GRB Spectra and their Evolution:

- prompt GRB spectra in the γ-regime

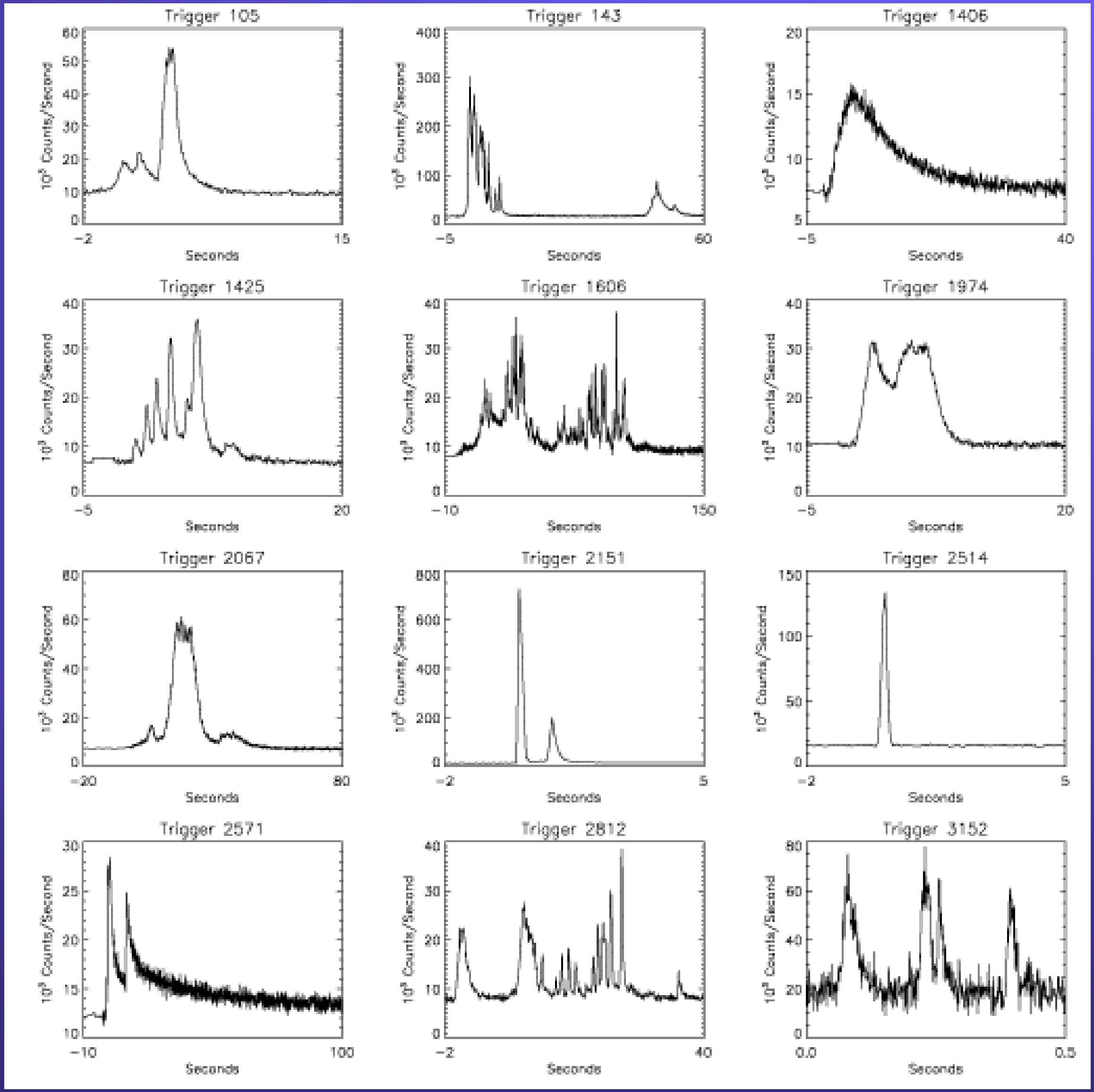
TUM GRB Seminar
Andreas von Kienlin MPE -Gamma

Outline

- Time averaged GRB spectra
  - Example spectra
  - Instrumental response
  - Band function
  - Spectral parameters α, β and E_{peak}
  - Prompt γ-ray emission from GRBs
  - Comparison of the SSM with spectral parameters
- Temporal evolution of the spectral parameters
  - Hardness-intensitiy correlation
  - Hard-to-soft spectral evolution
- GRB spectra at very high energies
- XRF's

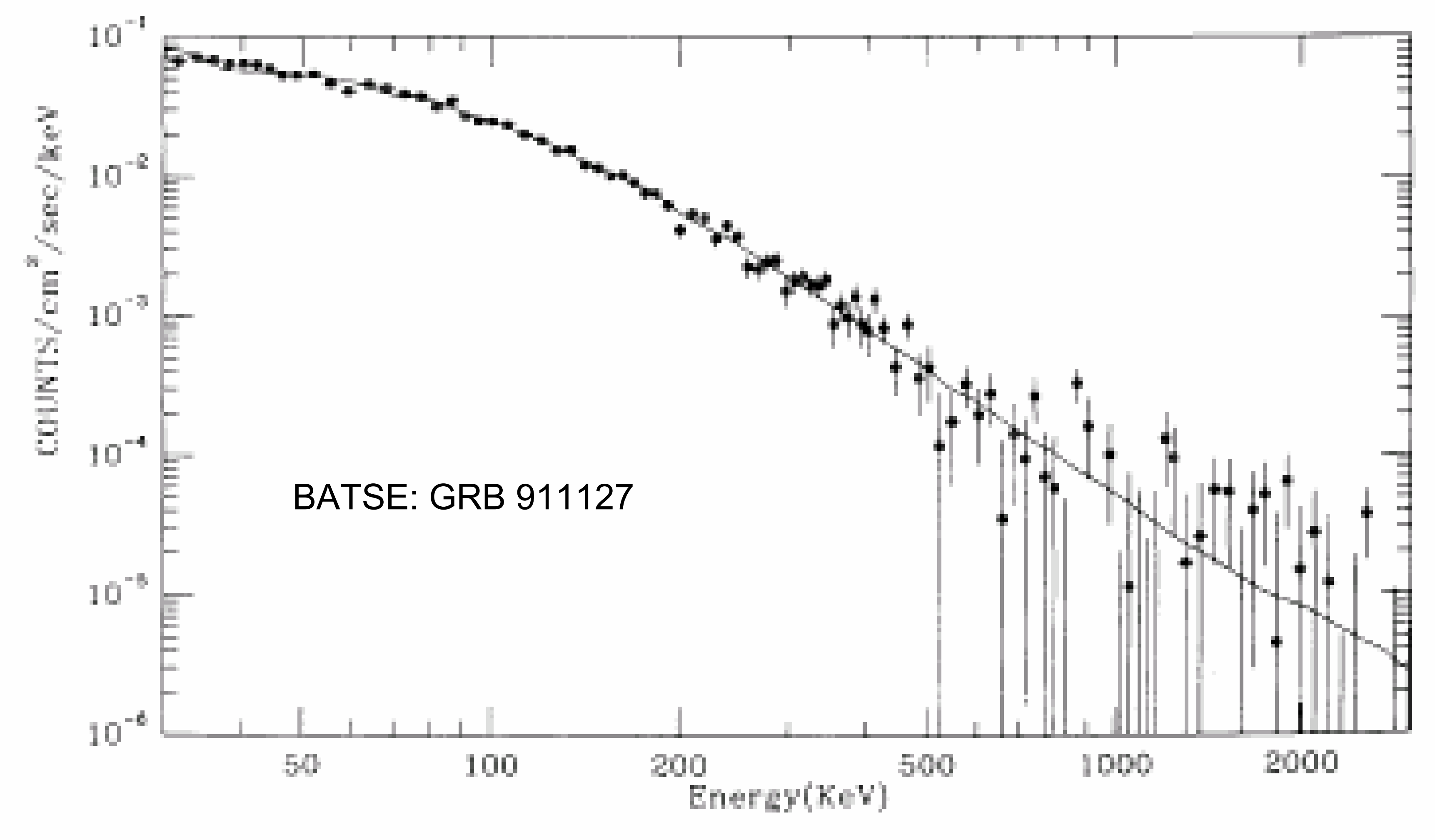
GRB pulse profile variety

- already presented by R. Diehl



GRB spectra

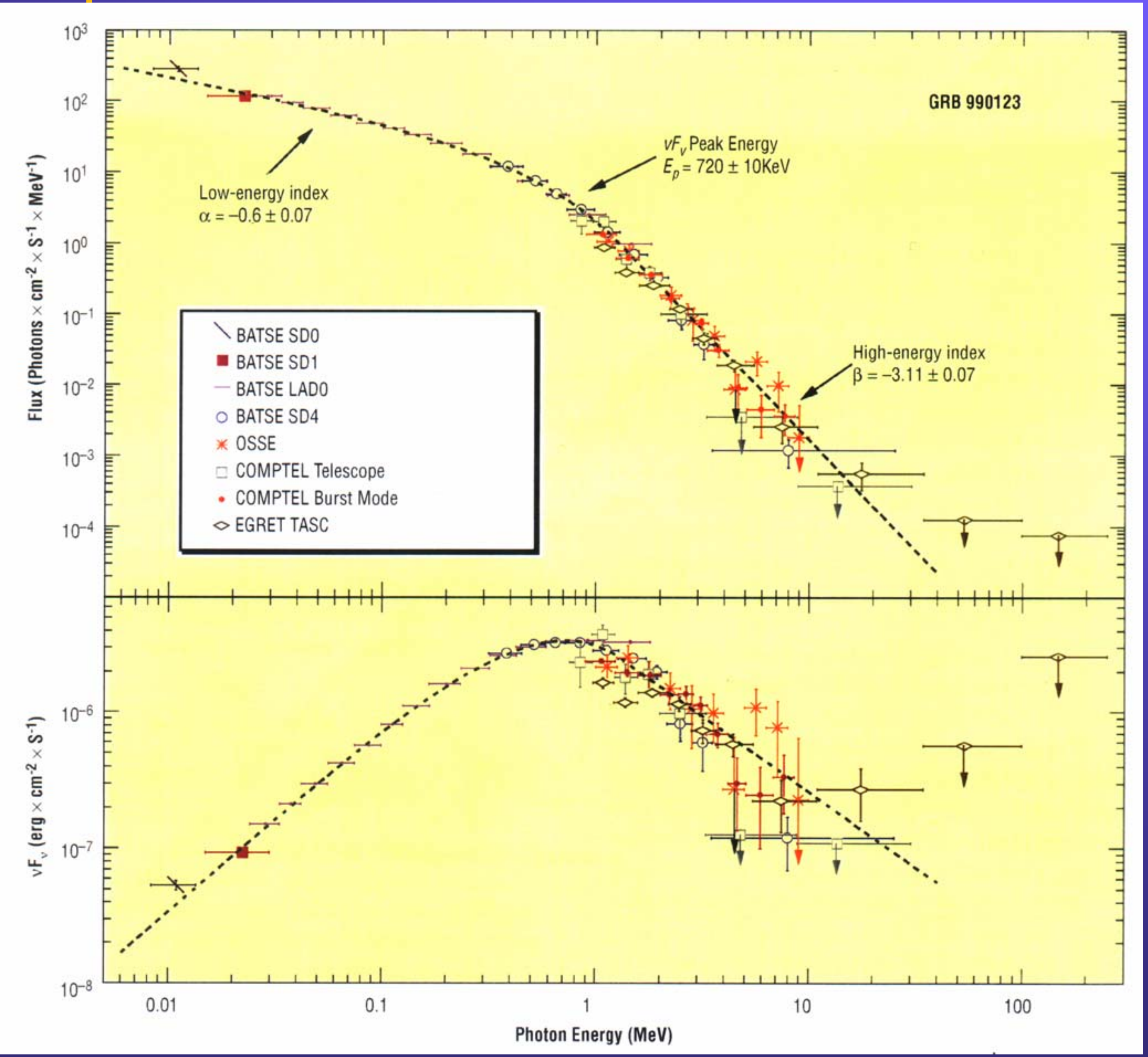
- In contrast to the lightcurves of GRBs
  - shape of GRB spectra is quite simple



Common GRB spectrum of all CGRO instruments

Upper plot:

- Photon number flux N_E:



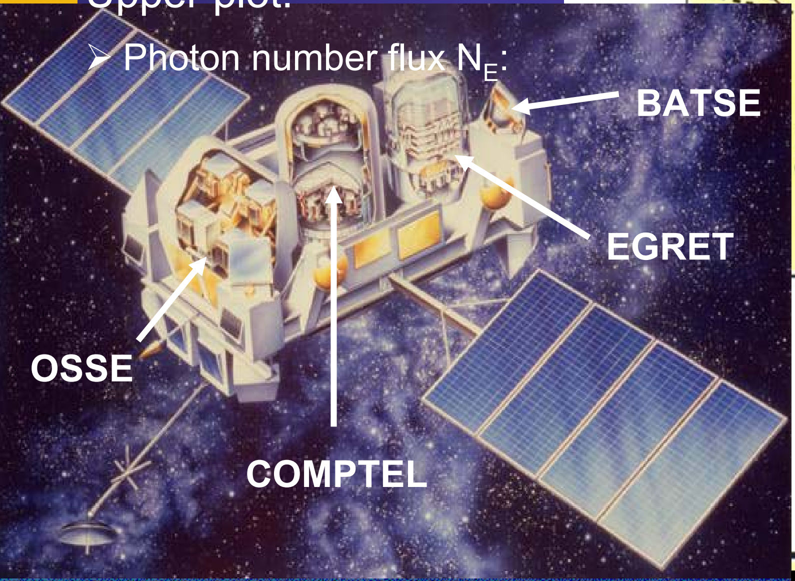
νF_ν – Plots:

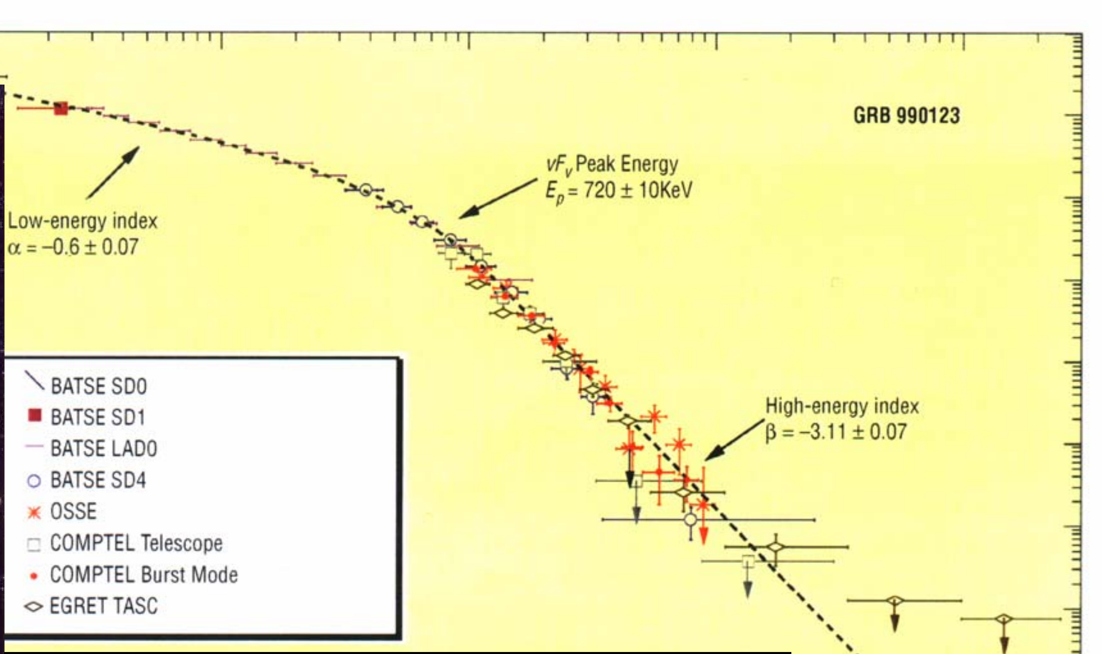
- Energy flux $E^2 \times N_E = \nu F\nu$
- allows easy comparison of source luminosities in different wavelength bands.
- GRB luminosity maximal at E_P

Common GRB spectrum of all CGRO instruments

Upper plot:

- Photon number flux N_E:





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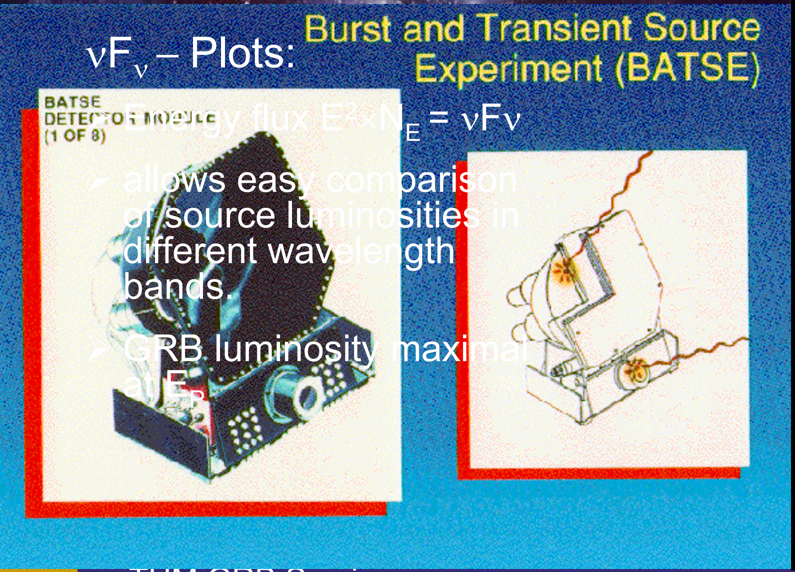
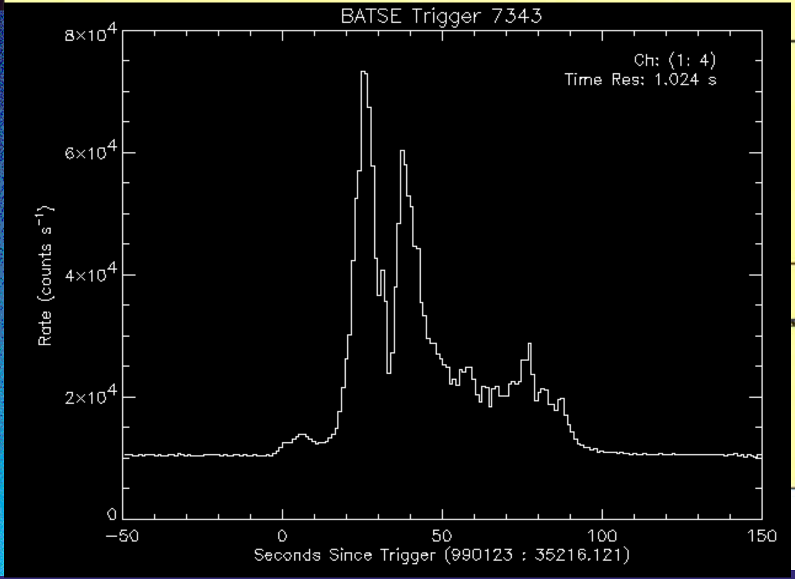
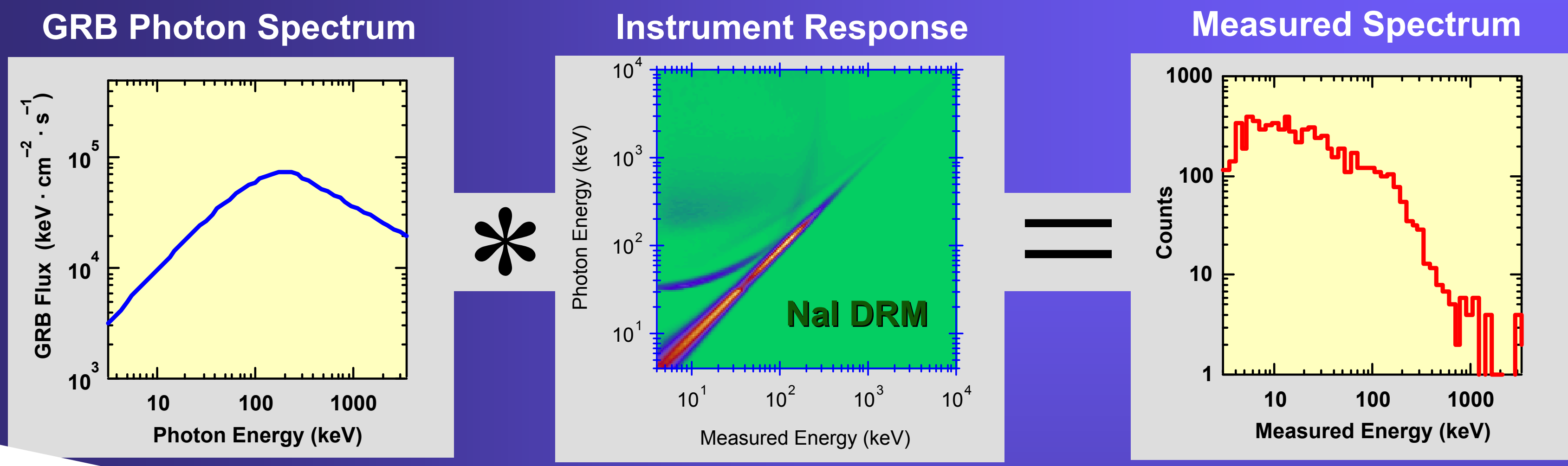
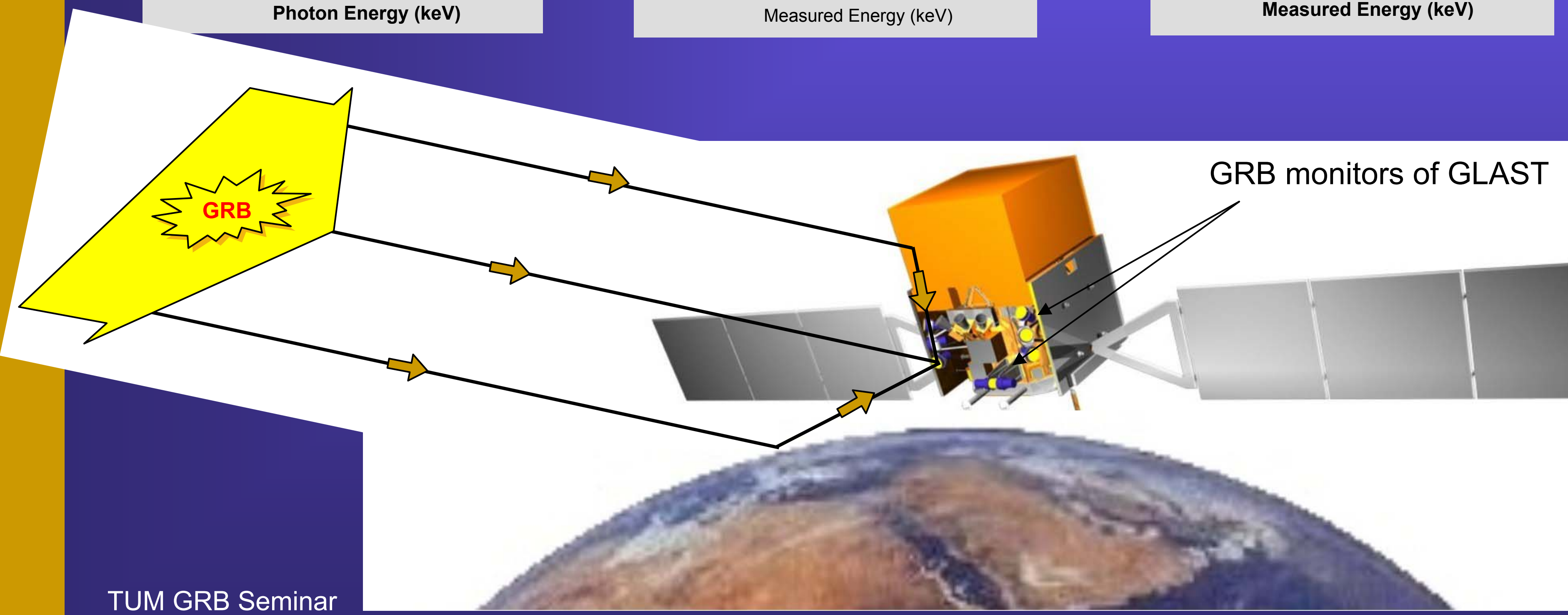




Instrument Response:



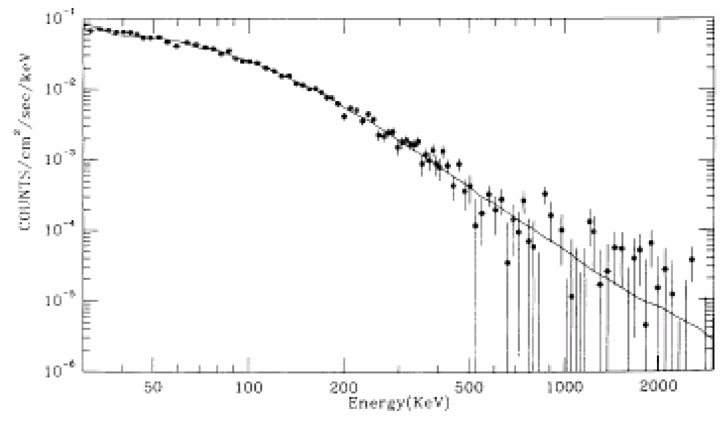


Band - function

- Spectral analysis by D. Band (D. Band et al. 1993, ApJ 413, 281)
  - time-averaged GRB-spectra of BATSE spectroscopy detectors
  - Spectra are well described by:
    - at low energies by a powerlaw with an exponential cutoff

      $N_E(E) \propto E^{\alpha} \exp(-E/E_0)$
    - at high energies by a steeper powerlaw

      $N_E(E) \propto E^{\beta}$ with $\alpha > \beta$



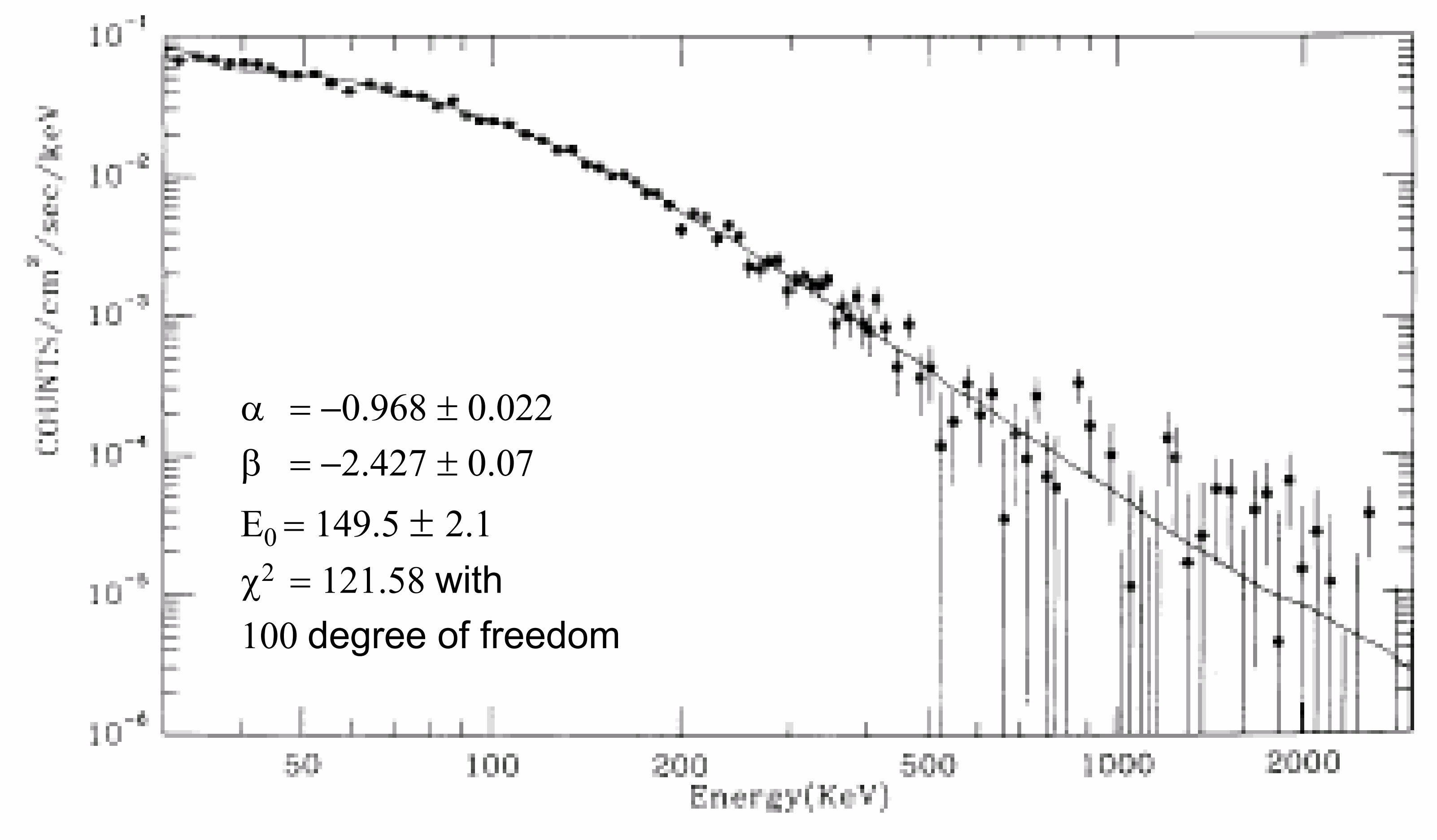
"Band" – Function (empirical fit)

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

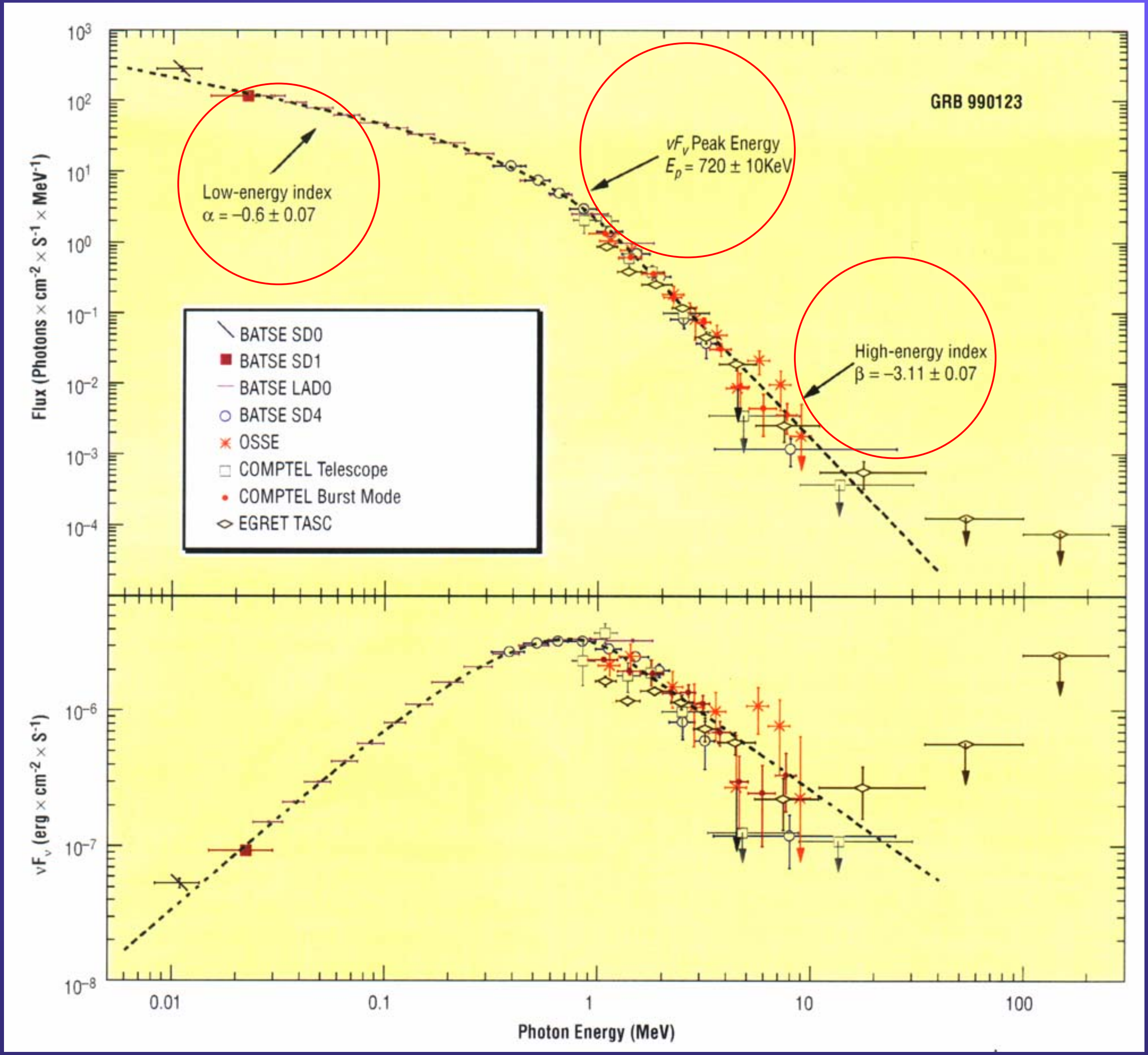
$E_{peak} = E_0 \ (2+\alpha)$

BATSE spectra

- Example of spectral fit:
  - Band function was fitted to the average spectrum of GRB 911127

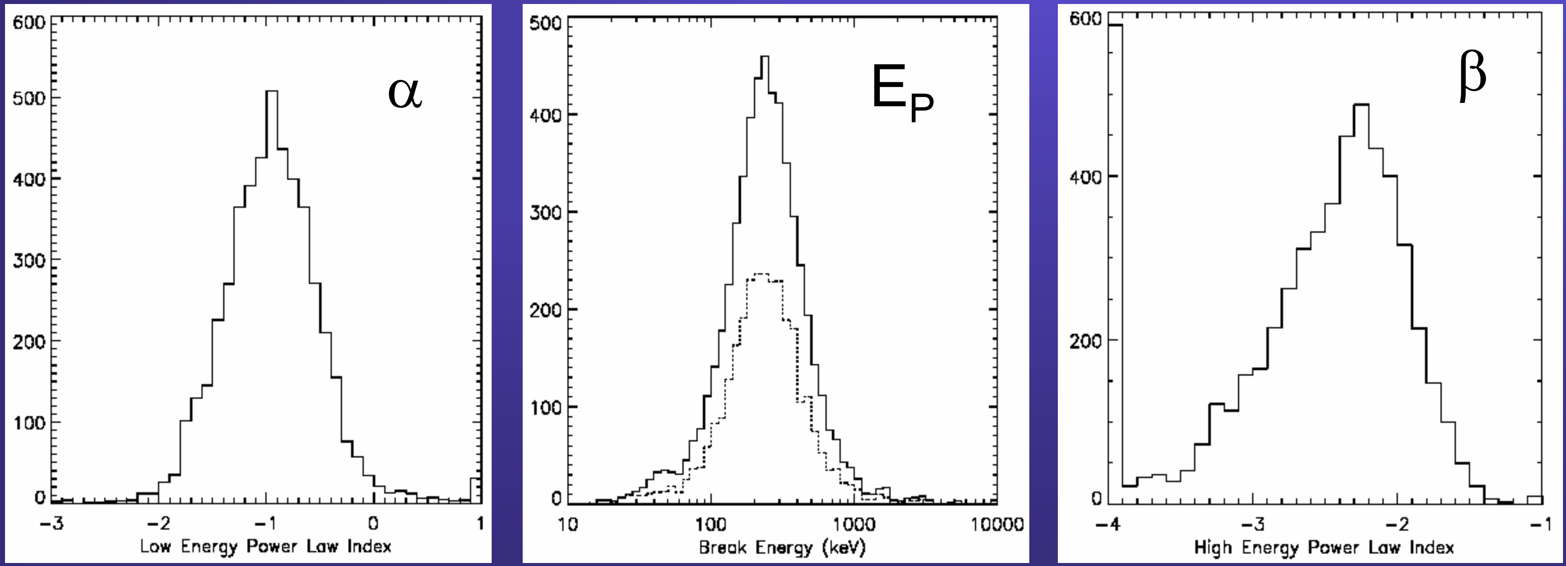


Common GRB spectrum of all CGRO instruments



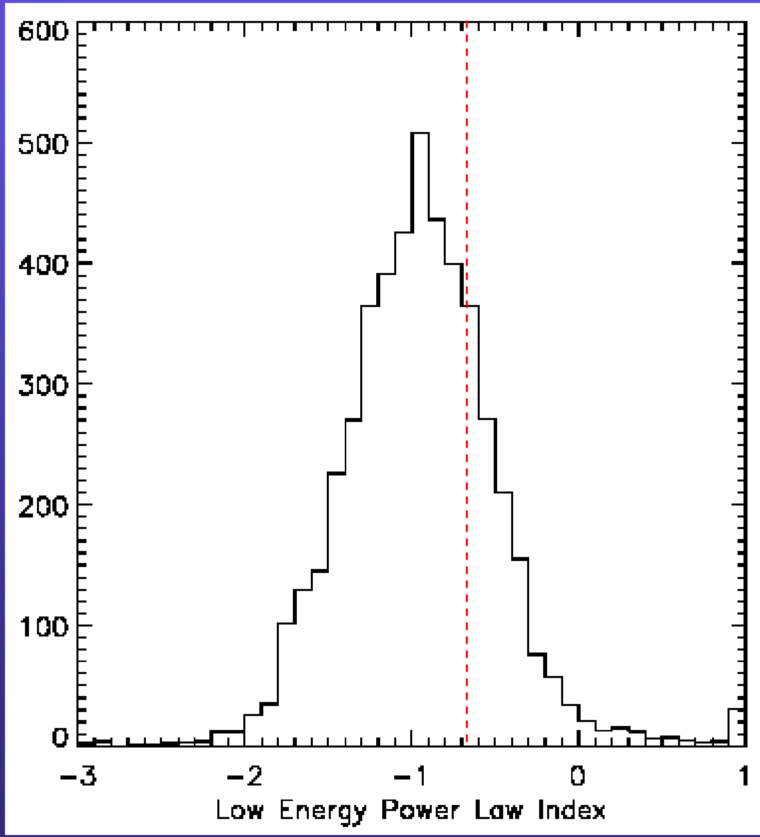
BATSE spectra

- The spectral parameters α, β, and E_0 vary from burst to burst
- Distribution of these parameters obtained from 5500 spectra of 156 bursts (Preece et al. 2000)
- Spectral models used:
  - "GRB Model": Bands GRB function
  - "COMP model": in case the GRB model break energy lies above the detector energy range
  - "BPL Model": in cases a sharp curvature of the spectrum results in a bad χ^2 of GRB model



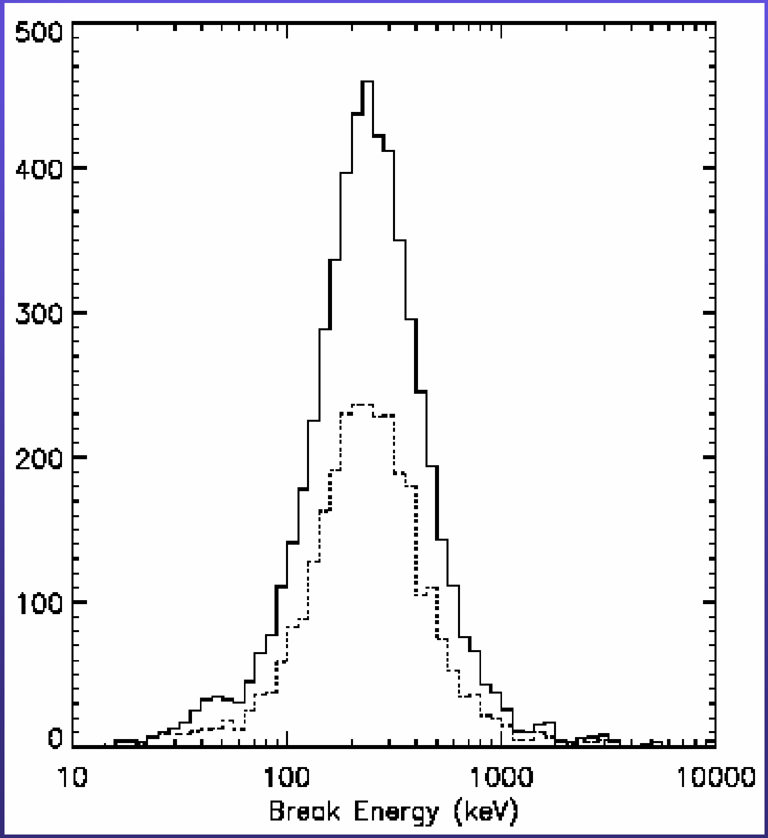
Low energy power-law index

- Distribution
  - peaks at $\alpha = -1$
  - broader than expected statistical error for $\alpha = -1$
- Constrains the applicability of popular burst emission models
  - "Blast wave model"
  - "synchrotron emission from shocked electrons"
    - expectation from theory for single-particle synchrotron emission: $\alpha = -2/3$



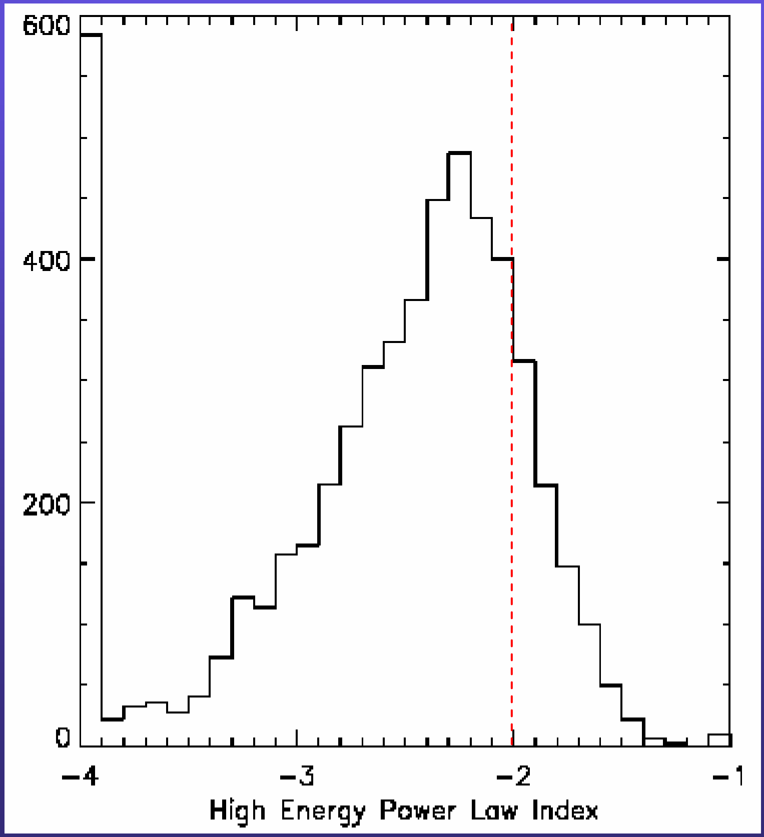
Break Energy

- Synchrotron shock model (SSM) identifies spectral break with the characteristic synchrotron energy in the emitter's rest frame, boosted into the observer's frame
  - spectral break contain information about the bulk Lorentz motion of the emitter
- Most important signifier for spectral evolution
- Log-normal distribution
  - Peaking at 250 keV
  - FWHM less than a decade in energy



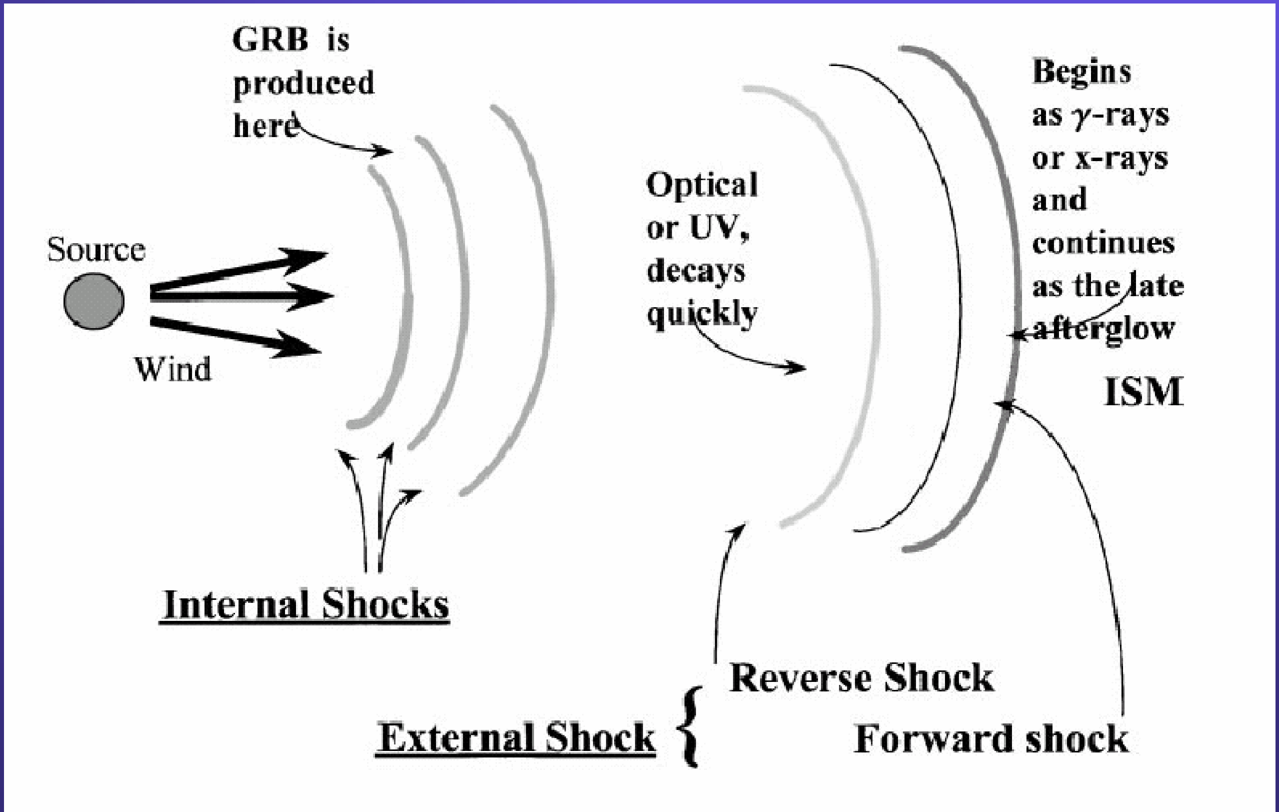
High energy power law index

- Peak of high energy power law distribution at: - 2.35
- For $\beta \geq 2$ spectra diverges
  - cut-off hat high energies expected
- Blast wave model is quite sensitive to the relationship between the two power-law indices



Prompt γ-ray emission from GRBs

- Internal – external shock scenario
  - Inner compact source produces a variable relativistic wind
  - GRBs are produced by relativistic internal shocks arising from the wind
    - Faster shells catch up with slower ones and collide
  - Afterglow emission is produced by the external shock → see later talks



Prompt γ-ray emission from GRBs (Preece 2002)

- Optically thin synchrotron shock emission (SSM: synchrotron shock model)
  1. Power-law distribution for shocked electrons

     $N(\gamma_e) \sim \gamma_e^{-p} \quad \text{for } \gamma_{\min} < \gamma_e < \gamma_{\lim}$ with spectral index $p > 2$

     $\gamma_{\min} \simeq \gamma_E$ bulk Lorentz factor of the shock
  2. Single particle synchrotron emissivity
     - Asymptotically –2/3 power law at low frequencies
     - Exponentially attenuated at high frequencies
     - Characteristic synchrotron energy in the observer frame

$$E_c = h\nu(\gamma_e)_{\text{obs}} = \gamma_e^2 \gamma_E \frac{\hbar q_e B}{m_e c}$$

- 2. must be integrated over 1. in the comoving frame
  - Results in $\nu^{-2/3}$ power law below $h\nu(\gamma_{\min})$

    $\nu^{-(p+1)/2}$ power law above $h\nu(\gamma_{\min})$

Prompt γ-ray emission of GRBs

- Important quantity: γ_{cool}
  - is the electron energy, where the hydrodynamic cooling timescale just balances the energy dependent synchrotron cooling time
  - "slow cooling" spectrum

$$N_{\nu,\,\mathrm{slow}} \sim \begin{cases} \nu^{-2/3} & \nu < \nu_{\mathrm{min}} \ , \\ \nu^{-(p+1)/2} & \nu_{\mathrm{min}} < \nu < \nu_{\mathrm{cool}} \ , \\ \nu^{-(p/2)-1} & \nu_{\mathrm{cool}} < \nu \ , \end{cases}$$

  - During GRB phase, fast cooling of electrons by synchrotron
    - Two component electron distribution
    - Below γ_{cool}: energy index $p_{cool} = 2$
    - Above γ_{cool}: electron power law index has steepened to p +1
  - "fast cooling" spectrum

$$N_{\nu,\,\mathrm{fast}} \sim \begin{cases} \nu^{-2/3} & \nu < \nu_{\mathrm{cool}} \ , \\ \nu^{-3/2} & \nu_{\mathrm{cool}} < \nu < \nu_{\mathrm{min}} \\ \nu^{-(p/2)-1} & \nu_{\mathrm{min}} < \nu \ . \end{cases}$$

Comparison of the SSM with the spectral parameter

- Comparison of the SSM with the spectral Parameter
  - Preece, R.D. et al. 2002, ApJ 581, 1248
  - Evidence that basic model for synchrotron emission from internal shocks during GRB phase is inconsistent with the observation
  - Possible solution: due to deceleration each spectrum is composed of a set of seed spectra, shifted in energy
  - Particle acceleration during the prompt emission should not be ignored

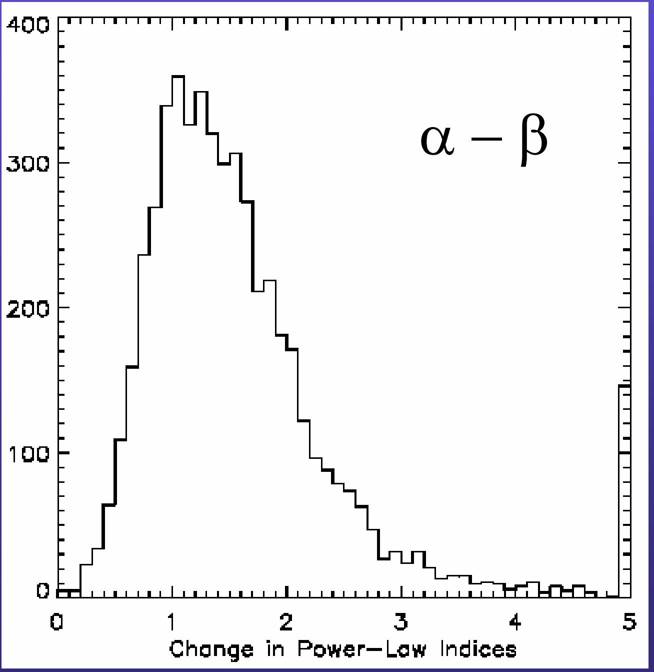
$$\text{fast, low}: \Delta s_{\text{fast}}(\nu_{\text{cool}}) = -\frac{2}{3} + \frac{3}{2} = \frac{5}{6},$$

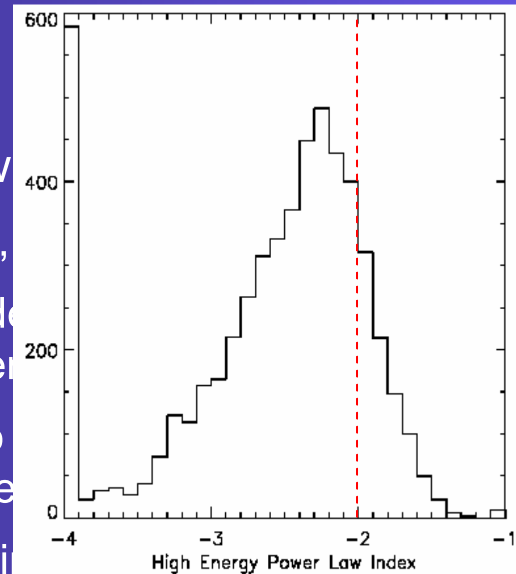
$$\text{fast, high}: \Delta s_{\text{fast}}(\nu_{\text{min}}) = -\frac{3}{2} - \left(-\frac{p}{2} - 1\right) = \frac{p-1}{2},$$

$$\text{slow, low}: \Delta s_{\text{slow}}(\nu_{\text{min}}) = -\frac{2}{3} + \frac{p+1}{2} = \frac{p}{2} - \frac{1}{6},$$

$$\cancel{\text{slow, high}: \Delta s_{\text{slow}}(\nu_{\text{cool}}) = \frac{p+1}{2} - \left(-\frac{p}{2} - 1\right) = \frac{1}{2}}$$

$$\text{both}: \Delta s_{\text{both}}(\nu_{\text{peak}}) = -\frac{2}{3} - \left(-\frac{p}{2} - 1\right) = \frac{p}{2} + \frac{1}{3}$$



Comparison of the  pectral parameter

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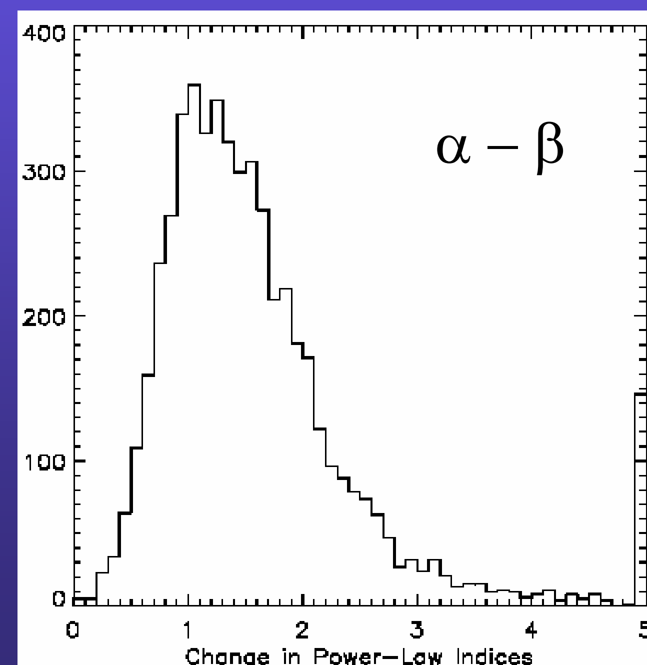
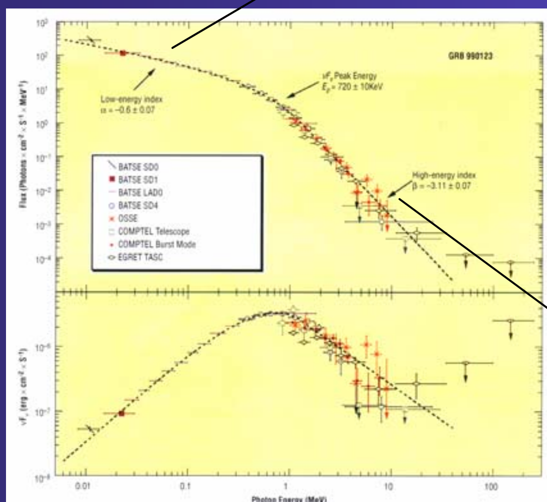
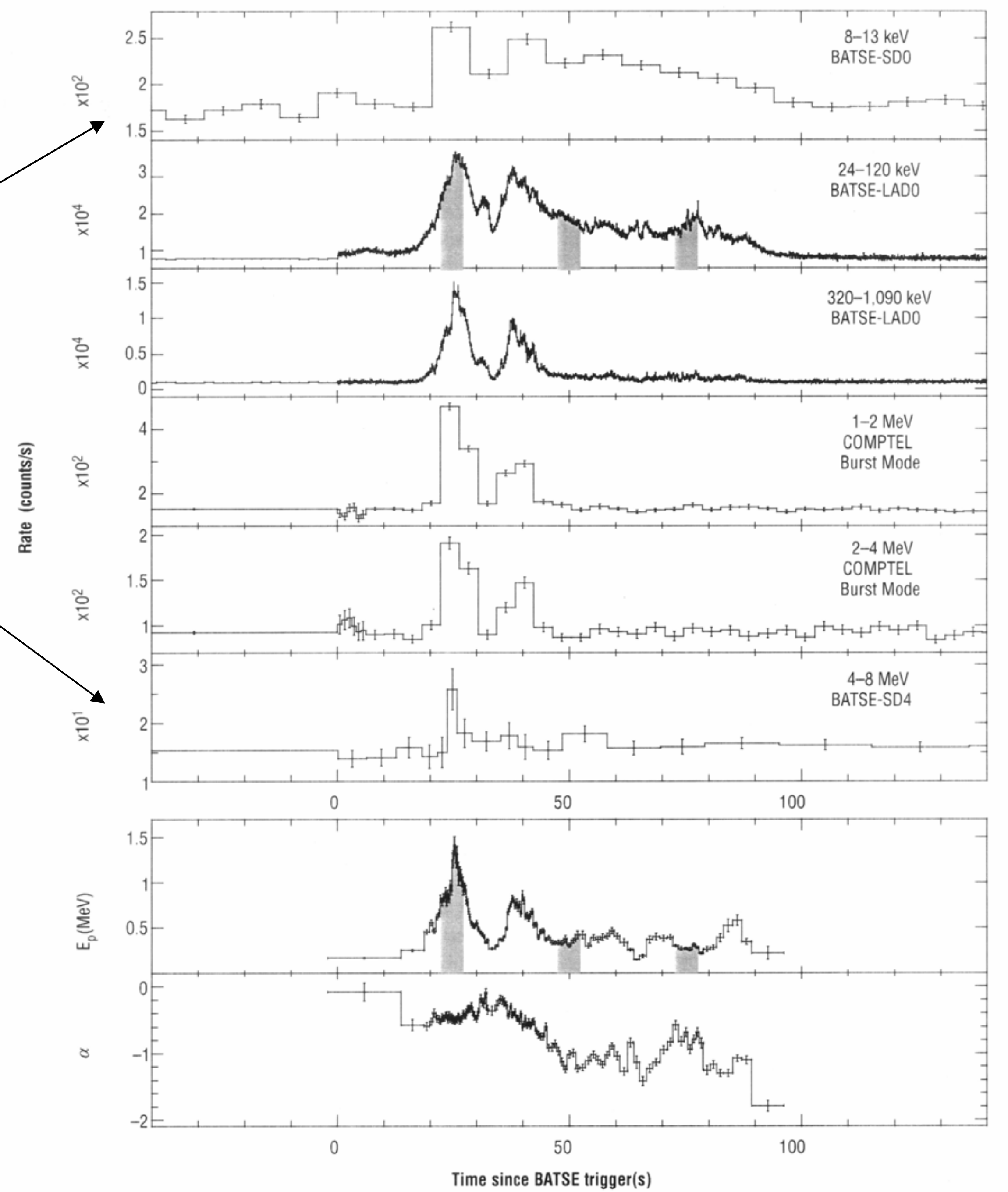


GRB 990123

- Lightcurves in different energy-bands
  - BATSE
  - COMPTEL

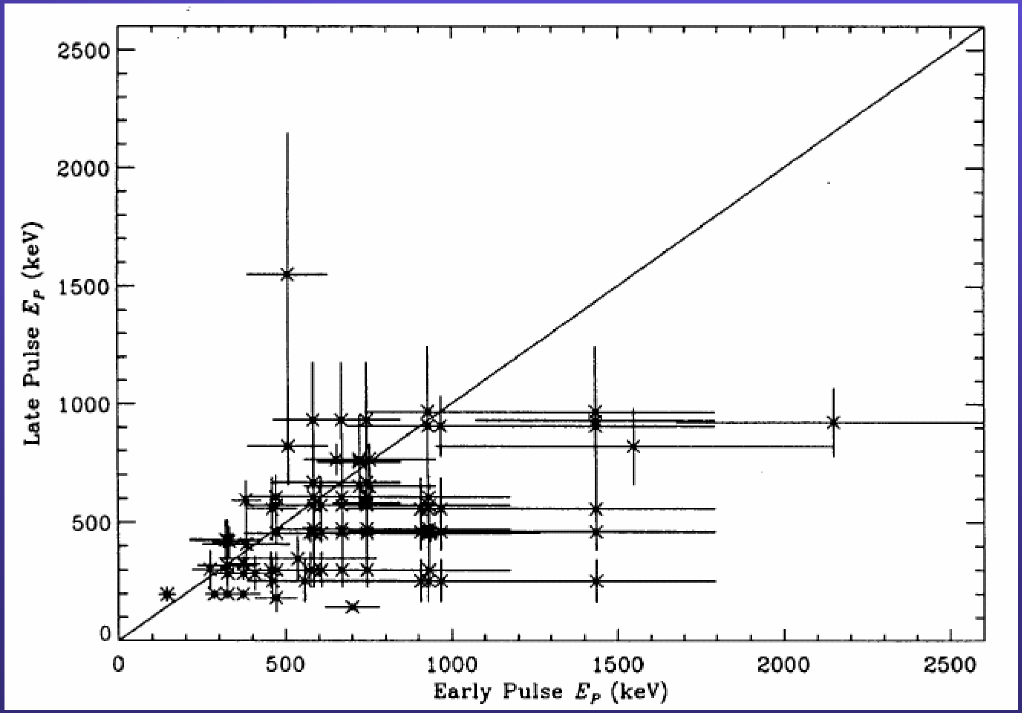


- Time evolution of Band function parameters α and E_P
  - hardness-intensity correlation
  - hard-to-soft evolution



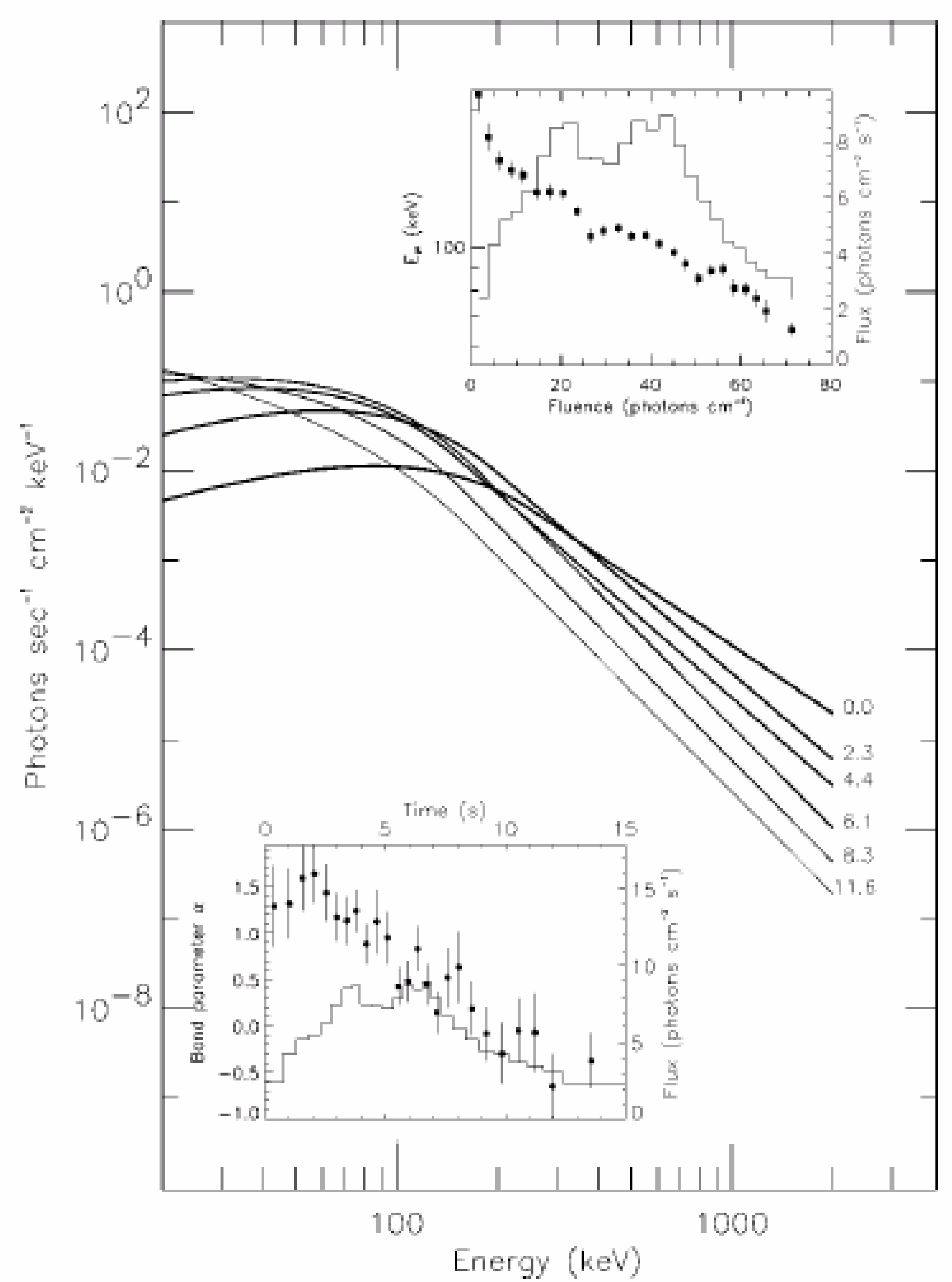
Temporal evolution of spectral parameters

- GRB 990123
  - Hard-to-soft
  - Hardness-intensity correlation
- Peak energy evolution in bright long BATSE bursts (37):
  - Ford, L.A. et al. 95, ApJ 439, 307



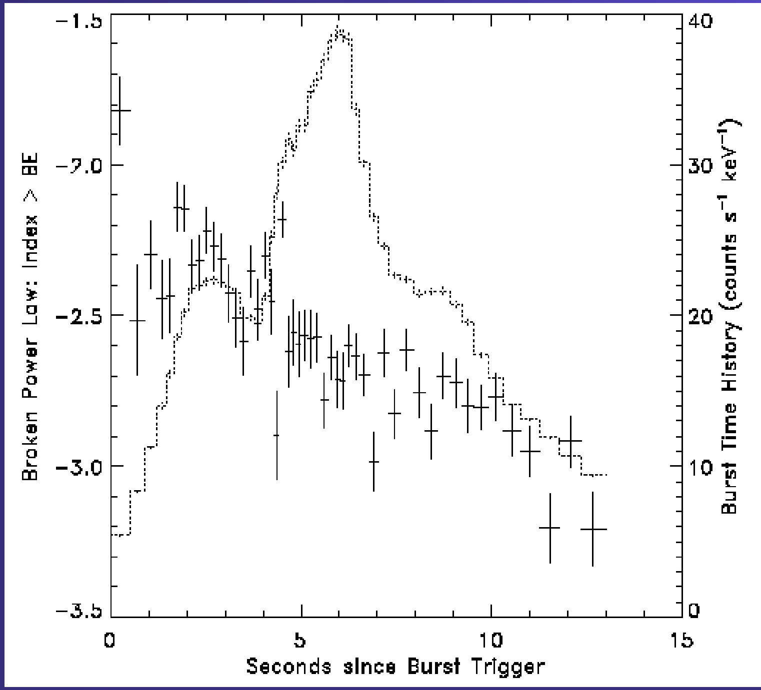
Temporal evolution of spectral parameters

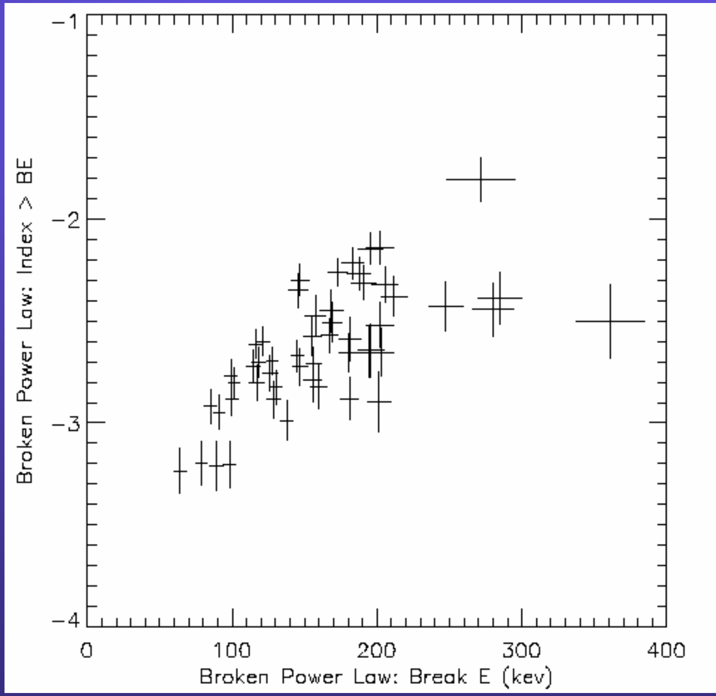
- Evolution of the low-energy photon spectra in GRBs
  - Crider, A. et al. 97, ApJ 479, L39
  - GRB spectral evolution for GRB 910927
  - High degree of positive correlation exists between the time resolved spectral break energy E_{pk} and α.



Temporal evolution of spectral parameters

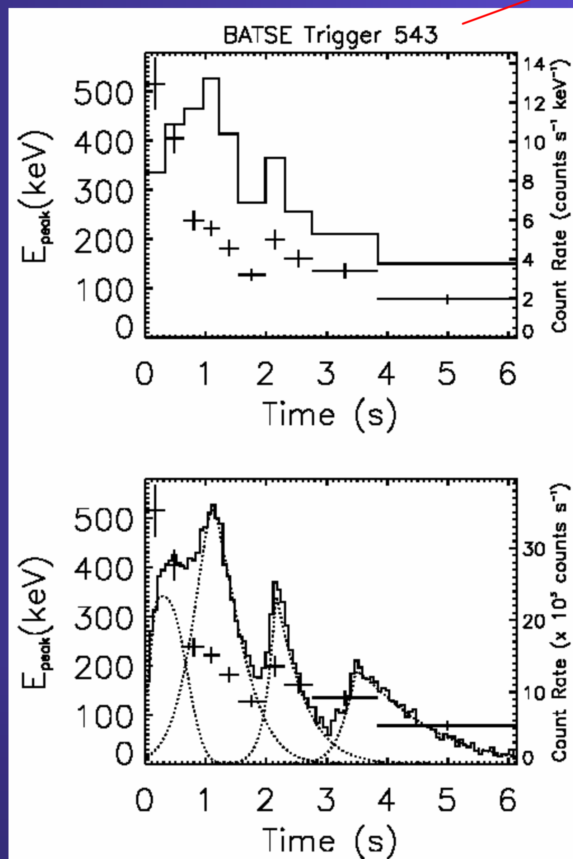
- Temporal behavior of the high-energy power-law portion of GRB spectra of 126
  - Preece, R.D. et al. 98, ApJ 496, 849
  - Hard-to-soft spectral evolution in β for GRB 911118
  - β in dependence of E_{peak} for GRB 911118 ⇨ correlation in time evolution

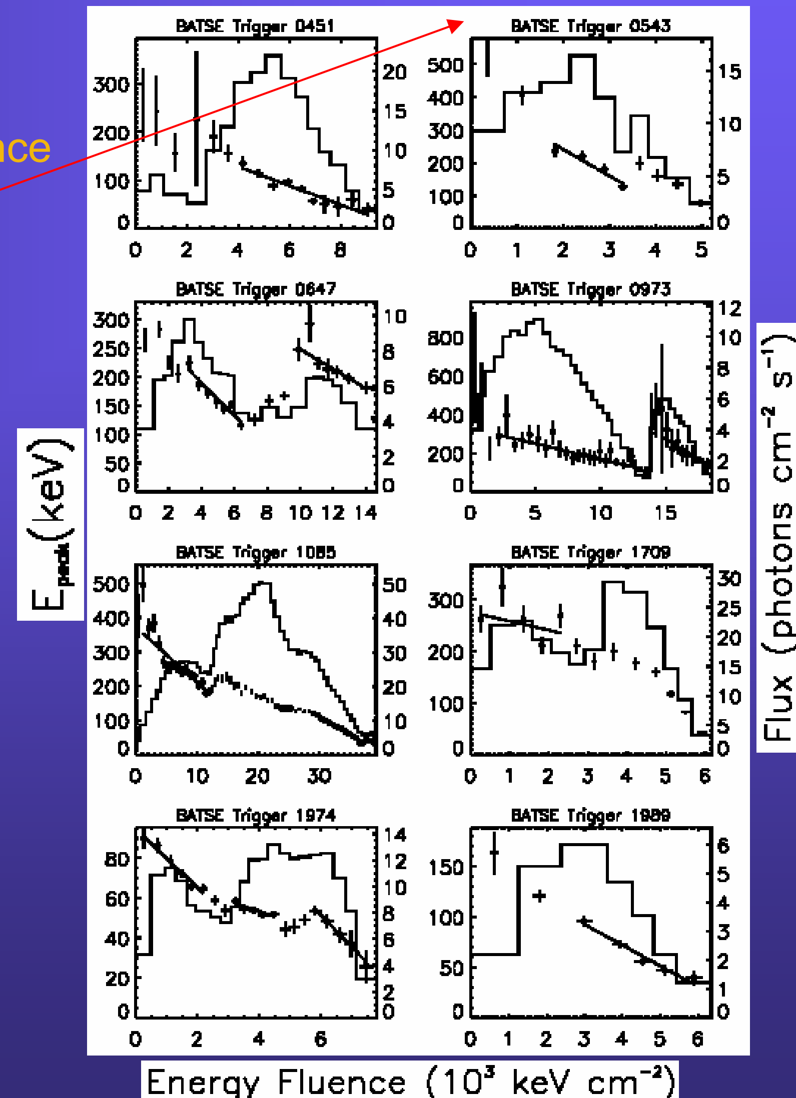




Temporal evolution of spectral parameters

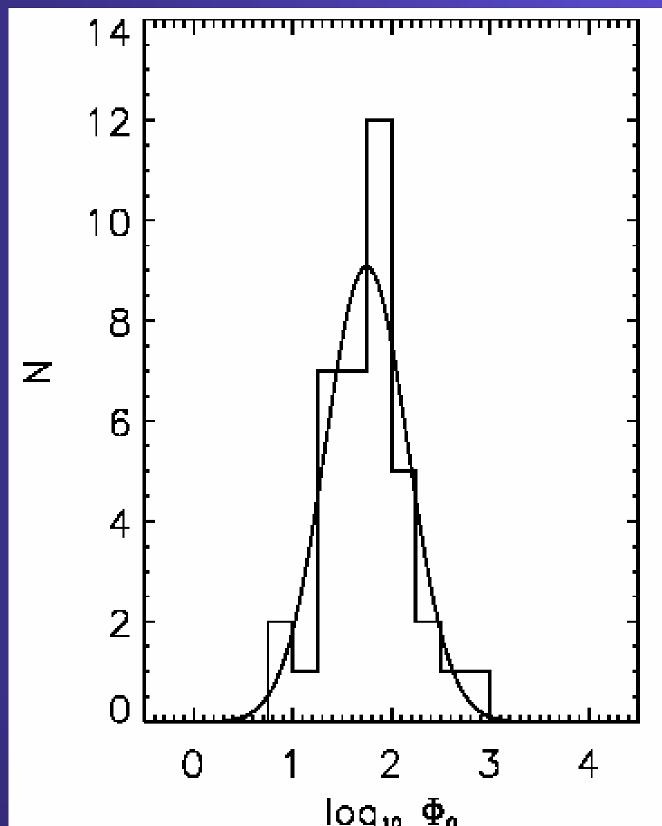
- Evolution of the spectral hardness E_{pk} as function of the fluence for 41 pulses in 26 GRBs
  - Crider, A. et al. 99, ApJ 519, 206
  - Trend: E_{pk} decays linearly with energy fluence

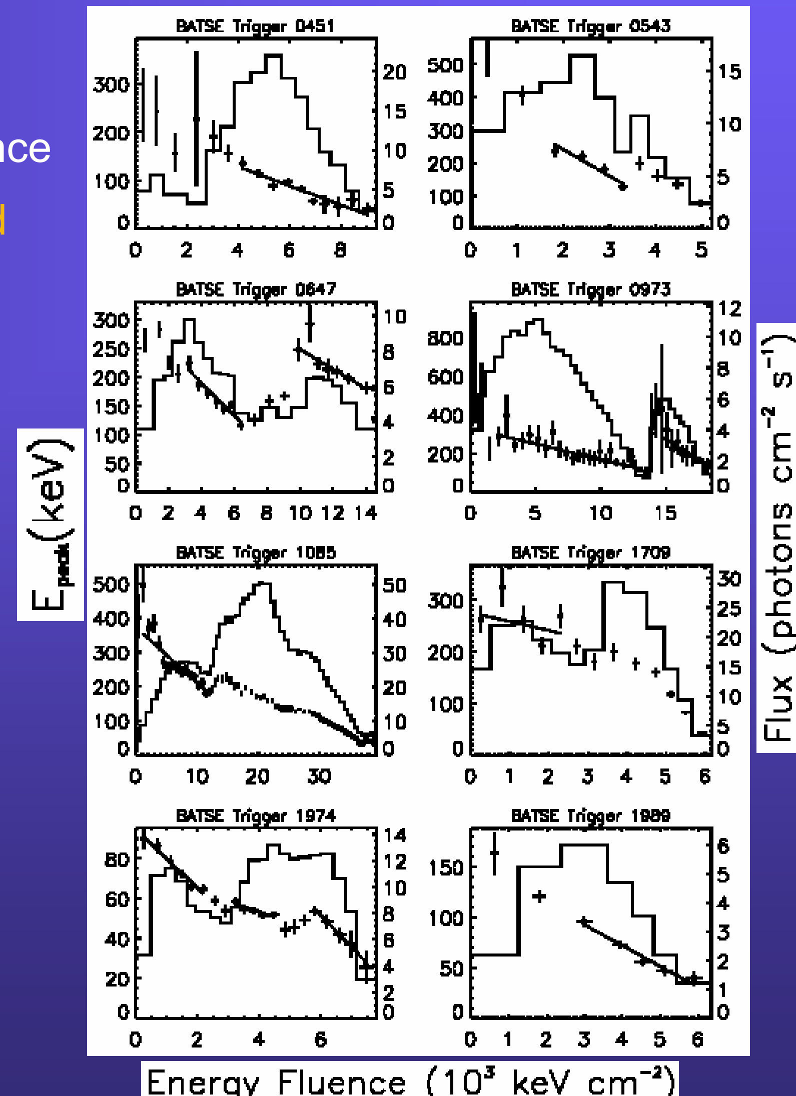




Temporal evolution of spectral parameters

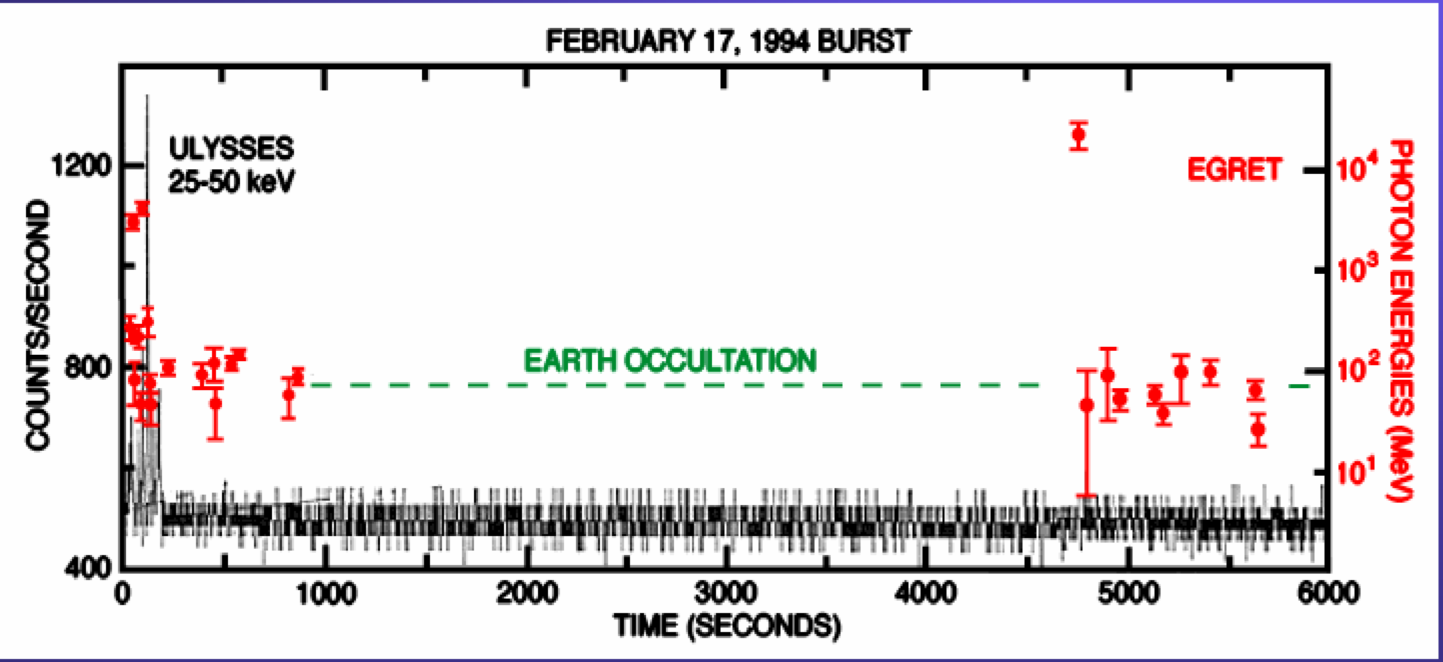
- Evolution of the spectral hardness E_{pk} as function of the fluence for 41 pulses in 26 GRBs
  - Crider, A. et al. 99, ApJ 519, 206
  - Trend: E_{pk} decays linearly with energy fluence
  - Decay constant Φ_0 is log-normal distributed





Bursts with high-energy γ-Ray Emission

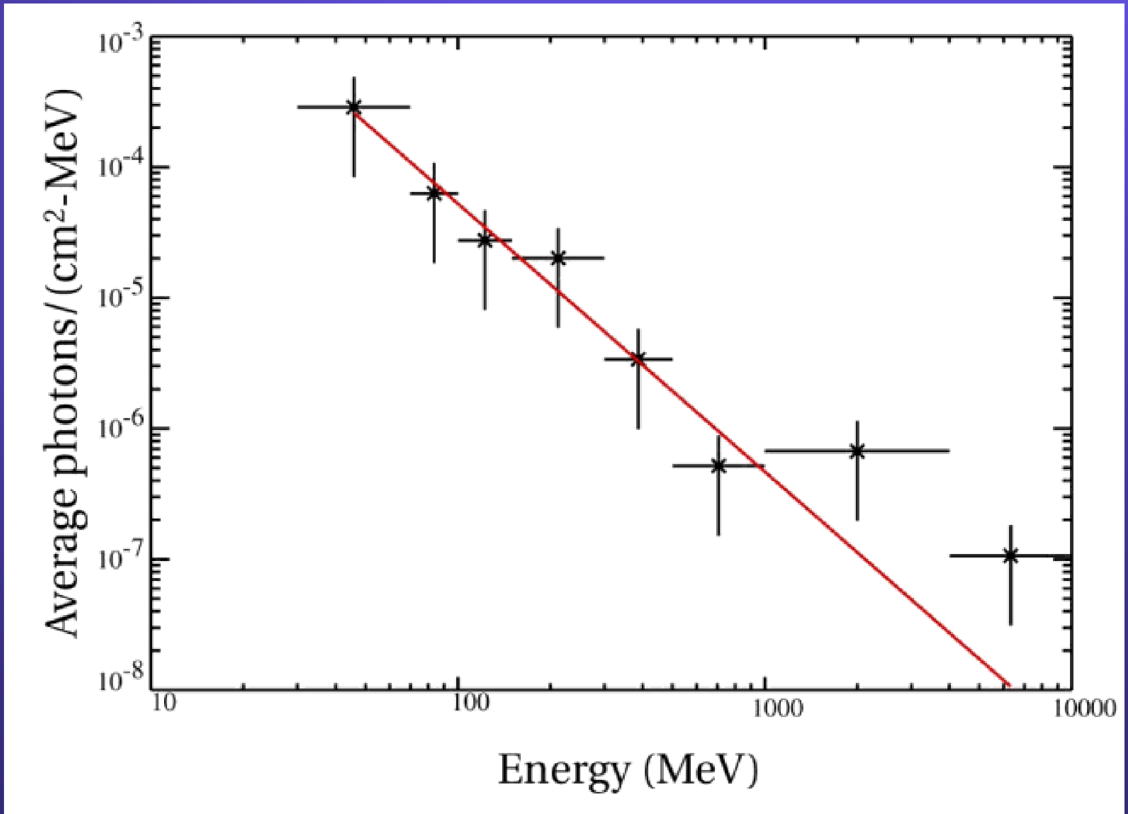
- In 1994 EGRET observed a γ-ray burst which showed high-energy
- (> 50 MeV) γ-ray emission
  - till 1.5 hours after start of burst
  - highest-observed energy: 18 GeV



- The relation between high- and low-energy emission not yet understood!

EGRET-spectra in the MeV-GeV-range

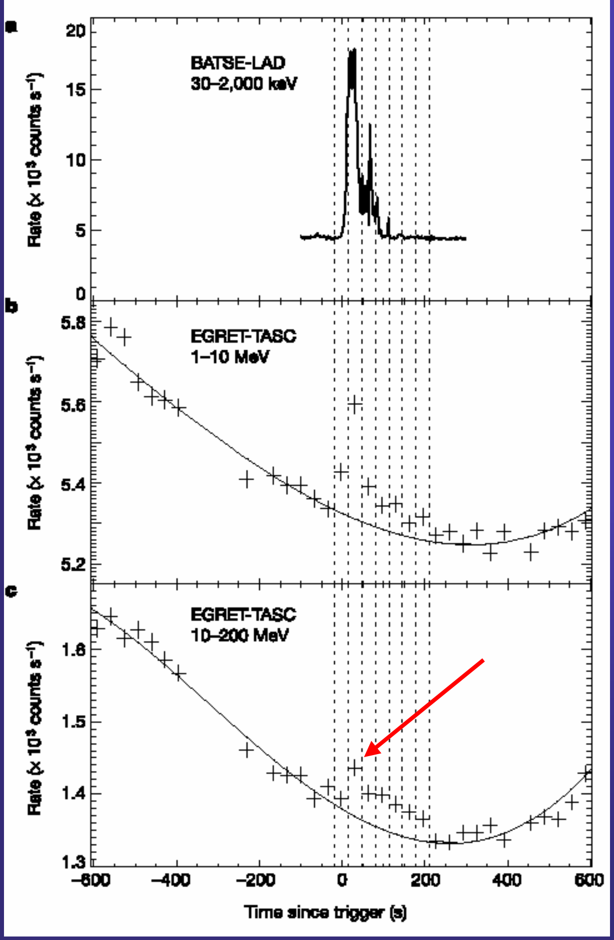
- "Observation of the Highest Energy Gamma-Rays from GRBs"
  - Dingus, B.L. 2001, AIP 558, 383
  - Average spectrum measured by EGRET for 4 bursts (45 γ-rays above 30 MeV, 4 above 1 GeV, within BATSE T90 interval), Photon spectral index: 1.95 $\pm$ 0.25
  - Consistent with an extension of the electron synchrotron component



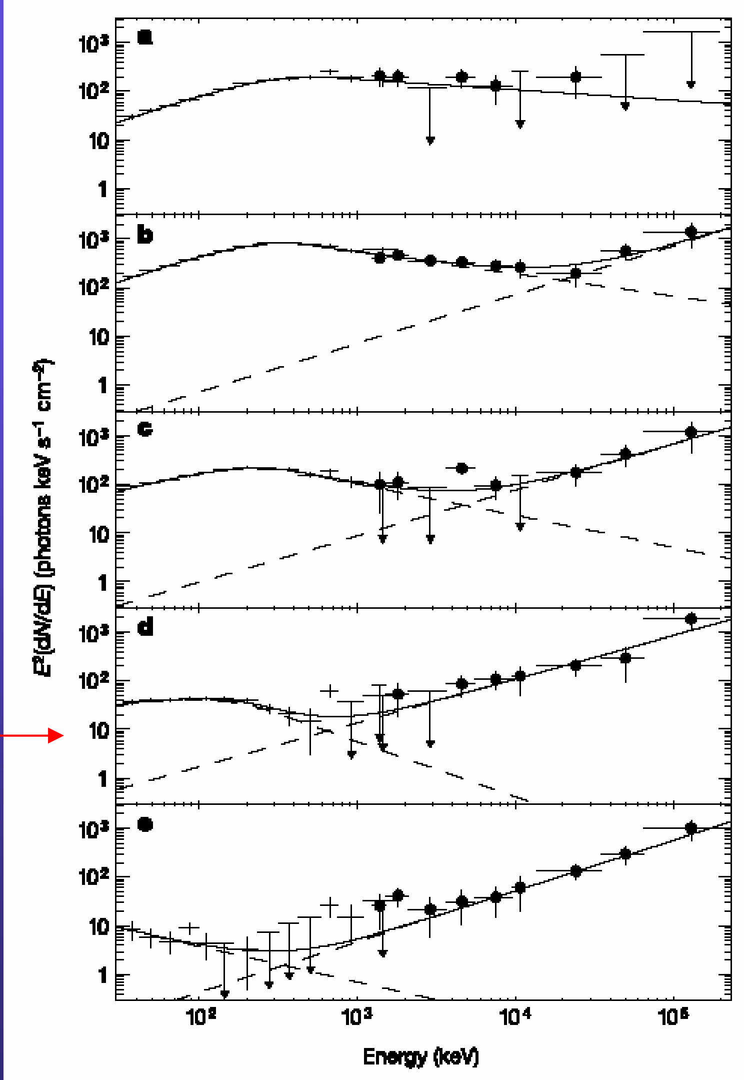
GRB 941017 measured with EGRET-TASC

(Total Absorption Shower Counter)

- "A γ-ray burst with a high-energy spectral component inconsistent with the synchrotron shock model"
  - Gonzales, M.M. et al. 2003, Nature 424, 749

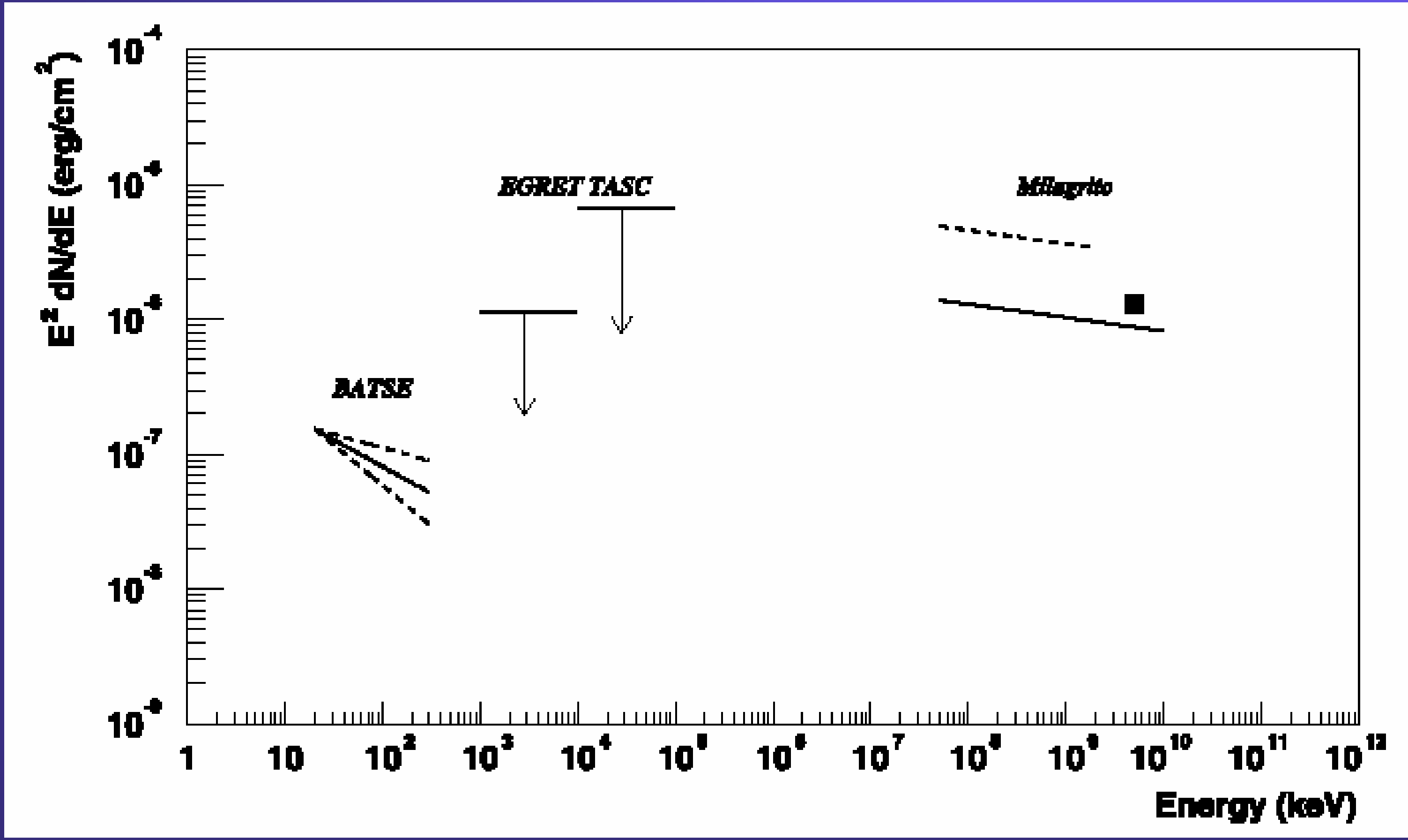


Spectral fit by Band-function + A_{PL} [E(keV)/30MeV]$^{\gamma}$



TeV emission from GRBs

- Evidence of TeV emission from GRB 970417a using data from the Milagrito
  - photons with energies above 650 GeV
  - R. Atkins, R. et al. 03, ApJ 583, 824



X-Ray Flashes and GRBs

- Spectral Characteristics of X-Ray Flashes
  - Kippen, R.M. et al. 02, astro-ph/0203114
  - T_{90}: 10 – 200 sec → similar to GRBs
  - α: ~ -1, β: ~ -2.5 → similar to GRBs
  - Main difference: E_{peak} in the X-ray range

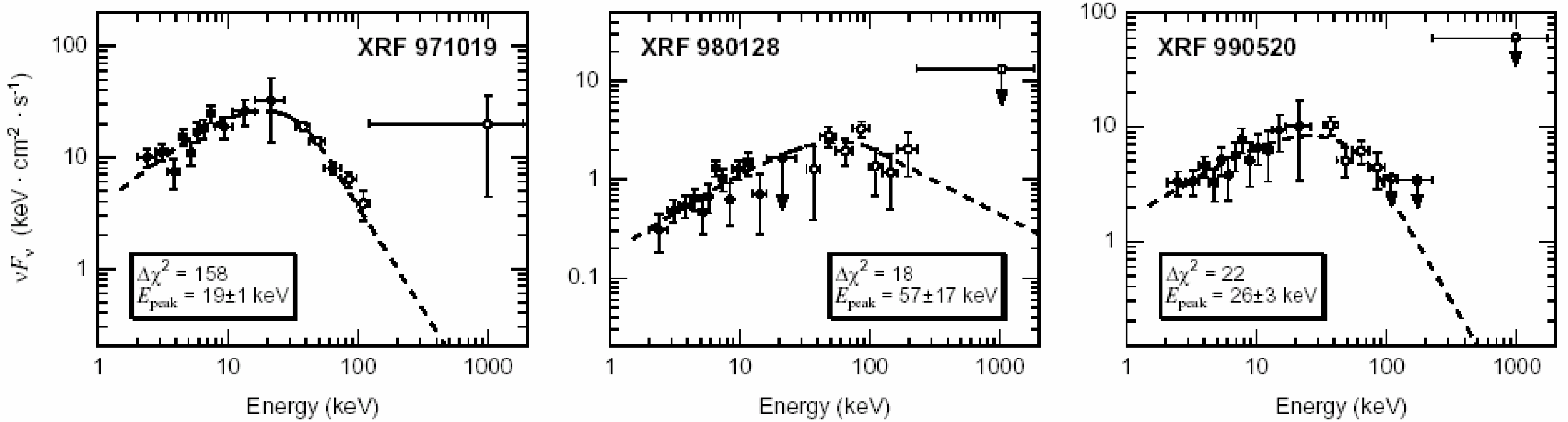
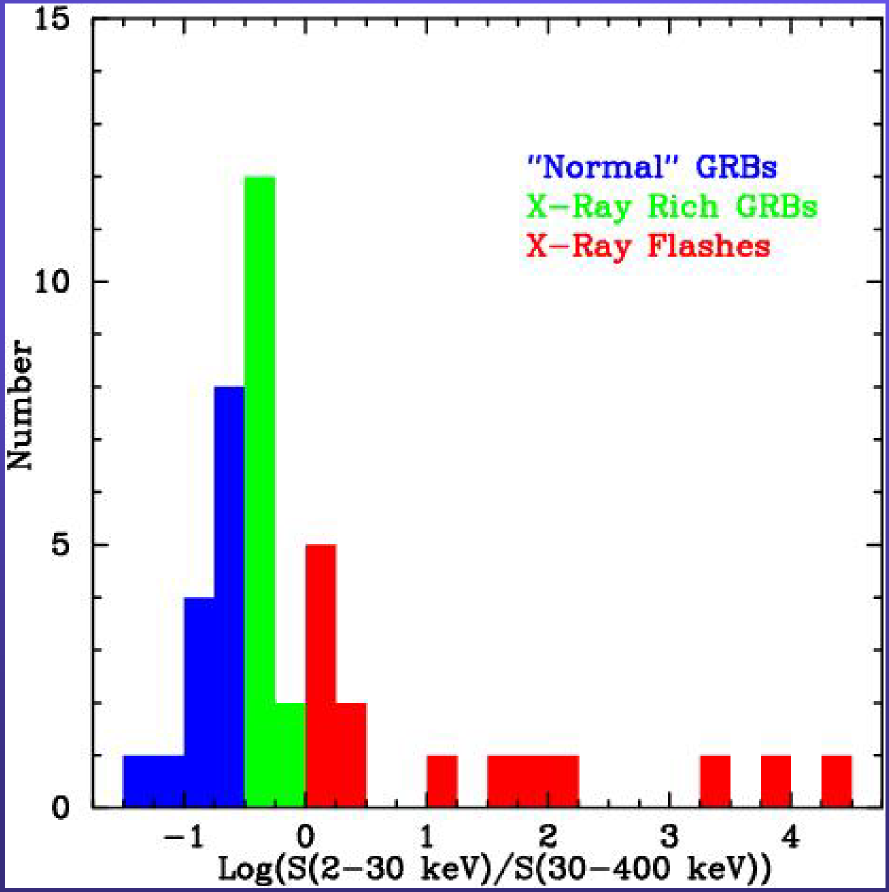


FIGURE 1. Model-dependent deconvolution of spectral data from WFC (*solid diamonds*) and BATSE (*open circles*) for three X-ray flashes. The best-fit Band GRB function is shown as dashed lines. Also indicated are the change in chi-squared ($\Delta\chi^2$) from a single power law to the Band function and the best-fit values of E_{peak} with 1σ errors.

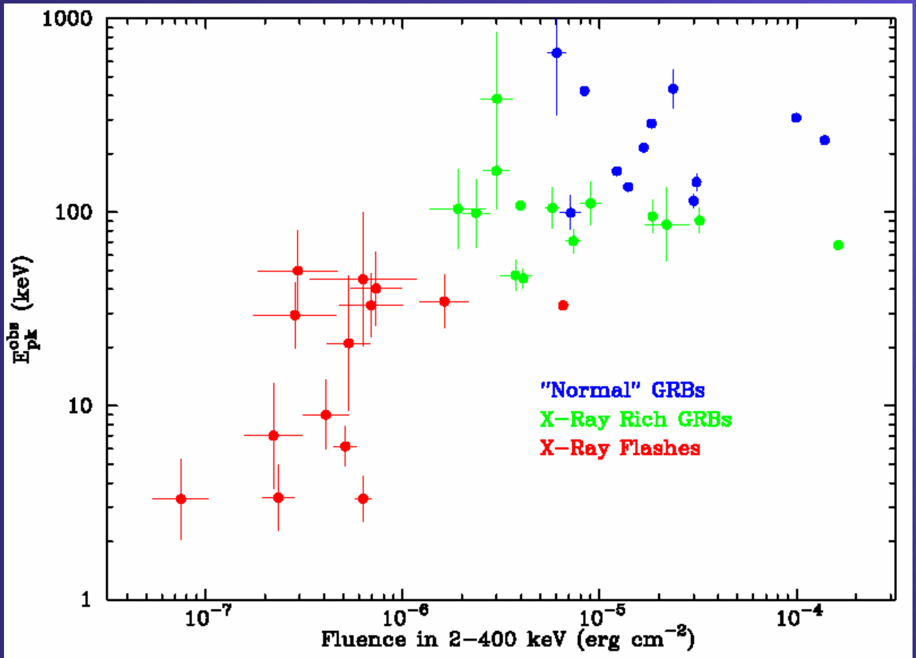
X-Ray Flashes observed by HETE-2

- Defining "X-ray flashes" (Heise et al. 2000) as bursts for which $\log (S_X / S_\gamma) > 0$ (i.e., > 30 times that for "normal" GRBs)
  - 1/3 of bursts localized by HETE-2 are XRFs
  - 1/3 are "X-ray-rich" GRBs

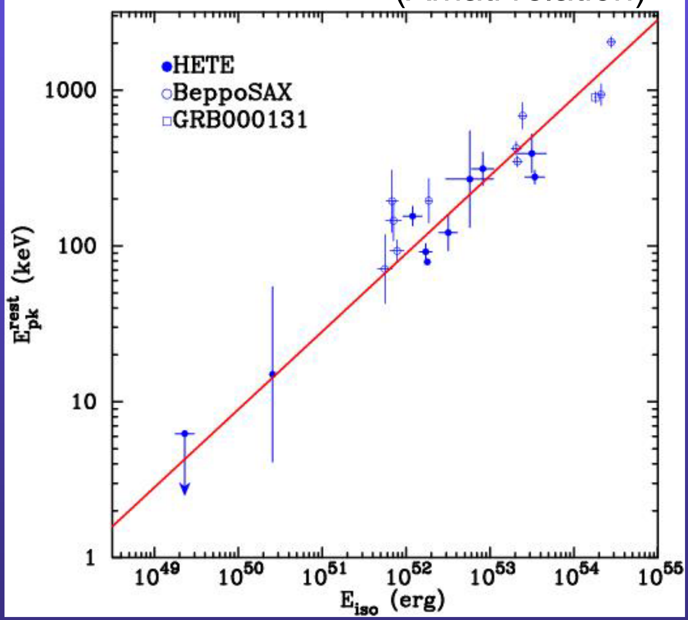


X-Ray Flashes and GRBs

- Strong evidence that properties of XRFs and GRBs form a continuum
  - Both types of bursts are the same phenomenon
  - Lamb, D.Q. et al. 03, astro-ph/0309456



(Amati relation)



Extremely Soft X-Ray Flash XRF 020903

- HETE-2 WXM observation
  - Sakamoto, T. et al. 03, astro-ph/0309455
- Redshift determination $\rightarrow$ $z = 0.251$ (first X-ray flash with optical afterglow)
  - Soderberg, A.M. et al. 03, astro-ph/0311050