Fermi Gamma-ray Space Telescope

Tutorial on
Fermi-LAT data analysis

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Material from P.Bruel, M.Razzano,
S.Buson and R.Desiante

PhD course 2021 – Padova

Outline

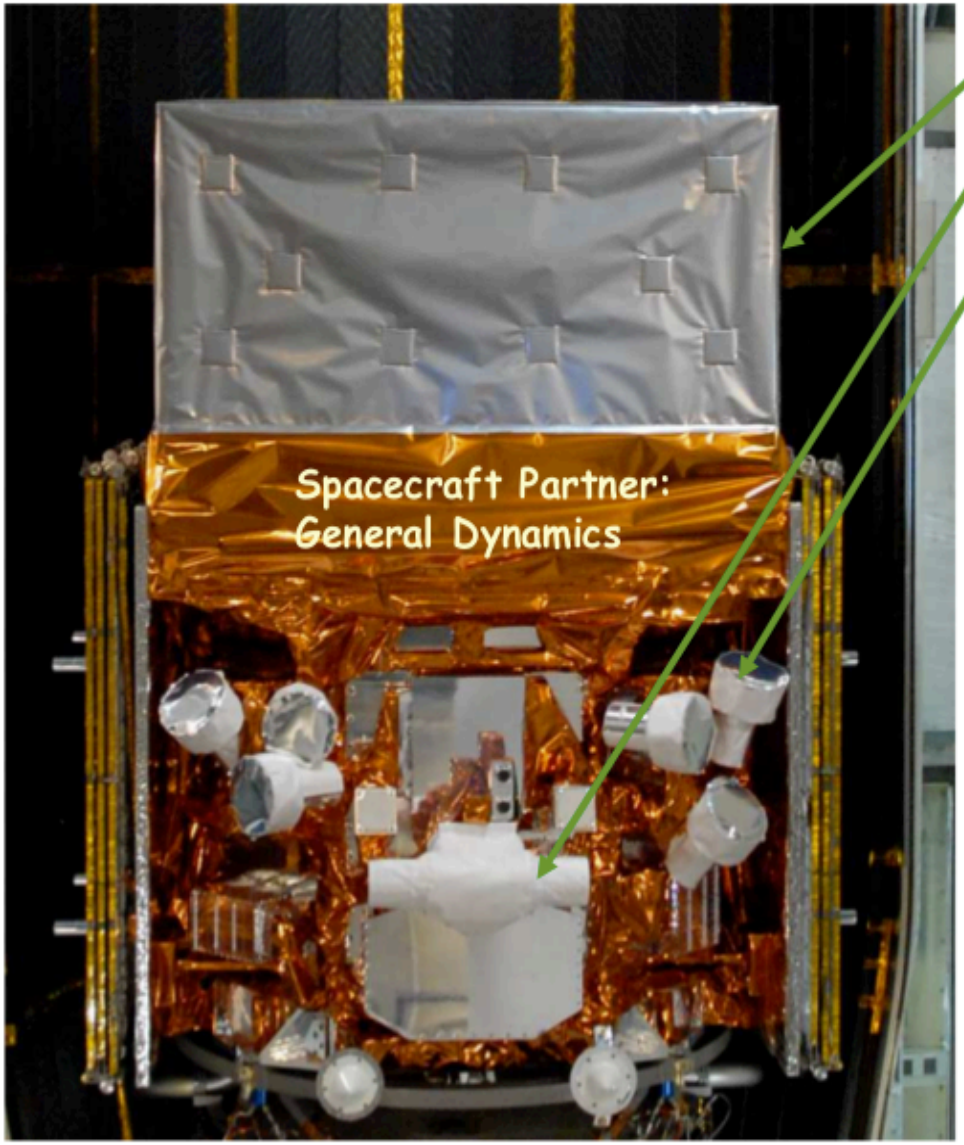
- **Overview of the Fermi Large AreaTelescope**
  - How it works
  - **LAT data**
  - LAT performance
- **Fermi Science Tools**
  - **General Introduction**
- Maximum Likelihood Overview
  - Source modeling
- One study case:
  - 3c454.3: Fermipy analysis tutorial
- **gtburst Analysis of GRBs**

Organization

- **Yesterday**
  - Introduction to the LAT data analysis
  - LAT data introduction
  - LAT data exploration & preparation
  - Likelihood analysis of LAT data
  - Description of Sky models
  - Introduction to Fermipy
  - Trouble shooting on SW installation

- **Today**
  - gtburst fast analysis of GRB
  - fermipy Hands-on on an Extragalactic source
    - SED & Light Curves

The observatory



Large AreaTelescope (LAT)
20 MeV - >300 GeV

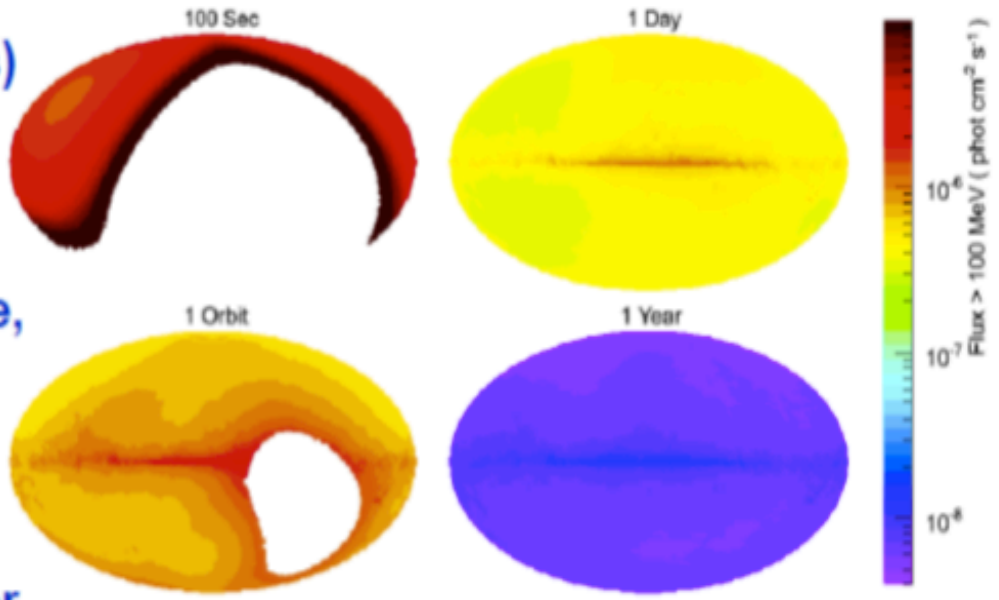
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 30 MeV

KEY FEATURES

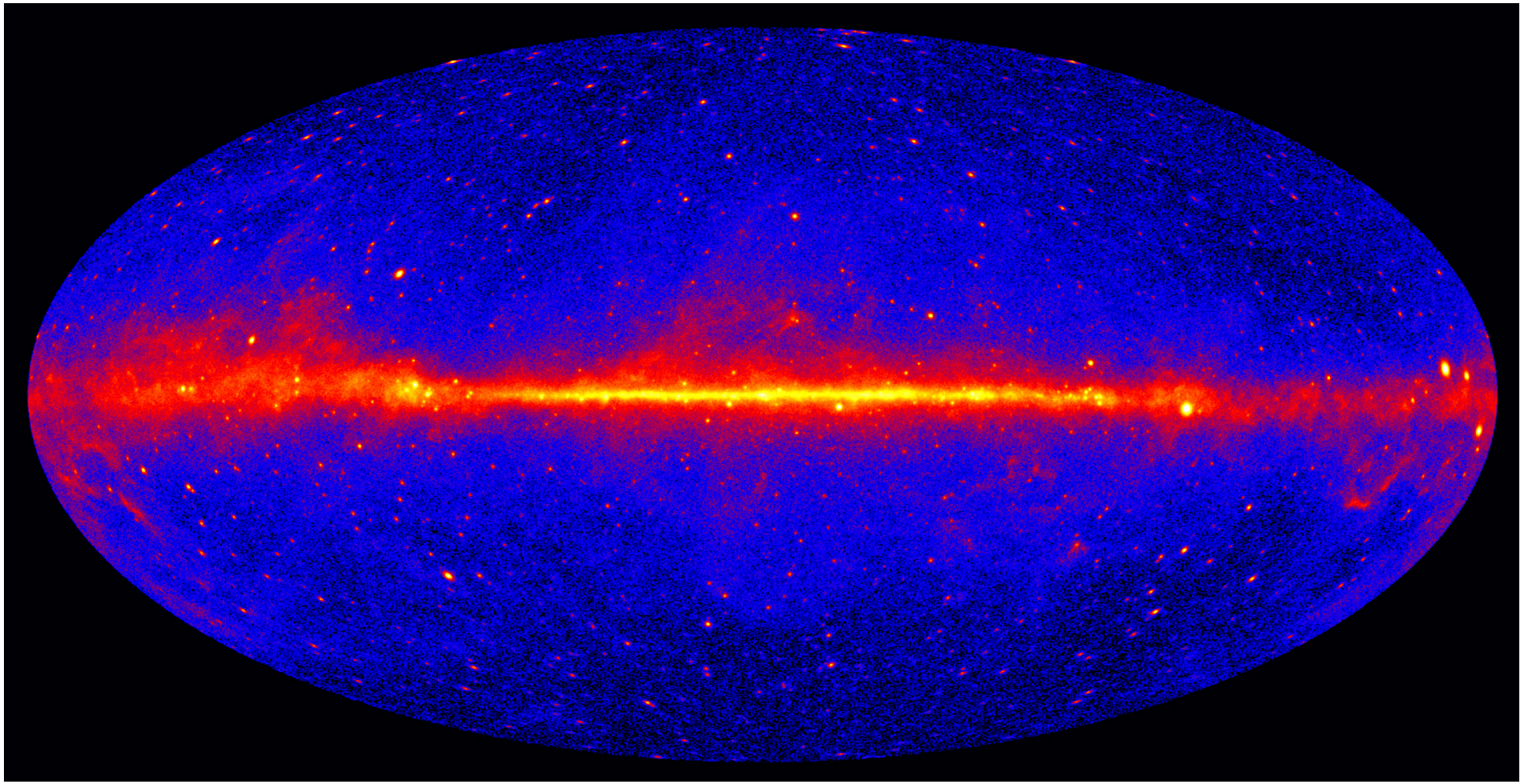
- **Huge field of view**
  - –LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV. **Total of >7 energy decades!**
- Large leap in all key capabilities. Great discovery potential.

Operating Mode

- Primary observing mode is Sky Survey
  - Full sky every 2 orbits (3 hours)
  - Uniform exposure, with each region viewed for ~30 minutes every 2 orbits
  - Best serves majority of science, facilitates multiwavelength observation planning
  - Exposure intervals commensurate with typical instrument integration times for sources
  - EGRET sensitivity reached in days

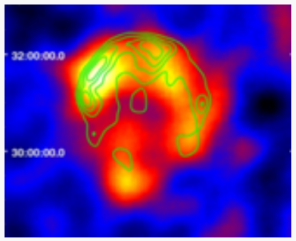


The Fermi Sky



10 years of Fermi !

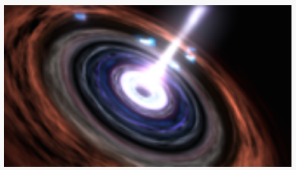
Exploring the Extreme Universe



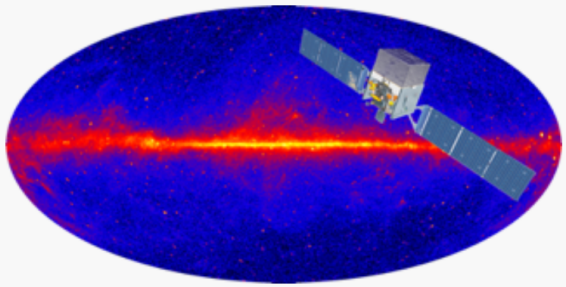
Supernova Remnants

Gamma-ray Bursts

Pulsar Wind Nebulae

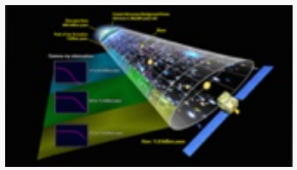


Active Galactic Nuclei

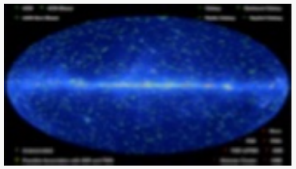


About Fermi

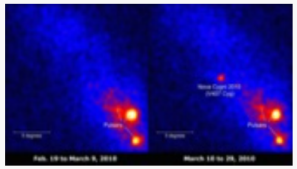
Click on the images or topic name for information about these science topics.



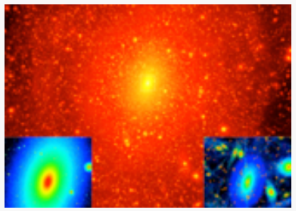
Extragalactic Background



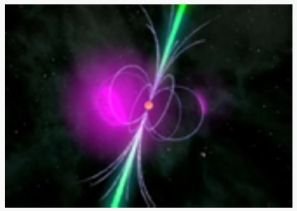
Catalogs



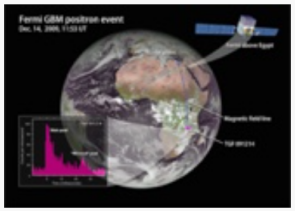
Binary Sources



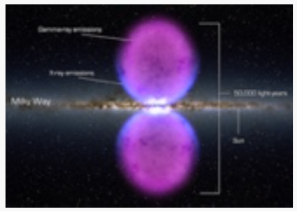
Dark Matter



Pulsars



Terrestrial Gamma-ray Flashes



Diffuse Gamma Radiation

How to access LAT Data

http://fermi.gsfc.nasa.gov/ssc/data/analysis/

LAT Data

- **LAT data products can be downloaded by the FSSC website**
  - **LAT Data server** http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi
  - **Archive of weekly files**
  - https://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/weekly/photon/

- **Two main data products (stored in FITS format)**
  - **Events file (FT1)**
  - **i. e. "what the LAT sees"**
    - (photons, their energy, coordinates, time, event classes etc..)
  - **Spacecraft files (FT2)**
  - **i. e. "where the LAT is"**
    - (position, angles..)

LAT catalogs

- LAT catalogs and associated products (high-level products only)
  - LAT Source Catalog
    - LAT 10-year Source Catalog (4FGL-DR2)
    - LAT 8-year Source Catalog (4FGL)
    - Preliminary LAT 8-year Source List (FL8Y)
    - LAT 4-year Source Catalog (3FGL)
    - LAT 2-year Source Catalog (2FGL)
    - LAT 1-year Source Catalog (1FGL)
    - LAT 3-month Bright Source List (0FGL)
  - Aperture Photometry Light Curves
    - Aperture Photometry Light Curves for LAT 10-year Catalog Sources (Updated Weekly)
    - Flaring Sources in the LAT 10-year Aperture Photometry Light Curves (Updated Weekly)
    - Aperture Photometry Light Curves for LAT 4-year Catalog Sources
    - Flaring Sources in the LAT 4-year Aperture Photometry Light Curves
    - Aperture Photometry Light Curves for the LAT 2-year Source Catalog
    - Flaring Sources in the LAT 2-year Aperture Photometry Lightcurves
  - LAT High Energy Source Catalog
    - LAT Third High Energy Source Catalog (3FHL)
    - LAT Second High-Energy Source Catalog (2FHL)
    - LAT First High-Energy Source Catalog (1FHL)
  - The Fourth Catalog of Active Galactic Nuclei -- Data Release 2 (4LAC-DR2)
  - The Fourth Catalog of Active Galactic Nuclei (4LAC)
  - LAT Monitored Source List Light Curves
  - LAT GRB Catalog
  - Extended Sources in the Galactic Plane (FGES)
  - Second Fermi All-sky Variability Analysis Catalog (2FAV)
  - 1st Fermi-LAT SNR Catalog
  - LAT 3-year Catalog of Gamma-ray Pulsars

https://fermi.gsfc.nasa.gov/ssc/data/access/

Event classes

Standard Hierarchy for LAT Event Classes				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT020	16		X	Transient event class with background rate equal to two times the A10 IGRB reference spectrum.
P8R3_TRANSIENT010	64		X	Transient event class with background rate equal to one times the A10 IGRB reference spectrum.
P8R3_SOURCE	128	X	X	This event class has a residual background rate that is comparable to P7REP_SOURCE. This is the recommended class for most analyses and provides good sensitivity for analysis of point sources and moderately extended sources.
P8R3_CLEAN	256	X	X	This class is identical to SOURCE below 3 GeV. Above 3 GeV it has a 1.3-2 times lower background rate than SOURCE and is slightly more sensitive to hard spectrum sources at high galactic latitudes.
P8R3_ULTRACLEAN	512	X	X	This class has a background rate very similar to ULTRACLEANVETO.
P8R3_ULTRACLEANVETO	1024	X	X	This is the cleanest Pass 8 event class. Its background rate is 15-20% lower than the background rate of SOURCE class below 10 GeV, and 50% lower at 200 GeV. This class is recommended to check for CR-induced systematics as well as for studies of diffuse emission that require low levels of CR contamination.
P8R3_SOURCEVETO	2048	X	X	This class has the same background rate than the SOURCE class background rate up to 10 GeV but, above 50 GeV, its background rate is the same as the ULTRACLEANVETO one while having 15% more acceptance.

Event classes

Extended Hierarchy				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT020E	8		X	Extended version of the P8R3_TRANSIENT020 event class with a less restrictive fiducial cut on projected track length through the Calorimeter.
P8R3_TRANSIENT010E	32		X	Extended version of the P8R3_TRANSIENT010 event class with a less restrictive fiducial cut on projected track length through the Calorimeter.
NON-ACD Hierarchy				
Event Class	**evclass**	**Photon File**	**Extended File**	**Description**
P8R3_TRANSIENT015S	65536		X	Transient event class designed for analysis of prompt solar flares in which pileup activity may be present. This class has a background rate equal to 1.5 times the A10 reference spectrum.

Recommendations

Event Selection Recommendations (P8R3)

Analysis Type	Minimum Energy (emin)	Maximum Energy (emax)	Max Zenith Angle (zmax)	Event Class (evclass)	IRF Name
Galactic Point Source Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2
Off-plane Point Source Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2
Burst and Transient Analysis (<200s)	100 (MeV)	500000 (MeV)	100 (degrees)	16	P8R3_TRANSIENT020_V2
Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	128	P8R3_SOURCE_V2
Extra-Galactic Diffuse Analysis	100 (MeV)	500000 (MeV)	90 (degrees)	1024	P8R3_ULTRACLEANVETO_V2 or P8R3_SOURCEVETO_V2 (when interested in E>1 GeV energy range)
Impulsive Solar Flare Analysis	100 (MeV)	500000 (MeV)	100 (degrees)	65536	P8R3_TRANSIENT015S_V2

Recommendations

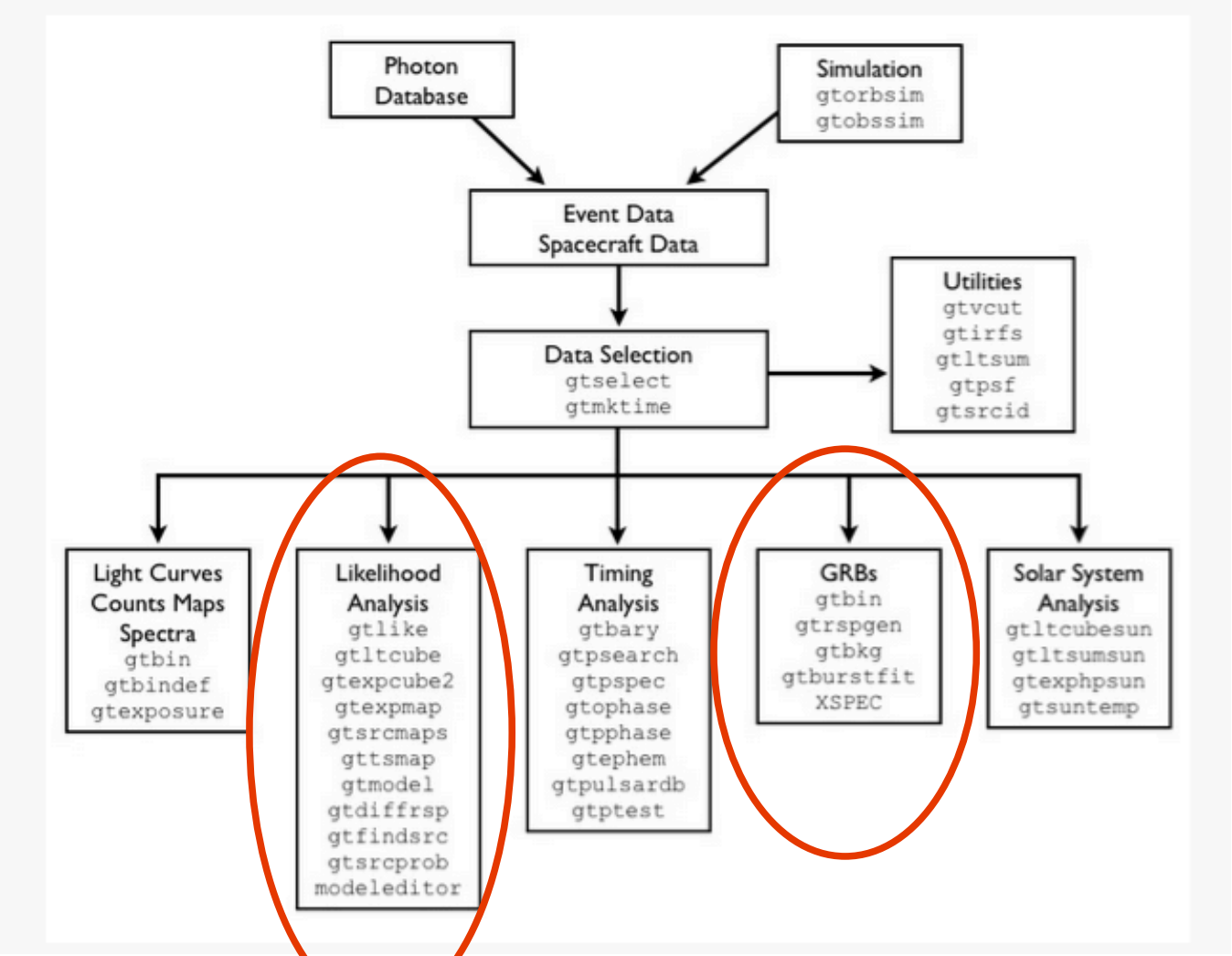
Time Selection Recommendations

Analysis Type	ROI-Based Zenith Angle Cut (roicut)	Relational Filter Expression (filter)
Galactic Point Source Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Off-plane Point Source Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Burst and Transient Analysis	yes	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Galactic Diffuse Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Extra-Galactic Diffuse Analysis	no	(DATA_QUAL>0)&&(LAT_CONFIG==1)
Burst and Transient Analysis	yes	(DATA_QUAL>0||DATA_QUAL==-1)&& (LAT_CONFIG==1)

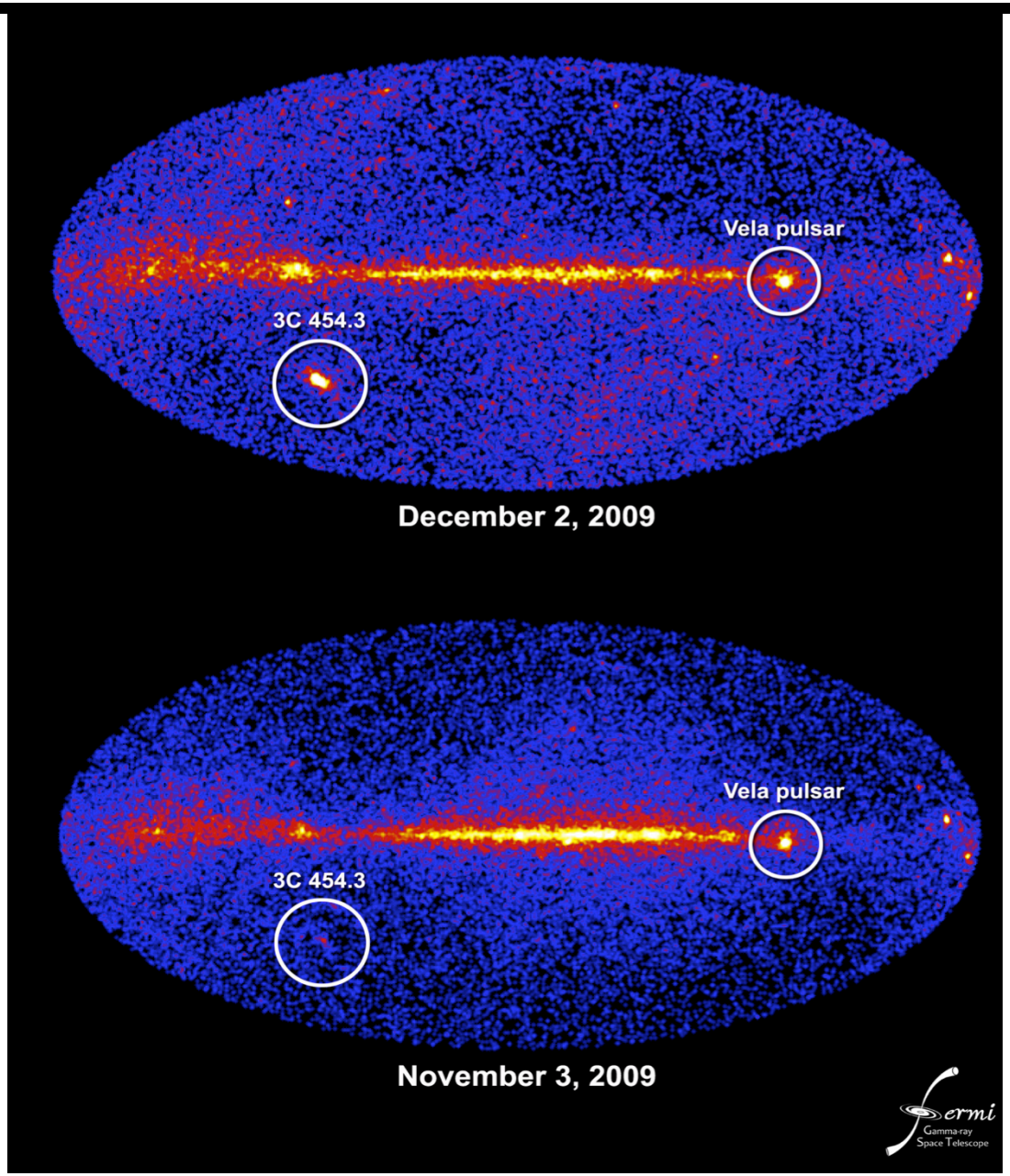
IMPORTANT: For analyses where an ROI-based zenith cut is NOT performed, an exposure correction must be made using the "zmax" option in the gtltcube tool.

Explore LAT data

Overview of Fermi Science Tools

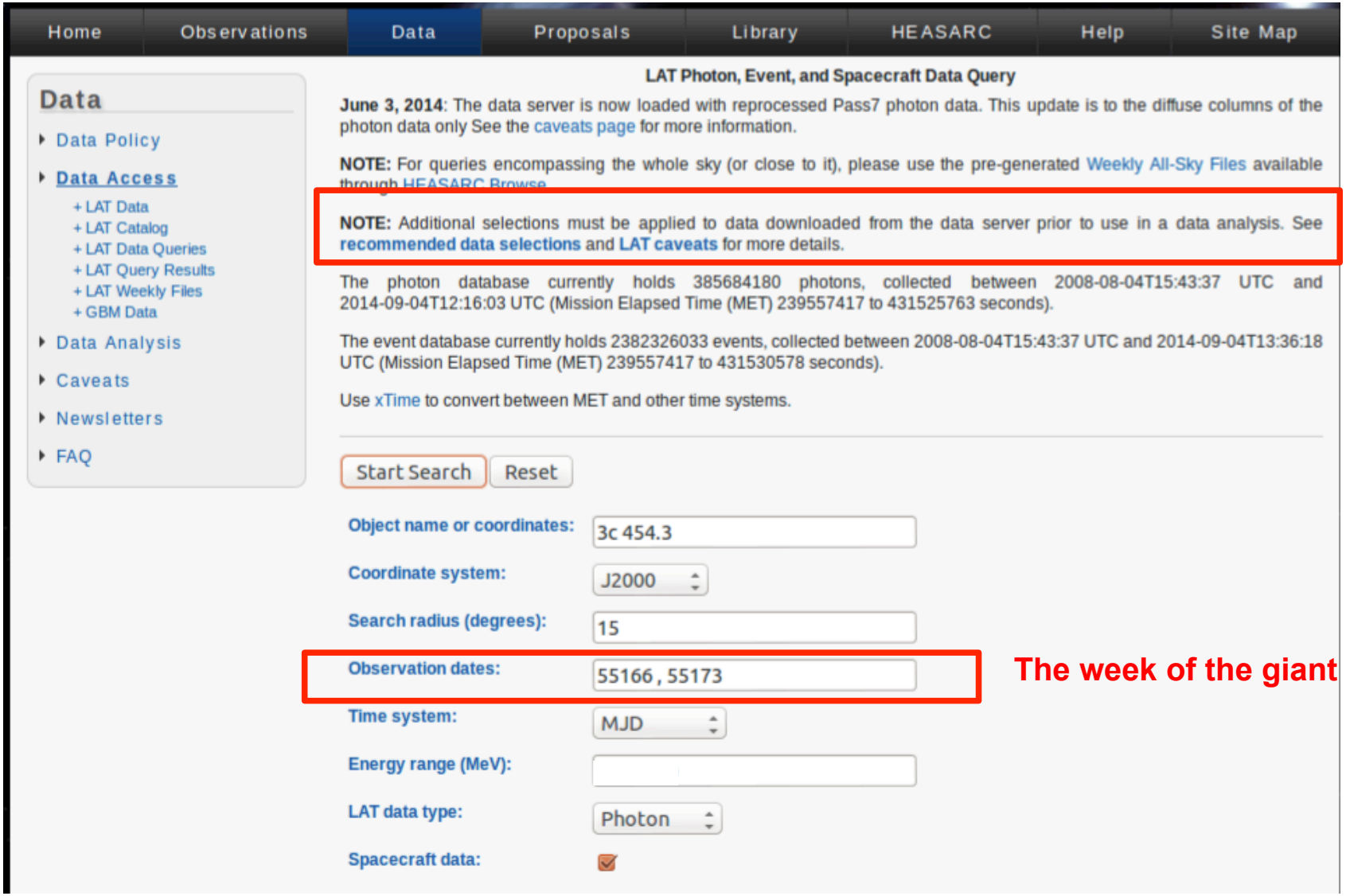


Blazar one of … 3c454.3's record flares!



How to download data

http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi



The week of the giant outburst!!

→ Download both spacecraft and photon data ←

Take note of the start and stop MET

follow the link

- Data Policy
- **Data Access**
  - + LAT Data
  - + LAT Catalog
  - + LAT Data Queries
  - + LAT Query Results
  - + LAT Weekly Files
  - + GBM Data
- Data Analysis
- Caveats
- Newsletters
- FAQ

Your search criteria were:

Equatorial coordinates (degrees)	(343.491,16.1482)
Time range (MET)	(281318400,281923200)
Time range (Gregorian)	(2009-12-01 00:00:00,2009-12-08 00:00:00)
Energy range (MeV)	(100,300)
Search radius (degrees)	15

The state of your query is 2 (Query complete)

Server	Position in Queue	Estimated Time Remaining (sec)
Photon Server	Query complete	N/A
Spacecraft Server	Query complete	N/A

The filenames of the result files consist of the query ID string with an identifier appended to indicate which database the file came from. The identifiers are of the form: _DDNN where DD indicates the database and NN is the file number. The file number will generally be '00' unless the query resulted in a large data volume. In that case the data is broken up into multiple files. The values of the database field are:

- PH - Photon Database
- SC - Spacecraft Pointing, Livetime, and History Database
- EV - Extended Database

In the event that you do not see any files with the data type you requested listed below, you should try resubmitting your query as there may have been a problem.

Filename	Number of Entries	Size (MB)	Status
L14090420274034A4AC2B81_PH00.fits	3372	0.33	Available
L14090420274034A4AC2B81_SC00.fits	17120	2.52	Available

If you would like to download the files via wget, simply copy the following commands and paste them into a terminal window. The files will be downloaded to the current directory in the terminal window.

```
wget http://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L14090420274034A4AC2B81_PH00.fits
wget http://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L14090420274034A4AC2B81_SC00.fits
```

gtselect (select data)

[/home/]$ gtselect evclass=128 evtype=3
Input FT1 file[photon.fits]
Output FT1 file[filtered.fits]
RA for new search center (degrees) (0:360) [343.494812]
Dec for new search center (degrees) (-90:90) [16.1495]
radius of new search region (degrees) (0:180) [10]
start time (MET in s) (0:) [281318400]
end time (MET in s) (0:) [281923200]
lower energy limit (MeV) (0:) [100]
upper energy limit (MeV) (0:) [500000]
maximum zenith angle value (degrees) (0:180) [90]

Events with a high prob. to be gammas

Setting the max ZA, filter gammas from albedo events (gamma from the Earth that can be a significant source of background)

> gtselect evclass=128 evtype=3 infile=ph.fits outfile=filtered.fits \
ra=343.49 dec=16.15 rad=15 tmin=281318400 tmax=281923200 \
emin=100 emax=500000 zmax=90

Note: all analysis steps are scriptable via explicit assign parameters on command-line. Look at the manual for details.

gtmktime (cut the bad time intervals)

Filter out events collected while passing in SAA and other low-quality events

[/home/]$ gtmktime
Spacecraft data file[spacecraft.fits]
Filter expression[(DATA_QUAL>0)&&(LAT_CONFIG==1)]
Apply ROI-based zenith angle cut[no]
Event data file[filtered.fits]
Output event file name[filtered_gti.fits]

Use ZA to filter only proper GTIs

gtbin (Counts Map)

[/home]$ gtbin

Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [CMAP]

Event data file name[filtered_gti.fits]

Output file name[cmap.fits]

Spacecraft data file name[spacecraft.fits]

Size of the X axis in pixels[120]

Size of the Y axis in pixels[120]

Image scale (in degrees/pixel)[0.25]

Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL]

First coordinate of image center in degrees (RA or galactic l) [343.494812]

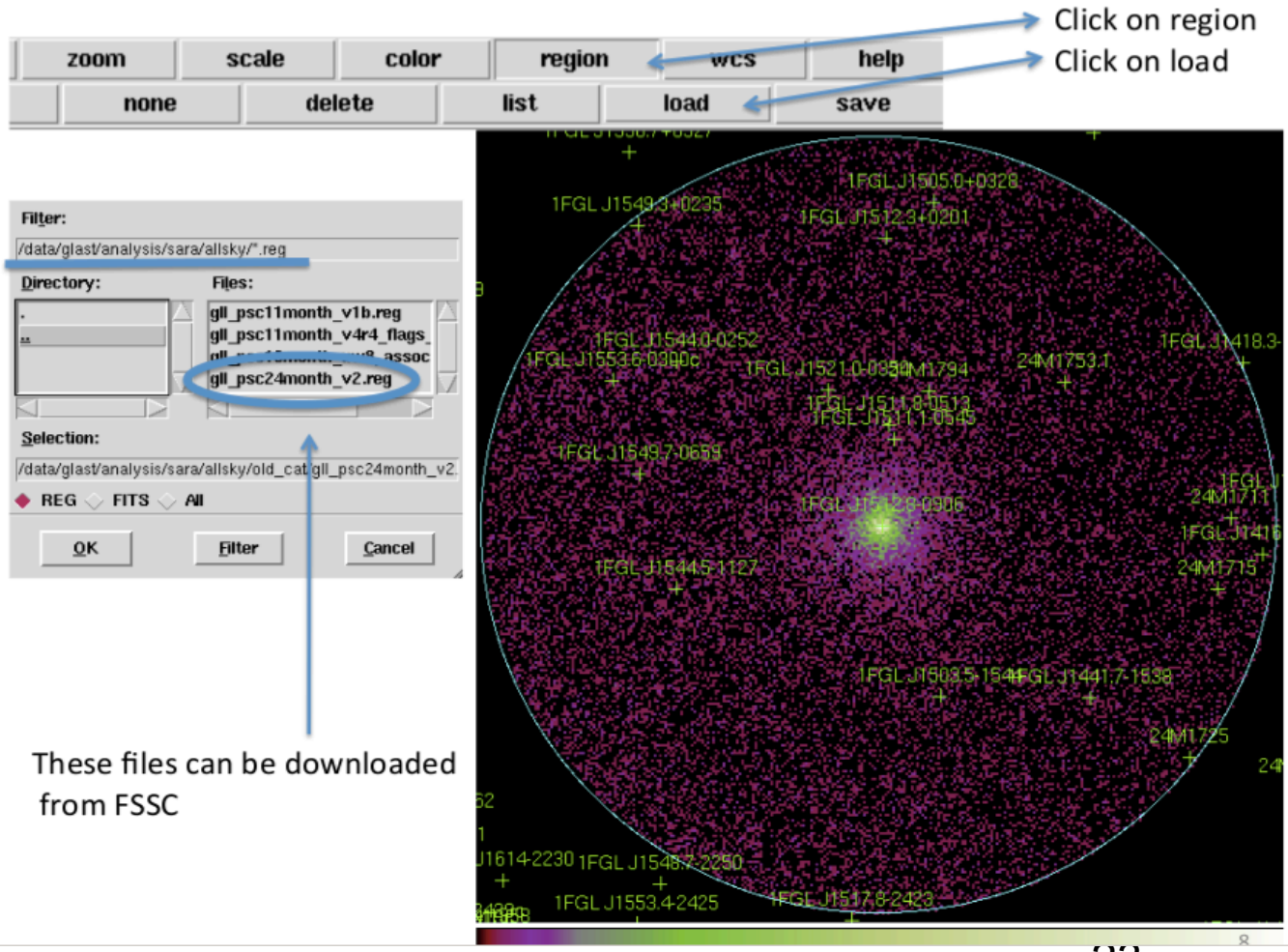
Second coordinate of image center in degrees (DEC or galactic b) [16.1495]

Rotation angle of image axis, in degrees[0]

Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN: [AIT]

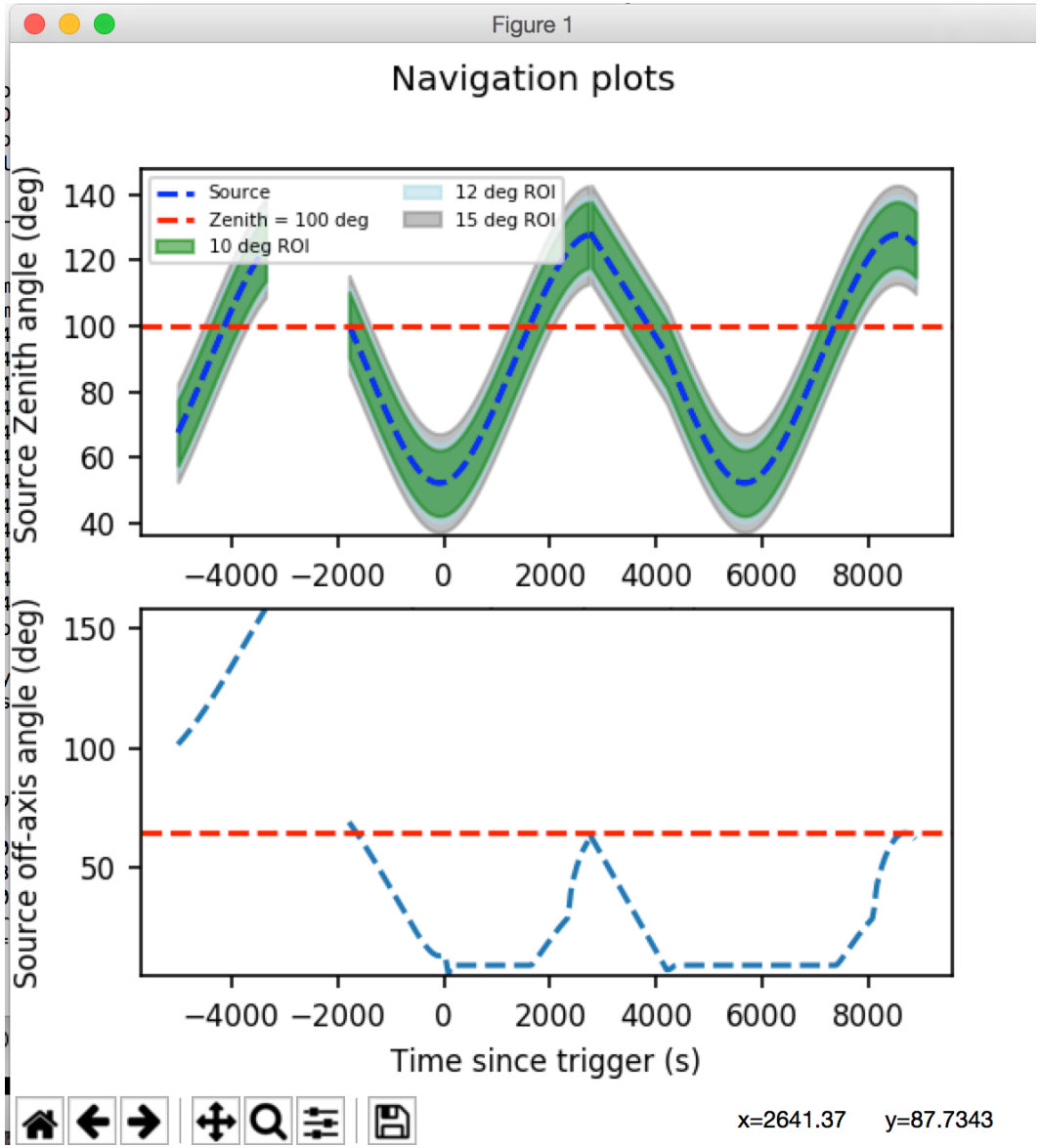
Look at the counts map

Use DS9 to look at the counts map of your ROI and check for close-by sources
> ds9 CMAP.fits &



Analysis Tutorial
likelihood analysis with gtburst

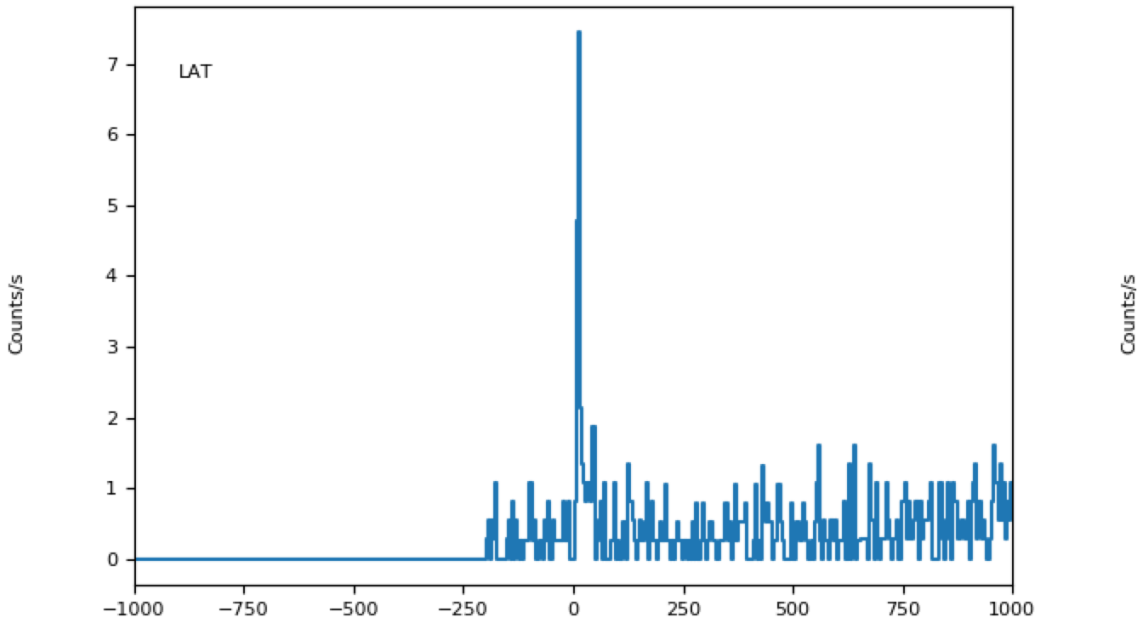
Check the “Navigation” plot



Likelihood with gtburst

Fermi bursts analysis GUI

Trigger name	bn160905471
R.A. (J2000)	162.245
Dec. (J2000)	-50.801
Trigger date (MET)	494767139.912



Detectors to display in the LC:

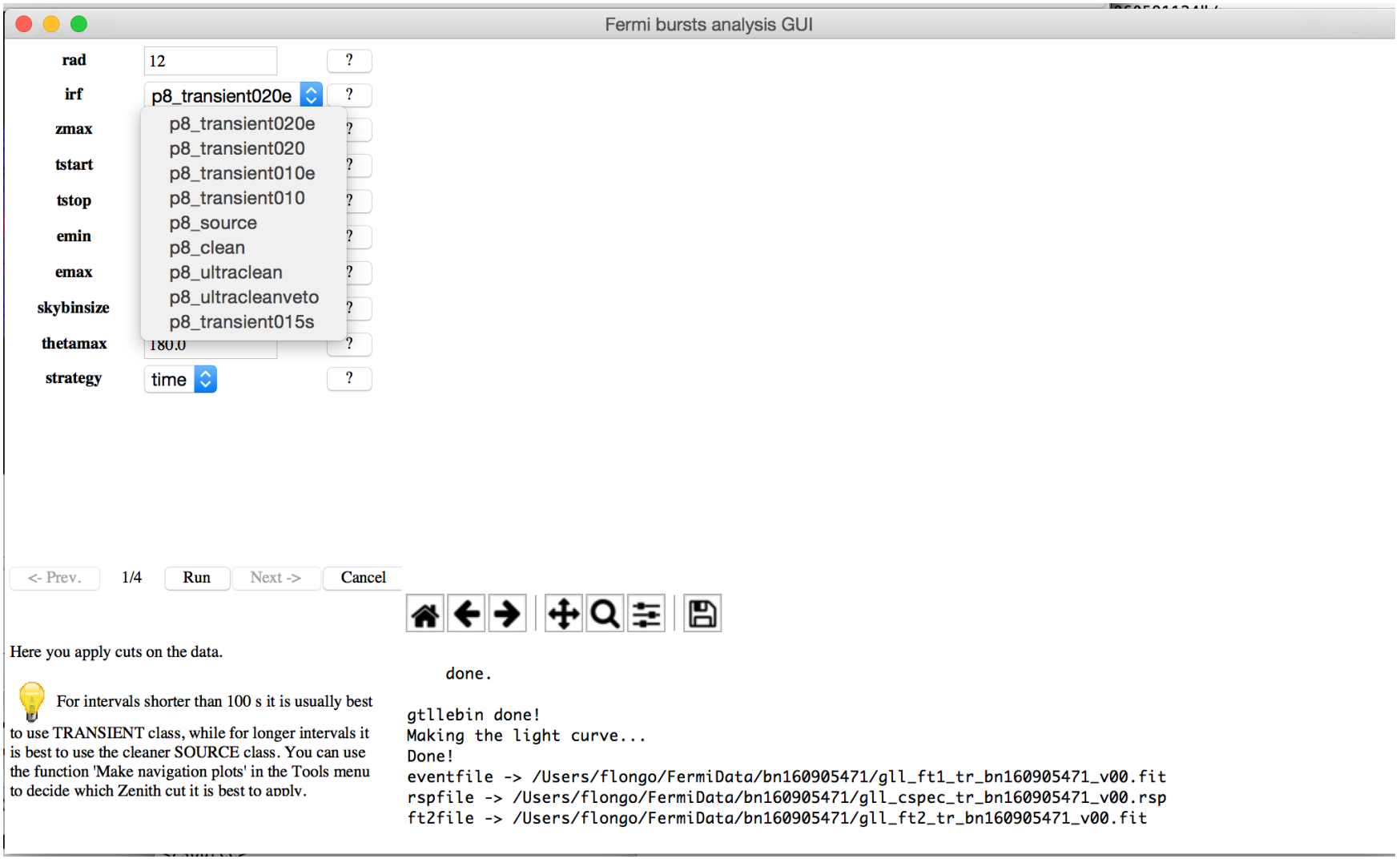
☑ LAT (16 deg)

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

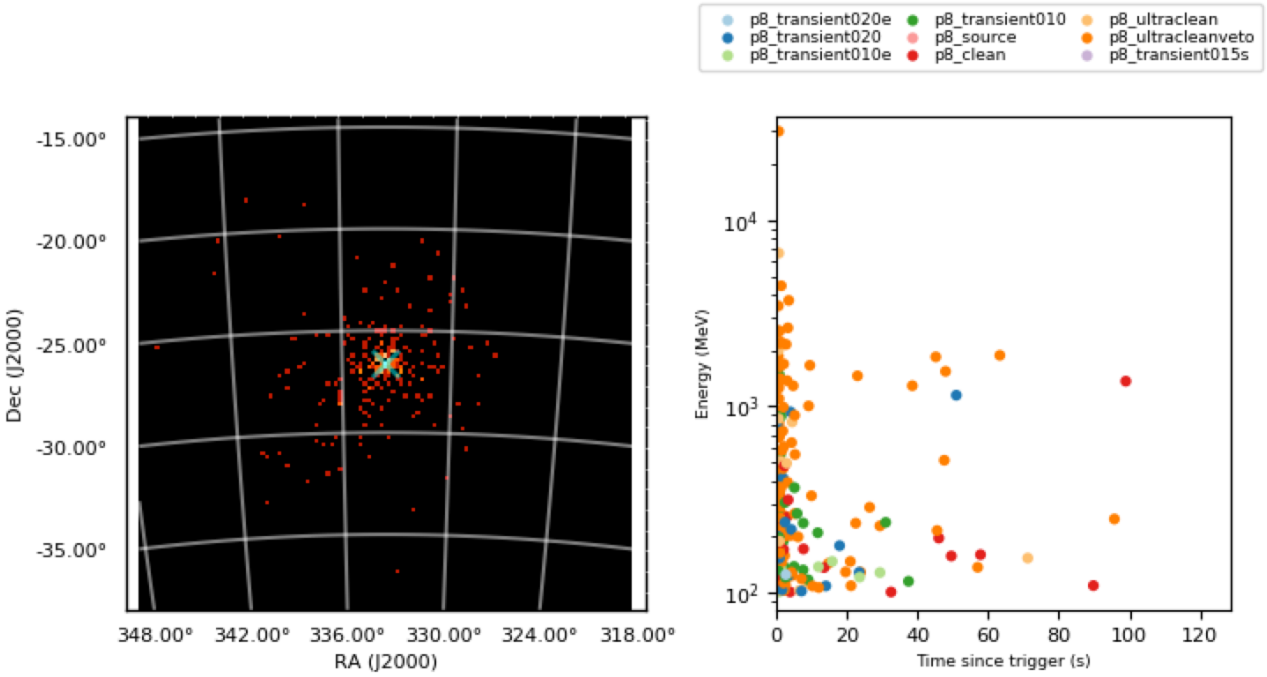
```
    done.

 *  Updating keywords in the headers of the CSPEC file...

    done.

gtllebin done!
Making the light curve...
Done!
```

Select event class



See count map and list of photons

rad	12	?
irf	p8_transient020e	?
zmax	100	?
tstart	0	?
tstop	100	?
emin	100	?
emax	100000	?
skybinsize	0.2	?
thetamax	180.0	?
strategy	time	?



<- Prev. 1/4 Run Next -> Cancel

Here you apply cuts on the data.

For intervals shorter than 100 s it is usually best to use TRANSIENT class, while for longer intervals it is best to use the cleaner SOURCE class. You can use the function 'Make navigation plots' in the Tools menu to decide which Zenith cut it is best to apply.

```
Class p8_transient010 only:                47
Class p8_source only:                      0
Class p8_clean only:                       32
Class p8_ultraclean only:                  19
Class p8_ultracleanveto only:              123
Class p8_transient015s only:               0

============================================================
```

Create XML model

Fermi bursts analysis GUI

particle_model	isotr template	?
galactic_model	template	?
source_model	powerlaw2	?
fgl_mode	fast	?

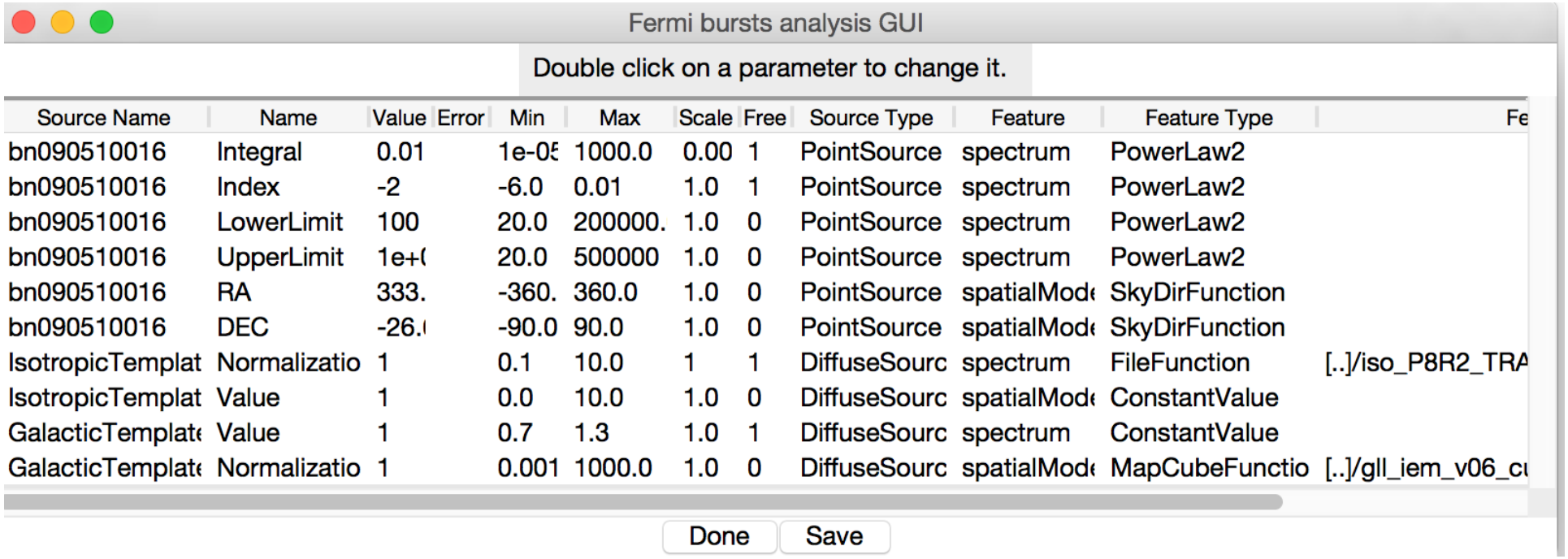
<- Prev. 2/4 Run Next -> Cancel

You have to choose which model include in the likelihood analysis. See http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html for the list of available spectral model for the source_model parameter.

Use 'PowerLaw2' for normal GRB analysis.

```
Cutting the template around the ROI:

Keeping diffuse source 3FGL J0852.7-4631e (19.39 deg away) using template /Users/flongo/FermiTools/miniconda2/envs/fermi/share/fermitools/data/pyBurstAnalysisGUI/templates/VelaJr.fits...
Kept 1 point sources from the FGL catalog

 ============================================================
```

Select the parameters of the model



Fit plots

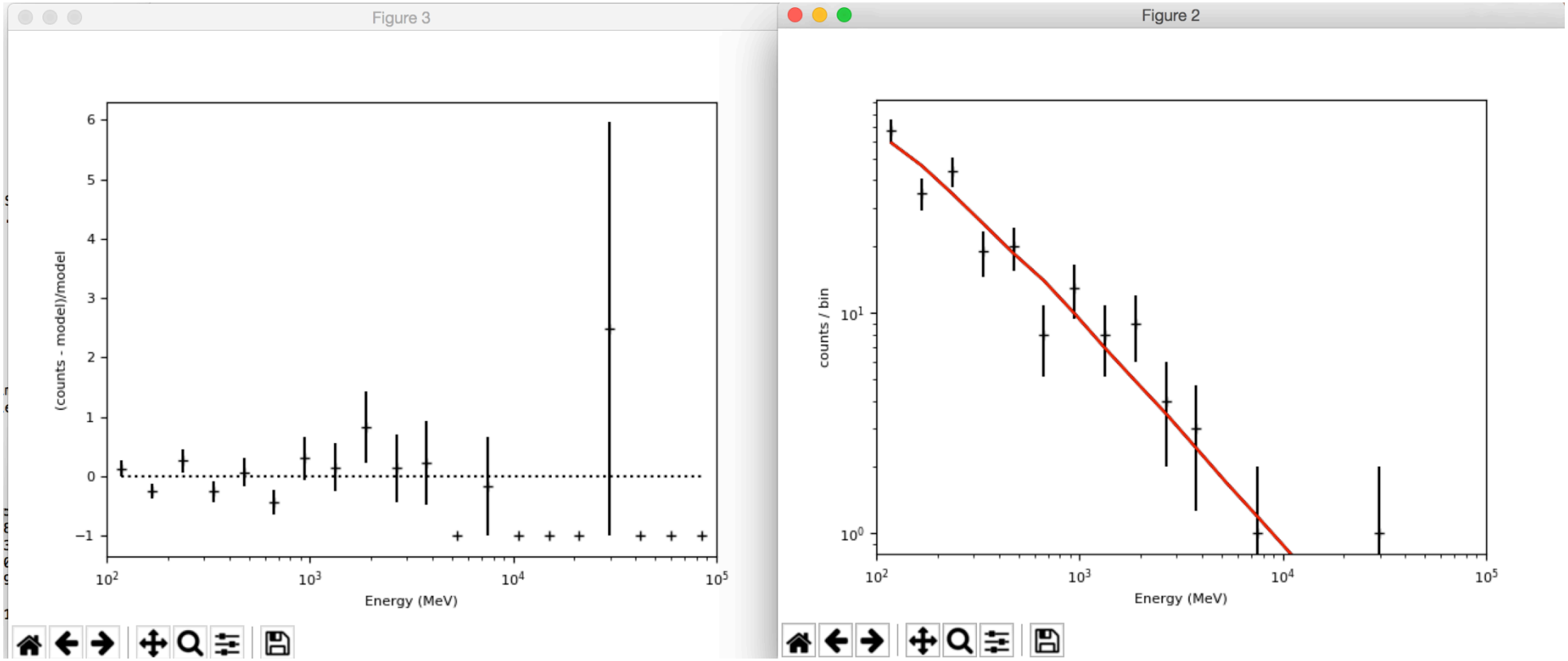


Figure 3
(counts - model)/model
Energy (MeV)
Figure 2
counts / bin
Energy (MeV)

Fit results

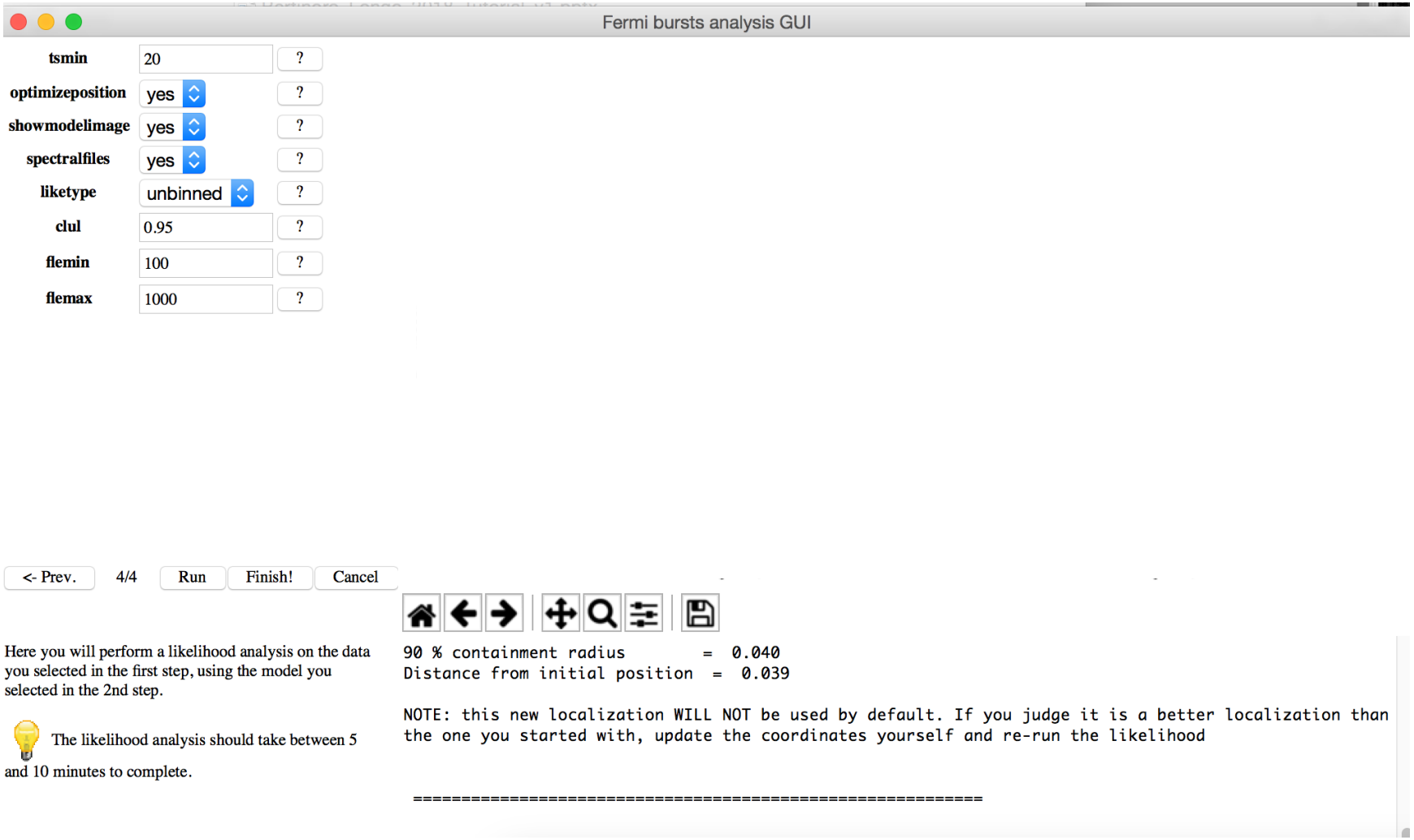
Likelihood results

Source name	Par. Name	Value	Error	Units	TS
GalacticTemplate					0
	Value	1	0.15	-	
	Energy flux	2.1e-07	3.14e-08	erg/cm2/s	
	Photon flux	0.000443	6.63e-05	ph./cm2/s	
IsotropicTemplate					1
	Normalization	0.426	1.32	-	
	Energy flux	4.75e-08	1.47e-07	erg/cm2/s	
	Photon flux	0.000134	0.000413	ph./cm2/s	
bn090510016					2056
	Integral	0.000363	2.31e-05	ph./cm2/s	
	Index	-2.03	0.0628	-	
	LowerLimit	100	n.a. (fixed)	MeV	
	UpperLimit	1e+05	n.a. (fixed)	MeV	
	Energy flux	1.33e-07	8.44e-09	erg/cm2/s	
	Photon flux	0.00033	2.2e-05	ph./cm2/s	

```
*** All fluxes and upper limits have been computed in the 100.0 - 1000.0 energy range.
*** Upper limits (if any) are computed assuming a photon index of -2.0, with the 95.0 % c.l.
Log(likelihood) = 769.199818608

New localization from gtfindsrc:

(R.A., Dec)                    = (333.567, -26.625)
68 % containment radius        =  0.028
90 % containment radius        =  0.040
Distance from initial position  =  0.039
```

Results of the last likelihood analysis. Select 'close' from the file menu to close this window.

Fit results


Fermi bursts analysis GUI
tsmin
20
?
optimizeposition
yes
?
showmodelimage
yes
?
spectralfiles
yes
?
liketype
unbinned
?
clul
0.95
?
flemin
100
?
flemax
1000
?
<- Prev.
4/4
Run
Finish!
Cancel
Here you will perform a likelihood analysis on the data you selected in the first step, using the model you selected in the 2nd step.
The likelihood analysis should take between 5 and 10 minutes to complete.
90 % containment radius = 0.040
Distance from initial position = 0.039
NOTE: this new localization WILL NOT be used by default. If you judge it is a better localization than the one you started with, update the coordinates yourself and re-run the likelihood
==========

Where to find info?

Analysis Threads

Analysis Threads

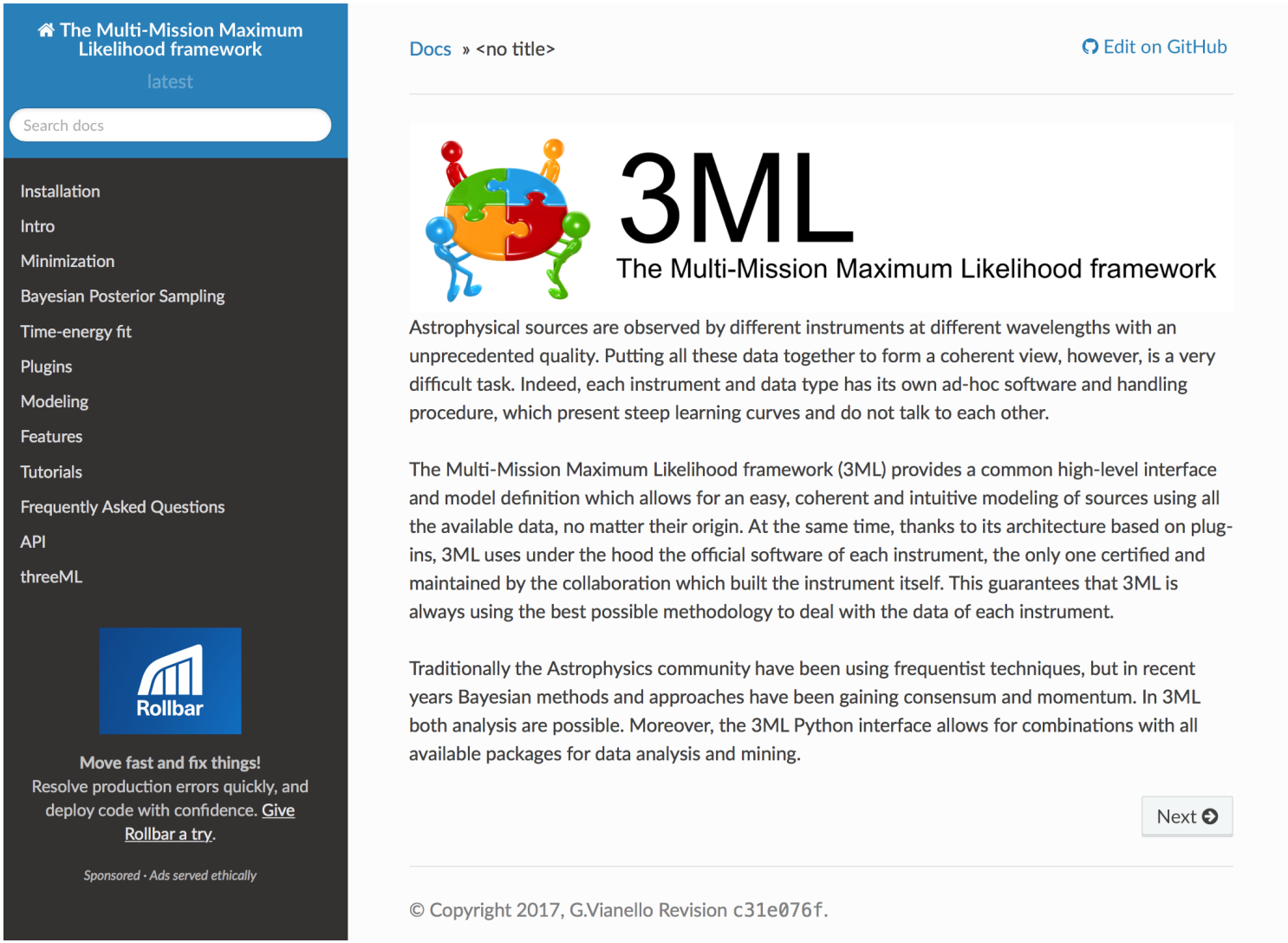
NOTE: These threads are based on the use of Pass 8 data. If you need information on Pass 7 data analysis, look here. Pass 6 analysis is no longer available with the Fermitools. A description of modifications made for the Pass 8 data set is available here.

- Overview
- LAT Analysis Start Page
- Data Selection
  - Extract LAT Data
  - Data Preparation
  - Explore LAT Data
  - Explore LAT Data (for Burst)
  - Using LAT All-sky Weekly Files
- Source Analysis
  - Binned Likelihood Tutorial
  - Unbinned Likelihood Tutorial
  - Likelihood Analysis with Python
  - Summed Likelihood Analysis with Python
  - Binned Likelihood with Energy Dispersion (Python)
  - Upper Limits with Python
  - Extended Source Analysis (Binned Analysis from Python)
  - LAT Aperture Photometry Analysis
  - Pulsar Gating Tutorial
  - Evaluating Effective Area Systematics
- GRB Analysis
  - LAT GRB Analysis
  - GBM GRB Analysis Using RMFIT (includes XSPEC)
  - GRB Analysis Using GTBurst
- Pulsar Analysis
  - Pulsar Analysis Tutorial(Video Part 1)
  - Pulsar Analysis Tutorial(Video Part 2)
  - Pulsar Analysis Overview
  - Ephemeris Data File
  - Pulse Phase Calculation
  - Periodicity Test
  - Ephemeris Computation Utility
  - Period Search
  - Pulsation Search
  - Binary Orbital Phase Calculation

https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/

New Tools

3ML fitting tool



https://threeml.readthedocs.io/en/latest/

10 years of Fermi !