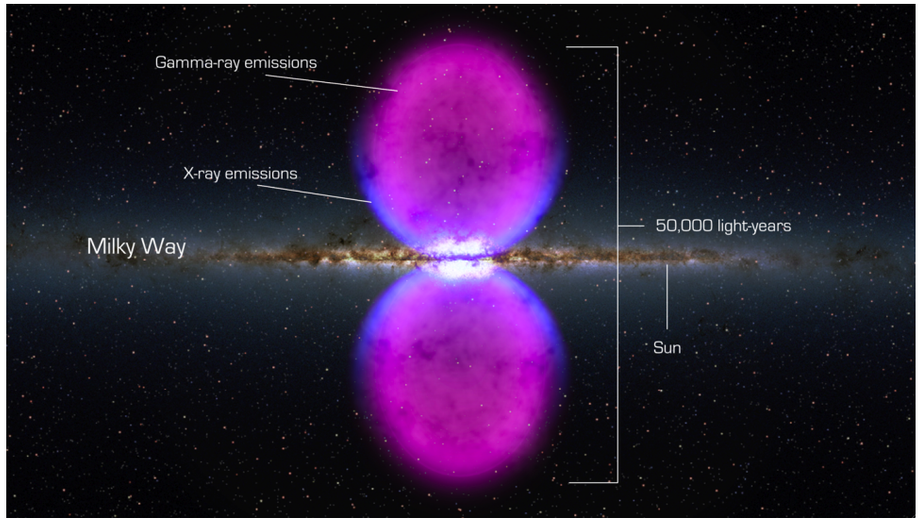
Gamma-ray bubbles, cocoons, and... jets?!?

Douglas Finkbeiner - Harvard CfA
Meng Su - Harvard -> MIT

IAU 303 Santa Fe
October 4, 2013

Background:

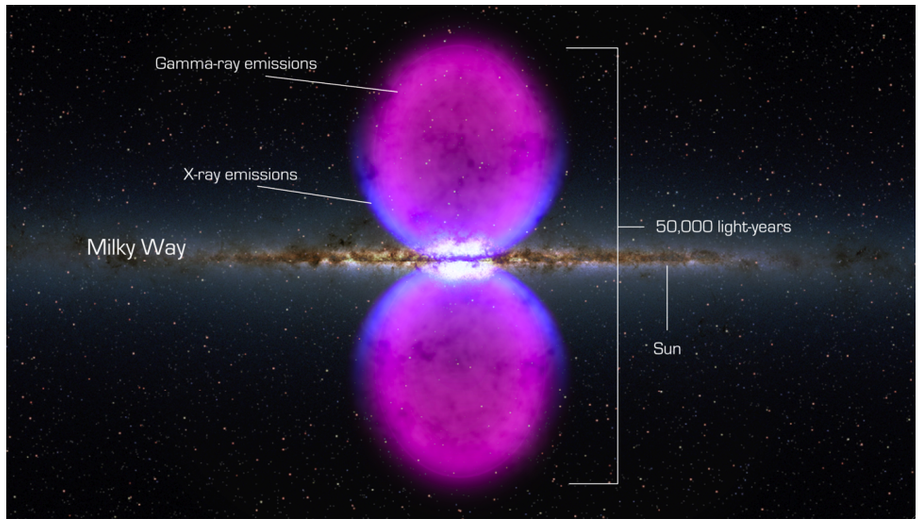
Based on analysis of 1.6 years of *Fermi* data, we claimed in 2010 that there were "bubble" structures spanning ~ $|b| < 50$ deg and $|l| < 20$ deg. (Su, Slatyer, Finkbeiner, arXiv:1005.5480)



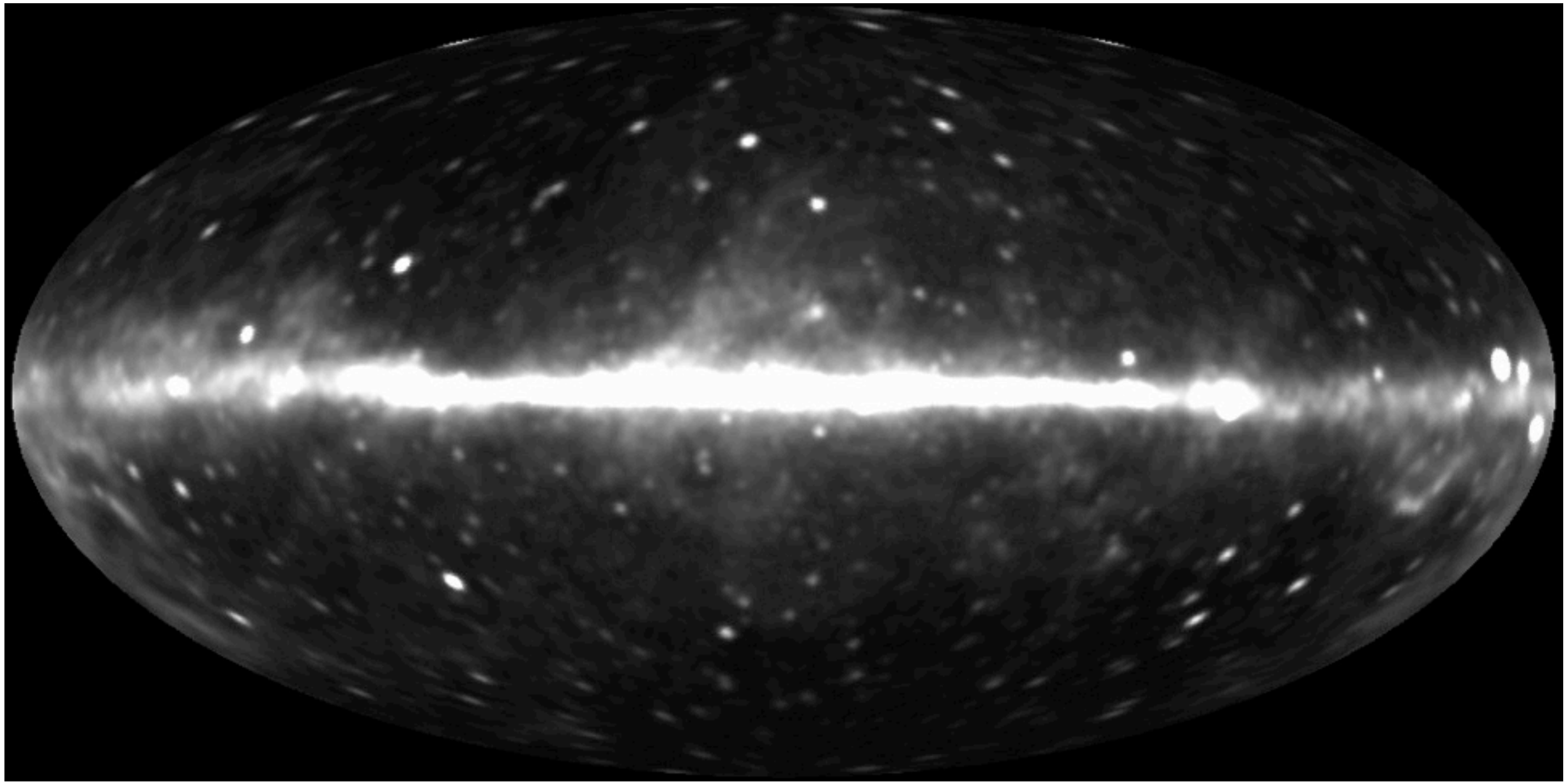
Background:

Based on analysis of 1.6 years of *Fermi* data, we claimed in 2010 that there were "bubble" structures spanning ~ $|b| < 50$ deg and $|l| < 20$ deg. (Su, Slatyer, Finkbeiner, arXiv:1005.5480)

By last year, with 3+ years of data and Pass 7 processing, we could see the bubble structures clearly and began to look for substructure. (Su & Finkbeiner, arXiv:1205.5852)



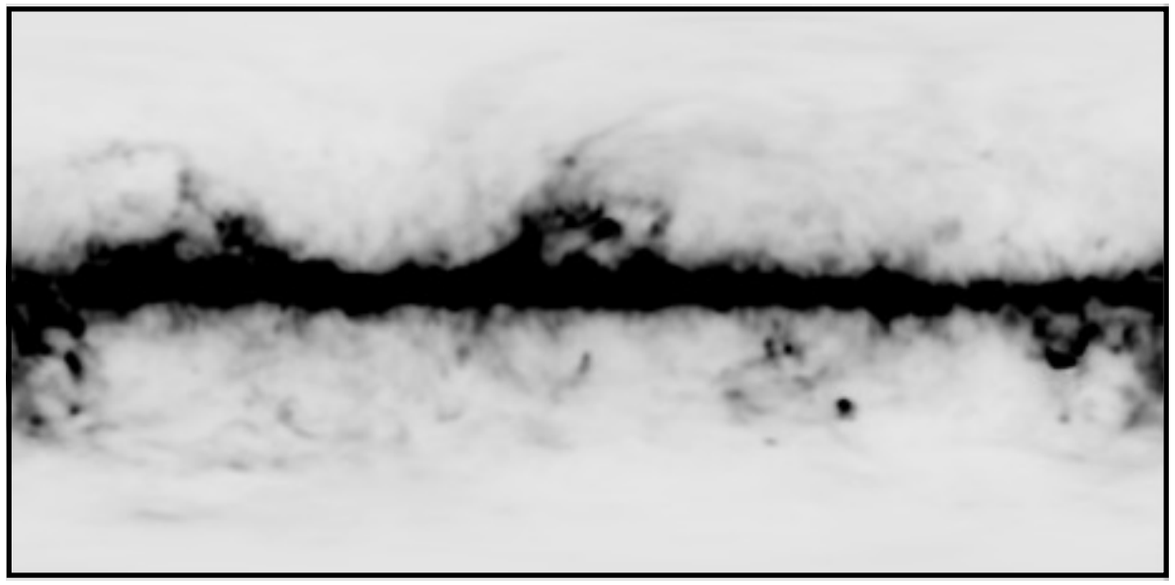
Fermi bubbles processing steps:



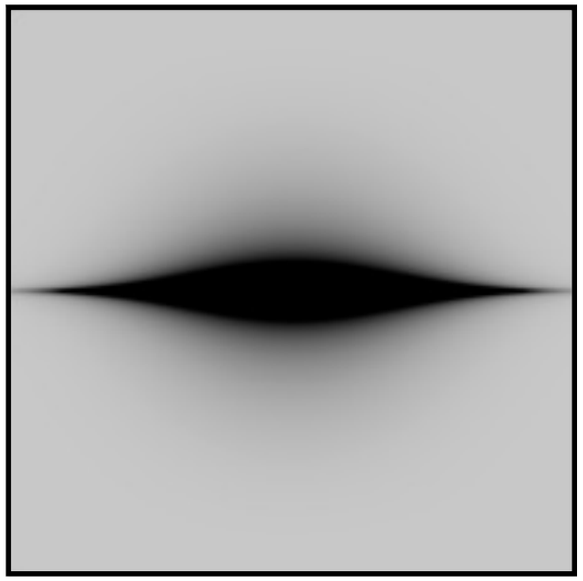
Point sources / diffuse model / stretch

Make maps in energy bins.
Model each map as a linear combination of 4 templates.
Maximize Poisson likelihood of observations given model.
Plot template coefficients as a function of energy.

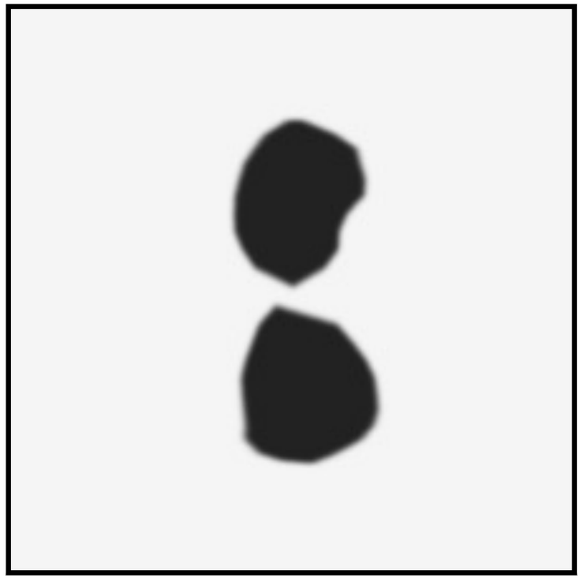
dust



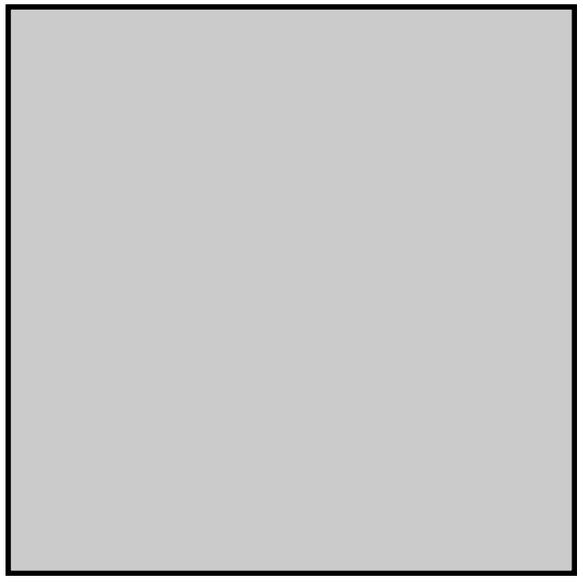
disk

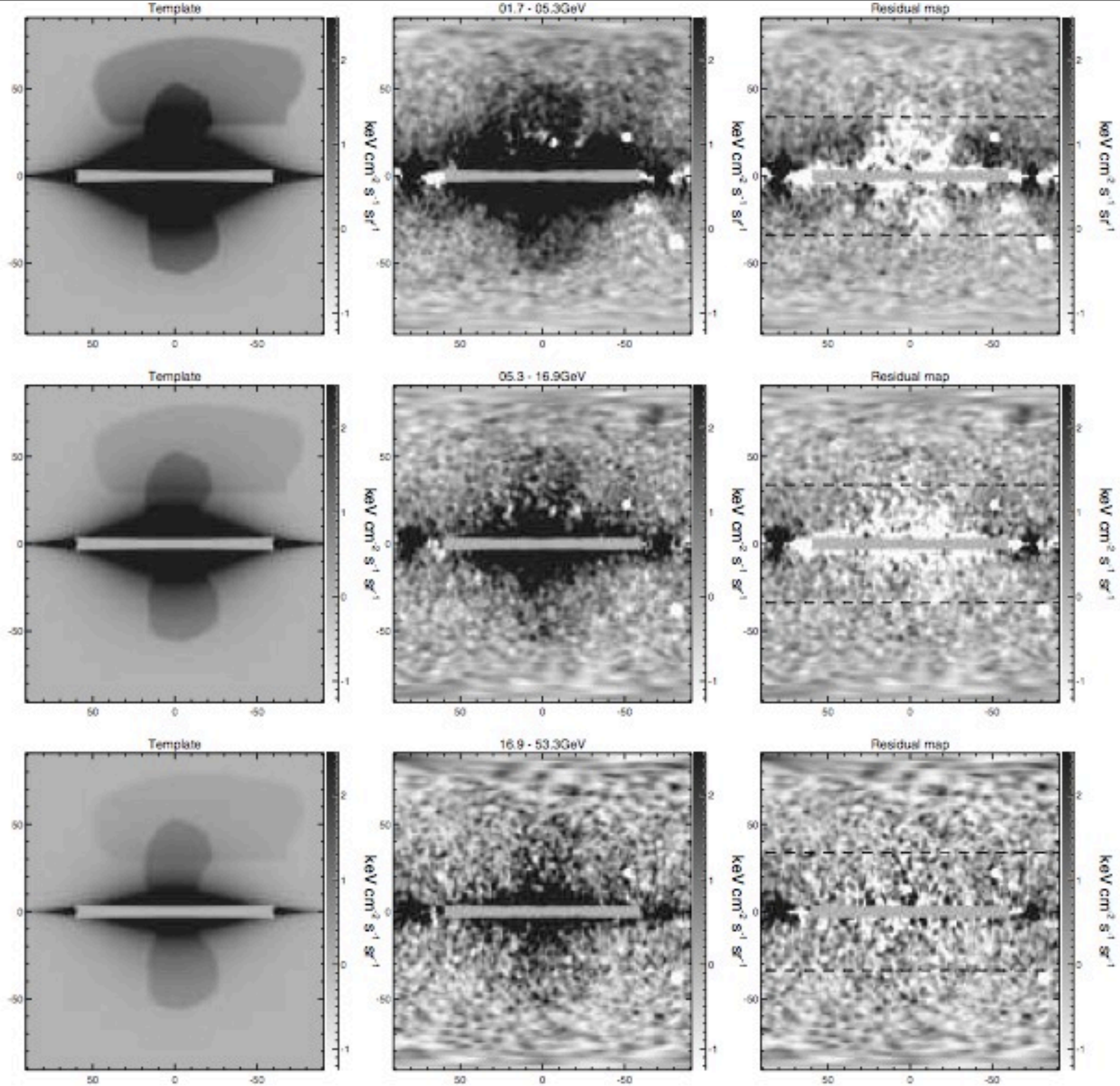


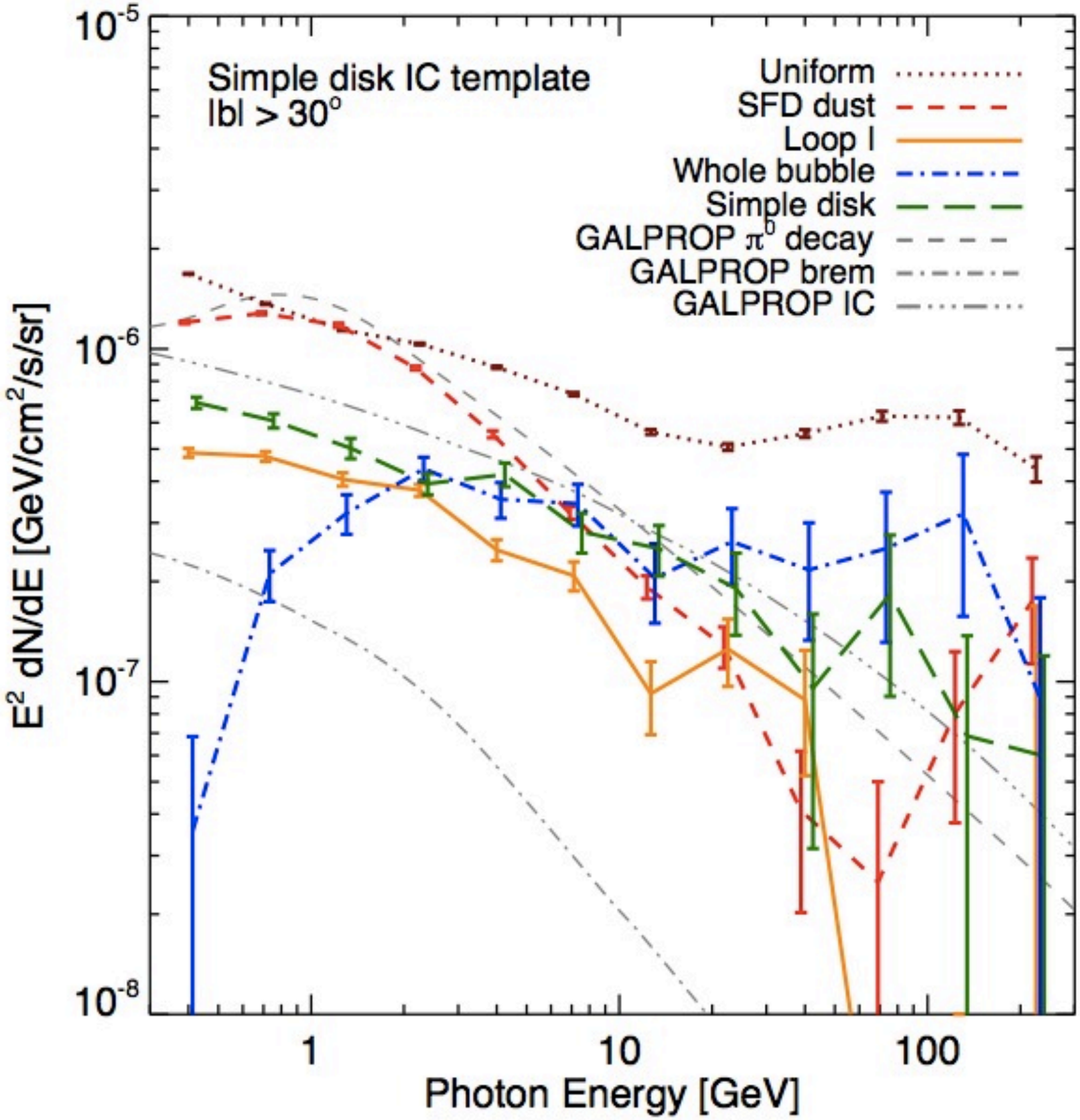
bubbles



background

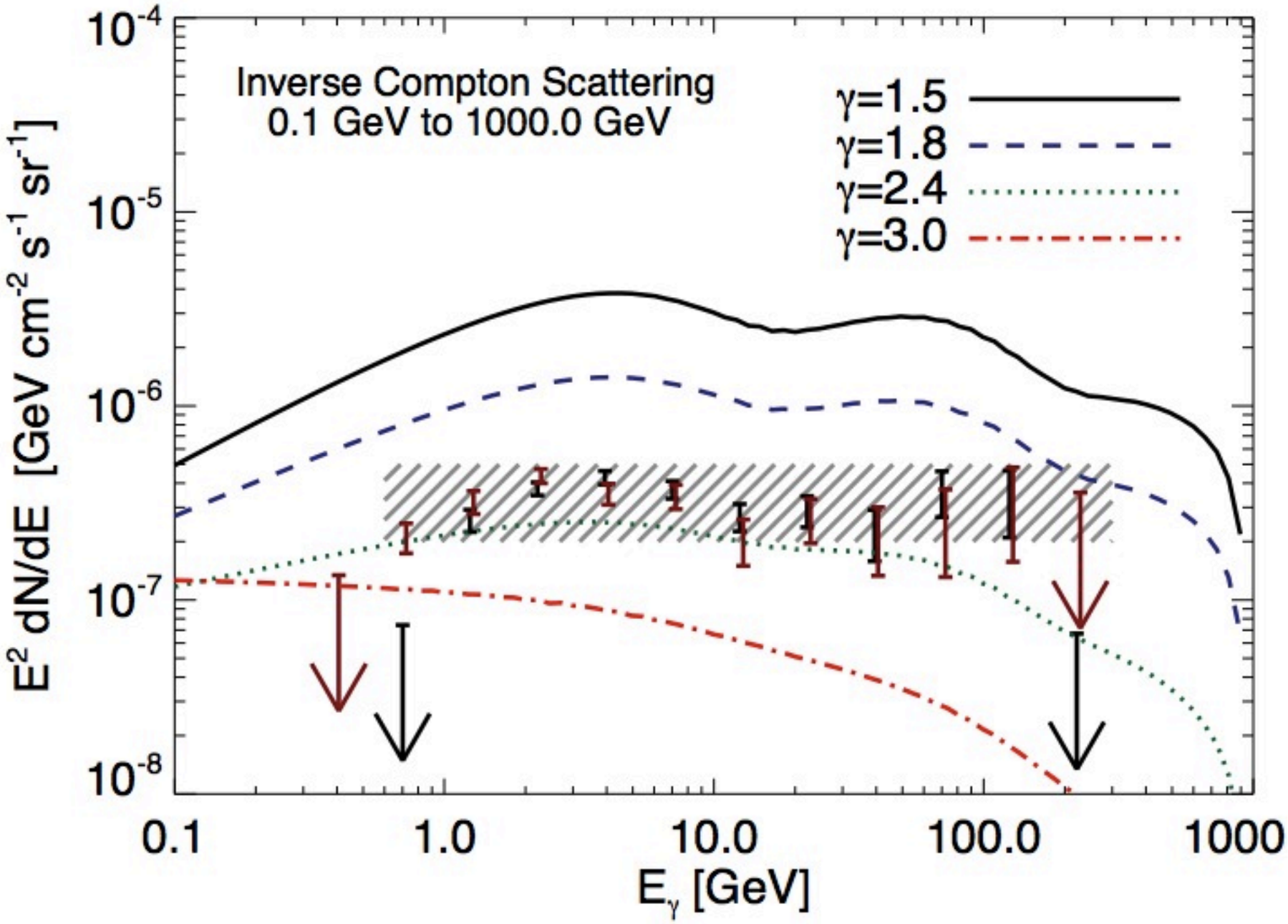



Template
01.7 - 05.3GeV
Residual map
Template
05.3 - 16.9GeV
Residual map
Template
16.9 - 53.3GeV
Residual map
keV cm^{-2} s^{-1} sr^{-1}



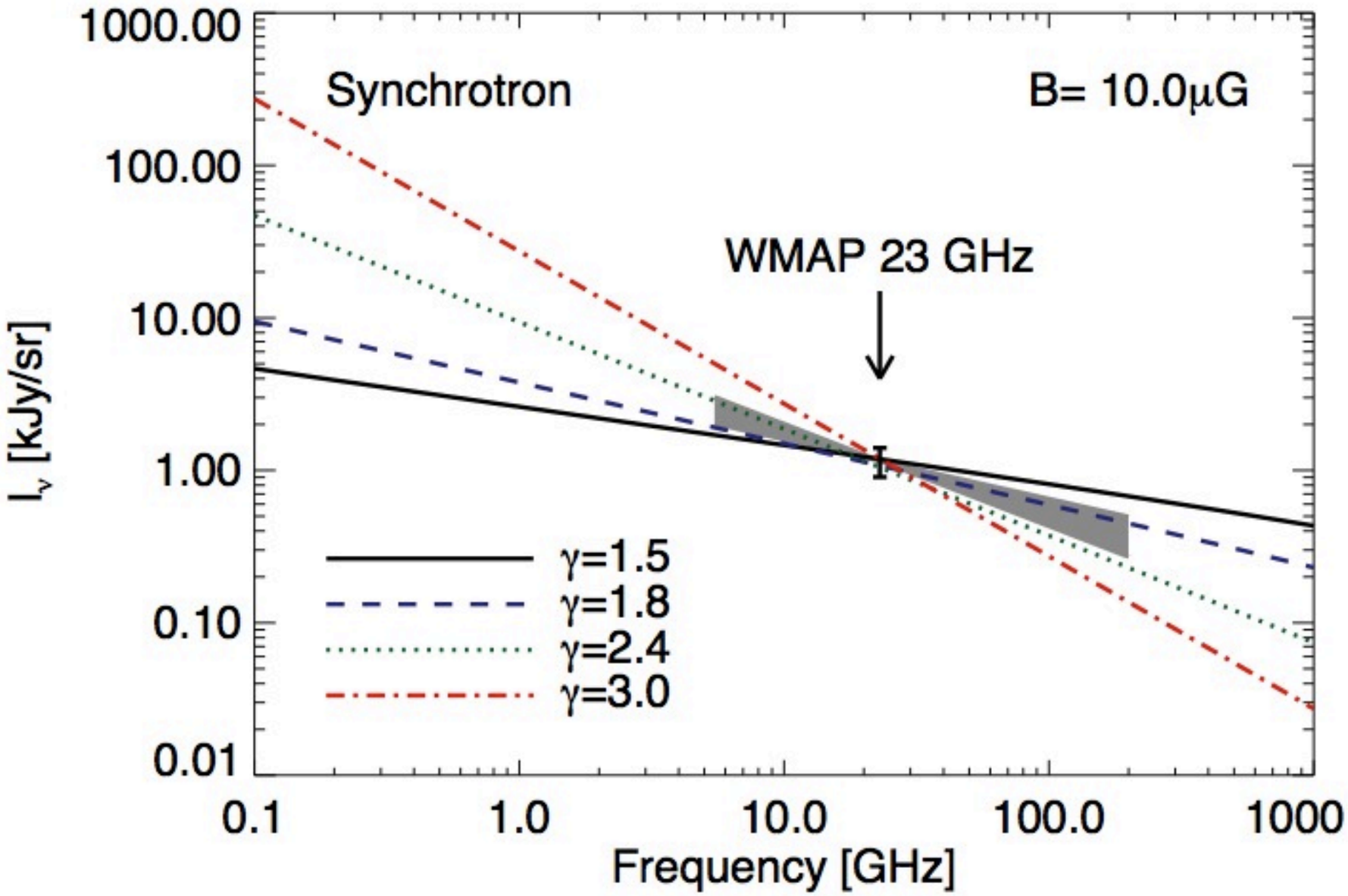
(Su, Slatyer, Finkbeiner 2010, 1005.5480)

Could be IC gammas from e^+e^- scattering ISRF.
Need a fairly hard electron spectrum.



(Su, Slatyer, Finkbeiner 2010, 1005.5480)

Compatible with synchrotron explanation for the WMAP haze (Finkbeiner, astro-ph/0311547)



(Su, Slatyer, Finkbeiner 2010, 1005.5480)

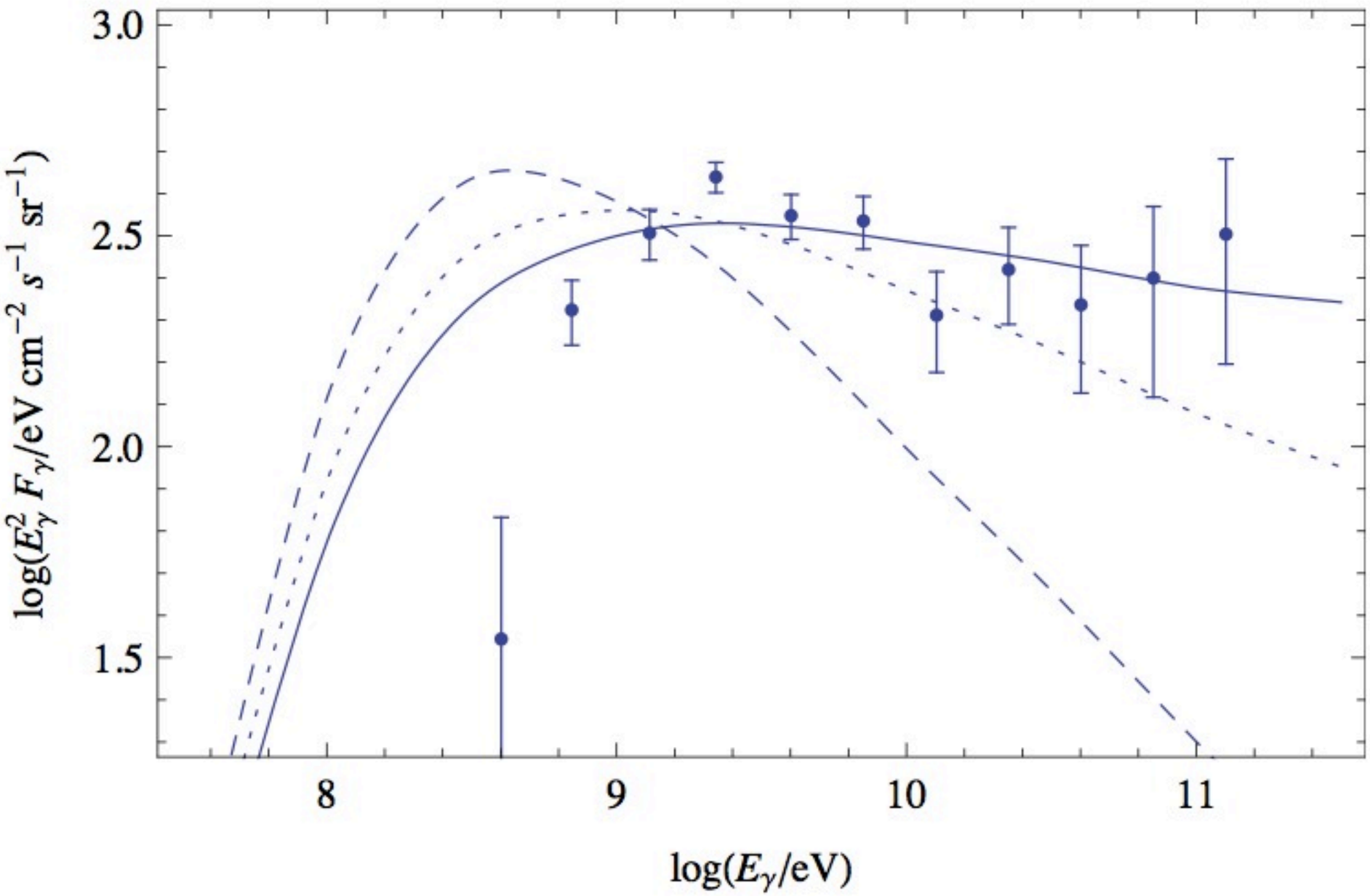
Origin of the Fermi Bubbles

- Crocker & Aharonian (1008.2658): *The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays*

- Dogiel et al. (1109.6087): *Fermi Bubbles as a Result of Star Capture in the Galactic Center*

- Guo & Mathews; Guo et al. (1110.0834): AGN activity

- Carretti et al. (1301.0512): 2.3 GHz S-PASS radio polarization survey indicates star formation



Crocker & Aharonian (1008.2658)

Origin of the Fermi Bubbles

- Crocker & Aharonian (1008.2658): *The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays*

- Dogiel et al. (1109.6087): *Fermi Bubbles as a Result of Star Capture in the Galactic Center*

- Guo & Mathews; Guo et al. (1110.0834): AGN activity

- Carretti et al. (1301.0512): 2.3 GHz S-PASS radio polarization survey indicates star formation

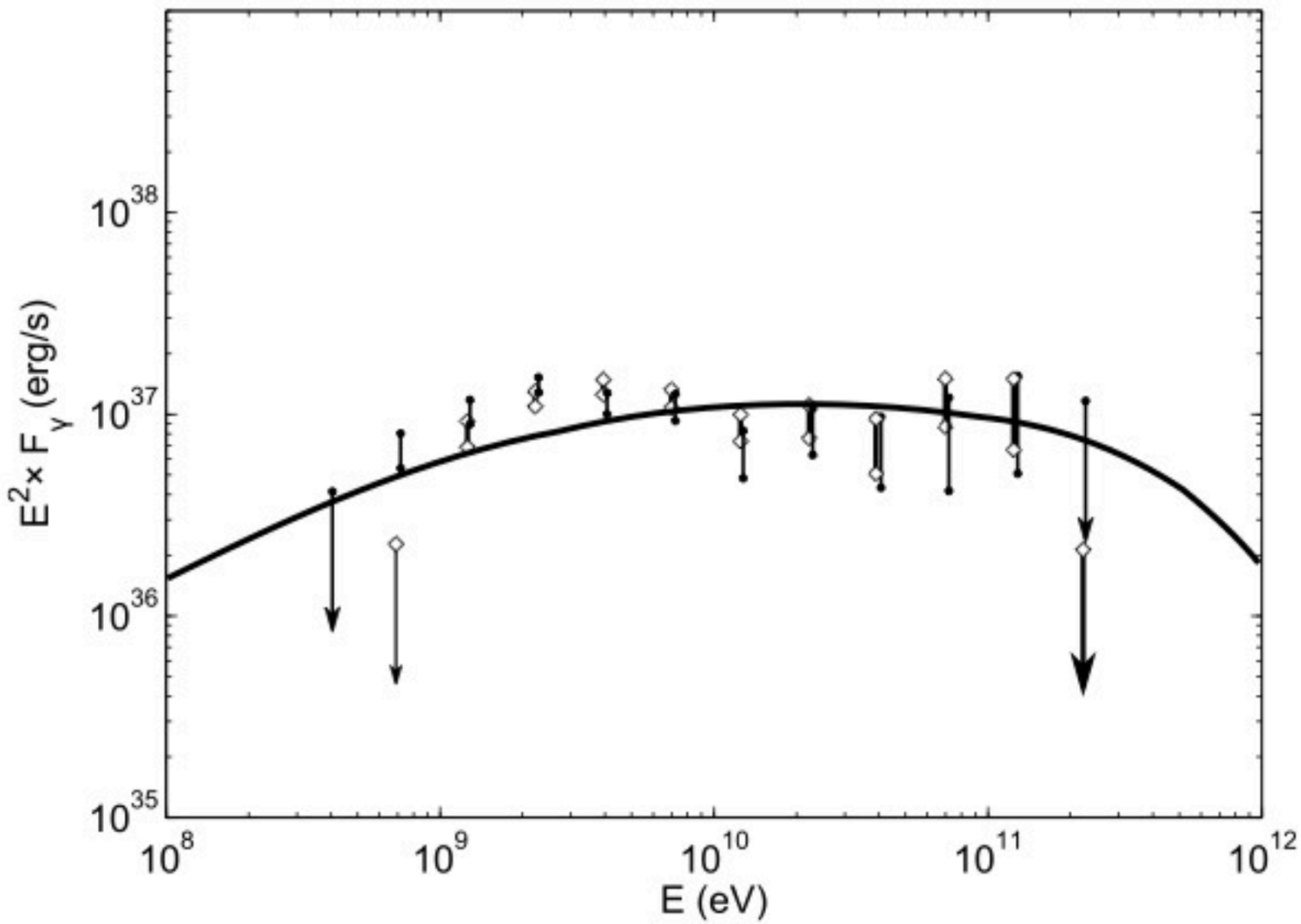


FIG. 2: The spectrum of gamma-ray emission from Fermi bubble in case of multi-shock acceleration. Data points are taken from [1].

Dogiel et al. (1109.6087)

Origin of the Fermi Bubbles

- Crocker & Aharonian (1008.2658): *The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays*

- Dogiel et al. (1109.6087): *Fermi Bubbles as a Result of Star Capture in the Galactic Center*

- Guo & Mathews; Guo et al. (1110.0834): AGN activity

- Carretti et al. (1301.0512): 2.3 GHz S-PASS radio polarization survey indicates star formation

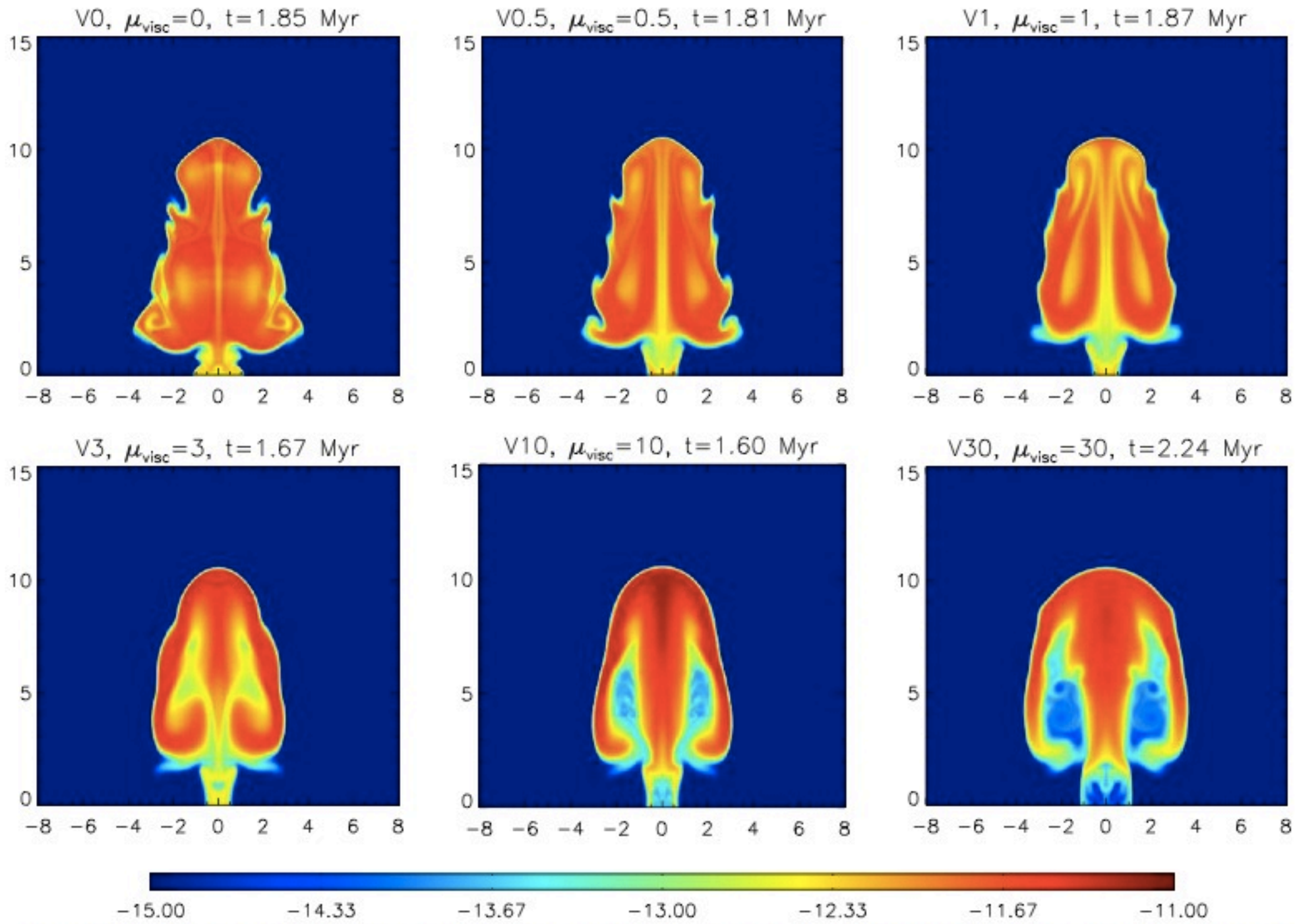
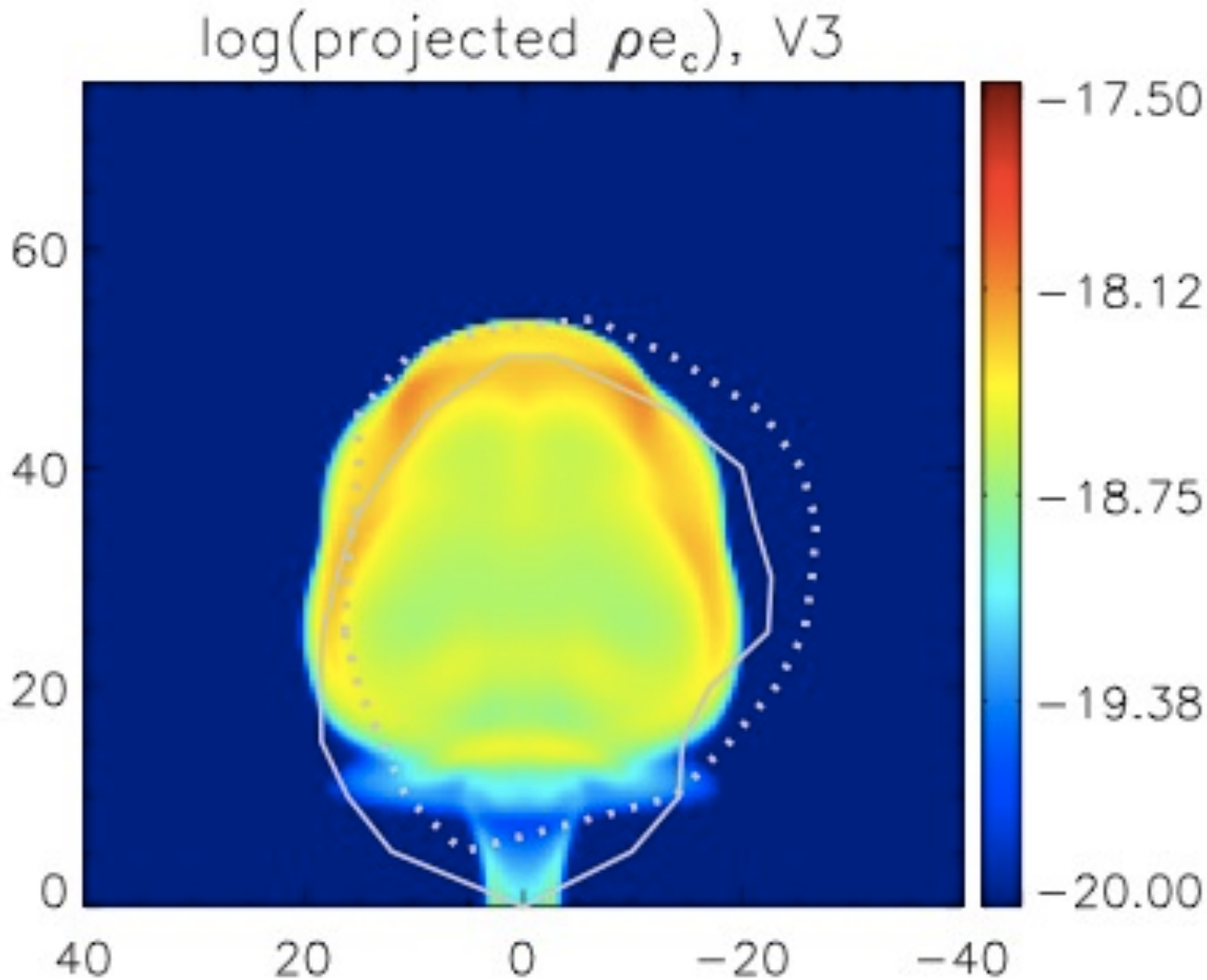


FIG. 2.— Central slices (16 × 15 kpc) of CR energy density in logarithmic scale in runs V0, V0d5, V1, V3, V10, and V30 at $t = t_{\rm Fermi}$, which is shown at the top of each panel for the corresponding run. Horizontal and vertical axes refer to R and z respectively, labeled in kpc. The stabilizing effect of viscosity on bubble edges can be clearly seen here as viscosity increases from panel to panel, and the Kelvin-Helmholtz and Rayleigh-Taylor instabilities are fully suppressed when $\mu_{\rm visc} \gtrsim 3$ g cm^{-1} s^{-1}.



Guo et al. (1110.0834)

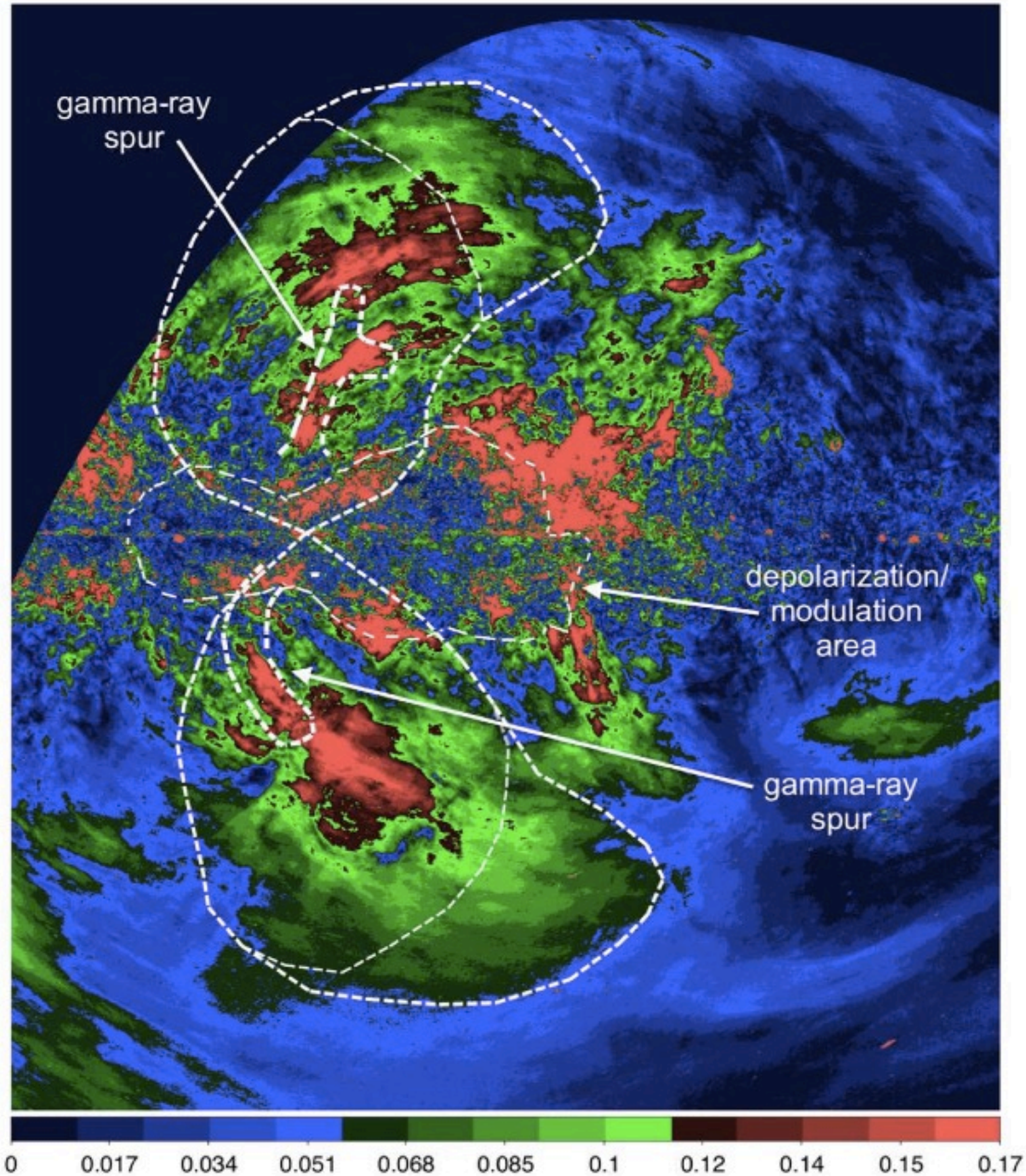
Origin of the Fermi Bubbles

- Crocker & Aharonian (1008.2658): *The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays*

- Dogiel et al. (1109.6087): *Fermi Bubbles as a Result of Star Capture in the Galactic Center*

- Guo & Mathews; Guo et al. (1110.0834): AGN activity

- Carretti et al. (1301.0512): 2.3 GHz S-PASS radio polarization survey indicates star formation



Carretti et al. (1301.0512)

Origin of the Fermi Bubbles

... and many other papers...

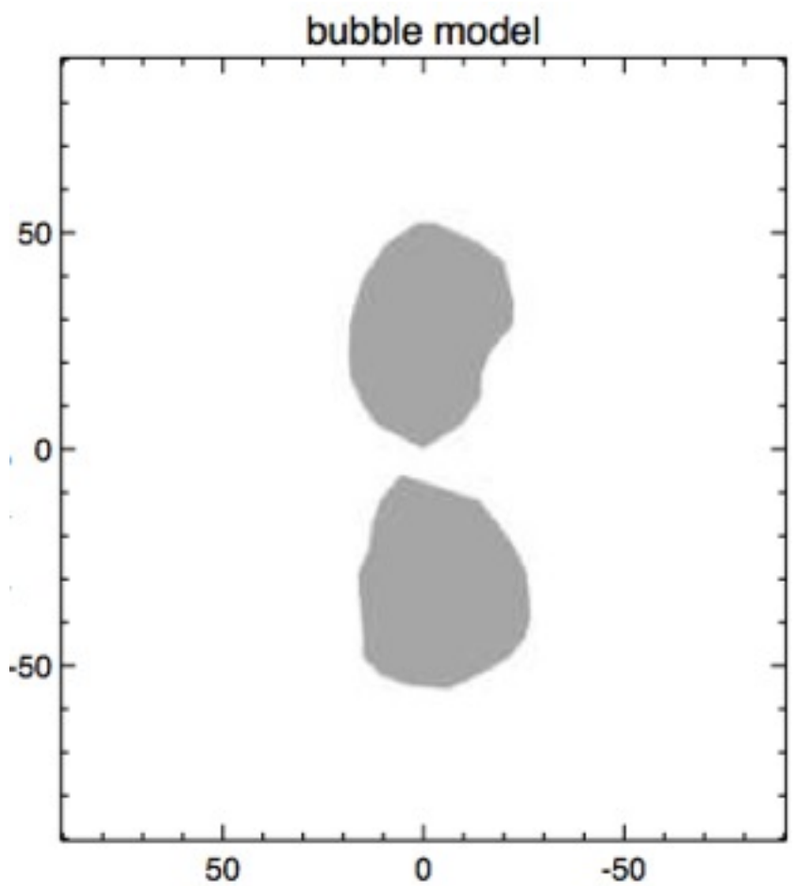
Origin of the Fermi Bubbles

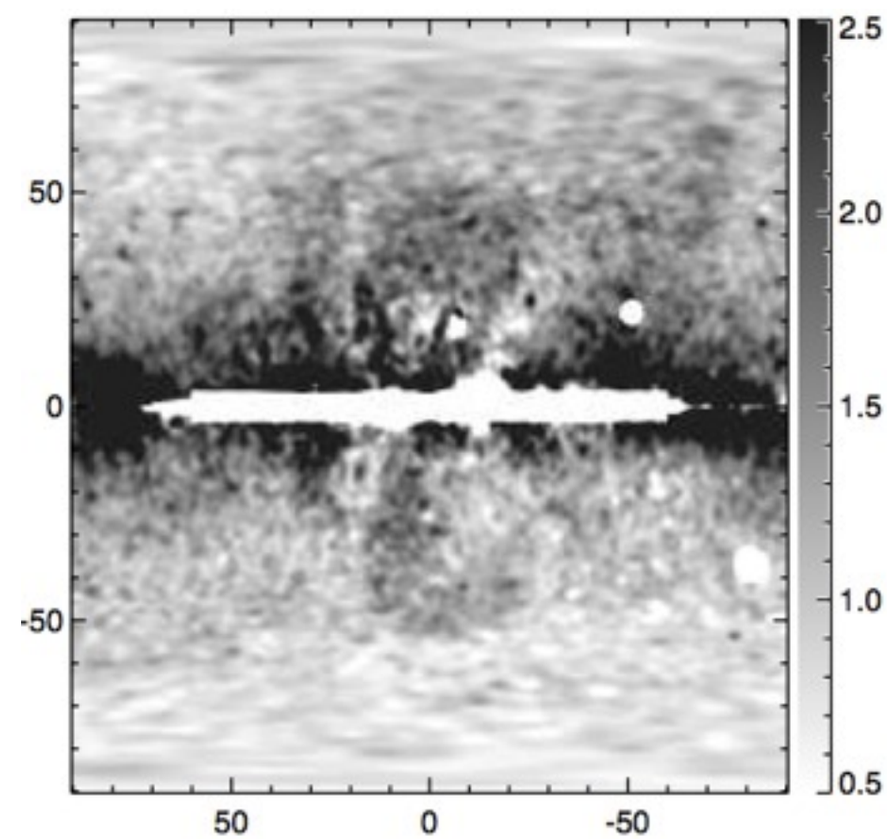
- Last year, Meng Su and I looked for substructure in the Bubbles that might give a clue about their origins.

Simple templates...

Our first paper used a uniform intensity template for the Fermi bubbles.

This was correct to zeroth order.

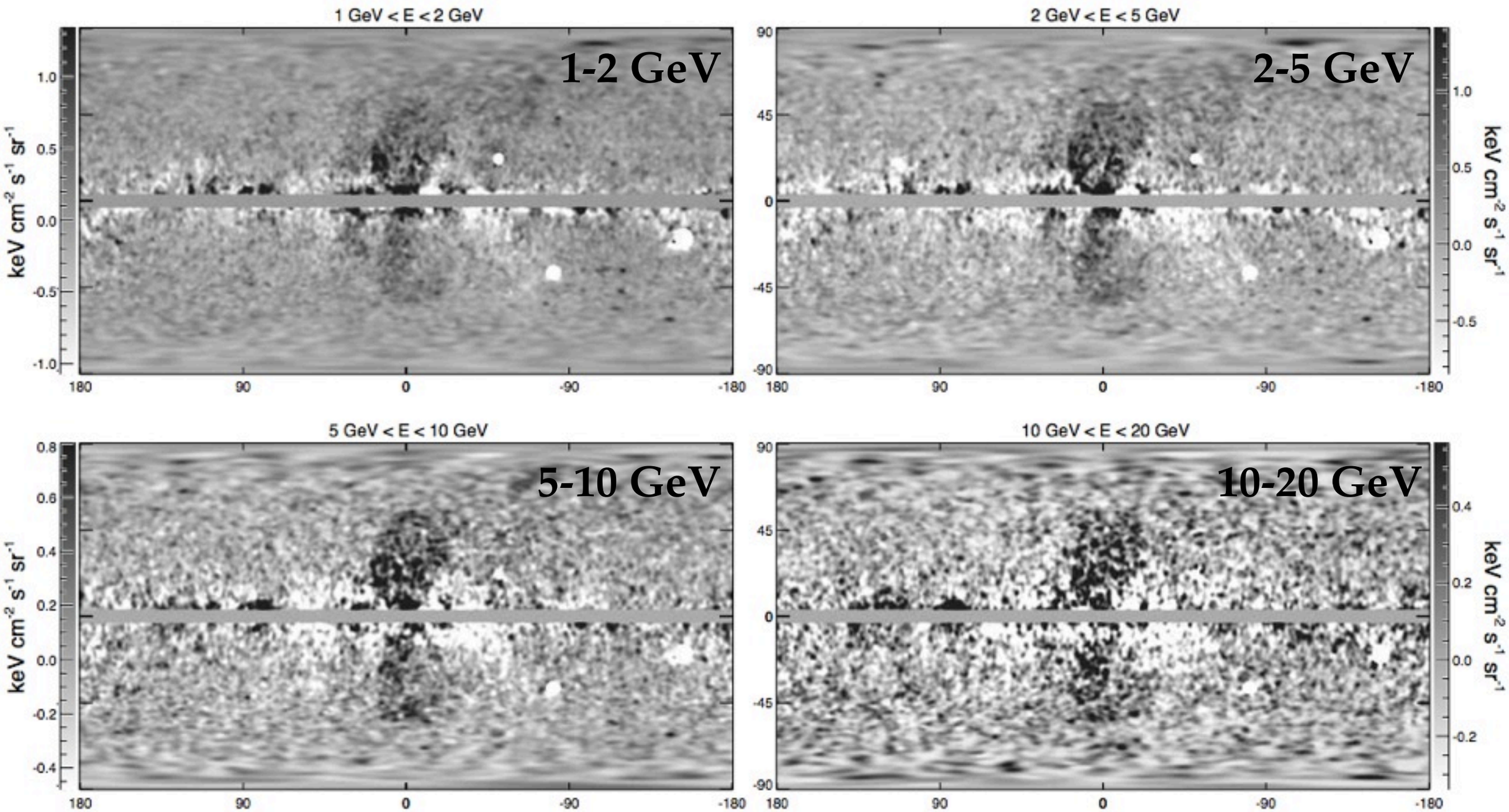




Su & Finkbeiner (2010)

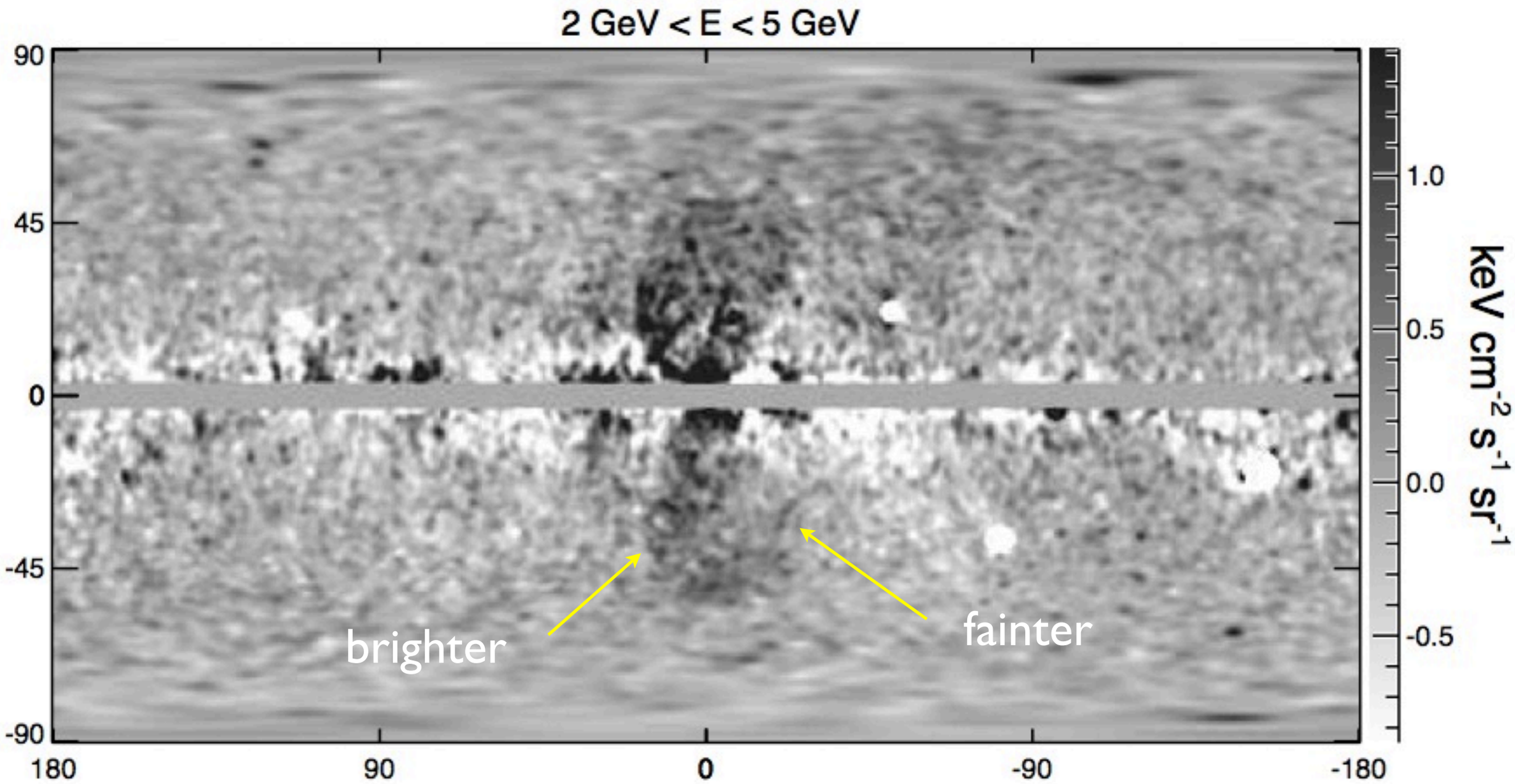
Can see the structures simply by subtracting the LAT team's diffuse model:

Data minus Fermi diffuse model in 4 energy bins. (1.6 yr data)



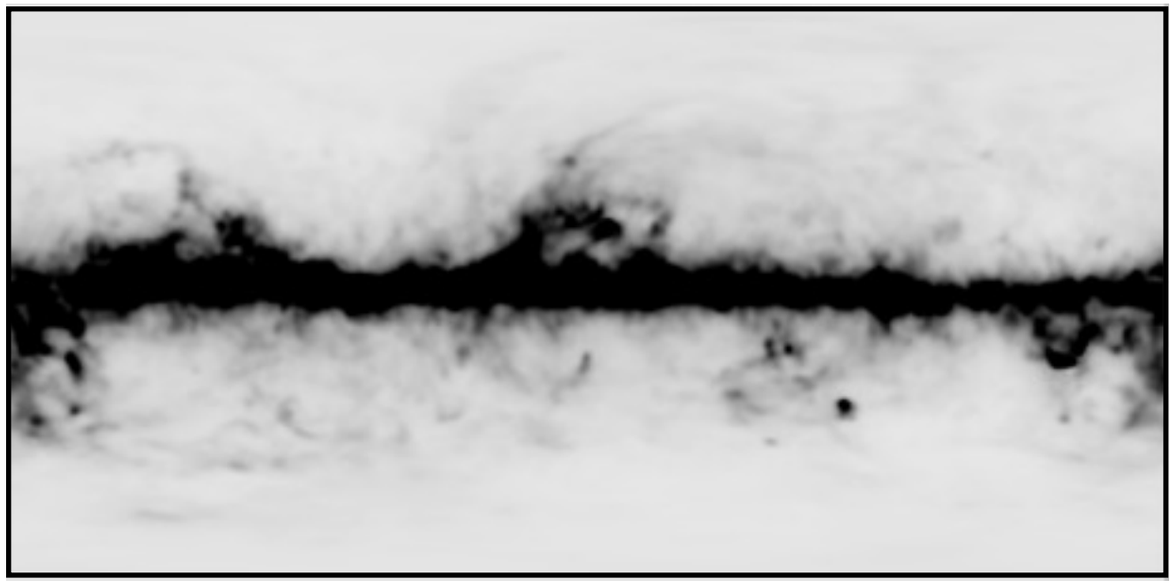
Su & Finkbeiner (2010)

We always wondered why the left (east) part of the southern bubble was brighter, and if this was significant.

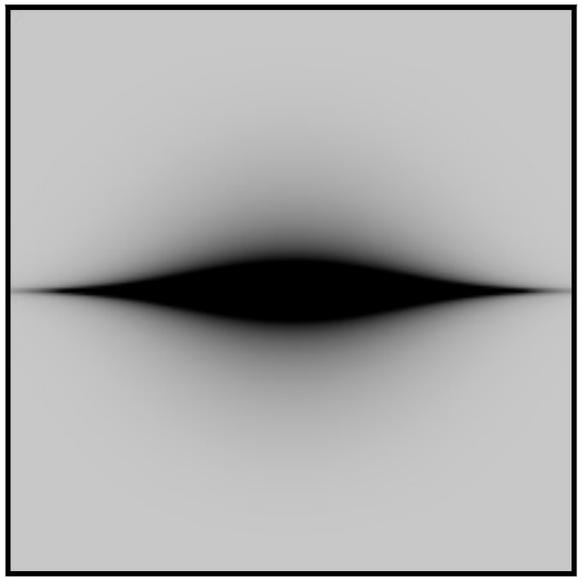


So we made another template...

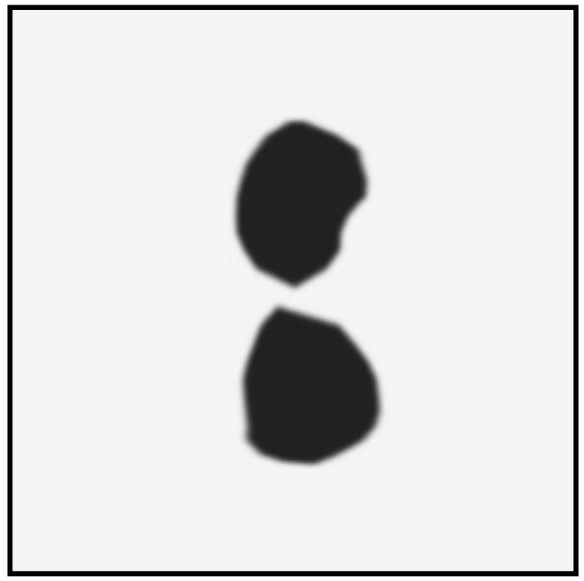
dust



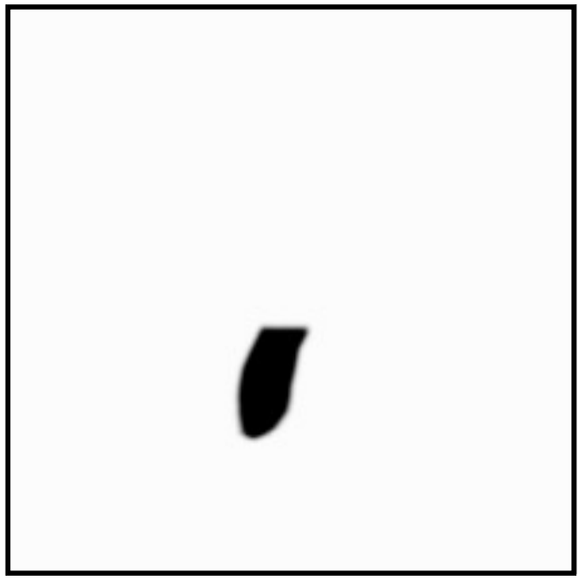
disk



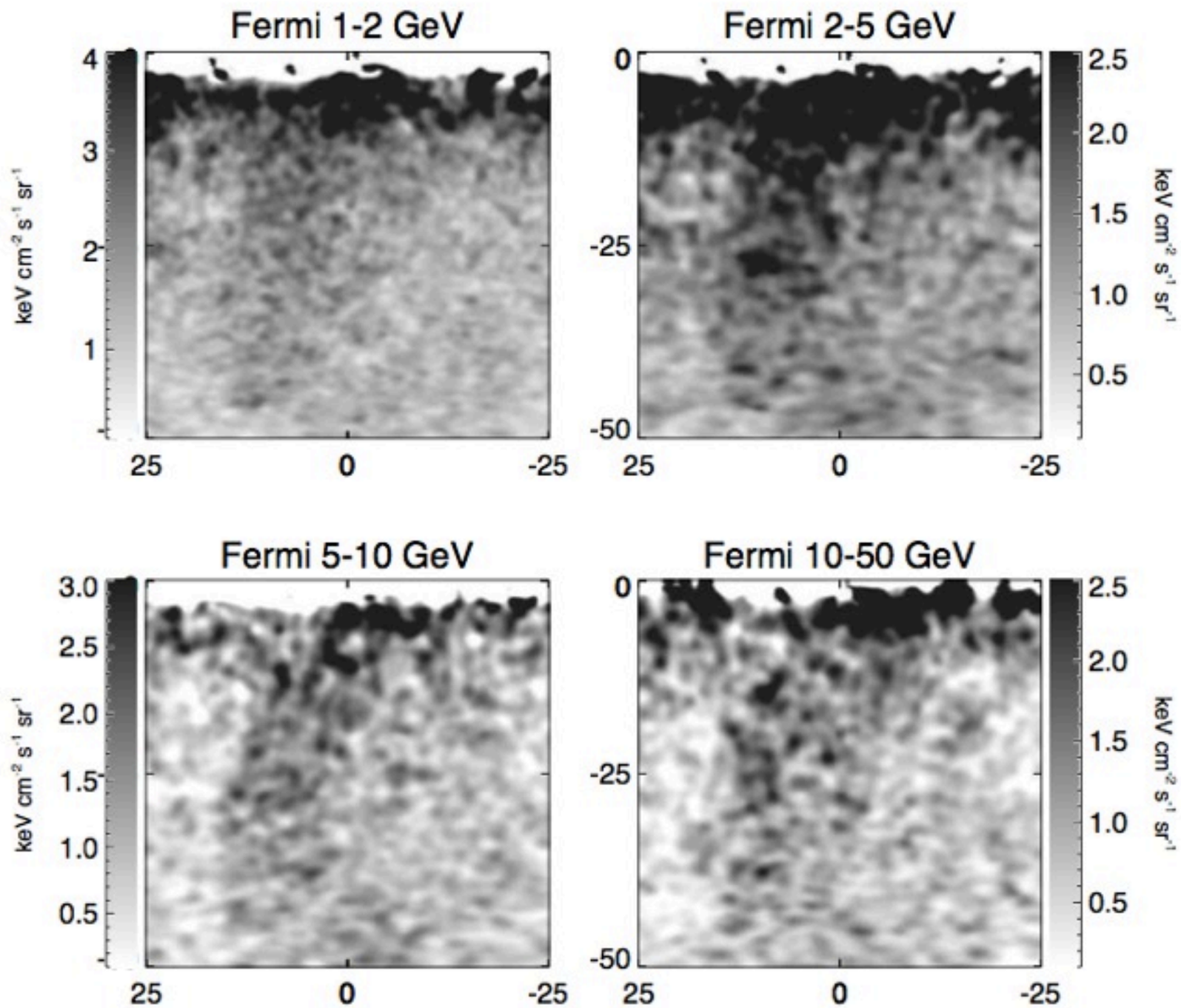
bubbles



cocoon



“Cocoon” feature on east (left) side of southern bubble

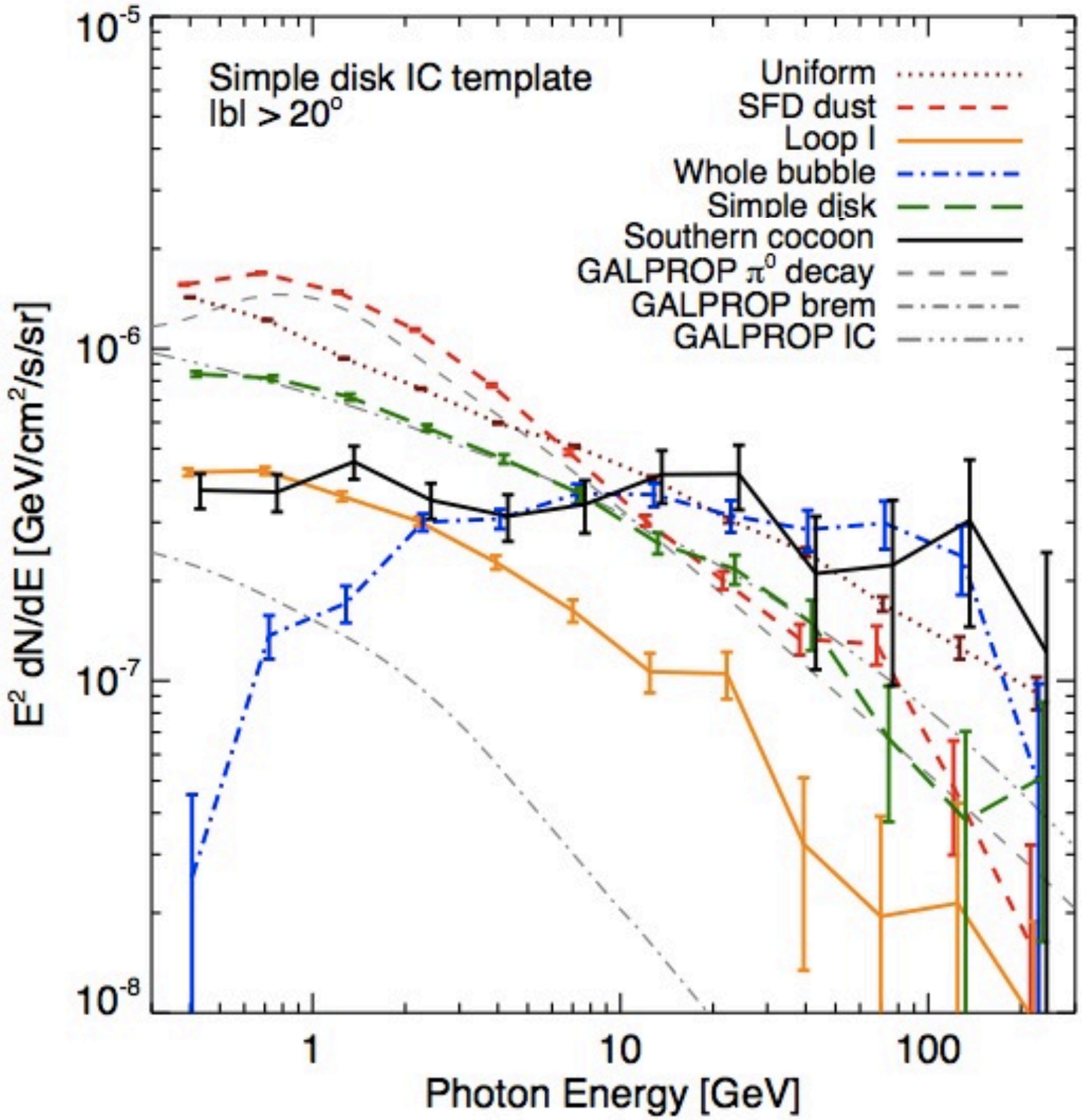


Su & Finkbeiner (2012)

The cocoon is detected as a distinct feature in the multilinear regression at 12 sigma.

The spectrum is consistent with flat (in E^2 dN/dE)
L ~ 2×10^{36} erg/sec for 1-100 GeV

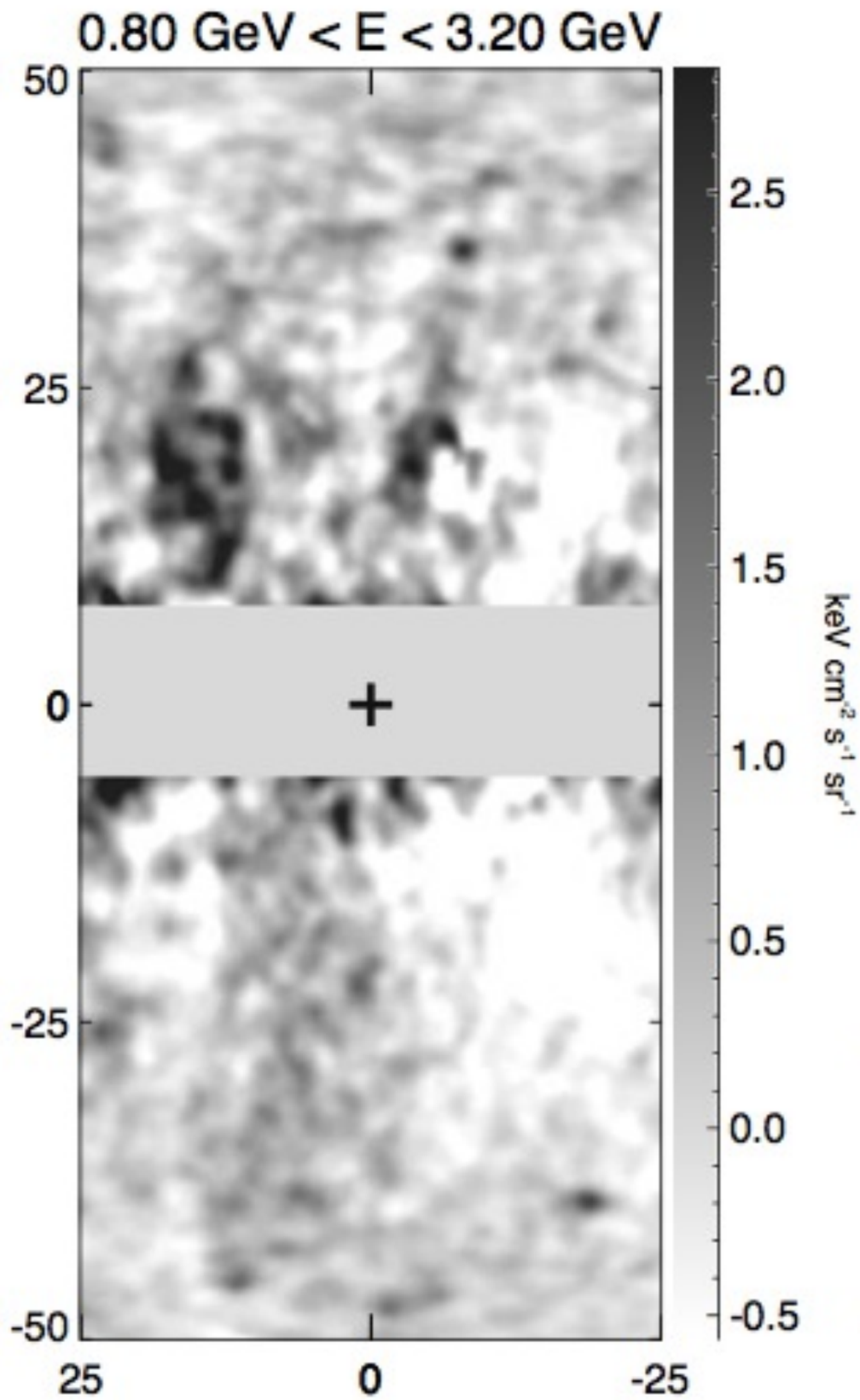
Su & Finkbeiner (2012)

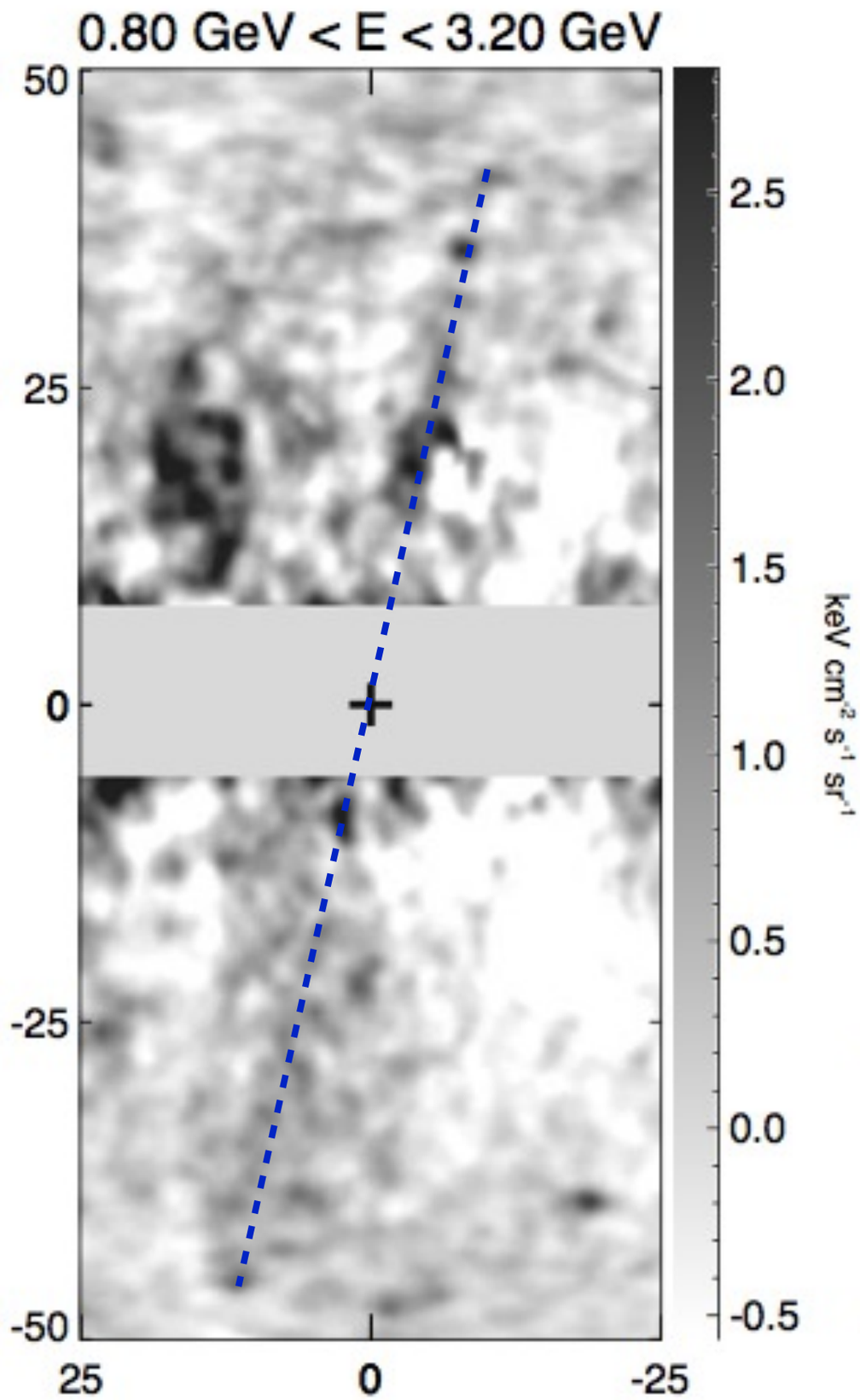


Su & Finkbeiner (2012)

It is tempting to imagine that this “cocoon” contains a jet, but the jet must be very faint.

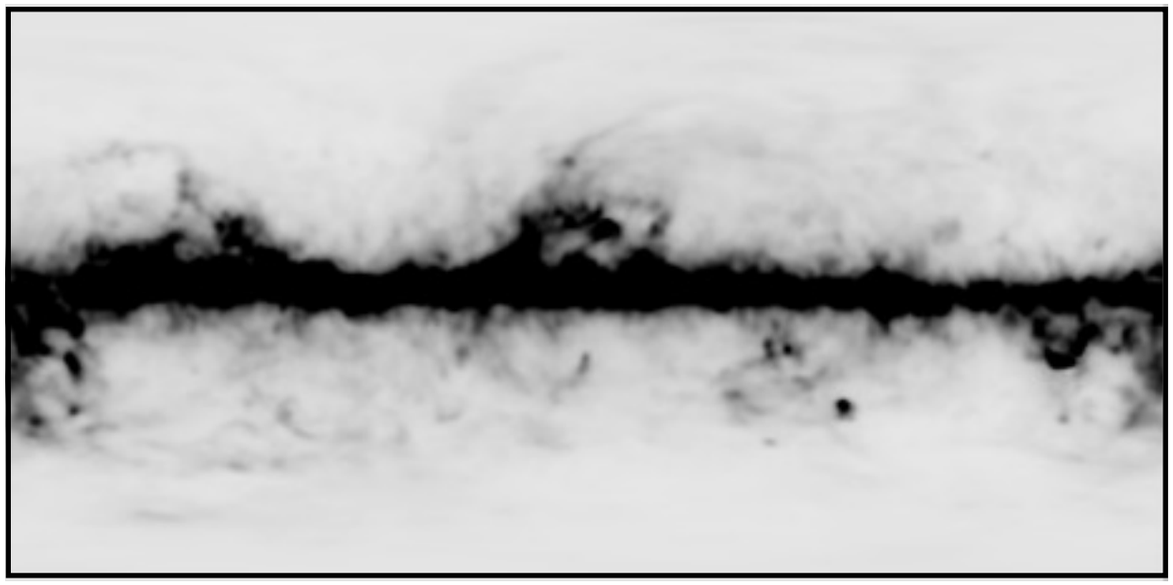
Let’s look more carefully at 90 arcmin maps, binning counts from 0.8 to 3.2 GeV, after subtracting the usual templates (but not the cocoon)...


0.80 GeV < E < 3.20 GeV
50
25
0
-25
-50
25
0
-25
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm^{-2} s^{-1} sr^{-1}

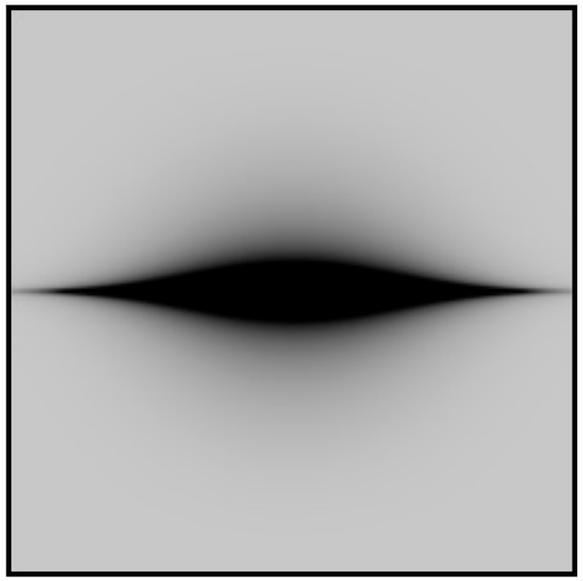

0.80 GeV < E < 3.20 GeV
50
25
0
-25
-50
25
0
-25
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm^{-2} s^{-1} sr^{-1}

So we made *yet* another template...

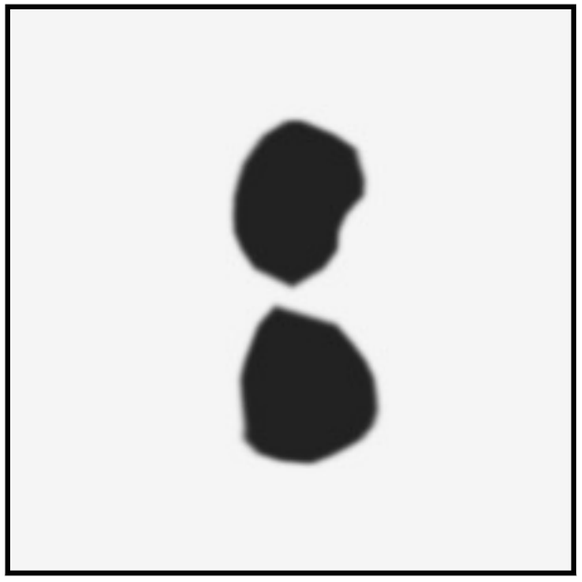
dust



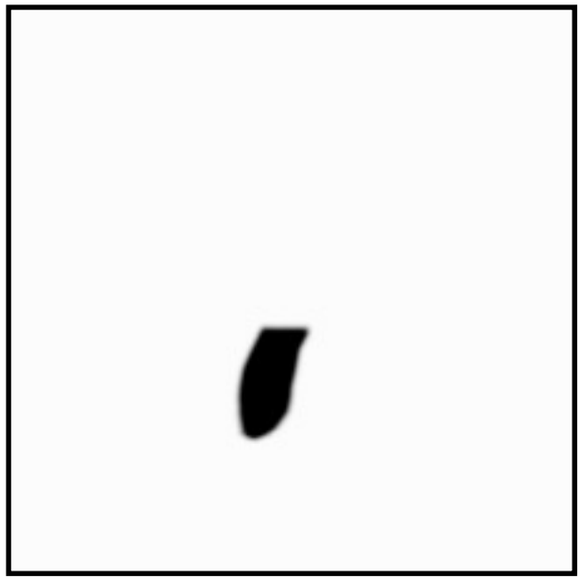
disk



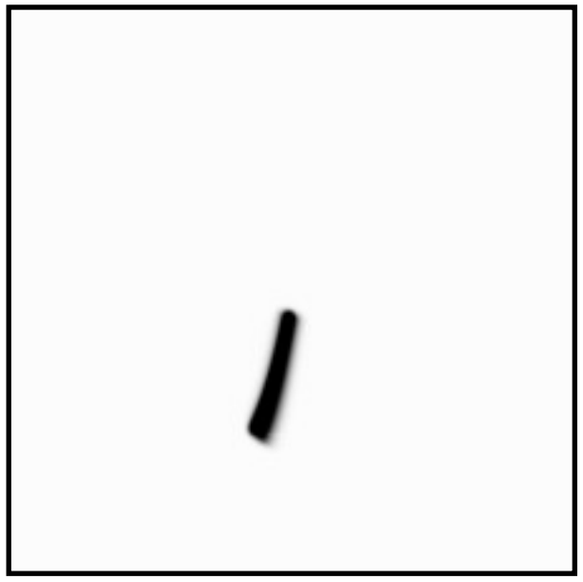
bubbles

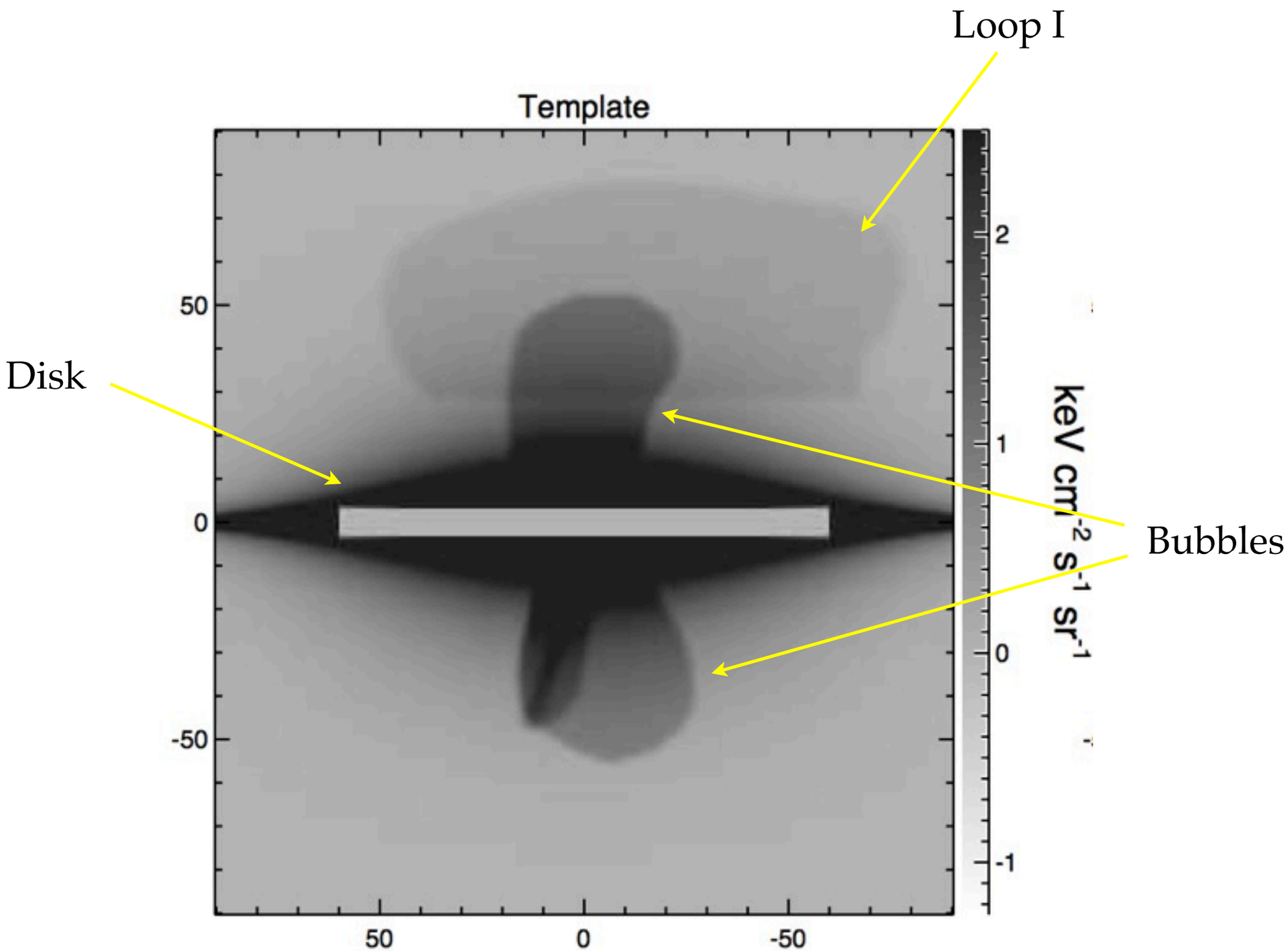


cocoon

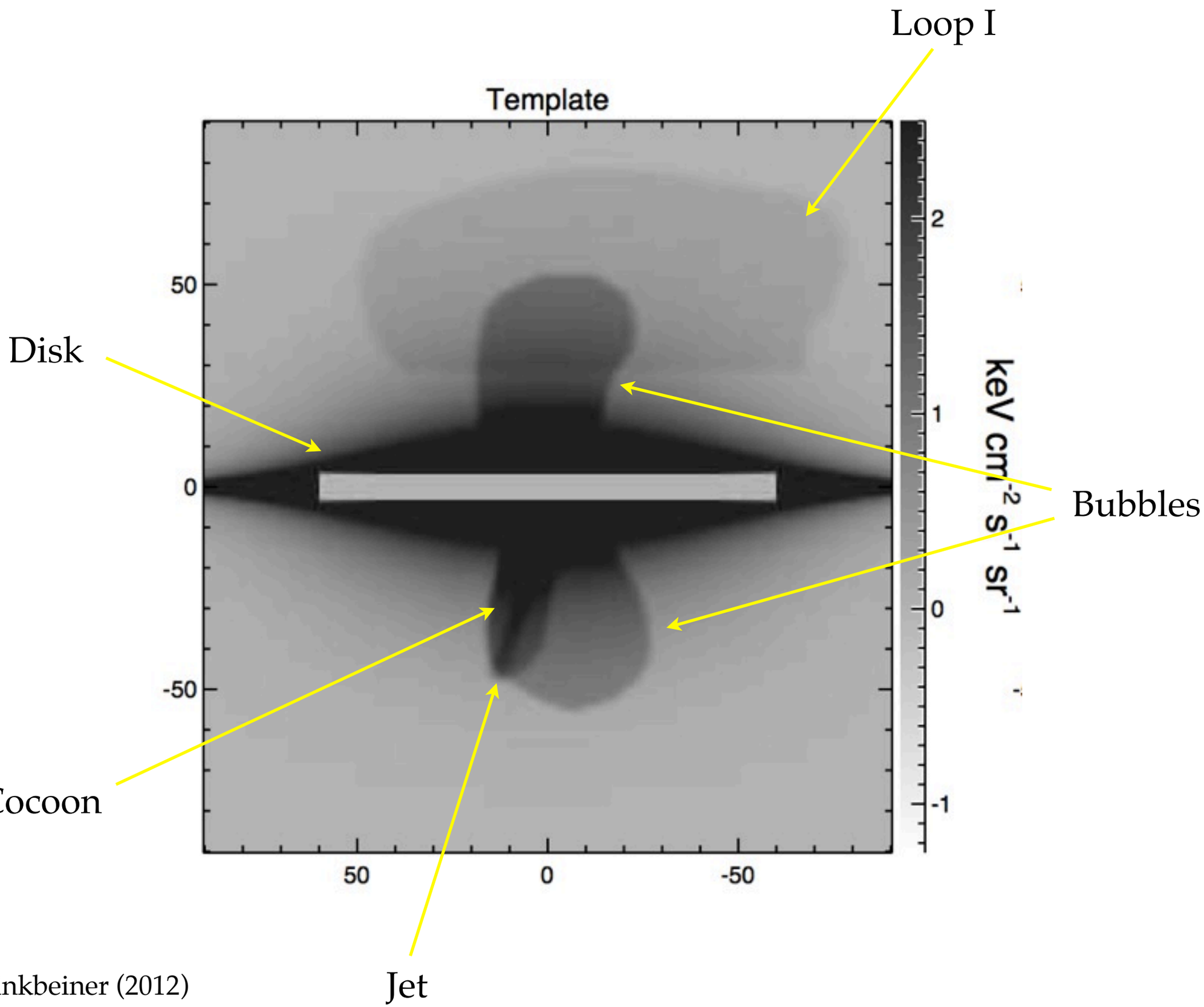


south jet



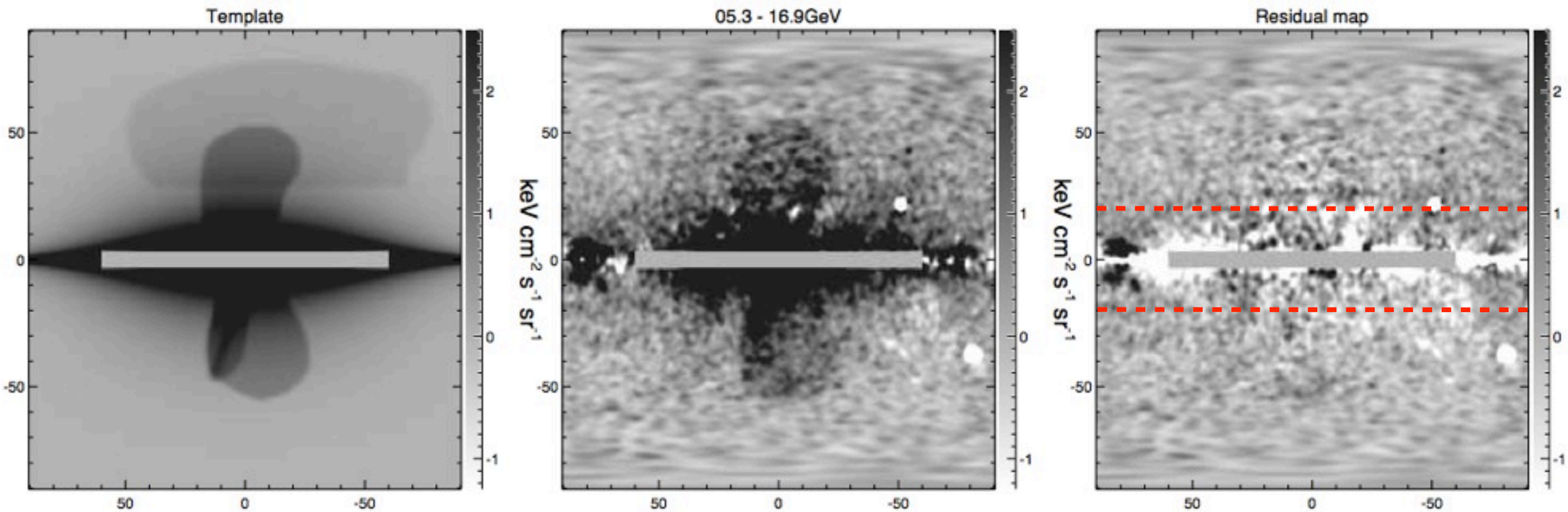


Su & Finkbeiner (2012)



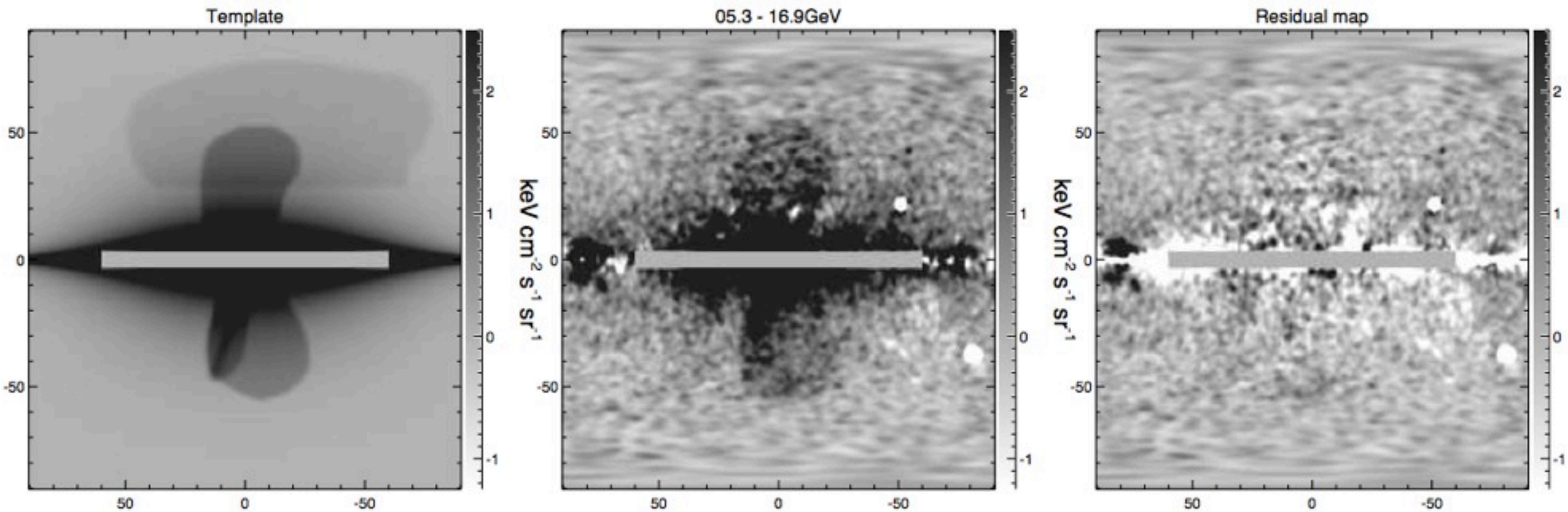
Su & Finkbeiner (2012)

Leaving out dust-correlated π^0 emission
Fit is done for $|b| > 20^o$



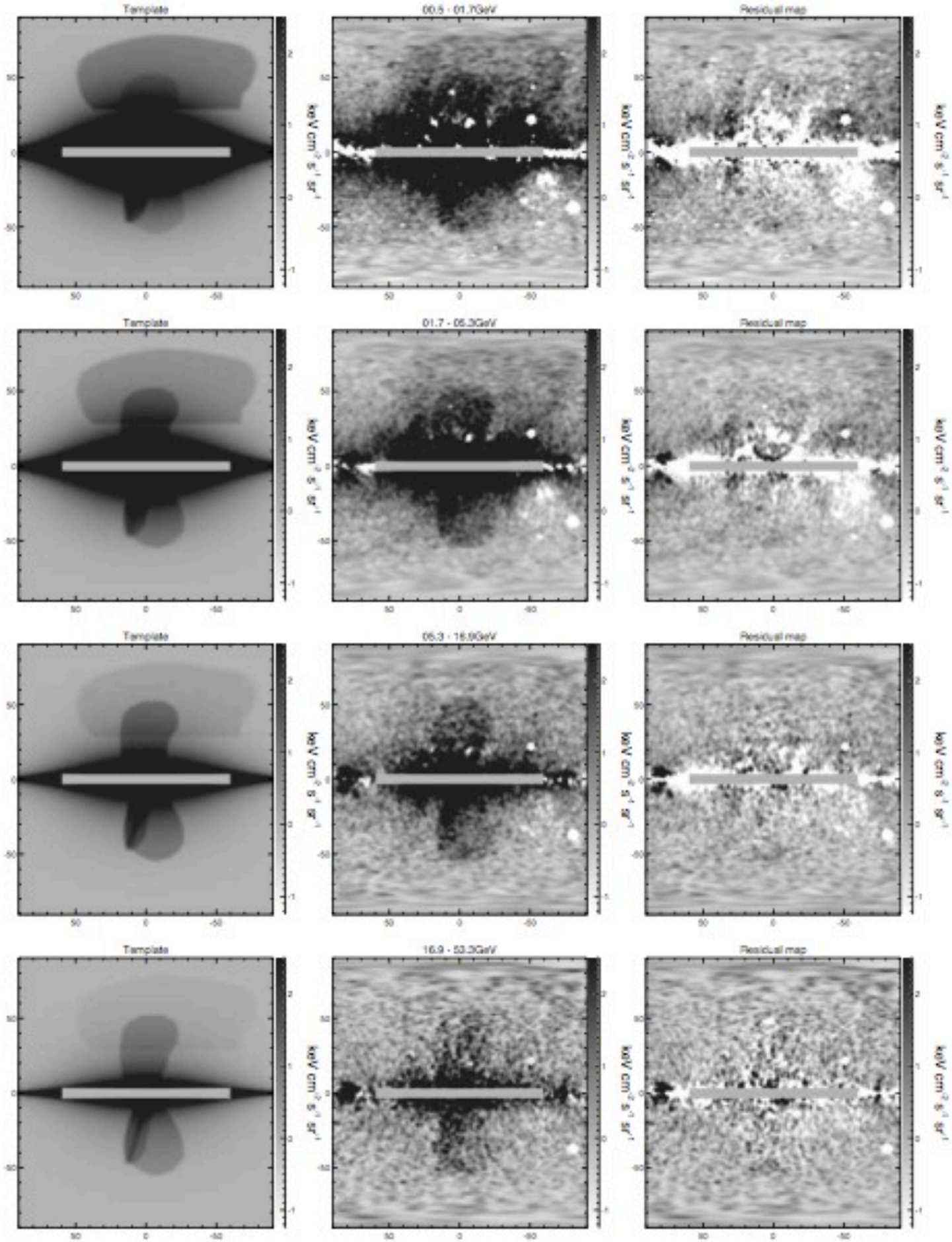
Su & Finkbeiner (2012)

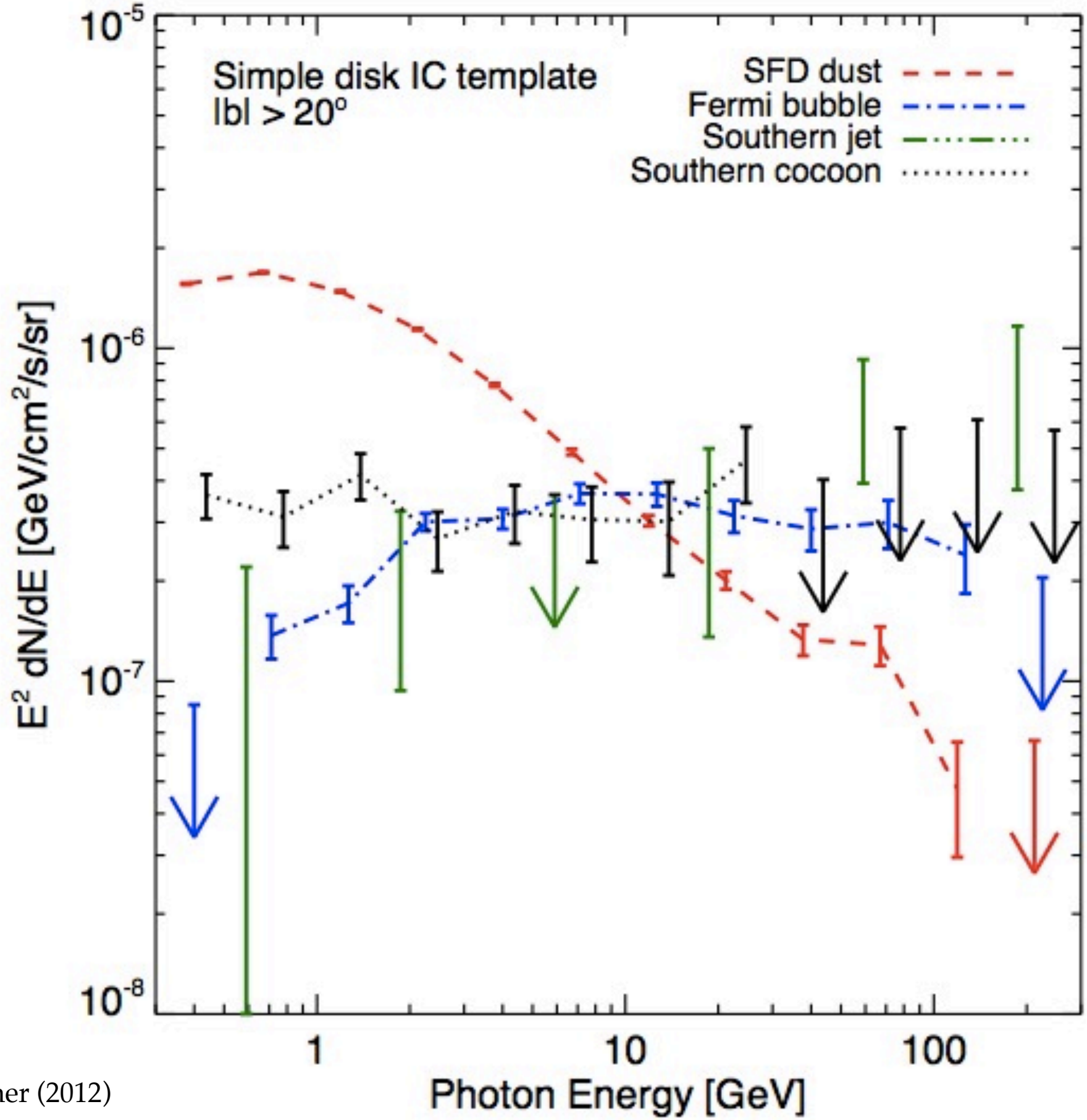
Leaving out dust-correlated π^0 emission
Fit is done for $|b| > 20^o$



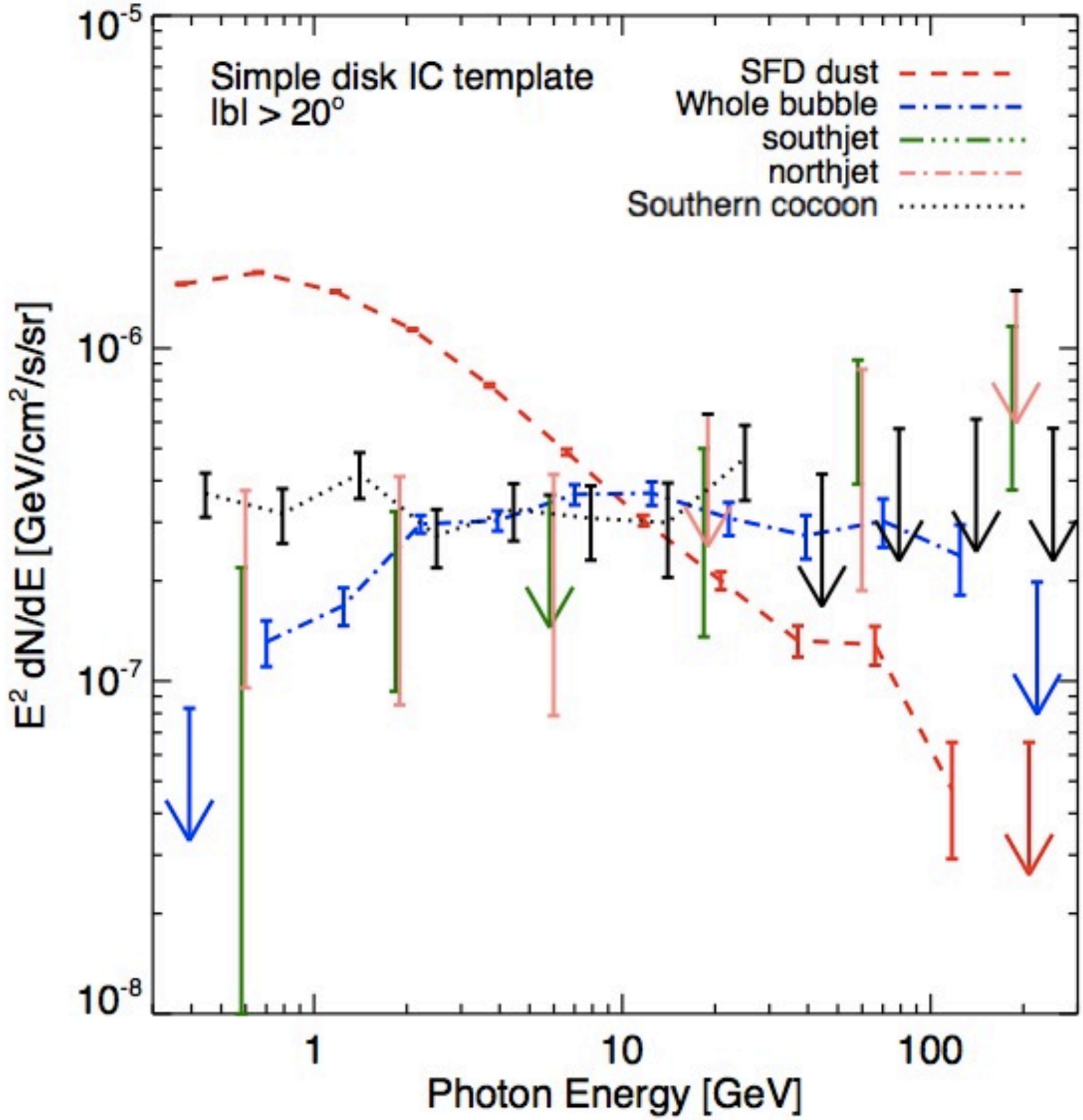
Now do this in each energy bin...

Su & Finkbeiner (2012)

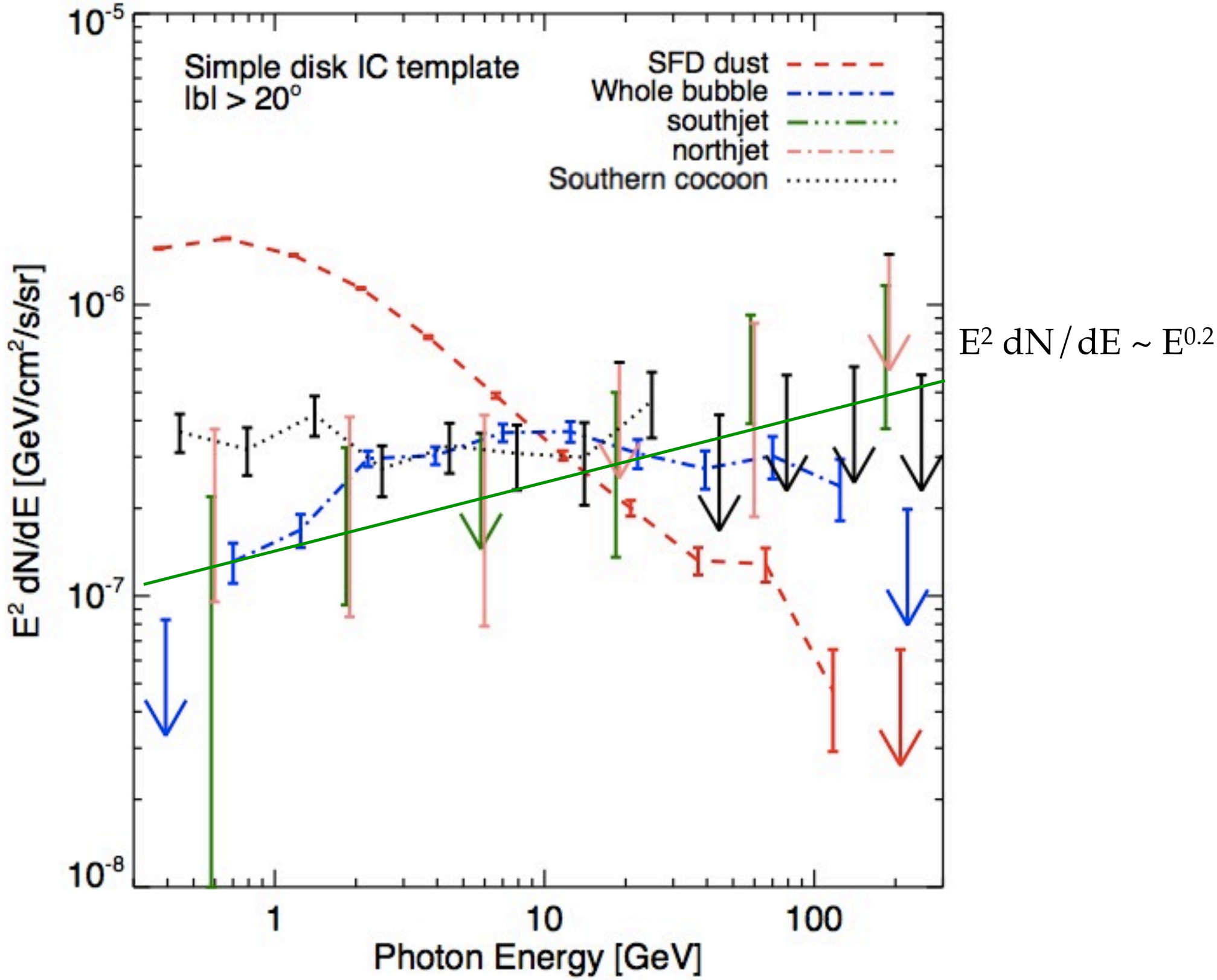

Template
00.5 - 01.7GeV
Residual map
01.7 - 05.3GeV
05.3 - 16.9GeV
16.9 - 53.3GeV
keV cm^{-2} s^{-1} sr^{-1}



Su & Finkbeiner (2012)



Su & Finkbeiner (2012)



Su & Finkbeiner (2012)

Significance (over 0.3-300 GeV):

- North jet: 3.1 sigma
- South jet: 4.1 sigma
- Jointly: 5.1 sigma

- Cocoon: 12 sigma

Conclusions (so far)

- With significance levels like these, why is this not "a discovery?"

- We are calling this "evidence for" jets. We would like to see these confirmed at another wavelength.

- Future all-sky x-ray data (*eRosita*) and microwave data (*Planck*) may clarify the situation.

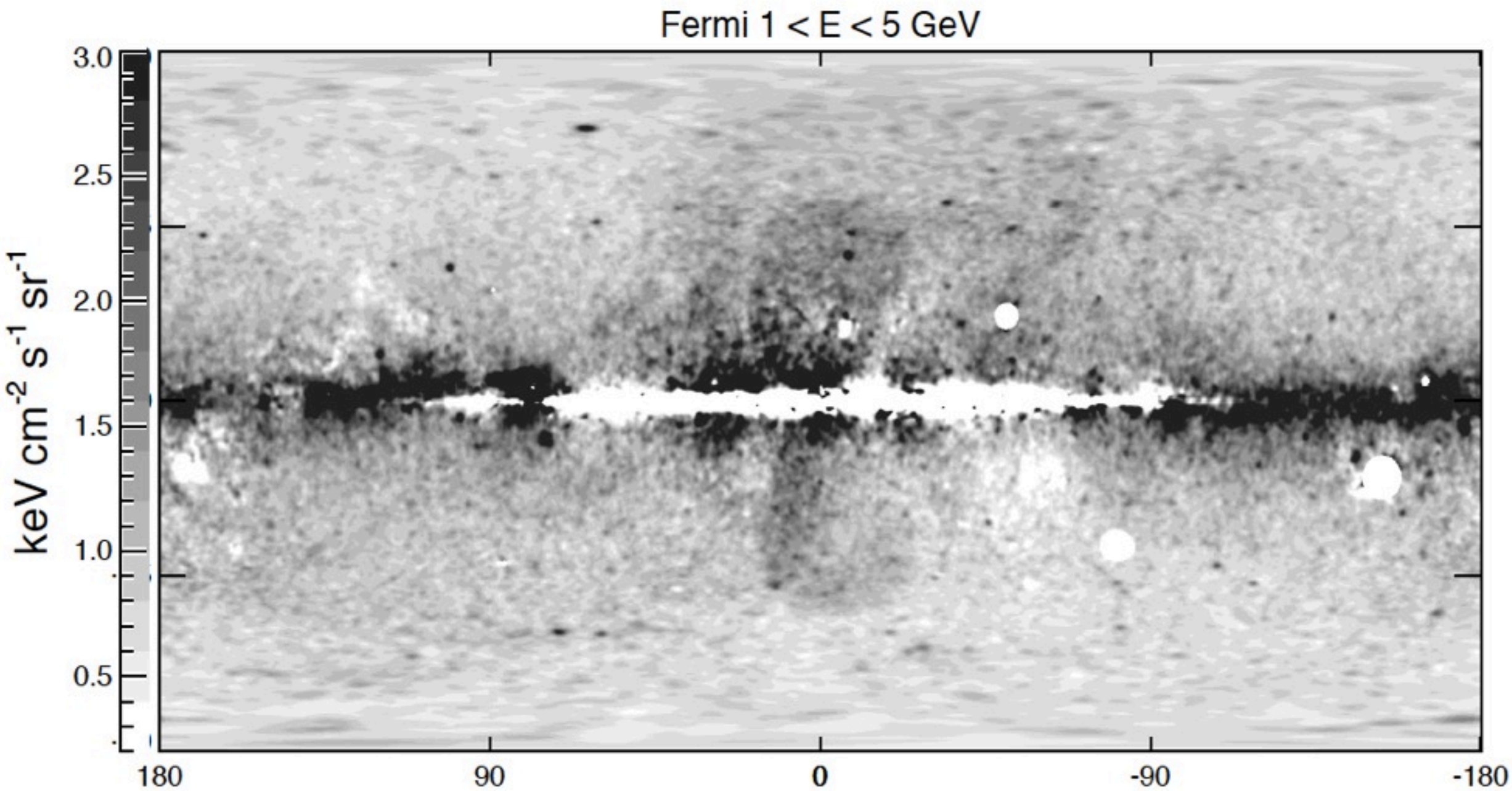
- See arXiv:1205.5852

Hot off the press (4.5-5.0 years of data, thanks to Meng Su)

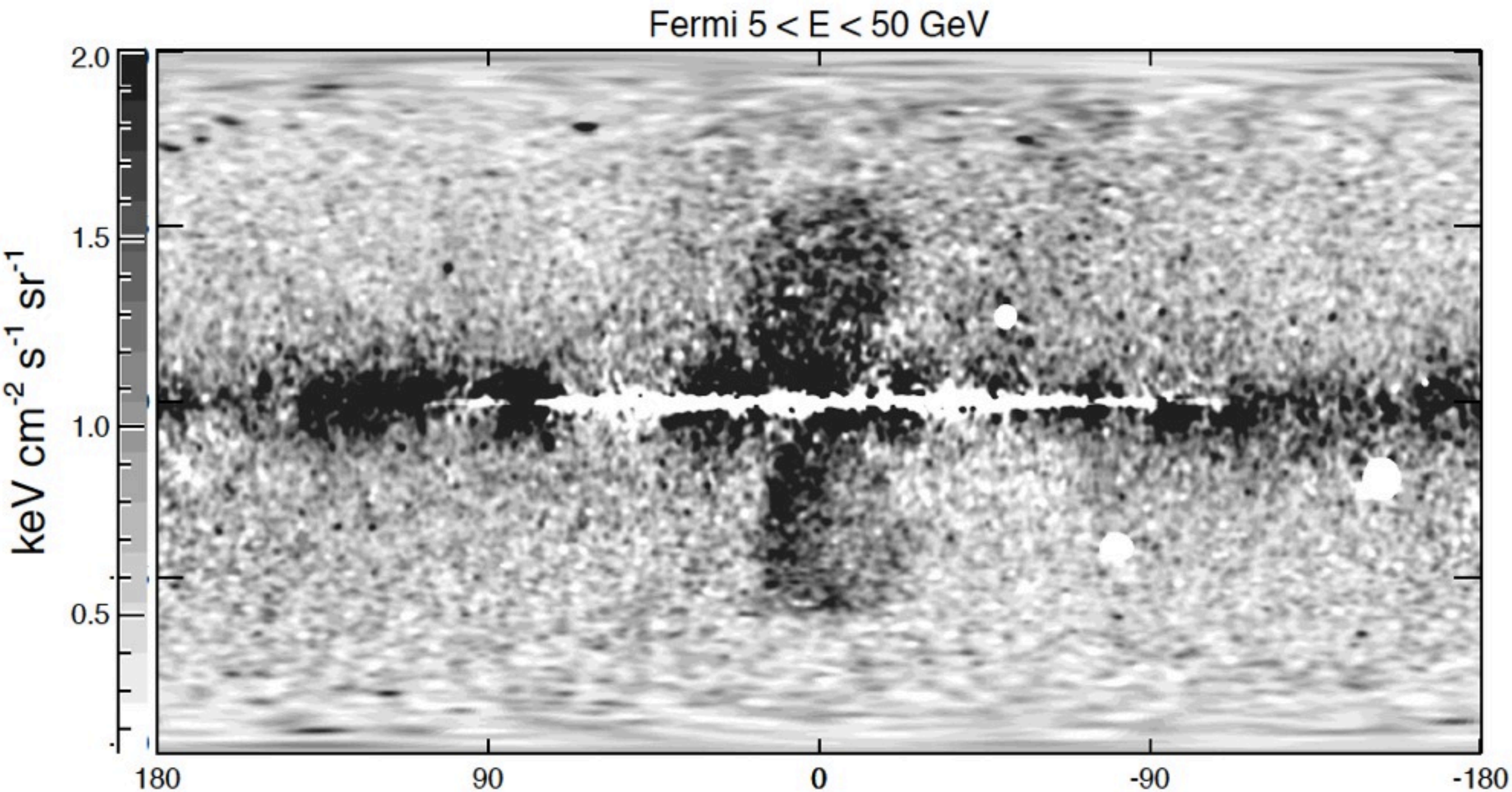
- Many of these predict that the Fermi Bubble spectrum is ~ flat up to E >> 100 GeV.

- But the energy spectrum falls above 100 GeV.

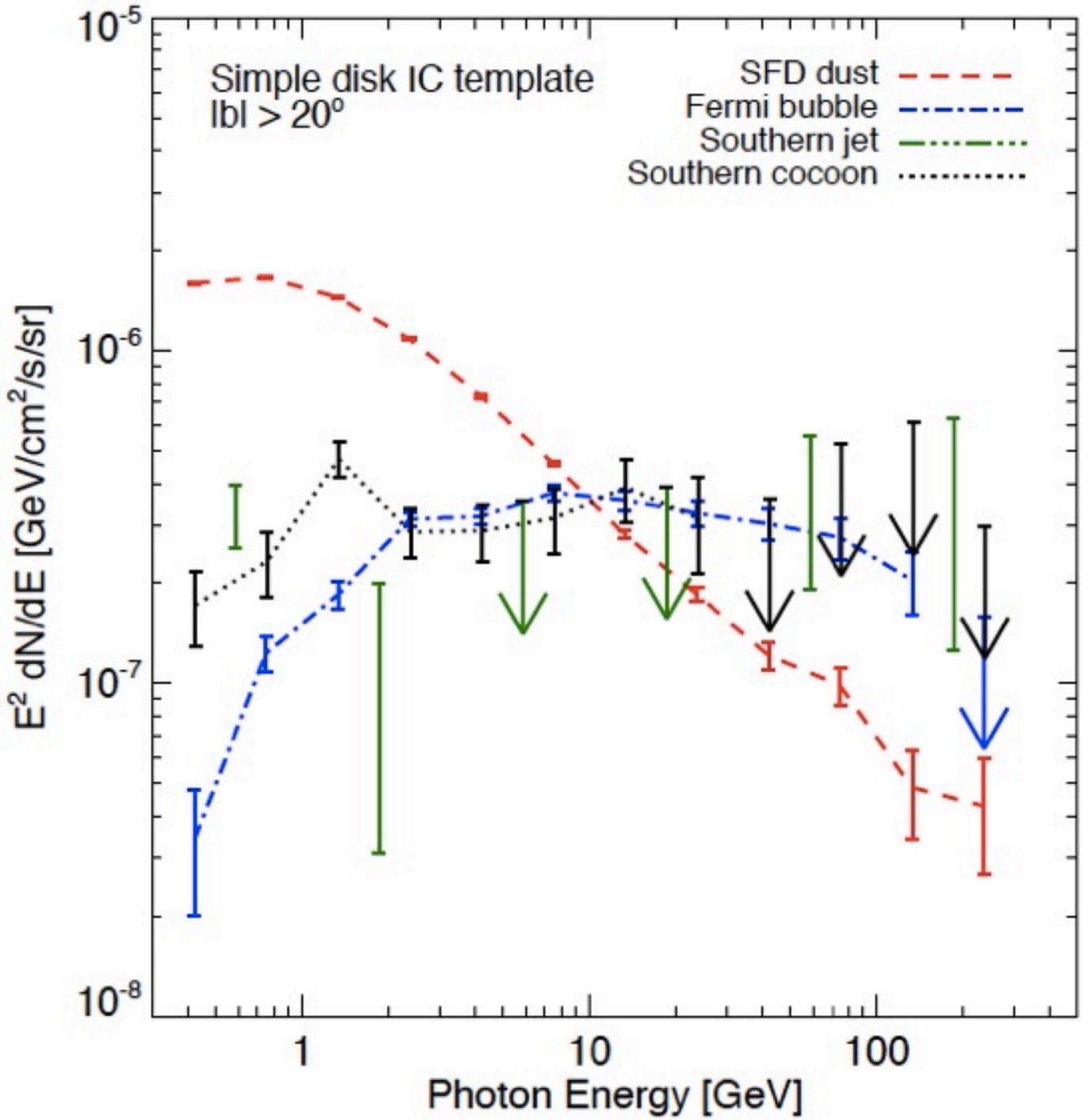
Bubbles, cocoon are obvious at 1-5 GeV
(extra point sources have appeared)



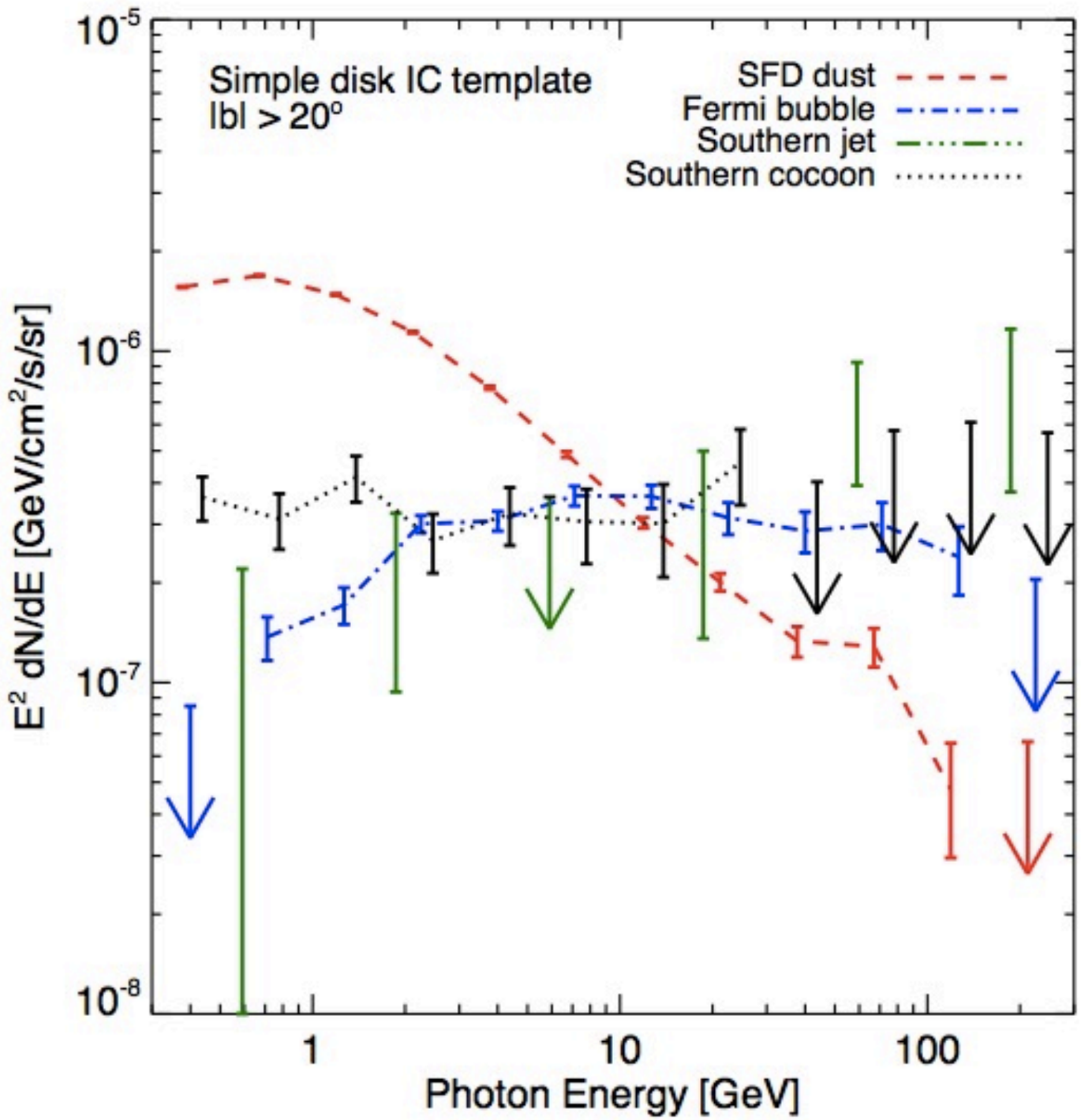
Also at 5-50 GeV...



4.5 yr: Jet fluctuated up in lowest bin, down in next bin...



3 year data



Su & Finkbeiner (2012)

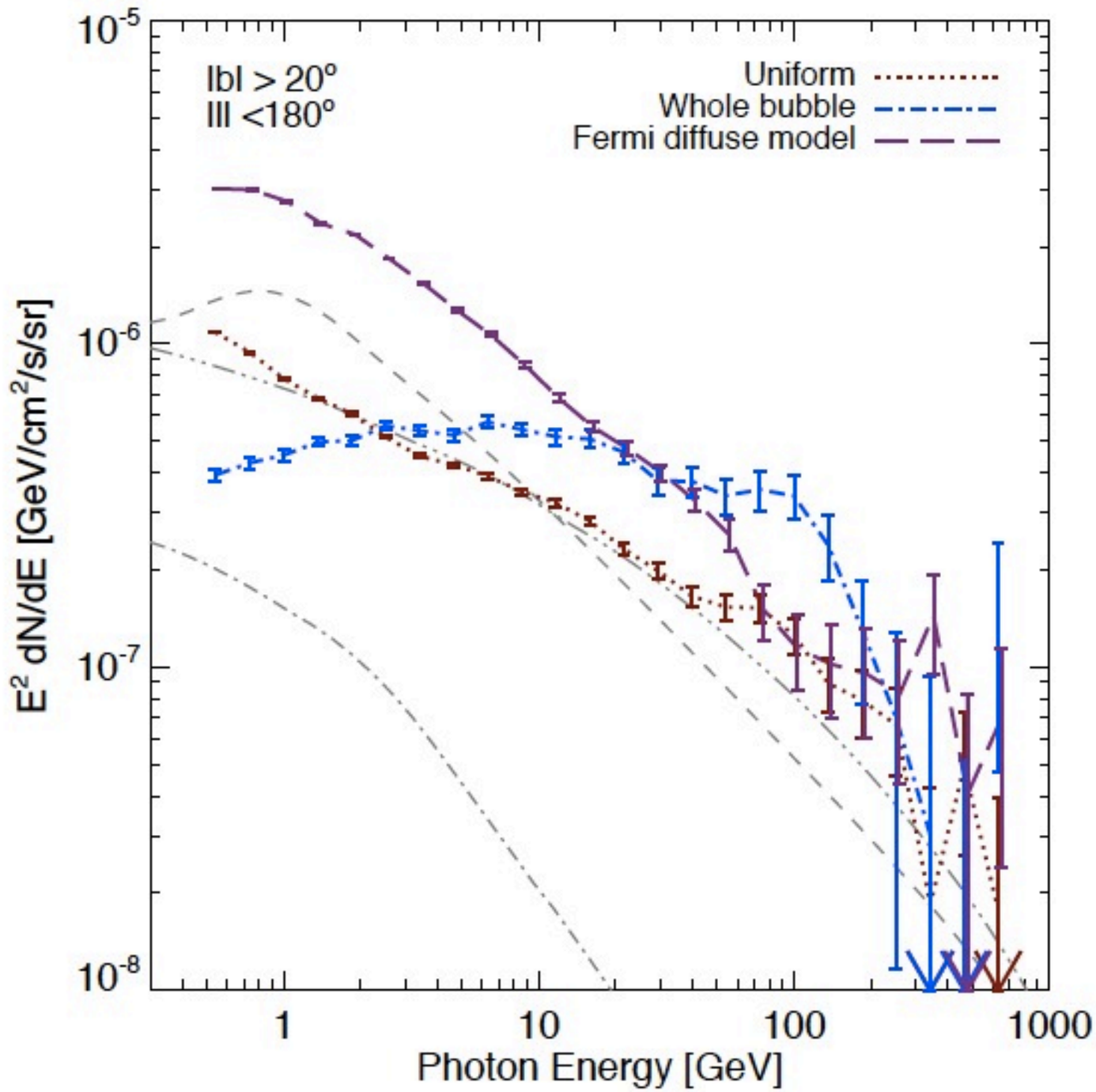
Now with 5 years of data we have enough photons to use finer E bins...

Because the π^0 emission is the largest component of our fit, we are especially concerned about our template.
We try various assumptions for the π^0 template:

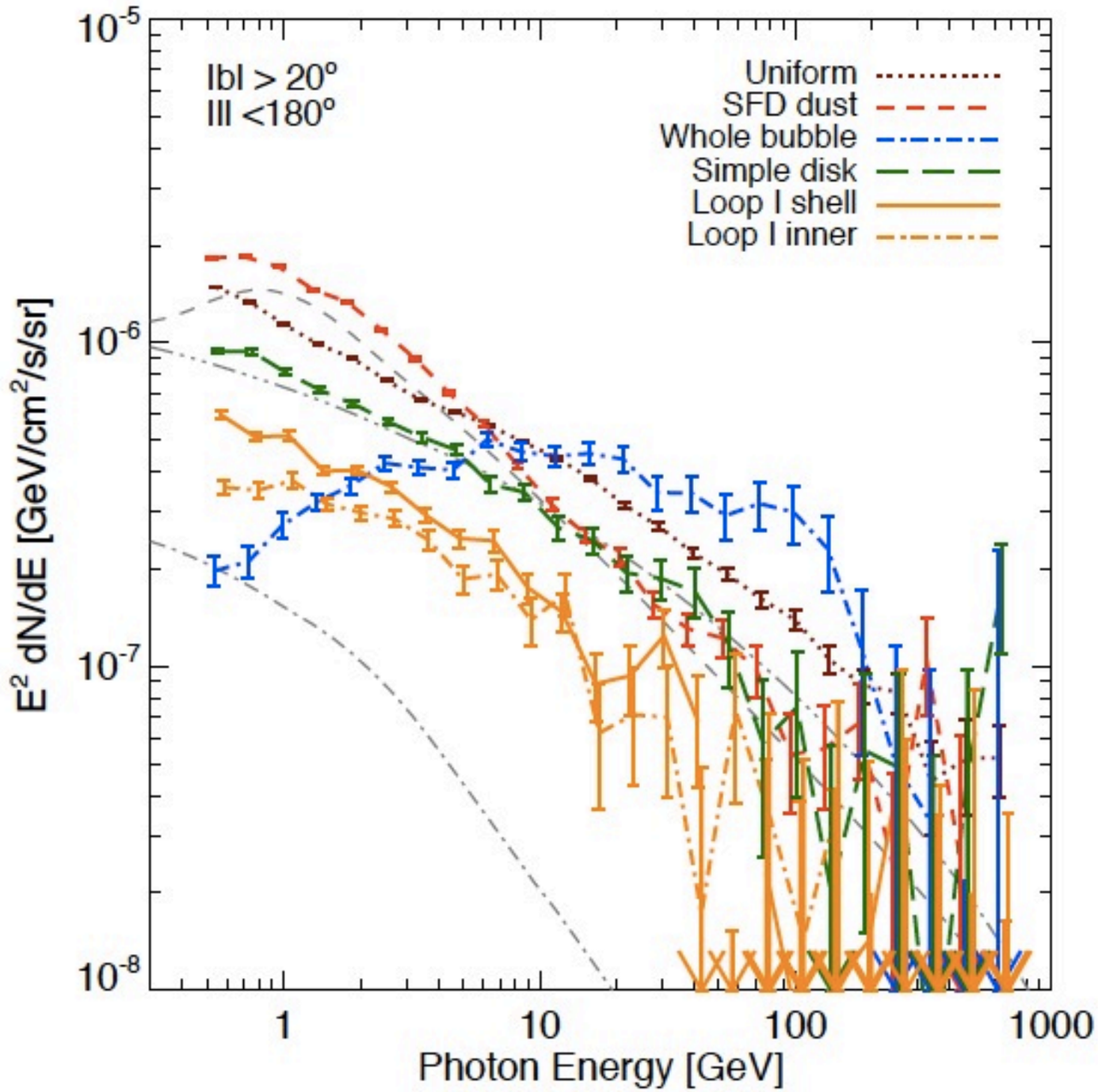
- SFD (1998) dust
- Fermi diffuse model (P6 -- no bubbles included)
- Planck 857 GHz
- Planck dust

All give similar results

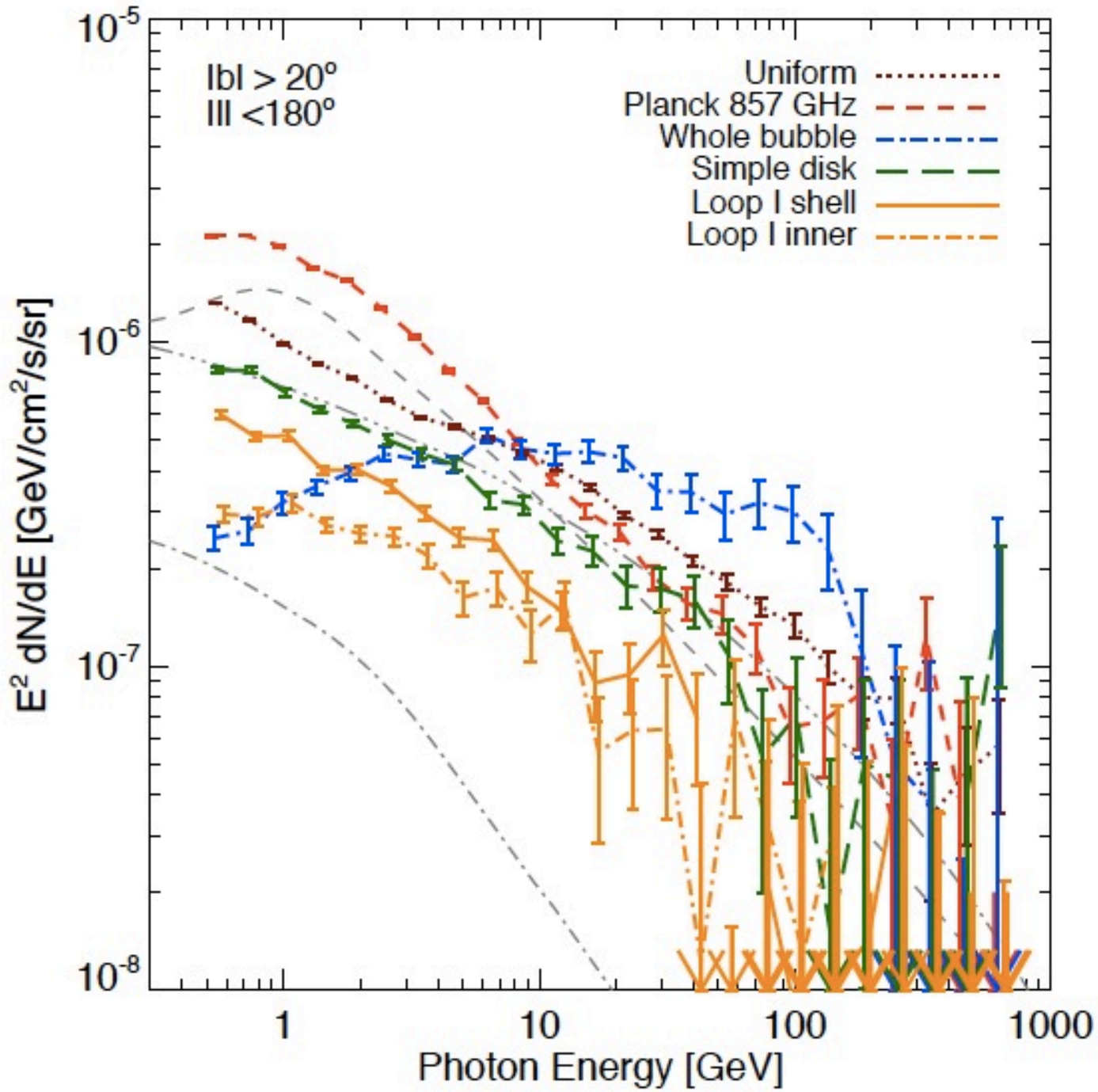
π^0 template: Fermi diffuse model



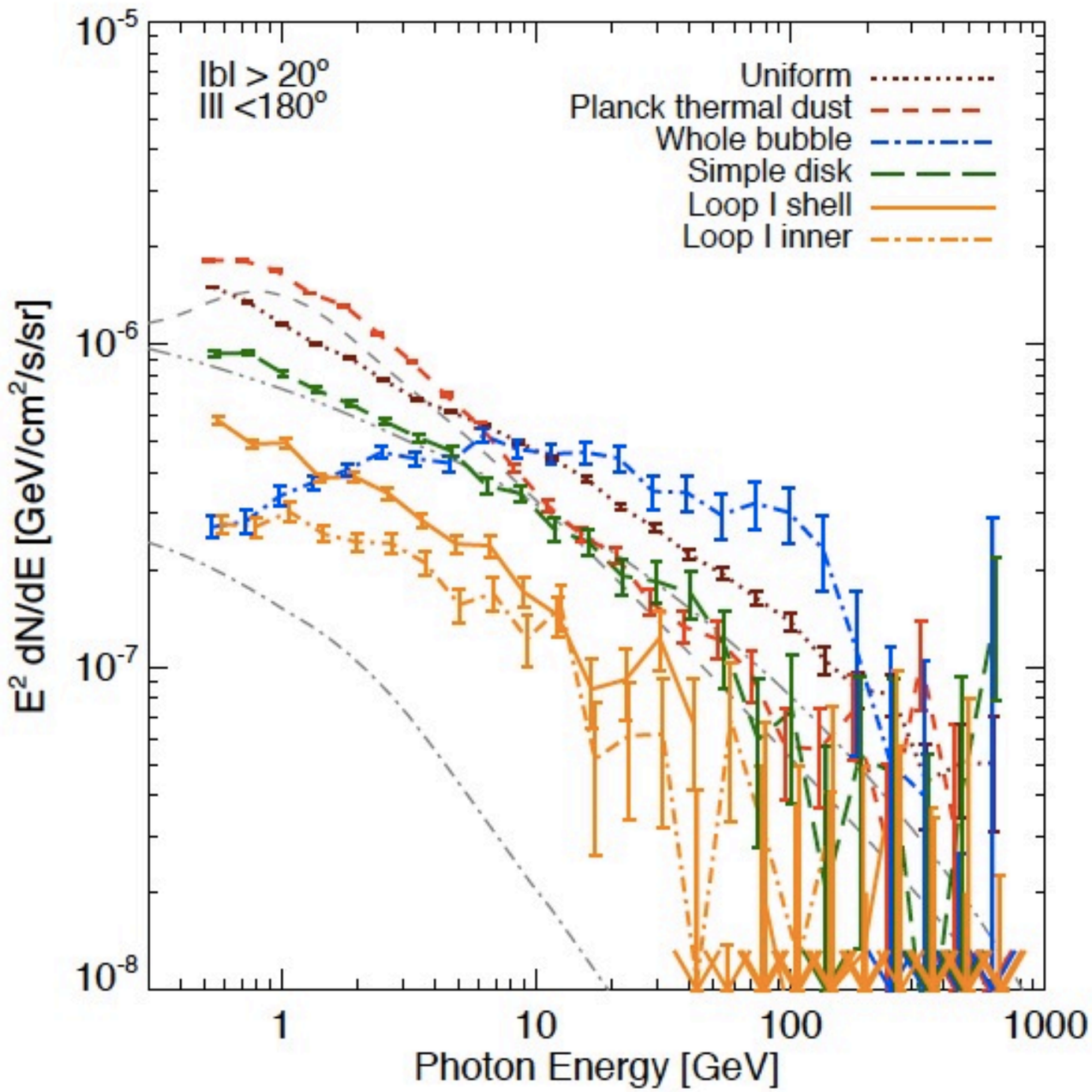
π^0 template: SFD (1998) dust map



π^0 template: Planck 857 GHz

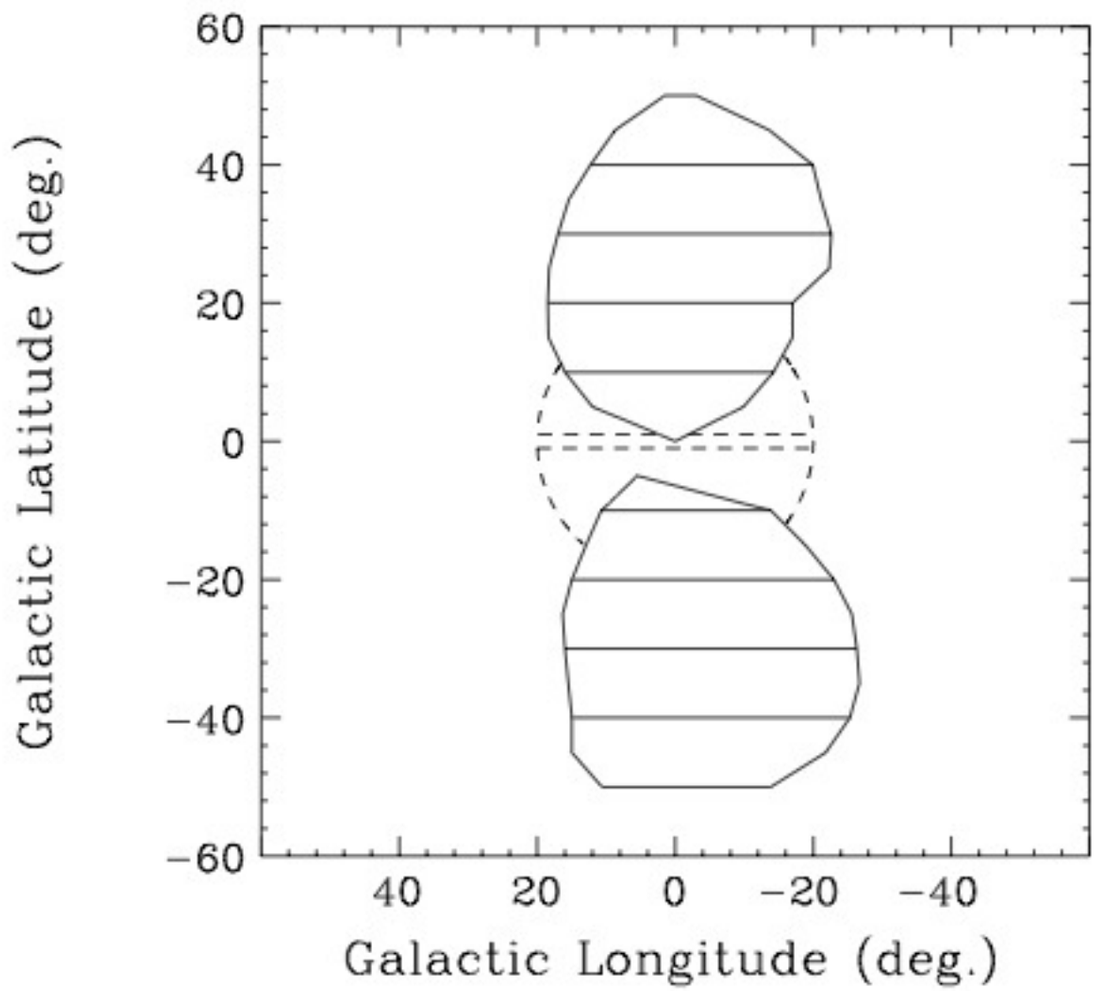


π^0 template: Planck thermal dust

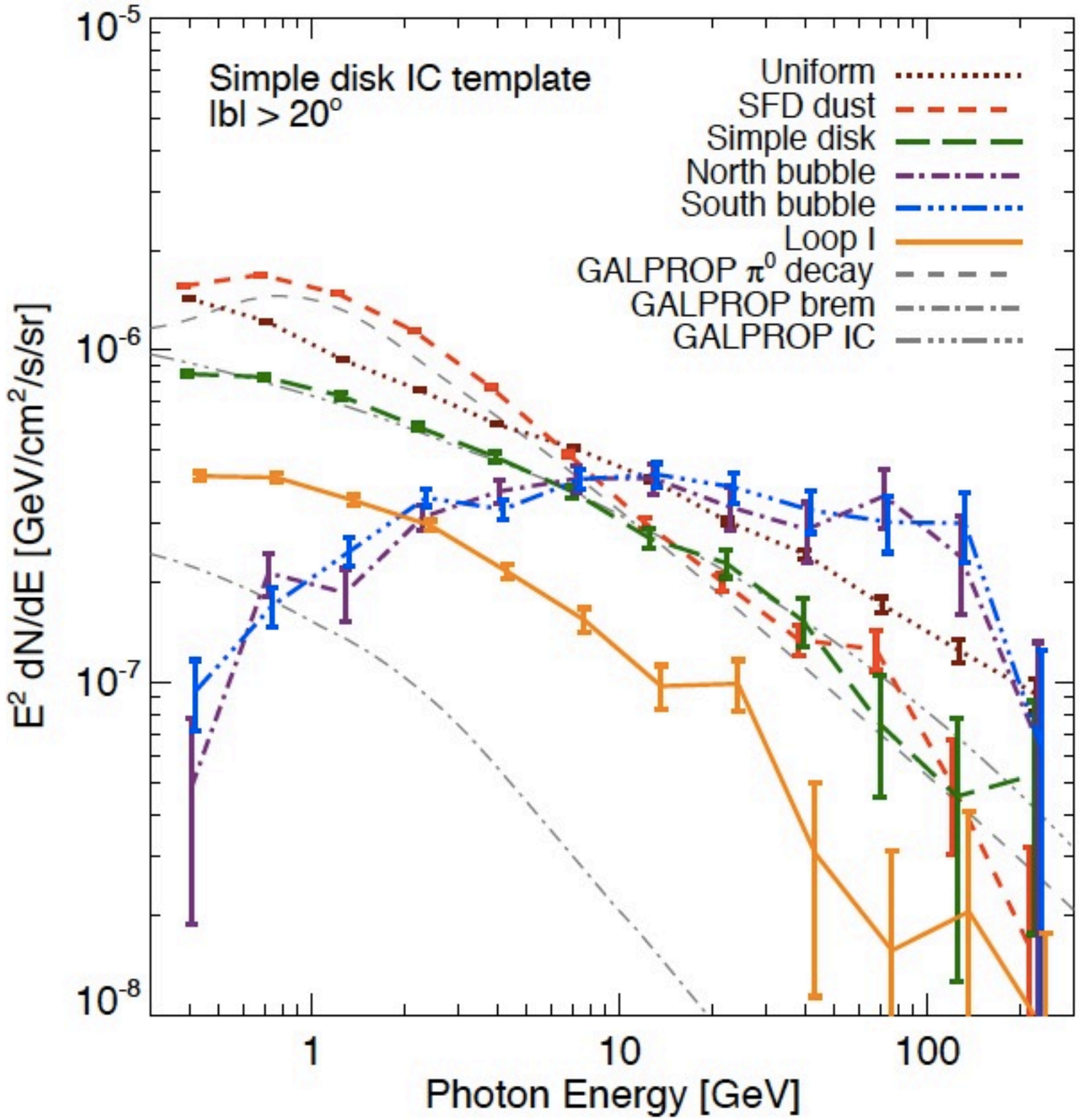


Regardless of template choice, the Fermi bubble spectrum falls “off a cliff” between 100 and 200 GeV.

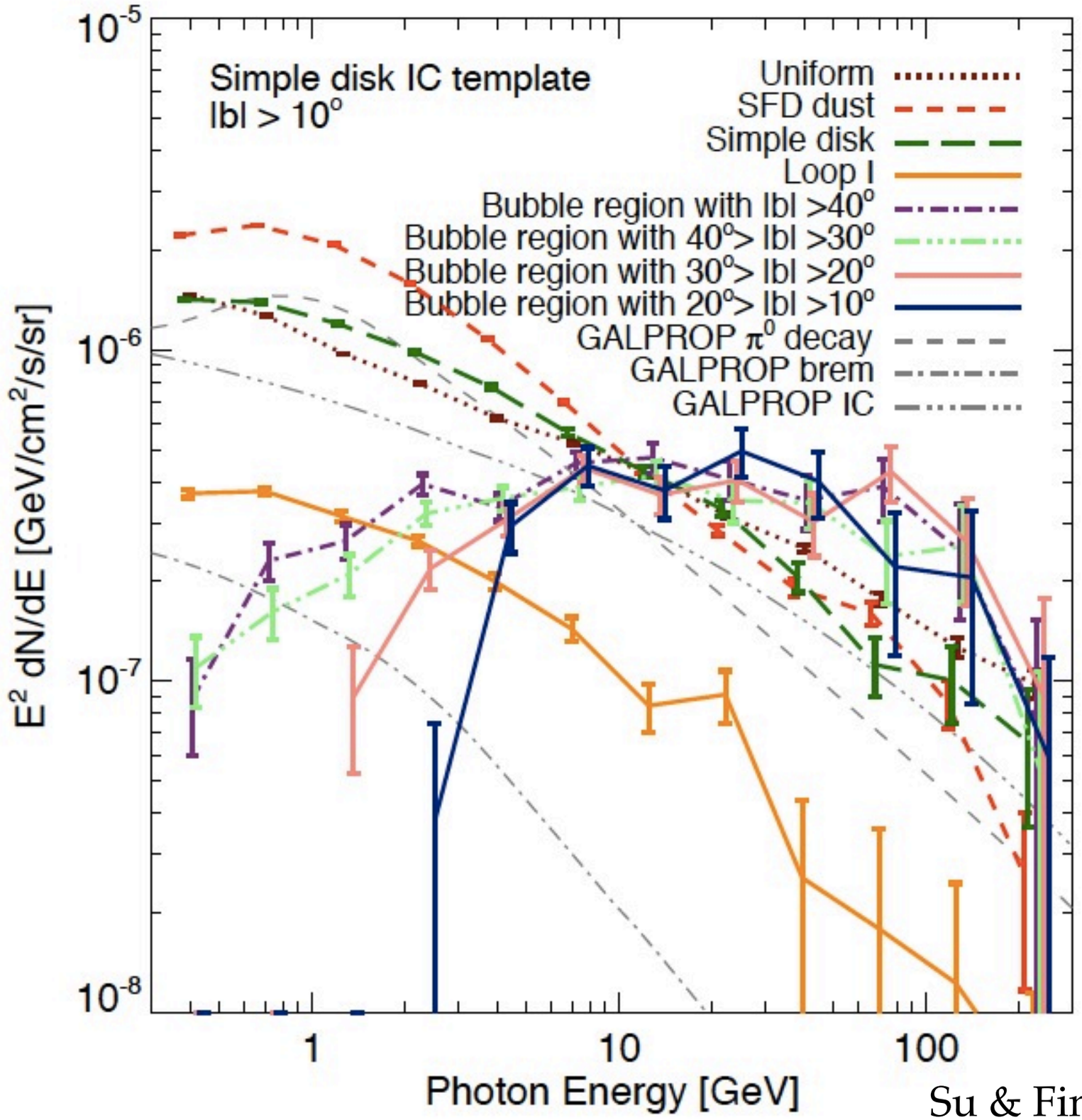
We can also use our 5 years of photons to split the Fermi Bubbles into latitude bins and see how the spectrum varies...



Hooper & Slatyer (2013)

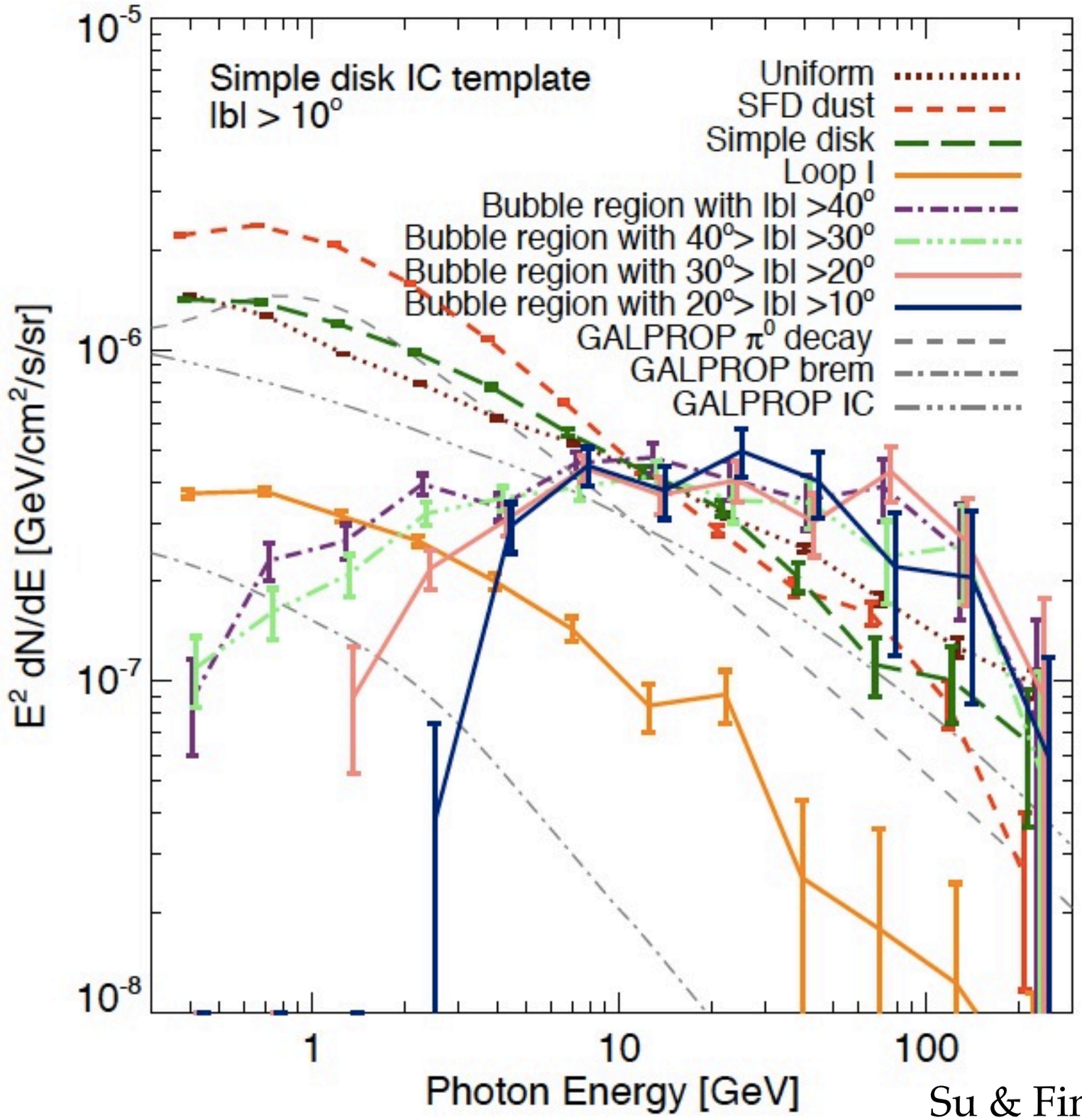

Simple disk IC template
|b| > 20°
Uniform
SFD dust
Simple disk
North bubble
South bubble
Loop I
GALPROP π0 decay
GALPROP brem
GALPROP IC
E2 dN/dE [GeV/cm2/s/sr]
10-5
10-6
10-7
10-8
1
10
100
Photon Energy [GeV]

From 10-40 deg, spectrum at E > 5 GeV is the same



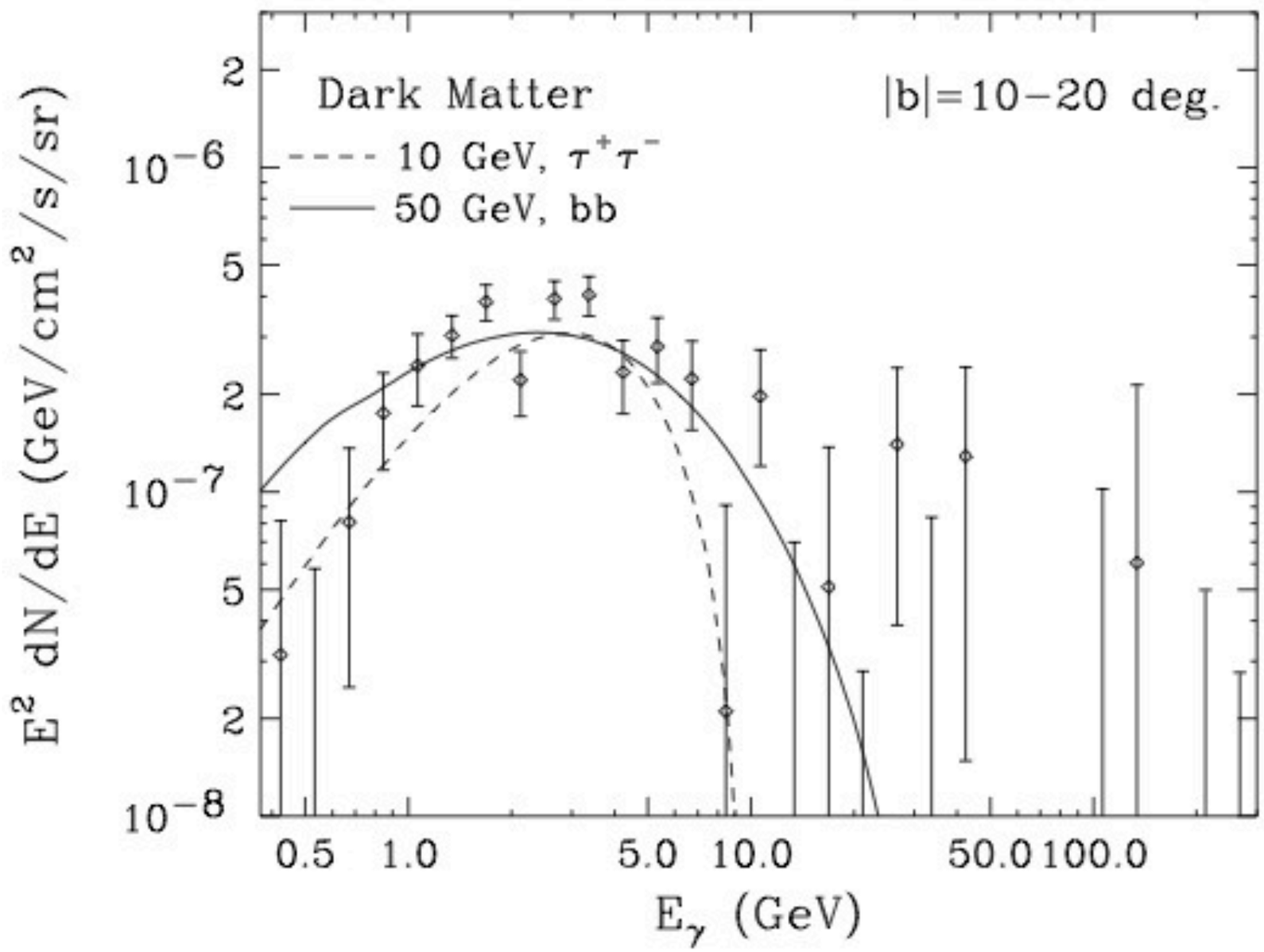
Su & Finkbeiner (2014)

Not sure we believe variation at low E...

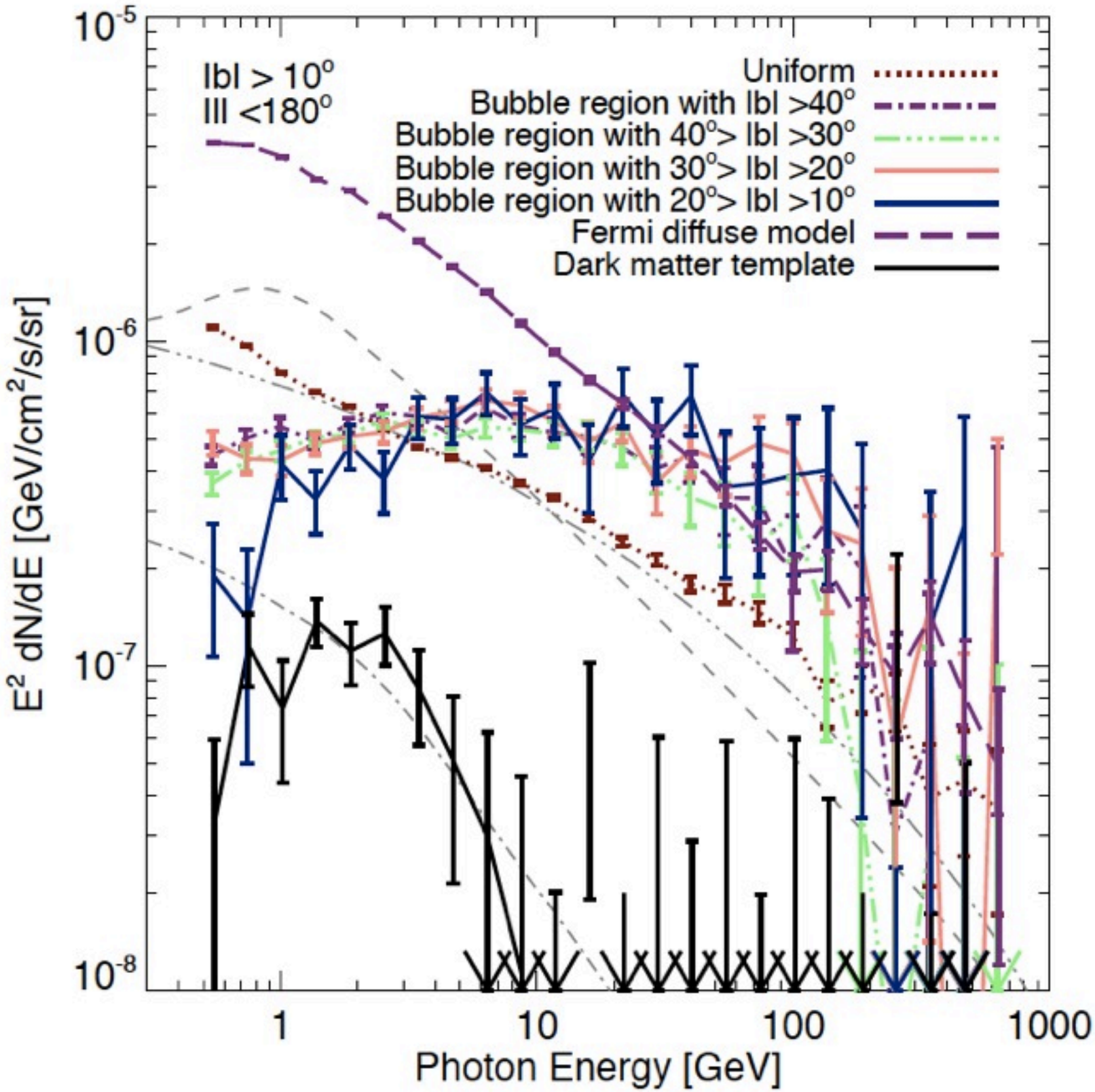


Su & Finkbeiner (2014)

This variation drove Hooper & Slatyer (1302.6589) to include a "dark matter" (NFW-like) template in the fit. (building on previous work with Tim Linden)



So we did the same:



Outstanding questions

- What does it mean that the spectrum falls so rapidly at high energy?
- Is the gamma-ray edge a shock or a contact discontinuity?
- Do we believe the low energy fall off yet? Why is it latitude dependent?
- Are the "jets" real?
- What is the ~ few GeV ~ NFW bump?
- What additional data would shed light on these questions?

Need more data!

Thanks

- Meng Su (analysis)
- Fermi Team
- Jerry Ostriker, Roland Crocker, Mateusz Ruszkowski, Tim Linden (helpful conversations)
- IAU SOC (for inviting me to speak)