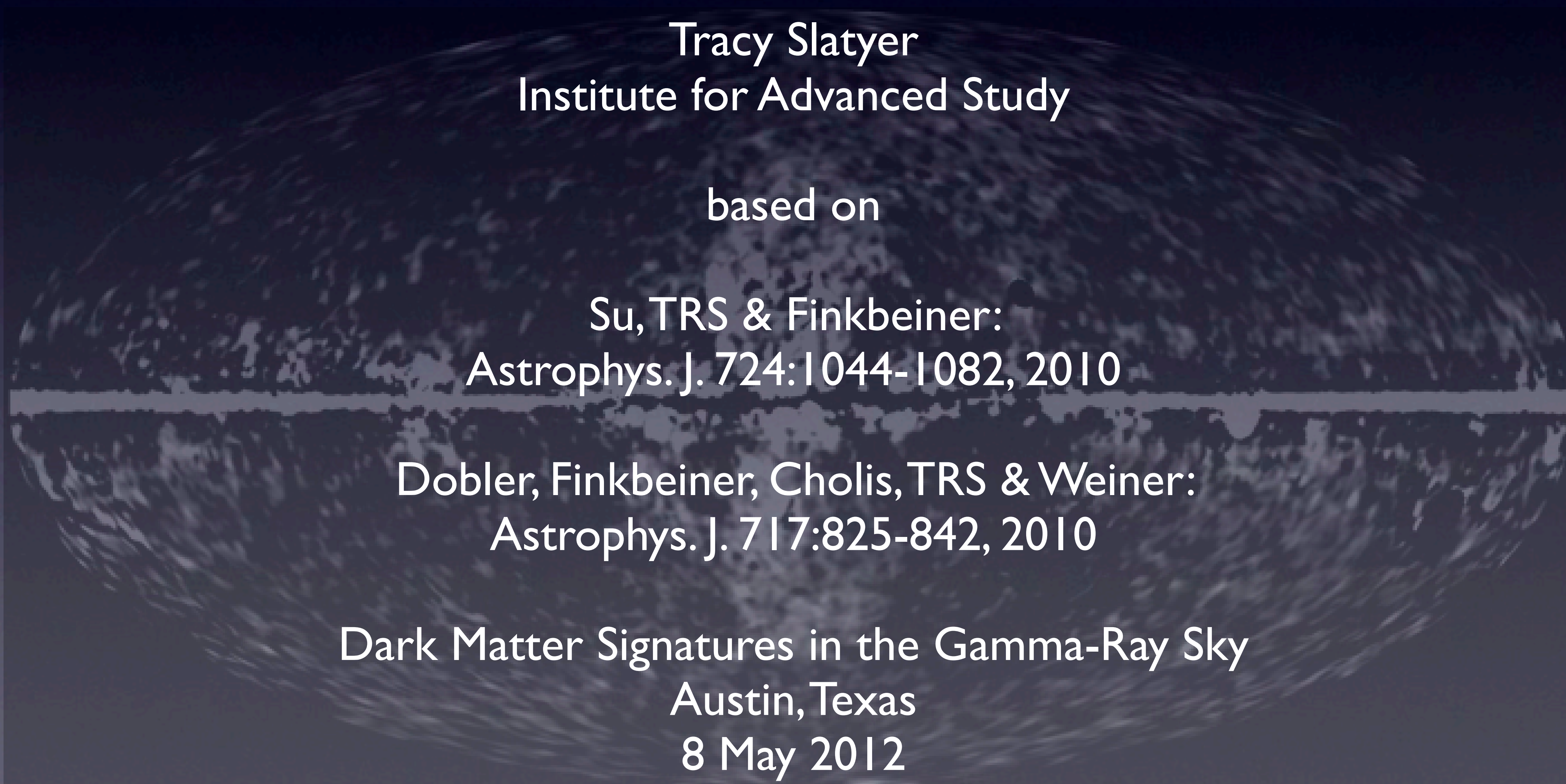
Status of the Fermi Bubbles



Tracy Slatyer
Institute for Advanced Study

based on

Su, TRS & Finkbeiner:
Astrophys. J. 724:1044-1082, 2010

Dobler, Finkbeiner, Cholis, TRS & Weiner:
Astrophys. J. 717:825-842, 2010

Dark Matter Signatures in the Gamma-Ray Sky
Austin, Texas
8 May 2012

Goals of this talk

- Review of the Fermi Bubbles: how we extract them from the data, their salient properties, their relation to the Fermi Haze.
  - 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.
- Some updated plots.
- Where we stand on multiwavelength follow-ups (see Greg's talk).
- Where we stand on interpretation.

Searching for a hard diffuse excess with *Fermi*

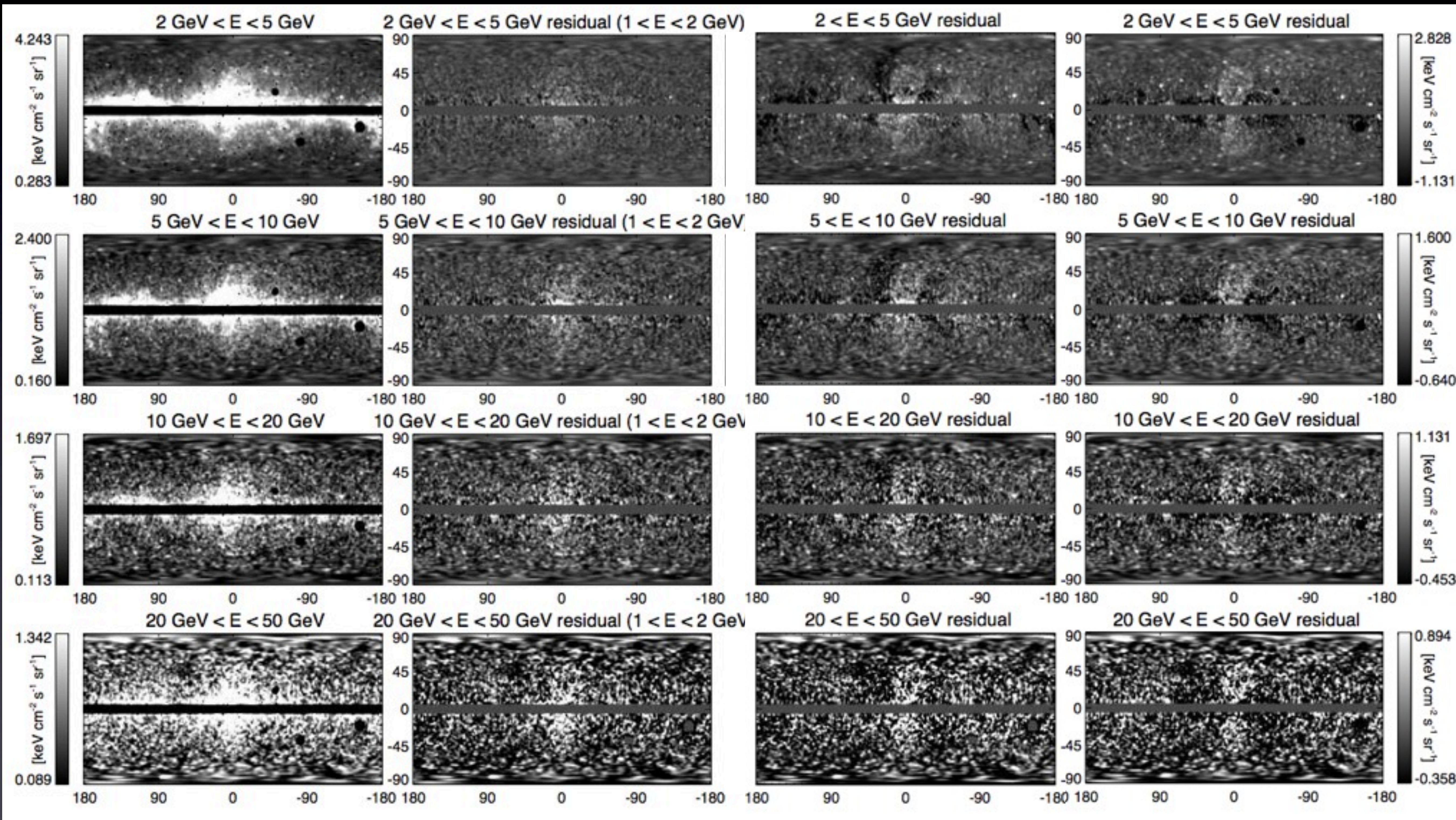
Three principal approaches (Dobler, Finkbeiner, Cholis, TRS & Weiner 2010):

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.**

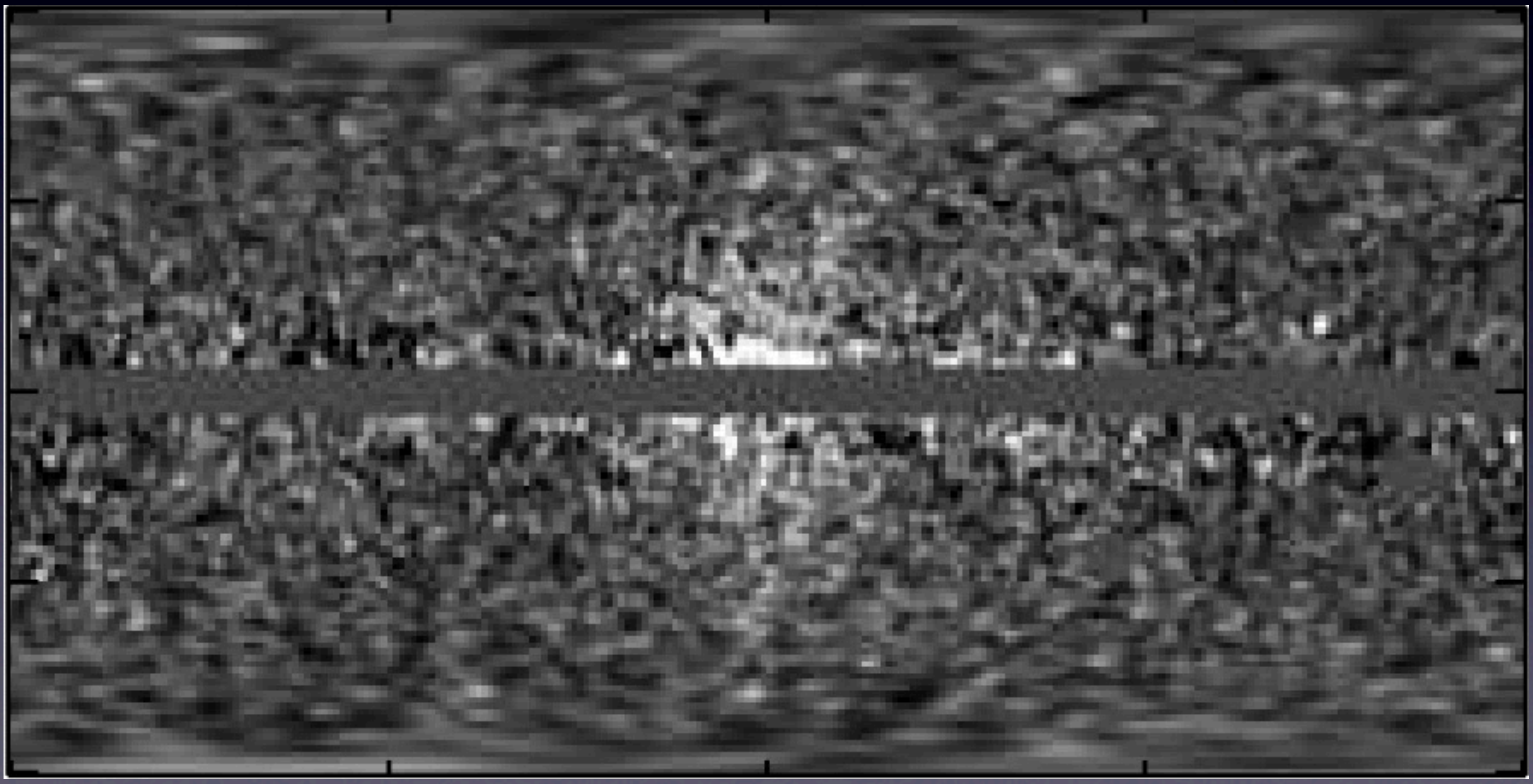
3. Template analysis using Schlegel-Finkbeiner-Davis dust map (from far IR) as tracer of gamma-rays from collisions between interstellar medium and CRs, + try a range of templates to remove "standard" ICS associated with the Galactic plane. Allows **simple few-parameter characterization** of diffuse emission, but need to assess residuals carefully.

5. Subtract diffuse model provided by Fermi Collaboration from the data, examine residuals. Model is quite complex, but **physically motivated**. Need to ask if adjustments to model could reproduce residuals.

The "Fermi Haze"



Haze => bubbles?



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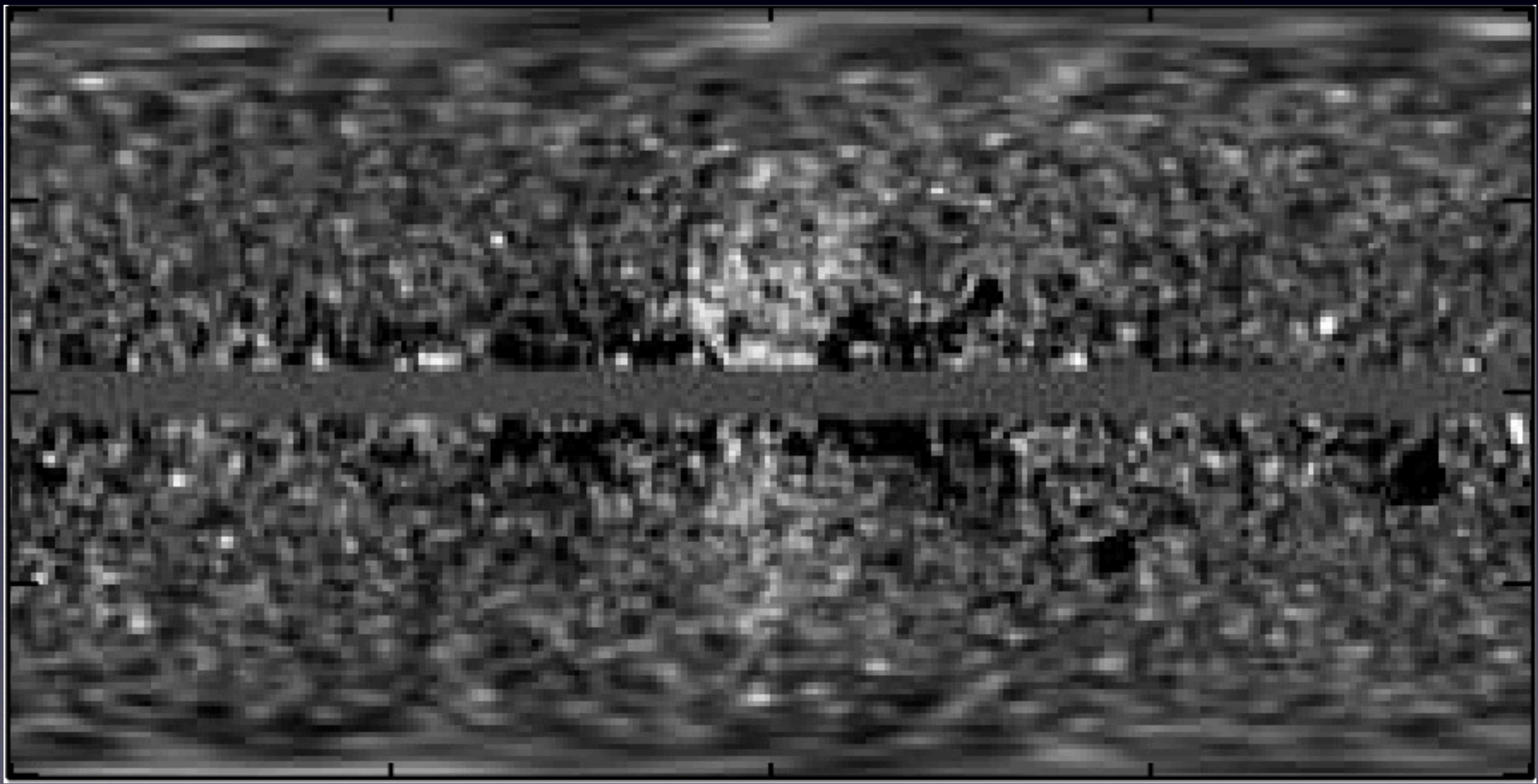
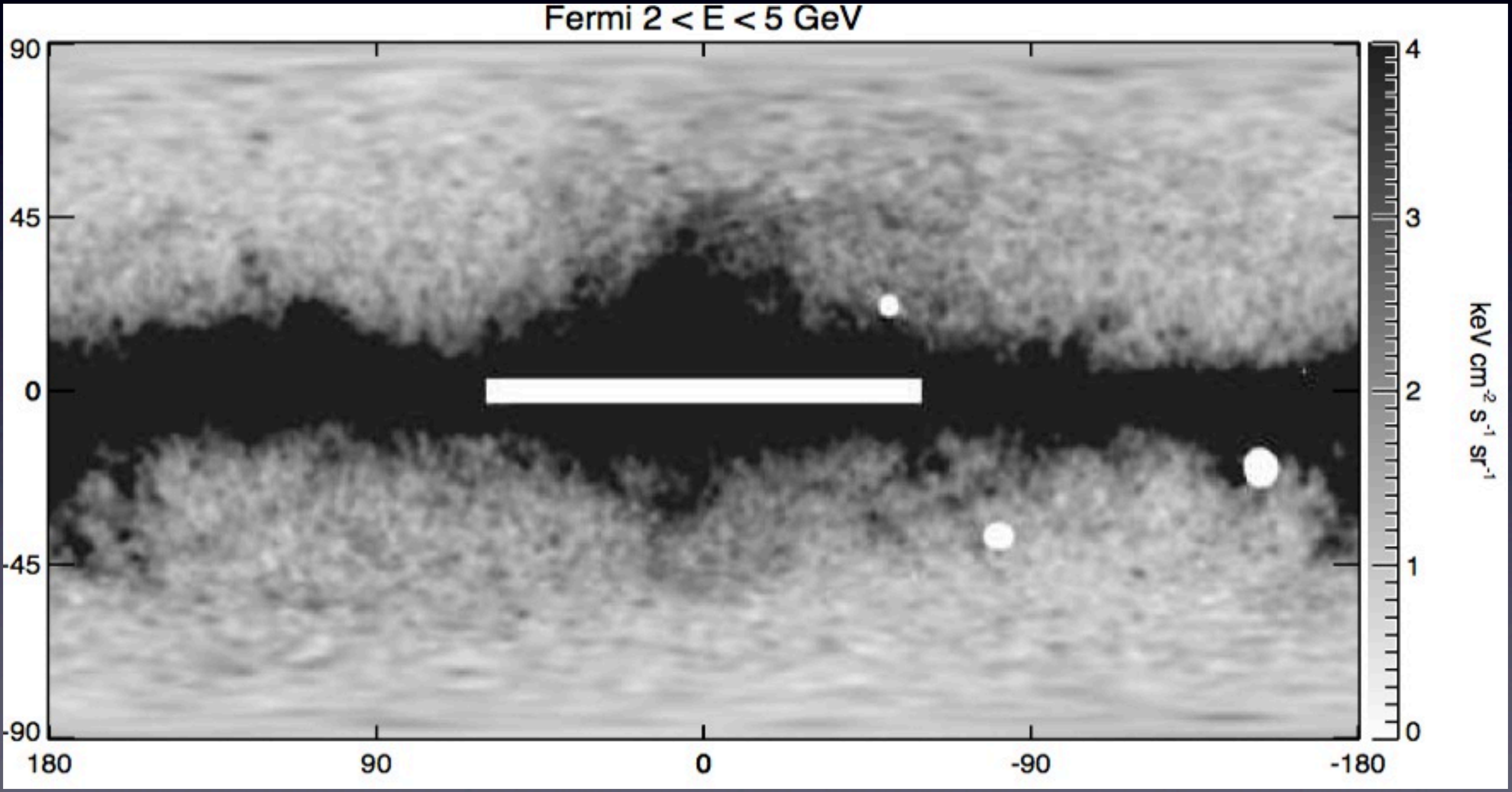


The “Fermi Bubbles”

Su, TRS and Finkbeiner 2010

Sharp-edged “bubbles”



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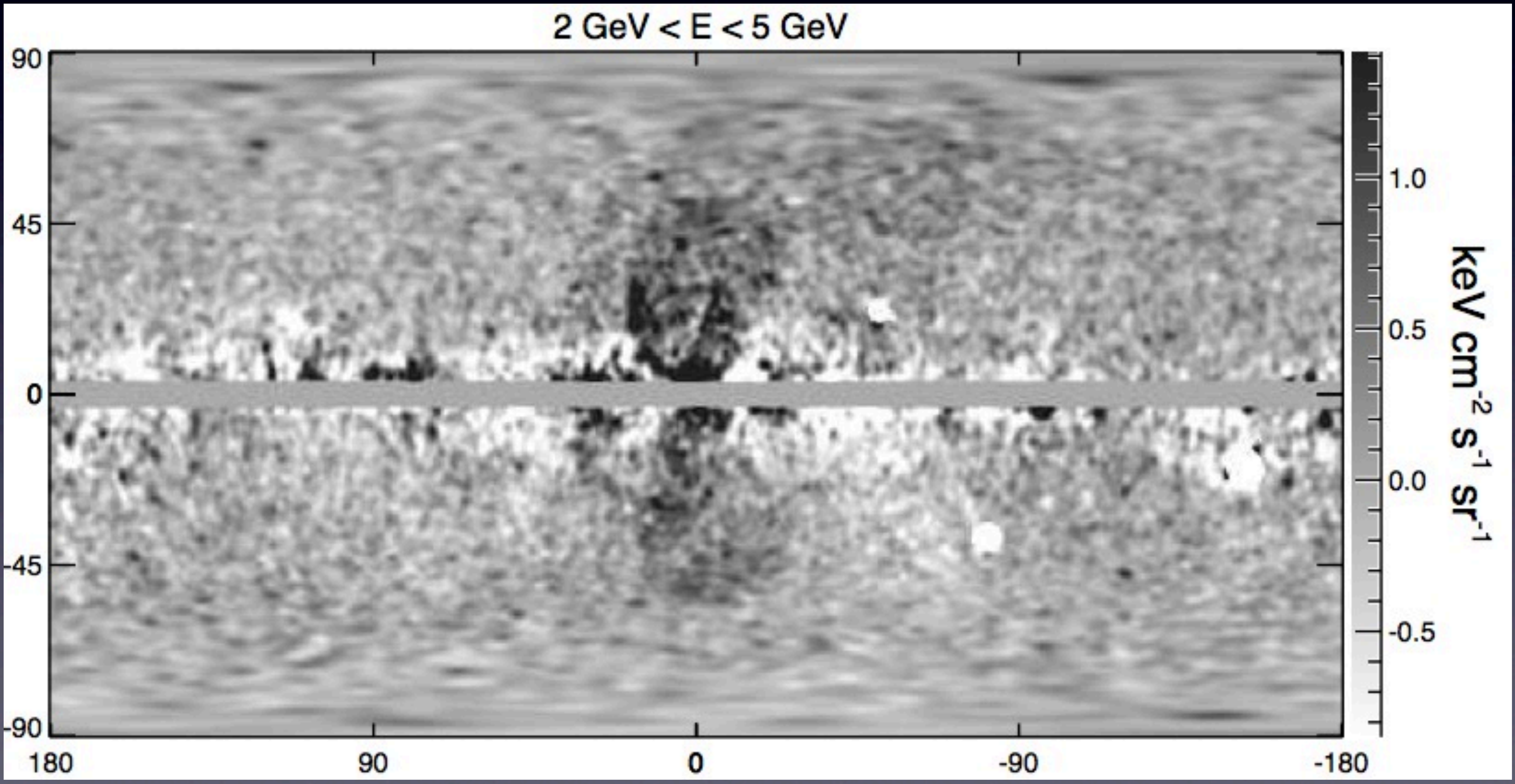

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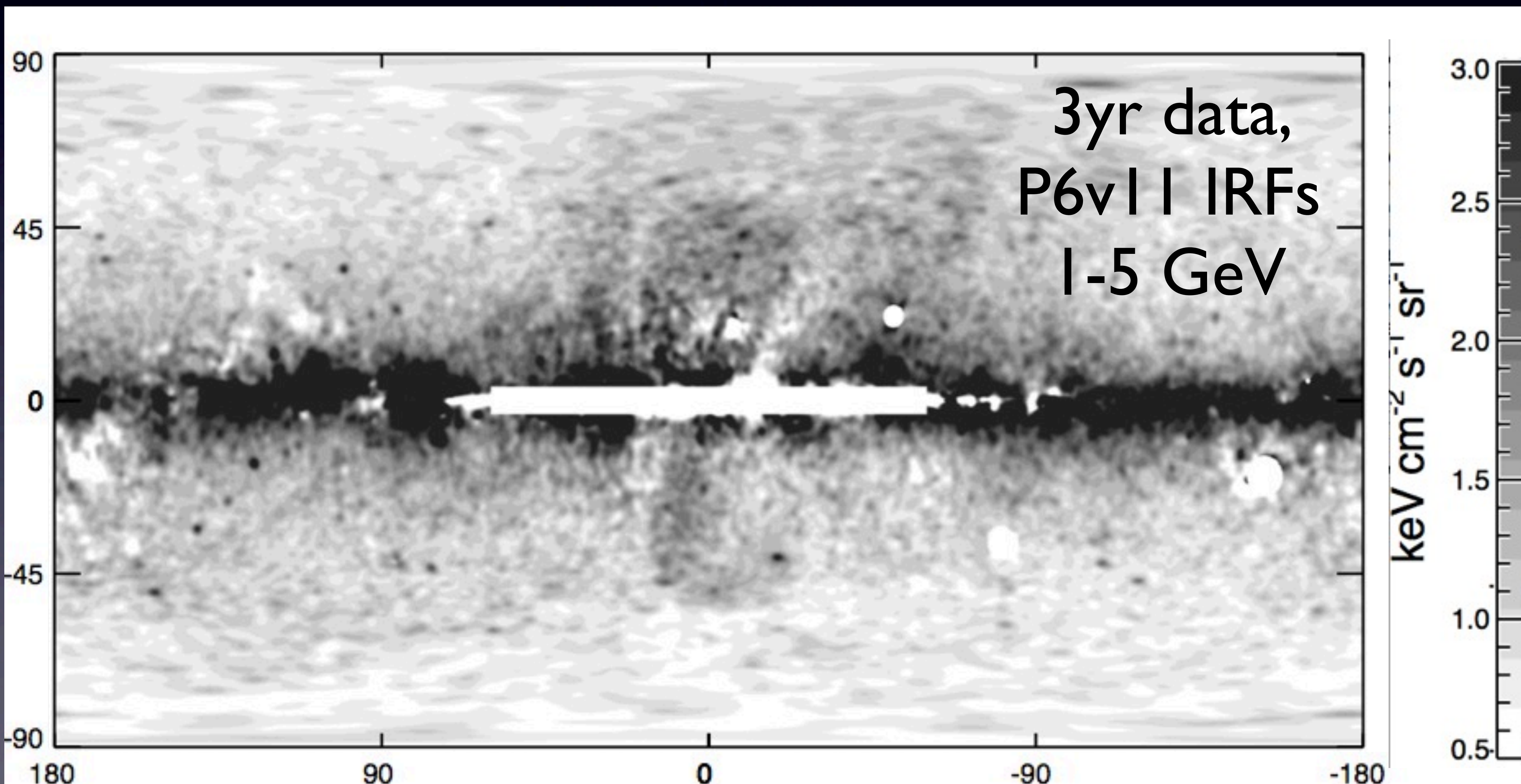

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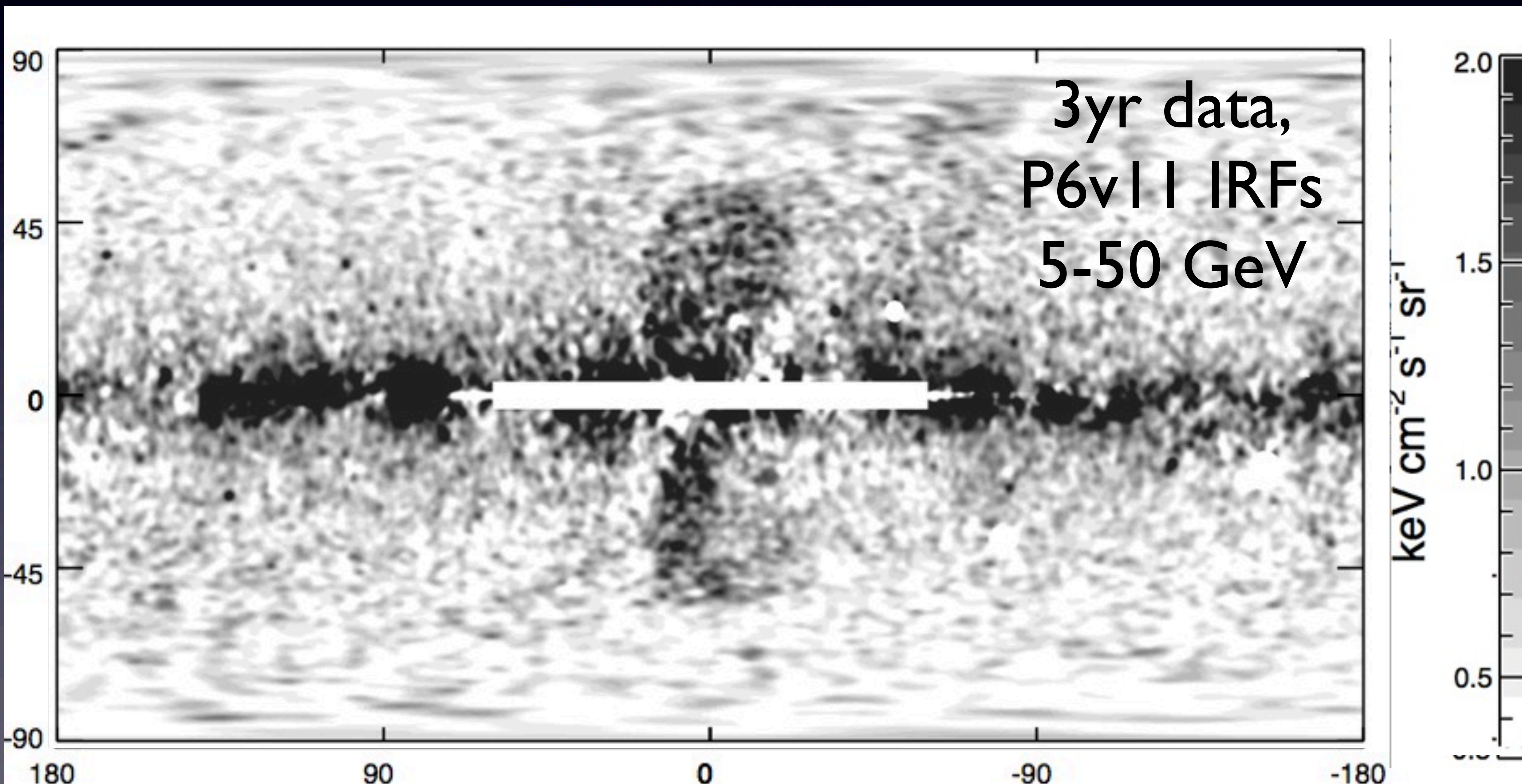

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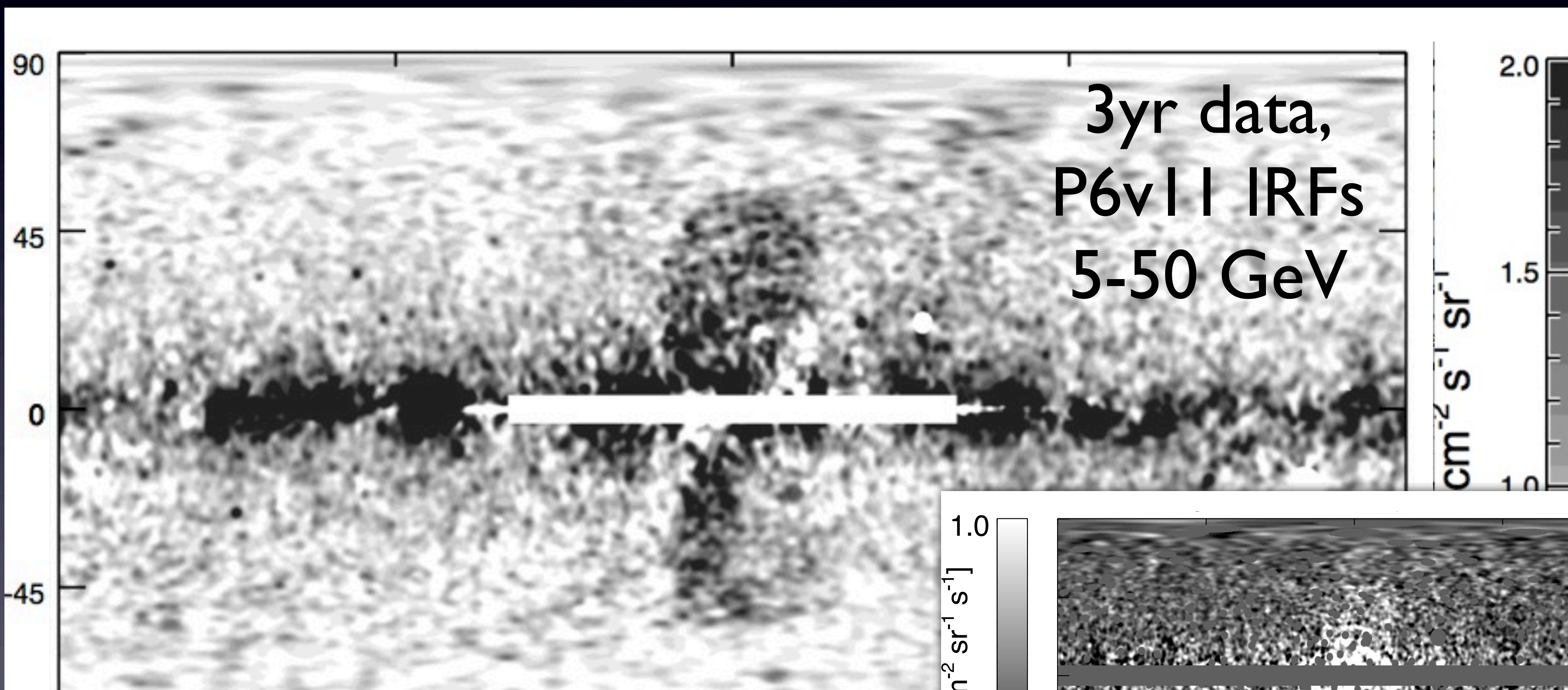
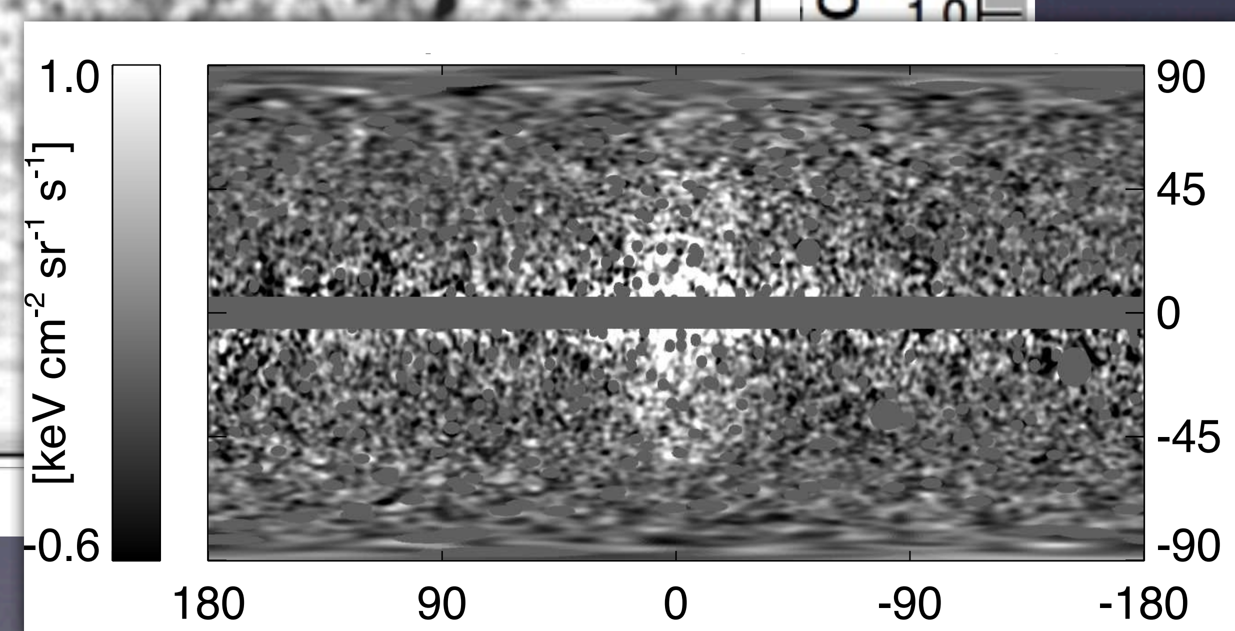


Region of hard emission ⟶



Haze vs Bubbles

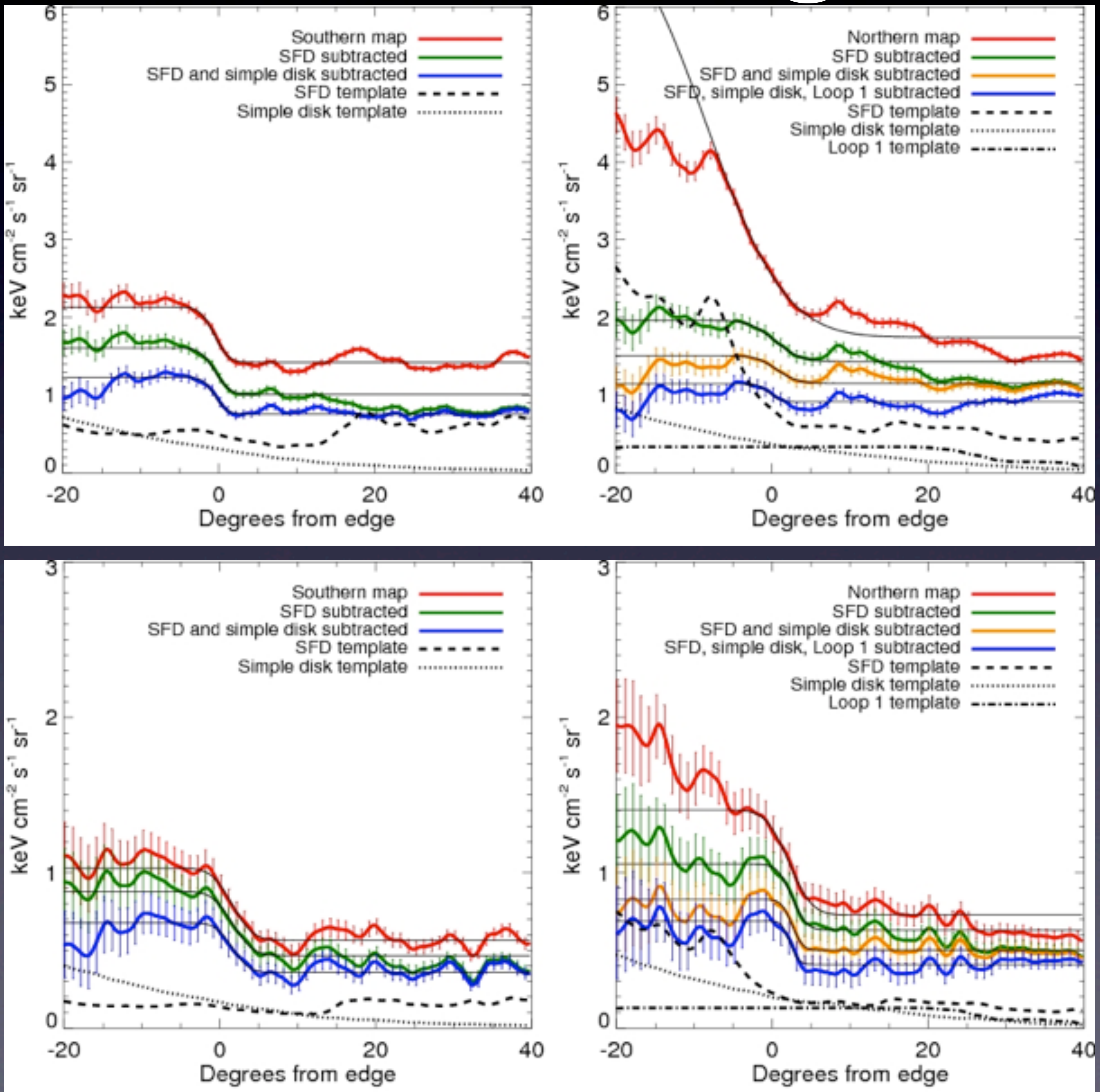
- In newer data, before subtraction we see sharp-edged, spectrally hard structures at high latitudes. (How sharp are the edges? Next slide.)

- 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.



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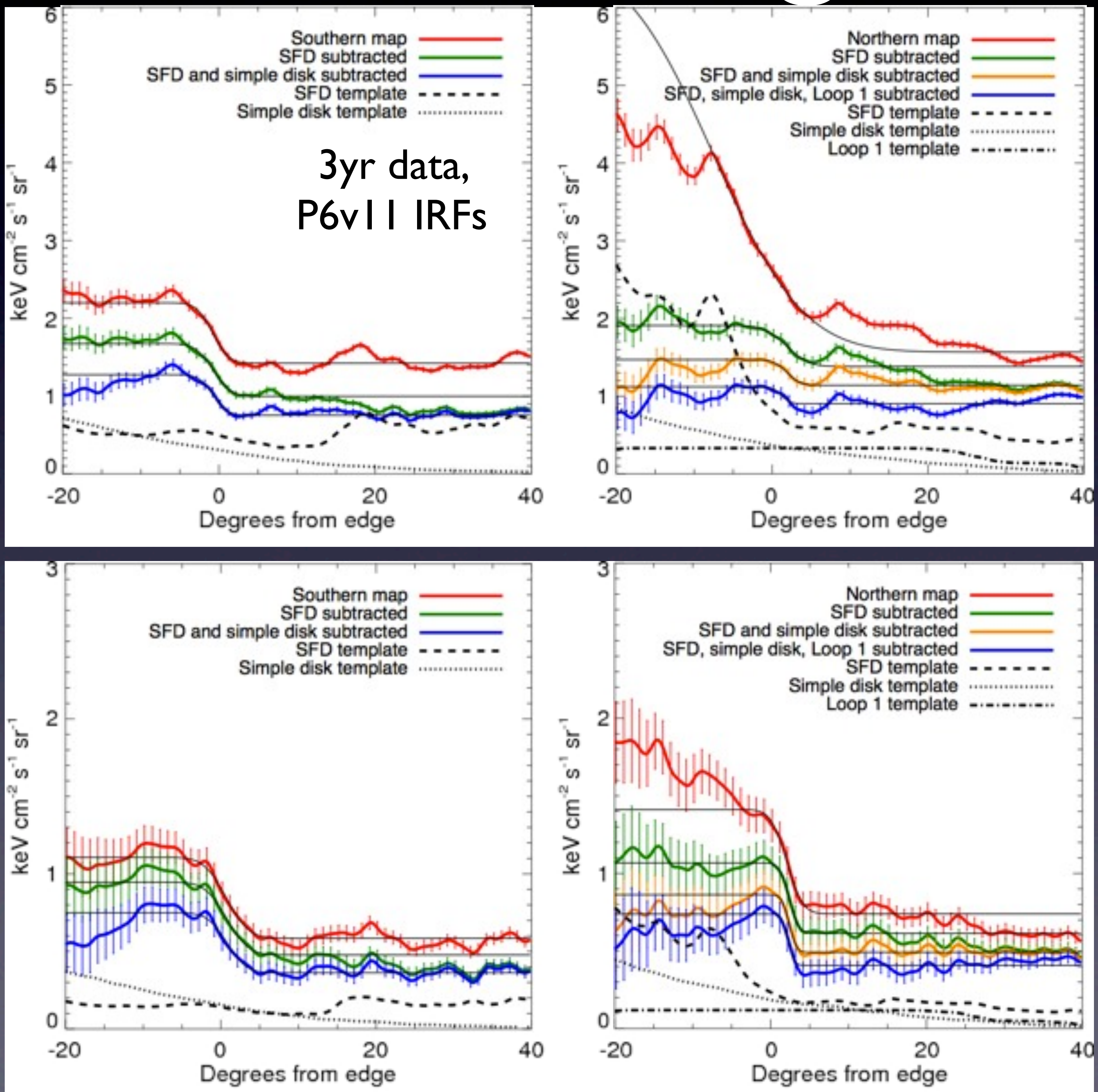
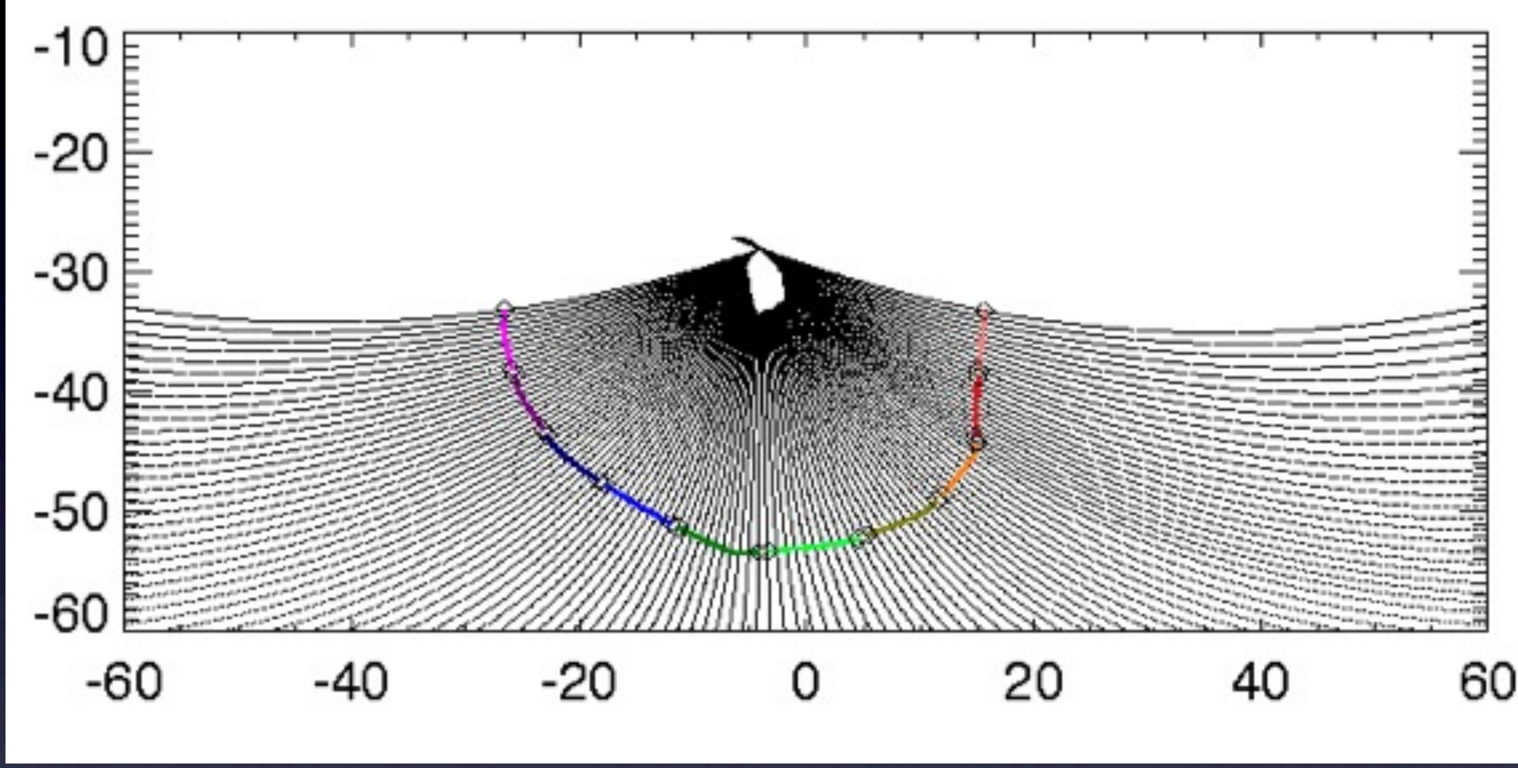
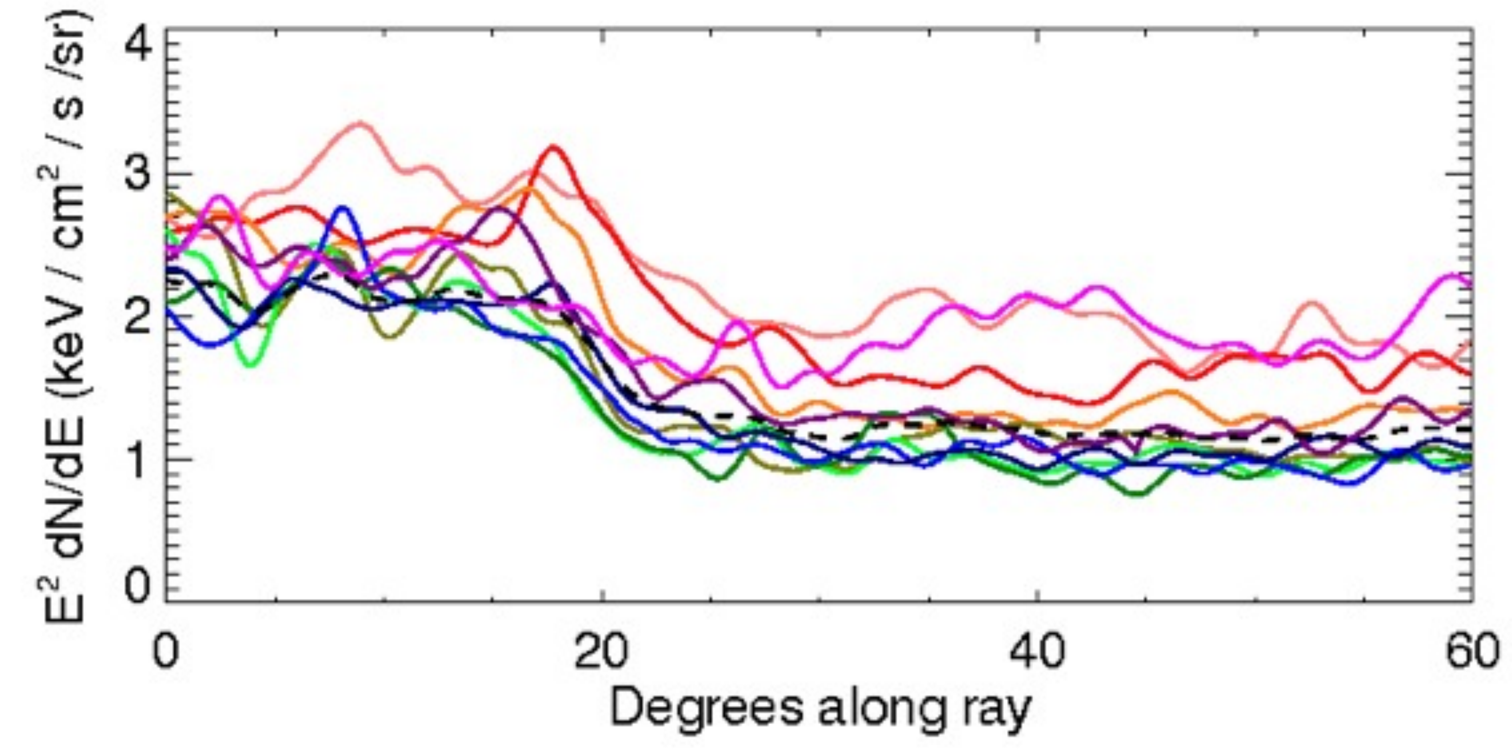


Scatter in edge profiles

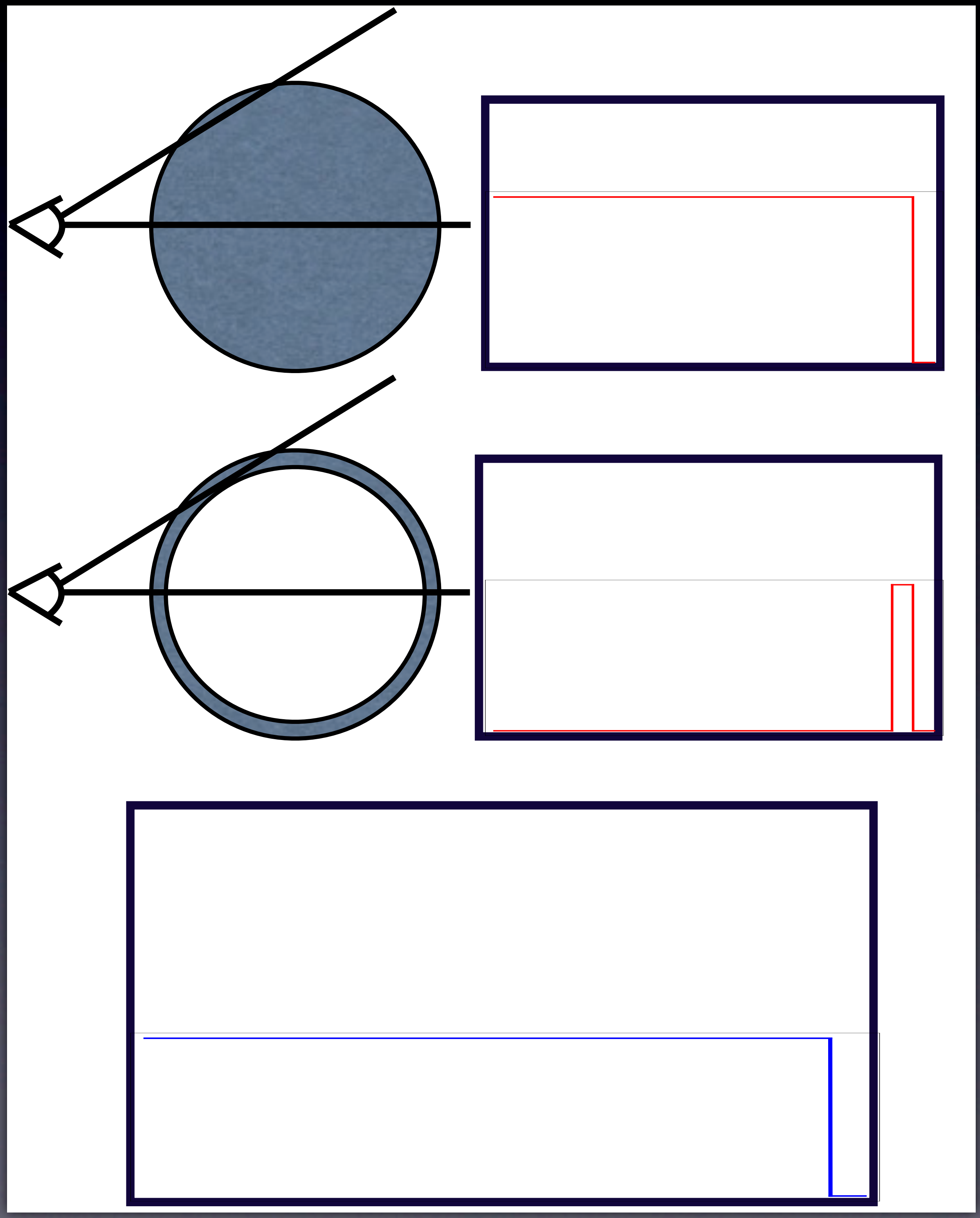
- Divide southern bubble into ten wedges, plot surface brightness profile in each of them (for south, 1-5 GeV).
- Statistics not as good as stacked profile (this is based on Pass 6, code not yet fully updated).
- However, already clear that edge is present over the full arc (perhaps fading in the wedges closest to the disk), not contaminated by point sources.





The (projected) profile puzzle

- Generally expect 3D structures to be either:
    - Centrally brightened in projection (constant volume emissivity), or
    - Limb brightened (hollow shell).
- Bubbles do not look like either: spatial projected-intensity profile is consistent with being flat (also consistent with slight limb-brightening or central brightening).
- If a spherical structure, suggests steep rise in volume emissivity at edge, but presence of emission in interior; however, data not yet sufficient to reconstruct full profile. For example, a thick shell (width ~ half radius of bubbles) provides an equally good fit.



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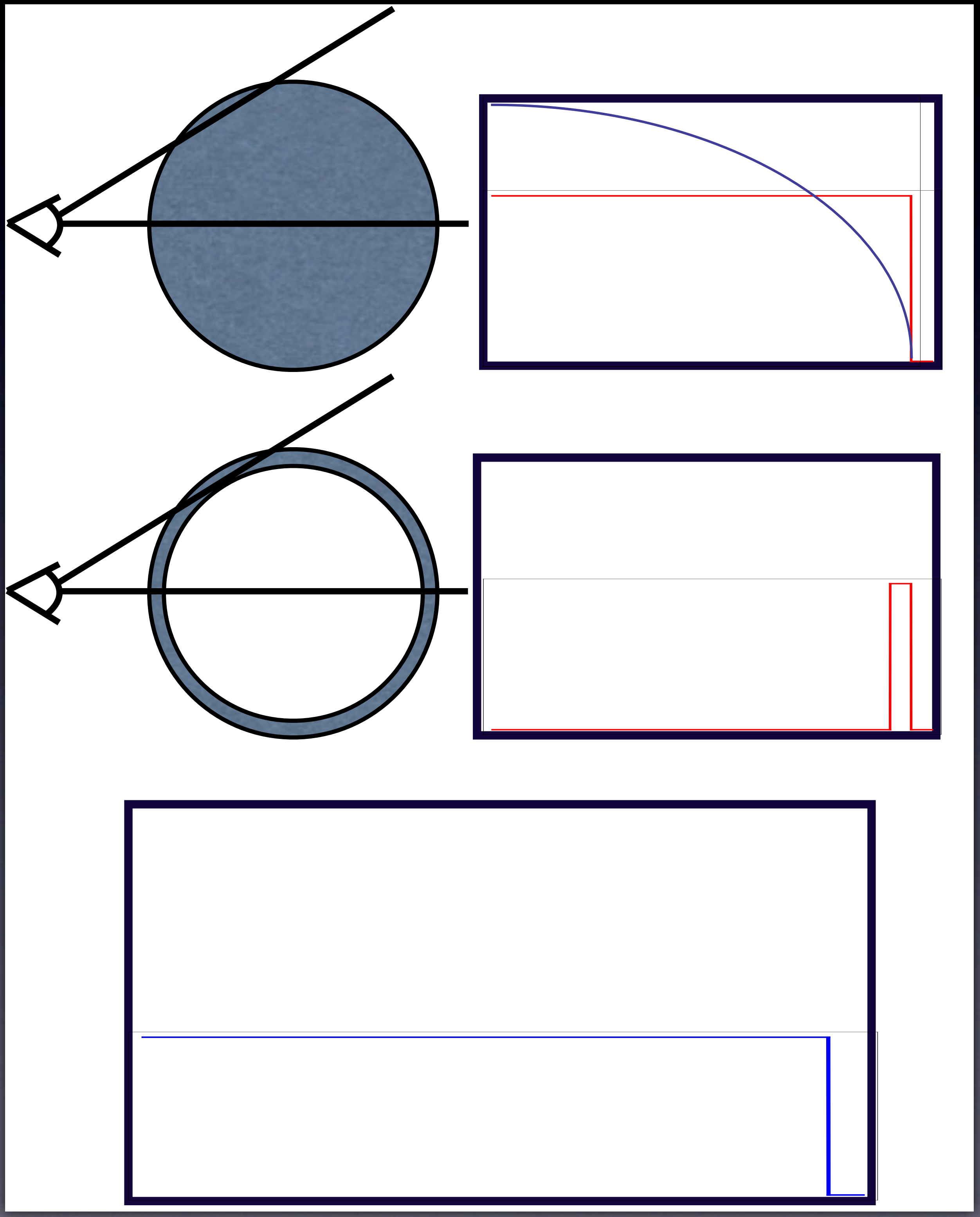

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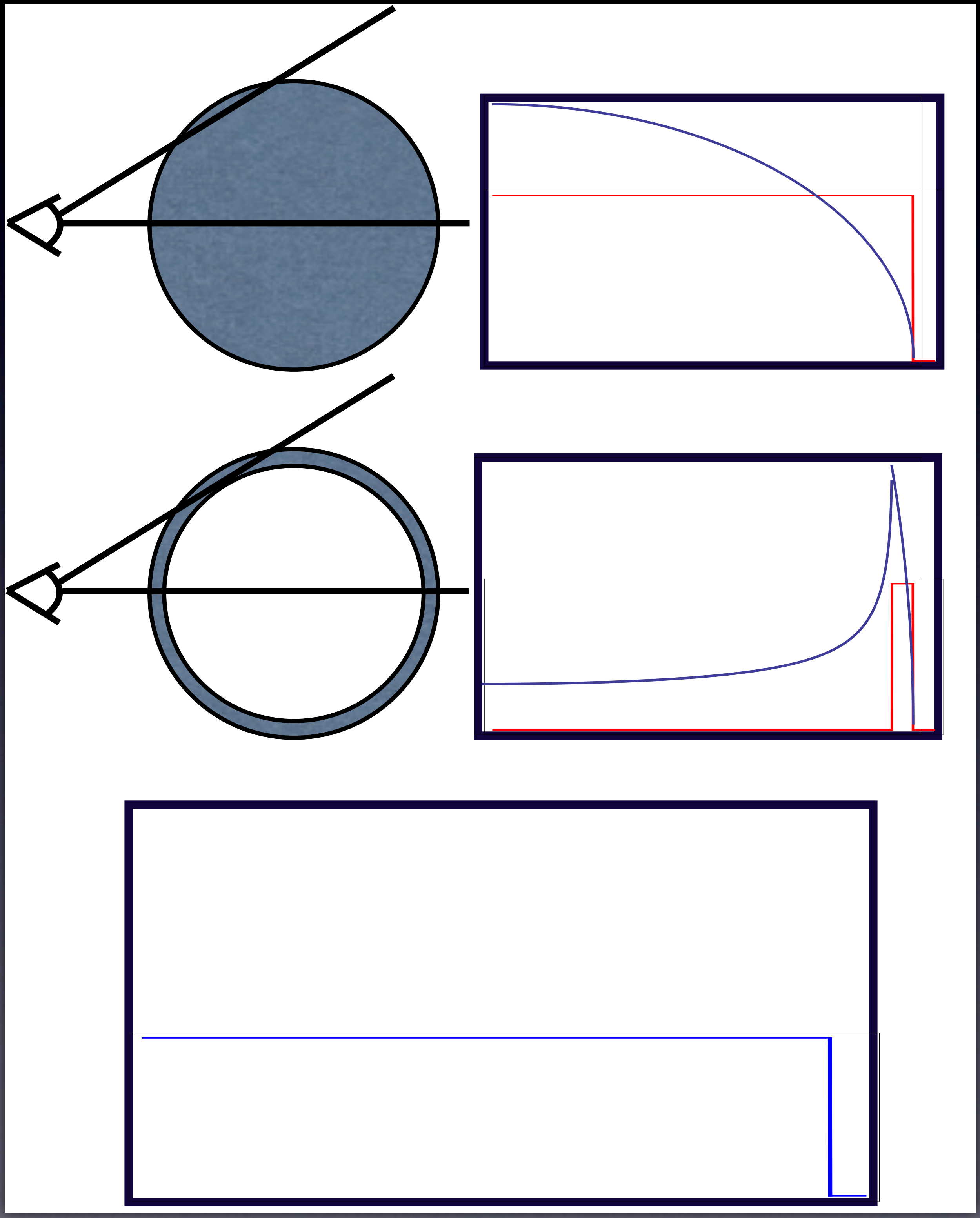

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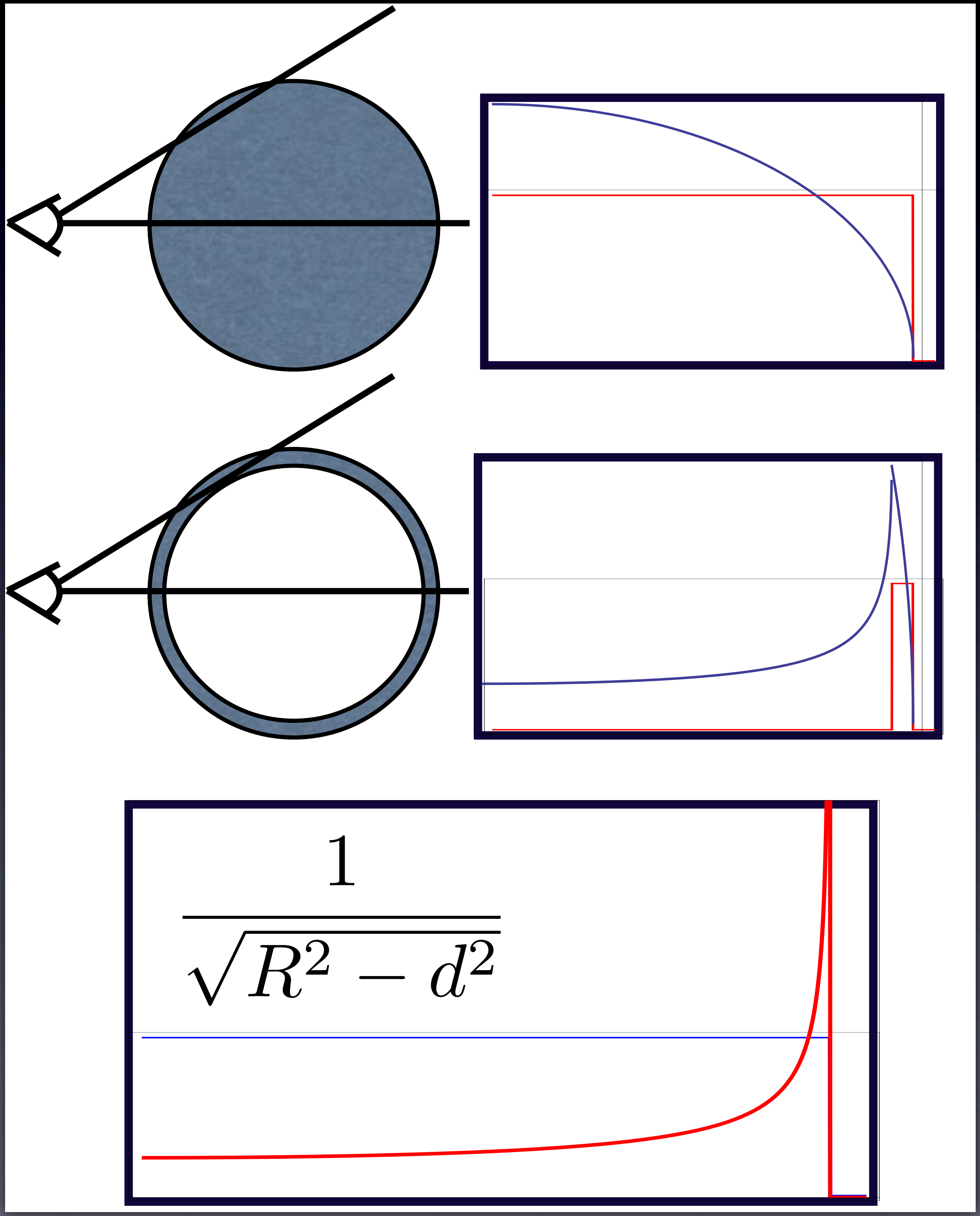

Acceleration inside the bubble?

- Not much activity on this puzzle yet.
- Mertsch and Sarkar (1108.1754) suggest stochastic acceleration of electrons on plasma wave turbulence throughout the bubble volume (2nd order Fermi acceleration), as well as a shock at the edge. Prediction for spatial variation of spectrum: useful diagnostic?
- Cheng et al (1103.1002, 1109.2619, 1109.6087) instead invoke multiple shocks filling the volume, originating from repeated stellar capture onto the supermassive black hole.

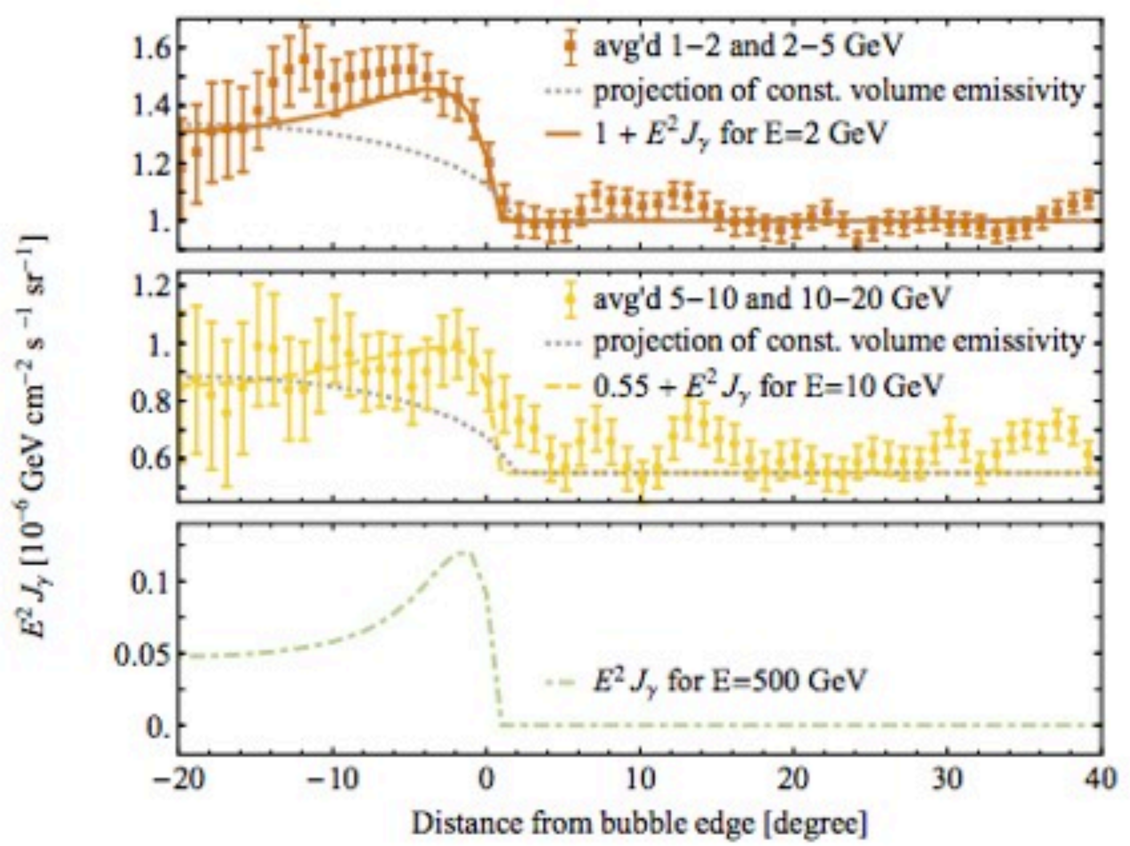

Figure 4: The intensity $E^2 J_\gamma$ in gamma-rays is shown as a function of the distance from the bubble edge at 2 GeV (solid line), 10 GeV (dashed line) and 500 GeV (dot-dashed line), together with the data [1] from the averaged $1-2$ and $2-5$ GeV and the averaged $5-10$ and $10-20$ GeV maps. We also show the profile expected from a constant volume emissivity (dotted line) which clearly does not reproduce the observed profile.

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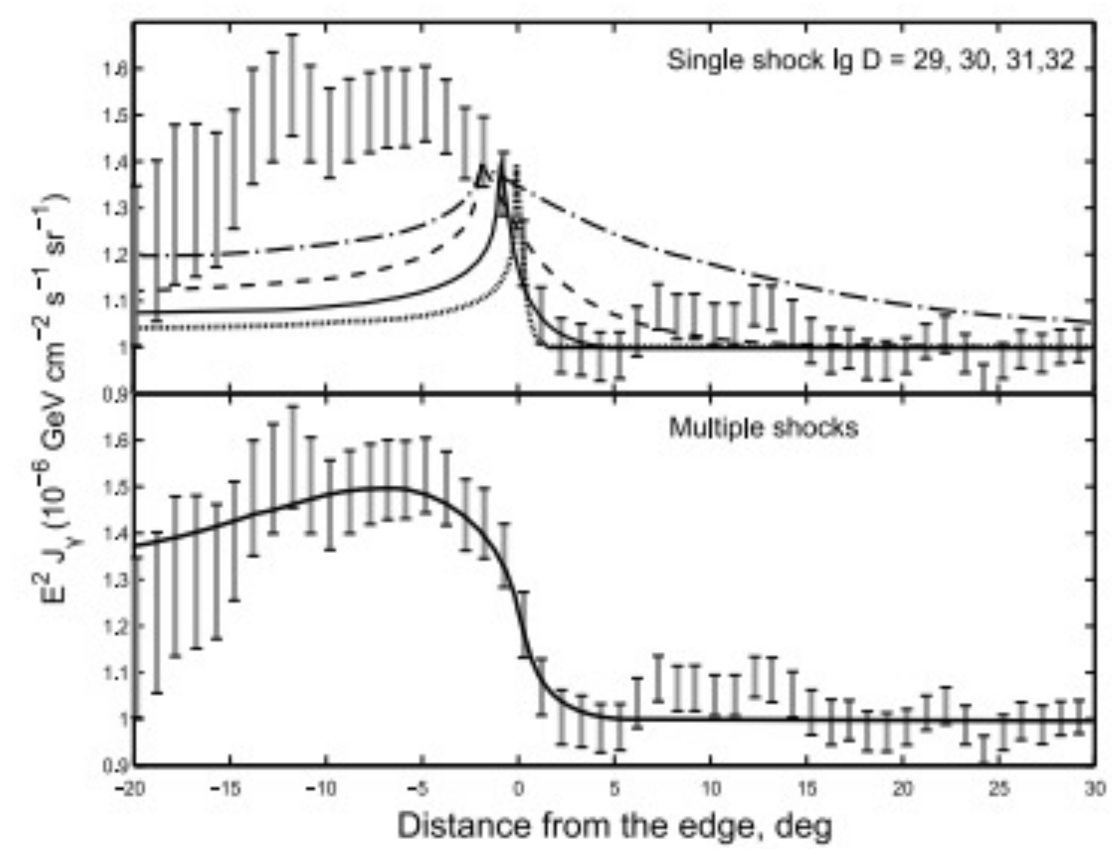
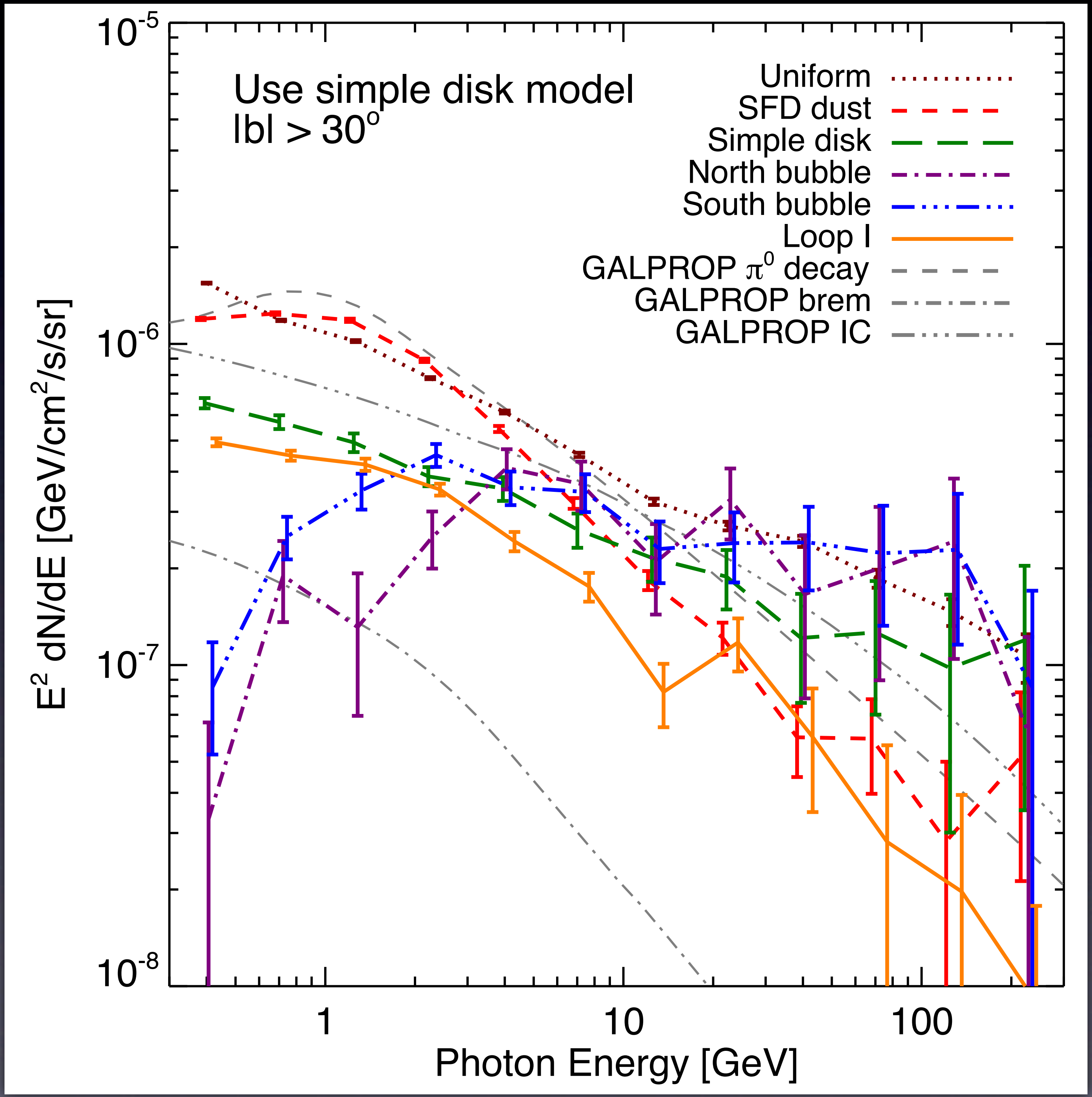


Figure 4: Spatial distribution of the gamma-ray emission. Data are from [16]. *Top:* in case of single shock. Dotted line correspond to D=10^{29} cm^2/s, solid to D=10^{30} cm^2/s, dashed to D=10^{31} cm^2/s and dash-dotted D=10^{32} cm^2/s, *Bottom:* in case of several shocks distributed in accordance with (2).

Haze/Bubbles Spectra

- Haze/Bubbles have E^2dN/dE ~constant from 1-100 GeV. No significant evidence for spectral variation from edge to center, or north to south.
- Apparent break in spectrum below 1 GeV, above 100 GeV (former may be less significant in P7 data).
- Note: In P6v11, going from Class 3 (diffuse) to Class 4 (DATACLEAN, improved CR rejection) affects spectra of backgrounds/foregrounds, but not bubbles.



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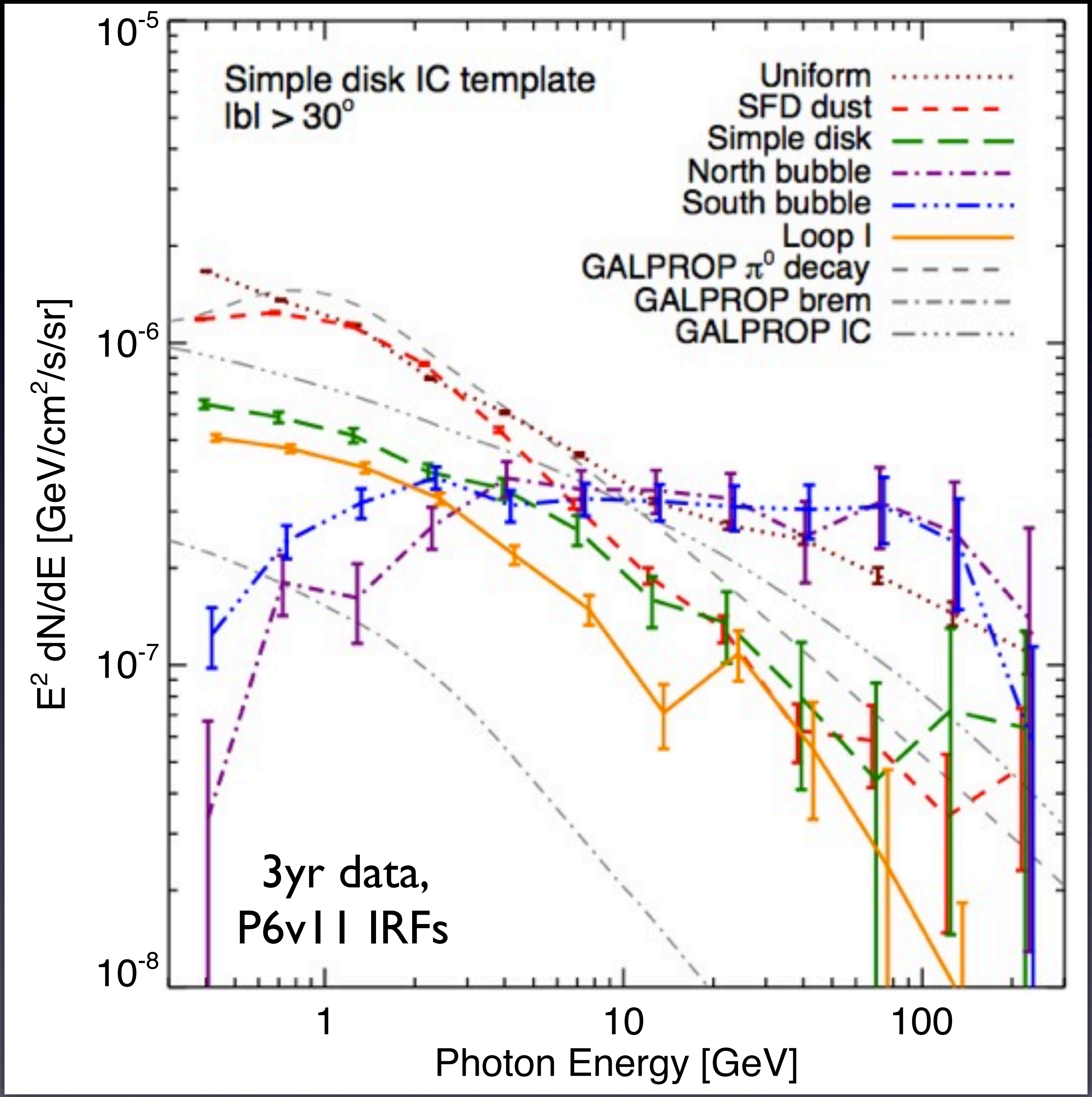

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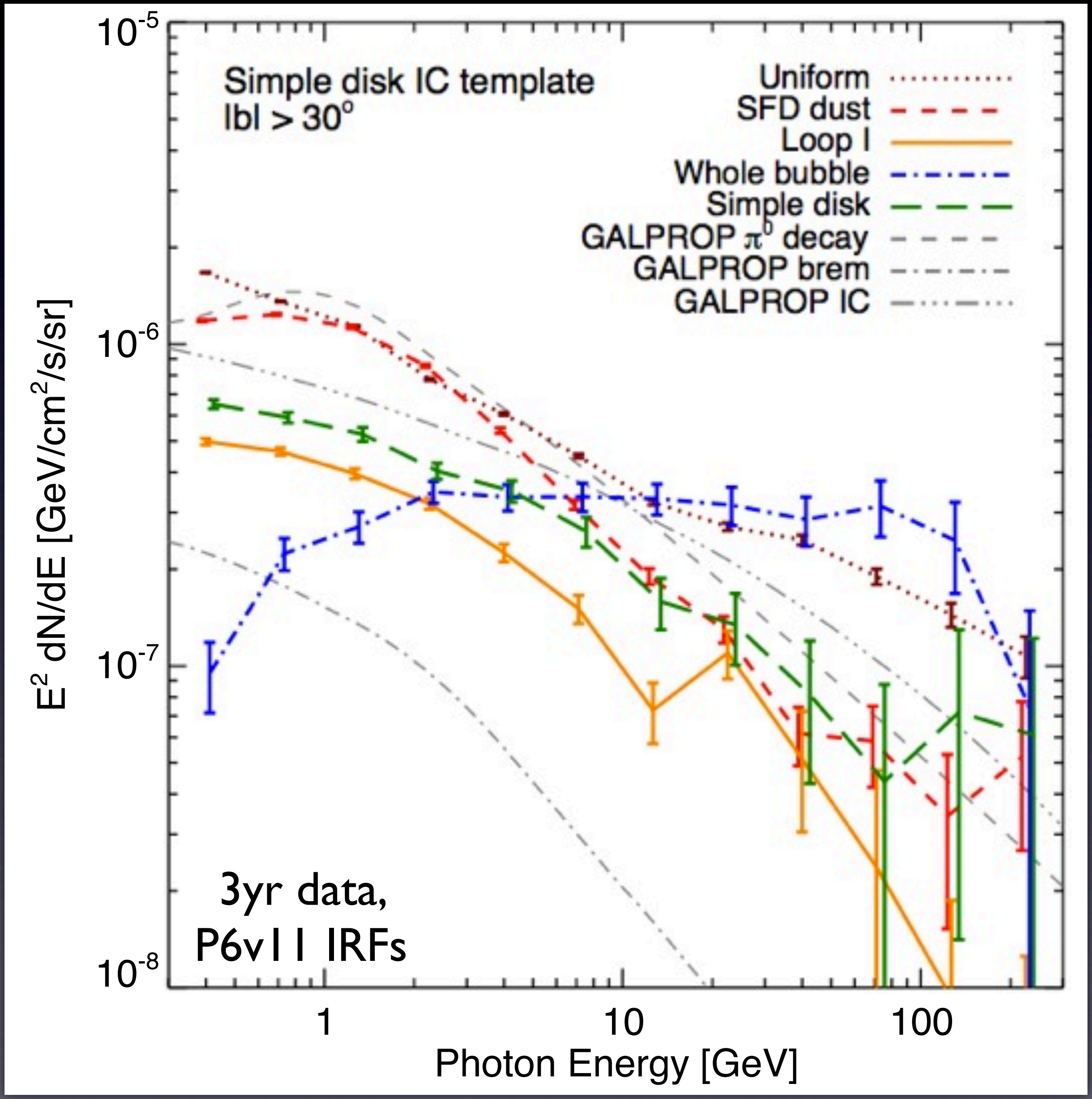

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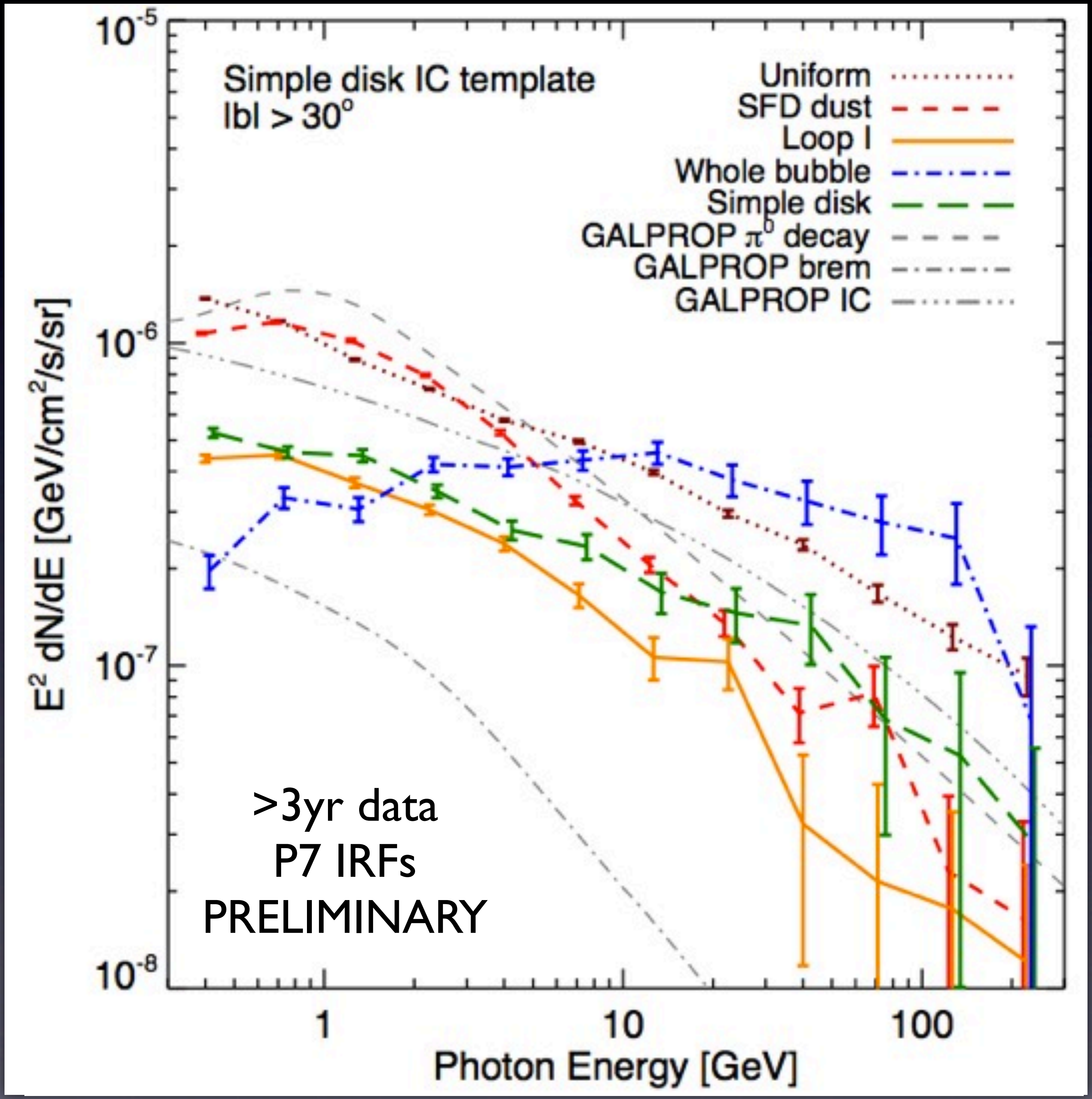
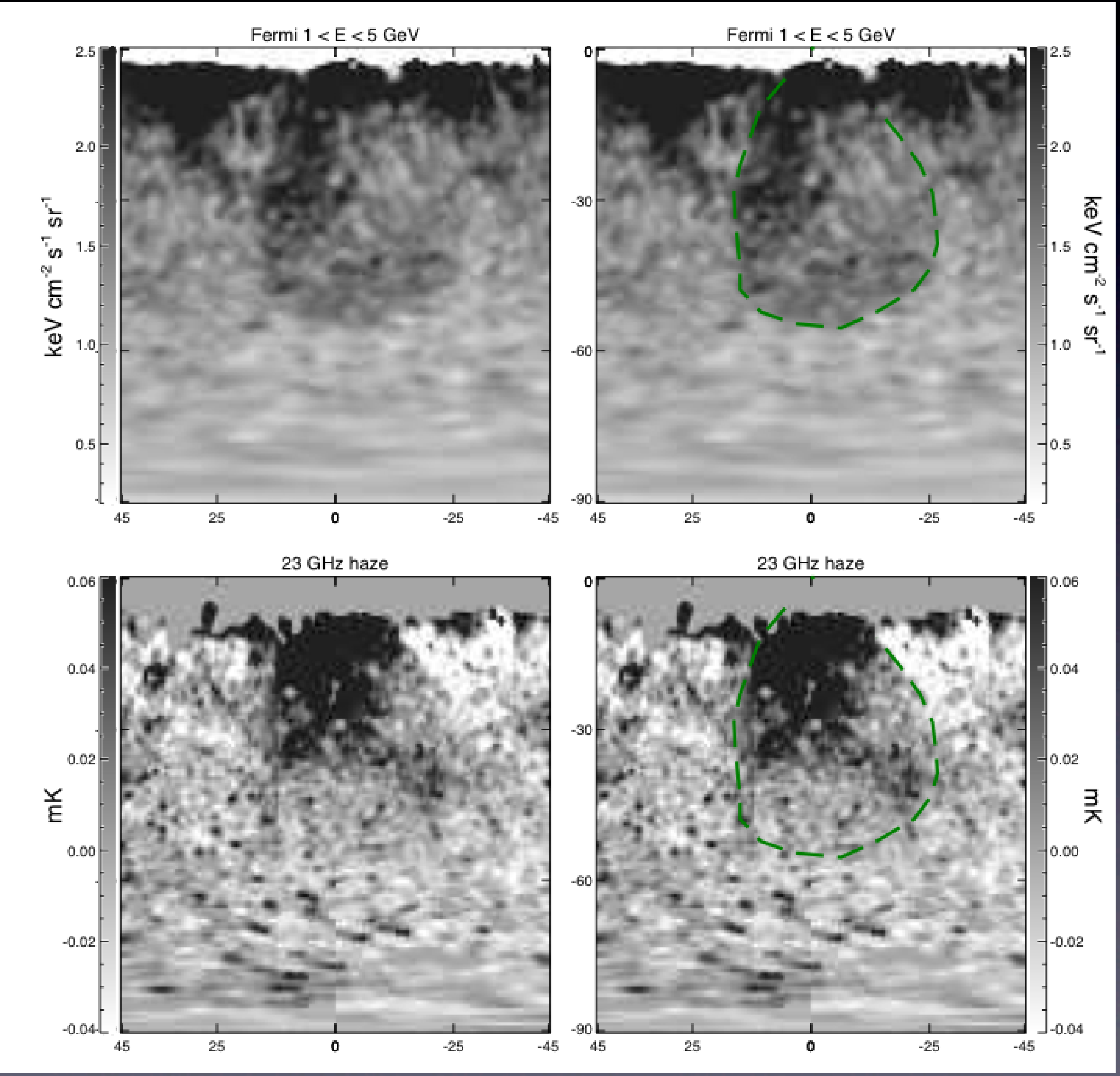
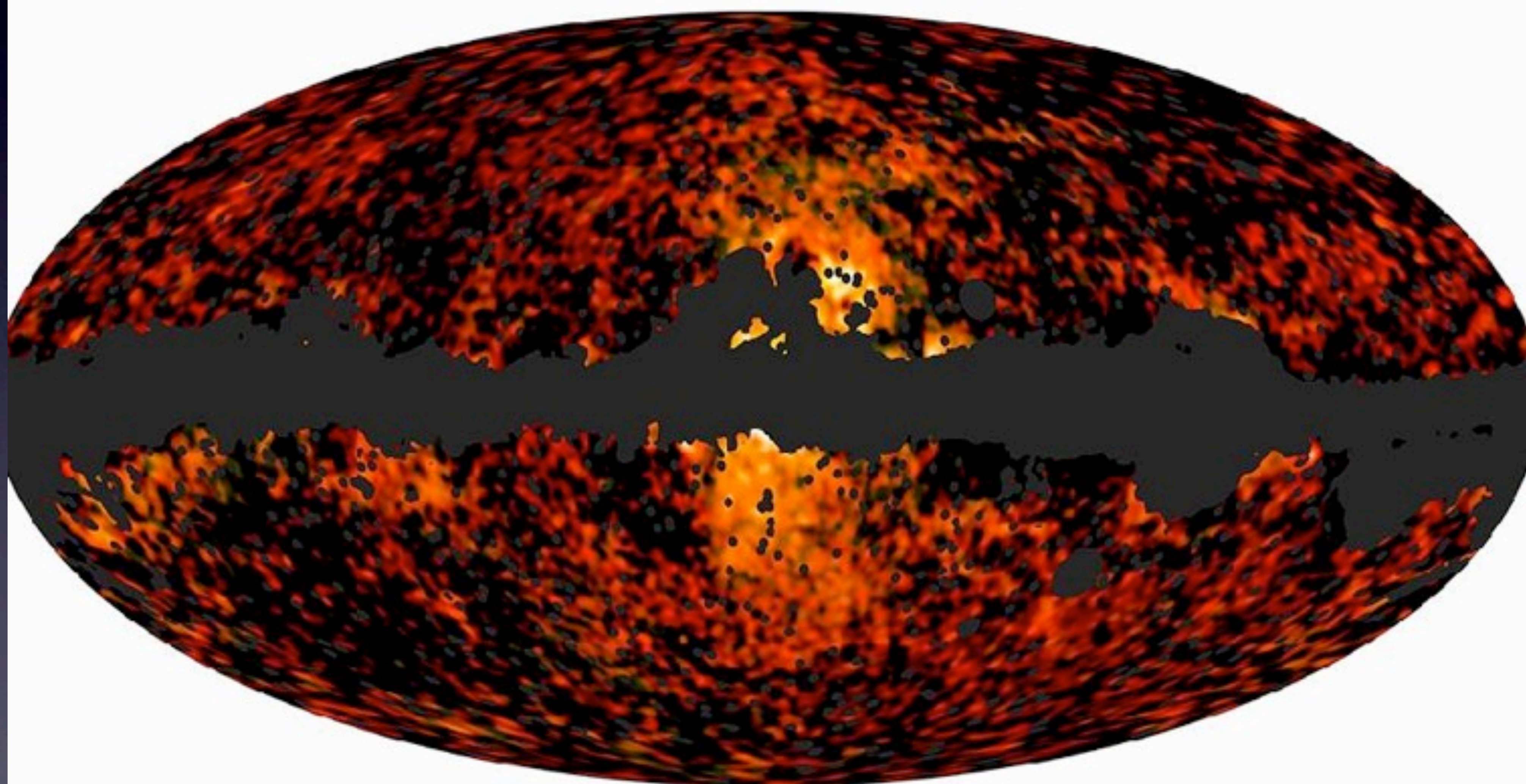


Microwave bubbles?

- Initial motivation for Haze search was to find the gamma-ray counterpart to the WMAP Haze.
- As Greg just showed us, very nice spatial agreement at high latitudes! (also hints at lower latitudes, although more uncertain due to background subtraction)

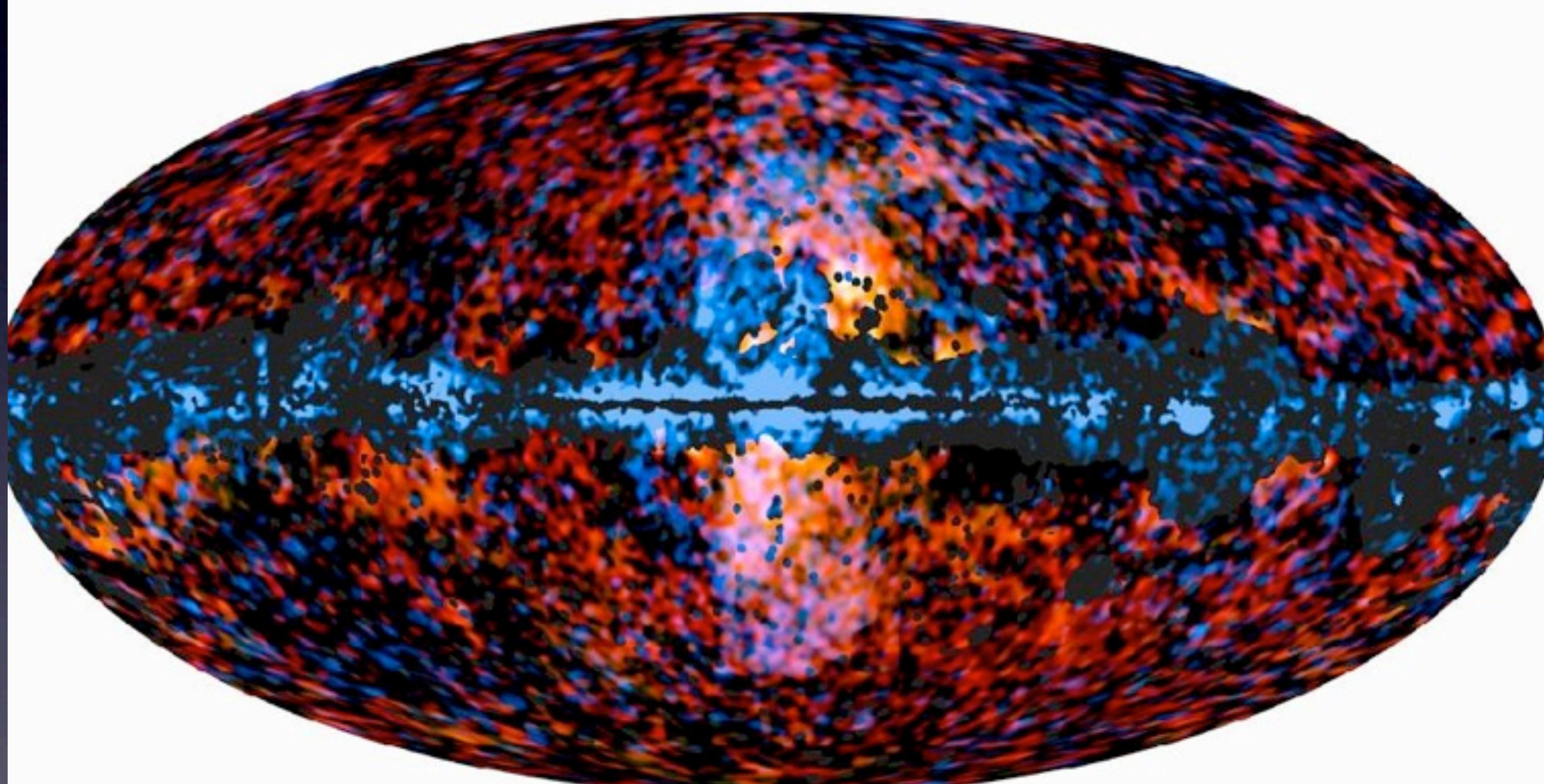


The Planck Bubbles?



ESA / Planck Collaboration press release image

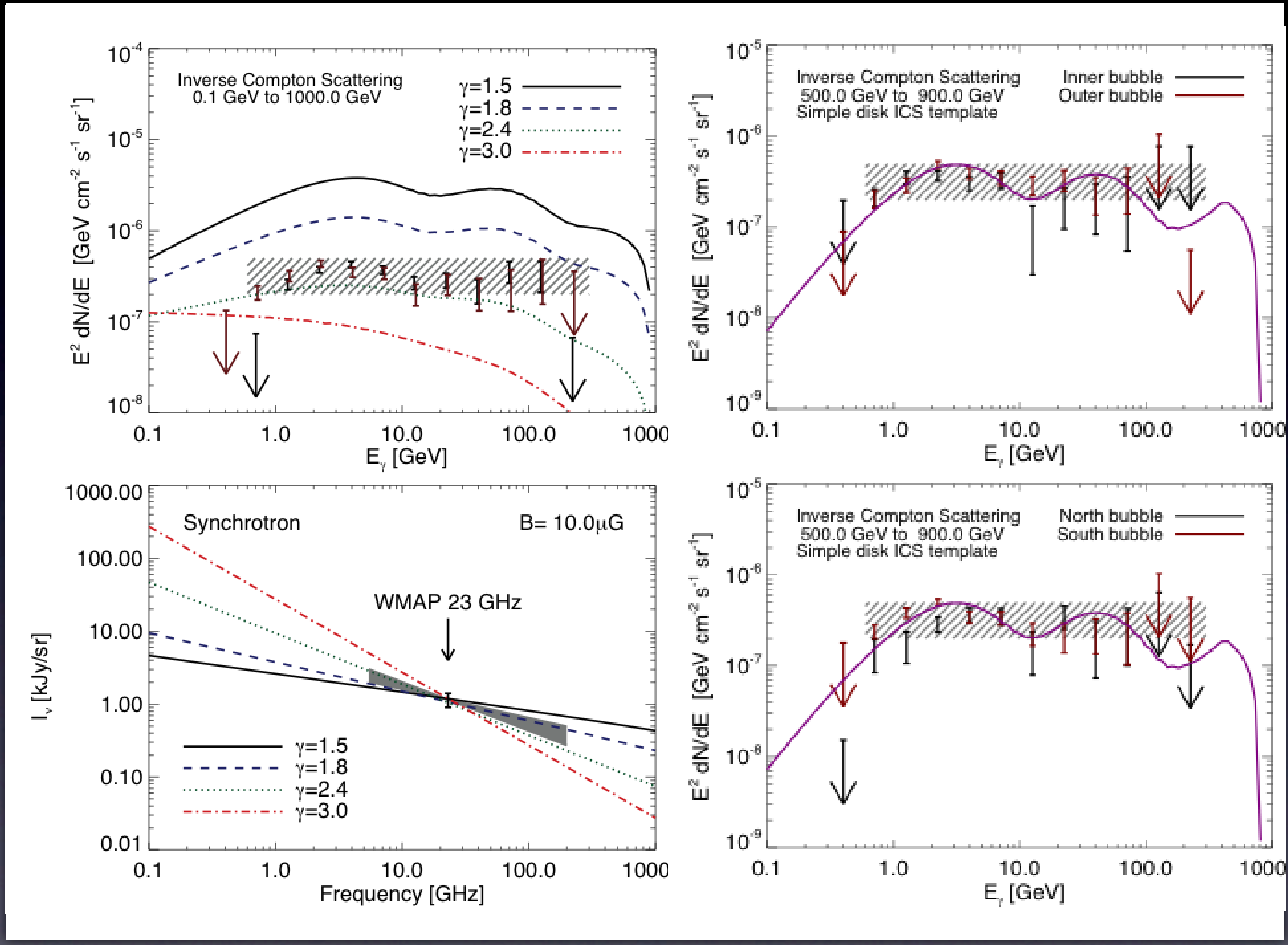
The Planck Bubbles?



ESA / Planck Collaboration press release image

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.

Microwave polarization?

- Found structures apparently tracing bubble edge in the North, in WMAP polarization data at 23 GHz. However, many spurs in this region...
- From paper: "The magnetic field structure revealed by the WMAP polarization data at 23 GHz suggests that neither the emission coincident with the Bubble edge nor the Galactic center spur are likely to be features of the local interstellar medium"

Jones et al 1201.4491

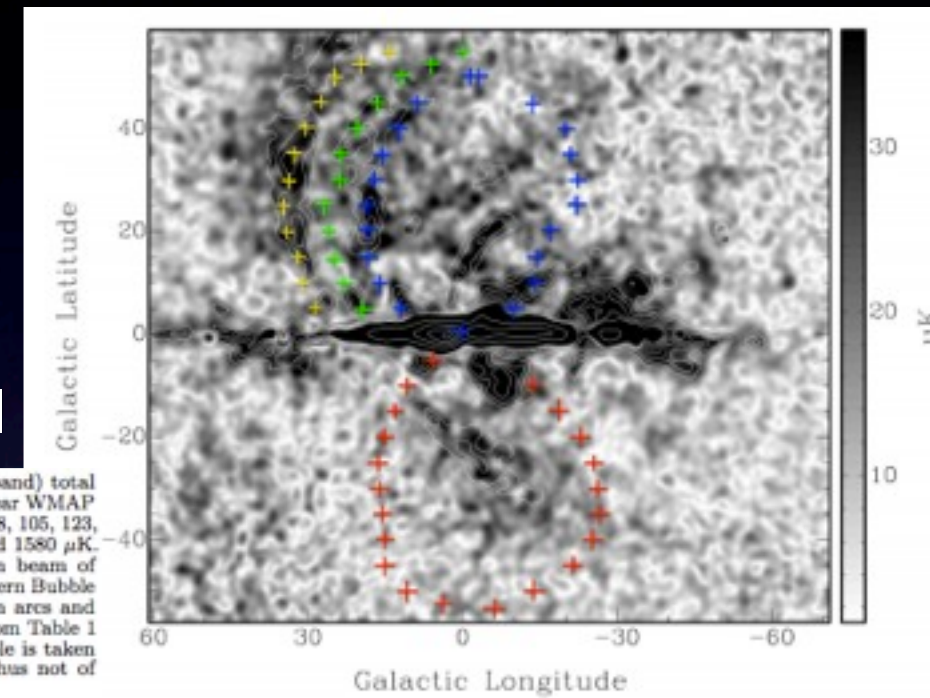


FIG. 1.— View of the inner Galaxy in 33 GHz (Ka-band) total polarized intensity overlaid upon a 23 GHz (K-band) 5-year WMAP data in total polarized intensity (white) contours at 70, 88, 105, 123, 140, 158, 175, 350, 530, 700, 878, 1054, 1230, 1400, and 1580 μK. Both data-sets have been convolved with a Gaussian beam of FWHM 2°. The crosses denote the positions of the northern Bubble edge (blue), inner (green) and outer (yellow) northern arcs and southern (red) Bubble edge, respectively, and taken from Table 1 of Su et al (2010). The emission in the southern Bubble is taken to be a continuation of the North Polar Spur, and thus not of consideration here.

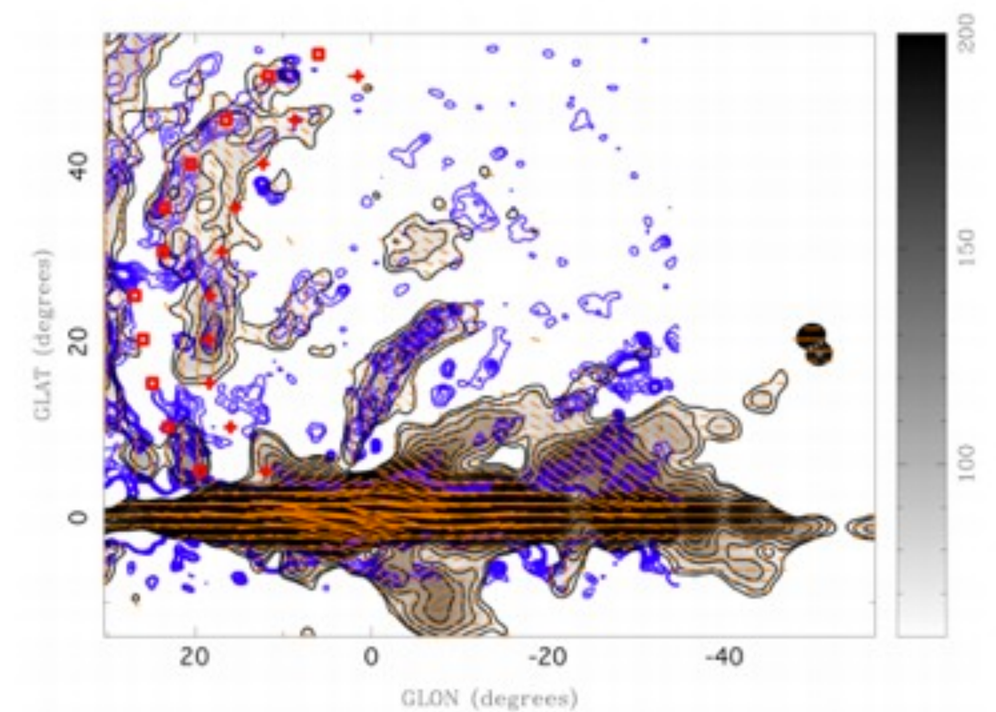
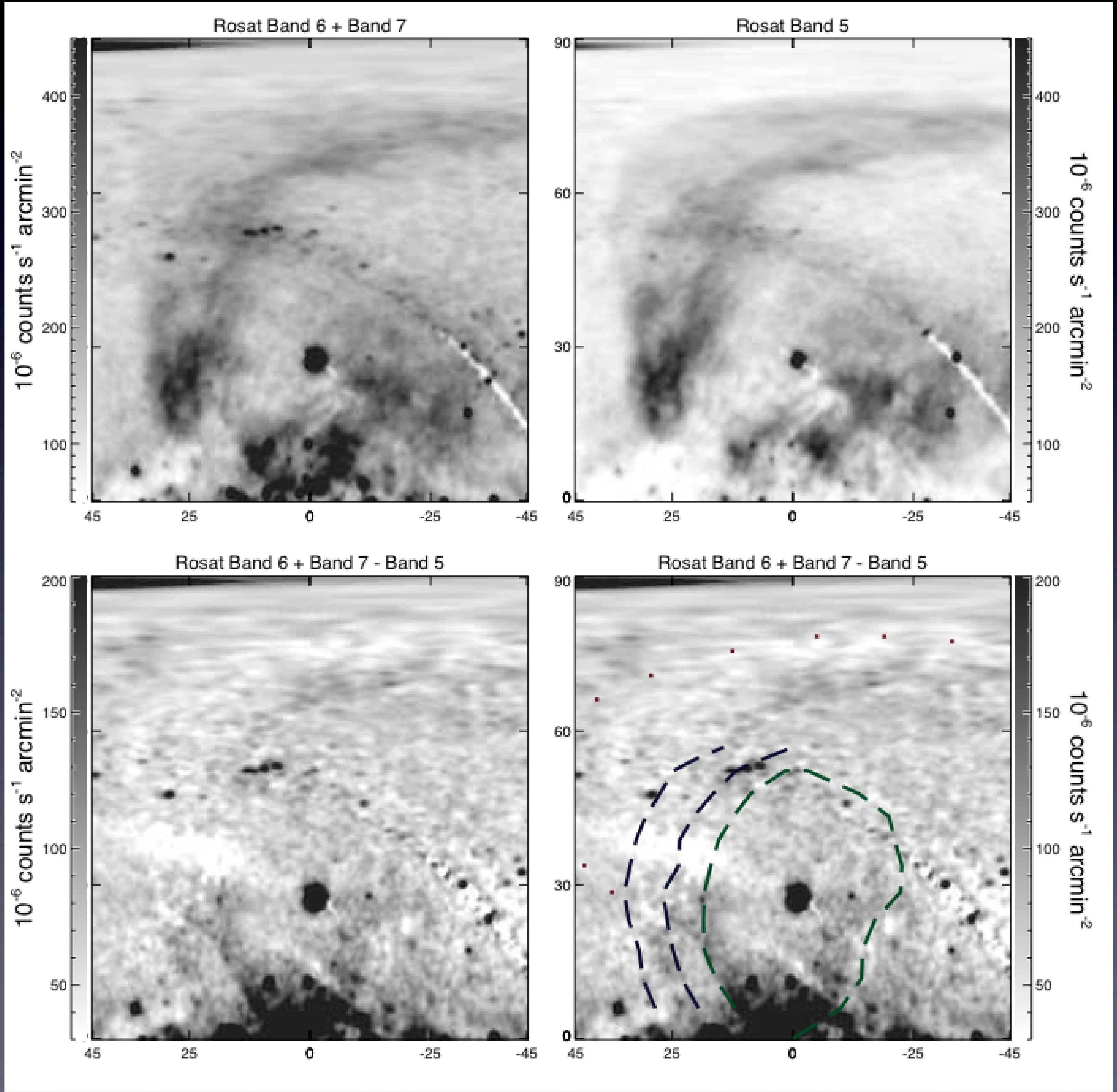


FIG. 2.— Image of the northern Bubble section comprised of WMAP 23 GHz (K-band) polarized intensity overlaid with the same (black) contours as in fig. 1, and (blue) 408 MHz contours at levels of 6, 8, 10 and 12 K. Also plotted are vectors with length proportional to the polarized intensity and orientation at 90 degrees to the observed polarization direction (i.e., tracing the magnetic field orientation). The 408 MHz image has had the large-scale emission filtered above 2.0° (i.e., the size of the Gaussian beam of the large-scale emission image). The intensity scale runs from 60 to 200 μK as indicated by the colored wedge at the right. The Fermi Bubble edges are indicated by the crosses, whilst the inner and outer northern arcs are denoted by squares and circles respectively.

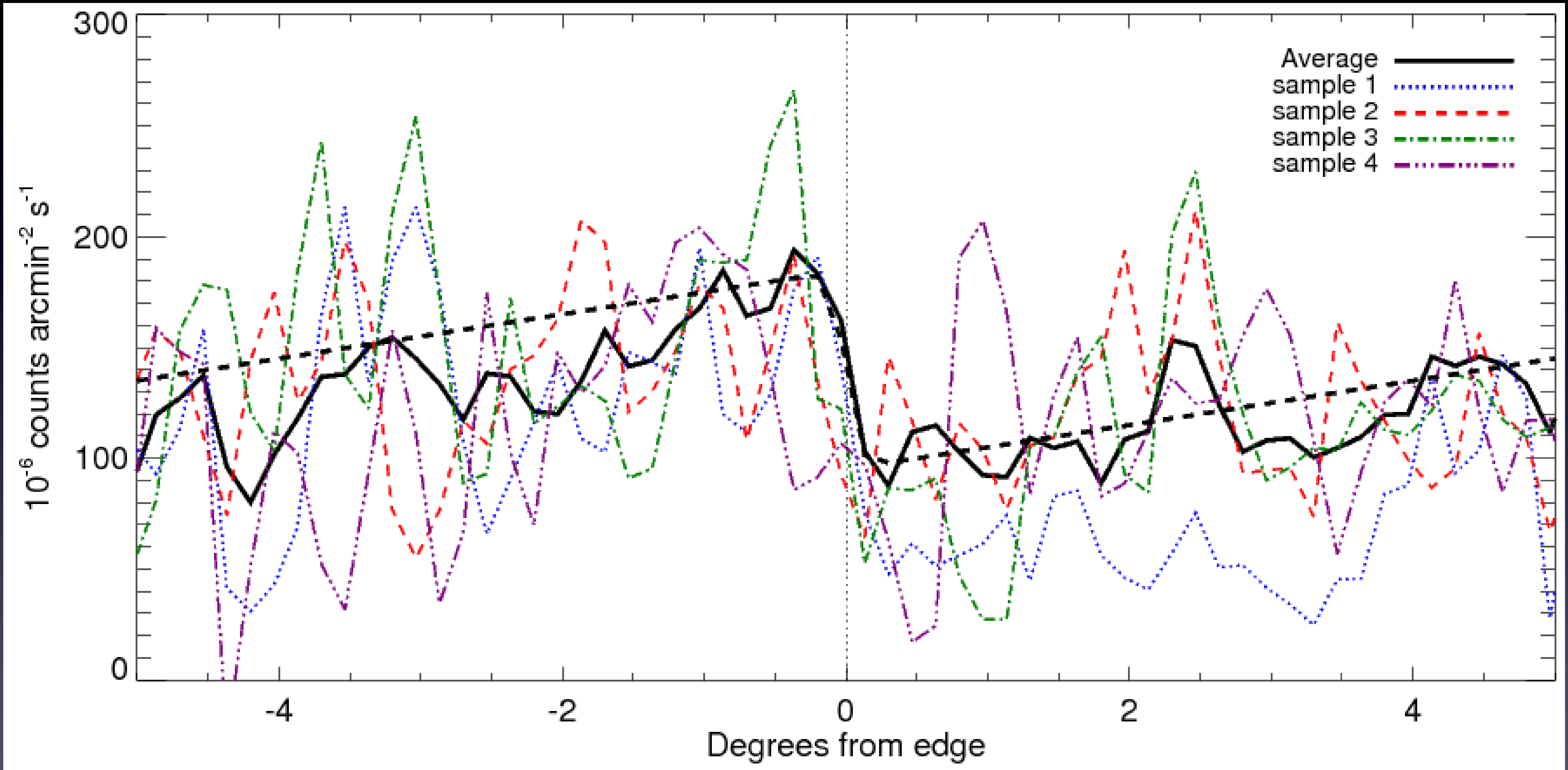
X-ray bubbles?

- 1.5-2 keV X-rays (data from ROSAT) show edges in north that seem to line up with Bubbles.

- XMM follow-up observations have been performed by Su & Finkbeiner and confirm the edge, but more time required to get the spectrum.



How sharp is the X-ray edge?



- Consistent with a step function in ROSAT (~0.2° or less).
- XMM also sees, but does not resolve, the edge (Finkbeiner & Su, private communication).

Leptonic or hadronic?

- If electrons are responsible, the main emission mechanism at high latitudes is inverse Compton scattering on the CMB.
  - Need ~TeV electrons to generate observed gamma rays, i.e. cooling time is only ~few x 10^5 years.
  - Consequently, need high-latitude acceleration/production, or extremely fast transport from GC.
  - Shock acceleration at edges? Acceleration in bubble interior? (e.g. Mertsch & Sarkar) Production in situ? (e.g. DM annihilation)

- If proton scattering provides the bulk of the emission, the main emission mechanism is pion production on the gas.
  - Need to explain why signal doesn't seem to trace gas density (natural in steady-state "saturated limit"?)
  - Does low-energy part of spectrum fit?

Interpretation survey

Considerable theoretical activity over the past two years, many competing ideas. Three basic model classes:

(1) Hadronic + steady-state: bubbles are giant, multi-billion-year-old reservoirs of hot protons, fueled by GC star formation (Crocker & Aharonian 1008.2658 + several follow-up papers).

(2) Leptonic + steady-state: dark matter annihilation injects high-energy electrons which inverse Compton scatter, combined with anisotropic diffusion. Likely need magnetic confinement to achieve sharp edges (Cholis, Dobler & Weiner 1102.5095).

(3) Outflow from GC black hole, leptonic/hadronic transient event. As well as studies already mentioned, scenarios include:

- Energetic bipolar jet from the black hole in the past 1-2 Myr (Guo & Mathews 1103.0055, Guo, Mathews Dobler & Oh 1110.0834)
- Infall of a satellite galaxy ending a few Myr ago, material falling onto the Milky Way's black hole triggers an outflow (Lang et al, 1107.2923)
- Wide-angle (near-isotropic) outflow from the GC black hole, associated with an accretion event ~6 Myr ago; outflow collimated by Central Molecular Zone; emission originates from high-energy protons (Zubovas, King & Nayakshin1104.5443, Zubovas & Nayakshin1203.3060)

Morphology questions

- Morphology I: bubbles are fat, not collimated, and oriented perpendicular to plane. Challenge for AGN interpretations?
  - Fairly easy to generate with a not-too-energetic jet: gas density gradient and/or Central Molecular Zone shapes the outflow.
  - For the same reason, for weak jets, north-south symmetry does not require fine-tuning of the initial jet direction.

- Morphology II: flat profile + sharp edges + no evidence for spatial variation in spectrum.
  - Steady-state interpretations invoke magnetic confinement at the edges, but no detailed modeling yet.
  - Flat projected intensity generally challenging, but there are ideas - spatial dependence of the spectrum may allow them to be distinguished.

Implications for DM search

- Sharp edges + X-ray signal suggest that something other than just DM annihilation is occurring.

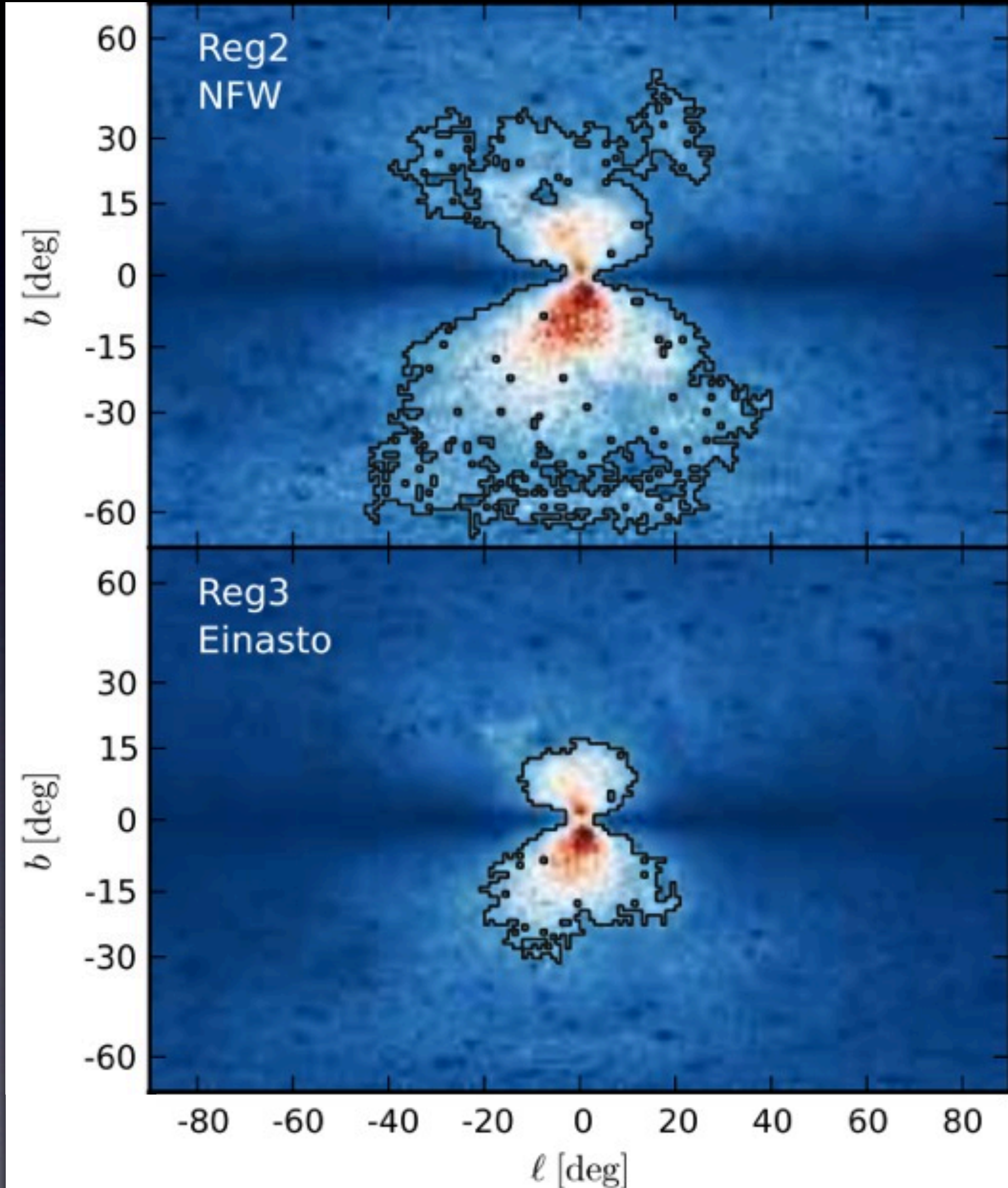
- Doesn’t mean there’s no DM signal in this region, but we need to understand the astrophysics first.
  - DM annihilation producing photons directly or through a decay chain: Fermi bubbles are a bright, hard-spectrum background. Look outside the edges?
  - DM annihilation producing CRs that then produce 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 close-to-flat spectrum in E^2 dN/dE with no evidence for spatial variation, close-to-uniform (projected) intensity, and sharp edges.
- The spectrum and morphology suggest a relation to the microwave Haze, and there appears to be a coincident signal in few-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!
- Until the astrophysics is understood, studies of DM constraints and potential signals from this region of the sky should proceed with care.

A 130 GeV line?

- Recent claim of a gamma-ray line detection at 130 GeV in the inner galaxy (Bringmann et al 1203.1312, Weniger 1204.2797).
- Regions in which the signal is detected have significant overlap with the bubbles, although not the same. (Second paper mentions testing a bubble region, but results are not shown: stated to be less "interesting".)



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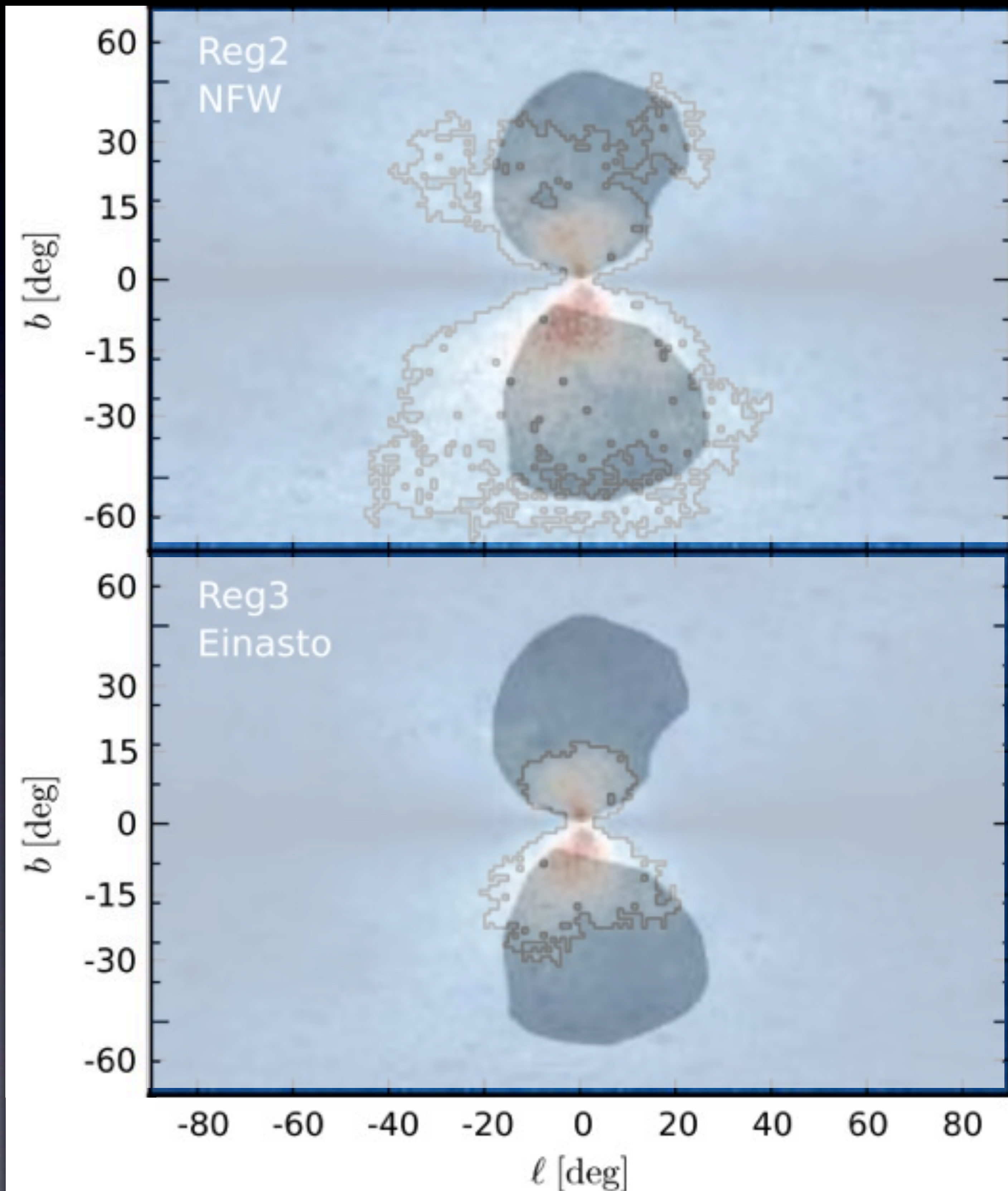
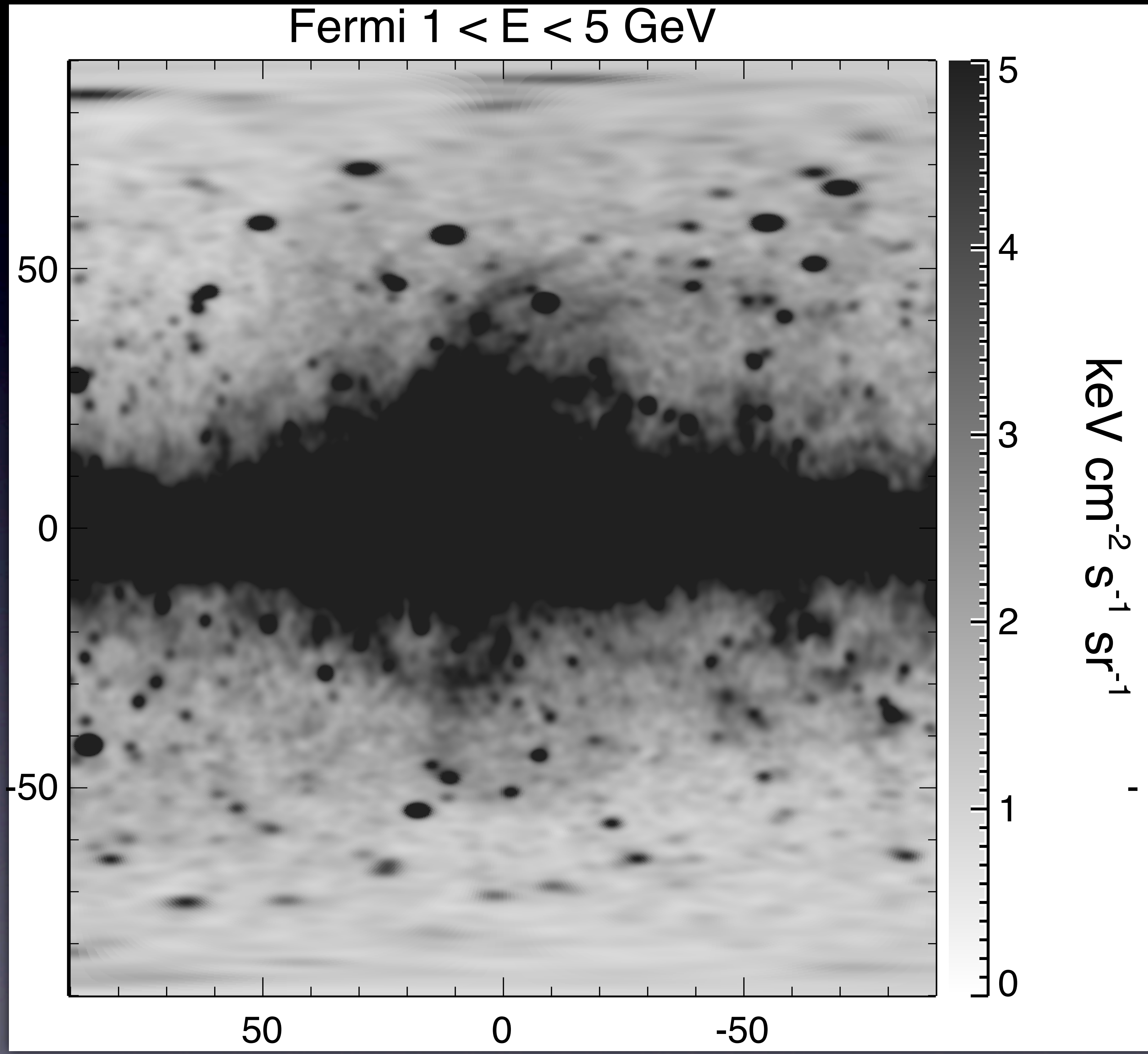


BONUS SLIDES

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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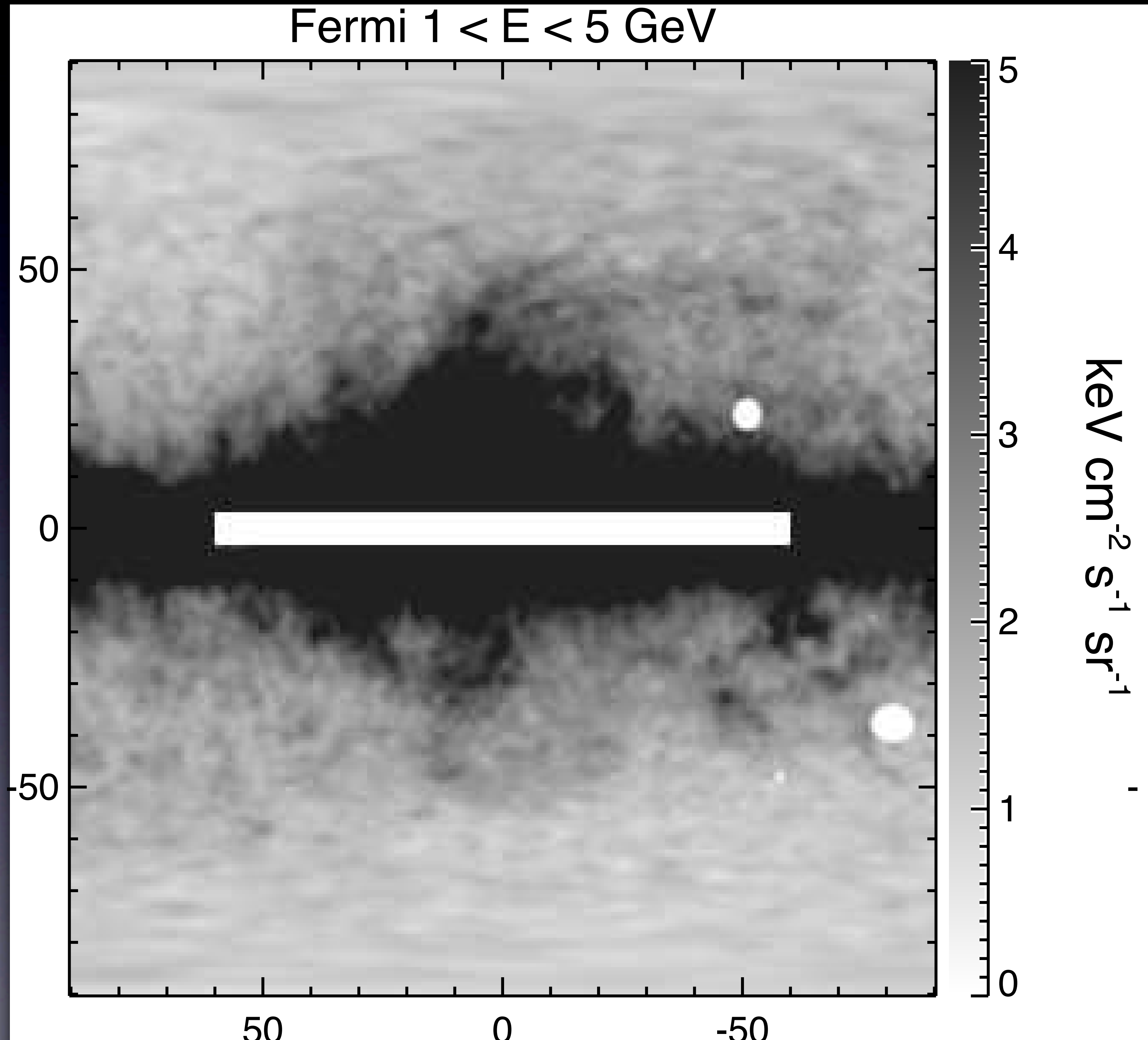


The diffuse γ-ray sky

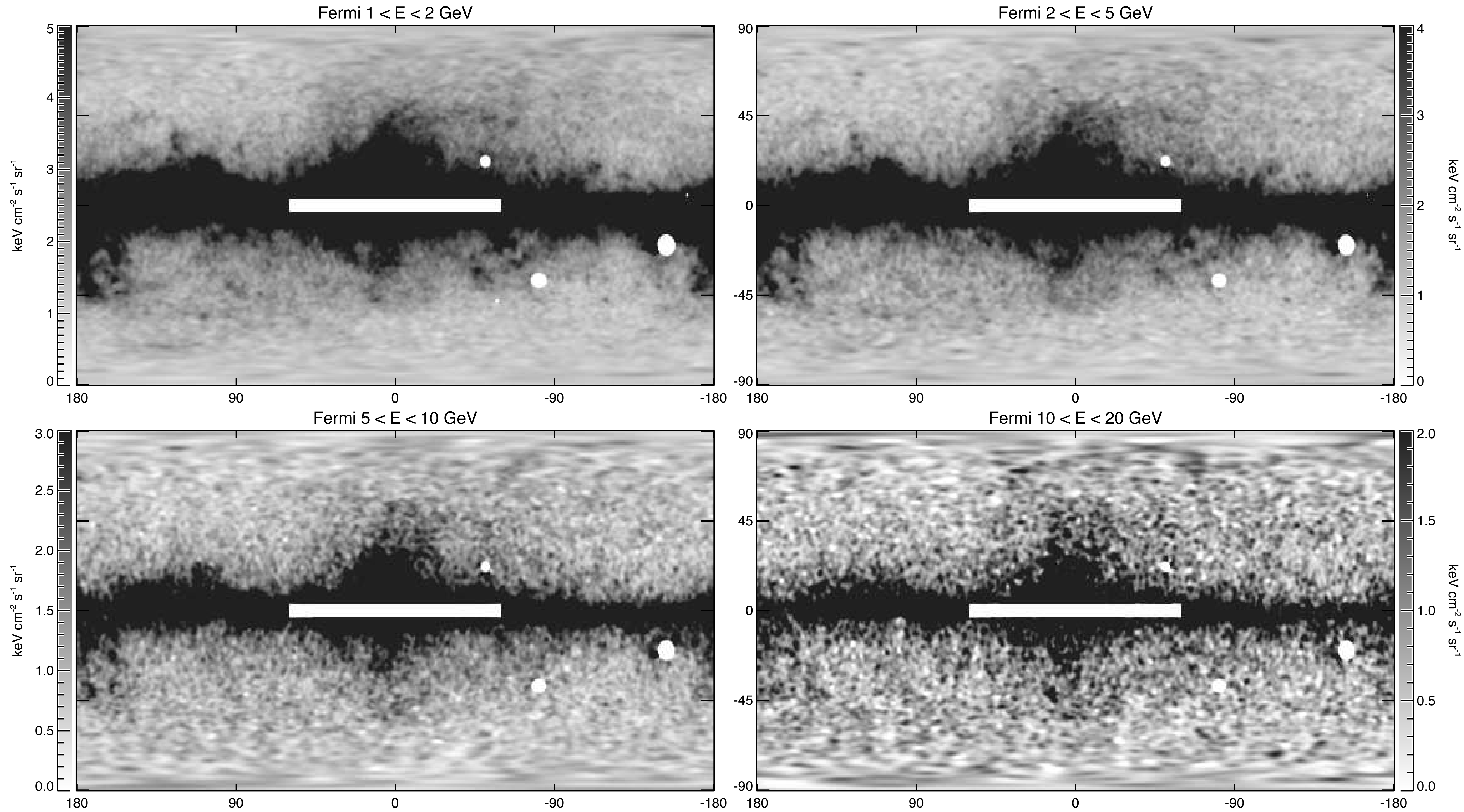


FIG. 1.— All-sky *Fermi*-LAT 1.6 year maps in 4 energy bins. Point sources have been subtracted, and large sources, including the inner disk ($-2^\circ < b < 2^\circ, -60^\circ < \ell < 60^\circ$), have been masked.

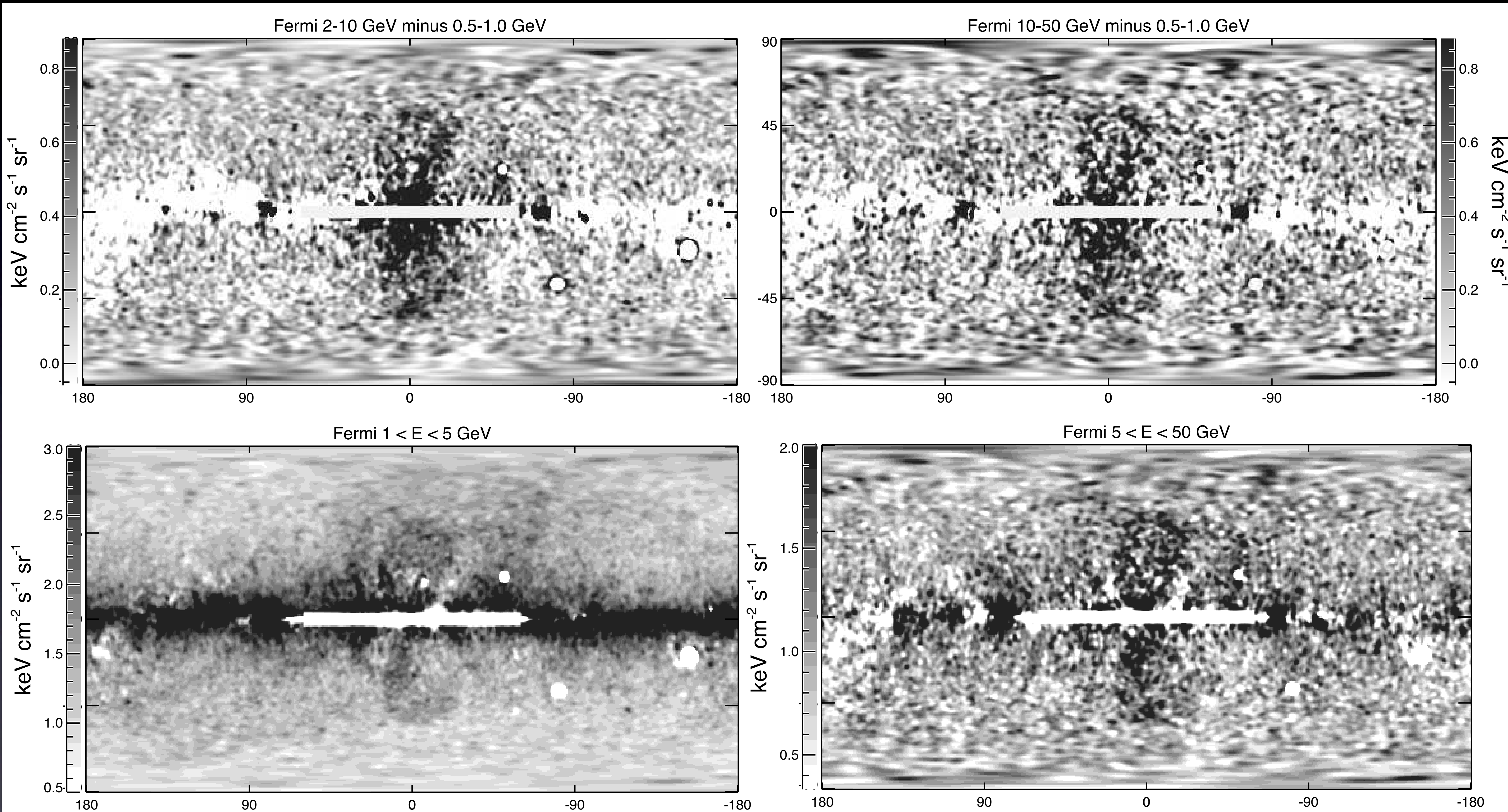
Known emission mechanisms

- π^0 emission: 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.
- Isotropic emission: extragalactic gamma-ray background + residual cosmic ray contamination.

Template analysis

- Model known emission mechanisms by spatial templates; fit their amplitude in each energy bin.
- Pro: if templates are well chosen, gives a few-parameter characterization of almost all the emission. Very simple - we know everything that goes into the subtraction.
- Con: templates are never perfect, need to assess residuals carefully.
- Ideally, use simple template analysis to identify any unexpected features and inform a full physical model.

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)

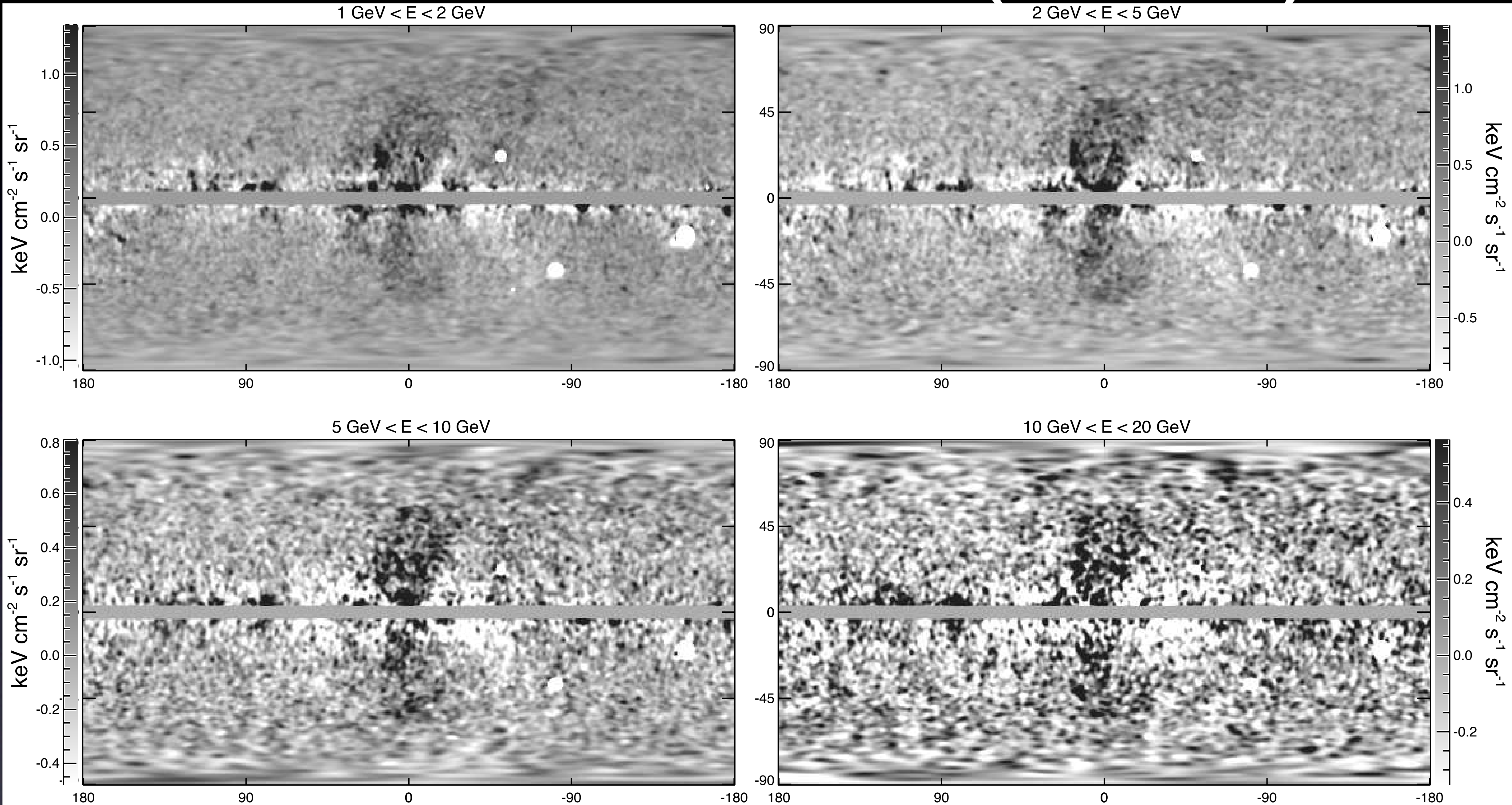
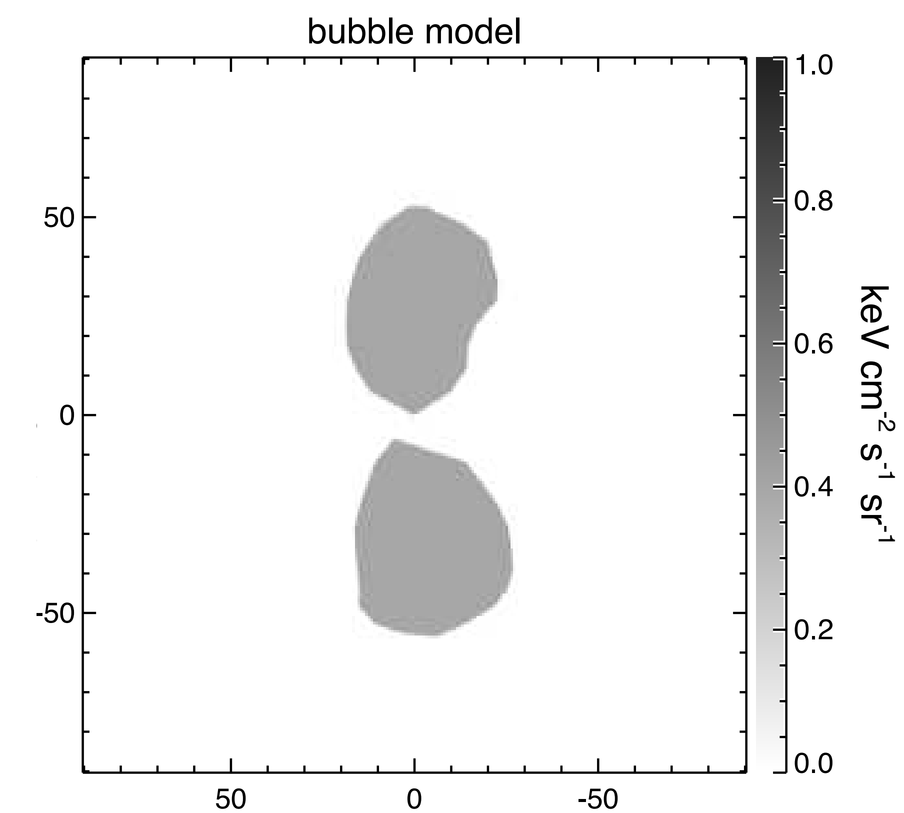


FIG. 2.— All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins (see §3.1.1). Two bubble structures extending to $b \pm 50^\circ$ appear above and below the GC, symmetric about the Galactic plane.

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

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 interior and edge of template separately (test for edge-brightening, spectral uniformity).
    - Fit north and south bubbles separately.
    - Add separate template for Loop I (large, faint, soft-spectrum arc across northern sky).



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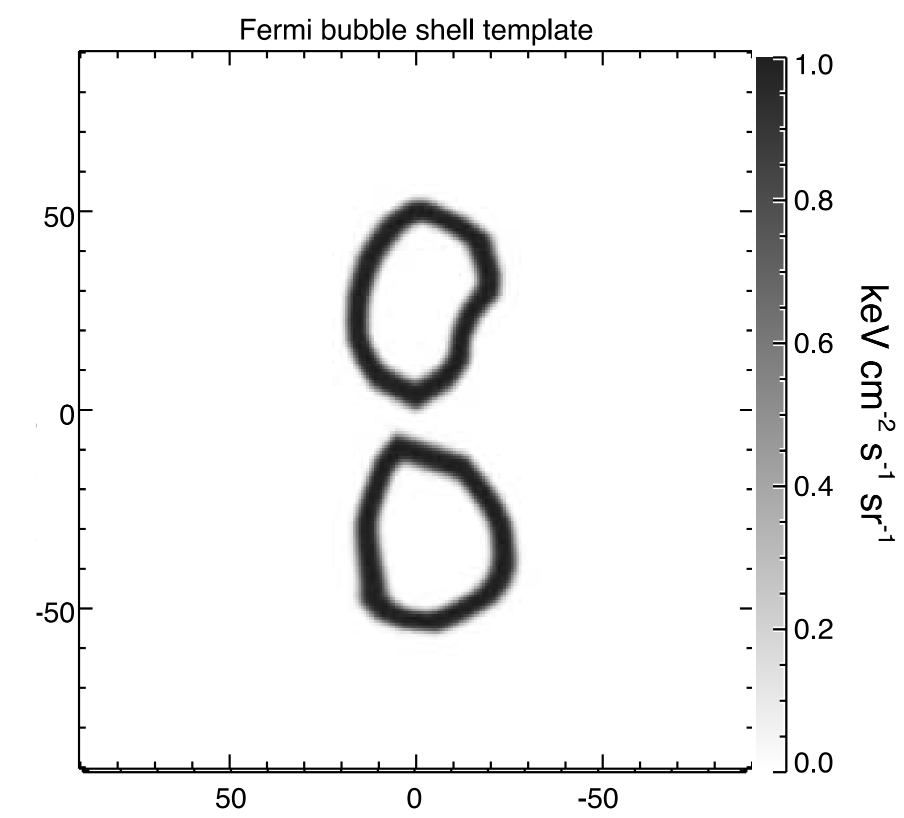

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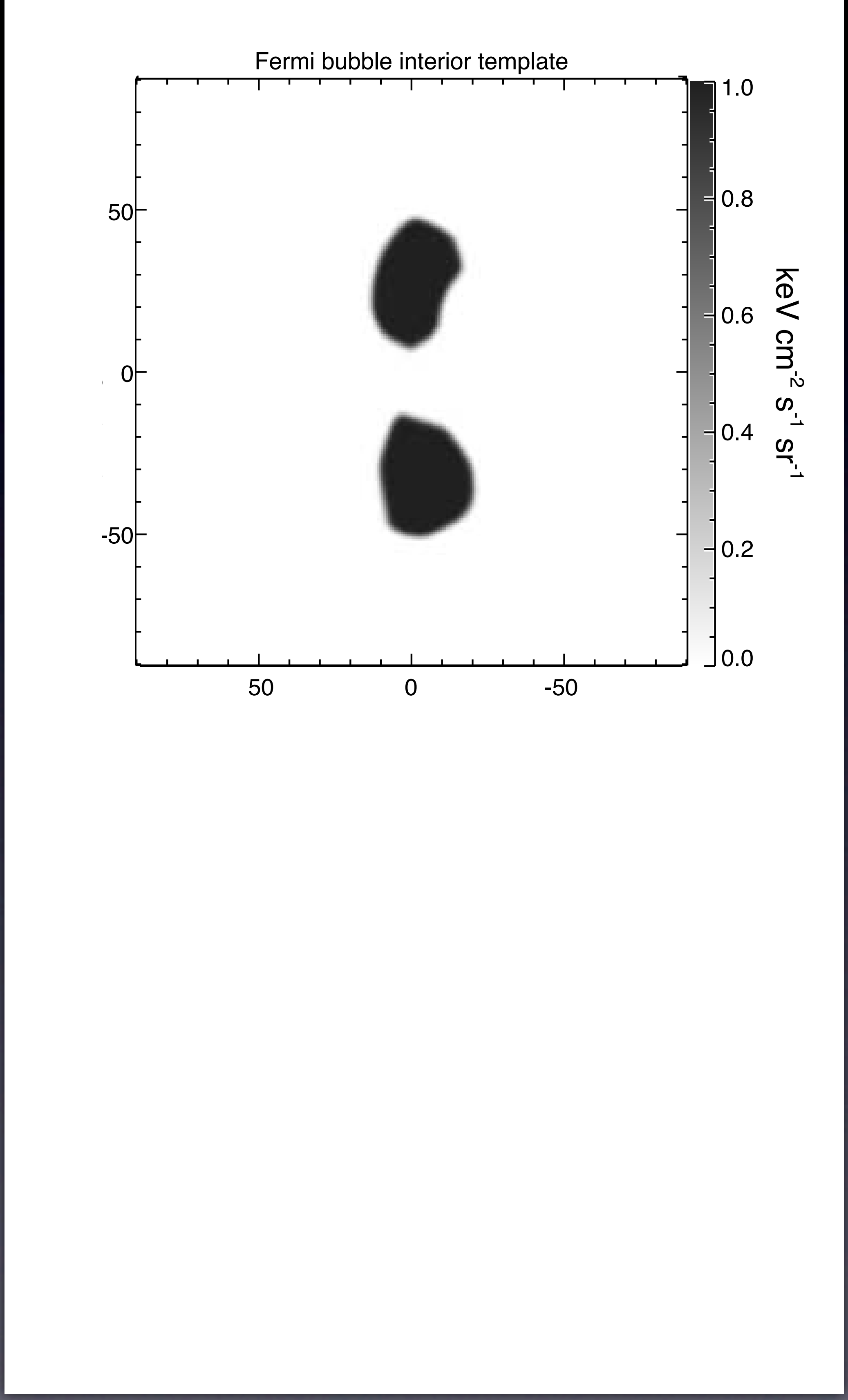

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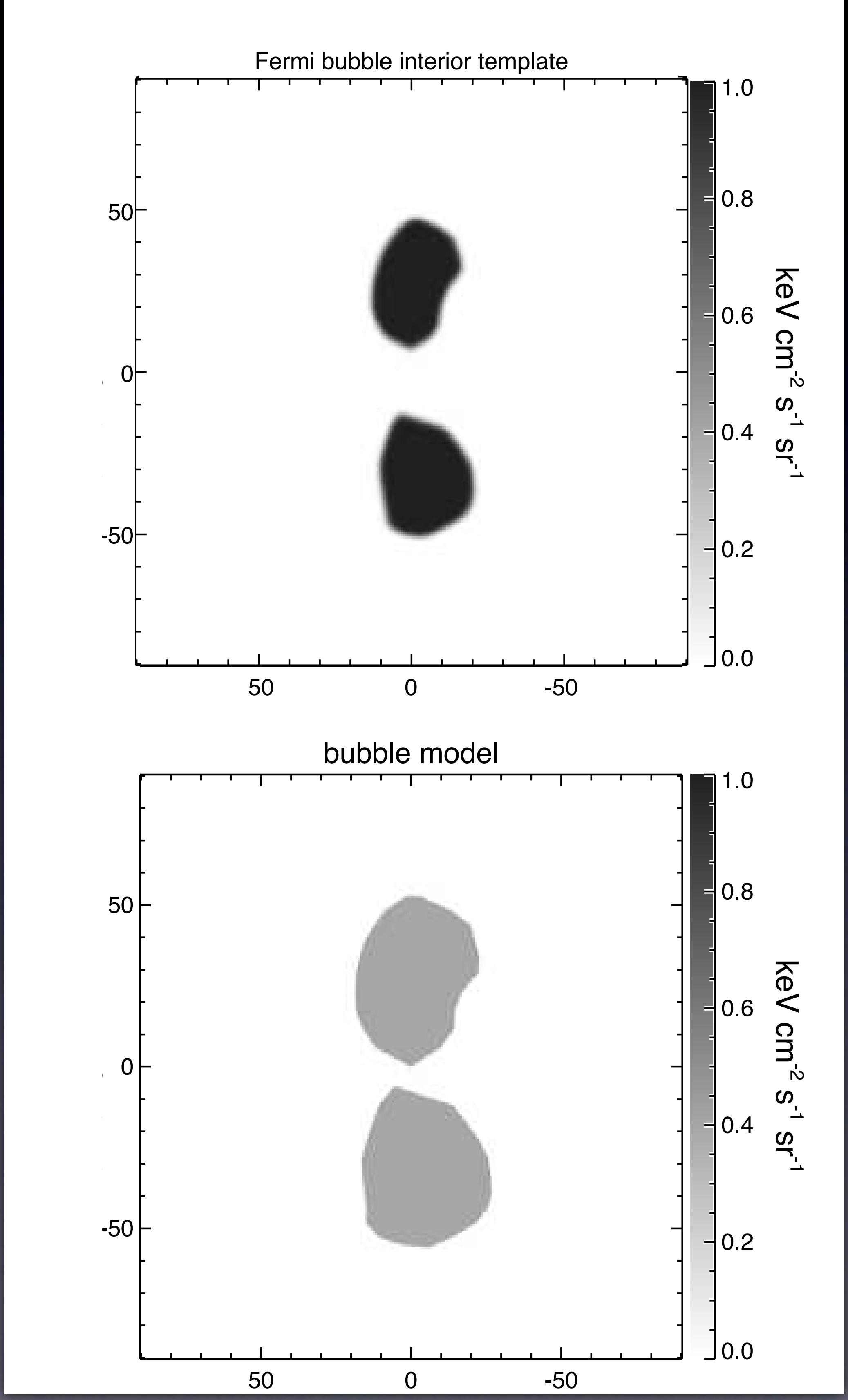

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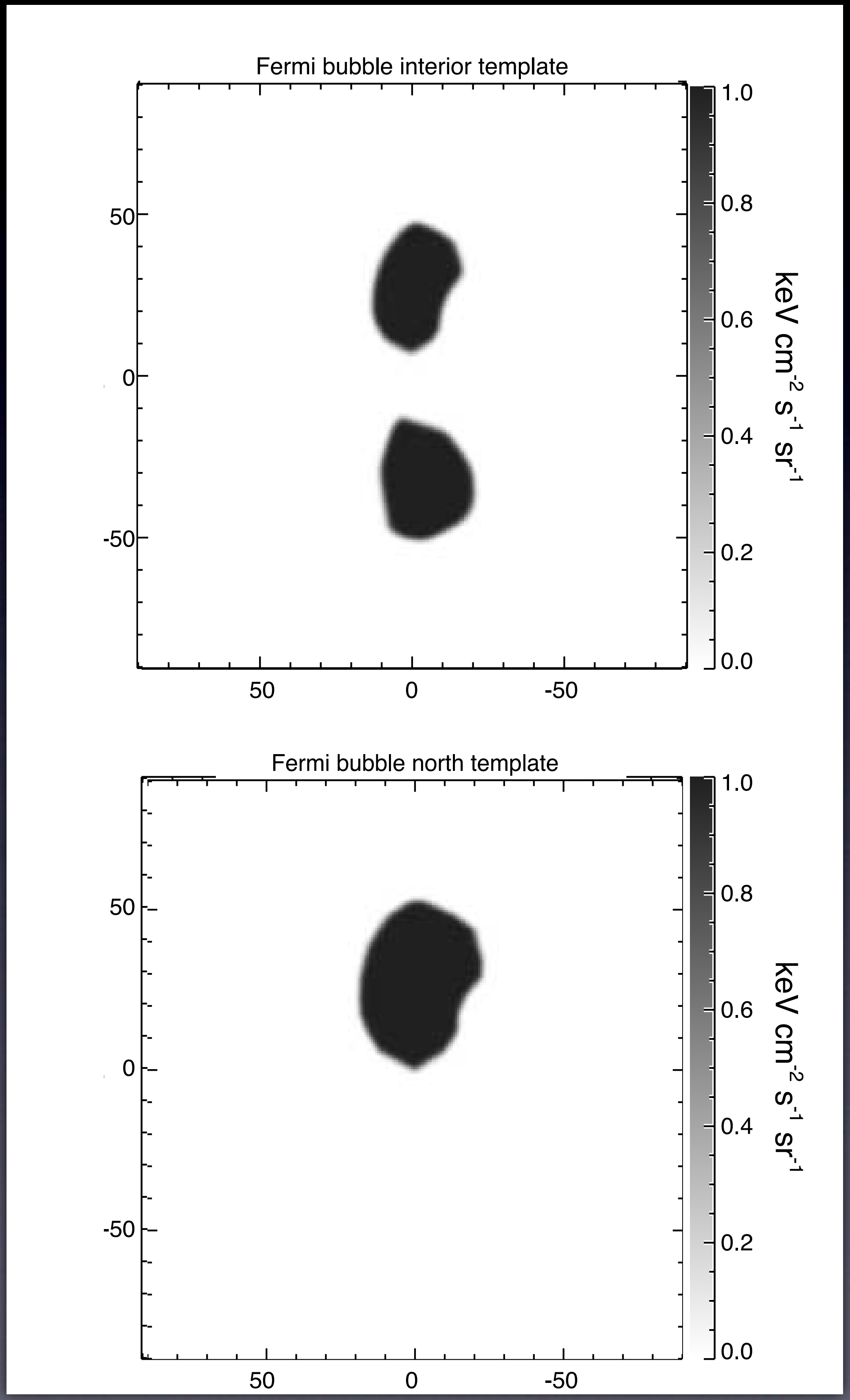

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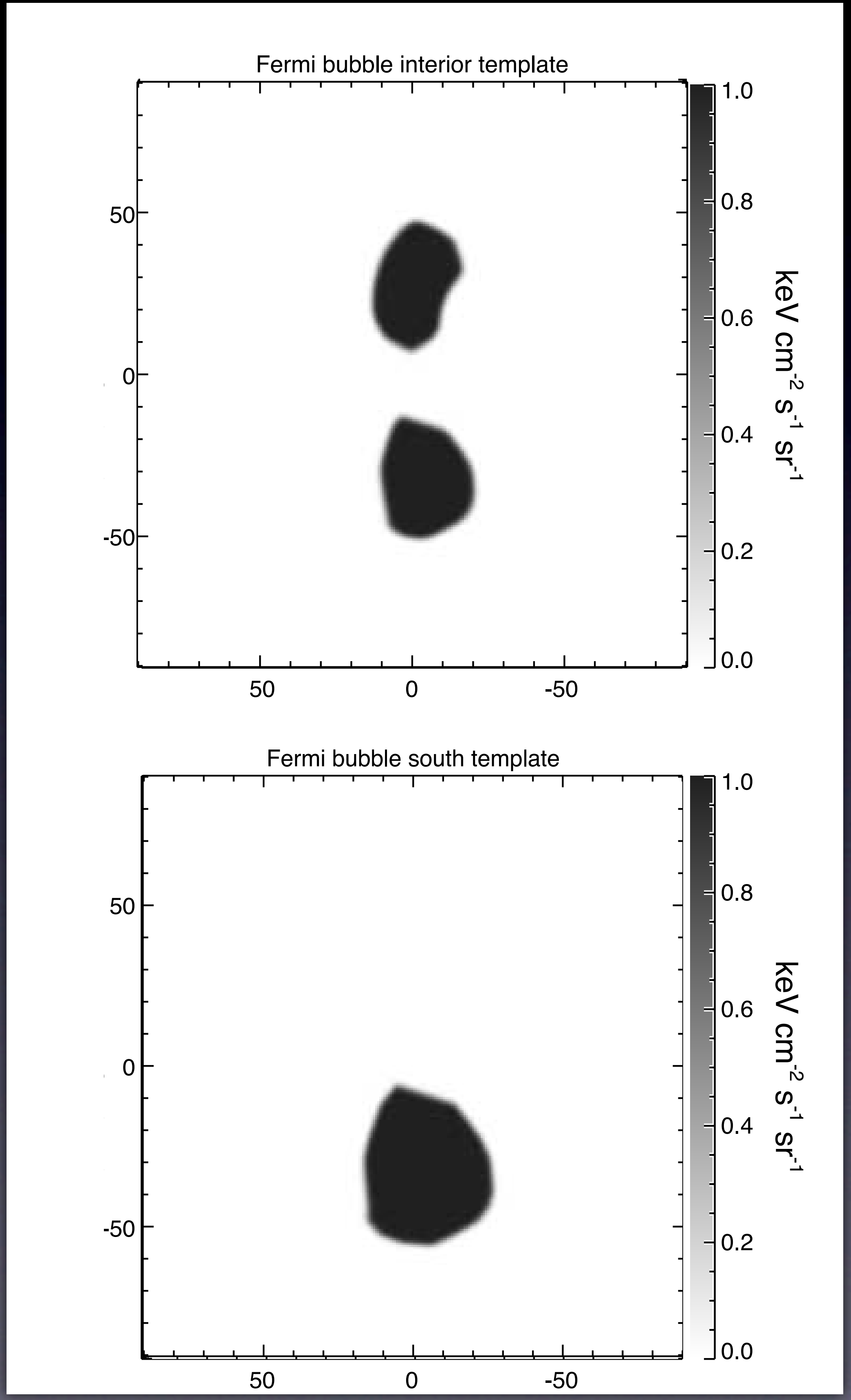
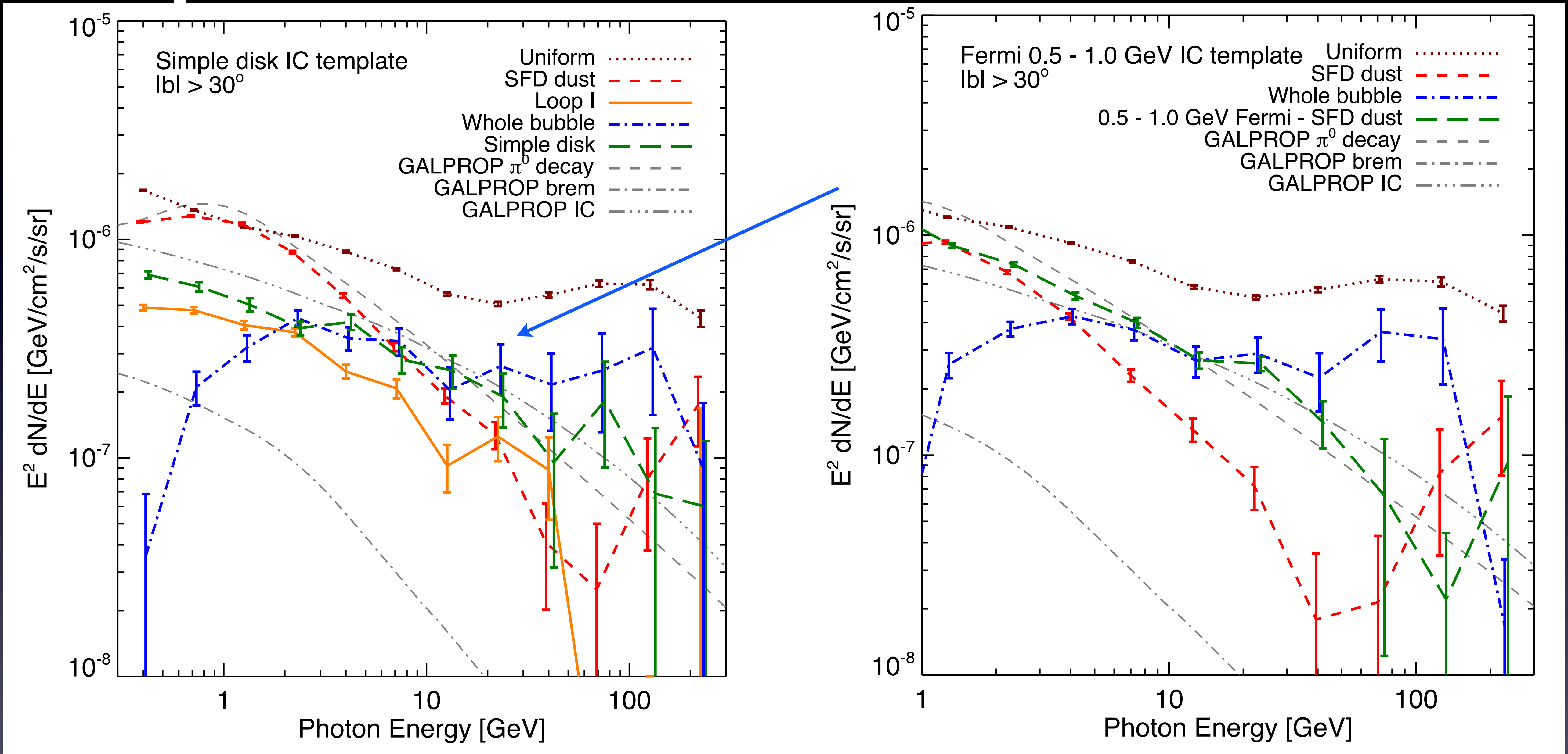


Spectrum of the Bubbles



- Good consistency with GALPROP spectra for π^0 and ICS/brem.
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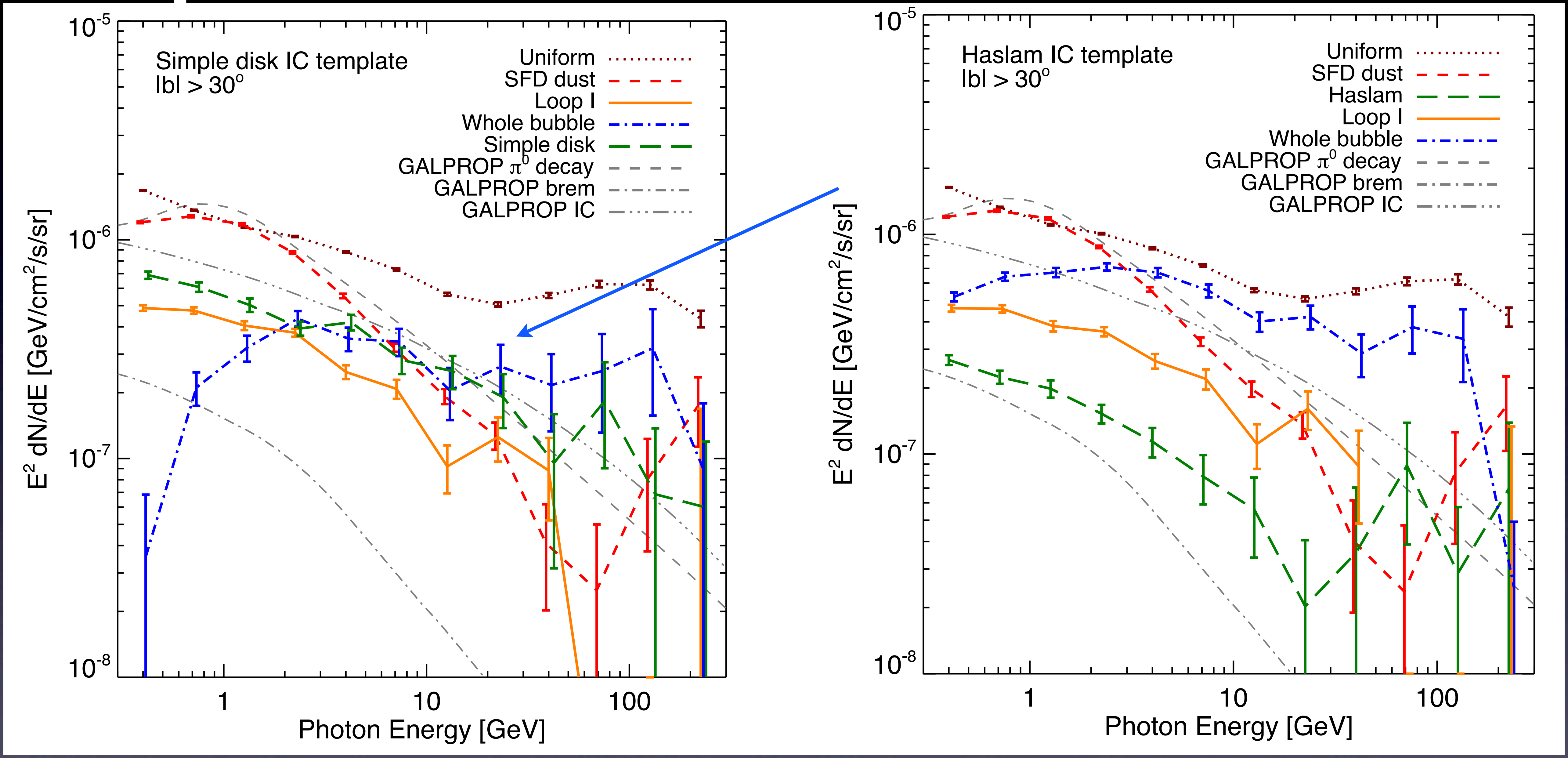

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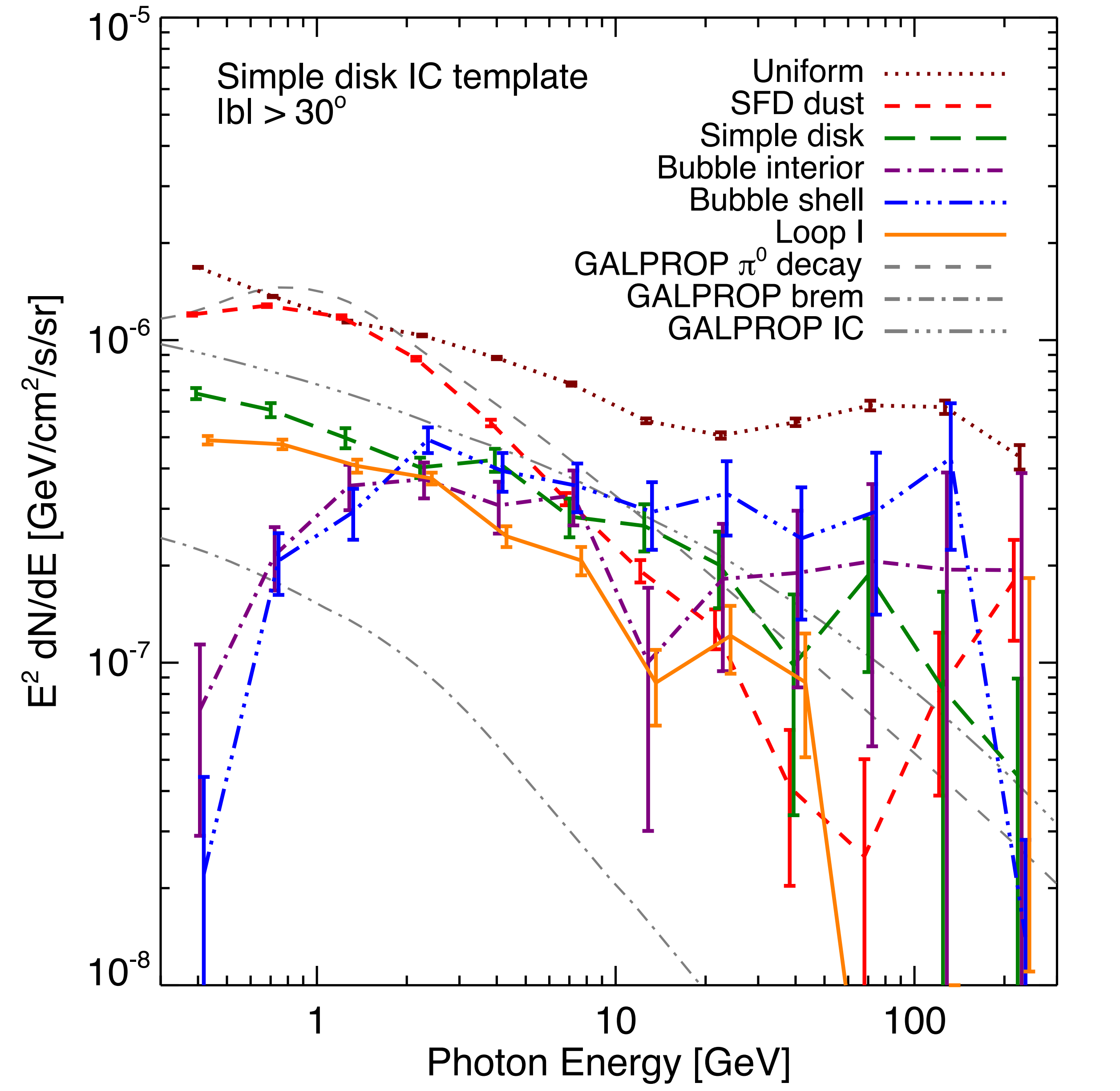
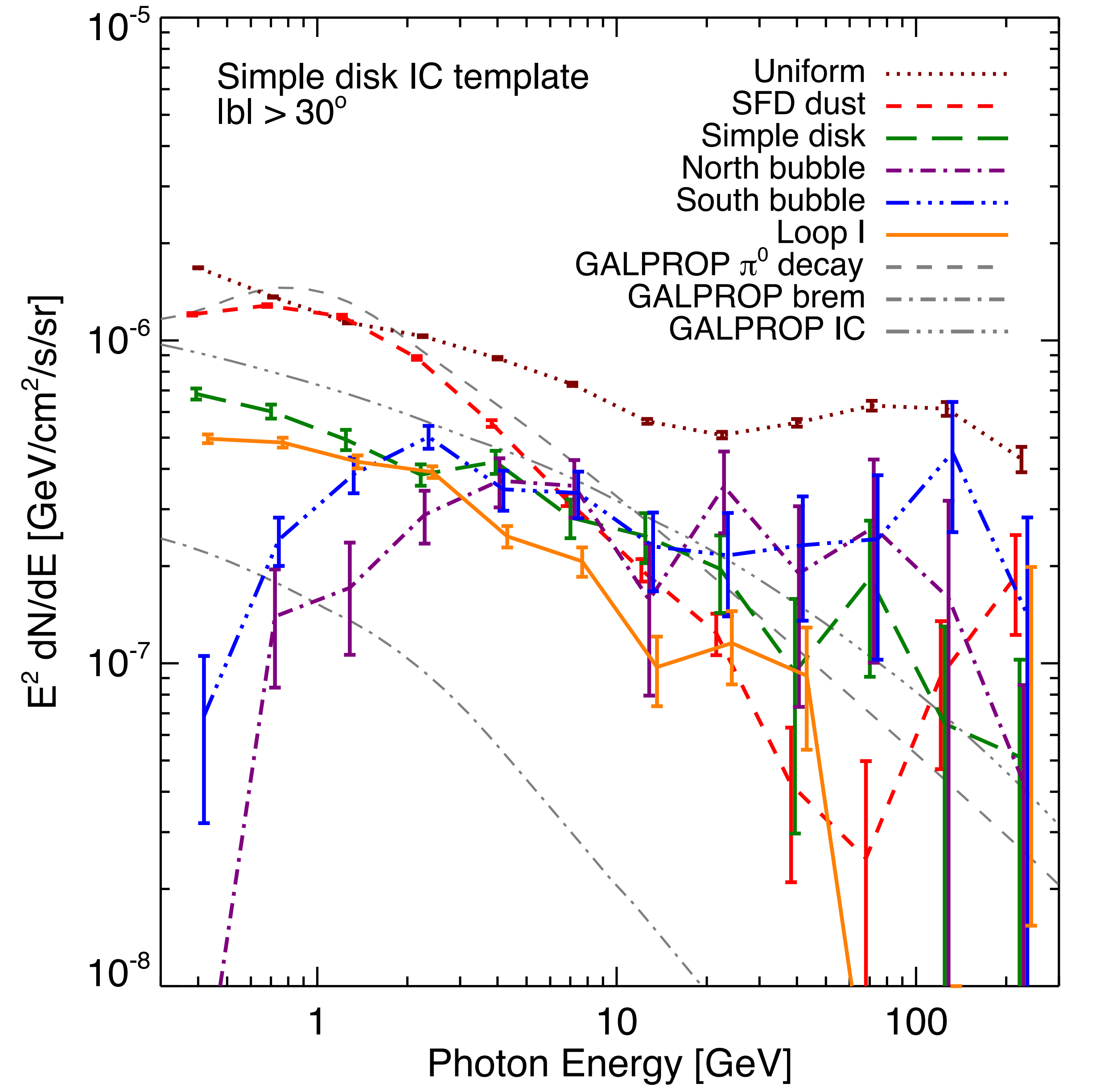
Tests for spectral variation





- Fit for north and south bubbles, interior and shell separately, with several different ICS templates. No evidence of spectral variation (of course, some variation can still be accommodated).

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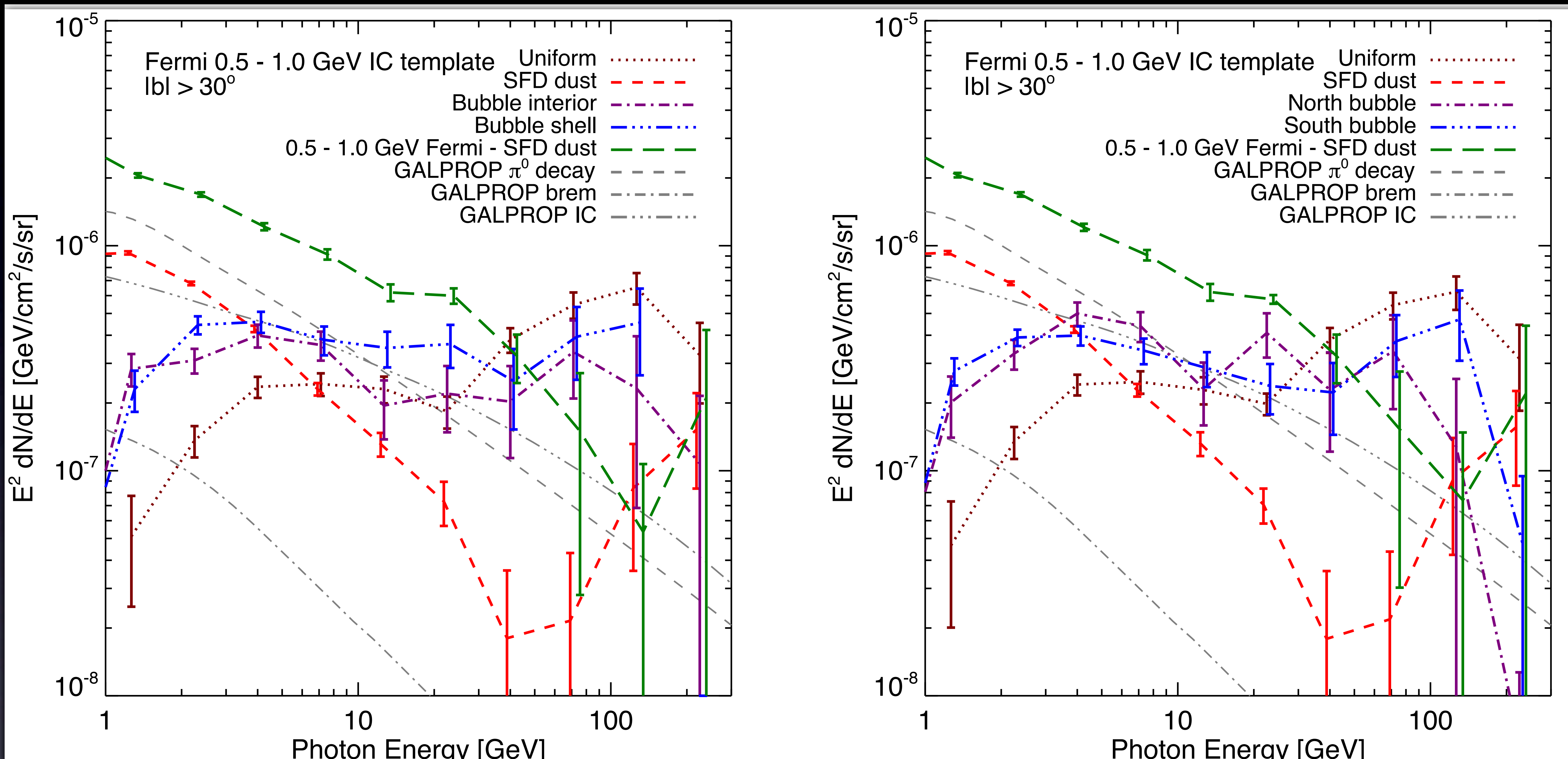

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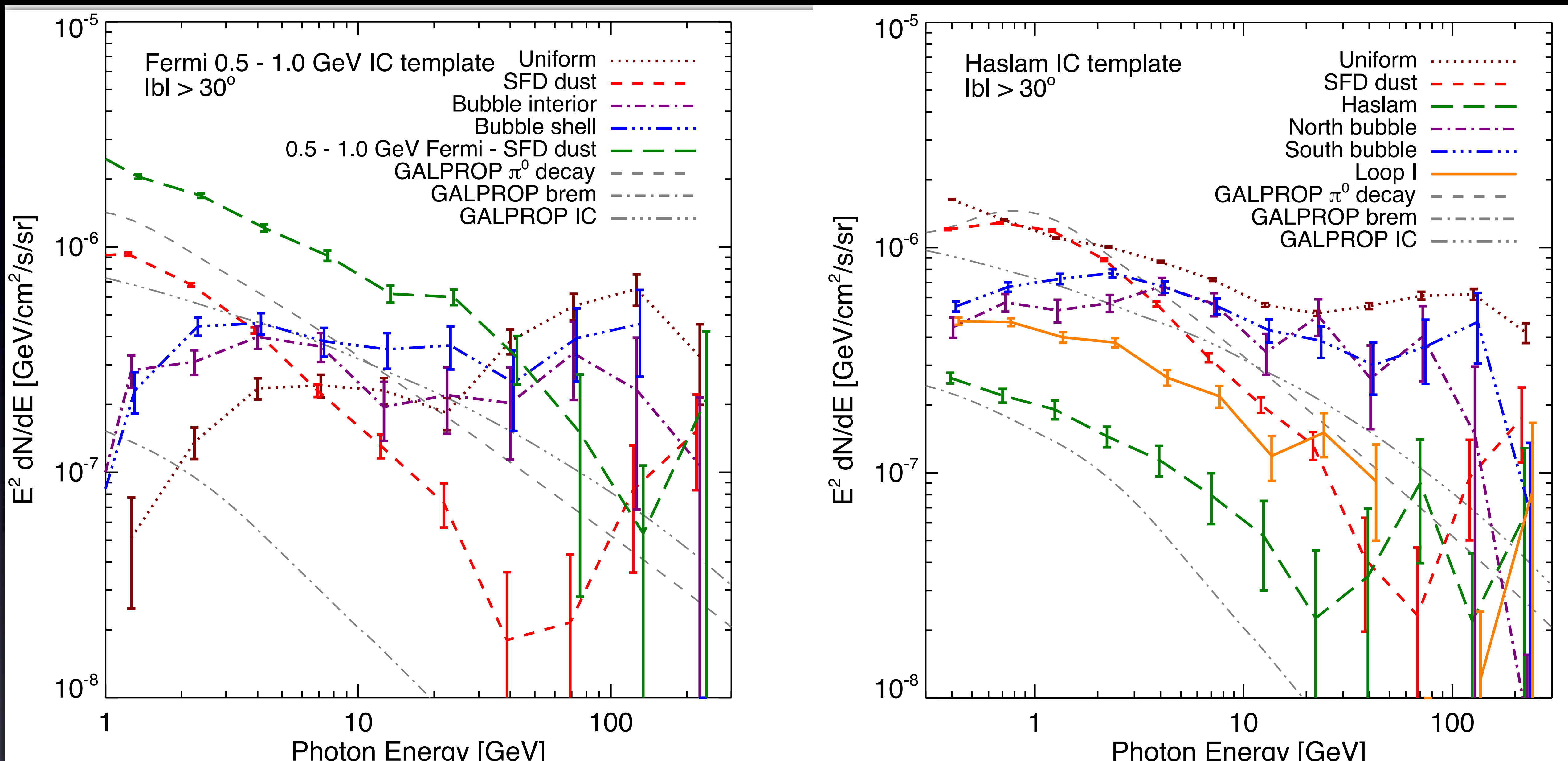

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New DATACLEAN class

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- In DATACLEAN up to mid-November, relative to Class 3 data used in paper:
  - Isotropic spectrum is fainter and much softer.
  - Strange “upturn” in dust-correlated emission goes away.
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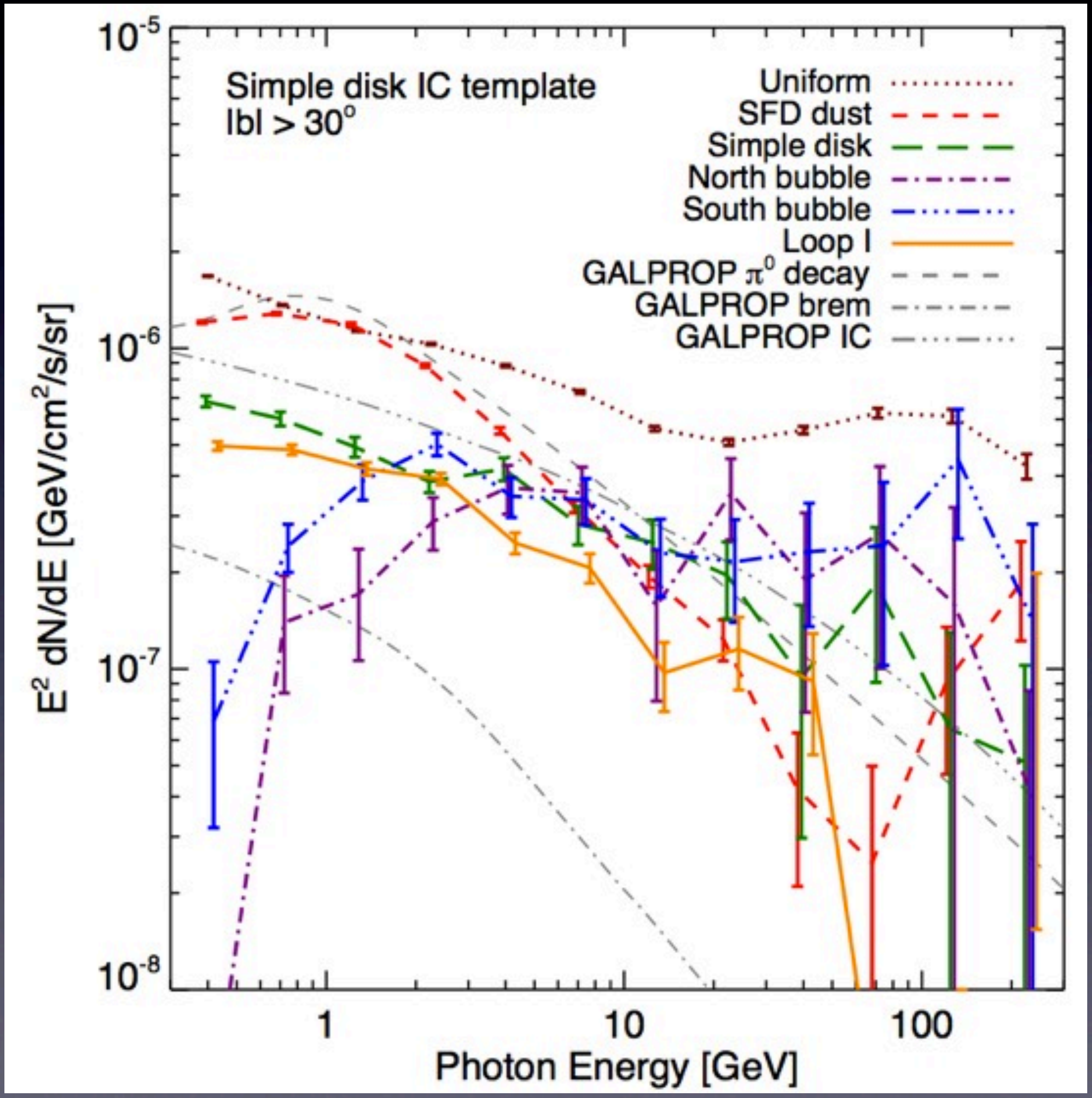

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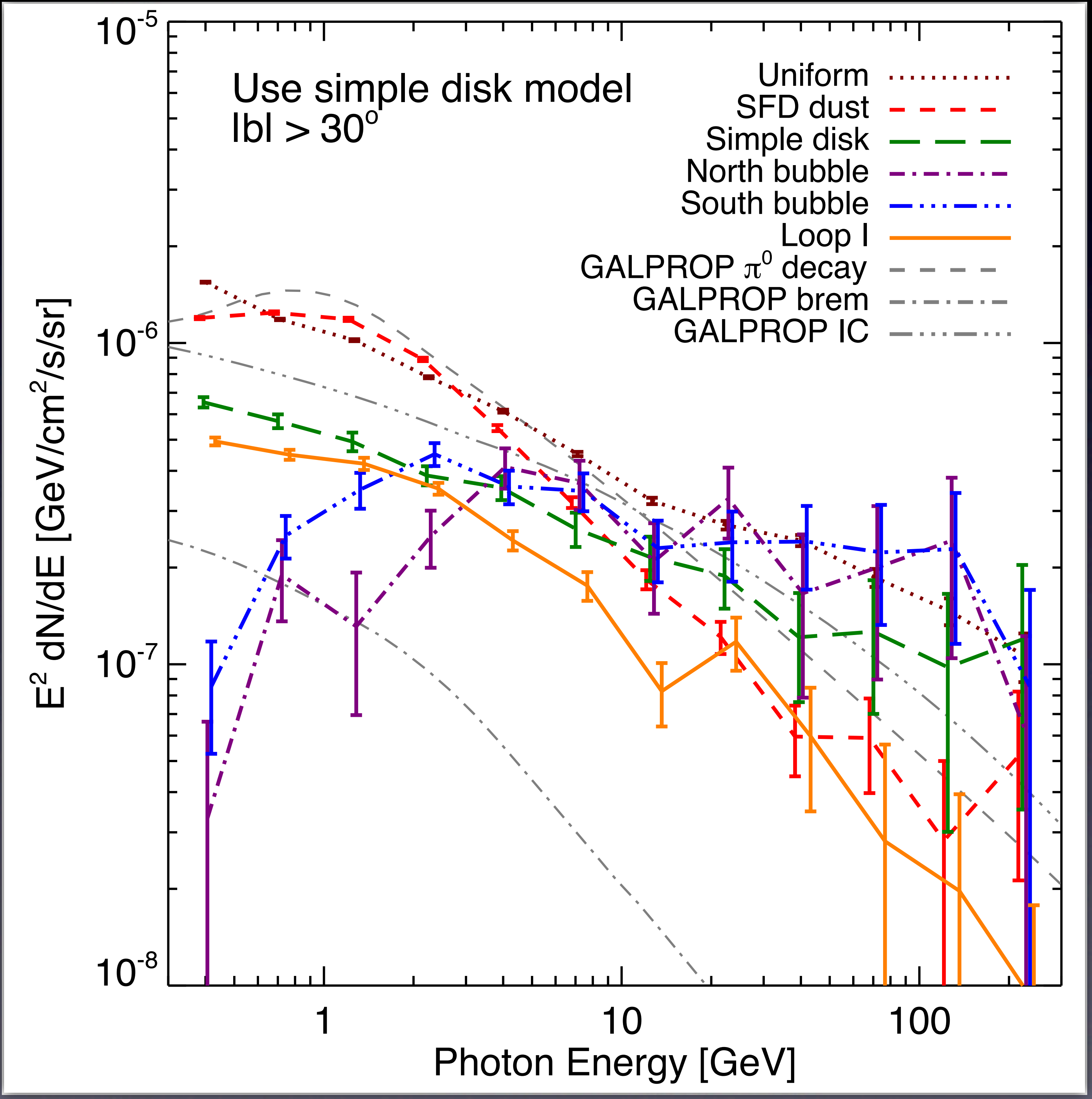
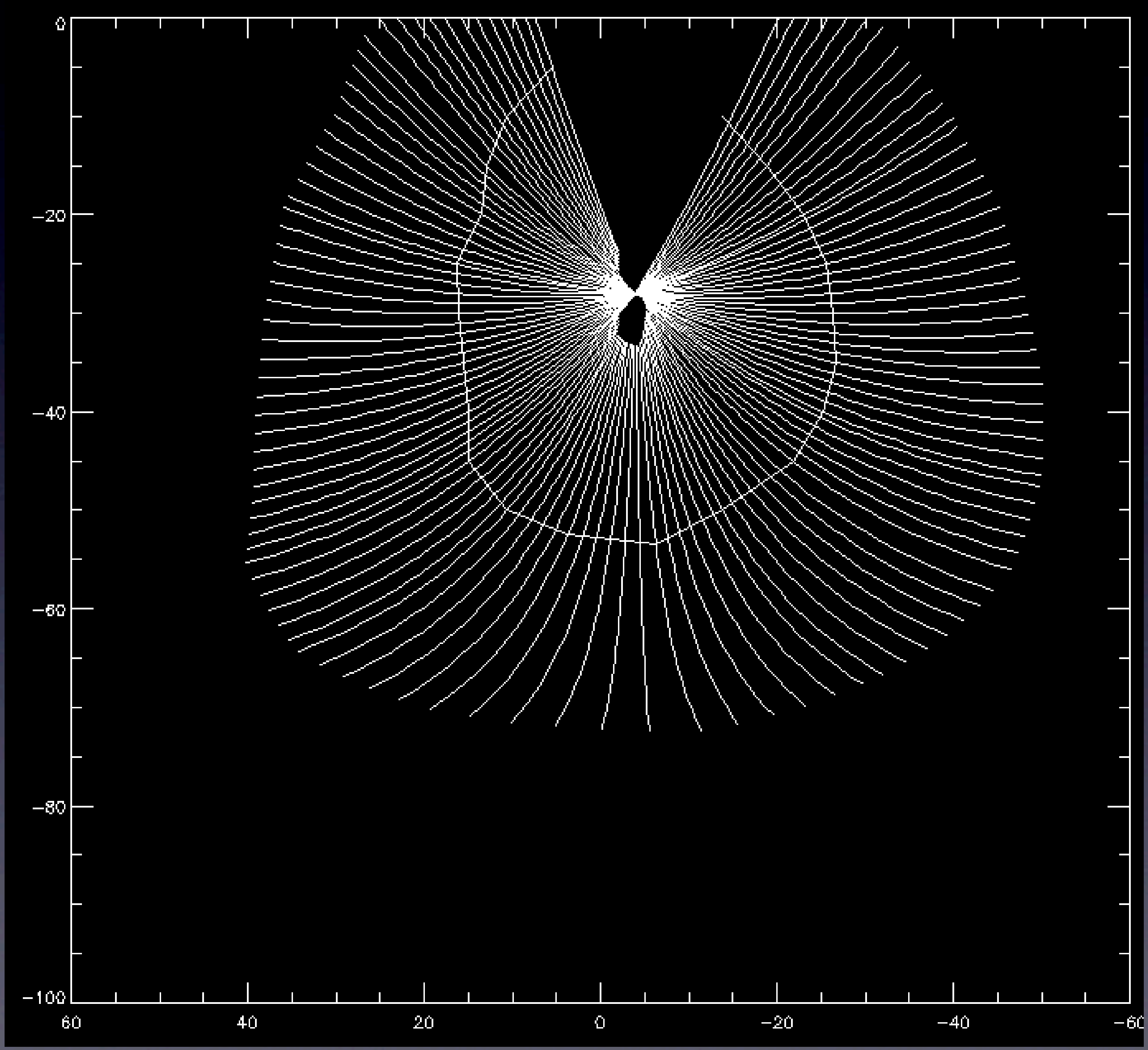
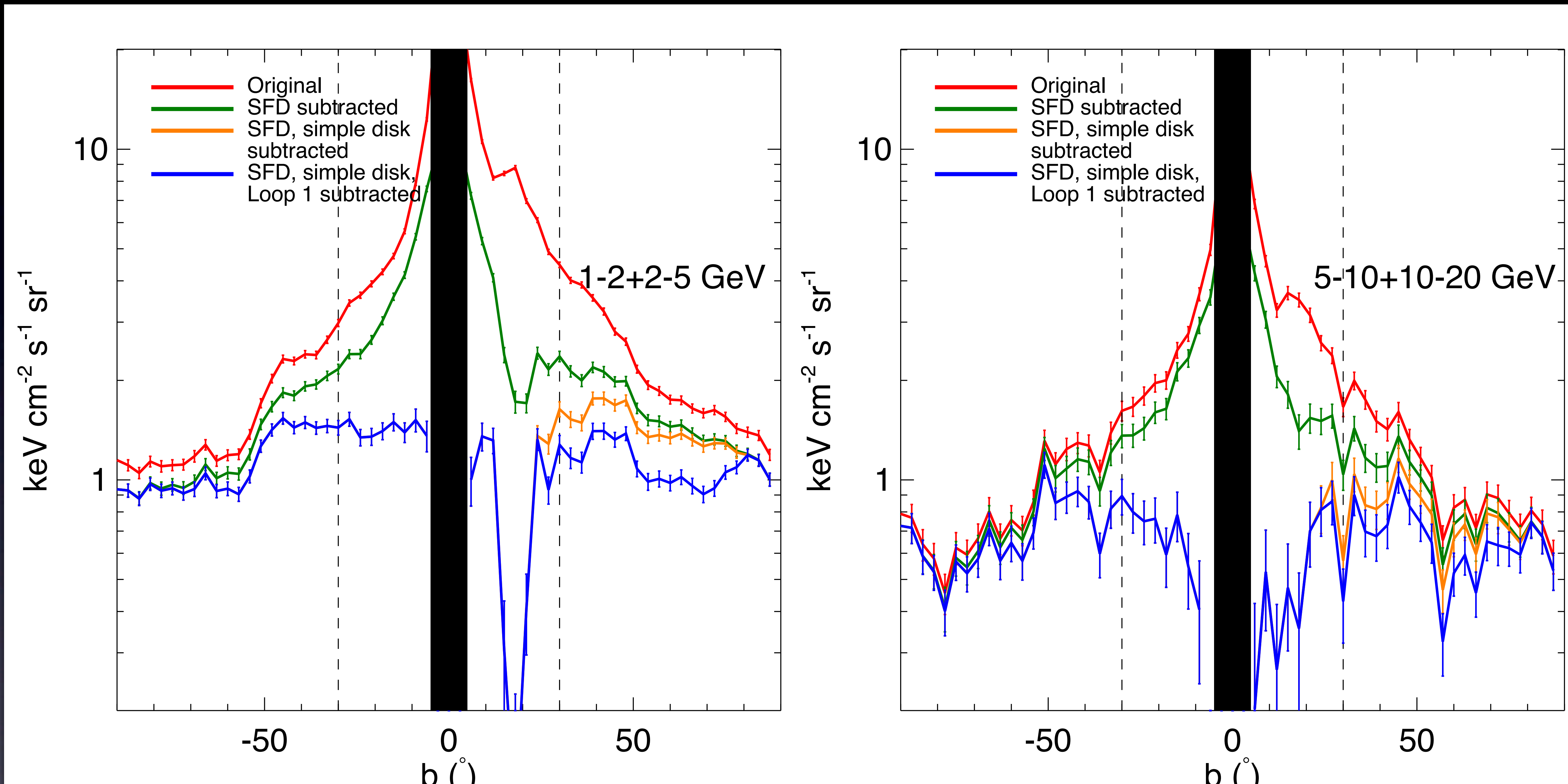


How sharp are the edges?

- Trace rays from center of each bubble to edge.
- Measure (projected) intensity along each ray, and average results together.
- Restrict to high latitude (|b| > 30°) to minimize uncertainty in subtractions.

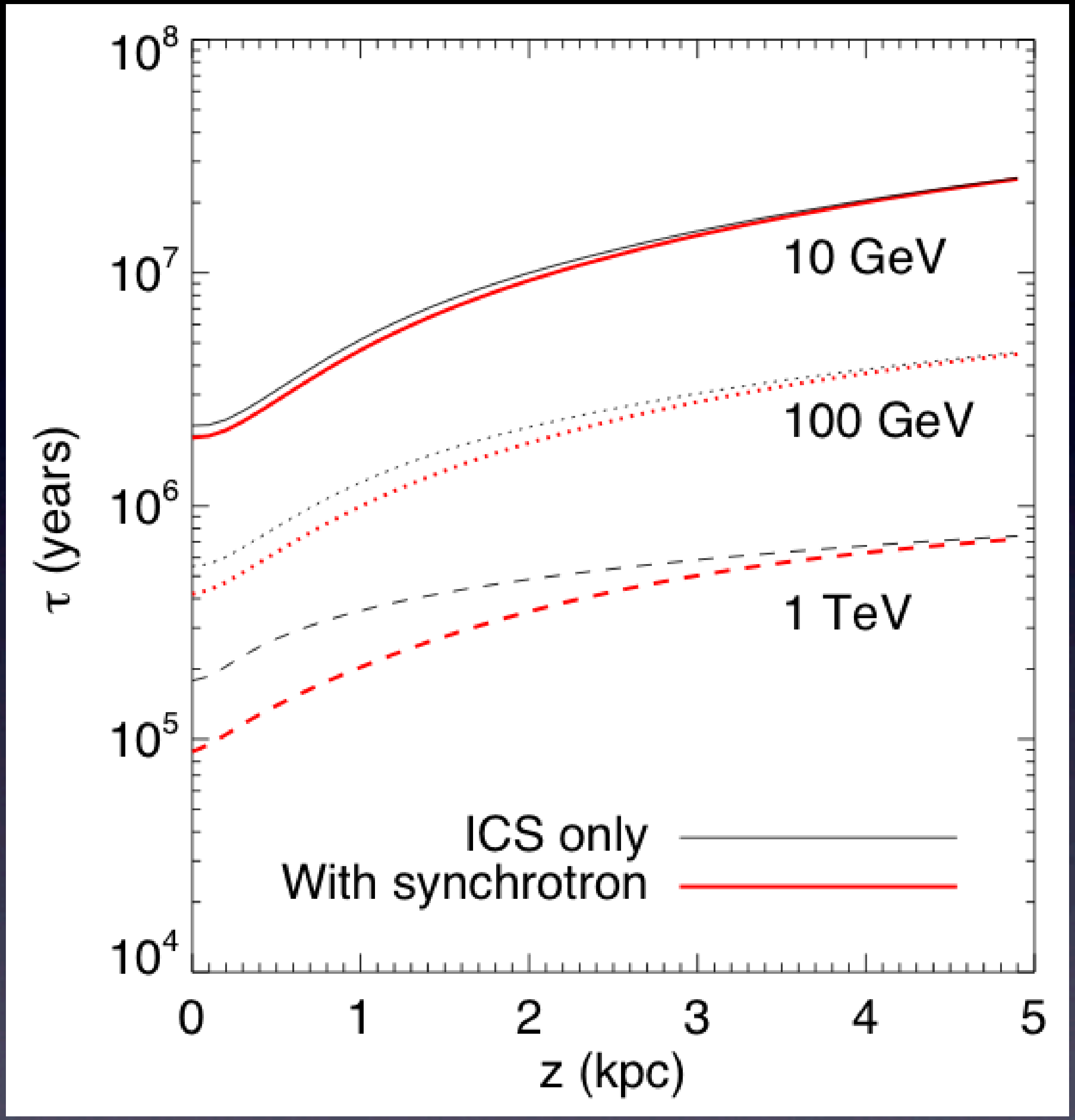


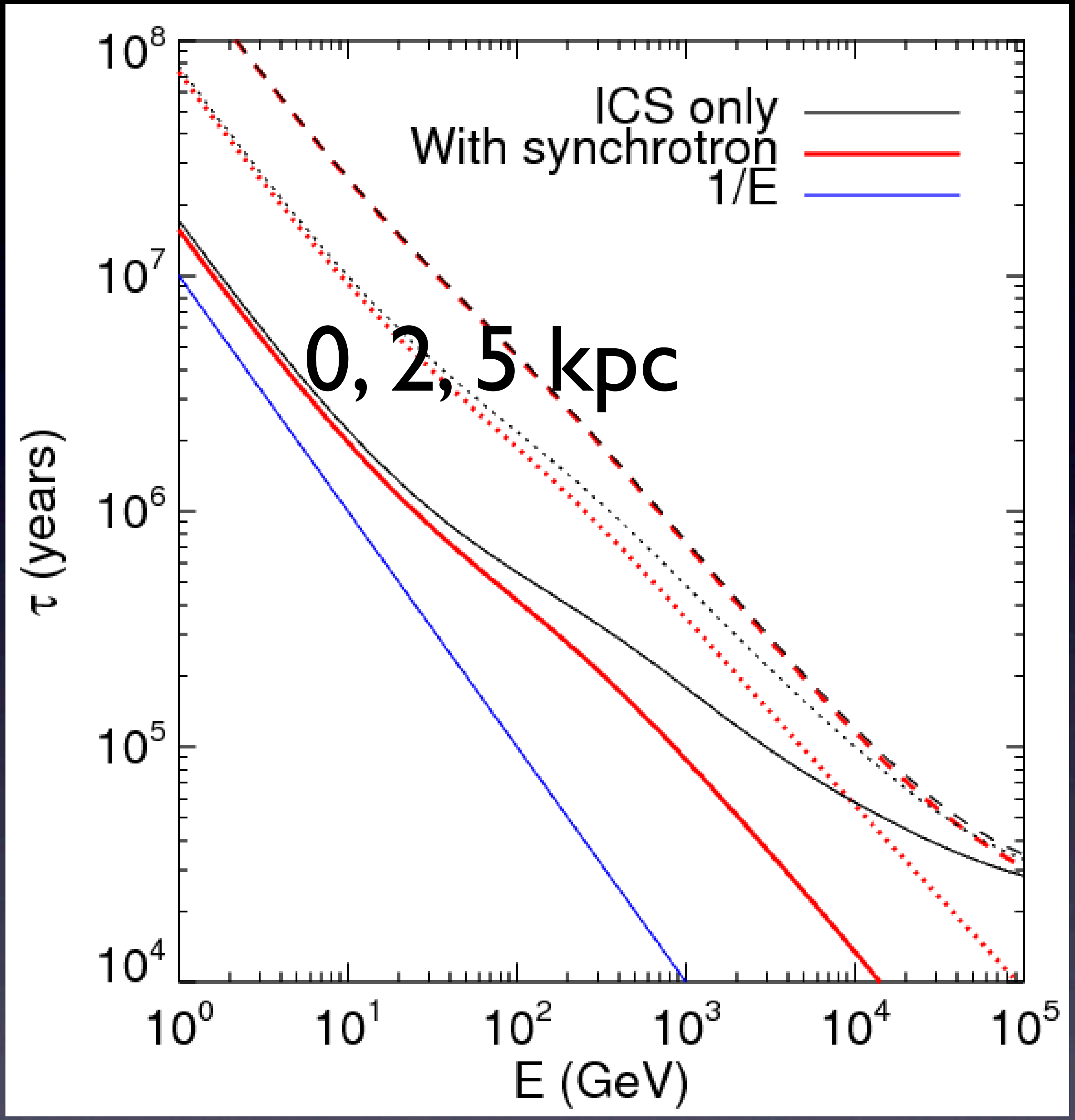
Profile in b



- 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°.

Cooling time problem



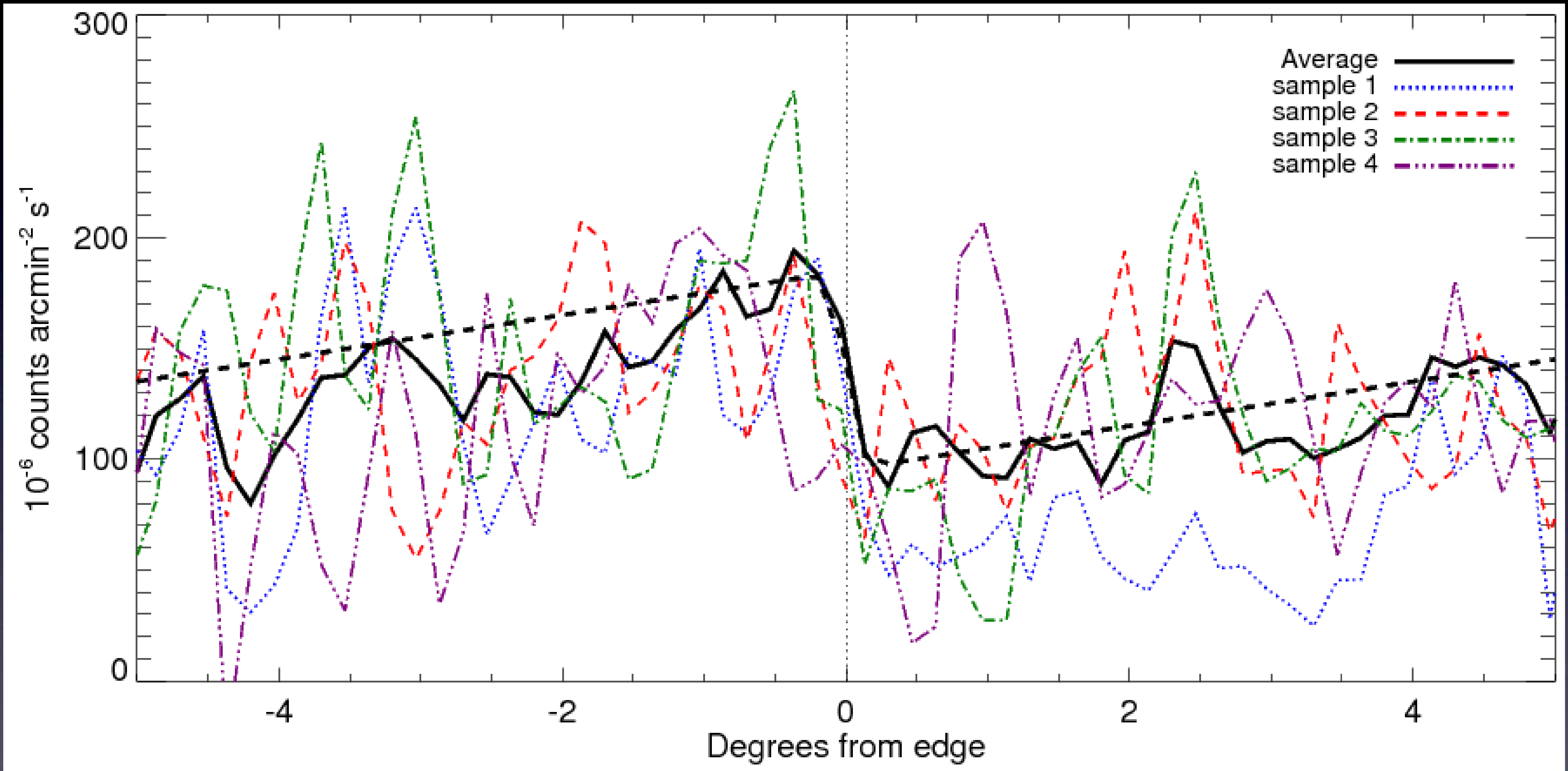


- However, if the bubbles are coming from ICS by O(TeV) electrons, there is another problem: such electrons cool quite quickly!

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.

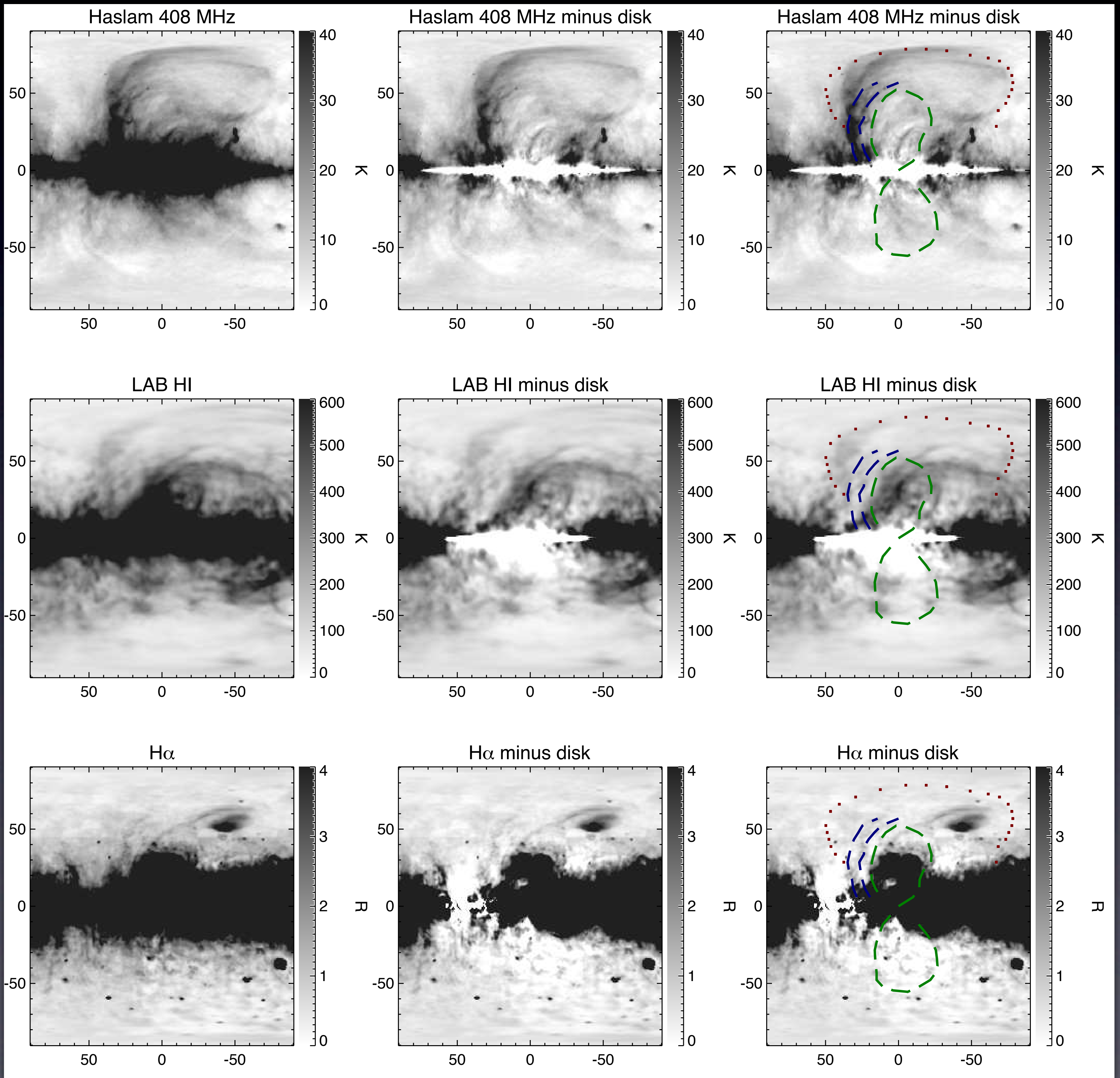
How sharp is the X-ray edge?



- 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.



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 $\sim 4\times 10^{37}$ ergs/s ($\sim 2.5\times 10^{40}$ GeV/s).
- For reference, typical supernova outputs $\sim 10^{51}$ 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%...)

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.

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

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.

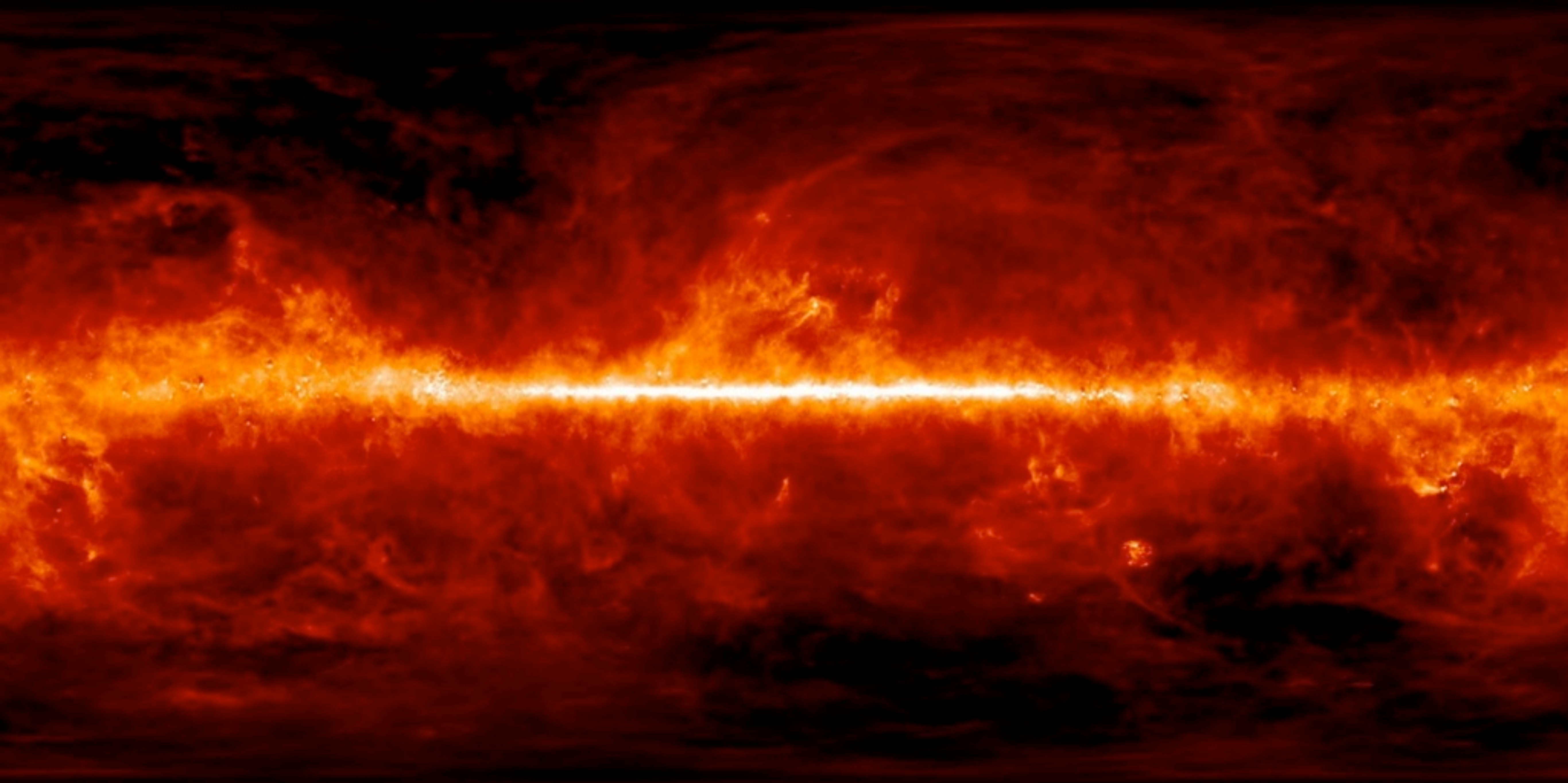
Conclusion: we know how to do statistics.

WMAP foreground templates

Available templates (as of 2003):

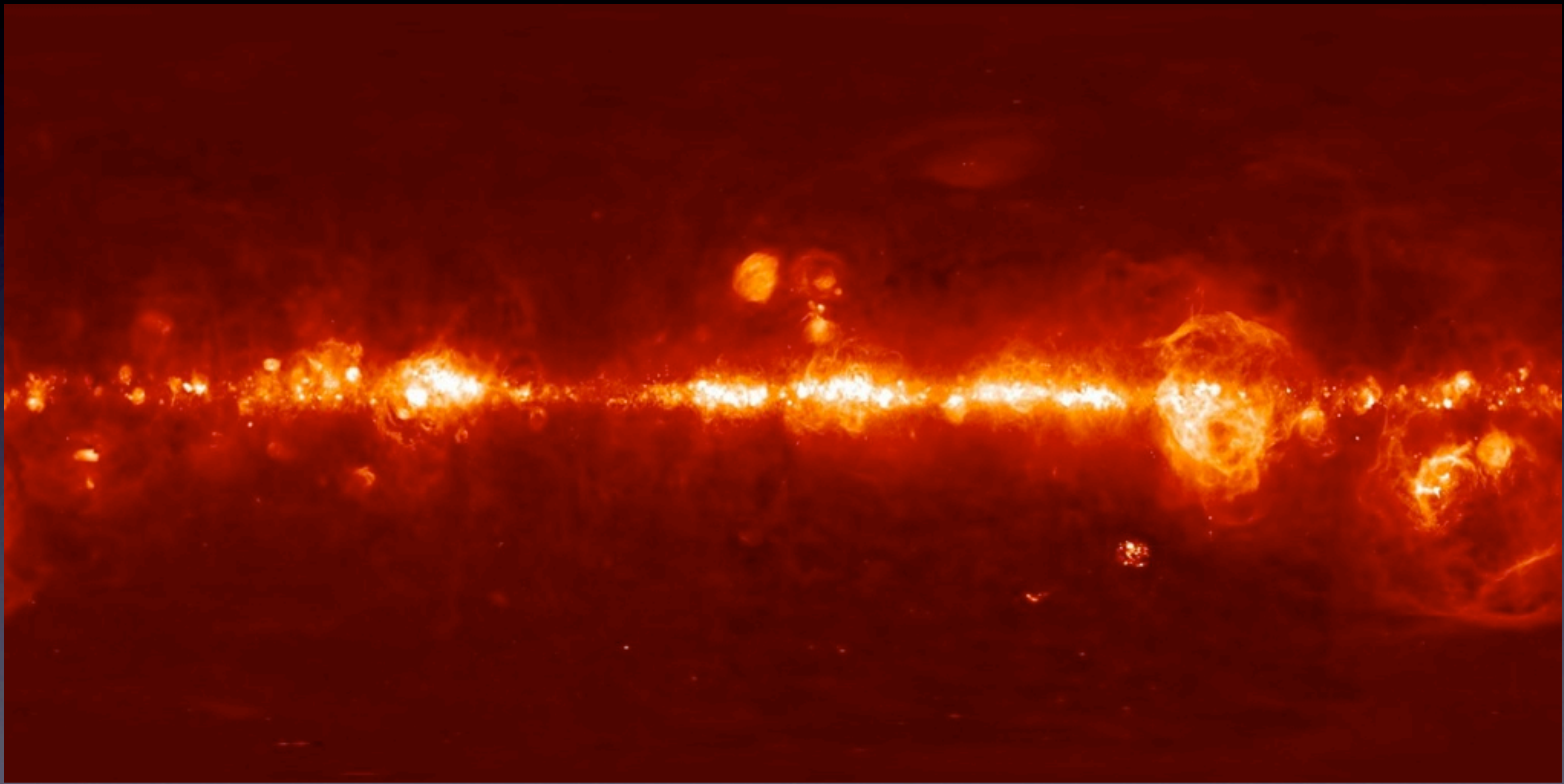
SFD dust - Far IR based dust map
Halpha - free-free template, must correct for extinction
Haslam - 408 MHz radio survey

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

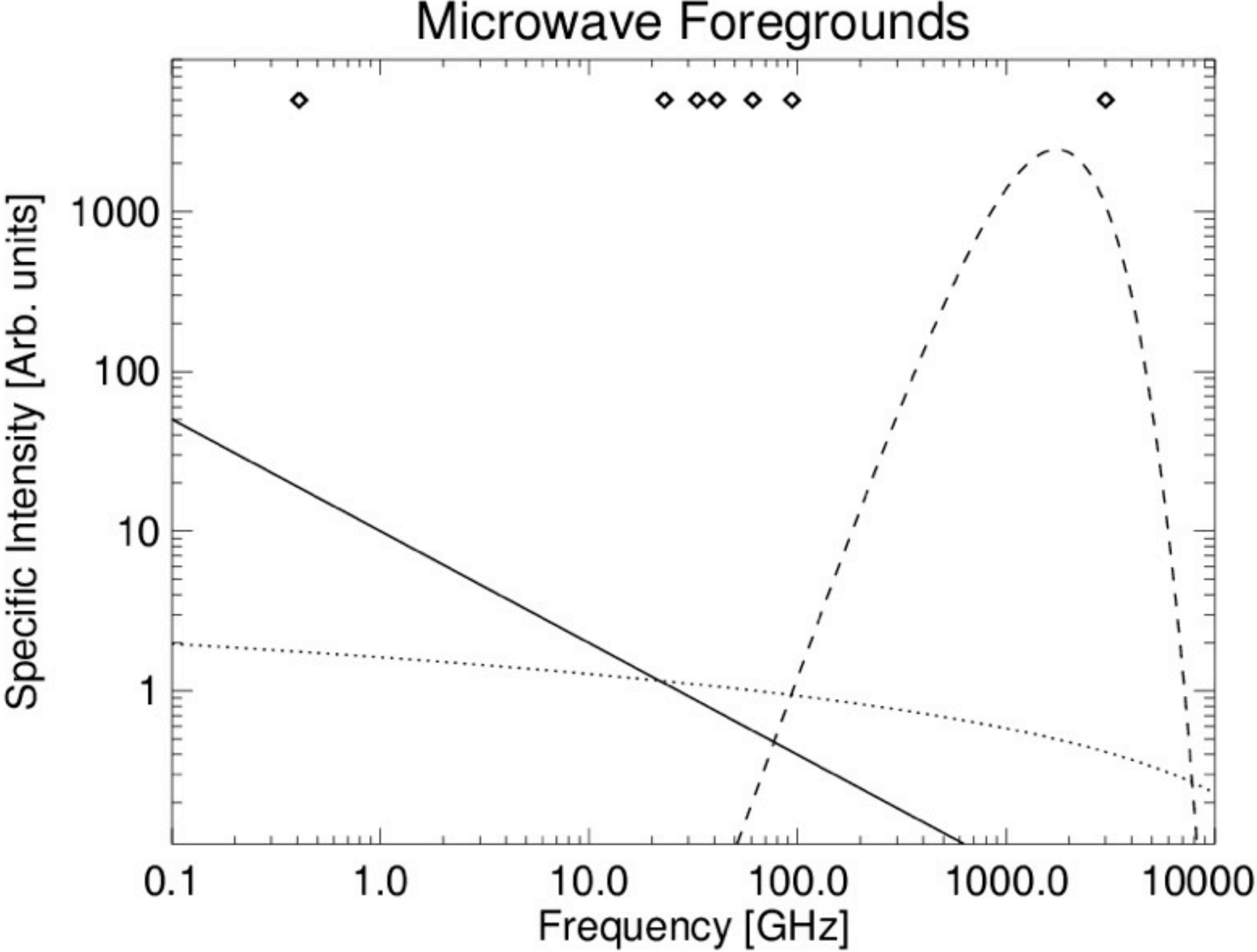


Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)

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]