Bubbles & Bumps: Disentangling Two Spectral Components in the Fermi Bubbles

Tracy Slatyer, Institute for Advanced Study
work in progress with
Dan Hooper, Fermilab / University of Chicago

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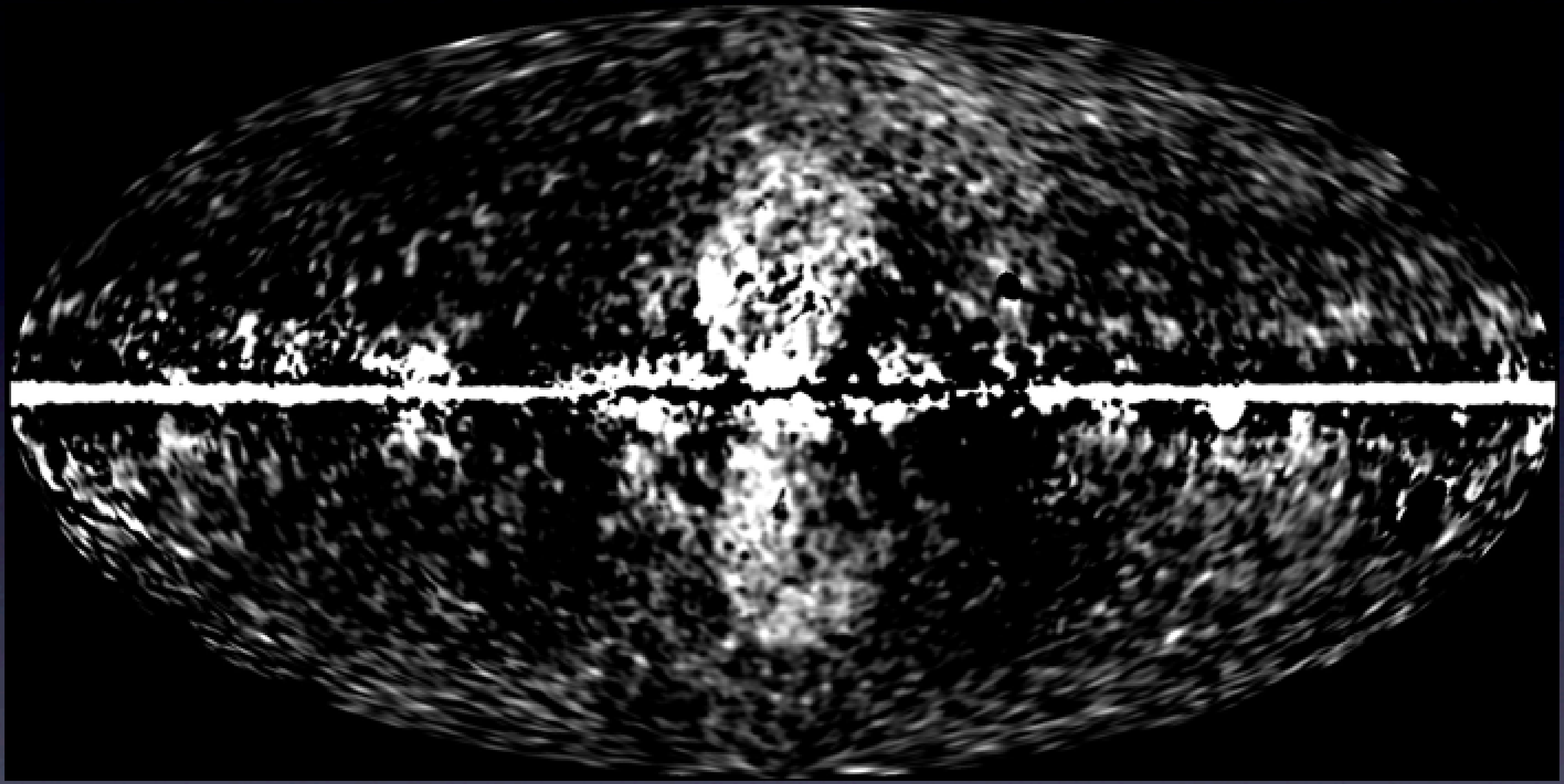
Outline

- Background
  - The Fermi bubbles
  - The microwave haze
- What we can learn from the high-latitude spectrum
  - Invariance of the high-latitude spectrum
  - Comparison to synchrotron emission
- A new emission component at low latitudes?
  - Spectrum and morphology
  - Comparison to the extended Galactic Center excess

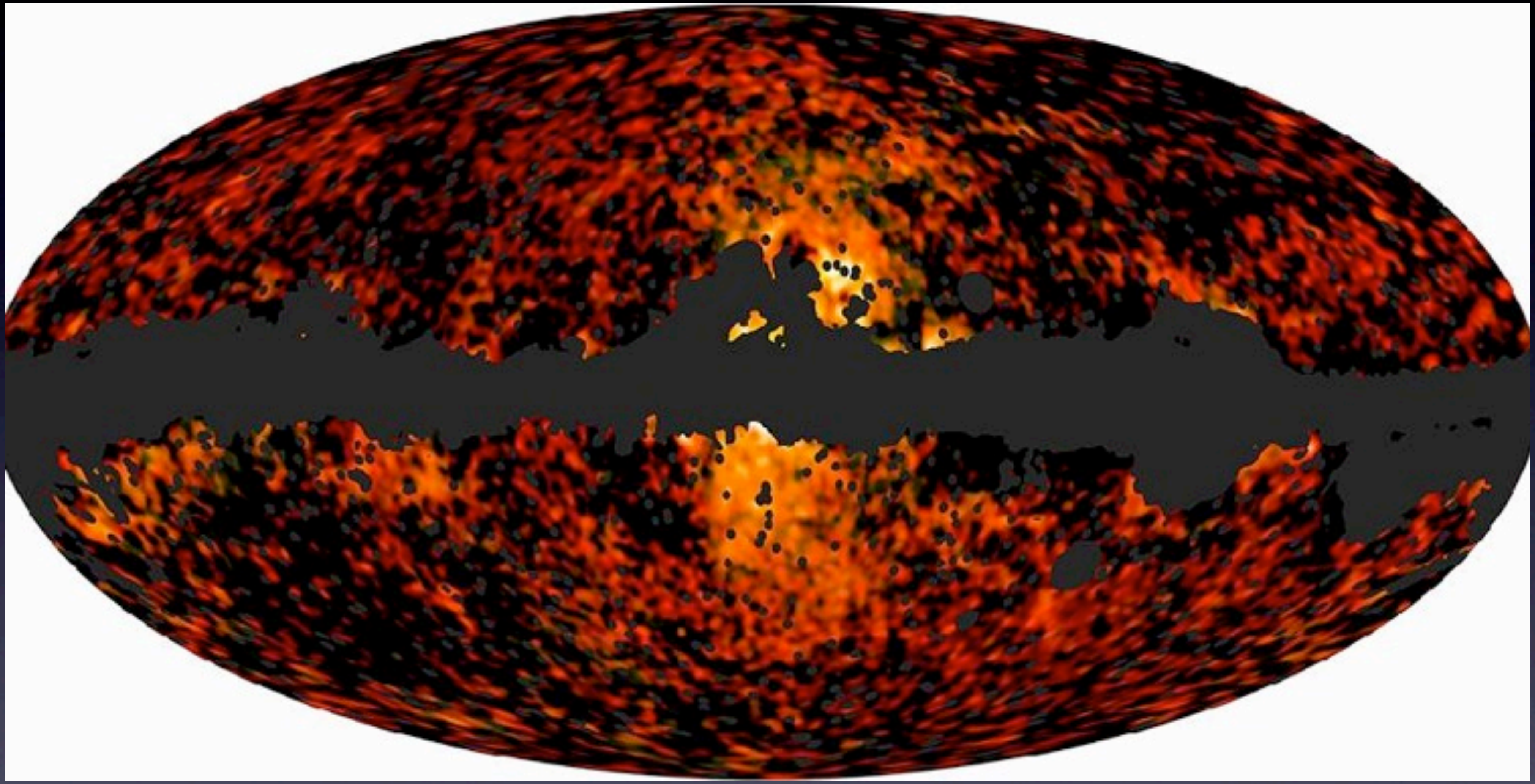
Note: Everything in this talk is PRELIMINARY! Rather than label every single plot, I'm adding this general disclaimer.

The Fermi Bubbles



- Discovered 2010 by Su, TRS & Finkbeiner in public data from the Fermi Gamma-Ray Space Telescope.
- Large-scale gamma-ray lobes extending to b ~ ±50°.
- Hard spectrum ($dN/dE \sim E^{-2}$) from ~1-200 GeV.

The microwave haze



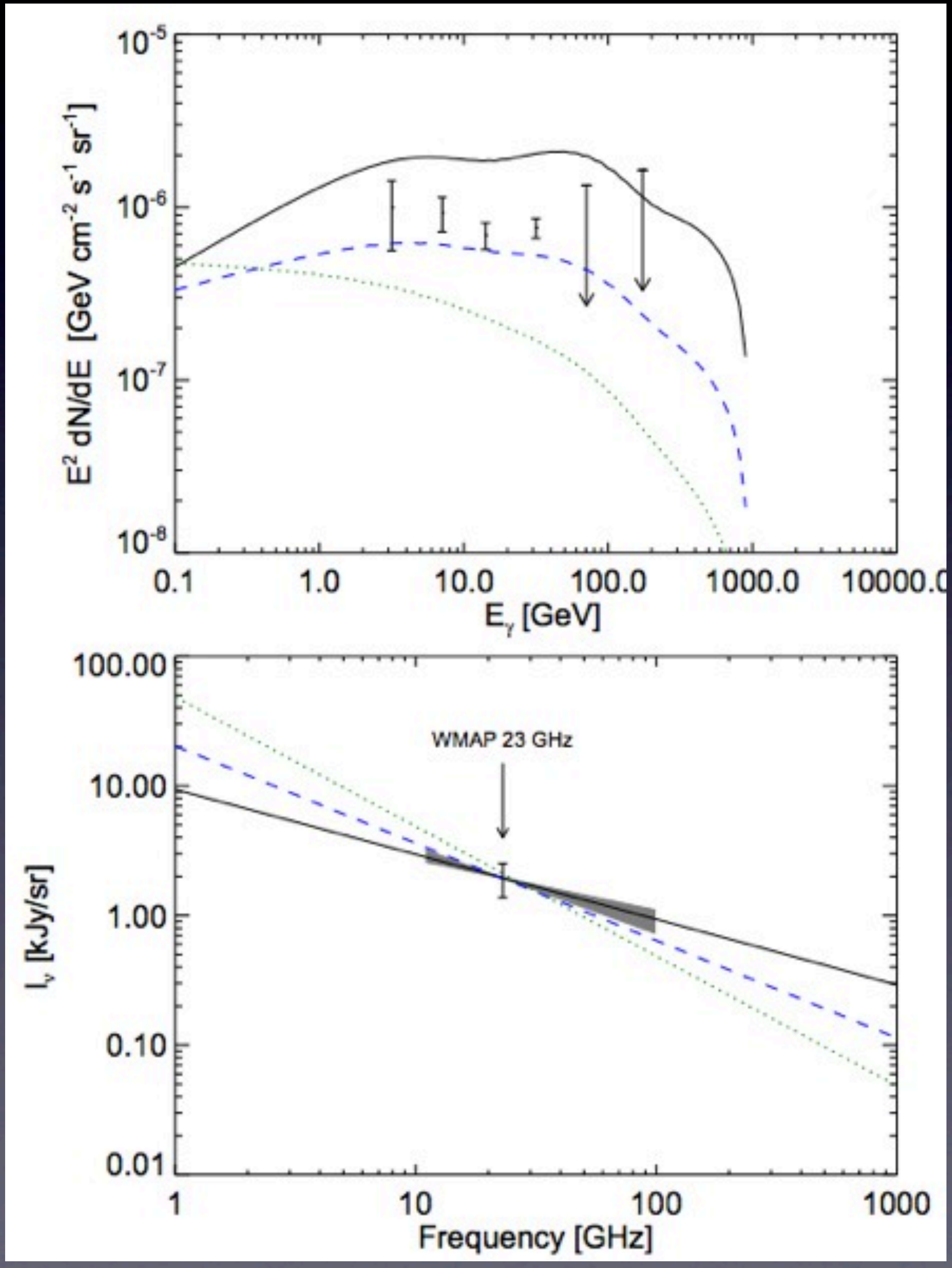
- Discovered 2003 by Finkbeiner in WMAP data, confirmed in later WMAP measurements and recently by Planck (1208.5483).
- Extended emission consistent with spectrally hard synchrotron in the inner Galaxy.

What are the Bubbles?

- Conventional sources of gamma rays in this energy range:
  - Decay of neutral pions produced by cosmic-ray protons striking the interstellar medium ("π^0 gammas").
  - Inverse Compton scattering of photons of the interstellar radiation field (CMB + direct and scattered starlight) by cosmic-ray electrons: "ICS gammas".
  - Bremsstrahlung from cosmic-ray electrons scattering on the gas (subdominant).
- Require hard cosmic-ray spectra (protons or electrons) extending to high latitudes.

The bubbles and the haze

- Most proposed models for the bubbles over the past 2.5 years involve cosmic-ray electrons, accelerated in shocks or turbulence, upscattering photons.
- Same cosmic-ray electrons produce synchrotron radiating in magnetic fields.
- Original motivation to look for the Bubbles: seeking gamma-ray counterpart of microwave haze (Dobler, Finkbeiner, Cholis, TRS & Weiner 2009).

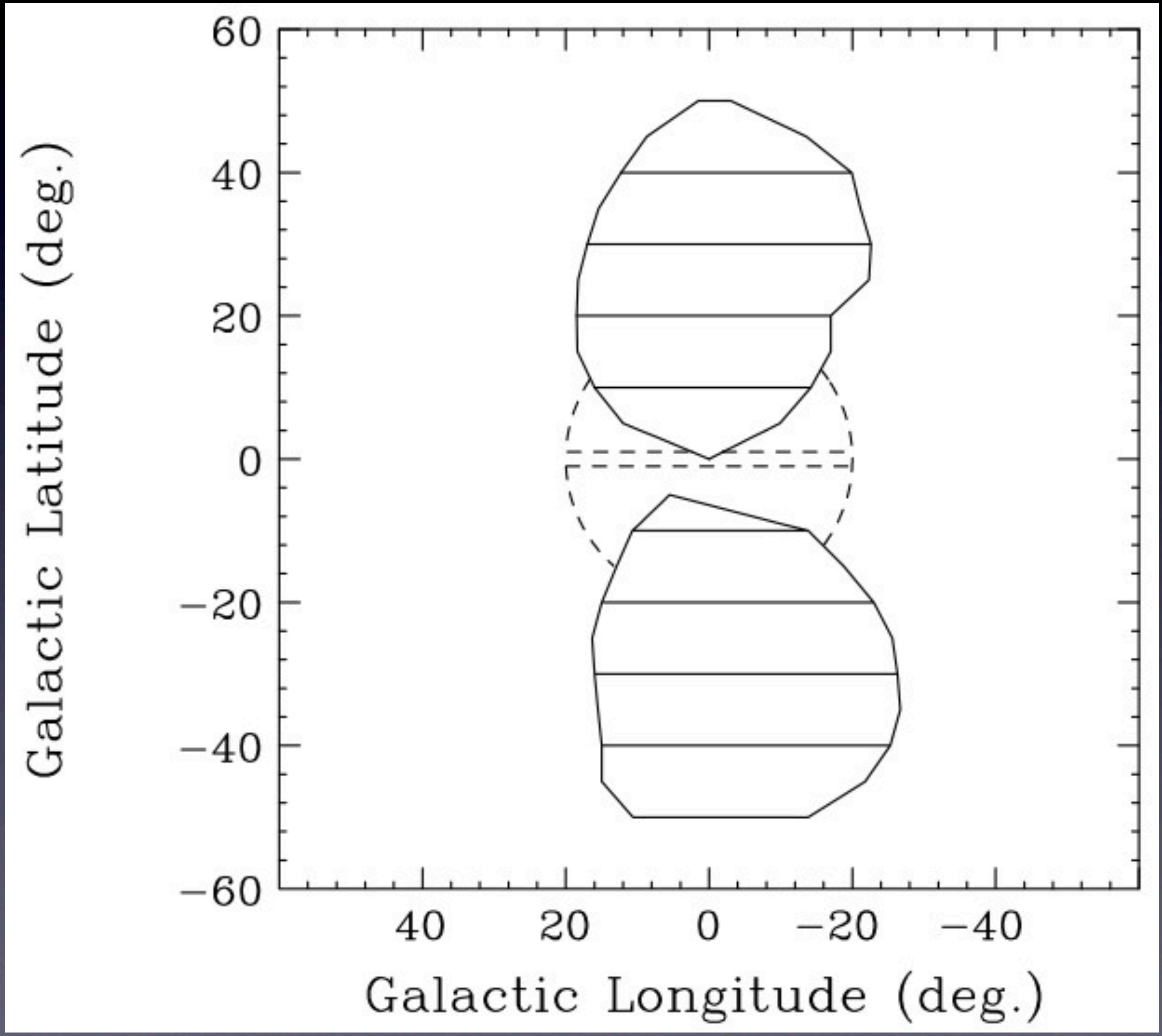


Spectral variation with latitude

- Original Bubbles study modeled them as having a single constant spectrum, found no evidence of variation from bubble edge to center, or north to south (however, only studied the spectrum for $|b| > 30°$).
- Spectral variation is a potential tool for distinguishing models for the bubbles.
  - Often the injection/acceleration mechanism varies over the bubbles.
  - In leptonic models, the expected propagation distance for electrons is << the extent of the bubbles.
- Test consistency between gamma-rays and microwaves as a function of latitude.
- Identify unexpected spectral features?

Template analysis

- Split the "bubbles template" into five 10-degree-wide bands in latitude.
- Separately float the spectrum in each of these bands.



Modeling backgrounds

- In each energy band, fit the (smoothed) data map as a linear combination of templates designed to account for the background emission, + the sliced bubble templates.
- Always include a (floating) uniform offset to account for isotropic emission and any residual cosmic-ray contamination.
- Use Schlegel-Finkbeiner-Davis (SFD) map of interstellar dust as a template for π^0 gammas.

The Galactic diffuse model

- Method 1: use a diffuse-emission model made available by the Fermi Collaboration, using dust and gas maps to model the π^0 emission and modeling ICS using GALPROP.
- Model was developed using the p6v11 data (we do not use the Pass 7 model as it contains an artificial template for the Fermi Bubbles already).
- Advantages: physically motivated, accounts for expected spectral variation of separate contributions to the emission with distance from the plane.
- Disadvantages: complicated, fitted to data not taking the Bubbles into account.
- Fit parameters in each energy bin:
  - Coefficient of the diffuse model (interpolated to that energy).
  - Uniform offset.
  - Coefficients of the sliced bubble templates.

Low-energy subtraction

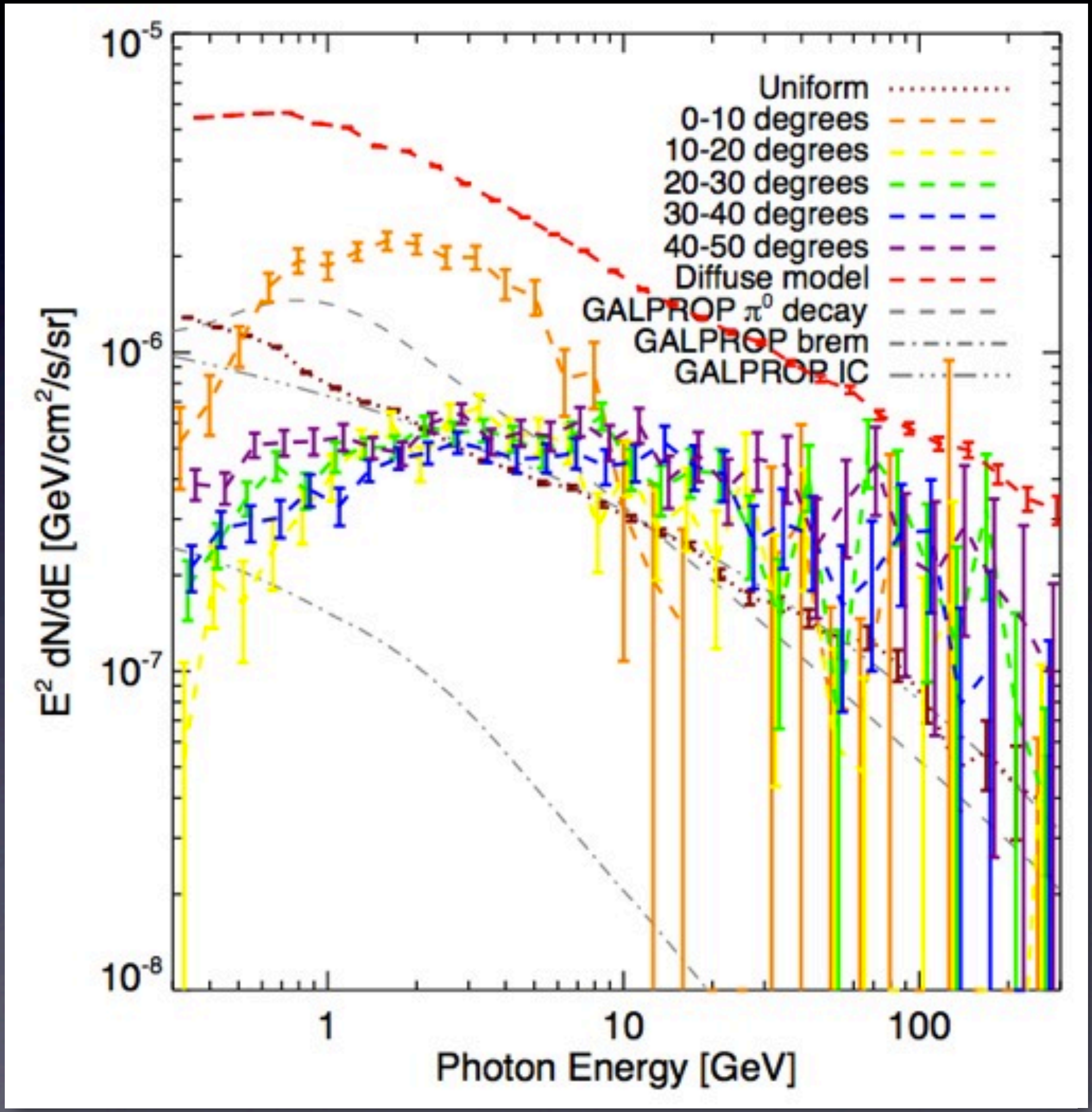
- Method 2: use the 0.5-1 GeV map with dust-correlated emission subtracted as an ICS template.
- Advantages: data-driven, simple to interpret (identifies spectrally hard emission).
- Disadvantages: spectrum of any new components must go to zero by construction at 0.5-1 GeV, can't probe spectrum in this range.
- Fit parameters in each energy bin:
    - Coefficient of the (0.5-1 GeV map - dust-correlated emission).
    - Coefficient of the SFD dust map.
    - Coefficient of a template for Loop 1 (large soft-spectrum structure in the northern sky, believed to be local).
    - Uniform offset.
    - Coefficients of the sliced bubble templates.

A simple geometric model

- Method 3: use a simple smooth geometric template (Gaussian in longitude, cosec b in latitude), to remove ICS emission.
- Advantages: cannot introduce or hide sharp spatial features, works well at high latitude (primary method for original Fermi Bubbles analysis).
- Disadvantages: poor model of emission at low latitudes, large residuals and fit dominated by the region closest to the plane (unstable to masking of the disk).
- Fit parameters in each energy bin:
    - Coefficient of the "simple disk" template.
    - Coefficient of the SFD dust map.
    - Coefficient of a template for Loop 1 (large soft-spectrum structure in the northern sky, believed to be local).
    - Uniform offset.
    - Amplitudes of the sliced bubble templates.

Spectra by latitude

- At high latitudes (|b| > 30°) the spectrum is nearly invariant with latitude.
- At low latitudes (|b| < 10°), in all background subtraction methods, there is a pronounced bump peaking at several GeV.



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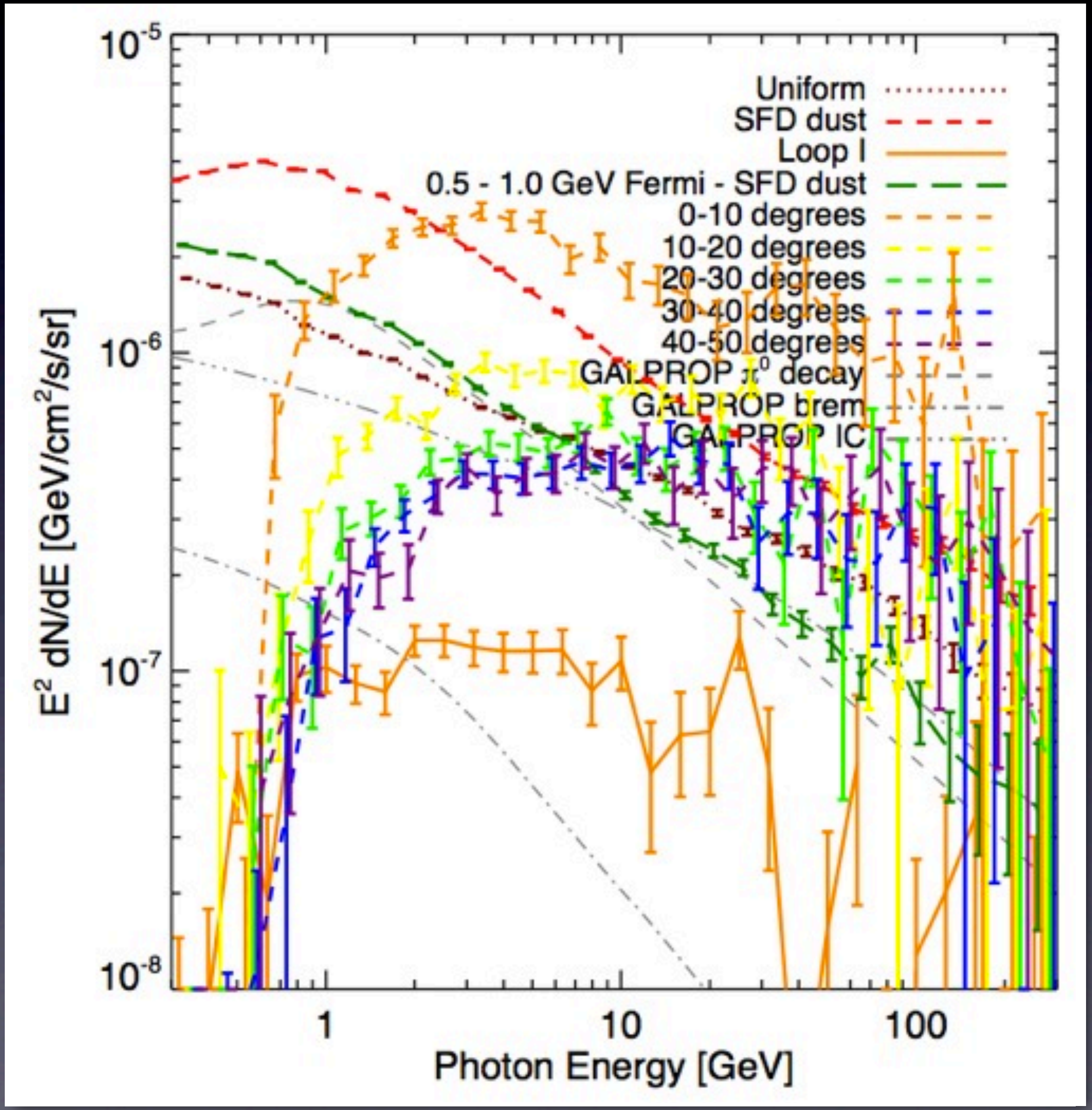

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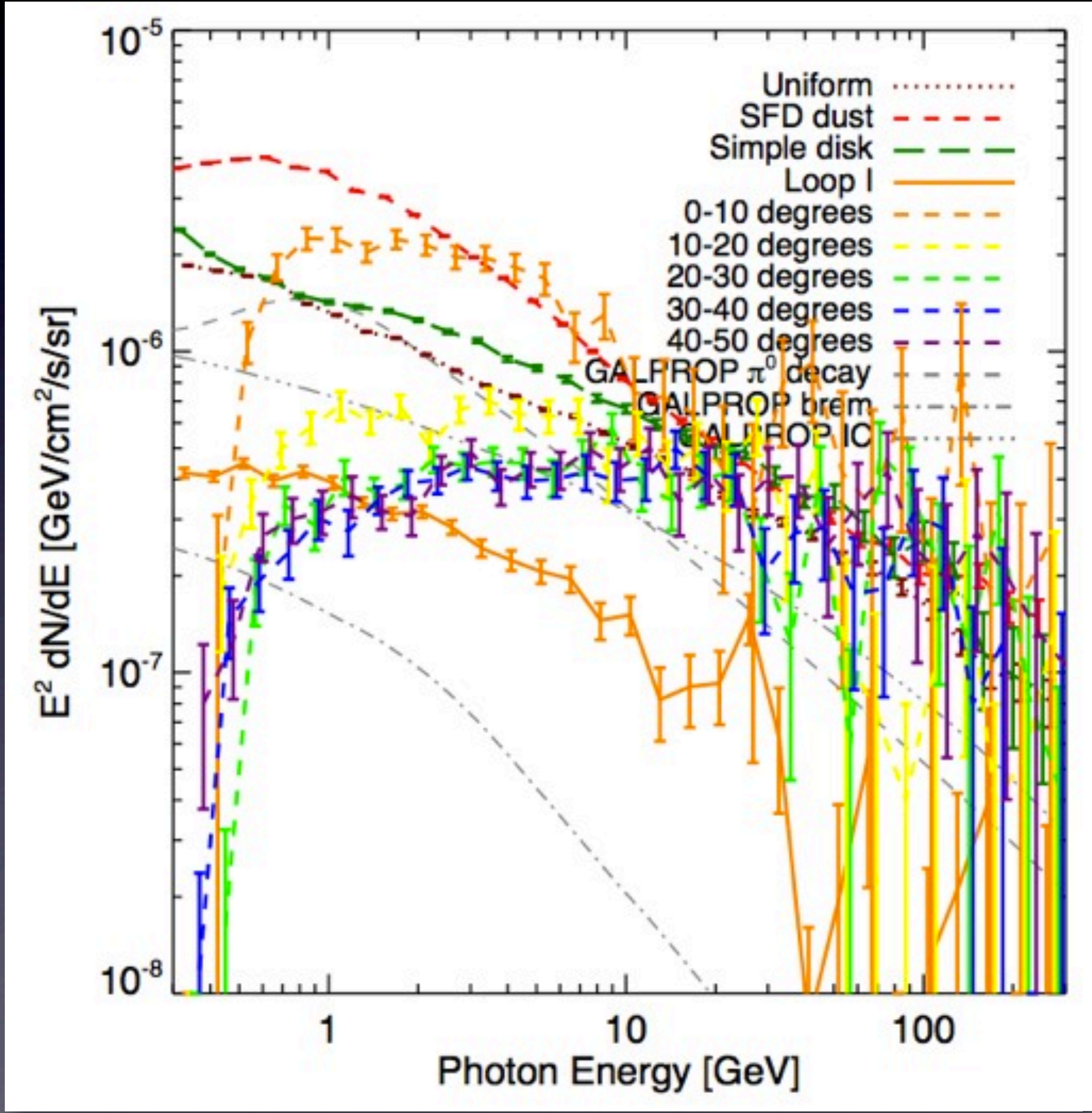
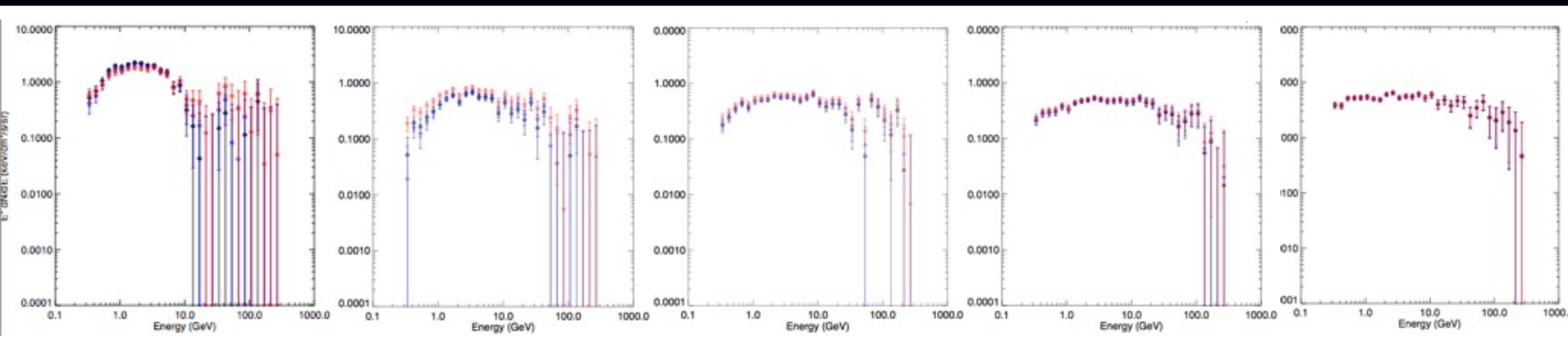


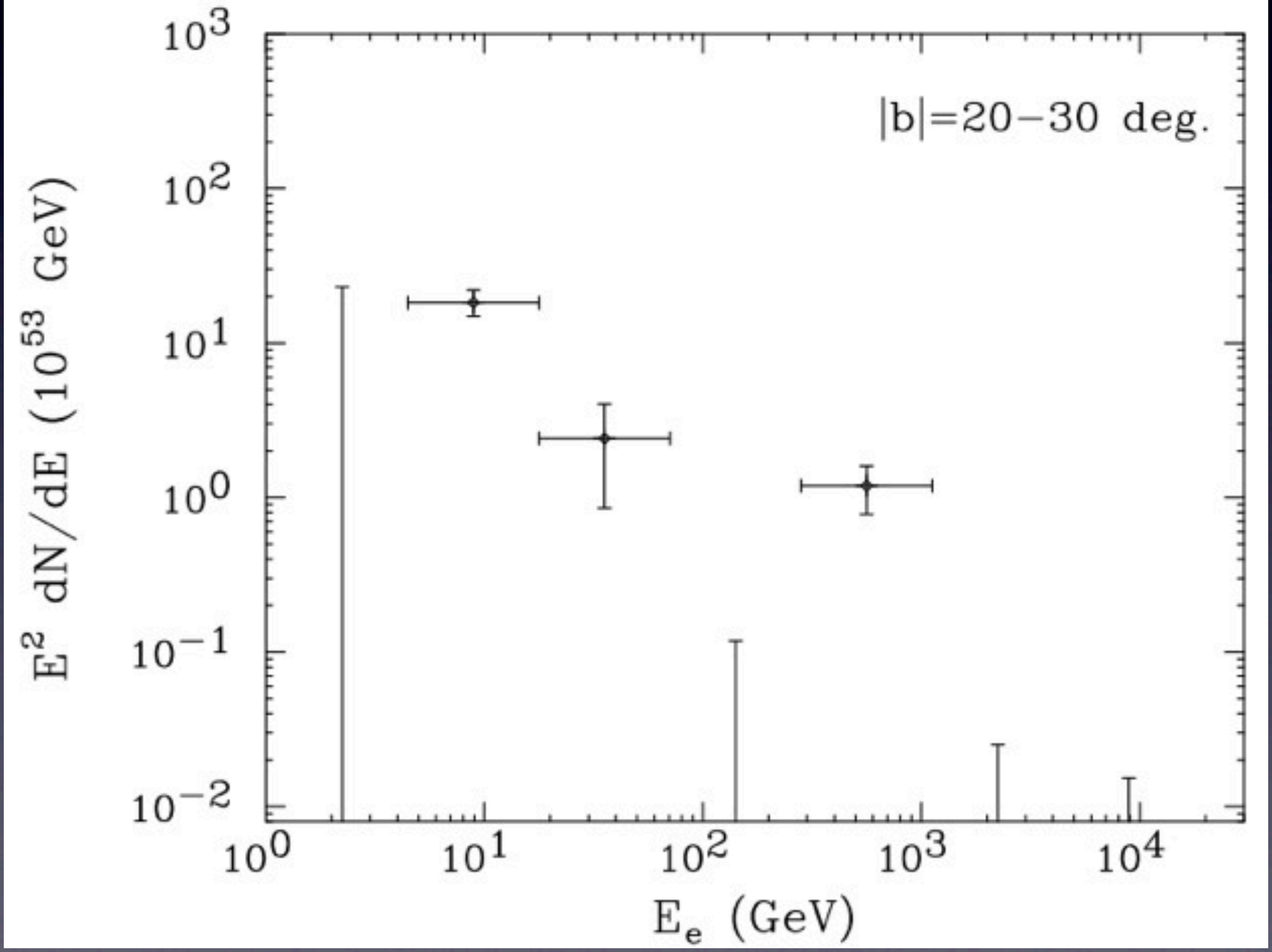
Contamination from the Galactic disk?



- One concern is bright disk-correlated emission, especially at low energies where the PSF is large.
- Vary the masking of the disk through |b| < 1°, 2°, 5°.
- Stable for diffuse model and low-energy template. Badly unstable for simple disk template (which poorly models the emission at low latitudes).

High-latitude emission as ICS

- Using standard GALPROP ISRF model, extract electron spectrum from gamma-rays: ~power law dN/dE ~ E^{-3} between a few GeV and several TeV.
- Hints of a dip around 100 GeV.
- Spectrum is harder and less power-law-like at lower latitudes (but also a worse fit to the data).



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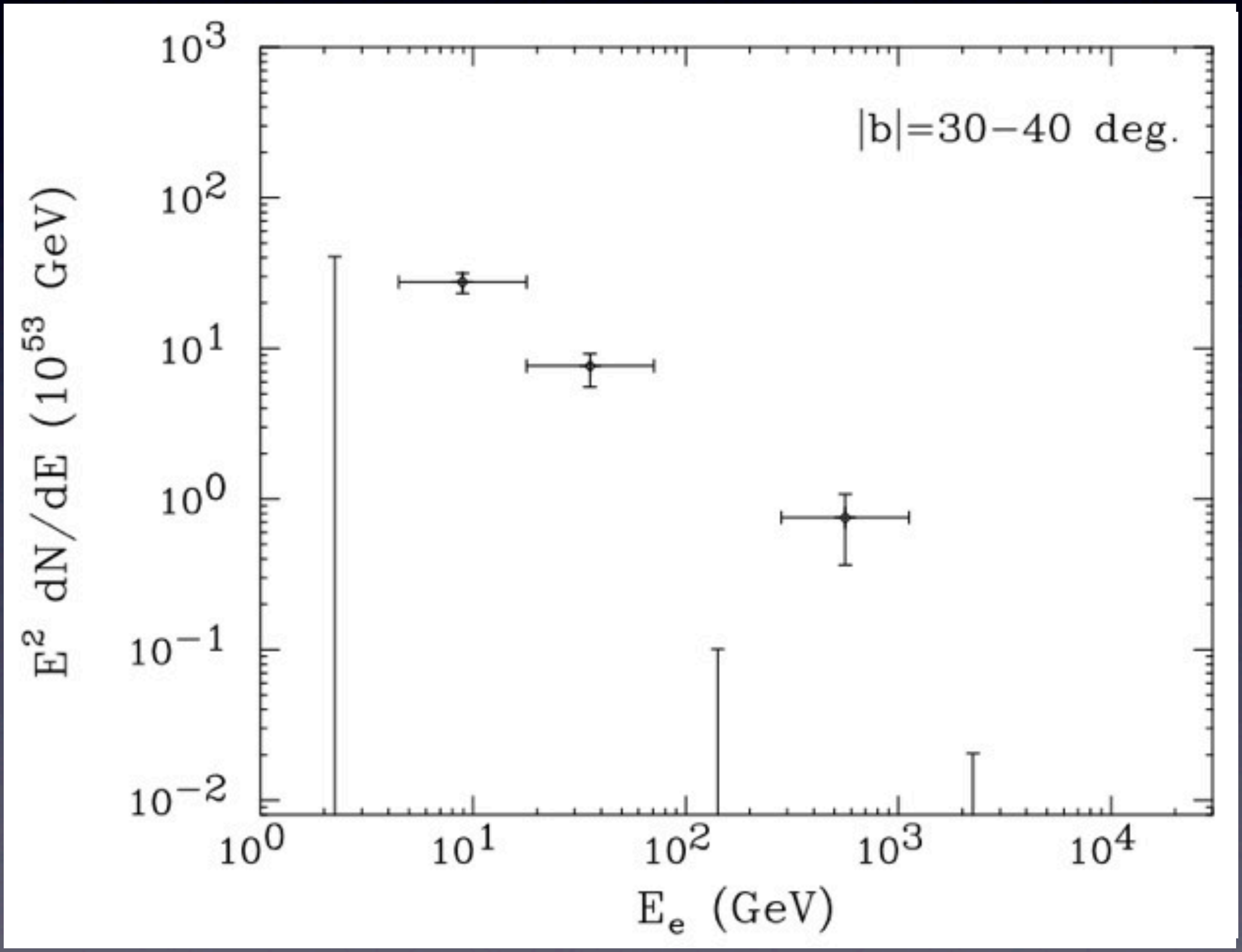

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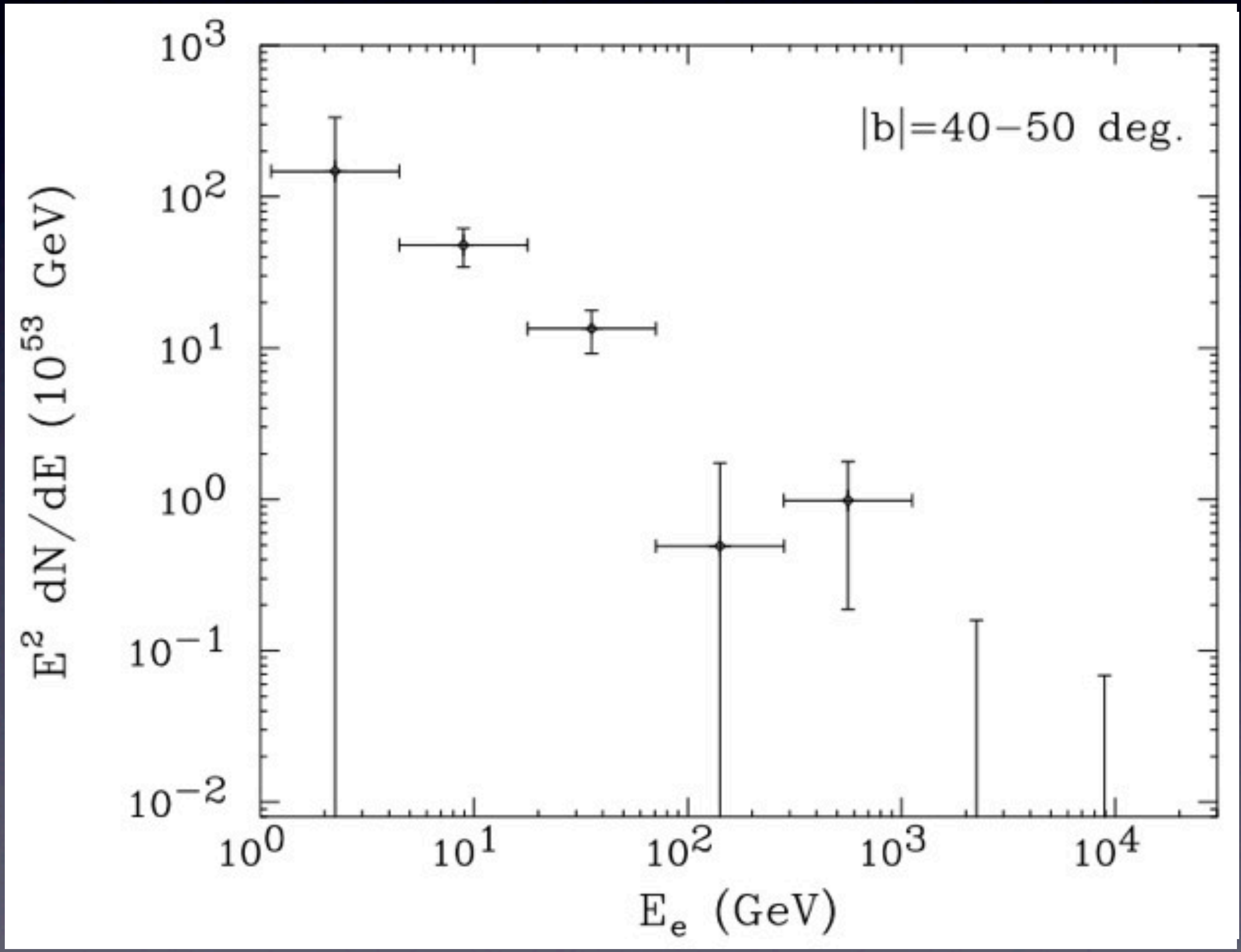
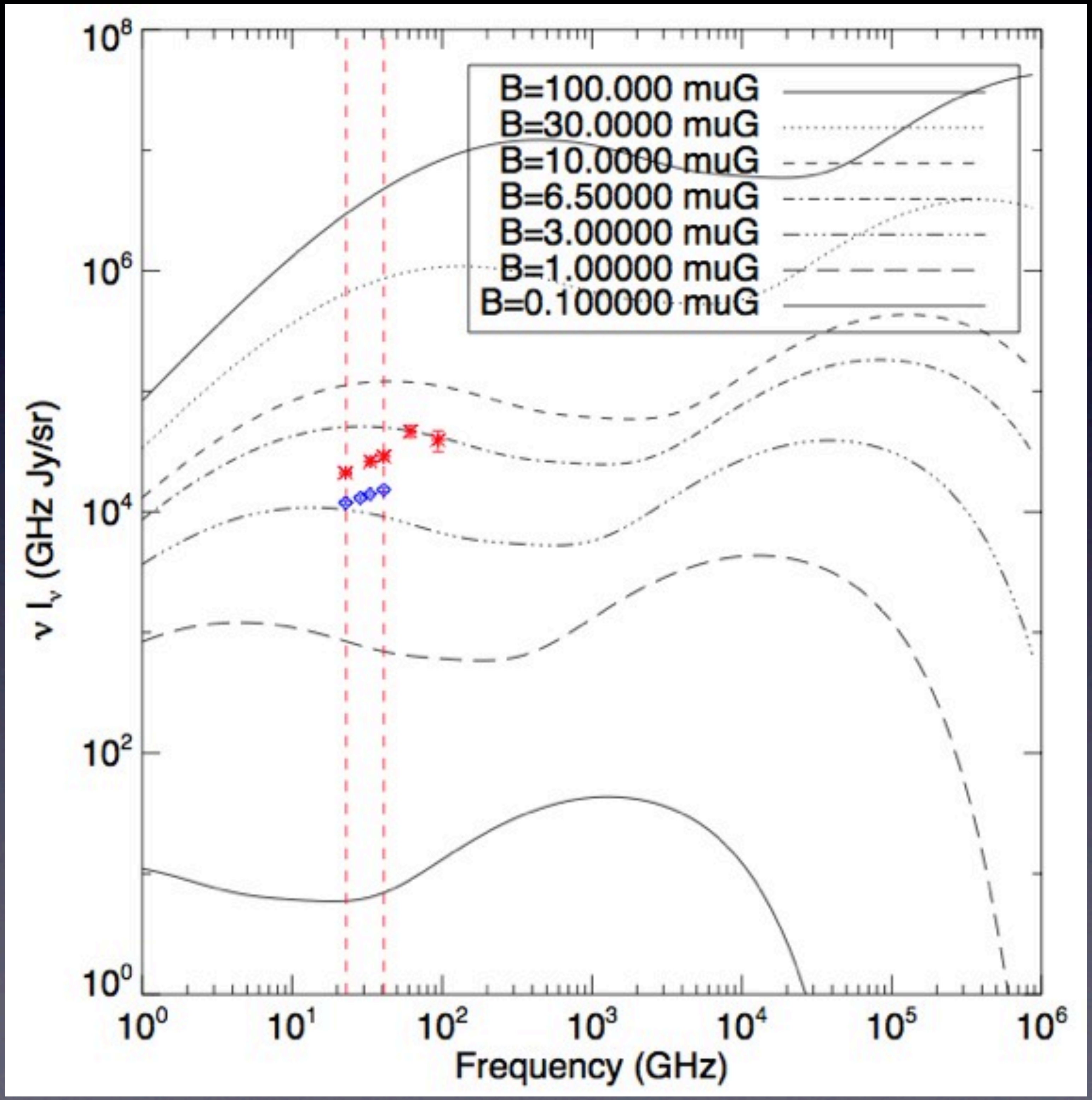


From ICS to synchrotron

- Striking spatial correspondence between microwaves and gamma-rays.
- Compute synchrotron spectrum from electron spectrum (central values only here), compare to observed haze emission in the same latitude bands (Dobler 2011).
- Amplitudes consistent for few-microGauss fields, microwaves prefer a harder spectrum.



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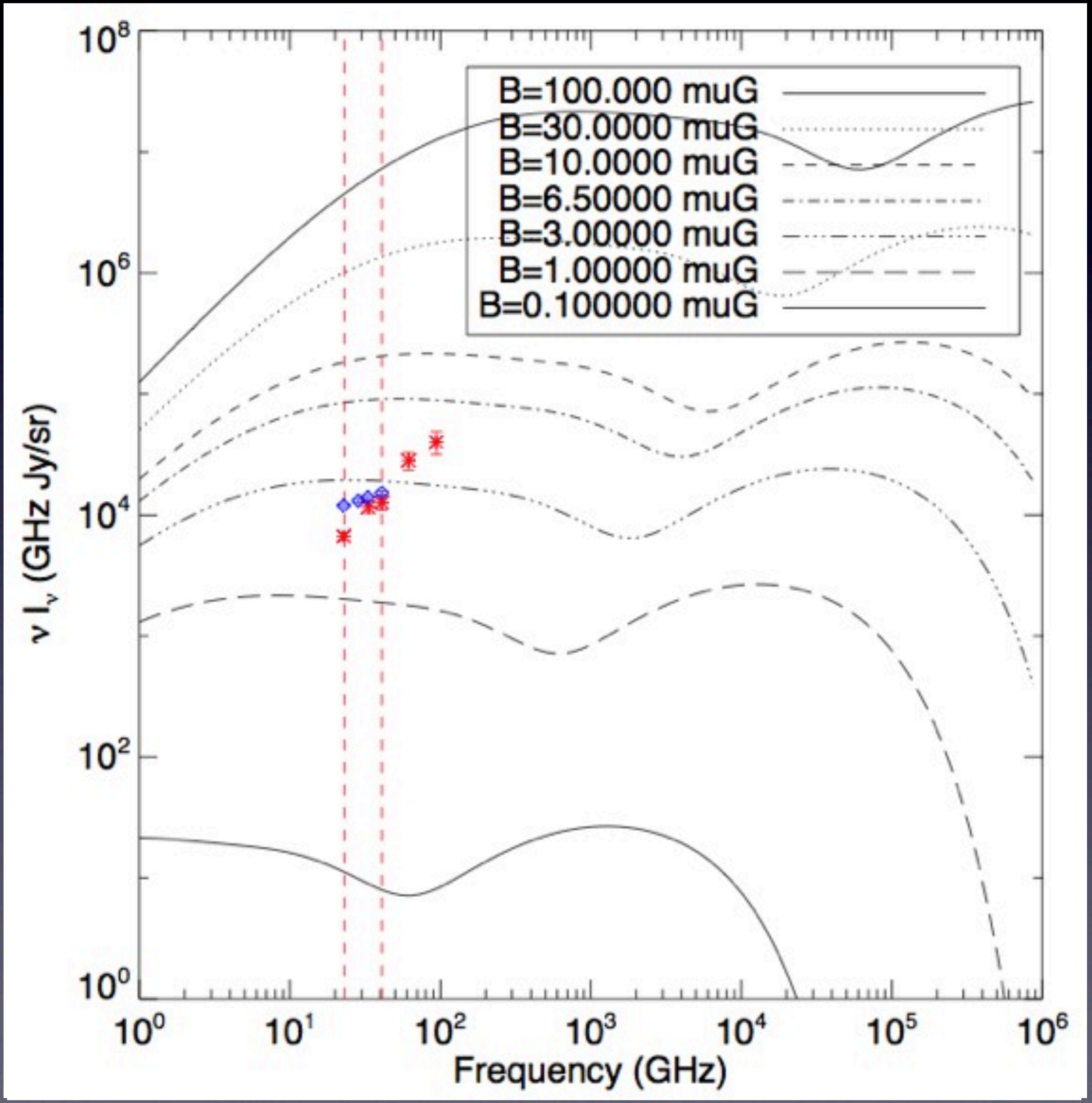

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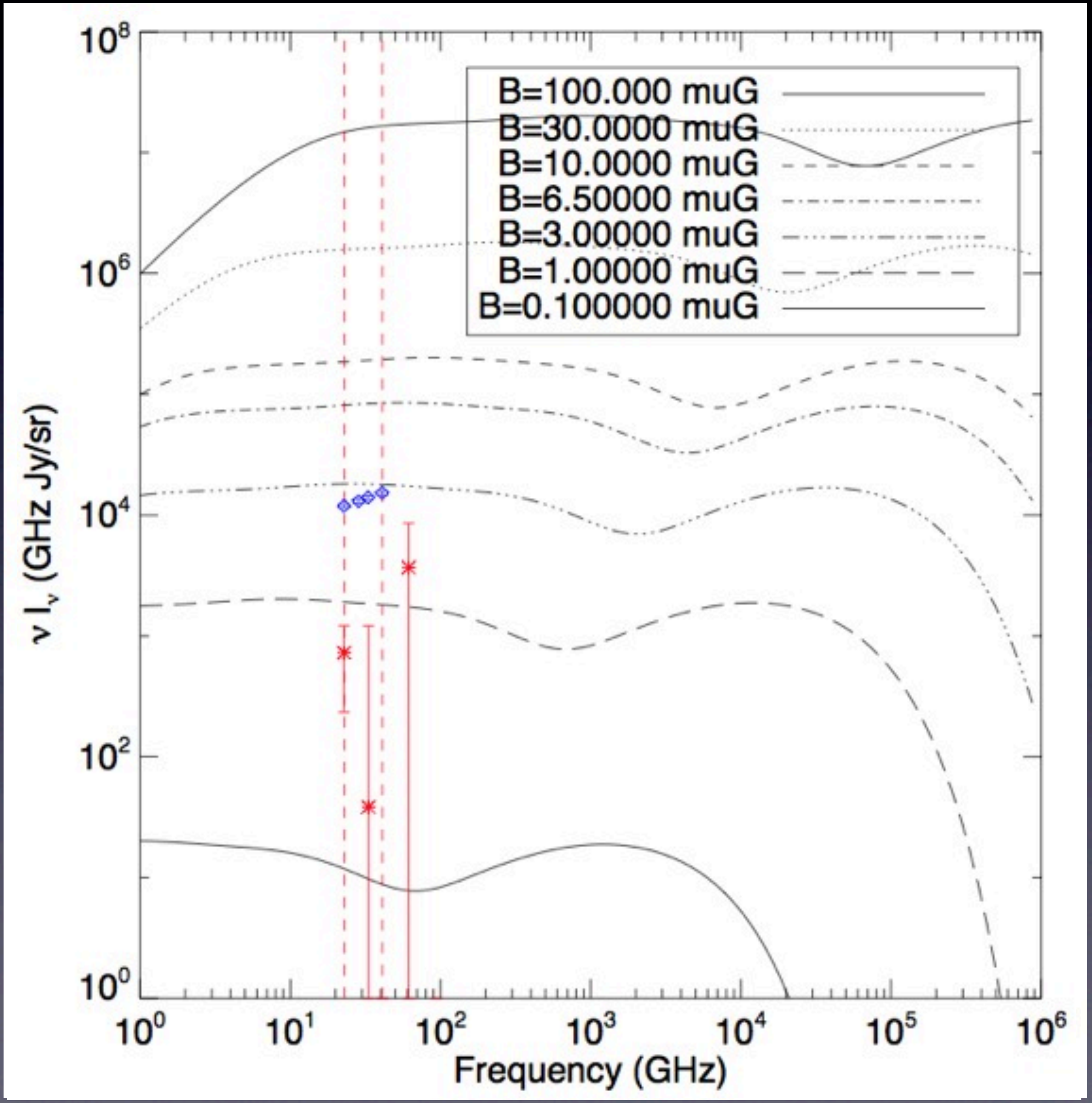
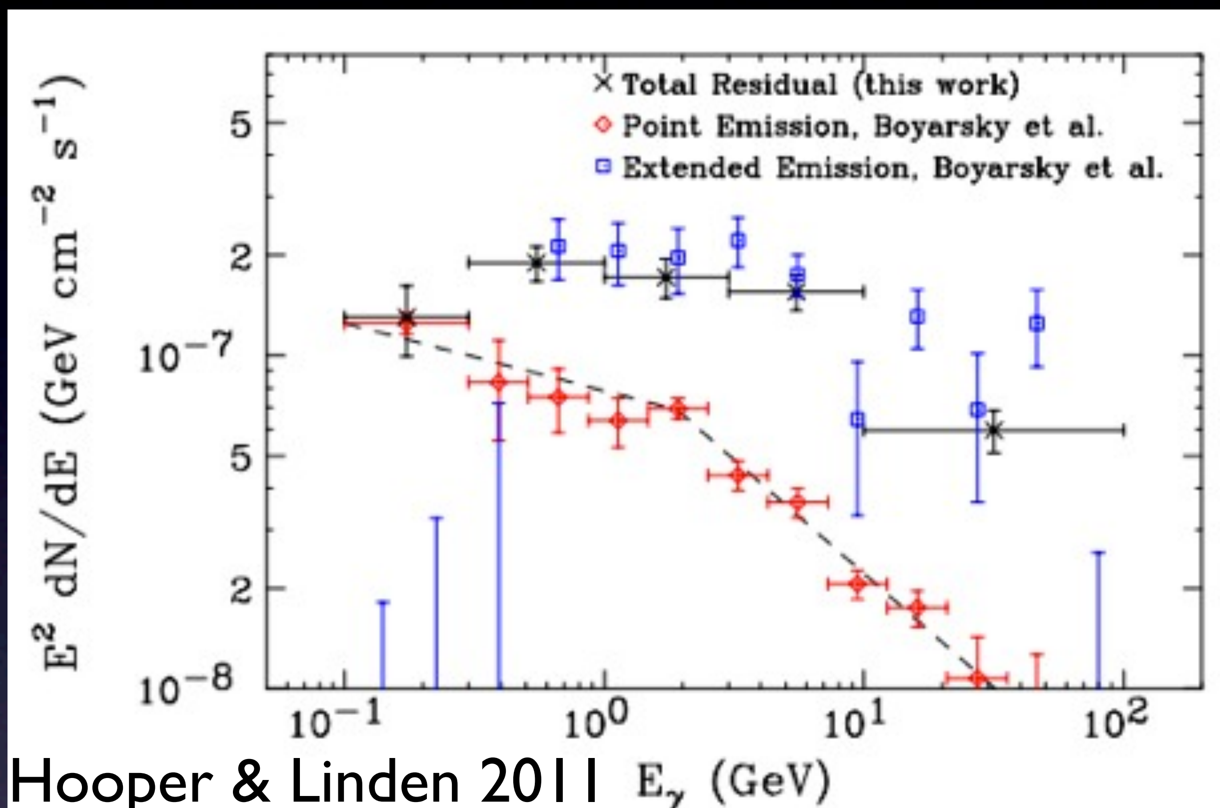
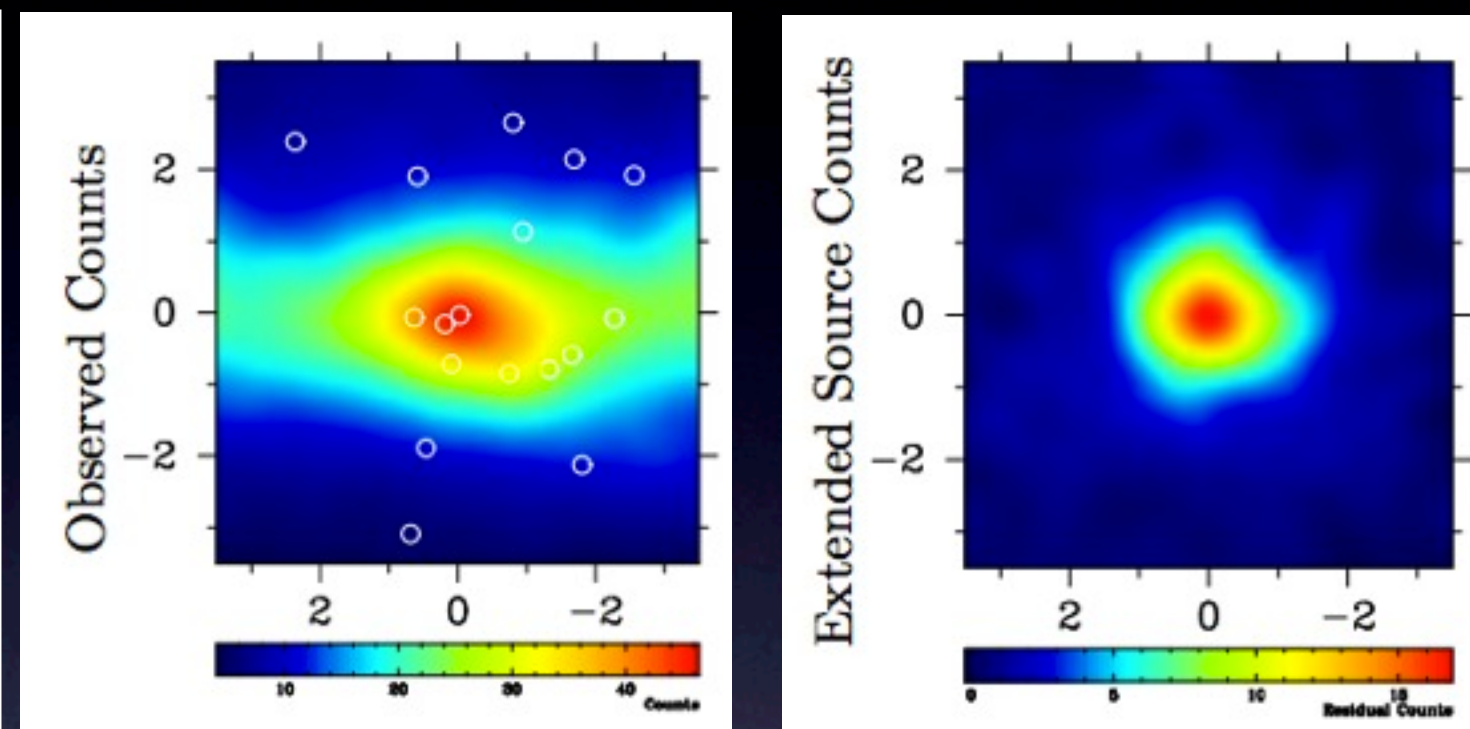


The Galactic Center excess



Hooper & Linden 2011

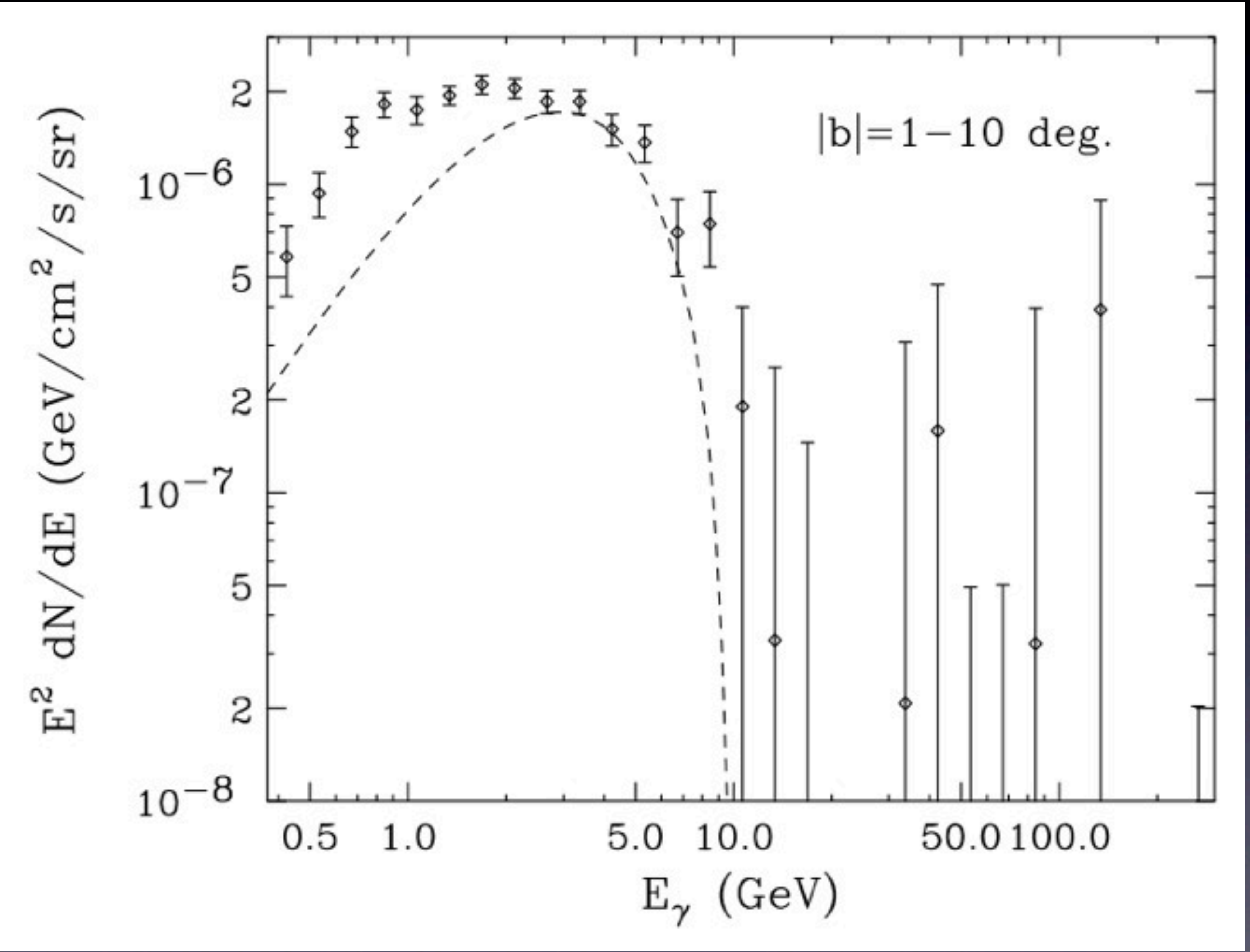


Abazajian & Kaplinghat 2012

- Spectrum reminiscent of the few-GeV bump in the inner Galaxy studied by Hooper & Goodenough; Hooper & Linden; Boyarsky, Malyshev & Ruchayskiy; Abazajian & Kaplinghat.
- Discussed extensively in earlier talks, so I will not reiterate details.
- However, that signal was detected dominantly in the ~1° surrounding the GC - a region we always mask completely.

A consistent signal?

- Assume high-latitude emission is ICS.
- Take the high-latitude electron spectrum, assume the same spectrum at low latitudes, compute photon spectrum from scattering on the ISRF.
- In each band, normalize ICS spectrum to fit high-energy data, subtract it and look at the residual bubble-correlated emission.



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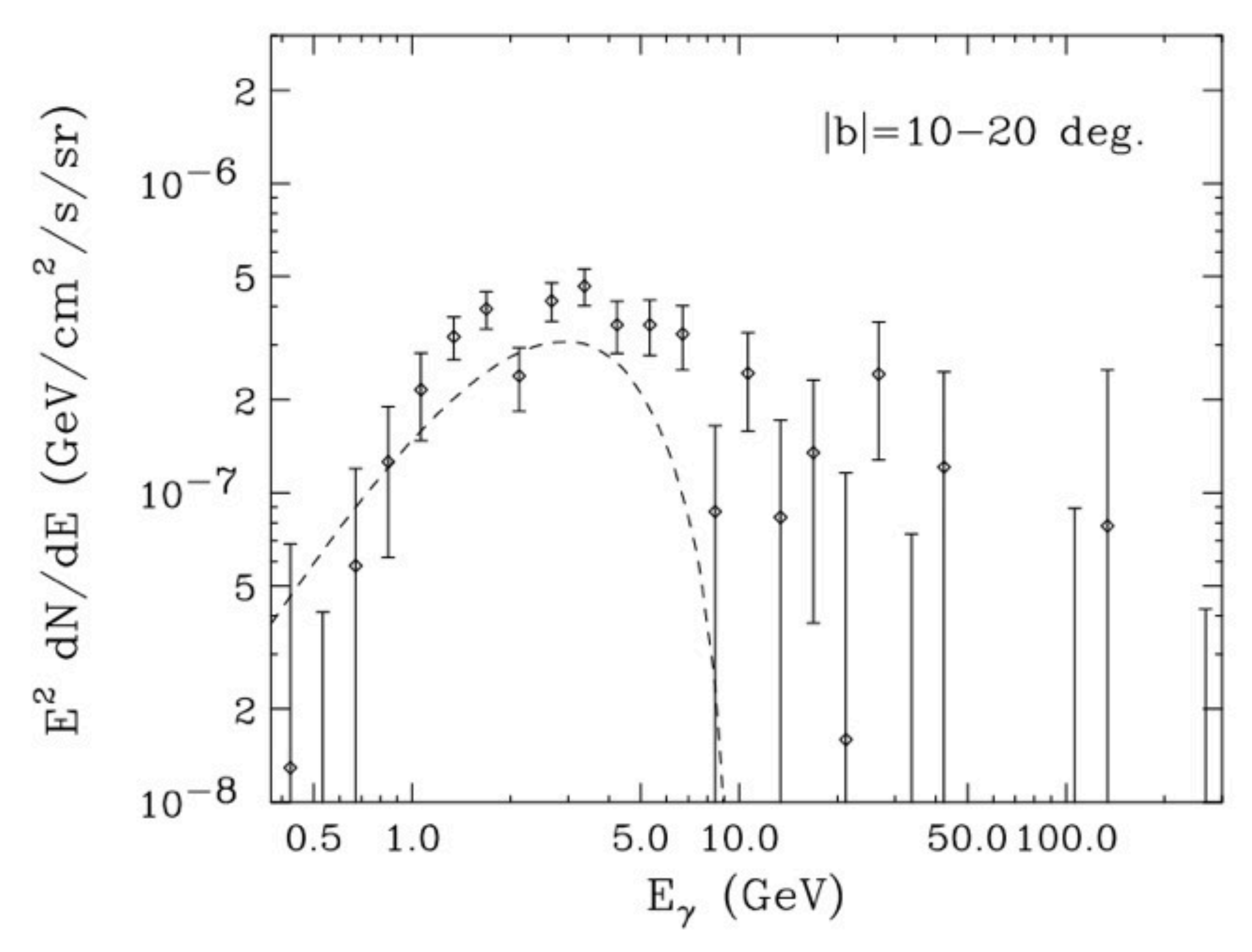

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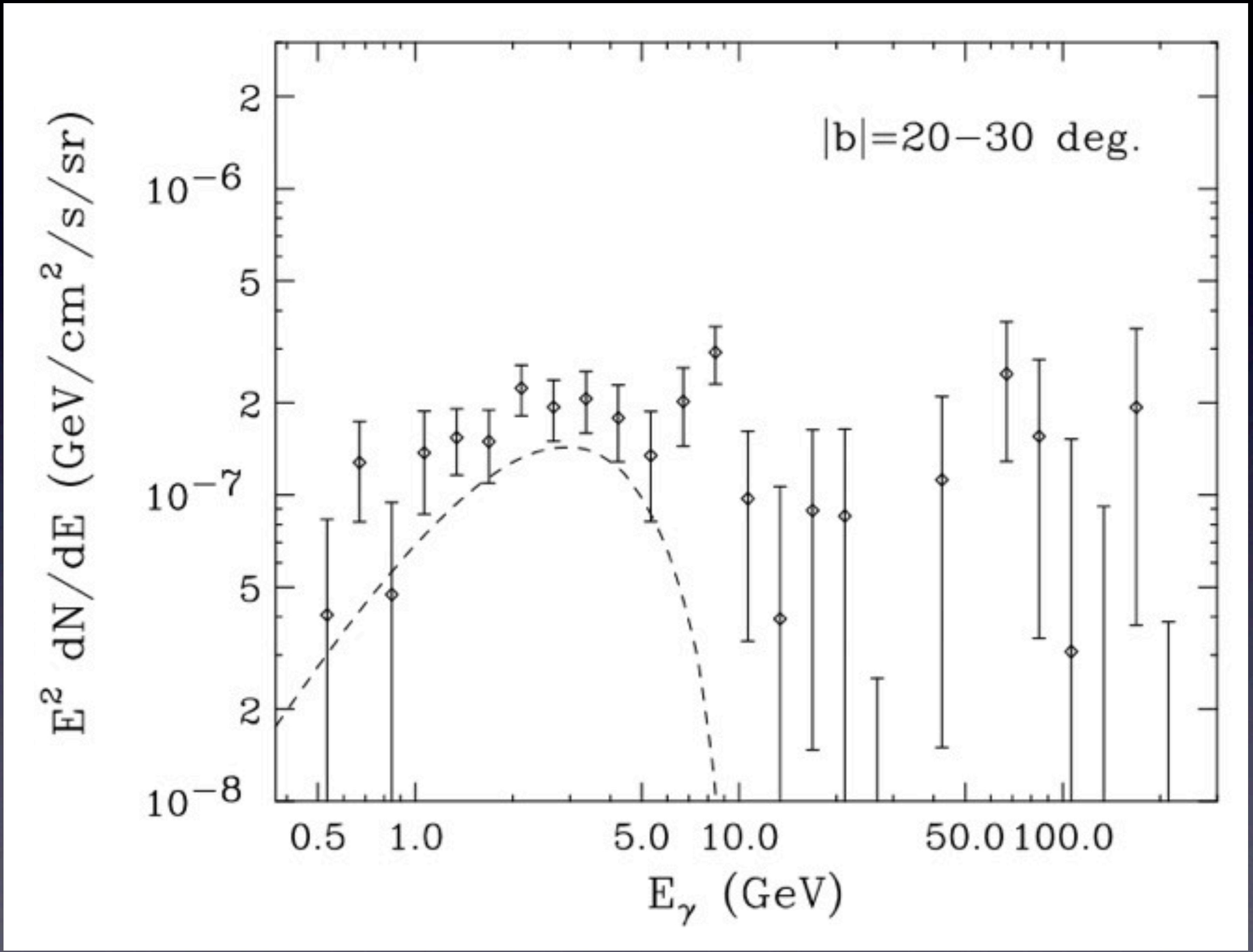

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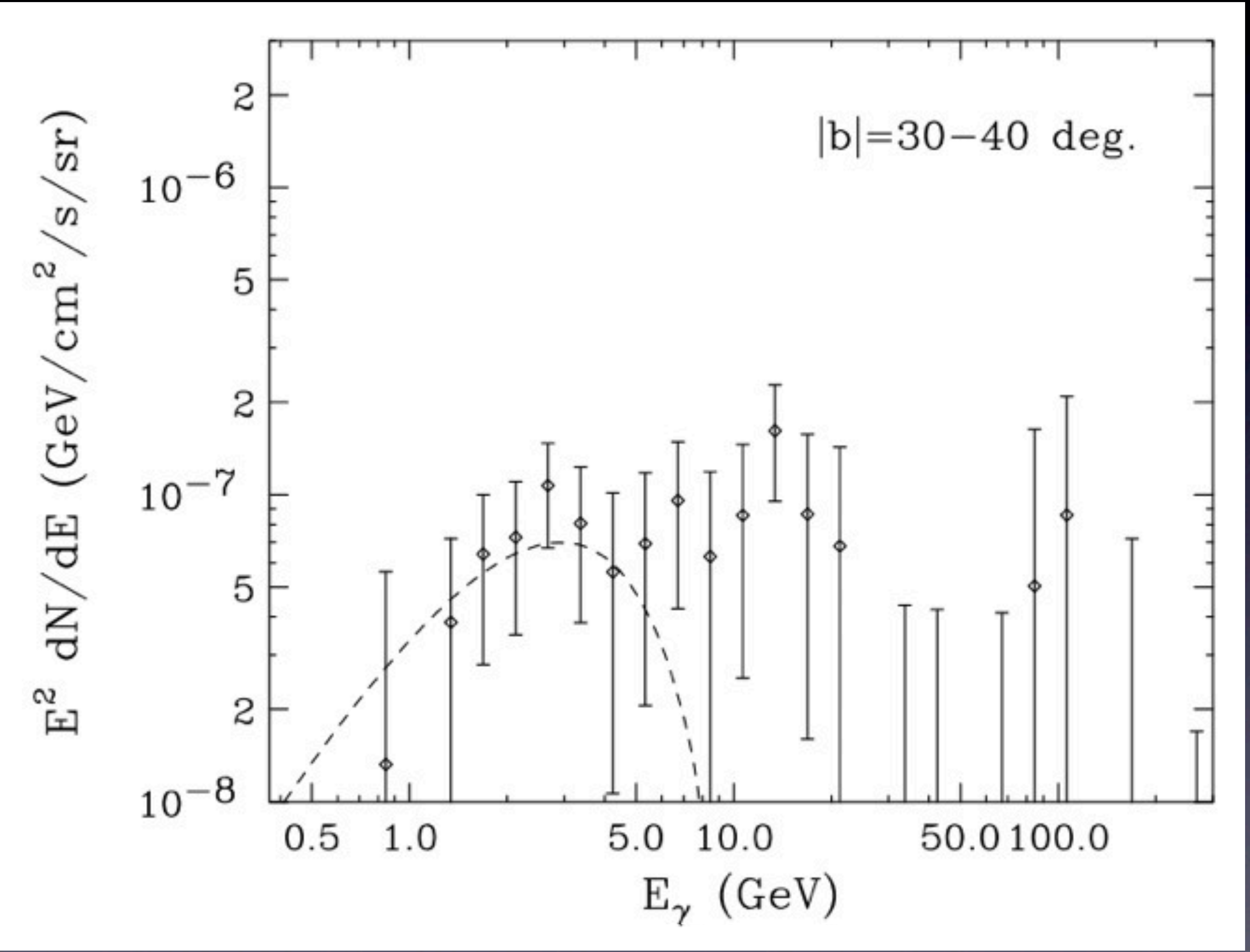

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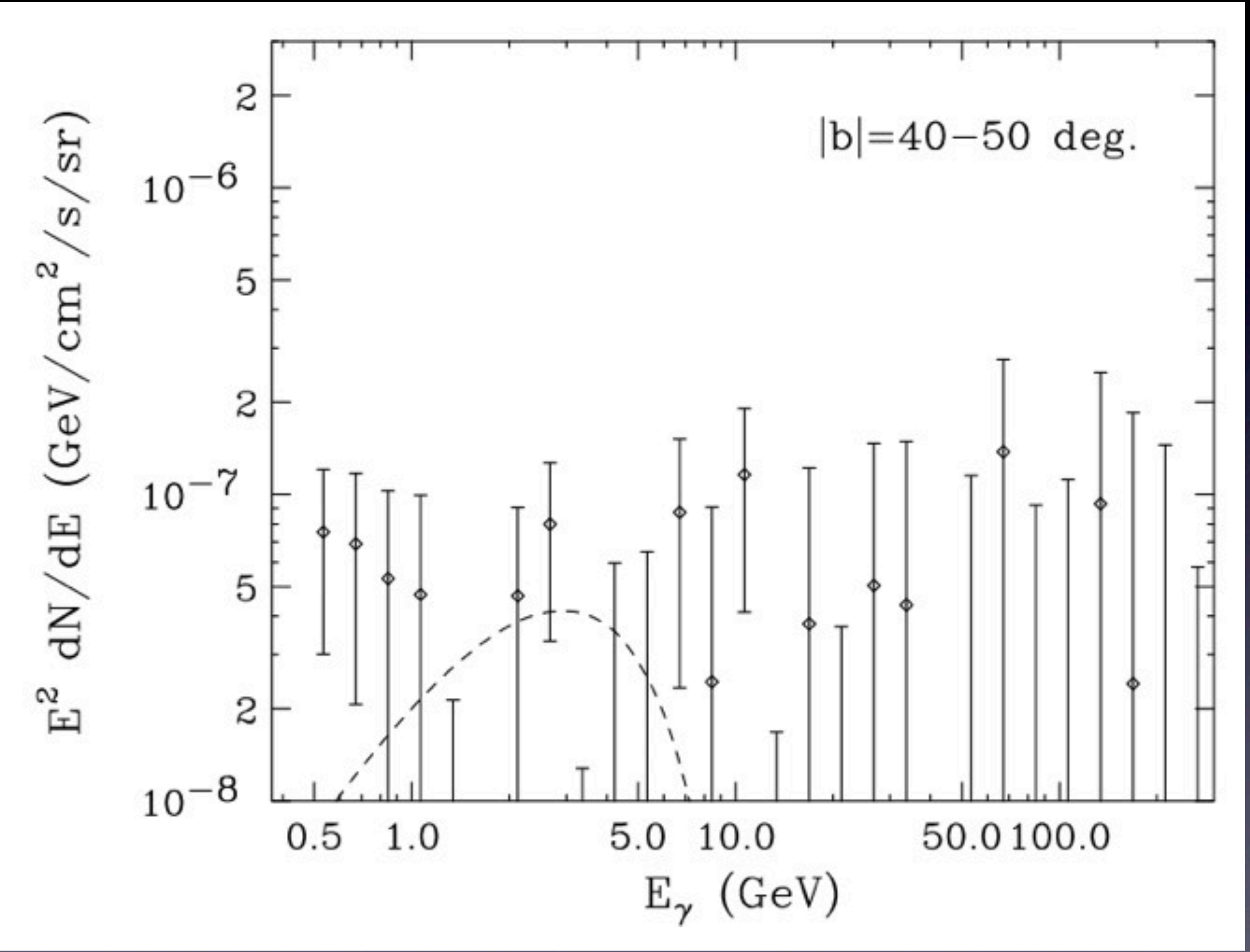

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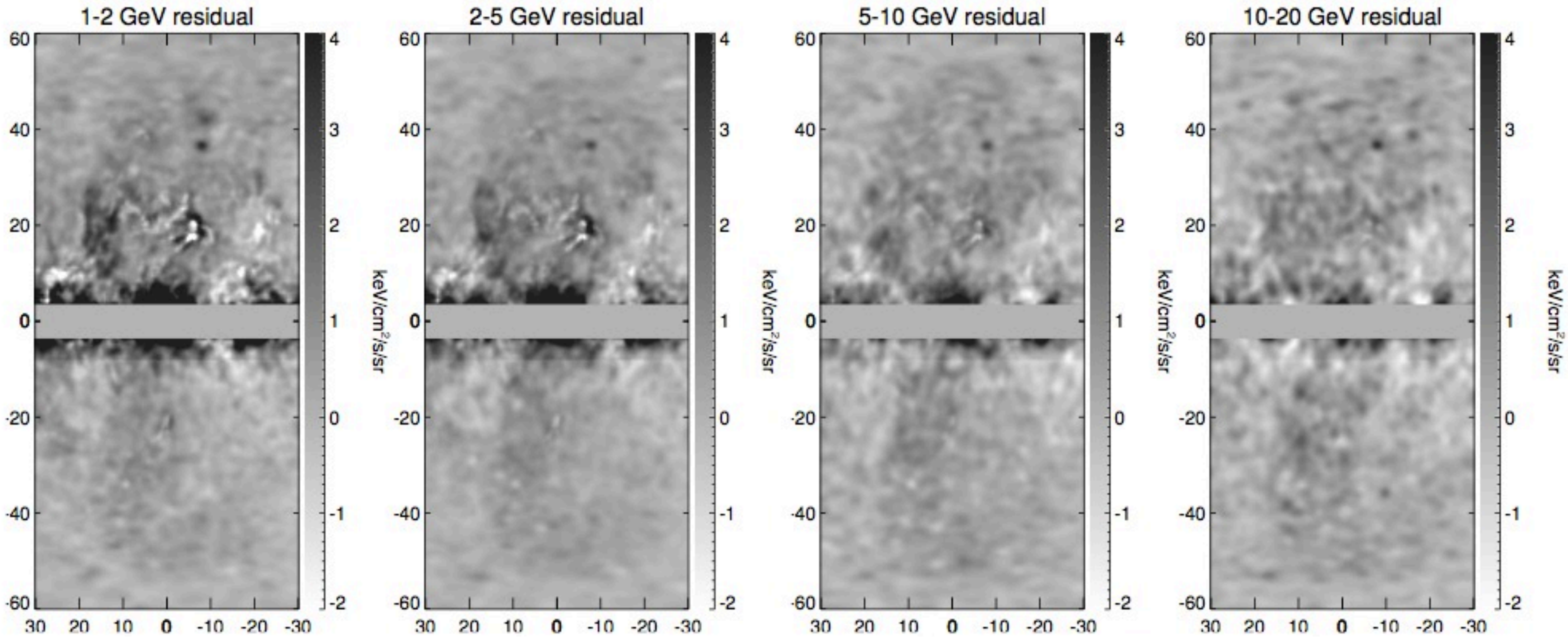
Spatial distribution



- Data map - (background maps) * (best-fit coefficients), in E^2 dN/dE.
- Fermi bubbles are clearly visible, with a close-to-flat spectrum; the excess in the inner Galaxy is most pronounced in 1-2 and 2-5 GeV maps.

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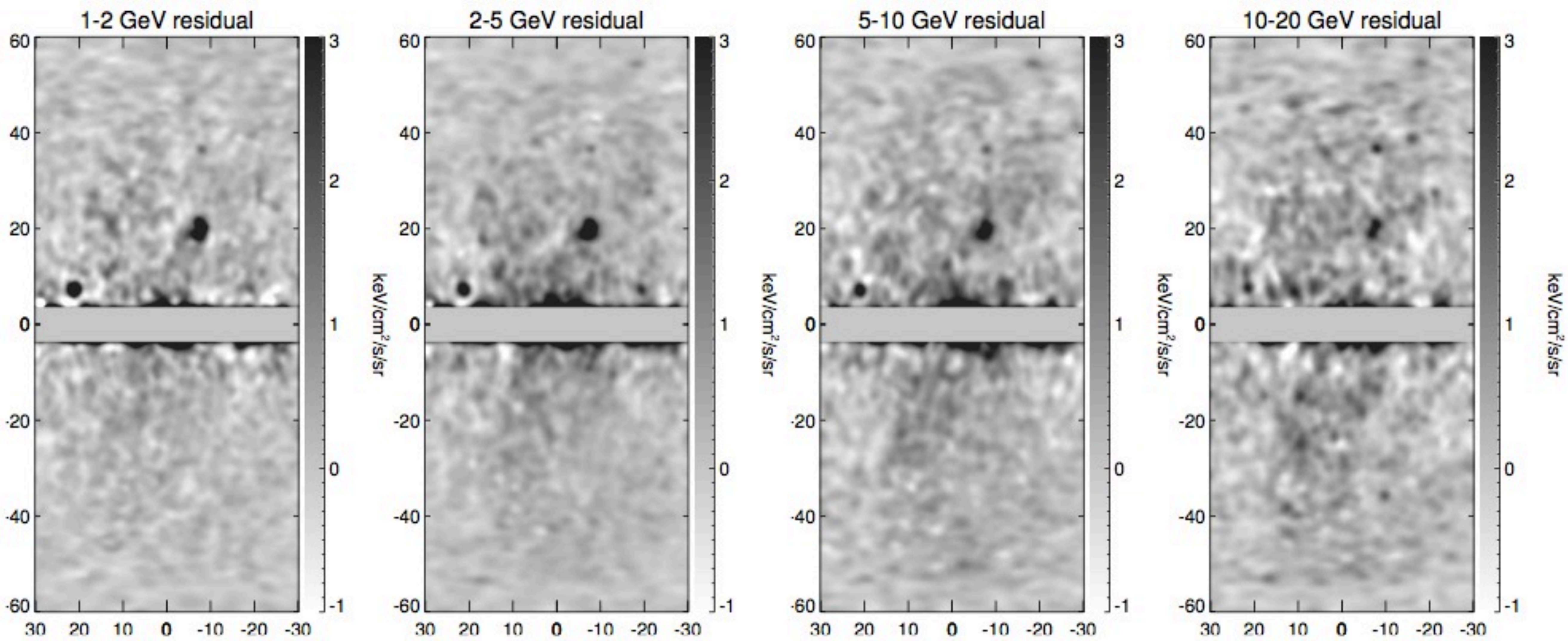

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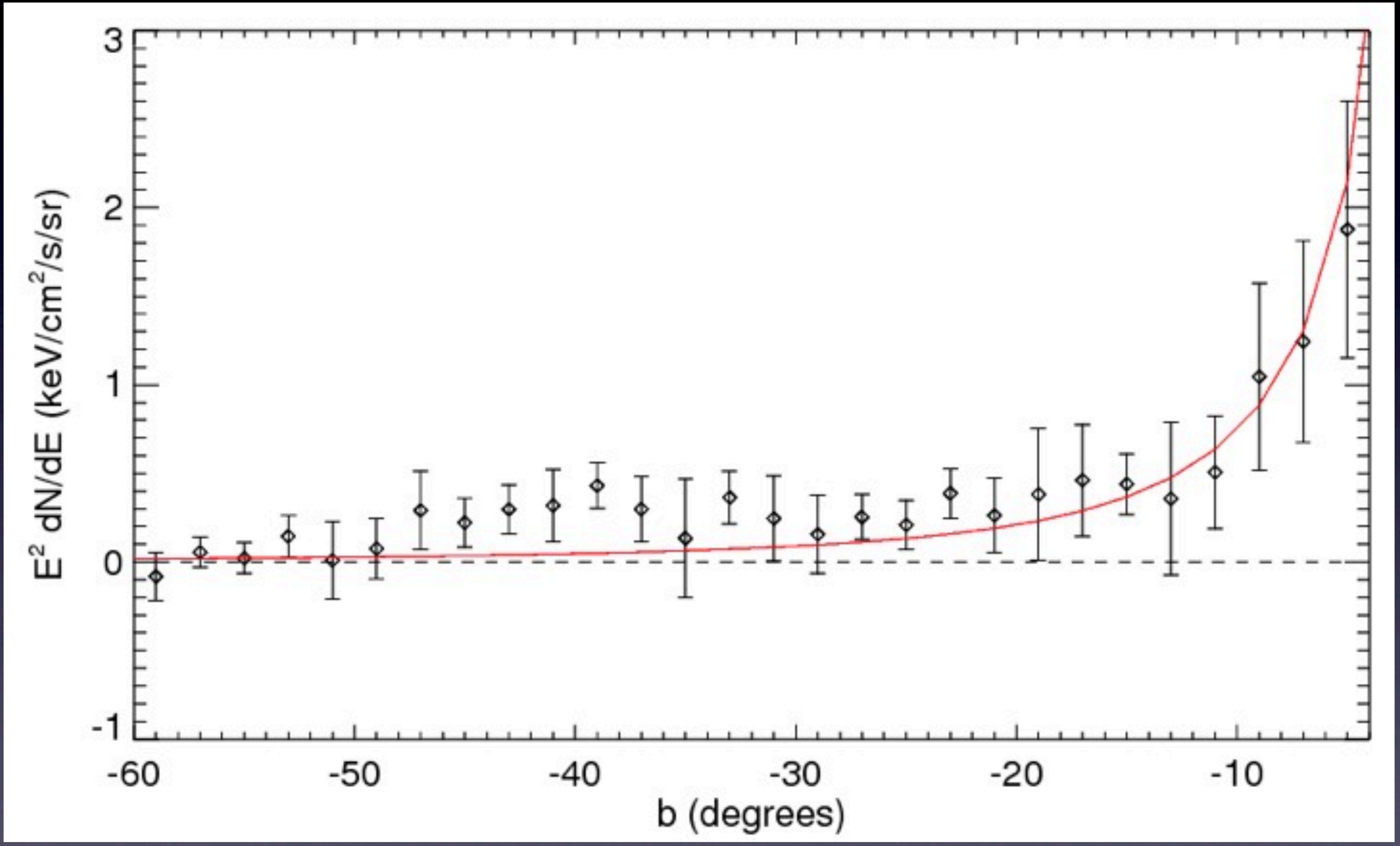
Off-peak vs on-peak



- Compare the residuals + bubble templates for 1-10 GeV maps and 10-300 GeV $E^2 dN/dE$ maps - difference provides a measure of spectral variation.
- Red line = profile expected from projected squared NFW density profile with inner slope $r^{-1.2}$ (normalization set by eye, not fitted).

Conclusions

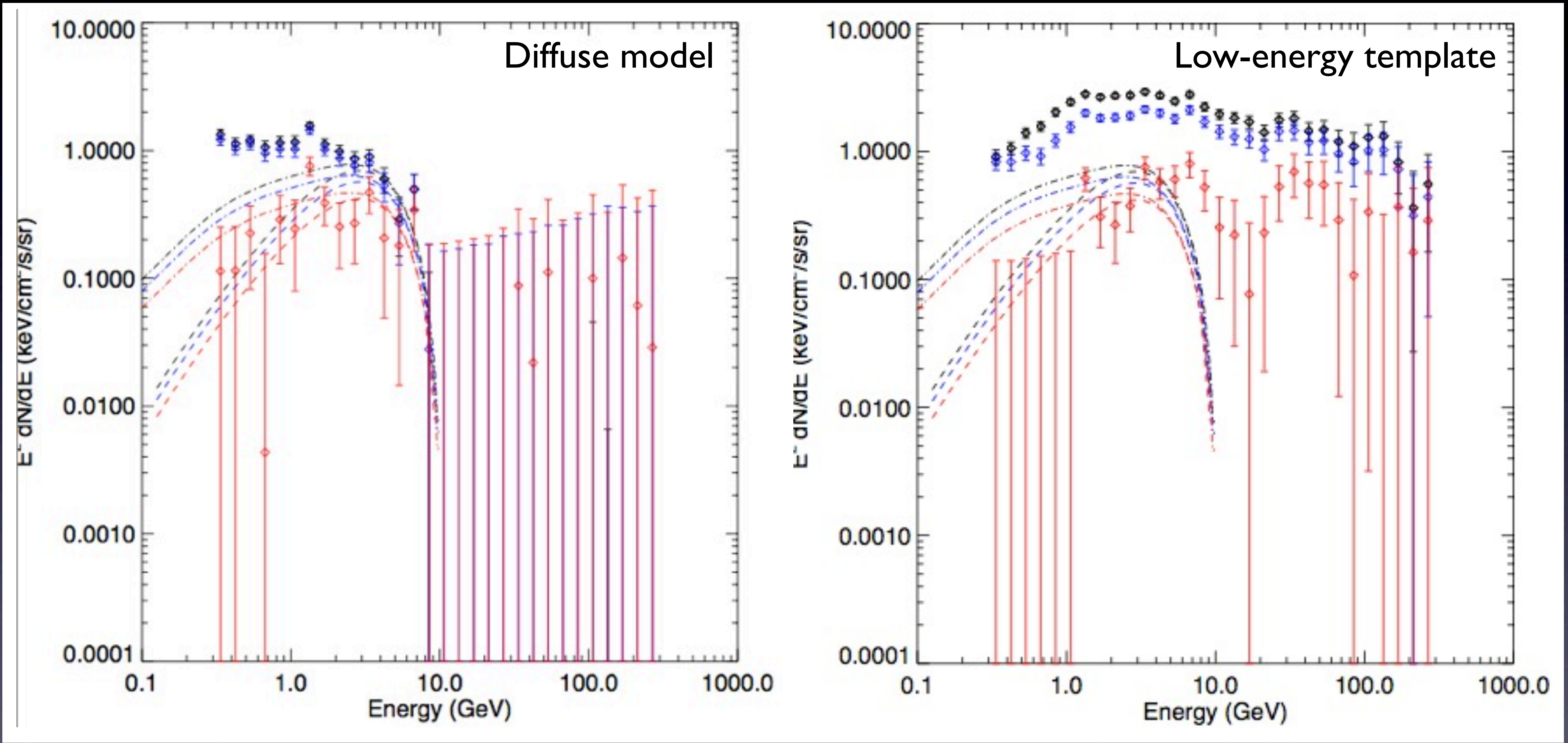
- At high latitudes (|b| ~ 20-50°) the spectrum of the Bubbles has no significant dependence on latitude and can be generated by inverse Compton scattering of a near-power-law electron spectrum.
- At lower latitudes, there is a pronounced excess at a few GeV, visible within the bubbles. At this stage we cannot firmly say whether this excess is confined within the bubbles.
- This excess appears broadly consistent in spectrum and amplitude with the excess observed in the neighborhood of the Galactic Center, if the emission follows a squared NFW profile with inner slope -1.2.
- Immediate questions:
  - Could it be a template/modeling subtraction artifact?
  - If it's real, what is it? Something associated with the mechanism forming the Bubbles? Millisecond pulsars? Dark matter?
  - Currently large error bars on morphology, but could potentially provide a handle on the rate at which the GC signal falls off away from the center.

BONUS SLIDES

Is there signal outside the bubbles?

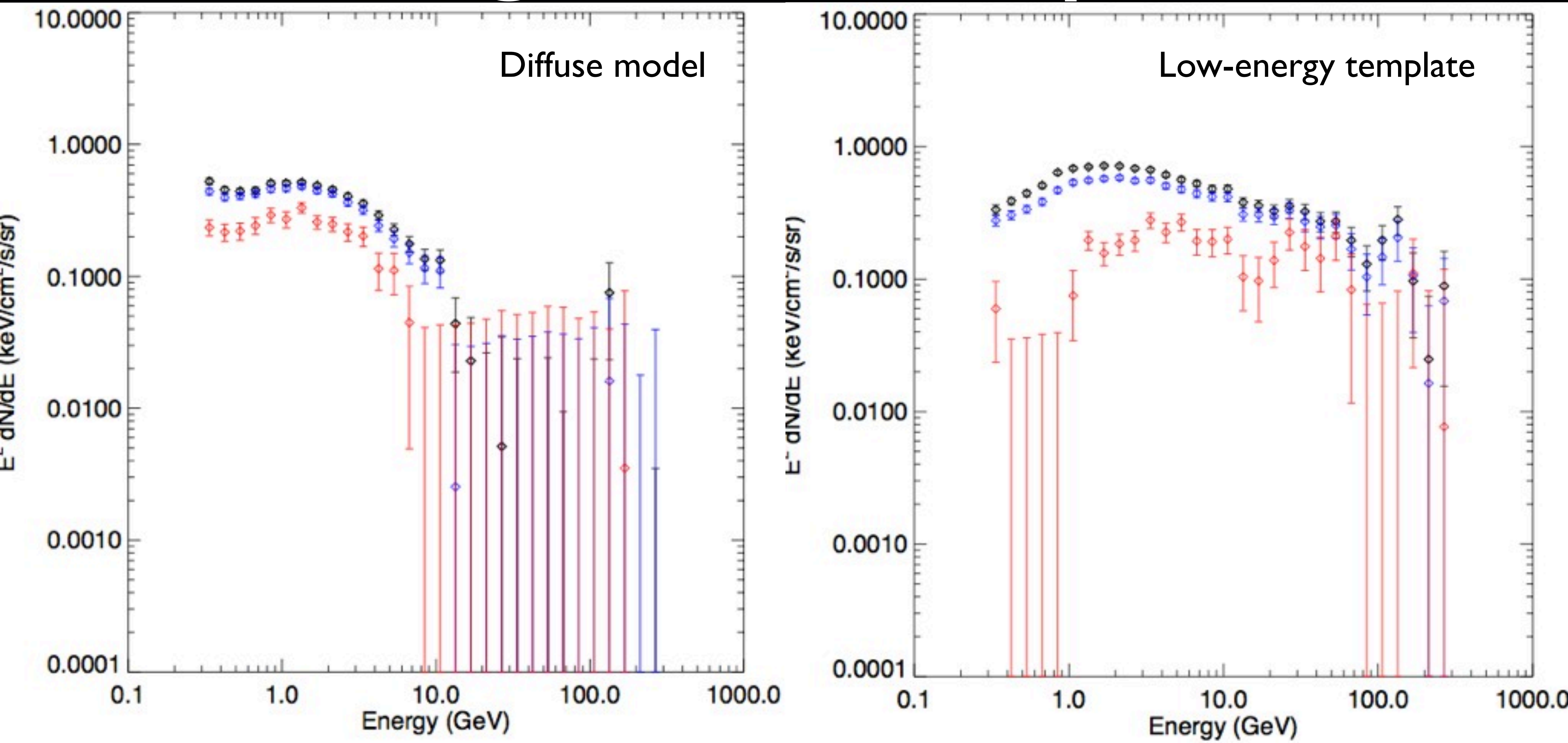
- Difficult to answer because of emission from the disk and other structures (gamma-ray spurs, Loop 1) - looking inside the bubbles minimizes these.
- In other words, even if the signal has nothing to do with the bubbles, the region with high S/B may still look like the bubbles.
- Nonetheless, we can try some fits...

“Bubble complement” region



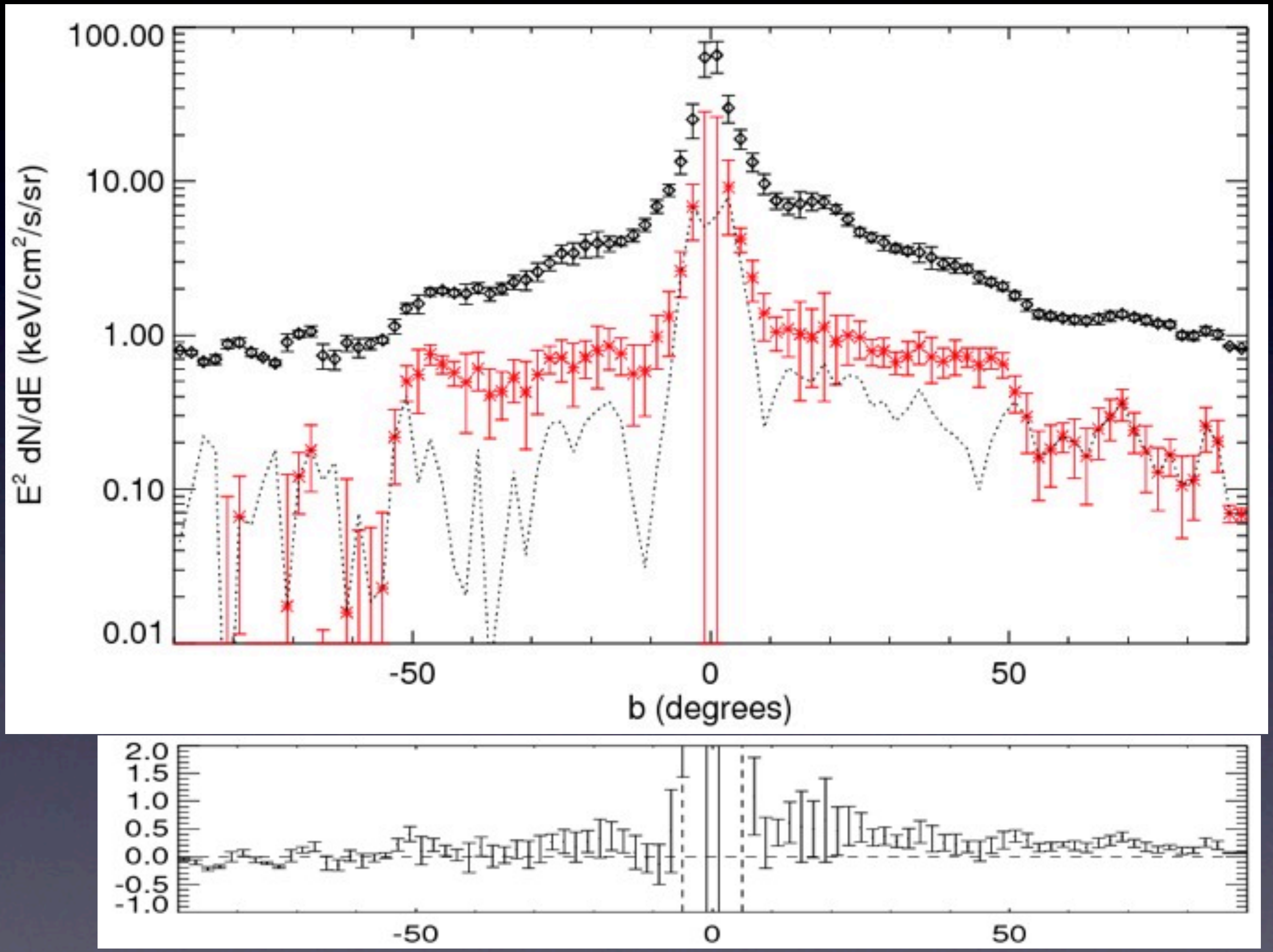
- Add an additional (flat) template for the region within 20° of the GC but outside the bubbles.
- Colors indicate masking of the disk, lines indicate predictions from two DM models fitting the GC excess.

Adding an NFW profile



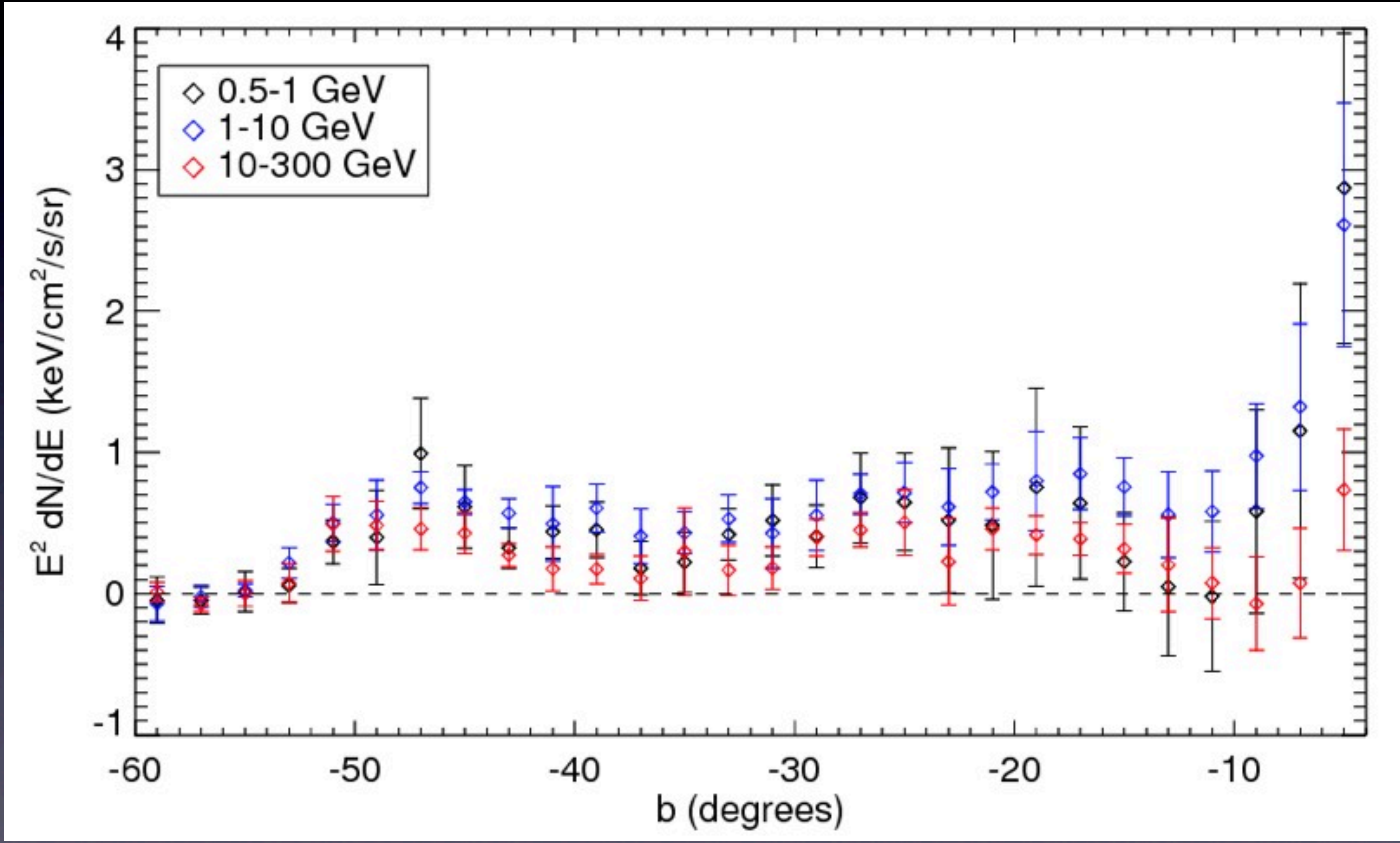
- Can also add a spherically symmetric template corresponding to a (projected, squared) NFW profile.
- Few-GeV bump is visible, but also low- and high-energy emission comparable to that seen in the region outside the bubbles - undersubtracted disk emission? Loop I / northern spurs?

Residuals



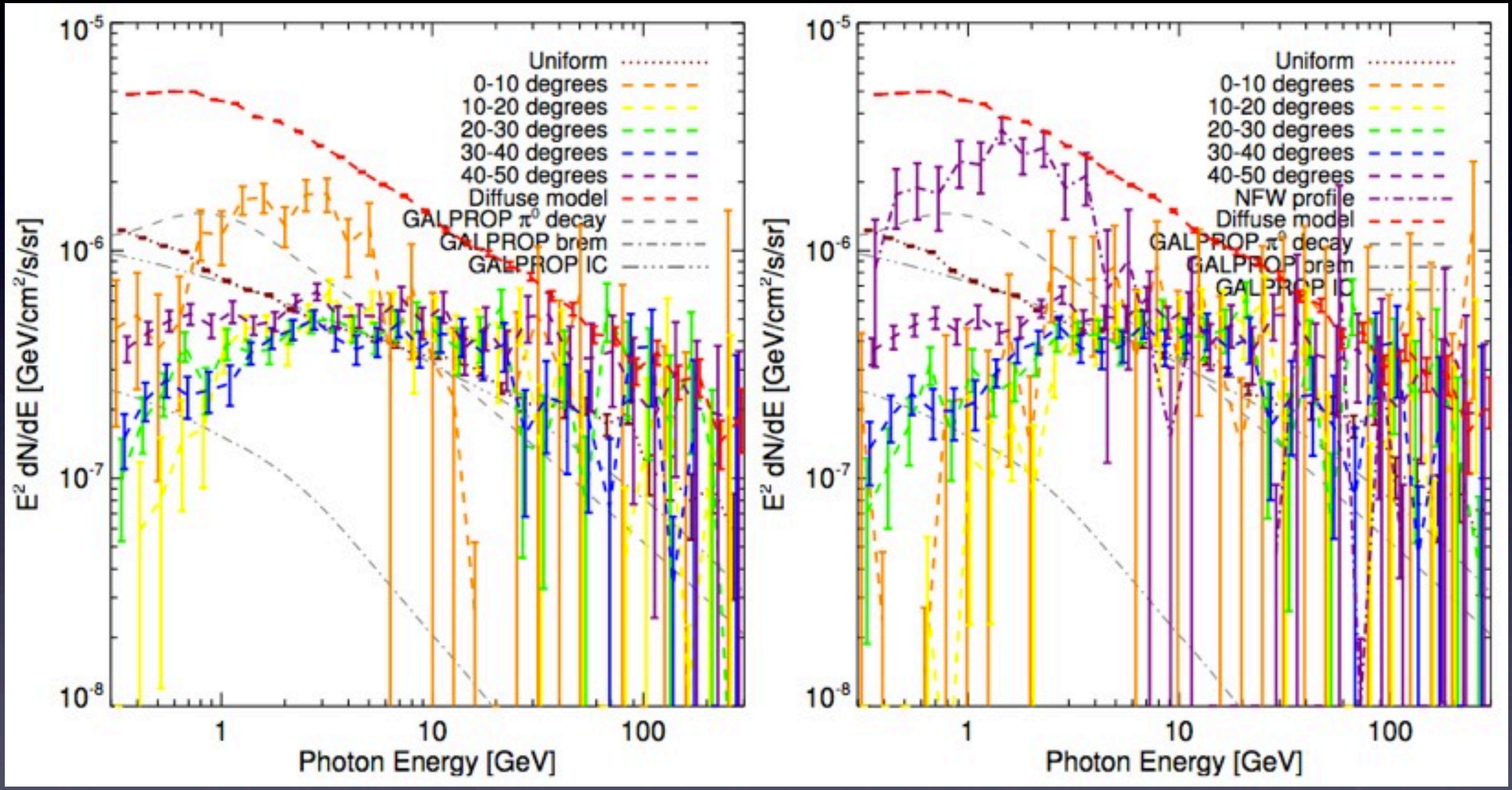
- Total emission (black points), residual + bubble spectrum (red points), absolute value of residual (dotted line). Lower panel shows value of residuals.

Residuals by energy



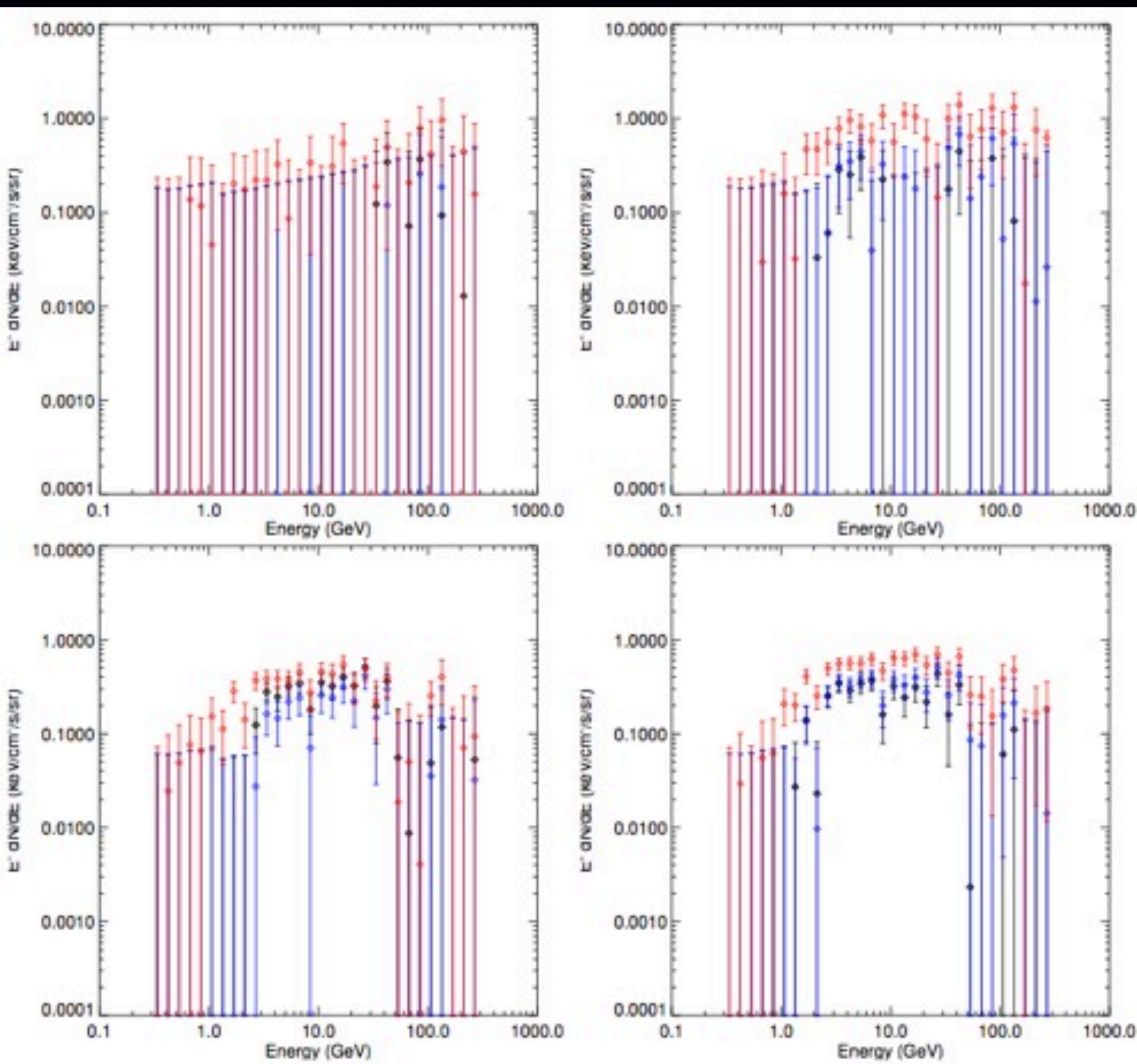
- Residuals + bubble templates in the southern sky.

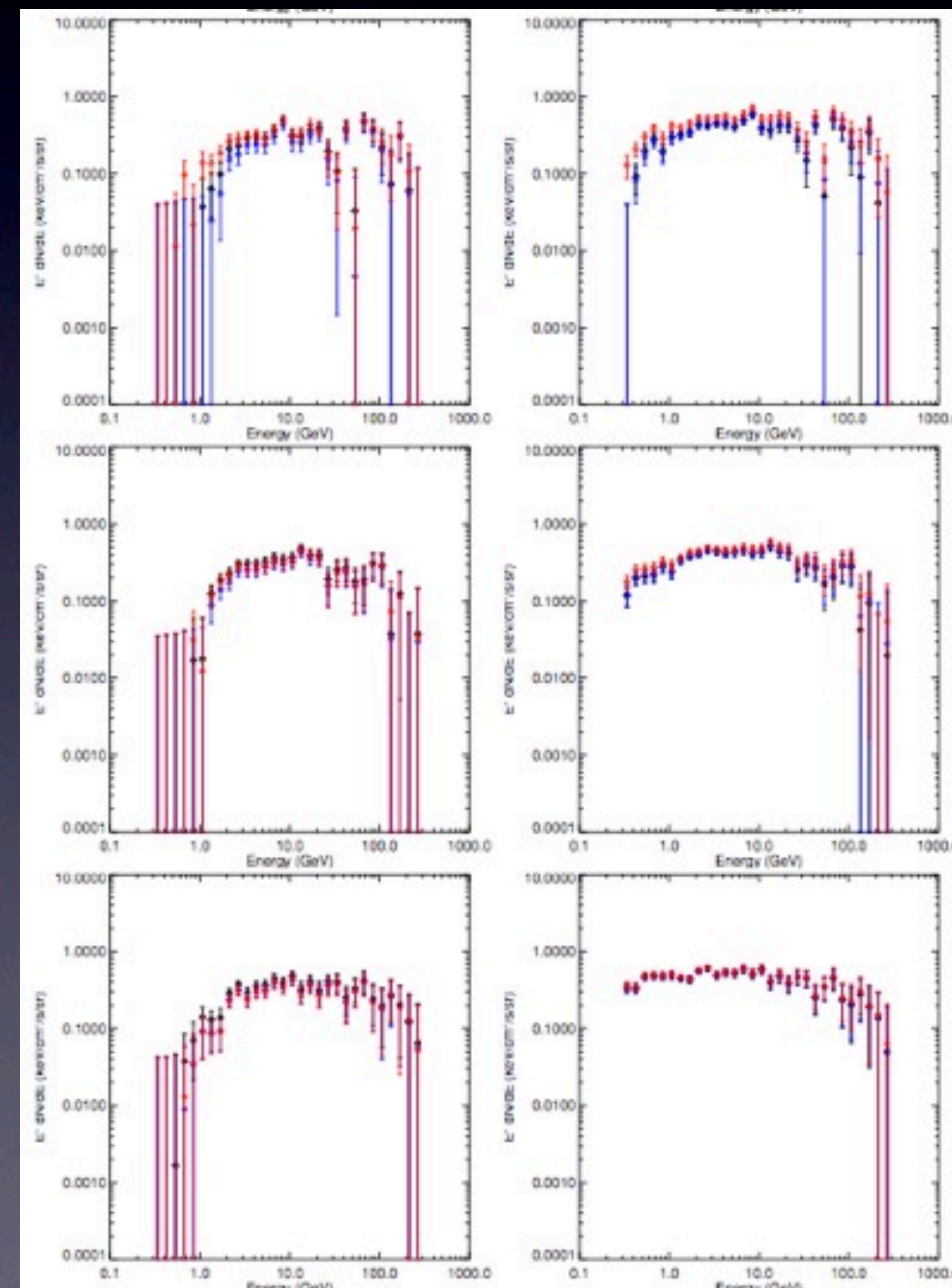
The southern sky



- To avoid structures in the north (e.g. Loop 1), fit in the southern sky only.
- Mask the area where b > -5° to minimize disk emission.
- Left panel: bubble templates only, right panel: NFW profile included.

Bubble spectrum in presence of NFW template





- Above: 0-10, 10-20 degrees
- Right: 10-20, 20-30, 30-40 degrees

Left panels: low-energy template, right panels: diffuse model