Gamma-Ray Burst Spectral Analysis

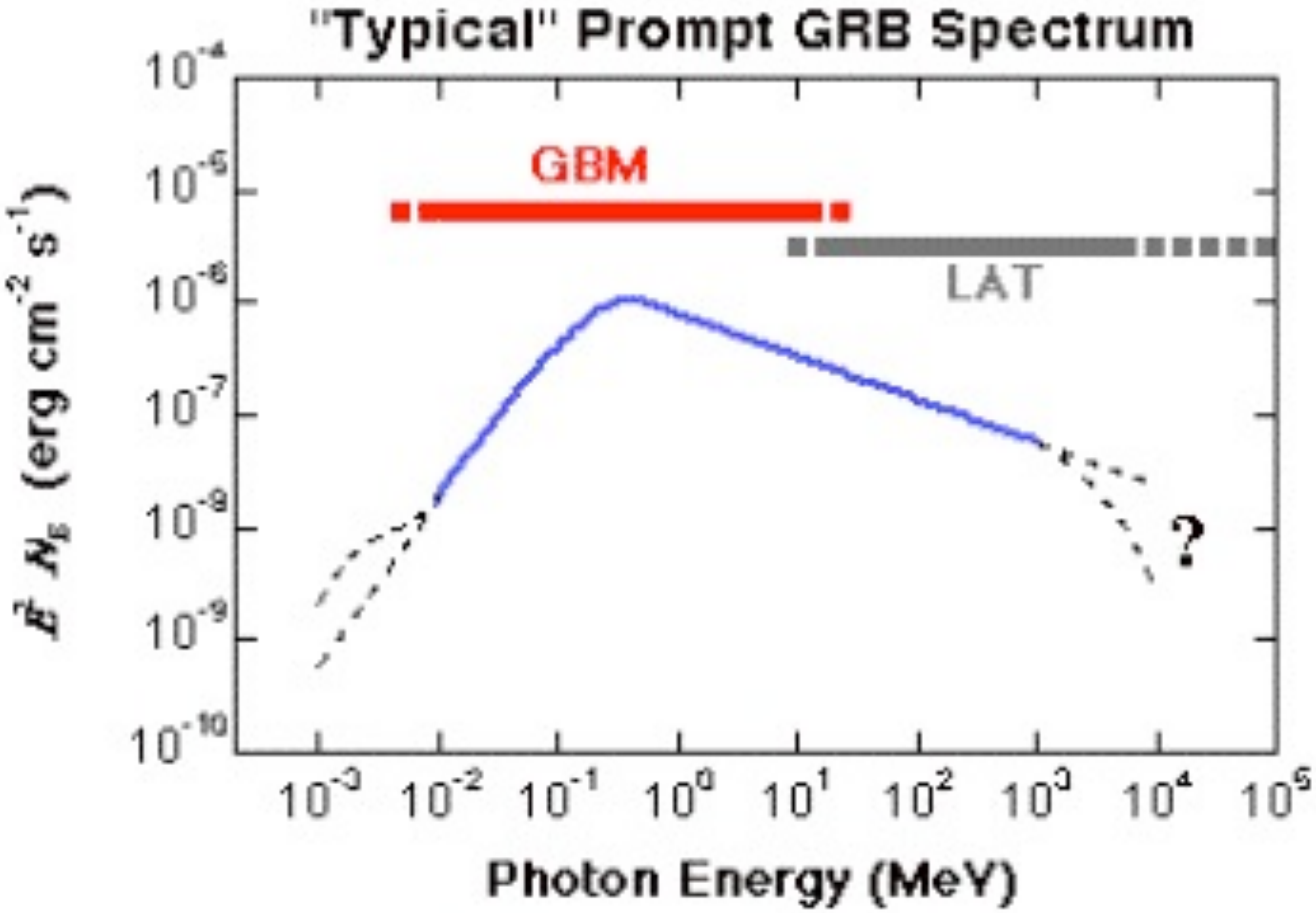
Valerie Connaughton

University of Alabama in Huntsville

What is spectroscopy and why do it?

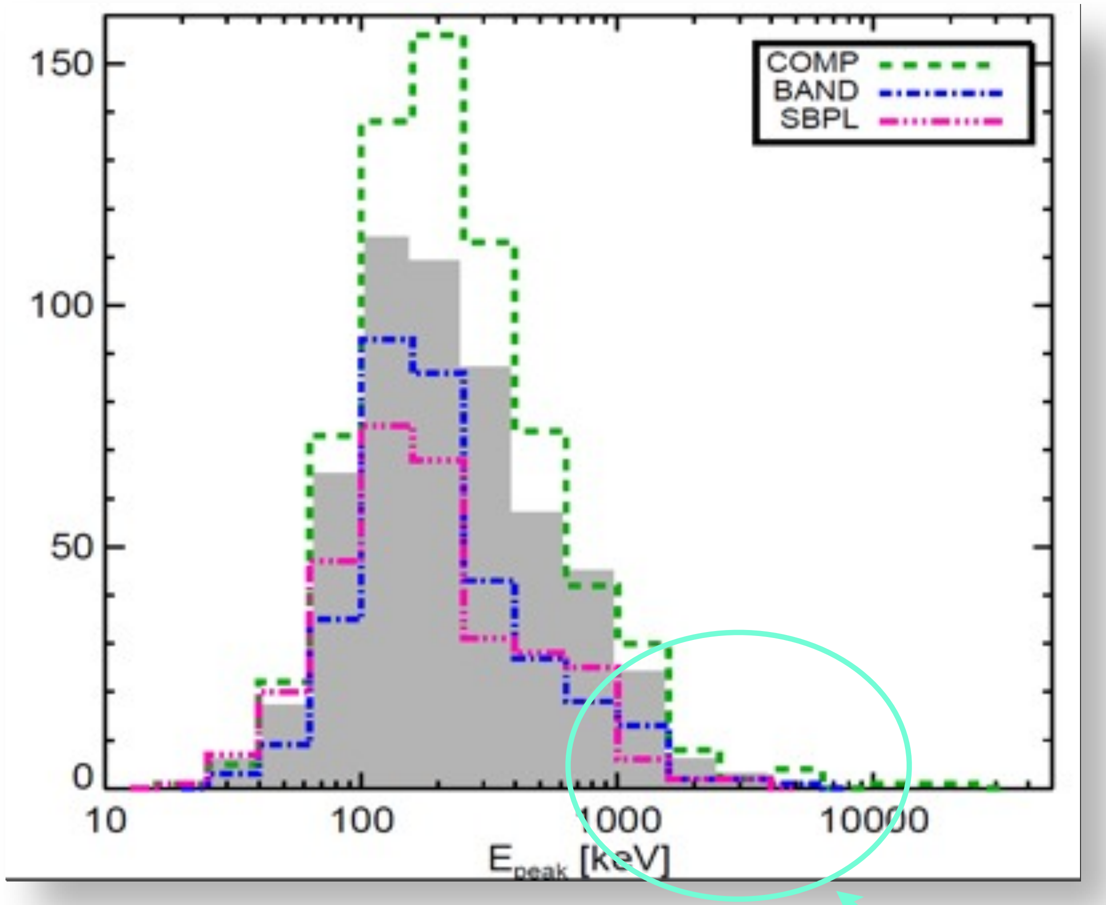
- The study of the distribution of counts from a source as a function of energy.
- Spectroscopy offers a view of the radiative processes fueling a source (which may be modified during their path to us or in our detector).
- Time-resolved spectroscopy shows how these processes might change over time.
- GBM offers a wide energy range (8 keV -- 40 MeV) to do time-resolved spectroscopy of numerous phenomena e.g. GRBs, but also Soft Gamma-ray Repeaters, Solar Flares... and other phenomena which emit bursts of gamma rays powerful enough over a short (sub-millisecond -- several sec) enough period to be visible above the background rates measured by GBM.

Gamma-Ray Burst spectra: the Band function was invented to describe the spectral shape of GRBs



$$N(E) = \begin{cases} E^{\alpha} \exp\left(-\frac{E}{E_0}\right), & \text{if } E \leq (\alpha-\beta)E_0 \\ \left[(\alpha-\beta)\,E_0\right]^{(\alpha-\beta)} E^{\beta} \exp\left(\beta-\alpha\right), & \text{if } E > (\alpha-\beta)E_0 \end{cases}$$

GBM has a broad energy range suitable for studying GRB spectra



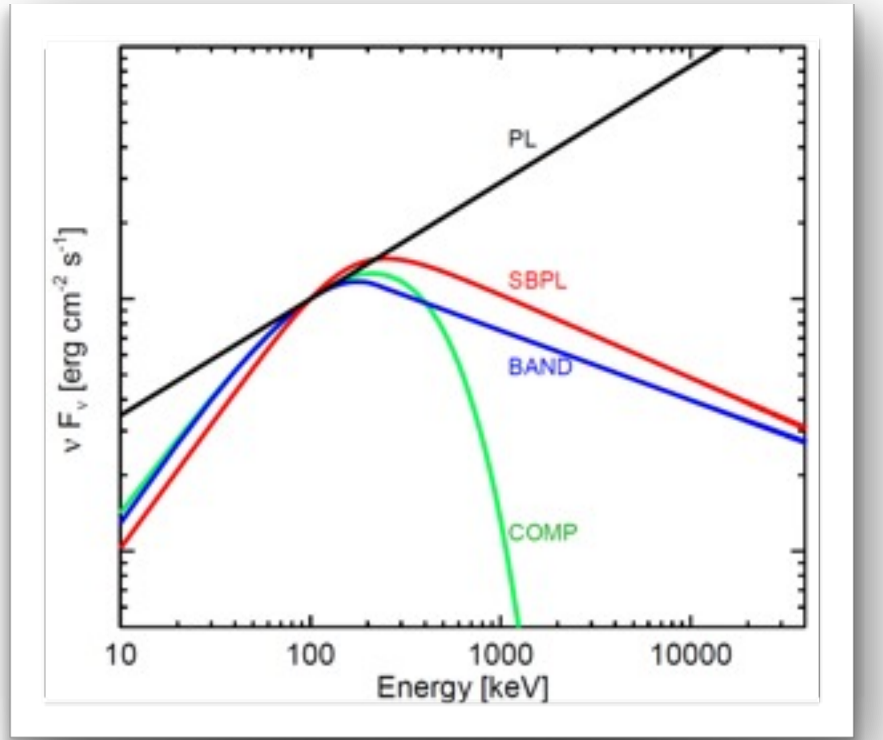
Extending the EPeak distribution:
Better study of short bursts.

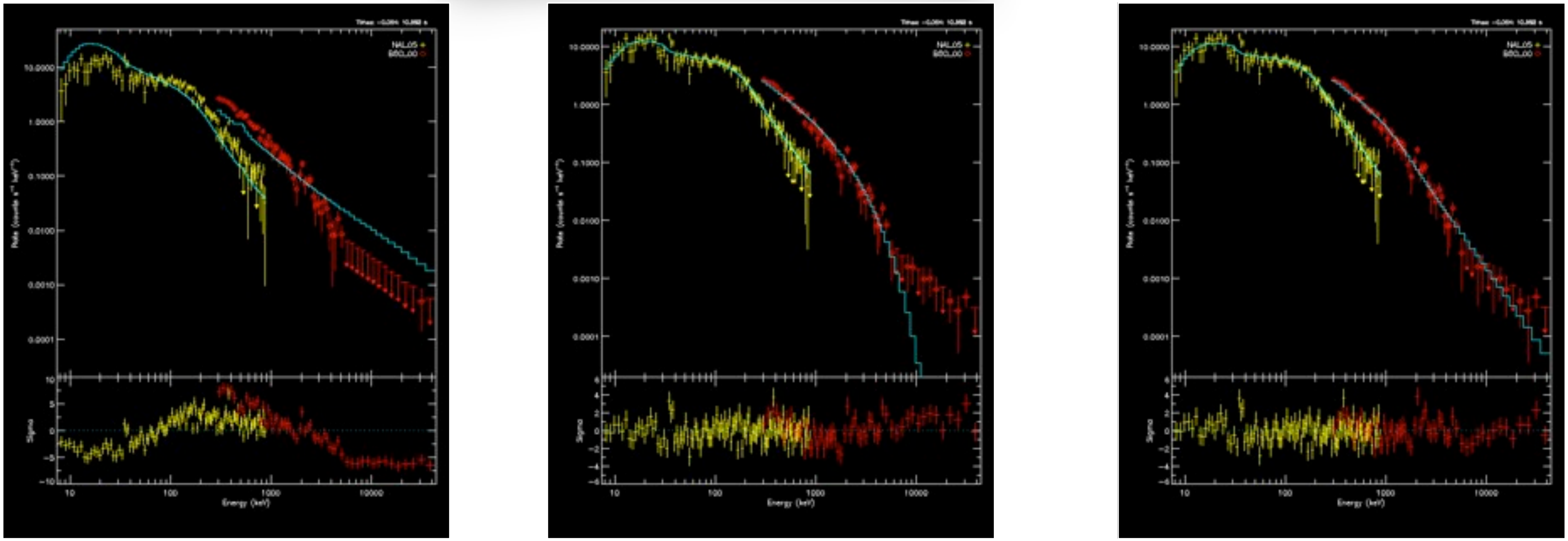
Gruber+ in preparation

Spectroscopy tools

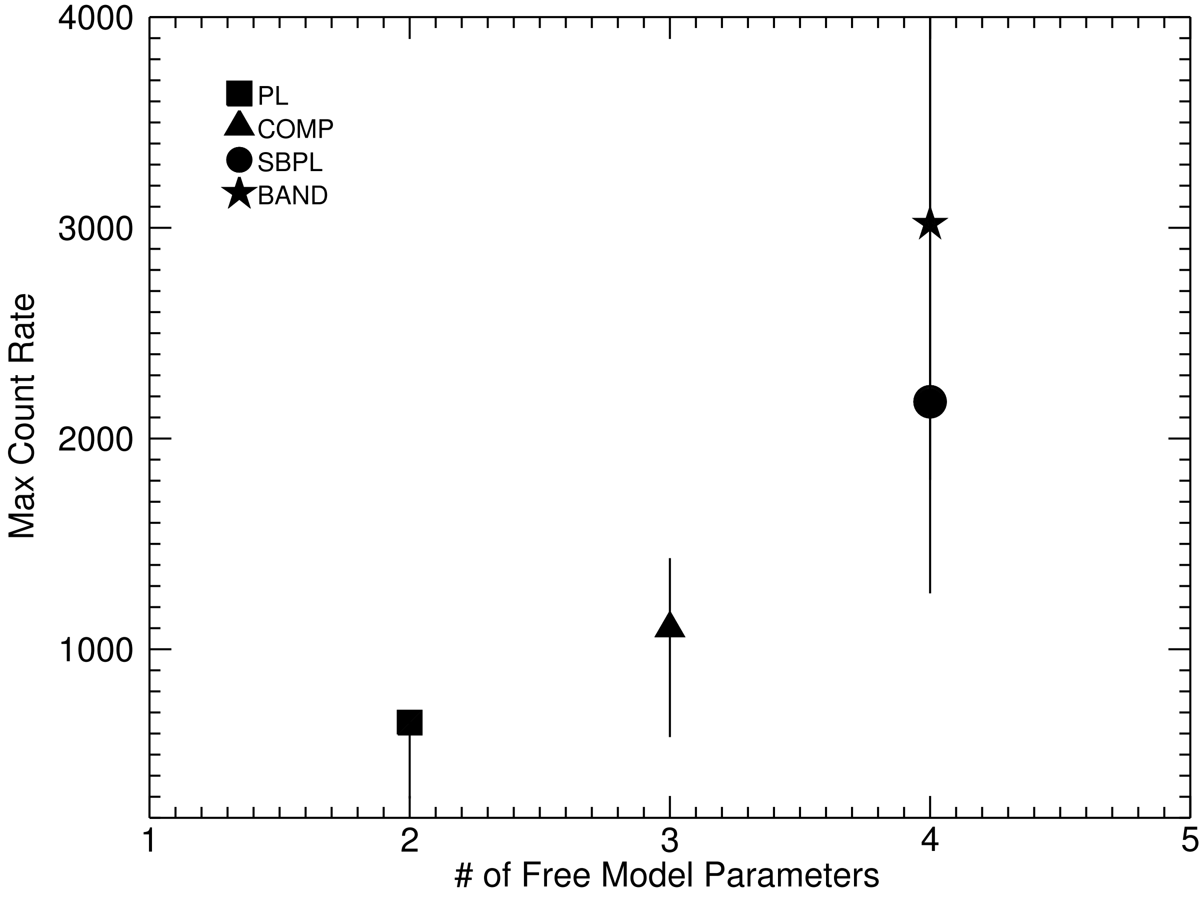
- We use the rmfit package, developed by the BATSE team for GRB studies.
- It is available from the FSSC: http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/
- Tutorial in step-by-step format http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/vc_rmfit_tutorial.pdf
- New rmfit version available... this week? Or from Valerie on a USB stick!

Common models to fit GRBs





Brighter GRBs allow more complex models to be constrained

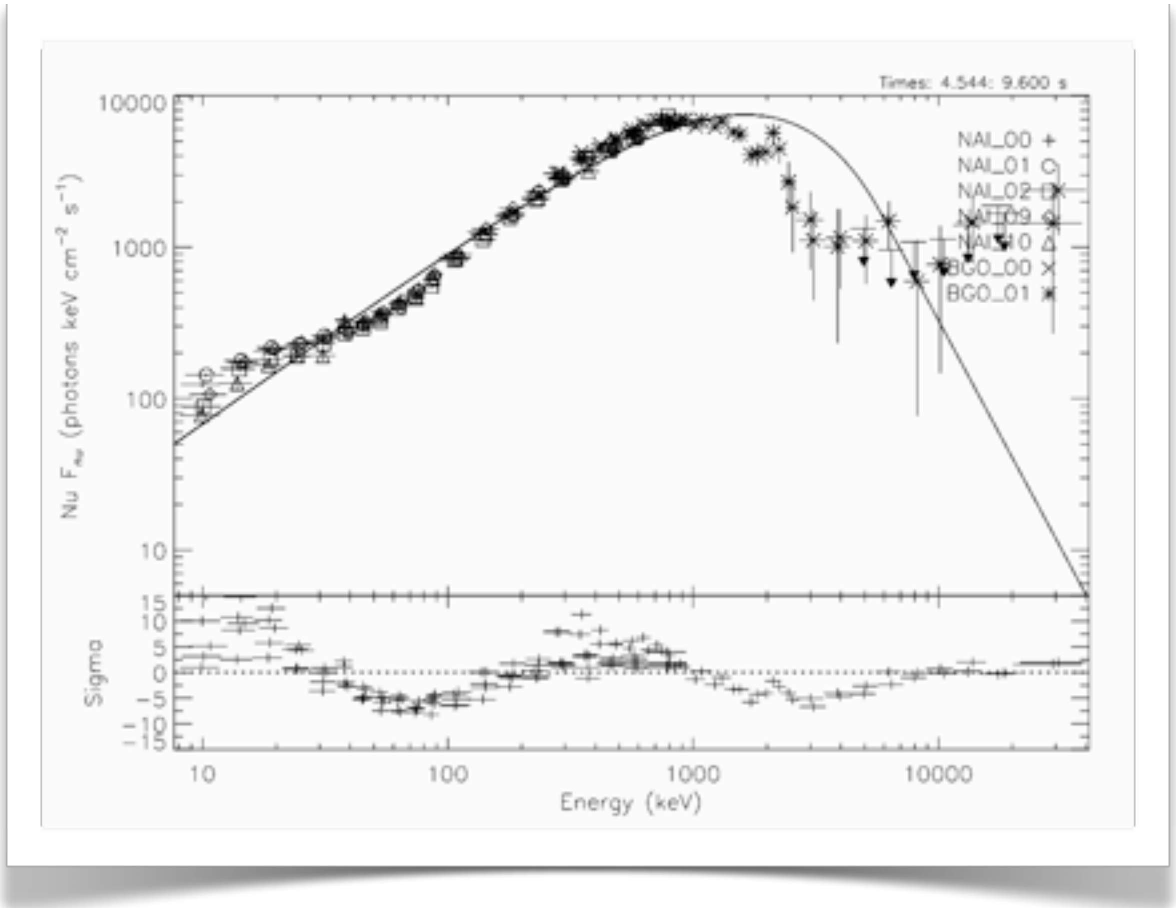


PL	SBPL	BAND	COMP
Fluence Spectra			
113 (23%)	67 (14%)	75 (15%)	231 (48%)
Peak Flux Spectra			
152 (31%)	48 (10%)	69 (14%)	214 (44%)

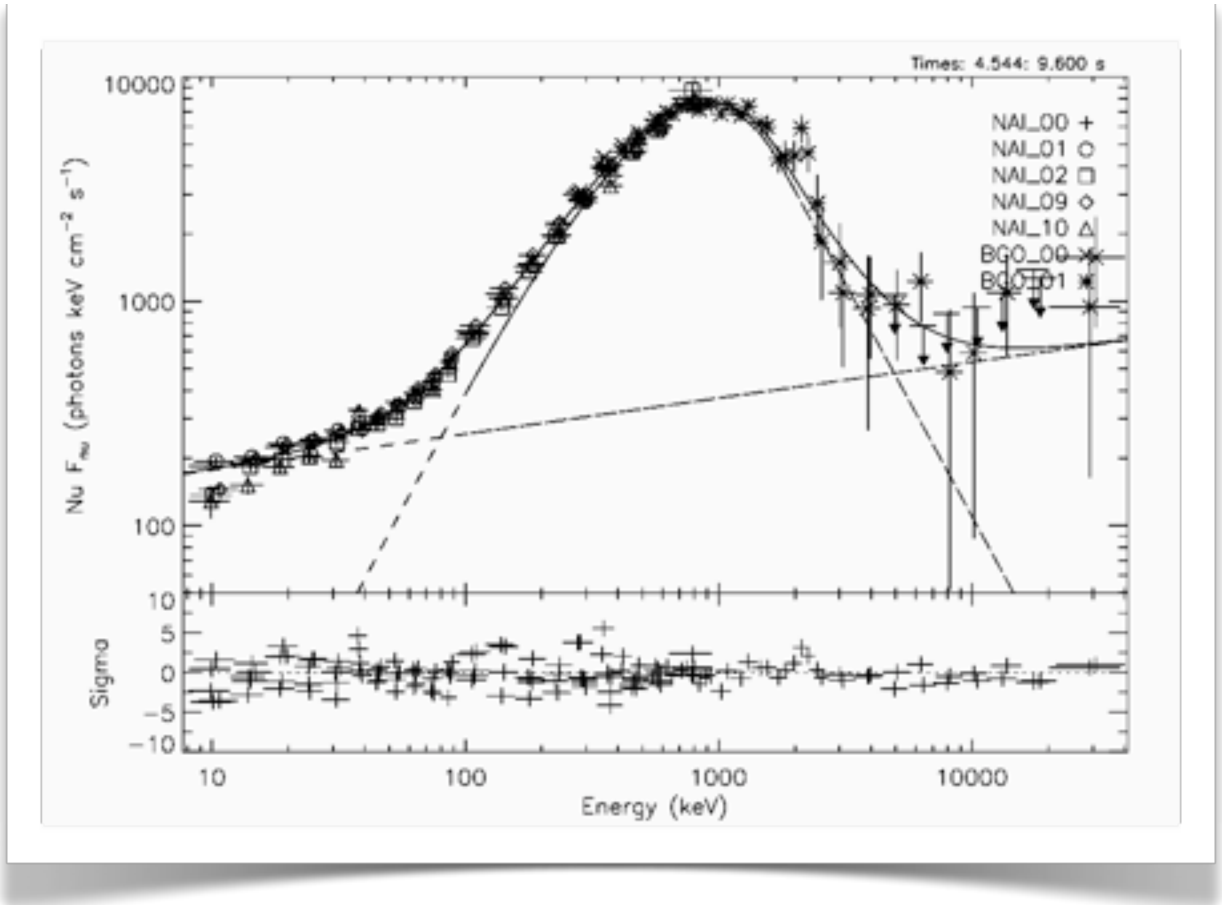
Goldstein+ 2012

Sometimes the Band function doesn’t work
(i) extra power law components

GRB 090902B

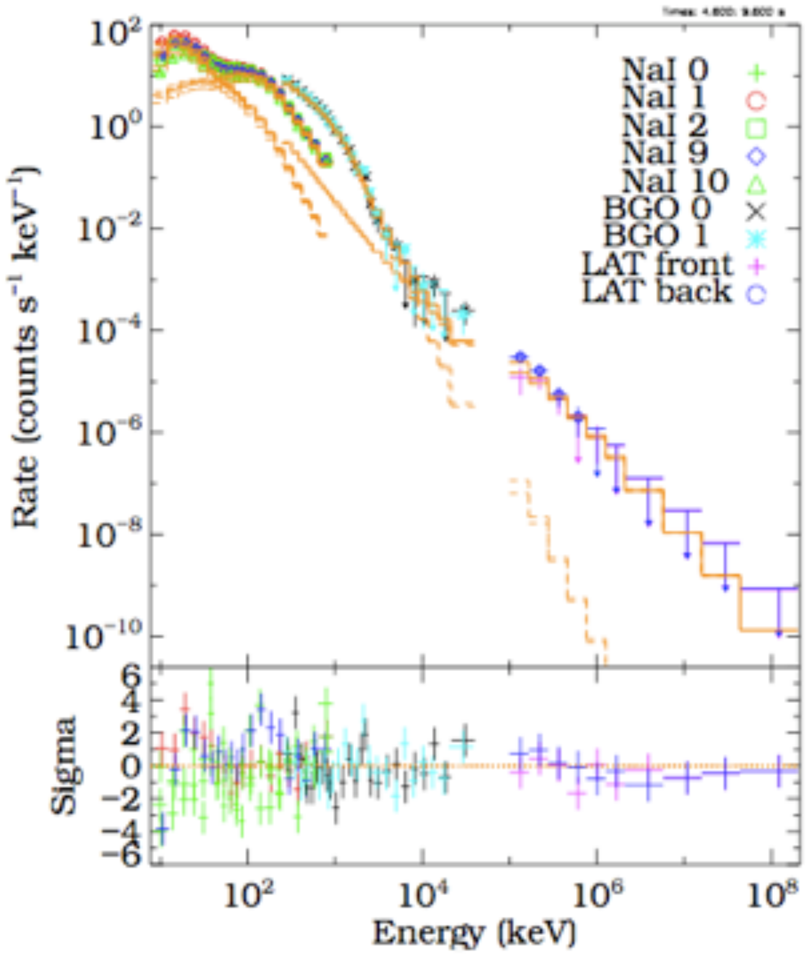


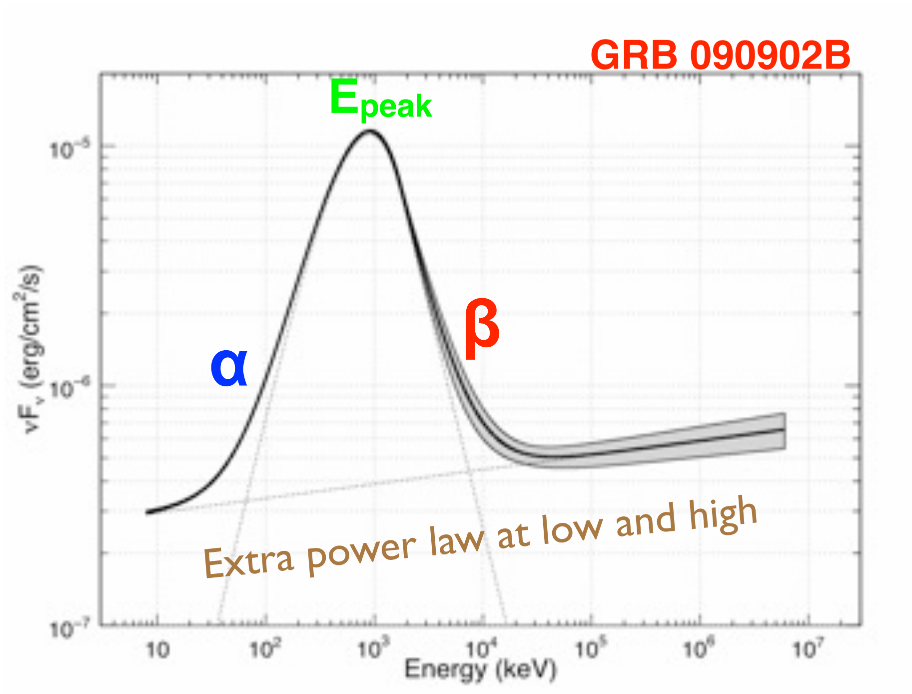
Deviations from Band function at LE



Addition of power-law improves fit

The extra power-law extends to LAT energies

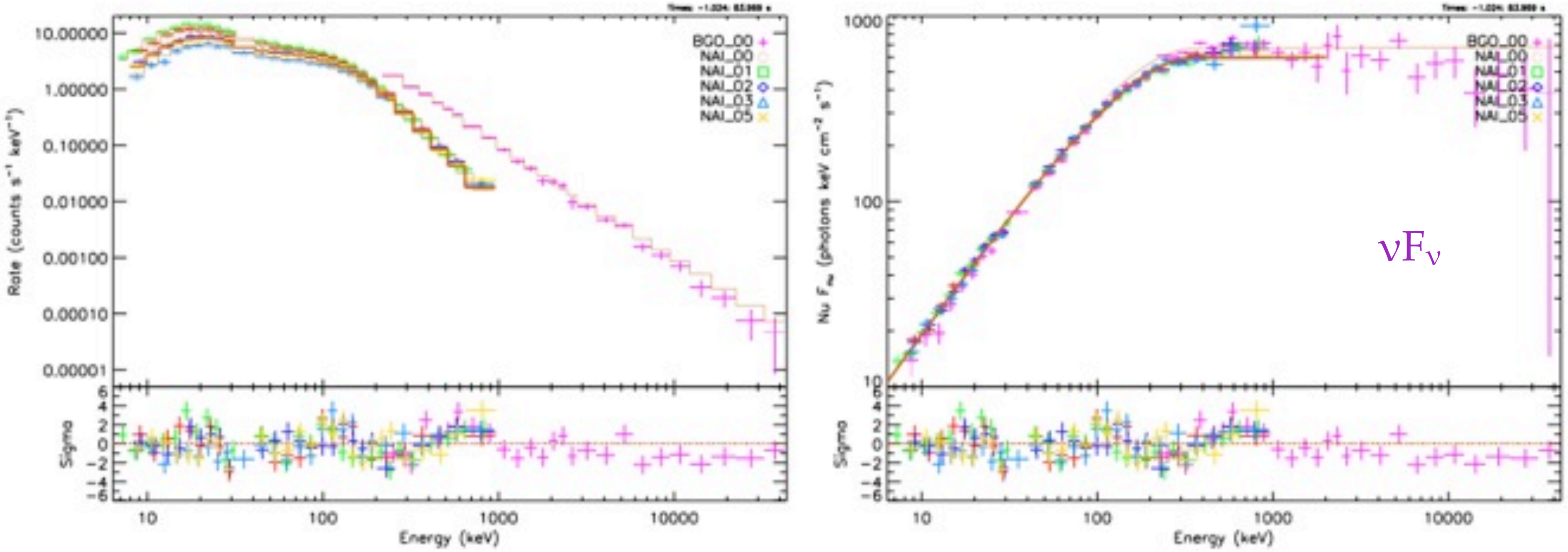




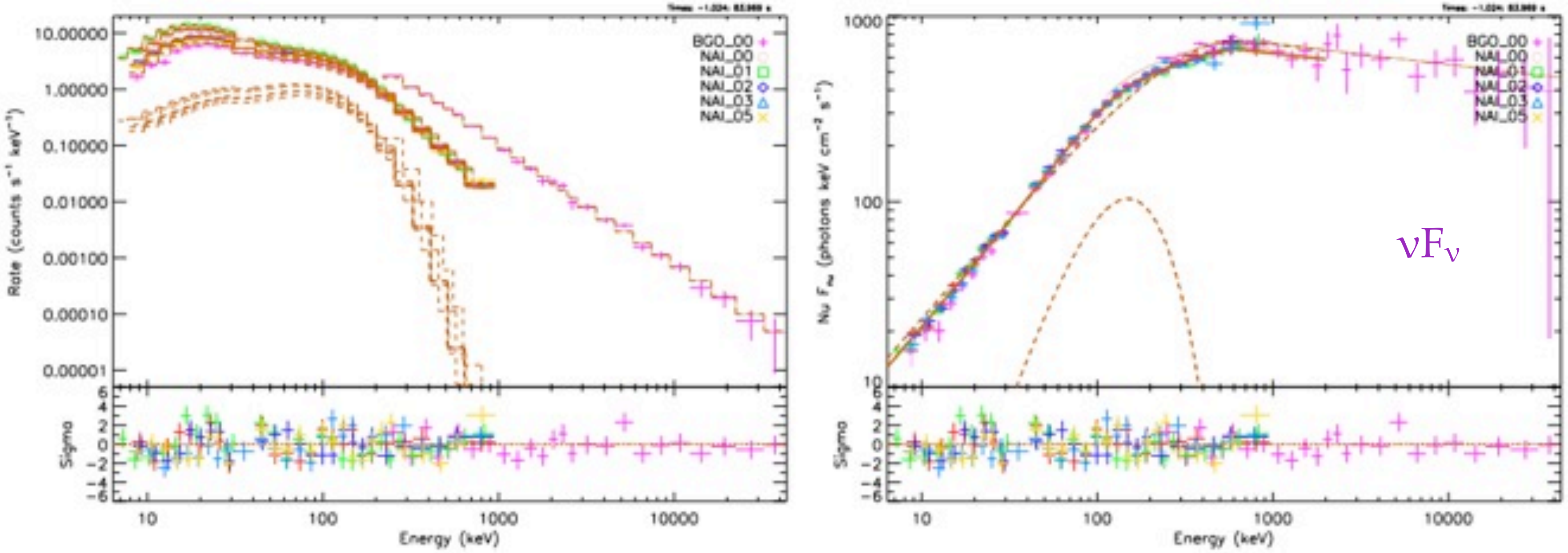
Abdo+ ApJ 2009

When the Band function fails
(ii) thermal components

GRB100724B: Count spectra show systematic deviations in "heart" of GBM energy range.



Count spectra residuals improve with addition of blackbody.

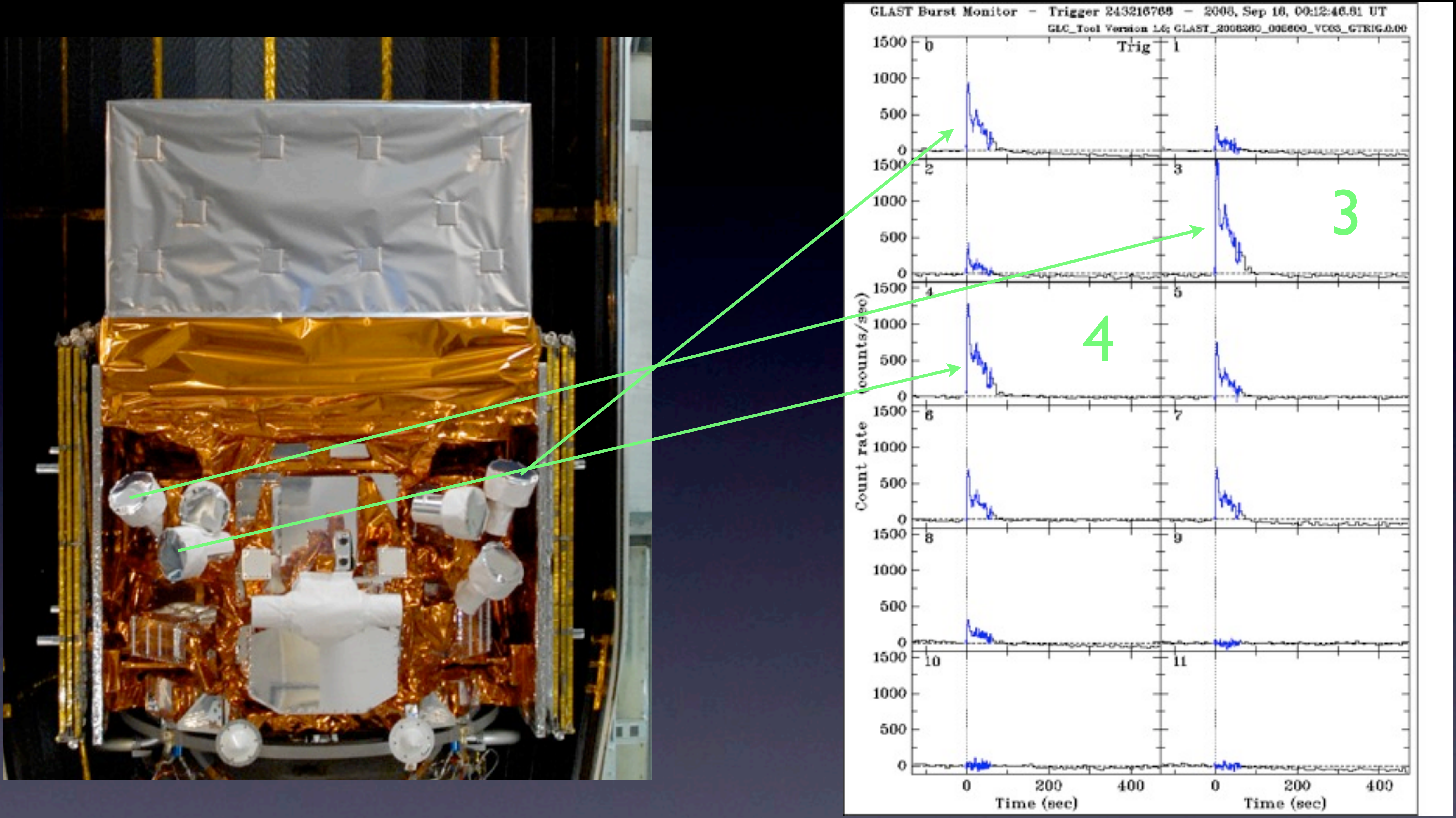


Guiriec+ ApJL, 2011

Data selection for rmfit tutorial

- NaI, BGO, LAT Low Energy (LLE) can be retrieved from the FSSC http://fermi.gsfc.nasa.gov/ssc/data/access/ under LAT and GBM data
- We will use GRB 080916C as a test case
- We will use CSPEC or TTE data for GBM and GLL_CSPEC data for the LAT LLE data + associated detector responses (CSPEC and GLL_CSPEC).
- Basic steps: read in data, select energy ranges, select & fit background regions, select source region(s), fit spectra using detector responses and models
- Rebin in energy or time, plot different quantities, look at temporal evolution of parameters (batch fit for quick & dirty)
- The tutorial gives details... just a few select slides to give a flavor of the analysis

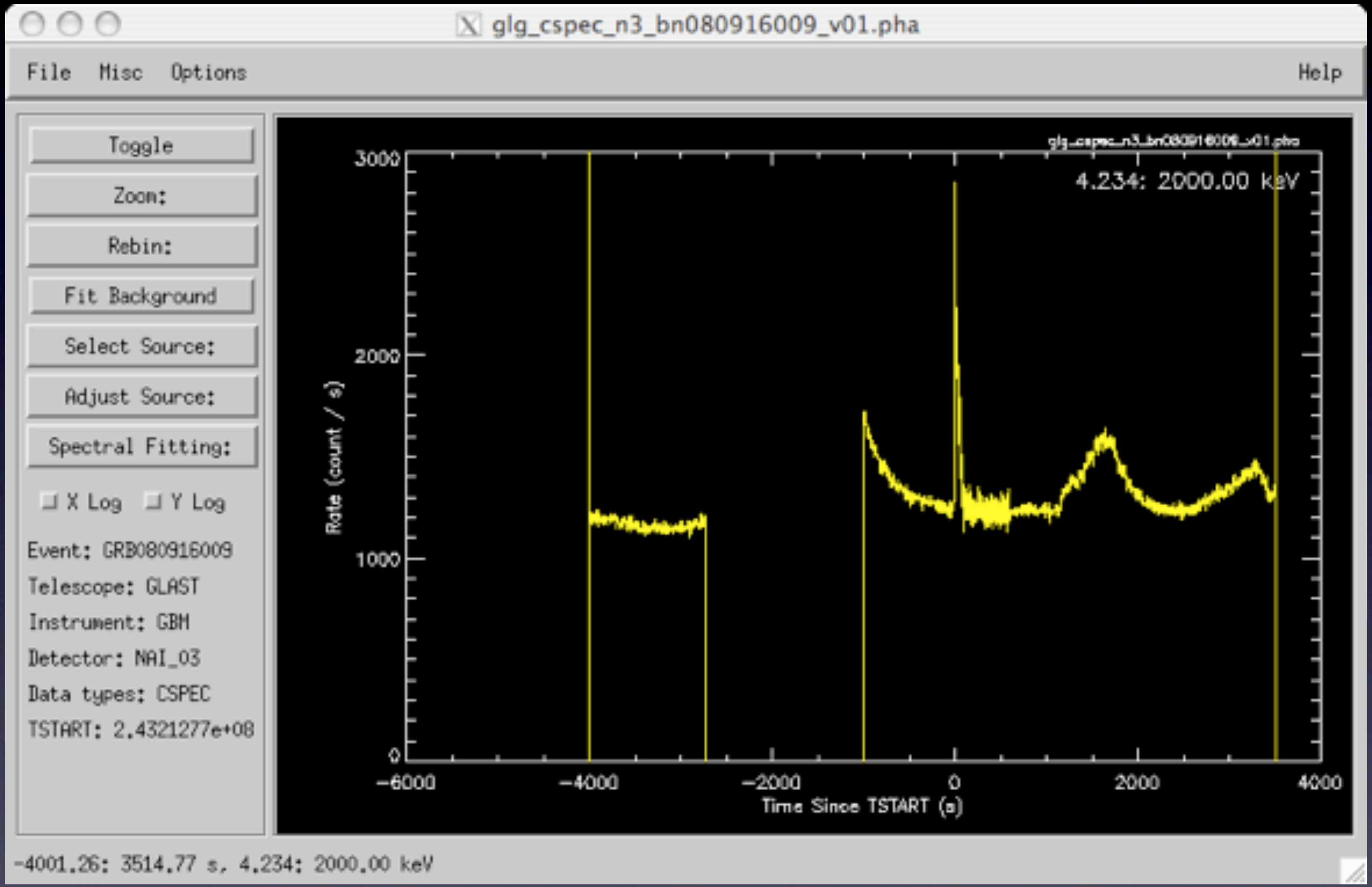
The GBM view of a burst.



- Each detector views part of sky i.e. has a different "ROI". Information is stored in separate files for separate detectors.
- Find out from quicklook plots which detectors had a good view of the burst.

The lightcurve window

- A window will pop up showing the lightcurve for what this detector saw from -4000 s before the trigger to 4000 s afterwards. The gaps are Fermi passages through SAA.



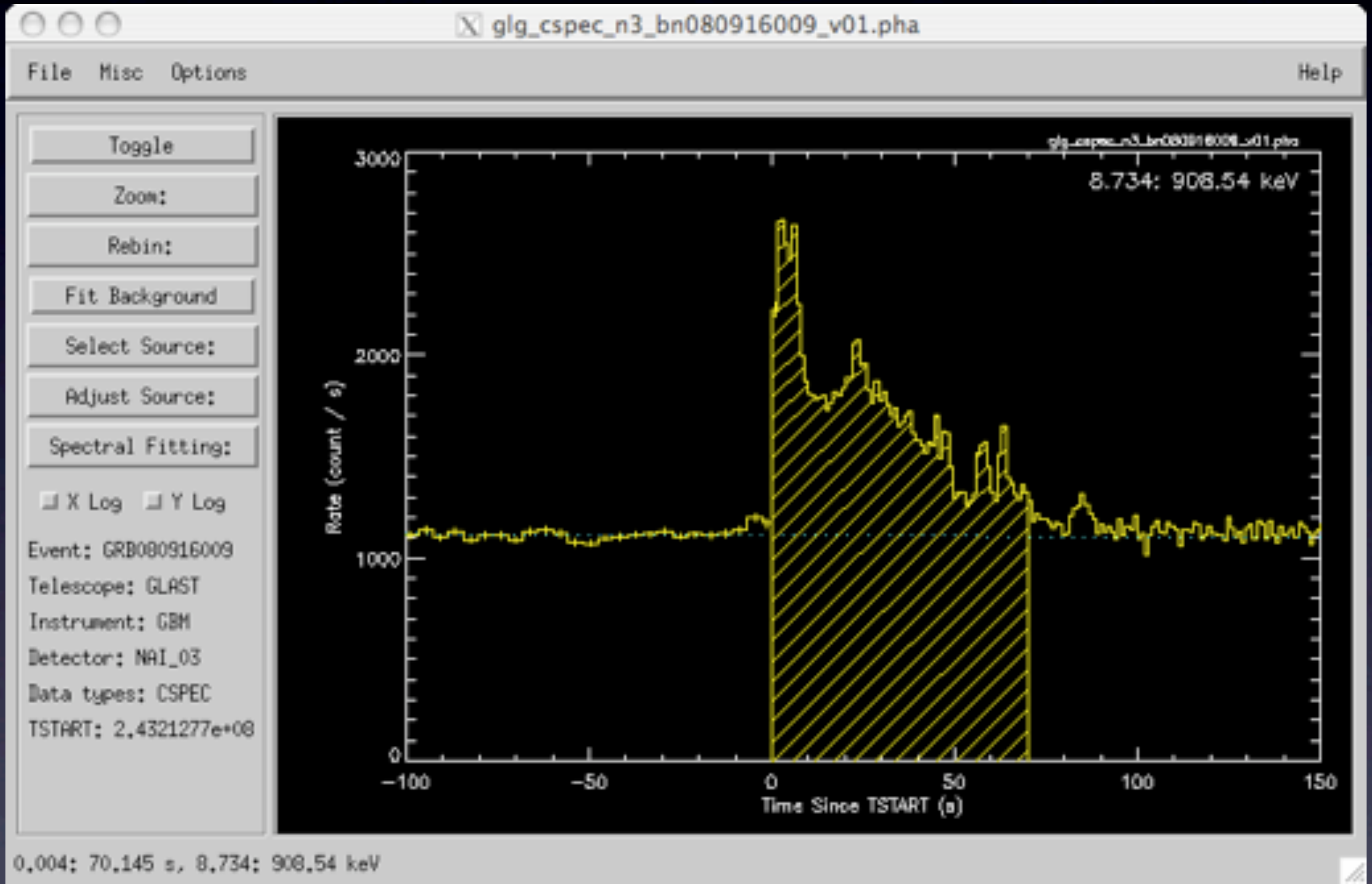
Event: GRB080916009
Telescope: GLAST
Instrument: GBM
Detector: NAI_03
Data types: CSPEC
TSTART: 2.4321277e+08

-4001.26: 3514.77 s, 4.234: 2000.00 keV

- Each point in the lightcurve shows the counts registered in that time bin over the energy range shown top right, converted to a rate (cts/sec). The resolution changes from 4.096 s to 1.024 s at trigger time for CSPEC data. TTE data (which are unbinned in time) are binned here to a default 128 ms, but you can refine this for individual bins. CSPEC data cannot be refined below their native resolution, but can be combined to coarser resolution.

Selecting your source interval

- Zoom in on the region of the burst using the "Zoom" "X Zoom" options. You will now get a better idea if the background you chose is appropriate. If it is, you are ready to select the interval in time you want to analyze i.e. the burst emission.



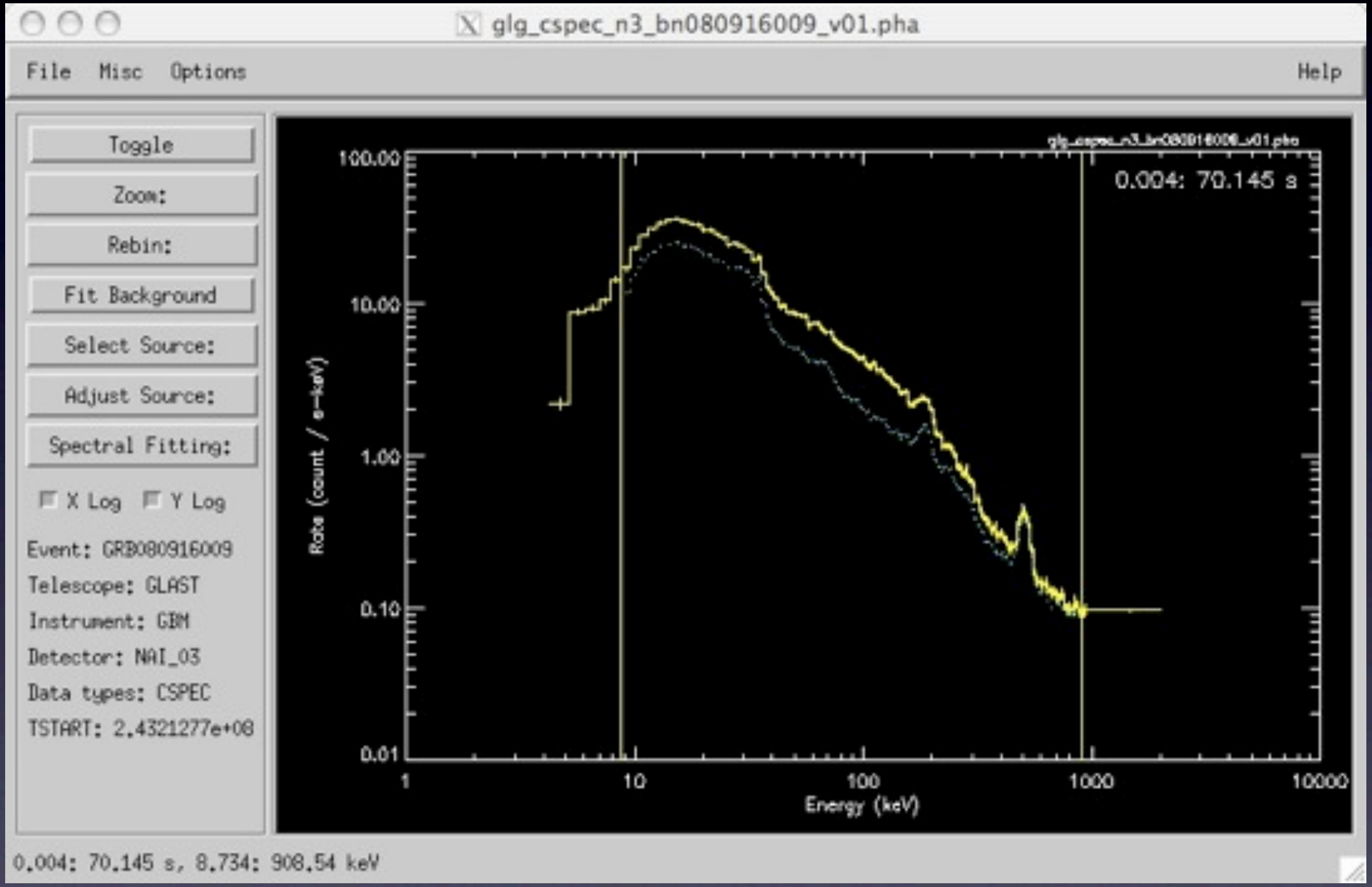
Event: GRB080916009
Telescope: GLAST
Instrument: GBM
Detector: NAI_03
Data types: CSPEC
TSTART: 2.4321277e+08

0.004: 70.145 s, 8.734: 908.54 keV

- Click "Select Source" then "Source interactive" and click the plot to select your source interval. There is a limit to how long a single response function is appropriate [This limit will soon go away owing to the implementation of rsp2 (multiple response) files that generate and allow rmfit to use a new response for every 5 deg of spacecraft slew]. Here, I choose about 70 s of the brightest part.

Looking at your spectrum

- Click toggle on the lightcurve window to reveal the spectrum integrated over the source interval you selected (all time bins summed). Remember these spectra are in count space and the shape is more a display of the effective area of the detector as a function of energy than the true source/background spectrum.



Event: GRB080916009
Telescope: GLAST
Instrument: GBM
Detector: NAI_03
Data types: CSPEC
TSTART: 2.4321277e+08

```
0.004: 70.145 s, 8.734: 908.54 keV
```

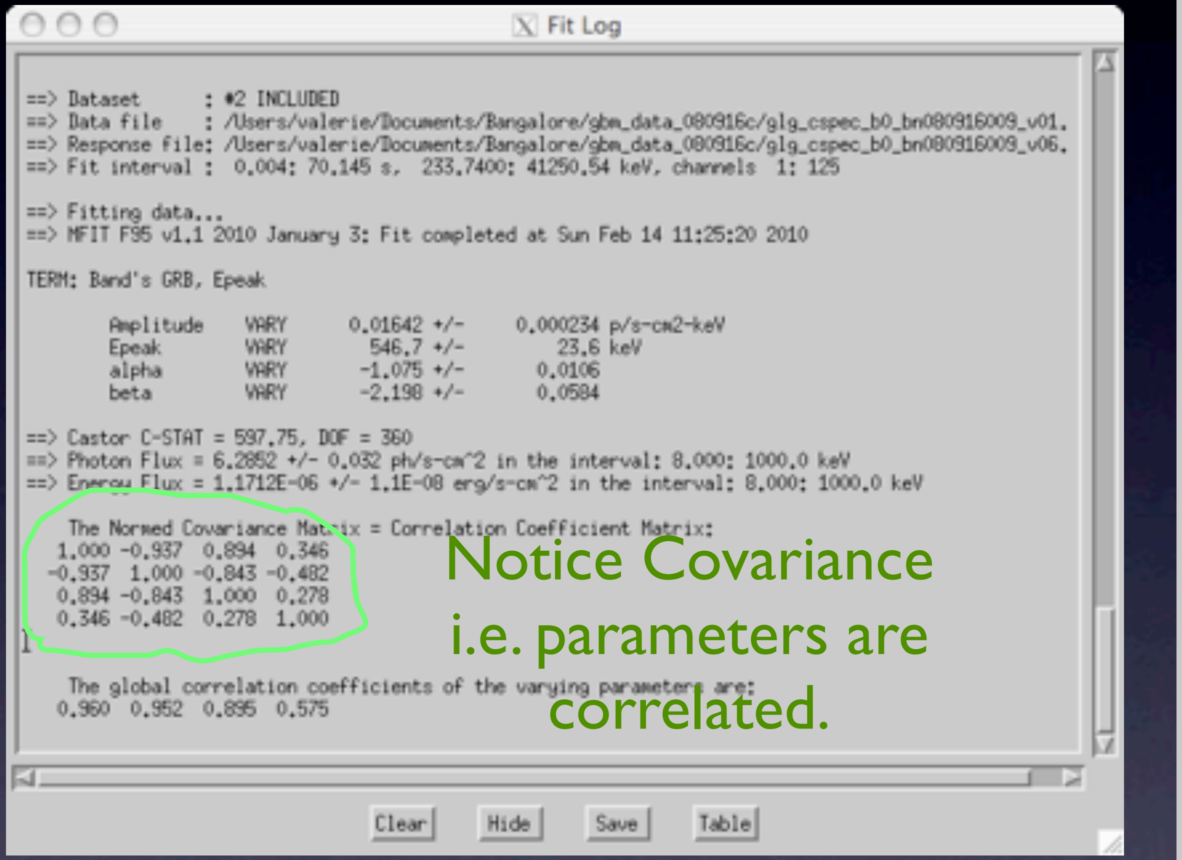
- The blue line is the estimated background during your chosen source interval. Anything above this is emission from the burst during this time. This gives an idea in count space of how high in energy this burst can be seen by GBM. Here, it is clearly seen over the entire energy range. You can bin the spectrum in energy as you binned the lightcurve in time. This does not change the binning in the fits, it is just for display.

Fitting GBM Spectra

- The technique uses forward folding to walk through parameter space, using the detector response to evaluate the expected rates for the model with the set of parameters at each stop on the way. The test statistic compares these model rates with the observed rates, The fitting process converges (we hope!) on the best set of parameters for that particular model and returns the parameters and the value of the test statistic.
- rmfit supplies several test statistics: We always use C-Stat which is -2*log(likelihood) though for historical reasons, the default statistic is χ^2 .
- C-stat can not be used to select the "best-fit" model unless the models are nested (see Steve Fegan's slides on spectral analysis and Wilks' theorem)
  - Simulations can be used to see whether a more complicated model is actually favored
  - Alternatively, we can find the best-fit parameters using C-Stat and then calculate χ^2 for these parameters to get the "goodness-of-fit" - statistically dodgy...

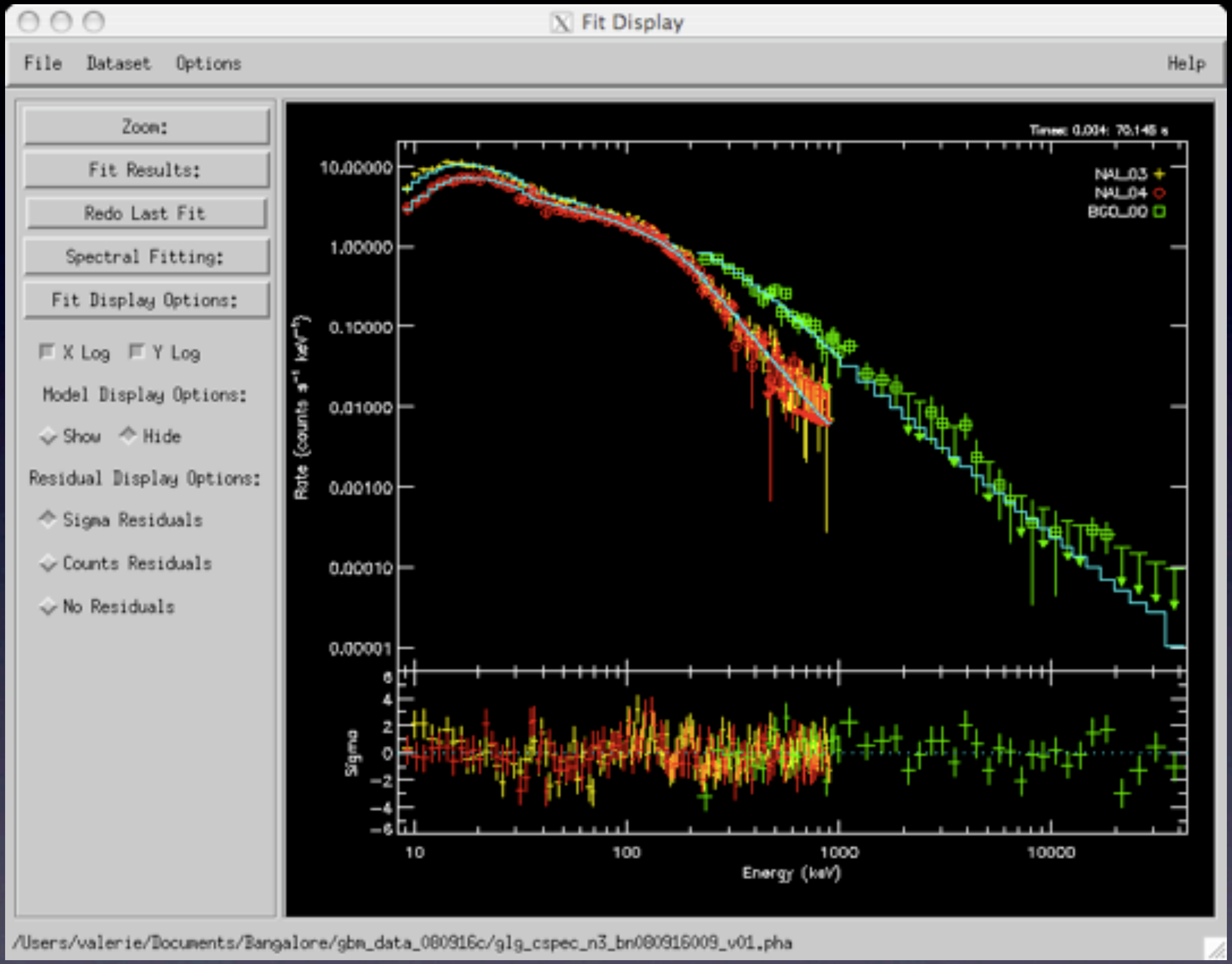
A Good Fit

- From the Fit Display window, click "Redo Last Fit" and choose "5", the Band GRB function. This is the same as "7", but with a power-law above the cut-off energy instead of an exponential fall-off.



```
==> Dataset      : #2 INCLUDED
==> Data file    : /Users/valerie/Documents/Bangalore/gbm_data_080916c/glg_cspec_b0_bn080916009_v01.
==> Response file: /Users/valerie/Documents/Bangalore/gbm_data_080916c/glg_cspec_b0_bn080916009_v06.
==> Fit interval :  0.004: 70.145 s,  233.7400: 41250.54 keV, channels  1: 125

==> Fitting data...
==> MFIT F95 v1.1 2010 January 3: Fit completed at Sun Feb 14 11:25:20 2010

TERM: Band's GRB, Epeak

      Amplitude    VARY      0.01642 +/-     0.000234 p/s-cm2-keV
      Epeak        VARY        546.7 +/-         23.6 keV
      alpha        VARY       -1.075 +/-       0.0106
      beta         VARY       -2.198 +/-       0.0584

==> Castor C-STAT = 597.75, DOF = 360
==> Photon Flux = 6.2852 +/- 0.032 ph/s-cm^2 in the interval: 8.000: 1000.0 keV
==> Energy Flux = 1.1712E-06 +/- 1.1E-08 erg/s-cm^2 in the interval: 8.000: 1000.0 keV

   The Normed Covariance Matrix = Correlation Coefficient Matrix:
  1.000 -0.937  0.894  0.346
 -0.937  1.000 -0.843 -0.482
  0.894 -0.843  1.000  0.278
  0.346 -0.482  0.278  1.000

   The global correlation coefficients of the varying parameters are:
  0.960  0.952  0.895  0.575
```

Notice Covariance i.e. parameters are correlated.



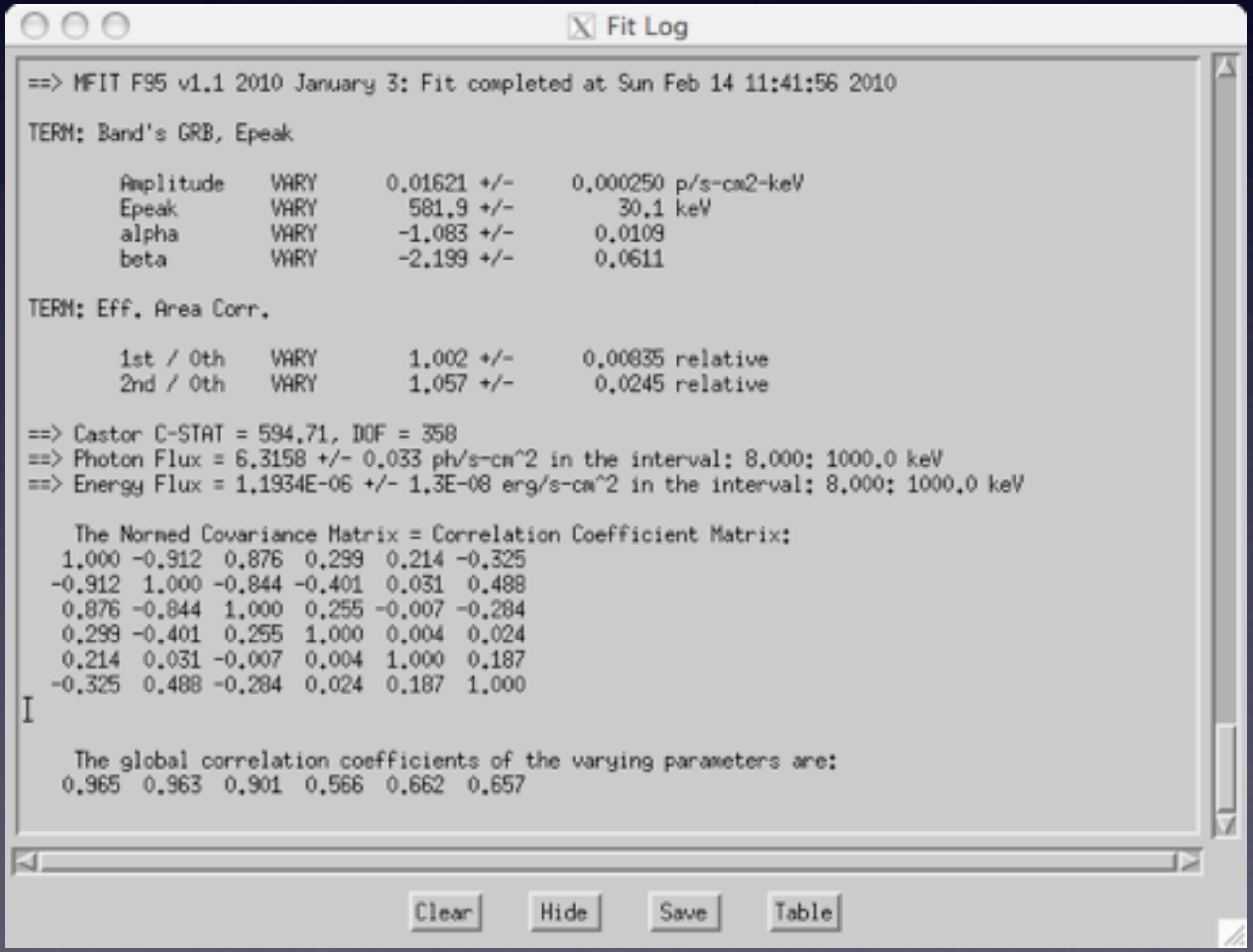
- ΔC-Stat = -28 for 1 extra parameter. These are nested models so can be compared as for X^2.

- Residuals look better, with no systematic excess above E_{peak}.

Correcting any normalization issues.

- Allow the normalization of detectors to vary using the “Effective Area Correction” in addition to the chosen model. Select “Redo Last Fit” and hold <ctrl> key to select from the model window, in addition to option “5”, option “40”. Click “Set Parameters” to choose which detector areas to vary. Click “Accept”.

- A window will pop up with all your starting parameters. At the bottom, click “Vary” for each of the 2 normalization parameters. Click “accept”.



```
==> MFIT F95 v1.1 2010 January 3: Fit completed at Sun Feb 14 11:41:56 2010

TERM: Band's GRB, Epeak

        Amplitude    VARY      0.01621 +/-      0.000250 p/s-cm2-keV
        Epeak        VARY        581.9 +/-          30.1 keV
        alpha        VARY       -1.083 +/-        0.0109
        beta         VARY       -2.199 +/-        0.0611

TERM: Eff. Area Corr.

        1st / 0th    VARY        1.002 +/-       0.00835 relative
        2nd / 0th    VARY        1.057 +/-        0.0245 relative

==> Castor C-STAT = 594.71, DOF = 358
==> Photon Flux = 6.3158 +/- 0.033 ph/s-cm^2 in the interval: 8.000: 1000.0 keV
==> Energy Flux = 1.1934E-06 +/- 1.3E-08 erg/s-cm^2 in the interval: 8.000: 1000.0 keV

    The Normed Covariance Matrix = Correlation Coefficient Matrix:
   1.000 -0.912  0.876  0.299  0.214 -0.325
  -0.912  1.000 -0.844 -0.401  0.031  0.488
   0.876 -0.844  1.000  0.255 -0.007 -0.284
   0.299 -0.401  0.255  1.000  0.004  0.024
   0.214  0.031 -0.007  0.004  1.000  0.187
  -0.325  0.488 -0.284  0.024  0.187  1.000


    The global correlation coefficients of the varying parameters are:
   0.965  0.963  0.901  0.566  0.662  0.657
```

With only -3 as an improvement in likelihood, and 2 extra parameters, this does not seem to be a necessary addition to the model, particularly with such small effective area corrections. These corrections are for NaI 4 relative to NaI 3 and BGO 0 relative to NaI 3. Possibly there is a couple % normalization factor between the BGO and the NaI detector, but it is not required statistically so we will not apply it.

Redo last fit with model 5 only.