Double Bubble Trouble: Mysterious Extended Gamma-Ray Structures in the Milky Way

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with Douglas Finkbeiner & Meng Su (ApJ 724:1044-1082, 2010)
building on prior work with
Ilias Cholis, Greg Dobler, Douglas Finkbeiner & Neal Weiner
(ApJ 717:825-842, 2010)

Cornell University
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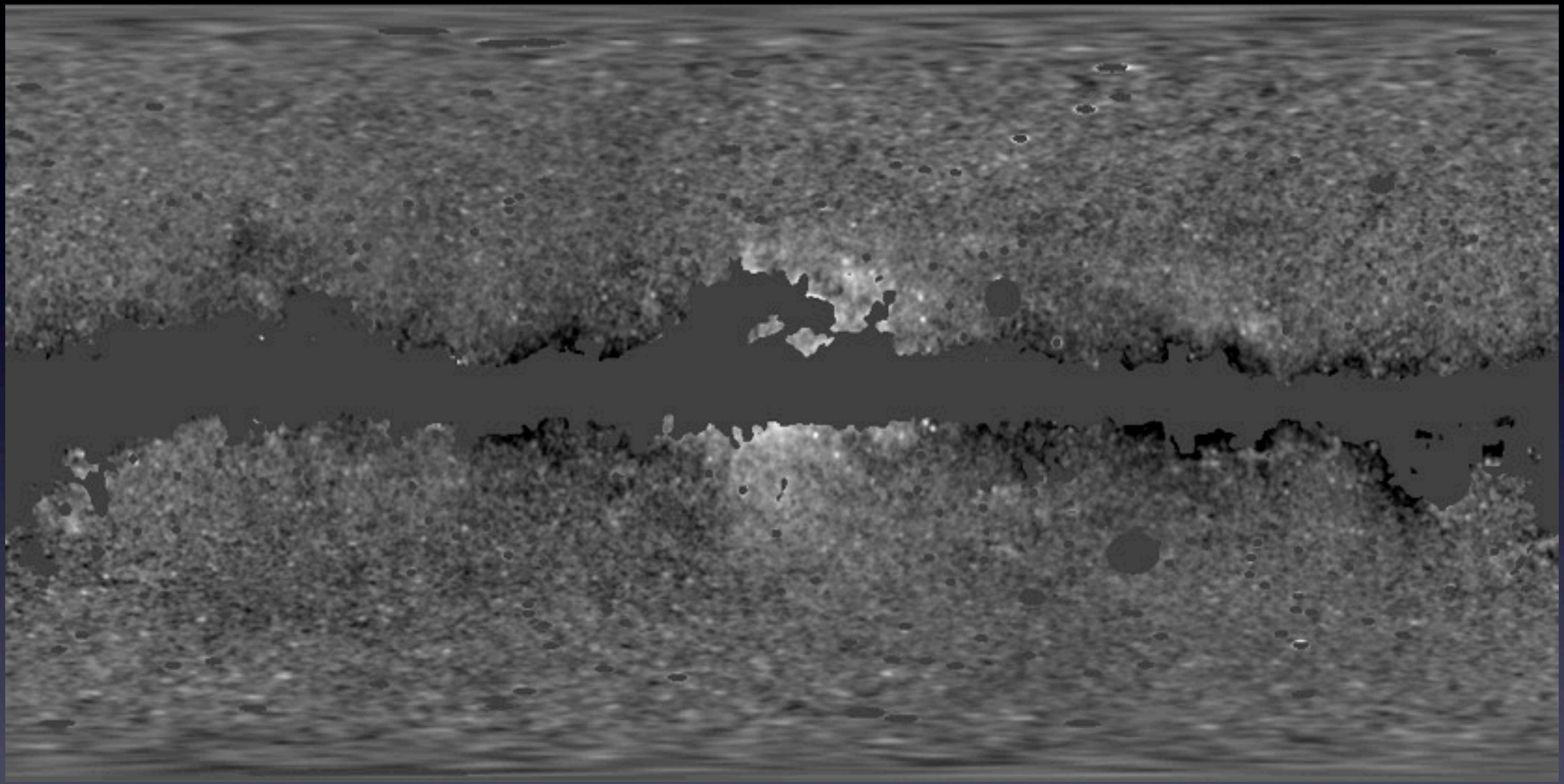
Main points

- There are unexplained excesses of both hard microwaves (“WMAP haze”) and hard gamma-rays (“Fermi haze”) in the inner Galaxy.
    - Neither have disk-like profiles; gamma-ray emission is extended perpendicular to the plane.
    - Spectra and intensities of the signals are broadly consistent with synchrotron + ICS from same power-law electron population.
- At high latitudes (|b| ~ 30-50°), hard gamma-ray emission has sharp edges (degree-scale or less), and is visible **before** any background/foreground subtraction. NOT an artifact.
- Sharp edges appear to extend in to the GC, although here the subtraction matters. Not all “hazy” hard emission is contained in sharp-edged structure.
- Most likely some kind of outflow from the GC. Unlikely to be purely dark matter (robust high-latitude sharp edges, hints at X-ray counterpart) - but needs to be understood for DM search in this region!

The WMAP Haze



Finkbeiner 2004, 23 GHz residual

- Finkbeiner 2004: take WMAP data, regress out spatial templates for known emission components - thermal dust + soft synchrotron (Haslam 408 MHz radio survey) + thermal bremsstrahlung (Hα map for ionized gas) + CMB.
- Hard-spectrum residual in inner ~20°: spherical shape? extended latitudinally?

Haze Hypotheses

1. Synchrotron vs free-free emission
   - Free-free:
     - Predicted spectrum harder than observed,
     - Energy implies thermally unstable gas - not a steady state.
   - Synchrotron:
     - Observed spectrum implies harder electron spectrum than elsewhere in the Galaxy,
     - We expect a polarization signal and none is observed (due to tangled B-fields?),
     - Robustly predicts gamma-ray emission due to inverse Compton scattering of starlight by same electron population.
2. If synchrotron, where do hard electrons come from? Expected from normal production, or do we need an exotic source? DM annihilation?

The WMAP Haze as DM

Hooper, Finkbeiner & Dobler 2007

- Need to produce hard electron(/positron) spectrum, spatially extended around the Galactic Center (pulsars have trouble here).
- Required DM annihilation cross section / decay rate depends on SM final state, magnetic field, DM density profile, CR propagation parameters.
- However, DM annihilation works for reasonable values of these parameters (for heavy DM, requires higher than thermal relic xsec). Radial profile fits well.
- Can fit simultaneously with local e^+e^- spectrum measurements by PAMELA, Fermi (Lin, Dobler & Finkbeiner 2010).

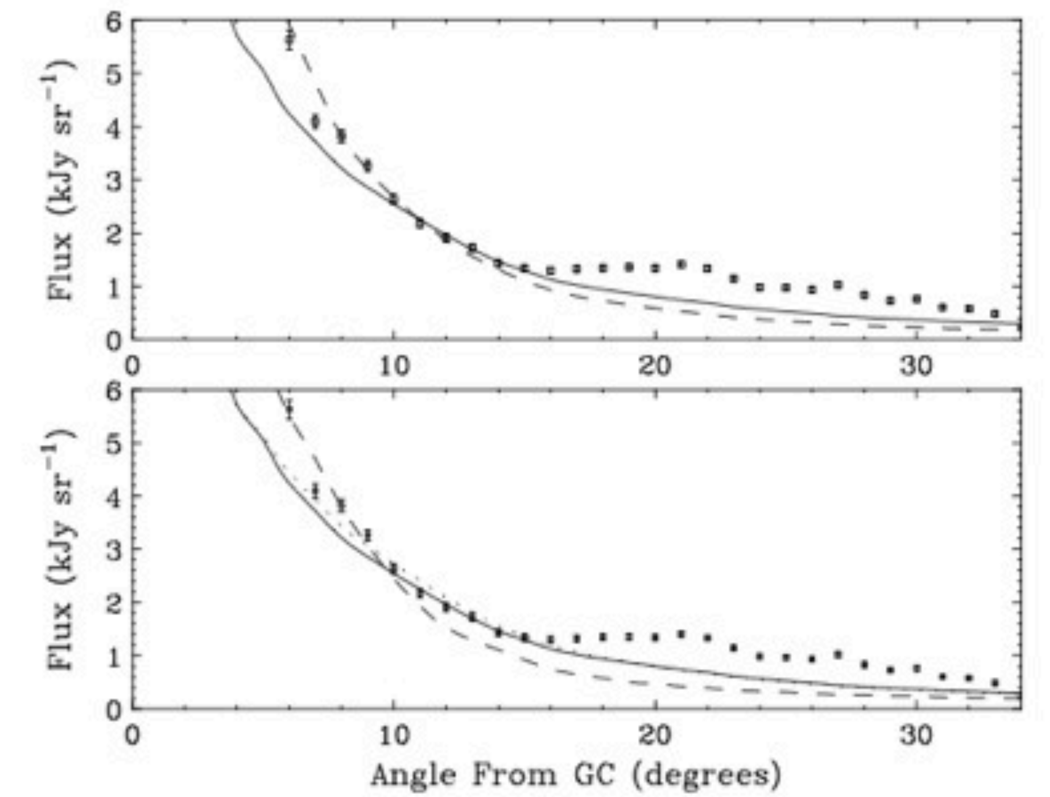
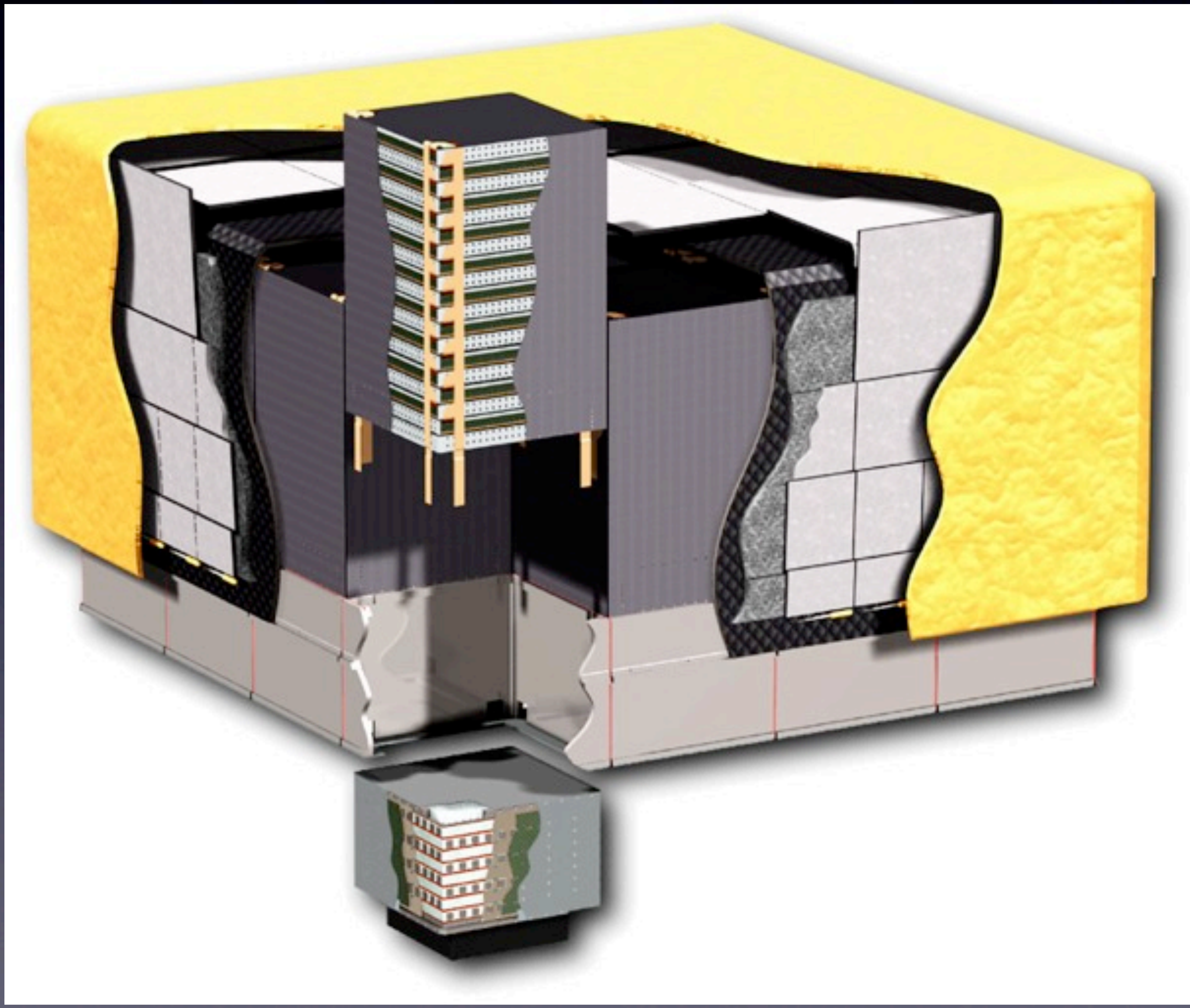


FIG. 2: The specific intensity of microwave emission in the 22 GHz WMAP channel as a function of the angle from the Galactic Center, compared to the synchrotron emission from the annihilation products of a 100 GeV WIMP annihilating to e^+e^-. In the upper frame, our default diffusion parameters have been used. The solid line denotes the choice of an NFW halo profile, while the dashed line is the result from a profile with a somewhat steeper inner slope, $\rho(r) \propto r^{-1.2}$. In the lower frame, we have used an NFW profile with our default propagation parameters (solid), and with a smaller diffusion zone of $L = 2$ kpc (dashed), and a longer energy loss time of $\tau(1\,\mathrm{GeV}) = 4 \times 10^{15}$ s (dotted).

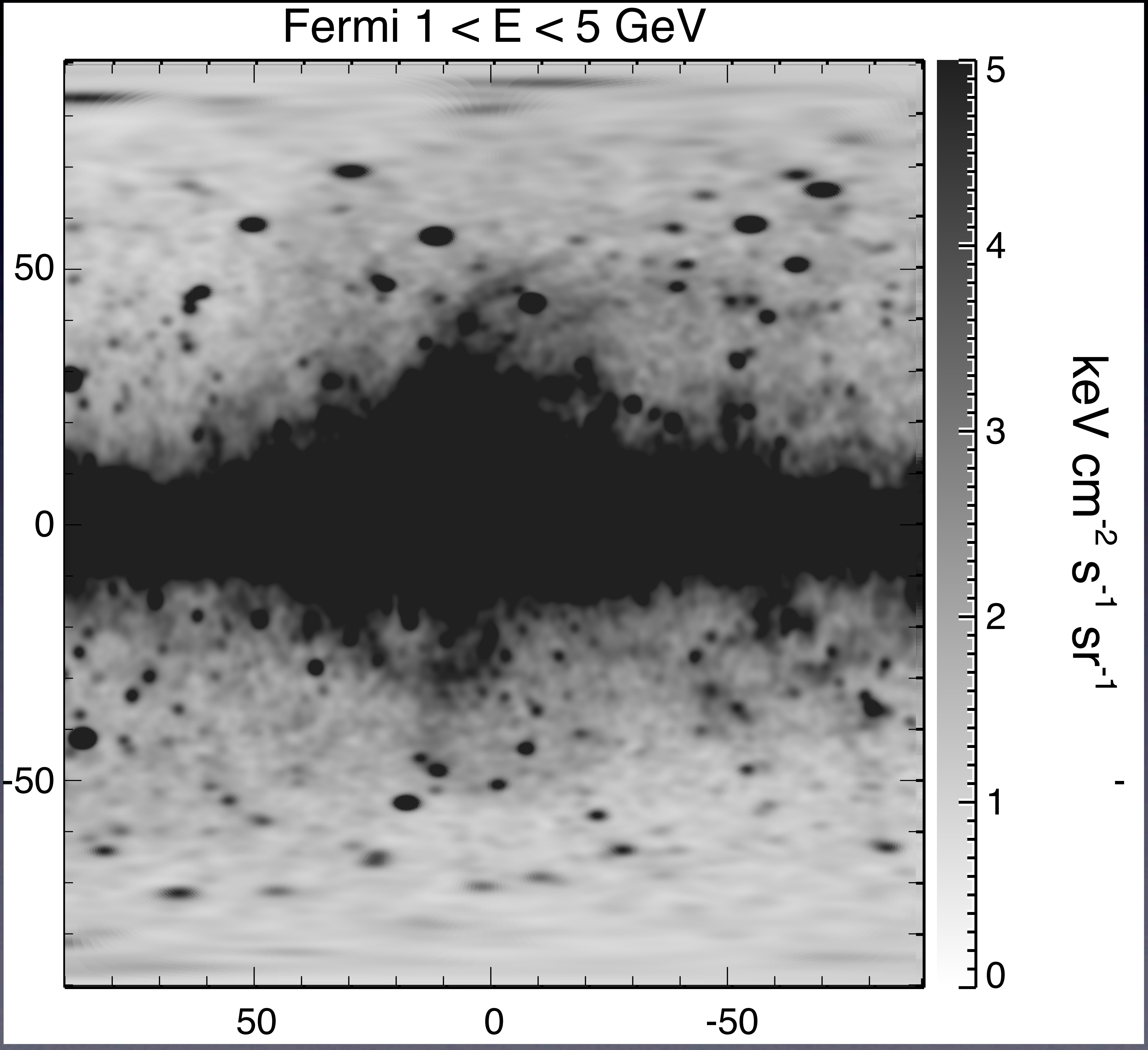
The Fermi LAT (Large Area Telescope)

- Pair-conversion telescope in low-Earth orbit
- 16 tungsten layers (where pair conversion occurs) interleaved with silicon-strip trackers, + calorimeter (thickness ~7 radiation lengths).
- Entire sky covered every two orbits
- Energy range 30 MeV - 300+ GeV
- >2 years of data publicly available



Point source subtraction

- Using 1-year Fermi point source catalog, subtract each point source from maps in each energy bin.
- For brightest + most variable sources, interpolate over core of PSF after best-estimate subtraction.
- Mask brightest point sources: Geminga, 3C 454.3, and LAT PSR J1836+5925.



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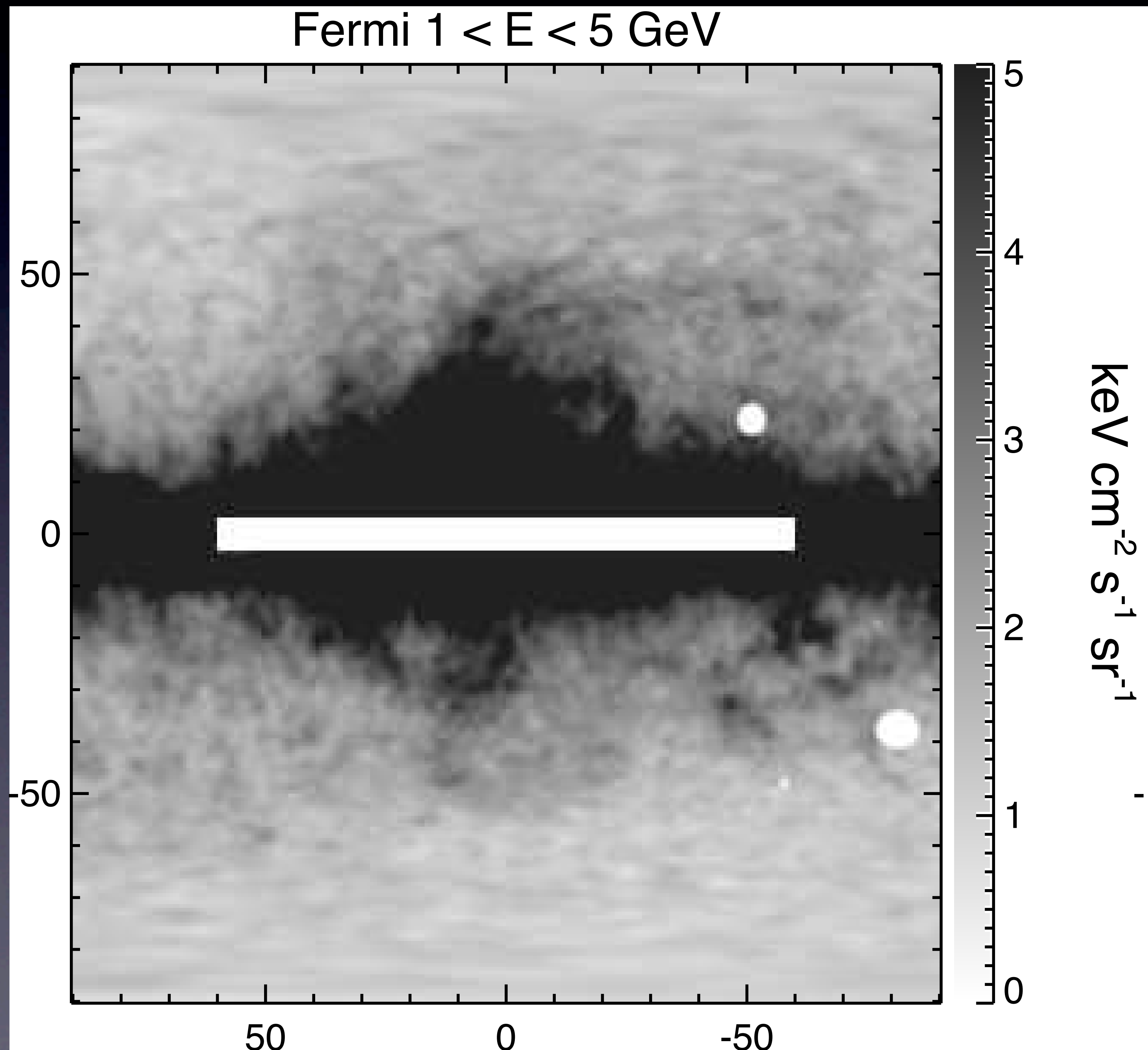


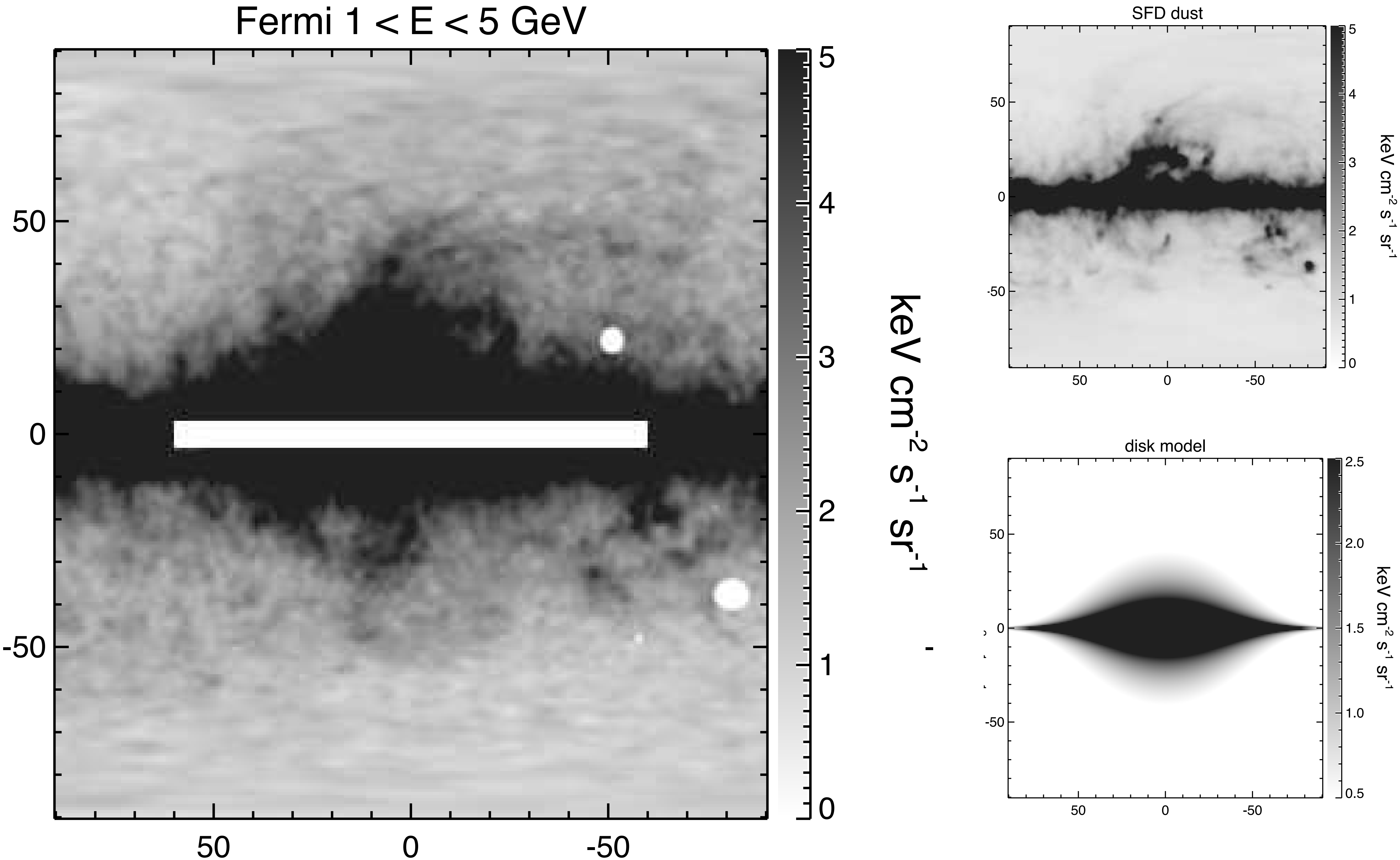
Gamma-ray backgrounds

- π^0 decay: Proton/heavy nuclei cosmic ray interactions with the ISM produce neutral pions, decay to pair of gamma-rays. Emission traces CR proton density (roughly constant) × gas density.
- Inverse Compton scattering (ICS): Electron CRs upscatter photons from the radiation field (starlight, infrared, CMB) to gamma-ray energies. Strongest along Galactic plane (closest to CR sources, strongest radiation field).
- Isotropic emission: extragalactic gamma-ray background + residual cosmic ray contamination.
- Bremsstrahlung: Electron CRs scattering on charged particles in the ISM radiate gamma rays. Generally subdominant.

Template analysis

- Let’s try something very simple...
- Model emission at each energy as a linear combination of (a small number of) spatial templates for the known emission components: describe the data with a very small number of parameters.
- We can then reconstruct spectra for each component from the coefficient of each template, as a function of energy.
- Does this give a reasonable approximate model of the data?

Example subtraction



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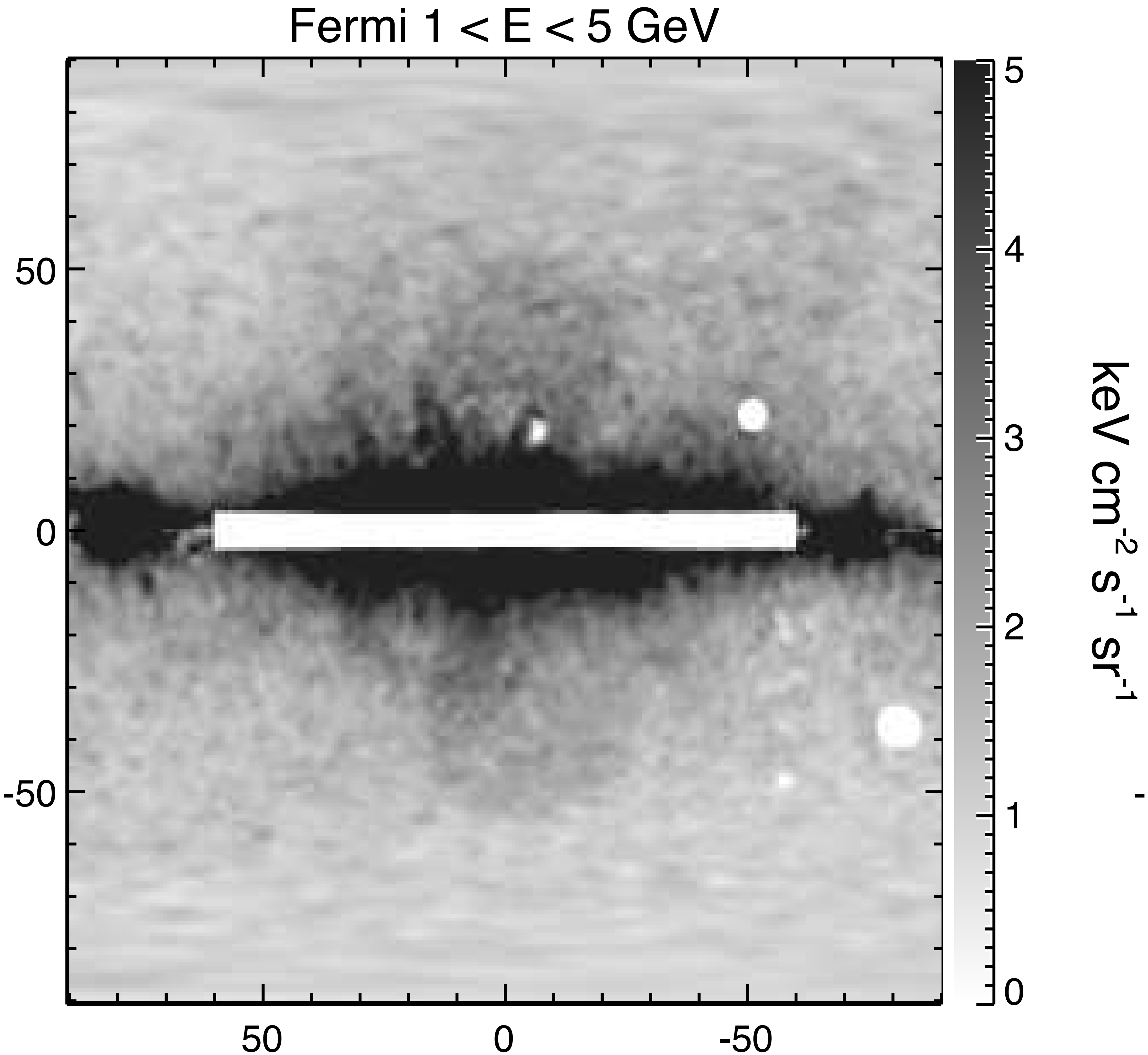

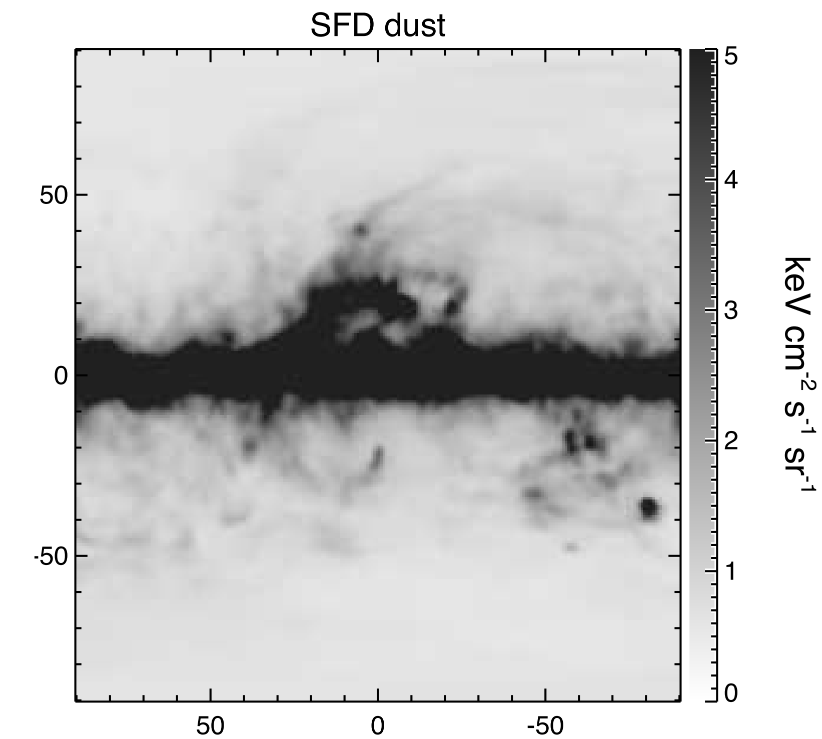

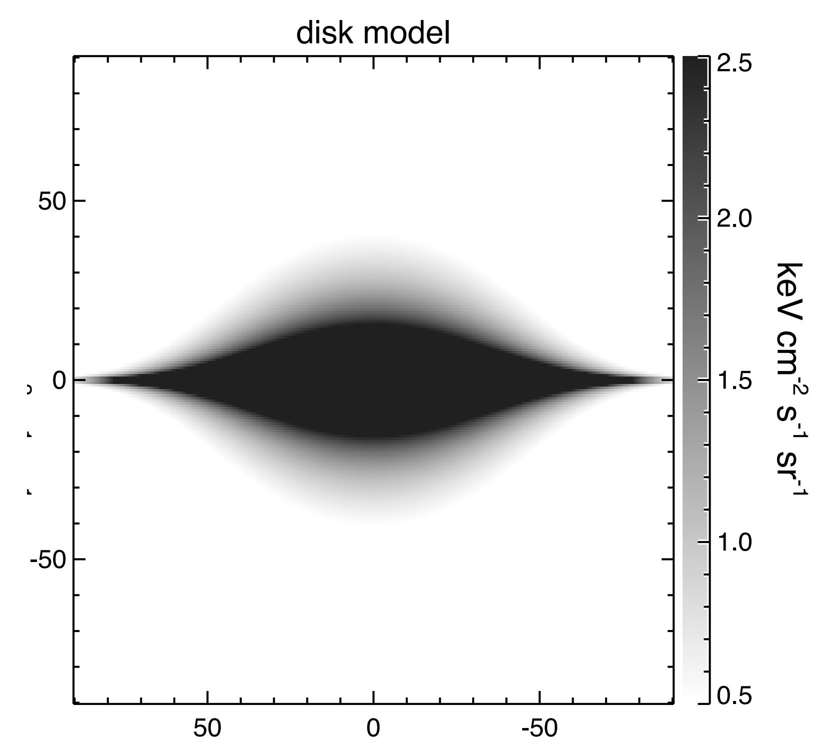

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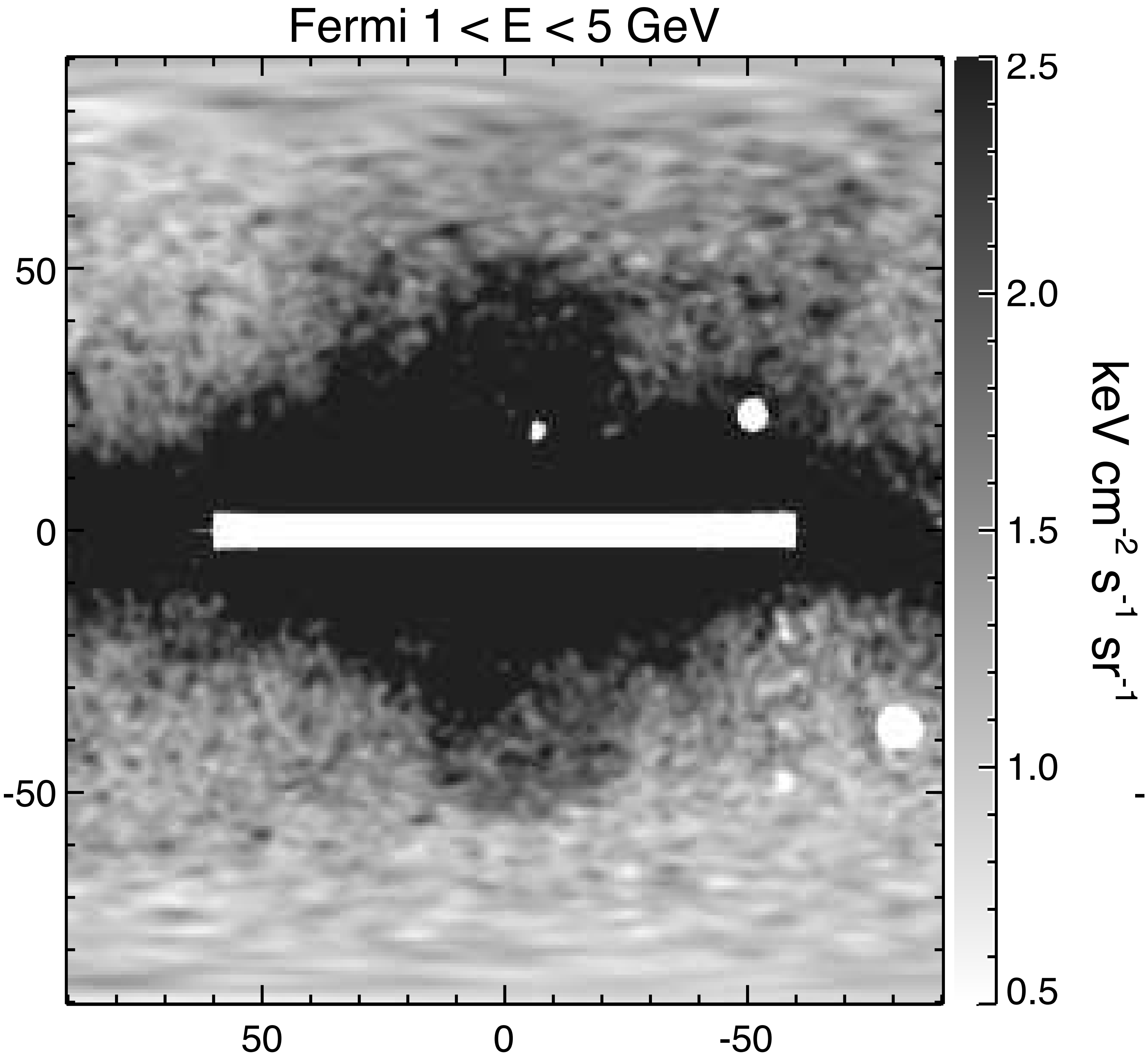

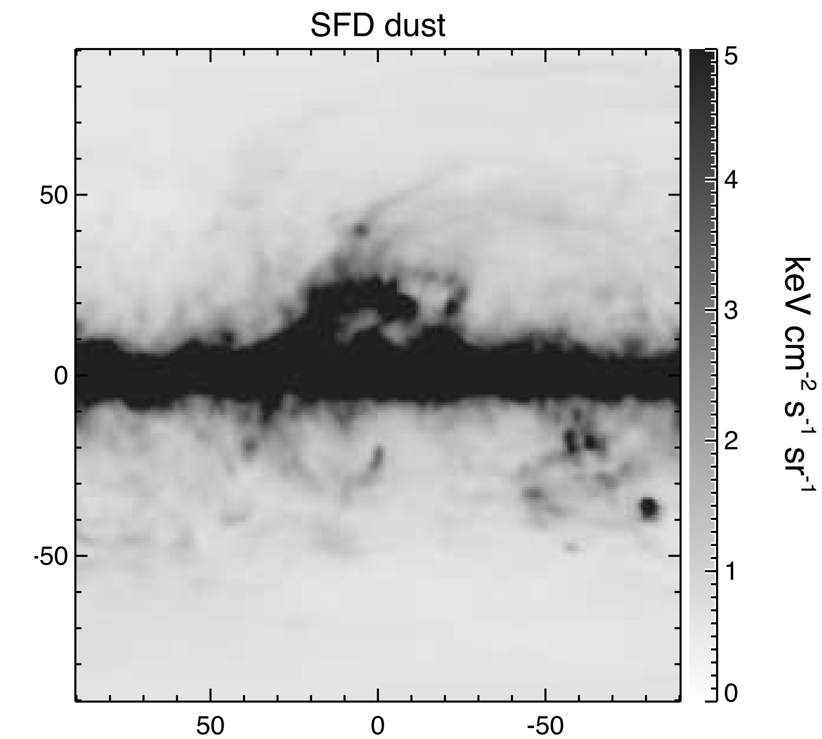

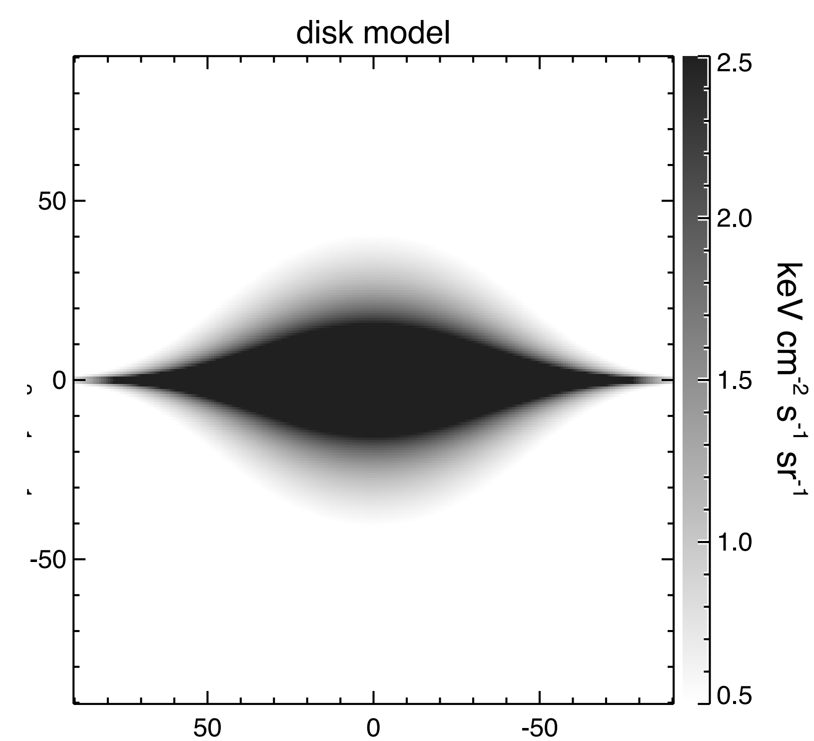

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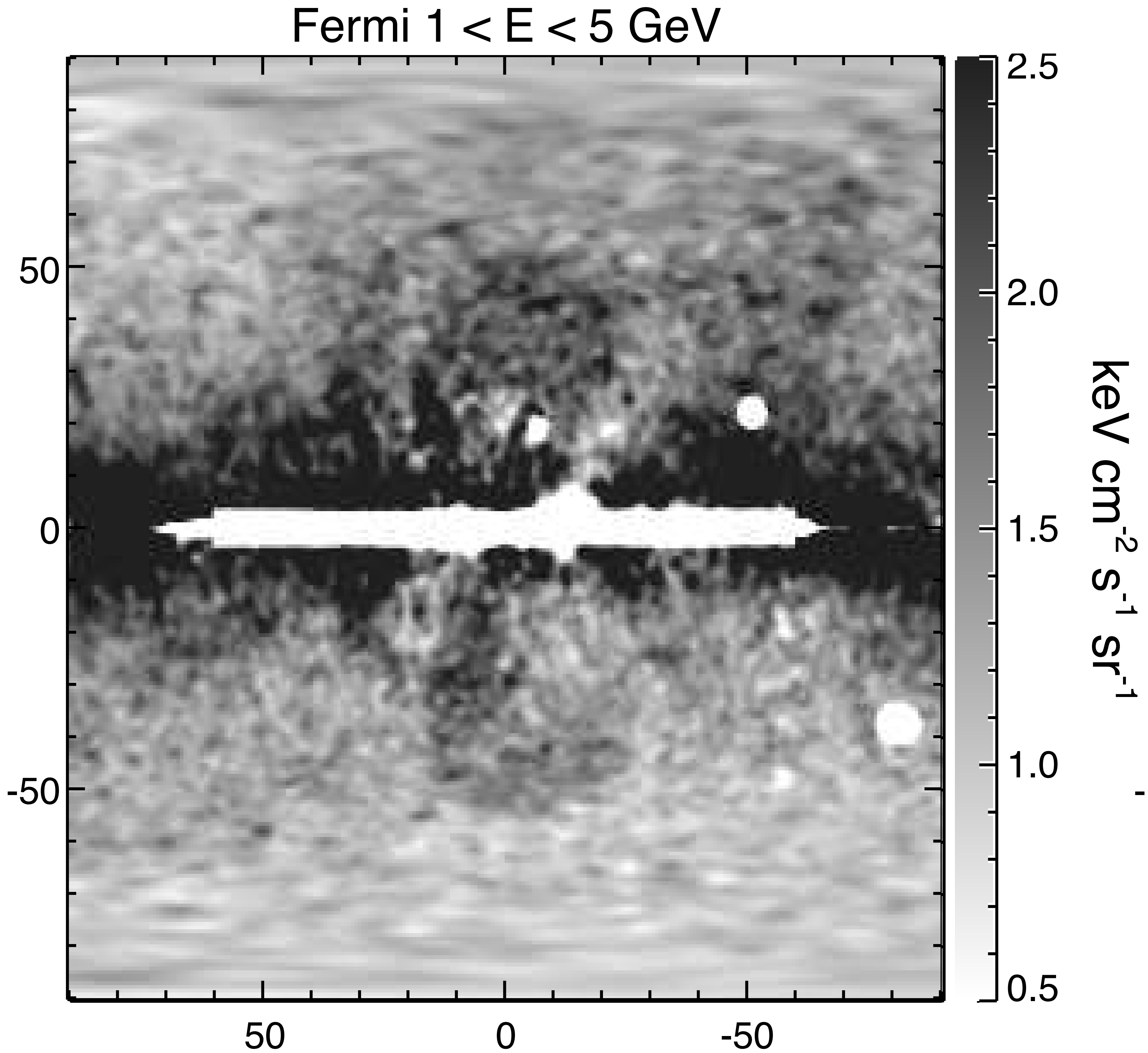
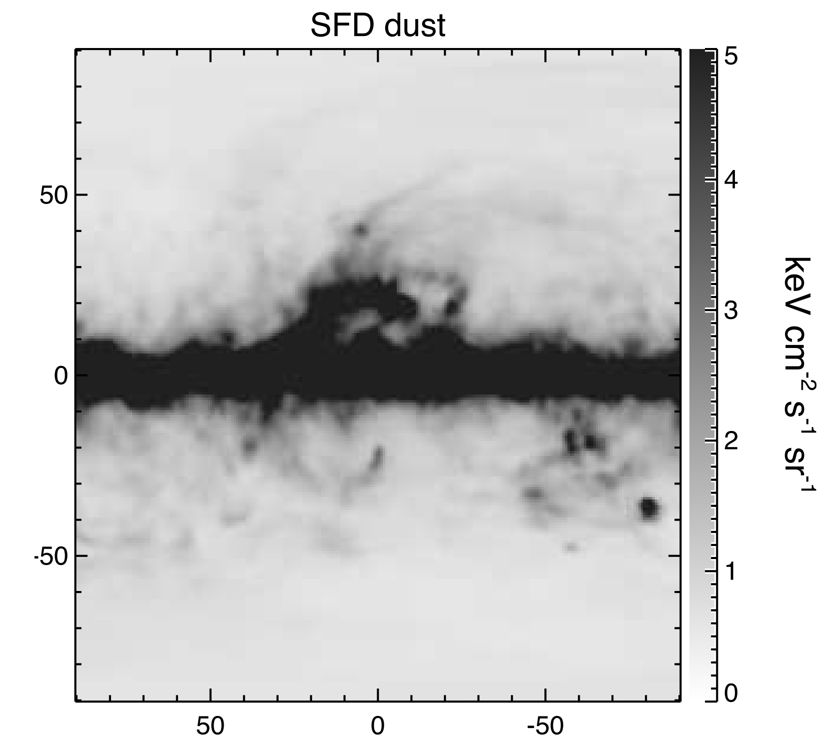
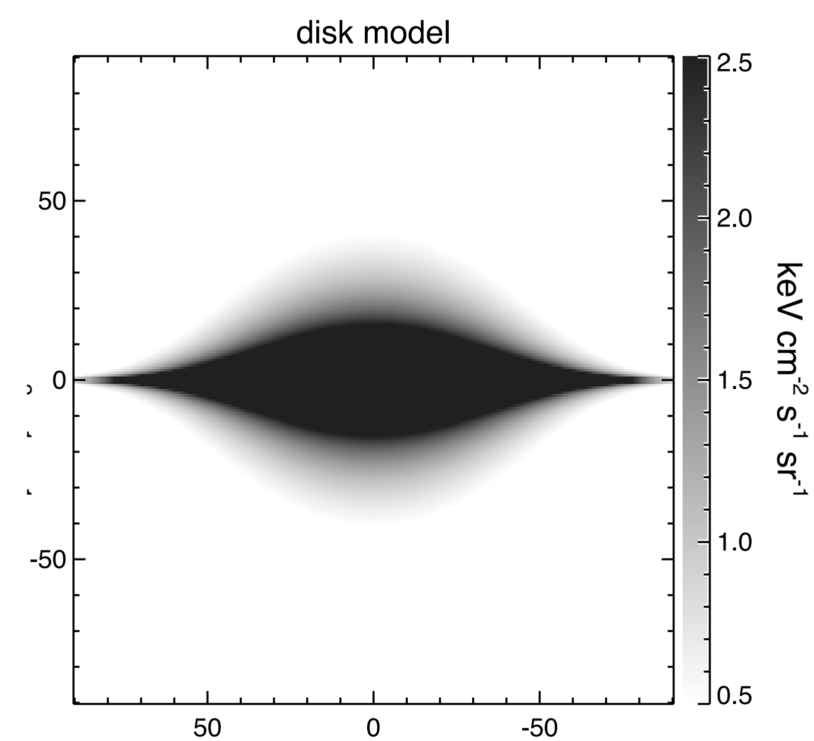






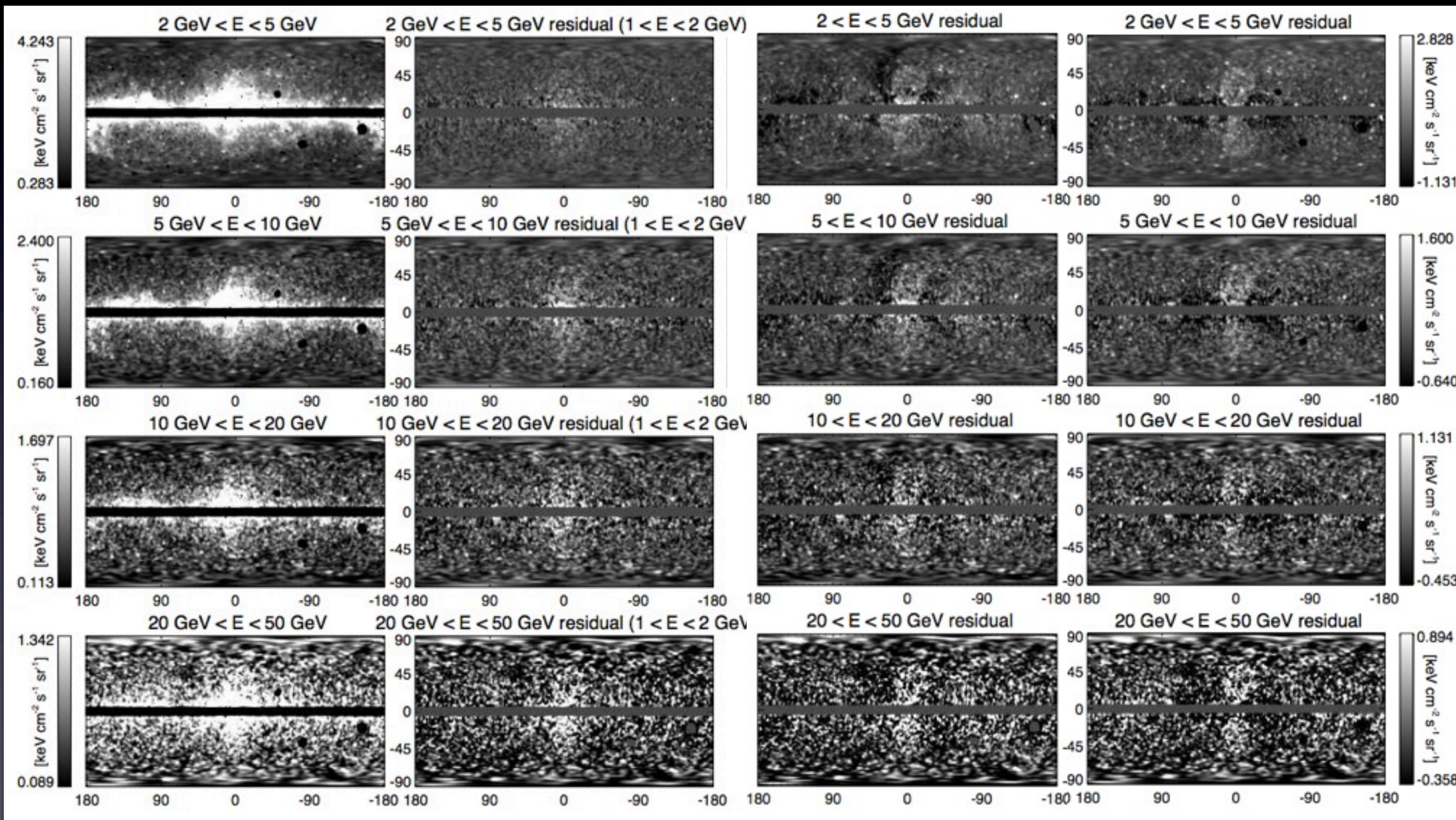
Searching for an ICS "haze" with *Fermi*

Three principal approaches (Dobler, Finkbeiner, Cholis, TRS & Weiner 2010):

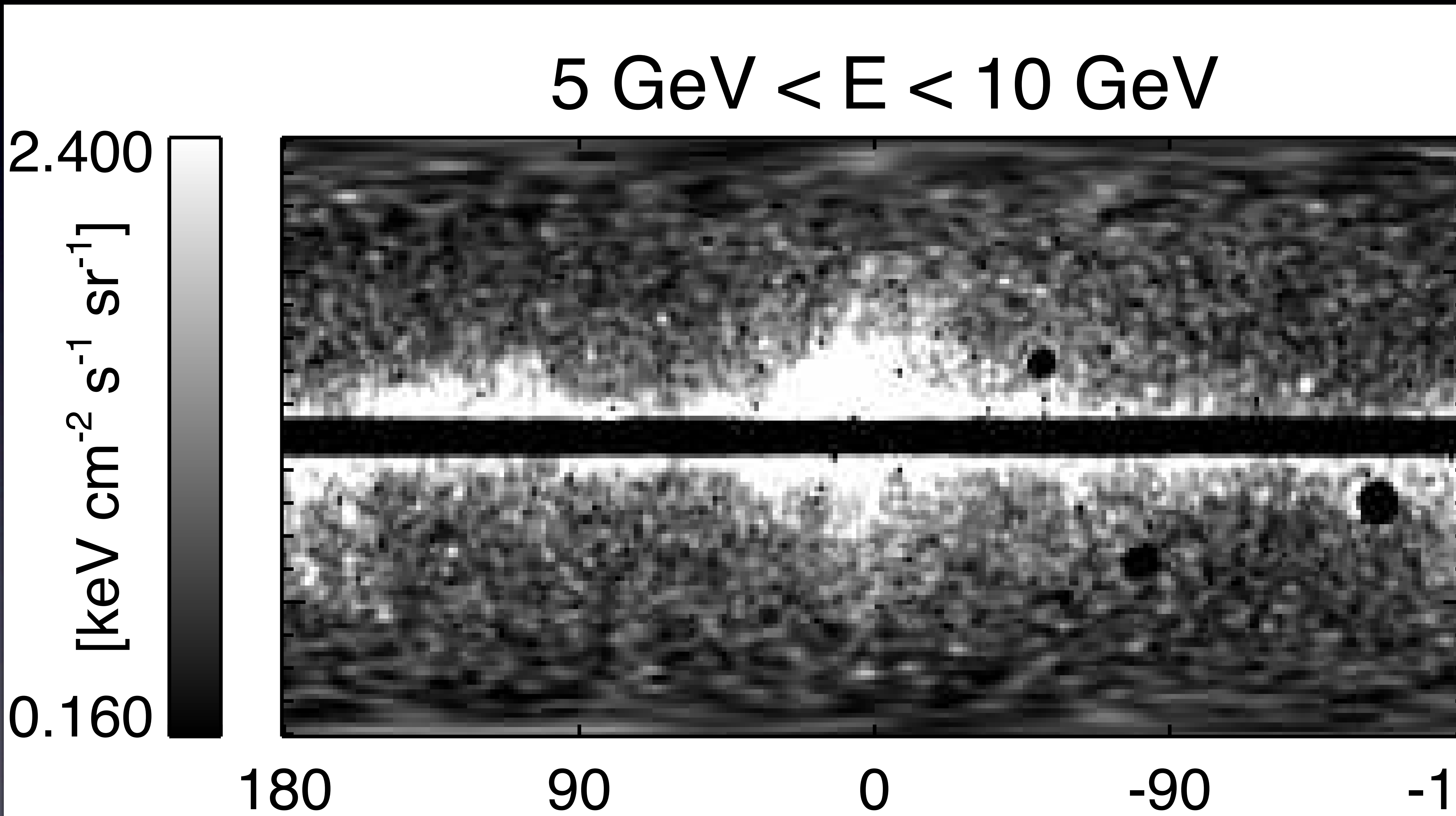
1. Subtract low-energy sky map (with best-fit prefactor) from high-energy sky map: positive residuals indicate regions with harder-than-average gamma-ray spectra. **No theoretical modeling involved, only Fermi data.**
2. Template analysis using Schlegel-Finkbeiner-Davis dust map (from far IR) as tracer of gamma-rays from collisions between interstellar medium and CRs, + try a range of templates to remove "standard" ICS associated with the Galactic plane. Allows **simple few-parameter characterization** of diffuse emission, but need to assess residuals carefully.
3. Subtract diffuse model provided by Fermi Collaboration (available from http://fermi.gsfc.nasa.gov/ssc/data) from the data, examine residuals. Model is complicated, but **physically well-motivated**. Need to ask if adjustments to model could reproduce residuals.

The “Fermi Haze”

Data | High energy - low energy | Data - templates | Data - diffuse model



Different subtractions



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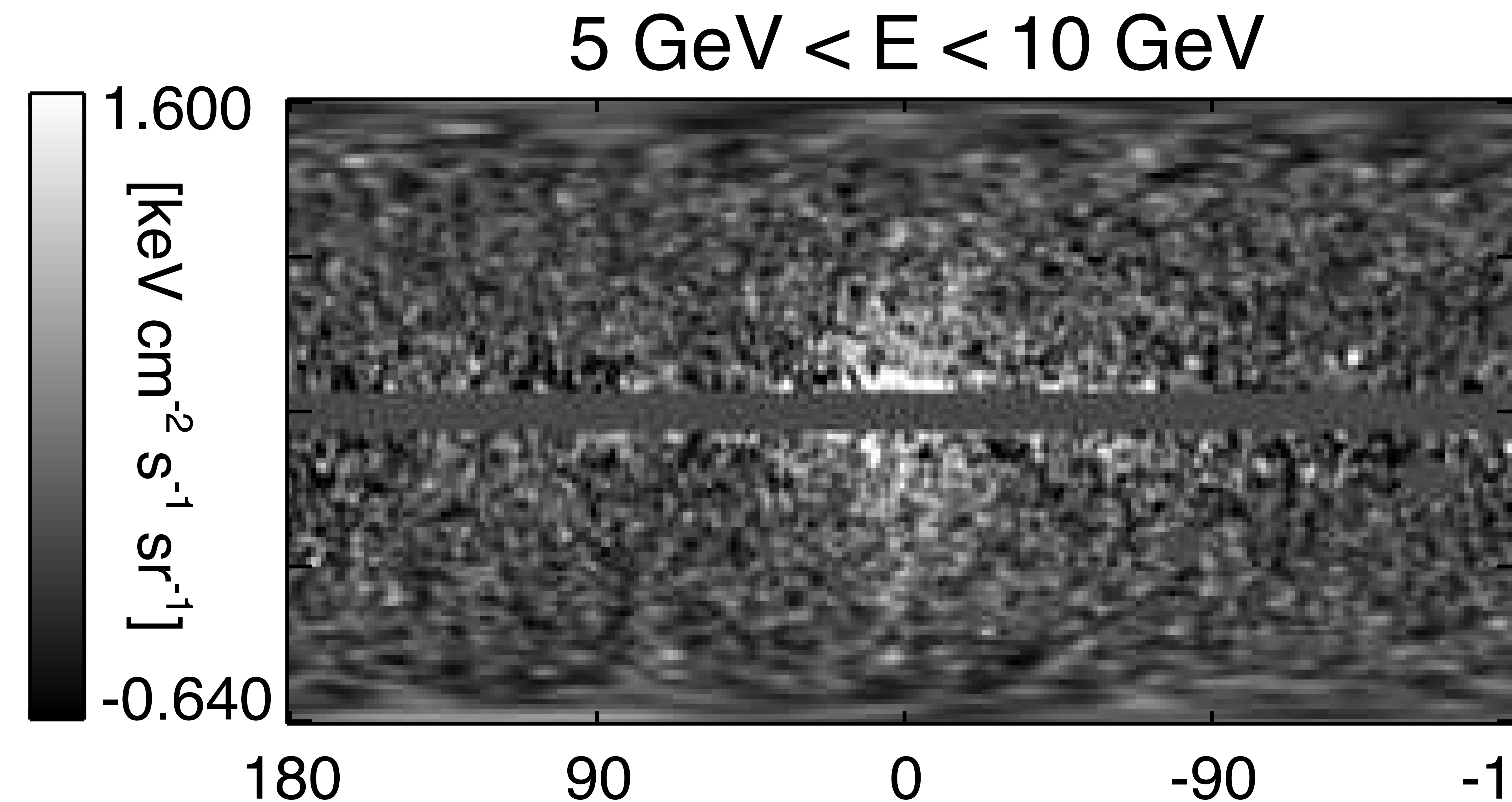

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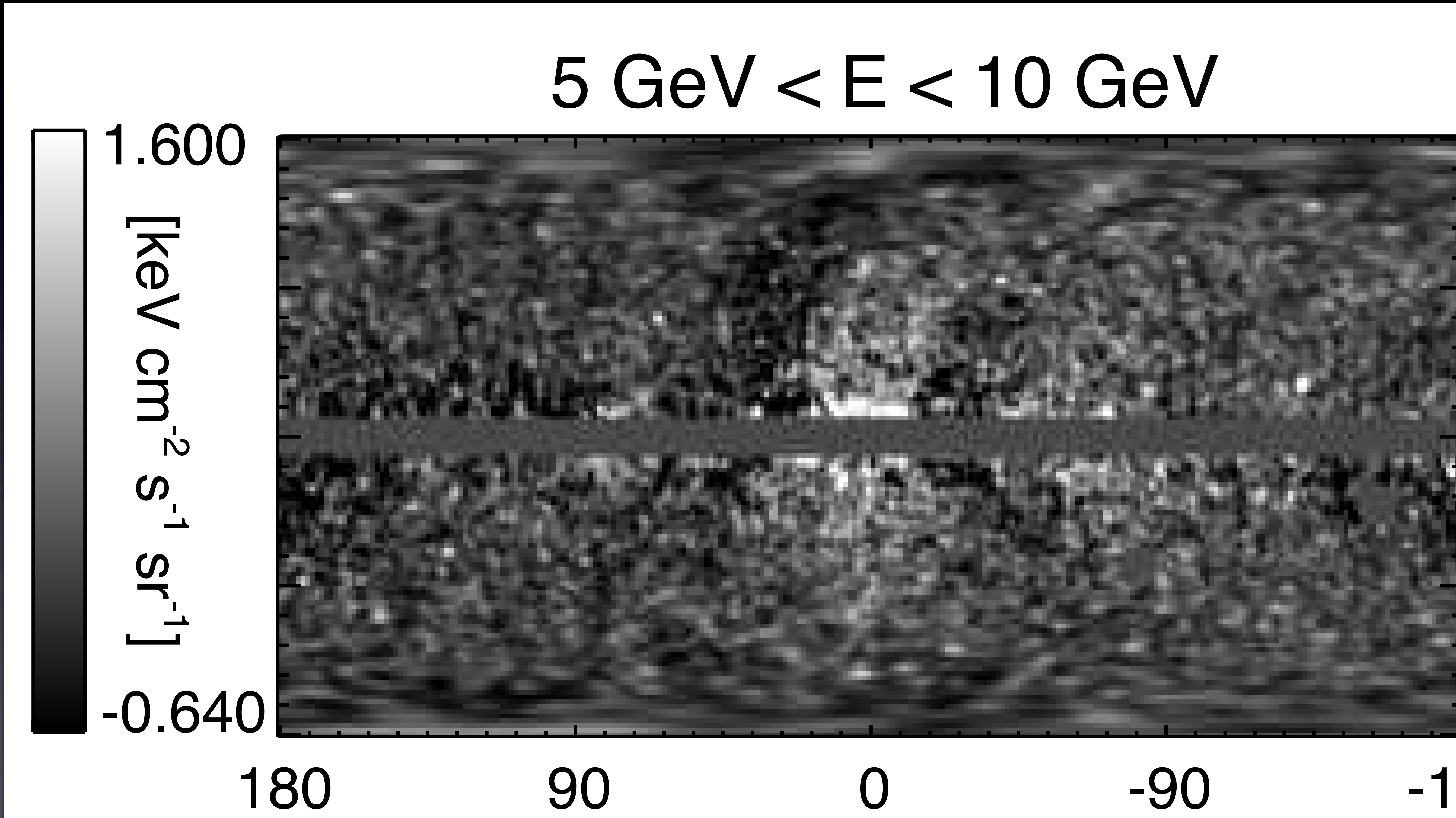

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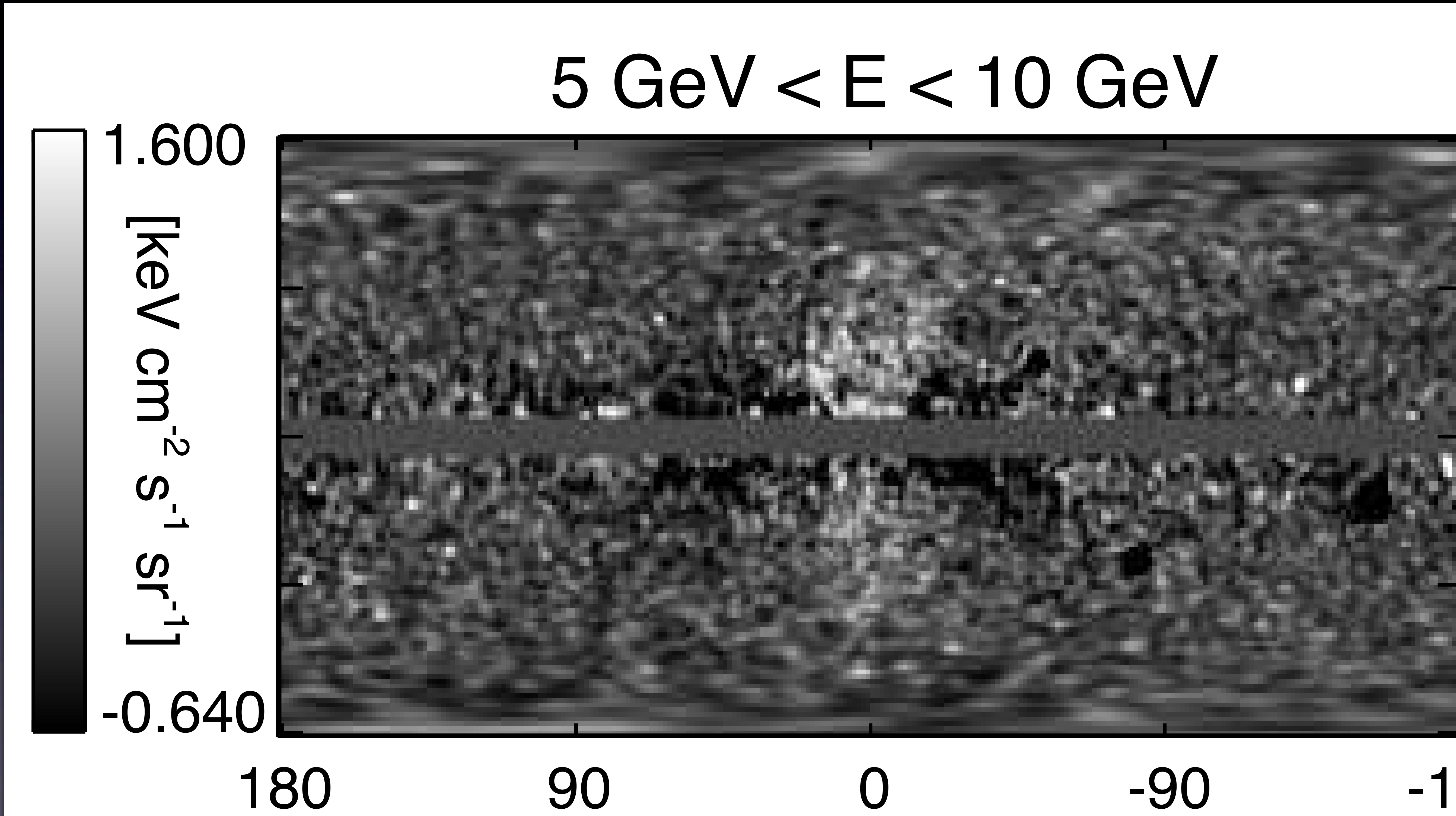
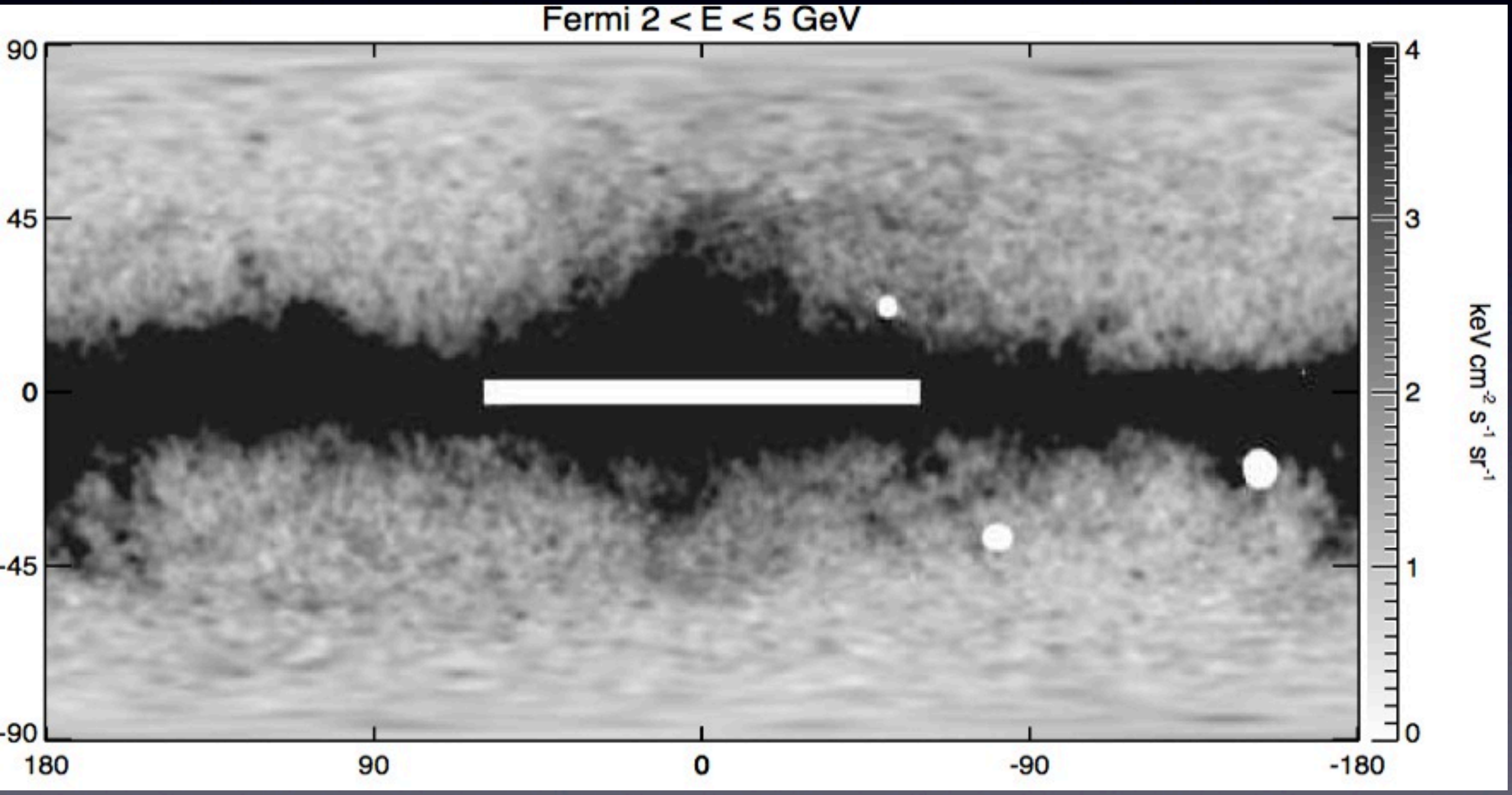


The “Fermi Bubbles”

Su, TRS and Finkbeiner 2010



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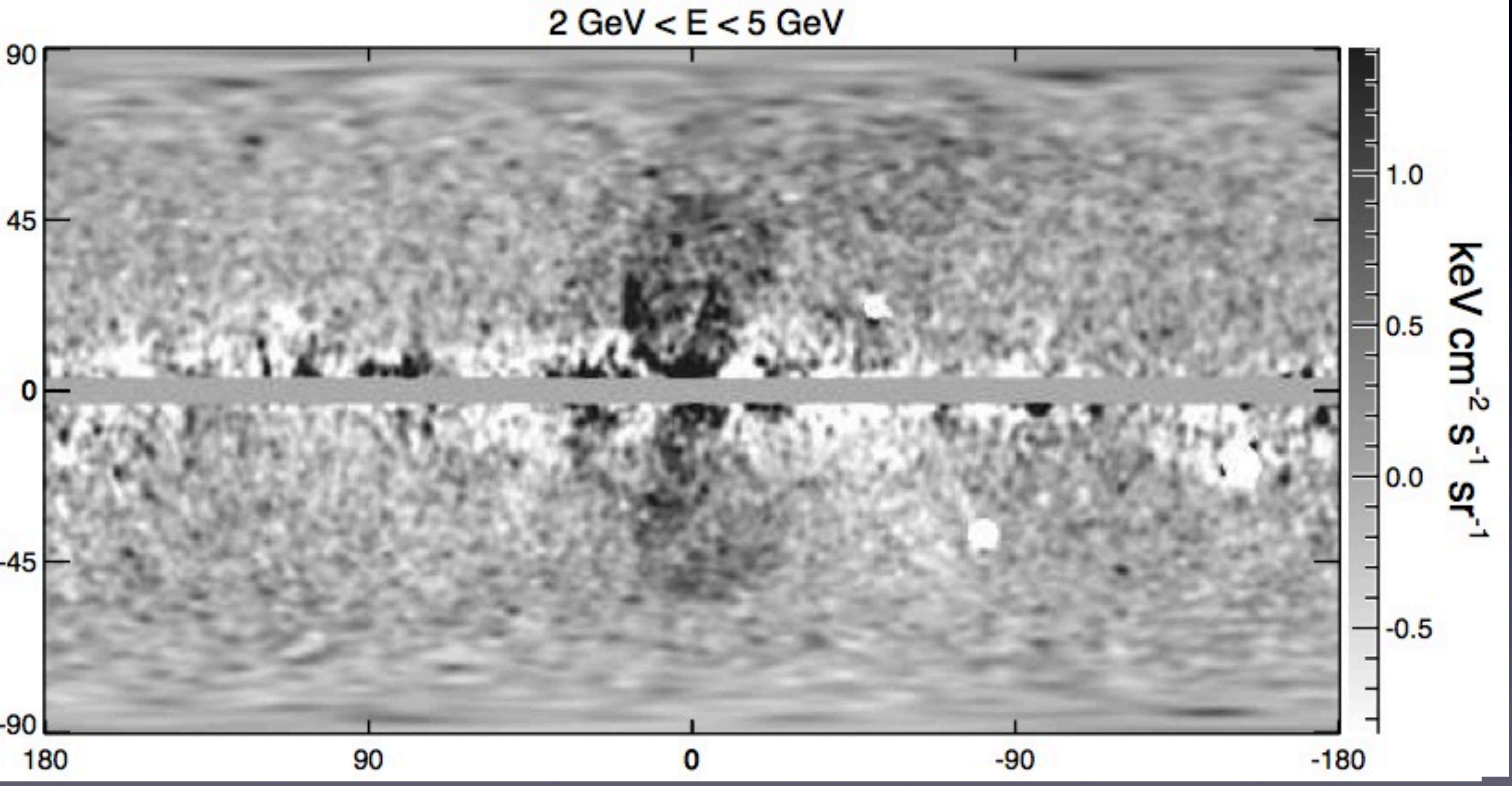

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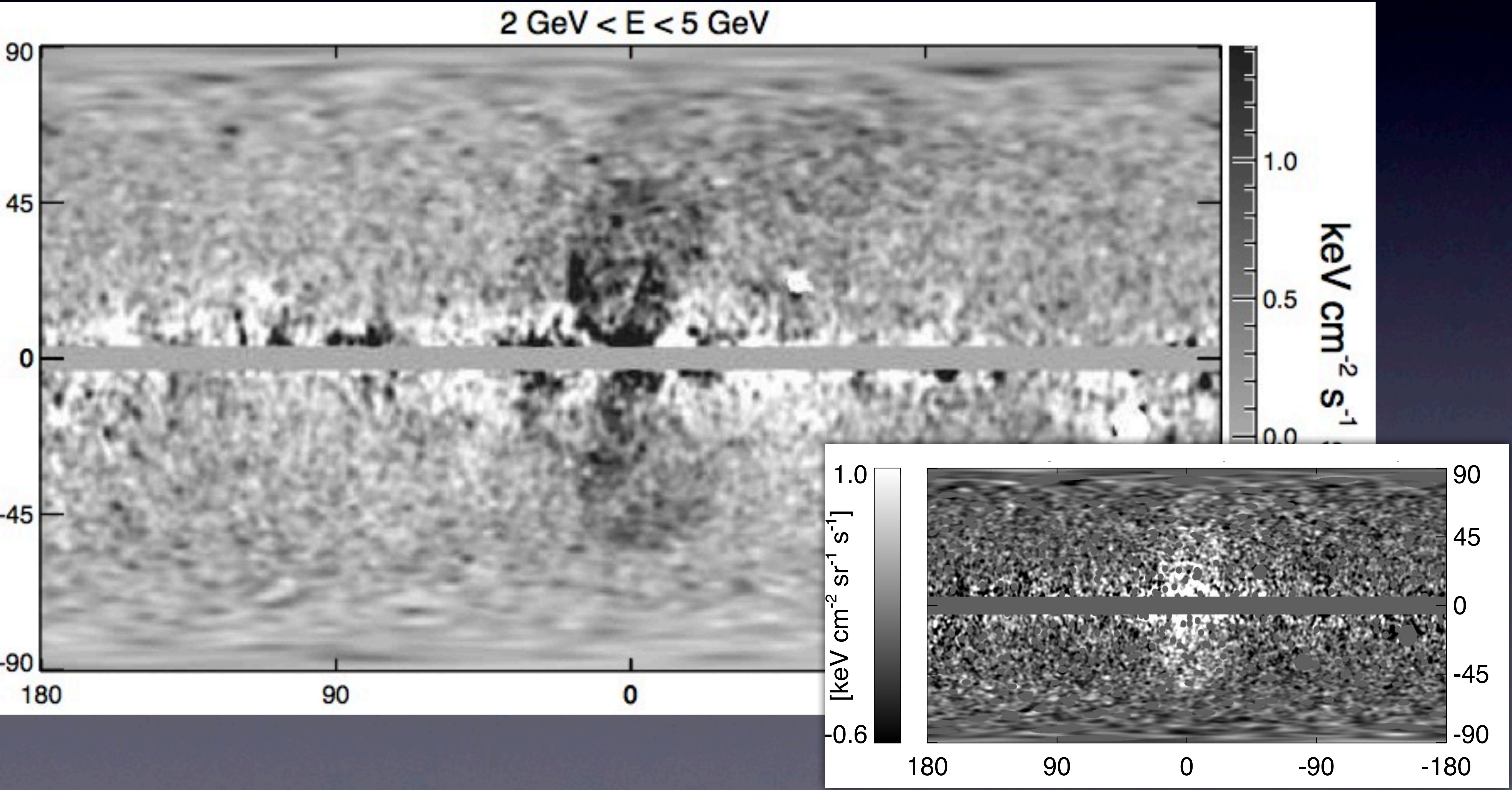
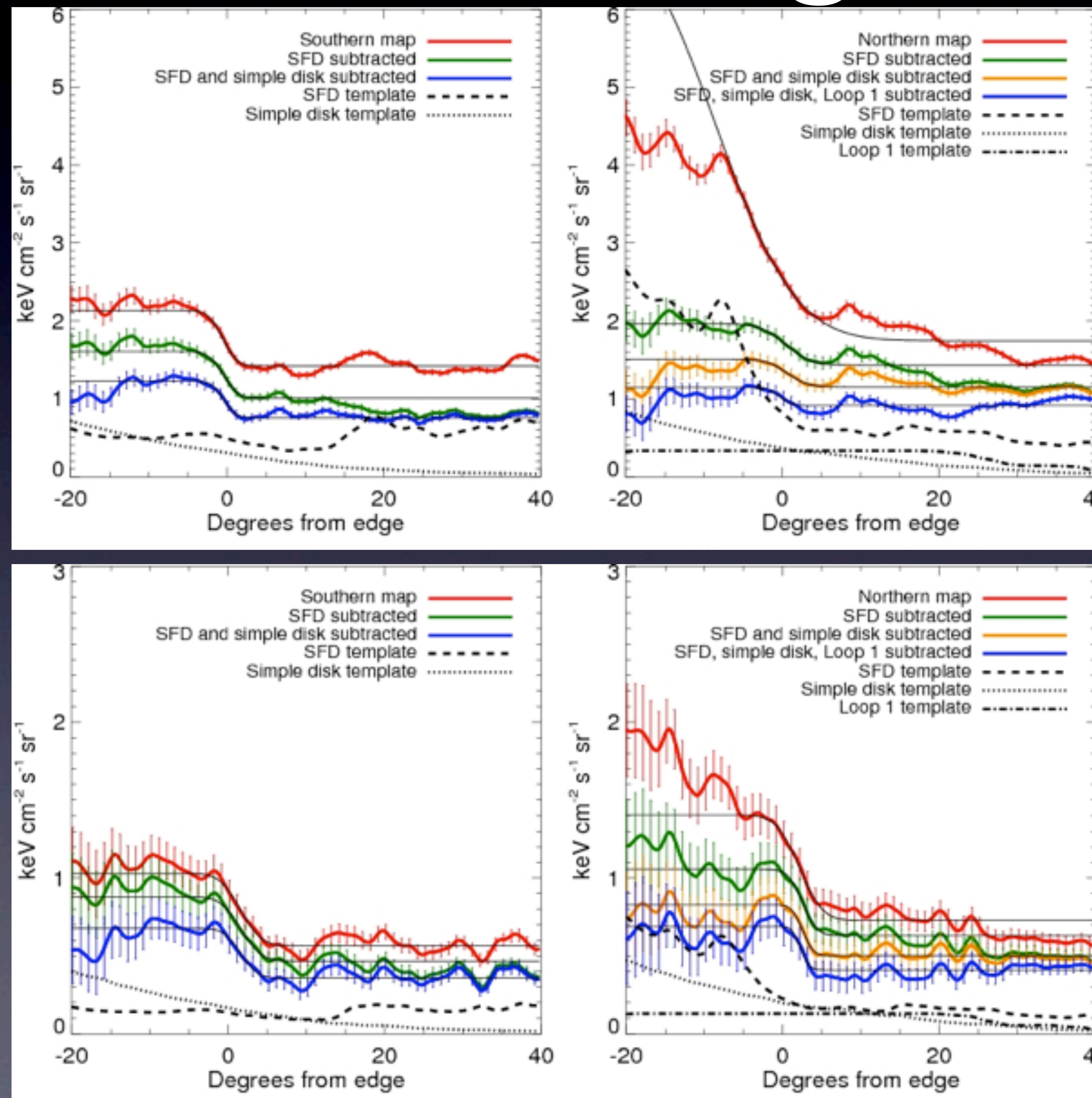


Haze vs Bubbles

- In newer data, before subtraction we see sharp-edged, spectrally hard structures at high latitudes. (How sharp are the edges? Next slide.)
- Subtracting the Fermi diffuse model or any of our template combinations, these edges appear to extend in to the Galactic Center.
- However, there does appear to be hard-spectrum emission that does not follow these sharp edges, close to the GC - this gets included in the “haze”, but not the “bubbles”.

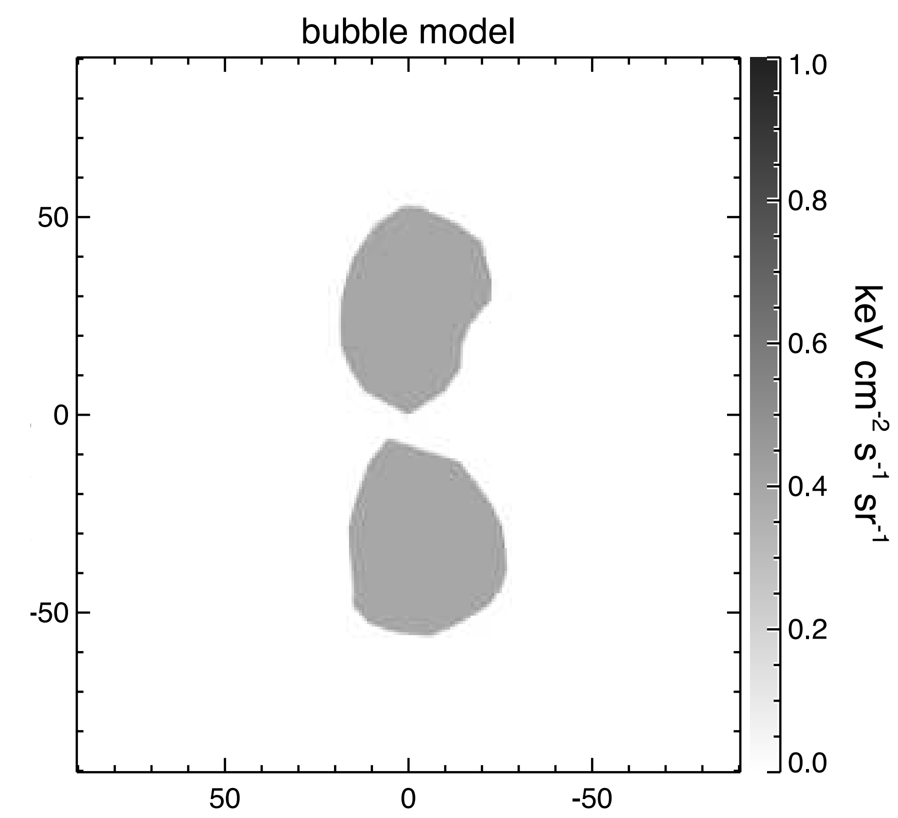
Sharp high-latitude edges

- 1-5 GeV (top), 5-20 GeV (bottom).
- Best-fit width of edge typically 2-3° in 2° smoothed maps. No robust lower limit on edge width.
- For comparison, radius of bubbles is of order 20° at high latitude.
- Note also the uniformity of the bubble brightness, inside the edge.



Fitting the Bubbles

- Add an extra template to the fit: model bubbles as uniform brightness (i.e. uniform projected emissivity), since no strong gradient is observed.
- Limit fit to |b| > 30 to minimize uncertainties in foreground subtraction.
- Several perturbations possible:
  - Fit north and south bubbles separately.
  - Add separate template for Loop I (large, faint, soft-spectrum arc across northern sky).
  - Fit interior and edge of template separately (test for edge-brightening, spectral uniformity).



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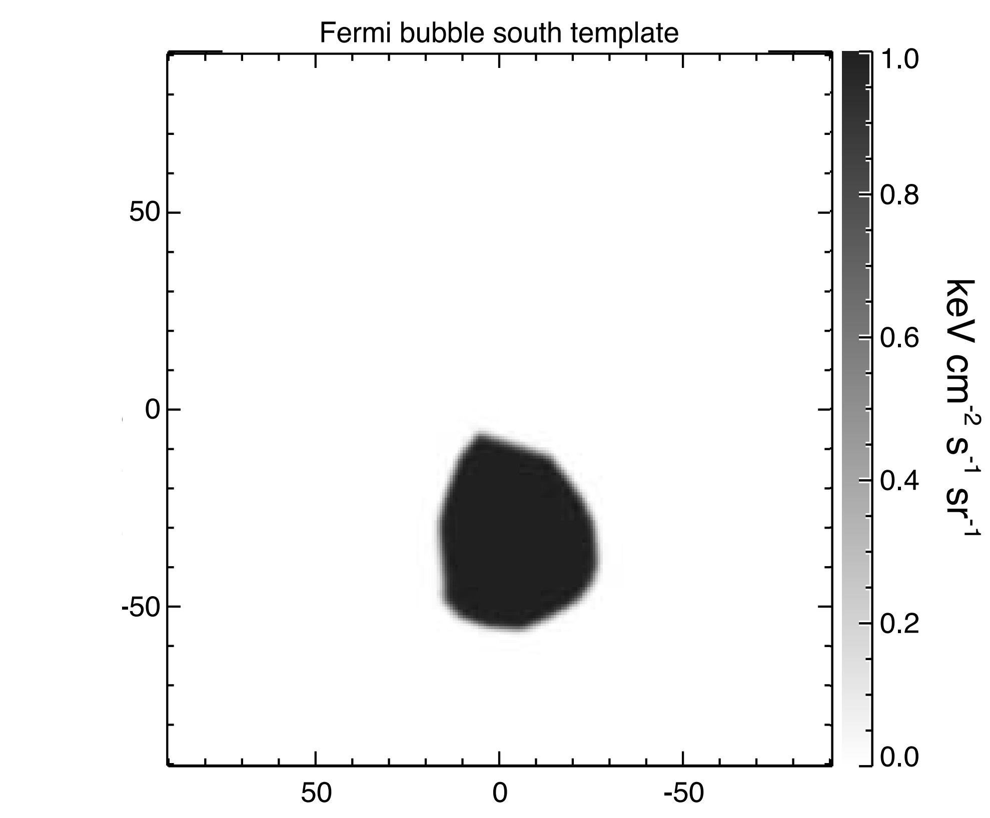

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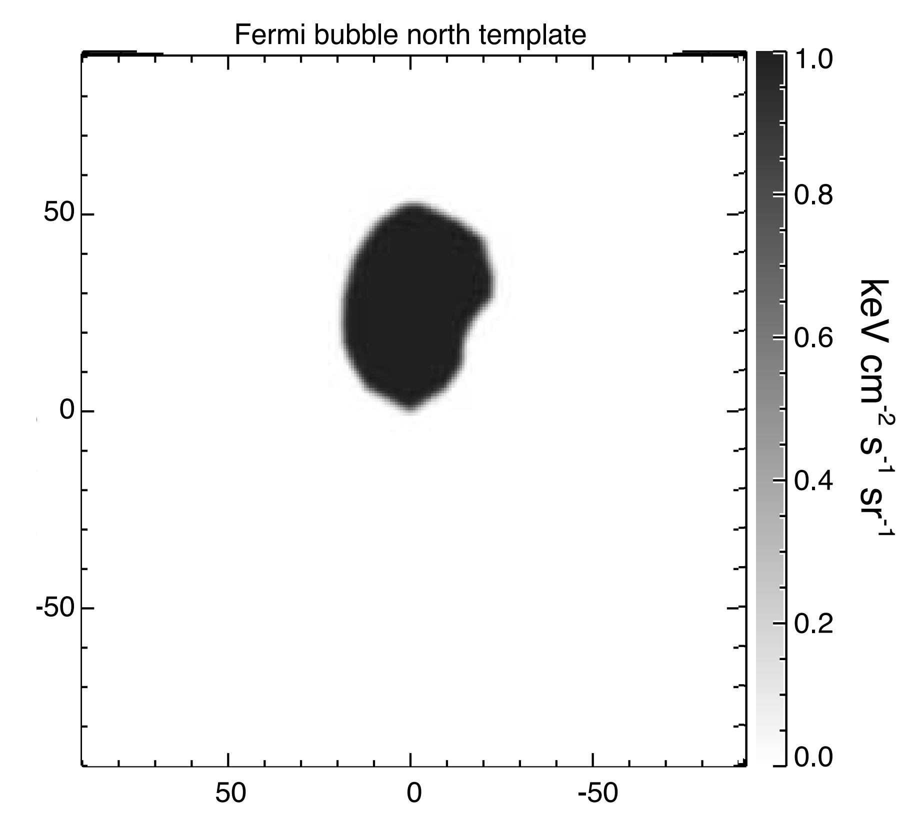

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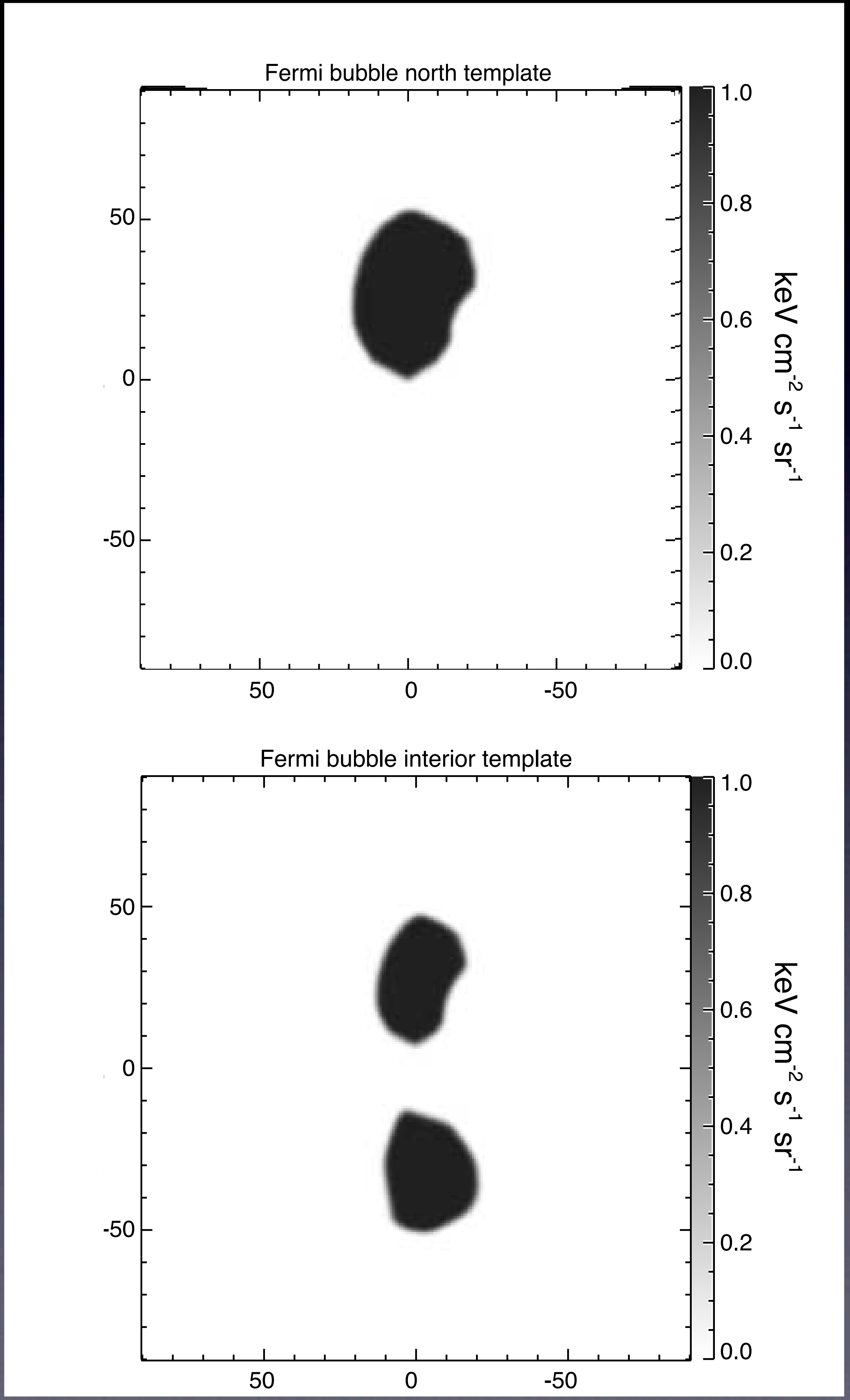

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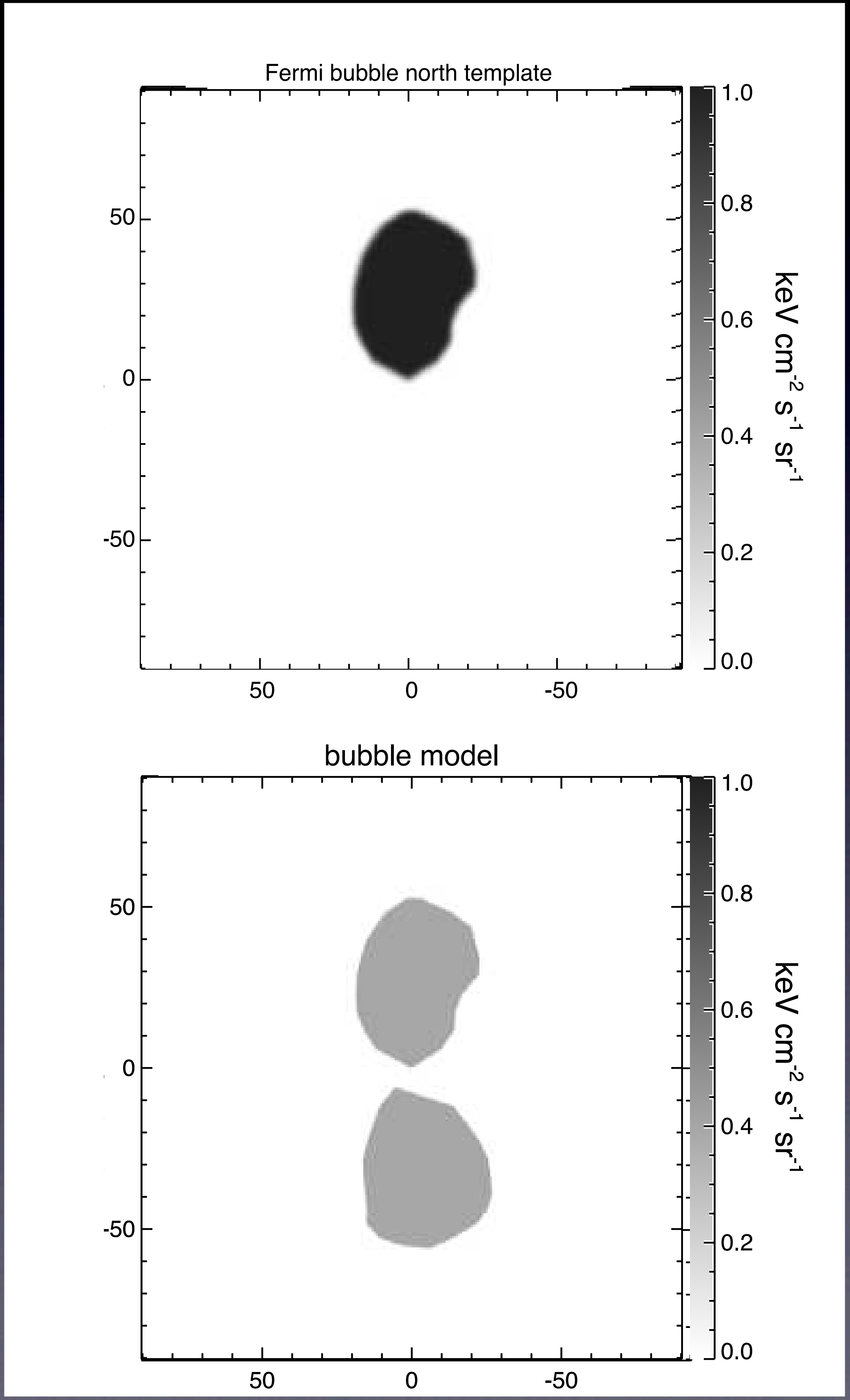

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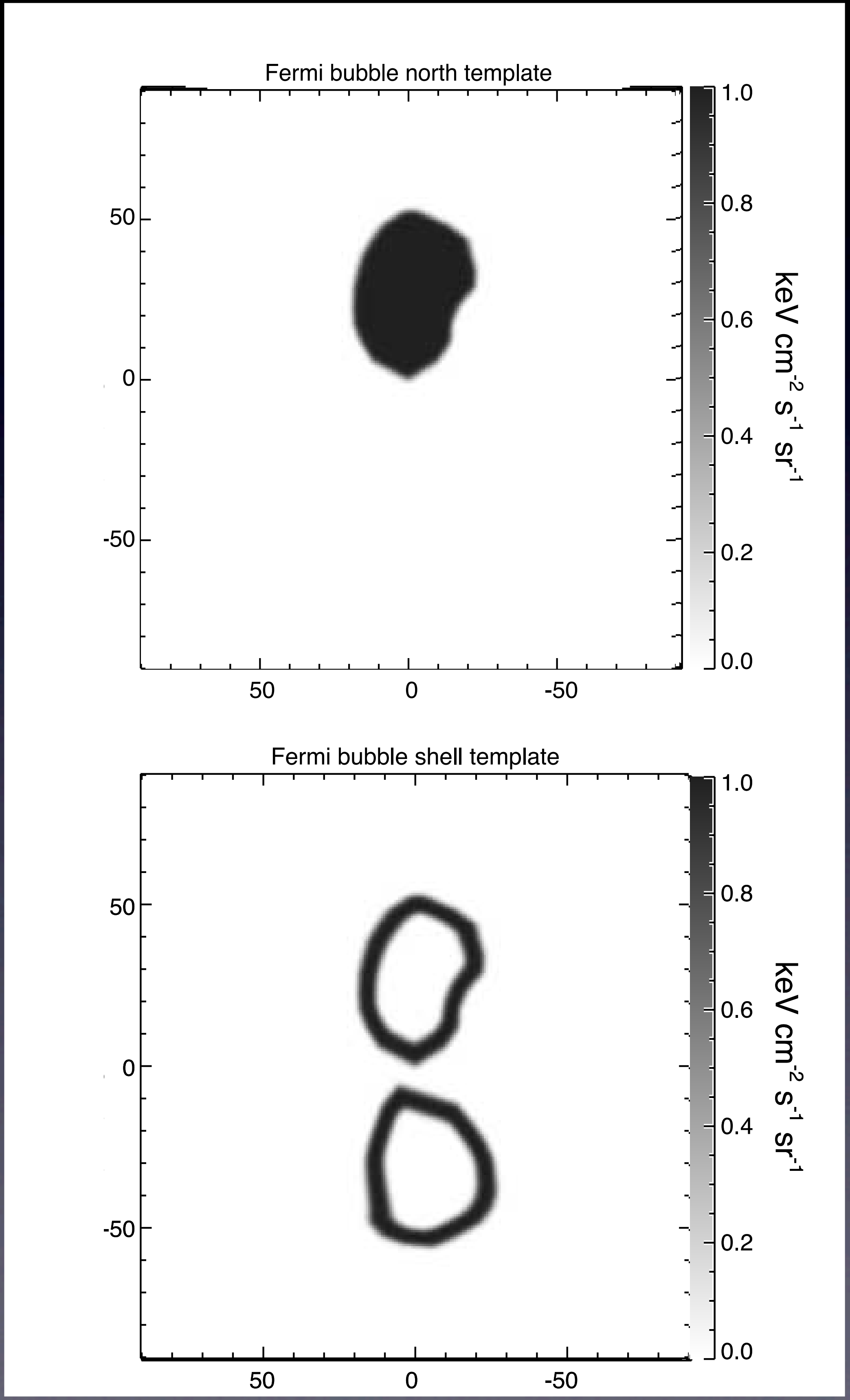
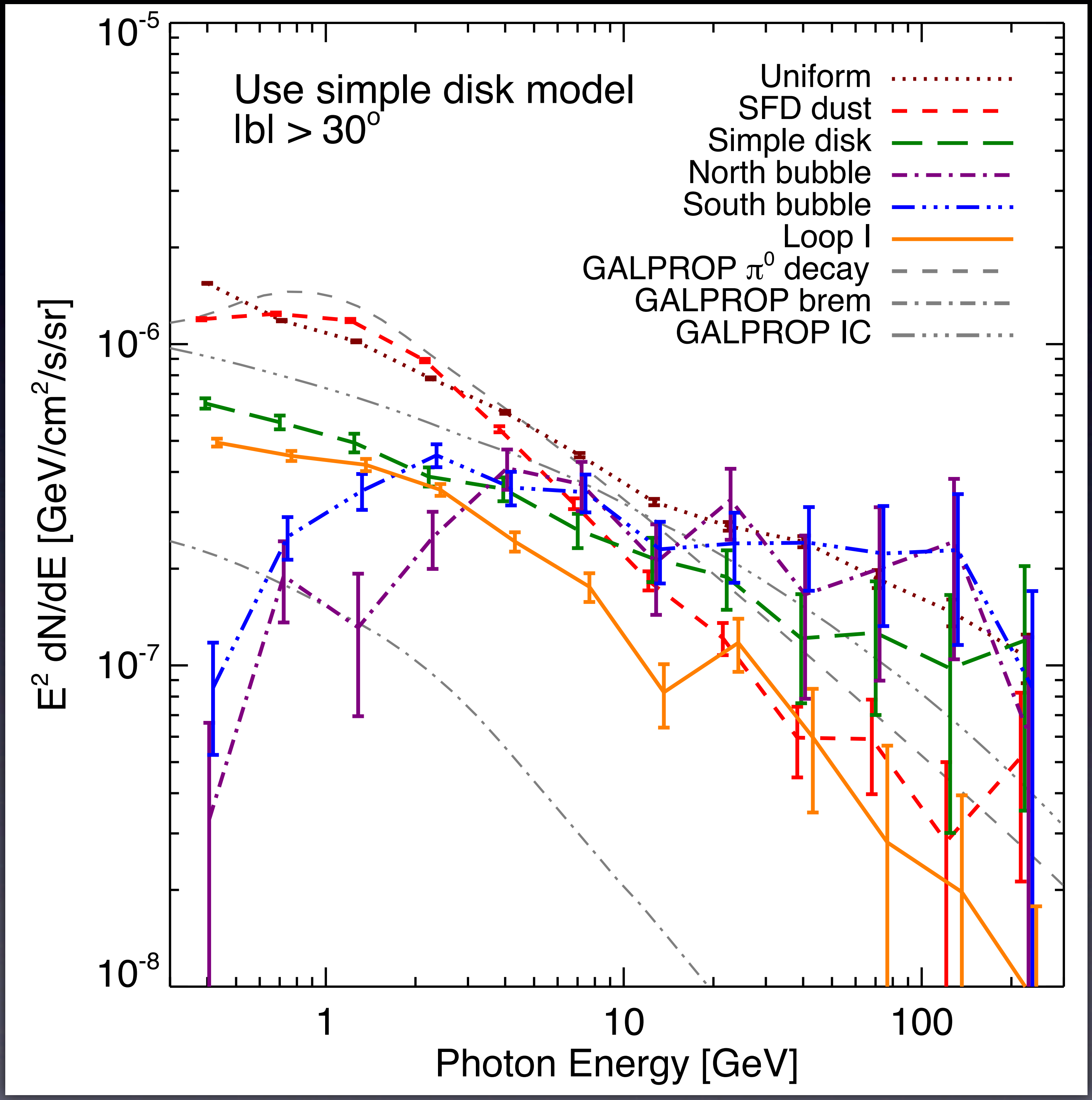


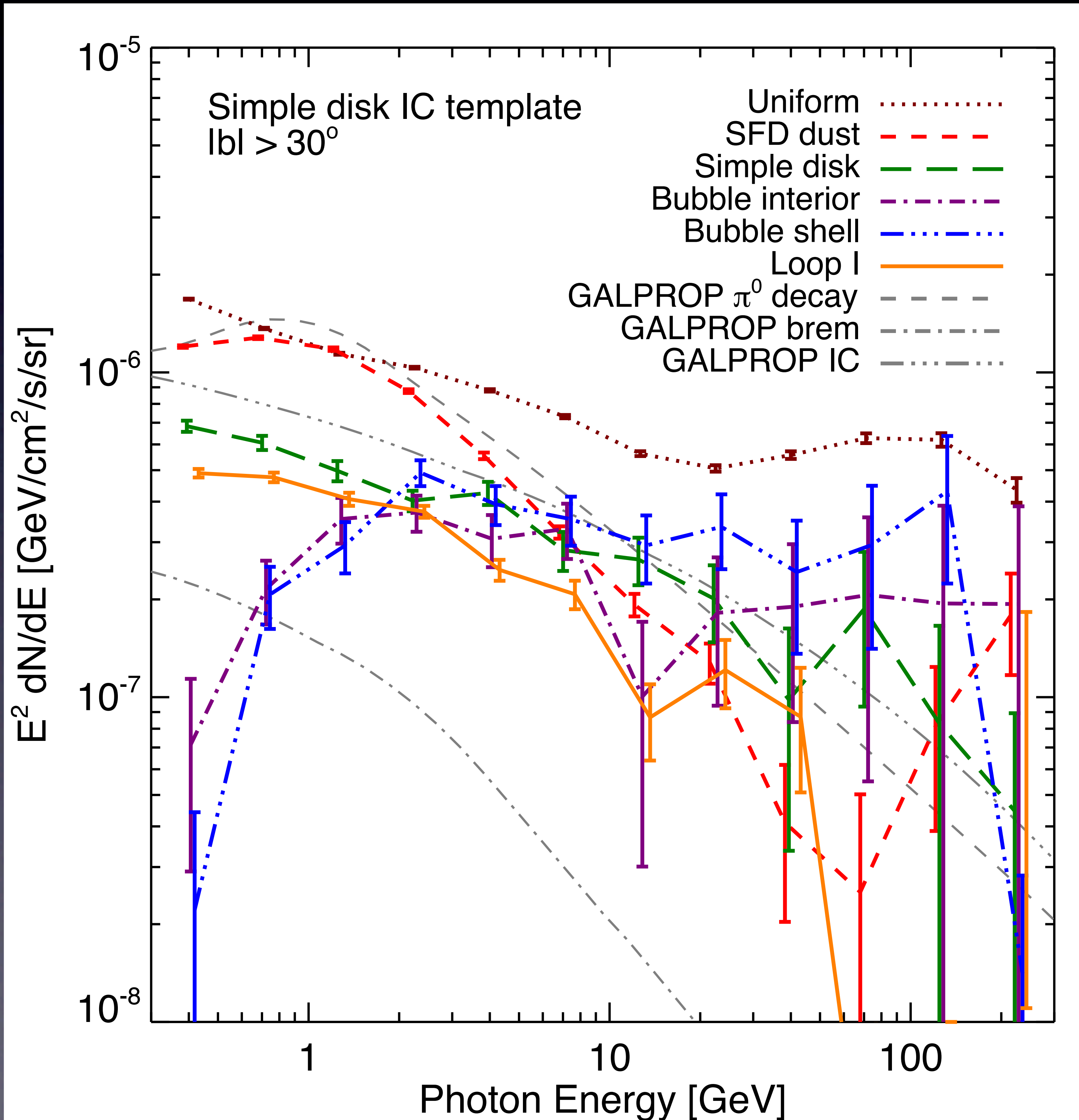
Spectra (north & south)

- Haze/Bubbles have $E^2 dN/dE$~constant from 1-100 GeV. No evidence for variation in intensity or spectral index from north to south.
- Apparent break in spectrum below 1 GeV (maybe also above 100 GeV?)



Edge or central brightening?

- No evidence of variation in (projected) intensity across the bubbles (at least at high latitudes).
- This is puzzling: generically expect either central brightening (e.g. from constant volume emissivity) or limb brightening (e.g. from particle acceleration shock).
- No evidence for spectral variation across the bubbles.



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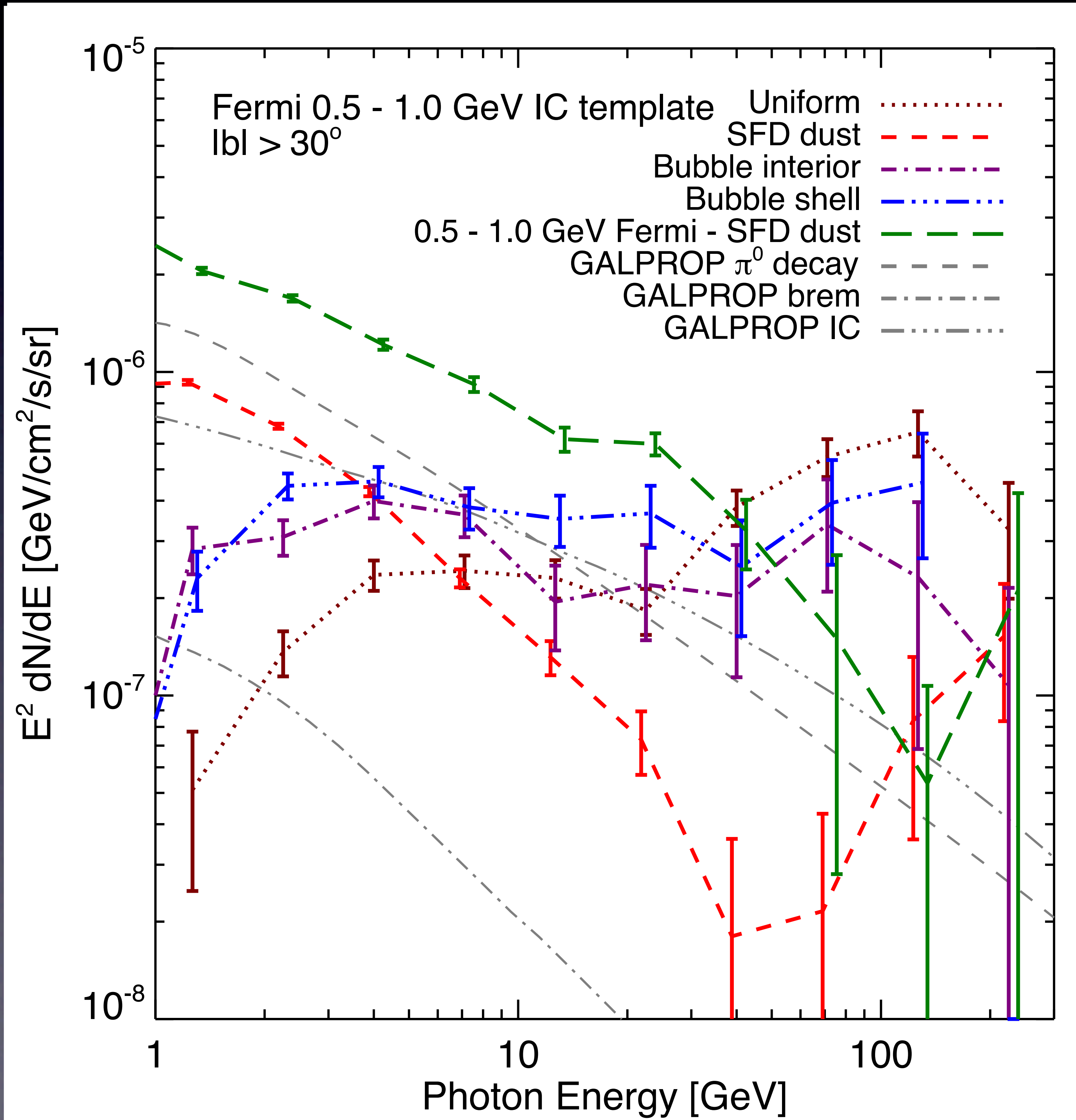


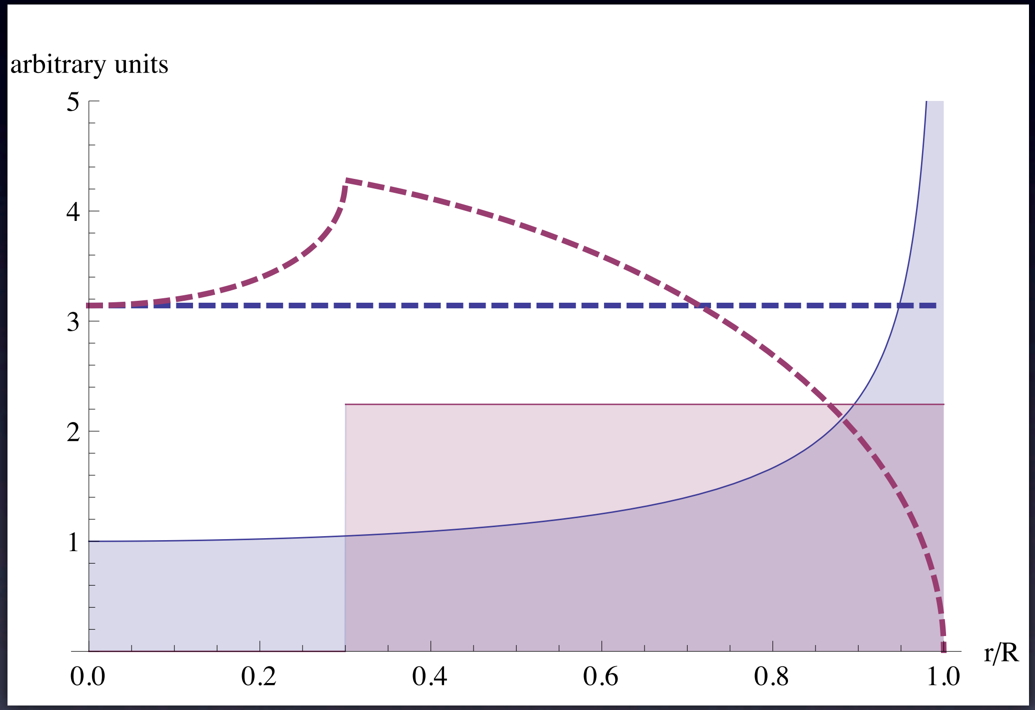
Uniform projected intensity

- What does flat projected intensity imply?
  - Thin shell of emission => edge-brightened in projection
  - Uniform volume emissivity => centrally brightened
- Flat projected intensity => bright outer shell, but significant interior emission?
- Treating high-latitude bubbles as spherical and modeling the projected intensity as a step function, volume emissivity

$$\propto R/\sqrt{R^2 - r^2}$$

(R = radius of bubble, r = distance from center of bubble).

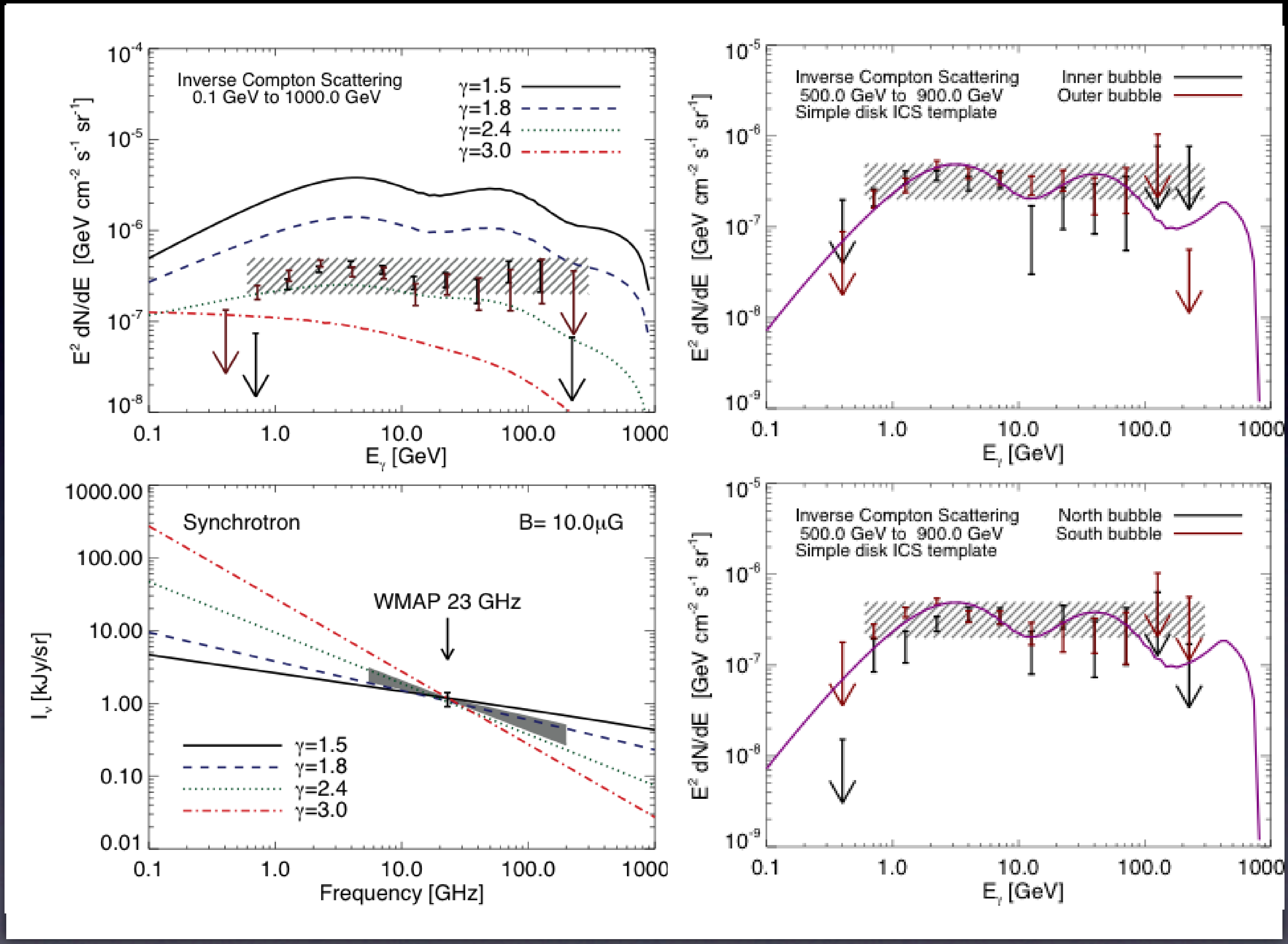
- Preliminary work indicates that a thick shell of constant emissivity (width more than ~ half the bubble radius) provides an equally good fit to the edge profile.



Example volume emission profiles that would fit the data well at 1-5 GeV. Dashed lines show the corresponding **projected** intensity profiles (pre-smoothing).

Synchrotron -> ICS (spectrum)

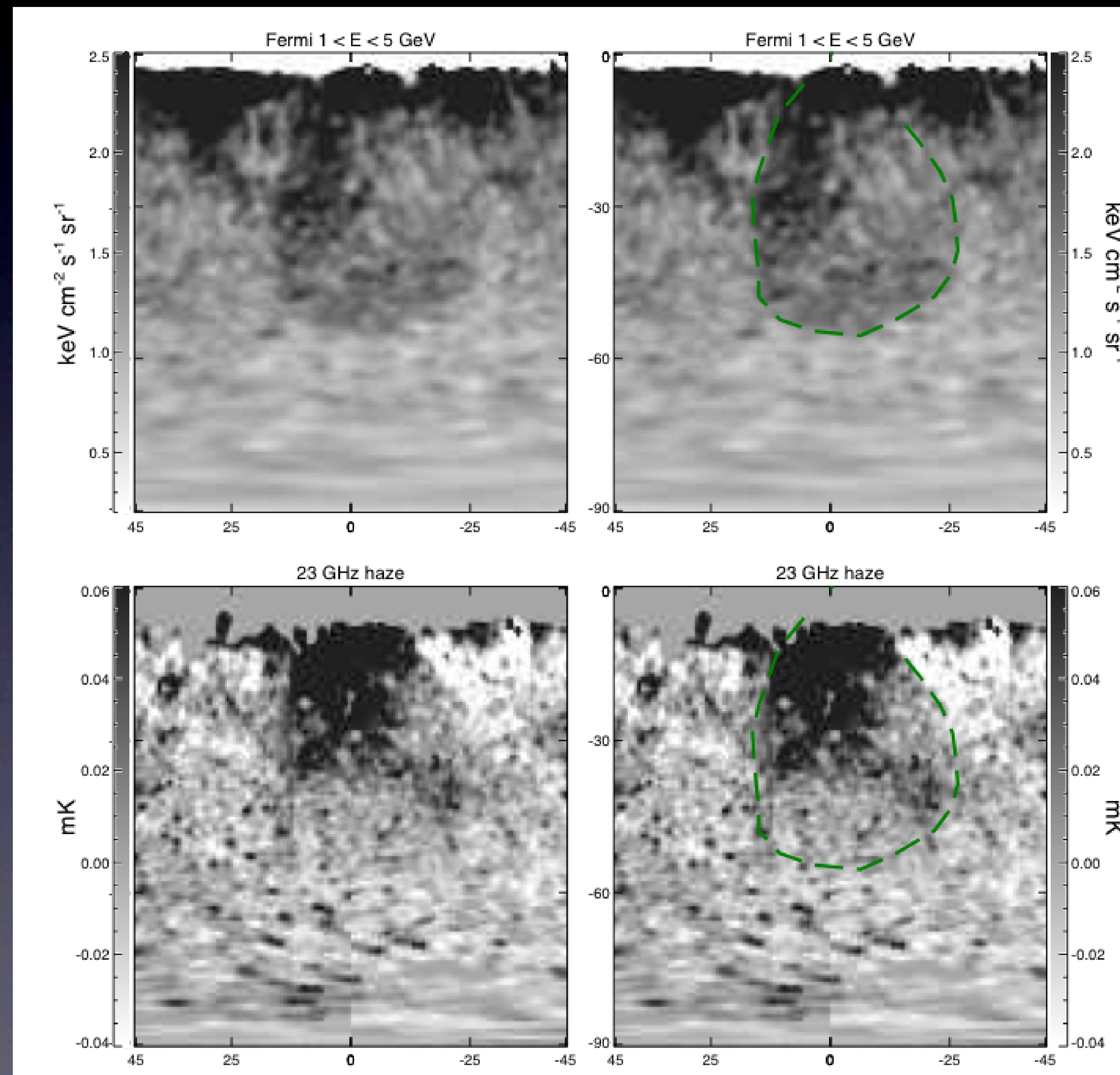
- At high latitude, few-GeV gammas probe TeV electrons scattering on CMB, WMAP Haze probes O(10) GeV electrons.
- Good agreement between gamma-ray (ICS) and microwave (synchrotron) spectra if electron spectrum is a power law between ~0.1 GeV-1 TeV.



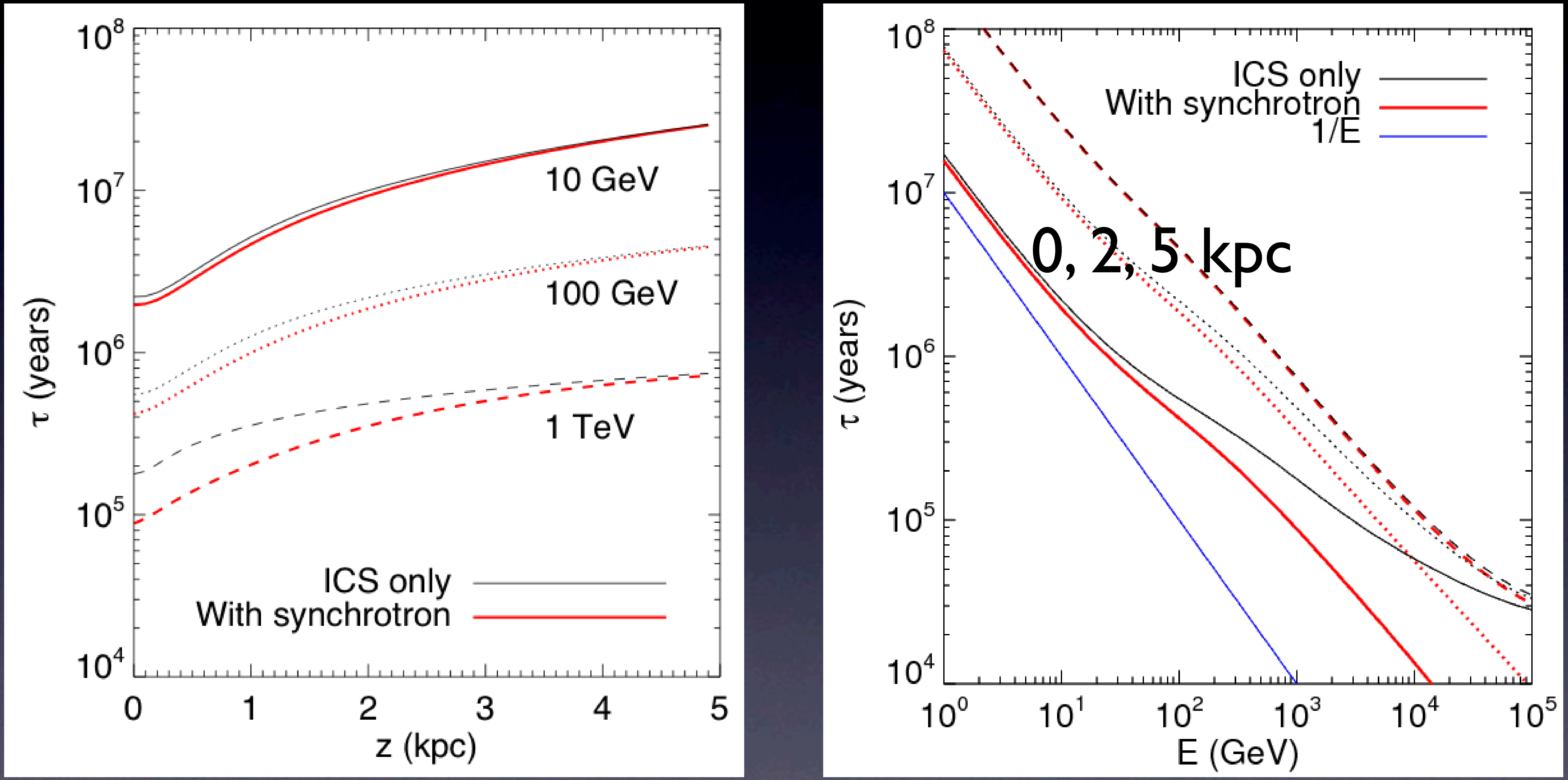
- If gamma-ray spectral downturn below 1 GeV is taken seriously, spectra with more power at high energies (~500-900 GeV) are preferred.
- Need rather large high-latitude B-fields, ~10μG at z=2kpc and ~5μG at z=4kpc.

Synchrotron -> ICS (spatial)

- WMAP Haze has smaller latitudinal extent: expected since B-field falls off at high latitude.
- Hints of bubble edges in WMAP 23GHz? Hope that Planck can improve spectrum, spatial information.



Cooling time problem



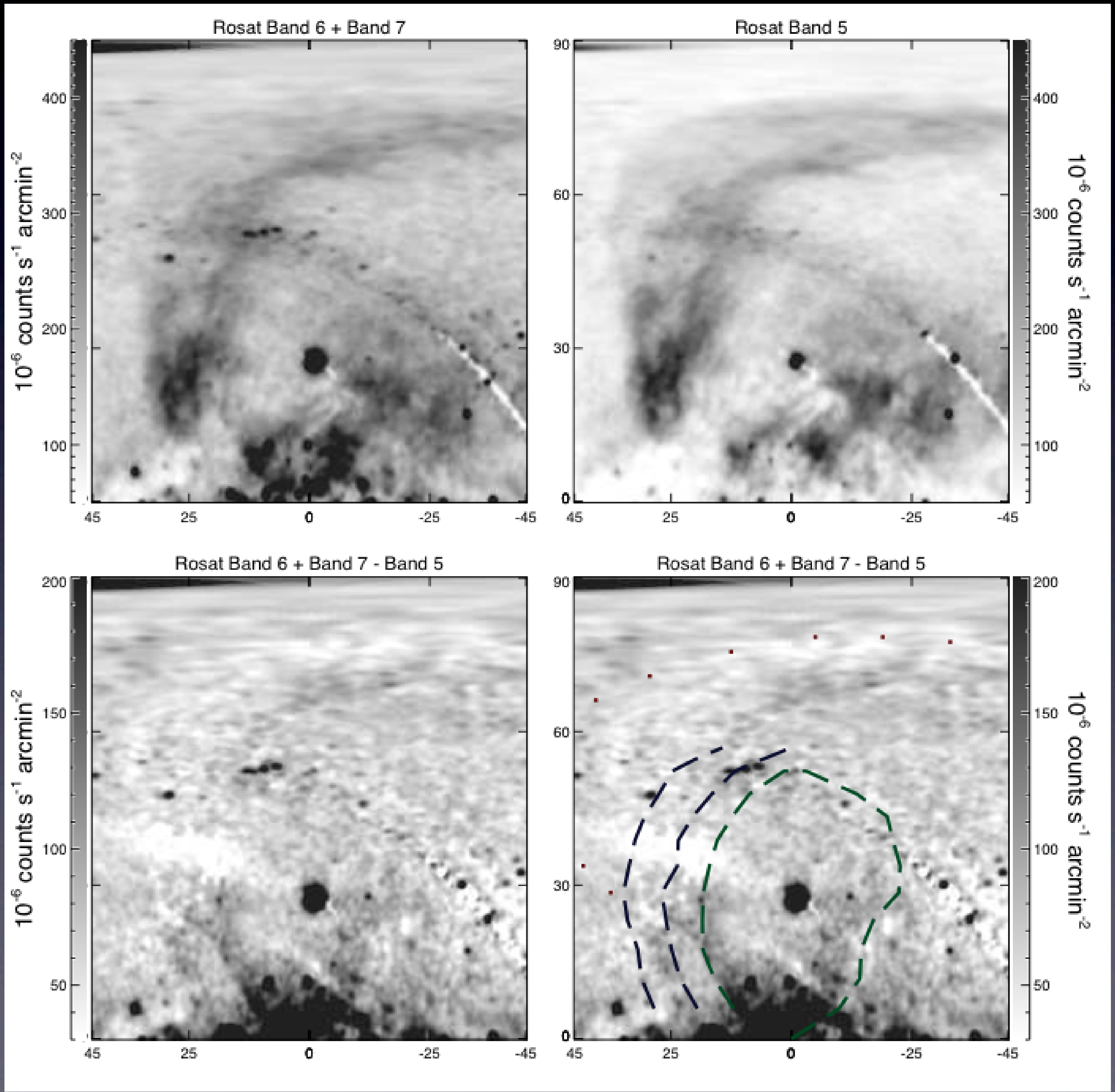
- However, if the bubbles are coming from ICS by O(TeV) electrons, there is another issue: such electrons cool quite quickly!

Cooling time problem

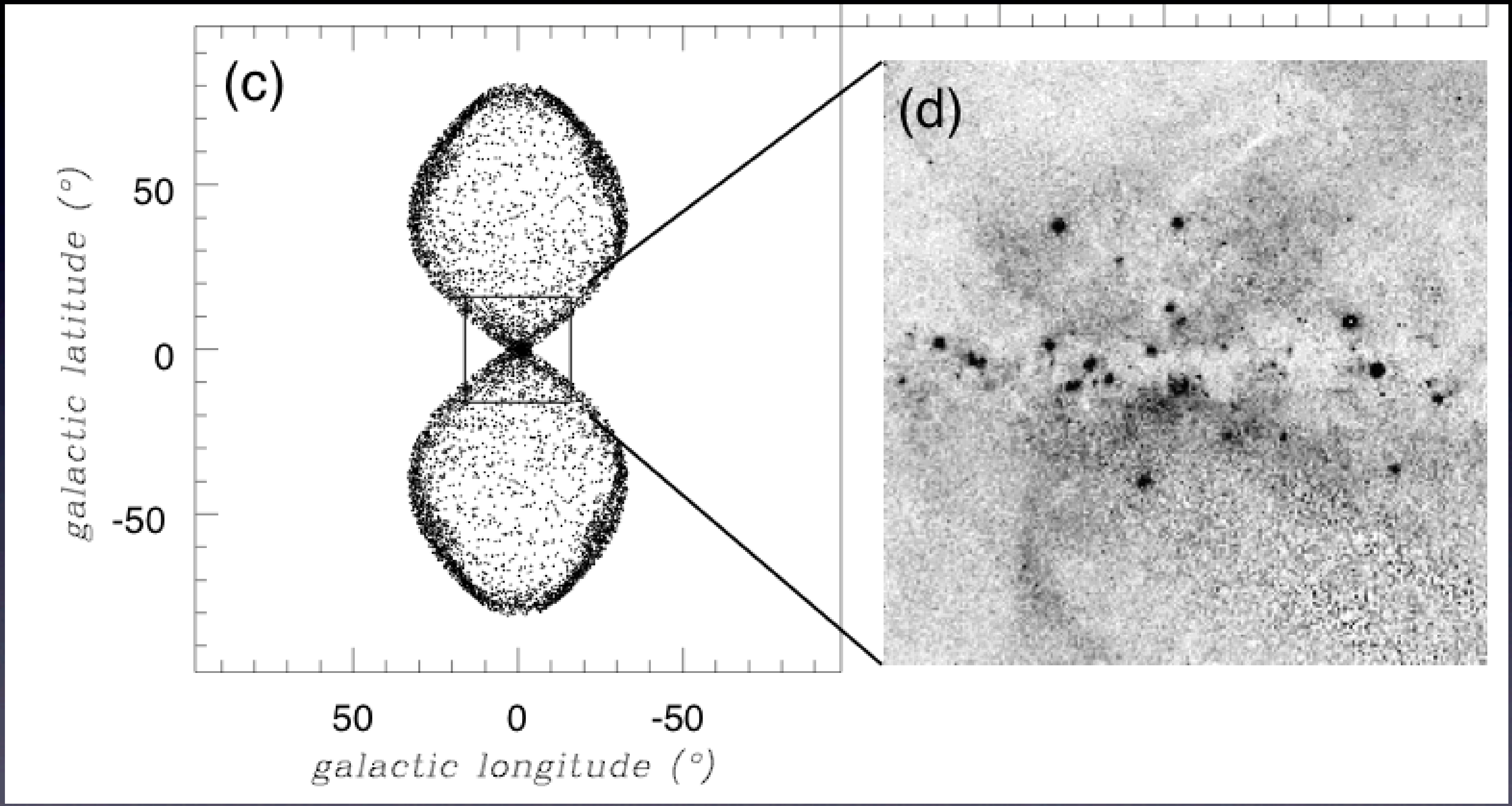
- Takes 10^7 years to go 10kpc at 1000km/s - in contrast, lifetime of a TeV electron 5kpc off the plane is less than 10^6 years.
- Need a very fast transport mechanism from GC, or acceleration/production of electron CRs at high latitudes - shock acceleration at bubble edge?
- If the latter, must avoid too much edge-brightening or hardening of the spectrum at the edge.

X-ray bubbles?

- 1.5 keV X-rays (data from ROSAT) show edges in north that seem to line up with Bubbles.
- Finkbeiner proposal for XMM follow-up recently accepted.
- Using ROSAT data and FIR measurements from MSX, Bland-Hawthorn & Cohen (2003) suggested giant bubble structures...



A bipolar Galactic wind



- Proposal: bubbles fueled by starburst in Galactic center, filled with hot gas, ~10^{55} ergs thermal energy - X-rays are thermal bremsstrahlung.
- Morphology looks very like gamma-ray bubbles - but no gamma ray signal expected.

Astrophysical explanations

- North-south symmetry and centering on GC suggest some kind of outflow.
- Hadronic or leptonic emission?
  - Hadronic = hard-spectrum protons produce hard π^0 emission.
  - Leptonic = accelerated electrons inverse Compton scatter on the interstellar radiation field.
- Transient or steady-state?
- Power source?

Hadronic vs leptonic

- Hadronic:
  - Protons lose energy slowly: no cooling problem.
  - May be possible to map pion bump to downturn below 1 GeV (although not obvious this will work in detail).
  - Emission does not seem to trace ISM inhomogeneities or expected density gradient of gas (falling steeply away from Galactic plane).
  - Hot gas (from X-rays) should be less dense: seems to need large proton CR overdensity to compensate.
  - Link to WMAP Haze via secondary electrons from high-energy protons.
- Leptonic:
  - Direct link to WMAP Haze.
  - Spectral downturn below 1 GeV can be explained with appropriate electron spectrum.
  - Cooling time problem, as discussed previously - ameliorated by fast-moving shock/wind/jet, but this requires a very large energy injection.

Transient vs steady-state

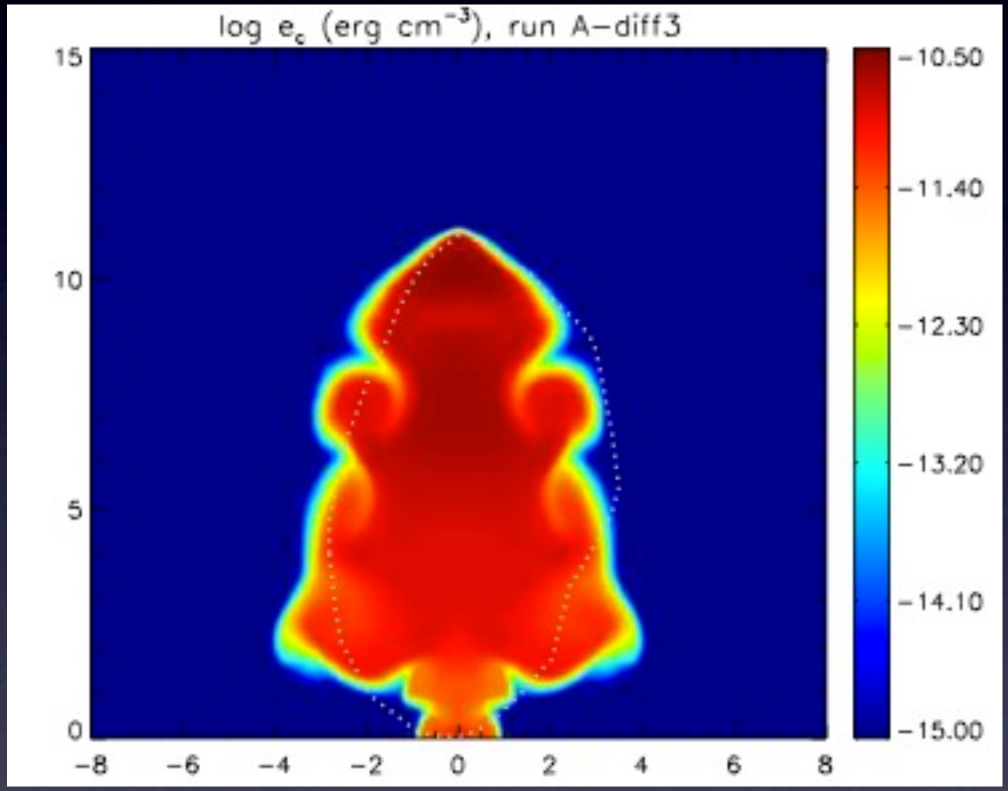
- Transient (e.g. shock erupting from GC):
  - Explain sharp edges of bubbles (rapidly moving outward).
  - Apparent spectral uniformity surprising - might expect a spectrally hard edge, if particle acceleration occurs in shock.
  - Uniform projected intensity suggests more emission at edge - but in a thick shell, or with significant emission from interior.
- Steady state (see Crocker & Aharonian arXiv:1008.2658, Crocker et al arXiv:1009.4340):
  - In hadronic case, "saturation regime" can explain why gammas do not trace ISM inhomogeneities (less proton absorption = more protons present).
  - Sharp edges are challenging: Crocker and Aharonian posit magnetic confinement. Synchrotron constraints?
  - Uniform projected intensity surprising - why not centrally brightened?

Power source: jet, starburst?

- Nuclear starburst
  - If we follow Bland-Hawthorn and Cohen 2003, natural explanation for X-rays.
  - However, speed of wind is only ~200-300 km/s: not appropriate for leptonic model.
  - Consistent with lack of H-alpha signal?
- Jet from the supermassive black hole
  - Large possible energy injection.
  - Jets seen in other galaxies tend to be quite collimated - but of course also larger. Blast wave expanding out from “dead jet”?
  - North-south orientation of bubbles: expected? Perhaps set by density gradient of gas/CRs in Galaxy?

Breaking news: feasibility study on jets

- Guo & Matthews arXiv:1103.0055, released today, studies jet scenario.
- 2 Myr old pair of jets from AGN
  - Each lasting 0.1-0.5 Myr
  - Each with ~10^{57} ergs of energy
  - Jet velocity ~ 0.05-0.3 c (CR transport advection-dominated).
- Need CR diffusion to be suppressed across edges, unsuppressed inside bubble - natural from magnetic field?
- Jets are overpressured relative to ambient hot gas, from high CR pressure & shocked thermal gas: leads to lateral expansion of bubbles.

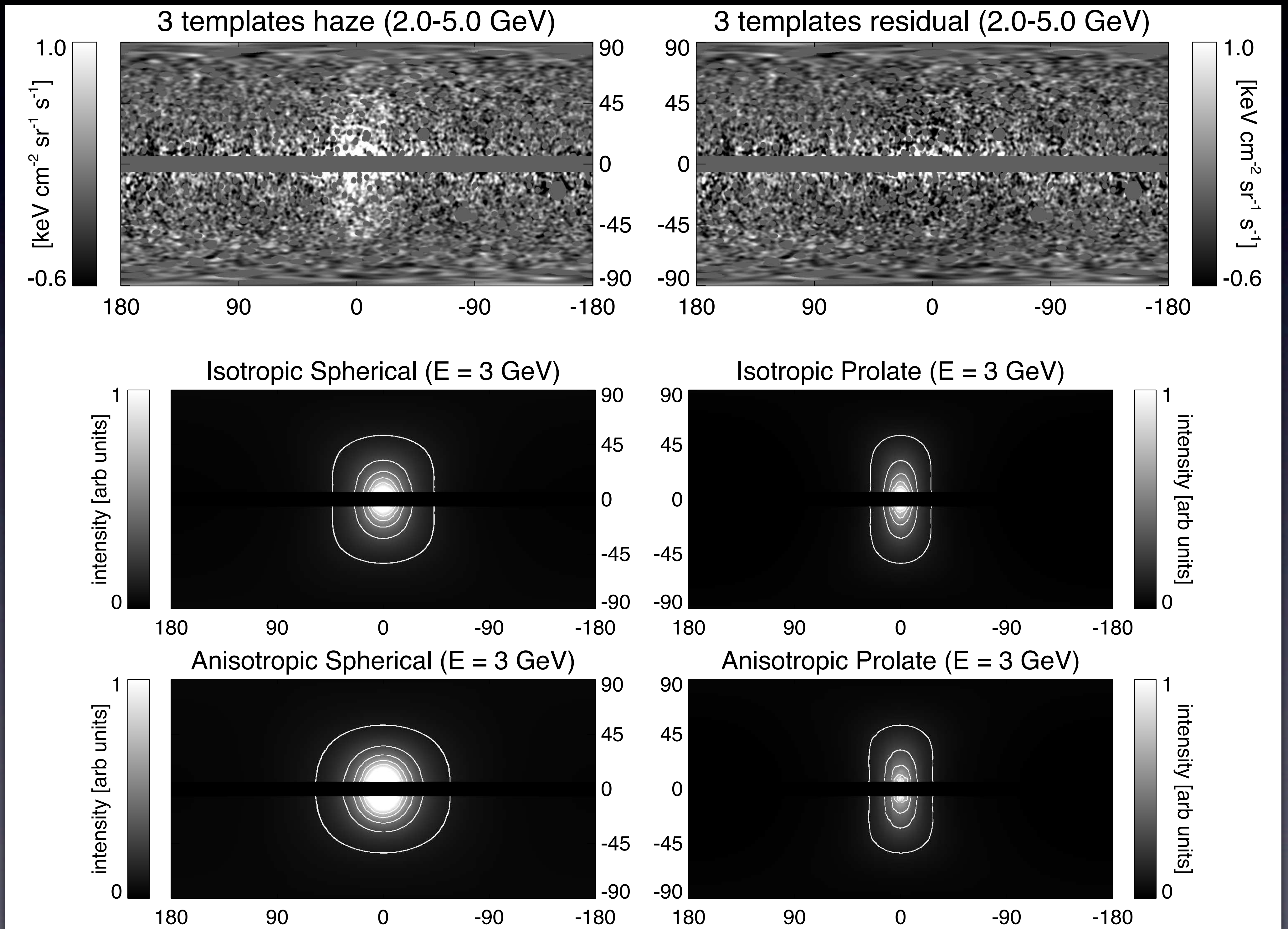


Example CR energy density from sample jet simulation, with suppressed diffusion at edges

Could it be dark matter?

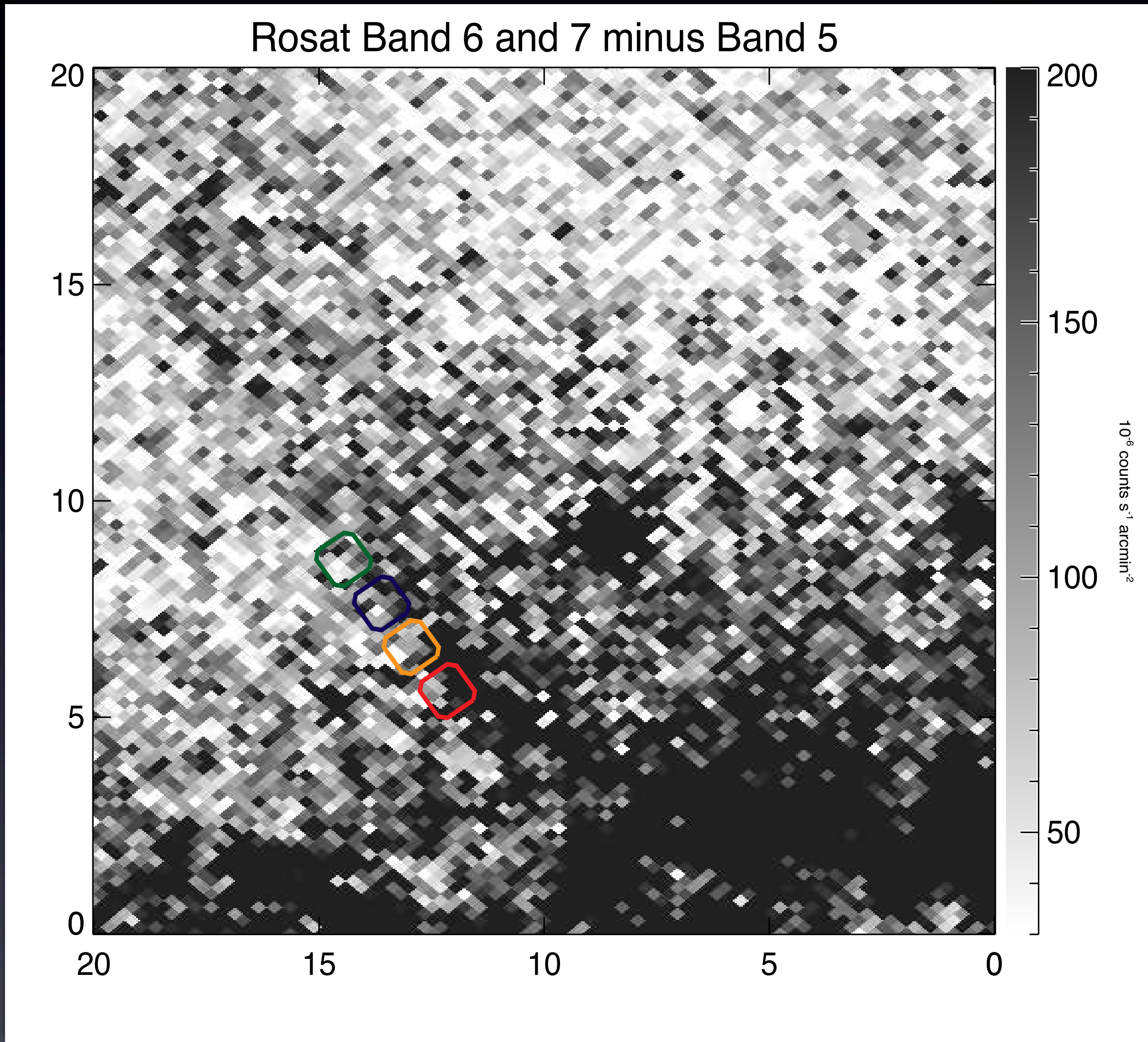
- Prolate DM halo gives uniform hard spectrum, latitudinally extended signal.
- Doesn't explain sharp edges; assume low-latitude edges (in X-rays and subtracted gammas) unrelated to hard high-latitude emission.

Greg Dobler, Ilias Cholis & Neal Weiner. Plots provided by NW.



Follow-up observations

- X-rays: accepted proposal by Finkbeiner et al for XMM mosaics across edges. Should clarify sharpness and spectrum of edges.
- Gamma-rays: H.E.S.S. has data from Galactic plane that may be relevant, search ongoing. High-latitude H.E.S.S study would require long exposure.
- Other ideas?



Plot supplied by D. P. Finkbeiner

Implications for DM search

- Sharp edges + X-ray signal suggest that something other than just DM annihilation is occurring. (Hopefully XMM observations will clarify X-ray situation.)
- Doesn't mean there's no DM signal in this region, but we need to understand the astrophysics first.
  - DM annihilation producing photons directly or through a decay chain: Fermi bubbles are a bright, hard-spectrum background. Look outside the edges?
  - DM annihilation producing CRs that then produce photons: if bubbles indicate a fast outflow, CR propagation, e^+e^- residence time are affected. Can this **weaken** constraints?

Conclusions

- The gamma-ray bubbles are ROBUST features in 1-100 GeV gamma rays, with a spatially uniform close-to-flat spectrum in E^2 dN/dE, close-to-uniform projected emissivity, and sharp edges.
- At high latitudes they are what we previously called the "Fermi Haze"; close to the GC there is hard emission not included in the sharp-edged "bubbles".
- The spectrum and morphology suggest a relation to the WMAP Haze, and there appears to be a coincident signal in 1.5-2 keV X-rays.
- While DM physics might contribute, the sharp edges of the bubbles and coincident X-ray signal seem likely to have an astrophysical origin - however, this remains an open problem!
- The combination of sharp edges, lack of edge or central brightening, and uniform spectrum are challenging for ALL ideas so far (maybe with one brand-new exception?)
- Until the astrophysics is understood, studies of DM constraints and potential signals from this region of the sky should proceed with care.

BONUS SLIDES

The diffuse γ-ray sky

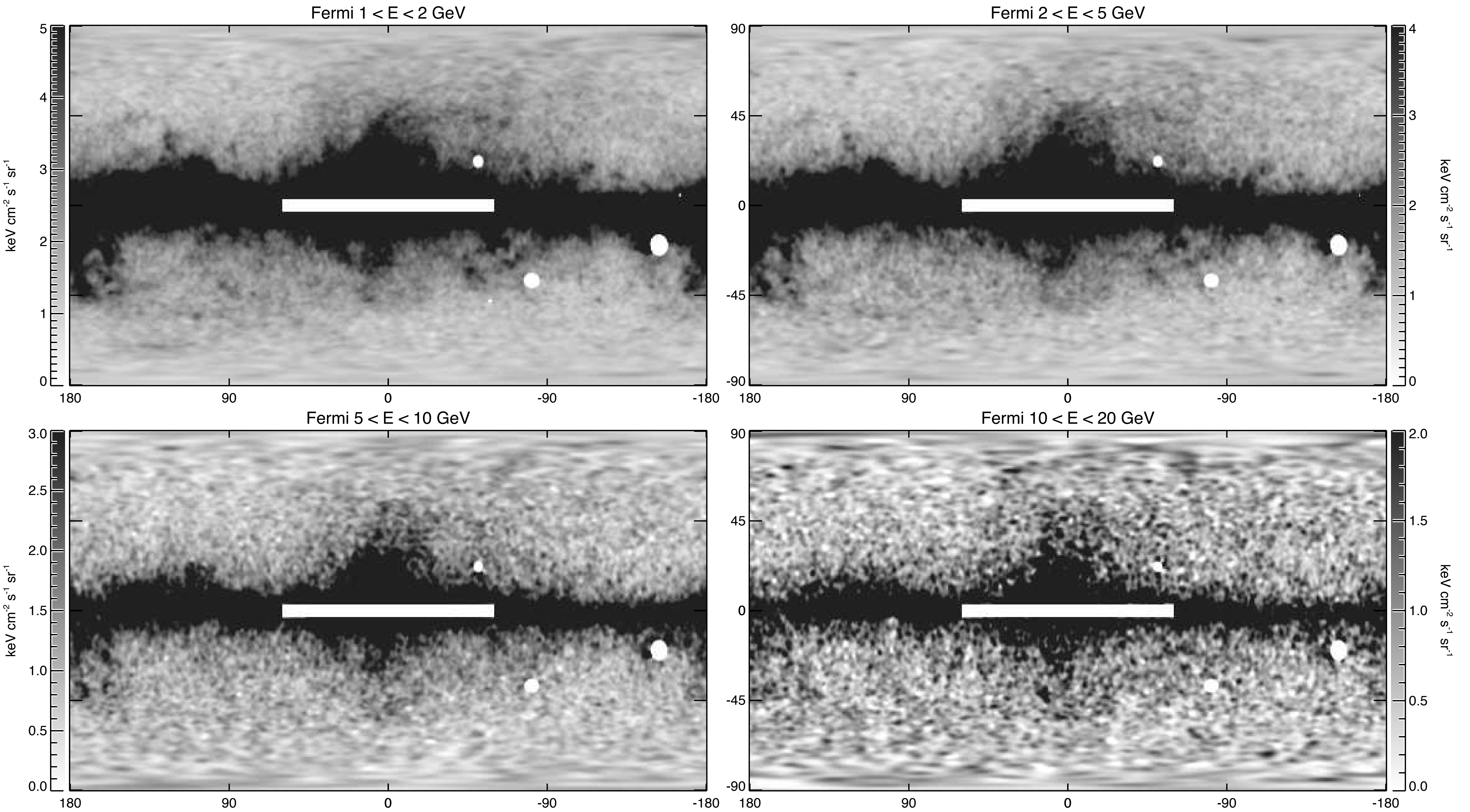
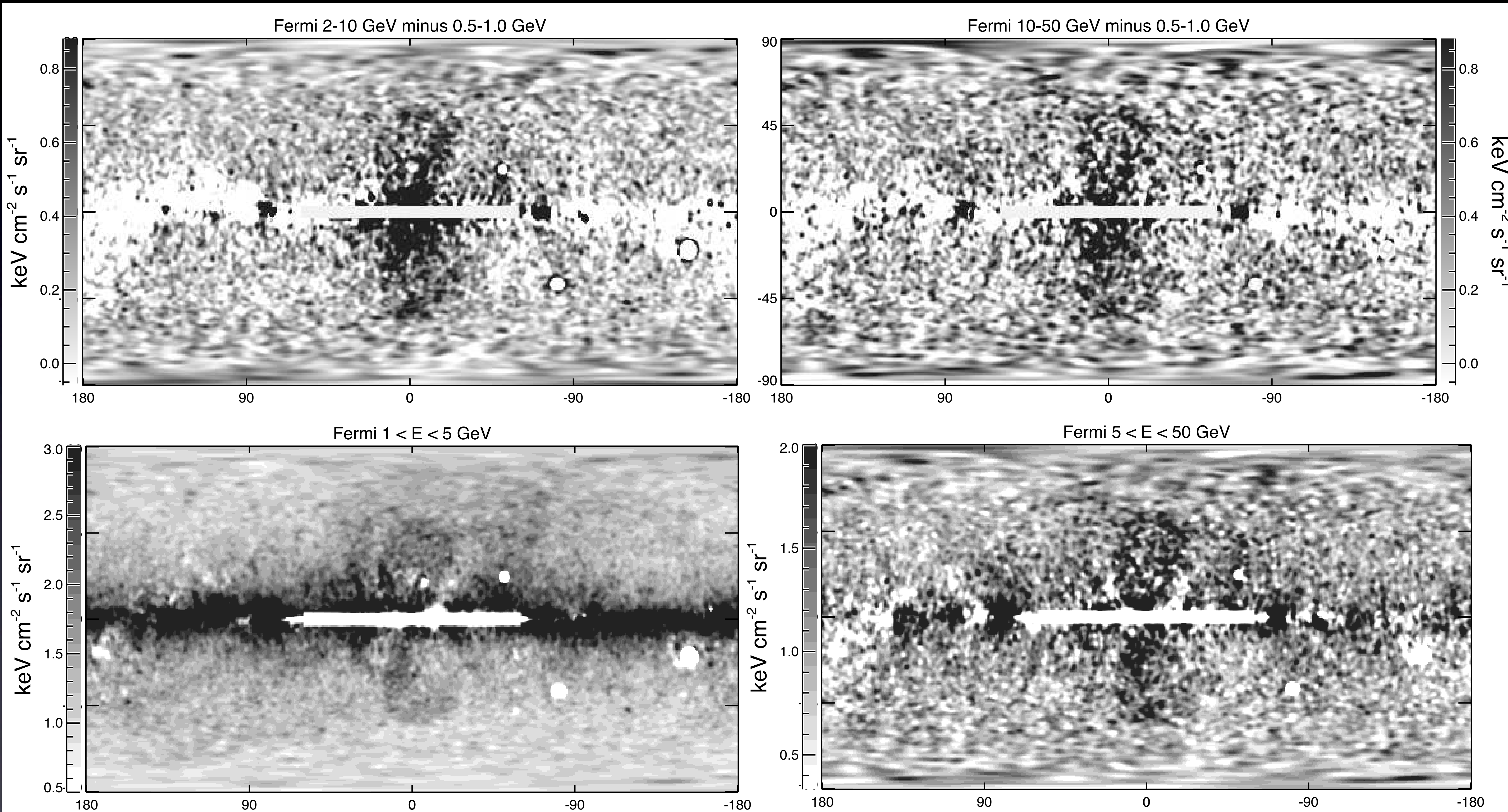


FIG. 1.— All-sky *Fermi*-LAT 1.6 year maps in 4 energy bins. Point sources have been subtracted, and large sources, including the inner disk ($-2° < b < 2°, -60° < \ell < 60°$), have been masked.

Example bubble



- A large, double-lobed residual remains, apparently sharp-edged and centered on Galactic Center. The residual is seen over a wide range of energy, and all ICS templates.

Data - model (FDM)

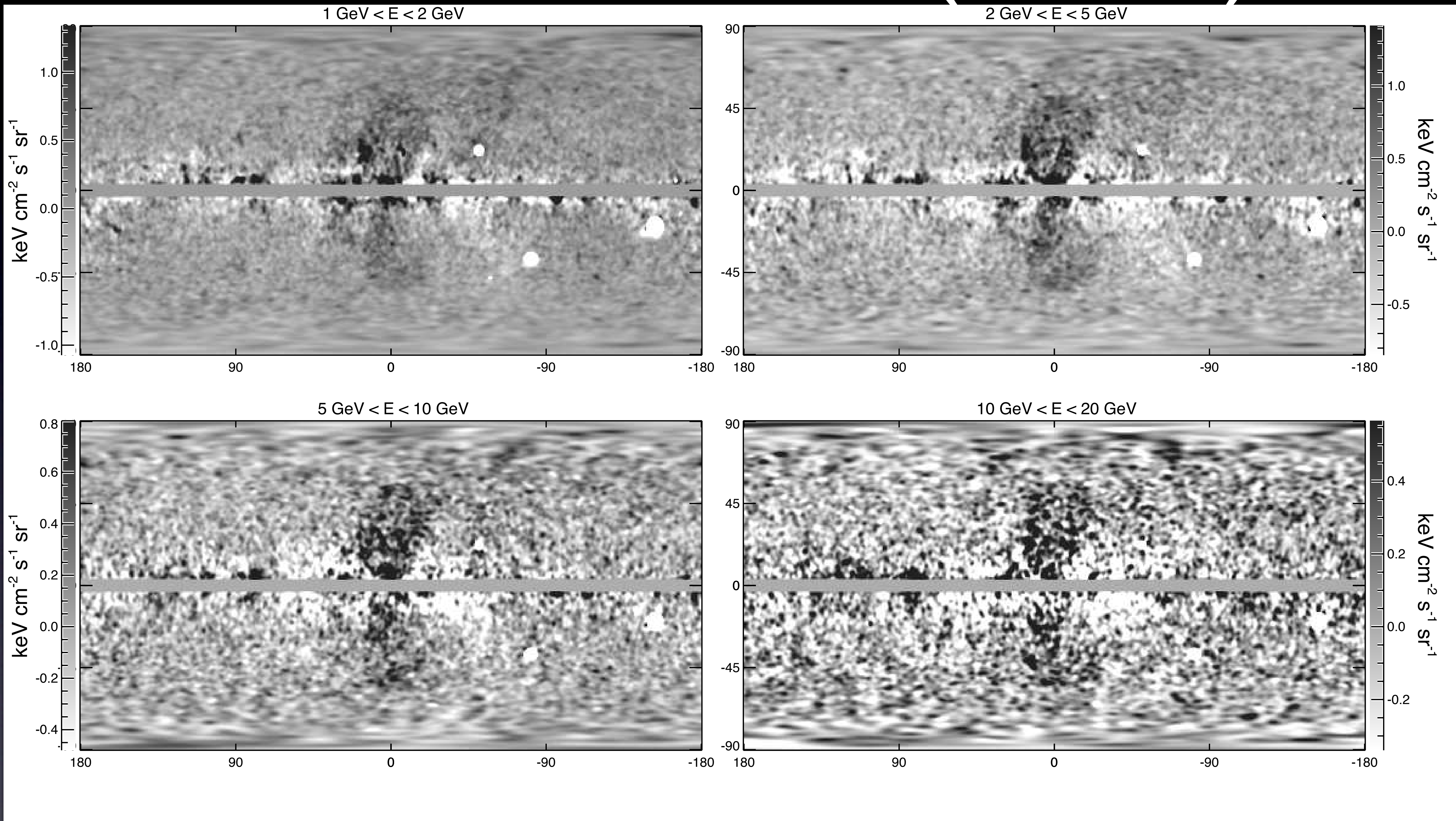
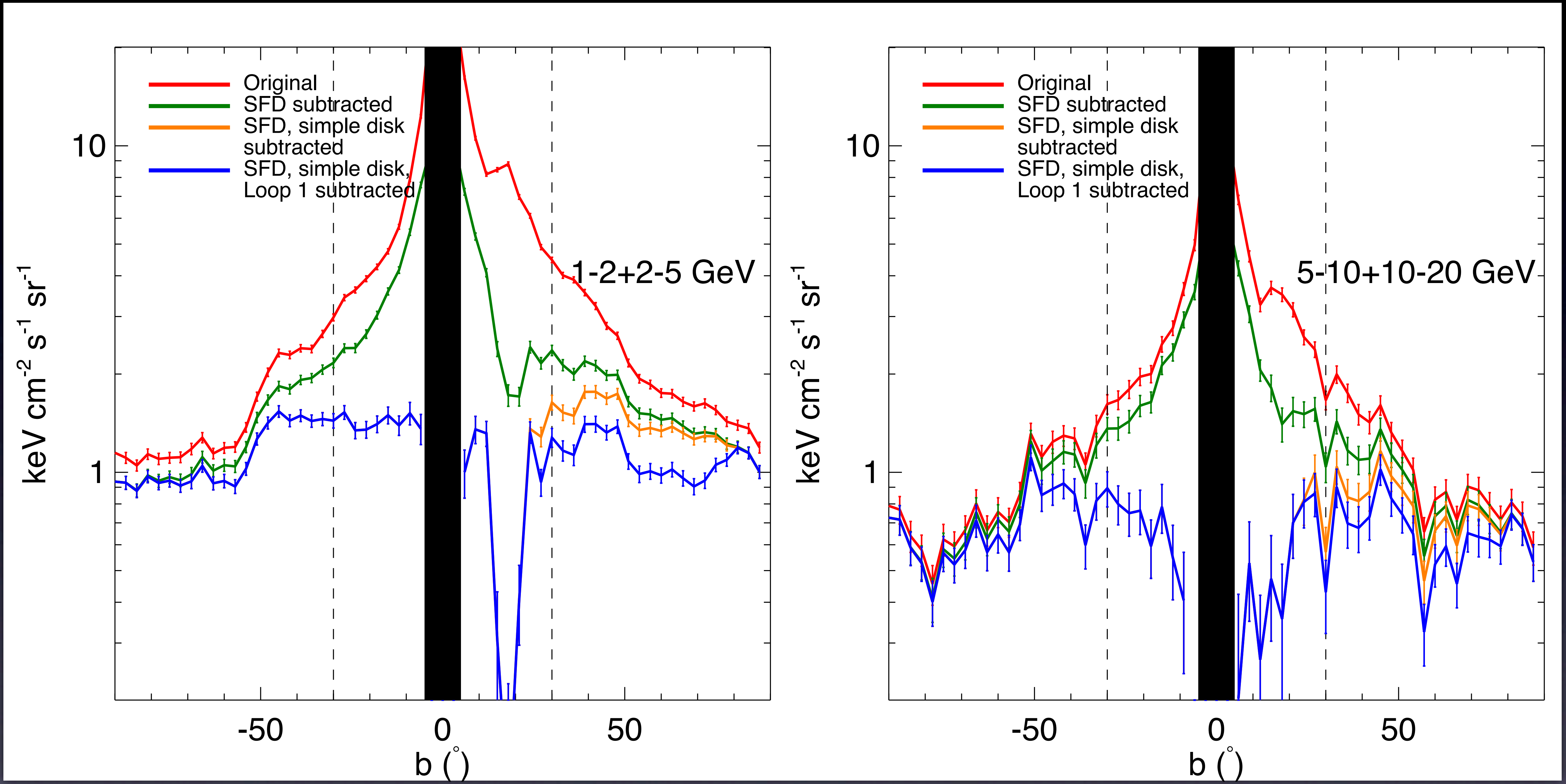


FIG. 2.— All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins (see §3.1.1). Two bubble structures extending to $b \pm 50°$ appear above and below the GC, symmetric about the Galactic plane.

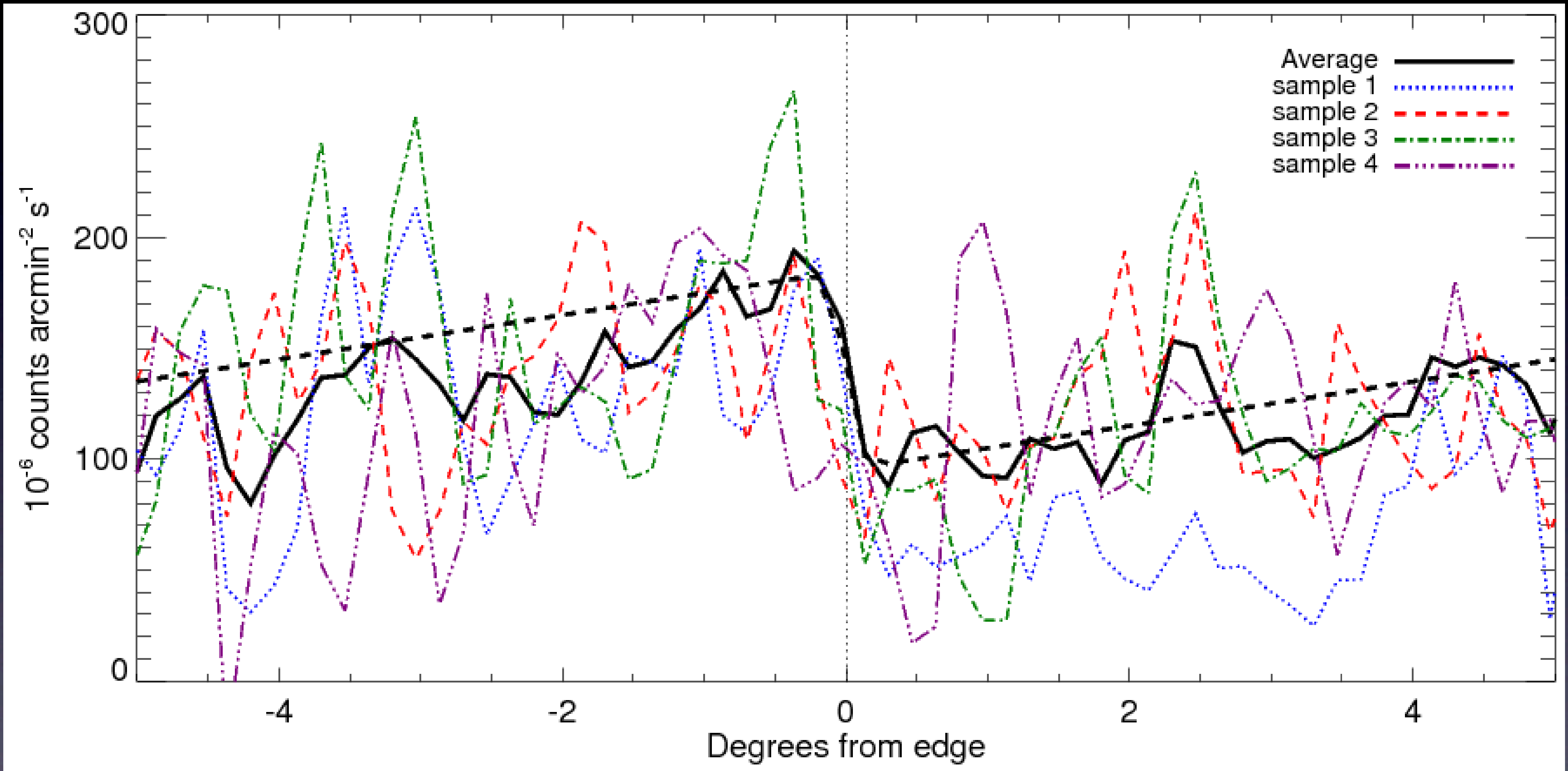
- Cancels emission well over much of the sky, but sharp-edged, double-lobed residual remains, as previously.

Profile in b



- Average over |l|<20°, for two different energies.
- In the |b|>30° fit region, profile appears roughly flat in l, until the edges around |b|=50°.

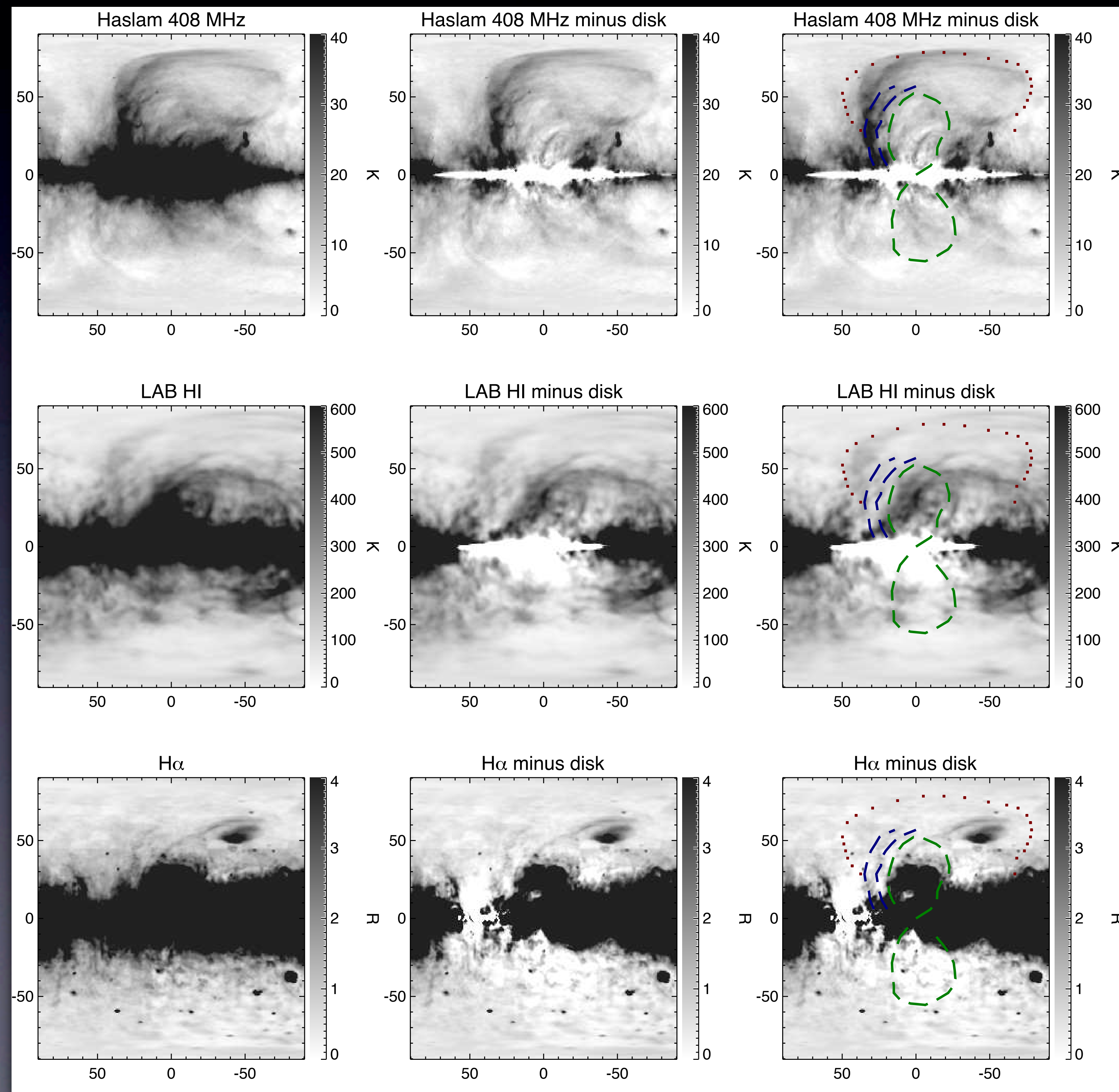
How sharp is the X-ray edge?



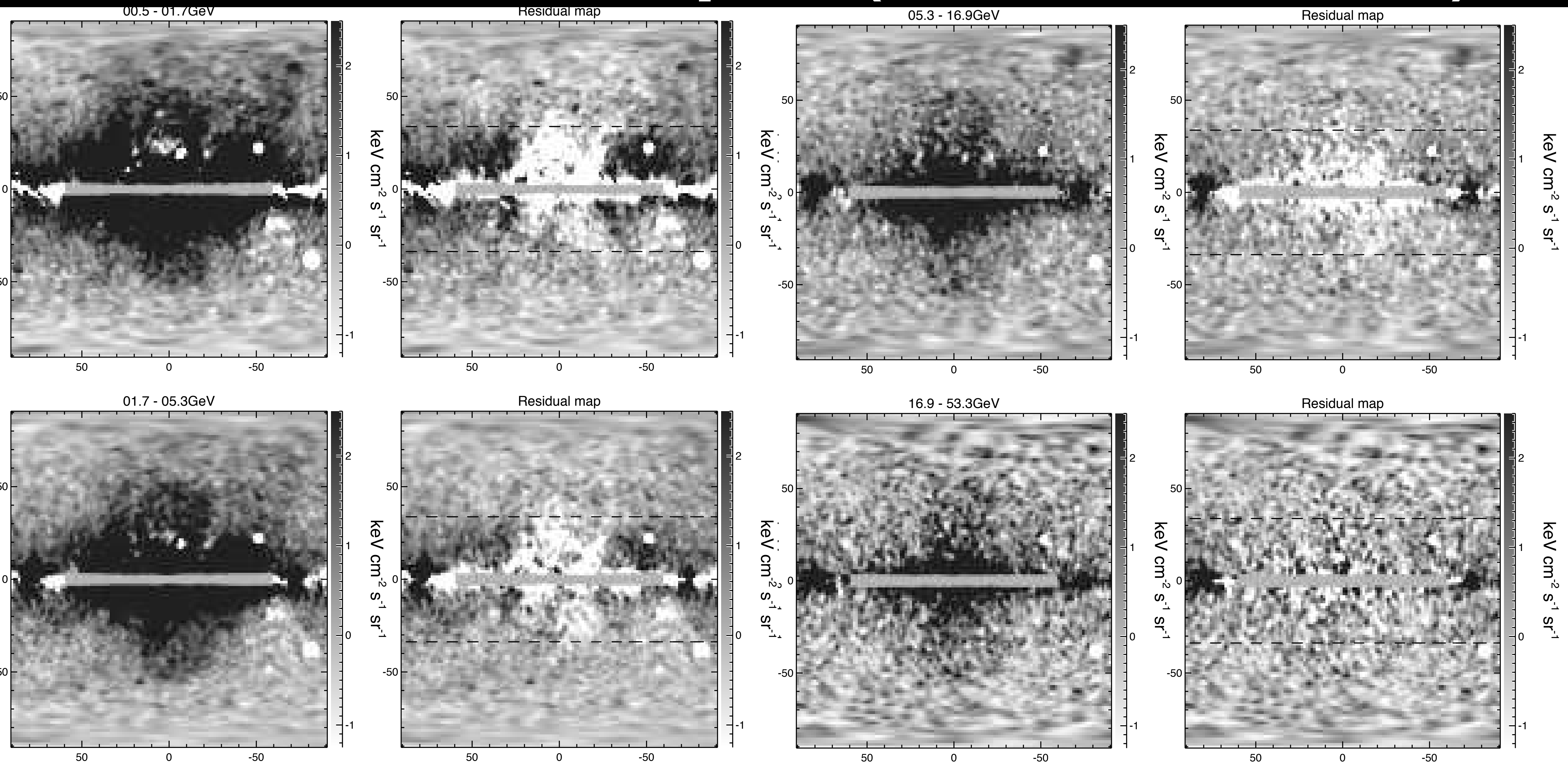
- Consistent with a step function (~0.2° or less).

Other wavelengths

- No obvious Bubbles-like features in 408 MHz Haslam survey, HI or H-alpha.

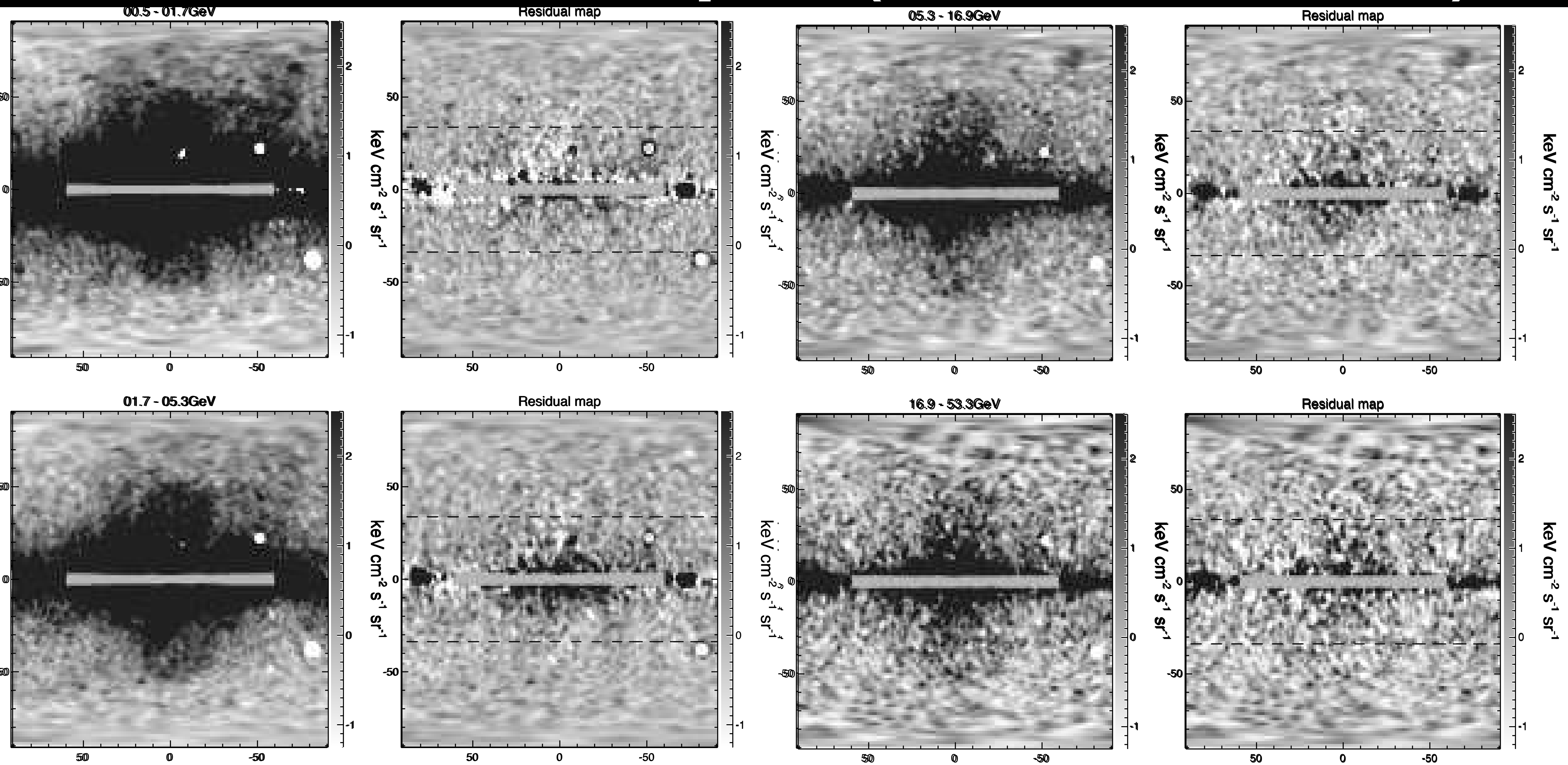


Residual maps (no bubbles)



- Dust-subtracted maps (left) and residuals after subtracting the "simple disk" and the bubbles (right), for four different energy bins.

Residual maps (no bubbles)

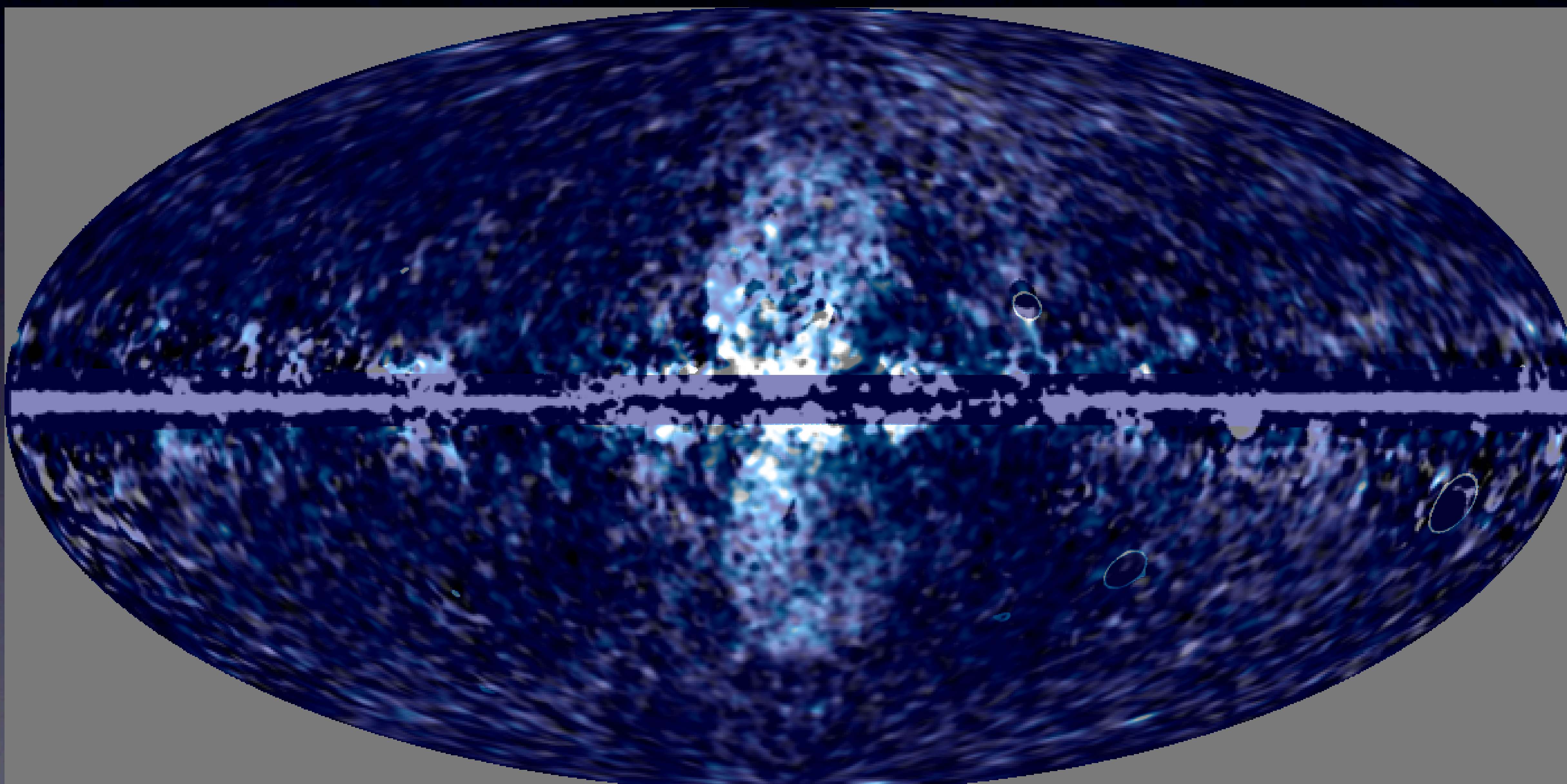


- As previously, but using the dust-subtracted 0.5-1 GeV Fermi map as an ICS template. Note the smaller residuals, although there still appears to be a hard residual excess around the inner Galaxy.

Total power?

- Treat bubbles as a pair of spheres, centered at b=±28°, directly above and below the GC.
- Distance to bubble centers ~9.6kpc.
- Total gamma-ray luminosity in 1-100 GeV range is then ~4×10^{37} ergs/s (~2.5×10^{40} GeV/s).
- For reference, typical supernova outputs ~10^{51} ergs: the gamma-ray luminosity corresponds to 1 supernova per 10^6 years. Of course whatever is making this may require more energy (efficiency to gamma rays is probably not 100%...)

Aitoff projection

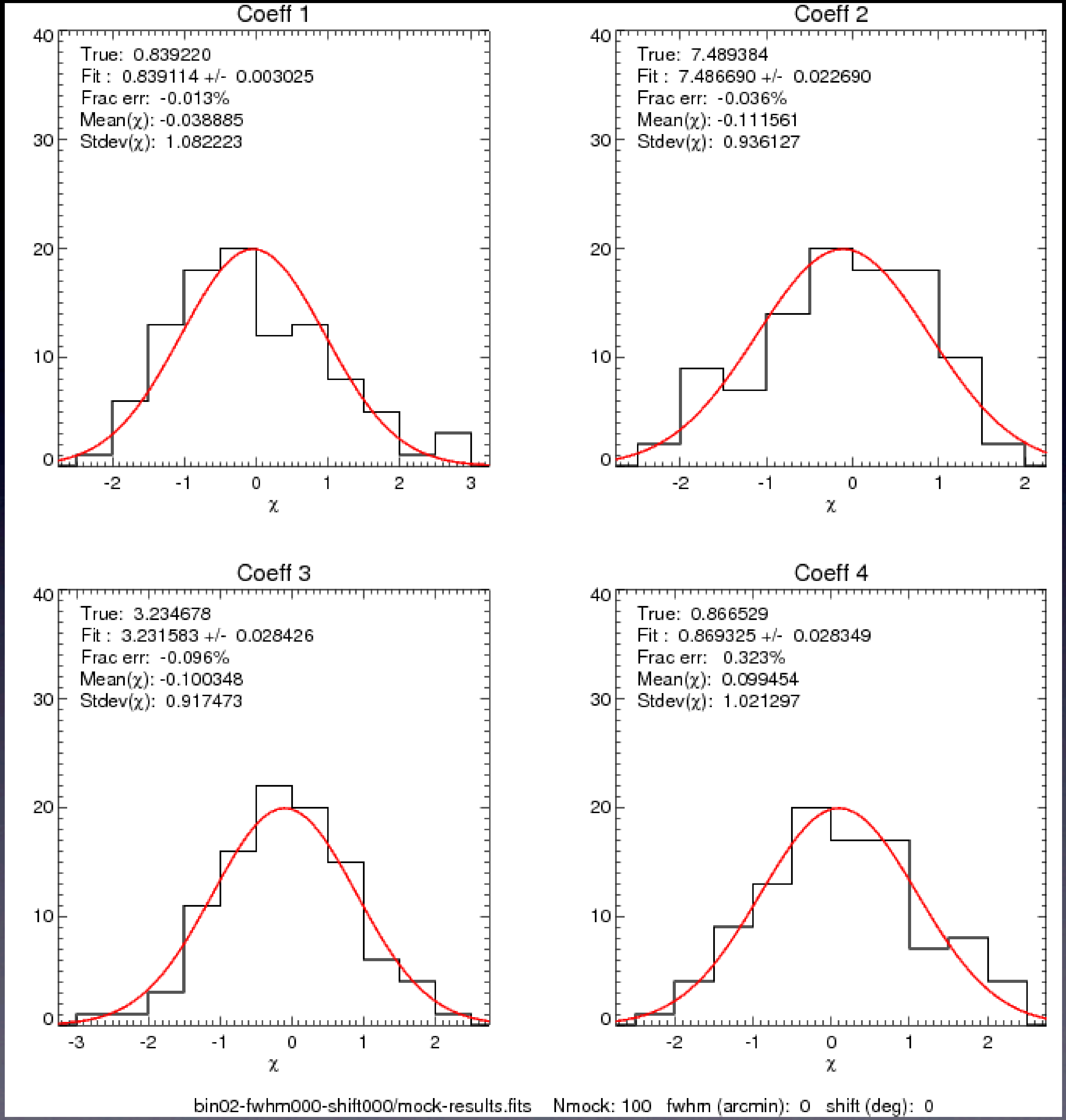


1. You don't know how to do statistics.

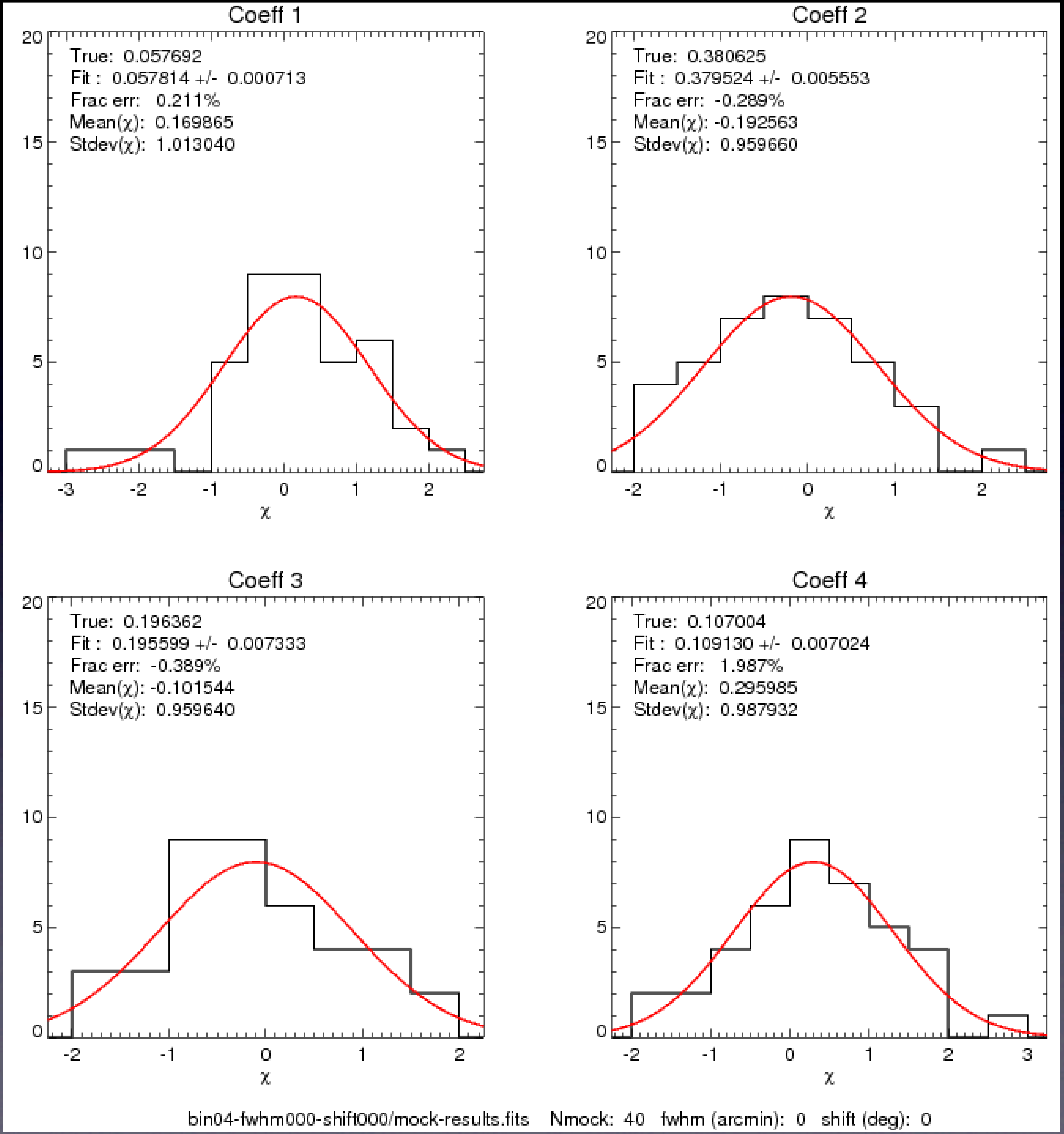
For each set of model parameters, we evaluate the Poisson likelihood of the Fermi exposure yielding the observed counts (outside of point source regions) after PSF matching templates and data.

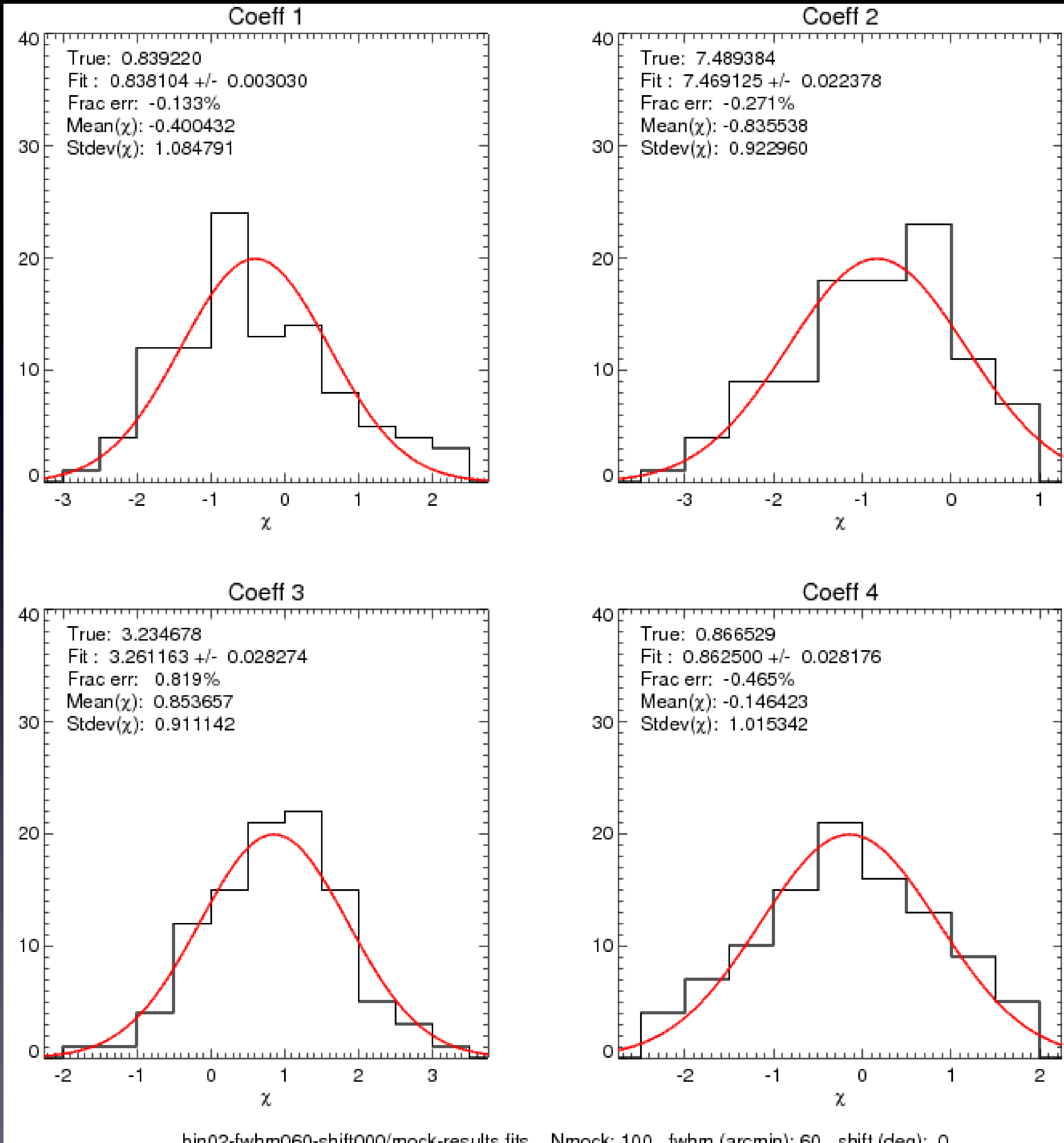
We generate mock maps (given parameters and the exposure map) and run them through the analysis to verify that the estimated parameters and uncertainties are correct.

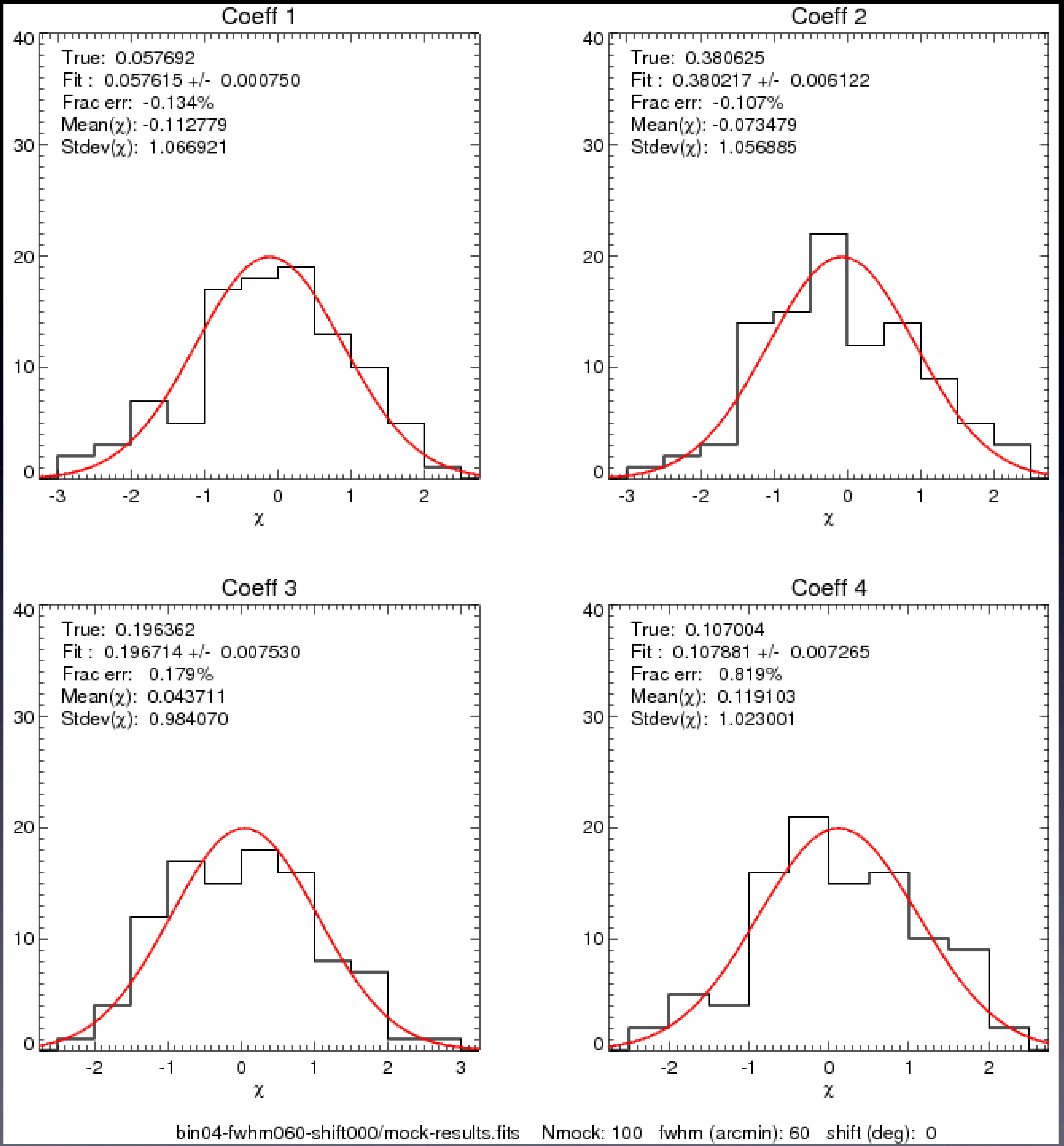
$$\log \mathcal{L} = \sum_i k_i \log \mu_i - \mu_i - \log(k_i!)$$



Coeff 1
True: 0.839220
Fit : 0.839114 +/- 0.003025
Frac err: -0.013%
Mean(χ): -0.038885
Stdev(χ): 1.082223
Coeff 2
True: 7.489384
Fit : 7.486690 +/- 0.022690
Frac err: -0.036%
Mean(χ): -0.111561
Stdev(χ): 0.936127
Coeff 3
True: 3.234678
Fit : 3.231583 +/- 0.028426
Frac err: -0.096%
Mean(χ): -0.100348
Stdev(χ): 0.917473
Coeff 4
True: 0.866529
Fit : 0.869325 +/- 0.028349
Frac err: 0.323%
Mean(χ): 0.099454
Stdev(χ): 1.021297
χ
bin02-fwhm000-shift000/mock-results.fits Nmock: 100 fwhm (arcmin): 0 shift (deg): 0


Coeff 1
True: 0.057692
Fit : 0.057814 +/- 0.000713
Frac err: 0.211%
Mean(χ): 0.169865
Stdev(χ): 1.013040
χ
Coeff 2
True: 0.380625
Fit : 0.379524 +/- 0.005553
Frac err: -0.289%
Mean(χ): -0.192563
Stdev(χ): 0.959660
χ
Coeff 3
True: 0.196362
Fit : 0.195599 +/- 0.007333
Frac err: -0.389%
Mean(χ): -0.101544
Stdev(χ): 0.959640
χ
Coeff 4
True: 0.107004
Fit : 0.109130 +/- 0.007024
Frac err: 1.987%
Mean(χ): 0.295985
Stdev(χ): 0.987932
χ
bin04-fwhm000-shift000/mock-results.fits Nmock: 40 fwhm (arcmin): 0 shift (deg): 0


Coeff 1
True: 0.839220
Fit : 0.838104 +/- 0.003030
Frac err: -0.133%
Mean(χ): -0.400432
Stdev(χ): 1.084791
Coeff 2
True: 7.489384
Fit : 7.469125 +/- 0.022378
Frac err: -0.271%
Mean(χ): -0.835538
Stdev(χ): 0.922960
Coeff 3
True: 3.234678
Fit : 3.261163 +/- 0.028274
Frac err: 0.819%
Mean(χ): 0.853657
Stdev(χ): 0.911142
Coeff 4
True: 0.866529
Fit : 0.862500 +/- 0.028176
Frac err: -0.465%
Mean(χ): -0.146423
Stdev(χ): 1.015342
χ
bin02-fwhm060-shift000/mock-results.fits Nmock: 100 fwhm (arcmin): 60 shift (deg): 0


Coeff 1
True: 0.057692
Fit : 0.057615 +/- 0.000750
Frac err: -0.134%
Mean(χ): -0.112779
Stdev(χ): 1.066921
Coeff 2
True: 0.380625
Fit : 0.380217 +/- 0.006122
Frac err: -0.107%
Mean(χ): -0.073479
Stdev(χ): 1.056885
Coeff 3
True: 0.196362
Fit : 0.196714 +/- 0.007530
Frac err: 0.179%
Mean(χ): 0.043711
Stdev(χ): 0.984070
Coeff 4
True: 0.107004
Fit : 0.107881 +/- 0.007265
Frac err: 0.819%
Mean(χ): 0.119103
Stdev(χ): 1.023001
χ
bin04-fwhm060-shift000/mock-results.fits Nmock: 100 fwhm (arcmin): 60 shift (deg): 0

1. You don’t know how to do statistics.

The parameters are unbiased (at the 1/10th sigma level) and the uncertainties are correct (at the 10% level) as expected for 100 mock trials.

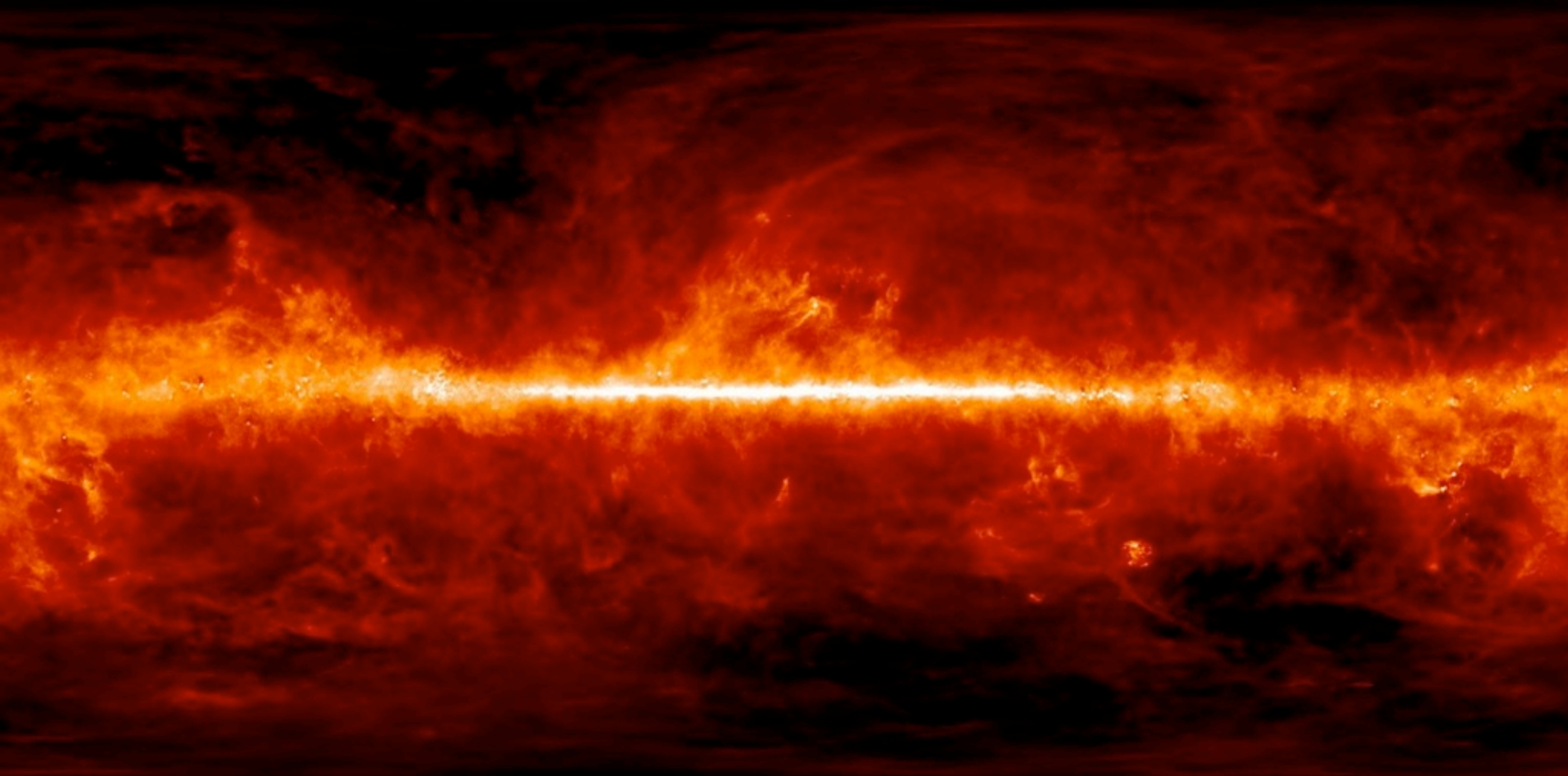
Conclusion: we know how to do statistics.

WMAP foreground templates

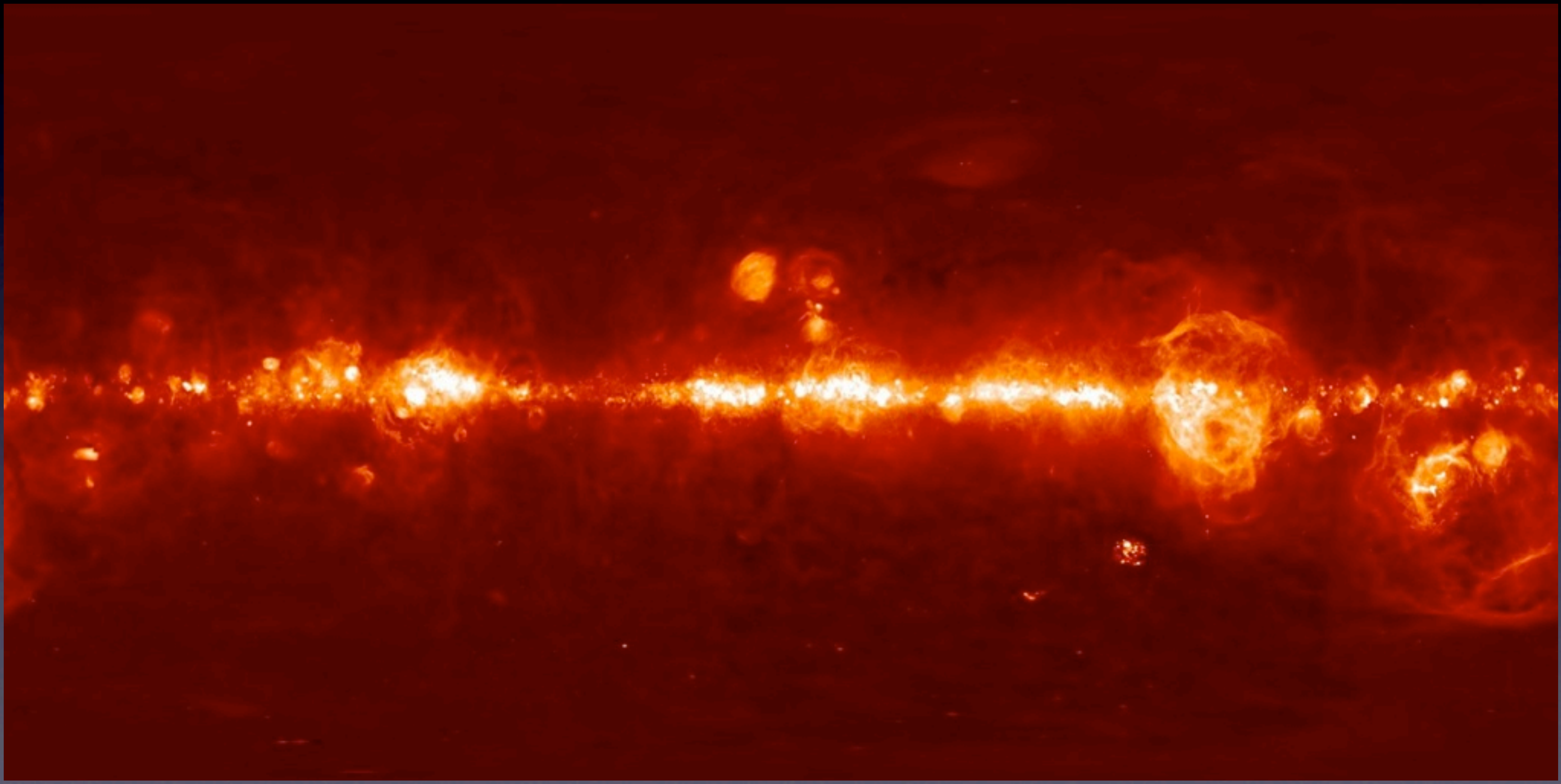
Available templates (as of 2003):

SFD dust - Far IR based dust map
Halpha - free-free template, must correct for extinction
Haslam - 408 MHz radio survey

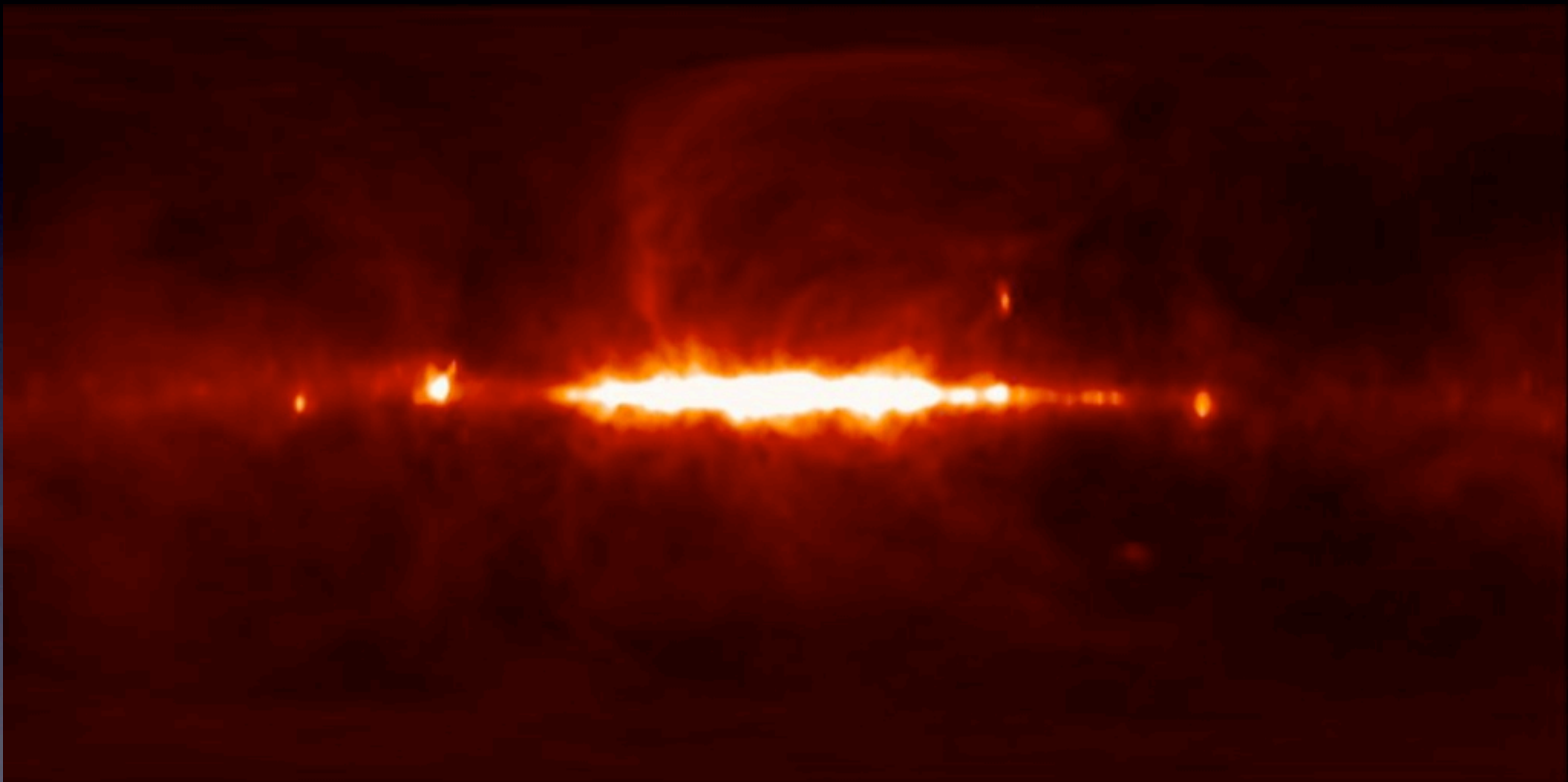
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999)
Map extrapolated from 3 THz (100 micron) with FIRAS.

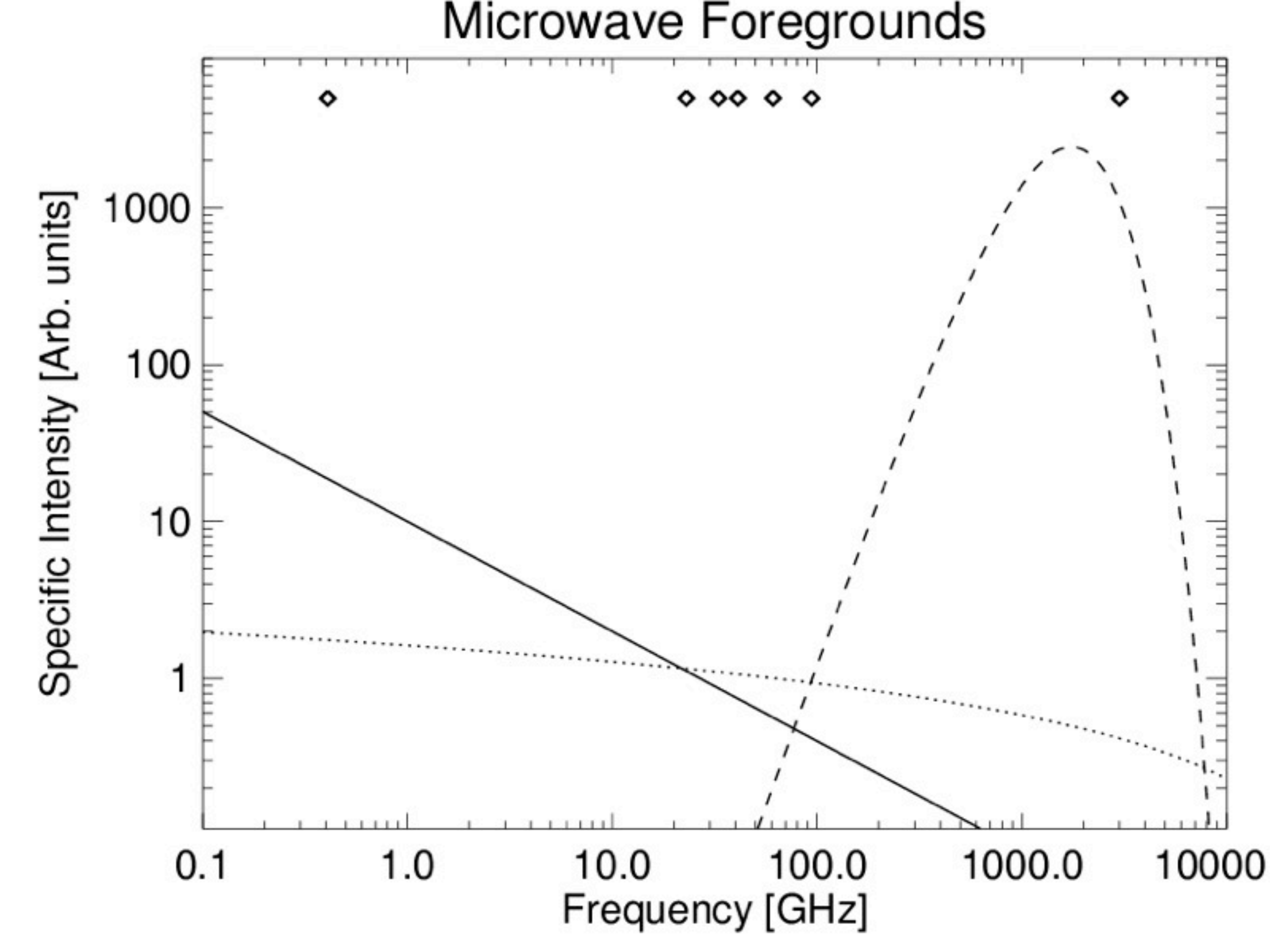


Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)
H-alpha emission measure goes as thermal bremsstrahlung.



Synchrotron at 408 MHz (Haslam et al. 1982)




Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]