fermi-hero Documentation

Release 0.1

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CONTENTS

Welcome to the Fermi Large Area Telescope (LAT) data analysis tutorial for the 2013 IMRPS summer school on high energy astrophysics!

The tutorial will be held by Christoph Deil and Victor Zabalza from MPIK Heidelberg.

- Monday, September 9, 17:00 - 18:00: Victor will give a 15 minute introduction to Fermi (link to slides). Then we'll do the *Software* and *Data* setup.
- Tuesday, September 10, 16:00 - 17:30: *Getting Started* tutorial
- Thursday, September 12, 16:00 - 19:00: *Galactic Center High-Energy View* tutorial, *Spectrum*, and if we are quick the *Aperture Lightcurve*.

If you have any question regarding the use of `enrico`, please post them in this forum. Don't be shy ... really any question is welcome ...installation issues, error messages, science questions ...

- Tutorial pages: http://fermi-hero.readthedocs.org
- Tutorial data: will be distributed with USB sticks on Monday ... after the tutorial we'll put a tarball online to get it.

The tutorial pages are generated from the fermi-hero Github repository, just in case you'd like to contribute corrections or improvements.

> **Warning:** Please **do not** download large files during the tutorial or the WIFI network will overload. We will distribute the software and data you need via USB sticks.

> **Warning:** In September 2013 a new version of the Fermi science tools and re-processed Pass 7 data was announced to be released. We will update this tutorial when this happens.

CHAPTER

ONE

VIRTUAL BOX

We have prepared a virtual box that contain all software and data you need for the tutorial.

We will pass around USB sticks that contain the 6.3 GB `fermi-hero.ova` virtual appliance as well as VirtualBox installers for Mac and Windows.

> **Warning:** Your machine should have have at least **10 GB of free disk space** and 6 GB or RAM. If you only have 4 GB of RAM you can try changing the VM RAM size to 3 GB or 2 GB in the VM settings, but then some or the ScienceTools might start to swap to disk and become really slow.

1.1 Installing the VirtualBox software

First you have to install the VirtualBox software.

- If you have a Windows laptop, please double-click `VirtualBox-4.2.18-88780-Win.exe` from the USB stick and click `OK` a few times to go through the installation process.
- For Mac, double-click `VirtualBox-4.2.18-88780-OSX.dmg`.

For Linux we did not put VirtualBox binaries on the USB sticks because there are too many Linux variants. Your best shot at installing VirtualBox on your Linux machine is probably to use your system package manager.

- On `Ubuntu` or other Debian-based Linuxes:

  ```
  $ sudo apt-get install virtualbox
  ```

- On `Fedora`:

  ```
  $ sudo yum install virtualbox
  ```

You can also try and download a VirtualBox binary installer from https://www.virtualbox.org/. In either case (package manager or binary installer) it's prabably a ~ 100 MB download, so it'll take a while with our WIFI.

1.2 Installing the `fermi-hero` virtual appliance

To install the `fermi-hero.ova` vitual appliance into VirtualBox, either open um VirtualBox and use `File -> Import` or double-click the `fermi-hero.ova` file.

You can install the virtual box directly from the USB drive or by first copying the `fermi-hero.ova` file to your hard drive.

In any case this will create a virtual box called `fermi-hero` on your had disk (a folder called `fermi-hero` with a large `fermi-hero.vdi` file, a small `fermi-hero.vbox` file as well as some other stuff inside. You'll never have to look at this folder, except if you are short on disk space check it's size.

Note: VMWare should also be capable of importing the `fermi-hero.vdi` appliance, so if you prefer VMWare (non-free, but a bit nicer in some ways) over VirtualBox (free), give it a try and let us know.

1.3 Starting and using the `fermi-hero` virtual machine

To start the `fermi-hero` virtual machine (VM), start VirtualBox (the window has `Oracle VM VirtualBox Manager` in the title) and double-click on the `fermi-hero` VM.

Fedora wil boot up and present you with a login screen for the user `hero`.

Some information on the VM:

- Distributed as 6.3 GB file `fermi-hero.ova` in the Open Virtualization Format
- 20 GB disk (VM file size grows dynamically) in VDI format
- 4 GB RAM
- 64-bit Fedora Linux Version 19 (specifically `Fedora-Live-Desktop-x86_64-19-1.iso`)
- Do all analysis as user `hero` in the home directory `/home/hero` ... no login password set.
- If you need `root` access ... the password is `root`. E.g. you can get a `root` terminal by typing `su` and then install software using yum.

CHAPTER

TWO

SOFTWARE

Warning: Please **do not** download large files during the tutorial or the WIFI network will overload. We will distribute the software and data you need via USB sticks.

To participate in the tutorial you should bring a Mac or Linux laptop.

This page describes how to install the software we need for the tutorial and how to check that it works properly.

If you have a Windows laptop, you can install VirtualBox and then install Linux in a virtual machine. It's best to install a Linux distribution that is officially supported by the Fermi science tools (see here): unfortunately the Scientific Linux distribution is very large (over 4 GB) and Ubuntu has known problems. Therefore we recomment you try Fedora, which should be similar enough to ScientificLinux for the Scientific Linux 6 64 bit libc 2.12 binary version of the ScienceTools to work.

Check: you should be able to open a terminal and do this:

```
$ echo "Hello world"
Hello world
$
```

2.1 Overview

You should install the following software:

- Fermi Science Tools
- FTOOLS = HEASOFT (includes fv)
- ds9
- TOPCAT
- Aladin (if you want)
- Enrico

2.2 Fermi Science Tools

The main analysis software you will use for this tutorial is the Fermi data analysis software, called the Fermi science tools.

The Fermi Science Support Center web pages contain a lot of information about Fermi data access and data analysis. If you have a problem you can't solve yourself (always try finding a solution yourself with Google first), you can contact the official NASA Fermi help desk or post in this forum.

The most important piece of advice on the Installing the Fermi Science Tools page is:

> Downloading and installing the Fermi science tools from the binary tar files below is strongly recommended. > The many minor variations in the various Unix systems makes building the tools from source challenging.

So download the binary tar file for your machine ... this will take a while because it's about 1 GB in size. As an example, for Mac the file you get will be called `ScienceTools-v9r31p1-fssc-20130410-x86_64-apple-darwin12.2.0.tar.gz` or maybe if it is automatically unzipped after download it will be called `ScienceTools-v9r31p1-fssc-20130410-x86_64-apple-darwin12.2.0.tar`.

After download you have to set up the Fermi science tools as described here.

Check: you should be able to use the Fermi science tools from the Shell command line and via Python:

```
$ which gtbin
$ gtbin
# abort with CTRL + C
$ which python
$ python
>>> import UnbinnedAnalysis
```

2.2.1 libcrypto and libssl shared library problem

If gtbin complains about missing `libcrypto.so.10`, then you need make a link to your installed version with the name requested. To do this first use `locate` to find your version, then cd to that directory and create a symbolic link. Example:

```
$ sudo -i
# locate libcrypto
/PATH TO FILE/libcrypto.so.0.9.8
# cd /PATH TO FILE/
# ln -s libcrypto.so.0.9.8 libcrypto.so.10
```

You see either a file called `libcrypto.so.0.9.8` or `libcrypto.so.1.0.0`. If locate finds a file called `libcrypto.so.1.0.0`, use that file instead of the `libcrypto.0.9.8` version.

After creating the `libcrypto` link, try to run `gtbin`. Sometimes a similar error regarding `libssl` will take place, if it does repeat the steps above with thelibssl file to (hopefully) correct it.

2.3 FTOOLS = HEASOFT

Next install the FTOOLS — A General Package of Software to Manipulate FITS Files following the installation instructions on the web. To install correctly you must run the `configure` script found in `heasoft-6.14/[platform version]/BUILD_DIR`, where `[platform version]` corresponds to the string of your platform (e.g., `x86_64-unknown-linux-gnu-libc2.5` for Linux64).

With the FTOOLS you install Fv: The Interactive FITS File Editor, a flexible tool to view and edit FITS files.

> E.g. the ftlist command line tool is very handy to check what is in a given FITS file.
>
> Use *ds9* as an image viewer and *fv* to look at the content of Fermi event lists (called photon files).
>
> **Check:** Open up a Fermi event list as described here with `fv`

2.4 ds9

SAOImage DS9 is one of the best viewers for astronomical 2D images and 3D cubes ... please download it from here.

Check: Download and open up the following FITS files:

- Hubble space telescope image of the Antennae Galaxies (FITS file of the 2D image)
- Fermi LAT diffuse emission model (an outdated version, used here because of the small file size) (FITS file of the 3D cube with *log(energy)* on the third axis).

If you want:

- Some Hubble space telescope optical images here.
- Some Chandra X-ray observatory X-ray images here

2.5 TOPCAT

TOPCAT <http://www.star.bris.ac.uk/~mbt/topcat/> is a Java program to view FITS tables. Follow the installation instructions on the web.

2.6 Aladin (optional)

Aladin — A FITS image viewer (alternative to ds9) is a nice astronomical image and catalog viewer ... an alternative to `ds9`.

Install it and give it a try if you want.

2.7 Enrico

Producing a spectrum (global model and flux points in energy bins) or light curve (flux points in time bins) requires calling a lot of Fermi science tools with the right parameters in the right order.

Luckily you have Enrico to help you. Enrico is a set of Python scripts that take a single config file as input where you specify what kind of analysis you want to run and the most important analysis parameters, and the run all Fermi science tools in the right order (or in parallel where possible) with the right parameters for you.

Please install Enrico as described here.

Check: To check that Enrico is installed correctly run this command:

```
$ enrico_setupcheck
```

2.8 Init file

You should create a file *fermi-hero-init.sh* which sets up your shell for this tutorial.

Once all software is installed all you have to do is:

```
$ source fermi-hero-init.sh
```

This is an example init file ... you'll have to adapt the PATHs / versions to your system:

```
export FERMI_HERO = /Users/deil/FERMI_HERO

export HEADAS=$FERMI_HERO/heasoft-6.14/x86_64-unknown-linux-gnu-libc2.5
source $HEADAS/headas-init.sh

export FERMI_DIR=$FERMI_HERO/ScienceTools-v9r31p1-fssc-20130410-x86_64-apple-darwin12.2.0/x86_64-appl
source $FERMI_DIR/fermi-init.sh

export ENRICO_DIR=$FERMI_HERO/enrico
source $ENRICO_DIR/enrico-init.sh

alias topcat="java -Xms512m -Xmx4024m -jar /Applications/TOPCAT.app/Contents/Resources/Java/topcat-fu
alias aladin="java -Xms512m -Xmx4024m -jar /Applications/Aladin.app/Contents/Resources/Java/Aladin.ja

# Add location of binaries to your PATH, e.g. for ds9:
export PATH=$PATH:$FERMI_HERO
```

CHAPTER THREE

DATA

> **Warning:** Please **do not** download large files during the tutorial or the WIFI network will overload. We will distribute the software and data you need via USB sticks.

Download the *fermi-data.tar.gz* tarball from here (TODO), then execute the following commands:

```
tar zxvf fermi-data.tar.gz
cd fermi-data
$ du -hs *
637M  excercises
554M  solutions
637M  spacecraft.fits
```

As you can see the *fermi-hero* folder contains a file `spacecraft.fits` as well as two folders `excercises` and `solutions`:

- `excercises` contains the input data files you'll need for the excercises. This is where you can run the analyses yourself by following the instructions given in the various tutorial sections.
- `solutions` contains all files after you've run the commands. You can use it as a reference or to skip very time-consuming steps by just copying over the relevant file from `solutions` to `excercises`

TODO: give overview table of data sets used in this tutorial.

```
$ ls -1 exercises
getting_started
image
lightcurve
spectrum
```

CHAPTER

FOUR

GETTING STARTED

To get started, you will learn how to use some tools to download, prepare and explore Fermi LAT data.

Fermi LAT data consists of **event data files** and **spacecraft data files**.

Note: Throughout this tutorial we will use the terms **event** and **photon** interchangeably, because for the event classes we use the fraction of events that are not photons, but charged cosmic rays, is negligibly low (less than 1%).

Event file == Photon file == FT1 file

Spacecraft file == FT2 file

The spacecraft data file contains the information about the orbit position and pointing direction as well as some status and quality information ... you can use the same spacecraft file (~700 MB for 5 years) for all your analyses as long as it covers the time range you want to analyse. That's all you need to know about the spacecraft data file ... simply give it's filename to the tools that require it to do their job.

The event data file contains a table of observed and reconstructed events. where the most important event parameters are:

- **(RA, DEC)** (degrees). Equatorial coordinates ... called right ascension **RA** and declination **DEC**.
- **(L, B)** (degrees). Galactic coordinates ... called Galactic longitude **L** and latitude **B**.
- **ENERGY** (MeV)
- **TIME** (seconds). Mission elapsed time when the event was detected. (MET is the total number of seconds since 00:00:00 on January 1, 2001 UTC)

In this tutorial we will have a quick look at the Fermi LAT dataset by binning the events into histograms:

- A 2-dimensional **(L, B)** histogram is called a **counts image**.
- A 1-dimensional **ENERGY** histogram is called a **counts spectrum**.
- A 1-dimensional **TIME** histogram is called a **counts lightcurve**.

In the *Spectrum*, *Aperture Lightcurve* and *Galactic Center High-Energy View* tutorials we will then show you how to create a **flux spectrum**, **flux lightcurve** and **flux image**, where **flux = counts / exposure** and **exposure = (effective area) x (observation time)** and in addition to exposure the spatial resolution, called point spread function (PSF), and energy resolution have been taken into account.

If you are interested to at least get a basic understanding of the theory how Fermi LAT gamma-ray data analysis works, have a look at the Fermi LAT Instrument response functions and Fermi LAT Likelihood Analysis section of the Fermi LAT Manual, called Cicerone. In this short Fermi-Hero tutorial we focus on **how to use the tools to obtain results** instead of **what exactly the tools do and why (methods, theory)**.

4.1 Prerequisites

You should have installed and quickly tested the *Software* and downloaded and extracted the Fermi-Hero tutorial *Data*.

4.2 Steps

4.2.1 First look at Fermi LAT photon files with `ftlist` and `fv`

Event files like `L1309081333300B976F4377_PH00.fits` are FITS files. **FITS** is the standard data format in astronomy for arrays (e.g. 2D images) and tables (e.g. source catalogs or event lists).

Let's use a few different tools to explore the content of `L1309081333300B976F4377_PH00.fits`.

List photon file contents with `ftlist`

ftlist is a command-line tool to ... duh ... list the content of FITS files. A FITS file consists of **header-data units (HDUs)**, where each HDU is an array or table. For historic reasons the first HDU (a.k.a. primary HDU) has to be an array, so in FITS files that only contain tabular data the primary HDU will be a dummy, empty HDU.

Giving a filename and the print option `H` to list a 1-line summary of the HDUs to `ftlist` we get:

```
$ ftlist L1309081333300B976F4377_PH00.fits H

        Name               Type       Dimensions
        ----               ----       ----------
HDU 1   Primary Array      Null Array
HDU 2   EVENTS             BinTable     22 cols x 1065513 rows
HDU 3   GTI                BinTable      2 cols x 1790 rows
```

So this **event file** contains an `EVENTS` table with 1065513 events and a `GTI` (good time interval) table with 1790 GTIs. GTIs are needed to compute exposure. Exposure is needed to compute the flux of sources.

To list the names and units of the columns in the `EVENTS` and `GTI` table use the `C` print option with `ftlist`:

```
$ ftlist L1309081333300B976F4377_PH00.fits C
HDU 2

  Col  Name                Format[Units](Range)      Comment
    1 ENERGY                E [MeV] (0.:10000000.)
    2 RA                    E [deg] (0.:360.)
    3 DEC                   E [deg] (-90.:90.)
    4 L                     E [deg] (0.:360.)
    5 B                     E [deg] (-90.:90.)
    6 THETA                 E [deg] (0.:180.)
    7 PHI                   E [deg] (0.:360.)
    8 ZENITH_ANGLE          E [deg] (0.:180.)
    9 EARTH_AZIMUTH_ANGLE E [deg] (0.:360.)
   10 TIME                  D [s] (0.:10000000000.)
   11 EVENT_ID              J (0:2147483647)
   12 RUN_ID                J (0:2147483647)
   13 RECON_VERSION         I (0:32767)
   14 CALIB_VERSION         3I
   15 EVENT_CLASS           J (0:32767)
   16 CONVERSION_TYPE       I (0:32767)
   17 LIVETIME              D [s] (0.:10000000000.)
```

```
   18 DIFRSP0             E (0.:1.0E+38)
   19 DIFRSP1             E (0.:1.0E+38)
   20 DIFRSP2             E (0.:1.0E+38)
   21 DIFRSP3             E (0.:1.0E+38)
   22 DIFRSP4             E (0.:1.0E+38)

HDU 3

  Col  Name              Format[Units](Range)      Comment
    1 START               D [s] (0.:10000000000.)
    2 STOP                D [s] (0.:10000000000.)
```

To print the content of the `EVENTS` table extension give the extension name in square brackets after the filename use the `T` print option with `ftlist`:

```
$ ftlist L1309081333300B976F4377_PH00.fits[EVENTS] T rows=1-10 columns=ENERGY,RA,DEC,TIME

             ENERGY              RA             DEC                       TIME
                MeV             deg             deg                          s
  1         398.907         94.0848         5.88669        378713295.231454
  2         425.700         91.8646         7.99151        378724463.542101
  3         262.569         93.0315         4.90930        378724578.466829
  4         683.413         90.3001         3.16895        378725356.681894
  5         889.776         90.3241         7.67446        378725486.282723
  6         566.726         90.3723         7.70085        378719151.132736
  7         305.036         91.6181         6.04271        378719248.977633
  8         140.088         94.2944         5.68424        378736517.165258
  9         184.310         91.1134         4.95412        378736587.650162
 10         138.277         92.4515         5.60271        378742238.959606
```

`ftlist` is just one of many command line tools to work with FITS files, called the FTOOLS, which you get as part of a package called HEASOFT.

You should know that for each FTOOL you can get the help page locally quickly by using `fhelp <tool name>`:

```
$ fhelp ftlist
```

Sometimes this will open up the help page in the terminal, sometimes in HTML format in your web browser.

To quickly see list the parameters of a given FTOOL use plist:

```
$ plist ftlist
Parameters for /Users/deil/pfiles/ftlist.par
       infile = L1309081333300B976F4377_PH00.fits[EVENTS] Input file name
       option = T                 Print options: H C K I T
     (outfile = -)                Optional output file
     (clobber = No)               Overwrite existing output file?
     (include = *)                Include keywords list
     (exclude = )                 Exclude keywords list
     (section = *)                Image section to print, eg, '2:8,1:10'
     (columns = *)                Table columns to print
        (rows = -)                Table rows or ranges to print, eg, '2,6-8'
      (vector = -)                Vector range to print, eg, '1-5'
   (separator =  )                Column separator string
      (rownum = Yes)              Print row number?
   (colheader = Yes)              Print column header?
        (mode = ql)               Mode
```

You see the parameter name, last or default value and a short description. There are required parameters (the ones without parentheses) that you will be quoted for interactively if not given on the command line. And there are optional parameters (the ones in parentheses) that you have to give on the command line if you want to choose a different value than the default.

Plot a photon zenith angle histogram with `fv`

Next let's use Fv: The Interactive FITS File Editor. `ftlist` was a command line tool ... `fv` is a GUI (graphical user interface) tool.

Open `fv` and the event file like this:

```
$ fv L1309081333300B976F4377_PH00.fits
```

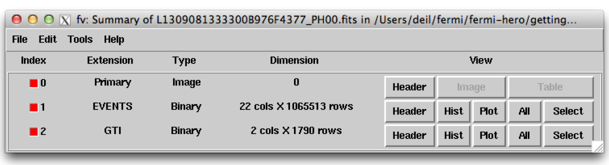
or if you prefer to run `fv` in the background like this:

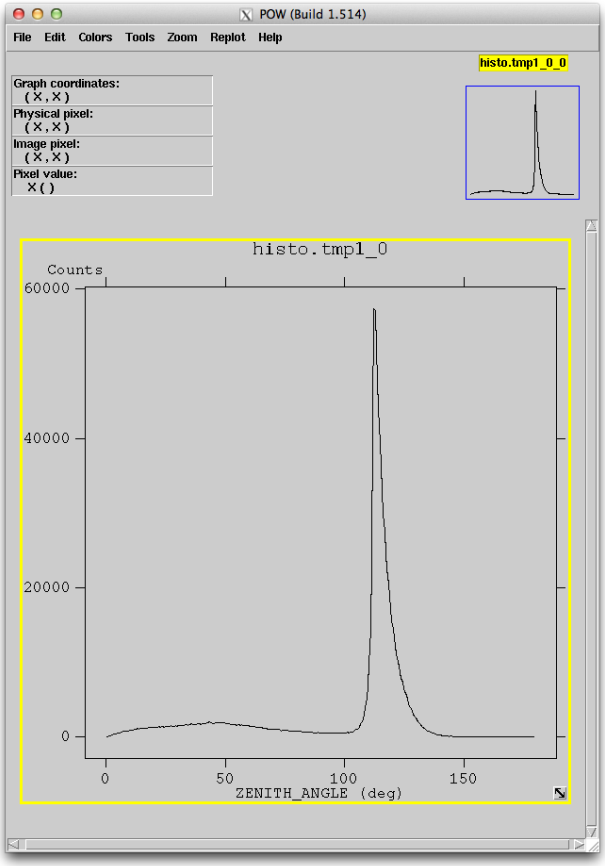
```
$ fv L1309081333300B976F4377_PH00.fits &
```

The advantage of running tools in the background is that you can execute other commands without having to wait for the tool to finish or having to open an extra terminal window.

`fv` is very powerful, but because it's so ugly that it probably makes your eyes hurt we'll only use it to do one thing: plot a the distribution of the `ZENITH_ANGLE` of the `EVENTS`.

- Click the `Histogram` button for the `EVENTS` HDU.
- In the dialog window called `Histogram` select `ZENITH_ANGLE` as column name for `X`. In this case the default binning options are reasonable ... click `Make/Close`.
- Done. A window called `POW` shows the zenith angle histogram.
- In the fv menu click `Quit`, then `No to All` in the exit dialog window to confirm that you don't want to permanently save the temp histogram file.





The zenith angle histogram shows a broad peak in the range 0 deg to 100 deg, and a narrow peak around 113 deg.

We'll explain the origin and relevance of this distribution in the next section *Prepare Fermi LAT data with gtselect and gtmktime*.

4.2.2 Get Fermi LAT data

Spacecraft file

The spacecraft file doesn't depend on the sky region or energy range you are interested in ... it is valid for the whole sky and all energies.

The only thing you have to watch out for is that your spacecraft file covers the time range you want to analyse. To obtain a spacecraft data file that covers the whole length of the Fermi mission (updated daily with new data) use this command

```
wget -O spacecraft.fits ftp://legacy.gsfc.nasa.gov/FTP/fermi/data/lat/mission/spacecraft/lat_spacecra
```

Photon files

Usually you will do this via the FSSC data query web interface as described in the Extract LAT Data analysis thread.

TODO: give screenshots and short description.

Tip: If you are a Fermi LAT power user (e.g. run analyses on several regions or update your analyses every once in a while) or if there are several Fermi LAT data analysts at your institute you should consider downloading the weekly photon and spacecraft files as described here:

```
wget -m -P . -nH --cut-dirs=4 -np -e robots=off \
ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/photon/
wget -m -P . -nH --cut-dirs=4 -np -e robots=off \
ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/spacecraft/
```

Note that the weekly photon files currently (2013, covering five years of Fermi observations) are about 30 GB (gigabytes) in size, so make sure you have the disk space and internet connection bandwidth.

Example: Getting data from the April 2011 Crab Nebula Flare

To carry out the aperture lightcurve excercise you will have to download the photon data from the FSSC data query web interface. We are interested in photons from a region of 1 degree radius around the Crab Nebula during the period of 16 days between April 8th and April 24th 2011. To convert between calendar dates, MJD and Fermi MET (Mission Elapsed Time, or seconds since January 1st, 2001), you can use the NASA HEASARC xTime tool.

Since we have already provided you with the whole-mission `spacecraft.fits` file, there is no need to download the spacecraft file for this period, so you uncheck the `Spacecraft data` box.

The parameters for the photon query should therefore be:

Table 4.1: LAT query parameters

Parameter	Value
Object Name	Crab Nebula
Equatorial coordinates (degrees)	(83.6331,22.0145)
Time range (MET)	(323913600,325296000)
Time range (Gregorian)	(2011-04-08 00:00:00,2011-04-24 00:00:00)
Energy range (MeV)	(100,300000)
Search radius (degrees)	1

After a brief wait, download the resulting photon file to the `$FERMI_HERO/excercises/lightcurve` directory and, optionally, rename it to `photon.fits` to make it easier to remember.

4.2.3 Prepare Fermi LAT data with `gtselect` and `gtmktime`

In the last section we made a histogram of the photon zenith angle distribution and found a broad peak in the range 0 to 100 deg and a narrow peak around 113 deg.

The narrow peak at a zenith angle of ~ 113 deg is due to “atmospheric gamma rays” as explained in the following Figure (which also explains what the zenith angle is).

We are not interested in atmospheric gamma rays, only in gamma rays from (non-atmospheric) astrophysical sources.

To apply selection cuts that remove the atmospheric gammas we will use the `gtselect` and `gtmktime` **Fermi Science Tools** (the Fermi LAT FTOOLS). Running these two tools has other purposes, too, e.g. selecting an **event class** (see LAT Data Selection Recommendations for more information).

We will not describe the details of what happens here ... if you are interested read the Fermi LAT Data Preparation analysis thread and follow the links given there.

`gtselect` takes an FITS event file as input and writes a subset of events to an output FITS event file. If you have more than one input FITS event file you have to create a text file containing the names of all FITS event files you’d like to process ... one file per line.

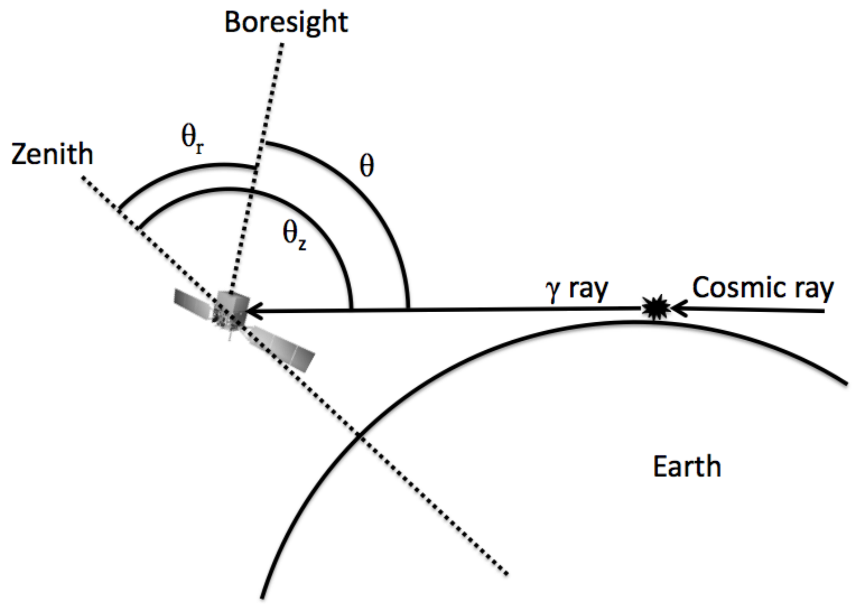


Figure 4.1: Schematic of Limb gamma-ray production by cosmic ray interactions in the Earth's atmosphere, showing the definitions of the zenith angle (θz), the spacecraft rocking angle (θr) and the incidence angle (θ). Reference: http://adsabs.harvard.edu/abs/2013arXiv1305.5597F

Use the command line ls utility to create the text file and the cat utility to print it's contents to the terminal to check that it worked:

```
$ ls -1 *_PH??.fits > events.txt
$ cat events.txt
L1309081333300B976F4377_PH00.fits
L1309081333300B976F4377_PH01.fits
```

Now run gtselect and select event class 2, corresponding to *P7SOURCE_V6*, as well as a maximum zenith angle of 100 deg as recommended here:

```
$ gtselect evclass=2
Input FT1 file[] @events.txt
Output FT1 file[] gtselect.fits
RA for new search center (degrees) (0:360) [] INDEF
Dec for new search center (degrees) (-90:90) [] INDEF
radius of new search region (degrees) (0:180) [] INDEF
start time (MET in s) (0:) [] INDEF
end time (MET in s) (0:) [] INDEF
lower energy limit (MeV) (0:) [] 100
upper energy limit (MeV) (0:) [] 1000000
maximum zenith angle value (degrees) (0:180) [] 100
Done.
```

Note that we had to specify the `evclass` parameter on the command line, because it's a hidden FTOOL parameter:

```
$ plist gtselect
Parameters for /Users/deil/pfiles/gtselect.par
       infile = @events.txt      Input FT1 file
      outfile = gtselect.fits    Output FT1 file
           ra = INDEF            RA for new search center (degrees)
```

```
         dec = INDEF            Dec for new search center (degrees)
         rad = INDEF            radius of new search region (degrees)
        tmin = INDEF            start time (MET in s)
        tmax = INDEF            end time (MET in s)
        emin = 100              lower energy limit (MeV)
        emax = 1000000          upper energy limit (MeV)
        zmax = 100              maximum zenith angle value (degrees)
   (evclsmin = INDEF)           Minimum event class ID
   (evclsmax = INDEF)           Maximum event class ID
    (evclass = 2)               Event class selection (e.g. 0=Transient, 2=Source)
   (convtype = -1)              Conversion type (-1=both, 0=Front, 1=Back)
   (phasemin = 0)               minimum pulse phase
   (phasemax = 1)               maximum pulse phase
    (evtable = EVENTS)          Event data extension
    (chatter = 2)               Output verbosity
    (clobber = yes)             Overwrite existing output files
      (debug = no)              Activate debugging mode
        (gui = no)              GUI mode activated
       (mode = ql)              Mode of automatic parameters
```

Sometimes it's convenient to give the parameters on the command line to avoid the interactive prompt.

E.g. after you've done a few Fermi data analyses you'll get tired of running the tools interactively and will want to use scripts where you substitute in the correct parameters in the correct places. Shell scripts, Makefiles or Python scripts are common choices.

Later in this tutorial you'll use a set of easy-to-use Fermi LAT data analysis Python scripts called Enrico to do the busywork.

The following command is equivalent to the `gtselect` command given above ... you can simply copy & paste it in you terminal:

```
$ gtselect infile=@events.txt outfile=gtselect.fits \
  ra=INDEF dec=INDEF rad=INDEF tmin=INDEF tmax=INDEF \
  emin=100 emax=1000000 zmax=100 evclass=2
```

The backslash tells the terminal that the command is not finished and will continue on the next line.

Did you note how we used `INDEF` to denote "don't apply an additional cut" for the region of interest (ROI) and the time range? `INDEF` doesn't work for the energy range apparently, so we had to repeat the selection we made when downloading the data: 100 MeV to 1,000,000 MeV = 1 TeV.

If you ever forget what **Data Sub Space (DSS)** selections you applied when downloading the data or processing it with `gtselect` or `gtmktime`, you can use the gtvcut tool to display a summary:

```
$ gtvcut L1309081333300B976F4377_PH00.fits EVENTS
DSTYP1: TIME
DSUNI1: s
DSVAL1: TABLE
DSREF1: :GTI

GTIs: (suppressed)

DSTYP2: BIT_MASK(EVENT_CLASS,2)
DSUNI2: DIMENSIONLESS
DSVAL2: 1:1

DSTYP3: POS(RA,DEC)
DSUNI3: deg
DSVAL3: CIRCLE(83.633083,22.0145,20)
```

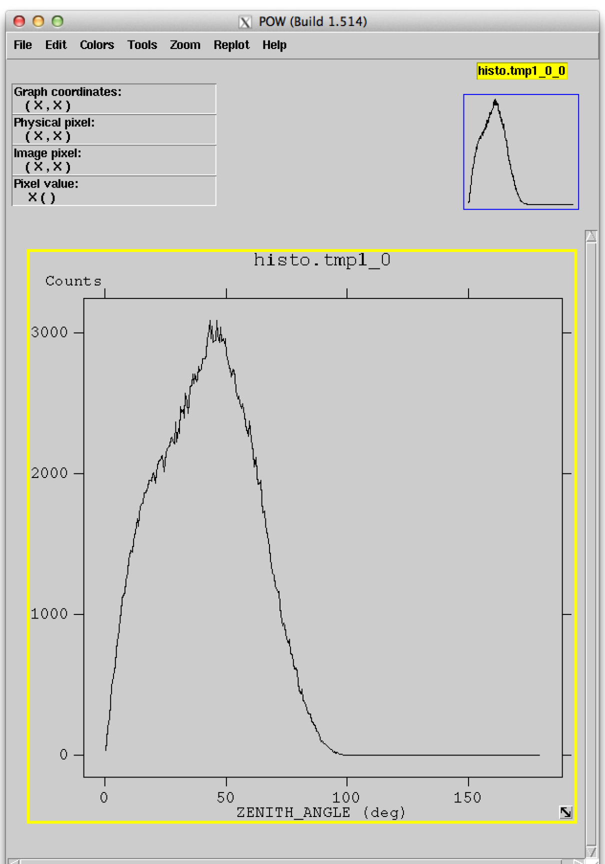
```
DSTYP4: TIME
DSUNI4: s
DSVAL4: 378691200:394329600

DSTYP5: ENERGY
DSUNI5: MeV
DSVAL5: 100:1000000
```

Back to business ... let's finish the data preparation by running `gtmktime` using the recommended parameters from here:

```
$ gtmktime
Spacecraft data file[] ../spacecraft.fits
Filter expression[] DATA_QUAL==1&&LAT_CONFIG==1&&ABS(ROCK_ANGLE)<52
Apply ROI-based zenith angle cut[] yes
Event data file[] gtselect.fits
Output event file name[] gtmktime.fits
```

Note: For this tutorial I chose to name the `gtselect` tool output file `gtselect.fits` and the `gtmktime` output file `gtmktime.fits`. I find this convention of using the tool name as output file name easy to remember, but you can choose any file names you like of course.

Before moving on to the next section, which will explain a bit what `gtselect` and `gtmktime` have done, let's use `fv` again to plot the `ZENITH_ANGLE` distribution of `gtmktime.fits`. As expected, there are no events with `ZENITH_ANGLE > 100` deg any more.



4.2.4 Compute data summaries with Python

In this section we will use the Python programming language interactive console and the PyFITS package and numpy (all come with the Fermi ScienceTools) to compute data summaries of the various event files.

To start Python, simply type `python` on the command line. This will show the Python prompt >>> where you can execute commands. To exit Python type `CTRL + D`:

```
$ python
Python 2.7.2 (default, Apr 12 2013, 00:51:51)
[GCC 4.2.1 (Based on Apple Inc. build 5658) (LLVM build 2336.11.00)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> 3 + 2
5
>>> ^D
$
```

To check that you are actually using the Python in the Fermi ScienceTools:

```
$ which python
/Users/deil/software/fermi/ScienceTools-v9r31p1-fssc-20130410-x86_64-apple-darwin12.2.0/x86_64-apple-
```

Remember that we had two photon files from the Fermi LAT data server and then ran `gtselect` to produce `gtselect.fits` and `gtmktime` to produce `gtmktime.fits`:

```
$ ftlist L1309081333300B976F4377_PH00.fits H

        Name               Type       Dimensions
        ----               ----       ----------
HDU 1   Primary Array      Null Array
HDU 2   EVENTS             BinTable    22 cols x 1065513 rows
HDU 3   GTI                BinTable     2 cols x 1790 rows

$ ftlist L1309081333300B976F4377_PH01.fits H

        Name               Type       Dimensions
        ----               ----       ----------
HDU 1   Primary Array      Null Array
HDU 2   EVENTS             BinTable    22 cols x 377253 rows
HDU 3   GTI                BinTable     2 cols x 1022 rows

$ ftlist gtselect.fits H

        Name               Type       Dimensions
        ----               ----       ----------
HDU 1   Primary Array      Null Array
HDU 2   EVENTS             BinTable    22 cols x 365387 rows
HDU 3   GTI                BinTable     2 cols x 2812 rows

$ ftlist gtmktime.fits H

        Name               Type       Dimensions
        ----               ----       ----------
HDU 1   Primary Array      Null Array
HDU 2   EVENTS             BinTable    22 cols x 312629 rows
HDU 3   GTI                BinTable     2 cols x 3419 rows
```

Just to get used to Python and PyFITS, let's explore a bit what `gtselect` and `gtmktime` have done to the EVENTS and GTIs:

```
$ python
Python 2.7.2 (default, Apr 12 2013, 00:51:51)
[GCC 4.2.1 (Based on Apple Inc. build 5658) (LLVM build 2336.11.00)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> 1790 + 1022
2812
>>> import pyfits
>>> ph00 = pyfits.open('L1309081333300B976F4377_PH00.fits')
>>> ph01 = pyfits.open('L1309081333300B976F4377_PH01.fits')
>>> gtselect = pyfits.open('gtselect.fits')
>>> gtmktime = pyfits.open('gtmktime.fits')
>>> ph00.info()
Filename: L1309081333300B976F4377_PH00.fits
No.    Name         Type      Cards   Dimensions   Format
0    PRIMARY     PrimaryHDU      31   ()           uint8
1    EVENTS      BinTableHDU    169   1065513R x 22C   [E, E, E, E, E, E, E, E, E, D, J, J, I, 3I, J, I
2    GTI         BinTableHDU     46   1790R x 2C    [D, D]
```

TODO: finish this with some numpy calculations

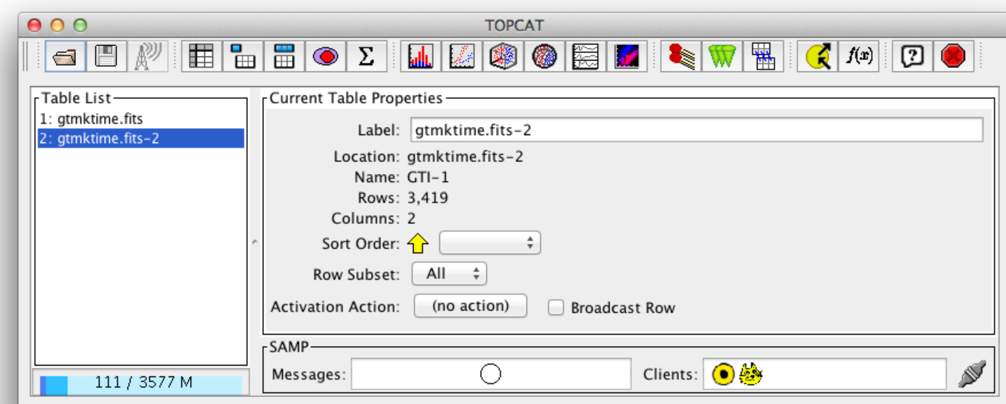
4.2.5 Explore Fermi LAT photon data with TOPCAT

Now that we have a prepared the event list to only contain astrophysical photons let's have a look at the `(RA, DEC)`, `(L, B)` as well as `ENERGY` and `TIME` distributions of the events.

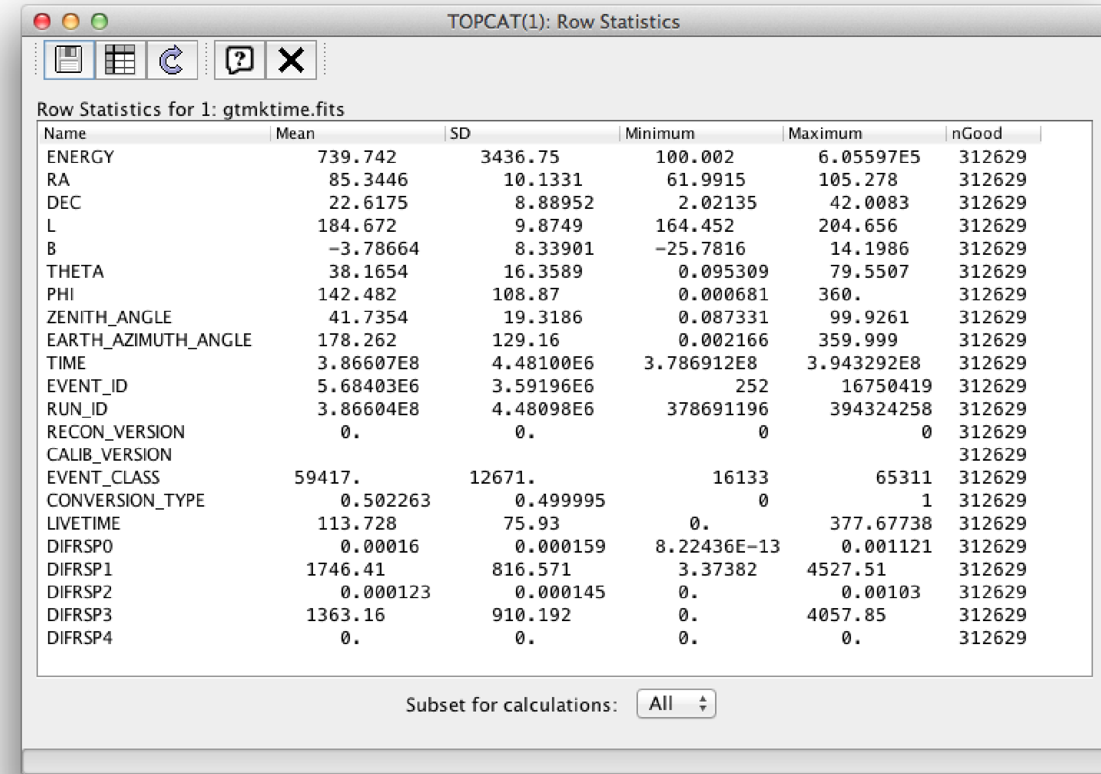
TOPCAT

TOPCAT is the "Tool for OPerations on Catalogues And Tables". Open the preprocessed event list with will open the main window with `TOPCAT` in the title and by default select the `GTI` HDU (called location `gtmktime.fits-2` and name `GTI-1`):

```
$ topcat gtmktime.fits
```



- In the table list on the left side of the main window, select the first HDU. You should see `Name: EVENTS-1` in the `Current Table Properties` section.
- Open the `Row Statistics` window by clicking the button with the upper-case greek sigma.



TOPCAT(1): Row Statistics

Row Statistics for 1: gtmktime.fits

Name	Mean	SD	Minimum	Maximum	nGood
ENERGY	739.742	3436.75	100.002	6.05597E5	312629
RA	85.3446	10.1331	61.9915	105.278	312629
DEC	22.6175	8.88952	2.02135	42.0083	312629
L	184.672	9.8749	164.452	204.656	312629
B	-3.78664	8.33901	-25.7816	14.1986	312629
THETA	38.1654	16.3589	0.095309	79.5507	312629
PHI	142.482	108.87	0.000681	360.	312629
ZENITH_ANGLE	41.7354	19.3186	0.087331	99.9261	312629
EARTH_AZIMUTH_ANGLE	178.262	129.16	0.002166	359.999	312629
TIME	3.86607E8	4.48100E6	3.786912E8	3.943292E8	312629
EVENT_ID	5.68403E6	3.59196E6	252	16750419	312629
RUN_ID	3.86604E8	4.48098E6	378691196	394324258	312629
RECON_VERSION	0.	0.	0	0	312629
CALIB_VERSION					312629
EVENT_CLASS	59417.	12671.	16133	65311	312629
CONVERSION_TYPE	0.502263	0.499995	0	1	312629
LIVETIME	113.728	75.93	0.	377.67738	312629
DIFRSP0	0.00016	0.000159	8.22436E-13	0.001121	312629
DIFRSP1	1746.41	816.571	3.37382	4527.51	312629
DIFRSP2	0.000123	0.000145	0.	0.00103	312629
DIFRSP3	1363.16	910.192	0.	4057.85	312629
DIFRSP4	0.	0.	0.	0.	312629

Subset for calculations: All

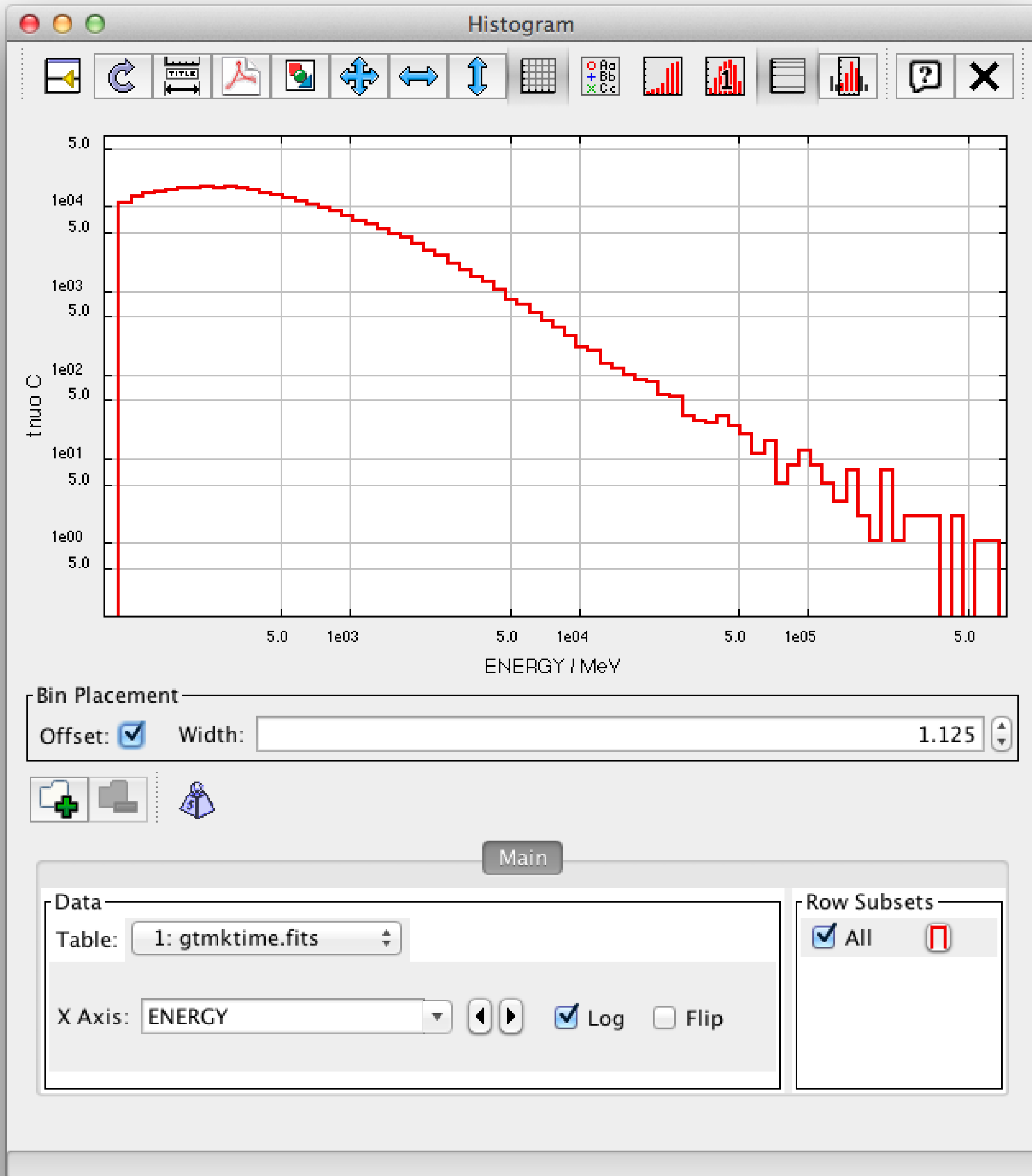
Using TOPCAT is quite easy and it has a good manual, so we will not give detailed instructions how to make the following plots ... with some trial and error you should be able to figure it out yourself.

Spatial distribution

TODO: explain sources and diffuse emission and PSF Point to *Make an image with gtbin and view it with ds9* tutorial and *Galactic Center High-Energy View* tutorial.

Energy distribution

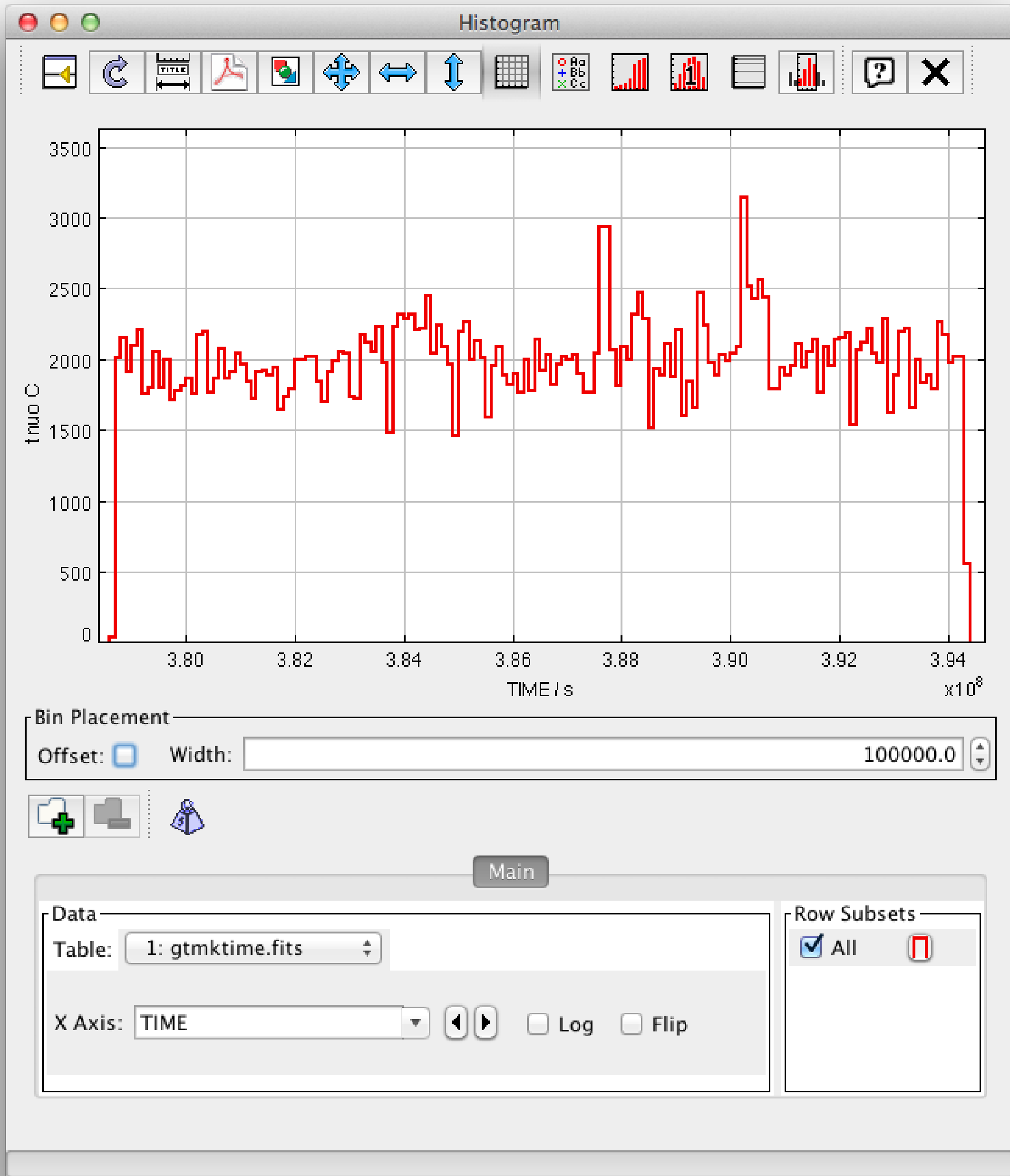
Try to create the following histogram to look at the energy distribution:



TODO: explain shape: source power-law spectra and Fermi-LAT effective area. Point to *Spectrum* tutorial.

Time distribution

Next try to create the following histogram to look at the time distribution (which is proportional to the event rate since we use equal-width time bins).



TODO: explain shape via obs strategy and IRF (and possibly source variability). Point to *Aperture Lightcurve* tutorial.

4.2.6 Make an image with `gtbin` and view it with `ds9`

gtbin

gtbin

ds9

ds9

4.2.7 Summary

In this "Getting Started" tutorial you have learned how to get, preprocess and explore Fermi LAT photon data files using many different tools:

- Command line tools: ftlist, fhelp, plist
- GUI tools: fv, TOPCAT and ds9
- (Command line) Fermi Science Tools: gtselect, gtmktime, gtvcut and gtbin

TODO: finish summary and point to next tutorial.

4.3 Additional reference

For more details, see the following official Fermi LAT analysis threads:

- Extract LAT Data
- Data Preparation
- Explore LAT Data
- Explore LAT Data (for Burst)

CHAPTER

FIVE

SPECTRUM

In this tutorial we will perform a full likelihood analysis of the AGN PG1553+113. We will use the same dataset already used in the official Fermi/LAT collaboration likelihood tutorial as well as in the enrico tutorial, so that you can check your results and have additional information by consulting the two other webpages. The results from the analysis of this dataset were published in Abdo, A. A. et al. 2010, ApJ, 708, 1310.

5.1 A note on directory structure

In order to avoid confusions, it is always best to provide absolute paths for all the files in the analysis. In this tutorial we will assume that you have extracted the `fermi-hero.tar.gz` data tarball to the home directory of your user (here, as an example, we use the username `hero`), so that the directory structure looks like this:

```
$ cd /home/hero/fermi-hero
$ ls
excercises  solutions  spacecraft.fits
$ ls excercises/spectrum/
L120405112547B0489E7F68_PH00.fits
```

To start the tutorial, change directory to `/home/hero/fermi-hero/excercises/spectrum`.

5.2 Make a config file

`enrico` uses configuration files to run analysis (for a full description see the enrico documentation on the configuration files).

You can use the *enrico_config* tool to quickly make a config file called *pg1553.conf*. It will ask you for the required options and copy the rest from a default config file *enrico/data/config/default.conf*:

```
$ enrico_config pg1553.conf
Please provide the following required options [default] :
Output directory [~/fermi-hero/excercises/spectrum] :
Target Name : PG1553+113
Right Ascension: 238.92935
Declination: 11.190102
Options are : PowerLaw, PowerLaw2, LogParabola, PLExpCutoff
Spectral Model [PowerLaw] : PowerLaw2
ROI Size [15] : 15
FT2 file [] : ~/fermi-hero/spacecraft.fits
FT1 list of files [] : ~/fermi-hero/excercises/spectrum/L120405112547B0489E7F68_PH00.fits
tag [LAT_Analysis] : spectrum
```

```
Start time [239557418] : 239557417
End time [334165418] : 256970880
Emin [100] : 200
Emax [300000] :
```

Note :

- Always give the full path for the files
- We used the PowerLaw2 model as in the Fermi tutorial.
- Time is give in MET
- Energy is given in MeV
- ROI size is given in degrees

Now you can edit this config file by hand to make further adjustments.

5.3 Generate a source model xml file

The Fermi Science Tools base their likelihood analysis on a source model written in xml format. Often, this model is complicated to generate. You can run `enrico_xml` to make such model of the sky and store it into a xml file which will be used for the analysis. The options for this step are provided in the config file. For the `enrico_xml` tool, the relevant options are in the `[space]` and `[target]` sections. The out file is given by `[file]/xml`.

This tool automatically adds the following sources to the xml source model file:

- your target source.
- The galactic (GalDiffModel) and isotropic (IsoDiffModel) diffuse components that are the dominant background sources in most LAT analysis.
- All the LAT sources from the two-year catalog (2FGL) that are inside the ROI. The spectral parameters of the sources within 3 degrees of our source are left free so they can be fit simultaneously with our source, whereas those further away are fixed to their catalog values.

```
$ enrico_xml pg1553.conf
use the default location of the catalog
use the default catalog
Use the catalog :  /CATALOG_PATH/gll_psc_v08.fit
Add  24  source(s) in the ROI of  15.0  degrees
3  source(s) have free parameters inside  3.0  degrees
0  source(s) is (are) extended
write the Xml file in /home/hero/fermi-hero/excercises/spectrum/PG1553+113_PowerLaw2_model.xml
```

You can explore the `PG1553+113_PowerLaw2_model.xml` output file with a text editor, where you will find a `source` xml environment for each of the sources. Additionally, the Science Tools provide the `modeleditor` command, which allows you to modify the model from a GUI.

Tip: You can find more information about the different spectral models available and their parameters at the source model definitions for gtlike and a few examples of model definitions in XML format webpages.

5.4 Run global fit

The gtlike tool finds the best-fit parameters by minimizing a likelihood function. Before running gtlike, the user must generate some intermediary files by using different tools. With enrico, all those steps are merged in one tool. `enrico_sed` will execute the following steps for you with the options you have selected in `pg1553.conf`:

1. **gtselect**: Perform event selection.
2. **gtmktime**: Perform time selection based on spacecraft file.
3. **gtbin**: Compute a counts cube map from the selected data. A counts cube map is a collection of counts maps for different energies.
4. **gtltcube**: Perform the calculation of the livetime cube. This is the most computationally intensive step, taking.
5. **gtexpcube2**: Use the previously generated livetime cube and apply it to your ROI to obtain an exposure cube.
6. **gtsrcmaps**: Create model counts maps for each of the sources in the source model catalog. This is used to speed up the likelihood calculation of `gtlike`.

From all the preliminary fits files generated in the previous steps, `enrico` is ready to run the likelihood minimisation routine that will result in the best-fit parameters for our source of interest with the tool `gtlike`.

To run the global fit just call:

```
$ enrico_sed pg1553.conf
```

> **Warning:** Computationally intensive! `enrico_sed` takes a long time to execute and requires significant amounts of RAM memory. As an example, in my 2011 i5 laptop the `gtltcube` step took 20 minutes and the `gtsrcmaps` took 10 minutes to run.

The command line output of the likelihood fitting should be similar to the following:

```
# *********************************************************
# *** SUMMARY:  ***
# *********************************************************
Source  =   PG1553
RA  =   238.929  degrees
Dec =   11.1901  degrees
Start   =   239557417.0   MET (s)
Stop    =   256970880.0   MET (s)
ROI =   15.0  degrees
E min   =   100.0  MeV
E max   =   300000.0  MeV
IRFs    =   P7SOURCE_V6

# *********************************************************
# ***   1     gtlike --- Run likelihood analysis
# *********************************************************

# *********************************************************
# ***   2 Remove all the weak (TS<1) sources
# *********************************************************
delete source :  2FGL J1506.6+0806  with TS =  0.767925309599
delete source :  2FGL J1602.4+2308  with TS =  -1.51036832301
delete source :  2FGL J1625.2-0020  with TS =  -0.595845252567

# *********************************************************
# ***   3 Re-optimize --- False
# *********************************************************
```

```
# **********************************************************
# ***   4    Results --- Print results of the fit
# **********************************************************
2FGL J1504.3+1029
   Spectrum: LogParabola
0           norm:  1.418e+00  0.000e+00  1.000e-05  1.000e+03 ( 1.000e-10) fixed
1          alpha:  2.147e+00  0.000e+00  5.000e-01  5.000e+00 ( 1.000e+00) fixed
2           beta:  1.237e-01  0.000e+00  5.000e-04  5.000e+00 ( 1.000e+00) fixed
3             Eb:  6.583e+02  0.000e+00  3.000e+01  3.000e+05 ( 1.000e+00) fixed

        .
        .
        .
<< Fit results for all 2FGL sources in ROI >>
        .
        .
        .

2FGL J1650.8+0830
   Spectrum: PowerLaw
60      Prefactor:  6.834e-01  0.000e+00  1.000e-05  1.000e+03 ( 1.000e-11) fixed
61          Index: -2.588e+00  0.000e+00 -5.000e+00 -5.000e-01 ( 1.000e+00) fixed
62          Scale:  5.007e+02  0.000e+00  3.000e+01  3.000e+05 ( 1.000e+00) fixed

GalDiffModel
   Spectrum: ConstantValue
63          Value:  9.683e-01  1.921e-02  1.000e-02  1.000e+01 ( 1.000e+00)

IsoDiffModel
   Spectrum: FileFunction
64    Normalization:  1.048e+00  2.588e-02  1.000e-03  1.000e+03 ( 1.000e+00)

PG1553
   Spectrum: PowerLaw2
65       Integral:  7.953e+01  5.898e+00  1.000e-05  1.000e+03 ( 1.000e-09)
66          Index: -1.652e+00  3.260e-02 -5.000e+00 -5.000e-01 ( 1.000e+00)
67     LowerLimit:  1.000e+02  0.000e+00  3.000e+01  3.000e+05 ( 1.000e+00) fixed
68     UpperLimit:  3.000e+05  0.000e+00  3.000e+01  3.000e+05 ( 1.000e+00) fixed


Source Name Npred   TS
2FGL J1504.3+1029   685.605 225.223
2FGL J1505.1+0324   46.157  8.439
2FGL J1506.9+1052   91.375  17.318
2FGL J1512.2+0201   82.526  22.541
2FGL J1516.9+1925   96.264  20.261
2FGL J1540.4+1438   95.445  5.211
2FGL J1546.1+0820   18.329  7.421
2FGL J1548.3+1453   183.234 24.980
2FGL J1549.5+0237   424.594 171.586
2FGL J1550.7+0526   197.593 39.120
2FGL J1551.9+0855   147.204 39.806
2FGL J1553.5+1255   981.741 808.294
2FGL J1607.0+1552   358.437 130.859
2FGL J1608.5+1029   563.097 41.313
2FGL J1612.0+1403   100.888 11.320
```

```
2FGL J1624.4+1123   141.388 8.021
GalDiffModel    27825.333   4090.152
IsoDiffModel    22819.444   2049.134
PG1553  1020.913    2189.417

# *********************************************************

Values and (MINOS) errors for PG1553
TS :  2189.41693741
Integral :  79.53 +/-  5.90 [ -5.79, + 6.01 ] 1e-09
Index :  -1.65 +/-  0.03 [ -0.03, + 0.03 ] 1e+00
LowerLimit :  100.00 +/-  0.00  1e+00
UpperLimit :  300000.00 +/-  0.00  1e+00
The covariance matrix is :
[[  3.47835182e+01  -1.46149842e-01]
 [ -1.46149842e-01   1.06305680e-03]]

Source Flux  [1.00e+02 MeV, 3.00e+05 MeV] :
2FGL J1551.9+0855   Integral Flux : 1.44e-08 +/-  5.41e-09 ph/cm2/s
2FGL J1553.5+1255   Integral Flux : 8.40e-08 +/-  8.63e-09 ph/cm2/s
GalDiffModel   Integral Flux : 4.68e-04 +/-  9.28e-06 ph/cm2/s
IsoDiffModel   Integral Flux : 2.17e-04 +/-  5.36e-06 ph/cm2/s
PG1553   Integral Flux : 7.95e-08 +/-  5.90e-09 ph/cm2/s


# *********************************************************
# ***   5    PlotSED --- Generate SED plot
# *********************************************************

Decorrelation energy : 2.50e+03 MeV
Diffential flux  at the Decorrelation energy : 2.55e-12 +/-  1.23e-13 ph/cm2/s/MeV
SED value at the Decorrelation energy : 2.56e-11 +/-  1.24e-12 erg/cm2/s

# *********************************************************
# ***   6    gtmodel --- Make model map
# *********************************************************
time -p /data/soft/fermi-st/ScienceTools/bin/gtmodel srcmaps=/home/vzabalza/lat-tut/excercises/spectr
real 35.64
user 32.12
sys 3.50
# *********************************************************
```

After the fit has converged, `enrico` prints the best-fit parameters for all the sources in the model file, including our source of interest:

```
Values and (MINOS) errors for PG1553
TS :  2189.41693741
Integral :  79.53 +/-  5.90 [ -5.79, + 6.01 ] 1e-09
Index :  -1.65 +/-  0.03 [ -0.03, + 0.03 ] 1e+00
LowerLimit :  100.00 +/-  0.00  1e+00
UpperLimit :  300000.00 +/-  0.00  1e+00
The covariance matrix is :
[[  3.47835182e+01  -1.46149842e-01]
 [ -1.46149842e-01   1.06305680e-03]]
```

In addition, it runs the tool `gtmodel` to generate a counts map from the best-fit model, which is subtracted from our original counts map file to identify any sources that have been imperfectly modeled.

A file with the extension 'results' will be produced and where all the results will be stored.

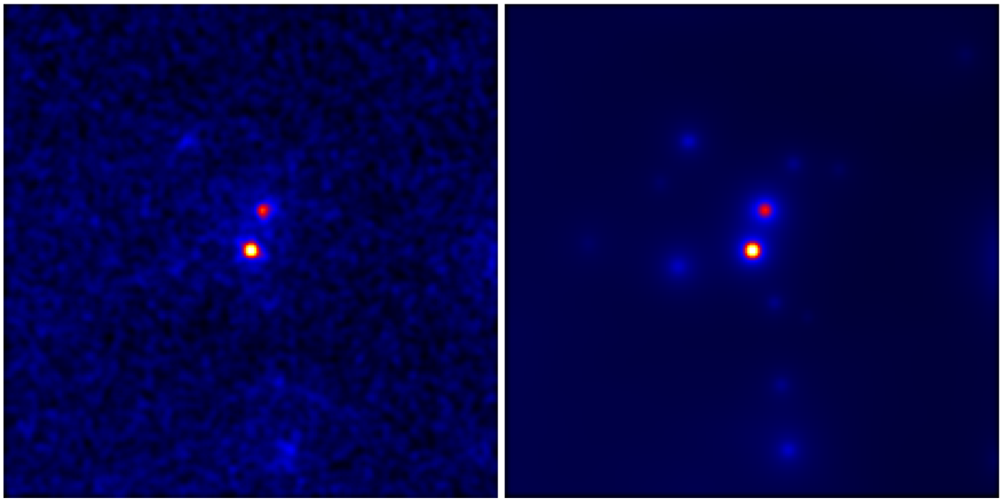


Figure 5.1: Observed (left, `PG1553_LAT_CountMap.fits`) and model (right, `PG1553_LAT_ModelMap.fits`) counts maps.

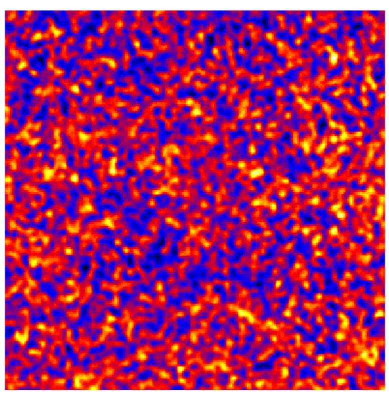


Figure 5.2: Residual counts map (`PG1553_Residual_Model_cmap.fits`) resulting of the substraction of the model map to the observed map. The uniform noise-like appearance and a low peak value of about 3% of the above maps indicate that the model accounts for all the observed emission.

Note: If you want to refit the data because e.g. you changed the xml model, you are not force to regenerate the fits file. Only the gtlike tool should be executed again. You can do this with enrico by changing the option `[spectrum]/FitsGeneration` from yes to no, and enrico will bypass all the preliminary calculations and perform only the fit.

You can use `enrico_testmodel` to compute the log(likelihood) of the models `PowerLaw`, `LogParabola` and `PLExpCutoff`. An ascii file is then produced in the Spectrum folder with the value of the log(likelihood) for each model. You can then use the Wilk's theorem to decide which model best describes the data.

5.5 Compute flux points

Warning: The computation of flux points takes very long, so we will not have time to execute it during the tutorial. It is here for information and future reference.

Note that for the above global fit, we have obtained a fit of the source parameters to the data, but we have not computed flux points to be plotted as a spectrum. To do so you should rerun the above analysis for each of the energy ranges for which you want to generate a spectral point. Fortunately, `enrico` can automate this process!

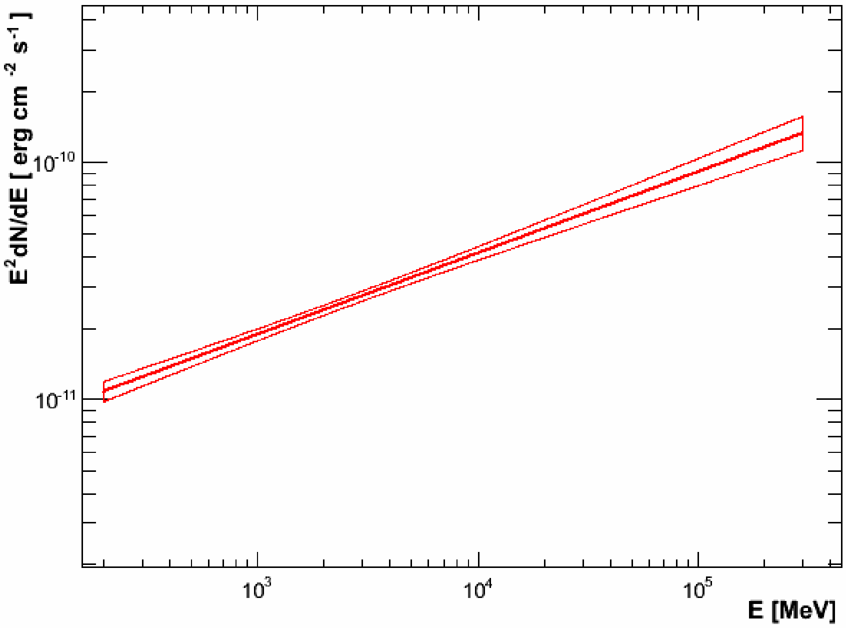
To compute flux points, the `enrico_sed` tool will also be used. It will first run a global fit (see previous section) and if the option [Ebin]/NumEnergyBins is greater than 0, at the end of the overall fit, enrico will run `NumEnergyBins` new analyses by dividing the energy range.

Each analysis is a proper likelihood analysis (it runs gtselect, gtmktime,gtltcube,..., gtlike), run by the same enrico tool than the full energy range analysis. If the TS found in any of the energy time bins is below [Ebin]/TSEnergyBins then an upper limit is computed.

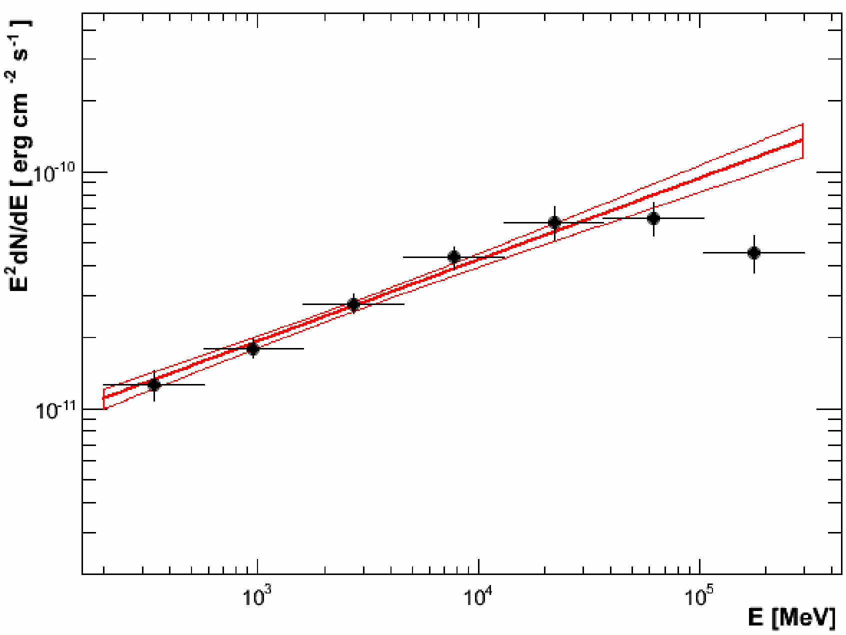
Note: If a bin failed for some reason or the results are not good, you can rerun the analysis of the bin by calling *enrico_sed* and the config file of the bin (named SOURCE_NumBin.conf and in the subfolder Ebin#).

5.6 Plotting the spectrum

Enrico will already have produced several diagnostic plots during the execution of the analysis tools. To plot the final spectrum, we will use the tool `enrico_plot_sed`, which will use the results from the likelihood fitting to produce an SED plot. If you have not run the spectral point computation routine, `enrico_plot_sed` will only plot a bowtie of the best-fit model and its uncertainty:



If we have run the `enrico_sed` tools with `[Ebin]/NumEnergyBins` larger than 0, the `Ebin#` directory will be populated with the results of the likelihood analyses of all the energy bins, and will be used to plot the SED containing the flux points:



CHAPTER

SIX

GALACTIC CENTER HIGH-ENERGY VIEW

The Galactic center and the Galactic plane are amongst the most interesting regions in the Fermi-LAT all-sky survey.

In this tutorial we will use the Fermi science tools to investigate images of the diffuse emission and sources in that region and end with a quick look at the hint for a spectral emission line at 130 GeV that has recently caused a lot of excitement because if real it would most likely consitute the first detection of dark matter.

6.1 Introduction

6.1.1 Overview

In this tutorial we want to make an image of the sources in the Galactic plane, using only photons above 10 GeV.

The Fermi LAT observes the whole gamma-ray sky in the energy band of roughly 100 MeV to 100 GeV, with some exposure below and above that range. The angular resolution (called the PSF) varies by almost two orders of magnitude from ~ 15 deg at 100 MeV to ~ 0.2 deg at 100 GeV. (Check out the Fermi LAT Performance page for further information.)

Because of the high source density in the Galactic plane and the vert poor Fermi LAT angular resolution at low energies it makes sense to only use the high-energy photons (we use E > 10 GeV here).

One point to keep in mind though is that the Fermi LAT only detects very few photons at high energies, because the Galactic diffuse and source emission roughly follows a differential power-law spectrum

$$\frac{dN}{dE} \sim F_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$$

which corresponds to an integral power law spectrum of

$$N(>E)\, E^{-\Gamma+1}$$

with a **power law spectral index** of $\Gamma \sim 2.6$ for the Galactic diffuse emission and often harder $\Gamma \sim 1.8$ to $\Gamma \sim 2.6$ source emission.

Note that for $\Gamma = 2.6$ there are more than two orders of magnitude difference in the number of photons above a given energy when moving up one decade in energy, i.e. for the Galactic diffuse emission the number of photons above 10 GeV in only 0.25% compared to the number of photons above 1 GeV, and above 100 GeV it's only 0.00063% compared to 1 GeV.

With this background knowledge you should be able to understand the basic facts about the following Fermi LAT count images in energy bands:

- Sources appear much smaller at high energies, simply because the PSF is so much better there.
- The drawback of only looking at high-energy photons is that they are few in numbers.
- The Galactic source to diffuse emission ratio increases with energy, i.e. sources are more prominent in the second panel compared to the first panel.

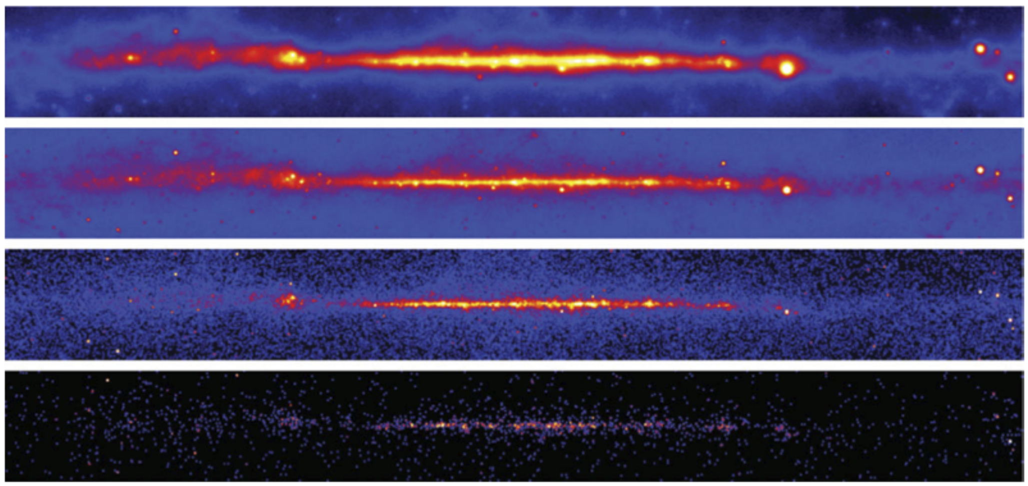
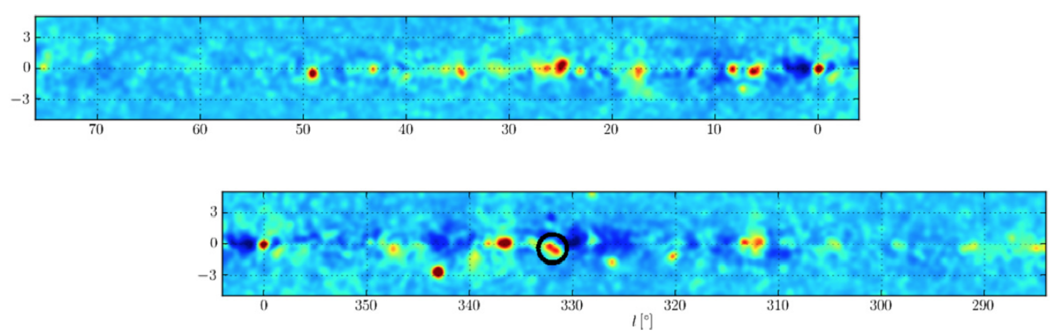


Figure 6.1: Fermi LAT count maps of the Galactic plane (GLON = -180 deg to +180 deg, GLAT = -10 deg to +10 deg), smoothed with a Gaussian of 0.5 deg width in the energy bands 0.1 – 1 – 10 – 100 – 1000 GeV (top to bottom). The Crab (pulsar and nebula) is the bright source below the Galactic plane that can be even above 100 GeV. Taken from Deil et al. (2012), IAU Symposium 284, 365D.

6.1.2 Sources

In this tutorial we would like to produce an image showing only the Galactic source emission above 10 GeV, with the diffuse Galactic and isotropic emission substracted.

We will do this via the formula `excess = (total counts) - (diffuse model counts)`, where the diffuse model consists of a Galactic and isotropic part. (For the Galactic plane the Galactic diffuse emission is much brighter than the isotropic diffuse emission, so you can't see the isotropic diffuse emission in the images above).



6.2 Prepare the data

The following procedure is explained in *Getting Started*.

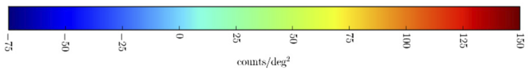


Figure 6.2: Fermi LAT source excess maps (counts / deg^2, smoothed with a Gaussian of 0.27 deg width) of the Galactic plane in the energy range 10 GeV to 316 GeV. Galactic and isotropic diffuse emission as well as known sources that have been identified as blazars are subtracted. Taken from Acero et al. (Fermi LAT collaboration) (2013), ApJ 773, 77A (top and bottom panel and colorbar only).

You start by creating a file `events.txt` that contains the photon data files you downloaded. Note that in this case there the Fermi LAT data server generated eight files, each only about 1 MB (mega-byte) large because there are only few events above 10 GeV.:

```
$ ls -1 *_PH??.fits > events.txt
$ du -hs *_PH??.fits
968K  L1309071835220B976F4330_PH00.fits
1004K L1309071835220B976F4330_PH01.fits
1.1M  L1309071835220B976F4330_PH02.fits
1.2M  L1309071835220B976F4330_PH03.fits
1.0M  L1309071835220B976F4330_PH04.fits
1.1M  L1309071835220B976F4330_PH05.fits
1.0M  L1309071835220B976F4330_PH06.fits
840K  L1309071835220B976F4330_PH07.fits
808K  L1309071835220B976F4330_PH08.fits
```

Now tun the following commands in sequence. `gtselect` will just take a few seconds, `gtmktime` a few minutes and `gtltcube` will take a few hours ... so we suggest you copy the file `gtltcube.fits` from the solutions folder so that you can continue quickly

```
$ gtselect infile=@events.txt outfile=gtselect.fits \
  ra=INDEF dec=INDEF rad=INDEF tmin=INDEF tmax=INDEF \
  emin=10e3 emax=316e3 zmax=100 evclass=2

$ gtmktime scfile=../../spacecraft.fits evfile=gtselect.fits \
  filter="DATA_QUAL==1&&LAT_CONFIG==1&&ABS(ROCK_ANGLE)<52" \
  roicut=yes outfile=gtmktime.fits

$ gtltcube evfile=gtmktime.fits scfile=../../spacecraft.fits \
  outfile=gtltcube.fits dcostheta=0.025 binsz=1
```

On my laptop `gtselect` takes 2 seconds, `gtmktime` takes 4 minutes and `gtltcube` takes two hours!

6.3 Create count and and model images with the Fermi Science Tools

6.3.1 Make a count image with `gtbin`

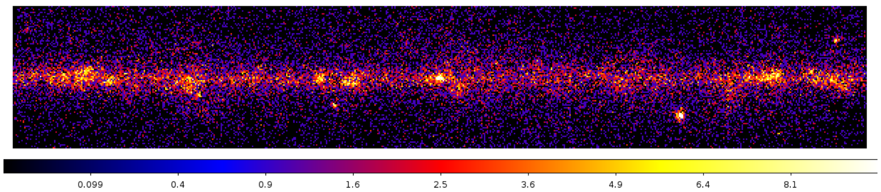
Run gtbin to make a counts image:

```
$ gtbin
This is gtbin version ScienceTools-v9r31p1-fssc-20130410
Type of output file (CCUBE|CMAP|LC|PHA1|PHA2|HEALPIX) [] CMAP
Event data file name[] gtmktime.fits
Output file name[] count_image.fits
Spacecraft data file name[] ../../spacecraft.fits
Size of the X axis in pixels[] 600
Size of the Y axis in pixels[] 100
```

```
Image scale (in degrees/pixel)[] 0.1
Coordinate system (CEL - celestial, GAL -galactic) (CEL|GAL) [] 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:[] CAR
```

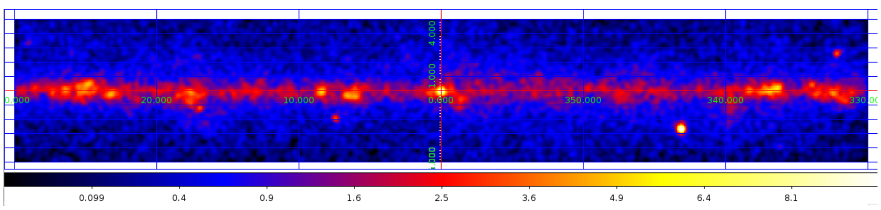
Open up the image in ds9 and use the following commands to get an image that looks like this:

- Select Scale -> Scale Parameters and `sqrt` with range 0 to 10.
- Color -> b



Now use these options to get the following view of the same counts image:

- `Analysis -> Smooth Parameters` with a 3 pixel Gauss kernel
- Analysis -> Coordinate grid
- WCS -> Galactic and WCS -> Degrees



6.3.2 Make a model image with `gtbin`, `gtexpcube2` and `gtmodel`

Next we want to make a model image (a.k.a an "expected counts image") for the diffuse Galactic and isotropic emission. See here for information on these diffuse model components that are considered "background" for gamma-ray source analysis.

To get this image we need to run the following three Fermi ScienceTools in sequence:

- gtbin with the `CCUBE` option.
- gtexpcube2
- gtmodel

First we need to describe the model, which we do in the XML file `diffuse_model.xml`:

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

<!-- Diffuse Sources -->
<source name="gal_2yearp7v6_v0" type="DiffuseSource">
        <spectrum type="PowerLaw">
                <parameter free="1" max="10" min="0" name="Prefactor" scale="1" value="1"/>
                <parameter free="0" max="1" min="-1" name="Index" scale="1.0" value="0"/>
                <parameter free="0" max="2e2" min="5e1" name="Scale" scale="1.0" value="1e2"/>
```

```
        </spectrum>
        <spatialModel file="gal_2yearp7v6_v0.fits" type="MapCubeFunction">
                <parameter free="0" max="1e3" min="1e-3" name="Normalization" scale="1.0" value="1.0
        </spatialModel>
</source>
<source name="iso_p7v6source" type="DiffuseSource">
        <spectrum file="iso_p7v6source.txt" type="FileFunction">
                <parameter free="1" max="10" min="1e-2" name="Normalization" scale="1" value="1"/>
        </spectrum>
        <spatialModel type="ConstantValue">
                <parameter free="0" max="10.0" min="0.0" name="Value" scale="1.0" value="1.0"/>
        </spatialModel>
</source>

</source_library>
```

Next we create symbolic links to the diffuse model files that come with the Fermi Science tools software distribution so that the tools will find them:

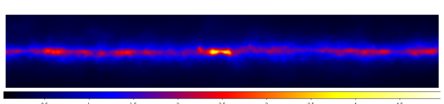
```
ln -s $FERMI_DIR/refdata/fermi/galdiffuse/gal_2yearp7v6_v0.fits .
ln -s $FERMI_DIR/refdata/fermi/galdiffuse/iso_p7v6source.txt .
```

Now we can run the tools to compute exposure and the PSF-convolved model image using these commands:

```
$ gtbin evfile=gtmktime.fits scfile=../../spacecraft.fits outfile=count_cube.fits \
  algorithm=CCUBE ebinalg=LOG emin=10e3 emax=316e3 enumbins=8 \
  nxpix=600 nypix=100 binsz=0.1 coordsys=GAL \
  xref=0 yref=0 axisrot=0 proj=CAR

$ gtexpcube2 infile=gtltcube.fits cmap=none outfile=gtexpcube2.fits \
  irfs=P7SOURCE_V6 nxpix=1800 nypix=900 binsz=0.2 coordsys=GAL \
  xref=0 yref=0 axisrot=0 proj=AIT \
  emin=10e3 emax=316e3 enumbins=8 bincalc=EDGE

$ gtmodel srcmaps=count_cube.fits srcmdl=diffuse_model.xml \
  outfile=model_image.fits irfs=P7SOURCE_V6 \
  expcube=gtltcube.fits bexpmap=gtexpcube2.fits
```

On my machine `gtbin` takes 5 seconds, `gtexpcube2` takes 1 minute and `gtmodel` takes 5 minutes.

Note: Exercise: Inspect the generated files with `ftlist` and `ds9` to see what they contain.



Consult the official Fermi LAT Binned Likelihood Tutorial analysis thread for detailed information.

6.4 Compute an excess and significance image with Python

We would like to compute correlated `excess = counts - background` and significance images of the sources detected by the Fermi LAT above 10 GeV in the inner part of the Galactic plane, similar to the one we showed previously from the Fermi publication.

Note: What is statistical significance and how can I compute it?

TODO http://en.wikipedia.org/wiki/Statistical_significance

This functionality is not readily available as a command line Fermi Science Tool.

If would be possible to do it by using fgauss and ftimgcalc.

Instead of using these command line FTOOLs let's use a Python script `make_source_images.py`:

```python
"""Compute correlated source excess and significance maps.

Christoph Deil, 2013-09-12
"""
import numpy as np
from numpy import sign, sqrt, log
from scipy.ndimage import convolve
import pyfits

def correlate_image(image, radius):
    """Correlate image with circular mask of a given radius.

    This is also called "tophat correlation" and it means that
    the value of a given pixel in the output image is the
    sum of all pixel values in the input image within a given circular radius.

    https://gammapy.readthedocs.org/en/latest/_generated/gammapy.image.utils.tophat_correlate.html
    """
    radius = int(radius)
    y, x = np.mgrid[-radius: radius + 1, -radius: radius + 1]
    structure = x ** 2 + y ** 2 <= radius ** 2
    return convolve(image, structure, mode='constant')

def significance_lima(n_observed, mu_background):
    """Compute Li & Ma significance.

    https://gammapy.readthedocs.org/en/latest/_generated/gammapy.stats.poisson.significance.html
    """
    term_a = sign(n_observed - mu_background) * sqrt(2)
    term_b = sqrt(n_observed * log(n_observed / mu_background) - n_observed + mu_background)
    return term_a * term_b


if __name__ == '__main__':
    print('Reading count_image.fits')
    counts = pyfits.getdata('count_image.fits')
    print('Reading model_image.fits')
    model = pyfits.getdata('model_image.fits')

    radius = 5 # correlation circle radius
    correlated_counts = correlate_image(counts, radius)
    correlated_model = correlate_image(model, radius)

    excess = correlated_counts - correlated_model
    significance = significance_lima(correlated_counts, correlated_model)

    header = pyfits.getheader('count_image.fits')
    print('Writing excess.fits')
    pyfits.writeto('excess.fits', excess, header, clobber=True)
    print('Writing significance.fits')
    pyfits.writeto('significance.fits', significance, header, clobber=True)
```

TODO: explain script a bit.

Run it by typing:

```
$ python make_source_images.py
```

Note: Exercise: Open up the `exercise.fits` and `significance.fits` images and see if the values roughly make sense.

6.5 Explore Sources

Download the First Fermi-LAT Catalog of Sources above 10 GeV (1FHL) like this:

```
$ wget http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1FHL/gll_psch_v07.fit
```

and the LAT 2-year Point Source Catalog in FITS and ds9 region format like this:

```
$ wget http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/gll_psc_v08.fit
$ wget http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/gll_psc_v07.reg
```

6.5.1 HESS Galactic plane survey

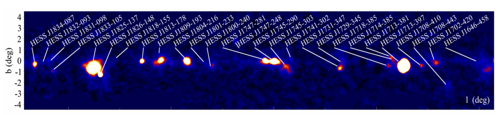


Figure 6.3: HESS survey image (TeV energy range). Reference: http://adsabs.harvard.edu/abs/2013arXiv1307.4690C

6.6 The 130 GeV line

6.6.1 What is it?

In April 2012 Christoph Weniger (not a member of the Fermi-LAT collaboration) reported "A tentative gamma-ray line from Dark Matter annihilation at the Fermi Large Area Telescope" (arXiv) with a statistical significance of 4.6 sigma at 130 GeV, and 3.2 sigma after taking into account the look-elsewhere effect, i.e. the fact that he did search for a line in multiple regions of the sky and at multiple energies.

This generated a lot of noise in the gamma-ray astrophysics community because, if real, this 130 GeV gamma-ray emission line cannot easily be explained by normal astrophysical sources ... for almost all sources we expect from theory and also see power-law spectra ... sometimes with curvature or cutoff, but never with a sharp line feature.

On the other hand ... if the dark matter we know exists in the inner part of our Galaxy (all galaxies, actually) consists of weekly interacting particles (Wimps), there are theories that predict them to annihilate and produce an emission line consistent with the feature discovered in the Fermi LAT data.

In May 2013 the Fermi LAT collaboration has reported their "Search for Gamma-ray Spectral Lines with the Fermi Large Area Telescope and Dark Matter Implications" (arXiv), computing the statistical significance of this line feature at 130 GeV at a lower statistical significance of 3.3 sigma, and only 1.6 sigma after taking the look-elsewhere effect into account.

You can find a nice summary and the latest results in this presentation by Andrea Albert at the recent TeVPA 2013 conference if you don't have time to read the 40-page paper.

The full analysis is very complex and not suitable for beginners, but because it's such an interesting feature, let's try to produce a similar plot as this one showing the line:

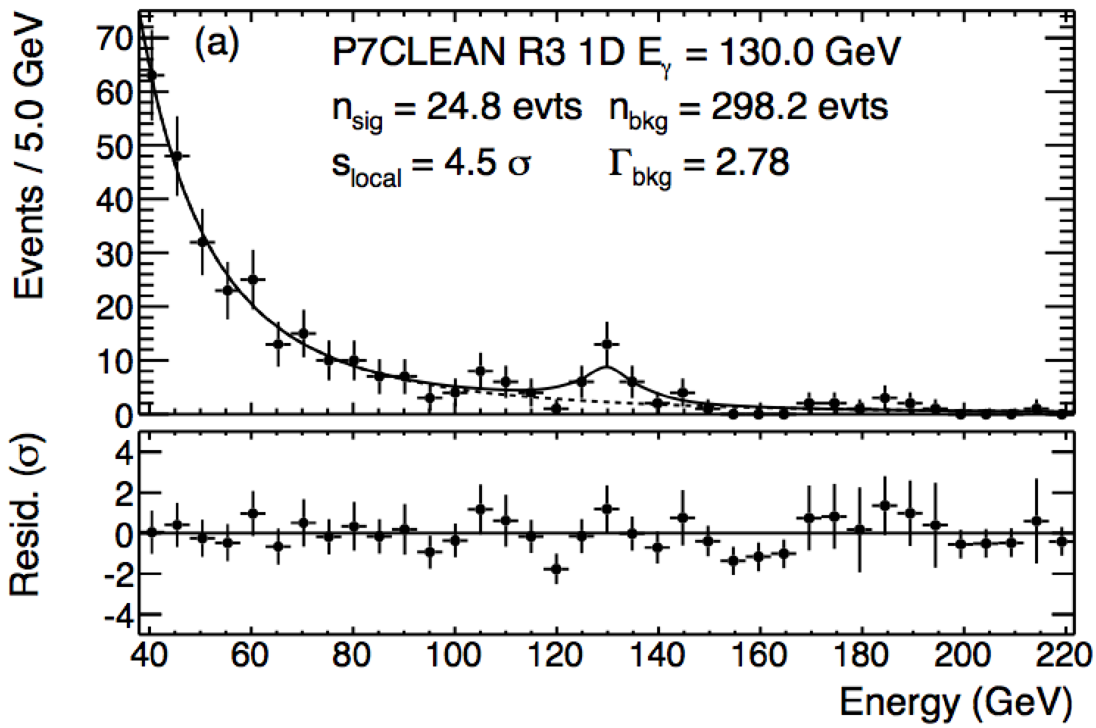


Figure 6.4: Count spectrum showing the 130 GeV line for the region of 3 degrees around the Galactic center. Reference: arXiv 1305.5597, Figure 11, top panel.

6.6.2 Event selection

As always we start by preparing the event list by running `gtselect` and `gtmktime`. Note that we can use the same photon files as input that we to make Galactic plane high-energy images, because in both cases our event selection is a subset the event selection we specified when downloading the data.

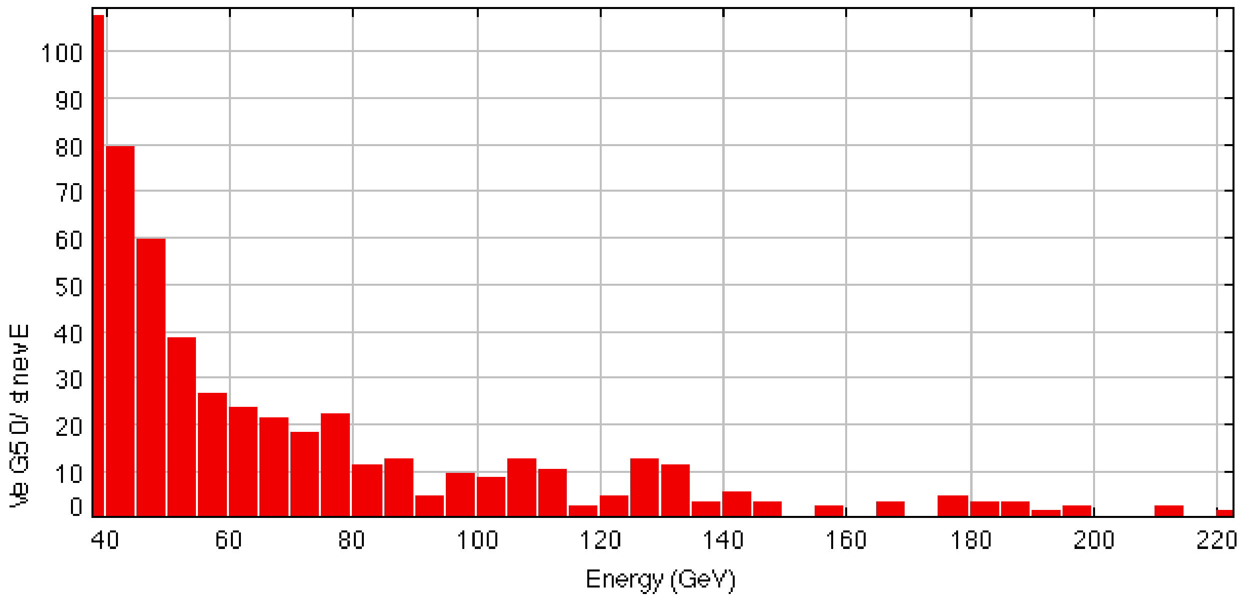
Let's use the same region of interest (ROI) of 3 deg around the Galactic center and no energy cut at this point:

```
$ gtselect infile=@events.txt outfile=line_gtselect.fits \
  ra=266.404996 dec=-28.936172 rad=3 tmin=INDEF tmax=INDEF \
  emin=10000 emax=1000000 zmax=100 evclass=2

$ gtmktime scfile=../../spacecraft.fits evfile=line_gtselect.fits \
  filter="DATA_QUAL==1&&LAT_CONFIG==1&&ABS(ROCK_ANGLE)<52" \
  roicut=yes outfile=line_gtmktime.fits
```

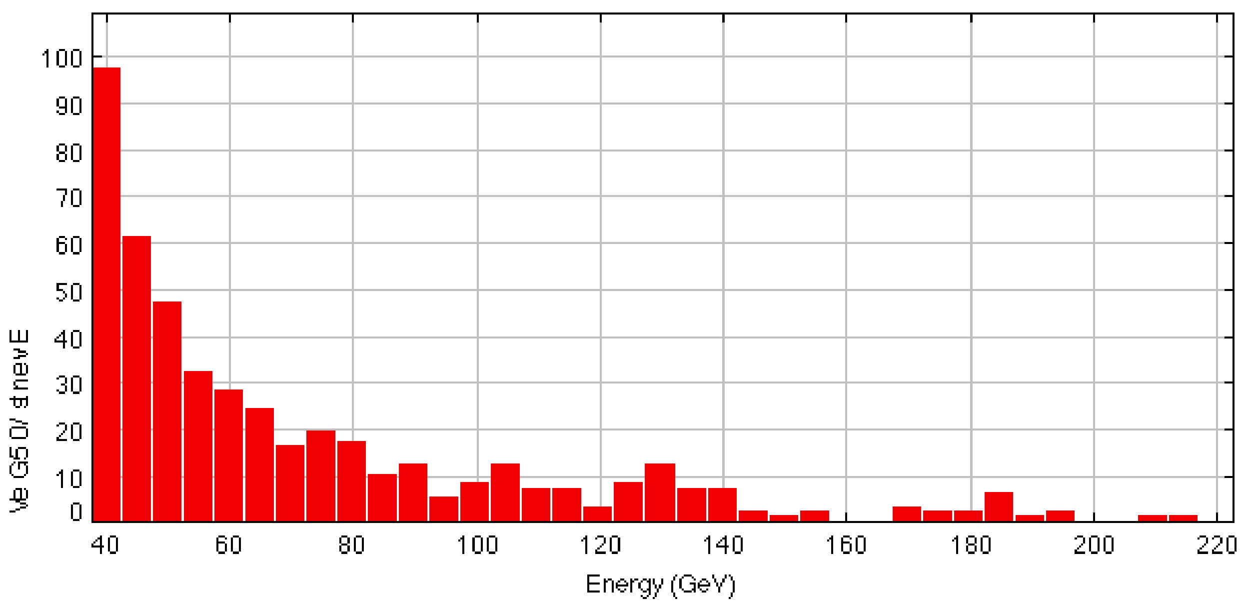
6.6.3 Quick look with TOPCAT

Try to use TOPCAT to reproduce this counts histogram.

- Enter `1e-3 * ENERGY` instead of only `ENERGY` to get GeV instead of MeV.
- Binning selection: 37.5 GeV to 222.5 GeV with 5 GeV bin width (37 bins)
- There should be TODO events.
- Please also label the axes as shown.
- Export the plot in PNG as well as PDF format and check it with some other viewer.



Note how the visual impression changes of the shape of the peak (amplitude, width) changes if you move the bins by half a bin width:



Note that we will not reproduce the Fermi LAT collaboration result exactly, the main reason being that we use a slightly longer exposure (i.e. a larger time range of observation) and thus will have more events.

The Fermi plot has 24.8 + 298.2 = 323 according to the label. If you click `Subsets -> New subset from visible` in TOPCAT you will see that we have 412 events.

6.6.4 Nice plot with Python `matplotlib`

The Fermi science tools ships with two Python packages that you can use to make plots:

- ROOT can be used from Python like this: `import ROOT`
- matplotlib can be used from Python like this: `import matplotlib.pyplot as plt`

Note: In my opinion, the `matplotlib` import looks more complicated, but apart from that it is better documented and easier to use and more powerful than `ROOT` plotting. But both have a learning curve ... we suggest you try out both a bit, then stick with the one you like better.

Let's use `matplotlib` to make the same plot with a Python script. The advantage of making plots with a script instead of interactively is that they are reproducible and usually will result in less human error, but also less work because typically you re-run your analyses many times, checking how results change when you vary parameters or update data or correct errors.

Here is the script ... put this in a file called `plot_line.py`:

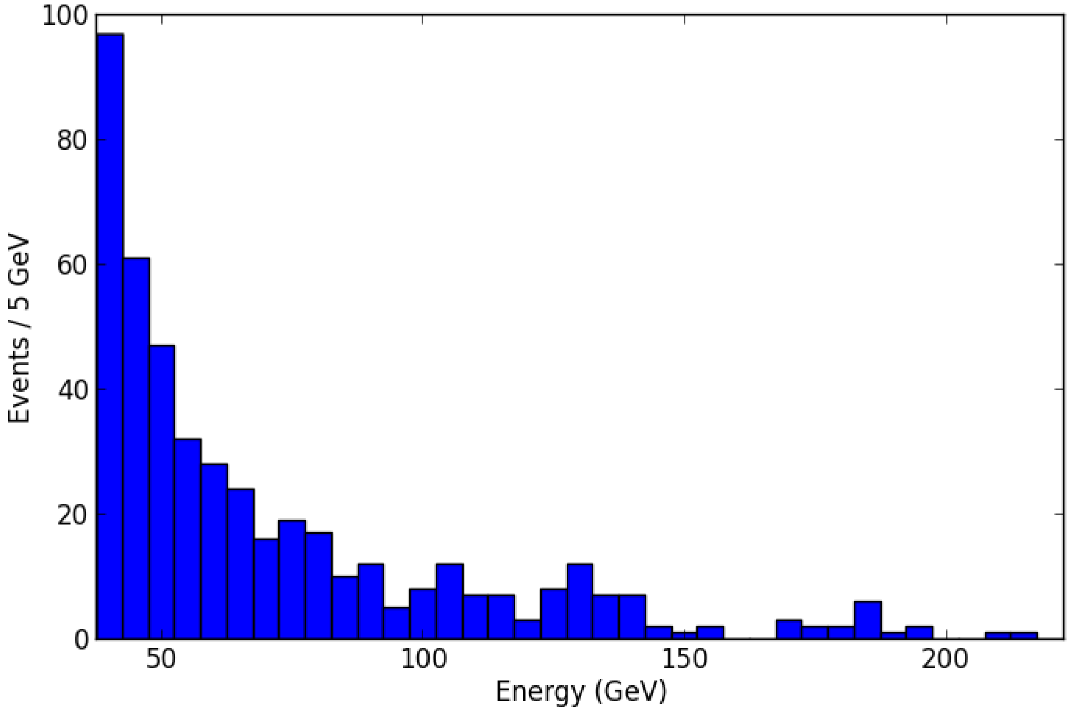
```python
"""Plot count spectrum of Galactic center events around 130 GeV line feature.

This script generates a plot comparable to Figure 11 in this paper:
http://adsabs.harvard.edu/abs/2013arXiv1305.5597F

Christoph Deil, 2013-09-12
"""
import pyfits
import matplotlib.pyplot as plt

MEV_TO_GEV = 1e-3
E_MIN, E_MAX = 37.5, 222.5

events = pyfits.getdata('line_gtmktime.fits')
energy = MEV_TO_GEV * events.field('ENERGY')
selection = (energy > E_MIN) & (energy < E_MAX)
n_events = len(energy[selection])
print('Number of events: {0}'.format(n_events))

plt.figure(figsize=(8, 5))
plt.hist(energy, bins=37, range=(E_MIN, E_MAX))
plt.xlabel('Energy (GeV)')
plt.ylabel('Events / 5 GeV')
plt.xlim(E_MIN, E_MAX)
plt.savefig('gc_line_matplotlib.png')
```

This is the command to run the script from the terminal:

```
$ python plot_line.py
Number of events: 462
$
```

TODO: Check why this number (462) is different from the one I got with TOPCAT (412)!?

And here's the output:

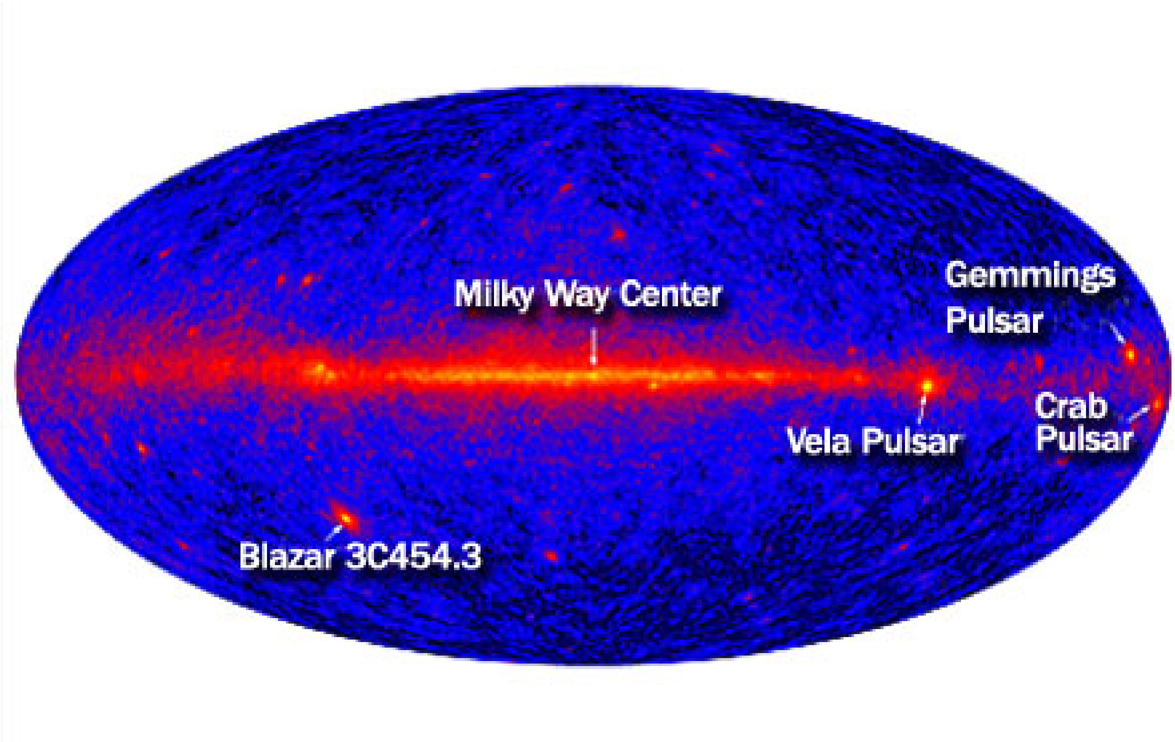


6.6.5 Conclusion

So what do you think is the origin of the line feature?

Note that there's a ~ 5% chance that the line is simply a Poisson background fluctuation. To compute this probability from the given significance you can use scipy.stats.norm, althogh for me currently the import fails with the Fermi ScienceTools Python:

```
$ ipython

In [1]: from scipy.stats import norm

In [2]: norm.sf(1.6)
Out[2]: 0.054799291699557974
```


Milky Way Center
Gemmings
Pulsar
Vela Pulsar
Crab
Pulsar
Blazar 3C454.3

CHAPTER

SEVEN

APERTURE LIGHTCURVE

7.1 Computing the aperture lightcurve

In this section of the tutorial we will learn how to generate an aperture lightcurve from Fermi/LAT.

There are two different kinds of lightcurves that can be computed from Fermi/LAT observations: using likelihood analysis on each of the lightcurve bins, or aperture analysis. The likelihood analysis leads to a better sensitivity and the ability to obtain background-substracted flux lightcurves, but is model-dependent and very computationally intensive, especially for longer periods of time. Aperture lightcurve generation, on the other hand, is less computationally demanding and provides a model-independent estimate of the variability of a given source. However, there is no way to do an estimation of the background, so it should not be used to estimate the source's flux.

Here we will compute the aperture lightcurve of the remarkable April 2011 flare from the Crab Nebula. The Crab Nebula has been used for decades as the standard candle in High Energy Astrophysics, as it is bright and expected to have a constant flux. However, Fermi/LAT discovered that its flux is far from constant, exhibiting flux changes of a factor of 10 or more over just a few hours. The astrophysical process behind these flares is still unkown.

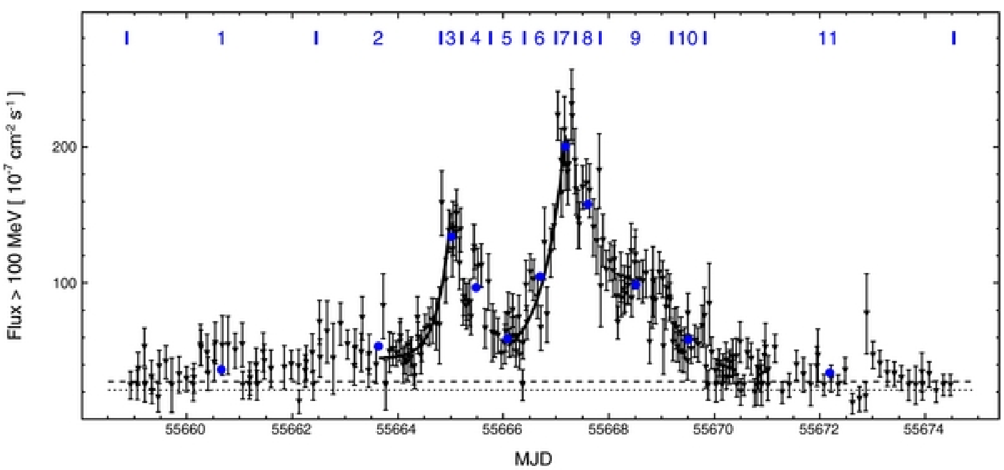


Figure 7.1: Fermi/LAT lightcurve of the April 2011 Crab Nebula flare as published in Buehler et al. (2012), ApJ 749, 26

In this tutorial we assume that you have already installed and initialized the Fermi Science Tools as well as `enrico`.

Change directory to where you have extracted the excercise data files and enter the `lightcurve` directory. You can explore the data selection applied to the event file with `gtvcut` command.

Generate an configuration file for this observation with the command:

```
$ enrico_config crab.conf
```

and enter the name and coordinates of the source (you will find them in the data selection cuts shown with `gtvcut`). For the aperture lightcurve, the model and ROI size parameters are not used, so leave them to their default values. Finally, select the initial and final analysis times as given in the server query file.

You can the edit the file `crab.conf` to check the parameters. In addition to the `target`, `space`, `file`, and `time` categories, the `AppLC` configuration category includes the values used by `enrico` when creating the aperture lightcurve. Use the `NLCbin` parameter to set the number of bins desired in the lightcurve between `tmin` and `tmax`. Given that the total selection time in the photon file is 16 days, 32 bins will result in a bin width of 12 hours, and 64 bins in a bin width of 24 hours. You can try different bin widths to check which one yields the most informative lightcurve, taking into account that shorter time bin widths will result in larger uncertainties.

During these observations the survey mode of the Fermi observatory was changed in favour of pointed observations towards the Crab Nebula. For this reason, one of the filter options in crab.conf (`ABS(ROCK_ANGLE)<52`) should be removed as it is related to the survey mode spacecraft rocking. The resulting filter expression in `[analysis]/filter` should be:

```
[analysis]
    filter = DATA_QUAL==1&&LAT_CONFIG==1
```

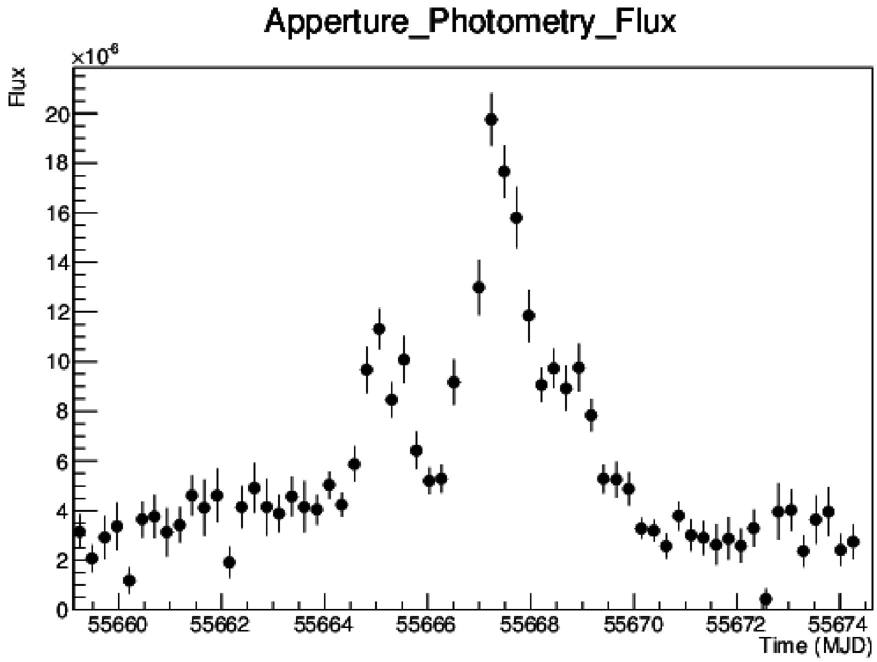
Finally, run the aperture lightcurve `enrico` script:

```
$ enrico_applc crab.conf
```

This scrip will run the following tasks:

1. **gtselect** : Select the events from the input FT1 file.
2. **gtmktime** : Compute good time intervals based on spacecraft pointing and SAA position.
3. **gtbin** : Bin the data into a lightcurve.
4. **gtexposure** : Compute the exposure (effective area*observation time) for each of the bins.
5. From the results of **gtbin** and **gtexposure**, lightcurve plots are generated in the `AppertureLightcurve` directory.

The resulting aperture lightcurve will be saved in `AppertureLightcurve/AppLC.eps`, and should reproduce the two peaks shown in Buehler et al. (2012) as seen in the following example:


Apperture_Photometry_Flux
Flux
×10⁻⁶
20
18
16
14
12
10
8
6
4
2
0
55660
55662
55664
55666
55668
55670
55672
55674
Time (MJD)

CHAPTER

EIGHT

MORE

Pointers to learn more gamma-ray data analysis ...

- http://python4astronomers.github.io
- https://astropy4mpik.readthedocs.org/en/latest/
- https://gammafit.readthedocs.org/en/latest/

Other Fermi LAT tutorials or useful links:

- http://adsabs.harvard.edu/abs/2013arXiv1307.4534S
- http://fermi.gsfc.nasa.gov/science/mtgs/summerschool/2013/program.html
- https://confluence.slac.stanford.edu/display/LSP/Fermi+Summer+School+2013
- http://nbviewer.ipython.org/urls/raw.github.com/kialio/fermi-summer-school/master/Data_Exploration.ipynb
- http://grbworkshop.wikidot.com/s6-fermi-lat-analysis-hands-on
- https://confluence.slac.stanford.edu/display/LSP/Installing+the+Virtual+Machine
- http://fermi.gsfc.nasa.gov/science/mtgs/workshops/da2012_solar/instructions.html
- http://www.asdc.asi.it/articles.php?id=52
- http://fermi.gsfc.nasa.gov/ssc/library/conferences/219aas/