
# LAT data products and analysis capability
# Standard LAT likelihood analysis of solar flares
# LAT analysis of long duration solar flares

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# Likelihood

- 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:

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

- If we let the bin sizes get infinitesimally small, then $n_k$=0 or 1, and we are left with a product running over the number of photons (unbinned likelihood).
- log L is easier to handle, this is usually the quantity that is maximized

$$\mathcal{L} = e^{-N_{pred}} \prod_i m_i \qquad \log\mathcal{L} = \sum_i \log(m_i) - N_{pred}$$

*Mattox et al. "The likelihood analysis of EGRET data" ApJ, 1996*

# Likelihood

- **The Test Statistic is defined as:** $TS = -2\log\left(\frac{\mathcal{L}_{\max,0}}{\mathcal{L}_{\max,1}}\right)$
- **Where $L_0$ is the maximum likelihood value for a model without an additional source (the 'null hypothesis') and $L_1$ 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 a $\chi_n^2$ where *n* is the number of parameters characterizing the additional source.**
- **As a basic rule of thumb, the square root of the TS is approximately equal to the detection significance for a given source.**

# The source model

**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

**The function to maximize is:**

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

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

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

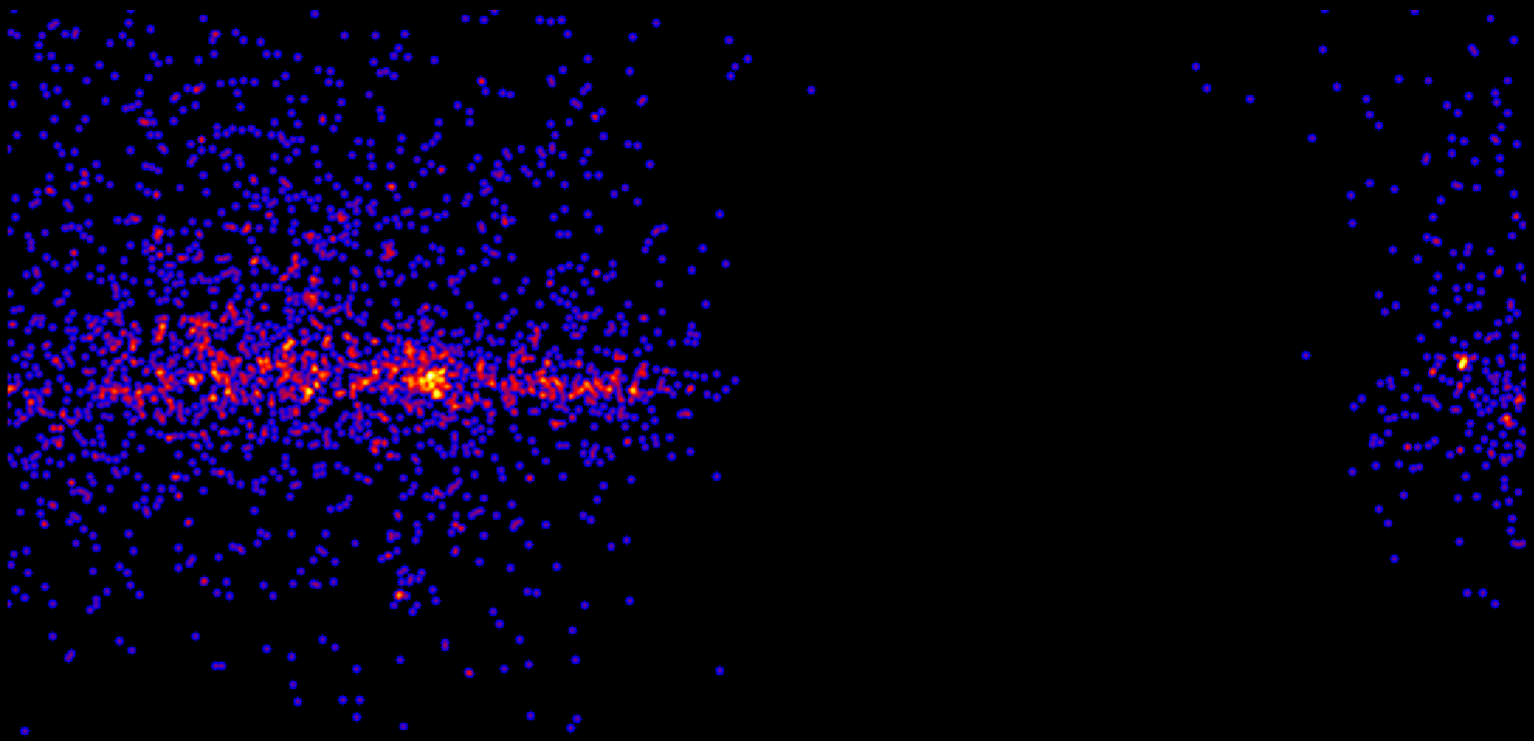
**To save CPU time, a model-independent quantity, « exposure map (*cube*)» is precomputed:**

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

**Then**

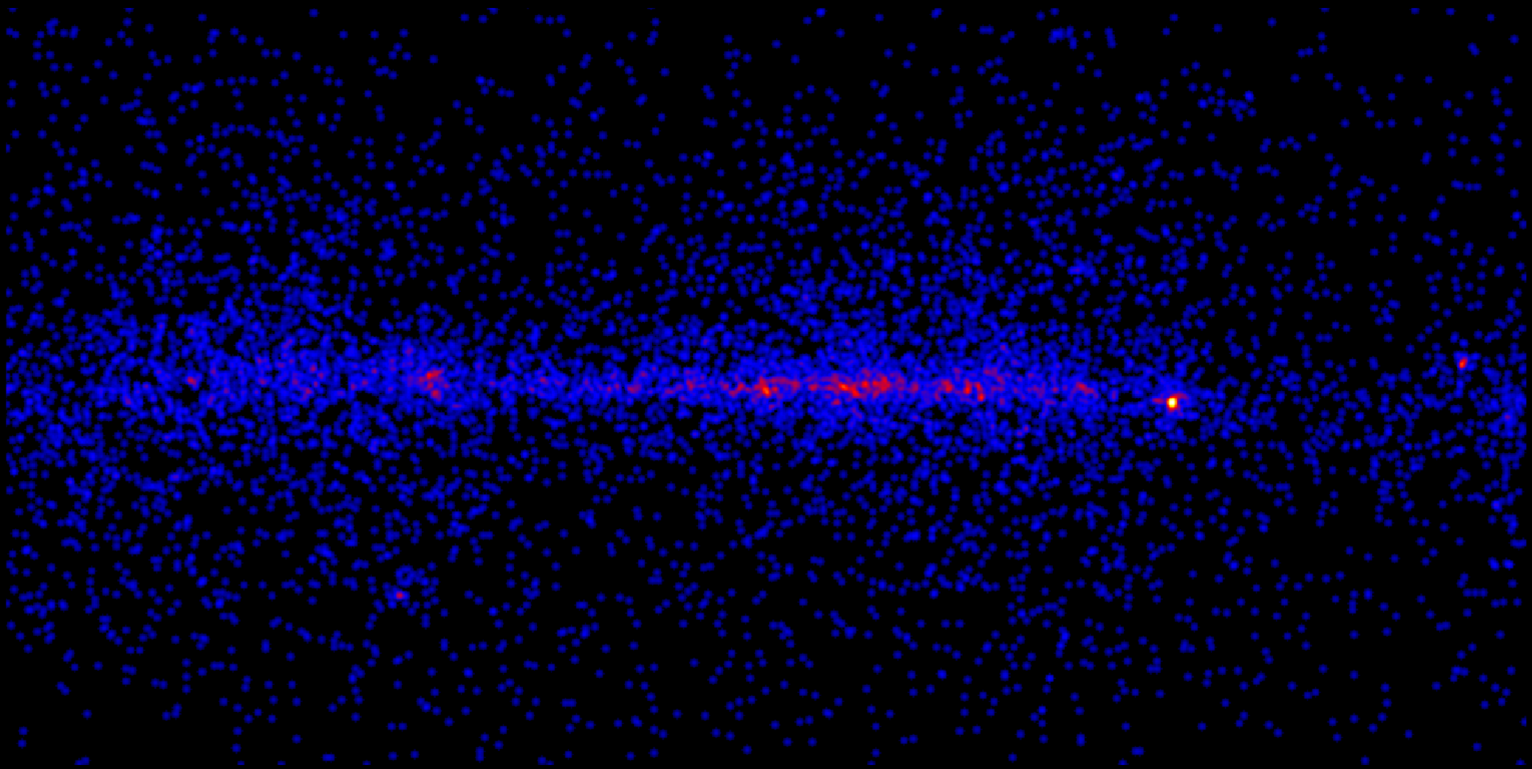
$$N_{\rm pred} = \int_{\rm SR} dE\, d\hat{p}\, S(E, \hat{p})\, \varepsilon(E, \hat{p})$$

# 1 hour



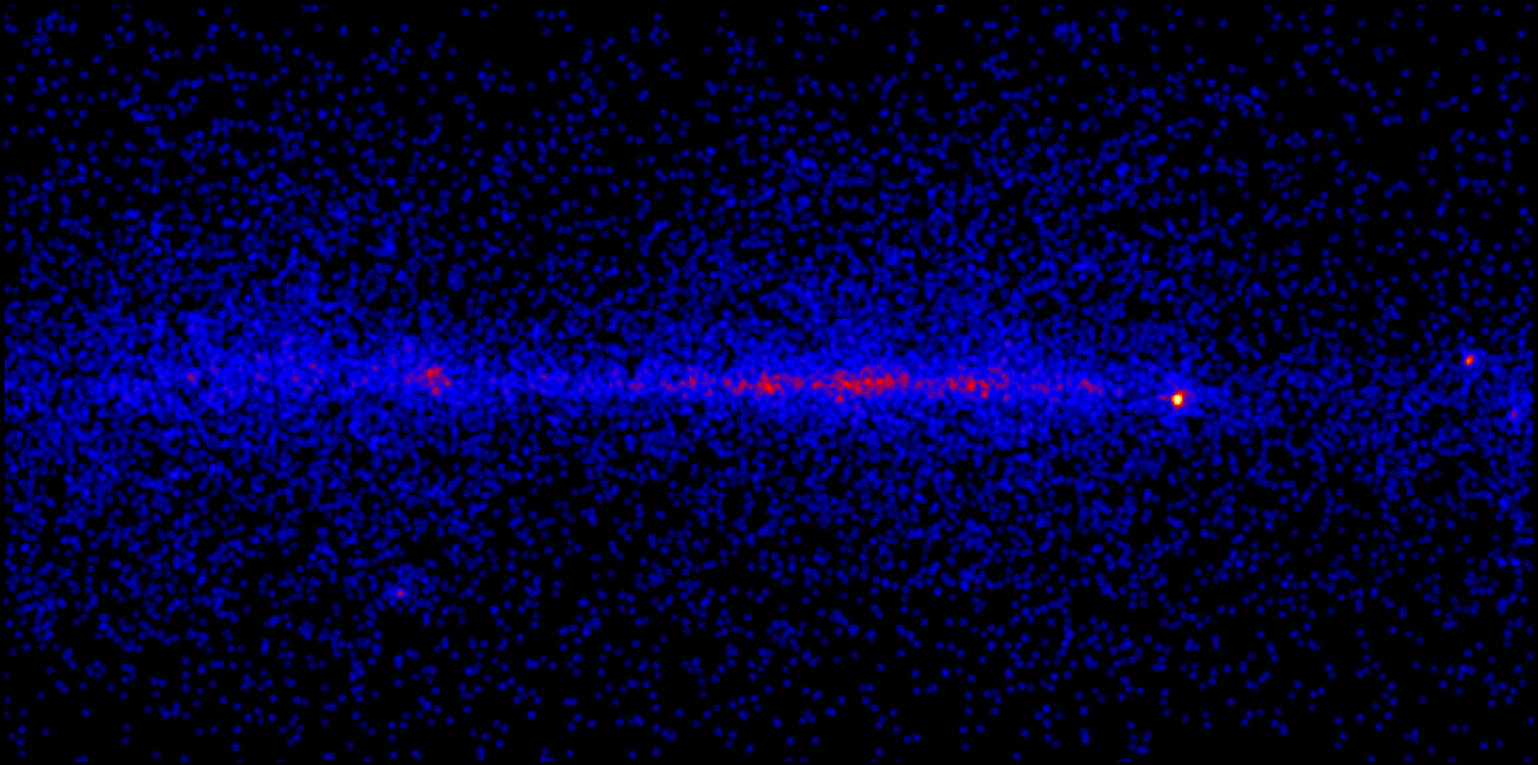
- Non uniform exposure

# 3 hours



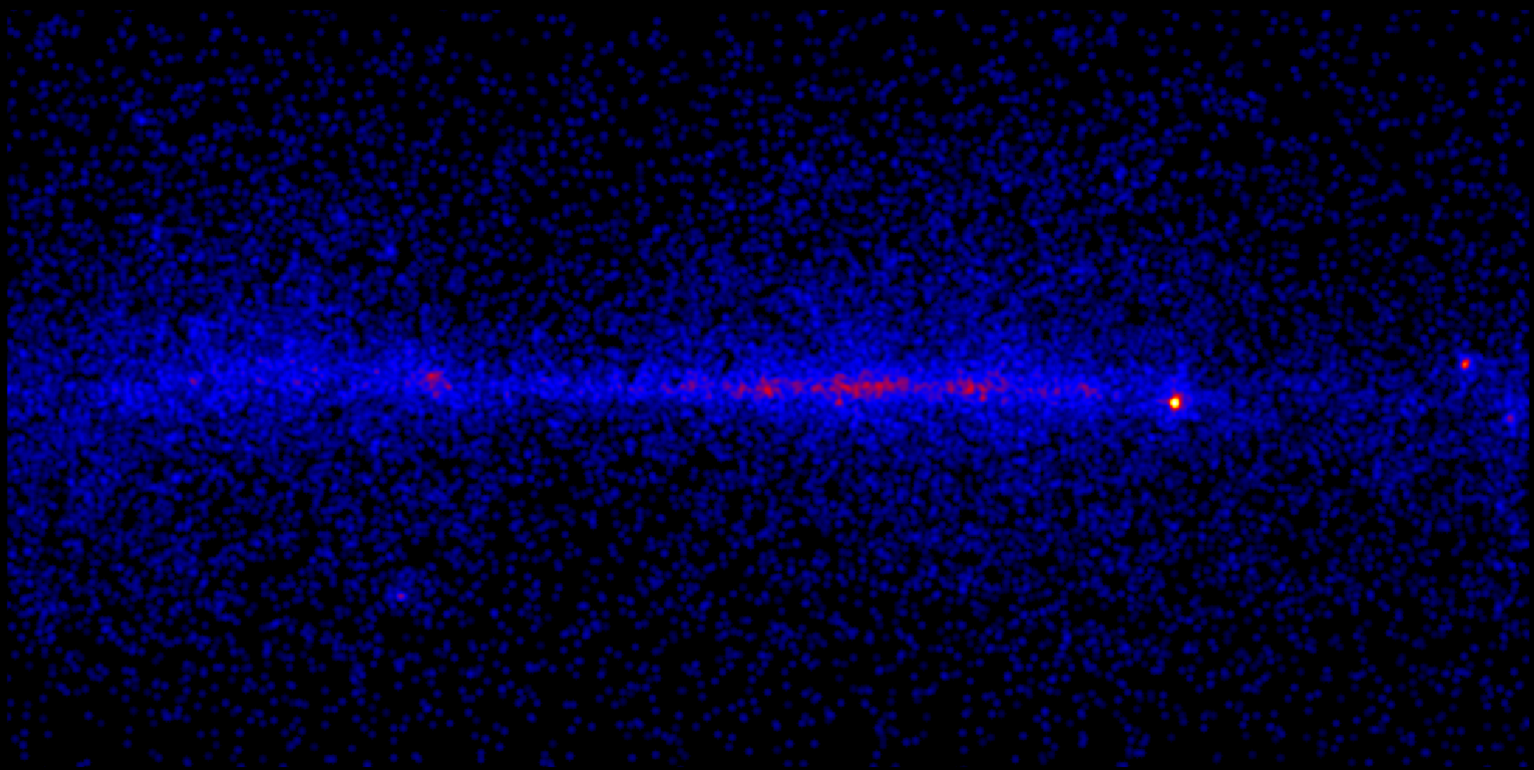
- Exposure more uniform:
- Point sources: Vela, Geminga, 3C454.3, PSR2021
- Galactic plane

# 6 hours



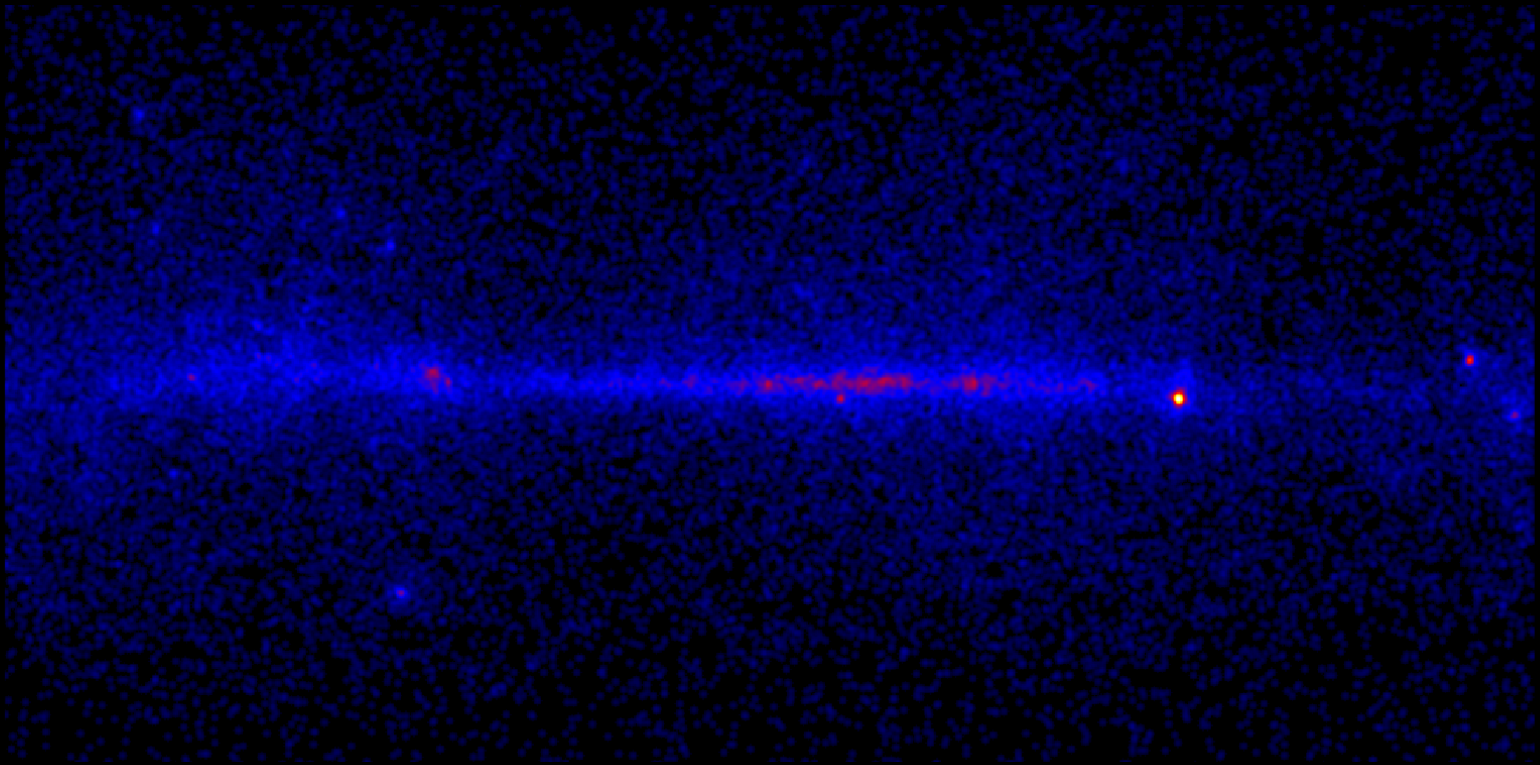
- Exposure more uniform:
- Point sources: Vela, Geminga, 3C454.3, PSR2021, Crab
- Galactic plane

# 12 hours



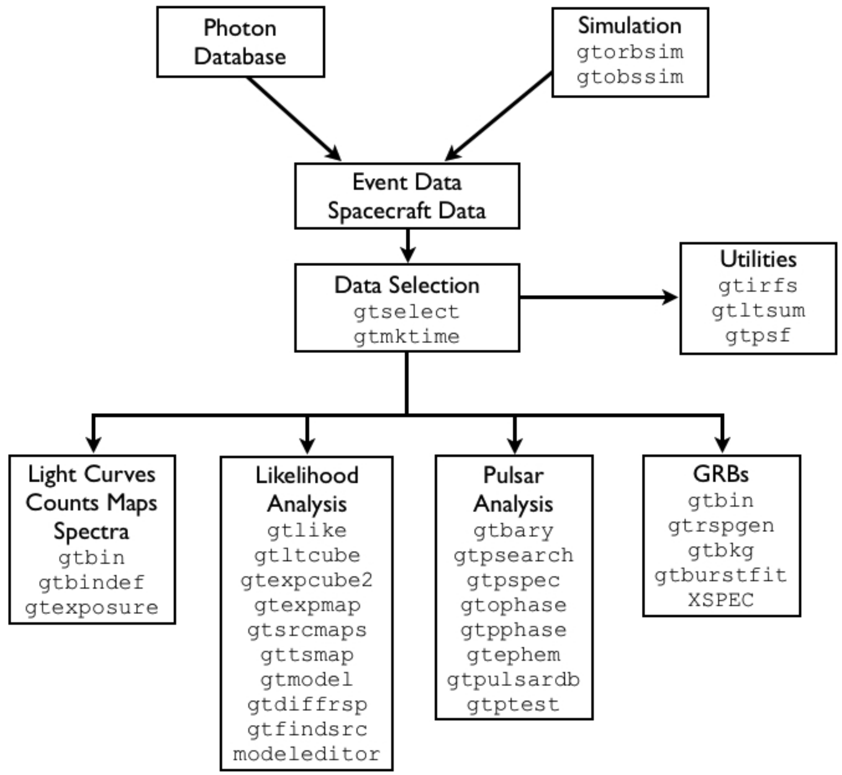
- Exposure more uniform:
- Point sources: Vela, Geminga, 3C454.3, PSR2021, Crab
- Galactic plane
- Some extragalactic sources start to be visible

# 1 day



- Exposure more uniform:
- Point sources: Vela, Geminga, 3C454.3, PSR2021, Crab
- Galactic plane
- Some extragalactic sources clearly visible

# The Fermi LAT science tools




- **Publically available at the FSSC:**
  - **http://fermi.gsfc.nasa.gov/ssc/data/analysis/**
- **Already installed in your VMBox!**

# Step of the analysis

1) select the data (gtselect, gtmktime)
2) calculate the exposure (gtltcube, gtexpmap)
3) Create a model
4) calculate the contribution of the diffuse emission components (gtdiffrsp)
5) Make a fit
6) Create the file for a fit with XSPEC, OSPEC or rmfit (new!)

# SolarTutorial

- **Get the needed files:**
- https://www.dropbox.com/sh/s8io1bq5yvk966j/3F6Rq3xTI4

- **Unpack the** SolarTutorial_src.tgz and SolarTutorial_data.tgz file into the **tools** directory.
- **tools/SolarTutorial** should look like:
  – **XSPEC/** (models for XSPEC)
  – **lleBackground/** (tool for extracting the LLE background)
  – **src/** (python code)

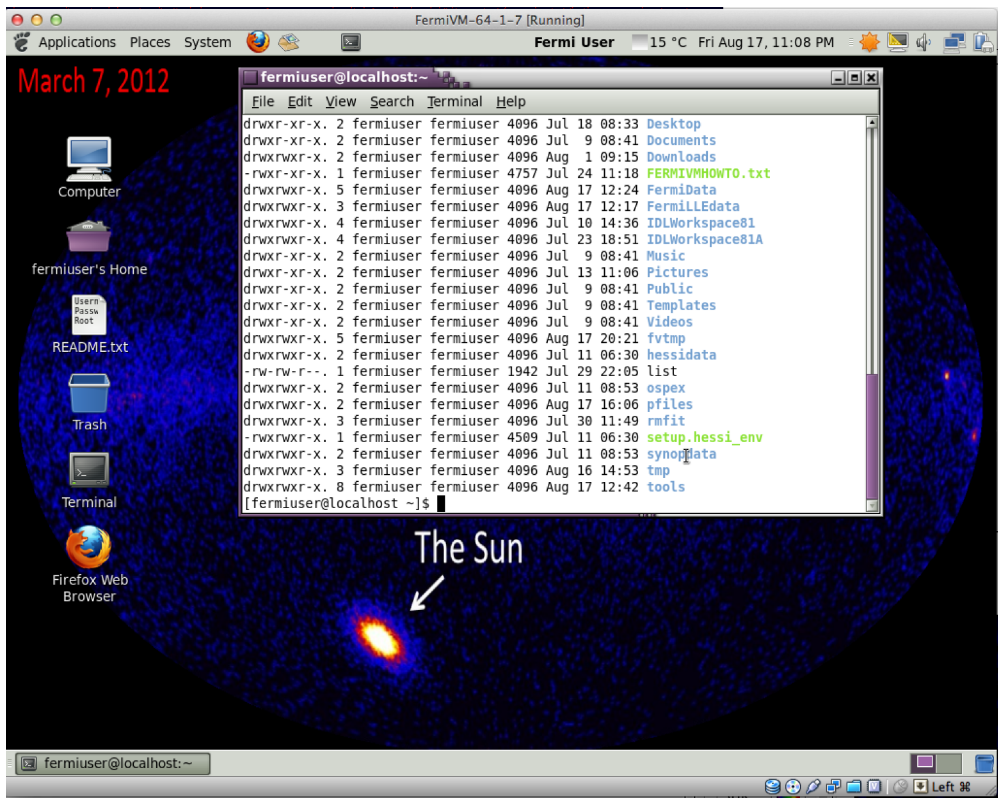
  – **data/** (data, FT1, FT2 and LLE, template file for likelihood analysis, isotropic model and galactic diffuse model)

# How to run this tutorial

1) Running each command shown in the next slides independently
2) Using the *script* in SolarTutorial/src
3) We will use the sun centered FT1 and FT2

SolarTutorial/data/lat_photon_weekly_w144_p120_v001_sun.fits

SolarTutorial/data/lat_spacecraft_weekly_w144_p01_v001.fits



# What’s in there

- ProgressBar.py* (helper function to display a progress bar…)
- SFLARE110307_analysis.py* (executable, run the analysis in different TIME bins, in equatorial coordinates)
- SFLARE110307_analysis_SC.py* (executable run the analysis in 1 time bin, in sun-centered coordinates)
- analysis.py (this is the script containing the analysis steps)
- makeProfileLikelihood.py* (Used to draw a profile likelihood, once the analysis is finished)
- myscripts.py (wrapper around ST)
- plotSED.py* (plot the SED)
- setup.sh (you can use to setup your environment (ignore for now)
- suncenter.py* (compute the sun center ft1 and ft2 files)
- sunpos.py* (compute the position of the sun)
- xspec_cmd.tcl (example of xspec command)

# Run the analysis automatically

- To run all the analysis automatically:
  - **cd tools/SolarTutorial/src**
  - ./SFLARE110307_analysis_SC.py

```
#!/usr/bin/env python
import math,os
from myscripts import *

import analysis as AN

diffuse_dir='/home/fermiuser/tools/ScienceTools-v9r27p1-fssc-20120410/external/
x86_64-unknown-linux-gnu-libc2.12/refdata/fermi/galdiffuse/'
IsoDiffuse='%s/iso_p7v6source.txt'  % diffuse_dir

AN.do(out_dir='../SF110307_SunCentered_ROI12',
      FT1='../data/lat_photon_weekly_w144_p120_v001_sun.fits',
      FT2='../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits',
      METStart= 321221742.6,
      METStop = 321269647.6,
      RA      = 0,
      DEC     = 0,
      GalDiffuse=None,
      IsoDiffuse=IsoDiffuse
      )
```

# Select the data

```
gtmktime
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    filter="DATA_QUAL==1 && (LAT_CONFIG==1) &&
    ABS(ROCK_ANGLE)<52" roicut=yes
    evfile=../SF110307_SunCentered_ROI12/selected.fits
    outfile=../SF110307_SunCentered_ROI12/selected_mkt.fits

gtbin algorithm=CMAP
    evfile=../SF110307_SunCentered_ROI12/selected_mkt.fits
    outfile=../SF110307_SunCentered_ROI12/selected_mkt_cmap.fits
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    nxpix=120 nypix=120 binsz=0.2 xref=0 yref=0 axisrot=0. proj=STG
    coordsys=CEL
```

# Compute the exposure

gtltcube evfile=../SF110307_SunCentered_ROI12/selected_mkt.fits
scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
outfile=../SF110307_SunCentered_ROI12/expcube.fits
dcostheta=0.025 binsz=1

gtexpmap evfile=../SF110307_SunCentered_ROI12/selected_mkt.fits
scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
expcube=../SF110307_SunCentered_ROI12/expcube.fits
outfile=../SF110307_SunCentered_ROI12/expmap.fits
irfs=P7SOURCE_V6 srcrad=22 nlong=20 nlat=20 nenergies=10

# Building the XML models

- The background will be simply an isotropic source, with a tabulated spectrum (standard)
- For the flare (in 0,0), we will use 3 different models:
  - PowerLaw2, ExpCutOff, FileFunction
- No other sources are needed in the analysis

Background

Source

PowerLaw2

```
<?xml version="1.0" standalone="no"?>
<source_library title="source library">
  <source name="EG_v02" type="DiffuseSource">
    <spectrum file="../data/iso_p7v6source.txt" type="FileFunction">
      <parameter error="0.2666735808" free="1" max="1000" min="0" name="Normalization" scale="1" value="2.143300159" />
    </spectrum>
    <spatialModel type="ConstantValue">
      <parameter free="0" max="10000" min="0" name="Value" scale="1" value="1" />
    </spatialModel>
  </source>
  <source name="SUN" type="PointSource">
    <spectrum type="PowerLaw2">
      <parameter error="1.142932488" free="1" max="100000" min="1e-06" name="Integral" scale="1e-05" value="13.67771087" /
>
      <parameter error="0.05507391535" free="1" max="0" min="-10" name="Index" scale="1" value="-2.560315152" />
      <parameter free="0" max="2000" min="30" name="LowerLimit" scale="1" value="30" />
      <parameter free="0" max="2000" min="30" name="UpperLimit" scale="1000" value="300" />
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter free="0" max="360" min="-360" name="RA" scale="1" value="0" />
      <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="0" />
    </spatialModel>
  </source>
</source_library>
```

# Building the XML models

## ExpCutOff

```
<?xml version="1.0" standalone="no"?>
<source_library title="source library">
  <source name="EG_v02" type="DiffuseSource">
    <spectrum file="../data/iso_p7v6source.txt" type="FileFunction">
      <parameter error="0.2736325957" free="1" max="1000" min="0" name="Normalization" scale="1" value="2.187871941" />
    </spectrum>
    <spatialModel type="ConstantValue">
      <parameter free="0" max="10000" min="0" name="Value" scale="1" value="1" />
    </spatialModel>
  </source>
  <source name="SUN" type="PointSource">
    <spectrum type="ExpCutoff">
      <parameter error="21.79387274" free="1" max="100000" min="0.01" name="Prefactor" scale="1e-09" value="243.1626555" />
      <parameter error="0.2466065089" free="1" max="-1" min="-5" name="Index" scale="1" value="-1.477365158" />
      <parameter free="0" max="2000" min="30" name="Scale" scale="1" value="100" />
      <parameter error="31.90118764" free="1" max="300" min="1" name="Ebreak" scale="1" value="196.4936646" />
      <parameter error="0.04354691277" free="1" max="300" min="0.1" name="P1" scale="1000" value="0.2162193044" />
      <parameter free="0" max="1" min="-1" name="P2" scale="1" value="0" />
      <parameter free="0" max="1" min="-1" name="P3" scale="1" value="0" />
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter free="0" max="360" min="-360" name="RA" scale="1" value="0" />
      <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="0" />
    </spatialModel>
  </source>
</source_library>
```

## FileFunction (Note the environment variable that points to the template location)

```
<?xml version="1.0" standalone="no"?>
<source_library title="source library">
  <source name="EG_v02" type="DiffuseSource">
    <spectrum file="../data/iso_p7v6source.txt" type="FileFunction">
      <parameter error="0.2675386966" free="1" max="1000" min="0" name="Normalization" scale="1" value="2.200673619" />
    </spectrum>
    <spatialModel type="ConstantValue">
      <parameter free="0" max="10000" min="0" name="Value" scale="1" value="1" />
    </spatialModel>
  </source>
  <source name="SUN" type="PointSource">
    <spectrum file="$(PITEMPL_FILE)" type="FileFunction">
      <parameter error="0.05382868664" free="1" max="100000" min="1e-05" name="Normalization" scale="0.0001" value="1.101545011" />
    </spectrum>
    <spatialModel type="SkyDirFunction">
      <parameter free="0" max="360" min="-360" name="RA" scale="1" value="0" />
      <parameter free="0" max="90" min="-90" name="DEC" scale="1" value="0" />
    </spatialModel>
  </source>
</source_library>
```

# Pre-computing the diffuse response

```
gtdiffrsp evfile=../SF110307_SunCentered_ROI12/selected_mkt.fits
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    srcmdl=../SF110307_SunCentered_ROI12/src_ExpCutoff.xml
    irfs=P7SOURCE_V6
```

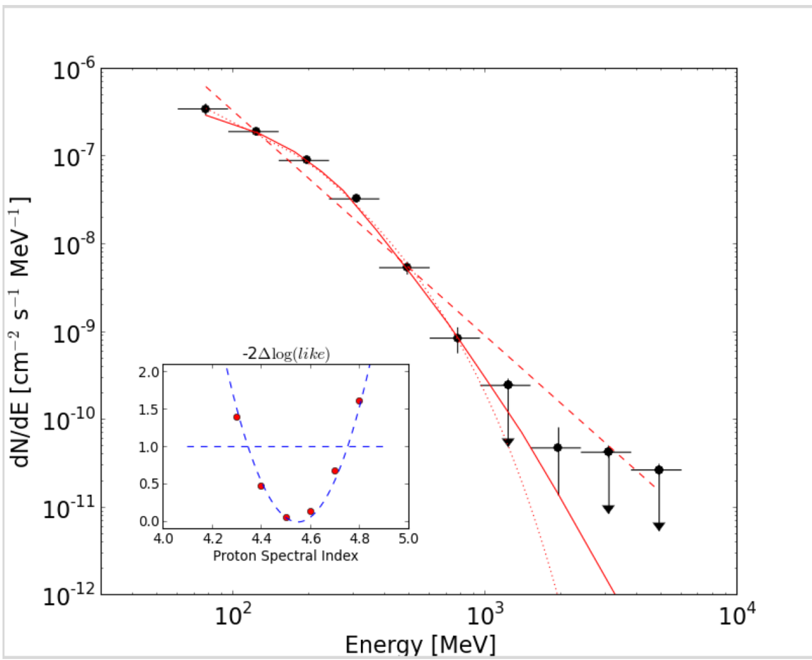
# Iterating!

- Try different models (Powerlaw, expcutoff, templates)
- Do a "profile likelihood" changing the model template
- "Spectral Energy Distribution":
  - A) fitting the full energy range with a given model in order to constrain the background;
  - B) selecting different energy bins, and fitting each energy bin with the constrained background + powelaw;
  - C) Calculate the energy flux (and its error). If the detection is not significant, calculate the UL;

- "Flux Light Curve" (in SFLARE110307_analysis.py):
  - A) select independent time bins
  - B) Calculate the flux

# Results…

- **Output directory: ../SF110307_SunCentered_ROI12**
  - **results.dat**
  - **results_all.dat (value of the logLike, TS for each template)**
  - **PhotonSED.txt (fluxes and UL).**
- **./plotSED.py ../SF110307_SunCentered_ROI12** *4 5*




Models are read from the results.dat files (parameters from the likelihood analysis)
Data points dNdE are from the PhotonSED.txt file (including UL)
The likelihood profile is taken from the results_all.dat file

A paper will come out soon containing this results.

# Create File for XSPEC

This is not the suggested analysis, but it might be useful to perform multi-instrument analysis in a user friendly environment, such XSPEC

Concept: using standard likelihood tool to find the best fit parameters

Freezing the background component

Extract a PHA file (signal + background) *gtbin*

Compute a PHA background file with *gtbkg*

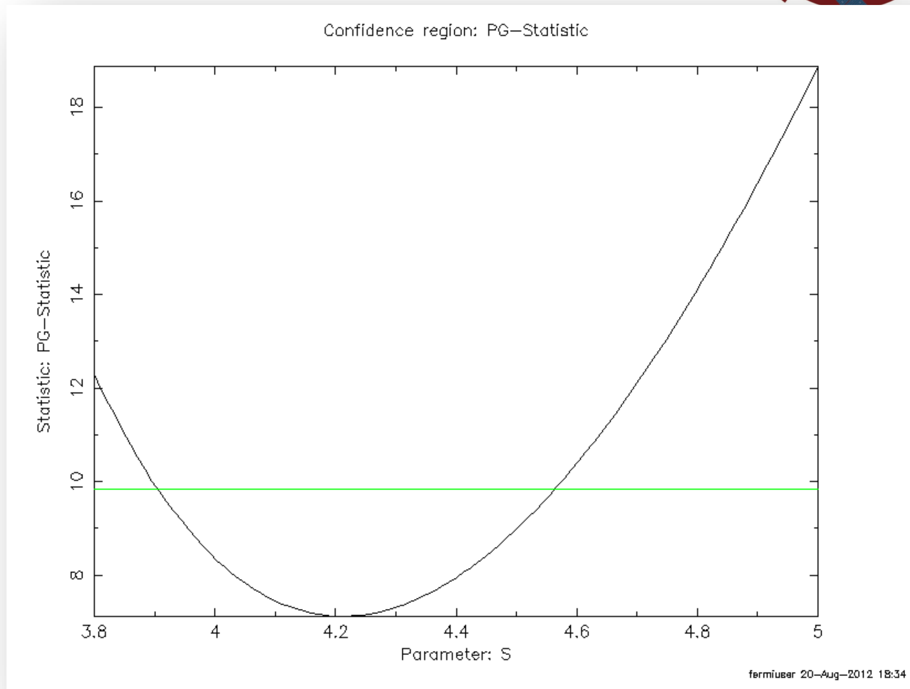
Responses are computed with *gtrspgen*

# Create File for XSPEC

```
gtbin algorithm=PHA1 evfile=../SF110307_SunCentered_ROI12/selected_mkt.fits
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    outfile=../SF110307_SunCentered_ROI12/spectrum.pha ebinalg=LOG emin=60
    emax=6000 enumbins=10

gtrspgen respalg=PS specfile=../SF110307_SunCentered_ROI12/spectrum.pha
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    outfile=../SF110307_SunCentered_ROI12/response.rsp irfs=P7SOURCE_V6
    ebinalg=LOG emin=30 emax=200000 enumbins=100 thetacut=70 dcostheta=0.05

gtbkg phafile=../SF110307_SunCentered_ROI12/spectrum.pha
    outfile=../SF110307_SunCentered_ROI12/background.pha
    scfile=../data/lat_spacecraft_weekly_w144_p01_v001_sun.fits
    expcube=../SF110307_SunCentered_ROI12/expcube.fits
    expmap=../SF110307_SunCentered_ROI12/expmap.fits irfs=P7SOURCE_V6
    srcmdl=../SF110307_SunCentered_ROI12/src_best.xml target=SUN
```

# Xspec-ing

```
[fermiuser@localhost SF110307_SunCentered_ROI12]$ xspec

                XSPEC version: 12.7.1
        Build Date/Time: Mon Jul  9 13:47:24 2012

XSPEC12>data spectrum.pha
***Warning: No TLMIN keyword value for response matrix FCHAN column.
            Will assume TLMIN = 1.
*** Warning: file contains COUNTS column but HDUCLAS3 keyword is set to COUNT

1 spectrum  in use

Spectral Data File: spectrum.pha  Spectrum 1
Net count rate (cts/s) for Spectrum:1  2.711e-02 +/- 1.380e-03 (79.8 % total)
 Assigned to Data Group 1 and Plot Group 1
  Noticed Channels:  1-10
  Telescope: GLAST Instrument: LAT  Channel Type: PI
  Exposure Time: 1.91e+04 sec
 Using fit statistic: chi
 Using Background File                ../SF110307_SunCentered_ROI12/background.pha
  Background Exposure Time: 1.91e+04 sec
 Using Response (RMF) File            ../SF110307_SunCentered_ROI12/response.rsp for Source 1

XSPEC12>setplot energy
XSPEC12>pl ld
XSPEC12>cpd /xs

XSPEC12>mod atable{../XSPEC/piontemplate.fits}

Input parameter value, delta, min, bot, top, and max values for ...
              4       0.1(      0.04)          2          2          6          6
1:piontemplate:S>
              1      0.01(      0.01)          0          0      1e+24      1e+24
2:piontemplate:norm>

========================================================================
Model atable{../XSPEC/piontemplate.fits}<1> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   piontemplateS               4.00000      +/-  0.0
   2    1   piontemplatenorm            1.00000      +/-  0.0
________________________________________________________________________
```




The result is not identical to likelihood , but it is compatible within errors

# What you can try…

- Run the tutorial and browse the results
- Run the tutorial in different time bins (you will need to change the script)
  - Is there a spectral evolution?
- Can you measure the spectrum of the Sun for the non-flaring period?