Fermi LAT Analysis: Livetime, Exposure and gtLike

Fermi Summer School 2012, Lewes DE

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The One Slide Summary

- Observed a photon from a location, at a time, with an energy.
- Assume a model:

$$S(E,\hat{p},t) = \underbrace{\sum_i s_i(E,t)\delta(\hat{p}-\hat{p}_i)}_{\text{Point Sources}} + \underbrace{S_G(E,\hat{p}) + S_{\text{eg}}(E,\hat{p})}_{\text{Galactic \& EG Diffuse Sources}} + \underbrace{\sum_l S_l(E,\hat{p},t)}_{\text{Other Sources}},$$

- Calculated the probability of that photon being detected assuming our model:

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

- Calculate the total number of predicted counts assuming our model.

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

- Adjust the model until this is maximized:

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

- Calculate the TS:

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

We are (have) about (going) to calculate the stuff that we can before we run the actual fit.

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Remember...

- Part of the likelihood implementation in the LAT is the pre-calculation of a model-independent exposure* map (or cube):

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

- I'm going to talk about computing this bit right now.

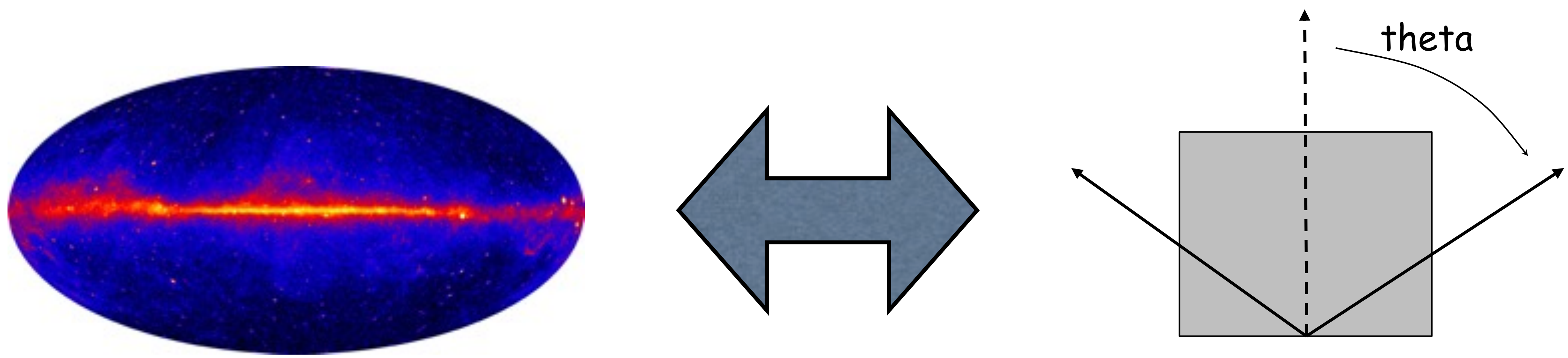
*Not really exposure but convenient nomenclature.

All of the information about the spacecraft is in the function 'R'.

LAT Specifics

- Calculating the exposure is a two-step process
  - **Livetime**: formally the time when the detector is available to collect data
    - For analysis, additionally require good data quality and select to remove high background
    - Large FoV with varying response: need to know **when** and **where**
  - **Exposure**: for practical purposes, the number that converts counts to photon flux
    - Apply expected photon detection efficiency and angular resolution
      - Depends on the event selection
      - Depends on the direction of the photon relative to the instrument boresight and energy

Livetime



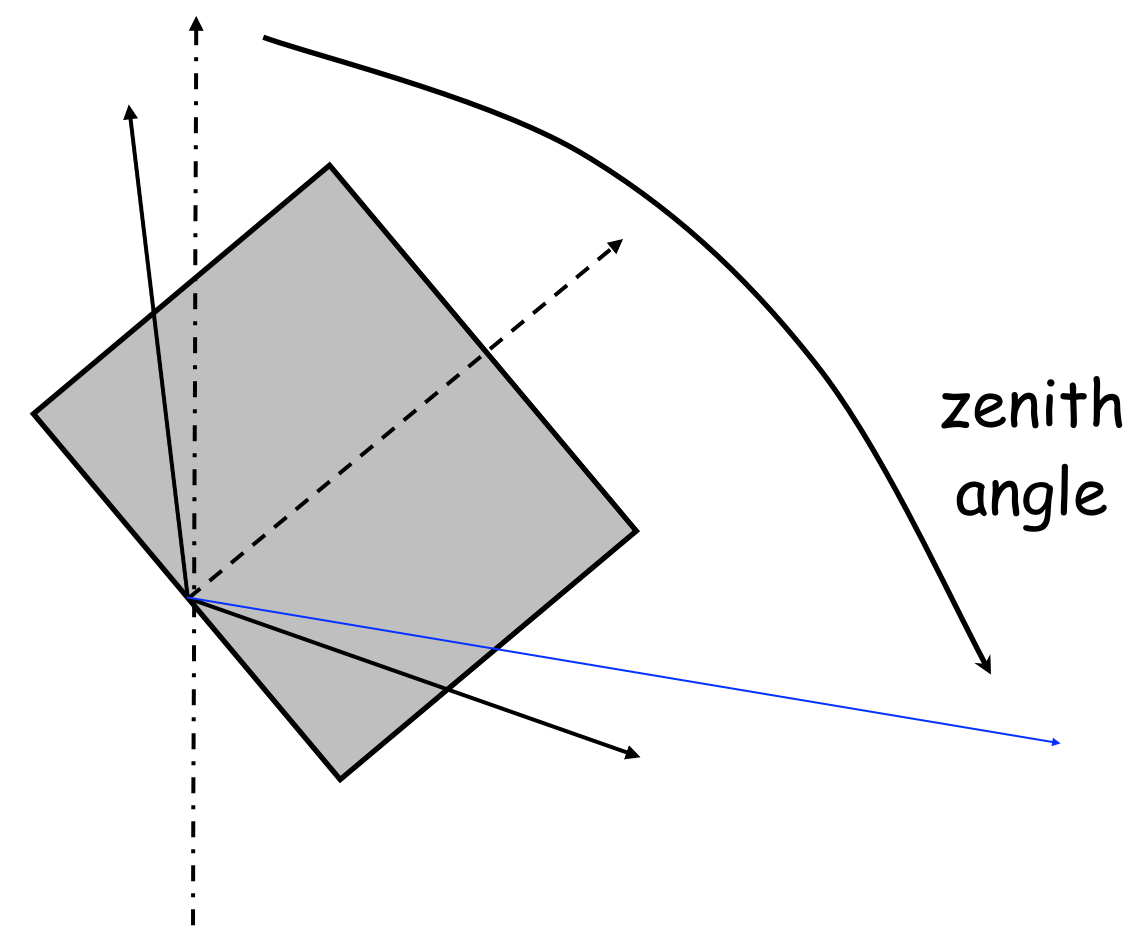
- Sum up time spent in the field of view for each position in the celestial sky
  - Inputs are the photon and spacecraft files
  - Options are pixel size and step size for the instrument angles
  - Output is a livetime ‘cube’
  - Respects time-based selection cuts made with gtmktime (GTIs)

Livetime and maximum zenith angle

Gtltcube knows about the field of view and the spacecraft pointing and can make exposure corrections related to those coordinate systems

if you use
gtselect zmax=105 …
and
gtmktime … ROIcut=no

then you must use
gtltcube zmax=105 …



- If you are doing an all-sky analysis or non-standard zenith cut, the gtltcube can make a correction for exposure loss from a zenith angle cut in gtselect
  - Note this assumes perfect reconstruction
- If you are doing a basic source analysis and using the standard ROIcut in gtmktime, you don't need to do this.

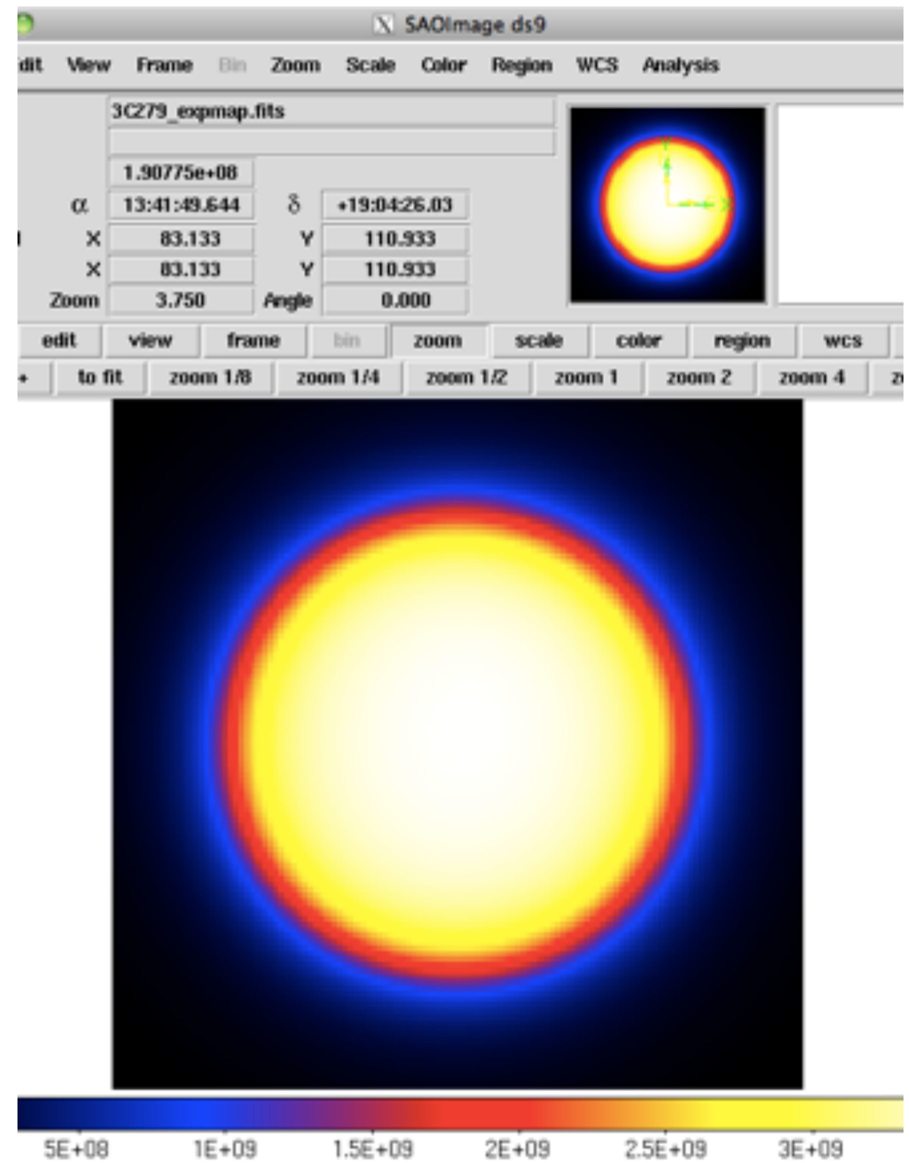
Practical Usage:

```
prompt> gtltcube
Event data file[] 3C279_events_gti.fits
Spacecraft data file[] L110729150643E0D2F37E79_SC00.fits
Output file[] 3C279_ltcube.fits
Step size in cos(theta) (0.:1.) [] 0.025
Pixel size (degrees)[] 1
Working on file L110729150643E0D2F37E79_SC00.fits
.....................!
prompt>
```

Takes ~30 minutes.

Exposure Map Output

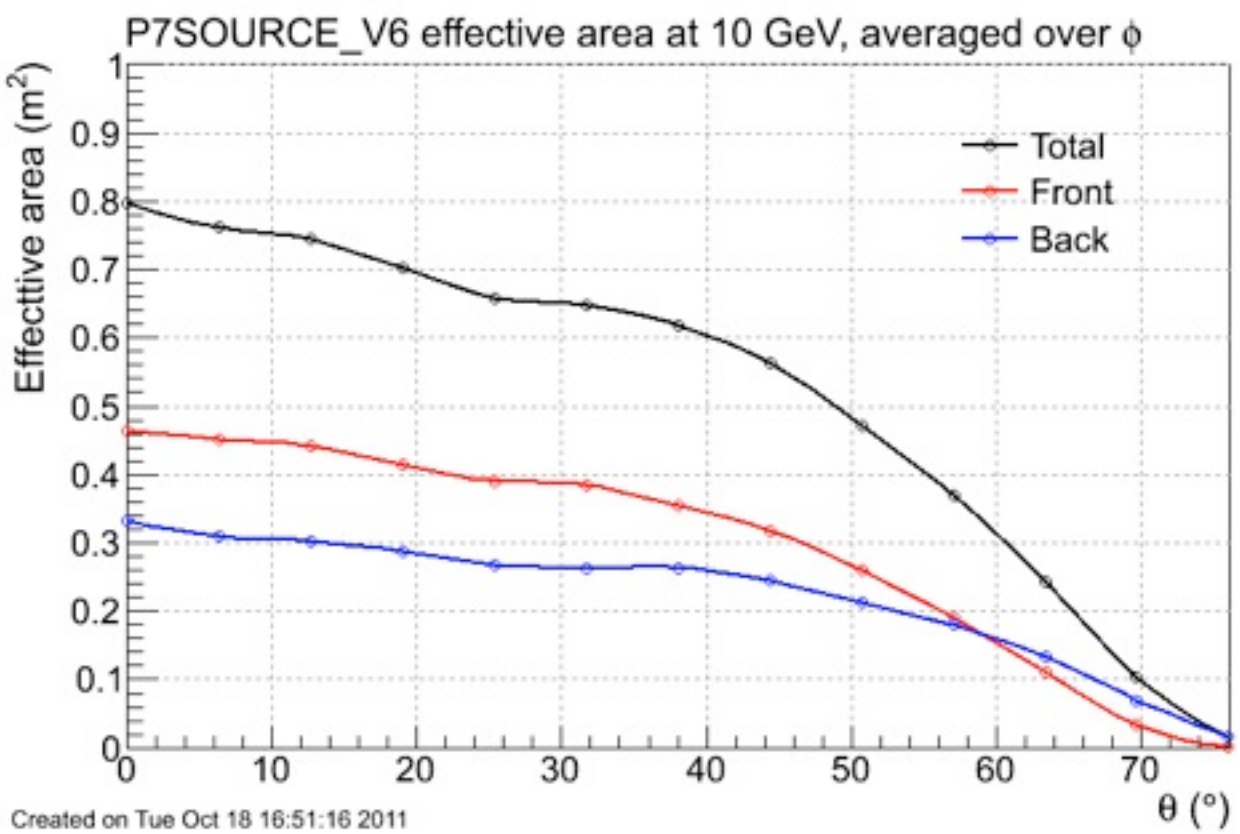
Open the exposure map in ds9 and you should see something like this.

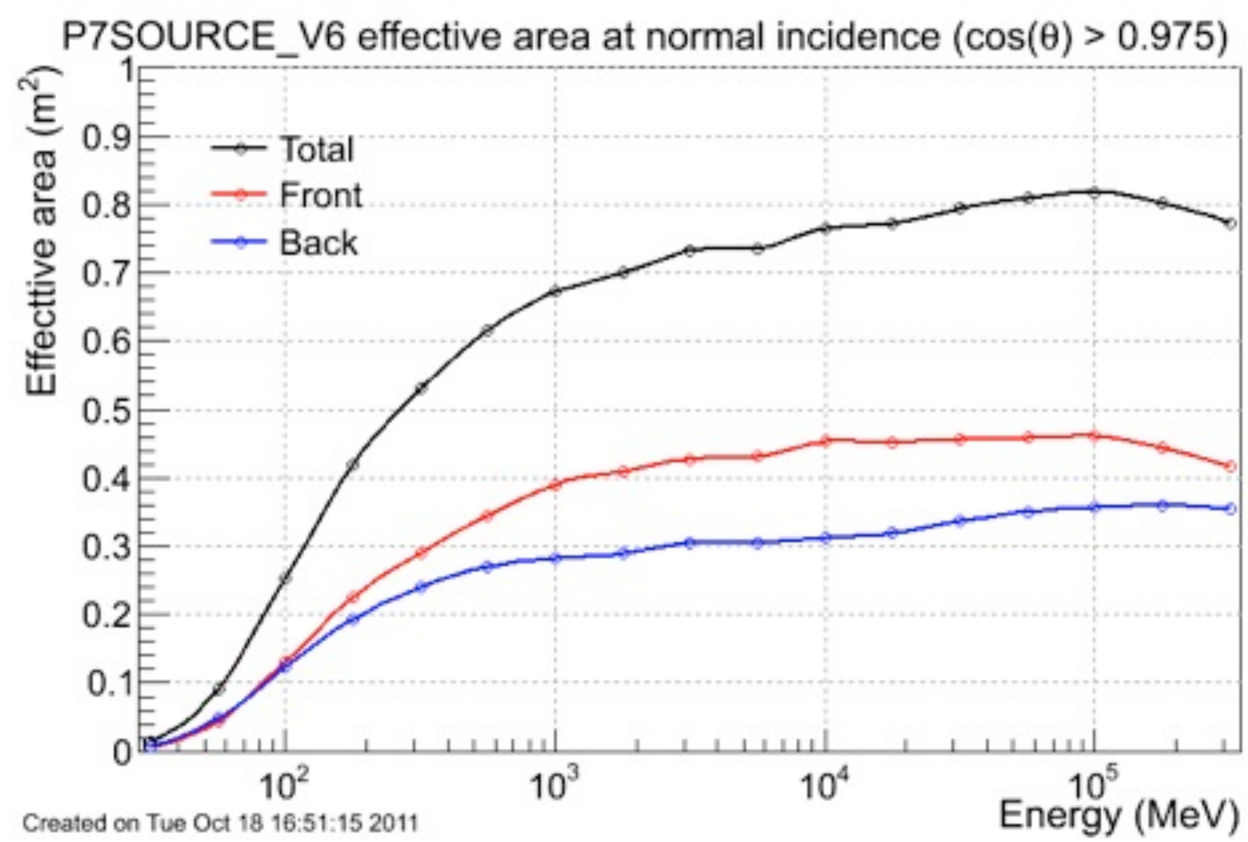


Exposure

- For a position in the sky fold the time spent in each part of the field of view (from livetime cube) with the detector efficiency for that position

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm





P7SOURCE_V6 effective area is parameterized in theta and energy

Go to the LAT performance page here and show some other information.

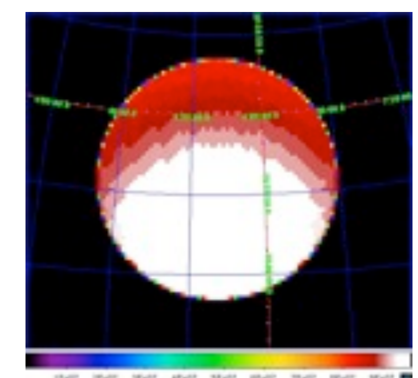
Binning Caveats

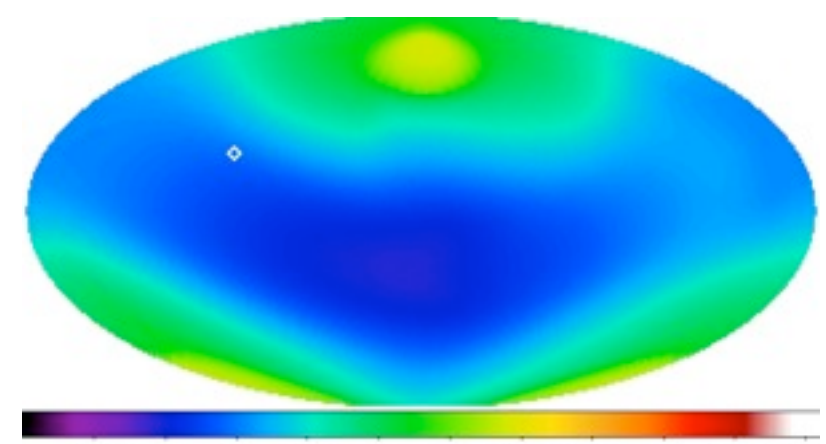
- Response functions are minimally parameterized in the inclination angle (theta) and energy
    - Bin or step sizes used in exposure calculations should consider how quickly the efficiency changes in space or energy
        - At least 10 bins per decade in energy to avoid errors in estimation where the effective area changes rapidly
        - No single, strict recommendation on spatial binning
            - 1 deg default sufficient for making maps
            - Binned likelihood matched to data binning - see threads
    - gtexposure invokes a spectral assumption - this has a noticeable impact
        - Remember that both the efficiency and angular reconstruction depend on energy

Exposure Applications

- Each type of analysis has a dedicated method to provide the exposure correction in the appropriate form
  - Aperture lightcurve ⇒ gtexposure
  - Unbinned likelihood ⇒ gtexpmap
  - Binned likelihood ⇒ gtsrcmaps/ gtexpcube
  - All-sky exposure maps ⇒ gtexpcube

xxx cm^2 s





If you want to get started on binned analysis tonight, you’ll need to run gtscrmaps/gtexpcube. Look at the FSSC website for details (we’ll go over this tomorrow).

Practical Usage:

```
prompt> gtexpmap
The exposure maps generated by this tool are meant
to be used for *unbinned* likelihood analysis only.
Do not use them for binned analyses.
Event data file[] 3C279_events_gti.fits
Spacecraft data file[] L110729150643E0D2F37E79_SC00.fits
Exposure hypercube file[] 3C279_ltcube.fits
output file name[] 3C279_expmap.fits
Response functions[] P7SOURCE_V6
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 3C279_ltcube.fits
.....................!
prompt>
```

Event Selection Menu

http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html

Analysis Type	Minimum Energy (emin)	Maximum Energy (emax)	Max Zenith Angle (zmax)	Event Class (evclass)	IRF Name
Galactic Point Source Analysis	100 (MeV)	-	100(degrees)	2	P7SOURCE_V6
Off-plane Point Source Analysis	100 (MeV)	-	100 (degrees)	2	P7SOURCE_V6
Burst and Transient Analysis (<200s)	100 (MeV)	-	100 (degrees)	0	P7TRANSIENT_V6
Galactic Diffuse Analysis	100 (MeV)	100000 (MeV)	100 (degrees)	2	P7SOURCE_V6
Extra-Galactic Diffuse Analysis	100 (MeV)	100000 (MeV)	100 (degrees)	3	P7CLEAN_V6

Time Selection Menu

http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html

Analysis Type	ROI-Based Zenith Angle Cut (roicut)	Relational Filter Expression (filter)
Galactic Point Source Analysis	yes	(DATA_QUAL==1)&&(LAT_CONFIG==1)&&ABS(ROCK_ANGLE)<52
Off-plane Point Source Analysis	yes	(DATA_QUAL==1)&&(LAT_CONFIG==1)&&ABS(ROCK_ANGLE)<52
Burst and Transient Analysis	yes	(DATA_QUAL>0)&&(LAT_CONFIG==1)&&ABS(ROCK_ANGLE)<52
Galactic Diffuse Analysis	no**	(DATA_QUAL==1)&&(LAT_CONFIG==1)&&ABS(ROCK_ANGLE)<52
Extra-Galactic Diffuse Analysis	no**	(DATA_QUAL==1)&&(LAT_CONFIG==1)&&ABS(ROCK_ANGLE)<52

** An exposure correction must be made using the zmax option in gtltcube

Now...

- We're going to perform a full likelihood analysis of a small data set.
- Here's the summary from yesterday about what's going to happen theoretically, the following tutorial will be hands on and explain how we actually do the steps.

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- Calculate the TS:

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

The model includes all of the information: the physical model of the sky folded with the pointing and livetime history and IRFs.

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Point Sources | Galactic & EG Diffuse Sources | Other Sources

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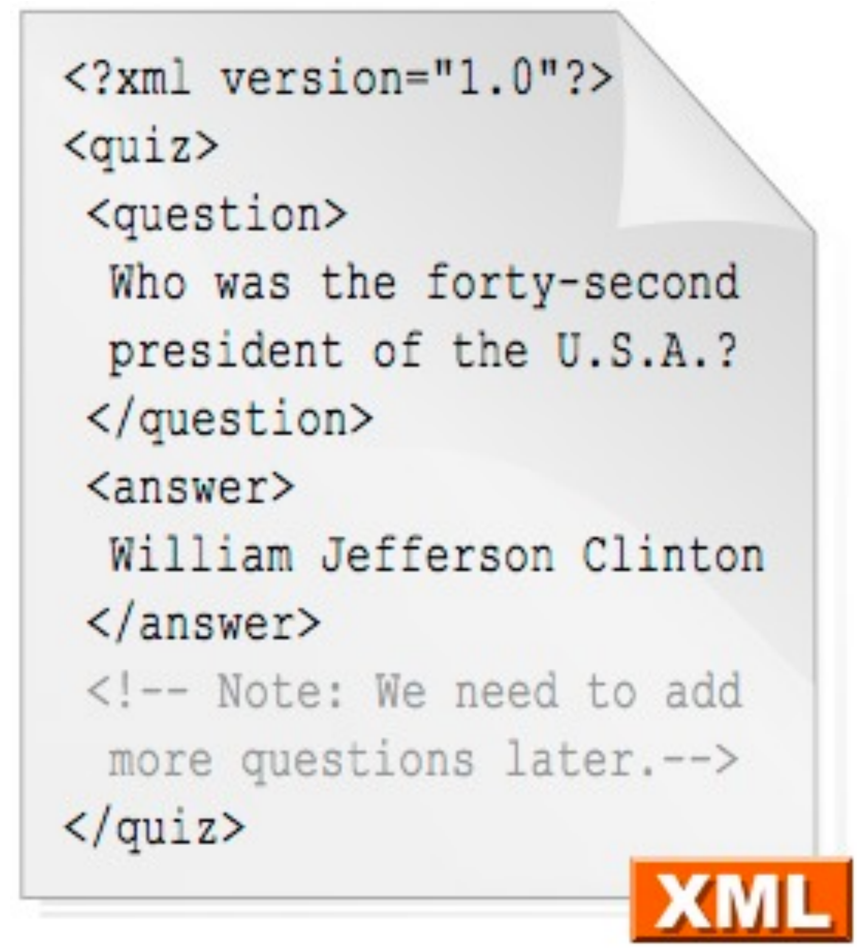
The Model File

We describe our region in a computer readable document called an XML file.
XML (eXtensible Markup Language) is just a set of rules to encode information in a text file.



Download this now:

http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/data/Likelihood/3C279_input_model.xml

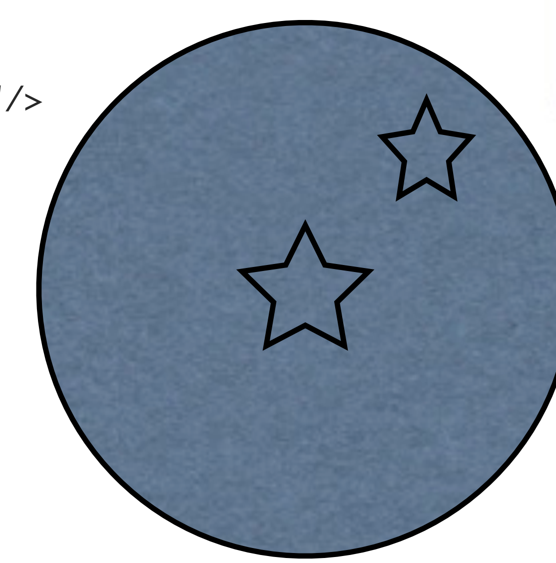
A very simple LAT XML Model file.

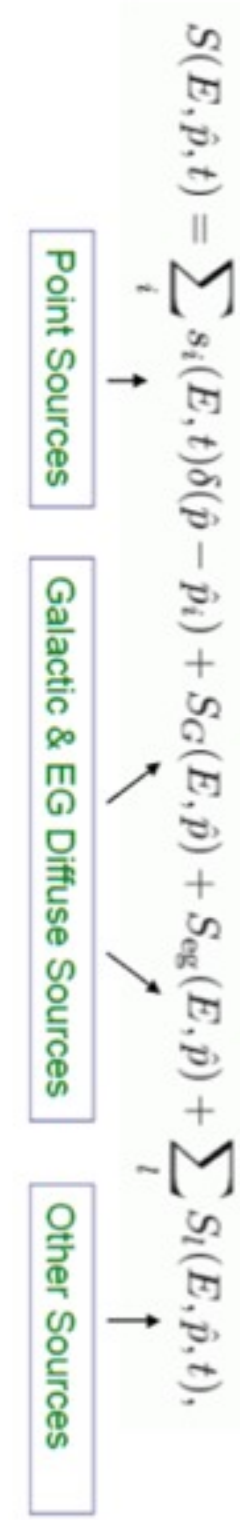
```
<?xml version="1.0" ?>
<source_library title="source library" xmlns="http://fermi.gsfc.nasa.gov/source_library">

<source name="iso_p7v6source" type="DiffuseSource">
<spectrum file="iso_p7v6source.txt" type="FileFunction">
<parameter free="1" max="1000" min="1e-05" 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>

<source name="gal_2yearp7v6_v0" type="DiffuseSource">
<spectrum type="ConstantValue">
<parameter free="1" max="10.0" min="0.0" name="Value" scale="1.0" value= "1.0"/>
</spectrum>
<spatialModel file="gal_2yearp7v6_v0.fits" type="MapCubeFunction">
<parameter free="0" max="1000.0" min="0.001" name="Normalization" scale= "1.0" value="1.0"/>
</spatialModel>
</source>

<source name="3C 273" type="PointSource">
<spectrum type="PowerLaw">
<parameter free="1" max="1000.0" min="0.001" name="Prefactor" scale="1e-09" value="10"/>
<parameter free="1" max="-1.0" min="-5.0" name="Index" scale="1.0" value="-2.1"/>
<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="360" min="-360" name="RA" scale="1.0" value="187.25"/>
<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="2.17"/>
</spatialModel>
</source>

<source name="3C 279" type="PointSource">
<spectrum type="PowerLaw">
<parameter free="1" max="1000.0" min="0.001" name="Prefactor" scale="1e-09" value="10"/>
<parameter free="1" max="-1.0" min="-5.0" name="Index" scale="1.0" value="-2"/>
<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="360" min="-360" name="RA" scale="1.0" value="193.98"/>
<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-5.82"/>
</spatialModel>
</source>

</source_library>
```

Isotropic Diffuse.

Galactic Diffuse.

Point Sources





Make sure you copy (or link) the diffuse models into your working directory or put full paths here.

Link the diffuse models to your local directory:

```
$> ln -s $FERMI_DIR/refdata/fermi/galdiffuse/gal_2yearp7v6_v0.fits

$> ln -s $FERMI_DIR/refdata/fermi/galdiffuse/iso_p7v6source.txt
```

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Practical Usage

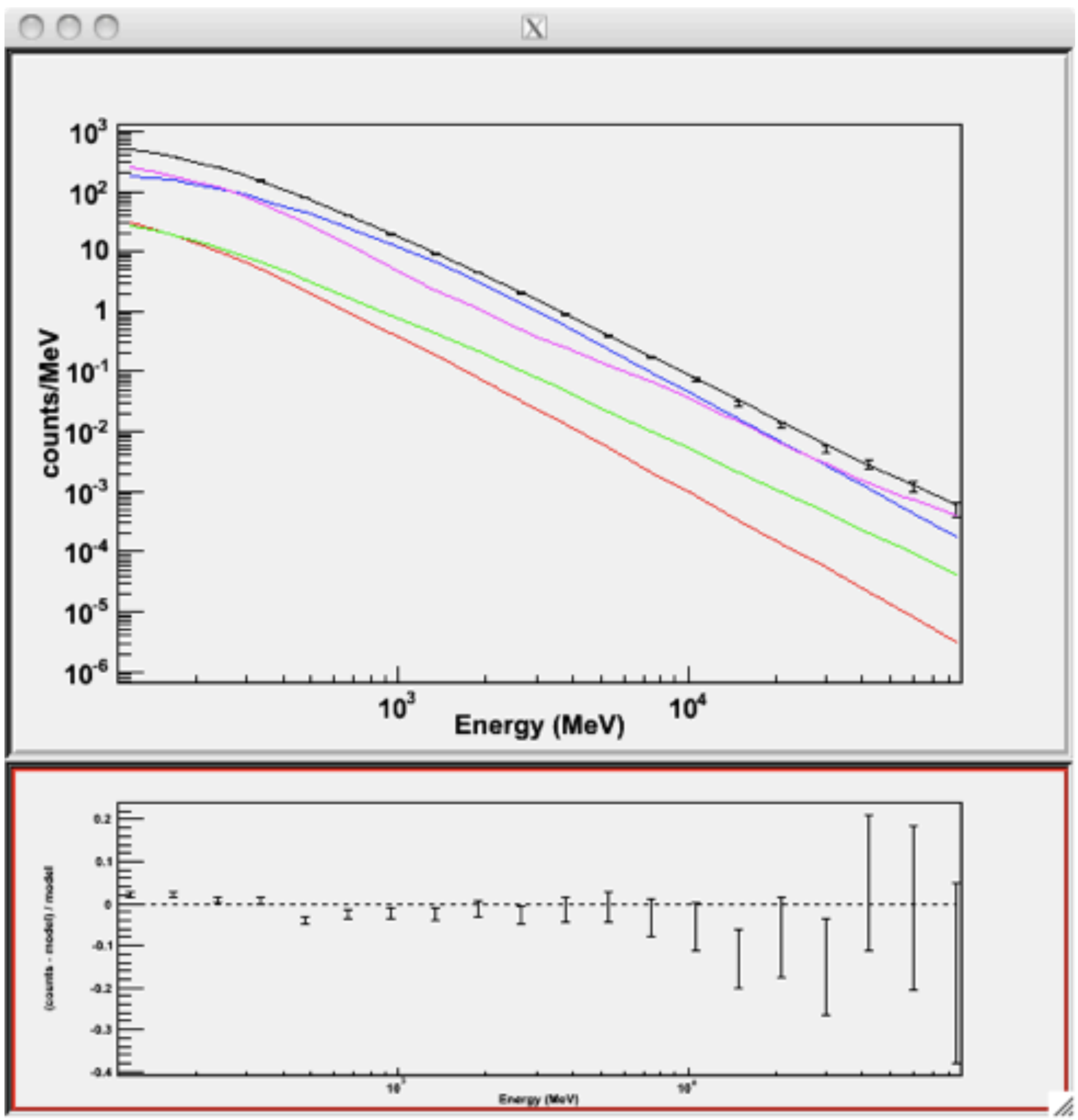
```
prompt> gtlike refit=yes plot=yes sfile=3C279_output_model.xml
Statistic to use (BINNED|UNBINNED) [] UNBINNED
Spacecraft file[] L110729150643E0D2F37E79_SC00.fits
Event file[] 3C279_events_gti.fits
Unbinned exposure map[] 3C279_expmap.fits
Exposure hypercube file[] 3C279_ltcube.fits
Source model file[] 3C279_input_model.xml
Response functions to use[] P7SOURCE_V6
Optimizer (DRMNFB|NEWMINUIT|MINUIT|DRMNGB|LBFGS) [] NEWMINUIT
```

Output

```
Minuit did successfully converge.
# of function calls: 118

(MUCH OUTPUT OMITTED.)

Computing TS values for each source (4 total)
....!

Photon fluxes are computed for the energy range 100 to 100000 MeV

3C 273:
Prefactor: 10.692 +/- 0.35955
Index: -2.66054 +/- 0.0249551
Scale: 100
Npred: 4711.6
ROI distance: 10.4409
TS value: 5468.7
Flux: 6.46428e-07 +/- 1.54052e-08 photons/cm^2/s

3C 279:
Prefactor: 8.50142 +/- 0.260389
Index: -2.24255 +/- 0.0169226
Scale: 100
Npred: 5771.43
ROI distance: 0
TS value: 10089.2
Flux: 6.86084e-07 +/- 1.44749e-08 photons/cm^2/s

gal_2yearp7v6_v0:
Value: 1.34998 +/- 0.016086
Npred: 59713.3
Flux: 0.00065192 +/- 7.76906e-06 photons/cm^2/s

iso_p7v6source:
Normalization: 1.01688 +/- 0.0144232
Npred: 51427.7
Flux: 0.00021073 +/- 2.98875e-06 photons/cm^2/s

WARNING: Fit may be bad in range [100, 199.526] (MeV)
WARNING: Fit may be bad in range [398.107, 794.328] (MeV)

Total number of observed counts: 121624
Total number of model events: 121624

-log(Likelihood): 1330050.195

Writing fitted model to 3C279_output_model.xml
```

You should save this output to a text file....

More Output



- Black - summed model
- Red - first source
- Green - second source
- Blue - third source
- Magenta - fourth source
- Cyan - the fifth source

(‘plot = yes’ option)

Even More Output...

- results.dat: summary of the analysis
- counts_spectra.fits: the plots above
- 3C279_output_model.xml: the final (maximum liklihood) model.

Open all of these and take a look at them now.

The 2FGL

- http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

LAT 2-year Point Source Catalog

The Fermi Gamma-ray Space Telescope (Fermi) Large Area Telescope (LAT) is a successor to EGRET, with greatly improved sensitivity, resolution, and energy range. This web page presents the second full catalog of LAT sources, based on the first 24 months of survey data. For a full explanation about the catalog and its construction see the LAT 2-year Catalog Paper draft on arxiv.

The source designation is 2FGL JHHMM.m+DDMM(c,e) where the 2 refers to the second catalog (one was released at 1 year, and another is planned for after 5 years) and FGL represents Fermi Gamma-ray LAT. The optional "c" and "e" designators are explained in the caveats below.

LAT Catalog Data Products

The LAT 2-year Point Source Catalog is currently available as a FITS file, as an XML model file to be used for data analysis within the Fermi Science Tools, and as a BROWSE table. Supporting tools and documentation have been provided and are linked below.

It is important that all users of this catalog review the caveats listed below the catalog links. These describe the content of the catalog at a high level, as well as some cautions for the user.

- LAT 2-year Point Source Catalog (FITS format)
- LAT 2-year Catalog column descriptions
- LAT 2-year Point Source Catalog (BROWSE table)
- LAT 2-year Catalog Paper draft
  - Full content of Table 3 (Main source table)
  - Full content of Table 6 (Fluxes in bands)
- XML Model File for LAT 2-year Catalog
- DS9 Region Files:
  - 2FGL positions (as crosses) and source names
  - 2FGL positions (as crosses) and association names
  - 2FGL 95% error ellipses (no source names)
- Extended Source template archive – Gzipped archive of extended source templates used in the catalog analysis.
- Python tool – to convert FITS information to XML

FITS File

Browse Table

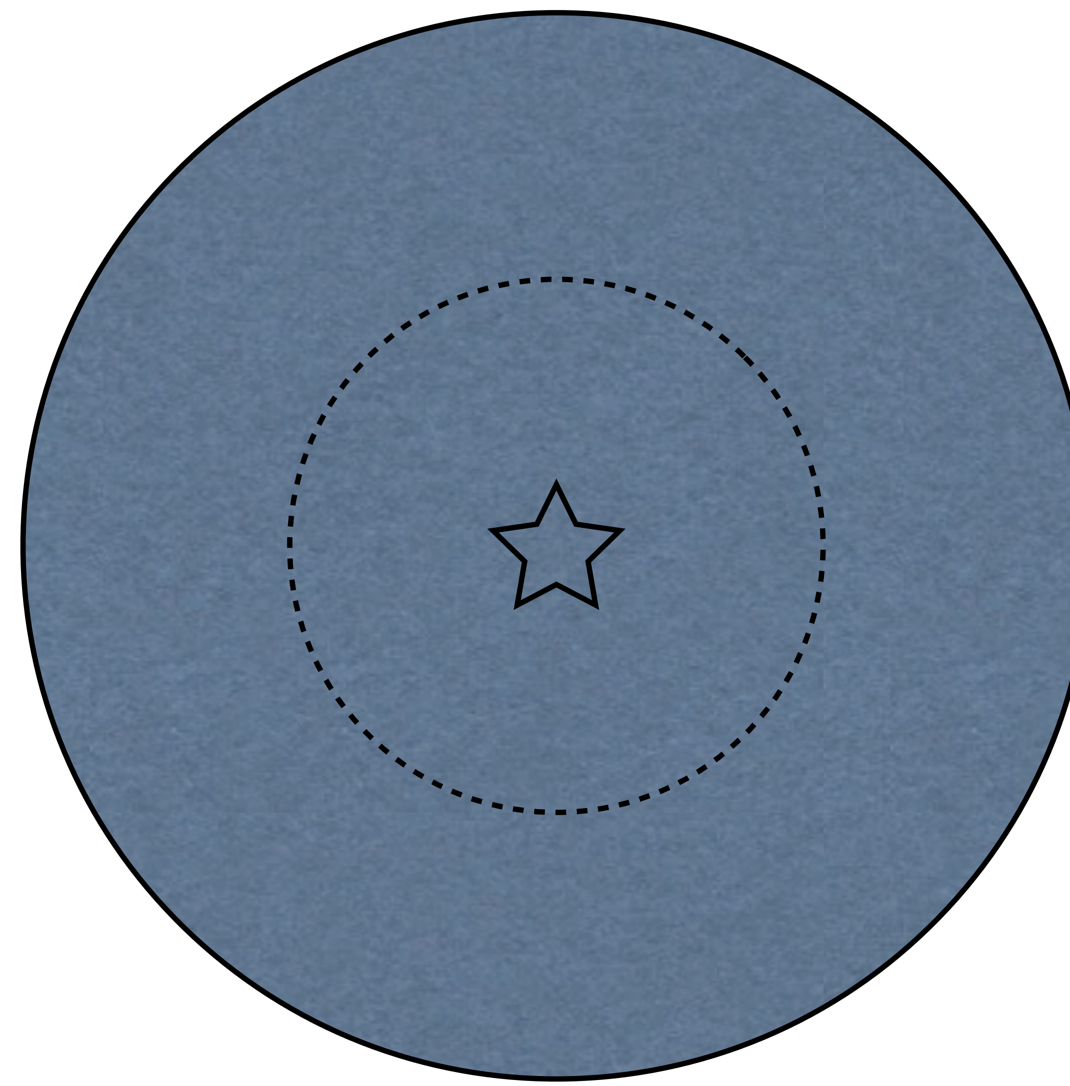
XML File

DS9 Reg File

Go to the browse table now and do a quick search.

Generating a model

- It's easiest to start from the 2FGL and include all sources within your ROI (set these free, ie, the optimizer can change these).
- You'll also want to include sources up to 5/10 degrees (depends on energy) outside your ROI because of the 'bleed in' effect (set these as fixed to their 2FGL values).



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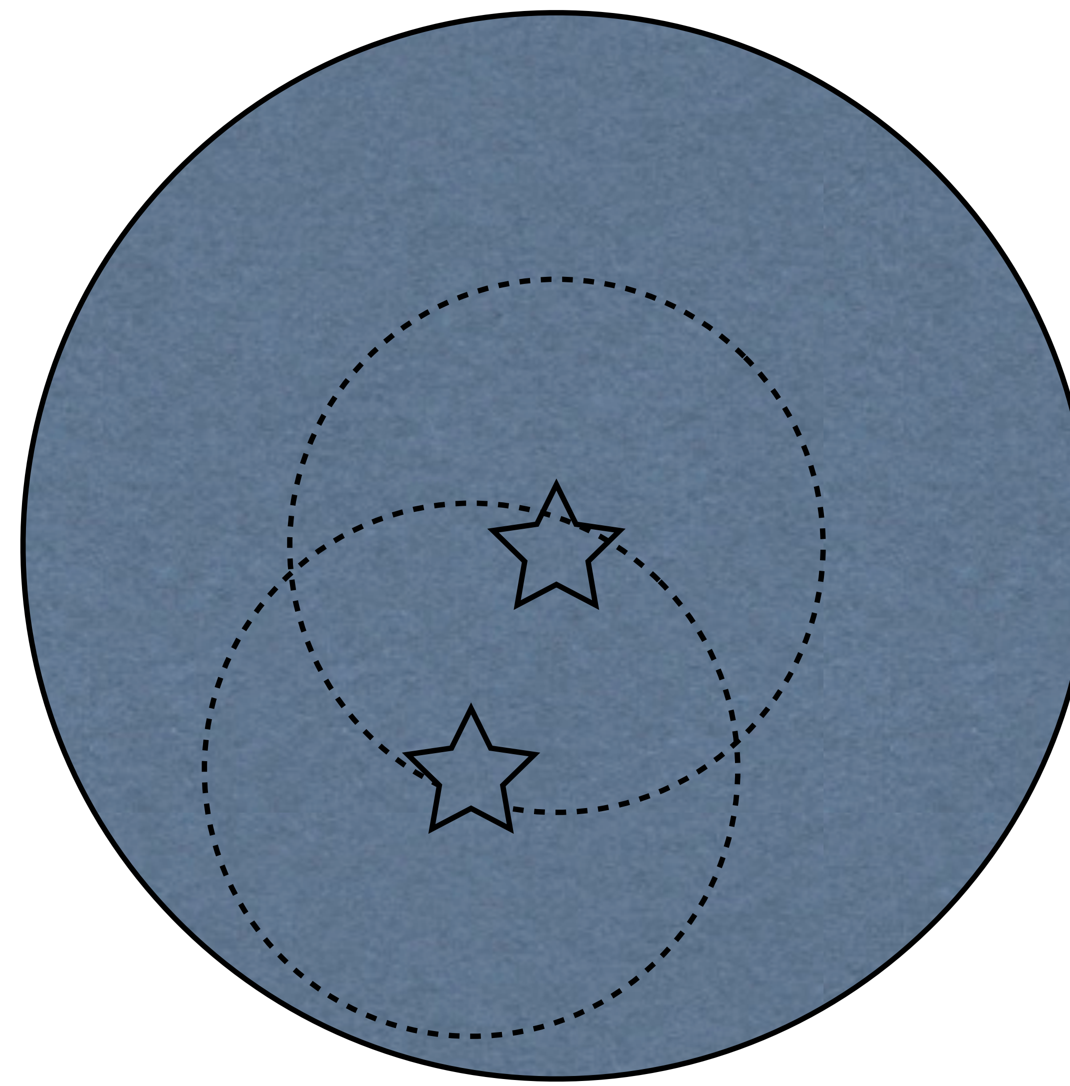
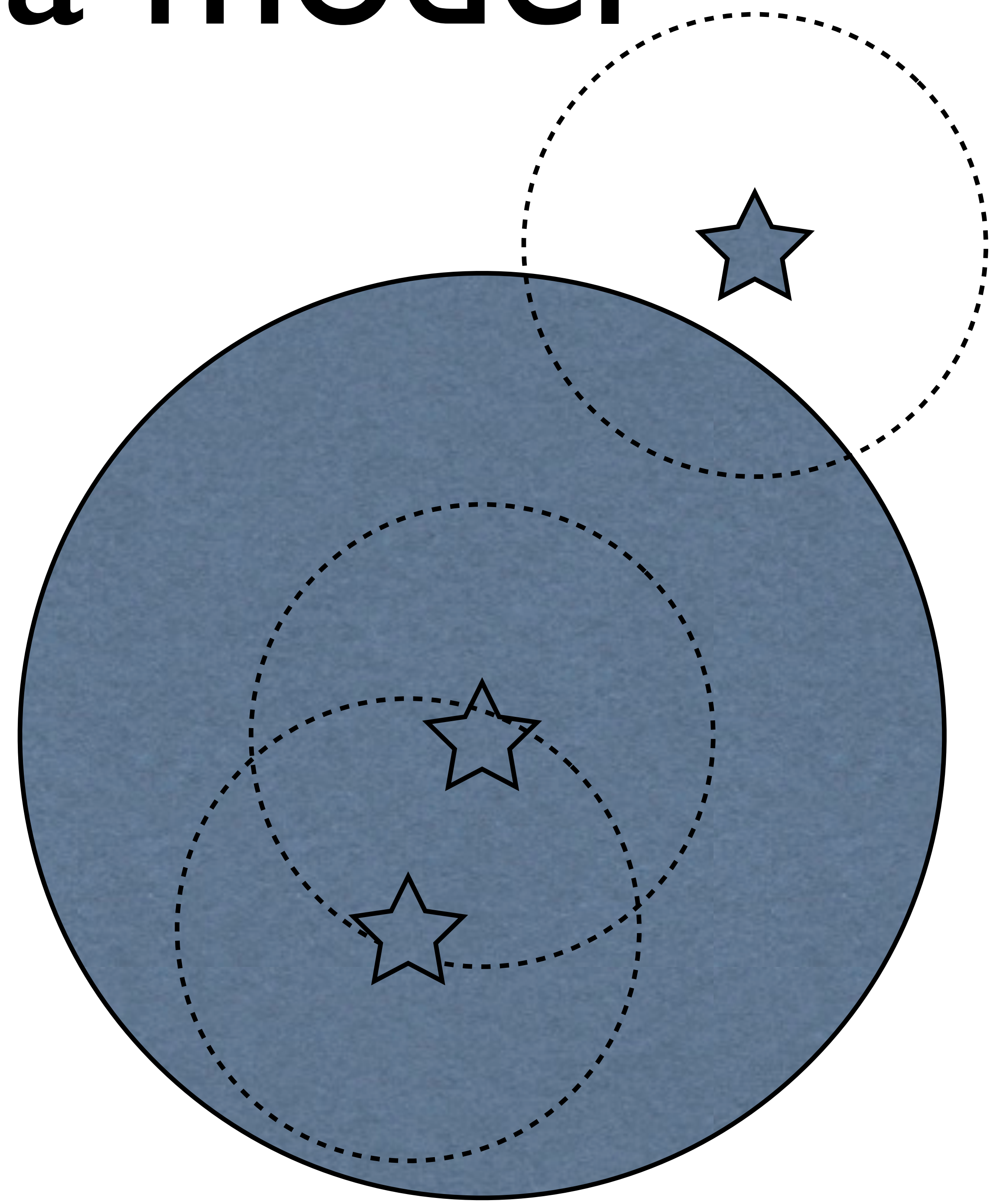


Generating a model

- It's easiest to start from the 2FGL and include all sources within your ROI (set these free, ie, the optimizer can change these).
- You'll also want to include sources up to 5/10 degrees (depends on energy) outside your ROI because of the 'bleed in' effect (set these as fixed to their 2FGL values).



Finding the Sources

- You could do this from the browse table and then cut and past from the full XML file but someone has done the hard work for you.
- Use the make2FGLxml python script that's in the user contributed tools section of the FSSC website.
- You need to have already downloaded your data and run gtselect on it.
- Copy the make2FGLxml.py file and the gll_psc_v06.fit file into your working directory. Also make sure the diffuse models are there (should be if you did the previous steps correctly).

make2FGLxml

```
prompt> python
Python 2.7.2 (default, Apr 10 2012, 10:33:45)
[GCC 4.2.1 (Apple Inc. build 5666) (dot 3)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> from make2FGLxml import *
This is make2FGLxml version 04r1.
For use with the gll_psc_v02.fit and gll_psc_v05.fit and later LAT catalog files.
>>> mymodel = srcList('gll_psc_v07.fit','3C279_events_gti.fits','3C279_model.xml')
>>> mymodel.makeModel('gal_2yearp7v6_v0.fits', 'gal_2yearp7v6_v0',
'iso_p7v6source.txt', 'iso_p7v6source')
Creating file and adding sources for 2FGL
Added 83 point sources and 0 extended sources
```

83 Sources!

Open the model file...

1. less


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

<!-- Point Sources -->

<!-- Sources between [0.0,5.0) degrees of ROI center -->
<source name="_2FGLJ1256.1-0547" type="PointSource">
	<spectrum type="LogParabola">
	<!-- Source is 0.0674145209519 degrees away from ROI center -->
		<parameter free="1" max="1e4" min="1e-4" name="norm" scale="1e-10" value="6.36375285801"/>
		<parameter free="1" max="5.0" min="0.0" name="alpha" scale="1.0" value="2.22124"/>
		<parameter free="1" max="10.0" min="0.0" name="beta" scale="1.0" value="0.0713682"/>
		<parameter free="0" max="5e5" min="30" name="Eb" scale="1.0" value="294.806"/>
	</spectrum>
	<spatialModel type="SkyDirFunction">
		<parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="194.042"/>
		<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-5.79369"/>
	</spatialModel>
</source>
<source name="_2FGLJ1313.0-0425" type="PointSource">
	<spectrum type="PowerLaw">
	<!-- Source is 4.4846126869 degrees away from ROI center -->
		<parameter free="1" max="1e4" min="1e-4" name="Prefactor" scale="1e-13" value="7.25251781374"/>
		<parameter free="1" max="5.0" min="0.0" name="Index" scale="-1.0" value="2.36892"/>
		<parameter free="0" max="5e5" min="30" name="Scale" scale="1.0" value="916.748657"/>
	</spectrum>
	<spatialModel type="SkyDirFunction">
		<parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="198.259"/>
		<parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-4.4234"/>
	</spatialModel>
</source>

<!-- Sources between [5.0,10.0) degrees of ROI center -->
<source name="_2FGLJ1219.8-0310" type="PointSource">
	<spectrum type="PowerLaw">
	<!-- Source is 9.38148672434 degrees away from ROI center -->
```


3C279

Free Bkgrnd Source

Closer Look at 3C279..

Source Type
(Point Source)

```
<source name="_2FGLJ1256.1-0547" type="PointSource">
        <spectrum type="LogParabola">
        <!-- Source is 0.0674145209519 degrees away from ROI center -->
                <parameter free="1" max="1e4" min="1e-4" name="norm" scale="1e-10" value="6.36375285801"/>
                <parameter free="1" max="5.0" min="0.0" name="alpha" scale="1.0" value="2.22124"/>
                <parameter free="1" max="10.0" min="0.0" name="beta" scale="1.0" value="0.0713682"/>
                <parameter free="0" max="5e5" min="30" name="Eb" scale="1.0" value="294.806"/>
        </spectrum>
        <spatialModel type="SkyDirFunction">
                <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="194.042"/>
                <parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-5.79369"/>
        </spatialModel>
</source>
```

Sky Location
(Fixed)

Spectrum,
(not a power law!)

Types of Spatial/Spectral Models

http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source_models.html

http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/xml_model_defs.html

- **Spectral Models:**
  - PowerLaw (1 and 2)
  - BrokenPowerLaw (1 and 2)
  - SmoothBrokenPowerLaw
  - LogParabola
  - ExpCutoff
  - BPLExpCutoff
  - PLSuperExpCutoff
  - ConstantValue
  - Gaussian
  - BandFunction
  - FileFunction
- **Spatial Models**
  - SkyDirFunction
  - ConstantValue
  - SpatialMap
  - MapCubeFunction

Scroll Down...

1. less


```
                <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="212.208"/>
                <parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-7.86593"/>
        </spatialModel>
</source>

<!-- Sources between [20.0,25.0] degrees of ROI center -->
<source name="_2FGLJ1121.5-0554" type="PointSource">
        <spectrum type="PowerLaw">
        <!-- Source is 23.467844161 degrees away from ROI center -->
        <!-- Source is outside ROI, all parameters should remain fixed -->
                <parameter free="0" max="1e4" min="1e-4" name="Prefactor" scale="1e-11" value="1.18582027878"/>
                <parameter free="0" max="5.0" min="0.0" name="Index" scale="-1.0" value="2.29972"/>
                <parameter free="0" max="5e5" min="30" name="Scale" scale="1.0" value="690.665527"/>
        </spectrum>
        <spatialModel type="SkyDirFunction">
                <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="170.387"/>
                <parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-5.91239"/>
        </spatialModel>
</source>
<source name="_2FGLJ1126.0-0743" type="PointSource">
        <spectrum type="PowerLaw">
        <!-- Source is 22.3991912593 degrees away from ROI center -->
        <!-- Source is outside ROI, all parameters should remain fixed -->
                <parameter free="0" max="1e4" min="1e-4" name="Prefactor" scale="1e-14" value="1.80018828078"/>
                <parameter free="0" max="5.0" min="0.0" name="Index" scale="-1.0" value="1.67335"/>
                <parameter free="0" max="5e5" min="30" name="Scale" scale="1.0" value="4810.831055"/>
        </spectrum>
        <spatialModel type="SkyDirFunction">
                <parameter free="0" max="360.0" min="-360.0" name="RA" scale="1.0" value="171.502"/>
                <parameter free="0" max="90" min="-90" name="DEC" scale="1.0" value="-7.72064"/>
        </spatialModel>
</source>
<source name="_2FGLJ1129.0-0532" type="PointSource">
:
```


Outside the ROI

Fixed Bkgrnd Source

make2FGLxml.py

- Queries your data file to determine the size of your ROI
- Queries the 2FGL to find all of the sources in your ROI plus all sources 5 degrees beyond.
- Generates a properly formatted XML file that can be used in your likelihood fitting.
- Remember! The 2FGL is the '2 year Fermi Gamma-ray LAT' catalog. Not the 10-month, 1 year, 3 year etc. It is a starting place, not a final answer.

Homework

- Run a preliminary likelihood analysis on your source of interest (the one you picked yesterday).
    - At the very least, download the data and produce all of the needed files (livetime cube, exposure cube or map etc.) everything up to actually running the fit.
    - You should also generate a model for your ROI using the make2FGLxml module.

Remember, if you want to run a binned analysis you'll need to do something slightly different.