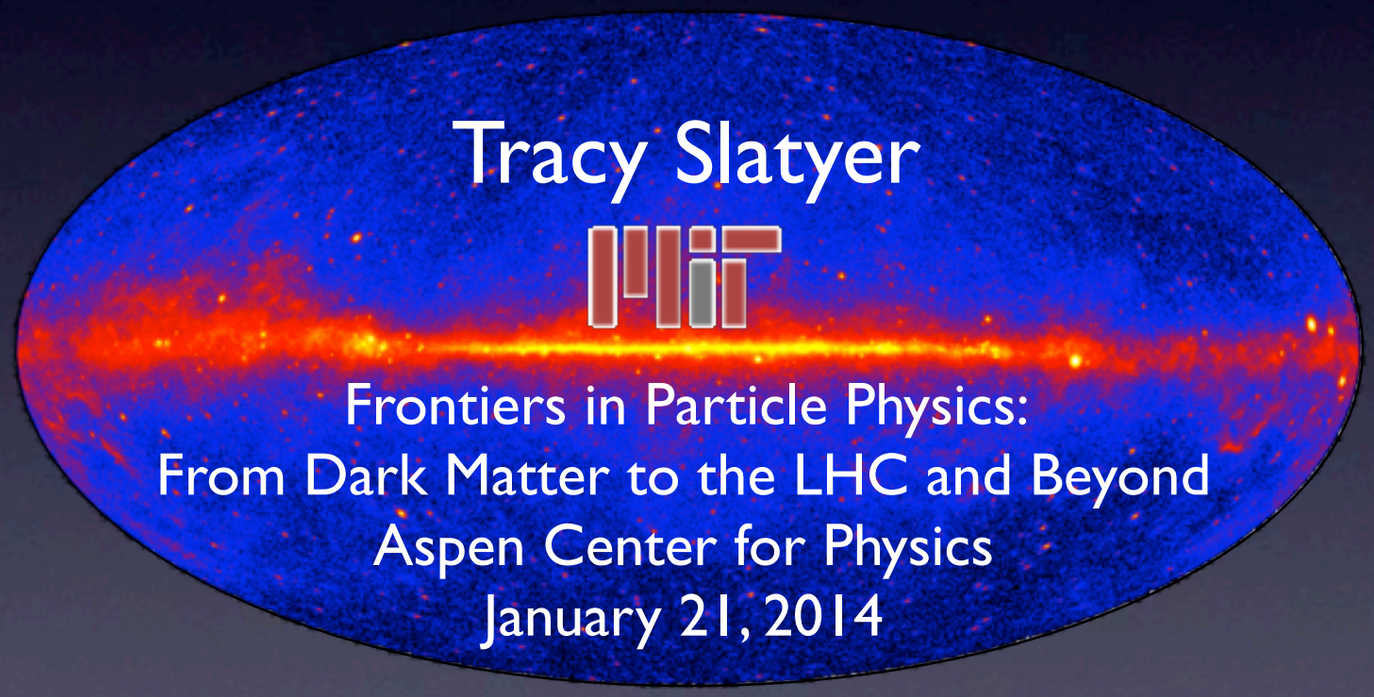
A Possible Dark Matter Signal in Gamma Rays from the Inner Galaxy



Tracy Slatyer

Frontiers in Particle Physics:
From Dark Matter to the LHC and Beyond
Aspen Center for Physics
January 21, 2014

Based on 1302.6589 (Hooper & TRS), 1305.0830 (Hooper, Cholis, Linden, Siegal-Gaskins & TRS), and upcoming work with Doug Finkbeiner, Dan Hooper, Tim Linden, Stephen Portillo & Nick Rodd

Dark matter in gamma rays

- DM does not carry electric charge, does not couple directly to photons (it is "dark").

Line signal - typically suppressed

$$\chi\chi \to \gamma\gamma \qquad \chi\chi \to \gamma Z$$

"Smoking gun" - distinctive spectral feature

Continuum signal (example)

$$\chi\chi \underset{?}{\to} \tau^+\tau^-$$

$$\tau^- \underset{25\%}{\to} \pi^-\pi^0\nu_\tau$$

$$\underset{9\%}{\to} \pi^- 2\pi^0\nu_\tau$$

$$\pi^0 \underset{99\%}{\to} \gamma\gamma$$

Expected to be a much larger signal in generic models, but not background-free.

This talk focuses on a possible "continuum" signal, and is based on public data from the Fermi Large Area Telescope, which:

- Launched in 2008.
- Scans the entire sky every two orbits (~3 hours).
- Is sensitive to gamma-rays from 30 MeV up to several TeV.

Features of a DM signal

- Look for both spatial and spectral identifiers.
- Astrophysical backgrounds for diffuse gamma-ray emission include photons produced by:
  - Cosmic ray protons striking the ambient gas, producing neutral pions which decay to photons ("π^0 gammas") - roughly traces the gas density.
  - Inverse Compton scattering of photons of the interstellar radiation field by cosmic-ray electrons: "ICS gammas".
  - Populations of faint point sources (e.g. active galactic nuclei, pulsars).
- Backgrounds *generally* have broken-power-law-like spectra - DM annihilation can produce spectral features localized in energy, with sharp cutoffs at the DM mass. (However, some DM annihilation modes also mimic astrophysical backgrounds.)

Features of a DM signal (II)

- DM should also have a roughly spherical distribution, not following the Galactic plane.
- There may be hot-spots corresponding to localized clumps of DM / satellite galaxies, but the signal is generally predicted to be brightest from the Galactic Center (of course, backgrounds are also bright there).
- The signal scales as DM density squared, we parameterize DM density by "generalized NFW profile" (motivated by simulations):

$$\rho \propto \frac{r^{-\gamma}}{\left(1+\frac{r}{R_s}\right)^{3-\gamma}}$$

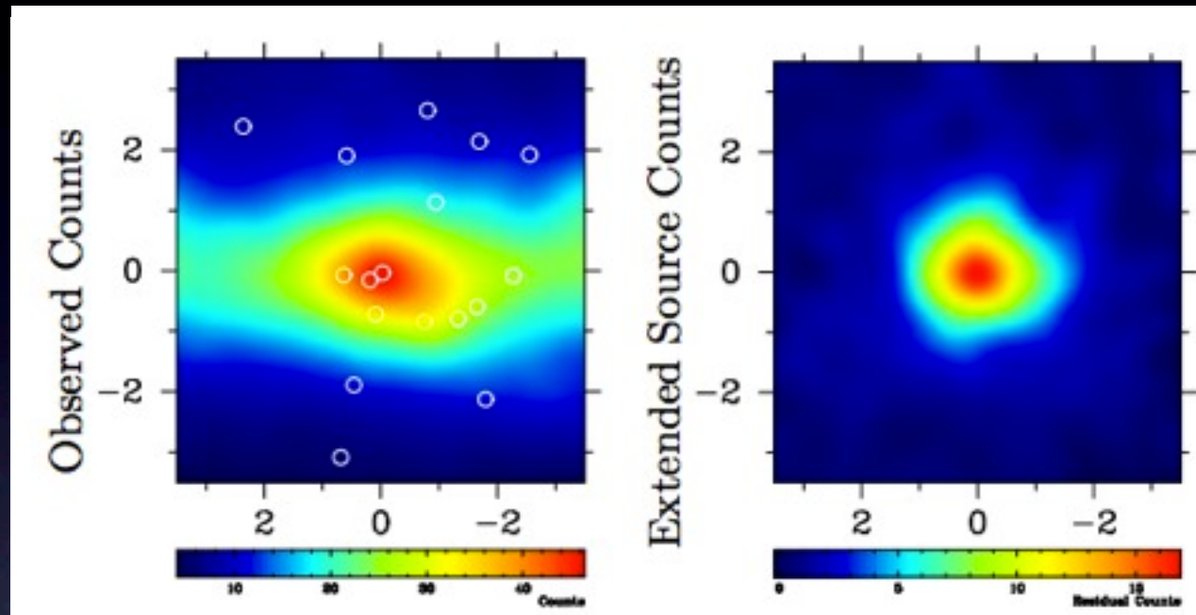
$\gamma = 1$ for classic NFW

"Scale radius" r_s ~ 20 kpc for Milky Way

The ~GeV Galactic Center

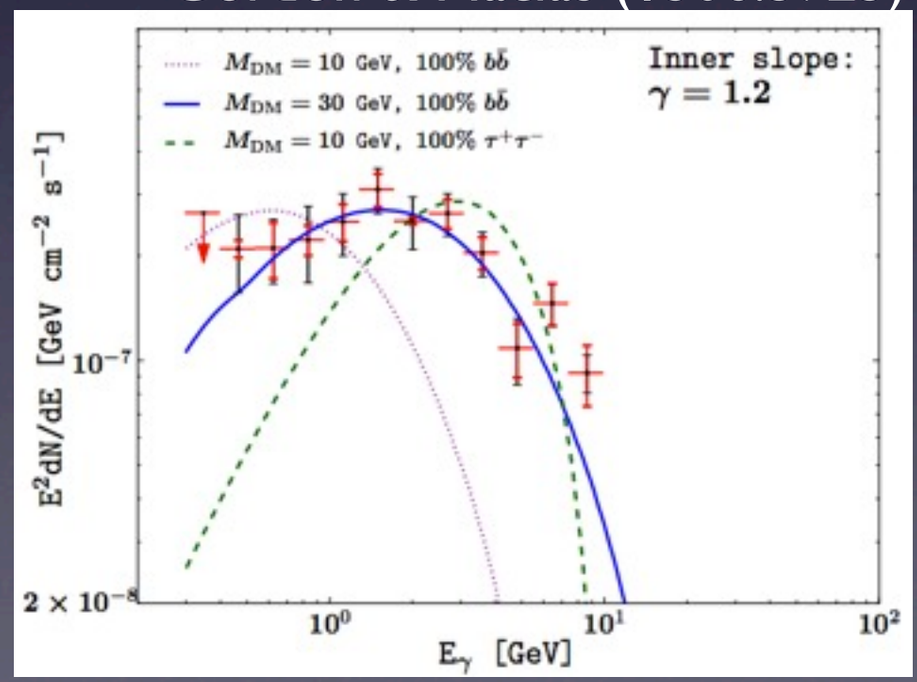
Abazajian & Kaplinghat 2012

- Extended (non-pointlike) emission, with an unusual spectrum, has been identified in the center of the Milky Way (initially by Goodenough & Hooper 09). Key features:
  - Peaks at a few GeV, spectrum consistent with ~30 GeV DM annihilating to $b\bar{b}$.
  - 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 $r^{-2.4\text{-}2.6}$.



spatial distribution

Gordon & Macias (1306.5725)



spectrum

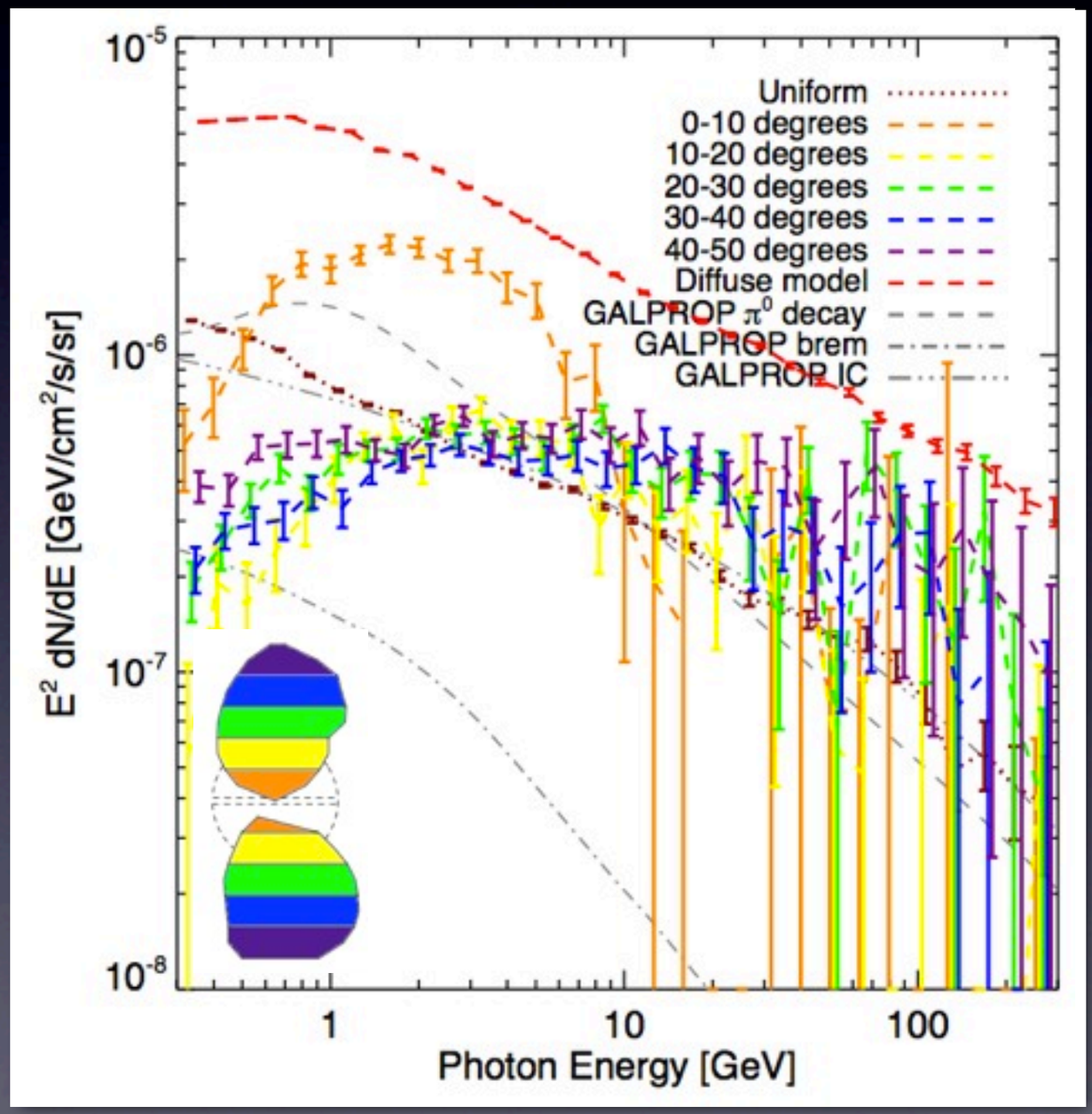
Tracy Slatyer - A Possible Dark Matter Signal in Gamma Rays from the Inner Galaxy

An all-sky template analysis

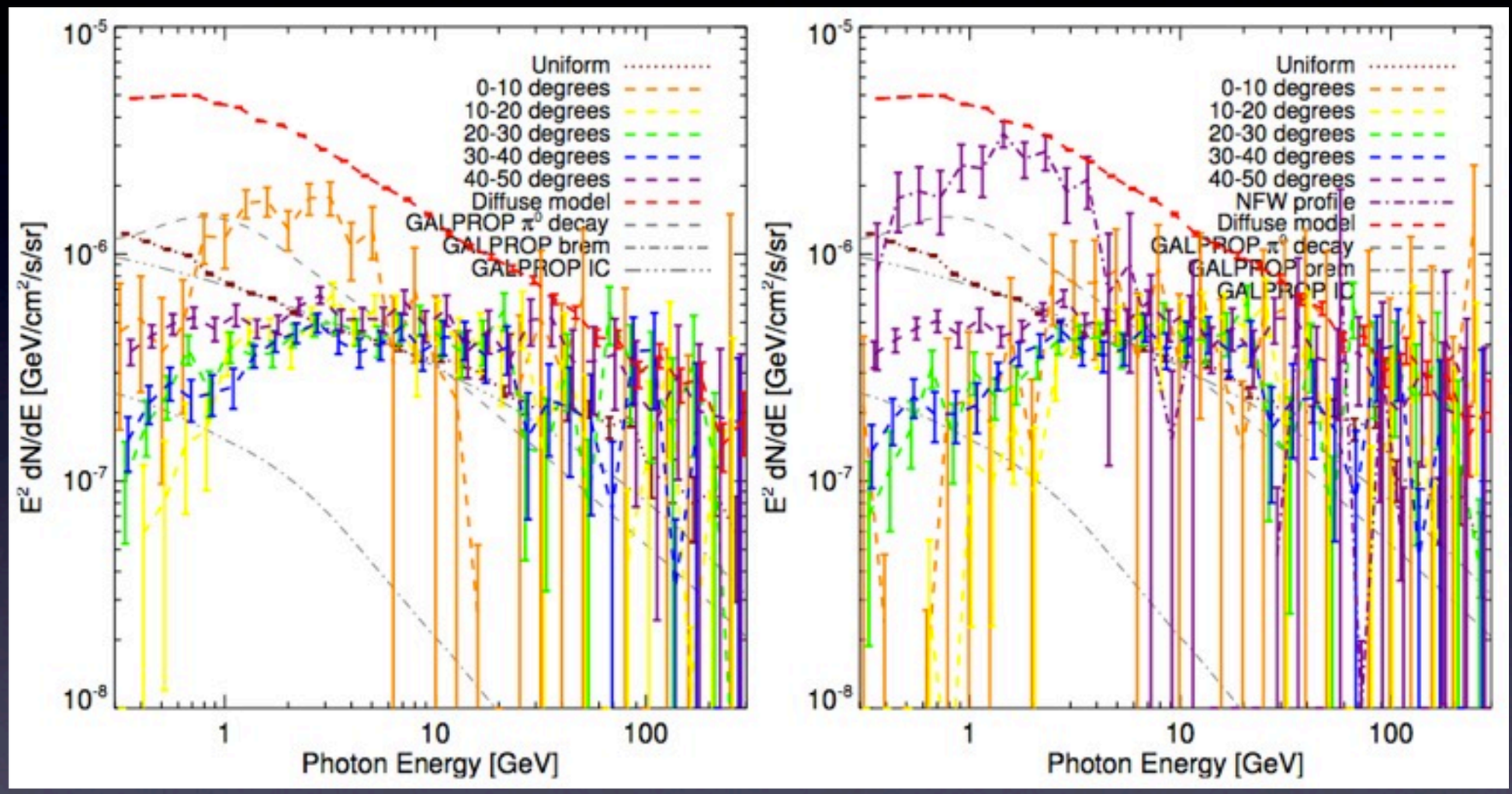
- Use a diffuse-emission model made available by the Fermi Collaboration, using dust and gas maps to model the π^0 emission and modeling ICS using the public code GALPROP.
- In each energy bin, fit the sky as a linear combination of:
  - The diffuse model (interpolated to that energy).
  - A uniform offset.
  - The "signal" templates.
- A spectrum for each template can then be extracted from its best-fit coefficients by energy - no spectral information is put into the fit.
- Initial study (TRS and Dan Hooper, 1302.6589) used this method to measure spatial variation in the "Fermi Bubbles" (giant hard-spectrum gamma-ray structures in the inner Galaxy). "Signal" templates were 10-degree slices in latitude through the Fermi Bubbles.

The inner Galaxy excess

- The spectrum of the Bubbles develops pronounced curvature at low Galactic latitudes.
- Consistent with two components, one flat in E^2dN/dE and latitude, the other with a bump at few-GeV energies and falling rapidly with latitude.
- The amplitude and spectrum of this second component is consistent with extrapolation of the GC excess.
- We hypothesize two signal components - so we add an additional spatial template, projected squared generalized-NFW profile with inner slope γ=1.2.



A DM-like morphology?

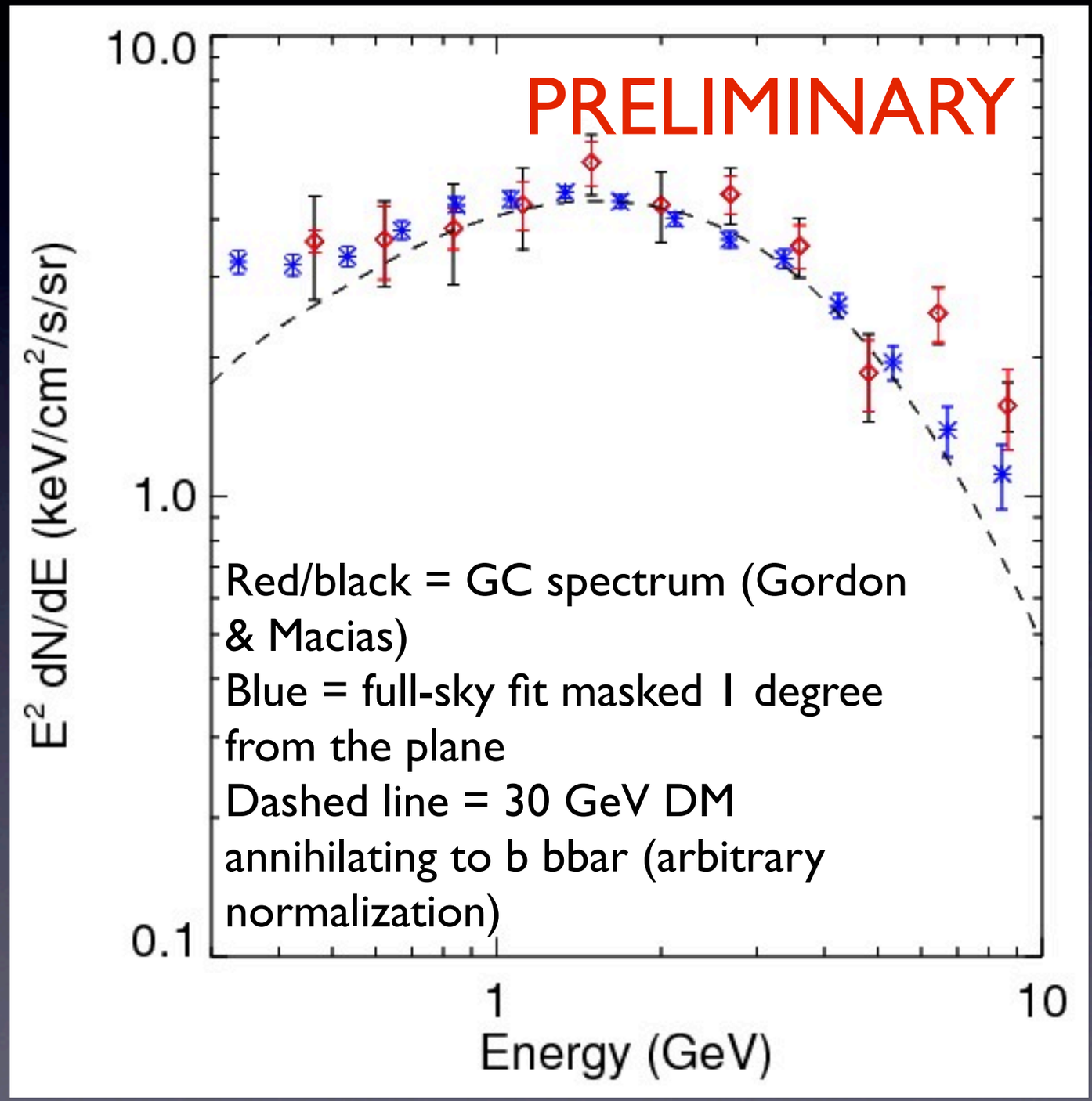


When given the choice, the fit prefers to correlate the spectral bump with a DM-like template, not the bubbles.

- 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. This should be a "clean" fit (and no spatial overlap with previous GC analyses).
- Left panel: bubble templates only, right panel: NFW profile included.

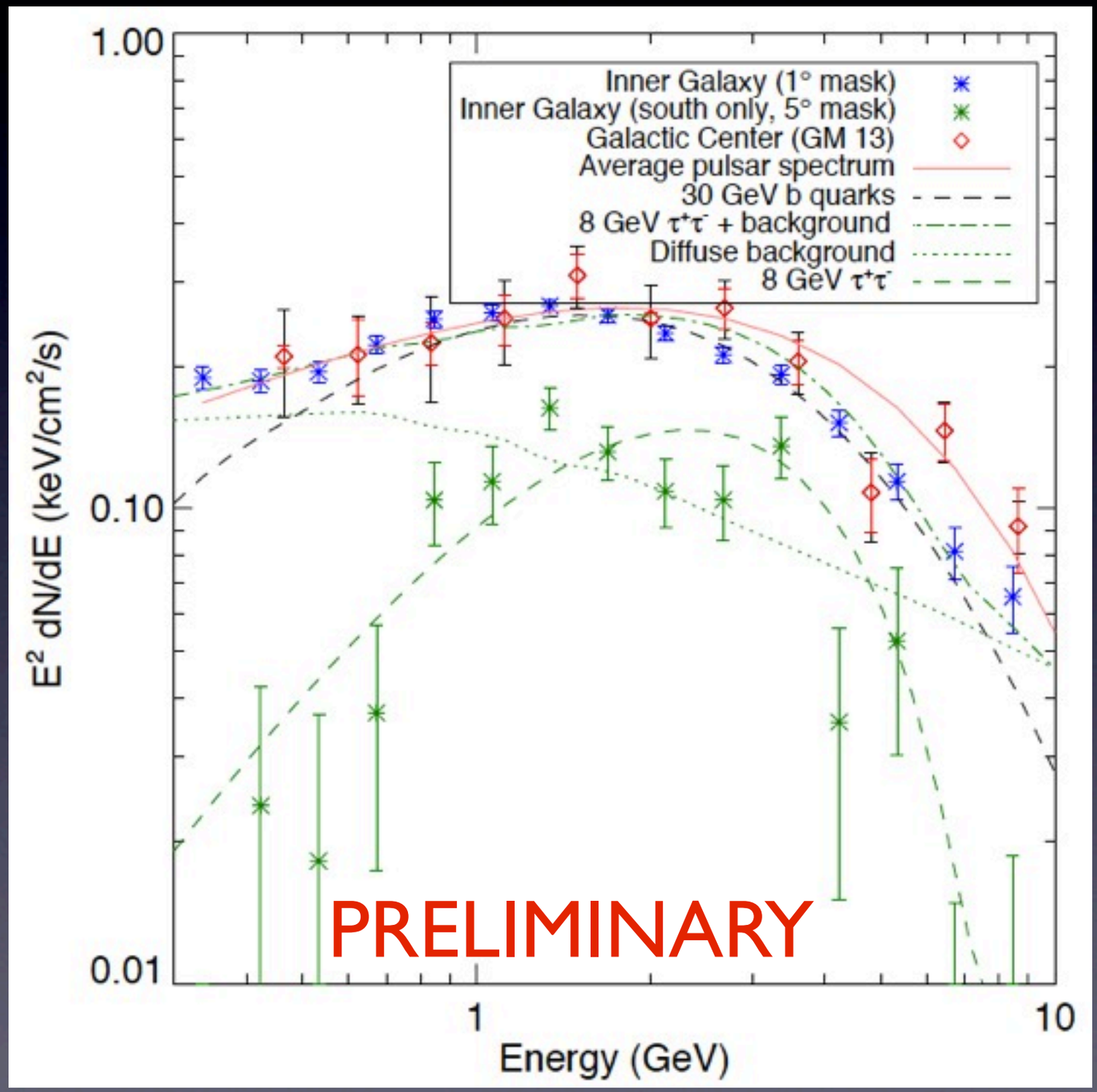
Inner Galaxy vs the GC

- Red/black points = latest analysis of Galactic Center signal, normalized assuming a generalized NFW profile with γ=1.2.
- Blue points = spectrum correlated with DM-like template from our full-sky fit, masking 1 degree from the Galactic plane.
- The two signals are in remarkable agreement, and almost certainly share an origin.



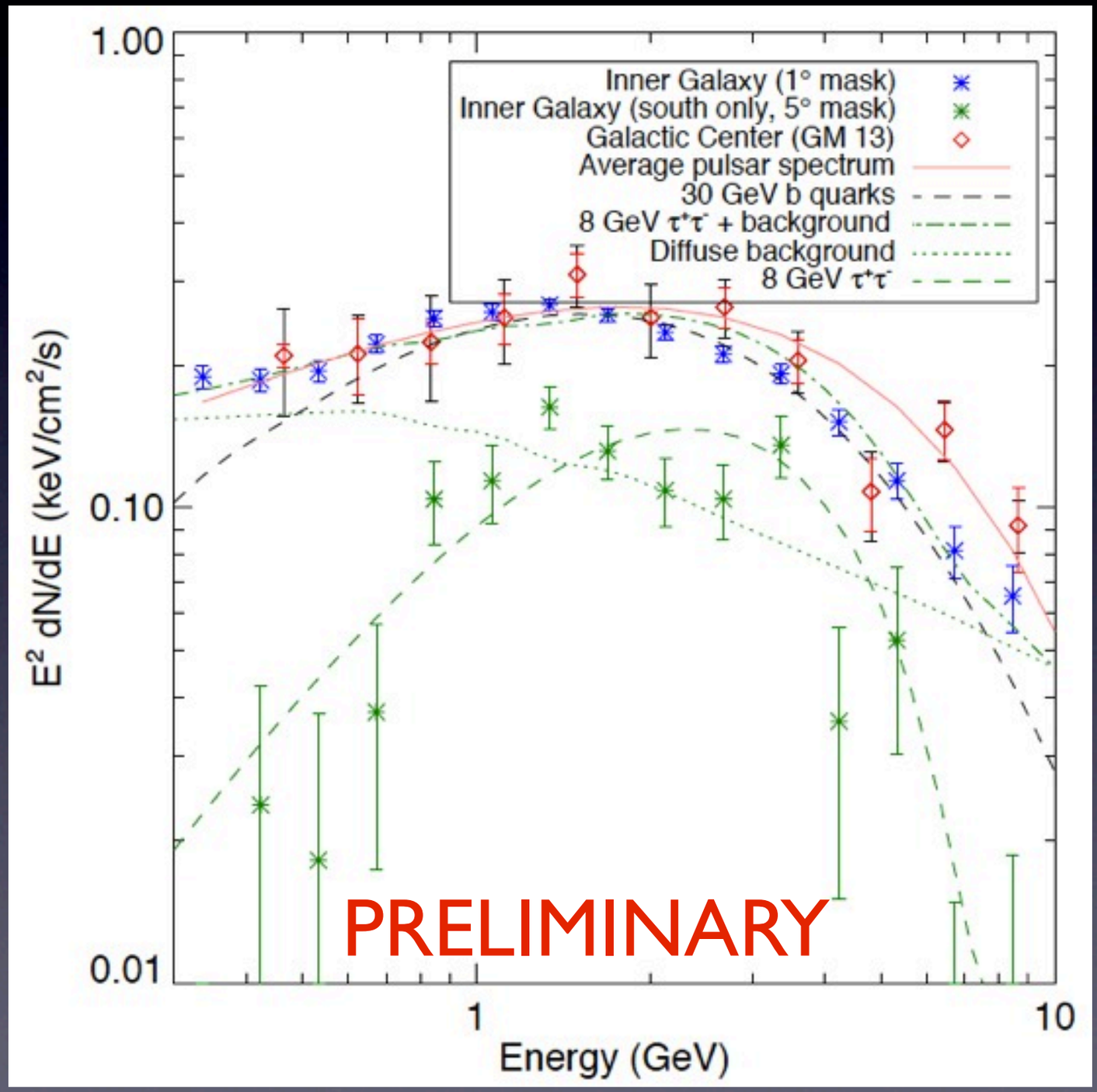
Robustness of the spectrum

- Independent of details of the DM-like spatial template, e.g. choice of low-r power-law slope (tested varying γ between 1 and 2).
- However, does depend on the sky region used for the fit.
- Green data points show best-fit spectrum for the DM-like template in the southern sky, masking b > -5°.
- This more sharply peaked spectrum, if interpreted as DM annihilation, prefers lighter DM annihilating to τ leptons (green dashed line).



Over/under-subtraction

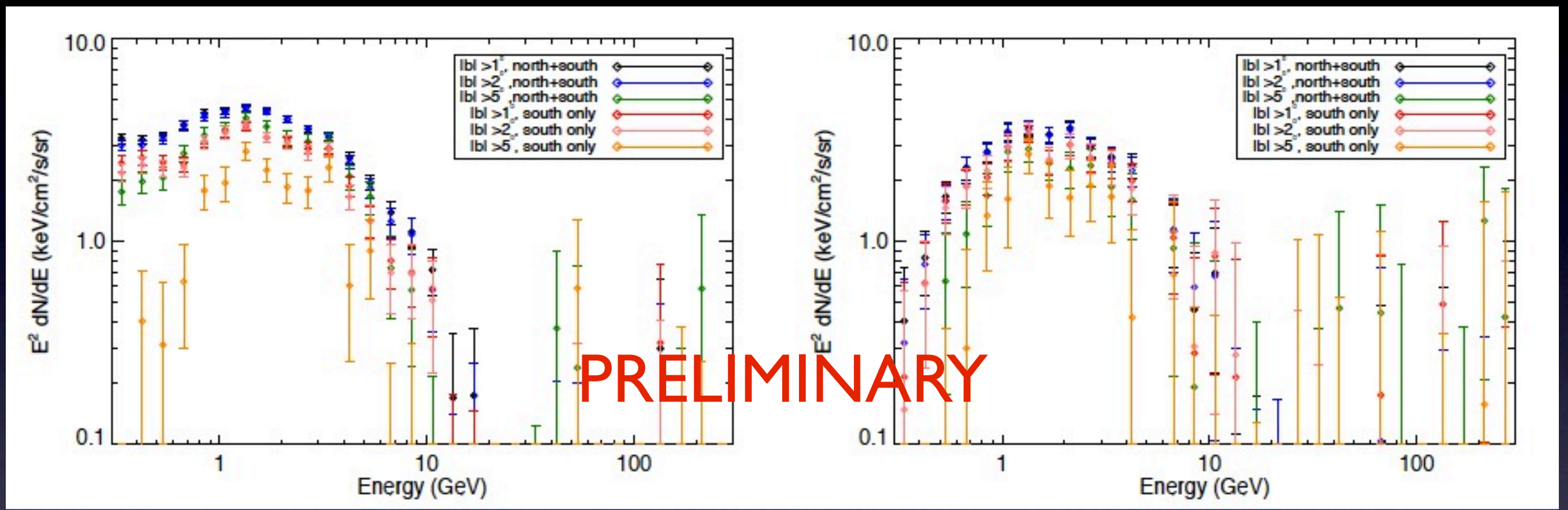
- Green dotted line = spectrum of diffuse background (shape extracted from data, normalization chosen by hand).
- Green dot-dashed line = green dotted line + spectrum from DM annihilating to taus.
- The difference between the two spectra can be well explained by mis-subtraction of the diffuse background.



A cleaner data sample

- The Fermi Collaboration has re-released their data set with a new parameter, CTBCORE - describes event reconstruction quality.
- Cutting on this parameter can give a photon sample with better angular resolution at the cost of lower statistics (work in progress by Finkbeiner & Portillo).
- Can redo the analysis with maps built from this high-angular-resolution sample.
- The hope: perhaps some of the mis-attribution of photons between templates (or from point sources?) is coming from the photons in the tails of the point spread function, and will be reduced in this new high-angular-resolution dataset.

Consistency of spectra

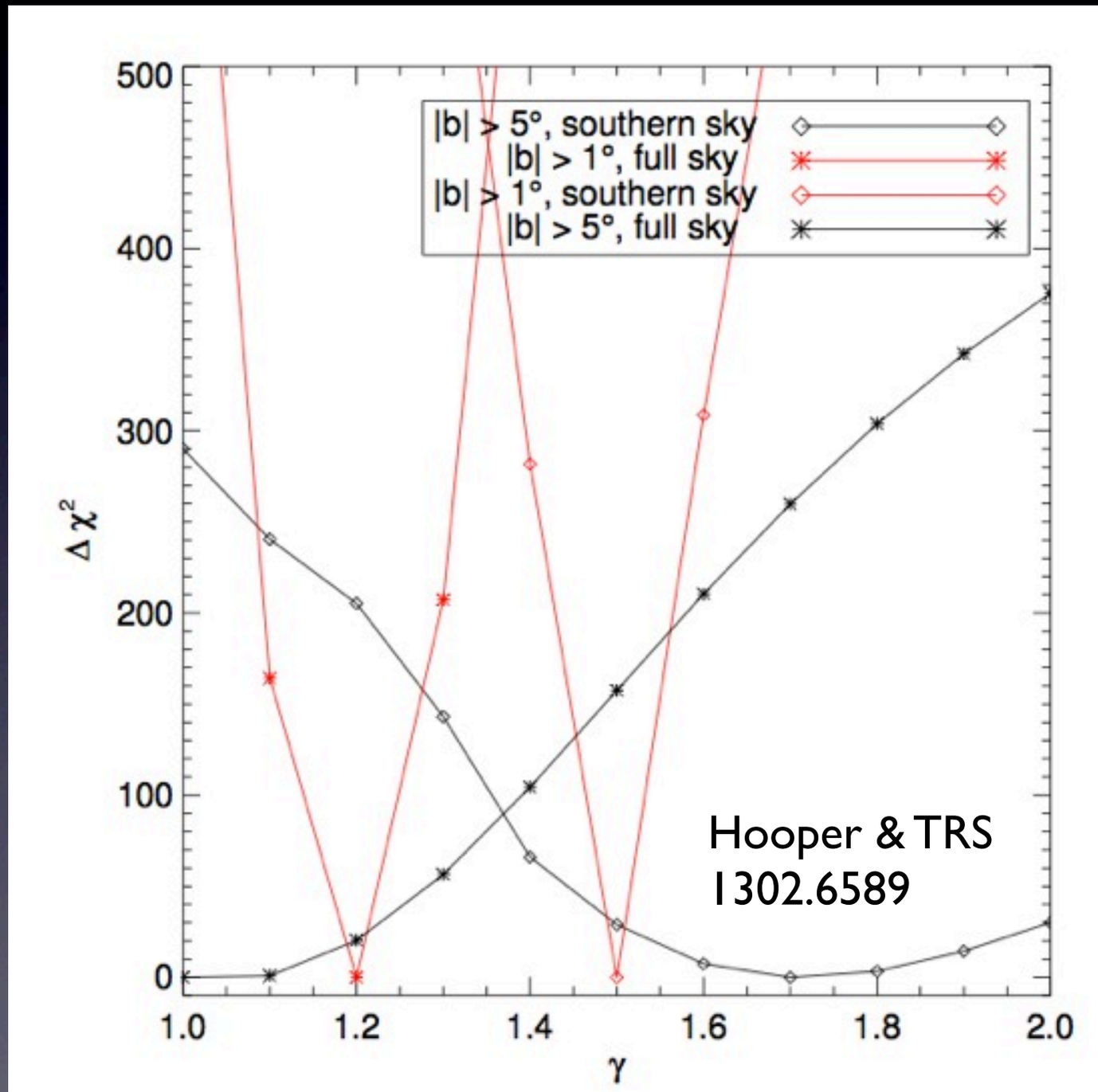


BEFORE AFTER

- Spectral shapes are much more consistent.
- The resulting spectrum is more peaked in E^2dN/dE than the previous fits close to the plane.
- Less consistent with the Fermi average pulsar spectrum. (The pulsar hypothesis also appears inconsistent with the spatial distribution of the excess, see 1305.0830.)

Morphology of the signal

- Previously there was also some evidence for north-south asymmetry in the inner Galaxy signal.
- New cuts remove this asymmetry - preferred profile has γ=1.3.
- Results look similar masking 5° from the plane (although the $\Delta\chi^2$ values are smaller), favoring slopes of 1.2-1.3.



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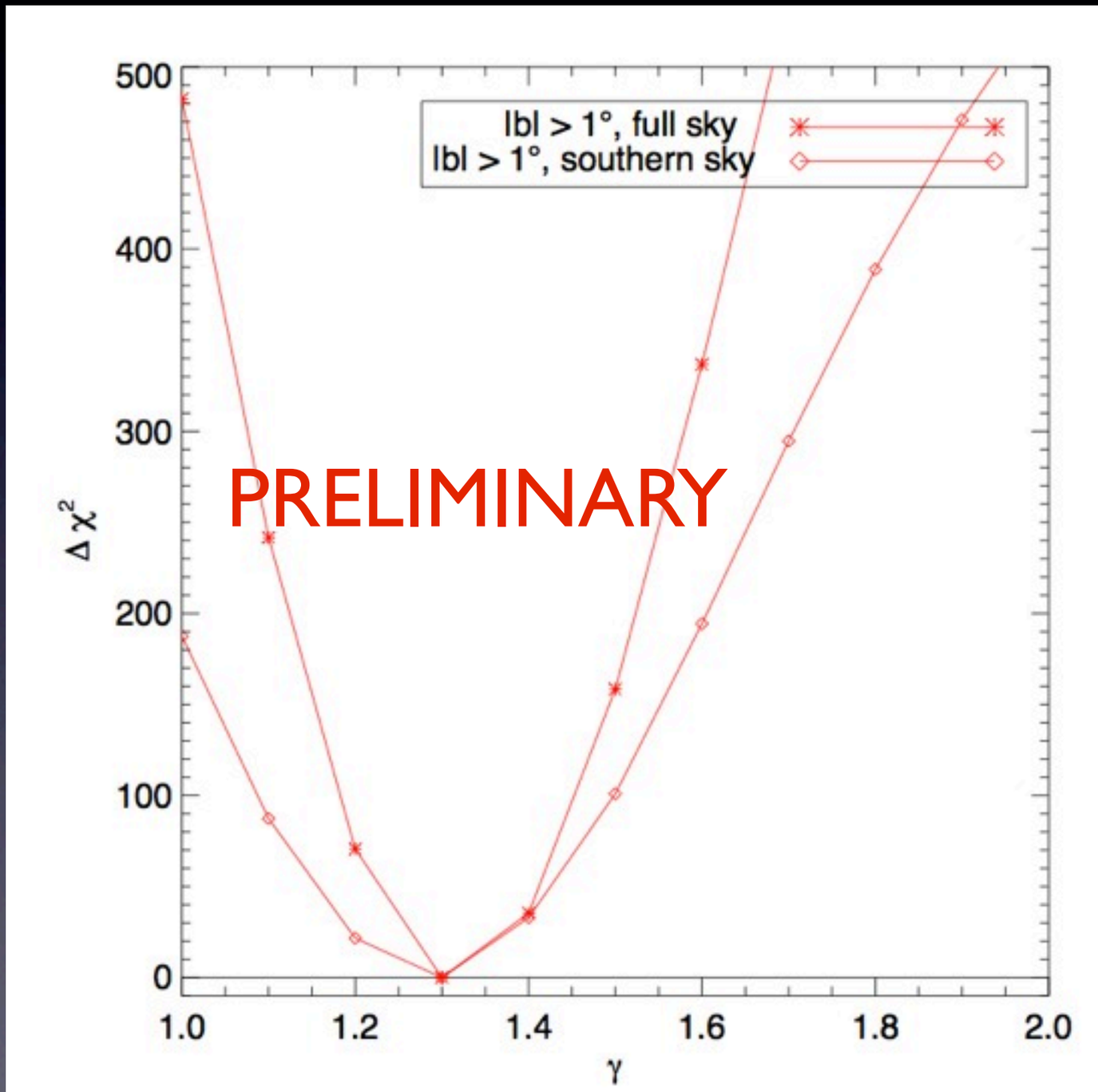
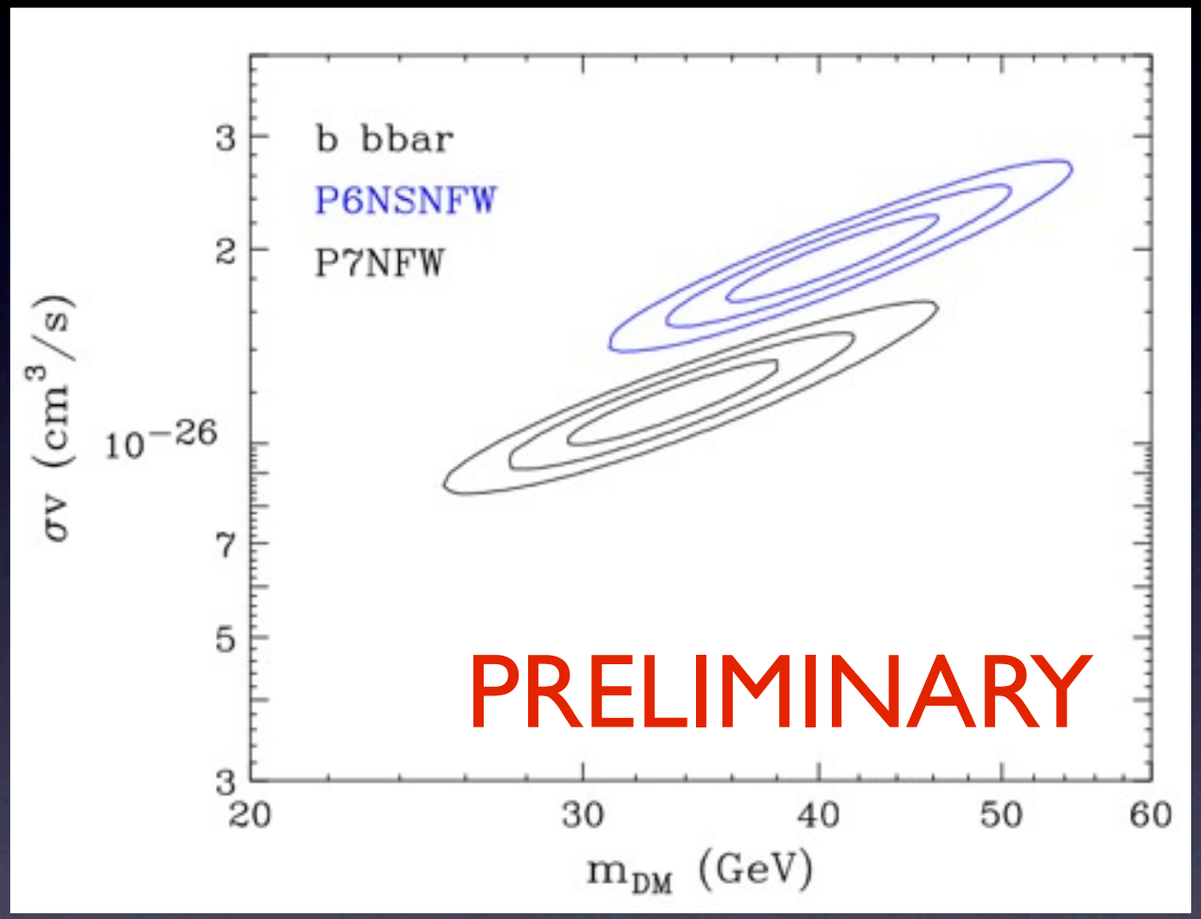


DM interpretation

- In agreement with previous studies, the signal prefers 30-50 GeV DM annihilating to b quarks with a close-to-thermal-relic cross section.
- Annihilation to taus only is acceptable if we allow a diffuse-Galactic-emission or power-law-like contribution to the spectrum (with free normalization).
- The two ellipses show two different models for the diffuse emission - work in progress on parameterizing this systematic uncertainty.



Some concrete toy models:

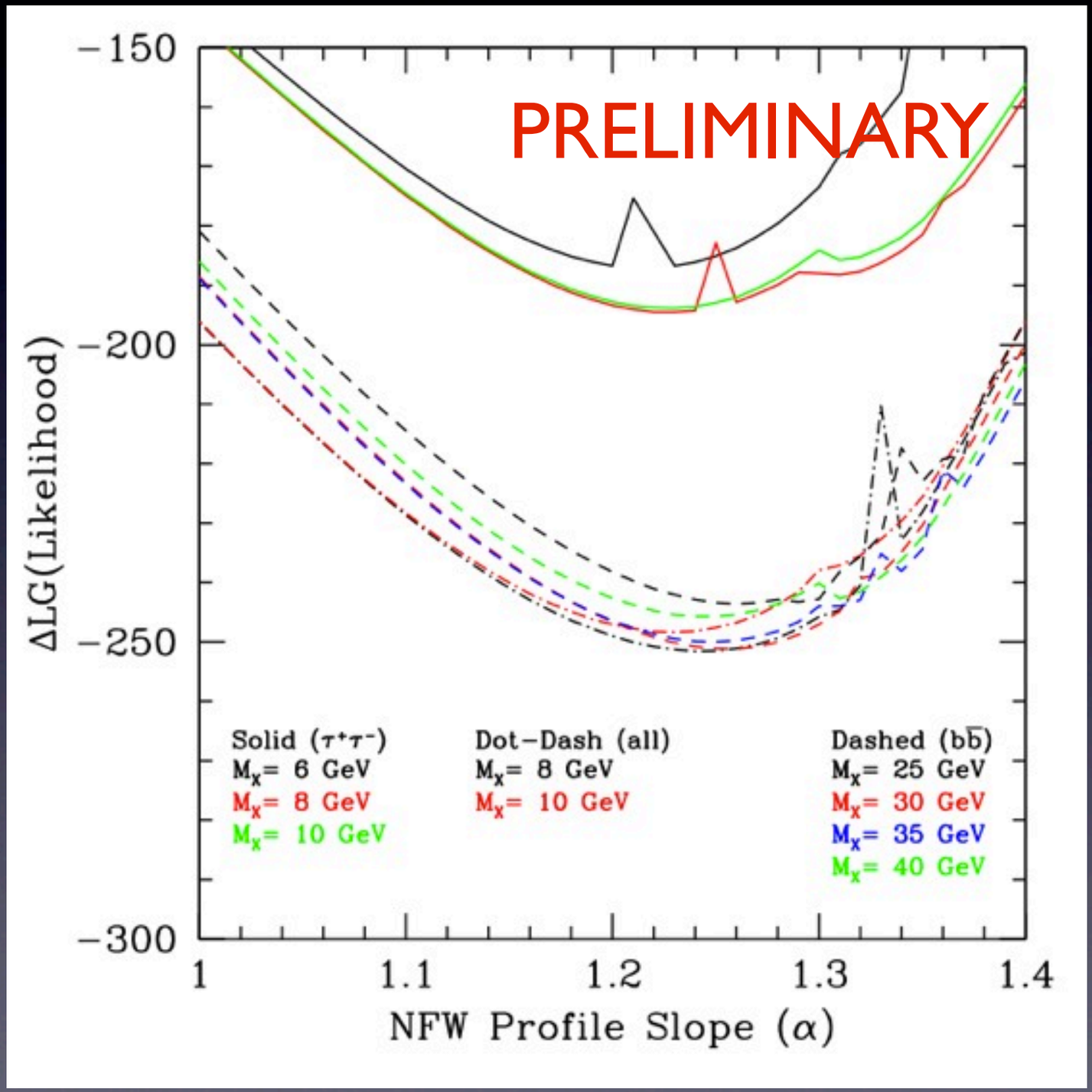
~10 GeV DM annihilating through a few-GeV dark photon (Hooper, Weiner & Xue 1206.2929),

~60 GeV scalar DM annihilating through the Higgs portal (1310.7609).

Effective field theory analysis done by Huang, Urbano & Xue in 1310.7609.

Galactic Center update

- Updated results from the Galactic Center using CTBCORE-cut data appear in agreement with Inner Galaxy results.
- Preferred profile slope ~1.3, preferred channel ~30 GeV DM annihilating to b's, or lighter DM annihilating to a mixture of final states.
- Fit performed using Fermi likelihood tools (unlike the inner Galaxy analysis which is done using independently developed code).



Status

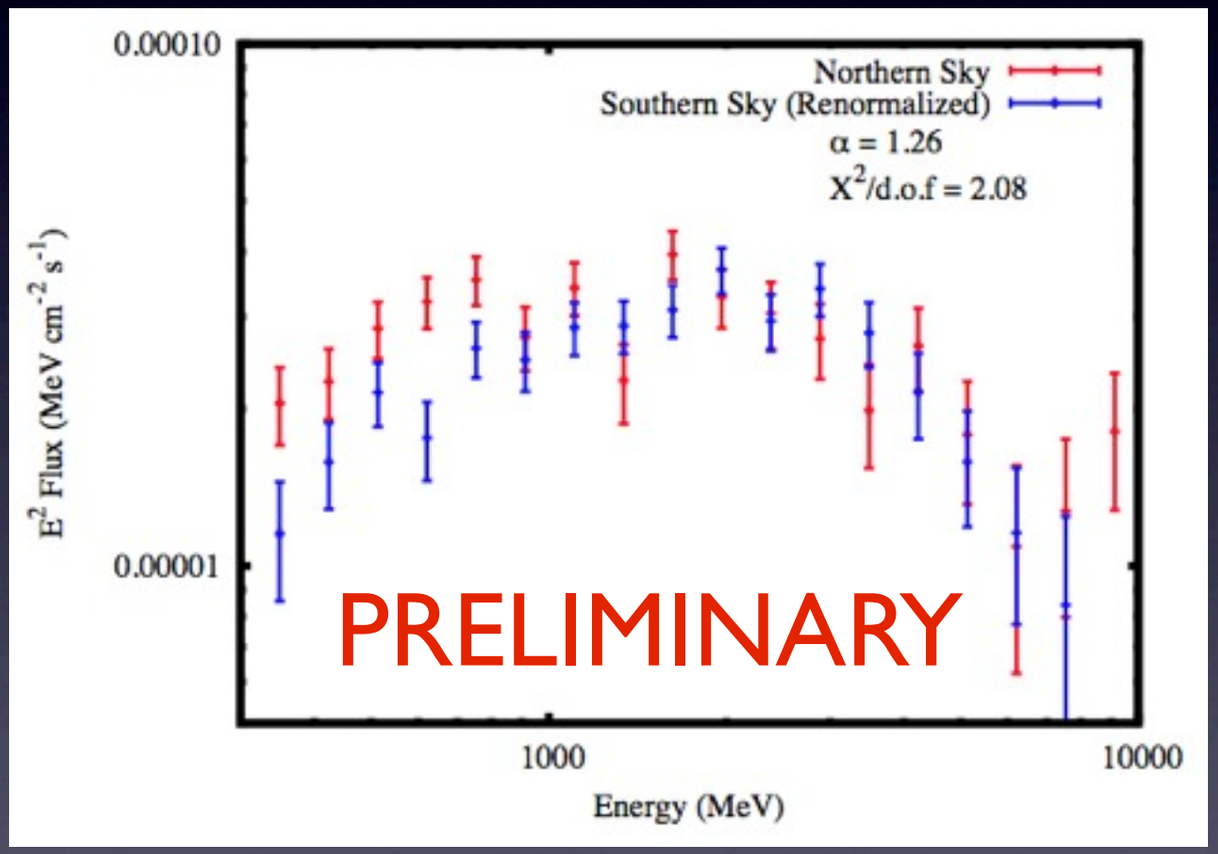
- We observe a spectral feature in few-GeV gamma rays from the inner Galaxy. It most likely shares an origin with the previously reported Galactic Center signal.
- This feature is spectrally distinct from the known backgrounds, and with recent improvements to the data selection, the spectrum seems quite stable with respect to the degree of masking of the Galactic plane, and symmetric between the northern and southern sky.
- The spatial distribution of the feature appears roughly spherically symmetric and falls off steeply with distance from the GC (consistent with DM annihilation from a generalized NFW profile with inner slope γ=1.2-1.3).

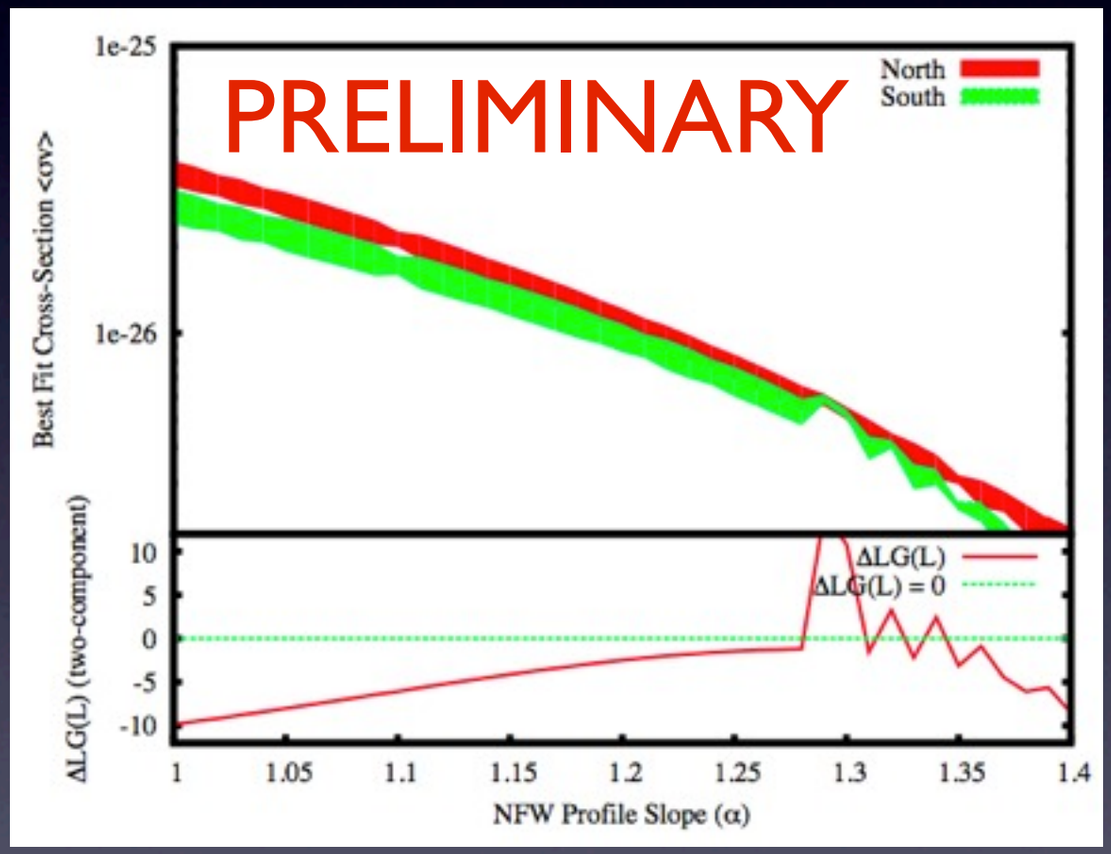
Open questions

- How dependent are these results on the background modeling? (in progress, + looking forward to Galactic Center analysis from the Fermi Collaboration)
- What regions of DM parameter space provide a good fit to the signal? (Tentative answer: annihilation of 10-50 GeV DM to b quarks and/or τ leptons, with a roughly thermal relic cross section.) What would this imply for DM model-building?
- Can simultaneous studies of the GC and inner Galaxy signals put better constraints on the morphology and spectrum? (in progress)
- How might we confirm or falsify the DM interpretation? (e.g. dwarf galaxies, cosmic microwave background)
- How might we confirm or falsify the hypothesis of a new astrophysical source population?

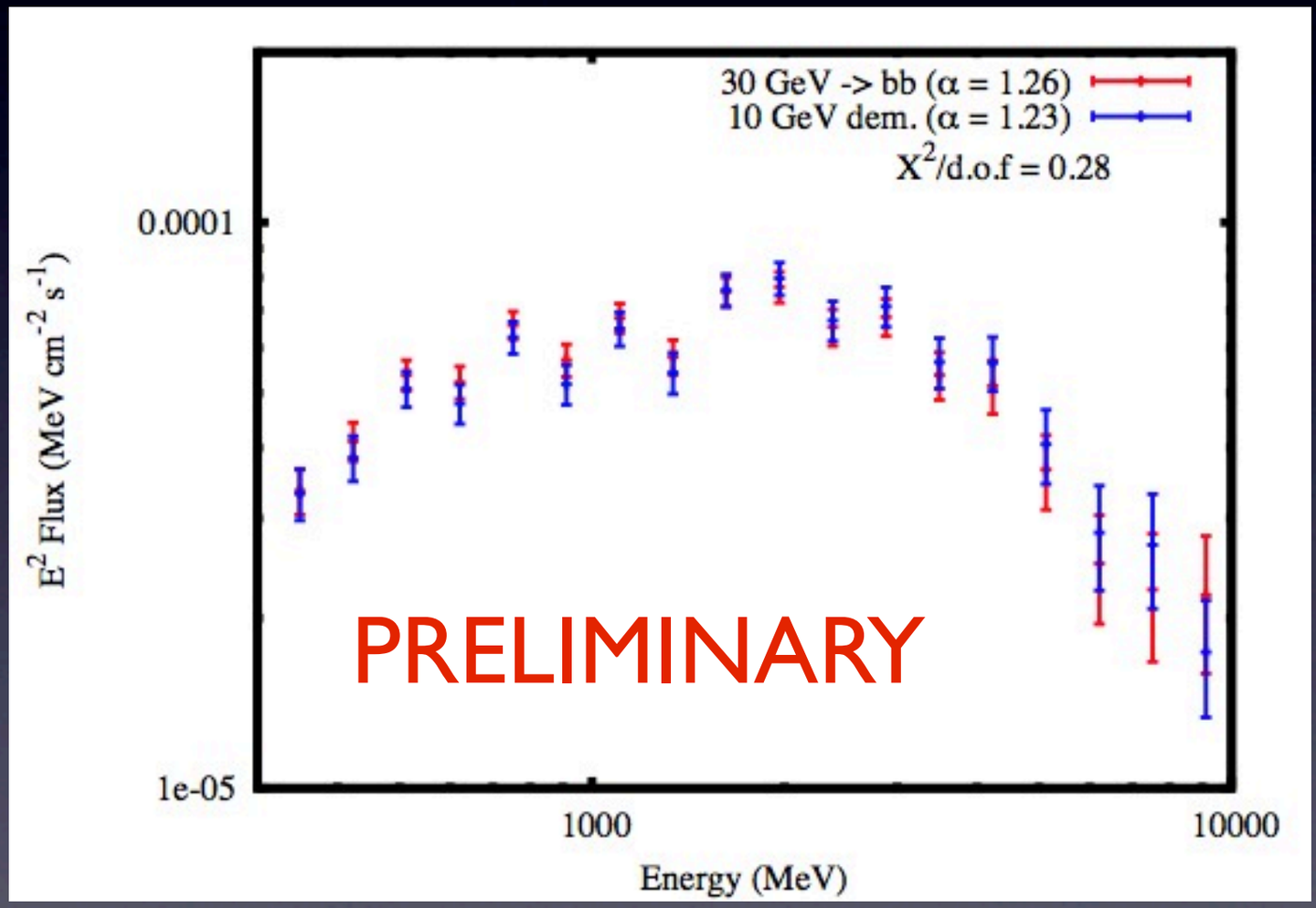
BONUS SLIDES

North-south symmetry in the GC

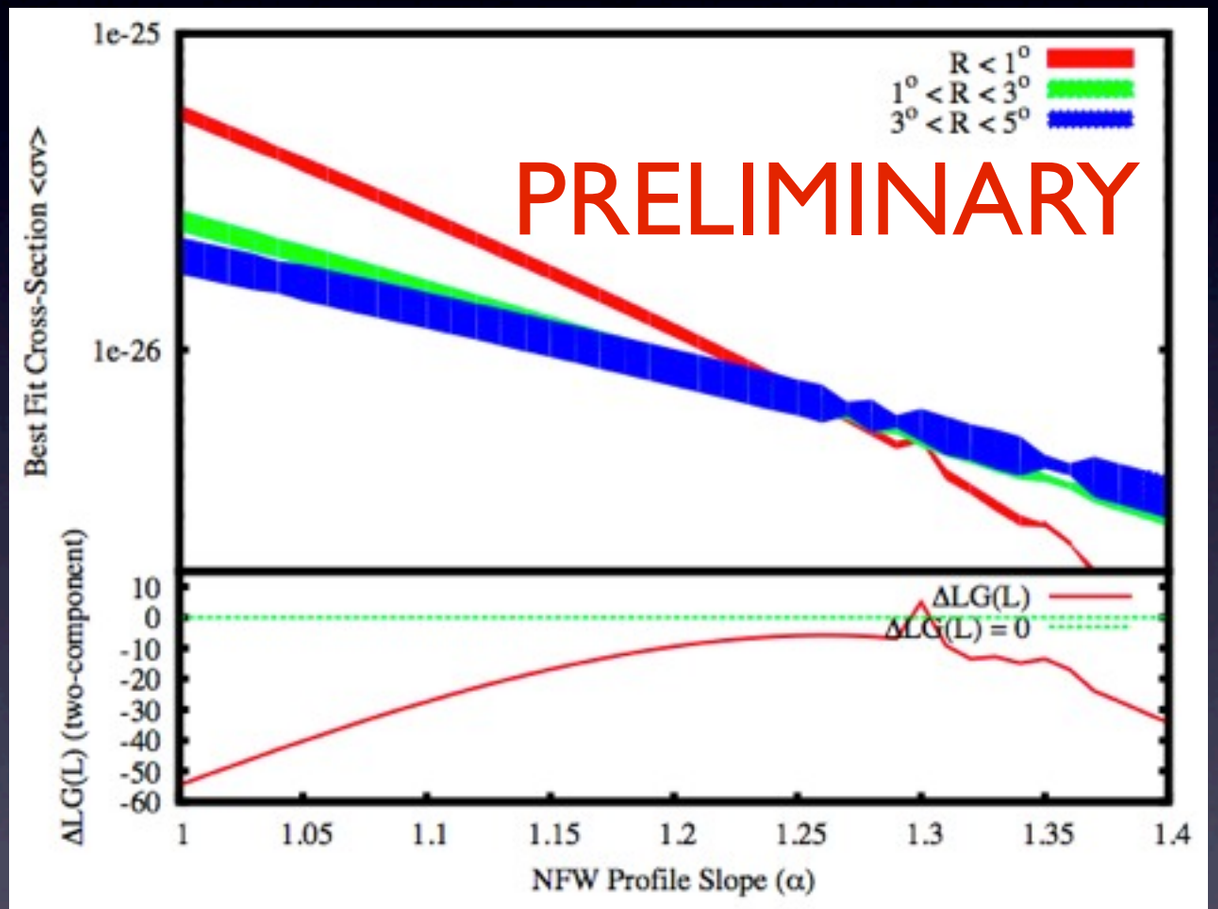


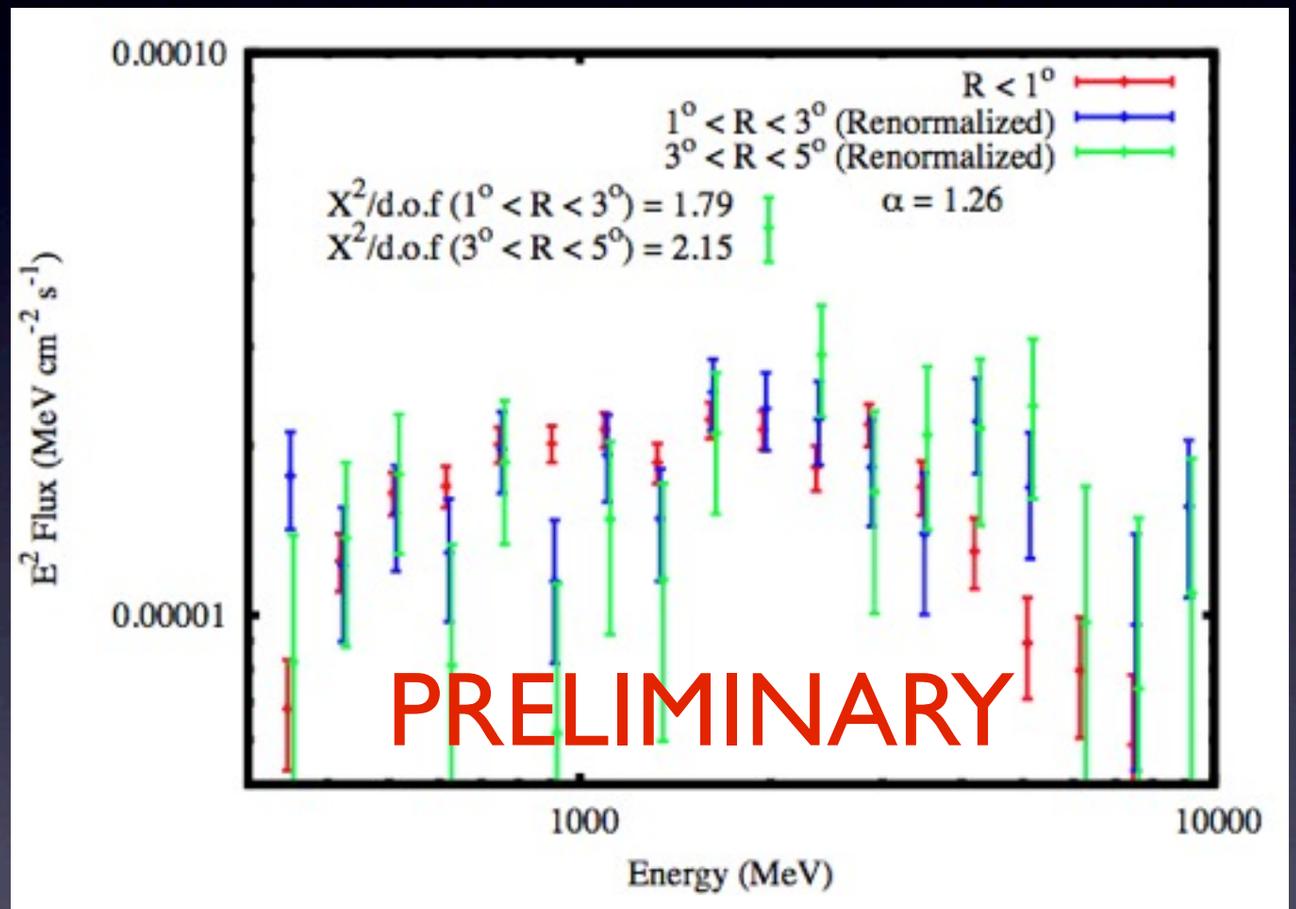


The GC spectrum

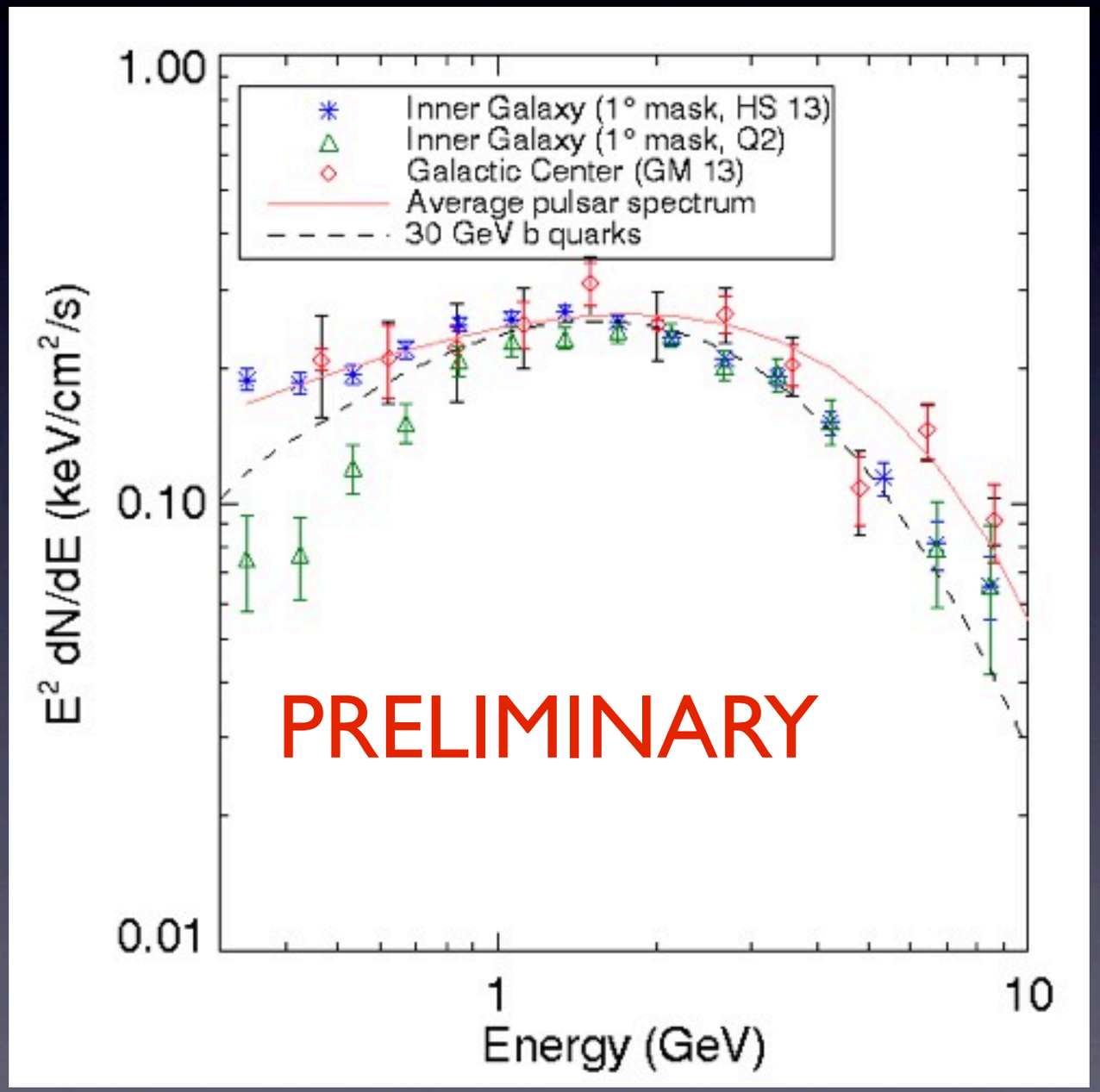


Moving away from the GC

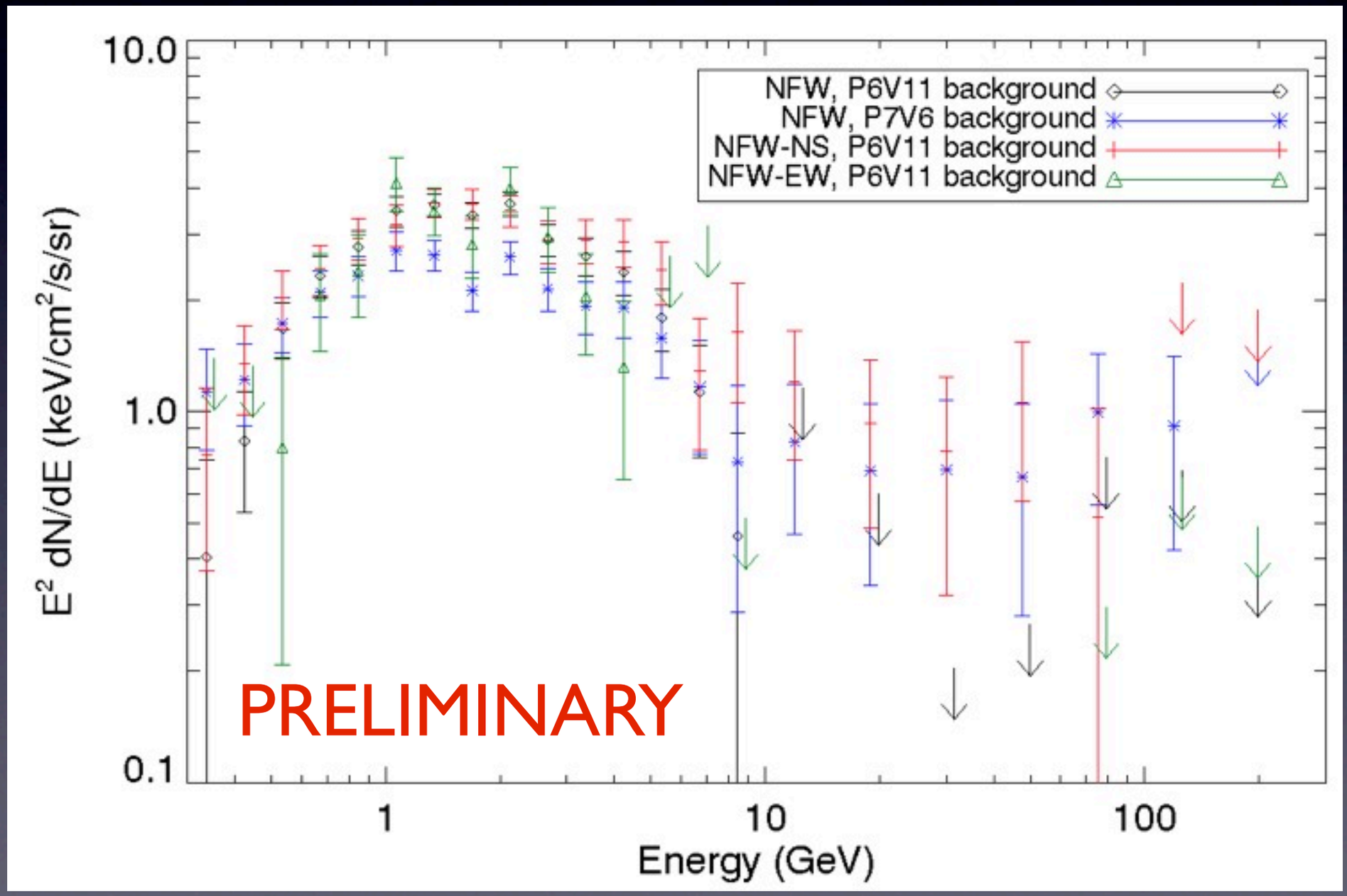




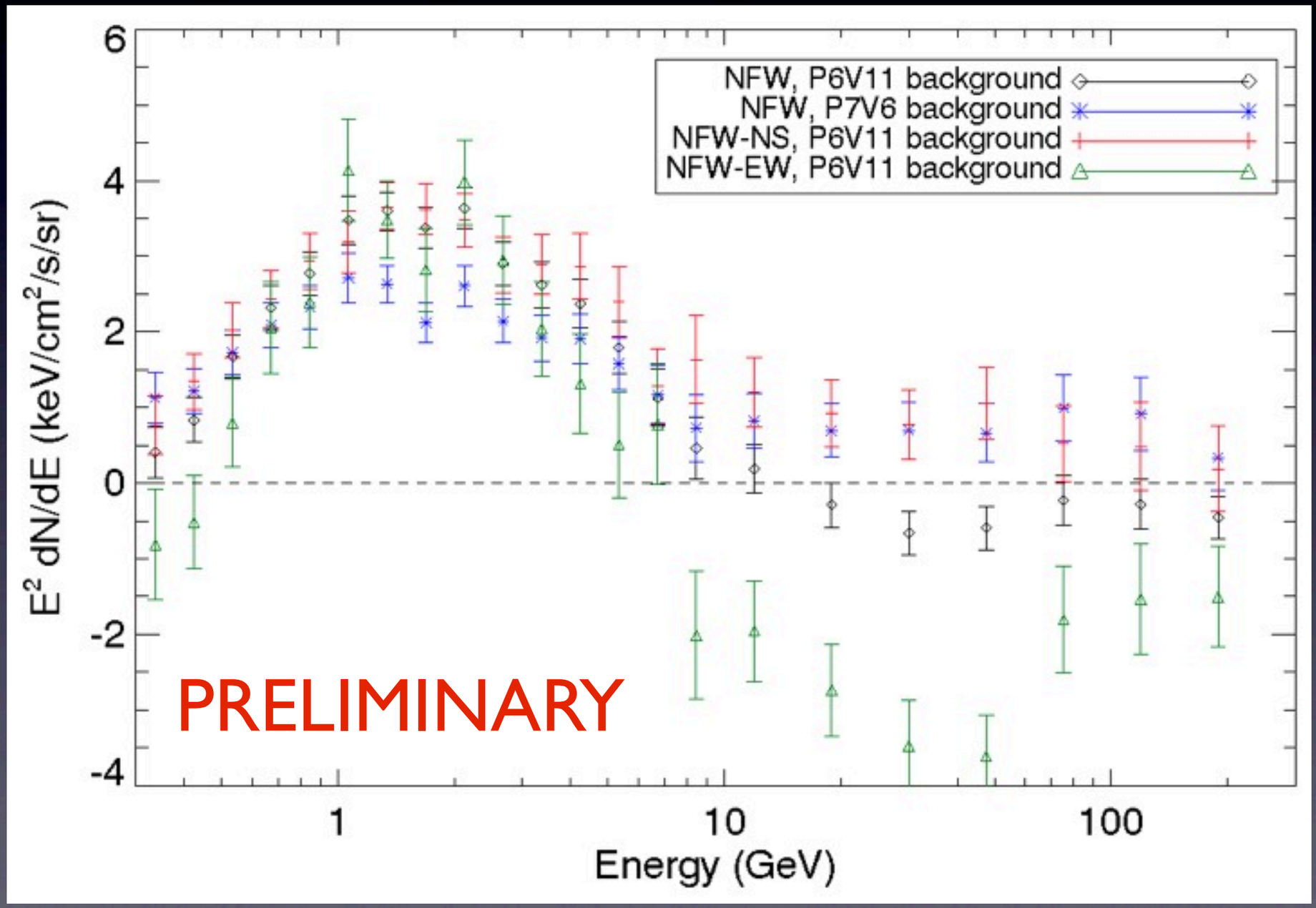
Impact of the CTBCORE cut (Q2)



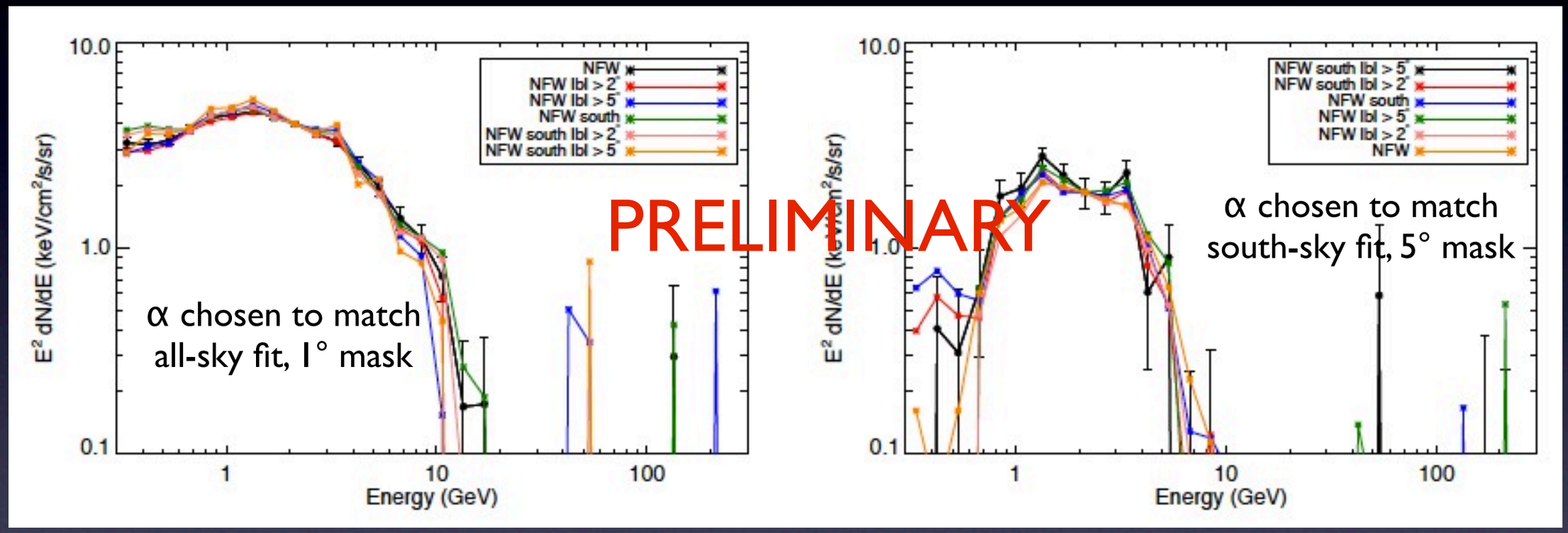
Spherical symmetry & background modeling



High-energy mismodeling



Diffuse background mis-subtraction (pre-CTBCORE)



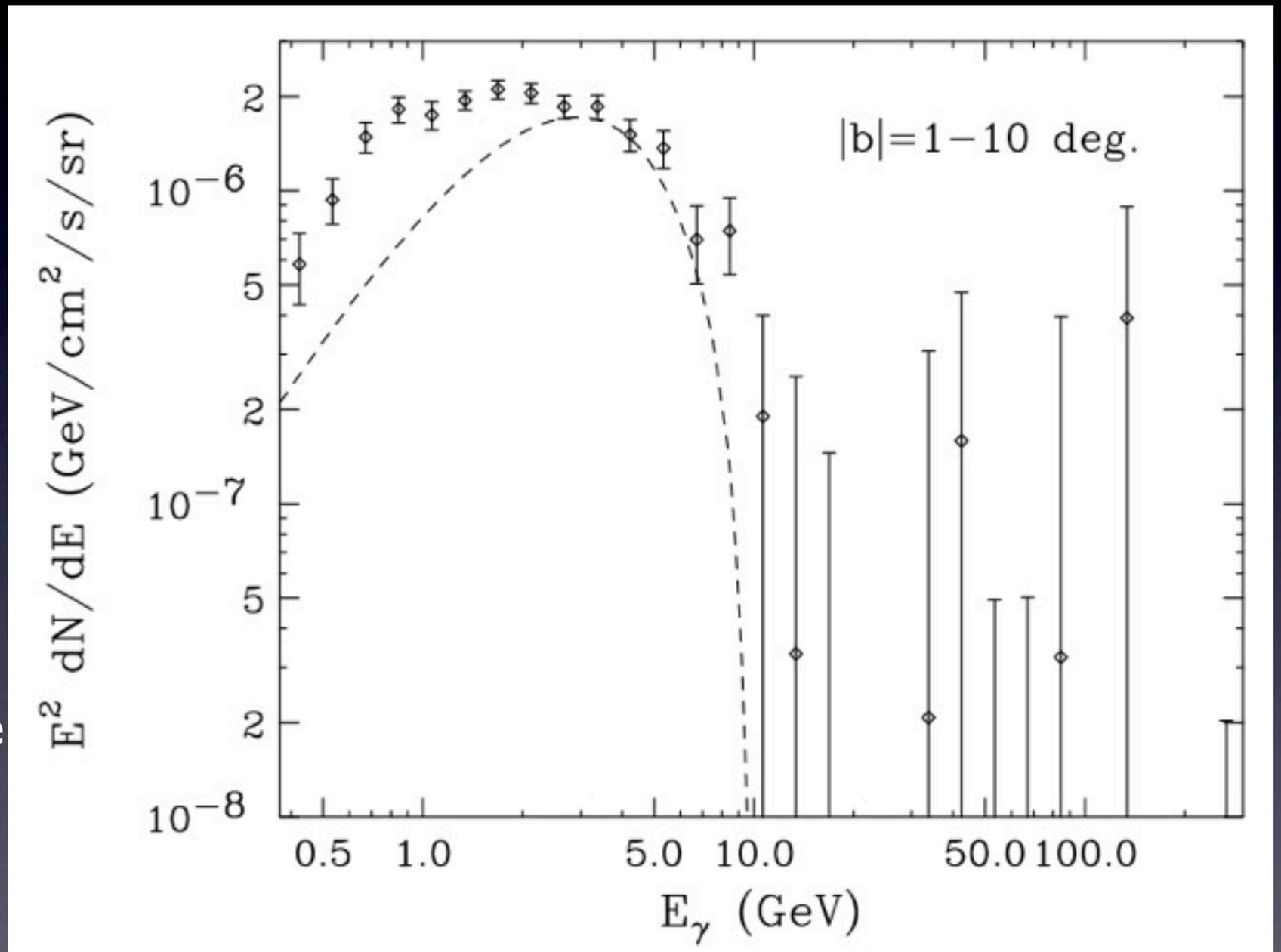
- It turns out that the spectra extracted from all our fits are members of the same one-parameter family of curves, related by:

$$f_{\mathrm{NFW}}(E) = f^{0}_{\mathrm{NFW}}(E) + \alpha f_{\mathrm{diffuse}}(E)$$

- Here α is the free parameter describing the family of curves, and the diffuse model spectrum is extracted from the data.
- The difference between the spectra in different regions can be explained by mis-subtraction of the diffuse model, rather than true variation in the spectrum.

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.



Dashed line = 10 GeV DM annihilating to taus, chosen to fit GC excess (no free normalization), extrapolated outward with squared modified NFW profile with inner slope $r^{-1.2}$.

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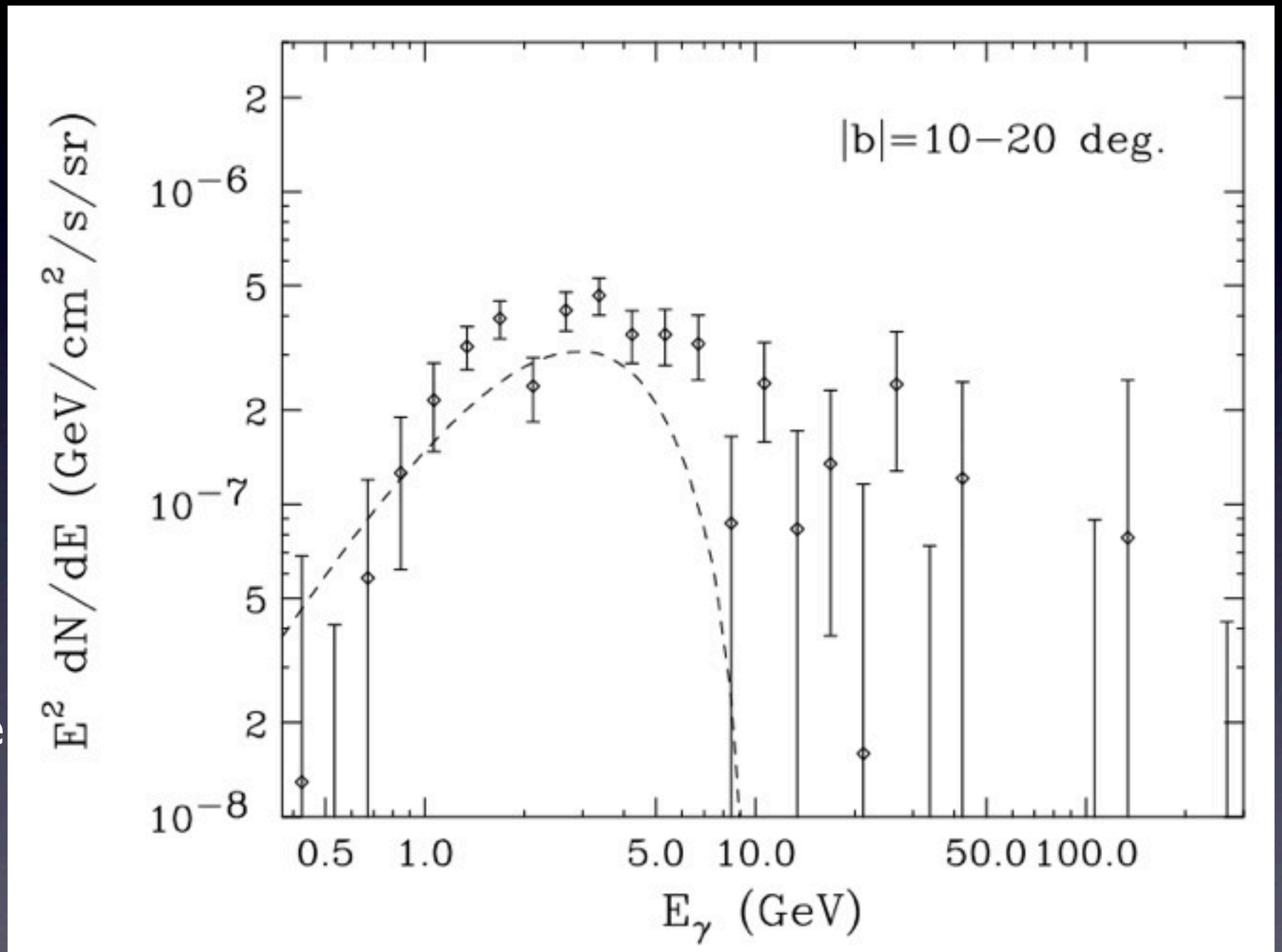

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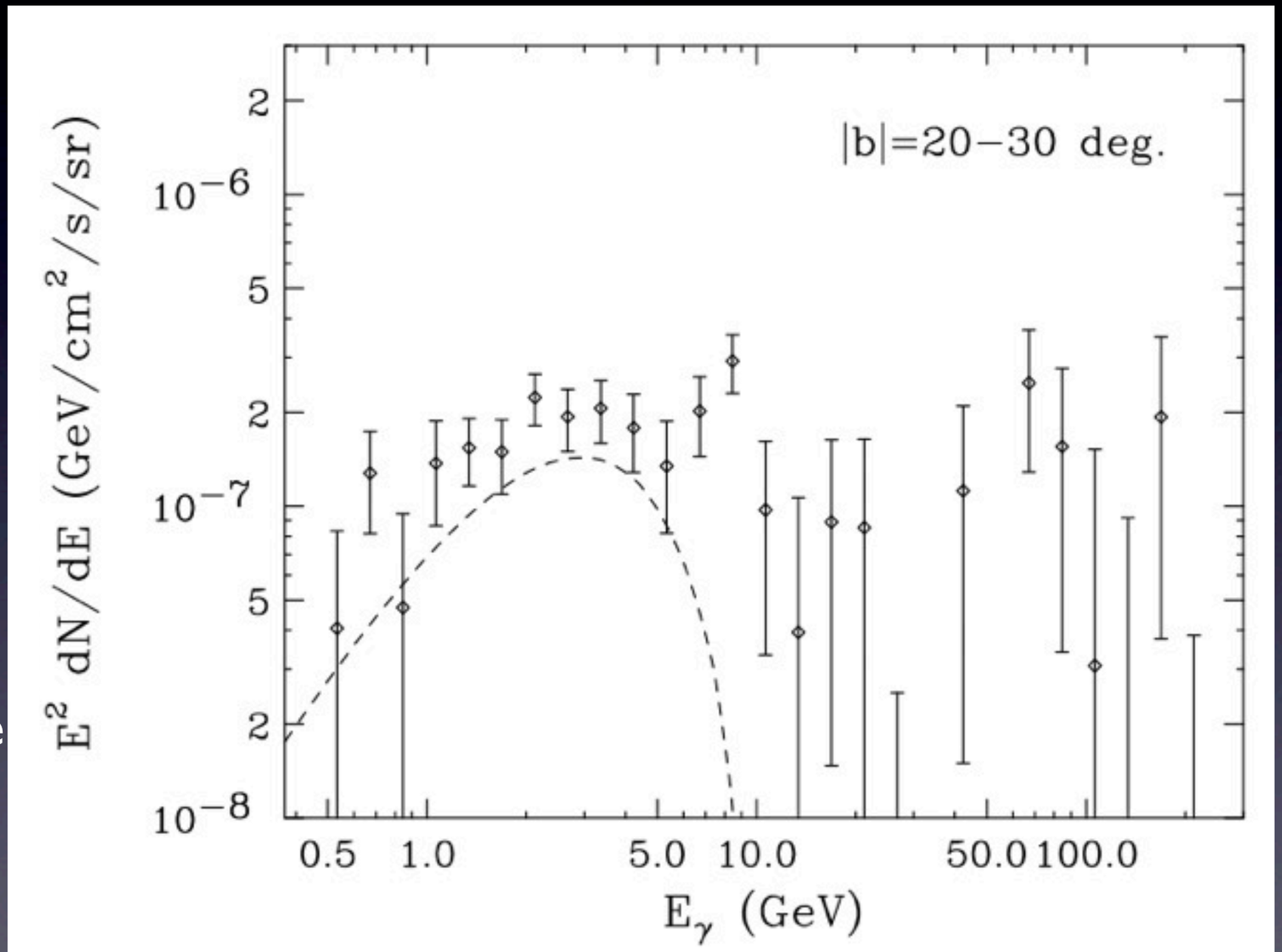

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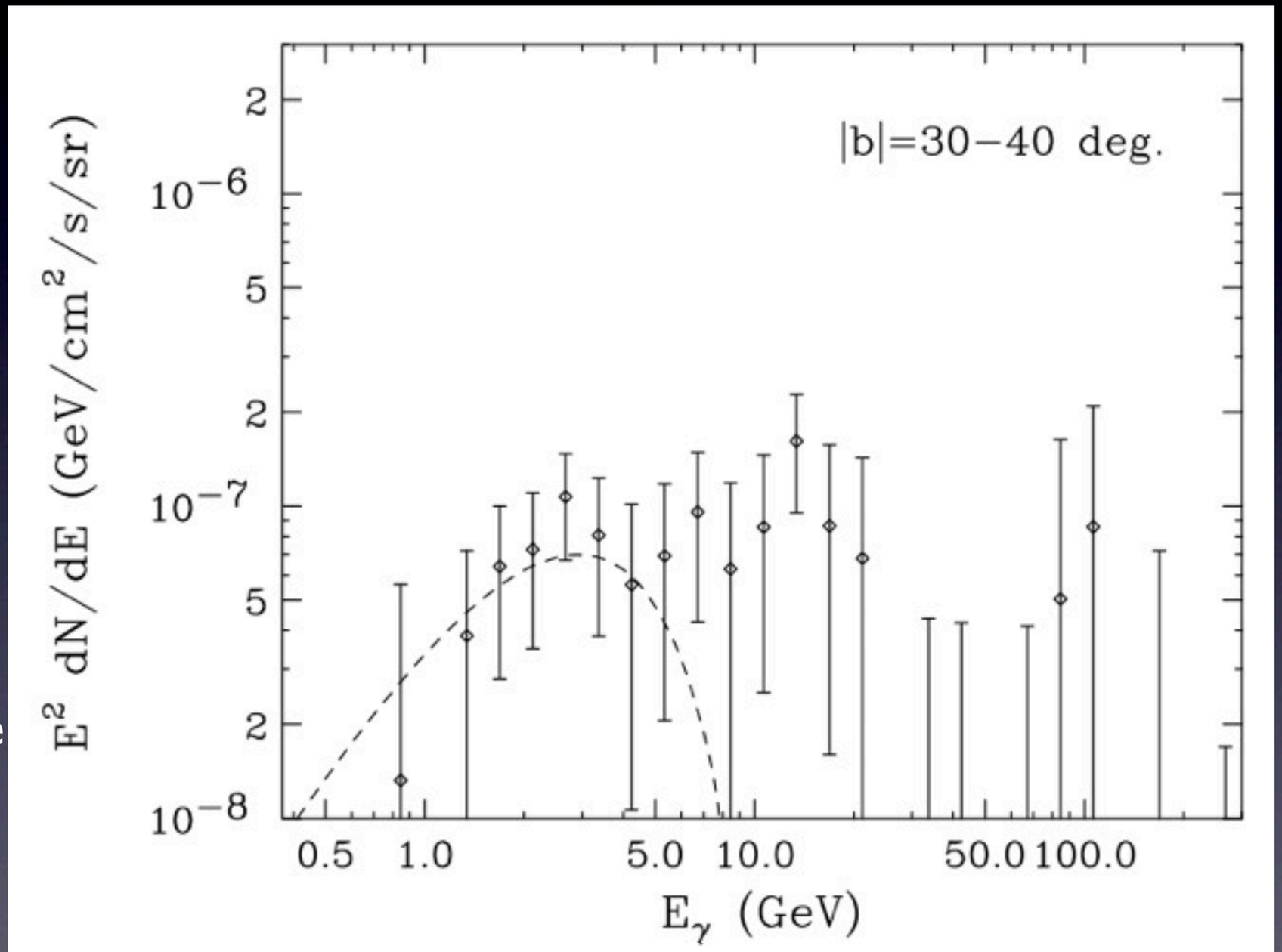

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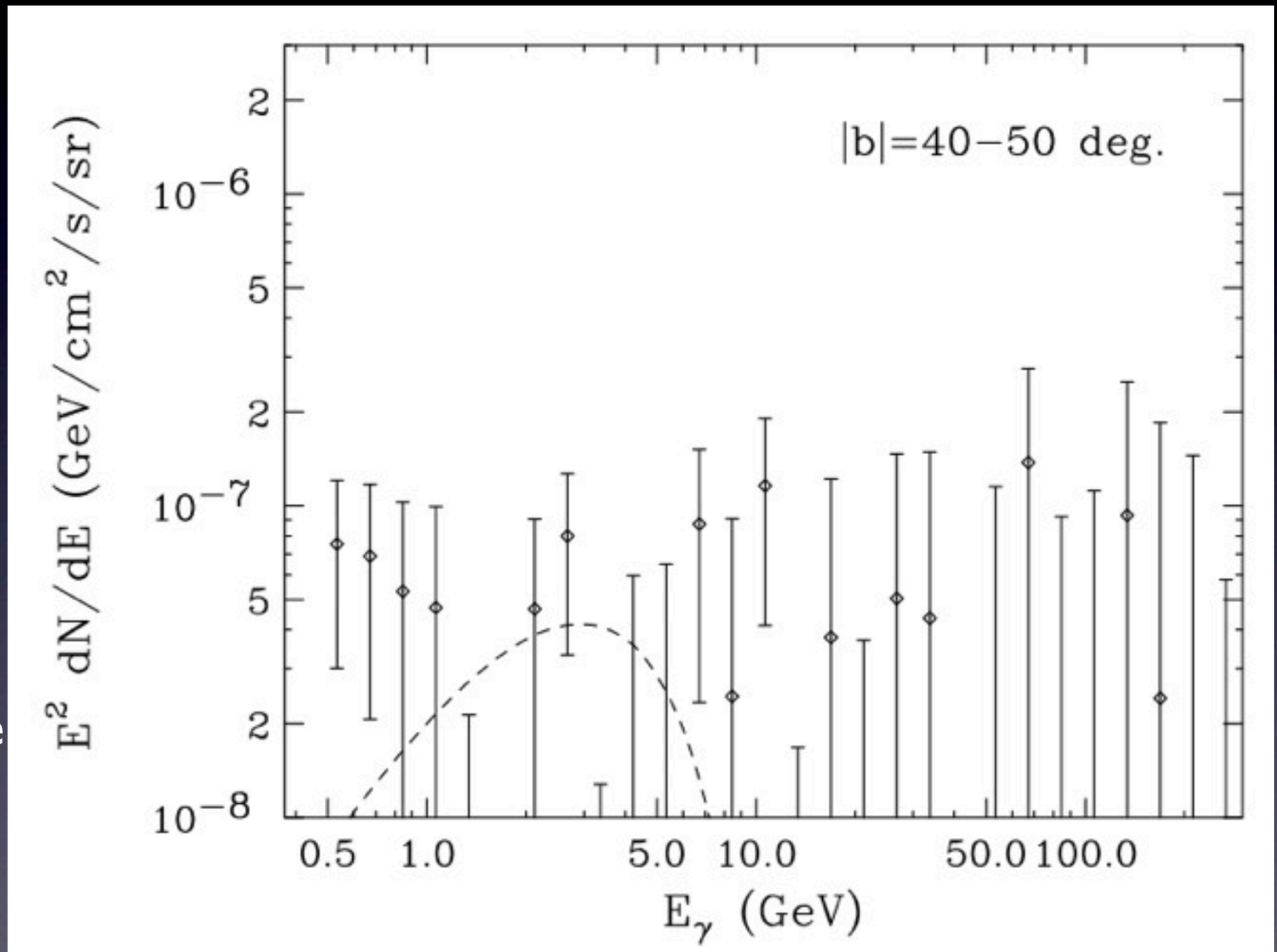

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