GIANT GAMMA-RAY BUBBLES FROM Fermi -LAT

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Fermi Bubble

Main points:

- *There are curious excesses of microwaves and gamma-rays in the inner Galaxy -- both with a hard spectrum ("WMAP haze" & "Fermi haze") (Finkbeiner 2004 & Dobler et al. 2010)*

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Fermi Bubble

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Fermi Bubble

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- *Synchrotron and inverse-Compton from a hard electron cosmic ray population can explain both.*

- *DM is a tempting possibility...*

- *AGN or starburst activity is more likely, though there are problems with both. (it's likely that there are 2 things going on...)*

Fermi Bubbles

Su, Slatyer, & Finkbeiner (2010); arXiv: 1005.5480

Giant gamma-ray structure with sharp edges
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!*

Fermi Bubble

Two motivations for looking at the Inner Galaxy with *Fermi*: :

- *1. Investigate the WMAP haze (Finkbeiner 2004)*
  (Microwave excess with hard spectrum in the inner galaxy)

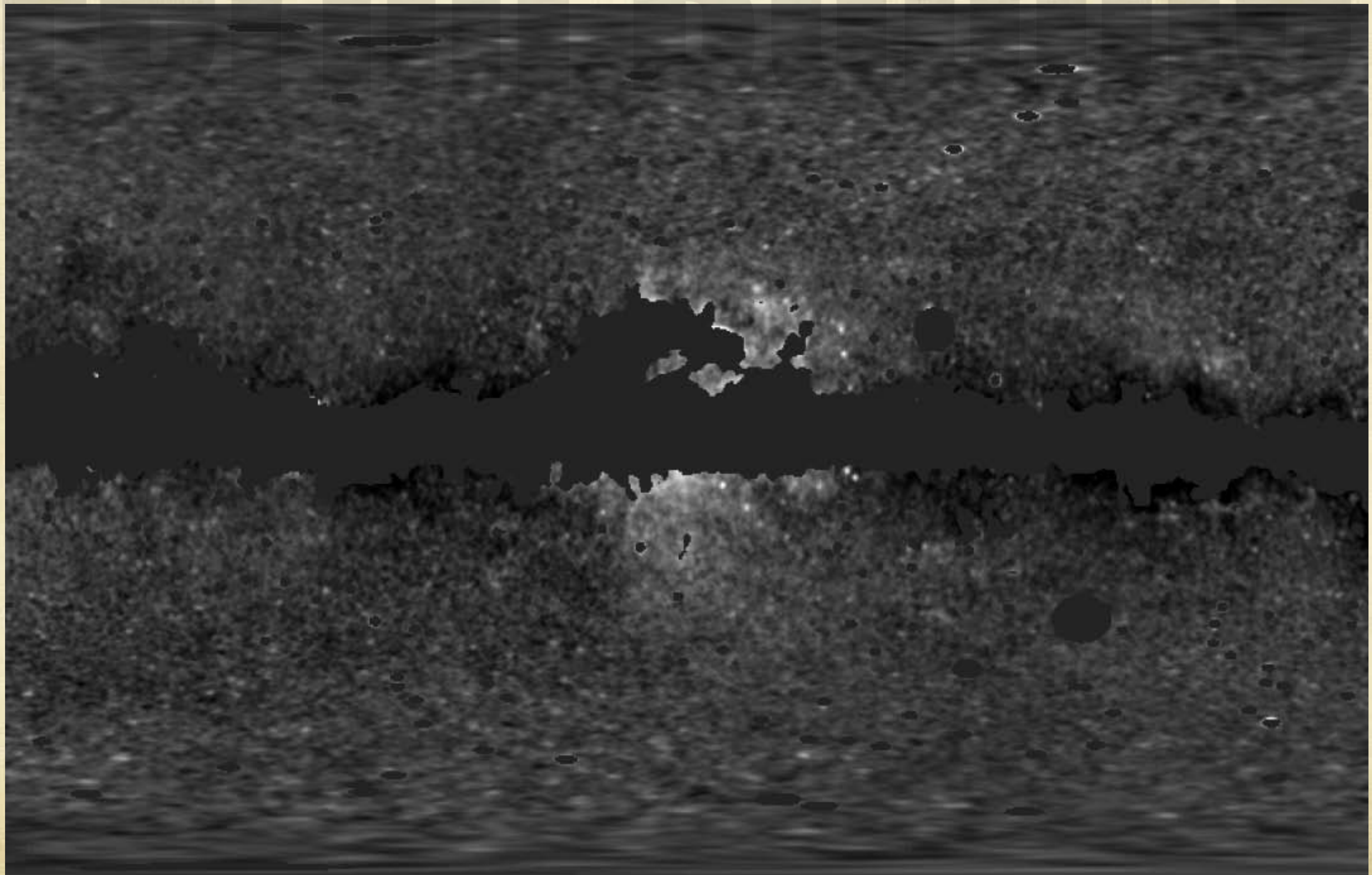
  Difficult to explain as free-free, dust, or spinning-dust

  If synchrotron, must be unusually hard electron spectrum.

- *2. Indirect detection of dark matter*

Dobler et al., arXiv:0910:4583
Su et al., arXiv:1005.5480

WMAP haze



(Finkbeiner 2004)

Fermi Bubble

3 views of the haze:

-Null 1: There is no excess synchrotron, merely free-free or spinning dust

Fermi Bubble

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-Null 2: The haze is synchrotron, but is normal spectral variation - nothing special.

Fermi Bubble

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-Null 1: There is no excess synchrotron, merely free-free or spinning dust

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- Haze hypothesis: Synchrotron from electrons produced by a distinct physical mechanism.

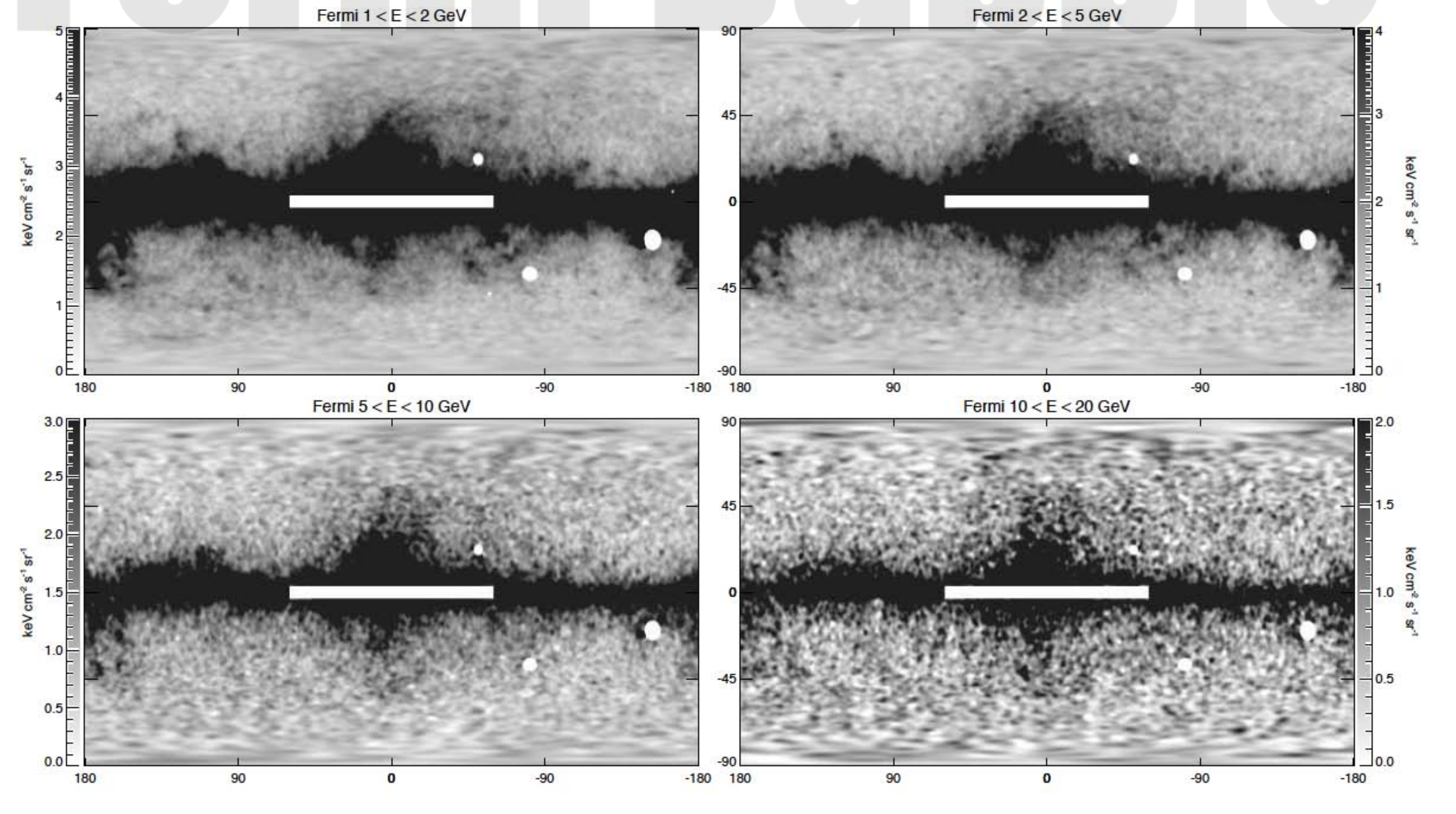
Fermi Bubble

How to test the WMAP haze idea?

1) Can we see the IC gammas expected if the WMAP haze is synchrotron? (this would rule out null hypothesis 1)

2) Does the structure look like a transient (have sharp edges), or steady state (look hazy)?

The Fermi-LAT data



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*

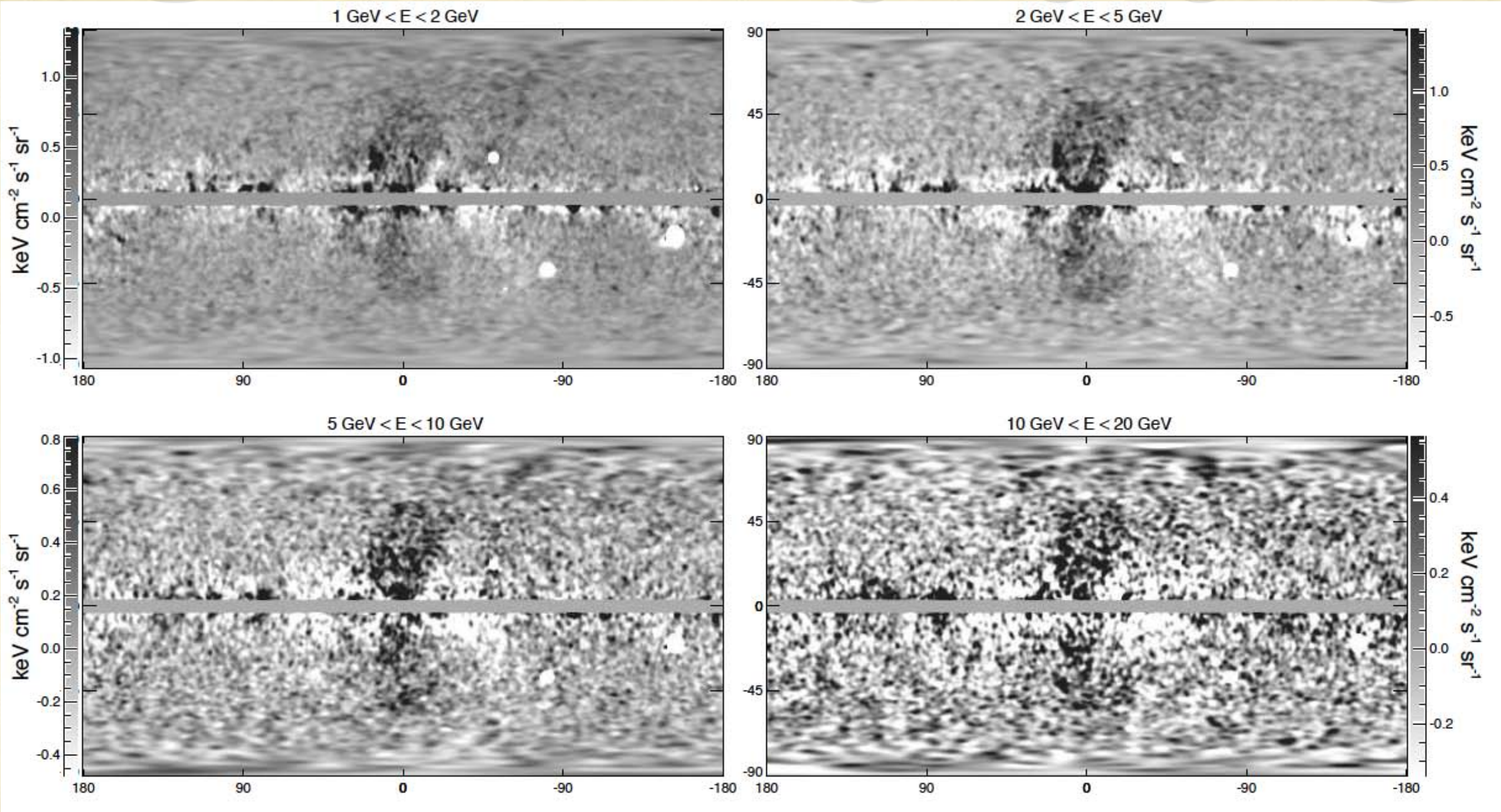
  Pro: the templates work pretty well; may reveal new emission mechanisms. Simple.

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

  Good for finding the unexpected!

Fermi Bubble

Data minus Fermi diffuse emission model:



Fermi Bubble

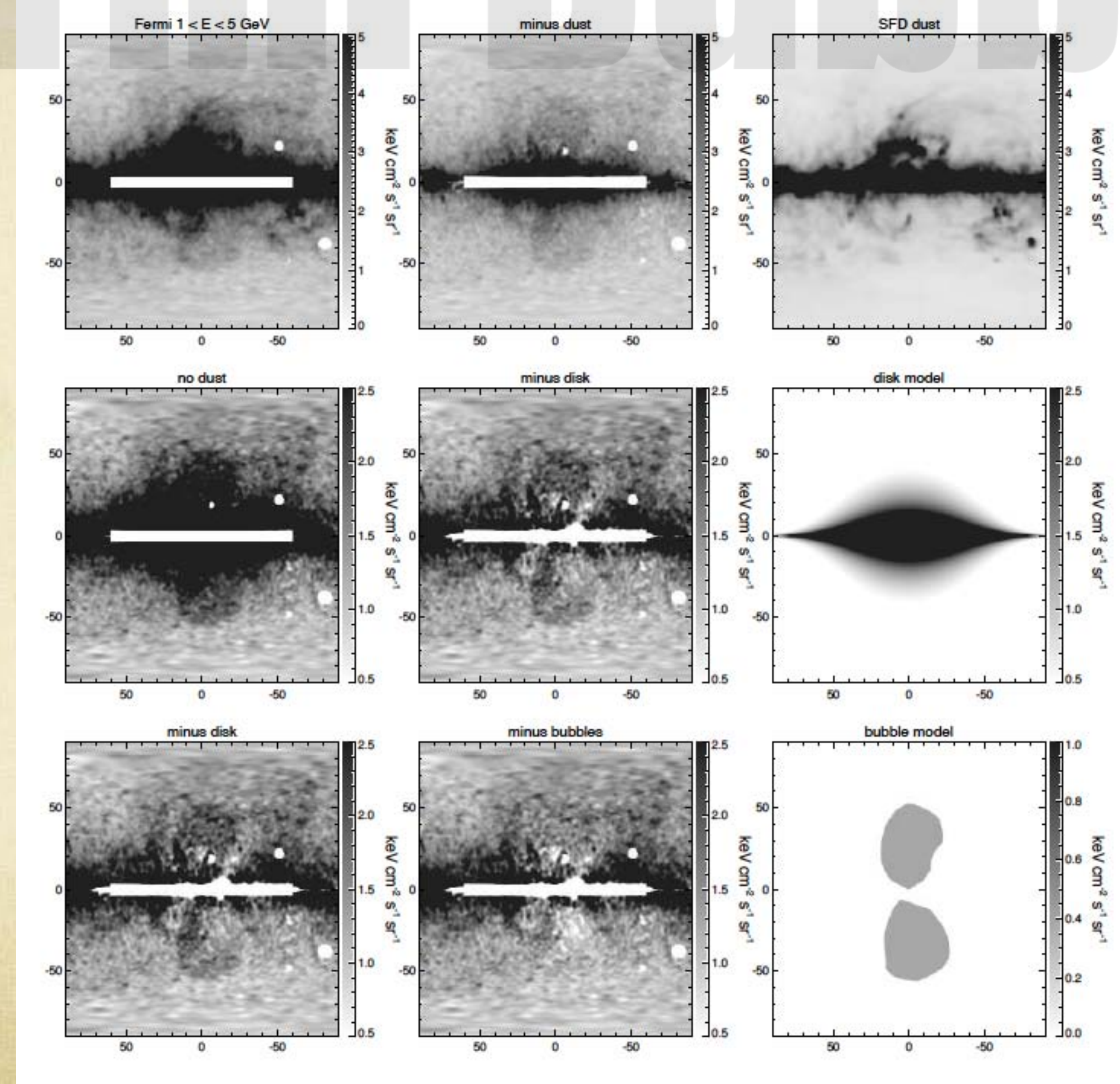
Subtracting the Fermi diffuse emission model reveals a faint bilobular structure in the inner Galaxy.

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

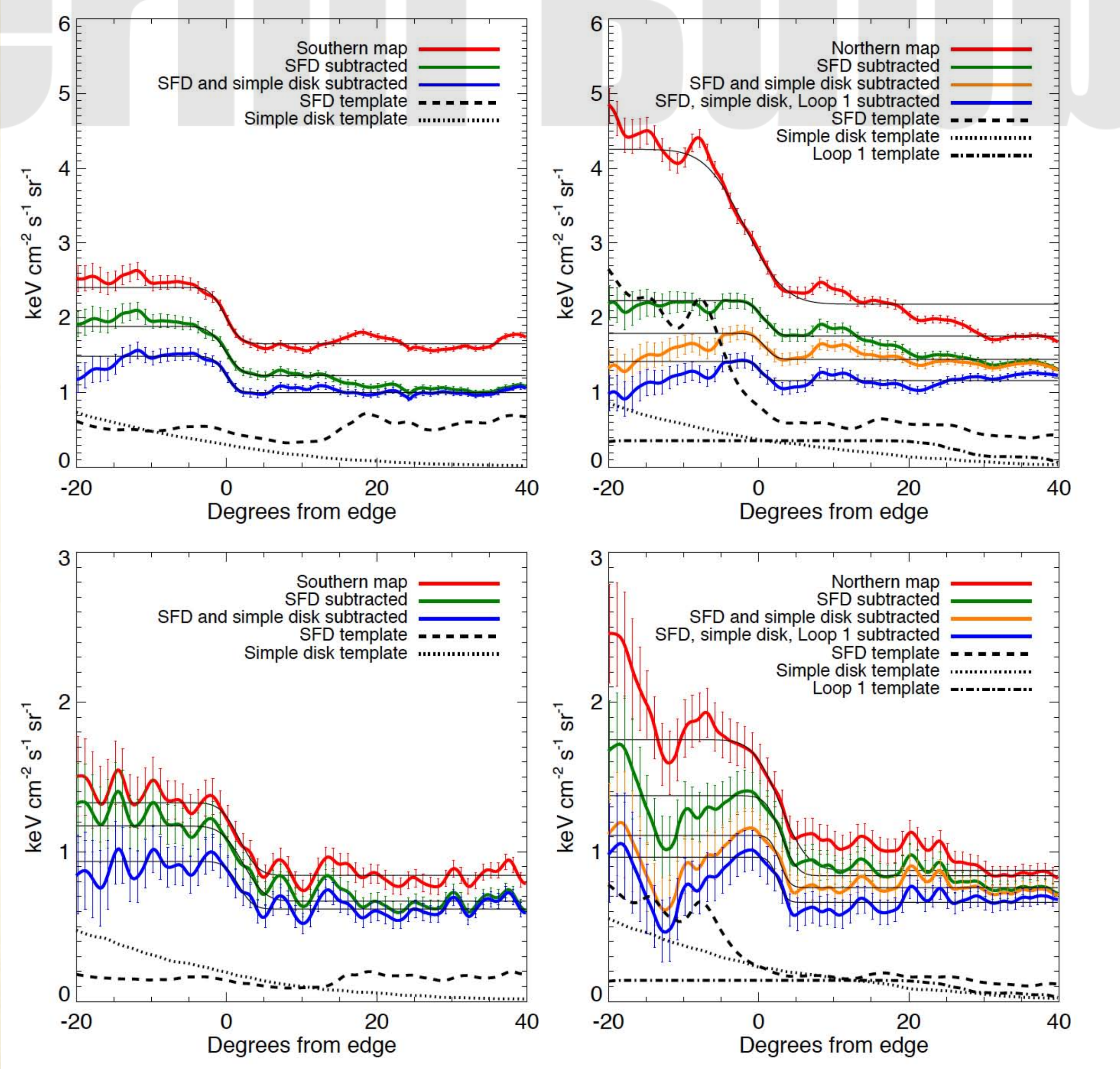
Model contains p^0 and bremsstrahlung from gas maps; IC from GALPROP; North Polar Spur feature from Haslam map.

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

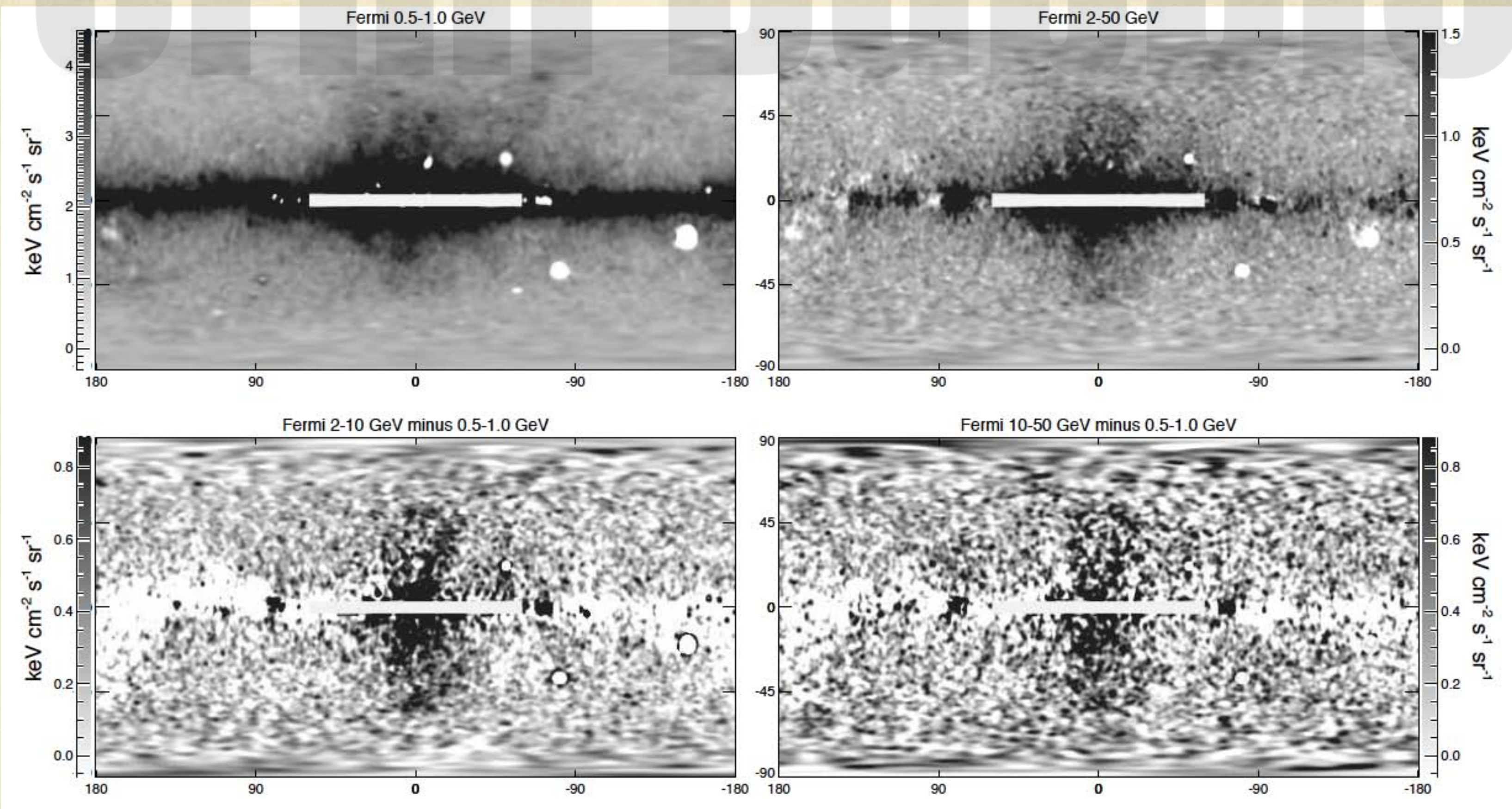
Simple disk model



The bubbles have Sharp edges!

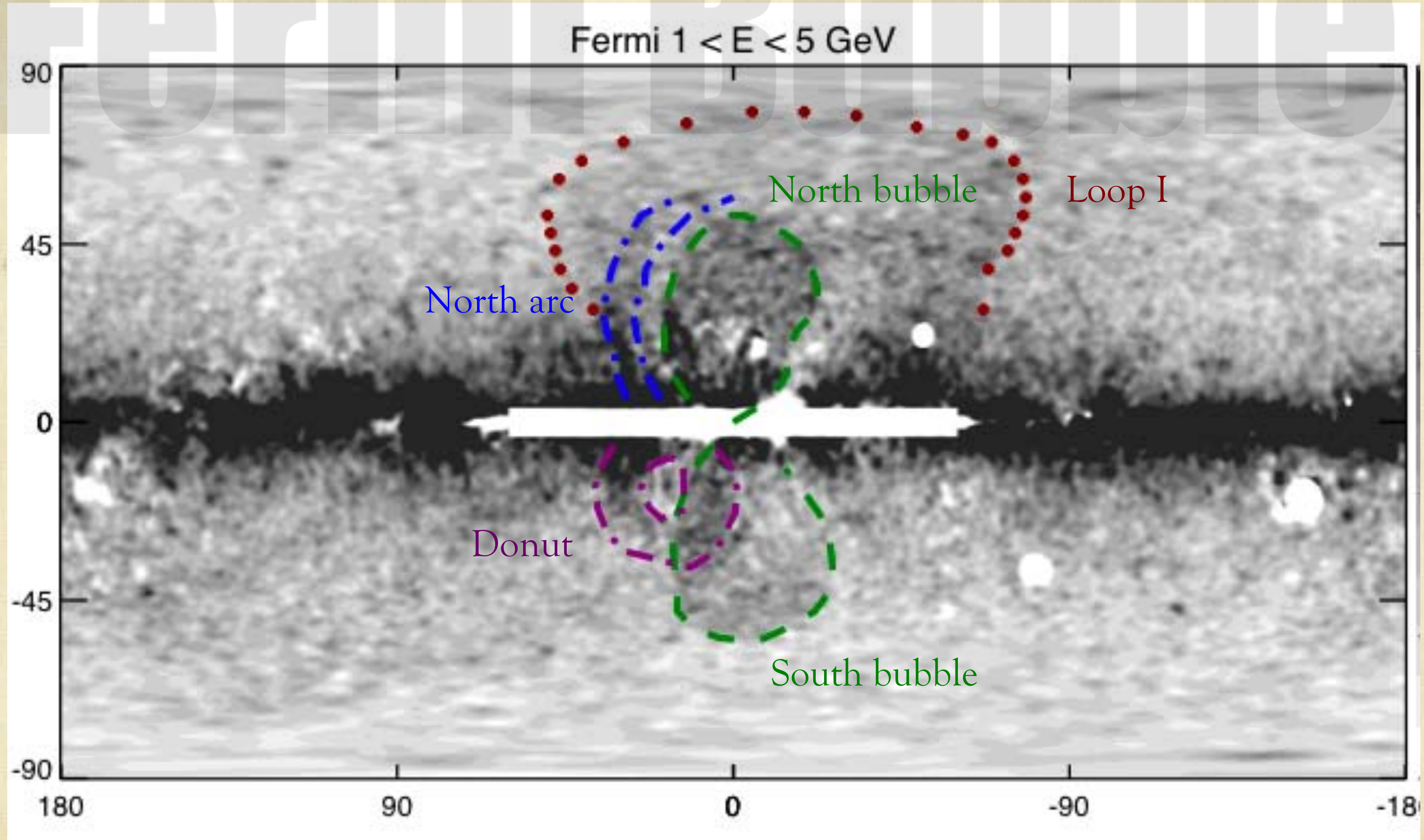


Fermi Bubble

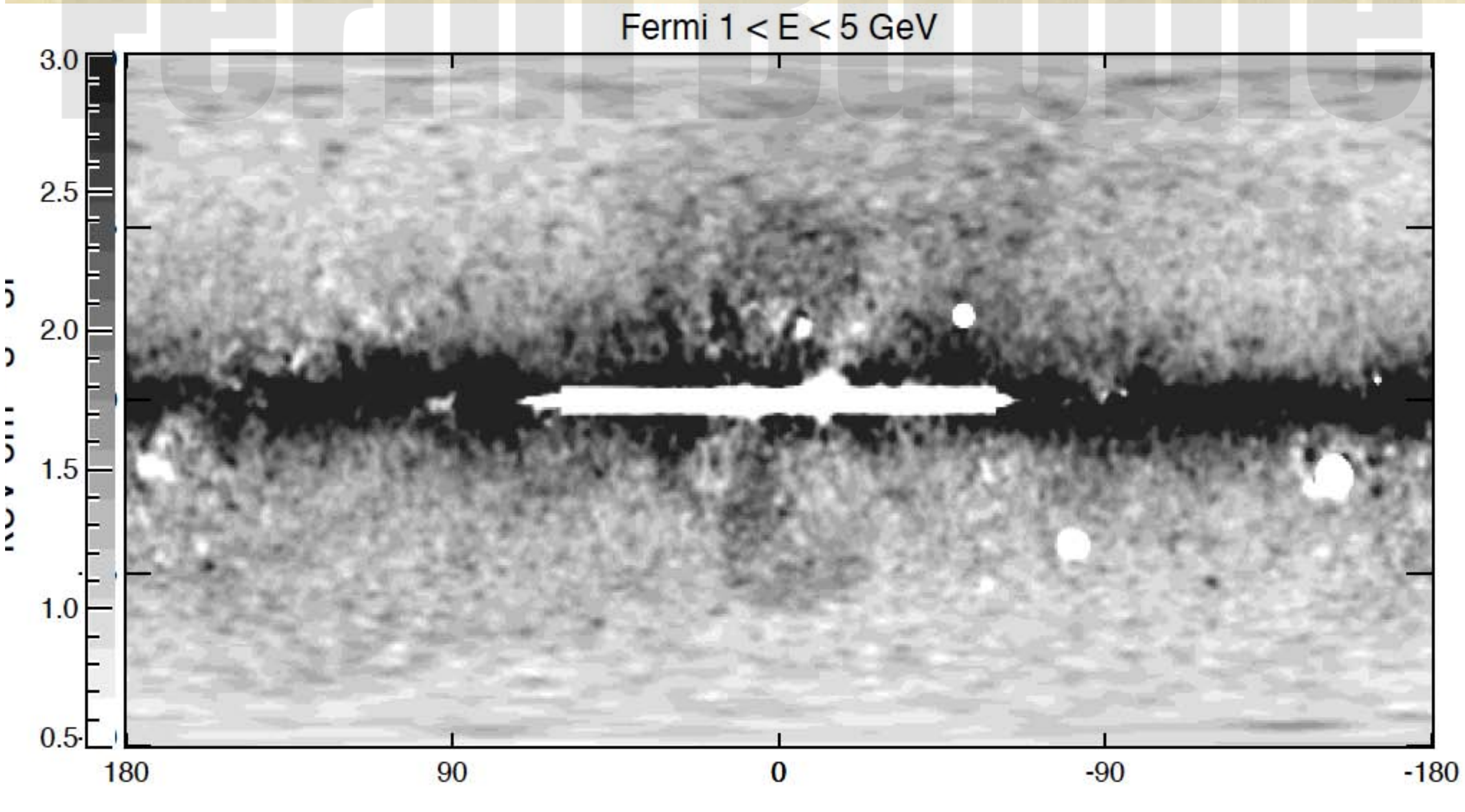


We use a low energy gamma-ray template (dust-subtracted) as the IC component.

Fermi Bubble



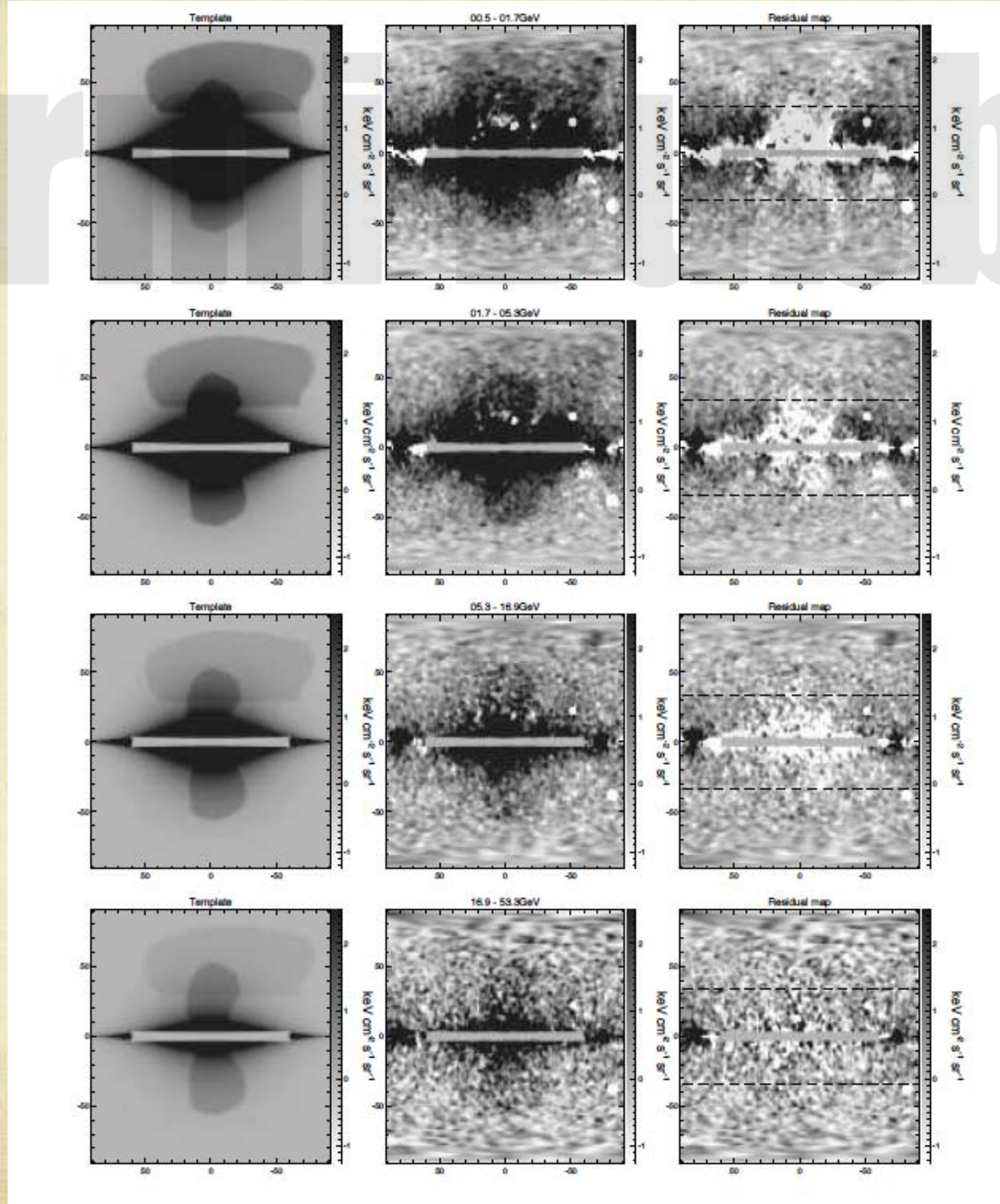
Fermi Bubble



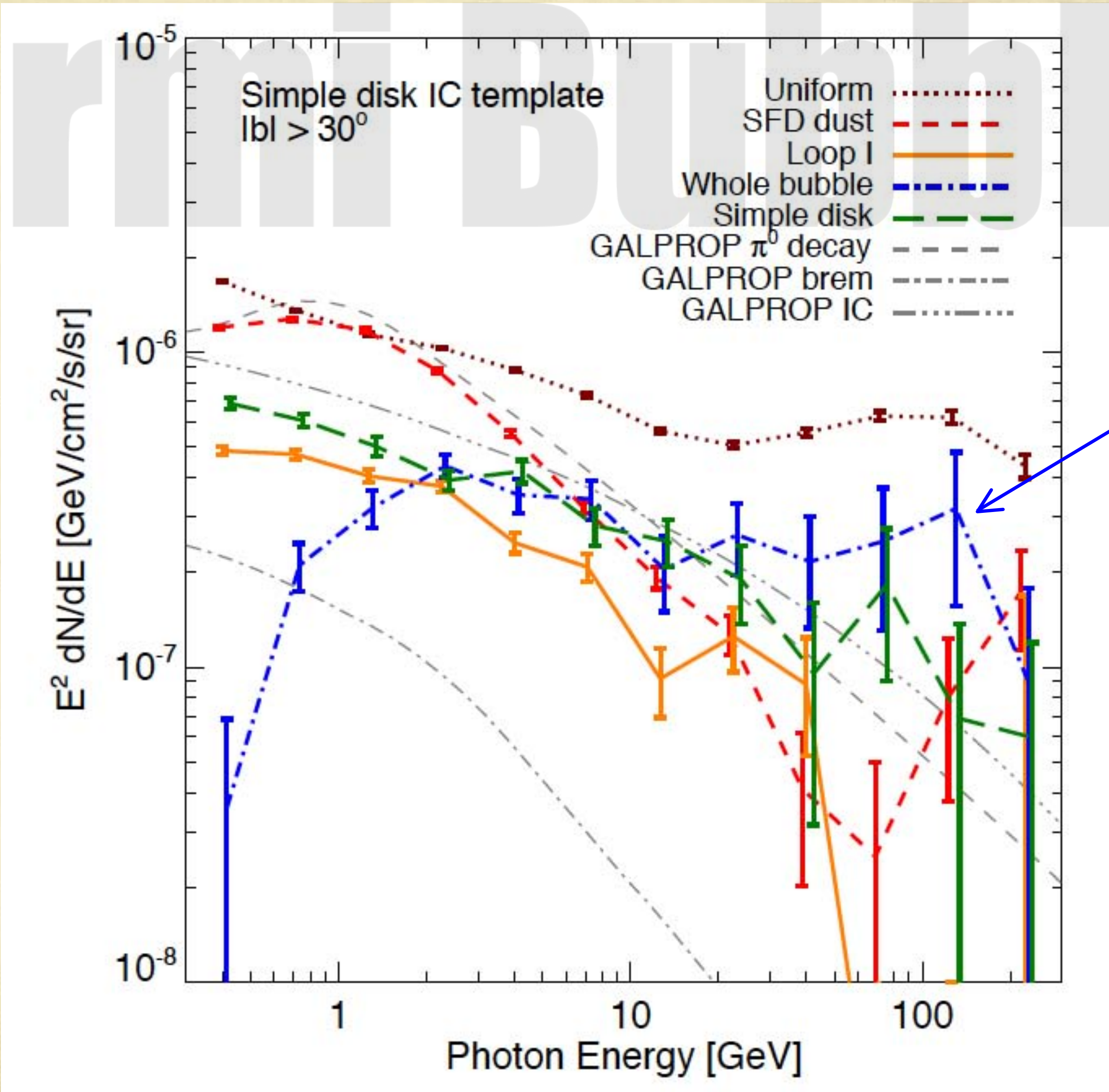
Fermi Bubble

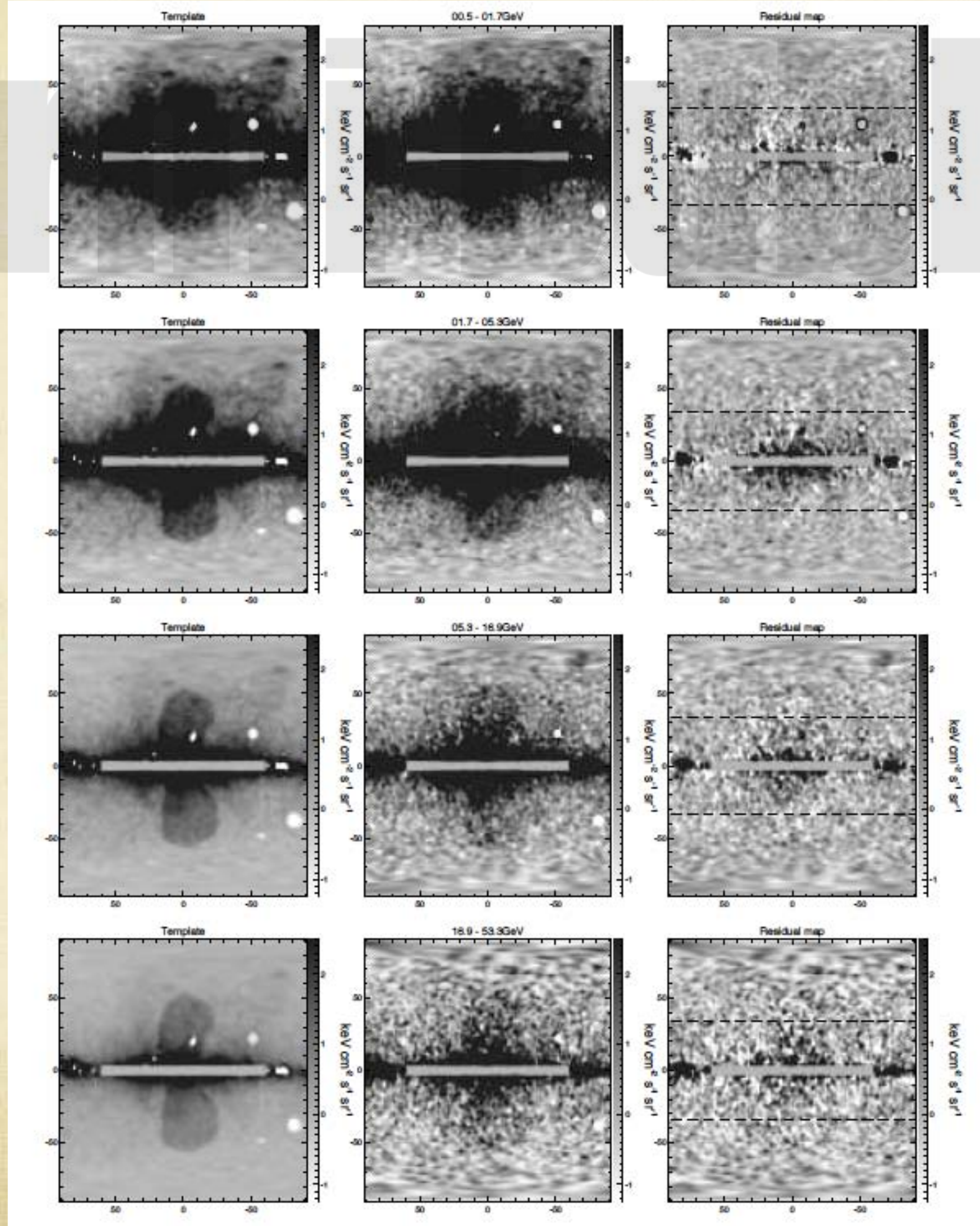
Now we can do a multilinear regression at each energy, including dust and simple templates for disk, Loop I, and the bubbles

Fermi Bubble

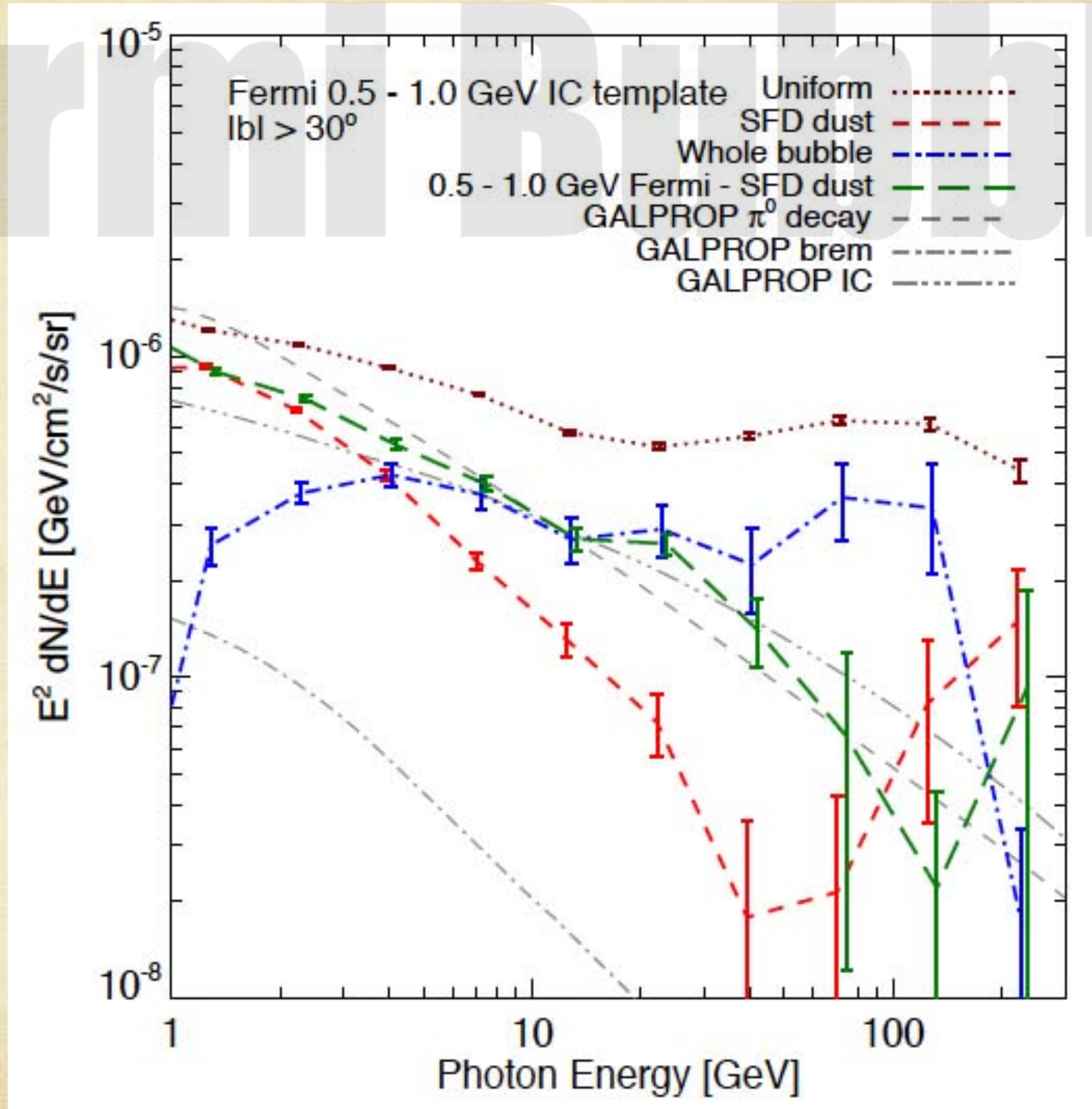


Fermi Bubble

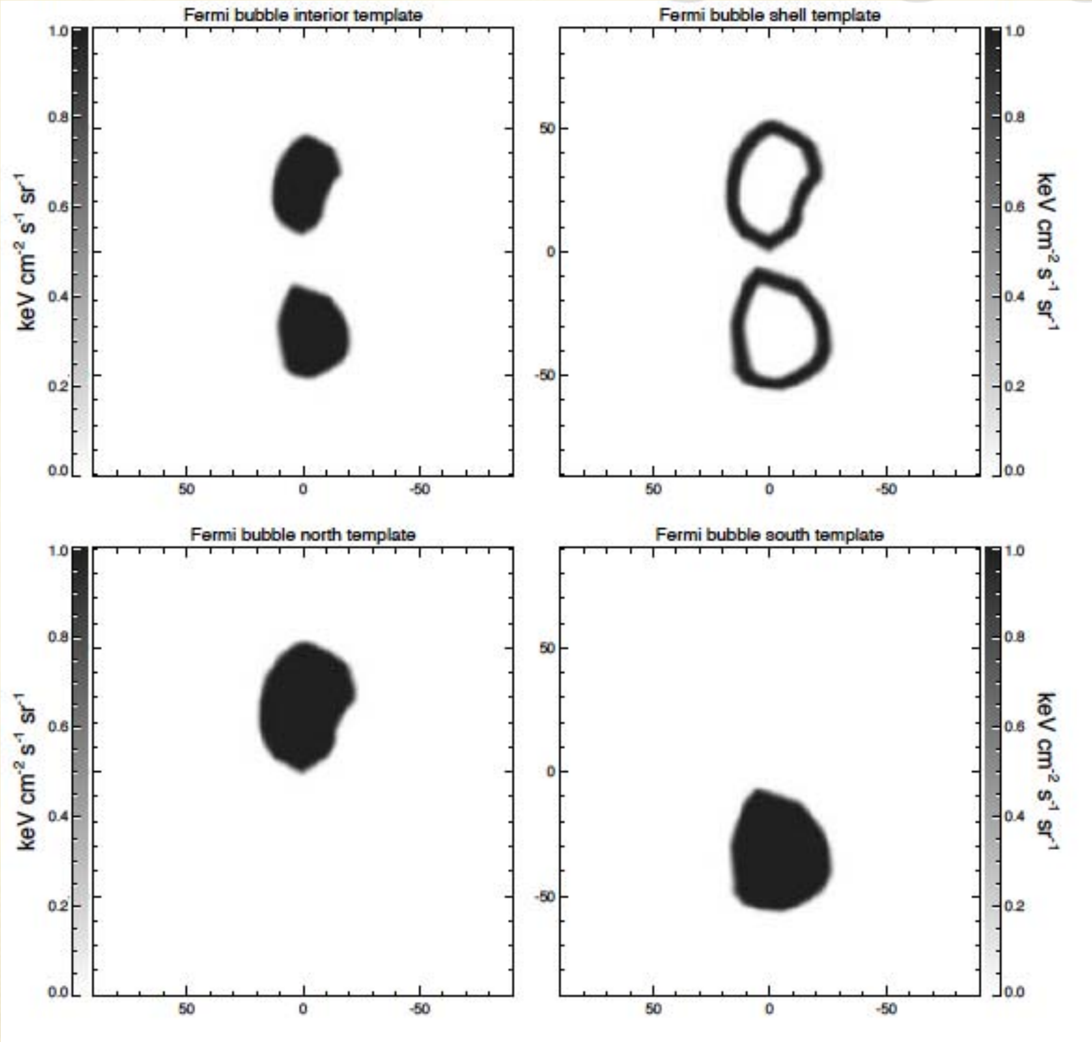


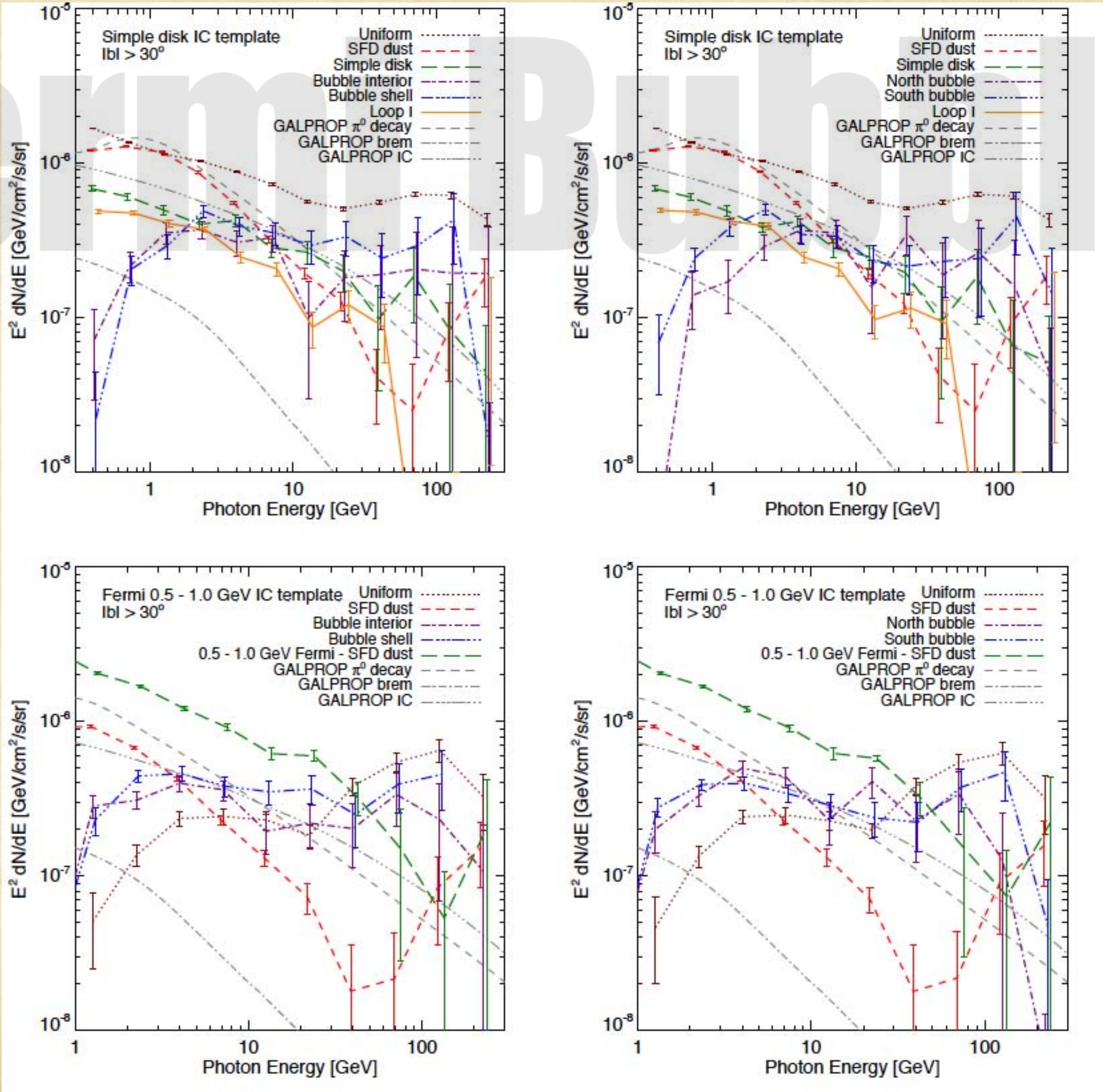

Template
00.5 - 01.7GeV
Residual map
Template
01.7 - 05.3GeV
Residual map
Template
05.3 - 16.9GeV
Residual map
Template
16.9 - 53.3GeV
Residual map
keV cm⁻² s⁻¹ sr⁻¹

Fermi Bubble



Any Substructure of the bubbles?




Simple disk IC template
|b| > 30°
Uniform
SFD dust
Simple disk
Bubble interior
Bubble shell
Loop I
GALPROP π⁰ decay
GALPROP brem
GALPROP IC
North bubble
South bubble
Fermi 0.5 - 1.0 GeV IC template
0.5 - 1.0 GeV Fermi - SFD dust
E² dN/dE [GeV/cm²/s/sr]
Photon Energy [GeV]

Fermi Bubble

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

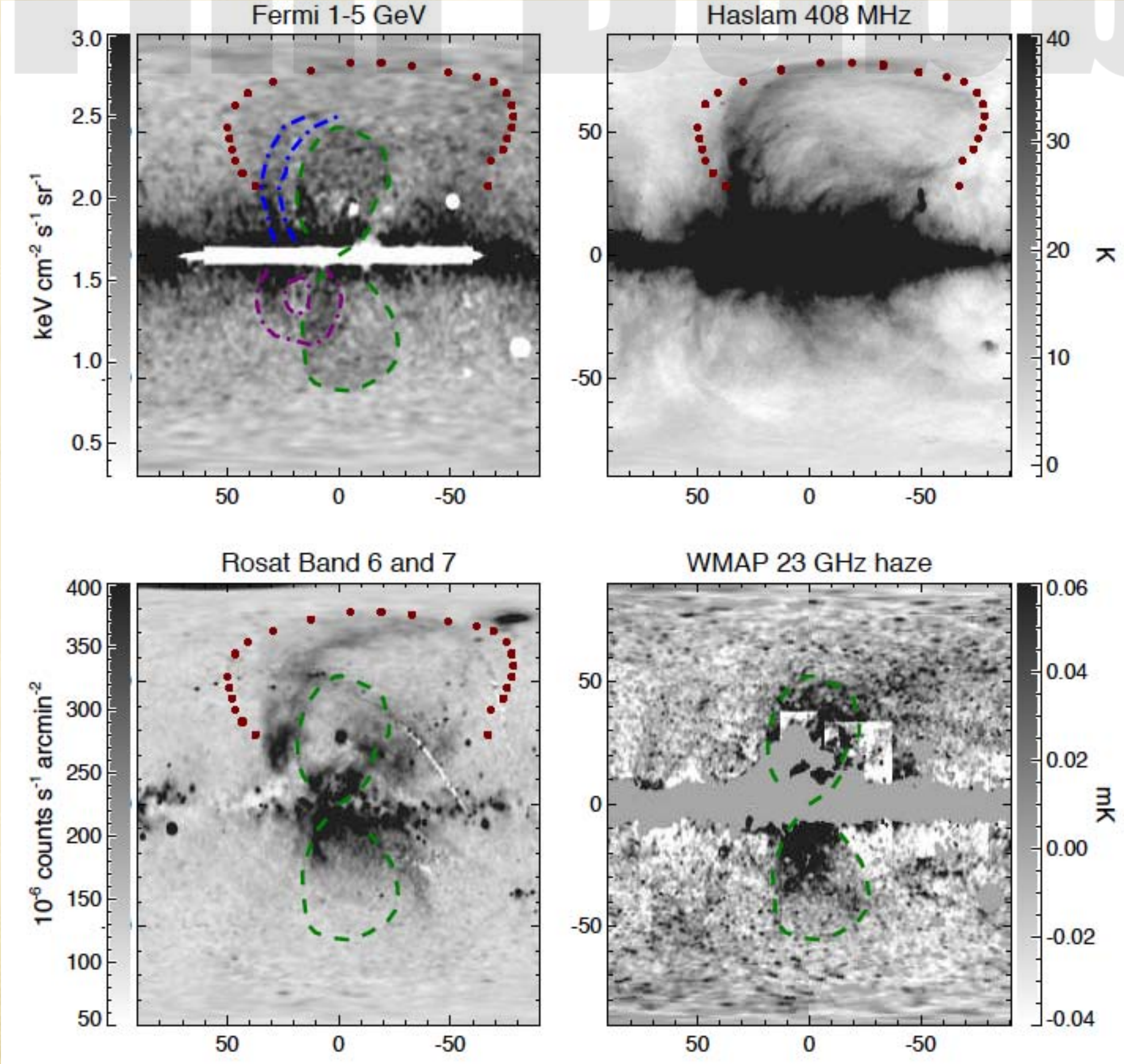
- *Is the north harder than the south?* NO.

- *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).

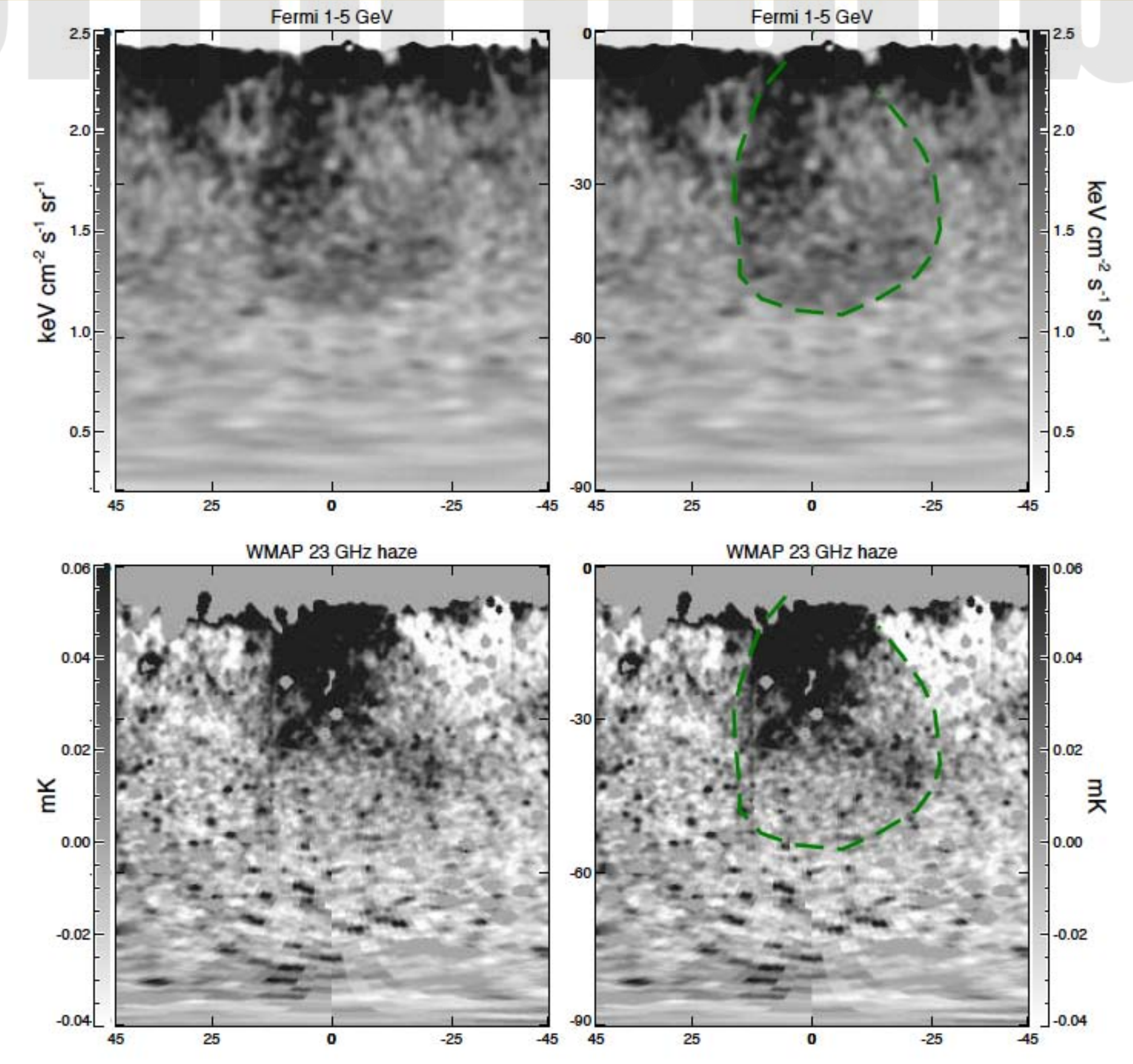
- *The gamma-ray spectrum extends up to ~ 50 GeV or more, implying >~ 100 GeV electrons.*

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

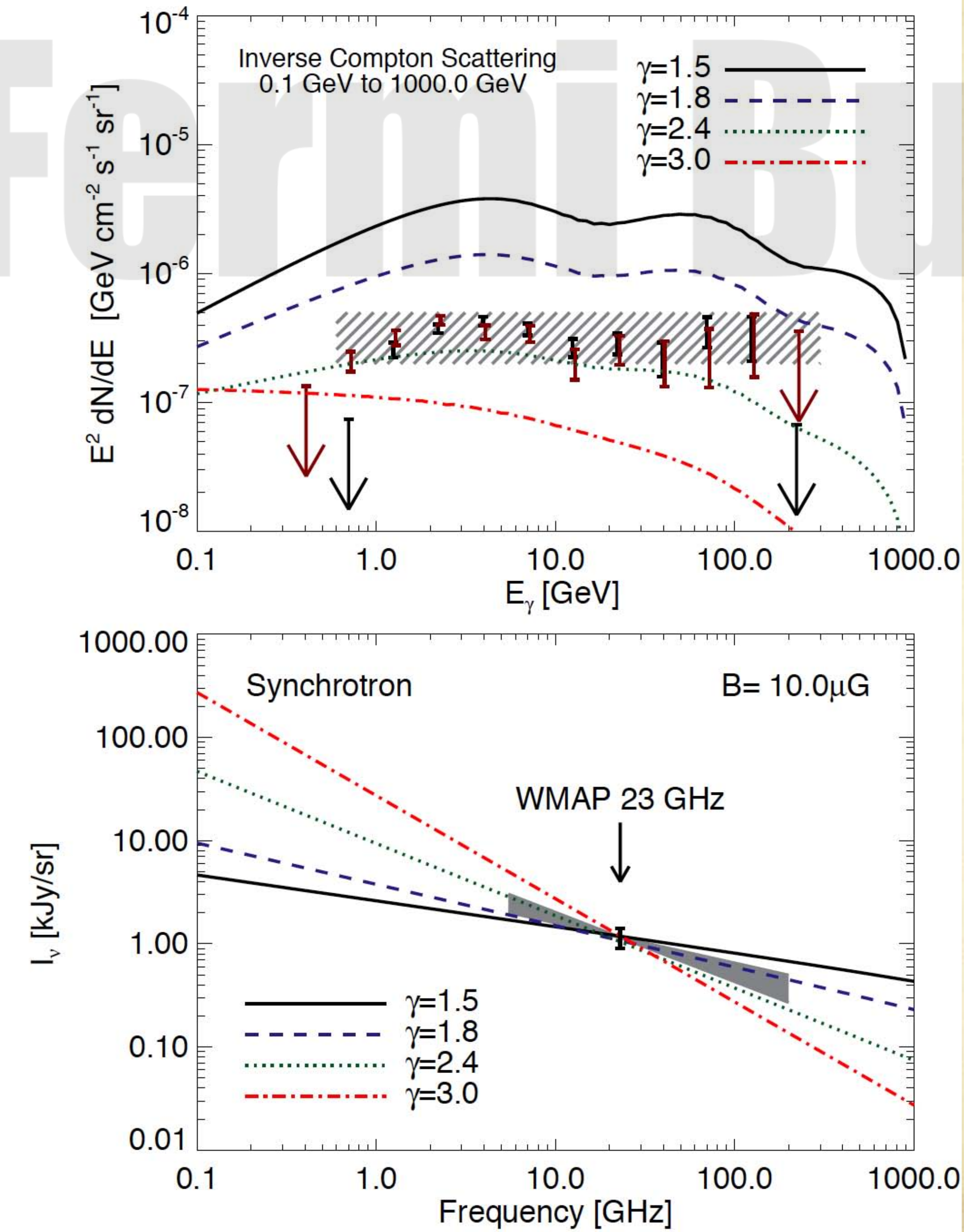
Fermi Bubble



Compare with WMAP haze



Fermi Bubble

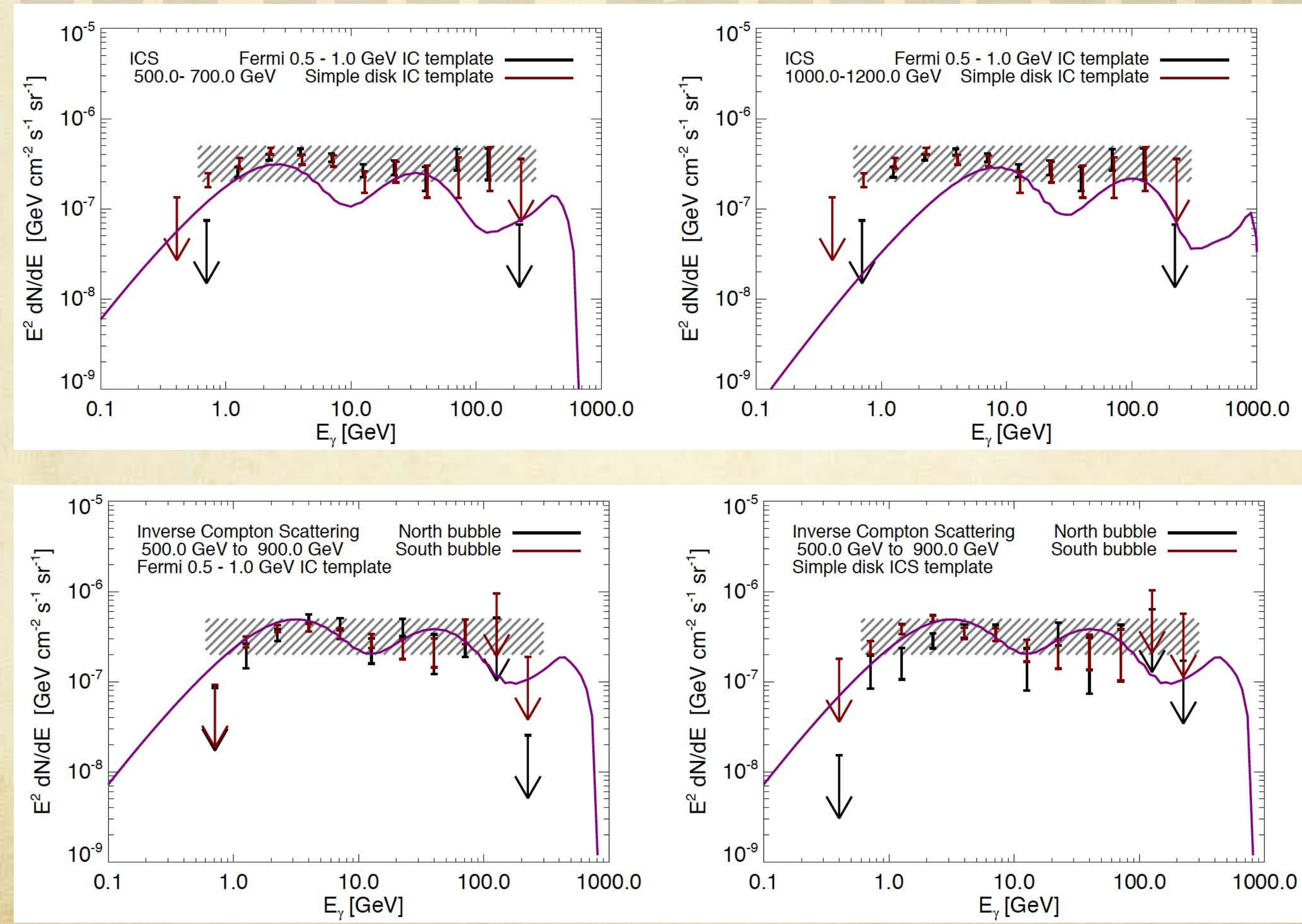


The Fermi bubbles are clearly associated with WMAP haze

The same electron spectrum can easily make both!

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.*

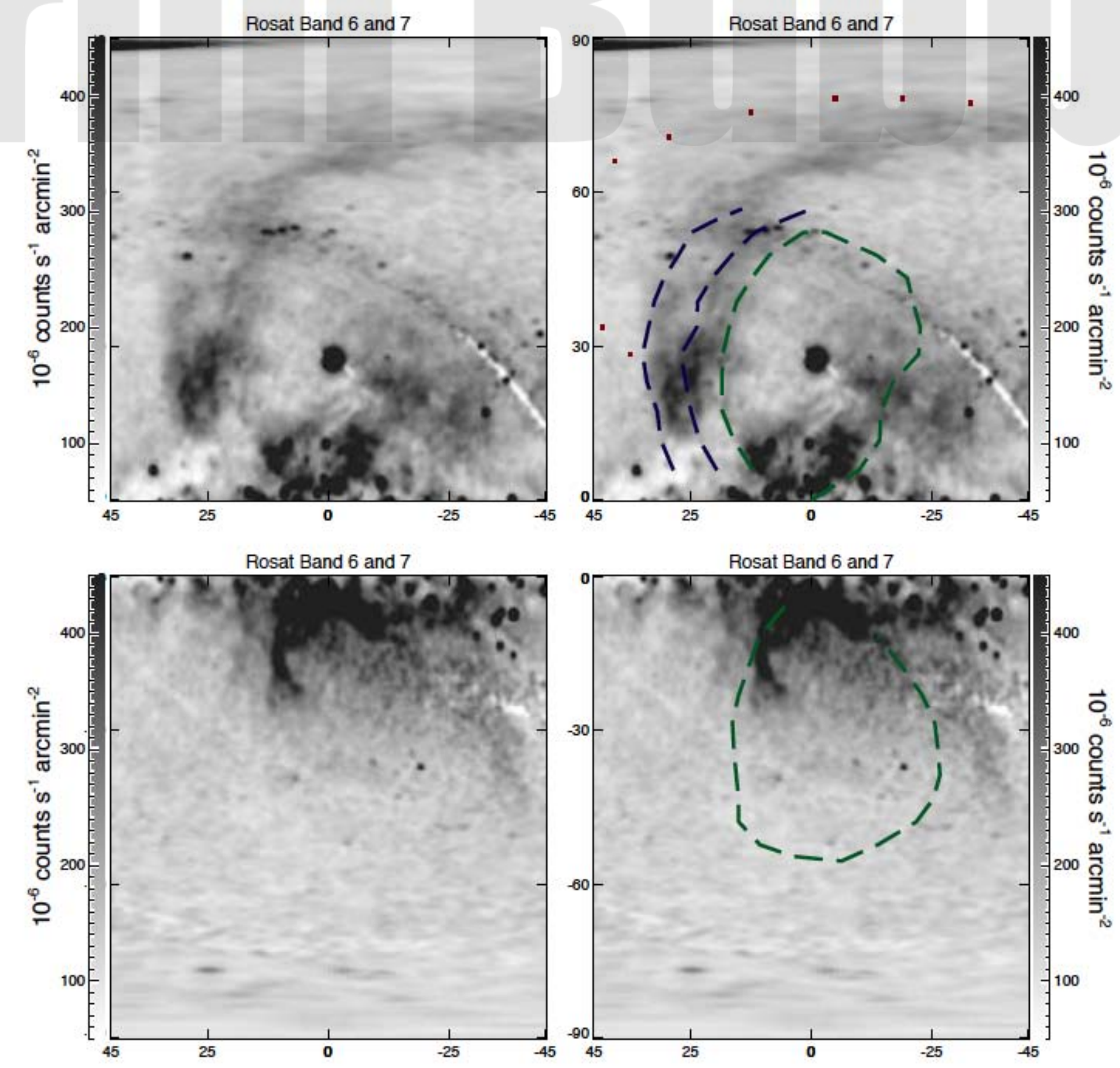
- *2. The shape of the IC spectrum.*

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.)

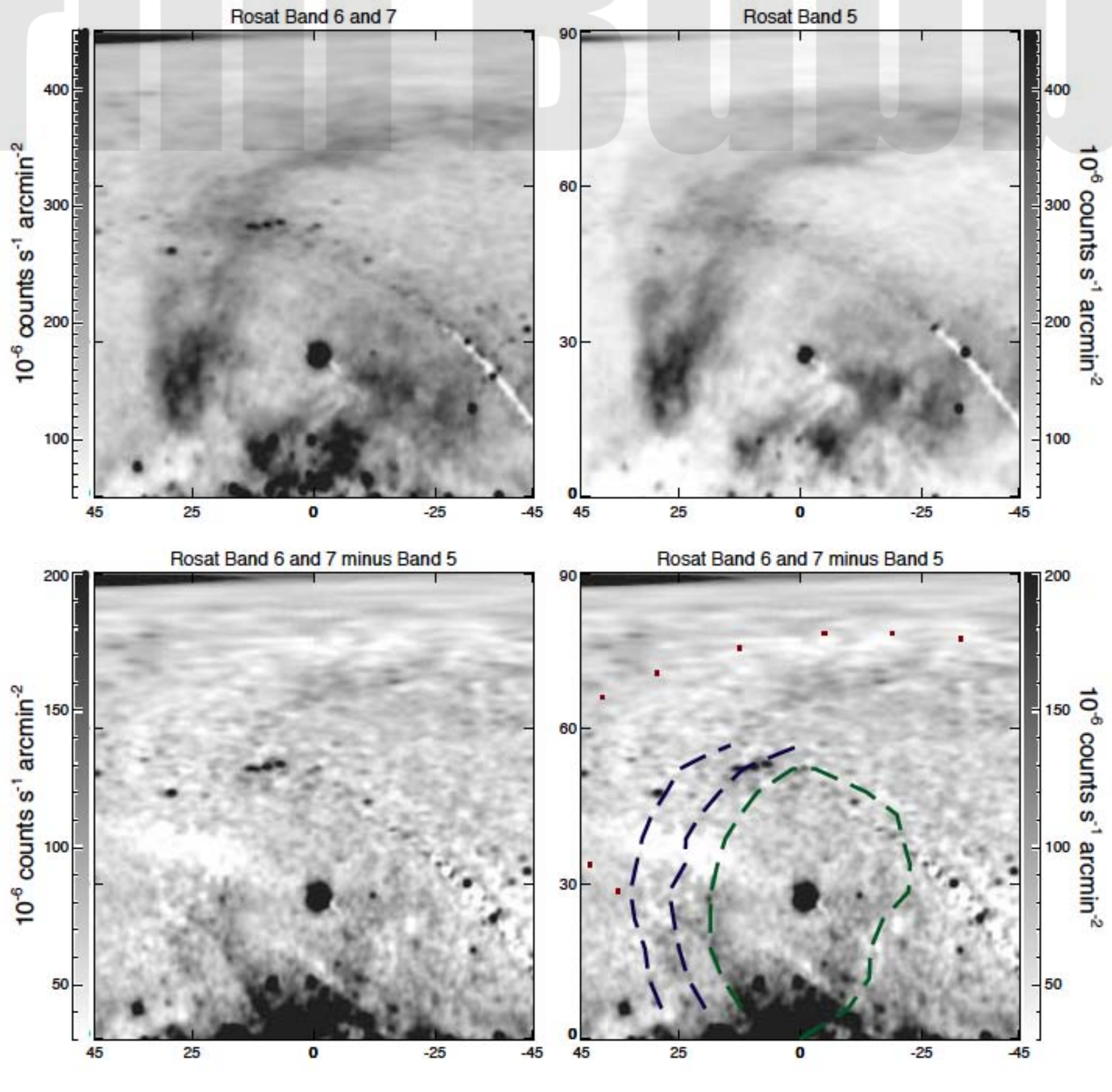
Now, how about X-rays?

ROSAT 1.5 keV



(See discussion in e.g. Sofue 2000a; Bland-Hawthorn and Cohen 2003a).

Fermi Bubble



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?

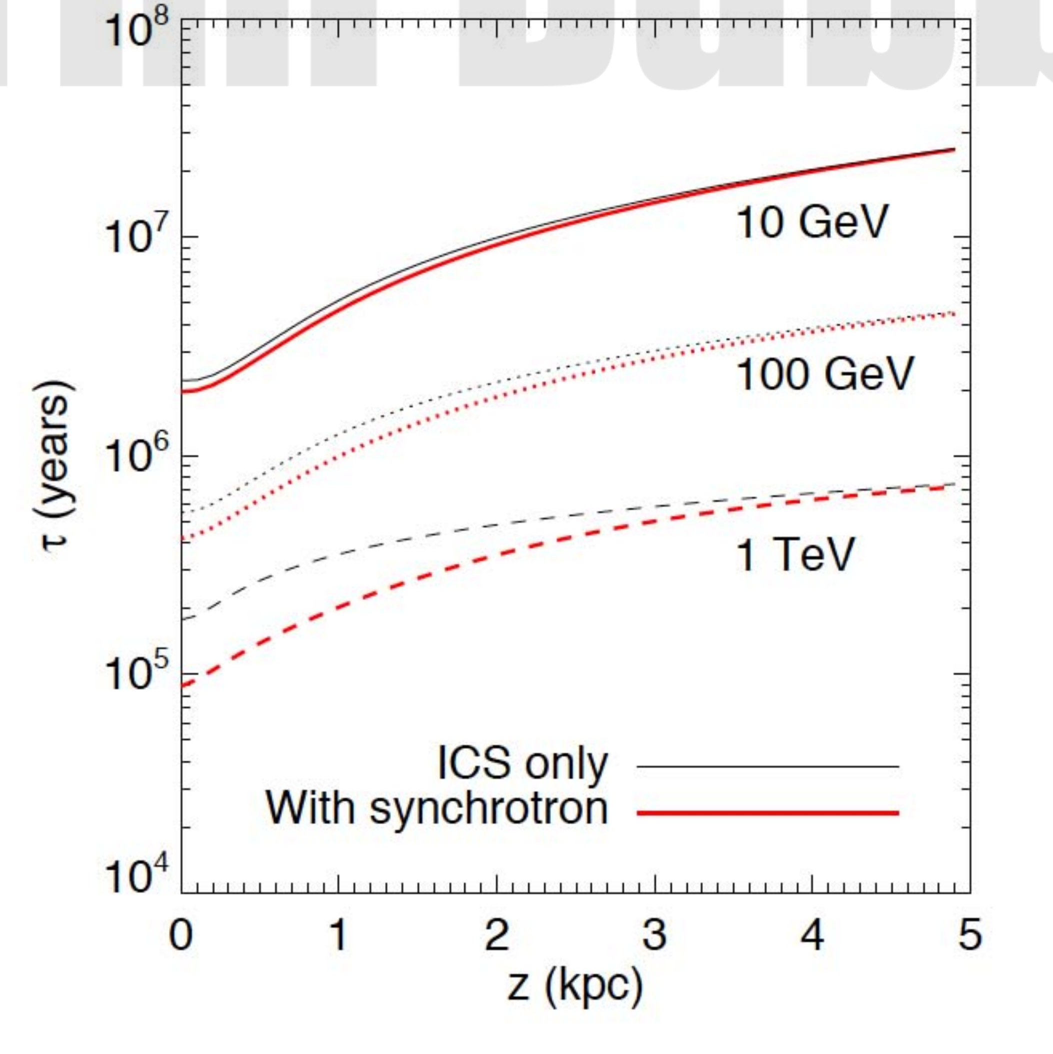
Black hole "burp"

Superwind bubble?

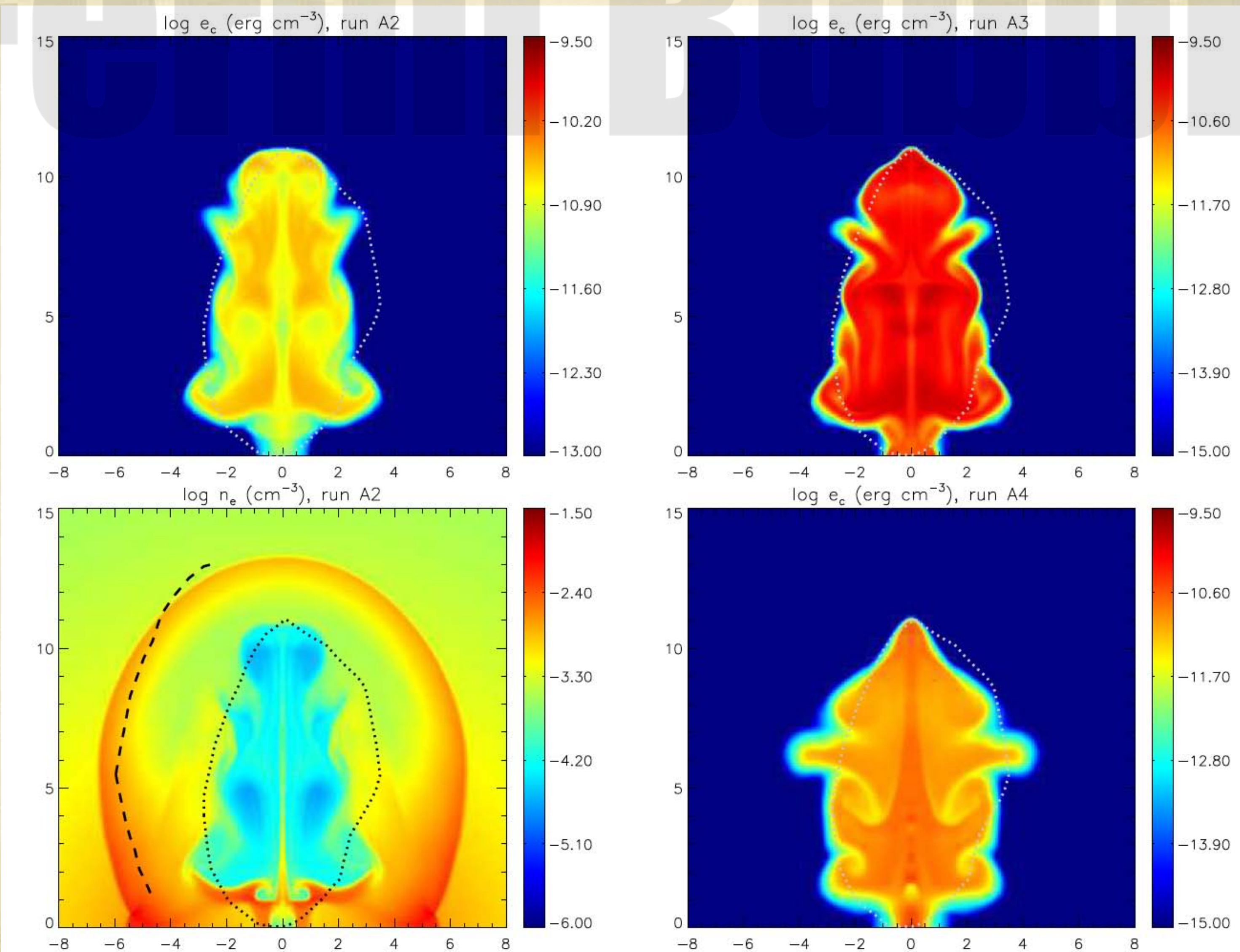
Dark matter? *(Dobler et al arXiv:1102.5095)*

Fermi Bubble

Cooling time is short!



Fermi Bubble



Guo & Mathews (arXiv:1103.0055)

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 ~10^7 yr old, but cooling time for TeV (or even 100 GeV) electrons is much shorter

Fermi Bubble

Disclaimer:

The purpose of the Su et al. paper is to study these sharp-edged "bubble" objects. This is not to say that these objects contain all of the "haze" emission; indeed there are interesting residuals in the data after subtracting a very simple model of the bubbles.

We should separate the question of whether there is any DM signal from the question of whether the bubbles are real.

Fermi Bubble

DM pessimist:
The existence of these structures, and the large episode of energy injection they imply, will make it nearly impossible to derive anything about dark matter in the inner Galaxy.

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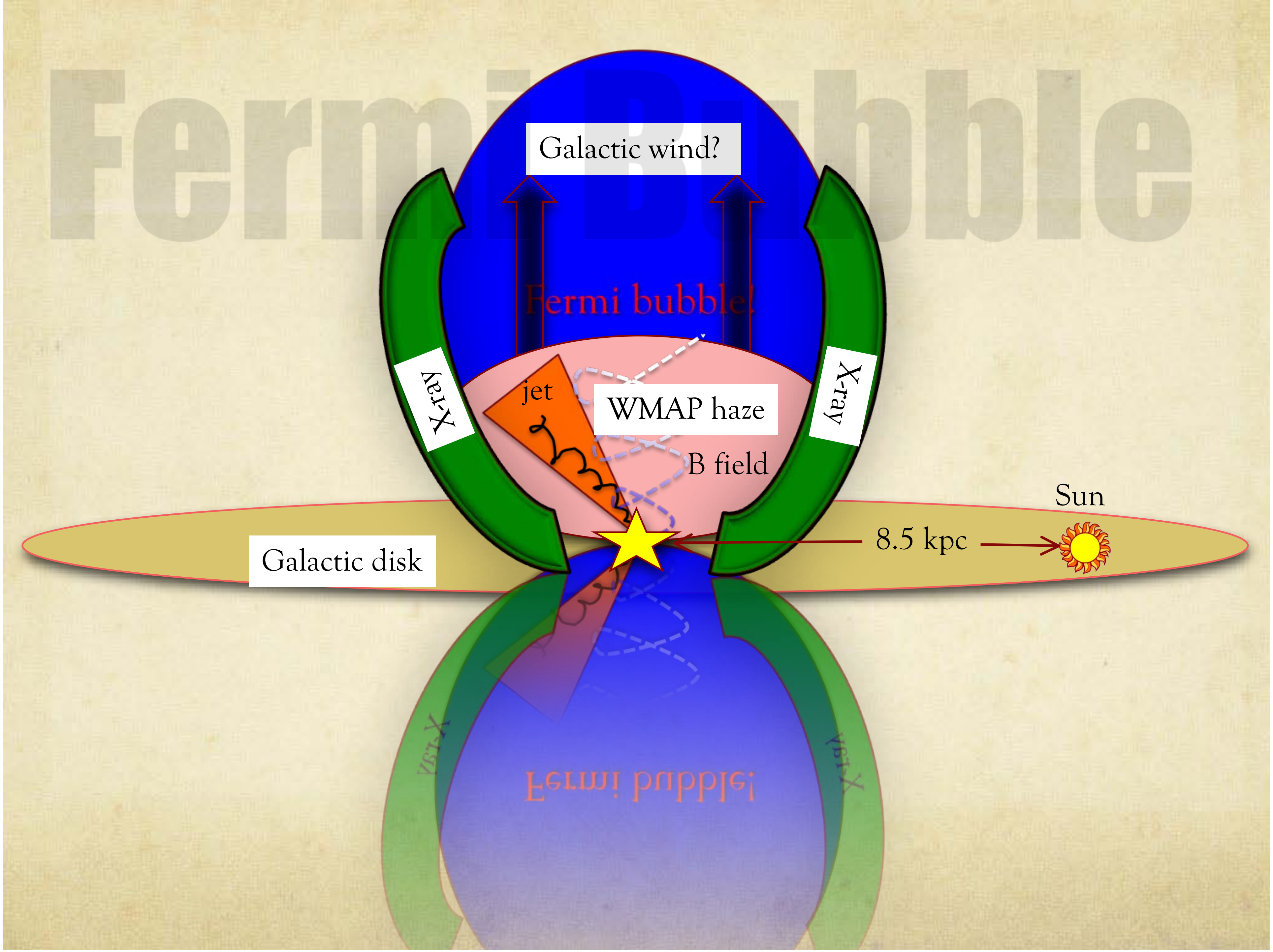
There are some structures there we didn't expect, but we can model them and dig deeper to find the DM annihilation signal. No worries!

DM agnostic:
Astrophysics is complicated. You're running out of time...

Fermi Bubble

Take home message



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

Fermi Bubble

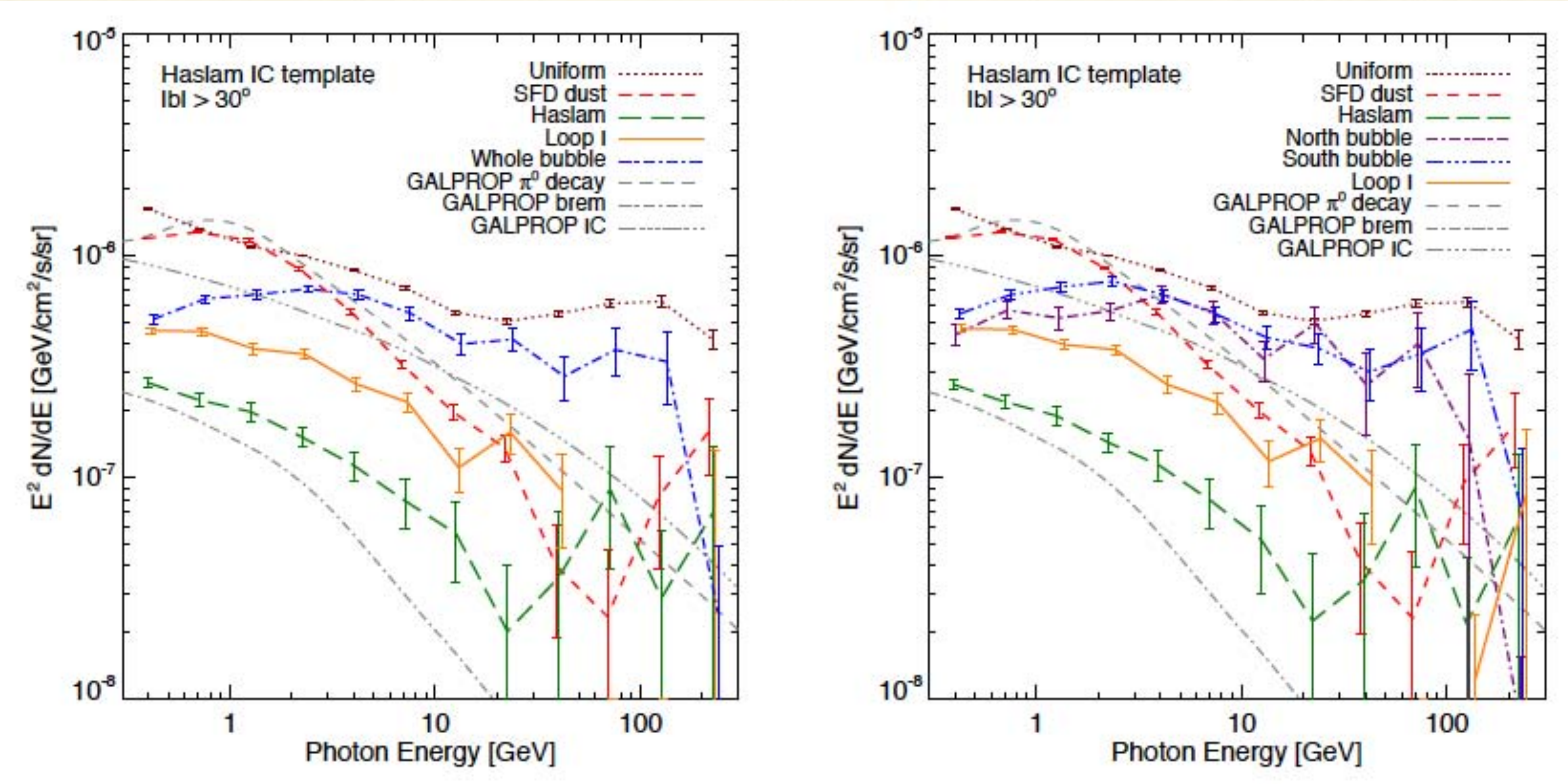
- *Continue observation of Fermi*
- *XMM-Newton data coming soon*
- *The eROSITA and Planck experiments will provide improved measurements of the X-rays and microwaves, respectively, associated with the Fermi bubbles*
- *Magnetic field structure of the bubbles*
- *Study of the origin and evolution of 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

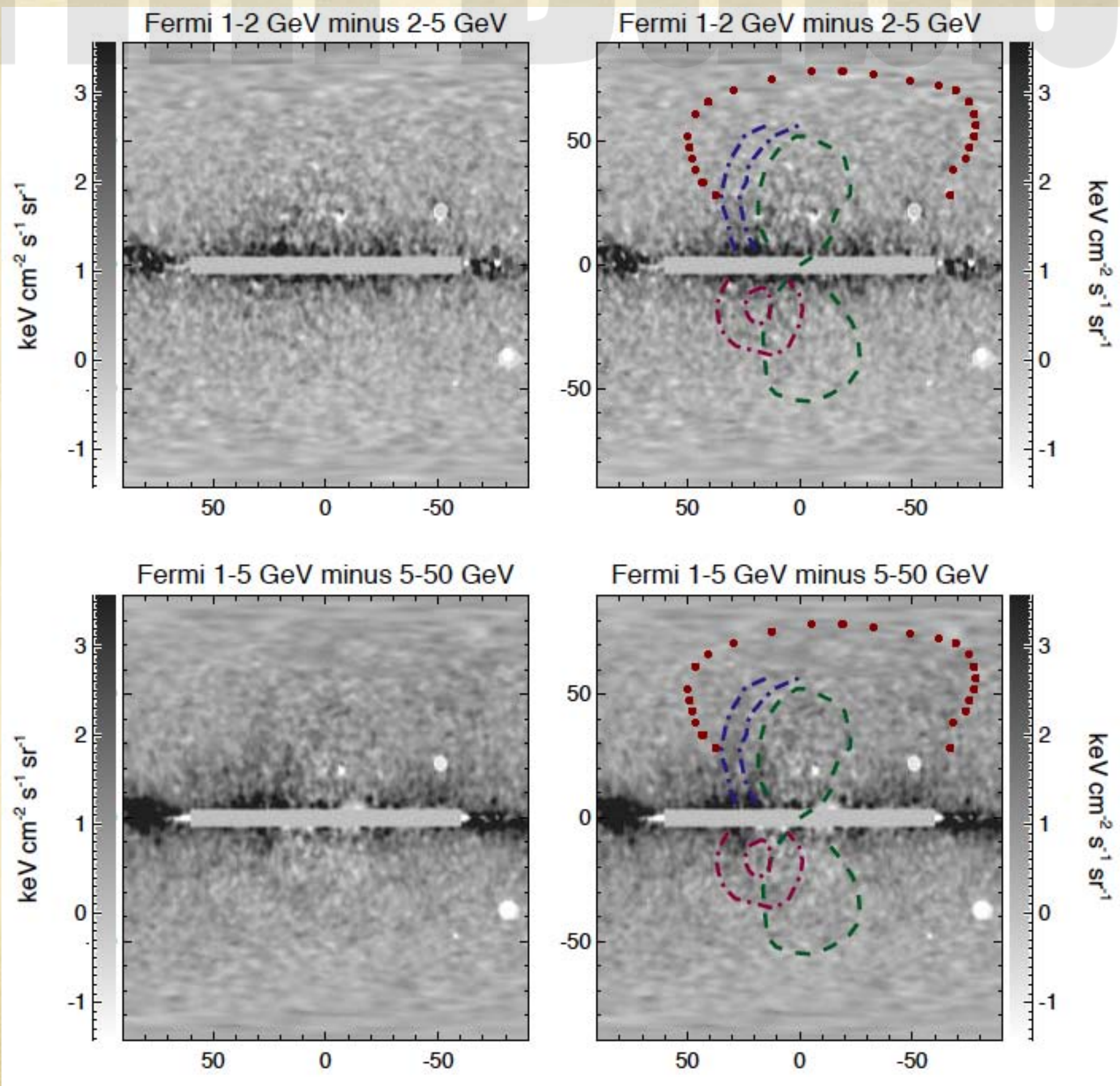
Thank You for Your Attention!

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

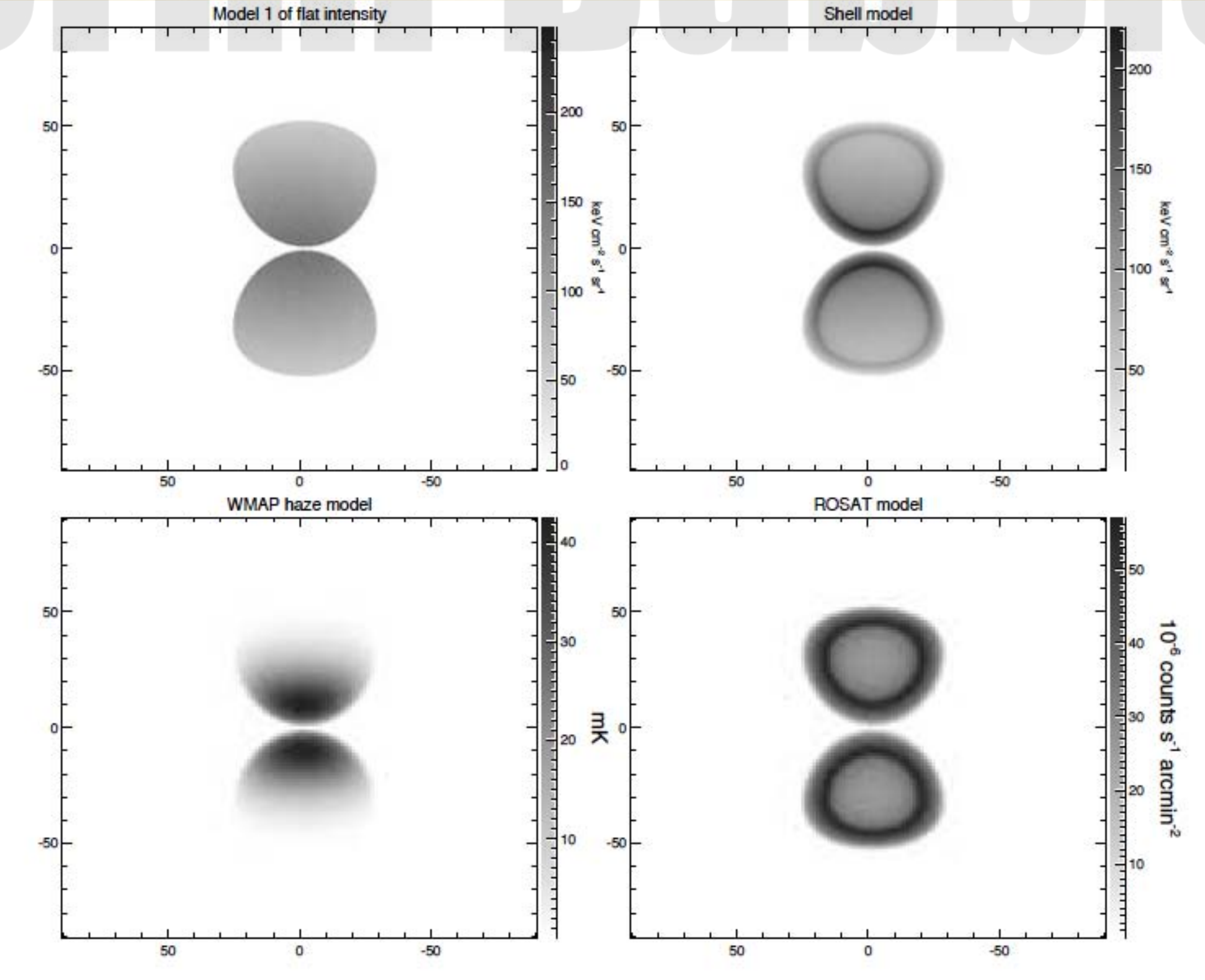
Fermi Bubble

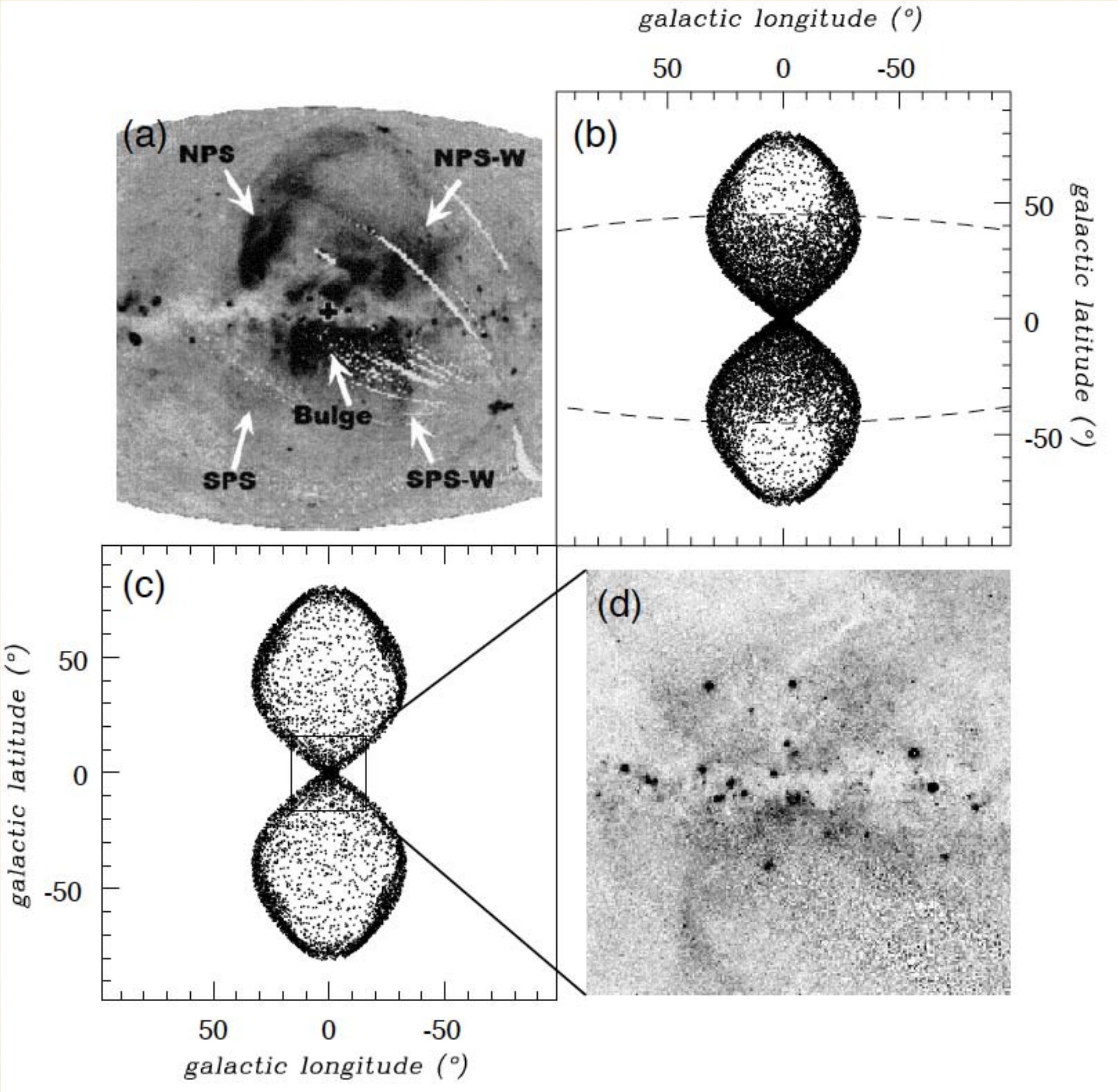


Fermi bubbles are uniform

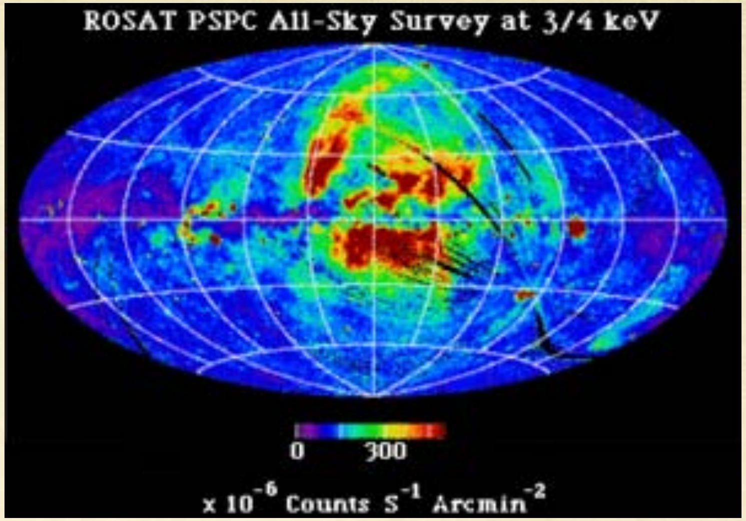


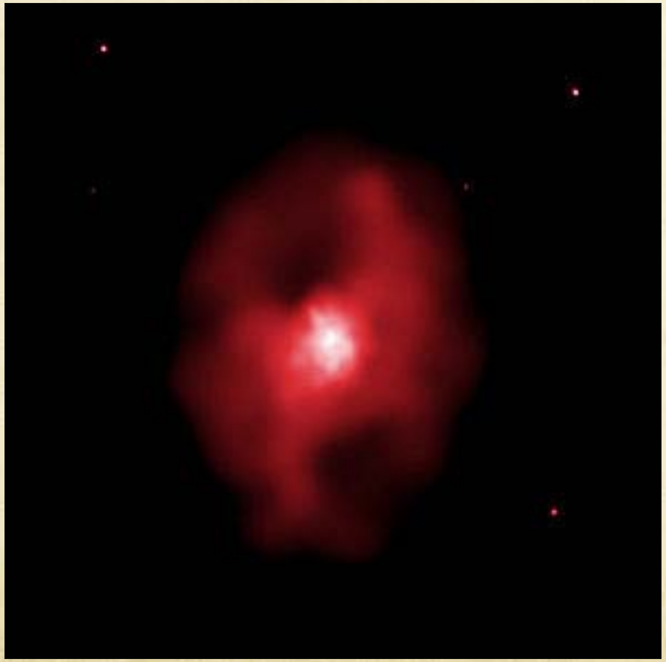
Why they are wired

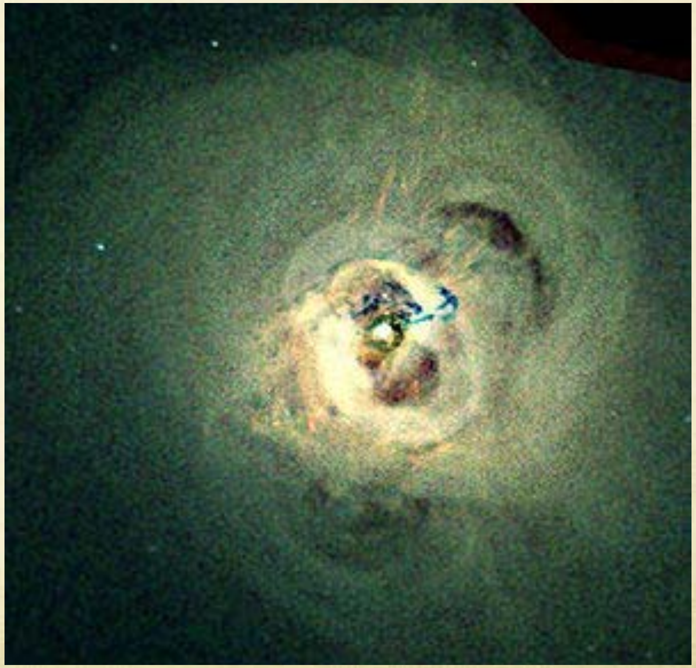




(Bland-Hawthorn and Cohen 2003)



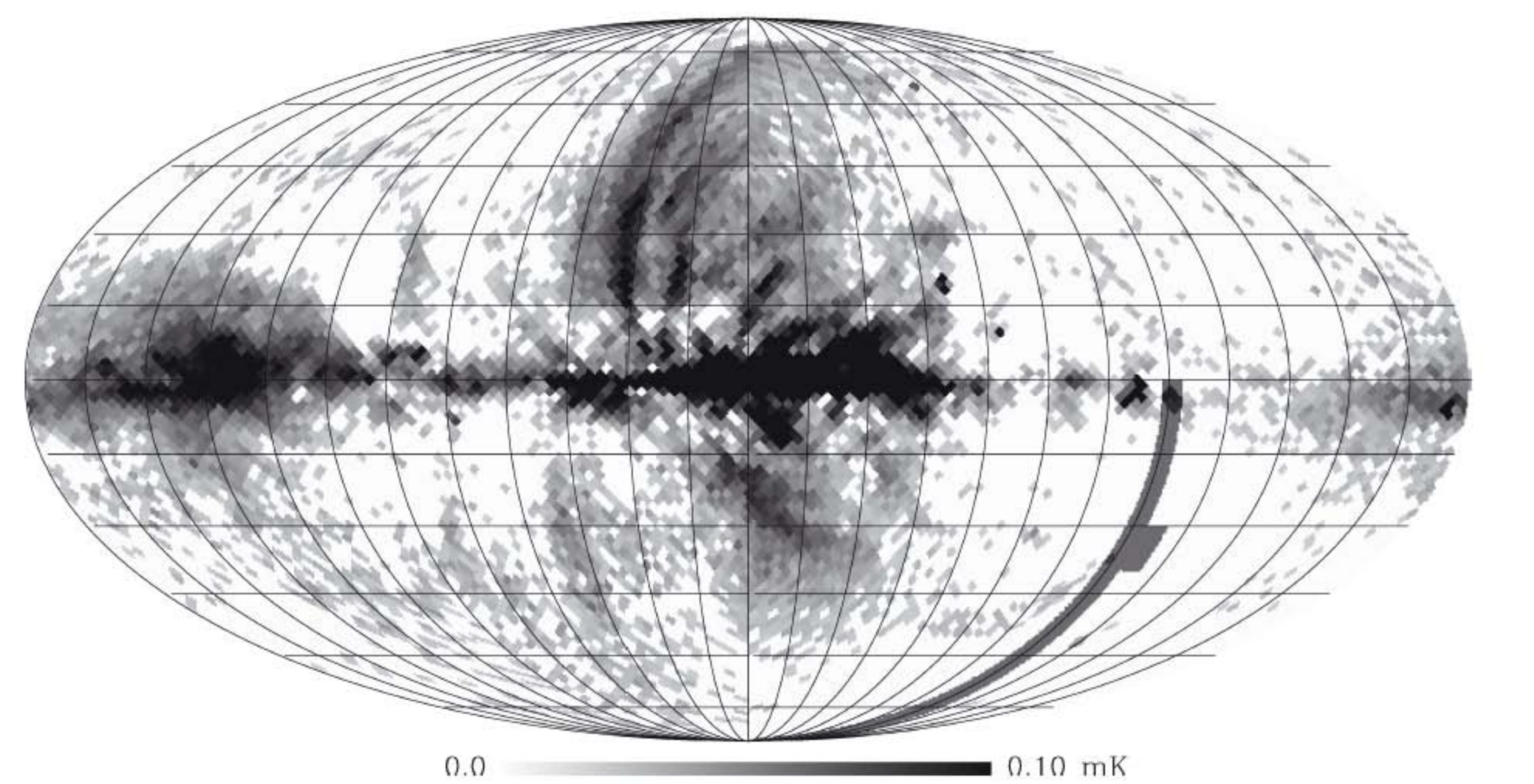


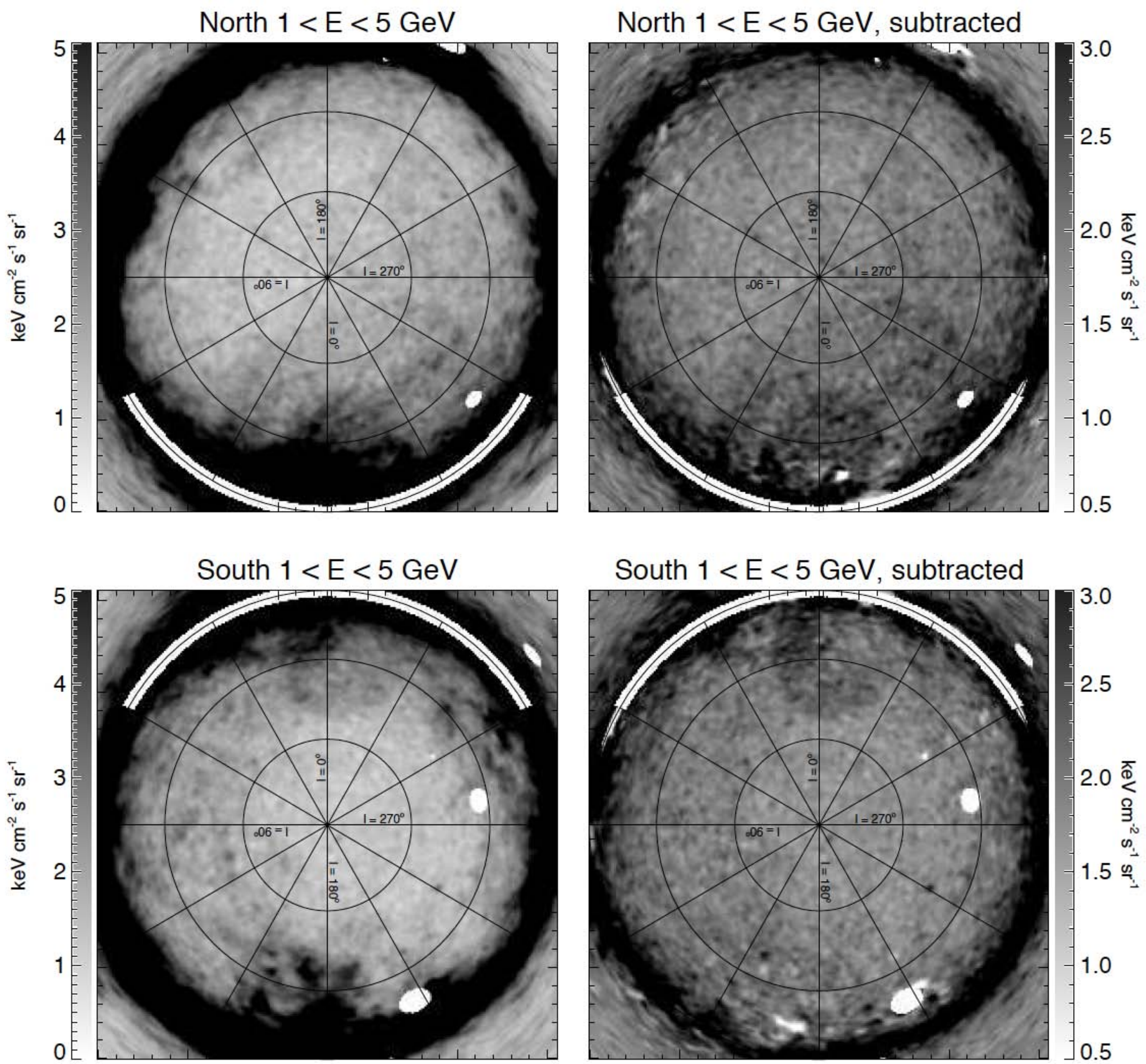


galaxy cluster MS 0735.6+7421 in Camelopardus

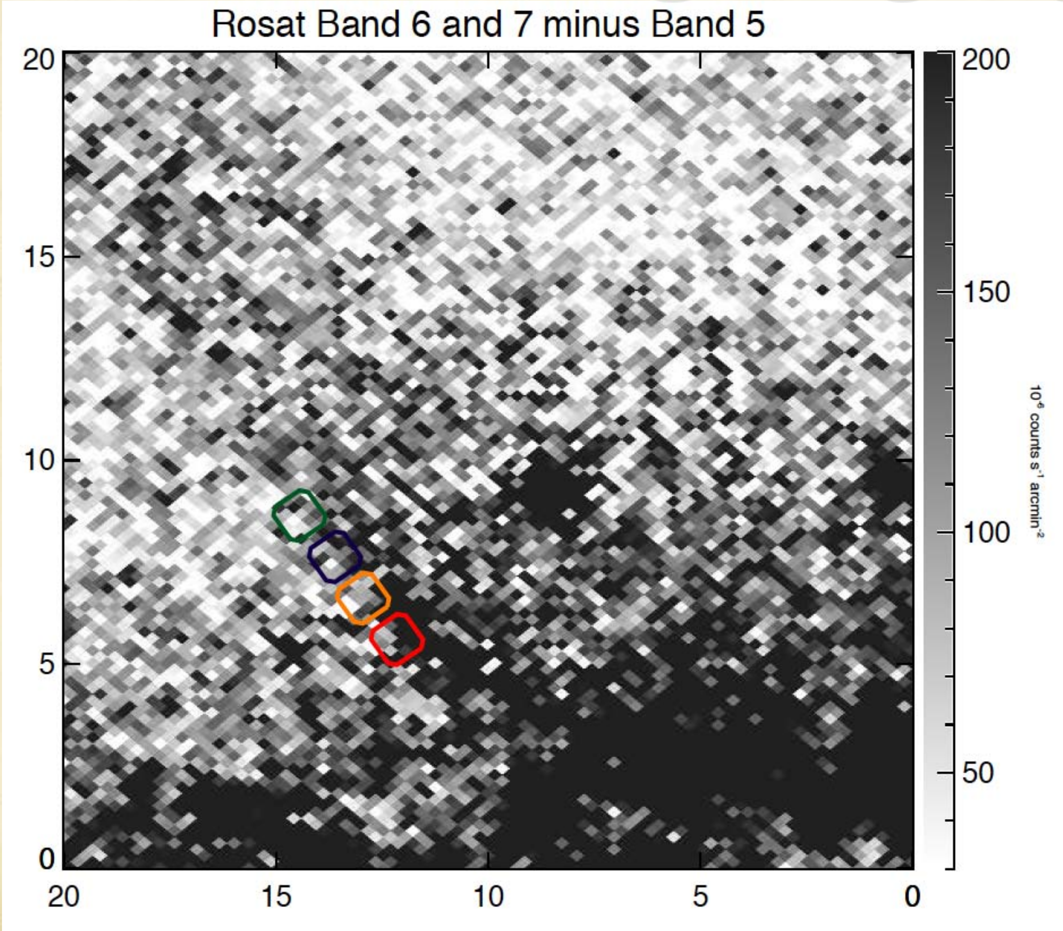
Perseus galaxy cluster

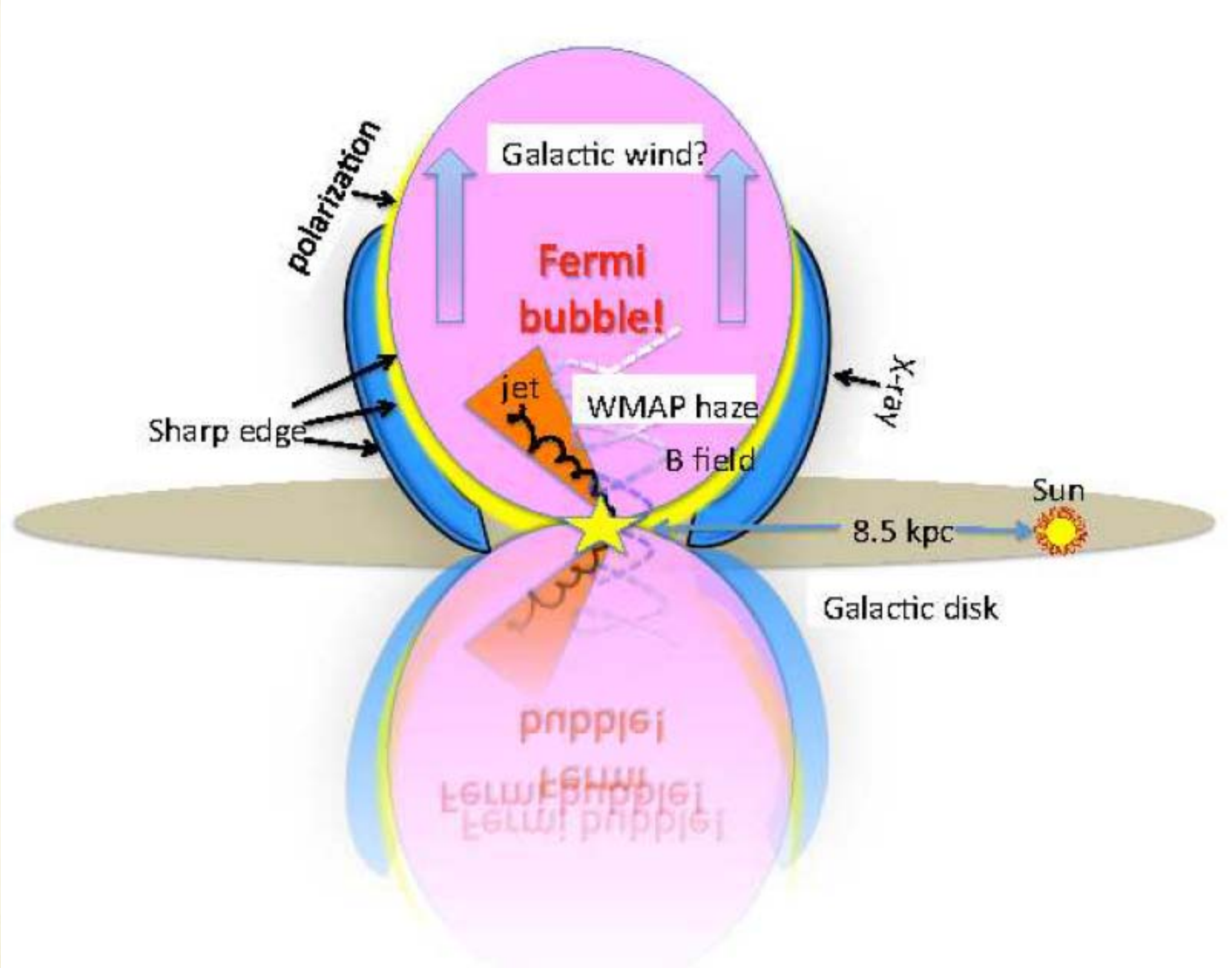
WMAP 23 GHz polarization




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

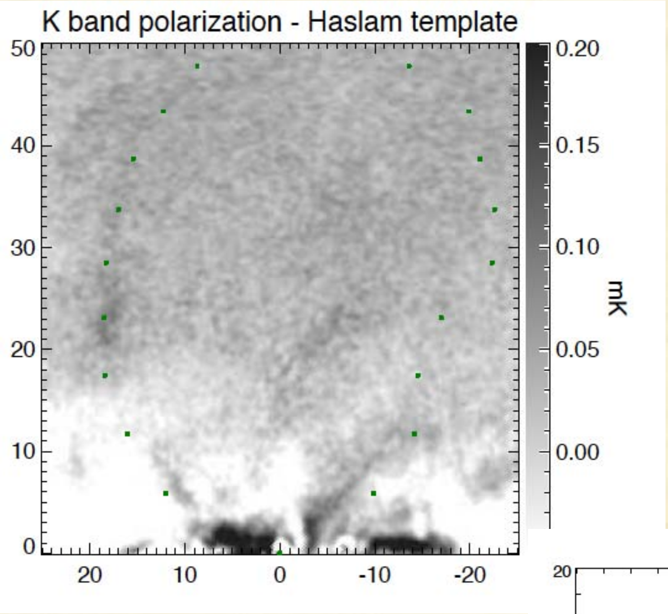
What's next?

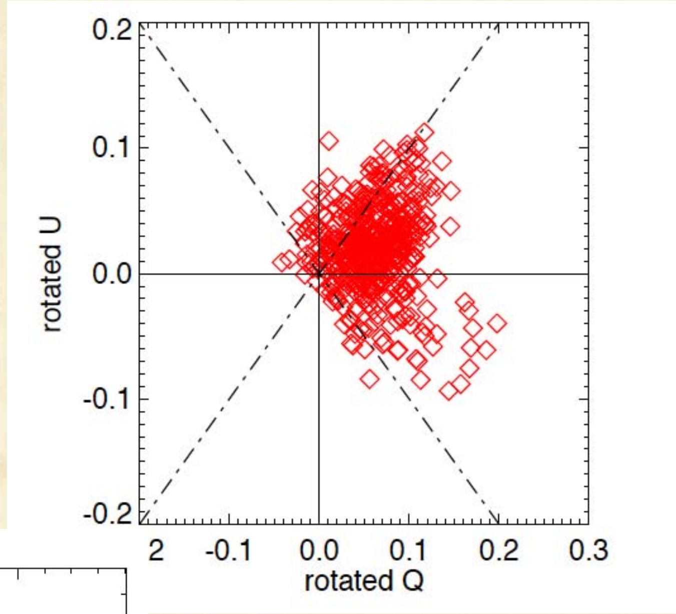

Rosat Band 6 and 7 minus Band 5
20
15
10
5
0
20
15
10
5
0
200
150
100
50
10^-6 counts s^-1 arcmin^-2

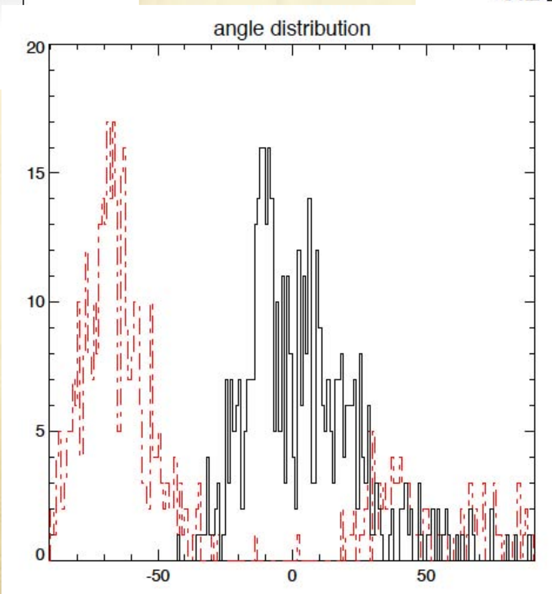


Galactic wind?
polarization
Fermi
bubble!
X-ray
jet
WMAP haze
Sharp edge
B field
Sun
8.5 kpc
Galactic disk

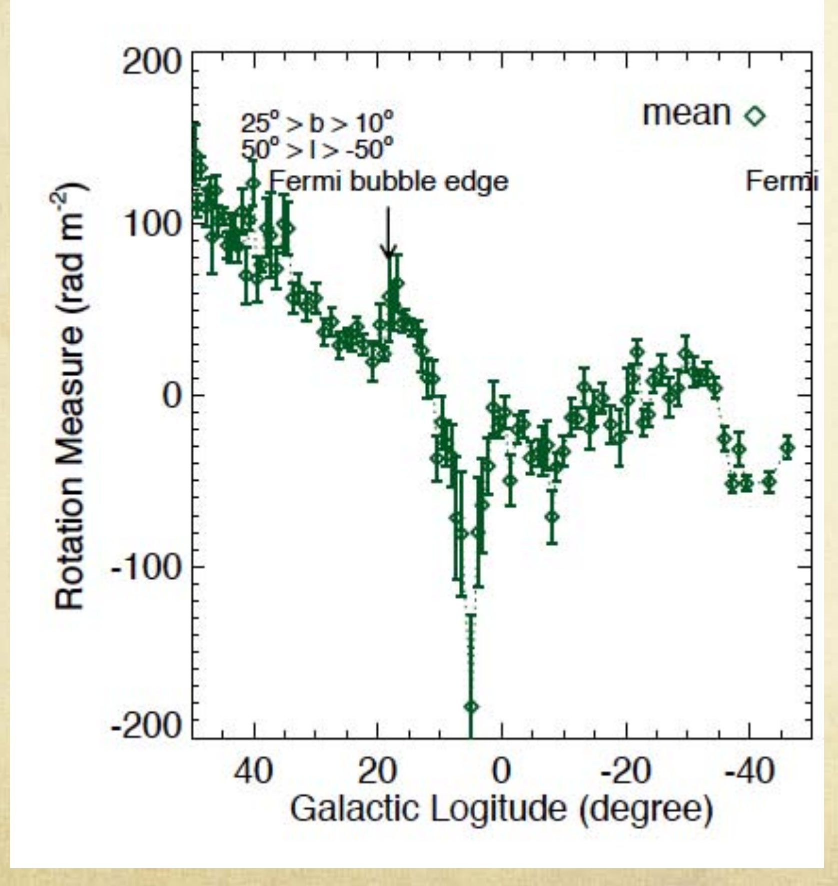
Magnetic field on bubbles

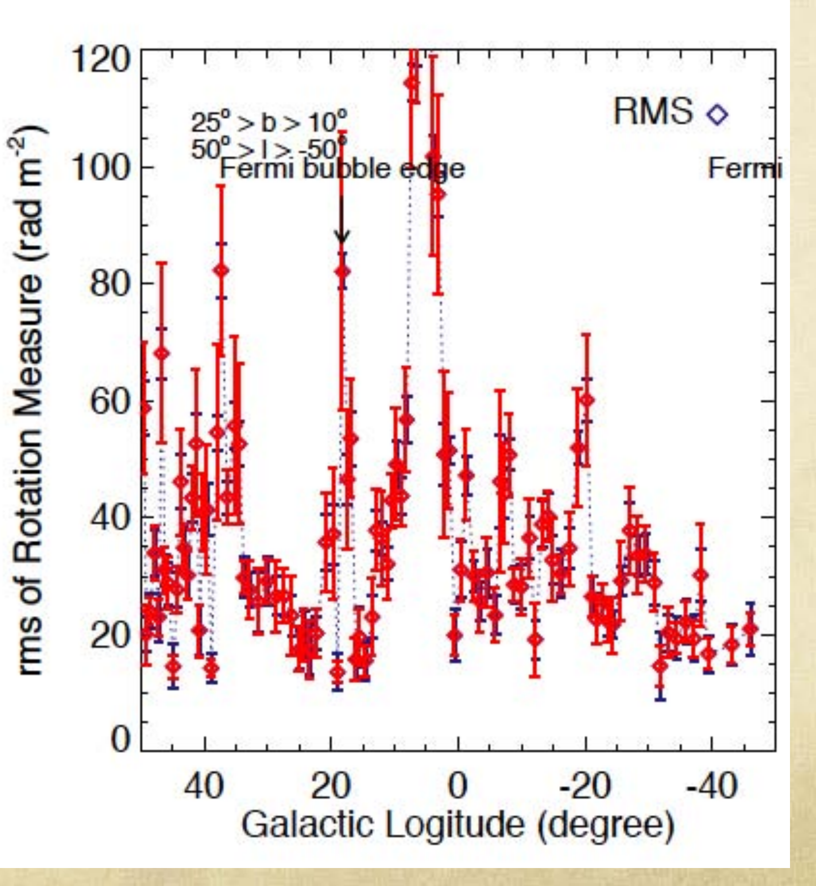






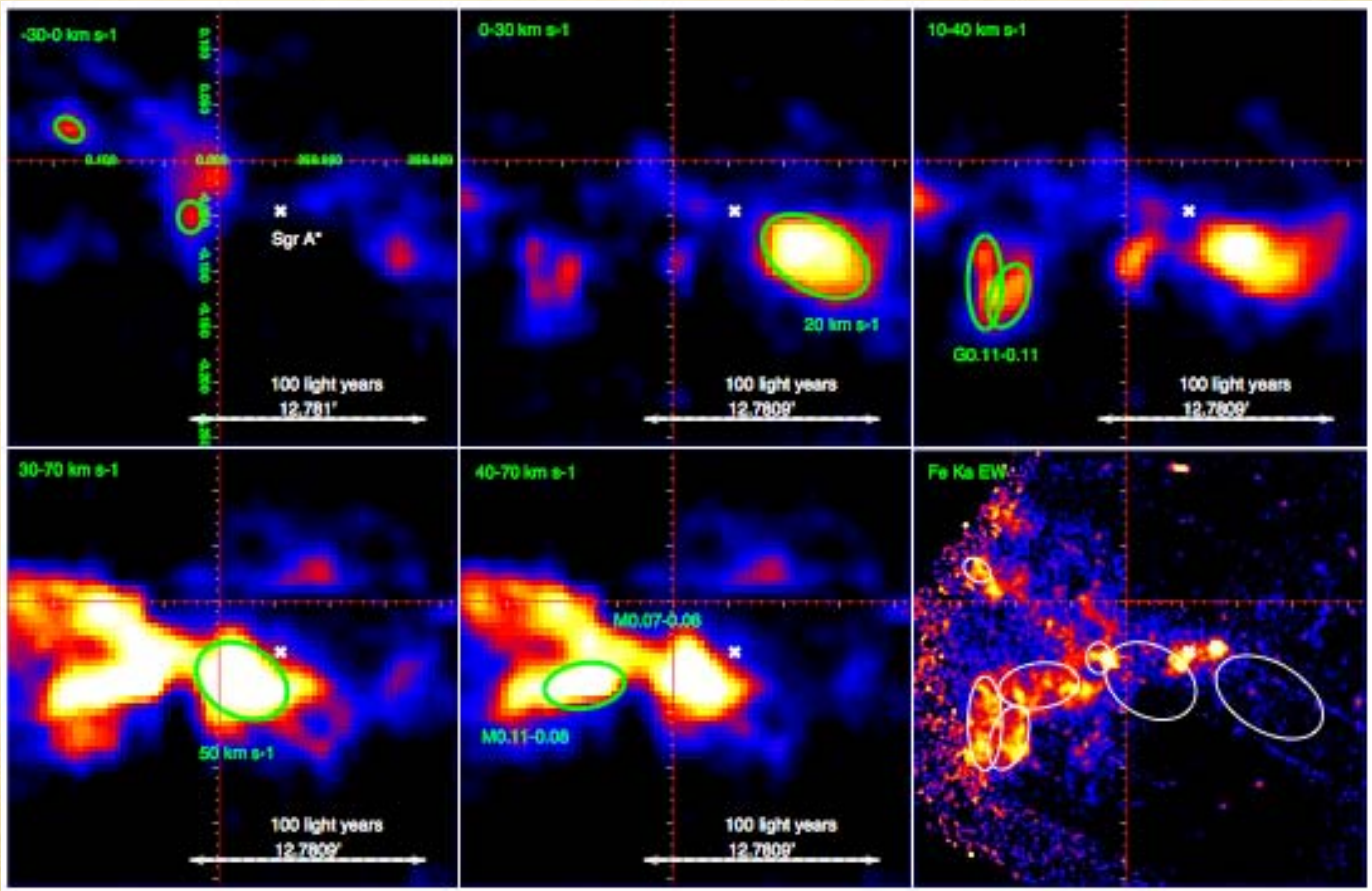
Signature of B-field compression





X-ray reflection nebulae in the GC.

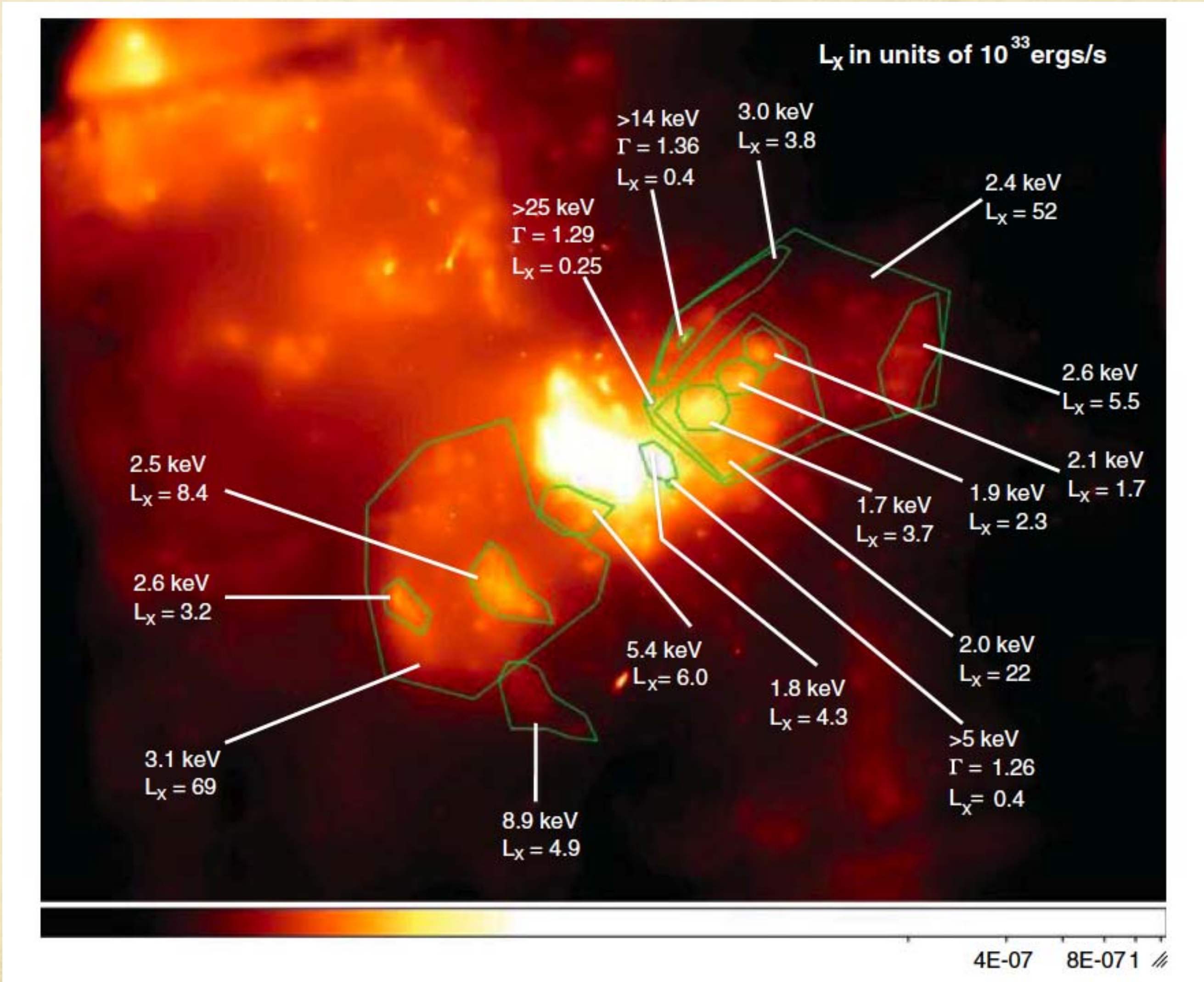
There are indications of previous GC activity from X-ray echoes and time variability of reflected X-ray lines (Sgr B1 and B2, Sgr C, and M0.11-0.11)
They are likely due to reflected X-rays from previous activity of Sgr A* with high luminosity ~300 yr ago.



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)

OB stellar disk and star clusters in the GC

Fermi Bubble

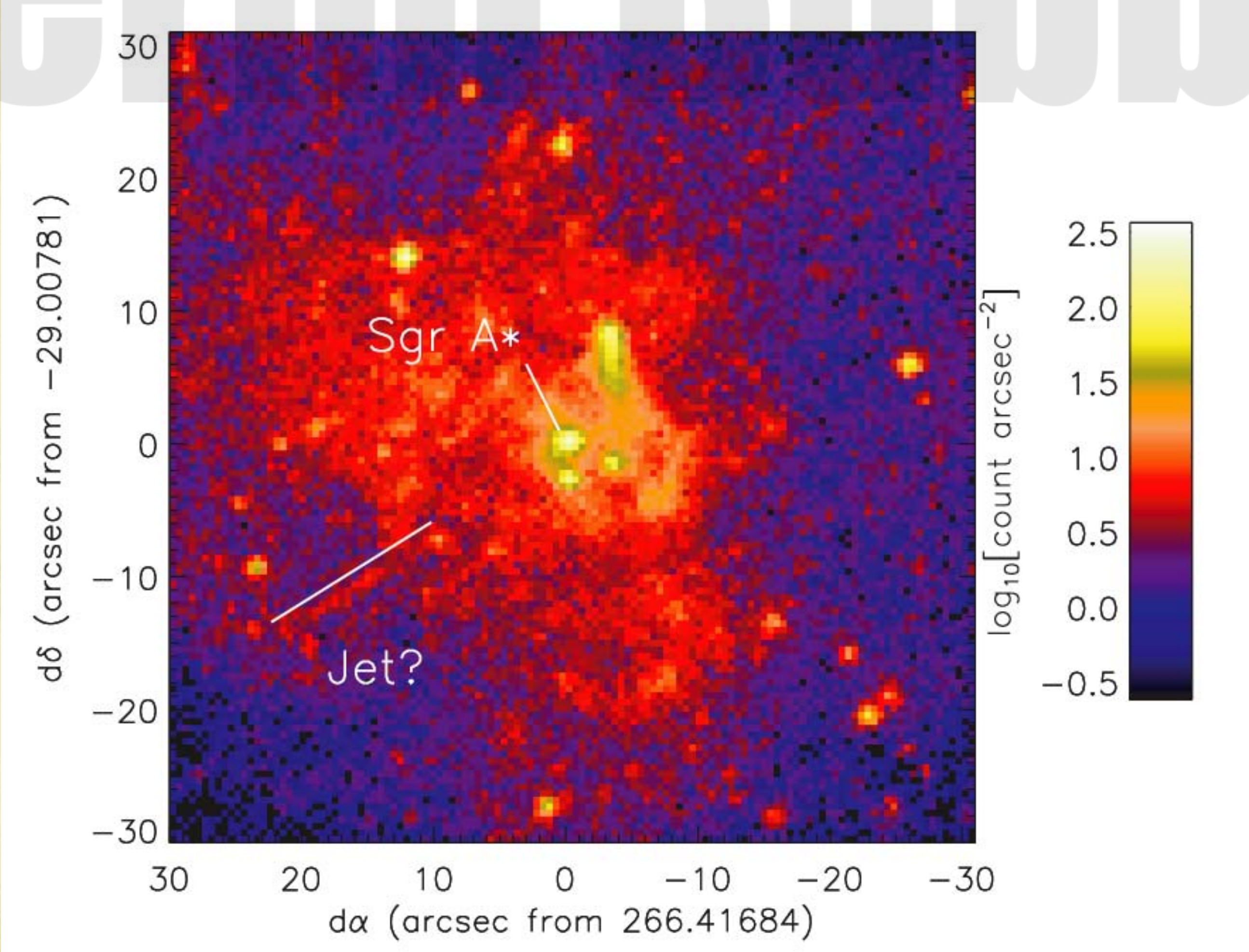
There are two young star disks that have been identified in the central parsec of the GC (Paumard et al. 2006).

Interestingly, the two star ormation events happened near simultaneously about 6 Myr ago and the two disks are coeval to within **~1Myr (Paumard** et al. 2006)

Star clusters Arches and Quintuplet in the central 50 pc, with similar stellar mass, content, and mass functions, were formed **~ 10^7 yr ago.**

Yusef-Zadeh &Konigl (2004) propose a jet model to explain the origin of nonthermal filaments in the GC region.

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

The jets:

Pro: no cooling problem, shock with sharp edge
Con: can go in any direction (symmetry of the bubble). Does the possible jet close to be perpendicular to the Galactic plane?
Hard to distribute the thermal energy isotropically? (flat intensity of the Fermi bubbles)

Episodic jets? Pervious bubbles? Loop I? (Cautions on gamma-ray background)

Starburst:

Galactic wind (thermal driven, momentum driven, CR driven)
Faster wind speed? (cooling problem) must have in situ acceleration

Jet + Starburst?

How to distinguish different scenario? Jets from GC in general do not imply a high metallicity, and detections of metal rich outflows may essentially constrain the energetic injection from jets or Galactic outflows from previous starburst toward the GC.

Fermi Bubble

Accretion of stars: If a 50 solar mass star is captured by the MBH in the GC, it gives an energy in relativistic protons as high as **~ 10^54 –10^55 erg on a very short timescale (~ 10^3 –10^4 yr), at a** rate of about **~ 10^43 erg/s**
(See recent work by Chen et al. arXiv:1103.1002v1)

Accretion of ISM: Quasi-periodic starbursts in the GC have been recently suggested as a result of the interactions between the stellar bar and interstellar gas (Stark et al. 2004)

Accretion of IMBH: A single 10^4 solar mass BH spiraling in to the GC may also trigger starbursts and change the spin of the Sgr A, producing precessing jets. It has been argued that one such event happens approximately every 10^7 years in order to create a core of old stars in the GC, of radius 0.1 pc.

More on CR

Bubble structures were there and electron just lighted it up?
(CR production might separate from bubble)

We need to generate electron CRs inside the Fermi bubbles, and also prevent them from efficiently leaving the bubbles.

CRs from the Galactic Center
CRs could be produced in the inner Galaxy by mechanisms such as OB association, accretion events, and SN explosions (Wind model)
Hard to explain: Sharp edge, uniform intensity, hard spectrum across the bubble

CR acceleration on the bubble edge
DSA, turbulence, magnetic reconnection, diffuse into the bubble interior (stability of bubble structure)

CR from Diffuse Production in the Bubble