The Fermi Bubbles: Overview

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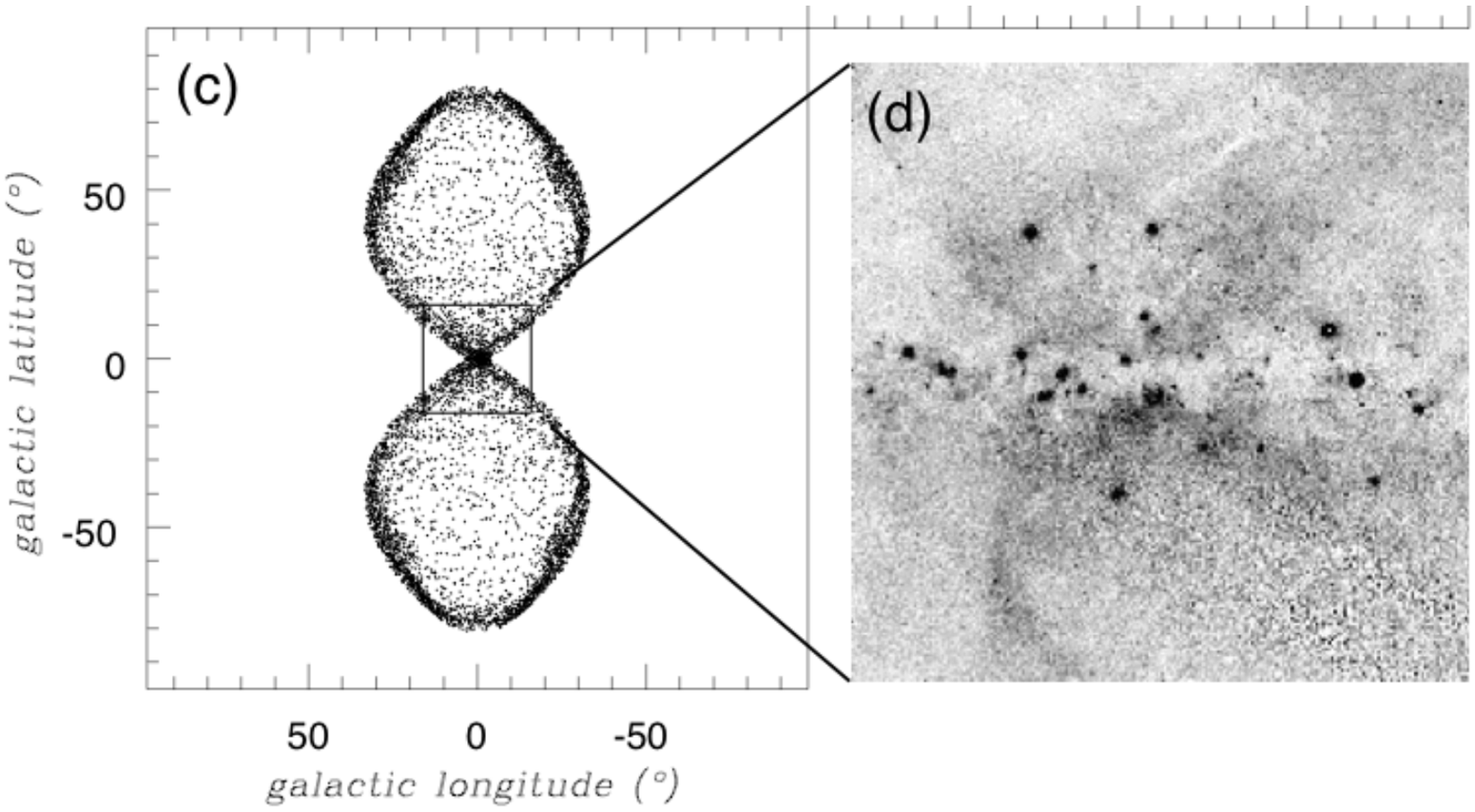
Three Elephants in the Gamma-Ray Sky
Garmisch-Partenkirchen
October 21, 2017

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- History: early hints of the Bubbles
- The discovery of the Bubbles in Fermi-LAT data
- Properties of the gamma-ray signal
- Multiwavelength counterparts and their implications
- A (very) brief survey of the theoretical landscape

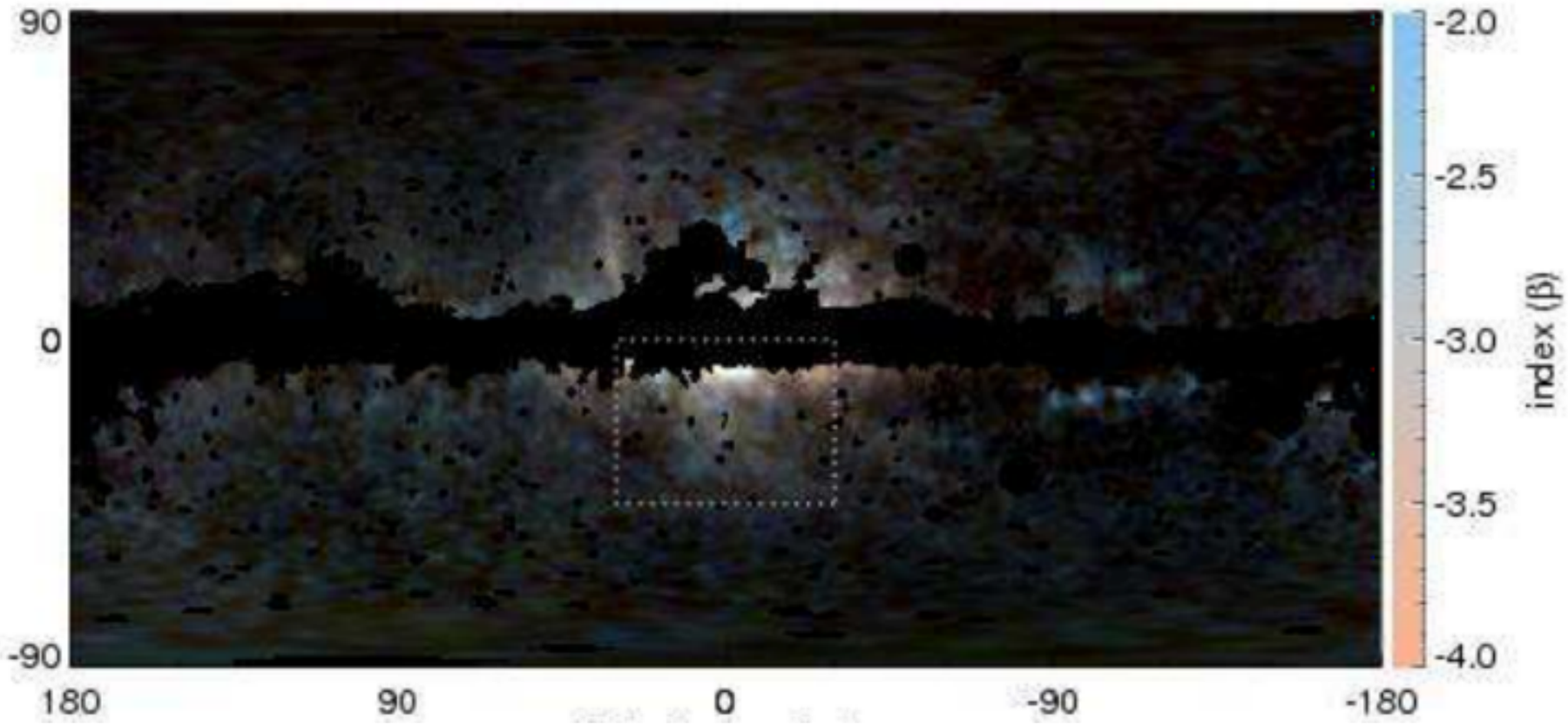
A bipolar Galactic wind seen in X-rays?



- Using ROSAT data and FIR measurements from MSX, Bland-Hawthorn & Cohen (2003) suggested giant bubble structures (see also Sofue 2000).
- Proposal: bubbles fueled by starburst in Galactic center, filled with hot gas, ~10^{55} ergs thermal energy - X-rays are thermal bremsstrahlung.
- At this point, no gamma ray signal was expected.

The WMAP Haze

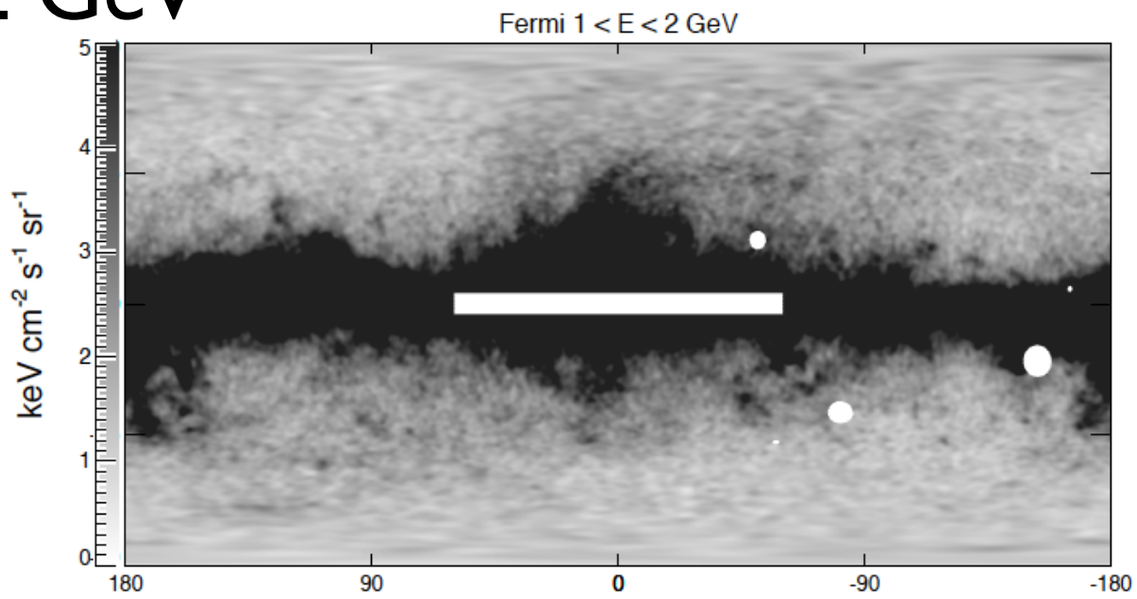
- Excess of hard-synchrotron-like emission in the inner Milky Way.
- Discovered in 2003 by Doug Finkbeiner using WMAP data.
- Consistent with a new population of hard electrons - if present, predicts gamma-ray emission from inverse-Compton-scattered starlight.



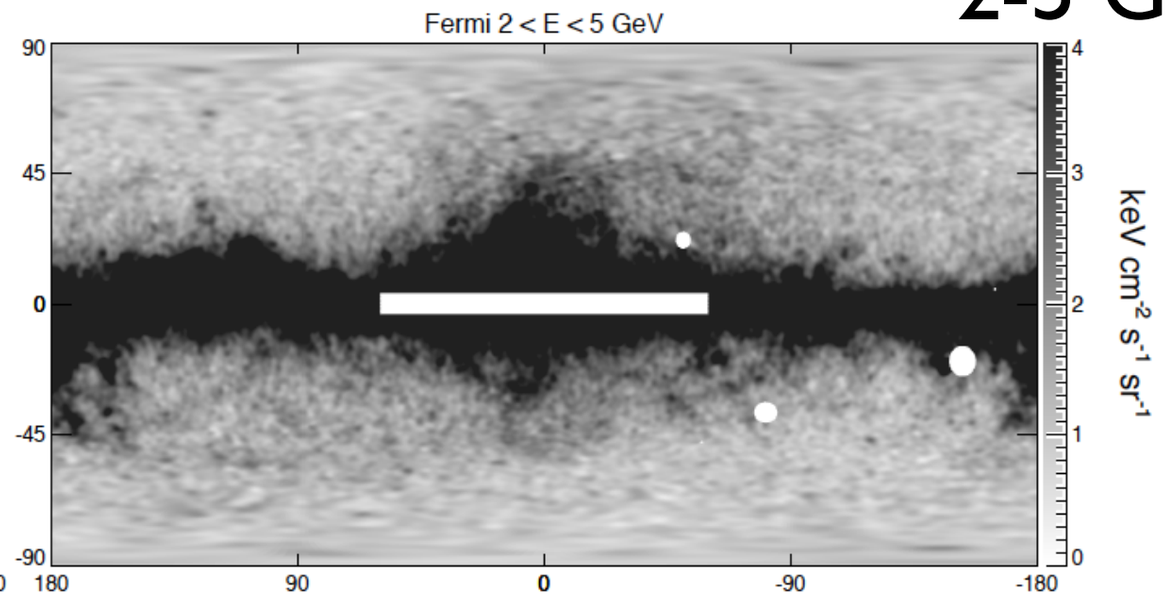
Dobler & Finkbeiner ‘08

Fermi 1.6 year all-sky gamma-ray maps by energy

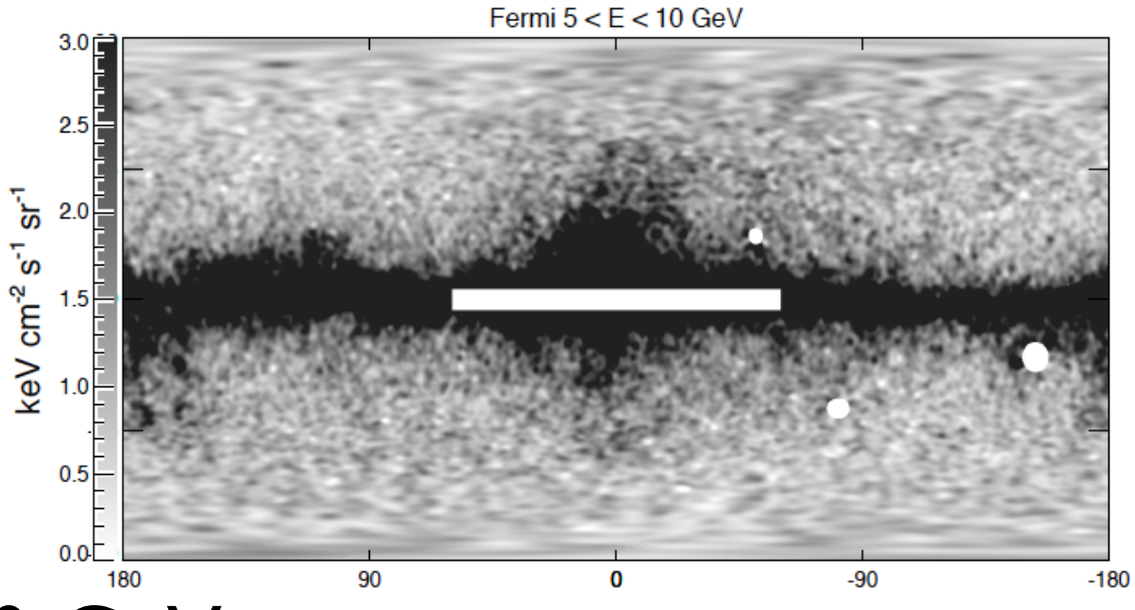
1-2 GeV



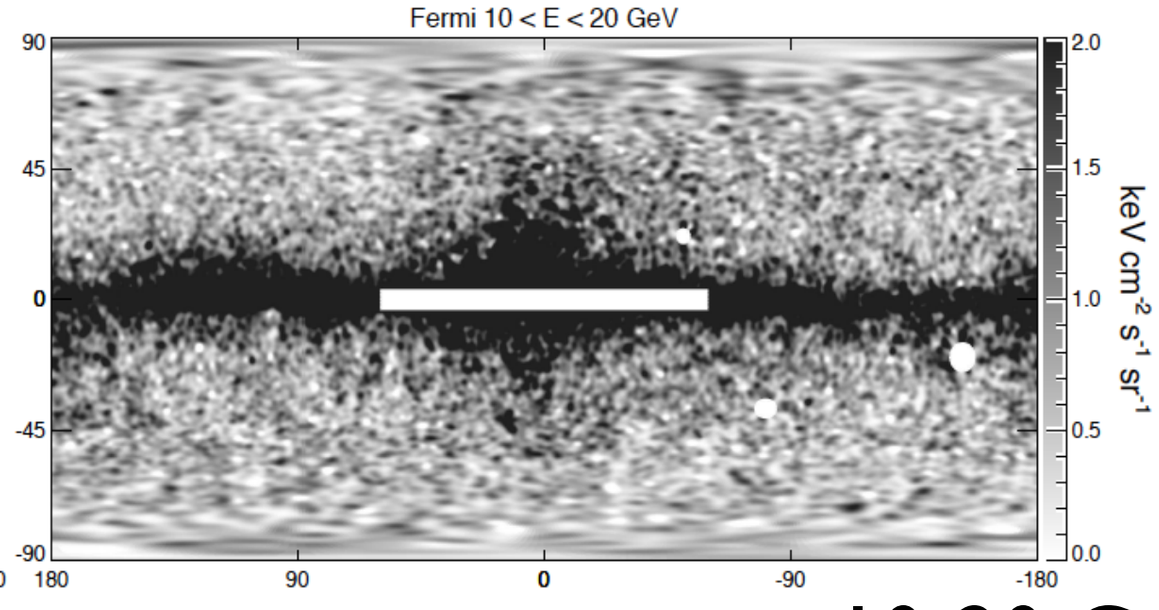
2-5 GeV



5-10 GeV

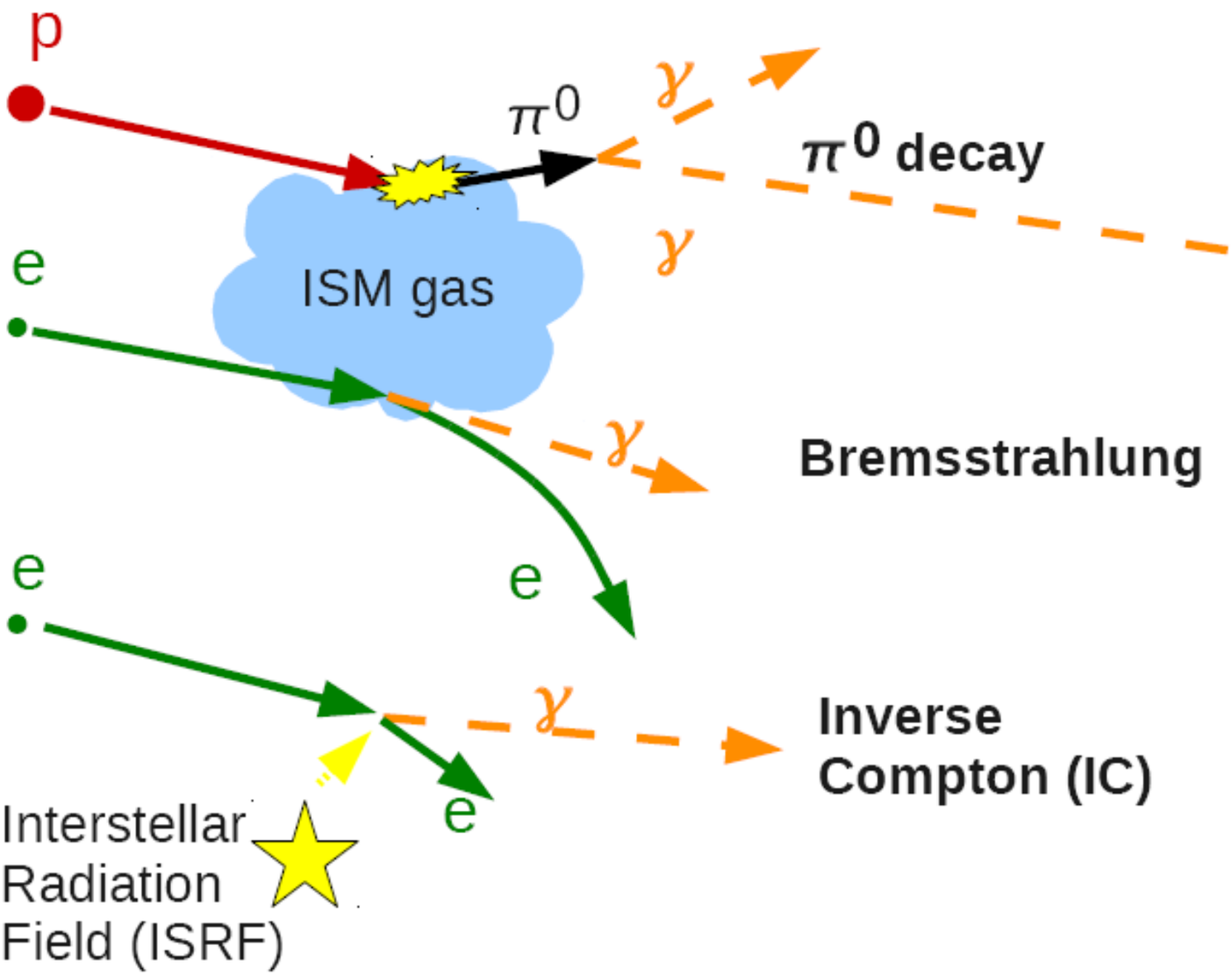


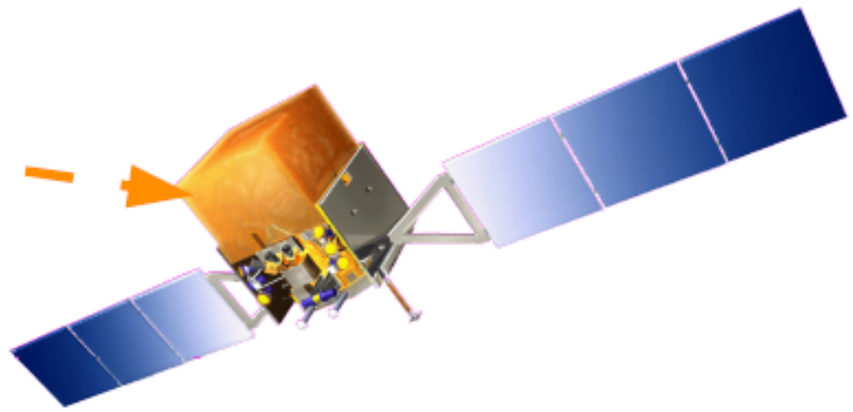
10-20 GeV



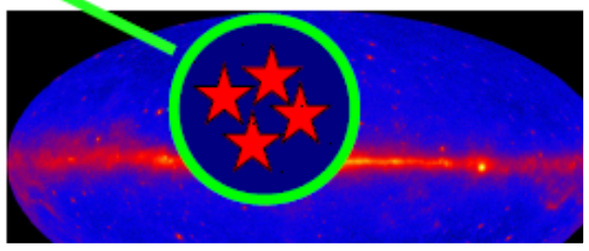
Su, TRS & Finkbeiner (2010)

Galactic Diffuse Gamma-ray Emission

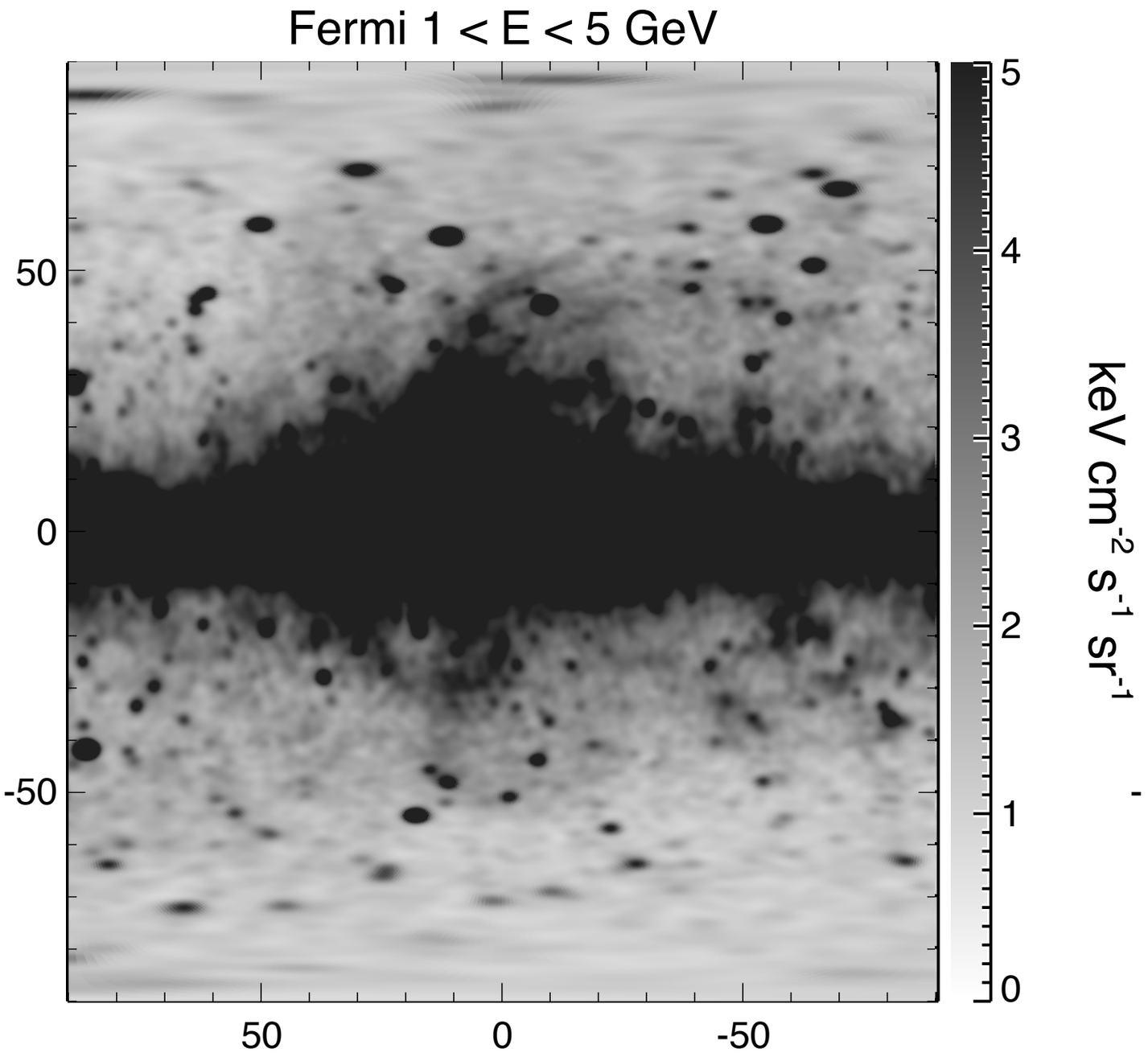


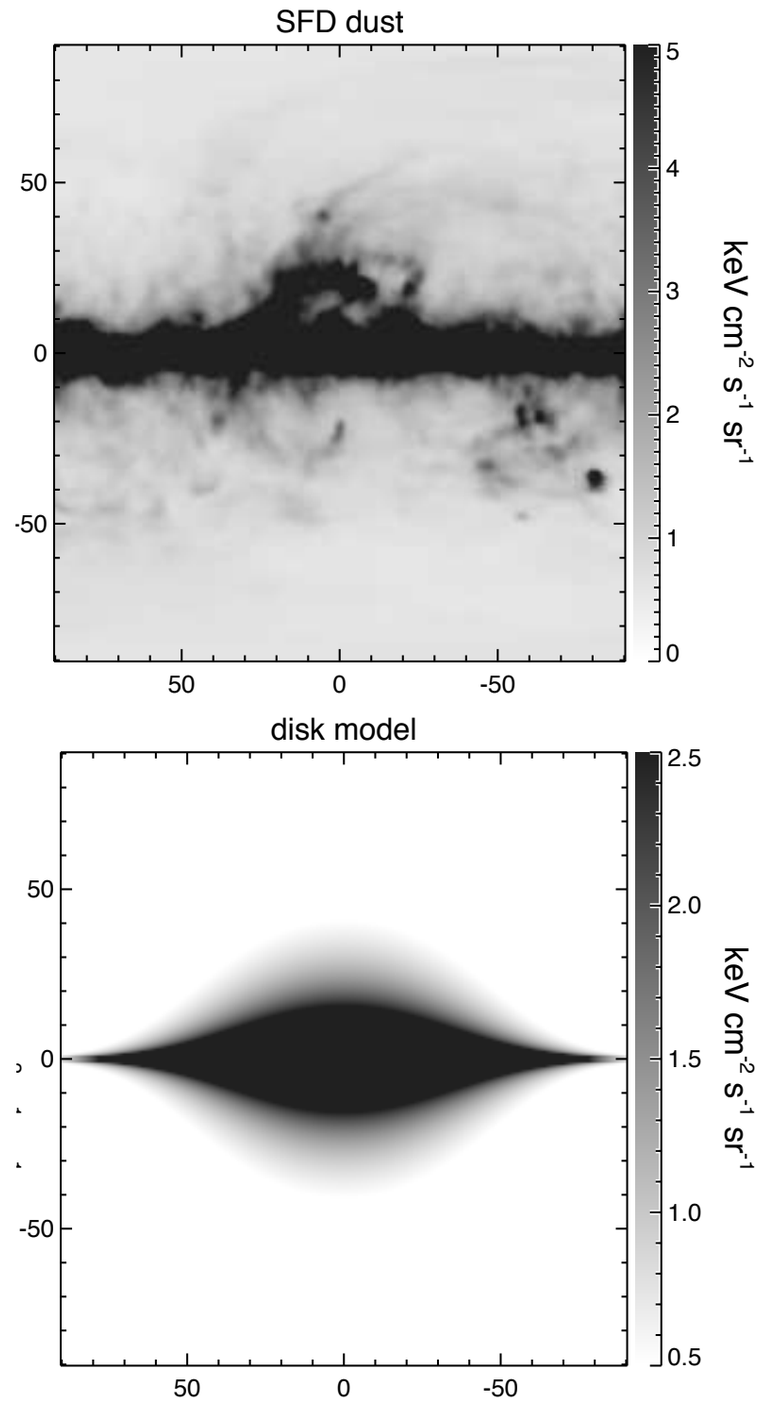


unresolved
sources are there!



A simple spatial background model





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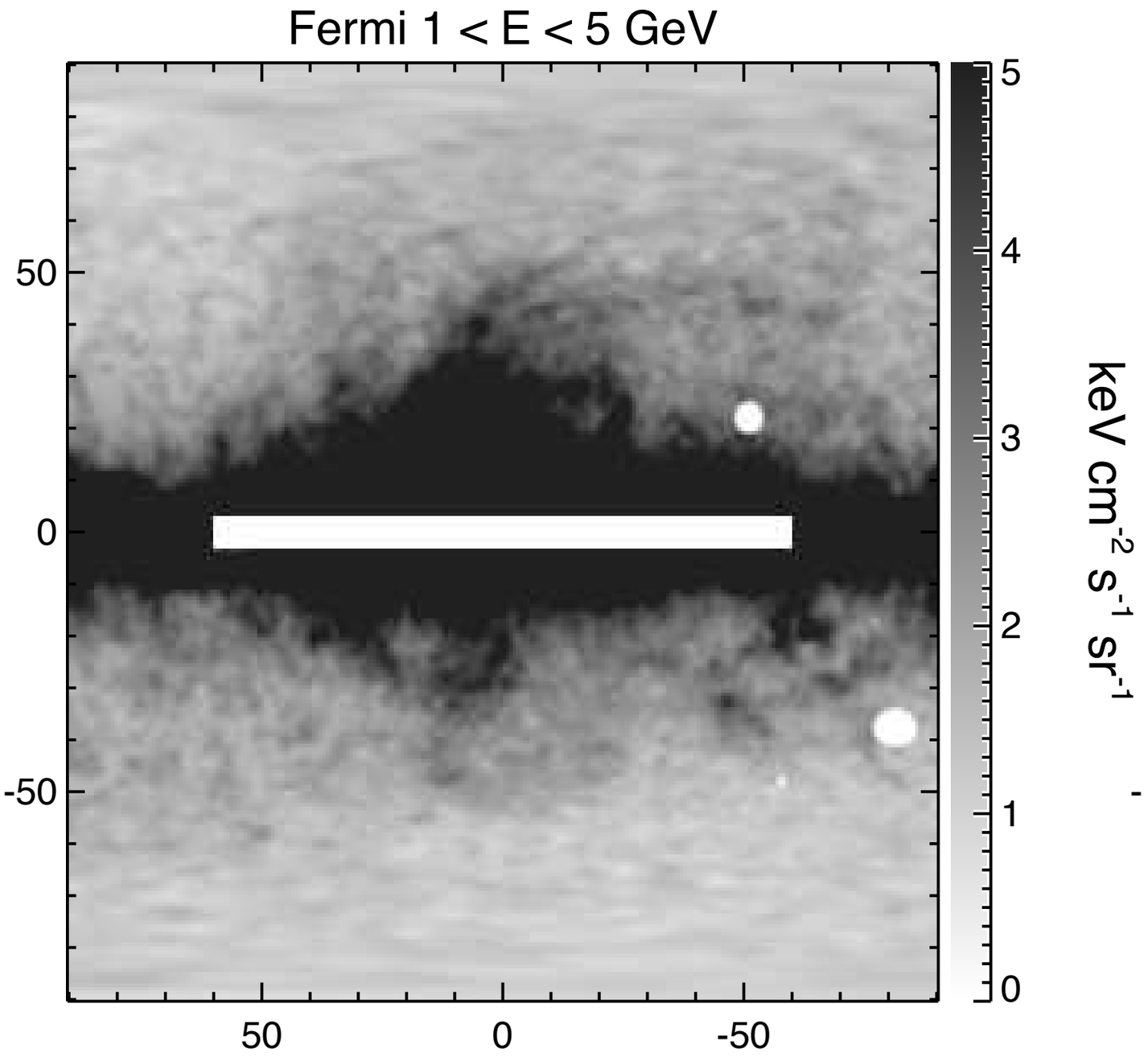

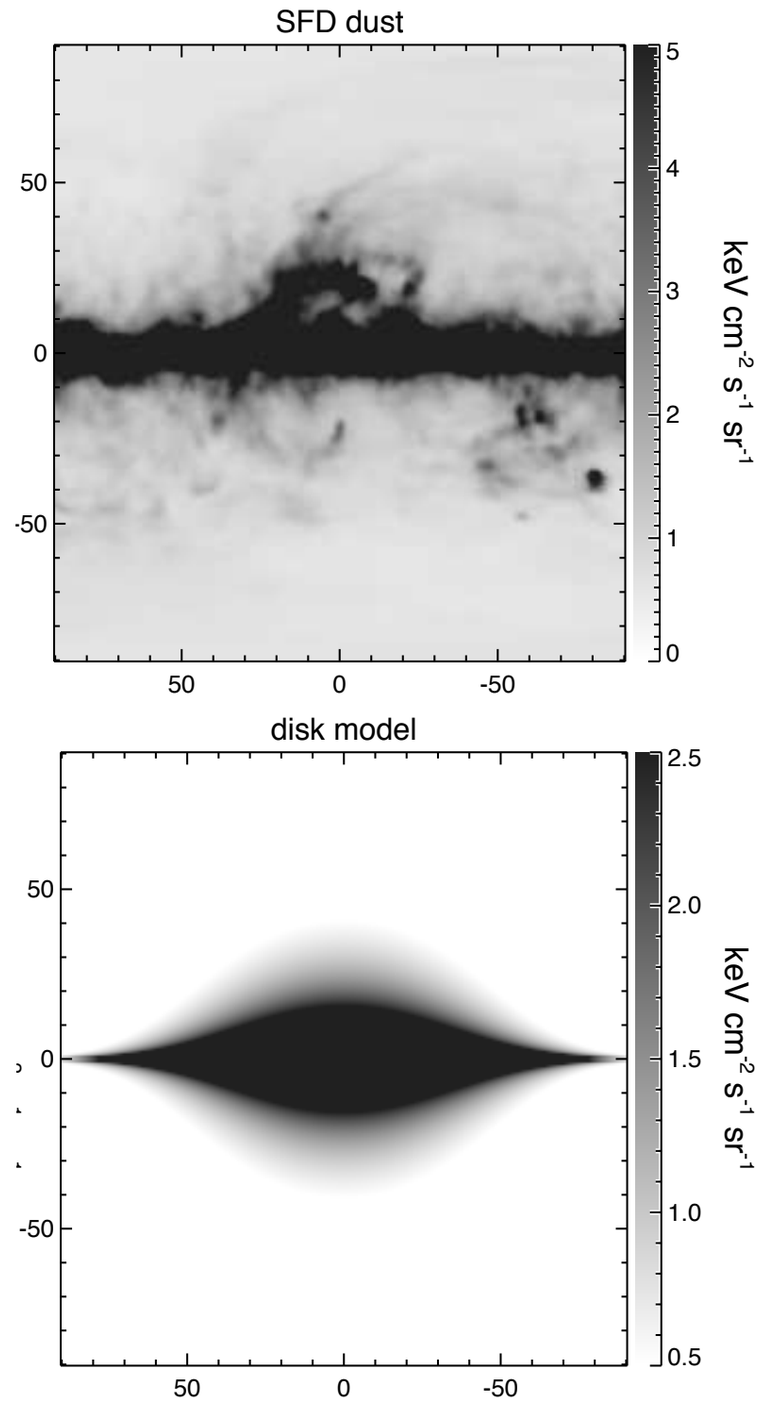

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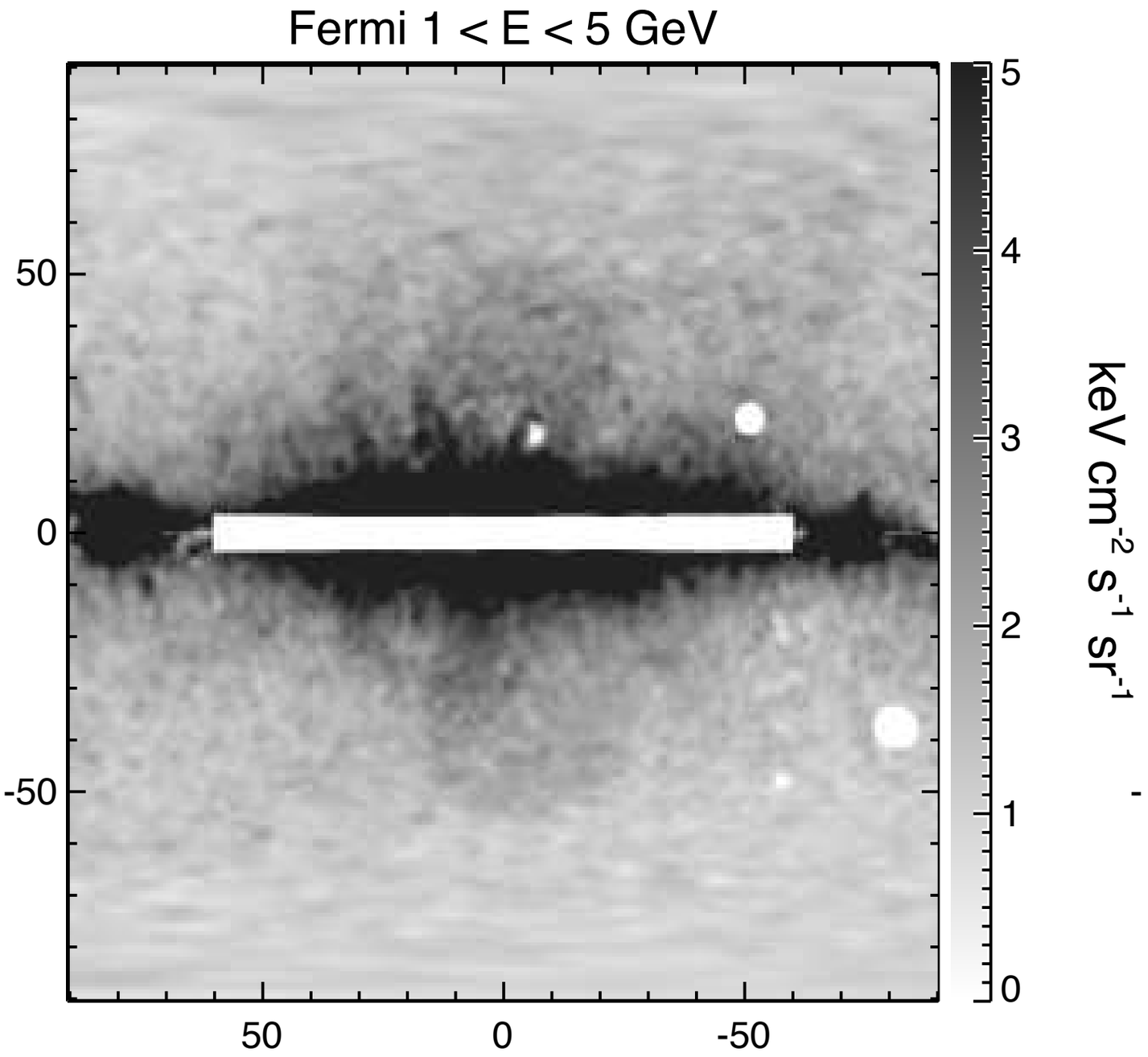

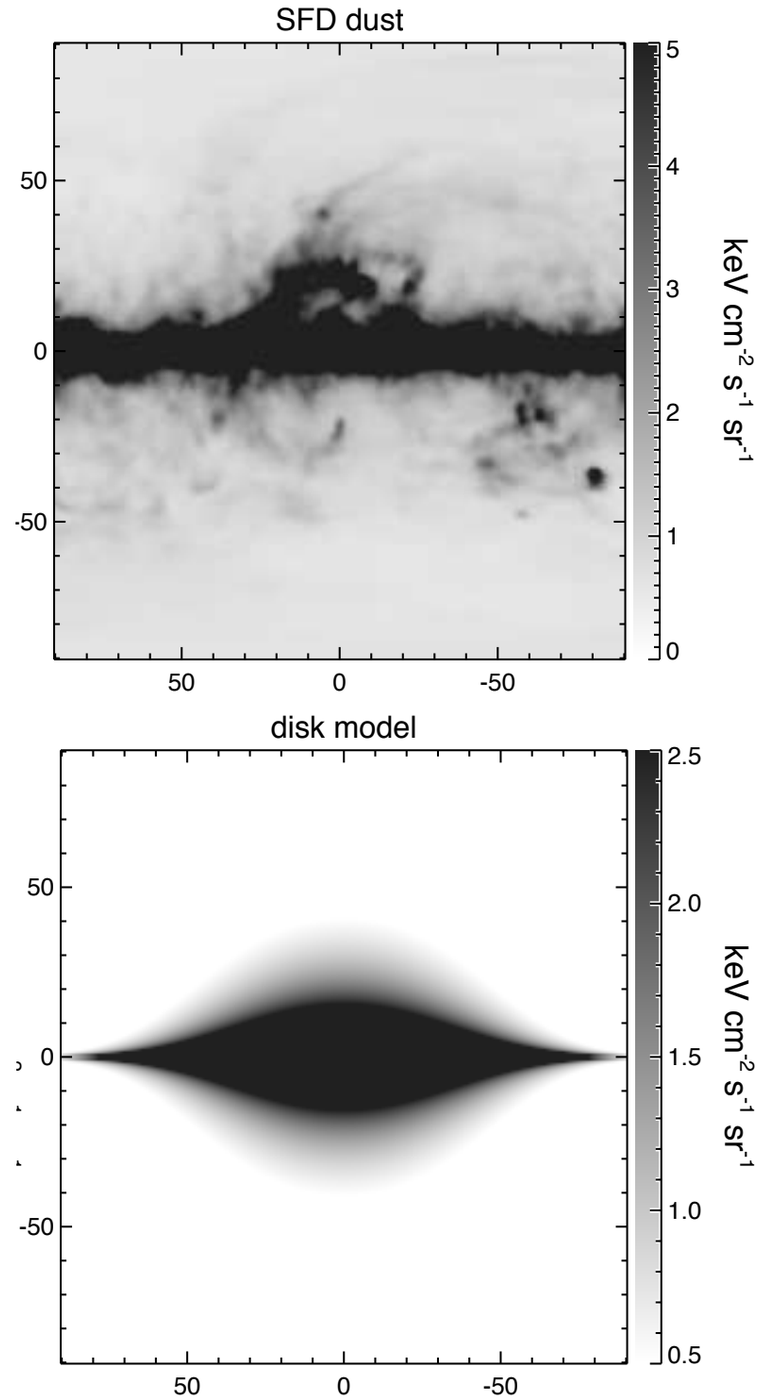

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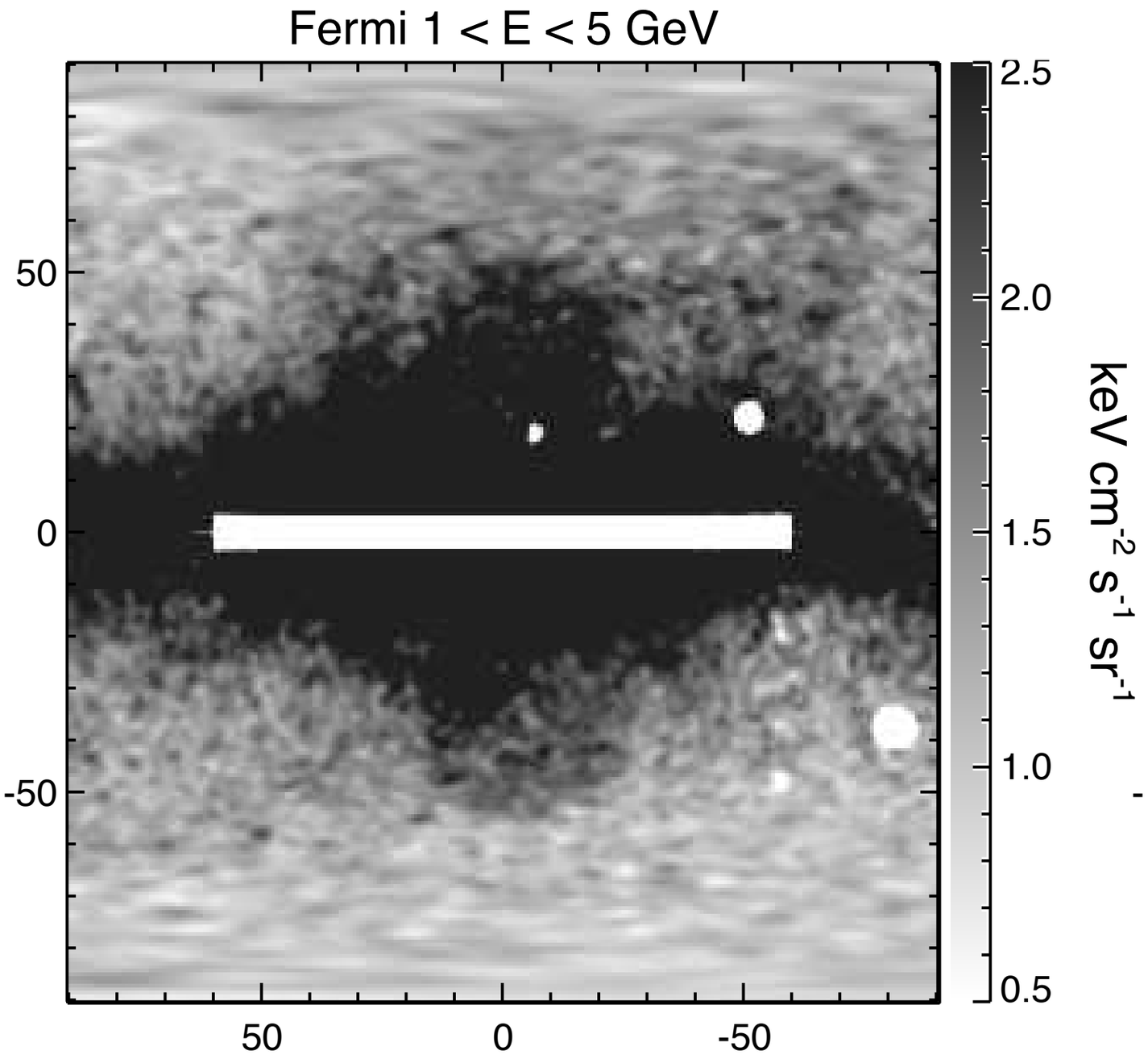

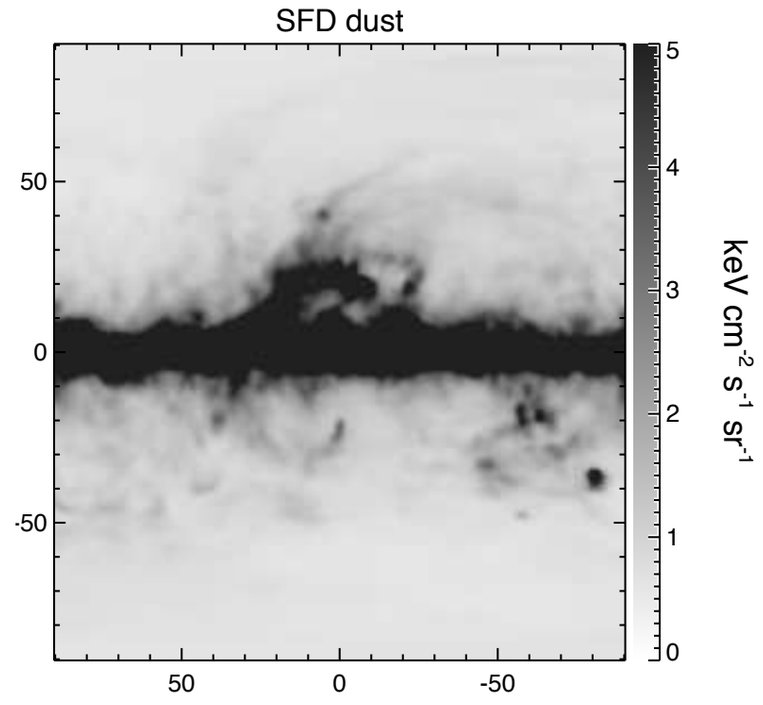

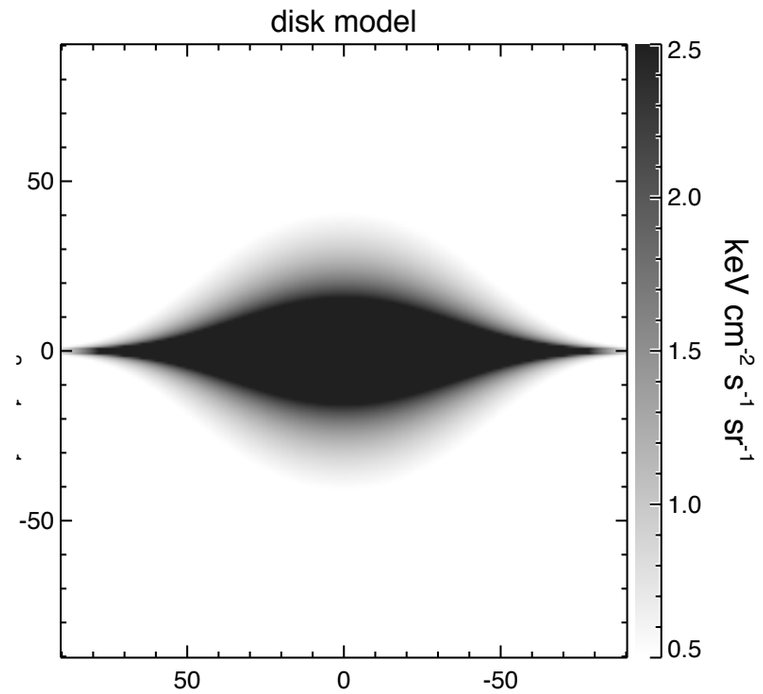

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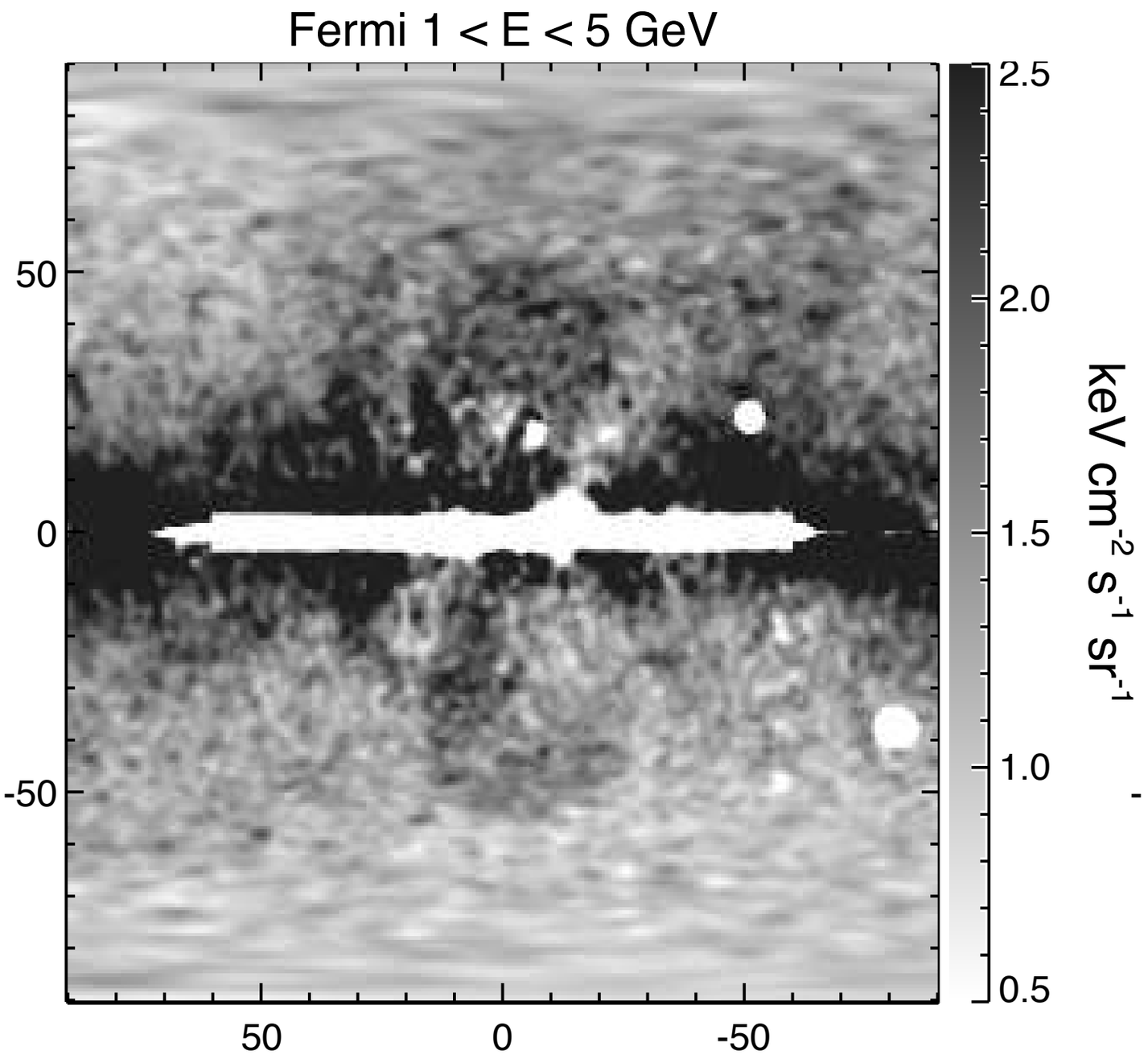
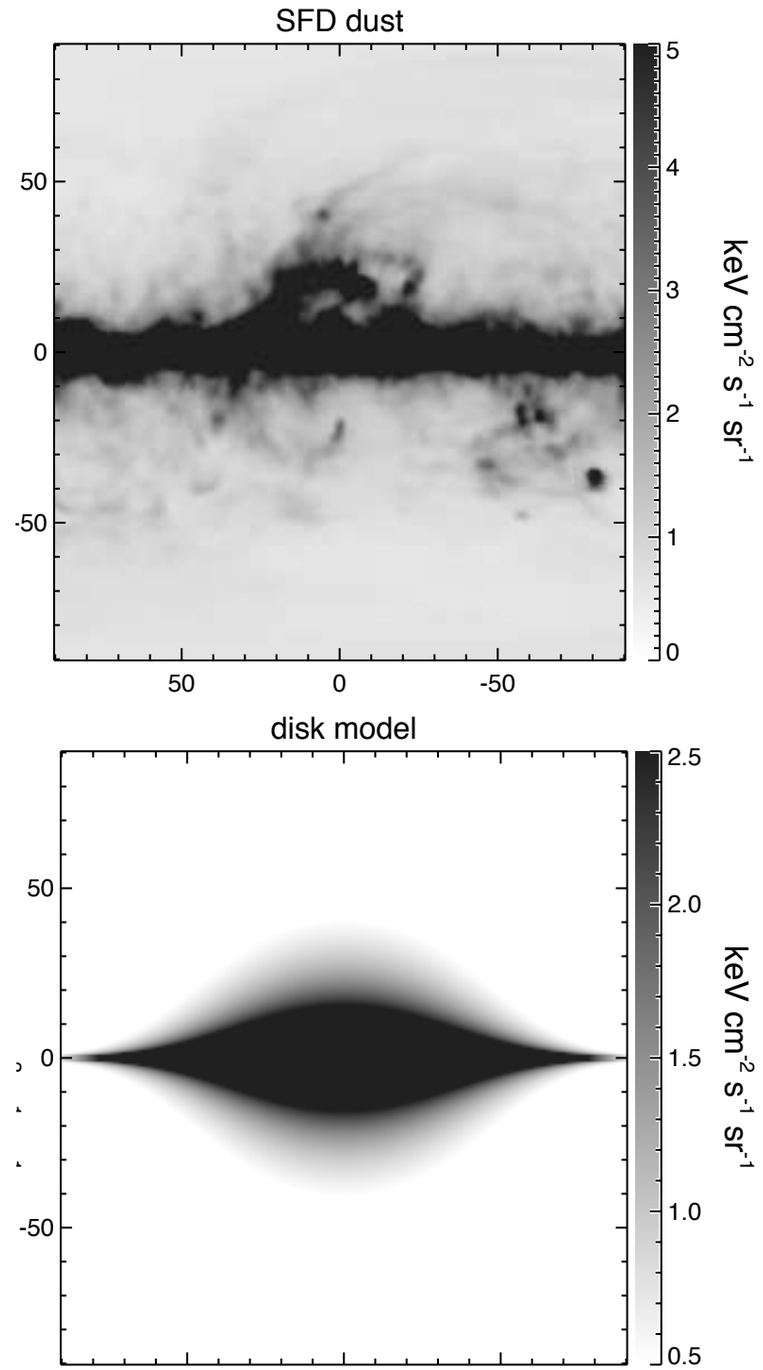
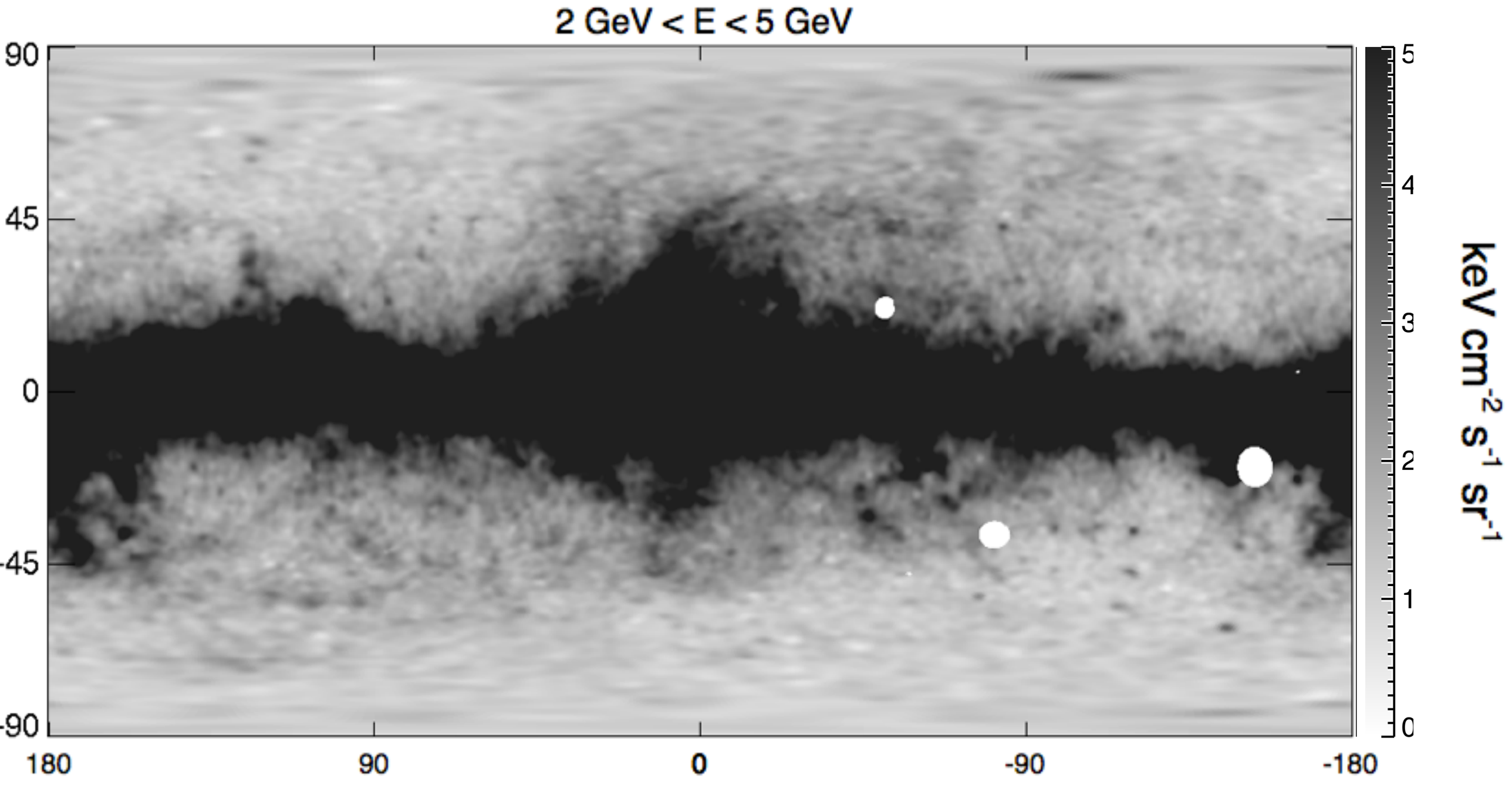




Data - Fermi diffuse model



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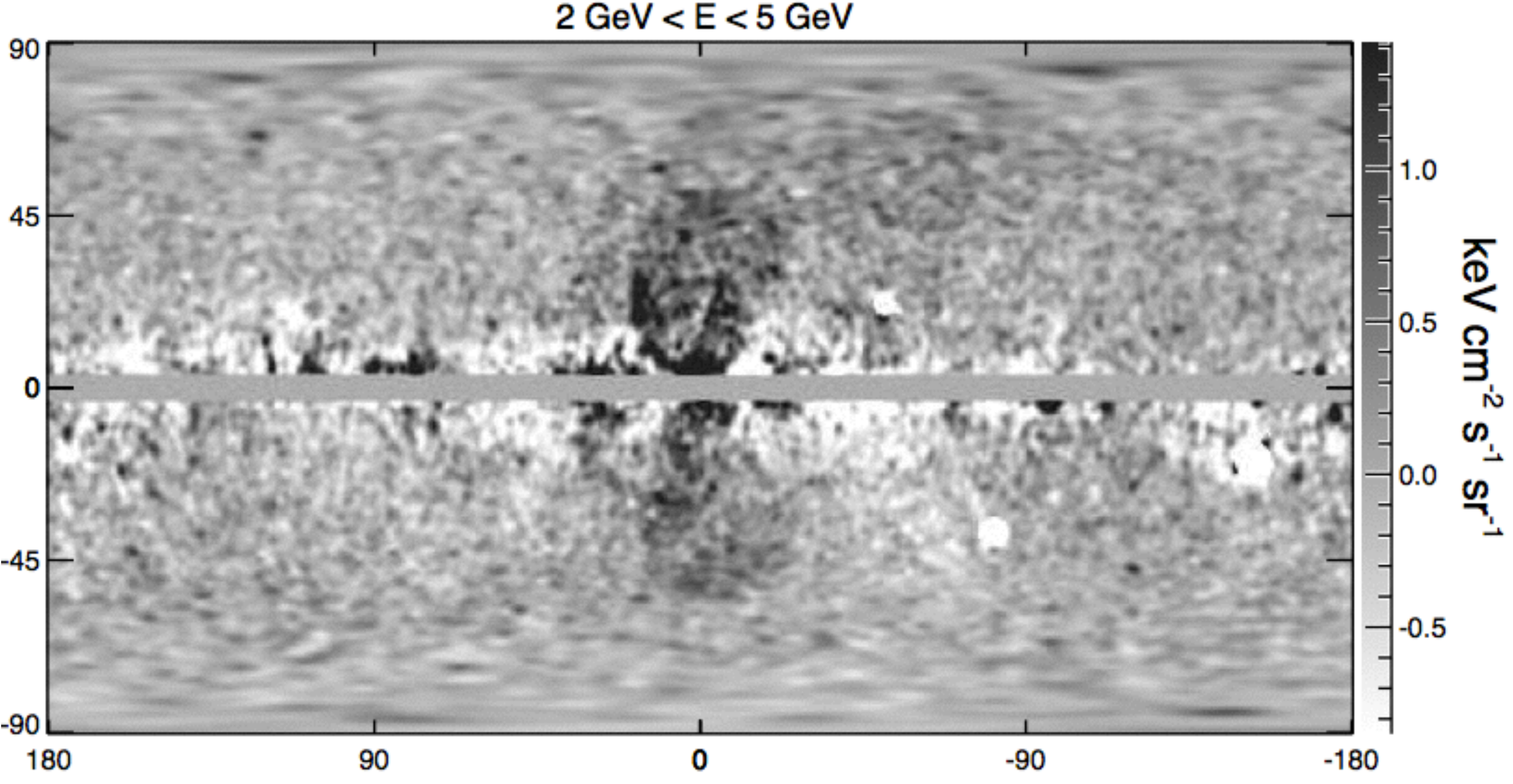

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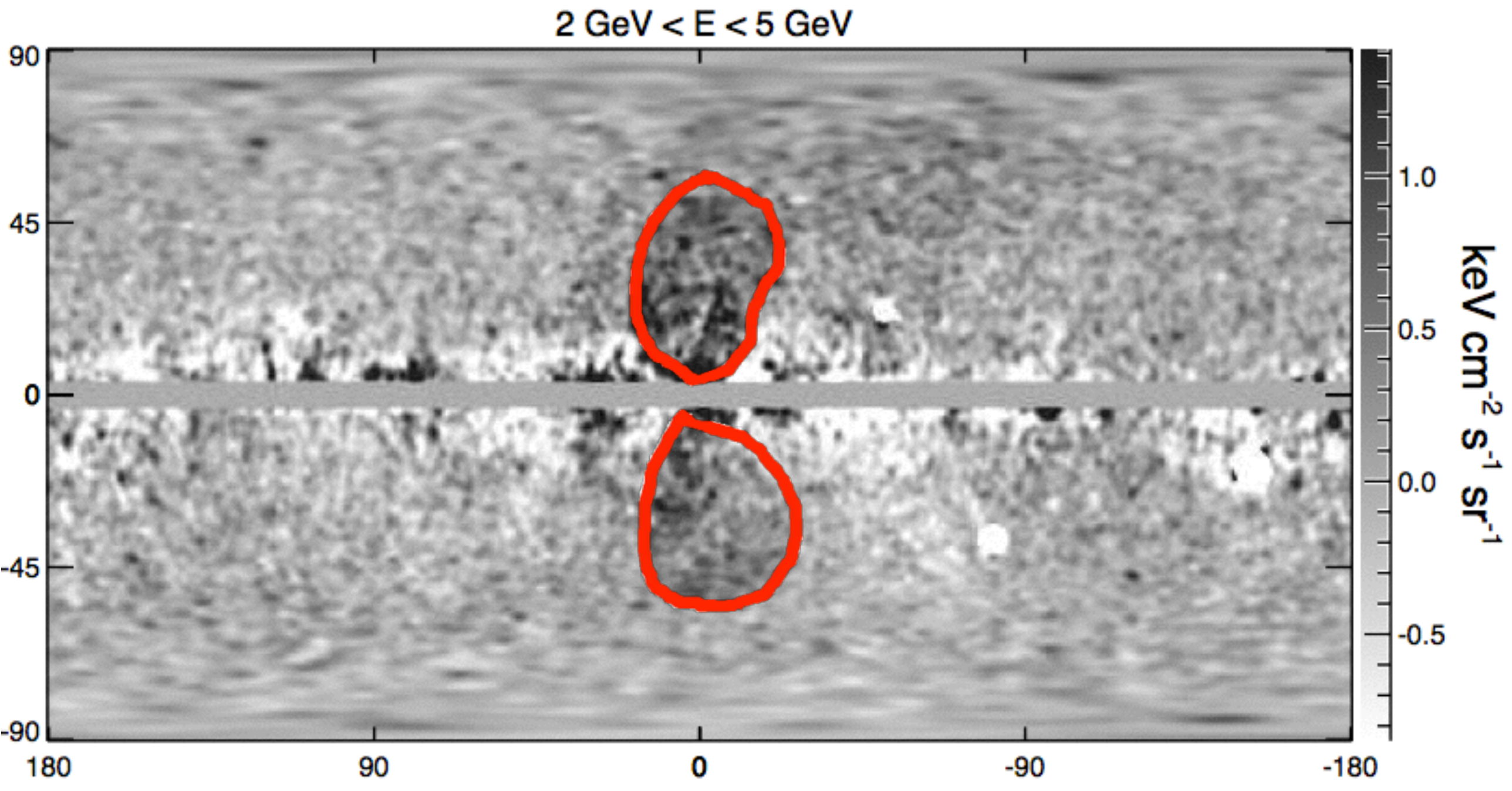
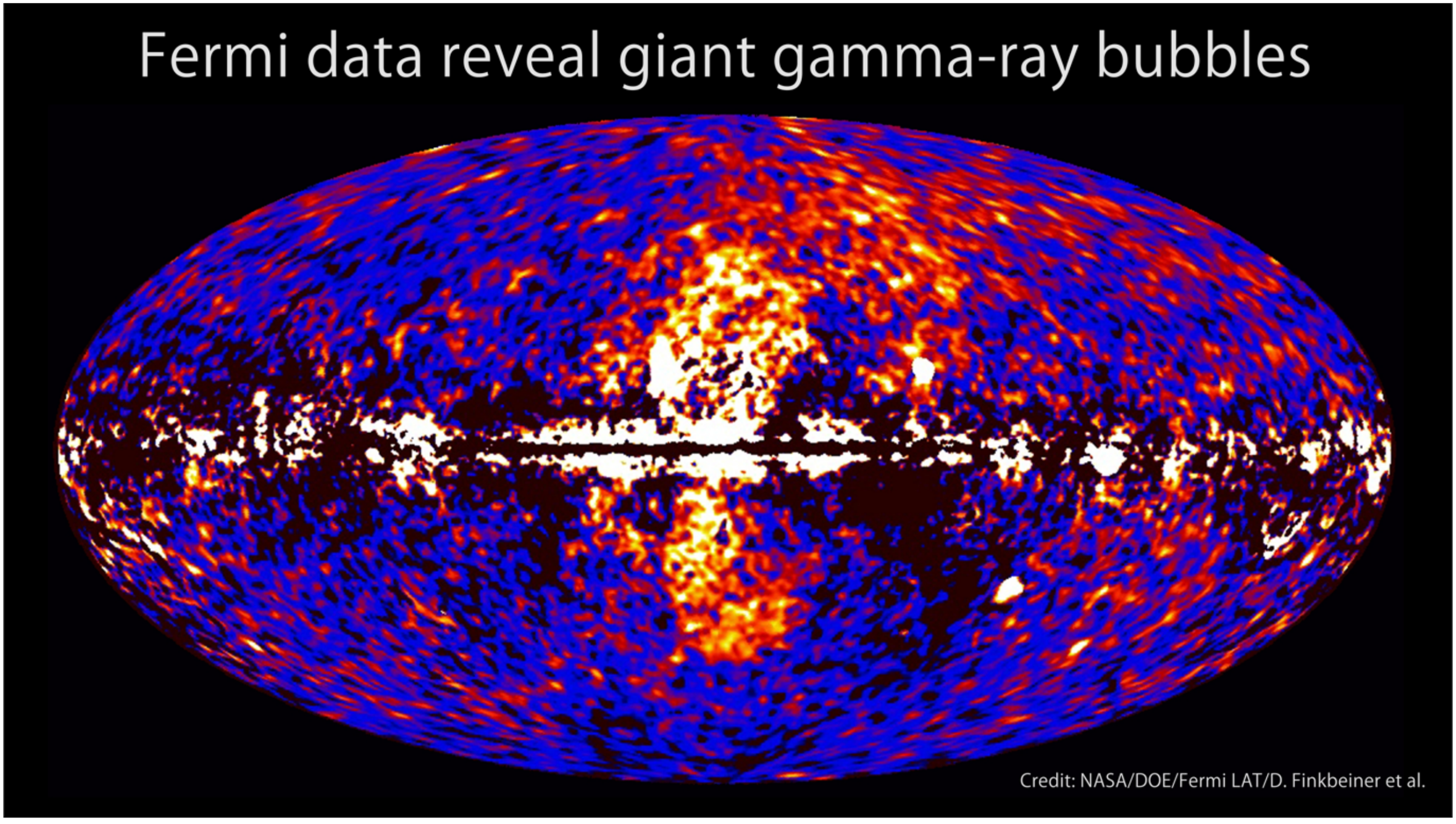
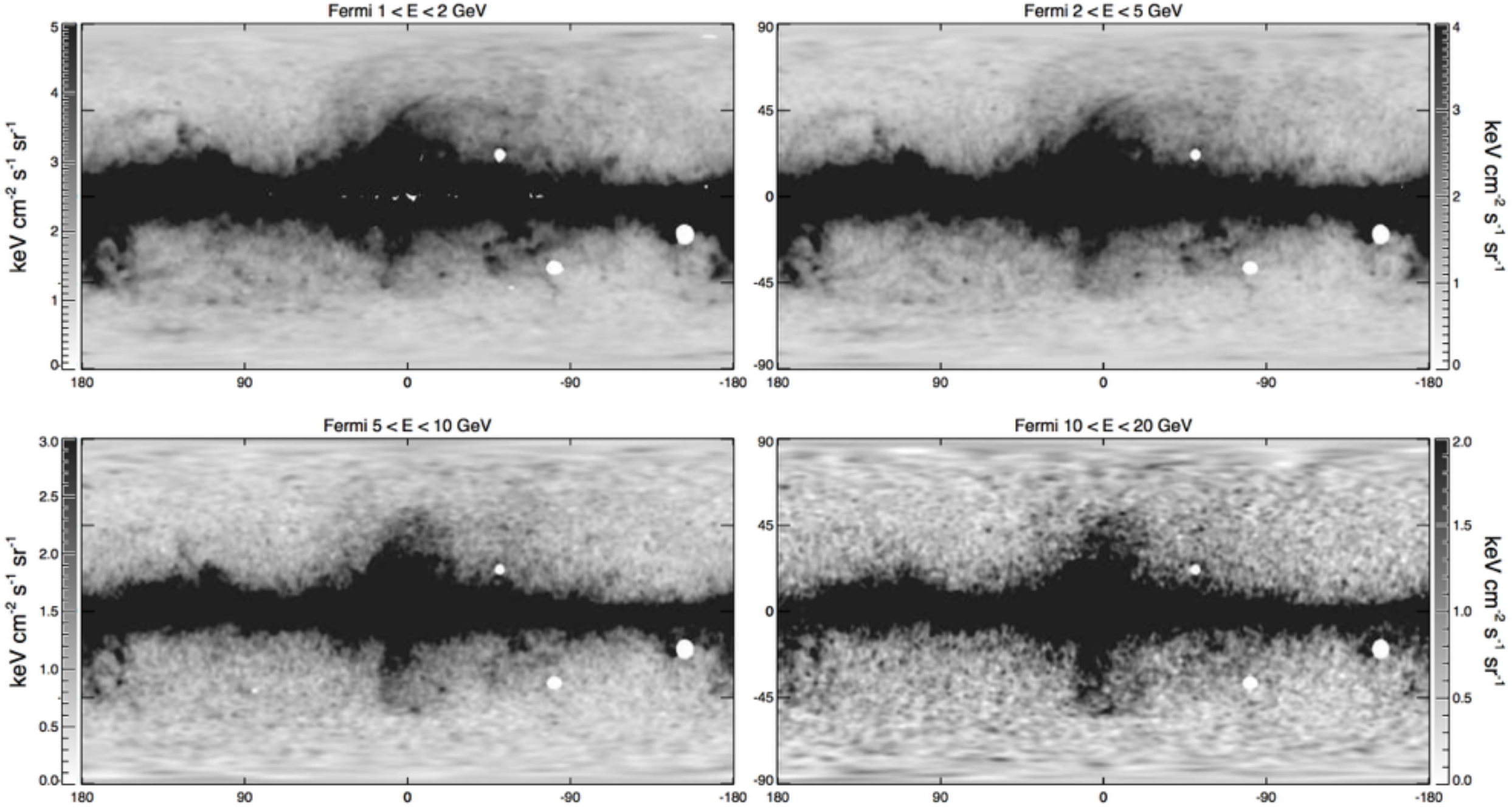


NASA press release on Nov.10, 2010



FB from 6.0 years Fermi data



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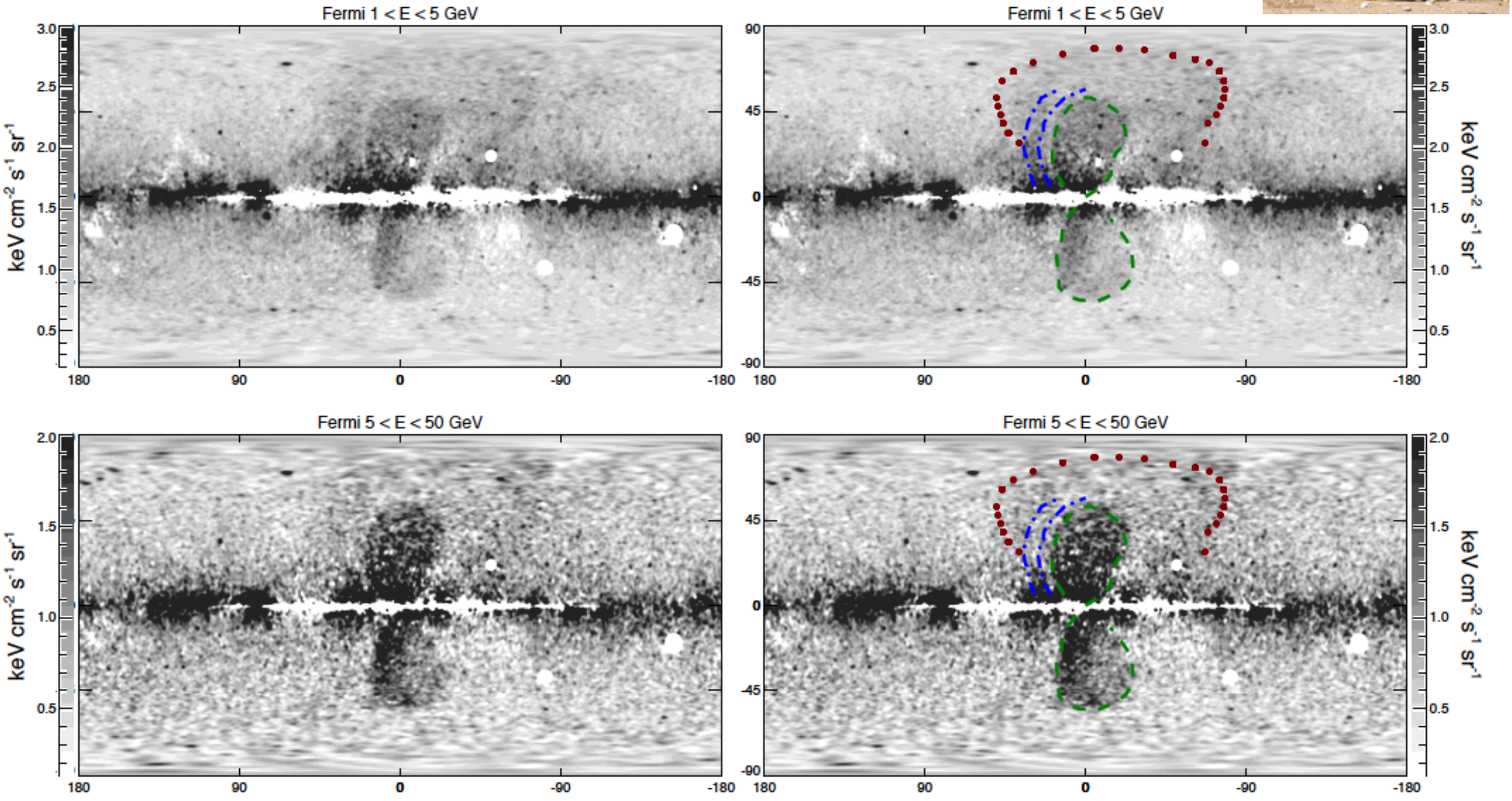
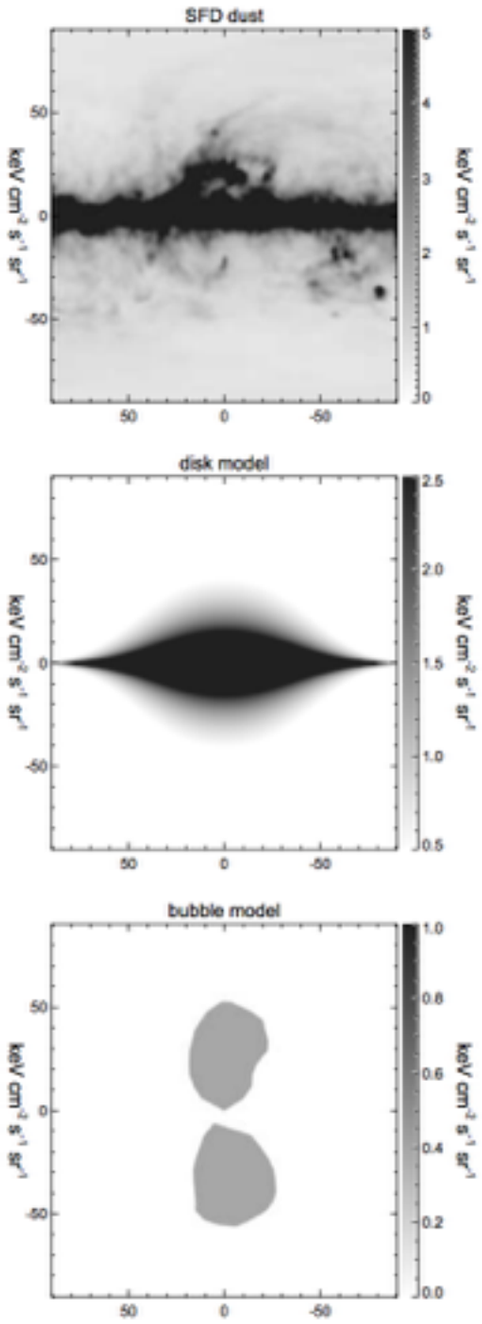


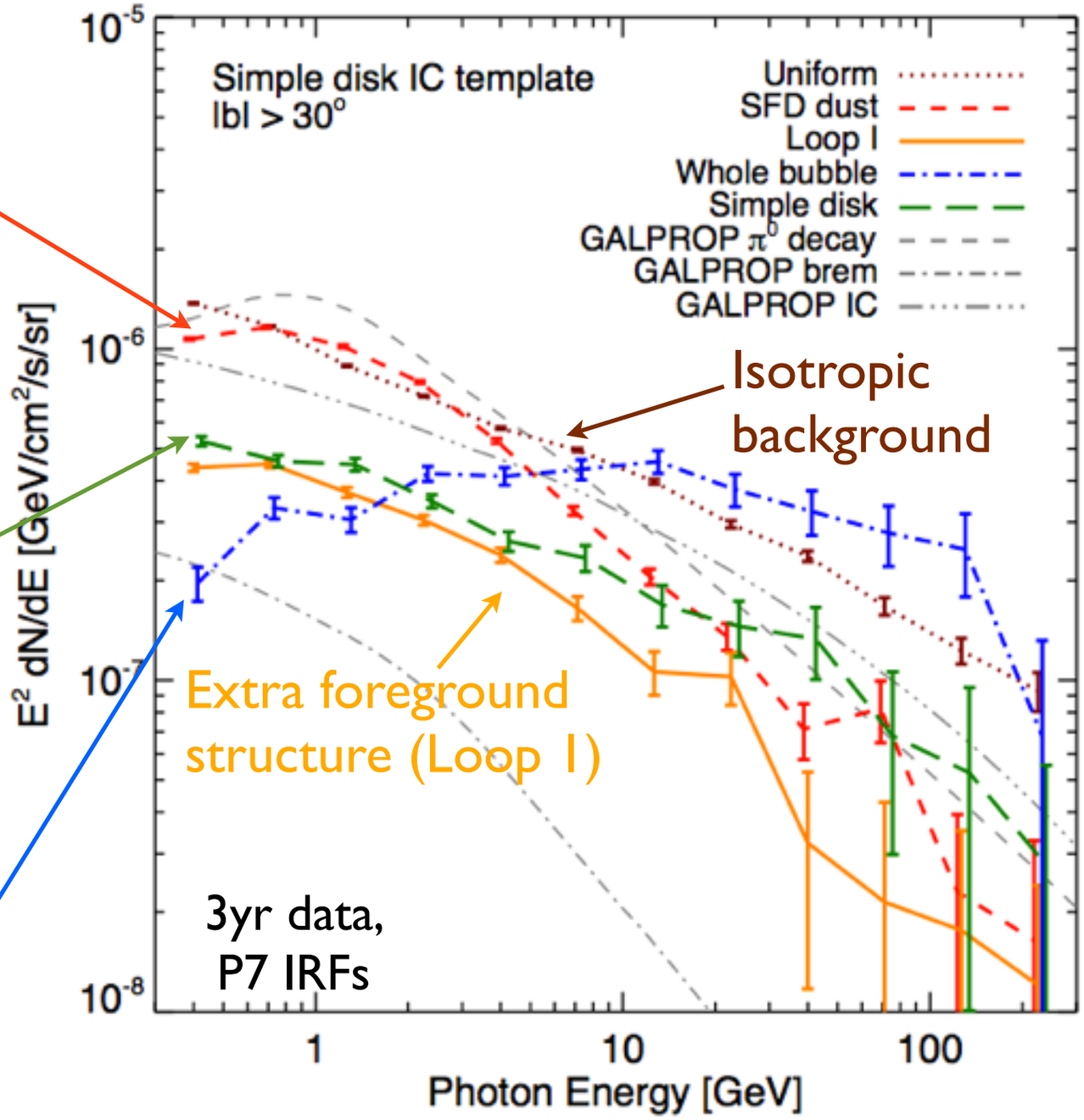
Template fitting



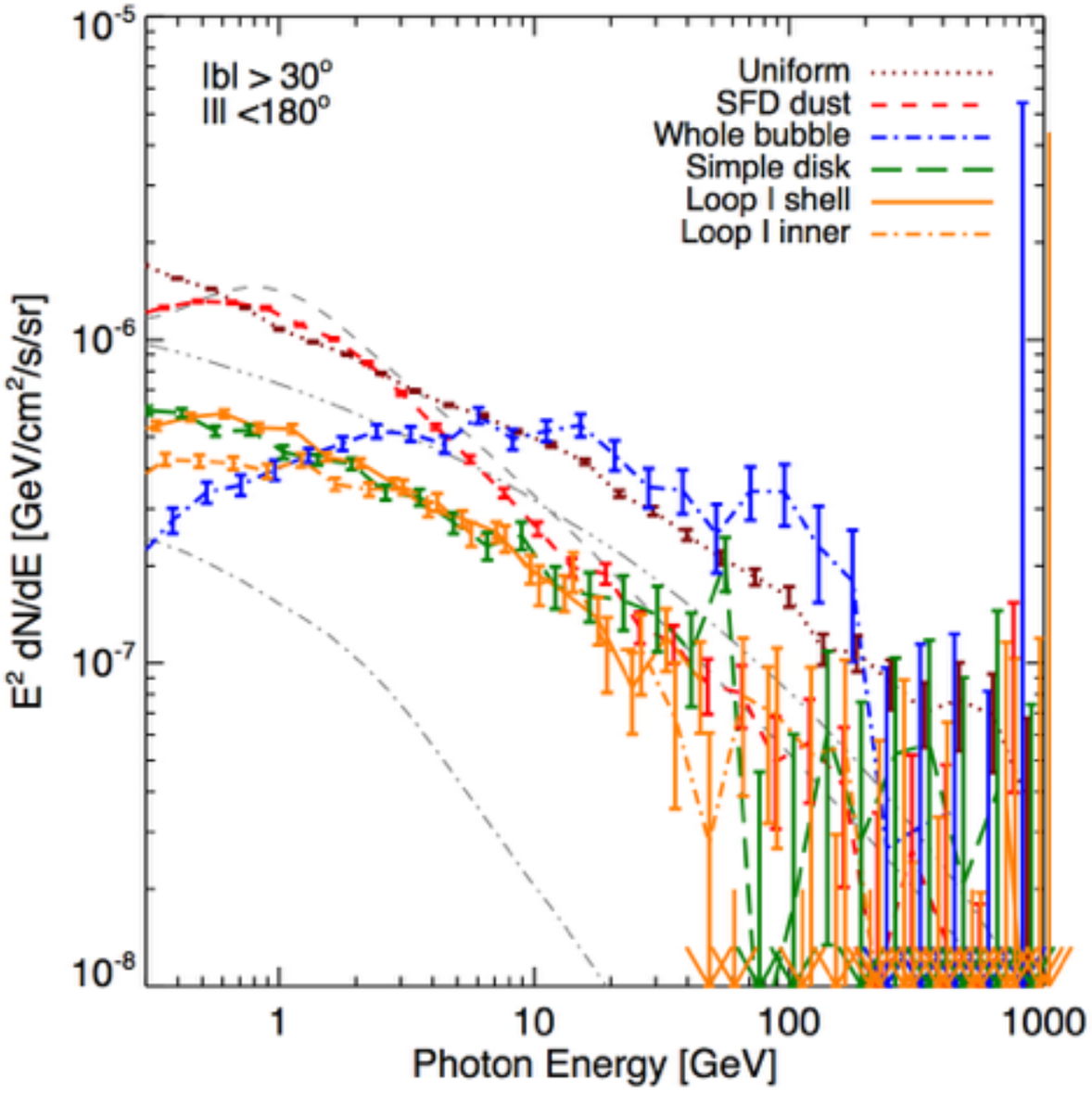
Gas-correlated emission

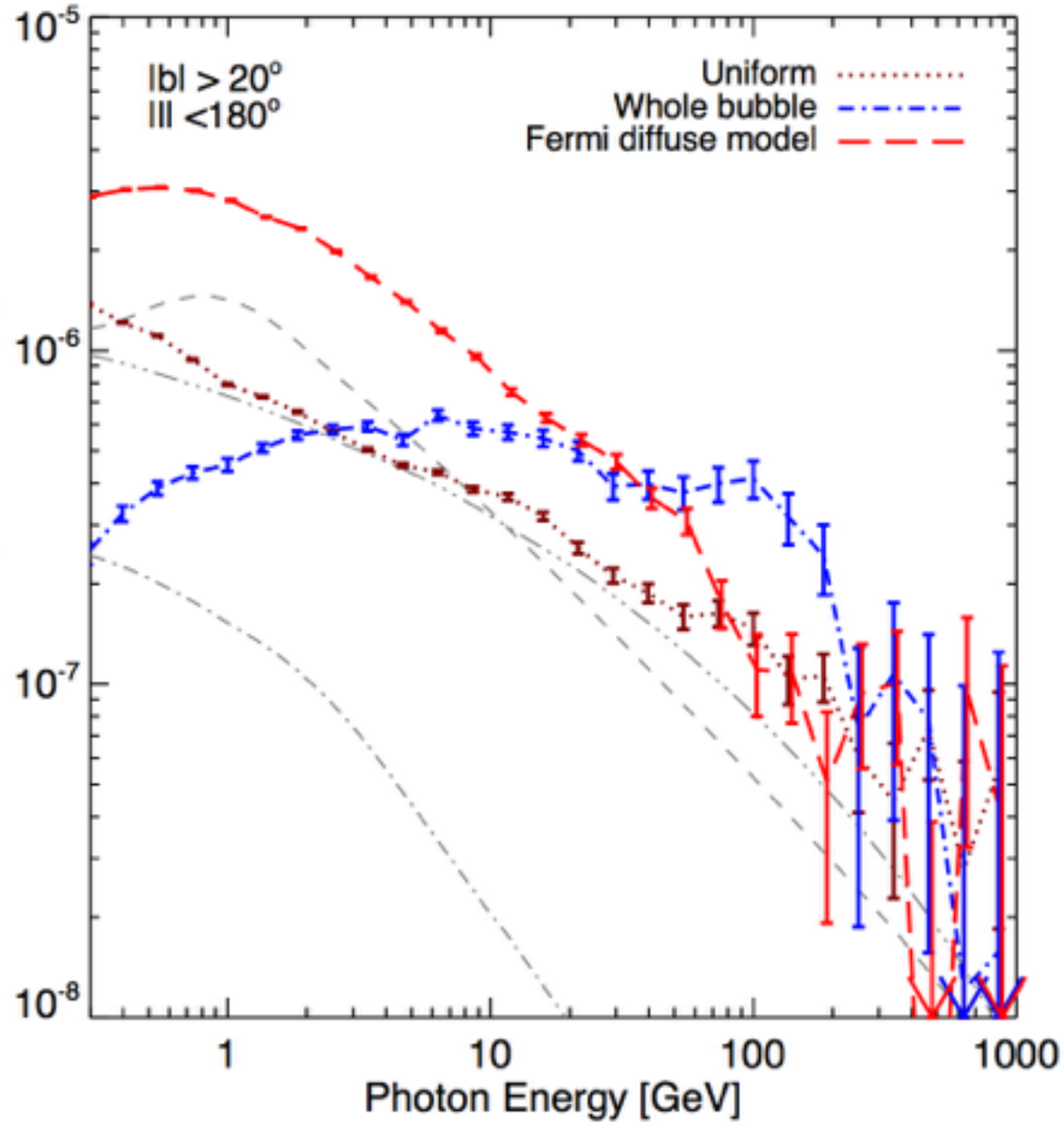
Disk-correlated emission

Bubbles-correlated emission



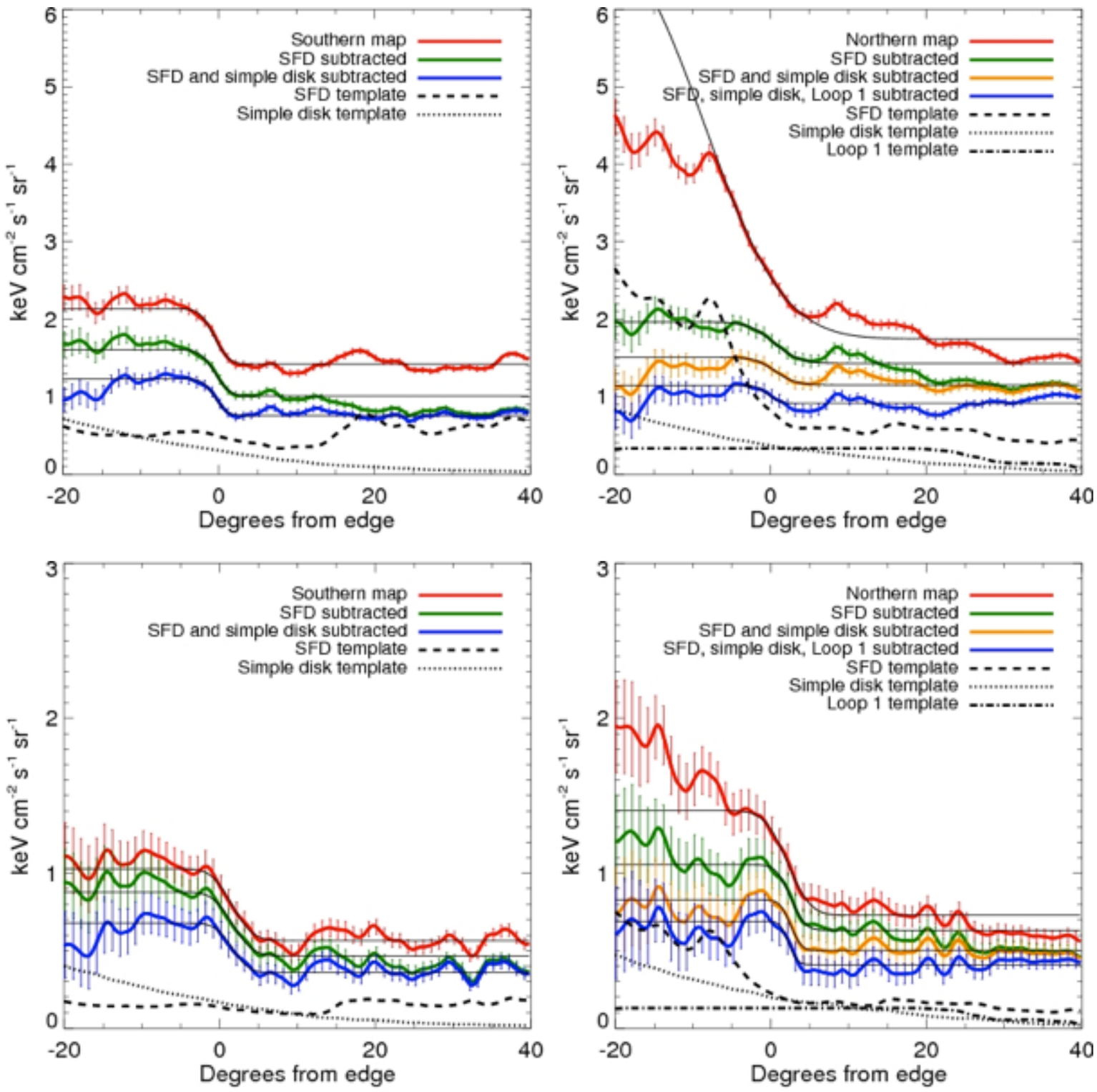
FB has a hard spectrum with high energy cut-off





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.
- Later study by Fermi-LAT Collaboration '14 finds width ~ $3.4^{+3.7}_{-2.6}$ degrees.
- For comparison, radius of bubbles is of order 20° at high latitude.



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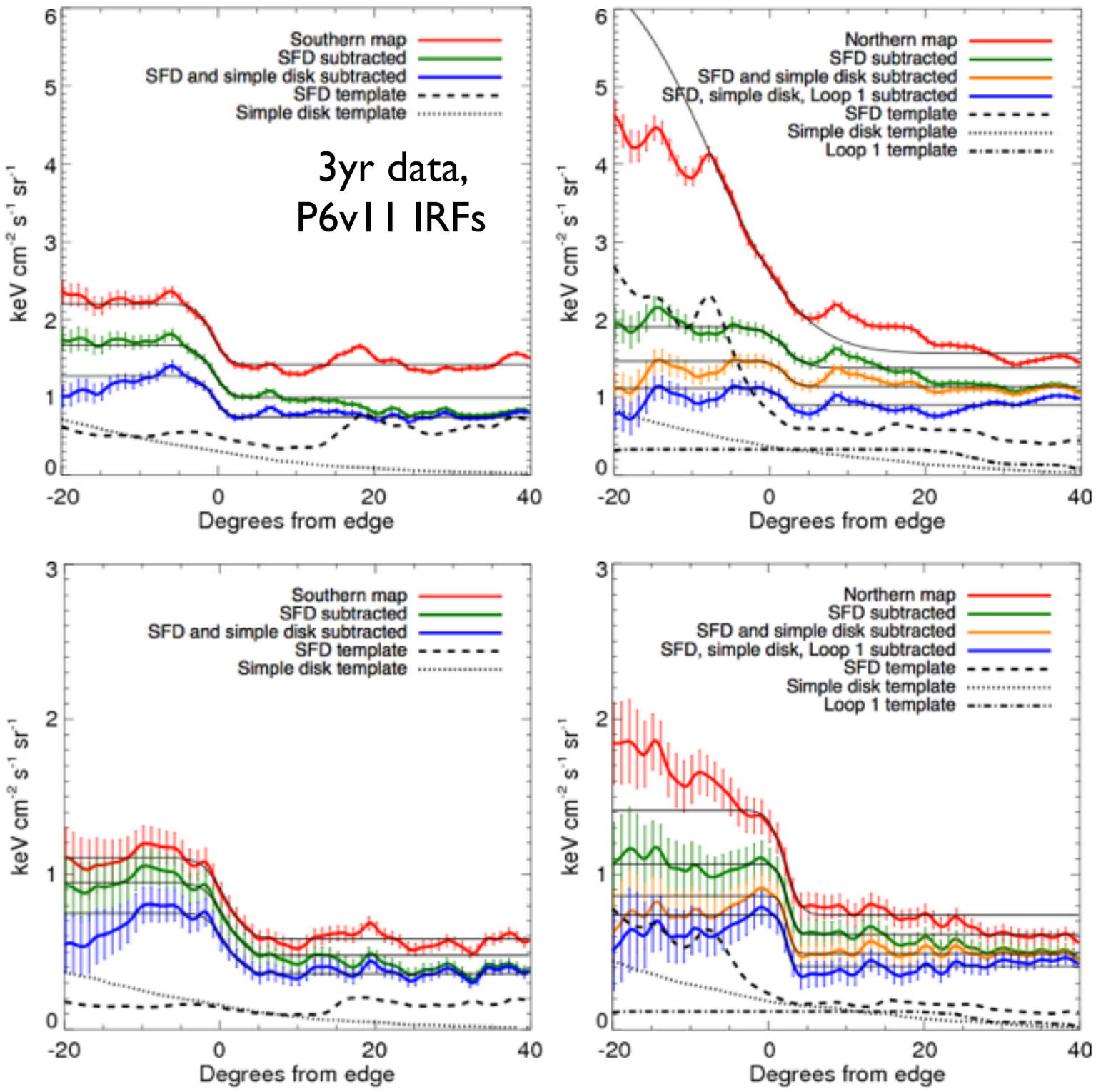
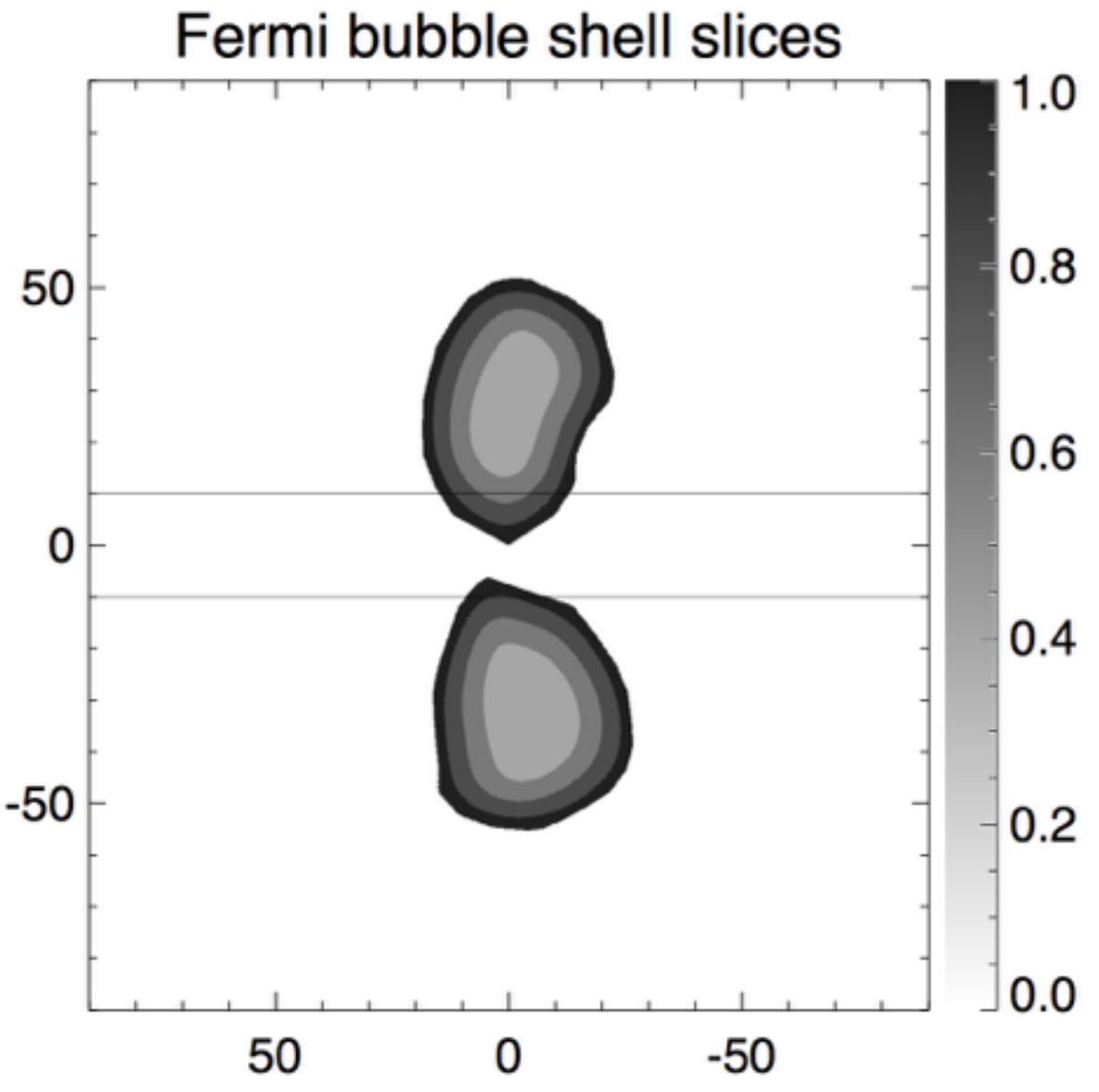
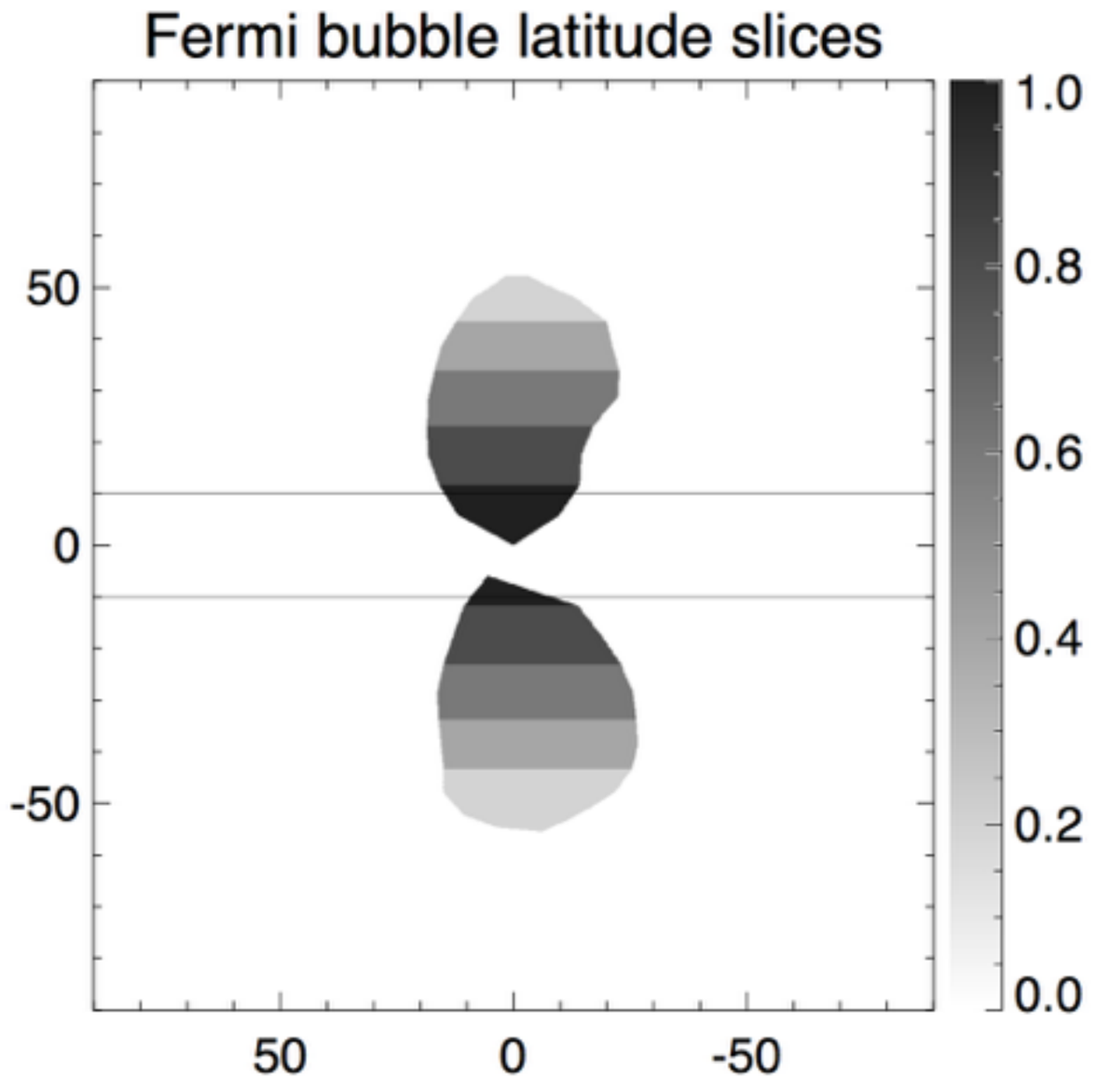
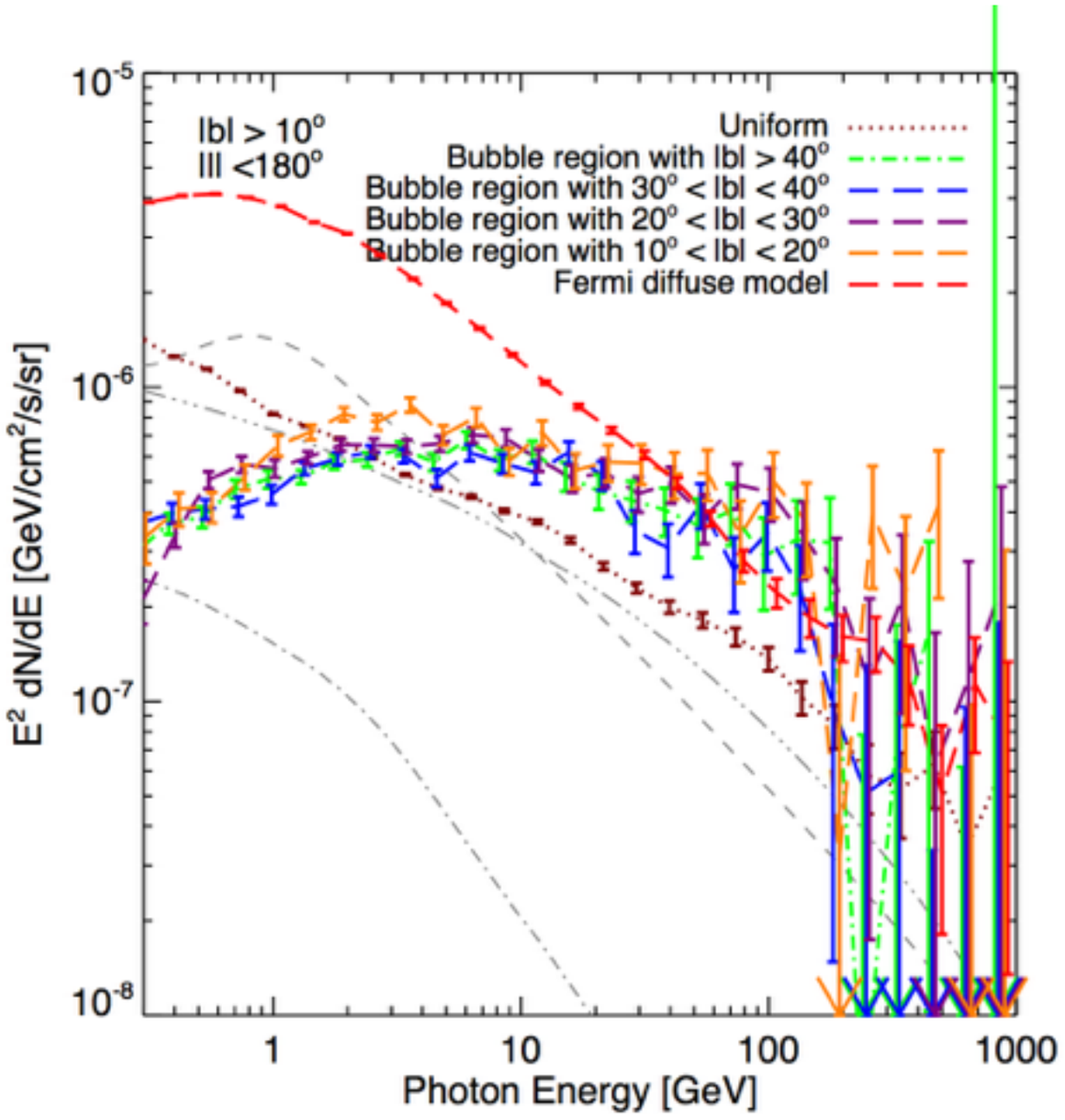


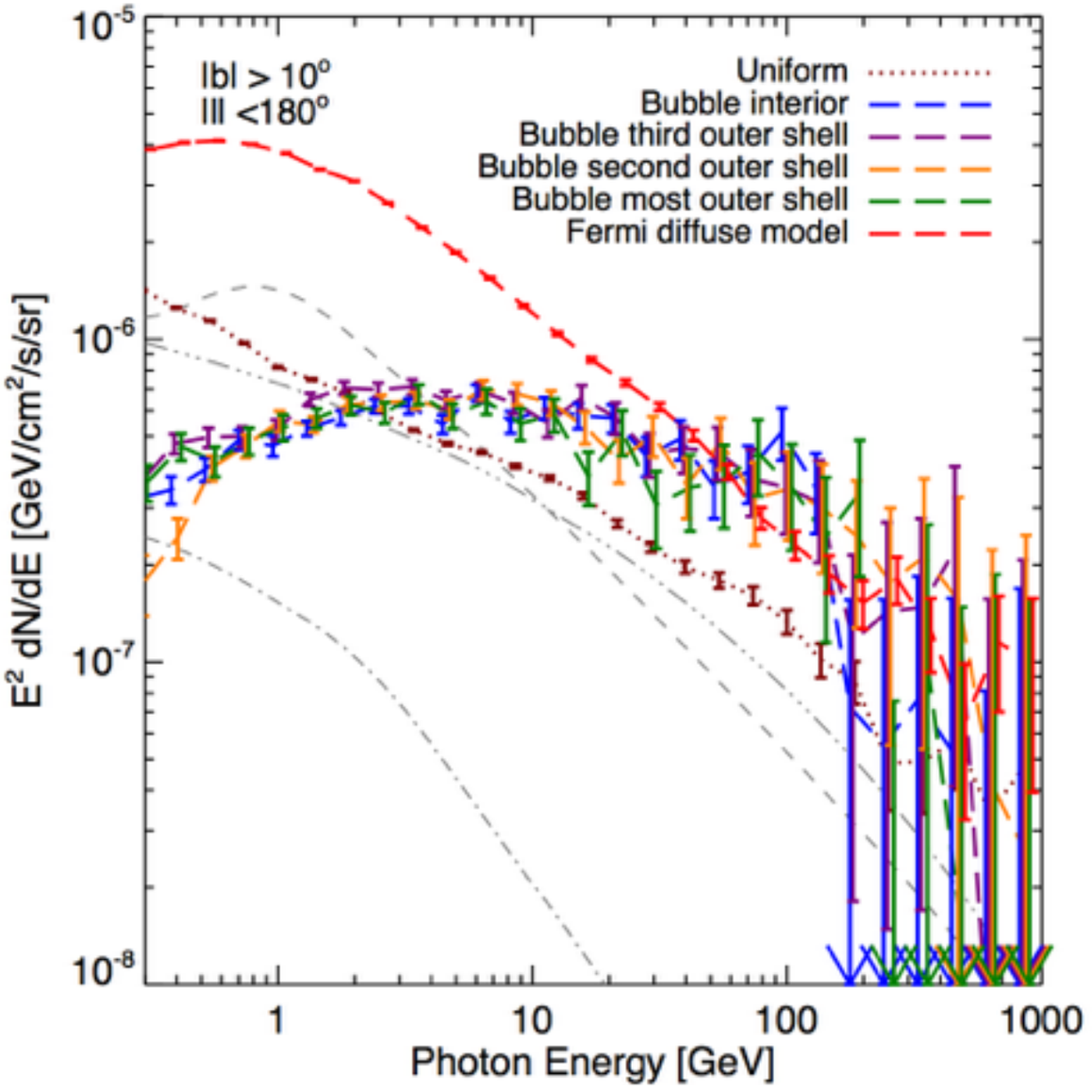
Divide the bubble into pieces…





Spectral variation across the Bubbles?



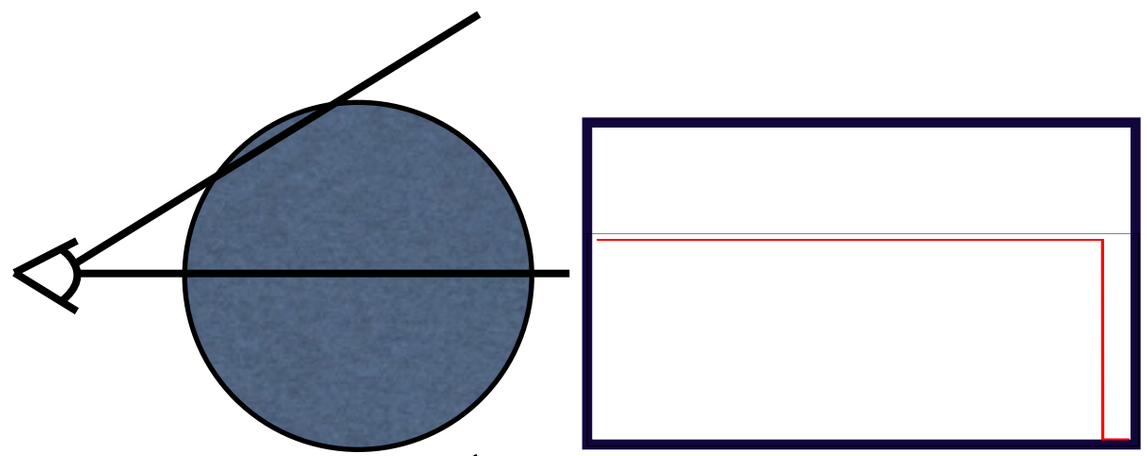


No evidence for spectral variation across Bubbles at mid-high latitude

Later analysis by Keshet & Gurwich '17 finds slight softening at Bubble edges

The (projected) profile puzzle

- Generally expect 3D structures to be either:
  - Centrally brightened in projection (constant volume emissivity), or
  - Limb brightened (hollow shell).



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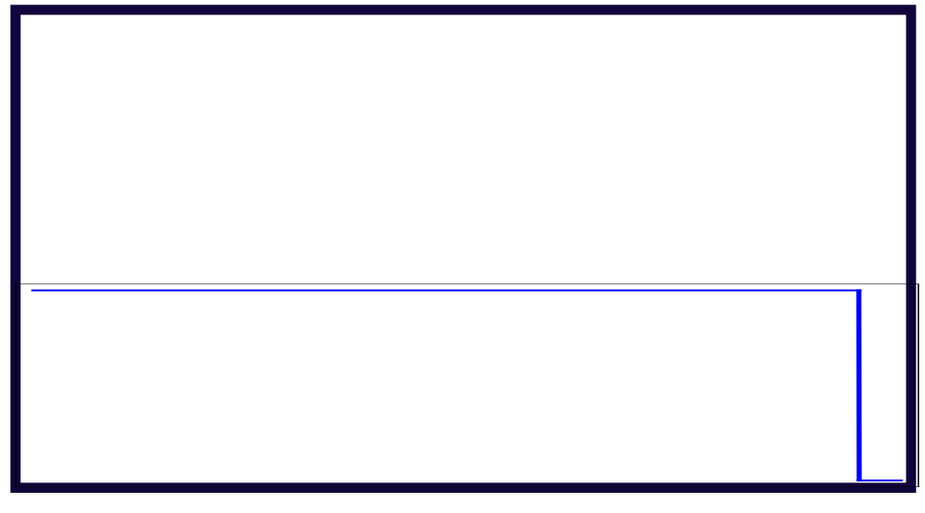

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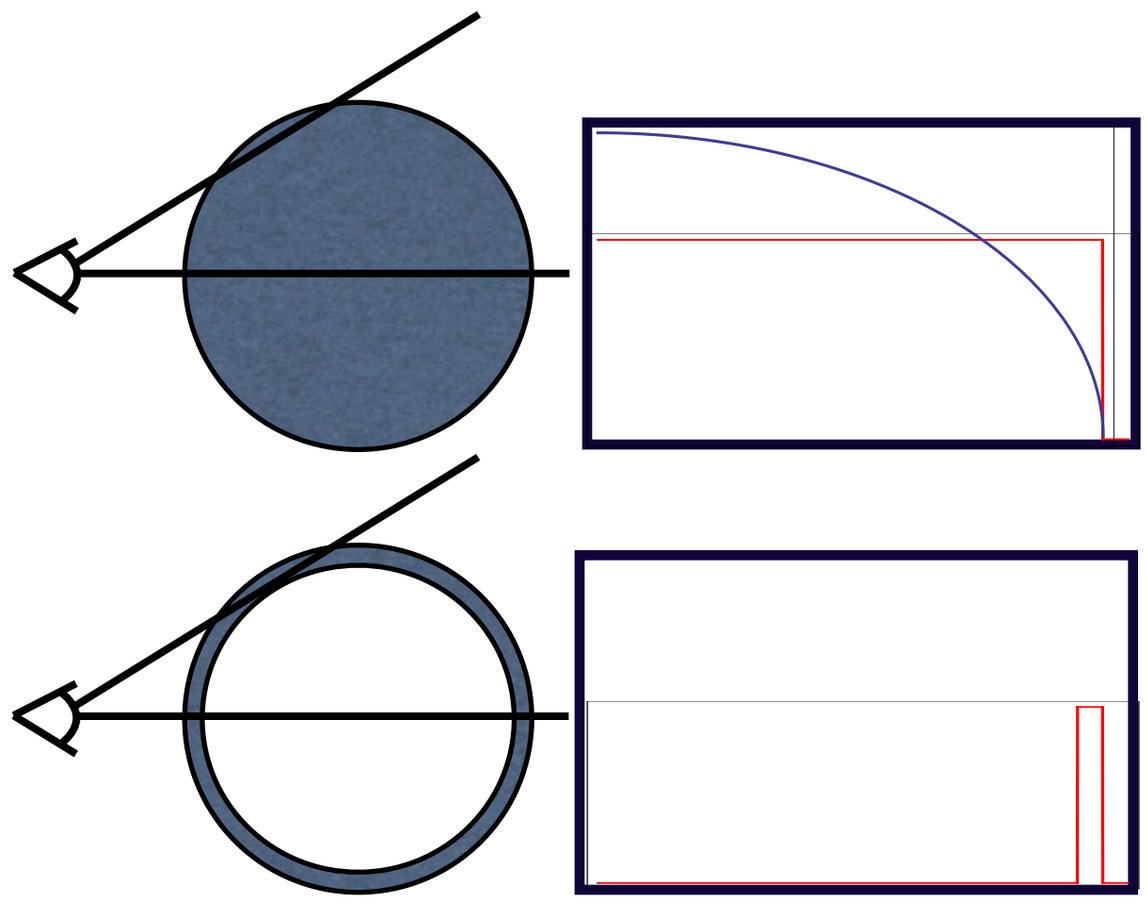

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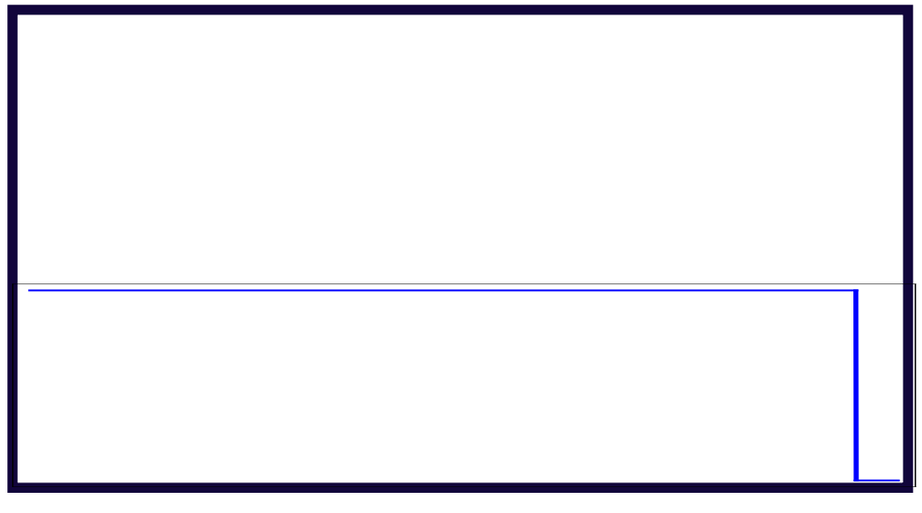

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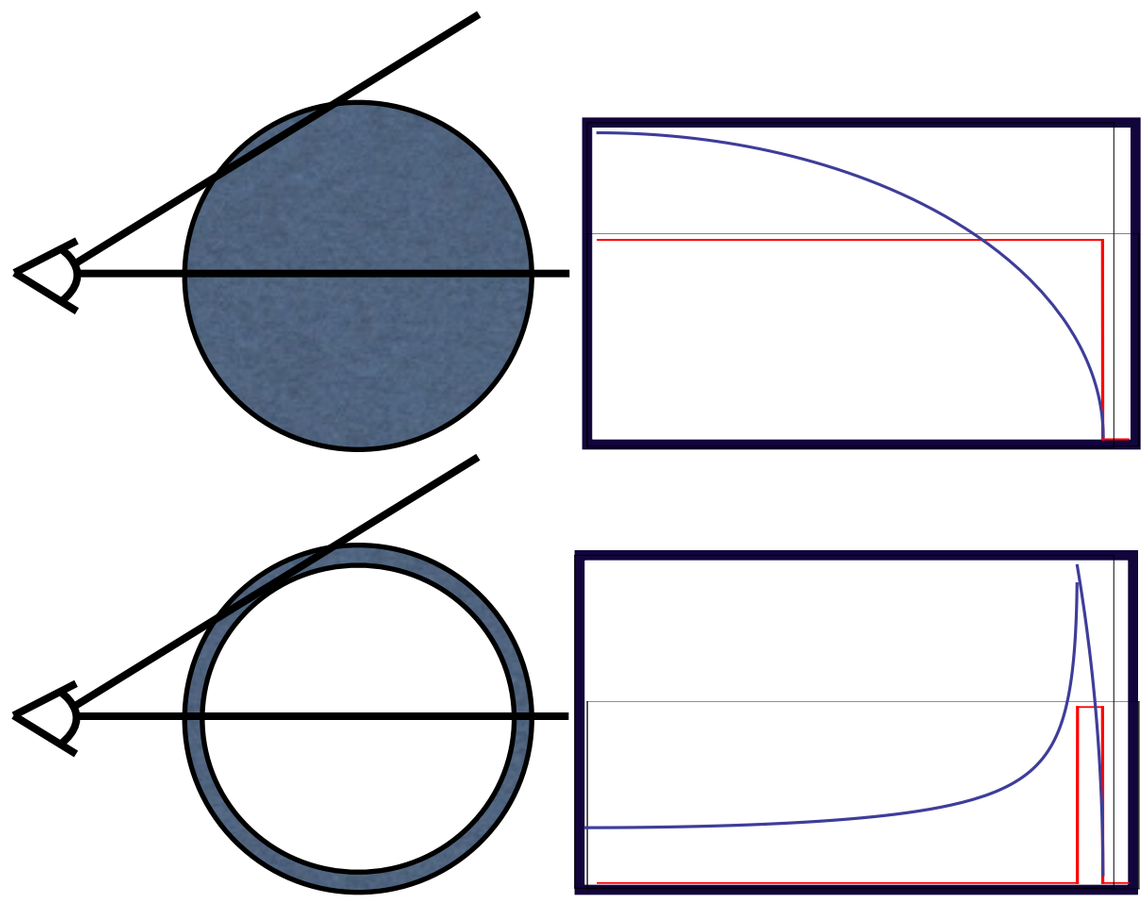

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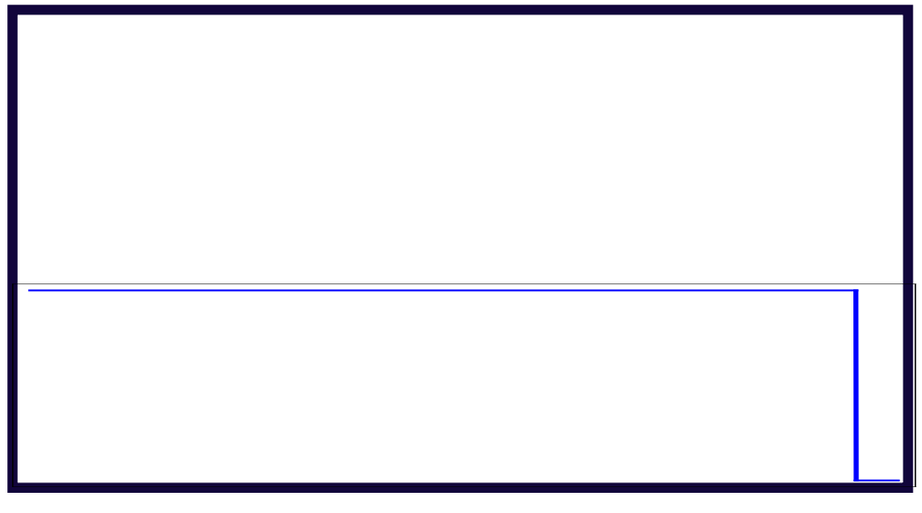

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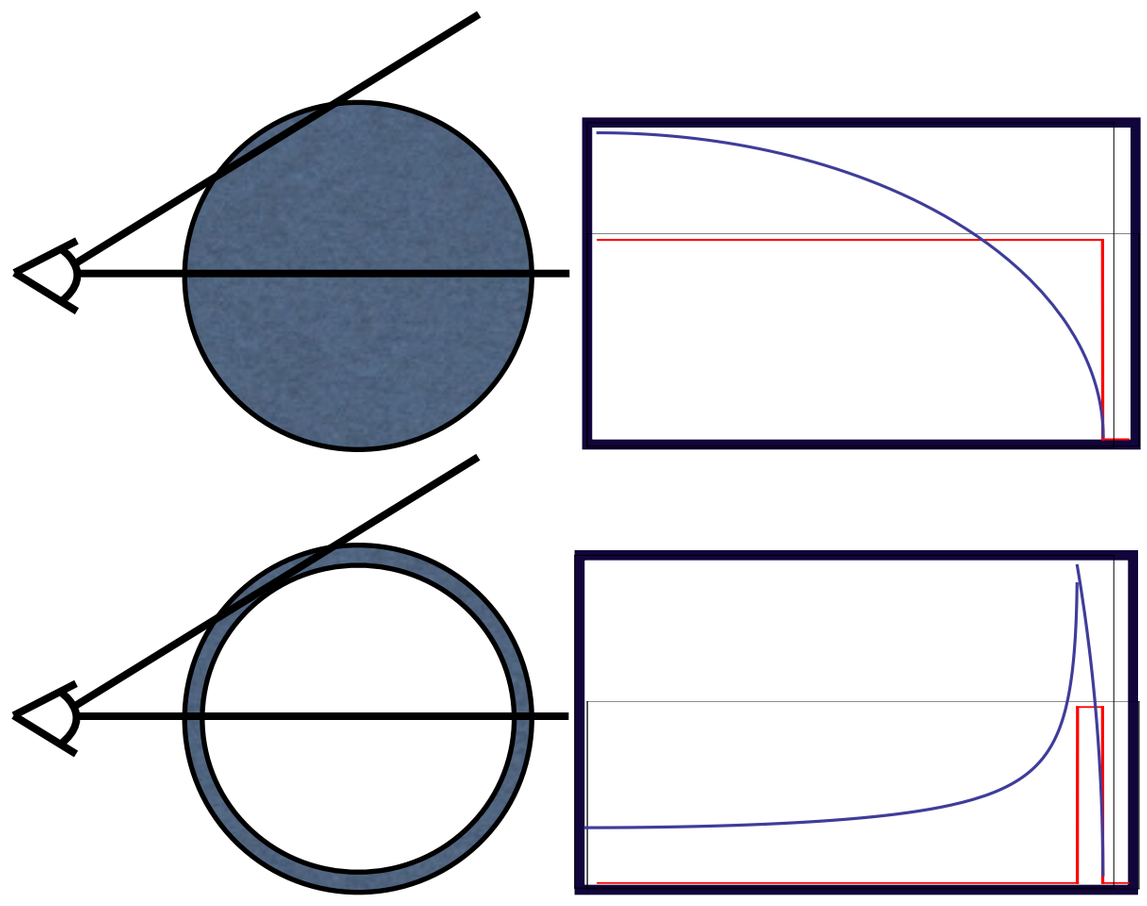

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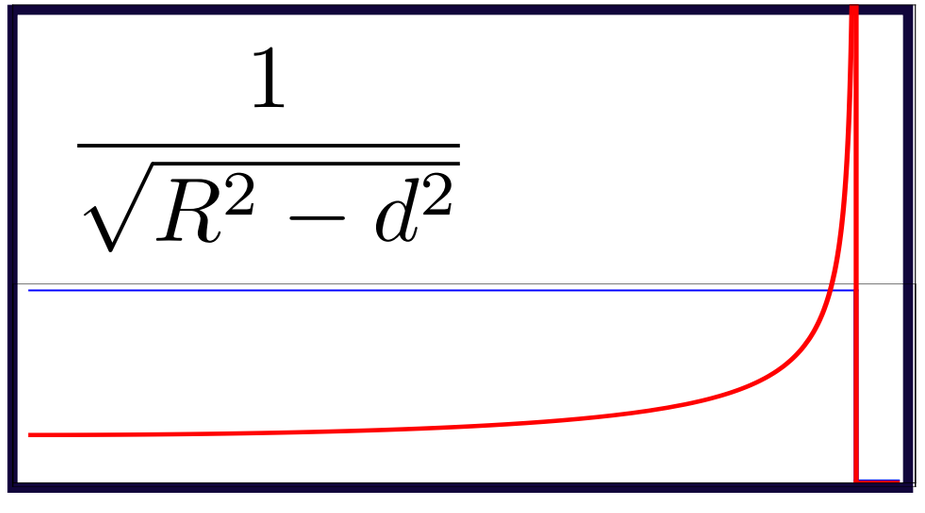
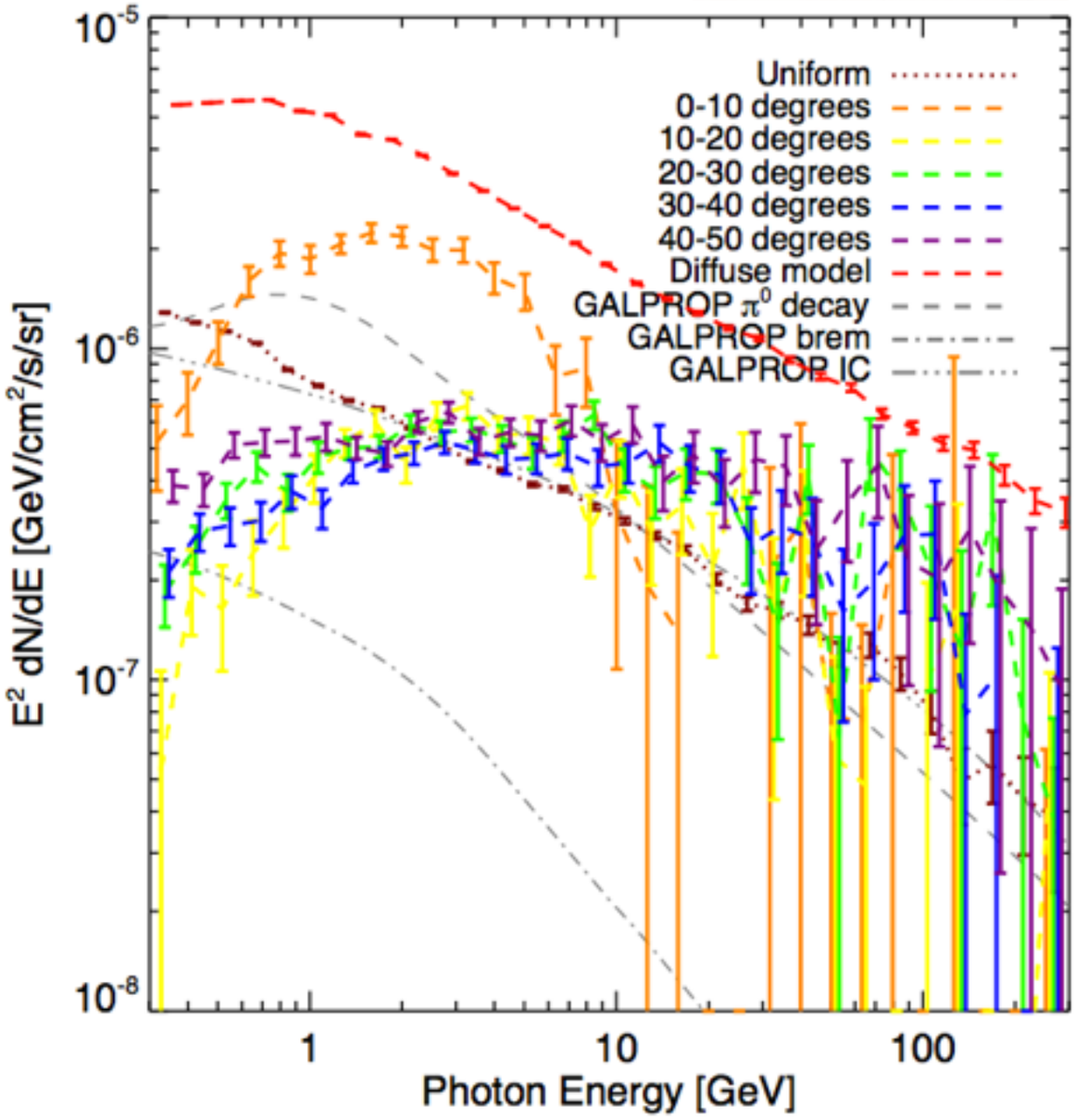


A second component at low latitudes?

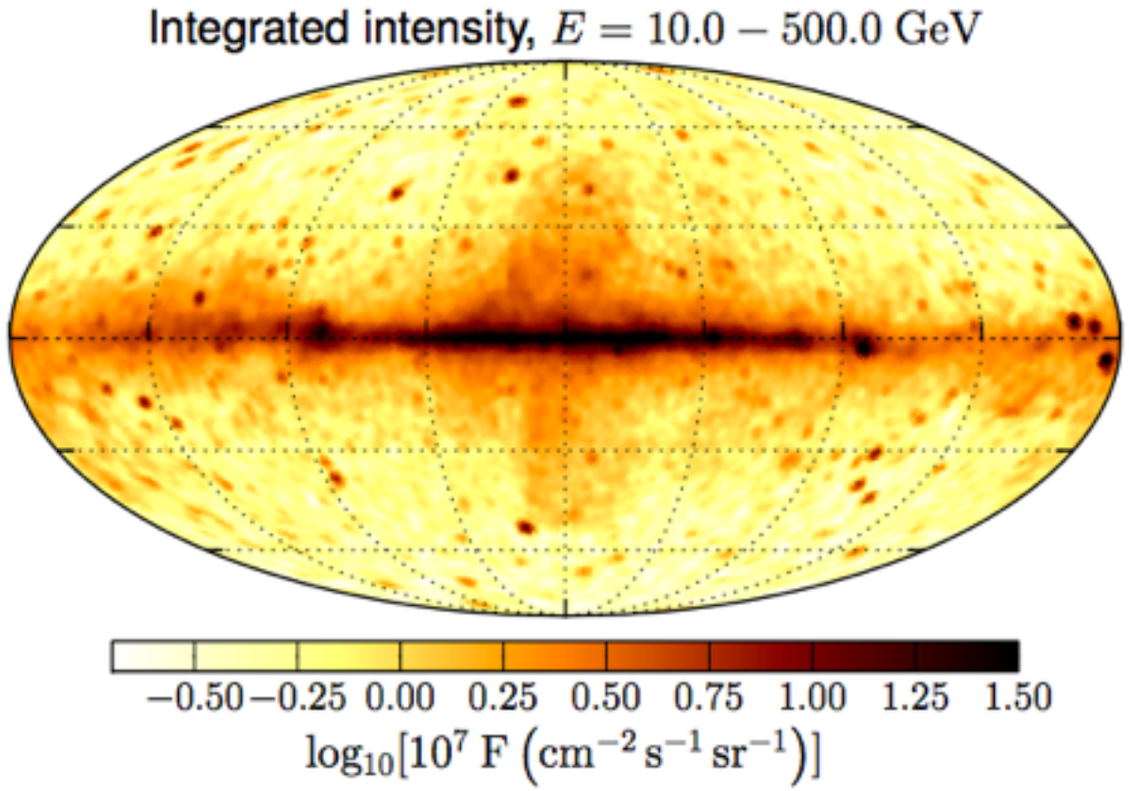
- Evidence for a new spectral component, peaked at a few GeV, within 10 degrees of the Galactic Center.

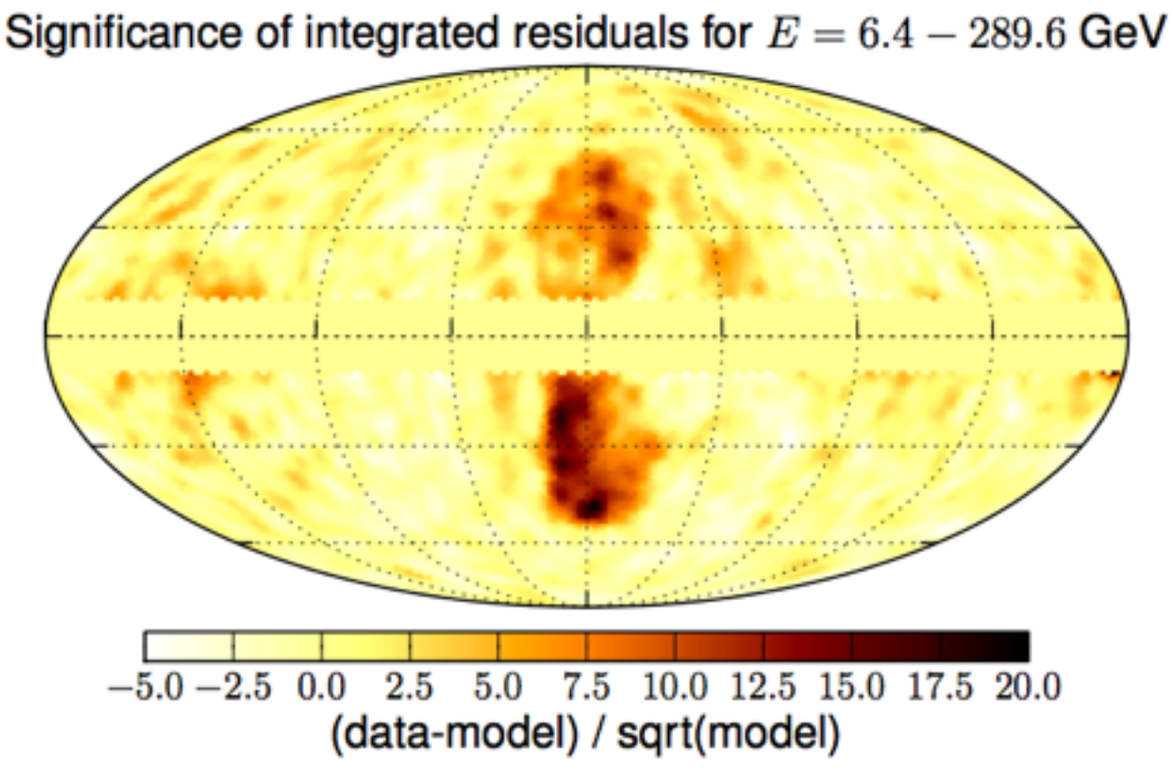
- This is the "Galactic Center excess" (GCE) - does NOT appear to be correlated with the Bubbles, prefers a more spherically symmetric spatial distribution (Hooper & Slatyer '13, Daylan et al '14, Calore, Cholis & Weniger '14).

- There is evidence that the GCE is comprised of point sources (Lee et al '16, Bartels et al '16) - physically distinct from Bubbles.

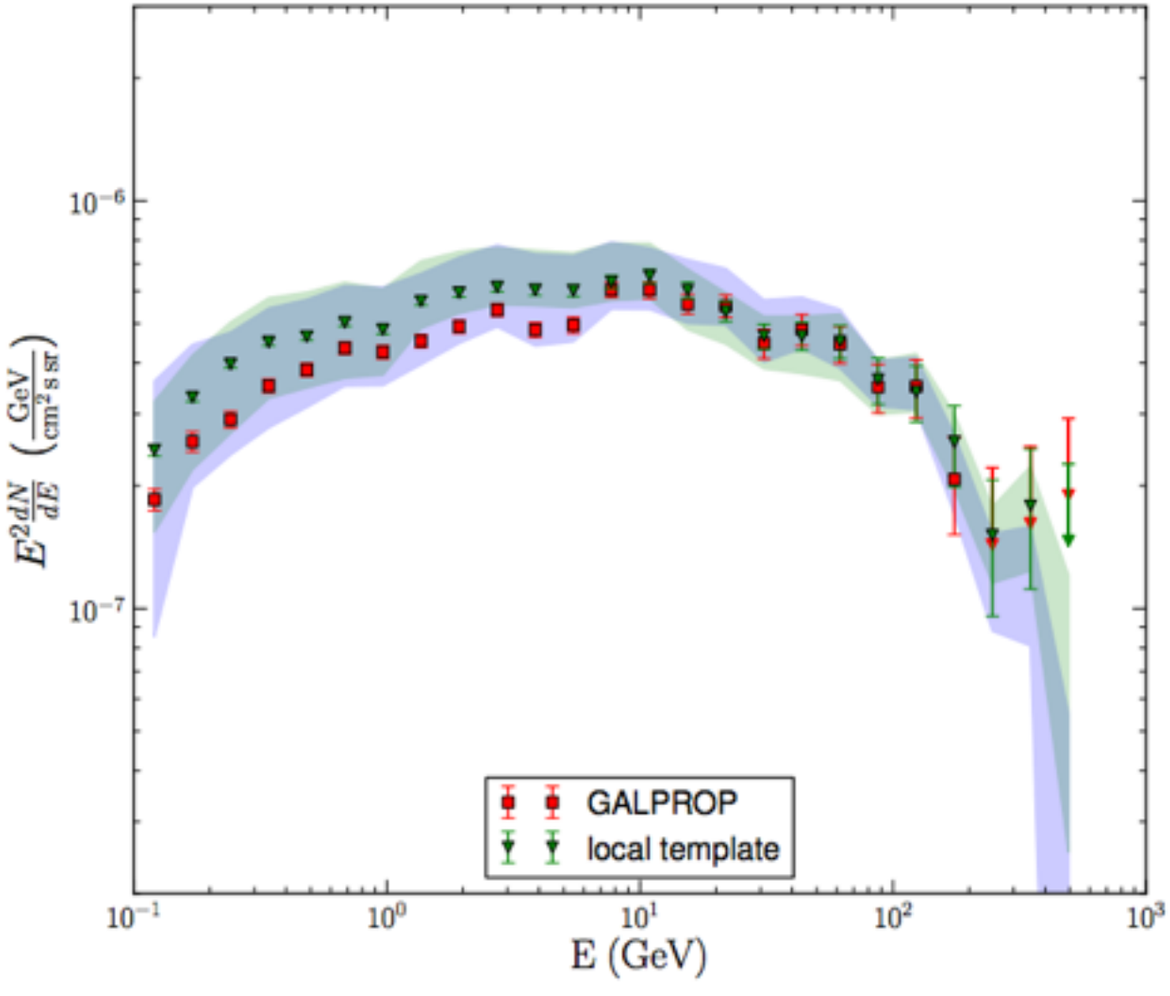


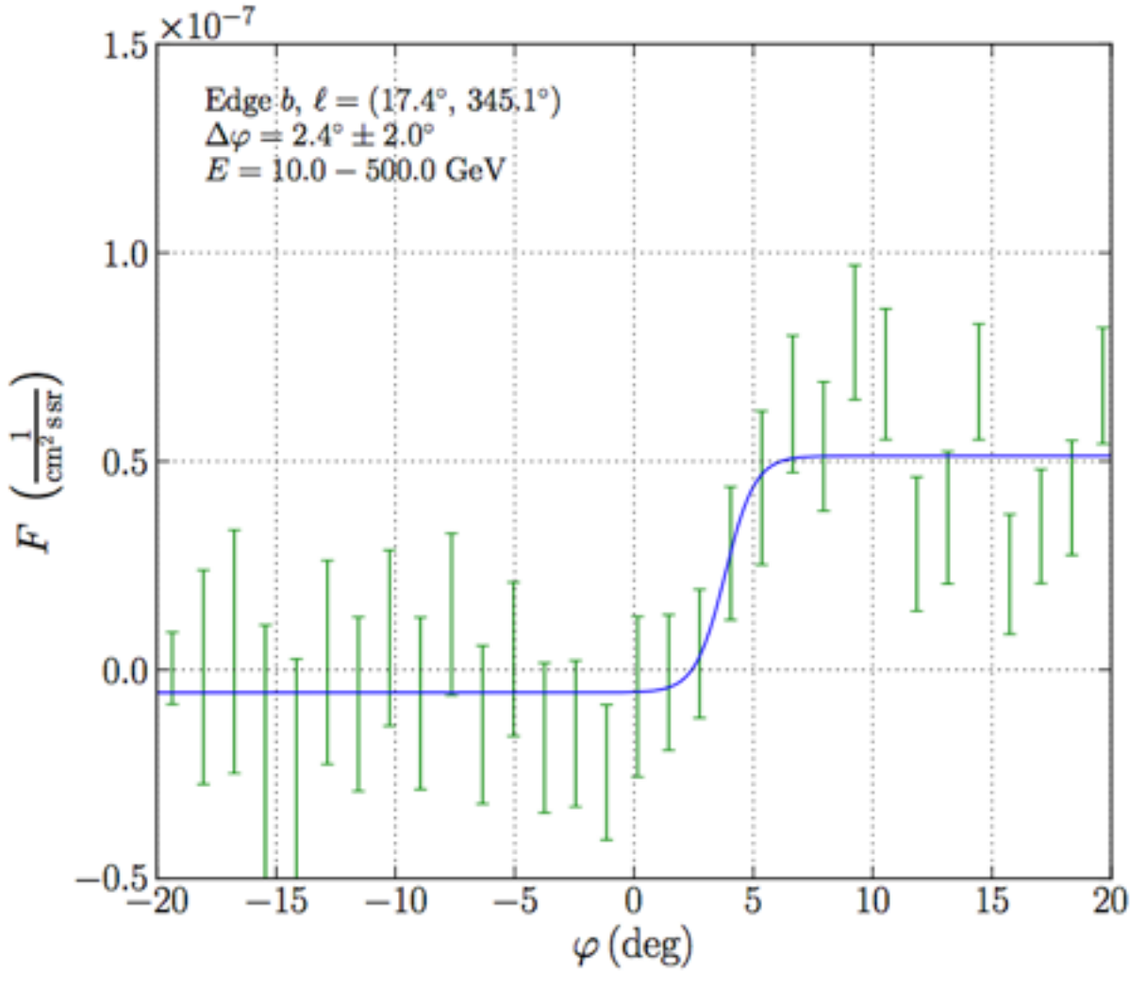
Hooper & TRS '13





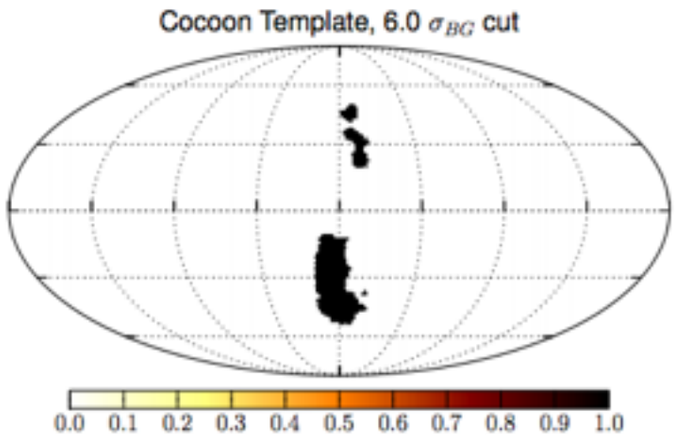
Analysis by Fermi Collaboration on 50 months data, Ackermann et al '14

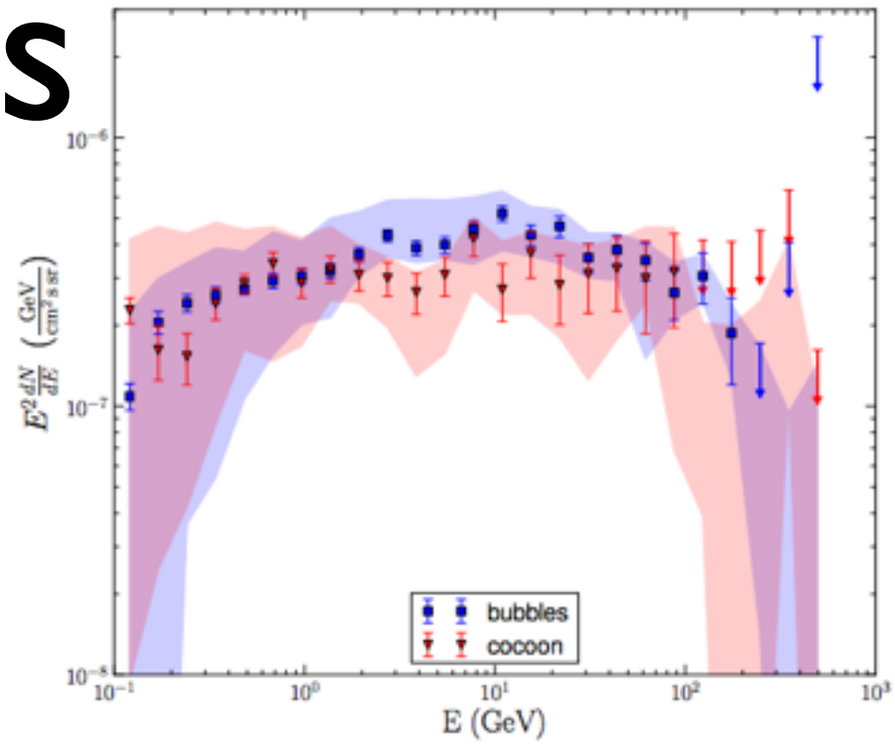


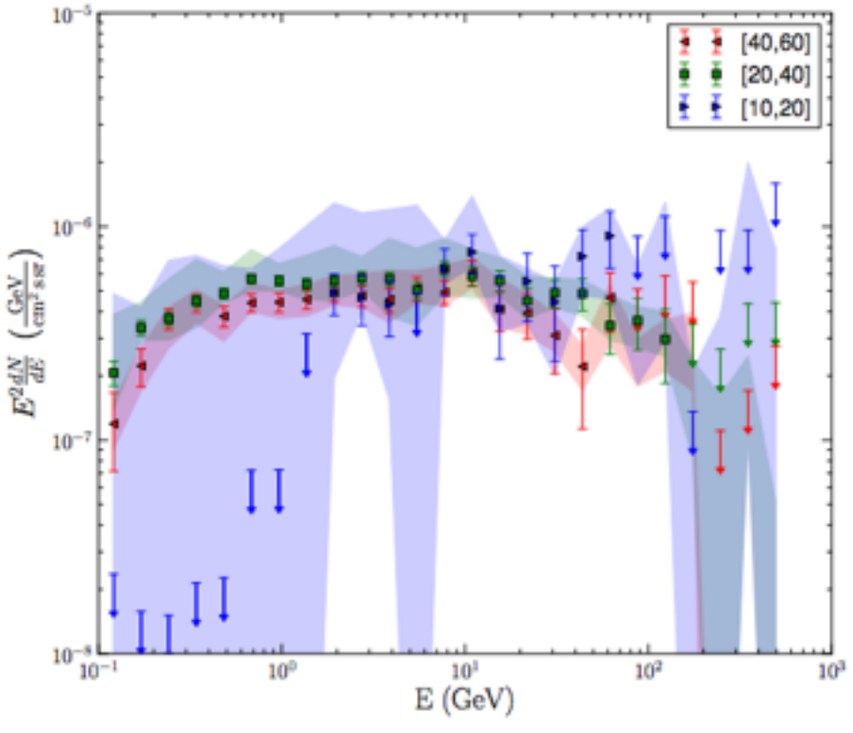


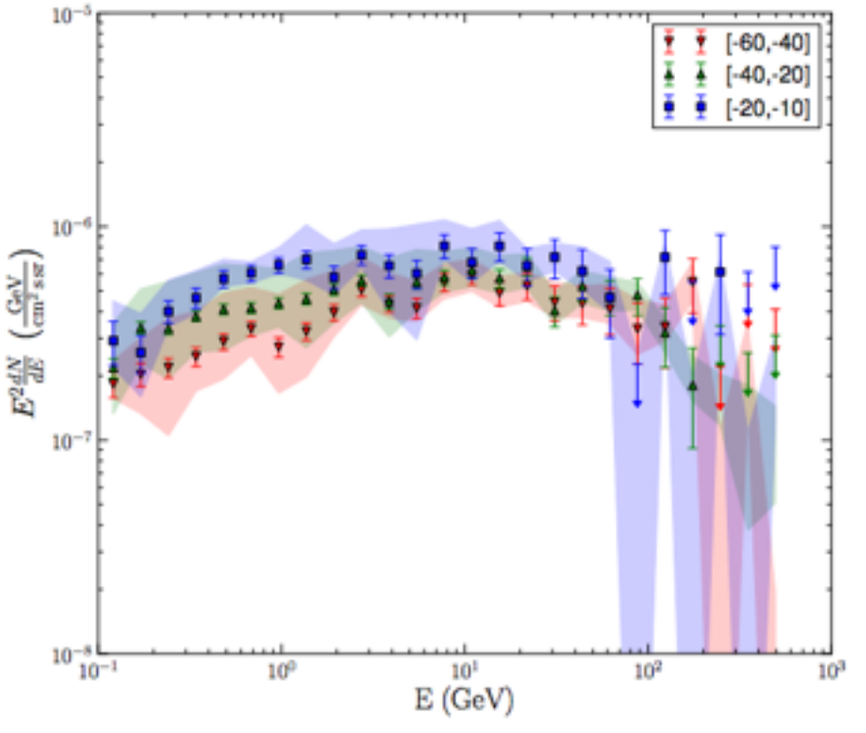
Spectral variation across the Bubbles

- "Cocoon" region in the southern Bubble, first identified by Su & Finkbeiner '12
- Cocoon = enhanced intensity, similar spectrum to the Bubbles as a whole (however, cutoffs not significantly detected)
- Little variation in the gamma-ray spectrum with latitude, confirming previous studies
- Northern and Southern Bubbles are symmetric



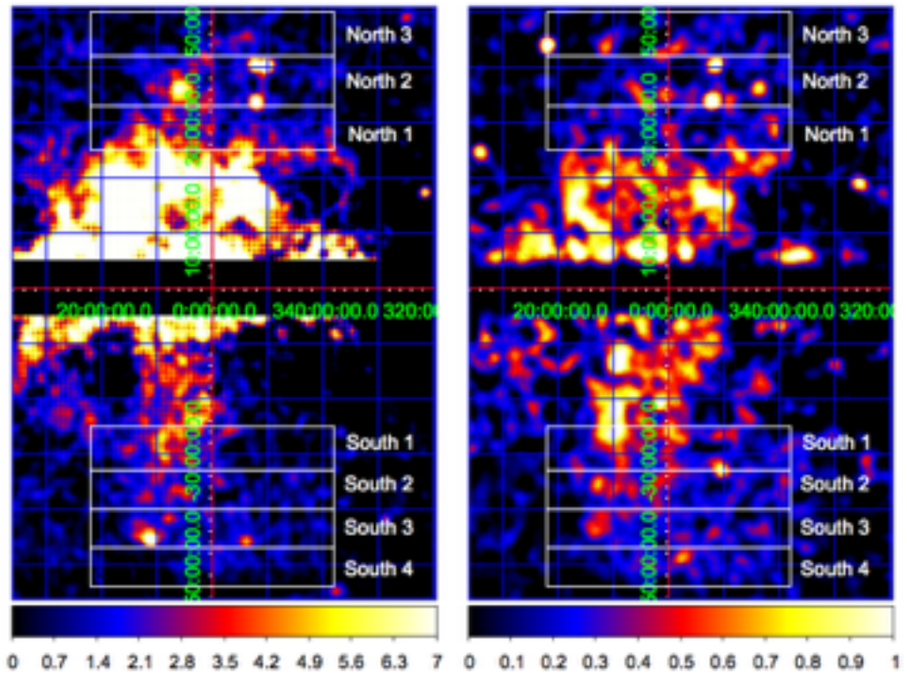


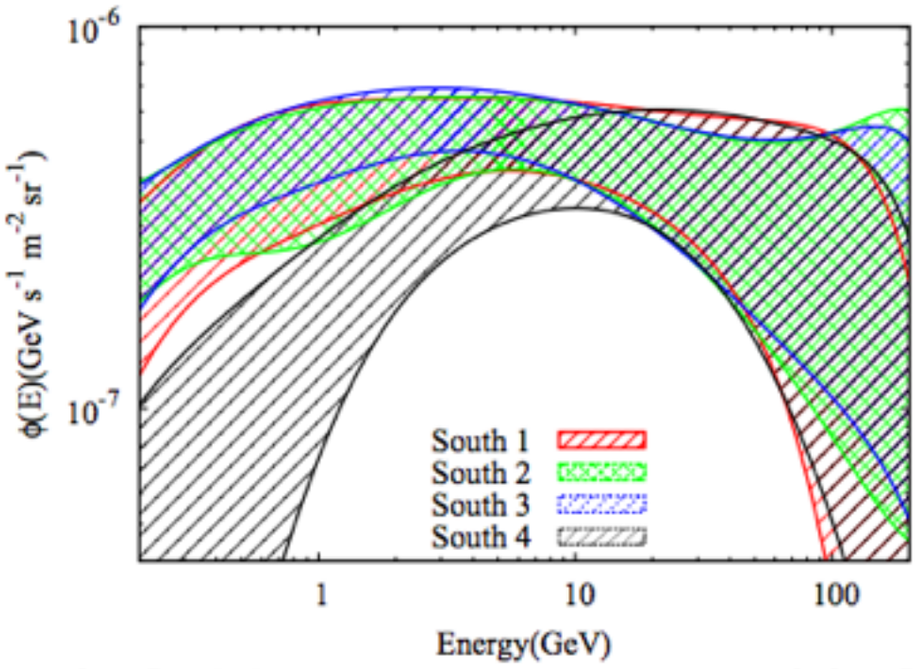




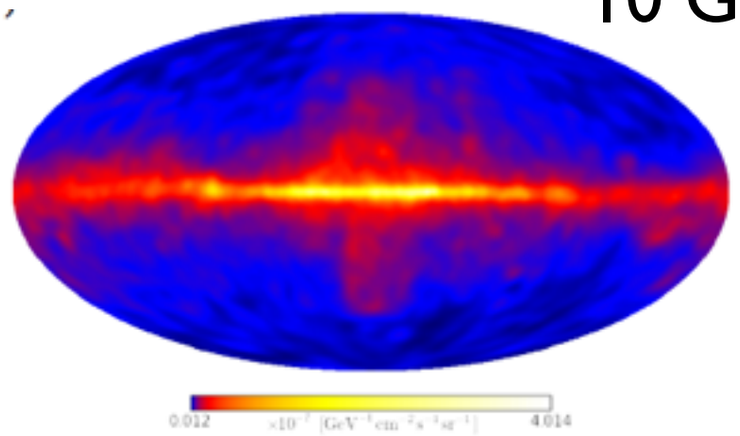
Spectral hardening in the South?

- Yang, Aaronian & Crocker '14 claim a low-energy deficit / spectral hardening in the southernmost part of the Southern bubble
- Possible theoretical explanation given by Barkov & Bosch-Ramon '14 (shock velocities higher at tops of Bubbles than at their sides)
- Selig et al '15 use the D^{3}PO inference algorithm (alternative to template fitting) to attempt to characterize spectrally distinct contributions to the gamma-ray sky
- Yang et al, Selig et al: the Bubbles appear more extended to the south and west at high energies

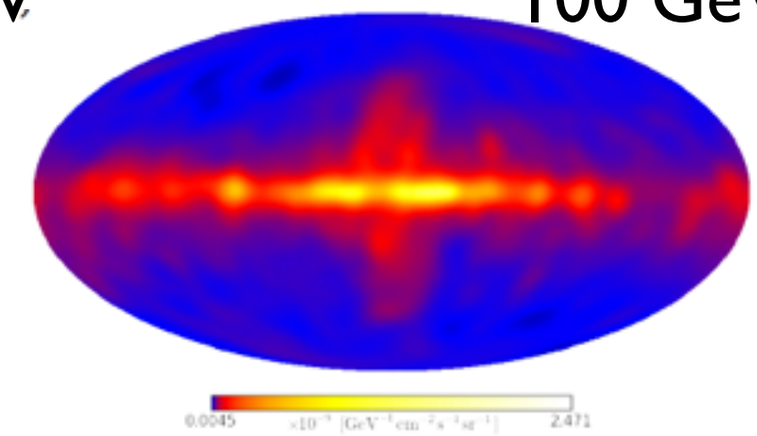




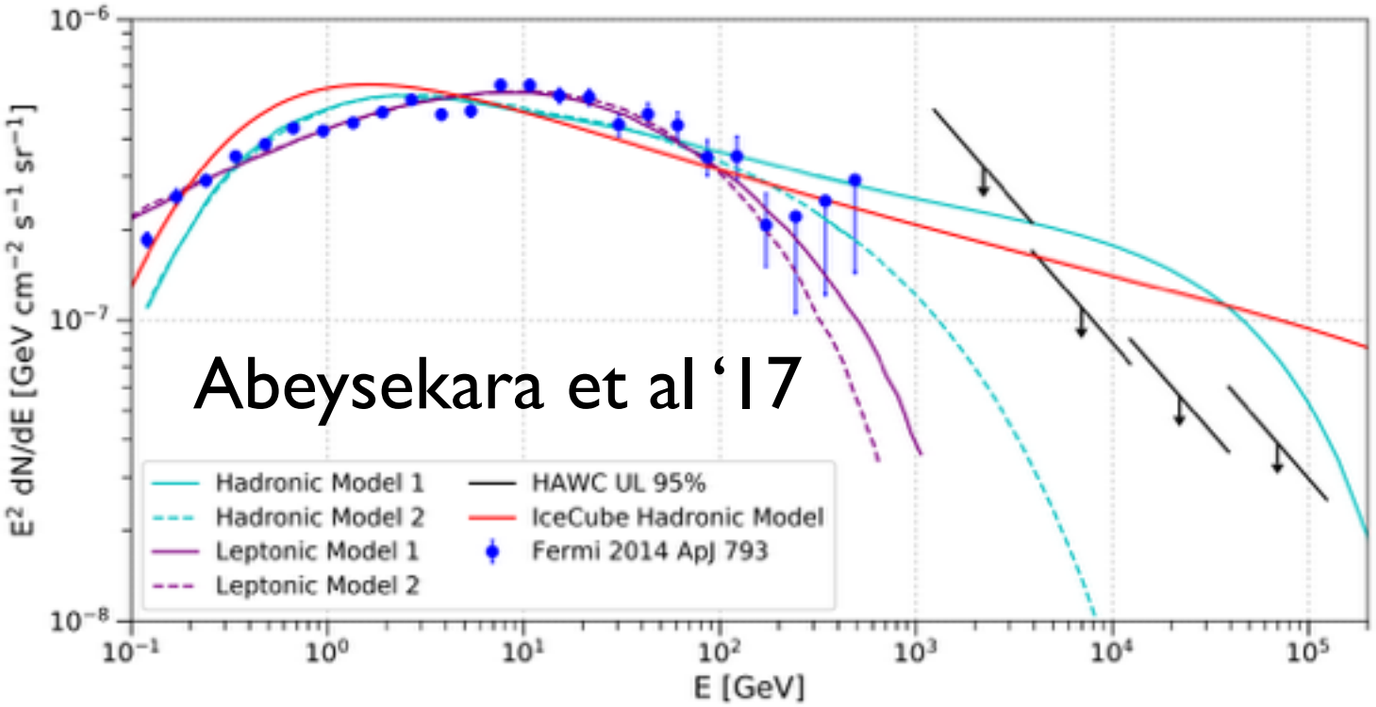
10 GeV

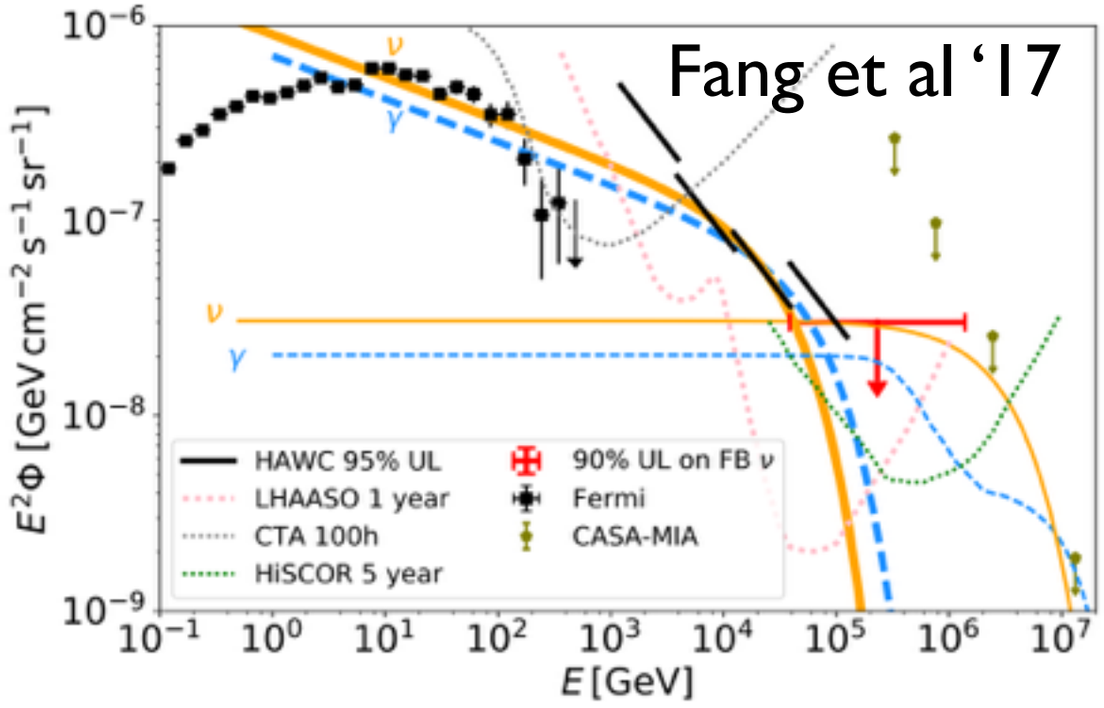


100 GeV



The Fermi Bubbles at TeV+ energies





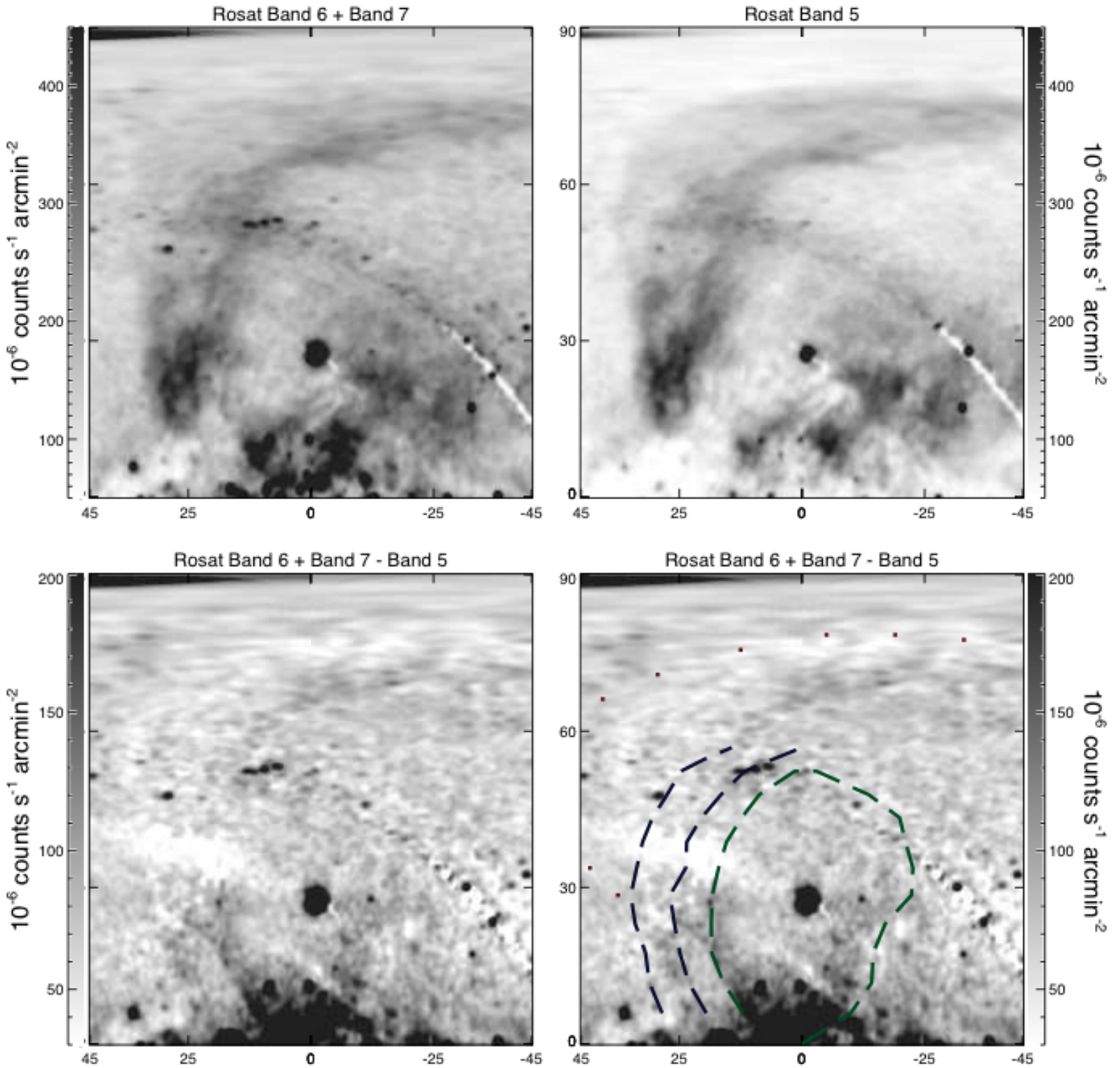
- HAWC Collaboration sets limits on high-energy gamma-ray emission from the Bubbles - if the emission is hadronic, implies a cutoff in the proton spectrum below 100 TeV
- Fang et al '17 calculates a similar bound on hadronic models based on non-observation of a neutrino signal (see also Sherf et al '17, & new neutrino limits from ANTARES, Hallmann et al '17)

Properties of the gamma-ray Bubbles

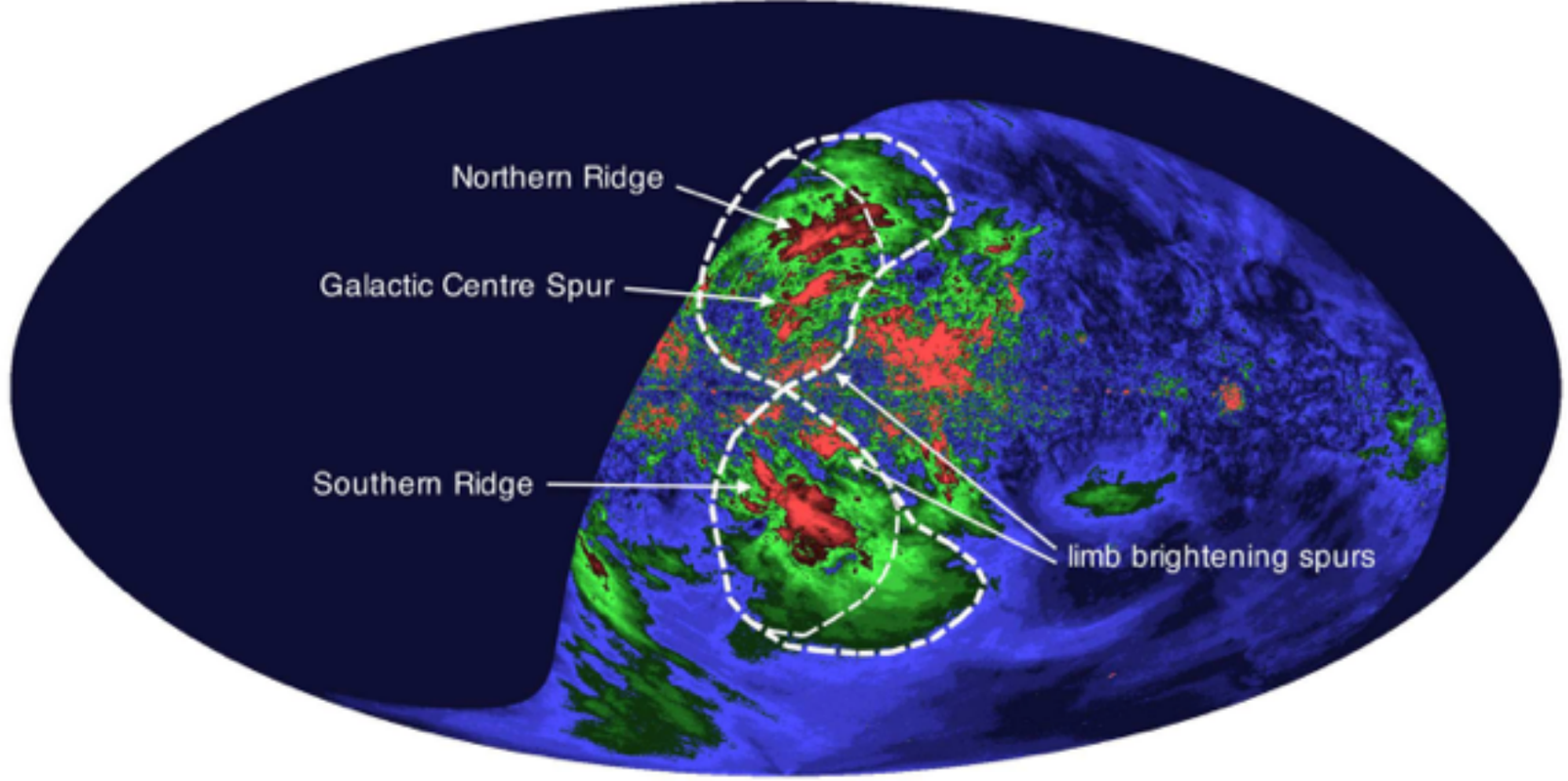
- ~Flat spectrum in E^2dN/dE from ~1-150 GeV, apparent cutoff above 150 GeV.
- Total gamma-ray luminosity ~5 x 10^{37} ergs/second.
- Spectrum appears close-to-uniform across the Bubbles, above 10 degrees in Galactic latitude; some indications of a harder spectrum in the southern Bubble far from the Galactic plane.
- Intensity shows no clear increase/decrease with latitude or distance from Bubble centers, but is enhanced in southern "cocoon".
- Sharp edges, ~few degrees in width.
- What about other wavelengths? Microwave, X-ray, radio?

X-ray bubbles?

- 1.5-2 keV X-rays (data from ROSAT) show edges in north that seem to line up with Bubbles (c.f. Bland-Hawthorn & Cohen '03).
- Keshet & Gurwich '17 gamma-ray edge reconstruction supports connection to X-ray edges.
- XMM-Newton and Suzaku observations suggest bubbles are hot, overpressurized relative to surrounding medium; expansion velocities of hundreds of km/s (e.g. Tahara et al '15, Kataoka et al '15, Miller & Bregman '16, Sarkar et al '17).
- See talk by Yoshiyuki Inoue on Sunday for an in-depth review of X-ray observations of the Bubbles.

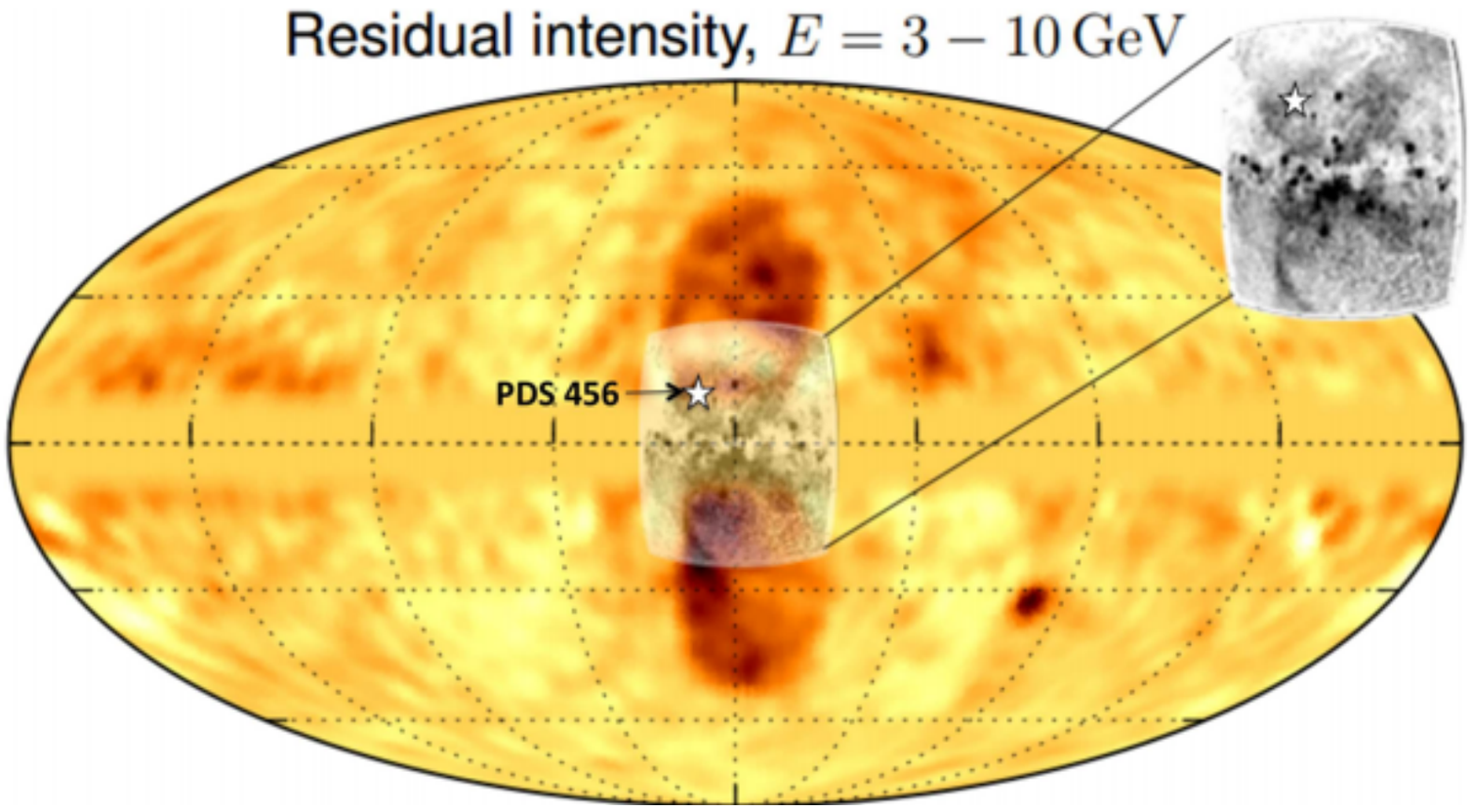


Radio bubbles?



- Carretti et al ’13 observe two “giant, linearly-polarized radio lobes”, extending ~60 degrees from the Galactic center, in data from S-PASS.
- Appear to have a close spatial correspondence with Fermi Bubbles at lower latitudes (radio lobes extend to higher latitudes).
- Suggests magnetic fields of up to 15 μG within the Bubbles.
- Radio “ridges” on Bubble surfaces may inscribe history of Bubbles’ rotation relative to the Galaxy.

UV absorption in the Bubbles



- Fox et al ’15 studied UV absorption-line spectra in light from a background quasar.
- Found two high-velocity metal absorption components - suggest an origin on the near and far sides of a biconical outflow from the Galactic Center.
- Measured velocities + biconical shape taken from X-rays implies an outflow velocity greater than 900 km/s.
- Bordoloi et al ’17 studied 47 sightlines inside and outside the northern Bubble, found blueshifted high-velocity component inside Bubbles - monotonically decreasing blueshifted outflow velocity with increasing Galactic latitude.
- Suggests entrained cool UV-absorbing gas within Fermi Bubbles, extending to ~6.5 kpc from Galactic plane (similar to gamma rays).
- Can be explained by simple outflow model with velocity ~1000 km/s and age 6-9 Myr - somewhat larger velocities than inferred from X-ray measurements.

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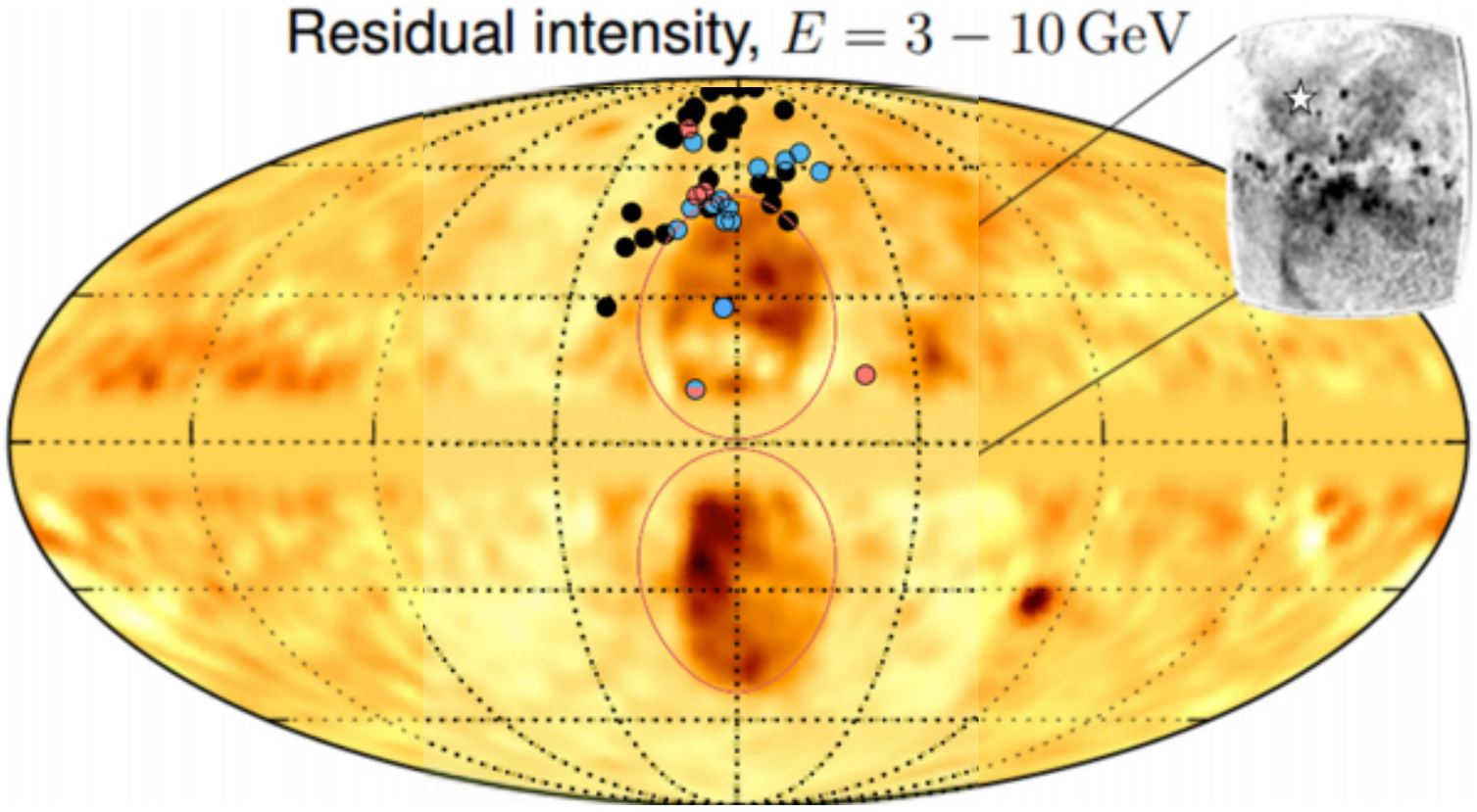

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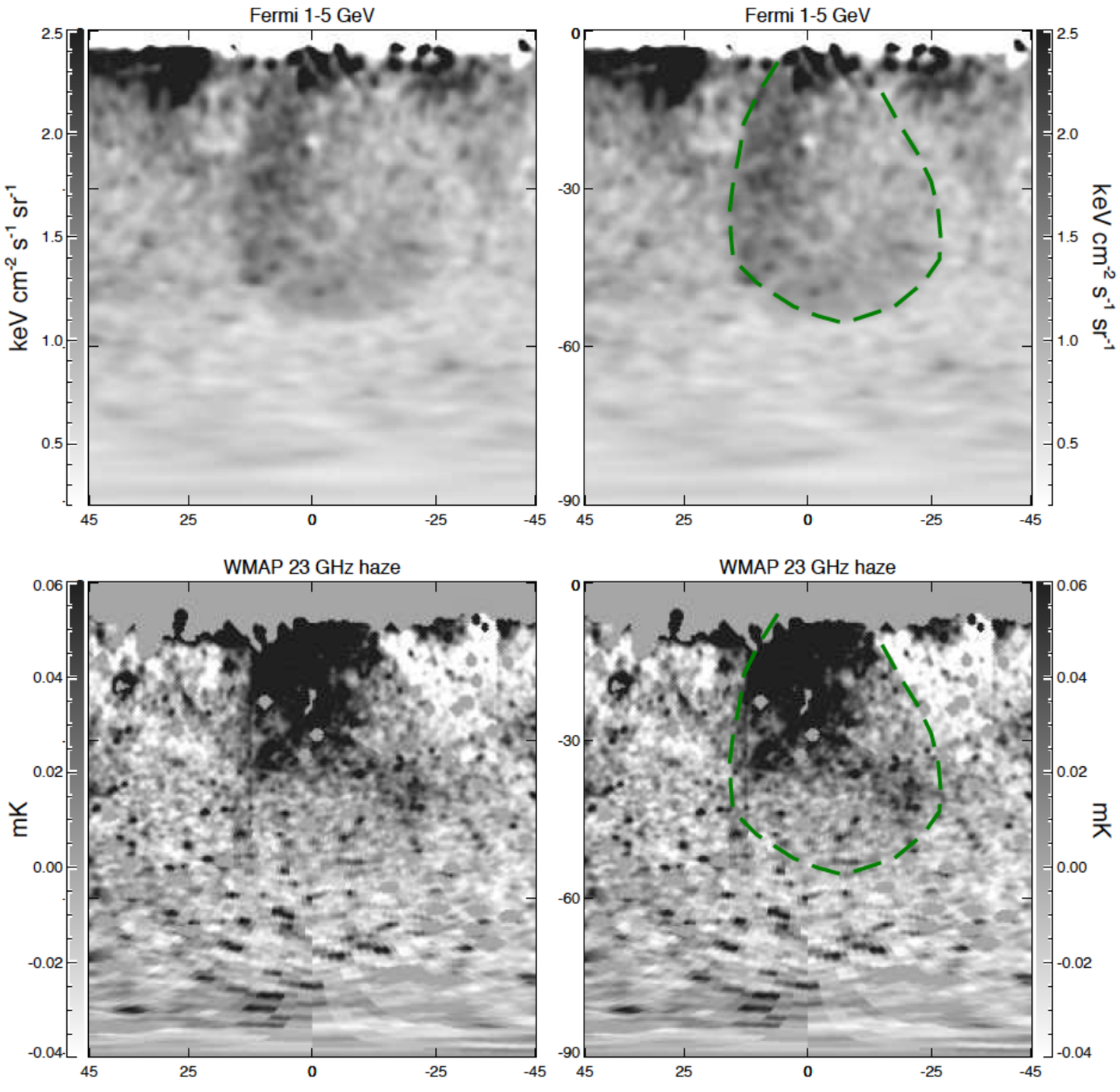
Microwave counterpart of FB

see also talk by Liu Hao

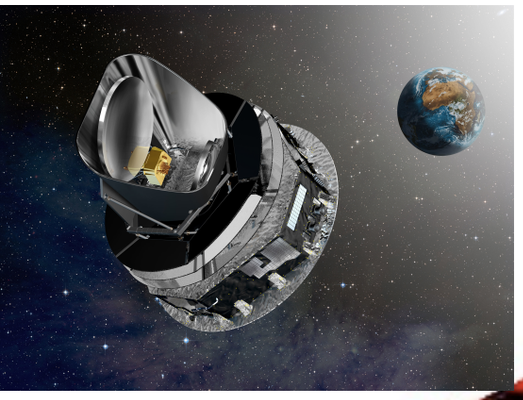
Fermi 1-5 GeV:

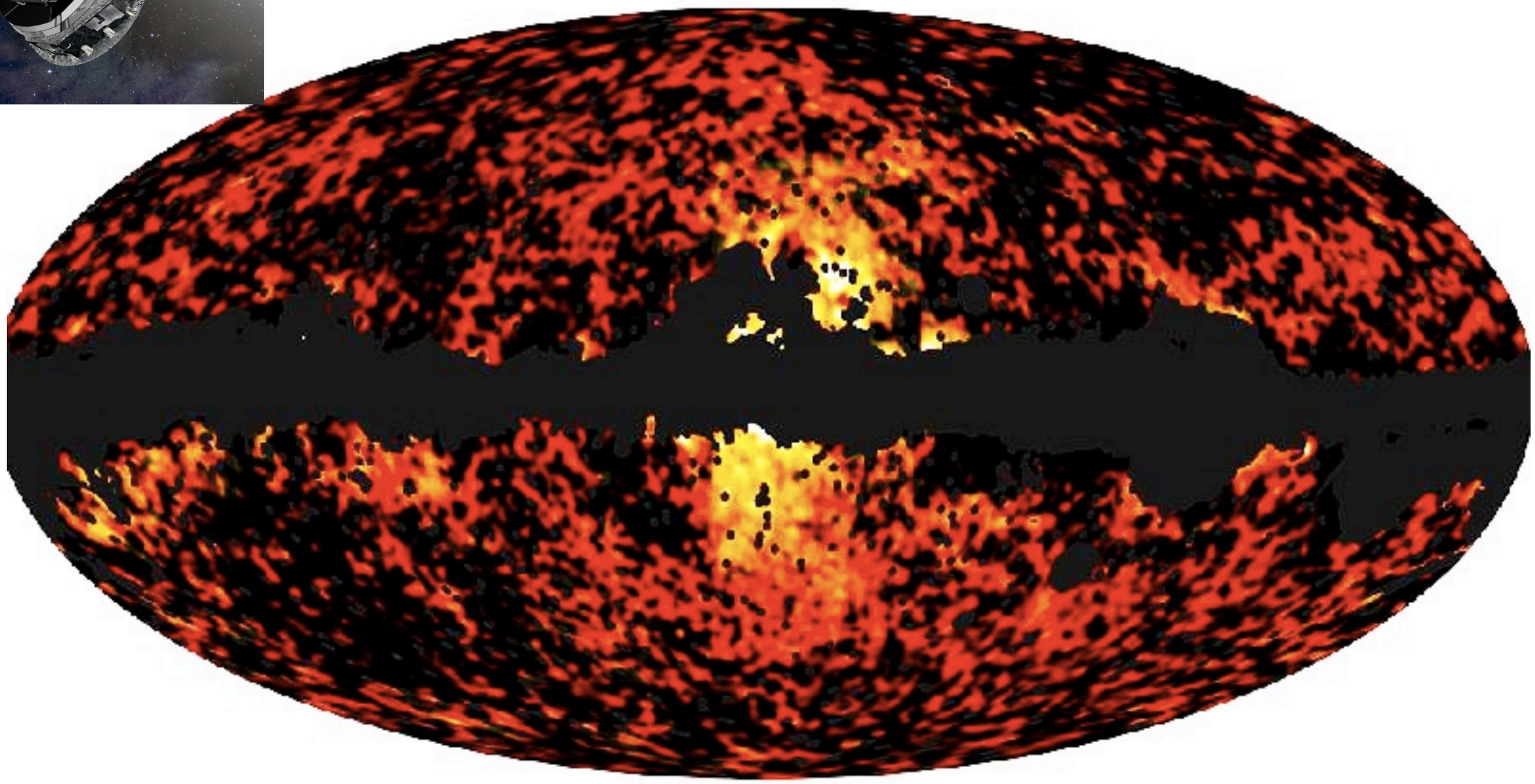


WMAP 23 GHz:

Su, TRS & Finkbeiner 2010

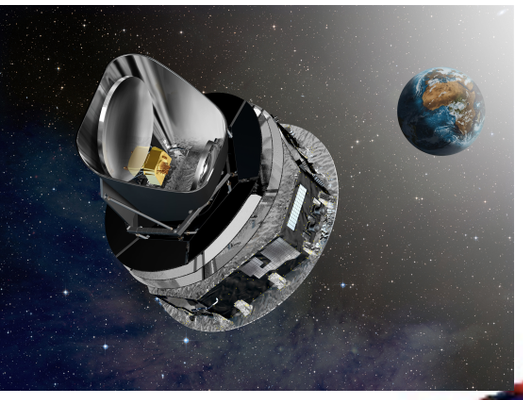
Planck 30 and 44 GHz haze map

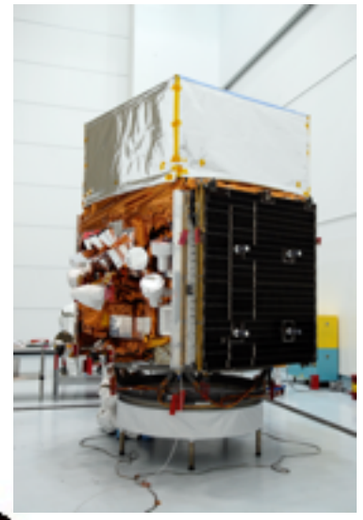


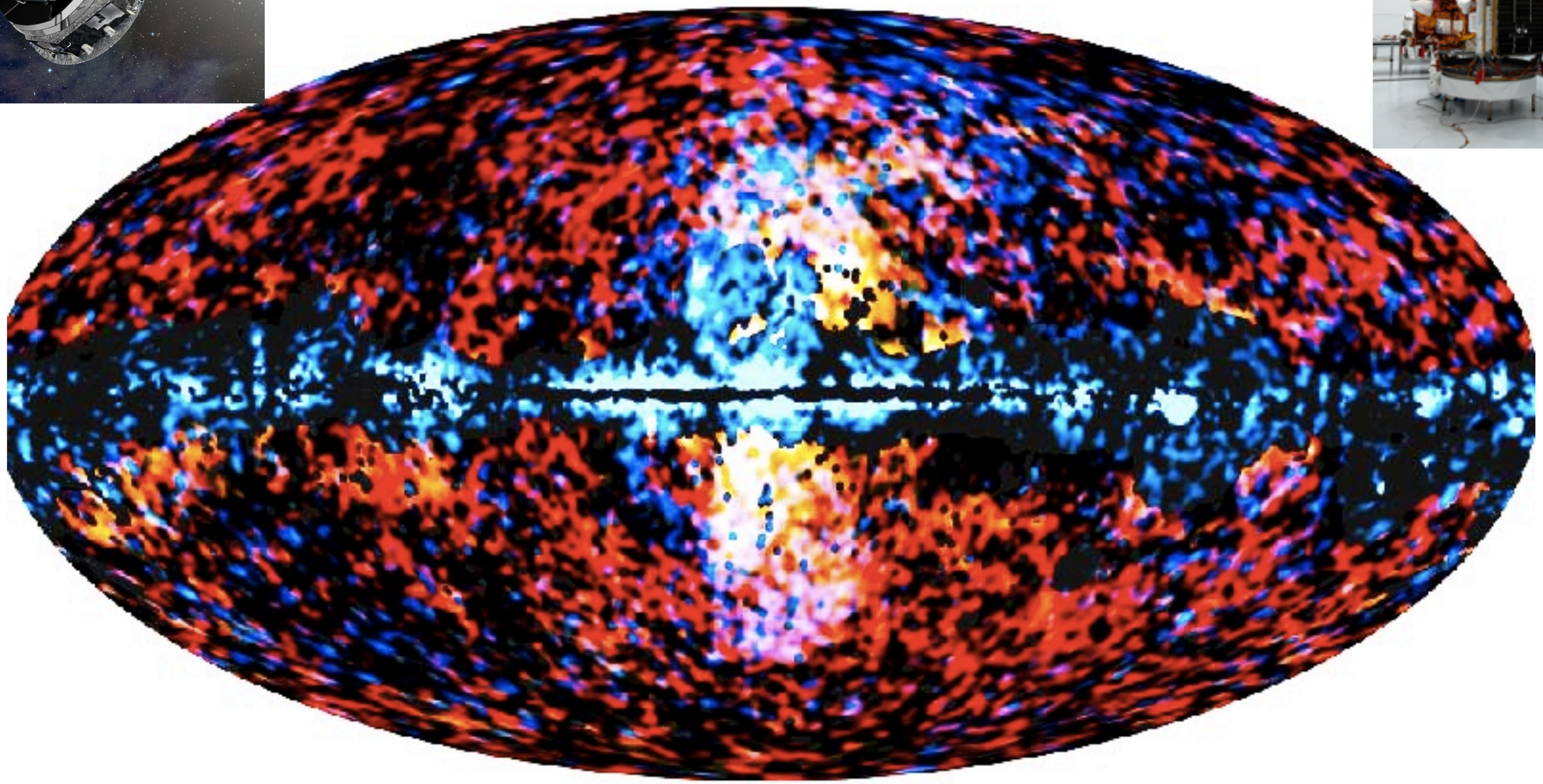


Credits: ESA/Planck Collaboration.

Haze superimposed over the FB



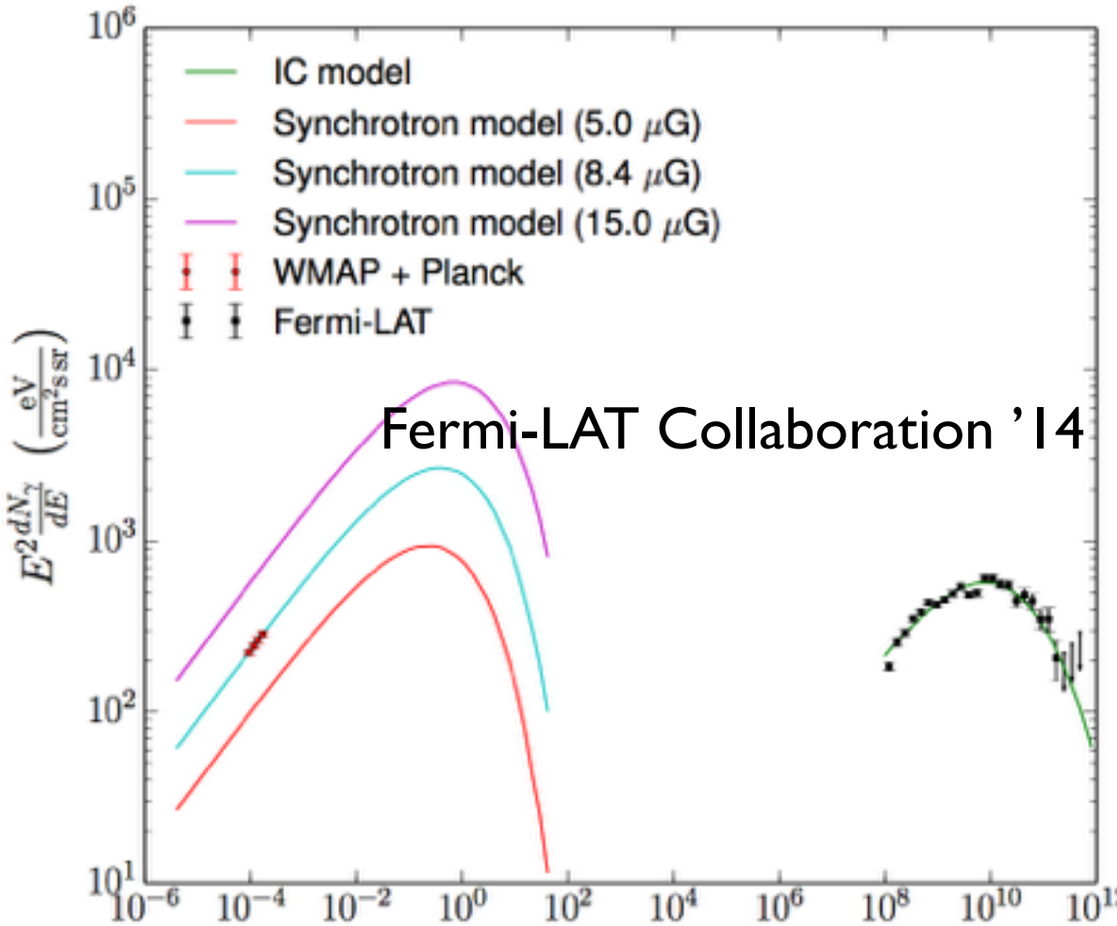


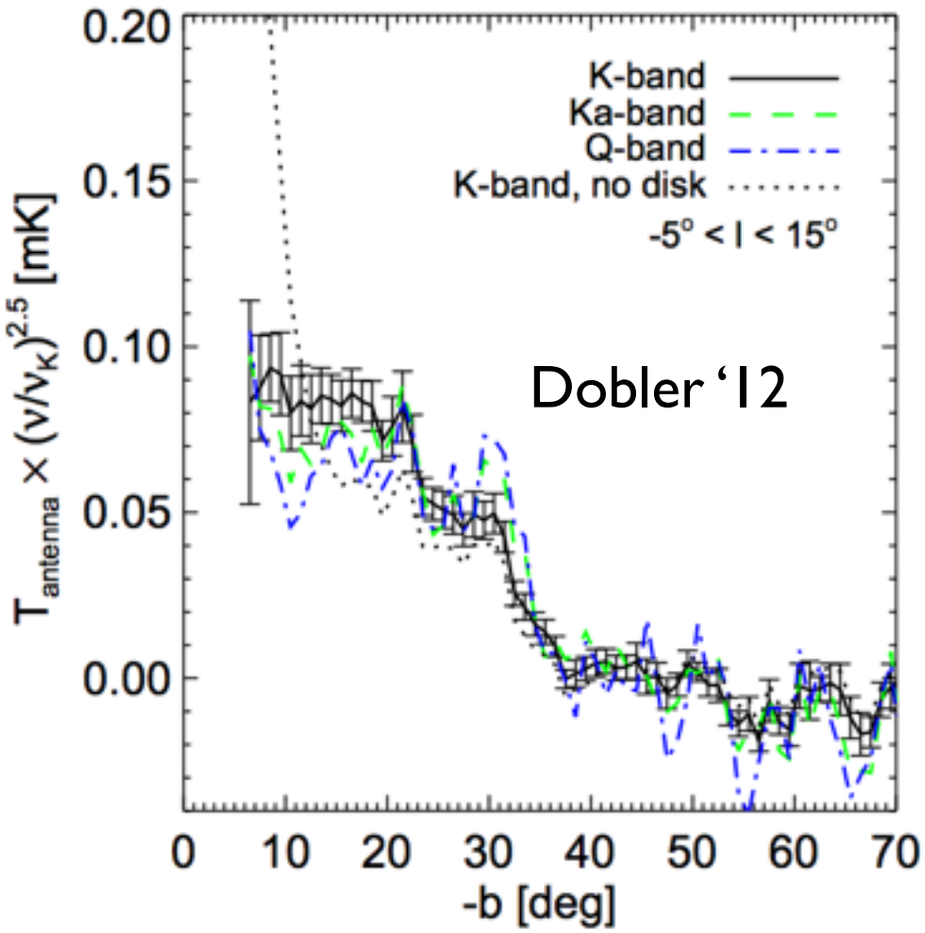


Credits: ESA/Planck Collaboration.

Microwave vs gamma-ray comparison

- Coincident microwave/gamma signals can be explained if origin is leptonic - hard electron spectrum generates microwaves via synchrotron, gammas via ICS.
- Favors at least partially leptonic scenarios.
- However, microwave haze seems to exhibit some spectral variation with latitude - not seen in gamma rays.
- Could suggest a multi-component scenario, or particular spectral evolution of electron spectrum with latitude.
- If microwaves are synchrotron, implies a B-field of at least 5μG up to ~6kpc from the Galactic plane.





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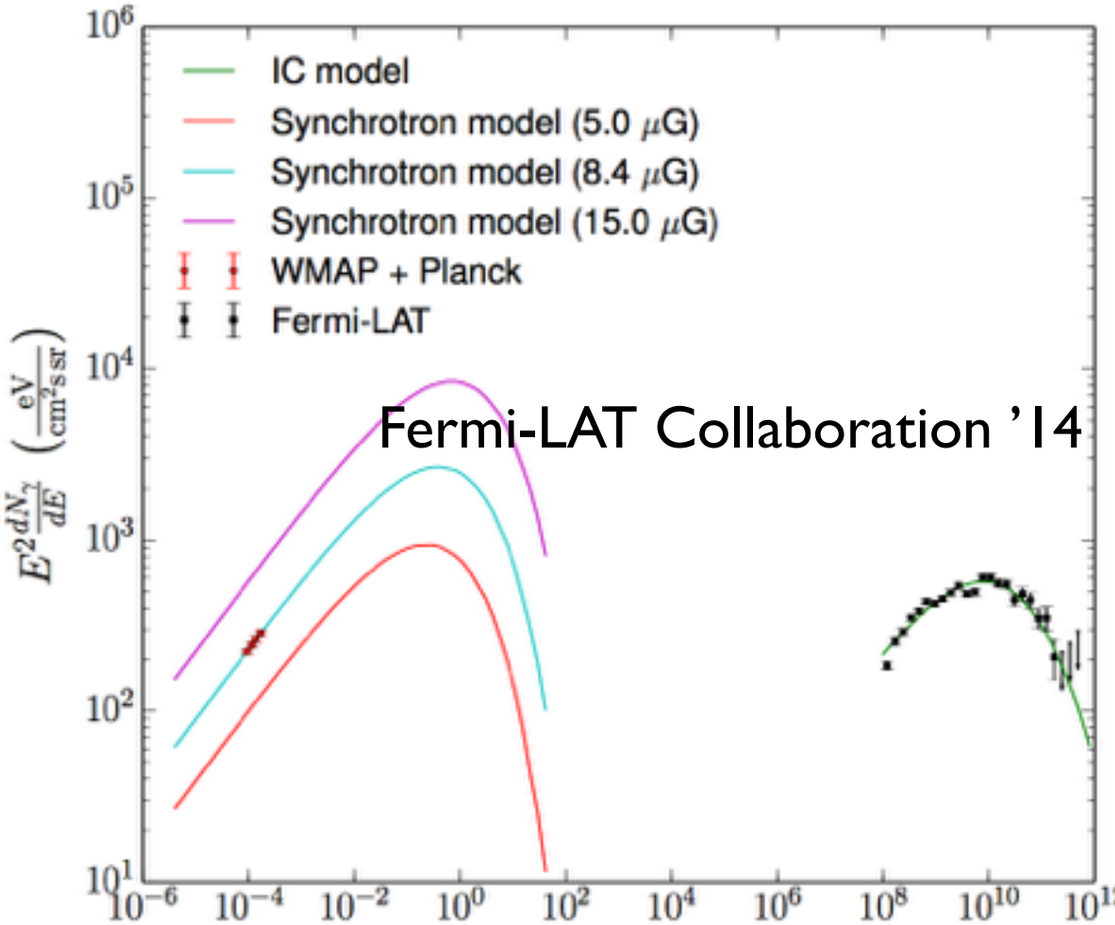

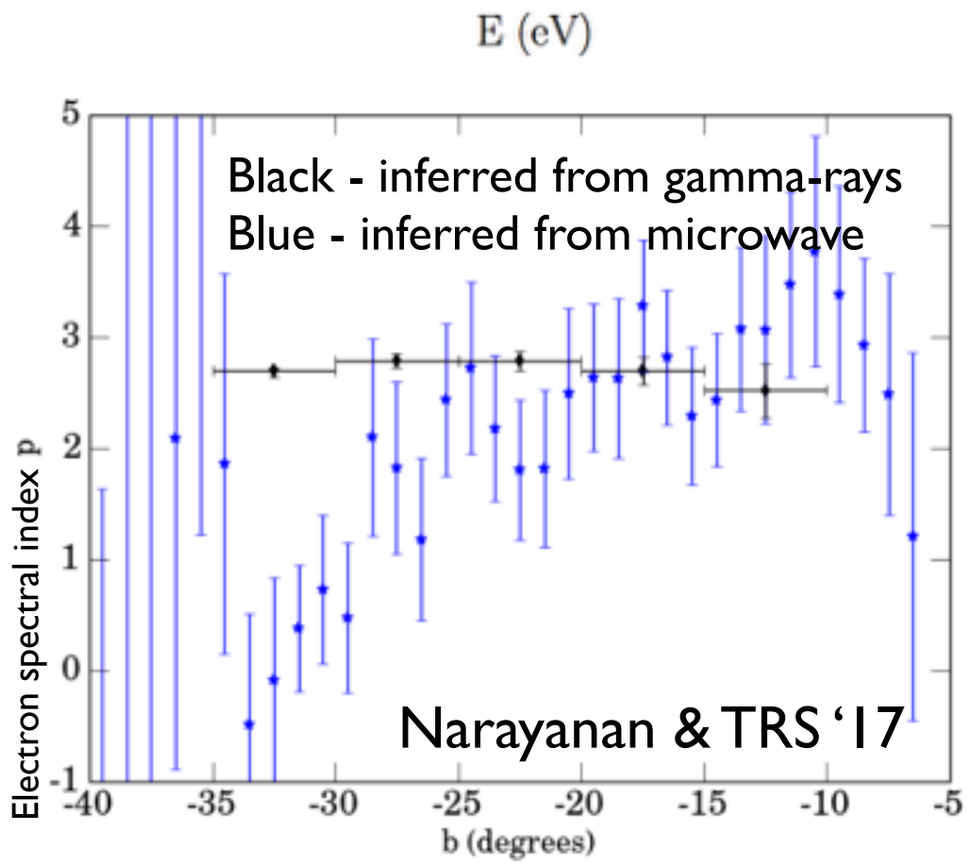

Modeling the Bubbles

see talks by Hsiang-Yi Karen Yang & Uri Keshet, and session on "Propagation in the Galaxy"

- Seems clear that the gamma rays originate from high-energy cosmic rays scattering on gas/radiation fields.
- What accelerates the cosmic rays? Where (if at all) does particle acceleration occur?
  - Stochastic Fermi acceleration in turbulent B-fields inside Bubbles (e.g. Mertsch & Sarkar '11, Cheng et al '14, '15)
  - Shocks at the expanding bubble edges (e.g. Lacki '14, Keshet & Gurwich '17)
  - Reverse shocks within the bubbles (e.g. Crocker et al '15)
- What is the source of the energy injection?
  - Jet from the supermassive black hole (SMBH) (e.g. Guo et al '12, Yang et al '12, '15, Yang & Ruszkowski '17)
  - Hot accretion phase of the SMBH fueling winds (e.g. Mou et al '14-15)
  - Starburst activity in the region surrounding the Galactic center leading to sustained nuclear outflow (e.g. Crocker et al '11, Crocker & Aharonian '11)
- Are the cosmic rays dominantly hadronic, leptonic or a mixture?
  - Hadronic (e.g. Crocker & Aharonian '11) - protons have long cooling times, can be injected over long timescales; some challenges in explaining sharp edges of Bubbles, lack of central brightening and microwave counterpart.
  - Leptonic (e.g. Yang et al '13, Yang & Ruszkowski '17) - electrons cool rapidly, need to be transported quickly or reaccelerated within Bubbles, some challenges in explaining uniform spectrum; typically connected with models where Bubbles are transient (e.g. sourced by a jet).
  - Mixture (e.g. Crocker et al '15) - gamma-rays dominantly from hadronic processes, but naturally accompanied by non-negligible leptonic component, which generates microwaves.

- How do the Fermi Bubbles behave close to the Galactic Center? How can we disentangle them from the Galactic Center Excess?
- Are Loop I and the Bubbles related to each other? If so, how?

Summary

- Fermi Bubbles are now well-established features of the gamma-ray sky, but many open questions.
- Multiwavelength counterparts in radio, microwave, UV absorption and X-rays can help narrow down the possibilities, and shed light on the history of the Galactic center.
- Aggregate data seem to suggest:
  - presence of outflows with velocities of hundreds - 1000+ km/s, over the last 5-10 Myr
  - appreciable magnetic fields (5+ μG) throughout the Bubbles
  - at least some leptonic contribution
- I look forward to many interesting results and discussions over the next few days!