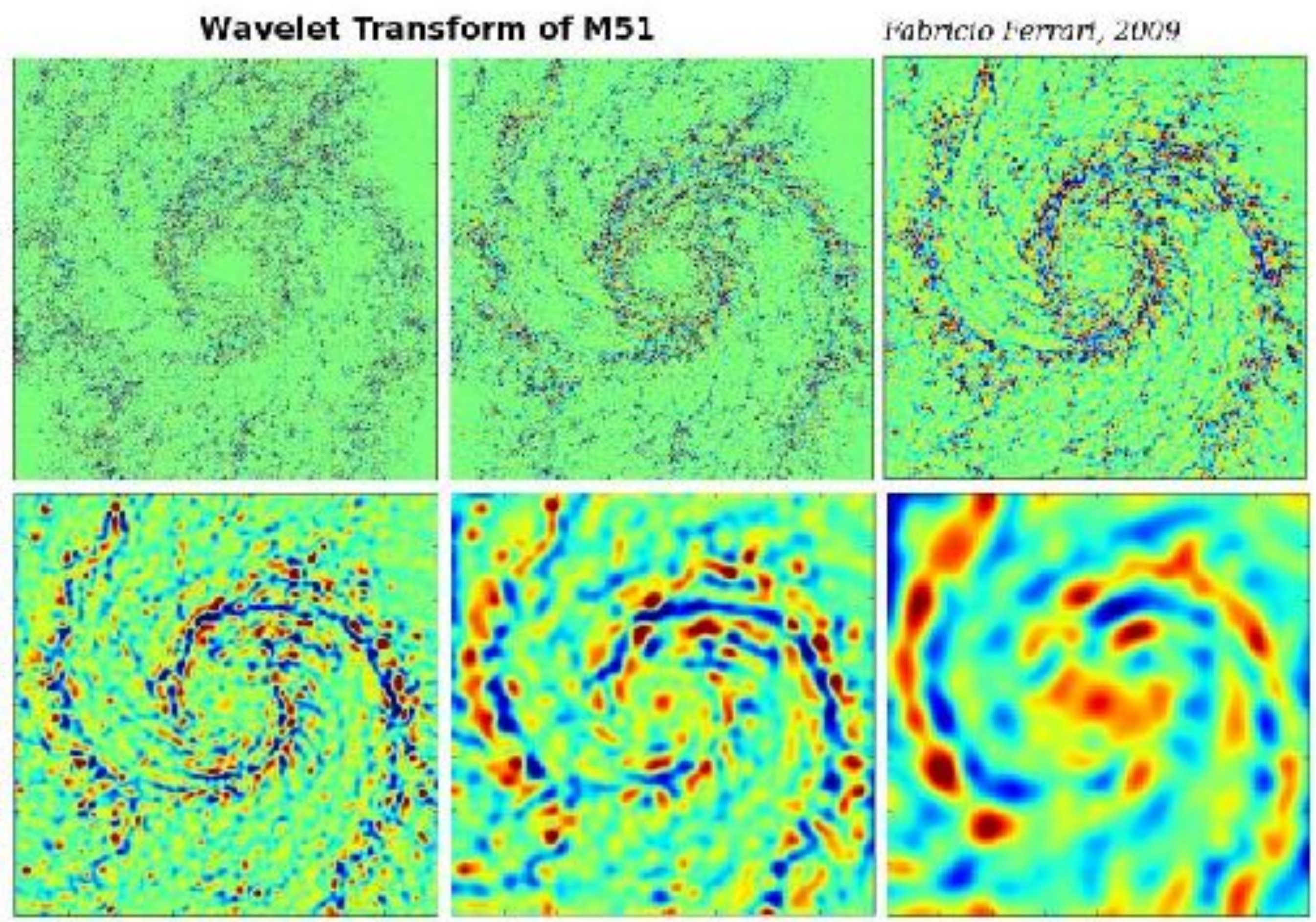
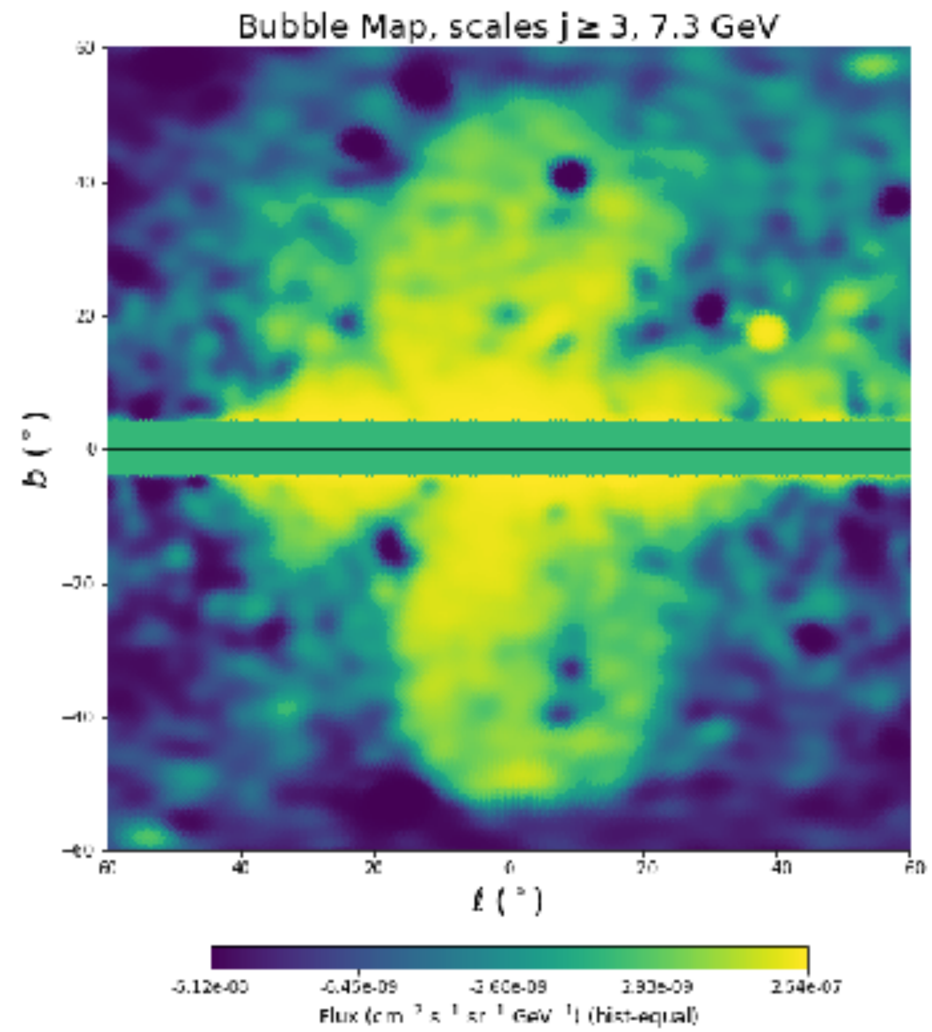
Analyzing the Gamma-Ray sky with Wavelets

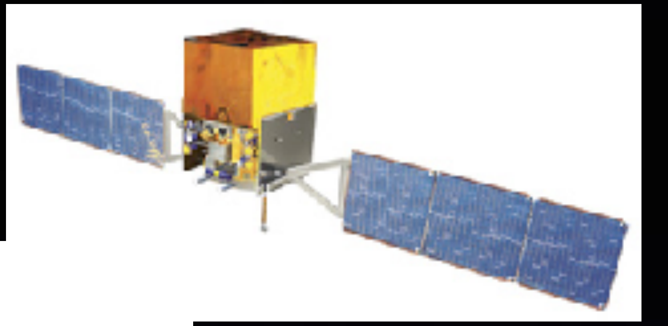


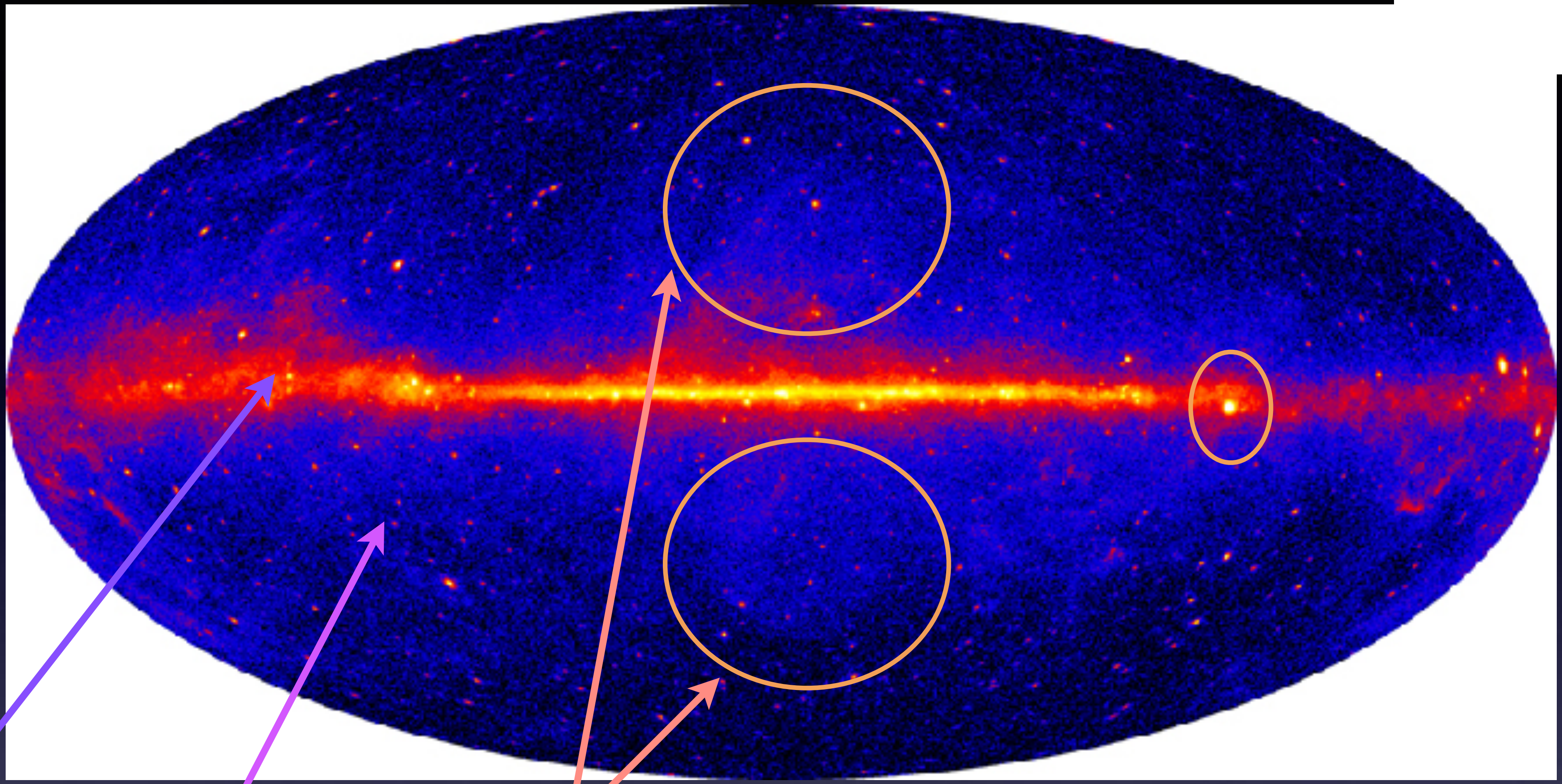


McDermott, Fox, IC, Lee JCAP 1607 (2016), (arXiv:
1512.00012
Balaji, IC, McDermott, Fox, arXiv:1803.1952

Ilias Cholis 5/10/2018

The Fermi-LAT Gamma-ray SKY





Sources for the observed gamma-rays are:

i)Galactic Diffuse Emission: decay of pi0s (and other mesons) from pp (NN) collisions in the ISM, bremsstrahlung radiation off CR e, Inverse Compton scattering: up-scattering of CMB and IR, optical photons from CR e

ii)from point sources (galactic or extra galactic)

iii)Extragalactic Isotropic

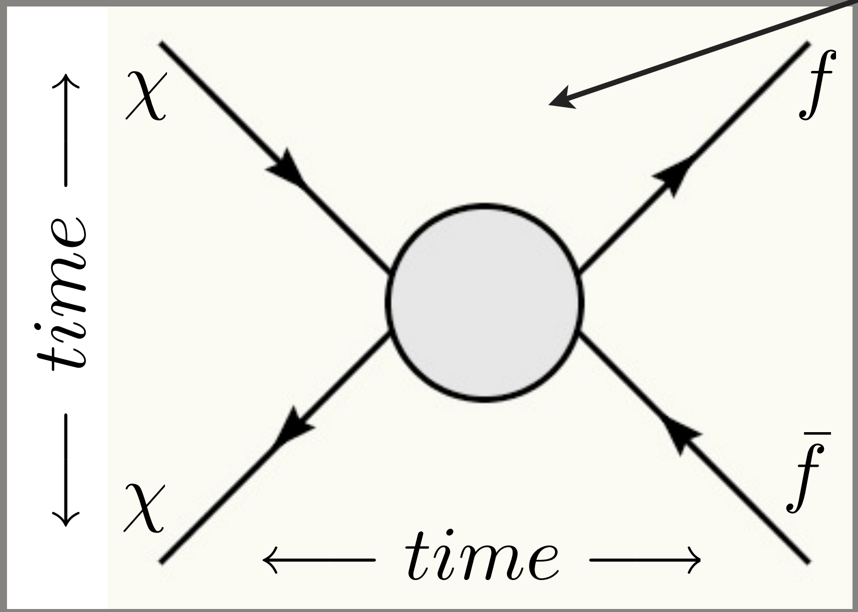
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

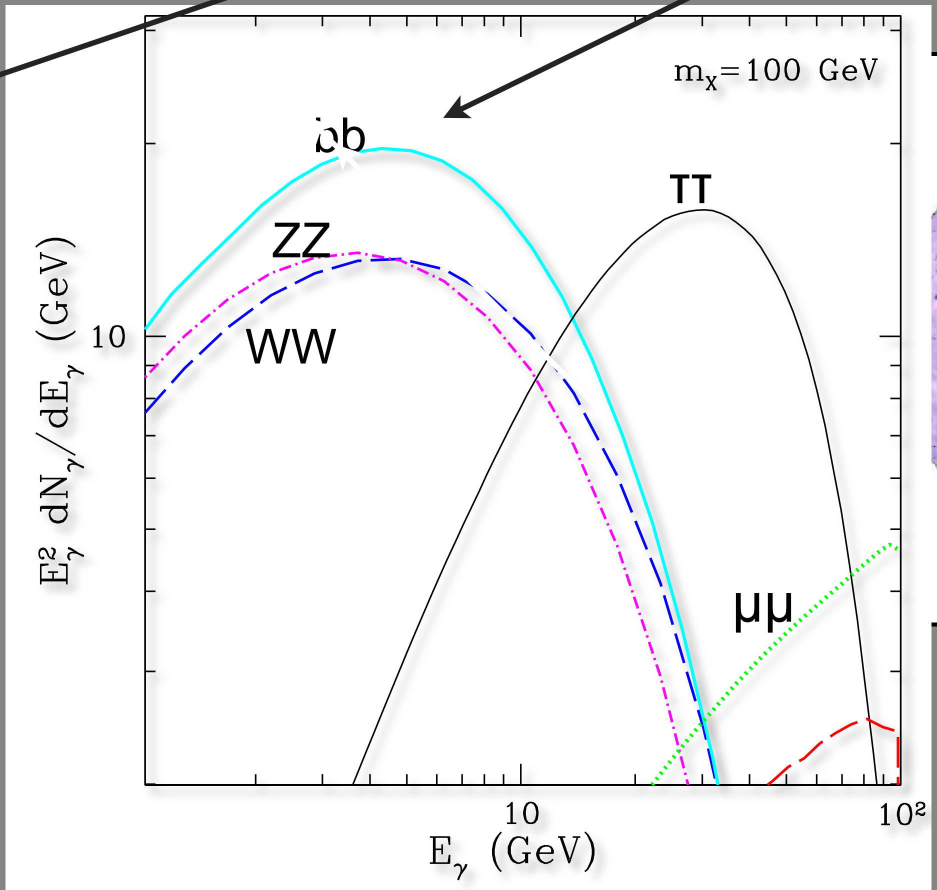
v)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

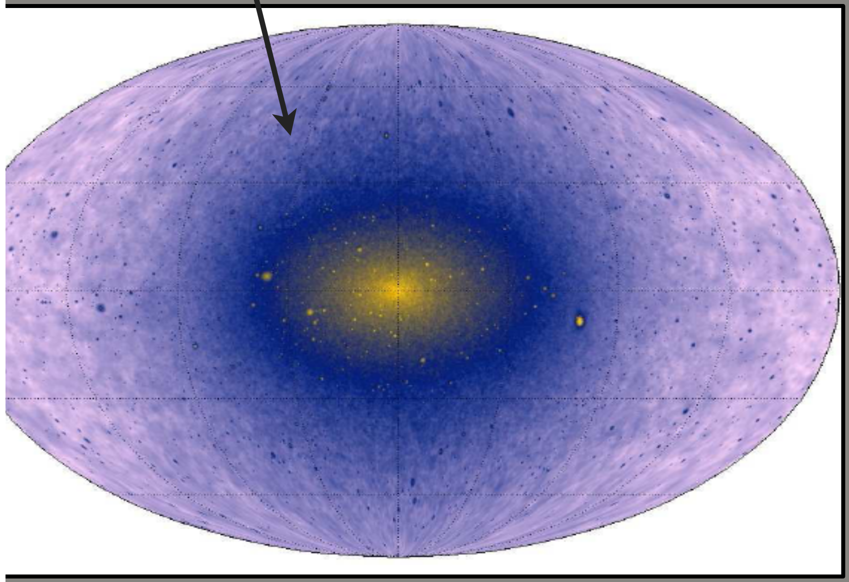
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

$$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\, m_\chi^2} dl d\Omega$$

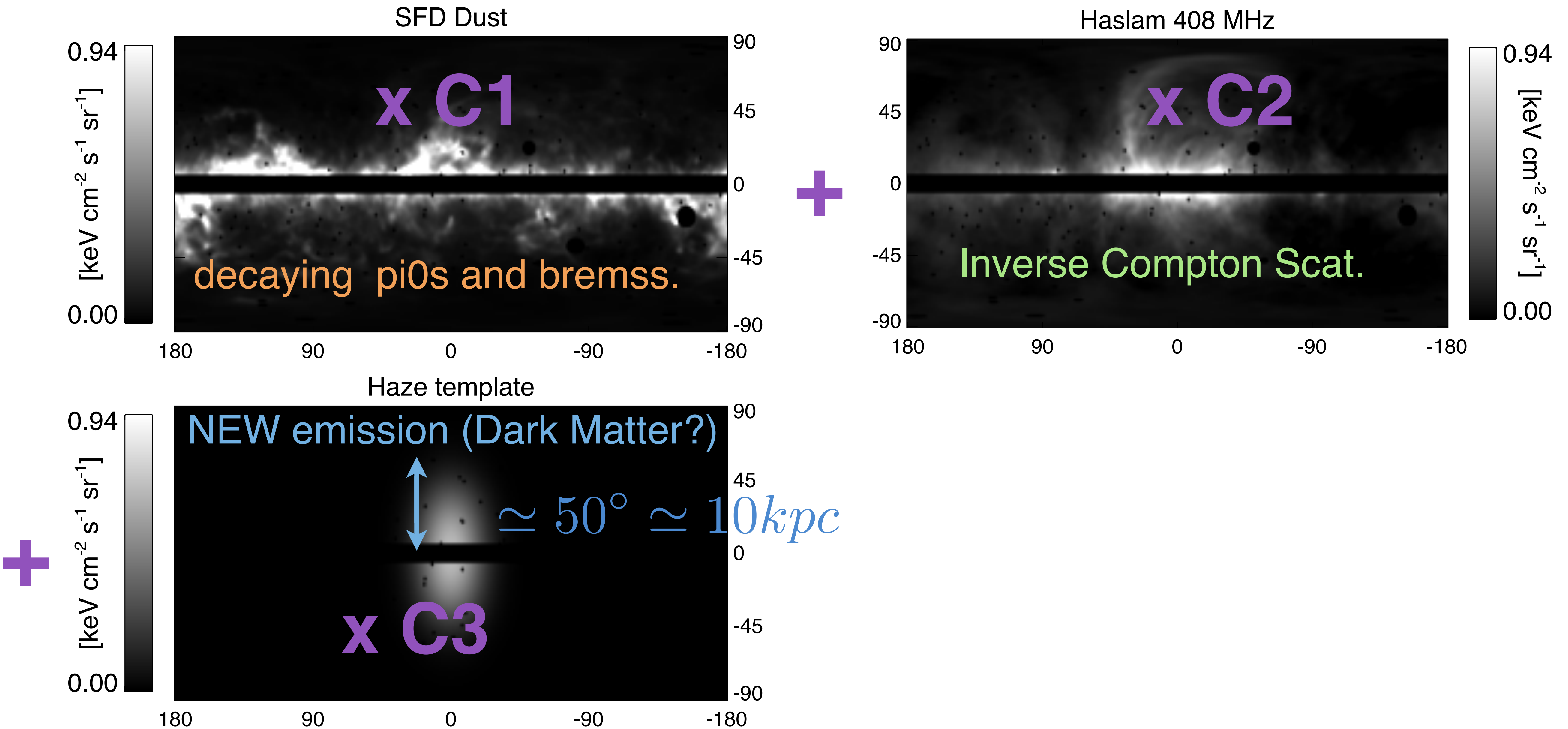






So How do we search for that ?

The first use of templates on Gamma-ray maps —> The discovery of the Fermi(Haze)-Bubbles



Dobler, Finkbeiner, IC, Slatyer, Weiner, ApJ, 2010

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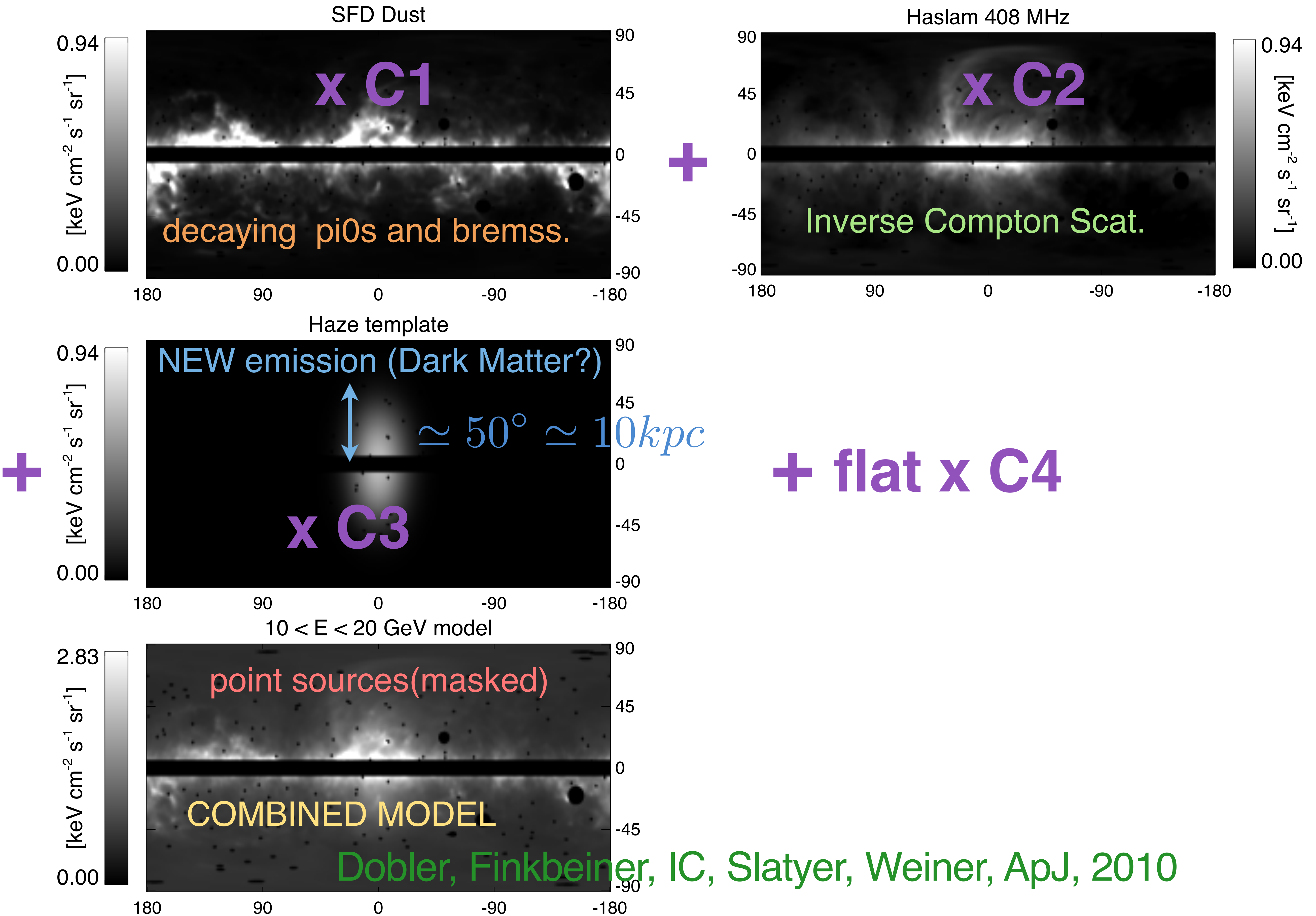

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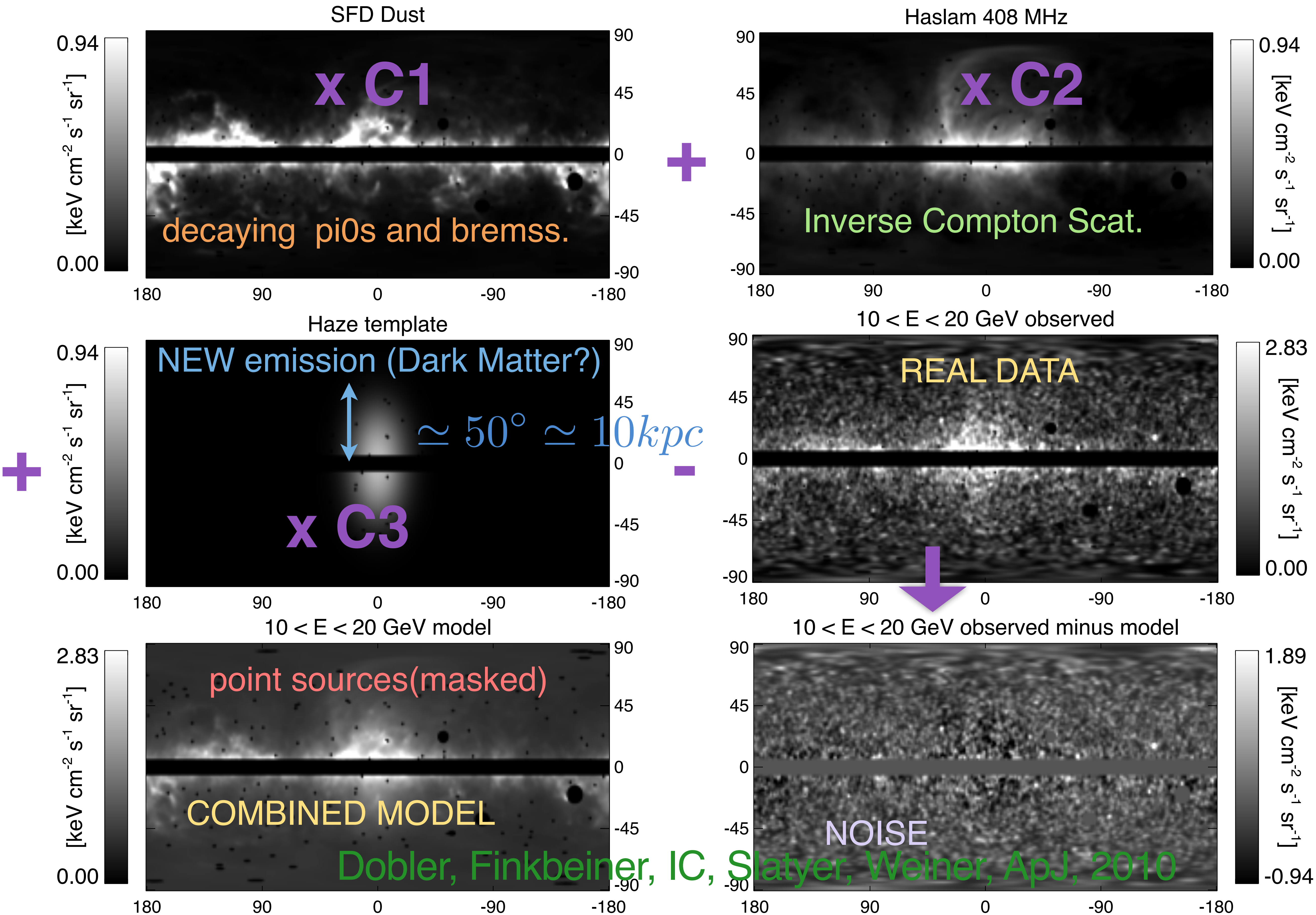
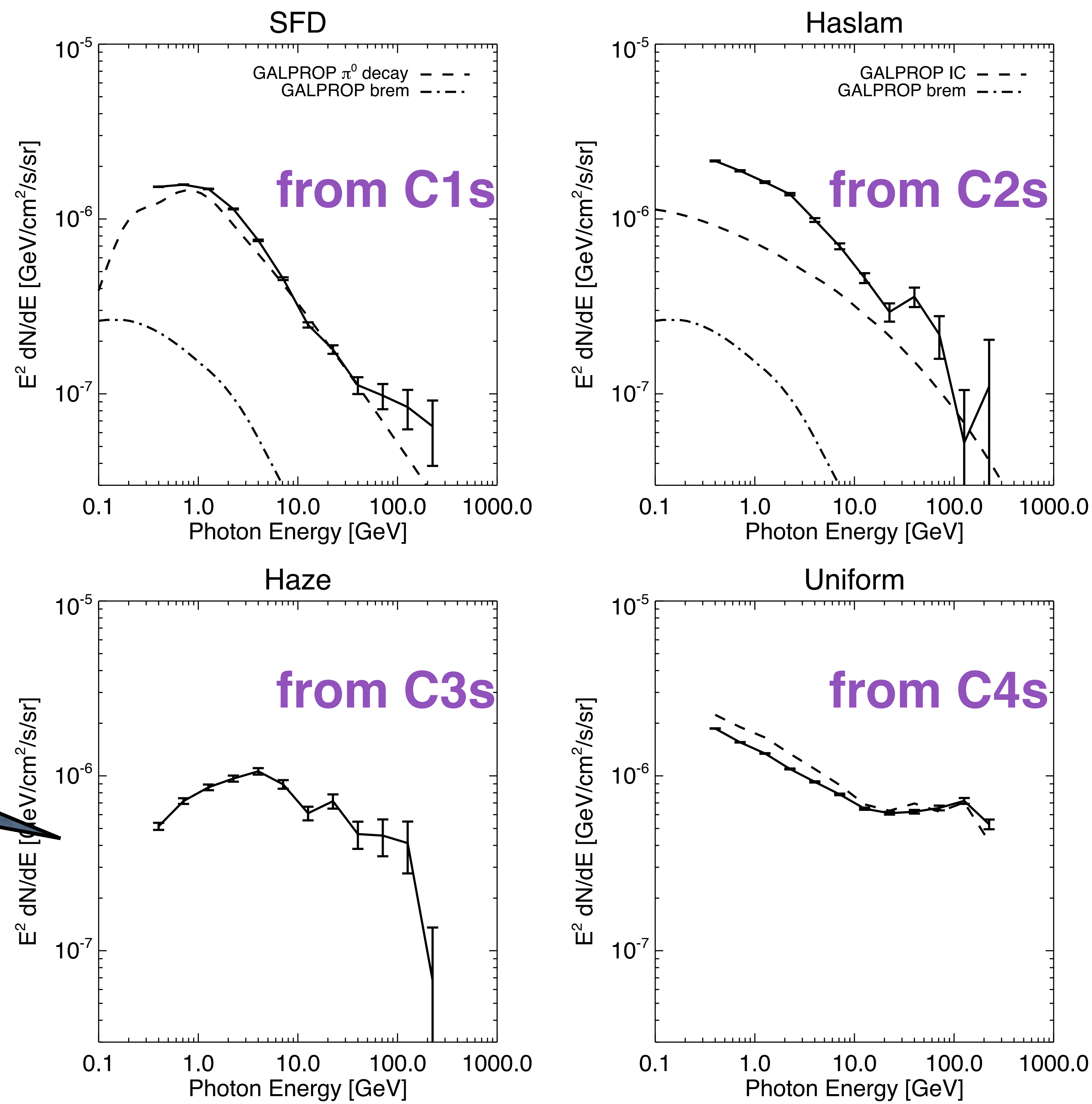


Dobler, Finkbeiner, IC, Slatyer, Weiner, ApJ, 2010

We repeat the fit the on gamma-ray sky at different energies

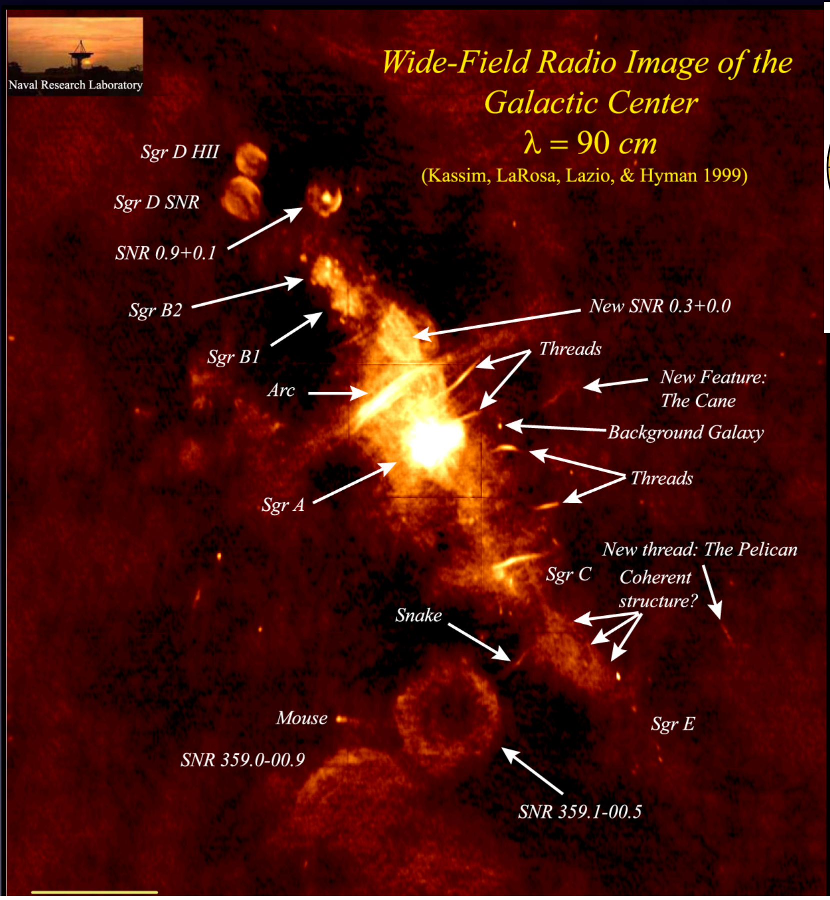


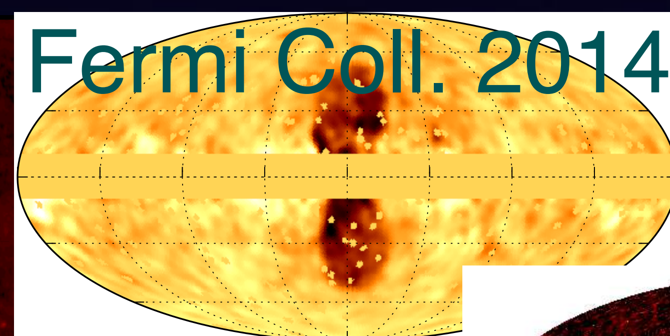
Harder than typical galactic! NEW Physics?

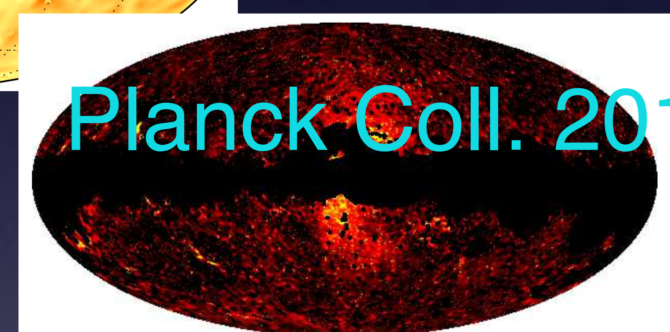
Dobler, Finkbeiner, IC, Slatyer, Weiner, ApJ, 2010

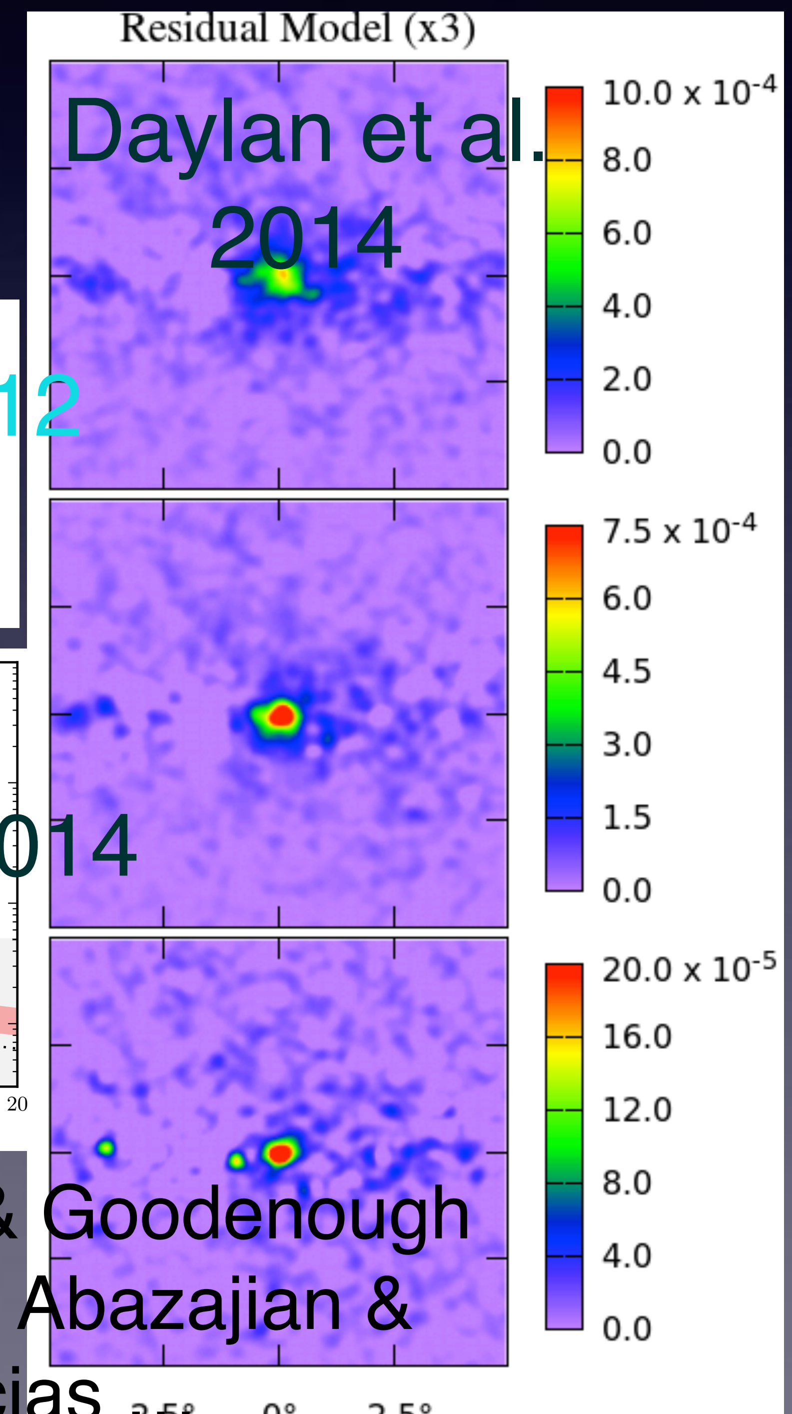
The Success Story of Templates:

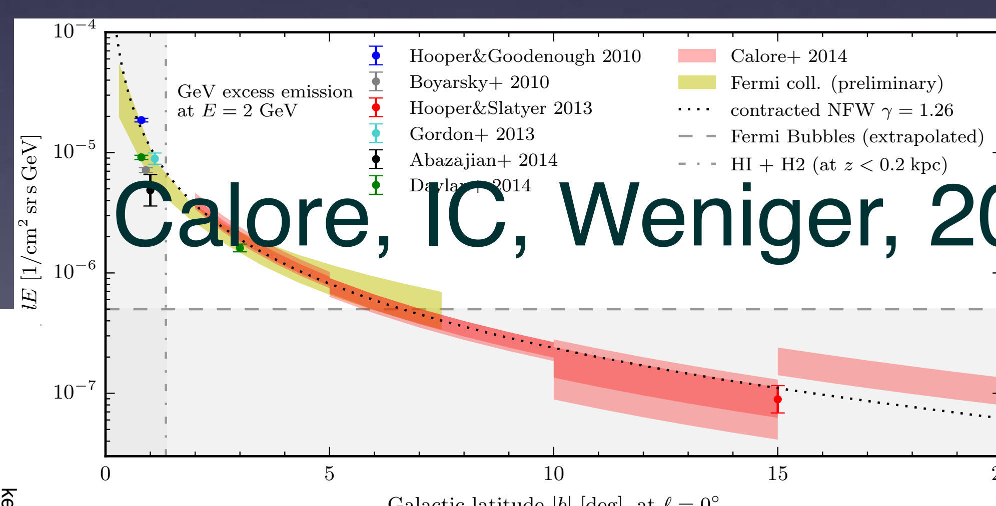
The galactic center and inner galaxy is a very interesting region but also very complicated. YET we discovered the "Fermi Haze/ Bubbles", the "Galactic Center Excess", also emission from Loop I.

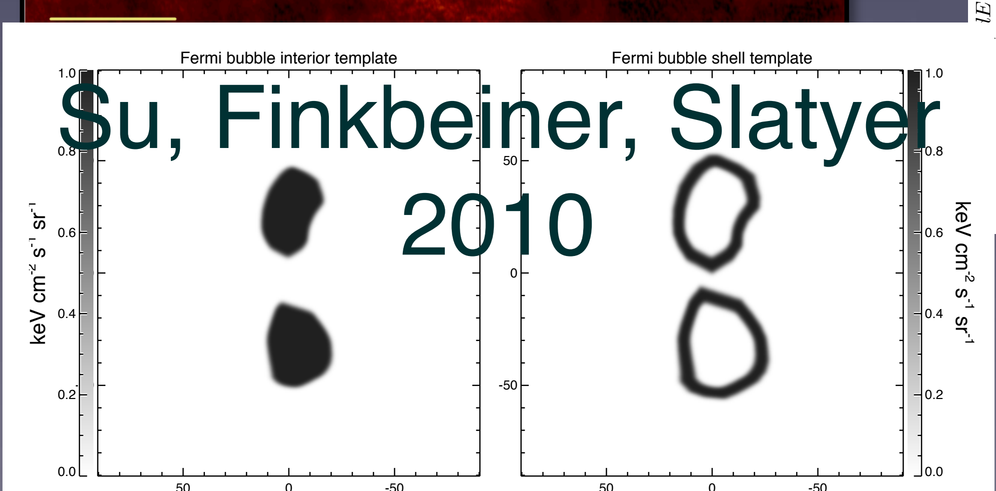








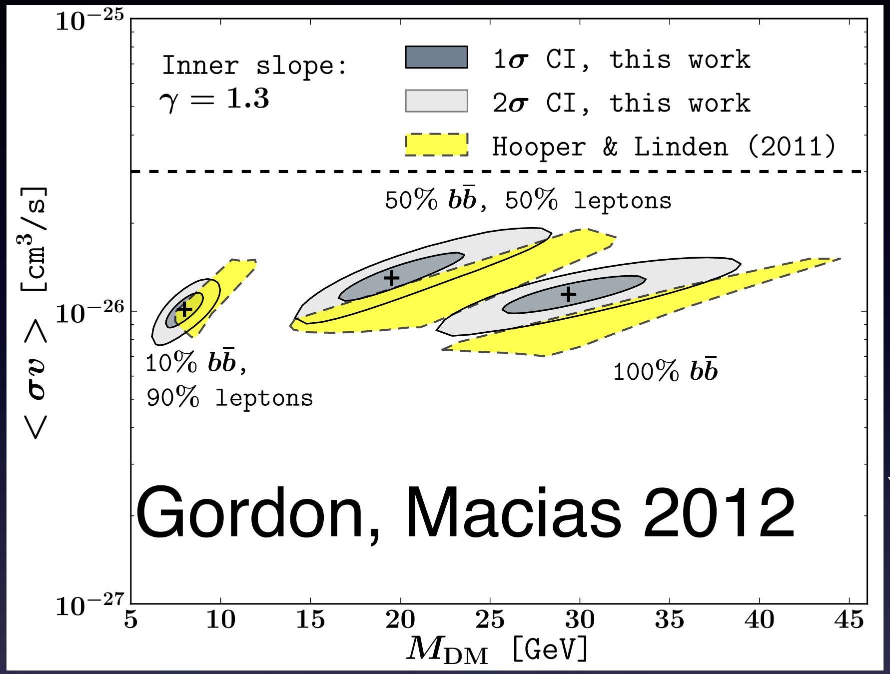




Also works from Hooper & Goodenough 2009-10, Hooper Linden, Abazajian & Kaplinghat, Gordon & Macias

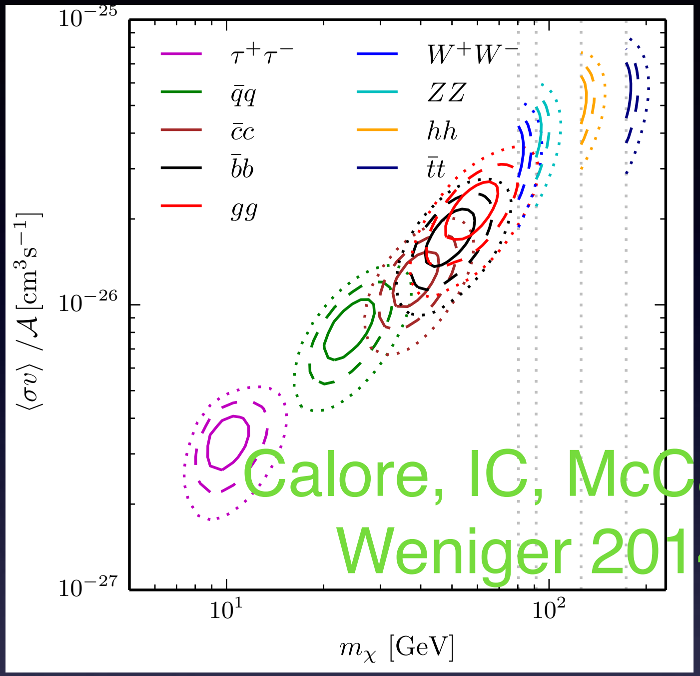
What are the explanations for these emissions?

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



DM

YES?



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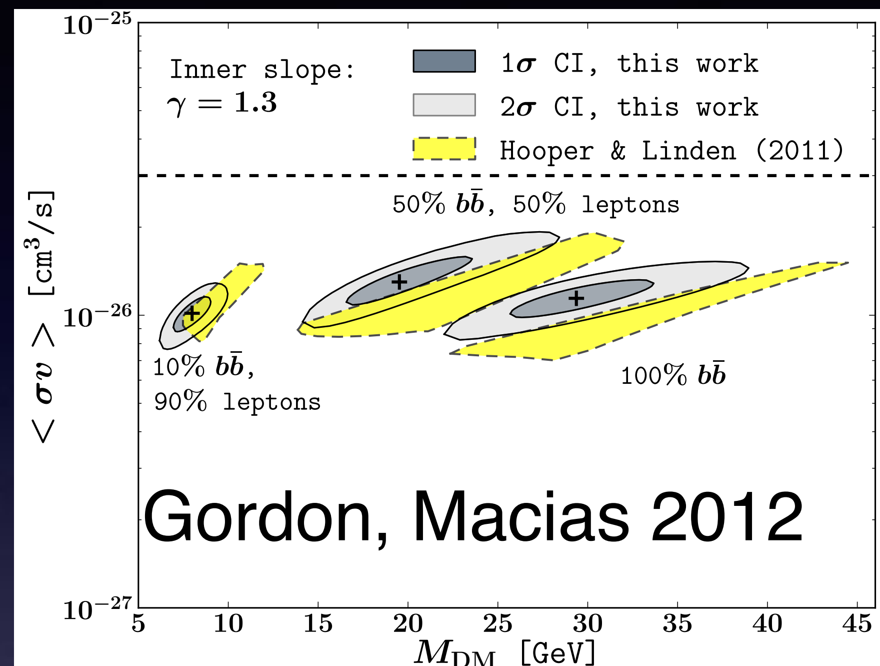

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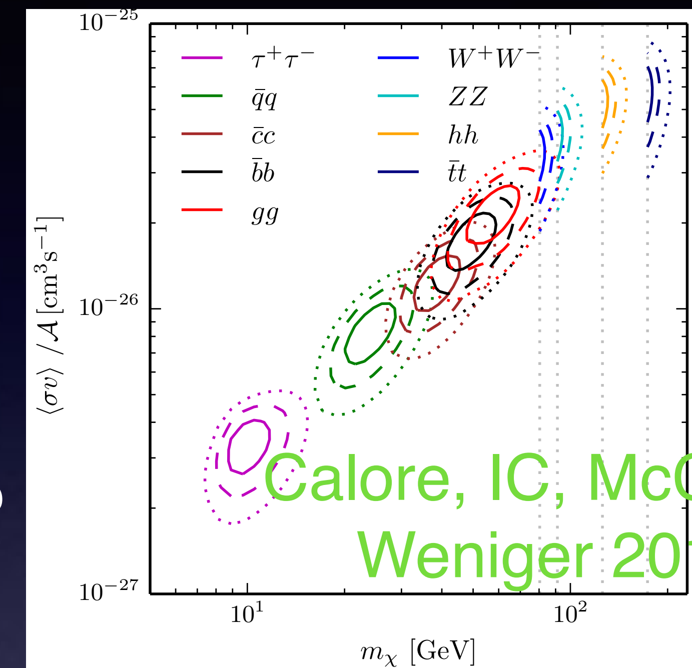

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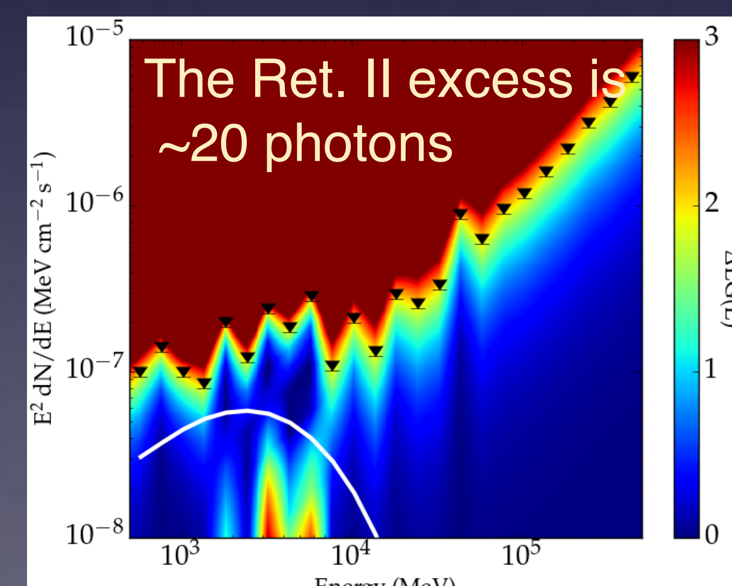

Geninger-Sameth, Kousiapas 2015

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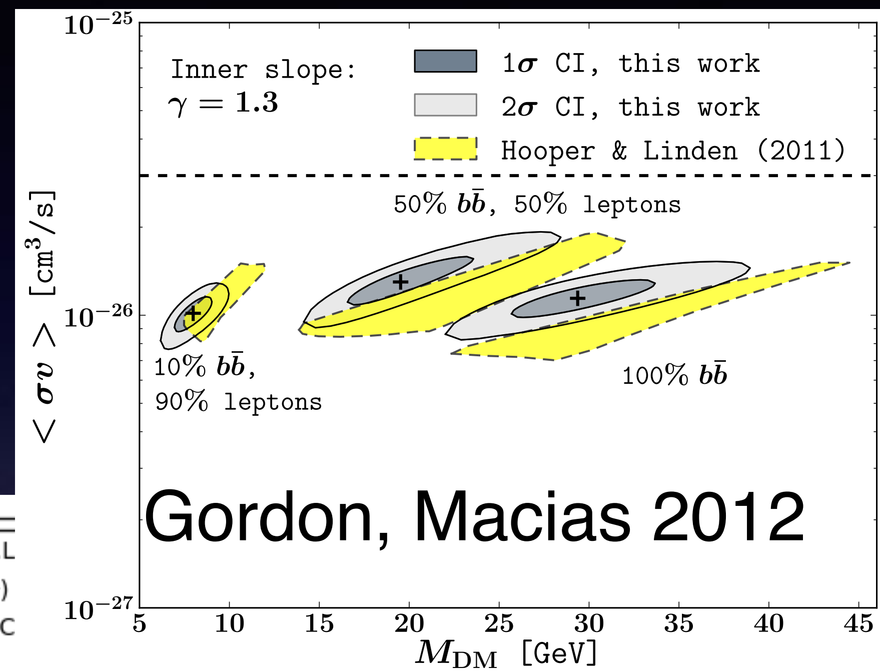

Gordon, Macias 2012

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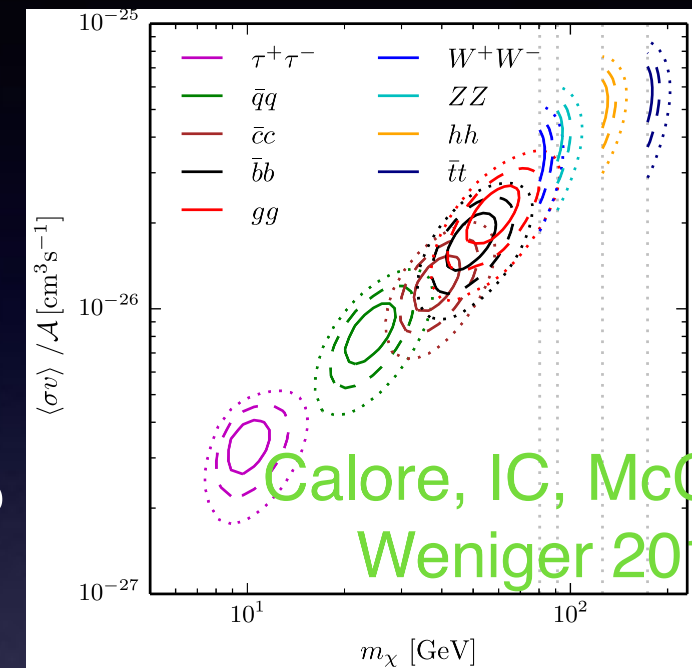
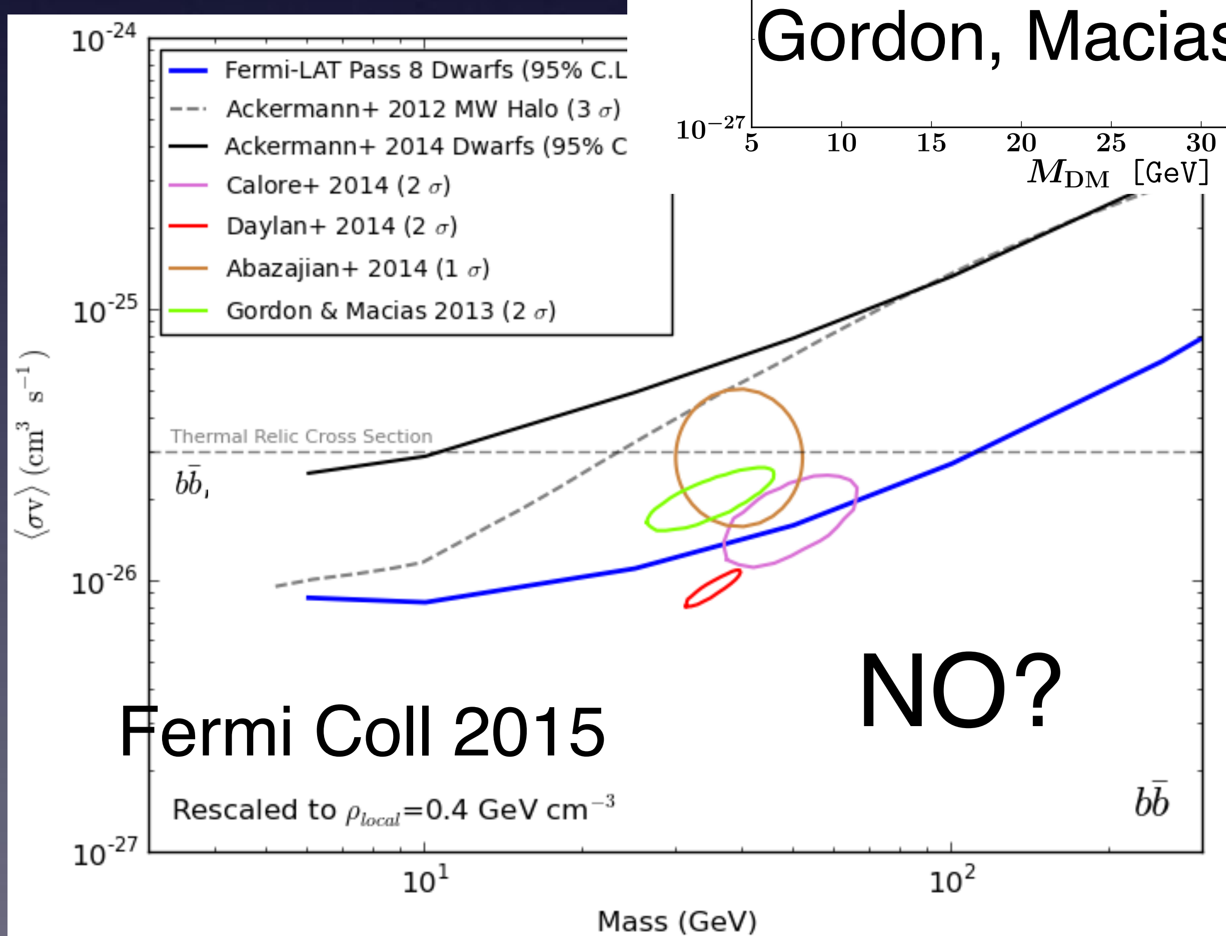


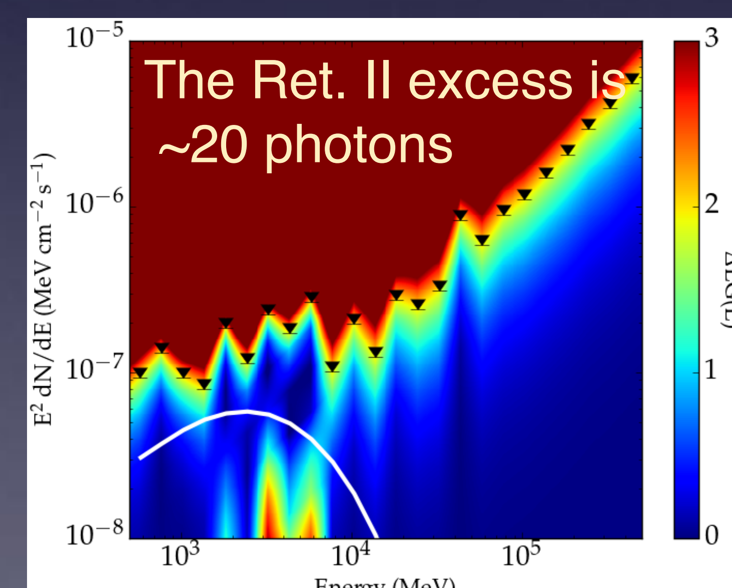
Calore, IC, McCabe, Weniger 2014



Fermi Coll 2015

NO?

YES?



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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)
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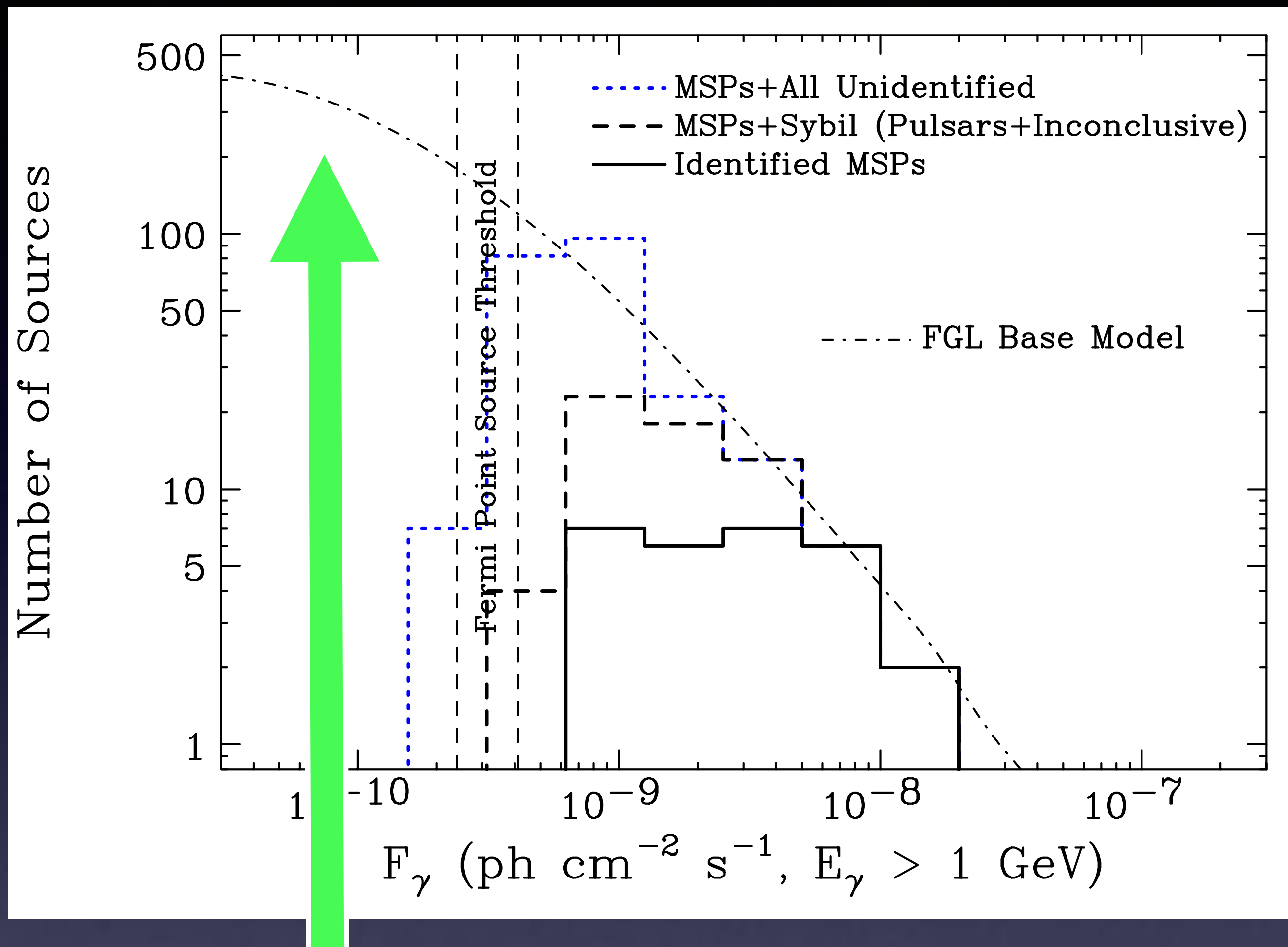

As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

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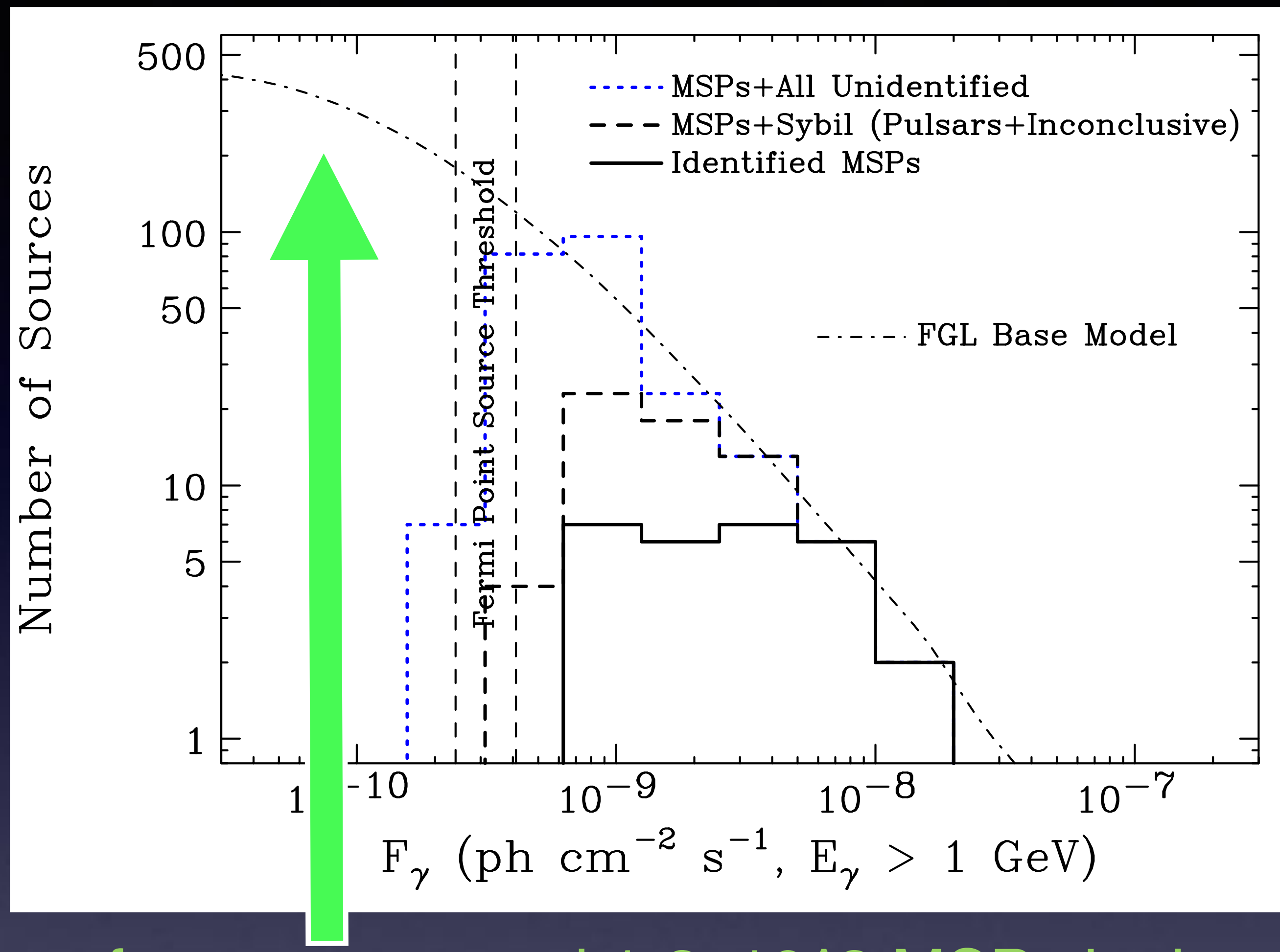

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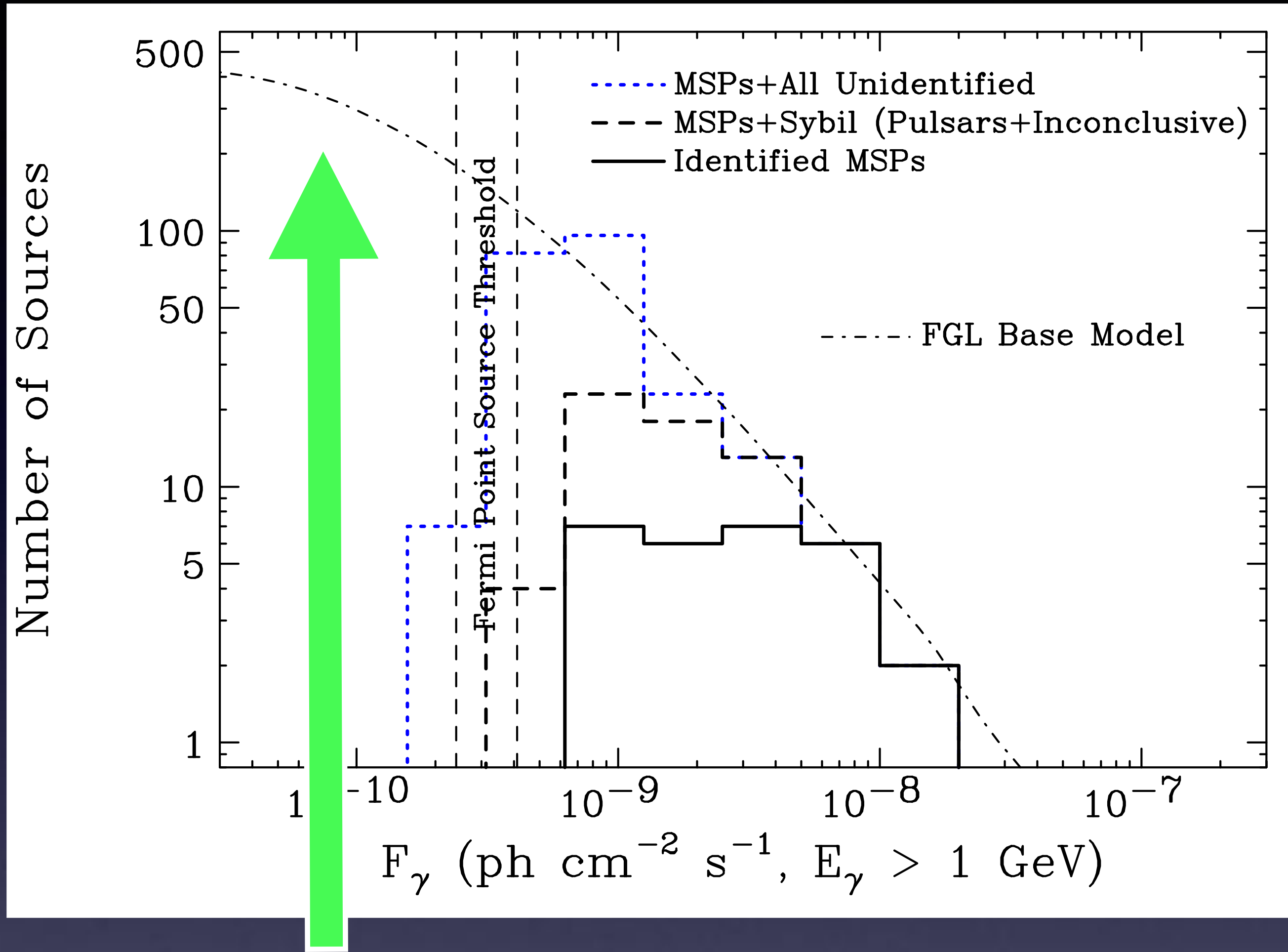

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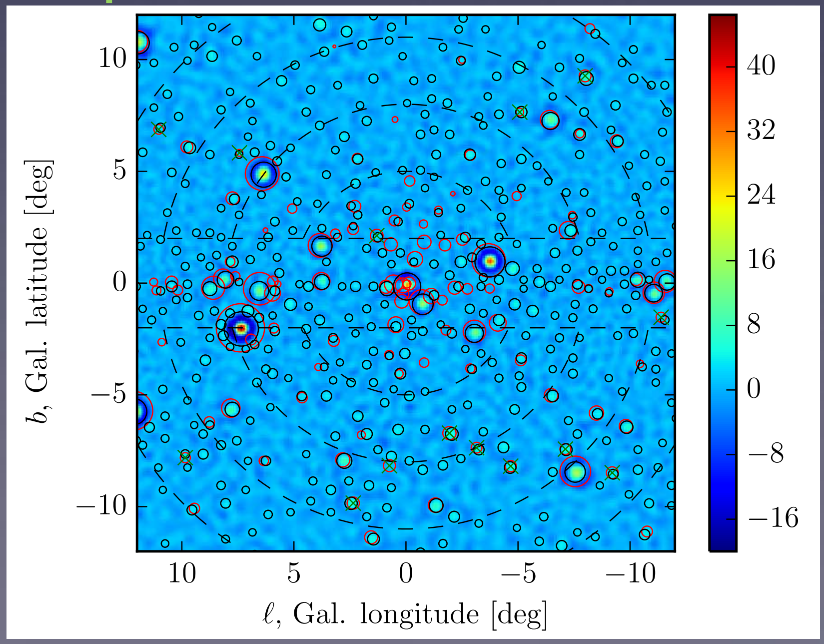

Sensitivity analyses on point-sources and astrophysics modeling:

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

Bursts of Cosmic Rays: Possible Connection to the Fermi Bubbles

Carlson and Profumo PRD 2014 (PROTONS MAYBE?) (actually no)
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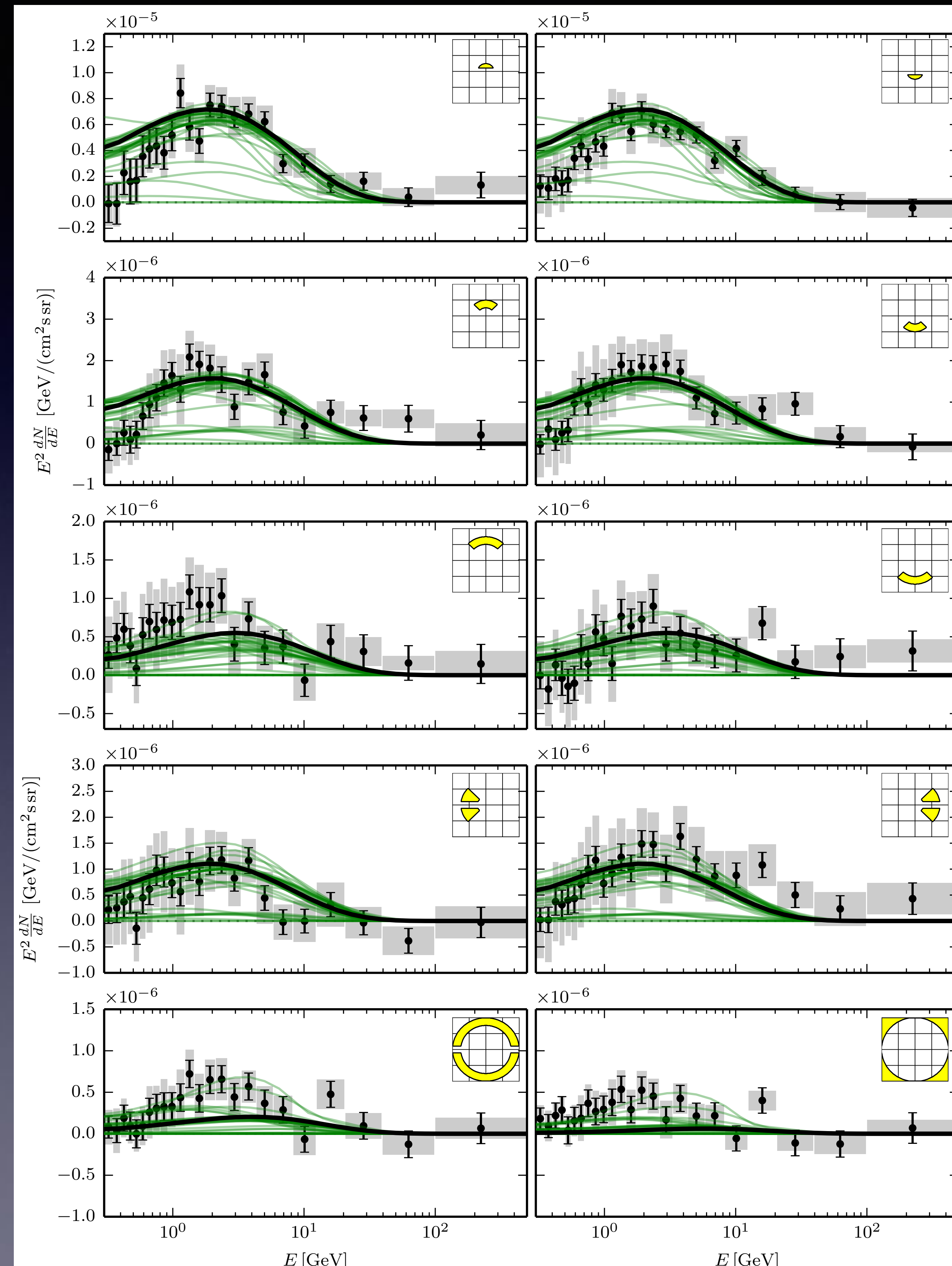

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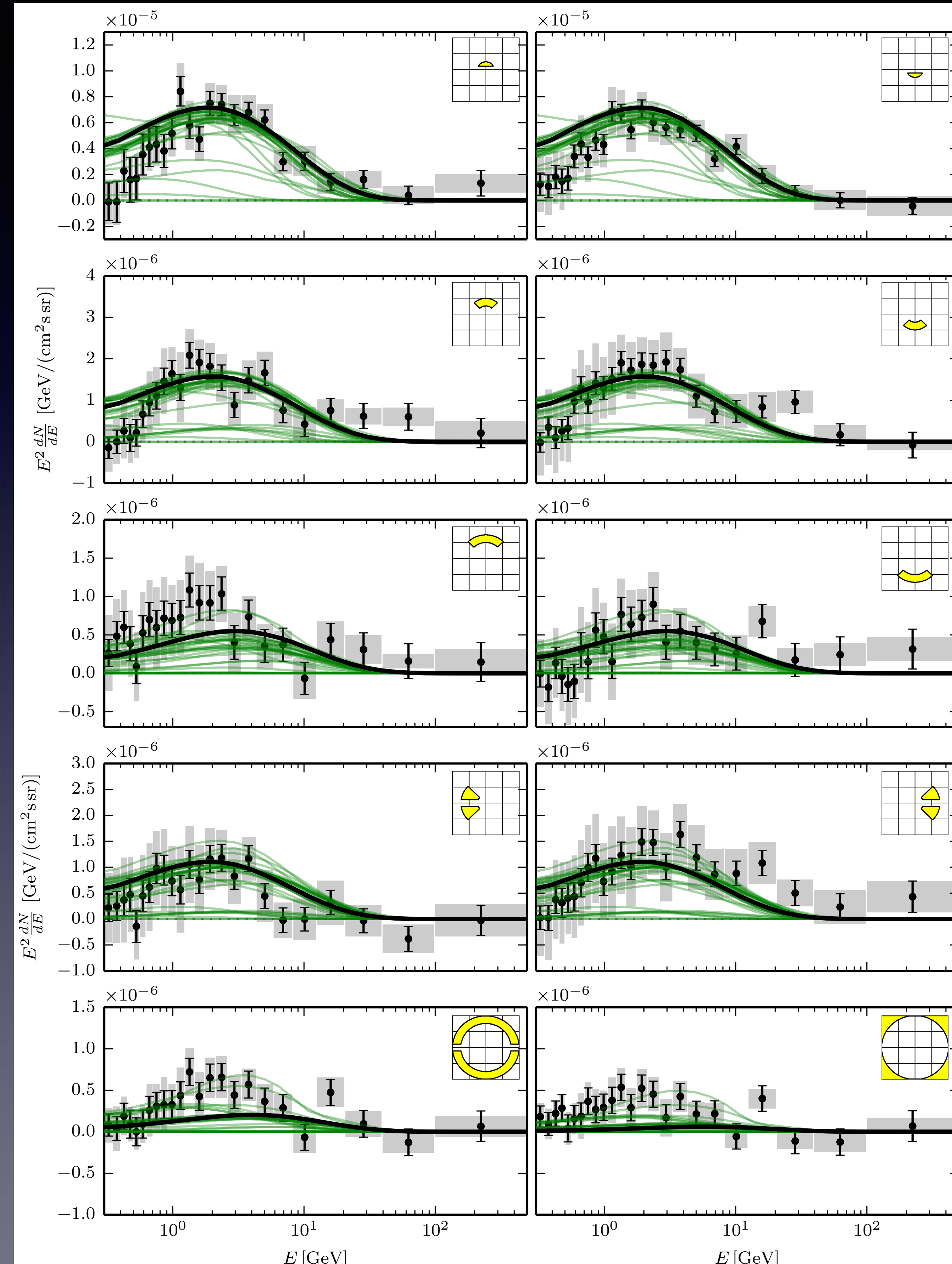

Radio Limits:

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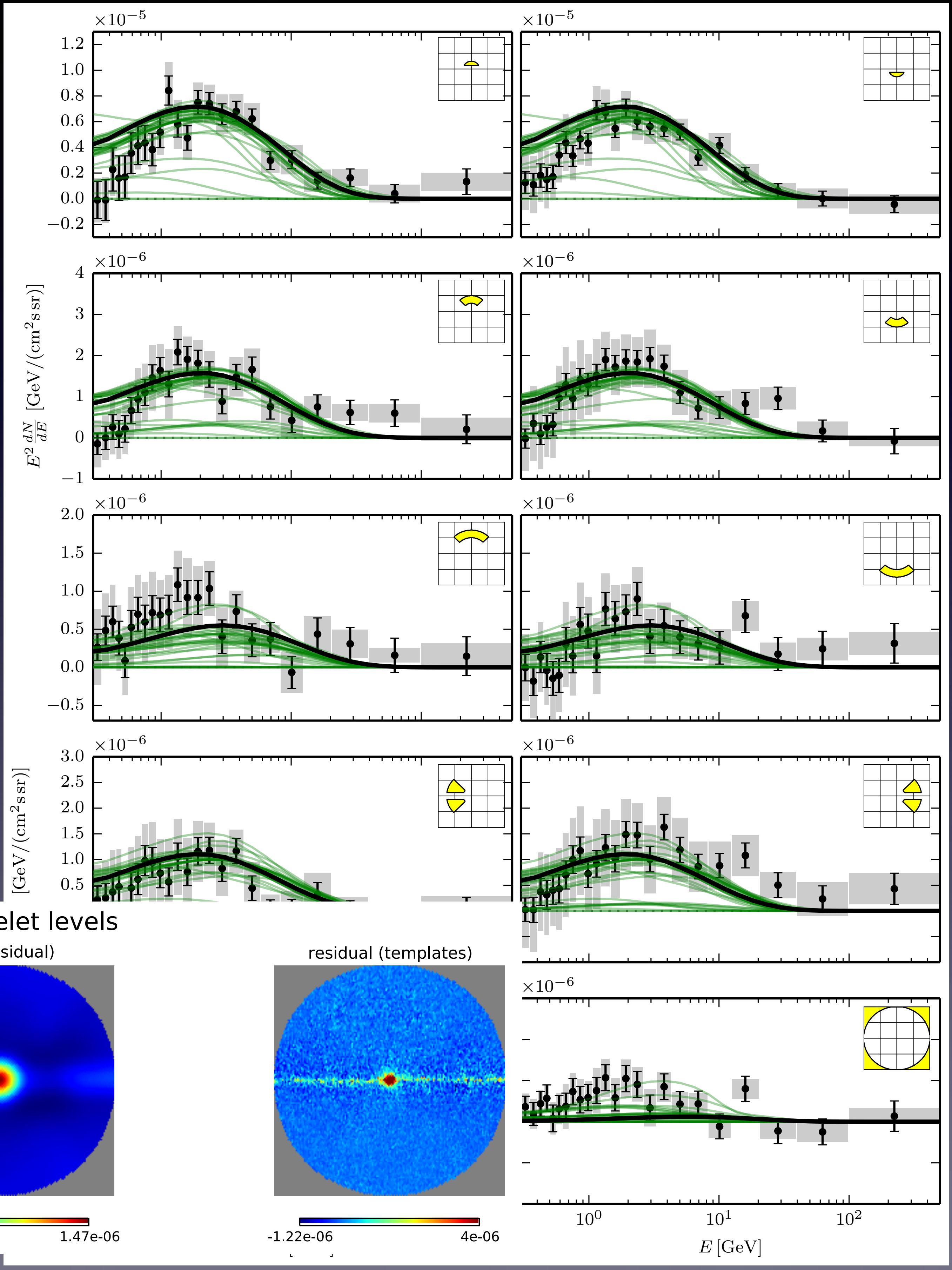
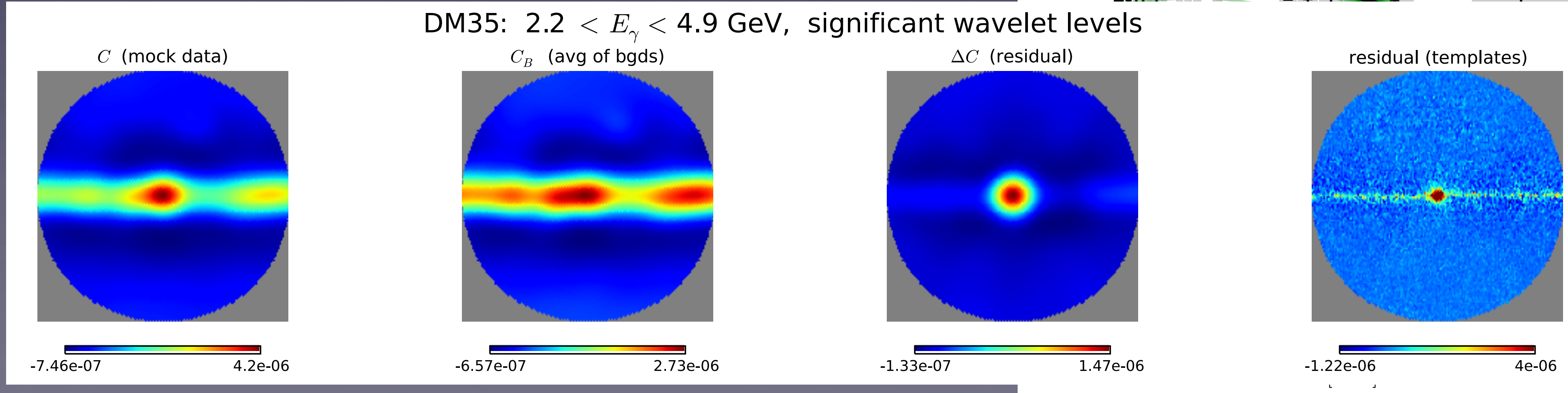
Wavelet techniques (TIE BRAKER?):

McDermott, Fox, IC, Lee JCAP 2016





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

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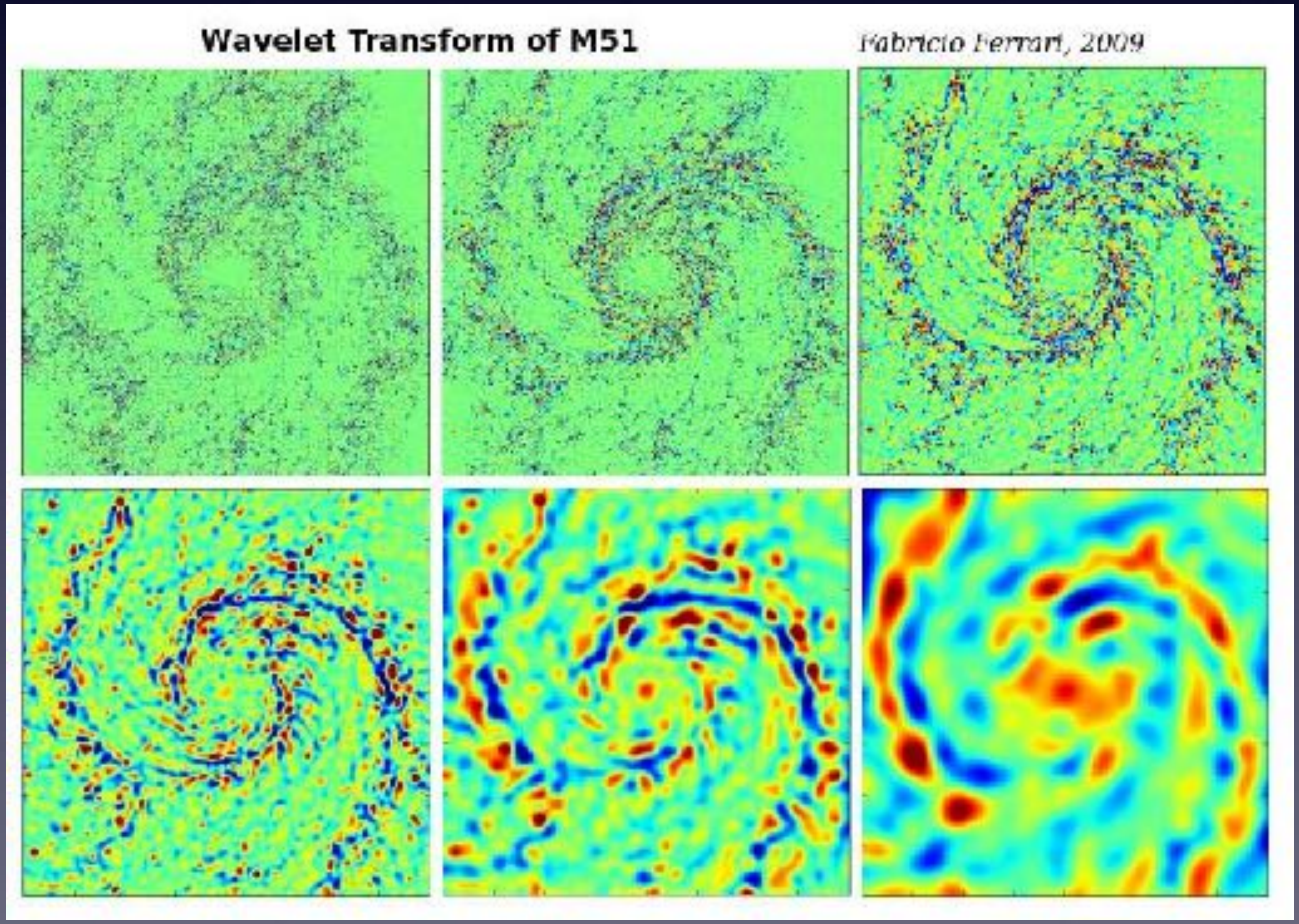
Allow analysis of data in both time/space and frequency space



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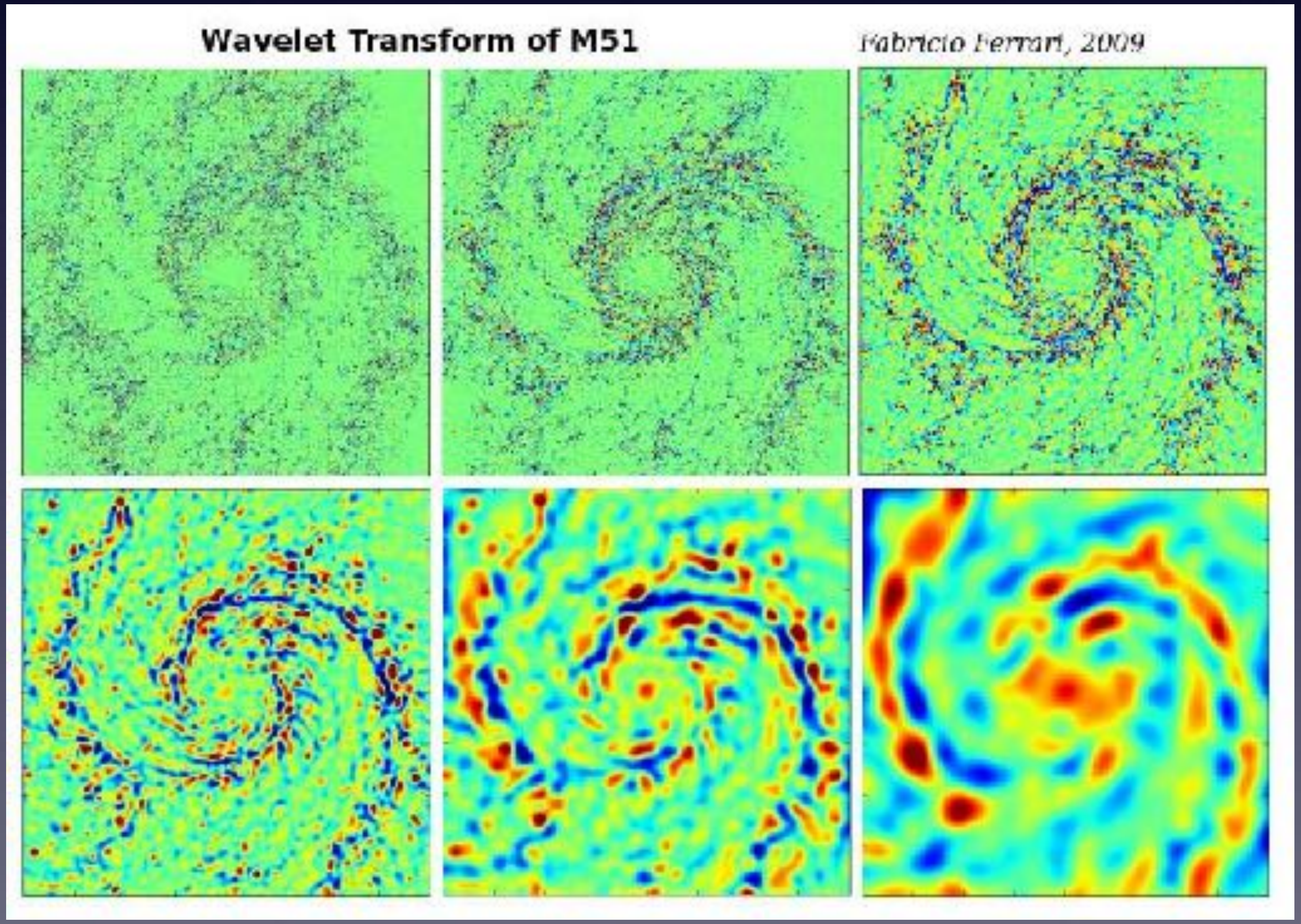
Allow analysis of data in both time/space and frequency space

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?

wavelet coefficients

original signal

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

scale

position

mother wavelet
(different choices)

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

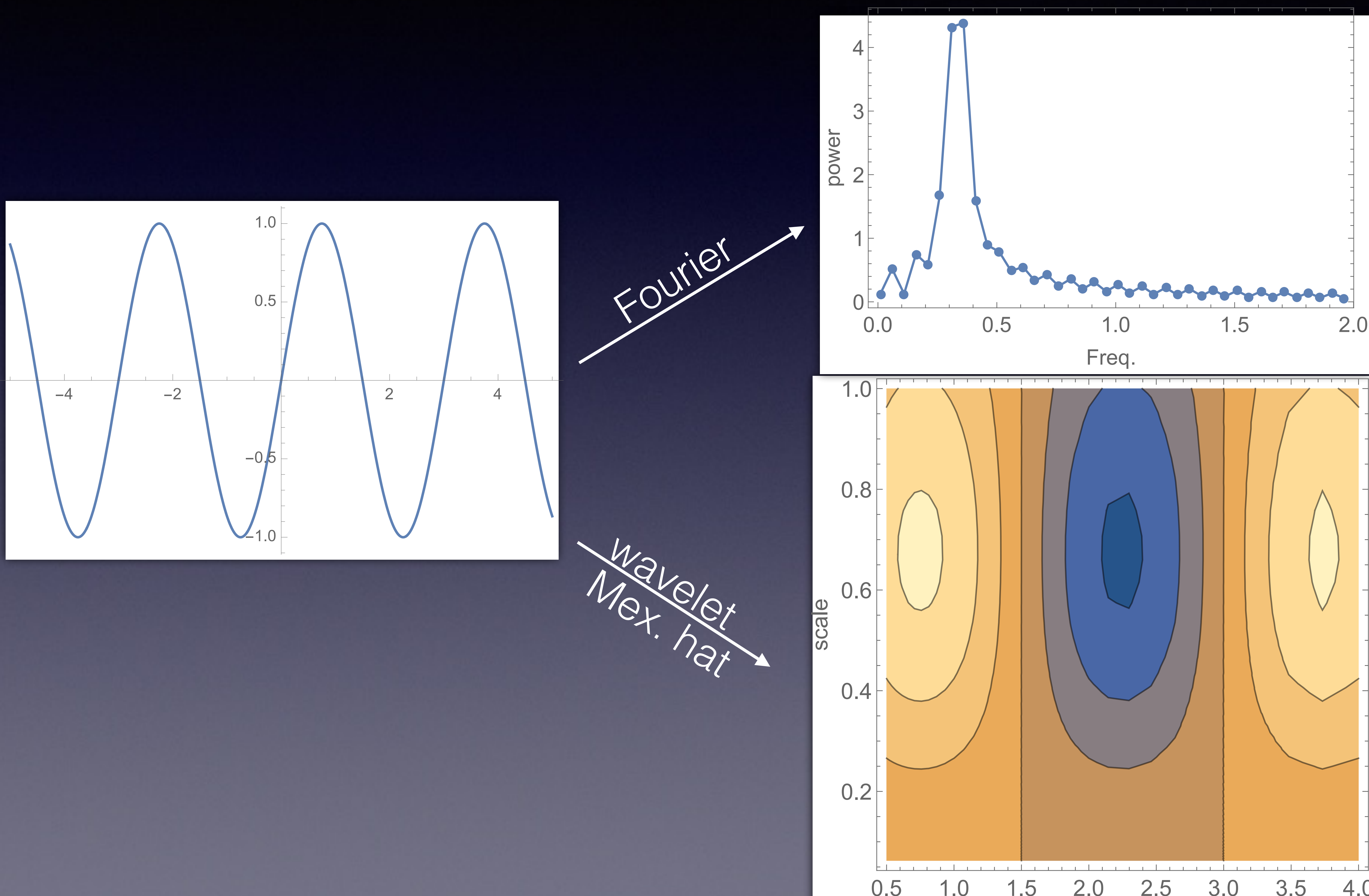
$\psi(x) \in \mathbb{L}^2(\mathbb{R})$ and

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

$$\psi_{m,n}(x) = \frac{1}{\sqrt{a^m}}\psi(\frac{x-nb}{a^m})$$

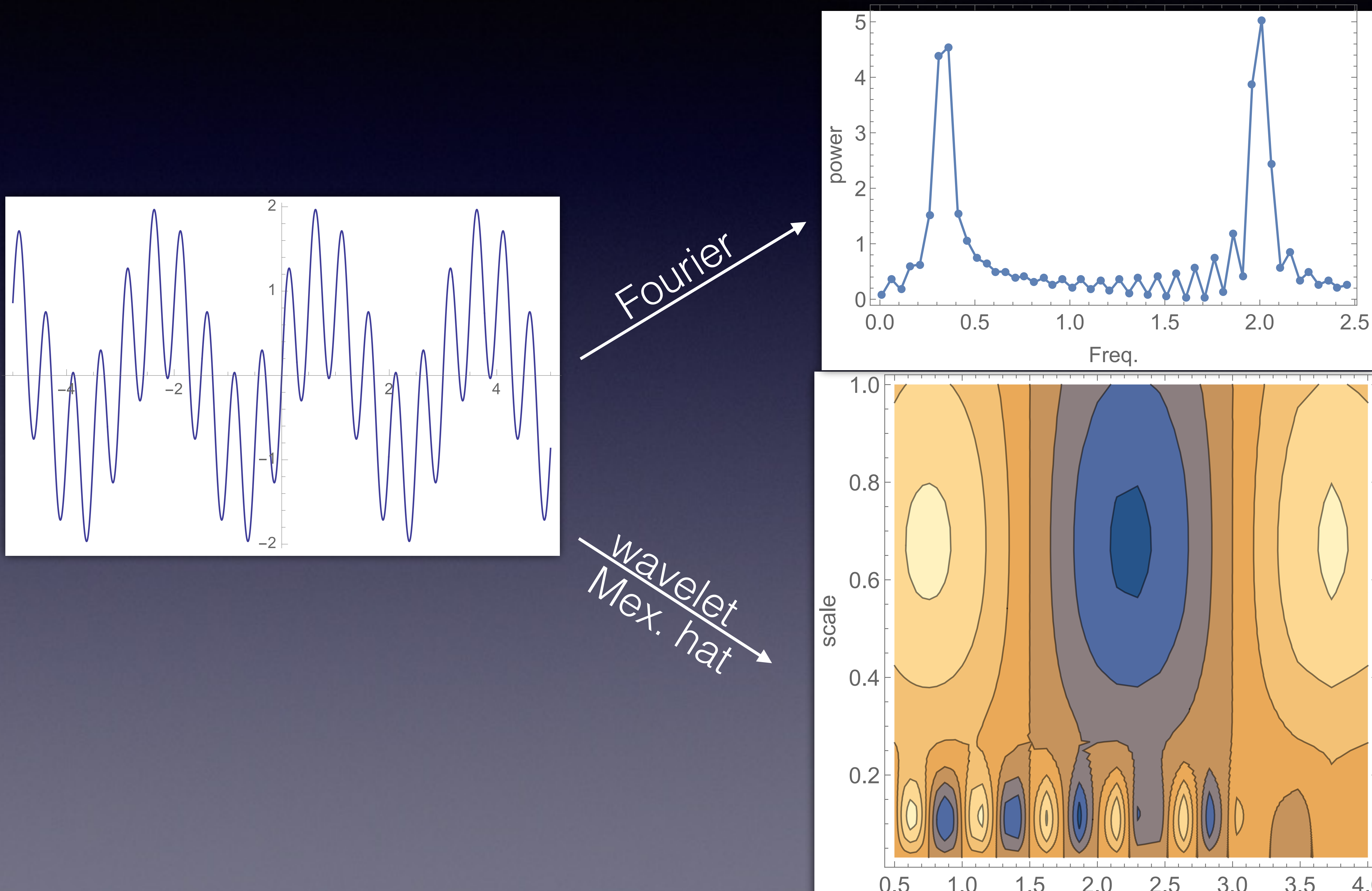
$$n, m \,\epsilon\, Z$$

sine wave

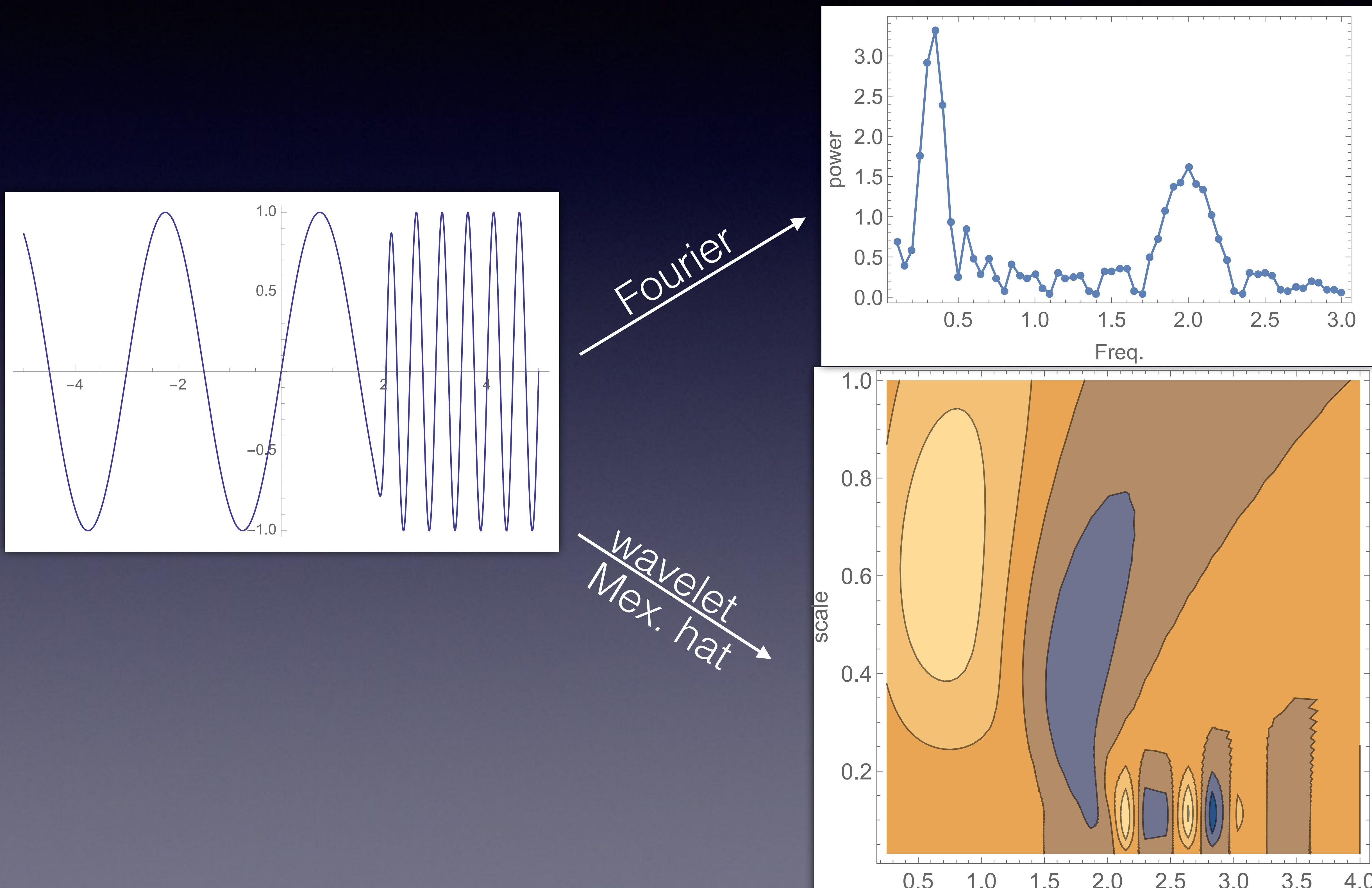


1.0
0.5
−0.5
−1.0
−4
−2
2
4
Fourier
power
Freq.
0.0
0.5
1.0
1.5
2.0
wavelet
Mex. hat
scale
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

two sine waves



sine waves with transition

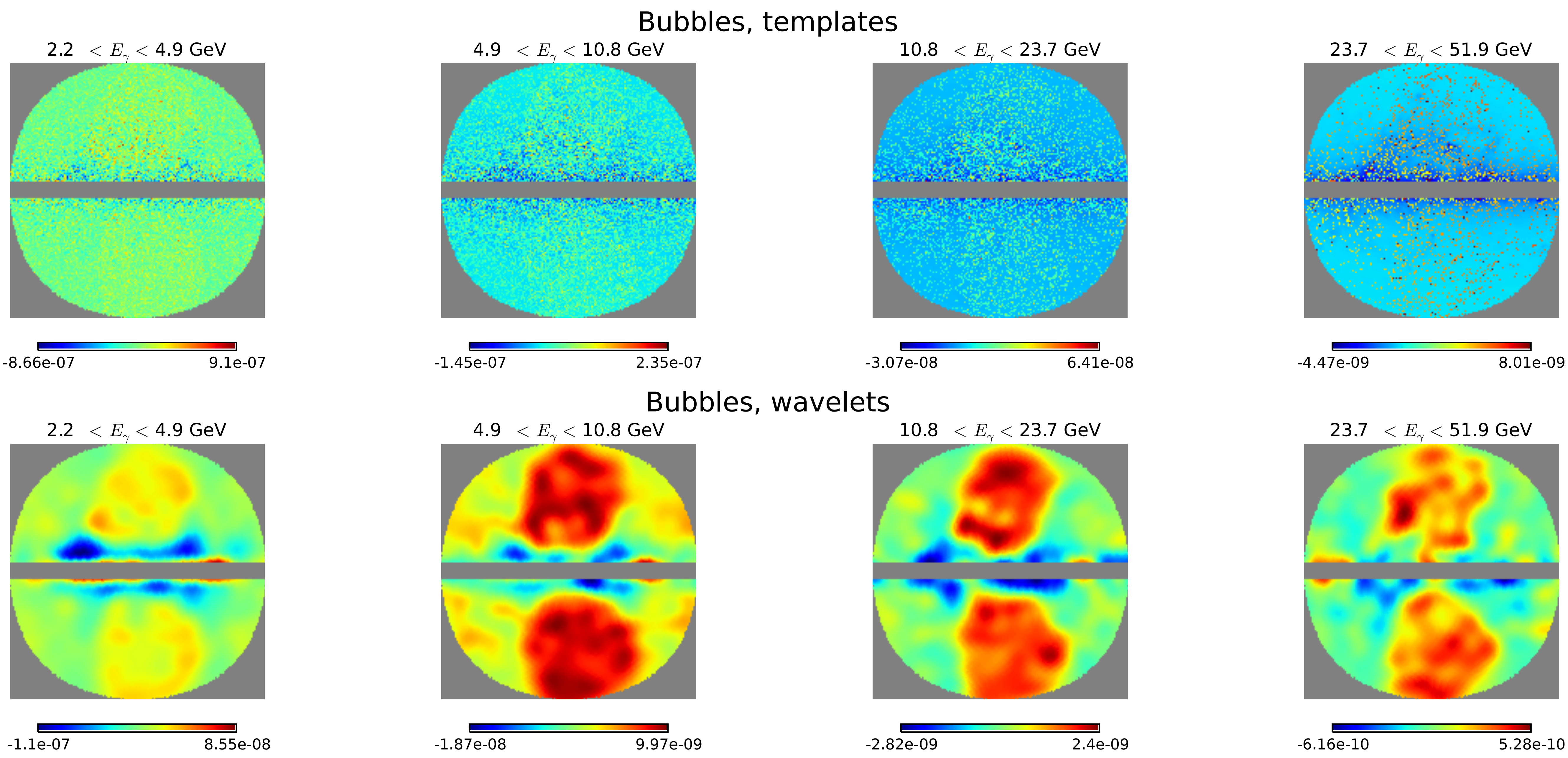


Is it better than the Templates?

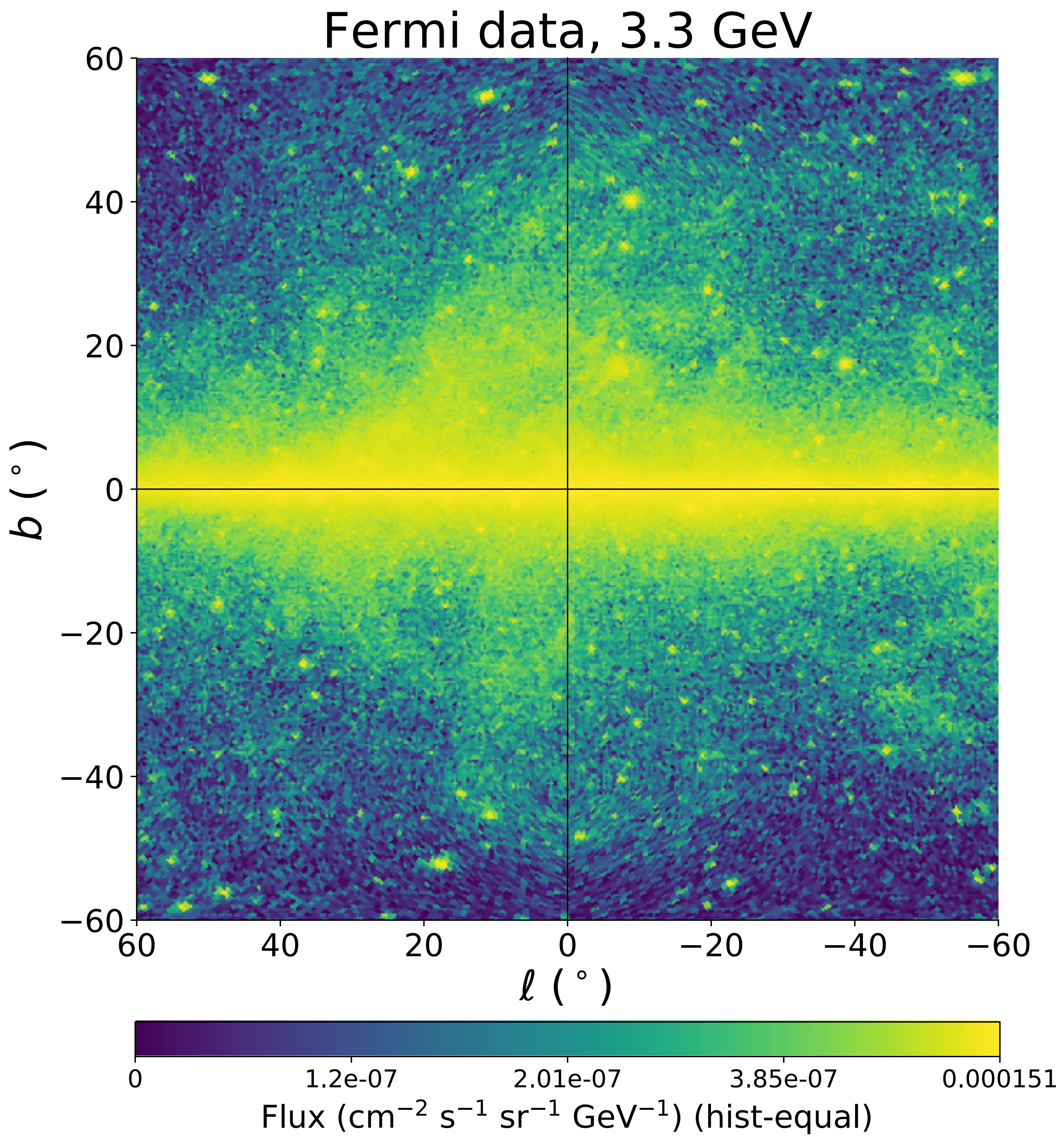
Technique was developed in McDermott, Fox, Cholis, Lee JCAP 2016 using simulated data. Requires statistics but has less dependence on fore-ground/background assumptions (in the end it does also have some systematics).

Decompose the sky into 8 scales (smallest 6):

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



Using the Fermi Data



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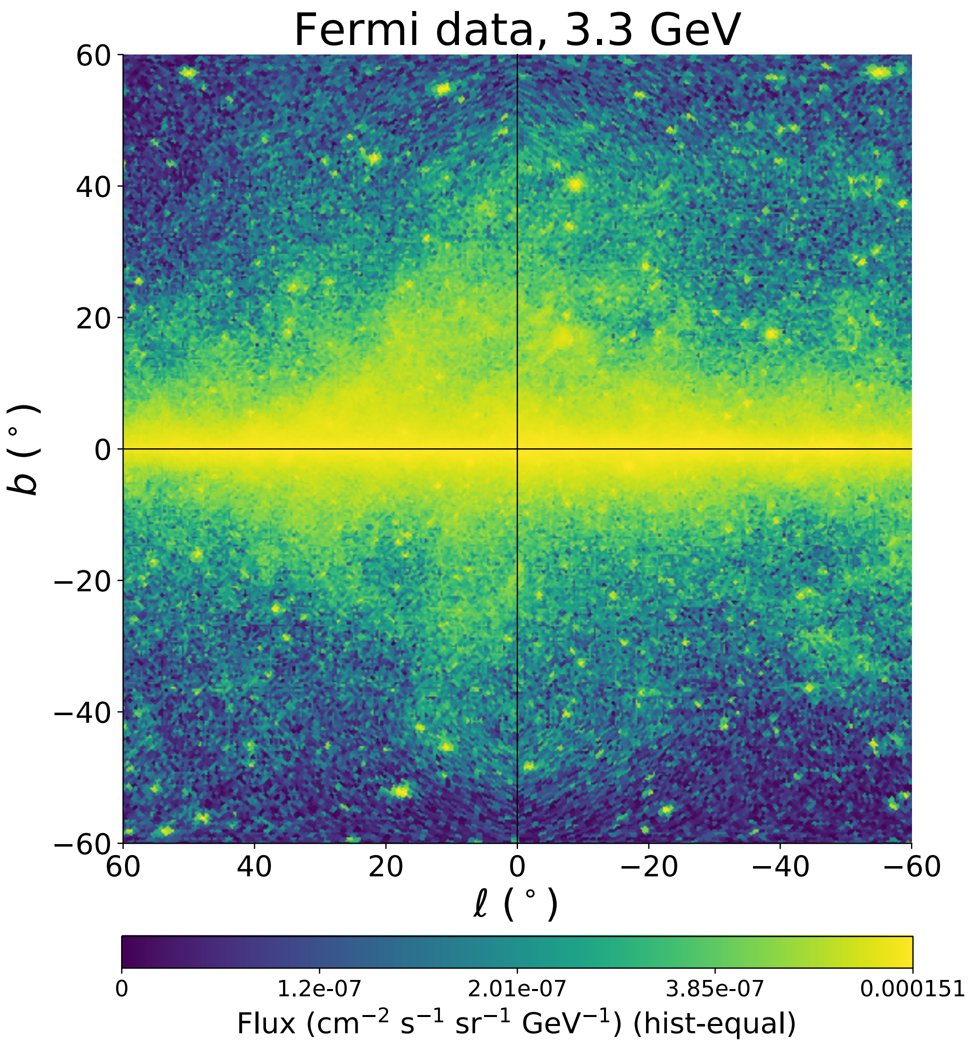

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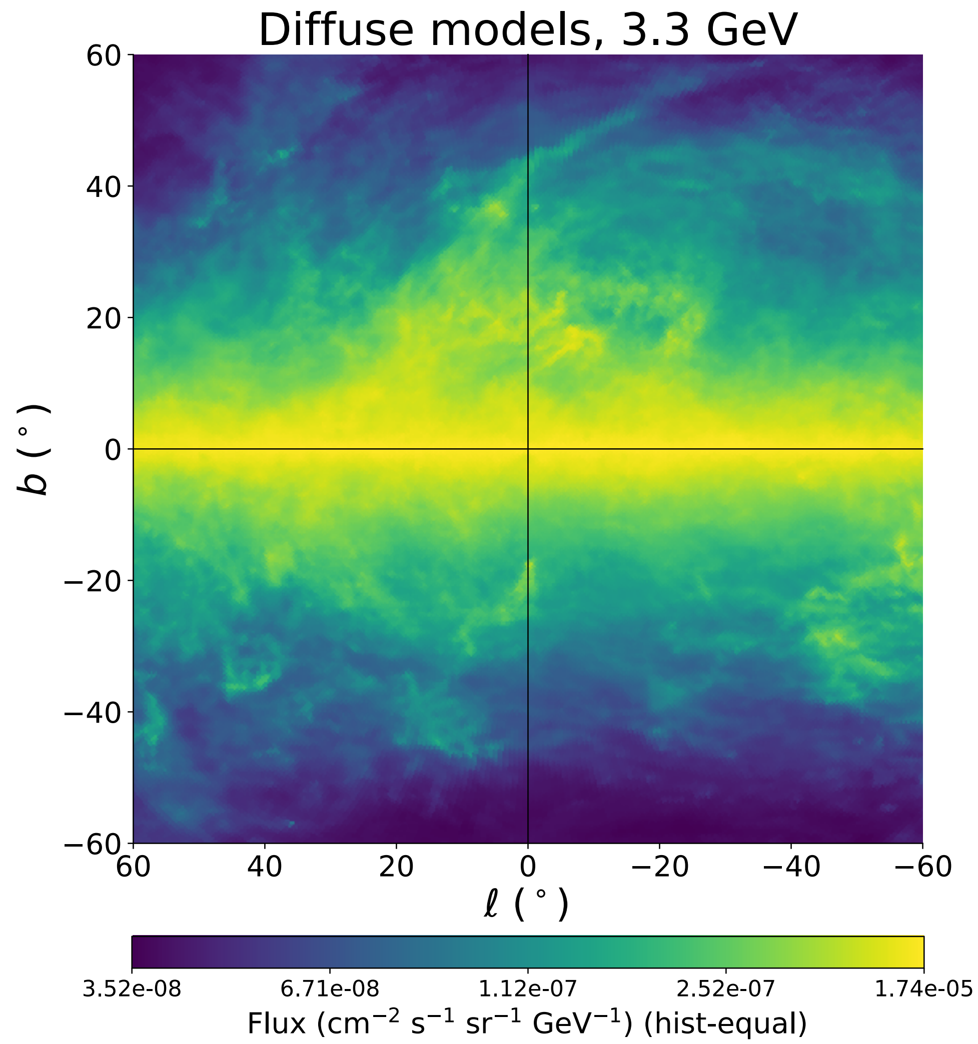
collection of ISM models



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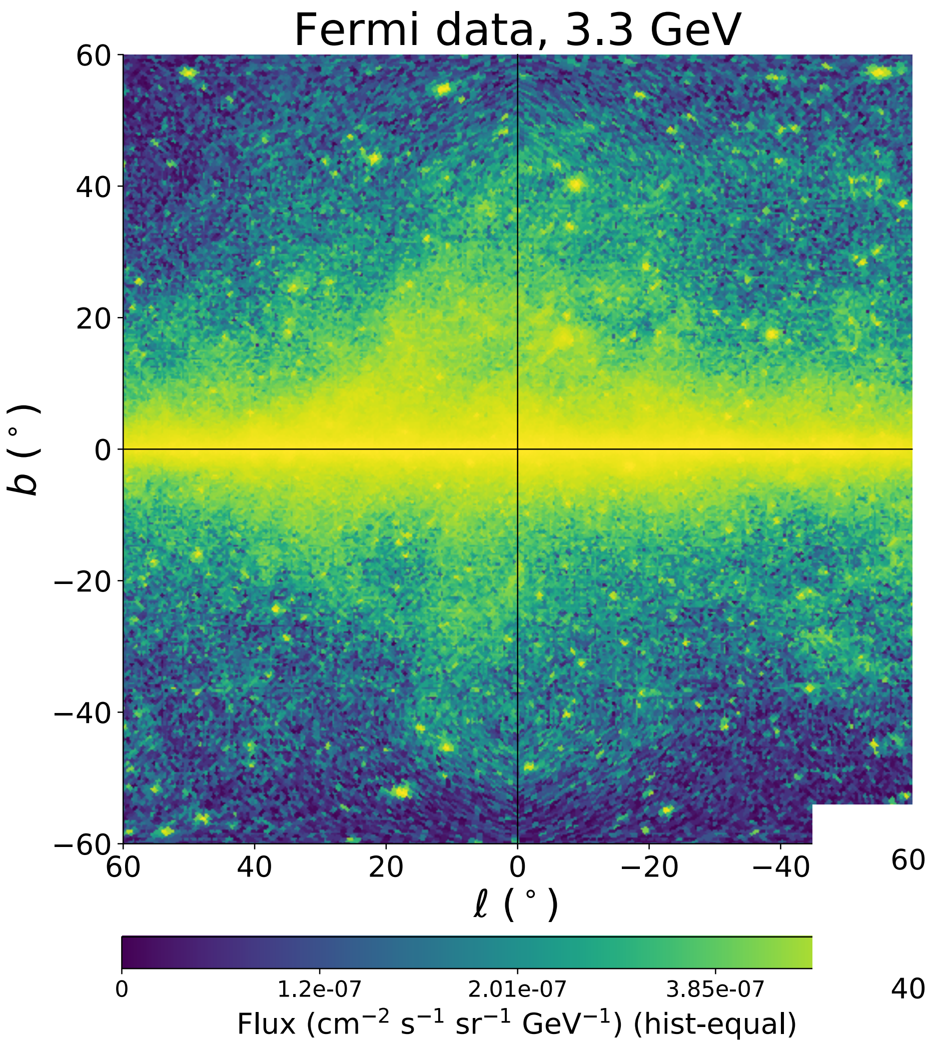

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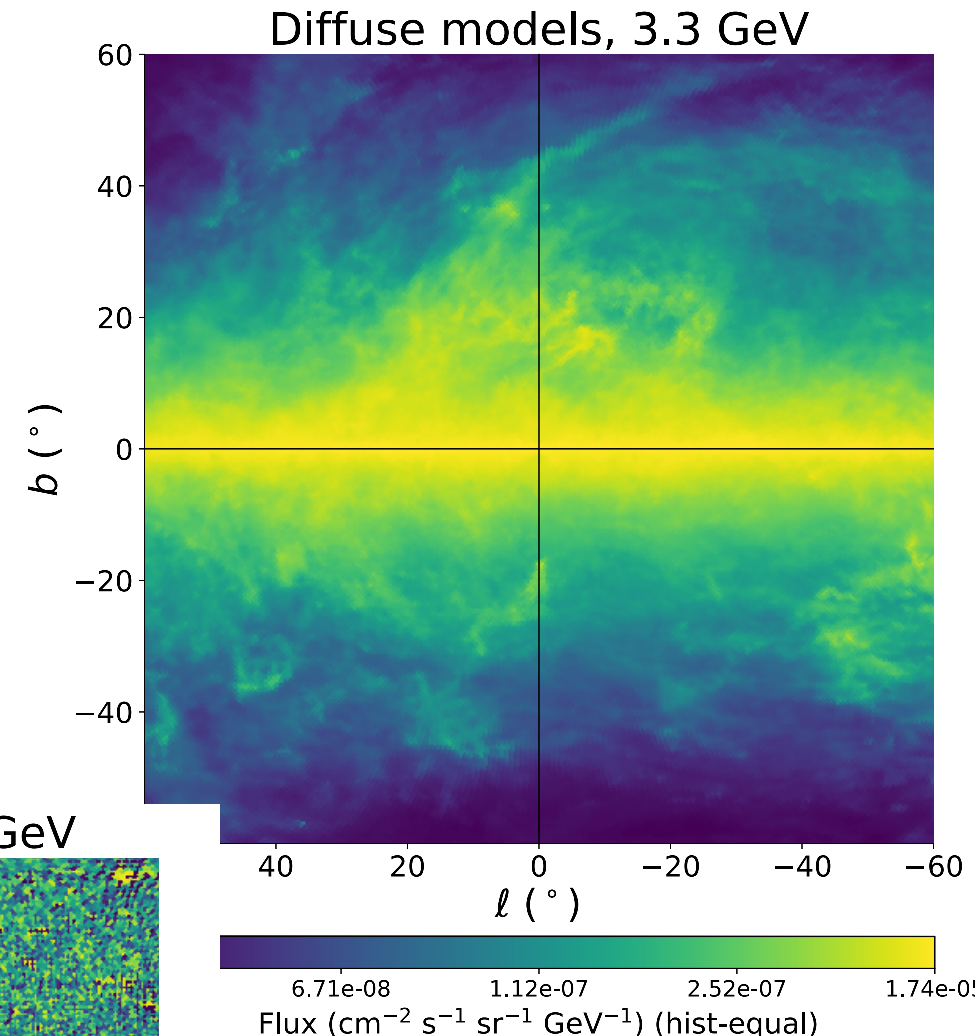
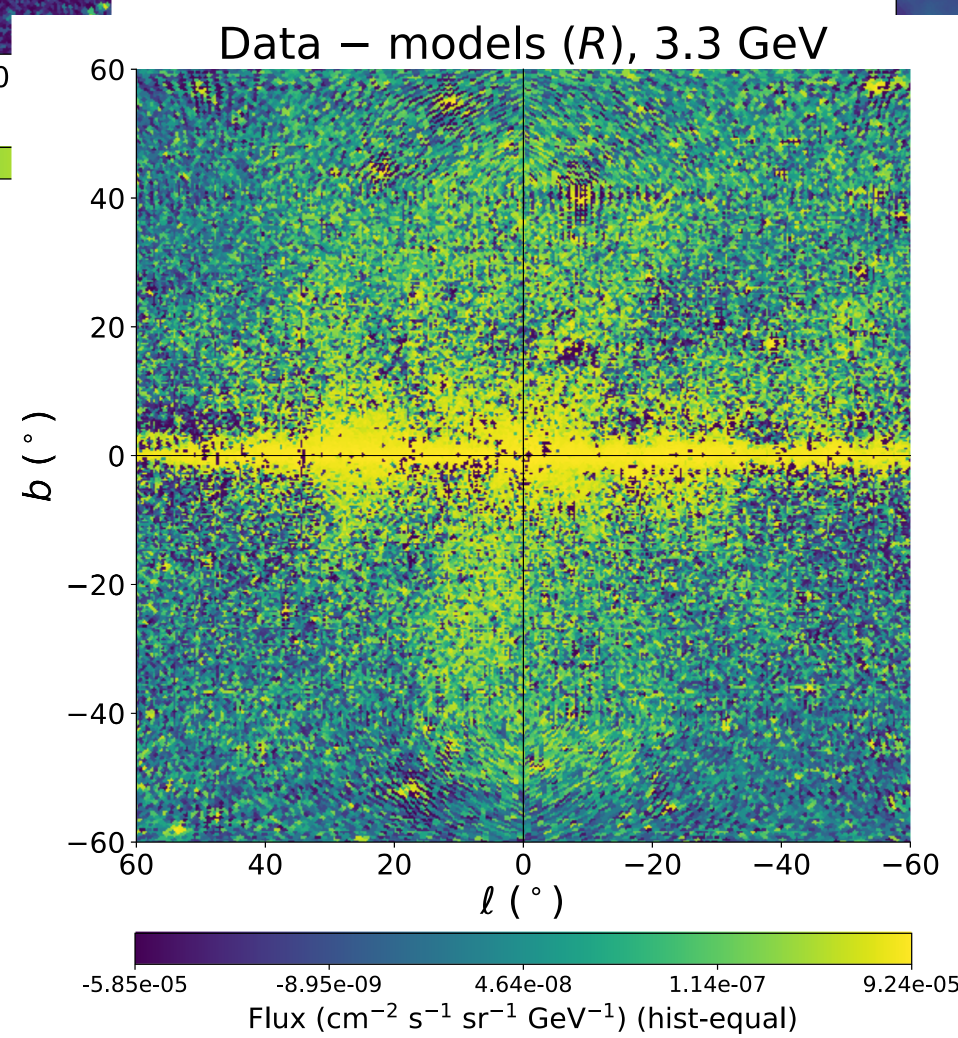
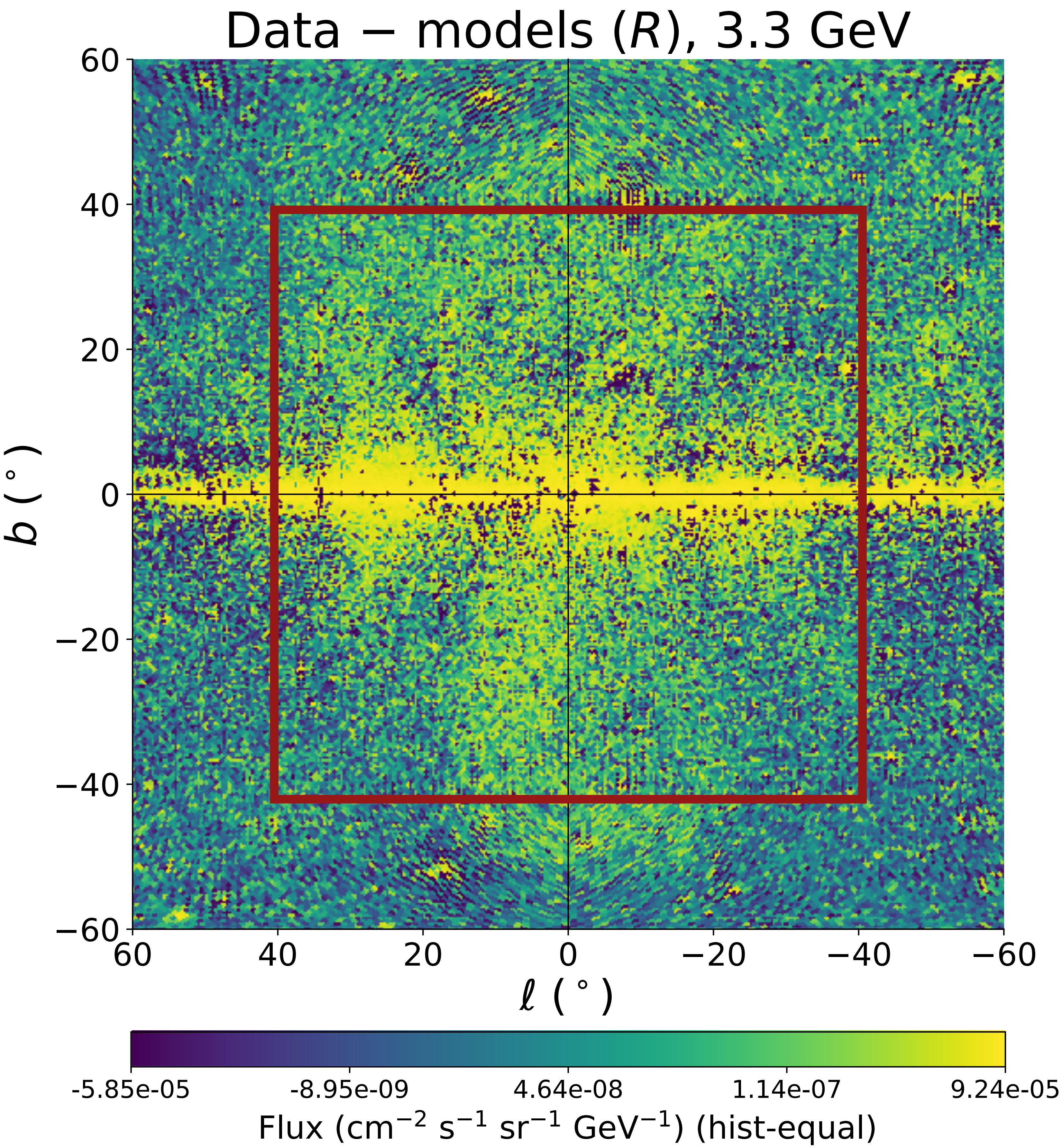


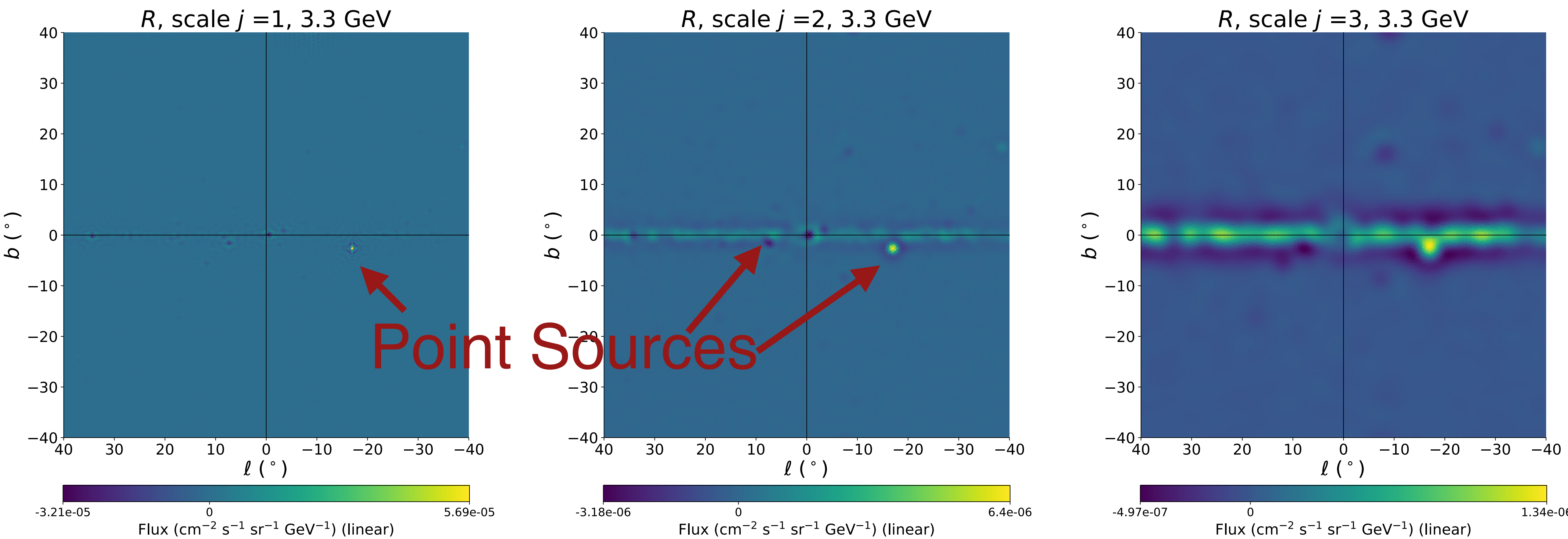
- 3FGL =



Zoom in the inner 80 x 80 degrees:



Subtracting the Average Emission AND Decomposing the Residual in different scales



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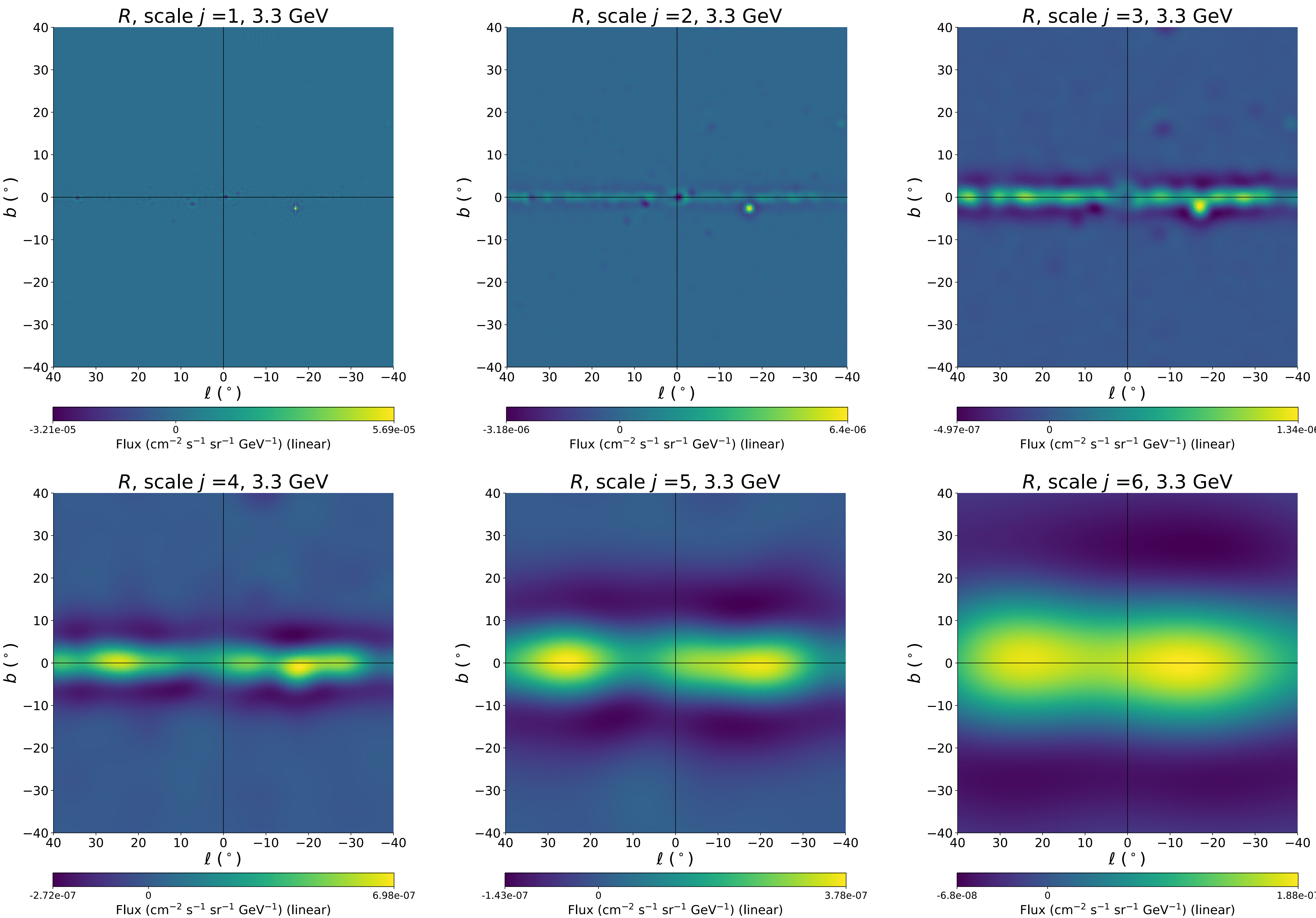

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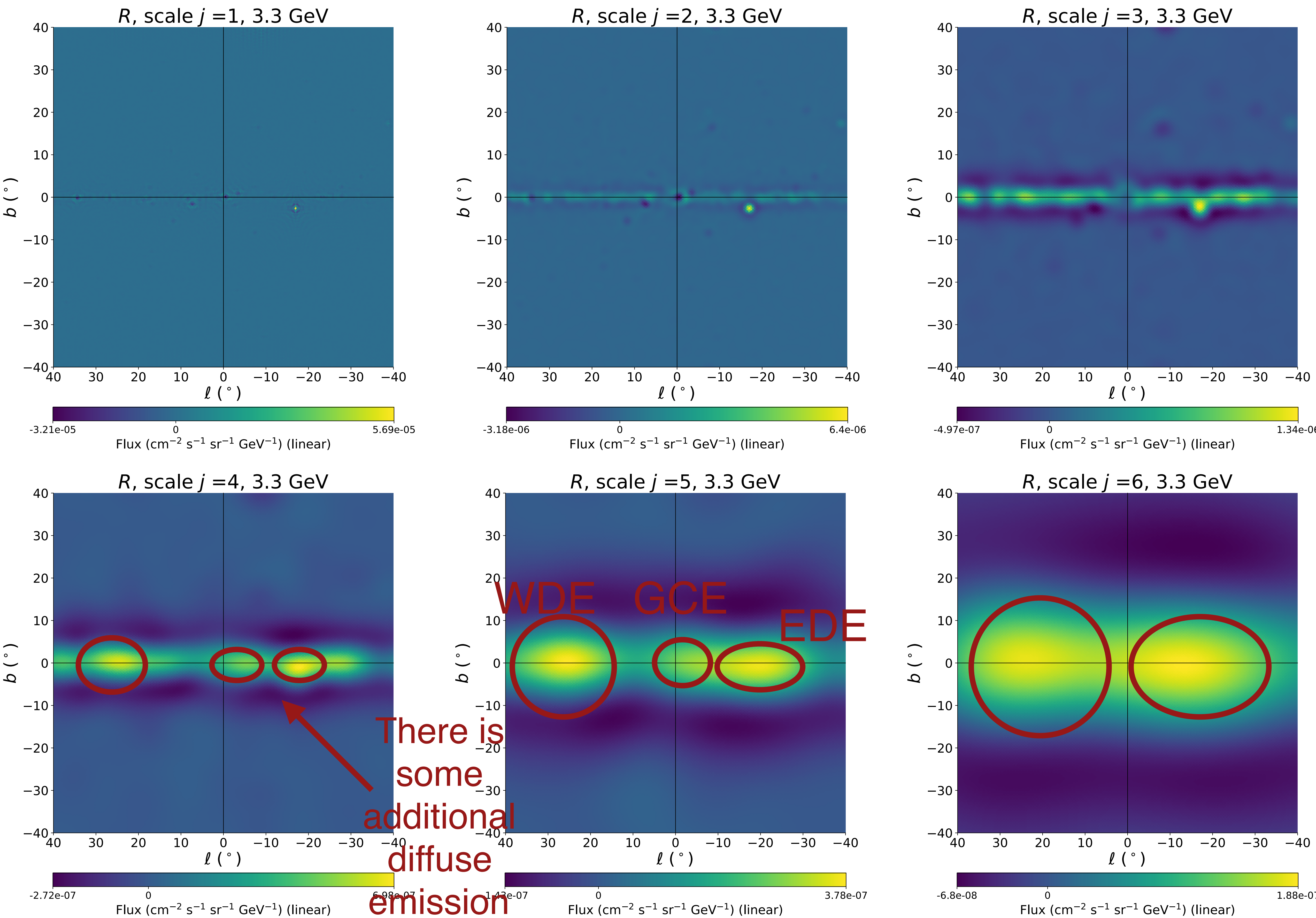

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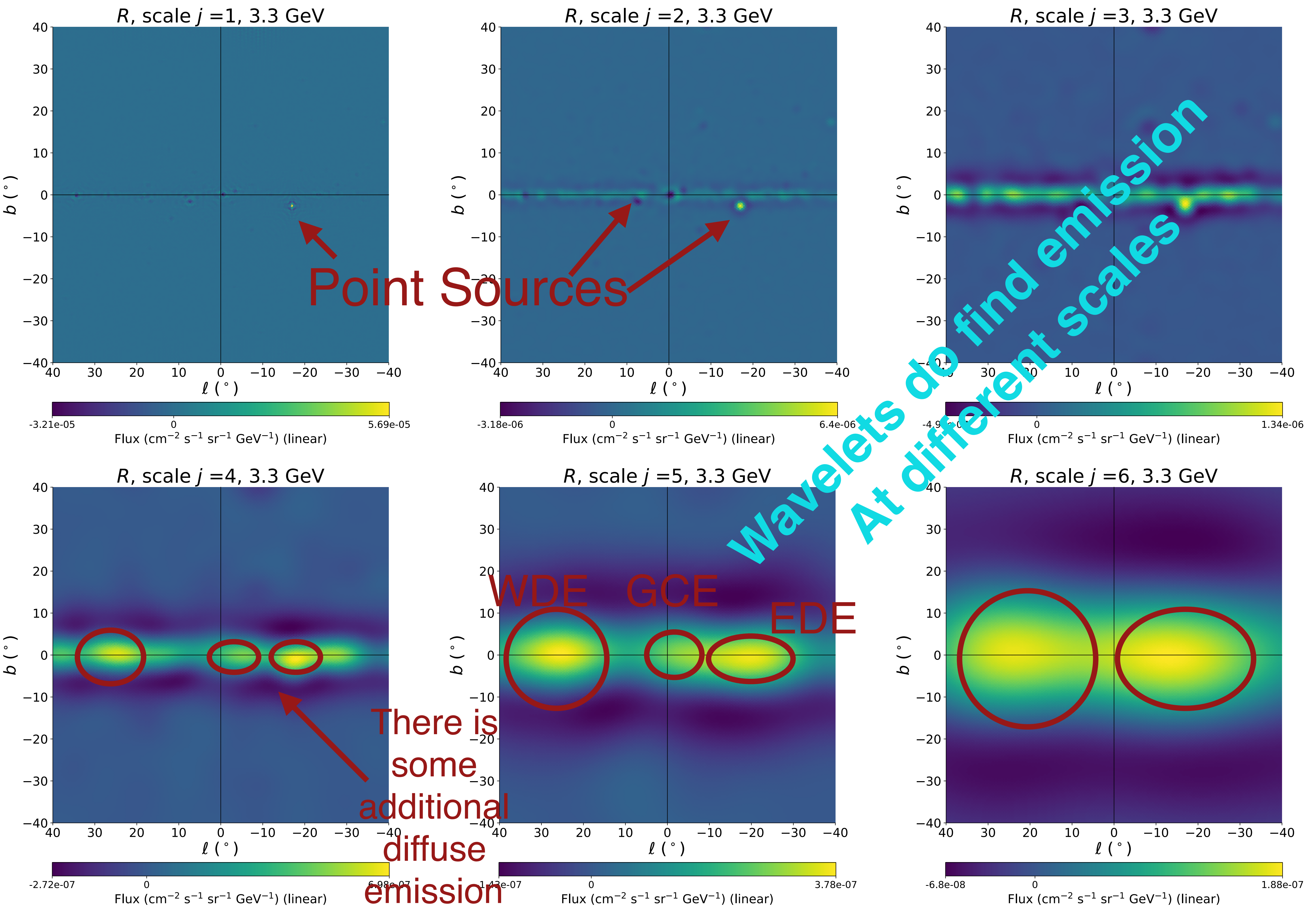
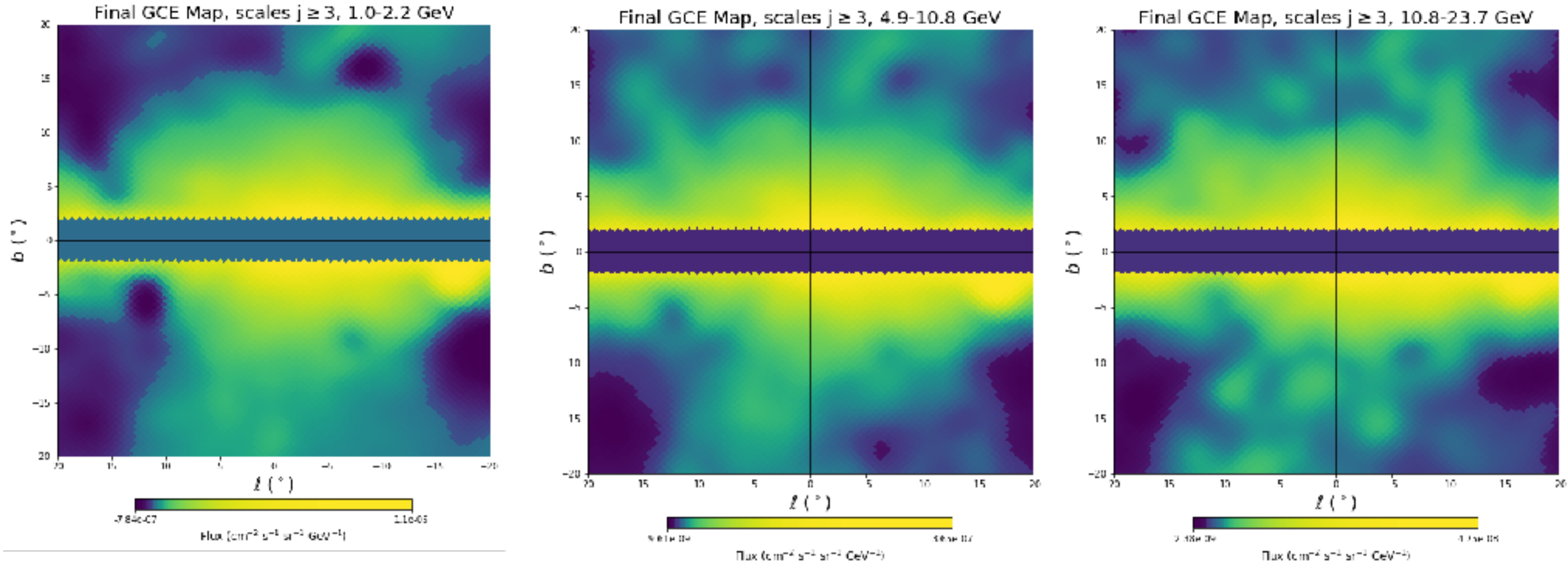


Adding everything back together (but not the map average):

Zooming further in and masking the galactic disk:



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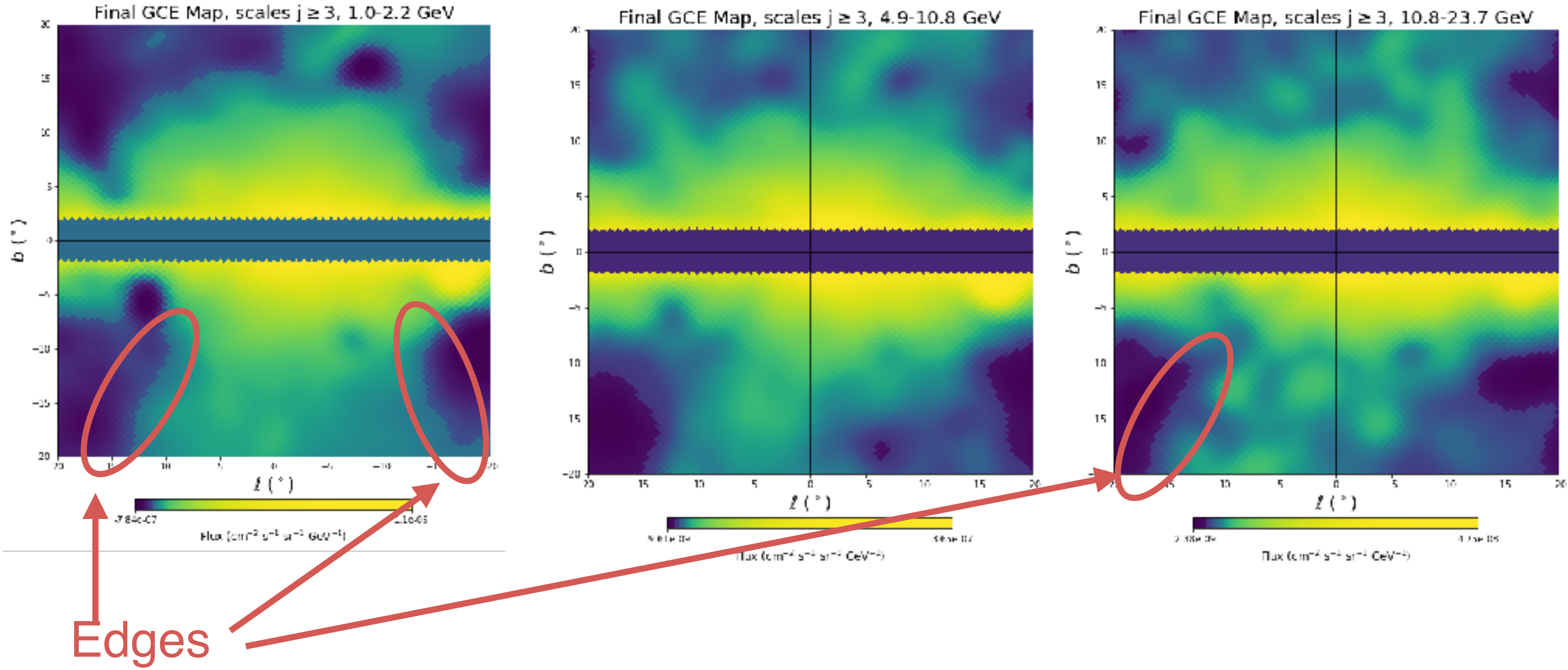
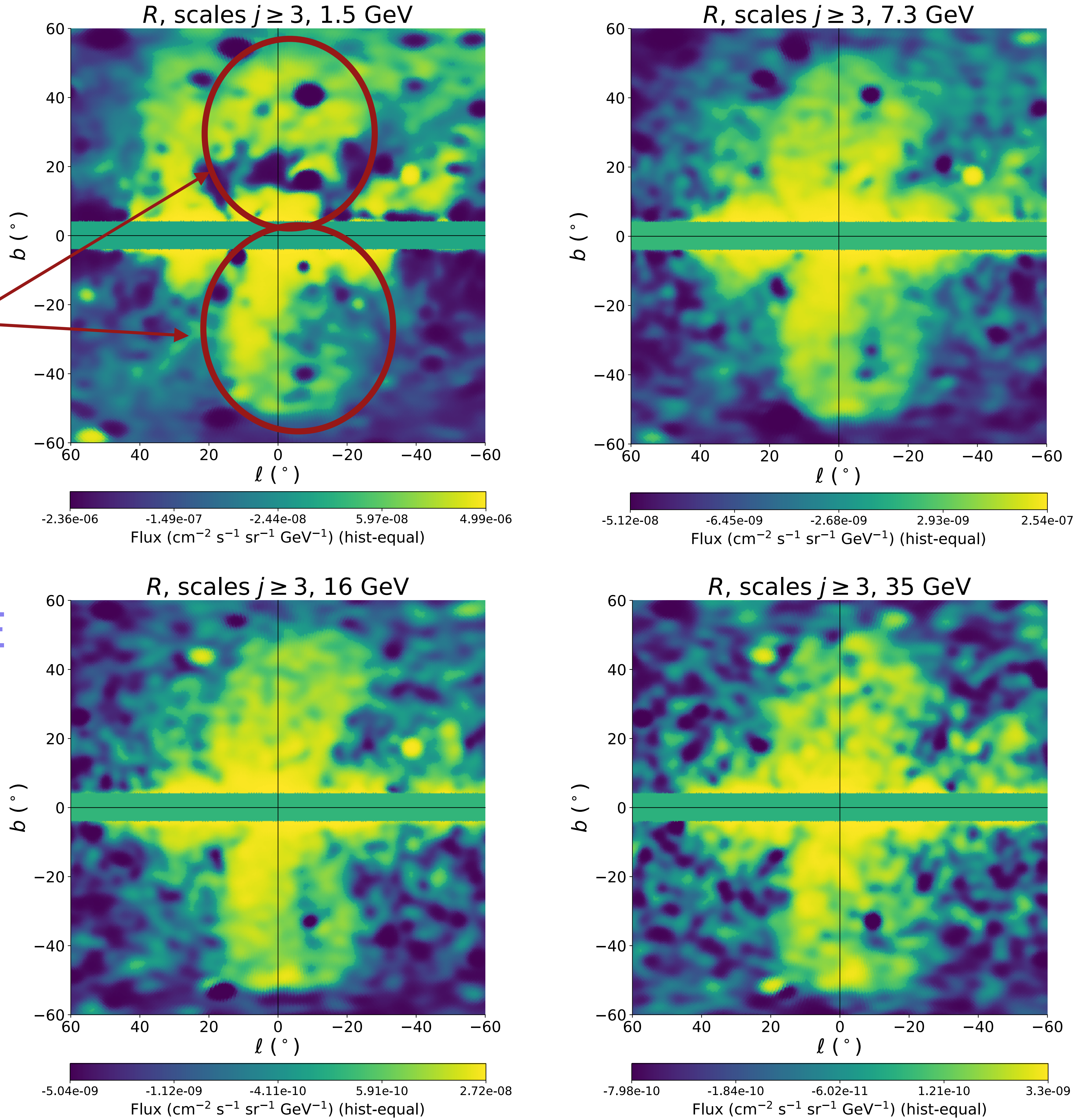


Zoom out

Fermi Bubbles: (we clearly find them)



We do not directly disentangle Fermi Bubbles from GCE

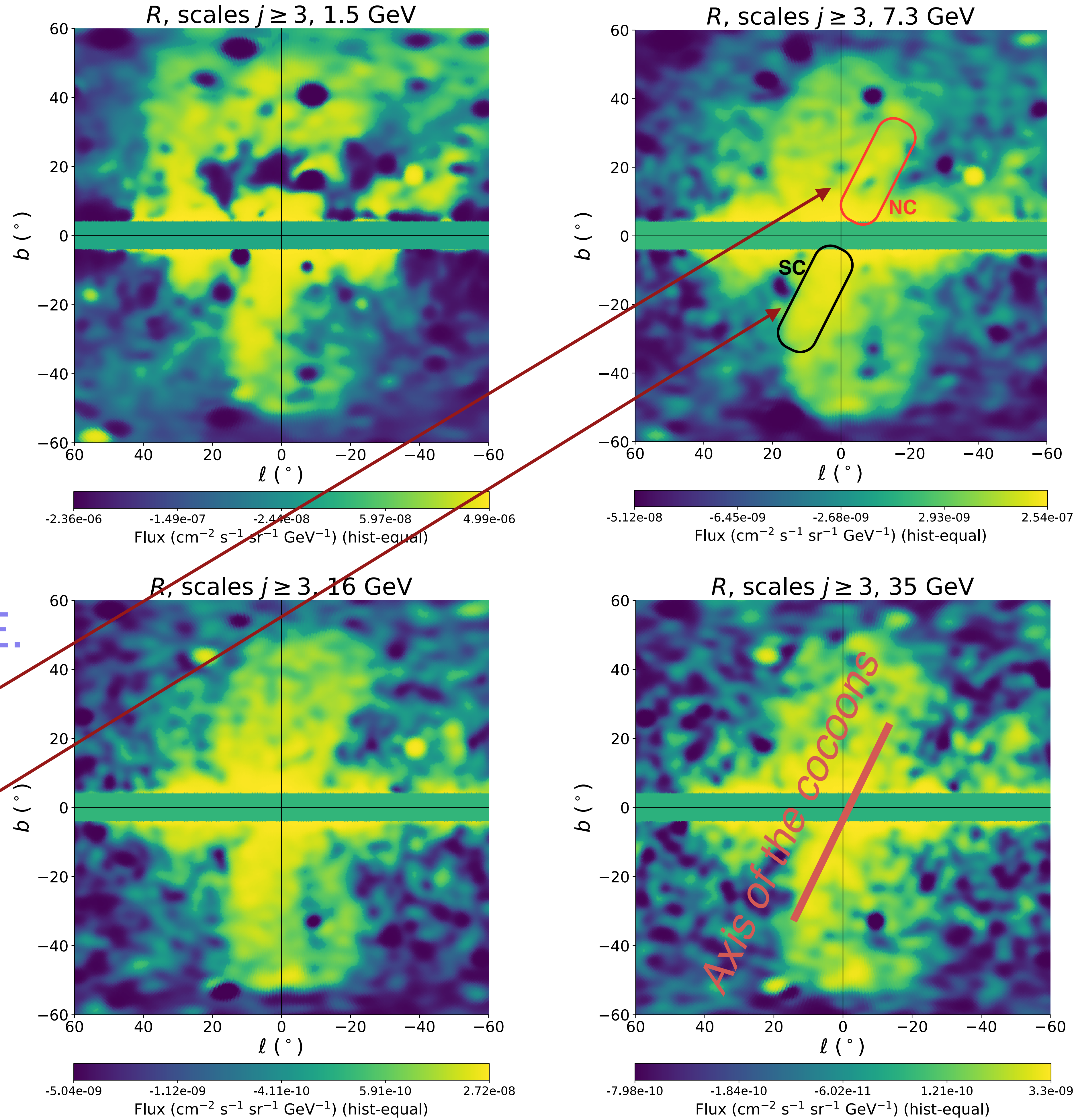
Zoom out

Fermi Bubbles: (we clearly find them)

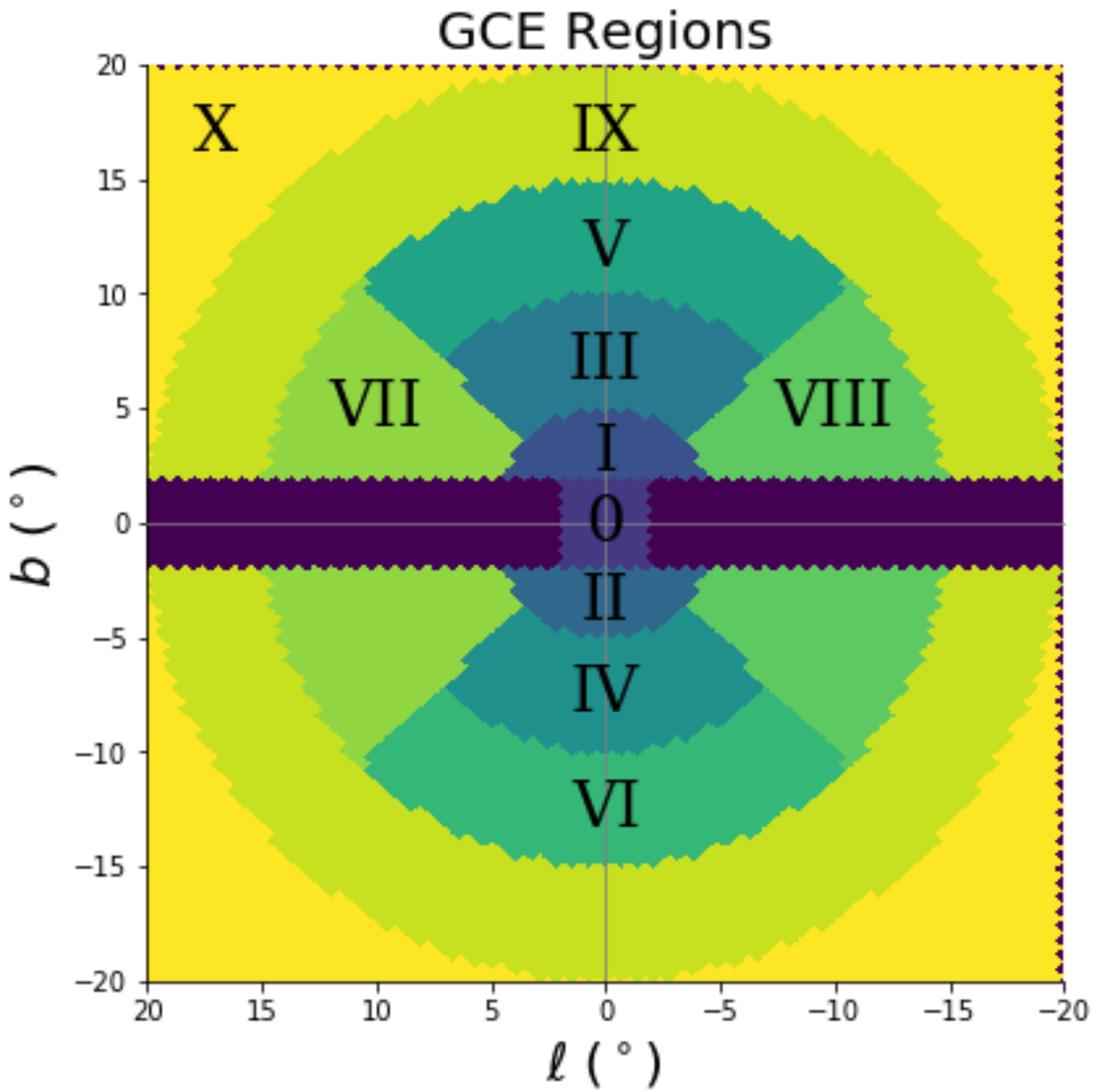
We do not directly disentangle Fermi Bubbles from GCE.

Northern cocoon

Southern cocoon

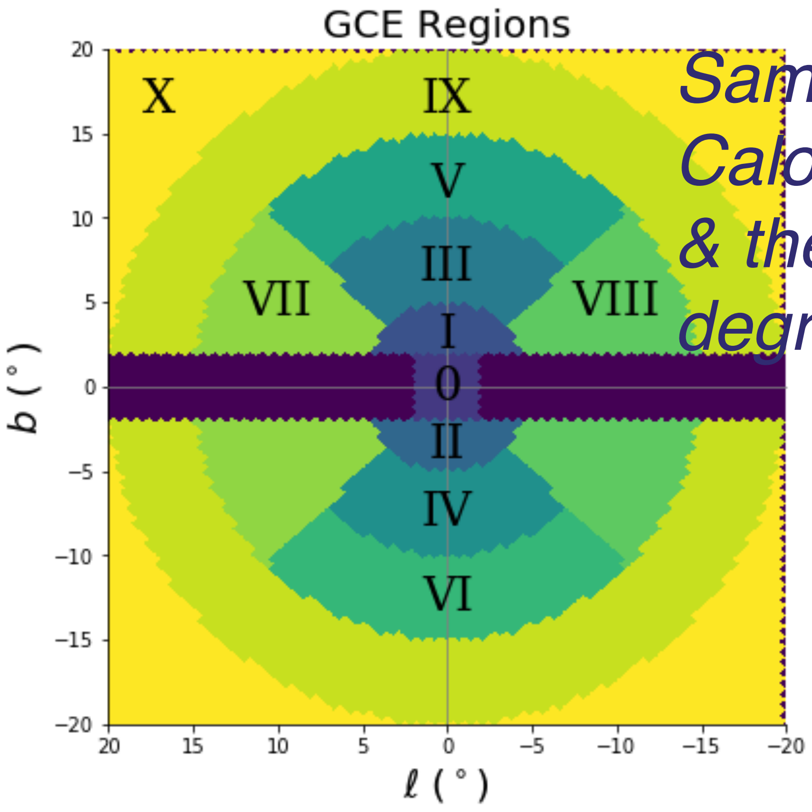


Profile of the Inner Galaxy Emission

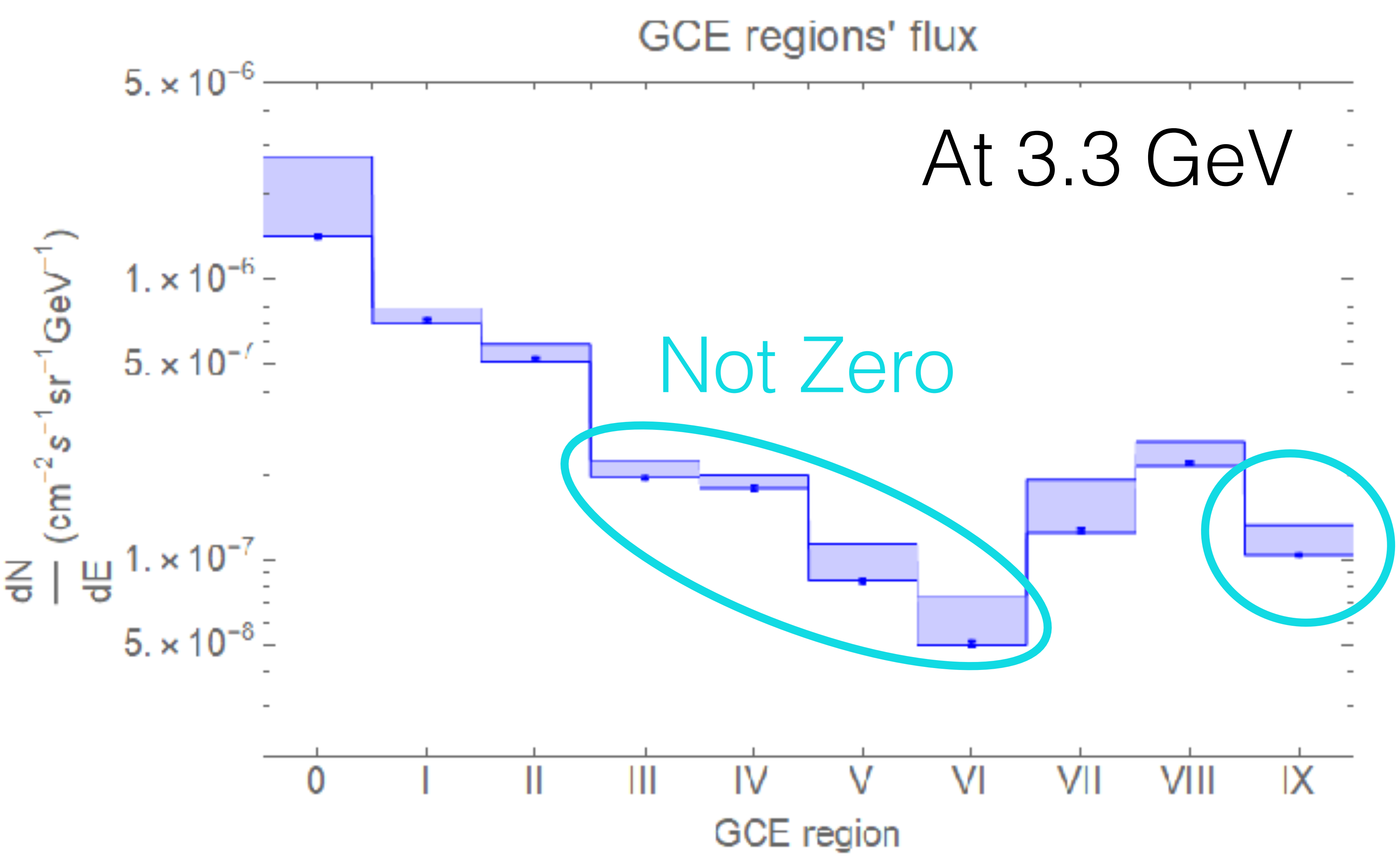


Same as in Calore et al. & the inner 2 degrees

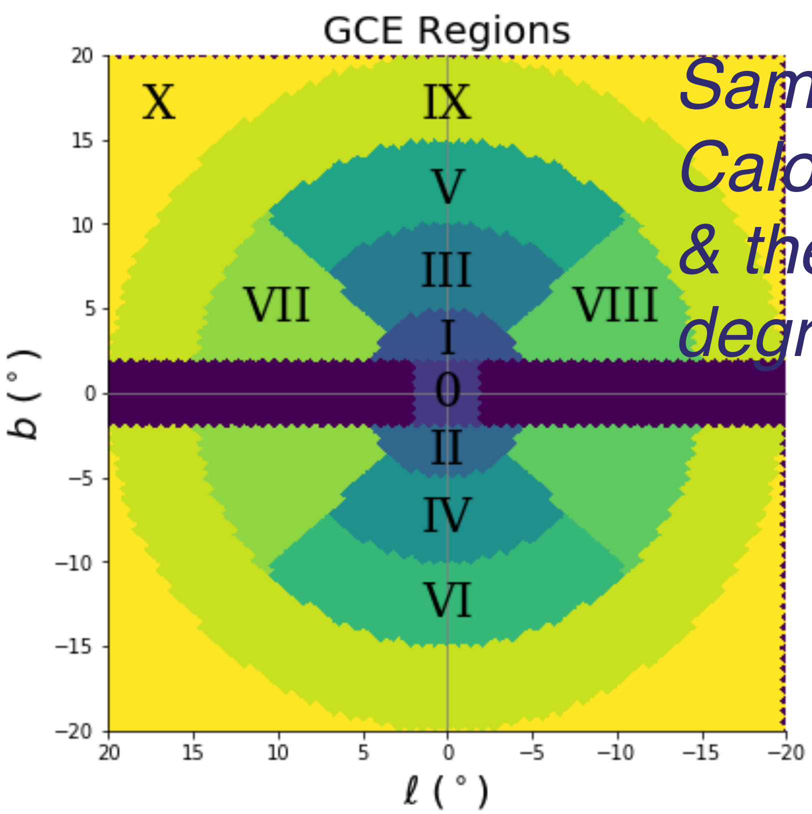
Profile of the Inner Galaxy Emission



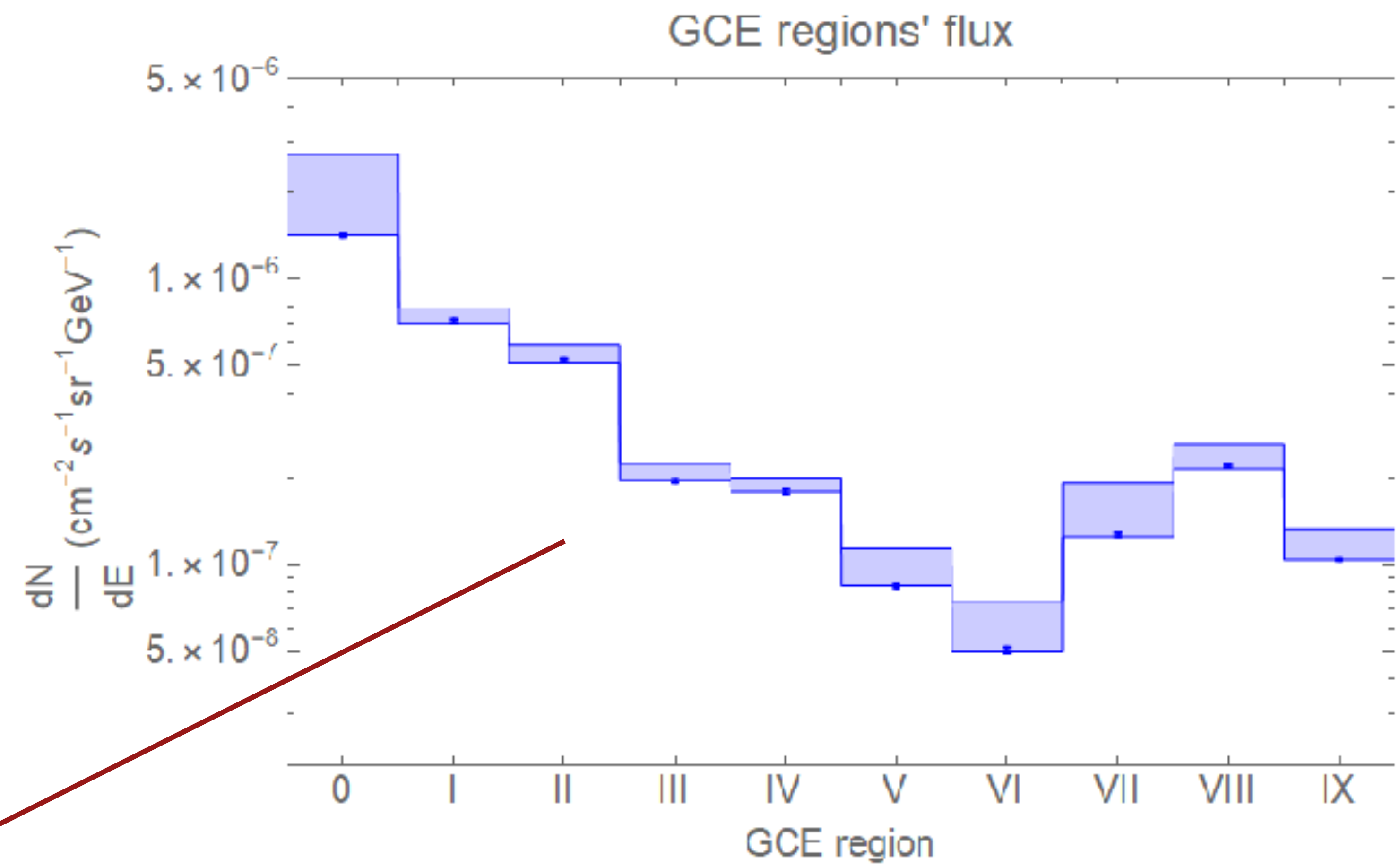
Same as in Calore et al. & the inner 2 degrees

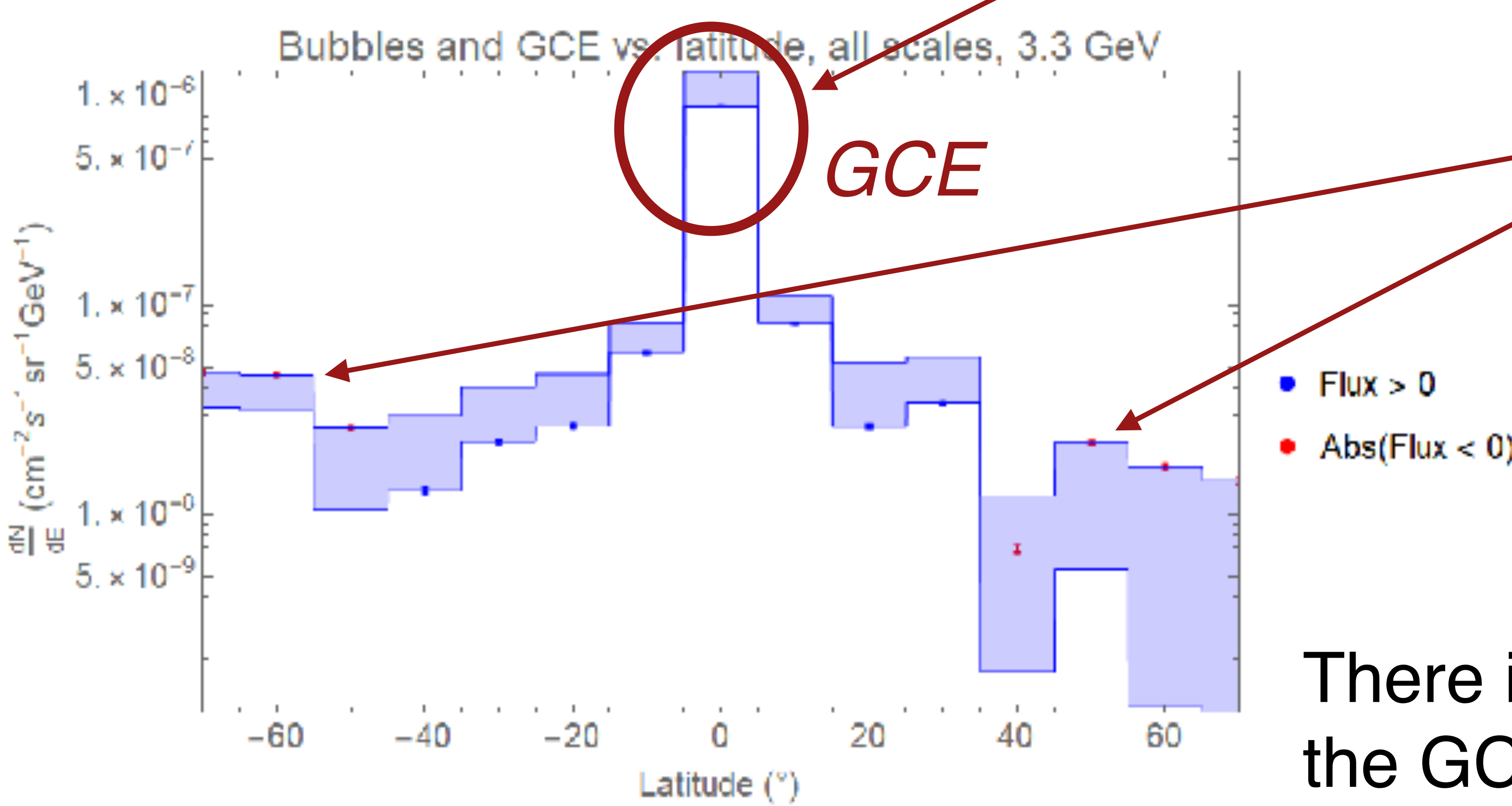


Profile of the Inner Galaxy Emission



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





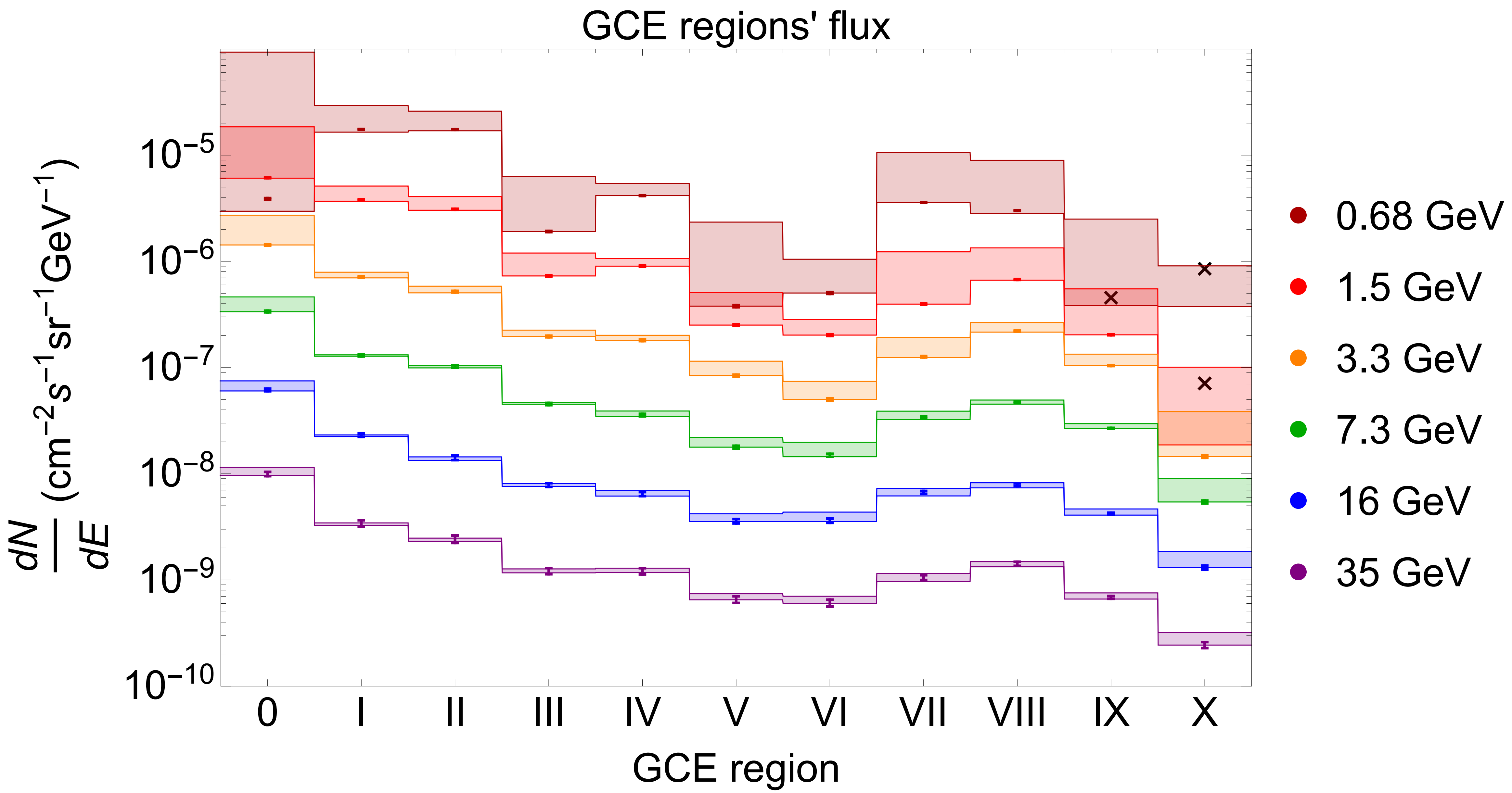
GCE

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

There is a smooth transition from the GCE to the Fermi Bubbles

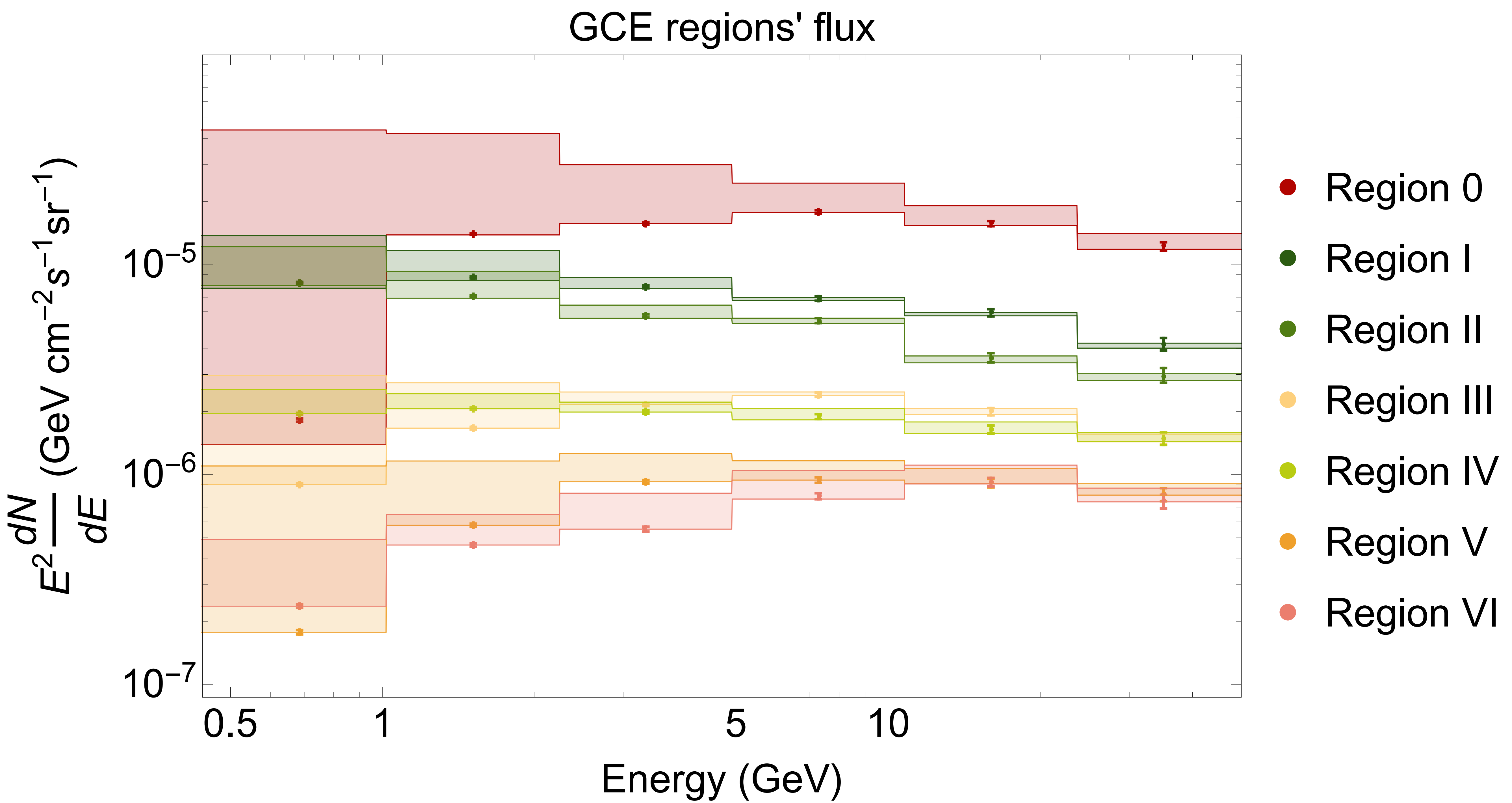
Additional Energies/Profiles

GCE:



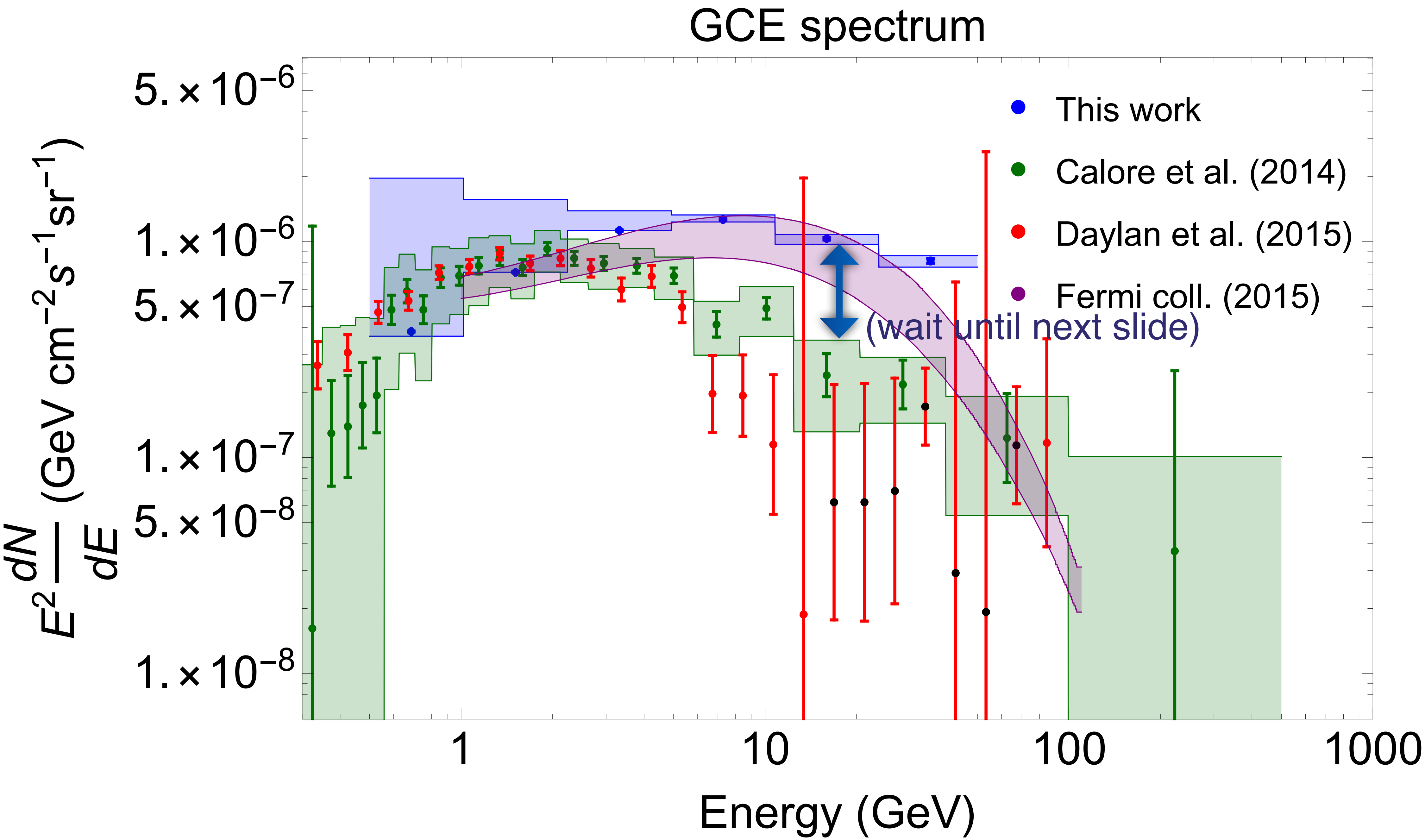
Statistical errors are smaller than systematics. Systematics come from the collection ISM that we average over in the first step when we subtract the galactic diffuse emission.

Spectra



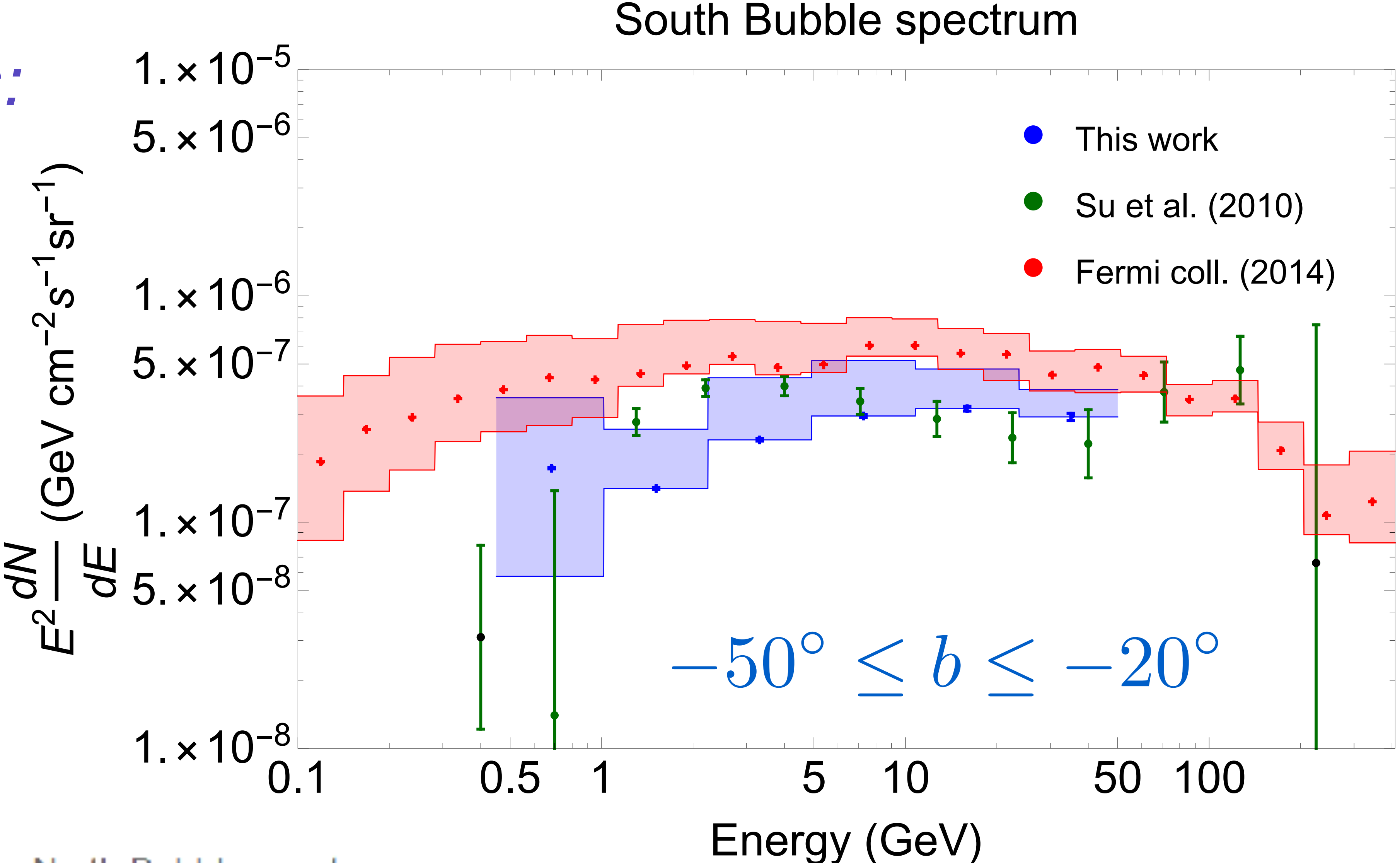
Spectra are harder than template works.

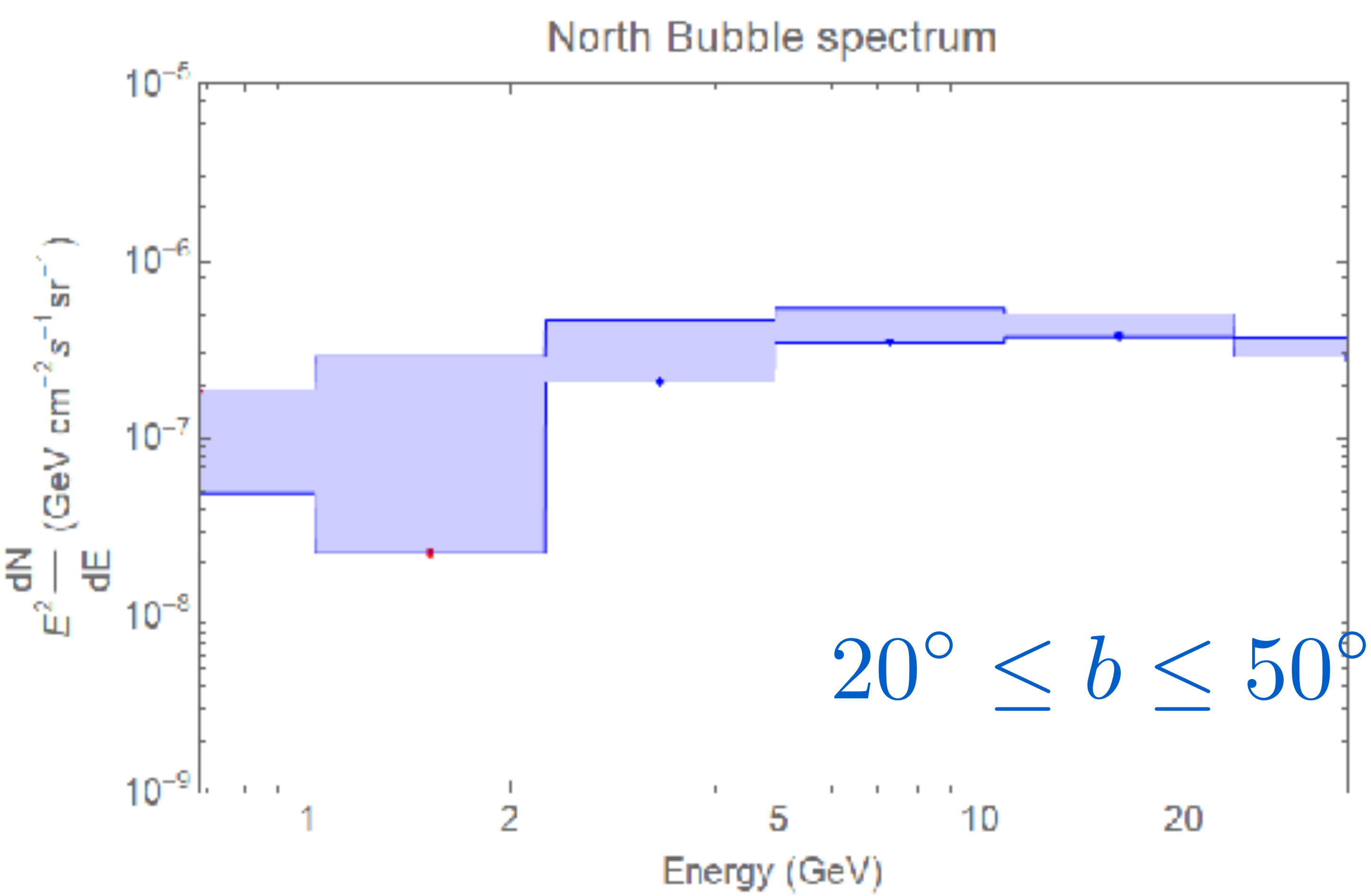
Spectra / Comparison to Templates



Wavelets are sensitive in finding features and characterizing the power at different scales (morphology). That is done by relying On large statistics, i.e. small number of energy bins —> at the expense of the spectral analysis (i.e. we can't find spectral features as well).

Fermi Bubbles:



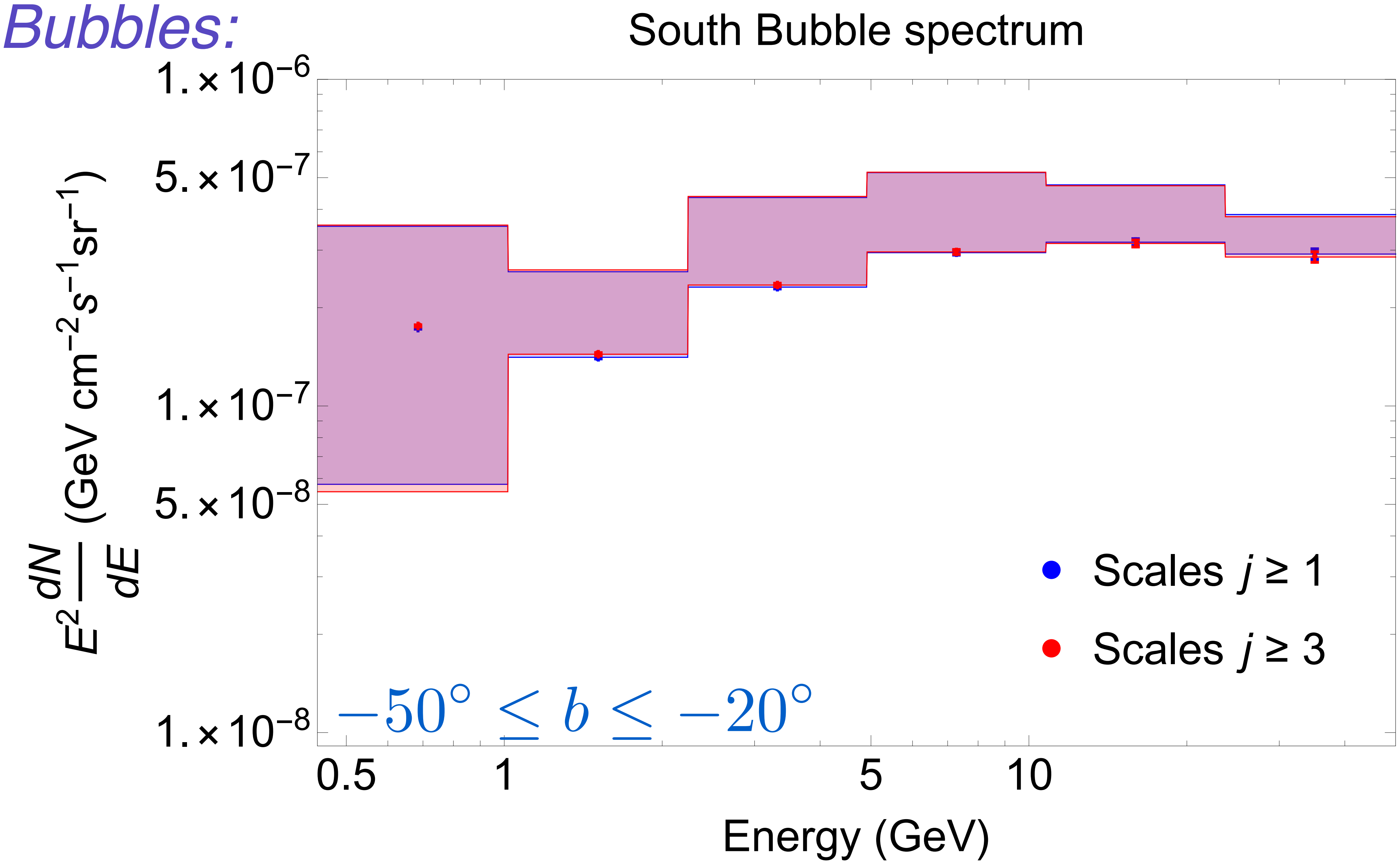


In agreement with Su et al. & ~ Fermi. Coll.

The Wavelet Promise:

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

Fermi Bubbles:



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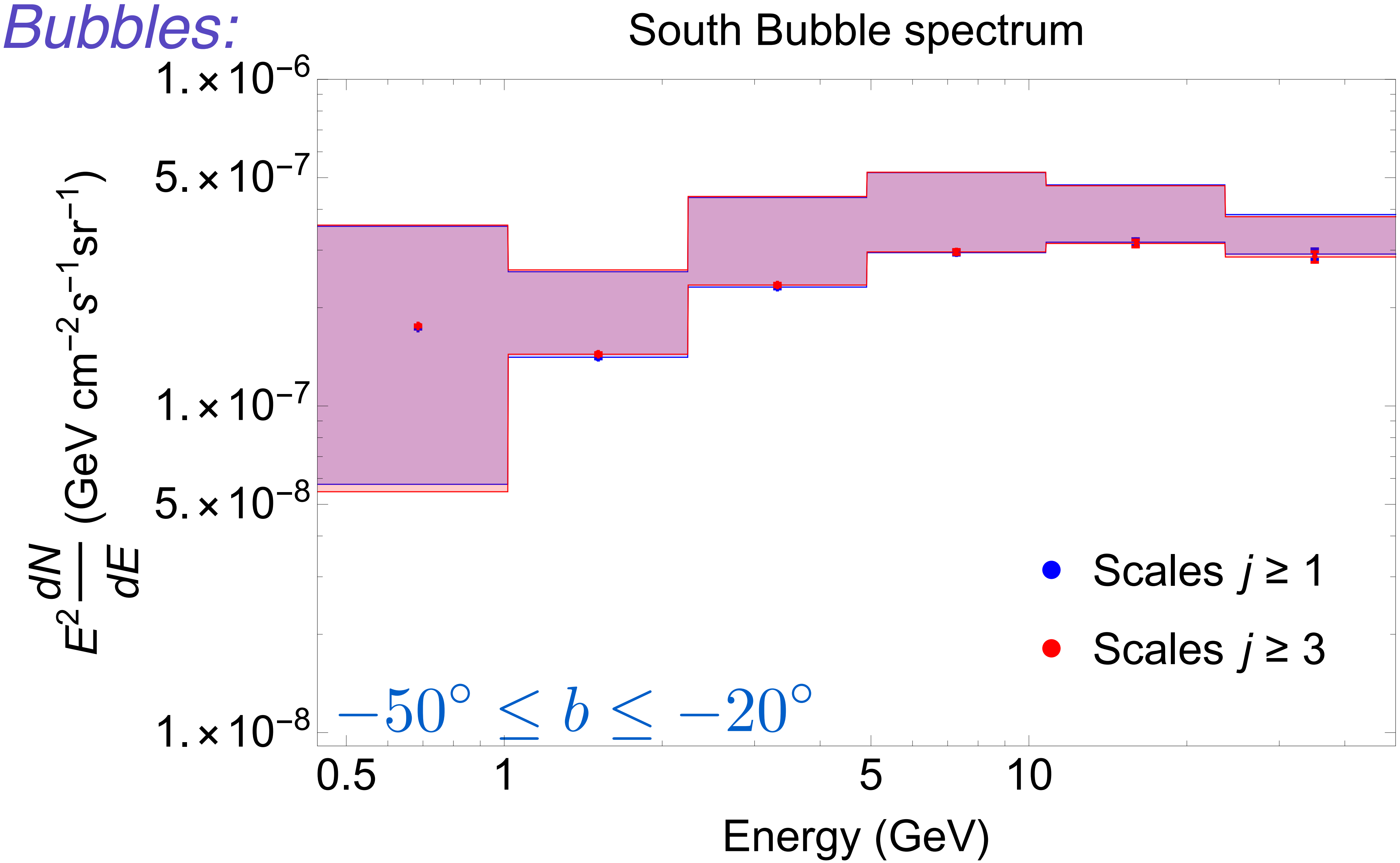
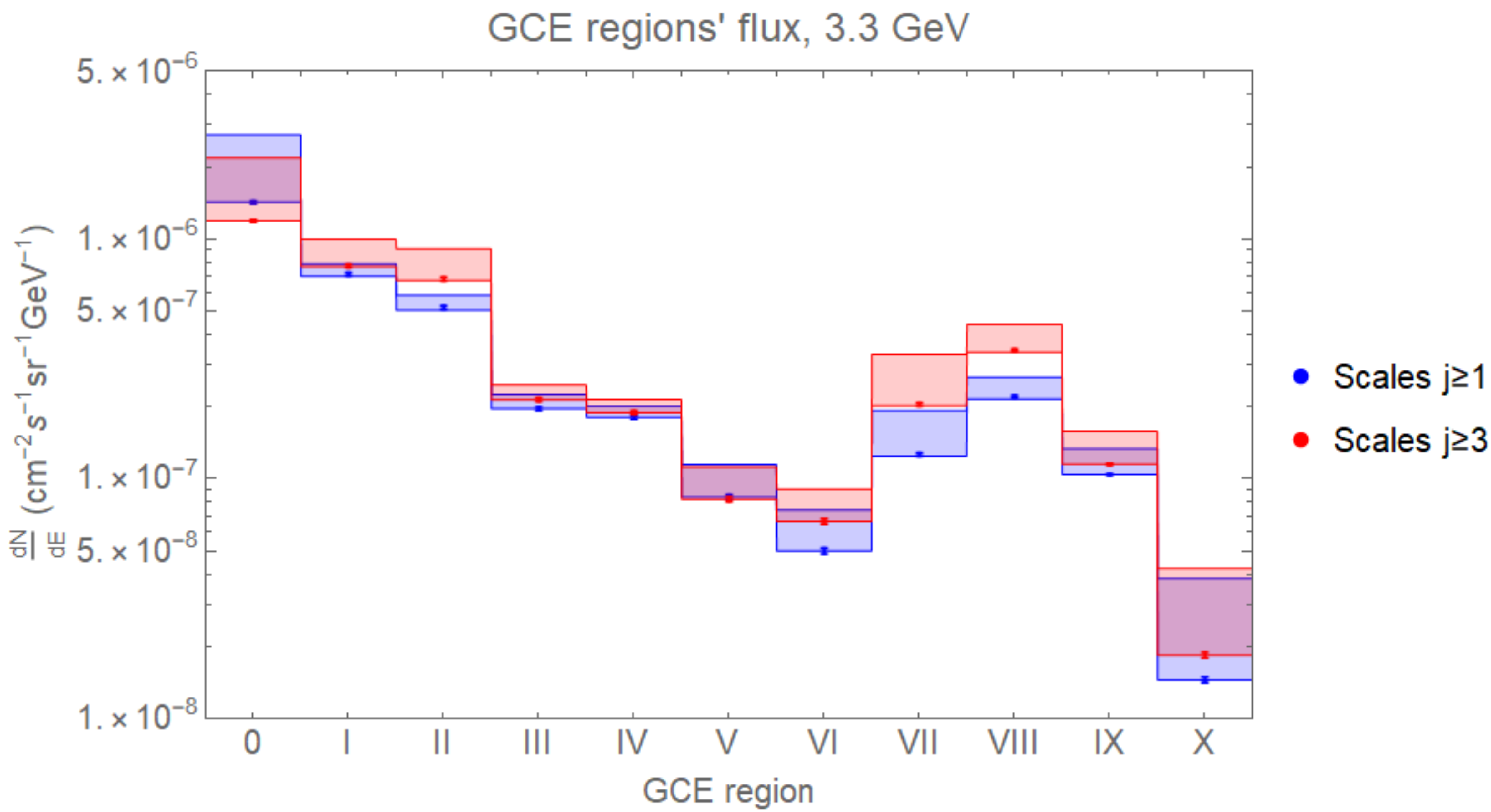
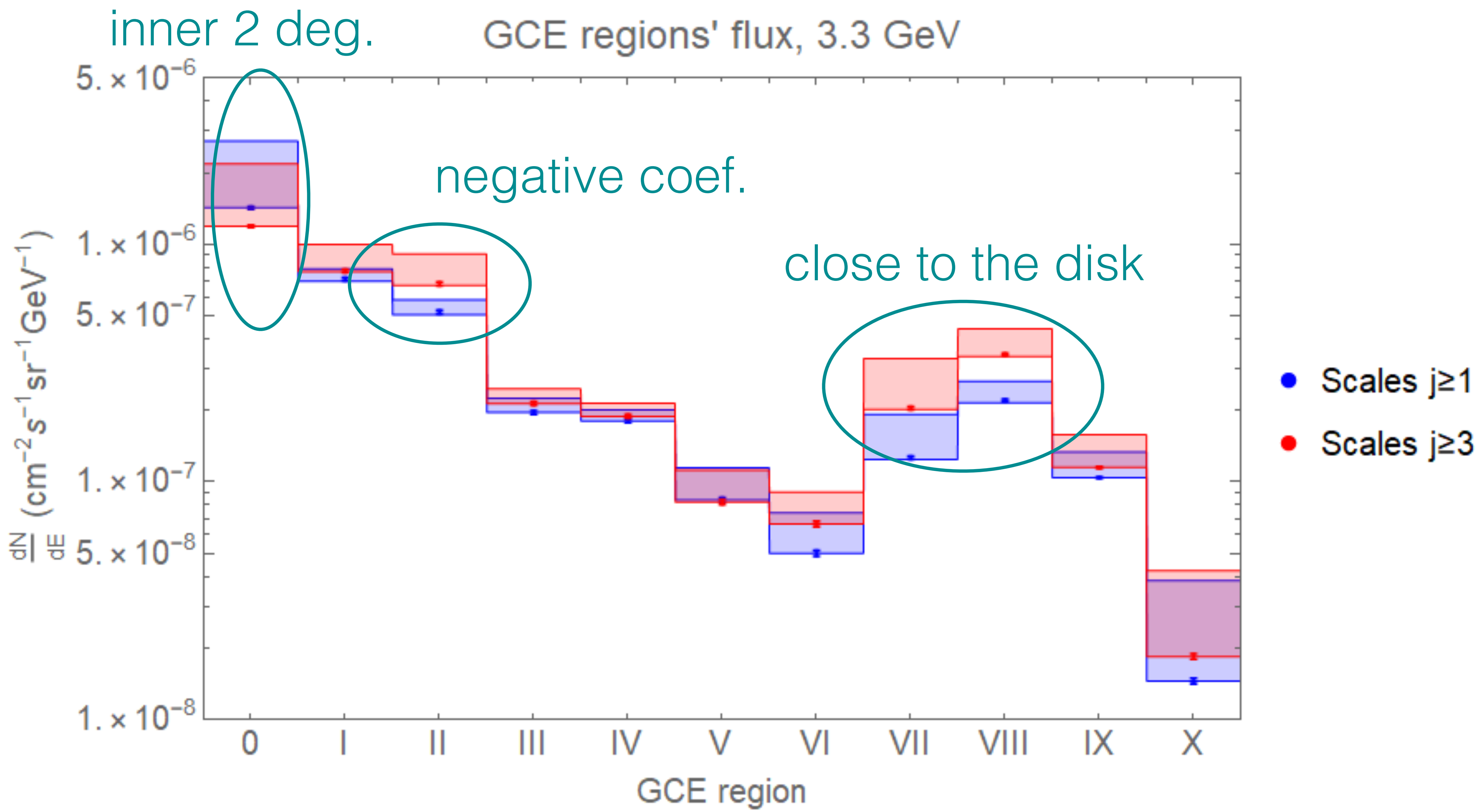
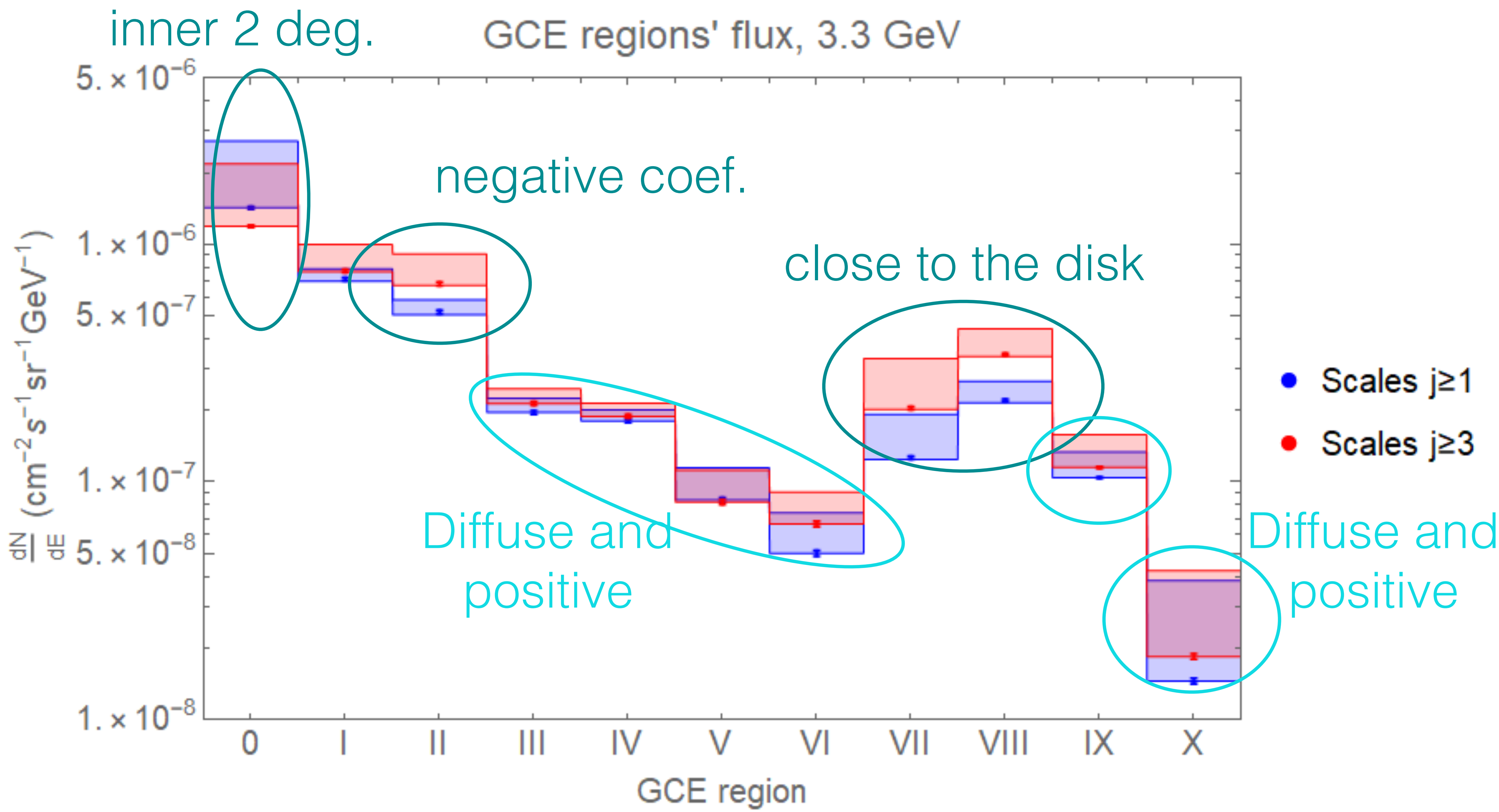
Fermi Bubbles:

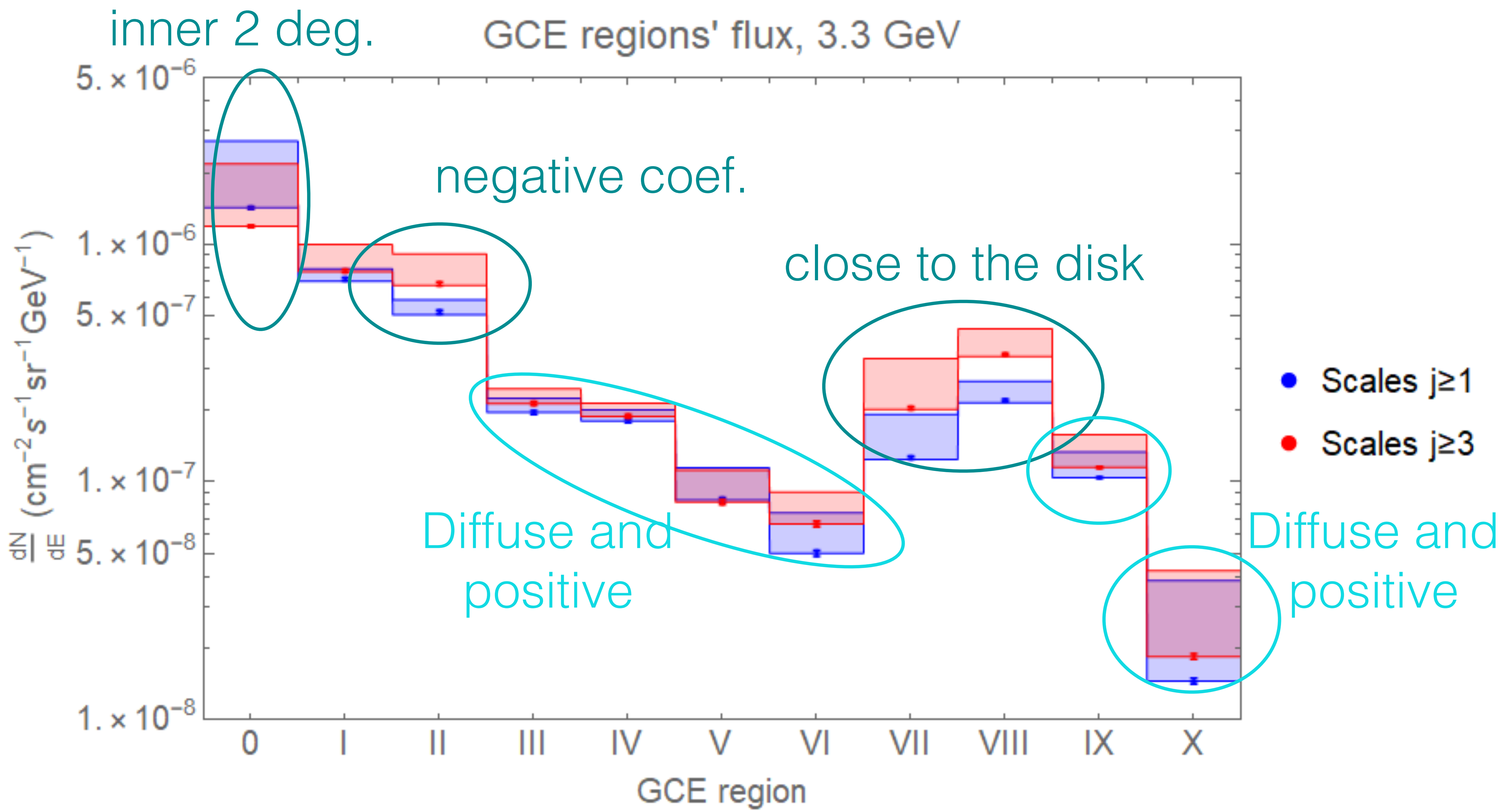


The Fermi Bubbles have *very little amplitude in small scales* in agreement with the leptonic association (WMAP/Planck Haze)


GCE regions' flux, 3.3 GeV
5. × 10^-6
1. × 10^-6
5. × 10^-7
1. × 10^-7
5. × 10^-8
1. × 10^-8
dN/dE (cm^-2 s^-1 sr^-1 GeV^-1)
0
I
II
III
IV
V
VI
VII
VIII
IX
X
GCE region
Scales j≥1
Scales j≥3


inner 2 deg.
GCE regions' flux, 3.3 GeV
negative coef.
close to the disk
5. × 10^-6
1. × 10^-6
5. × 10^-7
1. × 10^-7
5. × 10^-8
1. × 10^-8
dN/dE (cm^-2 s^-1 sr^-1 GeV^-1)
0
I
II
III
IV
V
VI
VII
VIII
IX
X
GCE region
Scales j≥1
Scales j≥3


inner 2 deg.
GCE regions' flux, 3.3 GeV
negative coef.
close to the disk
Diffuse and positive
Diffuse and positive
Scales j≥1
Scales j≥3
$\frac{dN}{dE}$ (cm^{-2}s^{-1}sr^{-1}GeV^{-1})
5. × 10^{-6}
1. × 10^{-6}
5. × 10^{-7}
1. × 10^{-7}
5. × 10^{-8}
1. × 10^{-8}
0
I
II
III
IV
V
VI
VII
VIII
IX
X
GCE region



The GCE has *small amplitude emission at small scales* apart from region 0. Regions 1 and 2 are 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) and analyzed data in Balaji et al. 1803.01952.
- 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…IC,McDermott, Yu-Dai, Fox, Balaji (early stages)
- 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**