The characteristics of the Galactic center excess measured with 11 years of Fermi-LAT data

Mattia Di Mauro

On behalf of the Fermi-LAT Collaboration

ICNFP 2020

September 5 2020

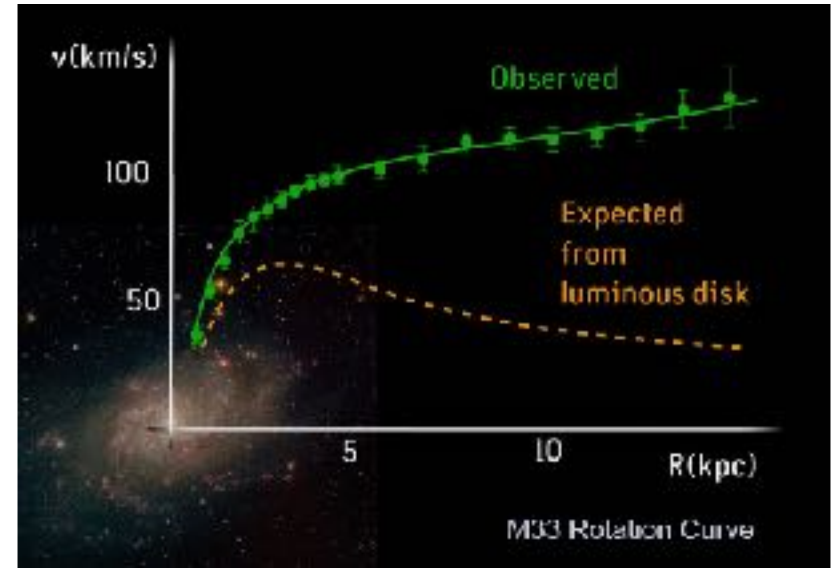
Fellini
Fellowship for Innovation at INFN

INFN
Istituto Nazionale di Fisica Nucleare

Overwhelming astrophysical evidences of the existence of dark matter

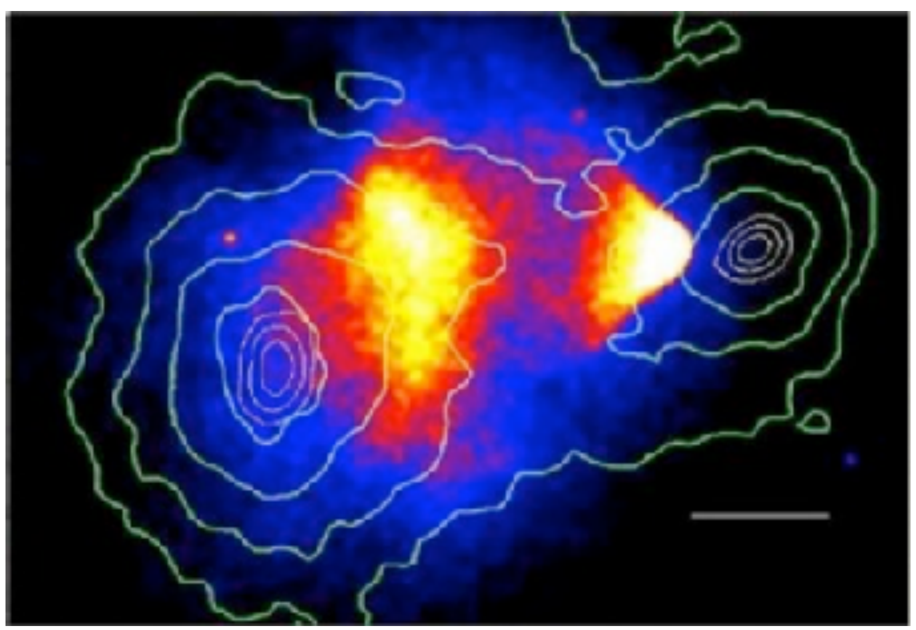
*Comprises **majority** of **mass** in Galaxies*
- Galaxy cluster dynamics

Zwicky (1937)



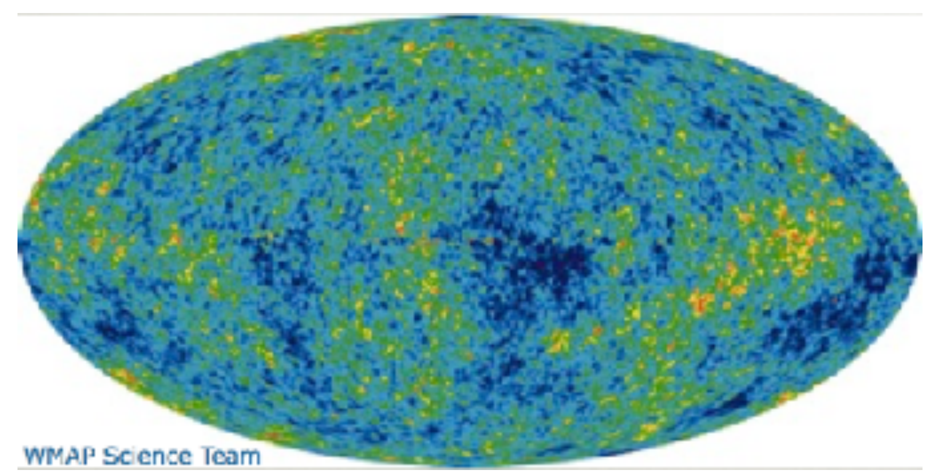
*Large **halos** around Galaxies*
- Galaxy rotation dynamics

Rubin+(1980)



*Almost **collisionless***
- "Bullet" cluster

Clowe+(2006)

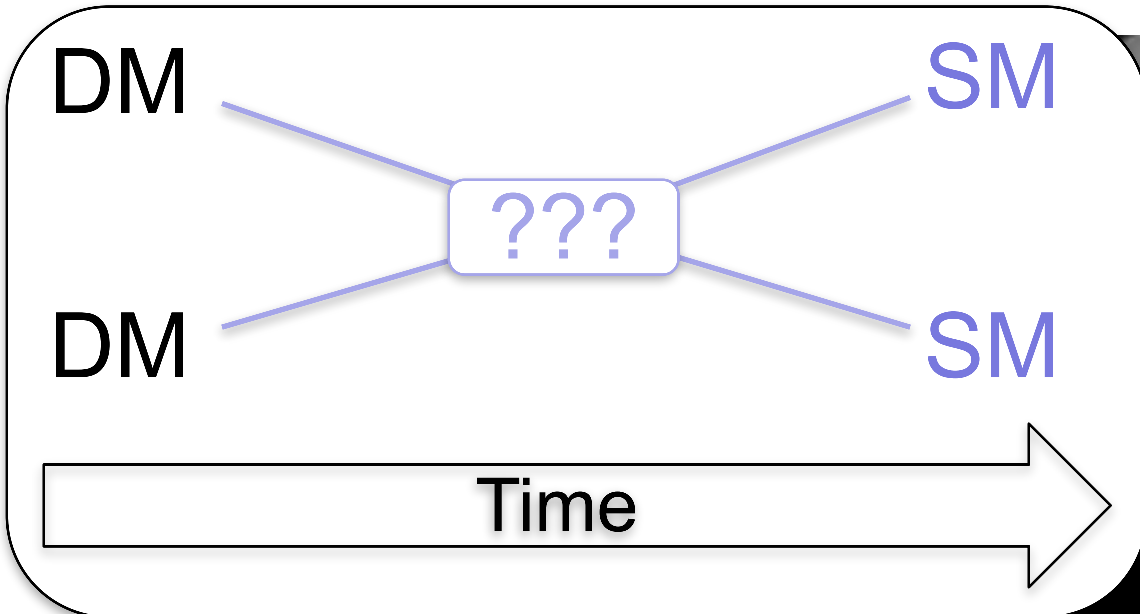


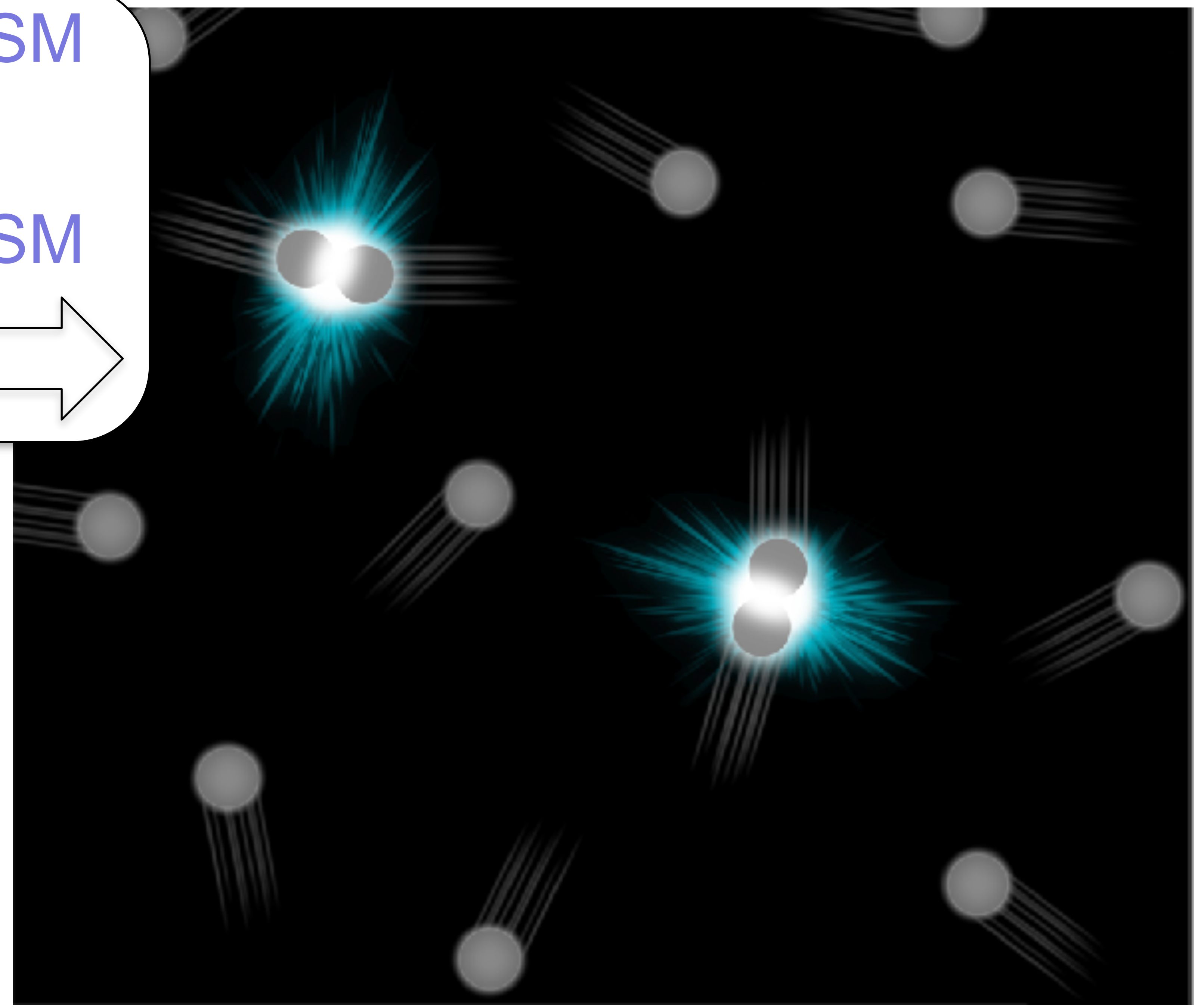
"Cold" and not baryons (p, n)
- Deuterium abundance

Schramm and others (1980s)
- Cosmic background structure

WMAP(2010), *Planck*(2015)

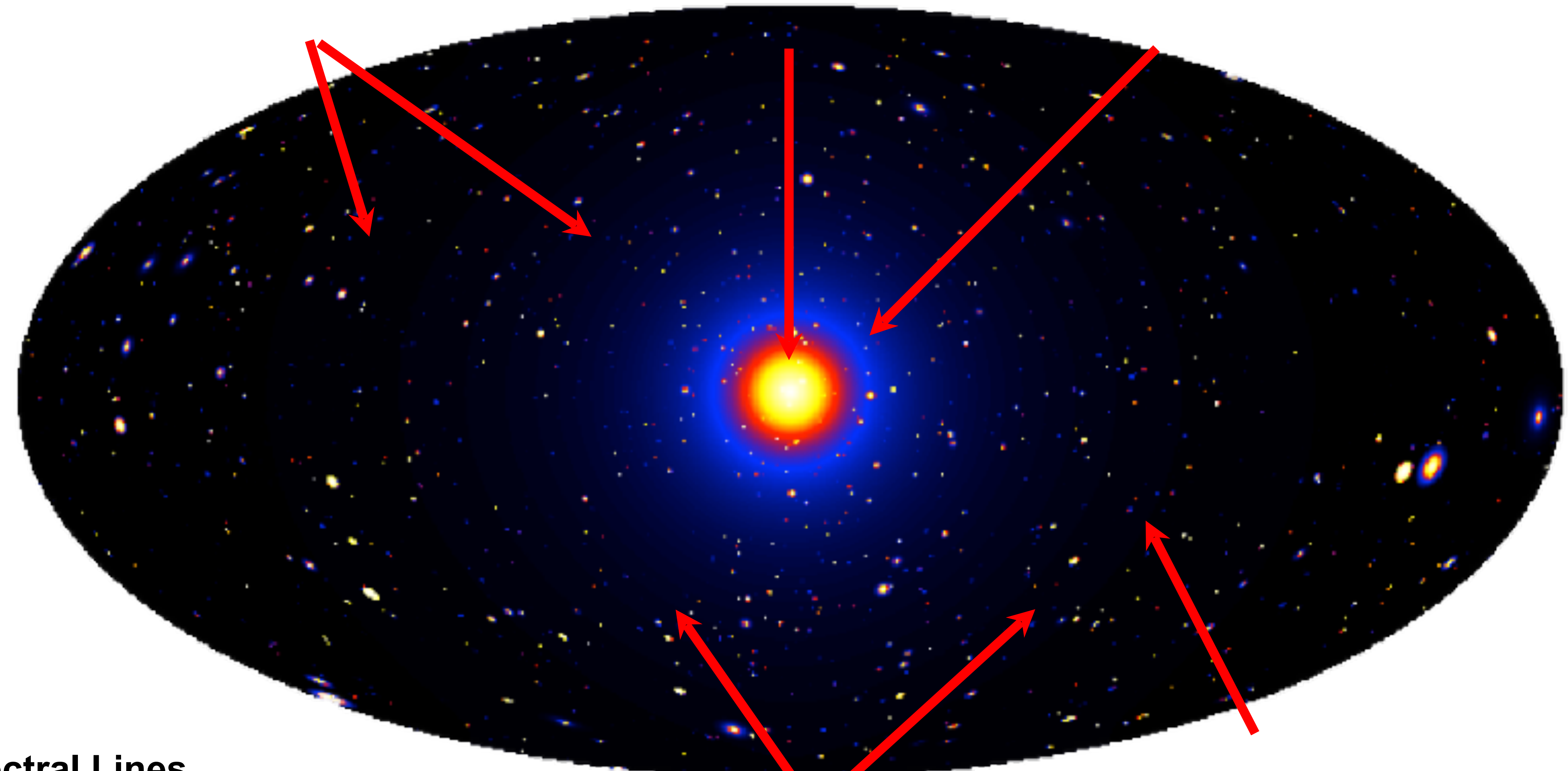
Dark matter annihilation





- In this case, dark matter particles annihilate with each other and produce standard matter.
- In general, the by-products of the annihilation will include many different types of particles.

Gamma-ray sky from dark matter



Satellite galaxies
Low background and good source id, but low statistics

Galactic Center
Good statistics, but source confusion/diffuse background

Milky Way Halo
Large statistics, but diffuse background

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

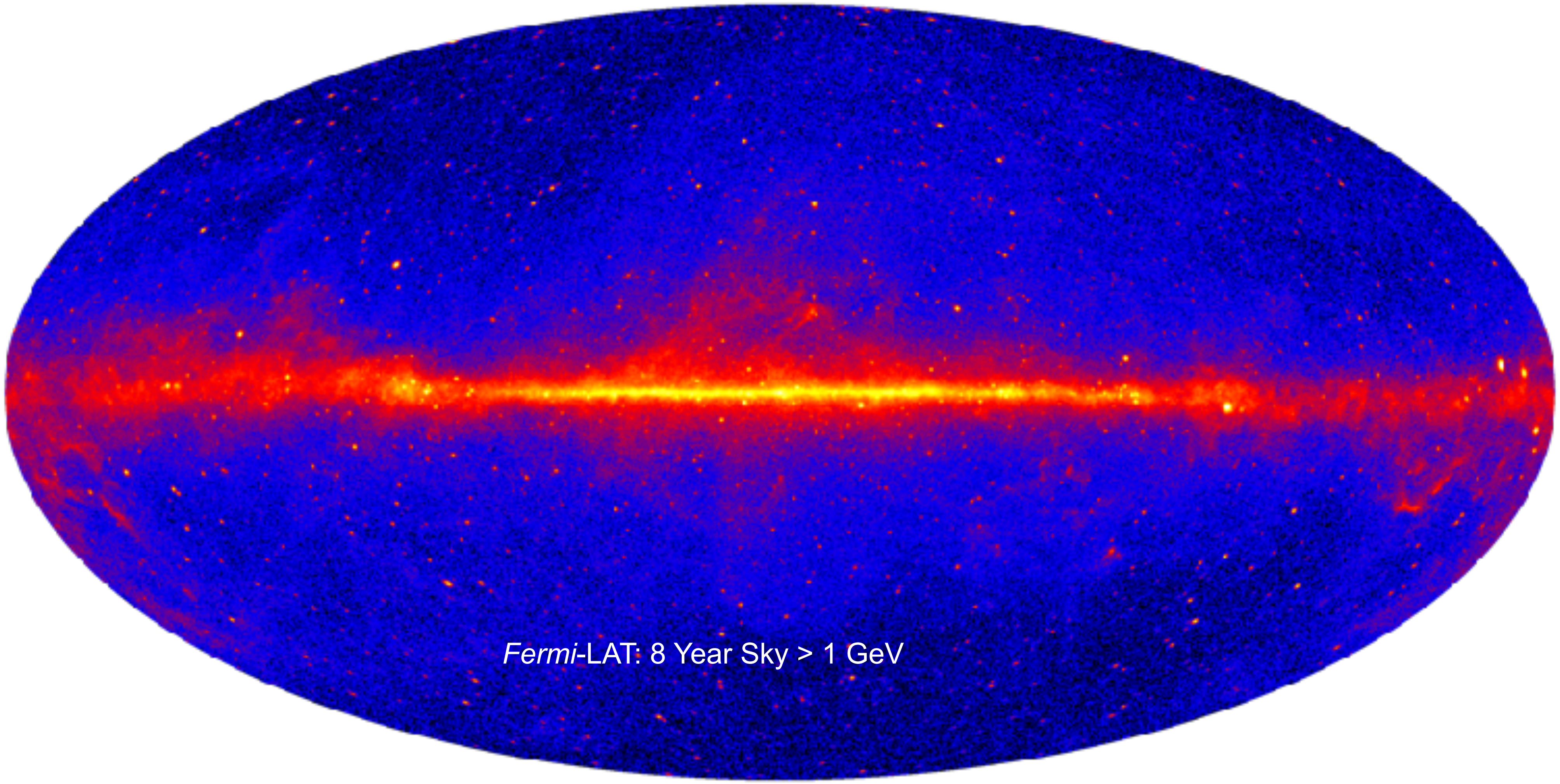
Galaxy Clusters
Low background, but low statistics

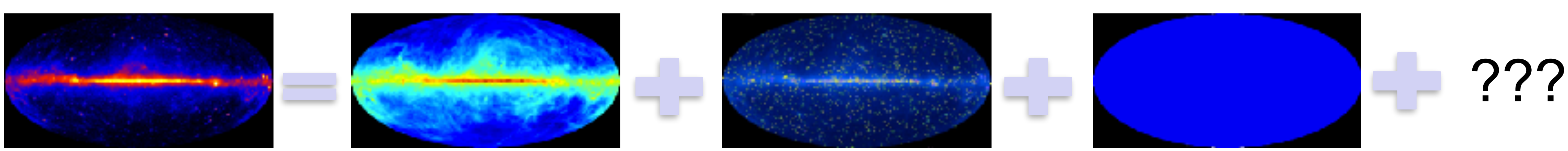
Isotropic contributions
Large statistics, but astrophysics, Galactic diffuse background

Simulation: Pieri+ 2011PhRvD..83b3518P

Fermi-LAT view of the sky

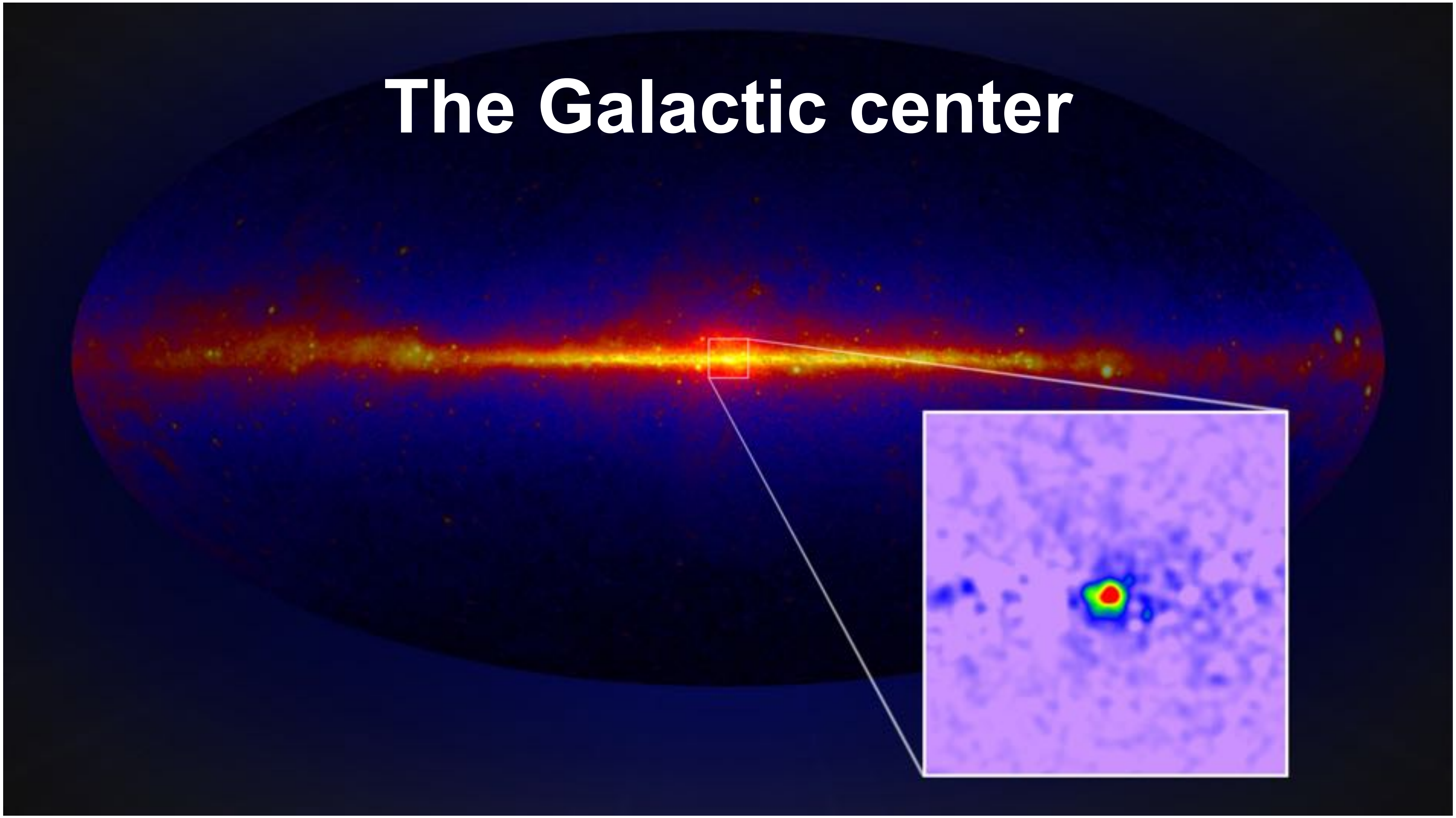
LAT sees the whole γ-ray sky every 3 hours with [0.02,2000] GeV energy range and a good angular resolution at the GeV scale.



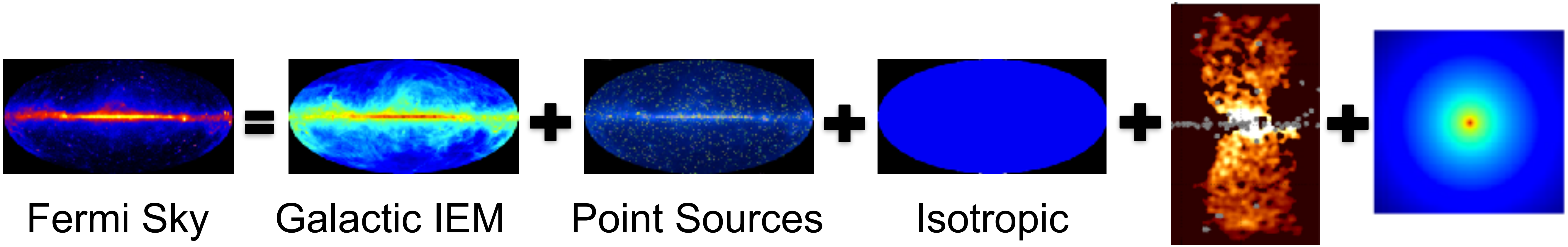


Fermi Sky = Galactic diffuse emission (IEM) + Point Sources + Isotropic + ???

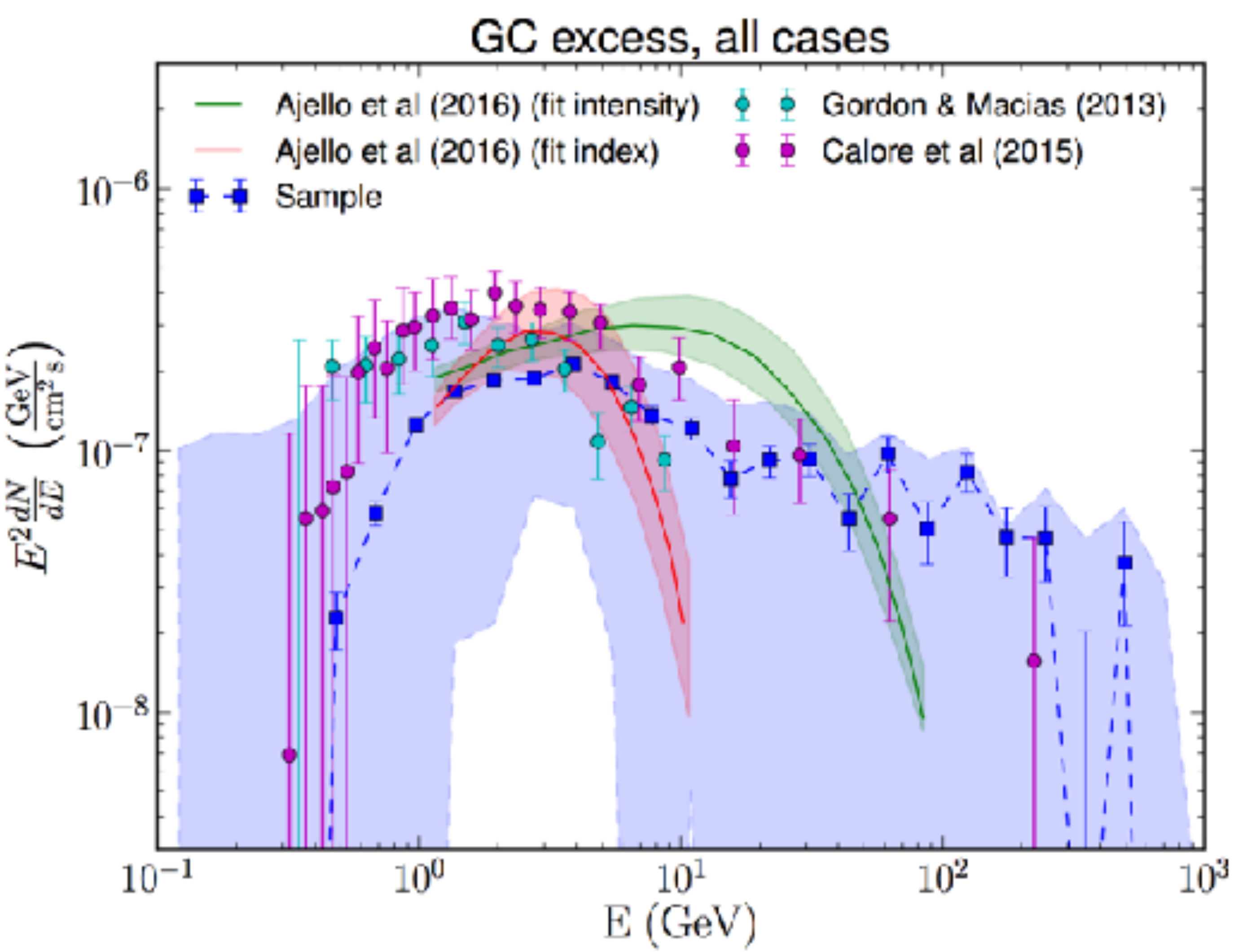
The Galactic center



The GeV Excess in the Galactic Center



Fermi Sky = Galactic IEM + Point Sources + Isotropic + Fermi Bubbles + DM



Ajello et al. 2017

Different groups have found an excess of gamma rays from the GC region.

- The GCE is spherically symmetric, centered in the GC and with a spectrum peaked at a few GeV.

Shape and intensity of the GeV excess depends on the choice of:

- Source catalog
- Fermi Bubble template
- Inverse Compton+ π^0 +bremsstrahlung (IEM).
- Data selection

Overview of the talk

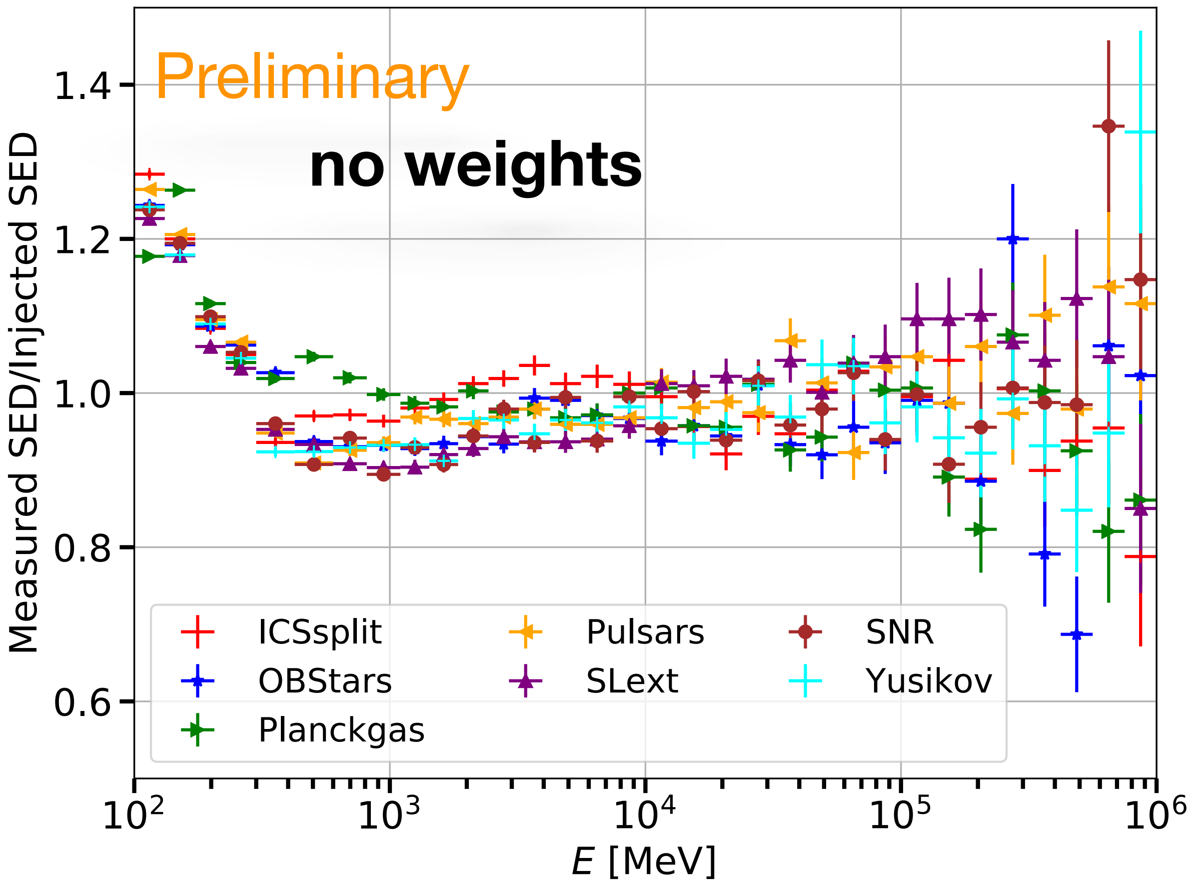
- This presentation is based on the following three papers and subjects:
    1. *Investigating the Fermi Large Area Telescope sensitivity of detecting the characteristics of the Galactic center excess.*
        - Under review by PRD
    2. *The characteristics of the Galactic center excess measured with 11 years of Fermi-LAT data*
        - Under review by PRD
    3. *The dark matter interpretation of the Fermi-LAT Galactic center excess.*
        - Under preparation.
- I should thank the *Fermi*-LAT Collaboration for the insightful comments I received during the preparation of these papers.

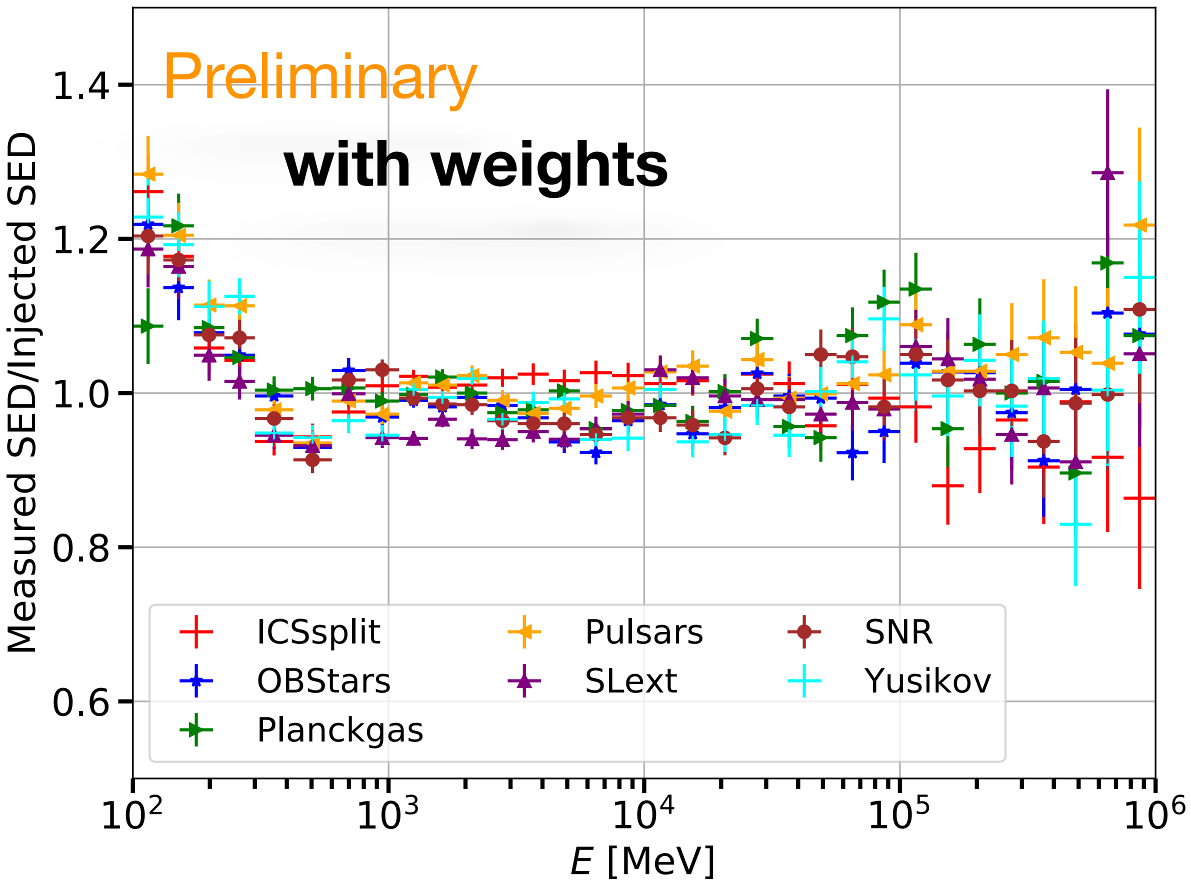
Goals of paper 1 and 2

- **I study the following characteristics of the Galactic center excess (GCE):**
  - Energy spectrum
  - Spatial morphology.
    - I will use two different techniques.
    - Presence of an energy dependent morphology.
  - Sphericity ellipticity.
  - Position of the GCE centroid.
- **Analysis details:**
  - 11 years of Pass 8 data.
  - Sourceveto IRFs
  - 4FGL catalog and IEM from Ackerman et al. 2017.
  - I apply the energy dispersion and use the weighted likelihood technique (https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/weighted_like.pdf).

Simulations: Energy spectrum

- I use in the analysis the new *weighted likelihood technique*.
  - It de-weights pixels with many counts.
  - Weights are significantly smaller than 1 for E<500 MeV and close to the Galactic plane.
- Using this technique we obtain a spectrum for the GCE that is more compatible with the injected signal (χ^2 improves by a factor of 30).





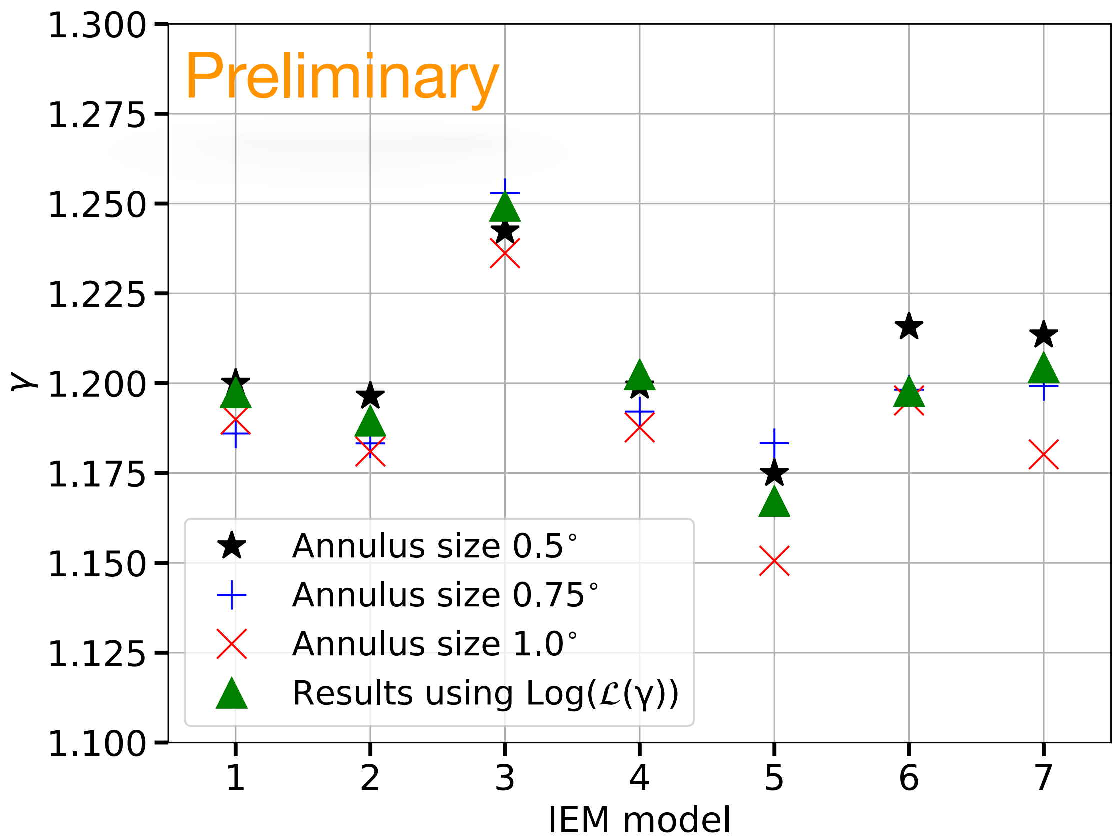
https://fermi.gsfc.nasa.gov/ssc/data/ analysis/scitools/weighted_like.pdf

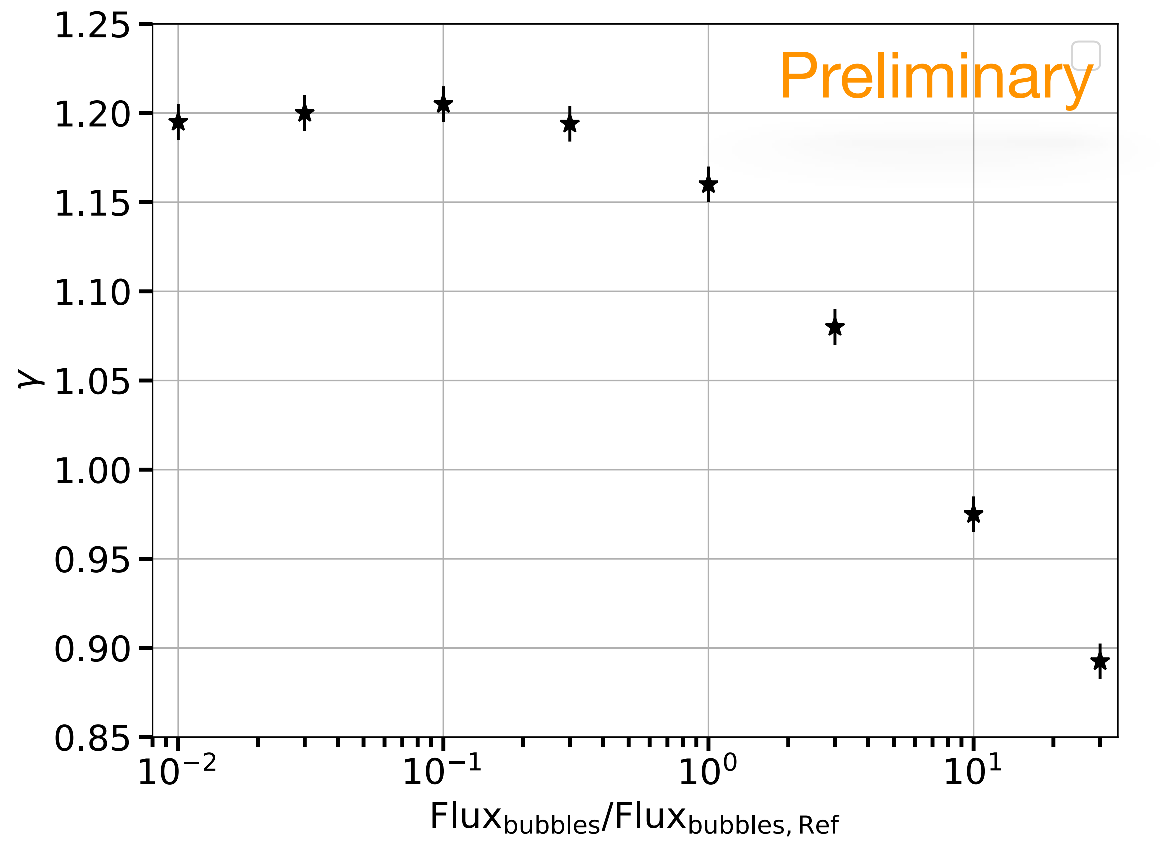
Simulations: Spatial morphology

- I investigate the spatial morphology of the GCE in two scenarios:
  - Imperfections of the IEM.
  - Missing component.

$$\rho_{\mathrm{NFW}} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

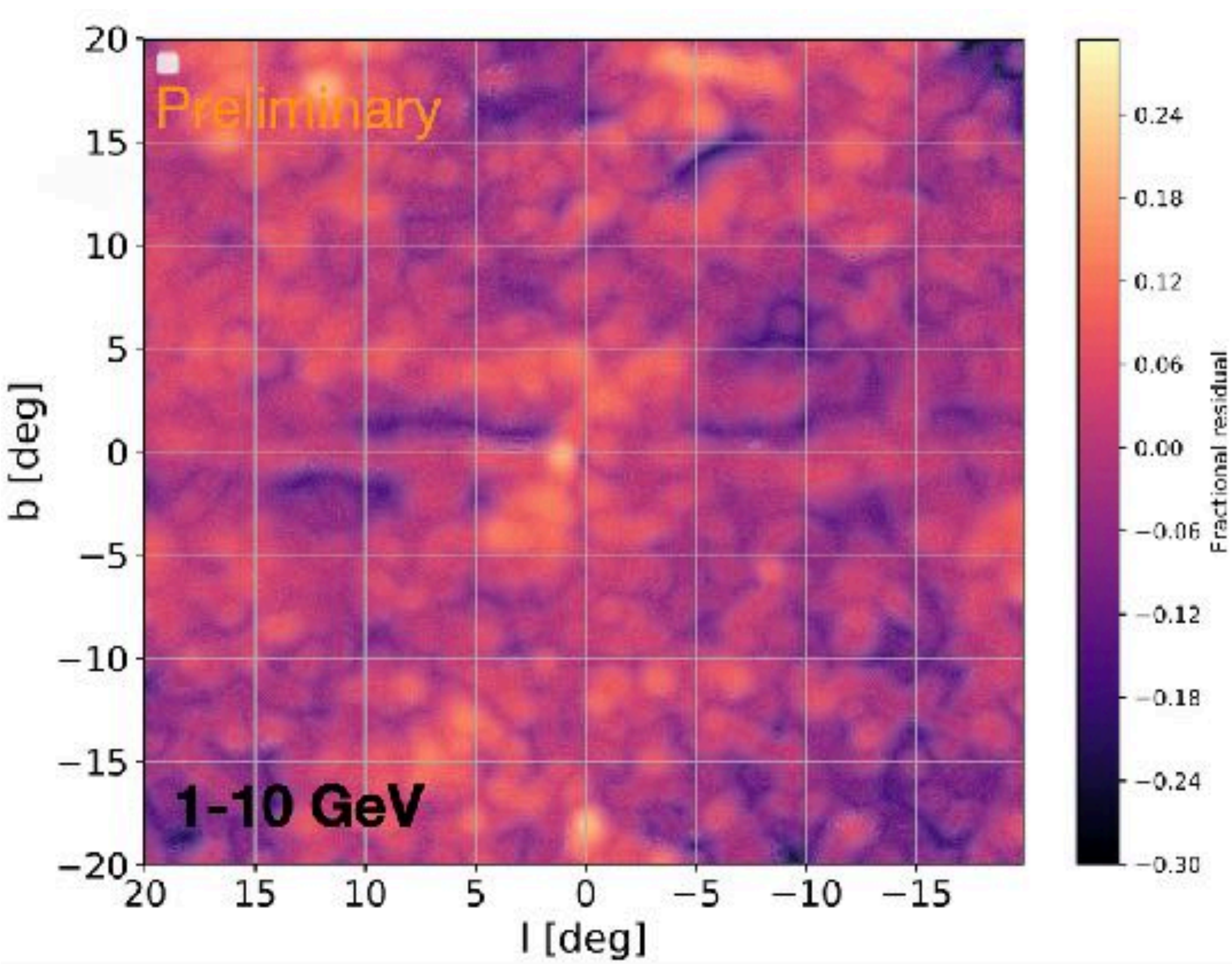
- A wrong IEM could generate a systematic of about 5% in the value of γ.
- A missing component as the inner component of the Fermi Bubbles influences the value of γ if its flux is > 10-20% of the GCE flux.

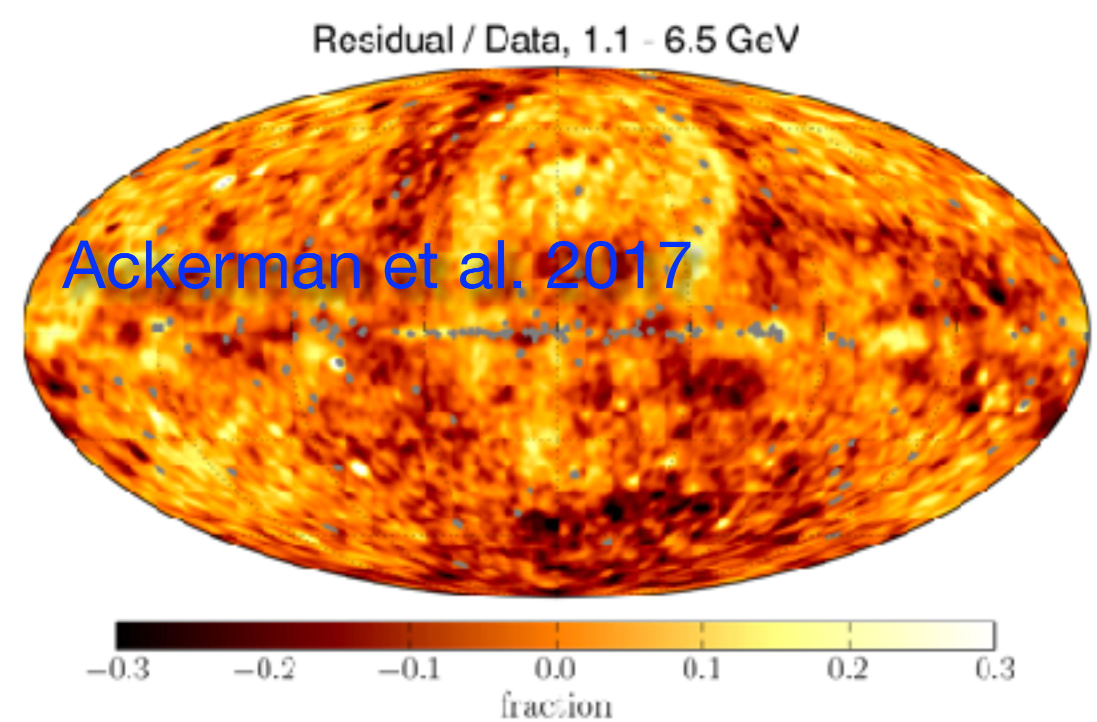




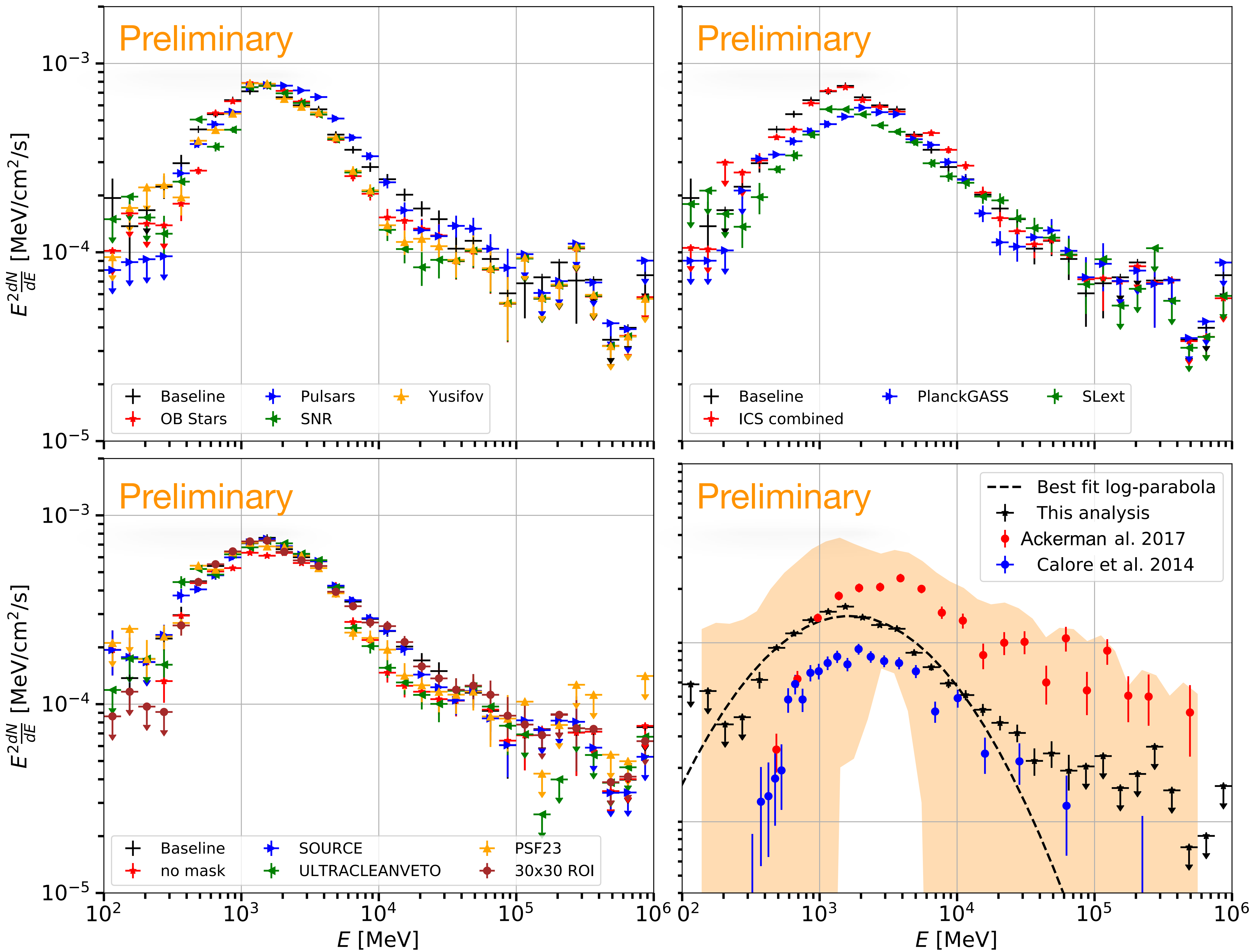
Real data analysis: Baseline model

- We use as in the reference the following components:
  - Bremsstrahlung, π^0, ICS divided into 1,2,3, isotropic component, Sun/Moon/Loop I in a unique component and the low and high latitude bubble components.
- The residuals are roughly at the level of 20-25% of the data.
  - Similar results have been found in Ackerman et al. 2017.



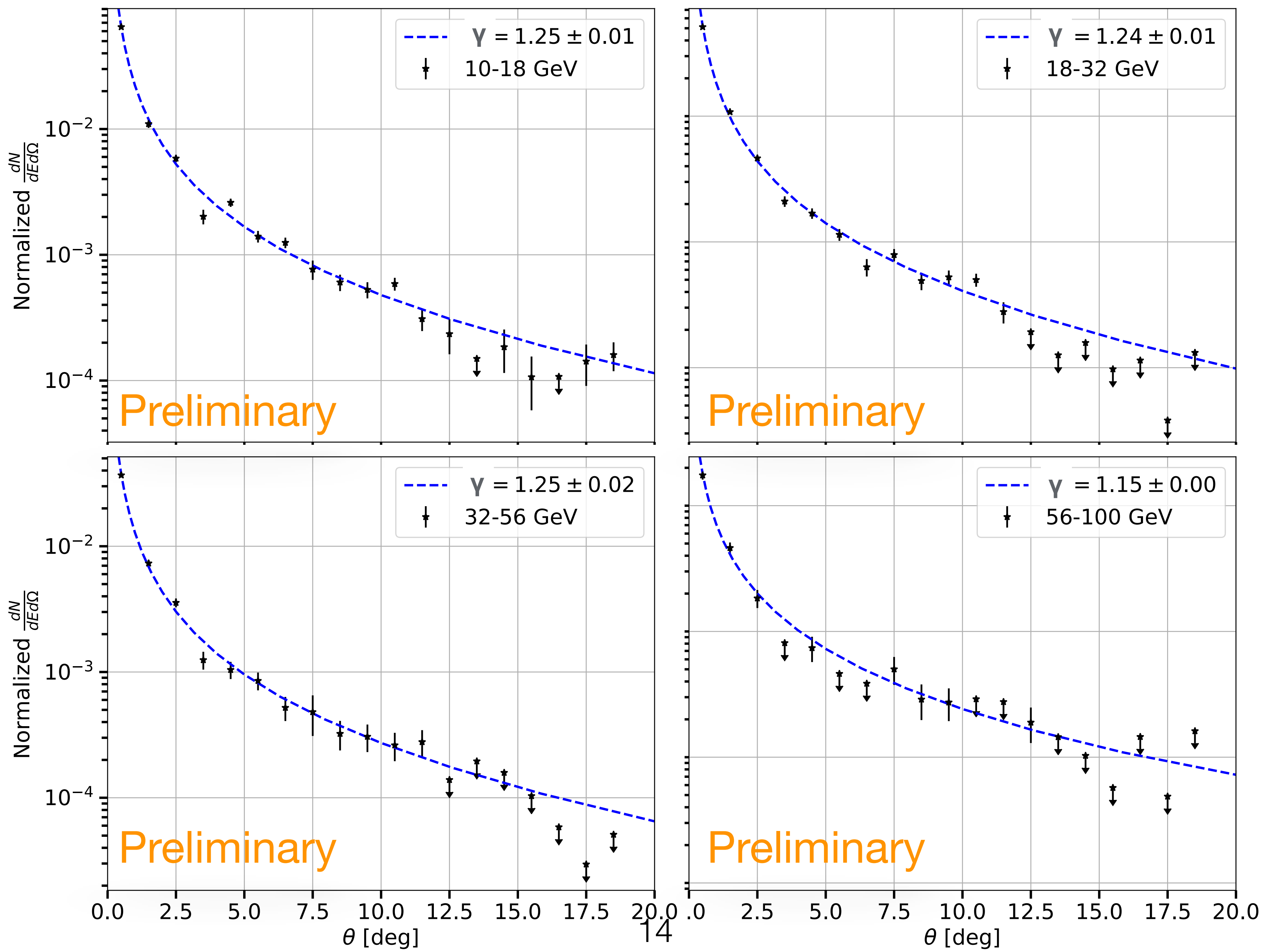


GCE Energy spectrum



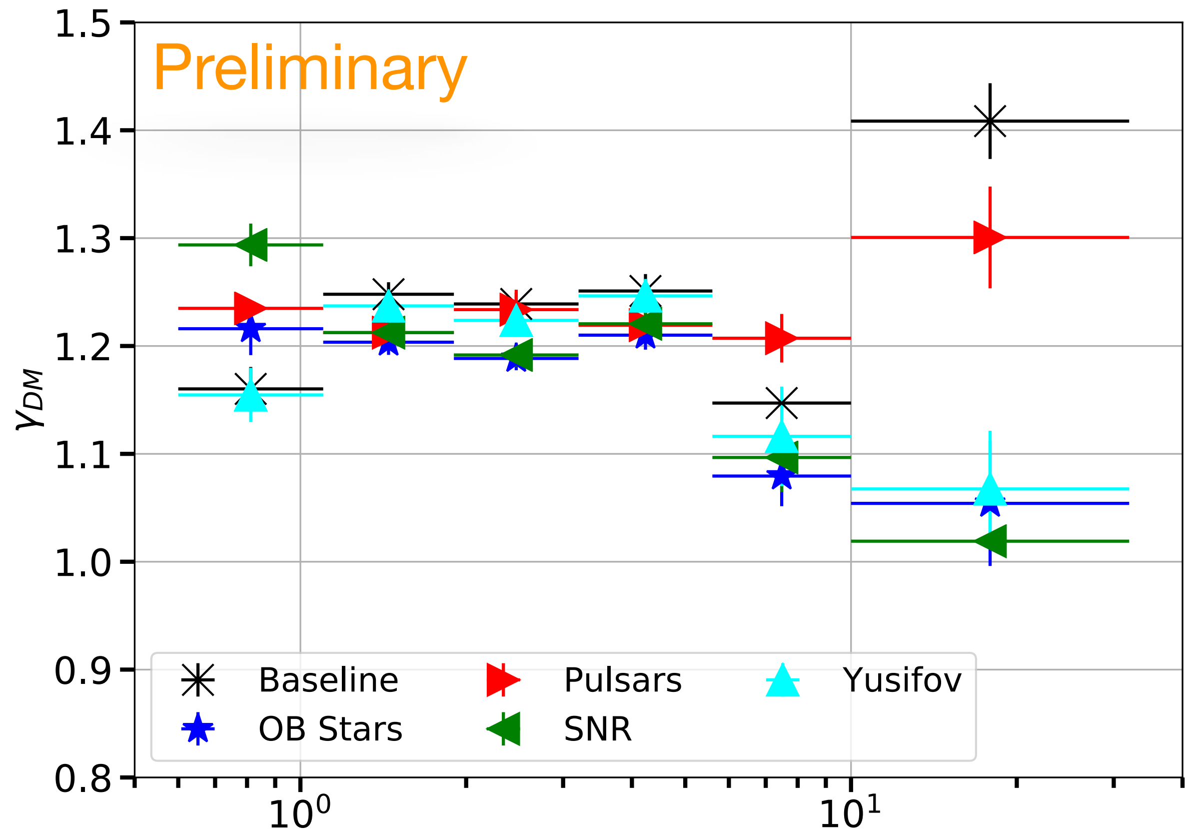
GCE spatial distribution

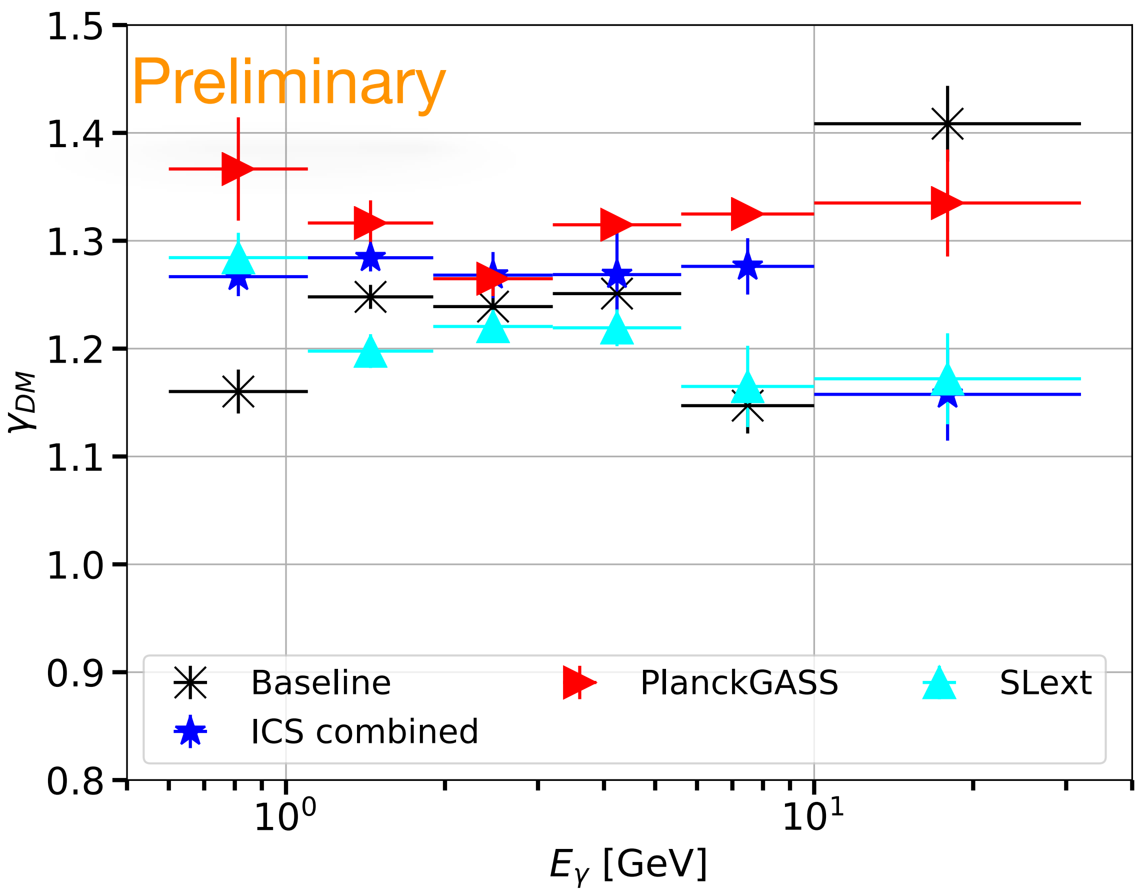
- We apply an analysis based on rings for determining the spatial distribution of the GCE.
  - We include in the model concentric and uniform annuli.
  - Then we fit the annuli to the data, derive their energy flux and calculate the surface brightness.

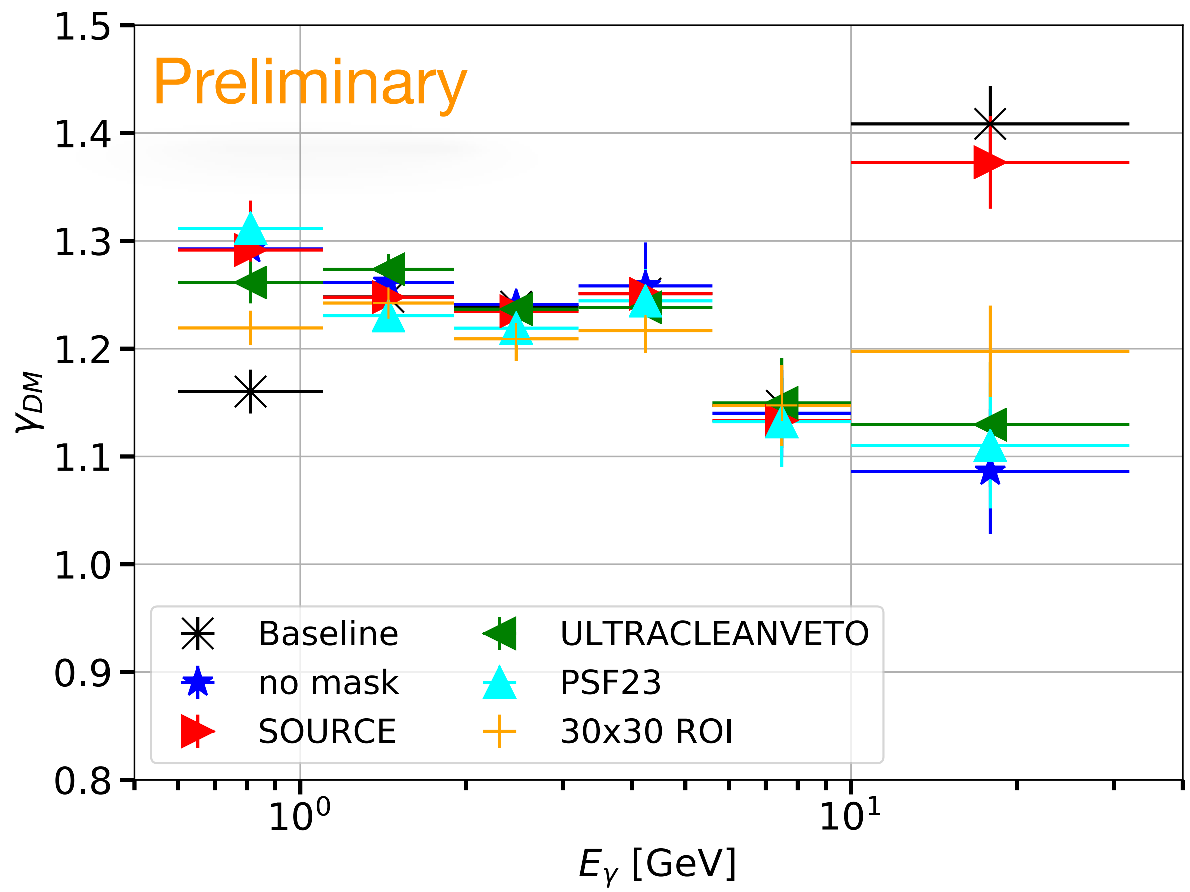


Value of gamma as a function of energy

- There is no clear evidence of an energy variation of the spatial morphology.
- **The value of γ is roughly 1.2-1.3.**
- I find similar results for different annuli sizes.
- *The systematics due to imperfections of the IEM are of the order of 5%.*

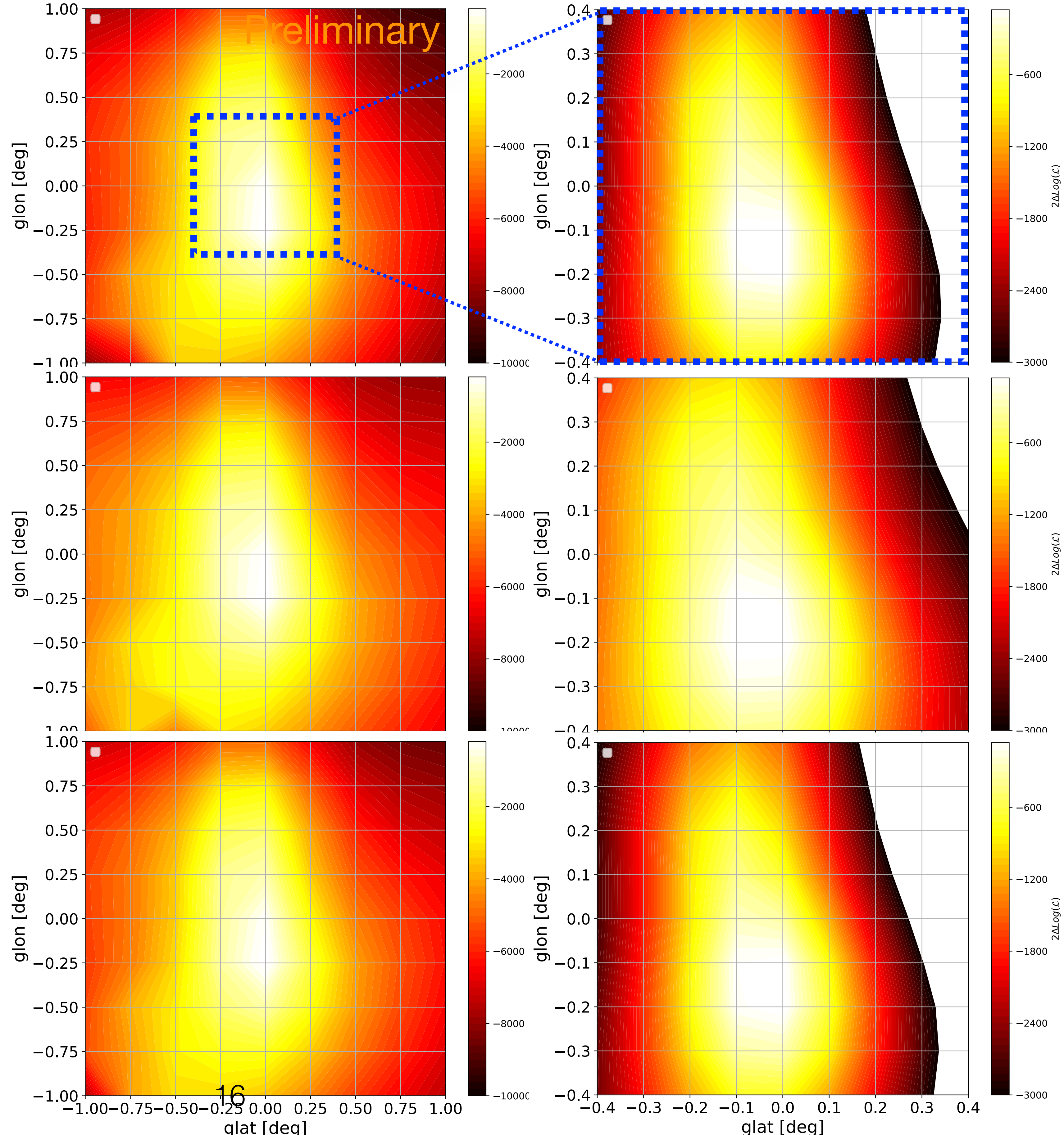






Position of the GCE

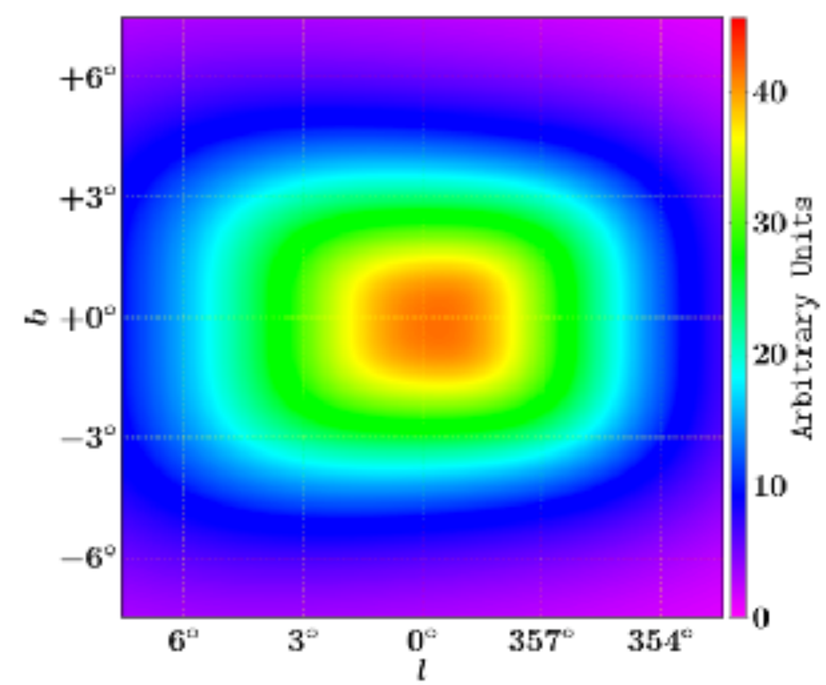
- I run the likelihood analysis moving the position of the GC template.
- *The position is peaked at*
    - *l = [−0.3°, 0.0°]*
    - *b = [−0.1°, 0.0°]*
- *Very close to dynamical position of the Galaxy (SagA*).*

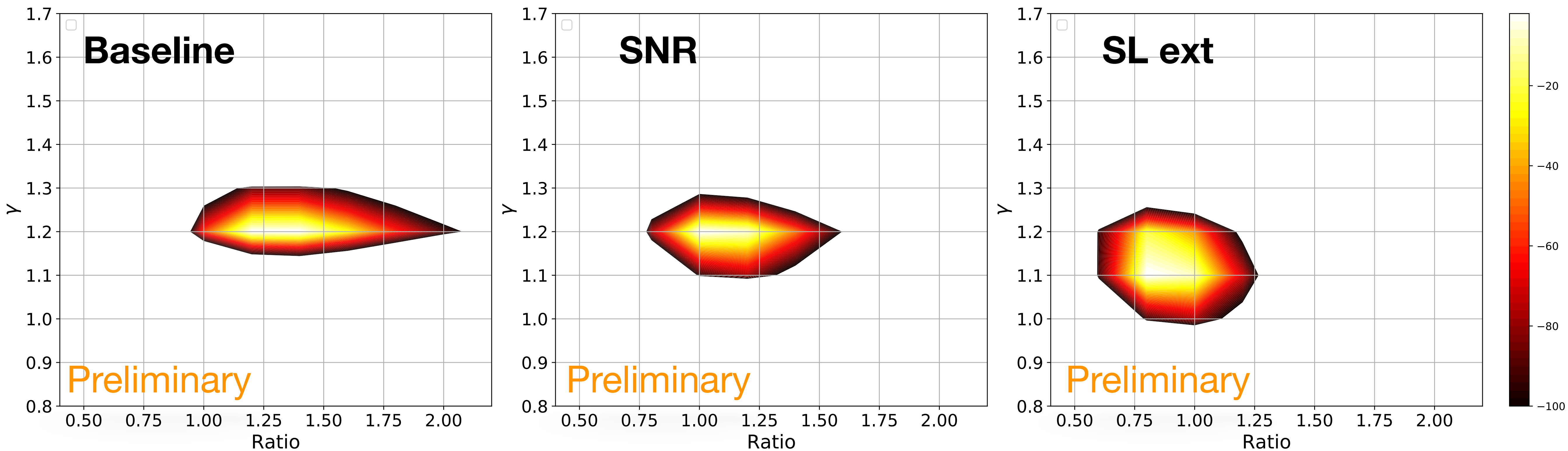


Sphericity of the GCE

- I use an elliptical morphology where I vary the ratio between the two axis (ratio) and the value of γ.
- **I find that ratio = [0.8-1.2] and γ=[1.1,1.2].**
- The result of the fit using the nuclear (NB) and boxy bulge (BB), from Macias et al. 2018, is worse than using the NB and DM templates (2ΔLogL~[140,250]).
  - A few caveat: we are using different IEM and the ellipsoidal templates are different from the BB.

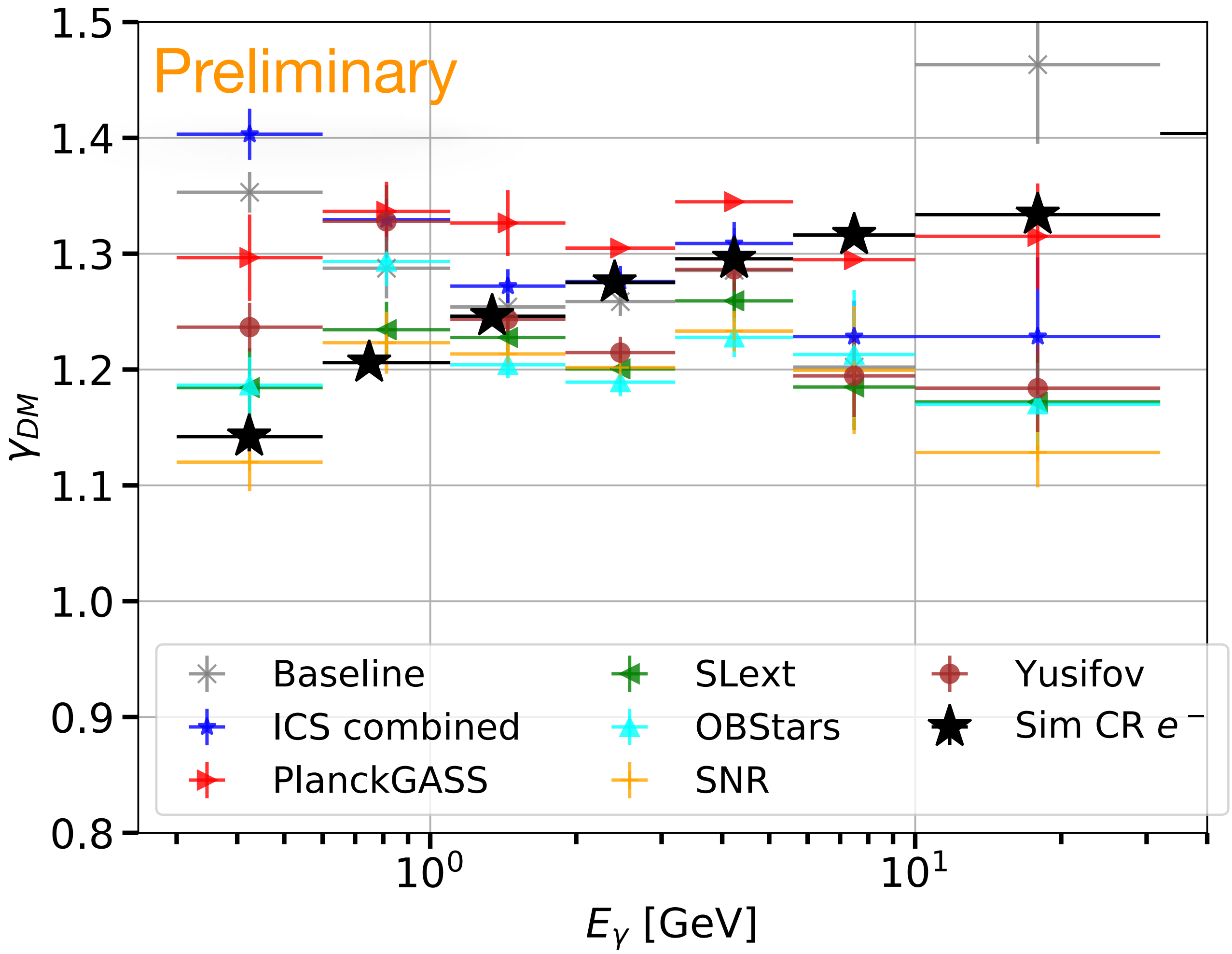
Macias et al. 2018

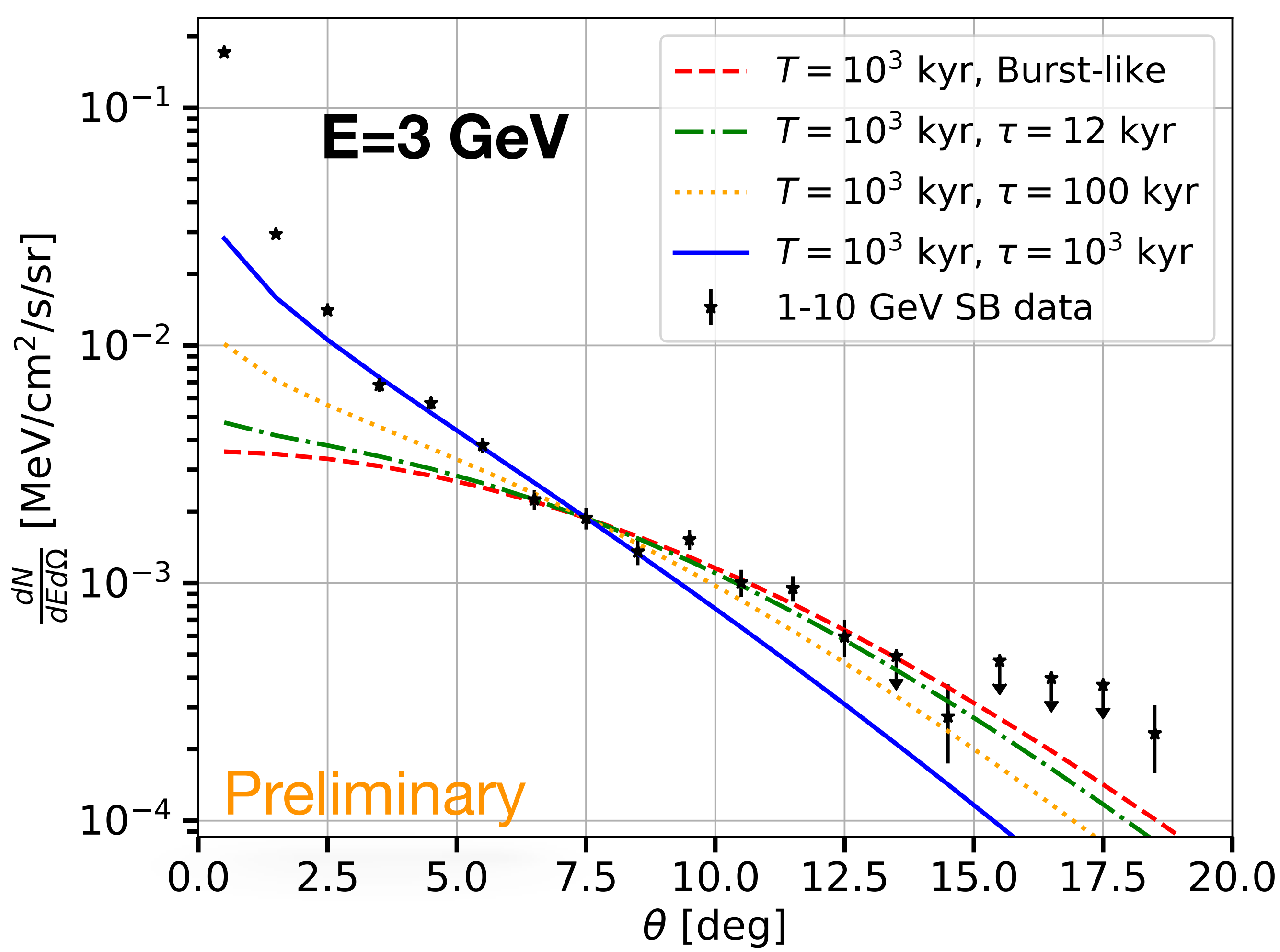




Interpretations of the GCE: CR electrons

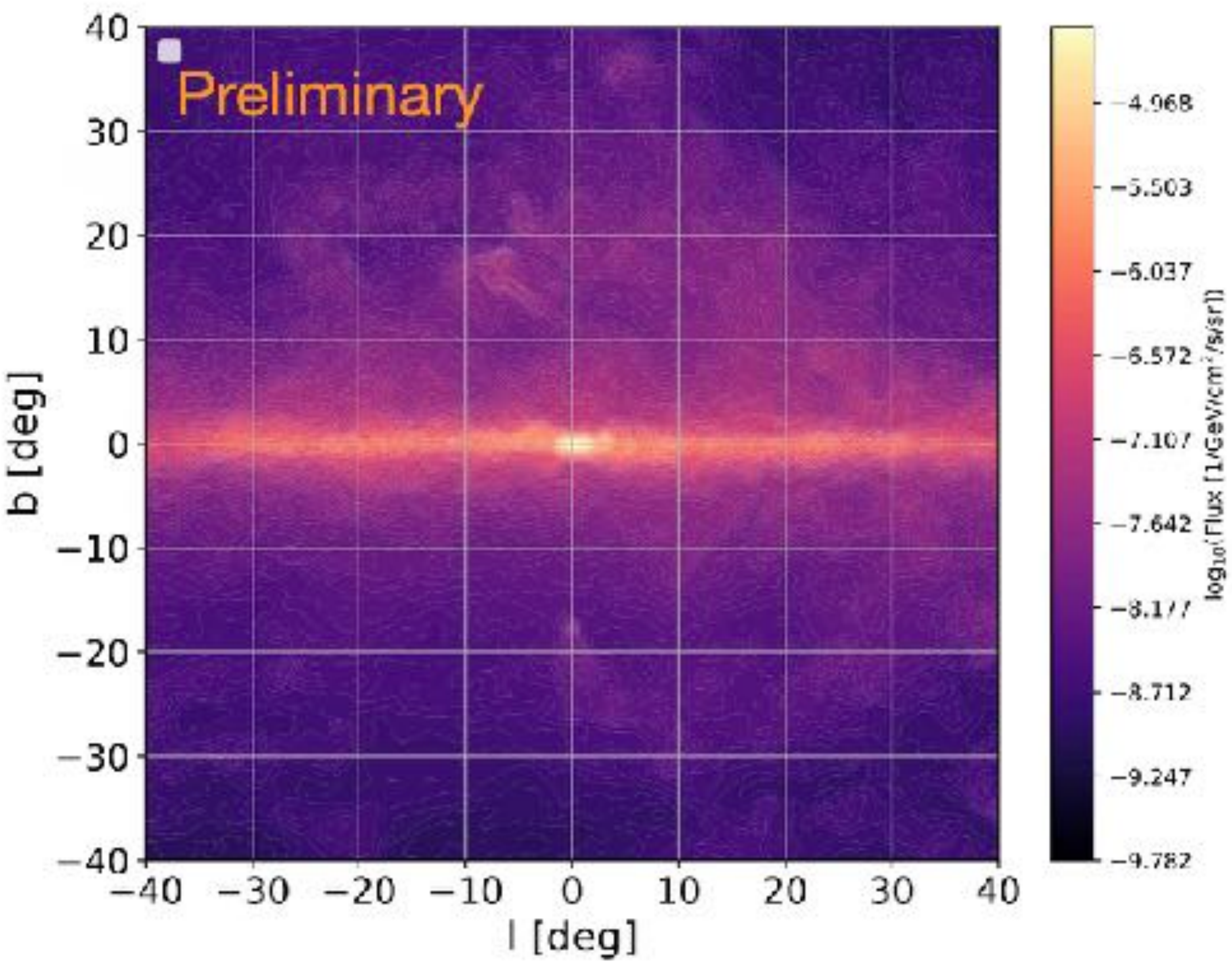
- Cosmic-ray electrons injected from the Galactic center have been invoked by different papers as a possible origin of the GCE (e.g. Carlson et al. 2014).
- This interpretation has a few issues:
  - *The spatial morphology of the GCE with CR e^- is energy dependent.*
  - *The surface brightness is incompatible with data in the inner few deg.*
  - *It is also challenging to fit well the GCE spectrum.*

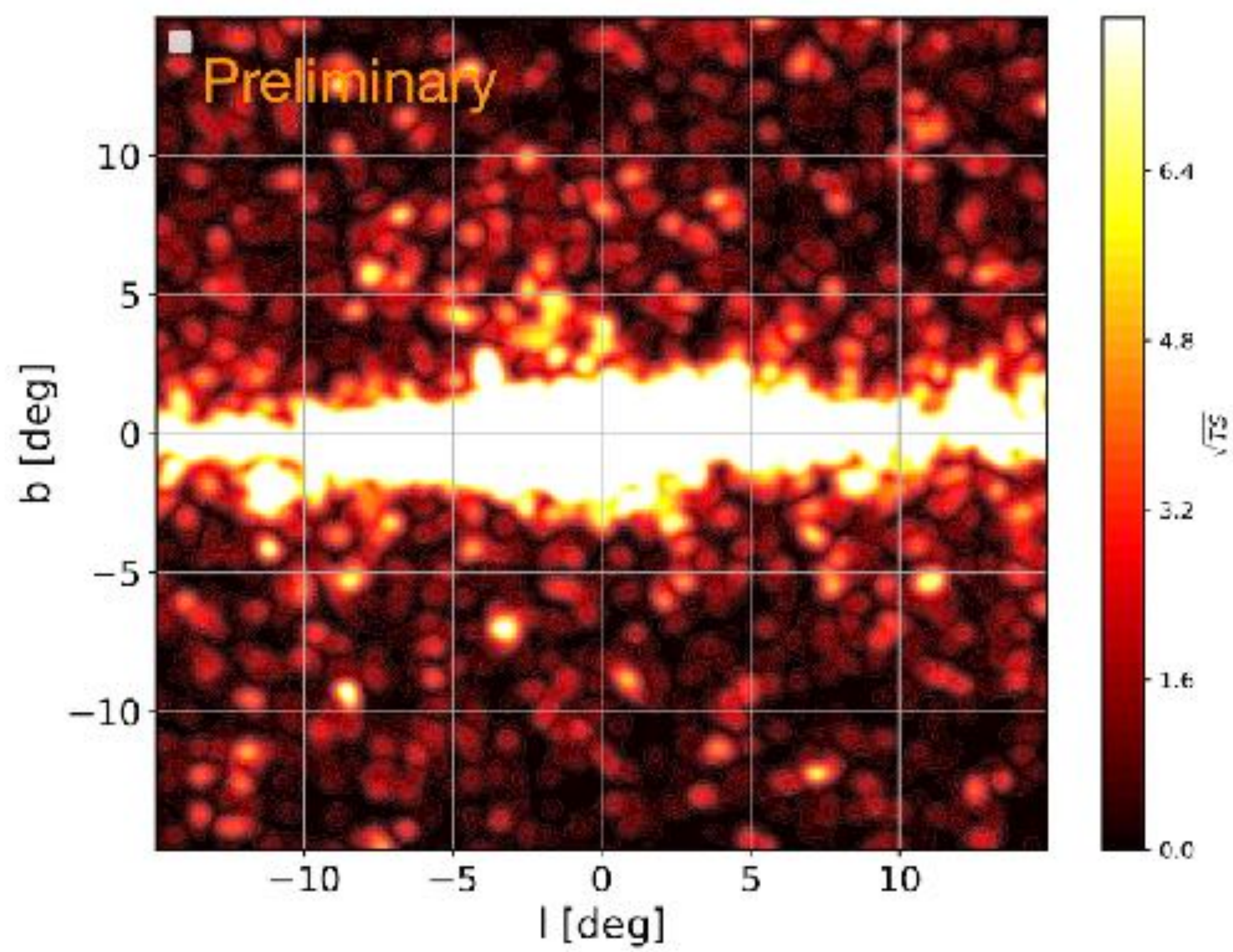




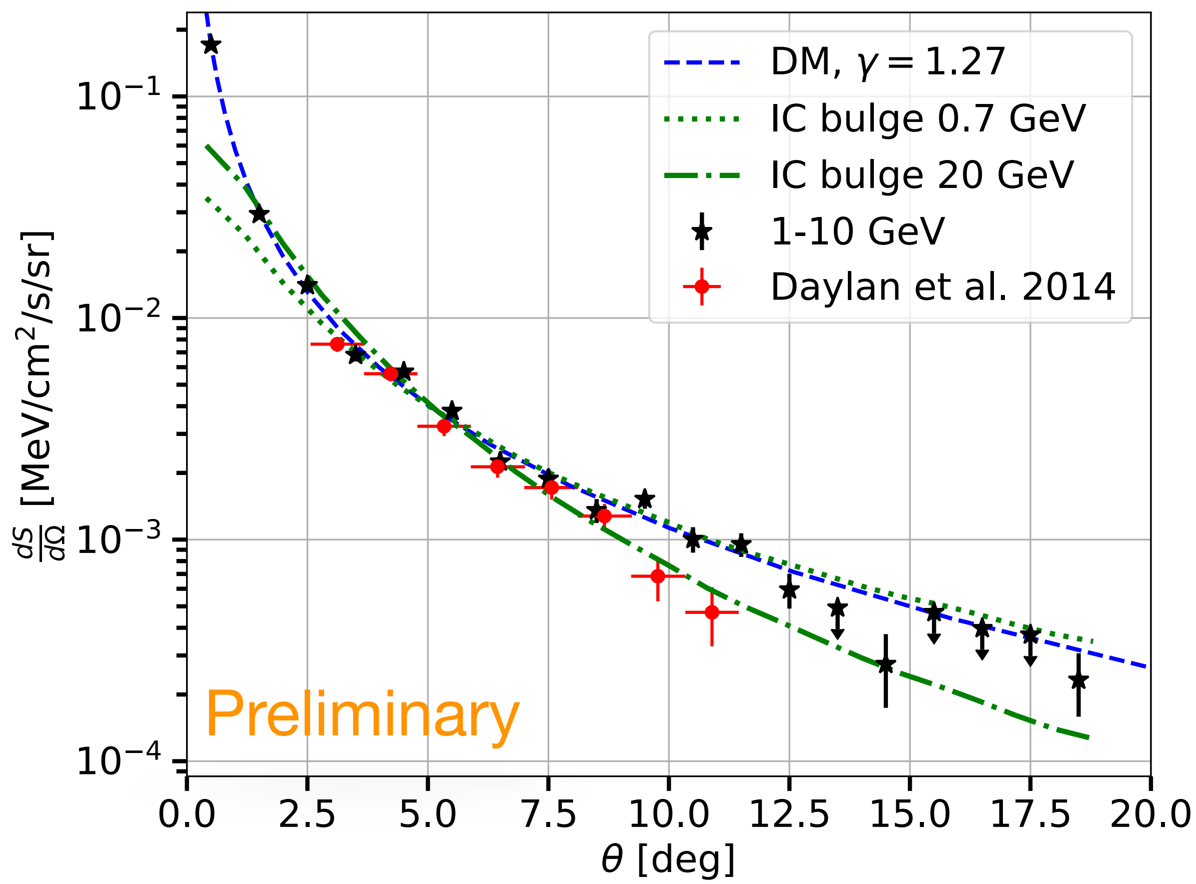
Interpretations of the GCE: CR protons

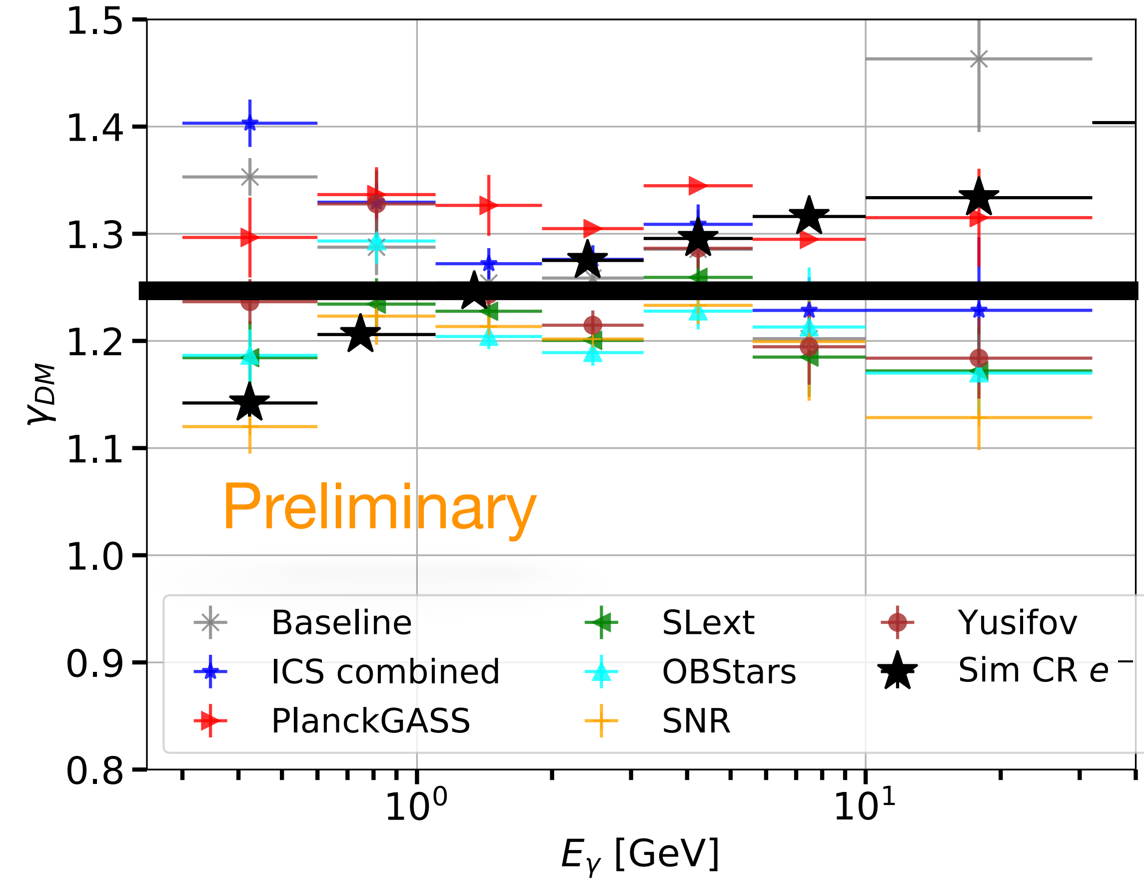
- The flux produced by a population of protons from the Galactic center (in the CMZ) would be elongated on the Galactic plane.
- As a consequence also the signal would have the same shape.
  - The main problem for this interpretation is the morphology.
- We would need a special spherically symmetric distribution of gas around the Galactic center and with an extension of at least 1.5 kpc.

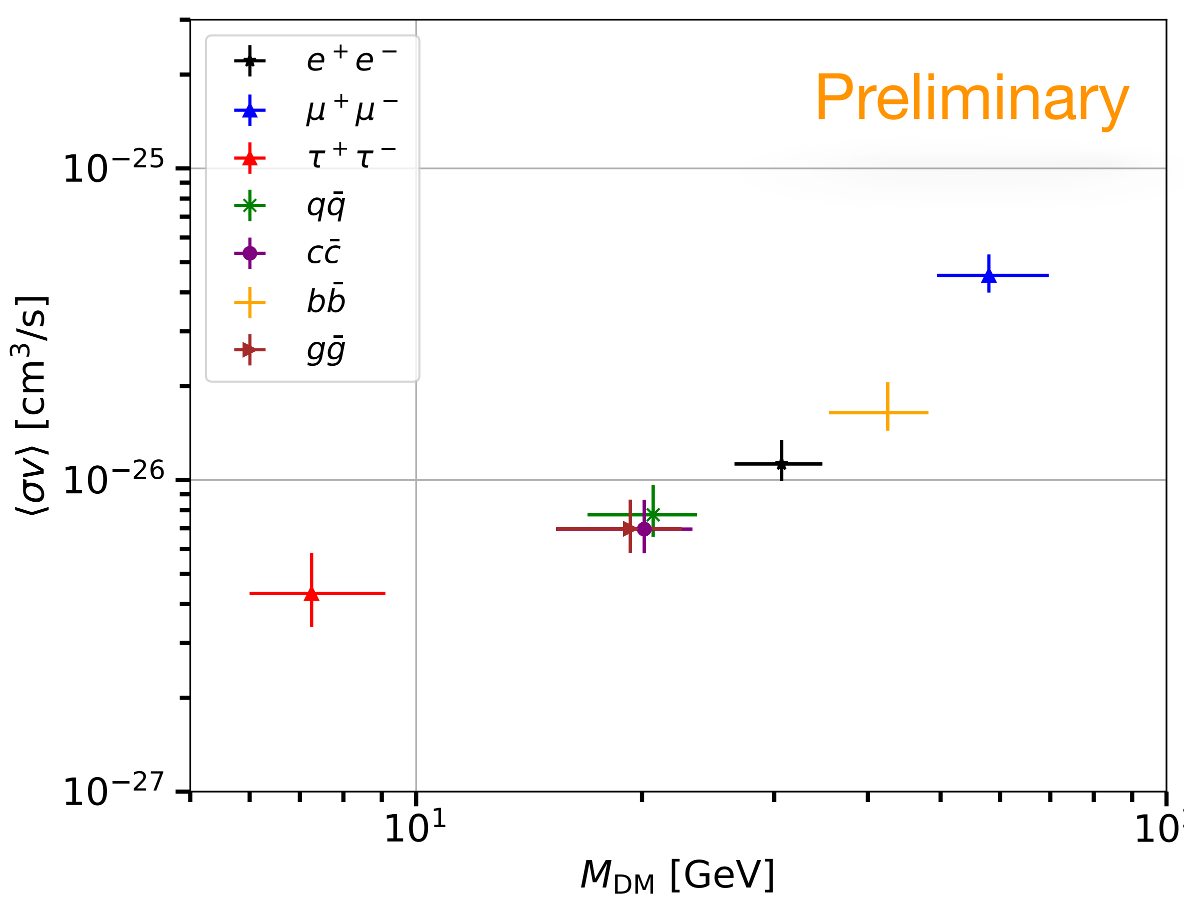


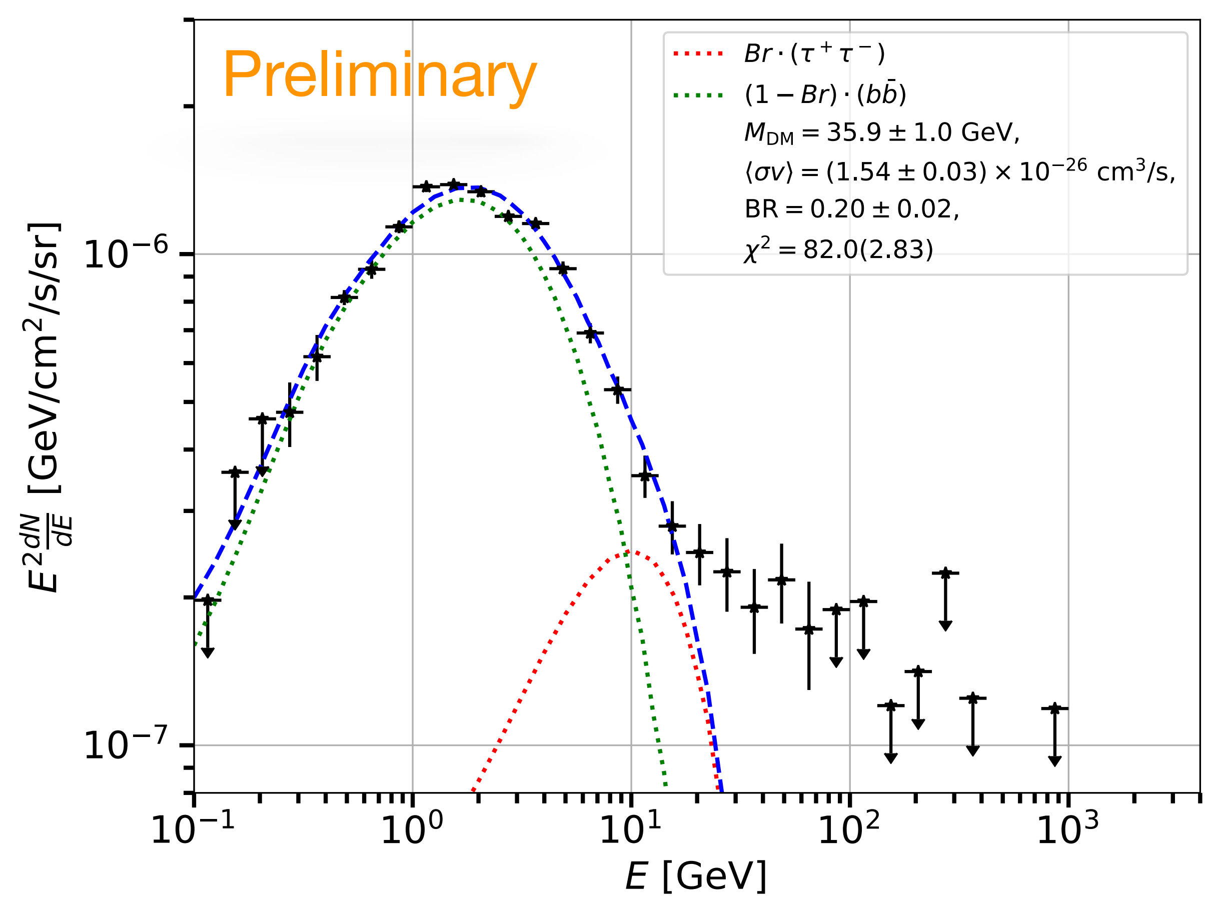


Dark matter interpretation





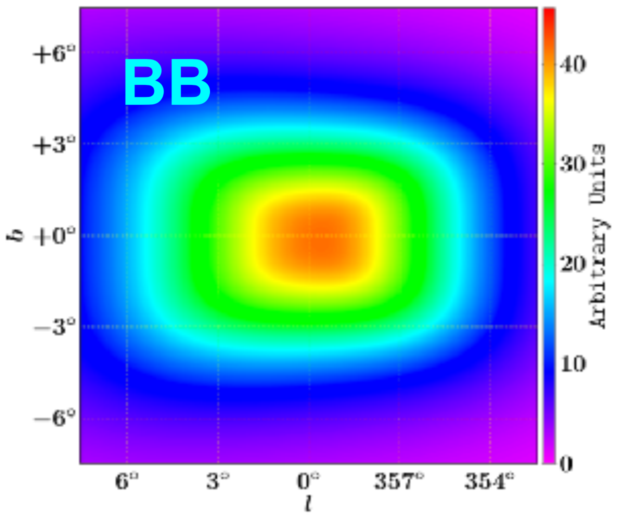


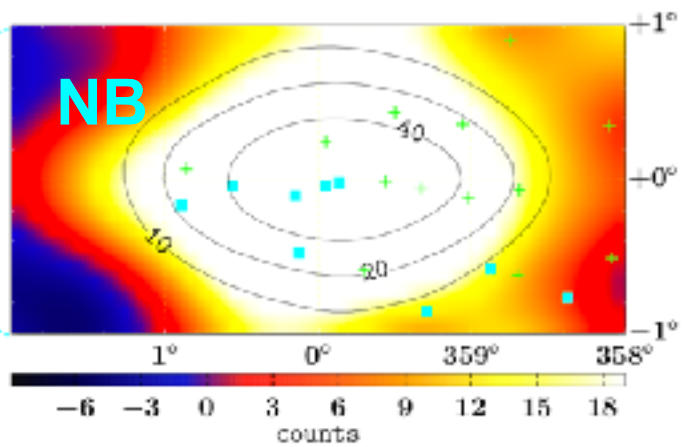


Millisecond pulsar in the Galactic bulge

- An other viable interpretation is due to pulsars located in the Galactic bulge.
    - See models in Macias et al 2018, 2019, 2020 where they have create and used a nuclear and a boxy bulge template.
- **Bartels et al. (2015) and Lee et al. (2015):** population of unresolved sources distributed in the Galactic bulge of our Galaxy.
- Recents papers casted doubts on the pulsar interpretations.
    - *Leane et al. 2019 and Chang et al. 2019* non-Poissonian template fitting.
    - *Zhong et al. 2019* wavelet method.
- *More work needs to be done in this subject to verify if it is a viable interpretation.*

Macias et al. 2018





Conclusions

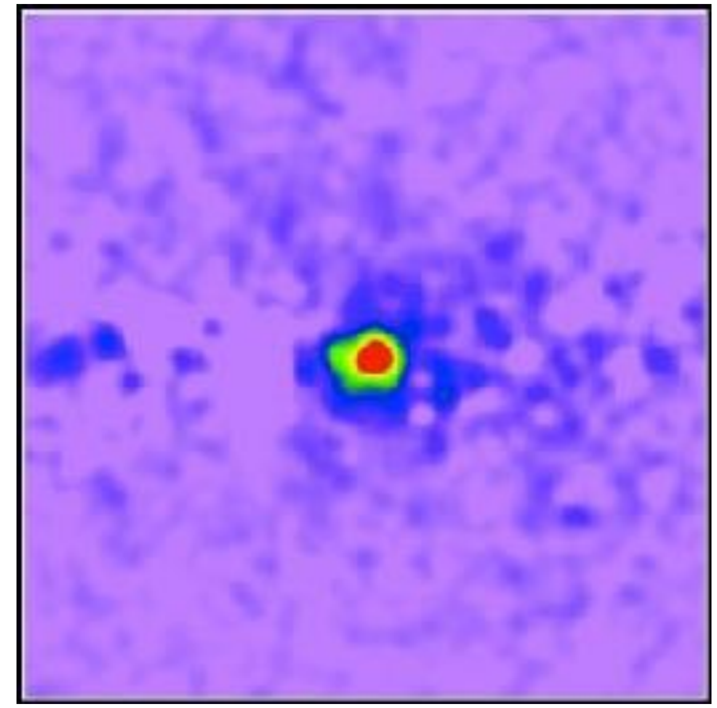
- Simulations
  - The systematics on the GCE spectrum(morphology) are about 10-15%(5% of γ).
  - A missing component with a flux >10-20% of the GCE would affect the GCE detection.
- GCE characteristics.
  - Spectrum peaked at few GeV with variation of about 60% using different IEMs.
  - Morphology: NFW DM density profile with γ=1.2-1.3.
  - The GCE is roughly spherically symmetric and centered in the dynamical center of the Galaxy.
- Interpretations.
  - CR e^-:
    - morphology would change with energy.
    - Surface brightness is not compatible with the GCE data.
  - CR p:
    - Morphology incompatible with the GCE data.
  - DM:
    - Morphology compatible with the DM and candidate not completely ruled out yet by other observations.
  - PSR:
    - Possible compatibility with the GCE characteristics but more tests need to be done to verify if this is preferred over the DM interpretation.

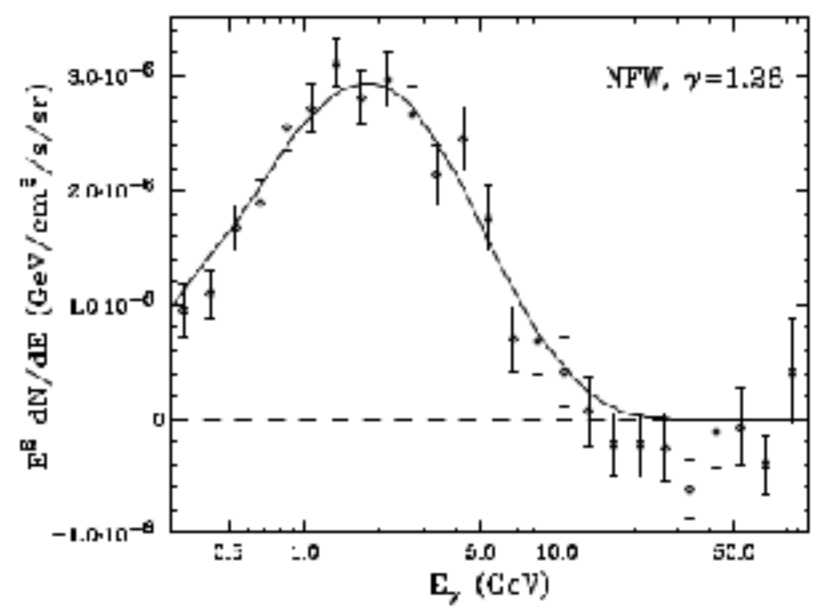
Backup slides

The GeV Excess in the Galactic Center

The GeV excess as originally found by Hooper and Goodenough (2009, 2010), Hooper and Linden (2011) has the following properties:

- It is bright and highly significant.
- It is specially symmetric around the Galactic center: $dN/dV \propto r^{-2.5}$ —> compatible with a gNFW profile.
- The energy spectrum it's peaked at a few GeV and it is compatible with a DM candiate that annihilates into a bottom-anti-bottom quarks and with a mass around 40 GeV.
- This DM candidate explains the intensity of the GeV excess with the thermal cross section.

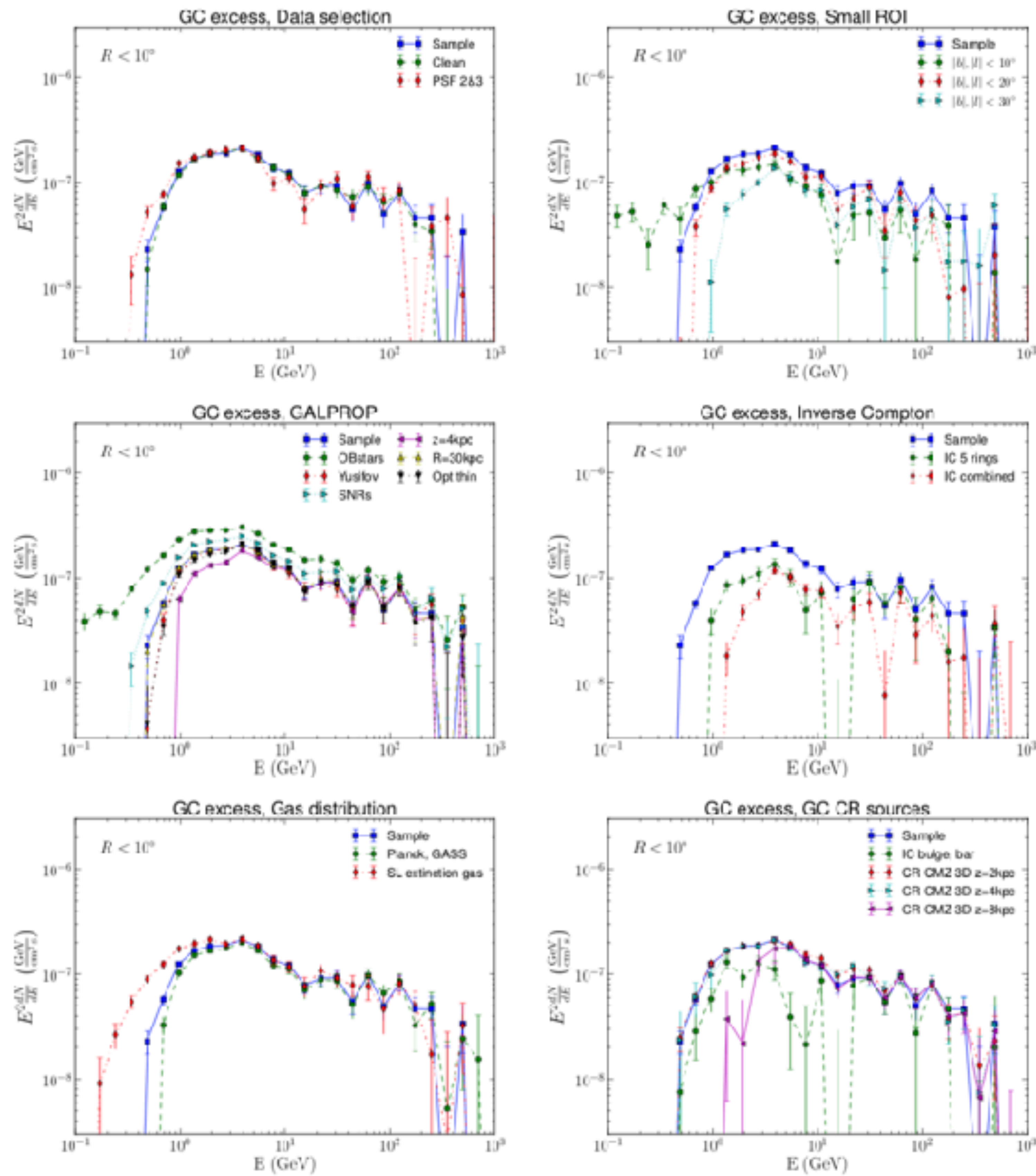




The GeV excess is thus perfectly compatible with DM in the halo of our Galaxy

IEM models used

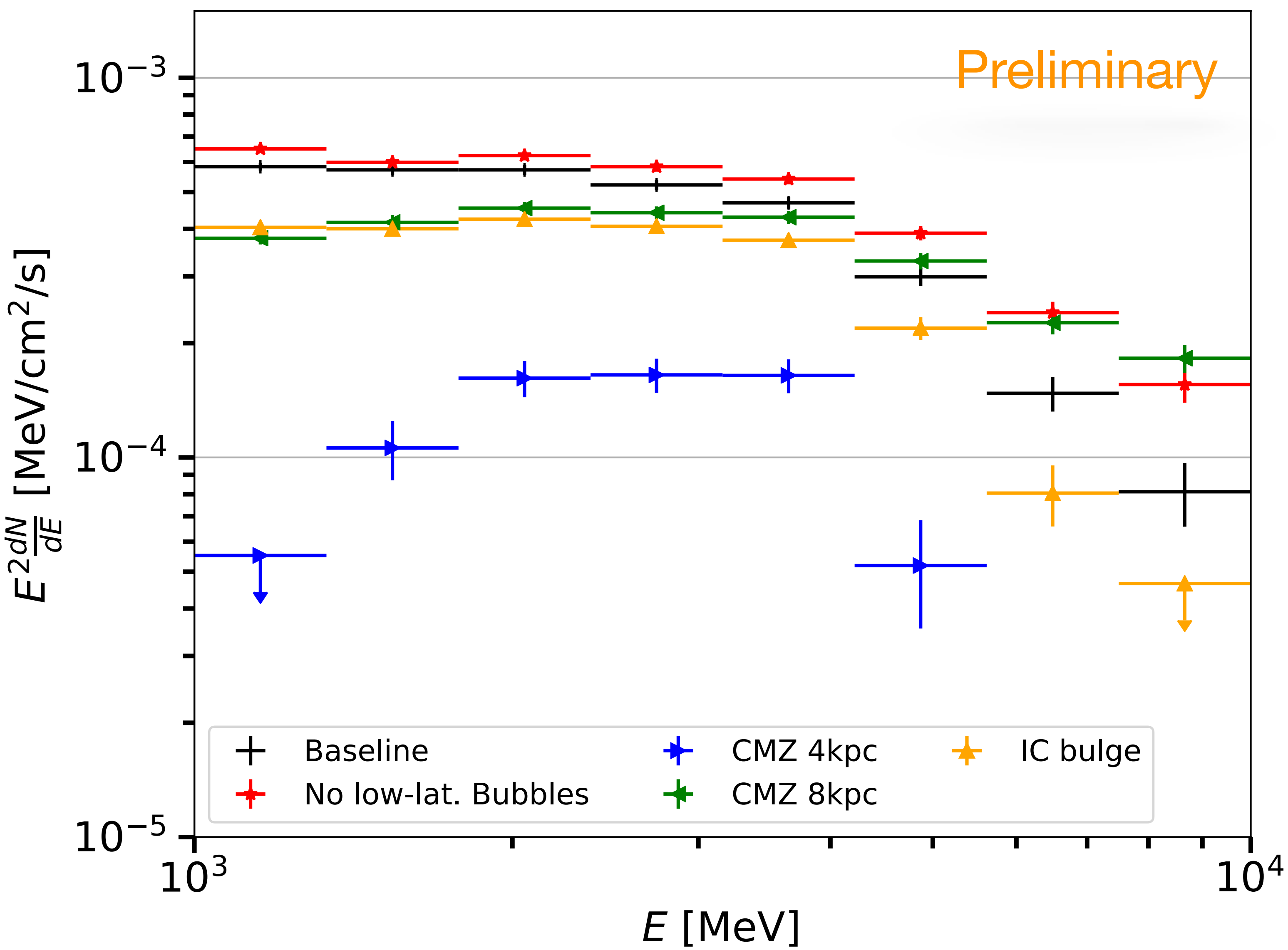
- All the IEM models have been produced in Ajello et al. 2017 using GALPROP.
- **Sources**:
  - SNR
  - Pulsars
  - OB Stars
  - Yusifov
- **Gas**
  - Planck and GASS
  - SL extinction
- **Additional components**:
  - CR electrons
  - CR protons
  - Pulsars in the Galactic bulge.



Ajello et al. 2017

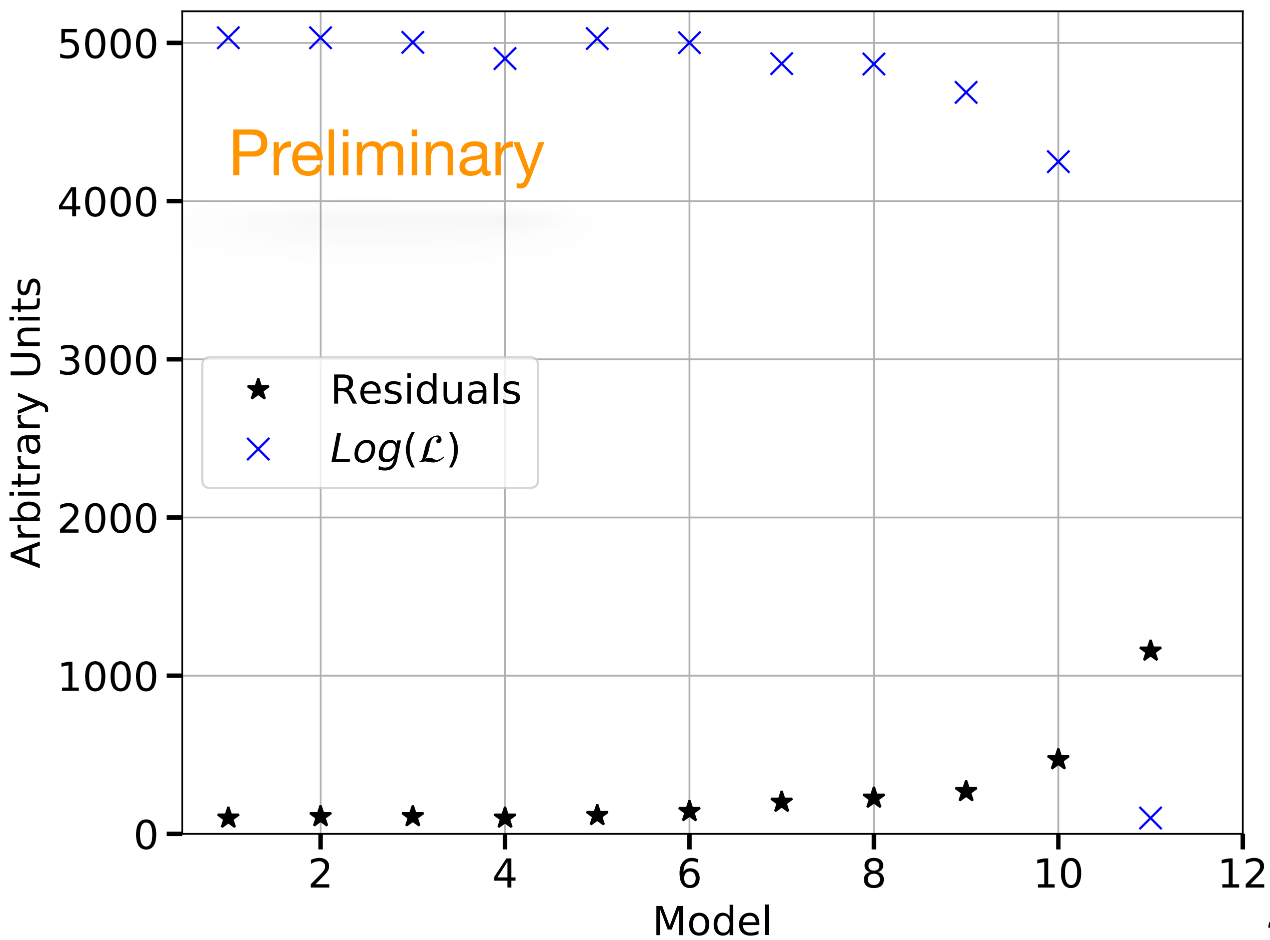
Energy spectrum with additional components in the GC

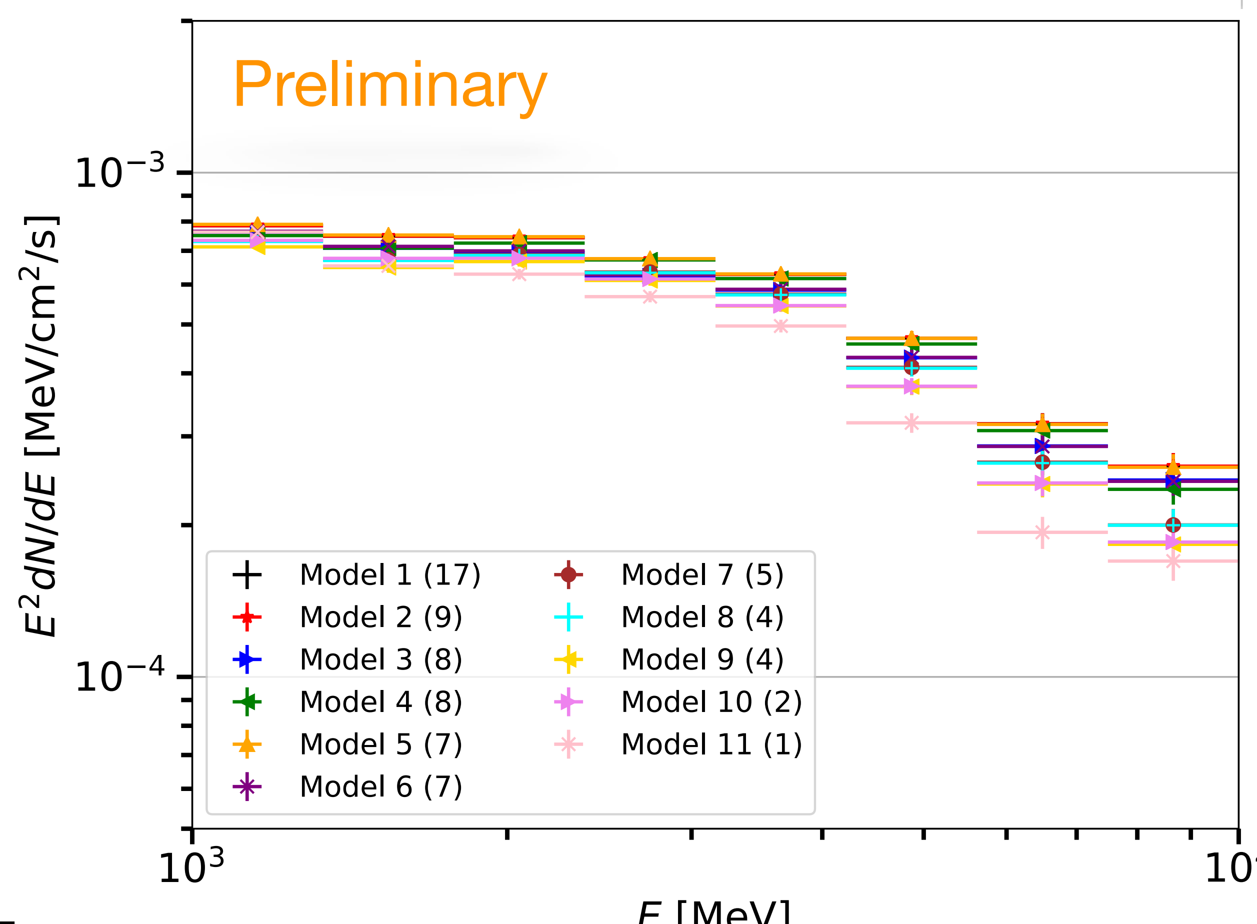
- I also tested different choices for the IEM in the region close to the GC.
  - No low-latitude bubble component
  - ICS component generated by the stellar Galactic bulge.
  - Additional CR population in the CMZ.
- These choices modify significantly the result for the GCE spectrum.



Test of the components to be left free

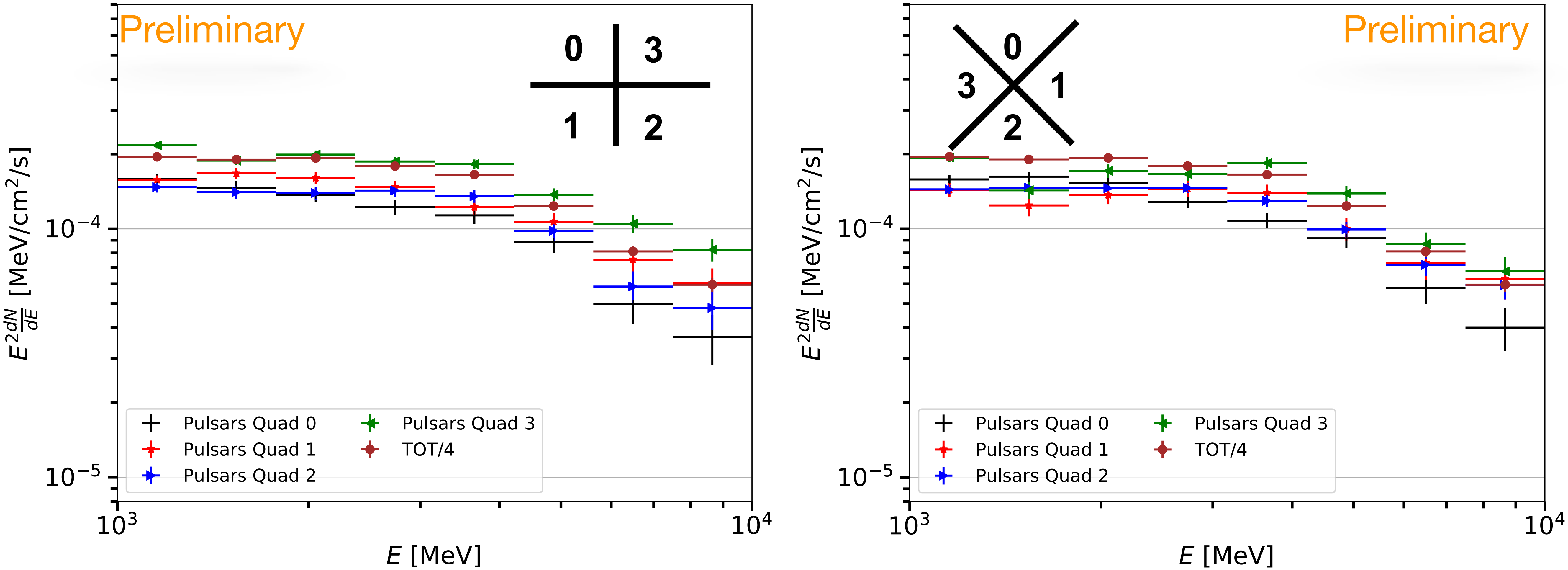
Model	N° comp.	list templates used for each component
1	17	5 rings for bremsstrahlung (Brem.) and π^0 emission, 3 for inverse Compton (CMB, SL. IR), 2 for low latitude bubbles, isotropic (ISO), 1 template for Loop I, the Sun and the Moon (LoopMoonSun).
2	9	1 Brem., 1 π^0, 3 for inverse Compton (IC), 2 for low latitude bubbles, 1 ISO, 1 LoopMoonSun.
3	8	1 Brem. and π^0, 3 IC, 2 for low latitude bubbles, 1 ISO, 1 LoopMoonSun.
4	8	1 Brem., 1 for π^0, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
5	8	2 for Brem. and π^0 divided into H1 and H2, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
6	7	1 Brem., 1 for π^0, 1 for IC, 2 for bubbles, 1 ISO, 1 LoopMoonSun.
7	7	1 Brem. and π^0, 3 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
8	5	1 Brem. and π^0, 1 IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
9	4	1 Brem. and π^0, 1 IC, 1 bubbles, 1 ISO and LoopMoonSun.
10	4	1 Brem. and π^0 and IC, 1 bubbles, 1 ISO, 1 LoopMoonSun.
11	1	1 unique template for all components.





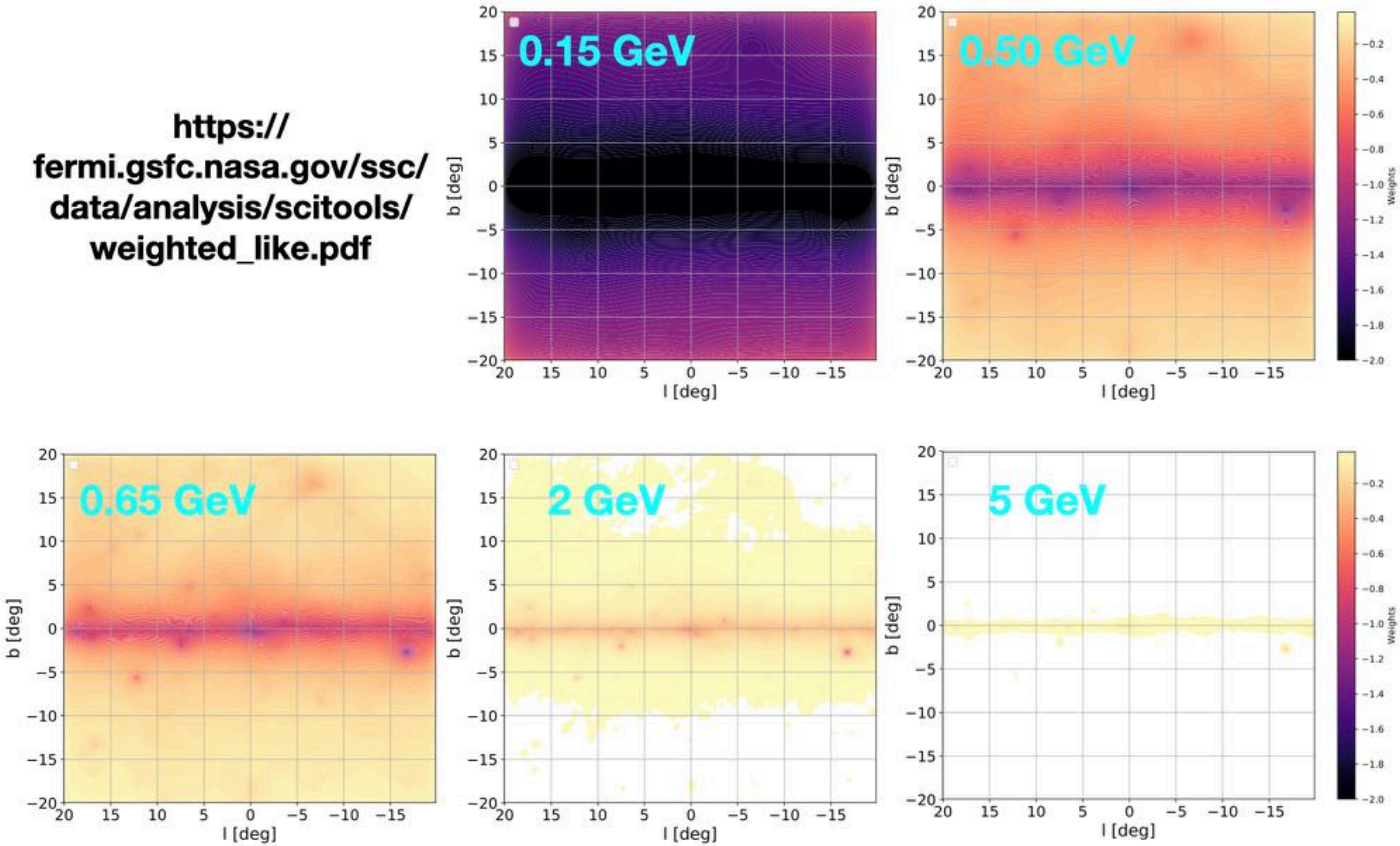
Analysis in quadrants: spectrum

- I divided the template in quadrants and run the fit to the ROI leaving free to vary independently the SED parameters of each quadrant.
- The SED is similar among the different quadrants for both configurations.
- *The differences I find are twice as large as the systematics due to uncertainties in the IEM (10%).*

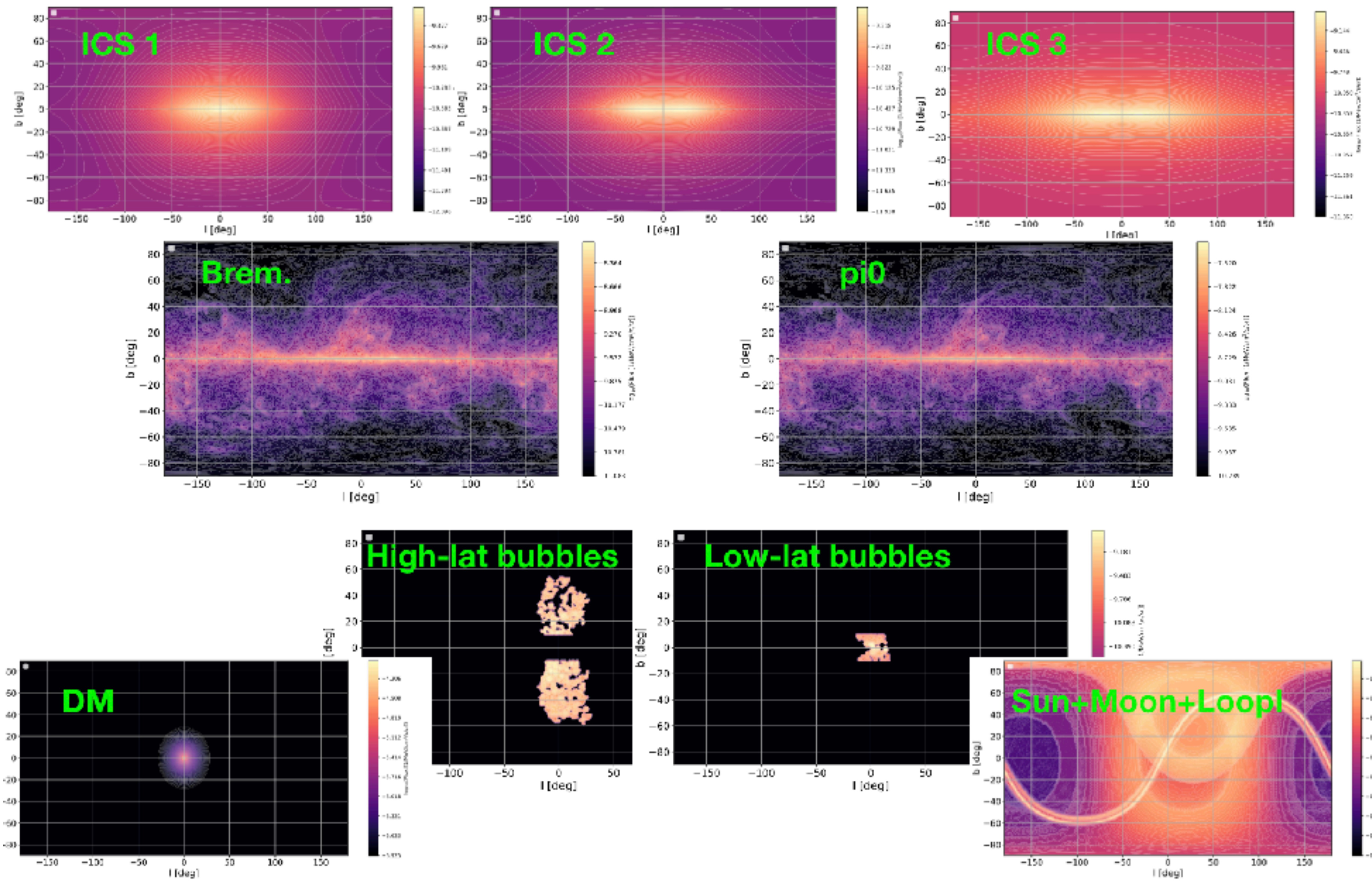


Weighted likelihood

https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/weighted_like.pdf

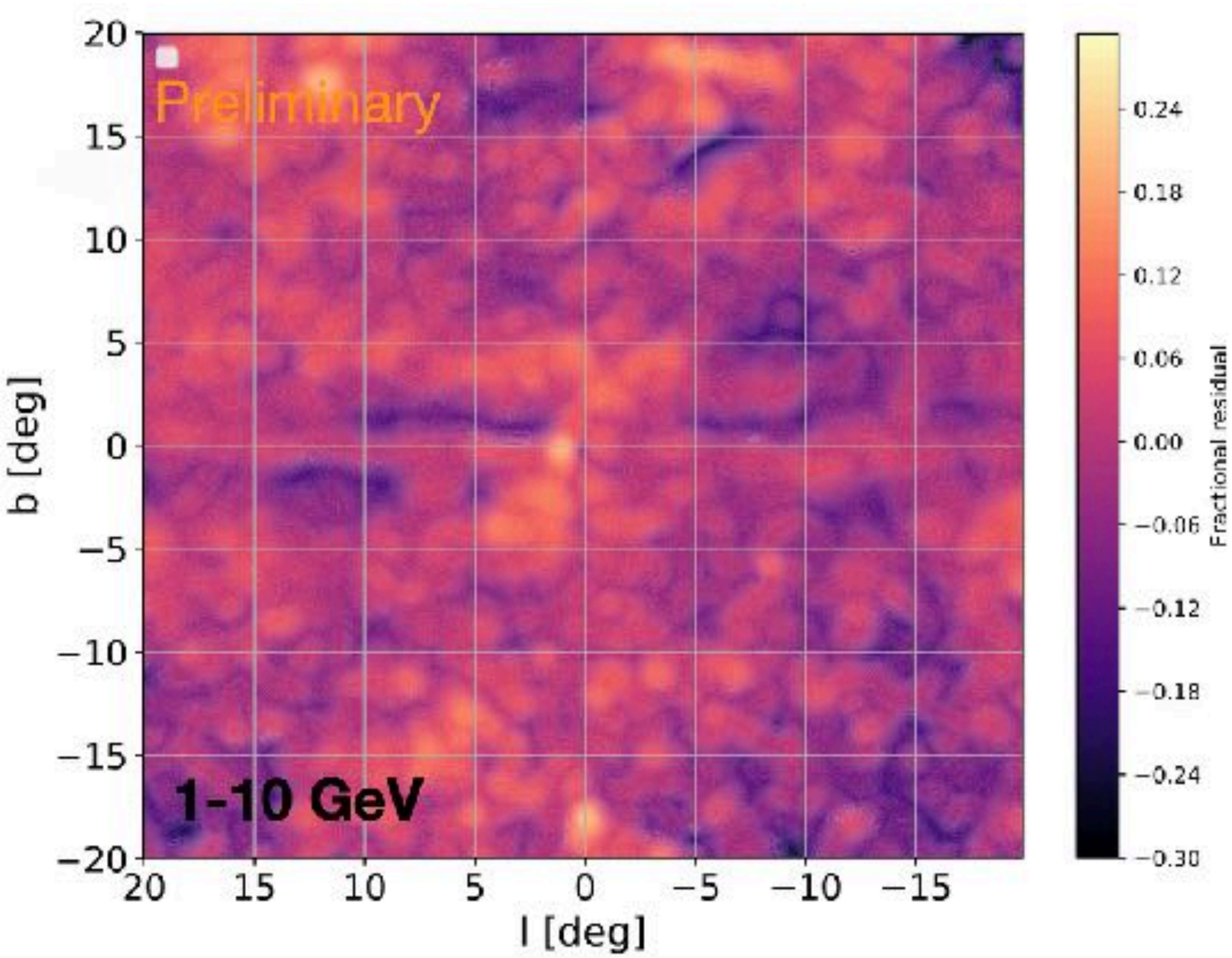


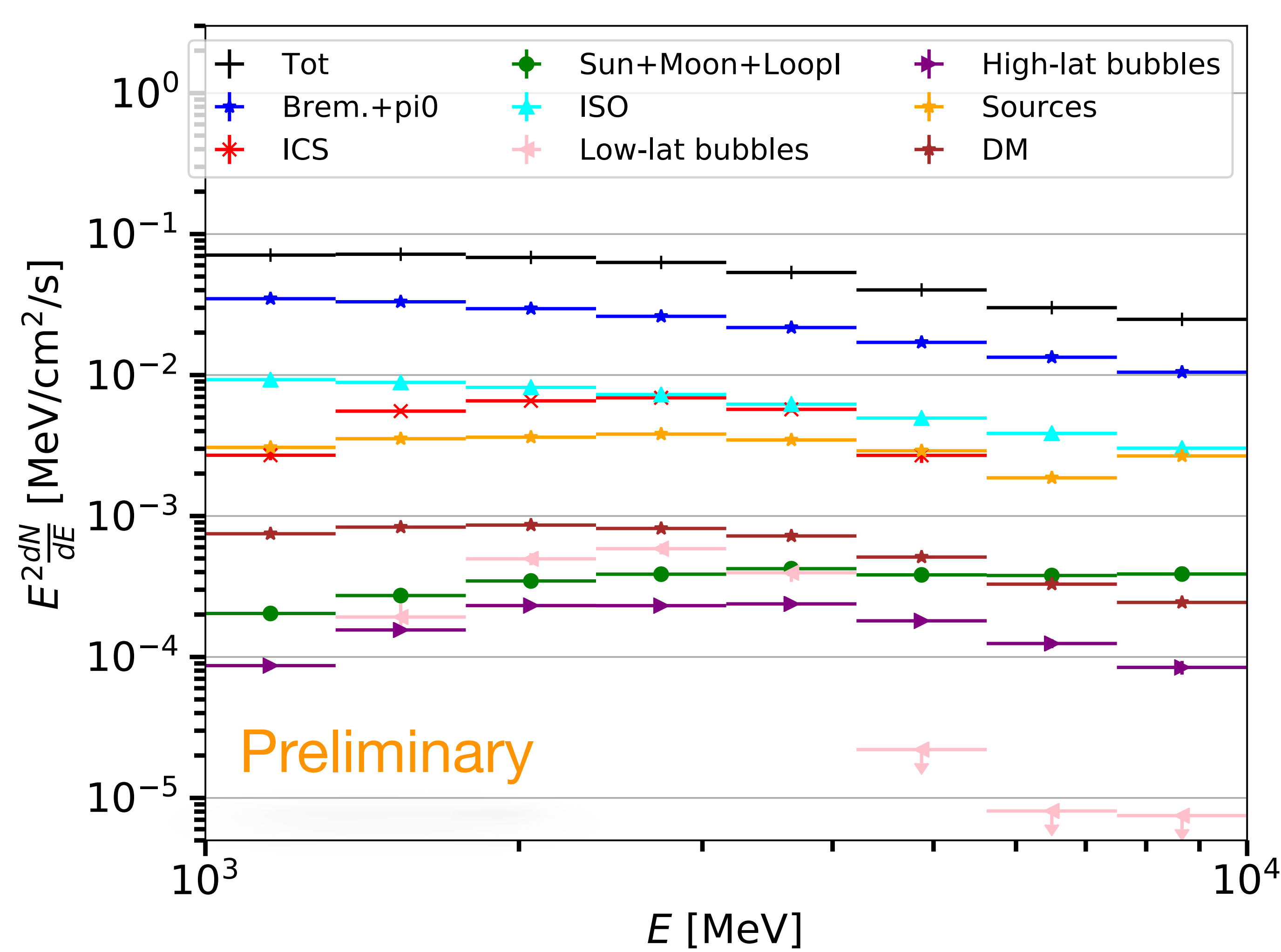
Components of the IEM



Reference model: components

- We use as in the reference the following components:
  - Bremsstrahlung, pi0, ICS divided into 1,2,3, isotropic component, Sun/Moon/Loop1 in a unique component and the low and high latitude bubble components.
- The residuals are roughly at the level of 20-25% of the data.
  - Similar results have been found in Ackerman et al. 2017.

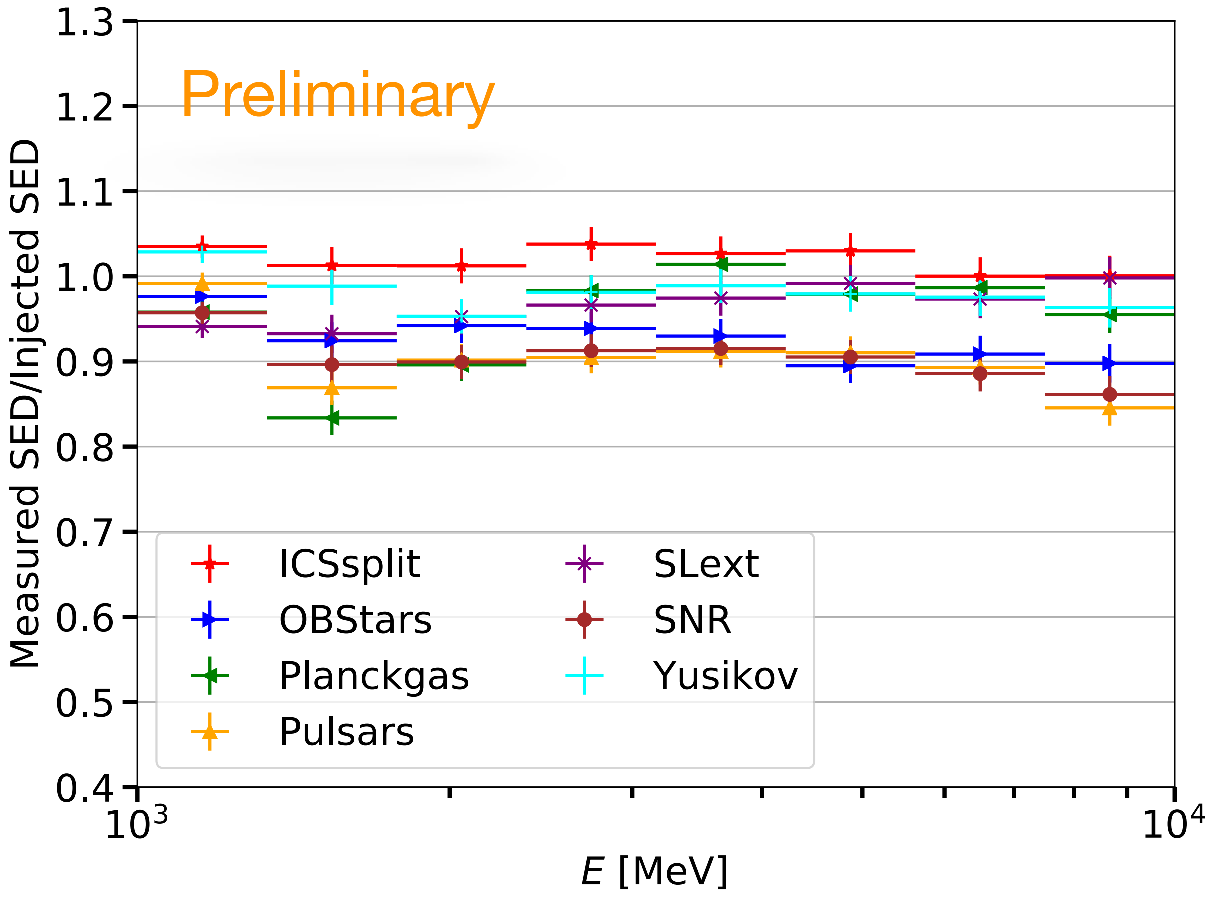


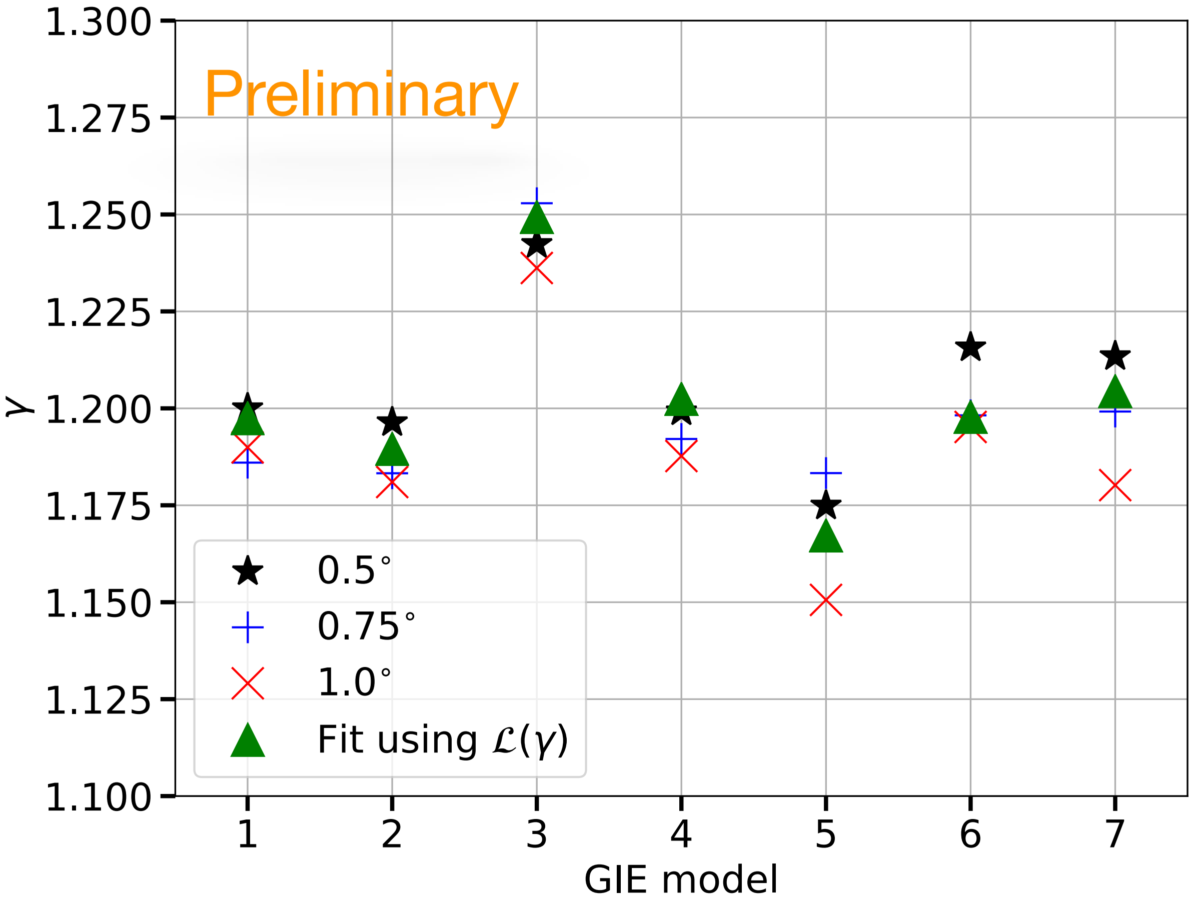


script_residplot_models_PAPER.py

A wrong GIE: energy spectrum and spatial morphology

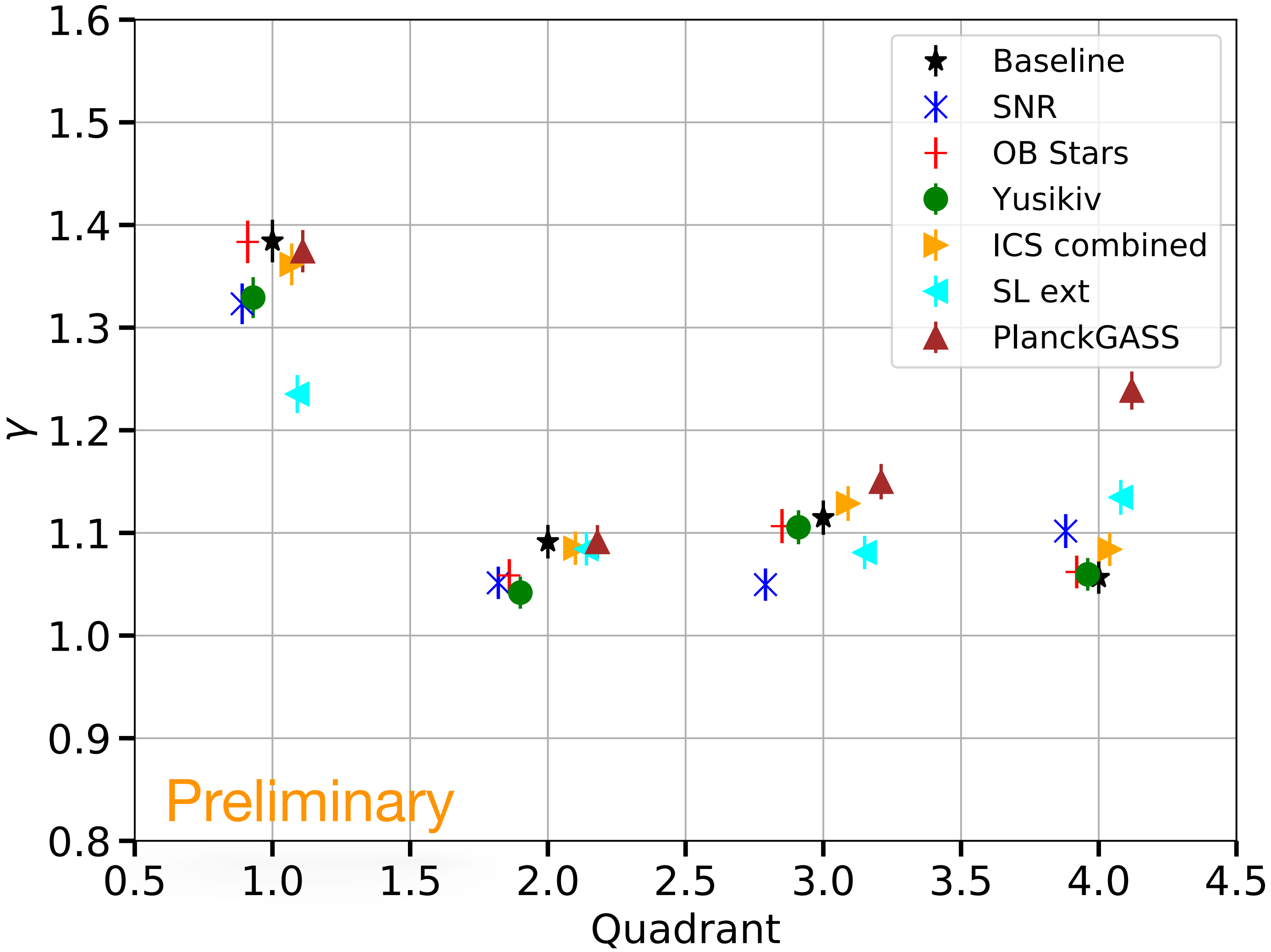
- We simulate the data with the Reference model and we analyze the simulations using the others GIE.
- The systematics in the energy spectrum is of the order of **10-15%**.
- In the spatial distribution and in the value of gamma is of the order of **5%**.





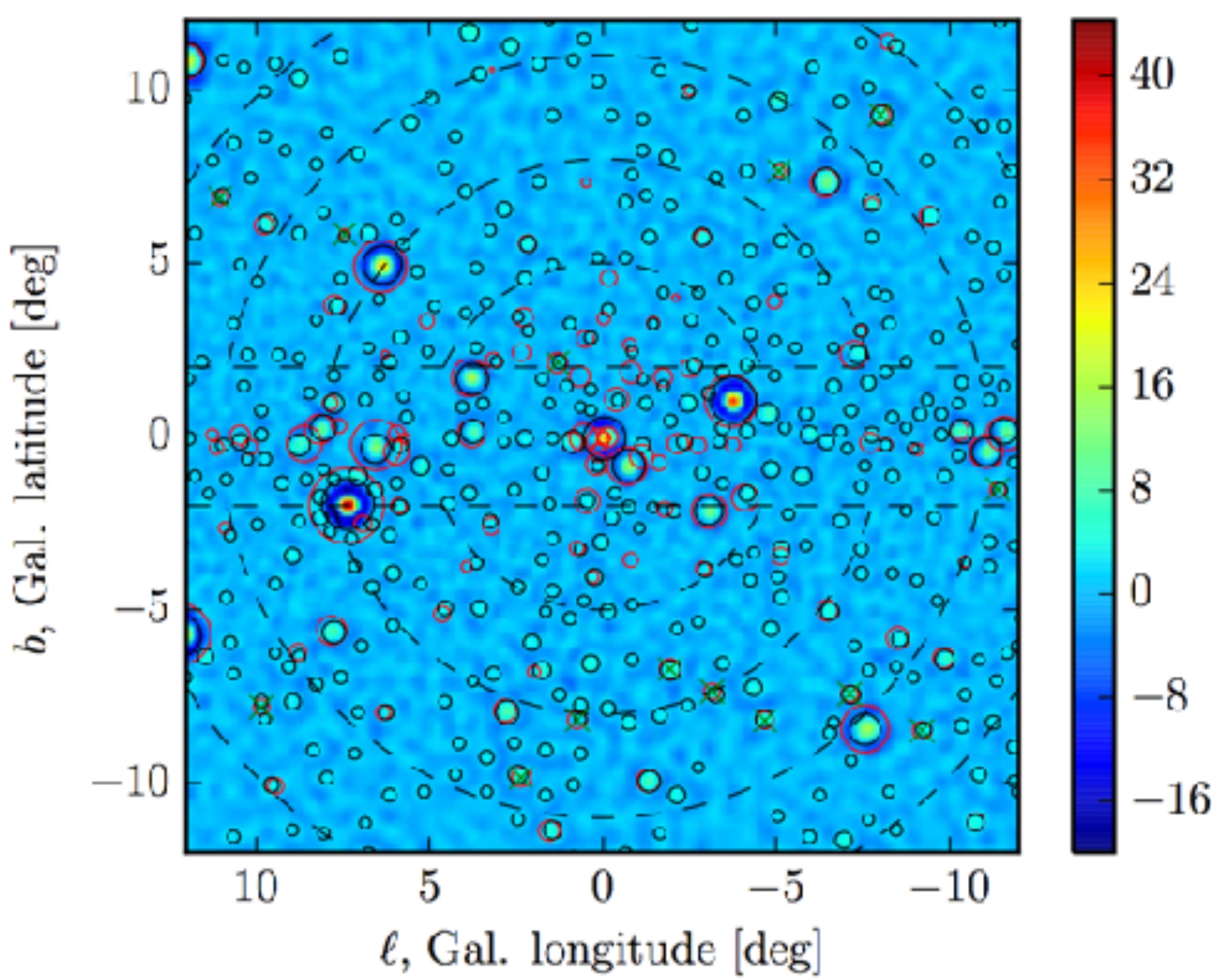
Analysis in quadrants: spatial morphology

- It is important also to test the spatial distribution of each quadrant.
- In order to do that I create quadrants of the different annuli (1.0deg size) and fit the ROI.
- Then I calculate the surface brightness of each portion of the annuli and derive the surface brightness of each quadrant.
- The first quadrant has a slightly larger gamma but the difference is not dramatic.

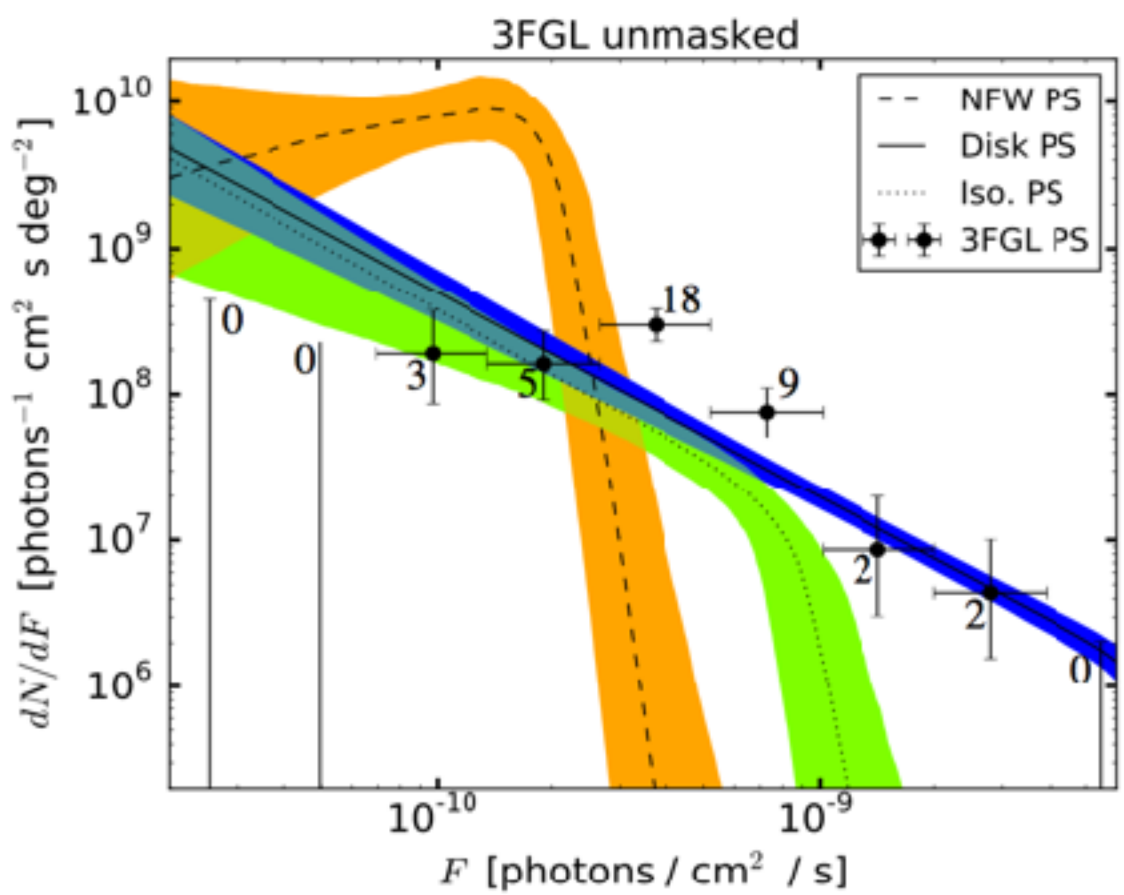


Pulsar interpretation

- **Bartels et al. (2015) and Lee et al. (2015):** population of unresolved sources distributed in the Galactic bulge of our Galaxy → Pulsars.
- The spatial distribution, total γ-ray emission and energy spectrum of this unresolved emission of pulsars is compatible with the GeV excess.
- A fraction of these faint sources should be detected with future Fermi-LAT catalogs (Bartels et al. 2015 and Hooper et al. 2014).



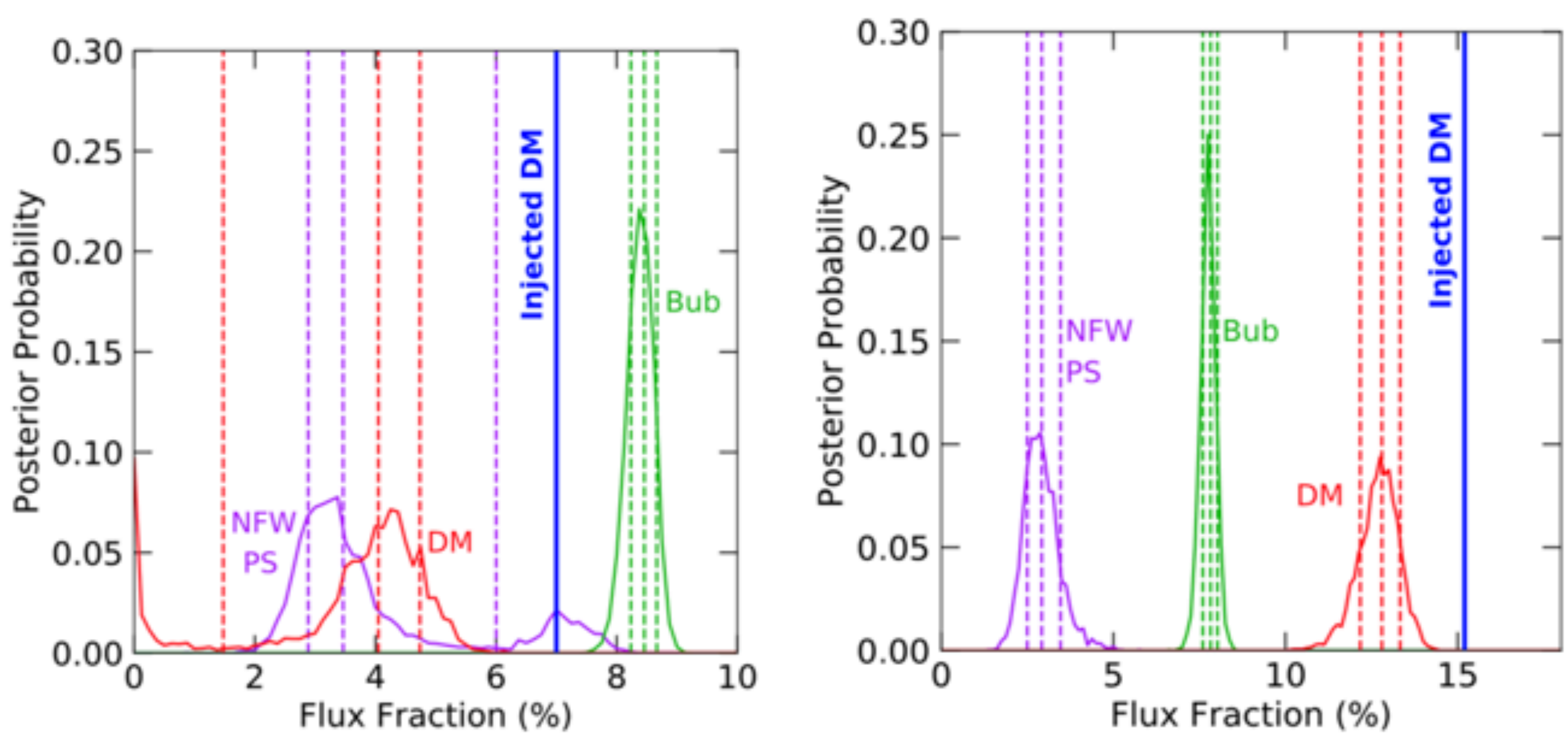
Bartels et al. 2015



Lee et al. 2015

Recent developments

- Recents papers casted doubts on the pulsar interpretations.
  - *Leane et al. 2019 and Chang et al. 2019* have shown that the non-Poissonian template fitting method can misattribute to point sources or DM un-modeled point sources or imperfection in the modeling of Fermi- LAT data (mainly associated to wrong IE).
  - *Zhong et al. 2019* have applied a wavelet method to the Galactic center region, using the 4FGL, and do not find any compelling evidence for the existence of a faint population of un-modeled sources which can be attributed to the GCE.



Zhong et al. 2019