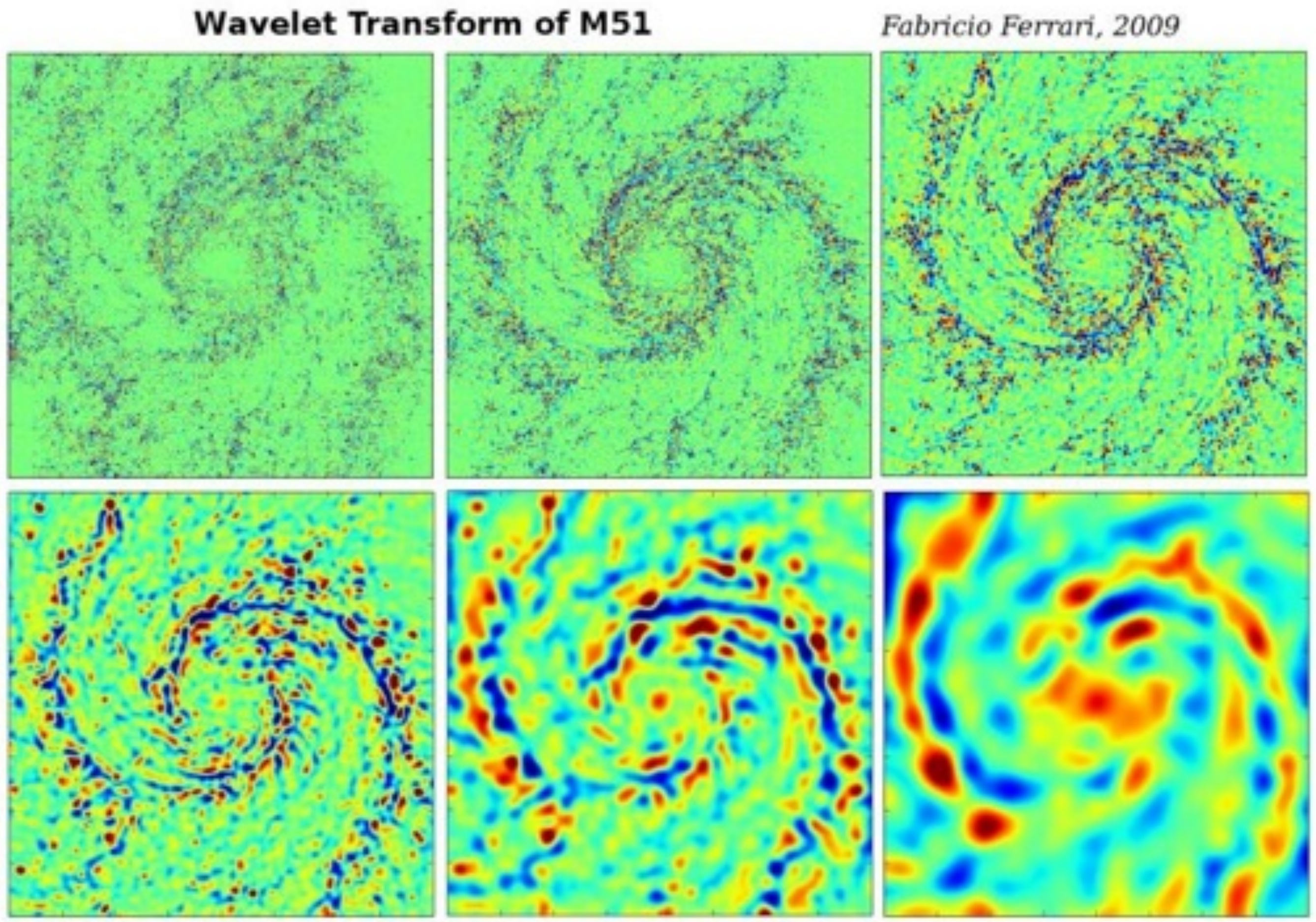
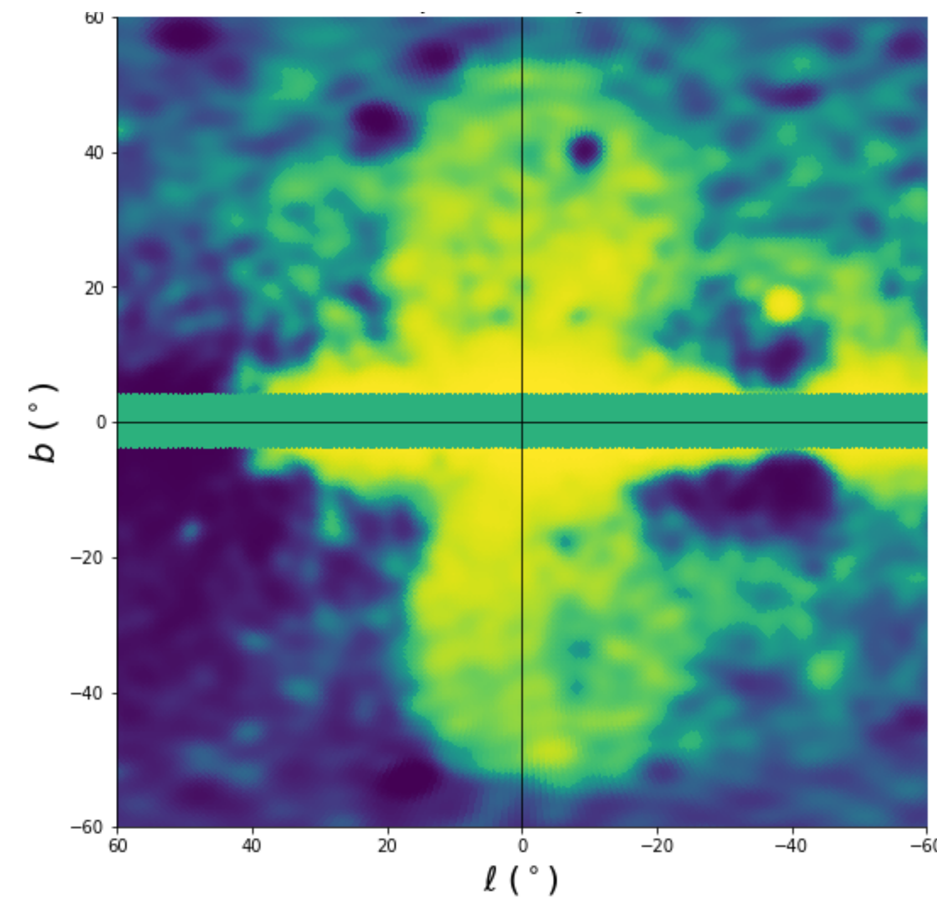
JOHNS HOPKINS UNIVERSITY

Wavelet analysis of the Inner Galaxy





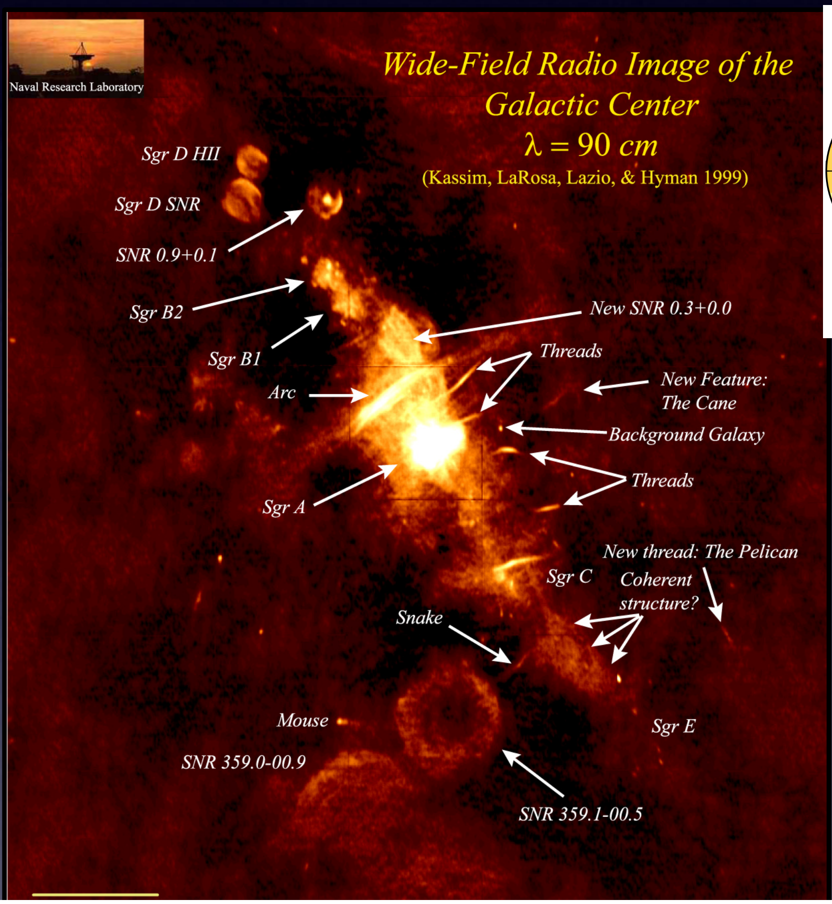
Sam McDermott, Paddy Fox, I.C, Samuel Lee JCAP 1607 (2016), (arXiv:1512.00012)
Bhaskar Balaji, I.C.,Sam McDermott, Paddy Fox ,arXiv: 171x.xxxxx

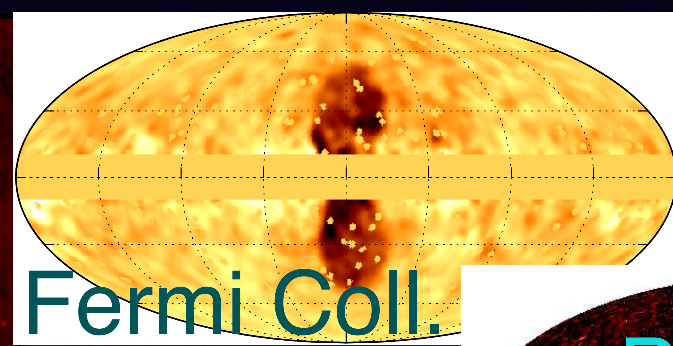
Three elephants in the gamma-ray sky

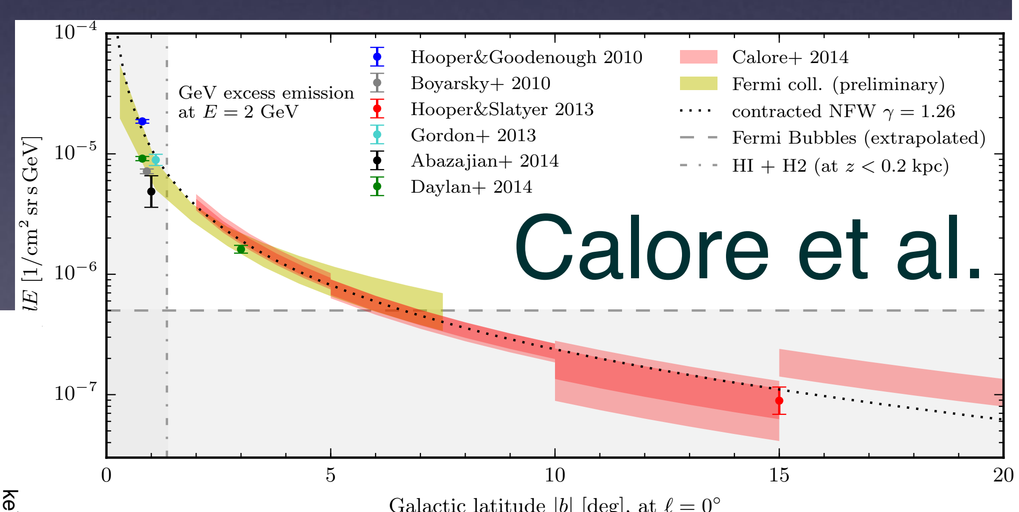
Ilias Cholis 10/23/2017

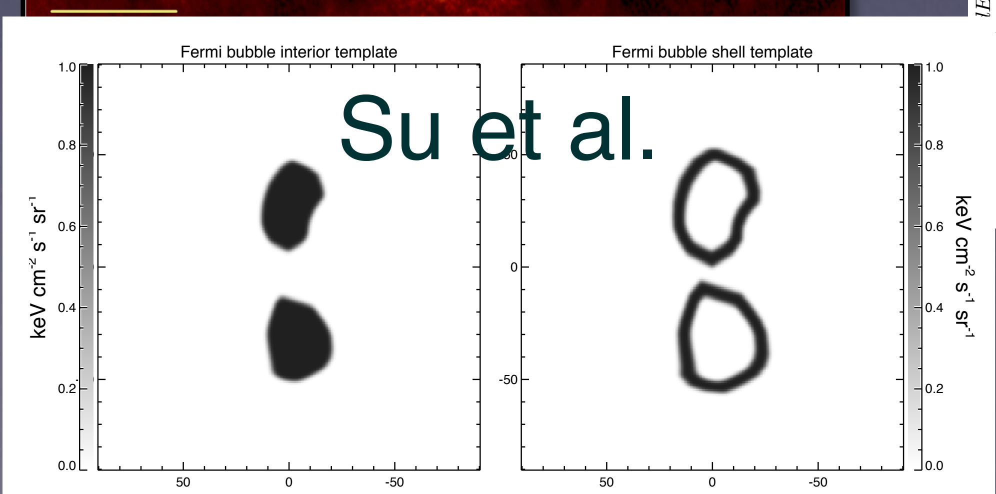
Why are we all here?

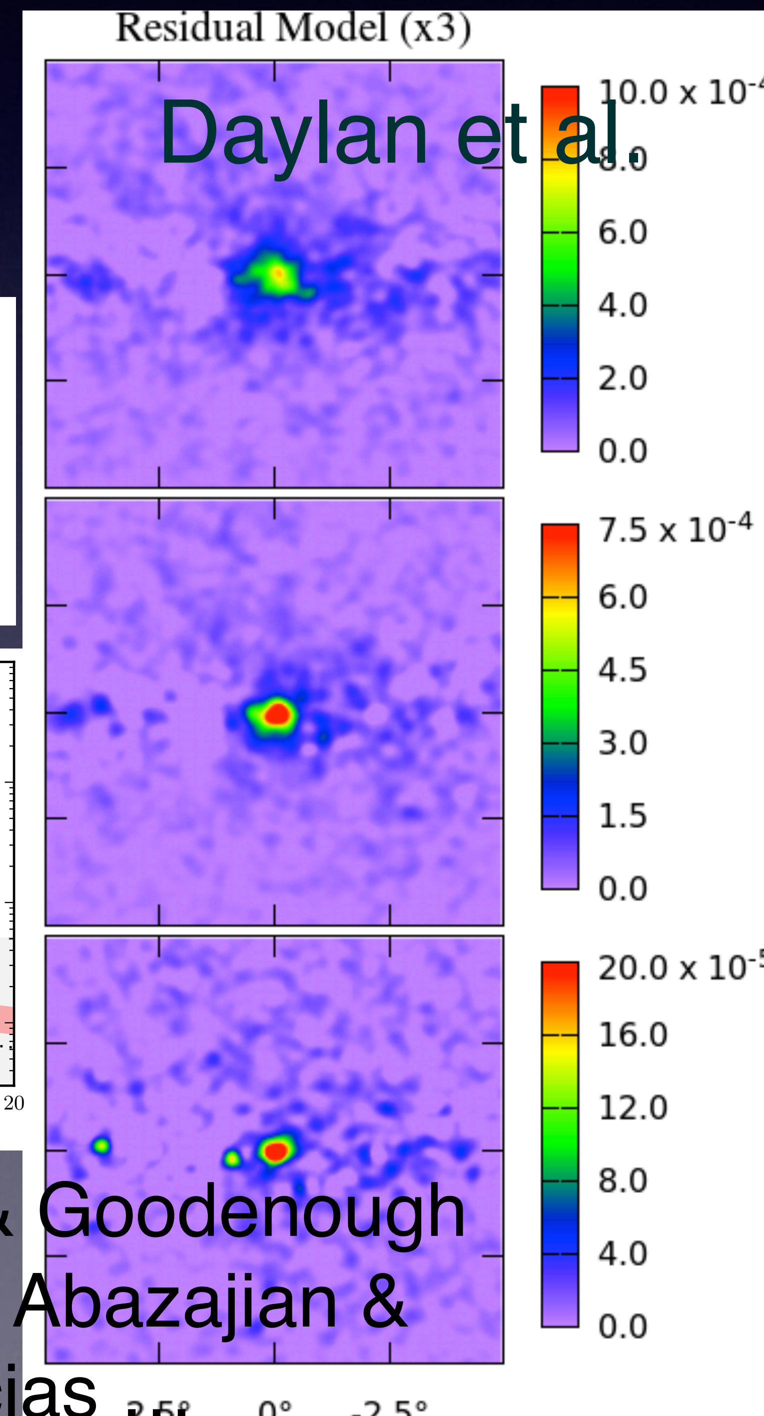
The galactic center and inner galaxy is a very interesting region. Interesting CR activity. Burst? Point Sources.
A possible signal of Dark Matter Annihilation?







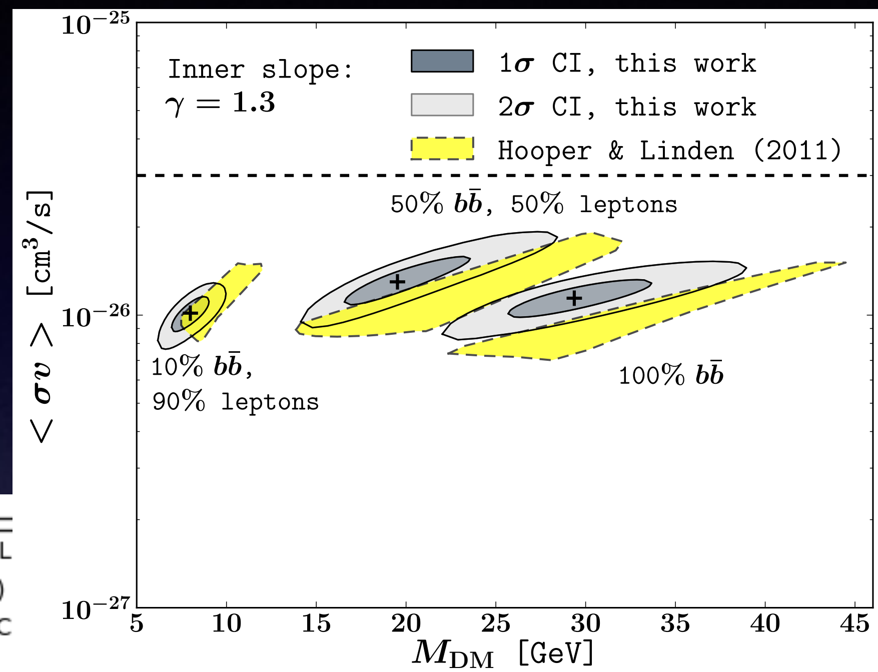




Also works from Hooper & Goodenough 2009-10, Hooper Linden, Abazajian & Kaplinghat, Gordon & Macias

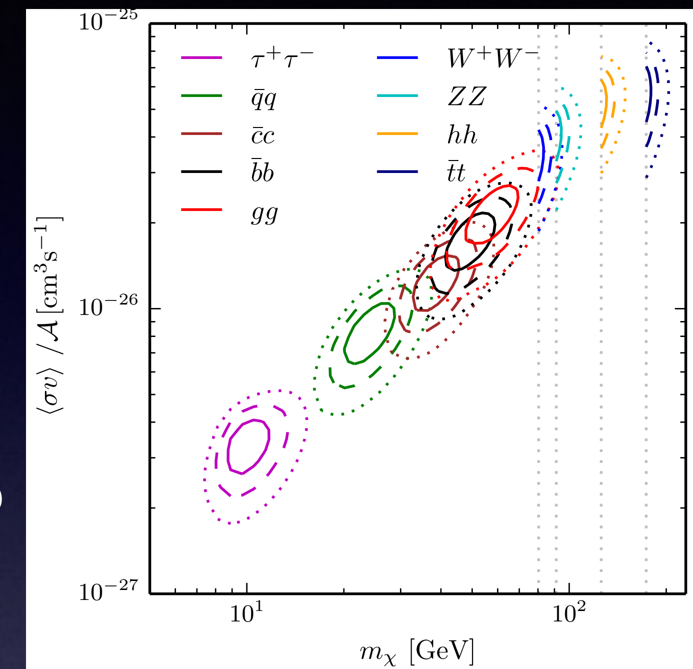
What are the explanations?

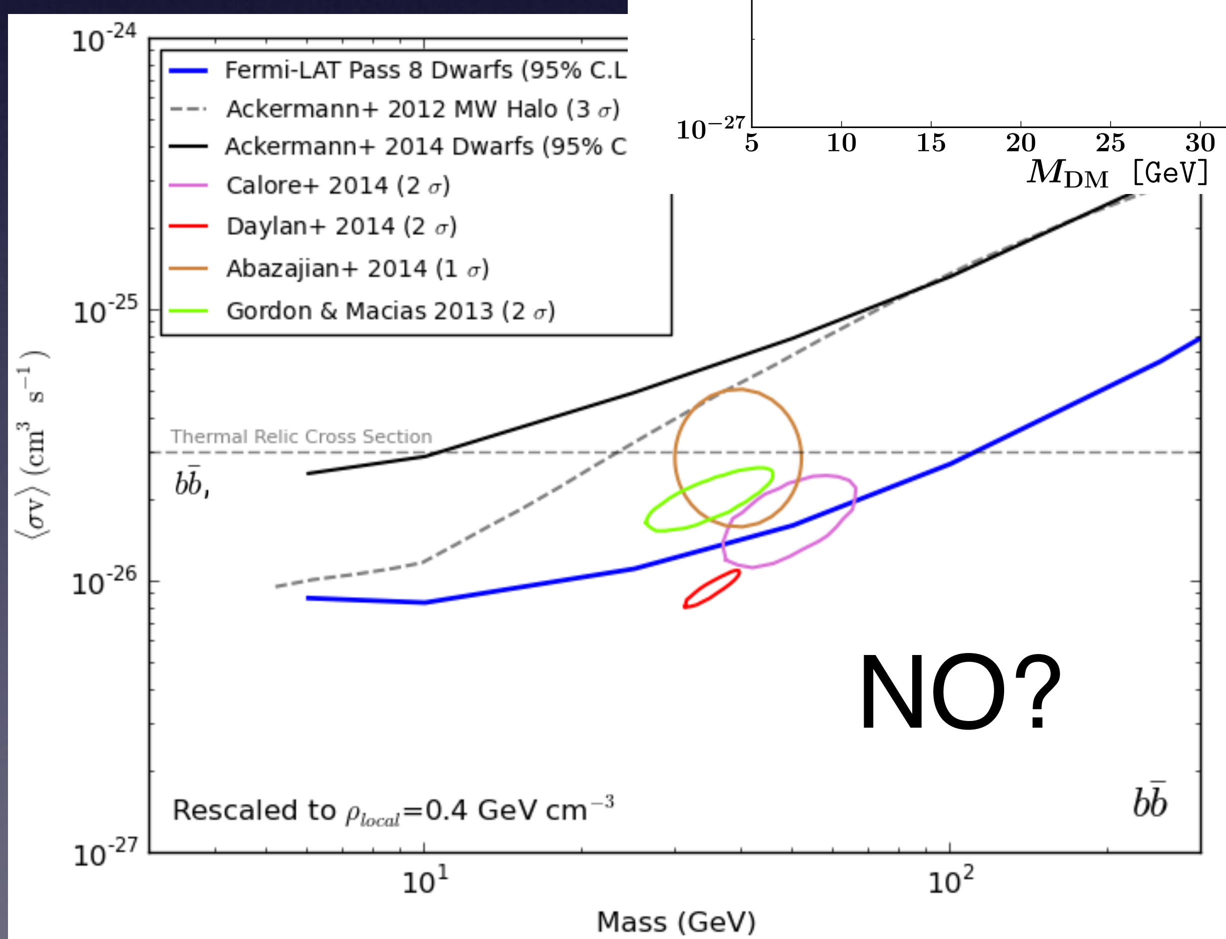
I will focus on the GCE but similar # of suggestions for the FBs.



DM

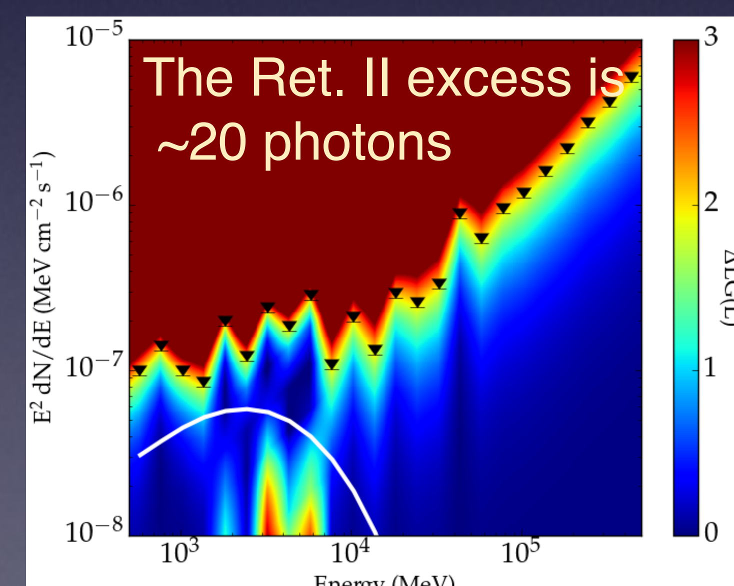
YES?





NO?

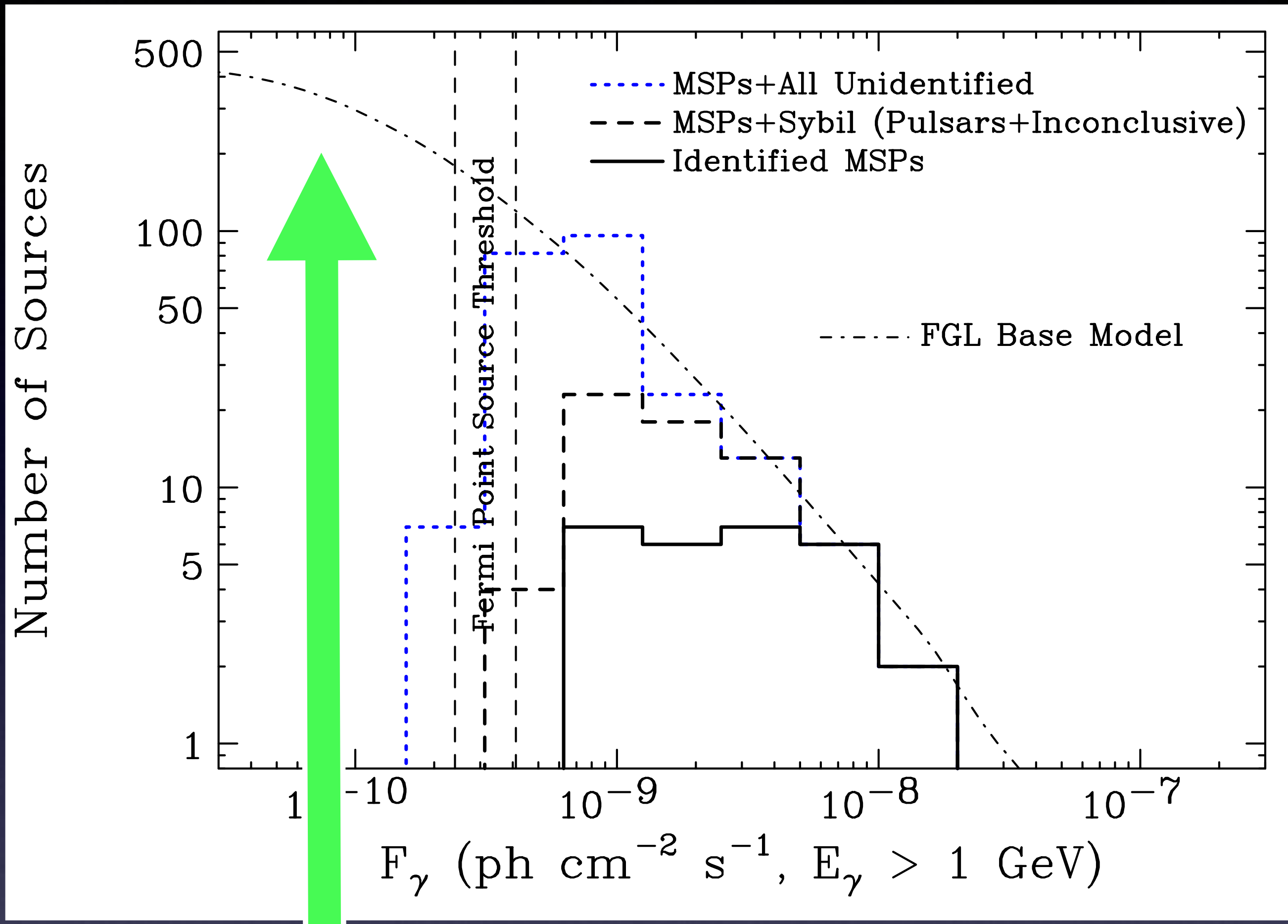
YES?



Alternative work related to the Galactic Center the GeV excess and it's interpretations

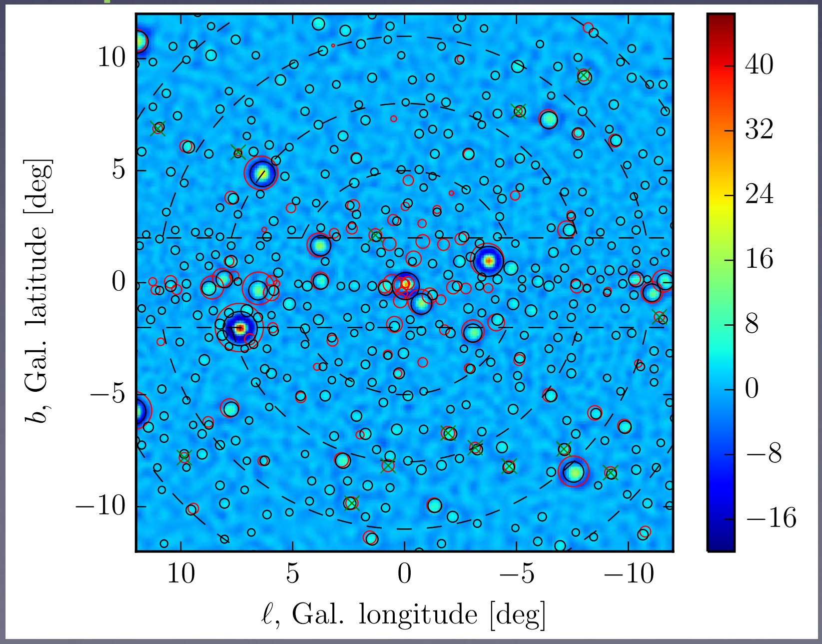
Millisecond Pulsars:

Hooper, IC, Linden, Siegal-Gaskins & Slatyer PRD 2013 (1305.0830), (<10% of total)
Calore, Di Mauro, Donato ApJ 2014 (1406.2706) (<10%)
IC, Hooper, Linden JCAP 2015 (1407.5625) NOT REALLY ABOVE 5deg
Calore, Di Mauro, Donato, Hessels, Weniger (1512.06825) MAYBE YES
Brandt, Cocsis ApJ 2015 YES BUT SPECIAL MSPs
O'Leary, Kistler, Kerr, Dexter 2016 PROBABLY



As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

Sensitivity analyses on point-sources and astrophysics modeling:



Bartels, Krishnamurthi, Weniger PRL 2016
Lee, Lisanti, Safdi, Slatyer, Xue PRL 2016
Huang, Ensslin, Selig JPCS 2016.

Bursts of Cosmic Rays:

Carlson and Profumo PRD 2014 (PROTONS MAYBE?)

Petrovic, Serpico, Zaharijias JCAP 2014 (ELECTRONS ?)

IC, Evoli, Calore, Linden, Weniger, Hooper JCAP 2015 (ELECTRONS CAN + FB CONNECTION?)

Radio Limits:

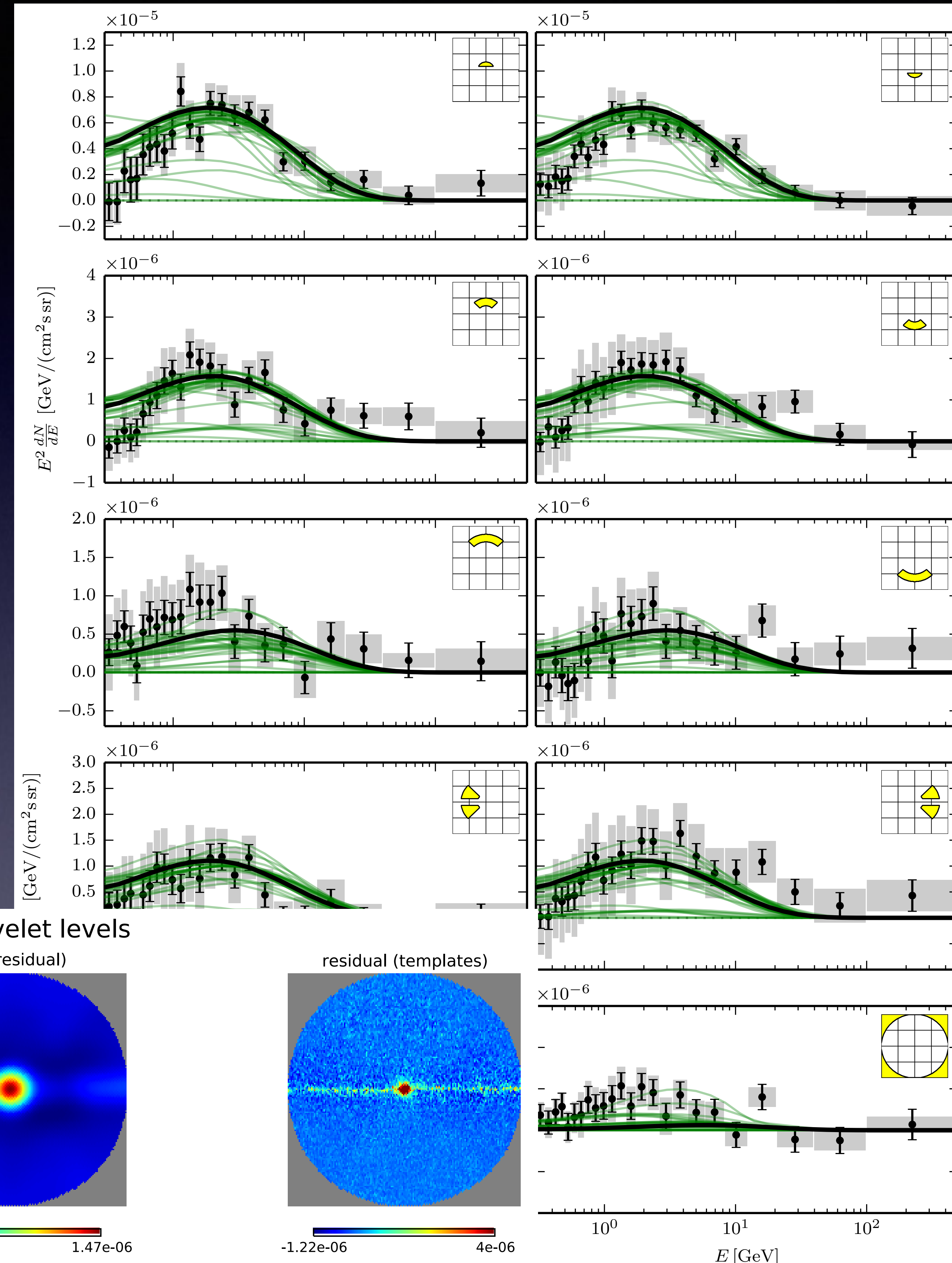
Bringmann, Vollmann, Weniger PRD 2014 (RELEVANT FOR DM)

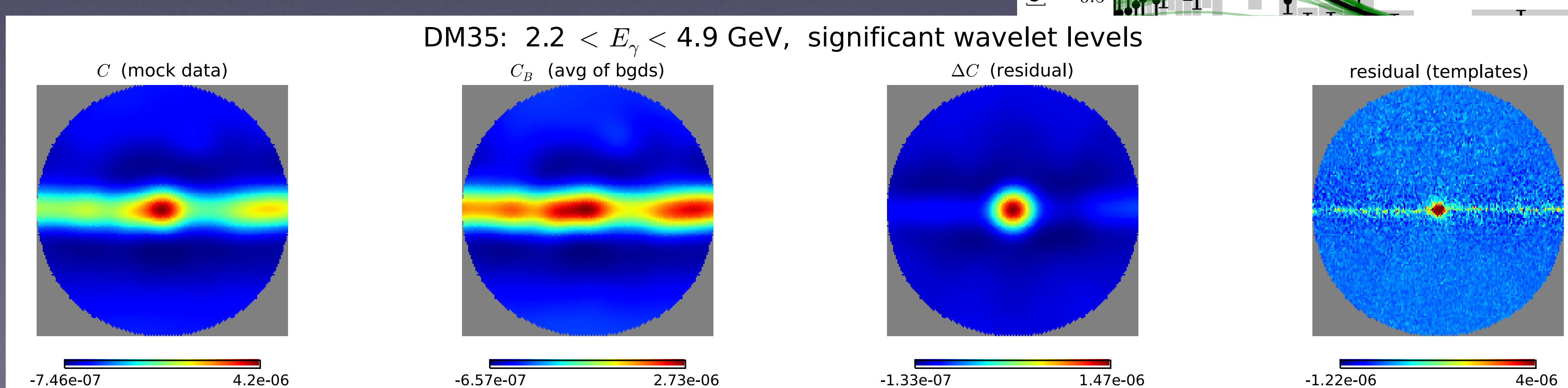
IC, Hooper, Linden PRD 2015 (NOT RELEVANT FOR DM)

Wavelet techniques (TIE BRAKER?):

McDermott, Fox, IC, Lee JCAP 2016

Possible Connection to the Fermi Bubbles

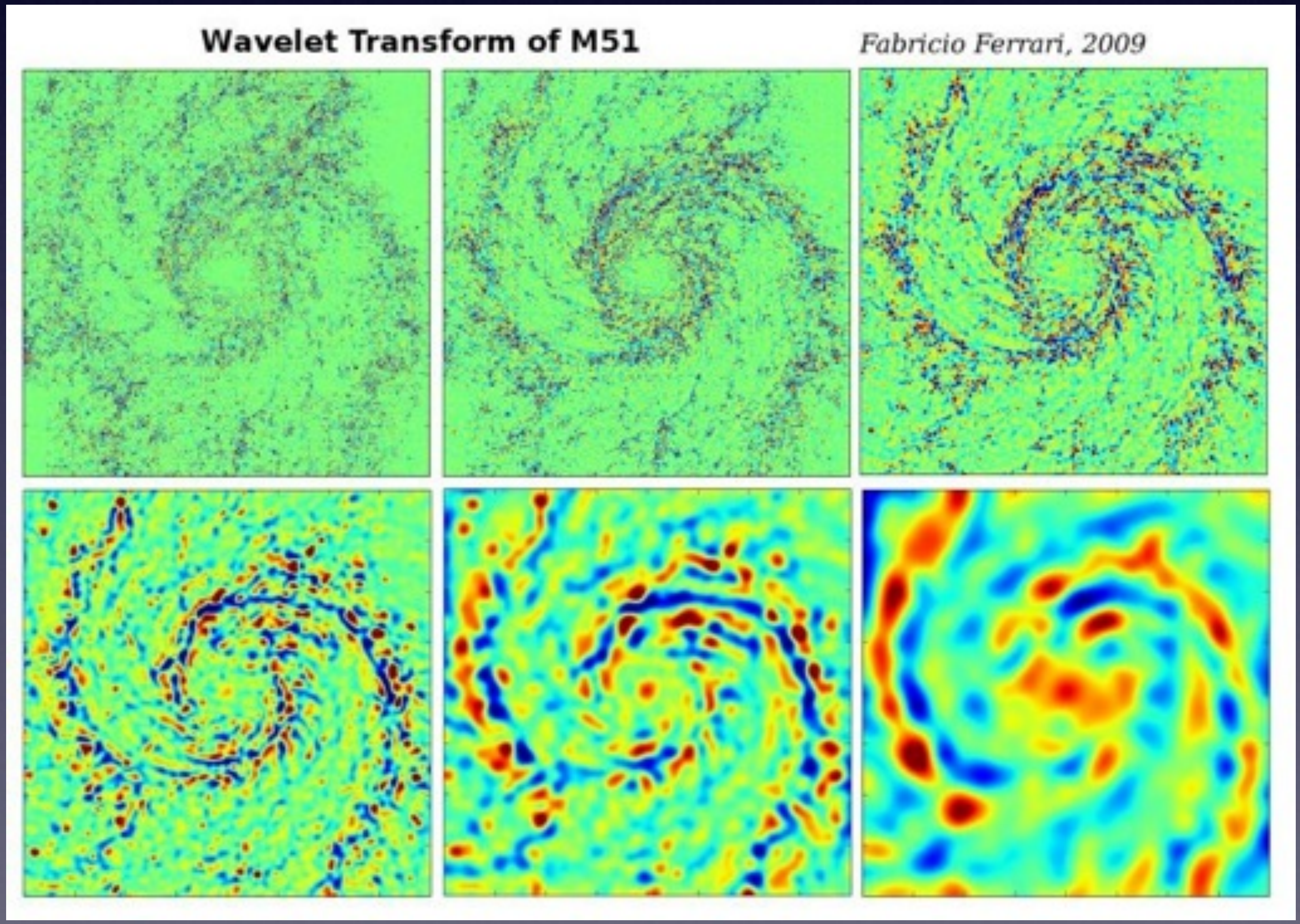




What are wavelets?

Wavelets have been used in image compression (JPEG), de-noising, fast signal identification, even in HEP data

Allow analysis of data in both time/space and frequency space



Different type of structures will have a different power at different levels of the deco-mposition (e.g. edges and other small scale structures vs larger scale variations).

Wavelets can find these different structures.

What are wavelets?

$$W(a,b) = \frac{1}{\sqrt{a}} \int f(x) \psi^* \left(\frac{x-b}{a} \right) dx$$

wavelet coefficients

original signal

scale

position

mother wavelet (different choices)

$$\int \psi(x) dx = 0$$

$$\int |\psi(x)|^2 dx = 1$$

$$\psi(x) \in \mathbb{L}^2(\mathbb{R}) \text{ and}$$

$$\frac{1}{\sqrt{a}} \psi \left(\frac{x-b}{a} \right) \in \mathbb{L}^2(\mathbb{R})$$

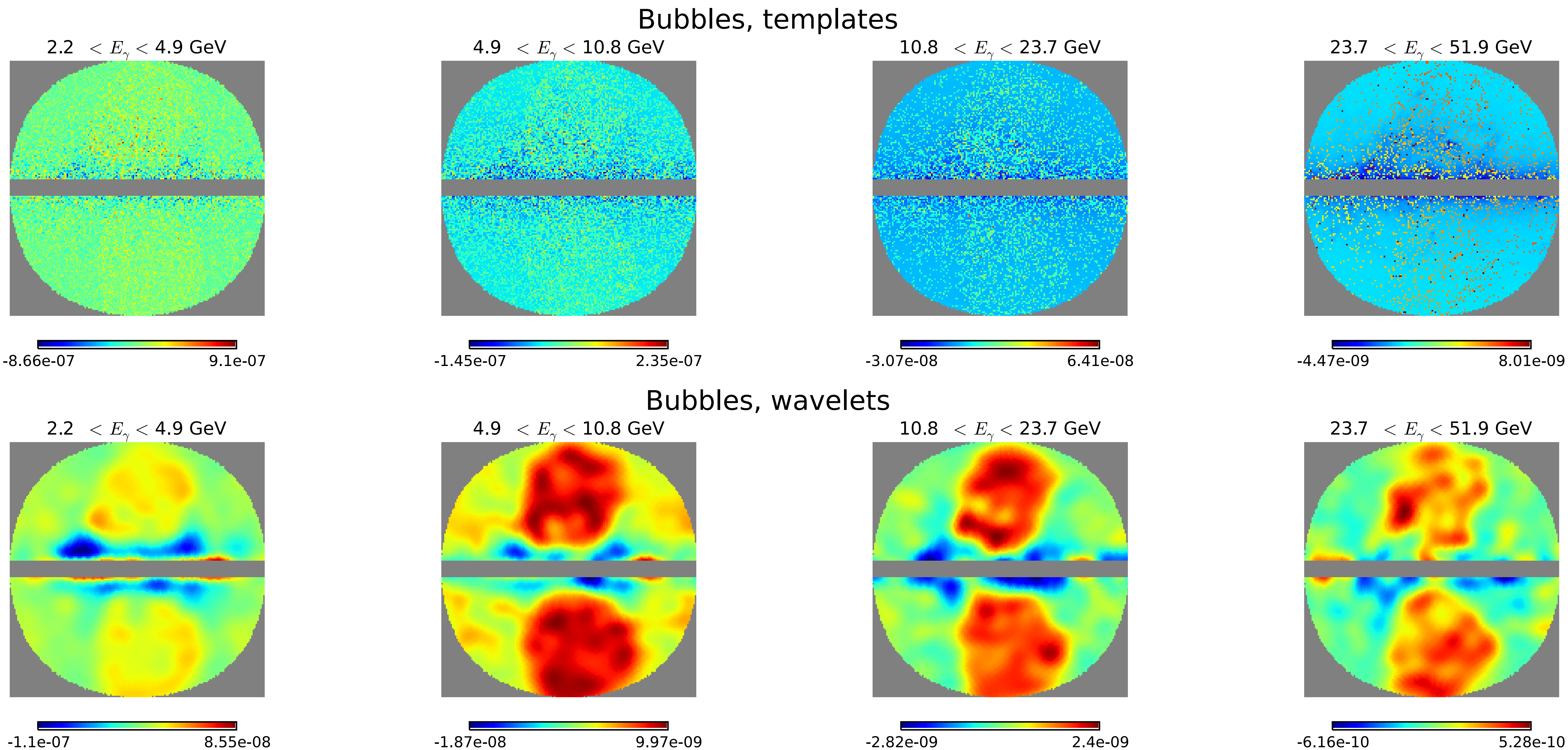
$$\text{for } a, b \in \mathbb{Z}$$

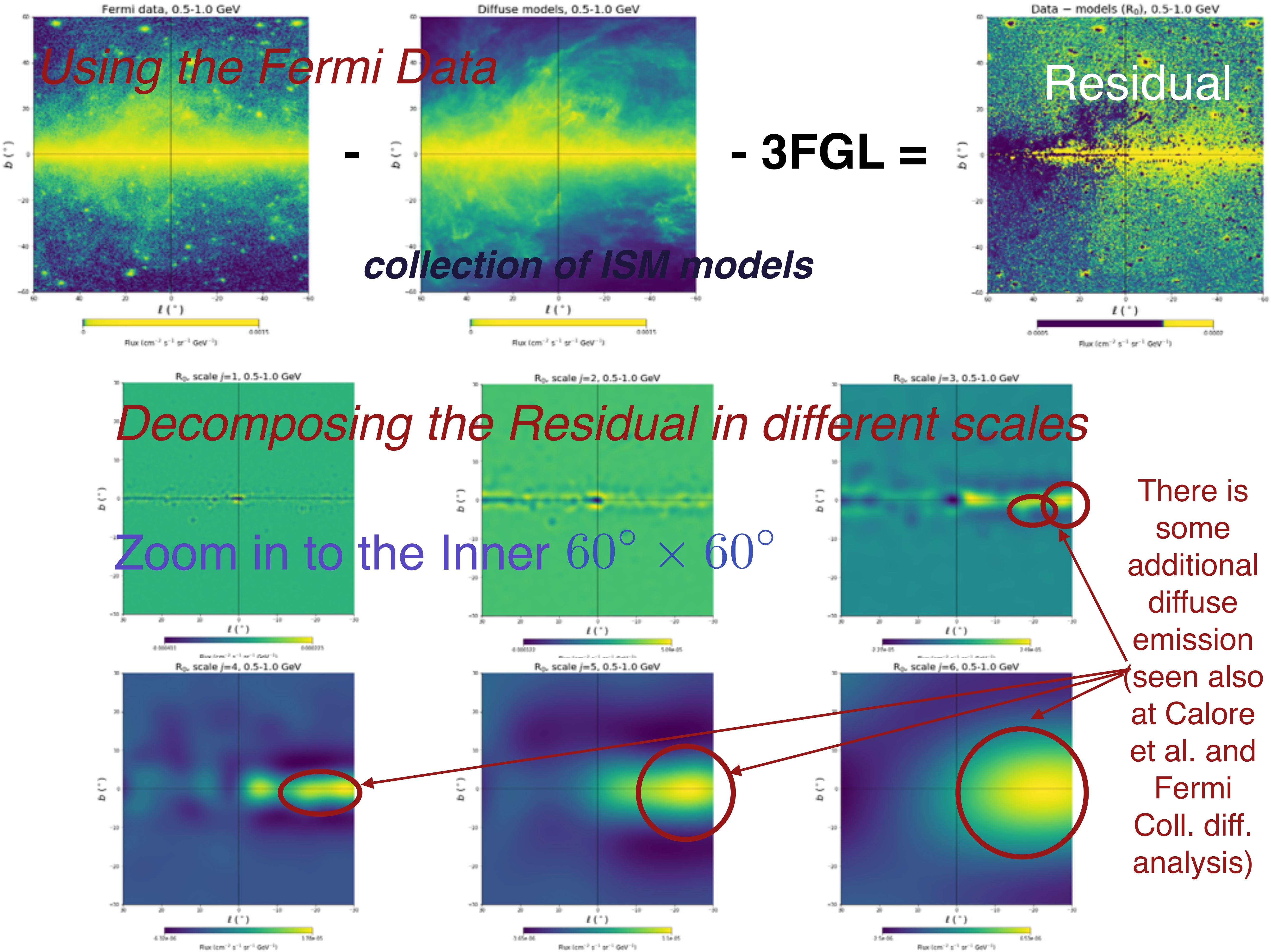
Is it better than the Templates?

Technique was developed in McDermott, Fox, Cholis, Lee JCAP 2016 using simulated data. Requires statistics but has less dependence on fore-ground/background assumptions (in the end it does also have some systematics).

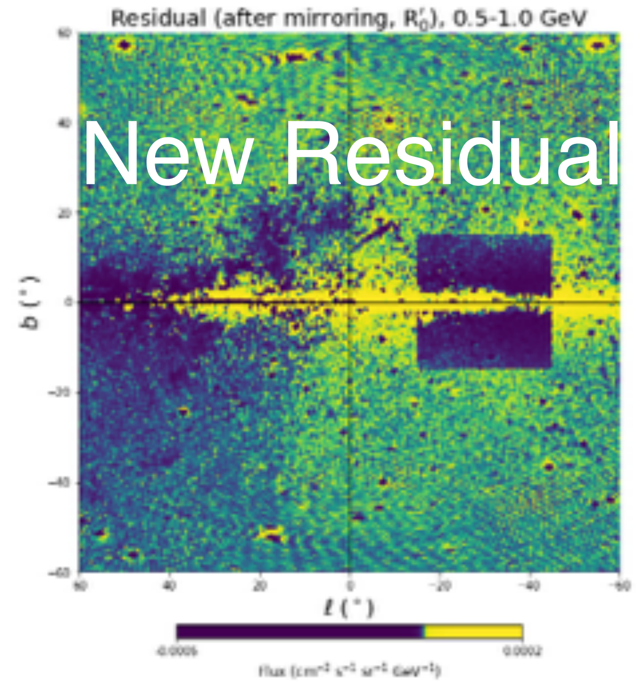
Decompose the sky into 8 scales (smallest 6):

j	w_1	w_2	w_3	w_4	w_5	w_6
θ	$[0.7°, 1.4°]$	$[1.4°, 2.8°]$	$[2.8°, 5.6°]$	$[5.6°, 11.3°]$	$[11.3°, 22.5°]$	$[22.5°, 45°]$

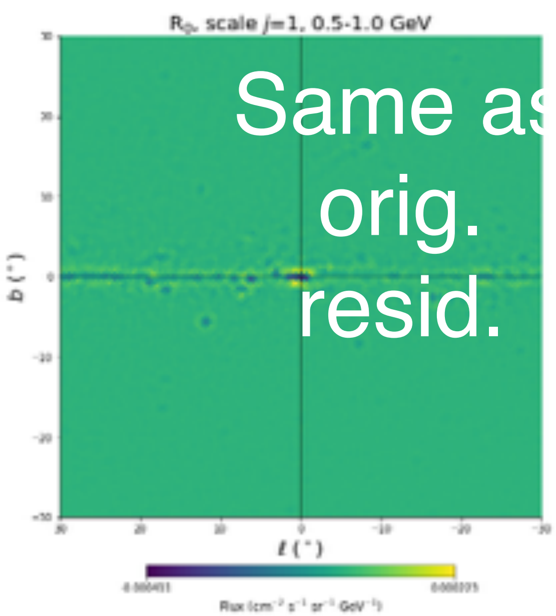


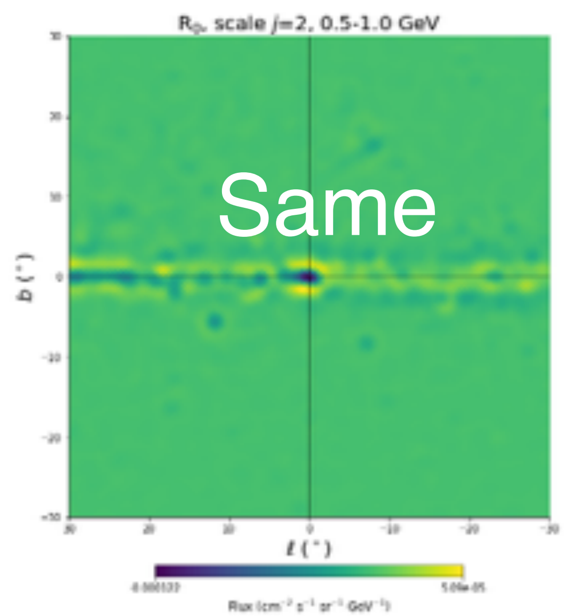

Fermi data, 0.5-1.0 GeV
Using the Fermi Data
-
Diffuse models, 0.5-1.0 GeV
collection of ISM models
- 3FGL =
Data − models (R_0), 0.5-1.0 GeV
Residual
Decomposing the Residual in different scales
R_0, scale j=1, 0.5-1.0 GeV
R_0, scale j=2, 0.5-1.0 GeV
R_0, scale j=3, 0.5-1.0 GeV
Zoom in to the Inner $60° \times 60°$
R_0, scale j=4, 0.5-1.0 GeV
R_0, scale j=5, 0.5-1.0 GeV
R_0, scale j=6, 0.5-1.0 GeV
There is some additional diffuse emission (seen also at Calore et al. and Fermi Coll. diff. analysis)

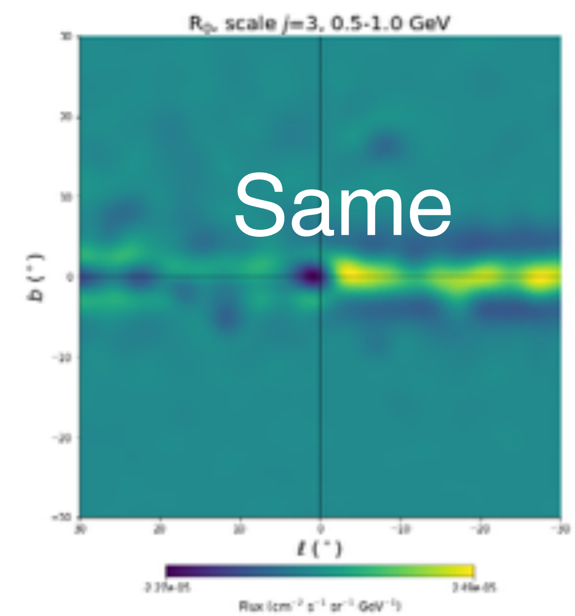
We mirror the wavelet coeff. for scales w4 and above (angles larger than 5 degrees) within a chosen window.



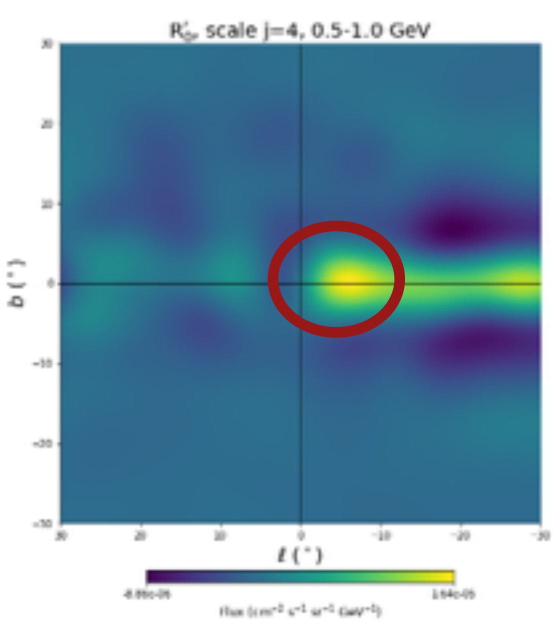
Zoom in to the Inner $60^\circ \times 60^\circ$



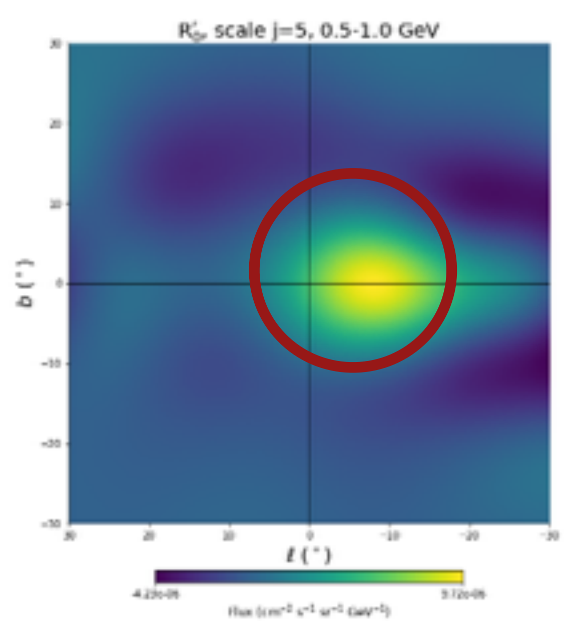




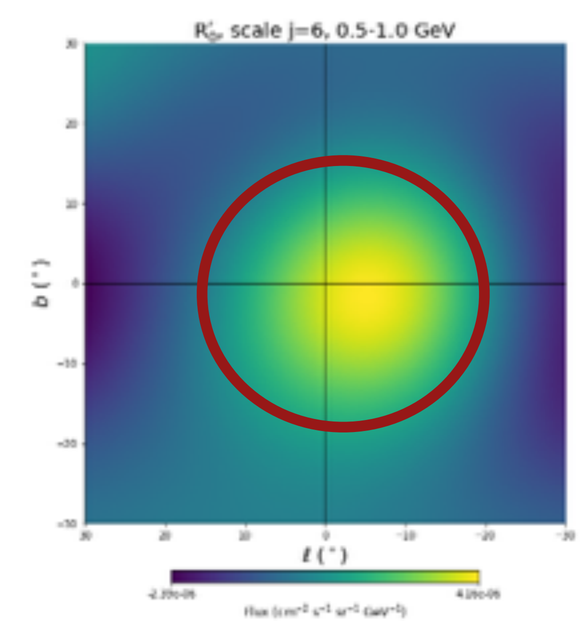
GCE defined for $j \geq 3$



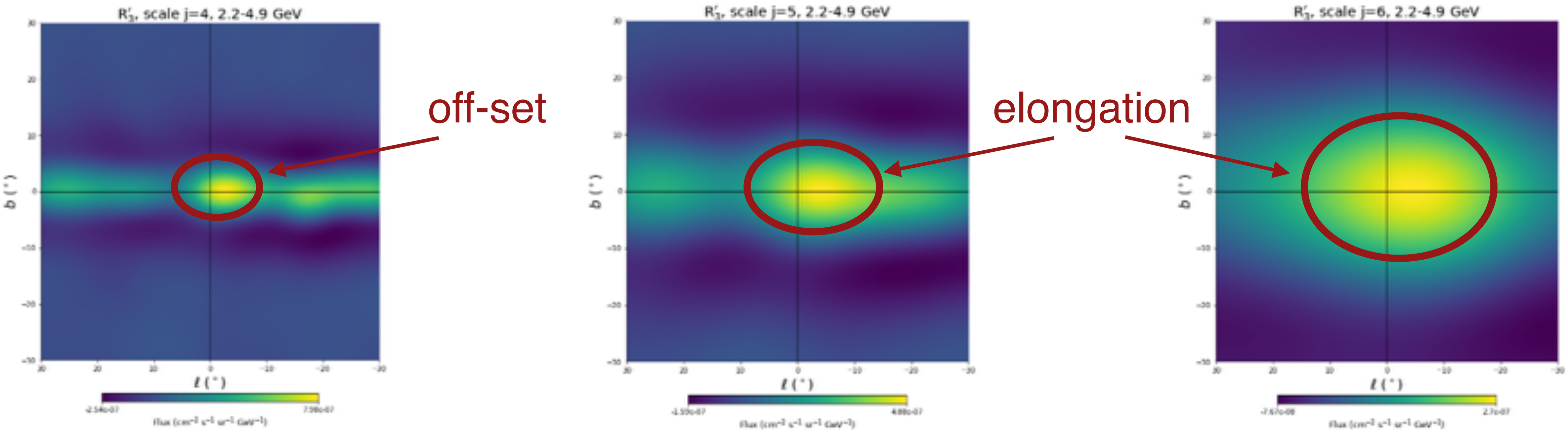
wavelet higher scales GCE?



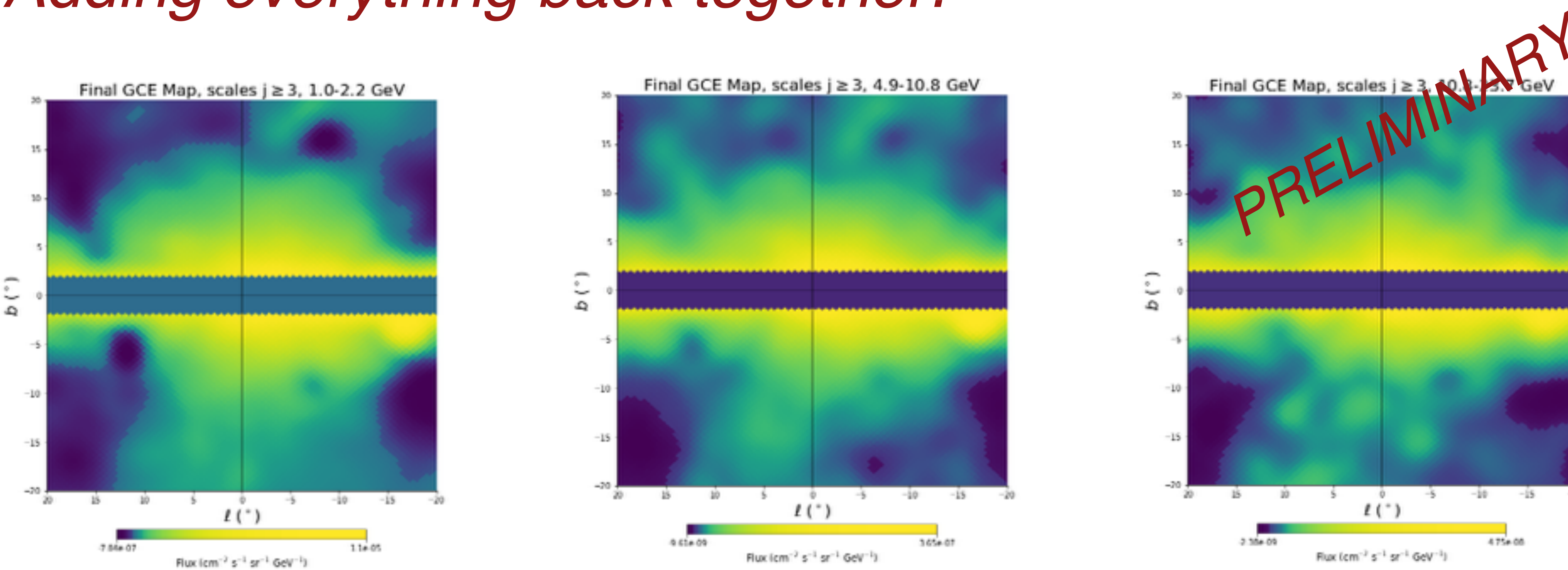
wavelet higher scales GCE?



After iterating in the higher scales

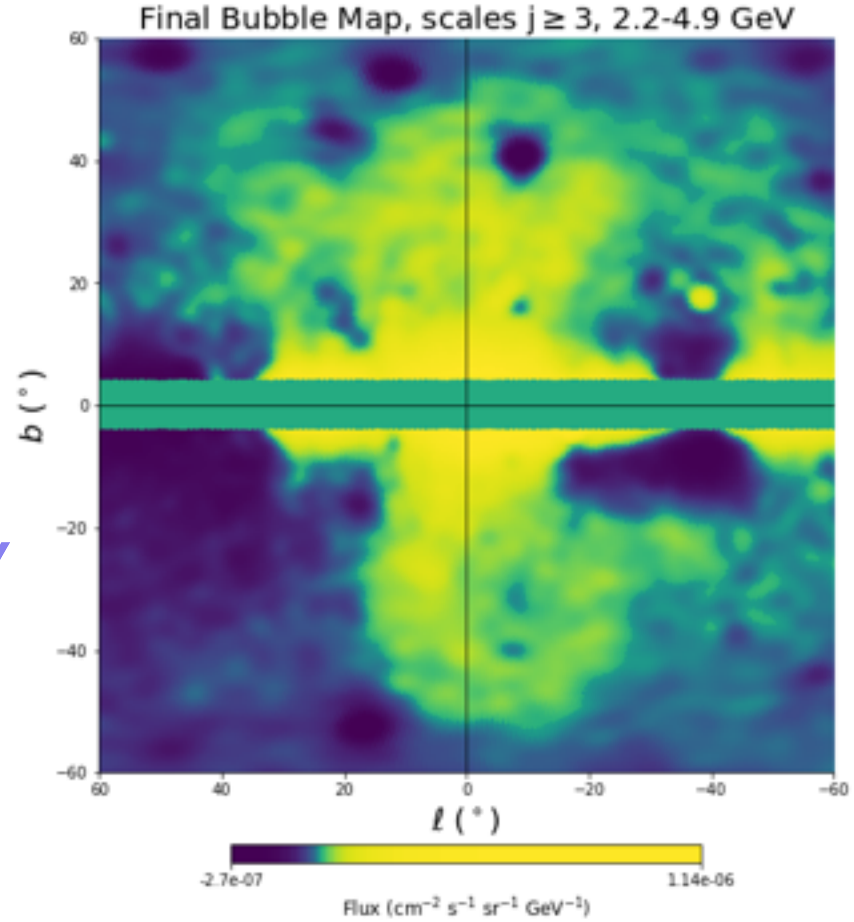


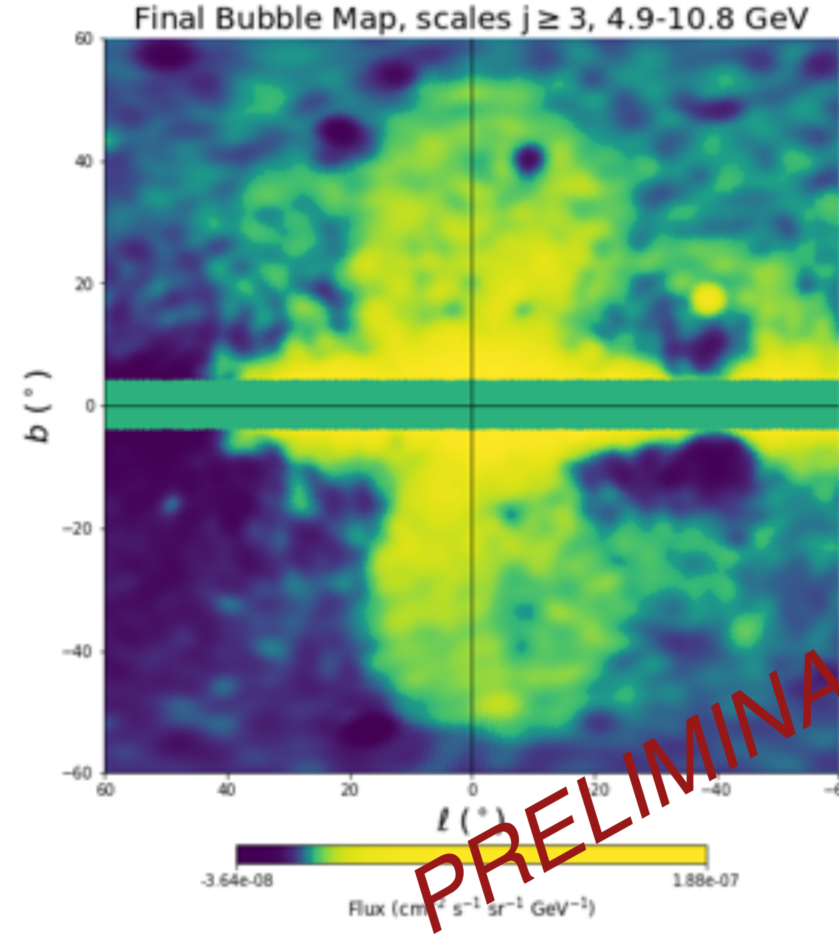
Adding everything back together:



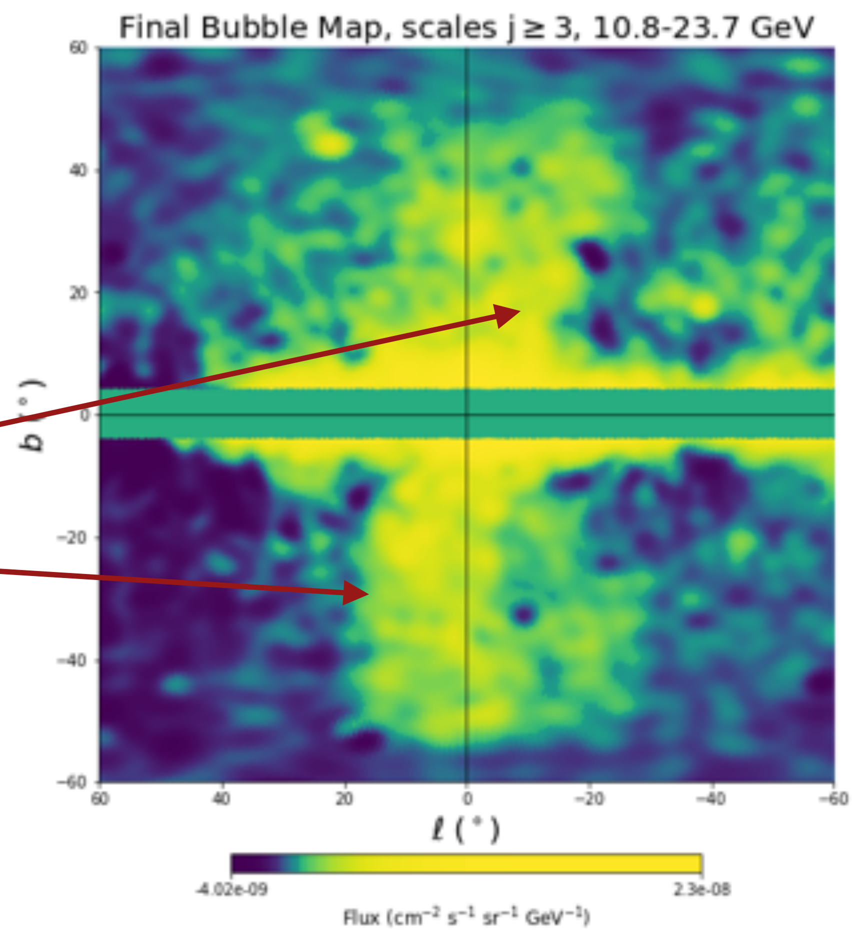
Fermi Bubbles:

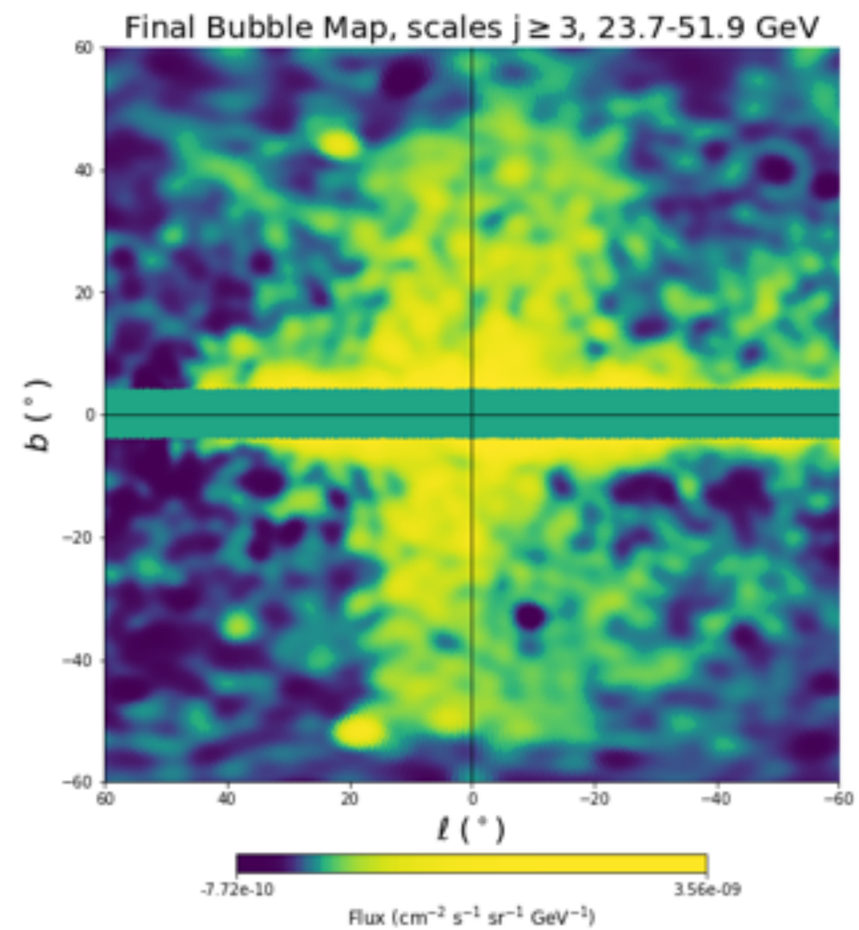
we do not directly disentangle FB from GCE.





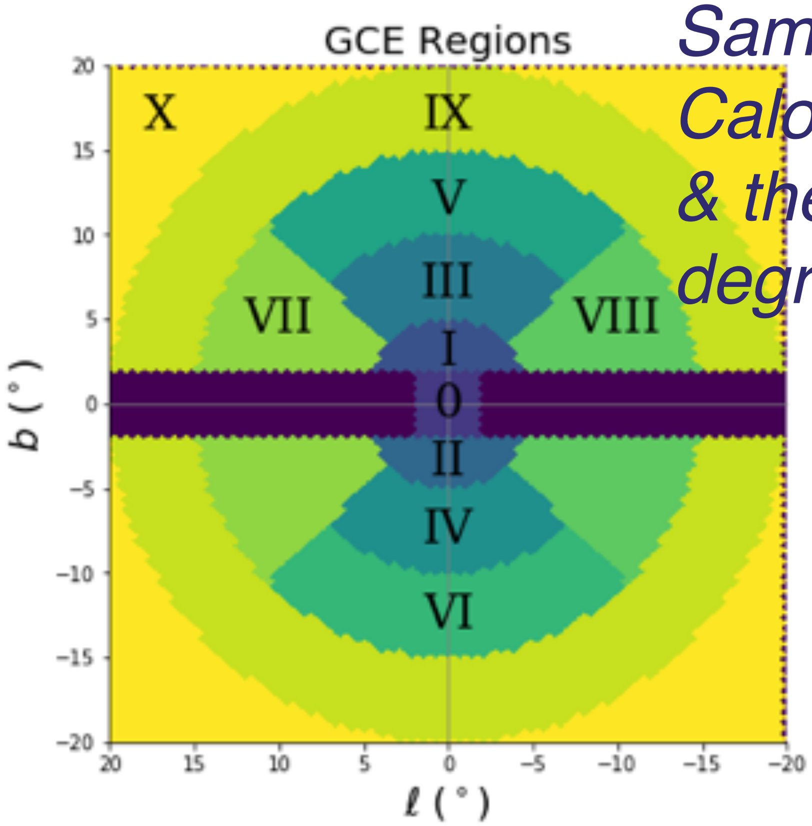
PRELIMINARY



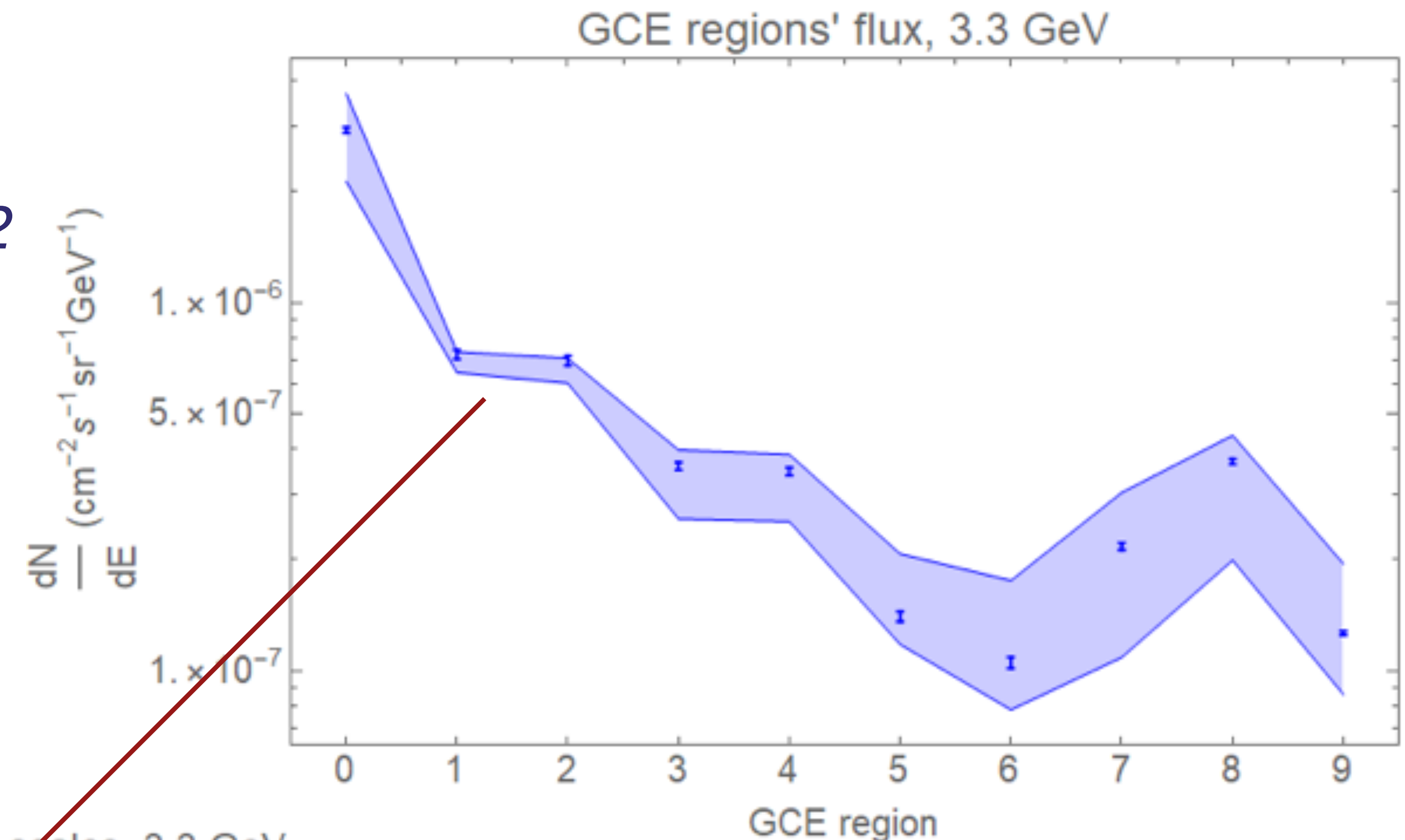


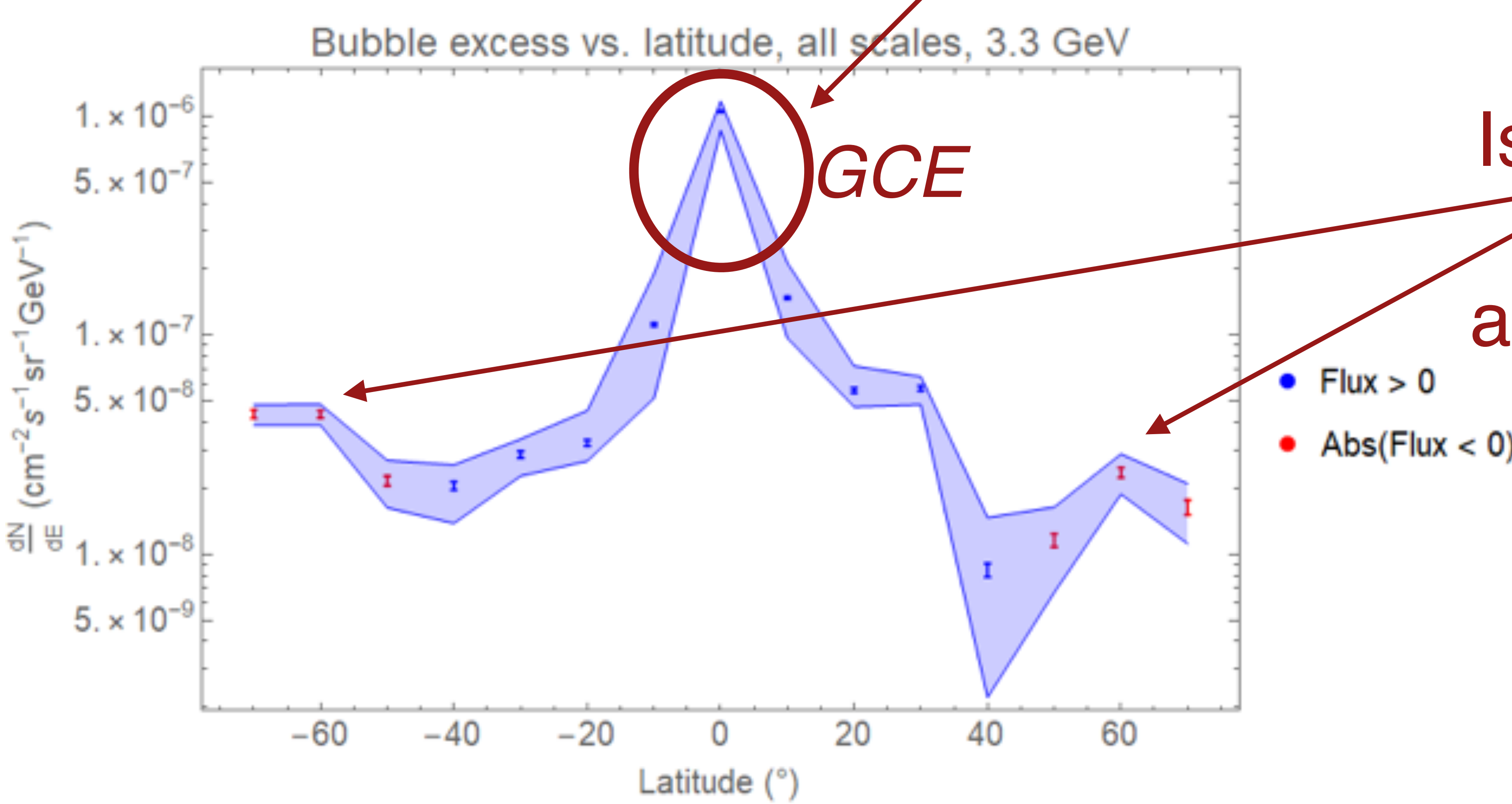
jets?
cocoon?

Profiles



Same as in Calore et al. & the inner 2 degrees

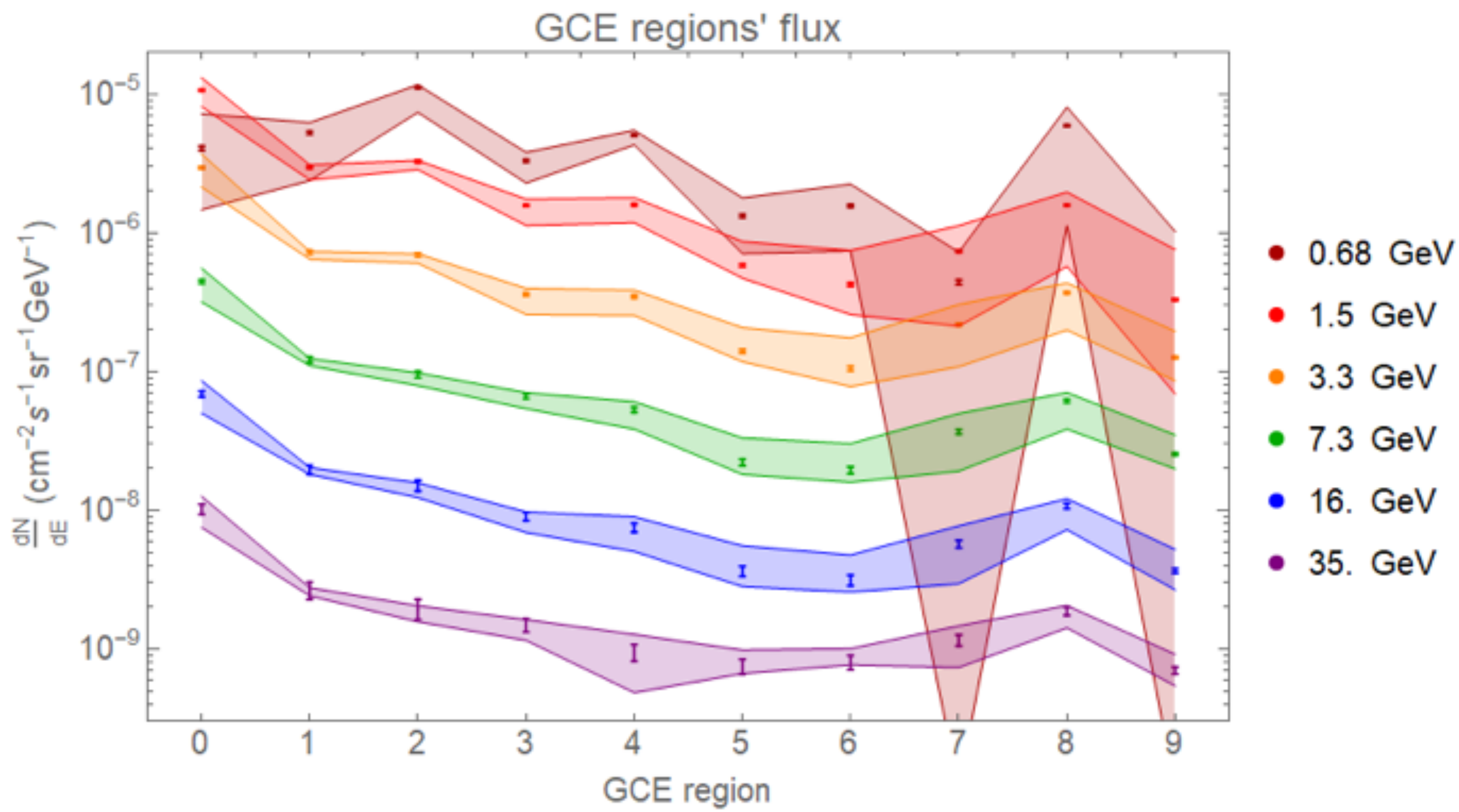




Isotropic Emission is subtracted in our analysis (flux outside of bubbles <0)

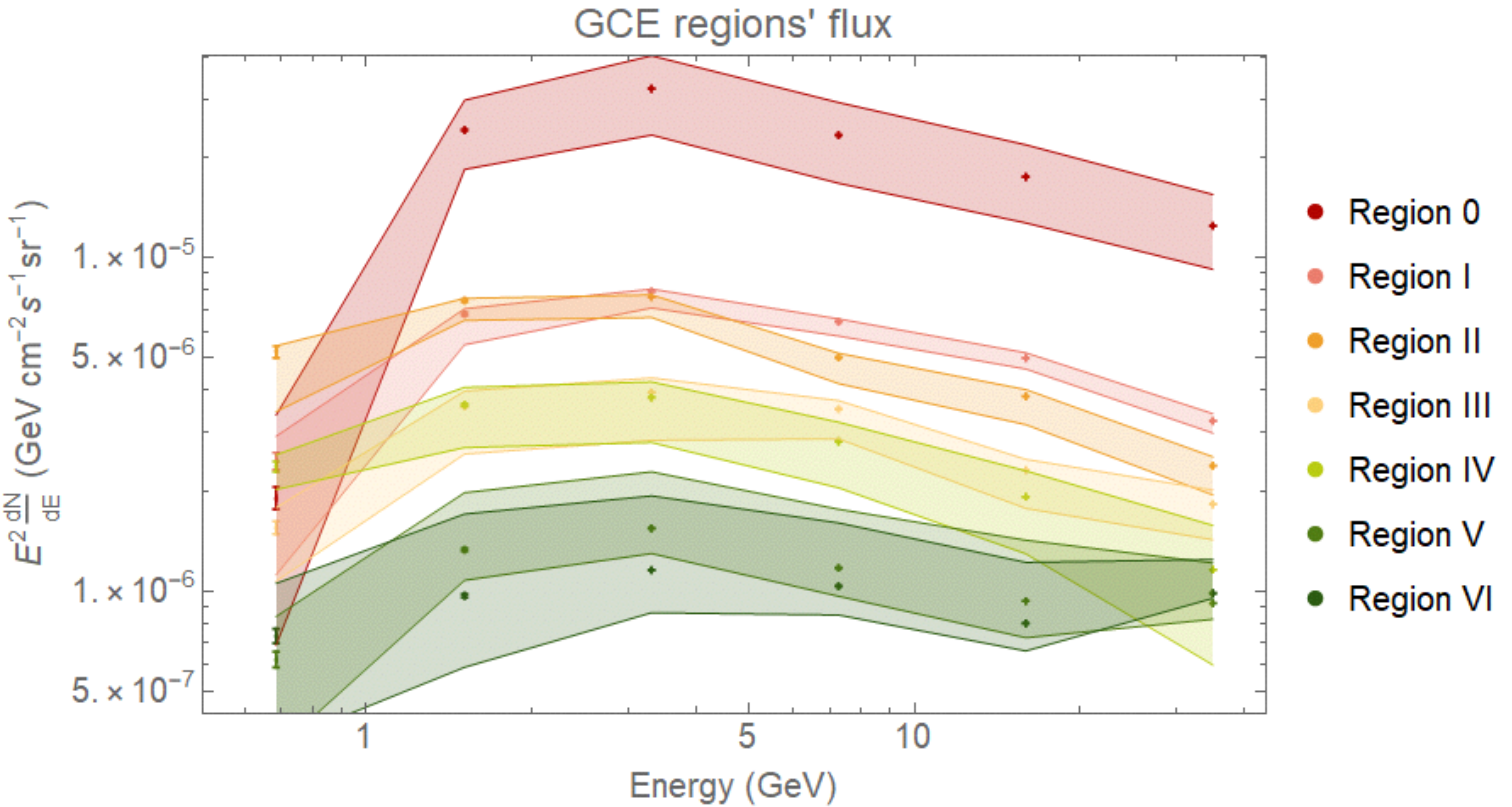
Additional Energies/Profiles

GCE:

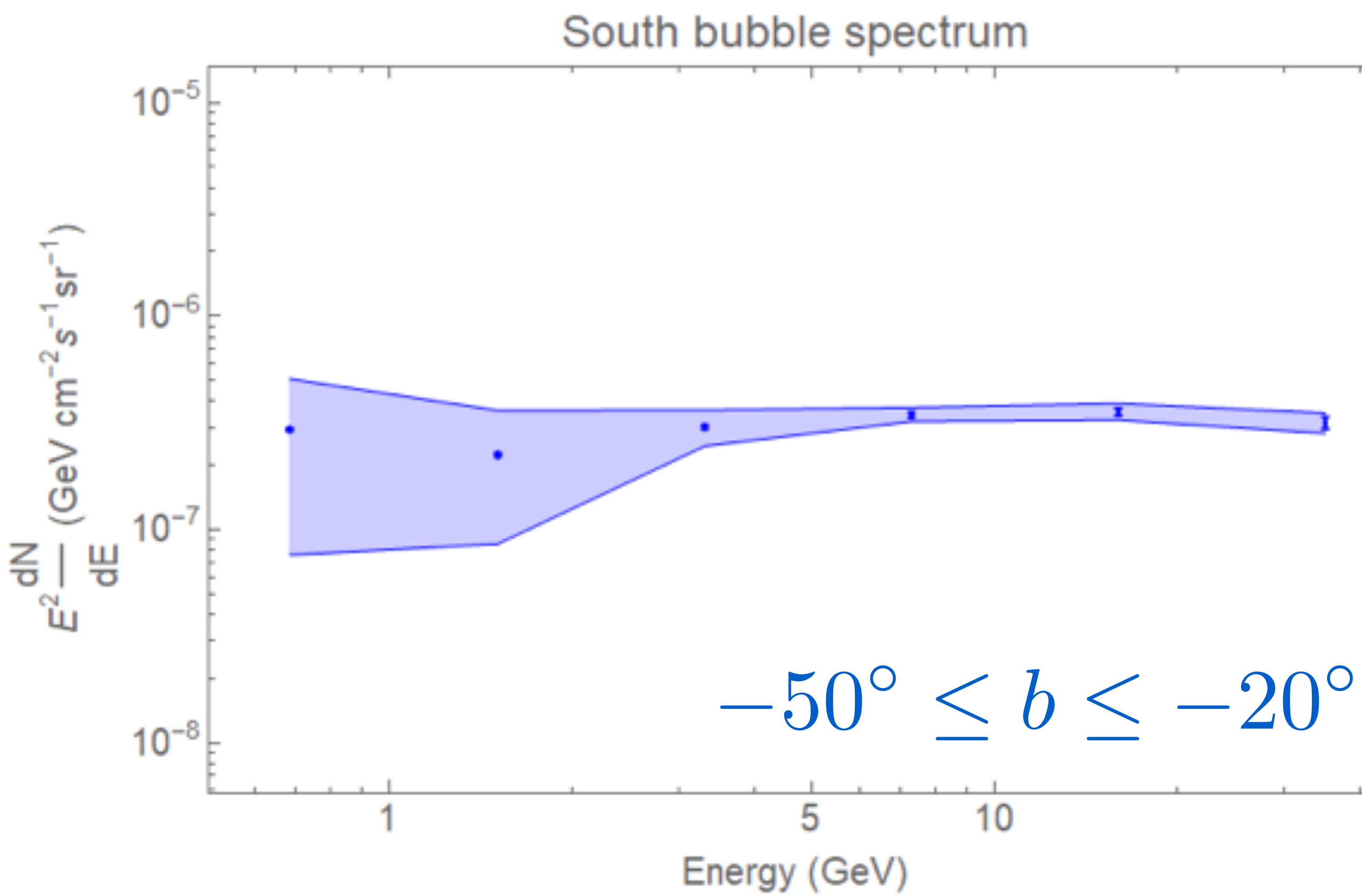


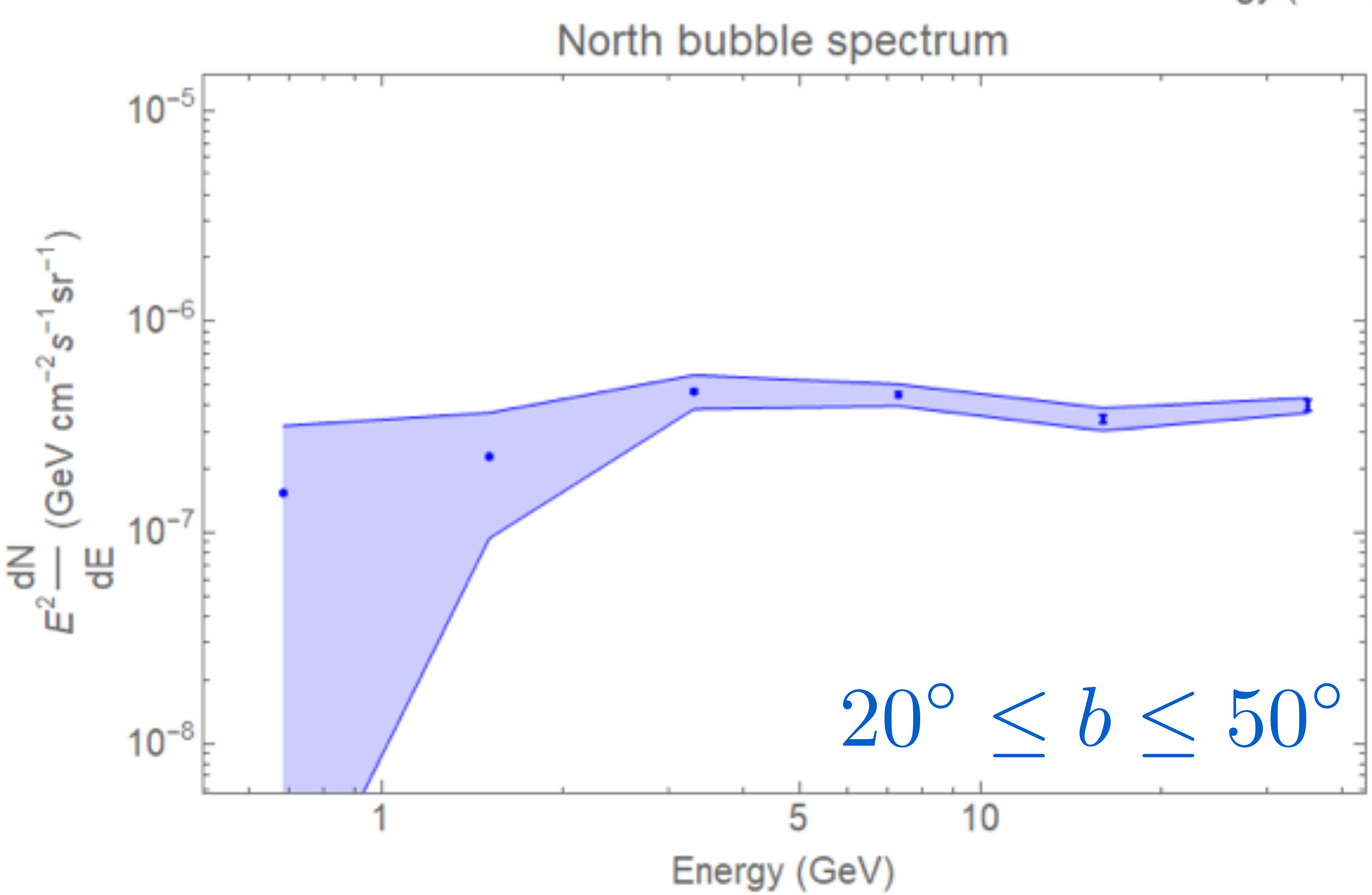
Statistical smaller than systematics.
Systematics come from the location/size of the mirroring area, the wavelet scales we choose to mirror and iterate over. The collection ISM that we average over in the first step when we subtract the galactic diffuse emission.

Spectra


GCE regions' flux
$E^2 \frac{dN}{dE}$ (GeV cm^{-2}s^{-1}sr^{-1})
$1.\times10^{-5}$
$5.\times10^{-6}$
$1.\times10^{-6}$
$5.\times10^{-7}$
1
5
10
Energy (GeV)
Region 0
Region I
Region II
Region III
Region IV
Region V
Region VI

Fermi Bubbles:



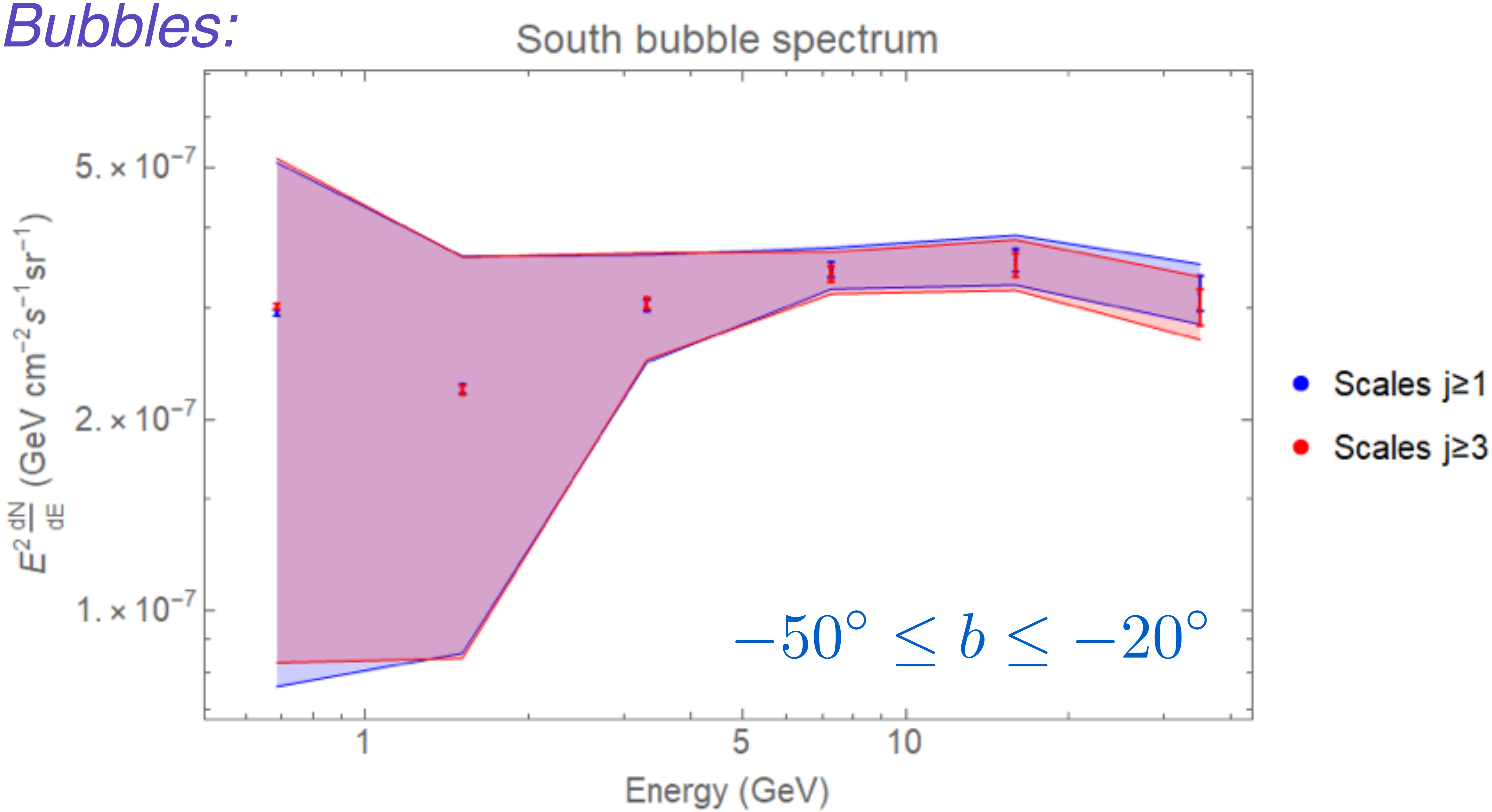


In agreement with Su et al. & Fermi. Coll.

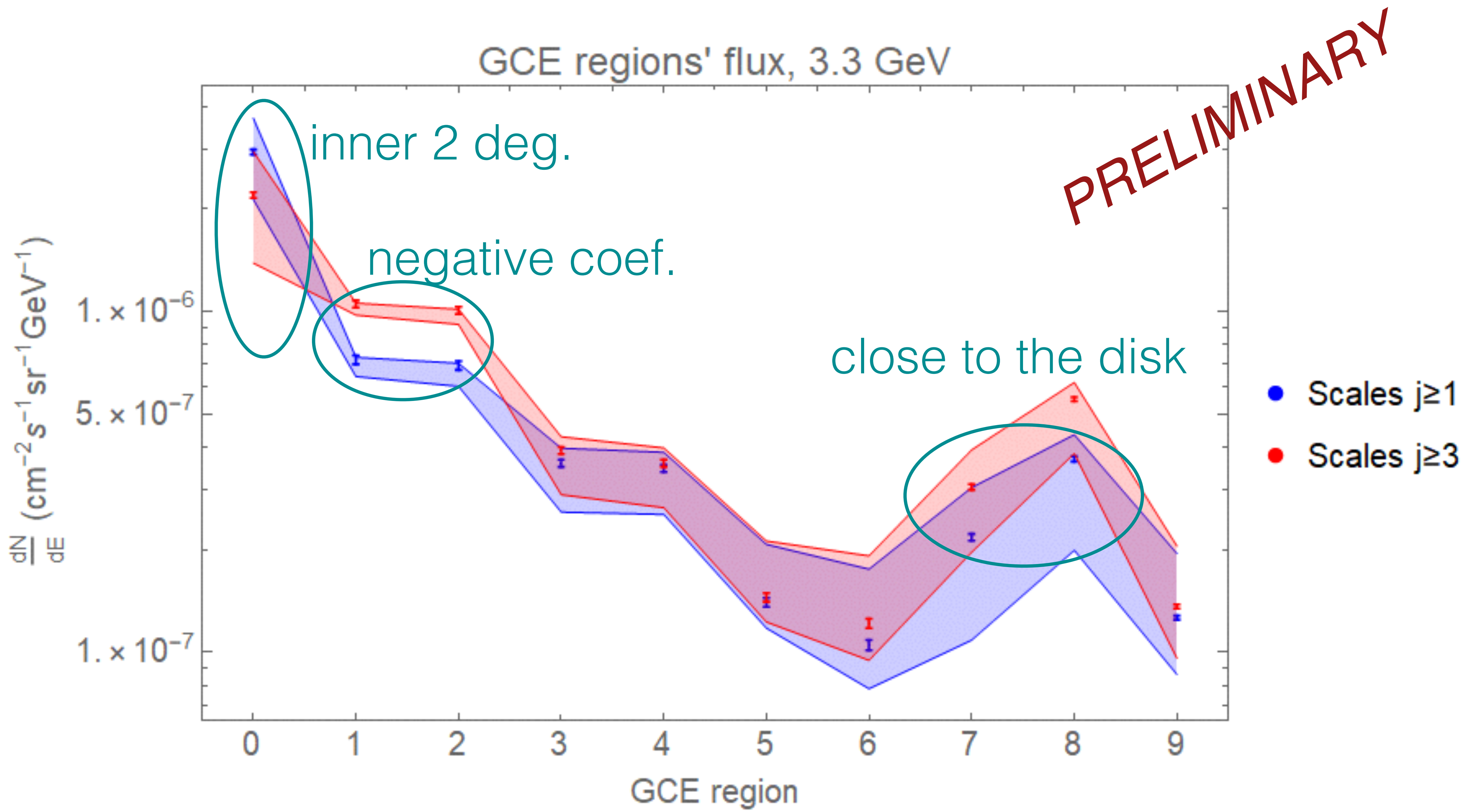
The Wavelet Promise:

Is the power more in small scales (e.g. point sources/filaments) or in large scales (diffuse emission as is ICS)?

Fermi Bubbles:



The Fermi Bubbles have *very little power in small scales* in agreement with the leptonic association (WMAP/Planck Haze)

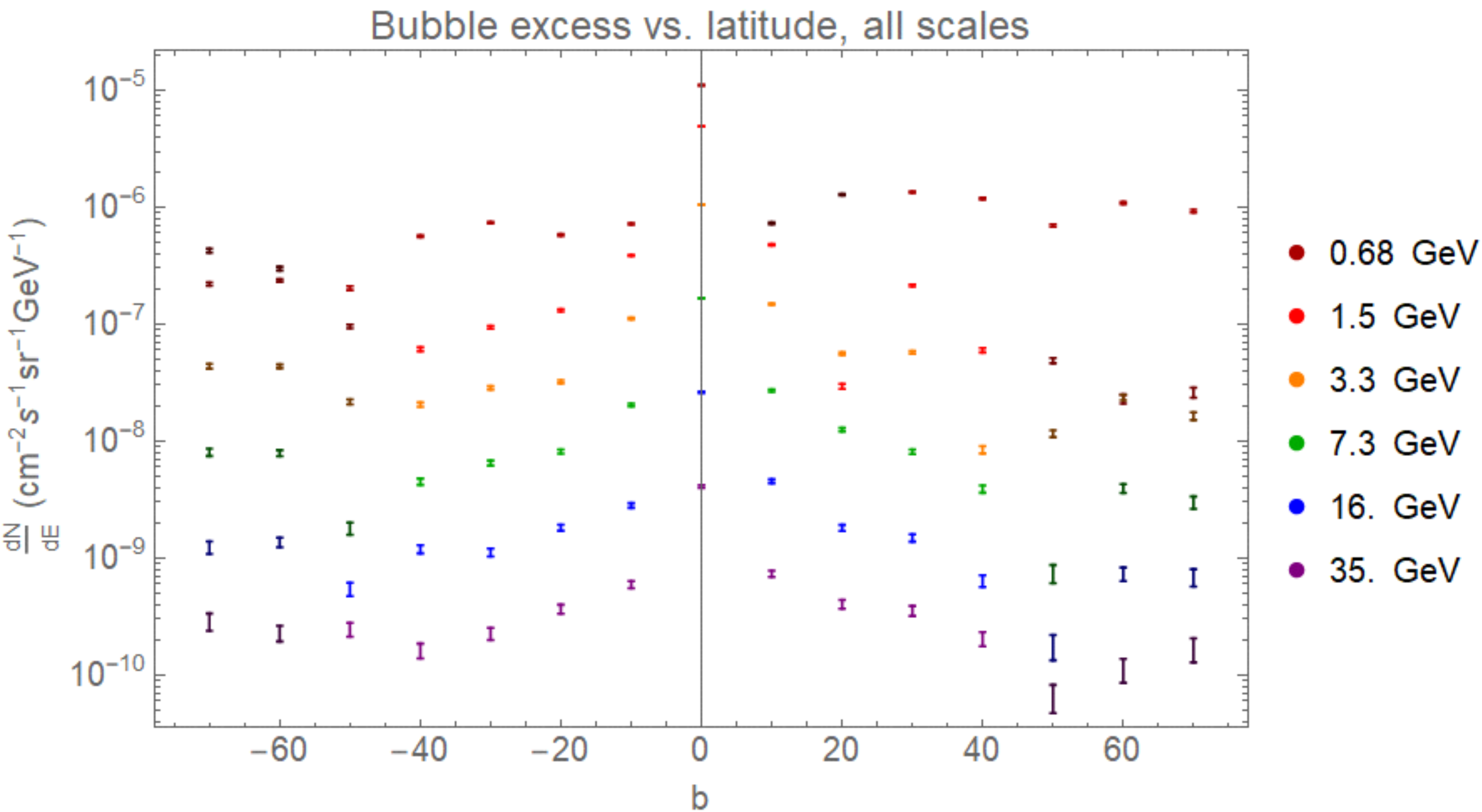


The GCE seems have also *little power in small scales* apart from region 0. Regions 1 and 2 also PS contaminated. For regions 3 and above (>5 degrees), there is agreement with the diffuse association (CE electron bursts or even DM?)

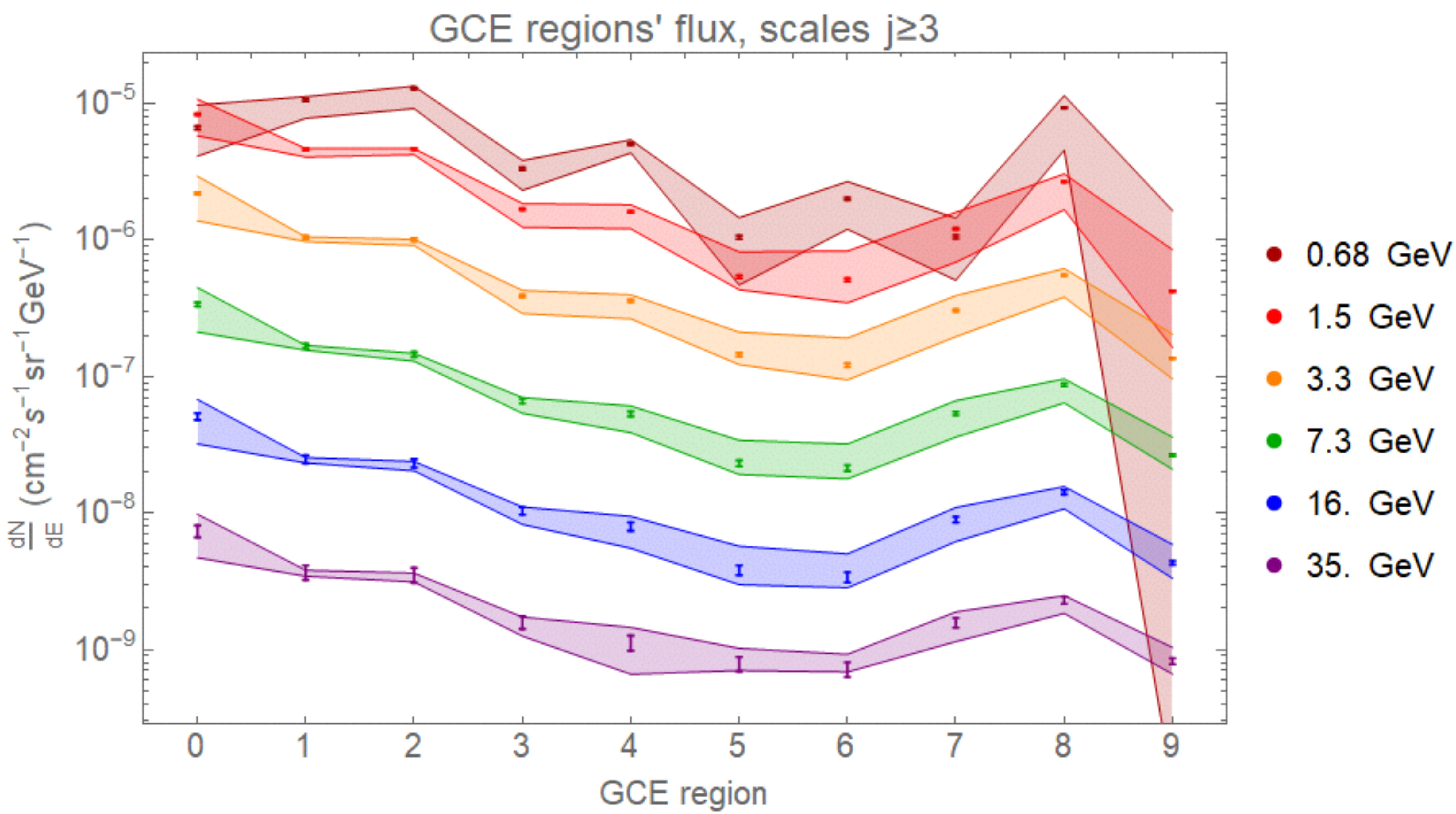
Conclusions, future directions

- Using the wavelet technique we developed in McDermott et. al JCAP 1607 (2016), (arXiv:1512.00012) we are analyzing data now **and writing the paper Balaji et al. 171x.xxxxx.**
- We also find the Fermi Bubbles and the Galactic Center Excess and are in agreement with most template results.
- Extract spectra both at different regions and also at different scales!
- We can ask questions on the underlying properties of these emissions.
- The GCE only in the inner 5 degrees has power in low scales (e.g from point sources and miss-modeling of gas distribution).
- Regarding the interpretations we still have to make a connection with simulations we have from 2016 and run some more…
- The Fermi Bubbles are diffuse above 20 degrees. We do find substructure that may be associated with a cocoon/jet.
- Use this technique to study other regions of the sky.
- A GREAT SET OF TOOLS TO STUDY THE GAMMA-RAY DATA

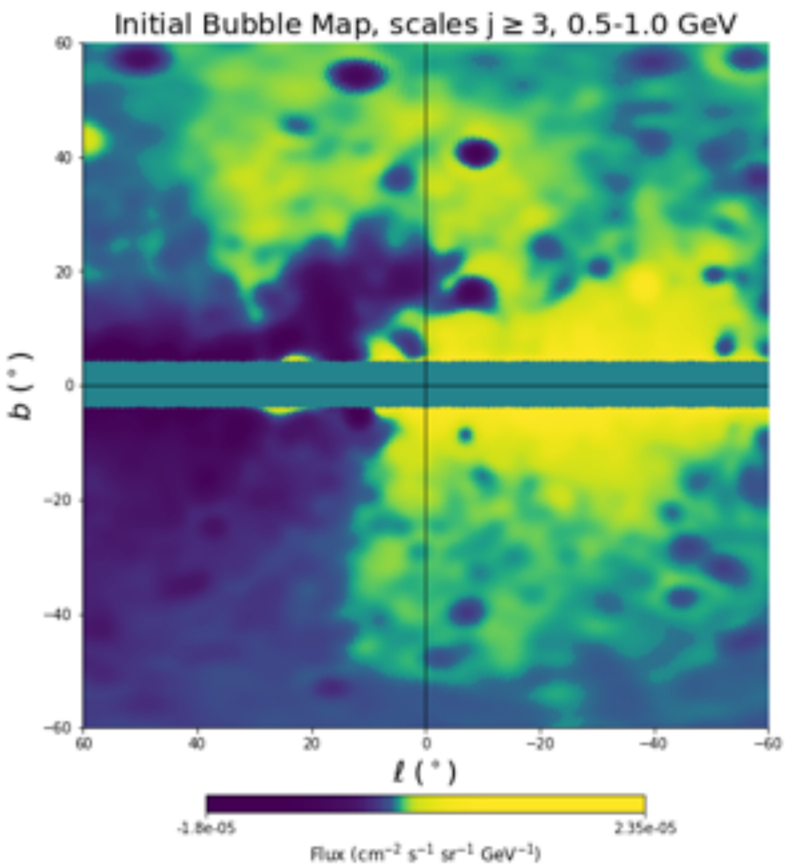
Additional Slides

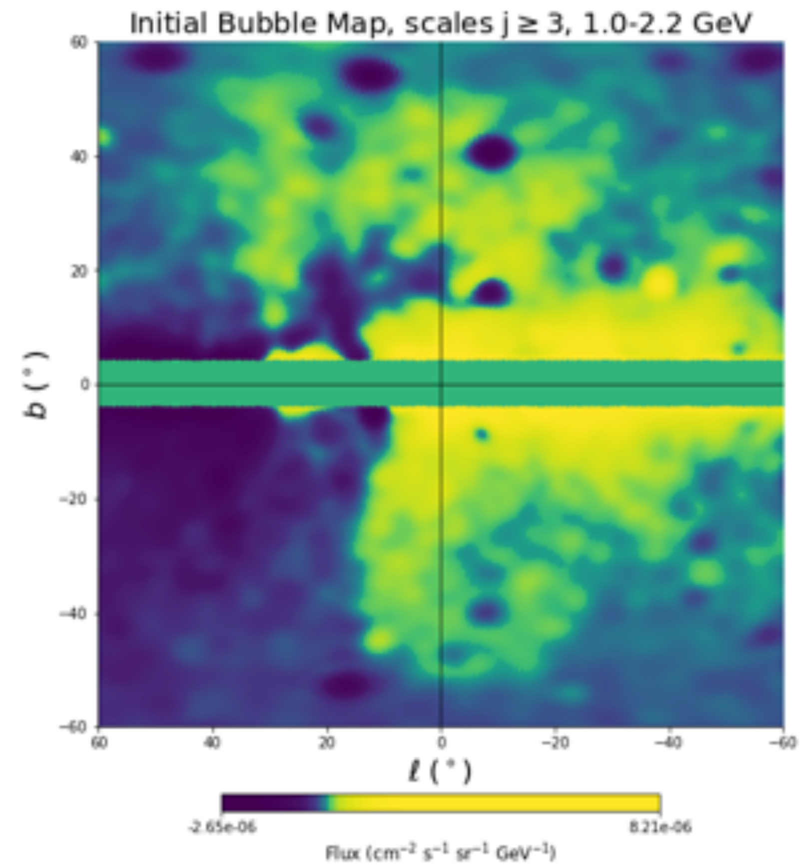


Statistical Errors ONLY

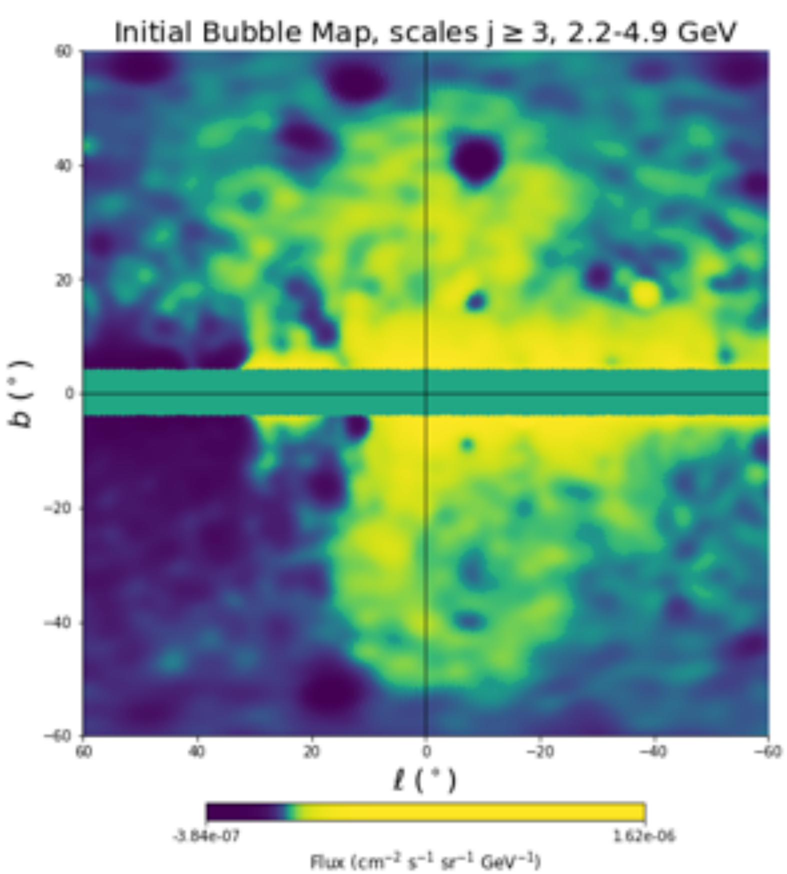


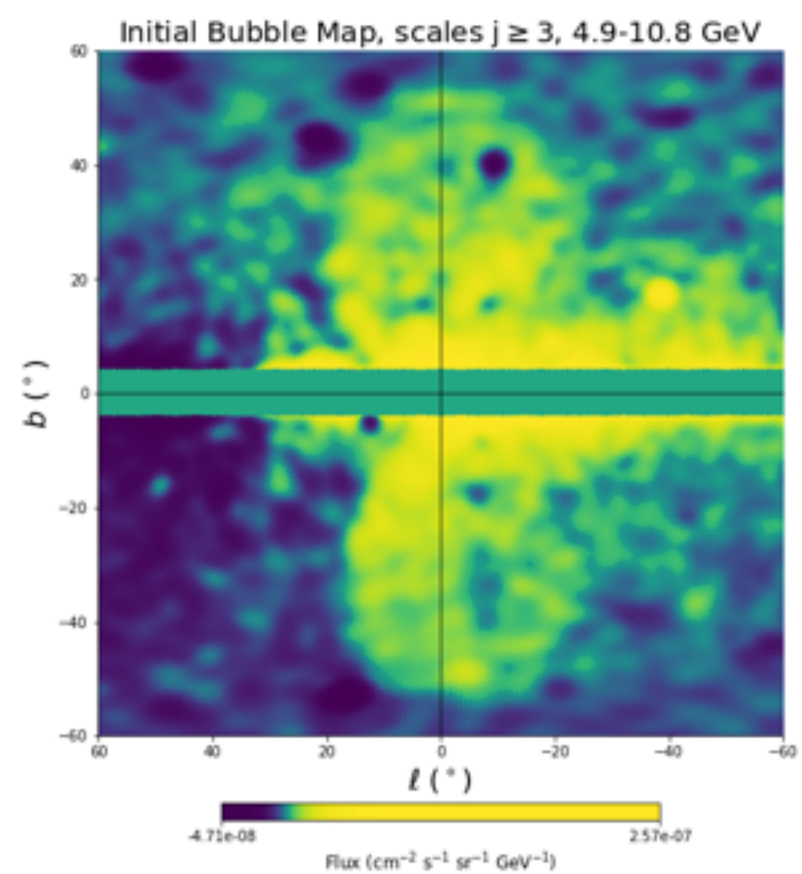
Diffuse Part of the GCE emission

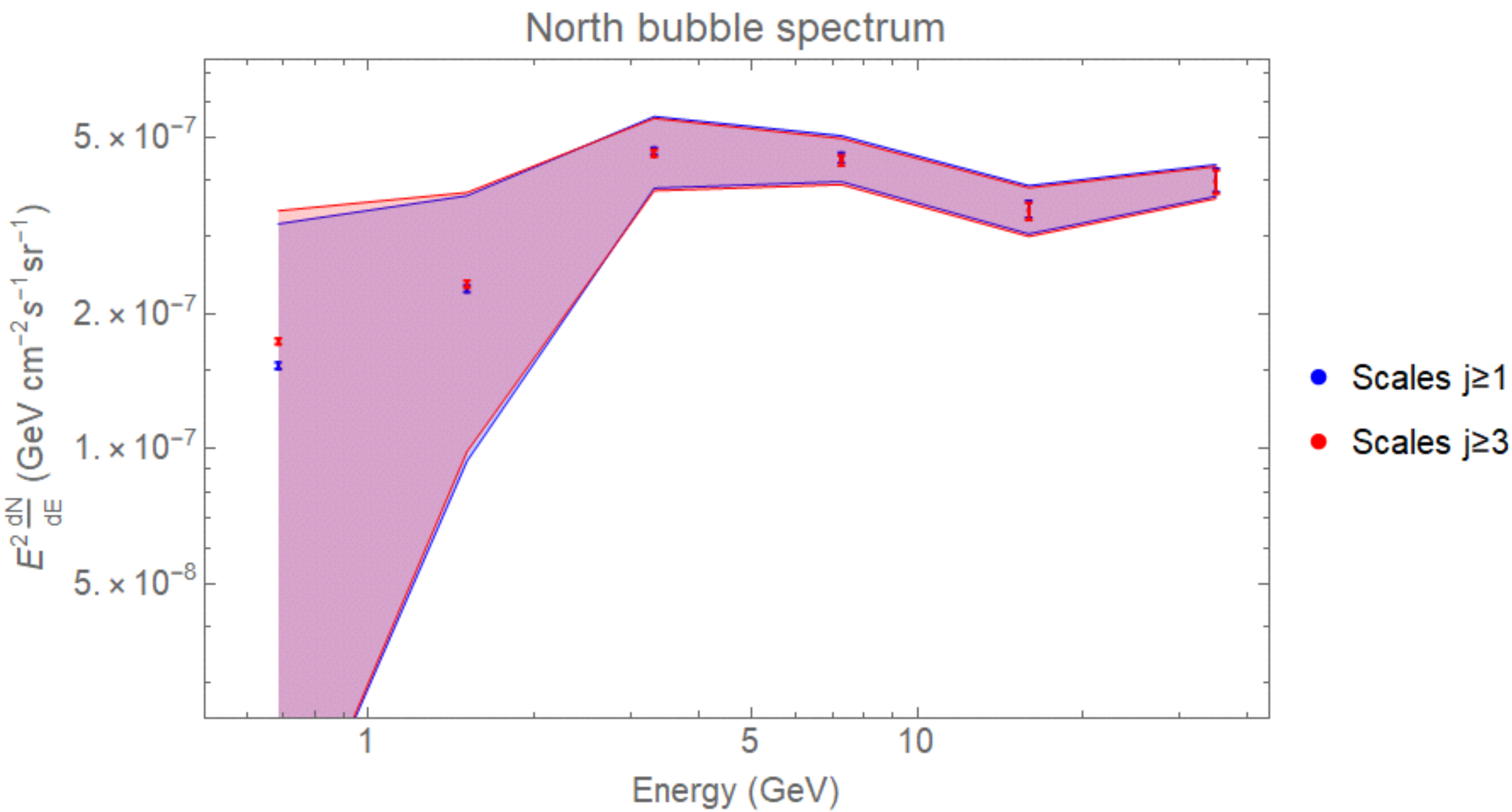




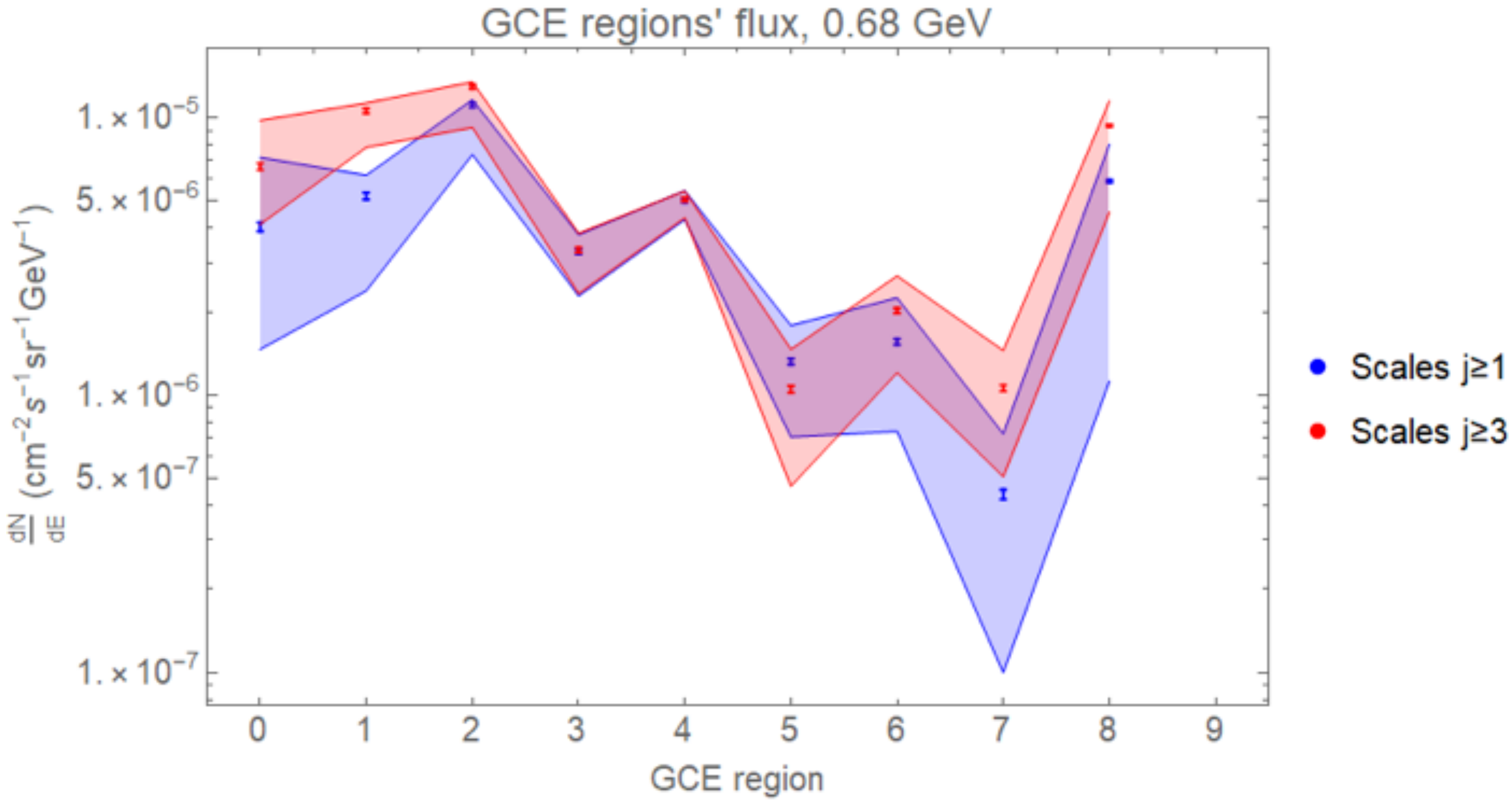
Bubble morphology without mirroring

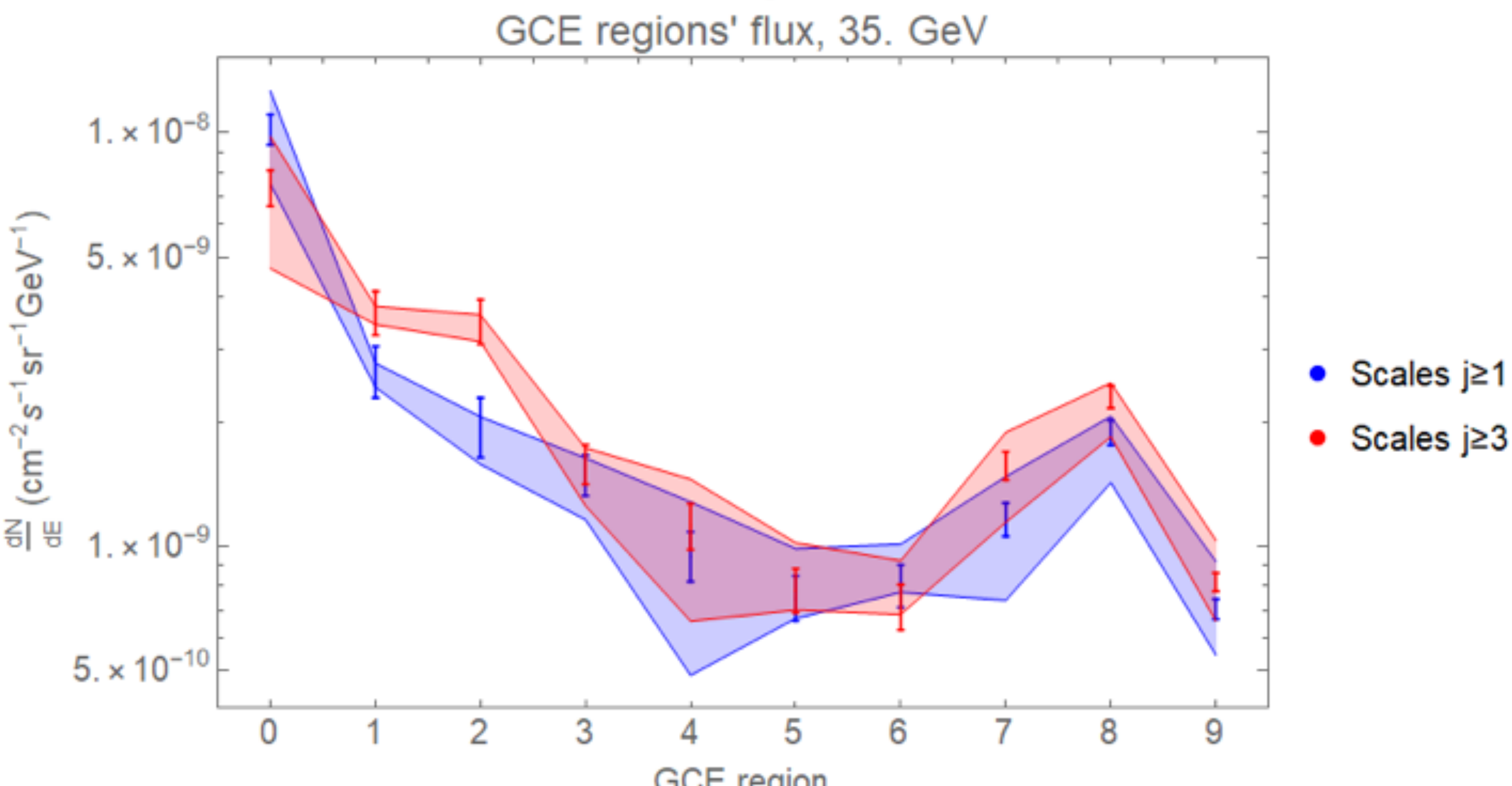


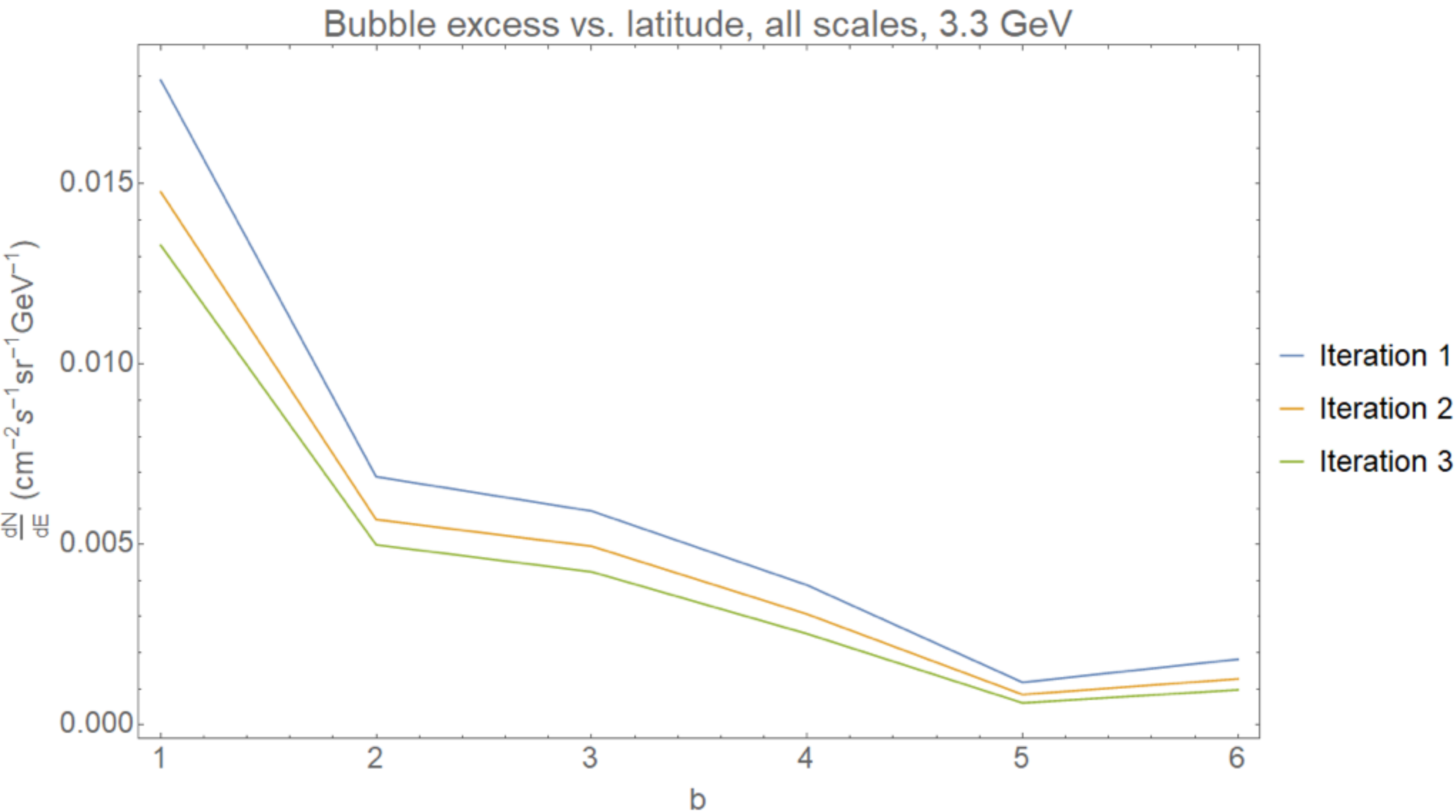




North bubble spectrum
$E^2 \frac{dN}{dE}$ (GeV cm^{-2}s^{-1}sr^{-1})
5.×10^-7
2.×10^-7
1.×10^-7
5.×10^-8
1
5
10
Energy (GeV)
Scales j≥1
Scales j≥3


GCE regions' flux, 0.68 GeV
dN/dE (cm⁻²s⁻¹sr⁻¹GeV⁻¹)
1. × 10⁻⁵
5. × 10⁻⁶
1. × 10⁻⁶
5. × 10⁻⁷
1. × 10⁻⁷
0 1 2 3 4 5 6 7 8 9
GCE region
Scales j≥1
Scales j≥3


GCE regions' flux, 35. GeV
dN/dE (cm⁻²s⁻¹sr⁻¹GeV⁻¹)
1. × 10⁻⁸
5. × 10⁻⁹
1. × 10⁻⁹
5. × 10⁻¹⁰
0 1 2 3 4 5 6 7 8 9
GCE region
Scales j≥1
Scales j≥3


Bubble excess vs. latitude, all scales, 3.3 GeV
0.000
0.005
0.010
0.015
dN/dE (cm^-2 s^-1 sr^-1 GeV^-1)
1
2
3
4
5
6
b
Iteration 1
Iteration 2
Iteration 3

Iteration procedure:

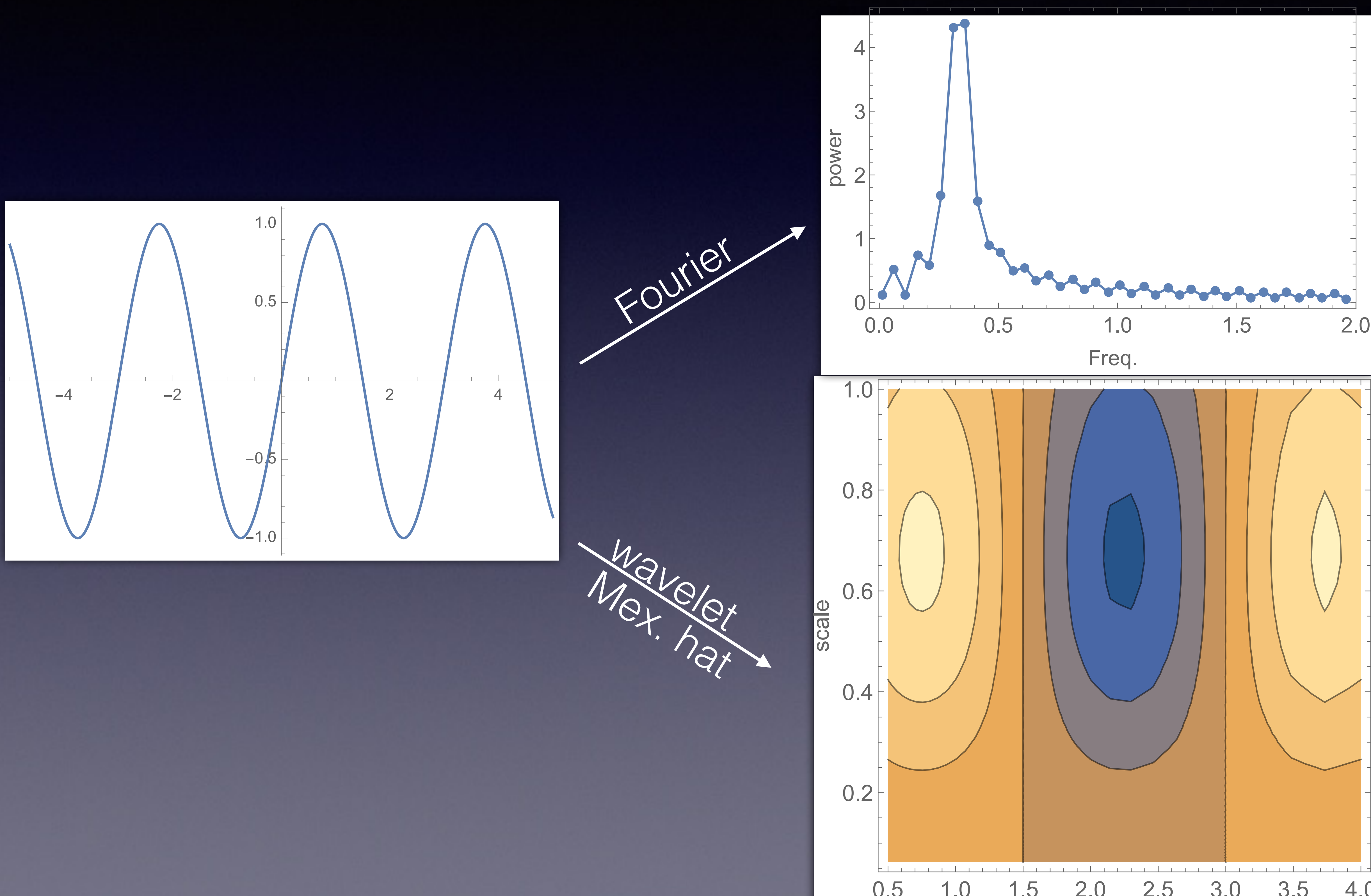
$$GCE_0 = \sum_{j=3}^{9} w_j (R_0')$$

$$blob_0 = \sum_{j=3}^{9} w_j (R_0 - GCE_0)$$

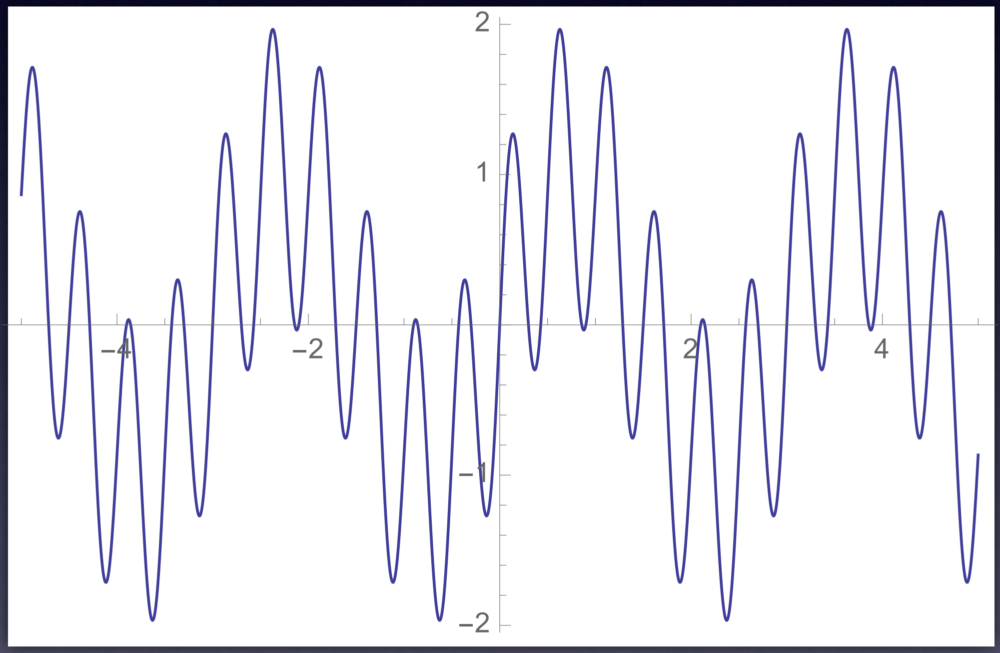
$$GCE_i = \sum_{j=3}^{9} w_j (R_0 - blob_{i-1})$$

$$blob_i = \sum_{j=3}^{9} w_j (R_0 - GCE_{i-1})$$

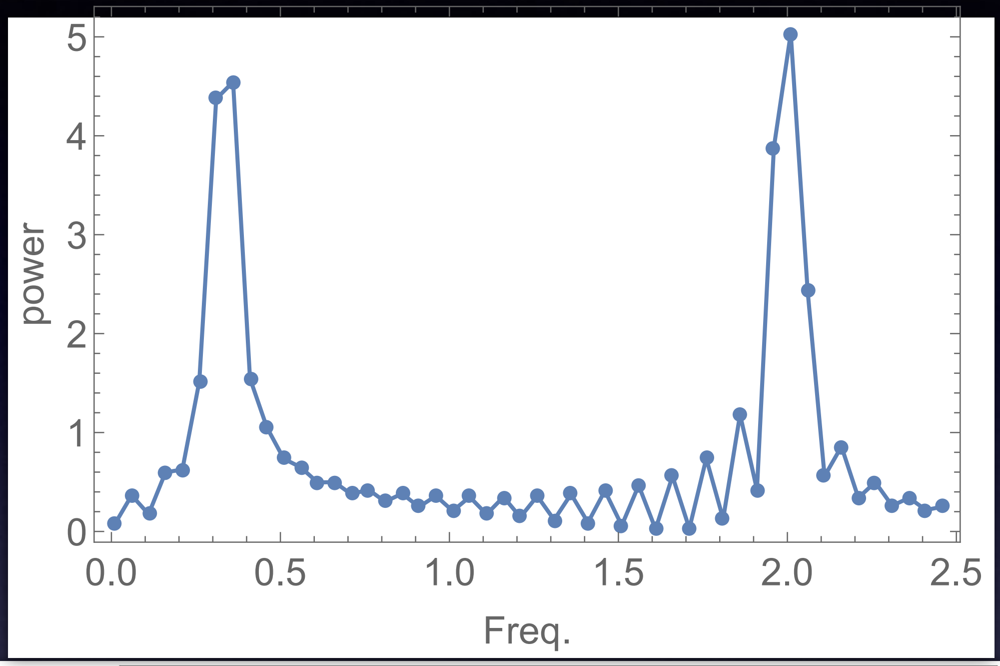
sine wave


1.0
0.5
−4
−2
2
4
−0.5
−1.0
Fourier
wavelet
Mex. hat
power
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
Freq.
scale
1.0
0.8
0.6
0.4
0.2
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

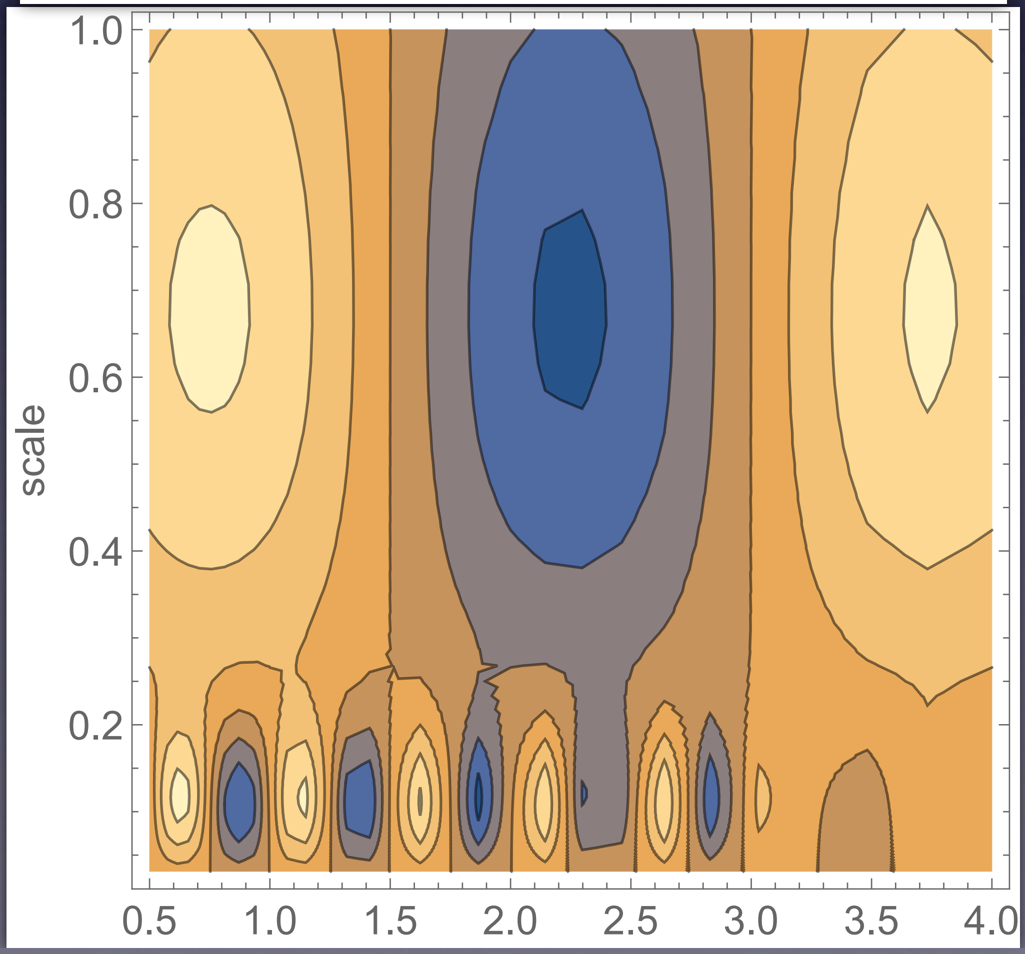
two sine waves



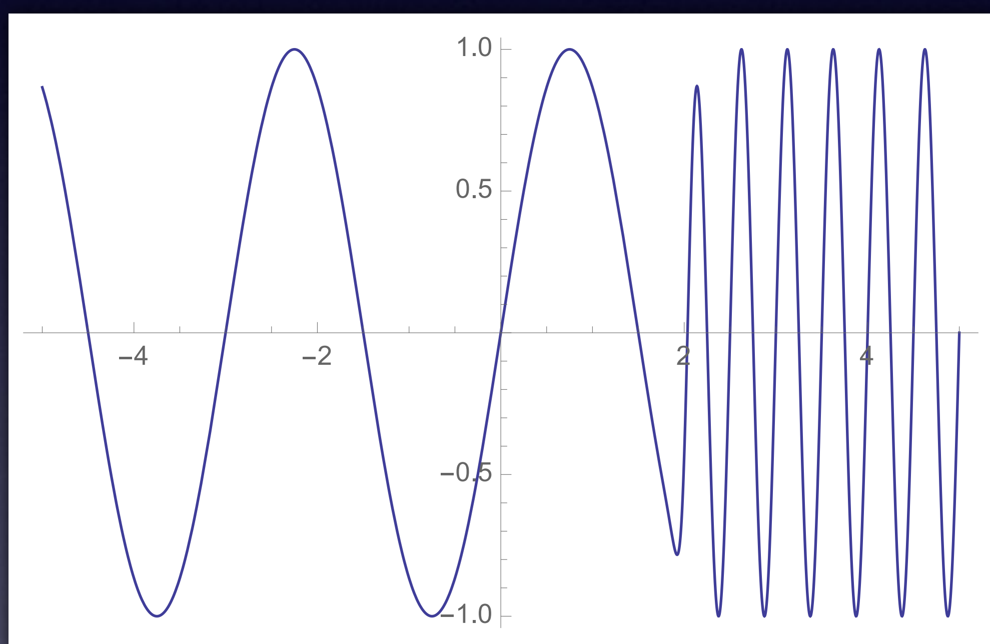
Fourier



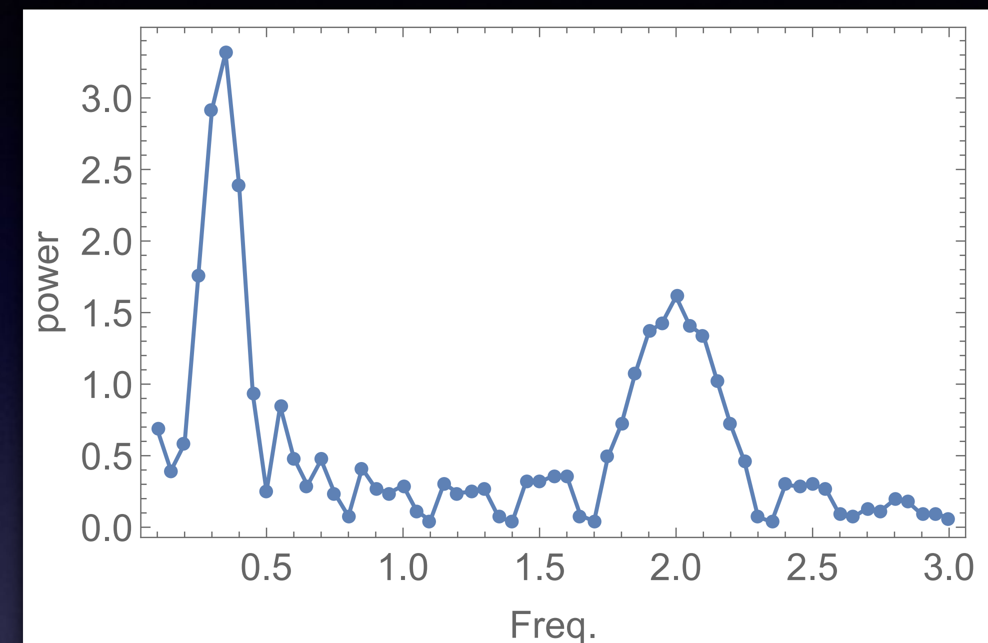
wavelet
Mex. hat



sine waves with transition



Fourier



wavelet
Mex. hat