Analyzing Data from the *Fermi* Satellite

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Fermitools

- The standard (and official) way of reducing raw *Fermi* Data, making it science-ready, and getting science-outputs from those data

- **What can you get?**
  Test-statistic (TS) Maps; energy spectra; light curves of *Fermi*-observed sources (*e.g.*, blazars), ...

- **What do you need?**
  A Unix (Linux/MacOS) System; `conda` and/or `mamba`; knowledge of command-line coding.
  `root` access is helpful but not mandatory.
  Some knowledge of Python is beneficial (if you want to use `fermipy`).

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

Installation (if you haven't already done it)

- Try `conda` at first. But it may take a lot of time.
- Then `mamba` may also be handy.
- Installation may be different for the Windows Subsystem for Linux (WSL). Please try to use Linux/MacOS.
- Do not try `pip`.

Install `mamba` from the official GitHub Bash File.

```
$ bash Mambaforge_()_().sh
```

Restart your Terminal and `mamba` will be ready. Then:

```
$ mamba create -n fermi -c
conda-forge -c fermi fermitools
numpy=1.20
```

Bingo! Now you have `Fermitools` on your device.

https://github.com/conda-forge/miniforge#mambaforge
https://github.com/fermi-lat/Fermitools-conda/wiki/Installation-Instructions

Extracting LAT Data

Event File(s)

Recorded events that correspond to your source of interest, as well as the area surrounding that source

(also called 'Photon' Files; extended files are required only for transients)

Spacecraft File

Spacecraft Position & Orientation at 30 s Intervals

(May be required) **Galactic & isotropic diffusion models**

Available here:

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

LAT Photon, Event, and Spacecraft Data Query

This is for the blazar **3C 279**.

Object name or coordinates: 193.98, -5.82

Coordinate system: J2000

Search radius (degrees): 20

Observation dates: START, 255398400

Time system: MET

Generally we use **MET** or **MJD** systems.

Energy range (MeV): 100, 500000

LAT data type: Photon

You can get **photon** or **energy** files. We shall use **photon** files.

Spacecraft data: ✓

Check this box. We need the **spacecraft** data.

Start Search Reset

Results for query L231204020125AD7426F135

Your search criteria were:

Equatorial coordinates (degrees)	(193.98,-5.82)
Time range (MET)	(239557417,255398400)
Time range (Gregorian)	(2008-08-04 15:43:36,2009-02-03 23:59:58)
Energy range (MeV)	(100,500000)
Search radius (degrees)	20

The state of your query is 2 (Query complete) (May need to refresh a few times)

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 These are needed only for transients.

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
L231204020125AD7426F135_SC00.fits	445088	69.63	Available
L231204020125AD7426F135_PH00.fits	249353	23.37	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 https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L2312040201
wget https://fermi.gsfc.nasa.gov/FTP/fermi/data/lat/queries/L2312040201
```

You will get something like this.

Files with a PH — **photon files**

File with a SC — **spacecraft file**

There may be multiple photon files, but only 1 spacecraft file.

You can also get them with `wget`.

Preparing LAT Data

2 steps:

- **`gtselect`** — makes cuts on time, energy, position *(RA, dec, radius)*, zenith angle, …

- **`gtmktime`** — makes cuts based on **good time intervals (GTIs)** with info from the **spacecraft file**

Good Time Intervals
Time Ranges when the data can be considered valid.
List of times the LAT was collecting data.

We shall create an **events list file**, `events.txt`, for our purposes:

```
$ ls *_PH* > events.txt
```

Rename the **spacecraft file** as: `spacecraft.fits`

```
prompt> gtselect evclass=128 evtype=3
Input FT1 file[] @events.txt
Output FT1 file[] 3C279_region_filtered.fits
RA for new search center (degrees) (0:360) [0] 193.98
Dec for new search center (degrees) (-90:90) [0] -5.82
radius of new search region (degrees) (0:180) [180] 20
start time (MET in s) (0:) [0] INDEF
end time (MET in s) (0:) [0] INDEF
lower energy limit (MeV) (0:) [30] 100
upper energy limit (MeV) (0:) [300000] 500000
maximum zenith angle value (degrees) (0:180) [180] 90
Done.
prompt>
```

RA, Dec for the source you are investigating (**3C 279** in this case).
Important — `evclass = 128 evtype = 3`.

```
prompt> gtvcut suppress_gtis=no
Input FITS file[] 3C279_region_filtered.fits
Extension name[EVENTS]
DSTYP1: BIT_MASK(EVENT_CLASS,128,P8R3)
DSUNI1: DIMENSIONLESS
DSVAL1: 1:1

DSTYP2: POS(RA,DEC)
DSUNI2: deg
DSVAL2: CIRCLE(193.98,-5.82,20)

DSTYP3: TIME
DSUNI3: s
DSVAL3: TABLE
DSREF3: :GTI

GTIs:
239557417.494 239558069.093
239559567.98 239563954.084
239565647.986 239569844.085
...
255384024.931 255388191.087
255390039.929 255394247.086
255396028.929 255398400

DSTYP4: BIT_MASK(EVENT_TYPE,3,P8R3)
DSUNI4: DIMENSIONLESS
DSVAL4: 1:1

DSTYP4: ENERGY
DSUNI4: MeV
DSVAL4: 100:500000

DSTYP5: ZENITH_ANGLE
DSUNI5: deg
DSVAL5: 0:90

prompt>
```

At this point you should check the output FITS File:

`$ gtvcut suppress_gtis = no`

Trick —
Using `suppress_gtis = yes` hides the list of GTIs and displays only the essential values.

gtmktime

```
prompt> gtmktime
Spacecraft data file[] spacecraft.fits
Filter expression[] (DATA_QUAL>0)&&(LAT_CONFIG==1)
Apply ROI-based zenith angle cut[] no
Event data file[] 3C279_region_filtered.fits
Output event file name[] 3C279_region_filtered_gti.fits
```

`DATA_QUAL > 0` — Good data

`LAT_CONFIG = 1` — Science Configuration

Importance — to make cuts based on GTIs, or, the times that the LAT is actually *observing*.

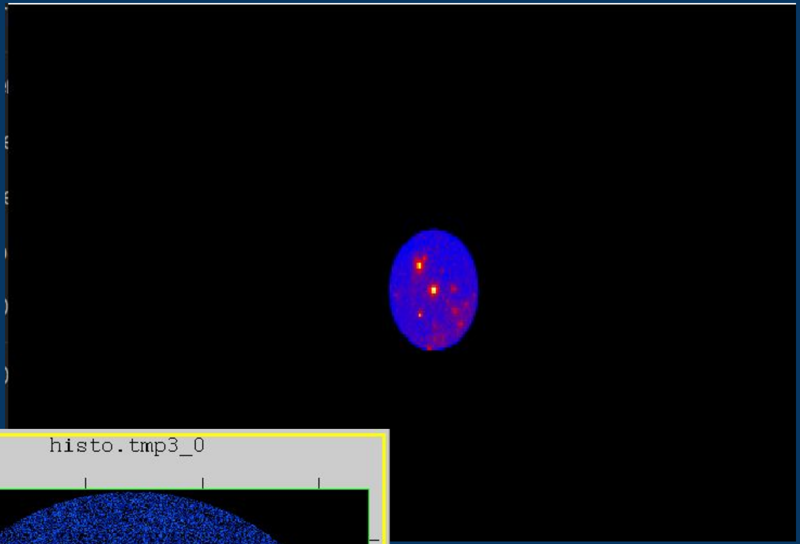
e.g., the LAT doesn't collect data when over the SAA or (more rarely) other spacecraft maneuvers.

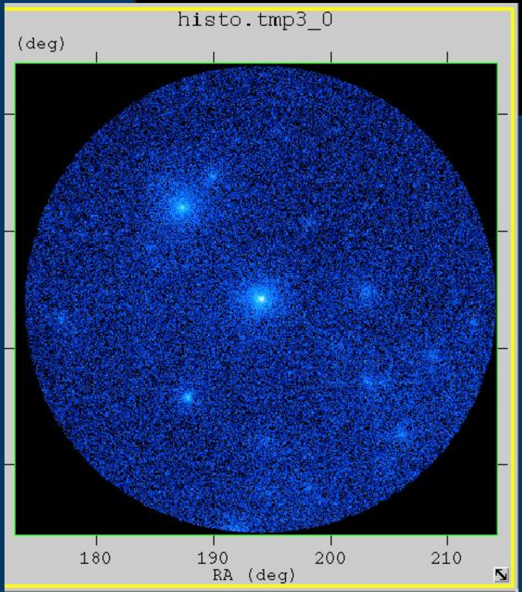
The source will probably **not** be in the FoV in the entire time the LAT was taking data.

Getting to see your data

- You can use **DS9** or `fv`.

- **Exercise:**
  Try making a counts-map in `fv`. (*Hint* — use the `HIST` Option.)
  It will look something like this:





Binning the data: `gtbin`

You can use gtbin to bin photon data into:

- Images (maps)
- Light curves
- Energy spectra

We shall see how to make a **color-map**.

```
prompt> gtbin
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2) [] CMAP
Event data file name[] 3C279_region_filtered_gti.fits
Output file name[] 3C279_region_cmap.fits
Spacecraft data file name[] 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]
First coordinate of image center in degrees (RA or galactic l)[] 193.98
Second coordinate of image center in degrees (DEC or galactic b)[] -5.82
Rotation angle of image axis, in degrees[0.]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[] AIT
gtbin: WARNING: No spacecraft file: EXPOSURE keyword will be set equal to
ontime.
prompt>
```

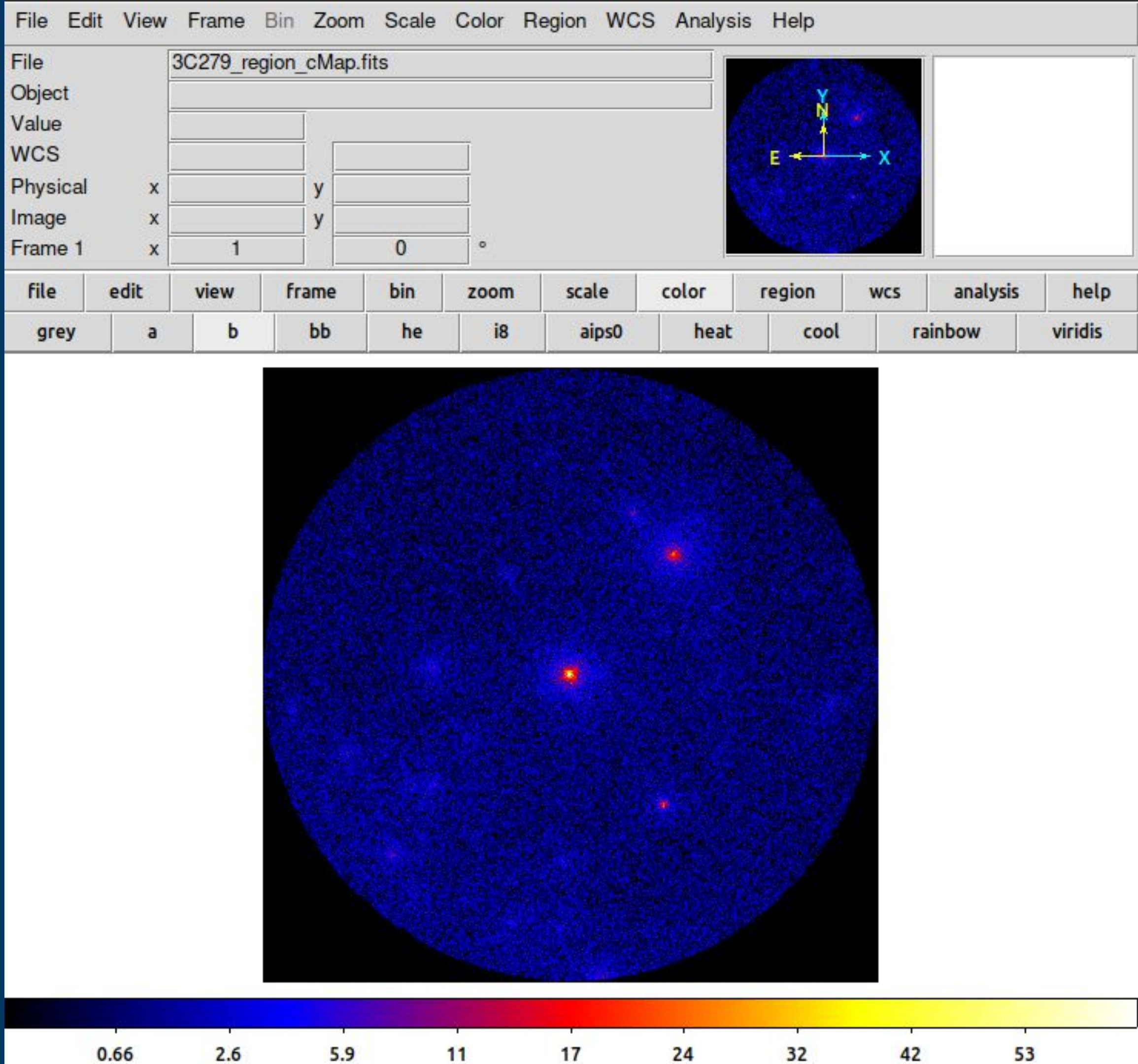
CCUBE produces a set of count-maps over several energy bins.
Spacecraft file — not needed for the CMap.

Binning the data: `gtbin`

- Note that this image is *flipped* along the *y*-axis.

- That is because coordinate system keywords have been added to the header.

- RA increases right to left, not left to right.



The Livetime Cube

```
prompt> gtltcube
Event data file [] 3C279_region_filtered_gti.fits
Spacecraft data file [] spacecraft.fits
Output file [] 3C279_region_ltcube.fits
Step size in cos(theta) (0.:1.) [] 0.025
Pixel size (degrees) [] 1
Working on file spacecraft.fits
.....................!
prompt>
```

To determine the exposure for a source:
How much the LAT has observed it in

- *Any* position on the sky (2 coordinates)
- at *any* given inclination angle (1 coordinate)

So, total of **3 coordinates** — the *livetime* ***cube***.

We do this for the entire sky, for the time-range provided by the spacecraft file.

Exposure Maps

How long the LAT has observed the source

- Exposure **maps** are mono-energetic, and each plane represents the exposure at the midpoint of the energy band, not integrated over the band's energy range. Exposure maps are used for **unbinned** analysis methods. You will specify the number of energy bands when you run the gtexpmap tool.

```
prompt> 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[] 3C279_region_filtered_gti.fits
Spacecraft data file[] spacecraft.fits
Exposure hypercube file[] 3C279_region_ltcube.fits
output file name[] 3C279_exposure_map.fits
Response functions[] P8R3_SOURCE_V3
Radius of the source region (in degrees)[] 30
Number of longitude points (2:1000) [] 500
Number of latitude points (2:1000) [] 500
Number of energies (2:100) [] 30
The radius of the source region, 25, should be significantly larger
(say by 10 deg) than the ROI radius of 20
Computing the ExposureMap using 3C279_exposure_cube.fits
.....................!
prompt>
```

Unbinned Likelihood Analysis

- Preferred method for time-series analysis of LAT Data
- No. of events in each time-bin is expected to be small.
- See — Abdo *et al*, 2009, ApJS, 183, 46.
- **Needed:**
  Event files; spacecraft file; background models
- We have already obtained **count-maps** & **exposure-maps**, which are needed for the unbinned analysis.

Unbinned Likelihood Analysis *(with **3C 279**)*

- Recommended: `$ pip install LATSourceModel`
- Get the source-model for 3C 279 with `wget`:
  `$ wget https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/data/Likelihood/3C279input_model.xml`

- **Computing diffuse source responses:** *(This step may take a lot of time!)*

```
%%bash
gtdiffrsp
    ./data/3C279_region_filtered_gti.fits
    ./data/spacecraft.fits
    ./data/3C279input_model.xml
    CALDB
```

Unbinned Likelihood Analysis *(with **3C 279**)* — `gtlike`

- Now we shall apply `gtlike`, the main workhorse of the unbinned likelihood analysis.

- Main philosophy of the maximum likelihood method:
  Mattox J. R. *et al.*, 1996, ApJ, 461, 396
  (This is for EGRET Data, but the same principle applies for *Fermi* as well.)

- Likelihood statistic, L = Probability of obtaining obs. data given an input model

- Input model = Distribution of GeV sources in the sky (+ intensities + spectra)

- For the detailed math, please see the Cicerone.

Unbinned Likelihood Analysis *(with **3C 279**)* — `gtlike`

```
%%bash
gtlike refit=yes plot=yes sfile=3C279output_model.xml
    UNBINNED
    ./data/spacecraft.fits
    ./data/3C279_region_filtered_gti.fits
    ./data/3C279_unbin_expmap.fits
    ./data/3C279_ltcube.fits
    ./data/3C279input_model.xml
    CALDB
    NEWMINUIT
```

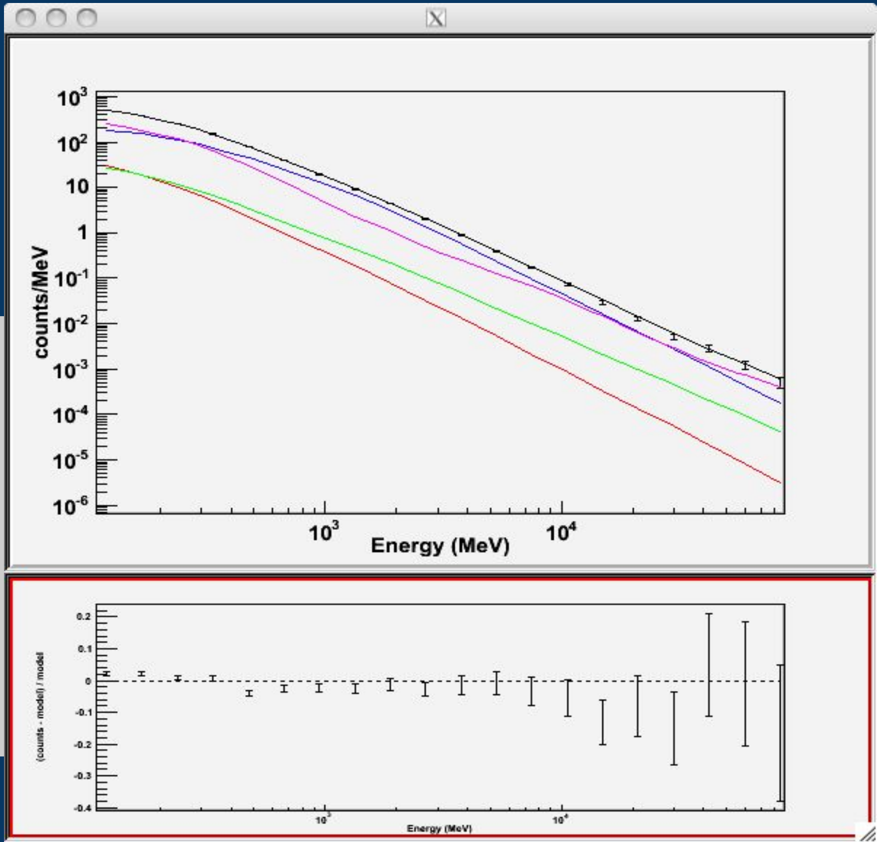
You are prompted for:

XML & FITS Files; choice of IRF (**`CALDB`**); type of statistics to use (binned/**unbinned**); and the optimizer (**`NEWMINUIT`**).

Unbinned Likelihood Analysis *(with **3C 279**)* — `gtlike`

- For a successful run, `NEWMINUIT` should successfully converge.
- For each source (within the search-radius), you should get:

```
3C 273:
Prefactor: 9.53263 +/- 0.262701
Index: -2.63212 +/- 0.0212044
Scale: 100
Npred: 6369.65
ROI distance: 10.4409
TS value: 7810.96
Flux: 5.85022e-07 +/- 1.14156e-08 photons/cm^2/s
```



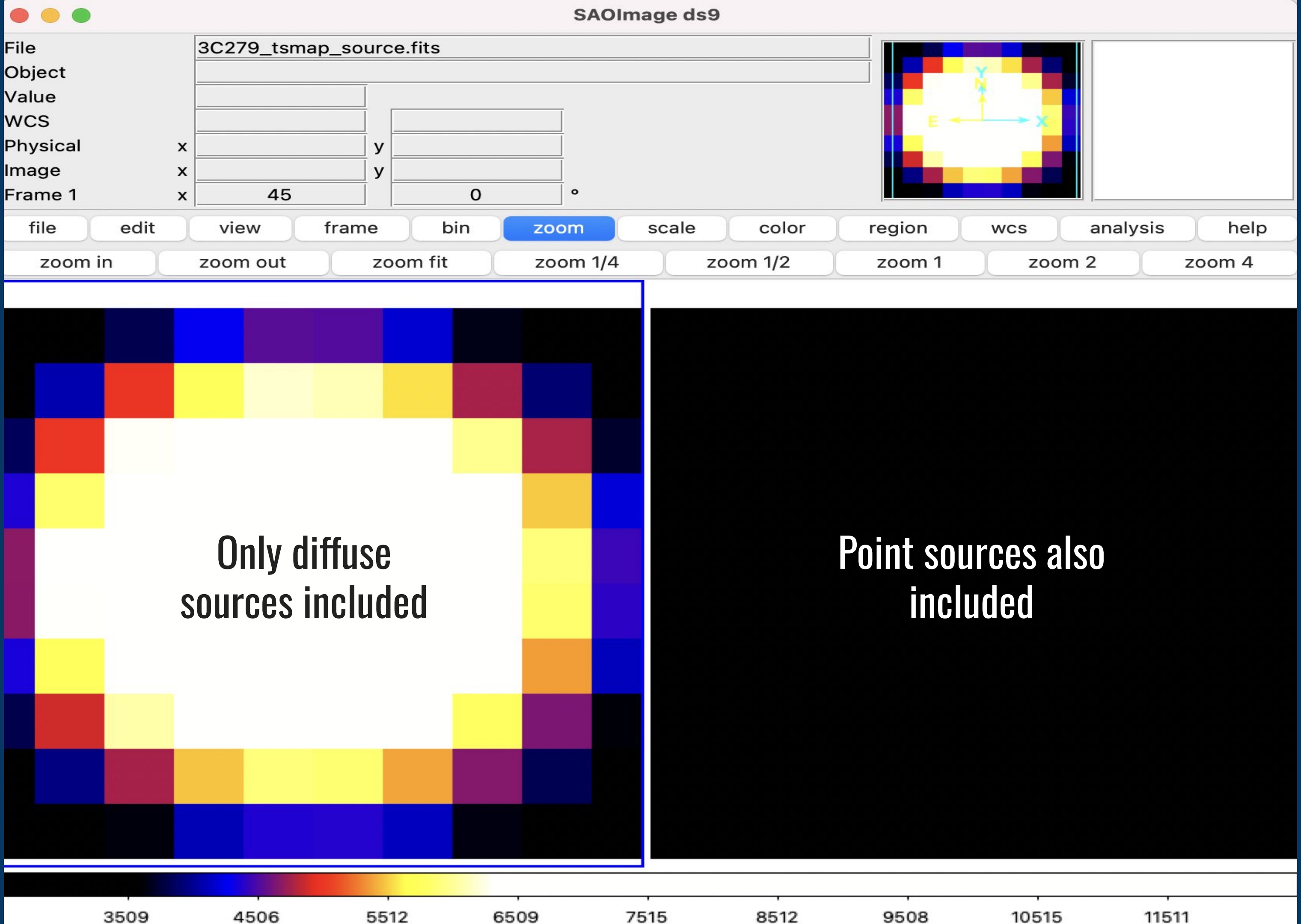
Test-statistic (TS) Maps

- Location with max. TS = Best fit source position
- Low value of TS — not good; means low probability of the location being the source
- Naturally, we always prefer high TS Values.

We fix all pt. source parameters before running the map:

```
!wget
https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/data/Likelihood/3C279output_model_resid.xml
```

```
%%bash
gttsmap
    UNBINNED
    ./data/spacecraft.fits
    ./data/3C279_region_filtered_gti.fits
    ./data/3C279_unbin_expmap.fits
    ./data/3C279_ltcube.fits
    ./data/3C279output_model_resid.xml
    CALDB
    DRMNGB
    ./data/3C279_tsmap_resid.fits
    10
    10
    0.25
    CEL
    193.98
    -5.82
    AIT
```


SAOImage ds9
File
3C279_tsmap_source.fits
Object
Value
WCS
Physical
Image
Frame 1
45
0
file edit view frame bin zoom scale color region wcs analysis help
zoom in zoom out zoom fit zoom 1/4 zoom 1/2 zoom 1 zoom 2 zoom 4
Only diffuse sources included
Point sources also included
3509 4506 5512 6509 7515 8512 9508 10515 11511

Creating light curves

- Combine multiple photon files (`gtselect`):

```
prompt> gtselect zmax=180 emin=100 emax=200000 infile=@events.txt
outfile=tmp_19290temp1.fits ra=180 dec=0 rad=180 evclass=128 tmin=0 tmax=0
```

- Determine Start & End Times of the combined file with `fkeypar`, `fv`, or `gtvcut`.

- **Select the event class:**

```
prompt> gtselect zmax=90 emin=100 emax=200000 infile=tmp_19290temp1.fits
outfile=tmp_19290temp2.fits ra=194.046527 dec=-5.789312 rad=1
tmin=239557517 tmax=255335817 evclass=128
```

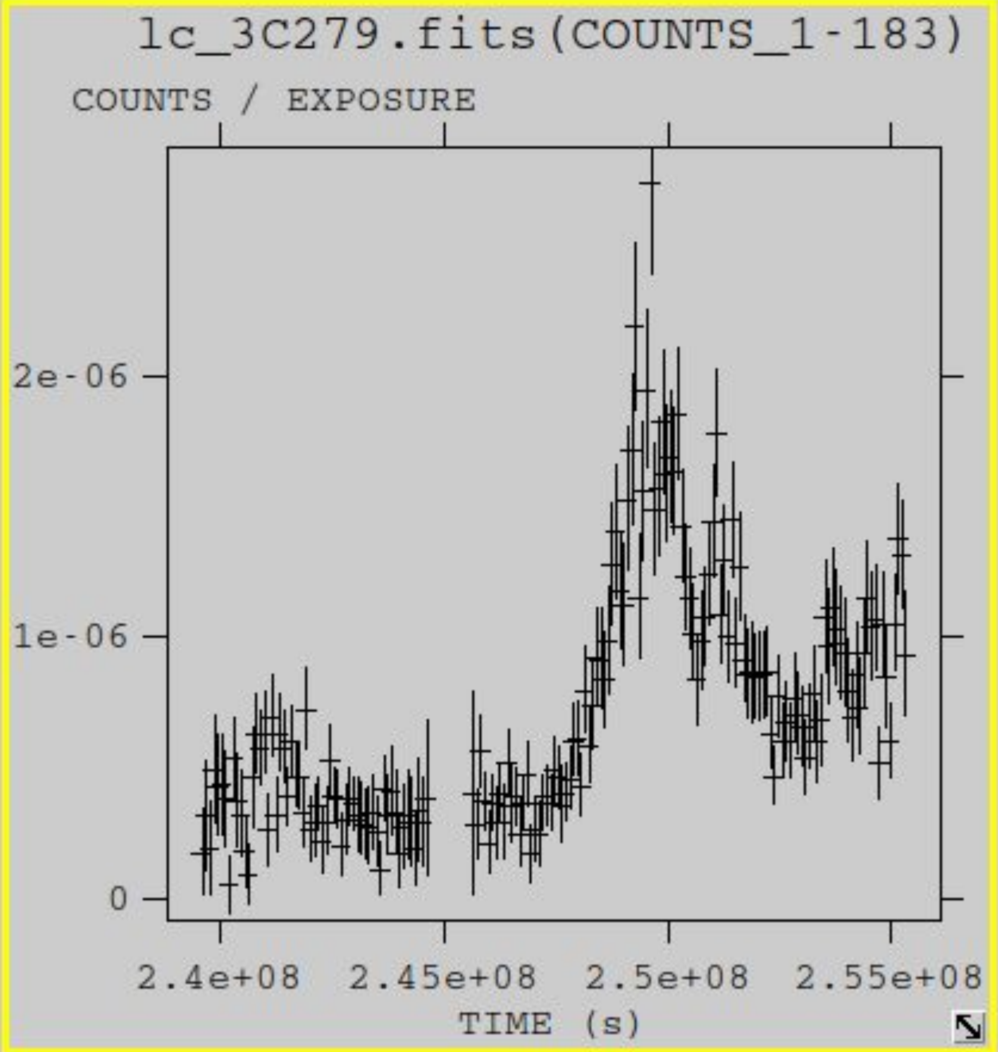
Creating light curves

- Use `gtbin` to create the light curve with the desired time-binning:

```
prompt> gtbin algorithm=LC evfile=tmp_19290temp3.fits outfile=lc_3C279.fits
scfile=L1506171513514365357F56_SC00.fits tbinalg=LIN tstart=239557517
tstop=255335817 dtime=86400
```

- Determine the exposure for each time-bin:

```
prompt> gtexposure infile=lc_3C279.fits
scfile=L1506171513514365357F56_SC00.fits irfs=P8R3_SOURCE_V2 srcmdl="none"
specin=-2.1
```


lc_3C279.fits(COUNTS_1-183)
COUNTS / EXPOSURE
2e-06
1e-06
0
2.4e+08
2.45e+08
2.5e+08
2.55e+08
TIME (s)