AGILE tutorial 2018

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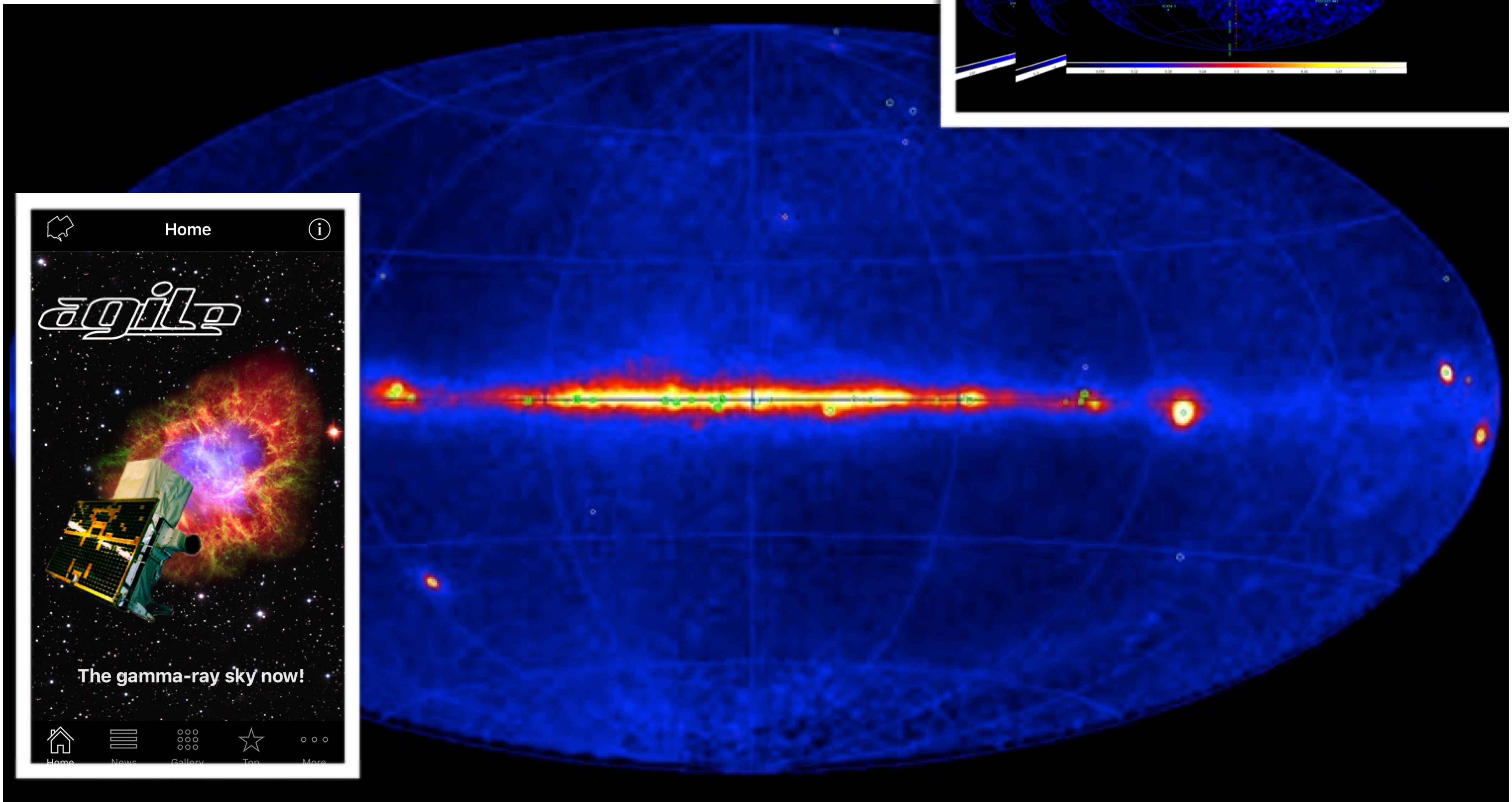
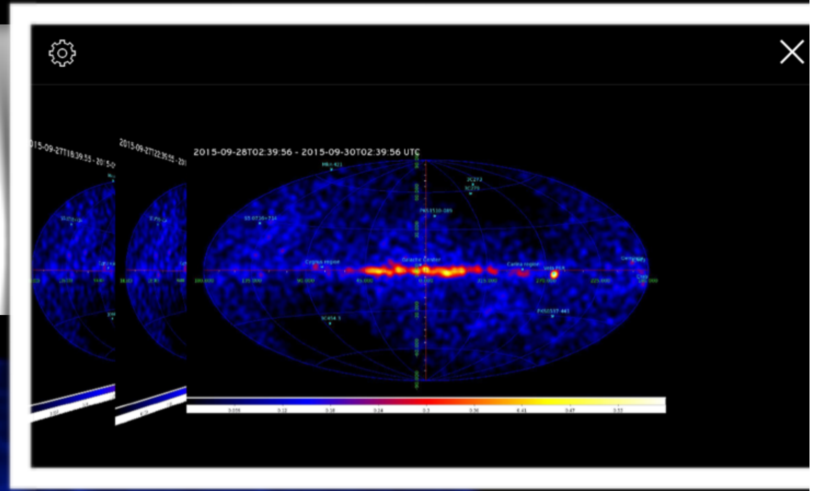
The AGILE Gamma-ray Sky

Download the App to see the gamma-ray sky now:
https://itunes.apple.com/it/app/agilescience/id587328264?mt=8
https://play.google.com/store/apps/details?id=com.agile.science&hl=it





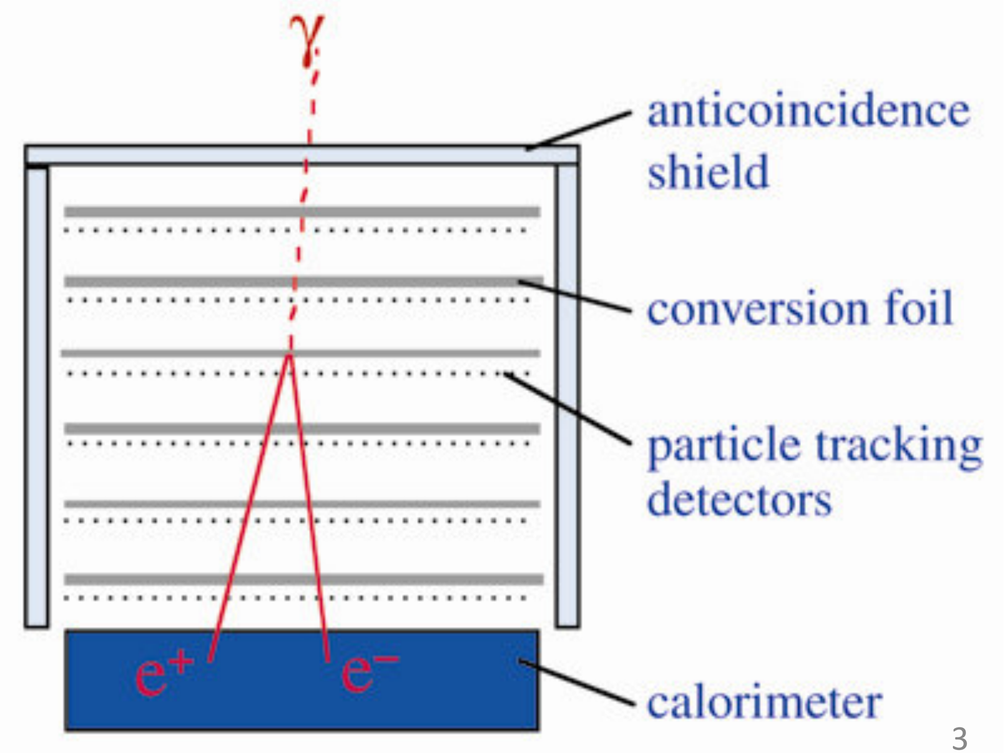
AGILE Gamma-ray telescope

AGILE: Italian Space Agency (ASI) Gamma-ray mission launched in 2007

AGILE mission composed by:

- **AGILE/GRID**: pair production telescope (silicon tracker)
  Energy range = 100 MeV – 50 GeV
- AGILE/MCAL: calorimeter
  Energy range = 350 keV – 100 MeV
- AGILE/SuperAGILE: coded mask hard X-ray instrument
  Energy range = 18 – 60 keV

Today exercise:
Analysis of AGILE/GRID observations

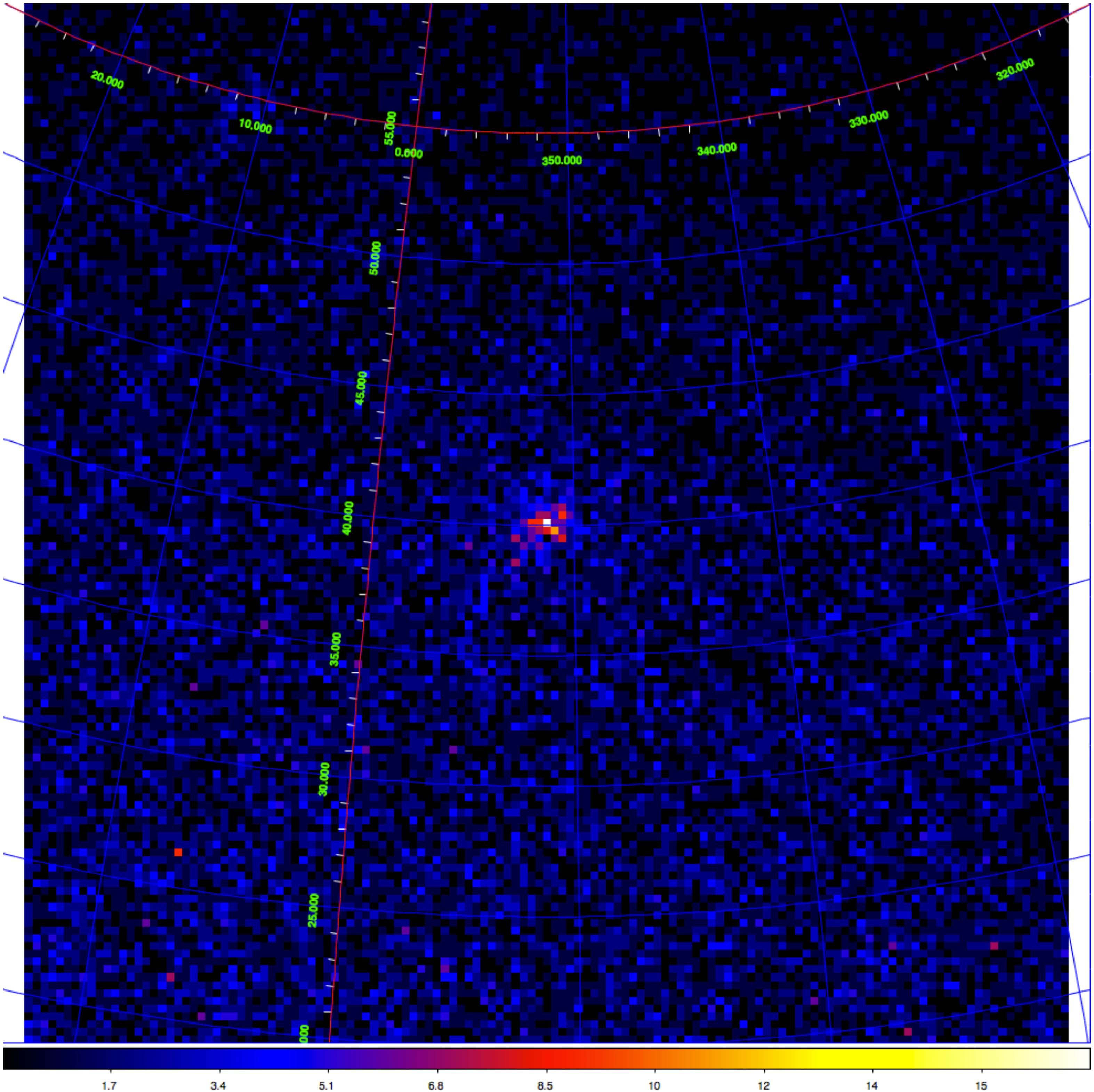


The data are photons that came from celestial sources or background.

THE DATA

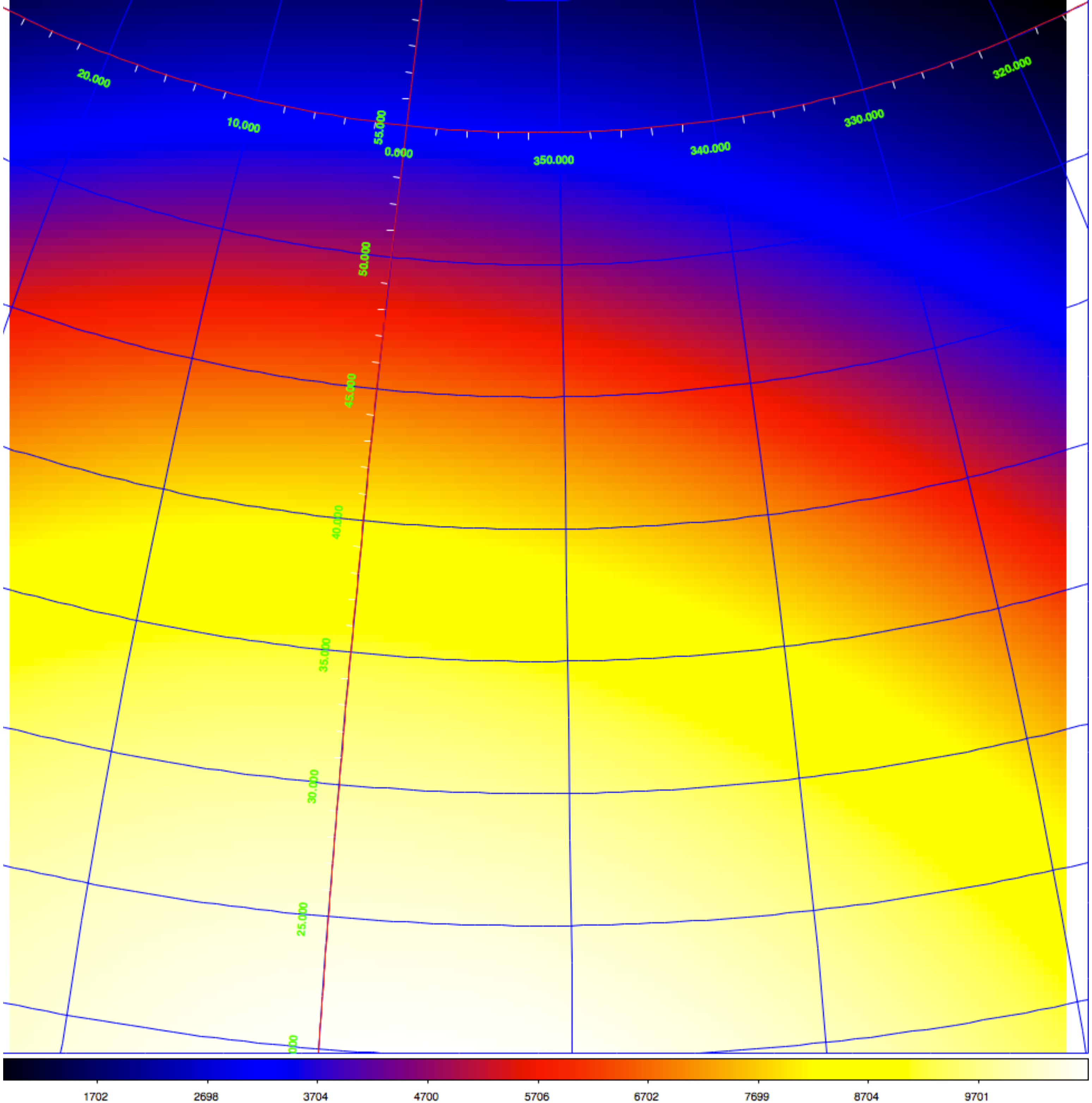
The data

- The data of a gamma-ray satellite is a list of **photons**
- Each photon is characterized by
  - Energy (in MeV)
  - Two coordinates (e.g., Galactic Coordinates (l,b)) that indicates the arrival direction
  - Time



A binned counts map in Galactic coordinates (ARC projection). Each bin is (e.g.) a 0.5° x 0.5° area of the sky. Each bin contains the number of photons detected by the instrument in the [Tstart, Tstop] time interval.

The color is proportional to the number of counts. The photons contained in this map comes from gamma-ray sources or from background components.



A binned exposure map (in units of cm^2 *s sr*) in Galactic coordinates. Each bin is (e.g.) a 0.5° x 0.5° area of the sky. The color is proportional to the exposure level in the [Tstart, Tstop] time interval.

MAKE MAPS

Load the environment for the AGILE analysis:

```
module load agile-AB
```

1. Make maps

map.rb FM3.119_ASDCe_I0025 OP06800 54894.50 54921.50 351.28925 40.138743 timetype=MJD binsize=0.5 skytype=4 <additional parameters>

- **OP06800** = Name of the maps (you can choose what you want!).
  E.g. OP06800.
  Results:
  OP06800.cts.gz ← Counts map
  OP06800.exp.gz ← Exposure map
  OP06800.gas.gz ← Diffuse emission map
  OP06800.maplist4 ← This file contains the list of all the generated maps
- **54894.50 54921.50** = MJD start and MJD end

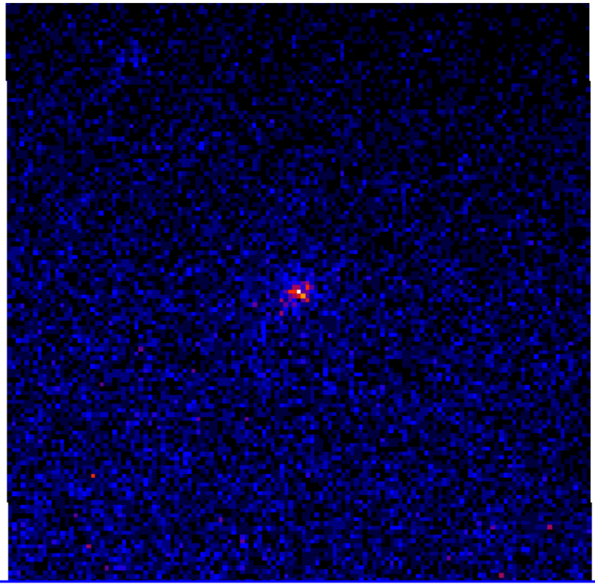
- **351.28925 40.138743** = l, b (in Galactic coordinates) of the map center

- **Additional parameters:**
- mapsize=50
- emin=100
- emax=50000
- **energybin=3 -> a set of maps with different energy bins (e.g [100,200], [200, 400], [400, 1000], [1000-3000] MeV**
- energybin=0 -> use emin, emax as energy range

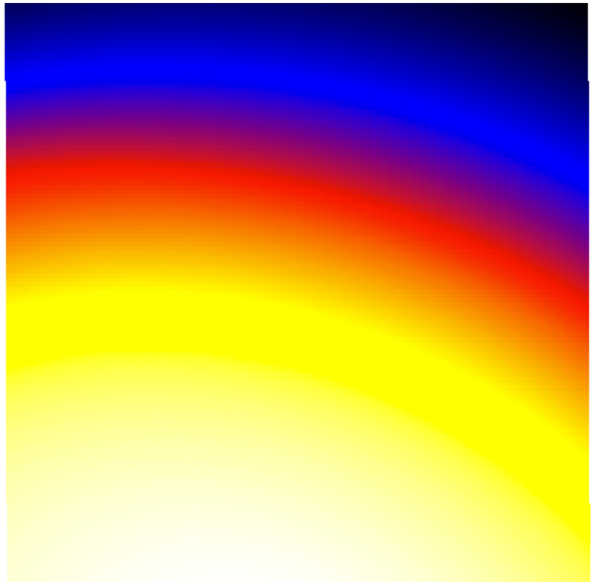
2. view the maps

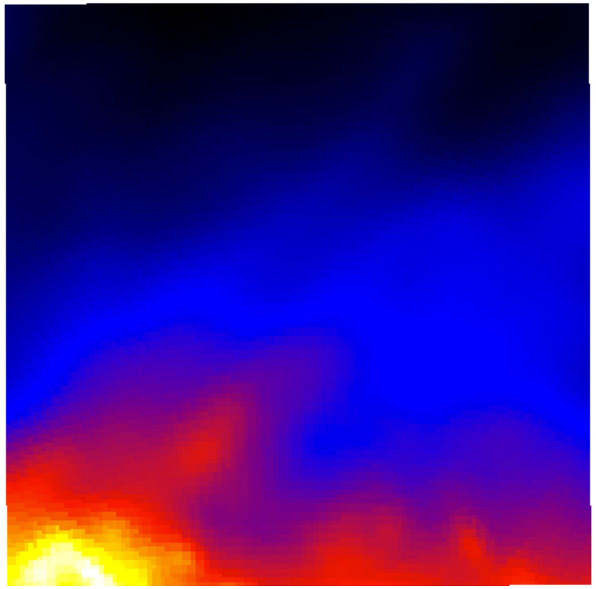
Use **ds9** to load the maps

Counts map: OP06800.cts.gz



Exposure map: OP06800.exp.gz





Galactic diffuse emission map: OP06800.gas.gz

MAXIMUM LIKELIHOOD ESTIMATOR

THE BACKGROUND

Gamma-ray sources and background

- Into the gamma-ray data we can found
  - The *gamma-ray (point) sources*
  - The *Galactic diffuse emission* (that is a background component with respect to the celestial point sources)
  - The *Isotropic diffuse emission* (that is a background component with respect to the celestial point sources)
- We are interested in the study of celestial point sources

The Galactic diffuse emission map

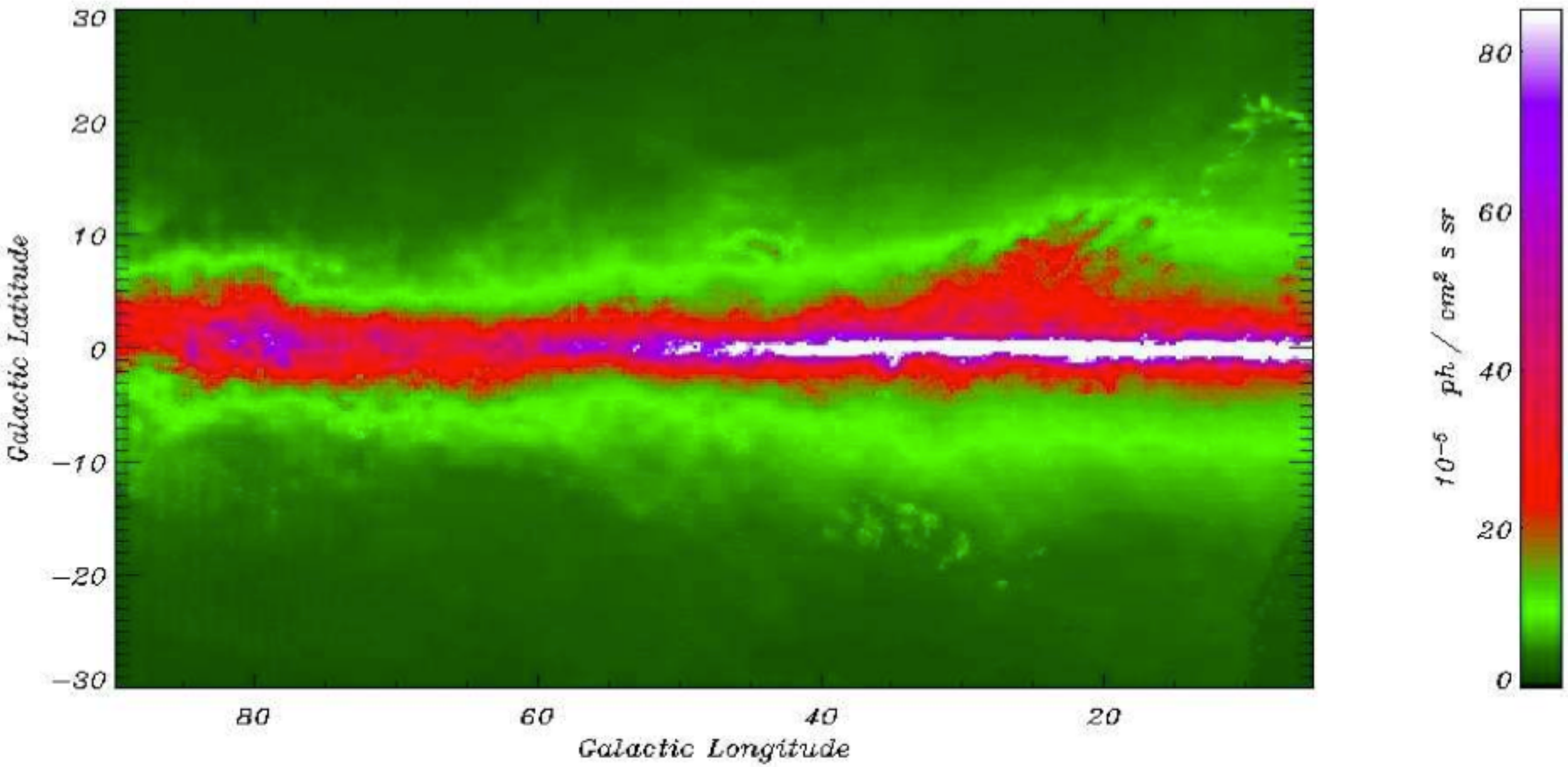


Figure 3.1: The AGILE emission model for the first Galactic quadrant.

The interaction between cosmic rays and the Galactic interstellar matter produces a non-thermal emission which is very intensive in the gamma-ray band, making the Milk way the most prominent source in the sky, producing the 80% of the observable photons. The interstellar matter is made mainly of H and, in smaller measure, He and minimal part of heavy elements

The Isotropic diffuse emission

- Extra-Galactic gamma-ray emission
- Instrumental charged particle background

Parameters for diffuse and isotropic gamma-ray emission

- The two parameters that we use to describe the Galactic (diffuse) and isotropic γ-ray emission are:
  - g_{gal}, the coefficient of the Galactic diffuse emission model
  - g_{iso}, the isotropic diffuse intensity (10^{-5} cm^{-2} s^{-1} sr^{-1})

*.maplist4

Open and see what’s in .maplist4 file

Example:

OP06800.cts.gz OP06800.exp.gz OP06800.gas.gz 30 -1 -1

This file is used

- To list all the maps used for the analysis
- To make hypothesis about the
  - Galactic diffuse emission = g_{gal}
  - Isotropic emission = g_{iso}

How to assign a value to gal and iso:

- -1 = keep the parameter free
- <val> (e.g. 0.7) = assign the value and keep the parameter fixed

For AGILE analysis outside the Galactic plane we keep g_{gal} = 0.7.

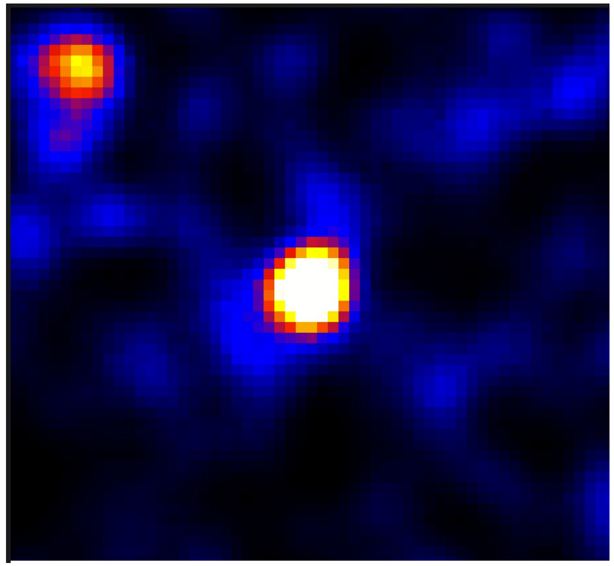
To fix the gal parameter see multi5.rb command (next slides)

How to model a gamma-ray source

GAMMA-RAY SOURCE PARAMETERS

Gamma-ray source parameters

- A **gamma-ray source** is characterized by a set of parameters
  - Position → (s_l, s_b)
  - Source counts (number of gamma-rays) → s_c
  - Spectral Index → s_{si}



In this counts map two point gamma-ray sources are present – NB: the two sources are not point-like due to the "distortion" introduced by the instrument. The calculation of s_c takes into account this effect.

The data and the models

- In the AGILE/GRID case, the data are
  - Binned counts maps,
- while each model is a linear combination of
  - Isotropic coefficient(s)
  - Galactic diffuse coefficient(s) of the γ-ray emission
  - point sources coefficients.
- The γ-ray counts maps, and Galactic diffuse emission maps are then used to evaluate the coefficients of the models.
  - The values of the parameters that maximize the likelihood are those that are most likely to reproduce the data.
- The exposure maps to evaluate the flux (from the number of photons) → ph /cm^2 s sr

Parameters of the models

- An (ensemble of) model is a set of parameters
  - g_{gal}
  - g_{iso}
  - For each source
    - Position → (s_l, s_b)
    - Source counts (number of gamma-rays) → s_c
    - Spectral Index → s_{si}

- It is possible to keep each parameter either free or fixed; a free parameter is allowed to vary to find the maximum likelihood.
- The values of the parameters are found by means of a maximum likelihood estimator (MLE) that maximizes the likelihood of producing the data given in the ensemble of models.

- Within R_{anal} circle
  - The Galactic diffuse radiation model is scaled by a multiplier g_{gal} (estimated by MLE) using the Galactic diffuse emission map as a reference
  - g_{iso} is used for the level of the isotropic diffuse intensity (estimated by MLE)
- For the point source, three types of analysis are possible:
  - (i) the flux parameter s_c is allowed to vary and the position kept fixed,
  - (ii) the flux s_c and position ($s_{l,}$ s_b) parameters are allowed to be free
  - (iii) in both (i) and (ii), the spectral index s_{si} (of a power low) is allowed to vary

For each free s_c parameter of a point source:

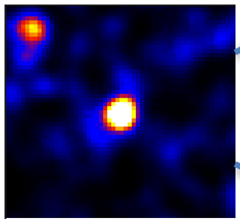
NULL HYPOTHESIS ($s_c = 0$)

g_{gal}

g_{iso}

For each point source i:

(s_c , s_l , s_b, s_{si})



Maximum likelihood estimator

Exp map

Gas map

Maximum likelihood estimator

g_{gal}

g_{iso}

For each point source i:

(s_c , s_l , s_b, s_{si})

ALTERNATIVE HYPOTHESIS (s_c is free)

The value of each free parameter:

g_{gal}

g_{iso}

for each point source i:

(L_0, $s_c = 0$)

$$T_s = -2 \ln \frac{L_0}{L_1},$$

The value of each free parameter:

g_{gal}

g_{iso}

for each point source i:

(L_1, s_c , s_l , s_b, s_{si})

3. Prepare the source list

Create the file *.multi (e.g.listSources.multi)
Modify listSources.multi file adding the source that you are looking for

```
2.0e-07 351.29 40.13 2.1 3 2 PKS1510-089
```

1. Flux (in ph. cm^{-2} s^{-1} sr^{-1})
2. l (Galactic coordinates)
3. b (Galactic coordinates)
4. Photon index
5. Fixflag
6. 2 (fixed)
7. Source name

listSources.multi

```
total 904
-rw-r--r--    1 bulgarelli   staff        48 26 Nov 00:32 listSources.multi
```

How to use the fixflag keyword

- Fixflag = 0: everything is fixed. This is for known sources which must be included in order to search for other nearby sources.

fixflag	Flux	Position	Photon index (power law)
0	Fixed	Fixed	Fixed
1	Variable	Fixed	Fixed
3	**Variable**	**Variable**	**Fixed**
5	Variable	Fixed	Variable
7	**Variable**	**Variable**	**Variable**

4. Evaluation of parameters of the model (MLE, Maximum Likelihood Estimator)

```
multi5.rb FM3.119_ASDCe_I0025 OP06800.maplist4
listSources.multi OP06800.res galcoeff=0.7
```

- OP06800.maplist4 = .maplist4 from the map creation
- listSources.multi = .multi file with all the sources to be analyzed
- OP06800.res = name of the output of the analysis
- galcoeff=0.7 = fixing the galactic diffuse emission to 0.7

OP06800.res

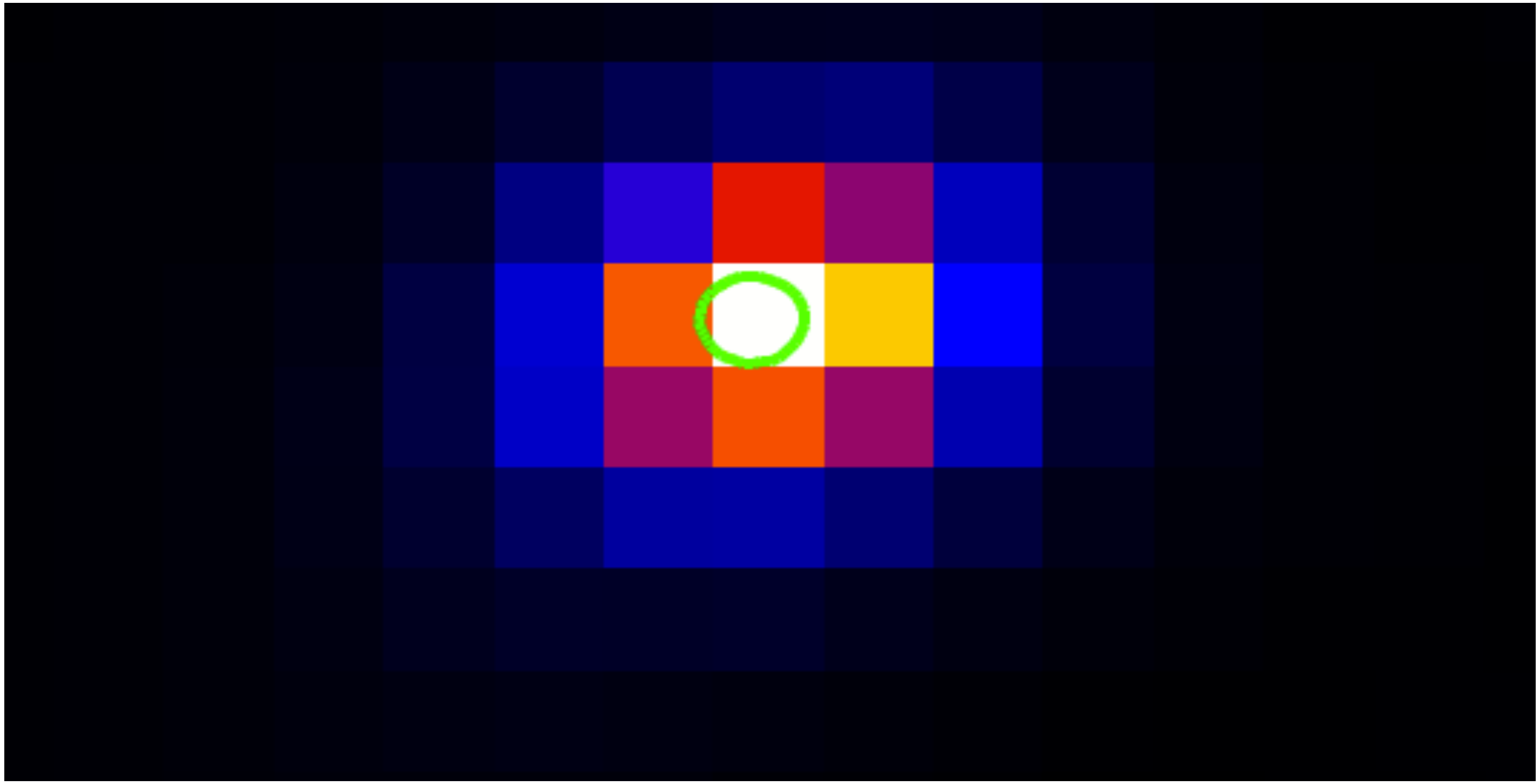
```
! DiffName, Coeff, Err, +Err, -Err
Galactic 0.7 0 0 0
Isotropic 12.3384 0.251798 0.253005 -0.250588
! SrcName, sqrt(TS), L, B, Counts, Err, Flux, Err, Index, Err
PKS1510-089 21.0946 351.293 40.075 609.346 41.9956 2.09337e-06
1.44273e-07 2.1 0
2009-03-04T12:01:06
2009-03-31T12:01:06
```

OP06800.res_PKS1510-089.source

```
! Label, Fix, index, UL conf. level, srcloc conf. level, start l, start b, start flux, [ lmin , lmax ], [ bmin, bmax ]
! sqrt(TS)
! L_peak, B_peak, Dist from initial position
! L, B, Dist from initial position, r, a, b, phi
! Counts, Err, +Err, -Err, UL
! Flux, Err, +Err, -Err, UL, Exp
! Index, Err
! cts, fcn0, fcn1, edm0, edm1, iter0, iter1
! Gal coeffs and errs
! Gal zero coeffs and errs
! Iso coeffs and errs
! Iso zero coeffs and errs
! Start date, end date
! Emin..emax, fovmin..fovmax, albedo, binsize, expstep, phasecode
PKS1510-089 3 2.1 2 5.99147 351.2 40.1387 2e-07 [ -1 , -1 ]  [ -1 , -1 ]
21.0265
351.293 40.0709 0.098022
351.298 40.0683 0.102907 0.130882 0.12864 0.116451 47.872
606.969 41.9371 42.5338 -41.3396 693.252
2.0852e-06 1.44072e-07 1.46122e-07 -1.4202e-07 2.38162e-06 2.91084e+08
2.1 0
4209 948.236 727.179 9.26366e-12 4.15762e-08 311 353
1.64313e-11 0.131777
7.49401e-13 0.0810538
13.5687 0.356715
15.6467 0.00250459
2009-03-04T12:01:06 2009-03-31T12:01:06
100..50000 0..60 80 0.5 0 2
```

If sqrt(TS) < 2 use the Upper Limit (UL)

OP06800.res_PKS1510-089.reg



> ds9 OP06800.cts.gz -region OP06800.res_PKS1510-089.source.reg

PLOT LIGHT CURVE

Plot light curves

Load the environment:
> module load python2.7-sci

To view the image:
> eog <image_name>

Light curve of PKS 1510-089

Create a file collecting the result to be plotted in the light curve.
The file must have 5 columns with the following information:

Flux (photons cm^{-2} s^{-1})	Flux error (photons cm^{-2} s^{-1})	Error type (0/1)	T start (MJD)	Time bin (MJD)

Error type:

- 0: flux value is NOT an upper limit (flux error ≠ 0)
- 1: flux value is an upper limit (flux error = 0)

Example:

```
3.394e-07       0               1       54305.50        6.00
8.61005e-07     5.27225e-07     0       54344.50        1.00
4.98313e-07     0               1       54345.50        1.00
```

Light curve of PKS 1510-089

Python script to build the light-curve: **visLightCurve.py (in $AGILE/LightCurve)**

Usage instruction:

```
> python $AGILE/LightCurve/visLightCurve.py out_name N_lc "Title"
inputfilename1 "label1" <inputfilename2 "label2”>
```

Parameters:

- out_name: name of the image to be hardcopied
- N_lc: number of loaded light curves (<= 5)
- "Title": plot title
- filename: path+name of the file
- "label": light curve label
- <filename2 "label2”> = optional (> 1 light curves to plot together)

Example (one lightcurve):

```
> python $AGILE/LightCurve/visLightCurve.py prova.png 1 "Prova”
lc_3.dat "curva 1”
```