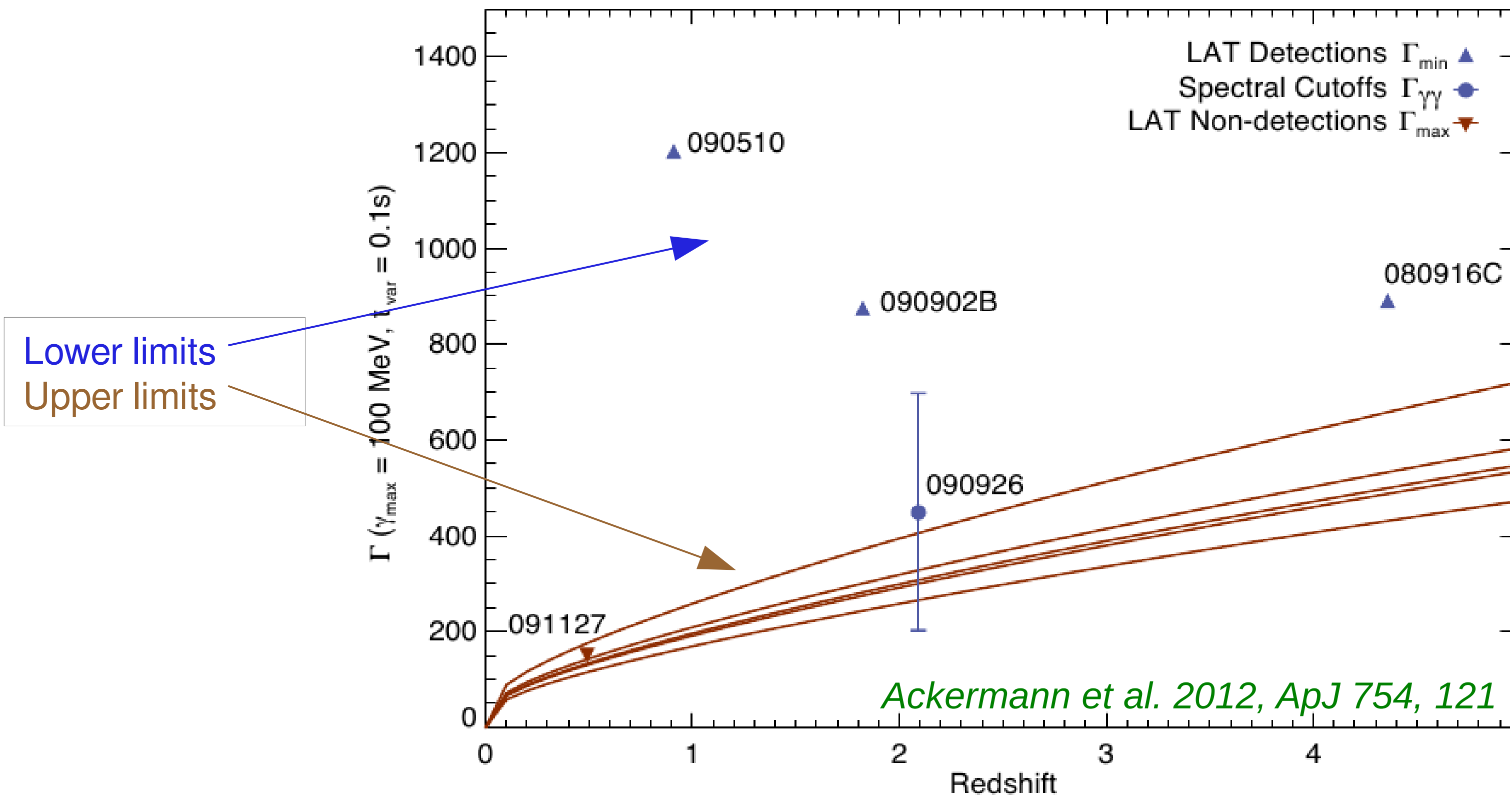
  - Wind environment *(Chevalier & Li 2000, Panaitescu & Kumar 2000)*

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



Jet Lorentz factor

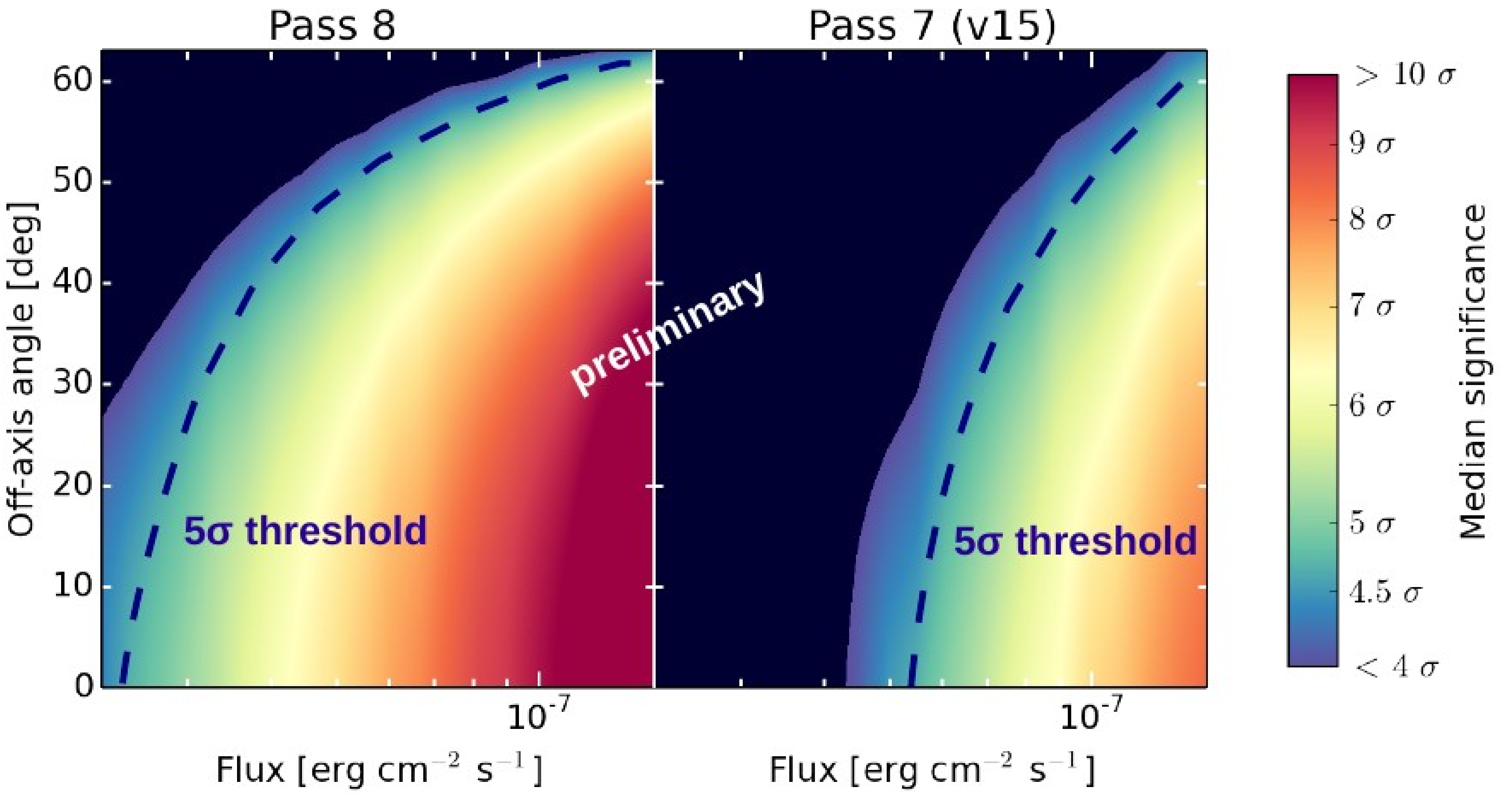
- **3 of the 4 brightest LAT bursts** show an extra PL component with no attenuation → **high Γ_{min}~1000**
- **6 GBM bright bursts not detected by the LAT** show some form spectral softening at tens of MeV → **Γ_{max}~150-650** assuming 100 ms variability and 1<z<5 (we only know the redshift for GRB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

Pass 8 expectations

- **100 s simulated GRBs with real background**
- **Transient class**



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

Origins of HE emission onset and extra PL component?

- **Leptonic models (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)
  - Hard to account for the Band α and the spectral index of the high-energy component
  - Models with photospheric emission component could help solve the last two issues
- **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
  - Proton synchrotron radiation requires large B-fields
  - Both scenarios require substantially more energy (1-3 orders of magnitude) than observed (much less stringent constraint with lower values of Γ)
  - Hard to produce correlated variability at low- and high-energies (e.g., spike of GRB 090926A)
- **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
  - Hard to explain rapid high-energy variability observed in some bursts (e.g., GRBs 090902B, 090926A)
  - Can not explain correlated light curves (e.g., spike of GRB 090926A)
  - IC of Band photons by high-energy electrons at the FS? → possible & can explain correlated light curves

Pass 8 expectations