GRB Spectroscopy: Clues for Magnetization

Rob Preece
Dept. of Space Science
The University of Alabama in Huntsville

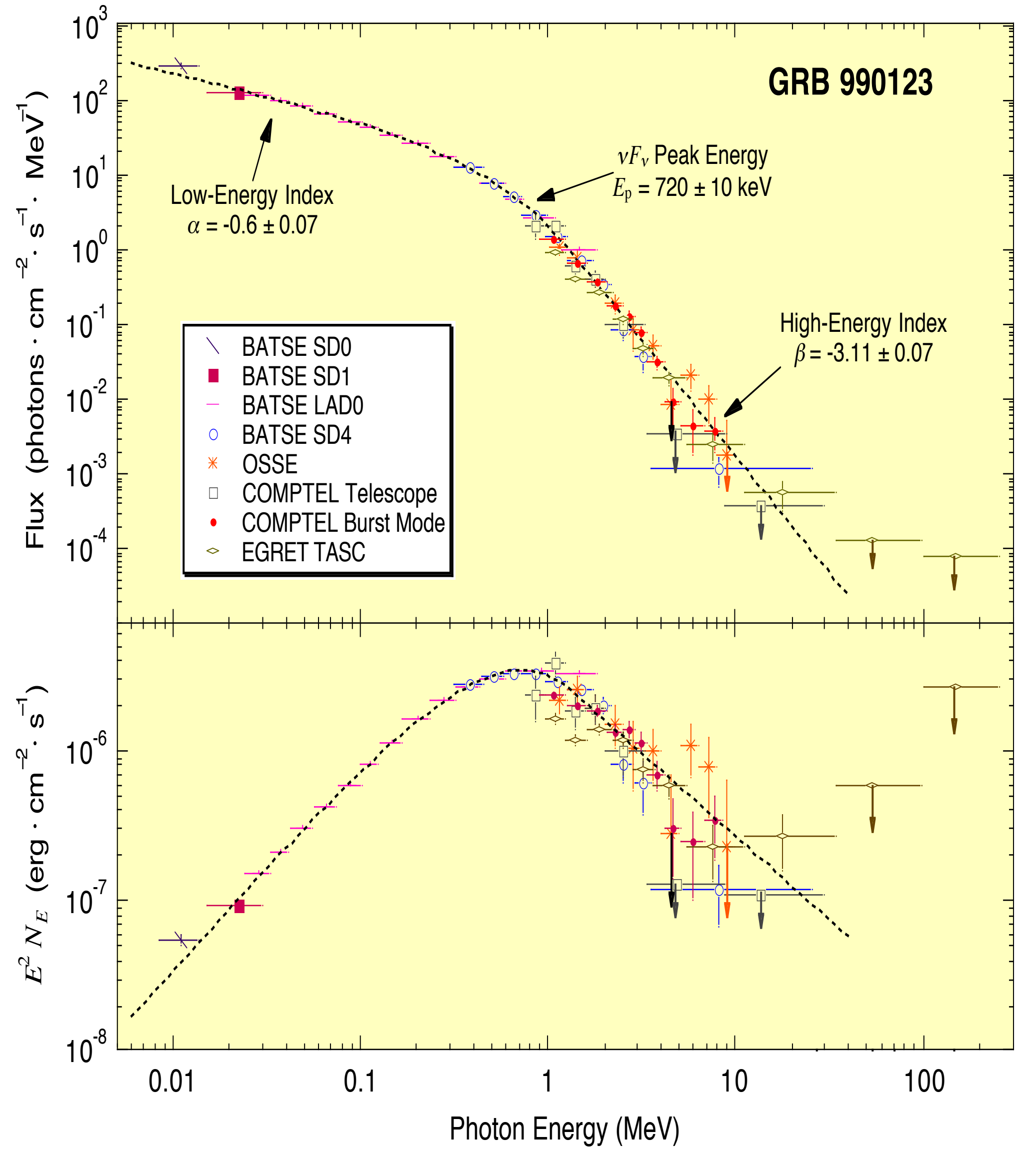
(with contributions by J. Michael Burgess, Nicola Omodei, Chuck Dermer, Andreas von Kienlin and a host of others on the Fermi GBM and LAT teams!)

Standard Spectrum: Band '93

- Unique function that joins two power laws with continuous 1st derivative
- Although it is completely empirical, it can mimic OTTB, OT synchrotron & BB, each in the appropriate limit
- Usually parametrized in terms of the energy at the peak of the PD distribution: $E_{\rm peak}$
  - This definition requires that HE PL index $\beta < -2$

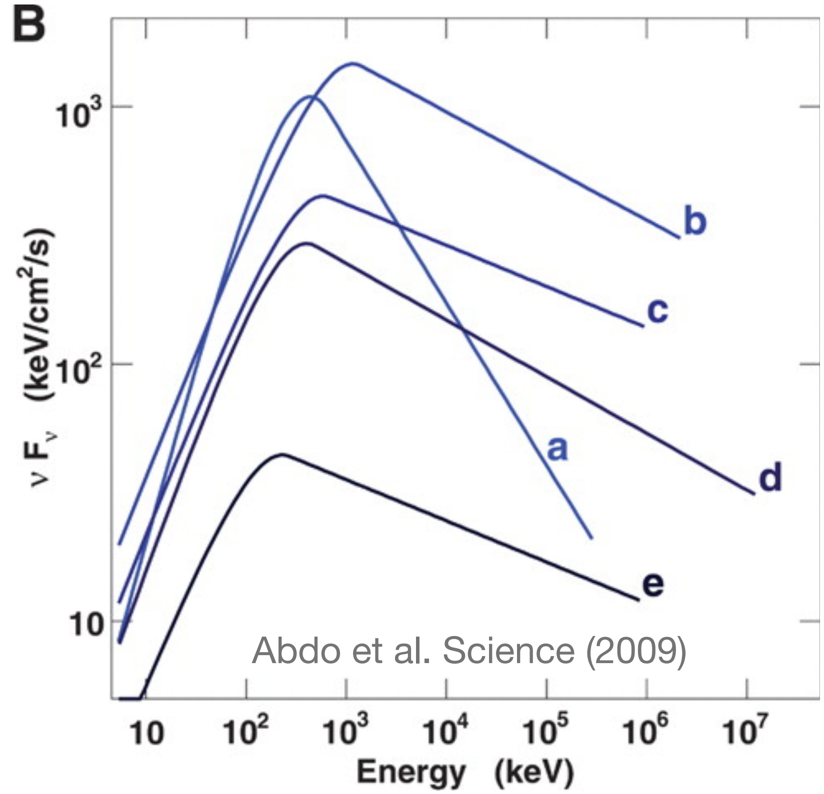
$$f(E) = \begin{cases} A(E/100)^{\alpha} e^{-E(2+\alpha)/E_{\rm peak}} \\ \quad \text{if } E < \dfrac{(\alpha-\beta)E_{\rm peak}}{(2+\alpha)} \equiv E_{\rm break}\ , \\ A\left[\dfrac{(\alpha-\beta)E_{\rm peak}}{100(2+\alpha)}\right]^{(\alpha-\beta)} \exp(\beta-\alpha)(E/100)^{\beta} \\ \quad \text{if } E \geq \dfrac{(\alpha-\beta)E_{\rm peak}}{(2+\alpha)}\ . \end{cases}$$

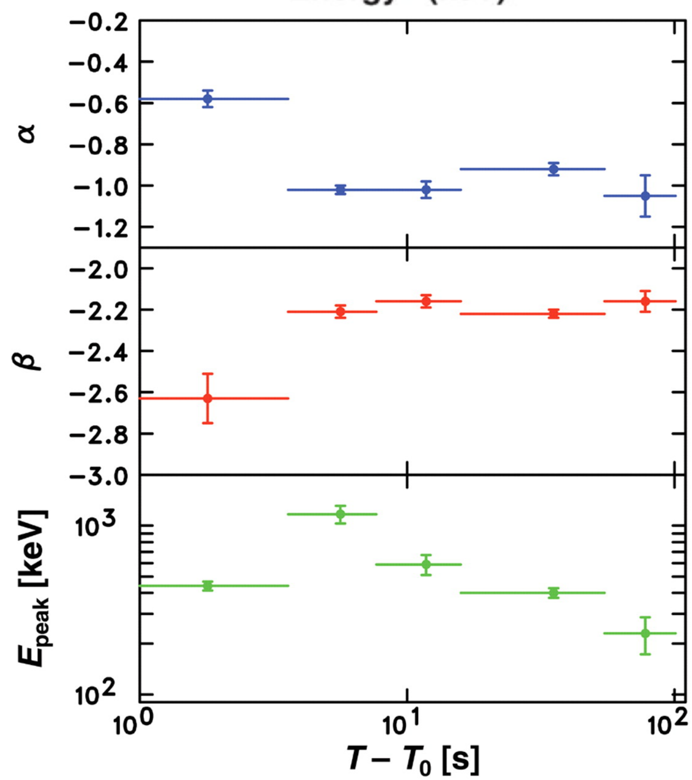
Briggs et al. 1999



GRB 080916C

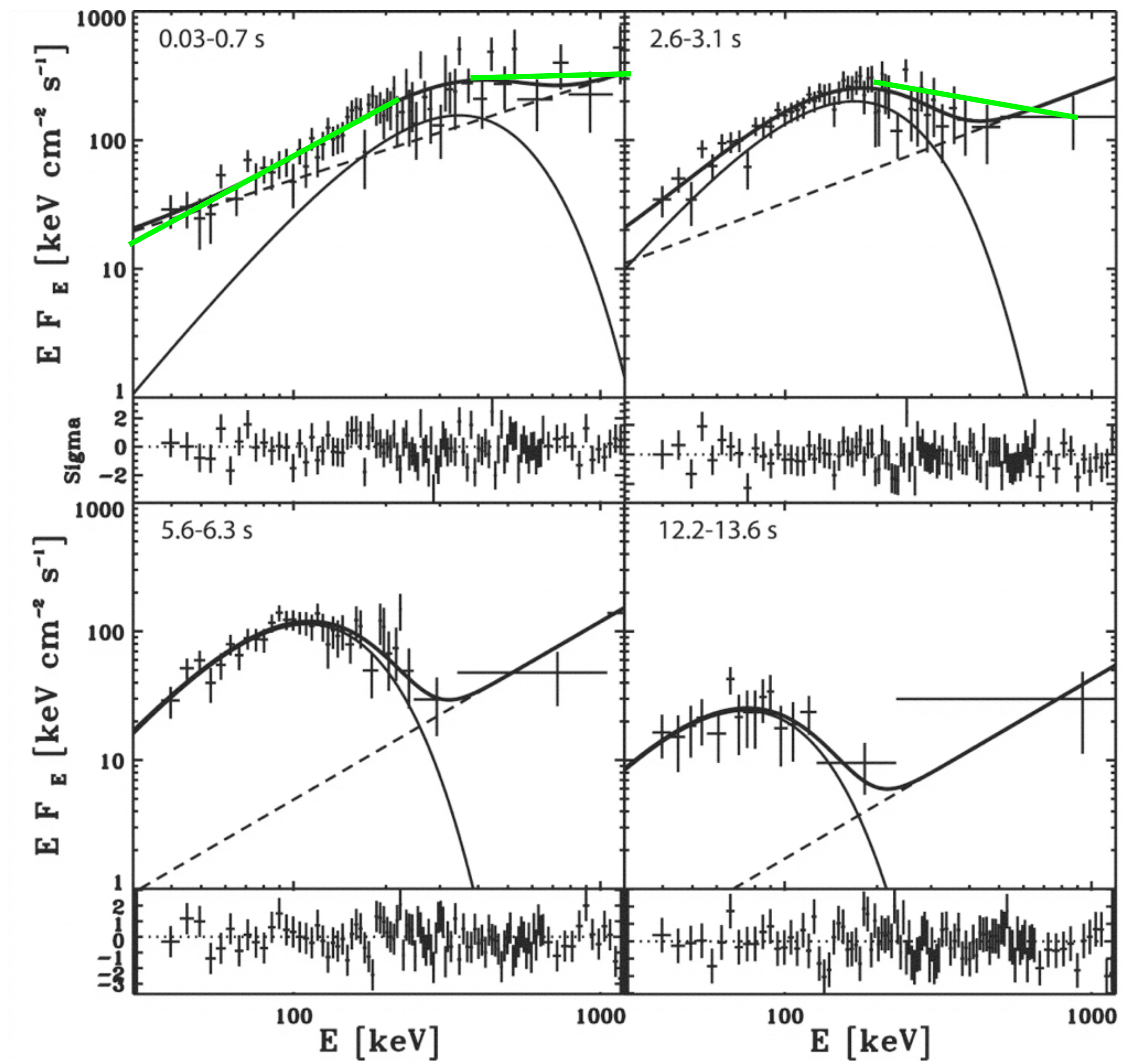
- Bright burst with very simple spectral shape over 7 decades (Band function)
  - Zhang & Pe'er (2009) claim that the *absence* of a thermal component indicates strong magnetization
  - But wait: only the first spectrum is indicative of OT synchrotron 'line of death' (Preece et al. 1998)
  - All are inconsistent with the 'fast cooling' limit (Cohen et al. 1997)
  - Uhm & Zhang (2014) propose magnetic field decaying with radius to get α ~ –1





The Case for a Photosphere

- Ryde et al., (2006): fitted photospheric function + PL to archival BATSE spectra
- Why does this work?
    - GRB spectra with sufficient statistics for spectral analysis (45 σ) typically allow only 4 free parameters for fitting, as with Band GRB function
    - BB + PL also has 4 free parameters
- Line of death problem replaced by physical values.
    - Band *α* values are replaced by sum of BB +1 index and fitted PL index
    - HE PL index change is also accounted for
- But: Photosphere not likely to show polarization!

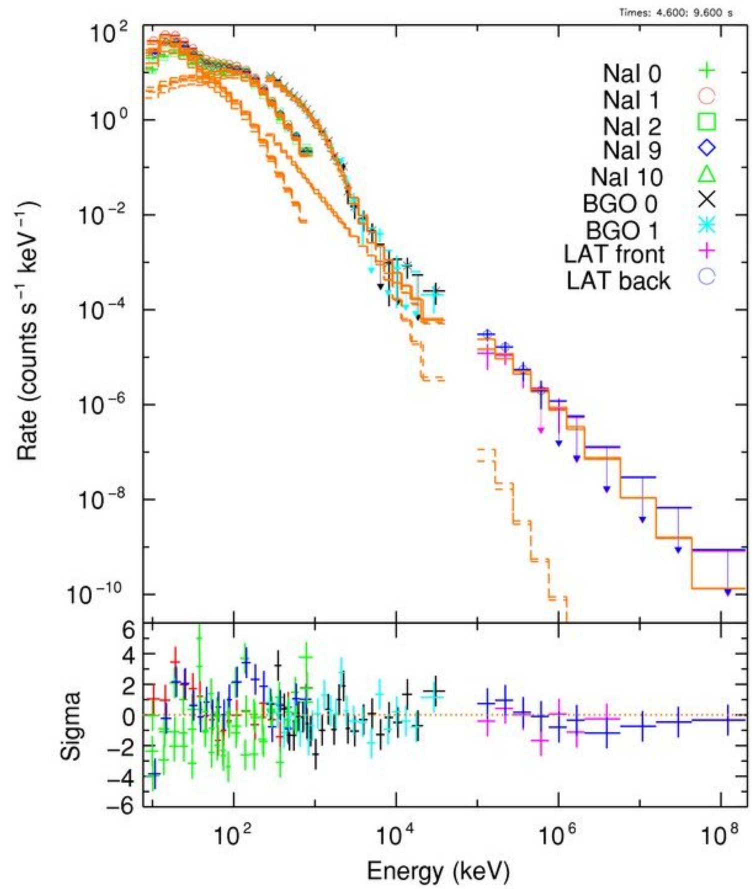


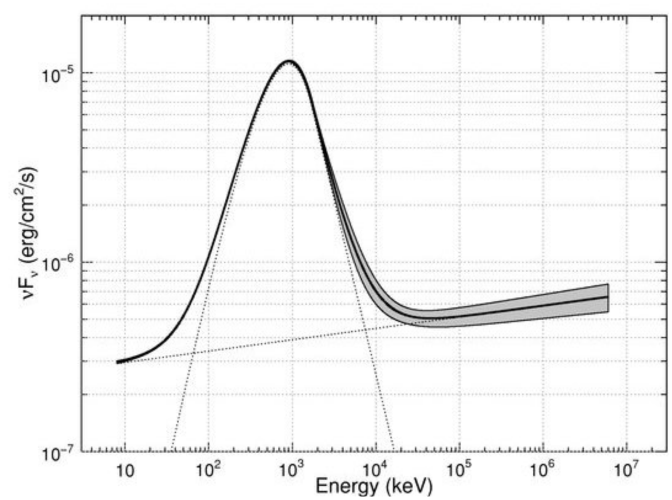
GRB 090902B

- Bright LAT burst with clear photospheric emission
  - The medium energy range should have no polarization signature
  - Still, lowest energies are dominated by possible synchrotron emission
    - Polarization fraction certainly reduced
  - Rare event type

Figure 3 from A. A. Abdo et al.

2009 ApJ 706 L138





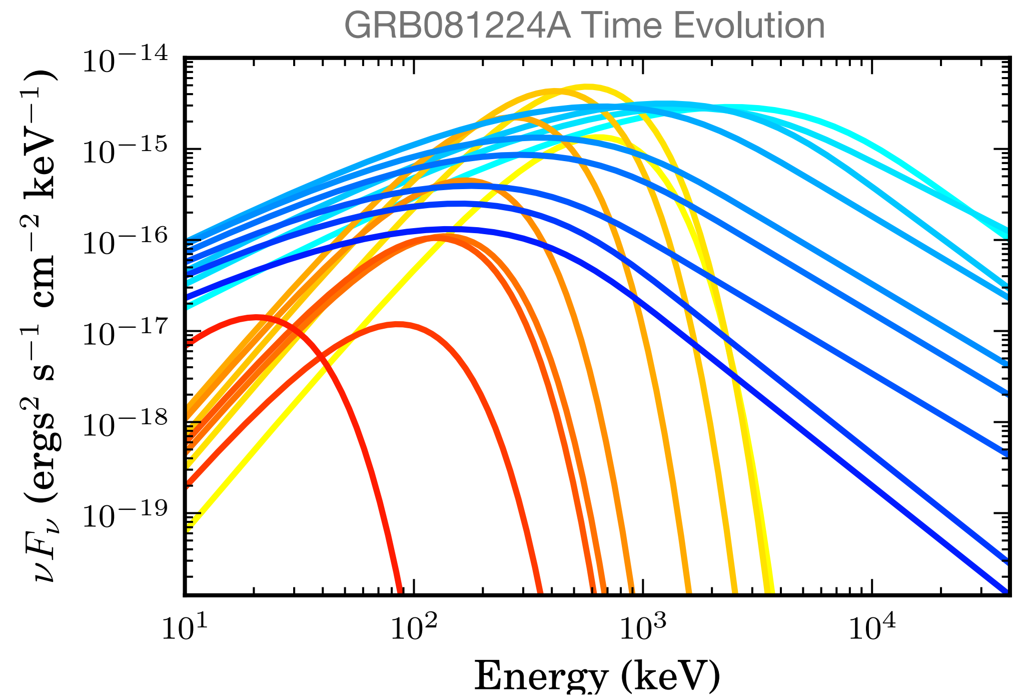
Physical Modeling

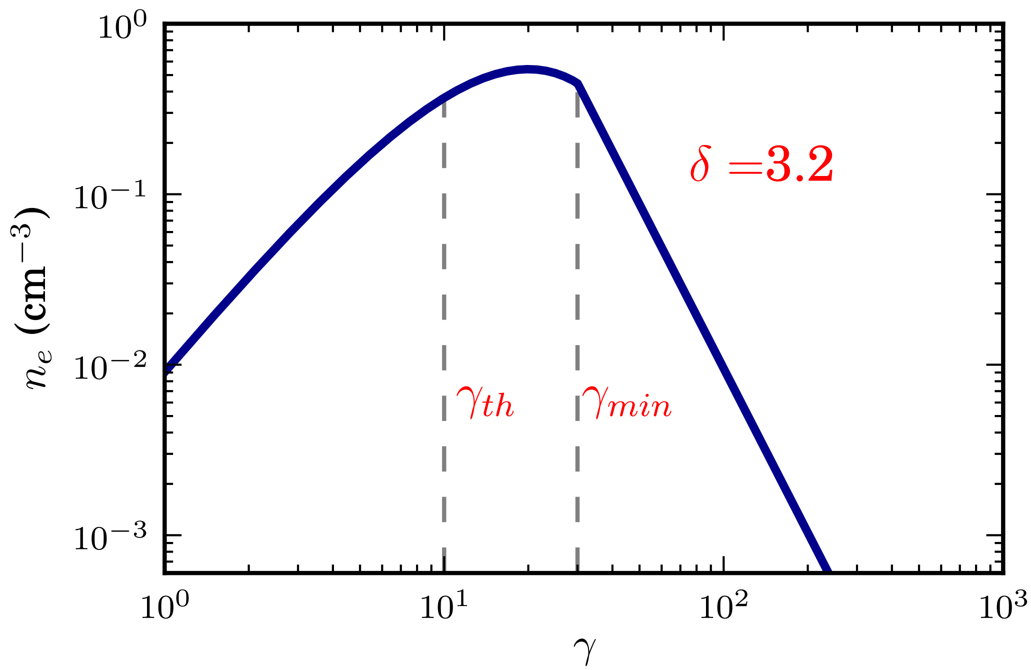
- Motivated by Baring & Braby (2004), Burgess et al. (2011) began fitting spectra with numerically integrated synchrotron emission from parametrized electron distributions

- Electron distributions are 'life-like': Fermi shock accelerated PL from a thermal (rel. Maxwellian) reservoir or fast cooling broken PL

- Fitting is done to the electron distribution, convolved with synchrotron emissivity kernel - too numerically intensive until recently

- If no HE gamma-rays: thermal synchrotron (may be most typical spectral form)

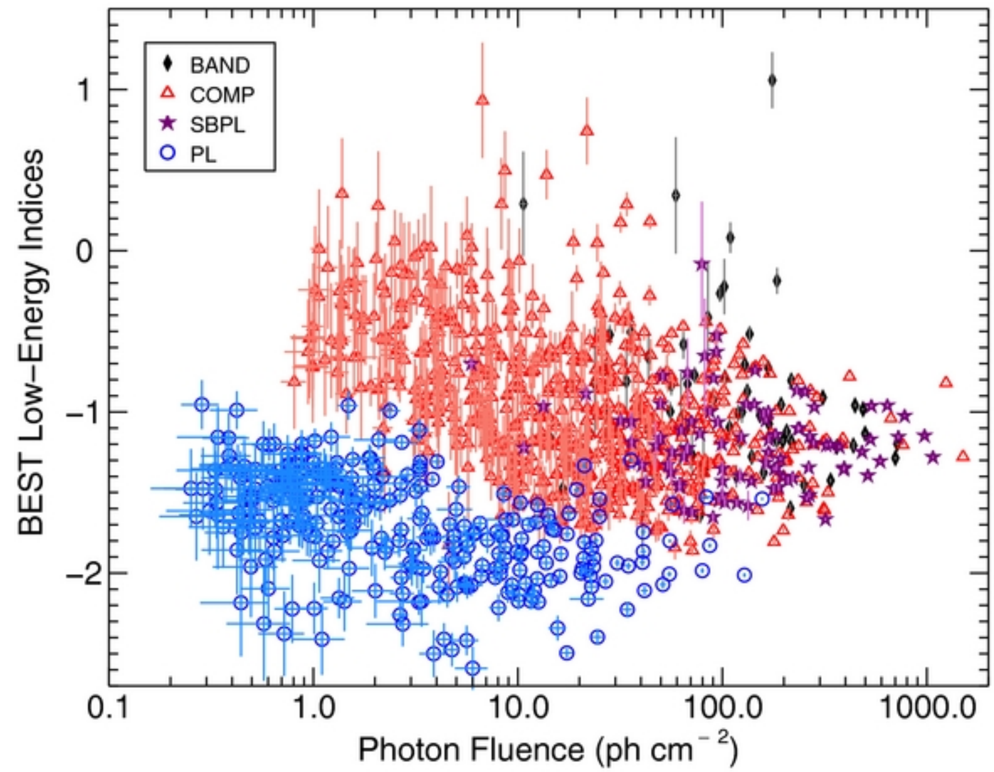




Burgess et al. 2013

Best Fit Spectra

- Clearly, the cut-off model power-law (COMP) is a better fit to most spectra by a huge margin
    - Some low-flux/fluence spectra don't constrain high-energy PL very well
    - OTOH: some very bright spectra are cut-off
    - Possible mechanisms: Thermal Synchrotron?
        - If so, polarization should be less than for PL electrons



(a)

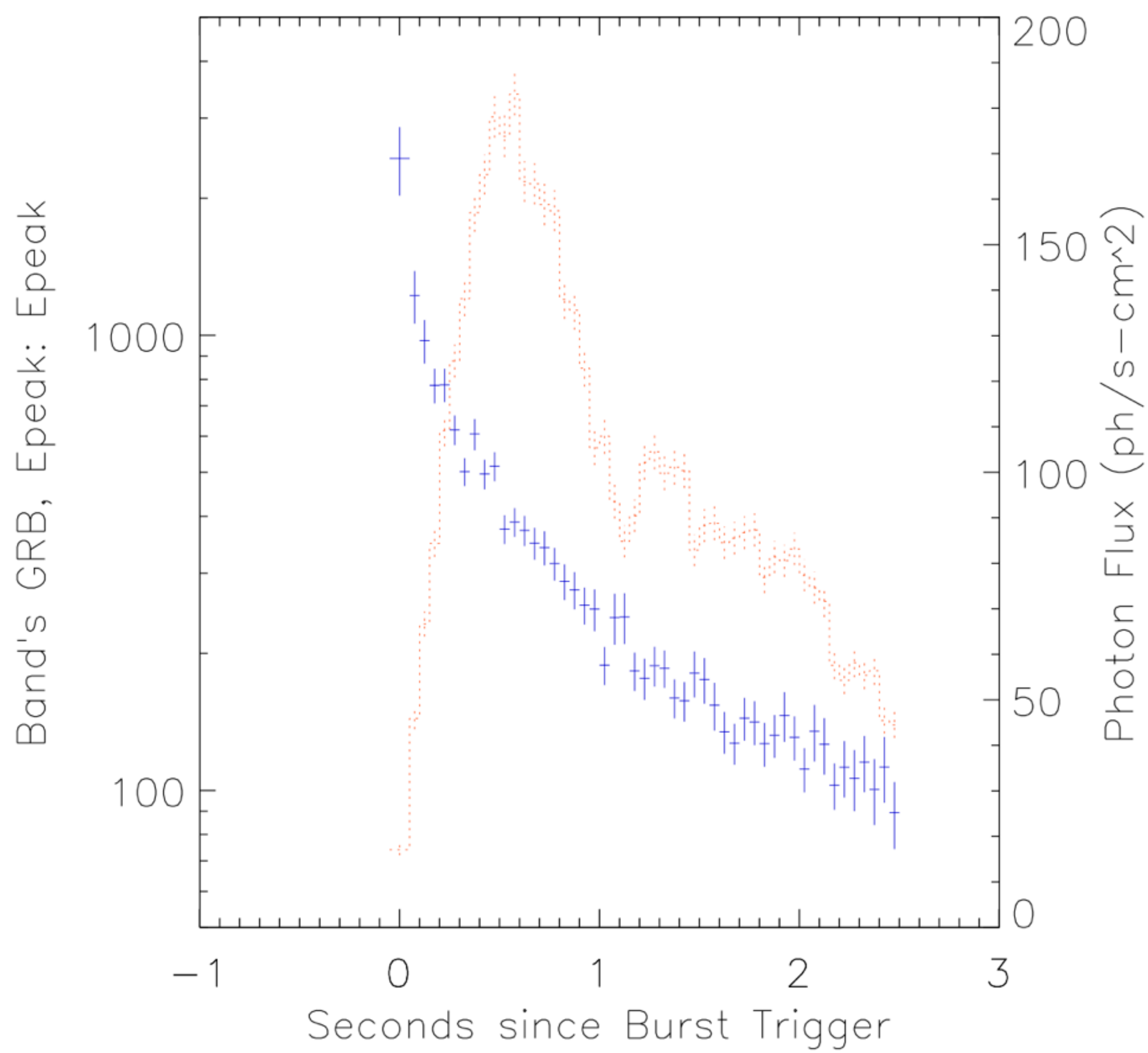
Table 2
BEST GRB models

PL	SBPL	BAND	COMP	GLOGE
Fluence Spectra				
506 (23%)	124 (6%)	77 (4%)	903 (42%)	535 (25%)
Peak Flux Spectra				
454 (21%)	150 (7%)	65 (3%)	847 (40%)	629 (29%)

BATSE 5B Spectral Catalog (Goldstein et al. 2013)

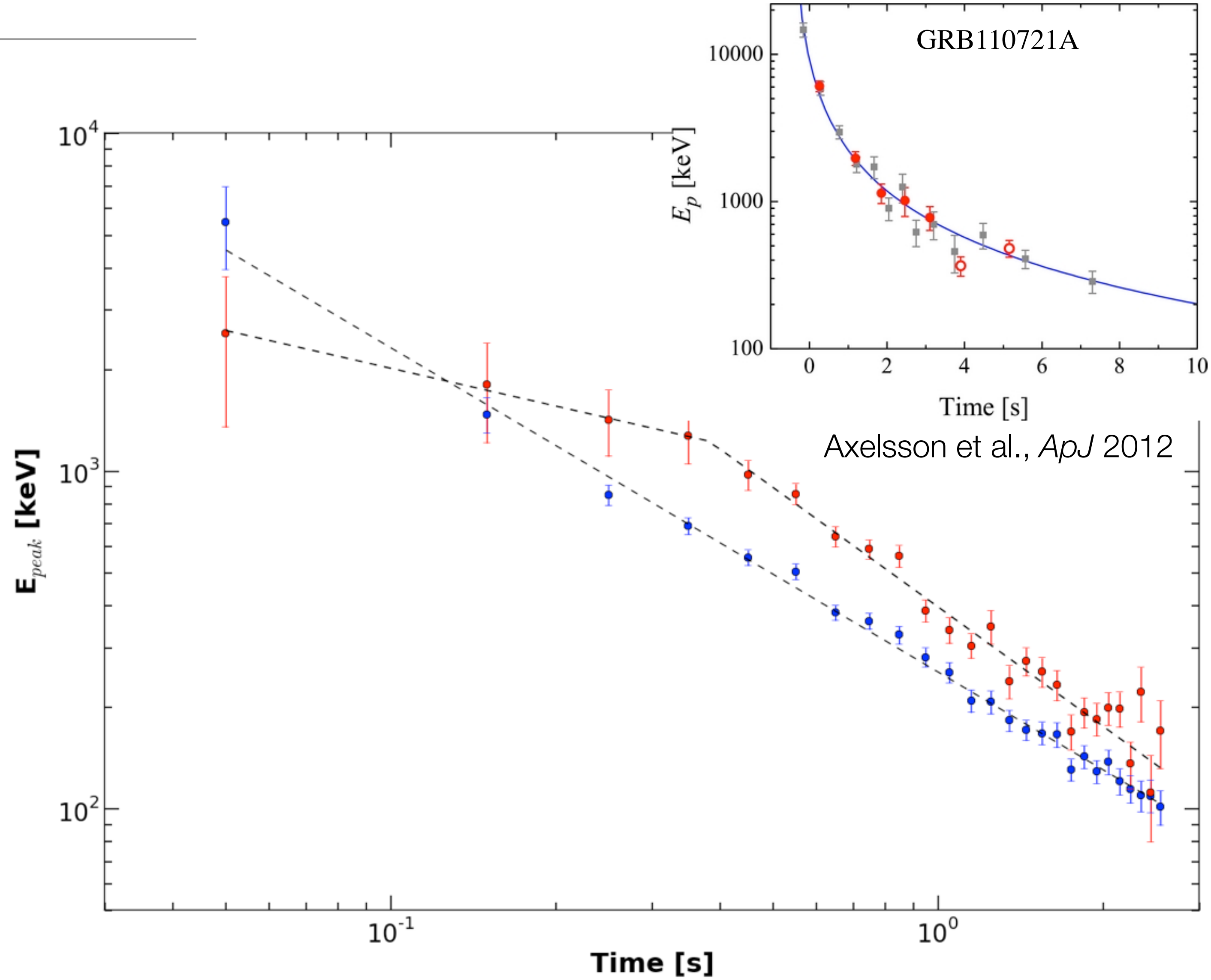
GRB130427A: Spectral Analysis

- Because the GBM data are saturated throughout the main emission episode, we looked instead at the cleaner, first pulse.
  - This pulse is brighter than most GRBs!
- The Band GRB function is fitted to 0.1 s intervals, using three datasets: GBM NaI, GBM BGO & LAT LLE.
- Strikingly, the peak energy shows a very simple behavior...



GRB130427A: Peak Energy Evolution

- Fitted Band function E_{peak} values (blue) for the first 2.5 s of 130427A in 0.1 s time bins. Fitted with a single power law (slope of –0. 96 +/– 0.02). Time has been offset by 0.1 s,
- The Burgess et al. Synchrotron + BB characteristic energy values are in red. A broken power-law fit is indicated by the dashed line (early time decay index is -0.37 +/- 0.23, with a break at 0.38 +/- 0.08 s., breaking to an index of -1.173 +/- 0.045).
- Similar behavior in several other single-pulse bursts (Burgess et al. 2014)

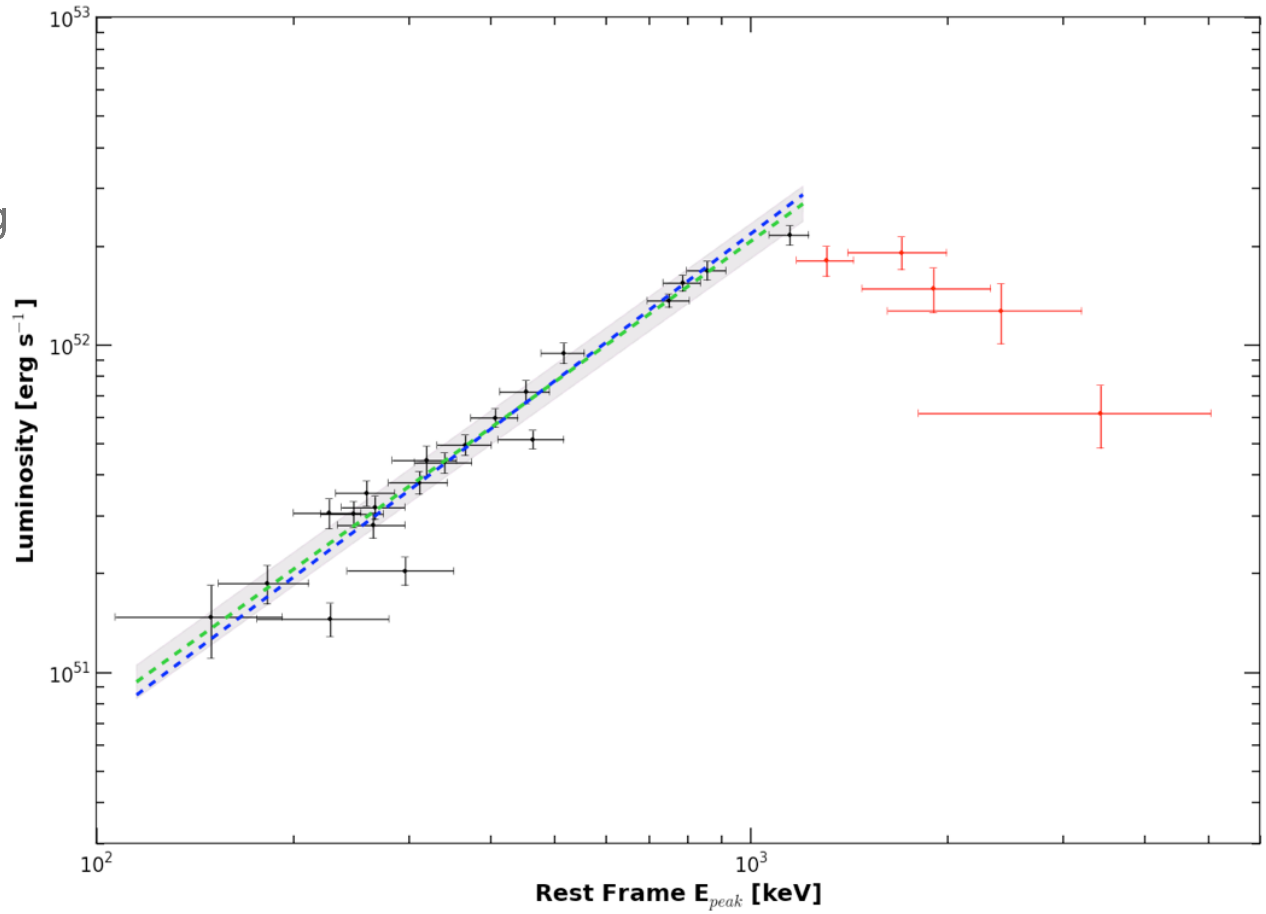


Axelsson et al., *ApJ* 2012

Preece et al., *Science* 2013

Luminosity-E_{peak} Correlation

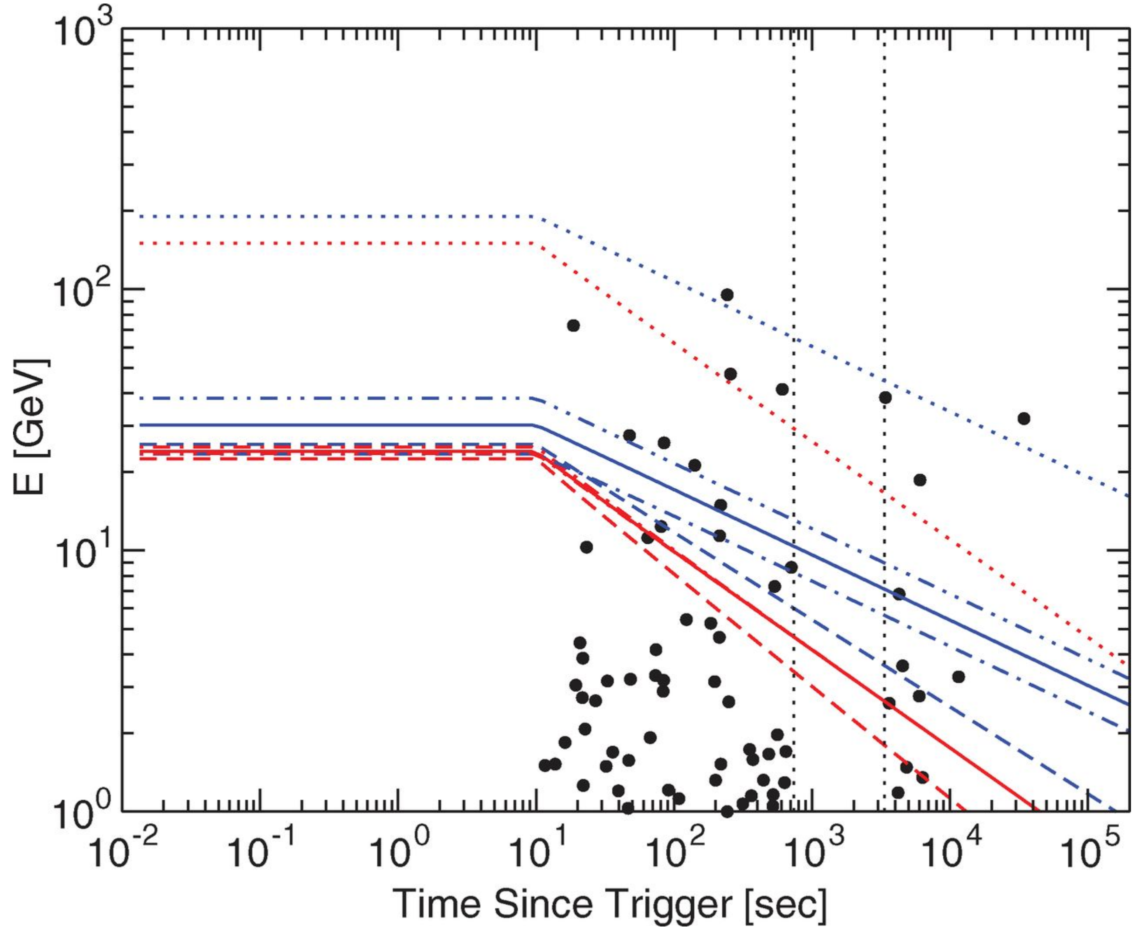
- The decay phase $L - E_{peak}$ correlation is fit with a power-law index of 1.43 +/- 0.04.
  - Spherical blast waves in shell collisions go as $L \propto E_{peak}^3$ during the decay phase of a pulse [Dermer 2004]
- We can obtain the 3/2 PL index by assuming magnetic flux freezing:
  - Usual relation for magnetized jets: $B \sim 1/R$
  - With minijets, you can get away with: $B \sim 1/R^2$



Preece et al., *Science* 2013

LAT High Energy Afterglow

- LAT Lightcurve belongs to the afterglow:
    - Except for 3 photons right at the trigger, nearly all the LAT photons come after 10 s.
    - LAT Photon flux is a broken power law
- Interestingly, the observation of late-time high-energy photons by the LAT is *inconsistent* with a synchrotron interpretation:
    - Maximum energy depends upon assumed size of the source and the balance between acceleration and radiation
    - May be due to SSC or external Compton



Ackermann et al., *Science* 2013

GRBs: Whither Magnetization?

- Polarization: direct measurement; no question
  - Prompt emission: dominated by γ-rays
  - Afterglows: all wavelengths
- Spectral and Temporal analyses: messy & indirect
  - Fitting Function: Band, Cut-off Model Power Law (COMP), BB, Synchrotron
  - Pulse Model: Norris; Hakkila & Preece; several others
  - Particle acceleration: Fermi shocks; magnetic reconnection; combo (ICMART)
  - Emission: Synchrotron; 'Jitter'; Inverse Compton; Photospheric