The AGILE gamma-ray data analysis

A. Bulgarelli

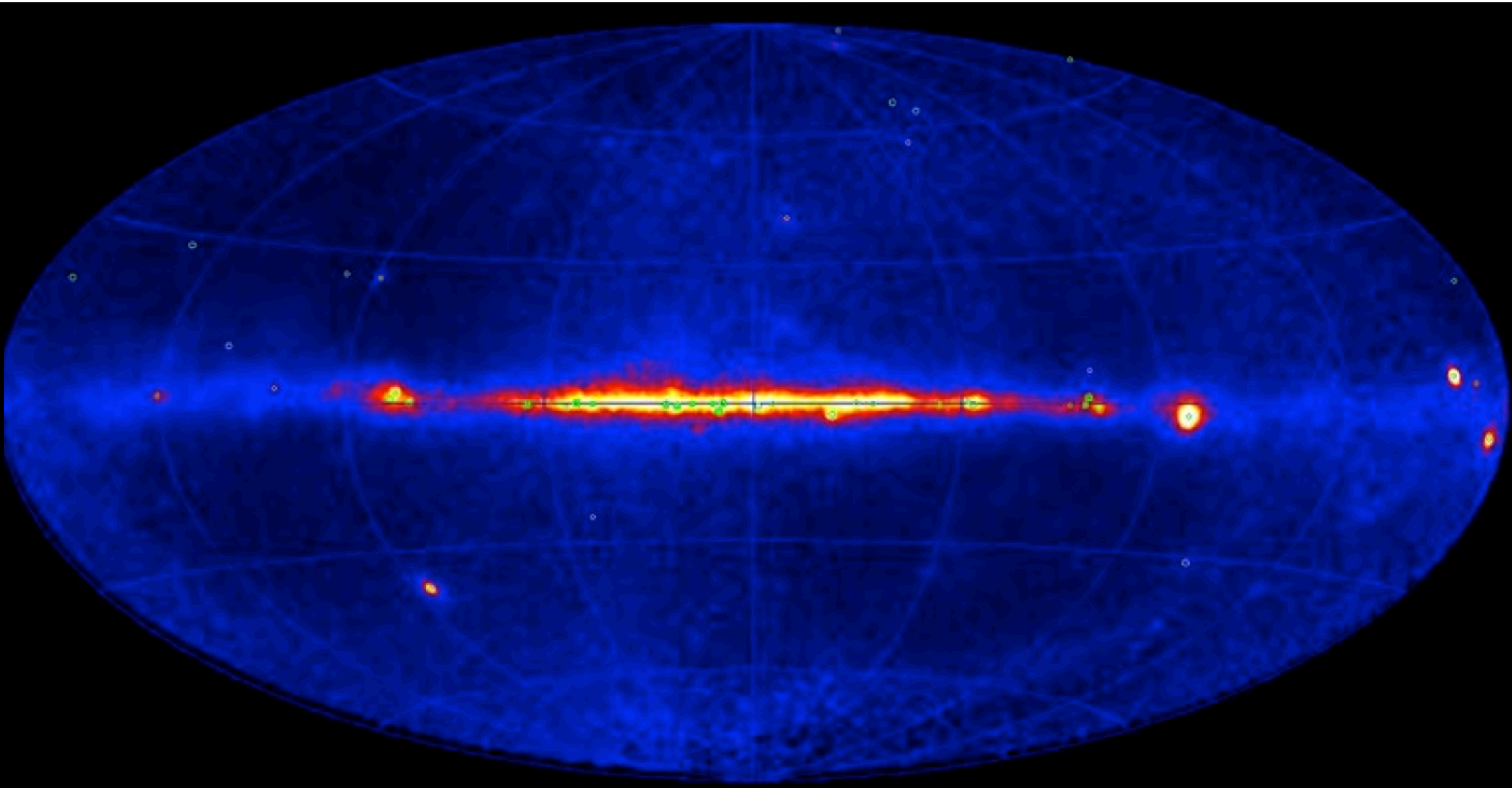
INAF/IASF Bologna

The Gamma-ray Universe

Gamma-ray sky: the most extreme and energetic phenomena of the Universe

$E > 100$ MeV

Gamma-ray sources: AGN, Supernova Remnants (SRN), Binaries, Gamma-ray bursts, Galactic Center, etc.

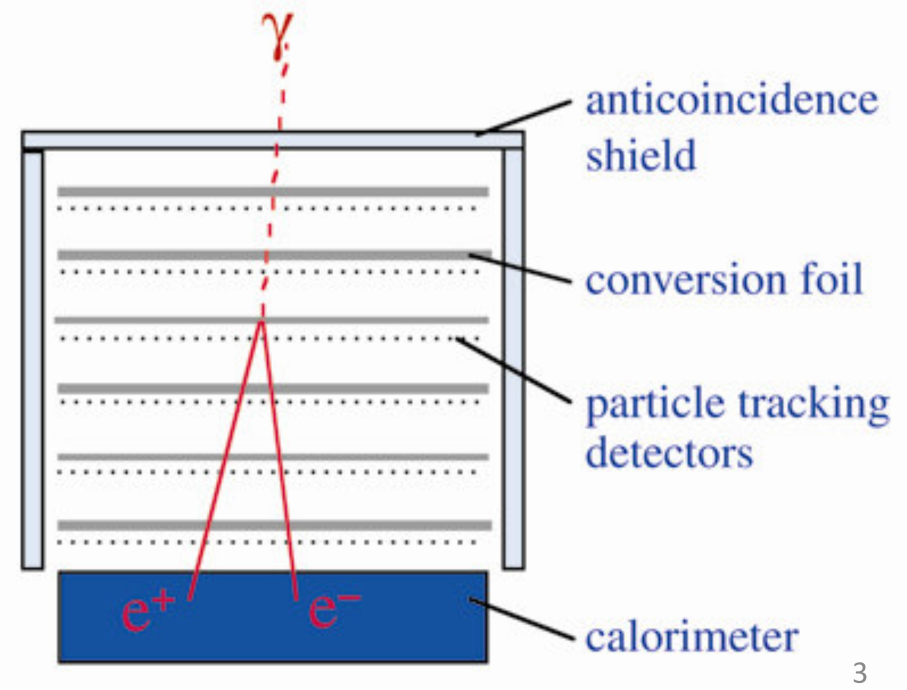


AGILE Gamma-ray telescope

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

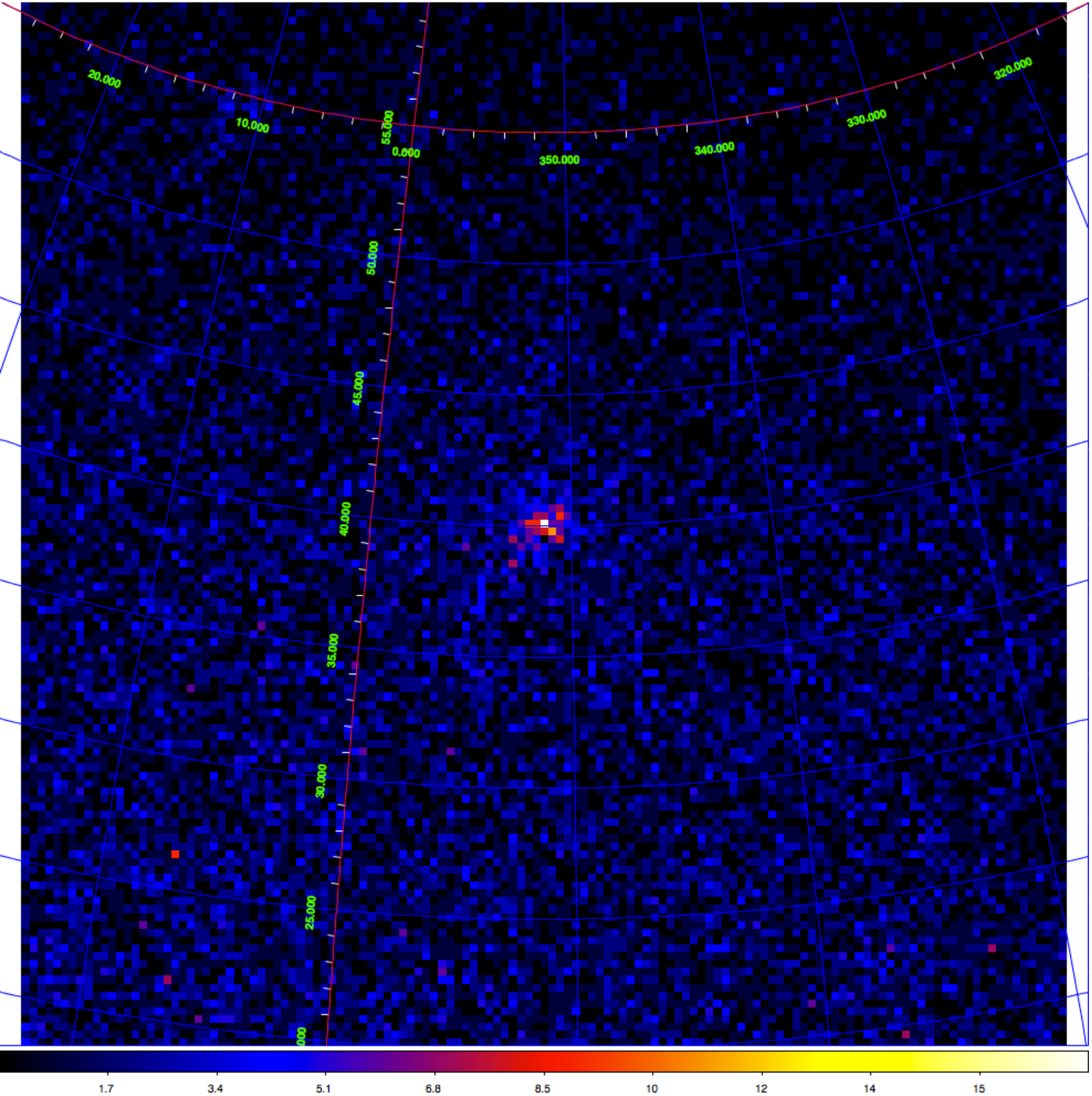


The data are photons that came from celestial sources or background.

THE DATA

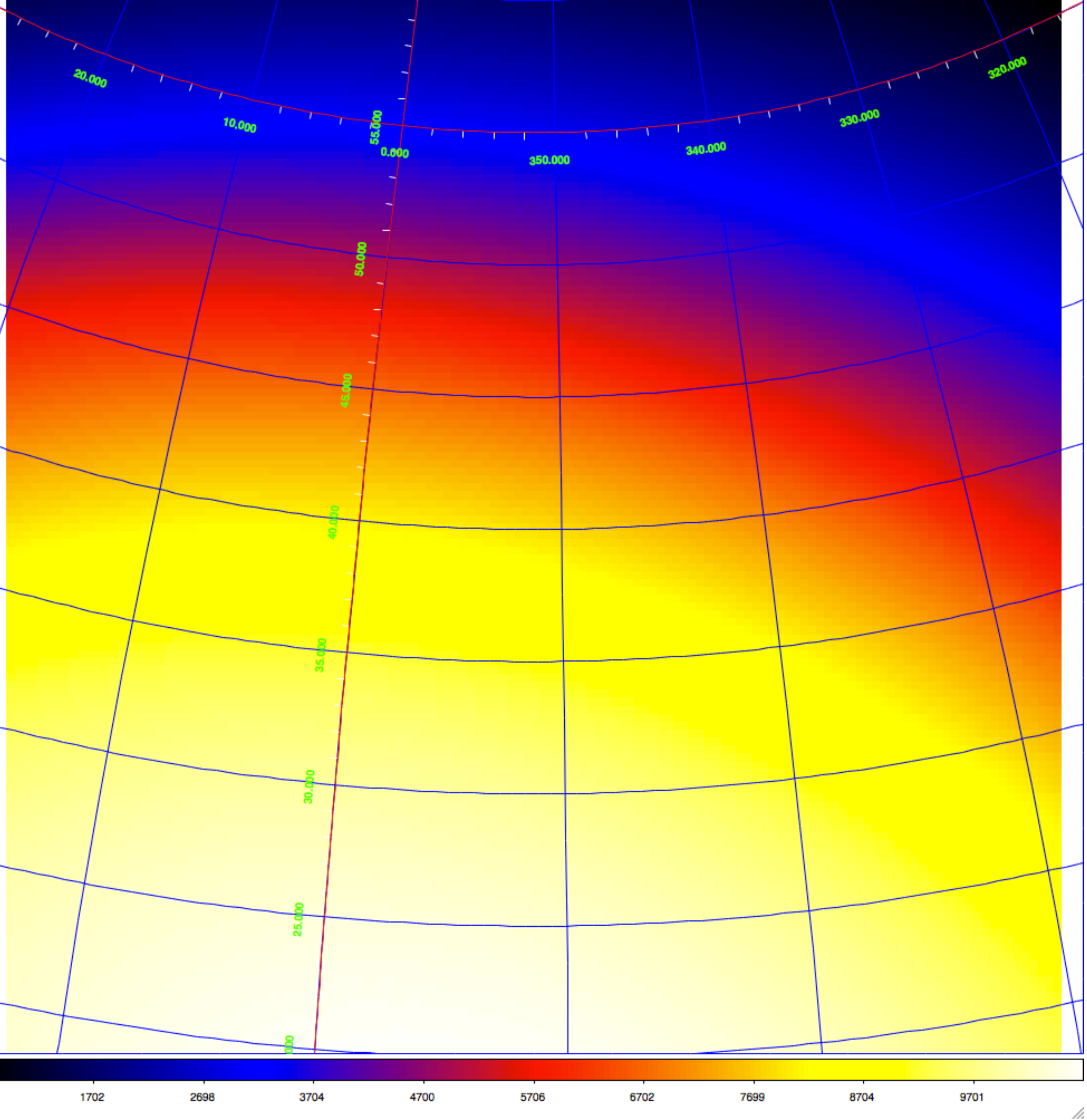
The data

- 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 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.

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

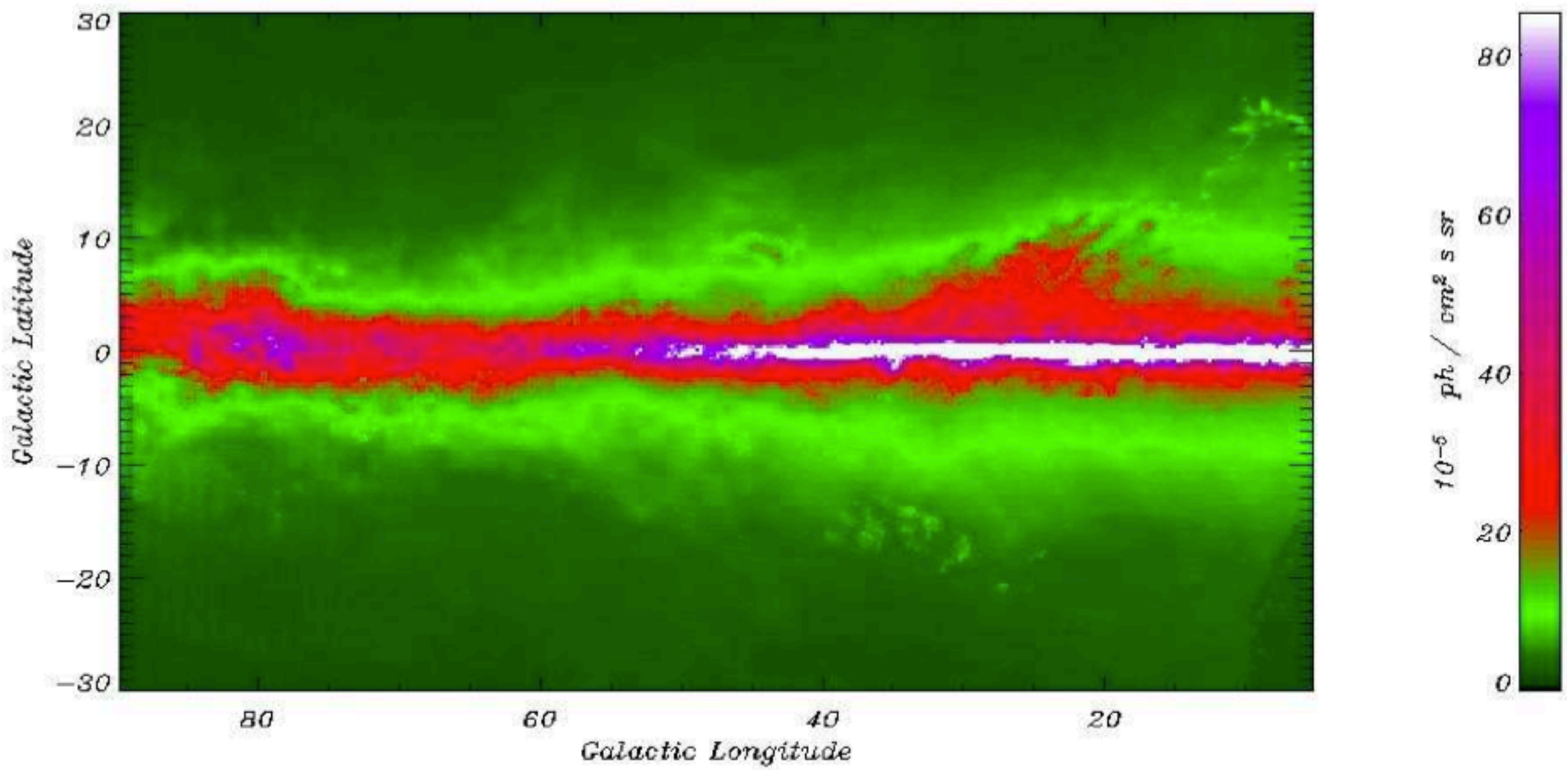


Figure 3.1: The AGILE emission model for the first Galactic quadrant.

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

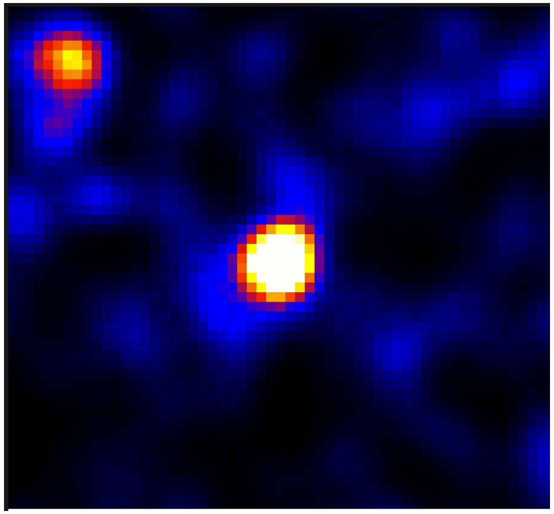
- The two parameters that we use to describe the Galactic (diffuse) and isotropic γ-ray emission are:
  - g_{gal}, the coefficient of the Galactic diffuse emission model
  - g_{iso}, the isotropic diffuse intensity (10^{-5} cm^{-2} s^{-1} sr^{-1})

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 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

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}

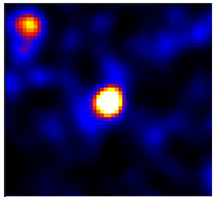
- It is possible to keep each parameter either free or fixed; a free parameter is allowed to vary to find the maximum likelihood.
- The values of the parameters are found by means of a maximum likelihood estimator (MLE) that maximizes the likelihood of producing the data given in the ensemble of models.

- Within R_{anal} circle
  - The Galactic diffuse radiation model is scaled by a multiplier g_{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, $s_c = 0$)

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

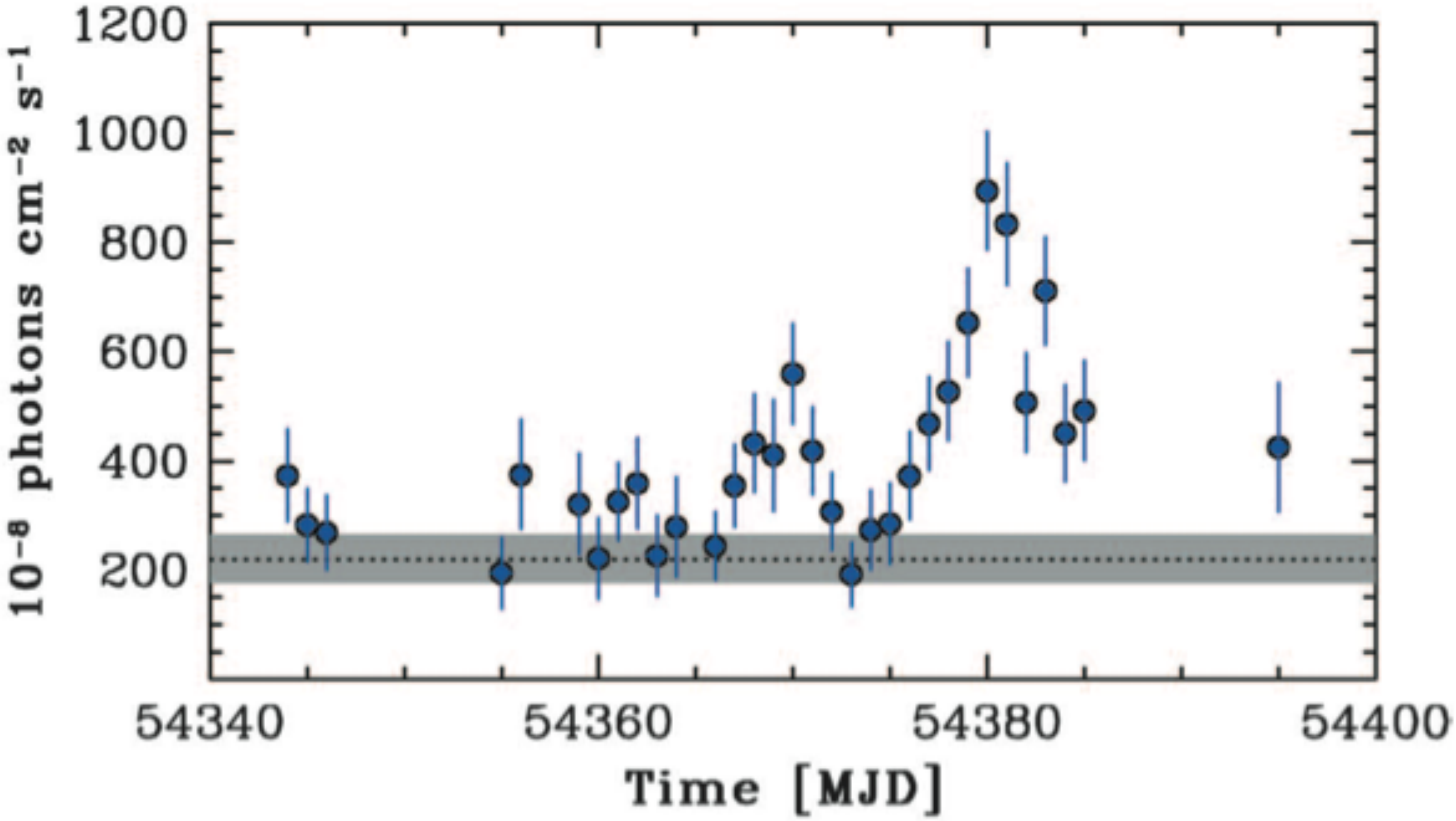
The value of each free parameter:
g_{gal}
g_{iso}
for each point source i:
(L_1, s_c , s_l , s_b, s_{si})

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.

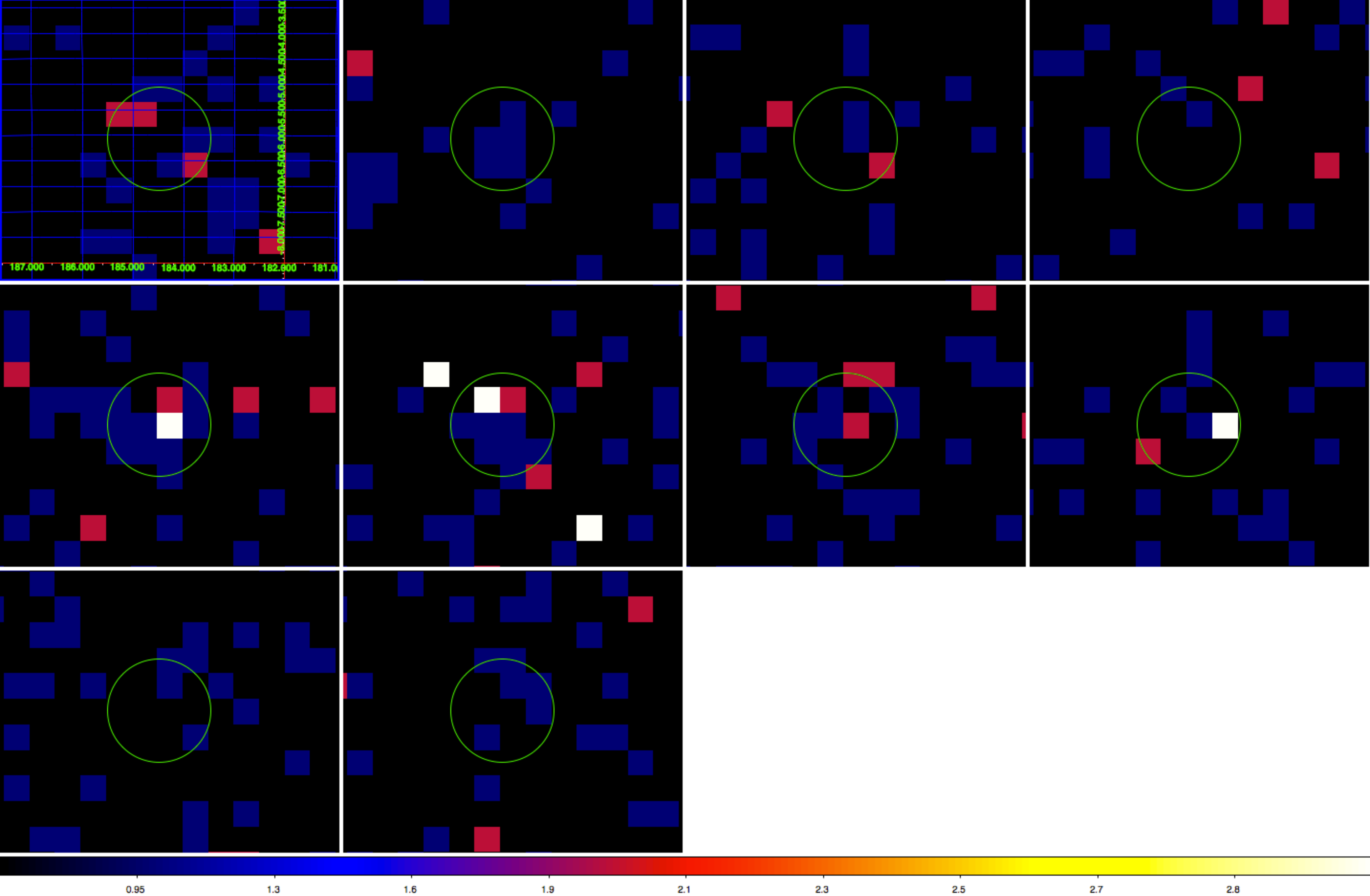


Fig. 1A: A set of counts maps of the same sky region with a gamma-ray flare from a celestial source. Each map contains 2 days of data. The green circle has a radius of 1°. The flux of the source is calculated for each map to build the light curve .

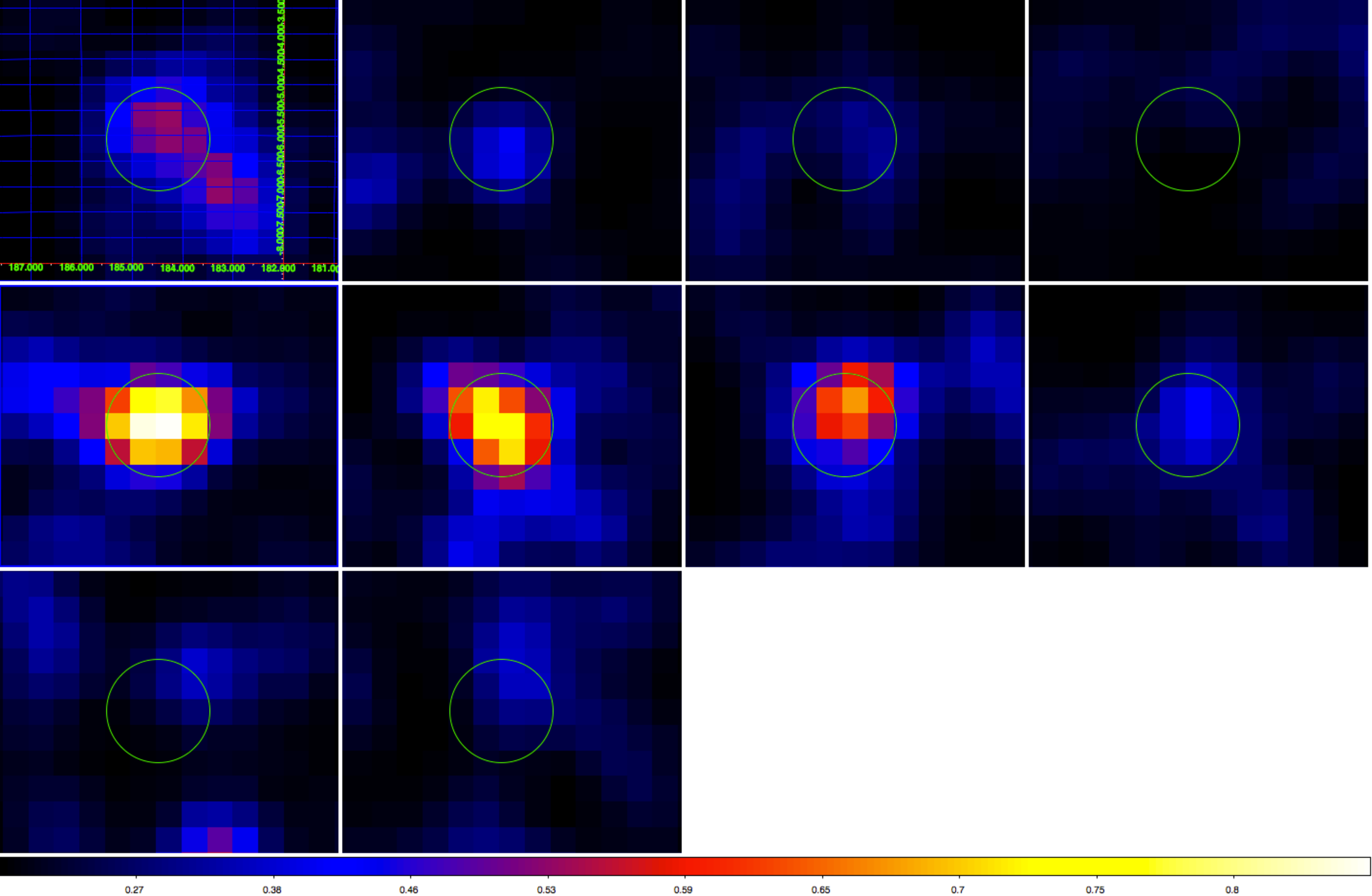


Fig. 1B: The same data of the Fig. 1A but each map is smoothed to show the effect of the the PSF.