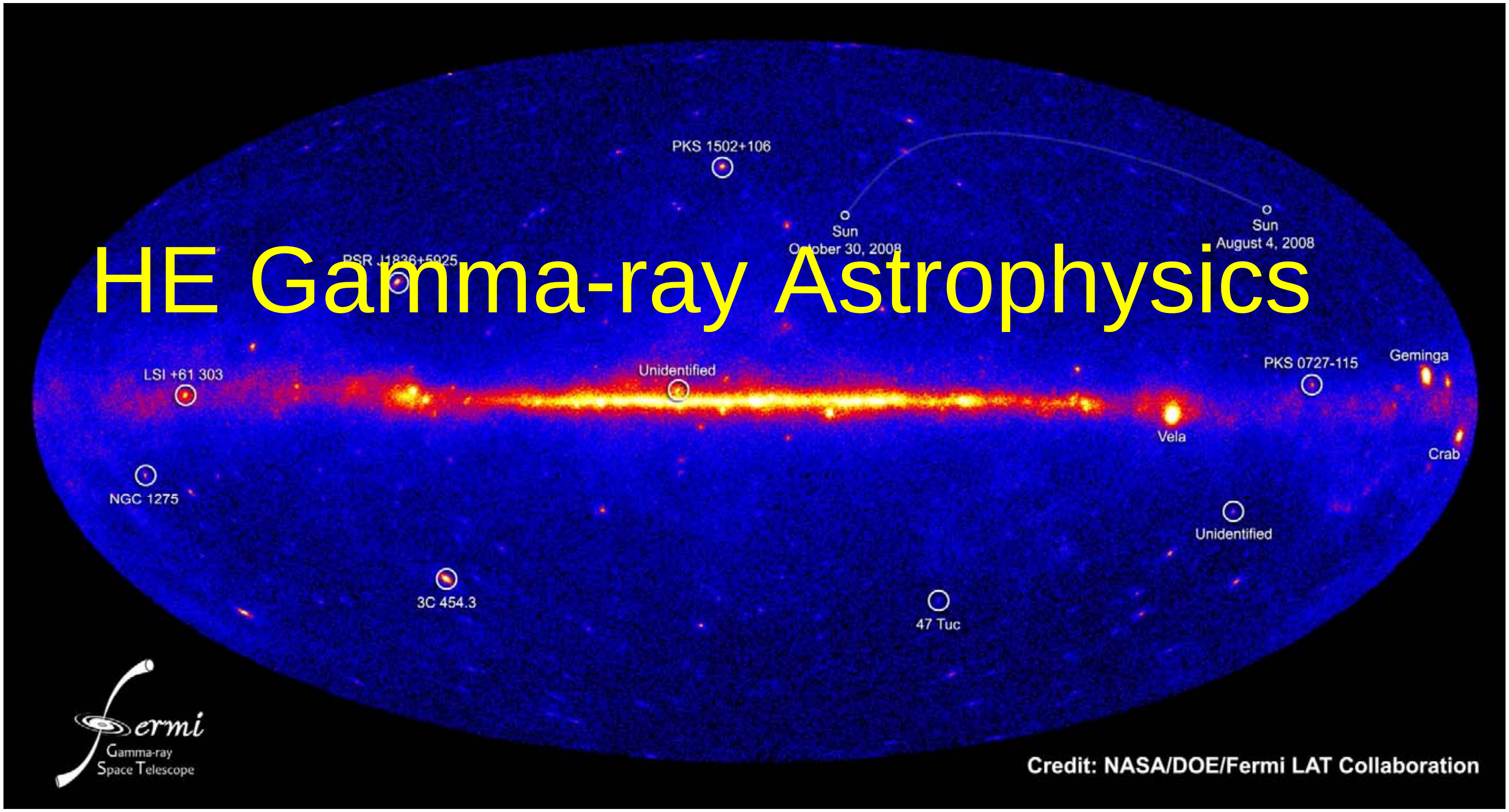
HE Gamma-ray Astrophysics



Francesco Longo

Department of Physics, University of Trieste and INFNTrieste

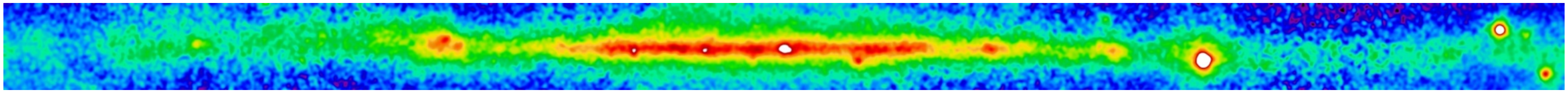
credits to the AGILE and Fermi LAT collaborations

Summary

- Brief Introduction to Gamma-ray Astrophysics
  - The Main Questions
- HE Gamma-ray astrophysics
  - From EGRET to AGILE and Fermi
- (Brief) Introduction to AGILE data analysis
- Introduction to Fermi LAT data analysis
  - Source simulation and detection
  - Documentation

Basics of HE data analysis

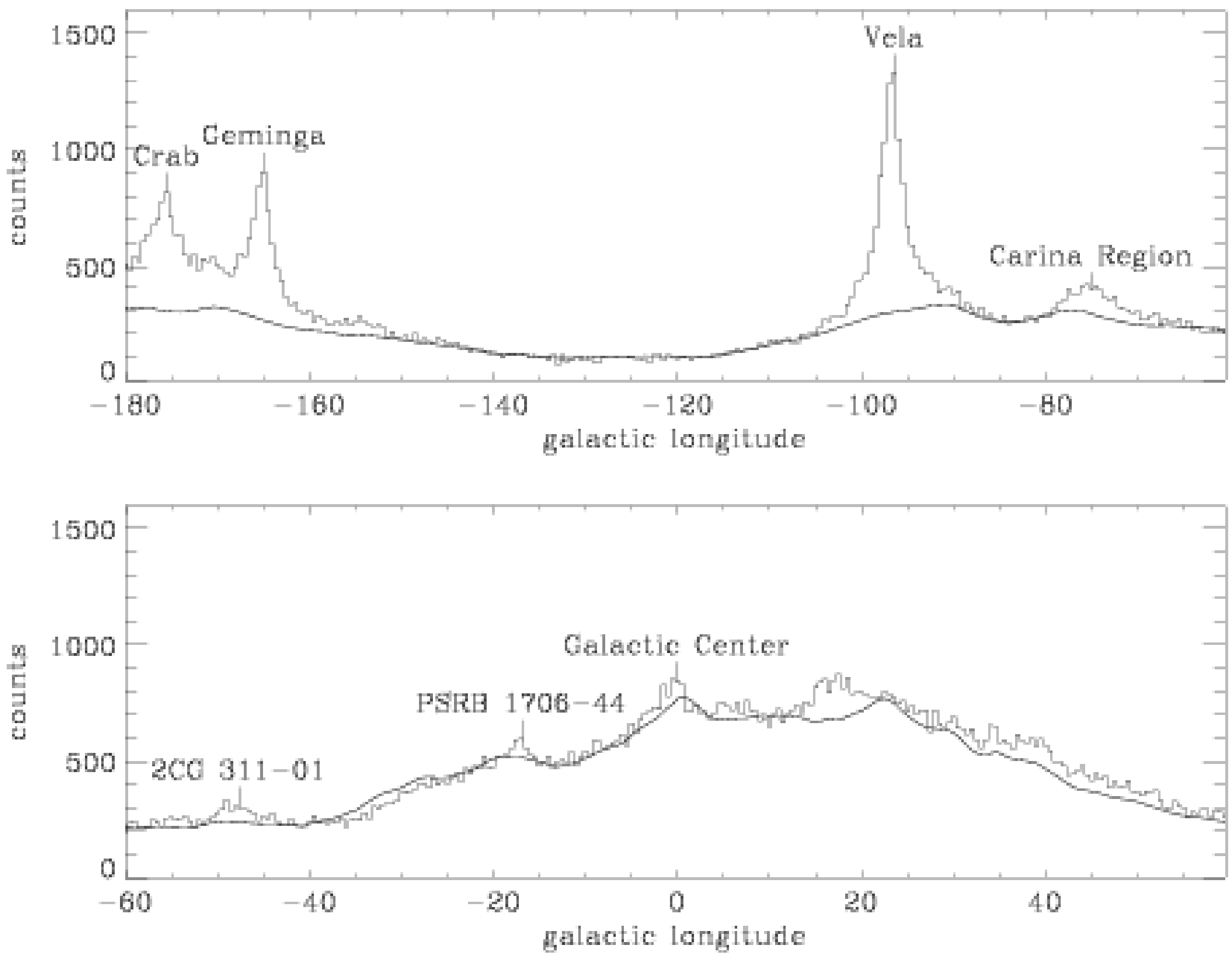
Analysis Topics



EGRET >300 MeV

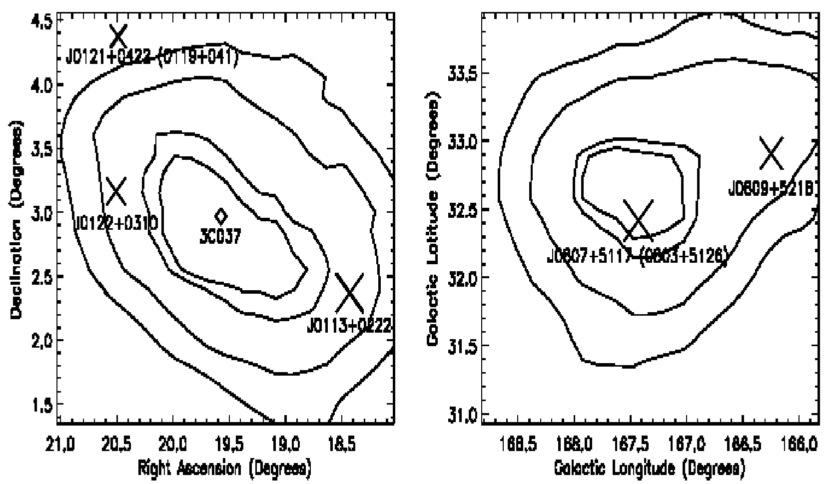
- First a word about interstellar gamma-ray emission:
- Brightest at low latitudes, but detectable over the whole sky
- >60% of EGRET celestial gamma rays
- It fundamentally affects the approach to the analysis

Data Analysis



Analysis Topics: Source detection

- Source detection means at least 2 things:
  - Recognizing that you've detected a point source that you didn't know about (and defining its statistical significance and location on the sky)



Source location contours for two 3EG sources (Hartman et al. 1999). Potential (additional) counterparts, unresolved by EGRET, are indicated

  - Determining the significance of the detection of (or measuring an upper limit for) an already-known source

Sowards-Emmerd, Romani, & Michelson (2003, ApJ, 590, 109)

Analysis Topics: Spectral analysis

- Well, this means measuring spectra
  - Mostly power laws resulting from shock acceleration, which is scale free
  - Spectral breaks occur for physics reasons and measuring them is diagnostic of the sources.
- For EGRET, the analysis of source spectra was a 2-step process
  - Fluxes were derived for fairly broad ranges of energy independently
  - Then a spectral model was fit
- The complication was that the exposure for a broad energy range depends on the source spectrum, so the fitting process was iterative.

$$F_\gamma = (2.01 \pm 0.12) \times 10^{-6} (E/0.214\ \mathrm{GeV})^{-2.18 \pm 0.08}\ \mathrm{photon\ (cm^2\ s\ GeV)^{-1}}\ .$$

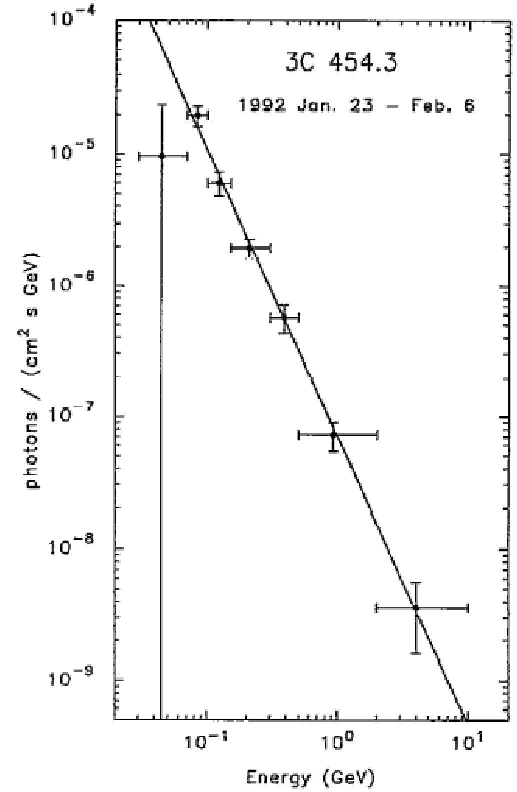
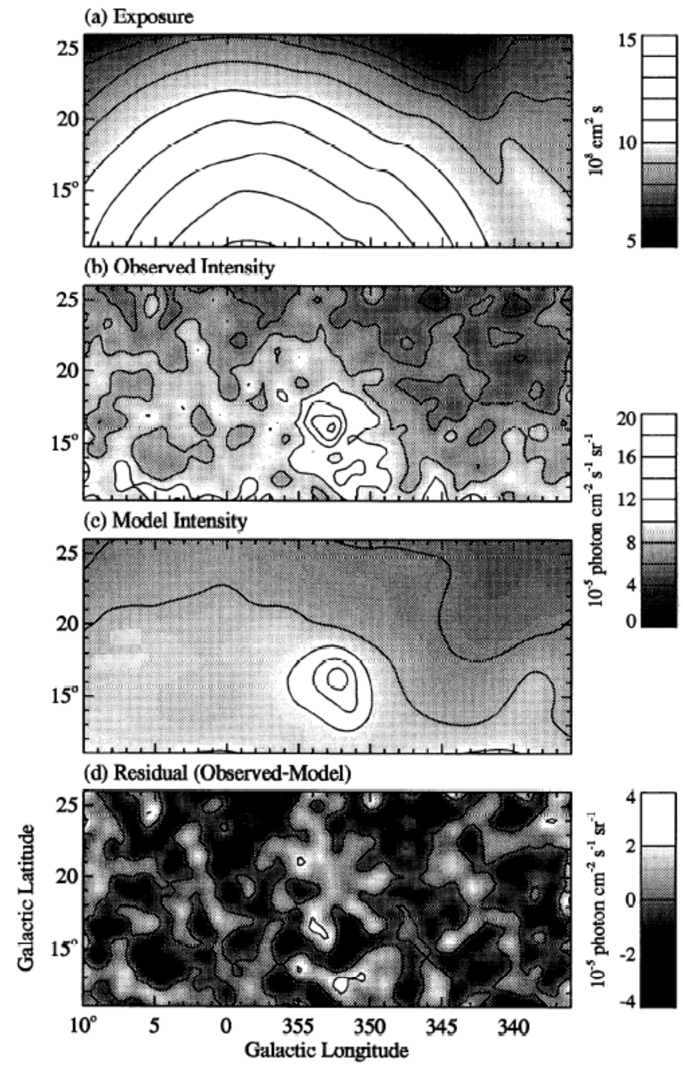


FIG. 3.—High-energy gamma ray spectrum of 3C 454.3 during the time interval 1992 January 23 to February 6. See text for comments on the 30–70 MeV point.

Hartman et al. 1993 (ApJ, 407,L41),

Analysis Topics: Extended Sources

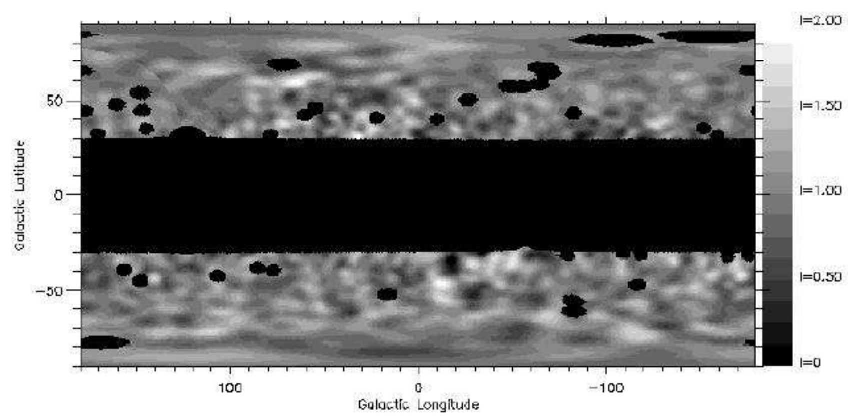
- Extended sources are more complicated to study, if you don't know their intrinsic intensity distributions
- For EGRET local molecular clouds were large enough (~15°) and bright enough to be resolved marginally
- A relatively bright source in Ophiuchus (a star-forming region ~100 pc distant with associated interstellar clouds) was detected by COS-B.
  - Based on the mass of interstellar gas, the inferred cosmic-ray density was 10×local and hard to understand
- With EGRET, the emission is marginally resolved. More importantly, the data indicated a variable source (i.e., not diffuse), identified as blazar PKS 1622-253, ~1° from the core of the main cloud



Hunter et al. (1994, ApJ, 436, 216)

Analysis Topics: Isotropic Emission

- Detected by SAS-2 and EGRET
- The analysis really rests on beating down or carefully characterizing the residual charged particle and gamma-ray albedo backgrounds
- Where the LAT will advance the subject is in resolving the isotropic emission into (presumably) point source constituents that could not be detected with EGRET
- The blazar contribution to the isotropic background is not an answered question



Willis (1996) Residual intensities, after MW and point sources were removed

What is Likelihood?

- The likelihood, L, of a set of data is the probability of observing that data, given our belief about the physical processes that produced the photons that were detected. When that belief takes the form of a model with adjustable parameters, the likelihood can be expressed as a function of the parameters. The parameter values which produce the maximum value of L are useful estimators of the “true” values. Under fairly mild conditions, this process is unbiased and efficient.

- The maximum likelihood value does not provide a test of “goodness of fit.” The statistical significance of a point source, for instance, can be determined by the ratio of maximum likelihood values for models with and without the source

Why Likelihood?

- There aren't many photons. In an interesting part of the sky we will collect thousands, but the instrument response has many dimensions: time, angles, energy, and instrument-specific quantities. With sensible binning, most bins won't contain enough photons for $\chi 2$ analysis to be valid.
- With the LAT's broad PSF, many sources will overlap. Care is required to distinguish nearby pairs.
- Direct image deconvolution is dangerous. Poisson noise is amplified to swamp the result. Some sort of regularization is needed, either by making assumptions about the statistical properties of the image or by assuming a simple physical model with adjustable parameters. We choose the latter.
  - Pro: Gives quantitative results.
  - Con: We won't discover anything we aren't looking for.

TS

A basic tool of the EGRET analysis is the “Test Statistic”, or TS.

When two models are compared, $TS \equiv -2\ln(L_2 / L_1)$

Where L_1 and L_2 are the maximum likelihood values for the two models.

TS is applied when the difference between the two models is the presence of an extra point source in model #2. The statistical significance of the new source can be determined by treating TS as a χ^2 value with one degree of freedom, or sqrt(TS) as the gaussian “sigmas” of detection.

A TS map can be made by placing the putative source in many places, calculating TS in each place. This is a means of searching for unknown point sources.

The Math of Likelihood

We use Extended Maximum Likelihood (EML). This is the proper form to use when the number of photons is not determined before the observation. The quantity to be maximized is

$$\ln(L) = \sum_i \ln M(x_i) - N_{pred}$$

where x stands for the measured properties of the photons, *i* labels the individual photons, M(x) is the model rate of photon detection, and

$$N_{pred} = \int M(x) dx$$

is the total number of photon detections predicted by the model. We call the two terms the "data sum" and the "model integral."

The Use of Response

For a photon of energy E arriving from direction $\mathbf{p}$ at time t, the probability density of a detection of type k with estimated energy E' and direction $\mathbf{p}'$ is

$$M_k(E', \mathbf{p}', t; E, \mathbf{p}) = h(t)\, H(\mathbf{u}(t) \cdot \mathbf{p}' - \mu_k(E'))$$
$$\times A_k(E, \theta(\mathbf{p}, t), \phi(\mathbf{p}, t))\, P_k(\mathbf{p}'; E, \theta(\mathbf{p}, t), \phi(\mathbf{p}, t))\, D_k(E'; E, \theta(\mathbf{p}, t), \phi(\mathbf{p}, t)).$$

Zenith cutoff

Effective area

Live fraction

Step function

PSF

Zenith direction

Energy dispersion

Angles in spacecraft coordinates

For a point source this must be integrated over the spectrum s(E)dE. If the spectrum is assumed to be steady, it can also be integrated over dt. Otherwise the model variation must be included in the integral.

The N_{pred} term is the integral of this function over all its arguments.

How to Evaluate the Likelihood

The photons are chosen from a Region of Interest (RoI) on the sky. However, some of them are produced by sources outside the RoI. The model must cover a larger area, the Source Region.

The adjustable parameters include the properties of all the point sources in the model (flux, spectrum, and perhaps position) as well as the flux and spectrum of the diffuse sources. In particular the Galactic diffuse flux can never be ignored and it must usually be treated with considerable care; most point sources are located in regions where it dominates the counting rate.

Most of the analysis time is spent evaluating the likelihood function and its derivatives. $M(x_i)$ requires evaluating the source spectrum and all three IRFs. N_{pred} requires integrating these over the whole observation, taking into account zenith cuts and changing angles.

Exposure

The calculation can be simplified by the use of “exposure”. If the source spectrum is the only set of parameters that can be adjusted, most of the integral needs to be calculated only once. Exposure has dimensions area $\times$ time. It describes how deeply a spot on the sky has been examined. For diffuse sources, exposure must be calculated at many points.

The exposure calculation isn’t simple. It looks like this for a particular energy E_m:

$$\begin{aligned}\mathcal{E}_m(\mathbf{p}) \;&=\; \int dE' \int d\mathbf{p}' \int dt\, h(t) \sum_k H(\mathbf{u}(t)\cdot\mathbf{p}' - \mu_k(E')) \\ &\times A_k(E_m, \theta(\mathbf{p},t), \phi(\mathbf{p},t))\, P_k(\mathbf{p}'; E_m, \theta(\mathbf{p},t), \phi(\mathbf{p},t))\, D_k(E'; E_m, \theta(\mathbf{p},t), \phi(\mathbf{p},t))\end{aligned}$$

The d**p**’ integral covers the ROI, but this must be evaluated for directions **p** within the larger source region.

The Starting Point

The model must have initial values for its parameters. This is easy for the cosmic and galactic diffuse components – use the EGRET numbers. The EGRET catalog can be used for the bright point sources. However, we expect to discover new point sources. Visual inspection of flux maps or by time-consuming production of “TS maps”. We need a first-pass source finding tool that’s fast and doesn’t require subjective judgment. Accurate positions and fluxes are not needed.

There might be some hope of a single tool which will automatically find the sources and decide which ones are statistically significant. This is close to the cutting edge of statistical theory.

A useful reference

- EGRET: Mattox et al. (1996) Astrophysical Journal v.461, p.396

THE ASTROPHYSICAL JOURNAL, 461:396–407, 1996 April 10

THE LIKELIHOOD ANALYSIS OF EGRET DATA

J. R. MATTOX,[1,2,3,4] D. L. BERTSCH,[1] J. CHIANG,[5] B. L. DINGUS,[1,3] S. W. DIGEL,[1,6] J. A. ESPOSITO,[1,3] J. M. FIERRO,[7] R. C. HARTMAN,[1] S. D. HUNTER,[1] G. KANBACH,[8] D. A. KNIFFEN,[9] Y. C. LIN,[7] D. J. MACOMB,[2,3] H. A. MAYER-HASSELWANDER,[8] P. F. MICHELSON,[7] C. VON MONTIGNY,[1,10] R. MUKHERJEE,[1,3] P. L. NOLAN,[7] P. V. RAMANAMURTHY,[1,10] E. SCHNEID,[11] P. SREEKUMAR,[1,3] D. J. THOMPSON,[1] AND T. D. WILLIS[7]
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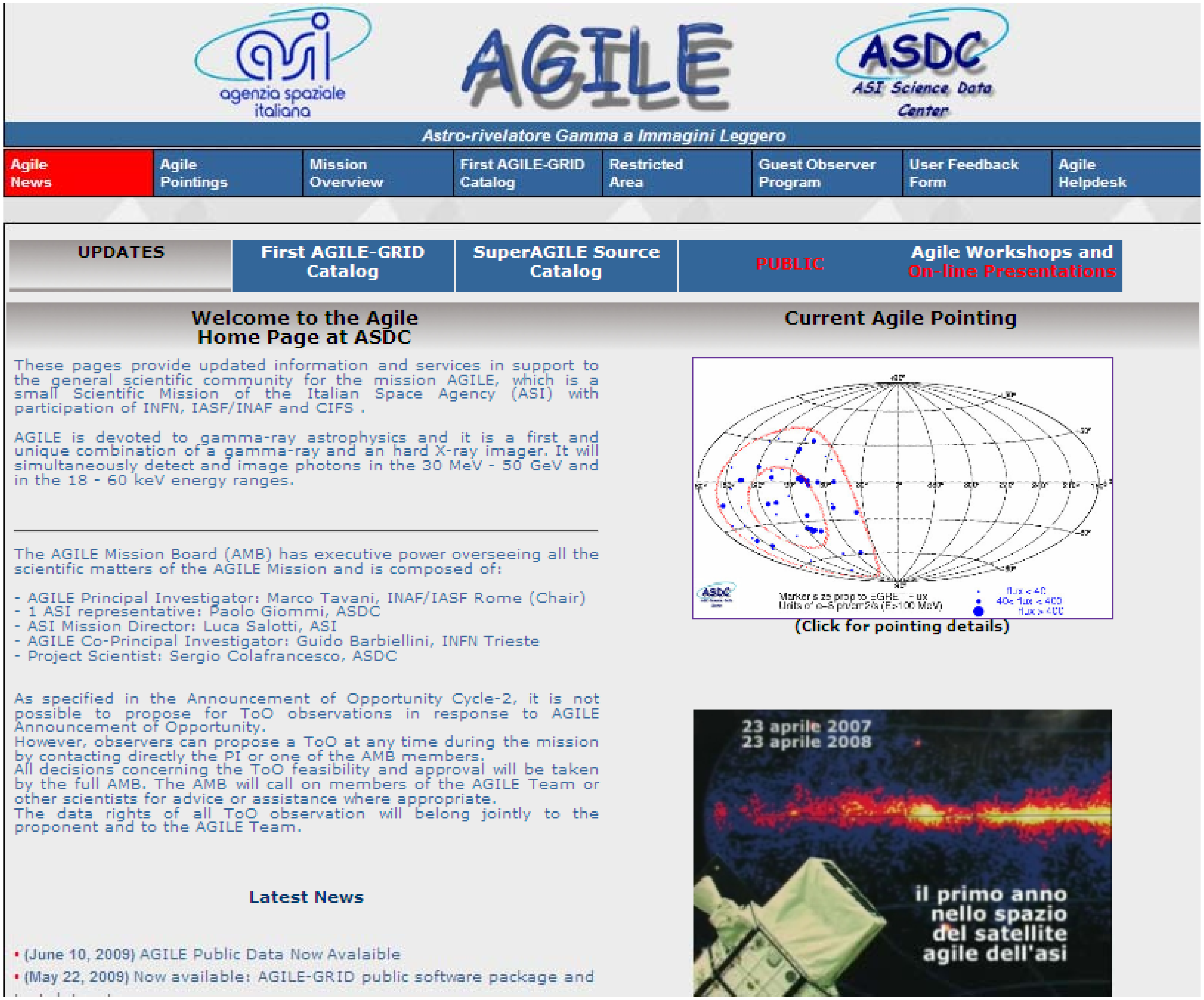
ABSTRACT

The use of likelihood for the analysis of high-energy γ-ray data from the EGRET instrument aboard the *Compton Gamma-Ray Observatory* is described. Maximum likelihood is used to estimate point-source flux densities, source locations, and background model parameters. The likelihood ratio test is used to determine the significance of point sources. Monte Carlo simulations have been done to confirm the validity of these techniques.

Subject headings: gamma rays: observations — methods: data analysis — methods: statistical

AGILE Data Analysis

Where?



agile.asdc.asi.it

Event Data

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File Edit Tools Help

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Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify
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2	1.114174070328E+08	2.549154E+01	1.249259E+02	1.227453E+02	-4.719992E+01	4.400000E+01	2.549154E+01
3	1.114174397364E+08	2.446780E+01	1.147412E+02	1.281985E+02	-4.493058E+01	2.080000E+02	2.446780E+01
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7	1.114177466411E+08	2.818289E+01	1.006006E+02	1.316400E+02	-3.833687E+01	6.200000E+01	2.818289E+01
8	1.114177594950E+08	3.616125E+01	1.152103E+02	1.179922E+02	-3.595031E+01	1.020000E+02	3.616124E+01
9	1.114177960168E+08	1.664606E+01	1.195181E+02	1.344282E+02	-5.163842E+01	8.800000E+01	1.664606E+01
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11	1.114178525104E+08	3.092299E+01	1.383755E+02	1.094268E+02	-4.817062E+01	4.920000E+02	3.092298E+01
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13	1.114178739451E+08	2.355818E+01	1.125495E+02	1.288761E+02	-4.498648E+01	1.414000E+03	2.355818E+01
14	1.114178833040E+08	2.341617E+01	1.479983E+02	1.154542E+02	-5.607359E+01	1.390000E+02	2.341616E+01
15	1.114179018183E+08	2.575085E+01	1.340501E+02	1.174440E+02	-5.000986E+01	1.270000E+02	2.575085E+01
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20	1.114179521209E+08	1.657254E+01	1.171190E+02	1.344091E+02	-5.094065E+01	4.720000E+02	1.657254E+01
21	1.114179973298E+08	2.206171E+01	1.243379E+02	1.258145E+02	-4.925007E+01	1.610000E+02	2.206171E+01
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25	1.114180281909E+08	2.212696E+01	1.071277E+02	1.324962E+02	-4.461108E+01	7.900000E+01	2.212696E+01
26	1.114180353780E+08	2.272880E+01	1.432341E+02	1.180047E+02	-5.482759E+01	3.180000E+02	2.272879E+01
27	1.114180492812E+08	2.443188E+01	1.256255E+02	1.225093E+02	-4.830602E+01	1.230000E+02	2.443187E+01

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Log File

File Edit Tools Help

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Counts Map generation

AGILE task: `AG ctsmapgen`

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   outfile,s,ql,"",,,"Enter output file name"
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   emax,r,ql,50000,,,"Enter max energy"
   fovrad,r,l,180.00,,,"Enter radius of field of view (degrees)"
   albrad,r,l,0.00,,,"Enter radius of earth albedo (degrees)"
   lonpole,r,l,180,,,"Rotation of map(degrees)"
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   filtercode,i,l,0,,,"Event filter code"
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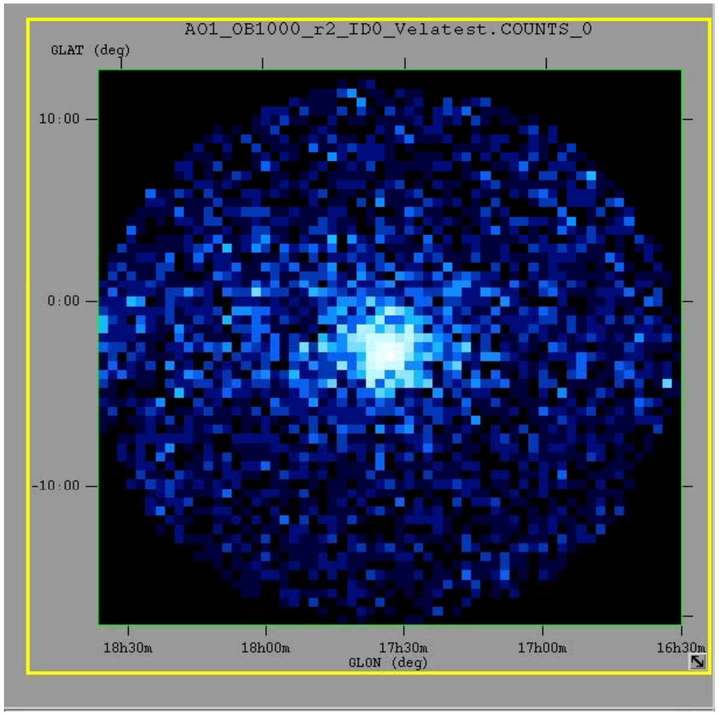


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Exposure Map generation

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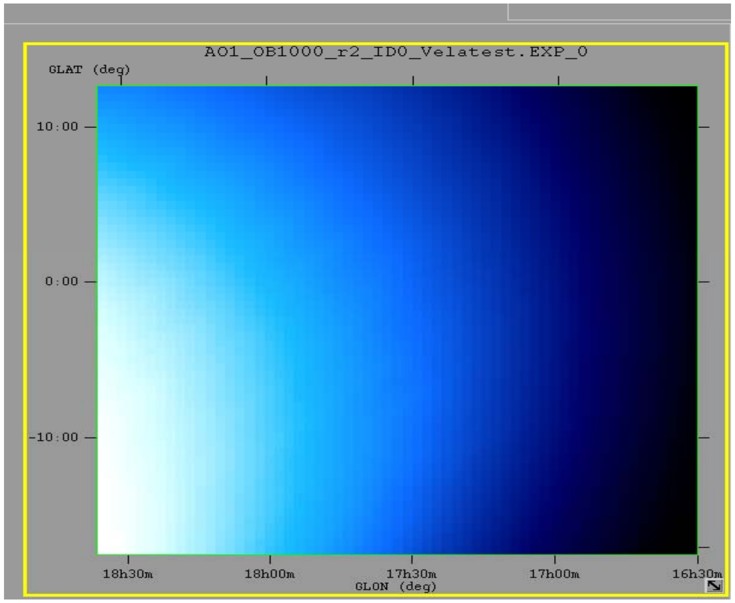


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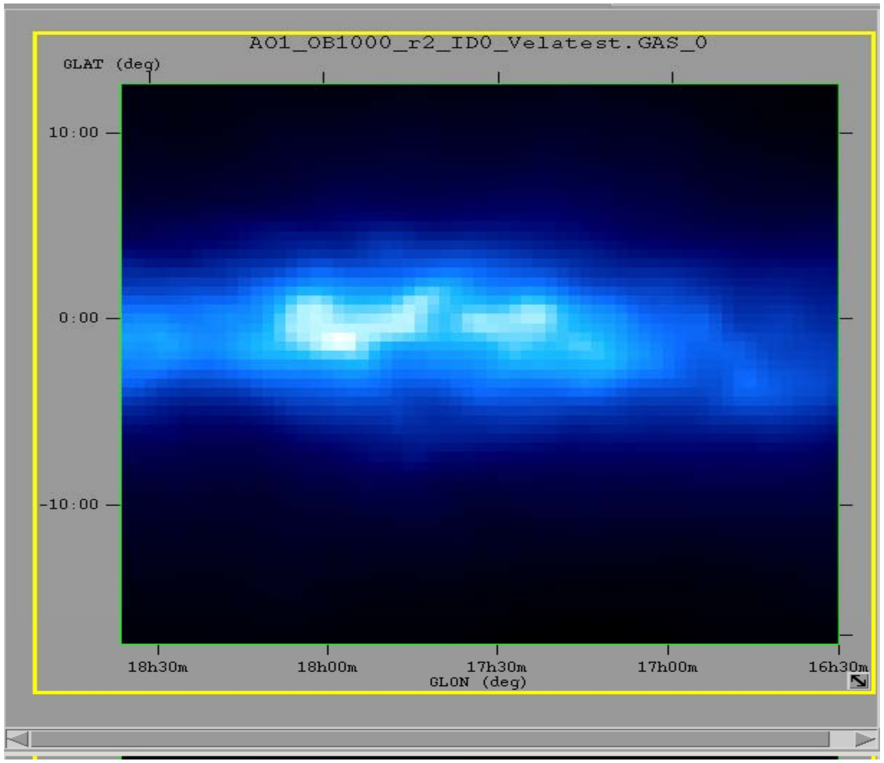
fovrad=60 albrad=80 y_tol=0.5 roll_tol=360.0 earth_tol=5.0
keepmono=NO phasecode=18 projection=ARC step=4 build=0
```

Diffuse Map generation



AGILE task: `AG_gasmapgen`

```
AG_gasmapgen.par:
 expfile,s,ql,"",,,"Enter exposure file name"
 outfile,s,ql,"s",,,"Enter output file name"
 diffusefile,s,ql,"~/ADC/scientific_analysis/data/100_50000.0.1.SFT3abG_I0007.conv.s
    "Enter diffuse model file name"
```

```
AG gasmapgen expfile=AO1 OB1000 r2 ID0 Velatest.EXP
outfile=AO1_OB1000_r2_ID0_Velatest.GAS diffusefile=
$ADC/scientific_analysis/data/100_50000.0.1.SFT3abG_I0007.conv.sky.gz
```

Likelihood Analysis

```
AG_srctest_fixed expfile=AO1_OB1000_r2_ID0_Velatest.EXP
ctsfile=AO1_OB1000_r2_ID0_Velatest.COUNTS
gasfile=AO1_OB1000_r2_ID0_Velatest.GAS
sarfile=$ADC/scientific_analysis/data/AG_GRID_G0017_SFT3abG_I0007.sar.gz
edpfile=$ADC/scientific_analysis/data/AG_GRID_G0017_SFT3abG_I0007.edp.gz
psdfile=$ADC/scientific_analysis/data/AG_GRID_G0017_SFT3abG_I0007.psd.gz
index=-2.1  Emin=100 Emax=50000 srcL=263.552 srcB=-2.78703
gascoeff=-999 isocoeff=-999 ranal=10 outfile=Srctest_VelaPSR.out
```

```
 No source
Gal          Iso
 1.54        3.93

Point source
Gal   Iso   Src cnts  -Err   + Err  sqrt(TS)  Flux      -Err        + Err cm^-2 s^-1
 0.625 8.28  979        -41   41.8     38.5   7.475e-06  -3.127e-07 3.193e-07
```

Likelihood Multi src

- Multiple Source Location Detection
- This task is performed by the procedure AG multi2 found in $ADC/scientific analysis/bin/.
- AG multi2 reads an exposure map produced by AG expmapgen, a counts map produced by AG ctsmapgen, and a diffuse emission map produced by AG gasmapgen, spectral index, and energy range, as well as a text file containing a source list, listed in the parameter file.
- It calculates the test statistic, significance, counts and flux of each of the point sources starting from a given positions in the presence of simultaneously optimized fluxes of all nearby sources in the list, and outputs the results to text files.
- The main purpose is to optmize both the flux and position of the sources given as input.

Likelihood Multi src

```
expfile,s,ql,"VELA.exp.gz",,,"Enter exposure file name"
ctsfile,s,ql,"VELA.cts.gz",,,"Enter counts file name"
gasfile,s,ql,"VELA.gas.gz",,,"Enter diffuse map file name"
sarfile,s,l,"~/ADC/scientific_analysis/data/AG_GRID_G0017_S0000F4G_I0007.sar.gz",,,
   "Enter SAR file name"
edpfile,s,l,"~/ADC/scientific_analysis/data/AG_GRID_G0017_S0000F4G_I0007.edp.gz",,,
   "Enter EDP file name"
psdfile,s,l,"~/ADC/scientific_analysis/data/AG_GRID_G0017_S0000F4G_I0007.psd.gz",,,
   "Enter PSD file name"
expcorrfile,s,ql,"~/ADC/scientific_analysis/data/expcorr.fits.gz",,,
   "Enter Exposure Correction file name"
Emin,r,ql,100.0,,,"Enter minimum energy"
Emax,r,ql,50000,,,"Enter maximum energy"
ranal,r,ql,10.0,,,"Enter radius of analysis region"
gascoeff,r,ql,-999,,,"Enter diffuse emission coefficient"
isocoeff,r,ql,-999,,,"Enter isotropic coefficient"
srclist,s,ql,"Vela_multi.det",,,"Enter source list"
outfile,s,ql,"Vela_multi.res",,,"Enter output file name"
ulcl,r,ql,2.0,,,"Enter upper limit confidence level"
loccl,r,ql,5.9914659,,,"Enter source location contour confidence level"
lpoint,r,l,-999,,,"Enter galactic longitude of instrument
   pointing direction (-999 for undefined)"
bpoint,r,l,-999,,,"Enter galactic latitude of instrument
   pointint direction (-999 for undefined)"
```

Likelihood Multi src

```
0.00E-06 263.65 -2.95 2.1 2 2.0 21
0.00E-06 260.35 0.35 2.1 2 2.0 22
0.00E-06 270.55 0.36 2.1 2 2.0 23
0.00E-06 268.46 -4.14 2.1 2 2.0 24
0.00E-06 267.56 -4.74 2.1 2 2.0 25
0.00E-06 261.53 -11.65 2.1 2 2.0 31
```

The lines beginning with "!" are comments and are ignored. Each of the remaining lines is an input source. The columns are as follows:

1 flux ($photons/cm^2/s$) If fix=0 this flux is fixed, otherwise a new optimum is found

2 l (deg) : Galactic latitude

3 b (deg) : Galactic longitude. Note that this parameter suffers from the bug noted in section "Known Issue"

4 spectral index : spectral index of the source, used to calculate the PSF

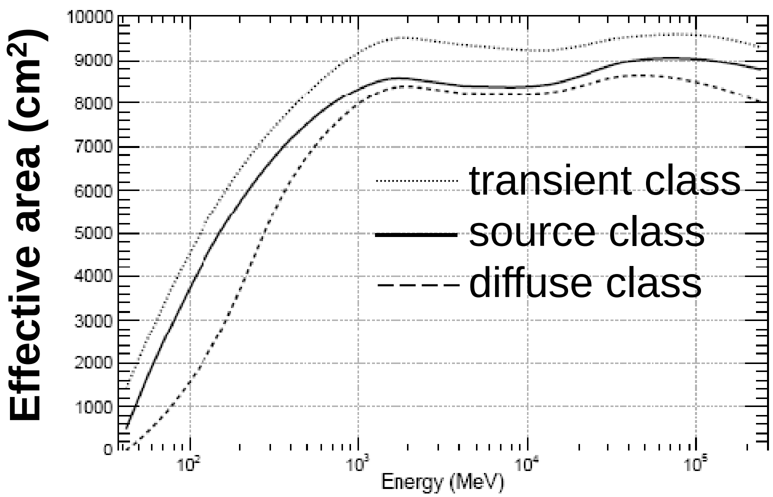
5 fix : 0 = leave fixed both the flux and position of the source; 1 = optimize the flux of the source while leaving the position fixed; 2 = optimize both the flux and the position of the source. Note that the initial TS of the source must be above both $(min(TS))^2$ and loccl in order for the position to be optimized.

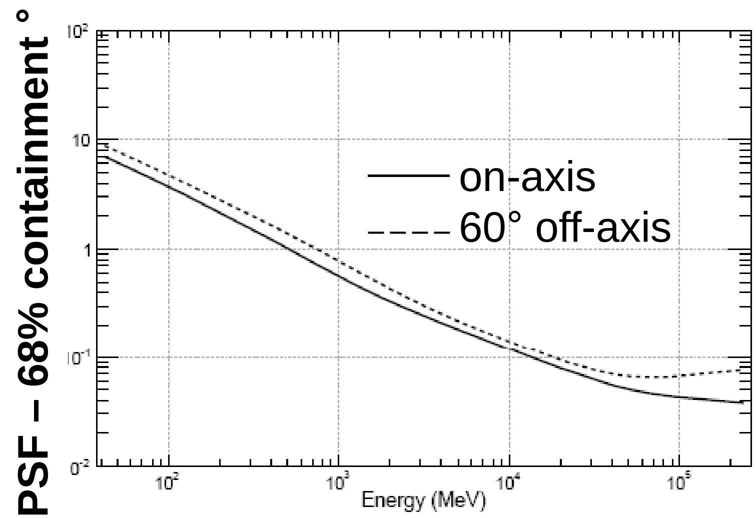
6 minTS : if the $\sqrt{(TS)}$ of the source is initially below this value and fix≥1, its flux will be set to zero during the analysis of the other sources

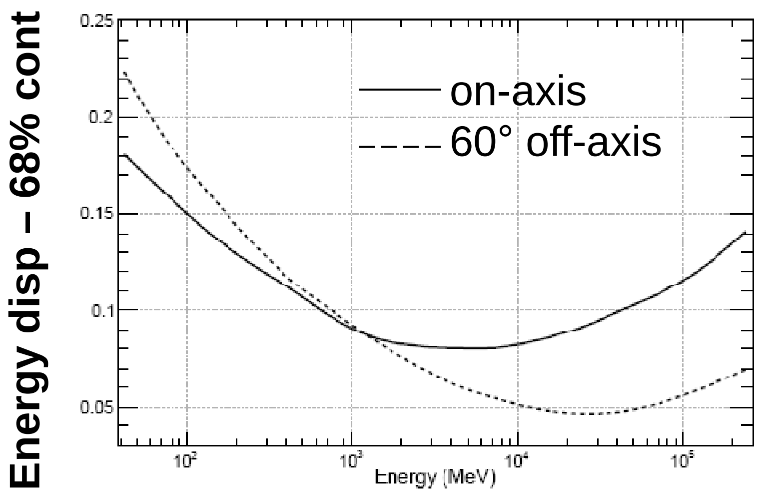
7 label : A unique string without spaces. It will be used as part of an output filename.

LAT Data Analysis

Instrument Response Functions





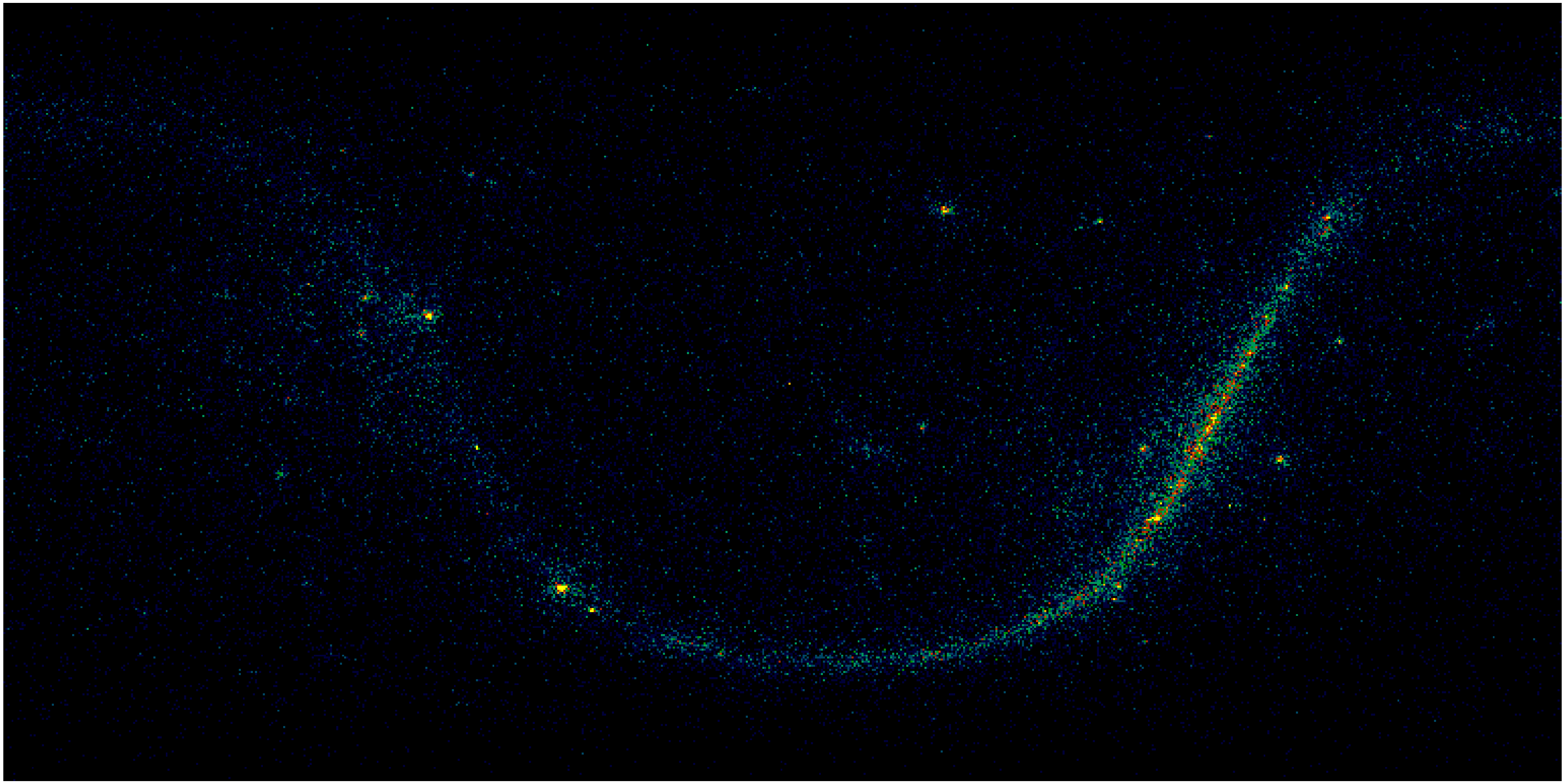


The Large Area Telescope on the Fermi Gamma-ray Space Telescope
Atwood, W. B. et al. 2009, ApJ, 697, 1071 doi: [10.1088/0004-637X/697/2/1071](10.1088/0004-637X/697/2/1071)

Post-launch performance tuning on-going

➢ IRF update for public data release + future updates

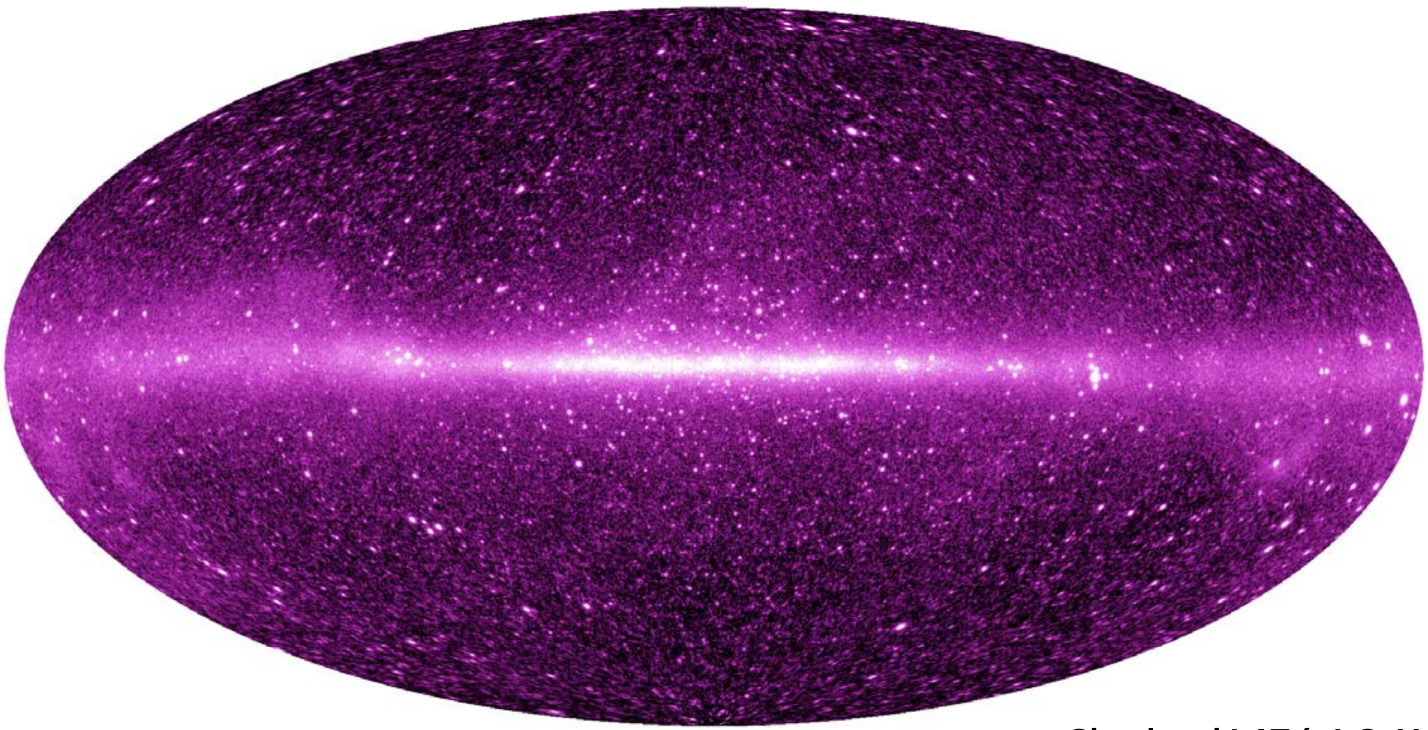
Data Challenge 2



http://antwrp.gsfc.nasa.gov/apod/ap060531.html

The Gamma-Ray Sky

- Comparing EGRET to Fermi LAT:
  - Illustrating the anticipated improvement in our knowledge of the sky



Simulated LAT (>1 GeV, 1 yr)

Data Analysis Issues

- The PSF is large at low energy, small at high energy.
- With the LAT's large effective area, many sources will be detected; their PSFs will merge at low energy.
  - ∴ Analysis is inherently 3D—2 spatial and 1 spectral (& users are interested in temporal!)
- For a typical analysis the source model must include
  - All point sources within a few PSF lengths of the region of interest
  - Diffuse sources (e.g., supernova remnants)
  - Diffuse Galactic emission (modeled)
  - Diffuse extragalactic emission
- Sources are defined by position, spectra, and perhaps time history. Initial values may be extracted from the point source catalog that will be compiled by the LAT team.
- The source model will have many parameters. In an analysis some will be fitted, some will be fixed.

Data Analysis Issues-II

- The instrument response (PSF, effective area, energy resolution) will most likely be a function of energy, angle to the LAT normal, conversion layer (the front or back of the LAT), and the electron-positron vertex angle. The IRF may also depend on the charged particle background resulting from the geomagnetic latitude, Solar cycle phase, etc.
- The LAT will usually survey the sky. Therefore a source will be observed at different instrument orientations.

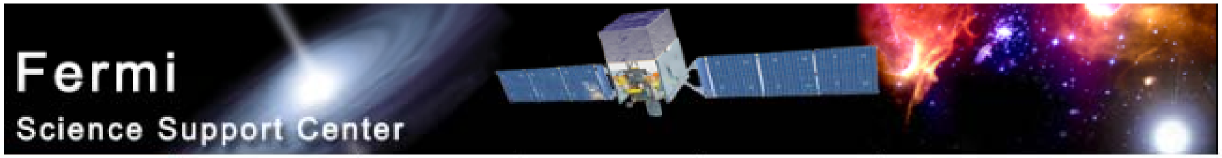
Observables

- The observables for a photon are:
  - Apparent energy
  - Apparent origin in sky coordinates (2 observables)
  - Apparent origin in instrument coordinates (2 observables)
  - Time
  - Front vs. back of LAT
  - …
- Therefore, a very large data space results. Even with 10^5 counts, this data space will be sparsely populated.

GODDARD SPACE FLIGHT CENTER

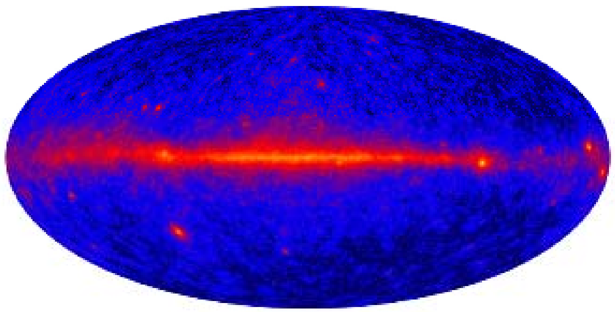
+ NASA Homepage
+ GSFC Homepage
+ Fermi Homepage

SEARCH Fermi: Search + GO



HOME | RESOURCES | PROPOSALS | DATA | HEASARC | HELP | SITE MAP

The Fermi Science Support Center (FSSC) runs the guest investigator program, creates and maintains the mission time line, provides analysis tools for the scientific community, and archives and serves the Fermi data. This web site is the portal to Fermi for all guest investigators.



This all-sky view from Fermi reveals bright emission in the plane of the Milky Way (center), bright pulsars and super-massive black holes.
Credit: NASA/DOE/International LAT Team

Look into the "Resources" section for finding schedules, publications, useful links etc. The "Proposals" section is where you will be able to find the relevant information and tools to prepare and submit proposals for guest investigator projects. At "Data" you will be able to access the Fermi databases and find the software to analyse them. Address all questions and requests to the helpdesk in "Help".

Quicklist

- 2009 Fermi Symposium
- GLAST Fellowship Program
- Fermi Guest Investigator Program
- Fermi Sky Blog
- Multiwavelength Observation Reporting Form
- Fermi User's Group (FUG)

News

June 18, 2009

Selections for the Cycle-2 Guest Investigator Program

Selections for the Cycle-2 Guest Investigator Program were announced by NASA HQ on June 18, 2009. A list of these programs can be viewed here.

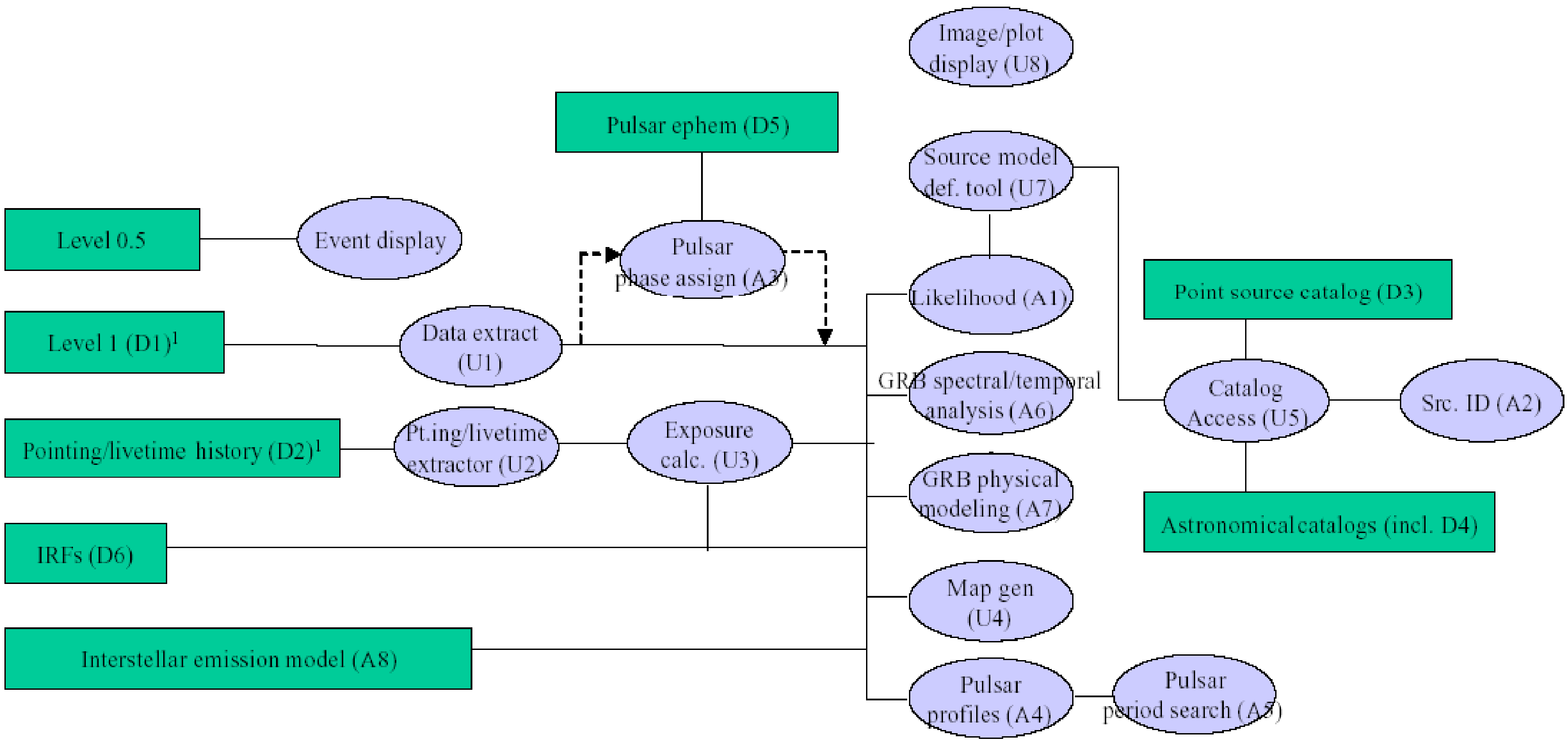
April 20, 2009

Fermi Symposium

The 2009 Fermi Symposium is dedicated to results and prospects for scientific exploration of the Universe with the Fermi Gamma-ray Space Telescope and related studies. The symposium will be held shortly after the Fermi data release, offering an opportunity for the astrophysical community to share in the excitement of discoveries being made with the Fermi instruments. Topics will include: blazars and other active galactic nuclei, pulsars, gamma-ray bursts, supernova remnants, diffuse gamma radiation, unidentified gamma-ray sources, and searches for dark matter. The meeting will be held November 2-5, 2009 in downtown Washington, D.C.

fermi.gsfc.nasa.gov/ssc

LAT Science Tools



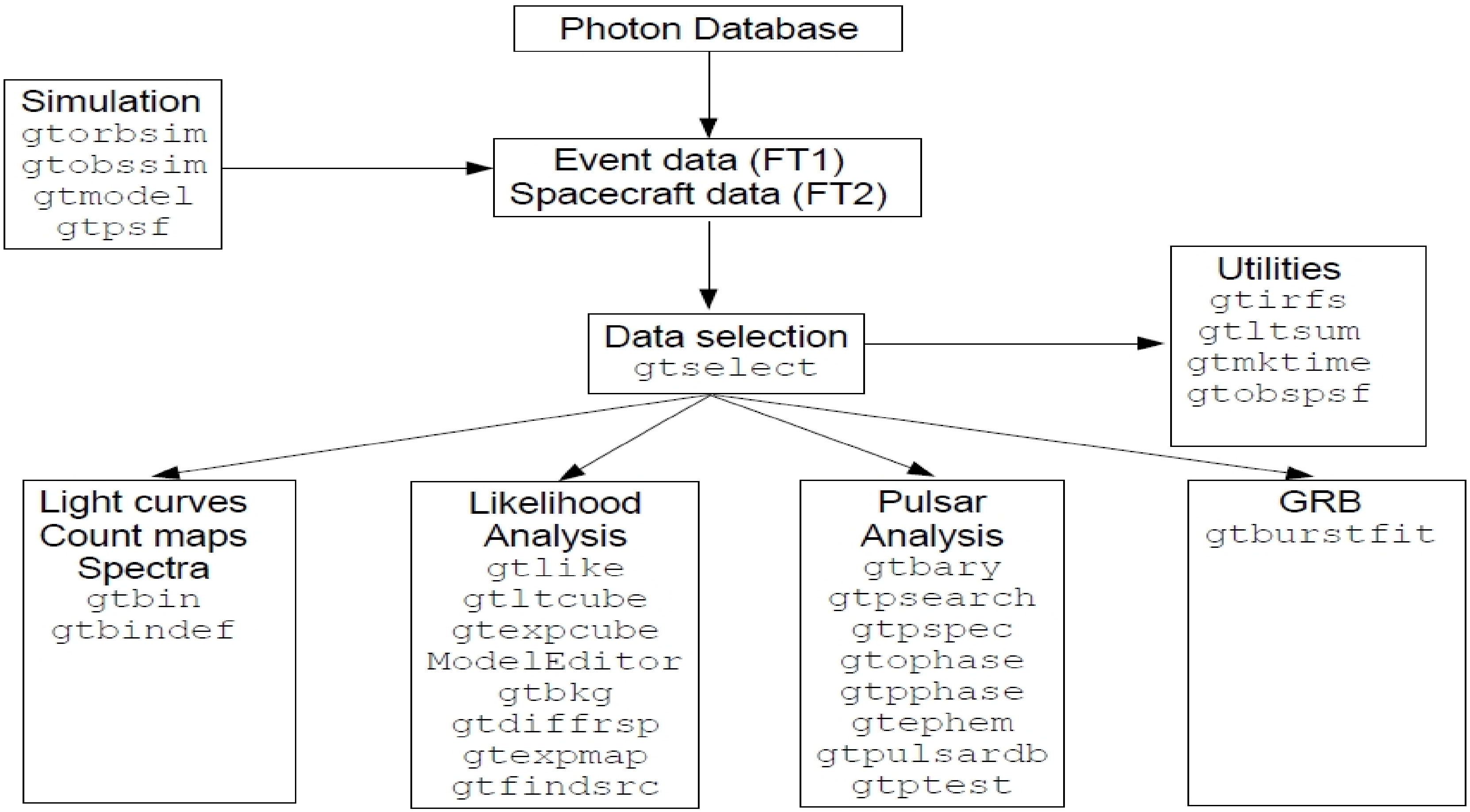
Science Tools: Summary

- Collaborative effort: FSSC, LAT & GBM Team
- Is released as an FTOOLS package
  - Adherence to broader HEASARC standards
  - “Atomic” executables, FITS i/o, IRAF style param files
  - Scriptable, with GUI implementation
  - Existing tools used when possible and appropriate
    - e.g. FV, DS9, XSPEC
- Full set of LAT tools prior to Cycle 2 (2/6/09)!
- LAT analysis has challenges associated w/PSF, backgrounds, scanning mode
  - Usability and viability demonstrated
  - Early mission science!
  - Data challenges (GLAST LAT collaboration)
  - Beta testing (1st: hands-on tutorial, 2nd: distribute SW & docs)

Science Analysis Tools

- Overview of capabilities
  - Maximum likelihood tool—spatial-spectral analysis of region (source detection, flux)
    - Includes background models
  - Pulsars—period analysis, blind searches
    - Includes ephemerides DB
  - Event-level observation simulator
    - enables modeling of a large variety of sources: flaring and periodic sources with spectral variability, diffuse sources, etc.
  - GRBs—temporal cuts, spectral analysis: Ftools, XSPEC
- Tools and documentation are released through FSSC website

Science Tools: Flowchart



Science Tools: Documentation

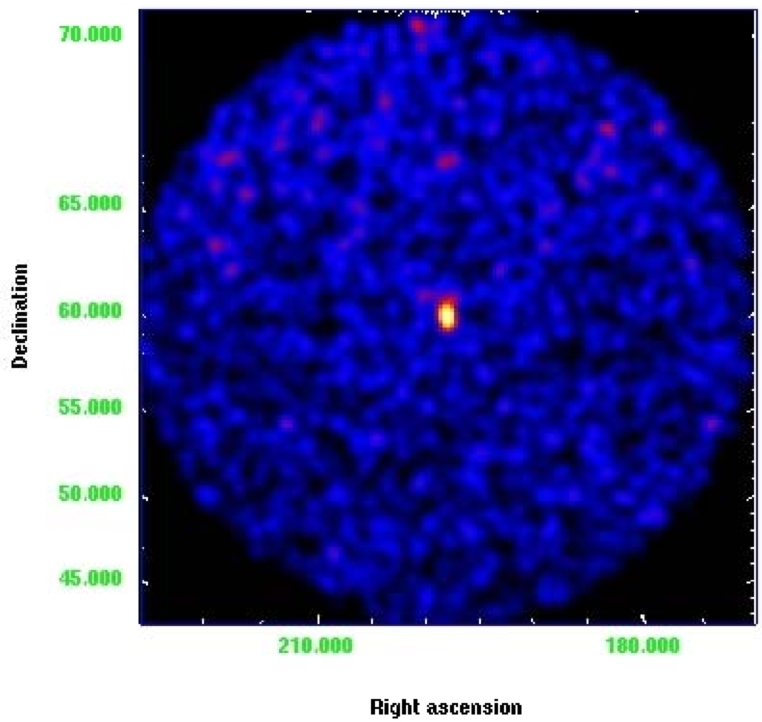
- Multi-Tier Documentation
  - Full set accompanies SW release
    - Fermi Mission Technical Handbook
  - Multiple levels:
    - Detailed analysis description (‘Cicerone’)
    - Individual tool descriptions (like fhelp)
    - Analysis threads (cook book examples)
    - Also, ‘Crash Course’ guide

Science Tools: Simulations

Science Tools include simulation tool; *gtobssim.* Proposers can simulate more realistic scenarios than with web based tools*, e.g.* multiple point sources of differing intensities, spectra including backgrounds, mono-energetic sources, pulsed or transient sources.

Science Tools: Simulations cont

```xml
<source_library title="Example1">

 <source name="mysource" flux="0.005">
      <spectrum escale="MeV">
        <particle name="gamma">
          <power_law emin="30.0" emax="200000." gamma="2"/>
        </particle>
        <celestial_dir ra="198" dec="67"/>
      </spectrum>
 </source>
   <source name="Galactic_diffuse">
     <spectrum escale="MeV">
       <SpectrumClass name="MapCube" params="18.58,GP_gamma.fits"/>
       <use_spectrum frame="galaxy"/>
     </spectrum>
   </source>

   <source name="Extragalactic_diffuse">
    <spectrum escale="MeV">
      <SpectrumClass name="Isotropic" params="10.7, 2.1, 20., 2e5"/>
      <use_spectrum frame="galaxy"/>
    </spectrum>
   </source>
</source_library>
```



Observation Simulation

- Simple example source model:
  - LSI +61 303, flux estimated from LAT monitored source page: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc model as a constant source even though BSL paper shows that it varies
  - PKS 2155–304, high state
  - Galactic diffuse component
  - Isotropic extragalactic diffuse (EGRET measurement)
- Could also use Bright Source List to build model: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/bright_src_list
- Perform a week-long simulation

Observation Simulation

- Define a source model in xml:

A more recent version of the GALPROP model will be available from the FSSC site

```
% cat gtobssim_model.xml
<source_library title="my LSI +60 303 model">
  <source name="GALPROP_diffuse">
    <spectrum escale="MeV">
      <SpectrumClass name="MapCube" params="12.59,
       $(FERMI_DIR)/refdata/fermi/galdiffuse/GP_gamma_v0r0p1.fits"/>
      <use_spectrum frame="galaxy"/>
    </spectrum>
  </source>
  <source name="Extragalactic_diffuse">
    <spectrum escale="MeV">
      <SpectrumClass name="Isotropic" params="10.7, 2.1, 20., 2e5"/>
      <use_spectrum frame="galaxy"/>
    </spectrum>
  </source>
  <source flux="0.041" name="LSI_p61_303">
    <spectrum escale="MeV">
      <particle name="gamma">
        <power_law emax="1000000.0" emin="20.0" gamma="2.1"/>
      </particle>
      <celestial_dir dec="61.2290" ra="40.1310"/>
```

Flux units for the gtobssim models are ph m^{-2} s^{-1}

Observation Simulation

```
    </spectrum>
  </source>
  <source flux="0.03" name="PKS_2155m304">
    <spectrum escale="MeV">
      <particle name="gamma">
        <power_law emax="1000000.0" emin="20.0" gamma="1.81"/>
      </particle>
      <celestial_dir dec="-30.226" ra="329.717"/>
    </spectrum>
  </source>
</source_library>
```

- Other examples are distributed with the ScienceTools and can be found in **`${FERMI_DIR}/xml/fermi/observationSim`**

▶ *Running gtobssim:*

```
% gtobssim
File of flux-style source definitions[none] xmlFiles.txt
File containing list of source names[source_names.txt]
Pointing history file[none]
Prefix for output files[test] LSI_sim
Simulation time (seconds)[86400] 604800
Simulation start date[2001-01-01 00:00:00] 2009-03-06 00:00:00
Apply acceptance cone?[no]
Response functions[] P6_V1_DIFFUSE
Random number seed[293049] 4909141
added source "GALPROP_diffuse"
added source "Extragalactic_diffuse"
added source "LSI_p61_303"
added source "PKS_2155m304"
Generating events for a simulation time of 604800 seconds....
```

The pointing history will be generated with idealized survey mode

Auxiliary files for gtobssim:

Can include multiple xml files here

```
% cat xmlFiles.txt
gtobssim_model.xml
```

Entries can be commented out with a "#"

```
% cat source_names.txt
GALPROP_diffuse
Extragalactic_diffuse
LSI_p61_303
PKS_2155m304
```

Pointing file

Event files

```
% ls LSI_sim*
LSI_sim_events_0000.fits  LSI_sim_scData_0000.fits
LSI_sim_events_0001.fits  LSI_sim_srcIds.txt
```

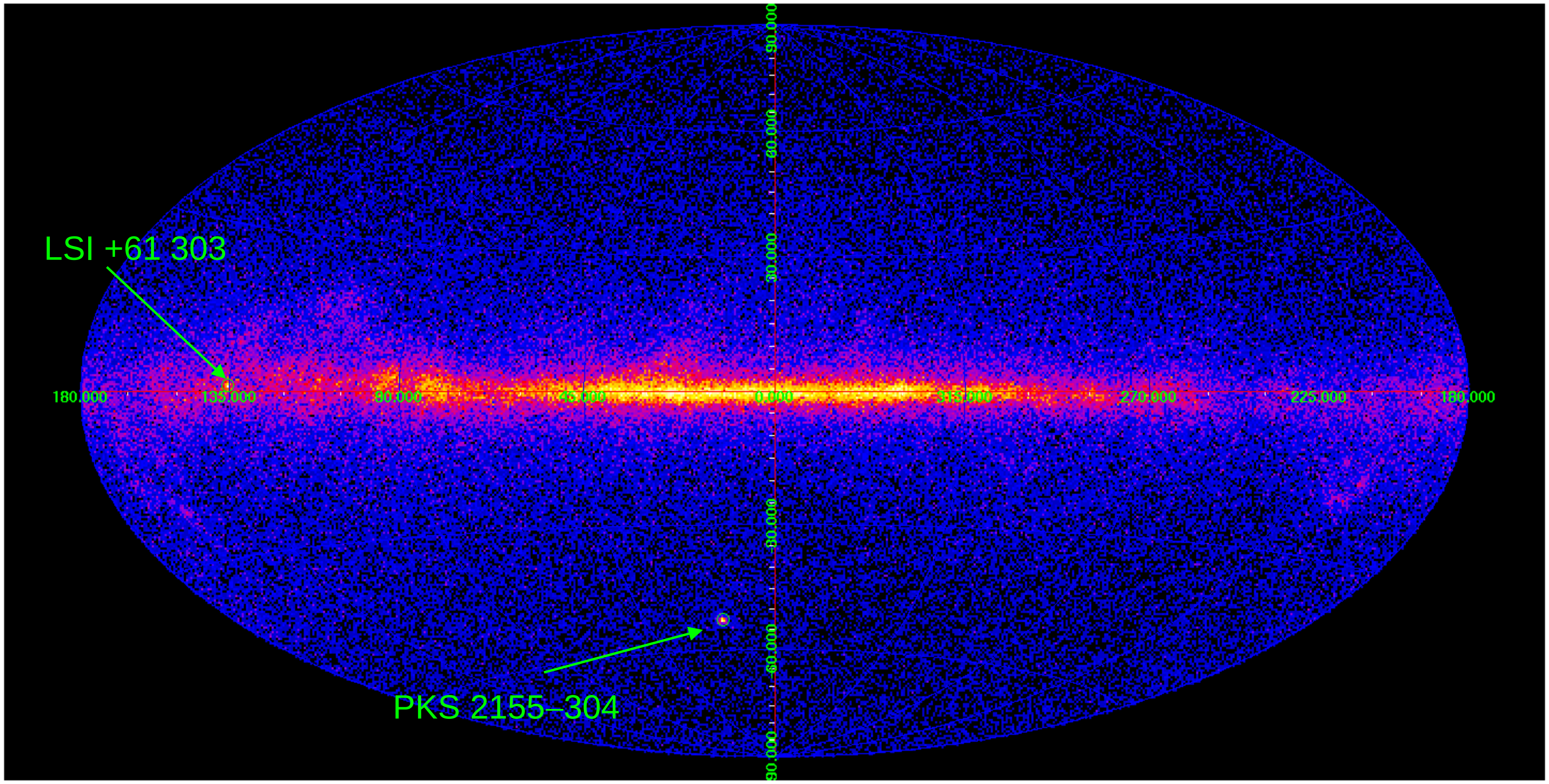
contains MC_SRC_ID mapping

a list of event files as input to the tools

```
% ls LSI_sim_events* > evfiles
```

Counts Maps

- All-sky map created with gtbin:



Counts Maps

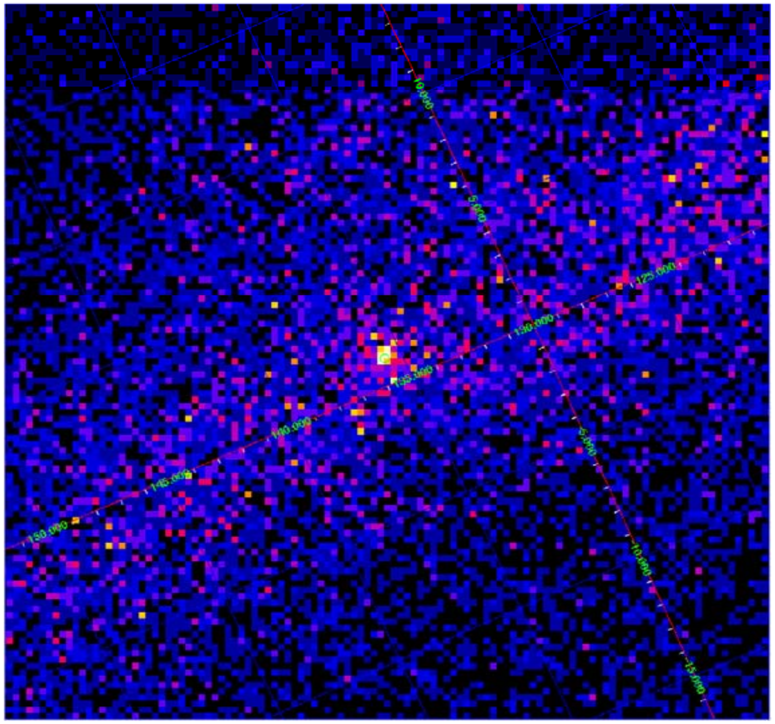
- Counts maps with gtbin, all-sky map example:

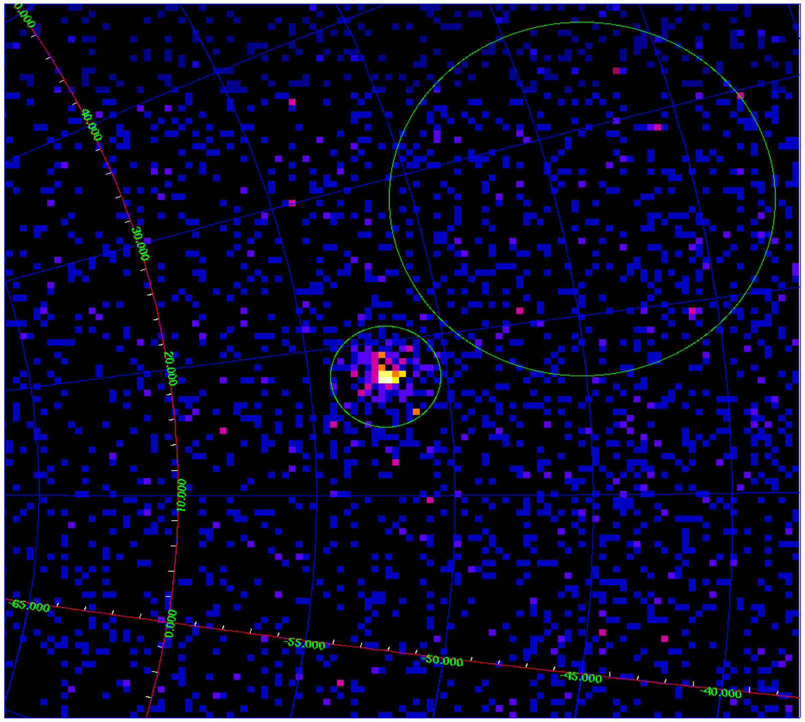
```
% gtbin
This is gtbin version ScienceTools-v9r8p2-fssc-20090206
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2) [PHA2] cmap
Event data file name[] @evfiles
Output file name[] cmap_allsky.fits
Spacecraft data file name[NONE] LSI_sim_scData_0000.fits
Size of the X axis in pixels[] 720
Size of the Y axis in pixels[] 360
Image scale (in degrees/pixel)[] 0.5
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [CEL] GAL
First coordinate of image center in degrees (RA or galactic l)[] 0
Second coordinate of image center in degrees (DEC or galactic b)[] 0
Rotation angle of image axis, in degrees[0.]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT]
```

event file or list of event files

Counts Maps

- LSI +61 303 and PKS 2155–304 regions:





Likelihood Analysis: Introduction

The final aim of to derive the best possible estimate for the characteristics of a source.

The Maximum Likelihood Analysis has been successfully used in the analysis of gamma-ray data and it has also a central role in the LAT Data analysis.

The Fermi Science Analysis Software provides a tool to perform:

- **Unbinned   Maximum Likelihood Analysis**
- **Binned   Maximum Likelihood Analysis**

Likelihood Analysis: Introduction

The Maximum Likelihood is used to compare source measured counts with the predicted counts derived from a source model.
In the Unbinned version of MLA the source Model considered is:

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

Point Sources | Galactic & EG Diffuse Sources | Other Sources

This model is folded with the Instrument Response Funcion (IRF) to obtain the predicted counts in the measured quantities 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 total IRF and the integral is done over the Source Region (SR), that is the region of the sky containing all the sources that can contribute to the Region of Interest (ROI). In the standard Analysis "steady" sources are considered:

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

Likelihood Analysis: Introduction

The function that is maximized is

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

Where the sum is performed over the ROI. The predicted counts are given by:

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

To reduce the CPU time, a quantity, indipendent from any source model and similar to an exposure map, is precomputed:

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

Then

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

Likelihood Analysis

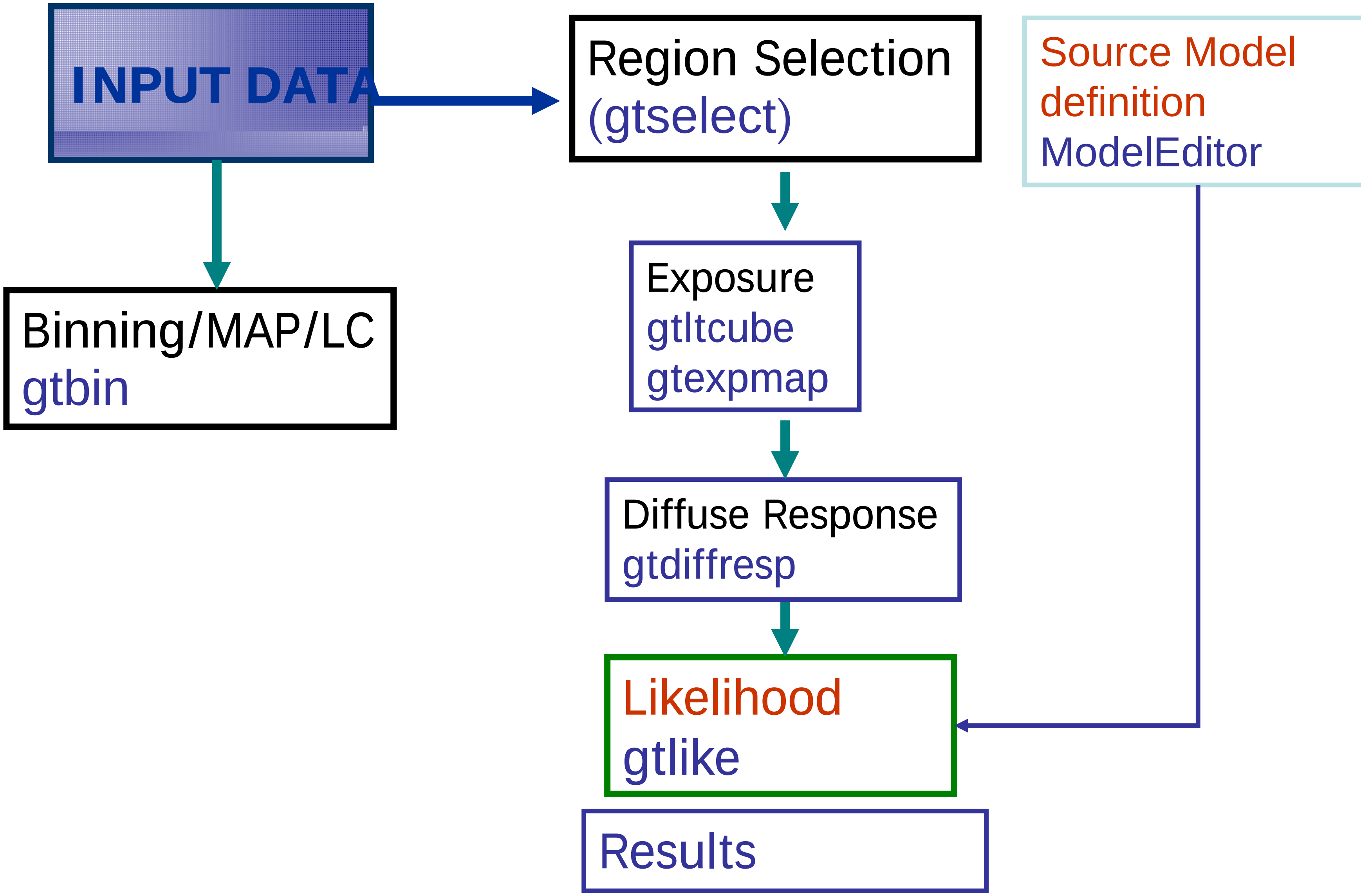
- Unbinned and binned modes are available. I'll describe unbinned analysis.
- Several tools are needed to define the model and prepare the data
  - modeleditor: GUI for preparing the xml model definition file
  - gtselect: applies region-of-interest cuts – sky acceptance cone, energy range (0.2 – 300 GeV), time range, zenith angles (< 105°)
  - gtmktime: constructs good time intervals (GTIs) based on pointing information selections and zenith angle cuts

Likelihood Analysis cont.

- gtdiffrsp: pre-computes integrals over spatial distribution of diffuse sources and adds a column per source to the event file.
- gtltcube: integrates LAT livetime as a function of sky position and off-axis angle
- gtexpmap: computes RoI-specific exposure maps
- gtlike: fits model parameters using maximum likelihood

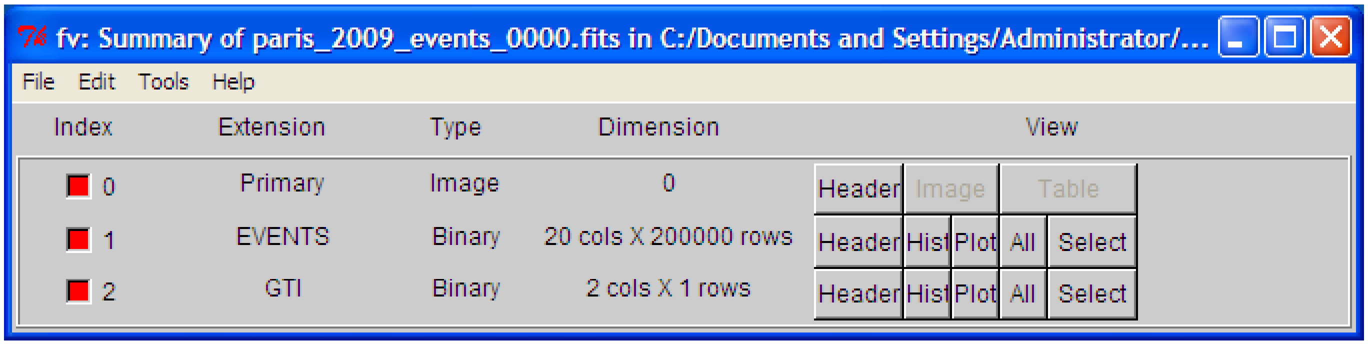
- Details of the method can be found in http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone

The Unbinned Likelihood Analysis Diagram

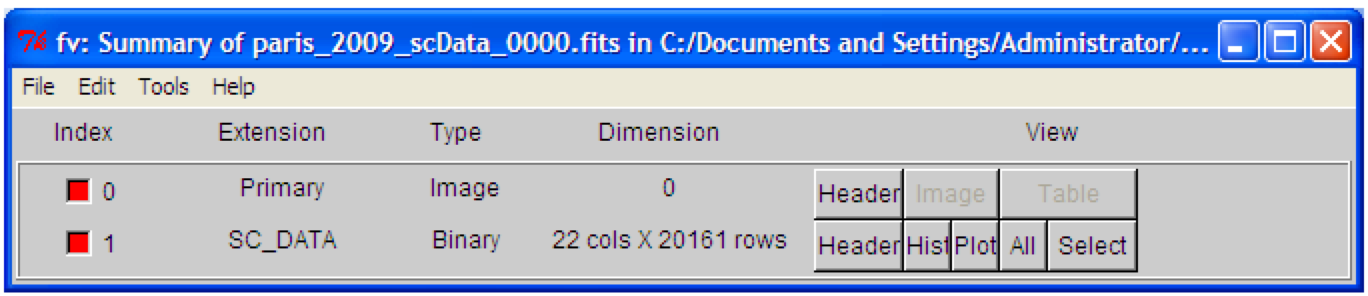


INPUT DATA

- **The photon FT1 fits FT1 file:**



- **and the pointing and livetime history FT2 files.**



Event File

fv: Binary Table of paris_2009_events_0000.fits[1] in C:/Documents and Settings/Administrator/Des...

File Edit Tools Help

Select	ENERGY	RA	DEC	L	B	THETA
	E	E	E	E	E	E
All	MeV	deg	deg	deg	deg	deg
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	1.665734E+002	4.689456E+001	8.151215E+000	1.708539E+002	-4.171476E+00	3.596782E+001
2	1.597547E+002	1.736912E+001	6.372568E+001	1.249272E+002	9.238764E-001	4.191966E+001
3	3.674128E+002	3.806548E+001	4.898215E+001	1.394540E+002	-1.062812E+00	2.708342E+001
4	2.956612E+002	8.659884E+001	-1.219475E+00	2.167855E+002	-1.987053E+00	5.076315E+001
5	3.100398E+001	4.280964E+001	2.789939E+001	1.528871E+002	-2.791385E+00	2.551058E+001
6	5.925673E+002	6.684470E+001	-1.196784E+00	2.073215E+002	-3.733567E+00	4.860555E+001
7	1.698496E+002	8.279141E+001	3.798893E+001	1.707380E+002	2.291375E+000	9.215265E+000
8	2.435646E+002	8.189124E+001	3.545148E+001	1.724559E+002	2.889103E-001	8.490270E+000
9	6.722176E+001	1.025168E+002	4.057747E+001	1.755183E+002	1.701170E+001	2.448024E+001
10	3.219784E+001	8.773401E+001	4.020052E+001	1.708707E+002	6.716216E+000	1.324010E+001
11	4.207299E+001	8.340757E+001	1.073564E+001	1.941546E+002	-1.190259E+00	2.774345E+001
12	9.347469E+001	4.080465E+001	5.439264E+001	1.388280E+002	-4.992523E+00	2.789460E+001
13	7.186378E+001	7.747270E+001	4.608567E+001	1.618267E+002	3.660231E+000	1.076391E+001
14	5.082564E+001	6.764105E+001	2.609037E+001	1.723907E+002	-1.509452E+00	1.067392E+001
15	3.448770E+002	7.907454E+001	2.827078E+001	1.770271E+002	-5.747601E+00	9.761881E+000
16	2.328190E+003	3.224036E+001	5.427679E+001	1.341868E+002	-6.892139E+00	3.288110E+001
17	4.355560E+002	3.226205E+001	1.575787E+001	1.489291E+002	-4.316180E+00	4.079770E+001
18	2.451982E+002	3.015611E+001	3.070033E+001	1.400766E+002	-2.985760E+00	3.520302E+001
19	9.015894E+001	6.803927E+001	3.842157E+001	1.632826E+002	-6.590471E+00	4.062911E+000
20	2.348078E+002	6.780315E+001	4.403956E+001	1.590328E+002	-2.894286E+00	8.746648E+000

Go to: Edit cell:

FT2 file

fv: Binary Table of paris_2009_scData_0000.fits[1] in C:/Documents and Settings/Administrator/Desktop/

File Edit Tools Help

Select	RA_SCZ	DEC_SCZ	RA_SCX	DEC_SCX	LAT_MODE	LIVETIME
	E	E	E	E	J	D
All	deg	deg	deg	deg		s
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	7.101110E+001	3.664213E+001	1.610111E+002	-1.576456E-01	0	2.700000000000E+001
2	7.266277E+001	3.574522E+001	1.626628E+002	-1.757924E-01	0	2.700000000000E+001
3	7.431376E+001	3.484769E+001	1.643138E+002	1.616135E-014	0	2.700000000000E+001
4	7.596489E+001	3.395029E+001	1.659649E+002	-2.382351E-01	0	2.700000000000E+001
5	7.761697E+001	3.305376E+001	1.676170E+002	3.261932E-014	0	2.700000000000E+001
6	7.927081E+001	3.215886E+001	1.692708E+002	-9.466344E-01	0	2.700000000000E+001
7	8.092722E+001	3.126632E+001	1.709272E+002	-6.714418E-01	0	2.700000000000E+001
8	8.258699E+001	3.037692E+001	1.725870E+002	-4.406861E-01	0	2.700000000000E+001
9	8.425093E+001	2.949140E+001	1.742509E+002	-5.527844E-01	0	2.700000000000E+001
10	8.591983E+001	2.861052E+001	1.759198E+002	2.643147E-014	0	2.700000000000E+001
11	8.759448E+001	2.773505E+001	1.775945E+002	-2.836467E-01	0	2.700000000000E+001
12	8.927565E+001	2.686576E+001	1.792757E+002	2.022605E-013	0	2.700000000000E+001
13	9.096411E+001	2.600342E+001	1.809641E+002	3.406657E-013	0	2.700000000000E+001
14	9.266061E+001	2.514883E+001	1.826606E+002	9.765112E-014	0	2.700000000000E+001
15	9.436588E+001	2.430278E+001	1.843659E+002	-5.634963E-01	0	2.700000000000E+001
16	9.608066E+001	2.346605E+001	1.860807E+002	3.599373E-014	0	2.700000000000E+001
17	9.780563E+001	2.263947E+001	1.878056E+002	-3.869739E-01	0	2.700000000000E+001
18	9.954150E+001	2.182384E+001	1.895415E+002	-3.264378E-01	0	2.700000000000E+001
19	1.012889E+002	2.101999E+001	1.912889E+002	2.140934E-014	0	2.700000000000E+001
20	1.030485E+002	2.022875E+001	1.930485E+002	-9.044703E-01	0	2.700000000000E+001

Go to: Edit cell:

The Source Model

- Source models should be written in an XML file:

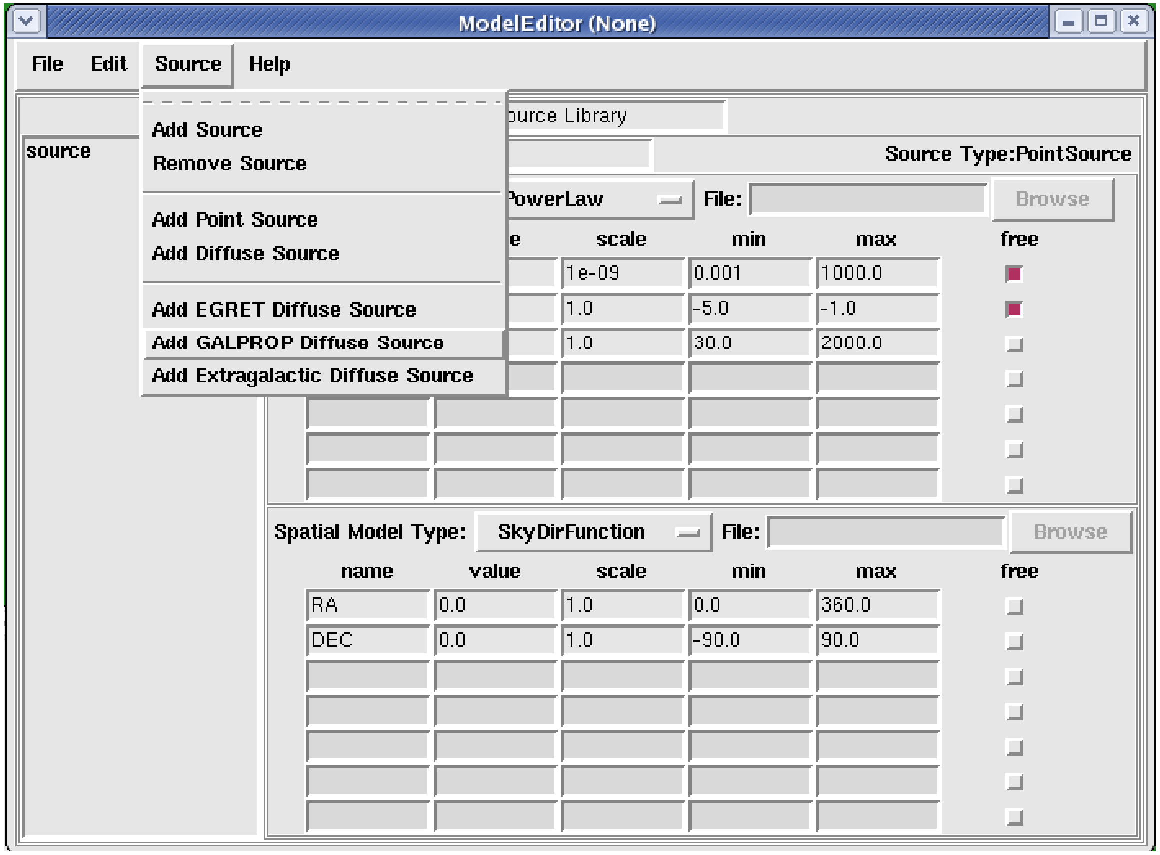
[Source Model description]

```xml
<?xml version="1.0" ?>
<source_library title="source library">

   <source name="Extragalactic Diffuse" type="DiffuseSource">
     <spectrum type="PowerLaw">
       <parameter free="1" max="100" min="1e-05" name="Prefactor" scale="1e-07" value="1.32"/>
       <parameter free="0" max="-1" min="-3.5" name="Index" scale="1" value="-2.1"/>
       <parameter free="0" max="200" min="50" name="Scale" scale="1" value="100"/>
     </spectrum>
     <spatialModel type="ConstantValue">
       <parameter free="0" max="10" min="0" name="Value" scale="1" value="1"/>
     </spatialModel>
   </source>

<source name="PKS 0528+134" type="PointSource">
     <spectrum type="PowerLaw">
       <parameter free="1" max="1000.0" min="0.001" name="Prefactor" scale="1e-009" value="13.65"/>
       <parameter free="1" max="-1.0" min="-3.5" name="Index" scale="1.0" value="-2.46"/>
       <parameter free="0" max="2000.0" min="30.0" name="Scale" scale="1.0" value="100.0"/>
     </spectrum>
     <spatialModel type="SkyDirFunction">
       <parameter free="0" max="3.40282e+038" min="-3.40282e+038" name="RA" scale="1.0" value="82.74"/>
       <parameter free="0" max="3.40282e+038" min="-3.40282e+038" name="DEC" scale="1.0" value="13.38"/>
     </spatialModel>
   </source>

</source_library>
```

Likelihood Analysis cont.

- Using the ModelEditor GUI:

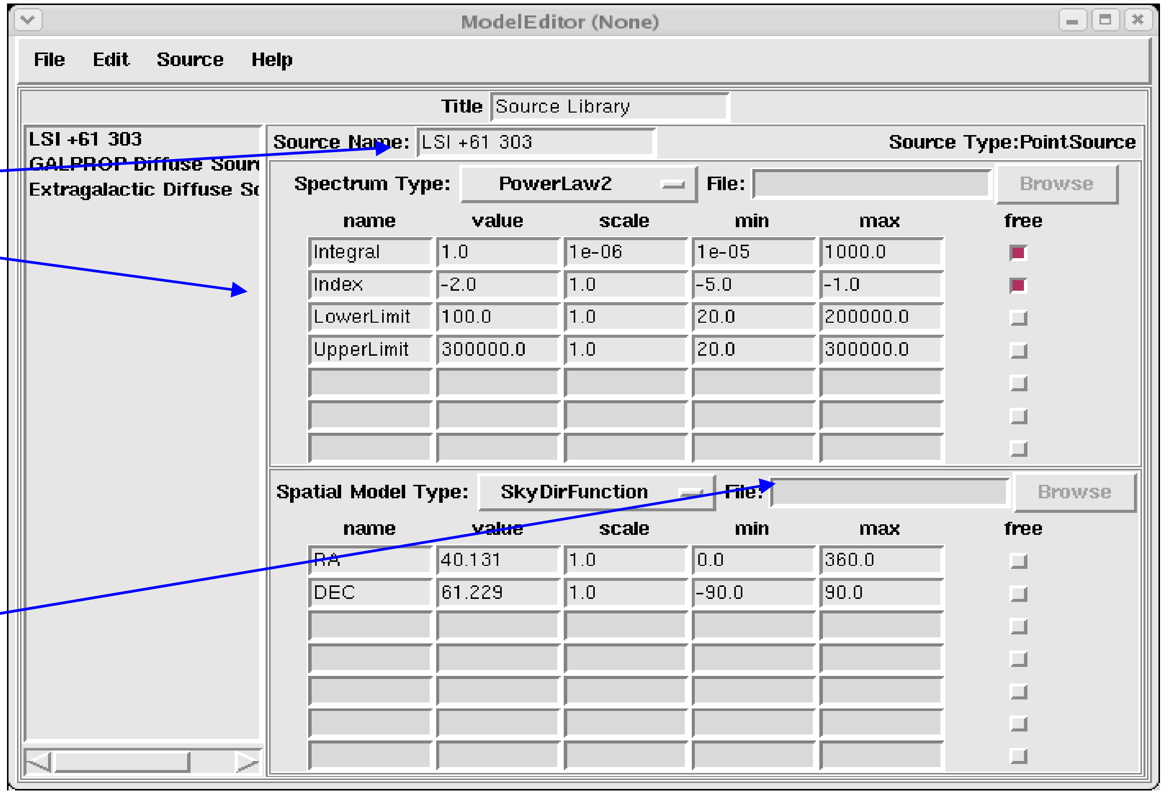
Add sources (point-like or diffuse) using the drop down menu



Likelihood Analysis cont.

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



Likelihood Analysis cont.

- Extract the data in the RoI:

```
% gtselect
Input FT1 file[@evfiles]
Output FT1 file[lsi_filtered_3deg.fits] lsi_filtered.fits
RA for new search center (degrees) (0:360) [40.131]
Dec for new search center (degrees) (-90:90) [61.229]
radius of new search region (degrees) (0:180) [3] 10
start time (MET in s) (0:) [0]
end time (MET in s) (0:) [0]
lower energy limit (MeV) (0:) [200]
upper energy limit (MeV) (0:) [300000]
maximum zenith angle value (degrees) (0:180) [105]
Done.
```

Choose an acceptance cone large enough to characterize any sources that may overlap with target

These defaults mean "no time selection"

Effective area varies strongly below 200 MeV

Zenith angle cut to avoid Earth albedo photons. Important at low energies and for pointed mode.

Likelihood Analysis

- gtmktime, gtltcube

```
% gtmktime
Spacecraft data file[] LSI_sim_scData_0000.fits
Filter expression[IN_SAA!=T]
Apply ROI-based zenith angle cut[yes]
Event data file[] lsi_filtered.fits
Output event file name[] lsi_filtered_zmax_roi.fits
```

This removes time intervals when the RoI is intersected by the zenith angle cut

```
% gtltcube
Event data file[] lsi_filtered_zmax_roi.fits
Spacecraft data file[] LSI_sim_scData_0000.fits
Output file[expCube.fits]
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
Working on file LSI_sim_scData_0000.fits
.....................!
```

Likelihood Analysis

- gtexpmap

```
% 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[] lsi_filtered_zmax_roi.fits
Spacecraft data file[] LSI_sim_scData_0000.fits
Exposure hypercube file[] expCube.fits
output file name[] expMap.fits
Response functions[] P6_V1_DIFFUSE
Radius of the source region (in degrees)[30] 20
Number of longitude points (2:1000) [120]
Number of latitude points (2:1000) [120]
Number of energies (2:100) [20]
Computing the ExposureMap using expCube.fits
....................!
```

Likelihood Analysis

- gtdiffrsp

```
% gtdiffrsp
Event data file[] lsi_filtered_zmax_roi.fits
Spacecraft data file[] LSI_sim_scData_0000.fits
Source model file[] lsi_model.xml
Response functions to use[] P6_V1_DIFFUSE
adding source Extragalactic Diffuse
adding source GalProp Diffuse
Working on...
lsi_filtered_zmax_roi.fits.....................!
```

Likelihood Analysis

- Finally, running gtlike:

```
% gtlike
Statistic to use (BINNED|UNBINNED) [UNBINNED]
Spacecraft file[none] LSI_sim_scData_0000.fits
Event file[none] lsi_filtered_zmax_roi.fits
Unbinned exposure map[none] expMap.fits
Exposure hypercube file[none] expCube.fits
Source model file[] lsi_model.xml
Response functions to use[] P6_V1_DIFFUSE
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [DRMNFB] NEWMINUIT

<... skip some output ...>

Computing TS values for each source (3 total)
...!

Extragalactic Diffuse:
Prefactor: 1.609157 +/- 1.0376564
Index: -2.1576144 +/- 0.21421358
Scale: 100
Npred: 392.94834
```

This is the xml model

```
GalProp Diffuse:
Value: 0.99102047 +/- 0.041932682
Npred: 4577.3401

LSI +61 303:
Integral: 4.4176578 +/- 1.3154204
Index: -2.1117783 +/- 0.097404512
LowerLimit: 20
UpperLimit: 200000
Npred: 228.61496
ROI distance: 0
TS value: 306.72589
WARNING: Fit may be bad in range [399.052, 796.214] (MeV)
WARNING: Fit may be bad in range [2244.04, 3169.79] (MeV)

Total number of observed counts: 5207
Total number of model events: 5198.9034

-log(Likelihood): 52165.72877

Elapsed CPU time: 33.91
```

The Test Statistic (TS) is distributed as χ^2 for n dof. For a power law model TS = 25 is roughly 5σ

Warning messages based on Poisson probability of observed counts given the model prediction in these bands

and more ..

To analyze the time & spectral variations of a source you have to run iteratively the likelihood tool, using procedures similar to the following

- Step 1 -Download data for your ROI from the DATA server over the entire time interval (T) where you want to study variability;
- Step 2 -Build a Source Model for your ROI
- Step 3 -Divide T in N time bins, and for each bin obtain a FT1 file with gtselect;
- Step 4 -Compute the livetimecube (gtltcube) for each time
- Step 5 -Calculate the ExposureMap (gtexpmap)
- Step 6 - Run gtlikelihood and rename the output result file

Repeat steps 3-6 for each time bin……

Hands On Session

Fermi Tools setup

- `cd /your_directory/ScienceTools-v9r8p2/your_oper_system/`
- `(eg. /home/franz/Paris_School/ScienceTools-v9r8p2/i686-pc-linux-gnu-libc2.3.4)`
- `setenv FERMI_DIR $PWD`
- `source fermi_init.csh`

preliminary

- Create a file in your own data dir with all the names of fits events file contained there (eg. `eventFiles.txt`)
- This file will contain these 4 lines

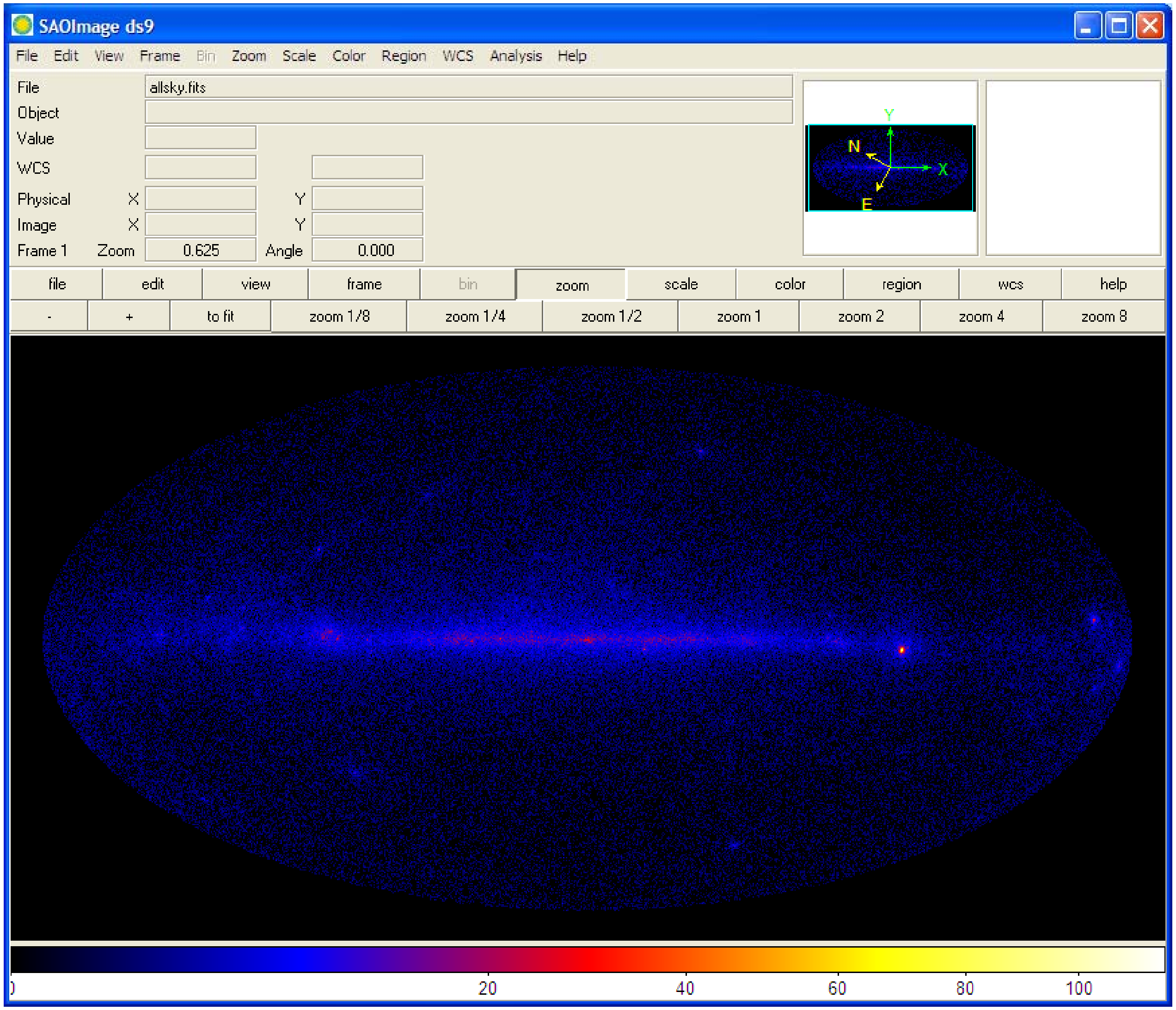
```
paris_2009_events_0000.fits
paris_2009_events_0001.fits
paris_2009_events_0002.fits
paris_2009_events_0003.fits
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **gtbin**

```
This is gtbin version ScienceTools-v9r8p2-fssc-20090225
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2) [CMAP] CMAP
Event data file name[@eventFiles.txt] @eventFiles.txt
Output file name[allsky.fits] allsky.fits
Spacecraft data file name[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Size of the X axis in pixels[1440] 1440
Size of the Y axis in pixels[720] 720
Image scale (in degrees/pixel)[0.25]
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [GAL] GAL
First coordinate of image center in degrees (RA or galactic l)[0] 0
Second coordinate of image center in degrees (DEC or galactic b)[0] 0
Rotation angle of image axis, in degrees[0]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT] AIT
```

All Sky Cts Map – Exercise I



Likelihood Analysis of 3C 279 and 3C 273
Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **gtselect**

```
Input FT1 file[paris_2009_events_0000.fits]@eventFiles.txt
Output FT1 file[3c279_filtered.fits] 3c279_filtered.fits
RA for new search center (degrees) (0:360) [193.98] 193.8
Dec for new search center (degrees) (-90:90) [-5.82] -5.82
radius of new search region (degrees) (0:180) [20] 20
start time (MET in s) (0:) [267926400] 267926400
end time (MET in s) (0:) [268111497] 268531200
lower energy limit (MeV) (0:) [30] 30
upper energy limit (MeV) (0:) [300000] 300000
maximum zenith angle value (degrees) (0:180) [105] 105
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **gtltcube**

```
Event data file[3c279_filtered.fits] 3c279_filtered.fits
Spacecraft data file[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Output file[3c279_expCube.fits] 3c279_expCube.fits
Step size in cos(theta) (0.:1.) [0.025]
Pixel size (degrees)[1]
Working on file paris_2009_scData_0000.fits
.....................!
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- gtbin

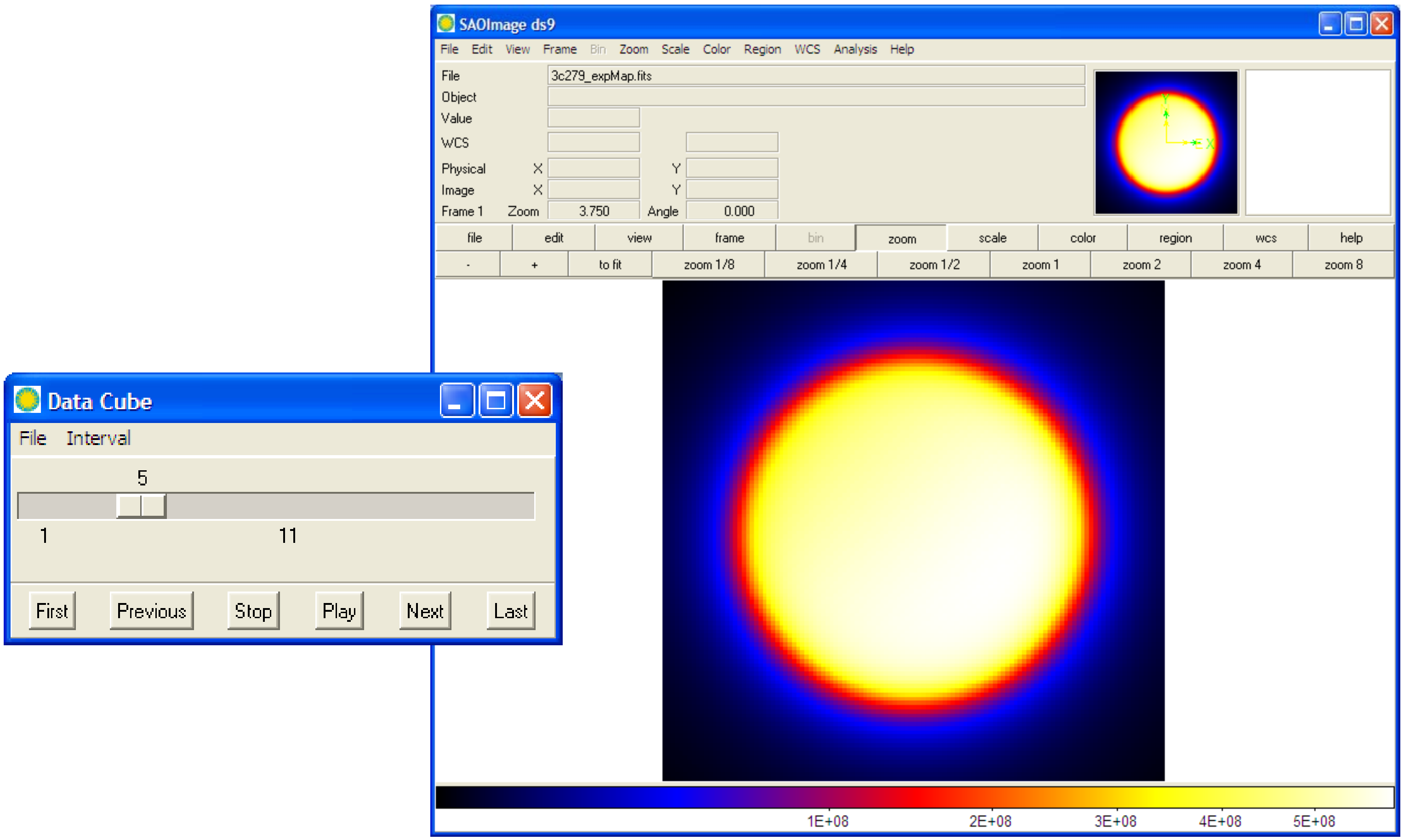
```
This is gtbin version ScienceTools-v9r8p2-fssc-20090225
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2) [CMAP] CMAP
Event data file name[@eventFiles.txt] @eventFiles.txt
Output file name[allsky.fits] allsky.fits
Spacecraft data file name[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Size of the X axis in pixels[1440] 1440
Size of the Y axis in pixels[720] 720
Image scale (in degrees/pixel)[0.25]
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [GAL] GAL
First coordinate of image center in degrees (RA or galactic l)[0] 0
Second coordinate of image center in degrees (DEC or galactic b)[0] 0
Rotation angle of image axis, in degrees[0]
Projection method e.g. AIT|ARC|CAR|GLS|MER|NCP|SIN|STG|TAN:[AIT] AIT
```

Likelihood Analysis of 3C 279 and 3C 273
Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **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_filtered.fits] 3c279_filtered.fits
Spacecraft data file[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Exposure hypercube file[3c279_expCube.fits] 3c279_expCube.fits
output file name[3c279_expMap.fits] 3c279_expMap.fits
Response functions[P6_V1_TRANSIENT] P6_V1_TRANSIENT
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 3c279_expCube.fits
.....................!
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II



Likelihood Analysis of 3C 279 and 3C 273 Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **gtdiffrsp**

```
Event data file[3c279_filtered.fits] 3c279_filtered.fits
Spacecraft data file[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Source model file[model_3c273_279.xml] model_3c273_279.xml
Response functions to use[P6_V1_TRANSIENT] P6_V1_TRANSIENT
adding source Extragalactic Diffuse
adding source Galpro Diffuse
Working on...
3c279_filtered.fits.....................!
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

- cd /your_dir/your_data/
- (eg. /home/franz/Paris_School/Exercise)
- **gtlike**

```
Statistic to use (BINNED|UNBINNED) [UNBINNED] UNBINNED
Spacecraft data file[paris_2009_scData_0000.fits] paris_2009_scData_0000.fits
Event file[3c279_filtered.fits] 3c279_filtered.fits
Unbinned exposure map[3c279_expMap.fits] 3c279_expMap.fits
Exposure hypercube file[3c279_expCube.fits] 3c279_expCube.fits
Source model file[model_3c273_279.xml] model_3c273_279.xml
Response functions to use[P6_V1_TRANSIENT] P6_V1_TRANSIENT
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [MINUIT] MINUIT
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

```
**********
**    1 **SET PRINT     .000
**********
**********
**    2 **SET NOWARN
**********

PARAMETER DEFINITIONS:
   NO.   NAME         VALUE      STEP SIZE      LIMITS
    1 'Prefactor '    10.000       1.0000         .10000E-02   1000.0
    2 'Index     '   -2.1000       1.0000        -5.0000      -1.0000
    3 'Prefactor '    10.000       1.0000         .10000E-02   1000.0
    4 'Index     '   -2.0000       1.0000        -5.0000      -1.0000
    5 'Prefactor '    1.6000       1.0000         .10000E-04   100.00
**********
**    3 **SET ERR    .5000
**********
**********
**    4 **SET GRAD    1.000
**********
**********
**    5 **MIGRAD    200.0       1924.
**********

MIGRAD MINIMIZATION HAS CONVERGED.

MIGRAD WILL VERIFY CONVERGENCE AND ERROR MATRIX.
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

```
 MIGRAD MINIMIZATION HAS CONVERGED.

MIGRAD WILL VERIFY CONVERGENCE AND ERROR MATRIX.

FCN=   96074.81     FROM MIGRAD    STATUS=CONVERGED    113 CALLS      114 TOTAL
                    EDM=   .57E-01    STRATEGY= 1      ERROR MATRIX ACCURATE

 EXT PARAMETER                                        STEP         FIRST
 NO.   NAME          VALUE           ERROR            SIZE      DERIVATIVE
  1  Prefactor     3.0659          .62559          .25254E-03   -24.522
  2  Index        -2.4555          .14634          .15321E-01   -3.7361
  3  Prefactor     9.7420          .72209          .15490E-03    4.7243
  4  Index        -2.0819          .43929E-01      .53196E-03    .75360
  5  Prefactor     1.8229          .34196E-01      .70550E-04   -19.589
                              ERR DEF=  .500
**********
**    6 **HESSE
**********

FCN=   96074.81     FROM HESSE     STATUS=OK            31 CALLS      145 TOTAL
                    EDM=   .58E-01    STRATEGY= 1      ERROR MATRIX ACCURATE

 EXT PARAMETER                                     INTERNAL      INTERNAL
 NO.   NAME          VALUE           ERROR         STEP SIZE       VALUE
  1  Prefactor     3.0659          .60884           .50508E-04   -1.4600
  2  Index        -2.4555          .14246           .30642E-02    .27575
  3  Prefactor     9.7420          .72086           .30979E-04   -1.3731
  4  Index        -2.0819          .43856E-01       .10639E-03    .47692
  5  Prefactor     1.8229          .34133E-01       .14110E-04   -1.2999
                              ERR DEF=  .500
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

```
Final values:
  Prefactor  = 3.06591
  Index      = -2.45546
  Prefactor  = 9.74201
  Index      = -2.08191
  Prefactor  = 1.82295
Minuit fit quality: 3   estimated distance: 0.0576487
Minuit parameter uncertainties:
  1  0.608849
  2  0.14259
  3  0.720871
  4  0.0438607
  5  0.034133
Computing TS values for each source (4 total)
....!
```

Likelihood Analysis of 3C 279 and 3C 273 Exercise II

```
3C 273:
Prefactor: 3.06591 +/- 0.608849
Index: -2.45546 +/- 0.14259
Scale: 100
Npred: 183.945
ROI distance: 10.4409
TS value: 80.3637

3C 279:
Prefactor: 9.74201 +/- 0.720871
Index: -2.08191 +/- 0.0438607
Scale: 100
Npred: 772.871
ROI distance: 0
TS value: 1143.31

Extragalactic Diffuse:
Prefactor: 1.82295 +/- 0.034133
Index: -2.1
Scale: 100
Npred: 5581.79

Galpro Diffuse:
Value: 1
Npred: 3049.25

Total number of observed counts: 9628
Total number of model events: 9587.85

-log(Likelihood): 96074.81263

Elapsed CPU time: 245.24
```