GRB Data Analysis

Judy Racusin
NASA/GSFC

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Multiwavelength Analysis

- Astrophysical context
  - Source association
  - Emission mechanisms
- *Fermi* data probe a region of the spectrum that
  - Can be the high energy anchor for your model
  - Or bridge lower energy regimes and TeV
- How you fit/extrapolate/interpolate over many decades can strongly influence the physical models you walk away with, and correctly accounting for errors over those decades is really important

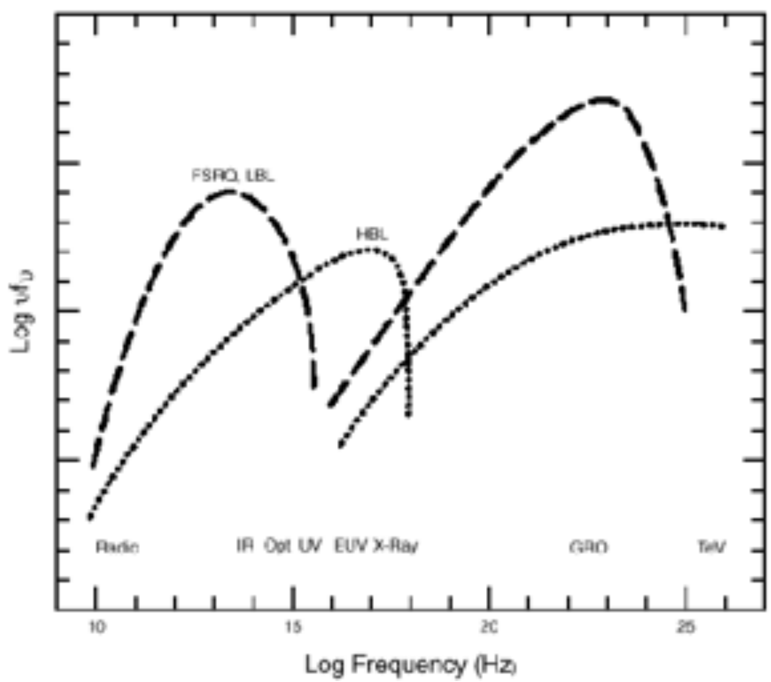
Caveats

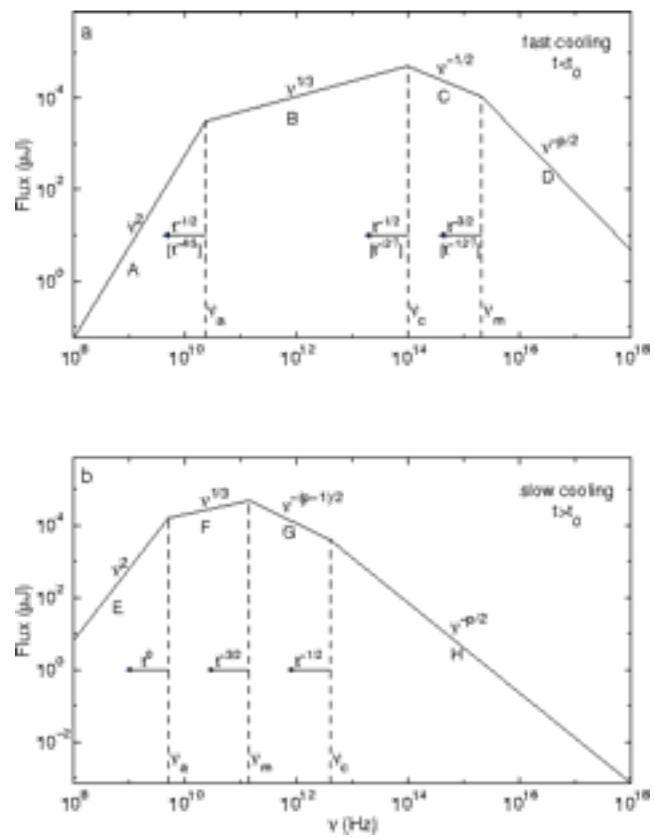
- I ~~stole~~ borrowed some of this material from Alan Marscher's 2012 Fermi Summer School Talk
  - See that talk for a more blazar focused discussion
- I will use a GRB as an example, but most of this is relevant/ applicable to other source types
- 2 primary ways to build an SED
  - Input ~raw data, response functions, etc. and fit the whole spectrum together
  - Collect individually fit datasets and combine them fitting more complex physical models around already fit model dependent data (will come back to this issue)
- There are lots and lots of ways to do this
  - Software (XSPEC, RMFIT, Sherpa, likelihood, custom software …)
  - Units (energy, frequency, wavelength, ...)

Measuring a spectrum across the spectrum

- Radio/mm/microwave
  - temperature -> flux density
  - In frequency
- IR/Optical/UV
  - magnitudes in different filters
  - $F_\nu = 10^{k-0.4m}$ mJy where k depends on filter used
  - In wavelength
- X-ray
  - counting photons -> flux
  - Conversion depends on shape of spectrum
- Gamma-ray
  - counting photons -> flux
  - Likelihood often used to fit spectrum, background, etc.

Broadband Spectral Energy Distributions (SEDs)





Sari, Piran, Narayan (1998)

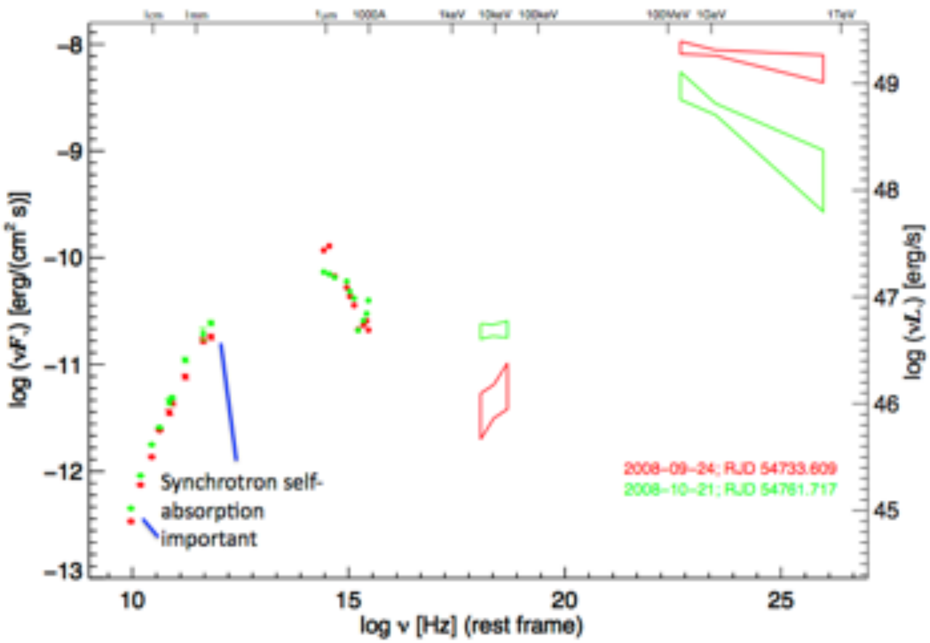
Spectral Energy Distributions

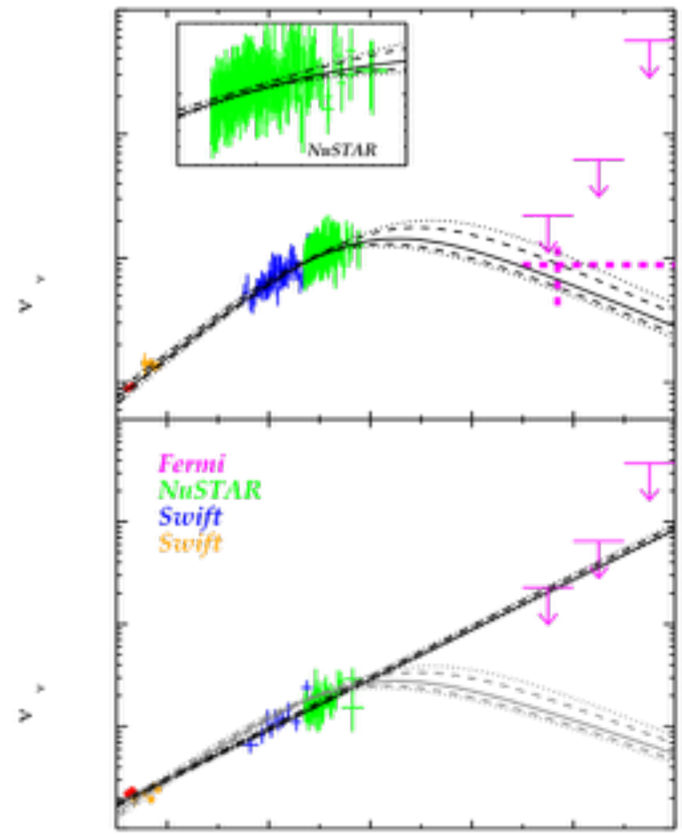
- **We want to plot of $\log_{10}\nu F_\nu$ vs $\log_{10}\nu$**
- **How is this measured?**

Measure known as	Unit	Formula	Measured where?	Details
Photon Flux Density*	ph cm^{-2} s^{-1} keV^{-1}	$N(E)=AE^{-\Gamma}$ (example)	X-ray, γ-ray	Instrument dependent
Spectral Flux Density or Energy Flux*	erg cm^{-2} s^{-1} keV^{-1} or Jy or mag	$f_\nu = E\,N(E) = B\,E^{-\alpha}$	X-ray, γ Optical, radio	Specific energy $\alpha=\Gamma-1$ 1 kev = 1.602×10^{-9} erg
Luminosity*	erg s^{-1} keV^{-1}	$L=f_\nu\, 4\pi D^2\, k$	X-ray, γ	k=k-correction, D=distance
Spectral Energy density	erg cm^{-2} s^{-1}	$\nu f_\nu=E^2\,N(E)$	Combined broadband spectrum	

*Integrate from E_1-E_2 to get flux measurement in specific band for light curves

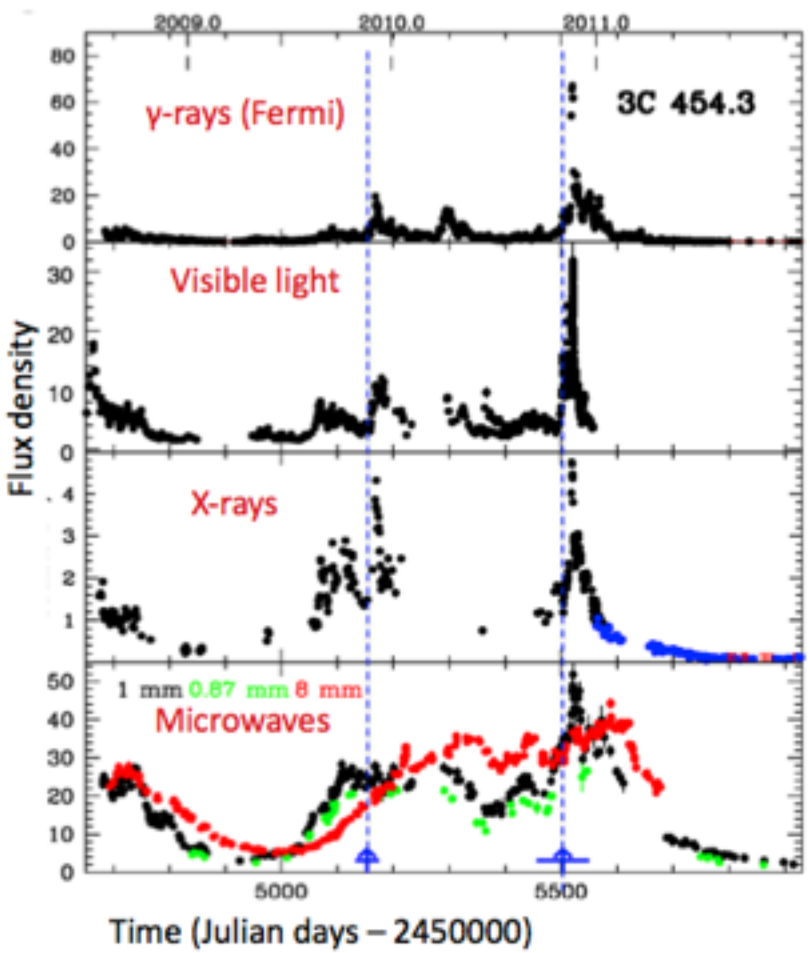
Broadband Spectral Energy Distributions (SEDs)





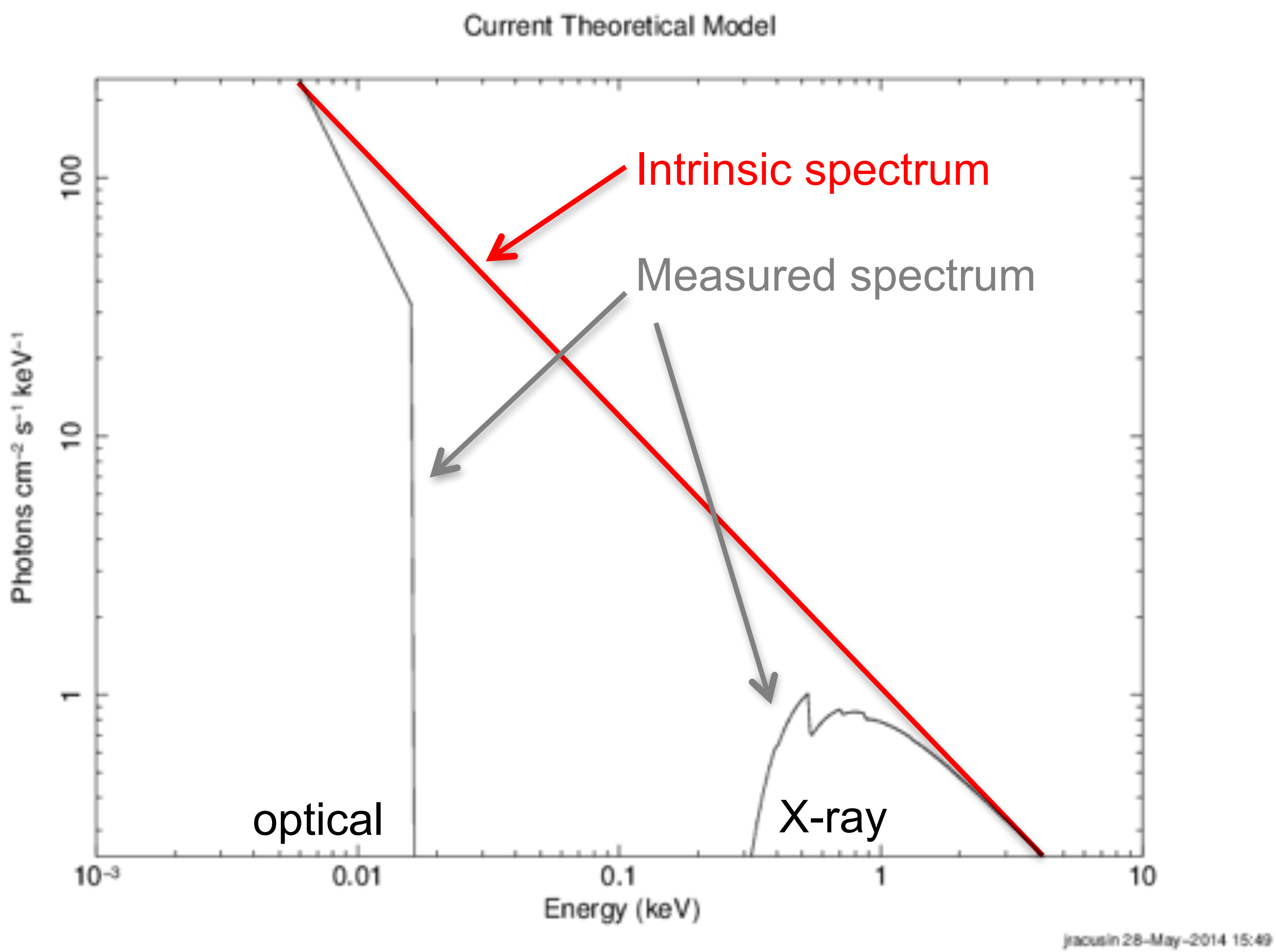
Kouveliotou et al. (2013)

Importance of Simultaneity



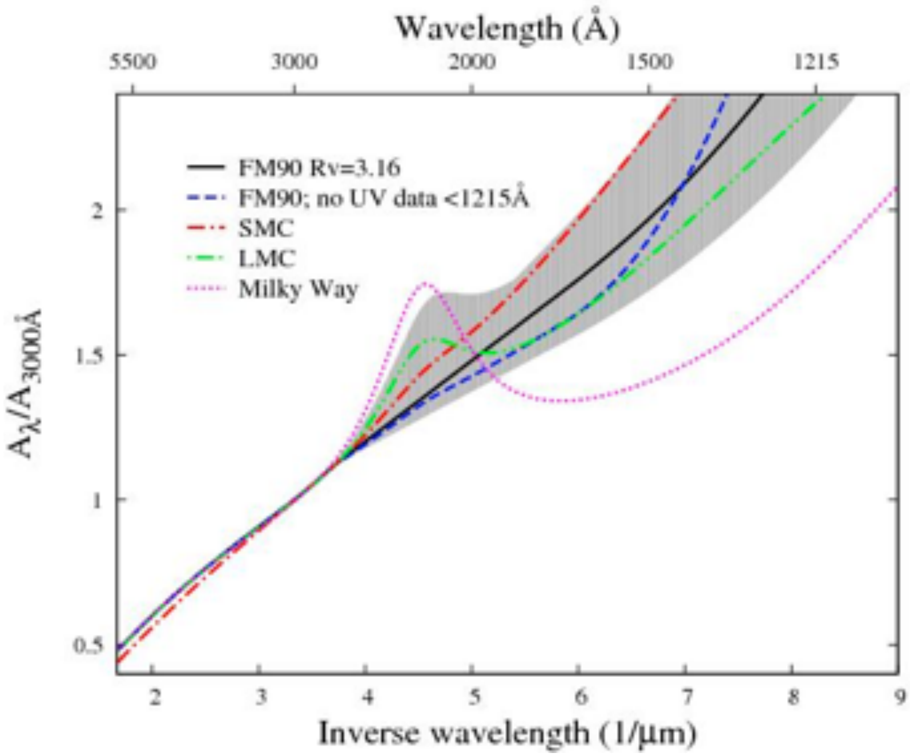
- Flux variations in different wavebands may or may not be correlated, or have delays
- Evidence of variation of different components
- Already messy, therefore simultaneous data at least constrains the same things at the same time (or different things at the same time)
- Talk by Betta next week

Extinction and Absorption



Extinction

- **Interstellar dust absorbs and scatters some of the IR, optical, UV light**
- **Different dust composition or grain size impacts absorption & scattering**
- **Well-mapped for Milky Way, LMC, SMC**
- **A_V=E(B-V) x R_V**
  - **R_V set specifically for MW, LMC, SMC**
  - **Fit E(B-V) or A_V**
  - **Get it from NED**
  - **Get it from literature where someone else has already fit it for the same object**
- **Cardelli et al. 1989 provides relations between A_V and other wavelengths, though depends on extinction curves**
- **XSPEC models (z)dust**

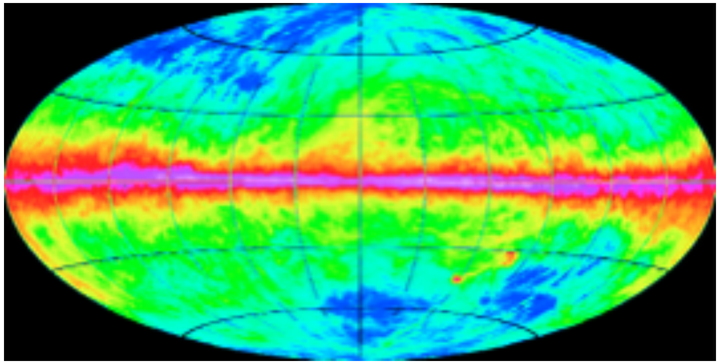


Schady et al. 2012
Pei 1992

http://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelZdust.html

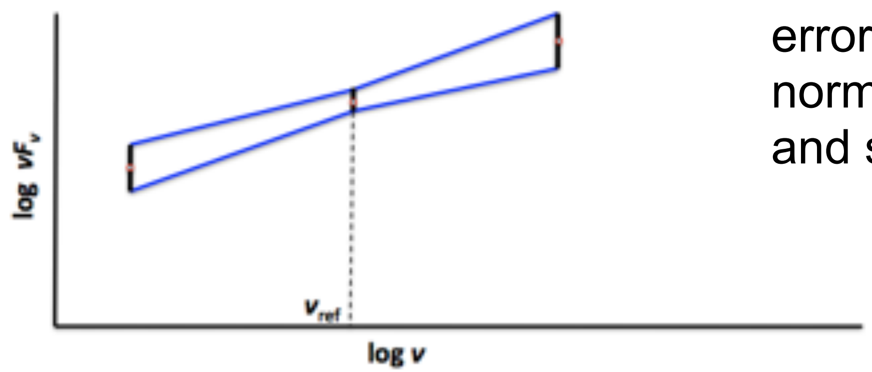
X-ray Absorption

- Interstellar neutral hydrogen gas absorbs soft X-rays
  - Photo-electric absorption using some set of photo-ionization cross-sections
- 2 sources of absorption for extragalactic sources (N_H – hydrogen column density)
  - Galactic – well mapped by Kalberla et al. 2005
    - ftool NH
    - http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
  - Intrinsic absorption should be fit, can account for redshift (if known)
- XSPEC models (z)wabs, (z)phabs



Adding γ-rays to SEDs

- Likelihood analysis needed to determine contribution of source and background components (fit/assume spectral model)
- If γ-ray source well characterized (bright), and the shape can be constrained (e.g. powerlaw) independently, you can just use results of likelihood over-plotted with broadband SED
  - Use bowtie shape to represent uncertainties centered at ν_{ref}
  - $\sigma_F(\nu) = (\nu/\nu_{ref})^{-\alpha} [\ln(\nu/\nu_{ref})^2 \sigma_\alpha^2 + \sigma_F^2 (\nu_{ref})]^{1/2}$
    - usually $\nu_{ref} = 2.42 \times 10^{17}$ Hz = 1 keV



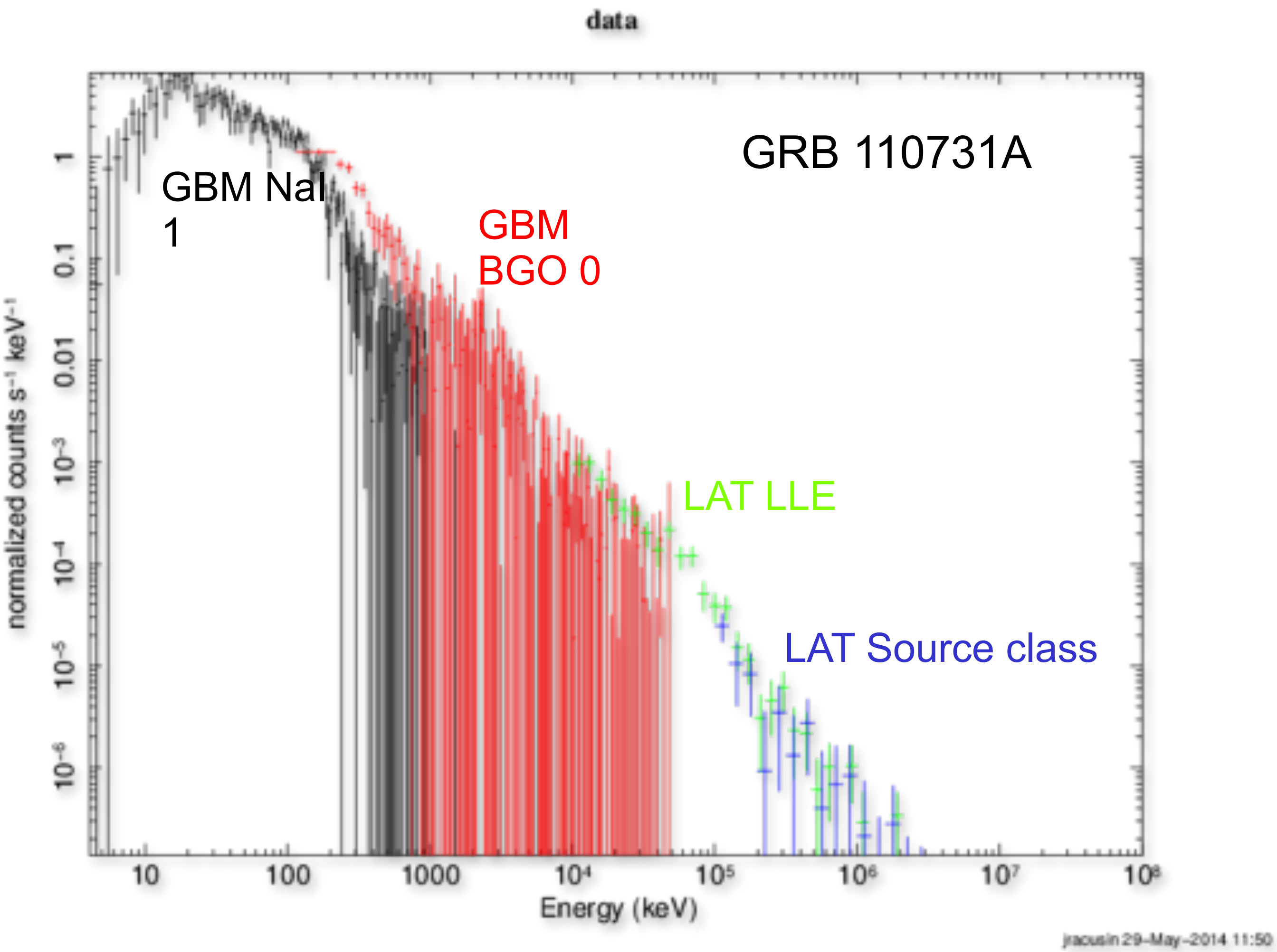
Taking into account error on both normalization (flux) and slope

- However, if shape of γ-ray spectrum affected by data in nearby parts of the spectrum (breaks, curvature, cutoffs, etc.), you should do joint fits given a spectral model, and solve for free parameters

νFν Spectra are Model Dependent

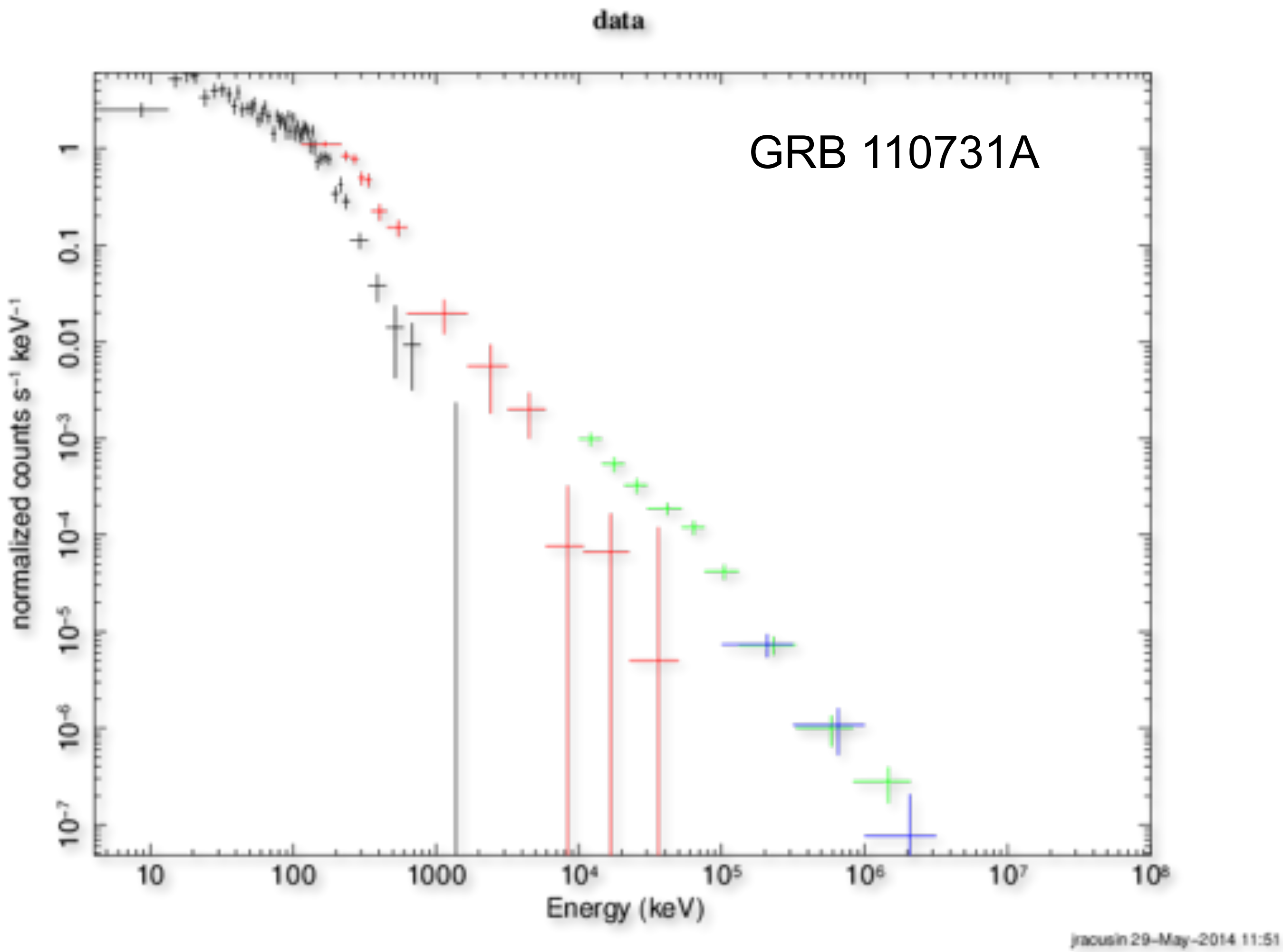
- In order to take data from raw (counts, magnitudes etc.), you must assume
  - Instrumental response function - which can depend on event class (LAT), readout mode (X-ray), filter (optical/IR/UV)
  - Background
    - Instrumental can depend on temperature of detector, hot pixels/ strips
    - Particle background – depends on proximity to SAA, orbit, solar activity
    - Real sources – earth, moon, sun, astrophysical sources, Galaxy, etc.
  - Things getting in the way
    - Extinction, absorption, emission lines
- To get to flux, you fit a model to your spectrum
- νFν is your unfolded (remove model and all of above) spectrum
  - So fitting a model to your νFν spectrum is kind of cheating …

νFν Spectra are Model Dependent



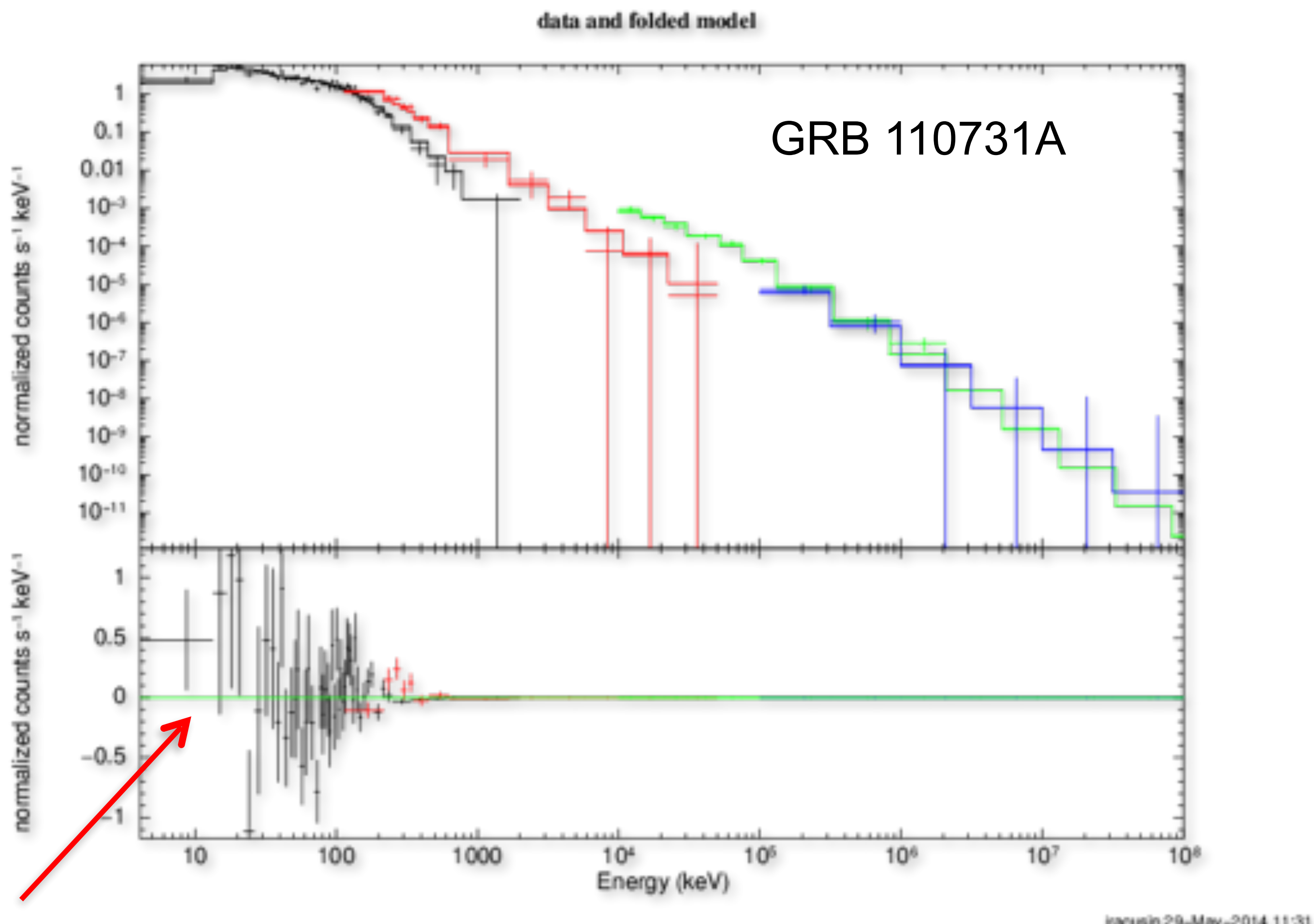
Unbinned (poorly binned) counts spectrum

vFv Spectra are Model Dependent



Binned counts spectrum
(only binned for plotting purposes)

vFv Spectra are Model Dependent

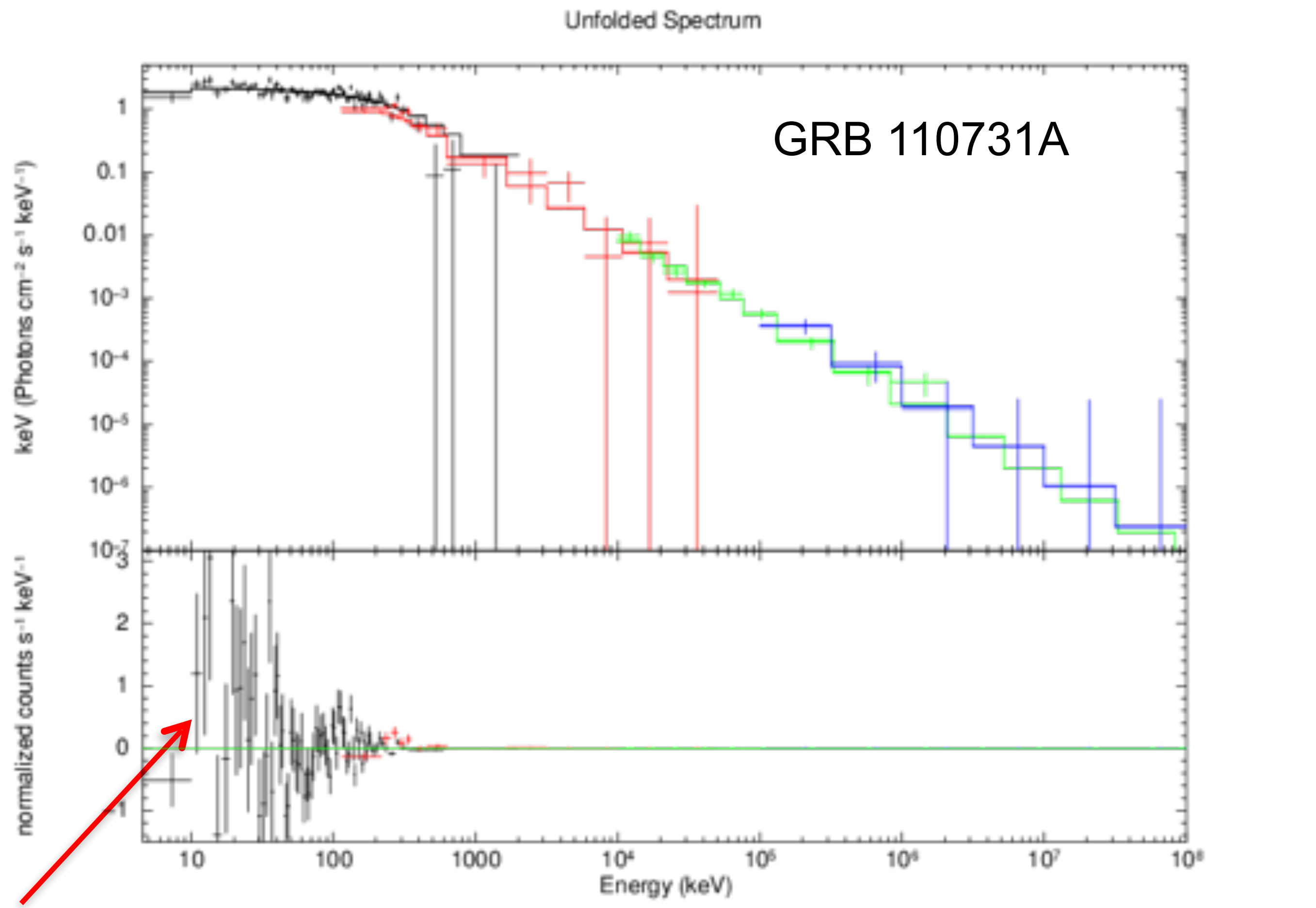


residuals

Binned counts spectrum
Fit to Band function (grbm in XSPEC)

$$A(E) = \begin{cases} K(E/100)^{\alpha_1} \exp(-E/E_c) & E < (\alpha_1 - \alpha_2)E_c \\ K[(\alpha_1 - \alpha_2)E_c/100]^{(\alpha_1-\alpha_2)} (E/100)^{\alpha_2} \exp[-(\alpha_1 - \alpha_2)] & E > (\alpha_1 - \alpha_2)E_c \end{cases}$$

νFν Spectra are Model Dependent

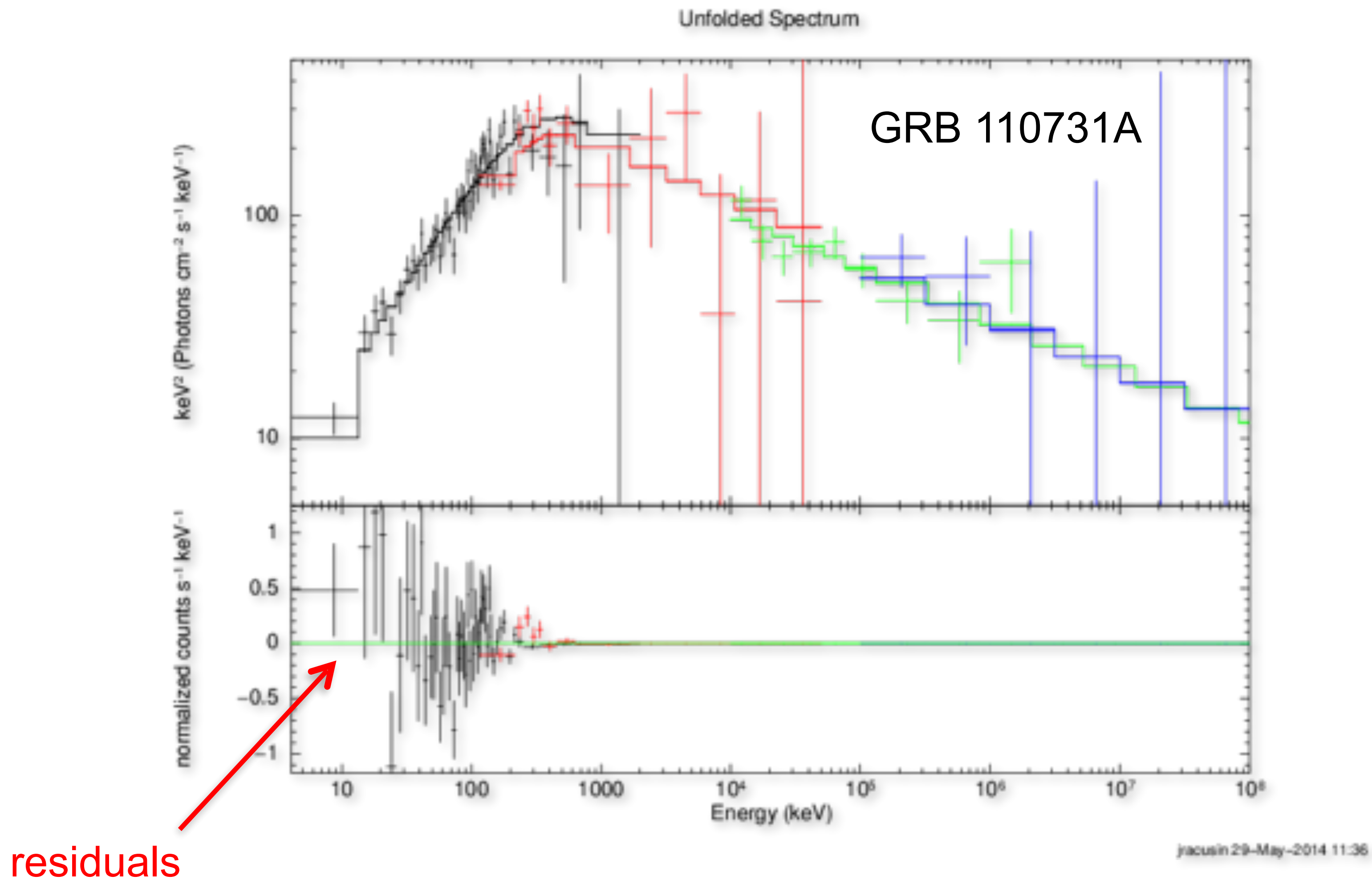


residuals

Binned unfolded F_ν spectrum

Fit to Band function (grbm in XSPEC)

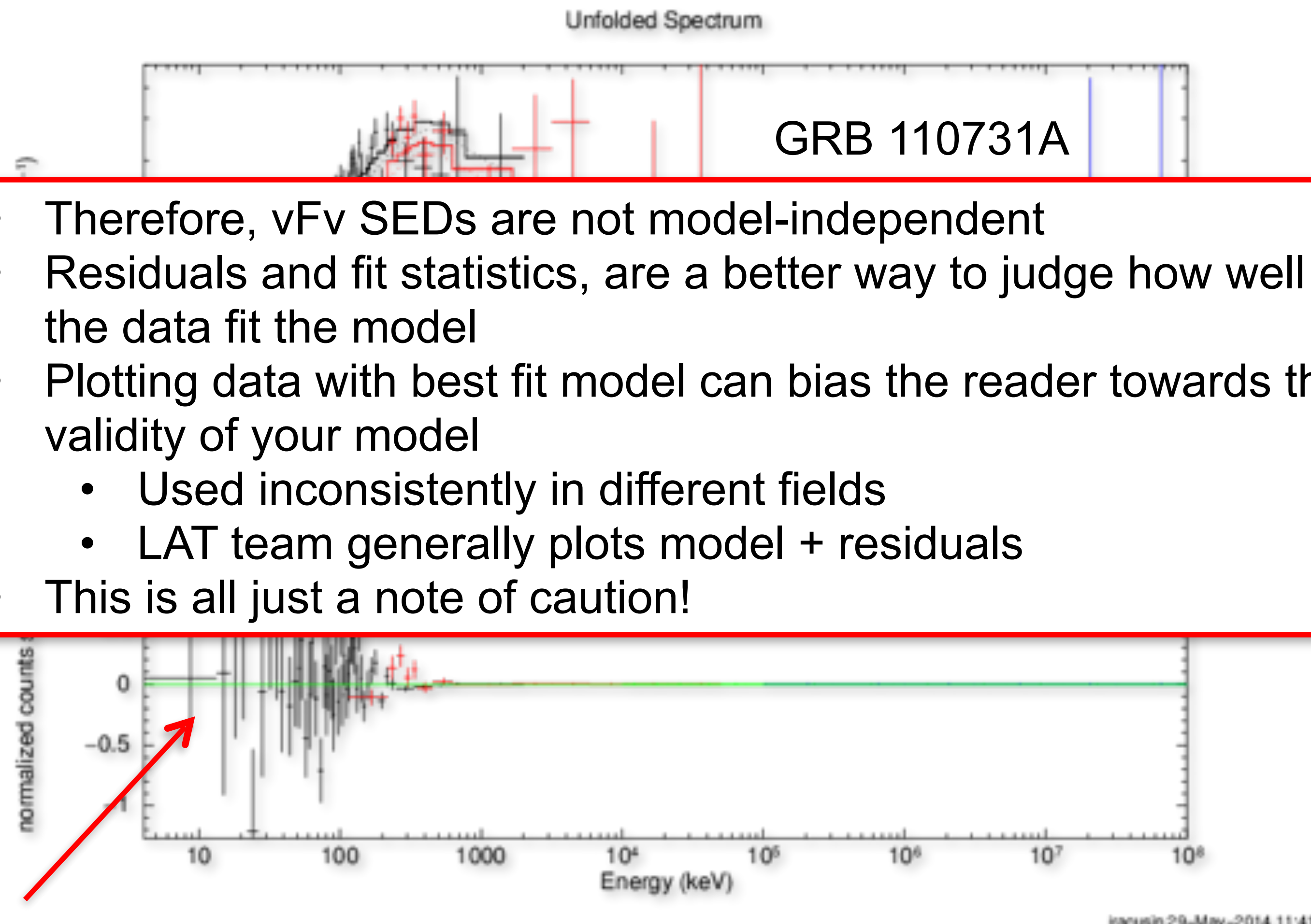
vFv Spectra are Model Dependent



$vF_v = E^2N(E)$ spectrum

Fit to Band function (grbm in XSPEC)

vFv Spectra are Model Dependent



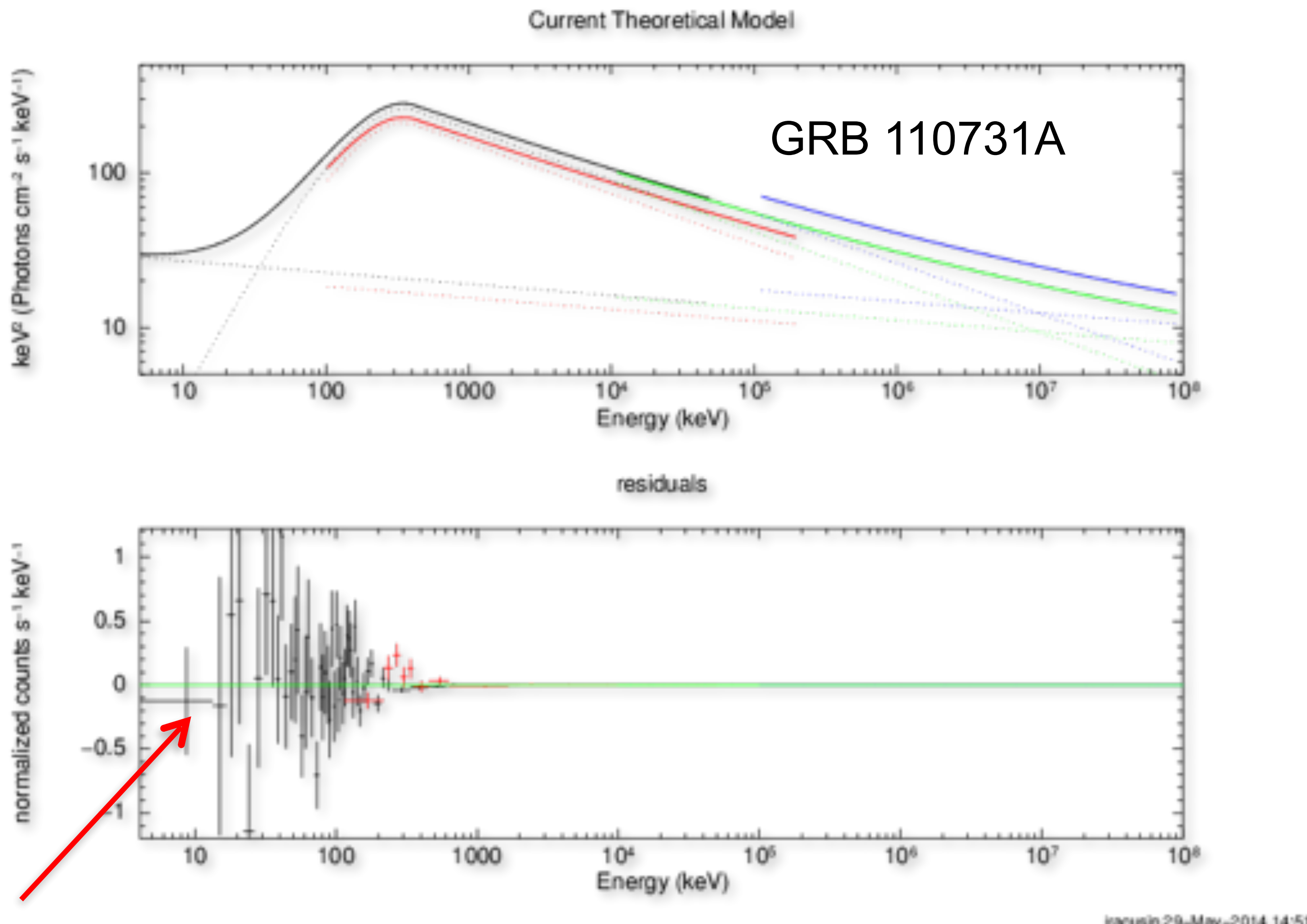
- Therefore, vFv SEDs are not model-independent
- Residuals and fit statistics, are a better way to judge how well the data fit the model
- Plotting data with best fit model can bias the reader towards the validity of your model
  - Used inconsistently in different fields
  - LAT team generally plots model + residuals
- This is all just a note of caution!

residuals

$vF_v = E^2N(E)$ spectrum

Fit to Pow+Band function (pow+grbm in XSPEC)

vFv Spectra are Model Dependent



residuals

$vF_v = E^2N(E)$ spectrum

Fit to Pow+Band function (pow+grbm in XSPEC)

Let's build a really simple SED

- Extract LAT Spectra
  - Standard Science Tools Method
    - gtmktime
    - gtselect
    - gtltcube
    - gtexpmap
    - gtdiffrsp
    - gtlike
    - (gtfindsrc)
    - gtbin
    - gtrspgen
    - gtbkg
    - http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/lat_grb_analysis.html
  - Shortcut/Wrapper Method
    - gtburst
    - https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/gtburst.html

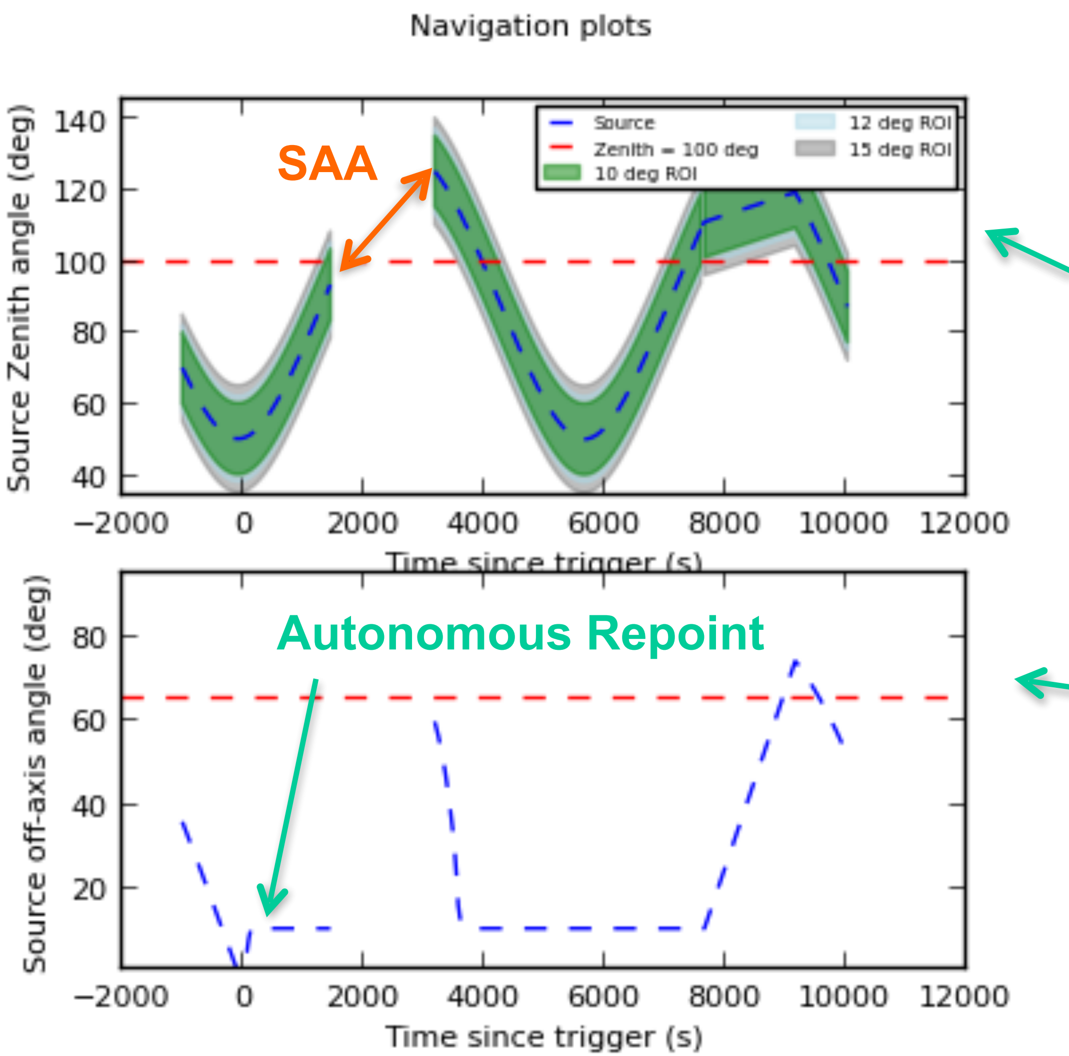
GRB Specific Uses of Event Classes

- LAT Low Energy (LLE)
  - really loose event classification that can be used down to ~30 MeV, useful during brightest part of bright bursts when source is really bright compared to background
- Transient class
  - Useful during bright prompt burst itself, while source in counts limited
- Source class
  - Useful over longer intervals like long extended emission (100's-1000's of seconds)

GRB Analysis Tools

- gtburst
  - Python GUI interface for
    - downloading GBM/LLE/LAT data
    - selecting background and source intervals (GBM, LLE)
    - likelihood analysis of LAT data
    - Localizing LAT GRBs
  - Also useful for other short transients (e.g. Solar Flares)
  - Is part of the science tools, but updates via git separately
  - It is on your VM now
  - Written by Giacomo Vianello & Nicola Omodei (LAT team)
- rmfit
  - IDL GUI for selecting background and source intervals
  - Spectral fitting of GBM data
  - Available on FSSC user contributed tools
  - Written by Rob Preece, Adam Goldstein (GBM team)
- XSPEC
  - Standard tool in X-ray astronomy
  - Written by Keith Arnaud (NASA/GSFC)

Common Time Interval



Too close to earth limb

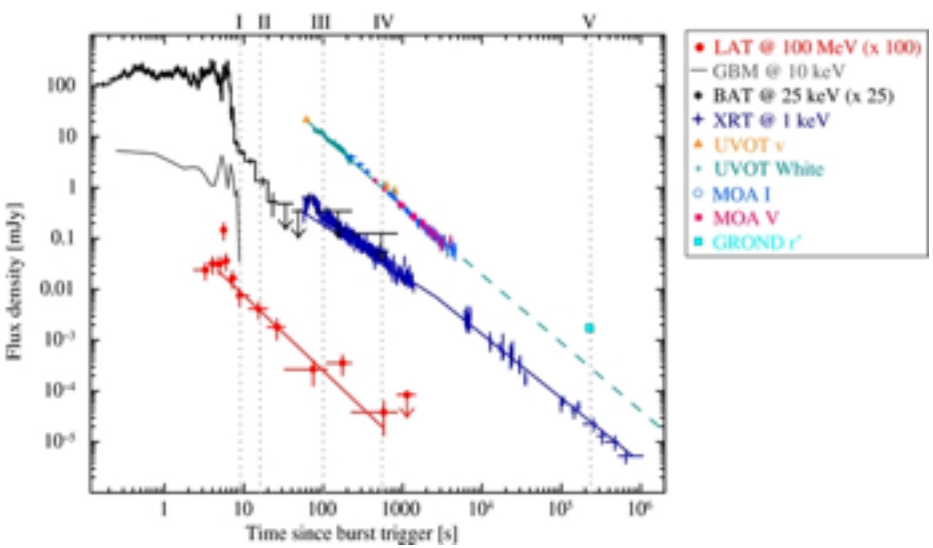
Outside FoV

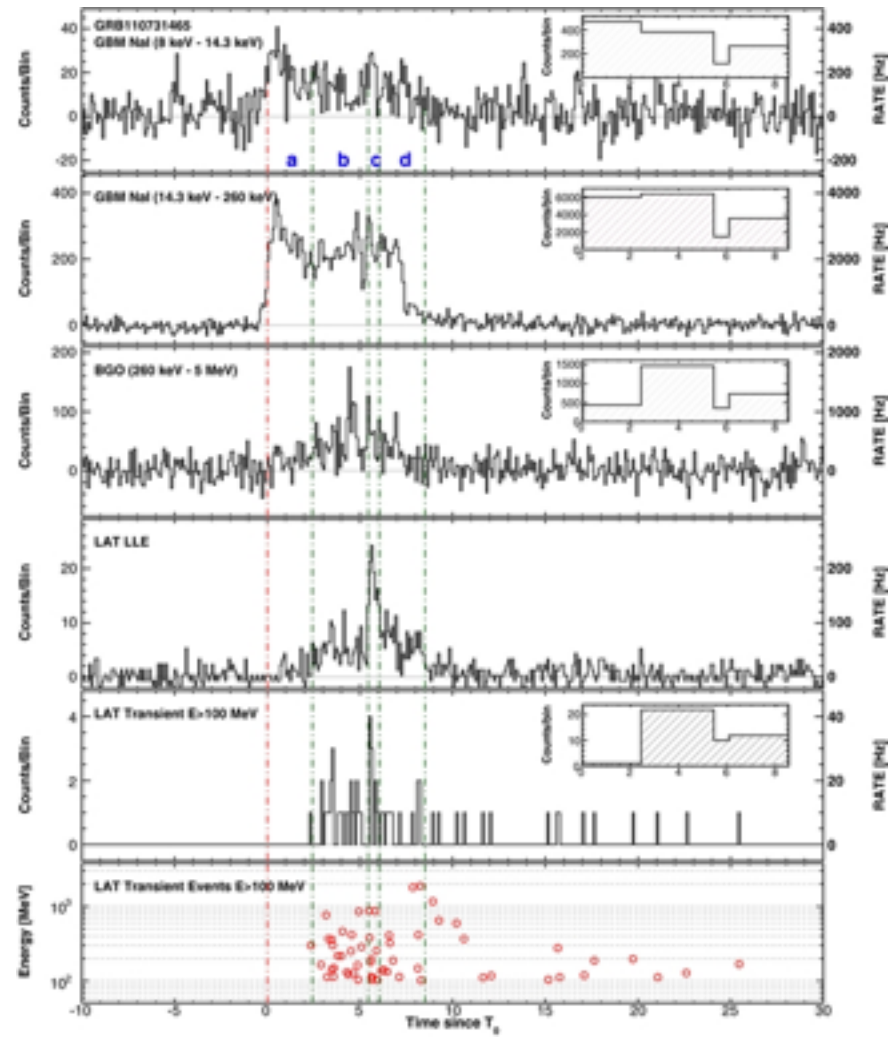
LAT GTIs:
T0 + -973 – 1331 s
T0 + 4290 – 7050 s

You can recreate all of this from the FT2 file
Or from the gtmktime output GTI extension

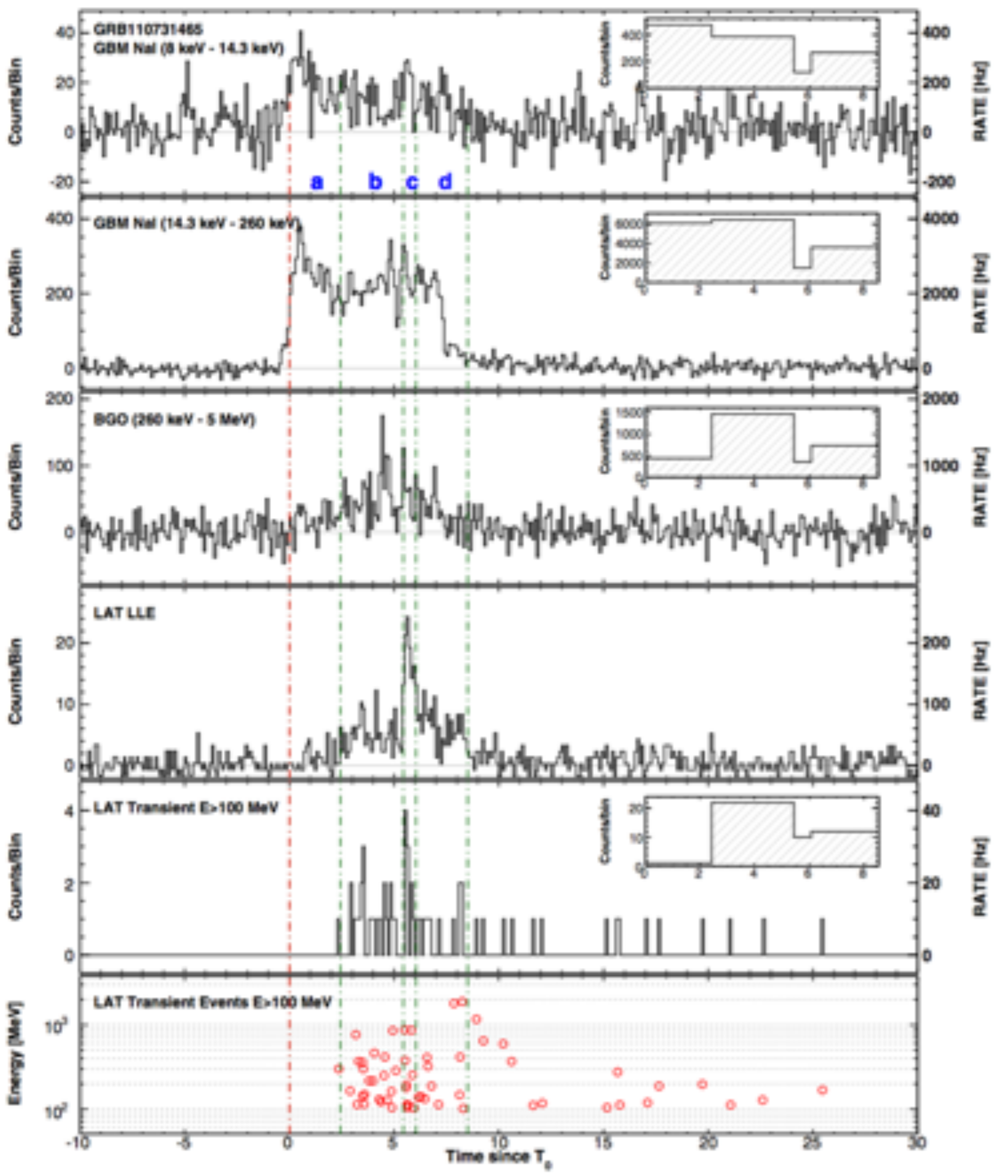
Example: GRB 110731A

- **Simultaneously detected by Swift & Fermi**
  - GBM, LAT clearly detected
  - BAT, XRT, UVOT + ground-based observations
- **Ackermann et al. 2012**
  - *Multiwavelength Observations of GRB 110731A: GeV Emission from Onset to Afterglow*





Common Time Interval



GBM T_{90} = 14.3 s

LAT detection for ~1000 s

Let's use joint GBM+LAT interval:
T0 + 0-20 s

GBM/LAT GRB Tutorial

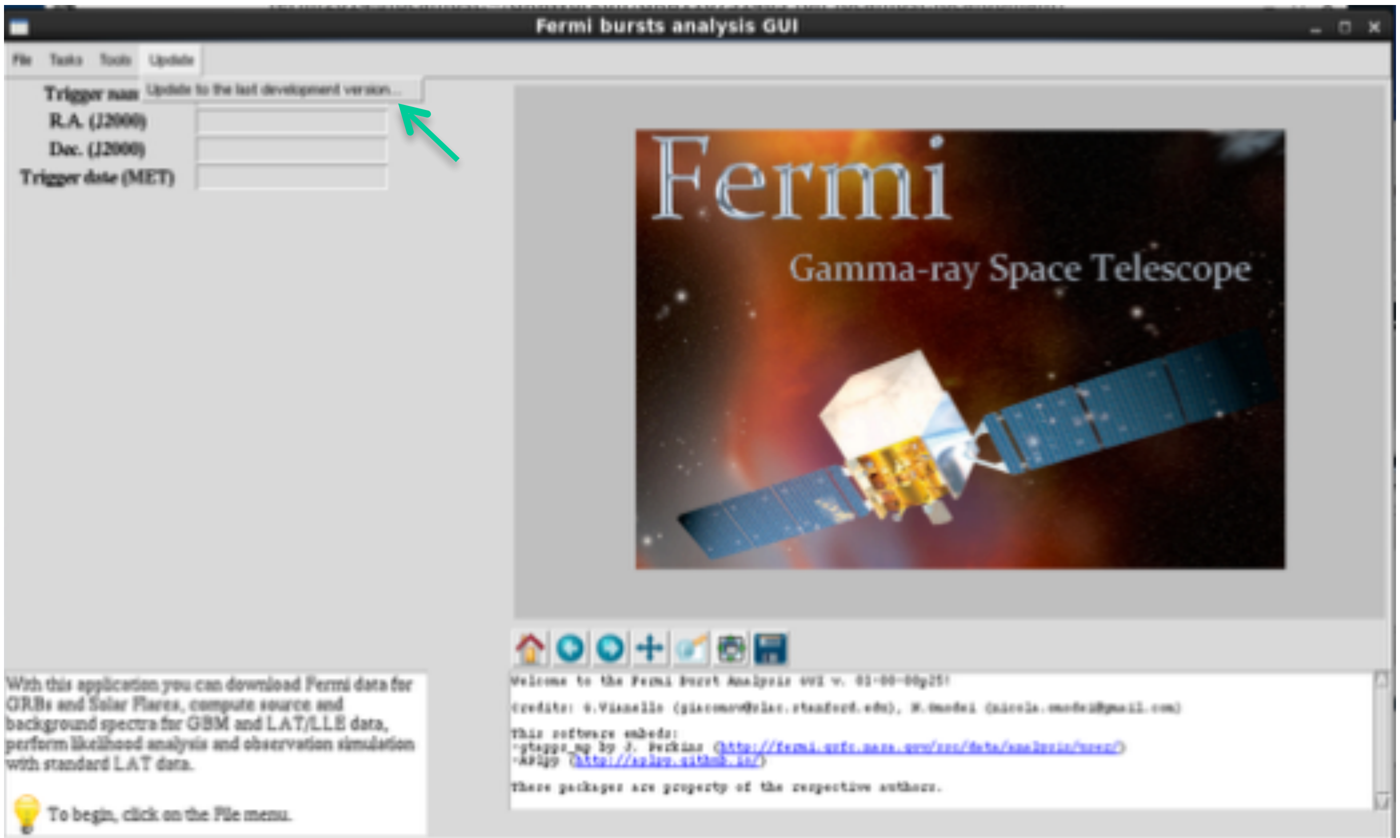
- Extract Data for GBM & LAT
- Likelihood analysis of LAT data using gtburst
  - Get simple fit to LAT spectrum, and contribution from background
- Get both GBM & LAT data in XSPEC
  - Joint band function fit
  - Different statistics for different instruments
    - GBM - C-stat
    - LAT - pgstat (Poisson data with Gaussian background)

GBM/LAT GRB Tutorial

- Data for tutorial
  - Extract it yourself
    - gtburst – we'll walk through it
  - Or grab data I already extracted
    - https://confluence.slac.stanford.edu/download/attachments/223229391/grb110731a.tar.gz?version=1&modificationDate=1496332971347&api=v2
  - put grb110731a.tar.gz in ssvm directory
  - in your VM home directory (/home/vagrant), type:
    - mv /vagrant/grb110731a.tar.gz ~/
    - tar xvfz grb110731a.tar.gz
      - it will create FermiData directory
    - mkdir /home/vagrant/grb110731a

GBM/LAT GRB Tutorial

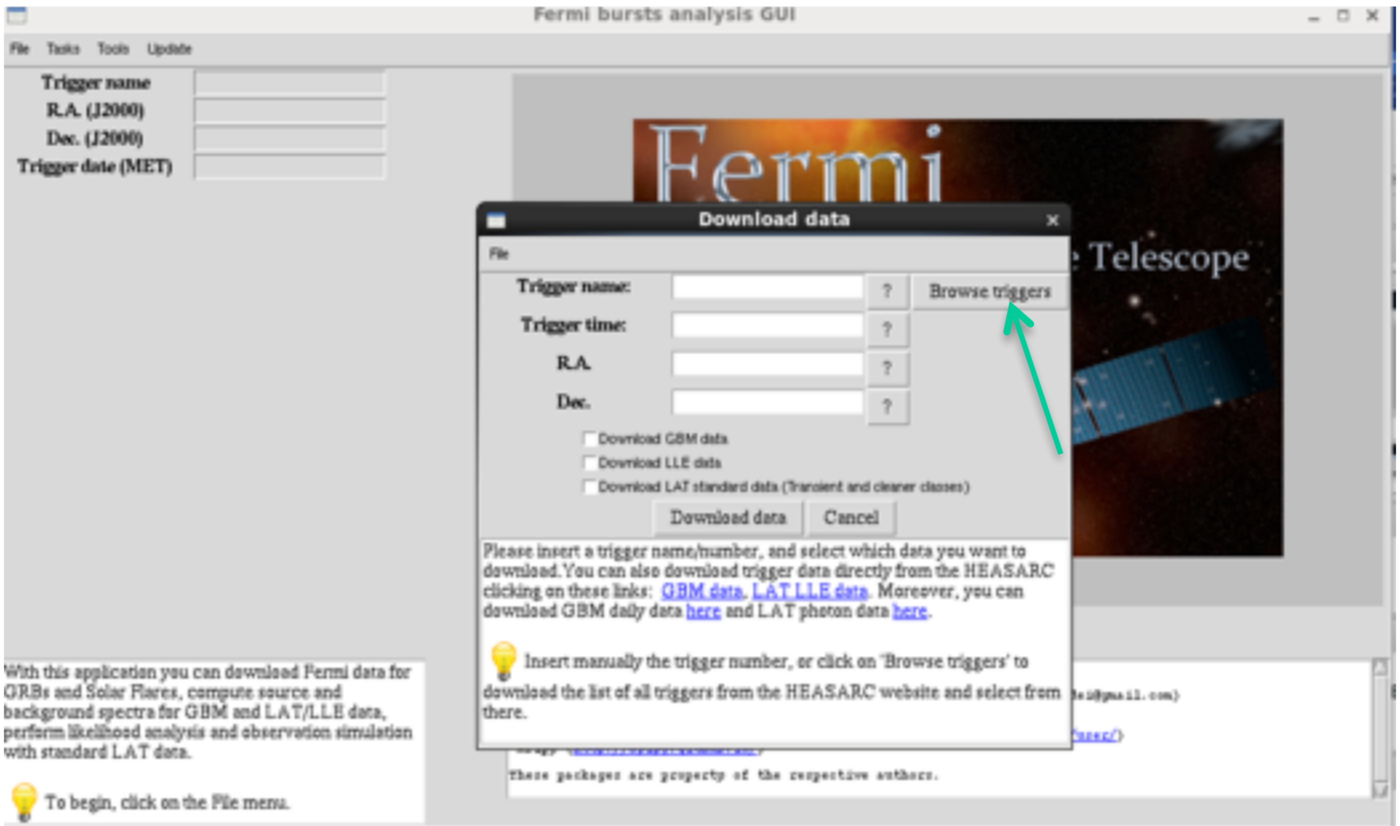
- **cd /home/vagrant/grb110731a**
- **gtburst**
  - **Update - always a good idea**



- **gtburst**
  - Download LAT dataset

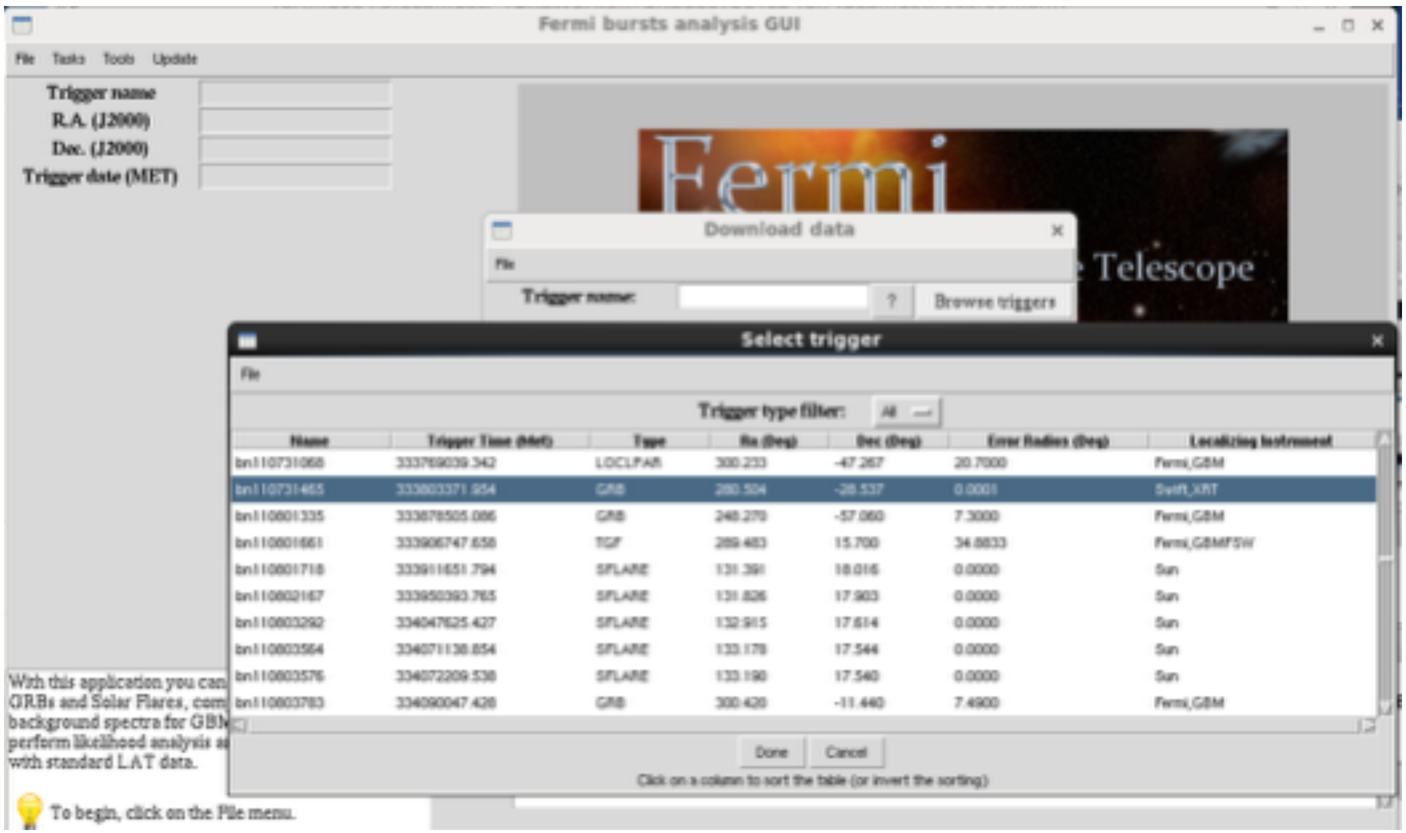
GBM/LAT GRB Tutorial

- **gtburst**
  - **Browse GBM/Swift triggers, or enter manual info**



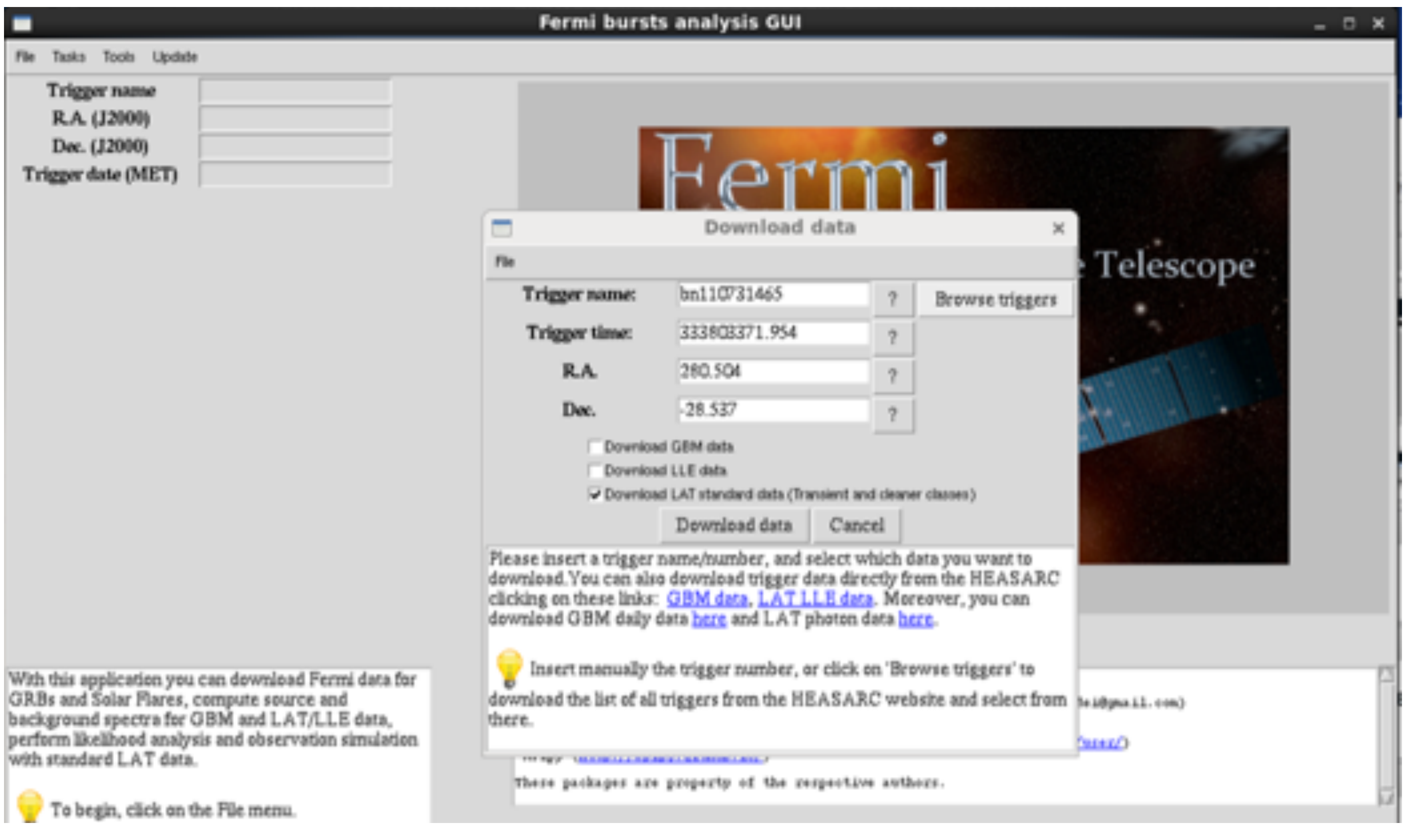
GBM/LAT GRB Tutorial

- **gtburst**
  - Choose your trigger



GBM/LAT GRB Tutorial

- **gtburst**
  - Choose the dataset
  - 10000 is standard interval to search



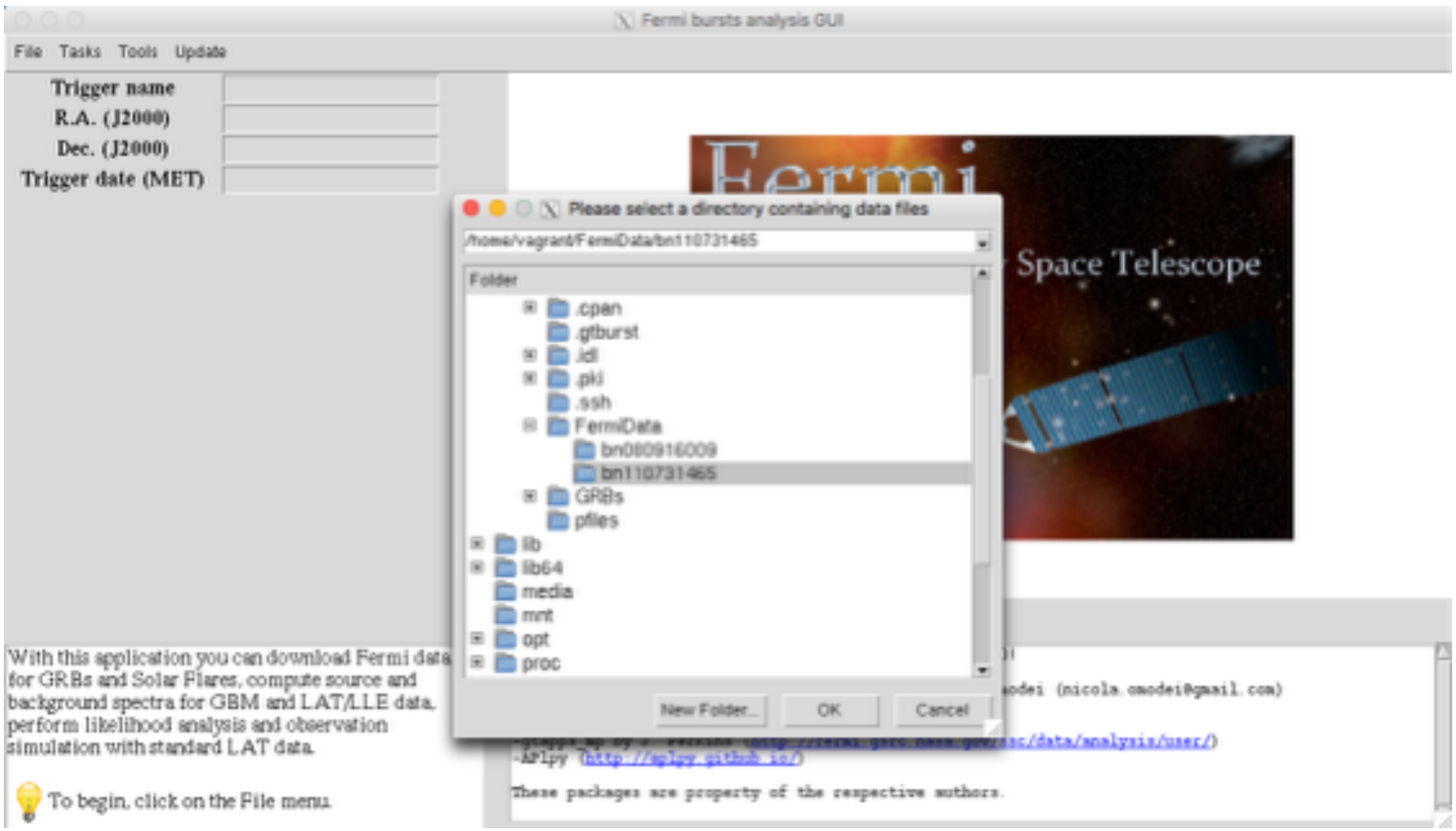
GBM/LAT GRB Tutorial

- **gtburst**
  - wait …

- **gtburst**
  - or grab data from directory

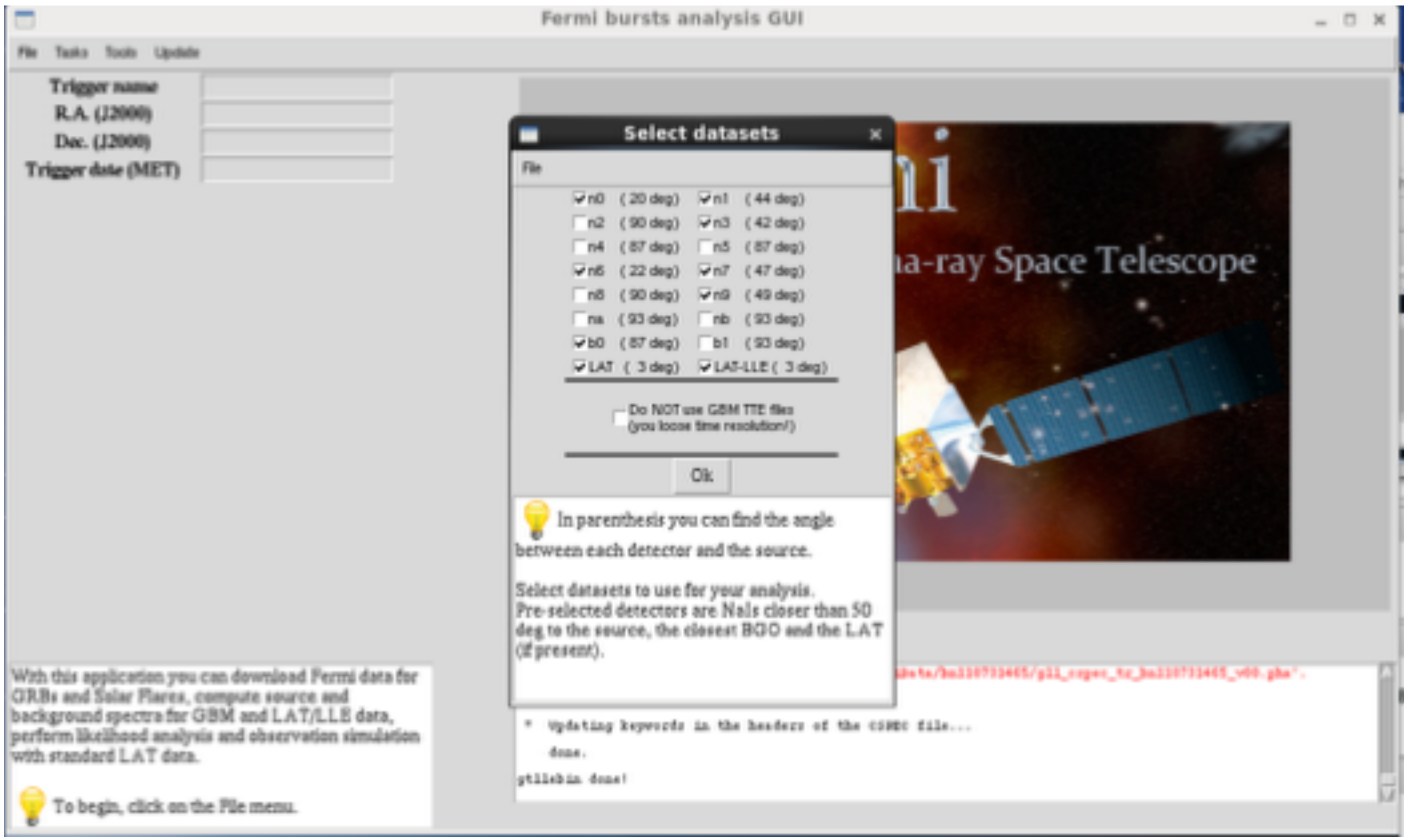
GBM/LAT GRB Tutorial

- **gtburst**
  - or grab data from directory



GBM/LAT GRB Tutorial

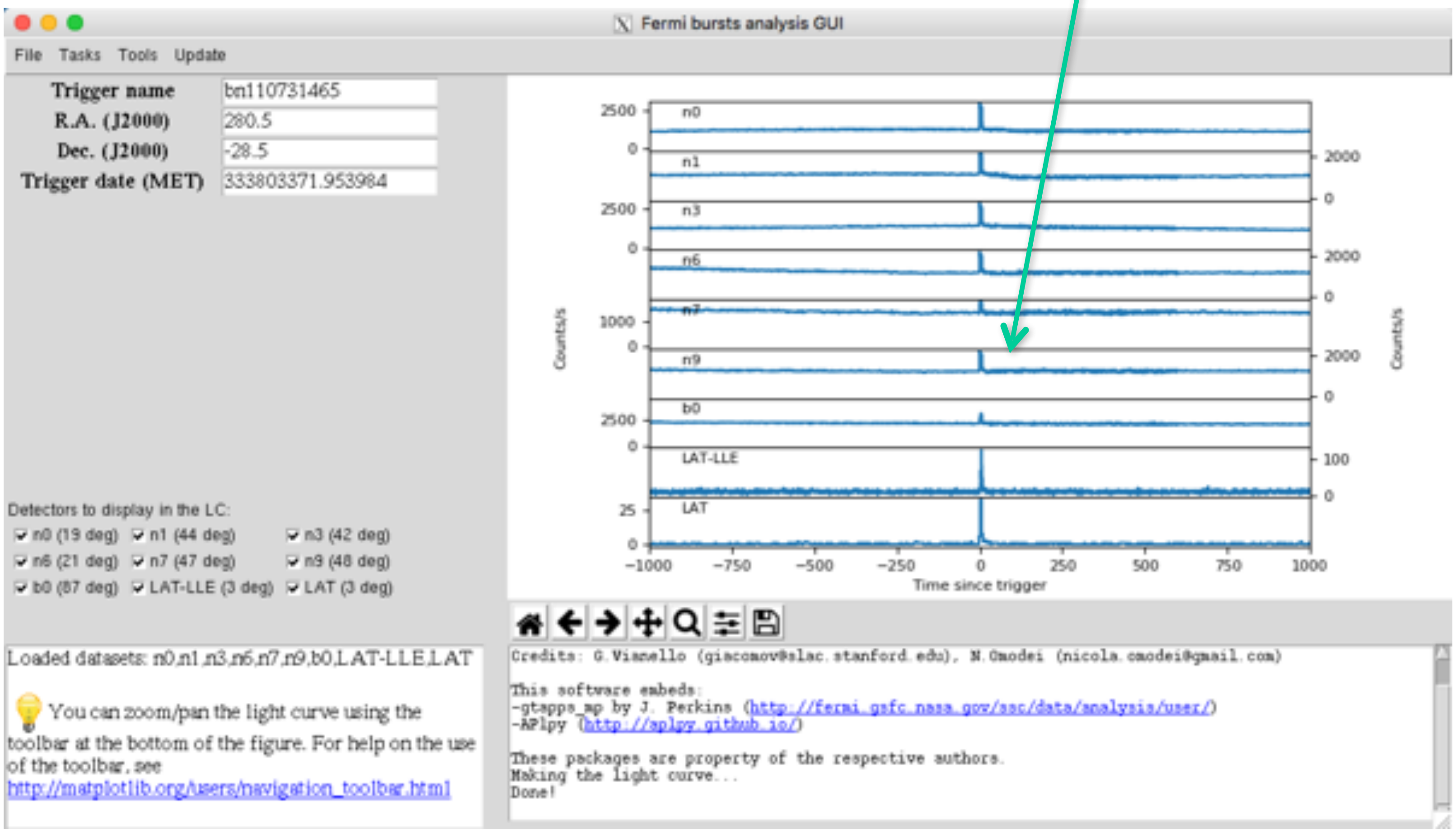
- **gtburst**
  - Choose the dataset



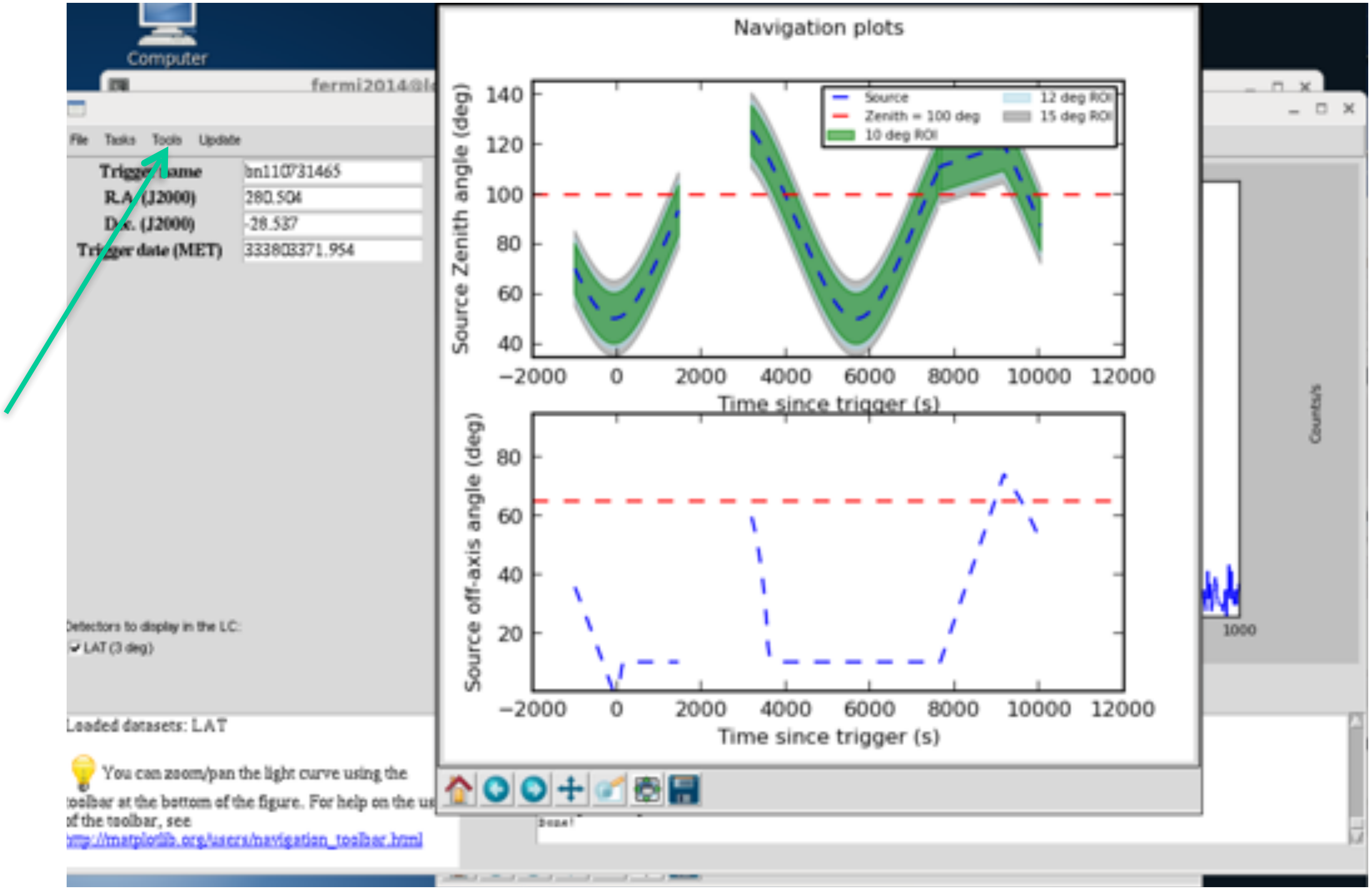
GBM/LAT GRB Tutorial

- **gtburst**

Clearly a burst!

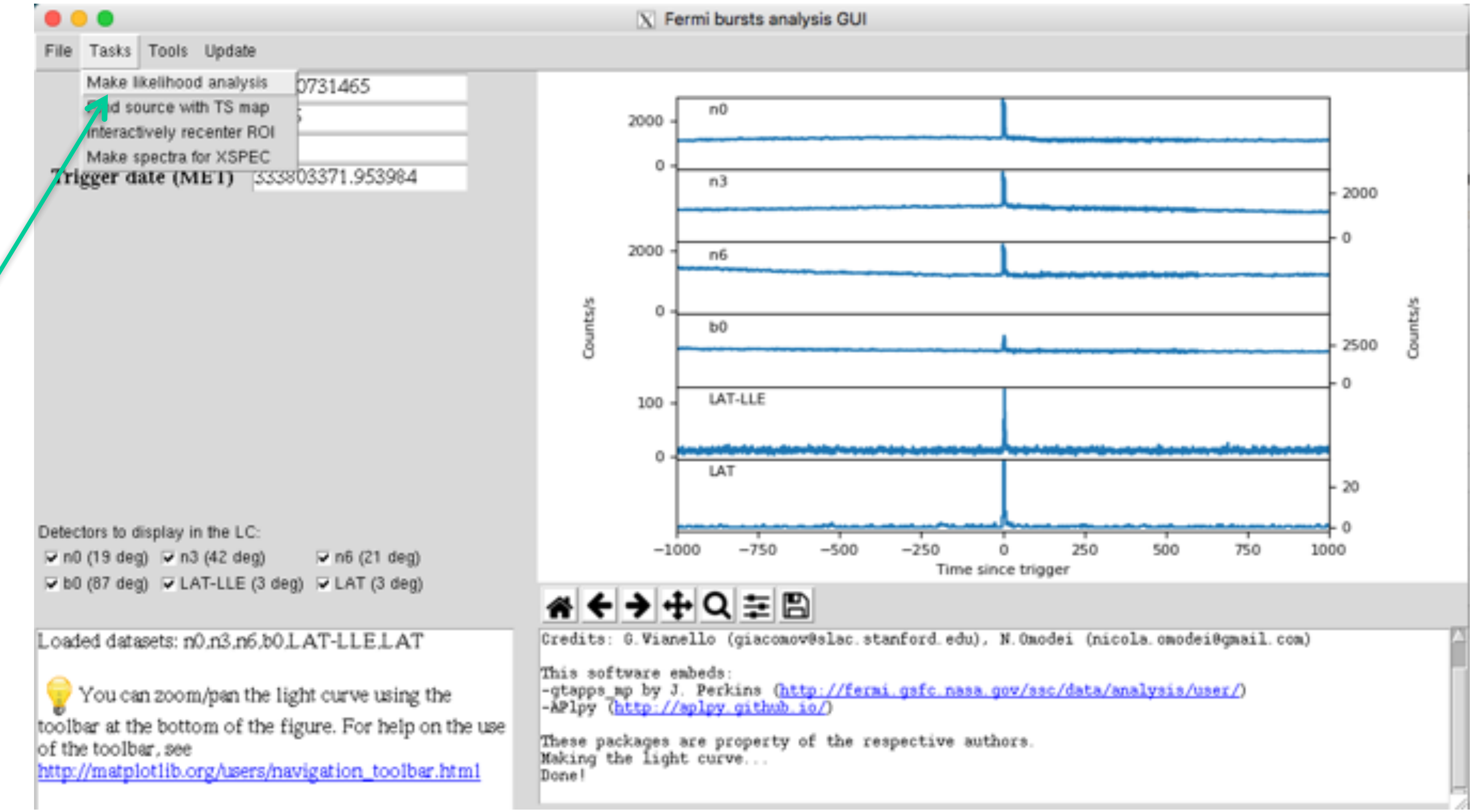


- **gtburst**


Computer
File Tasks Tools Update
Trigger name bn110731465
R.A. (J2000) 280.504
Dec. (J2000) -28.537
Trigger date (MET) 333803371.954
Navigation plots
Source
Zenith = 100 deg
10 deg ROI
12 deg ROI
15 deg ROI
Source Zenith angle (deg)
Time since trigger (s)
Source off-axis angle (deg)
Time since trigger (s)
Detectors to display in the LC:
LAT (3 deg)
Loaded datasets: LAT
You can zoom/pan the light curve using the toolbar at the bottom of the figure. For help on the use of the toolbar, see
http://matplotlib.org/users/navigation_toolbar.html

GBM/LAT GRB Tutorial

- **gtburst**

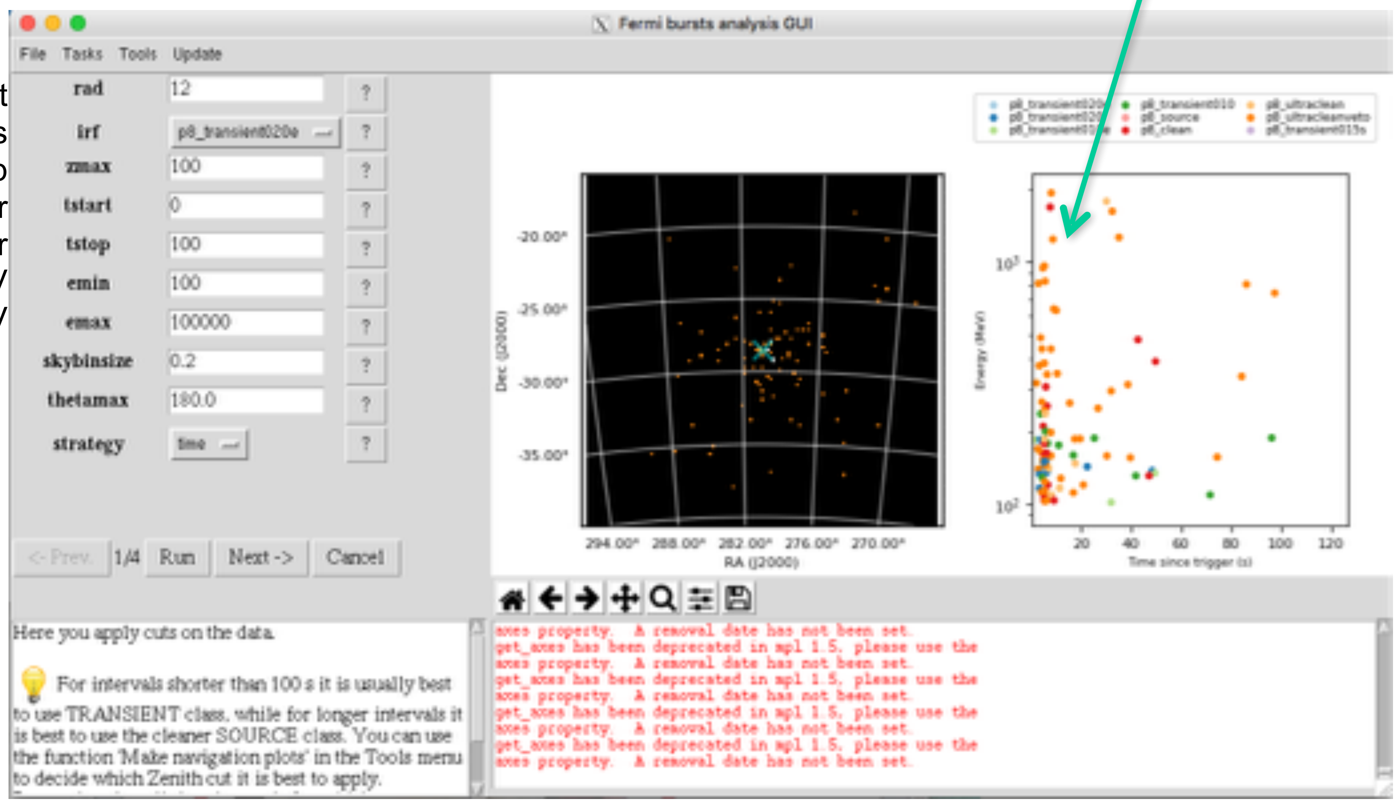


GBM/LAT GRB Tutorial

- **gtburst**

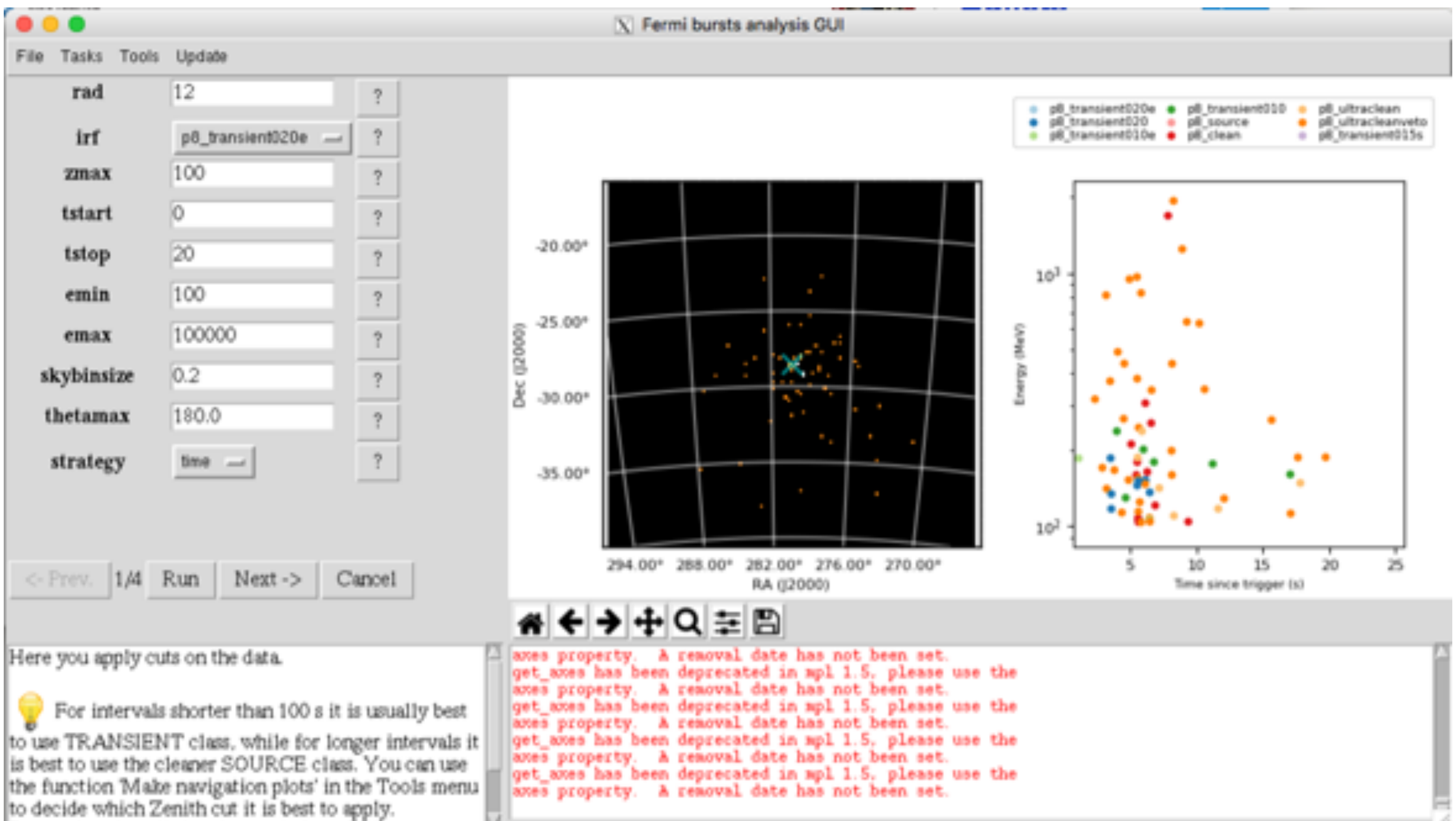
Click here

Radius of interest
Event class
Limit earth limb
Start time relative to trigger
Stop time relative to trigger
Min energy in MeV
Max energy in MeV



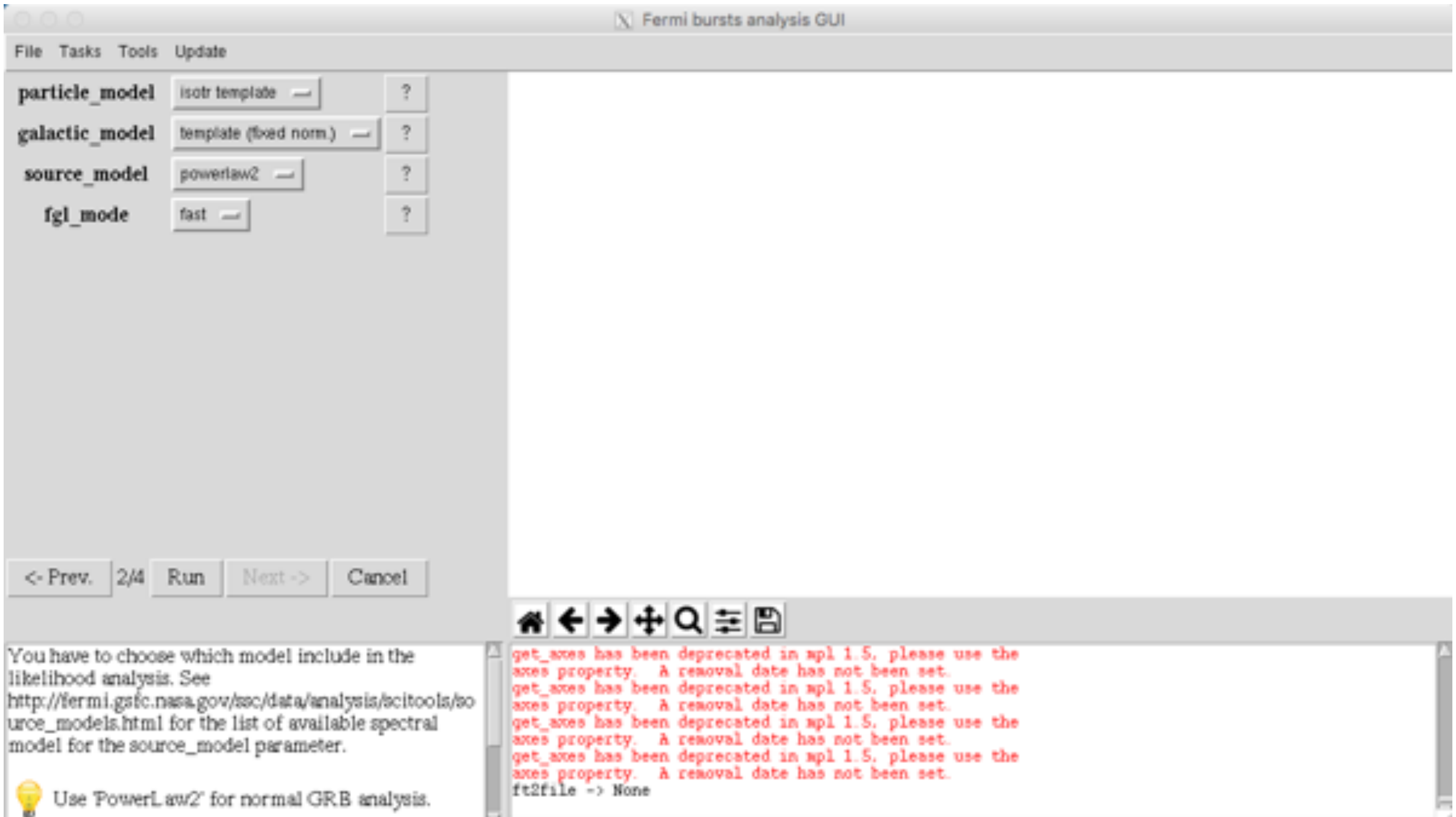
GBM/LAT GRB Tutorial

- **gtburst**
  - **Limit data selection to SED interval**
  - **Relevant event class (Transient20e)**



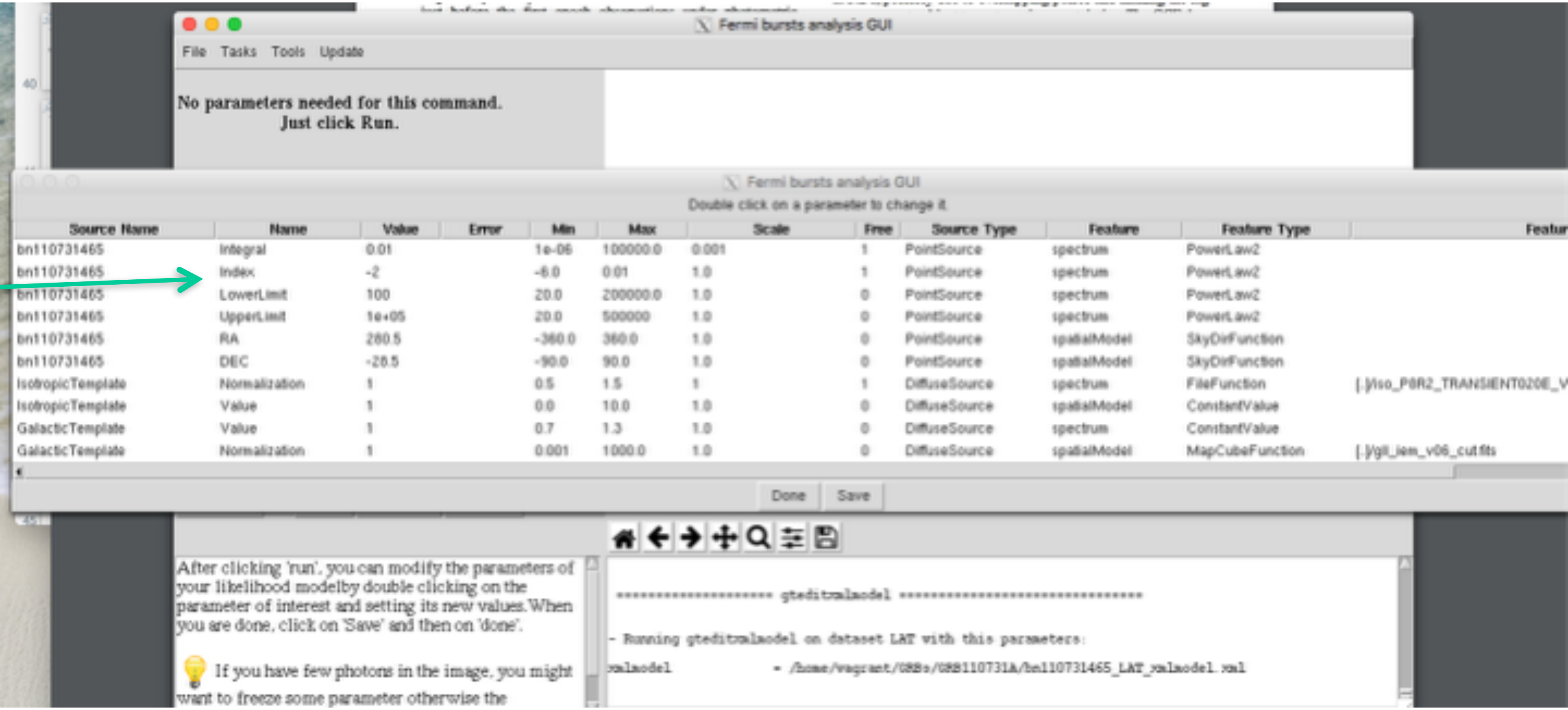
GBM/LAT GRB Tutorial

- **gtburst**
  - **Setting up background models for likelihood**
  - **next-run-next**



GBM/LAT GRB Tutorial

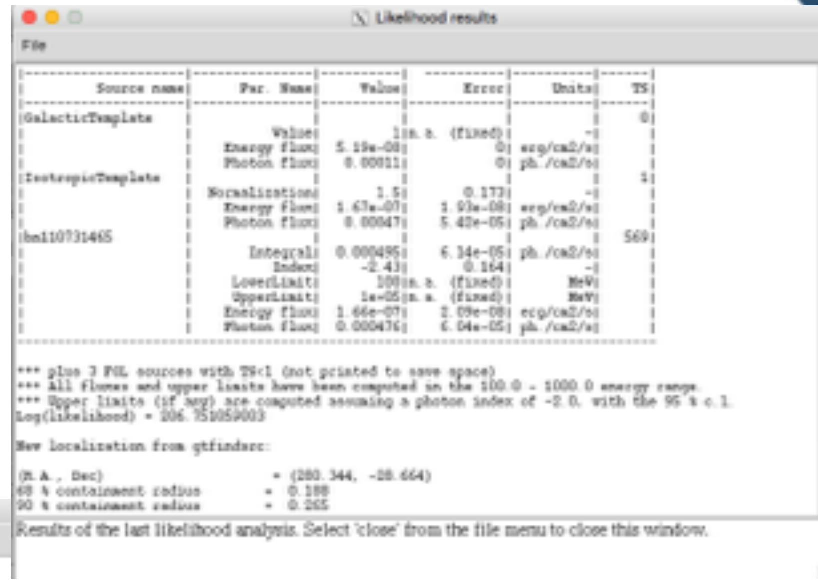
- **gtburst**
  - **XML file, default fits power-law with index=2**

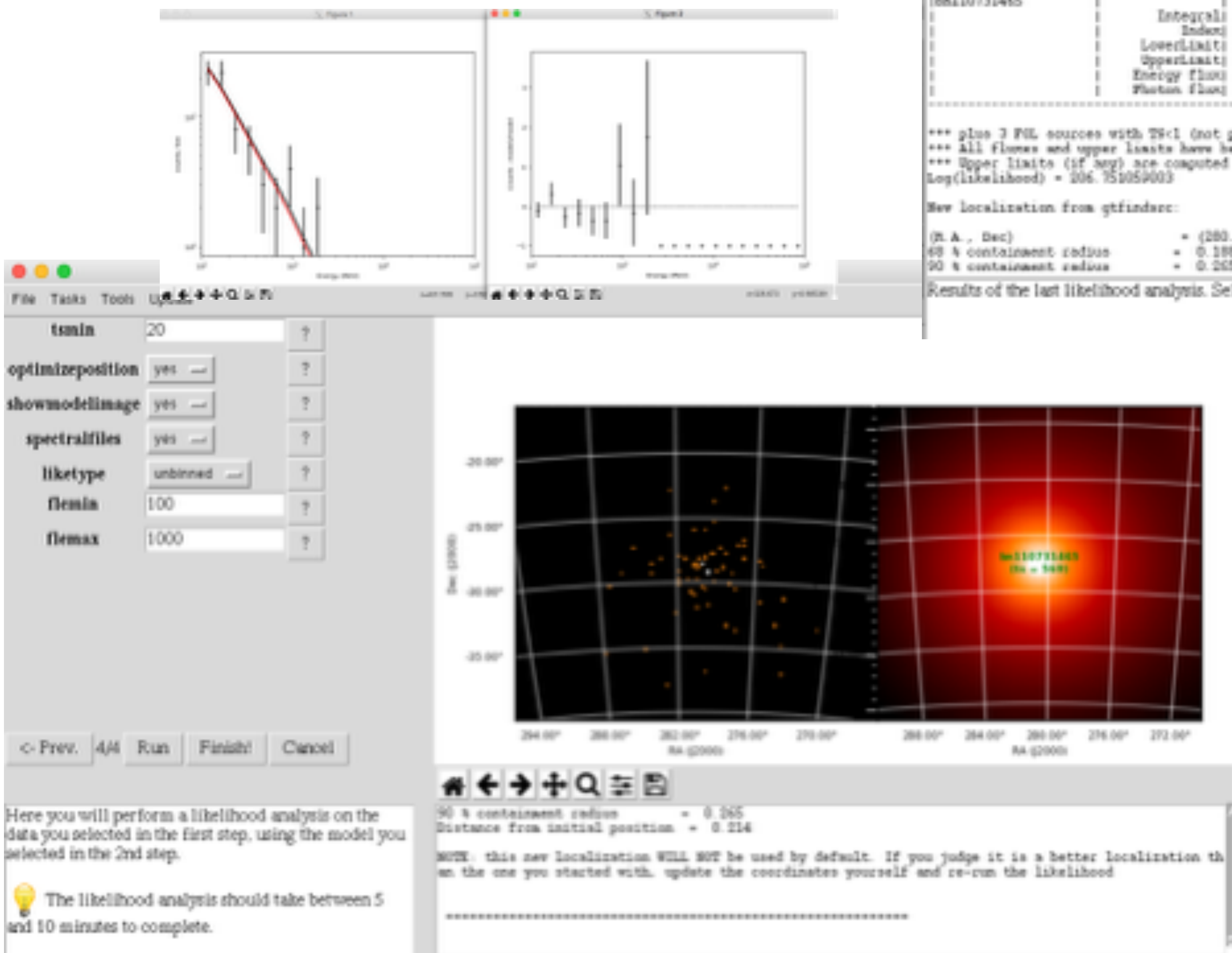


- **gtburst**
  - Optimizing position – runs gtfindsrc after gtlike
  - Show model image – makes TS map
  - Spectral files – makes XSPEC ready files
  - Run -> wait …

GBM/LAT GRB Tutorial

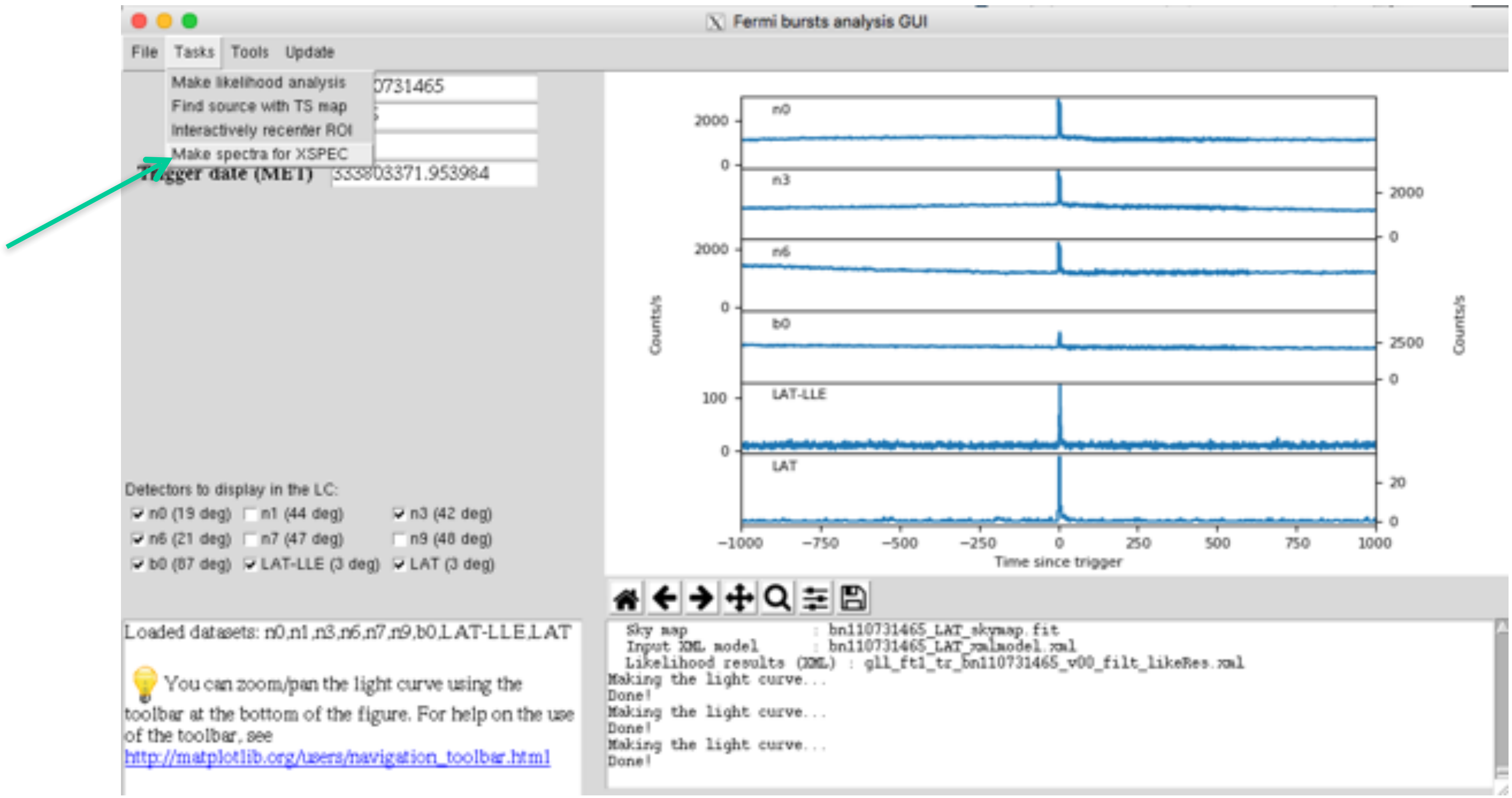
- **gtburst**
  - **LAT Likelihood results**
  - **Finish**





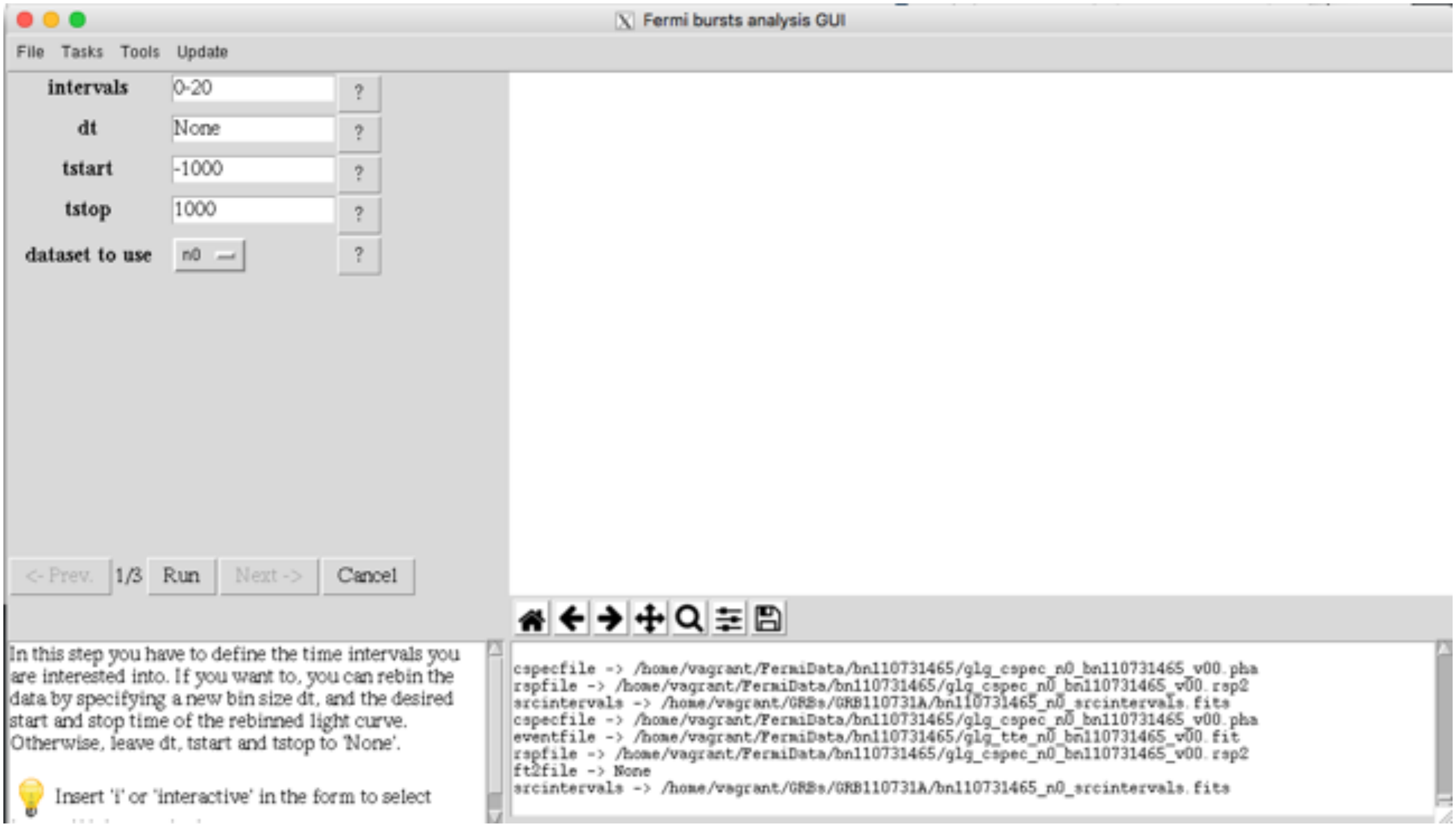
GBM Analysis in Gtburst

- **gtburst**
  - **Turn off some of the GBM detectors, only need 2 or 3 NaIs (with smallest angle) & 1 BGO**



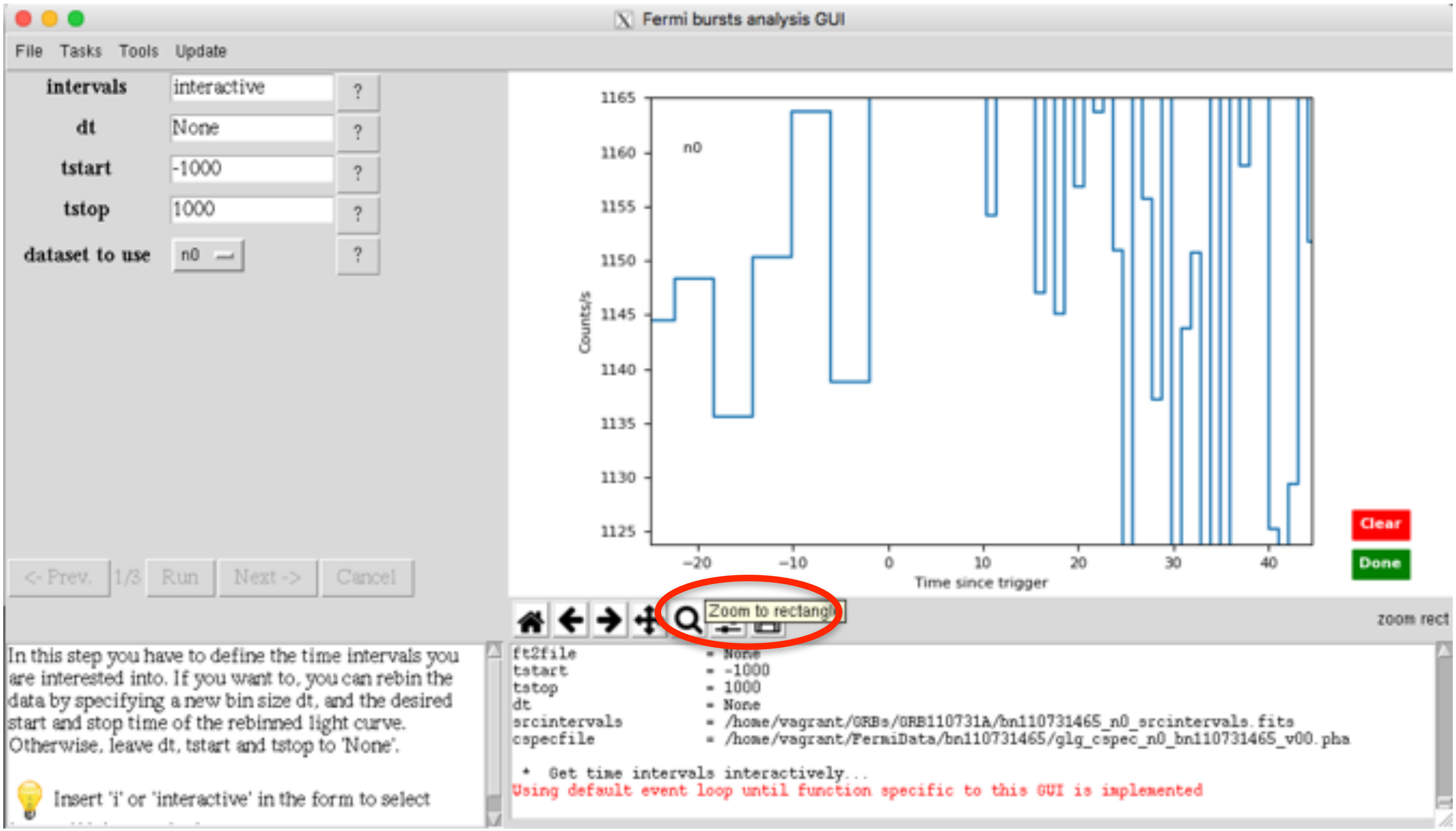
GBM Analysis in Gtburst

- **interactive or manual interval input**



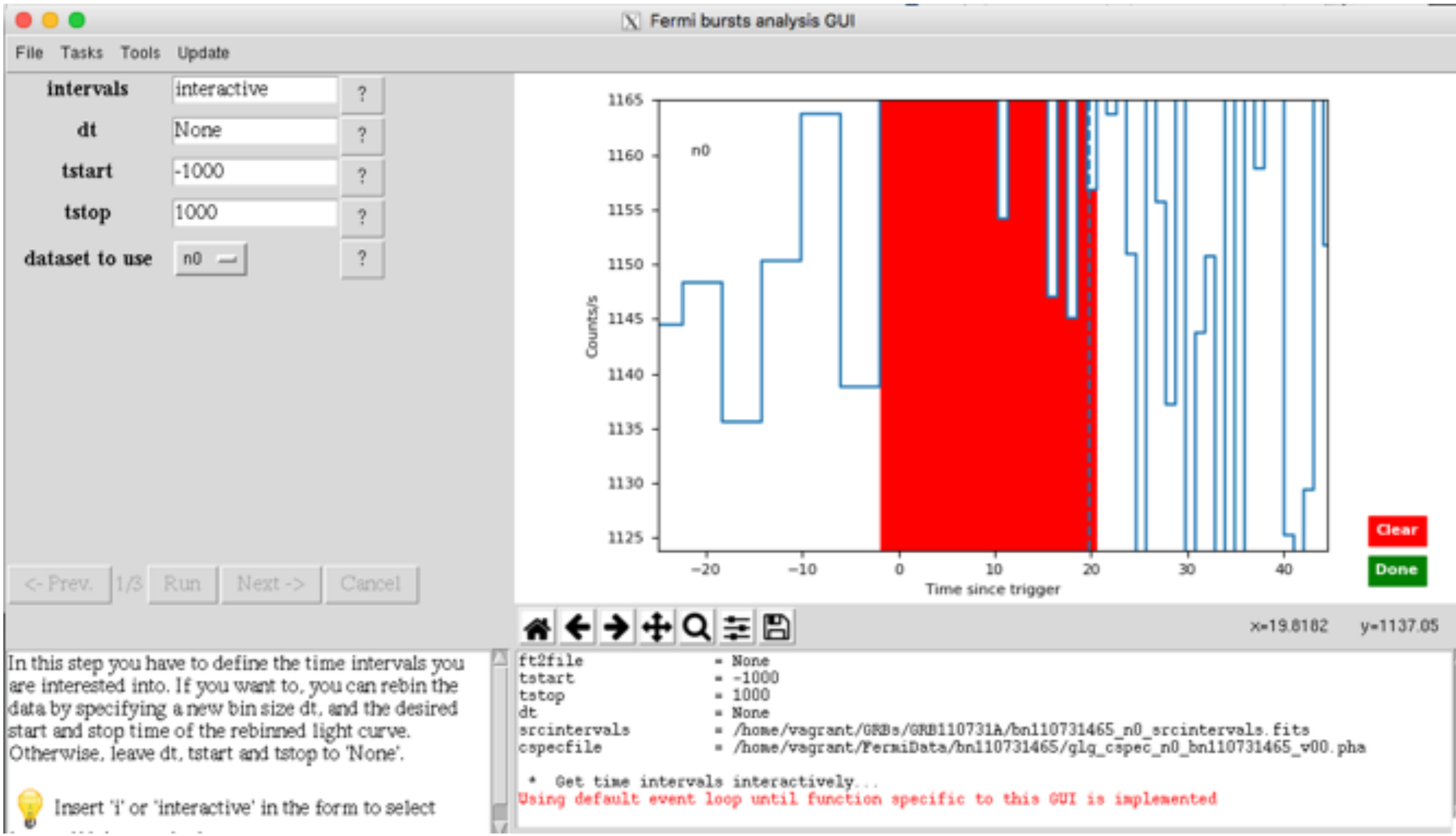
GBM Analysis in Gtburst

- **interactively zoom**



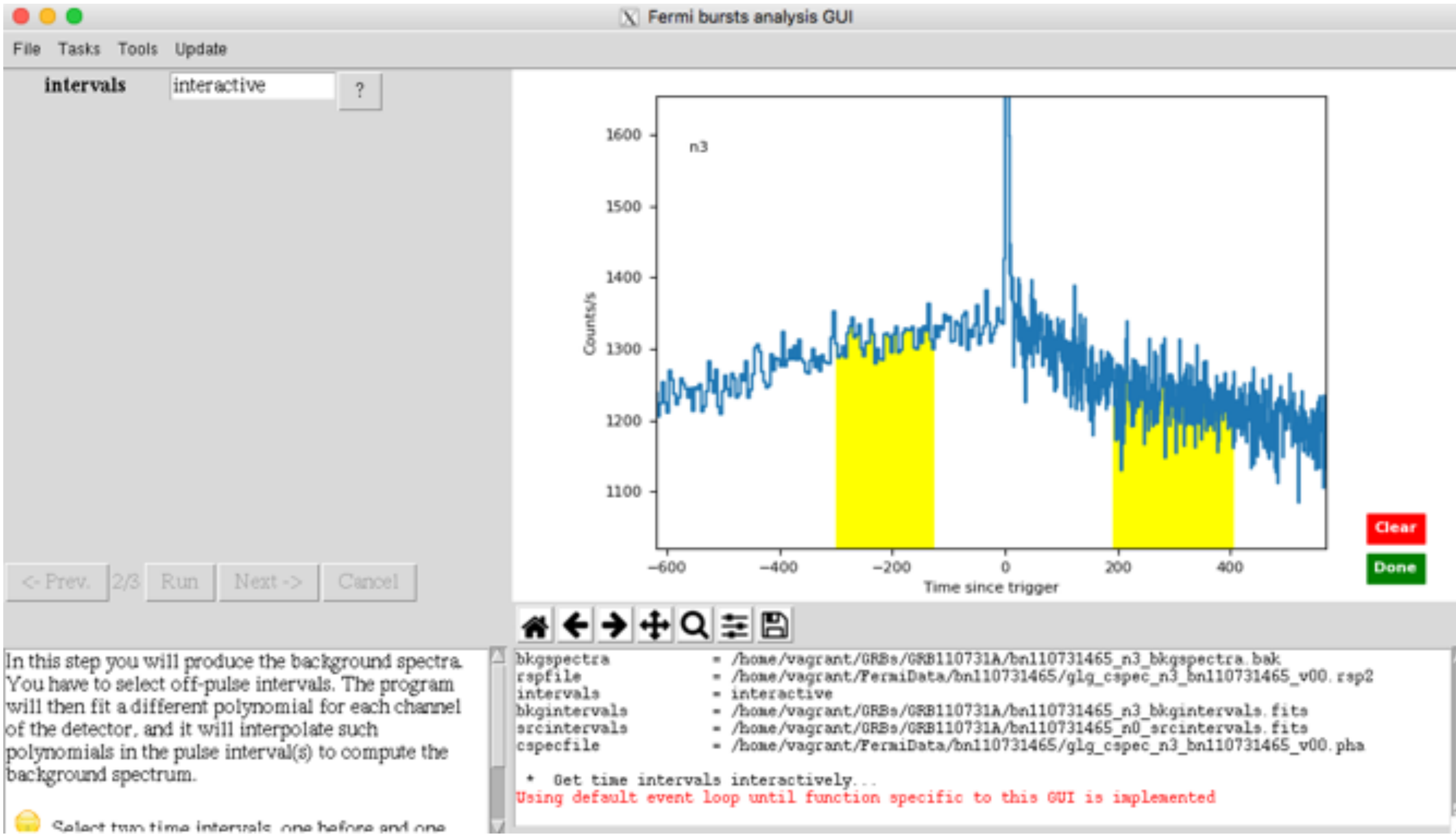
GBM Analysis in Gtburst

- **interactively choose source interval**



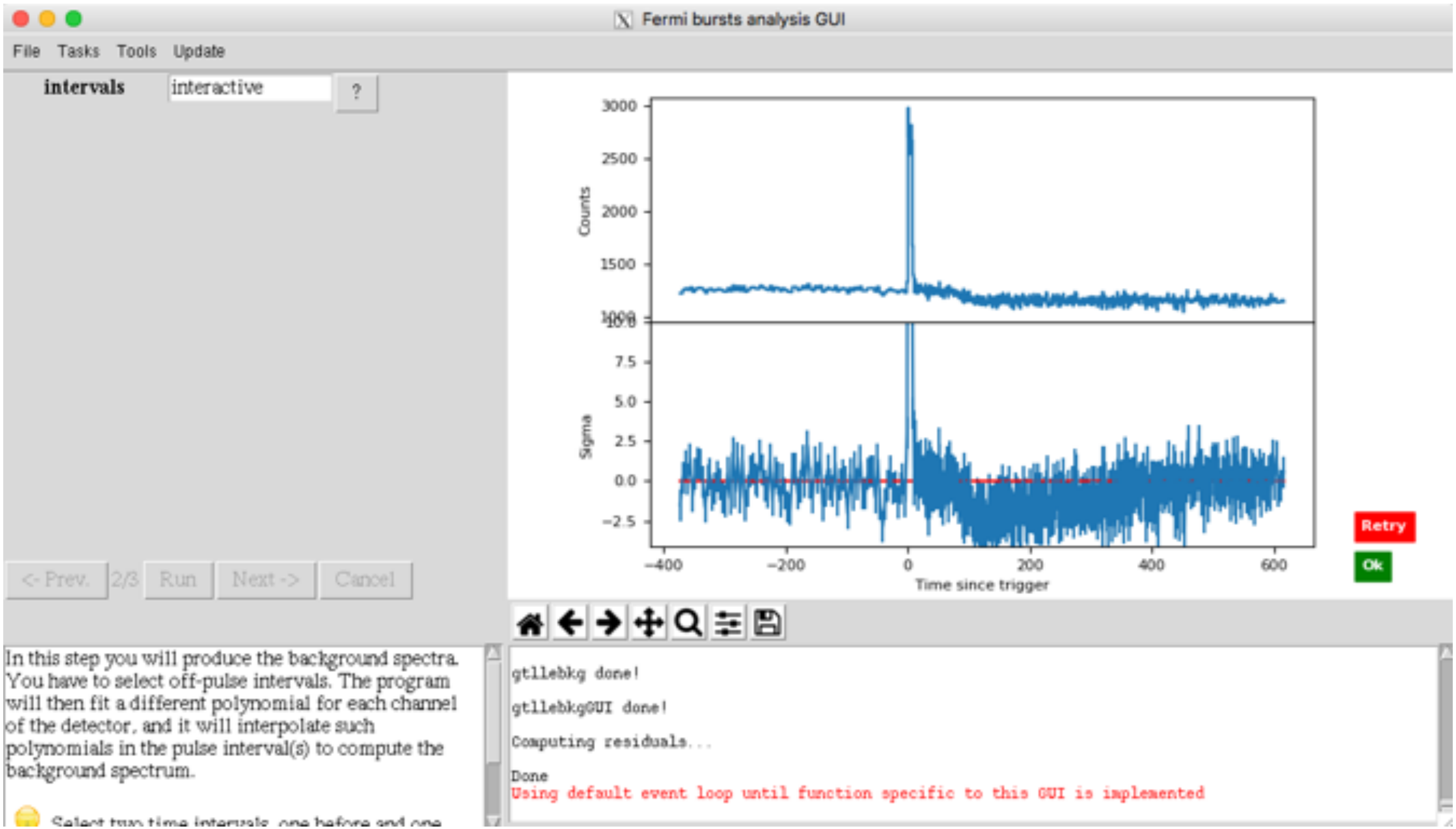
GBM Analysis in Gtburst

- interactively choose background for each detector



GBM Analysis in Gtburst

- resulting fit, retry if it doesn't look right



GBM Analysis in Gtburst

- **resulting files**

```
[vagrant@host-10-0-2-15 GRB110731A]$ ls *pha *rsp *bak
bn110731465_b0_bkgspectra.bak          bn110731465_n3_weightedrsp.rsp
bn110731465_b0_srcspectra.pha          bn110731465_n6_bkgspectra.bak
bn110731465_b0_weightedrsp.rsp         bn110731465_n6_srcspectra.pha
bn110731465_LAT-LLE_bkgspectra.bak     bn110731465_n6_weightedrsp.rsp
bn110731465_LAT-LLE_srcspectra.pha     bn110731465_n7_bkgspectra.bak
bn110731465_LAT-LLE_weightedrsp.rsp    bn110731465_n7_srcspectra.pha
bn110731465_n0_bkgspectra.bak          bn110731465_n7_weightedrsp.rsp
bn110731465_n0_srcspectra.pha          bn110731465_n9_bkgspectra.bak
bn110731465_n0_weightedrsp.rsp         bn110731465_n9_srcspectra.pha
bn110731465_n1_bkgspectra.bak          bn110731465_n9_weightedrsp.rsp
bn110731465_n1_srcspectra.pha          gll_ft1_tr_bn110731465_v00_filt_spec_0.000_20.000.bak
bn110731465_n1_weightedrsp.rsp         gll_ft1_tr_bn110731465_v00_filt_spec_0.000_20.000.pha
bn110731465_n3_bkgspectra.bak          gll_ft1_tr_bn110731465_v00_filt_spec_0.000_20.000.rsp
bn110731465_n3_srcspectra.pha
[vagrant@host-10-0-2-15 GRB110731A]$
```

GBM/LAT GRB Tutorial

- XSPEC
  - http://heasarc.nasa.gov/xanadu/xspec/manual/manual.html
  - Standard spectral model fitting package, developed in X-ray community, so a bit X-ray centric (units default in keV)
  - Inputs:
    - counts/channel spectra
    - Background files
    - Response files
  - Outputs:
    - Fit parameters
    - Model fit to data in counts space, F_ν, νF_ν in energy, frequency, etc.
- Other spectral fitting packages
  - RMFIT
  - SHERPA

- Download example_prompt.xcm
  - data 1:1 bn110731465_n0_srcspectra.pha{*}
  - data 2:2 bn110731465_n3_srcspectra.pha{*}
  - data 3:3 bn110731465_n6_srcspectra.pha{*}
  - data 4:4 bn110731465_b0_srcspectra.pha{*}
  - data 5:5 bn110731465_LAT-LLE_srcspectra.pha{*}
  - data 6:6 gll_ft1_tr_bn110731465_v00_filt_spec_0.000_20.000.pha

Setting up 4 data groups

- NaI
- BGO
- LLE
- LAT

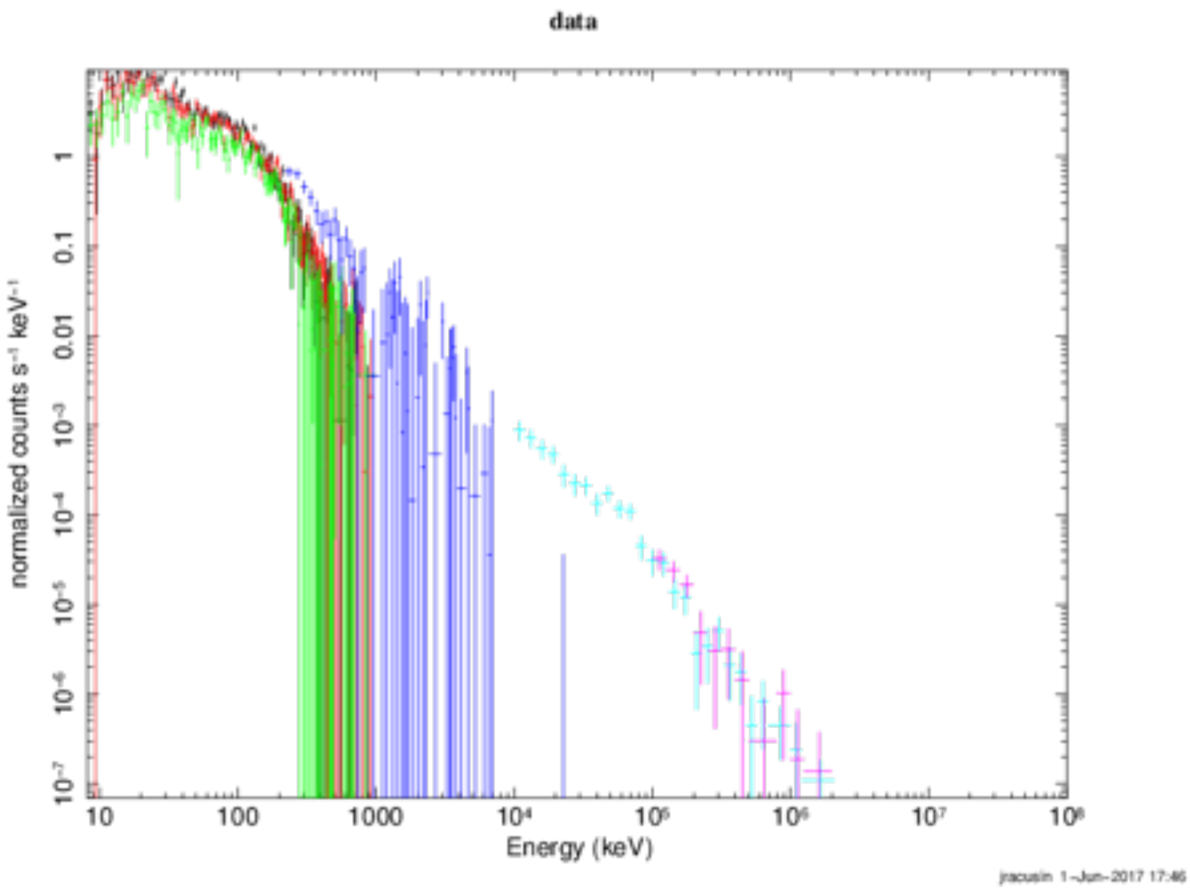
This allows us to do things like free parameters (e.g. normalization constant) in each group from each other

GBM/LAT GRB Tutorial

- **Let's set things up**
  - **cpd /xw**
  - **setplot en**
  - **ignore 1-3:**-8.0**
  - **ignore 1-3:1000.-****
  - **ignore 4:**-200.**
  - **ignore 4:40e3-****
  - **ignore 6:**-20e3**
  - **ignore bad**

  - **statistic cstat**
  - **statistic pgstat 5**
  - **statistic pgstat 6**

- **Let's plot our data**
  - **plot ldata**

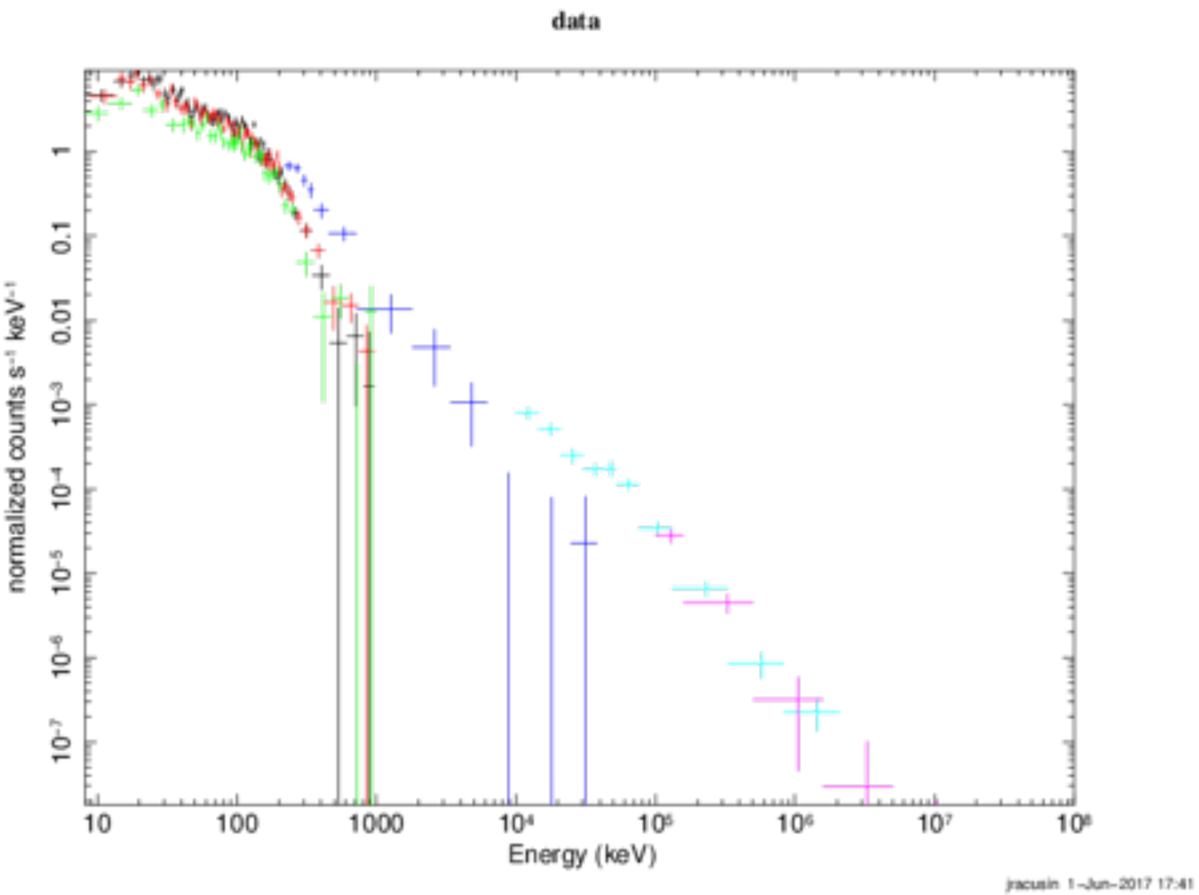


cstat = Cash Statistic, pgstat = poison signal with gaussian noise

GBM/LAT GRB Tutorial

- Let's bin our data (for plotting purposes only)
  - setplot rebin <min significance><max # bins><plot group>

  - setplot rebin 5 10 1
  - setplot rebin 5 10 2
  - setplot rebin 5 10 3
  - setplot rebin 5 20 4
  - setplot rebin 5 5 5
  - setplot rebin 5 5 6
  - plot ldata

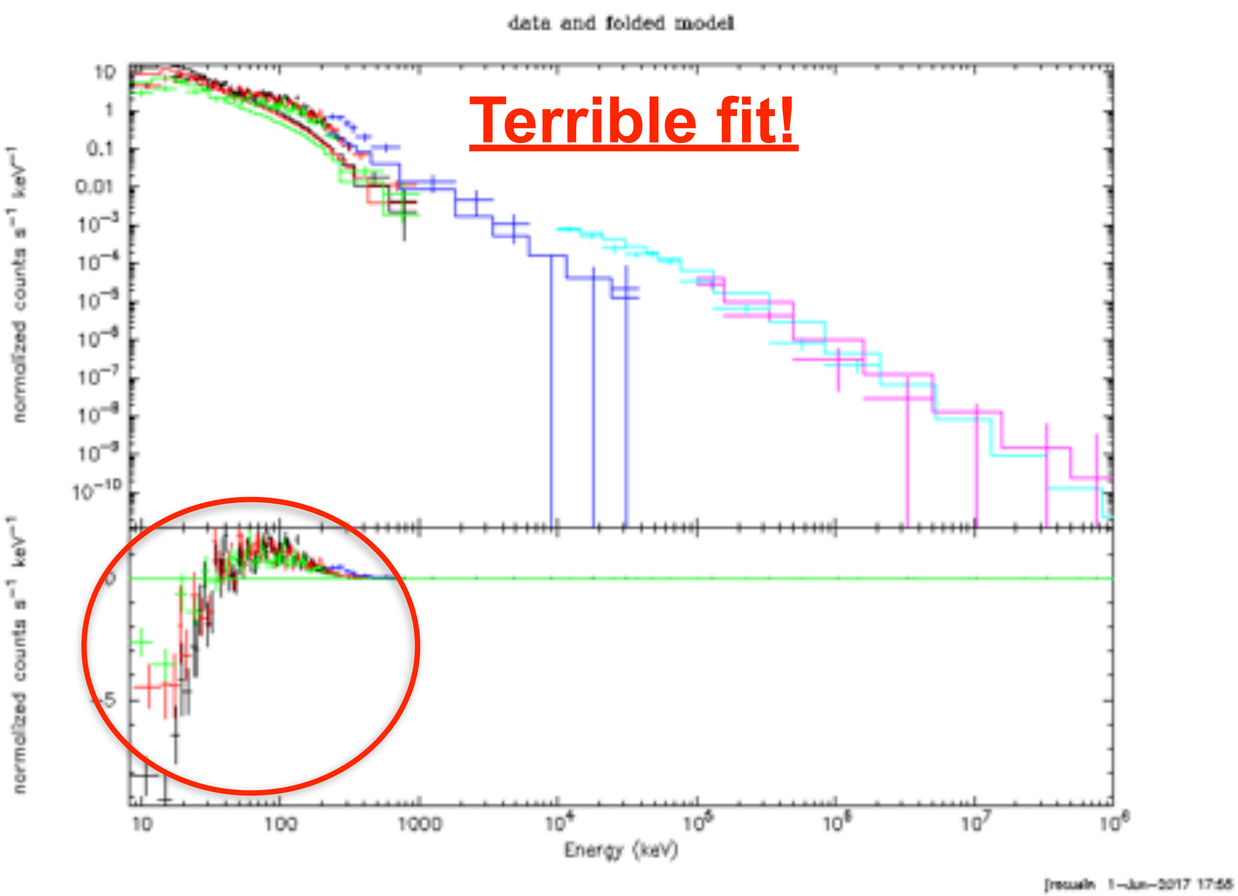


feel free to play with these numbers to make nicer looking plots, it won't affect the fits

GBM/LAT GRB Tutorial

- **Let's fit the data to some simple models**
  - mode
  - [press
    defau
  - fit 100

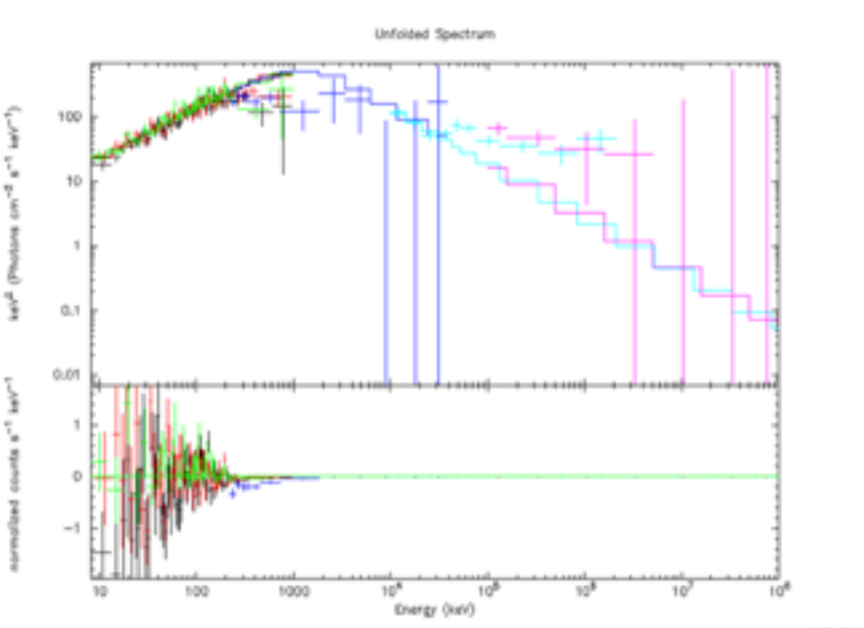
```
Model powerlaw<1> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
                           Data group: 1
```

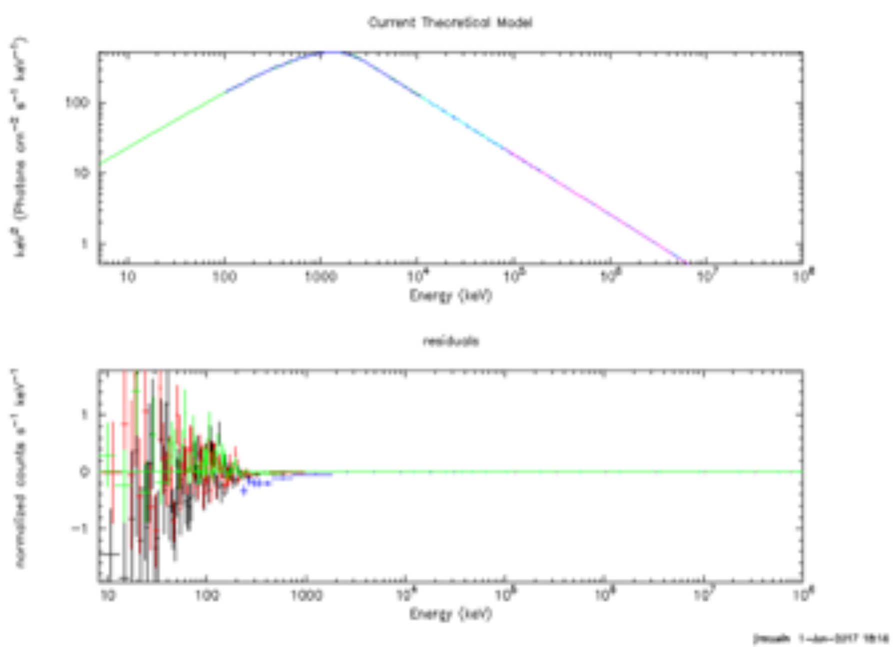


- **Let's plot residuals**
  - plot lc

GBM/LAT GRB Tutorial

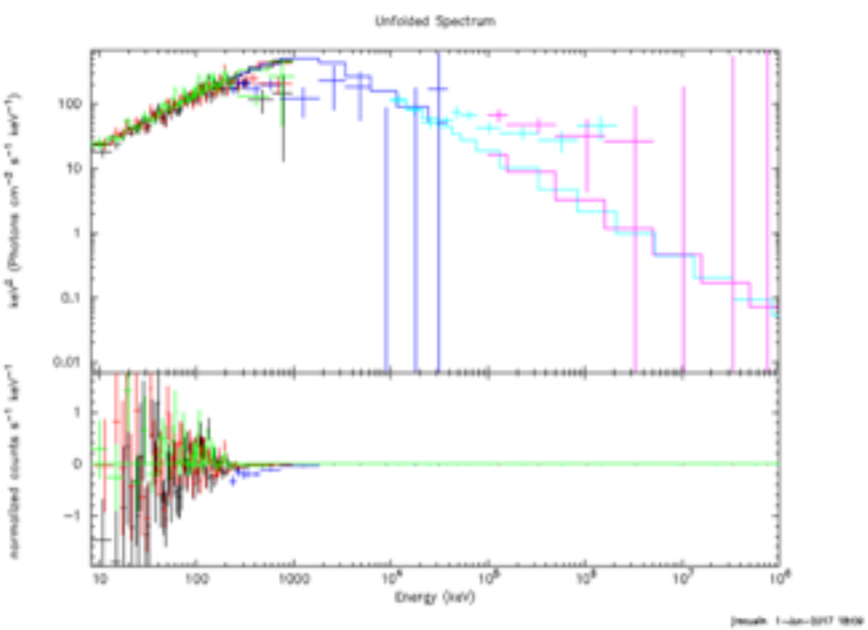
- Let's look at the plot like a SED plotting νF_ν to unfold the data using the response functions & model. This makes your spectrum plot model dependent, caution when interpreting physical models!
  - plot eeuf res
  - plot eemo res

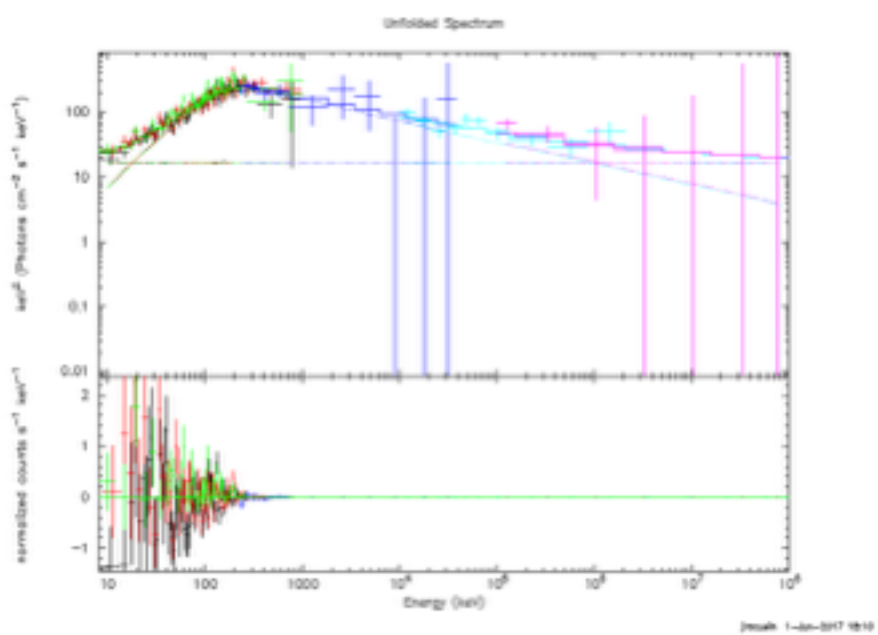




GBM/LAT GRB Tutorial

- Let's to a better fit to the data. Try these models
  - model grbm
  - model grbm+pow
  - model grbm+pow+bb
  - model const(grbm+pow+bb)
    - freeze 1
    - untie 19
    - newer 28=19





- Fit the data
  - fit 1000
    - May have to do this several times
- Tricks to refine the fit, get out of local minima
  - method migrad
    - Minuit2 migrad method, useful for getting into the right ballpark with wider parameter space
  - method leven
    - Default minimization method, useful for refining fit
  - Sometimes useful to go back and forth setting method, fitting, trying other method
- All these commands are documented here
  - http://heasarc.nasa.gov/xanadu/xspec/manual/XScommandSummary.html

- You have a fit
  - But don't believe the results just yet …

```
Model grbm<1> + powerlaw<2> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
                      Data group: 1
   1    1   grbm       alpha               -0.483338    +/-  0.153824
   2    1   grbm       beta                -2.33086     +/-  2.70428E-02
   3    1   grbm       tem        keV      169.561      +/-  29.4015
   4    1   grbm       norm                2.49647E-02  +/-  2.58037E-03
   5    2   powerlaw   PhoIndex            2.00173      +/-  4.51030E-02
   6    2   powerlaw   norm                16.8186      +/-  5.03555
                      Data group: 2
   7    1   grbm       alpha               -0.483338    = 1
   8    1   grbm       beta                -2.33086     = 2
   9    1   grbm       tem        keV      169.561      = 3
  10    1   grbm       norm                2.49647E-02  = 4
  11    2   powerlaw   PhoIndex            2.00173      = 5
  12    2   powerlaw   norm                16.8186      = 6
                      Data group: 3
  13    1   grbm       alpha               -0.483338    = 1
  14    1   grbm       beta                -2.33086     = 2
  15    1   grbm       tem        keV      169.561      = 3
  16    1   grbm       norm                2.49647E-02  = 4
  17    2   powerlaw   PhoIndex            2.00173      = 5
  18    2   powerlaw   norm                16.8186      = 6
                      Data group: 4
  19    1   grbm       alpha               -0.483338    = 1
  20    1   grbm       beta                -2.33086     = 2
  21    1   grbm       tem        keV      169.561      = 3
  22    1   grbm       norm                2.49647E-02  = 4
  23    2   powerlaw   PhoIndex            2.00173      = 5
  24    2   powerlaw   norm                16.8186      = 6
________________________________________________________________________


Fit statistic : C-Statistic =          379.10 using 490 PHA bins.

Warning: cstat statistic is only valid for Poisson data.
    Background file is not Poisson

PG-Statistic =          52.67 using 80 PHA bins.

Warning: pgstat statistic is only valid for Poisson data.
    Source file is not Poisson
    Background file is not Poisson

Total Statistic =          431.78 with 564 degrees of freedom.


Test statistic : Chi-Squared =          498.03 using 570 PHA bins.
 Reduced chi-squared =          0.88304 for    564 degrees of freedom
 Null hypothesis probability =   9.786358e-01

***Warning: Chi-square may not be valid due to bins with zero variance
            in spectrum number(s): 5

nTotal Test Statistic =          498.03 with 564 degrees of freedom.
```

Never believe these errors, ever!

Goodness of fit

- **Errors on parameters and local minima**
  - **Sometime will find new better fit, and you can start over**
  - **Confidence interval default = 90%, can change**

```
XSPEC12>error 1-6
 Parameter   Confidence Range (2.706)
Number of trials exceeded: continue fitting?
Number of trials exceeded: continue fitting?
Number of trials exceeded: continue fitting?
     1    -0.744889    -0.193892    (-0.260579,0.290418)
Apparent non-monotonicity in statistic space detected.
Current bracket values -2.25746, -2.25356
and delta stat 2.69048, 3.31576
but latest trial -2.25736 gives 2.685
Suggest that you check this result using the steppar command.
     2     -2.40369     -2.25551    (-0.0739512,0.0742339)
     3      127.898      232.325    (-41.8045,62.6225)
     4    0.0214608    0.0303339    (-0.00350109,0.00537204)
     5      1.93526      2.45999    (-0.0674719,0.457264)
     6      7.96772      39.5745    (-8.86897,22.7378)
```

- XSPEC can do lots of other useful things
  - Many spectral models
    - http://heasarc.nasa.gov/xanadu/xspec/manual/Models.html
  - Calculate fluxes over energy range
    - If you want de-absorbed X-ray fluxes (true emitted flux), you can set the nH=0 after fitting
  - Can even simulate data using fakeit command
  - Can fit offsets for different datasets if cross-calibration is uncertain
    - different fit parameters (e.g. normalizations) for different instruments
  - Plot data in counts, F_ν, νF_ν

What else?

- Do this in time-resolved analysis
  - measure evolution of parameters
  - are all components seen in every interval
  - ftest for nested models
  - more sophisticated simulations potentially required
- Rmfit also does these joint fits
  - Colleen will demonstrate rmfit next week