The AGILE gamma-ray data analysis

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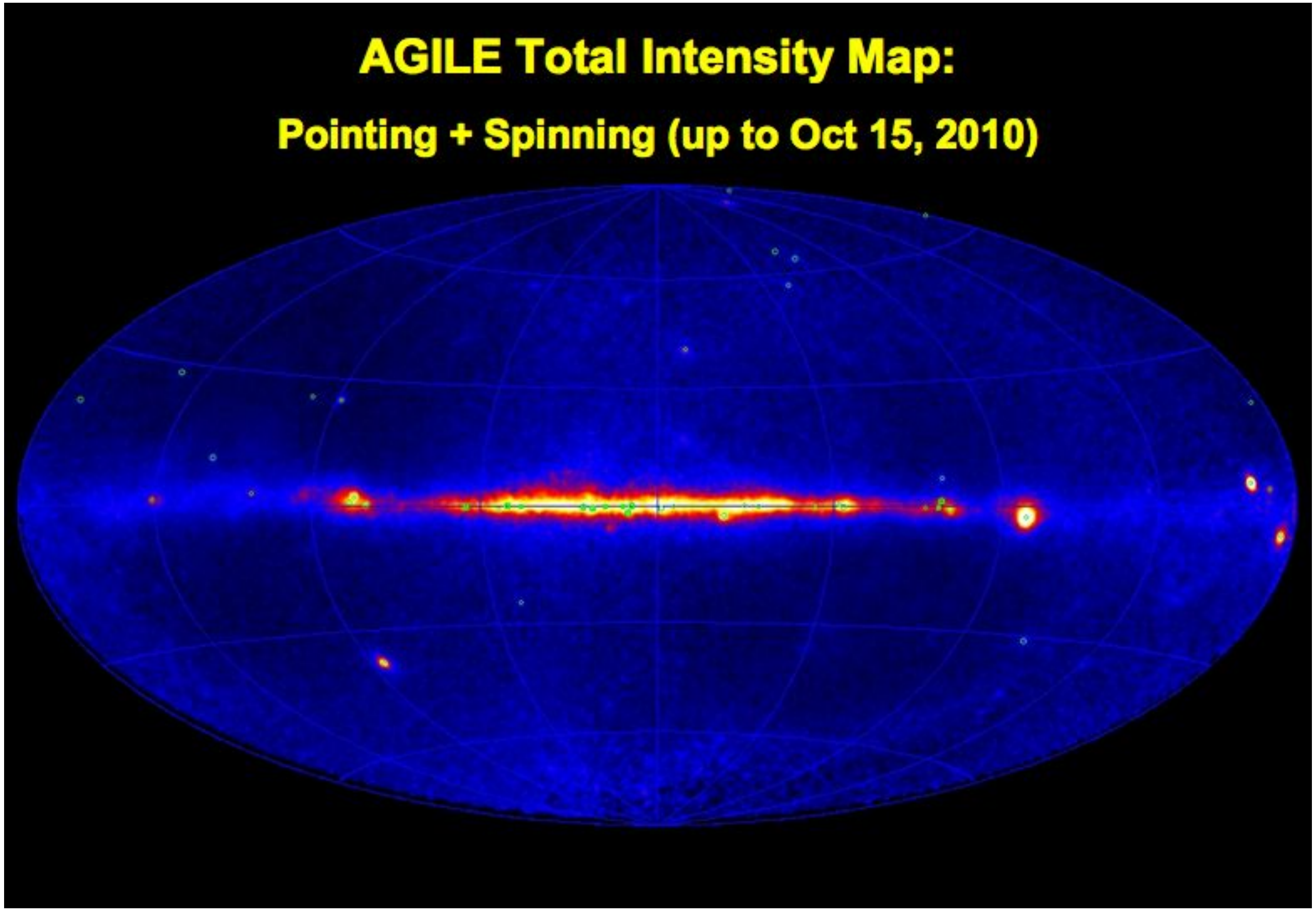
The Gamma-ray Universe

Gamma-ray sky: the most extreme and energetic phenomena of the Universe
Gamma-ray sources: AGN, Supernova Remnants (SRN), Binaries, Gamma-ray bursts, Galactic Center, etc.

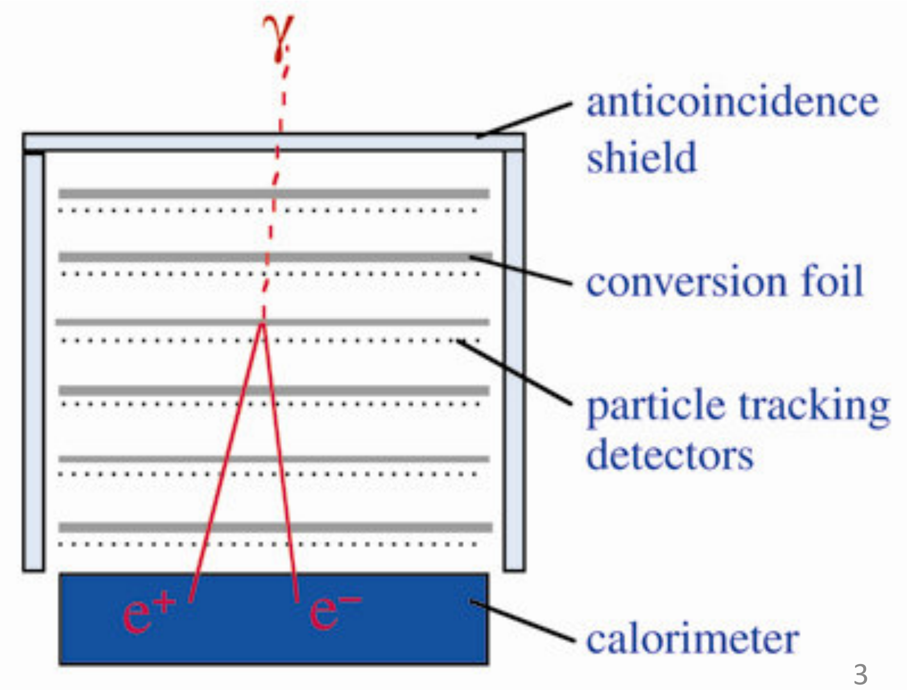


AGILE Gamma-ray telescope

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

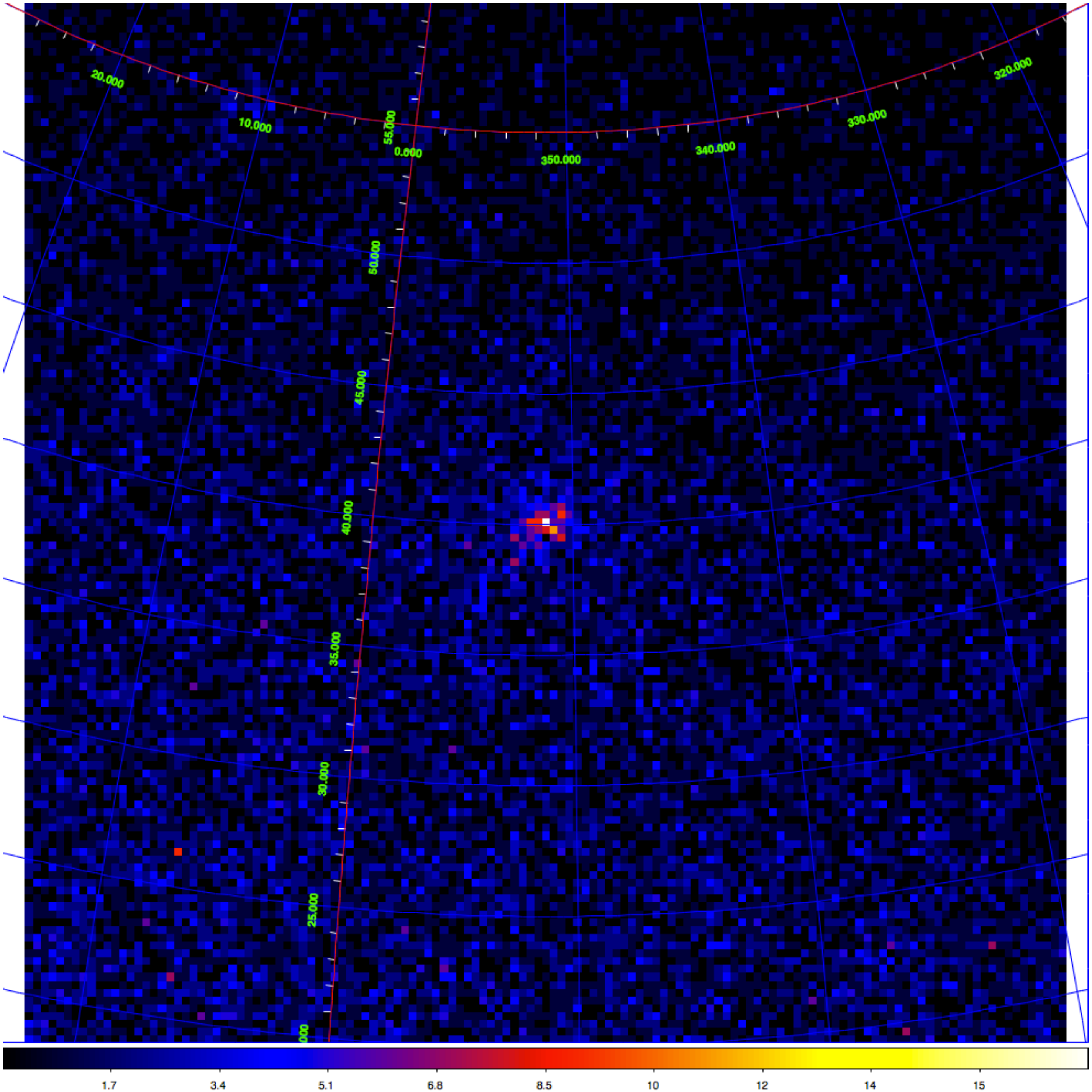


The data are photons that came from celestial sources or background.

THE DATA

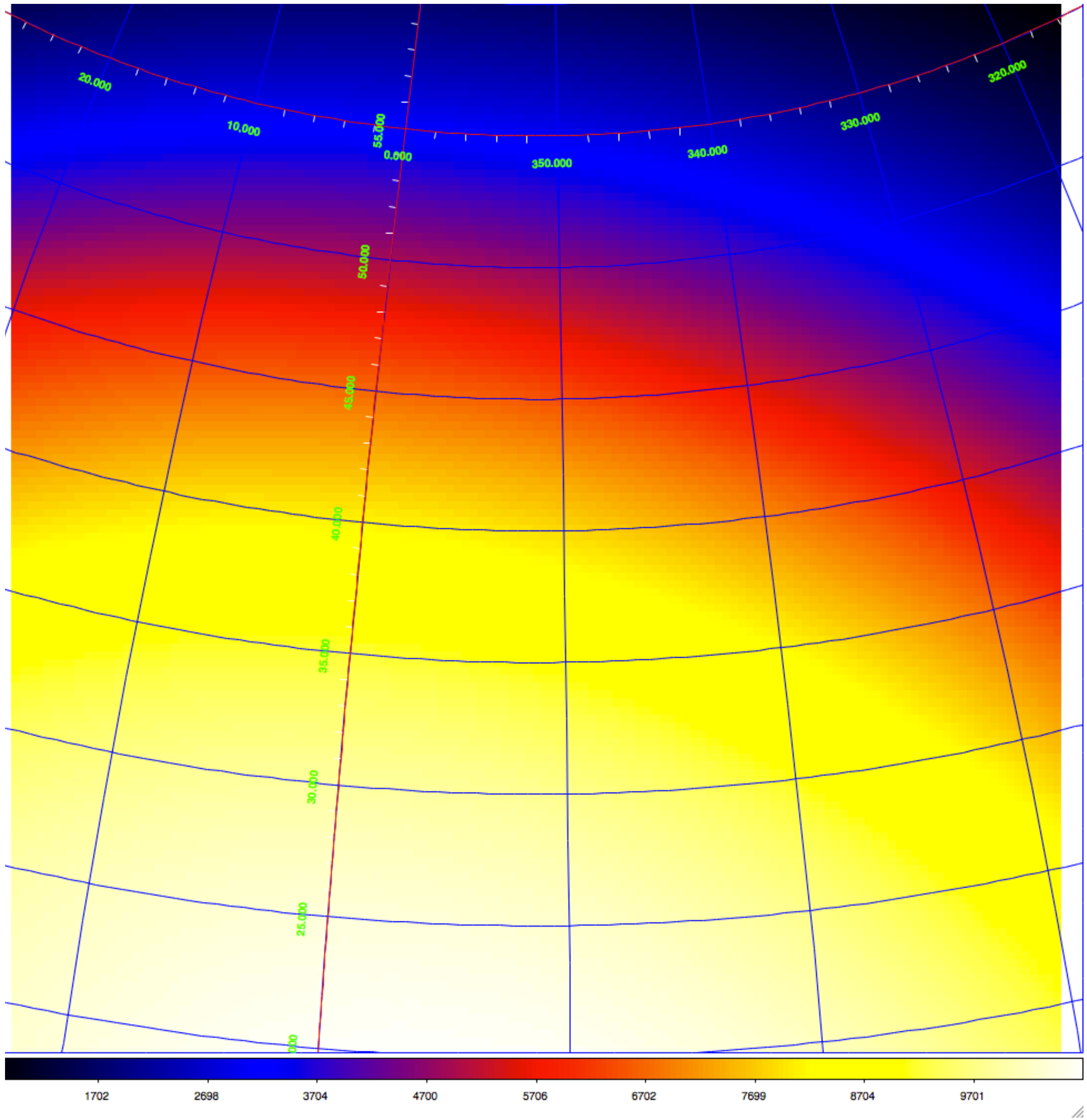
The data

- 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 with Galactic coordinates. 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 cames from gamma-ray sources or from background components.



A binned exposure map (in units of cm^2 *s sr*) with 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.

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

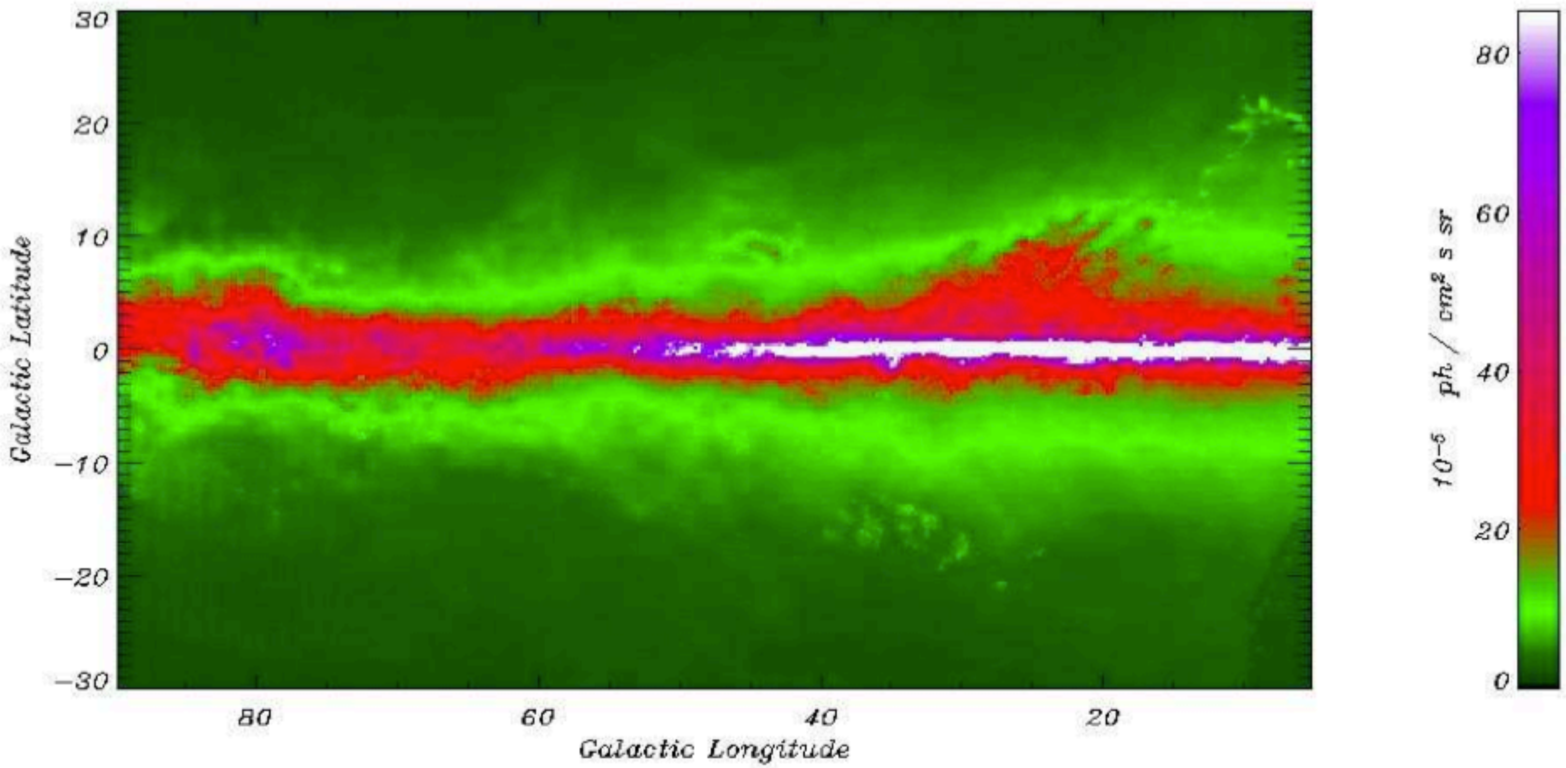


Figure 3.1: The AGILE emission model for the first Galactic quadrant.

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

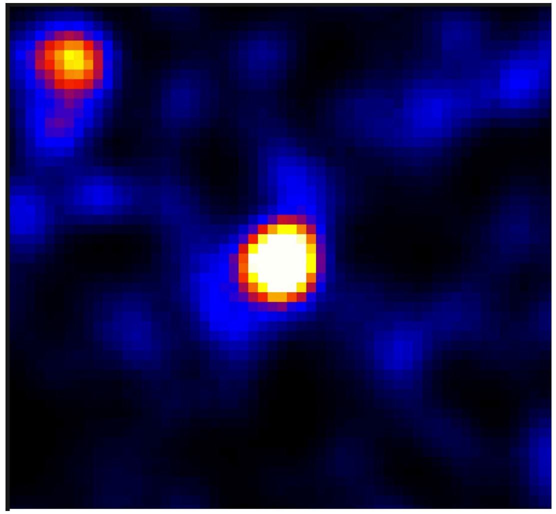
- The two parameters that we use to describe the Galactic (diffuse) and isotropic γ-ray emission are:
  - g_{gal}, the coefficient of the Galactic diffuse emission model
  - g_{iso}, the isotropic diffuse intensity (10^{-5} cm^{-2} s^{-1} sr^{-1})

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 a point 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 exposure maps, and Galactic diffuse emission maps are then used to calculate the models.
  - The values of the parameters that maximize the likelihood are those describing the that are most likely to reproduce the data.

How the flux and the significance of each celestial point source is calculated

THE LIKELIHOOD RATIO TEST

The likelihood ratio test

- The **likelihood ratio test** is used to compare two hypothesis.
- Each hypothesis can be characterized by a set of parameters.
  - One is the null hypothesis (e.g. the gamma-ray source do not exists) → L_0
  - The other is the alternative hypothesis (e.g. the gamma-ray source exists) → L_1

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

  - where *L0* and *L1* are the maximum value of the likelihood function

- 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}

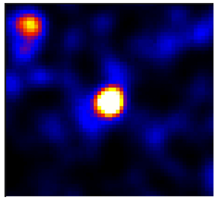
- It is possible to keep each parameter either free or fixed; a free parameter is allowed to vary to find the maximum likelihood.
- The values of the parameters are found by means of a maximum likelihood estimator (MLE) that maximizes the likelihood of producing the data given in the ensemble of models.

- Within R_{anal} circle
  - The Galactic diffuse radiation model is scaled by a multiplier g_m (estimated by MLE) using the Galactic diffuse emission map as a reference
  - g_b 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, $s_c = 0$)

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

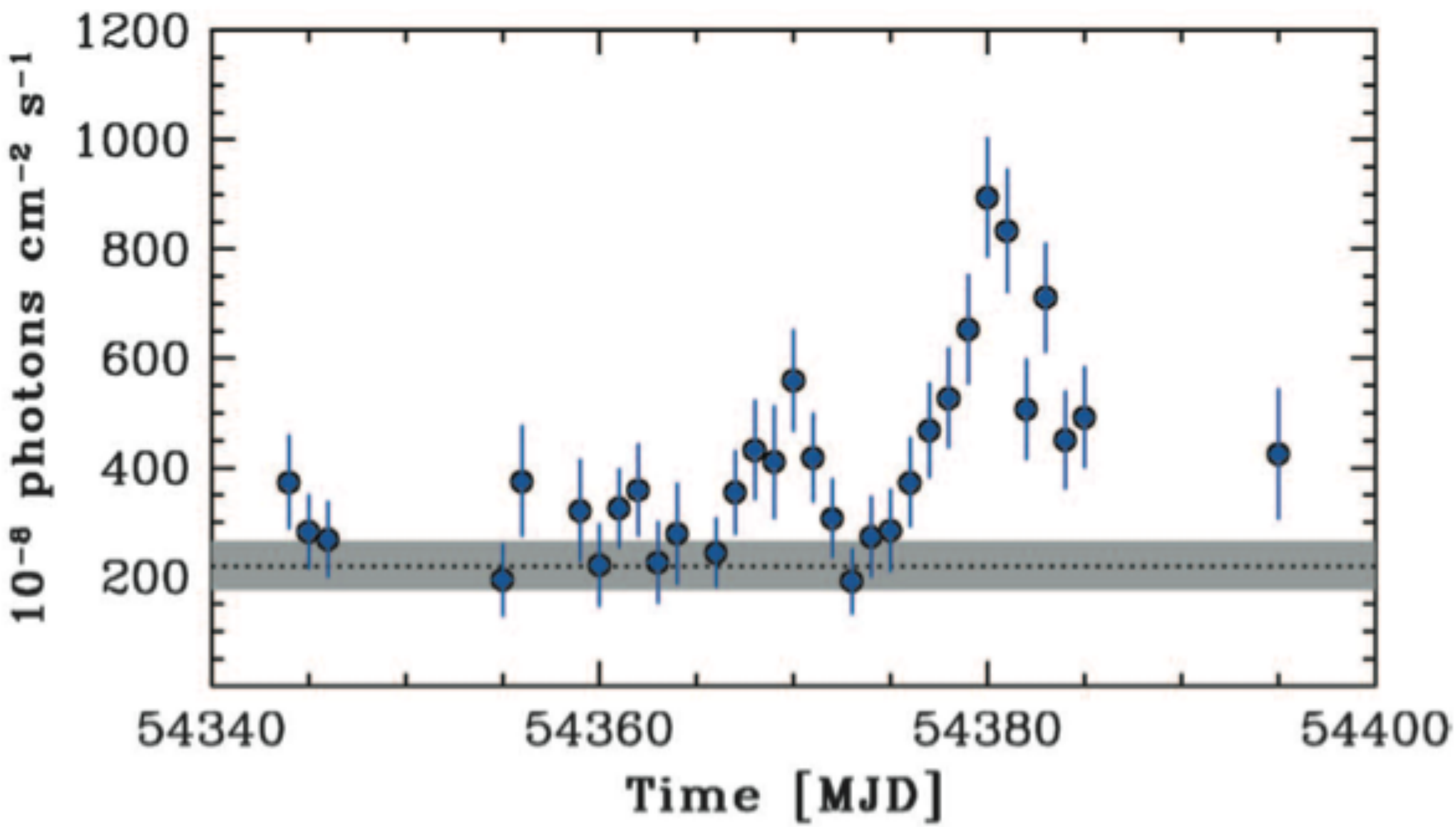
The value of each free parameter:
g_{gal}
g_{iso}
for each point source i:
(L_1, s_c , s_l , s_b, s_{si})

Thresholds

- We choose the null or the alternative hypothesis based on the value of T_s.
  - If $T_s > h$ we accept the alternative hypothesis (the point source exists)
- sqrt(T_s) is, more or less, the number of sigma in the gaussian standard distribution

The light curves

- A light curve is a graph which shows the brightness of a celestial object **(a celestial point source)** over a period of time. In the gamma-ray context we call this the flux of a gamma-ray source
- We divide an observation in N periods of time
  - For each period we calculate the brightness of the source



An example of light curve of a gamma-ray source. Each point is one day of data. There are two main gamma-ray flares, one around MJD (Modified Julian Day) 54370 and one around MJD 54380.

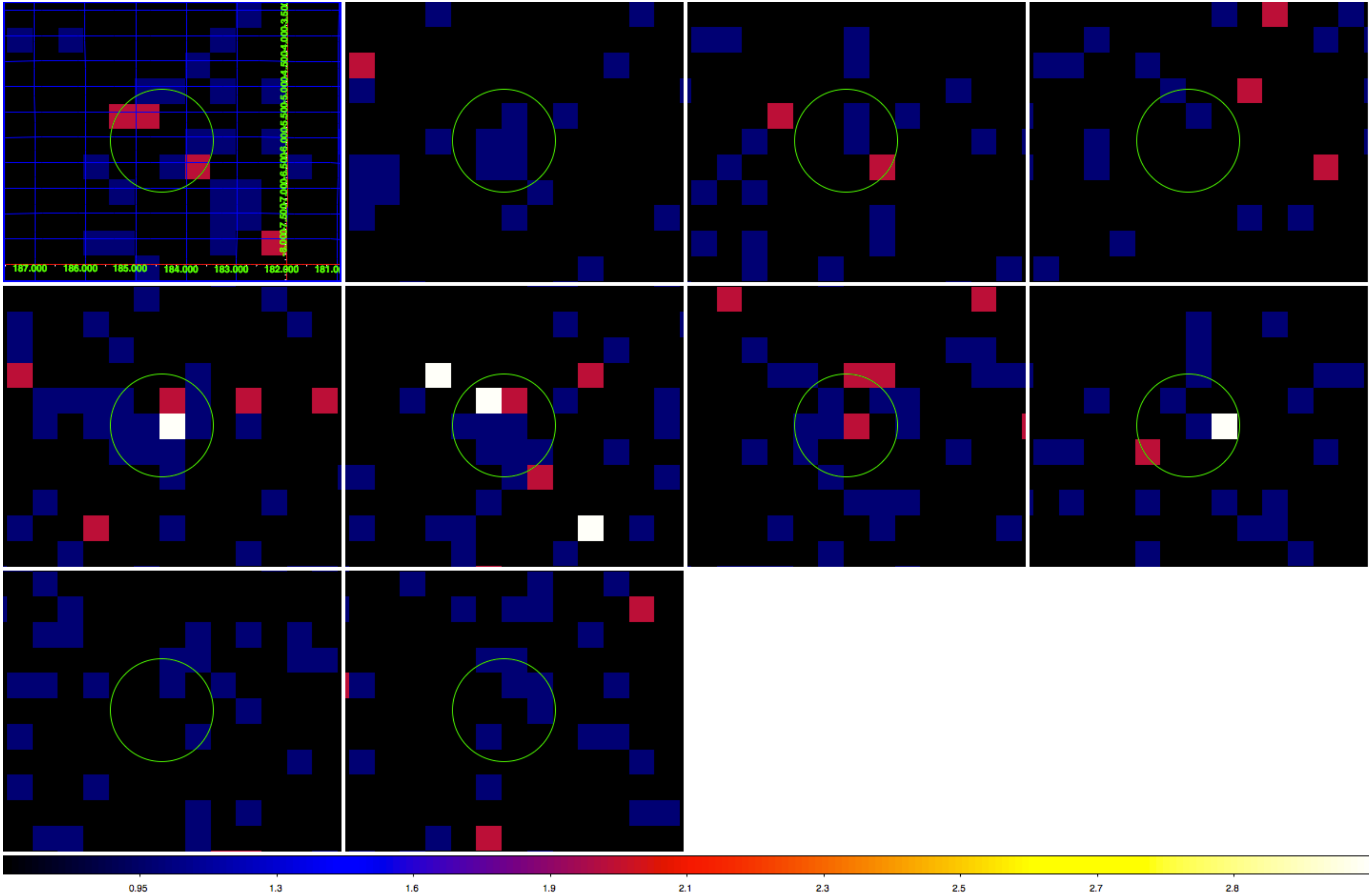


Fig. 1A: A set of counts maps of the same sky region with a gamma-ray flare from a celestial source. Each map contains 2 days of data. The green circle has a radius of 1°. The flux of the source is calculated for each map to build the light curve .

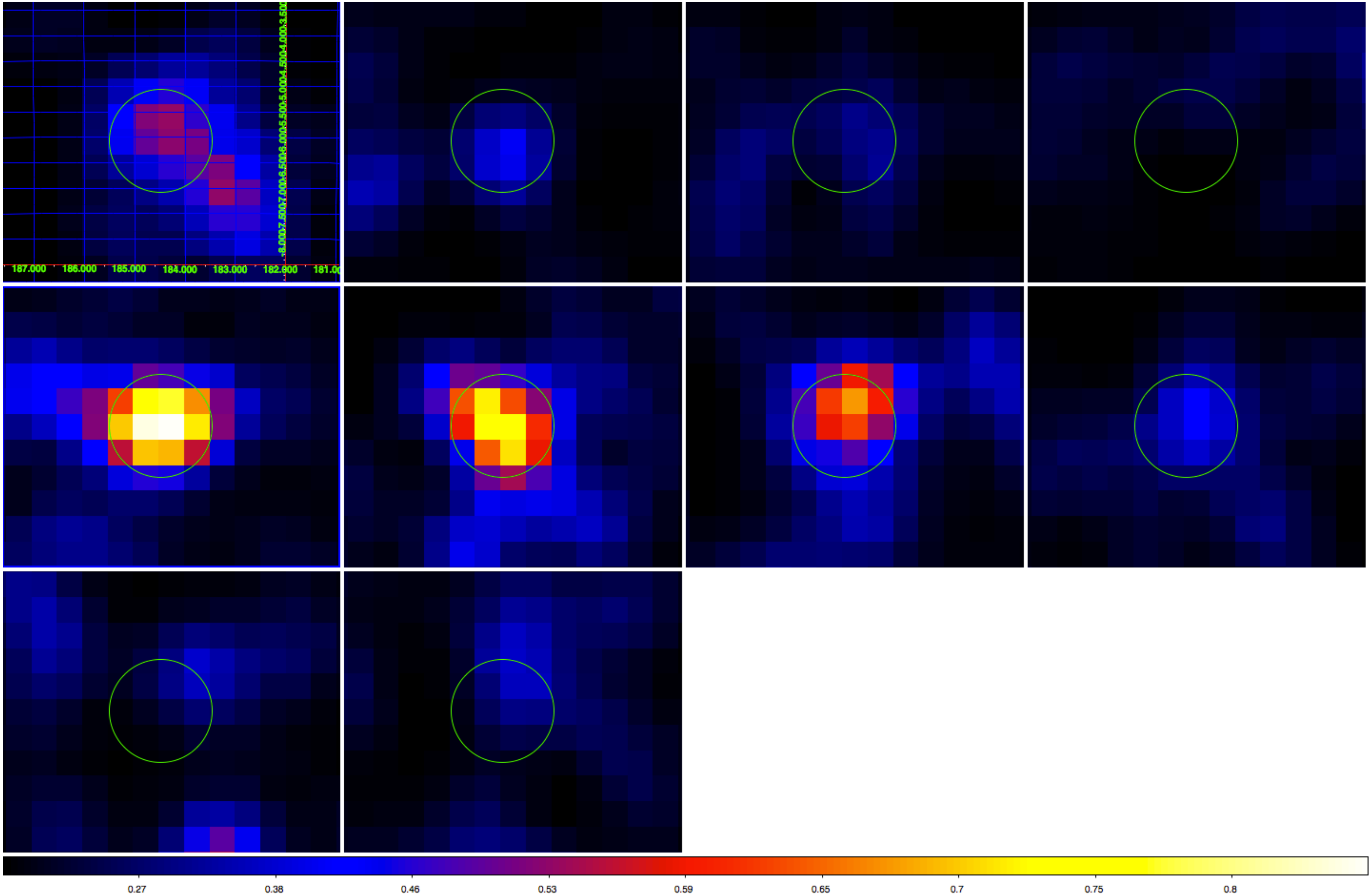
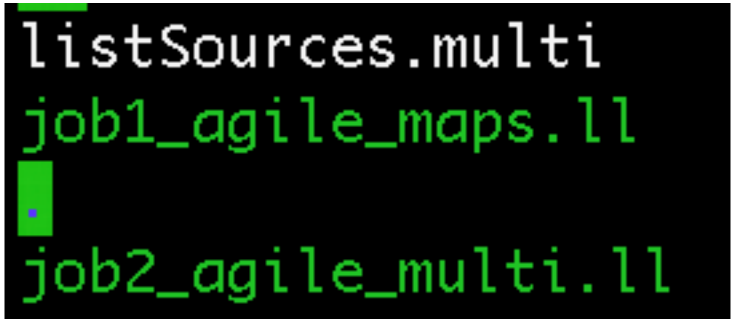


Fig. 1B: The same data of the Fig. 1A but each map is smoothed to show the effect of the the "distortion" introduced by the instrument.

AGILE TUTORIAL



Tutorial material in `LabX/LAB_2013_prove/PKS1510-089/AGILE`

1. Build the maps

Modify last line of job1_agile_maps.ll
`llsubmit job1_agile_maps.ll`

```
ruby /prod_iasfbo/agile/grid_scripts2/map.rb FM3.119_ASDCe_I0023
OP06800 54894.50 54921.50 351.28925 40.138743 <optional parameters>
```

Name of the maps. E.g. OP06800. Results:

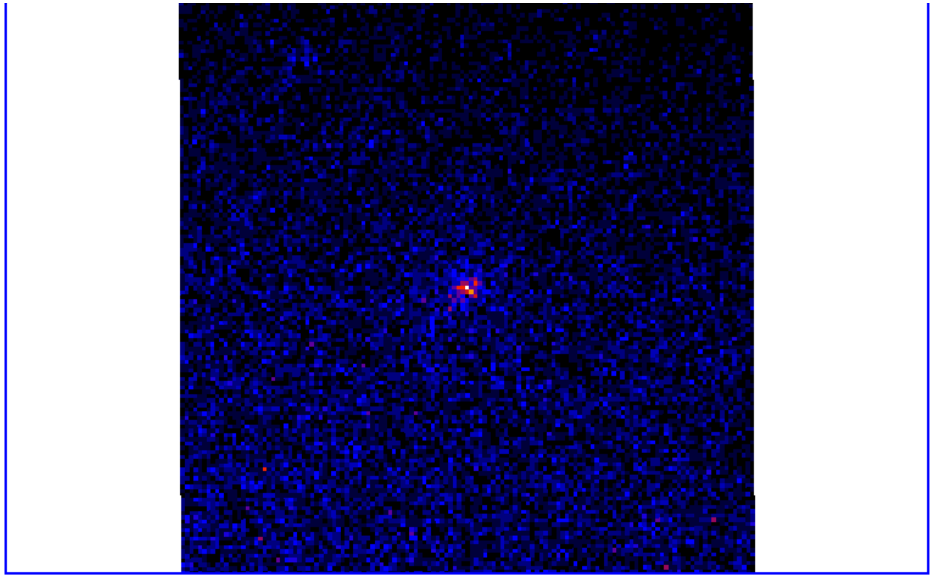
- OP06800.cts.gz ← Counts map
- OP06800.exp.gz ← Exposure map
- OP06800.gas.gz ← Diffuse emission map
- OP06800.maplist4 ← This file contains the list of all the generated maps

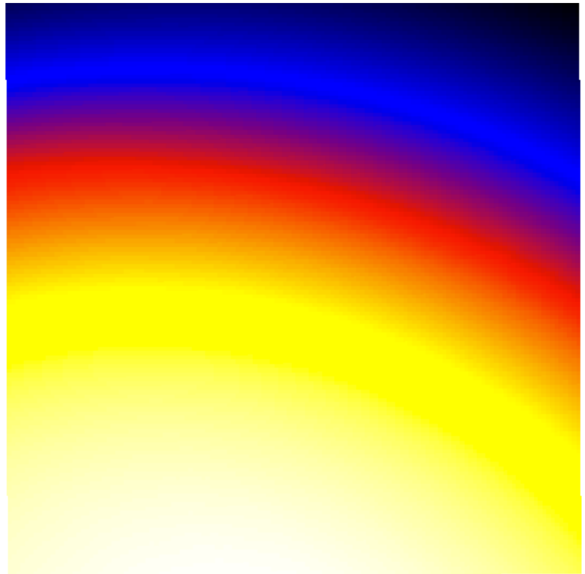
MJD start and MJD end

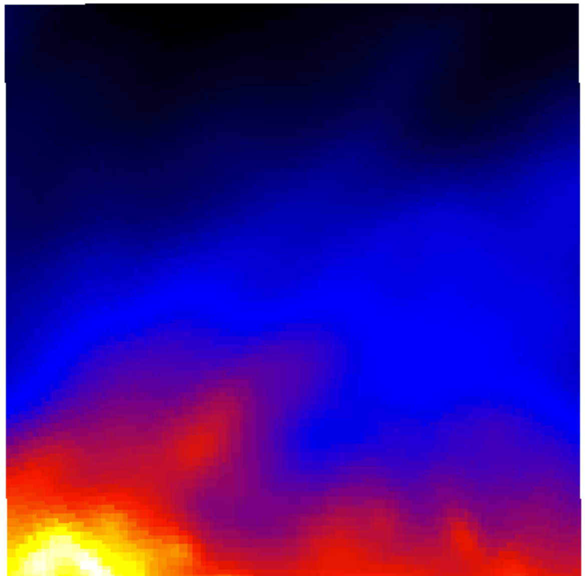
l, b (in Galactic coordinates) of the map center

Additional parameters:

- binsize=0.3
- 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







```
-rw-r--r--   1 bulgarelli  staff      56 26 Nov 00:32 0P06800.maplist4
-rw-r--r--   1 bulgarelli  staff    9133 26 Nov 00:32 0P06800.cts.gz
-rw-r--r--   1 bulgarelli  staff     941 26 Nov 00:32 0P06800.command.log
-rw-r--r--   1 bulgarelli  staff   46959 26 Nov 00:32 0P06800.gas.gz
-rw-r--r--   1 bulgarelli  staff  132195 26 Nov 00:32 0P06800.exp.gz
```

*.maplist4

Modify .maplist4 file

```
OP06800.cts.gz OP06800.exp.gz OP06800.gas.gz 30 0.7 -1
```

This file is used

- To list all the maps used for the analysis
- To make hypothesis about the
  - g_{gal}
  - g_{iso}

-1 = keep the parameter free

> 0 = keep the parameter fixed

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

2. Prepare the source list

Modify listSources.multi file

```
2.0e-07 351.28925 40.138743 2.1 3 2 PKS1510-089
```

1. Flux
2. l (Galactic coordinates)
3. b (Galactic coordinates)
4. Spectral 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
```

- 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	Spectral index (power law)
0	Fixed	Fixed	Fixed
1	Variable	Fixed	Fixed
3	**Variable**	**Variable**	**Fixed**
5	Variable	Fixed	Variable
7	**Variable**	**Variable**	**Variable**

2. Evaluation of parameters of the model (MLE)

```
ruby /prod_iasfbo/agile/
grid_scripts2/multi.rb
FM3.119_ASDCe_I0023 -999
listSources.multi
outfile=OP06800.res
maplist=OP06800.maplist4
```

Modify last line of job2_agile_likelihood.ll

`llsubmit job2_agile_likelihood.ll`

```
job1_agile_maps.ll
job1.105.err
OP06800.cts.gz
OP06800.exp.gz
OP06800.gas.gz
OP06800.command.log
OP06800.int.gz
OP06800.maplist4
job1.105.out
listSources.multi
job2_agile_likelihood.ll
OP06800.res.log
OP06800.res_PKS1510-089
OP06800.res_PKS1510-089.con
OP06800.res_PKS1510-089.ellipse.con
OP06800.res_PKS1510-089.reg
OP06800.res.html
OP06800.res2
OP06800.res.multi
OP06800.res.resconv
job1.106.err
listSources.multi.reg
OP06800.res.command.log
OP06800.res
```

OP06800.res

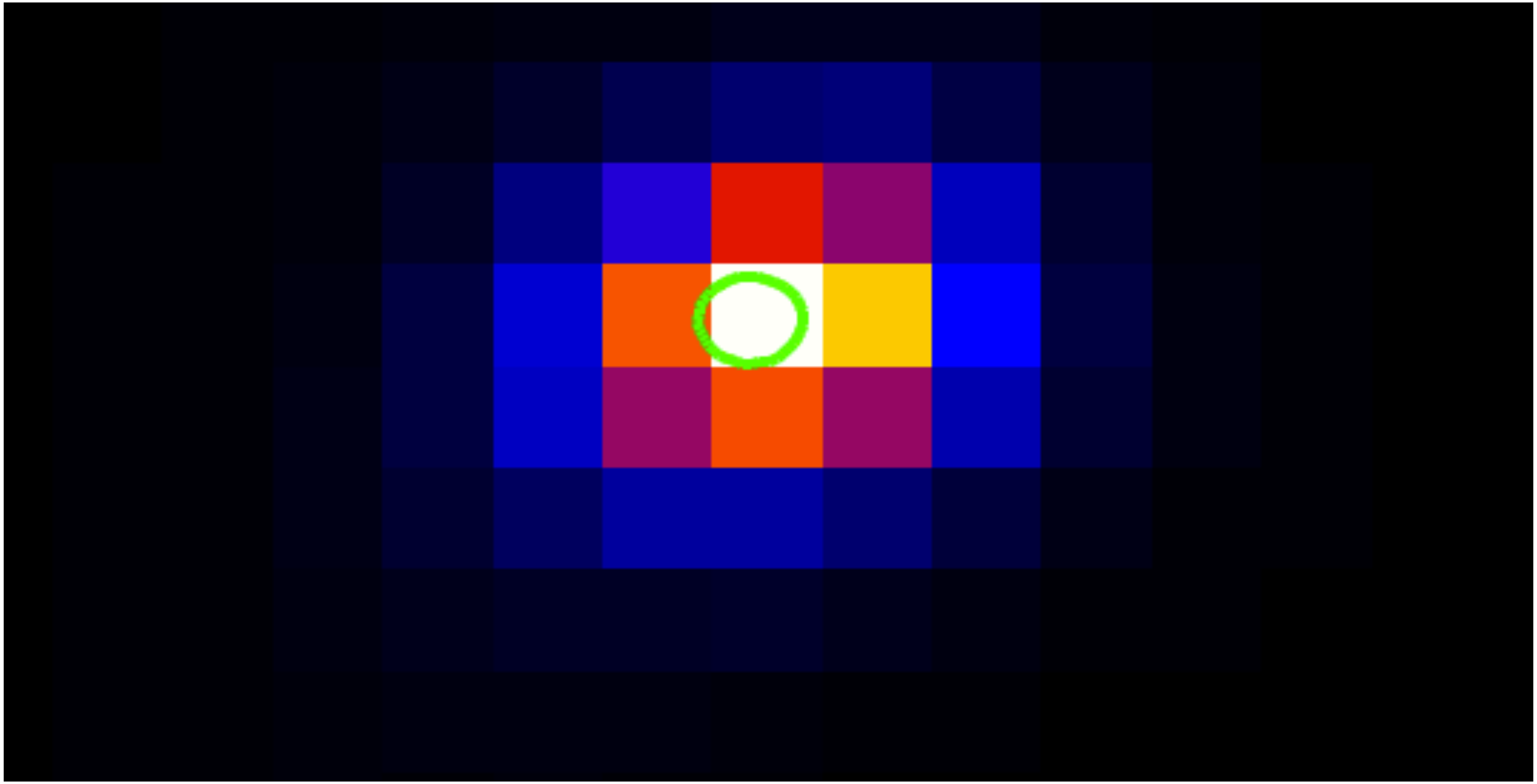
```
! DiffName, Coeff, Err, +Err, -Err
Galactic 0.7 0 0 0
Isotropic 12.4039 0.252454 0.253692 -0.251244
! SrcName, sqrt(TS), L, B, Counts, Err, Flux, Err, Index, Err
PKS1510-089 21.3767 351.417 40.0527 607.899 41.8411 2.08671e-06
1.43627e-07 2.1 0
'2009-03-04T12:01:06'
'2009-03-31T12:01:06'
```

OP06800.res_PKS1510-089

```
! Label, Fix, index, UL conf. level, srcloc conf. level
! sqrt(TS)
! L_peak, B_peak
! L, B, r, a, b, phi
! Counts, Err, +Err, -Err, UL
! Flux, Err, +Err, -Err, UL, Exp
! Index, Err
PKS1510-089 3 2.1 2 5.99147
21.3767
351.417 40.0527
351.403 40.0665 0.144307 0.143233 0.127464 -2.19913
607.899 41.8411 42.45 -41.2371 694.009
2.08671e-06 1.43627e-07 1.45717e-07 -1.41553e-07 2.3823e-06 2.91319e+08
2.1 0
```

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

OP06800.res_PKS1510-089.reg



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

Light curve of PKS 1510-089

File in input formatting (5 columns required):

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**

Usage instruction:

> python visLightCurve.py out_name N_lc "Title" filename1 "label1" filename2 "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

Example (one lightcurve):

> python visLightCurve.py prova.png 1 "Prova" lc_3.dat "curva 1"