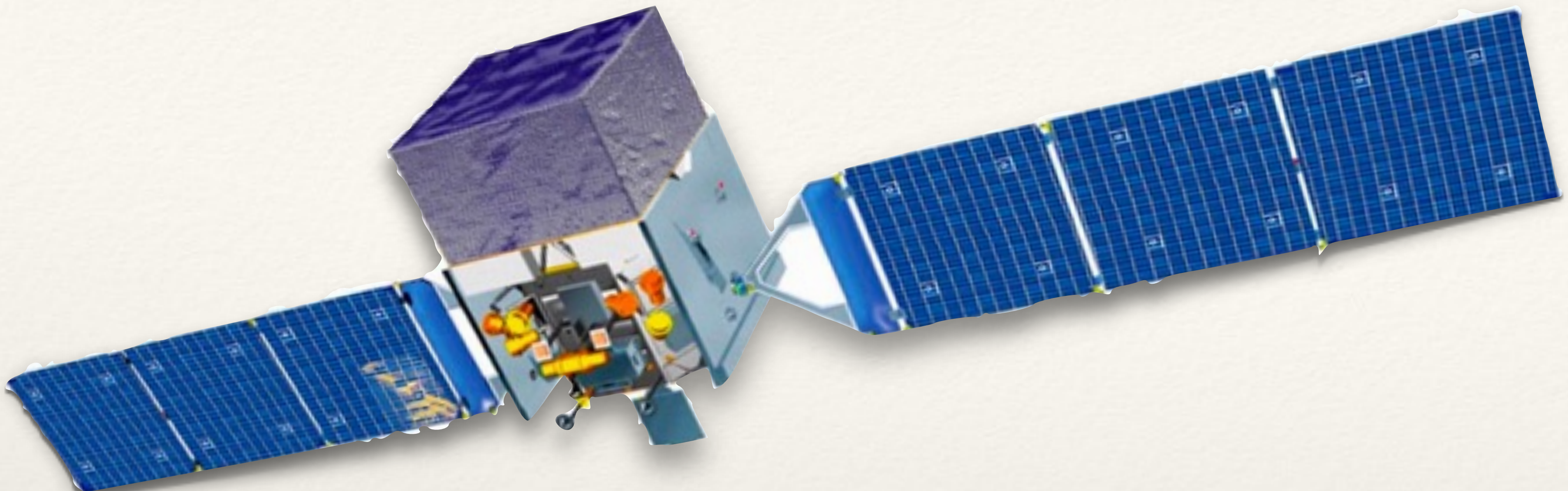

Fermi-LAT Data Analysis

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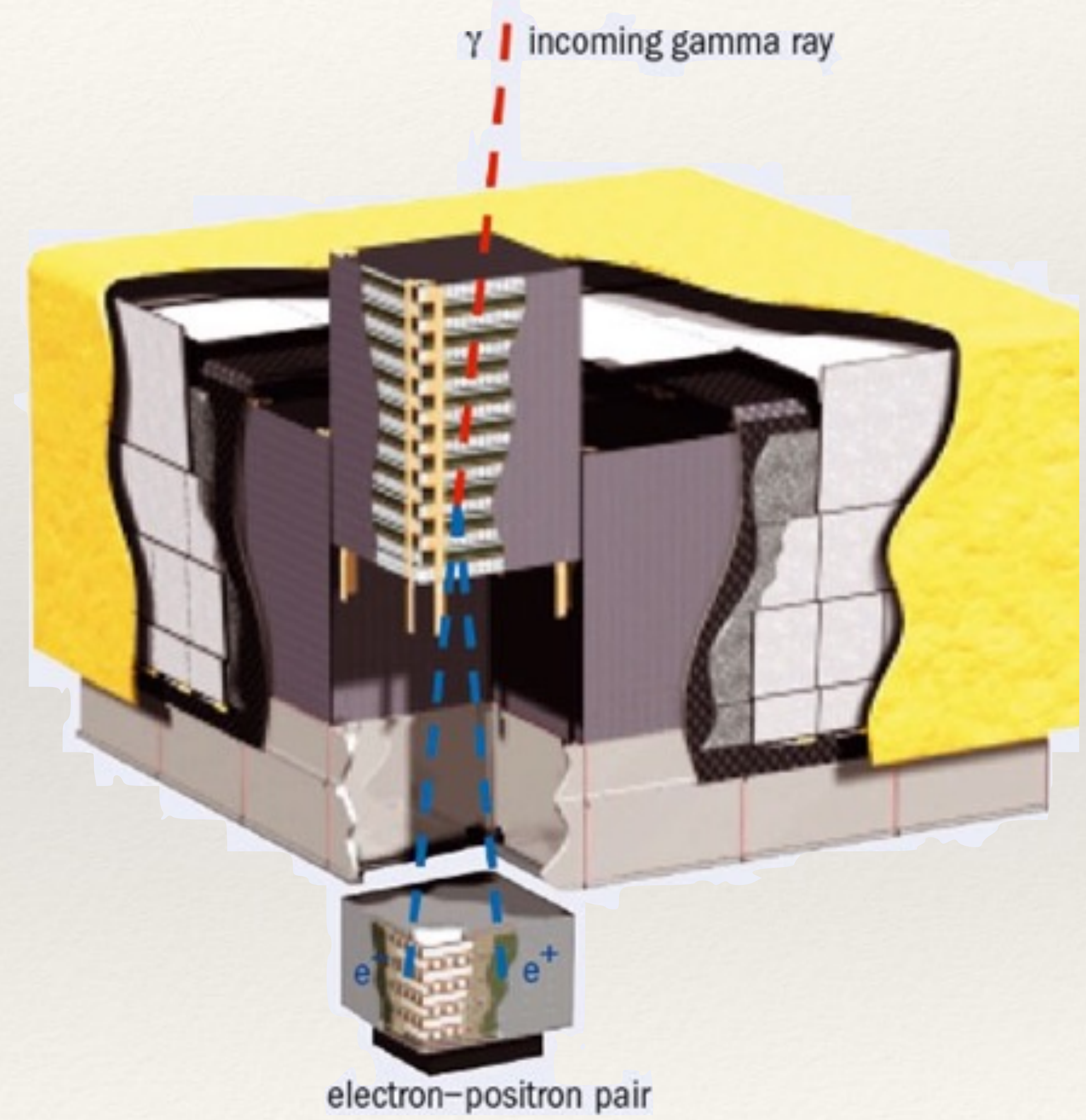
Introduction

- *Fermi* γ-ray Space Telescope is the most sensitive γ-ray satellite ever built by mankind
- It works in 20-500 GeV energy range
- *Fermi* has two onboard instruments
  - Large Area Telescope
  - Gamma-ray Burst Monitor

Introduction

- LAT is the primary workhorse and GBM is the secondary instrument
- LAT is used to study the extremely energetic events (novae, pulsars, AGN, starburst galaxies etc.)
- The primary function of GBM is to detect fast γ-ray transient events i.e., γ-ray bursts



Introduction

- We will analyze LAT data of the blazar 3C 279 (z=0.536)
- It was in an extremely high activity state in 2015 June
- The observed flux is the highest ever measured from this object (see details in Paliya, ApJ Letters, 2015, 808, L48)

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L48 (6pp), 2015 August 1 doi:10.1088/2041-8205/808/2/L48

FERMI-LARGE AREA TELESCOPE OBSERVATIONS OF THE EXCEPTIONAL GAMMA-RAY FLARE FROM 3C 279 IN 2015 JUNE

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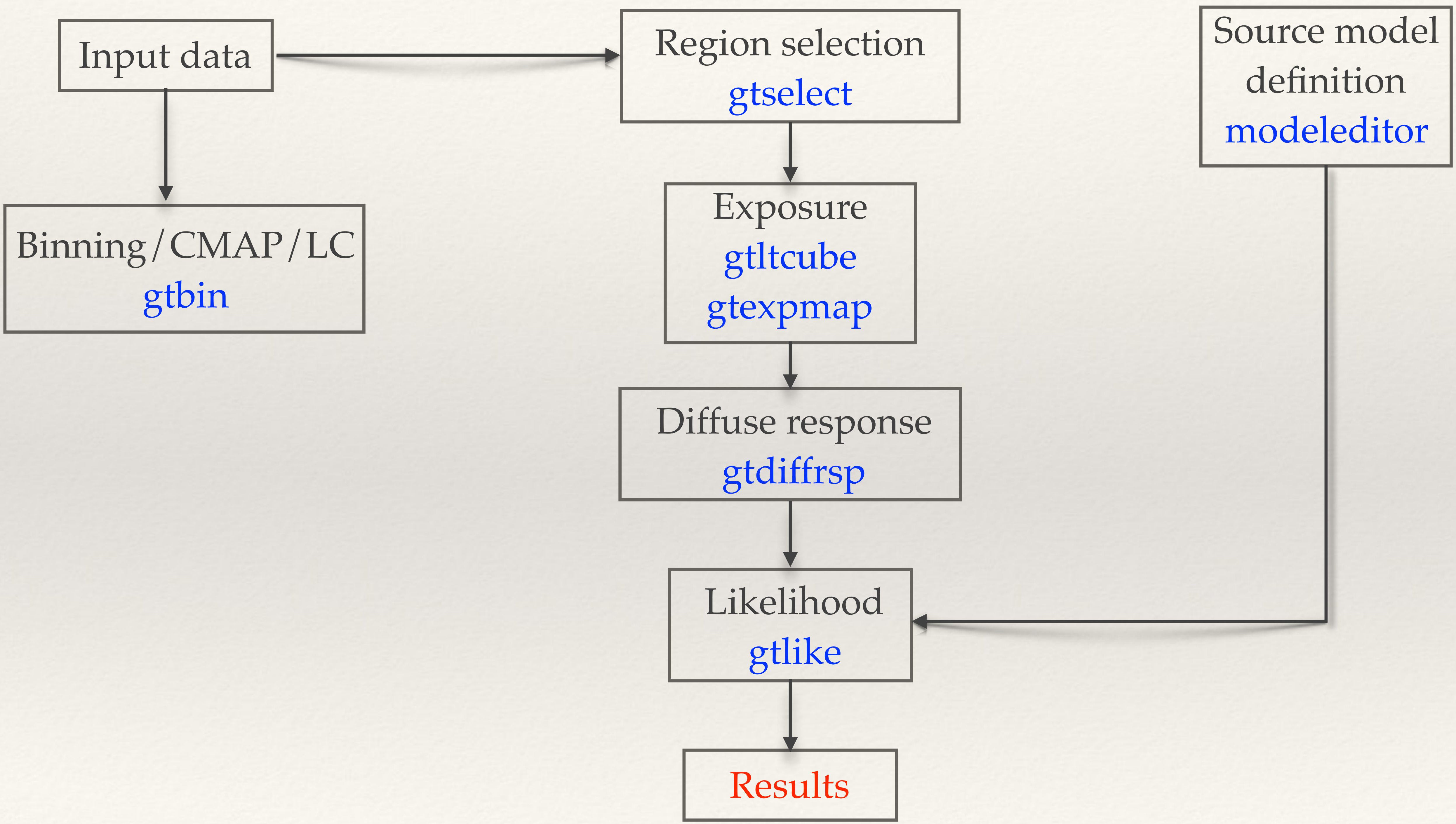
Aim of the work & Methodology

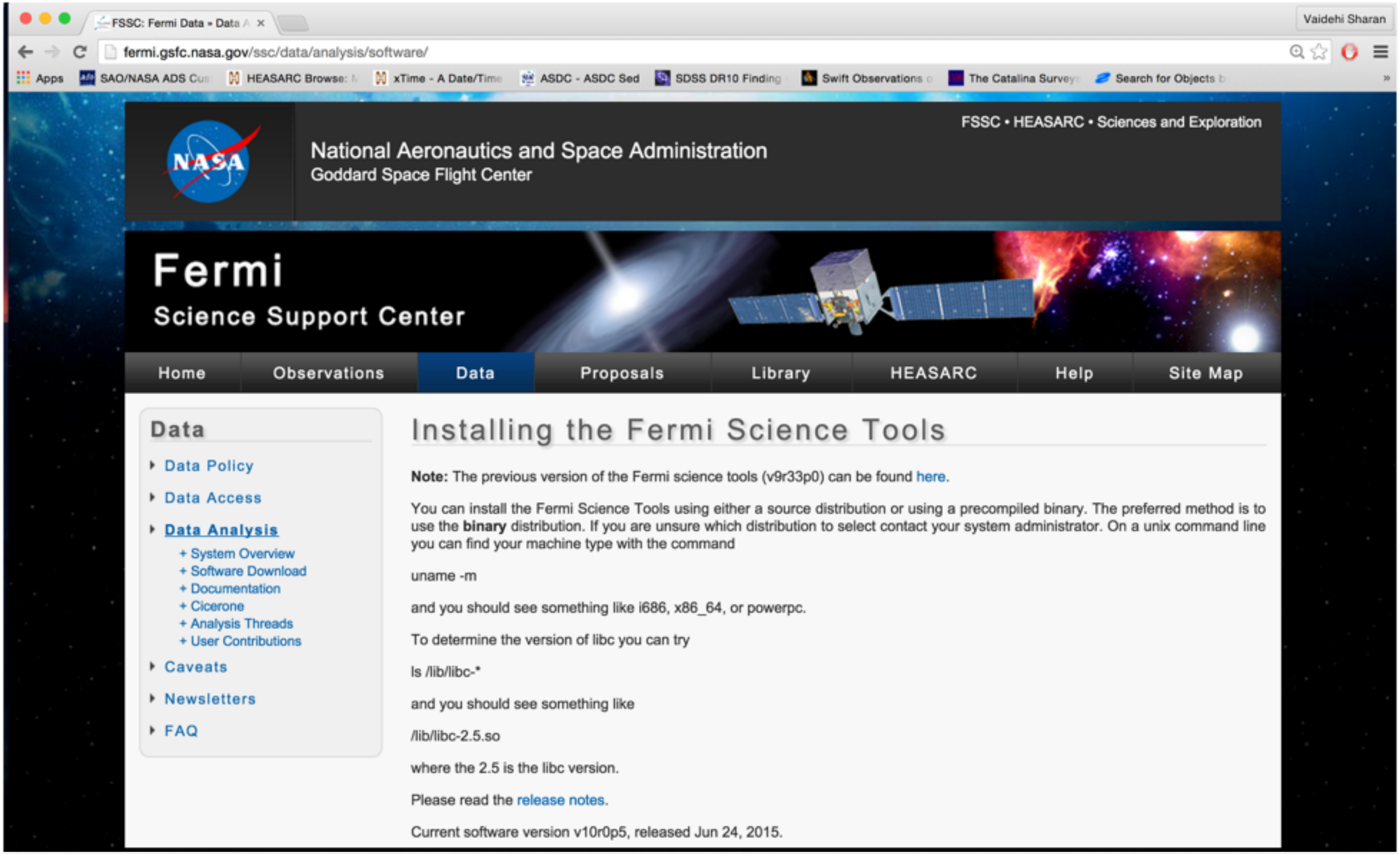
- The final aim of any data analysis work is to derive the best possible estimate for the characteristics (flux & spectral info) of a source
- We will use the Maximum Likelihood Analysis which has been successfully used in the γ-ray analysis of EGRET data and has also a central role in LAT data analysis
- The likelihood (L) is the probability of obtaining the data given an input model
- In our case, the input model is the distribution of γ-ray sources in the sky, and includes their intensity and spectra
- One will maximize L to get the best match of the model to the data

Likelihood Analysis in a Nutshell

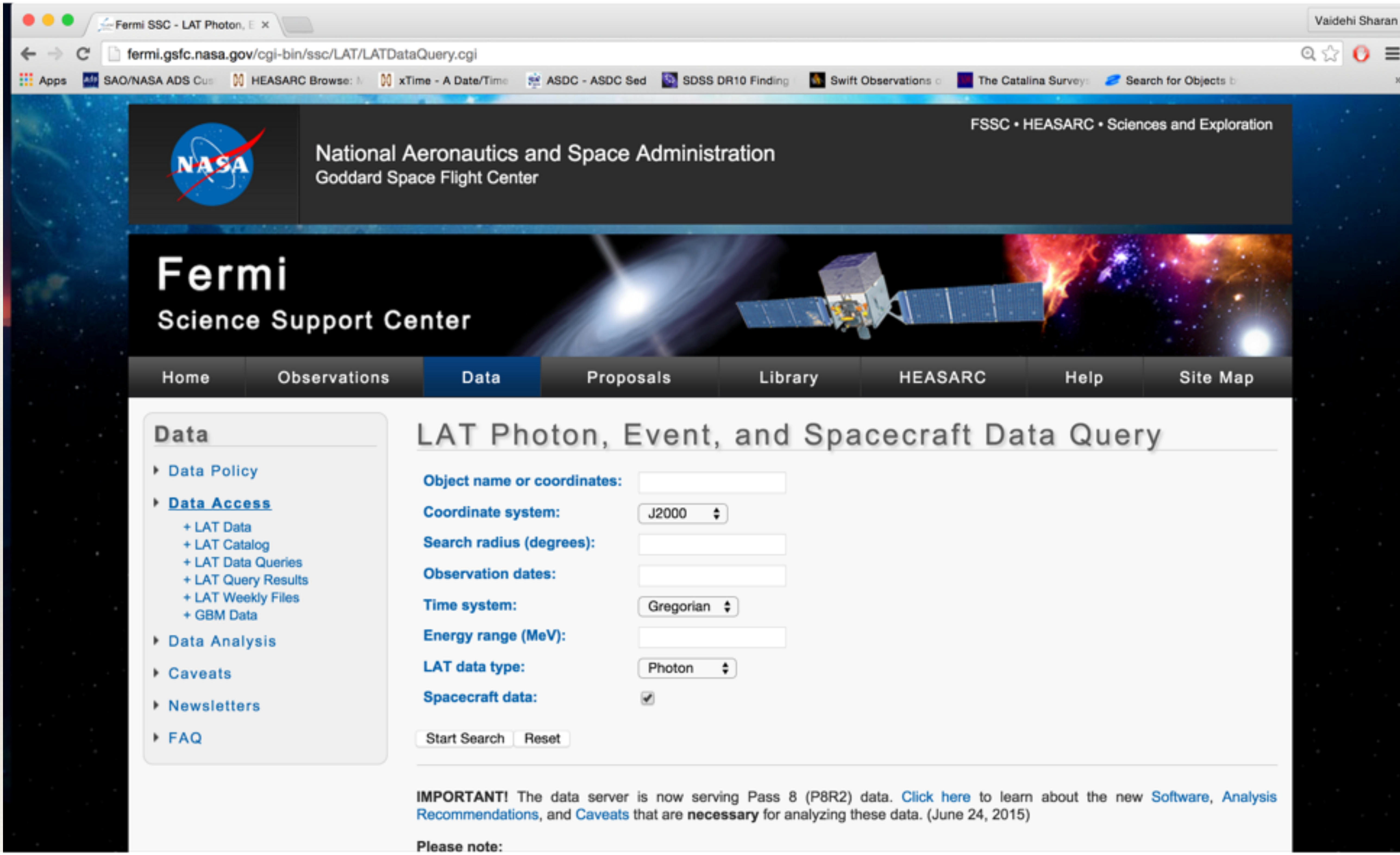


Before we start: Prerequisites

- *Fermi*-LAT analysis is an extremely computational intensive task
- It demands both high computer memory and hard disk space
- To perform a standard analysis, we need the following
  - *Fermi* analysis software: ScienceTools
  - Event files
  - Spacecraft file



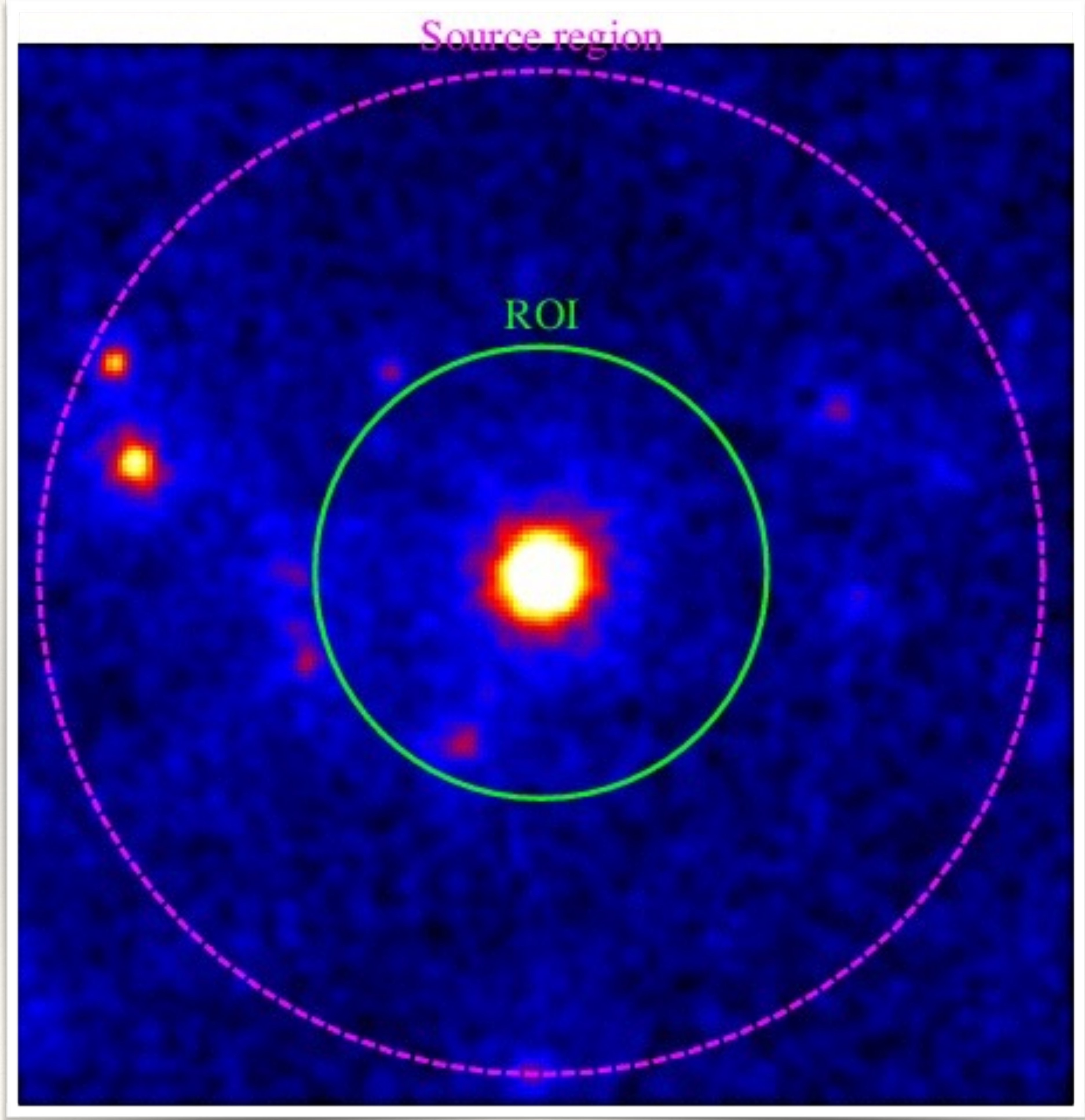
fermi.gsfc.nasa.gov/ssc/data/analysis/software/



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

Source region & ROI

- Due to large LAT psf at low energies, to analyze a single source, the counts within a region around the source have to be included
- This region is called "region of interest" (ROI)
- The ROI should be several times the typical psf size
- Nearby sources will contribute to the ROI, so they have to be modeled as well. The region that includes these additional sources is called the "source region"
- The "source region" is centered on the ROI, with a radius that is larger than the ROI radius by several psf length scales


Source region
ROI

Tools initiation

- Open two terminals
- Go to the directory containing LAT data (the folder I distributed)
- Type ‘fermiinit’ in the first terminal and press Enter
- Type ‘heainit’ in the second terminal and press Enter
- Let’s start with the first terminal (with ‘fermiinit’)

Step 1: Event selection

```
[Oracle@localhost 3C279_ICTS]$ gtselect evclass=128 evtype=3
Input FT1 file[] PH.fits
Output FT1 file[] filtered.fits
RA for new search center (degrees) (0:360) [INDEF] 194.041
Dec for new search center (degrees) (-90:90) [INDEF] -5.7912
radius of new search region (degrees) (0:180) [INDEF] 20
start time (MET in s) (0:) [INDEF] 455932803
end time (MET in s) (0:) [INDEF] 456192003
lower energy limit (MeV) (0:) [30] 100
upper energy limit (MeV) (0:) [300000] 300000
maximum zenith angle value (degrees) (0:180) [180] 90
Done.
[Oracle@localhost 3C279_ICTS]$
```

- Performs selection cuts in event data file, typically to define the ROI with event belonging to certain class (here SOURCE class)

Step 1: Good time selection

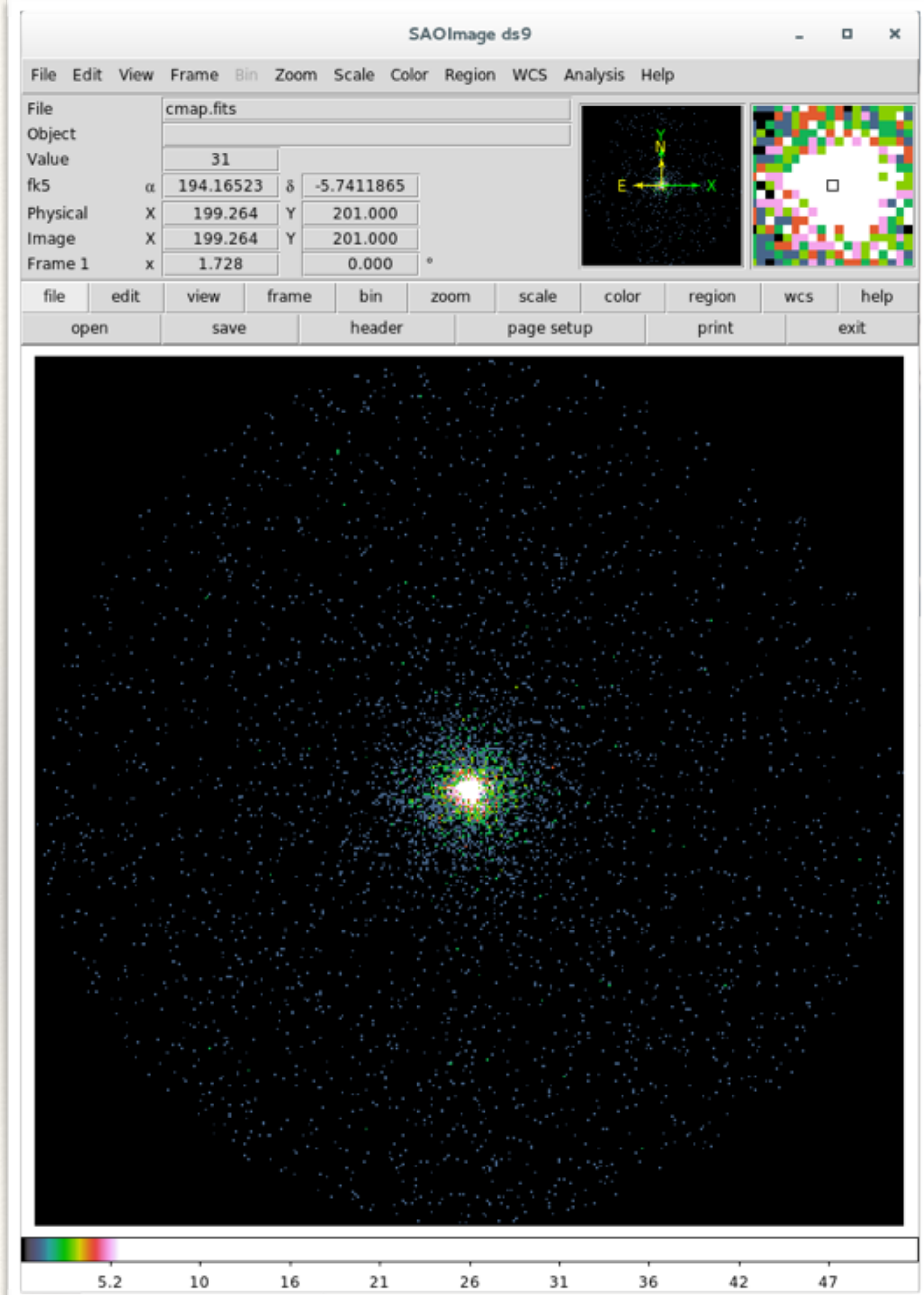
```
[Oracle@localhost 3C279_ICTS]$ gtmktime
Spacecraft data file[] SC.fits
Filter expression[DATA_QUAL>0 && LAT_CONFIG==1 && ABS(ROCK_ANGLE)<52] (DATA_QUAL>0) && (LAT_CONFIG==1)
Apply ROI-based zenith angle cut[yes] no
Event data file[] filtered.fits
Output event file name[] gti.fits
[Oracle@localhost 3C279_ICTS]$ 
```

- Create Good Time Intervals (GTIs) based on selections made using the spacecraft (SC) data file variables
- The tool gtmktime is used to update the GTI extension and make cuts based on SC parameters contained in the SC file. A GTI is a time range when the data can be considered valid

Step 2: Inspecting the ROI

```
[Oracle@localhost 3C279_ICTS]$ gtbin
This is gtbin version ScienceTools-v10r0p5-fssc-20150518
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [PHA2] CMAP
Event data file name[] gti.fits
Output file name[] cmap.fits
Spacecraft data file name[NONE] NONE
Size of the X axis in pixels[] 400
Size of the Y axis in pixels[] 400
Image scale (in degrees/pixel)[] 0.1
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL] CEL
First coordinate of image center in degrees (RA or galactic l)[] 194.041
Second coordinate of image center in degrees (DEC or galactic b)[] -5.7912
Rotation angle of image axis, in degrees[0.] 0.0
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT] AIT
gtbin: WARNING: No spacecraft file: EXPOSURE keyword will be set equal to ontime.
[Oracle@localhost 3C279_ICTS]$ 
```

- This step is optional but it is always a good practice to take a look of the ROI, identify sources, and to ensure that the field looks sensible as simple sanity check


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File cmap.fits
Object
Value 31
fk5 α 194.16523 δ -5.7411865
Physical X 199.264 Y 201.000
Image X 199.264 Y 201.000
Frame 1 x 1.728 0.000 °
file edit view frame bin zoom scale color region wcs help
open save header page setup print exit
5.2 10 16 21 26 31 36 42 47

Exposure map calculation

```
[Oracle@localhost 3C279_ICTS]$ gtltcube zmax=90
Event data file[] gti.fits
Spacecraft data file[] SC.fits
Output file[expCube.fits] ltcube.fits
Step size in cos(theta) (0.:1.) [0.025] 0.025
Pixel size (degrees)[1] 1
Working on file SC.fits
.....................!
[Oracle@localhost 3C279_ICTS]$ 
```

- gtltcube calculates integrated livetime as a function of sky position and off-axis angle

Exposure map calculation

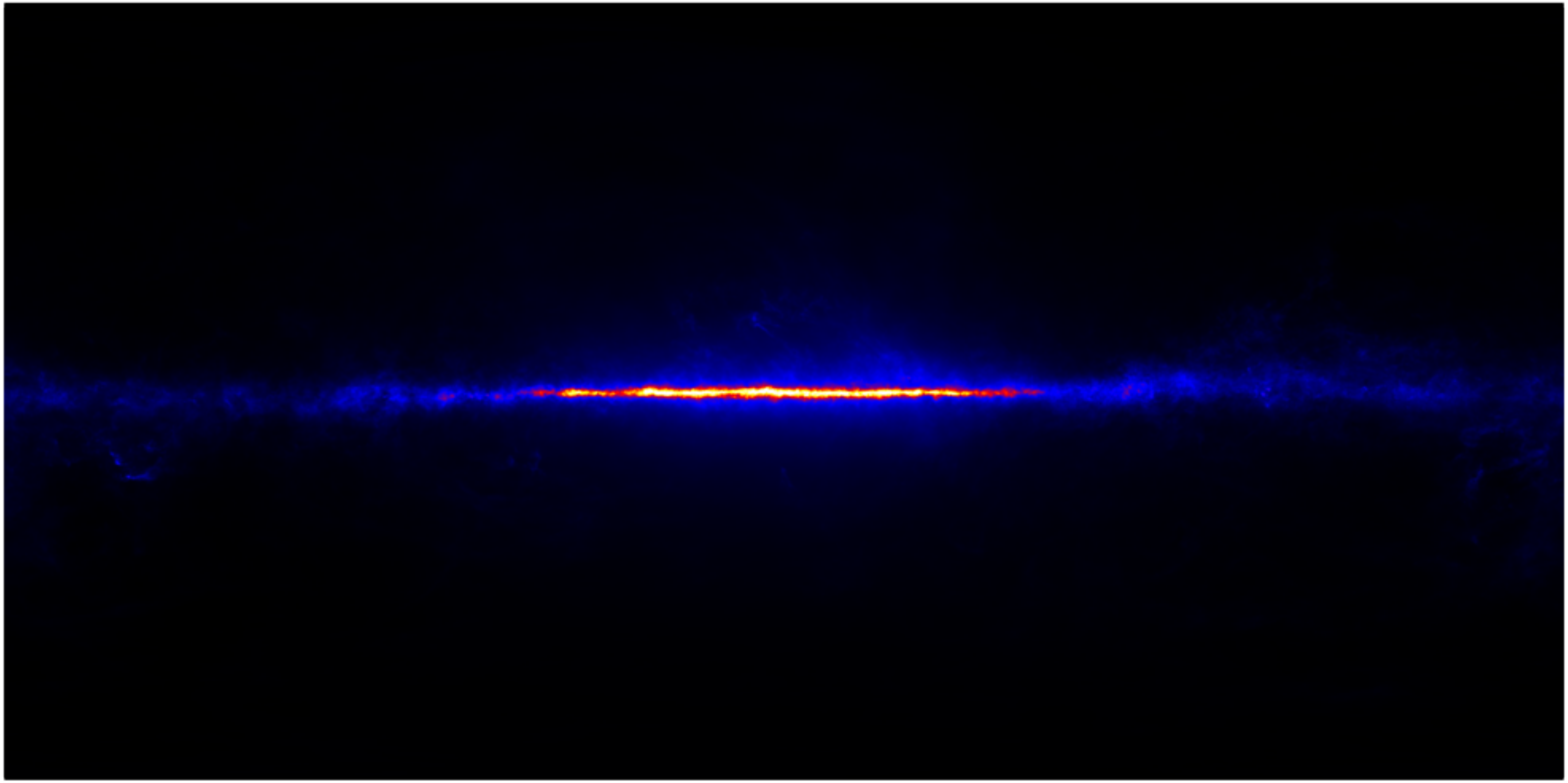
```
[Oracle@localhost 3C279_ICTS]$ gtexpmap
The exposure maps generated by this tool are meant
to be used for *unbinned* likelihood analysis only.
Do not use them for binned analyses.
Event data file[] gti.fits
Spacecraft data file[] SC.fits
Exposure hypercube file[] ltcube.fits
output file name[] expmap.fits
Response functions[CALDB] CALDB
Radius of the source region (in degrees)[30] 30
Number of longitude points (2:1000) [120] 120
Number of latitude points (2:1000) [120] 120
Number of energies (2:100) [20] 20
Computing the ExposureMap using ltcube.fits
....................!
[Oracle@localhost 3C279_ICTS]$ 
```

- It creates exposure maps needed to compute the predicted number of photons within a given ROI
- Integral of the total response (effective area x energy dispersion x psf) over entire ROI

Source model

model.xml

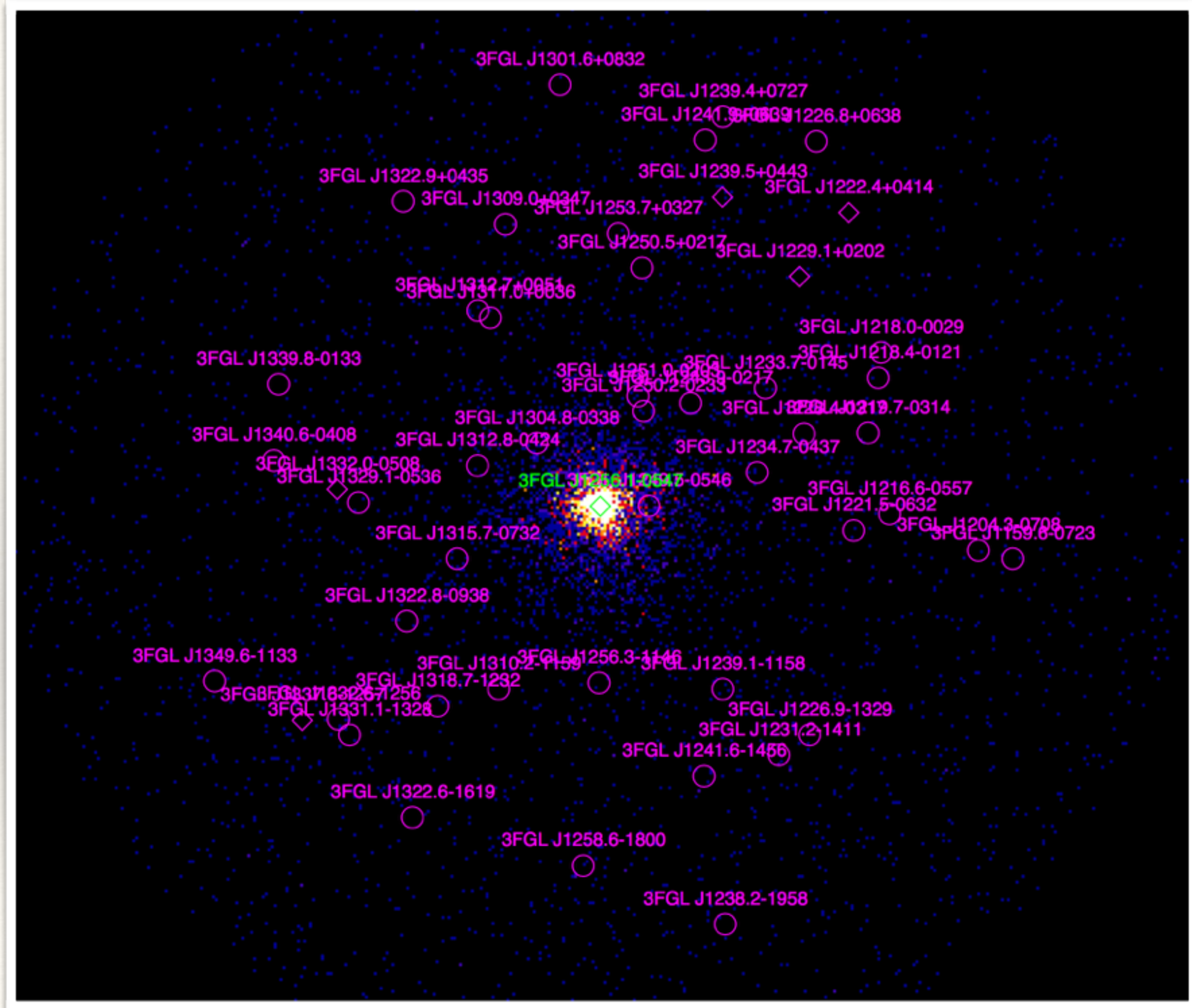
```xml
<?xml version="1.0" standalone="no"?>
<source_library title="source library">
  <source name="_3FGLJ1256.1-0547" type="PointSource">
    <spectrum type="PowerLaw">
      <parameter free="1" max="10000" min="1e-04" name="Prefactor" scale="1e-8" value="1.0" />
      <parameter free="1" max="5" min="0" name="Index" scale="-1" value="2.2" />
      <parameter free="0" max="30000" min="20" name="Scale" scale="1" value="100" />
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter free="0" max="360" min="-360" name="RA" scale="1" value="194.041" />
      <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="-5.7912" />
    </spatialModel>
  </source>
  <source name="gll_iem_v06" type="DiffuseSource">
    <spectrum type="PowerLaw">
      <parameter error="0.091" free="1" max="10" min="0" name="Prefactor" scale="1" value="1.14" />
      <parameter free="0" max="1" min="-1" name="Index" scale="1" value="0" />
      <parameter free="0" max="200" min="50" name="Scale" scale="1" value="100" />
    </spectrum>
    <spatialModel file="$(FERMI_DIR)/refdata/fermi/galdiffuse/gll_iem_v06.fits" type="MapCubeFunction">
      <parameter free="0" max="1000" min="0.001" name="Normalization" scale="1" value="1" />
    </spatialModel>
  </source>
  <source name="iso_P8R2_SOURCE_V6_v06" type="DiffuseSource">
    <spectrum file="$(FERMI_DIR)/refdata/fermi/galdiffuse/iso_P8R2_SOURCE_V6_v06.txt" type="FileFunction">
      <parameter error="0.10" free="1" max="10" min="0.01" name="Normalization" scale="1" value="1.08" />
    </spectrum>
    <spatialModel type="ConstantValue">
      <parameter free="0" max="10" min="0" name="Value" scale="1" value="1" />
    </spatialModel>
  </source>
</source_library>
```



Diffuse Galactic γ-ray background

Source model

- For this analysis, a simple model including just 3C 279 and the Galactic and isotropic backgrounds are OK
- This is reasonable because 3C 279 was extremely bright during the time period covered in this work and the effect of other faint sources can be neglected
- In general, one should include more sources, lying in the source region, in the model file
- This is because of overlapping psf of nearby sources
- Check out user contributed script “make3FGLxml.py”



3FGL J1301.6+0832
3FGL J1239.4+0727
3FGL J1322.9+0435
3FGL J1239.5+0443
3FGL J1222.4+0414
3FGL J1253.7+0327
3FGL J1250.5+0217
3FGL J1229.1+0202
3FGL J1218.0-0029
3FGL J1233.7-0145
3FGL J1339.8-0133
3FGL J1250.2-0233
3FGL J1304.8-0338
3FGL J1340.6-0408
3FGL J1312.8-0424
3FGL J1234.7-0437
3FGL J1329.1-0536
3FGL J1216.6-0557
3FGL J1221.5-0632
3FGL J1315.7-0732
3FGL J1322.8-0938
3FGL J1349.6-1133
3FGL J1239.1-1158
3FGL J1318.7-1232
3FGL J1331.1-1328
3FGL J1226.9-1329
3FGL J1231.2-1411
3FGL J1241.6-1456
3FGL J1322.6-1619
3FGL J1258.6-1800
3FGL J1238.2-1958

Diffuse response calculation

- Calculates the integral over solid angle of a diffuse source model convolved with the instrumental response function
- The gtdiffrsp tool will perform these integrations and add the results as an additional column for each diffuse source into the event file
- First, let us check whether the diffuse response columns are present or not

{Run this command in the second terminal}

```
[Oracle@localhost 3C279_ICTS]$ fkeyprint gti.fits DIFRSP

# FILE: gti.fits
# KEYNAME: DIFRSP

# EXTENSION:    0

# EXTENSION:    1
DIFRSP0 = 'NONE    '           / Diffuse response label for component 0
DIFRSP1 = 'NONE    '           / Diffuse response label for component 1
DIFRSP2 = 'NONE    '           / Diffuse response label for component 2
DIFRSP3 = 'NONE    '           / Diffuse response label for component 3
DIFRSP4 = 'NONE    '           / Diffuse response label for component 4

# EXTENSION:    2
[Oracle@localhost 3C279_ICTS]$
```

Diffuse response calculation

```
[Oracle@localhost 3C279_ICTS]$ gtdiffrsp
Event data file[] gti.fits
Spacecraft data file[] SC.fits
Source model file[] model.xml
Response functions to use[CALDB] CALDB
adding source gll_iem_v06
adding source iso_P8R2_SOURCE_V6_v06
Working on...
gti.fits.......................!
[Oracle@localhost 3C279_ICTS]$
```

```
[Oracle@localhost 3C279_ICTS]$ fkeyprint gti.fits DIFRSP

# FILE: gti.fits
# KEYNAME: DIFRSP

# EXTENSION:    0

# EXTENSION:    1
DIFRSP0 = 'p8r2_source_v6__gll_iem_v06' / Diffuse response label for component 0
DIFRSP1 = 'p8r2_source_v6__iso_p8r2_source_v6_v06' / Diffuse response label for
DIFRSP2 = 'NONE    '           / Diffuse response label for component 2
DIFRSP3 = 'NONE    '           / Diffuse response label for component 3
DIFRSP4 = 'NONE    '           / Diffuse response label for component 4

# EXTENSION:    2
[Oracle@localhost 3C279_ICTS]$
```

{Run this command in the second terminal}

Likelihood fitting

- Now, we are ready for likelihood fitting
- The input model file (model.xml) represents the initial guess of the spectral parameters
- The software will perform the fitting & the output parameters associated with the best fit will be extracted (output_1.xml)
- But, keep in mind that the software does not know whether a power law is a good fit or a log parabola would be better
- We will fit both the models and will compare the results

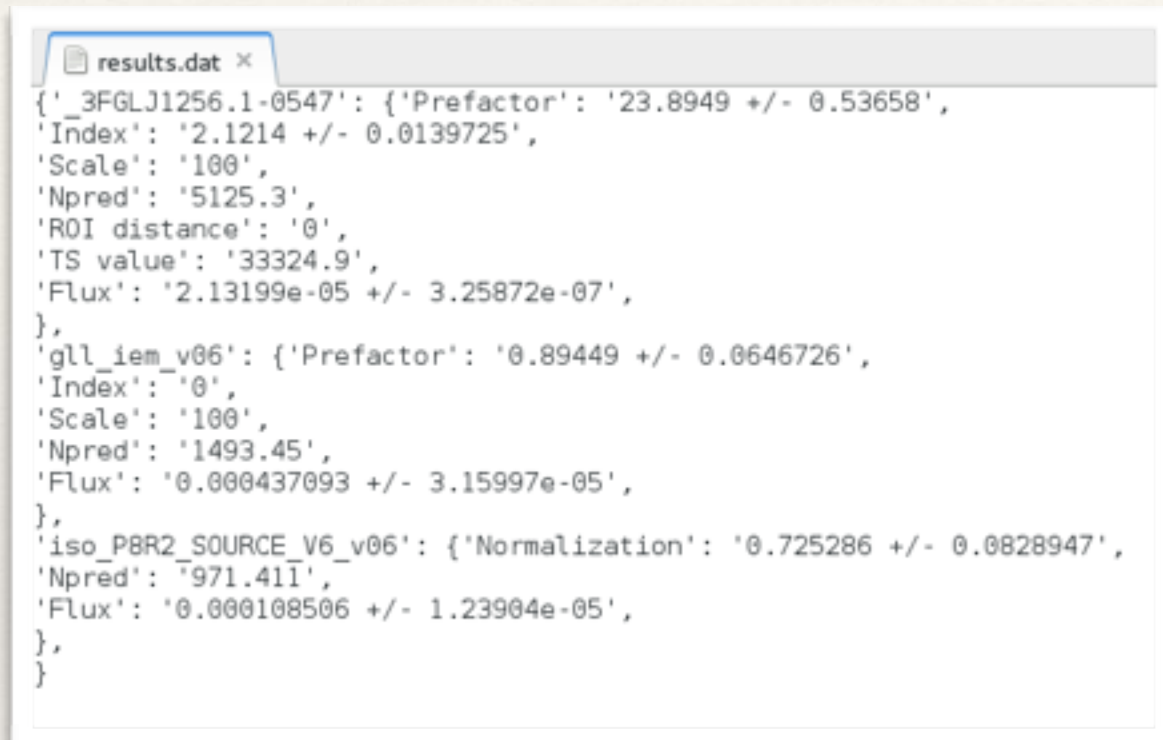
First fitting: PL model

```
[Oracle@localhost 3C279_ICTS]$ gtlike sfile=output_1.xml plot=yes
Statistic to use (BINNED|UNBINNED) [UNBINNED] UNBINNED
Spacecraft file[none] SC.fits
Event file[none] gti.fits
Unbinned exposure map[none] expmap.fits
Exposure hypercube file[none] ltcube.fits
Source model file[] model.xml
Response functions to use[CALDB] CALDB
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT] NEWMINUIT

Minuit did successfully converge.
# of function calls: 82
```

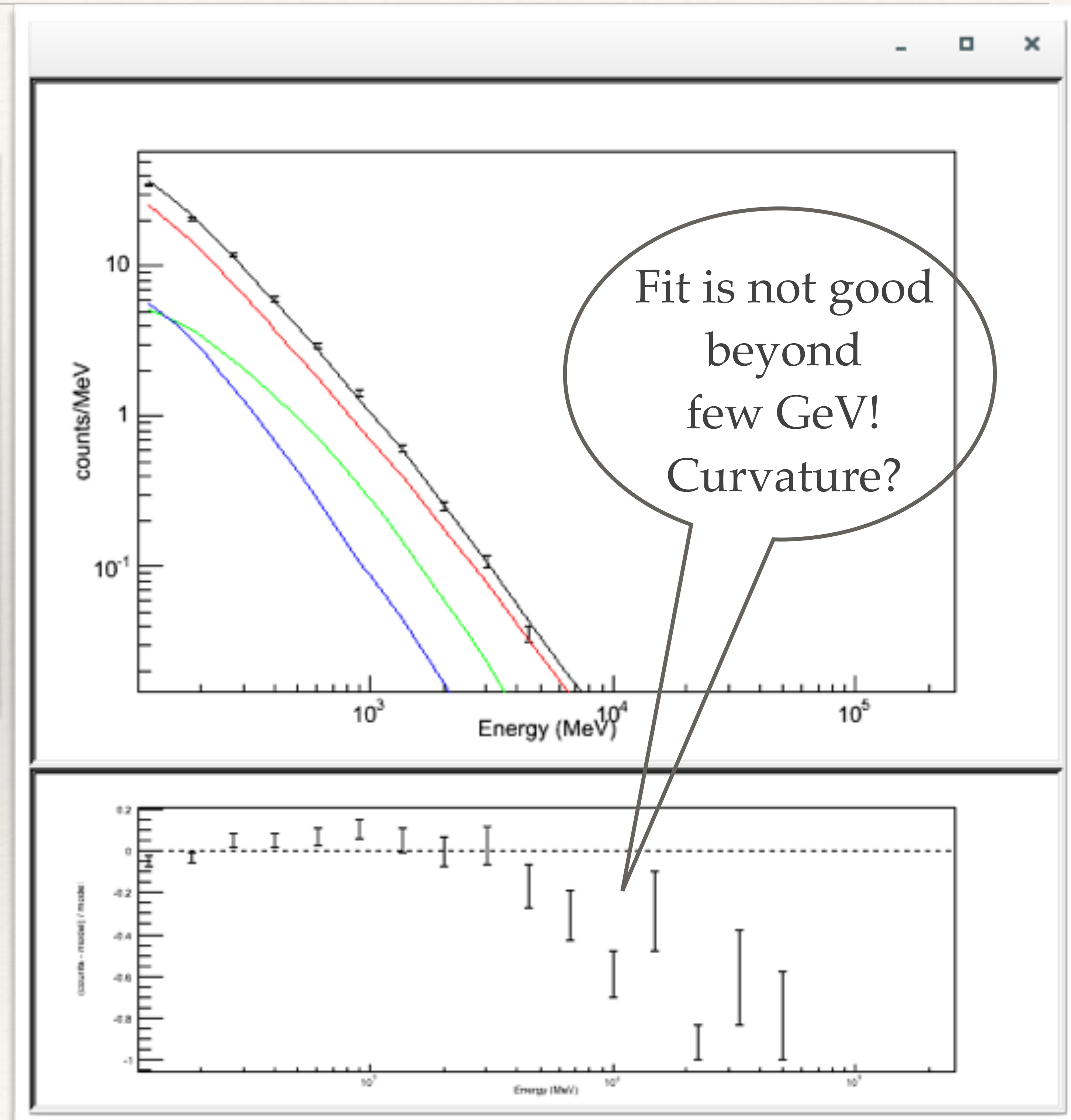
```
WARNING: Fit may be bad in range [100, 149.23] (MeV)
WARNING: Fit may be bad in range [740.083, 1104.43] (MeV)
WARNING: Fit may be bad in range [5477.23, 12197.6] (MeV)
WARNING: Fit may be bad in range [18202.4, 90272] (MeV)

Total number of observed counts: 7589
Total number of model events: 7590.17

-log(Likelihood): 58613.28979
```

Note down this number

PL fitting results



```
{'_3FGLJ1256.1-0547': {'Prefactor': '23.8949 +/- 0.53658',
'Index': '2.1214 +/- 0.0139725',
'Scale': '100',
'Npred': '5125.3',
'ROI distance': '0',
'TS value': '33324.9',
'Flux': '2.13199e-05 +/- 3.25872e-07',
},
'gll_iem_v06': {'Prefactor': '0.89449 +/- 0.0646726',
'Index': '0',
'Scale': '100',
'Npred': '1493.45',
'Flux': '0.000437093 +/- 3.15997e-05',
},
'iso_P8R2_SOURCE_V6_v06': {'Normalization': '0.725286 +/- 0.0828947',
'Npred': '971.411',
'Flux': '0.000108506 +/- 1.23904e-05',
},
}
```



save results.dat file as results_PL.dat

cp results.dat results_PL.dat

Second fitting: LP model

```
[Oracle@localhost 3C279_ICTS]$ gtlike sfile=output_2.xml plot=yes
Statistic to use (BINNED|UNBINNED) [UNBINNED] UNBINNED
Spacecraft file[none] SC.fits
Event file[none] gti.fits
Unbinned exposure map[none] expmap.fits
Exposure hypercube file[none] ltcube.fits
Source model file[] model_LP.xml
Response functions to use[CALDB] CALDB
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT] NEWMINUIT

Minuit did successfully converge.
# of function calls: 101
```

```
WARNING: Fit may be bad in range [8173.66, 12197.6] (MeV)
WARNING: Fit may be bad in range [18202.4, 27163.4] (MeV)

Total number of observed counts: 7589
Total number of model events: 7589.48

-log(Likelihood): 58565.67897
```

Note down this number

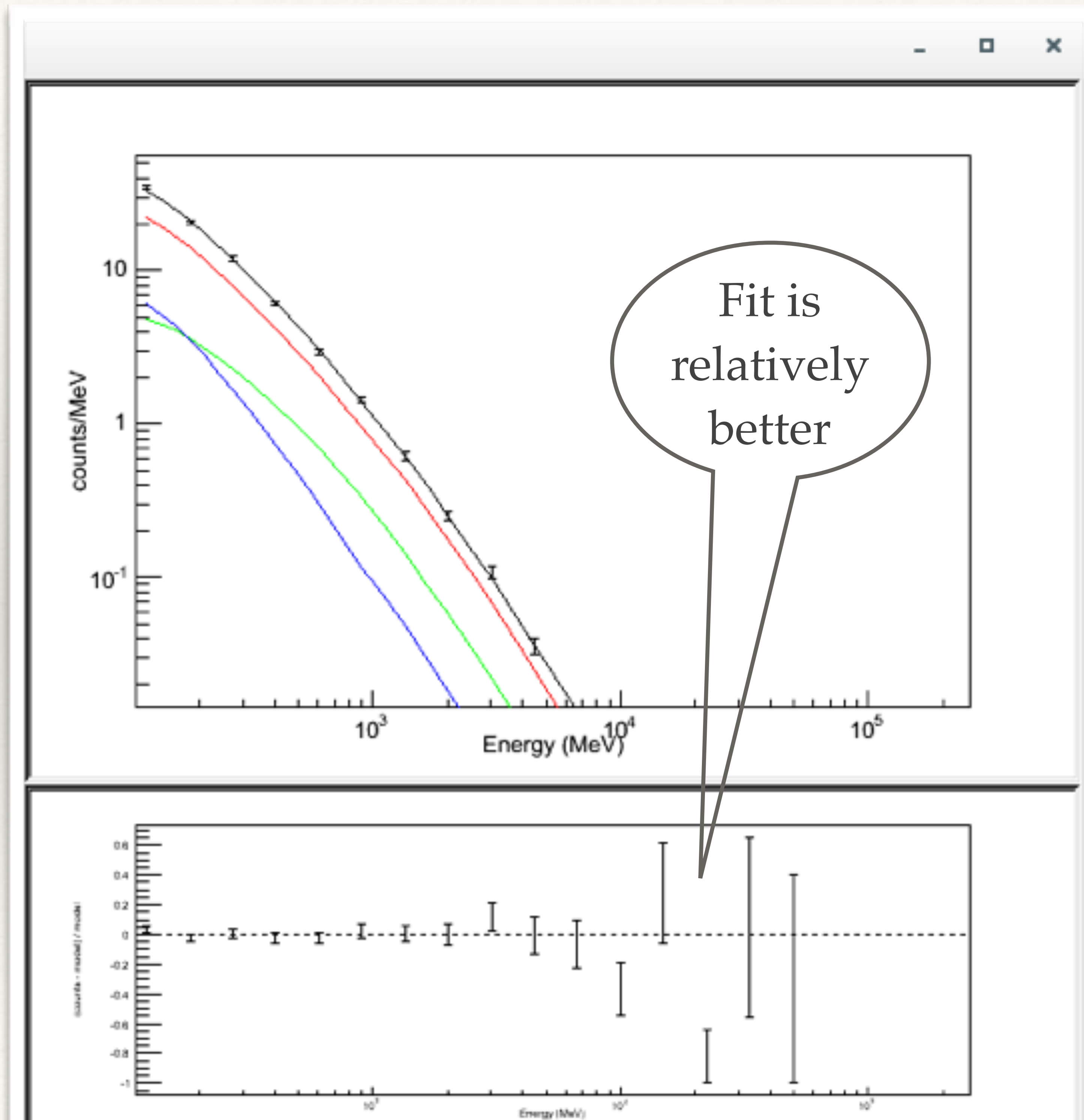
LP fitting results

results.dat


```
{'_3FGLJ1256.1-0547': {'norm': '2.5176 +/- 0.0426595',
'alpha': '1.97168 +/- 0.0215062',
'beta': '0.102215 +/- 0.0117347',
'Eb': '300',
'Npred': '5105.65',
'ROI distance': '0',
'TS value': '33386.6',
'Flux': '2.07604e-05 +/- 3.23544e-07',
},
'gll_iem_v06': {'Prefactor': '0.858735 +/- 0.0643229',
'Index': '0',
'Scale': '100',
'Npred': '1433.76',
'Flux': '0.000419622 +/- 3.14288e-05',
},
'iso_P8R2_SOURCE_V6_v06': {'Normalization': '0.784017 +/- 0.0830913',
'Npred': '1050.07',
'Flux': '0.000117292 +/- 1.24197e-05',
},
}
```


save results.dat file as results_LP.dat

cp results.dat results_LP.dat

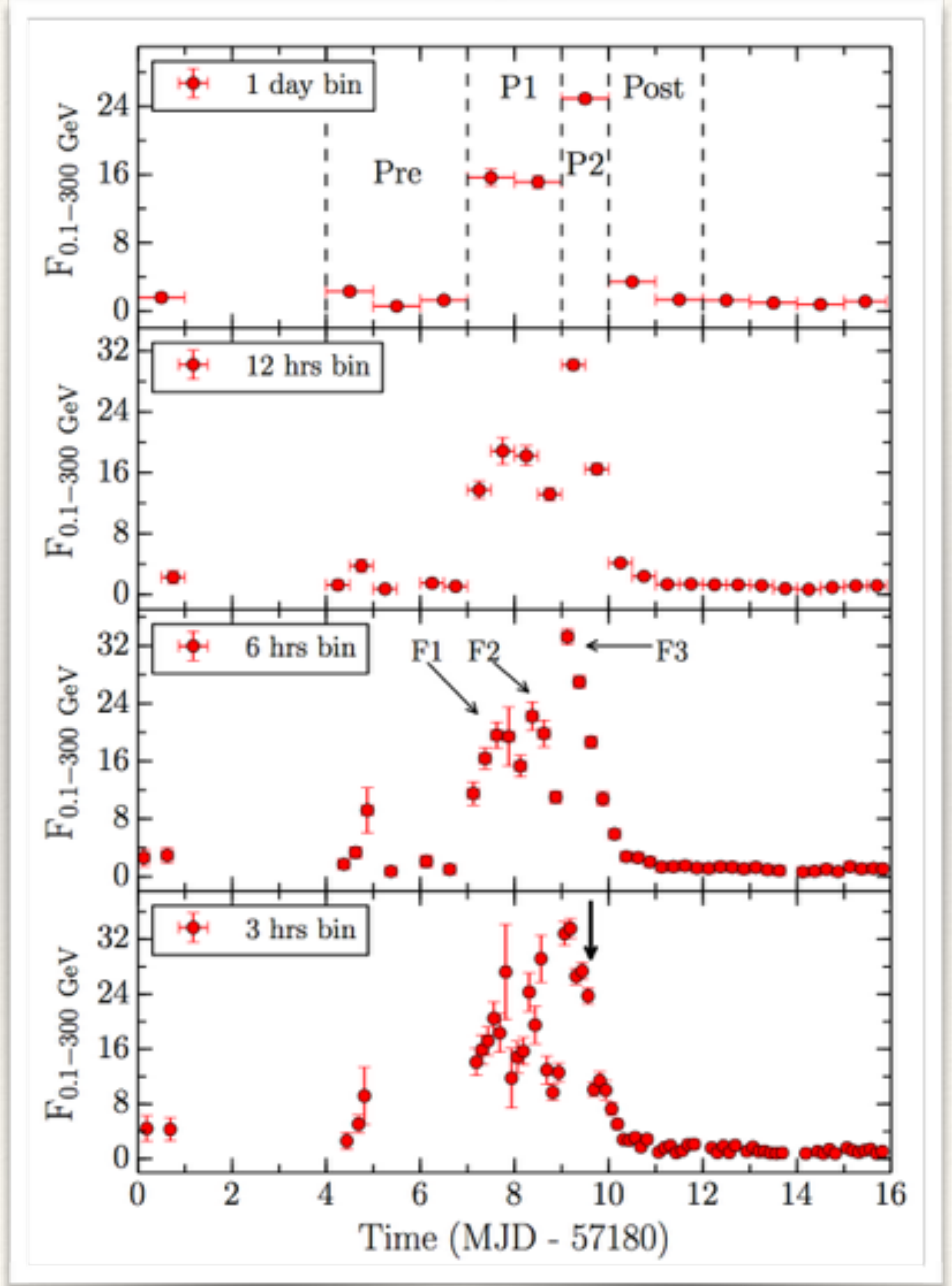


Comparing models

- TS_{curve} test
- TS_{curve} = 2[loglikelihood(LP) - loglikelihood(PL)]
- $TS_{curve} > 16$ implies a significant curvature in the spectrum
- $TS_{curve} \sim 100$
- This suggests that during 2015 June outburst, the γ-ray spectrum of 3C 279 was significantly curved (Why? Physics??)

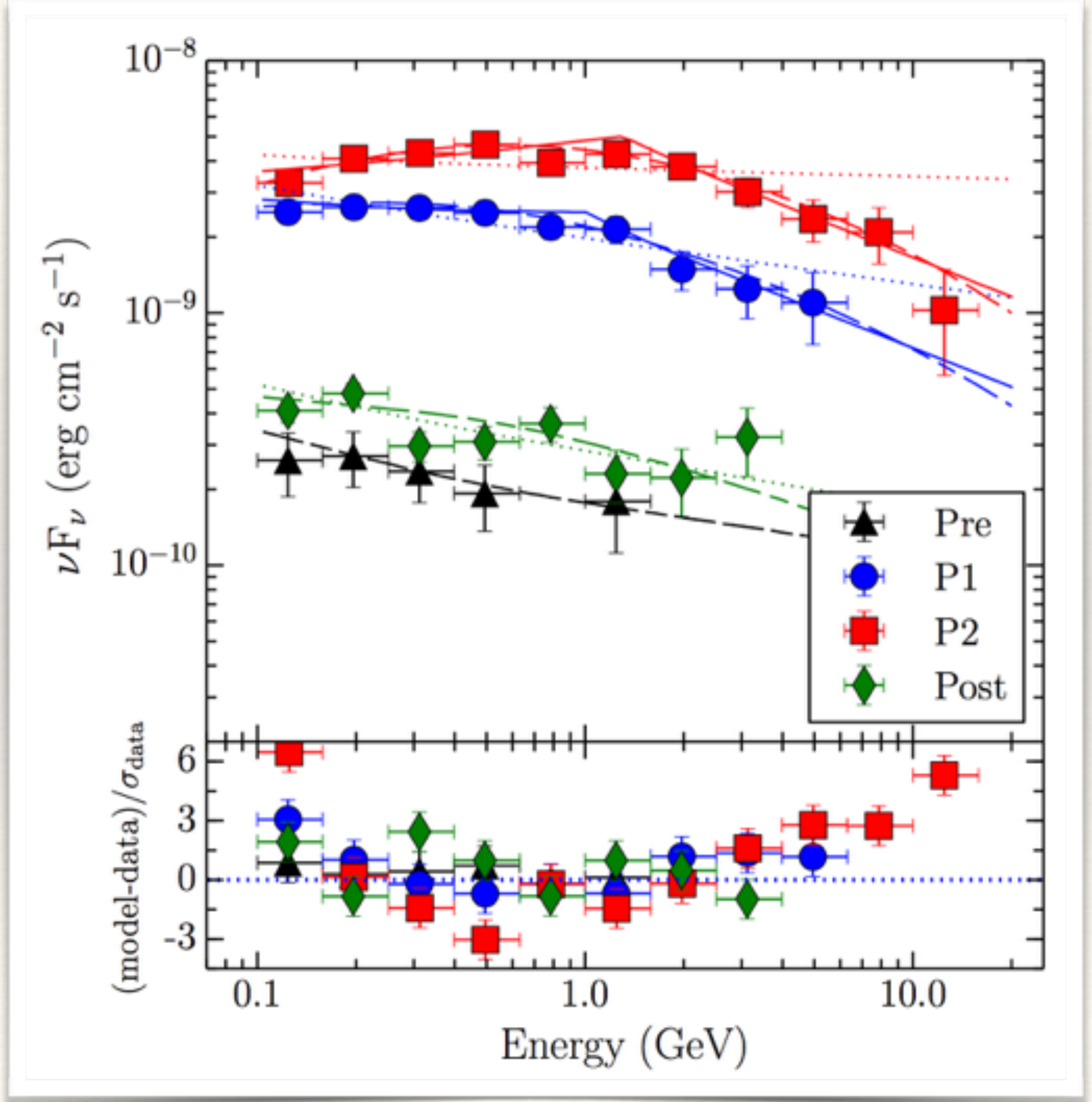
Light curves

- Scripting is required
  - determine required time binning
  - bin data in time with gtselect
  - run the analysis
  - parse the output files
- Beware of the number of free parameters! You may consider holding some parameters fixed
  - e.g., spectral index
  - parameters of steady or faint sources



Spectrum

- Scripting is required
  - determine required energy binning
  - bin data in energy with gtselect
  - run the analysis
  - parse the output files
- Beware of the number of free parameters! You may consider holding many parameters fixed
  - e.g., spectral index
  - parameters of steady or faint sources



Final remarks

- The entire *Fermi*-LAT analysis can be performed within Python environment
- Python has many advantages over the conventional analysis method (e.g., weak source removal, upper limit calculation)
- Search in Google to find out more about *Fermi* analysis as many interesting tools have not been discussed here

Conference over! Get some rest :)