Fermi Bubble

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

Evidence for Gamma-ray Jets in the Milky Way

Meng Su

Collaborators: Douglas P. Finkbeiner, Tracy R. Slatyer

Harvard University

Jet 2012, NRAO, Charlottesville

2012.03.04

Fermi Bubbles

Giant gamma-ray structure with sharp edges discovered using Large Area Telescope on board Fermi Gamma-ray Space Telescope

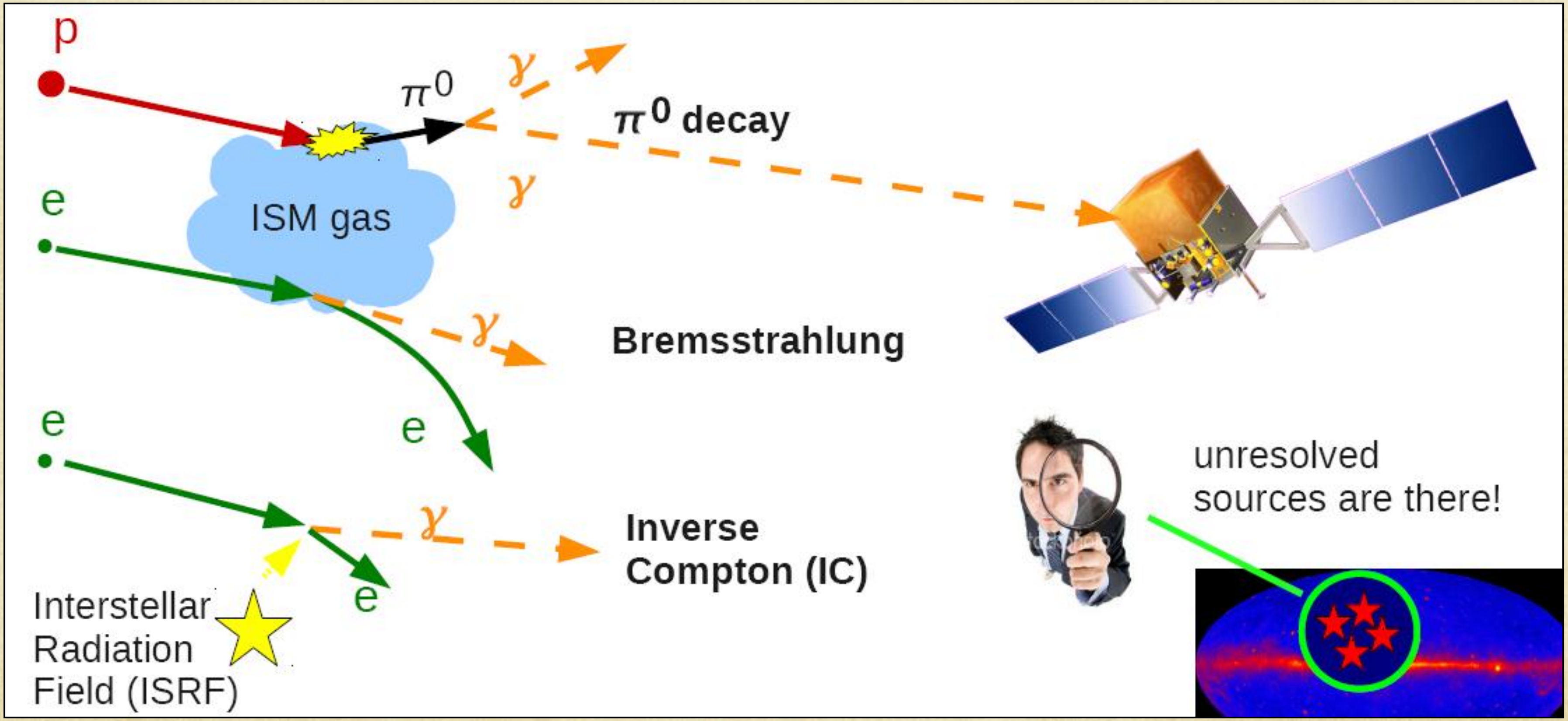
Appearing rise up & down from the Galactic center

They are:

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

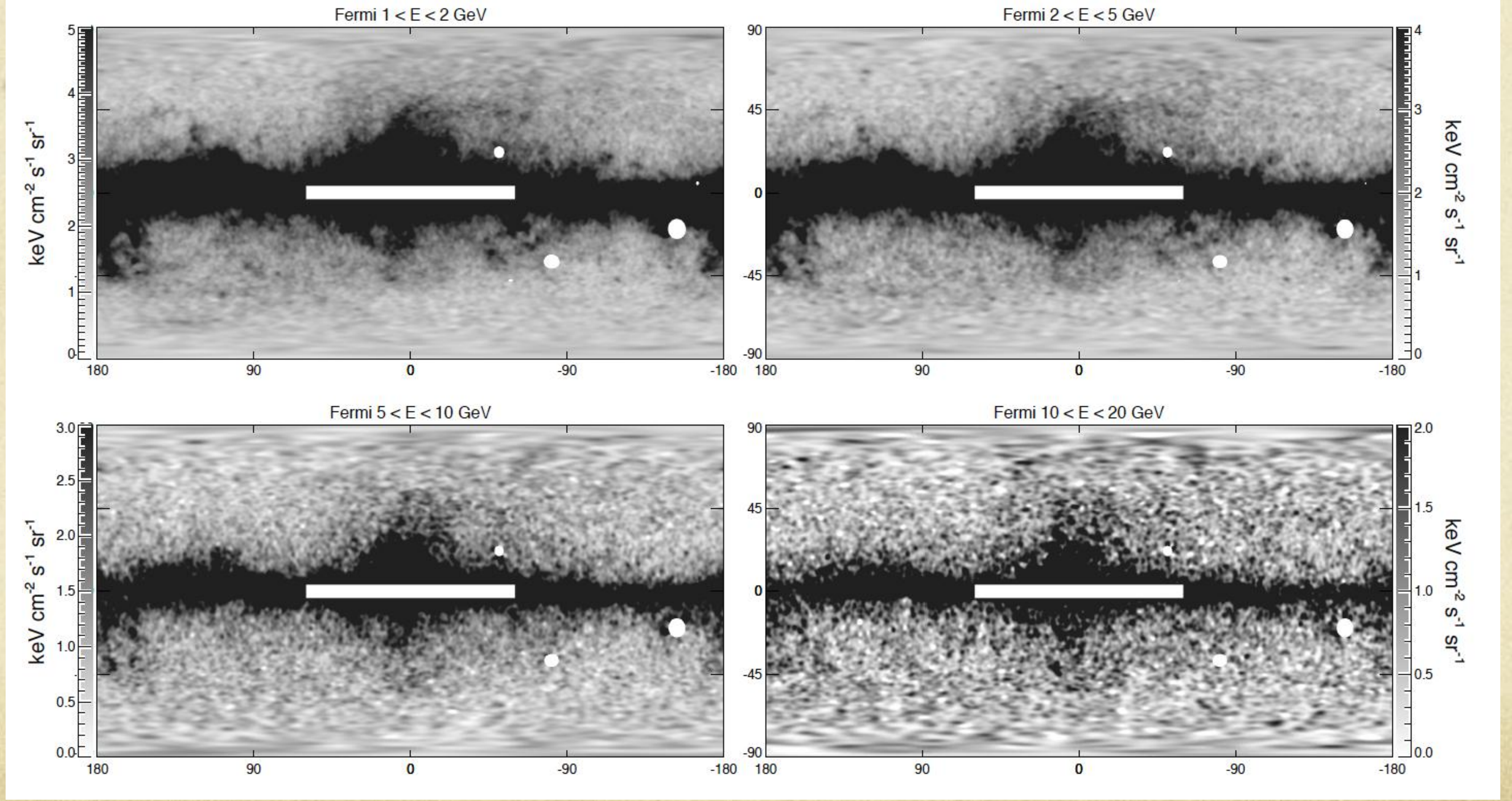
Su, Slatyer, & Finkbeiner (2010)

High energy gamma-rays are produced via interactions between cosmic-rays (CRs) and the interstellar medium (or the interstellar radiation field)



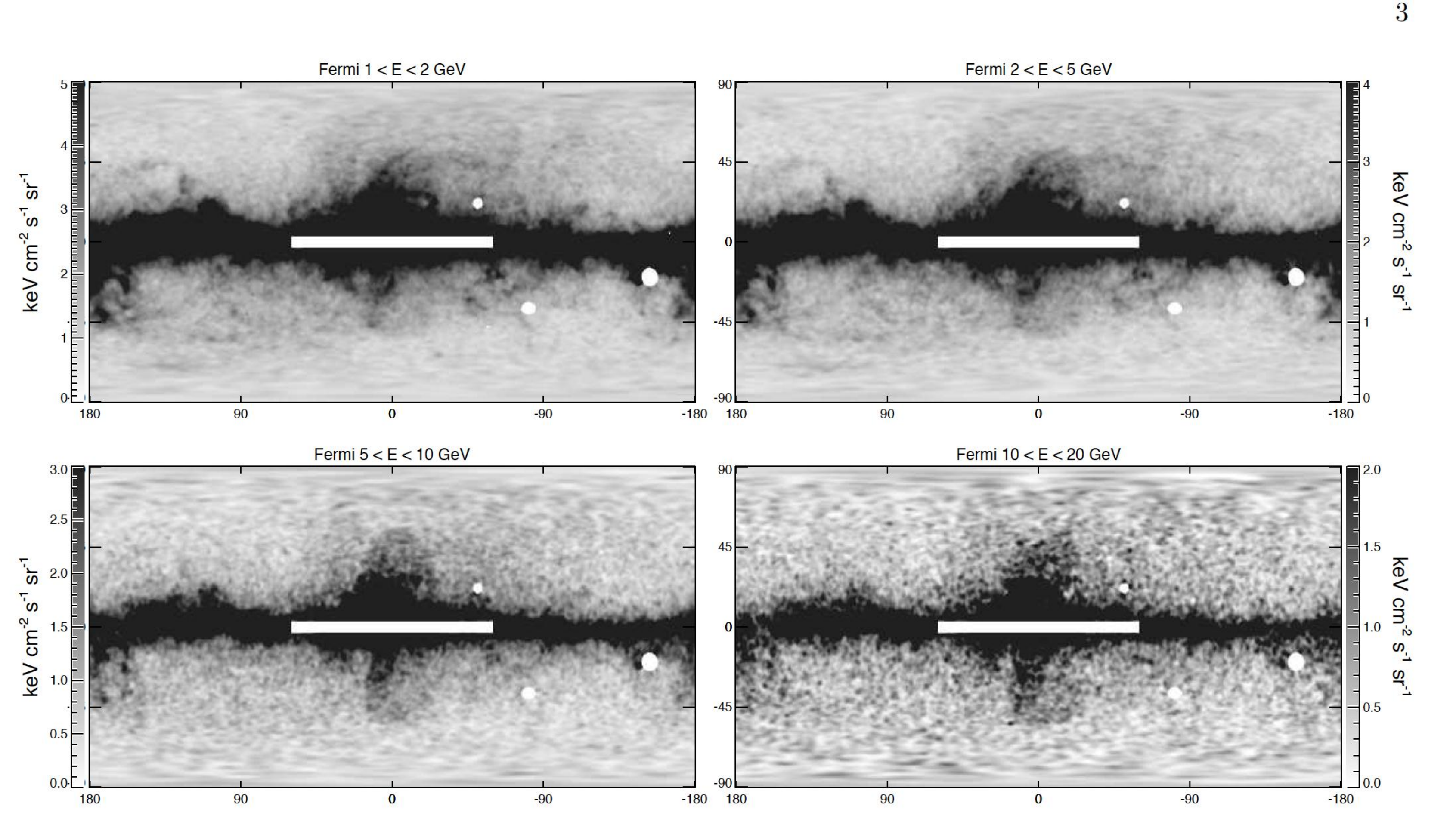
(from Tsunefumi Mizuno)

The Fermi-LAT 1.5 year maps



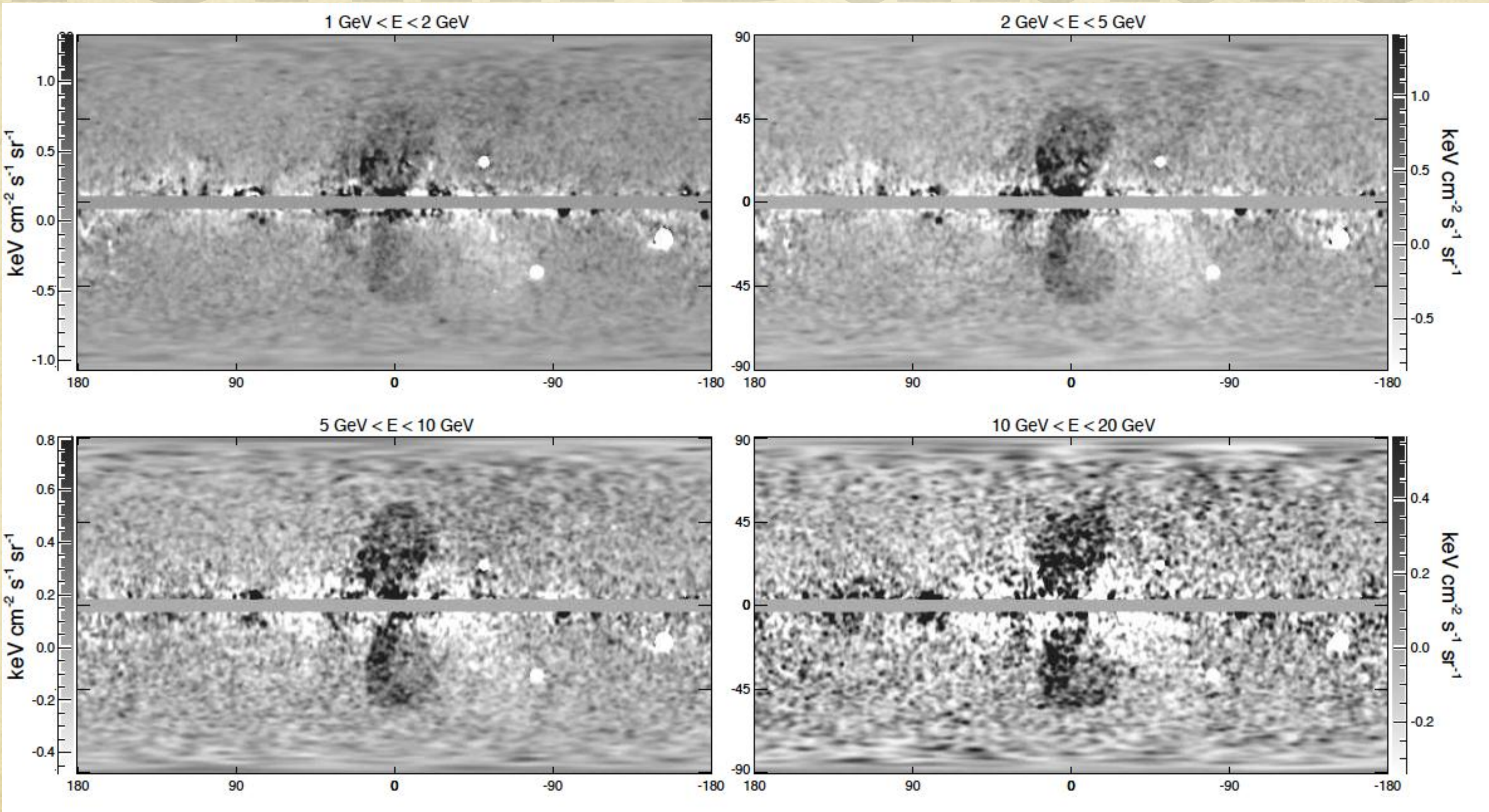
Su et al. (2010)

The Fermi-LAT three year maps



Su & Finkbeiner (2012)

Data minus Fermi diffuse emission model:



Su & Finkbeiner (2012)

Fermi Bubble

Subtracting the Fermi diffuse emission model reveals a faint bilobular structure in the inner Galaxy.

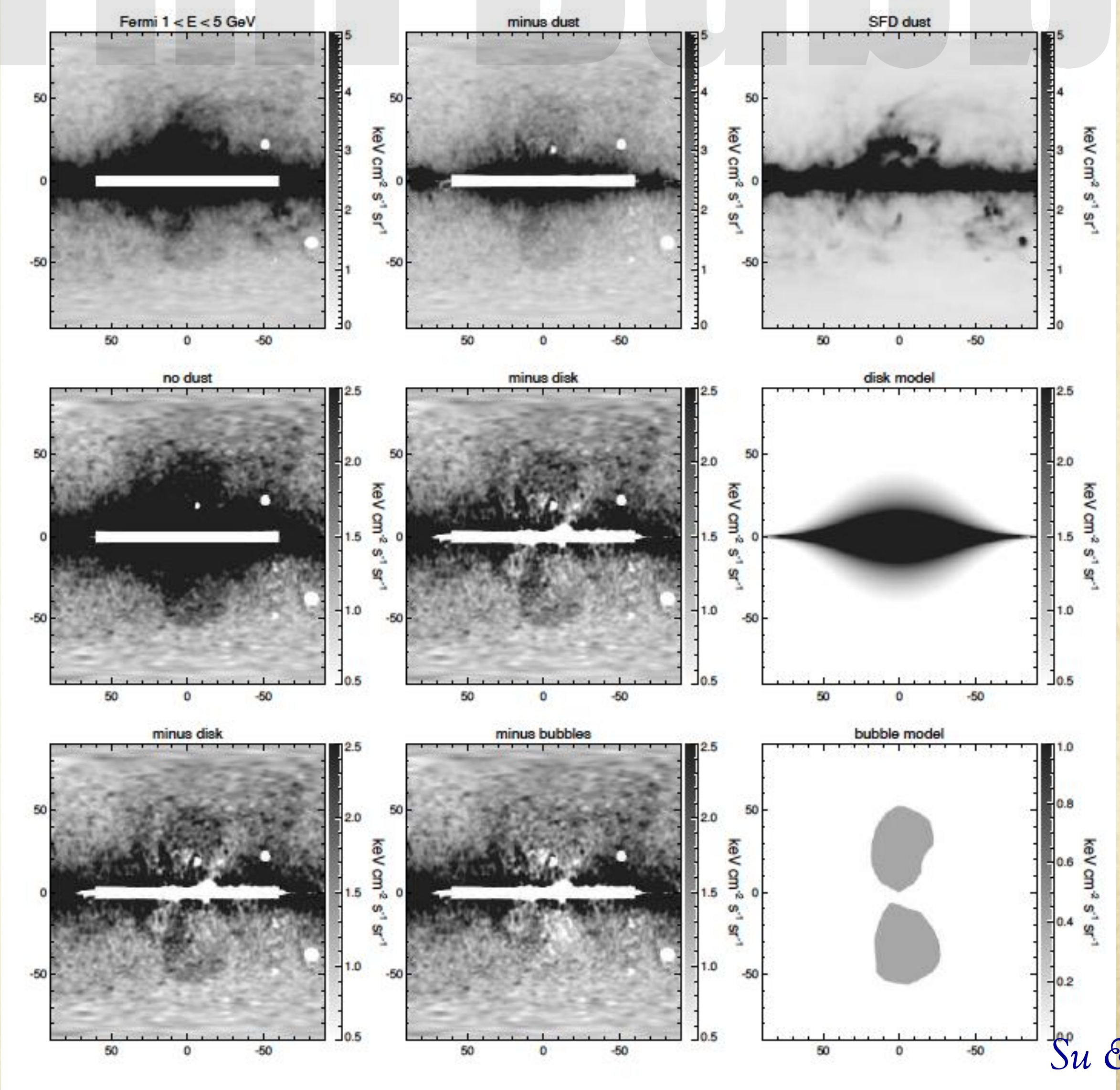
This is a complicated model - could the residual structure be an artifact?

Model contains ^{0} and bremsstrahlung from gas maps; IC from GALPROP; North Polar Spur feature from Haslam map.

Let's try something very simple and see how robust this is.

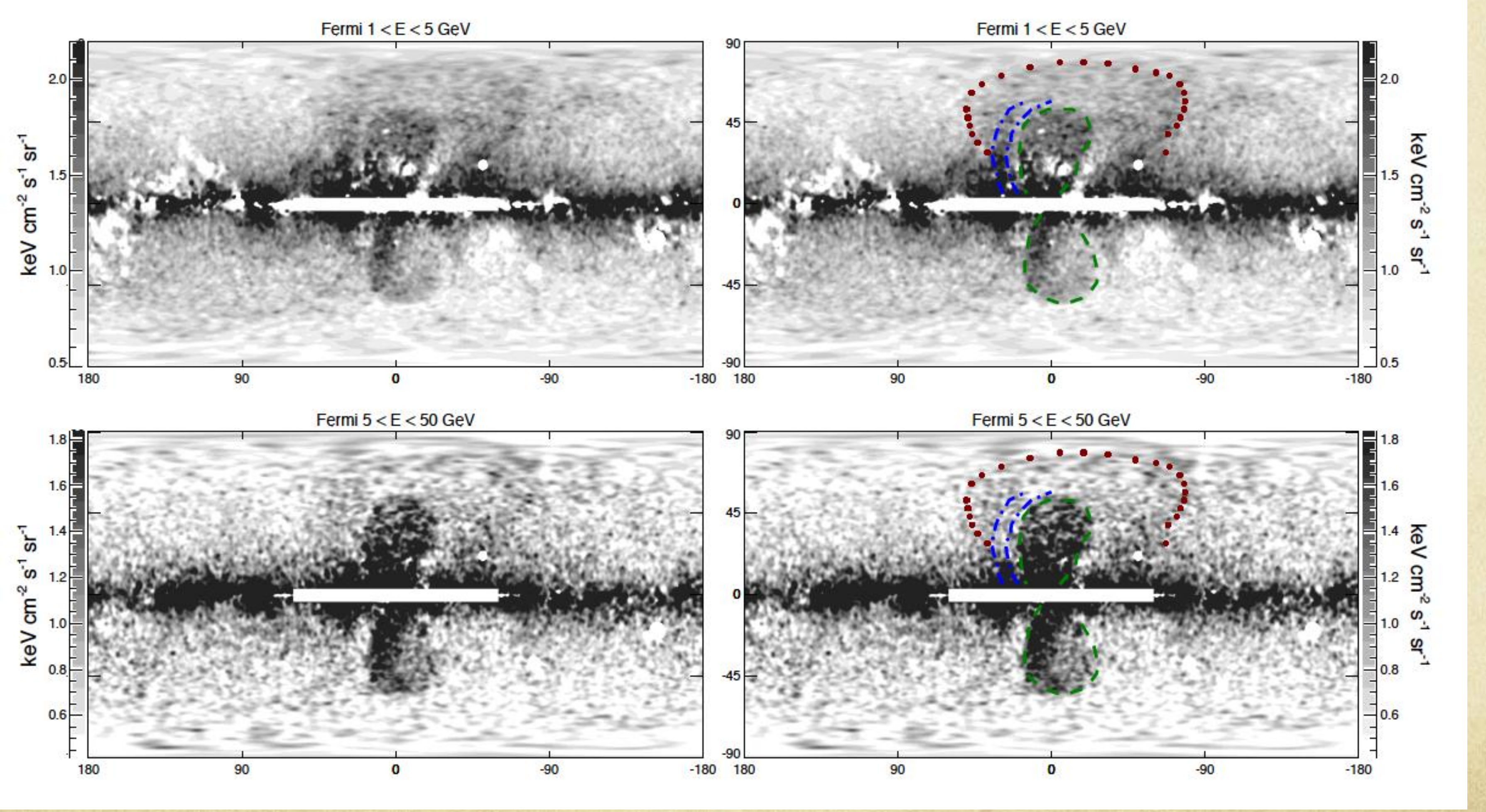
Fermi Bubble

Simple disk model



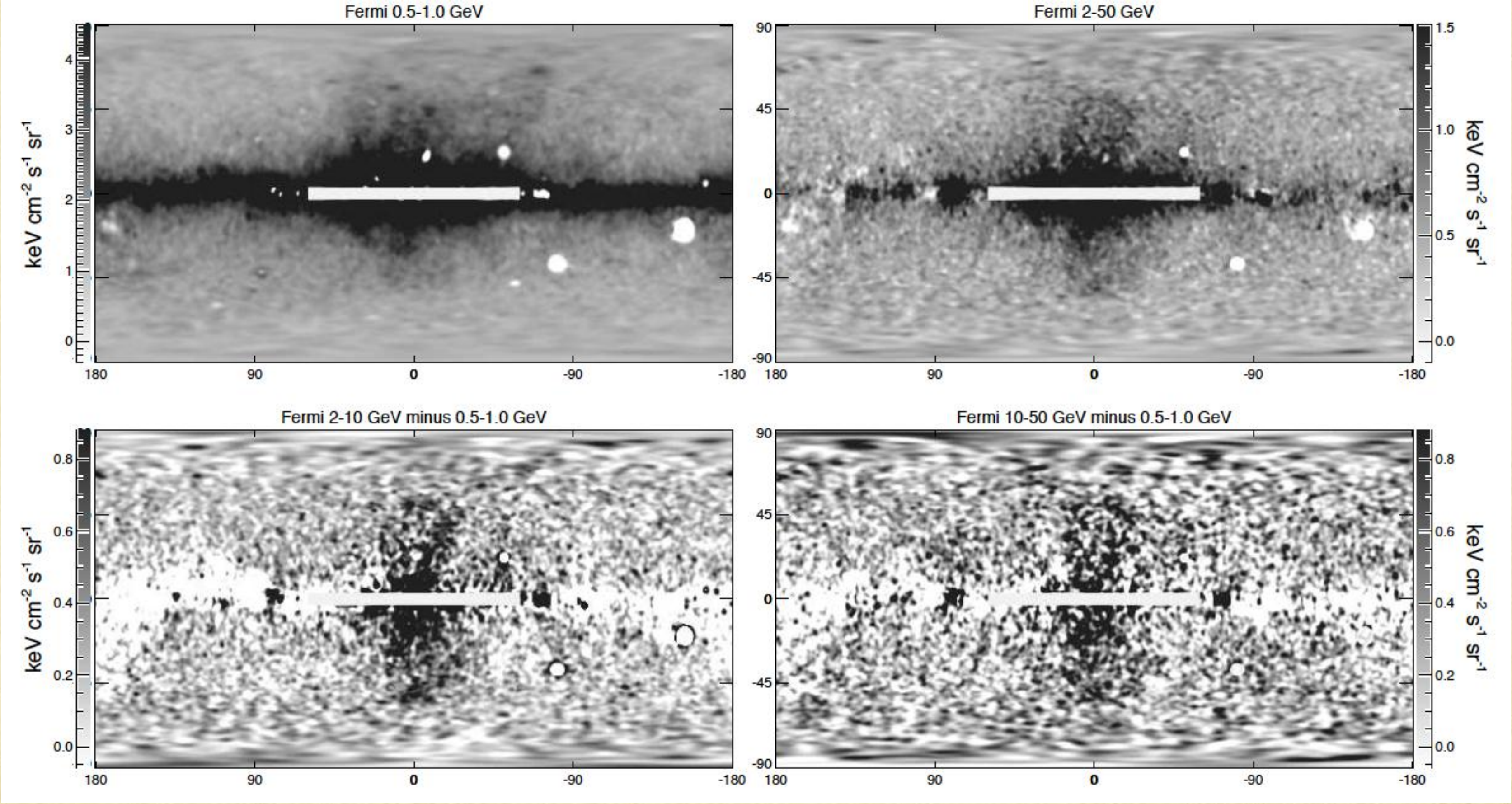
Su & Finkbeiner (2012)

Fermi Bubble from three year maps



Su & Finkbeiner (2012)

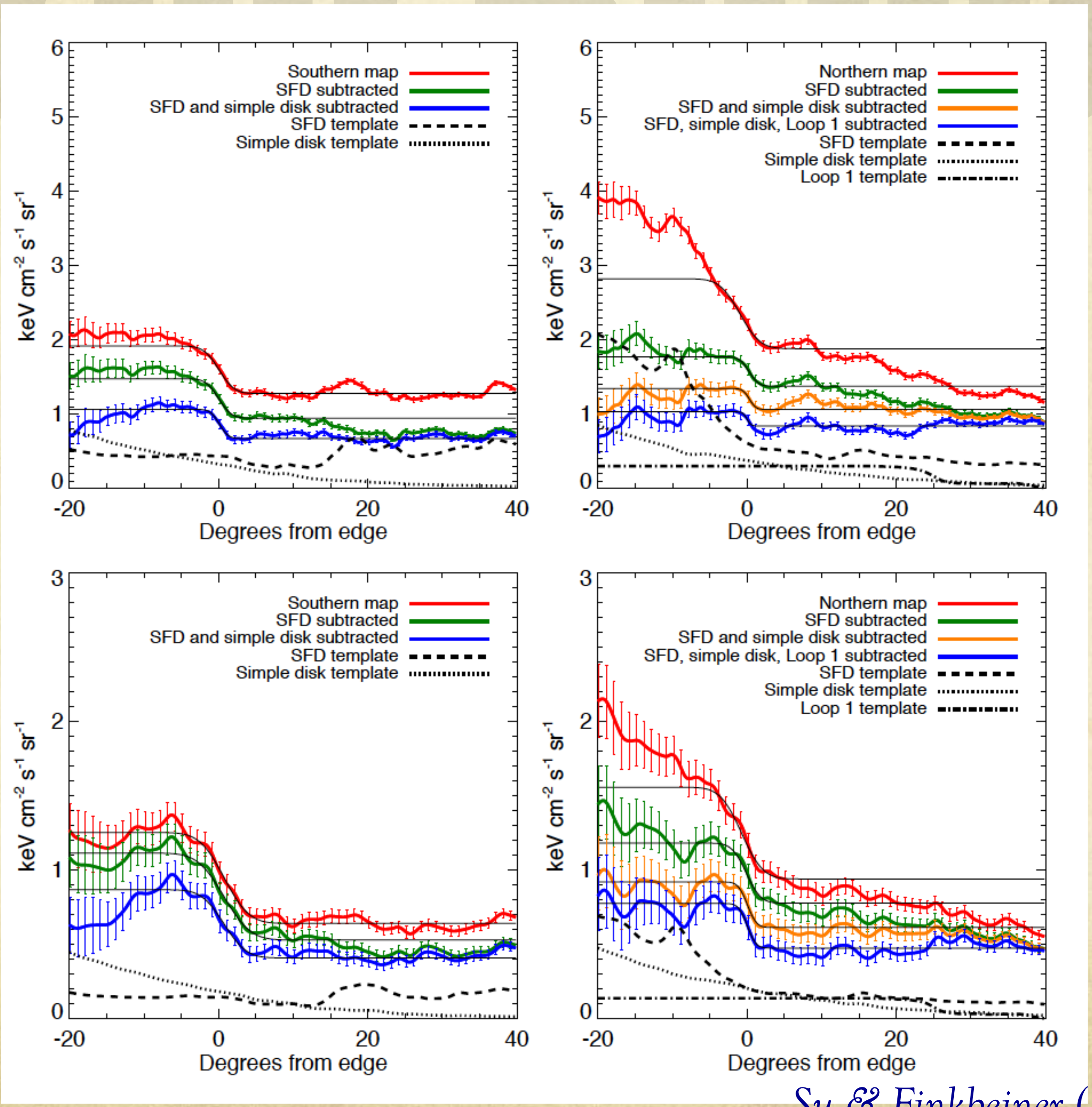
Fermi Bubble



low energy gamma-ray template (dust-subtracted) as the IC component.

Su & Finkbeiner (2012)

The bubbles have Sharp edges!

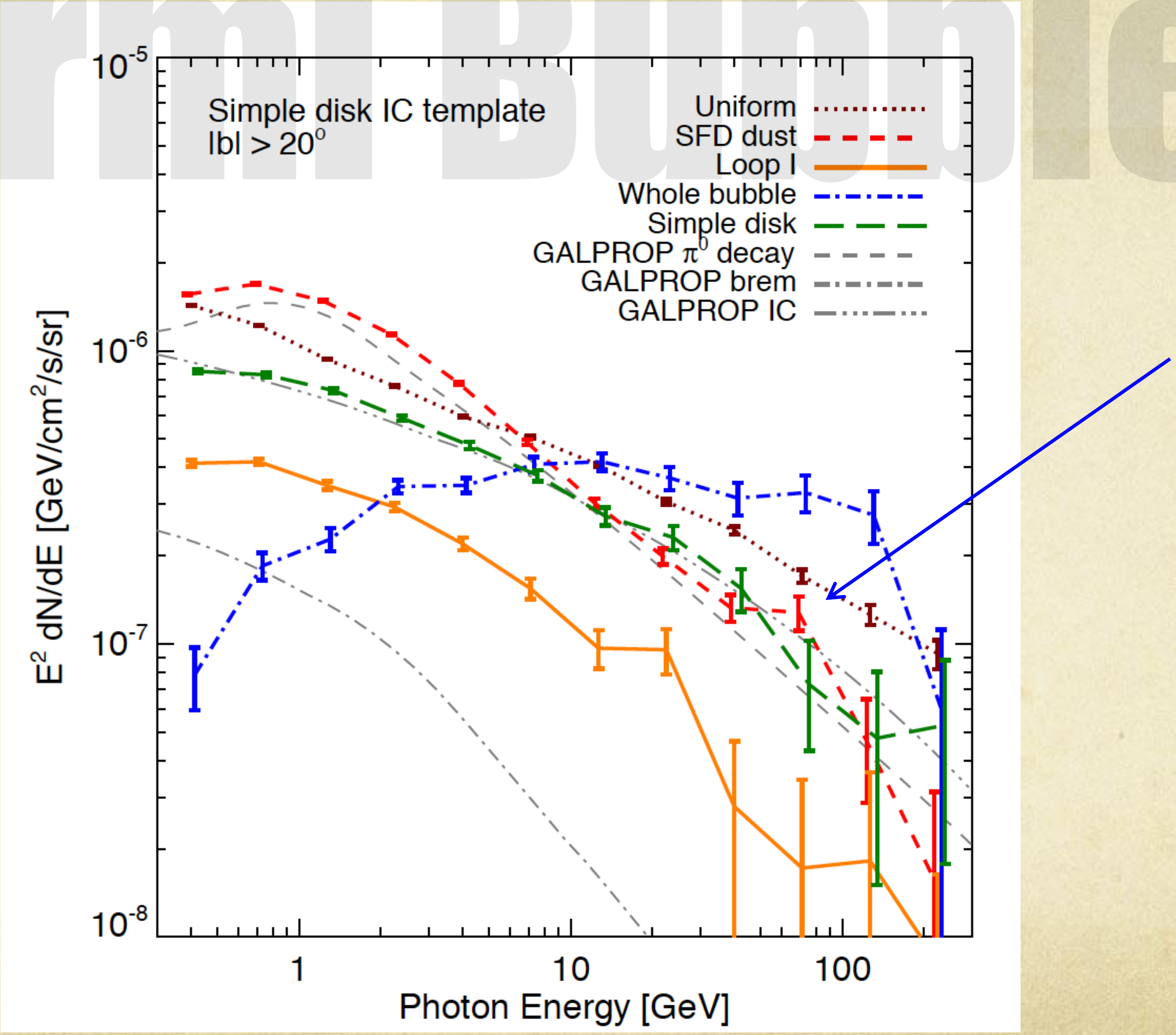


Su & Finkbeiner (2012)

Fermi Bubble

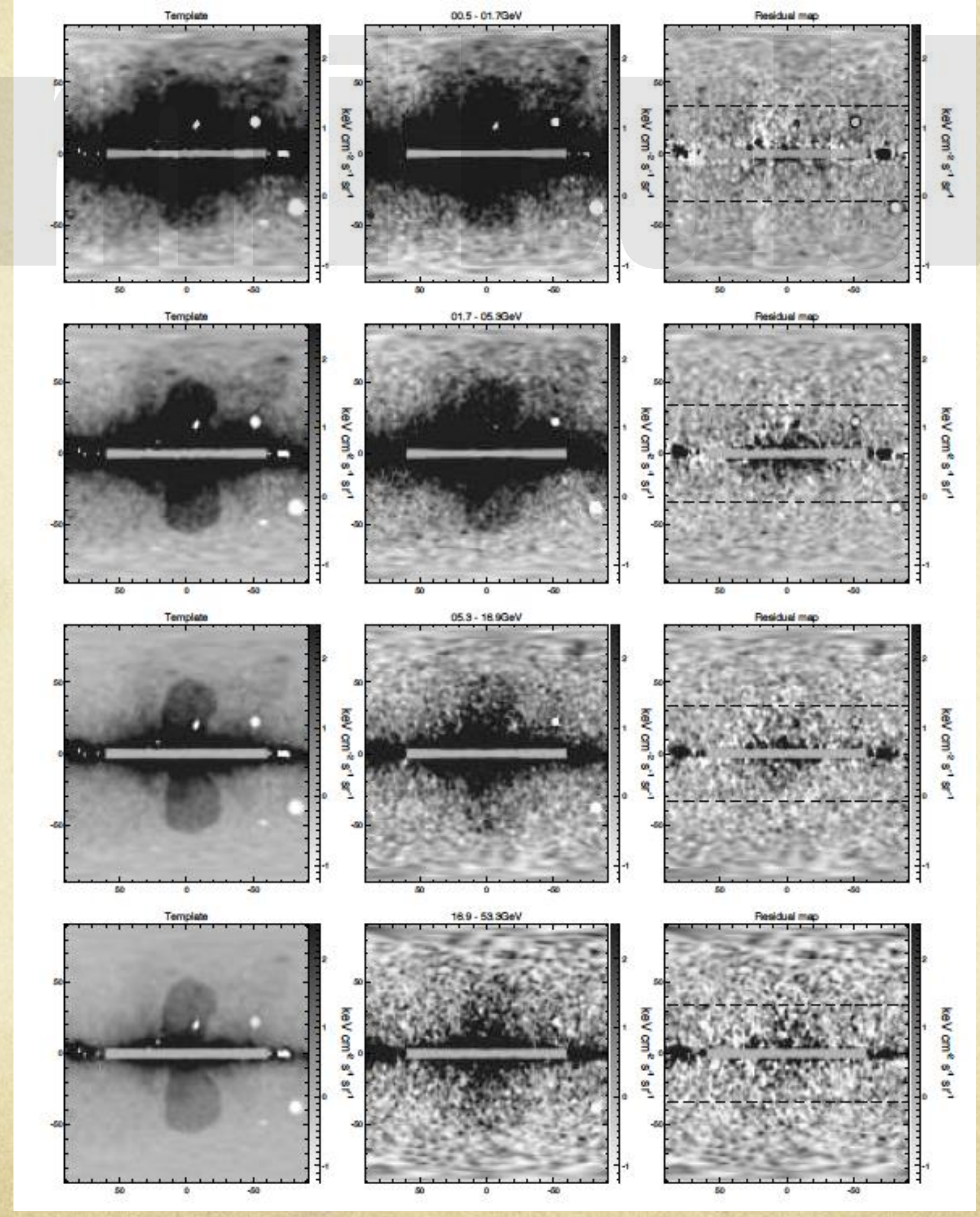
Now we can do a multilinear regression at each energy, including dust and simple templates for disk, Loop I, and the bubbles

Fermi Bubble



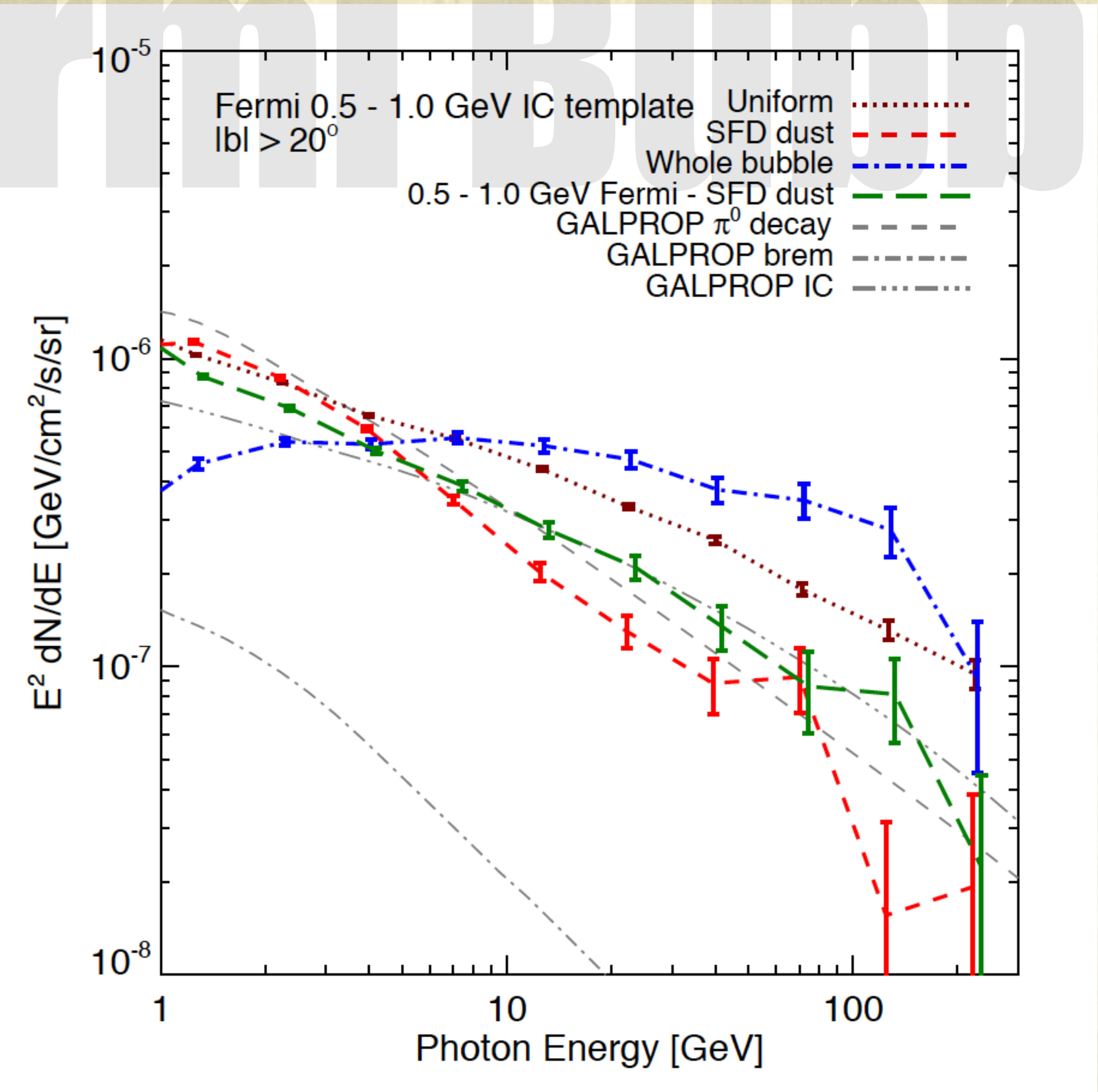
Su & Finkbeiner (2012)

Fermi Bubble



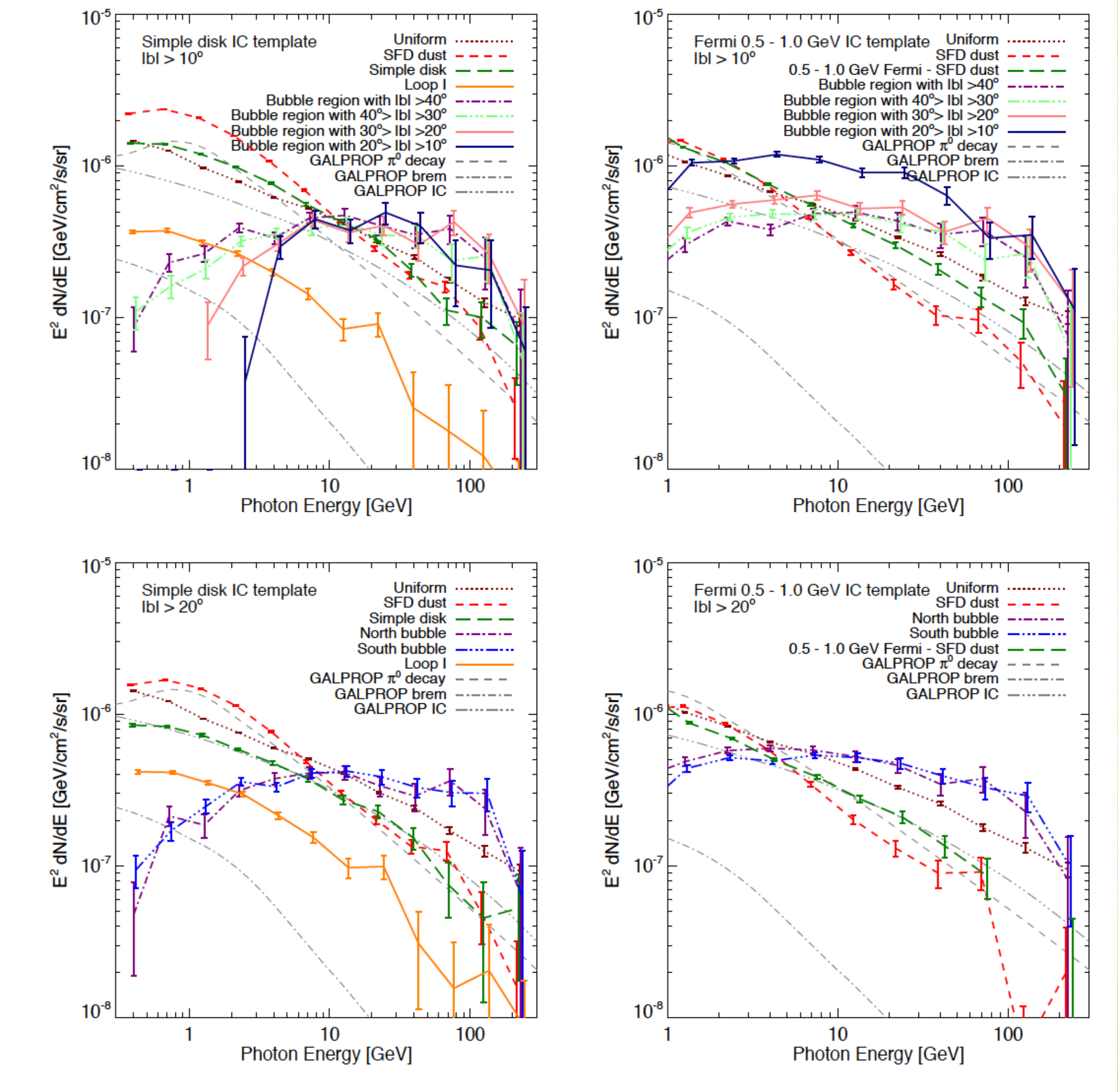
Su & Finkbeiner (2012)

Fermi Bubble



Su & Finkbeiner (2012)

Fermi Bubble



Su & Finkbeiner (2012)

Fermi Bubble

- *Does the edge have a harder spectrum than the interior?* NO.

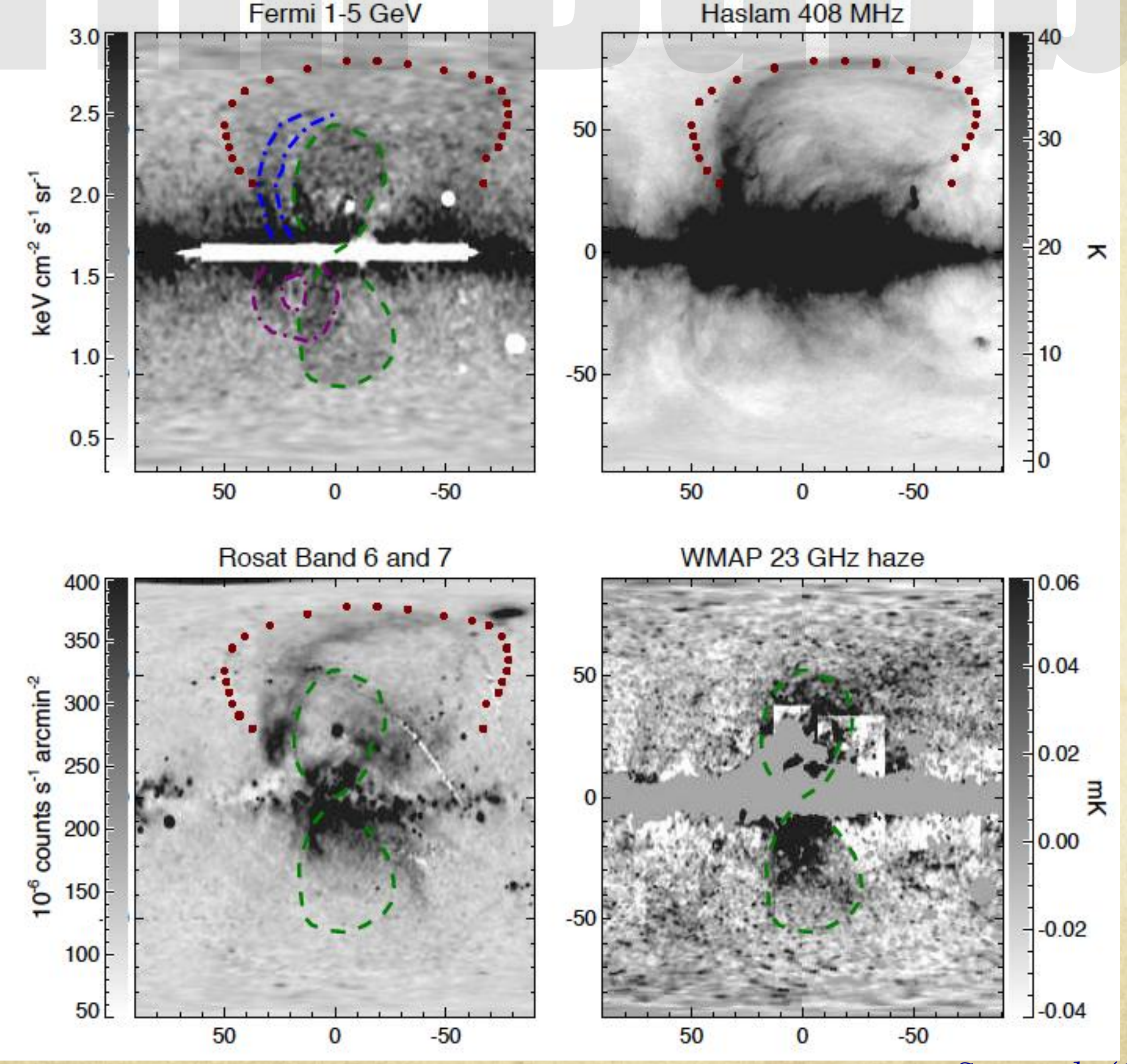
- *Is the north harder than the south?* NO.

- *Bottom line: No matter how we do the fit,
  the bubbles have a harder spectrum (index ~ -2)
  than the other IC emission (index ~ -2.5).*

- *The gamma-ray spectrum extends up to ~ 50 GeV or more, implying >~ 100 GeV electrons.*

- *If it is CMB scattering, we have ~ 1 TeV electrons!*

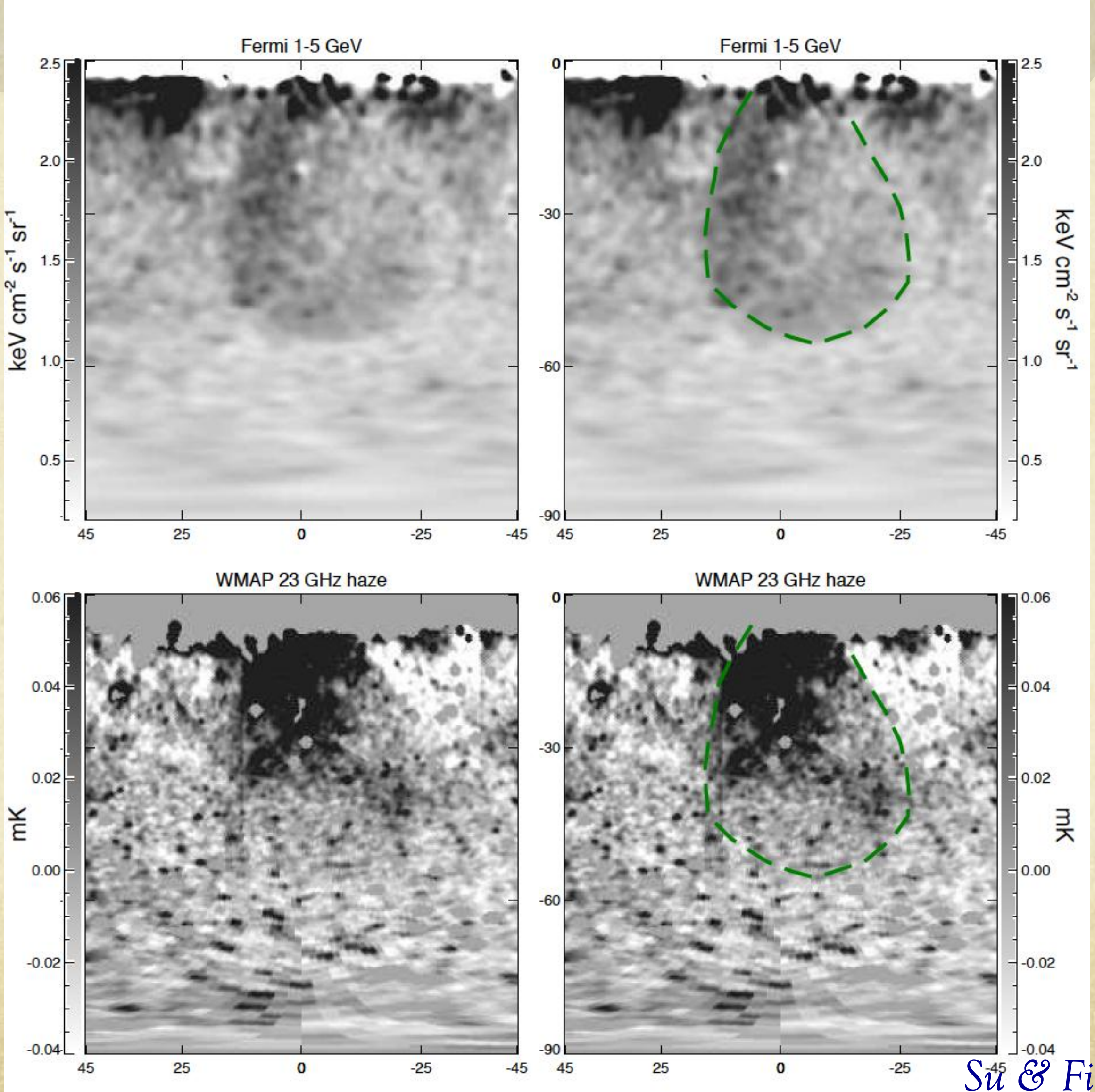
Fermi Bubble



Su et al. (2010)

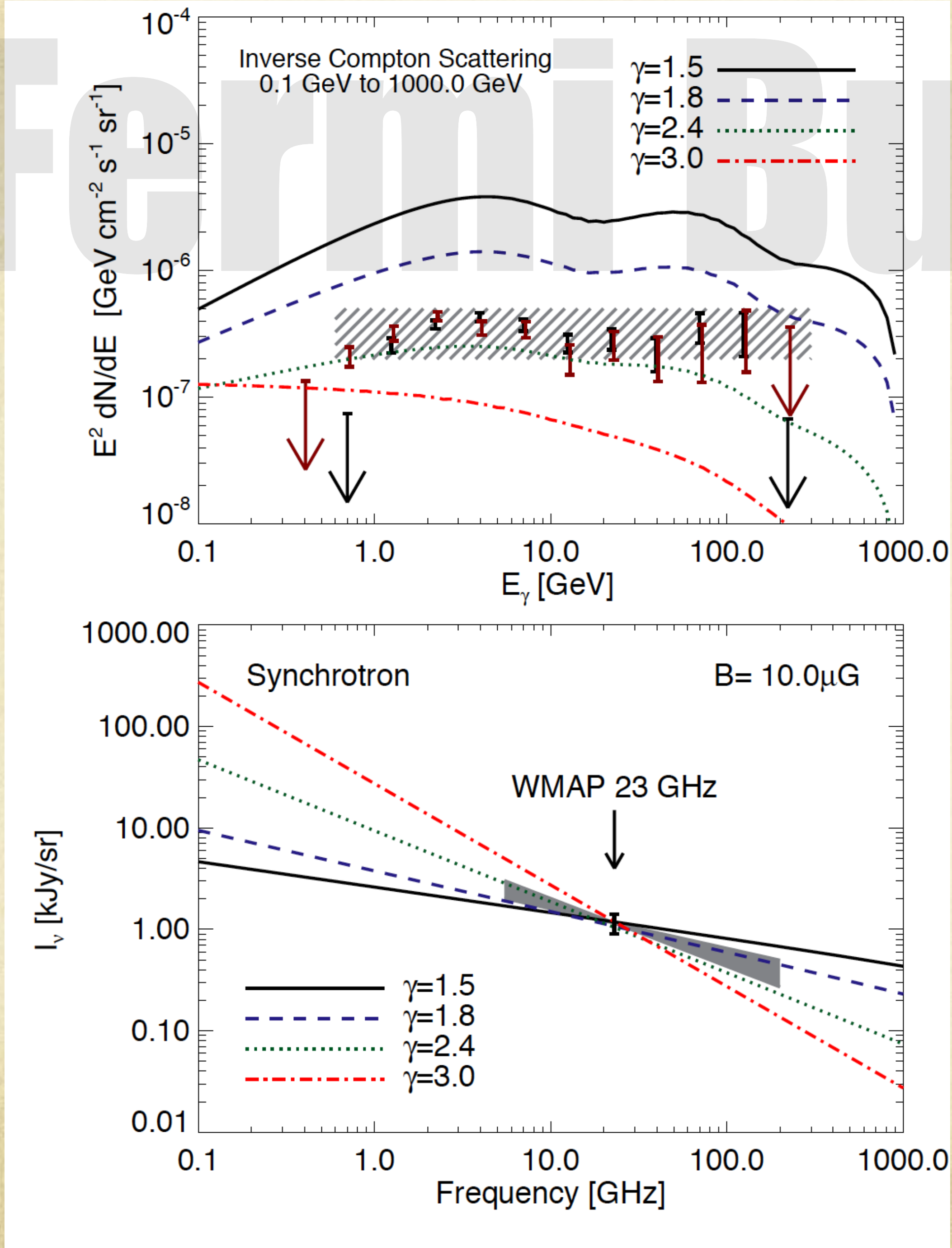
Compare with WMAP haze

Fermi Bubble



Su & Finkbeiner. (2012)

Fermi Bubble

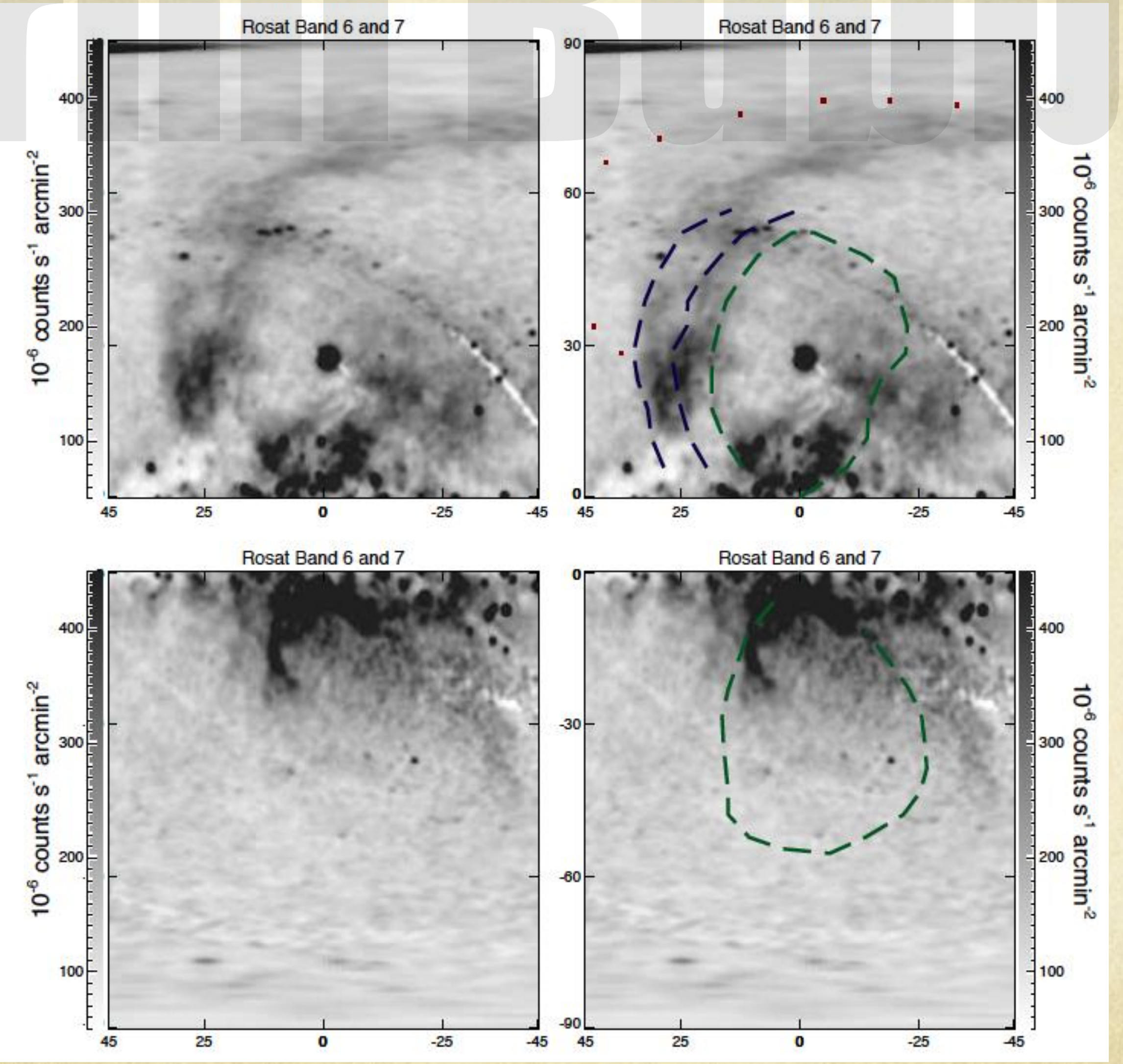


The Fermi bubbles are clearly associated with WMAP haze

The same electron spectrum can easily make both!

Su et al. (2010)

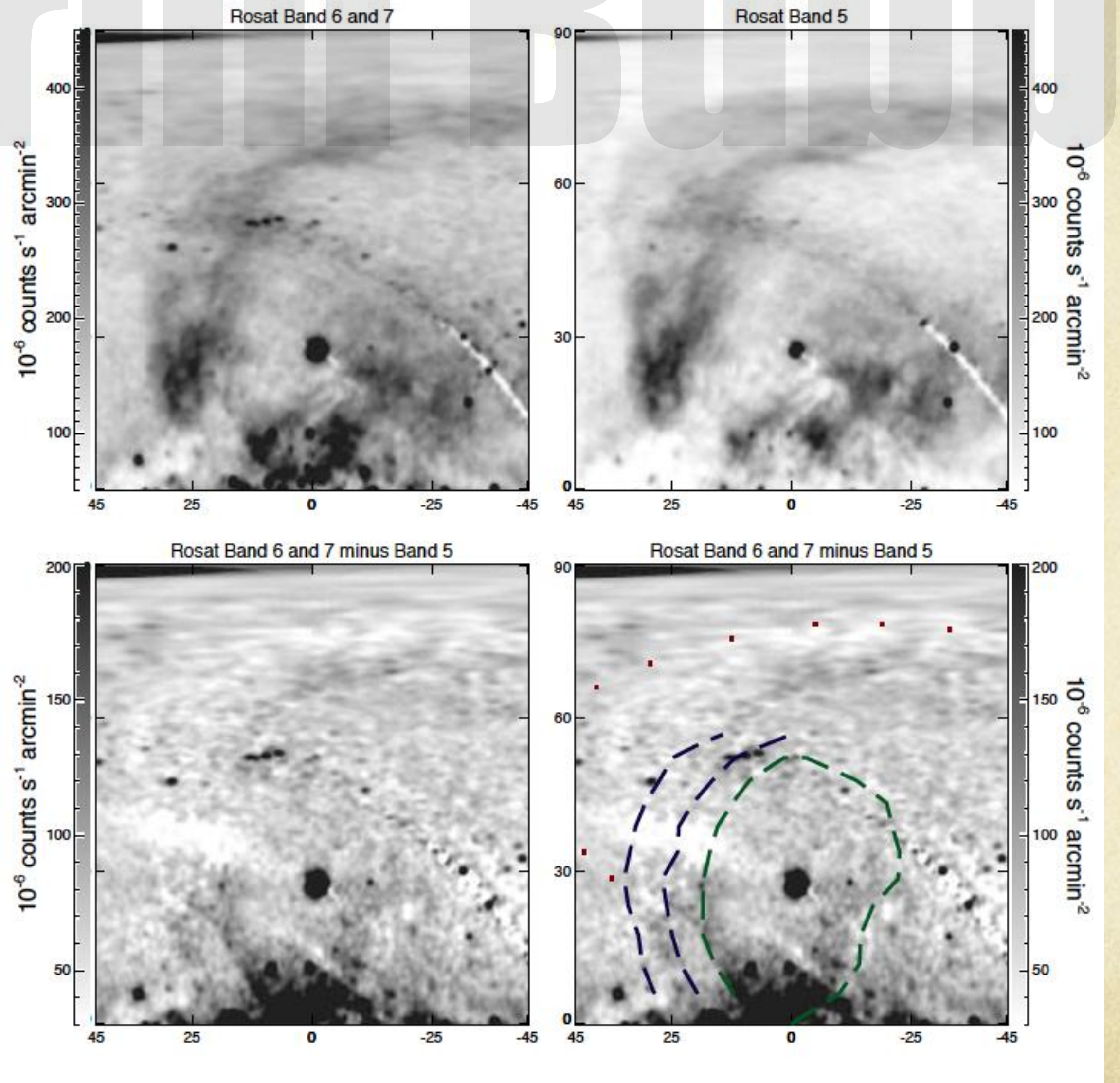
ROSAT 1.5 keV



(Su et al. 2010).

Fermi Bubble

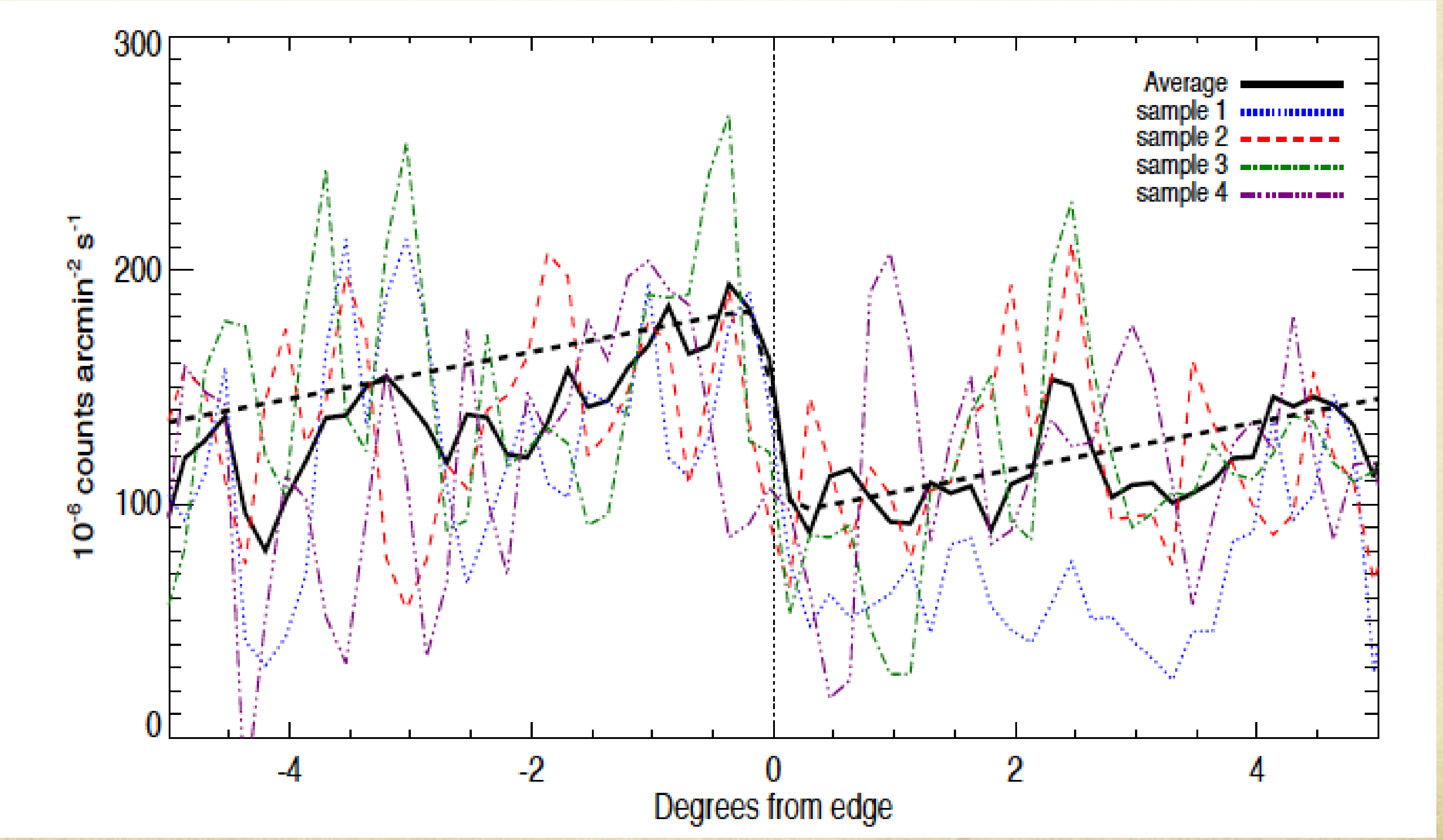
Fermi Bubble



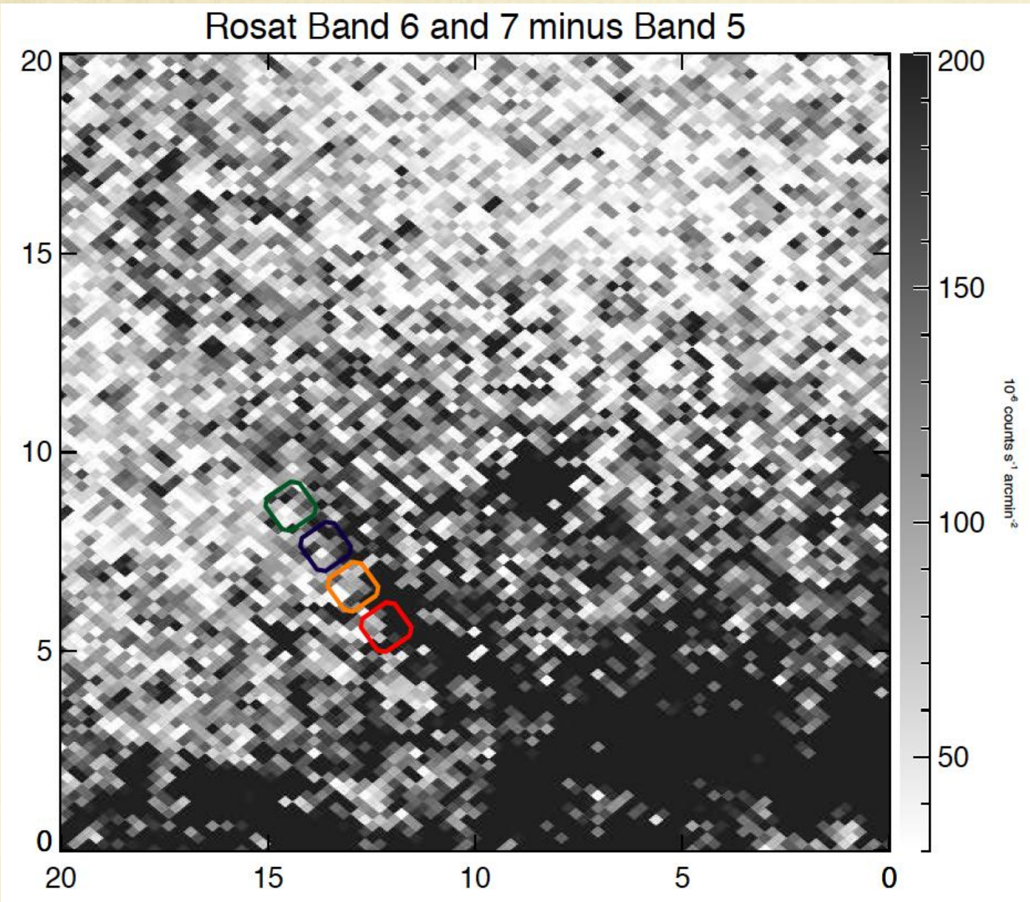
(Su et al. 2010).

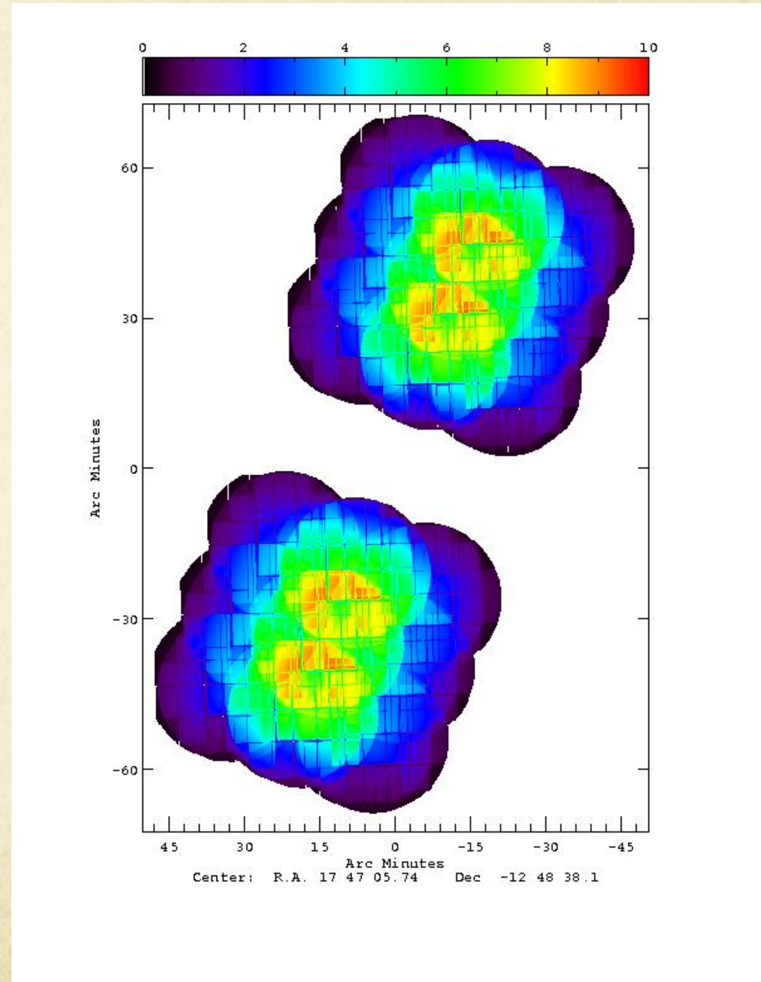
Sharp edge in X-ray too!

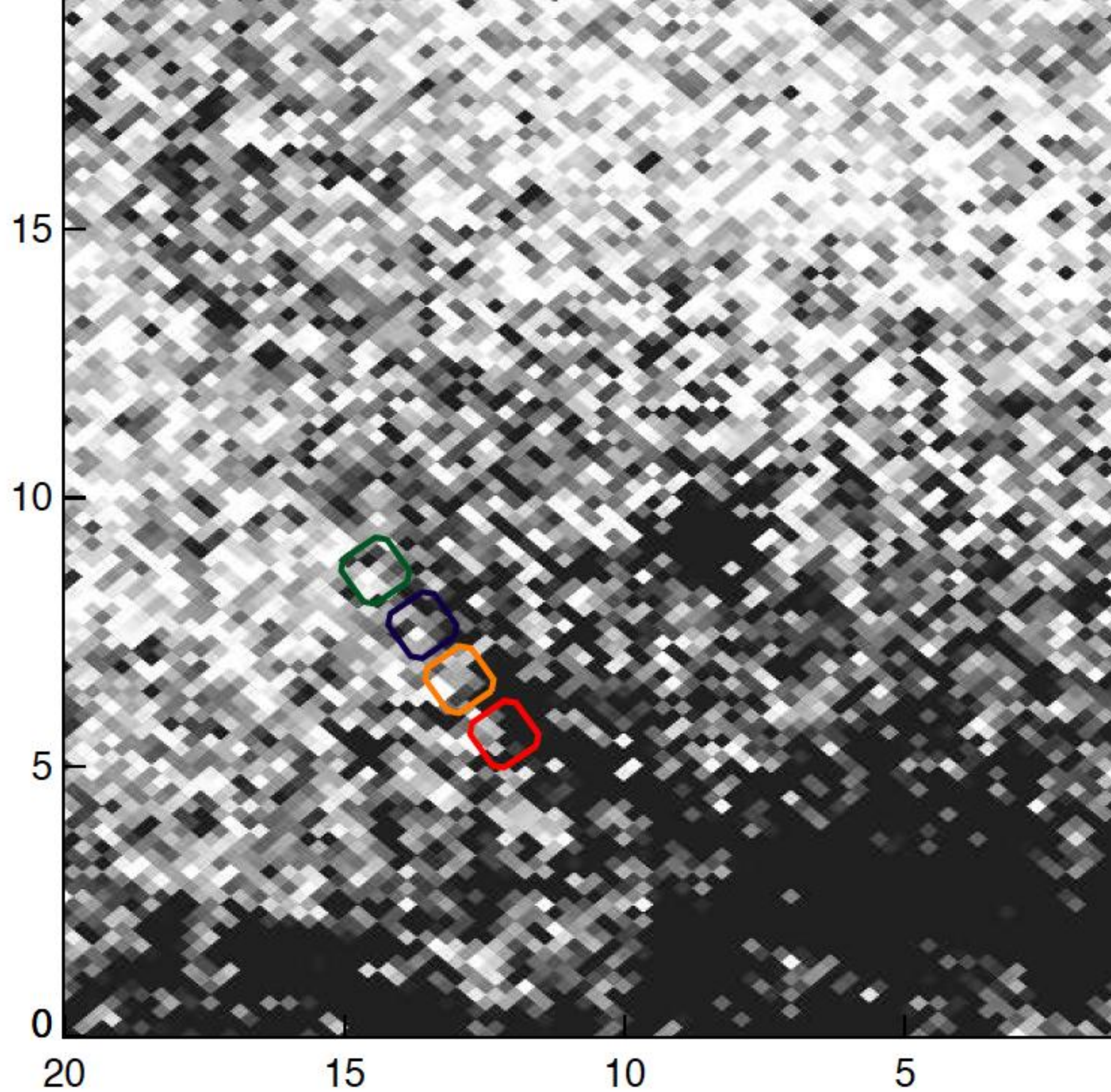
Fermi Bubble



XMM-Newton observation

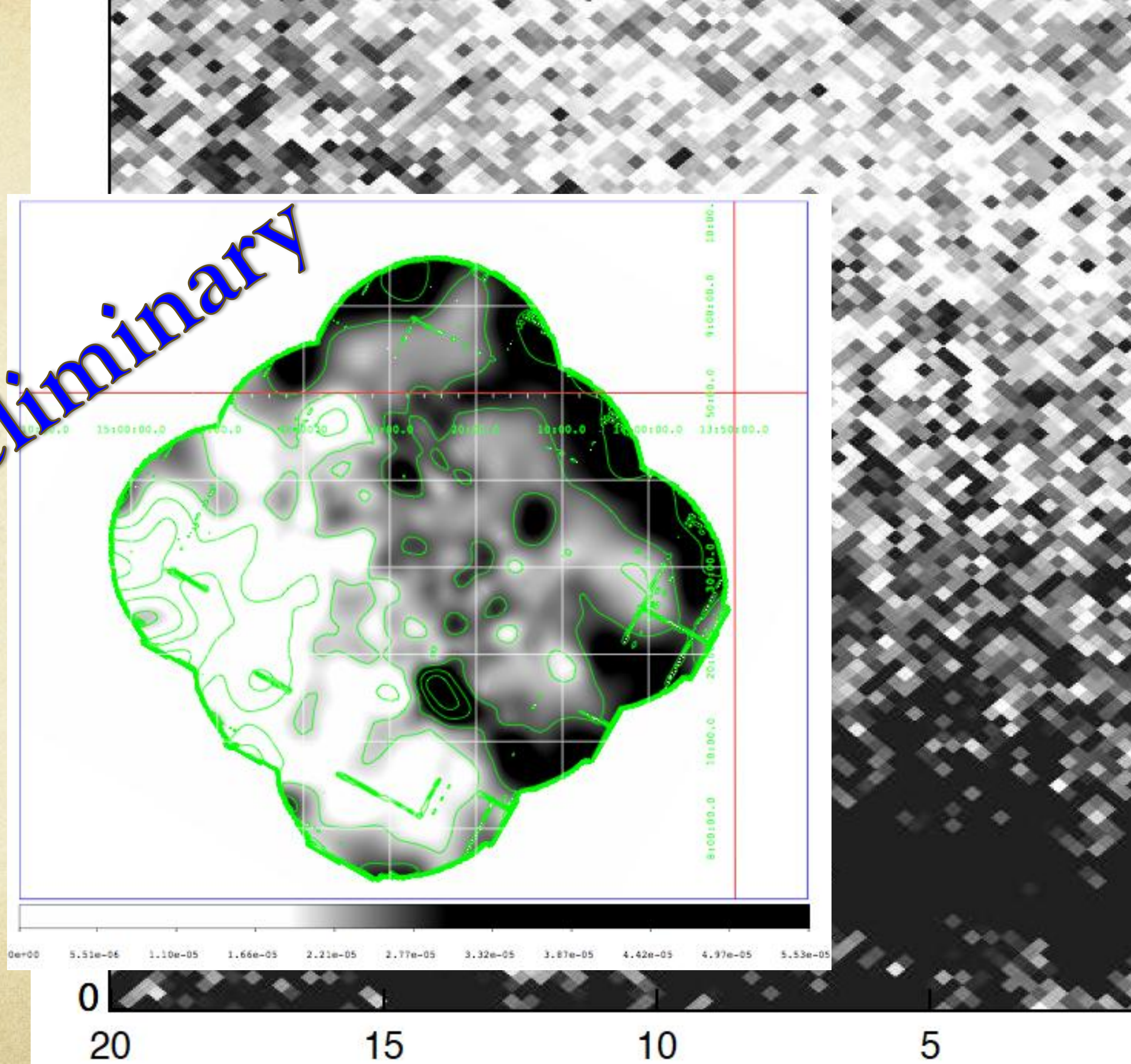






15
10
5
0
20
15
10
5

Preliminary



Fermi Bubble

So far: there appear to be a pair of giant (50 degree high) gamma-ray bubbles at 1-5 GeV, and probably up to at least 50 GeV.

What are they?

- *Black hole "burp"*
- *Superwind bubble?*
- *Dark matter?*

(Sylvain Veilleu's talk yesterday)

Fermi Bubble

Mystery: How do we get TeV electrons 10 kpc off the disk in the last < Myr?

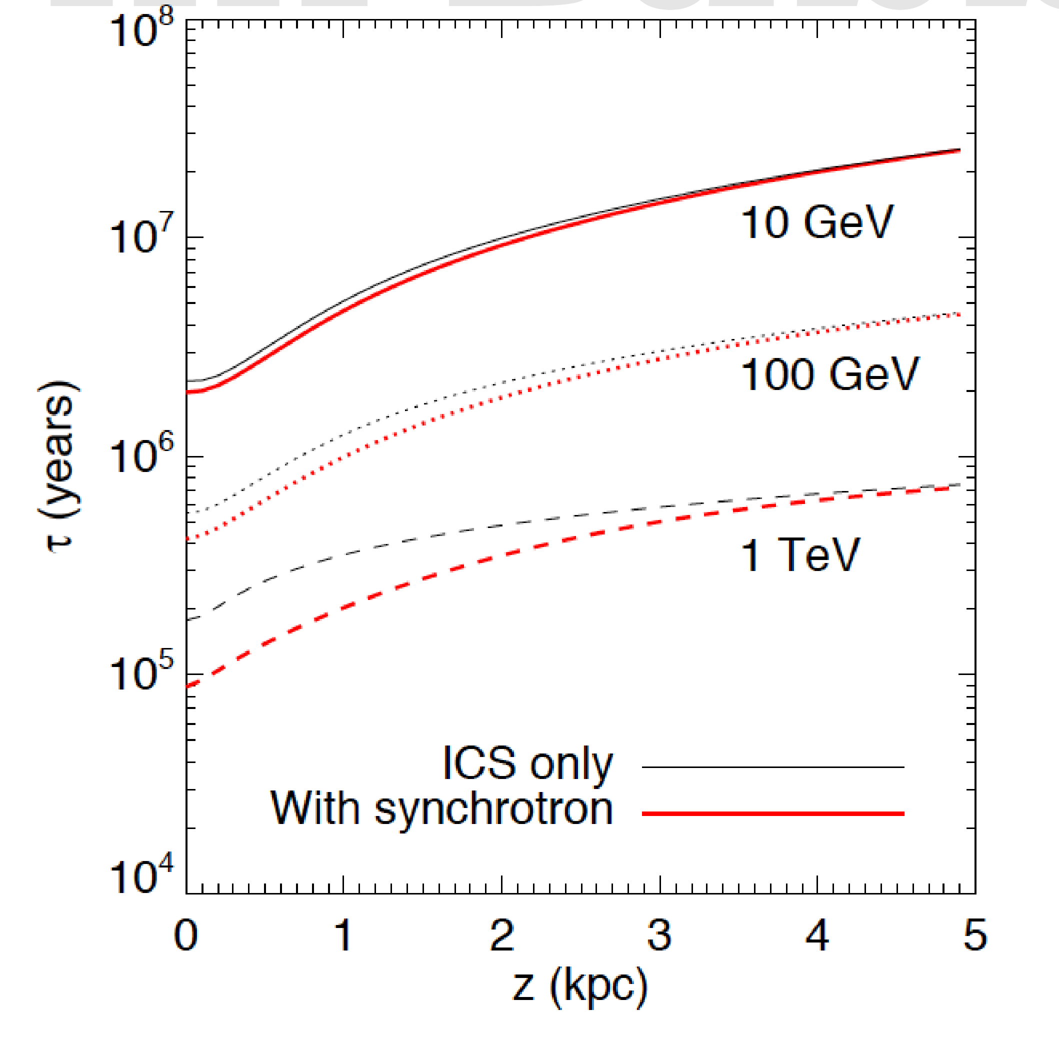
In situ acceleration. Shocks? Reconnection?

If they are formed quickly by AGN activity, then kinetic energy >> 10^{55} erg.
Could do, but this would be an impressive event for our humble little BH.

Large starburst-produced bubble has a severe cooling time problem. The bubbles should be $\sim 10^7$ yr old, but cooling time for TeV (or even 100 GeV) electrons is much shorter

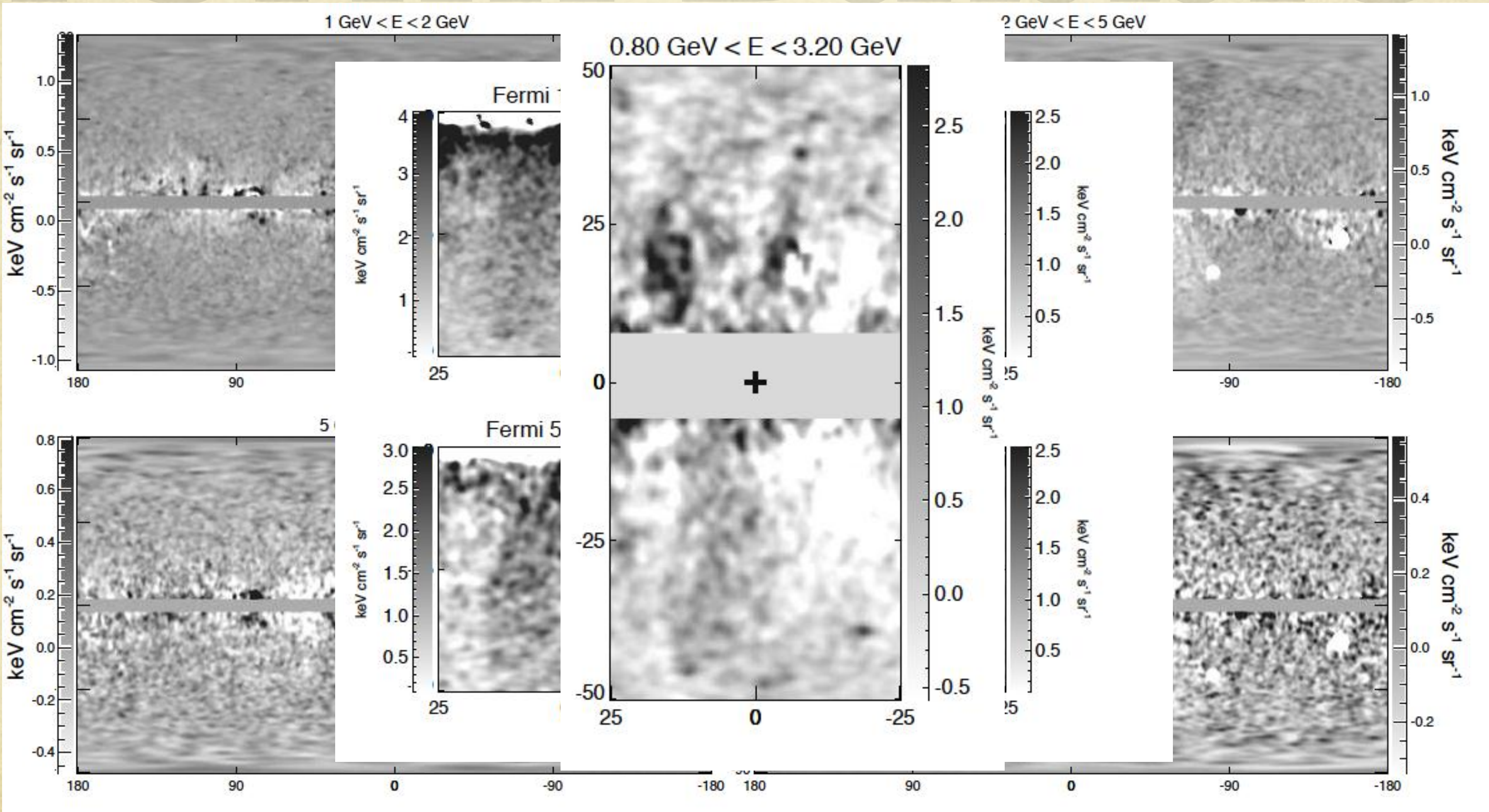
Fermi Bubble

Cooling time is short!



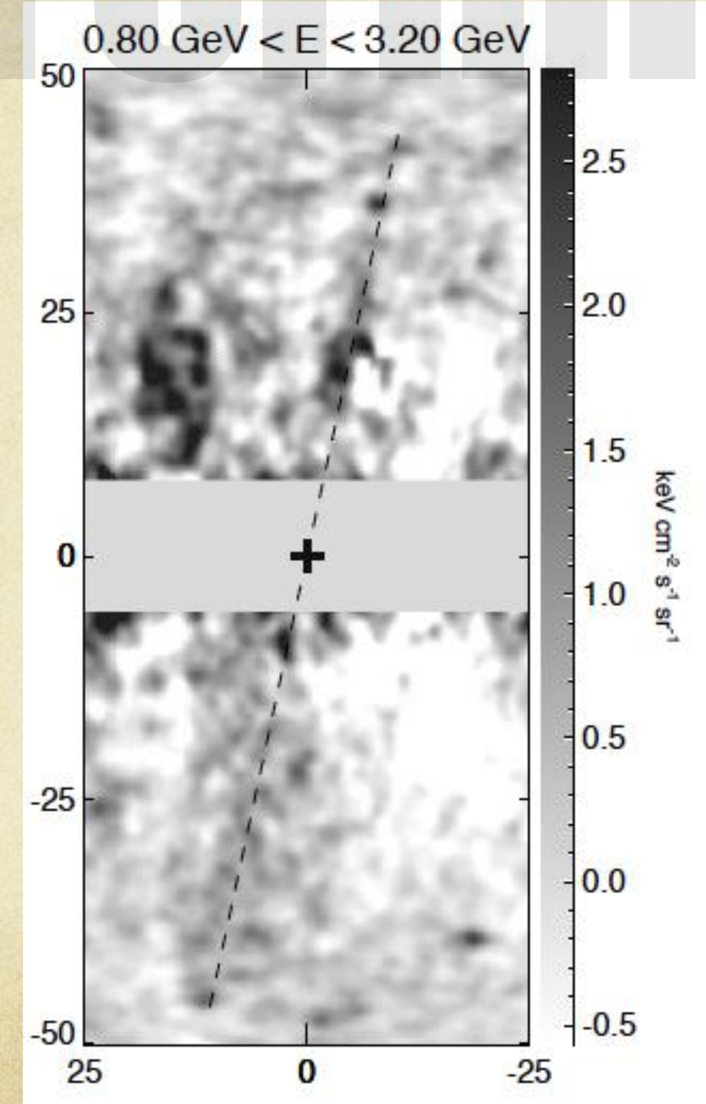
Su et al. (2010)

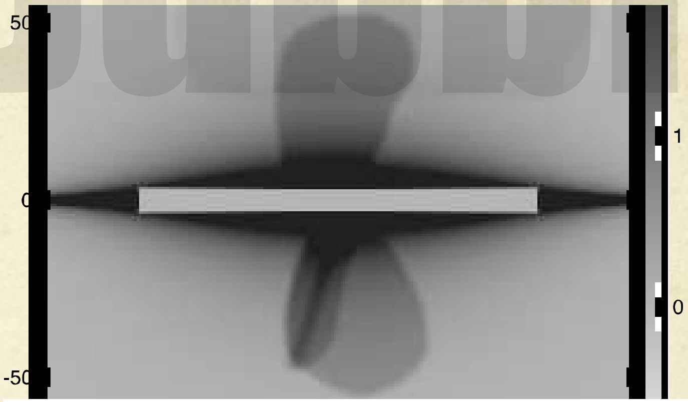
Is there any large scale jet feature?

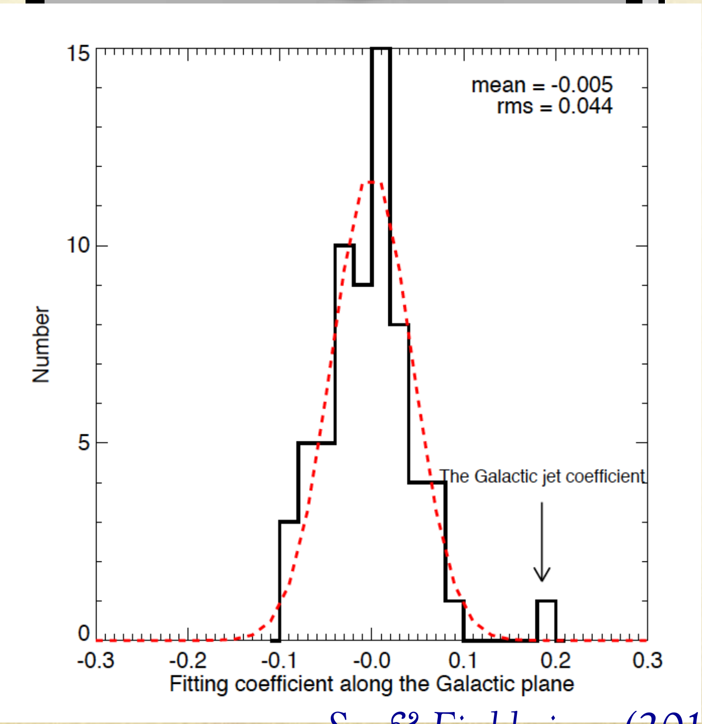


Su & Finkbeiner (2012)

Fermi Bubble

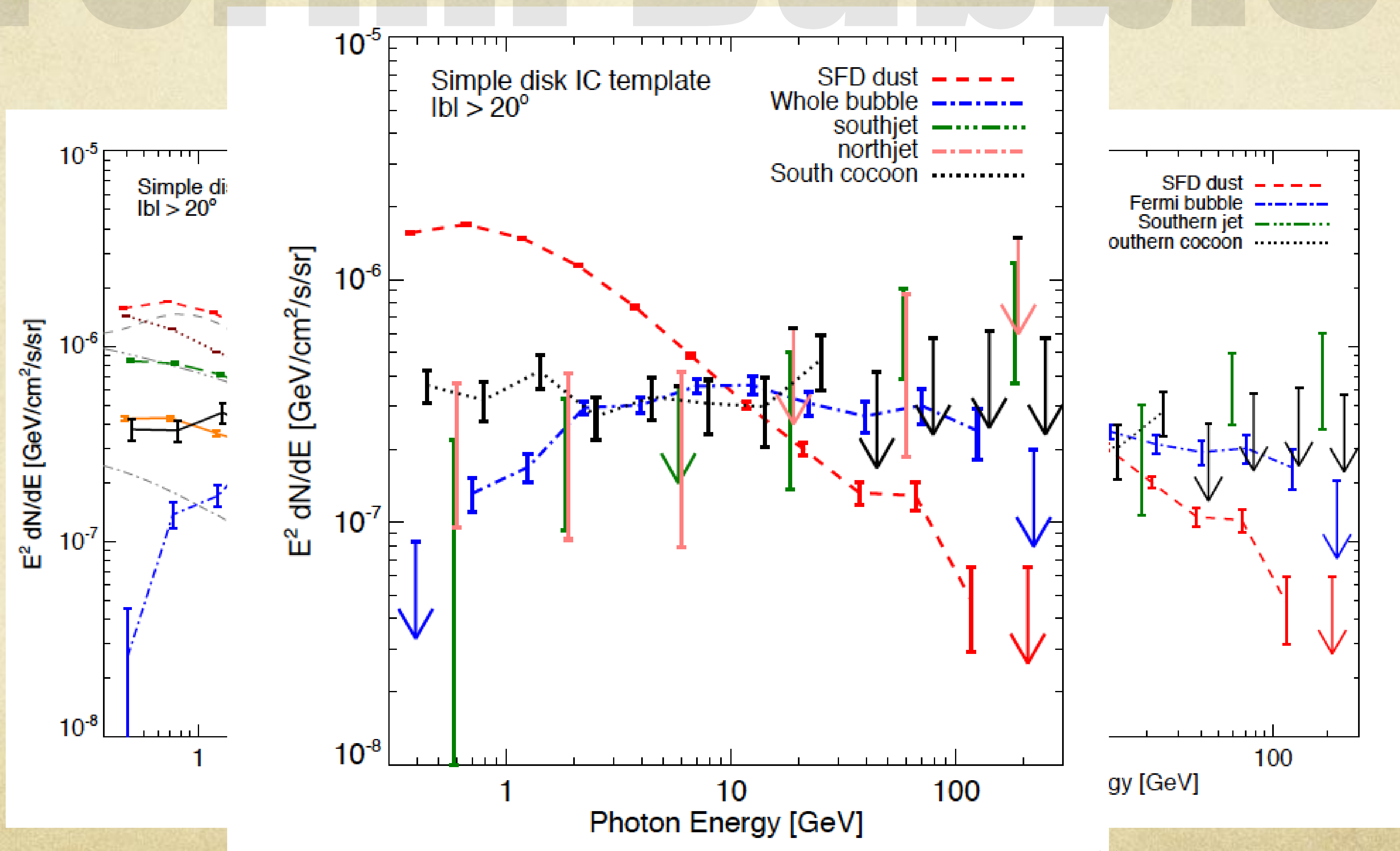






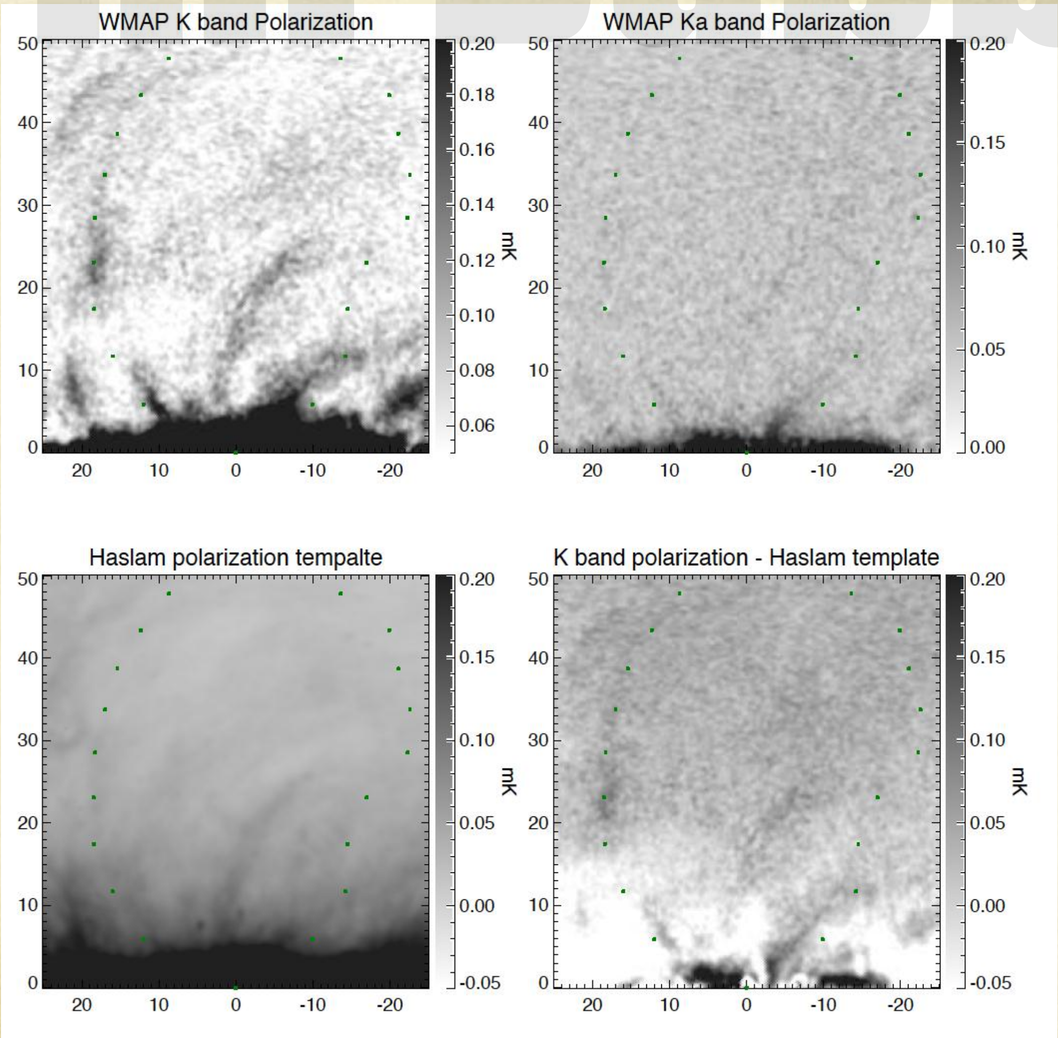
Su & Finkbeiner (2012)

Fermi Bubble



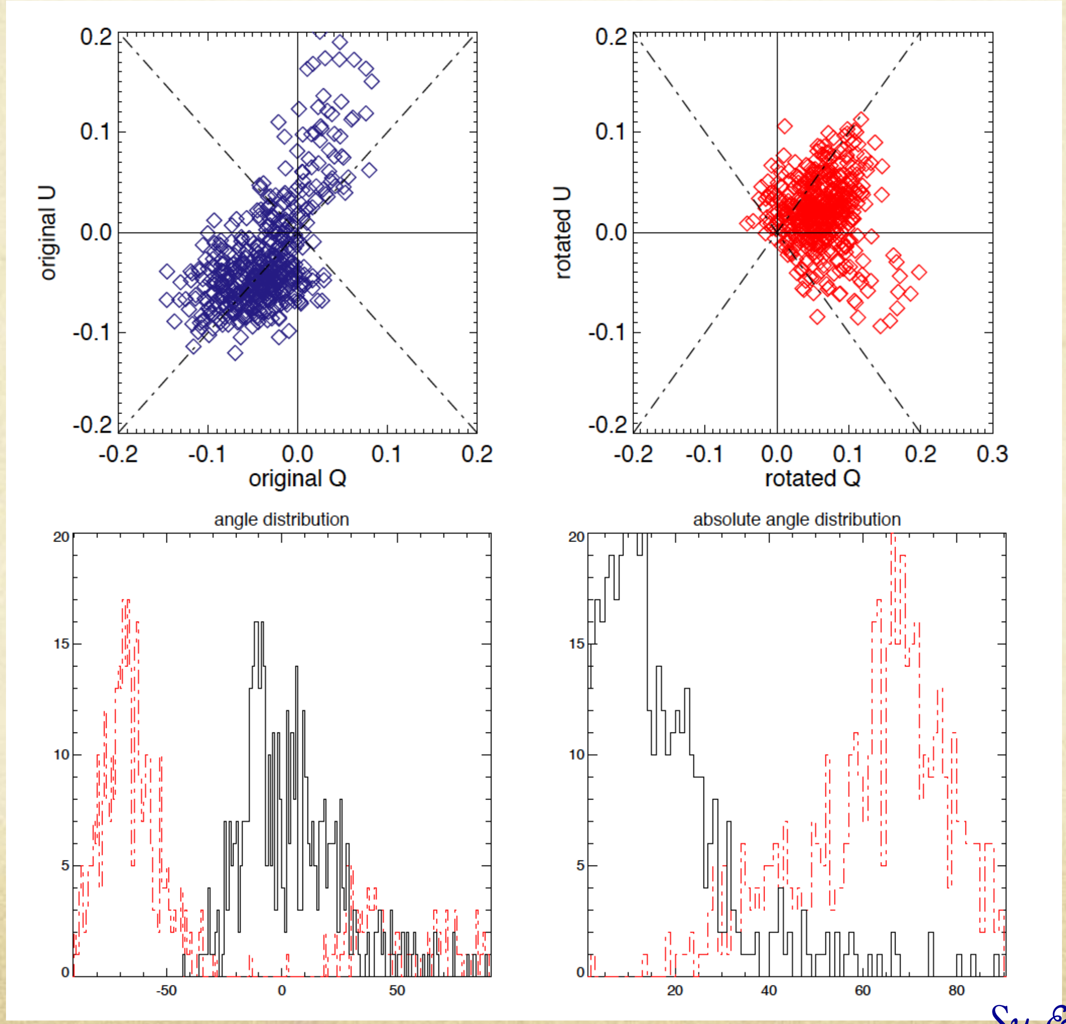
Su & Finkbeiner (2012)

WMAP 23 GHz polarization



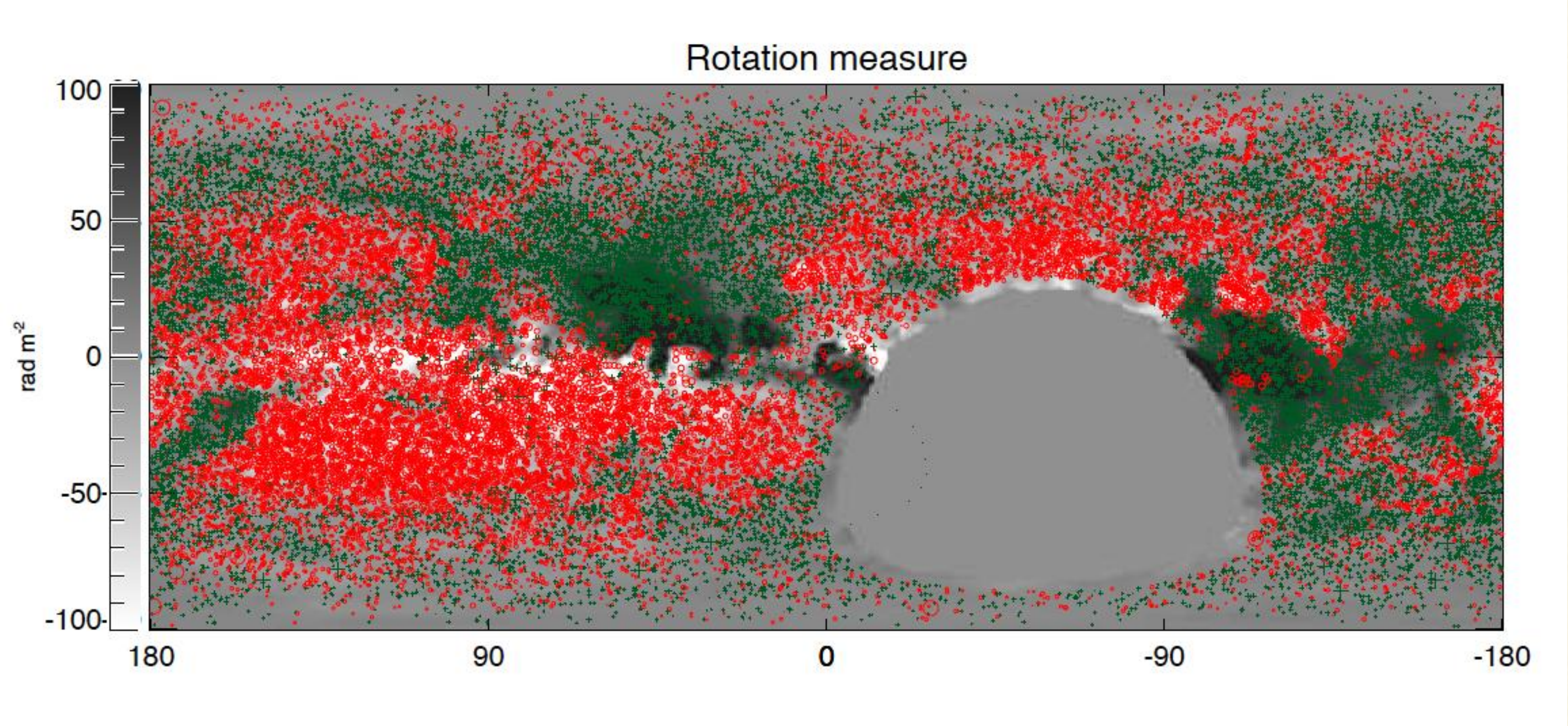
Su & Finkbeiner (2012)

Magnetic field on bubbles



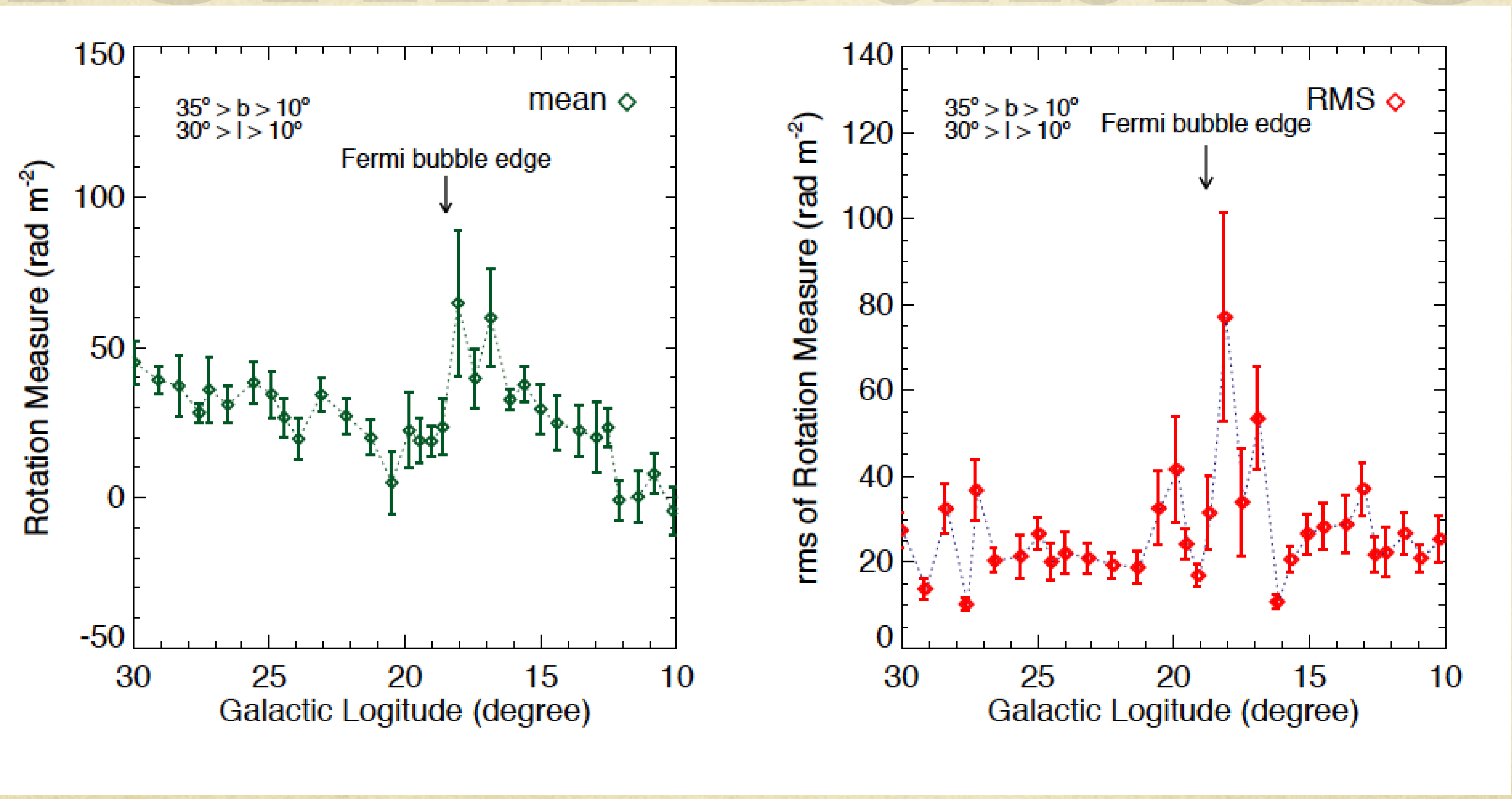
Su & Finkbeiner (2012)

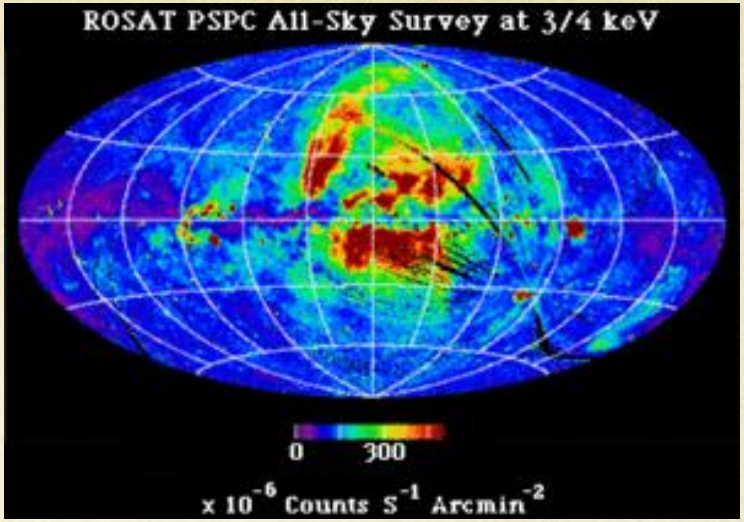
Rotation measure from the NRAO VLA Sky Survey

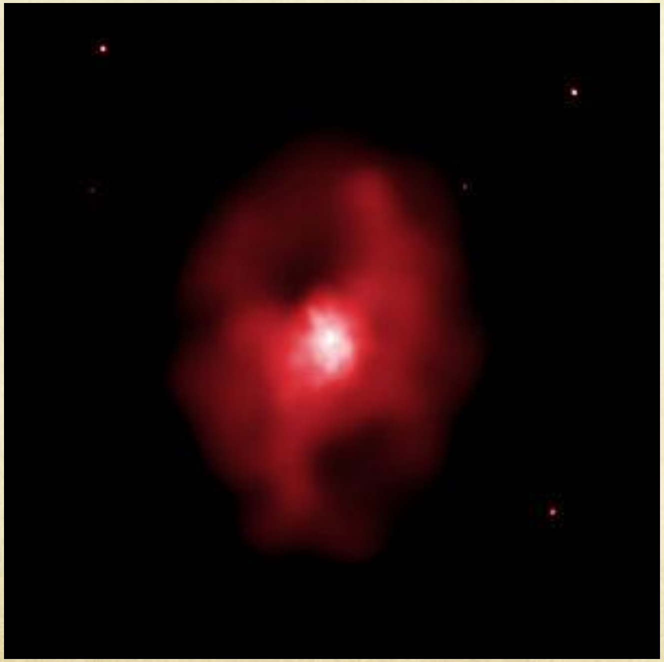


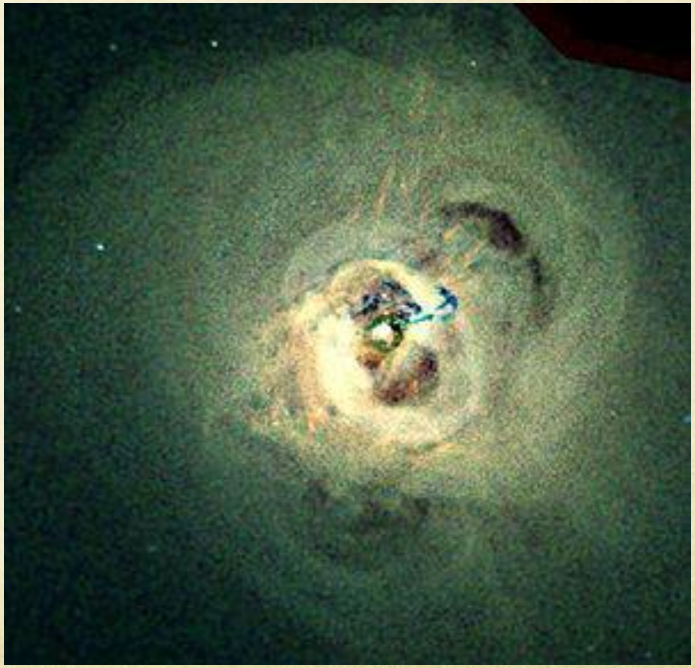
A. N. Taylor et al. (2009)

Signature of B-field compression





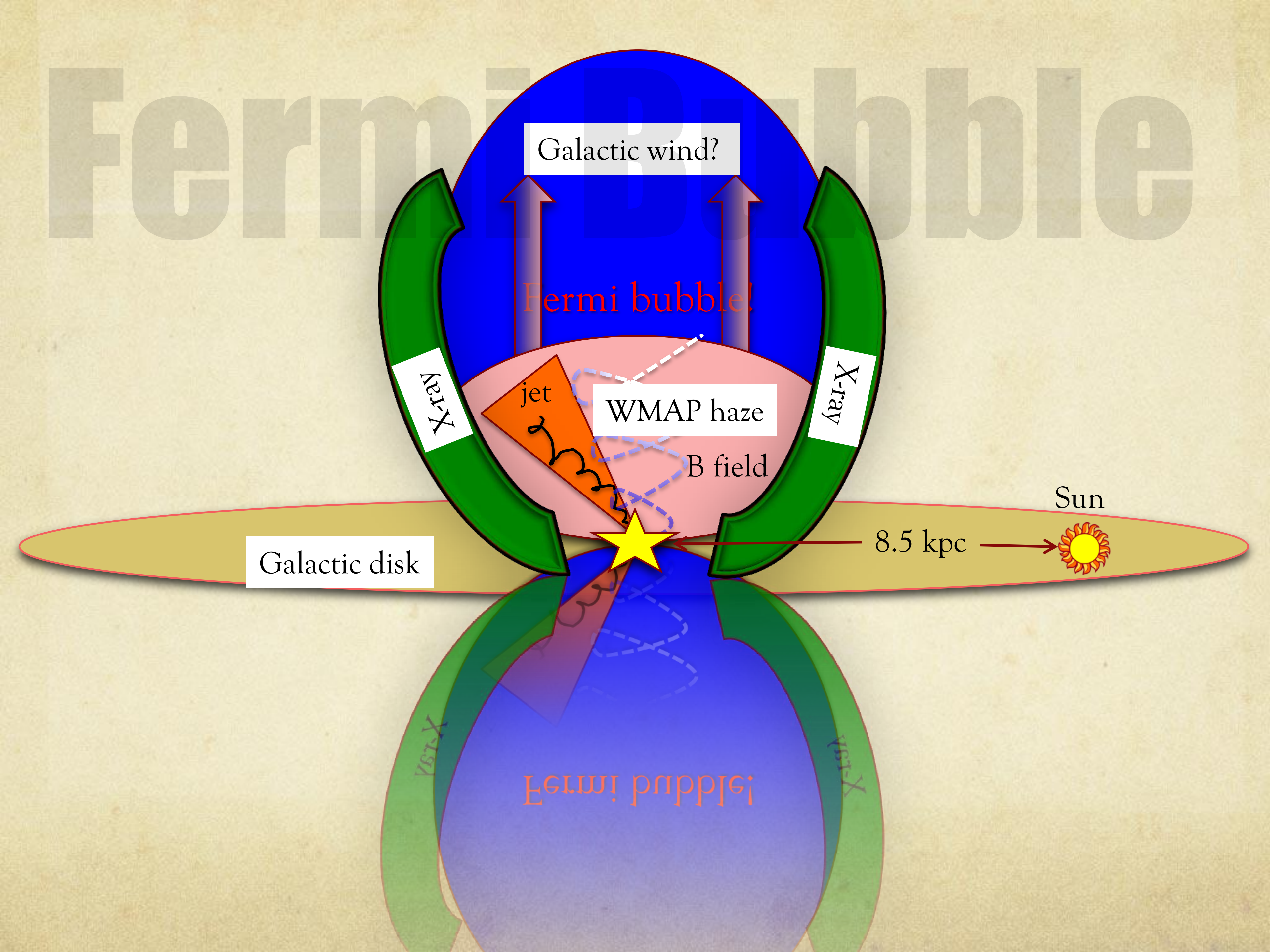




galaxy cluster MS 0735.6+7421 in Camelopardus

Perseus galaxy cluster

Take home message



Fermi Bubble
Galactic wind?
Fermi bubble!
X-ray
X-ray
jet
WMAP haze
B field
Sun
8.5 kpc
Galactic disk

Fermi Bubble

- *Fermi -LAT reveal two giant gamma-ray bubbles*
- *The gamma-ray emission associated with these bubbles has a significantly harder spectrum (dN/dE ~ E^{-2}) with sharp edges*
- *The bubbles are spatially correlated with the hard-spectrum microwave excess known as the WMAP haze; the edges of the bubbles also line up with features in the ROSAT X-ray maps at 1.5 - 2 keV.*
- *Faraday rotation measurement shows significant change on the edge of the bubbles, indicating the magnetic field structure or gas density variation.*

Fermi Bubble

- *The Galactic gamma-ray bubbles which were most likely created by some large episode of energy injection in the Galactic center, such as past accretion events onto the central massive black hole, or a nuclear starburst in the last ~10 Myr*
- *Dark matter annihilation/decay seems unlikely to generate all the features of the bubbles*
- *Study of the origin and evolution of the bubbles also has the potential to improve our understanding of recent energetic events in the inner Galaxy and the high-latitude cosmic ray population.*

Fermi Bubble

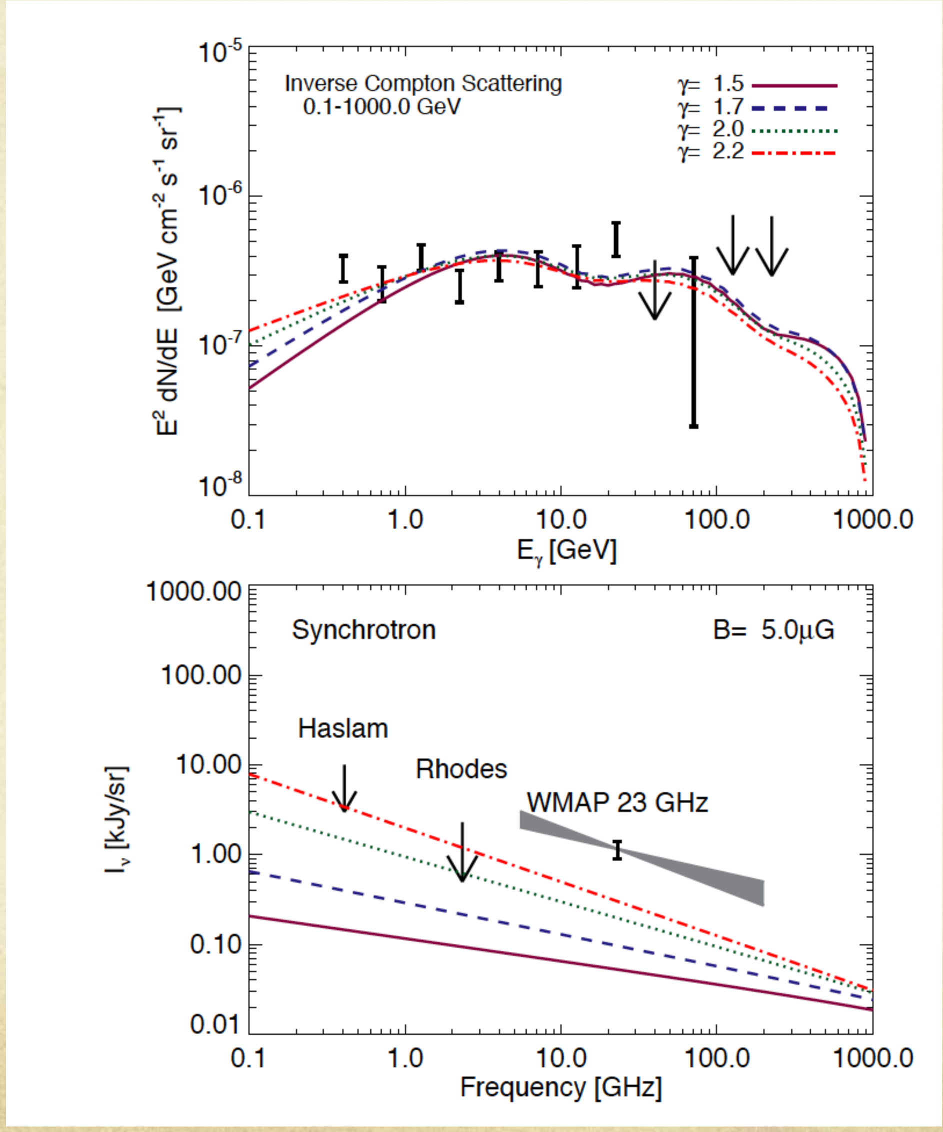
Promising Future

- *Continue observation of Fermi*
- *XMM-Newton data coming soon with other X-ray observations including Chandra and Suzaku*
- *The eROSITA and Planck experiments will provide improved measurements in X-rays and microwaves, respectively, associated with the Fermi bubbles*
- *Radio observations and magnetic field structure of the bubbles*

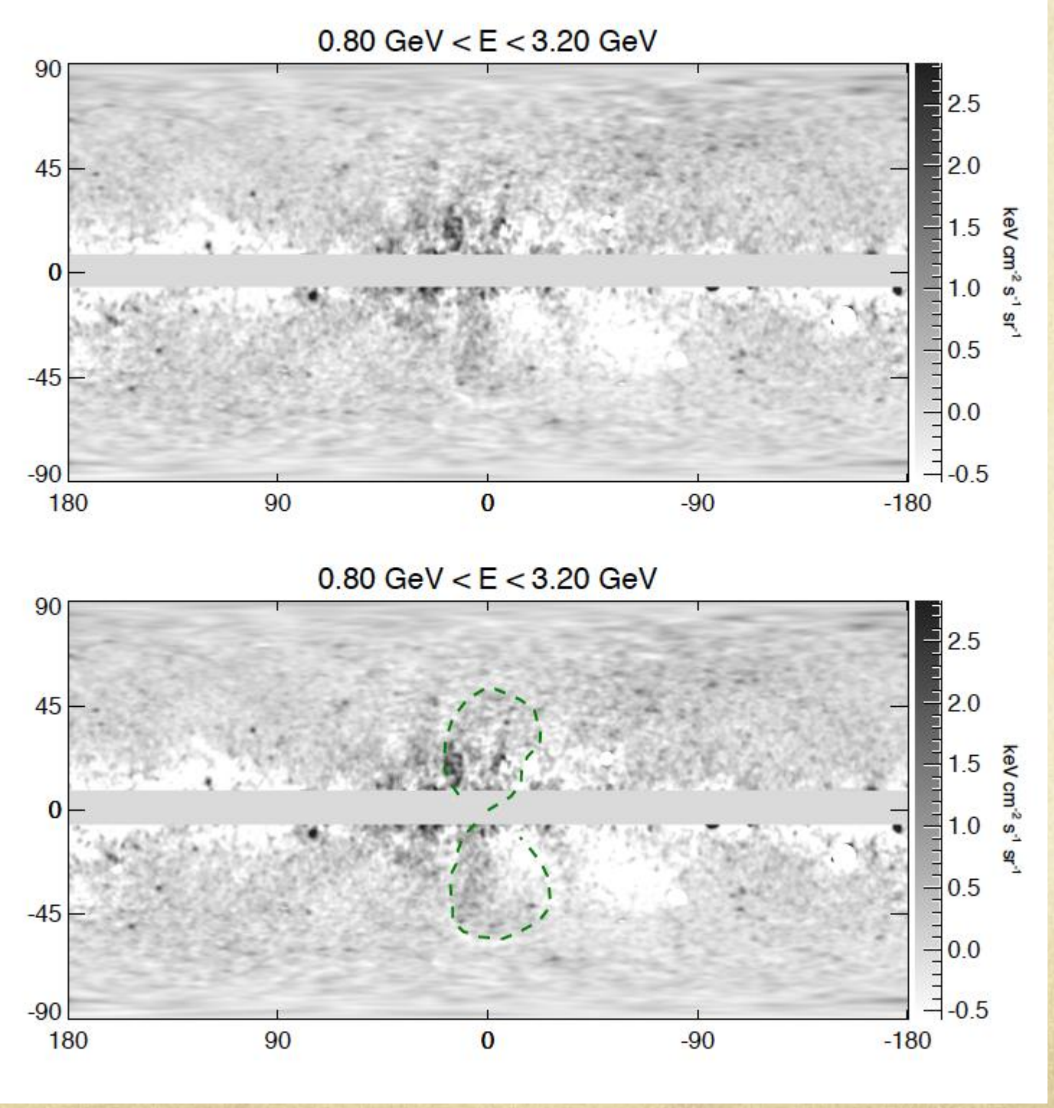
Fermi Bubble

Thank You for Your Attention!

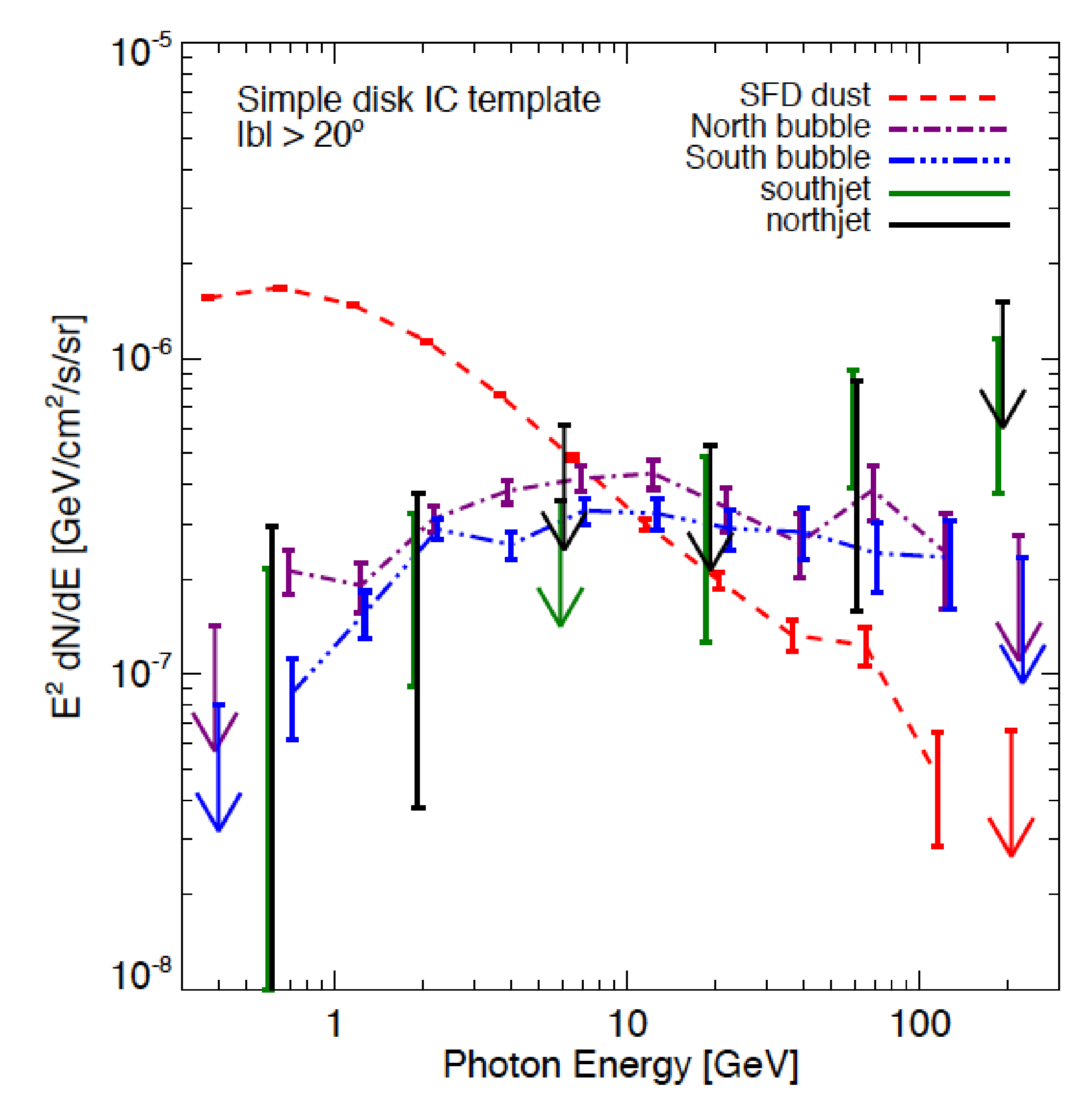
(Video credit: NASA's Goddard Space Flight Center)



Inverse Compton Scattering
0.1-1000.0 GeV
γ= 1.5
γ= 1.7
γ= 2.0
γ= 2.2
E² dN/dE [GeV cm⁻² s⁻¹ sr⁻¹]
E_γ [GeV]
Synchrotron
B= 5.0μG
Haslam
Rhodes
WMAP 23 GHz
I_ν [kJy/sr]
Frequency [GHz]



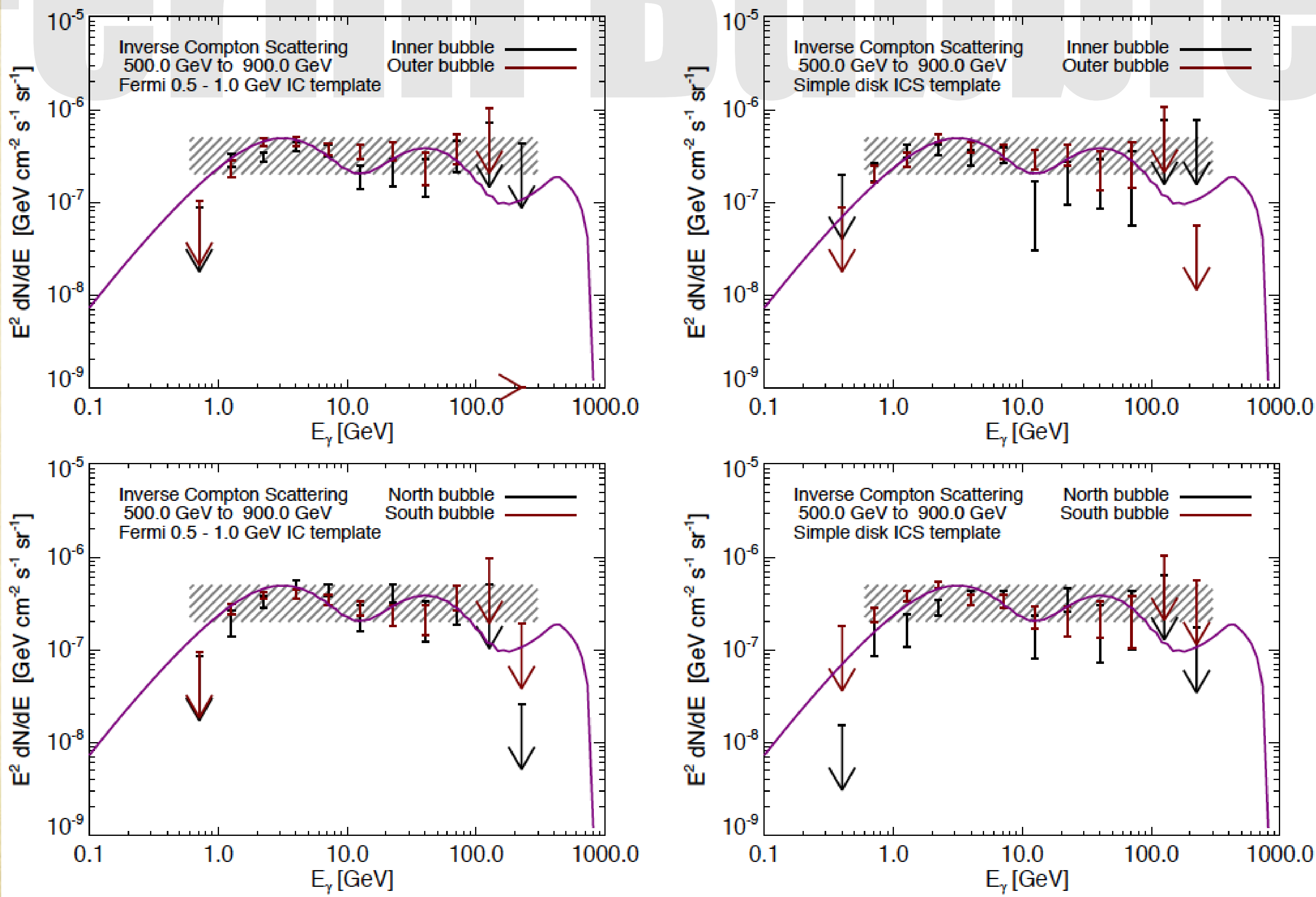
0.80 GeV < E < 3.20 GeV
90
45
0
-45
-90
180
90
0
-90
-180
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm^{-2} s^{-1} sr^{-1}
0.80 GeV < E < 3.20 GeV
90
45
0
-45
-90
180
90
0
-90
-180
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm^{-2} s^{-1} sr^{-1}



Simple disk IC template
|b| > 20°
SFD dust
North bubble
South bubble
southjet
northjet
E² dN/dE [GeV/cm²/s/sr]
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
1
10
100
Photon Energy [GeV]

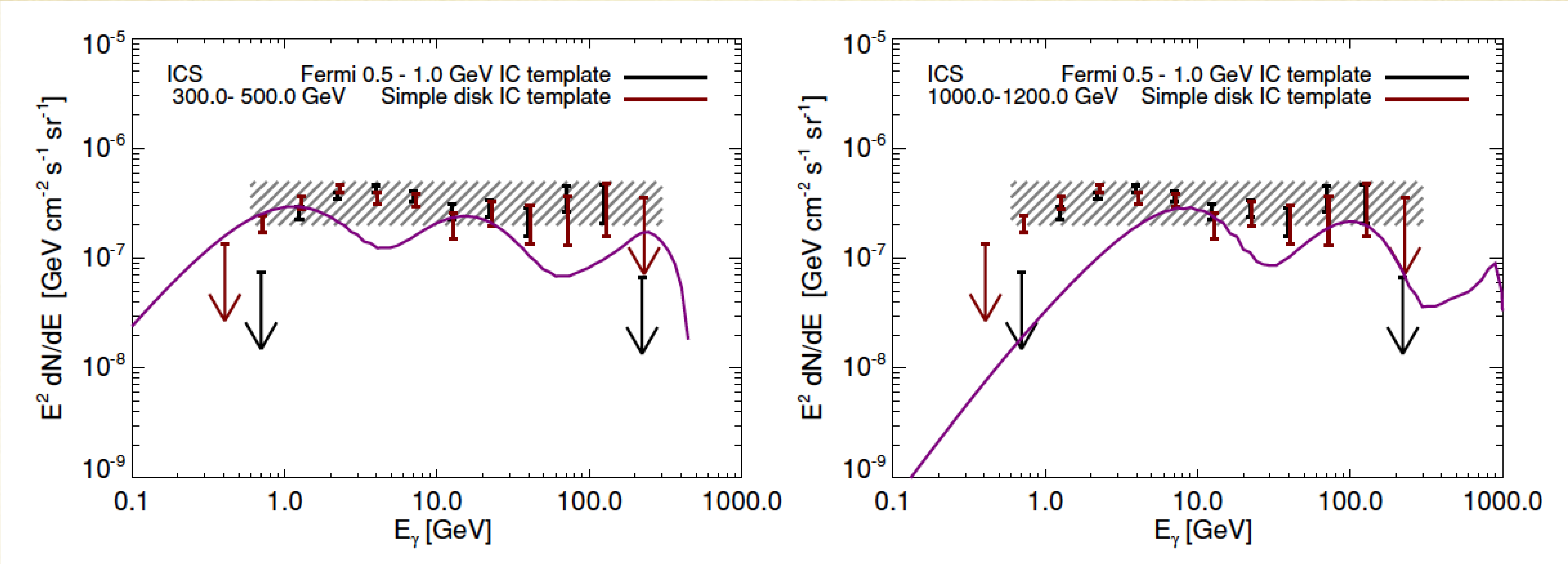
Fermi Bubble

500-900 GeV electrons scattering CMB roll off at the right (low) energy.



Fermi Bubble

It is easy to get bumps and wiggles in the wrong places...



Fermi Bubble

Two arguments for CMB scattering:

- *1. The bubble intensity is ~flat with latitude, while starlight density is falling.*

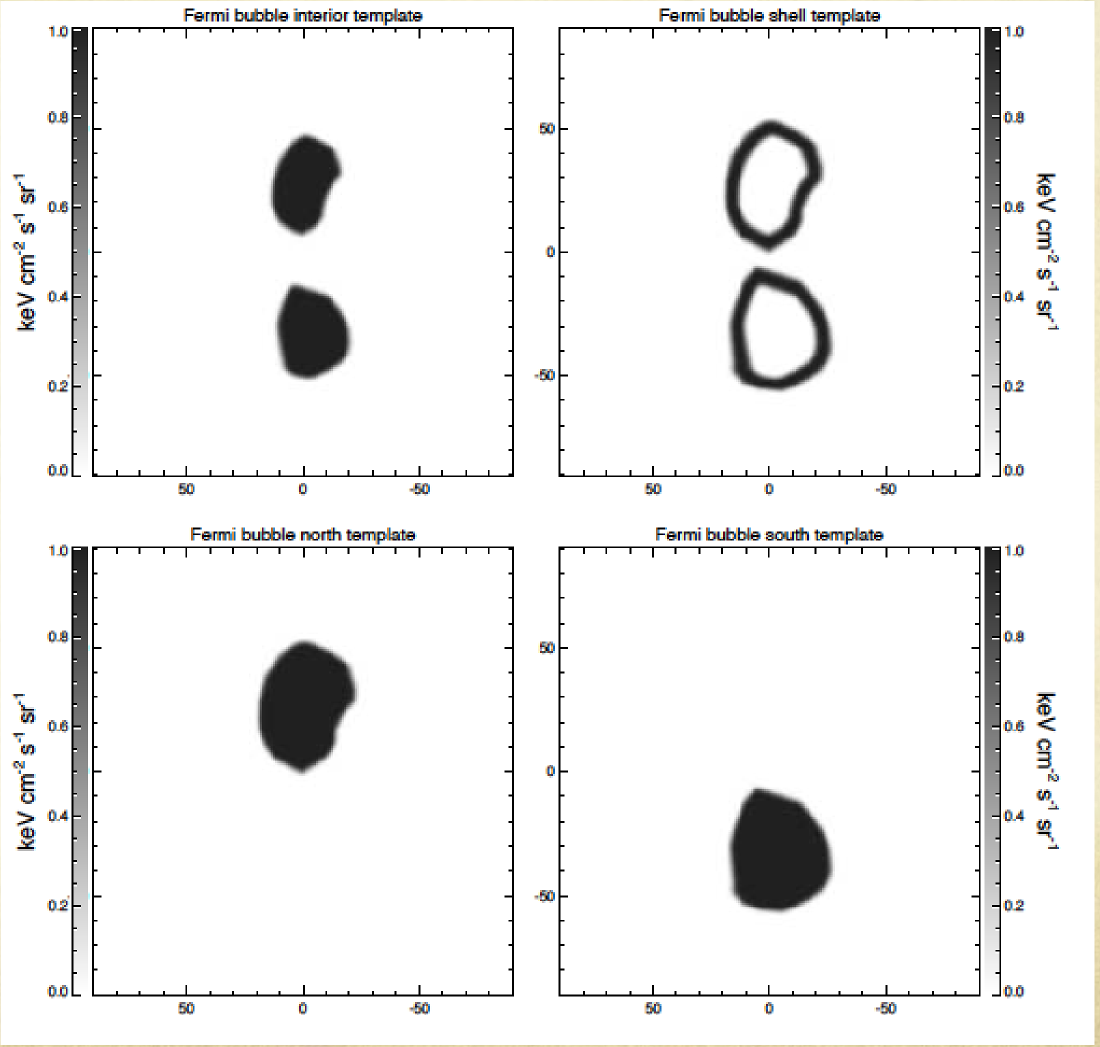
- *2. The shape of the IC spectrum.*

500-900 GeV electrons scattering CMB roll off at the right (low) energy.
(But see Crocker & Aharonian 2010)

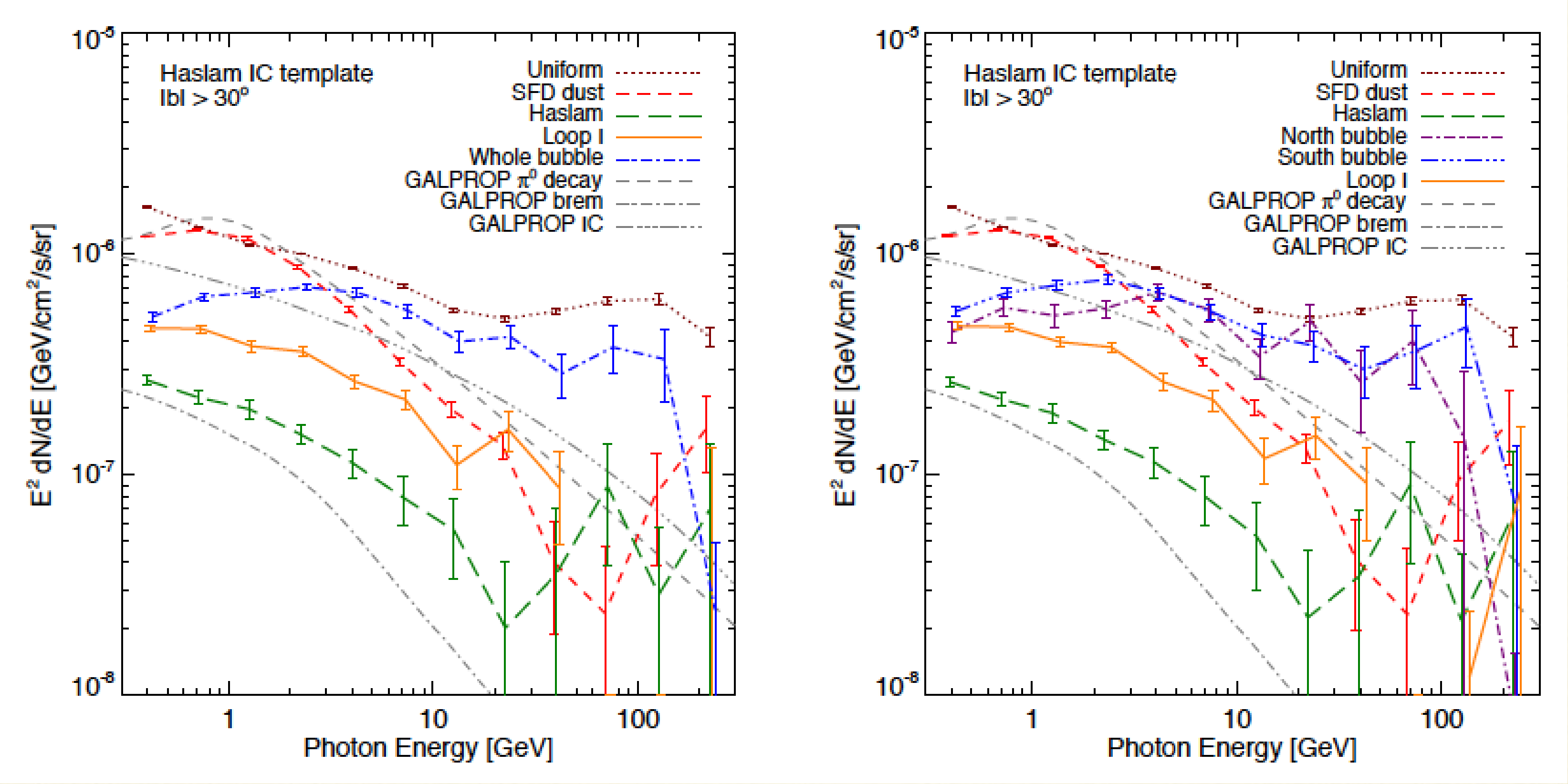
Together these imply that the Fermi bubbles are Mainly ~TeV electrons scattering the CMB.
(Note that the WMAP haze is produced by ~10 GeV electrons.)

Now, how about X-rays?

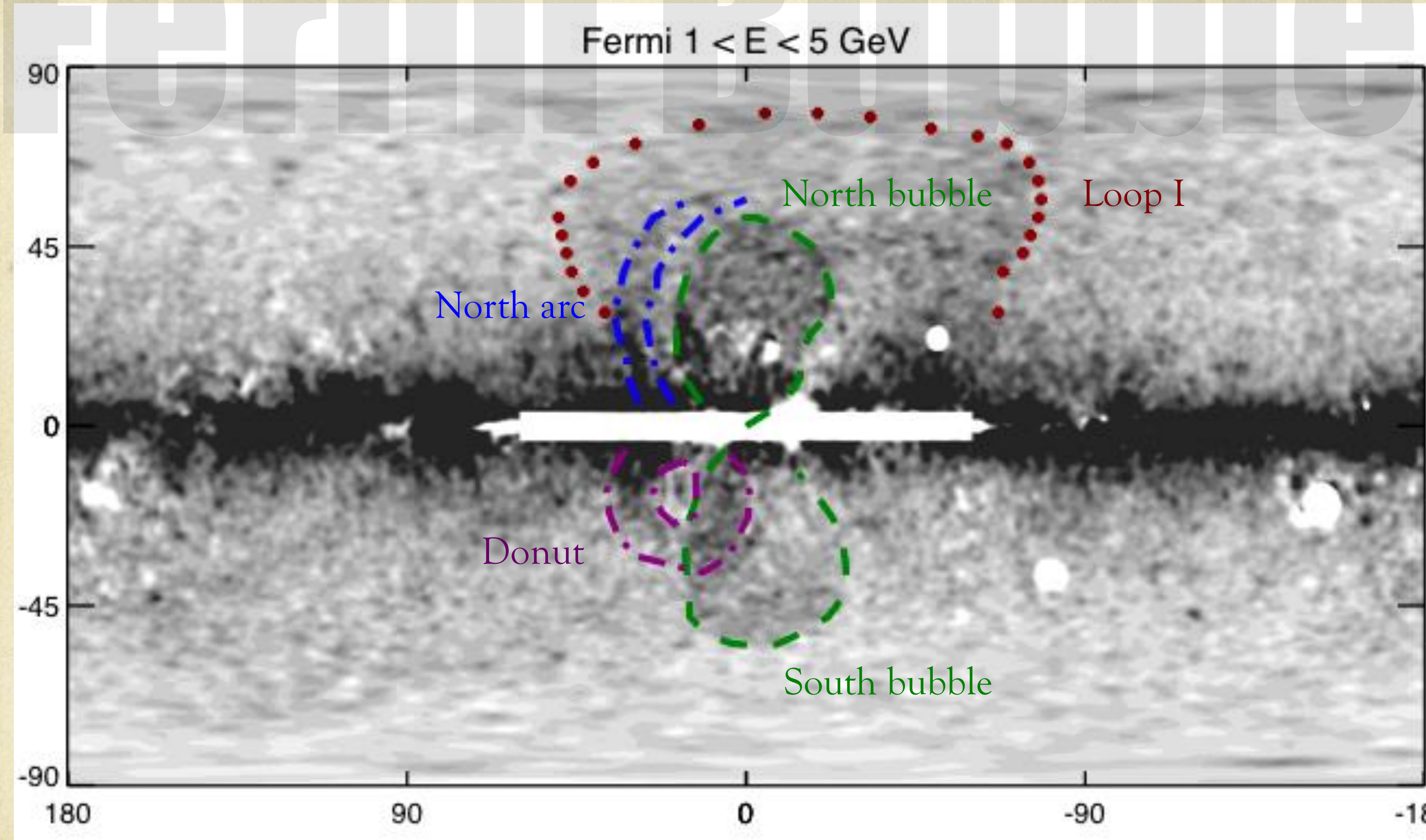
Any Substructure of the bubbles?



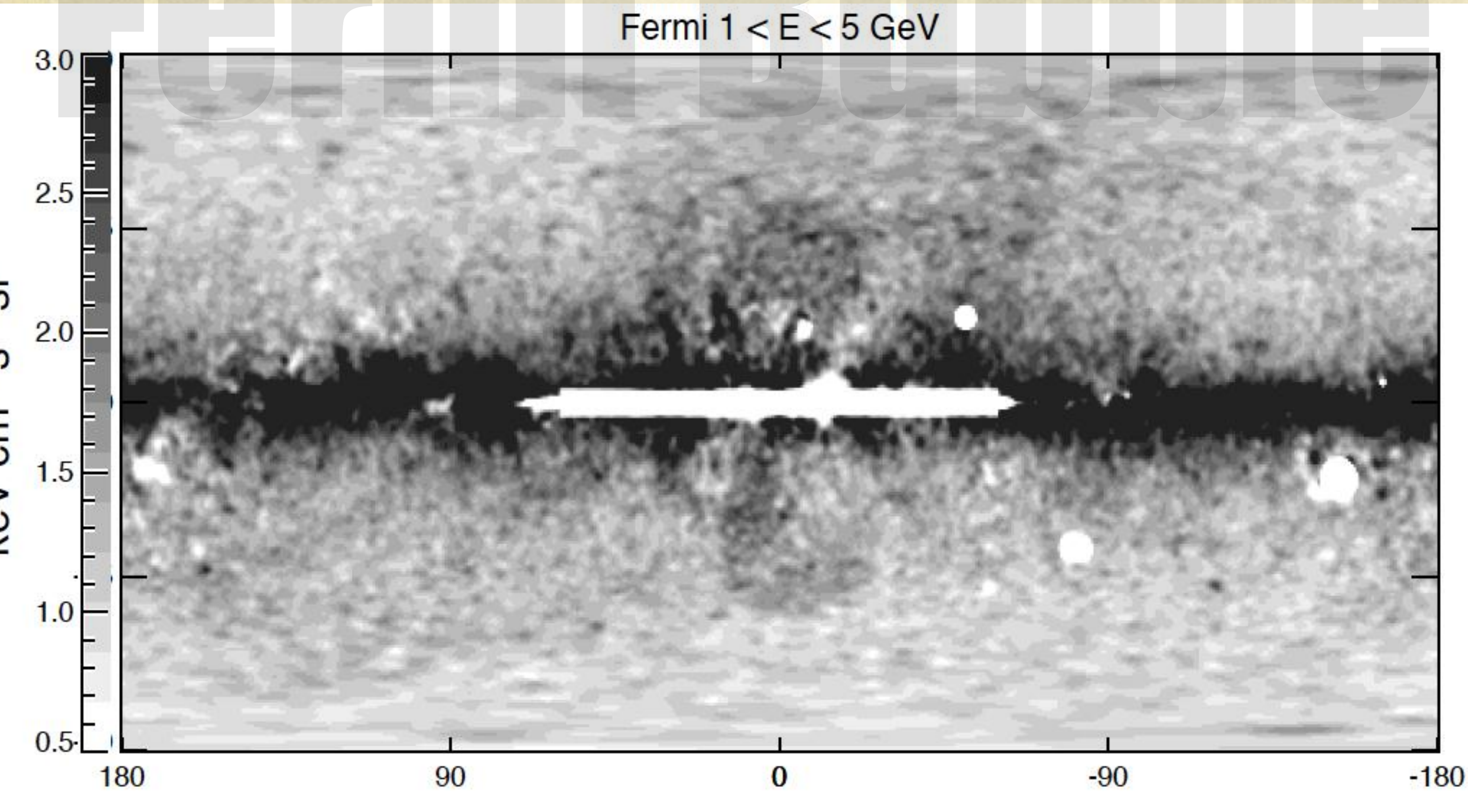
Fermi Bubble



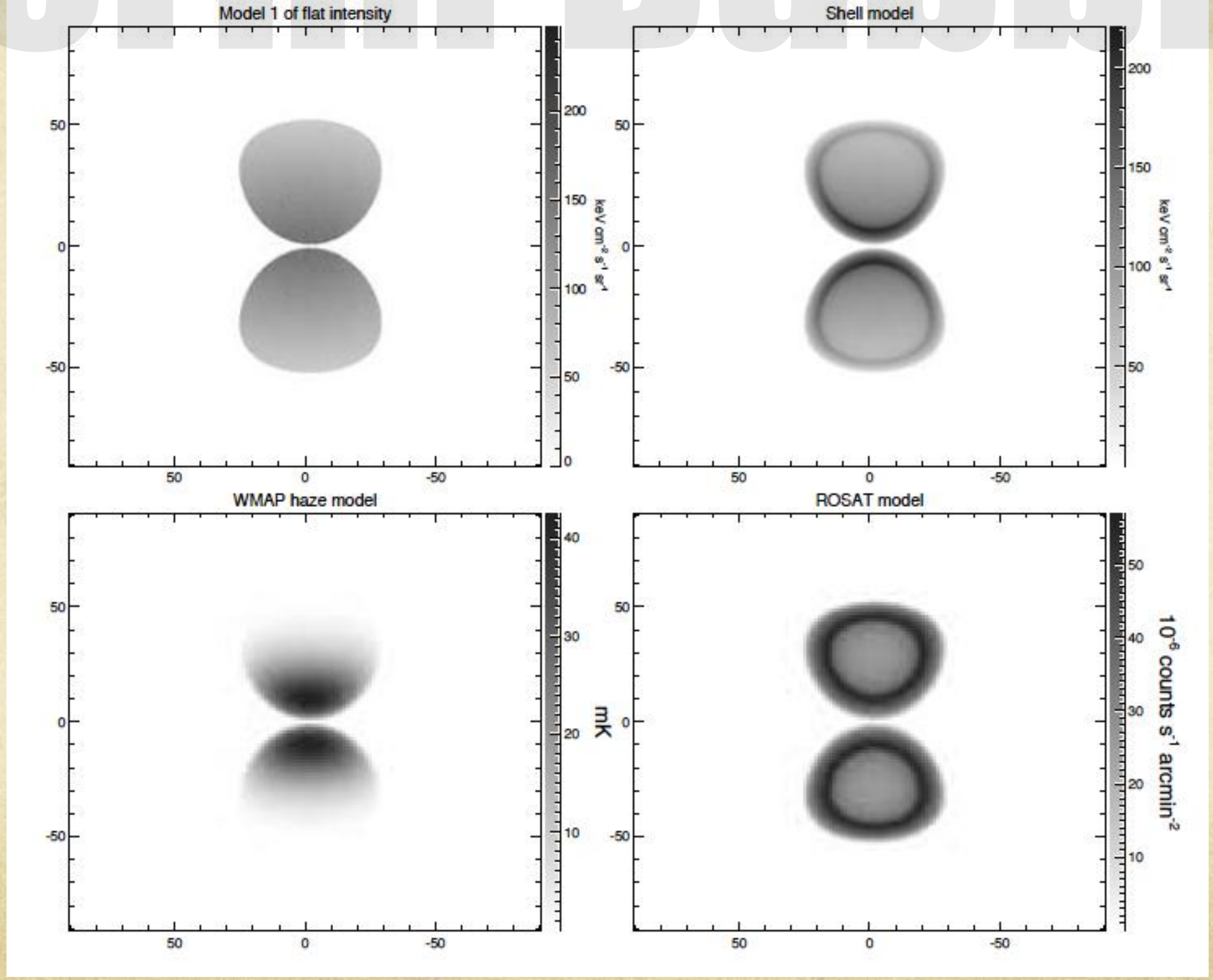
Fermi Bubble



Fermi Bubble



Fermi Bubble



Fermi Bubble

To understand the data...

- *Full physical model:*

  Pro: uses everything we know to fit data.

  Con: only used what we put in the model

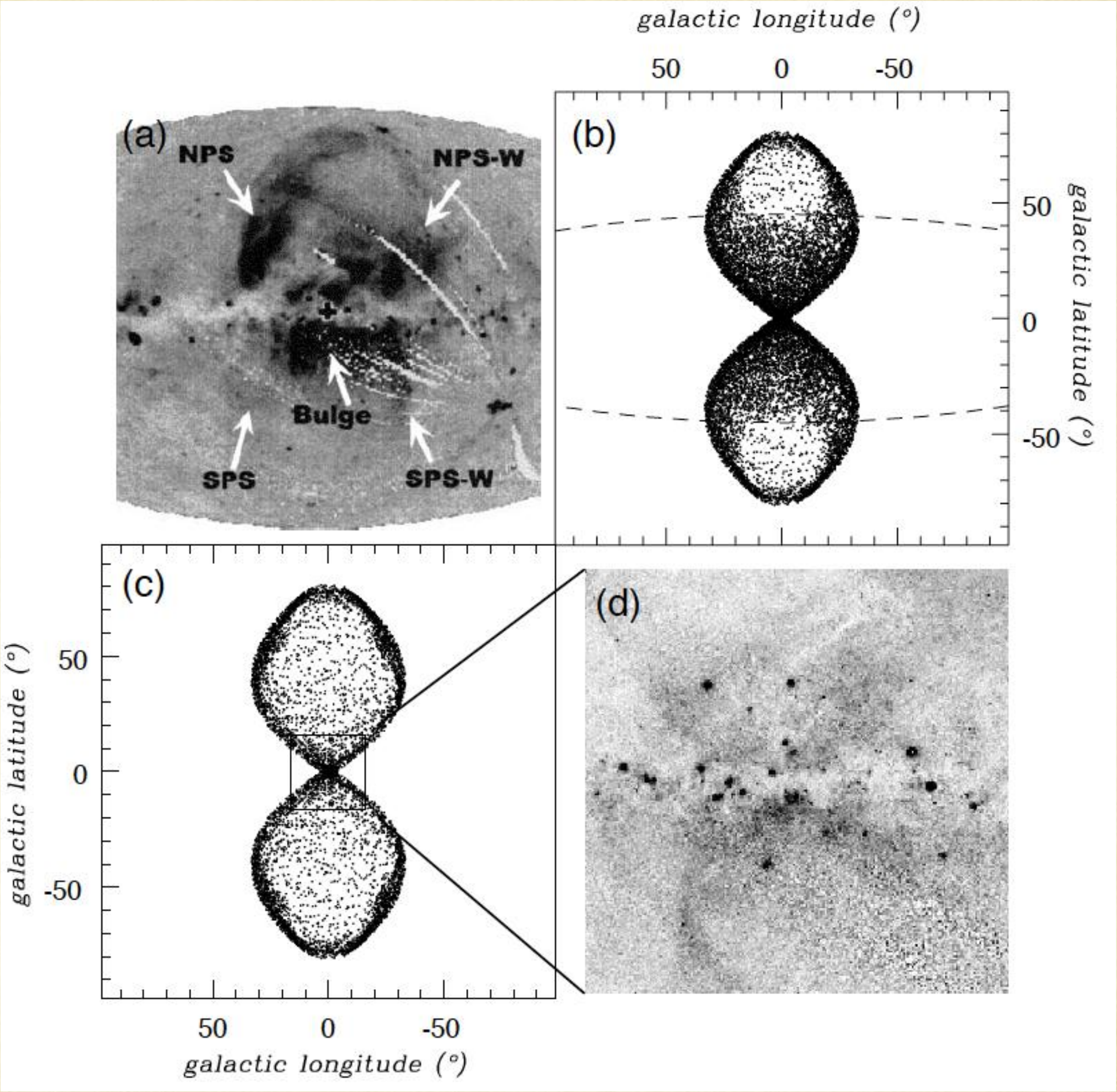
  Provides the most secure interpretation of the data

- *Template analysis*

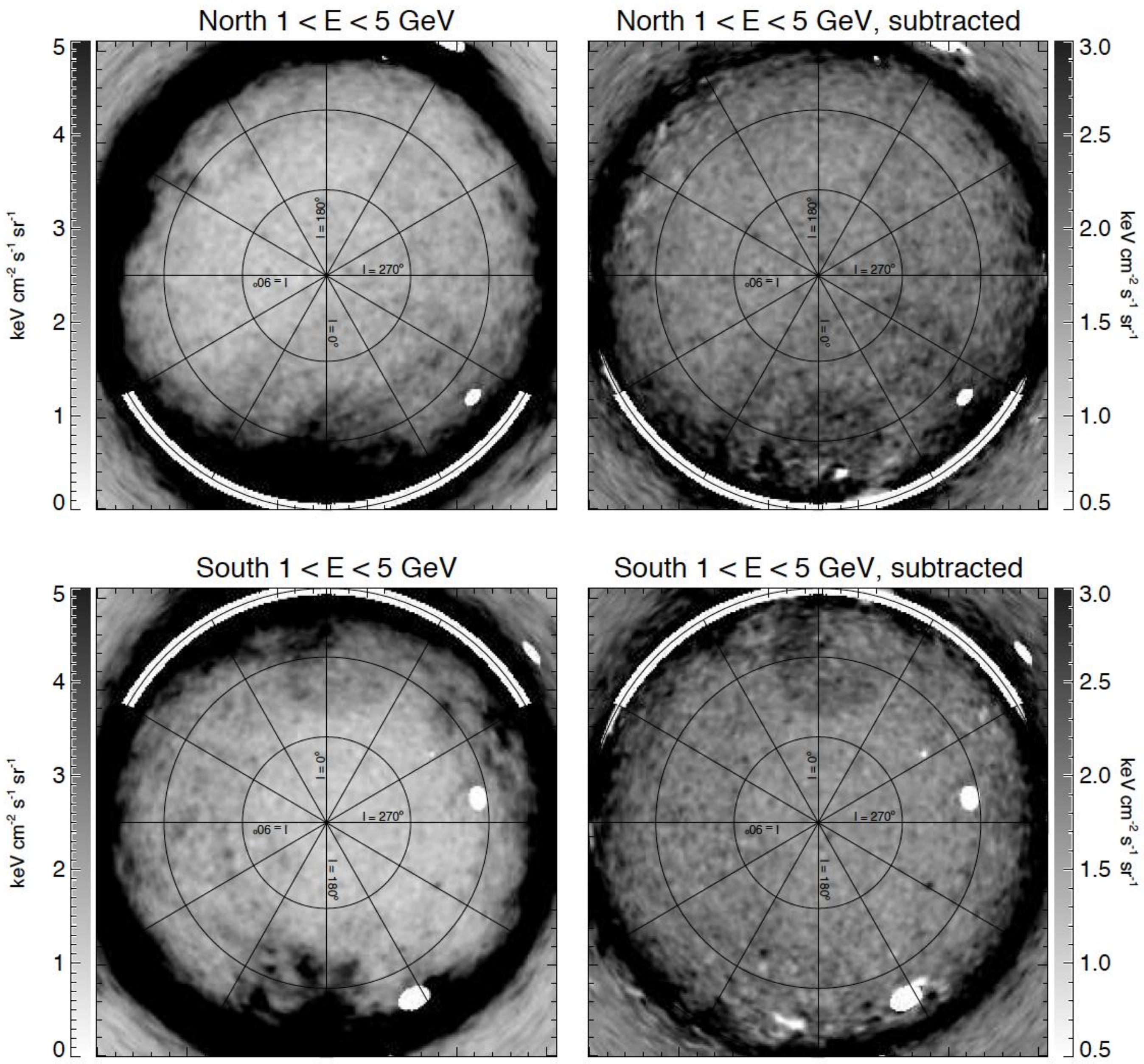
  Pro: the templates work pretty well; may reveal new emission mechanisms. Simple.

  Con: must assess fit residuals carefully, because fit is never perfect

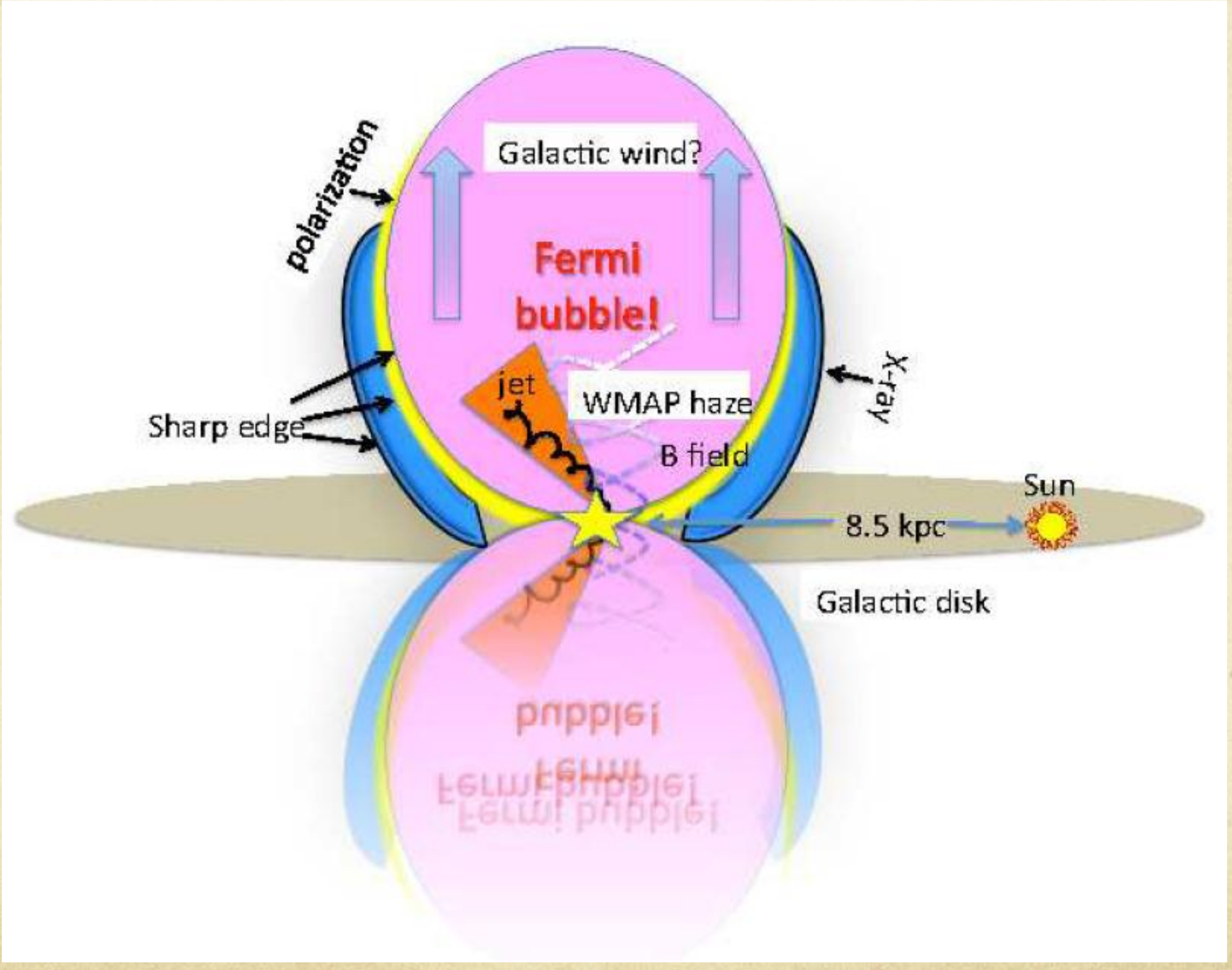
  Good for finding the unexpected!



(Bland-Hawthorn and Cohen 2003)

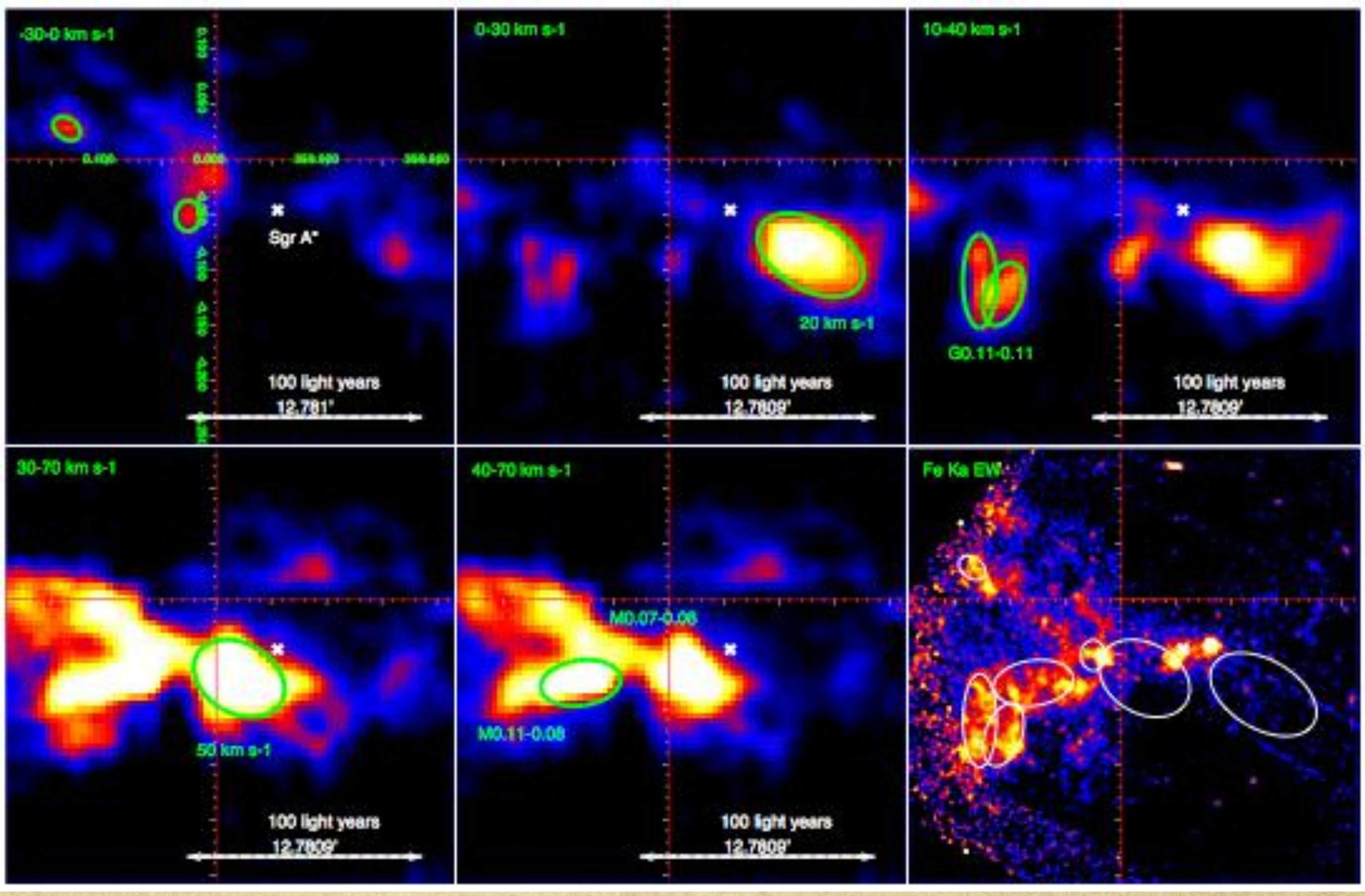


North 1 < E < 5 GeV
North 1 < E < 5 GeV, subtracted
South 1 < E < 5 GeV
South 1 < E < 5 GeV, subtracted
keV cm-2 s-1 sr-1
l = 180°
l = 270°
l = 90°
l = 0°
0
1
2
3
4
5
0.5
1.0
1.5
2.0
2.5
3.0


Galactic wind?
polarization
Fermi
bubble!
jet
WMAP haze
Sharp edge
B field
X-ray
Sun
8.5 kpc
Galactic disk

X-ray reflection nebulae in the GC.

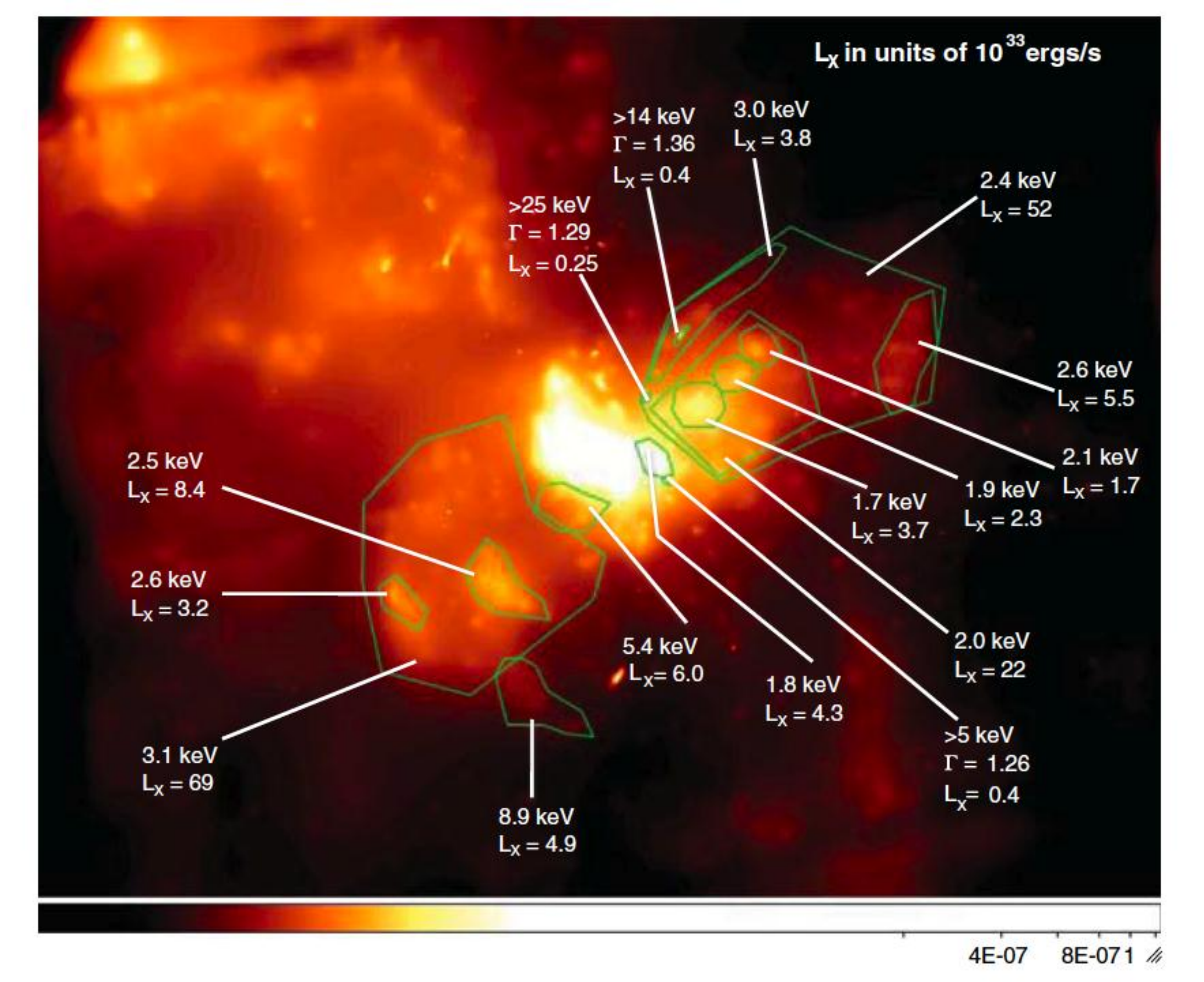
There are indications of previous GC activity from X-ray echoes and time variability of reflected X-ray lines (Sgr B1 and B2, Sgr C, and M0.11-0.11)
They are likely due to reflected X-rays from previous activity of Sgr A∗ with high luminosity ~300 yr ago.



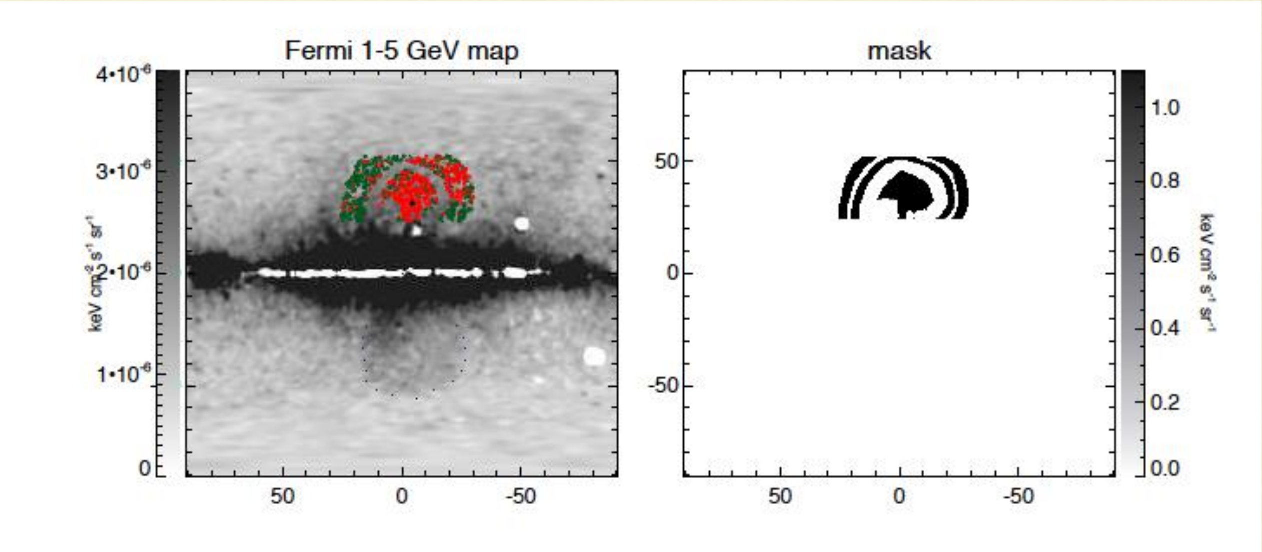
1, Thermal wind from the central cluster of massive young stars

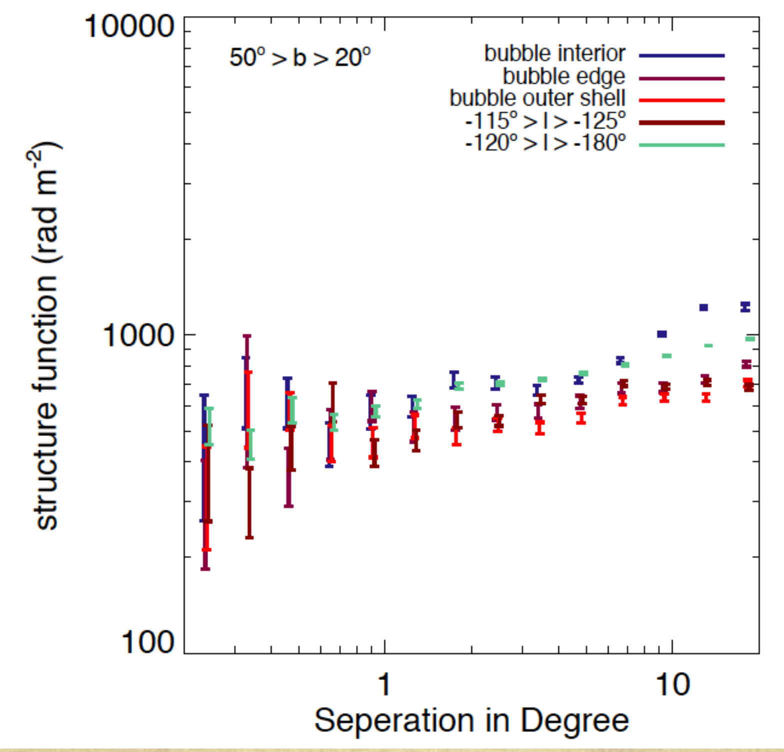
2, Steady outflows from Sgr A∗

3, Repeated episodic outbursts (jets) from Sgr A∗ (**Markoff 2010**)

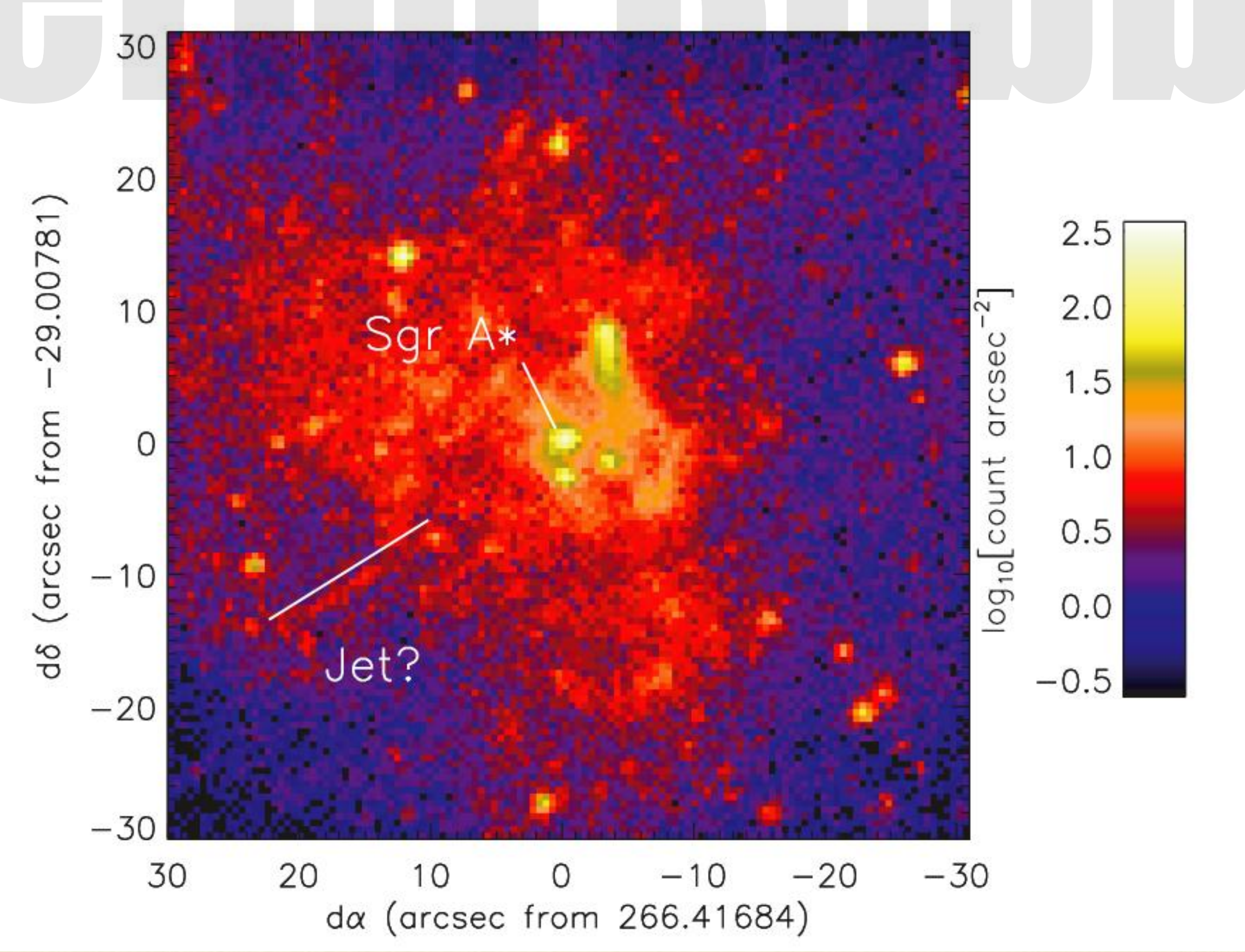


(Markoff 2010)


Fermi 1-5 GeV map
mask
keV cm⁻² s⁻¹ sr⁻¹
50
0
-50


50° > b > 20°
bubble interior
bubble edge
bubble outer shell
-115° > l > -125°
-120° > l > -180°
structure function (rad m⁻²)
Seperation in Degree
10000
1000
100
1
10

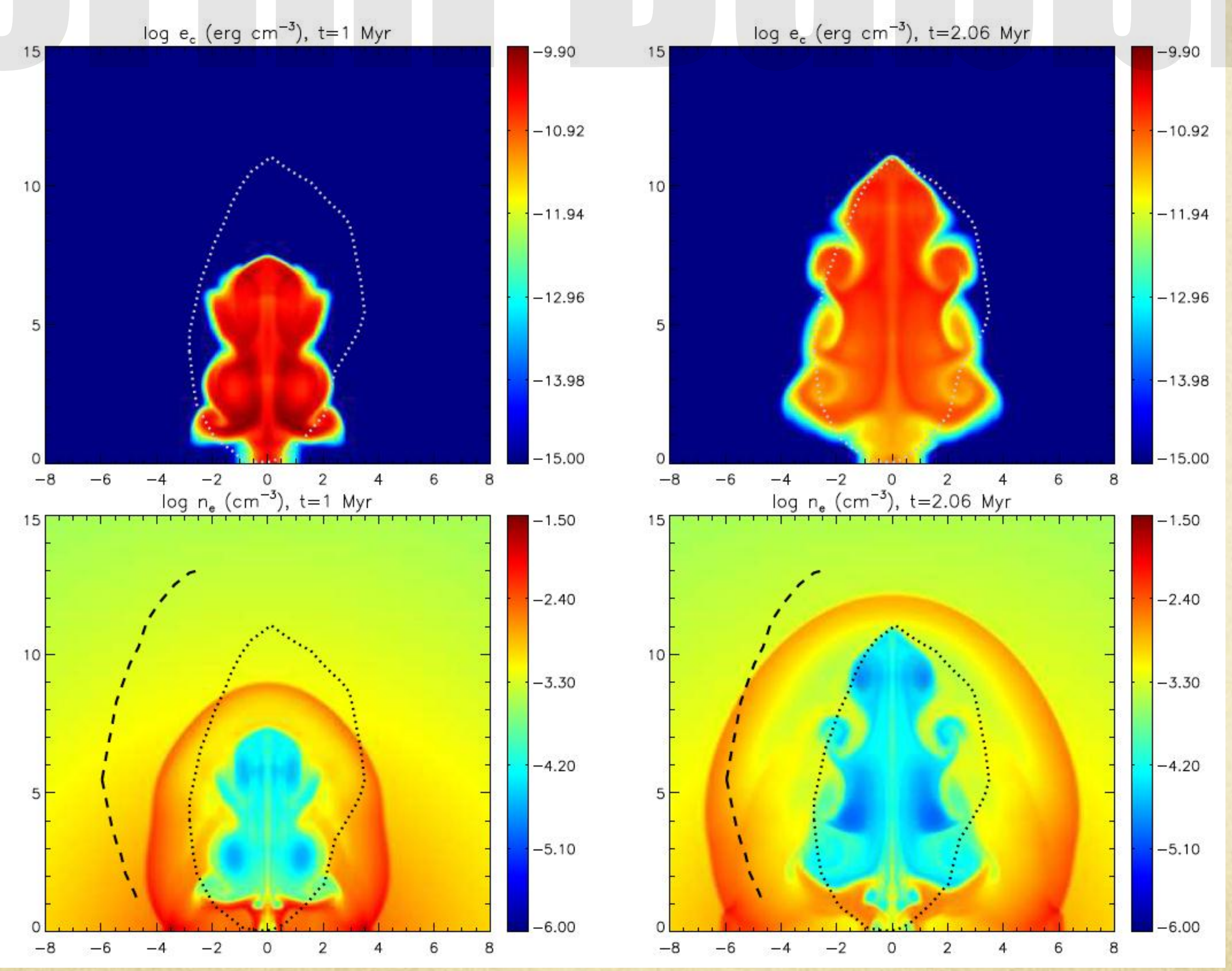
Is there jet in GC?



However, detailed examinations of the GCL have shown that the gas shell is deep into the disk, and do not support a jet origin for that structure (Law 2010).

Fermi Bubble

Kelvin-Helmholtz instabilities



Guo & Mathews (arXiv:1103.0055)

Fermi Bubble