GAMMA-RAY BUBBLES, JETS, AND LINES IN THE MILKY WAY

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Fermi Bubbles

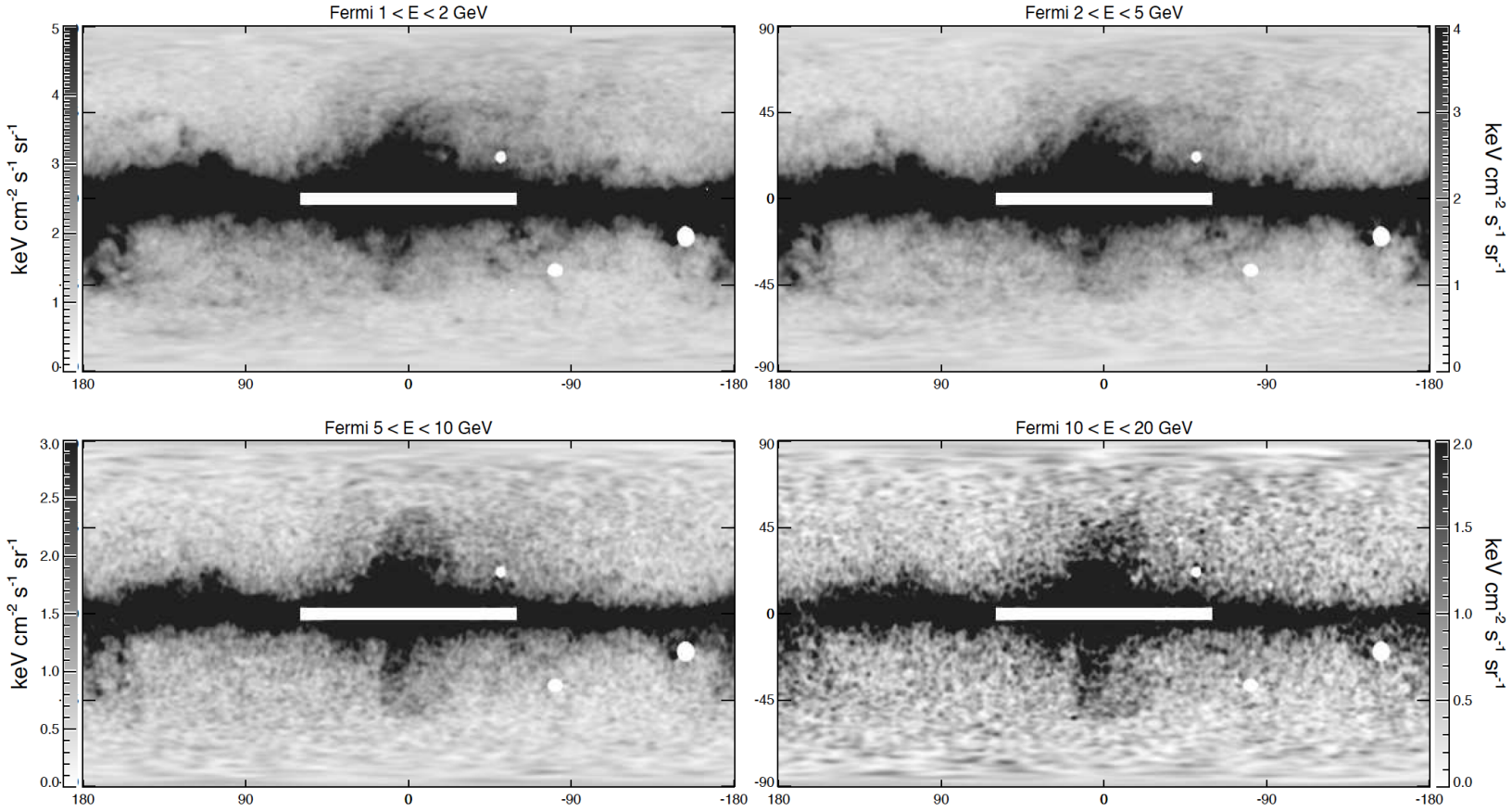
Giant gamma-ray structure with sharp edges
Discovered using data from Large Area Telescope (LAT)
on-board Fermi Gamma-ray Space Telescope

Rise up & down from the Galactic center

They are:

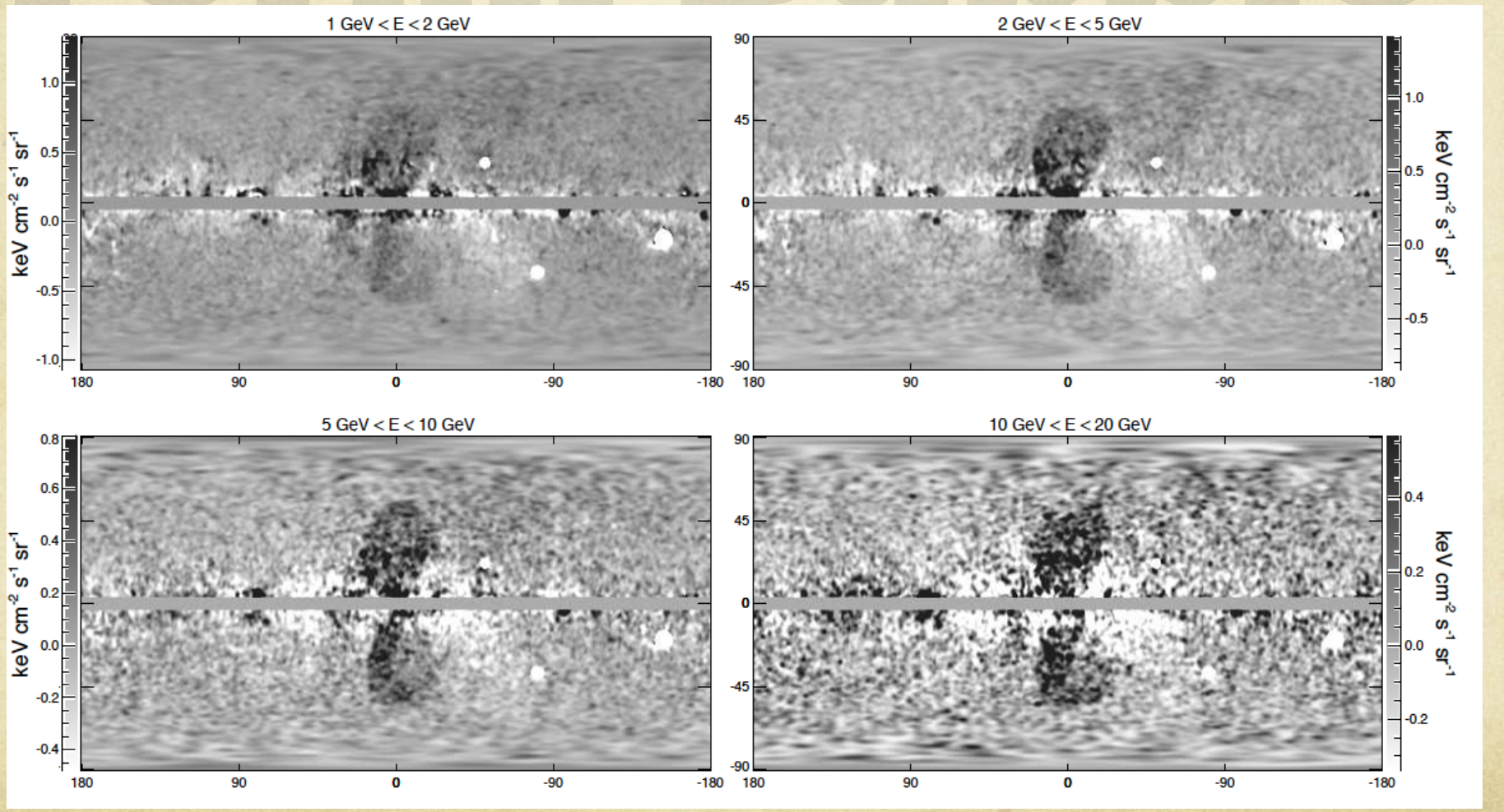
- *50 degrees high (~8.5 kpc)*
- *Well centered on longitude zero (close to latitude zero)*
- *Imply ~TeV electron energy!*

The Fermi-LAT three year maps



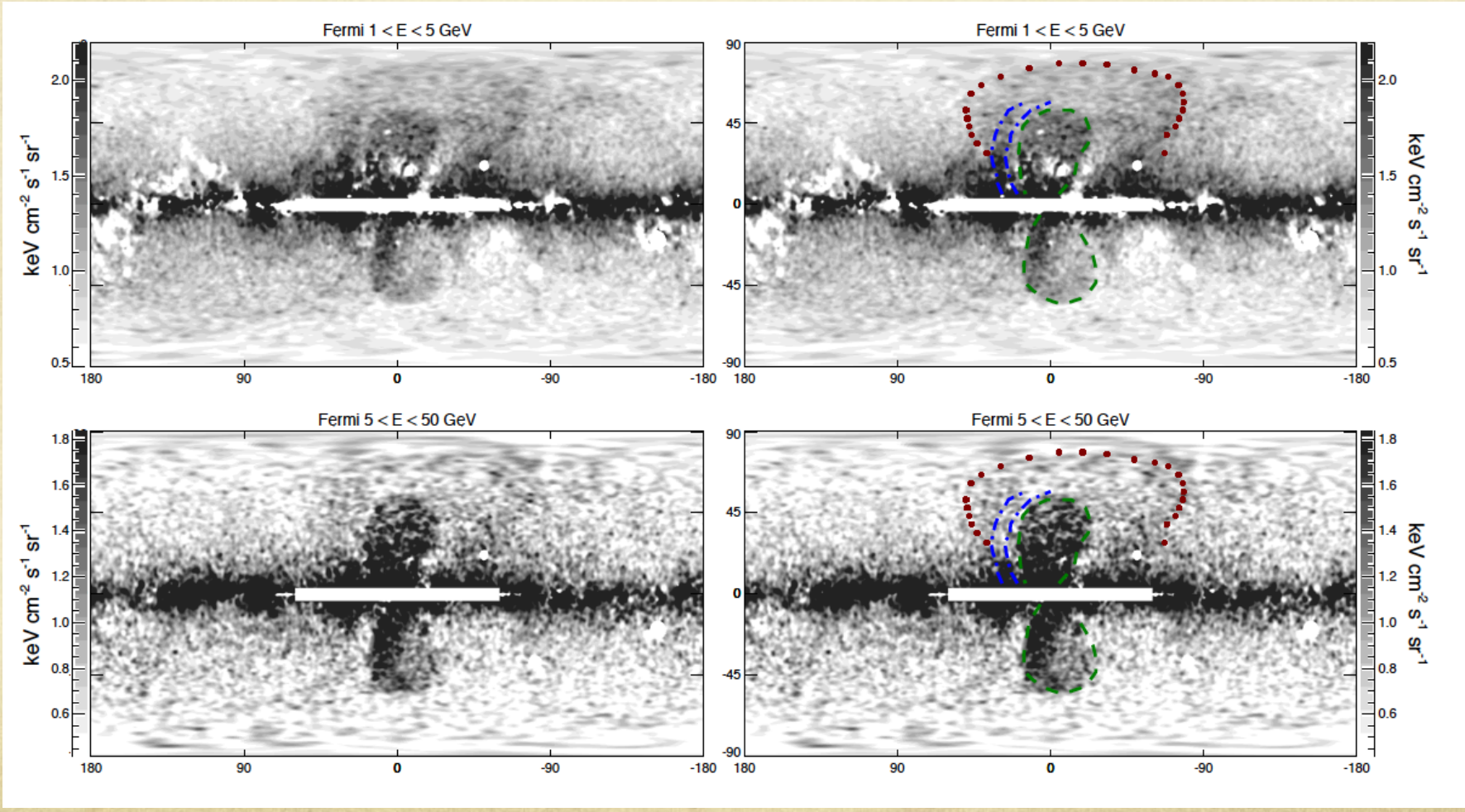
Su & Finkbeiner (2012)

Data minus Fermi diffuse emission model:

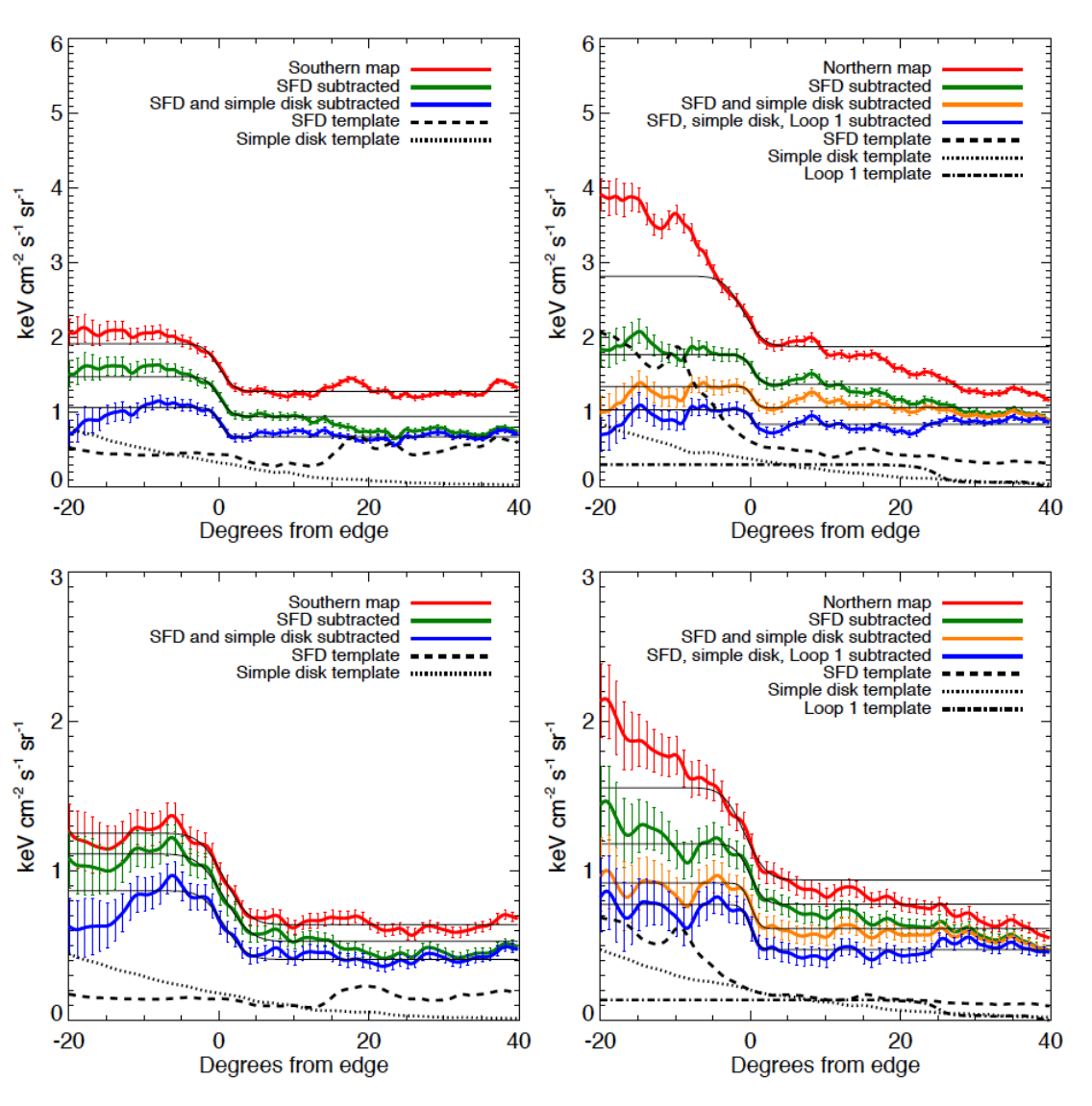


Su & Finkbeiner (2012)

Fermi Bubble from three year maps



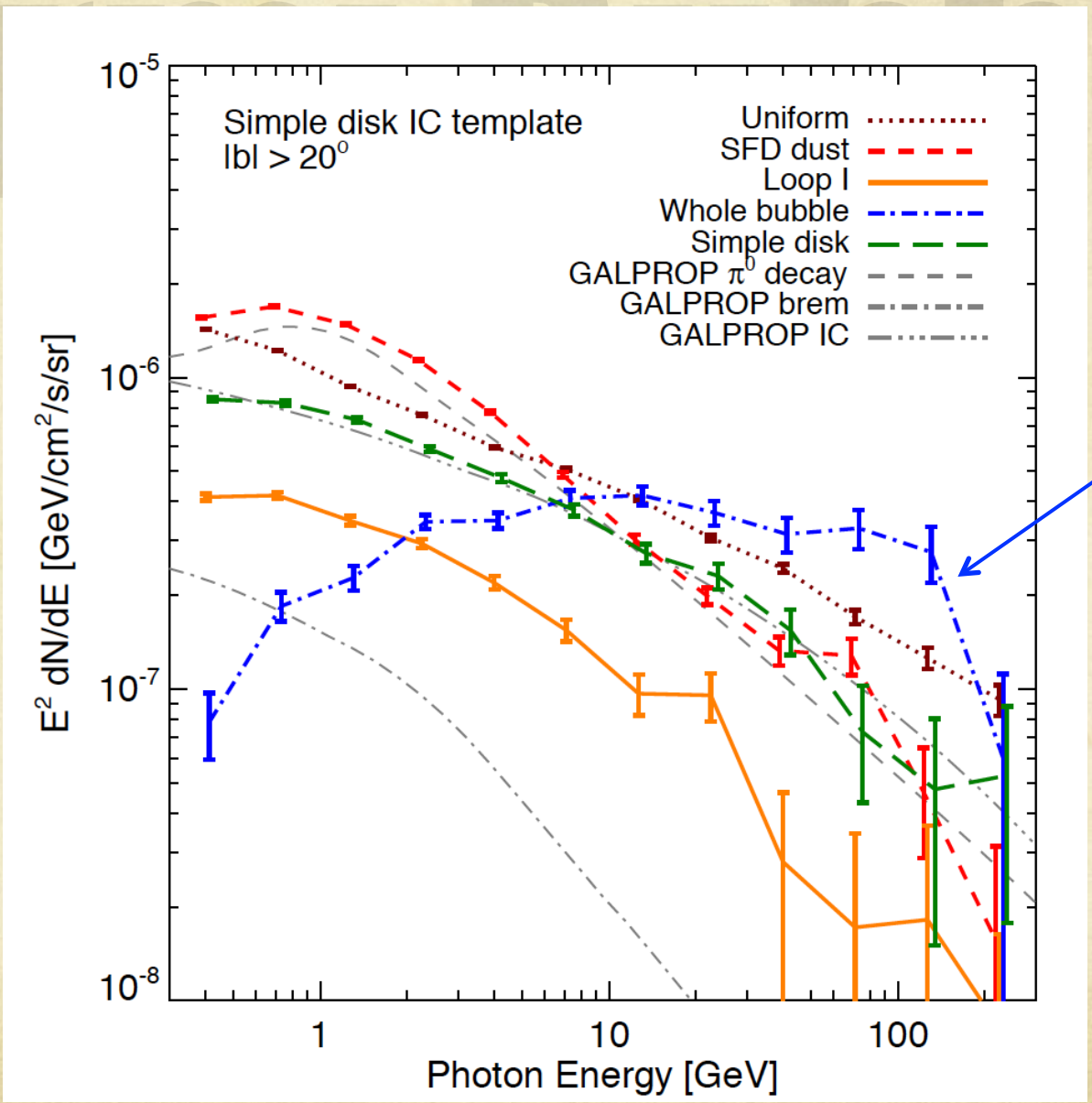
The bubbles have sharp edges!



Now we can do a multilinear regression at each energy!

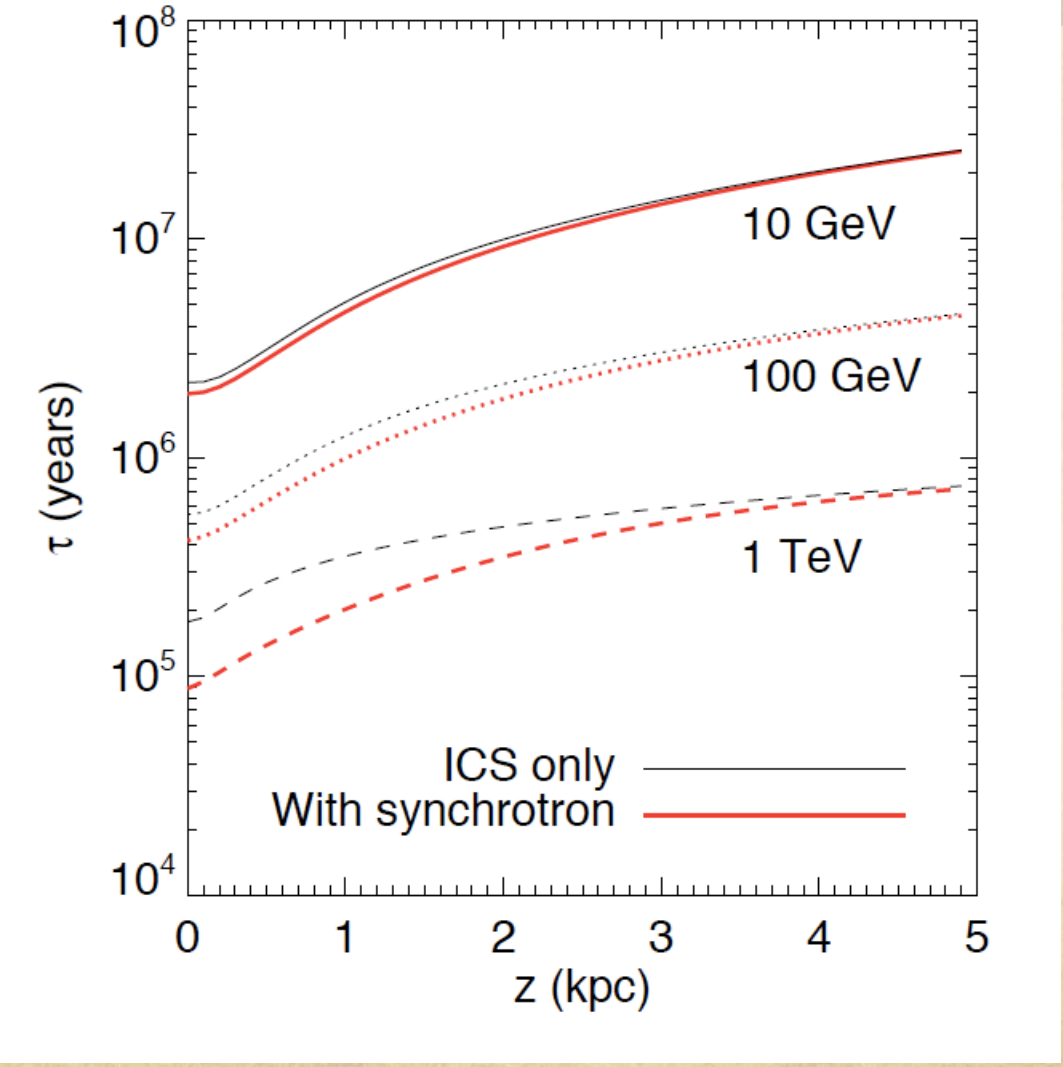
$$\ln \mathcal{L} = \sum_i k_i \ln \mu_i - \mu_i - \ln(k_i!)$$

where μ is the synthetic map (i.e., linear combination of templates) at pixel i, and k is the map of observed data. The last term is a function of only the observed maps. The 1 σ Gaussian error is calculated from the likelihood by $\Delta \ln L = 1/2$.



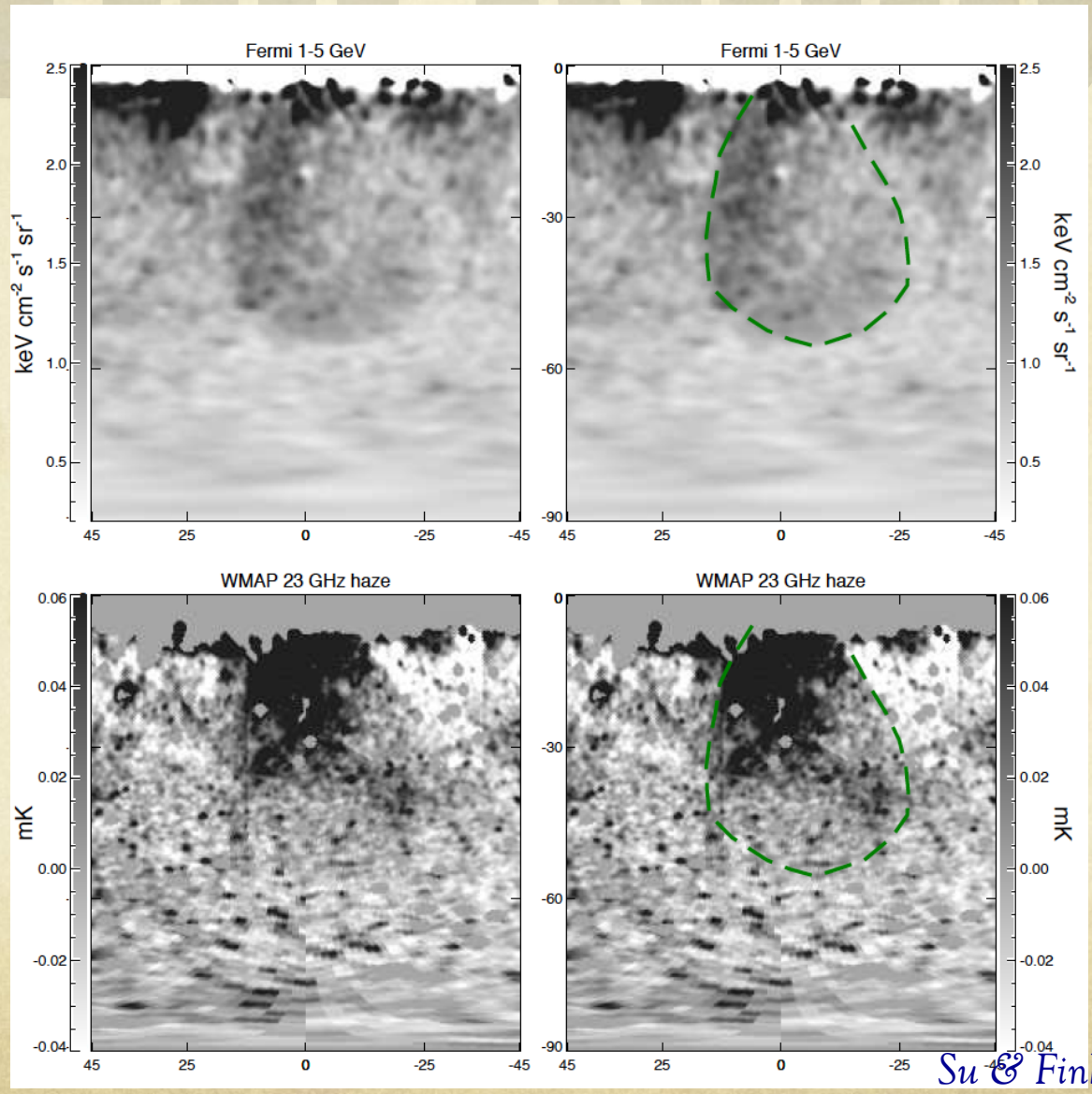
Su & Finkbeiner (2012)

Cooling time is short!

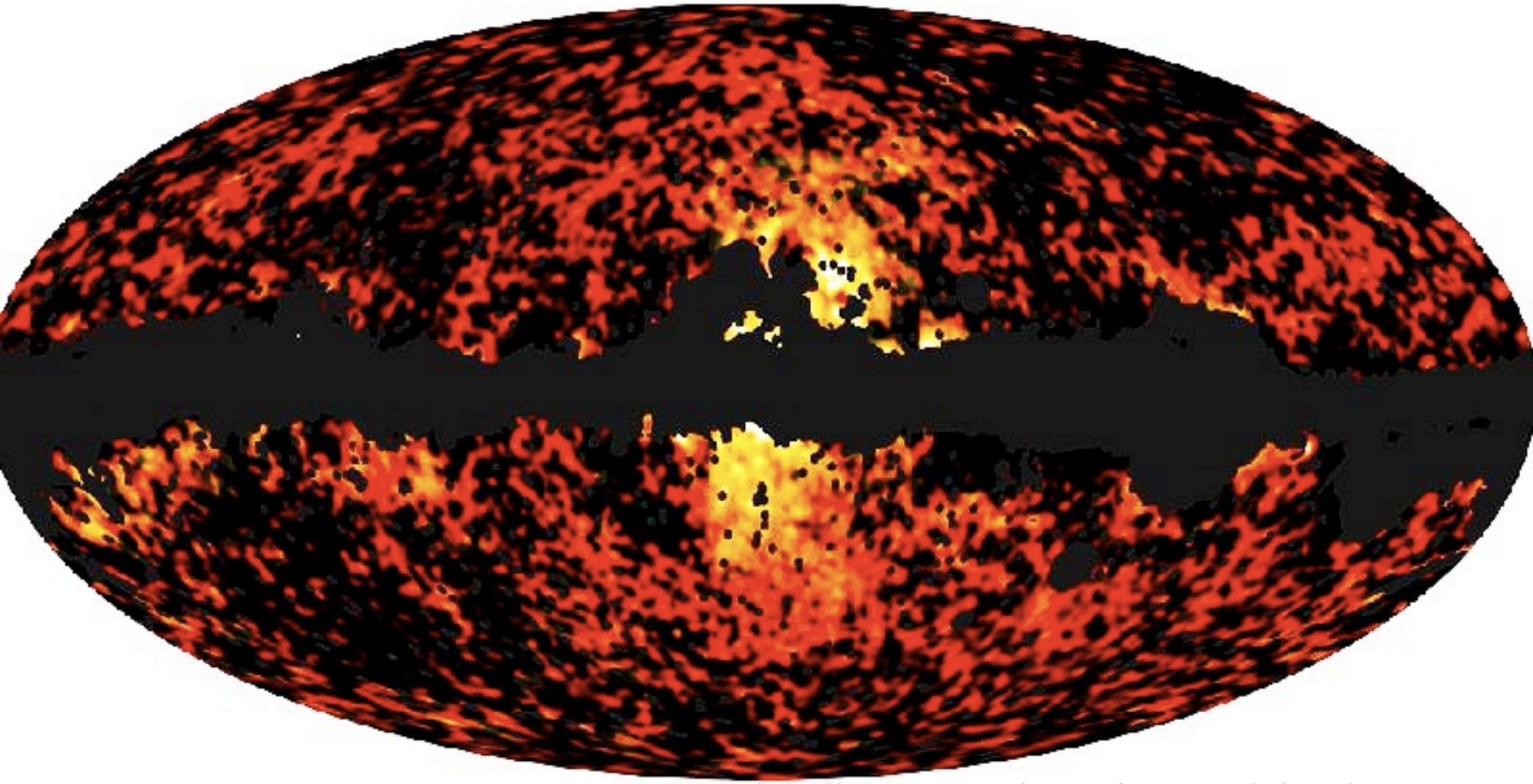


Su et al. (2010)

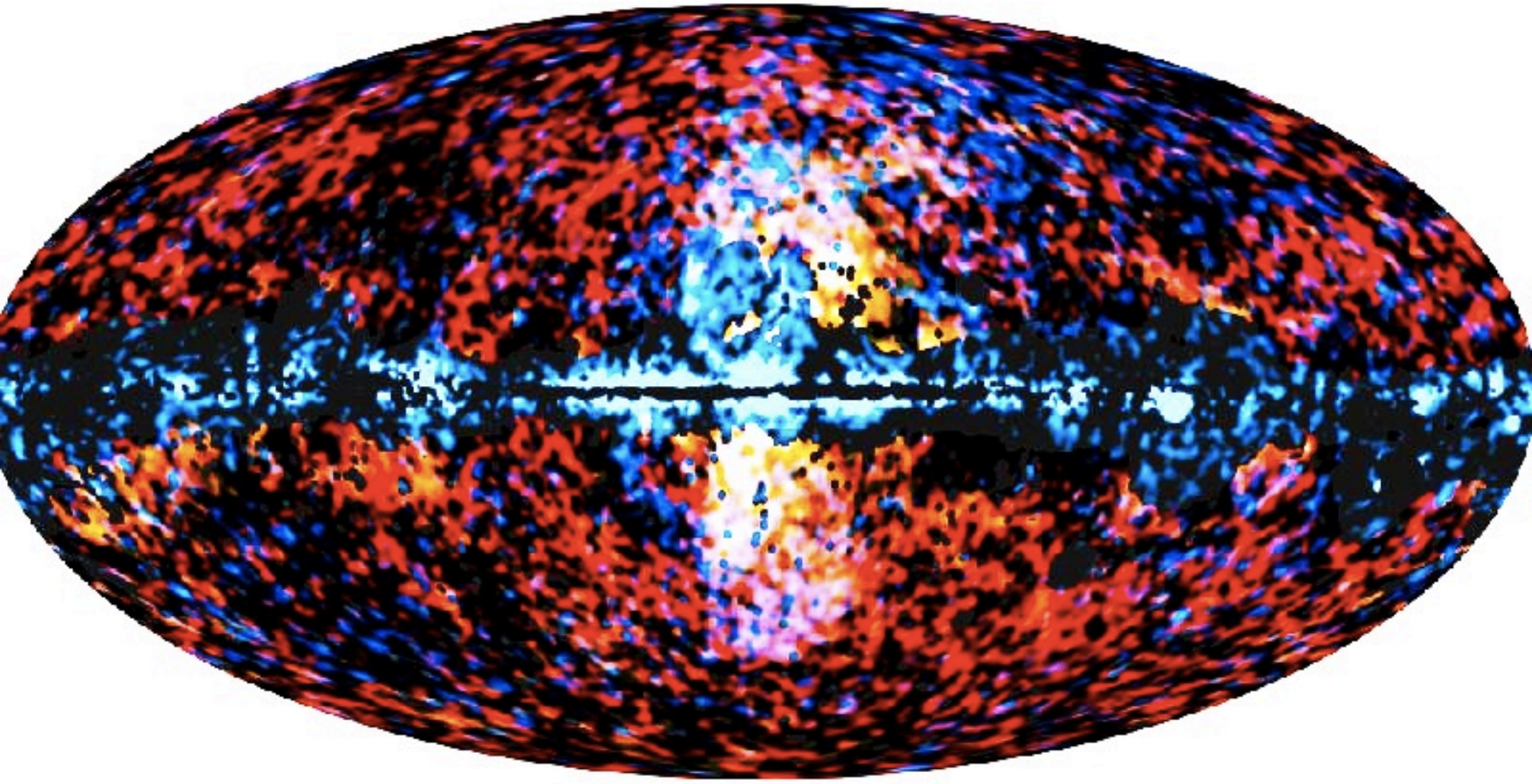
Compare with WMAP haze



Su & Finkbeiner (2012)

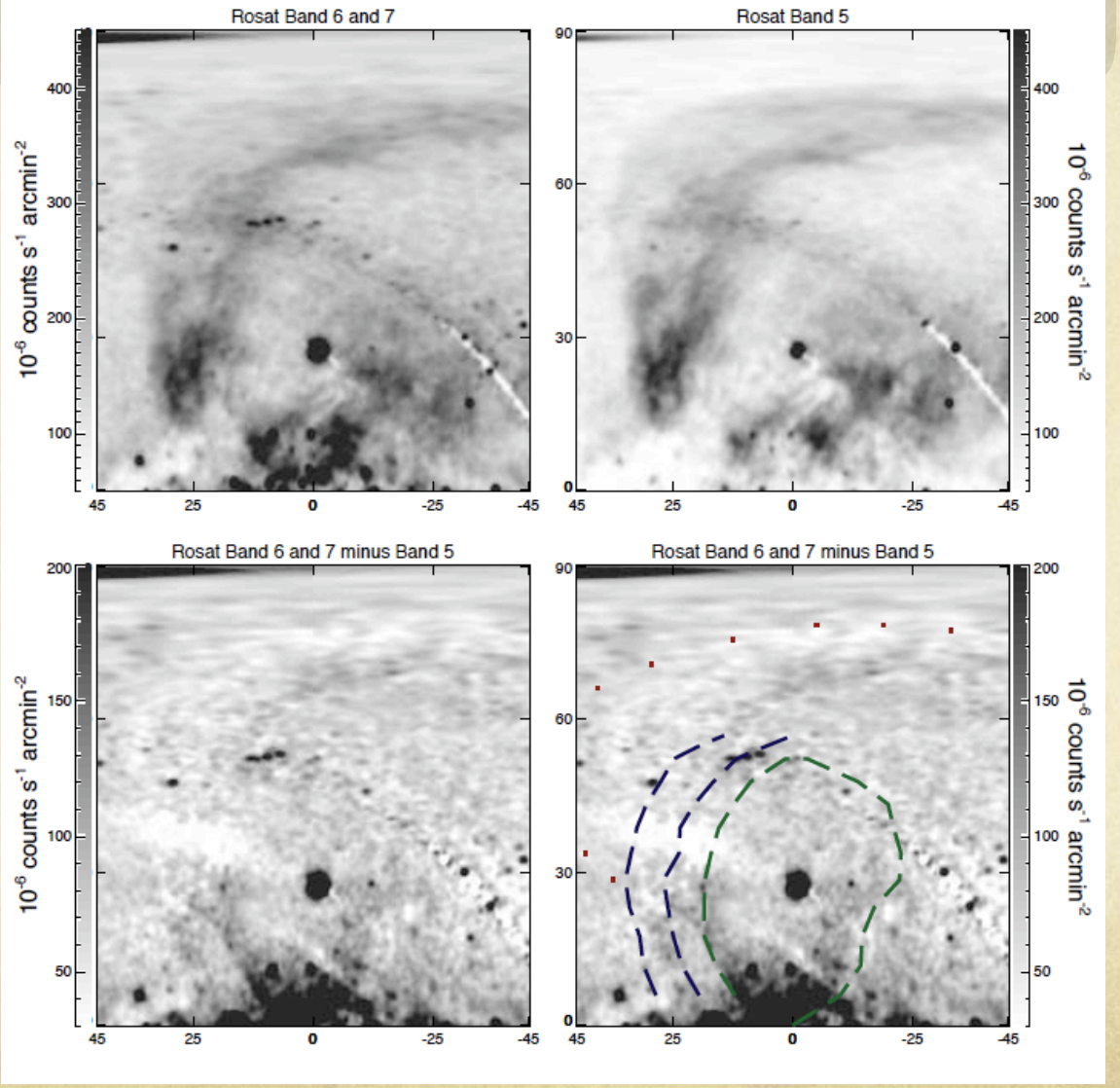


This all-sky image shows the spatial distribution over the whole sky of the galactic haze at 30 and 44 GHz, extracted from the Planck observations. Credits: ESA/Planck Collaboration.

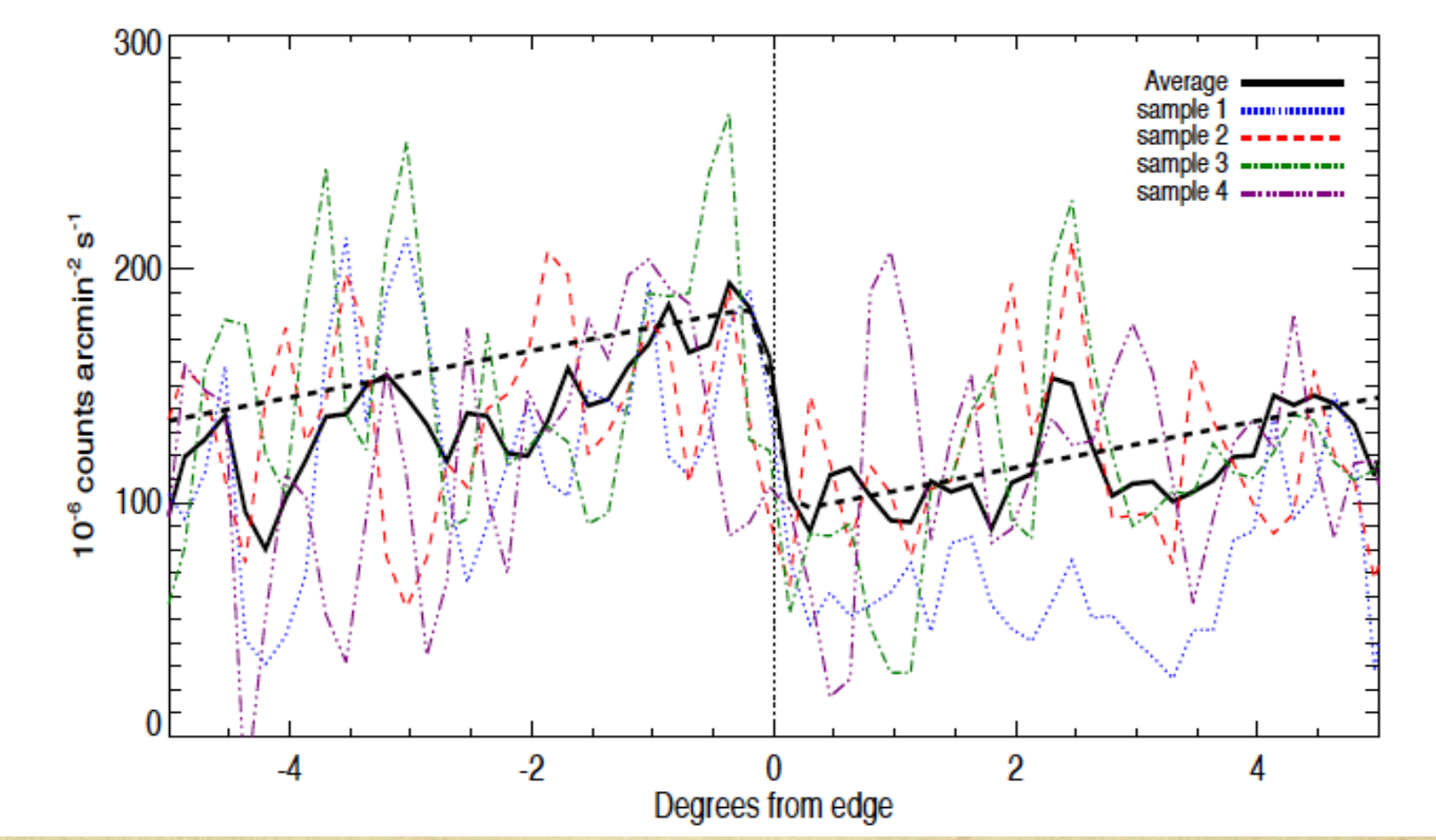


This all-sky image shows the distribution of the galactic haze seen by ESA's Planck mission at microwave frequencies superimposed over the high-energy sky, as seen by NASA's Fermi Gamma-ray Space Telescope. Credits: ESA/Planck Collaboration (microwave); NASA/DOE/ Fermi LAT/D. Finkbeiner et al.

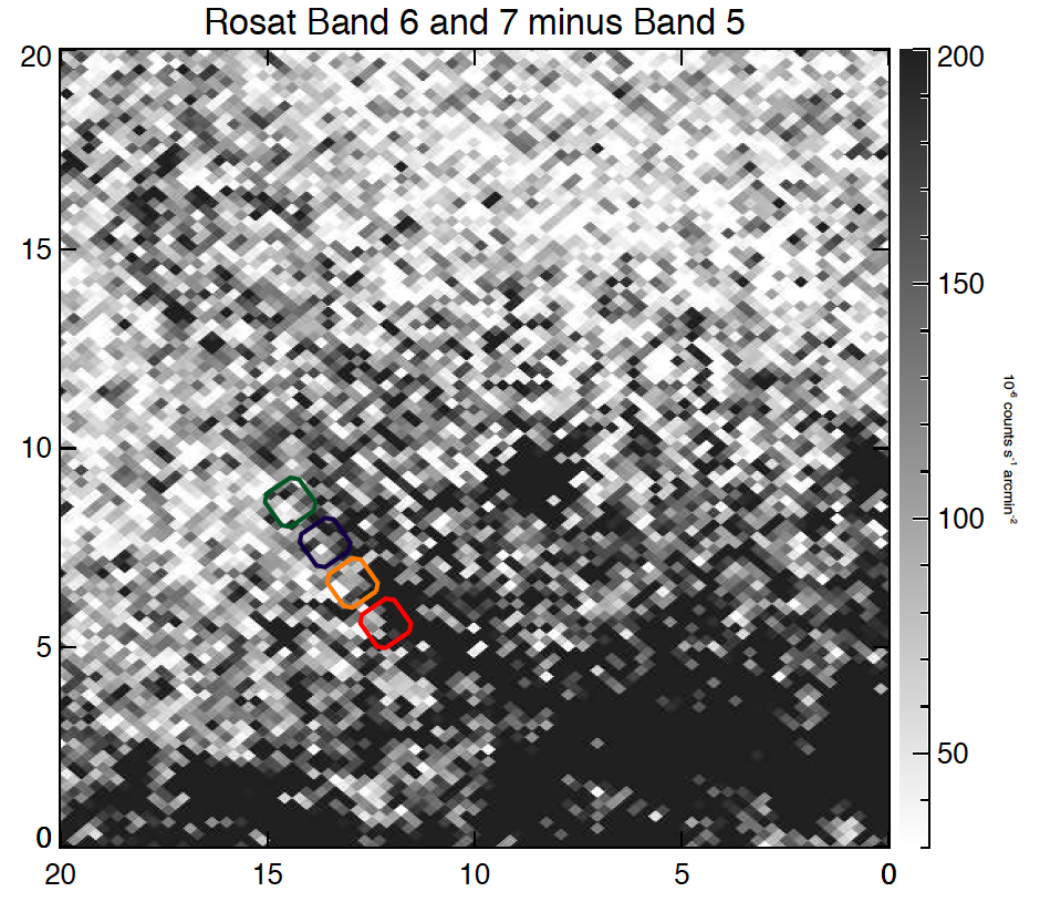
ROSAT 1.5 keV

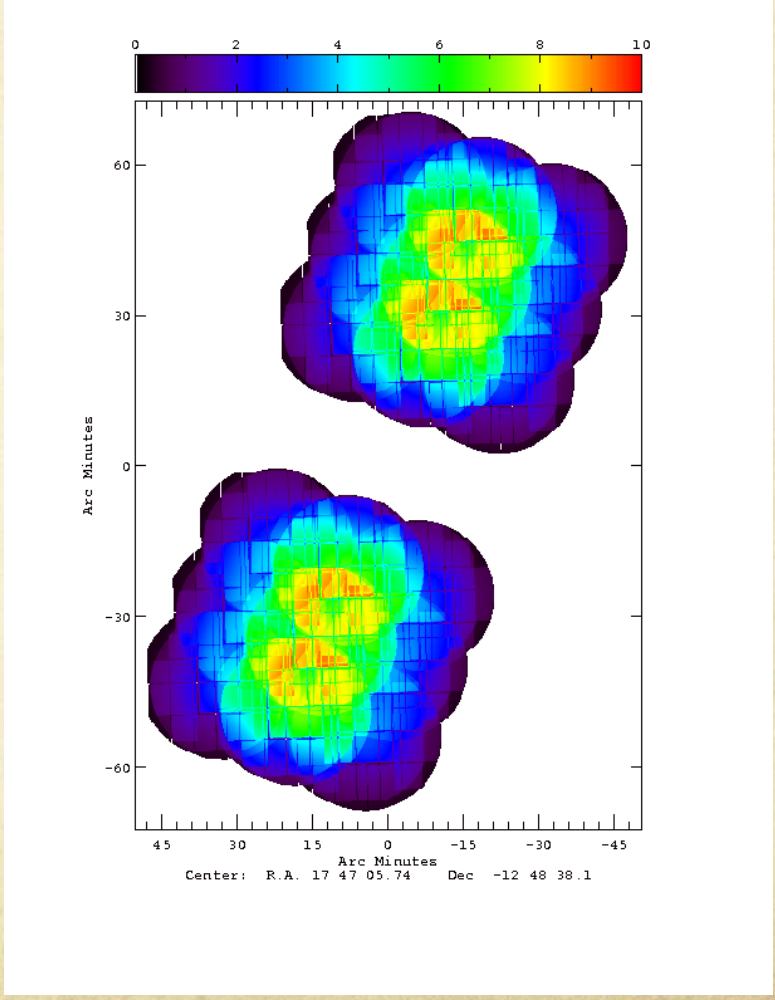

Rosat Band 6 and 7
Rosat Band 5
Rosat Band 6 and 7 minus Band 5
Rosat Band 6 and 7 minus Band 5
10^{-6} counts s^{-1} arcmin^{-2}
10^{-6} counts s^{-1} arcmin^{-2}
10^{-6} counts s^{-1} arcmin^{-2}
10^{-6} counts s^{-1} arcmin^{-2}
45
25
0
-25
-45

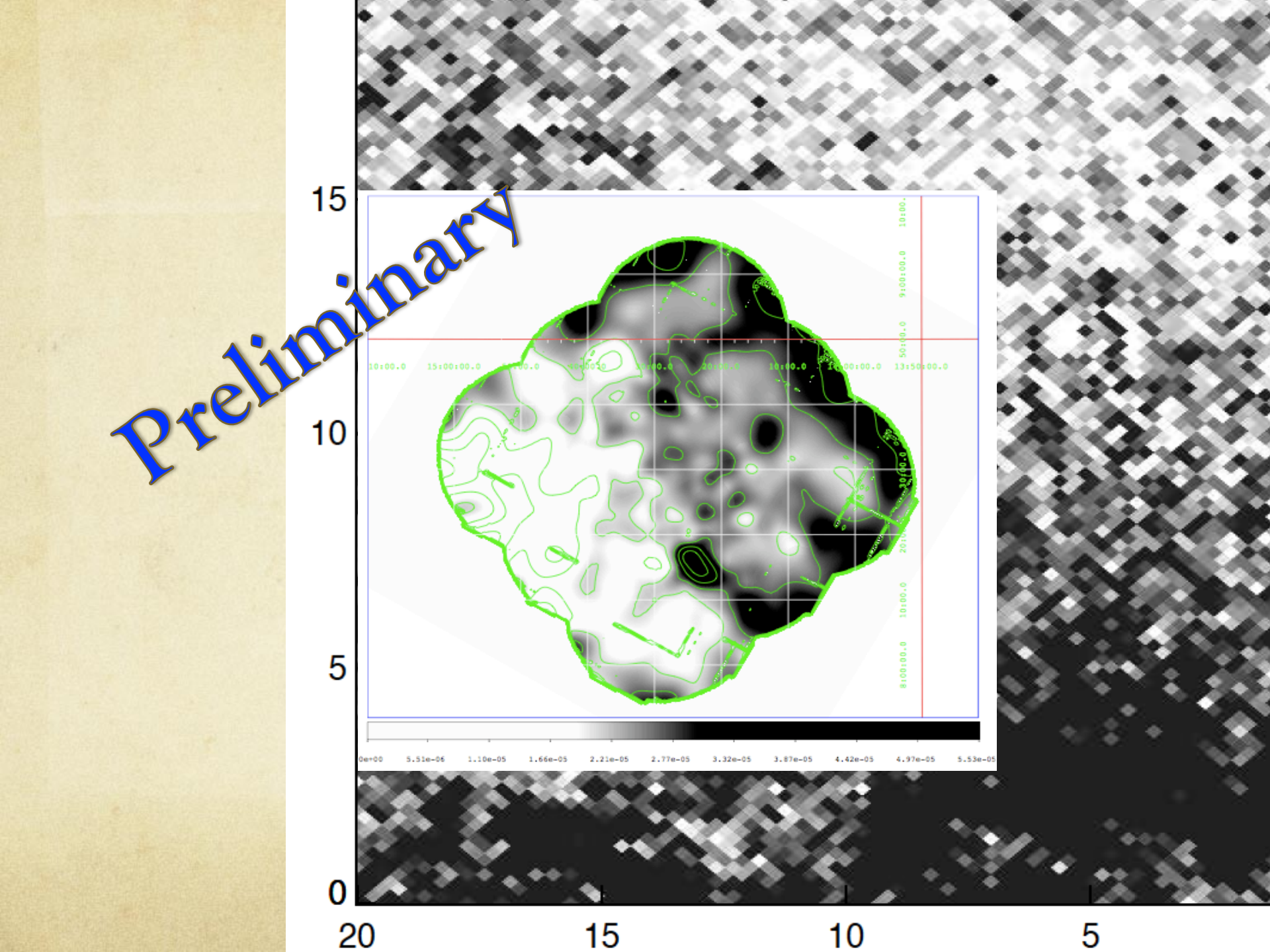
Sharp edge in X-ray too!

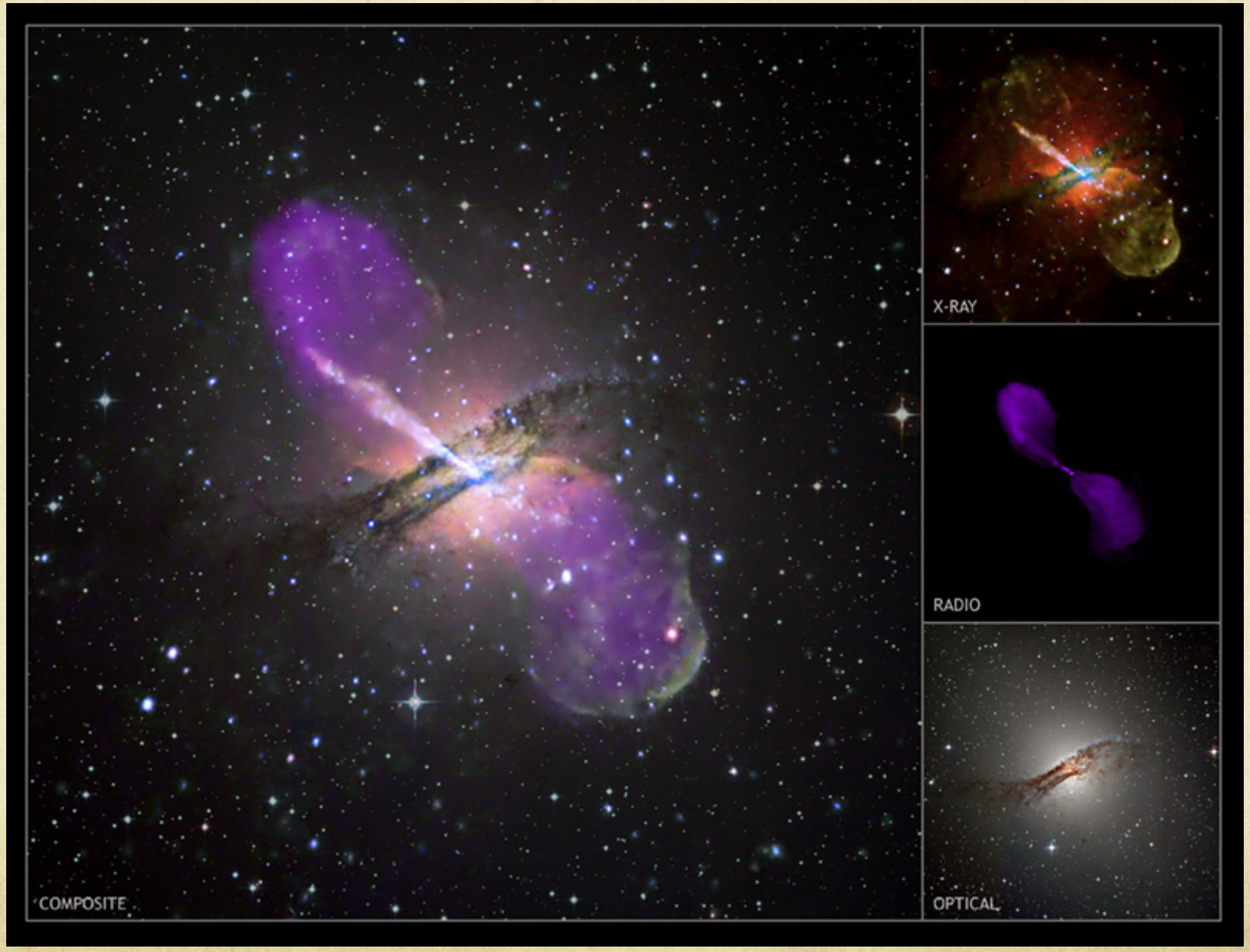


XMM-Newton observation

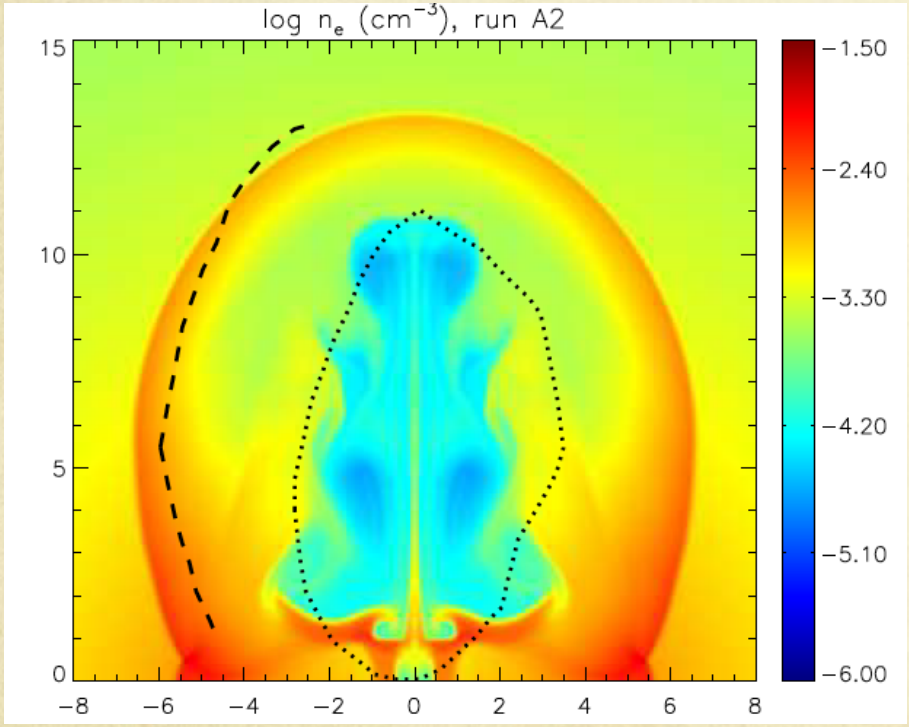




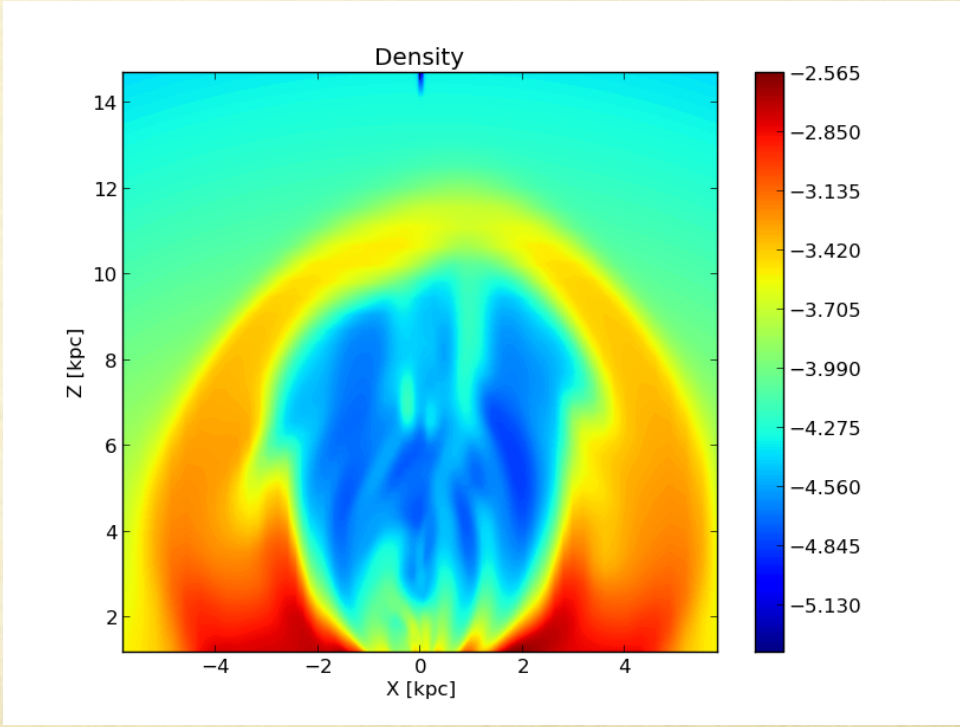

Preliminary
15
10
5
0
20
15
10
5


COMPOSITE
X-RAY
RADIO
OPTICAL

Jet or outflow?

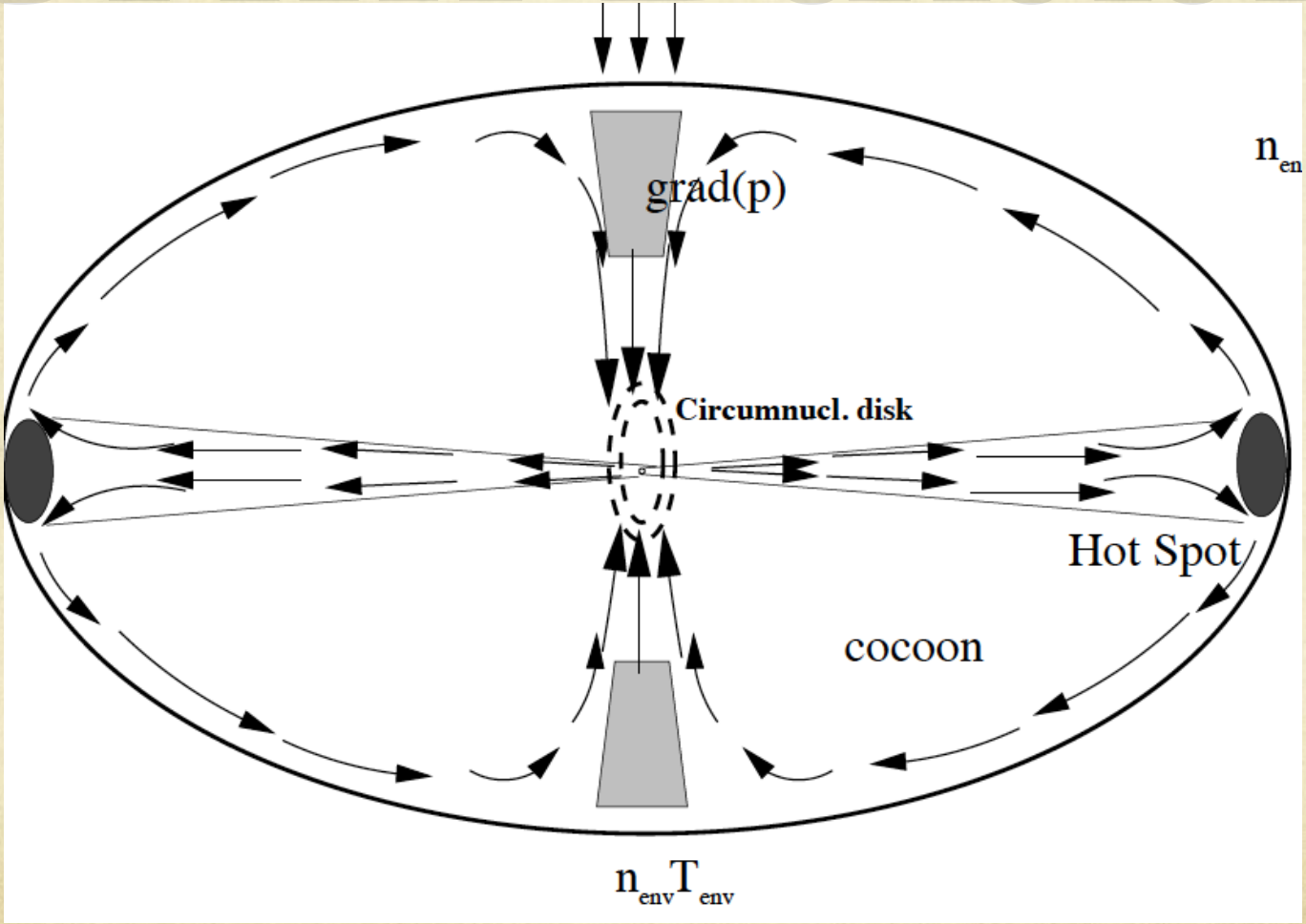


Guo & Mathews (2011)



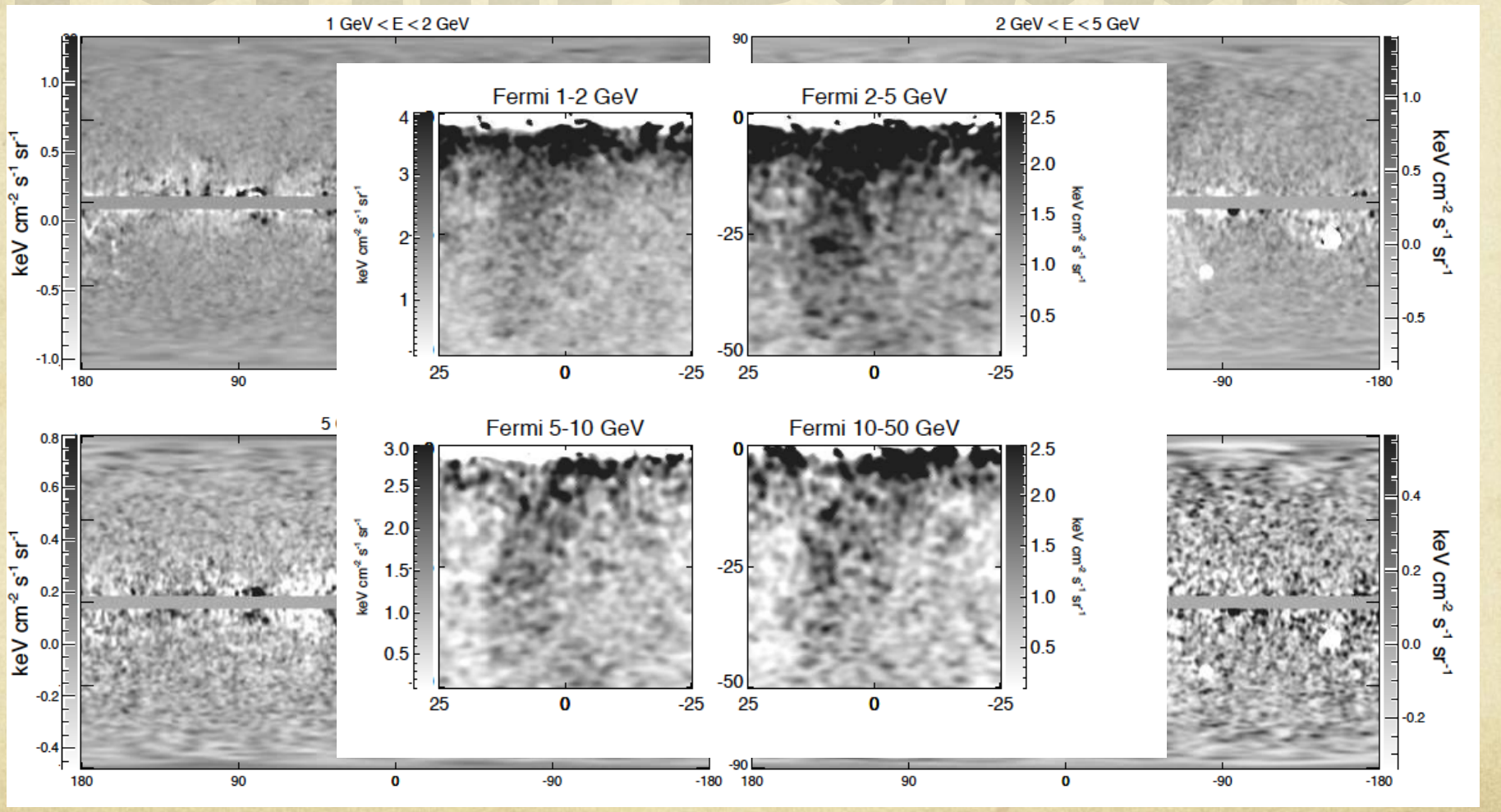
Yuan et al (2012)

Jet and Cocoon in the bubbles?

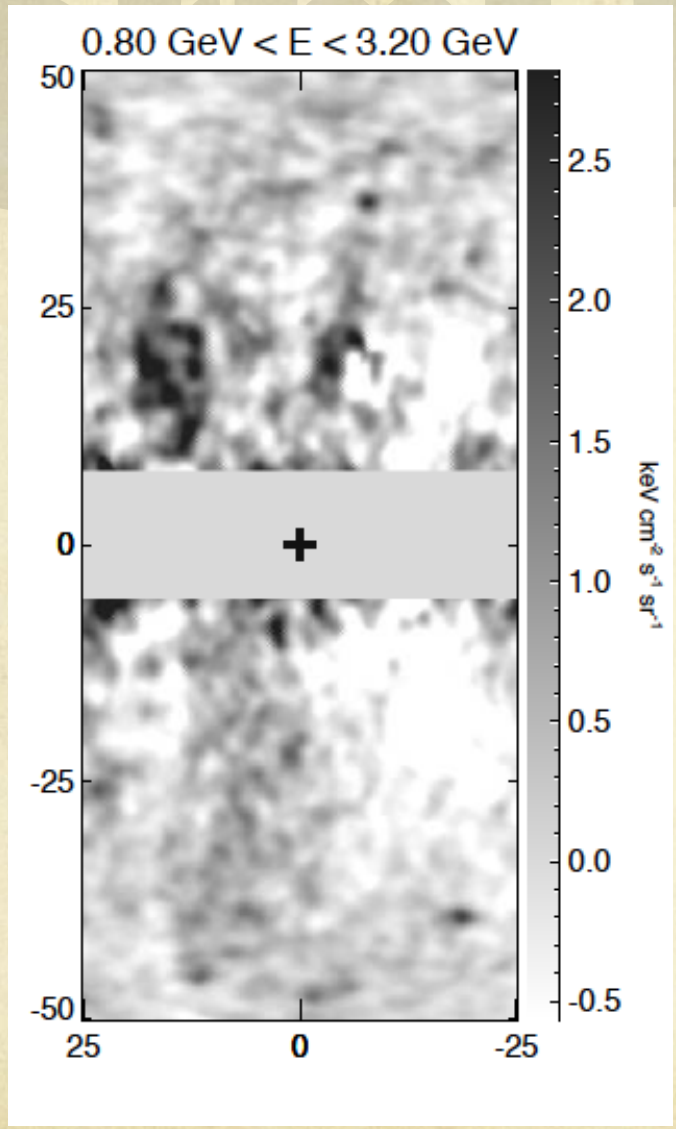


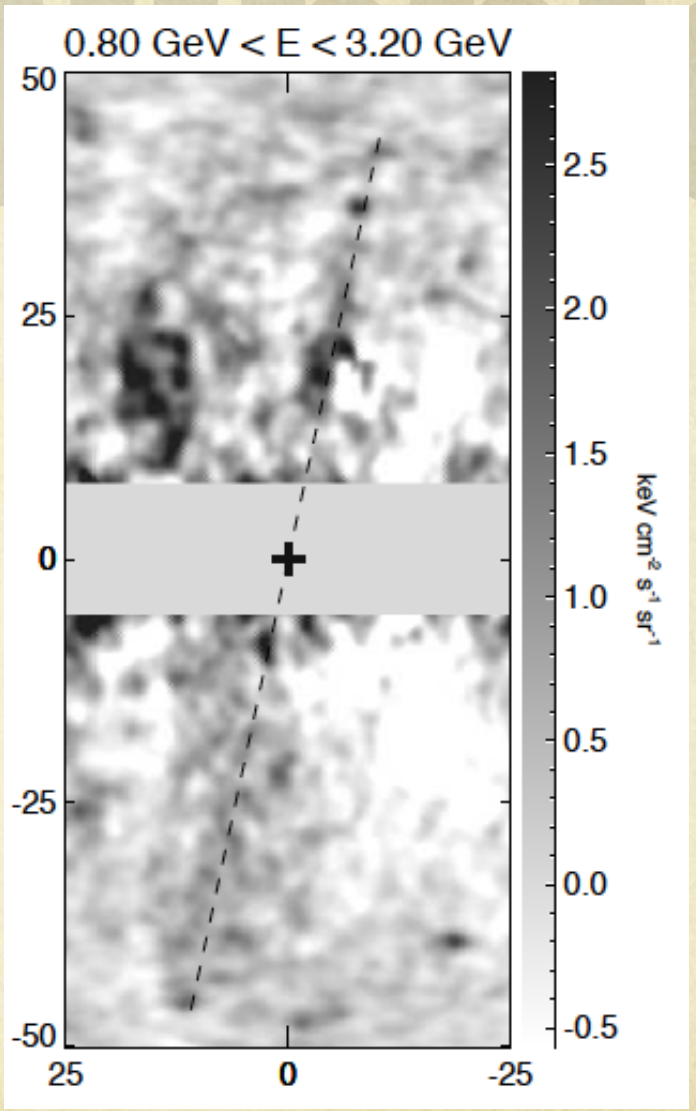
Antonuccio-Delogu & Silk (2010)

Fermi Bubble



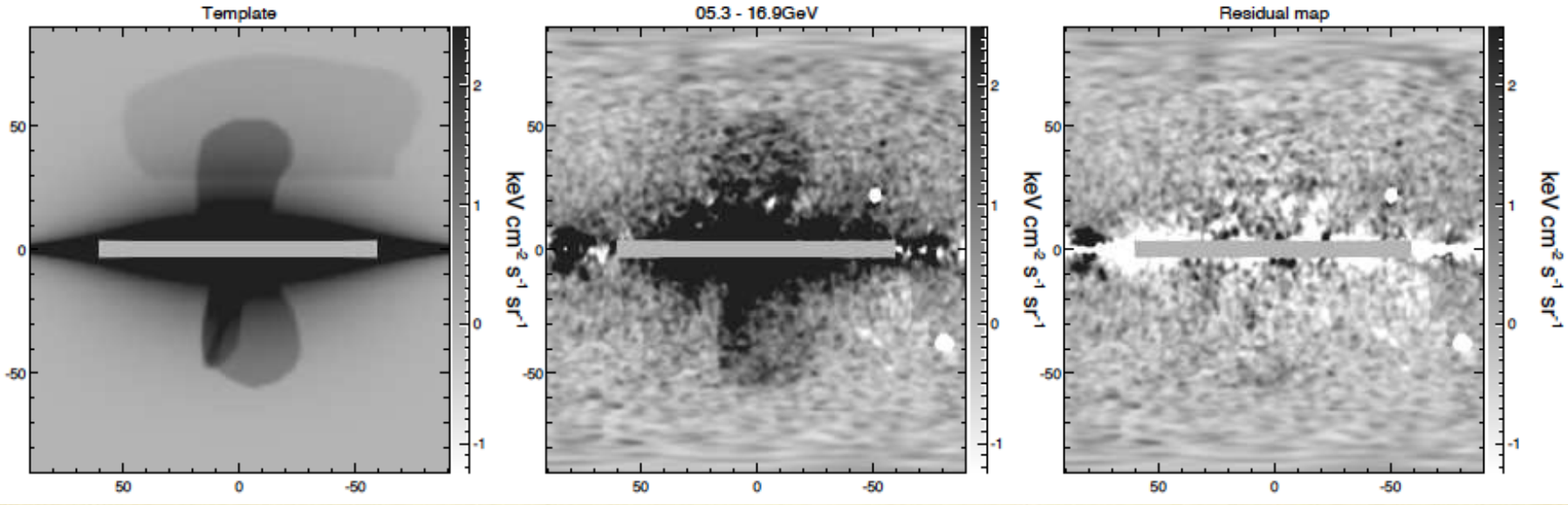
Su & Finkbeiner (2012)



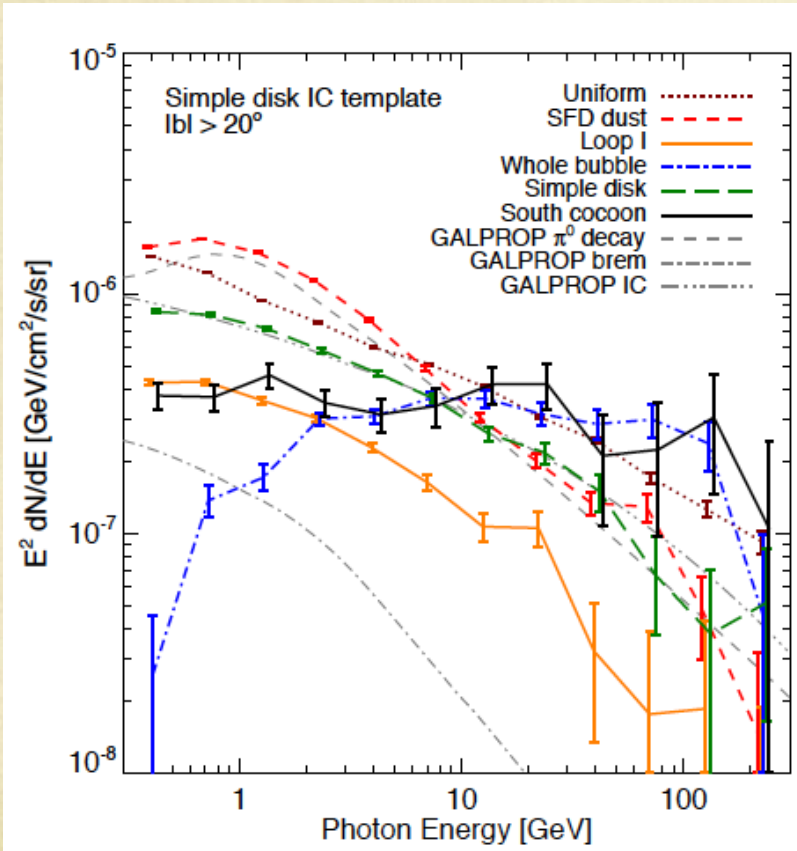


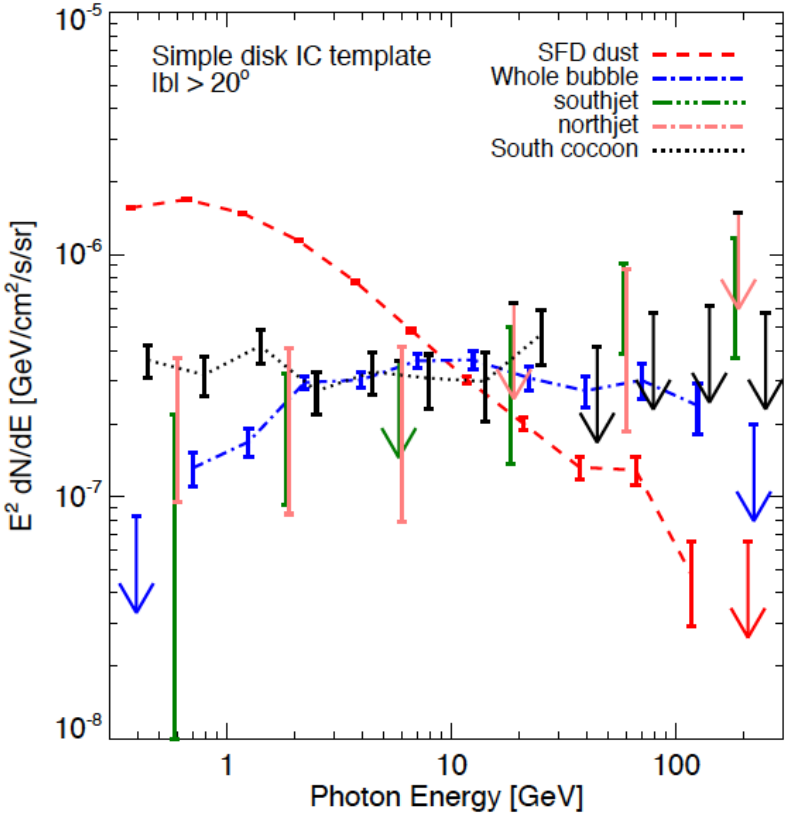
Su & Finkbeiner (2012)

Adding cocoon and jet template



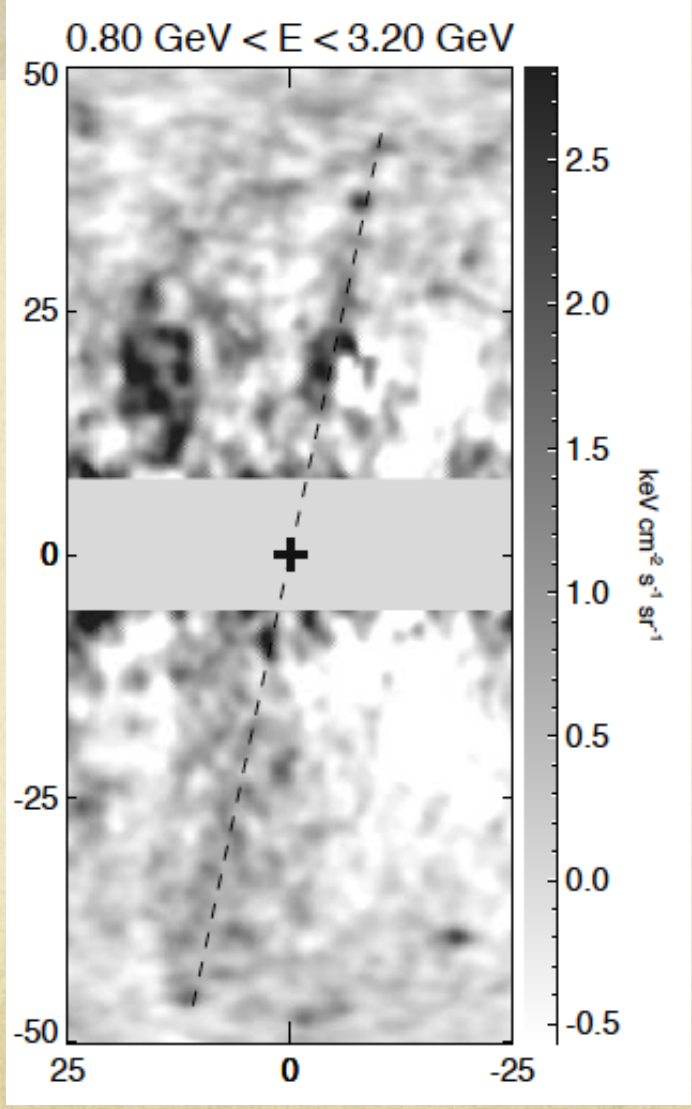
Fermi Bubble

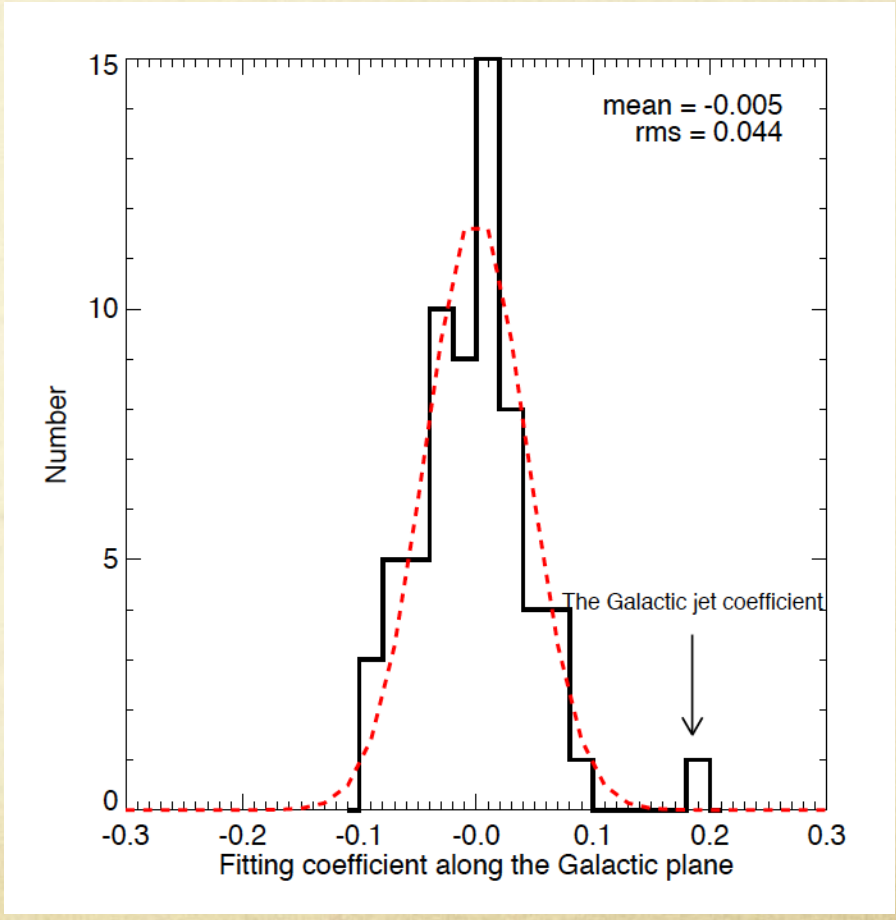




Su & Finkbeiner (2012)

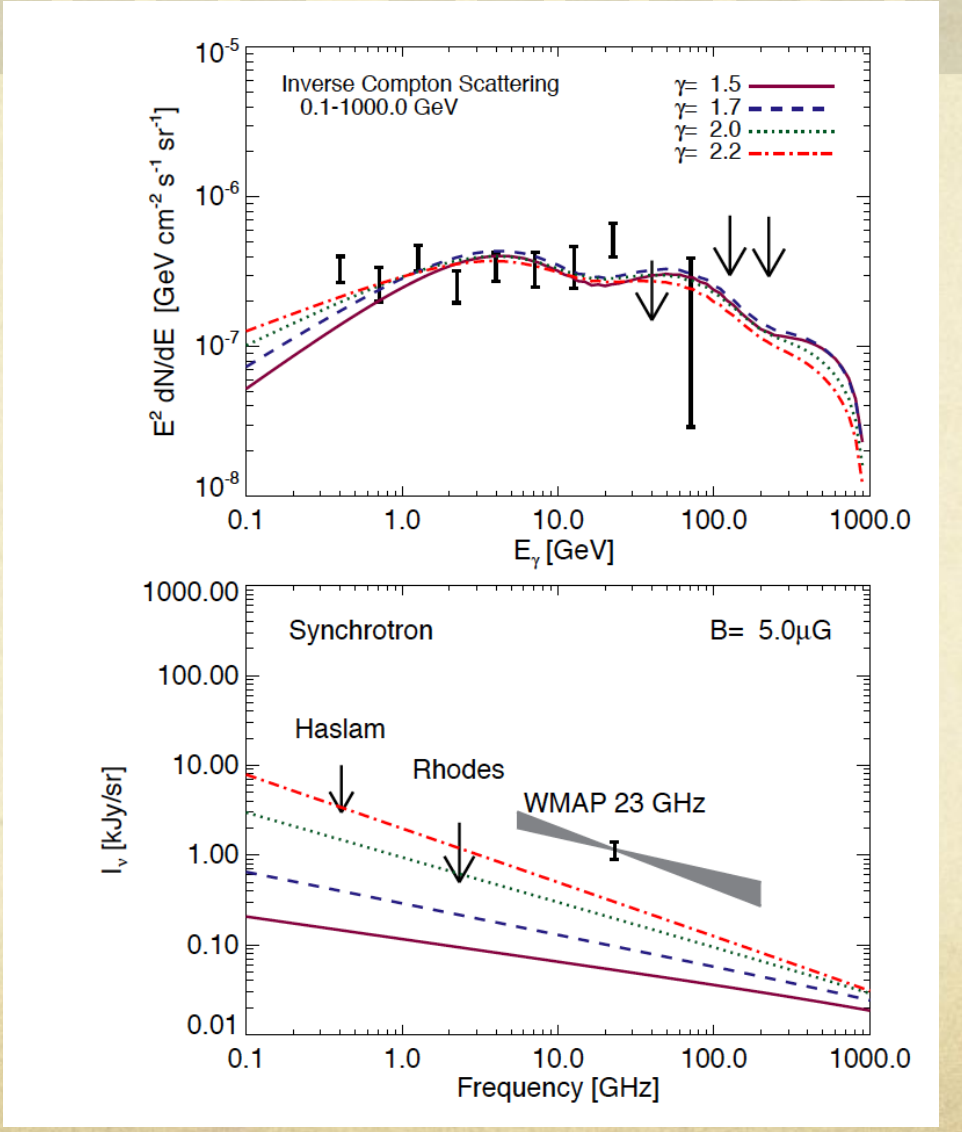
Fermi Bubble

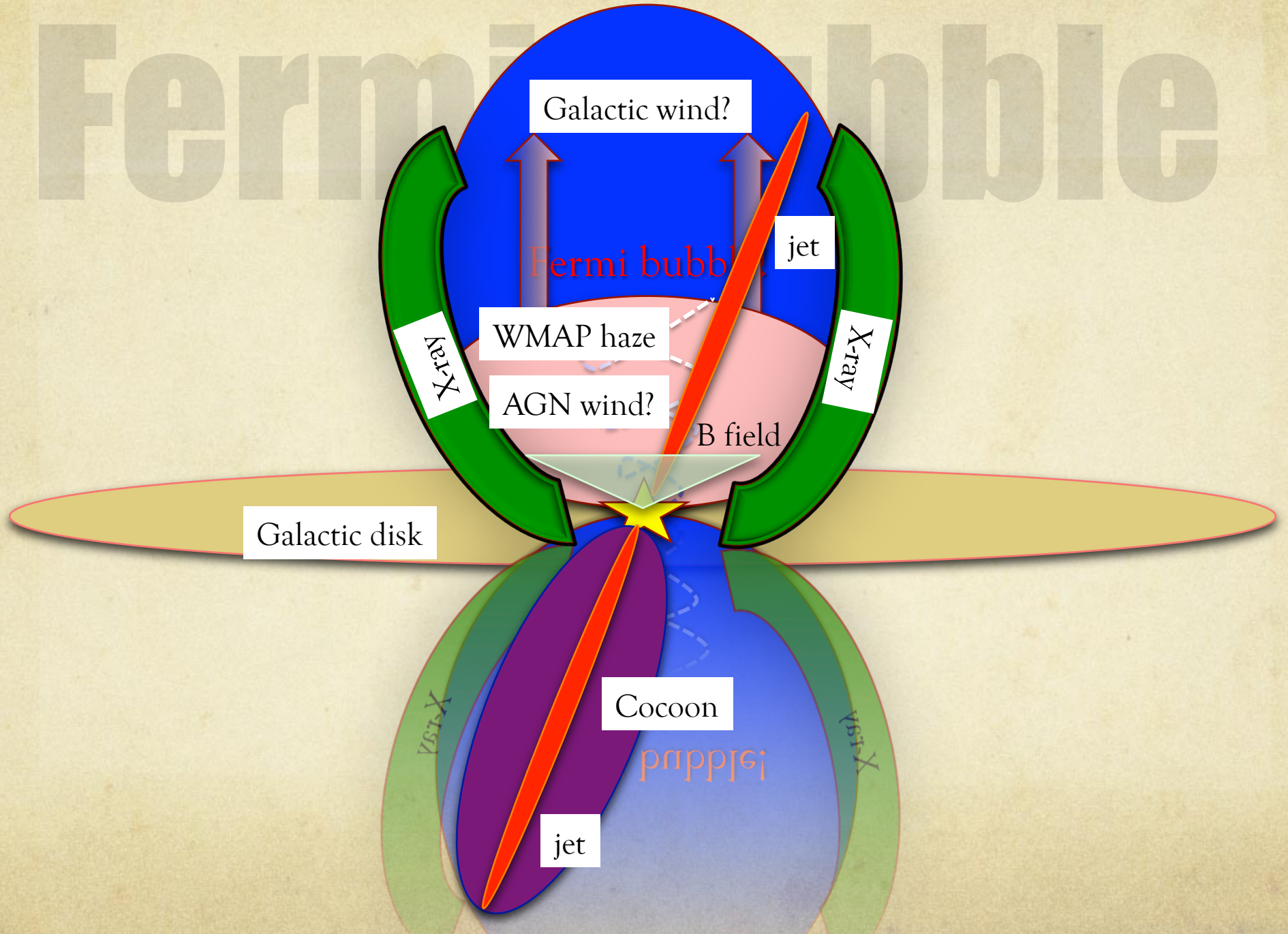




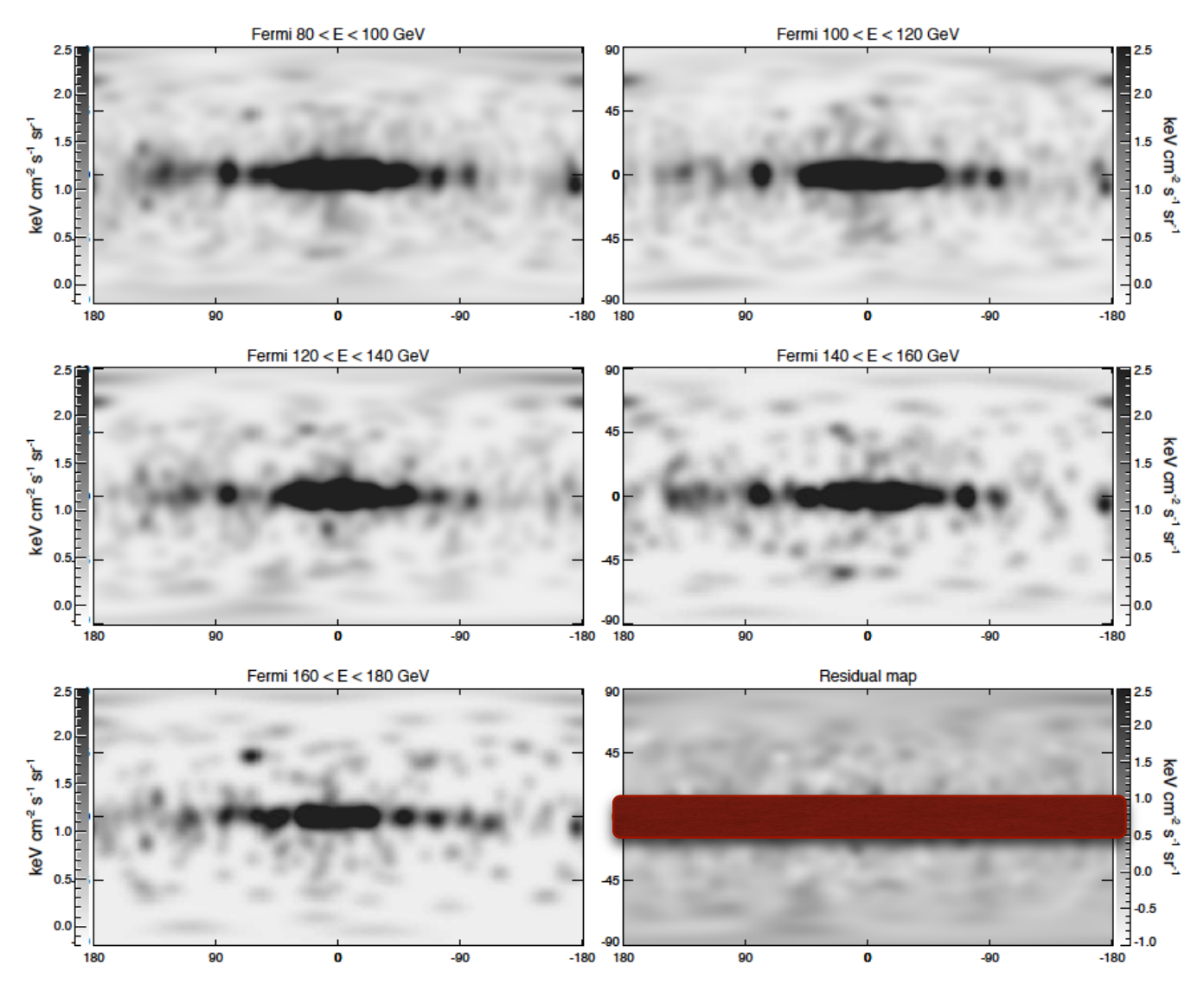
Su & Finkbeiner (2012)

Radio limit on the jet feature

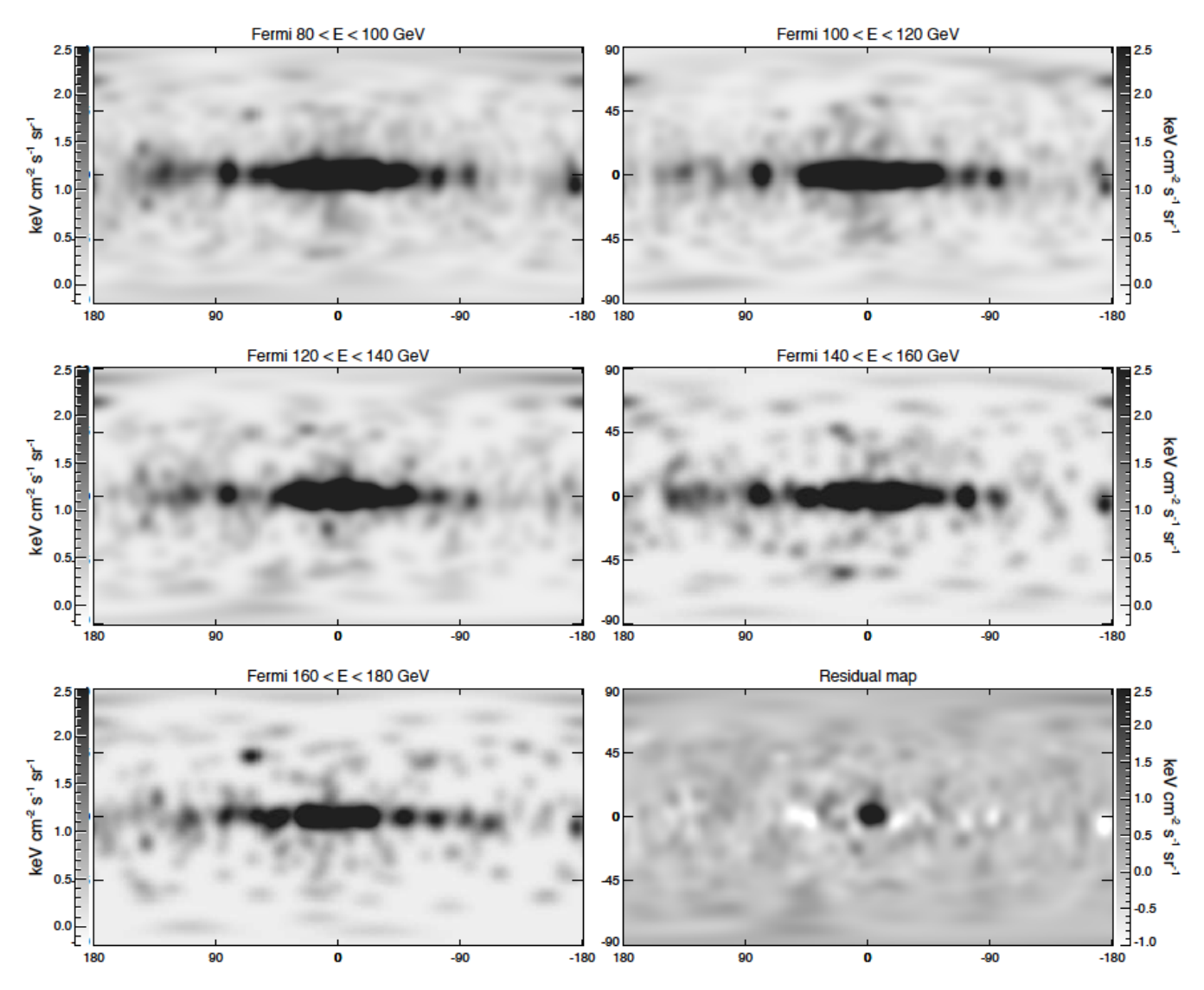



Galactic wind?
jet
Fermi bubble
WMAP haze
X-ray
X-ray
AGN wind?
B field
Galactic disk
Cocoon
jet

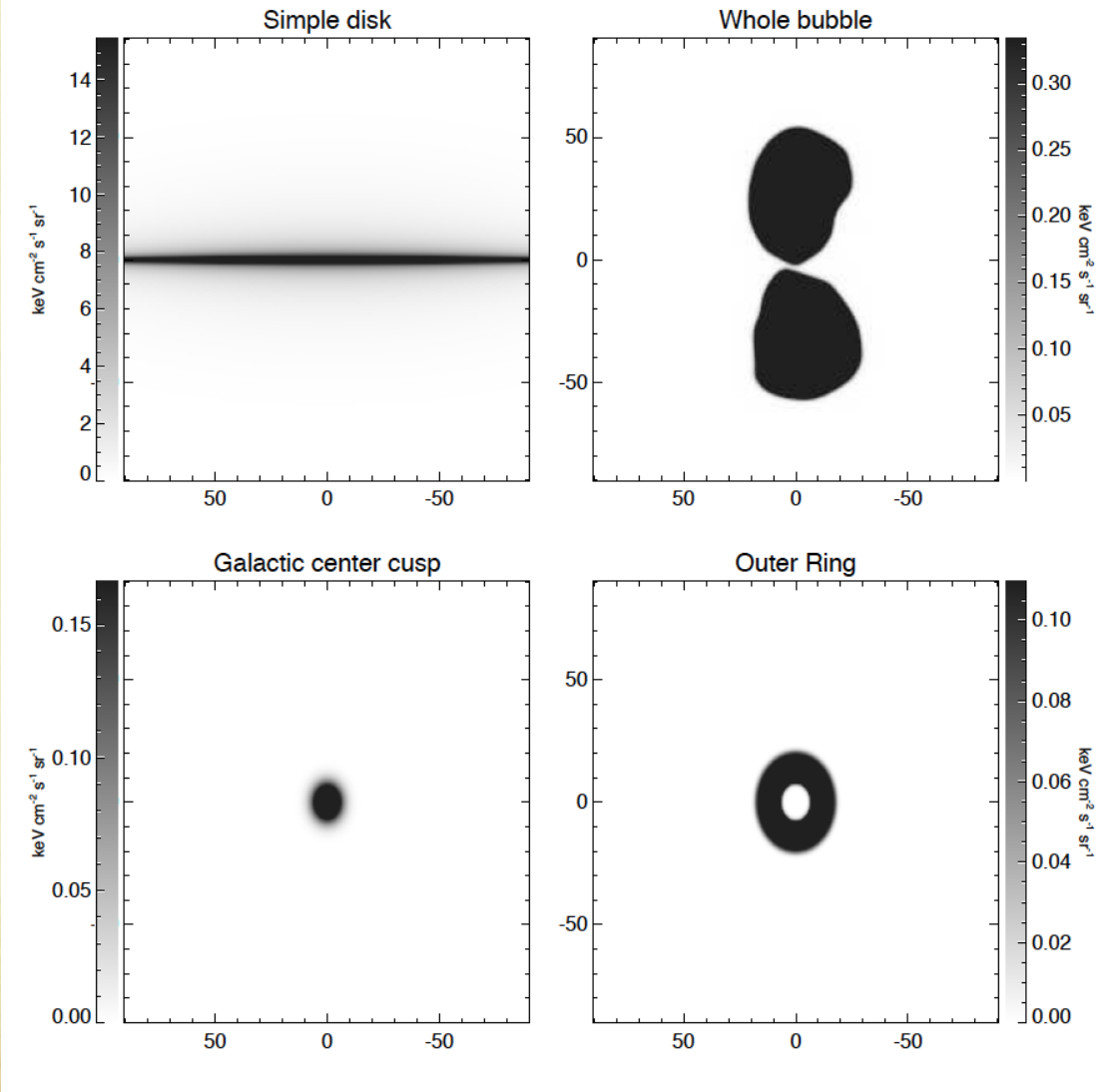
Fermi Smoothed maps



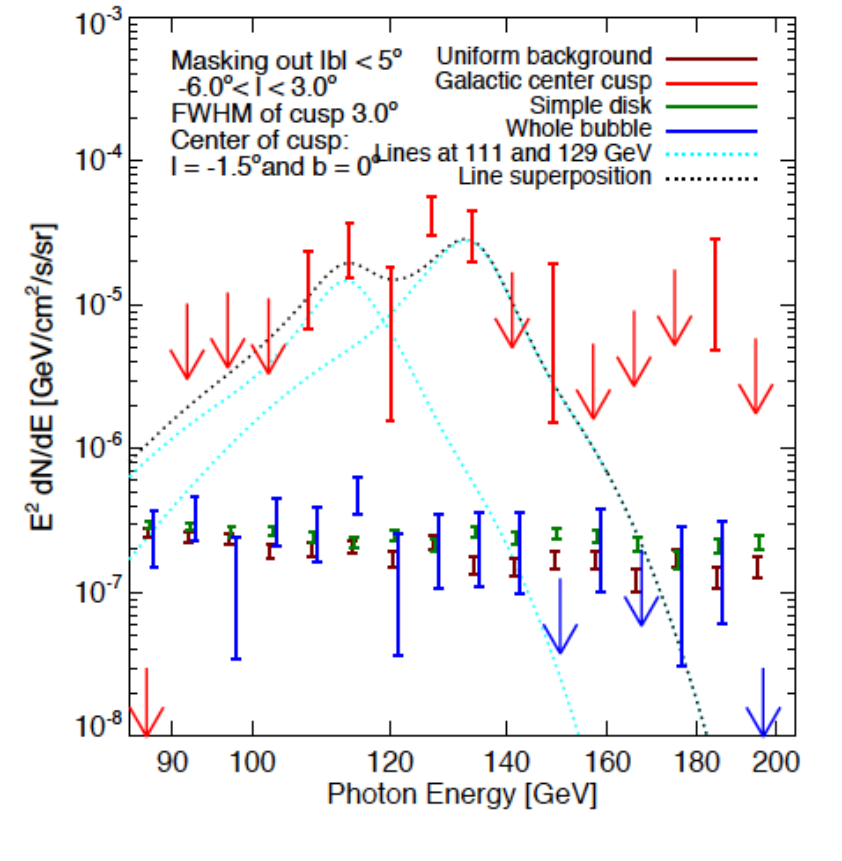
Gamma-ray line emission from GC

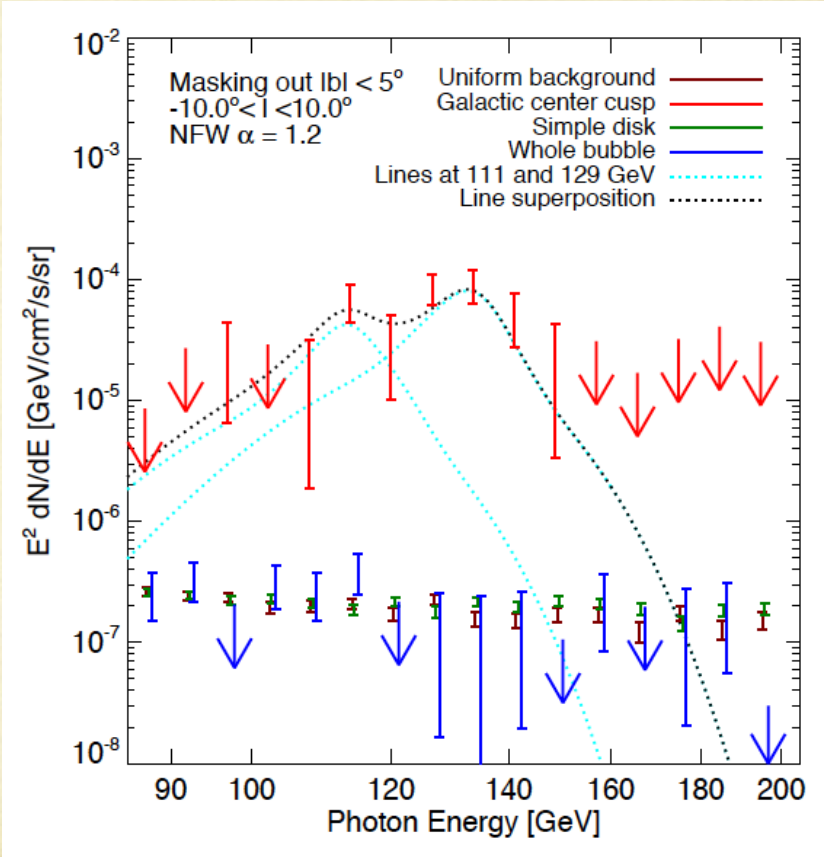


Templates for spectrum fitting



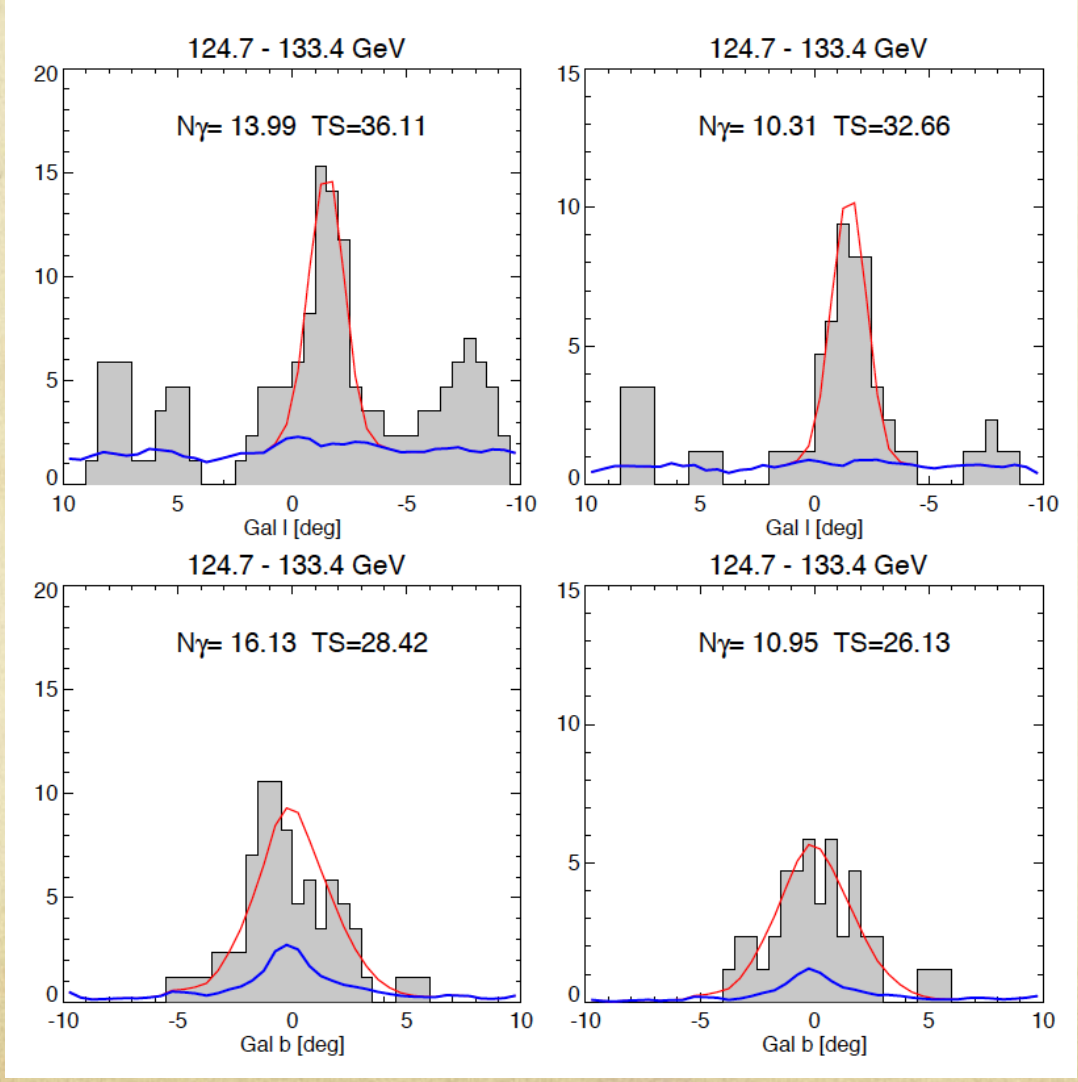
Energy spectrum of the cusp



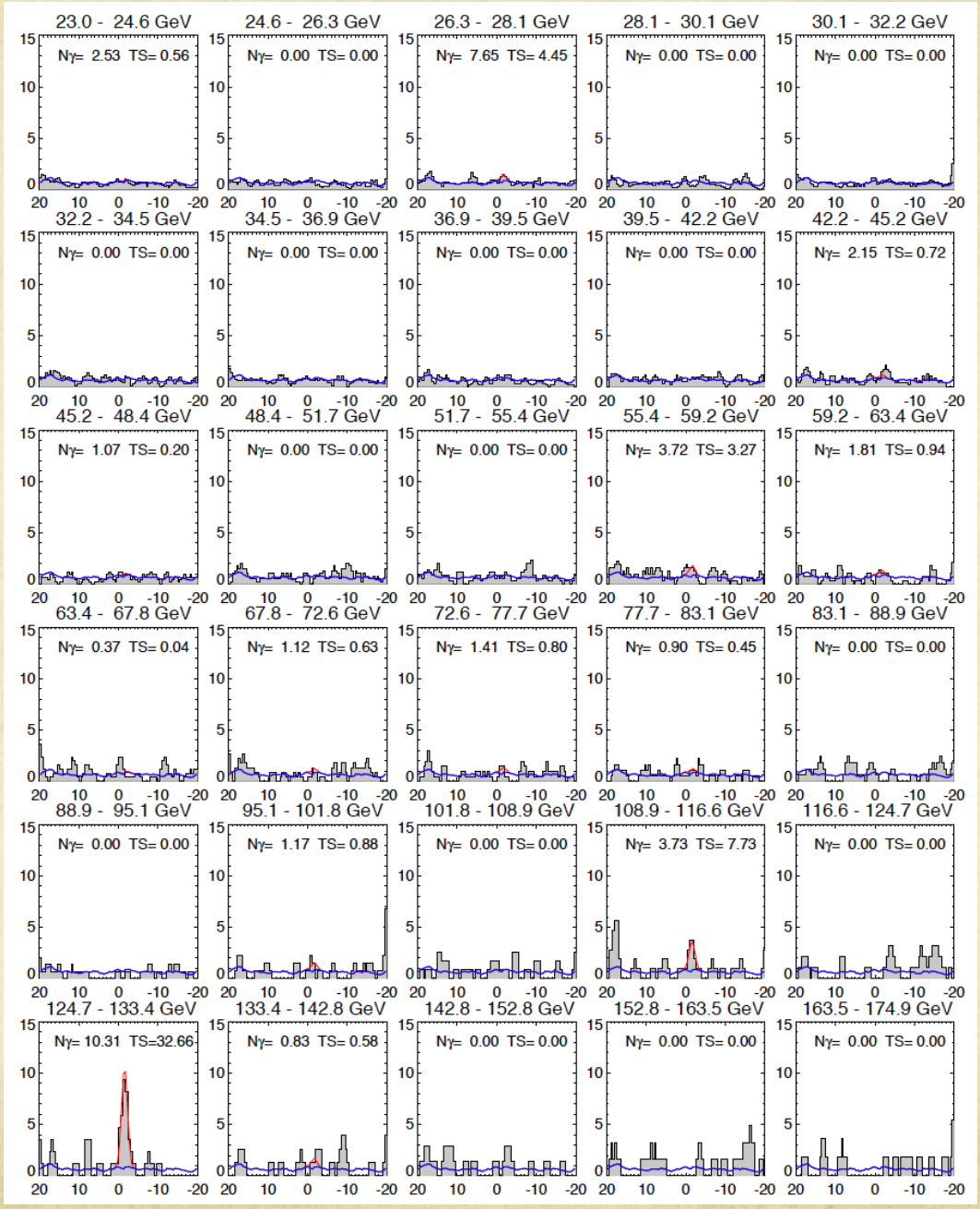


Galactic longitude and latitude profile

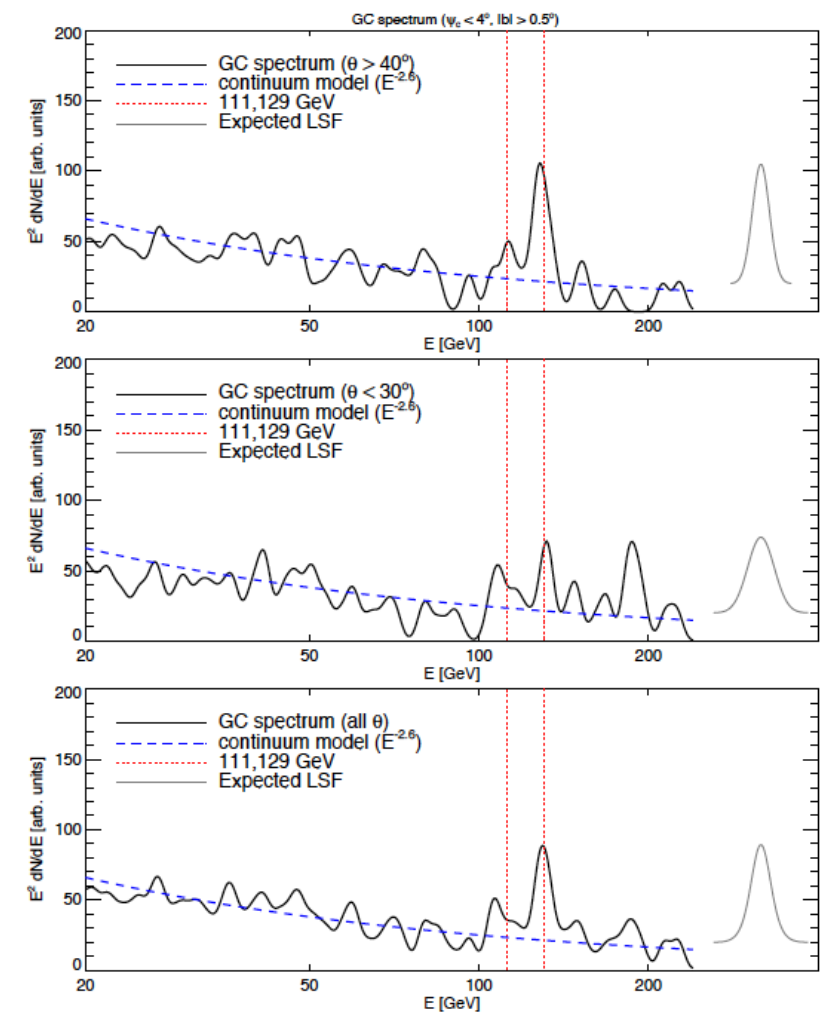
Offset from the GC!



Even though the high-incidence-angle photons ($\theta > 40°$; right) panels have half the exposure (9.7% vs. 19% for the left panels), they have more than half of the photons, and nearly the same TS due to lower off-line background leaking in.


23.0 - 24.6 GeV
Nγ= 2.53 TS= 0.56
24.6 - 26.3 GeV
Nγ= 0.00 TS= 0.00
26.3 - 28.1 GeV
Nγ= 7.65 TS= 4.45
28.1 - 30.1 GeV
Nγ= 0.00 TS= 0.00
30.1 - 32.2 GeV
Nγ= 0.00 TS= 0.00
32.2 - 34.5 GeV
Nγ= 0.00 TS= 0.00
34.5 - 36.9 GeV
Nγ= 0.00 TS= 0.00
36.9 - 39.5 GeV
Nγ= 0.00 TS= 0.00
39.5 - 42.2 GeV
Nγ= 0.00 TS= 0.00
42.2 - 45.2 GeV
Nγ= 2.15 TS= 0.72
45.2 - 48.4 GeV
Nγ= 1.07 TS= 0.20
48.4 - 51.7 GeV
Nγ= 0.00 TS= 0.00
51.7 - 55.4 GeV
Nγ= 0.00 TS= 0.00
55.4 - 59.2 GeV
Nγ= 3.72 TS= 3.27
59.2 - 63.4 GeV
Nγ= 1.81 TS= 0.94
63.4 - 67.8 GeV
Nγ= 0.37 TS= 0.04
67.8 - 72.6 GeV
Nγ= 1.12 TS= 0.63
72.6 - 77.7 GeV
Nγ= 1.41 TS= 0.80
77.7 - 83.1 GeV
Nγ= 0.90 TS= 0.45
83.1 - 88.9 GeV
Nγ= 0.00 TS= 0.00
88.9 - 95.1 GeV
Nγ= 0.00 TS= 0.00
95.1 - 101.8 GeV
Nγ= 1.17 TS= 0.88
101.8 - 108.9 GeV
Nγ= 0.00 TS= 0.00
108.9 - 116.6 GeV
Nγ= 3.73 TS= 7.73
116.6 - 124.7 GeV
Nγ= 0.00 TS= 0.00
124.7 - 133.4 GeV
Nγ= 10.31 TS=32.66
133.4 - 142.8 GeV
Nγ= 0.83 TS= 0.58
142.8 - 152.8 GeV
Nγ= 0.00 TS= 0.00
152.8 - 163.5 GeV
Nγ= 0.00 TS= 0.00
163.5 - 174.9 GeV
Nγ= 0.00 TS= 0.00

Assessment of line profile



- The 129 GeV feature shape is strikingly similar to that expected for a line. The 111 GeV feature is unconvincing, but is also compatible with a line.
- In some cases, fluctuations appear, but are not present in both low and high incidence spectra.
- This test did not have to succeed. The fact that the high-incidence photon sample has sharper spectral features is important.

The detection significance of the gamma-ray cusp for various models

Models	Before trials	After trials (one line)	Trials factor (one line)
Gaussian (centered)	5.0σ	3.7σ	300
Gaussian (off center, $\theta > 40^\circ$)	5.5σ	3.7σ	6000
unbinned ℓ	5.2σ	3.2σ	6000
unbinned ℓ ($\theta > 40^\circ$)	4.9σ	2.8σ	6000
unbinned b	4.8σ	3.5σ	300
unbinned b ($\theta > 40^\circ$)	4.6σ	3.2σ	300
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ	6000
NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ	6000
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ	6000
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ	6000
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ	6000
Einasto (off center)	$\mathbf{6.6\sigma}$	$\mathbf{5.1\sigma}$	**6000**

Two lines model

Models	After trials (two line)	Trials factor (two line)
Gaussian (centered)	4.3σ	36
Gaussian (off center, $\theta > 40°$)	4.2σ	720
NFW $\alpha = 1.0$ (off center)	4.9σ	720
NFW $\alpha = 1.2$ (off center)	5.4σ	720
NFW $\alpha = 1.3$ (off center)	4.8σ	720
NFW $\alpha = 1.4$ (off center)	4.3σ	720
NFW $\alpha = 1.5$ (off center)	3.8σ	720
Einasto (off center)	$\mathbf{5.5\sigma}$	**720**

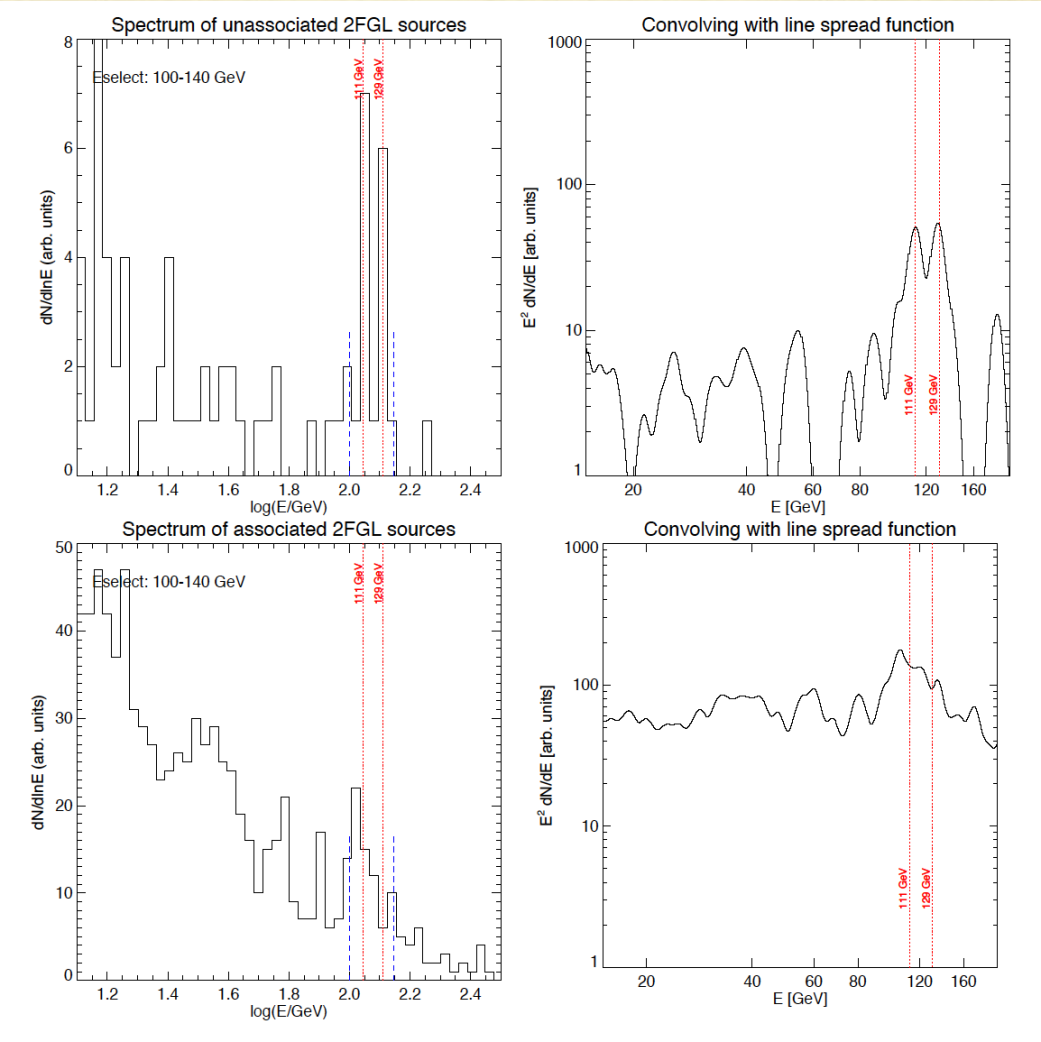
A MODIFIED SURVEY STRATEGY FOR FERMI

- The scan strategy of **Fermi**-LAT could be altered for 1 year to confirm the 130 GeV line!
- This current strategy is excellent for uniformity of full-sky coverage, but is far from optimal for collecting high-incidence-angle photons from the GC.
- The exposure time of our ($40^\circ < \theta < 60^\circ$) sample exceeds the current strategy (observed 9.7% of the time) by more than a factor of 4. Require GC have an incidence angle of $45^\circ < \theta < 55^\circ$.
- After 1 year of altered observing, we would have a sample of high incidence photons equal to the current sample, and could evaluate their significance directly, in the absence of any trials factor!

What has Fermi found: The LAT two-year catalog

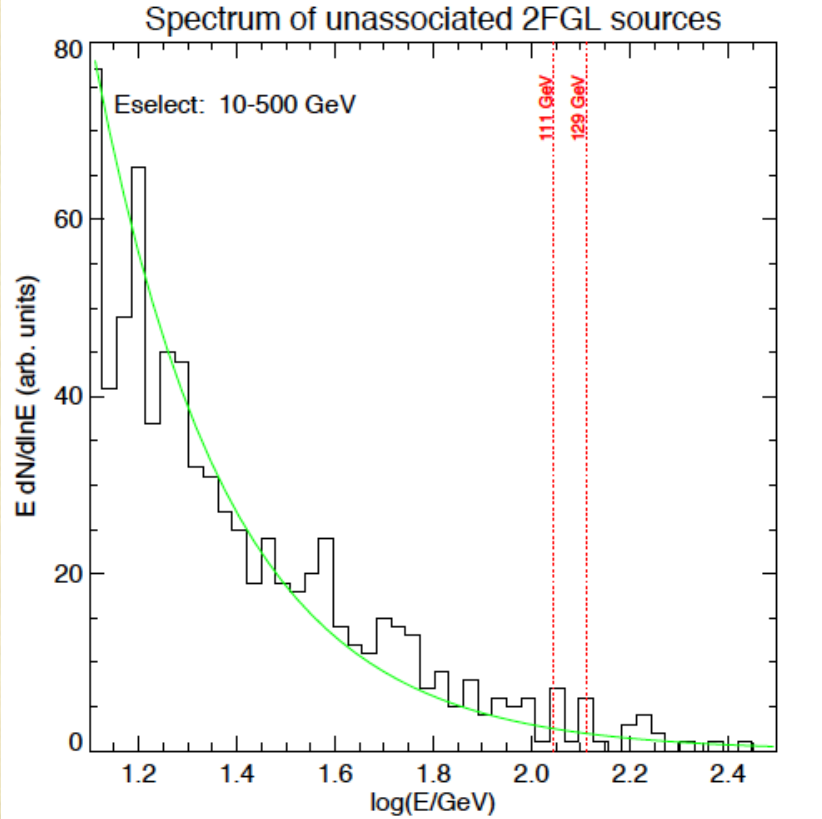
Credit: NASA/Goddard Space Flight Center

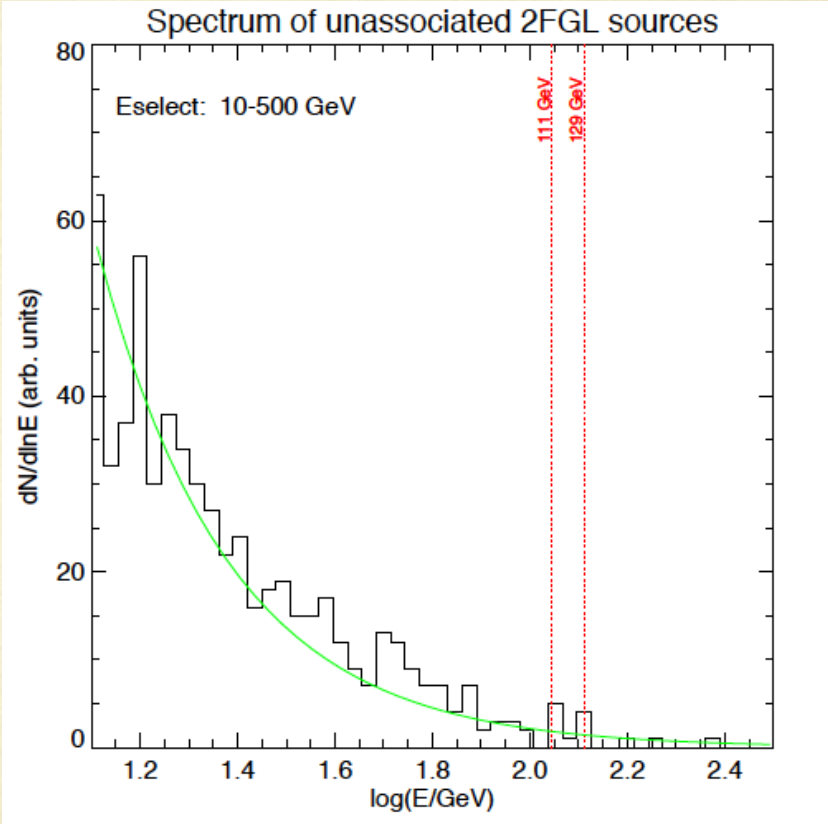
DOUBLE GAMMA-RAY LINES FROM UNASSOCIATED FERMI-LAT SOURCES



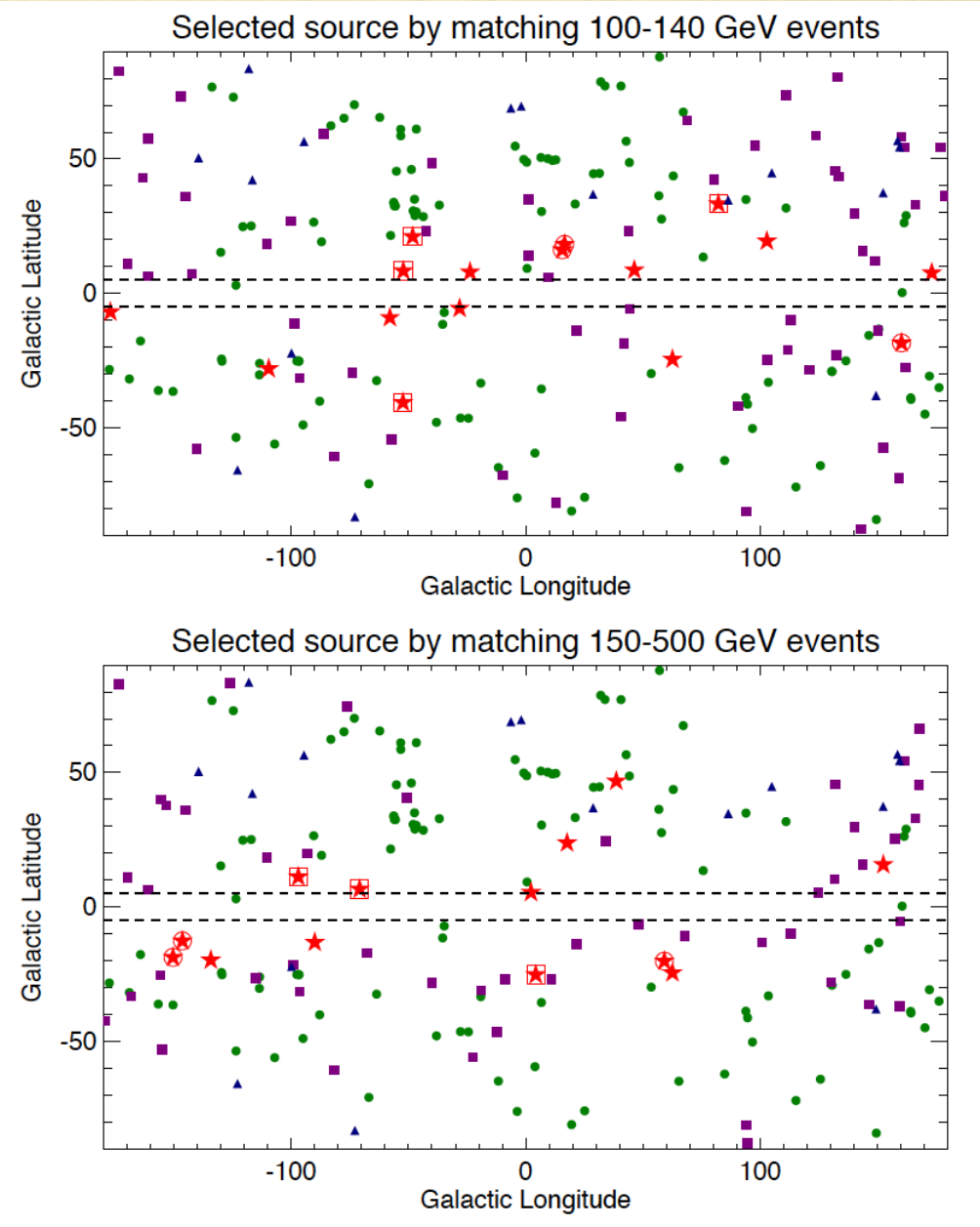
Su & Finkbeiner (arXiv:1207.7060)

Background estimation





Su & Finkbeiner (arXiv:1207.7060)



Su & Finkbeiner (arXiv:1207.7060)

Dark Matter?

(Video credit: NASA's Goddard Space Flight Center)