



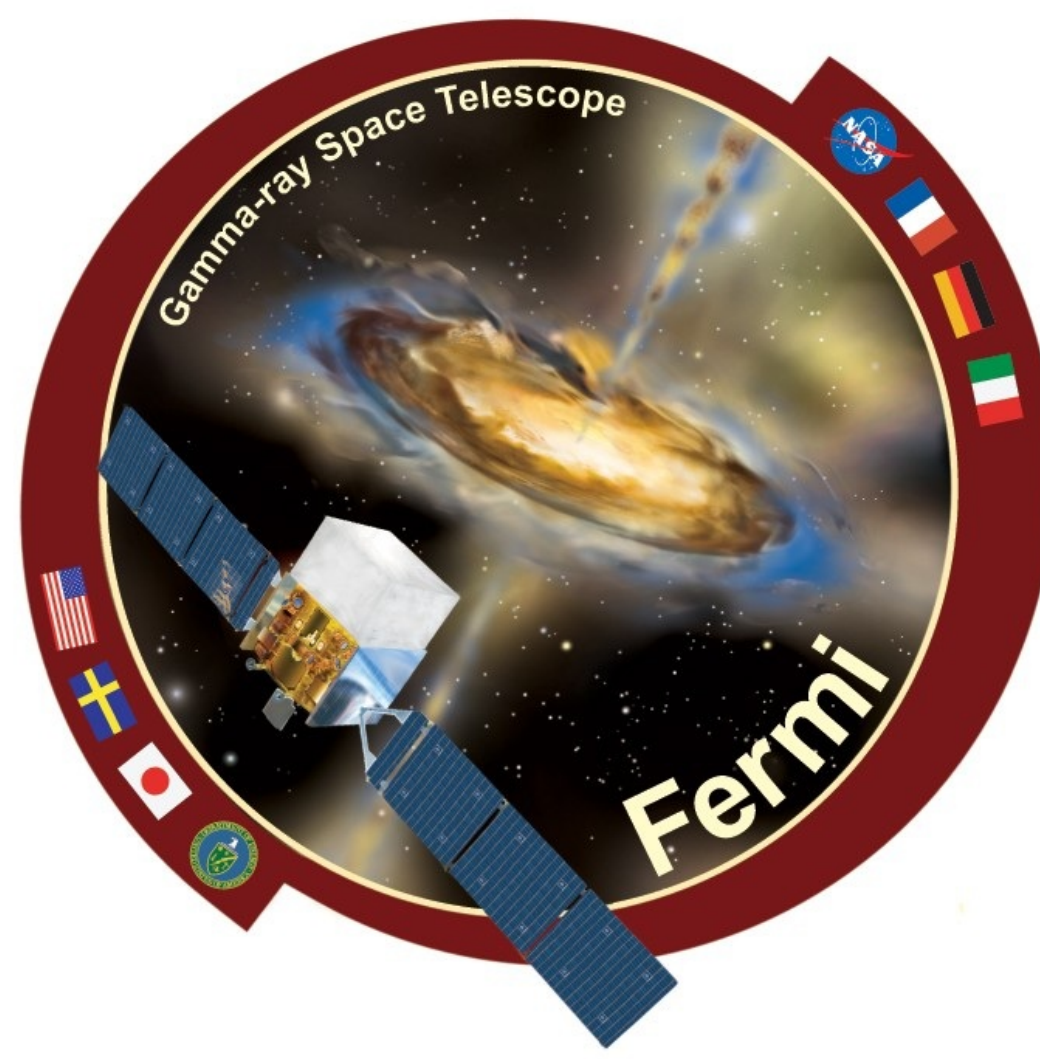
Fermi

Gamma-ray Space Telescope

The Fermi Bubbles: foreground subtraction and energy spectrum

**Dmitry Malyshev and
Anna Franckowiak
on behalf of the Fermi-LAT
Collaboration**

**TeVPA 2013
August 26 – 29, UC Irvine**

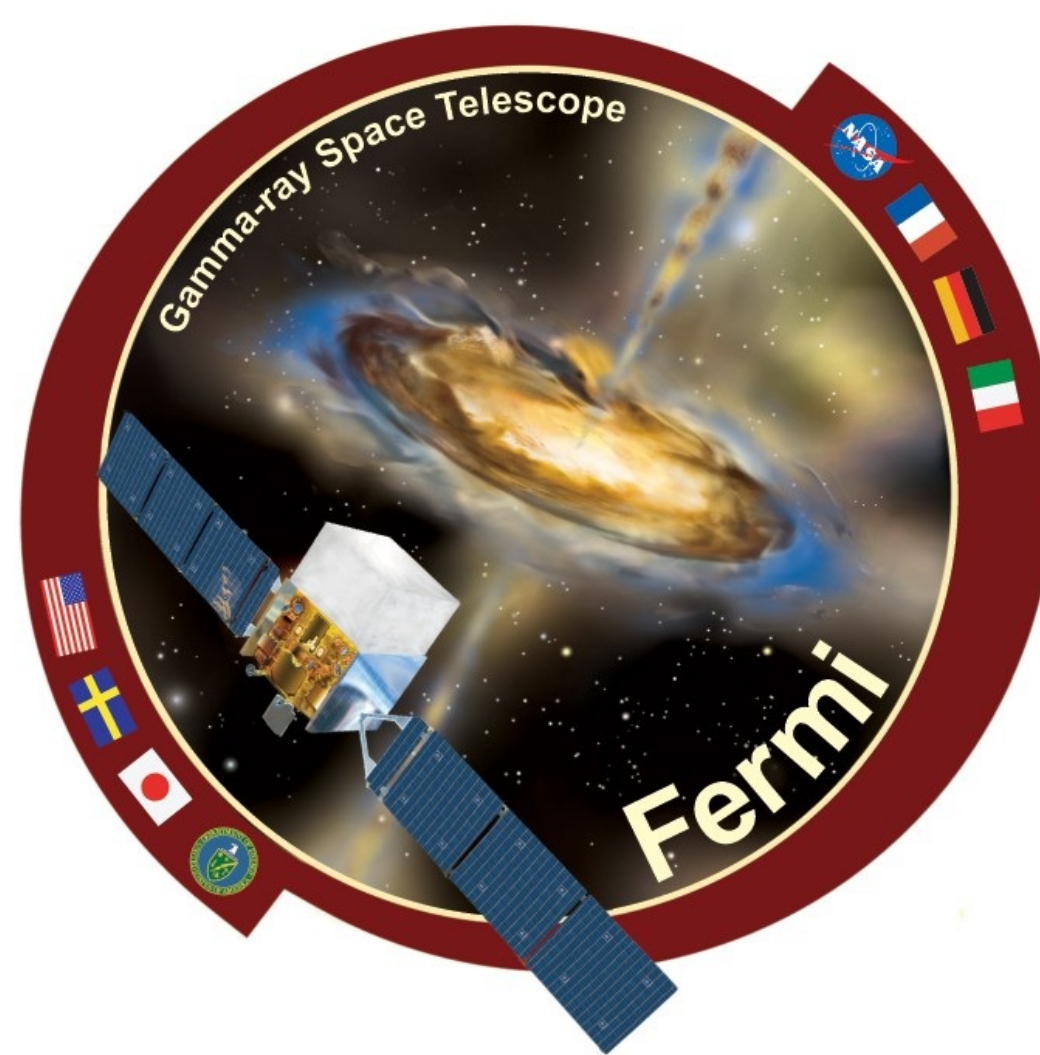


- **Fermi-LAT data selection**
- **Galactic diffuse emission model**
- **Determination of the Fermi bubbles template**
- **The spectrum of the Fermi bubbles**

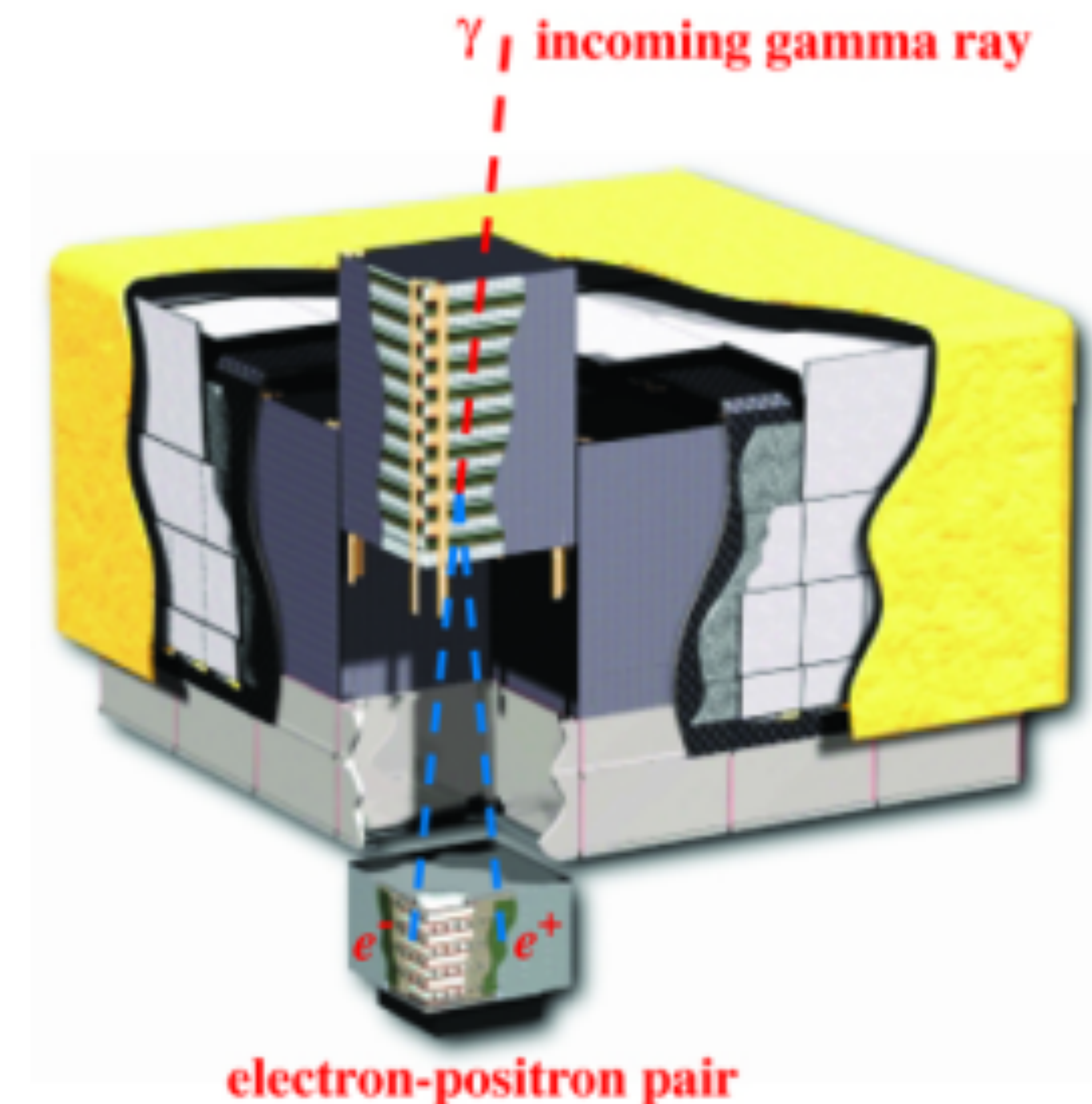
- **Fermi Large Area Telescope – pair conversion gamma-ray space telescope**
- **Launched on June 11, 2008 from Cape Canaveral, Florida**
- **5 years of data available for public use (since August 8, 2008)**
- **Minimal mission plan: 5 years**
- **Maximal mission: 10 years or more**
- **2.8 tons**
- **1.8 m² by 0.7 m**
- **650 watts**



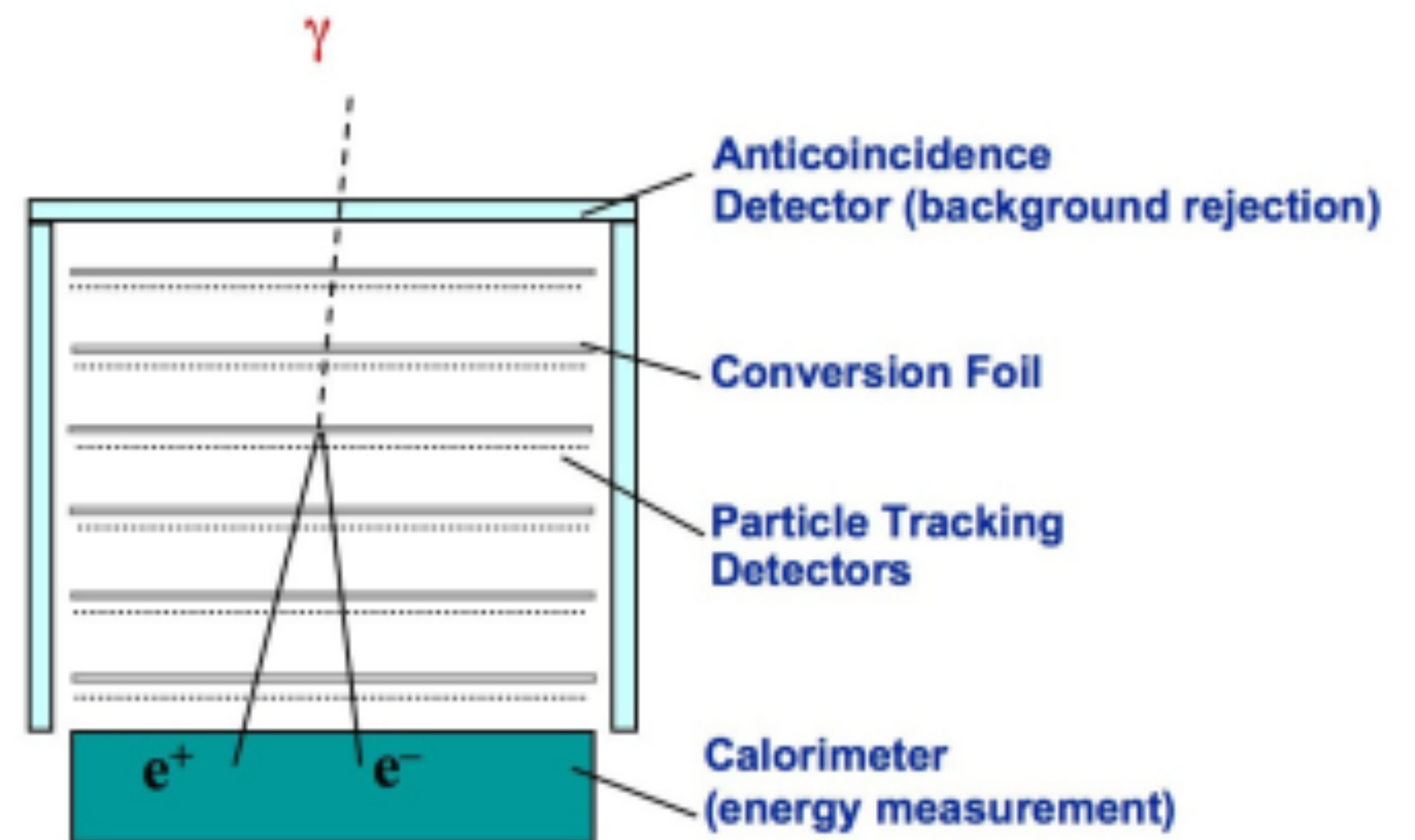
Fermi-LAT components

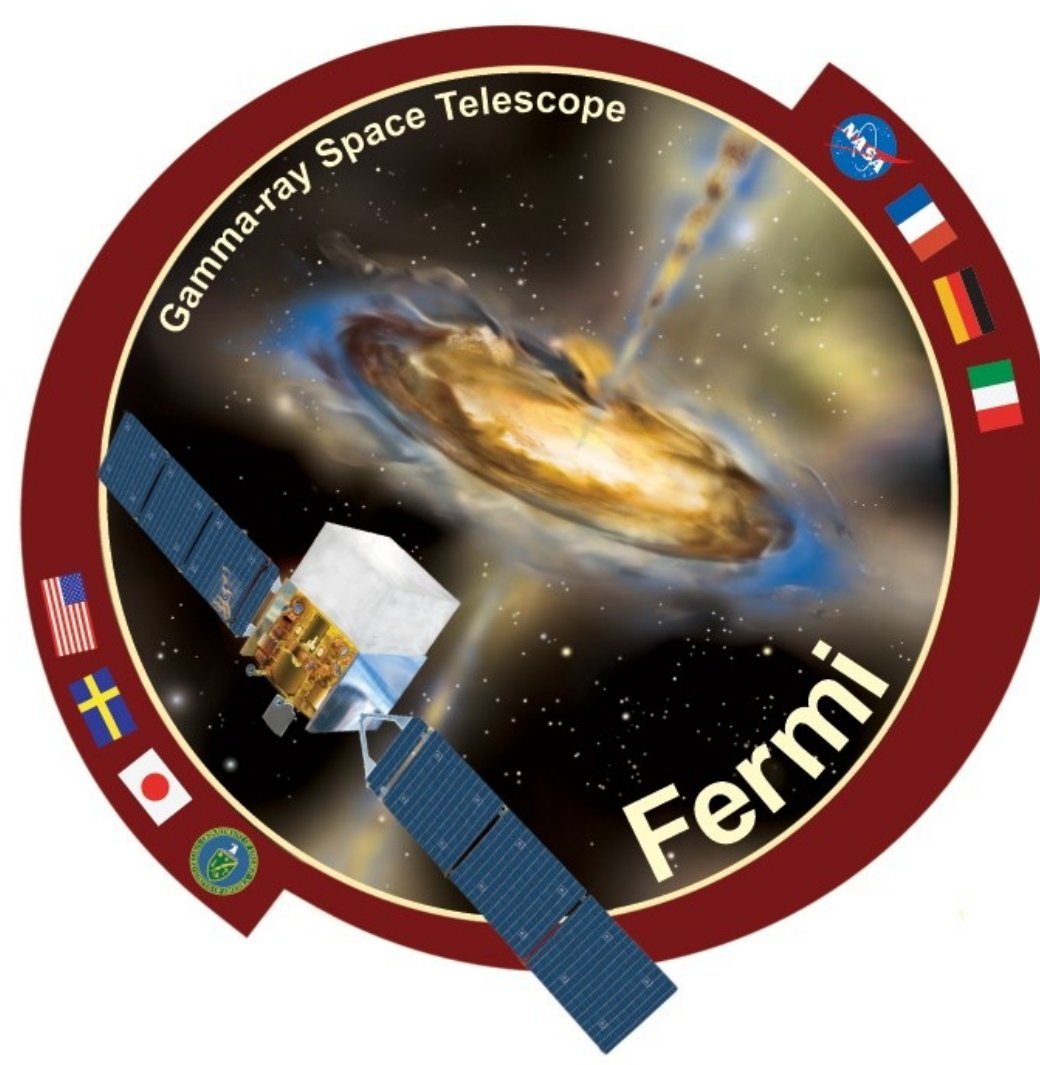


- **Anticoincidence detector** – separate charged particles from gamma-rays
- **Tracker-converter** – convert gamma-rays into e^+e^- pairs and track the arrival direction
- **Calorimeter** – determine the energy of the gamma-ray



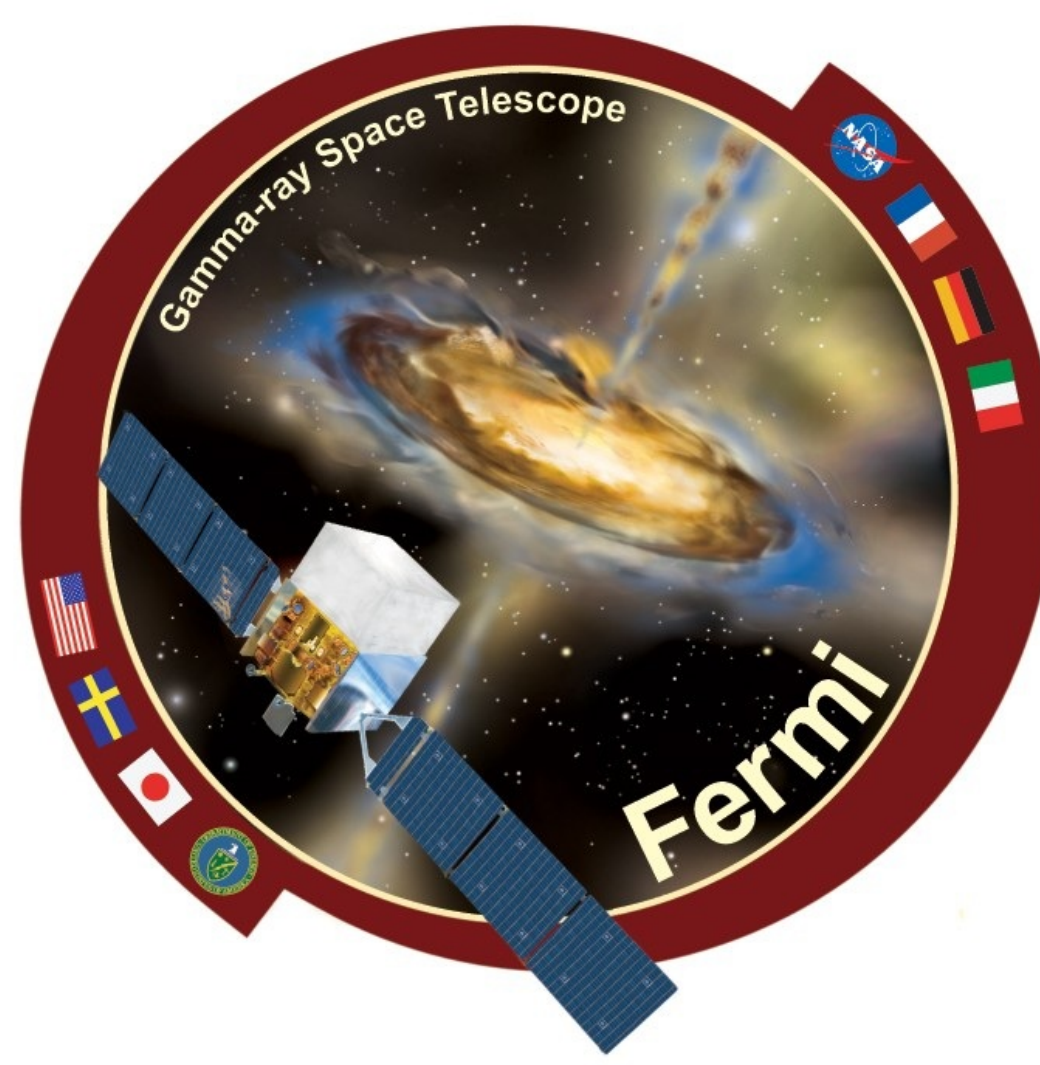
Energy: 20 MeV to above 300 GeV
 PSF: $< 1^\circ$ above 1 GeV
 Solid angle: 2.4 sr at 1 GeV
 Eff. area: 6500 cm² above 1 GeV



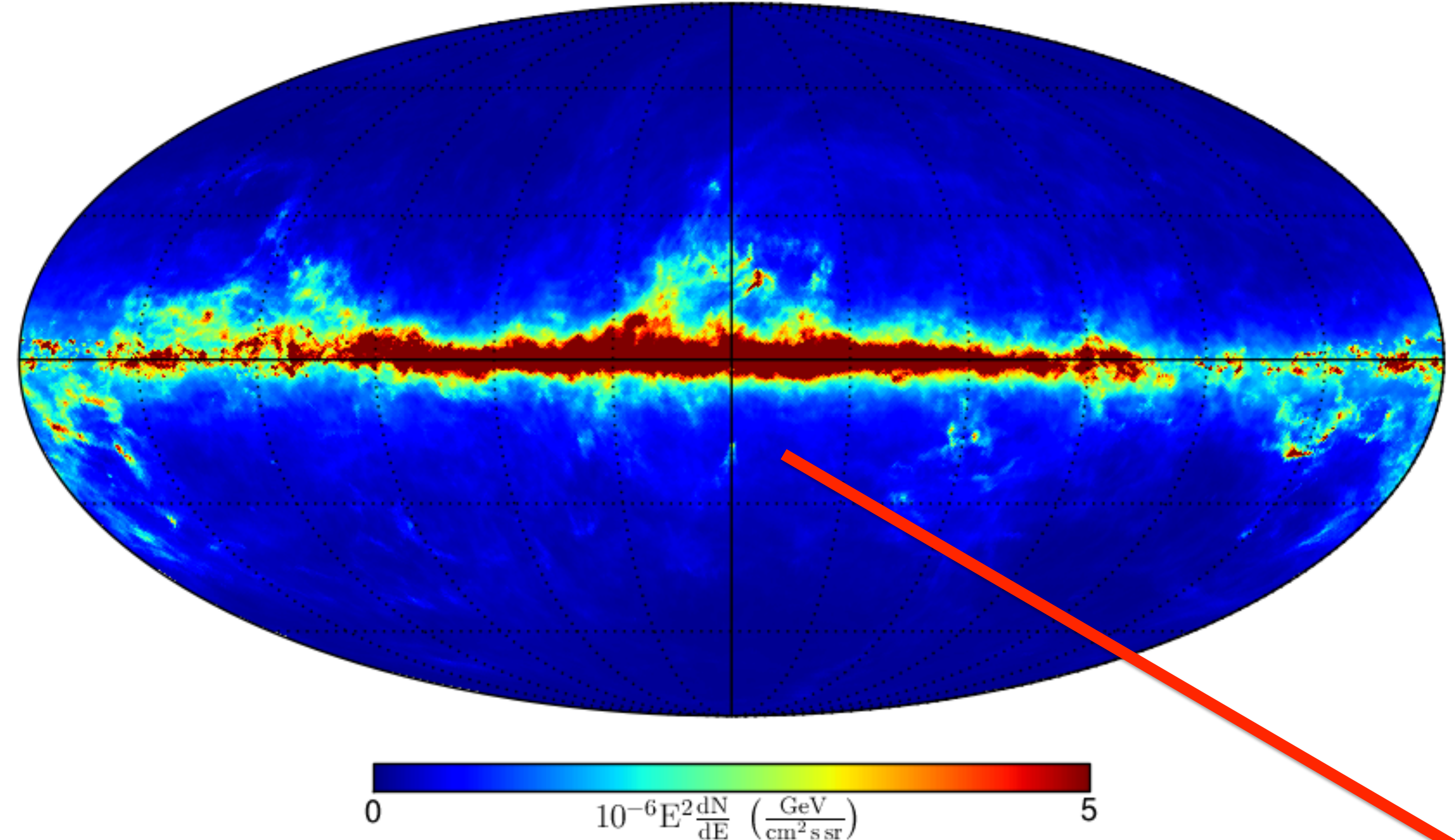


- In the Fermi bubbles analysis, we use:
 - 50 months of Pass 7 reprocessed data
 - 100 MeV to 500 GeV energy range (in 25 bins)
 - Ultraclean class
 - Mask $|b| < 10$ deg

Gamma-ray emission

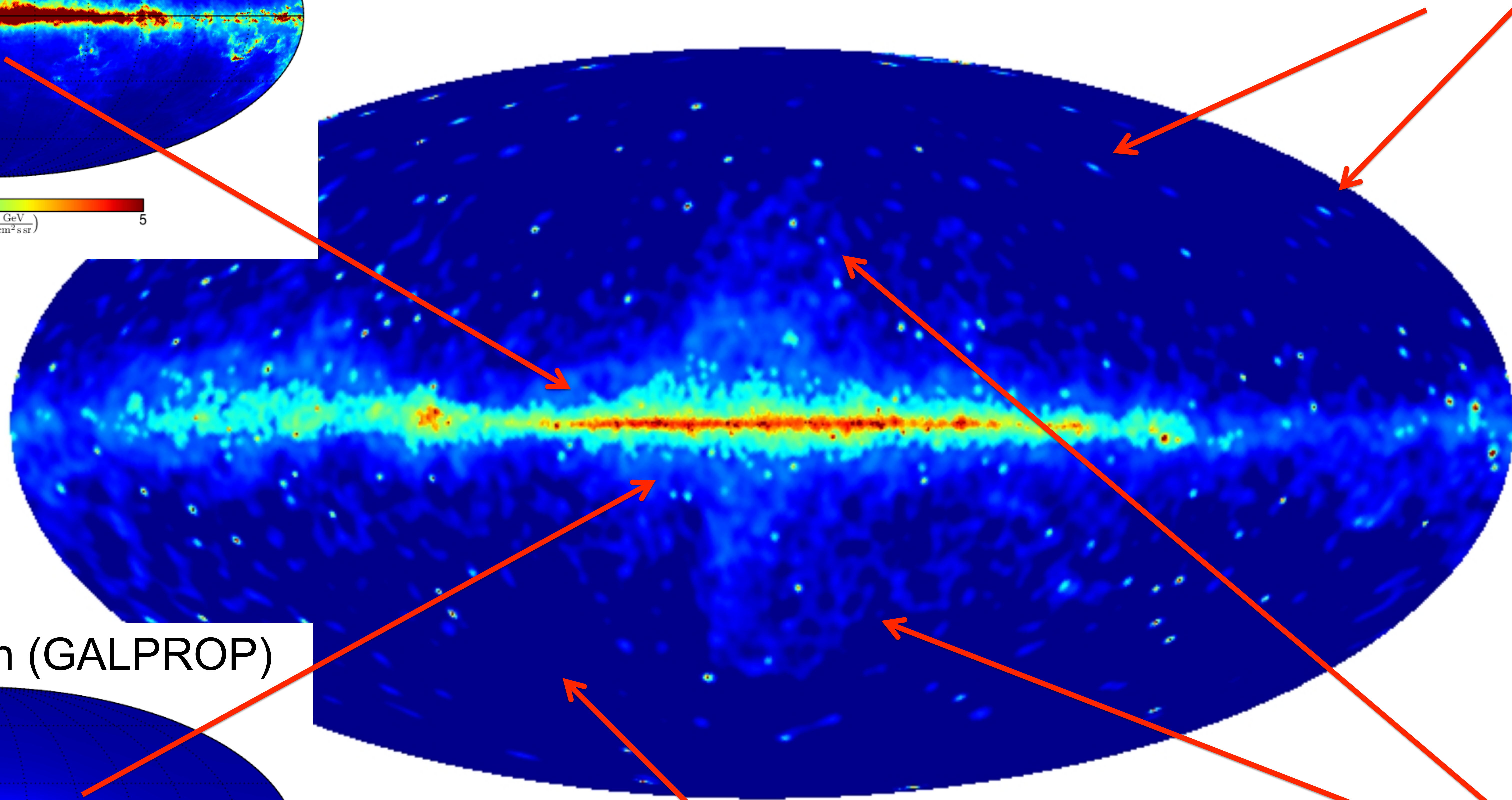


π^0 and brems (GALPROP)

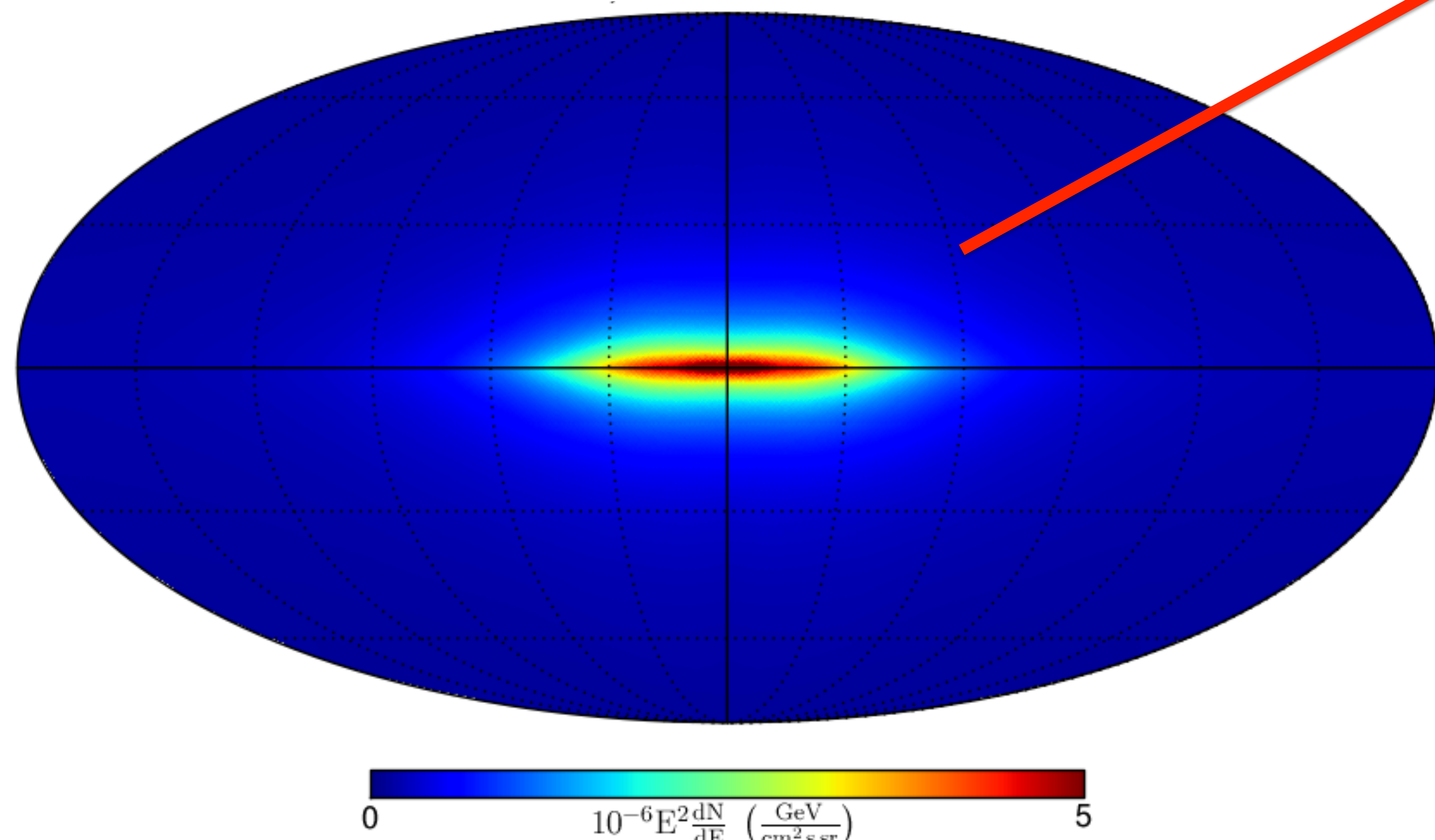


Fermi-LAT data (3 years, >10 GeV)

Point sources



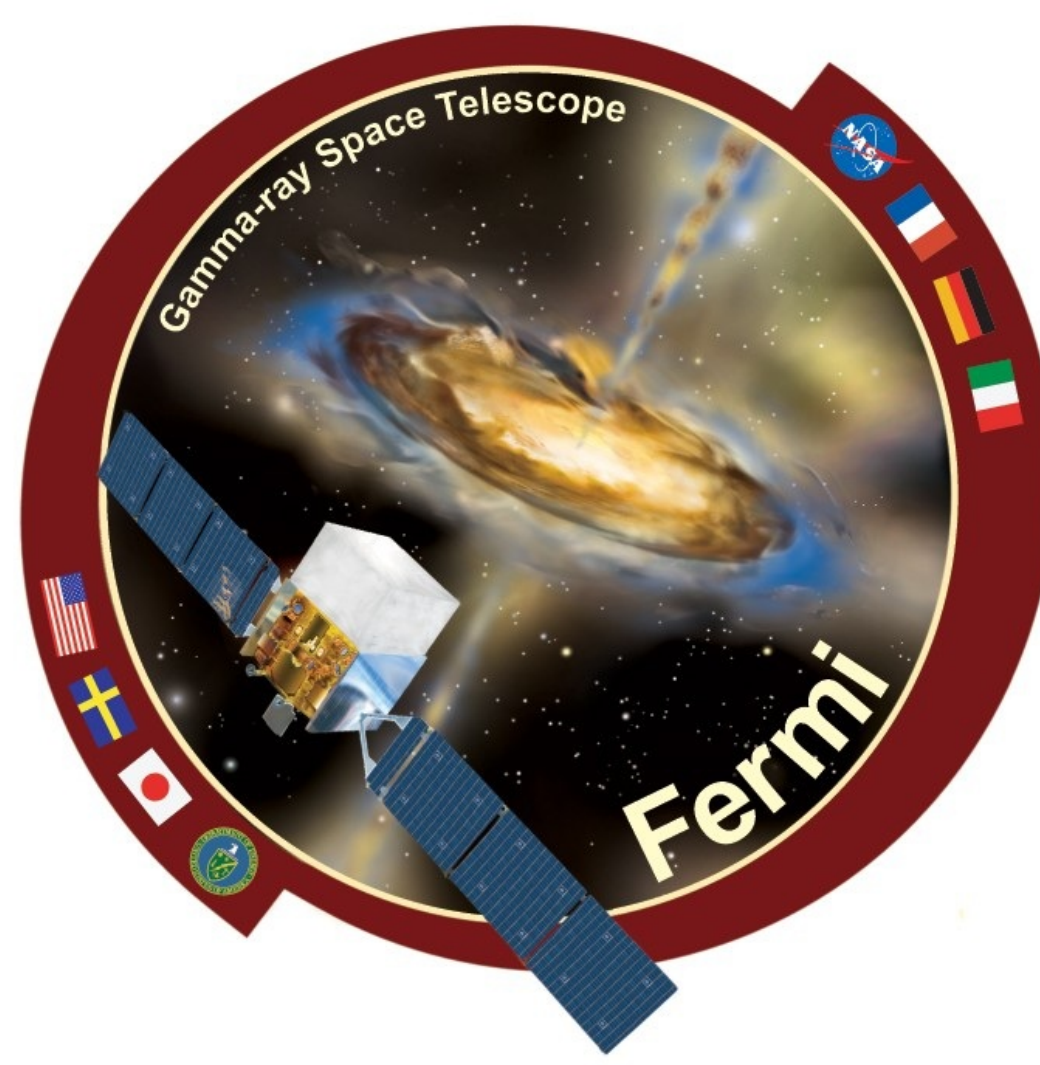
Inverse Compton (GALPROP)



Fermi bubbles

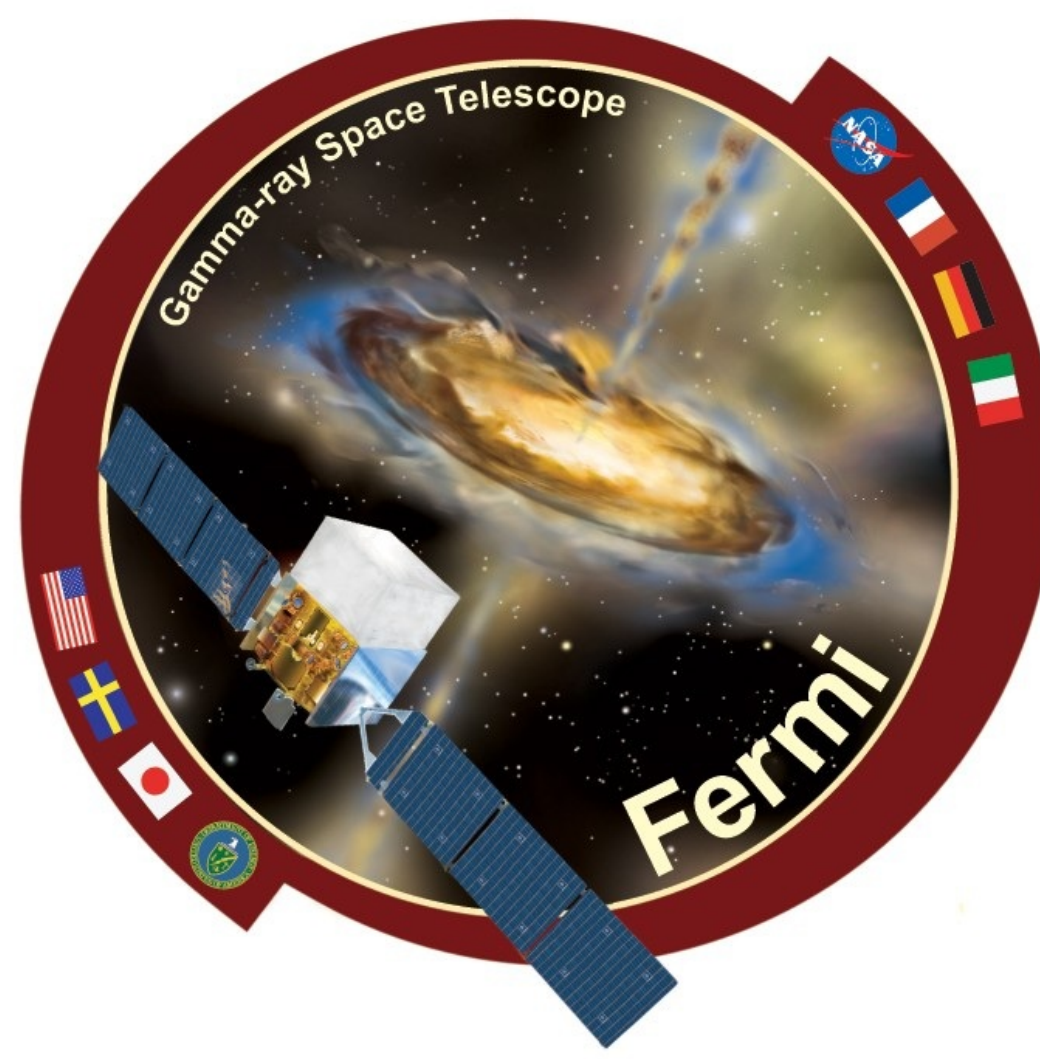
Isotropic background

Emission components



- **Most components have a model of the spatial distribution:**
 - **Point sources** – point spread function (PSF)
 - **Hadronic and brems** – distribution of gas (HI, HII, H₂) and a propagation model of cosmic rays (CR) – GALPROP
 - **Inverse compton (IC)** – distribution of interstellar radiation field and propagation of leptons – GALPROP
 - **Extragalactic and CR contamination** – isotropic
- **Fermi bubbles do not have a spatial distribution model:**
 - Neither the spatial distribution nor the spectrum are known a priori (no bright counterparts in other frequencies, e.g., radio, microwave, or X-rays).
 - **Have to define all properties of the Fermi bubbles from the gamma-ray data!**

Formulation of the problem



- **Fermi bubbles overlap with all other components of emission:**
 - **hadronic, IC, brems, point sources, isotropic**
- **The choice of the foreground / background model affects the properties of the bubbles.**
- **One of the main goals of our work is to study the effect of the foreground modeling on the Fermi bubbles.**

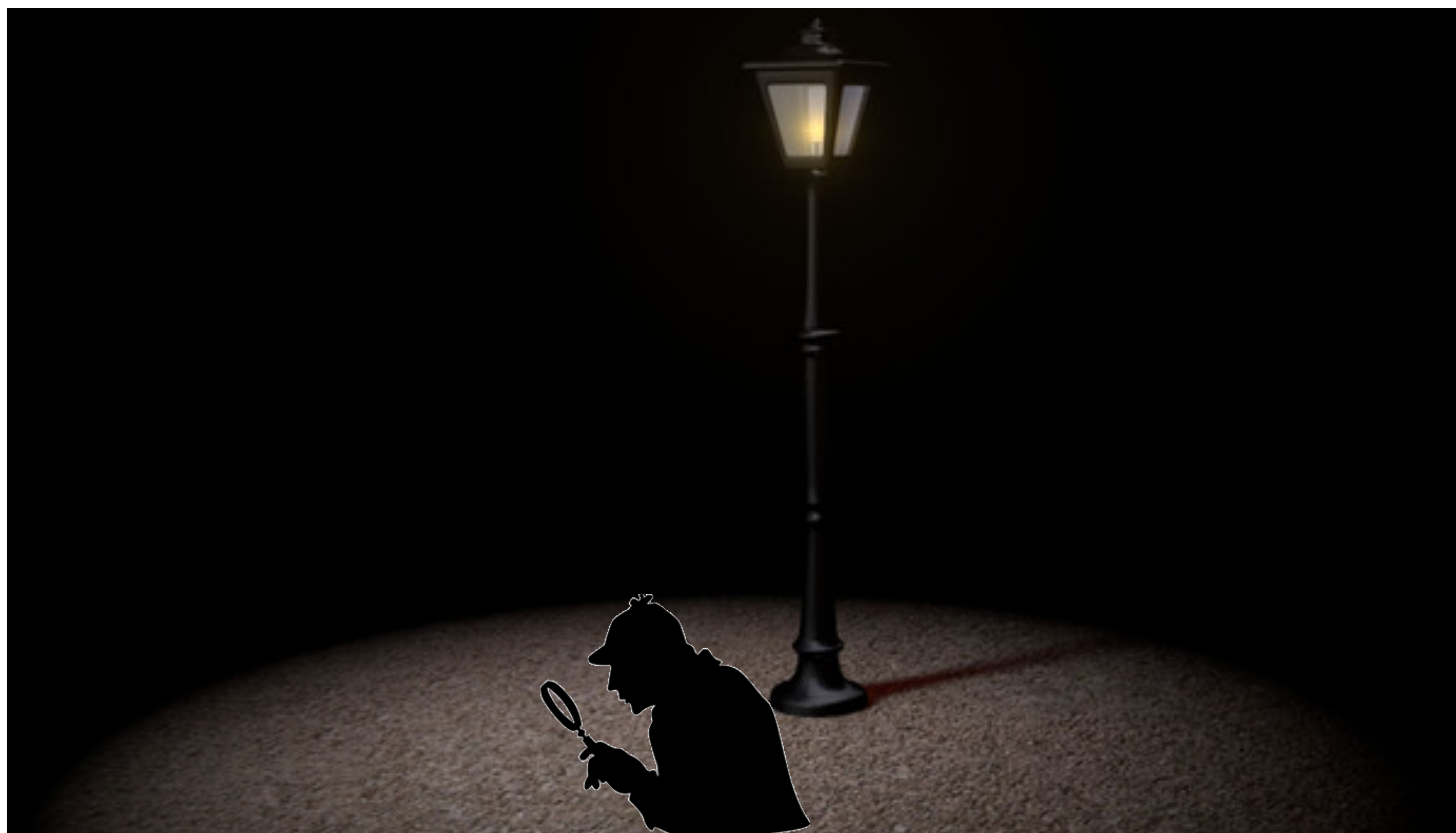
Theory driven:

- fit data by existing models
- may be biased

Data driven:

- fit data by a generic model
- may be hard to interpret

If the watch is here, we will find it:

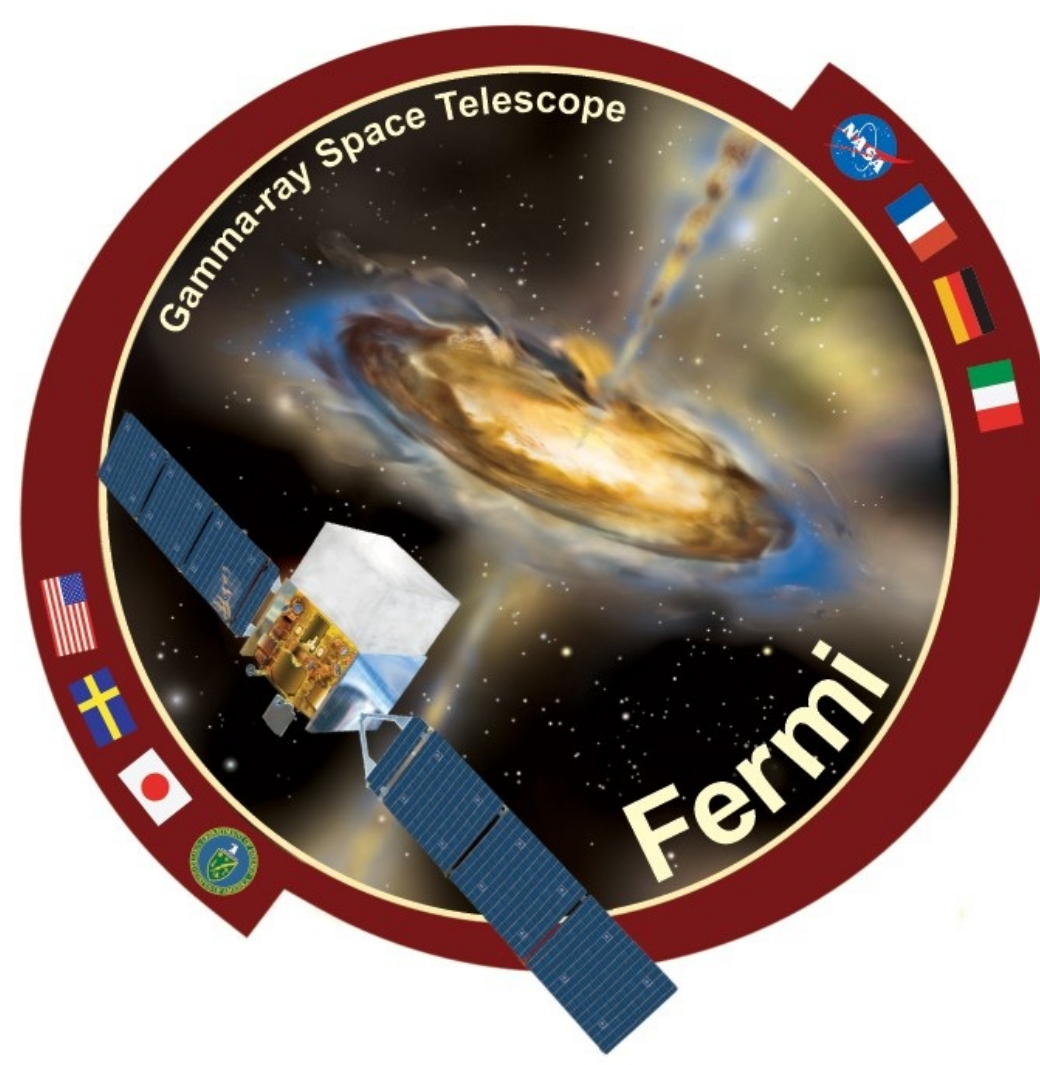


All watches are here:

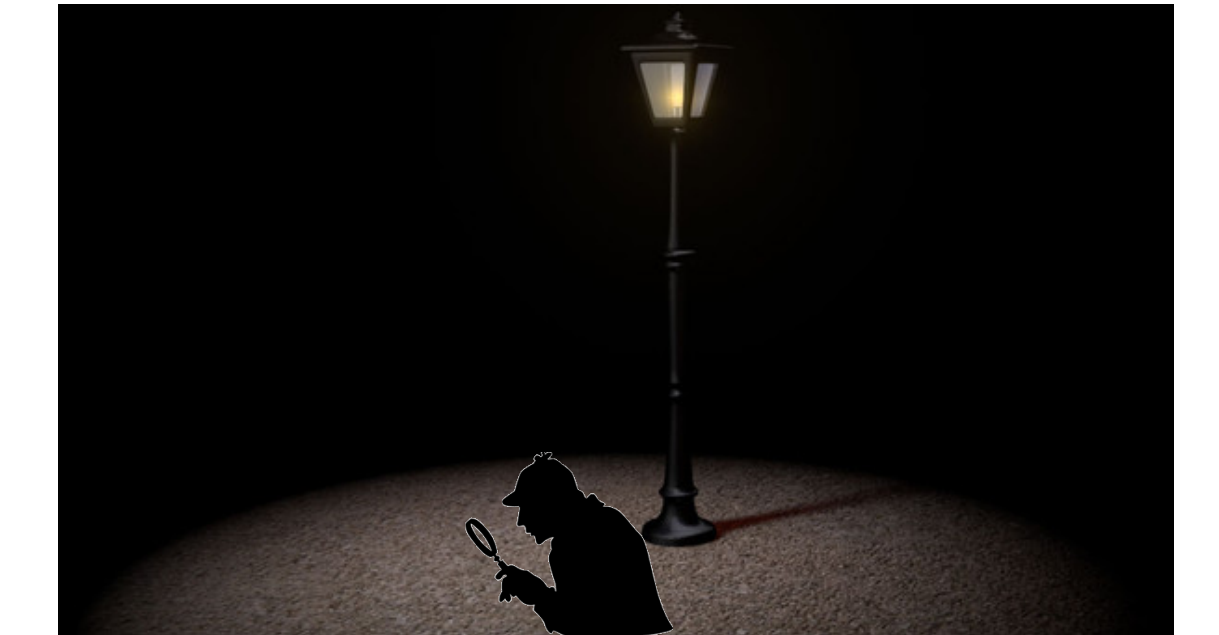


Solutions:

- start with a fixed model and relax some parts of it;
- start with a very general model and constrain it.



- **GALPROP templates analysis:**
 - Start with a fixed model
 - Change parameters (CR production and propagation)
 - Relax some of the model constraints
- **Local templates analysis:**
 - Start with a very general model
 - Gradually constrain the model to determine the Fermi bubbles
- These two methods give a ``**bracketing**'' in the space of **models**:
 - GALPROP templates come from the theory driven side
 - Local templates come from the data driven side



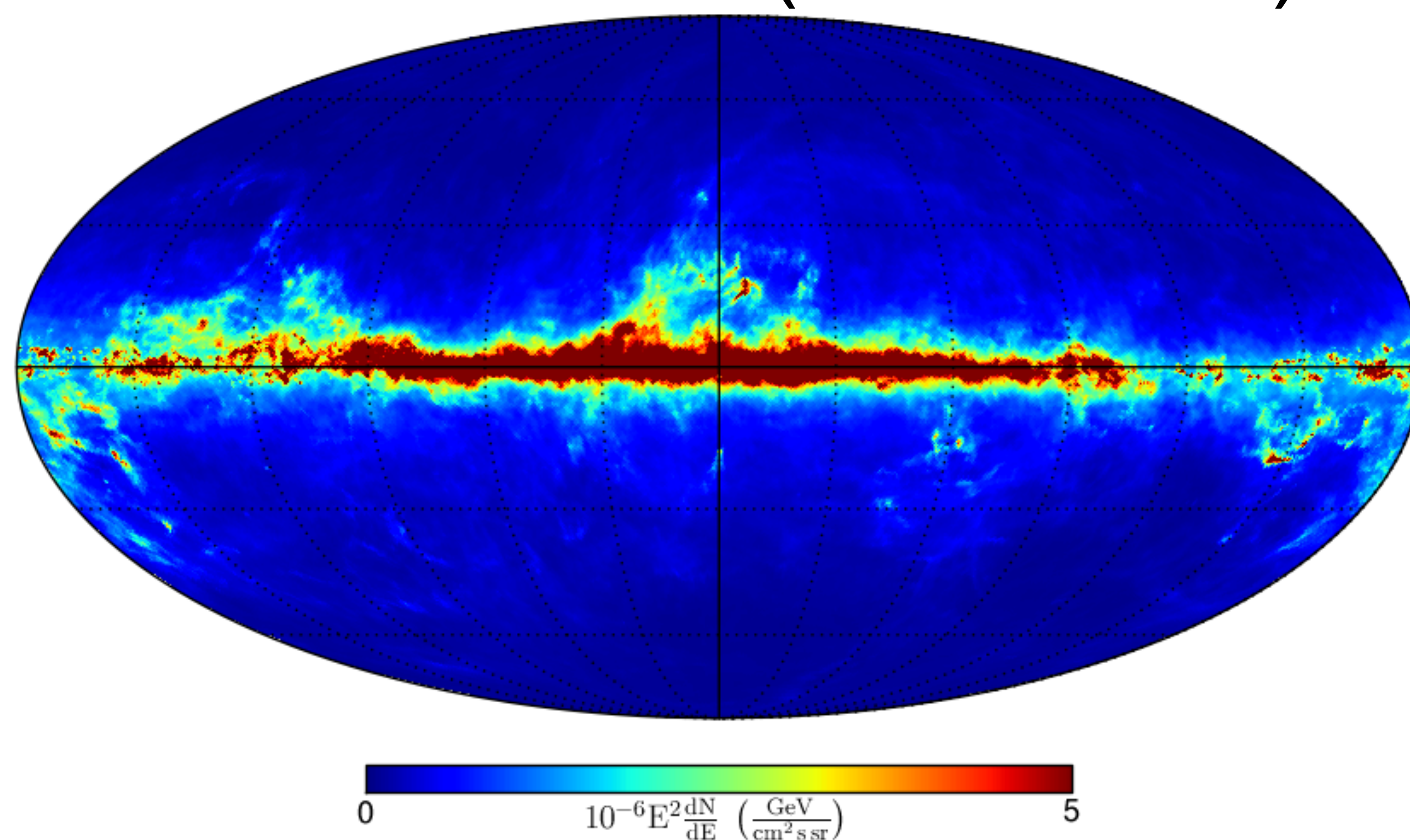
1. Determine templates

- **CR production** (tracers: pulsars, supernovae remnants)
- **CR propagation in the Galaxy** (diffusion height and radius)
- **CR interaction with target material** (HI, HII, H₂ gas, interstellar radiation field)

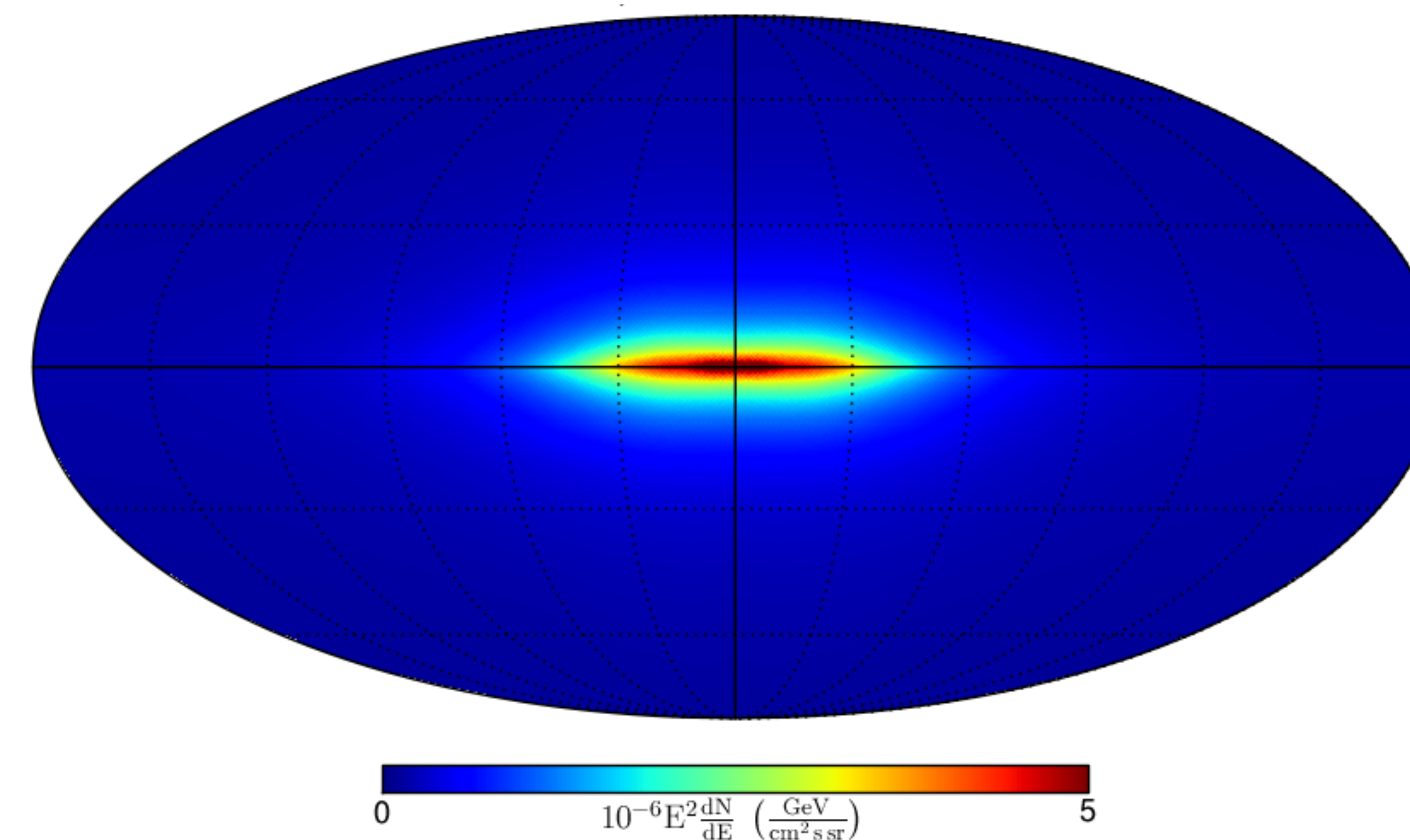
2. Fit the templates to the data

- **π^0 and bremsstrahlung**: gas correlated gamma-ray intensities in Galactocentric rings
- **Inverse Compton scattering**

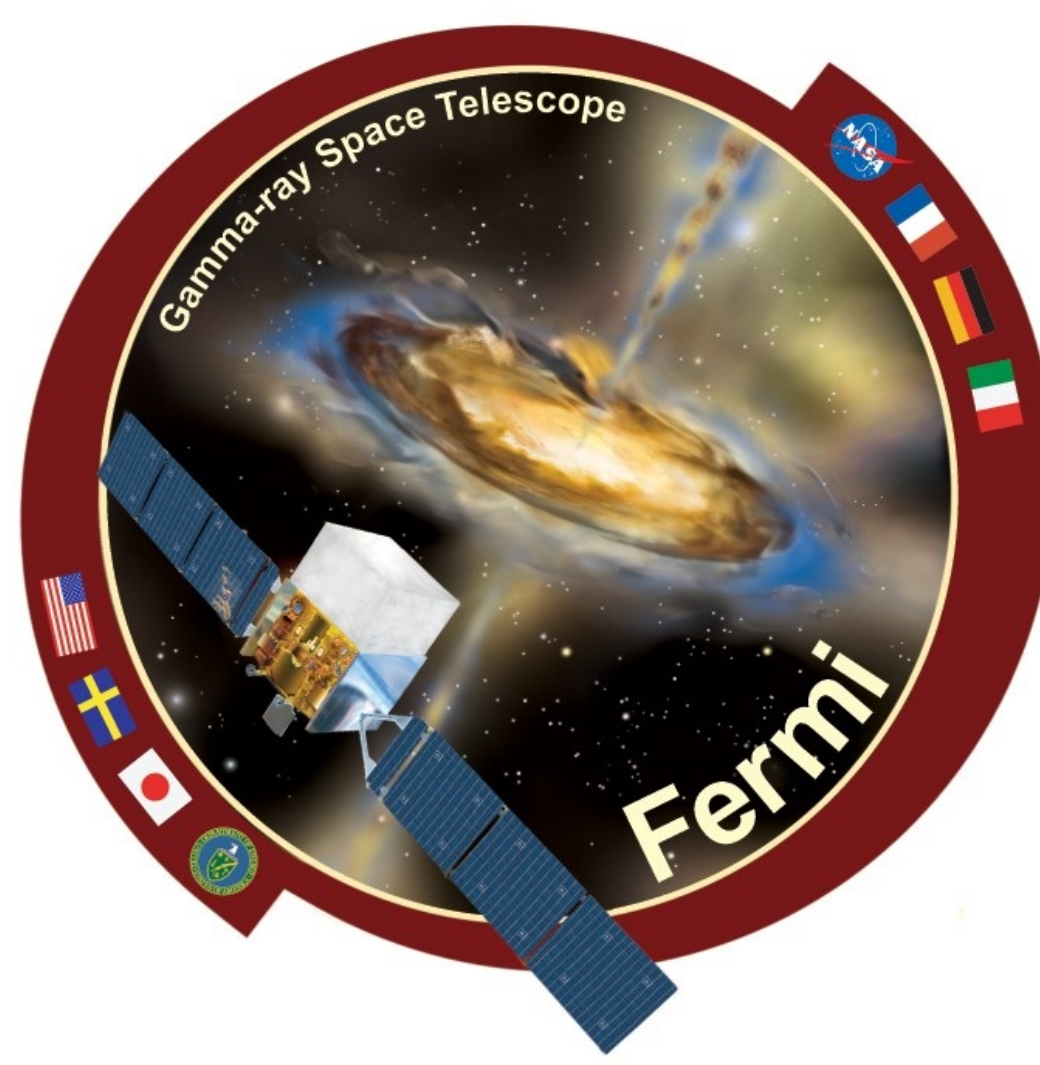
π^0 and brems (GALPROP)



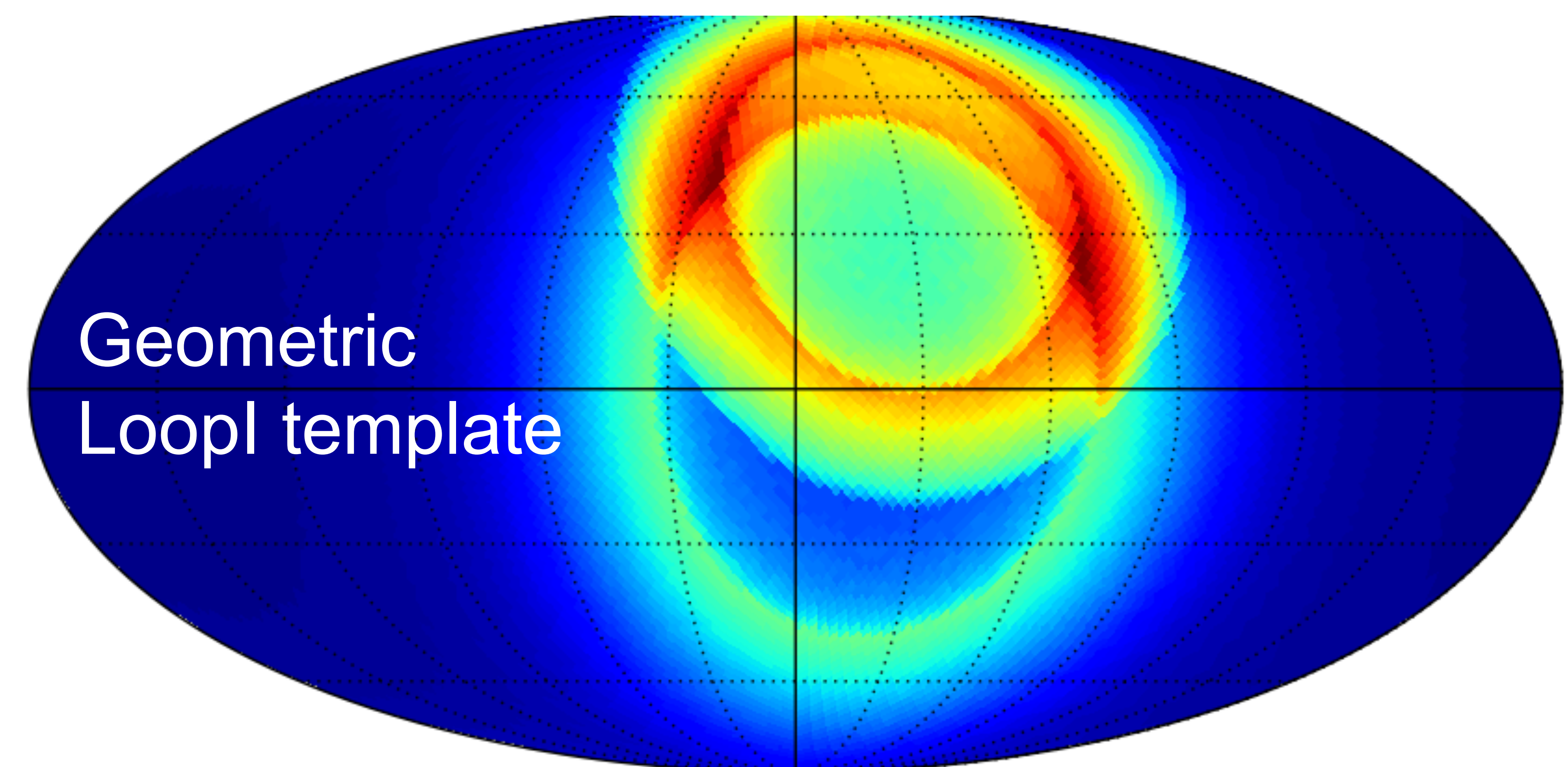
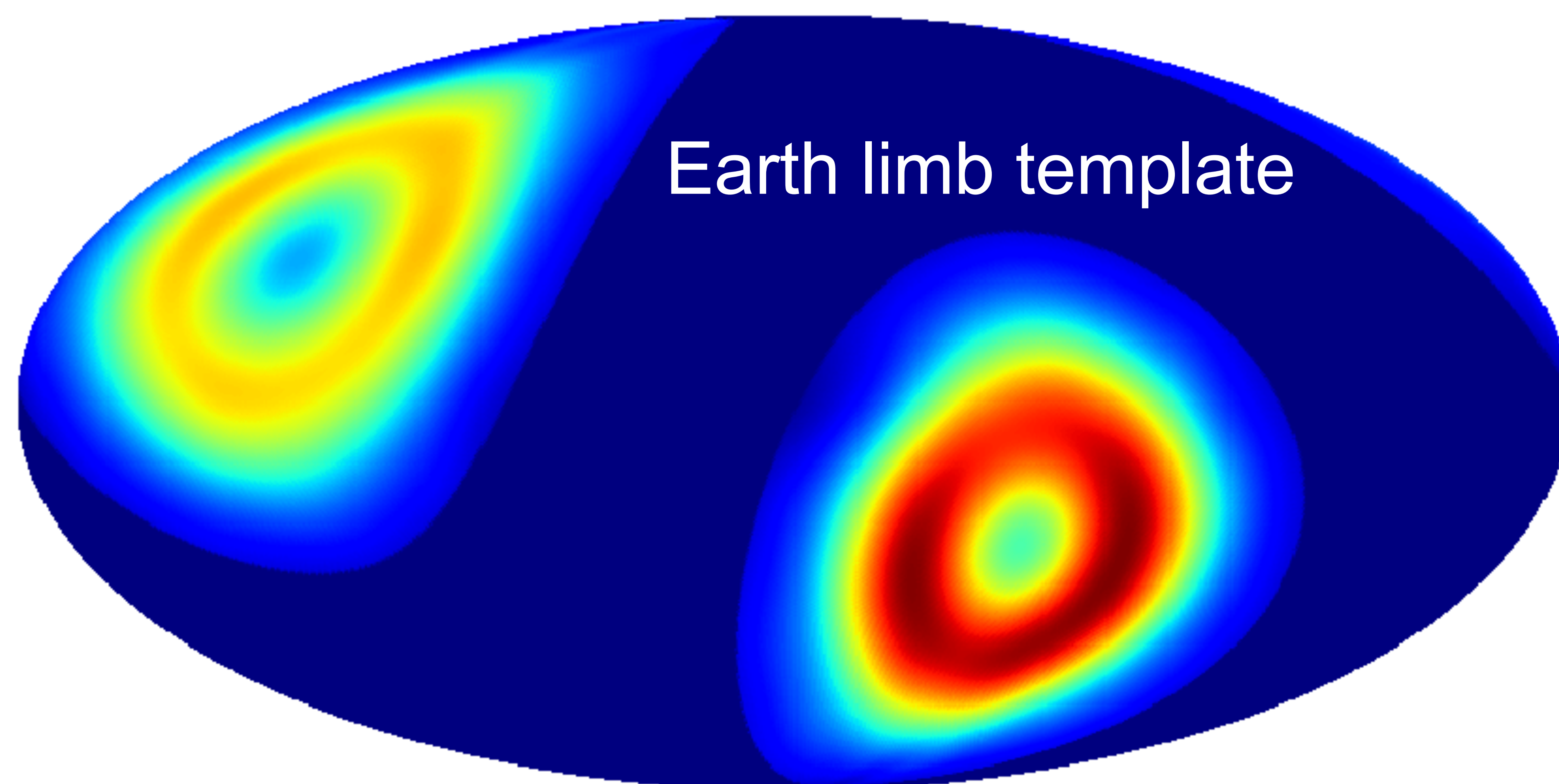
Inverse Compton (GALPROP)



Modeling of Additional Components

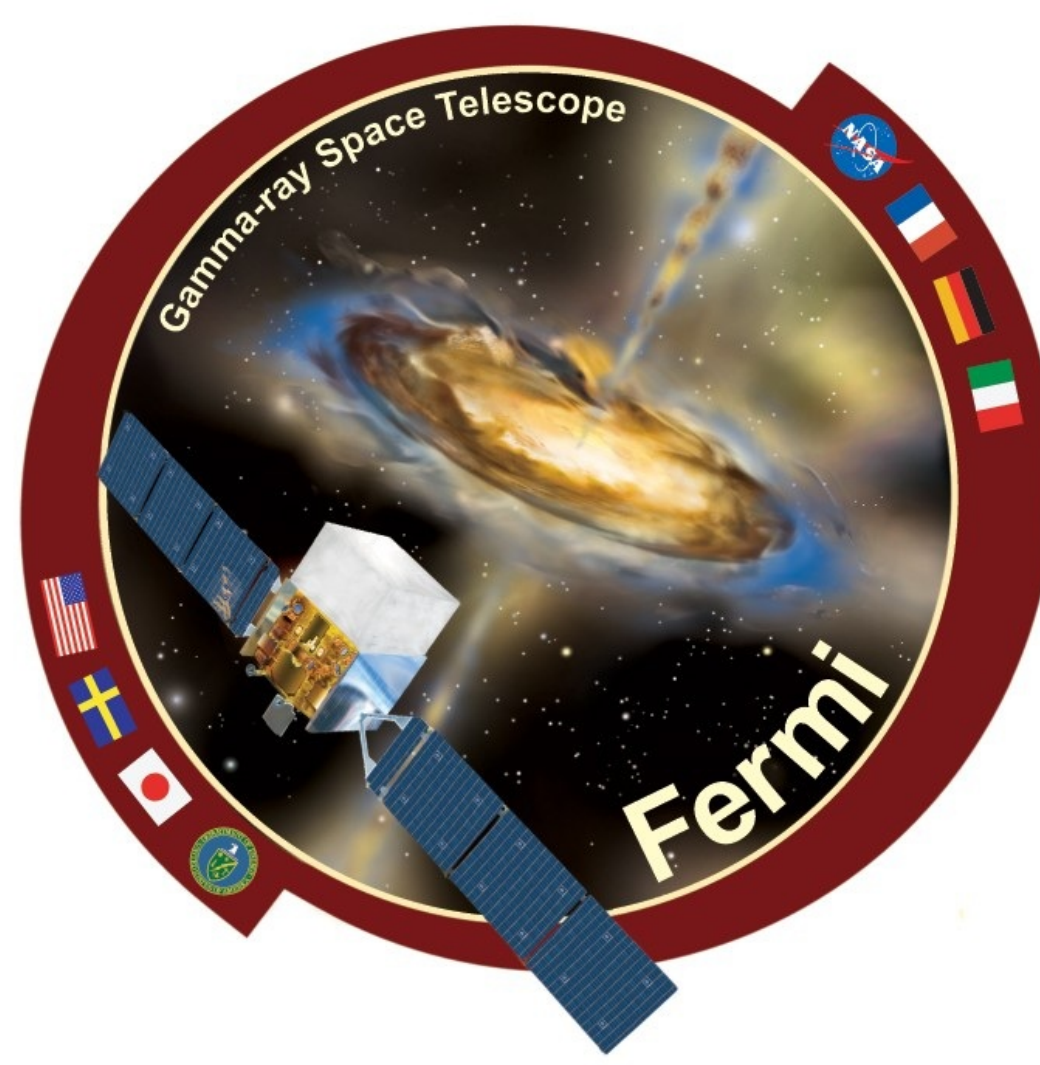


- Point sources from 2FGL catalog (spectra of bright sources are fitted, weak sources are fixed as in the 2FGL catalog)
- Isotropic component (extra-galactic and residual cosmic ray background)
- Earth limb emission (residual Earth limb component)
- Loop1 (geometric template or Haslam 408 MHz map)
- Bubble template obtained from Fermi-LAT data



Wolleben, M. 2007, *Astrophys.J.*, 664, 349

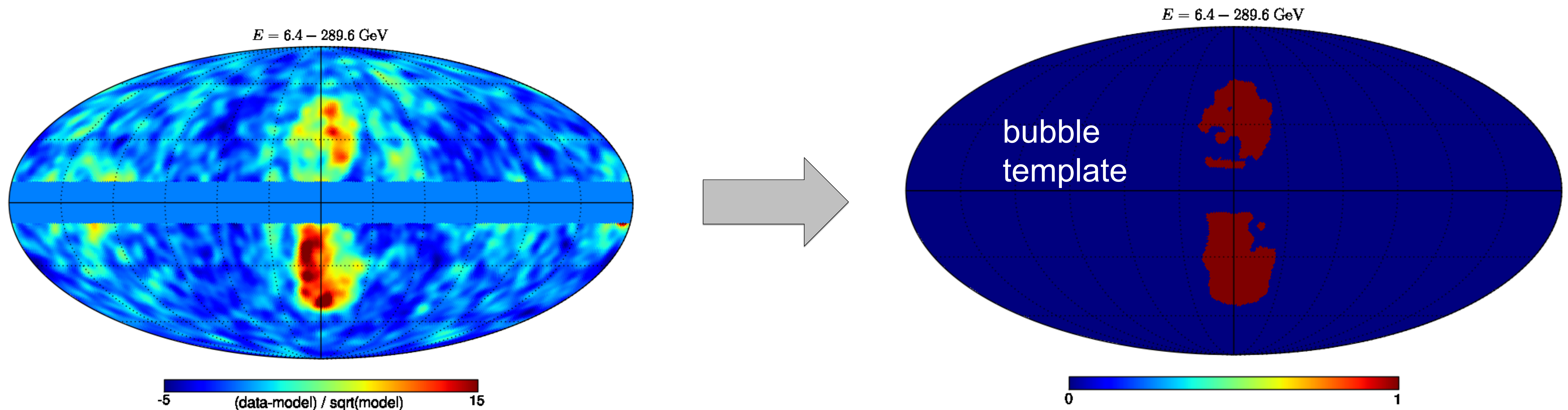
Bubble Template

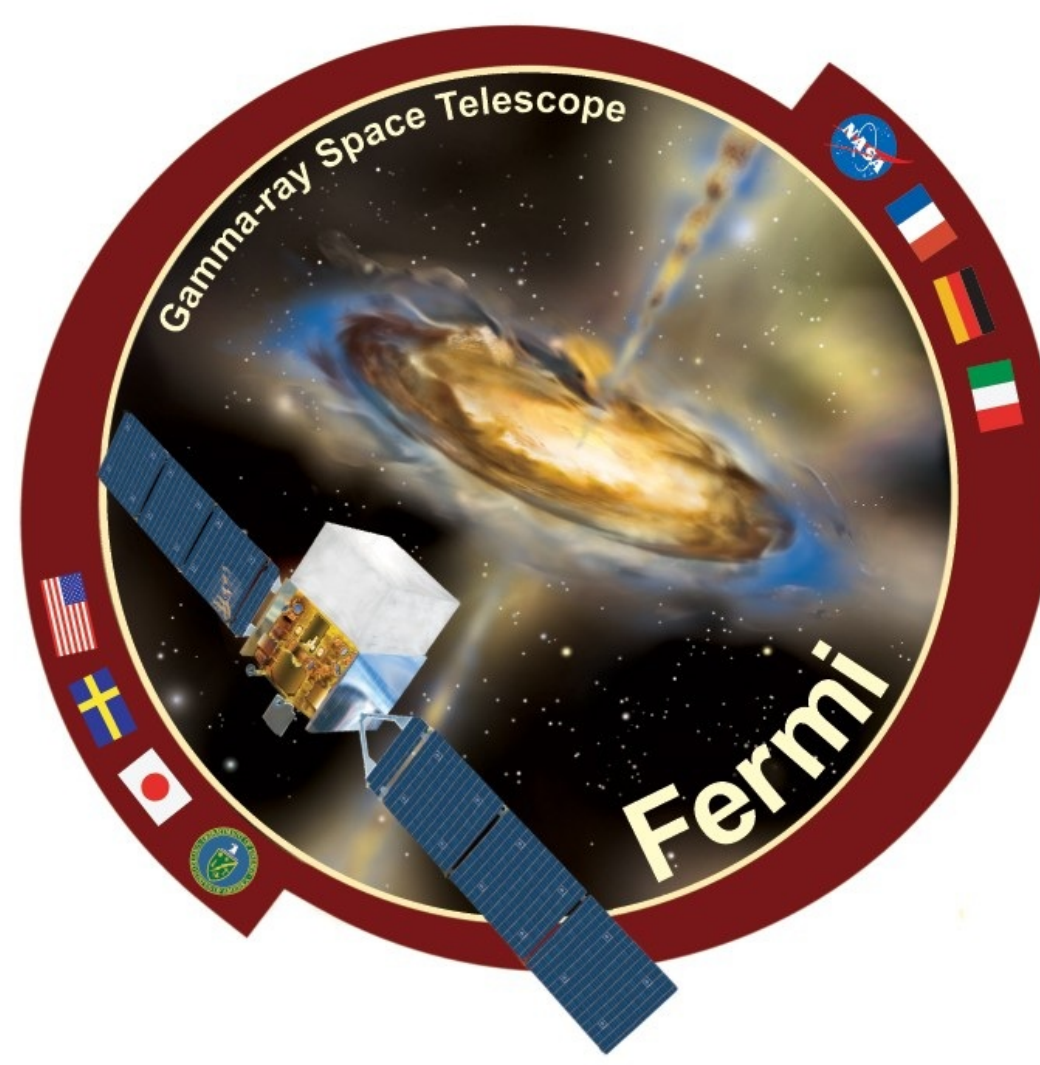


- All sky fit including all templates BUT bubble template, signal region masked



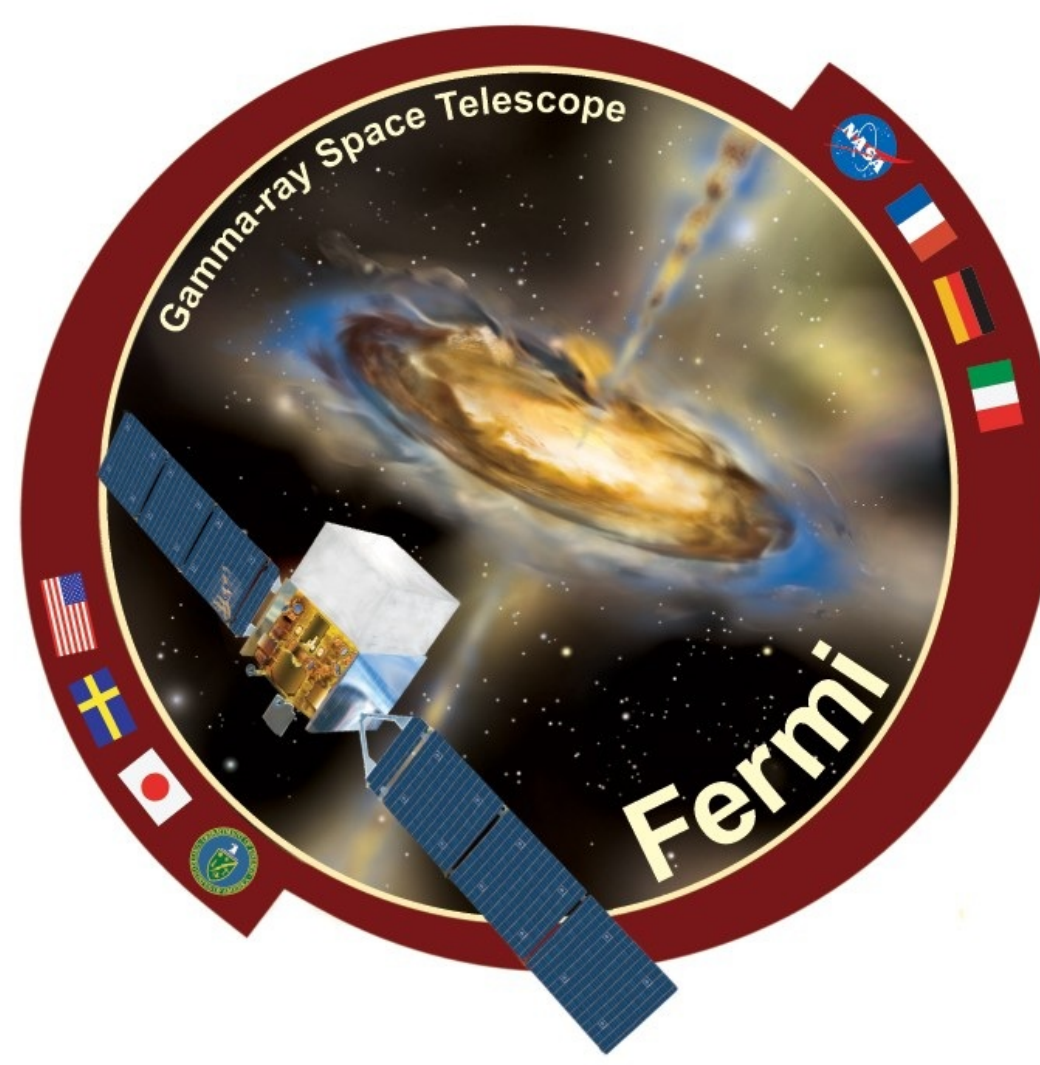
Integrated residual map from
6.4 to 300 GeV





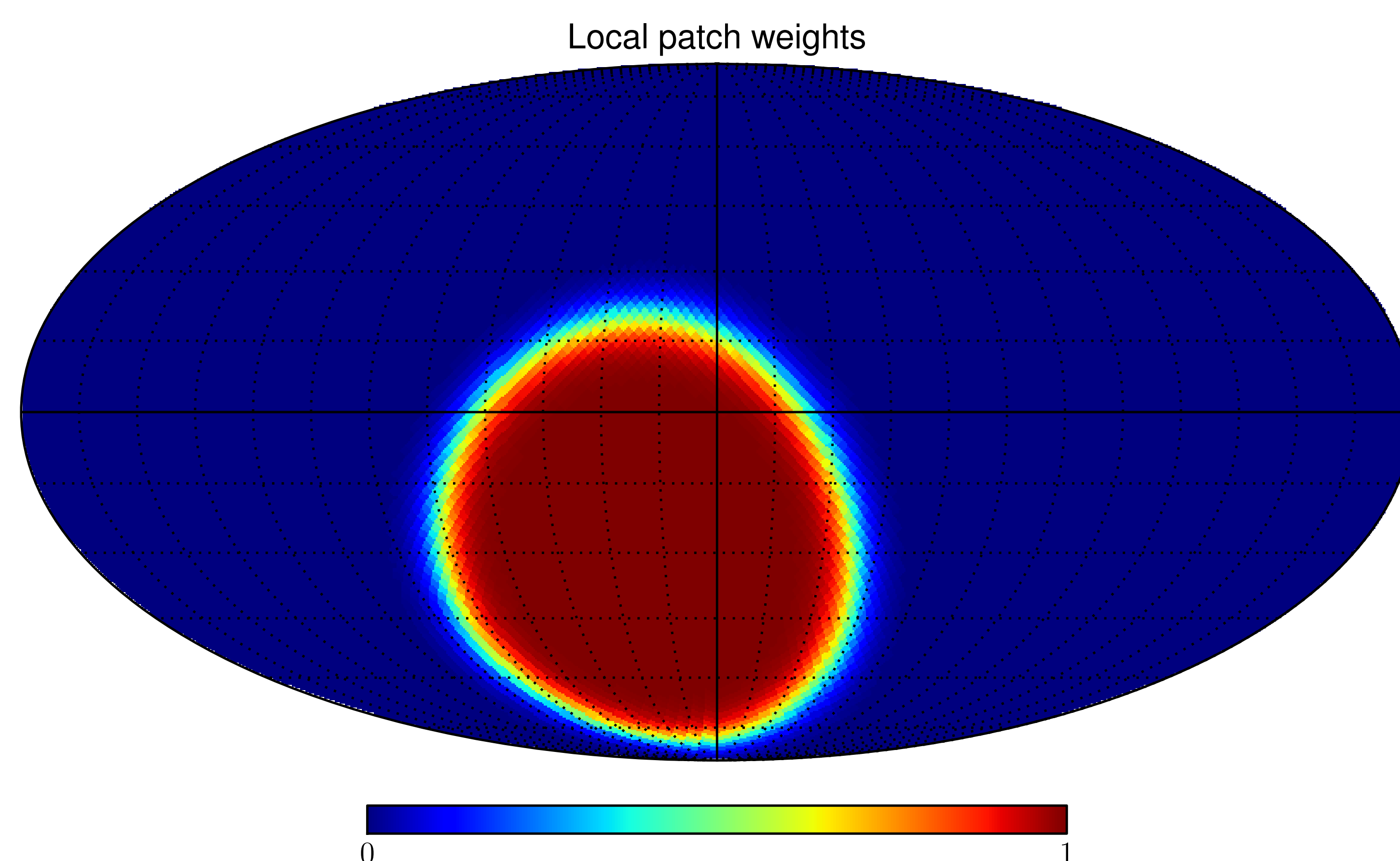
- **Galactic modeling (envelope):**
 - **The choice of the input GALPROP configuration:**
 - **Cosmic-ray source distribution:**
 - Pulsars, SNR
 - **Size of cosmic-ray confinement volume (halo size)**
 - Cylindrical geometry with $R = 20, 30$ kpc and $z = 4, 10$ kpc
 - **Spin temperature (optical depth correction of the HI component obtained from 21cm survey)**
 - $T = 150\text{K}$, optically thin
 - **Loop template**
 - **Bubble template**
- **Instrument related (added in quadrature to galactic modeling):**
 - **Systematic error in the effective area (2012 ApJS, 203)**

Local Template Fitting

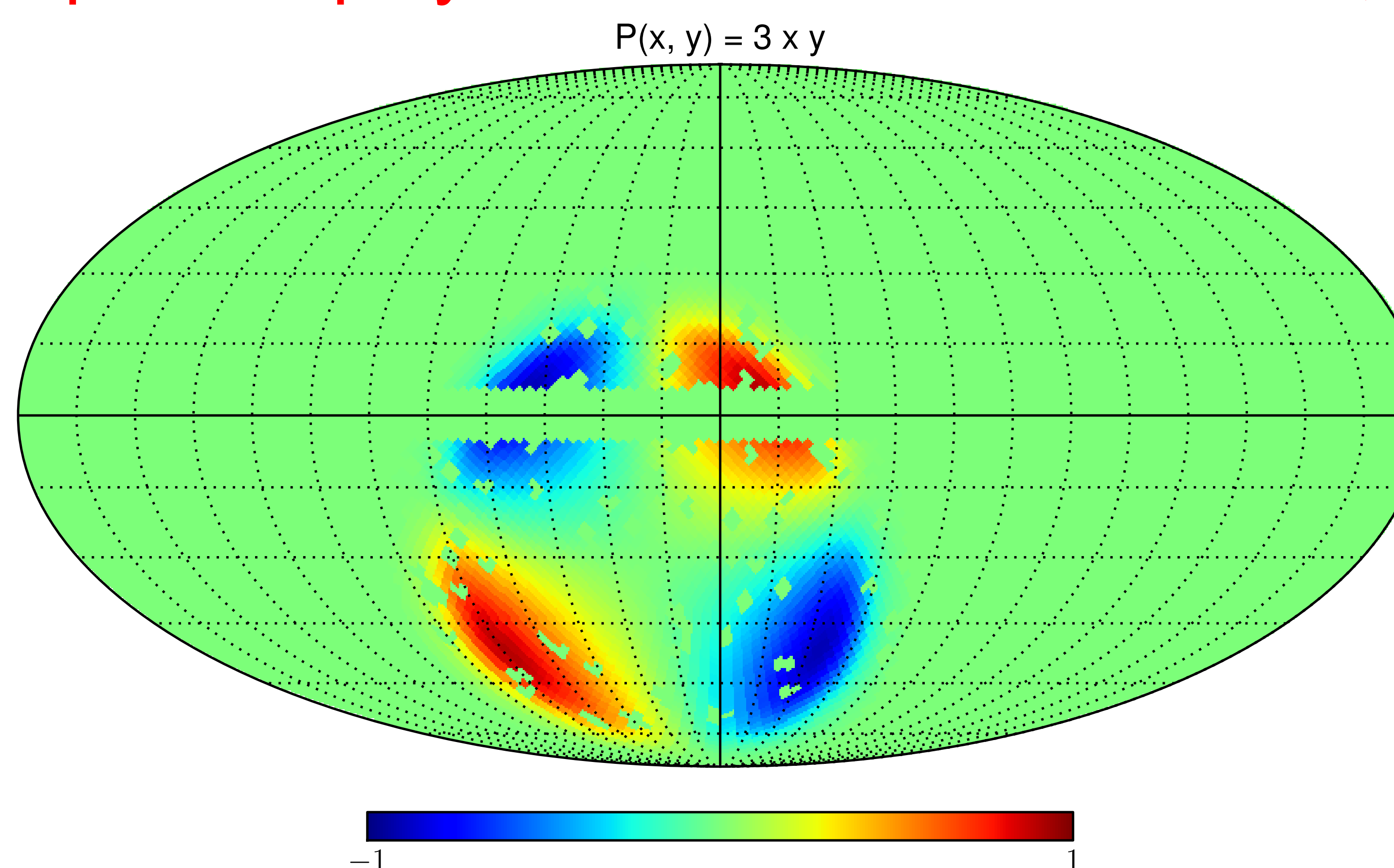


- **GALPROP: cylindrical symmetry, specific IC model.**
 - Relax the cylindrical symmetry
 - Start with a very general model for IC, bubbles, Loopl
- **Separate the sky in Gaussian patches. In each patch, model**
 - gas-correlated components as a combination of **GALPROP** gas templates
 - non gas-correlated components (isotropic, IC, Loopl, bubbles) as a linear combination polynomials in local coordinates (max degree determined from convergence of energy spectra)

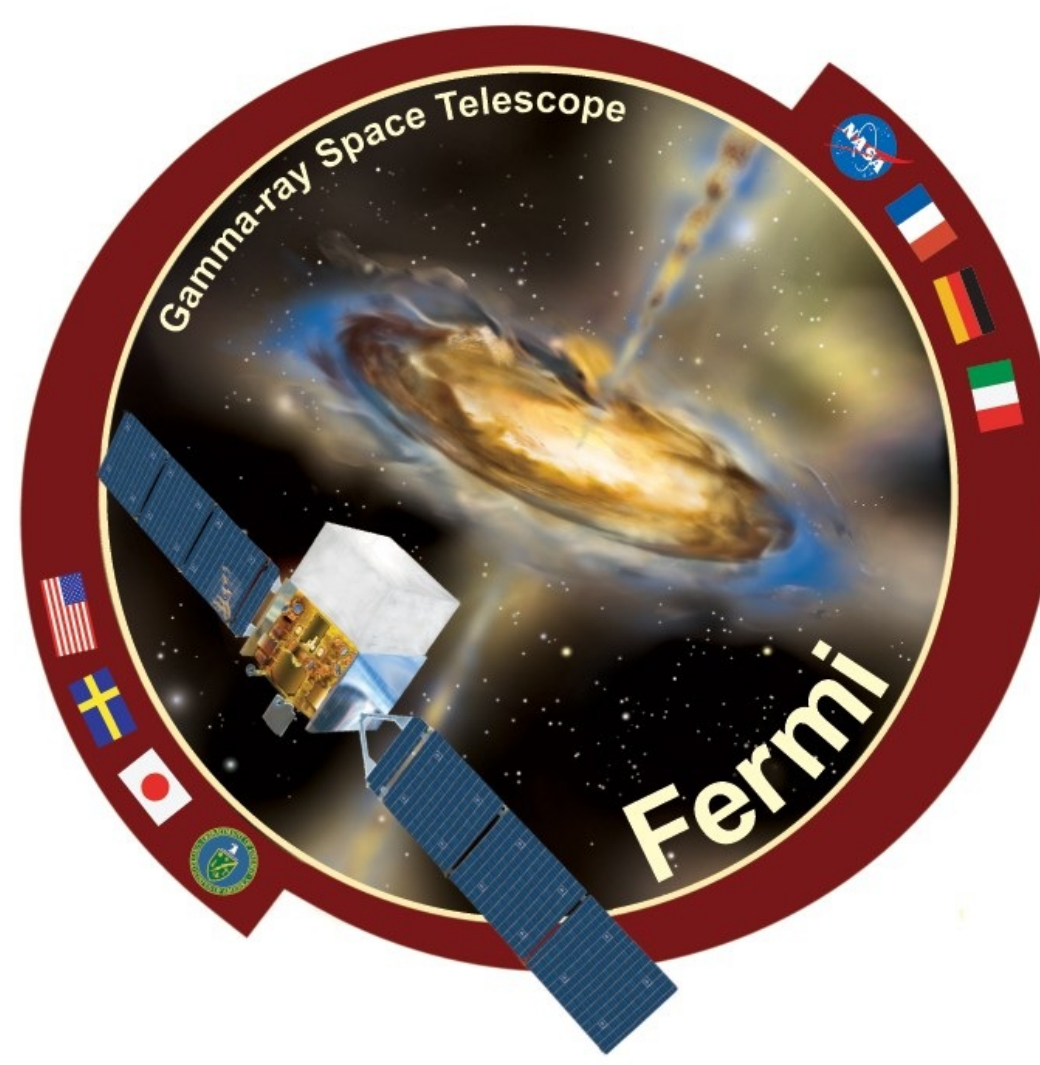
Local patch example



Example of a polynomial in local coordinates, $P(x, y) = 3xy$

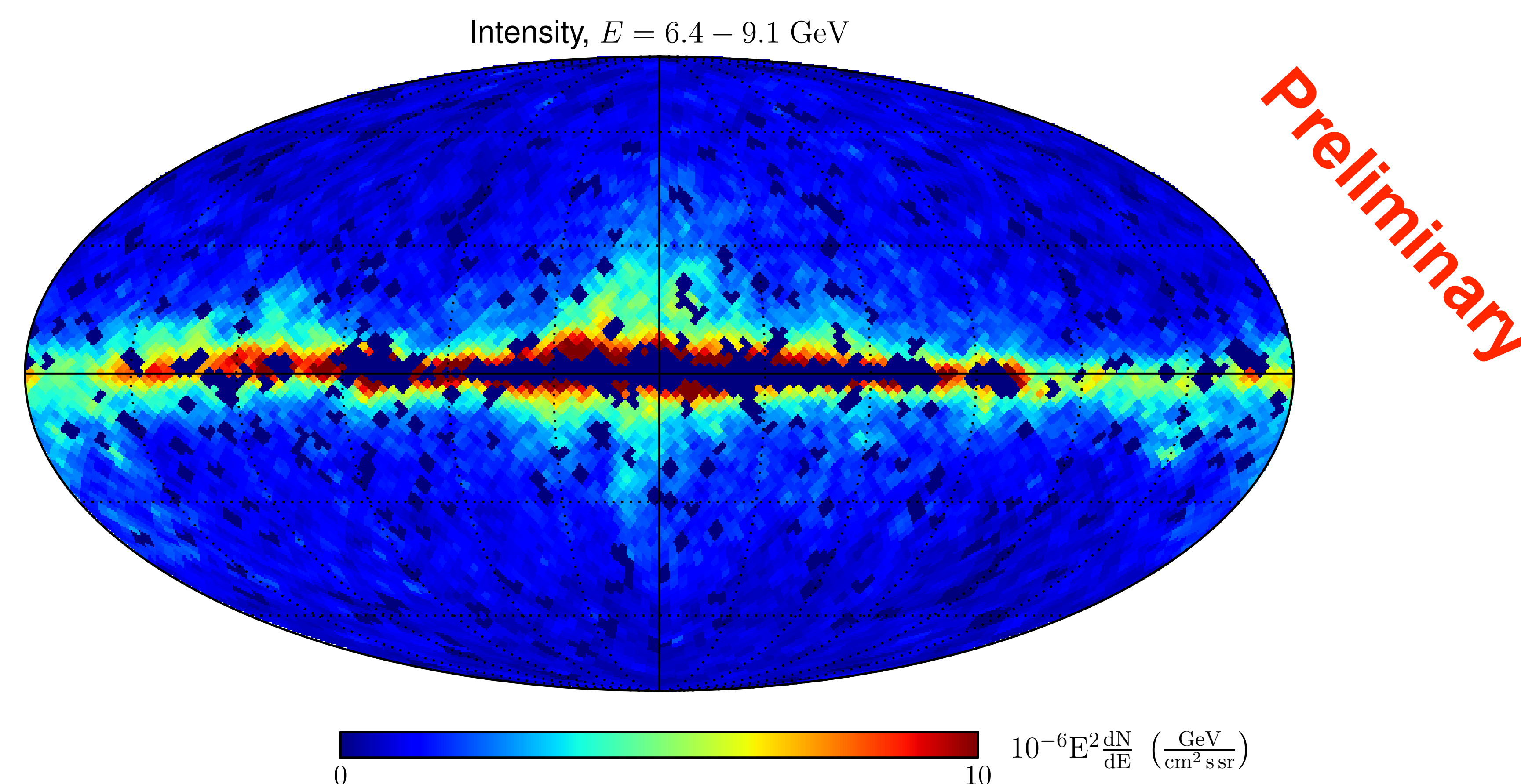


Local Template Fitting

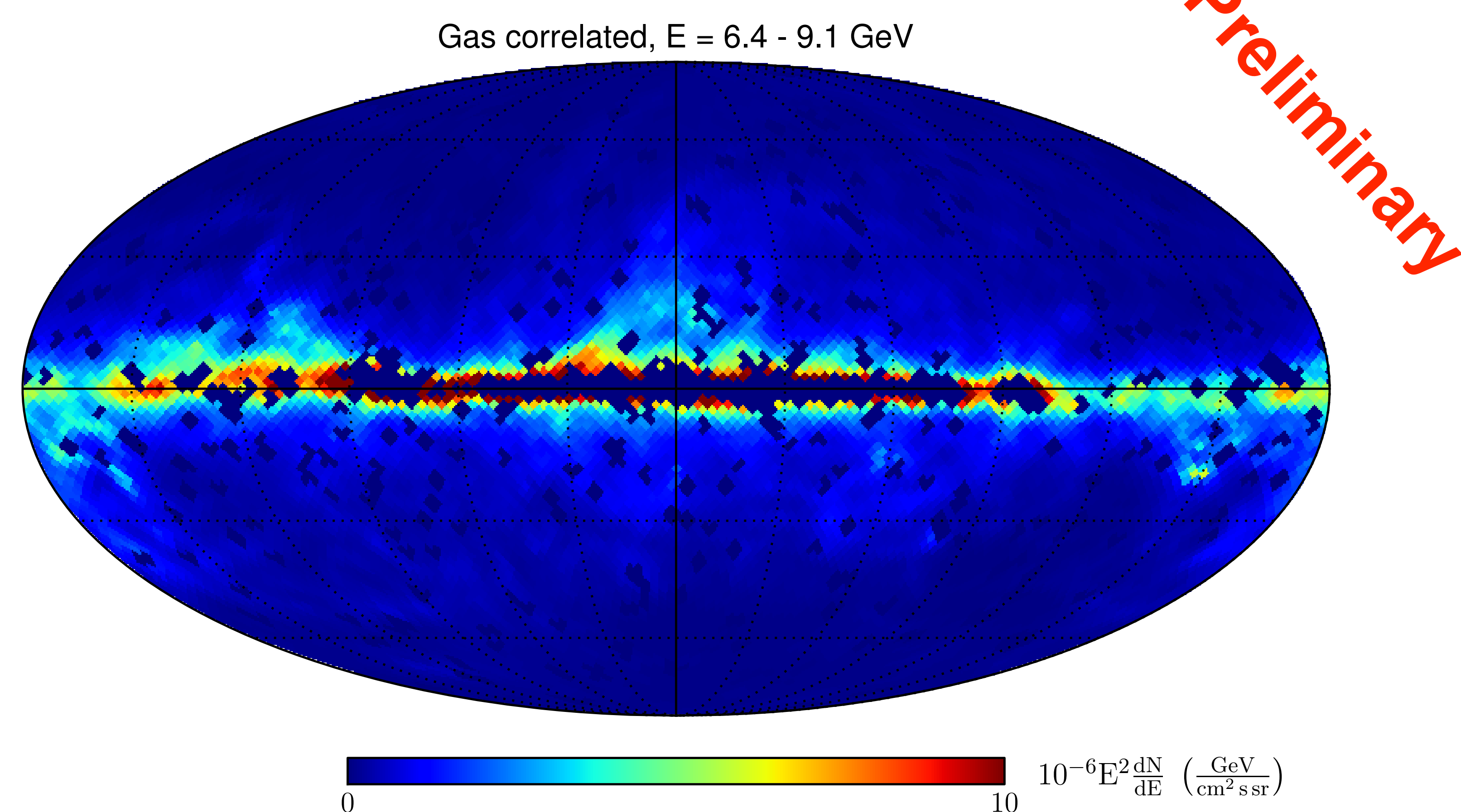


- Fit the data in 24 local patches
- Merge the patches together: on the intersection take the average model

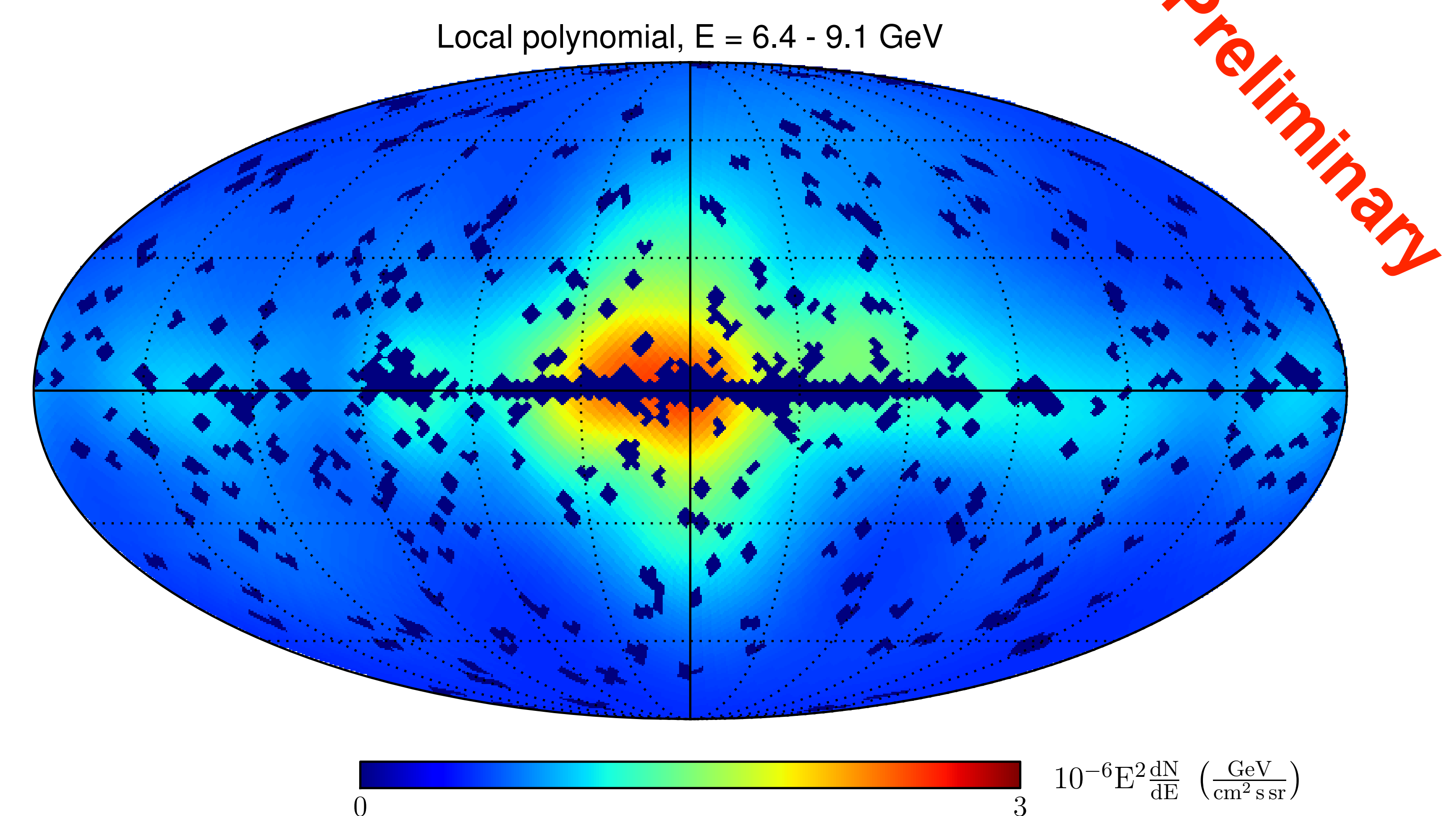
Intensity in $E = 6.4 - 9.1$ GeV energy bin



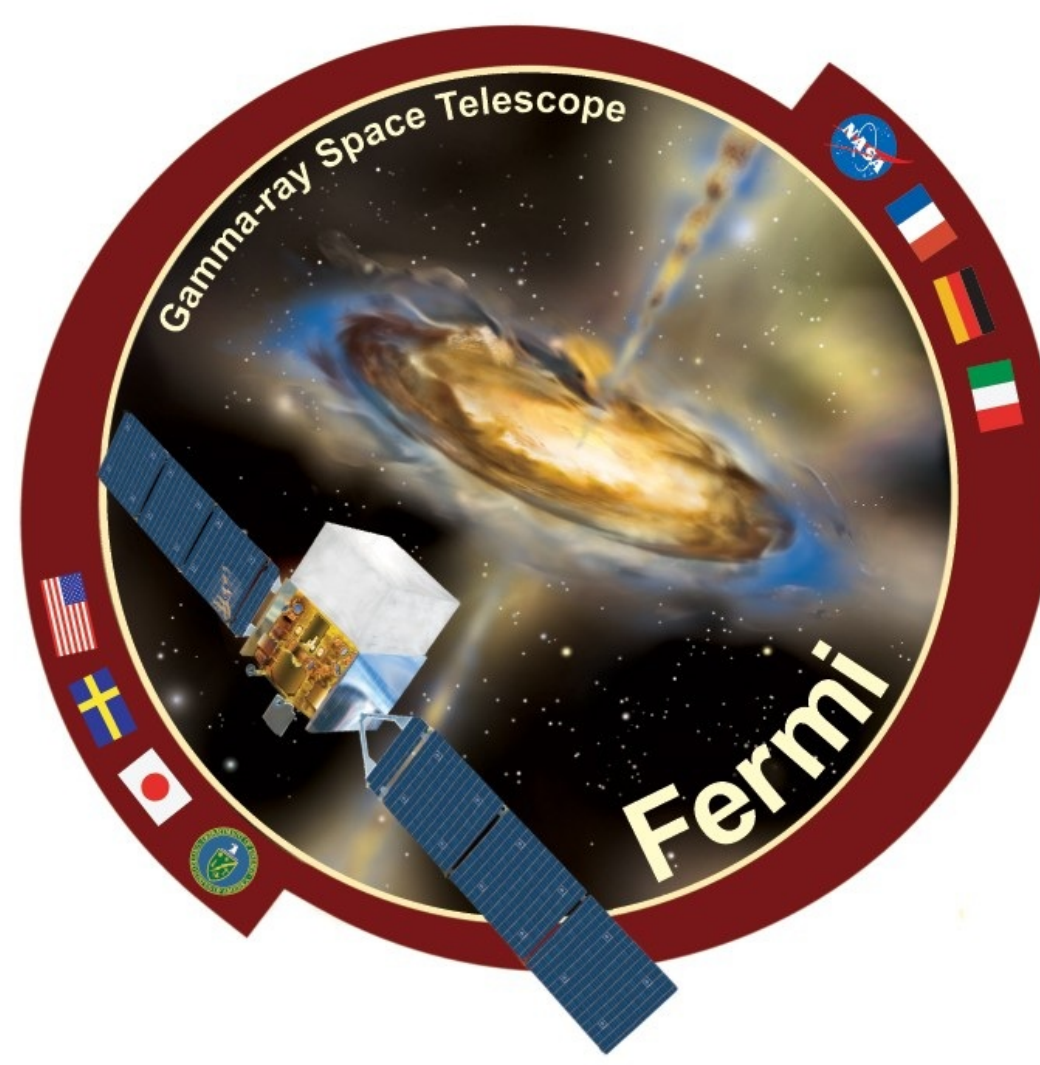
Gas correlated components



Local polynomial model



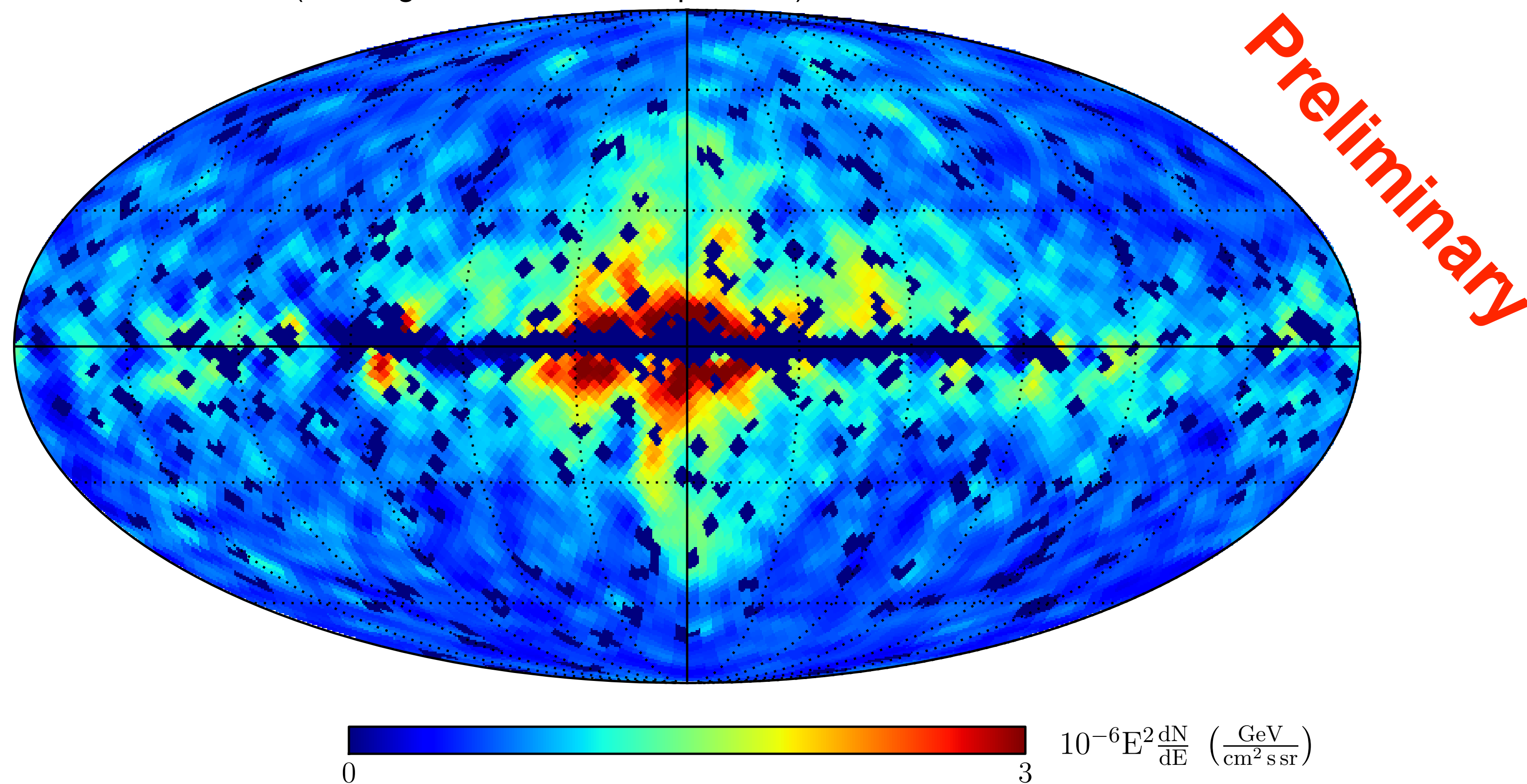
Local Template Fitting



- Subtract the gas-correlated component from the data
- Model the residual as a combination of
 - isotropic template
 - two Gaussians: Gaussian along the Galactic plane models the IC emission, Gaussian perpendicular to the plane is a proxy for the Loop I and the bubbles

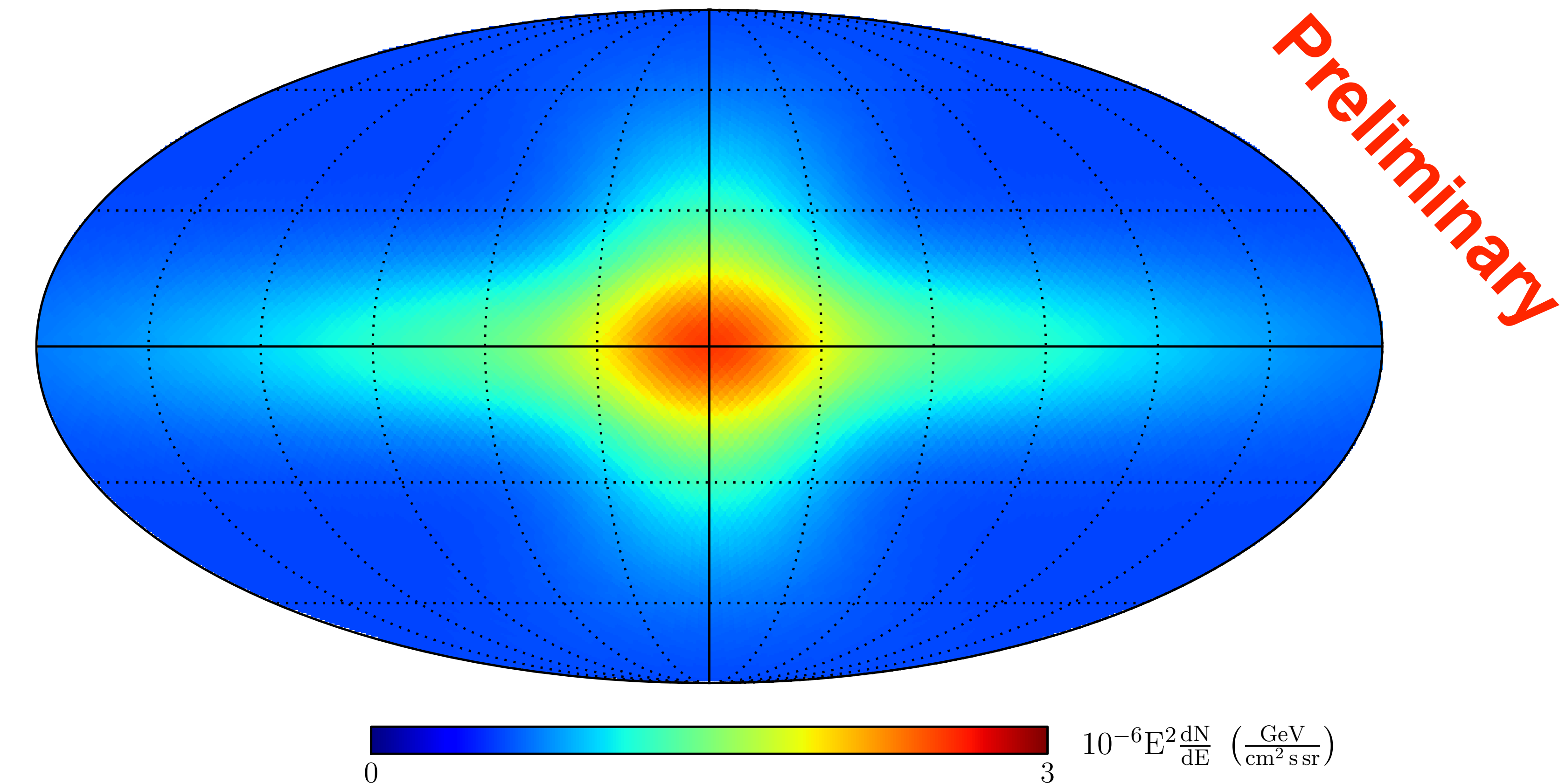
Data minus gas correlated components

(data - gas correlated components), E = 6.4 - 9.1 GeV

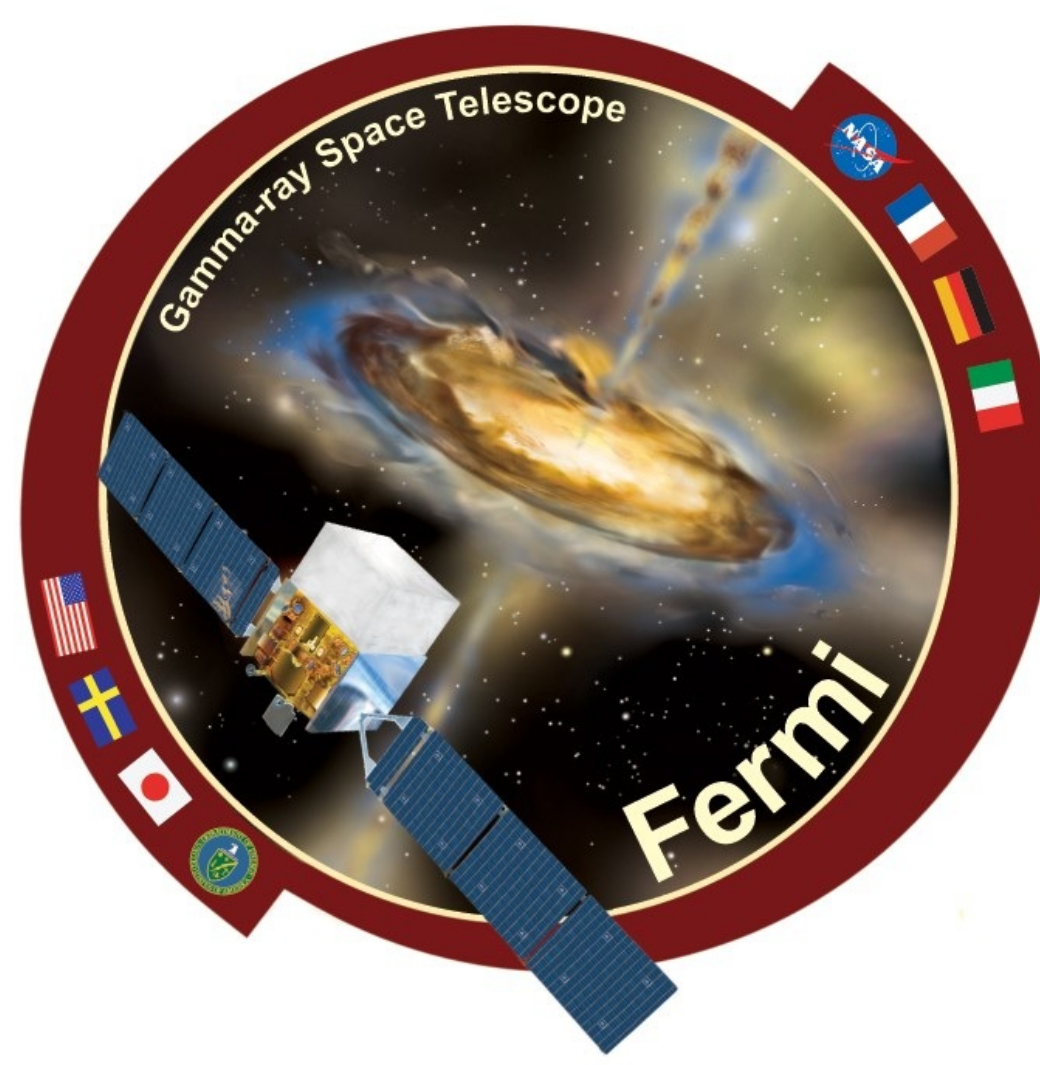


Gaussian model

Gauss model, E = 6.4 - 9.1 GeV



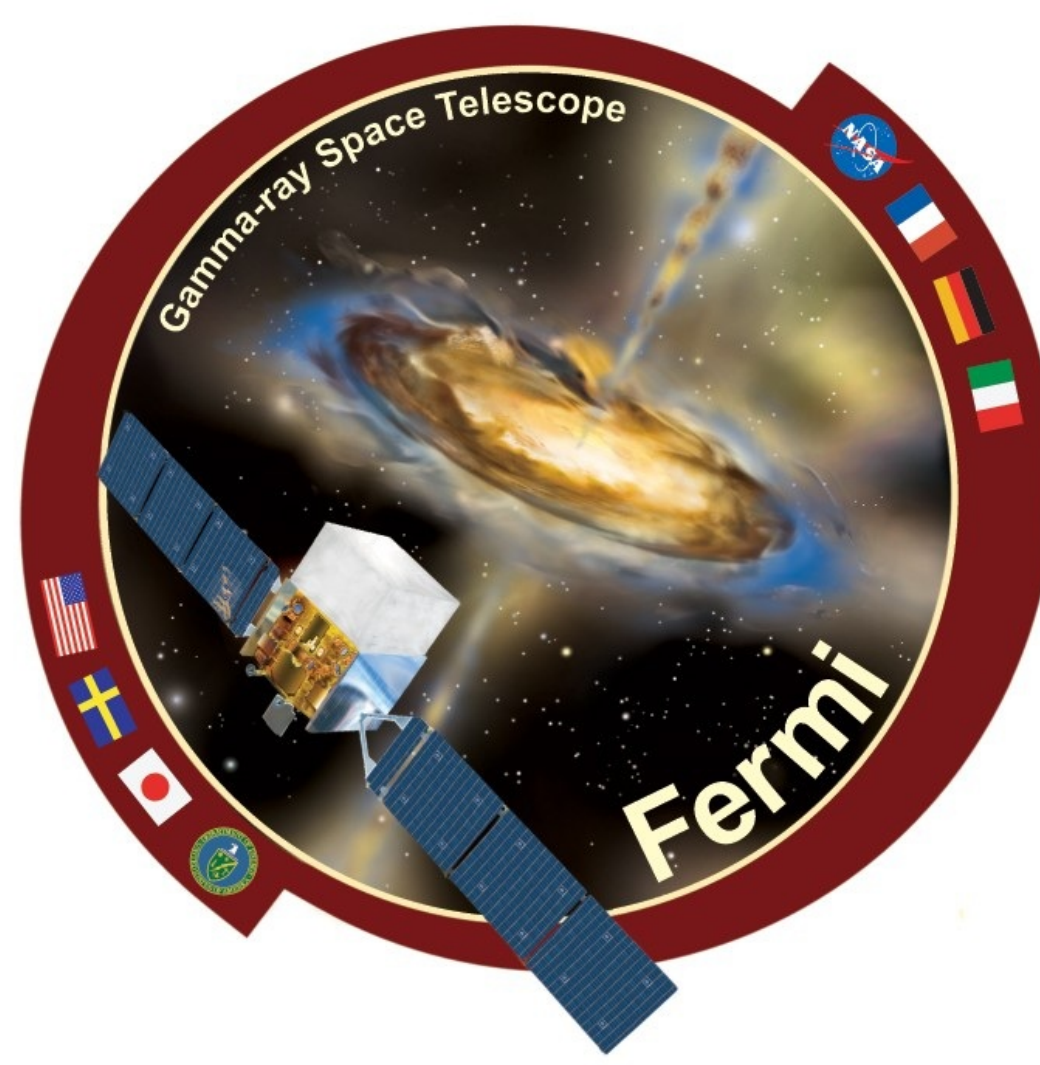
- Subtract gas-correlated, isotropic and IC emission from the data and define the bubbles (Loop I) from the residuals



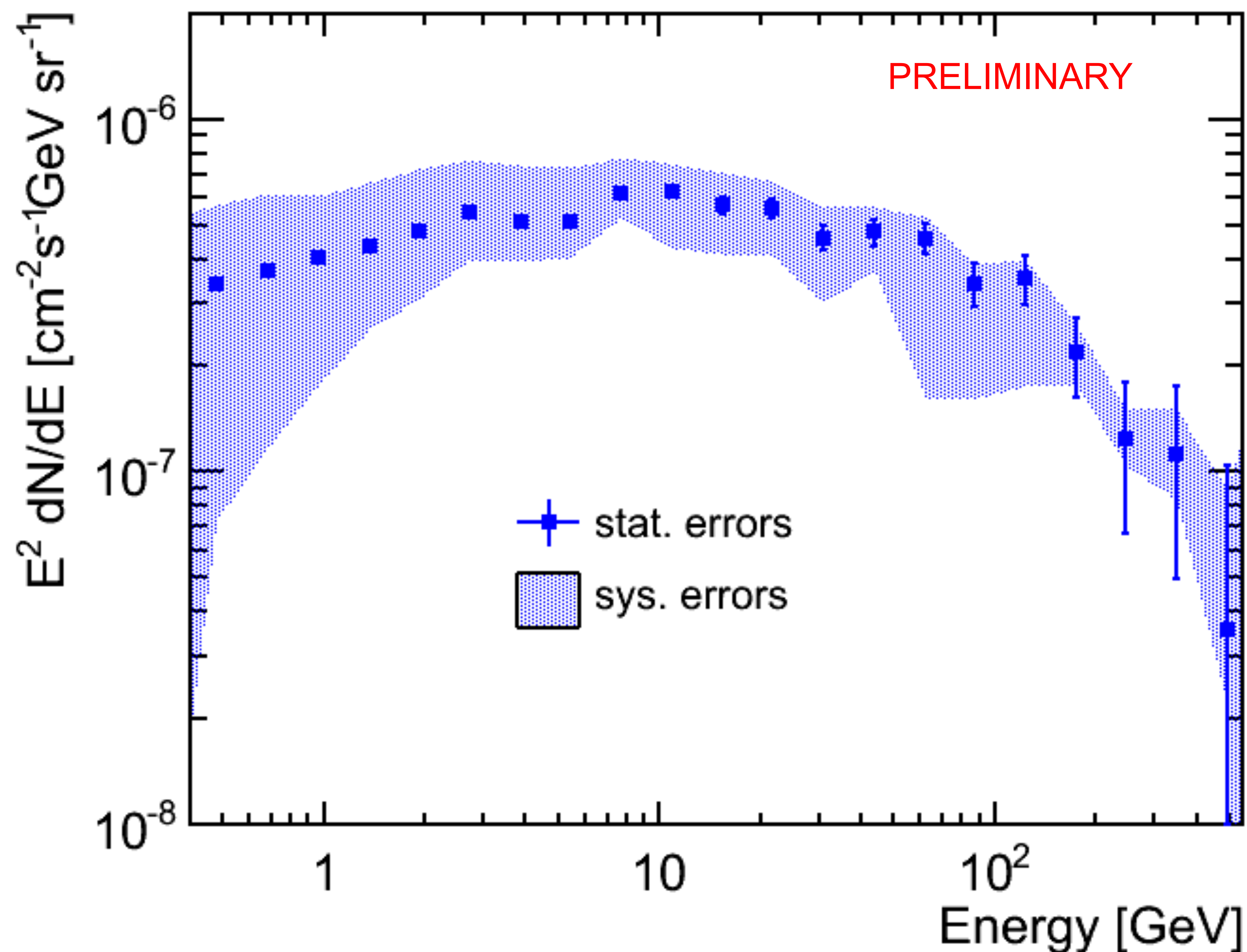
- **Templates (in the fit we use $|b| > 10$ deg):**
 - **Gas correlated**
 - **IC (Gaussian along the Galactic plane)**
 - **Isotropic**
 - **Loop I (from residuals)**
 - **Bubbles (from residuals)**
- **Systematic uncertainties:**
 - **Size of the patches**
 - **Degree of local polynomials**
 - **Definition of templates for the bubbles and Loop I**

Most of the systematic uncertainties in the local template fitting method are different from the GALPROP template method.

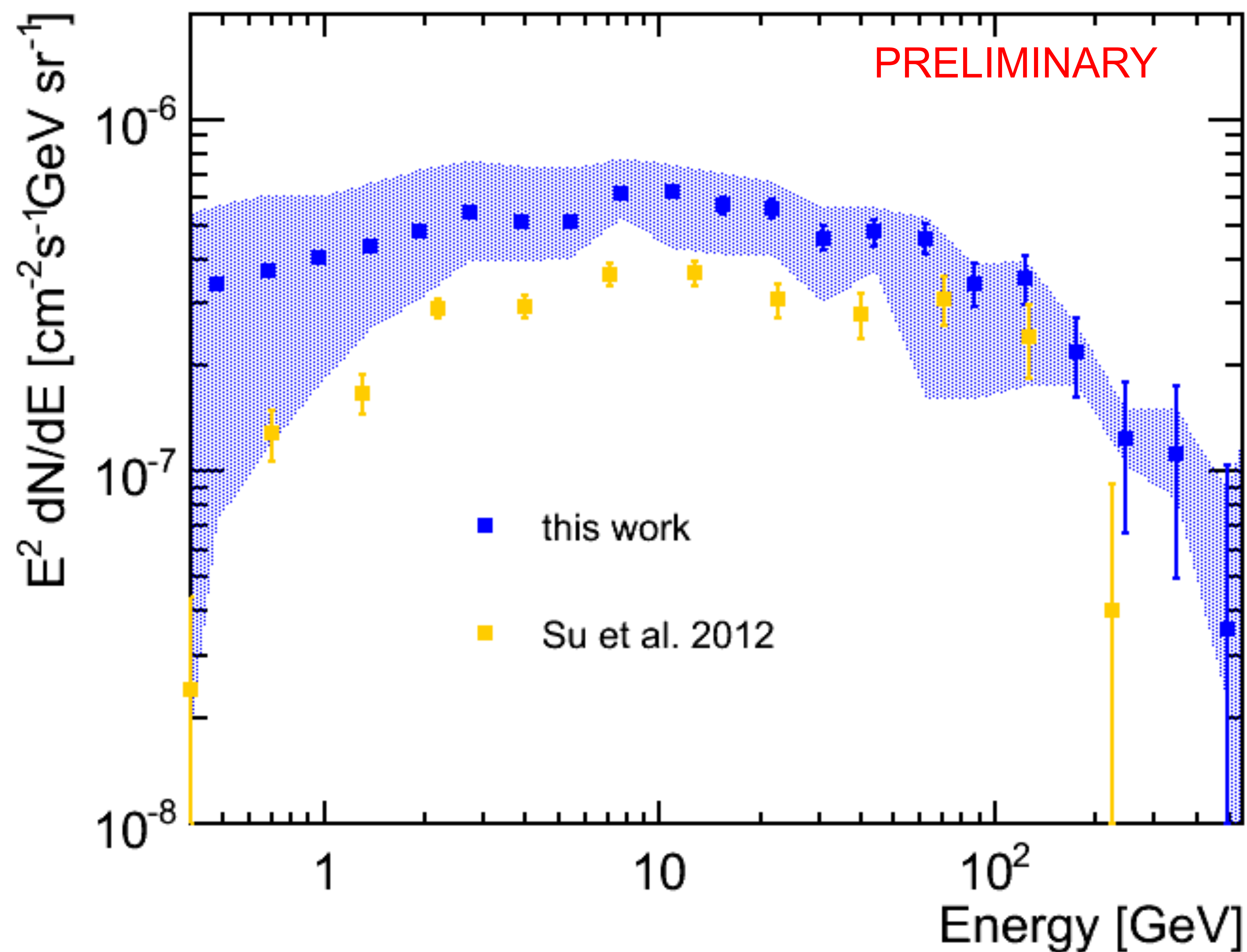
Spectrum of the Fermi bubbles



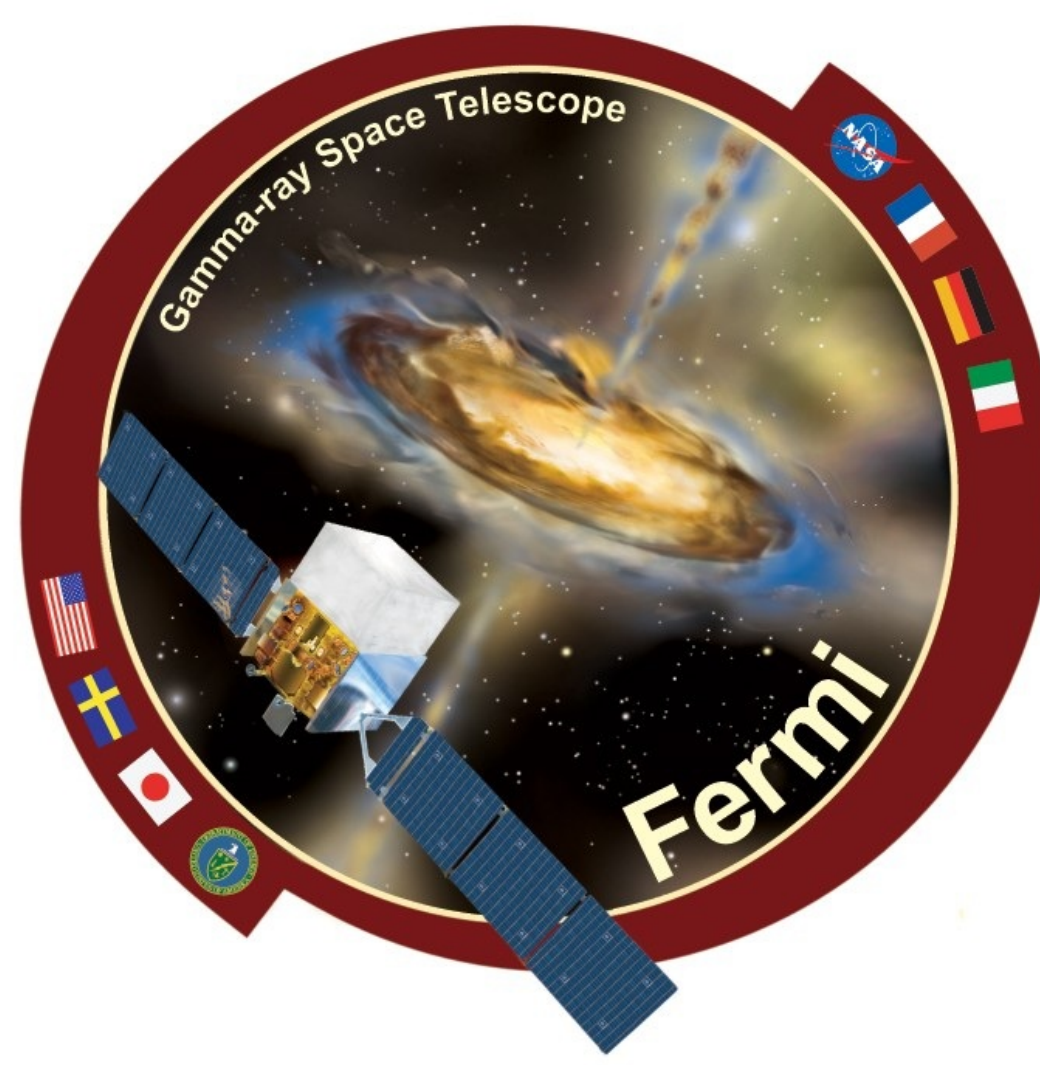
- Combine all methods together
- Shaded region: envelope of the models, error bars – statistical uncertainty



Comparison with previous results



- Spectra have similar shape.**
Shift in normalization can be explained by:
- Different foreground modeling
 - Different definition of the bubble template resulting in different area of the template



- **Fermi bubbles are a unique gamma-ray object: they don't have strong counterparts in other wavelengths**
 - **Need to define the template from the gamma-ray data itself**
 - **Systematic uncertainties:**
 - **Galactic emission model**
 - **Definition of Loop1 and bubbles templates**
 - **GALPROP templates and local templates analysis: ``bracketing'' of models**
- **Spectrum of the bubbles has been analyzed.**
 - **There is a cutoff in the spectrum at high energies**
- **Analysis of morphology:**
 - **in preparation...**