

A GeV Gamma-Ray Spectral Feature in the Inner Galaxy

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in collaboration with

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Based on arXiv:1302.6589, 1305.0830, and upcoming work.

TeV Particle Astrophysics, Irvine, CA

29 August 2013

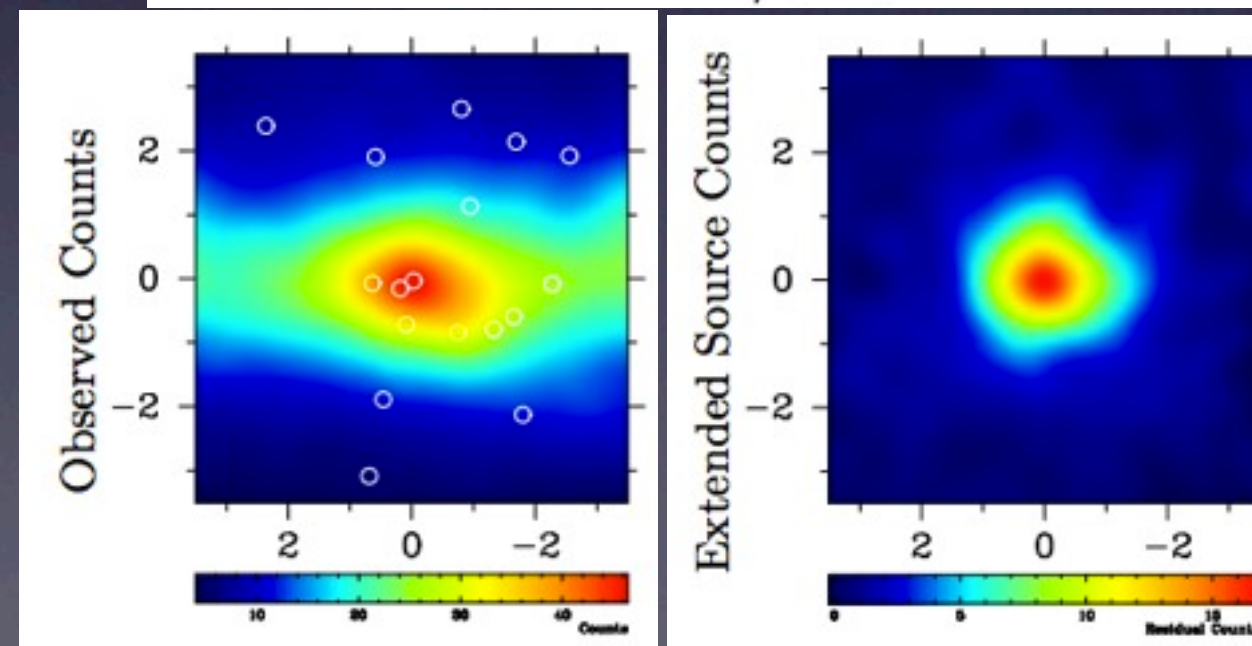
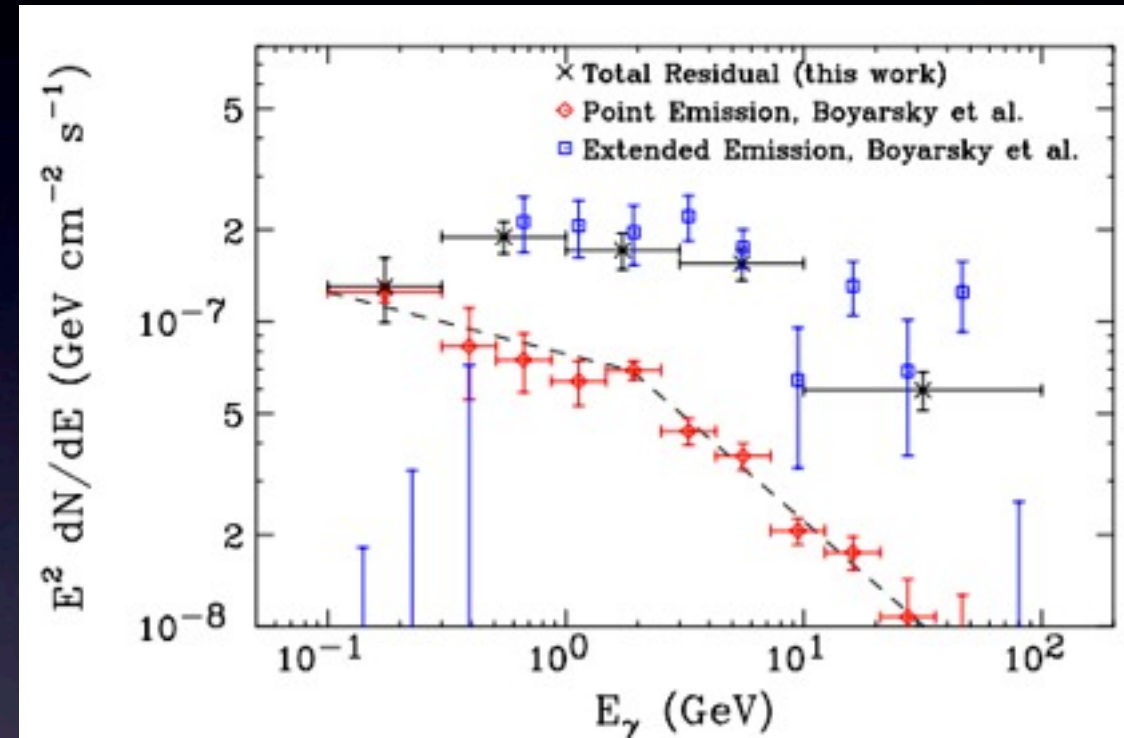
Outline

- Background
 - The Galactic Center GeV excess
 - The Fermi Bubbles and template analysis
- Isolating a GeV excess from the Bubbles in the inner Galaxy
 - Spectrum and morphology
 - Identification with the Galactic Center excess
 - Systematic uncertainties in the spectrum (work in progress)
- Interpretation
 - Dark matter models and the implications of systematic uncertainties (work in progress)
 - Can it be millisecond pulsars?
- Conclusions

The Galactic Center GeV excess

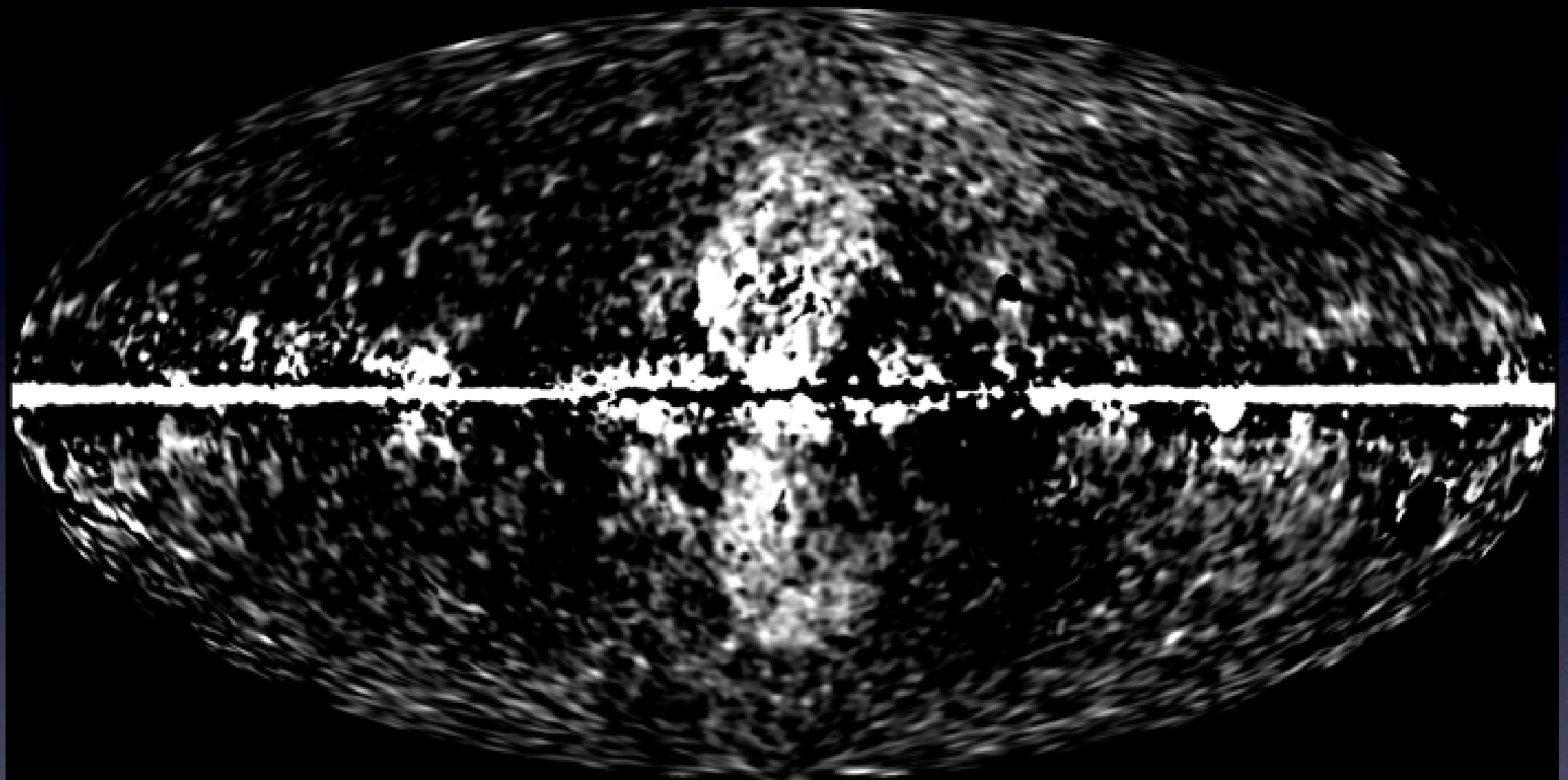
Hooper & Linden 2011

- See also talks by Savvas Koushiappas, Nicolas Canac, Stefano Profumo.
- Claims of a spectral feature found in Fermi public data by several groups, initially by Goodenough & Hooper in 2009, with subsequent studies by Hooper & Linden; Boyarsky, Malyshev & Ruchayskiy; Abazajian & Kaplinghat; Gordon & Macias. Key features:
 - Peaks at a few GeV.
 - Localized around the GC (most studies focus on 1 degree radius about the GC).
 - Roughly spherical morphology, with flux/volume scaling with Galactocentric radius approximately as $r^{-2.4}$.
 - DM interpretation: cross section depends on mass and annihilation channel, but comparable to thermal relic.
 - Consistent fits have been claimed for 10 GeV - 1 TeV DM annihilating to b quarks, and also 10-30 GeV DM annihilating to tau leptons.



Abazajian & Kaplinghat 2012

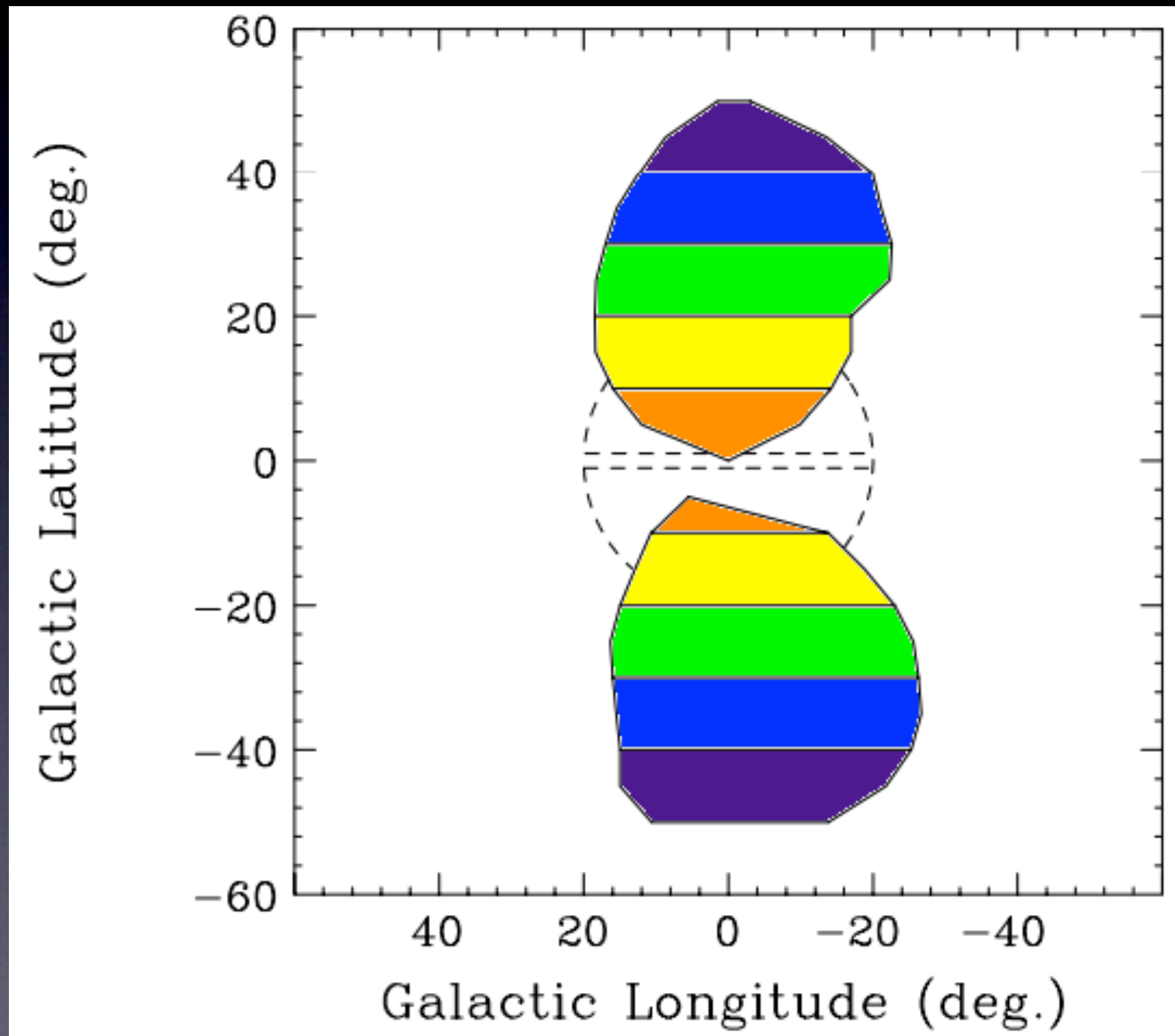
The Fermi Bubbles



- Discovered 2010 by Su, TRS & Finkbeiner in public data from *Fermi* - see talks by Meng Su, Dmitry Malyshev.
- Large-scale gamma-ray lobes extending to $b \sim \pm 50^\circ$, apparently centered on the Galactic Center.
- Visible in ~ 1 -100 GeV gamma rays, hard spectrum ($dN/dE \sim E^{-2}$), no initial evidence of spectral variation across bubbles.

Latitude variation

- Initial goal: study latitude variation in the spectrum of the Fermi Bubbles.
- Split the “bubbles template” into five 10-degree-wide bands in latitude.
- Separately float the spectrum in each of these bands.



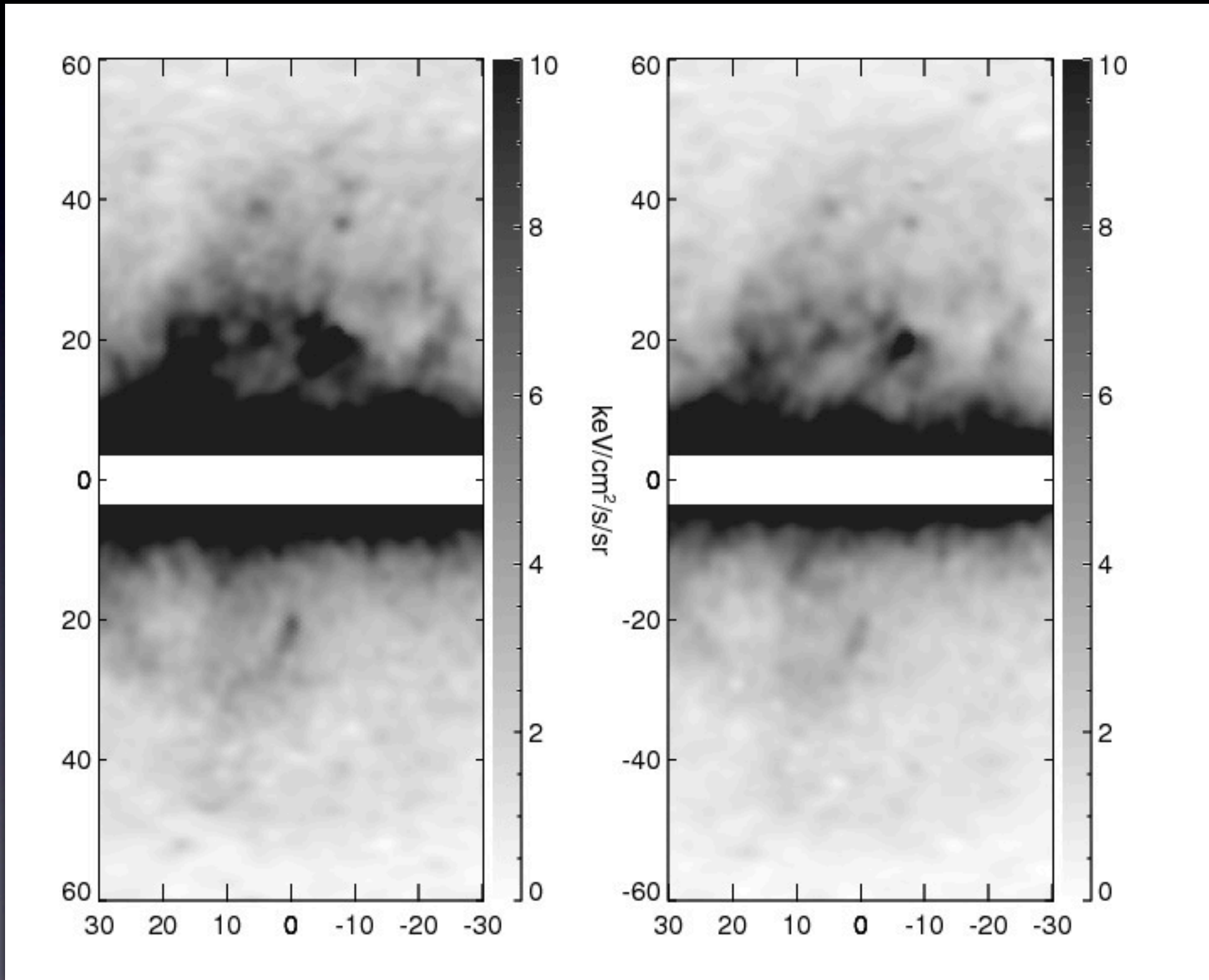
Template analysis

- 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.
- This yields a spectrum for each template, constructed from their coefficients in each energy band - for the “background” templates, the agreement of the resulting spectra with our expectations provides a cross-check. No spectral information is included in the fit a priori.
- Compute and maximize likelihood on pixelized map - done this way, rather than photon-by-photon, to allow matching of smoothing scales / PSF at different energies.
- Always include a (floating) isotropic offset to account for true isotropic emission + any residual cosmic-ray contamination.

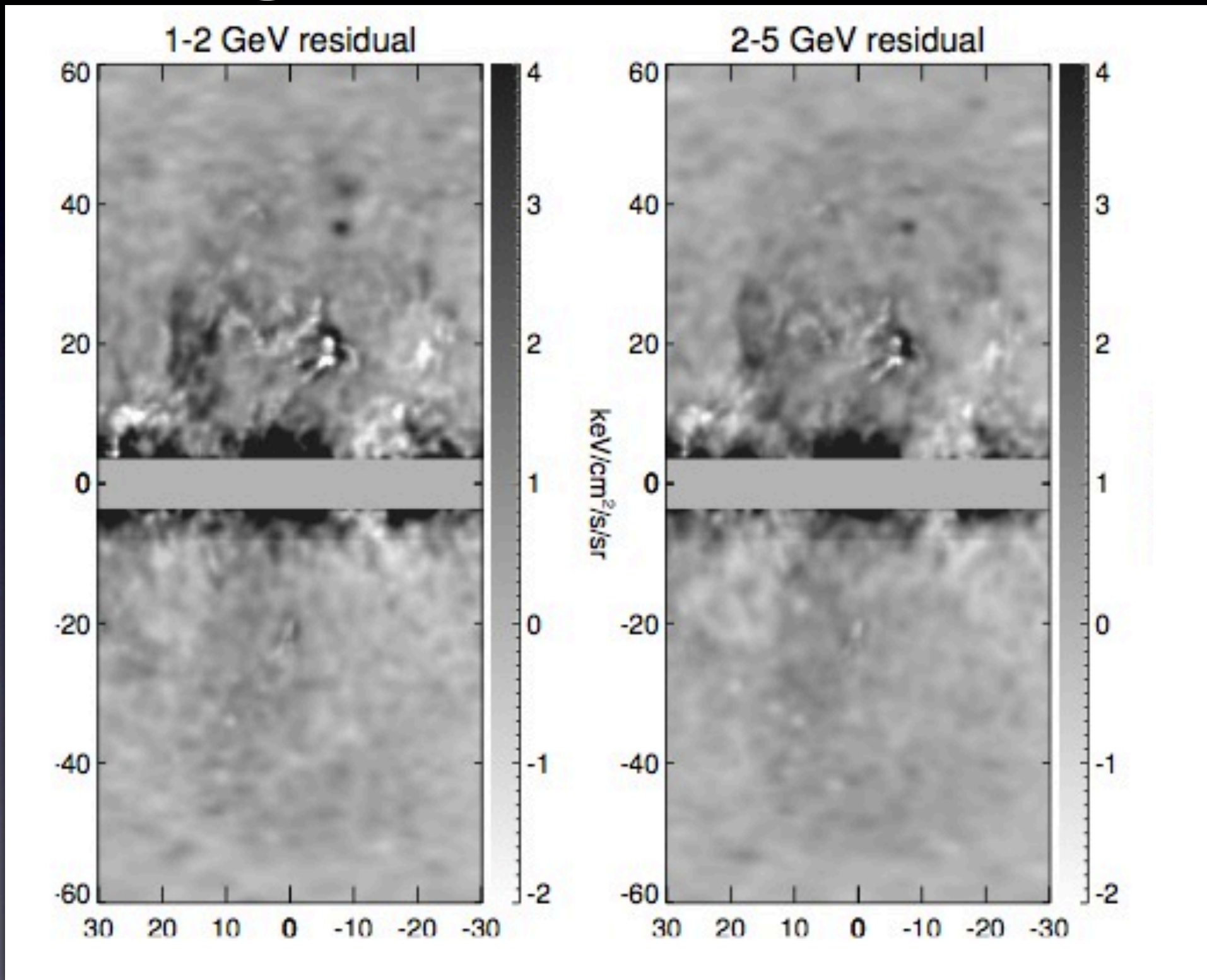
The Galactic diffuse model

- Principal method: 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).
- Fit parameters in each energy bin:
 - Coefficient of the diffuse model (interpolated to that energy).
 - Uniform offset.
 - Coefficients of the sliced bubble templates.
- We also perform a cross-check using Fermi low-energy data as a template for the background, and find consistent results - this approach cannot probe the low-energy signal spectrum, but is purely data-driven.

Background subtraction

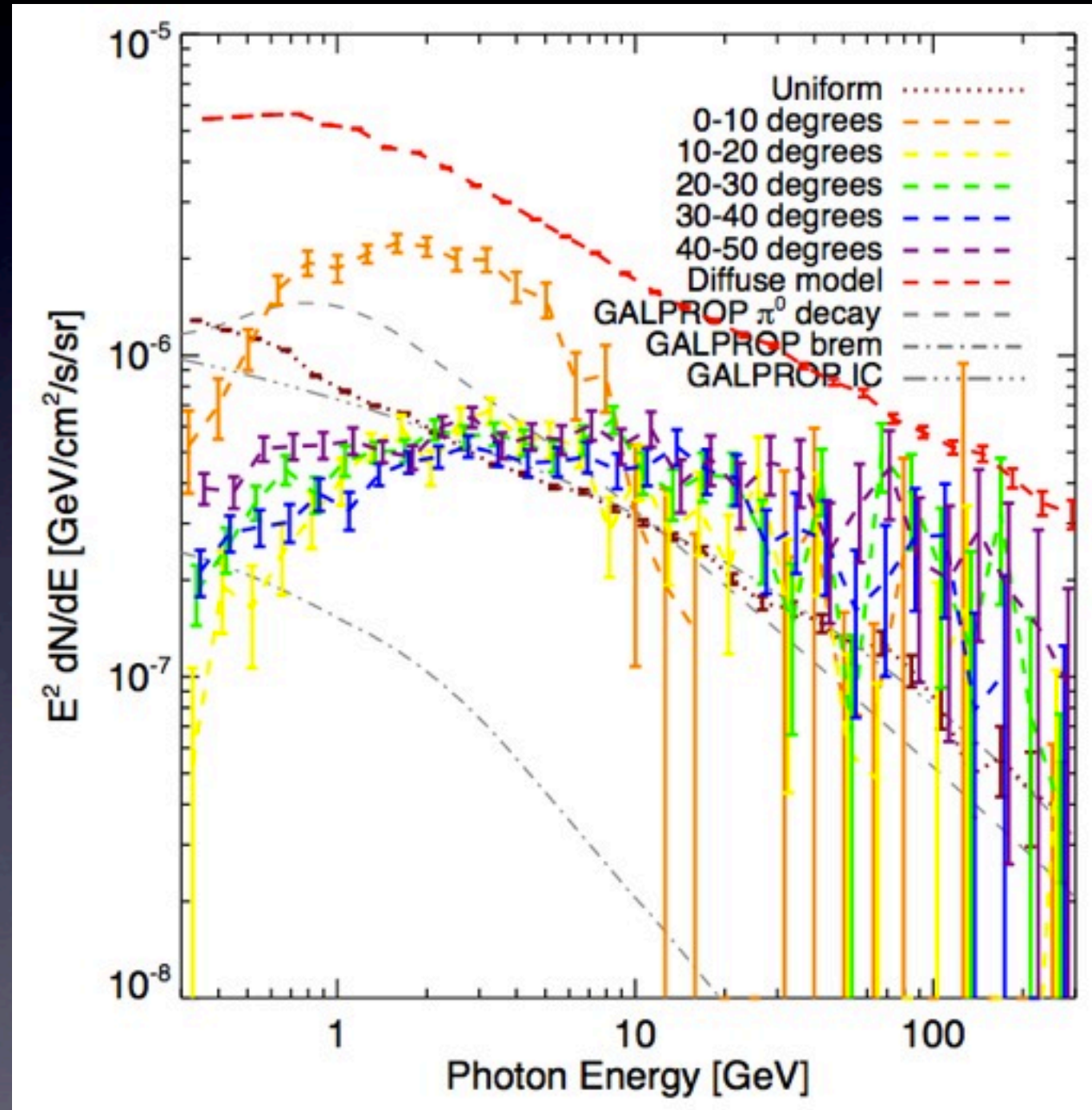


Background subtraction

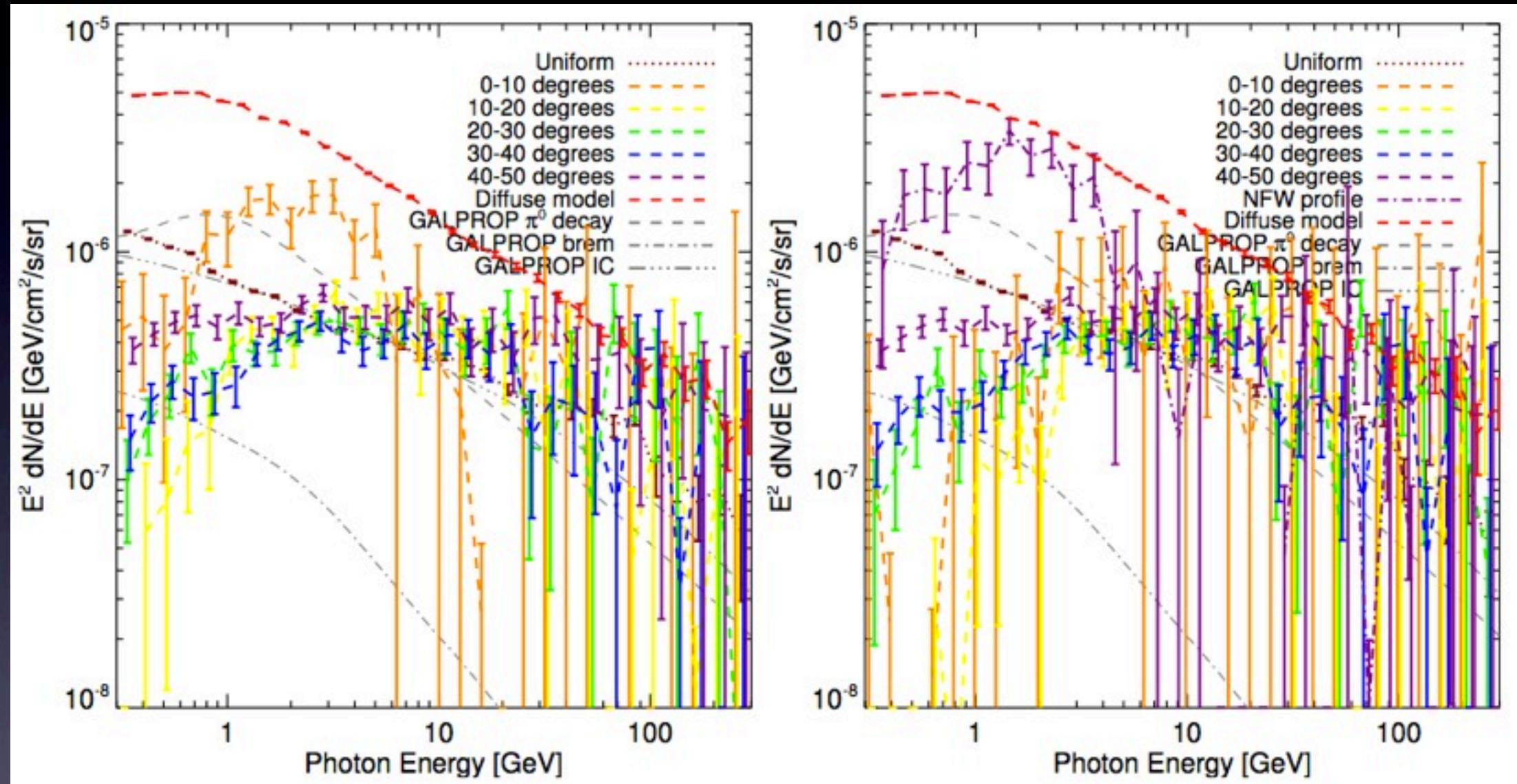


Spectra by latitude

- At high latitudes ($|b| > 30^\circ$) the spectrum is nearly invariant with latitude.
- At low latitudes ($|b| < 10^\circ$) there is a pronounced bump peaking at several GeV, resembling the GC excess.
- There is curvature in the spectrum in the $10\text{-}20^\circ$ band, consistent with the same bump (in addition to a flat spectrum resembling the high-latitude bubbles).
- Results have been largely confirmed with an independent analysis using a slightly different methodology (with some disagreement at low energies and the lowest latitudes, where they find a flatter spectrum) by Huang, Urbano and Xue 1307.6862.



Adding an NFW template



- We hypothesize two signal components - add additional template, generalized NFW profile with inner slope $\gamma=1.2$.
- To avoid structures in the north (e.g. Loop I), fit in the southern sky only; mask the area where $b > -5^\circ$ to minimize disk emission. This should be a “clean” fit (and no spatial overlap with GC analyses).
- Left panel: bubble templates only, right panel: NFW profile included.

A simplified fit PRELIMINARY

- This suggests that much of the low-latitude curvature in the bubble templates originates from this NFW-like component.
- We perform a simpler fit using a single flat template for the Bubbles, and the generalized NFW template.
- Results are consistent with previously extracted spectra for the NFW template, using the latitude-sliced fit.
- Left panels = full sky, right panels = southern sky only.
- Masking the plane at $l/2/5^\circ$ in 1st/2nd/3rd rows.

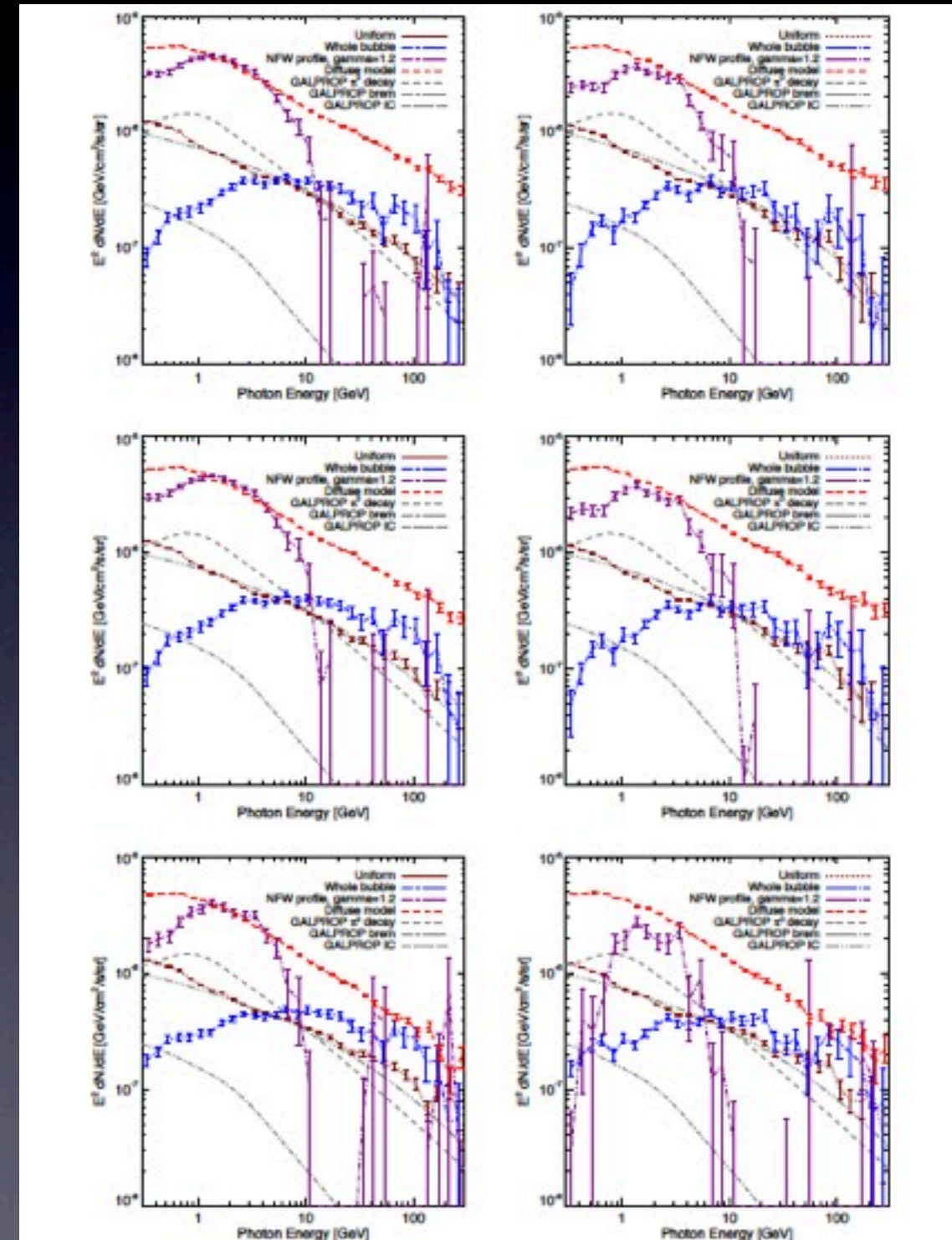
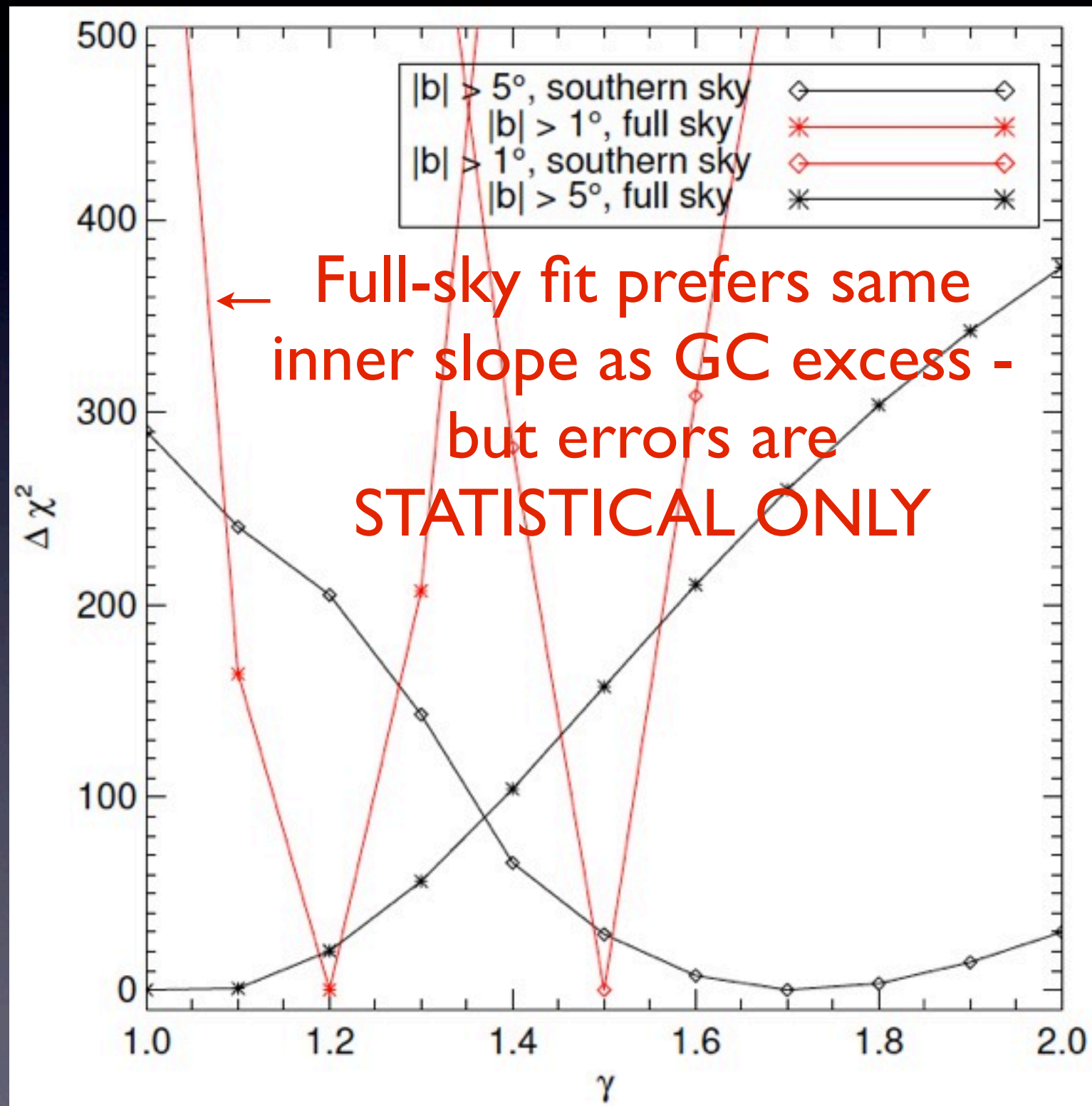


FIG. 1: Results of the fit including the diffuse model, the flat bubble template, and an NFW profile with $\gamma = 1.2$. The left panels show the fit over the whole sky, the right in the southern hemisphere only. From top to bottom the rows correspond to masking at $|b| = 1^\circ, 2^\circ, 5^\circ$.

Preferred slope

- Try re-fitting with NFW profiles with different choices of the γ parameter (i.e. power-law slope at small r).
- Preferred slope depends somewhat on region over which fit is taken - higher latitudes seem to prefer a steeper slope, but this would overproduce emission if extrapolated to lower latitudes.
- Note χ^2 numbers are based on statistical errors only.



Impact of inner slope on spectrum

The spectrum extracted for the excess is nearly independent of choice of inner slope for the signal template, except when masked 1 degree from the plane and below 600 MeV.

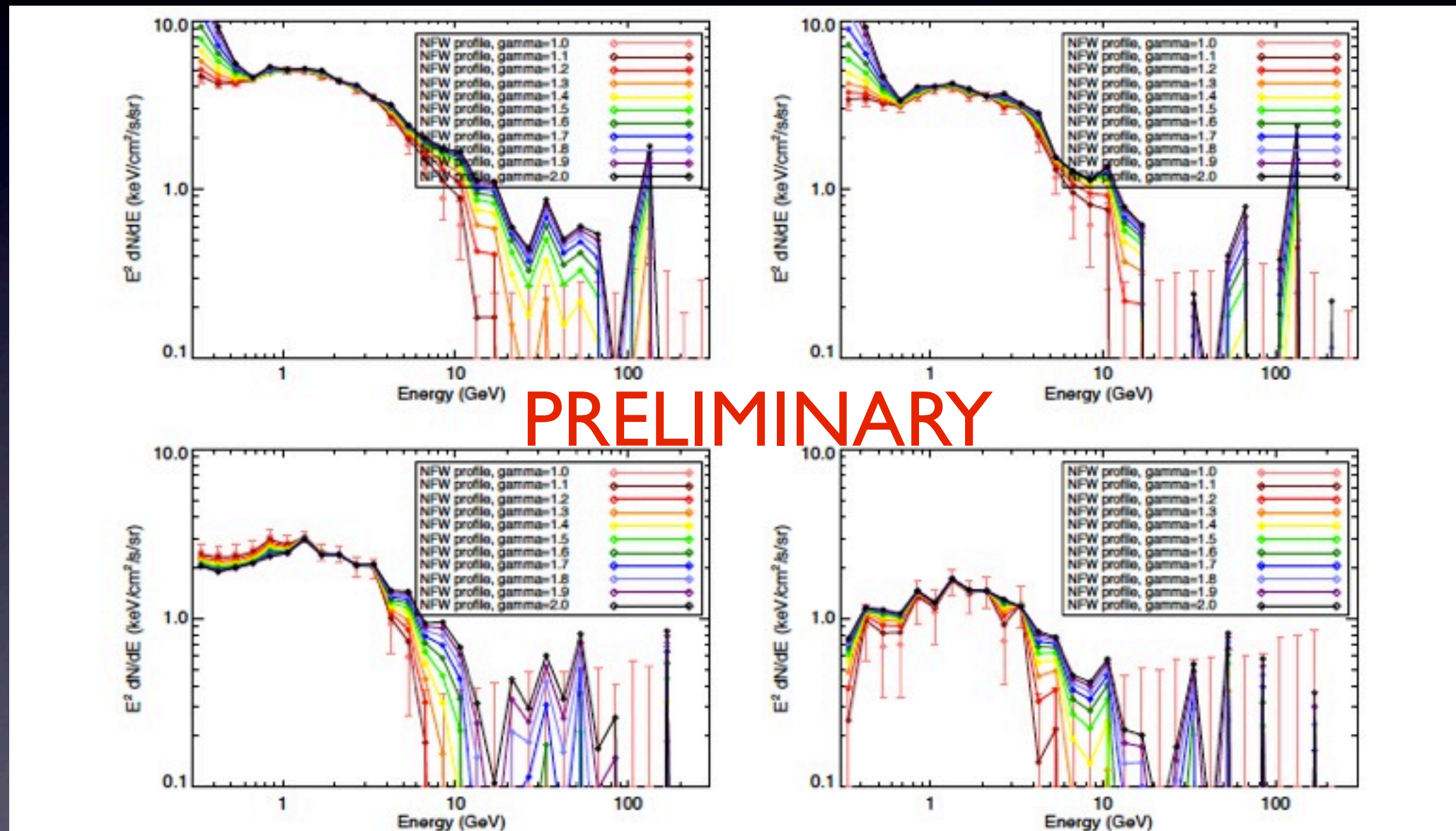


FIG. 5: Signal spectra obtained by fitting NFW profiles with different inner slopes γ . The left panels show the fit over the whole sky, the right over the southern hemisphere only. The upper panels correspond to masking 1° from the plane, the lower panels to 5° . Curves have been rescaled to match the $\gamma = 1.0$ curve at 2 GeV, to facilitate comparison of spectral shapes. All fits have been performed with the Fermi diffuse model and the five latitude-sliced templates for the bubbles.

Systematic uncertainties in the spectrum

- Fitting in different regions of the sky gives somewhat different spectra - effect of background contamination (e.g. more dust in the Northern sky), or real spectral variation?
- Cutoff at 10 GeV is fairly robust, but behavior below 1 GeV is not - and this is a key diagnostic of different models for the signal (e.g. millisecond pulsars or different DM annihilation channels).

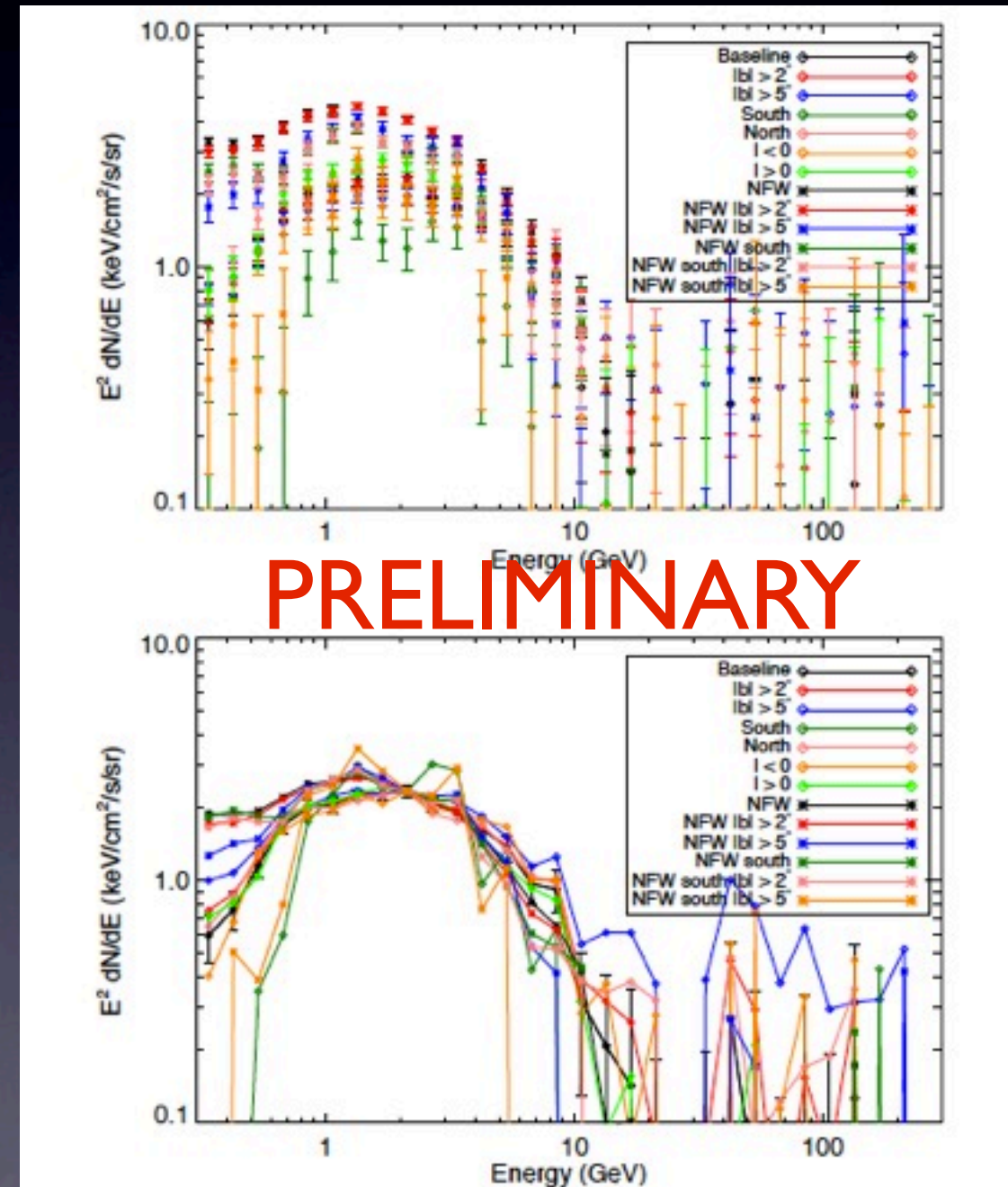
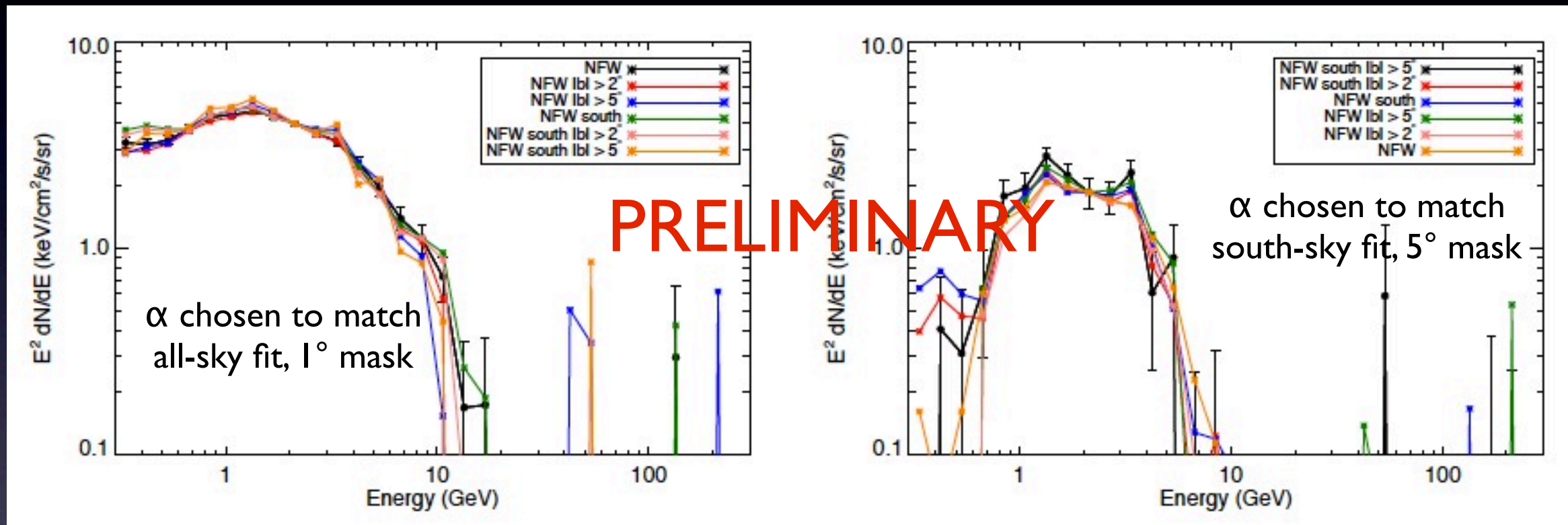


FIG. 4: Signal spectra obtained by a range of different fits, comparing the results for the NFW profile in the NFW + whole bubble fit (stars) to the results for the lowest latitude band (mask to 10 degrees) in the multi-latitude bubbles fit (diamonds). The baseline is a fullsky fit masked at 1° from the Galactic plane. The lower panel shows the same curves, but with the error bars omitted on all but the first, and rescaled to match the first curve at 2 GeV (to facilitate comparison of the spectral shapes).

Contamination and oversubtraction



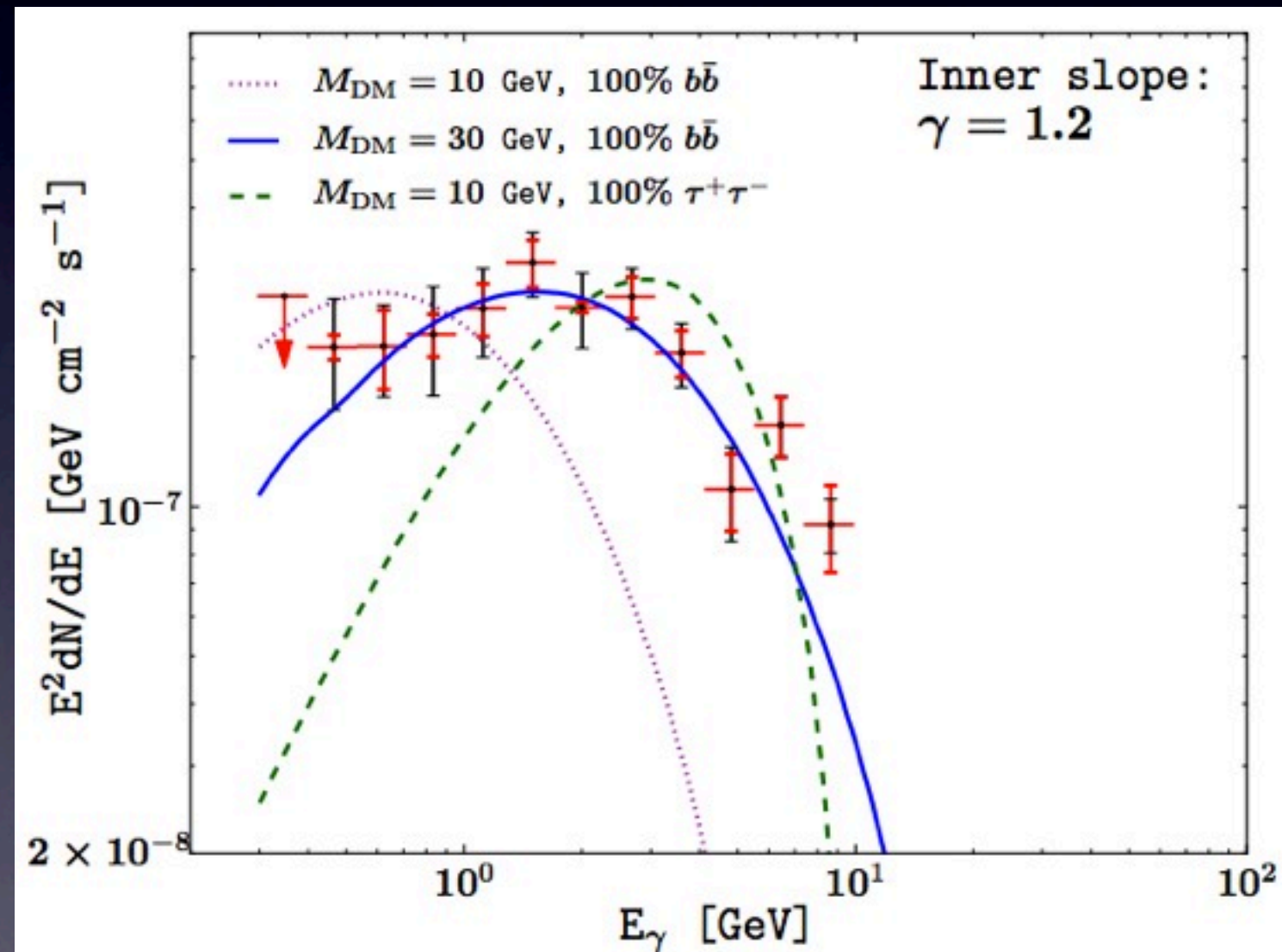
- New result: the spectra extracted from all our fits are members of the same one-parameter family of curves, related by:

$$f_{\text{NFW}}(E) = f_{\text{NFW}}^0(E) + \alpha f_{\text{diffuse}}(E)$$

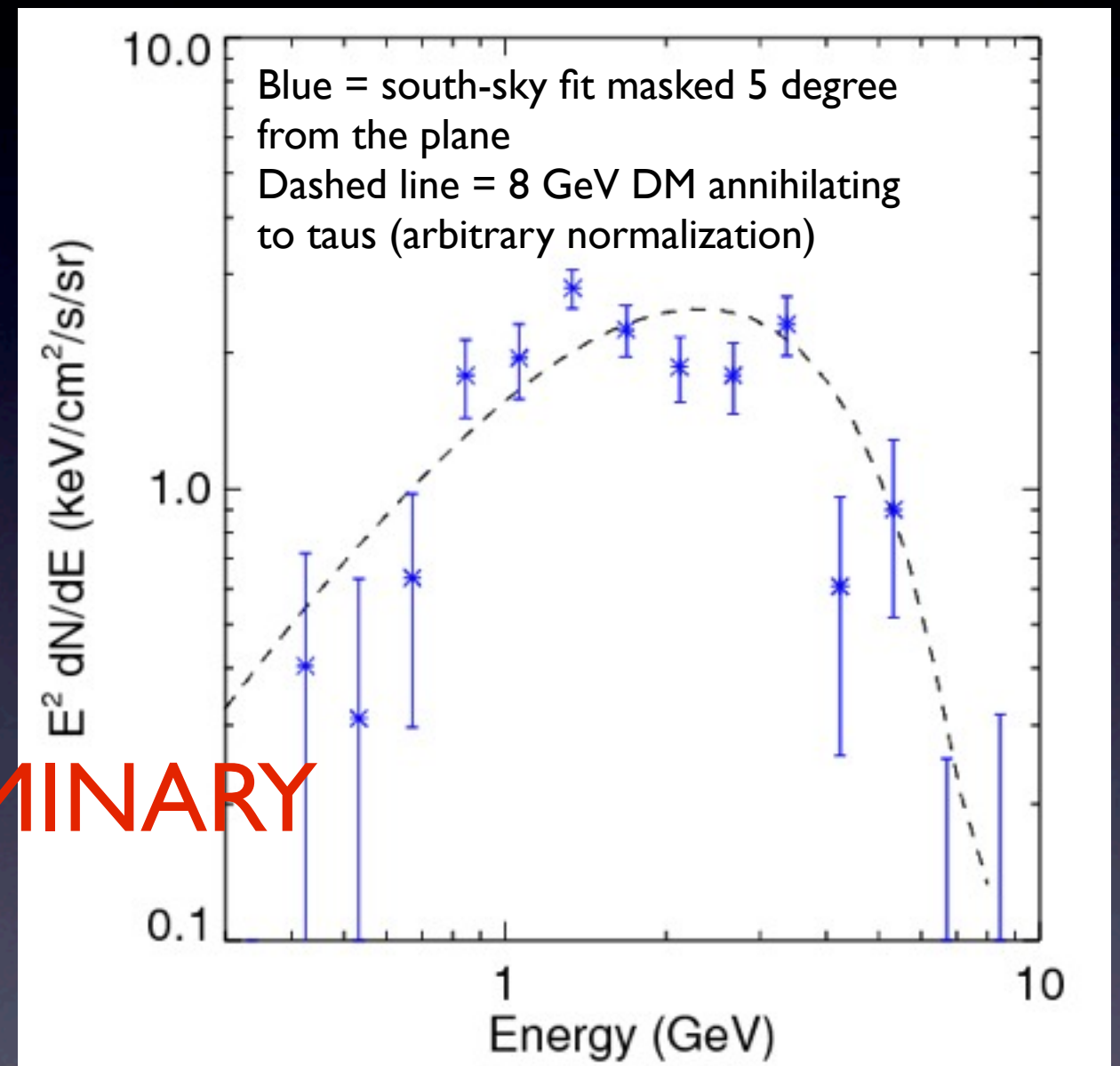
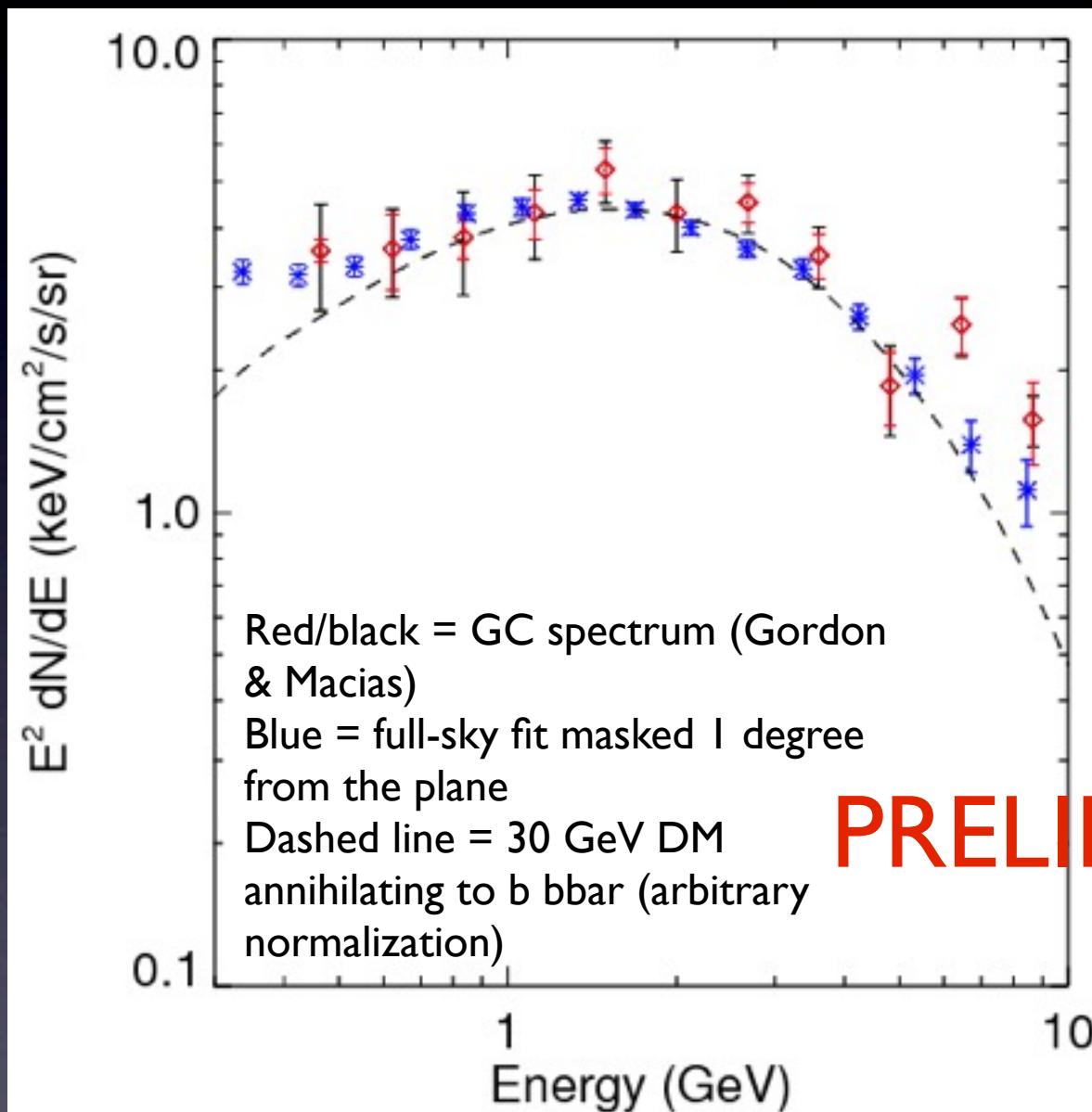
- Here α is the free parameter describing the family of curves, and the diffuse model spectrum is extracted from the data.
- Seems consistent with under- or over-subtraction of the diffuse model skewing the extracted spectra for the signal, especially at low energies.

DM interpretations of the spectrum (GC)

- For the Galactic Center signal, Gordon & Macias (1306.5725) find that 30 GeV DM annihilating to $b\bar{b}$ (and similar models with some branching fraction to leptons) provides a good fit.
- However, light dark matter annihilating to taus or $b\bar{b}$ does not: the spectrum is too sharply peaked.
- Does the GC signal lie along our one-parameter family of curves? If so, where?



Comparison to the GC



- The GC spectrum of Gordon and Macias agrees remarkably well with our spectrum from the full-sky NFW fit masked 1 degree from the plane.
- Moving along the one-parameter family of curves, subtracting more and more of the diffuse emission, would lead us to prefer lighter DM, harder spectra and lower cross sections.

The pulsar hypothesis

(see I305.0830 for details)

- Millisecond pulsars occur when pulsars are “spun up” by accretion from a companion. Because they are found in binary systems, their density can plausibly rise as rapidly as required ($\sim r^{-2.4}$) toward the Galactic Center.
- Average pulsar spectrum from Fermi-LAT has cutoff at approximately the correct energy (~ 10 GeV).
- Low-energy spectrum is uncertain, as we have seen - the average pulsar spectrum appears difficult to rule out within the systematic uncertainties.
- Diffuse gamma-ray emission from a few hundred to 2000 faint millisecond pulsars is claimed to provide a good fit to the GC signal (Gordon & Macias; the question has previously been discussed by Hooper & Linden, Abazajian & Kaplinghat). See also talk by Nicolas Canac.
- Can they produce the signal at 10-20 degrees from the Galactic plane?

Pulsar modeling

- We follow Loeb & Faucher-Giguere 2009 (0904.3102); their pulsar models are calibrated to / based on the results of existing large-scale radio surveys.

$$\frac{dN}{dP} \propto P^{-2}, P > P_{\min}$$

$$\frac{dN}{d \ln B} \propto e^{-(\ln(B/B_0))^2/2\sigma^2}$$

- Results agree with recent study by Gregoire & Knodlseder 1305.1584.

$$\rho_{\text{disk}}(r, z) \propto e^{-r^2/2r_0^2} e^{-|z|/z_0}$$

Distribution by B-field, period, position

$$\dot{E} = 4\pi^2 I \dot{P} / P^3$$

Luminosity as a function of B-field and period

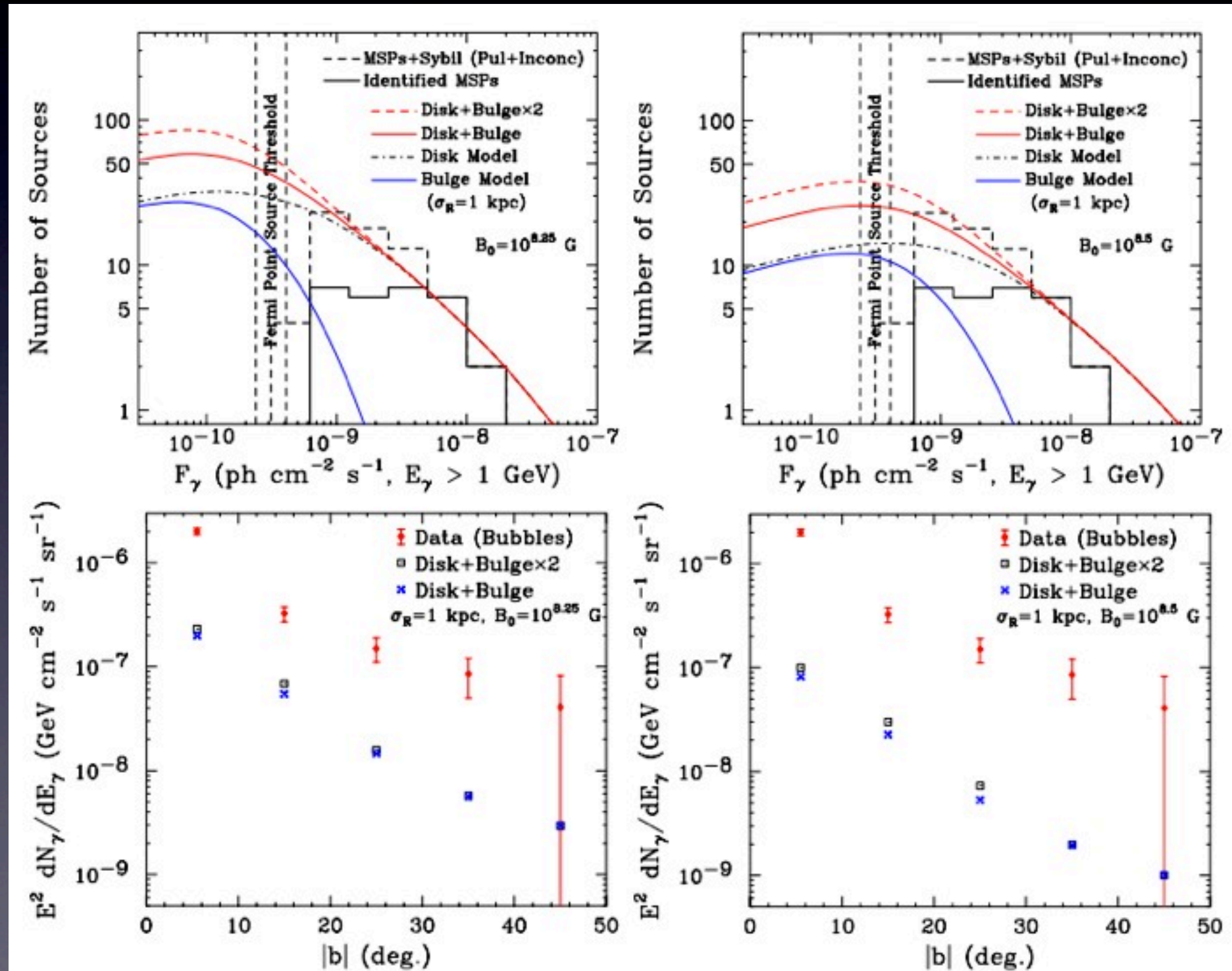
$$= 4.8 \times 10^{33} \text{ergs/s} (B/10^{12} \text{G})^2 (P/0.3 \text{s})^{-4} (I/10^{45} \text{gcm}^2)$$

$$L_{\gamma}(> 100 \text{MeV}) \approx 0.05 \dot{E}, \dot{E} < 10^{37} \text{ergs/s}$$

$$\propto \sqrt{\dot{E}}, \dot{E} > 10^{37} \text{ergs/s}$$

Can it be pulsars?

- Compare pulsar models to existing population of confirmed/possible gamma-ray MSPs; use this to calibrate the luminosity function.
- Lack of observed bright high-latitude pulsars limits number of faint pulsars, unless there is a new spatially distinct population with different intrinsic characteristics to the disk pulsars.



Conclusions

- A spectral feature peaking at a few GeV can be isolated in the inner Galaxy, within 5-20 degrees of the Galactic Center.
- Excellent spectral agreement with that of the Galactic Center GeV excess, strongly suggesting the two signals share an origin.
- Both signals independently prefer a squared (generalized) NFW spatial profile with an inner slope of -1.2 , as does the amplitude comparison between them.
- Over- or under-subtraction of the diffuse background can modify the extracted spectrum significantly, especially at energies below 1 GeV, changing the models which are favored to explain the signal.
- Our spectra obtained from different regions of interest lie along a one-parameter family of curves, distinguished by the varying coefficient of the diffuse background. Diffuse background is the key source of uncertainty in discriminating models.
- Unless millisecond pulsars in the bulge are intrinsically fainter than elsewhere in the Galaxy, in order to generate the observed excess with faint sources, Fermi should already have observed their bright counterparts. The shortfall is a factor of ~ 10 .