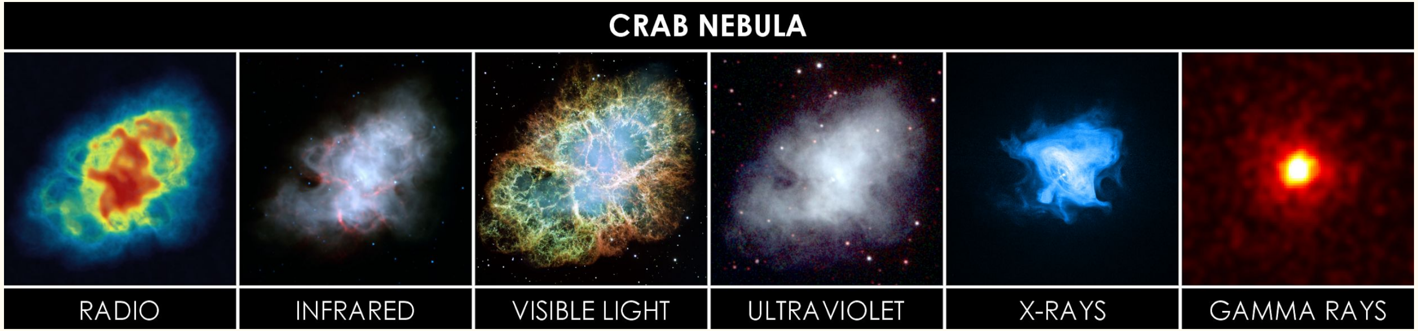
PhD Course Work for Multimessenger Astroparticle Physics:
Fermi LAT Data Analysis of Crab Nebula & Pulsar

Hevjin Yarar

Crab Nebula

- Remnant of a Supernova which exploded in 1054. Located at a distance of 2 kpc (1 pc = 3.26 light-years or 31×10^{12} km).
- Consists of a pulsar, a pulsar wind nebula, a cloud of expanding ejecta.
- Visible vortex around the center, which is a neutron star rotating with period of 33 ms and emitting pulsed gamma-rays.
- Standard candle for high energy photon emission (reference unit) due to high luminosity and stable flux over time (even if it flares from time to time!).
- The pulsar signal is used to check the timing of the X-ray detectors and calibration of γ-ray telescopes.
- Well studied in almost all wavelength bands from the radio to very high energy γ-rays.
- Recently observed to emit gamma rays in excess of 100 TeV! [1]



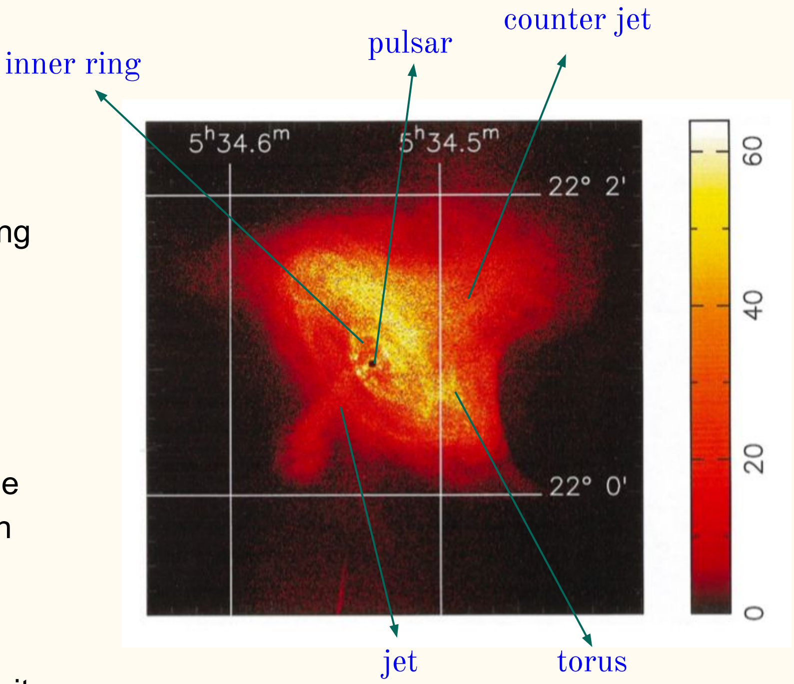
[2]

Crab Nebula

- The SN explosion left a pulsar behind which is emitting continuously a wind of magnetized plasma of electron/positron pairs. Electrons diffuse in the surrounding medium and interact with the magnetic and photon fields releasing energy → PWN

- PWN streams into the interstellar medium and creates a standing shock wave called 'termination shock', where the particles may undergo Fermi acceleration → inner ring on the plot with radius ~ 0.1 pc.

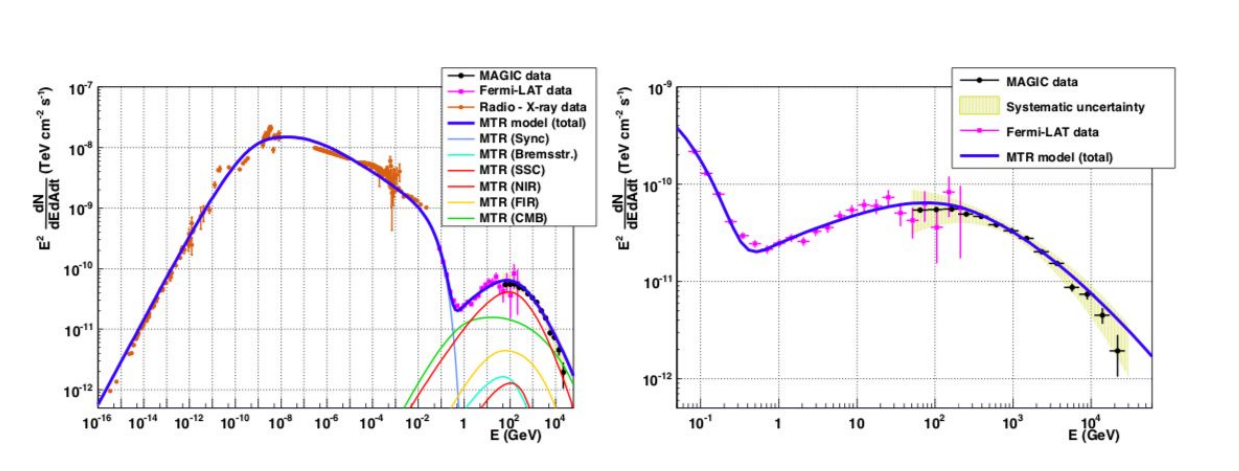
- At X-ray wavelengths a bright torus surrounds the pulsar; its radius is 0.4 pc and jets emerge perpendicular to it in both directions. [3]



[4]

Spatial structure of the nebula in the x-ray emission

Crab Nebula
Energy Spectrum



[5]

Spectral energy distribution of Crab Nebula (left), zoom in the gamma ray regime (right).

For my study: Fermi-LAT data with energy range 100 MeV - 500 GeV.

- The nebula emits synchrotron radiation observed from radio frequencies up to soft γ rays (first bump).
- Inverse Compton scattering of electrons off the synchrotron photons, infrared and cosmic microwave background and bremsstrahlung radiation of relativistic electrons produce the high energy gamma rays (second bump).

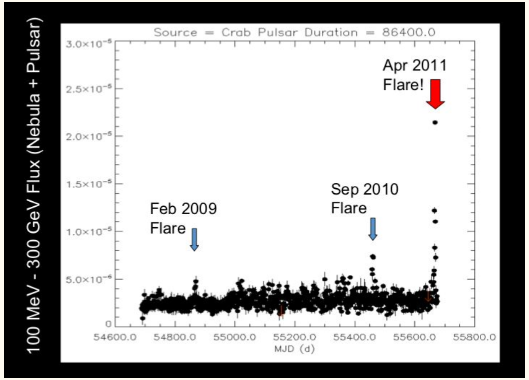
Crab Nebula

Main Photon Production Mechanisms

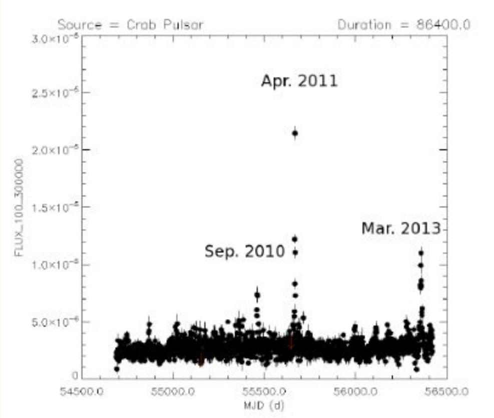
- Synchrotron radiation:
  - Due to electrons spiralling around magnetic field lines at relativistic speeds. The magnetic field generated by the pulsar is strong and so the radiation emission happens in narrow beams (The average magnetic field inside the Crab Nebula is estimated to be ~200 μG, 1 G = 10^4 T)
  - The radiation is polarized in the plane perpendicular to the magnetic field, so magnetic field of the nebula can be studied with the degree and orientation of the polarization.
  - The synchrotron radiation from the electron is over a range of frequencies which peaks at a certain critical frequency. The longer the electron travels around the magnetic field, the more energy it loses, the narrower the spiral gets and the smaller the critical frequency. This results in a power law decay of the synchrotron emission spectrum ~ v^{α} , where α is the spectral index (for pulsars: -3 < α < -2 while for AGNs: -1 < α < +1).
- Inverse Compton Scattering (Synchrotron Self-Compton):
  - Electrons interact with the synchrotron radiation created by the other electrons via inverse compton scattering.

Flares

- Variations of emission with unusually short durations (hours to days), high luminosities, and high photon energies (hundreds of MeV) from the Crab Nebula. A lot of theories about why they happen but no clear consensus.
- During the flares no flux change from the pulsar [3]
- April 2011 flare is 30x brighter than average pulsar + nebula flux!



Flares in Feb 2009, Sep 2010 and Apr 2011.



[6]

Flares in Sep 2010, Apr 2011 and Mar 2013.

Flares

- Short timescales hint to the originating phenomenon to be active in a small region.
  L: diameter of the flaring region
  t: flare duration
  D: Doppler factor (expected to be moderate, since typical velocities < 0.9c)

  $L < D \cdot c \cdot t$ results in an area smaller than 0.014 pc. This small structures are found only in the inner part of the nebula (in the shape of wisps, knots on the X-ray image), close to the termination shock and the base of the jet [3].

- The brevity of the flare suggests also synchrotron radiation. If the radiation was originating from Inverse Compton or Bremsstrahlung, the cooling time of the electrons emitting the photons would exceed the flare duration t.

  Via Bremsstrahlung: 10^6 years (particle density < 10 cm^{-3})
  Via IC: 10^7 years

Fermi LAT Data

The two point sources located within the nebula are cataloged as J0534.5+2200 and J0534.5+2201i, which respectively model the Crab pulsar and the Crab Nebula.

FermiLAT Data Server
https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

needs the following criteria

Query L1906041114415CA465FA73 submitted.

Please see LAT Data Caveats for important information about Fermi LAT data.

Your search criteria were:

Equatorial coordinates (degrees)	(83.6331,22.0145)
Time range (MET)	(323222402,325900802)
Time range (Gregorian)	(2011-03-31 00:00:00,2011-05-01 00:00:00)
Energy range (MeV)	(100,500000)
Search radius (degrees)	15

The estimated time for your query to complete is 26 seconds. The results of your query may be found at https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/QueryResults.cgi?id=L1906041114415CA465FA73.

fermipy and configuration

- Fermipy's GTAnalysis requires python2 (!).

- The first step is to compose a configuration file that defines the data selection and analysis parameters. fermiPy uses the YAML format for its configuration files. The configuration file has a hierarchical organization that groups related parameters into separate dictionaries.

photon data

spacecraft data

spatial bin size in deg

energy bins per decade

min, max energy

maximum zenith angle, selected to filter out gammas from Earth

events with the highest probability to be gammas

energy dispersion correction disabled for galactic and isotropic diffuse sources

likelihood analysis based on Poisson statistics

assume a model that will be convolved with the instrument response function (irf)

```
config_text ="data: \n\
  evfile : L1906041212485CA465FA35_PH00.fits\n\
  scfile : L1906041212485CA465FA35_SC00.fits\n\
\n\
binning:\n\
  roiwidth   : 10.0\n\
  binsz      : 0.1\n\
  binsperdec : 8\n\
\n\
selection :\n\
  ra : 83.6331\n\
  dec : 22.0145\n\
  emin : 100\n\
  emax : 500000\n\
  zmax     : 90\n\
  evclass : 128\n\
  evtype   : 3\n\
  tmin     : 323222402\n\
  tmax     : 325900802\n\
  filter   : null\n\
  target : 3FGL J0534.5+2201\n\
\n\
gtlike:\n\
  edisp : True\n\
  irfs : 'P8R3_SOURCE_V2'\n\
  edisp_disable : ['isodiff','galdiff']\n\
\n\
model:\n\
  src_roiwidth : 15.0\n\
  galdiff  : 'gll_iem_v07.fits'\n\
  isodiff  : 'iso_P8R3_SOURCE_V2_v1.txt'\n\
  catalogs : ['3FGL']";
```

```
with open("config.yaml",'w') as f:
    f.write(config_text)
```

fermipy’s GTAnalysis

```
gta = GTAnalysis('config.yaml',logging={'verbosity' : 3})
gta.setup()
```

```
2019-06-06 13:39:41 INFO    GTAnalysis.__init__():
------------------------------------------------------------------
fermipy version 0.17.3
ScienceTools version ScienceTools-11-04-00
```

- GTAnalysis runs the modules requested in the configuration file and creates
  - binned sky exposure maps
  - source maps in the ROI
  - 3D cube file which contains the distribution of events as a function of energy and two spatial coordinates

```
# Free Normalization of all Sources within 3 deg of ROI center
gta.free_sources(distance=3.0,pars='norm')

# Free all parameters of galactic diffuse components
gta.free_source('galdiff')
```

```
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0534.5+2201     : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0534.5+2201i    : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0534.5+2201s    : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0526.4+2247     : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0544.7+2239     : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for isodiff               : ['Normalization']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for galdiff               : ['Prefactor']
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for galdiff               : ['Index']
```

```
gta.free_source('3FGL J0534.5+2201')
```

```
2019-06-06 13:45:24 INFO    GTAnalysis.free_source(): Freeing parameters for 3FGL J0534.5+2201     : ['Index1', 'Cutoff']
```

- Parameters of the sources to be fit need to be freed before the likelihood analysis.

Likelihood Analysis

- Fermi LAT data is limited by statistics and a strong background.
- We apply statistical techniques. fermipy includes the maximum likelihood method with the following steps:
  - Assume a model for the signal from the telescope

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

  - Convolve it with the instrument response function, which describes the performance of the telescope as a function of photon energy, incidence angle, conversion point within the instrument and other parameters
  - Derive the probability (pdf) for the observed photon from a location, at a time with an energy given the model.

$$M(E',\hat{p}',t) = \int_{SR} dE\,d\hat{p}\,R(E',\hat{p}',t;E,\hat{p})S(E,\hat{p},t) \xrightarrow[\text{photons}]{\text{sum over}} \sum_j \log M(E'_j,\hat{p}'_j,t_j)$$

  - Calculate the total number of predicted counts of photons given the model by summing over all photons in the ROI.

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

[8]

Likelihood Analysis

- Treat the difference as a function of the model parameters (likelihood).

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

- Adjust the model parameters until the likelihood is maximized $\left.\frac{\partial \ln \mathcal{L}}{\partial \theta_j}\right|_{\{\hat{\theta}_k\}} = 0$ where θ_j are the model parameters.
- In the limit of large number of counts, Wilk's Theorem states that the Test Statistic for the null hypothesis is asymptotically distributed as the χ^2_k distribution where k is the number of parameters characterizing the additional source.

Null hypothesis max likelihood, h parameters

$$\mathrm{TS} = -2\ \log \frac{\mathscr{L}_0}{\mathscr{L}_1} \xrightarrow[N\to\infty]{} \chi^2_{m-h}$$

non fixed parameters

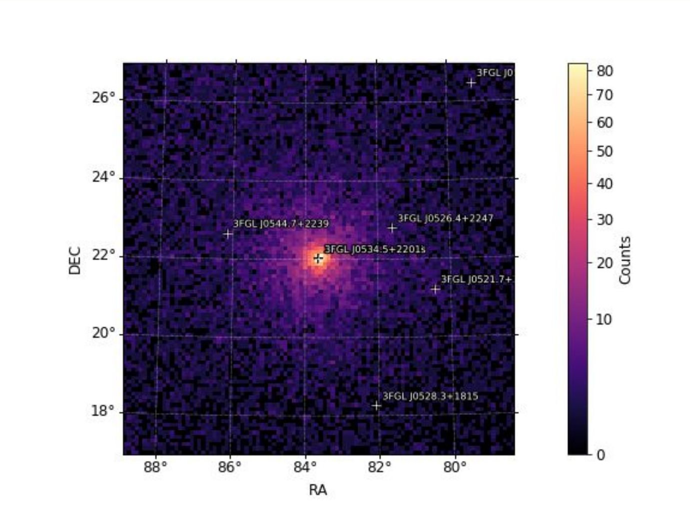
Alternative hypothesis max likelihood, m parameters

- In this case the null hypothesis is the model without the source. With large TS we reject the null hypothesis.
- The square root of the TS taken to be approximately equal to the detection significance for a given source.

Analysis

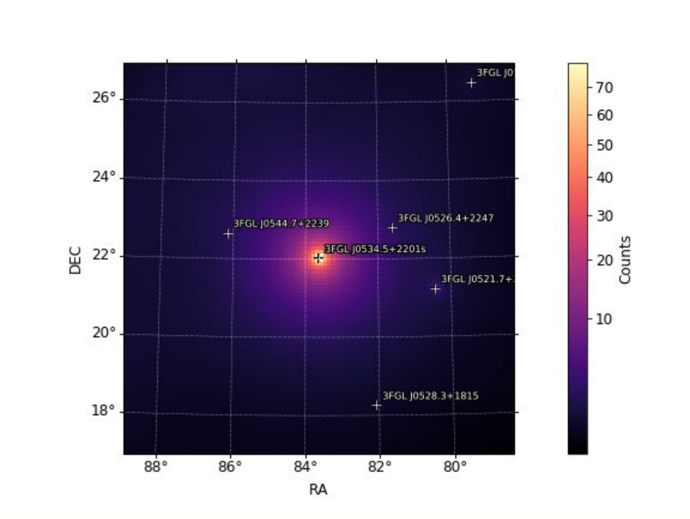
Crab Nebula during April 2011-flare (1 month)

Observed data:



- Counts map in the ROI with the nebula at the center (much higher counts than non-flare period) .

The model:

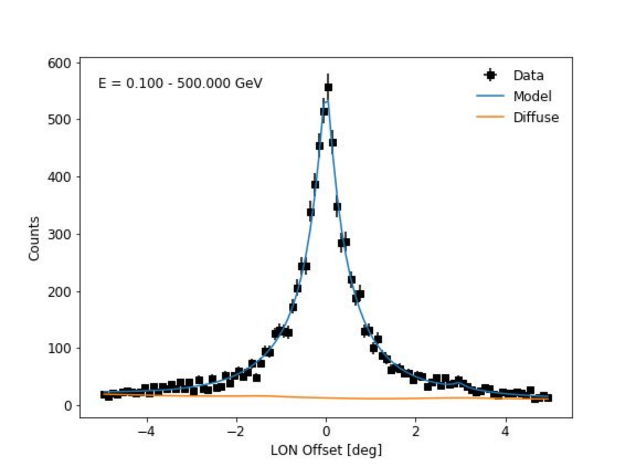


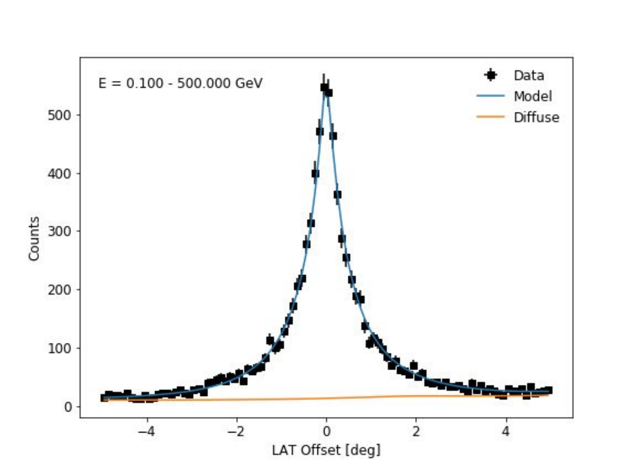
- Includes the distribution of gamma ray sources, their intensity and spectra.

Same analysis for non-flare time can be found in the backup.

Analysis

Crab Nebula during 2011-flare

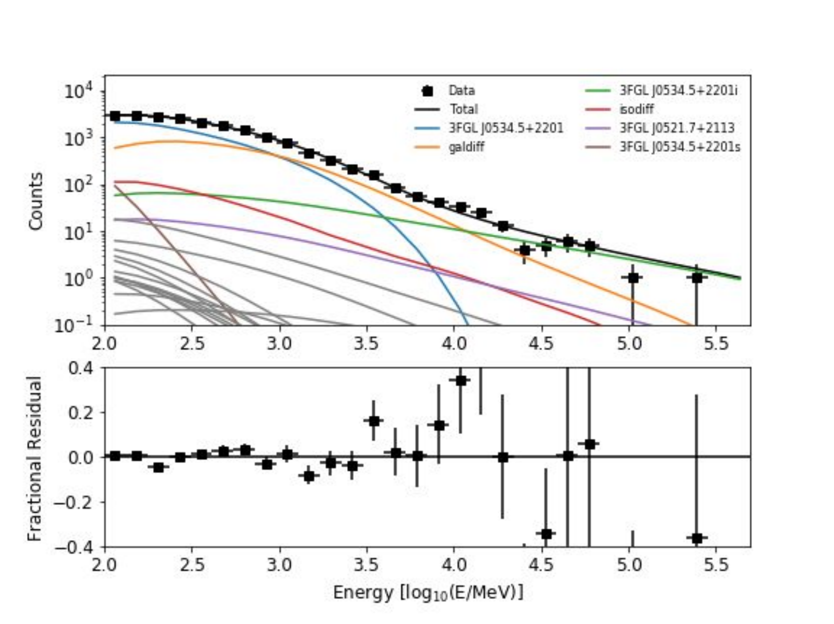




- Counts vs Longitude Offset: Projection onto x-axis
- Counts vs Latitude Offset: Projection onto y-axis

Analysis

Crab Nebula during 2011-flare



- Counts spectrum shows Crab Pulsar (blue), Crab Nebula (green) and the galactic (orange) and the isodiff sources (red).
- Nebula emission is much higher (~ 1 order of magnitude) than the non-flare period.
- Energy range of the emission is narrower during the flare.

Analysis

Crab Nebula during 2011-flare

```
print('Fit Quality: ',fit_results['fit_quality'])
print(gta.roi['3FGL J0534.5+2201'])
```

```
('Fit Quality: ', 3)
Name           : 3FGL J0534.5+2201
Associations   : ['3FGL J0534.5+2201', 'PSR J0534+2200', 'Crab', '1FHL J0534.5+2201', '2FGL J0534.5+2201', '1AGL J0535+2205', 'Crab Pulsa
r']
RA/DEC         :     83.637/    22.024
GLON/GLAT      :    184.551/    -5.776
TS             : 12962.88
Npred          : 11530.25
Flux           : 5.655e-06 +/-  1.7e-07
EnergyFlux     :  0.001581 +/- 4.56e-05
SpatialModel   : PointSource
SpectrumType   : PLSuperExpCutoff
Spectral Parameters
Prefactor      :  1.629e-09 +/-  1.314e-10
Index1         :     -2.051 +/-    0.06676
Scale          :      635.6 +/-        nan
Cutoff         :       1769 +/-      343.6
Index2         :          1 +/-        nan
```

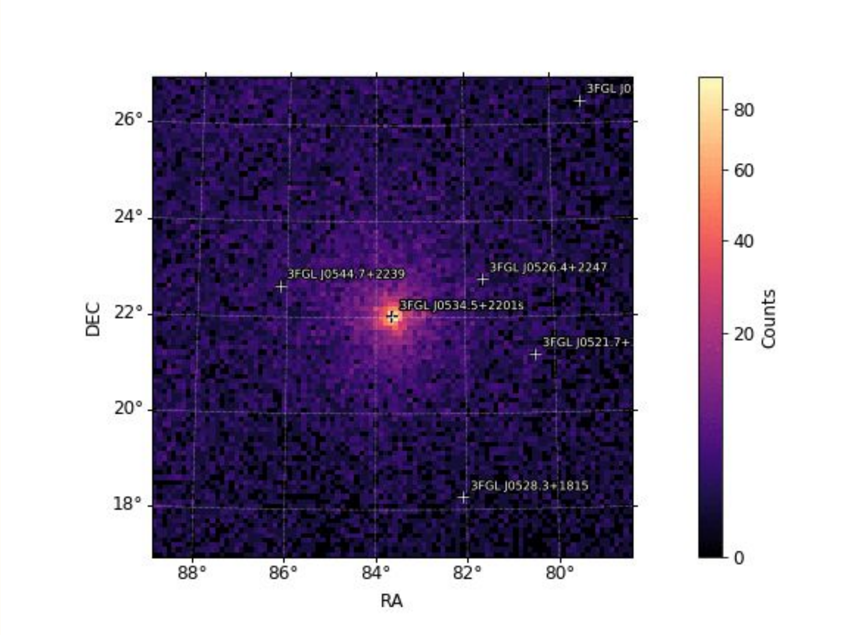
predicted number of photons

spectral index

- Large TS: null hypothesis rejection / high detection significance.

Analysis

Crab Nebula in 2008 - 2016

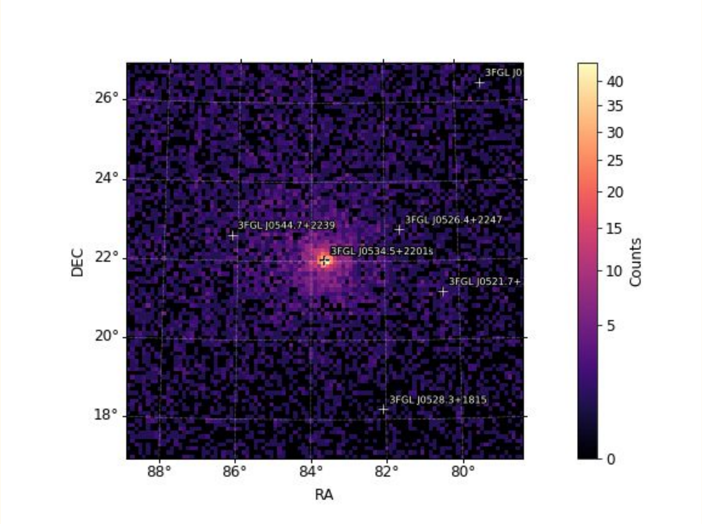


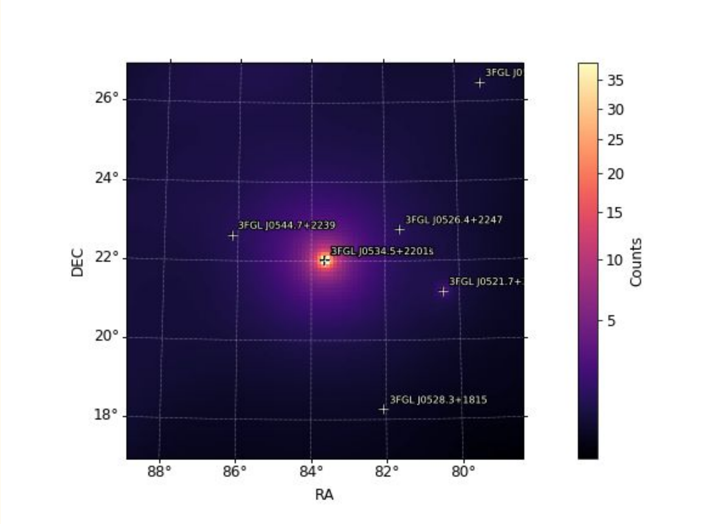
Counts per two months, one month overlapping.

Observations:

- The flares are visible.
- The general flux decreased at the end of 2010 (?).

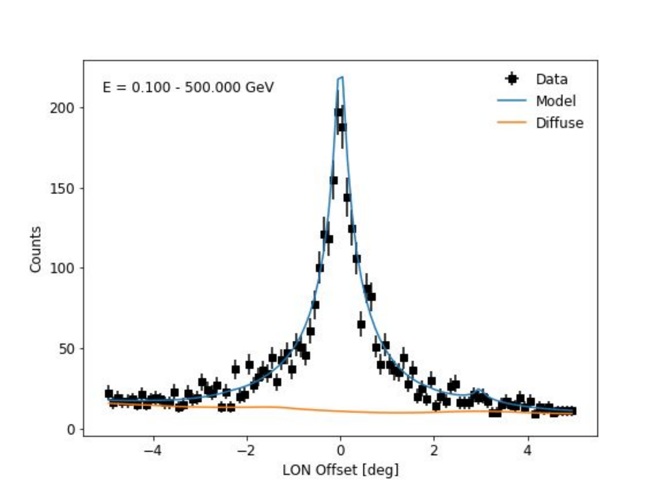
Backup 1 - Crab Nebula non-flare period (1 month)

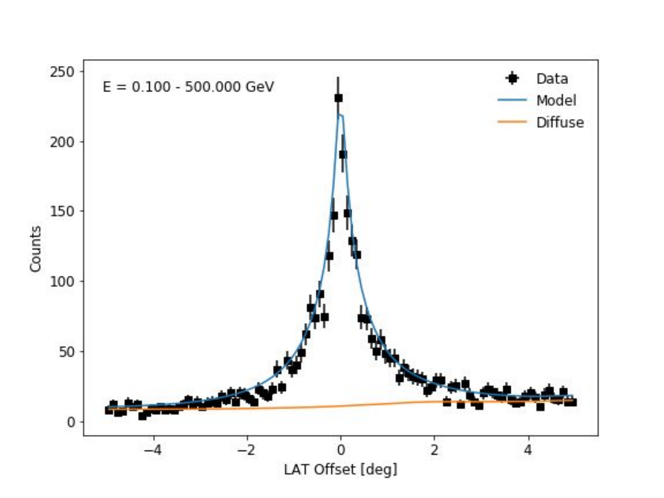




- Counts map in the ROI with the nebula at the center.
- Includes the distribution of gamma ray sources, their intensity and spectra.

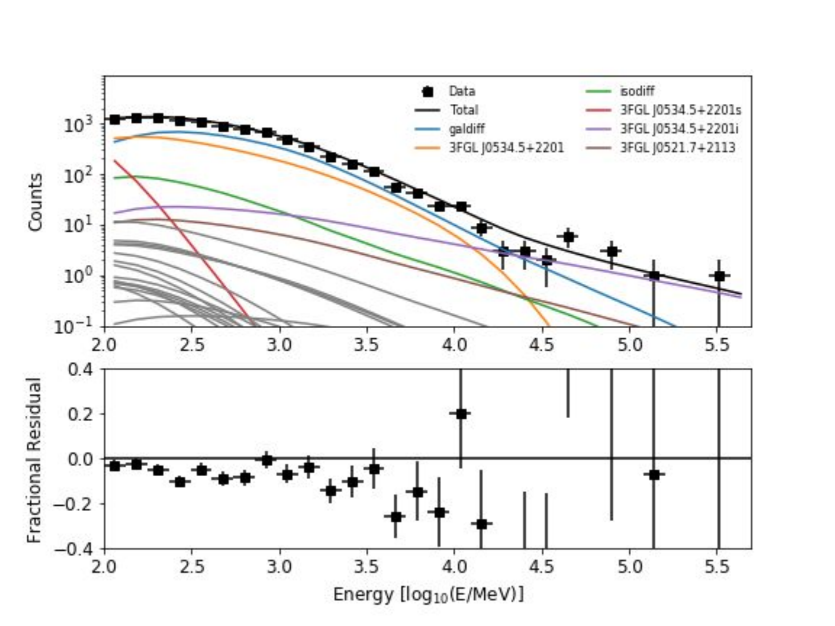
Backup - Crab Nebula non-flare period





- Projection onto x-axis
- Projection onto y-axis

Backup - Crab Nebula non-flare period



- Counts spectrum shows Crab Pulsar (orange), Crab Nebula (purple) and the galactic (blue) and the isodiff sources (green).

References

[1] arXiv:1906.05521 [astro-ph.HE]

[2] Wikipedia

[3] arXiv:1011.3855 [astro-ph.HE]

[4] arXiv:astro-ph/0003216

[5] arXiv:1406.6892 [astro-ph.HE]

[6] Fermi LAT Count Plots

[7] Lecture Slides from Prof Longo