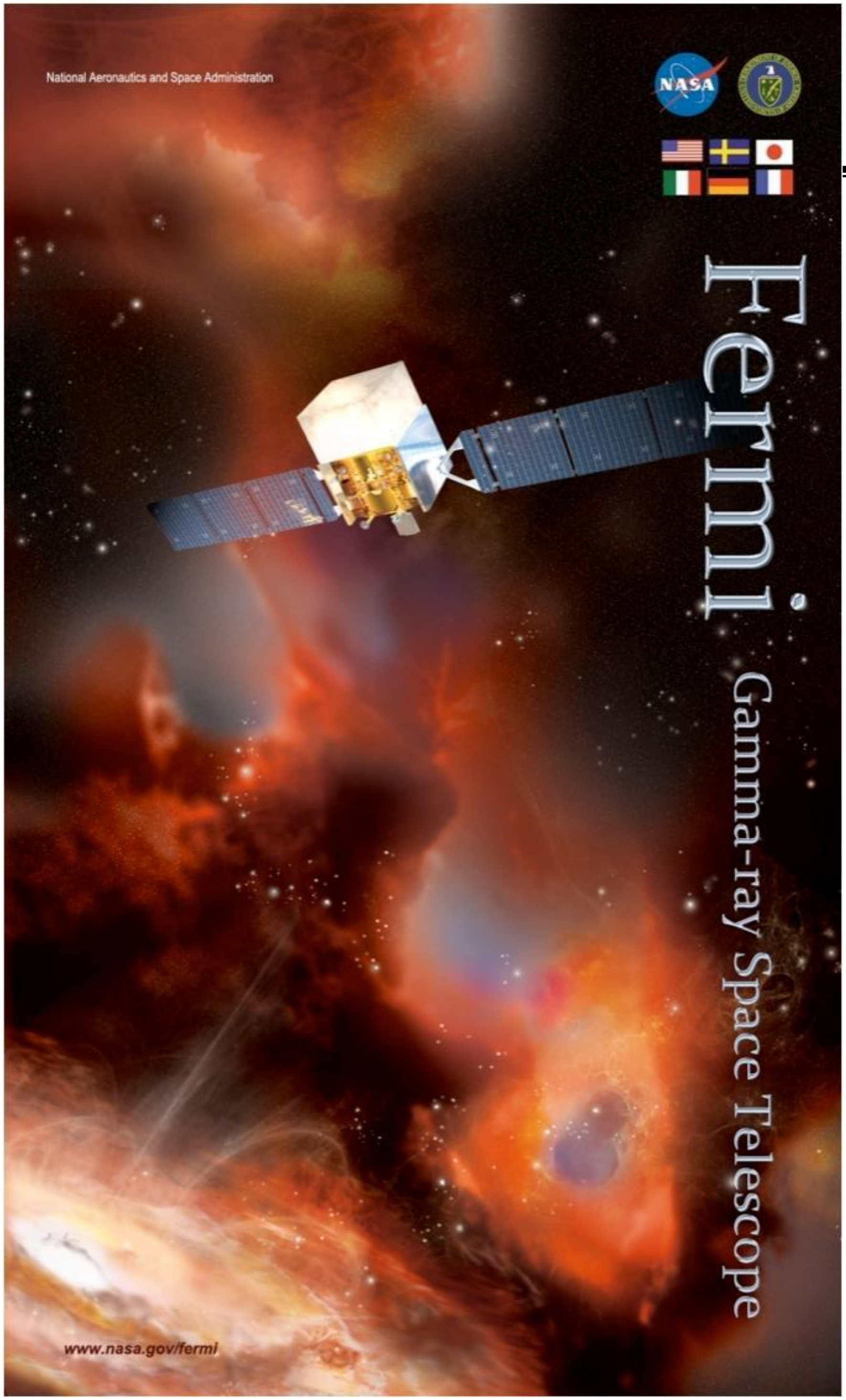

Fermi-LAT likelihood analysis

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

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 nk=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 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 χ^2_n 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:

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

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'*):

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

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 spacescraft. 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:

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

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

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

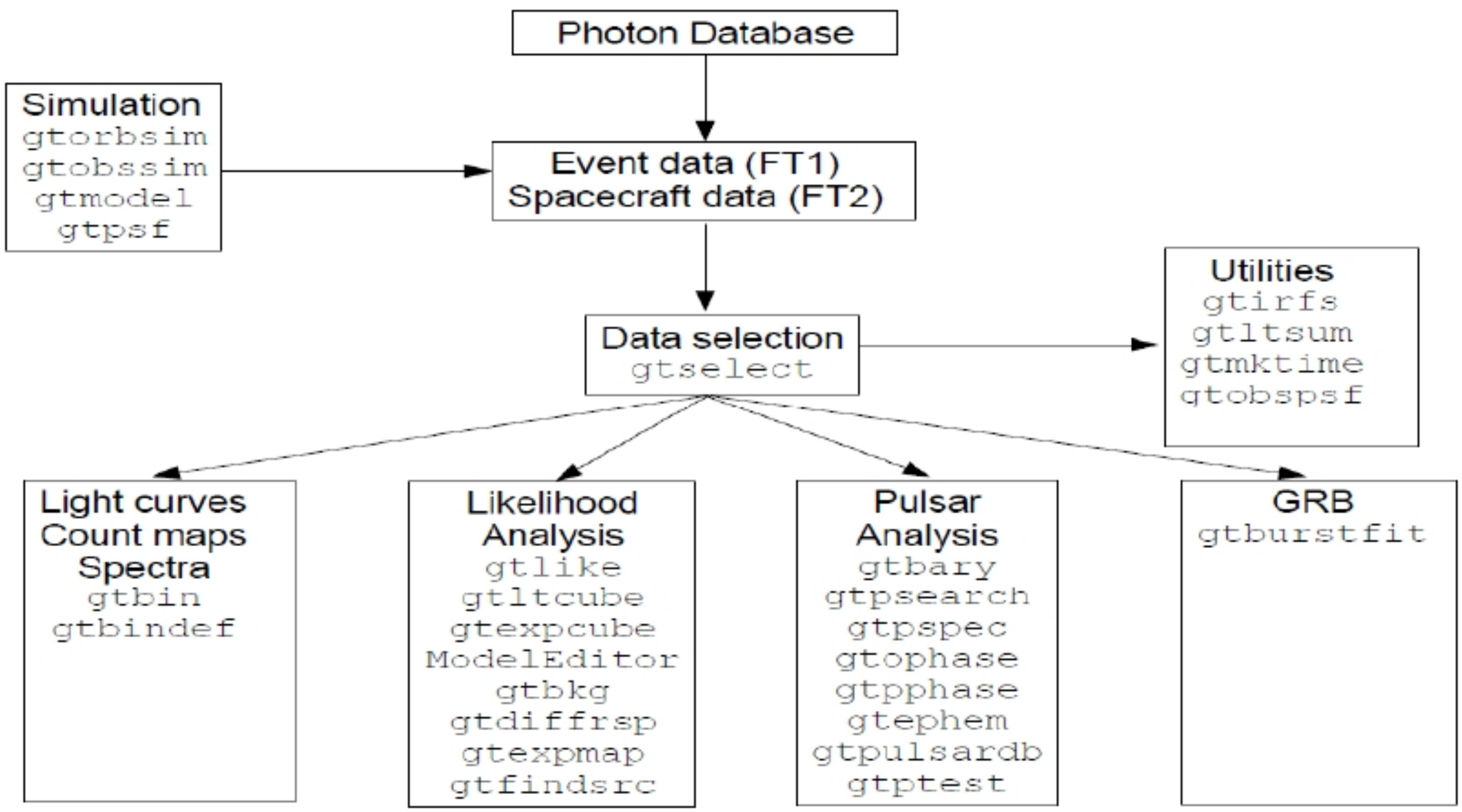
To save CPU time, a model-independent quantity, « exposure map (*cube*)» is precomputed:

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

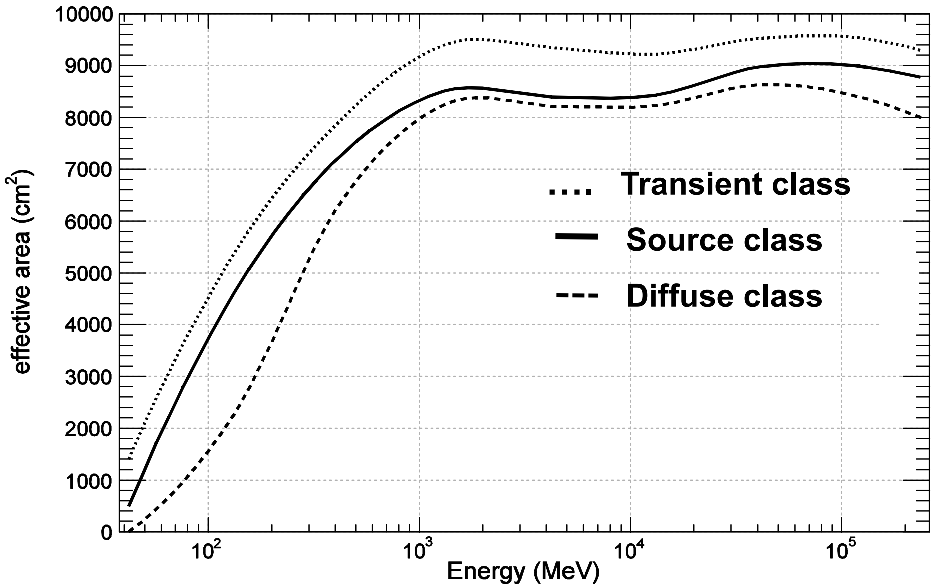
Then

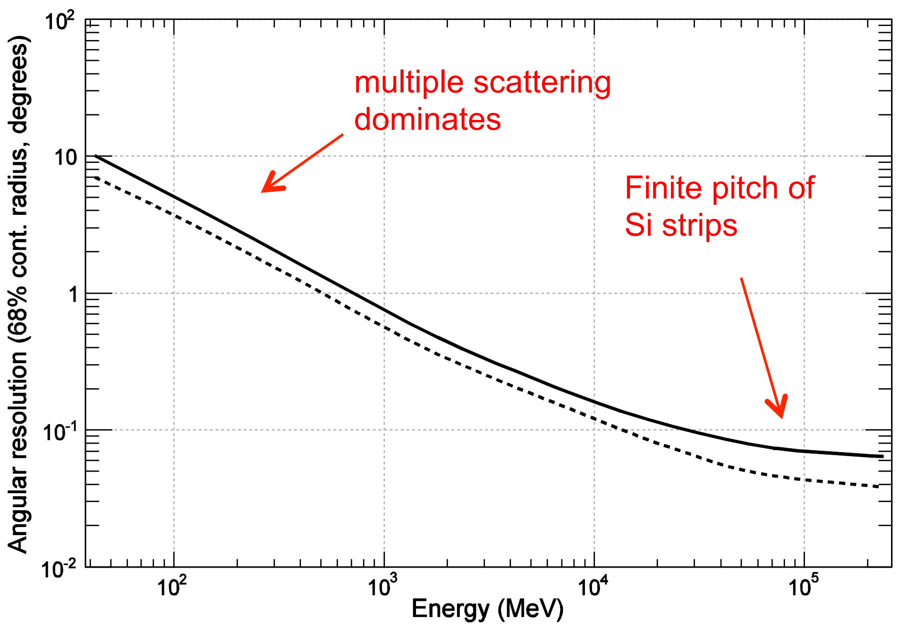
$$N_{\mathrm{pred}} = \int_{\mathrm{SR}} dE d\hat{p}\, S(E, \hat{p})\, \varepsilon(E, \hat{p})$$

Science Tools: Flowchart



Event classes

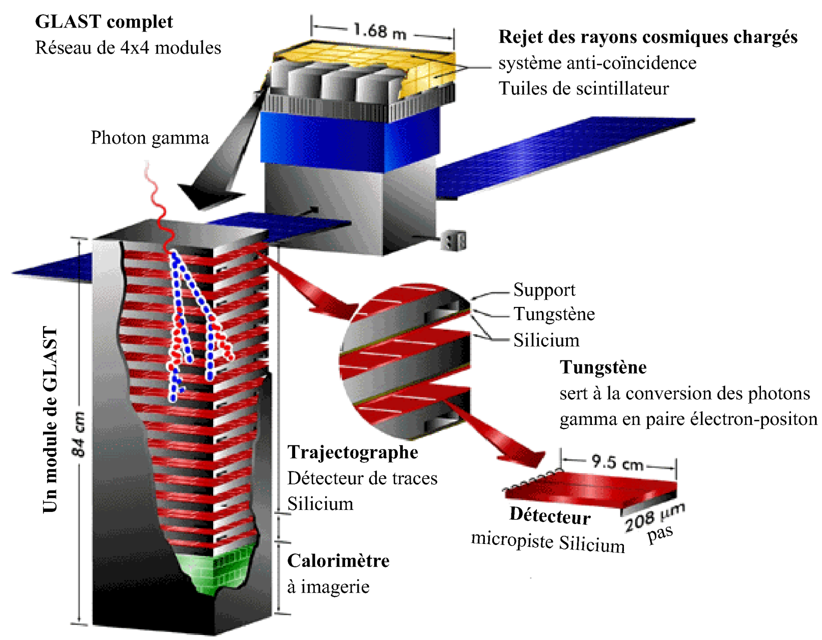




Event class: tradeoff between efficiency and purity

« data_clean » (Event_class=4) is the purest class

« Diffuse » (Event_class=3) is the second purest class



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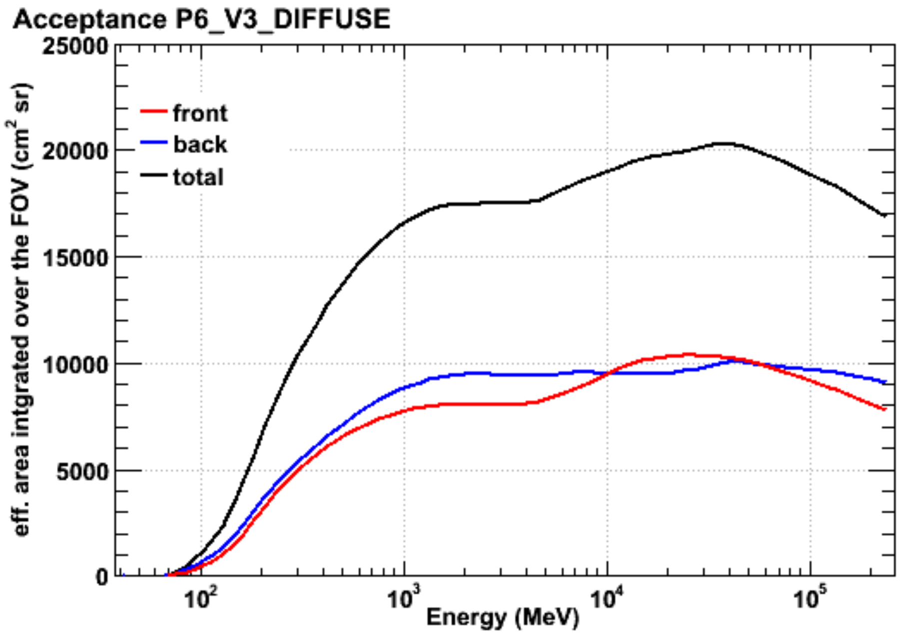
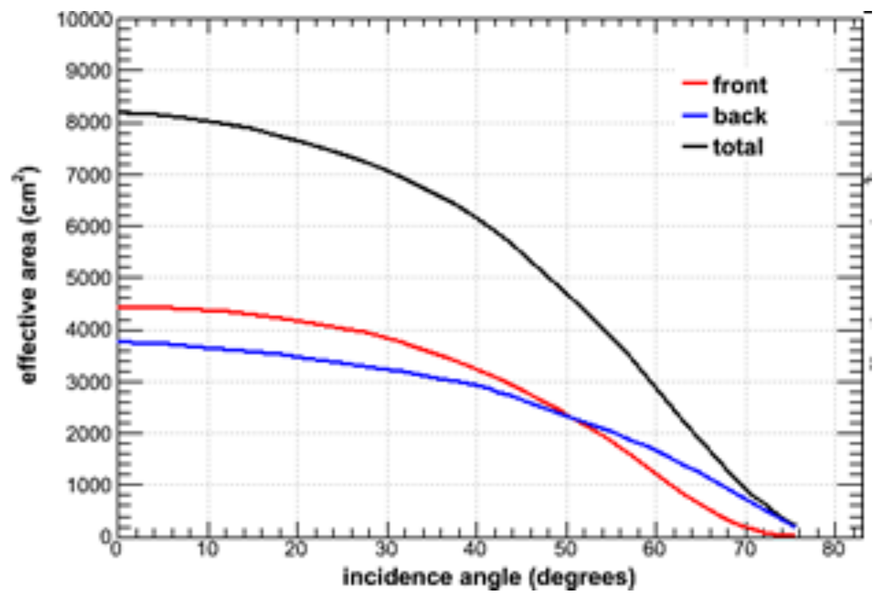
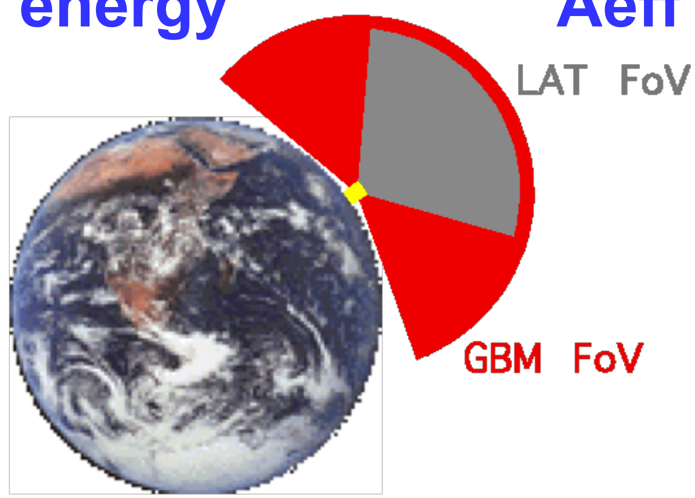
Effective area (Aeff)

http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm

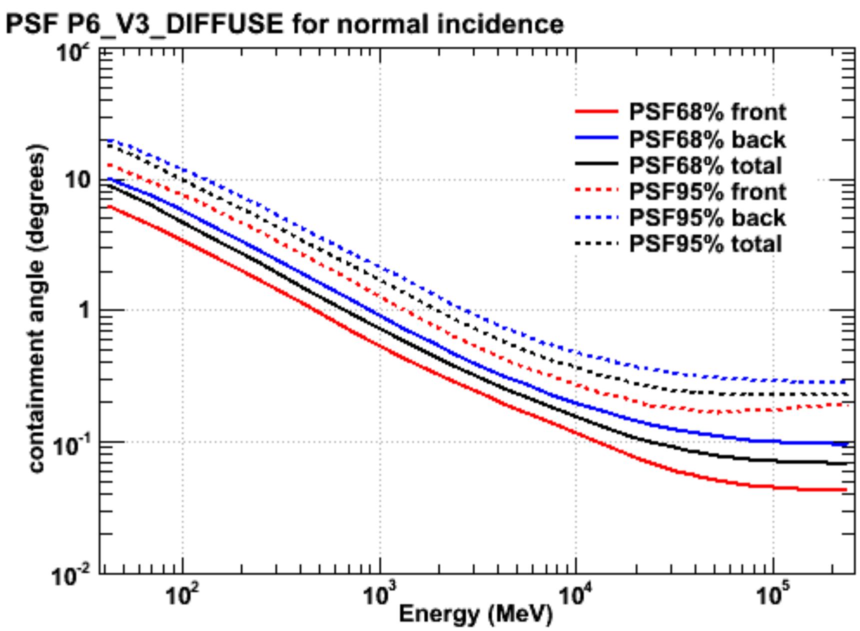


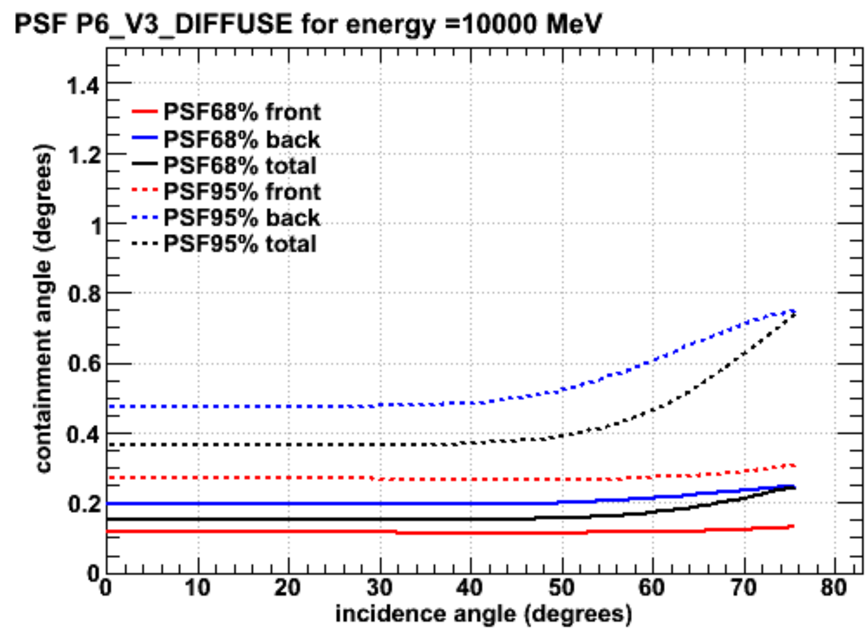


Aeff vs energy **Aeff vs incidence angle**



Point Spread Function (PSF)

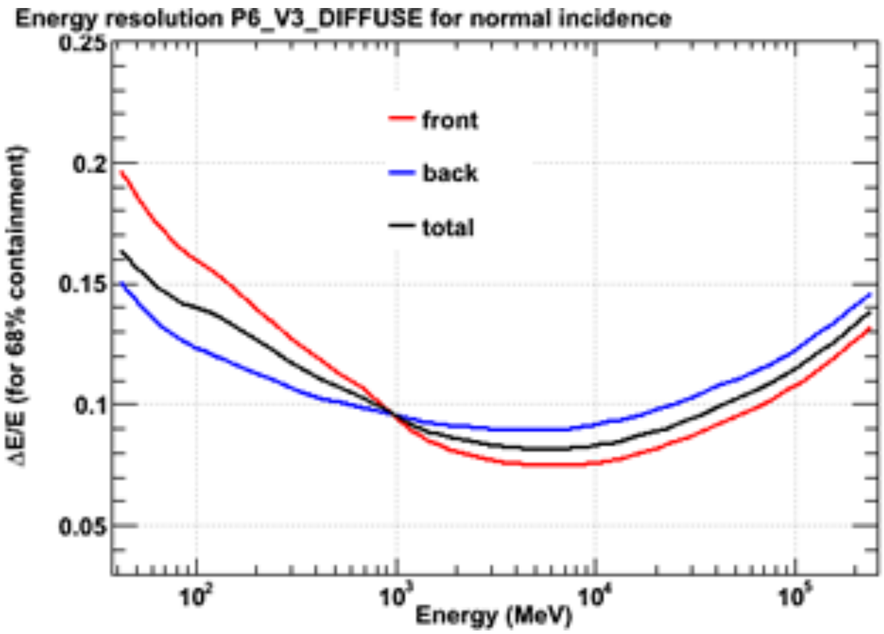


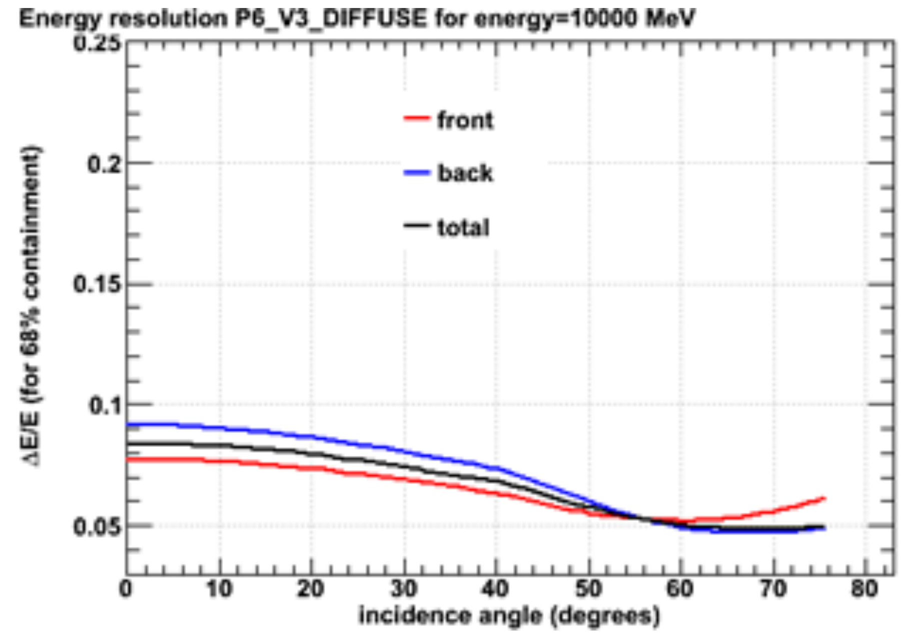


PSF vs Energy

PSF vs incidence angle

Energy resolution

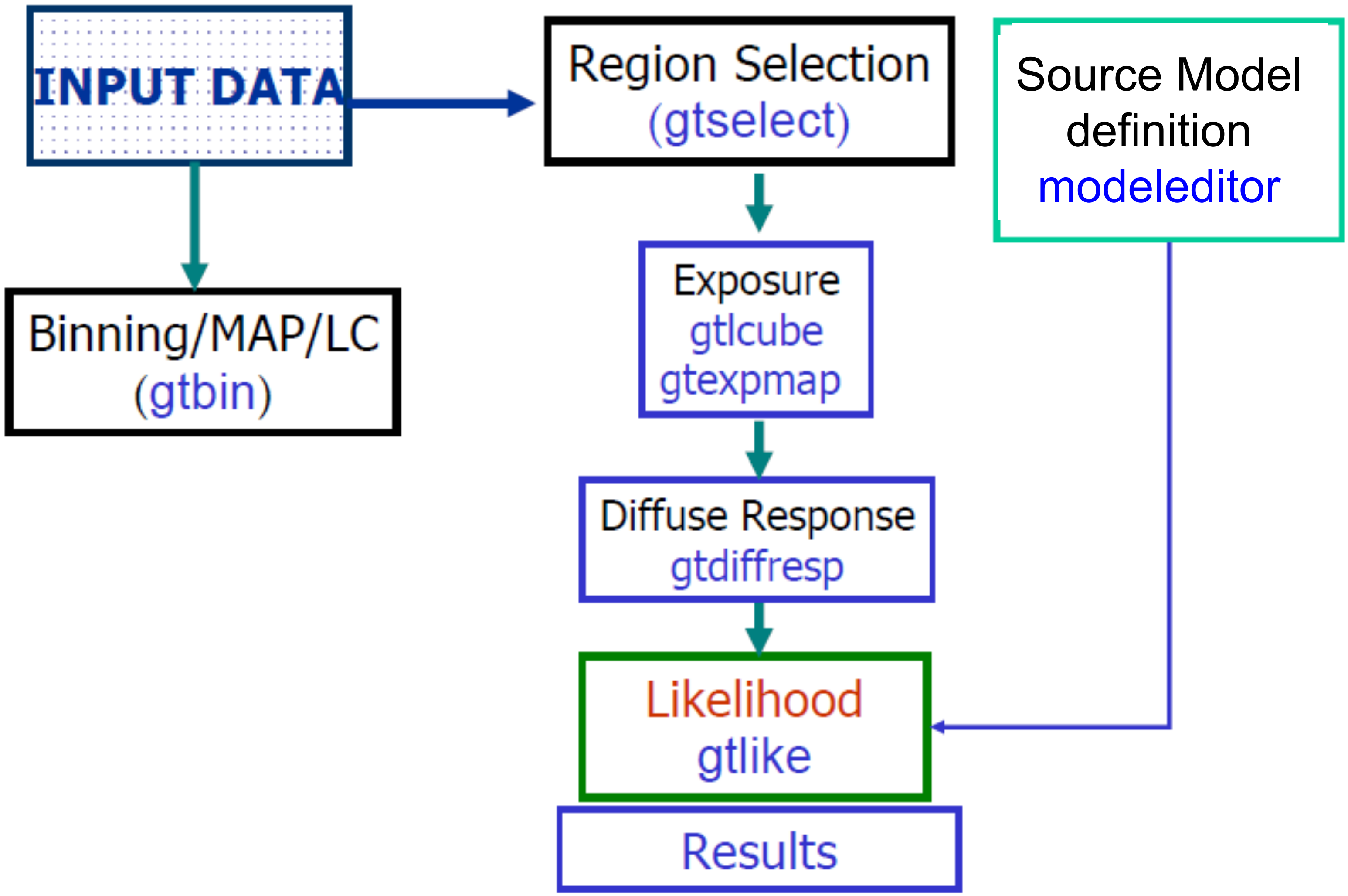




ΔE/E vs Energy

ΔE/E vs Incidence angle

Likelihood analysis in a nutshell



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

gtselect

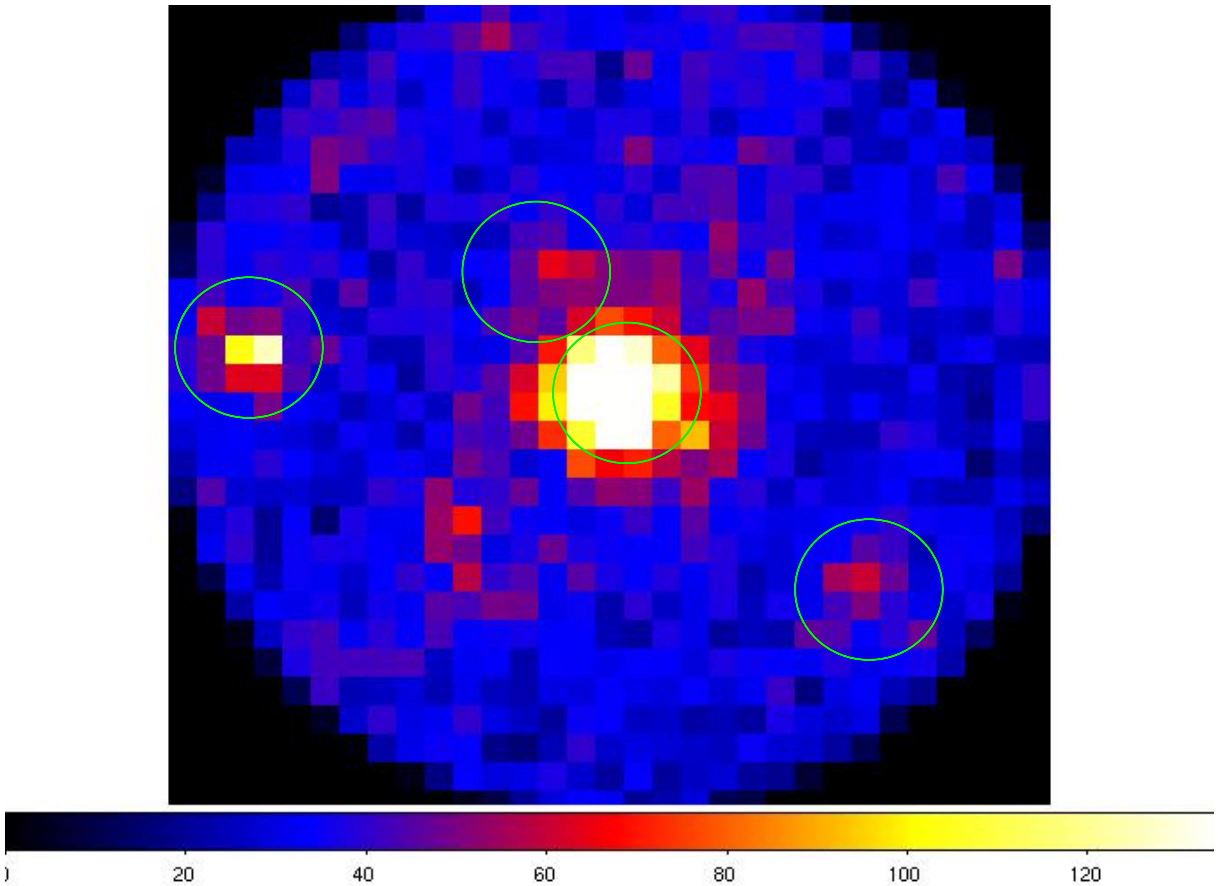
- http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtselect.txt
- Performs selection cuts in event data file, typically to define a Region-of-Interest (ROI) with events belonging to a certain class (standard is the « diffuse » class).
- gtselect infile outfile ra dec rad tmin tmax emin emax 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=4
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/

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

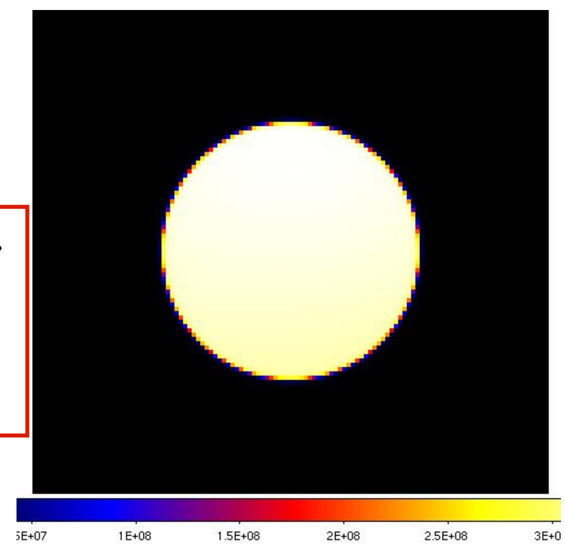
```
/COSPAR < 118 >gtltcube
Event data file[3c454_100_300000_evt02.fits]
Spacecraft data file[L09092311250 2E0D2F37E71_SC00.fits]
Output file[3c454_expcube.fits]
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
Working on file L090923112502E0D2F37E71_SC00.fits
.....................!
1536.331u 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-specificexposure 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[L090923112502E0D2F37E71_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
<?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="1.0"/>
        </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">
   <spectrum type="PowerLaw2">
      <parameter free="1" max="10000" min="0.0001" name="Integral" scale="1e-07" value="1.58" />
      <parameter free="1" max="5" min="1" name="Index" scale="-1" value="2.32" />
```

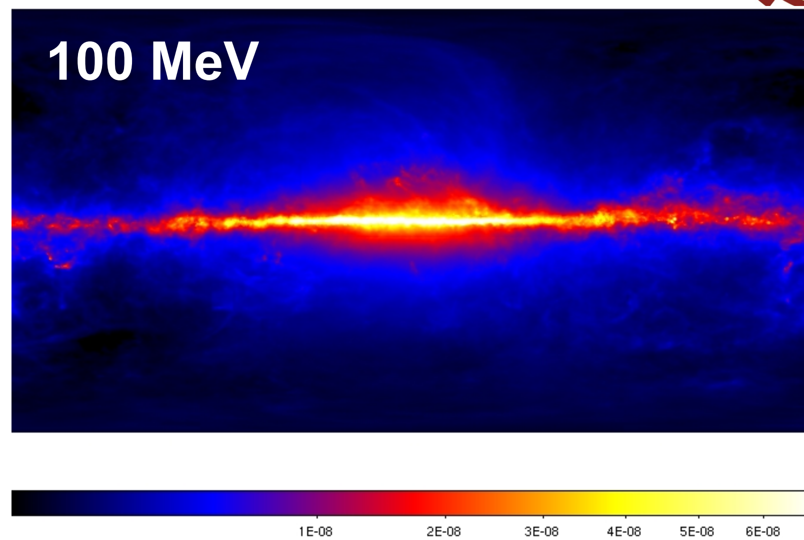
Diffuse models

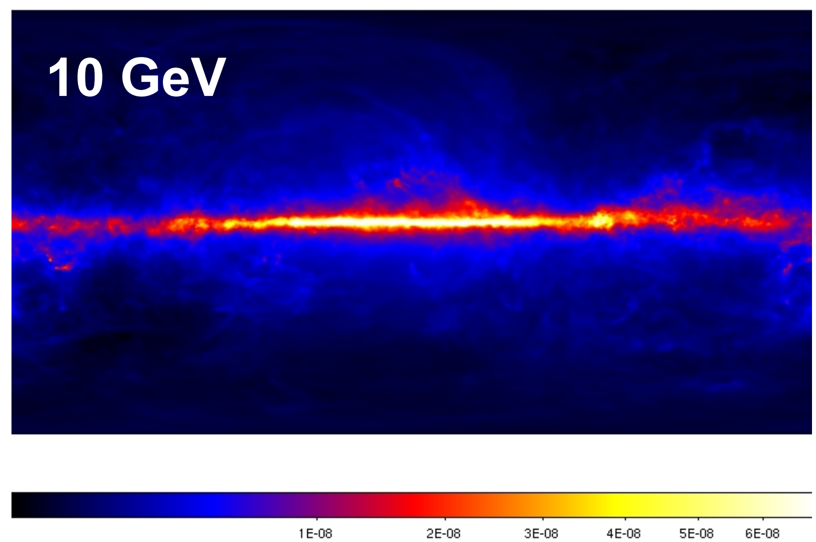
- **Galactic diffuse model:**
  gll_iem_v02.fit
  model adjusted to data

- **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

…..





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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/scitools/xml_model_defs.html

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

PowerLaw simple power law

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

- N_0 :Prefactor, Γ:spectral index
- E_0:energy scale

BrokenPowerLaw two component power law

$N(E) = N_0\ (E/E_b)^{\Gamma 1+1}\qquad E<Eb$

$\quad = N_0\ (E/Eb)^{\Gamma 2+1}\qquad E>Eb$

- N_0 :Prefactor $\Gamma 1$:low energy spectral index $\Gamma 2$:high energy spectral index
- Eb:break energy

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

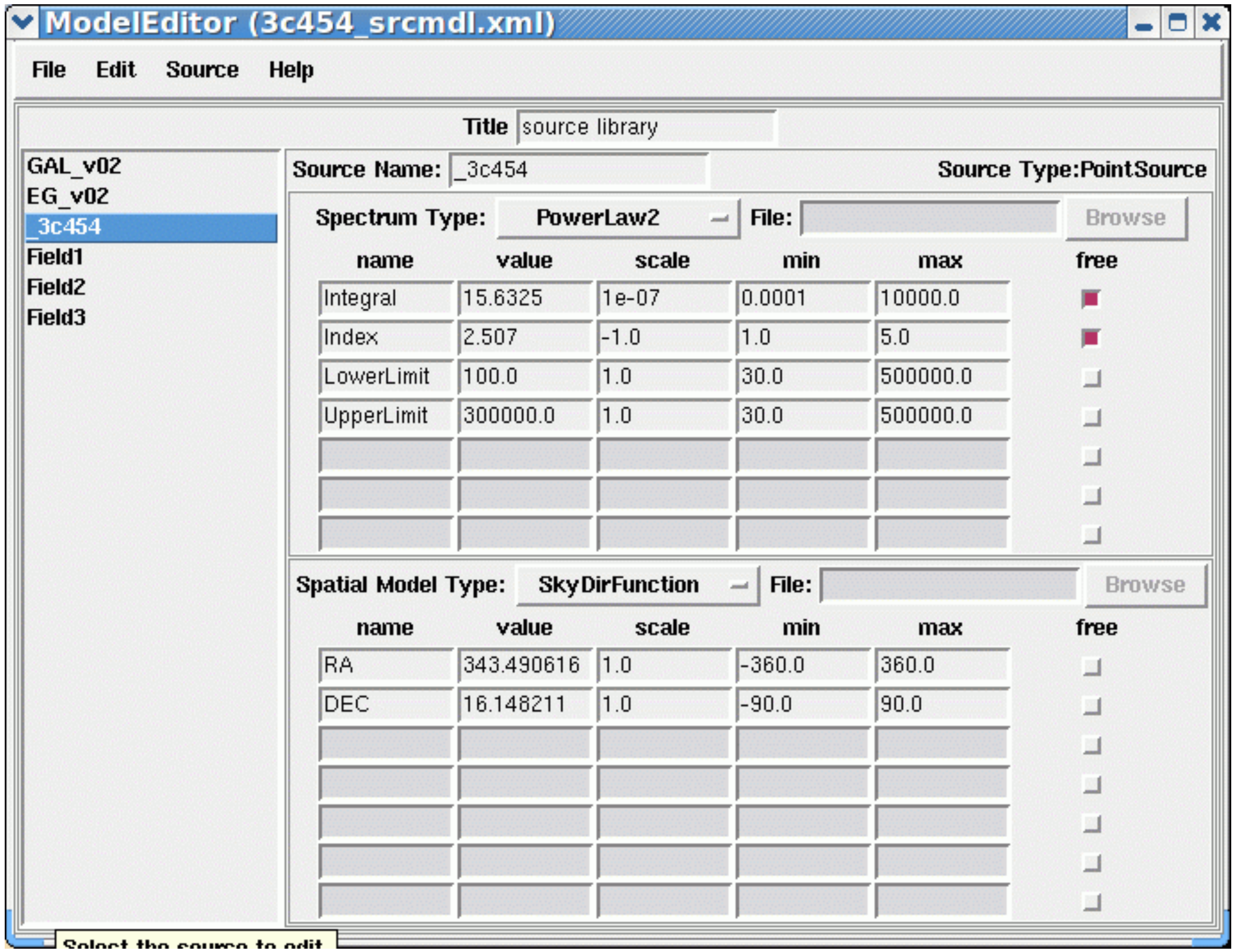
$N(E) = (\Gamma+1)N\ E^{\Gamma}/(Emax^{\Gamma+1} - Emin^{\Gamma+1})$

- N: Integral number of counts between Emax and Emin Γ:spectral index
- Emin:low end of energy range (always a fixed quantity)
- Emax:high end of energy range (always a fixed quantity)

…………..

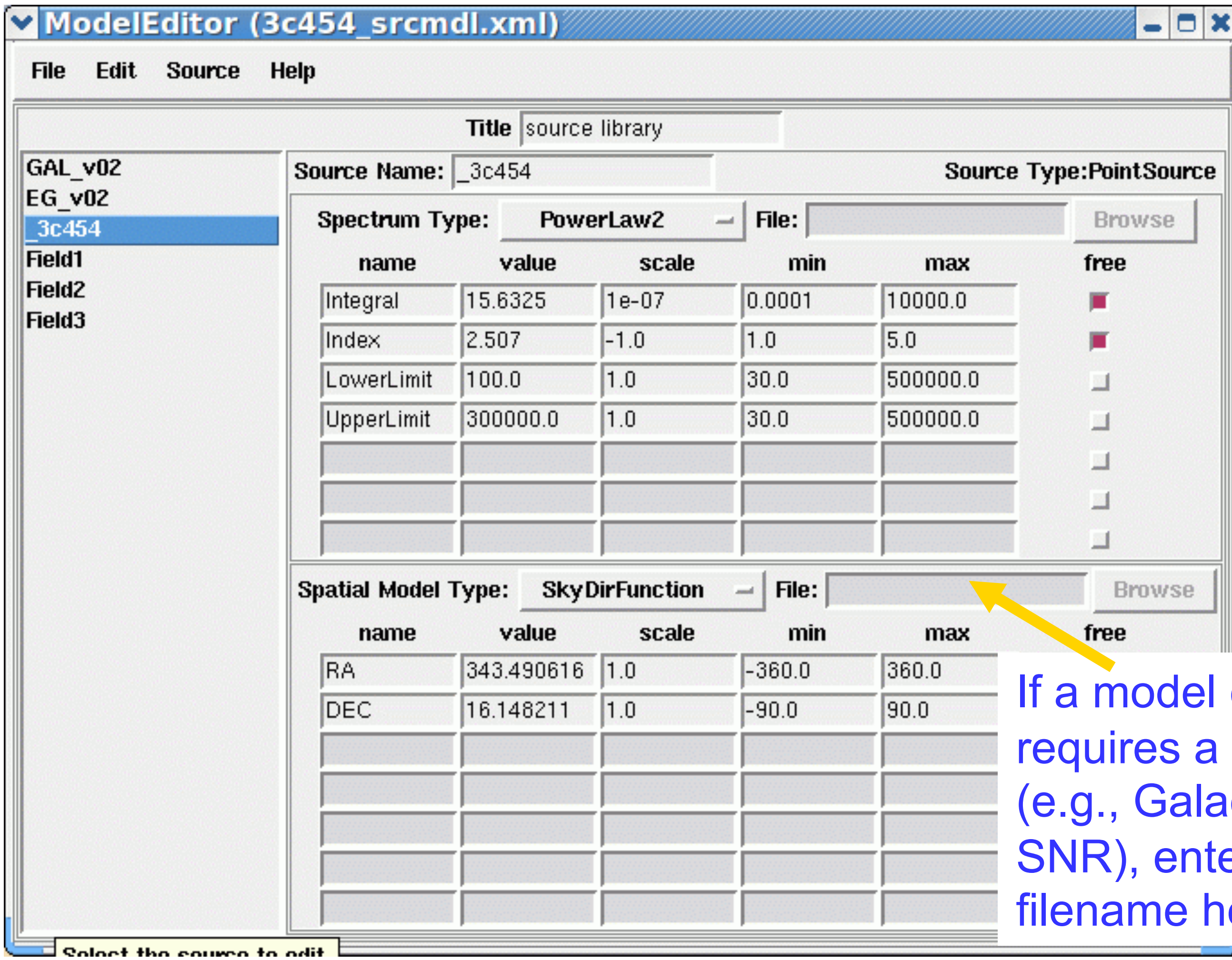
preparing the source model (1)

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



preparing the source model (2)

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



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 colum 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
```

gtlike

```
/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                                  STEP         FIRST
 NO.   NAME        VALUE          ERROR          SIZE       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                                INTERNAL      INTERNAL
 NO.   NAME        VALUE          ERROR       STEP SIZE       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)
......!
```

=

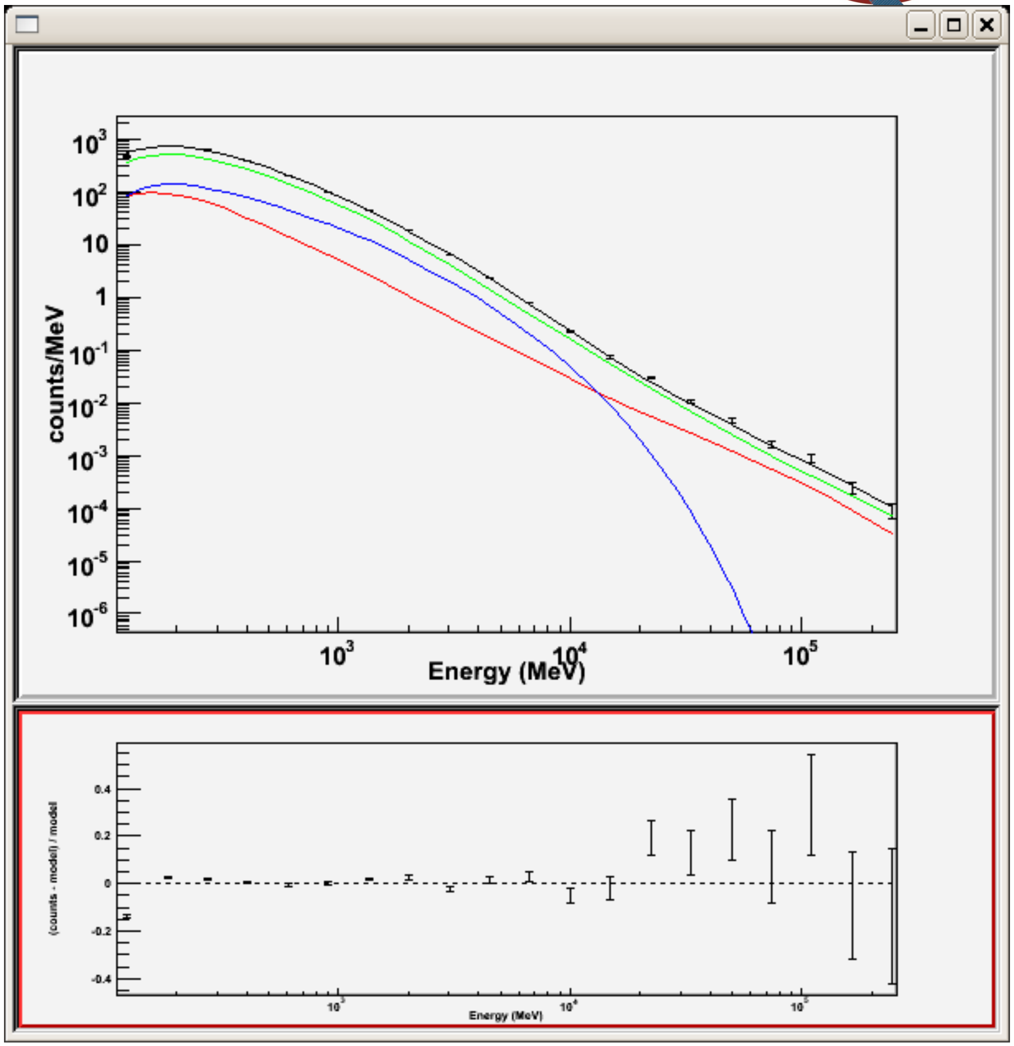
```
Field3:
Integral: 1.58531 +/- 0.207796
Index: 3.15383 +/- 0.148518
LowerLimit: 100
UpperLimit: 300000
Npred: 313.794
ROI distance: 10.5547
TS value: 136.841

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 >
```

Benoit Lott

Checking the fit quality

> gtlike plot=yes

Counts vs model predictions and residues *for the whole ROI*



Exploiting the results: output files

Results are stored:

- in an ascii file
  (default name: results.dat)

- in a fits.file
  (default name: counts_spectra.fits

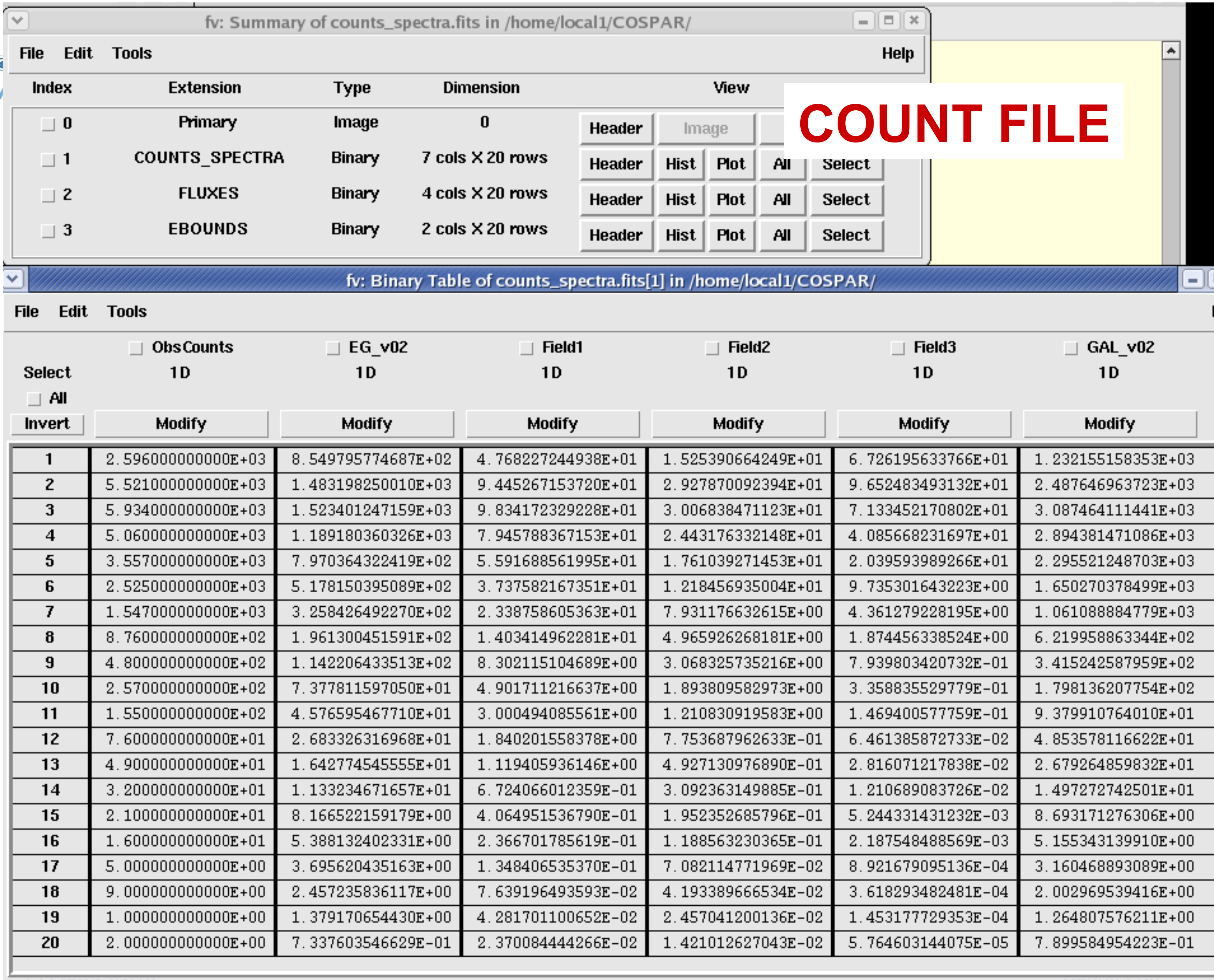
- in an xml file (optional)

```
/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')
```

COUNT FILE



fv: Summary of counts_spectra.fits in /home/local1/COSPAR/

File Edit Tools Help

Index	Extension	Type	Dimension	View
0	Primary	Image	0	Header Image
1	COUNTS_SPECTRA	Binary	7 cols X 20 rows	Header Hist Plot All Select
2	FLUXES	Binary	4 cols X 20 rows	Header Hist Plot All Select
3	EBOUNDS	Binary	2 cols X 20 rows	Header Hist Plot All Select

fv: Binary Table of counts_spectra.fits[1] in /home/local1/COSPAR/

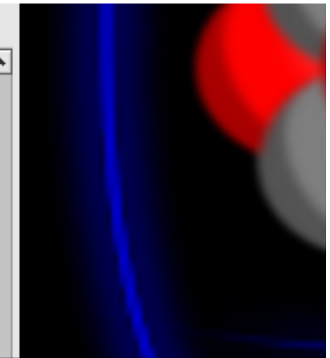
File Edit Tools H

Select	ObsCounts	EG_v02	Field1	Field2	Field3	GAL_v02
All	1D	1D	1D	1D	1D	1D
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
0	Primary	Image	0	Header Image Table
1	COUNTS_SPECTRA	Binary	7 cols X 20 rows	Header Hist Plot All Select
2	FLUXES	Binary	4 cols X 20 rows	Header Hist Plot All Select
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	Field1	Field2	Field3	3c454
All	1D	1D	1D	1D
Invert	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	E_MIN	E_MAX
All	1D	1D
Invert	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 Δn 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 Δn degrees of freedom.

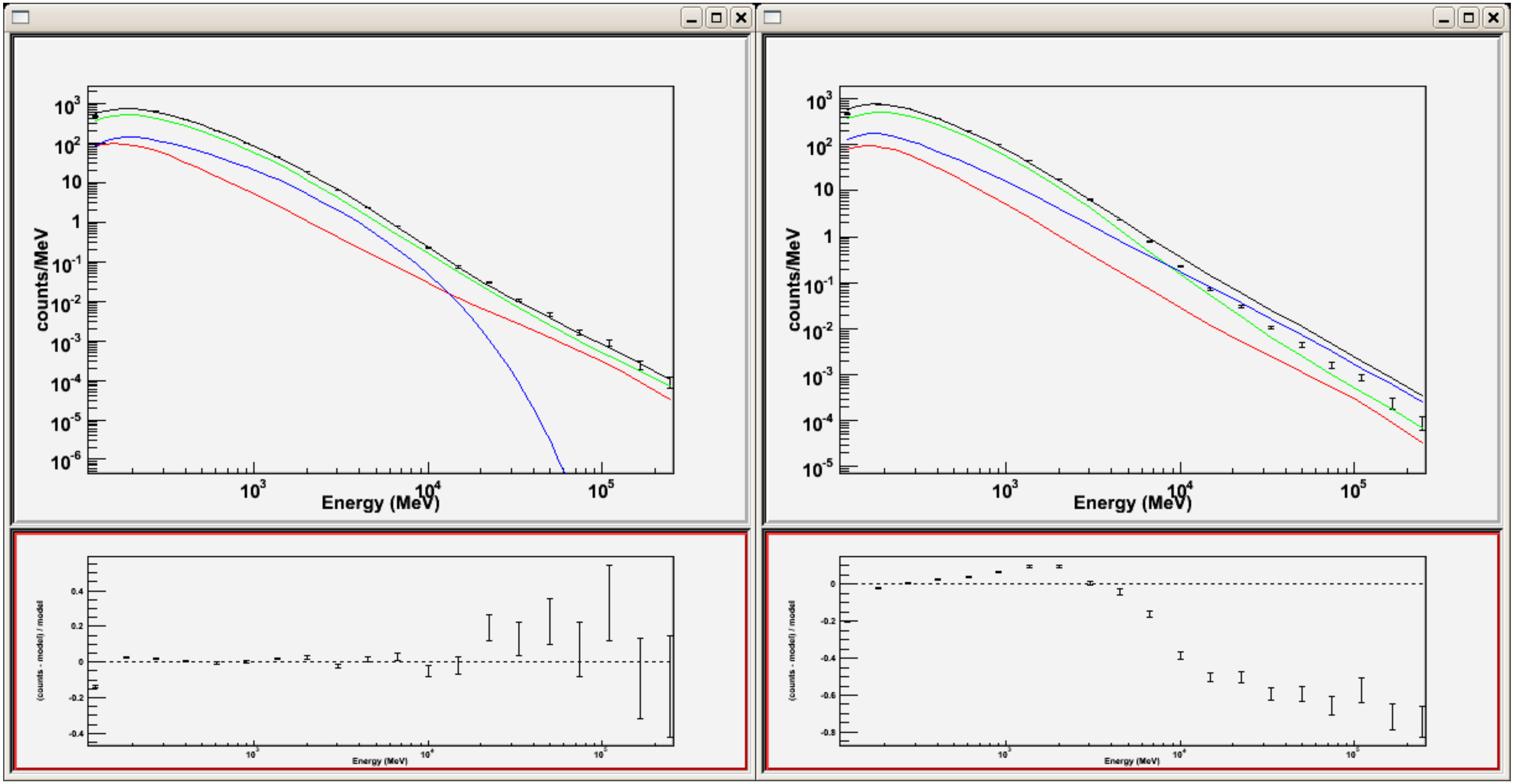
Ex: Vela
PLSuperExpcutoff: -log(Likelihood): 3321842.126
PowerLaw : -log(Likelihood): 3324727.121

Ex: Vela

PLSuperExpcutoff: -log(Likelihood): 3321842.126

PowerLaw : -log(Likelihood): 3324727.121

LRT= 2 Δlog(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 = γ_1
  - Scale = E_0
  - Cutoff = E_c
  - Index2 = γ_2

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

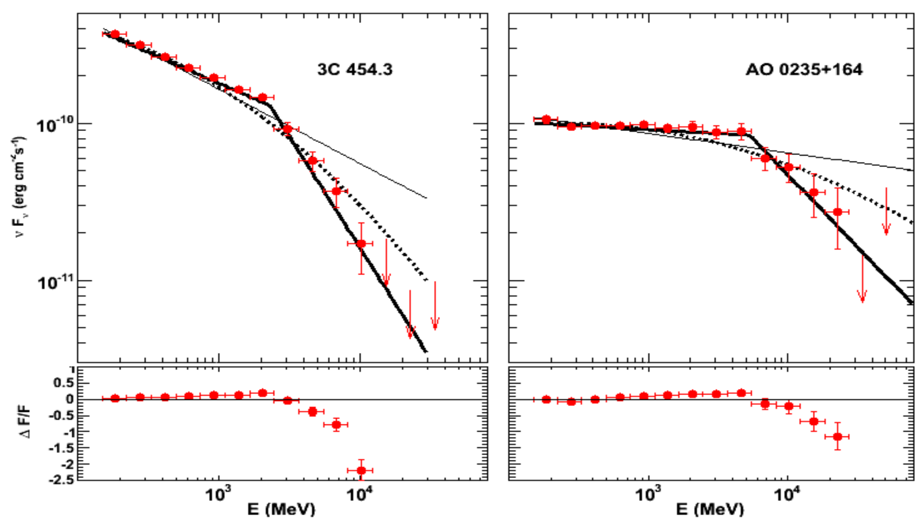
$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma}$$

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

  - Prefactor = N_0
  - Index = γ
  - 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.



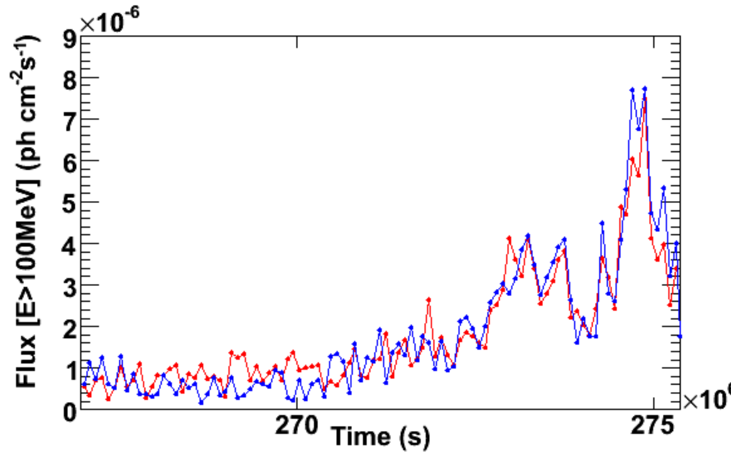
Exploiting the results: parsing the xml files

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, spectal index,
  - parameters of steady/or faint sources

- Monitor the source TS, compute upper limit if necessary (TS<TSthresh)

- Using $F(E>E_0)$ with $E_0 \neq 100$ MeV can provide better results.

Optimal results are obtained with E_0 being the « pivot energy ». Typically the pivot energy is 200-300 MeV.

Point-like sources

- Take a look at Vela (pulsar,steady source on the galactic plane)
  - Apply the cuts on EVENT_class, ZENITH_ANGLE using gtselect
  - determine the TIME distribution: orbital modulation. Period is 5739 s.
  - determine the ENERGY distribution (log-log): low-energy behavior, evidence for high-energy cutoff
  - determine the RA distribution: dispersion (PSF)
  - RA distribution vs ENERGY (lin-log) for different CONVERSION_TYPE

- Redo the same for 3C454.3 and PKS2155-304 (blazars, variable, off the galactic plane)