

## Fermi-LAT likelihood analysis

Benoît Lott  
CEN Bordeaux-Gradignan  
[lott@cenbg.in2p3.fr](mailto:lott@cenbg.in2p3.fr)

COSPAR Capacity Building Workshop

Credits: J. Chiang, S. Digel, F. Longo,



## Likelihood analysis

- Introduction to likelihood
- Analysis tutorial
- Using python
- Exploiting the results
- Spectral analysis in energy bands
- Light curves

# Likelihood analysis: basics (1)



The likelihood  $L$  is the probability of obtaining the data given an input model.

In our case, the input model is the distribution of gamma-ray sources on the sky, and includes their intensity and spectra.

One will maximize  $L$  to get the best match of the model to the data. Given a set of data, one can bin them in multidimensional (energy, sky pixels...) bins.

The observed number of counts in each bin is characterized by the Poisson distribution.  $L$  is the product of the probabilities of observing the detected counts in each bin,  $n_k$ , while  $m_k$  counts are predicted by the model:

$$\mathcal{L} = \prod_k \frac{m_k^{n_k} e^{-m_k}}{n_k!}$$

$L$  can be rewritten as:

$$\mathcal{L} = \prod_k e^{-m_k} \prod_k \frac{m_k^{n_k}}{n_k!} = e^{-N_{pred}} \prod_k \frac{m_k^{n_k}}{n_k!}$$

## Likelihood analysis: basics (2)

---



If we let the bin sizes get infinitesimally small, then  $n_k=0$  or 1, and we are left with a product running over the number of photons (**unbinned likelihood**).

$$\mathcal{L} = e^{-N_{pred}} \prod_i m_i$$

$\log \mathcal{L}$  is easier to handle, this is usually the quantity that is maximized

$$\log \mathcal{L} = \sum_i \log(m_i) - N_{pred}$$

## Likelihood analysis: basics (3)

---



The Test Statistic is defined as:

$$TS = -2 \log \left( \frac{\mathcal{L}_{\max,0}}{\mathcal{L}_{\max,1}} \right)$$

where  $\mathcal{L}_{\max,0}$  is the maximum likelihood value for a model without an additional source (the 'null hypothesis') and  $\mathcal{L}_{\max,1}$  is the maximum likelihood value for a model with the additional source at a specified location.

In the limit of a large number of counts, Wilk's Theorem states that the TS for the null hypothesis is asymptotically distributed as  $\chi_n^2$  where  $n$  is the number of parameters characterizing the additional source.

As a basic rule of thumb, the square root of the TS is approximately equal to the detection significance for a given source.

# Likelihood analysis: basics (4)



The source model is considered as:

$$S(E, \hat{p}, t) = \sum_i s_i(E, t) \delta(\hat{p} - \hat{p}_i) + S_G(E, \hat{p}) + S_{\text{eg}}(E, \hat{p}) + \sum_l S_l(E, \hat{p}, t),$$

Point Sources

Galactic & EG Diffuse Sources

Other Sources

This model is folded with the Instrument Response Functions (IRFs) to obtain the predicted counts in the measured quantity space  $(E', p', t)$ :

$$M(E', \hat{p}', t) = \int_{\text{SR}} dE d\hat{p} R(E', \hat{p}', t; E, \hat{p}) S(E, \hat{p}, t)$$

where

$$R(E', \hat{p}'; E, \hat{p}, t) = A(E, \hat{p}, \vec{L}(t)) D(E'; E, \hat{p}, \vec{L}(t)) P(\hat{p}'; E, \hat{p}, \vec{L}(t))$$

is the combined IRF.  $\vec{L}(t)$  is the orientation vector of the spacecraft. The integral is performed over the Source Region, i.e. the sky region encompassing all sources contributing to the Region-of-Interest (ROI). In the standard analysis, only steady sources are considered

$$S(E, \hat{p}, t) \rightarrow S(E, \hat{p})$$

## Likelihood analysis: basics (5)



The function to maximize is:

$$\log \mathcal{L} = \sum_j \log M(E'_j, \hat{p}'_j, t_j) - N_{\text{pred}}$$

where the sum is performed over photons in the ROI. The predicted number of counts is:

$$N_{\text{pred}} = \int_{\text{ROI}} dE' d\hat{p}' dt M(E', \hat{p}', t)$$

To save CPU time, a model-independent quantity, « exposure map (*cube*)» is precomputed:

$$\varepsilon(E, \hat{p}) \equiv \int_{\text{ROI}} dE' d\hat{p}' dt R(E', \hat{p}', t; E, \hat{p})$$

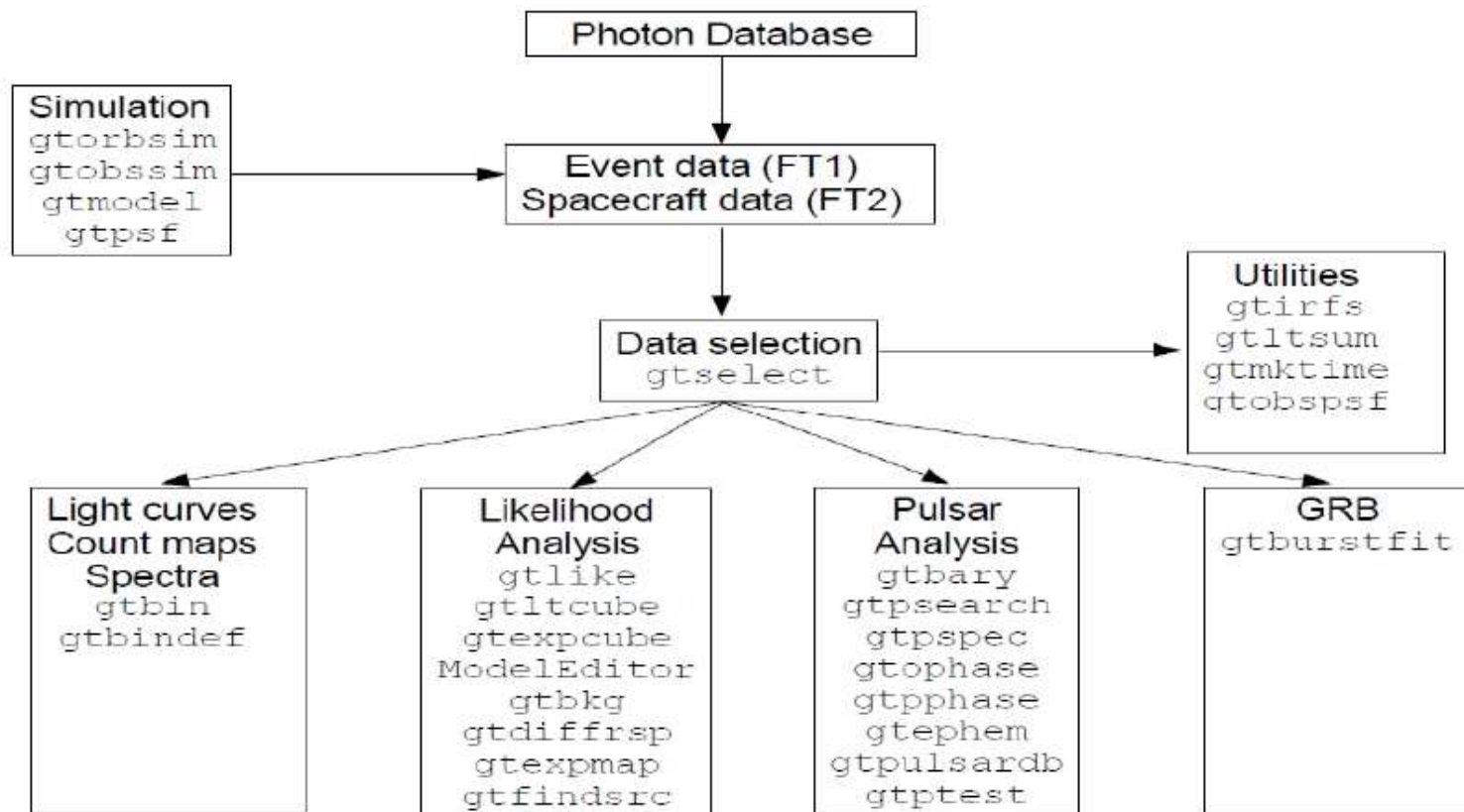
Then

$$N_{\text{pred}} = \int_{\text{SR}} dE d\hat{p} S(E, \hat{p}) \varepsilon(E, \hat{p})$$



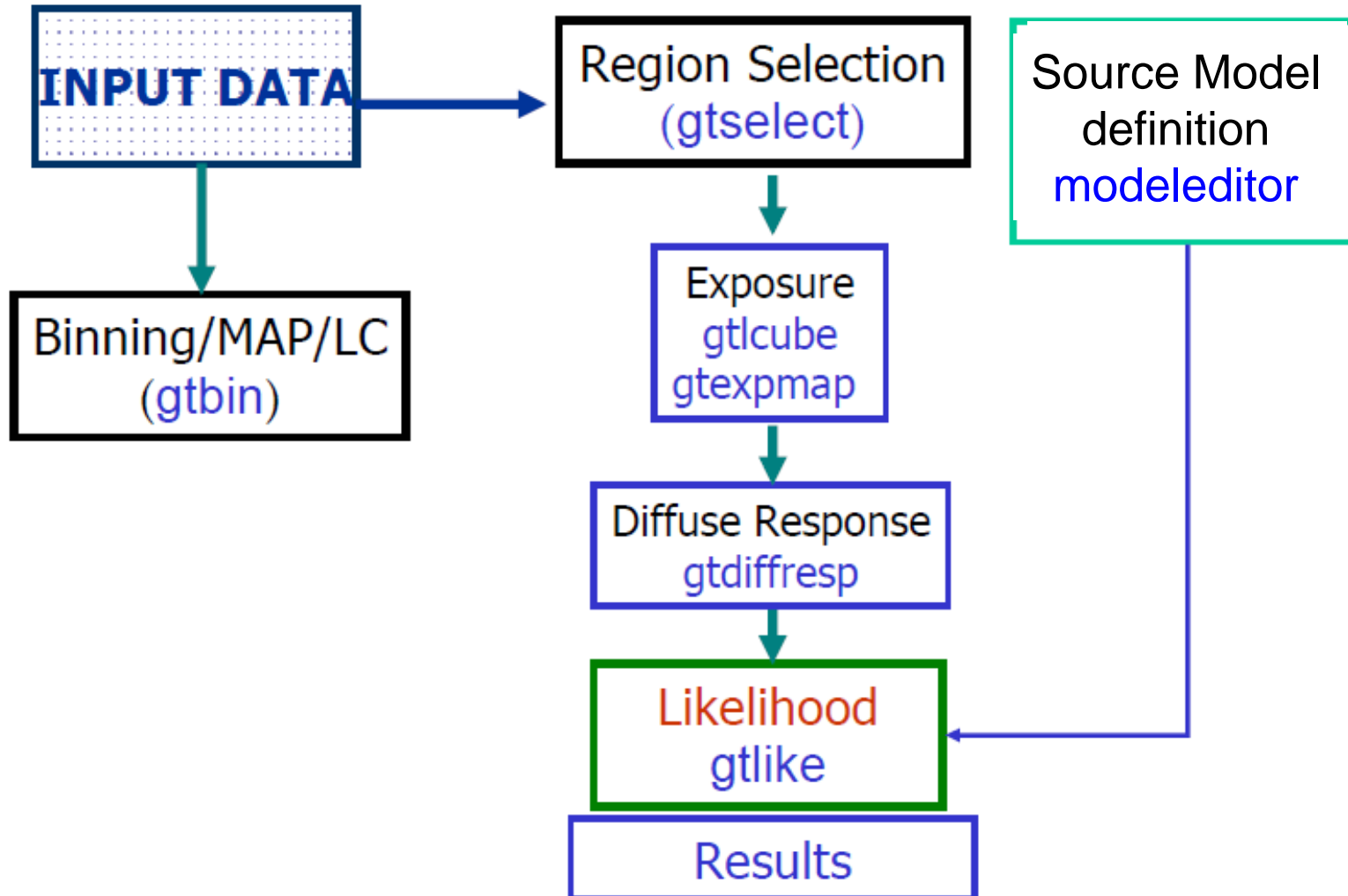


# Science Tools: Flowchart





# Likelihood analysis in a nutshell



*Details of the method can be found in  
<http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone>*

# gtselect



- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtselect.txt>
- Performs selection cuts in event data file, typically to define a Region-of-Interest (ROI) with events belonging to a certain class (standard is the « diffuse » class).
- `gtselect infile outfile ra dec rad tmin tmax emin emax zmax`
- Output fits file contains selected events. The header includes a record of the pruning history.
- Retrieving cuts applied to a given file can be obtained with `gtvcut`  
**USAGE** `gtvcut file_name EVENTS`

➤ `gtselect evclsmin=3 evclsmax=3`

`infile = L090923112502E0D2F37E71_PH00.fits`

`outfile = 3c454_100_300000_evt0.fits ra = 343.490616 dec = 16.148211 rad = 15`

`tmin = 266976000 tmax = 275369897 emin = 100 emax = 200000 zmax = 105`

`> gtvcut 3c454_100_300000_evt0.fits EVENTS`

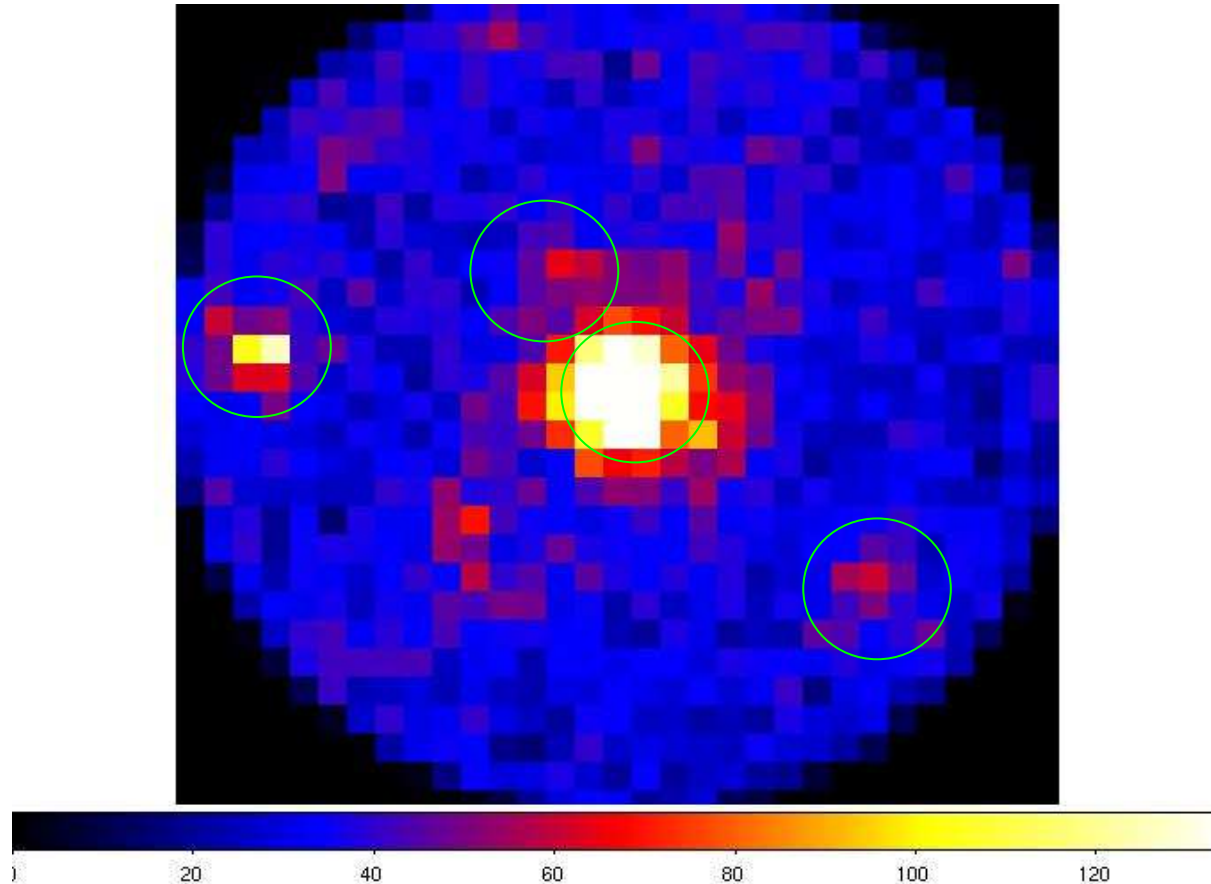
➤ note: `plist` returns the parameter list for a given `ftool`

`> plist gtselect`

# inspecting the ROI



`ds9 '3c454_100_300000_evt01.fits[EVENTS][RA,DEC]'`  
(EVENTS is the extension name)



Detected sources are listed in 1FGL Catalog:  
[http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr\\_catalog/](http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/)

# gtmktime



- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtmktime.txt>
- Create Good Time Intervals (GTIs) based on selections made using the spacecraft data file variables.
- gtmktime is used to update the Good Time Intervals (GTI) extension and make cuts based on spacecraft parameters contained in the Pointing and Livetime History (spacecraft) FITS file. A Good Time Interval is a time range when the data can be considered valid.
- USAGE gtmktime scfile filter roicut evfile outfile

```
> gtmktime scfile = L090923112502E0D2F37E71_SC00.fits  
filter = "(IN_SAA!=T) && (DATA_QUAL==1) &&  
ABS(ROCK_ANGLE)<52" roicut = yes  
evfile = 3c454_100_300000_evt0.fits  
outfile = 3c454_100_300000_evt1.fits
```

# gtltcube



- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtltcube.txt>
- Calculates integrated livetime as a function of sky position and off-axis angle.
- Output file contains a array of integrated livetime as a function off-axis angle for different (healpix-based) sky positions
- **USAGE** gtltcube evfile scfile outfile dcostheta binsz

```
/COSPAR < 118 >gtltcube
Event data file[3c454_100_300000_evt02.fits]
Spacecraft data file[L090923112502E0D2F37E71_SC00.fits]
Output file[3c454_expcube.fits]
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
Working on file L090923112502E0D2F37E71_SC00.fits
.....!
1536.331u 17.804s 32:48.37 78.9%          0+0k 0+0io 1pf+0w
```

# gtexpmap

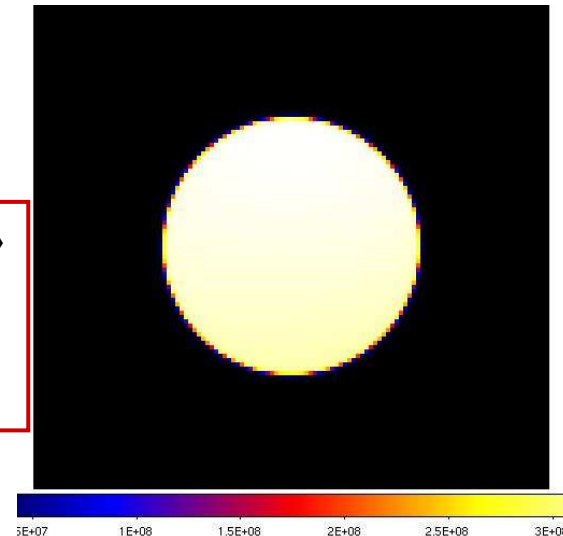


- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtexpmap.txt>
- calculates ROI-specific exposure maps for unbinned likelihood analysis.
- creates exposure maps needed to compute the predicted number of photons within a given Region-of-Interest (ROI) for diffuse components in your source model.
- integral of the total response (effective area x energy dispersion x point spread function) over the entire ROI.
- output fits file contains a cube of nlong x nlat x nenergies exposure maps for the specified ROI
- **USAGE** gtexpmap evfile scfile expcube outfile irfs srcrad nlong nlat nenergies

```

/COSPAR < 119 >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[3c454_100_300000_evt02.fits]
Spacecraft data file[L090923112502EOD2F37E71_SC00.fits]
Exposure hypercube file[3c454_expcube.fits]
output file name[3c454_expmap.fits]
Response functions[P6_V3_DIFFUSE]
Radius of the source region (in degrees)[30]
Number of longitude points (2:1000) [120]
Number of latitude points (2:1000) [120]
Number of energies (2:100) [20]
Computing the ExposureMap using 3c454_expcube.fits
.....!
252.669u 4.326s 10:00:28.68 0.7%          0+0k 0+0io 4pf+0w
/COSPAR < 120 >
  
```

«Source region »  
must exceeds  
the ROI radius  
by at least 10°



# xml model file

```
<?xml version="1.0" ?>
<source_library title="source library">
<!-- Diffuse Sources -->
<source name="GAL_v02" type="DiffuseSource">
  <spectrum type="PowerLaw">
    <parameter free="1" max="10" min="0" name="Prefactor"
      scale="1" value="1.22"/>
    <parameter free="0" max="1" min="-1" name="Index" scale="1.0" value="0"/>
    <parameter free="0" max="2e2" min="5e1" name="Scale" scale="1.0" value="1e2"/>
  </spectrum>
  <spatialModel file="gll_iem_v02.fit" type="MapCubeFunction">
    <parameter free="0" max="1e3" min="1e-3" name="Normalization" scale="1.0" value="1" />
  </spatialModel>
</source>
<source name="EG_v02" type="DiffuseSource">
  <spectrum type="FileFunction" file="isotropic_iem_v02.txt">
    <parameter free="1" max="10" min="1e-2" name="Normalization" scale="1" value="1"/>
  </spectrum>
  <spatialModel type="ConstantValue">
    <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
  </spatialModel>
</source>
<!-- Target Sources -->
<source name="_3c454" type="PointSource">
  <spectrum type="PowerLaw2">
    <parameter free="1" max="10000" min="0.0001" name="Integral" scale="1e-07" value="15.6325" />
    <parameter free="1" max="5" min="1" name="Index" scale="-1" value="2.507" />
    <parameter free="0" max="500000" min="30" name="LowerLimit" scale="1" value="100" />
    <parameter free="0" max="500000" min="30" name="UpperLimit" scale="1" value="300000" />
  </spectrum>
  <spatialModel type="SkyDirFunction">
    <parameter free="0" max="360" min="-360" name="RA" scale="1" value="343.490616" />
    <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="16.148211" />
  </spatialModel>
</source>
<!-- Target Sources -->
<source name="Field1" type="PointSource">
```

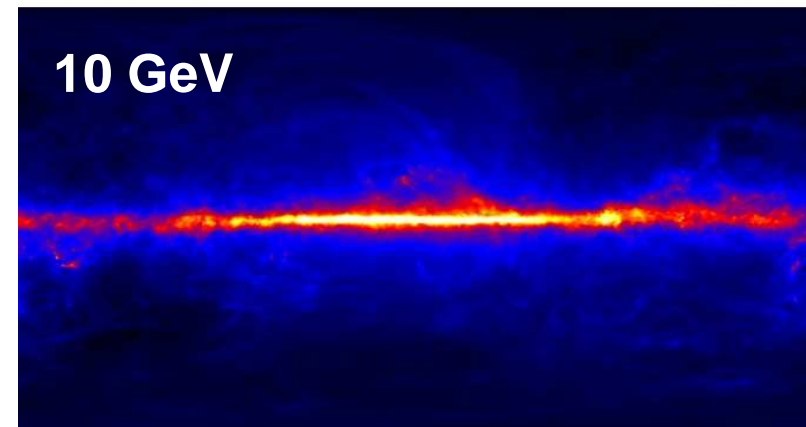
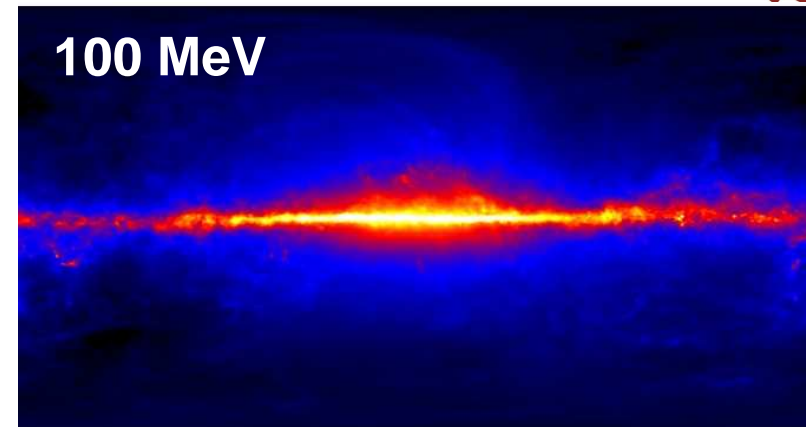


# Diffuse models



- **Galactic diffuse model:**  
gll\_iem\_v02.fit  
model adjusted to data
- **Extragalactic diffuse model**  
actually sum of true  
gamma-ray extragalactic diffuse+  
instrumental background  
isotropic\_iem\_v02.txt

```
39.3884 6.57144e-07 4.6946e-08
64.0414 4.09665e-07 5.72124e-09
104.125 1.72000e-07 8.35794e-10
169.296 6.60007e-08 2.15325e-10
275.257 2.24126e-08 7.58059e-11
447.539 7.21114e-09 2.95711e-11
727.651 2.20758e-09 1.16796e-11
1183.08 7.20365e-10 4.68072e-12
1923.57 2.35566e-10 1.93256e-12
3127.52 7.36933e-11 8.02165e-13
.....
```



# Source models



Many different models are available:

[http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone\\_Likelihood/Model\\_Selection.html](http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood/Model_Selection.html)

[http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/xml\\_model\\_defs.html](http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/xml_model_defs.html)

The units for the spectral models are  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$  for point sources and  $\text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \text{sr}^{-1}$  for diffuse sources. All energies are in MeV.

**PowerLaw** simple power law

$$N(E) = N_0 (E/E_0)^\Gamma$$

$N_0$  :Prefactor,  $\Gamma$ :spectral index

$E_0$ :energy scale

**BrokenPowerLaw** two component power law

$$N(E) = N_0 (E/E_b)^{\Gamma_1+1} \quad E < E_b$$

$$= N_0 (E/E_b)^{\Gamma_2+1} \quad E > E_b$$

$N_0$  :Prefactor  $\Gamma_1$ :low energy spectral index  $\Gamma_2$ :high energy spectral index

$E_b$ :break energy

**PowerLaw2** simple power law with the integral number of counts between two energies as the normalization

$$N(E) = (\Gamma+1)N E^\Gamma / (E_{\text{max}}^{\Gamma+1} - E_{\text{min}}^{\Gamma+1})$$

$N$ : Integral number of counts between  $E_{\text{max}}$  and  $E_{\text{min}}$   $\Gamma$ :spectral index

$E_{\text{min}}$ :low end of energy range (always a fixed quantity)

$E_{\text{max}}$ :high end of energy range (always a fixed quantity)

# preparing the source model (1)



Using the modeeditor GUI: Add sources (point-like or diffuse) using the drop down menu

ModelEditor (3c454\_srcmdl.xml)

File Edit Source Help

Title: source library

Source Name:  Source Type: PointSource

Spectrum Type: **PowerLaw2** File:  Browse

name	value	scale	min	max	free
Integral	15.6325	1e-07	0.0001	10000.0	<input checked="" type="checkbox"/>
Index	2.507	-1.0	1.0	5.0	<input checked="" type="checkbox"/>
LowerLimit	100.0	1.0	30.0	500000.0	<input type="checkbox"/>
UpperLimit	300000.0	1.0	30.0	500000.0	<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>

Spatial Model Type: **SkyDirFunction** File:  Browse

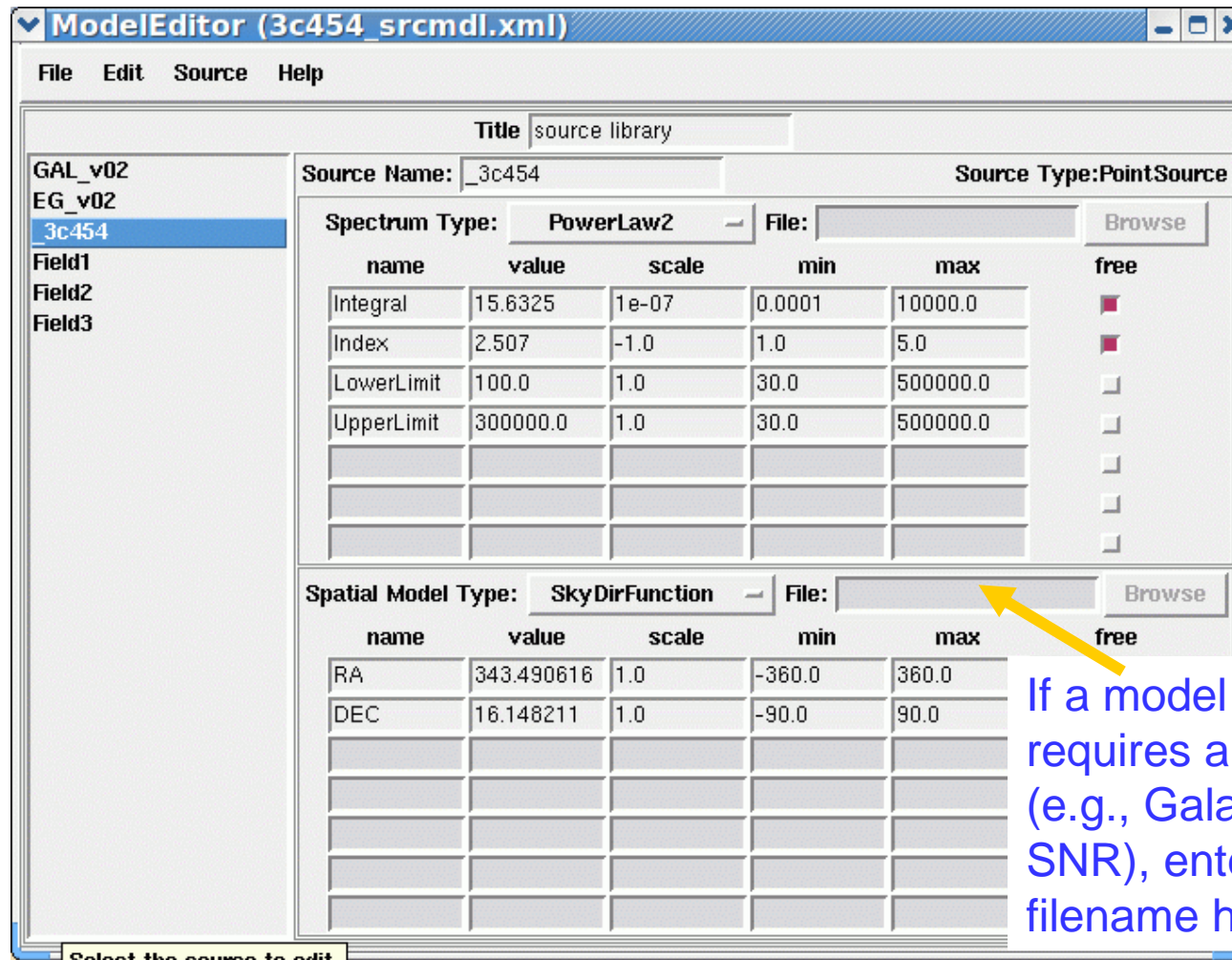
name	value	scale	min	max	free
RA	343.490616	1.0	-360.0	360.0	<input type="checkbox"/>
DEC	16.148211	1.0	-90.0	90.0	<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>

Select the source to edit

# preparing the source model (2)



Edit source name, default fit parameters, bounds, scaling, etc.



The screenshot shows the ModelEditor window for source '3c454'. The interface includes a menu bar (File, Edit, Source, Help), a title bar (ModelEditor (3c454\_srcmdl.xml)), and a main panel with the following sections:

- Title:** source library
- Source Name:** 3c454
- Source Type:** PointSource
- Spectrum Type:** PowerLaw2
- File:** (empty field with a 'Browse' button)
- Parameter Table (Spectrum):**

name	value	scale	min	max	free
Integral	15.6325	1e-07	0.0001	10000.0	<input checked="" type="checkbox"/>
Index	2.507	-1.0	1.0	5.0	<input checked="" type="checkbox"/>
LowerLimit	100.0	1.0	30.0	500000.0	<input type="checkbox"/>
UpperLimit	300000.0	1.0	30.0	500000.0	<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>
					<input type="checkbox"/>
- Spatial Model Type:** SkyDirFunction
- File:** (empty field with a 'Browse' button)
- Parameter Table (Spatial):**

name	value	scale	min	max	free
RA	343.490616	1.0	-360.0	360.0	
DEC	16.148211	1.0	-90.0	90.0	

A yellow arrow points to the 'File:' field in the Spatial Model Type section. A text box next to it contains the following instruction:

If a model component requires a FITS image (e.g., Galactic diffuse, SNR), enter the filename here

# gtdiffrsp



- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtdiffrsp.txt>
- **Calculates the integral over solid angle of a diffuse source model convolved with the instrumental response function**
- **USAGE gtdiffrsp evfile scfile srcmdl irfs**
- **The instrument response can be precomputed for each diffuse model component. The gtdiffrsp tool will perform these integrations and add the results as an additional column for each diffuse source into the input event file.**
- **This step can be skipped if you use standard data files, which include diffuse responses. The diffuse component names in your model and the FT1 file have to match.**



# gtlike



- <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtlike.txt>
- Performs unbinned (or binned) likelihood analysis of LAT data.
- USAGE **gtlike irfs expcube srcmdl statistic optimizer evfile scfile expmap cmap bexpmap**

## plist gtlike

Parameters for /home/local1/pfiles/gtlike.par

irfs = P6\_V3\_DIFFUSE Response functions to use  
 (edisp = no) Use energy dispersion?  
 expcube = 3c454\_expcube.fits Exposure hypercube file  
 srcmdl = 3c454\_srcmdl\_1.xml Source model file  
 (sfile = none) Source model output file  
 (check\_fit = yes) Issue warnings regarding fit?  
 (results = results.dat) Output file for fit results  
 (specfile = counts\_spectra.fits) Output file for counts spectra  
 statistic = UNBINNED Statistic to use  
 optimizer = MINUIT Optimizer  
 (ftol = 1e-2) Fit tolerance  
 (toltype = ABS) Fit tolerance convergence type (absolute vs relative)  
 (tsmin = no) Re-optimize for TS fits?  
 (save = yes) Write output files?  
 (refit = no) Allow for refitting?  
 evfile = 3c454\_100\_300000\_evt02.fits Event file  
 (evtable = EVENTS) Event table extension  
 scfile = L090923112502E0D2F37E71\_SC00.fits Spacecraft file  
 (sctable = SC\_DATA) Spacecraft table extension  
 expmap = 3c454\_expmap.fits Unbinned exposure map  
 (plot = no) Plot unbinned counts spectra?  
 cmap = none Counts map file  
 bexpmap = none Binned exposure map  
 (psfcorr = yes) apply psf integral corrections  
 (chatter = 2) Output verbosity  
 (clobber = yes) Overwrite existing output files  
 (debug = no) Activate debugging mode  
 (gui = no) GUI mode activated  
 (mode = ql) Mode of automatic parameters



```

/COSPAR < 120 >gtlike
Statistic to use (BINNED|UNBINNED) [UNBINNED]
Spacecraft file[L090923112502E0D2F37E71_SC00.fits]
Event file[3c454_100_300000_evt02.fits]
Unbinned exposure map[3c454_expmap.fits]
Exposure hypercube file[3c454_expcube.fits]
Source model file[3c454_srcmdl_1.xml]
Response functions to use[P6_V3_DIFFUSE]
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT]
*****
** 1 **SET PRINT      .000
*****
*****
** 2 **SET NOWARN
*****

PARAMETER DEFINITIONS:
NO.  NAME          VALUE      STEP SIZE  LIMITS
 1 'Normalizat'    1.0000     1.0000    .10000E-01  10.000
 2 'Integral '    1.5800     1.0000    .10000E-03  10000.
 3 'Index '       2.3200     1.0000     1.0000     5.0000
 4 'Integral '    .43200     1.0000    .10000E-03  10000.
 5 'Index '       2.2100     1.0000     1.0000     5.0000
 6 'Integral '    1.5900     1.0000    .10000E-03  10000.
 7 'Index '       3.1500     1.0000     1.0000     5.0000
 8 'Prefactor '   1.2200     1.0000     .0000     10.000
 9 'Integral '   15.633     1.0000    .10000E-03  10000.
10 'Index '       2.5070     1.0000     1.0000     5.0000
*****

```



MIGRAD MINIMIZATION HAS CONVERGED.

MIGRAD WILL VERIFY CONVERGENCE AND ERROR MATRIX.

FCN= 325758.9 FROM MIGRAD STATUS=CONVERGED 175 CALLS 176 TOTAL  
EDM= .26E-04 STRATEGY= 1 ERROR MATRIX ACCURATE

EXT PARAMETER NO.	NAME	VALUE	ERROR	STEP SIZE	FIRST DERIVATIVE
1	Normalizat	.61151	.31584E-01	.70564E-01	.33466
2	Integral	1.5789	.13091	.84476E-02	-.40981
3	Index	2.3207	.57567E-01	.32813	-.12866E-01
4	Integral	.43409	.92339E-01	.10990E-01	.50641
5	Index	2.2117	.11439	.50000	-.18973E-01
6	Integral	1.5853	.18111	.84133E-02	-.66377E-01
7	Index	3.1538	.11154	.50000	-.31552E-01
8	Prefactor	1.2937	.29627E-01	.34174E-01	.22873
9	Integral	15.650	.32651	.25325E-02	-4.1985
10	Index	2.5079	.19465E-01	.10779	.34593

ERR DEF= .500

\*\*\*\*\*  
\*\* 6 \*\*HESSE  
\*\*\*\*\*

FCN= 325758.9 FROM HESSE STATUS=OK 102 CALLS 278 TOTAL  
EDM= .36E-04 STRATEGY= 1 ERROR MATRIX ACCURATE

EXT PARAMETER NO.	NAME	VALUE	ERROR	INTERNAL STEP SIZE	INTERNAL VALUE
1	Normalizat	.61151	.45414E-01	.31227E-03	-1.0750
2	Integral	1.5789	.15452	.48950E-04	-1.5457
3	Index	2.3207	.68392E-01	.14478E-02	-.34657
4	Integral	.43409	.11134	.60392E-03	-1.5576
5	Index	2.2117	.13803	.27075E-01	-.40513
6	Integral	1.5853	.20780	.74058E-04	-1.5456
7	Index	3.1538	.14838	.29372E-01	.76991E-01
8	Prefactor	1.2937	.42609E-01	.21076E-03	-.83494
9	Integral	15.650	.34443	.38621E-04	-1.4917
10	Index	2.5079	.20544E-01	.47616E-03	-.24859

ERR DEF= .500

Final values:  
Normalizat = 0.611512  
Integral = 1.5789  
Index = 2.32065  
Integral = 0.434088  
Index = 2.21172  
Integral = 1.58531  
Index = 3.15383  
Prefactor = 1.29372  
Integral = 15.65  
Index = 2.50793

Minuit fit quality: 3 estimated distance: 3.5555e-05

Minuit parameter uncertainties:

1 0.0454168  
2 0.15452  
3 0.068407  
4 0.111335  
5 0.138158  
6 0.207796  
7 0.148518  
8 0.0426102  
9 0.344429  
10 0.020544

Computing TS values for each source (6 total)

.....!

Field3:

Integral: 1.58531 +/- 0.207796

Index: 3.15383 +/- 0.148518

LowerLimit: 100

UpperLimit: 300000

Npred: 313.794

ROI distance: 10.5547

TS value: 136.841

GAL\_v02:

Prefactor: 1.29372 +/- 0.0426102

Index: 0

Scale: 100

Npred: 16057

\_3c454:

Integral: 15.65 +/- 0.344429

Index: 2.50793 +/- 0.020544

LowerLimit: 100

UpperLimit: 300000

Npred: 4527.45

ROI distance: 0

TS value: 10657.7

WARNING: Fit may be bad in range [100, 222.696] (MeV)

Total number of observed counts: 28719

Total number of model events: 28719

-log(Likelihood): 325758.9218

Elapsed CPU time: 85.62

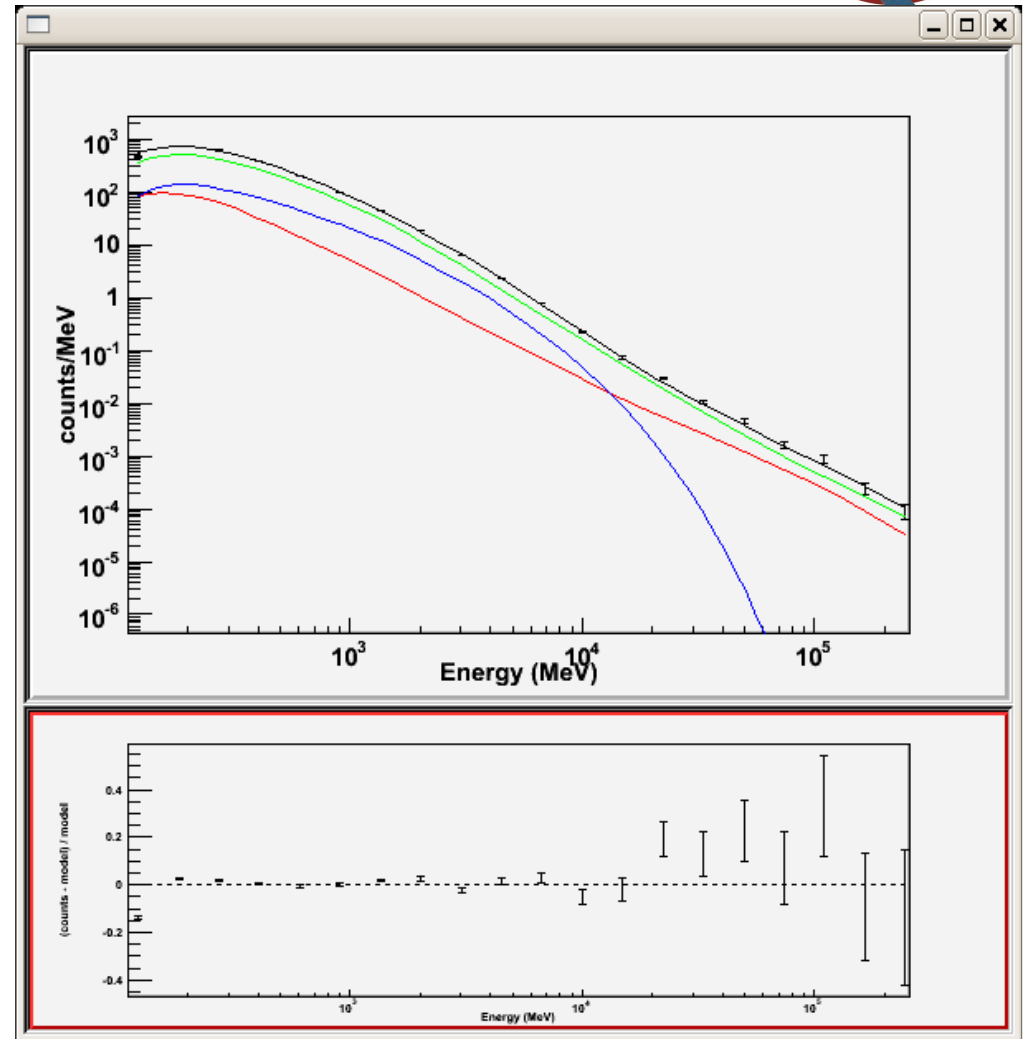
/COSPAR < 121 >

# Checking the fit quality



> gtlite plot=yes

Counts vs model predictions  
and residues for the whole ROI





## Results are stored:

- in an ascii file  
(default name: results.dat)
- in a fits file  
(default name: counts\_spectra.fits)
- in an xml file (optional)

```
/COSPAR < 93 >more results.dat
{'EG_v02': {'Normalization': '0.611512 +/- 0.0454168',
'Npred': '7199.26',
},
'Field1': {'Integral': '1.5789 +/- 0.15452',
'Index': '2.32065 +/- 0.068407',
'LowerLimit': '100',
'UpperLimit': '300000',
'Npred': '471.496',
'ROI distance': '12.0615',
'TS value': '508.292',
},
'Field2': {'Integral': '0.434088 +/- 0.111335',
'Index': '2.21172 +/- 0.138158',
'LowerLimit': '100',
'UpperLimit': '300000',
'Npred': '149.969',
'ROI distance': '4.71393',
'TS value': '97.6952',
},
'Field3': {'Integral': '1.58531 +/- 0.207796',
'Index': '3.15383 +/- 0.148518',
'LowerLimit': '100',
'UpperLimit': '300000',
'Npred': '313.794',
'ROI distance': '10.5547',
'TS value': '136.841',
},
'GAL_v02': {'Prefactor': '1.29372 +/- 0.0426102',
'Index': '0',
'Scale': '100',
'Npred': '16057',
},
'_3c454': {'Integral': '15.65 +/- 0.344429',
'Index': '2.50793 +/- 0.020544',
'LowerLimit': '100',
'UpperLimit': '300000',
'Npred': '4527.45',
'ROI distance': '0',
'TS value': '10657.7',
},
}
/COSPAR < 94 >
```

# using python

---



```
from UnbinnedAnalysis import *
my_obs=UnbinnedObs('3c454_100_300000_evt02.fits',
                  scFile='L090923112502E0D2F37E71_SC00.fits',
                  expMap='3c454_expmap.fits',
                  expCube='3c454_expcube.fits',
                  irfs='P6_V3_DIFFUSE')
analysis= UnbinnedAnalysis (my_obs,'3c454_srcmdl.xml',optimizer='MINUIT')
print analysis
dir(analysis)
loglike=analysis.fit(covar=True)
print loglike
cov=analysis.covariance
print cov
analysis.plot()
analysis.model
print analysis['_3c454']
analysis.writeCountsSpectra("spectra.fits")
analysis.writeXml("results.xml")
analysis.sourceNames()
ts=analysis.Ts('_3c454')
npred=analysis.logLike.NpredValue('_3c454')
```





fv: Summary of counts\_spectra.fits in /home/local1/COSPAR/

File Edit Tools Help

Index	Extension	Type	Dimension	View					
<input type="checkbox"/> 0	Primary	Image	0	Header	Image				
<input type="checkbox"/> 1	COUNTS_SPECTRA	Binary	7 cols X 20 rows	Header	Hist	Plot	All	Select	
<input type="checkbox"/> 2	FLUXES	Binary	4 cols X 20 rows	Header	Hist	Plot	All	Select	
<input type="checkbox"/> 3	EBOUNDS	Binary	2 cols X 20 rows	Header	Hist	Plot	All	Select	

**COUNT FILE**

fv: Binary Table of counts\_spectra.fits[1] in /home/local1/COSPAR/

File Edit Tools H

ObsCounts     EG\_v02     Field1     Field2     Field3     GAL\_v02

Select    1D    1D    1D    1D    1D    1D

All

Invert    Modify    Modify    Modify    Modify    Modify    Modify

1	2.596000000000E+03	8.549795774687E+02	4.768227244938E+01	1.525390664249E+01	6.726195633766E+01	1.232155158353E+03
2	5.521000000000E+03	1.483198250010E+03	9.445267153720E+01	2.927870092394E+01	9.652483493132E+01	2.487646963723E+03
3	5.934000000000E+03	1.523401247159E+03	9.834172329228E+01	3.006838471123E+01	7.133452170802E+01	3.087464111441E+03
4	5.060000000000E+03	1.189180360326E+03	7.945788367153E+01	2.443176332148E+01	4.085668231697E+01	2.894381471086E+03
5	3.557000000000E+03	7.970364322419E+02	5.591688561995E+01	1.761039271453E+01	2.039593989266E+01	2.295521248703E+03
6	2.525000000000E+03	5.178150395089E+02	3.737582167351E+01	1.218456935004E+01	9.735301643223E+00	1.650270378499E+03
7	1.547000000000E+03	3.258426492270E+02	2.338758605363E+01	7.931176632615E+00	4.361279228195E+00	1.061088884779E+03
8	8.760000000000E+02	1.961300451591E+02	1.403414962281E+01	4.965926268181E+00	1.874456338524E+00	6.219958863344E+02
9	4.800000000000E+02	1.142206433513E+02	8.302115104689E+00	3.068325735216E+00	7.939803420732E-01	3.415242587959E+02
10	2.570000000000E+02	7.377811597050E+01	4.901711216637E+00	1.893809582973E+00	3.358835529779E-01	1.798136207754E+02
11	1.550000000000E+02	4.576595467710E+01	3.000494085561E+00	1.210830919583E+00	1.469400577759E-01	9.379910764010E+01
12	7.600000000000E+01	2.683326316968E+01	1.840201558378E+00	7.753687962633E-01	6.461385872733E-02	4.853578116622E+01
13	4.900000000000E+01	1.642774545555E+01	1.119405936146E+00	4.927130976890E-01	2.816071217838E-02	2.679264859832E+01
14	3.200000000000E+01	1.133234671657E+01	6.724066012359E-01	3.092363149885E-01	1.210689083726E-02	1.497272742501E+01
15	2.100000000000E+01	8.166522159179E+00	4.064951536790E-01	1.952352685796E-01	5.244331431232E-03	8.693171276306E+00
16	1.600000000000E+01	5.388132402331E+00	2.366701785619E-01	1.188563230365E-01	2.187548488569E-03	5.155343139910E+00
17	5.000000000000E+00	3.695620435163E+00	1.348406535370E-01	7.082114771969E-02	8.921679095136E-04	3.160468893089E+00
18	9.000000000000E+00	2.457235836117E+00	7.639196493593E-02	4.193389666534E-02	3.618293482481E-04	2.002969539416E+00
19	1.000000000000E+00	1.379170654430E+00	4.281701100652E-02	2.457041200136E-02	1.453177729353E-04	1.264807576211E+00
20	2.000000000000E+00	7.337603546629E-01	2.370084444266E-02	1.421012627043E-02	5.764603144075E-05	7.899584954223E-01

fv: Summary of counts\_spectra.fits in /home/local1/COSPAR/

File Edit Tools Help

Index	Extension	Type	Dimension	View				
<input type="checkbox"/> 0	Primary	Image	0	Header	Image	Table		
<input type="checkbox"/> 1	COUNTS_SPECTRA	Binary	7 cols X 20 rows	Header	Hist	Plot	All	Select
<input type="checkbox"/> 2	FLUXES	Binary	4 cols X 20 rows	Header	Hist	Plot	All	Select
<input type="checkbox"/> 3	EBOUNDS	Binary	2 cols X 20 rows	Header	Hist	Plot	All	Select



fv: Binary Table of counts\_spectra.fits[2] in /home/local1/COSPAR/

File Edit Tools Help

Select  All  Invert

Field1 1D  Field2 1D  Field3 1D  3c454 1D

Modify Modify Modify Modify

1	6.483469258330E-08	1.668523929022E-08	9.159719558221E-08	7.092549170355E-07
2	3.821239957388E-08	1.027231606108E-08	3.867458475428E-08	3.878286515872E-07
3	2.252169977235E-08	6.324181237275E-09	1.632935917316E-08	2.120691156018E-07
4	1.327388403482E-08	3.893500558599E-09	6.894656340853E-09	1.159618032554E-07
5	7.823388072430E-09	2.397044934522E-09	2.911093176063E-09	6.340923229708E-08
6	4.610963962868E-09	1.475747680433E-09	1.229135008443E-09	3.467288906892E-08
7	2.717619076291E-09	9.085483484015E-10	5.189709767456E-10	1.895952991125E-08
8	1.601715715694E-09	5.593504311934E-10	2.191222875066E-10	1.036728649121E-08
9	9.440223820480E-10	3.443657185958E-10	9.251880940085E-11	5.668950110788E-09
10	5.563897819544E-10	2.120097554783E-10	3.906371273481E-11	3.099846366341E-09
11	3.279261120819E-10	1.305244221209E-10	1.649365855992E-11	1.695031232791E-09
12	1.932737416697E-10	8.035773981983E-11	6.964027575617E-12	9.268623475454E-10
13	1.139120608050E-10	4.947247606254E-11	2.940383414497E-12	5.068188683950E-10
14	6.713771609499E-11	3.045787366900E-11	1.241502066206E-12	2.771343188570E-10
15	3.956976013426E-11	1.875147844357E-11	5.241926521540E-13	1.515401960696E-10
16	2.332170362881E-11	1.154440220091E-11	2.213270070600E-13	8.286390195019E-11
17	1.374539189281E-11	7.107344766311E-12	9.344969612382E-14	4.531092359983E-11
18	8.101286307989E-12	4.375657461346E-12	3.945675596321E-14	2.477652812806E-11
19	4.774752175550E-12	2.693886232983E-12	1.665961106046E-14	1.354808724497E-11
20	2.814152897601E-12	1.658498888536E-12	7.034096795601E-15	7.408248122924E-12

fv: Binary Table of counts\_spectra.fits[3] in /home/

File Edit Tools Help

Select  All  Invert

E\_MIN 1D  E\_MAX 1D

Modify Modify

1	1.000000000000E+02	1.492299737993E+02
2	1.492299737993E+02	2.226958508013E+02
3	2.226958508013E+02	3.323289598029E+02
4	3.323289598029E+02	4.959344196413E+02
5	4.959344196413E+02	7.400828044923E+02
6	7.400828044923E+02	1.104425375237E+03
7	1.104425375237E+03	1.648133698098E+03
8	1.648133698098E+03	2.459509485849E+03
9	2.459509485849E+03	3.670325361324E+03
10	3.670325361324E+03	5.477225575052E+03
11	5.477225575052E+03	8.173662290577E+03
12	8.173662290577E+03	1.219755409467E+04
13	1.219755409467E+04	1.820240677963E+04
14	1.820240677963E+04	2.716344686808E+04
15	2.716344686808E+04	4.053600464421E+04
16	4.053600464421E+04	6.049186910983E+04
17	6.049186910983E+04	9.027200042329E+04
18	9.027200042329E+04	1.347128825798E+05
19	1.347128825798E+05	2.010319993780E+05
20	2.010319993780E+05	3.000000000000E+05



# Comparing models

---



## Likelihood Ratio Test (LRT)

Enable to compare two nested models (the more complex one derives from the other by adding  $\Delta n$  more parameters )

ex Power law (2 parameters) vs Broken Power Law (4 parameters):  $\Delta n=2$

Under regularity assumptions, the probability distribution of the test statistic TS is asymptotically a chi-square with  $\Delta n$  degrees of freedom.

**Ex: Vela**

**PLSuperExpcutoff:  $-\log(\text{Likelihood})$ : 3321842.126**

**PowerLaw :  $-\log(\text{Likelihood})$ : 3324727.121**



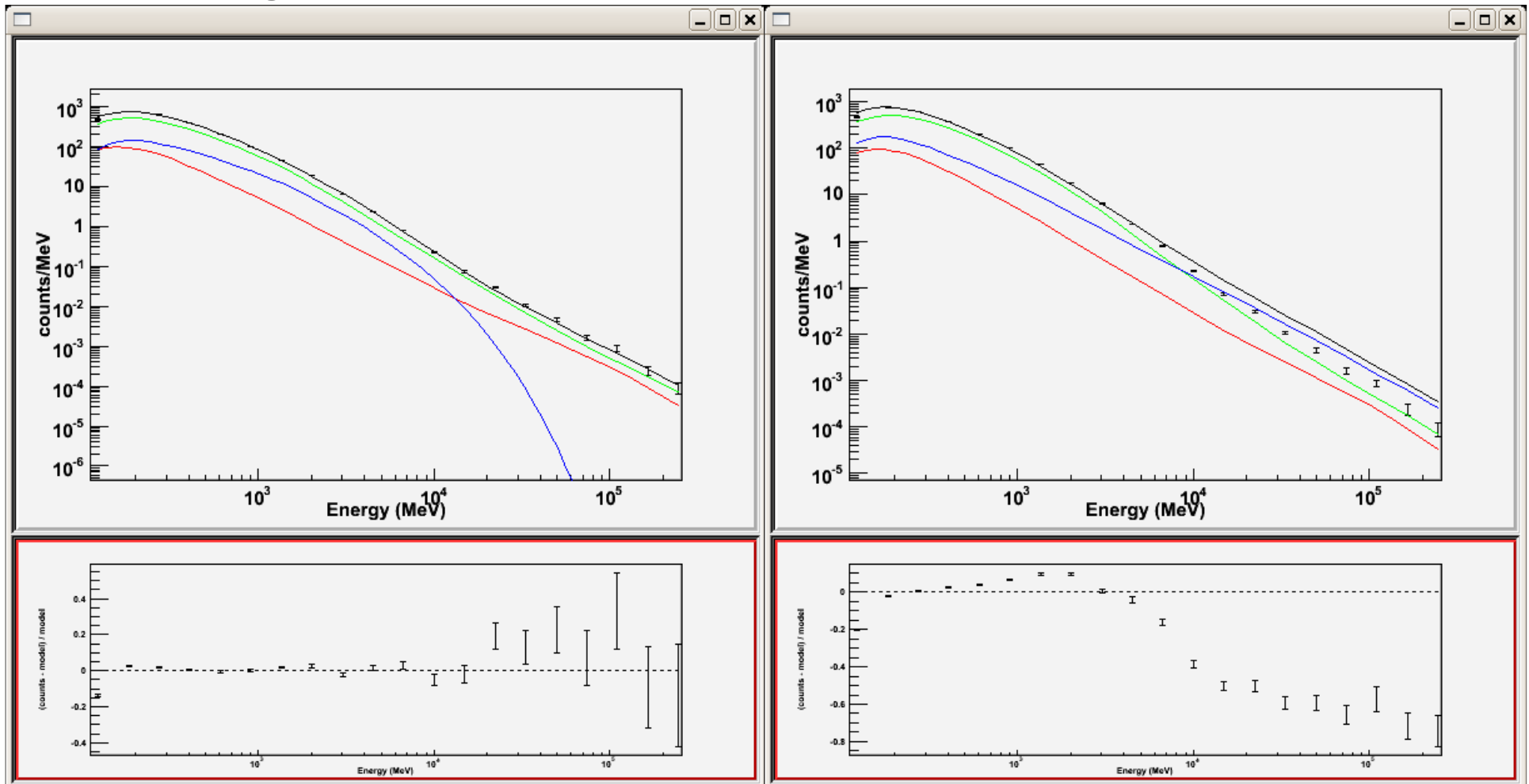


**Ex: Vela**

**PLSuperExp cutoff:  $-\log(\text{Likelihood}): 3321842.126$**

**PowerLaw :  $-\log(\text{Likelihood}): 3324727.121$**

**LRT= 2  $\Delta\log(\text{Likelihood})=5770$  « p-value » from a chi-square with 2 dof**





- **PLSuperExpCutoff** (see example [XML Model Definition](#)) For modeling pulsars.

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{\gamma_1} \exp \left( - \left( \frac{E}{E_c} \right)^{\gamma_2} \right)$$

where

- Prefactor =  $N_0$
- Index1 =  $\gamma_1$
- Scale =  $E_0$
- Cutoff =  $E_c$
- Index2 =  $\gamma_2$

- **PowerLaw** (see example [XML Model Definition](#)) This function has the form

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{\gamma}$$

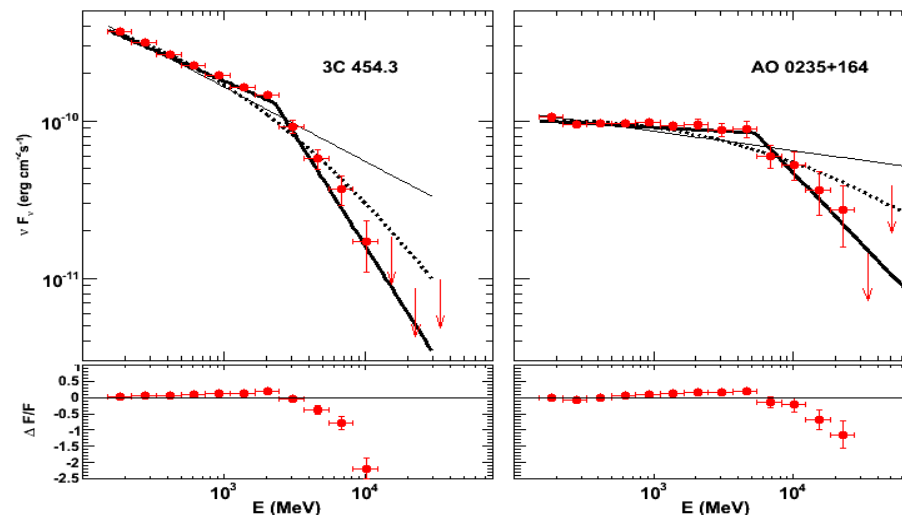
where the parameters in the XML definition have the following mappings:

- Prefactor =  $N_0$
- Index =  $\gamma$
- Scale =  $E_0$

# Spectral analysis in bands



- Standard analysis requires a model
- If enough statistics, the analysis can be performed independently in different energy bands. This assumes that the energy redistribution due to a finite resolution is negligible. That's essentially justified for Fermi.
- Use gtselect to define the bands.
- Beware of the TS and number of photons per bin.



# Exploiting the results: parsing the xml files

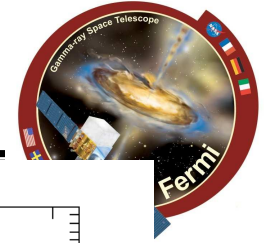
---



## Ex. minidom

```
from xml.dom import minidom
def results(file,name_source):
    doc = minidom.parse(file)
    srcs_glob = doc.getElementsByTagName('source')
    for src in srcs_glob:
        src_name=src.getAttribute('name')
        if (src_name==name_source):
            dir = src.getElementsByTagName('spectrum')[0]
            coords = dir.getElementsByTagName('parameter')
            for coord in coords[:4]:
                value = coord.getAttribute('value')
                error = coord.getAttribute('error')
                scale = coord.getAttribute('scale')
                if (coord.getAttribute('name').encode('ascii') == 'Integral'):
                    flux=float(value)
                    err=float(error)
```

# Producing 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 degrees of freedom left free! You may consider holding some parameters fixed**
  - e.g, spectral index,
  - parameters of steady/or faint sources
- **Monitor the source TS, compute upper limit if necessary (TS<TSthresh)**
- **Using F(E>E0) with E0 100 MeV can provide better results. Optimal results are obtained with E0 being the « pivot energy ». Typically the pivot energy is 200-300 MeV.**

