# Characterizing a Potential Dark Matter Signal in Gamma Rays from the Central Milky Way

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Based on arXiv:1402.6703 (submitted to PRD) with

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Nick Rodd — MIT

# The claim

- After fitting for modeled backgrounds, we detect a broad-spectrum gamma-ray excess in the Galactic Center and inner Galaxy, with the following properties:
  - Peaking at ~1-2 GeV in $E^2 dN/dE$, consistent morphology between 0.5 GeV and 10 GeV.
  - Consistent with spherical symmetry about the GC; we can exclude axis ratios larger than ~1.2 along the Galactic plane. (Mild hint of extension along an axis 35 degrees off the plane, with axis ratio ~1.3).
  - When modeled by a squared, projected Navarro-Frenk-White profile, prefers a density profile with small-r power-law slope ~1.1-1.2 in the Galactic Center analysis, 1.2-1.3 in the inner Galaxy analysis (hints of steepening at larger radii).
  - Centered on Sgr A* to within 0.05 degrees.
  - Detected out to 10 degrees from the GC.
  - Spectrum well described by 20-50 GeV DM annihilating to (mostly) quarks with a ~thermal relic annihilation cross section.

# Outline

- Review of previous studies of this excess in the Galactic Center + inner Galaxy.
- Methodology - characterizing the diffuse background, modeling a potential dark matter signal.
- What is new - implementation of cut on CTBCORE, allowing new analyses testing sphericity, centering, density profile.
- The dark matter interpretation and alternatives.

# Dark matter

- Roughly 80% of the matter in the universe. Multiple lines of evidence from rotation curves in galaxies and dwarf spheroidals, structure formation, colliding galaxy clusters, cosmic microwave background.
- Has only ever been detected by its gravitational interactions.
- Null searches for Massive Compact Halo Objects and constraints on the baryonic matter content suggest physics beyond the Standard Model.
- One leading candidate is a Weakly Interactive Massive Particle (WIMP) - associated with new physics around the scale of electroweak symmetry breaking.

# Why WIMPs?

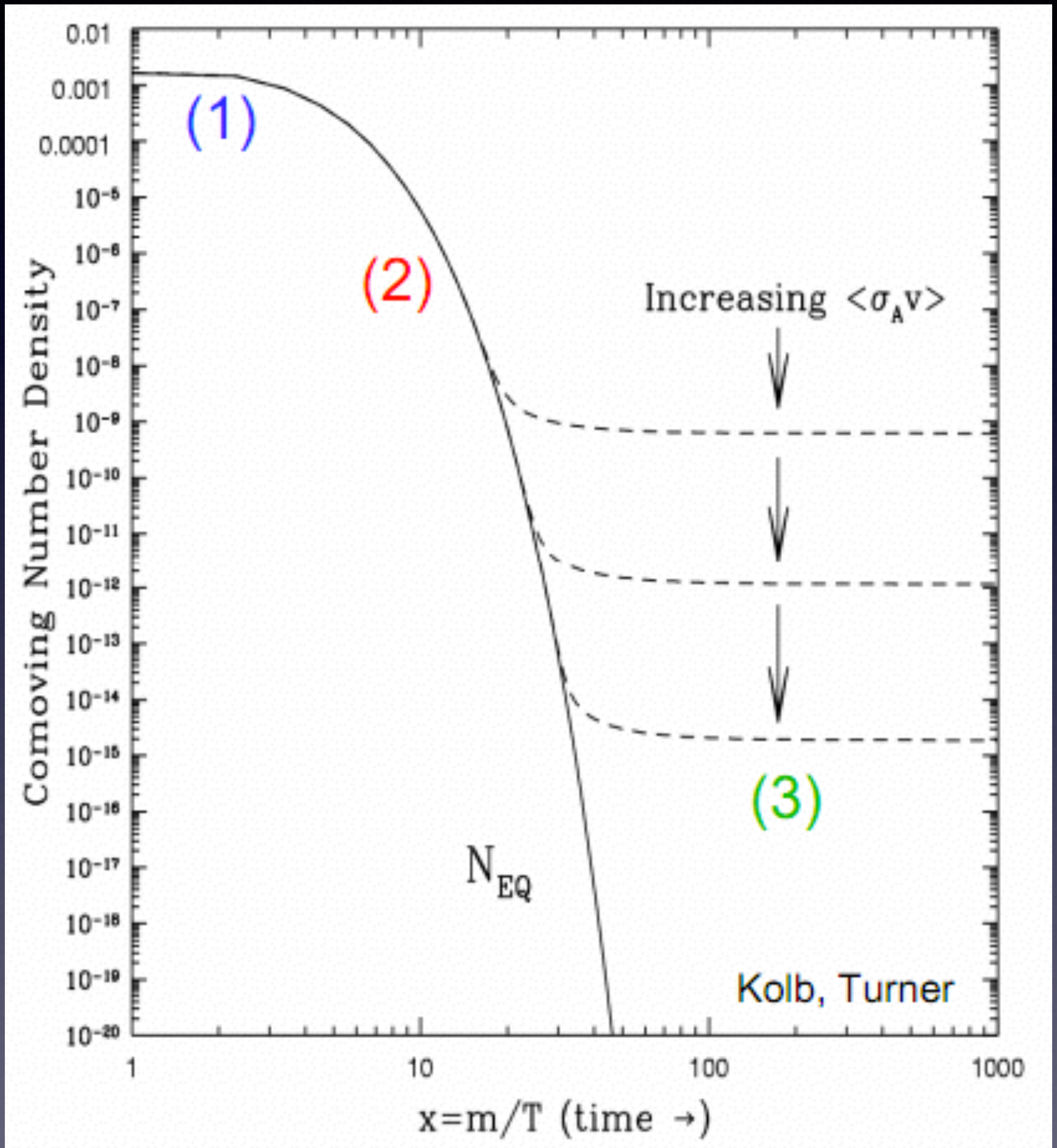
- In the early universe, let the DM particle be thermally coupled to the SM. Can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then freezes out.




So (known) late-time density is set by annihilation rate.

$$\langle \sigma v \rangle \sim 3\times 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

# Dark matter in gamma rays

- DM does not carry electric charge, does not couple directly to photons (it is "dark").
- But it can annihilate to something that produces photons - those photons should be in a similar energy range to the DM mass (but lower).
- For WIMPs, this means gamma rays.

Line signal - typically suppressed

$$\chi\chi \rightarrow \gamma\gamma \qquad \chi\chi \rightarrow \gamma Z$$

"Smoking gun" - distinctive spectral feature

Continuum signal (example)

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

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

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

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

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

We can use both spectral information (dependence on energy) and spatial information (dependence on location) to try to distinguish dark matter signals from astrophysics.

# Features of a DM signal

- Spectral information: backgrounds are mostly fairly smooth and power-law-like, a DM signal can be peaked and have a sharp cutoff near the DM mass.
- Spatial information: DM should 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.
- The signal scales as DM density squared as annihilation is a two-particle process, 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" $r_s \sim 20$ kpc for Milky Way

# The Fermi Gamma-Ray Space Telescope

- Launched successfully from Cape Canaveral on 11 June 2008.
- Now in low-Earth orbit, 340 mile altitude.
- Scans the entire sky every two orbits (~3 hours).
- Sensitive to gamma-rays from tens of MeV up to several TeV.
- All data is public.

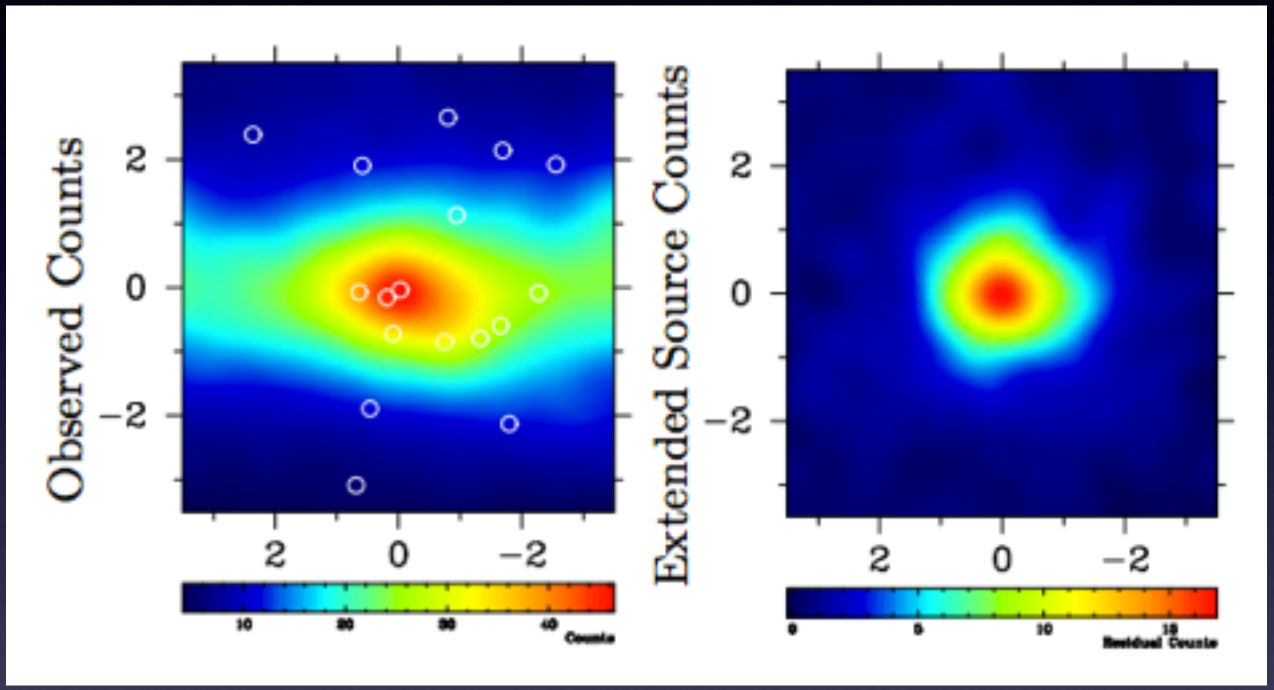
# The Galactic Center excess

- First detected by Goodenough & Hooper 2009.
- Since confirmed by several groups (Hooper & Goodenough 1010.2752, Boyarsky, Malyshev & Ruchayskiy 1012.5839, Hooper & Linden 1110.0006, Abazajian & Kaplinghat 1207.6047, Gordon & Macias 1306.5725 + 1312.6671, Abazajian, Canac, Horiuchi & Kaplinghat 1402.4090).
- Diffuse background modeling usually done using Fermi Collaboration diffuse model. Early studies used power-law extrapolation in to Galactic center. Most recent studies add templates for gas clouds.
- Most studies done using software tools released by the Fermi Collaboration.

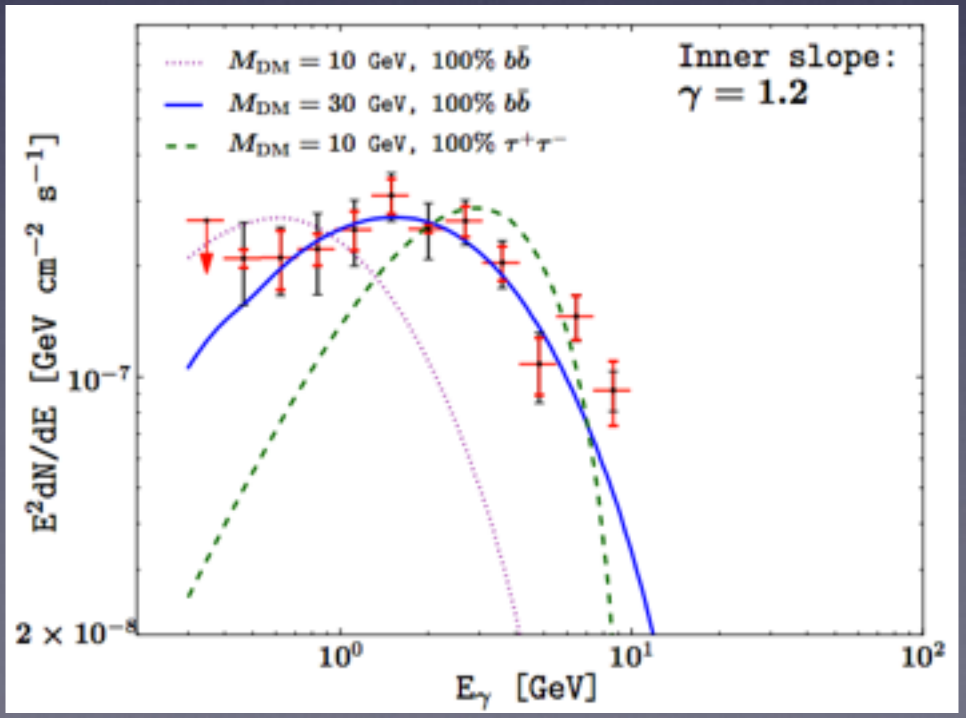
# The Galactic Center

- Excess peaks at a few GeV, spectrum consistent with ~30 GeV DM annihilating to $b\bar{b}$.
- Localized around the GC (typical ROIs are a few degrees around the GC).
- Roughly spherical morphology, with flux/volume scaling with Galactocentric radius approximately as $r^{-2.0-2.6}$
- Some variation in preferred spectrum depending on background modeling (e.g. whether light DM to tau's is acceptable).

spatial distribution Abazajian & Kaplinghat 2012

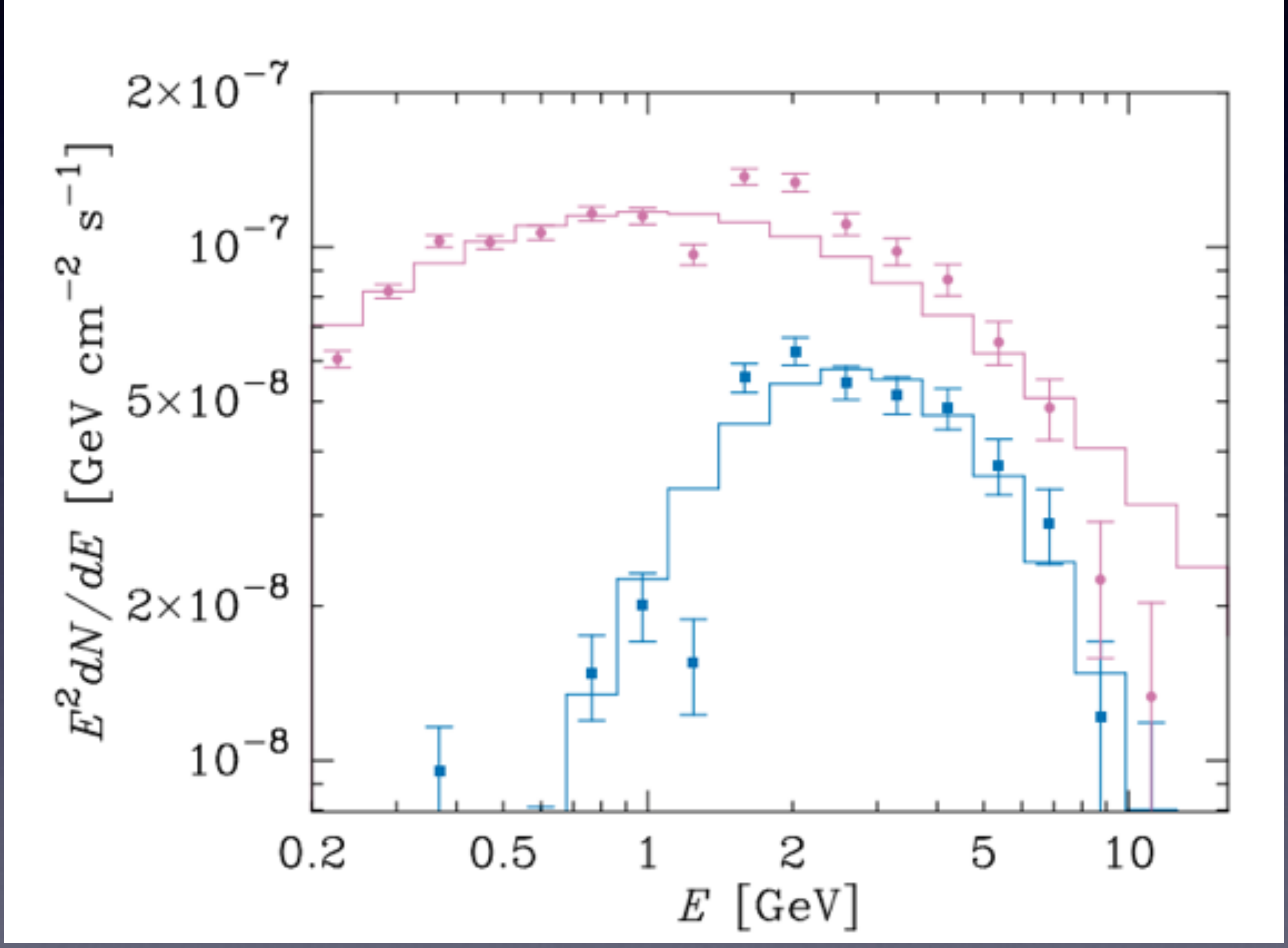



spectrum Gordon & Macias (1306.5725)



# Notes

- Angular resolution of Fermi at low energies is non-negligible compared to signal extent.
- Questions about robustness of results to diffuse background modeling, especially at low energies.
- Not a statistical fluctuation - delta log likelihood is always large, ~100 or higher depending on background modeling.
- Seems possible to explain with either (a few thousand) millisecond pulsars or DM.




Abazajian, Canac, Horiuchi & Kaplinghat 1402.4090

# The inner Galaxy

- Hooper & TRS 1302.6589 identified a similar excess in the “inner Galaxy”, since independently confirmed by Huang, Urbano & Xue 1307.6862.
- “Inner Galaxy” ~ the region within ~20° of the Galactic plane but outside the immediate vicinity (1-5 degrees) of the Galactic Center.
- Did not use the Fermi likelihood tools; adapted template fitting method used to discover the Fermi Bubbles (giant gamma-ray lobes apparently emanating from the Galactic Center).
- Initial goal was to study spectral variation inside the Bubbles.

# The sources of diffuse weak-scale gamma rays

- Two main types of charged cosmic rays - electrons and protons.
- Two main targets - the interstellar gas, and the sea of photons pervading the galaxy:
  - Starlight
  - Infrared radiation from thermal emission
  - The cosmic microwave background (residual photons from early universe)
- These scatterings produce diffuse gamma rays, from upscattering of radiation-field photons or decay of neutral pions produced in hadronic collisions.
- There are also gamma-ray point sources, Galactic and extra-Galactic - pulsars, active galactic nuclei, etc.

# A simple model for Galactic gamma rays

Good maps!

:-)

Roughly constant across the Galaxy; assume constant

gas density x cosmic ray proton density

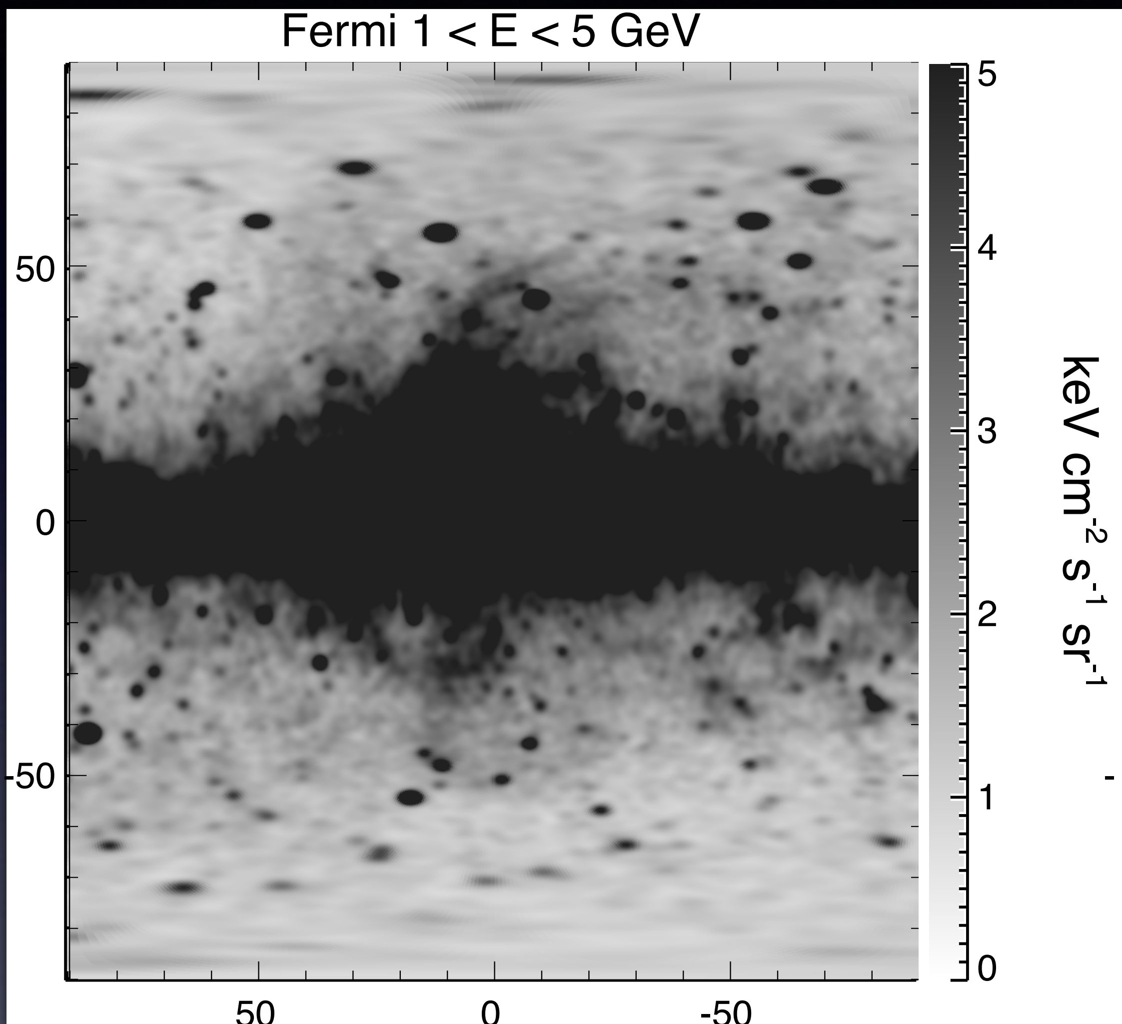
+ gas density x cosmic ray electron density

Always subdominant; neglect

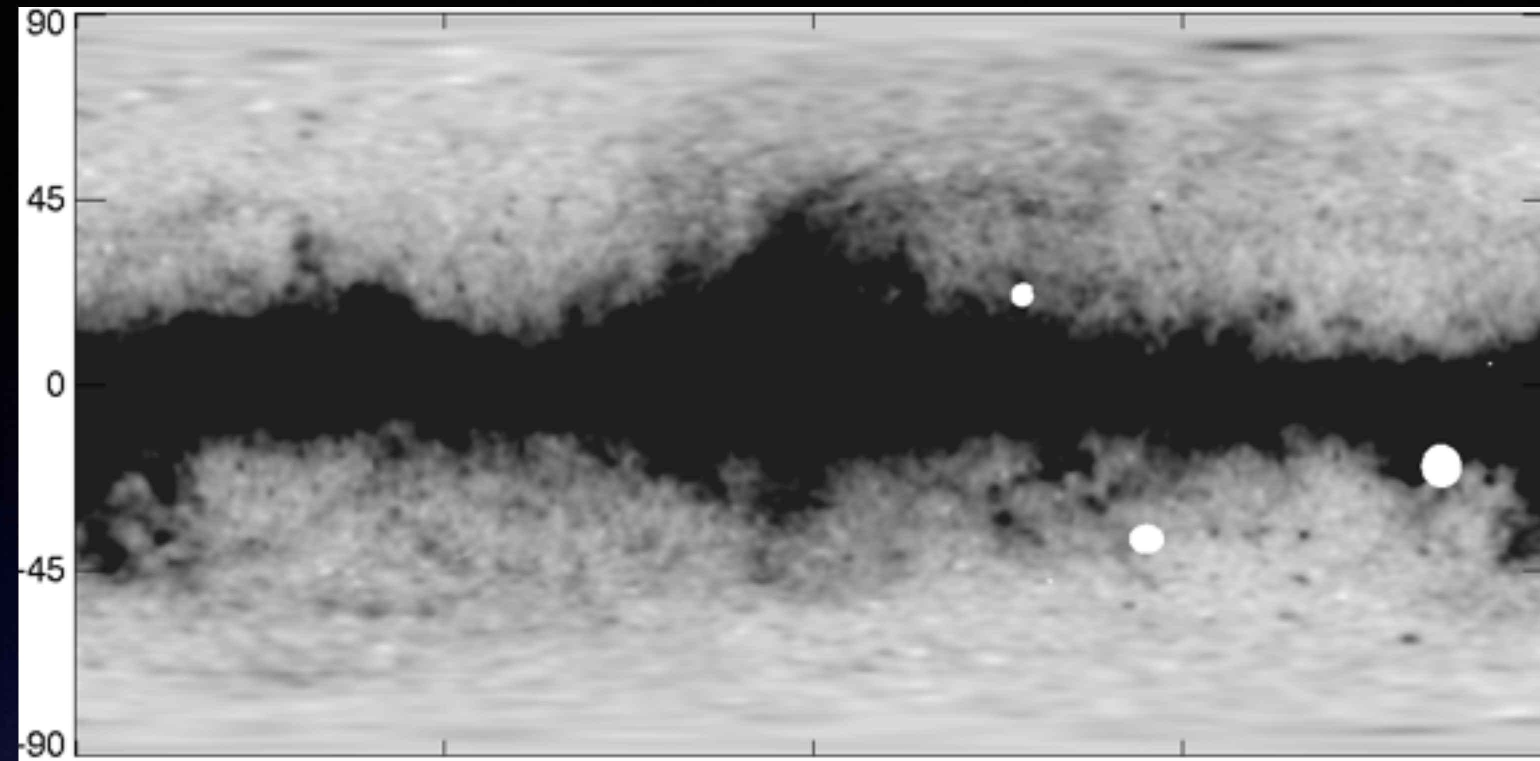
+ photon density x cosmic ray electron density

Should follow disk, where stars + supernovae are concentrated - put in some simple disk-like profile

Detailed model by the Fermi Collaboration uses same principles, models cosmic ray distribution using GALPROP.

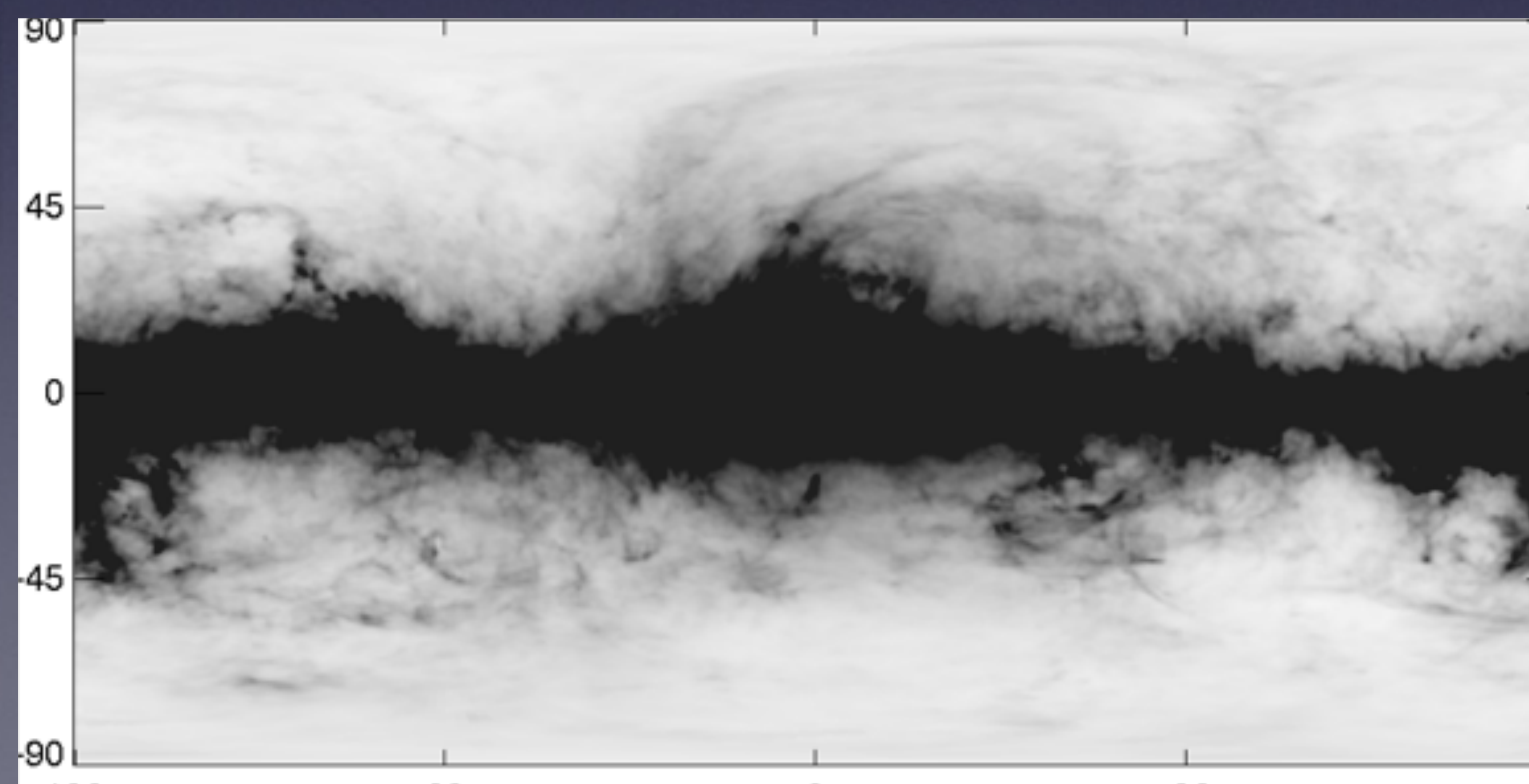


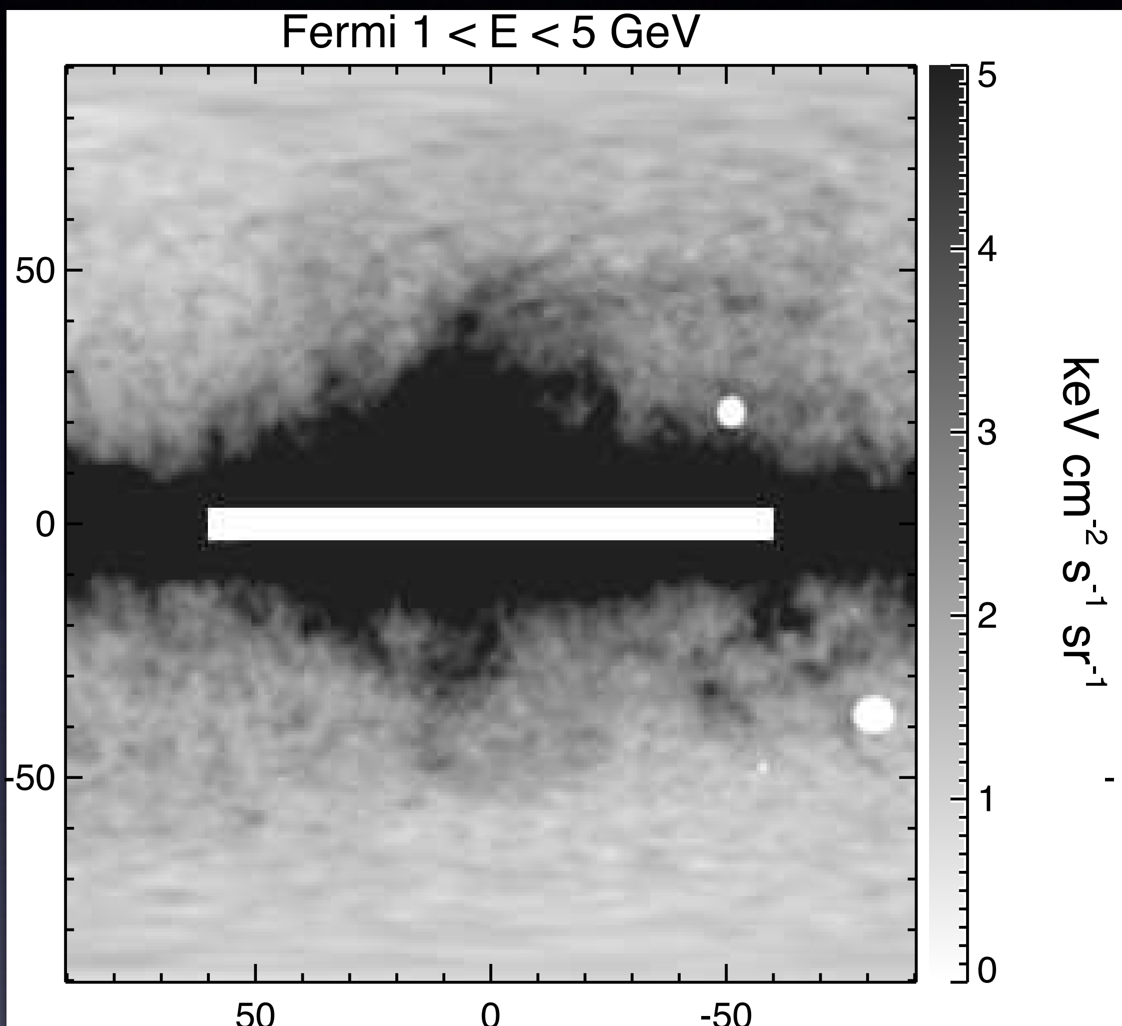

Point source subtraction




Data (1-5 GeV)

Model (1-5 GeV)



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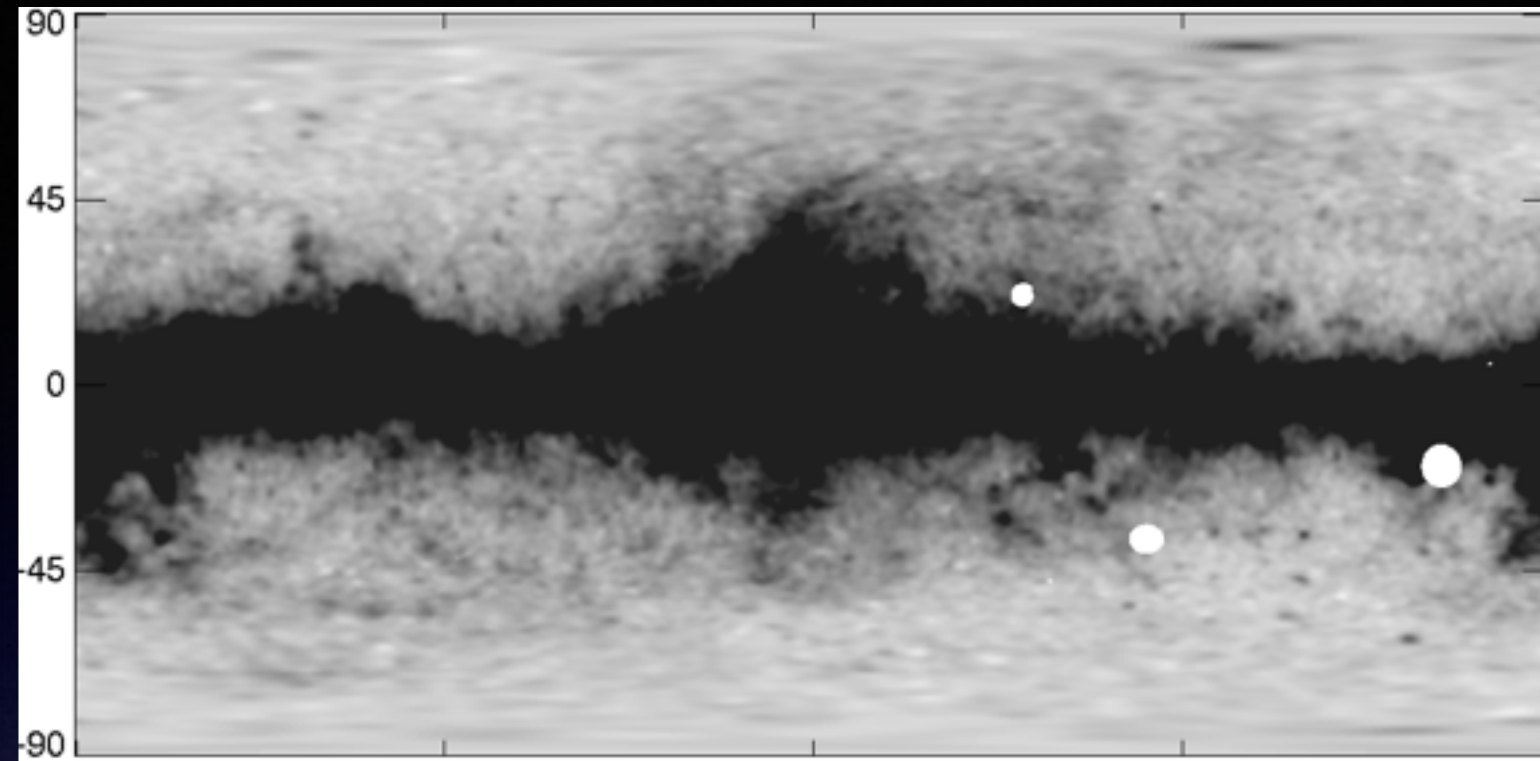


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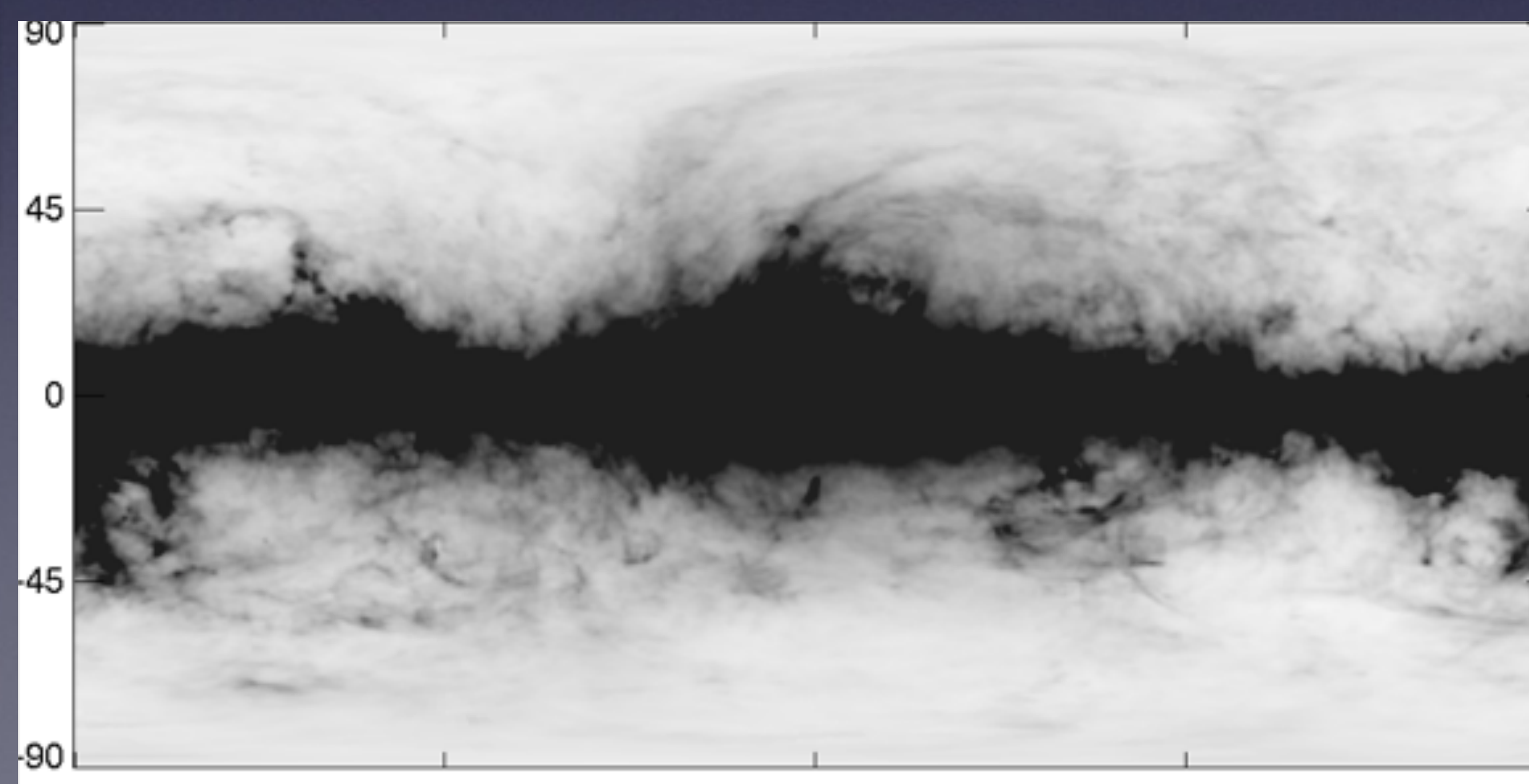
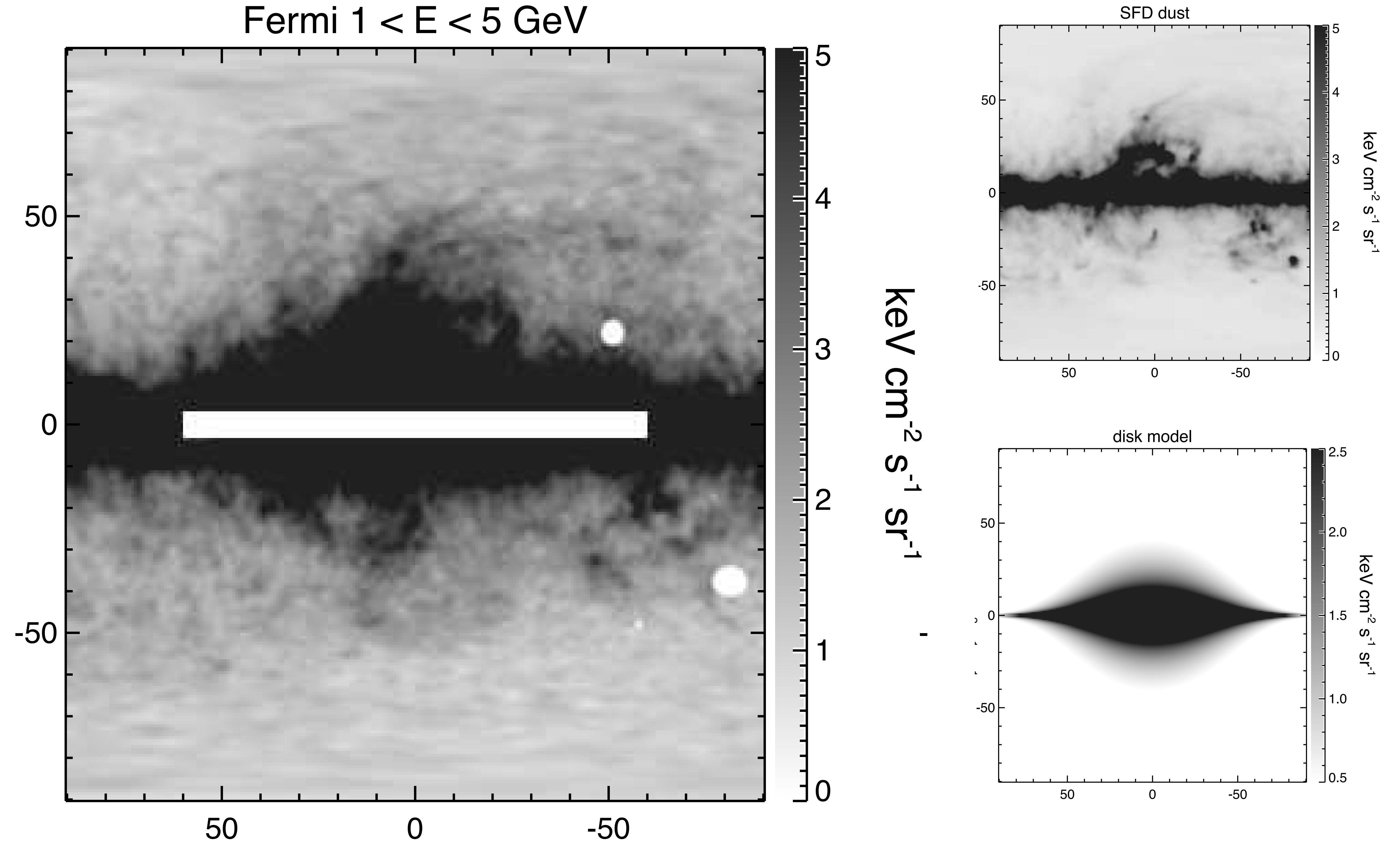


# Dust and ICS removal



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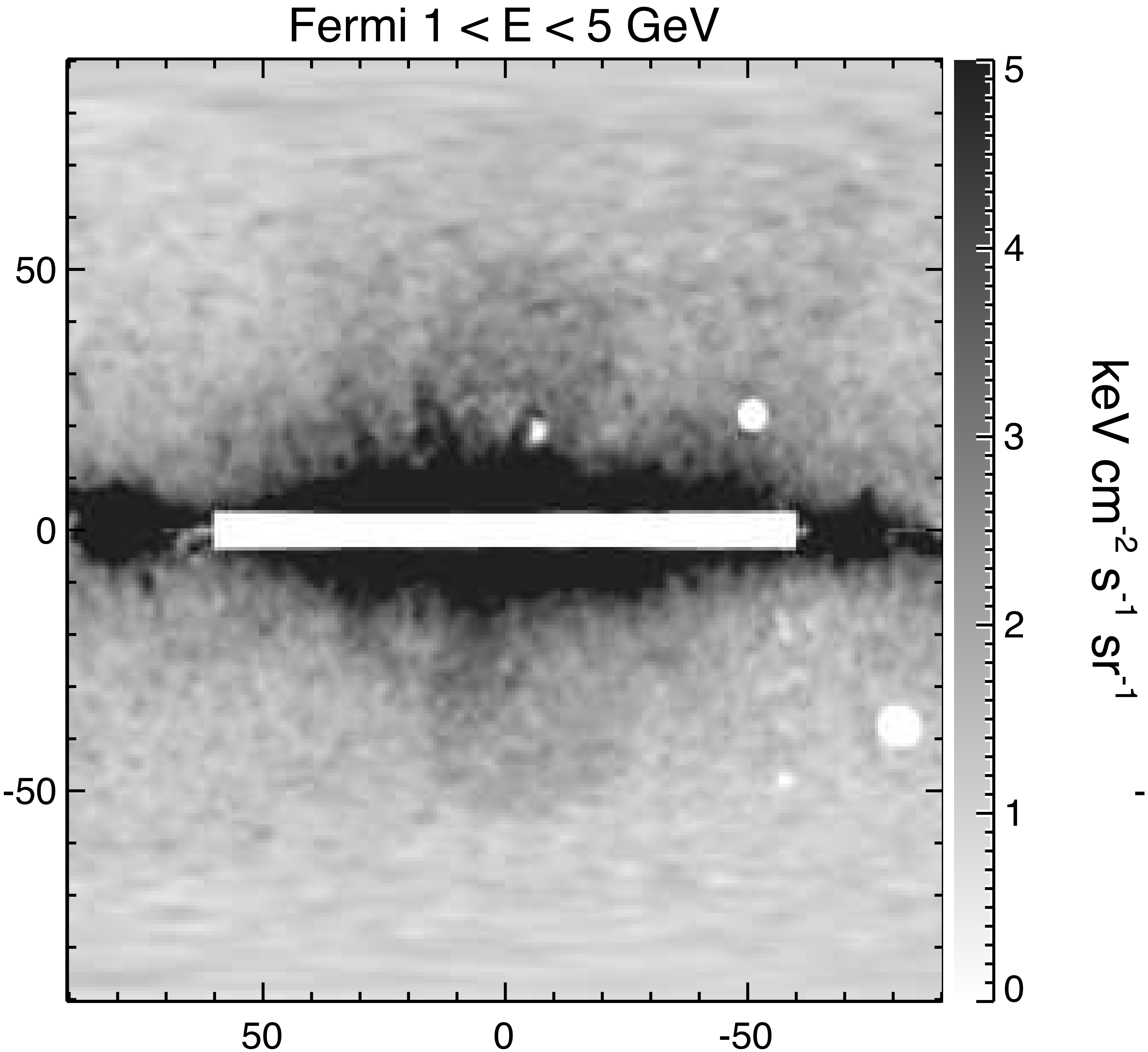


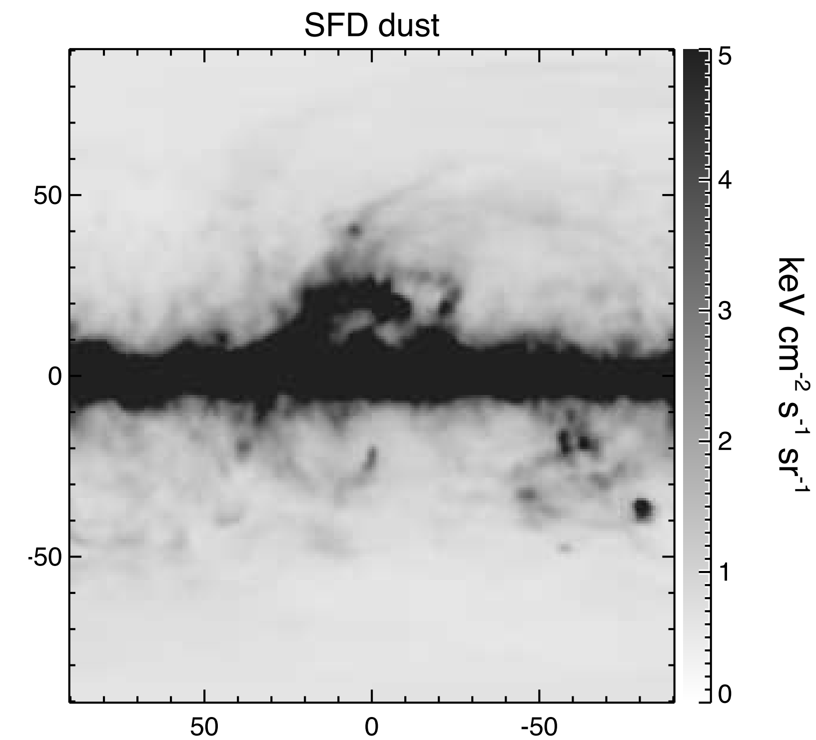


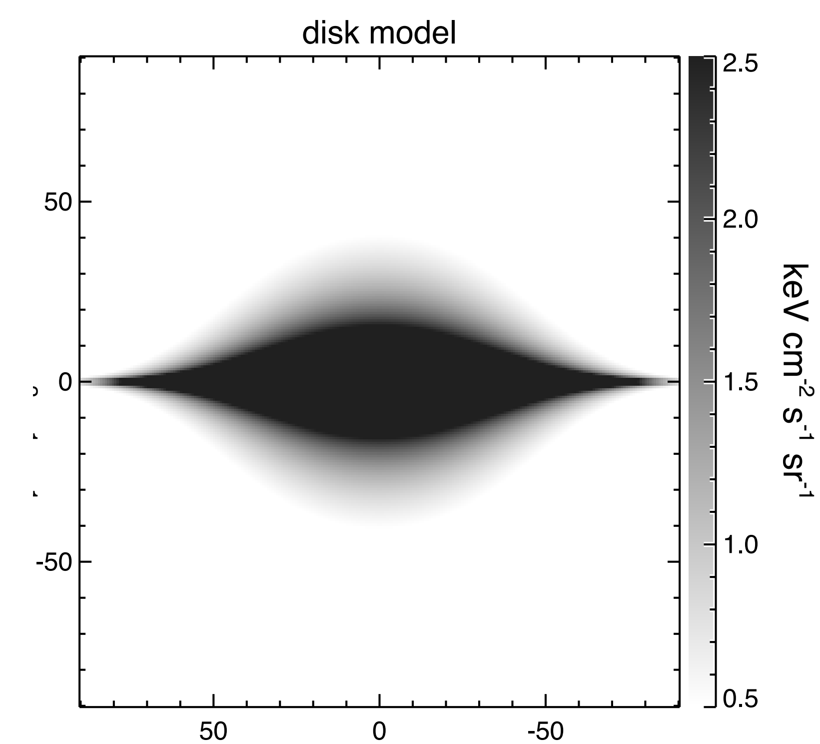

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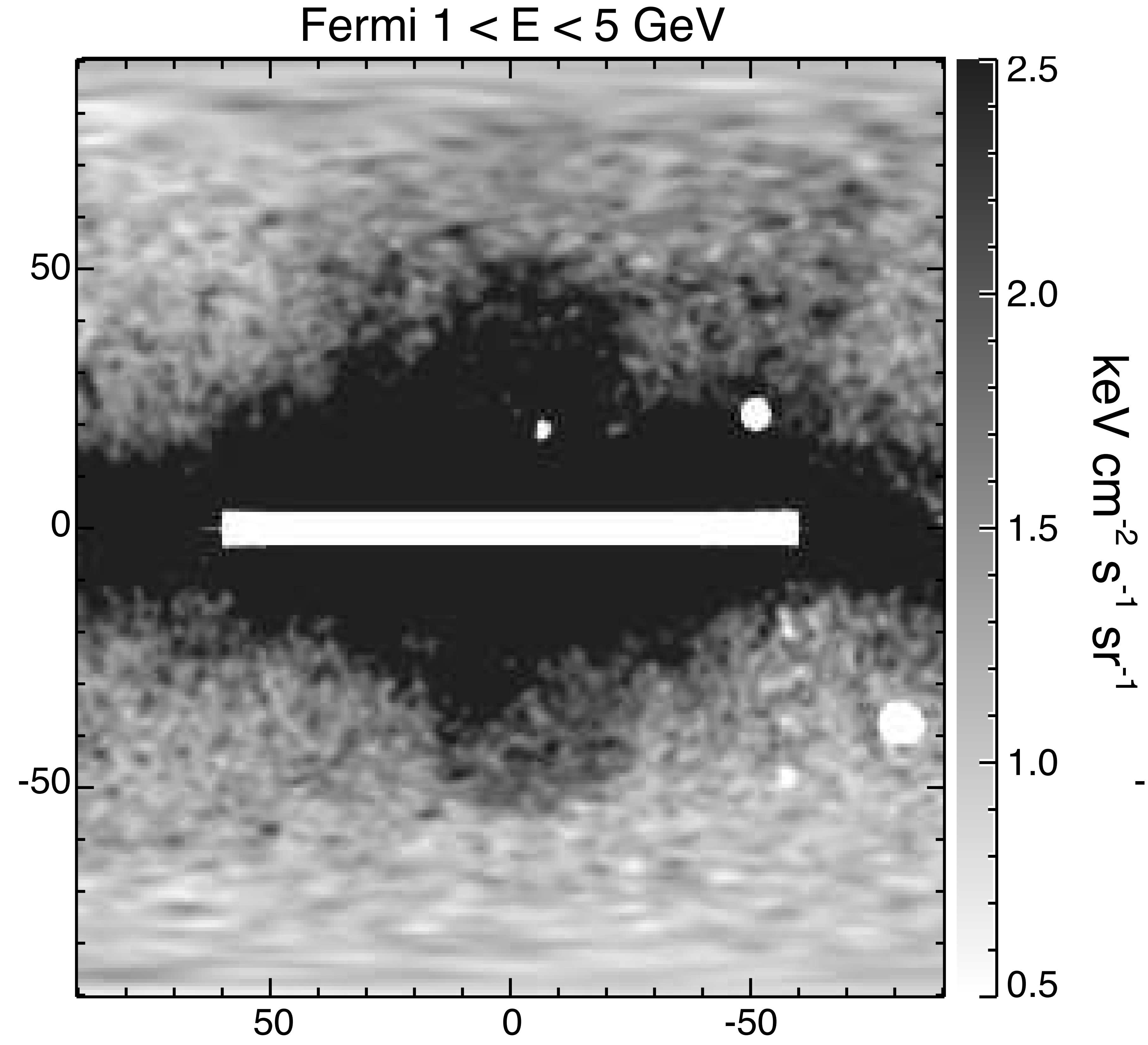


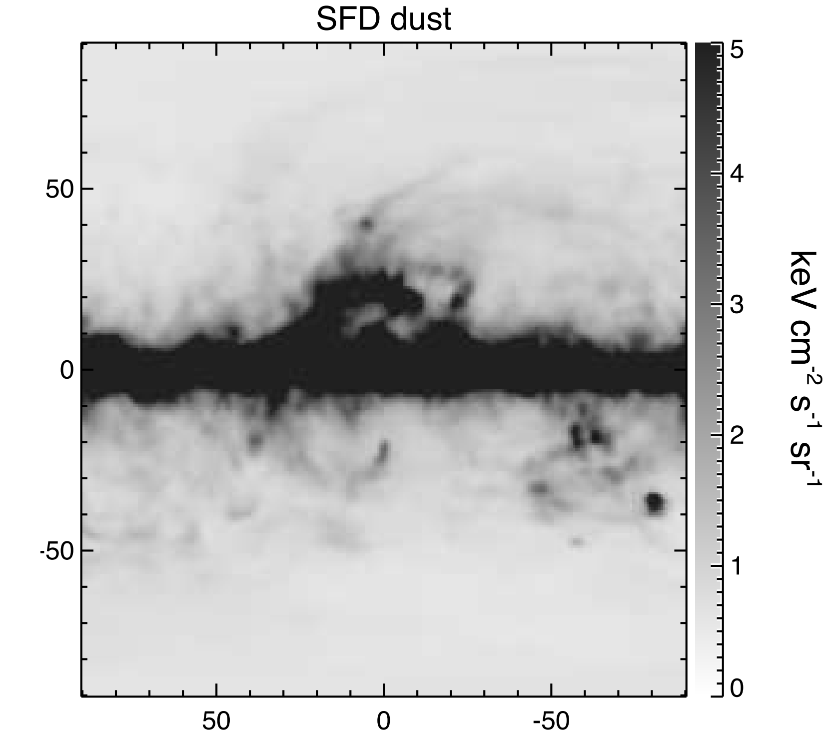


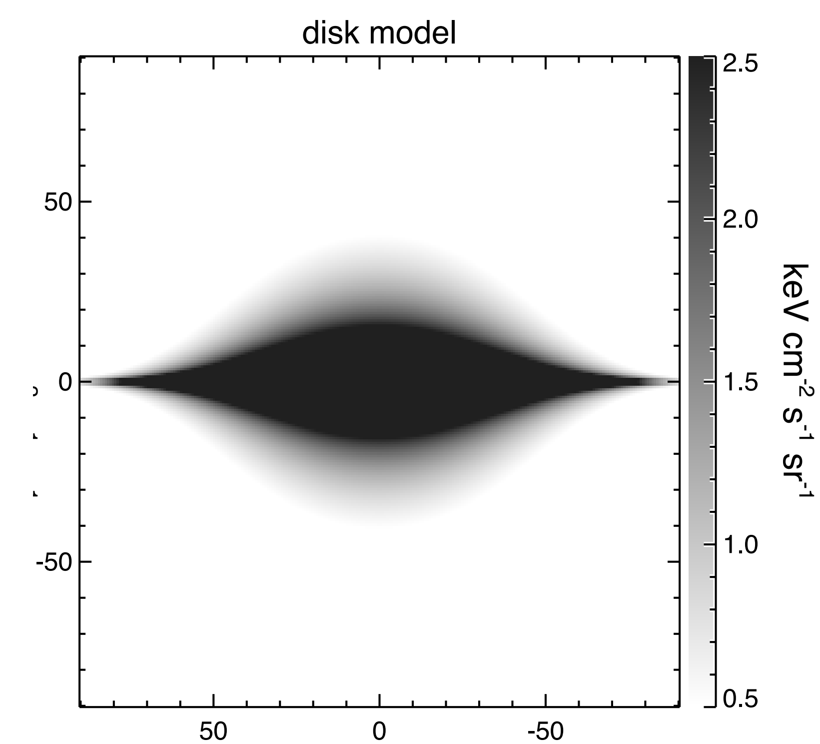

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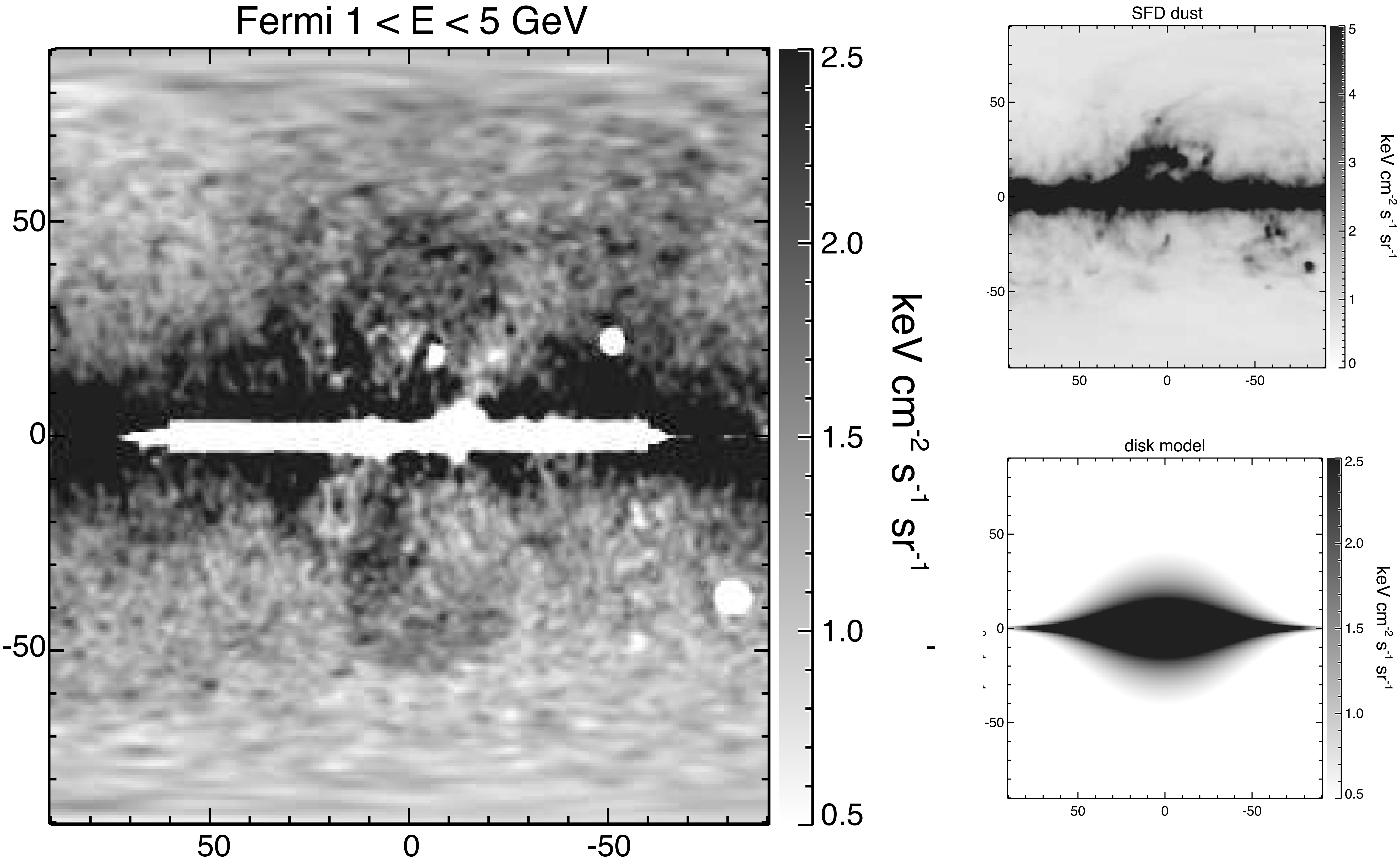
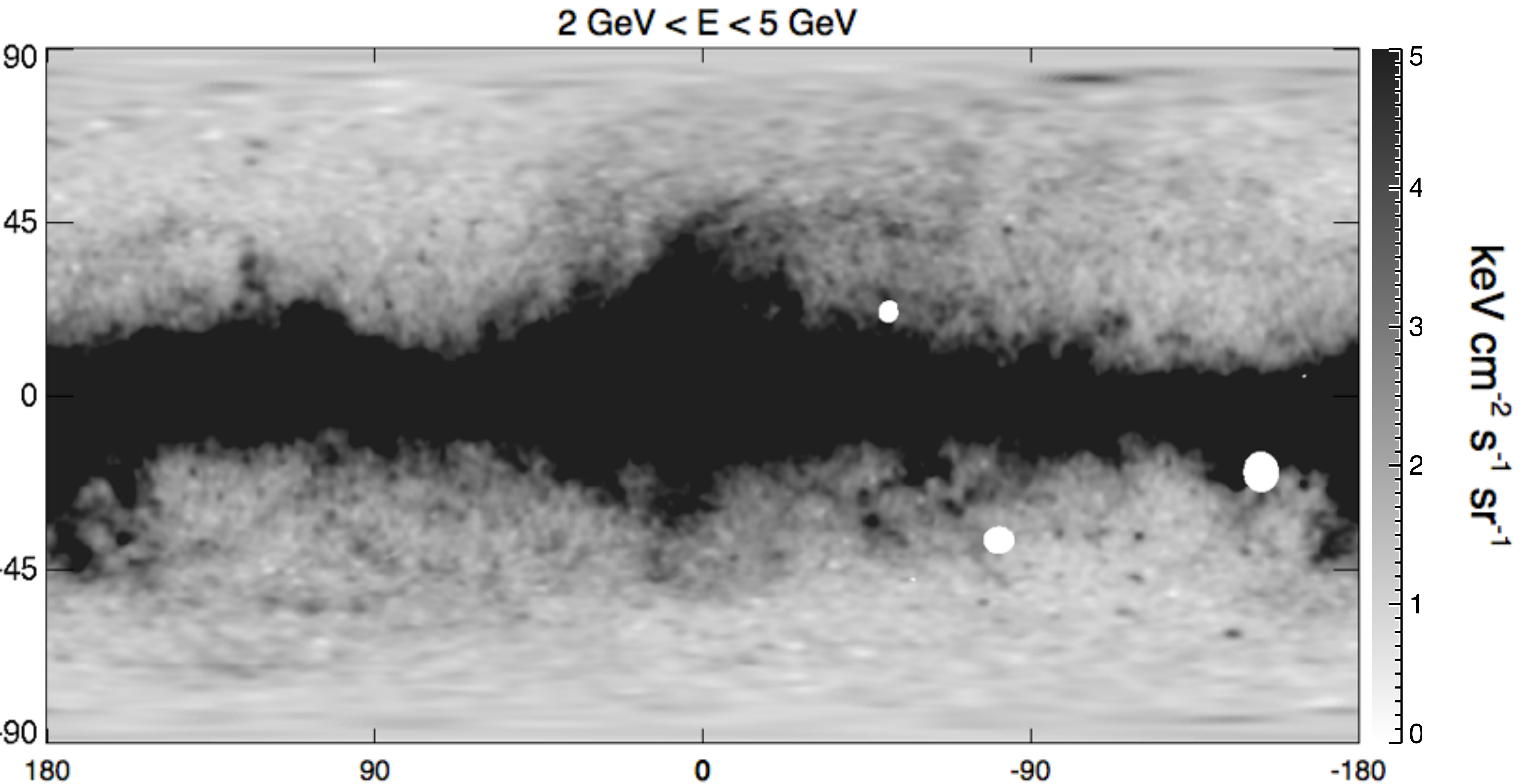


# Data - Fermi model



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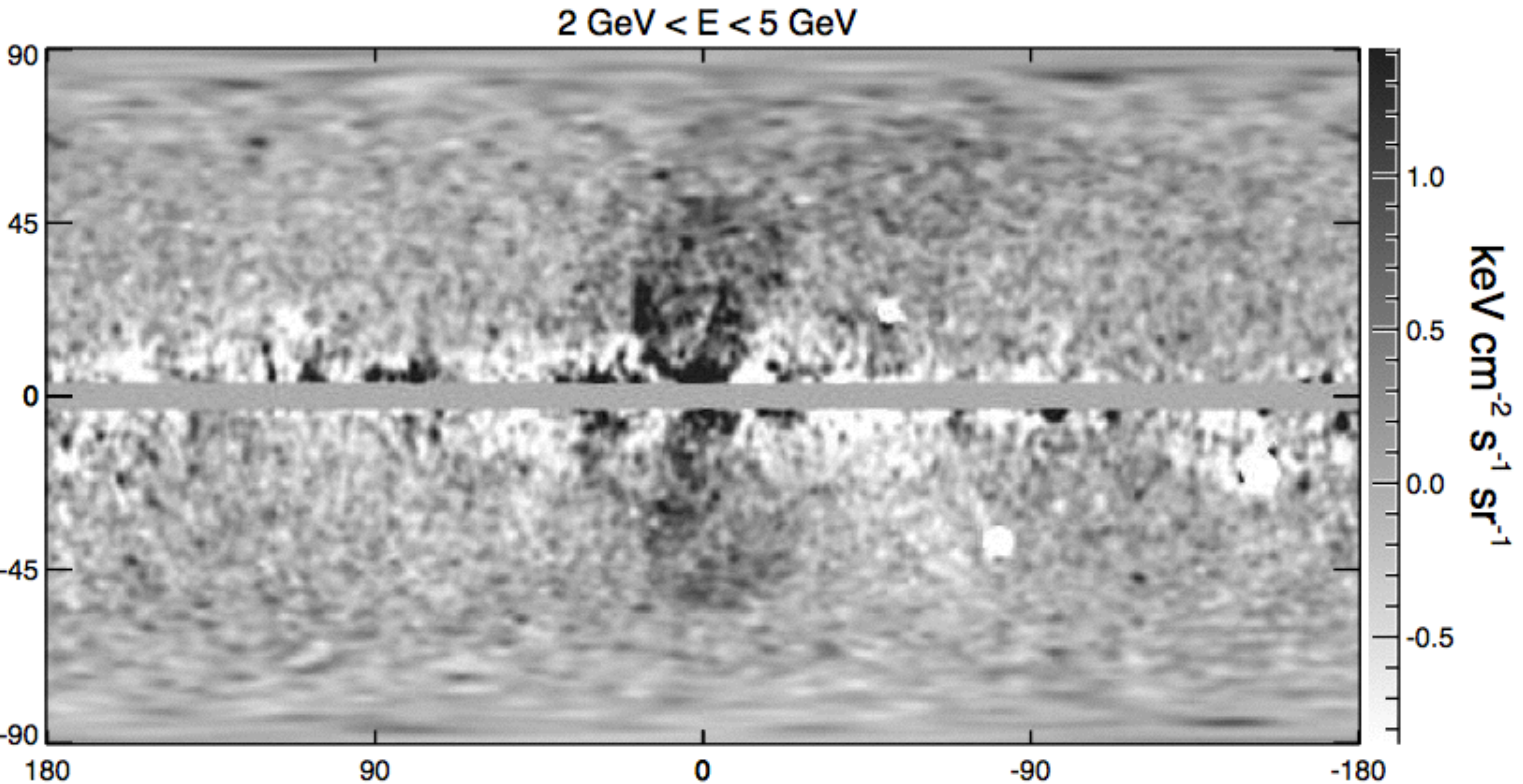

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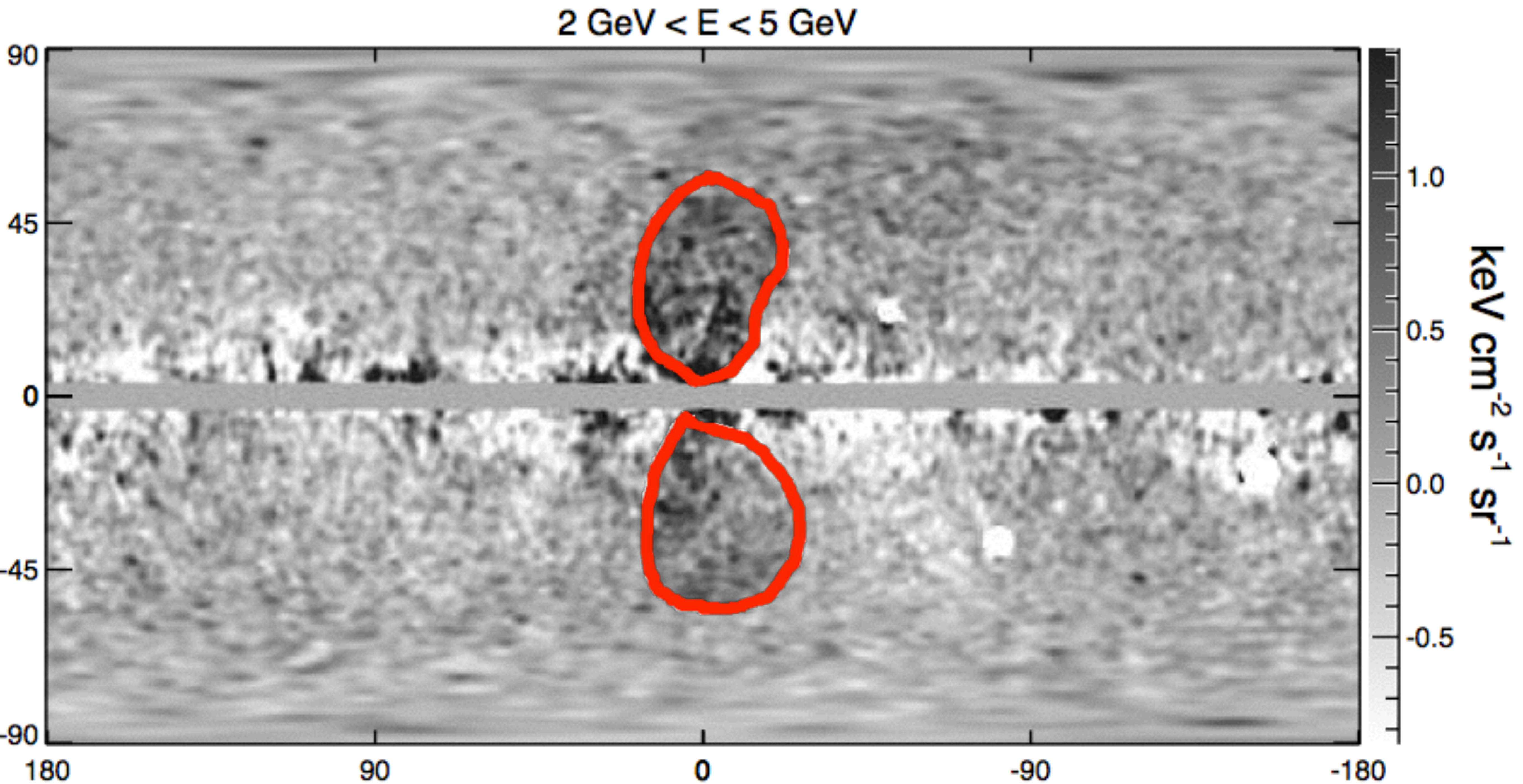
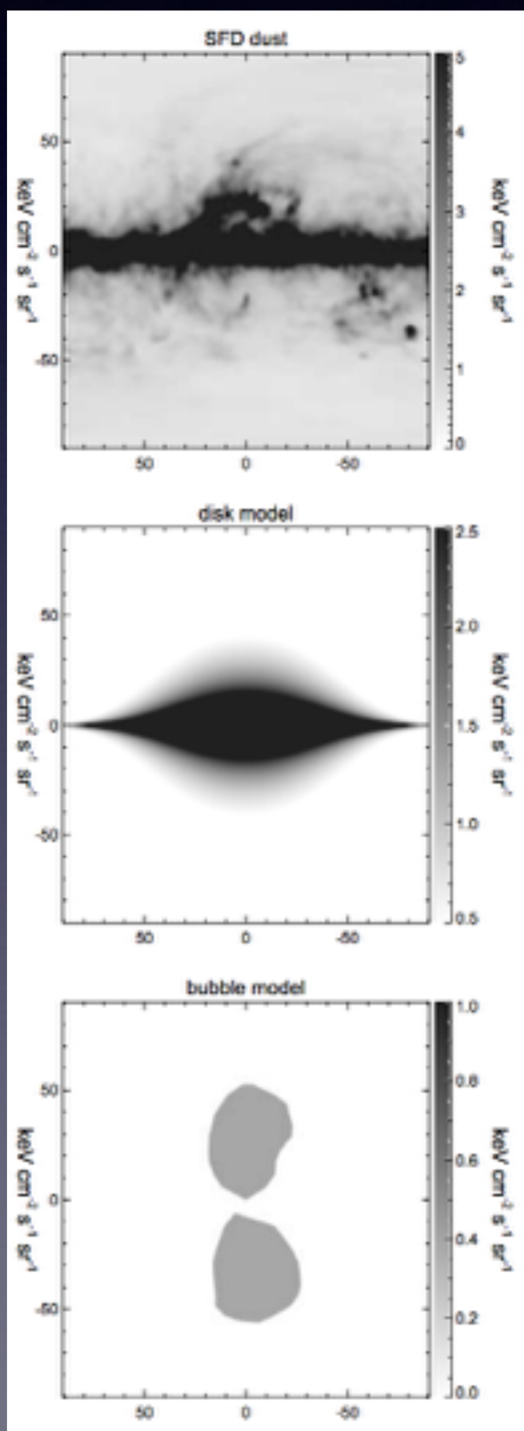


# Template fitting



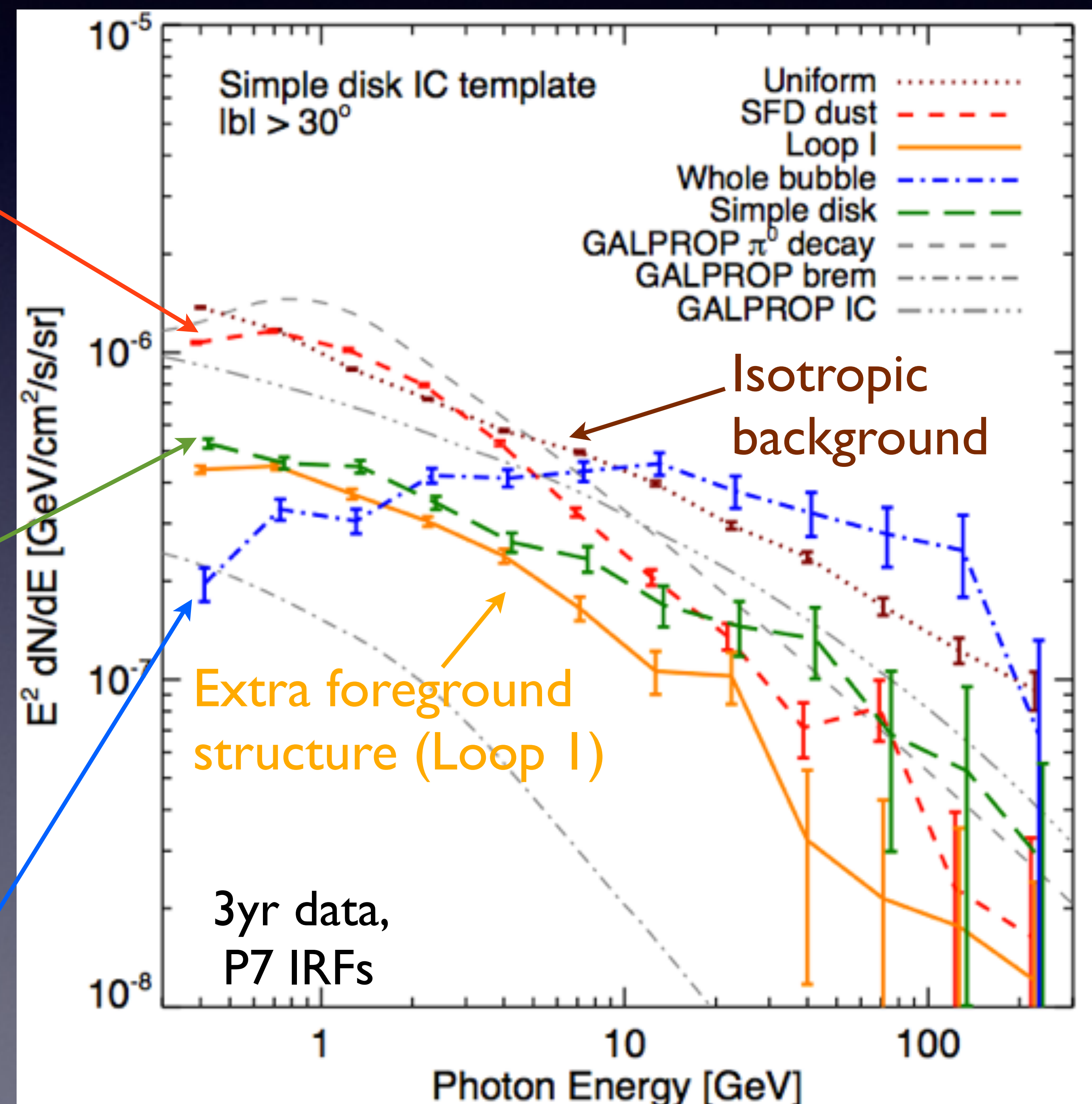

Gas-correlated emission

+

Disk-correlated emission

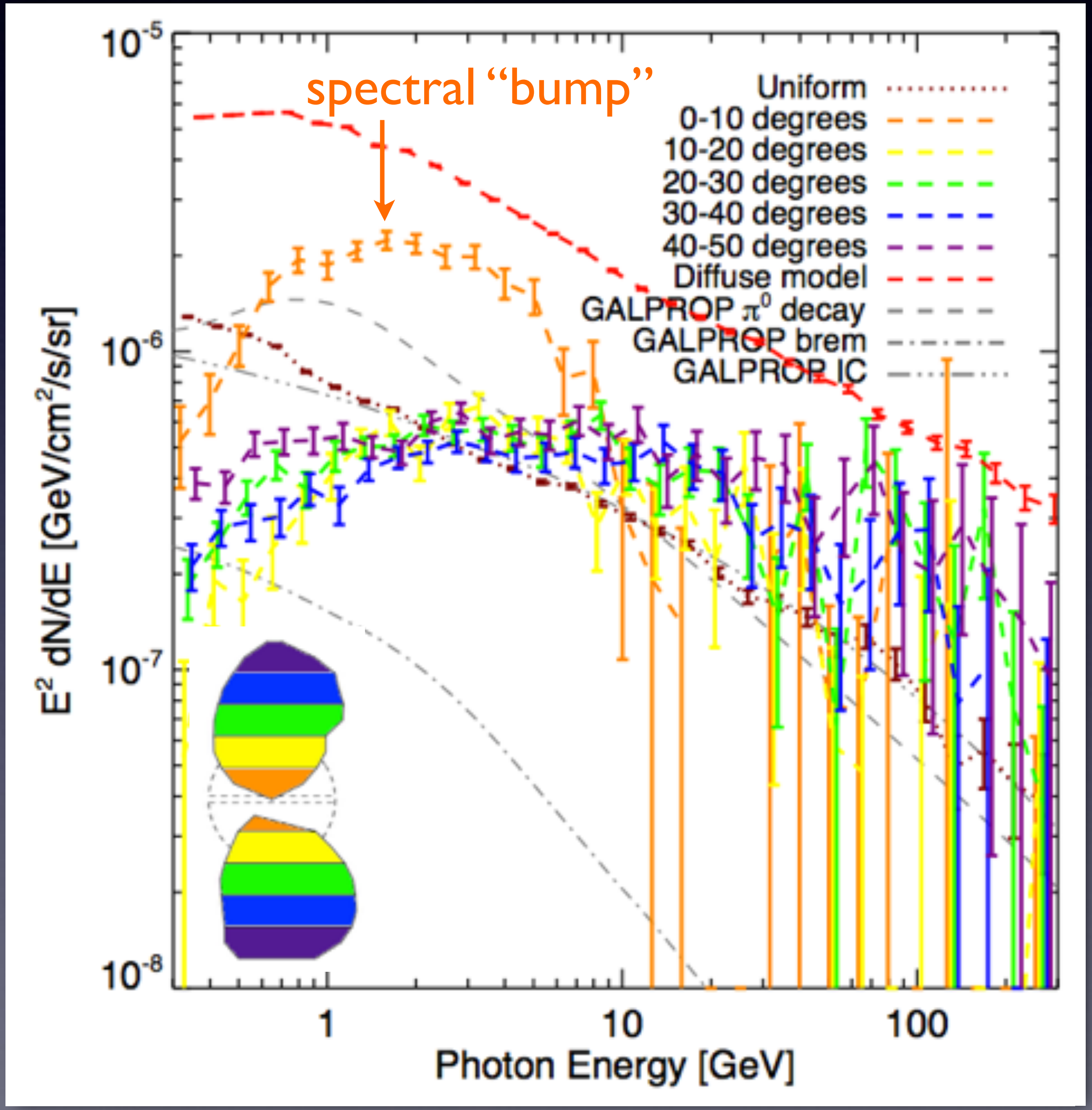
+

Bubbles-correlated emission



# The inner Galaxy excess

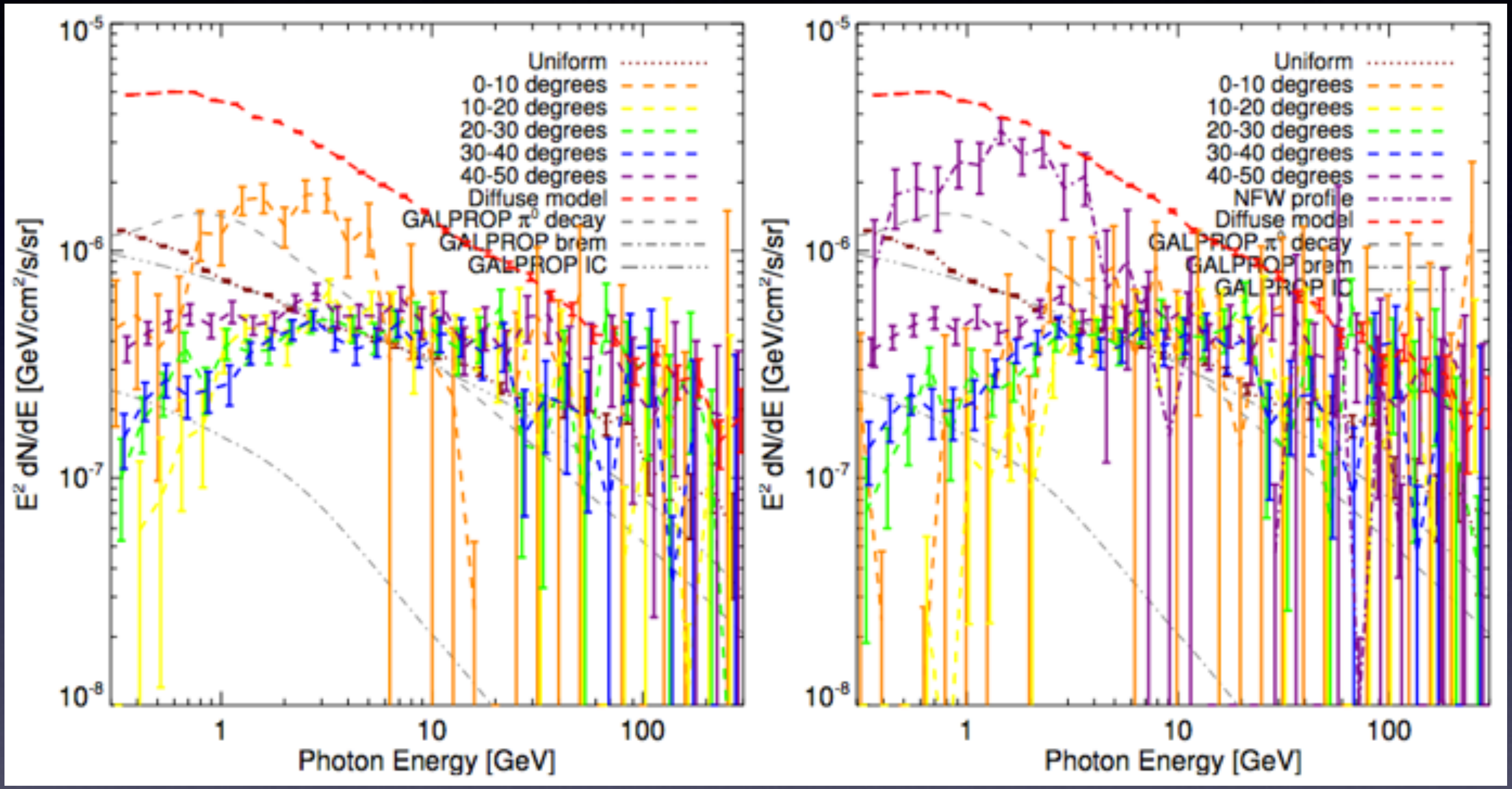
- Use Fermi diffuse model (p6v11) as background template (+ isotropic background).
- Allow Bubbles spectrum to vary with latitude.
- The spectrum of the Bubbles develops pronounced curvature at low Galactic latitudes.
- Consistent with two components, one flat in $E^2 dN/dE$ and latitude, the other with a bump at few-GeV energies and falling rapidly with latitude (flux/volume~$r^{-2.4}$).



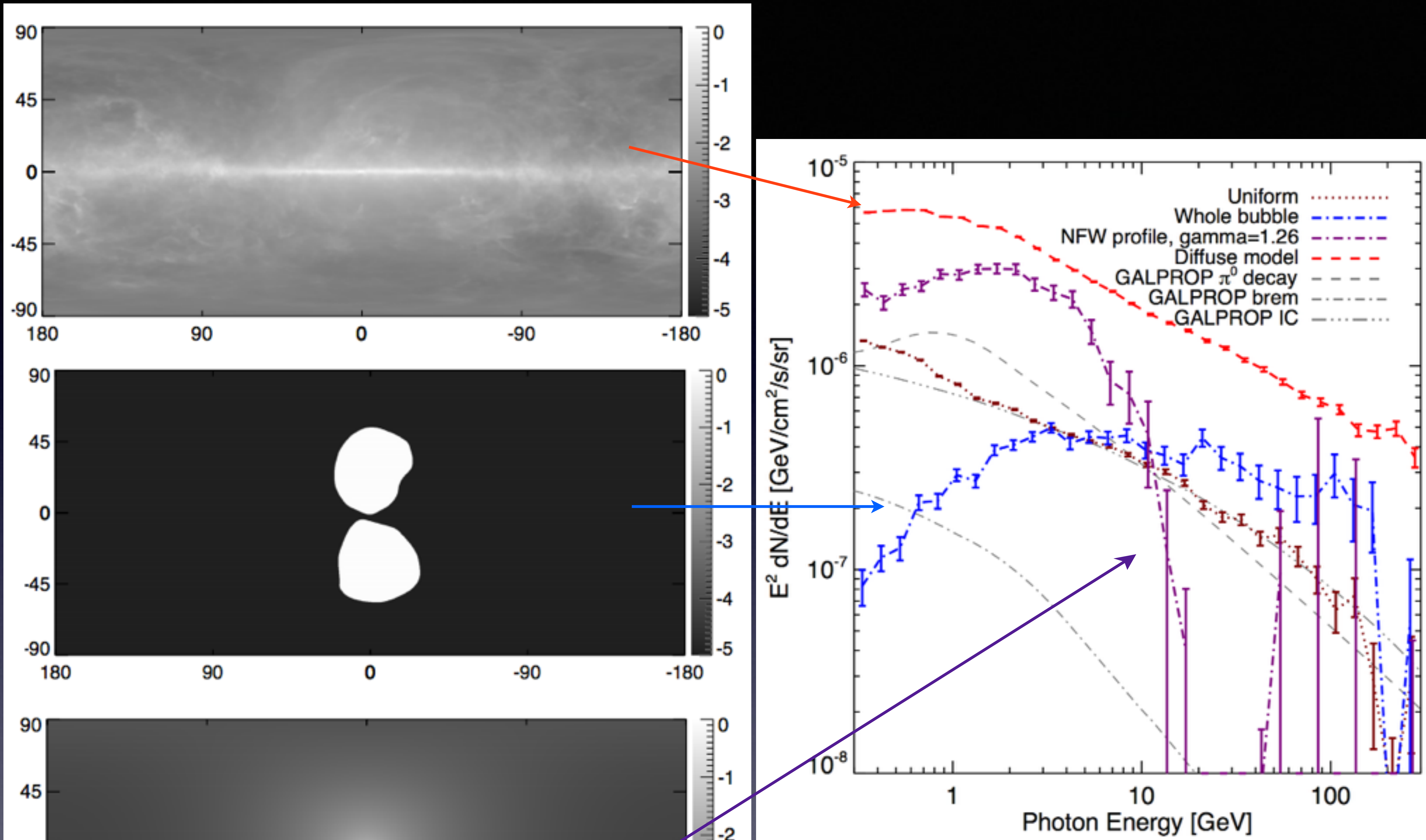
# A DM-like morphology?

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

We subsequently adopted this approach (correlation with a DM-like template) for extracting the spectrum of the excess.



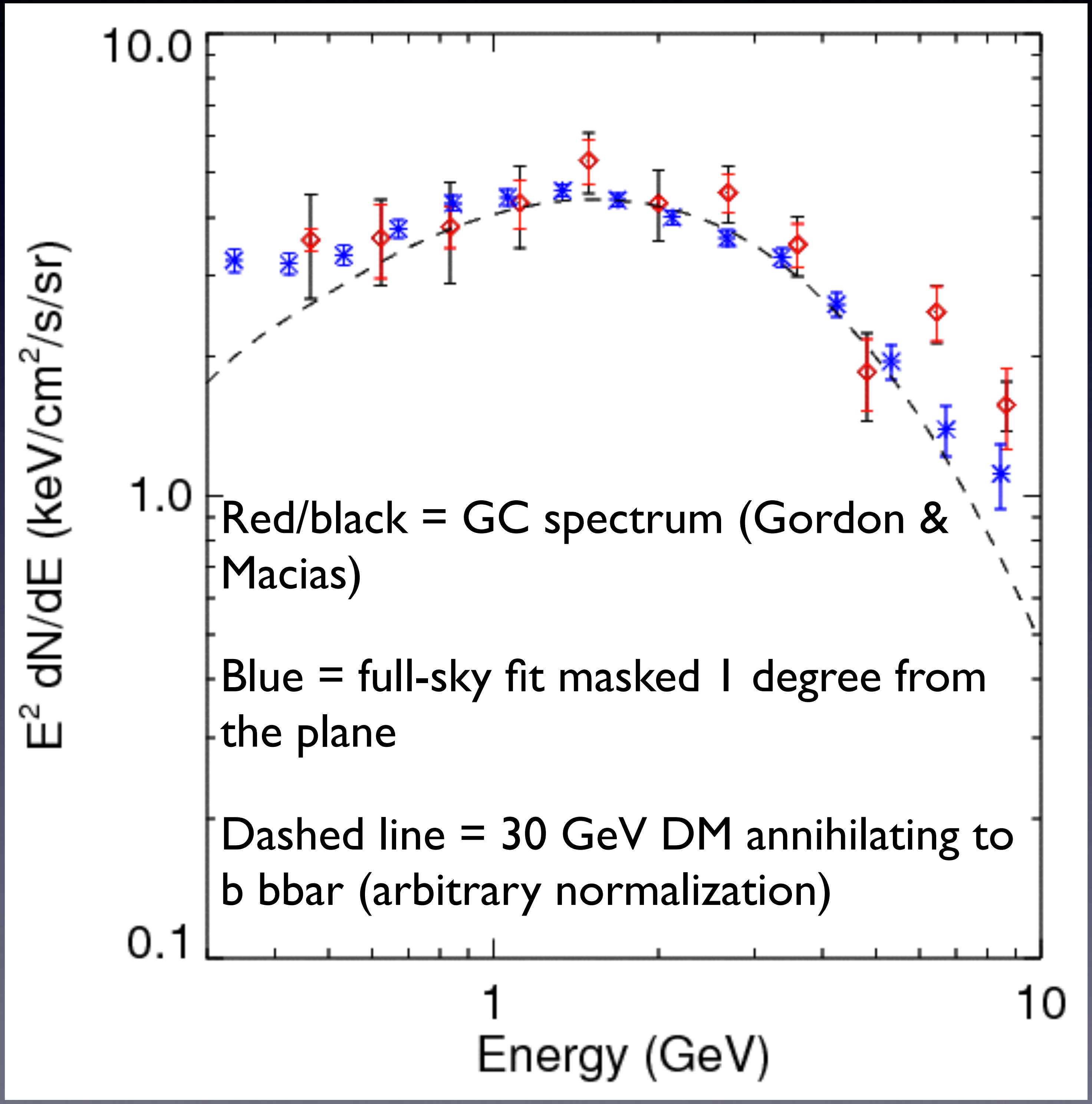

- To avoid structures in the north (e.g. Loop 1), fit in the southern sky only; mask the area where b > -5° to minimize disk emission. This should be a "clean" fit (and no spatial overlap with previous GC analyses).
- Left panel: bubble templates only, right panel: NFW profile included.




Use a single template for the Bubbles for simplicity; we have tested this does not bias the DM-template-correlated spectrum.

# Inner Galaxy vs the GC

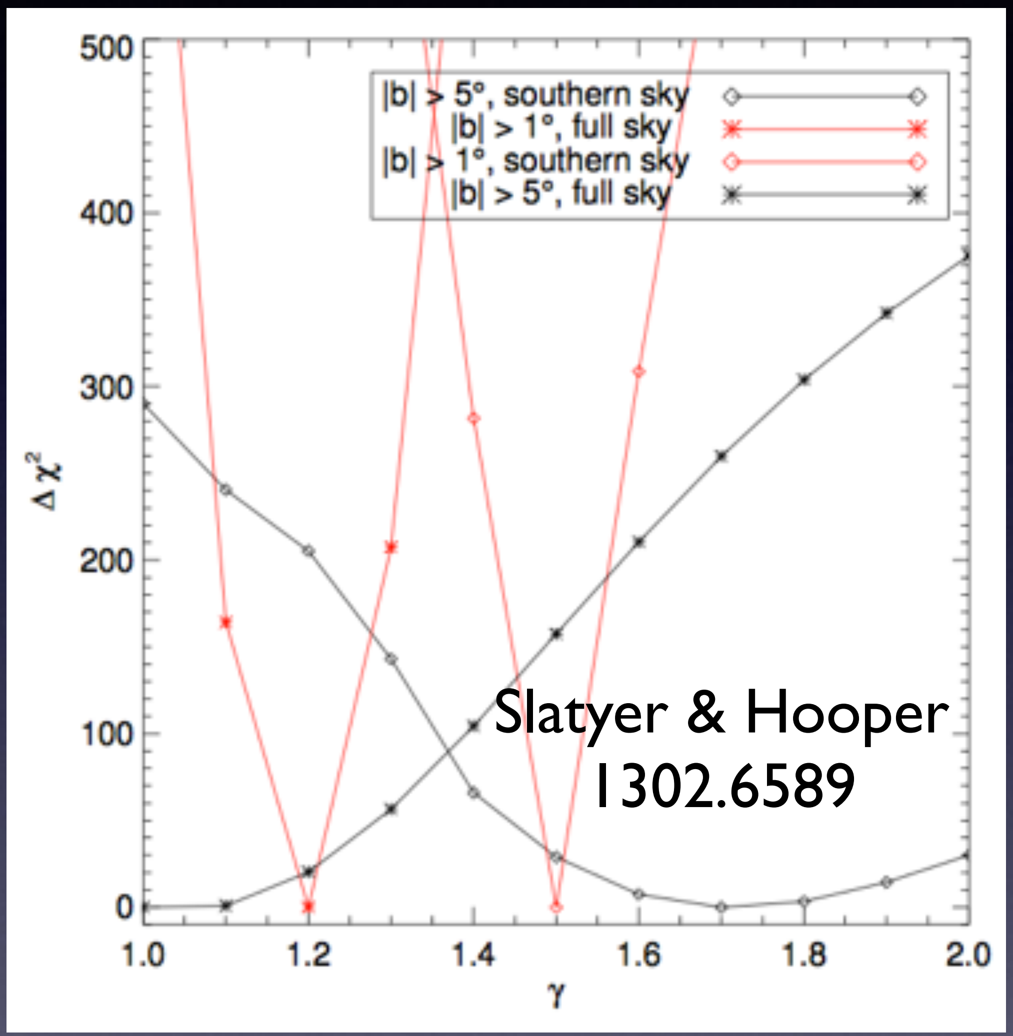
- Red/black points = Gordon & Macias '13 analysis of Galactic Center signal, normalized assuming a generalized NFW profile with $\gamma$=1.2.
- Blue points = spectrum correlated with DM-like template from the full-sky fit in 1302.6589, masking 1 degree from the Galactic plane.
- The two signals are in remarkable agreement, and almost certainly share an origin.

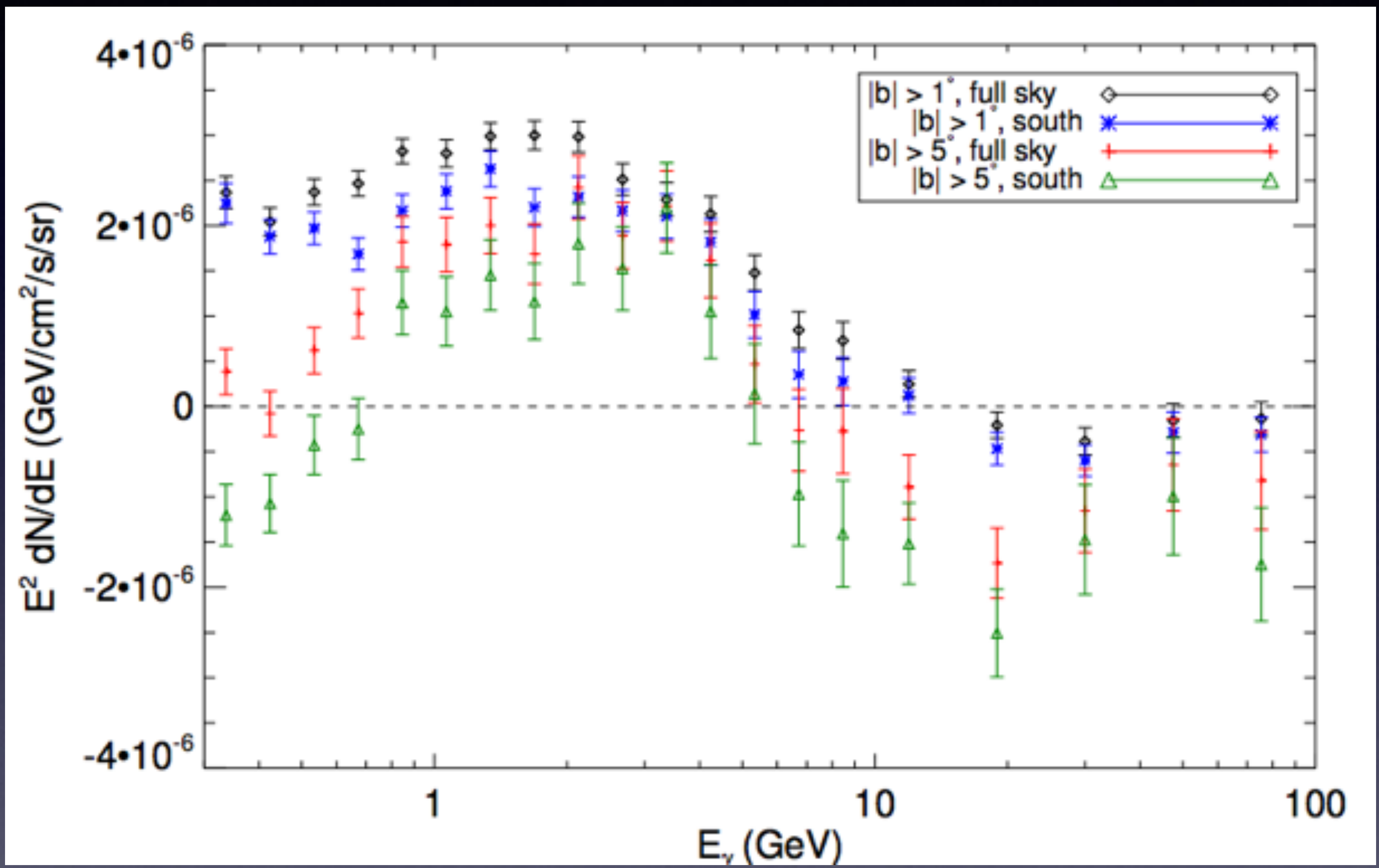


# Notes

- Presence of signal at high latitudes excludes hypothesis of poor angular resolution faking an extended signal.
- Still not a statistical fluctuation (formally 40 sigma based on stat errors only).
- In 1302.6589, found north/south asymmetry, and low-energy slope of extracted spectrum varied significantly as a function of masking of the Galactic plane.
- Modeling of diffuse background was a major source of uncertainty.

# Spectral variation

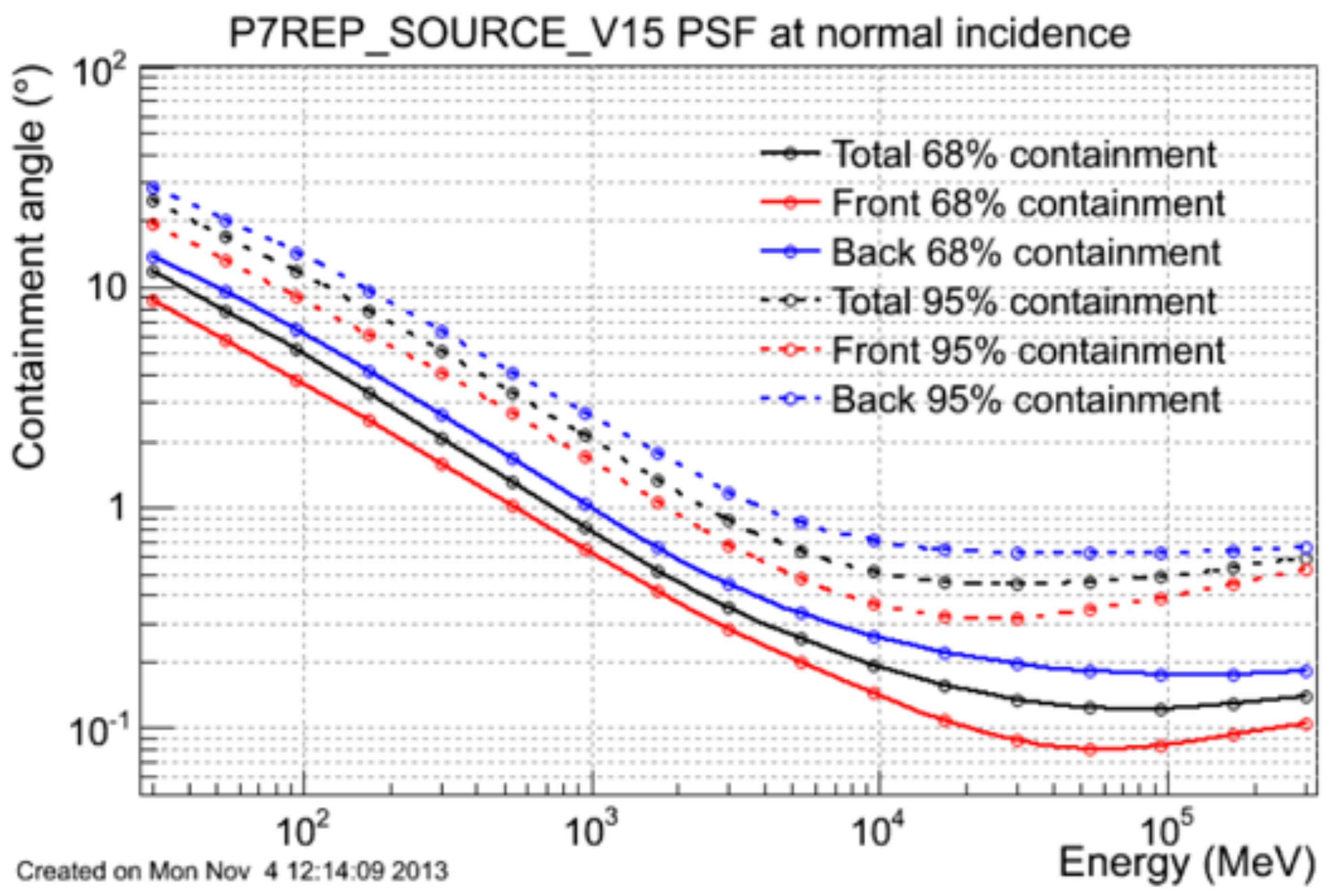



- Extracted spectrum depends on masking of the Galactic plane and north/south, as does power-law slope of profile.
- Differences between spectra well explained by mis-subtraction of few percent of diffuse background.

# A high-angular-resolution data sample

- We are relying on spatial information to distinguish the different diffuse emission components.
- The angular resolution of Fermi is quite poor at low energies, and the tails of the point spread function (PSF) are significantly non-Gaussian.
- Could better angular resolution improve our ability to separate out the diffuse background?

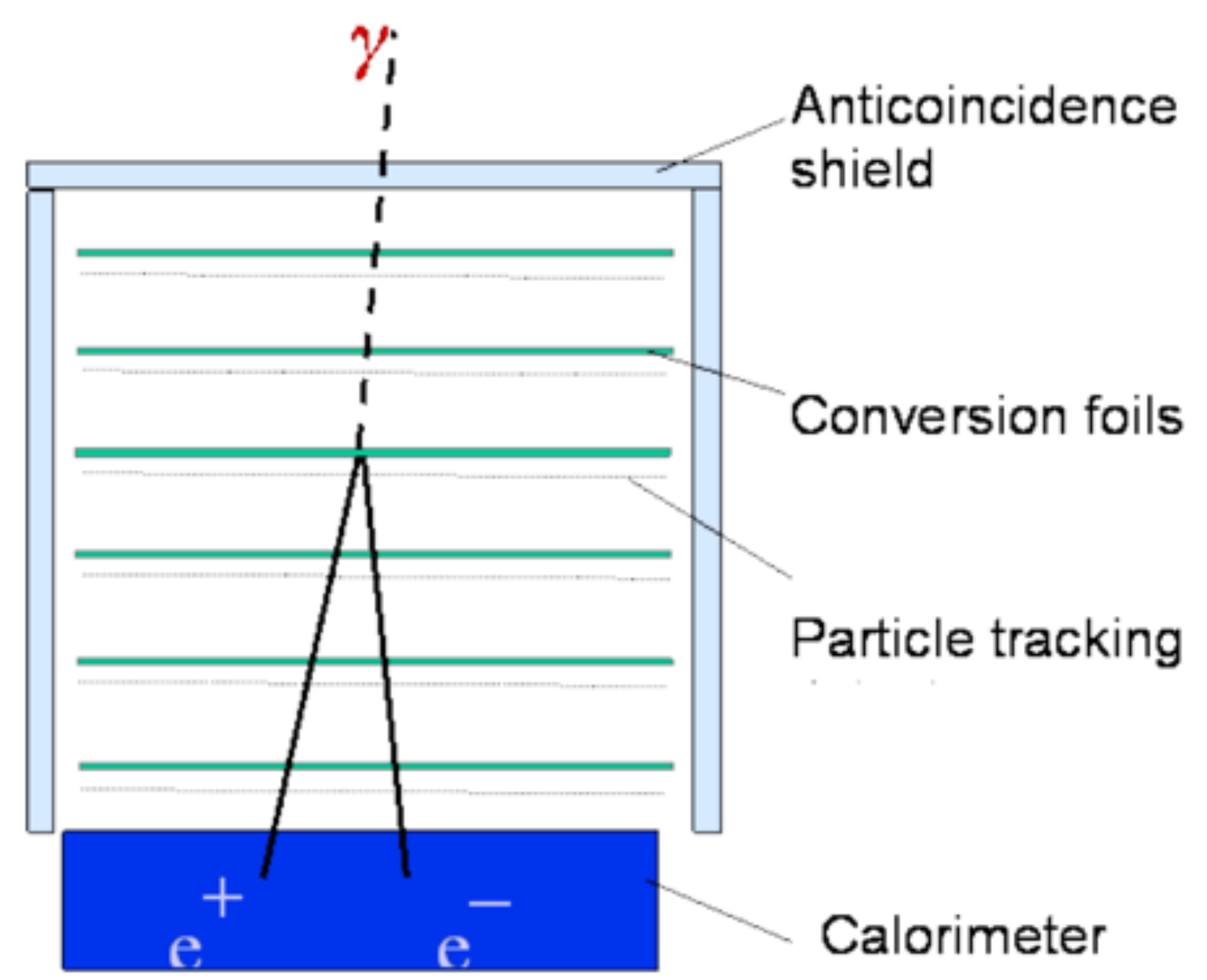



Fermi-LAT Performance

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

# CTBCORE

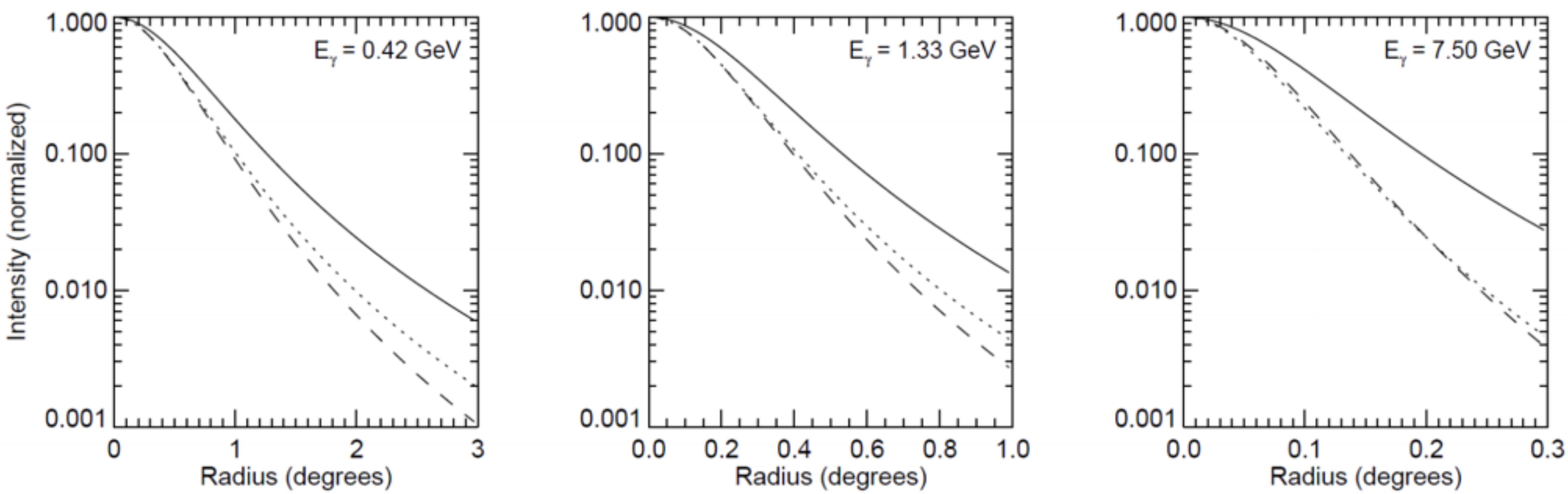
- Gamma rays pair produce in tungsten conversion foils. Resulting shower of secondaries is tracked through silicon strip detectors.
- Below 10 GeV, PSF limited by multiple scattering of pair in conversion foil.
- Missed tracker hits and hard scattering contribute to PSF tails.
- Classification tree estimates quality of direction reconstruction on event-by-event basis, parameterized by “CTBCORE”.



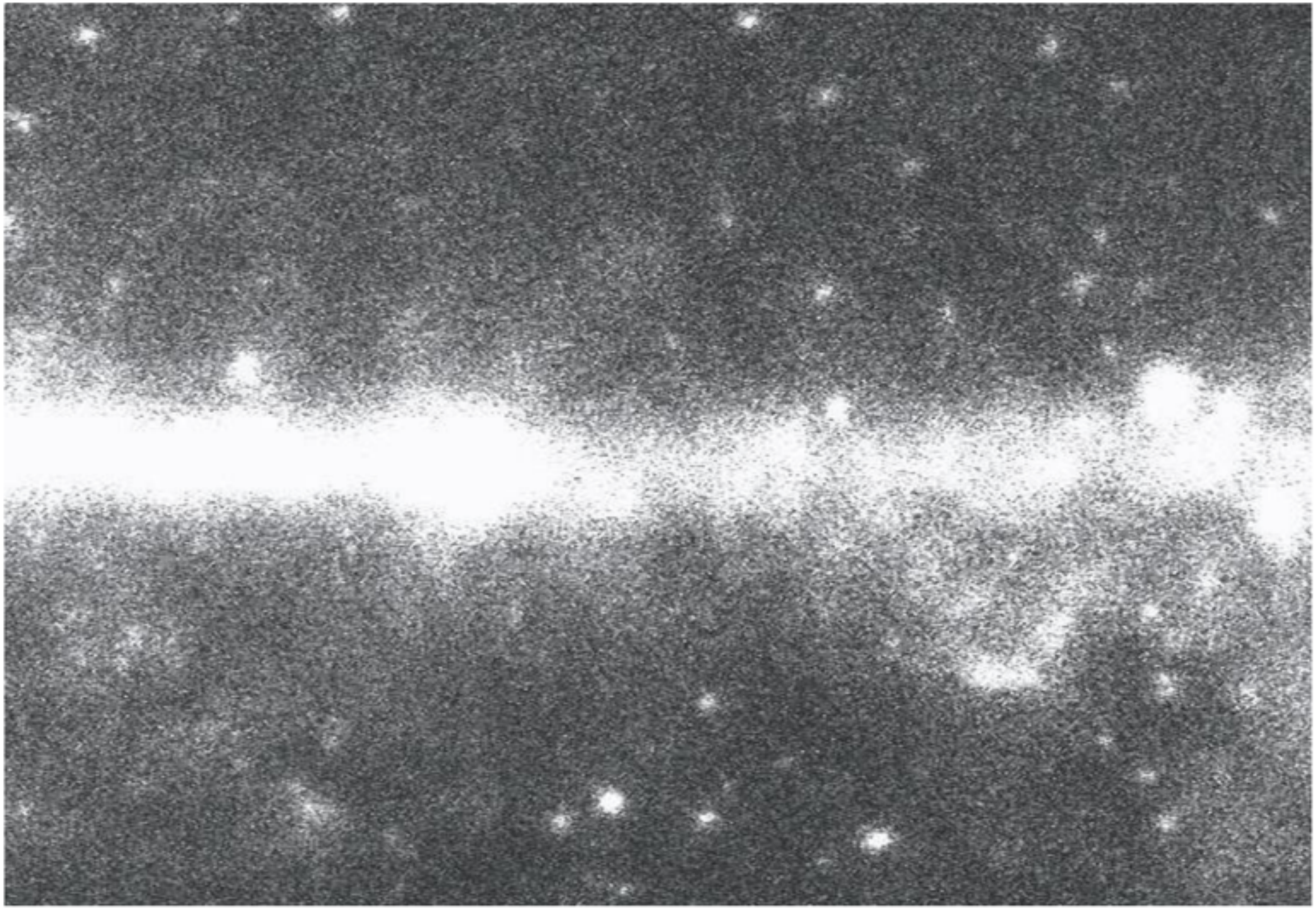

Fermi Science Support Center Cicerone
http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/

# Using CTBCORE

- We can cut on CTBCORE to remove events with poor angular reconstruction, responsible for non-Gaussian PSF tails.
- Use pulsars (bright sources) to calibrate new point spread function.
- Use entire photon data set to determine how these cuts affect effective area, binned by energy and incident angle. "Q2" and "Q1" cuts discard 50% or 75% of the total photons respectively.

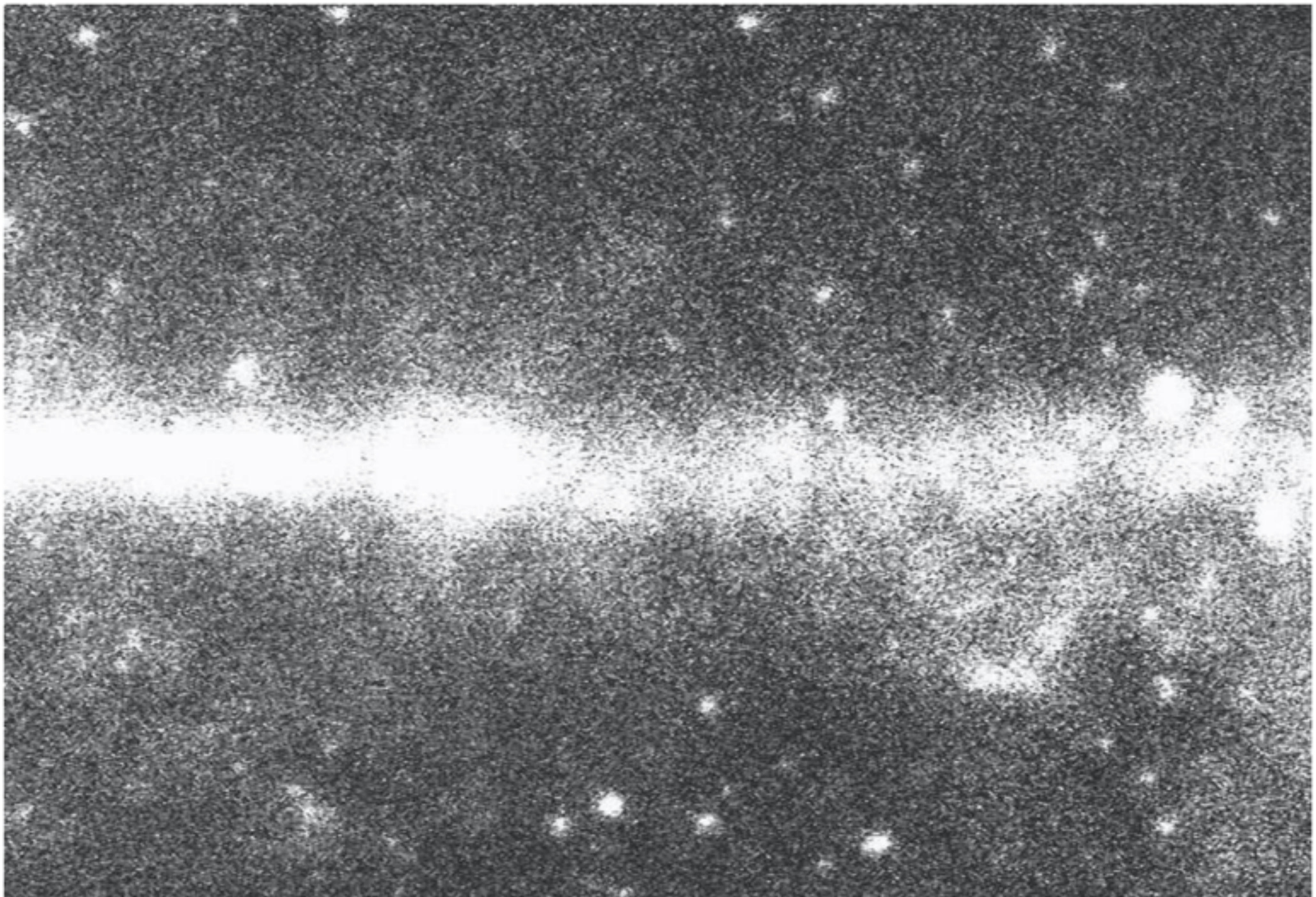


# 0.3-0.5 GeV, CLEAN (front)



Thanks to Stephen Portillo for providing these slides

# 0.3-0.5 GeV, CLEAN (front) Q2



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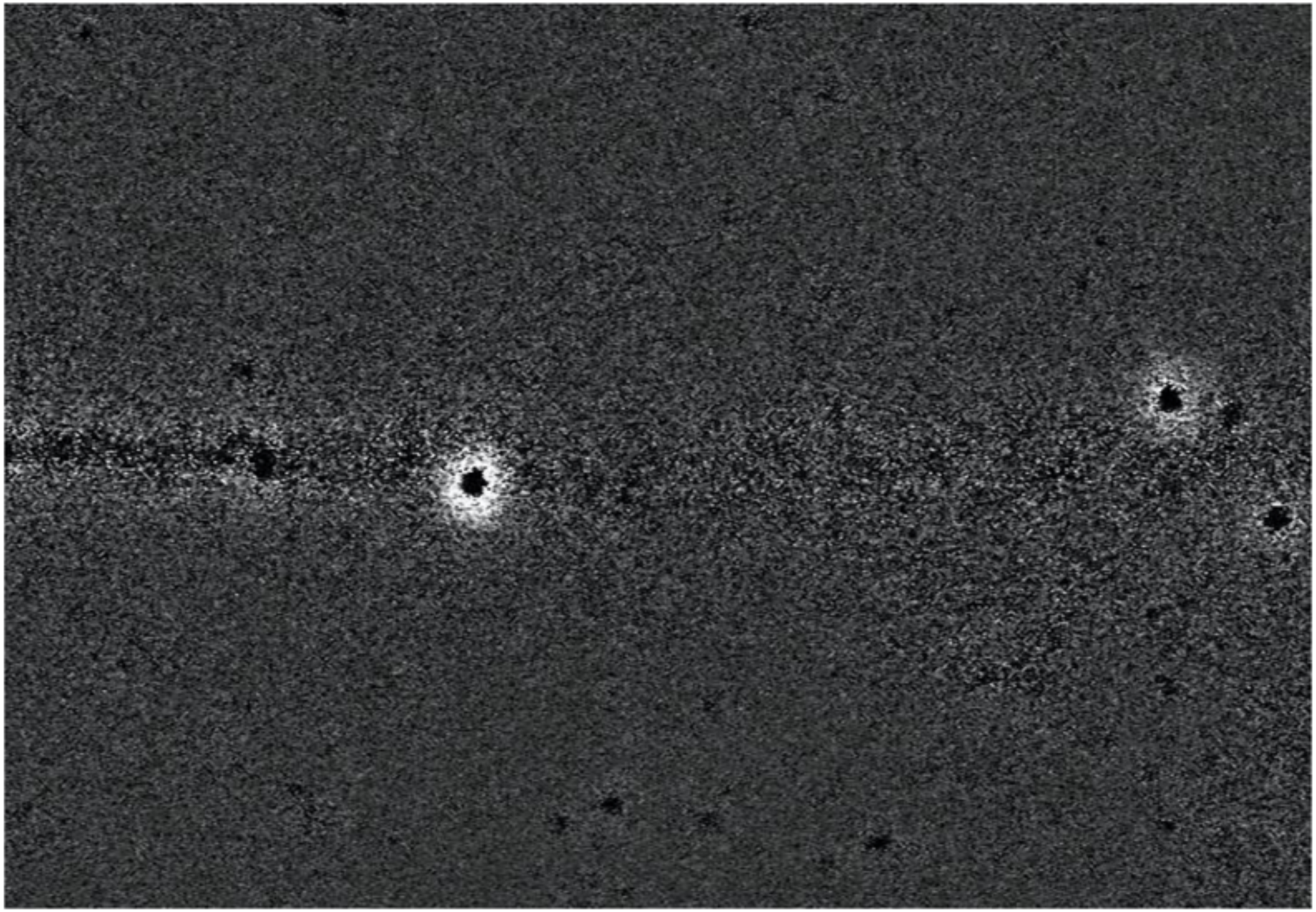
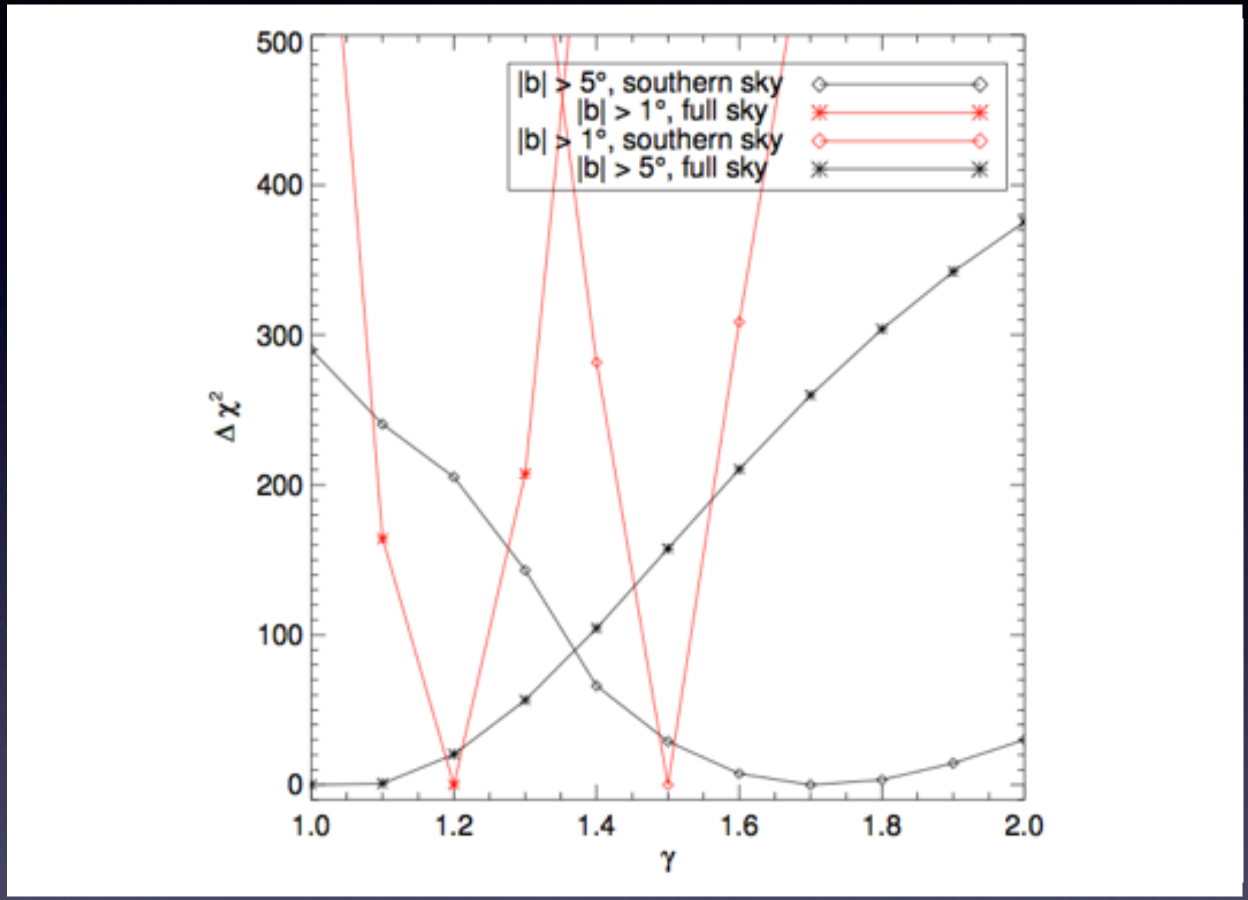
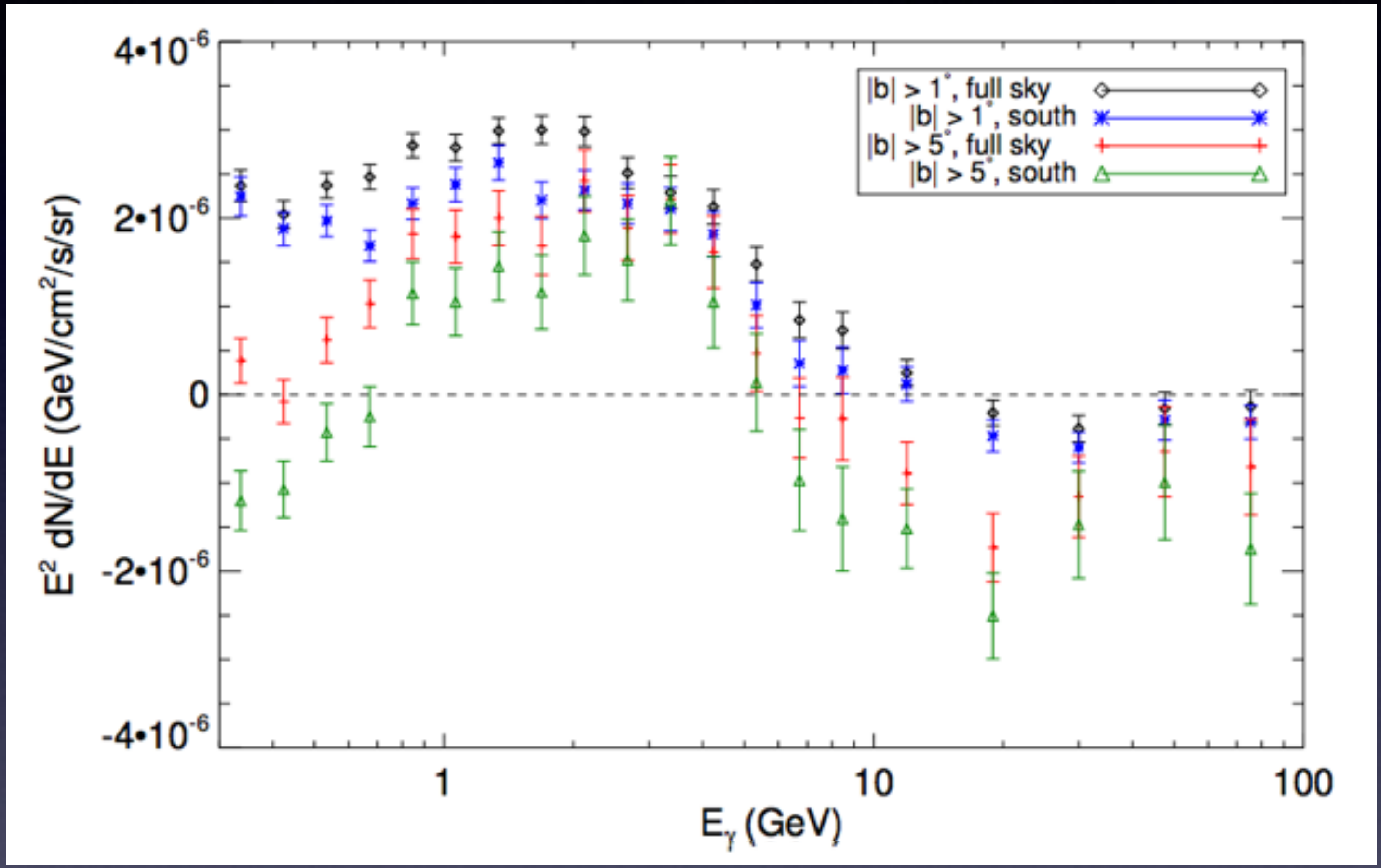
# difference



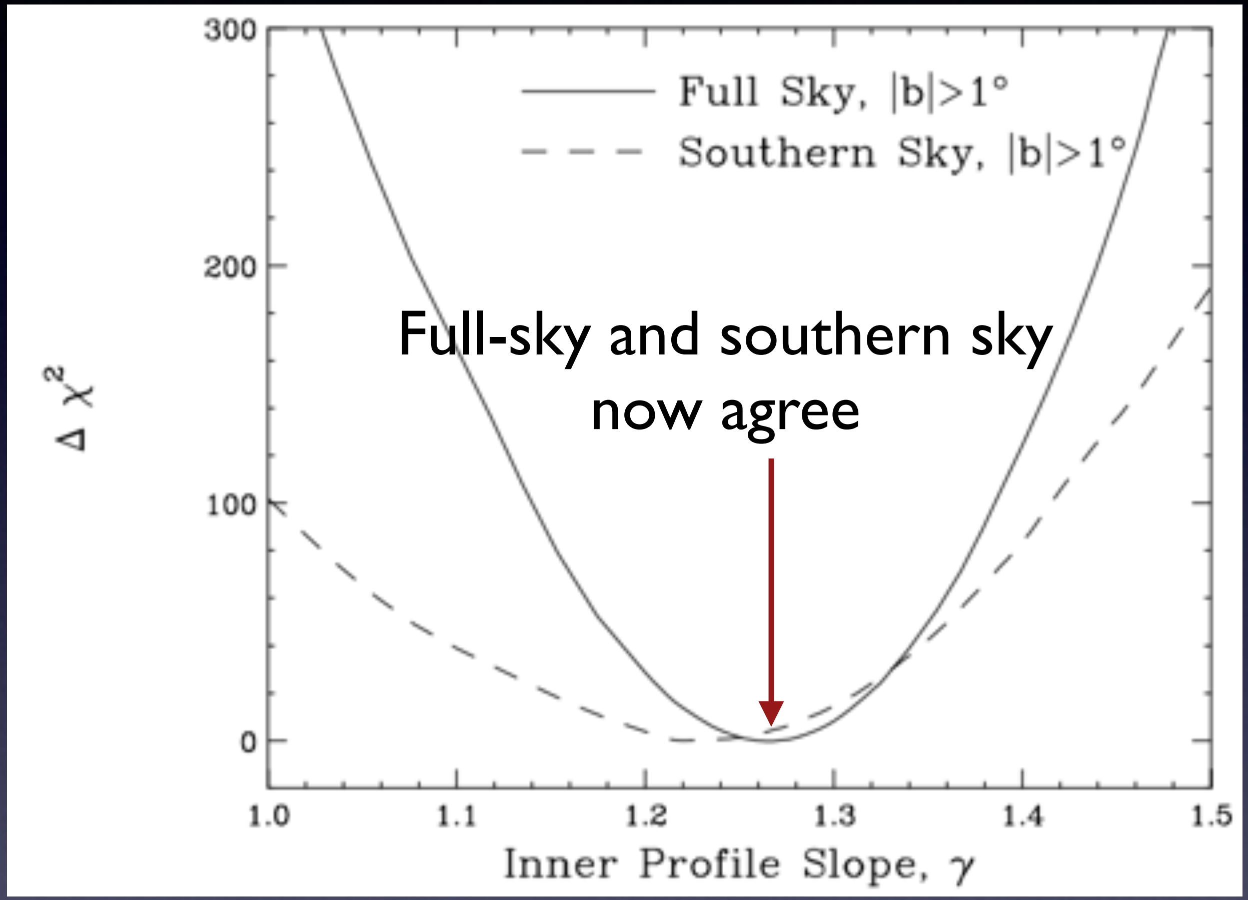
# Effects of CTBCORE cut

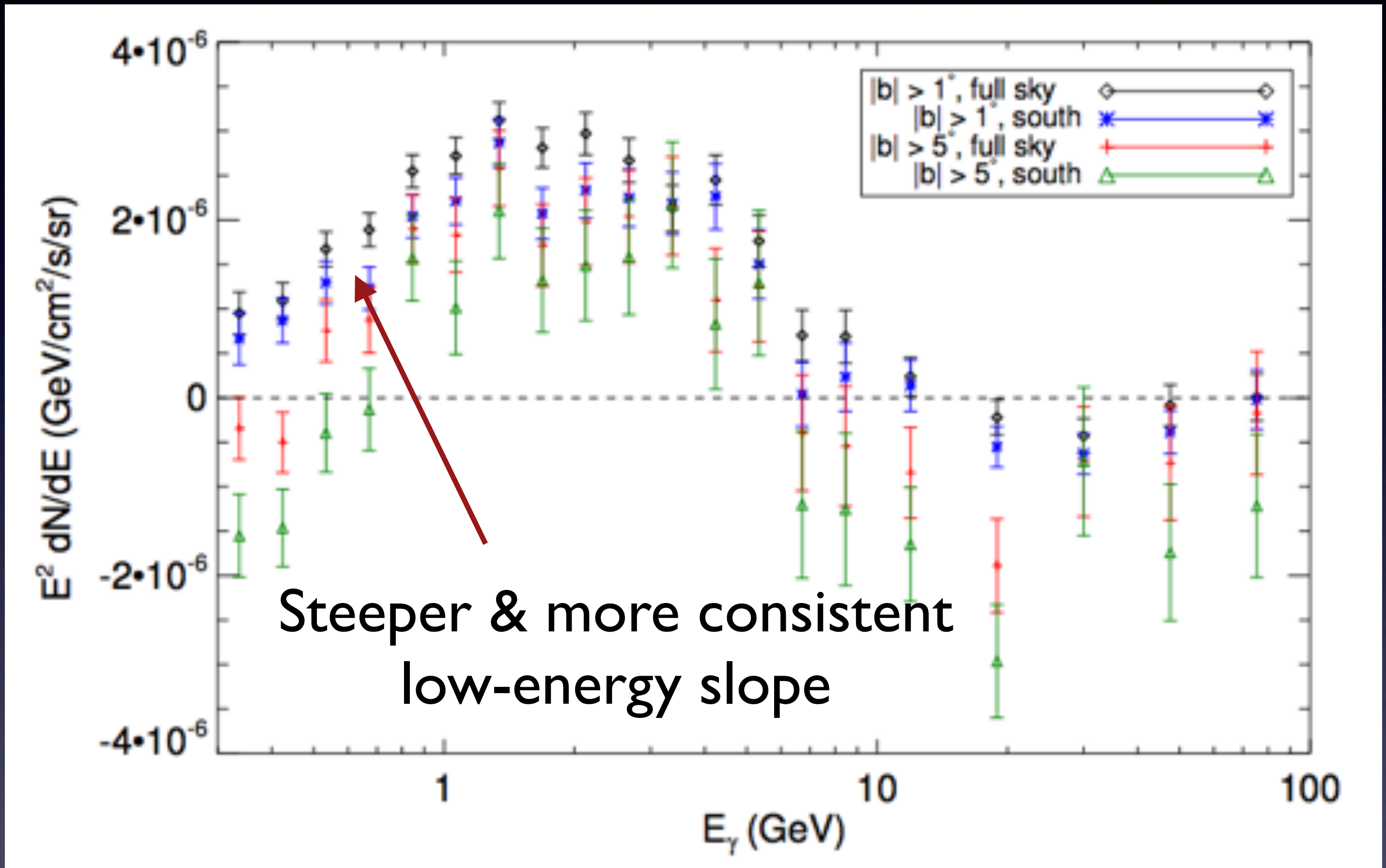



- Removing PSF tails seems to significantly improve consistency between spectra in different regions of the sky (for the inner Galaxy analysis), removes north-south asymmetry.
- Preferred slope in inner Galaxy analysis is now 1.26 - consistent for all bins between 0.5 GeV and 10 GeV.

# Effects of CTBCORE cut

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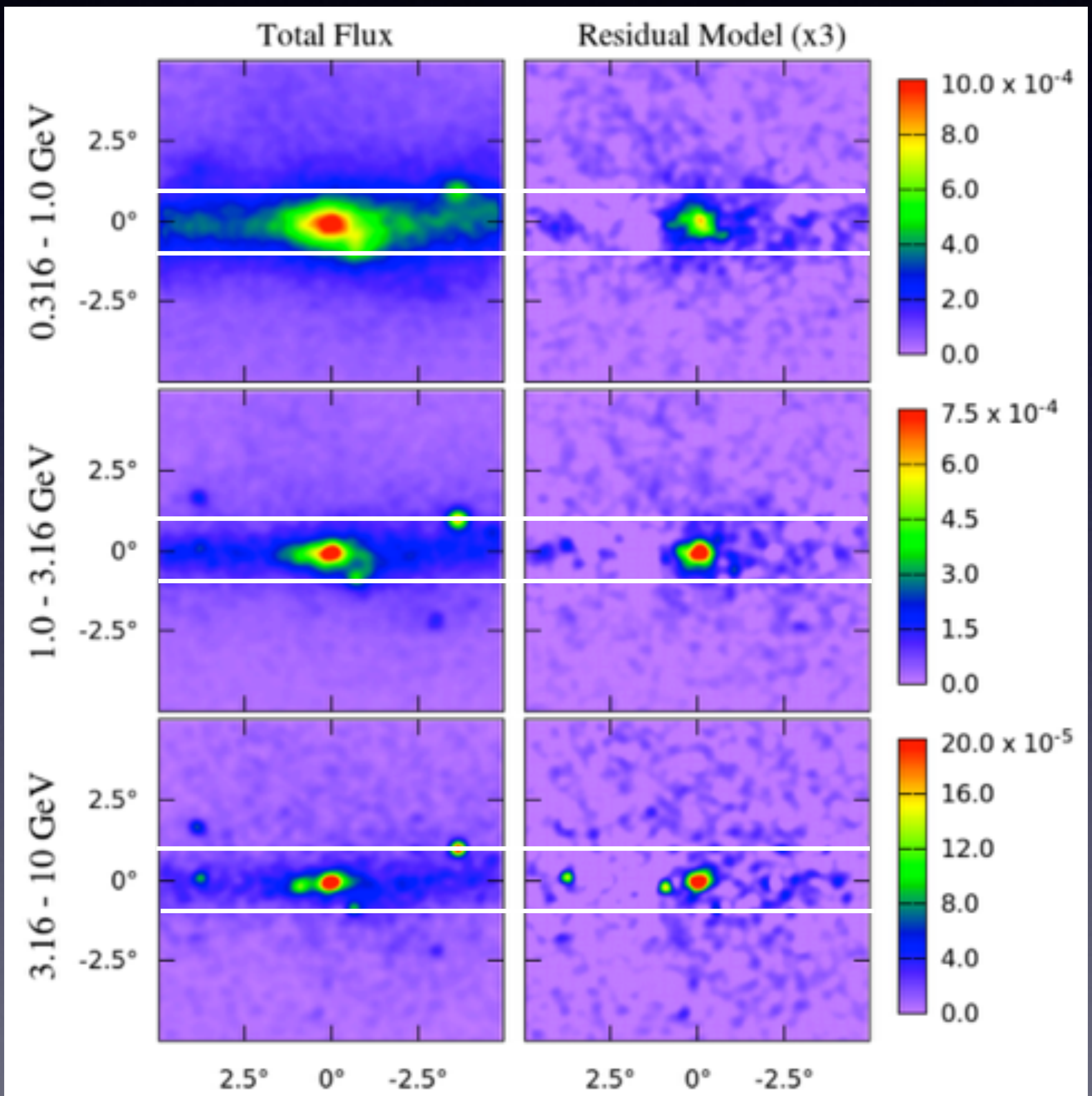
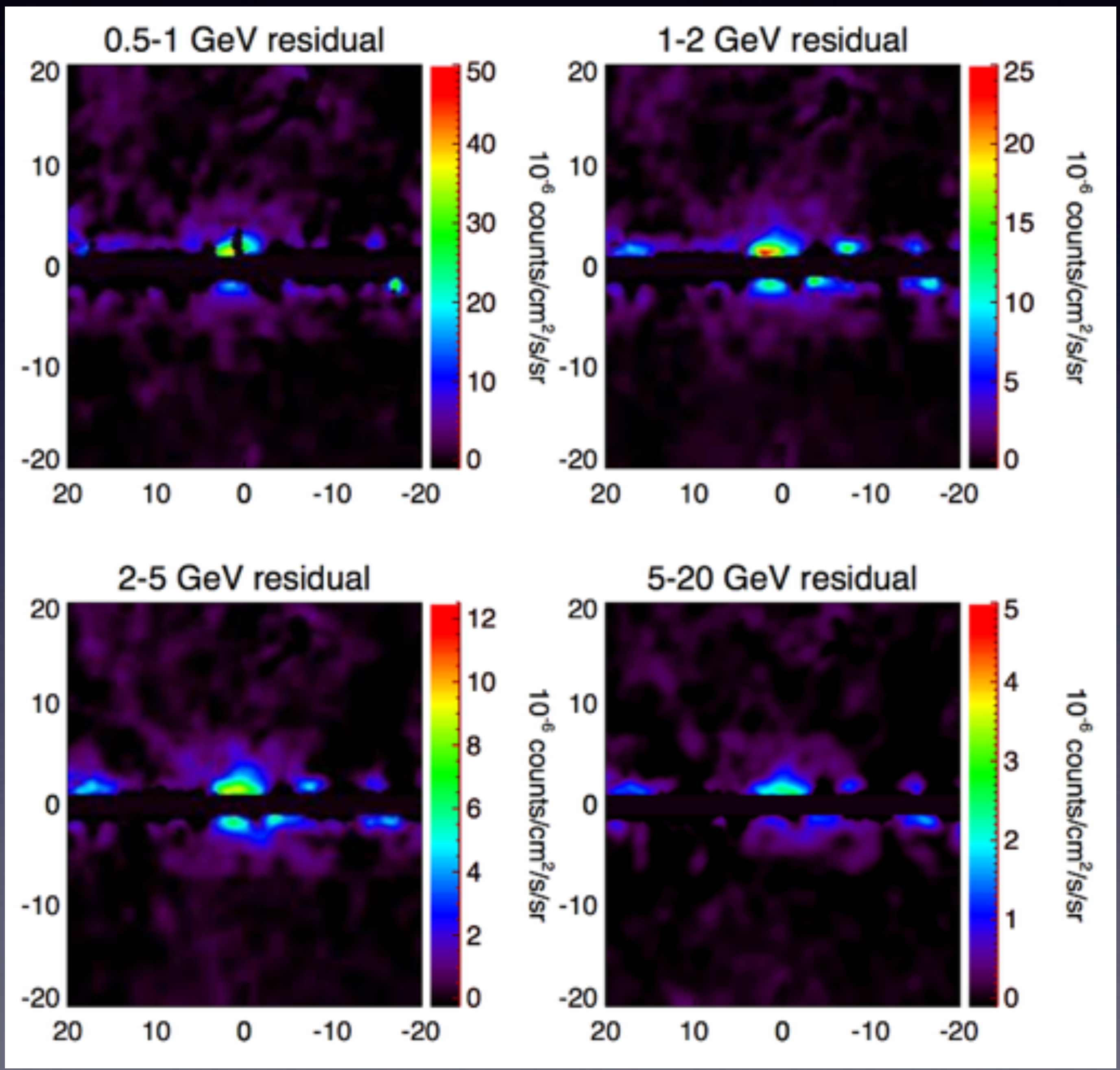
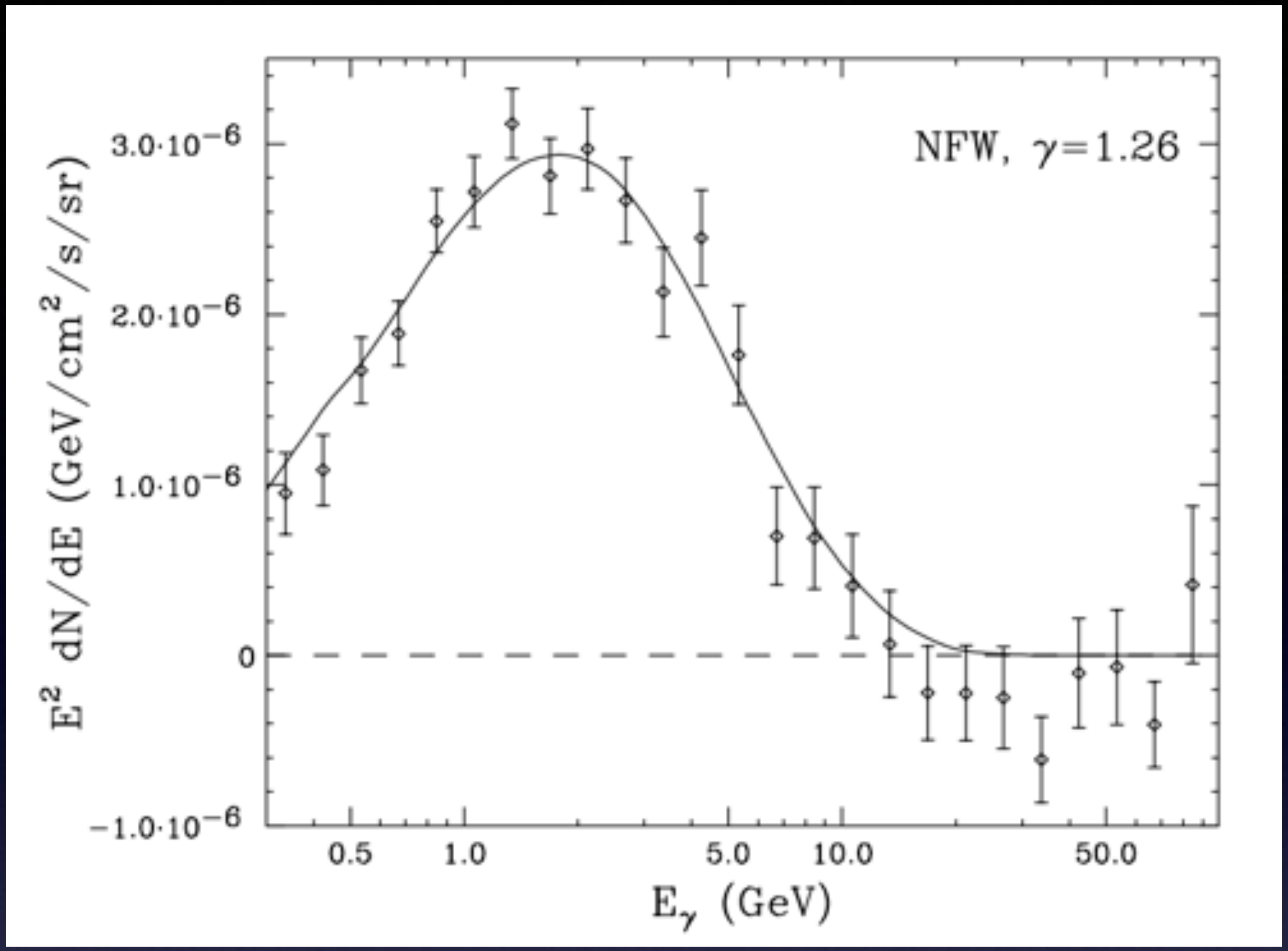
# Spatial residuals with new cut

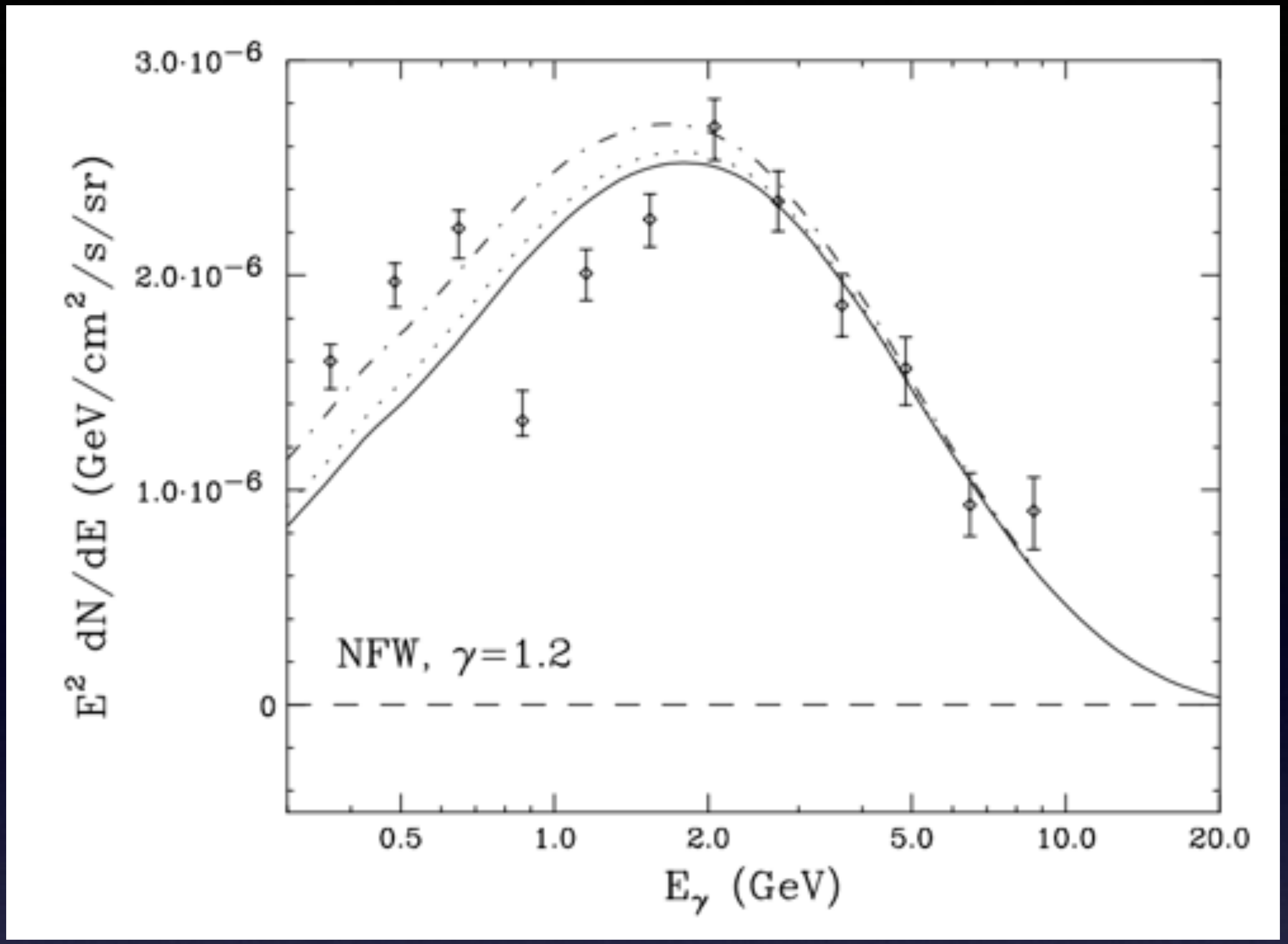



Galactic Center - data (left), residual (right)




Inner Galaxy residuals (Galactic plane is masked, note change in scale)




Inner Galaxy

Galactic Center

- After the cut on CTBCORE:
  - An apparent north/south asymmetry previously noted in the extended (inner Galaxy) excess is removed. The new preferred slope is γ=1.26 in the inner Galaxy analysis, γ=1.1-1.2 in the Galactic Center.
  - The spectra measured in different regions for the inner Galaxy analysis are more consistent, especially at low energies.
  - The low-energy spectrum becomes harder.

# The Galactic Center analysis

- Redo likelihood analysis using CTBCORE-cut data and new instrument response functions.
- Model backgrounds with diffuse model + 2FGL point sources + template tracing observed 20cm emission. Allow flux and spectrum of bright sources to vary, or just amplitude of spectrum for more distant or lower-significance sources.
- Take iterative approach - start with seed spectrum for dark matter component, fit for normalization and spectral shape of astrophysical components. Then fix astrophysical components to their best-fit values, fit for DM component in each energy bin. Iterate resulting DM spectrum.

# The Galactic Center

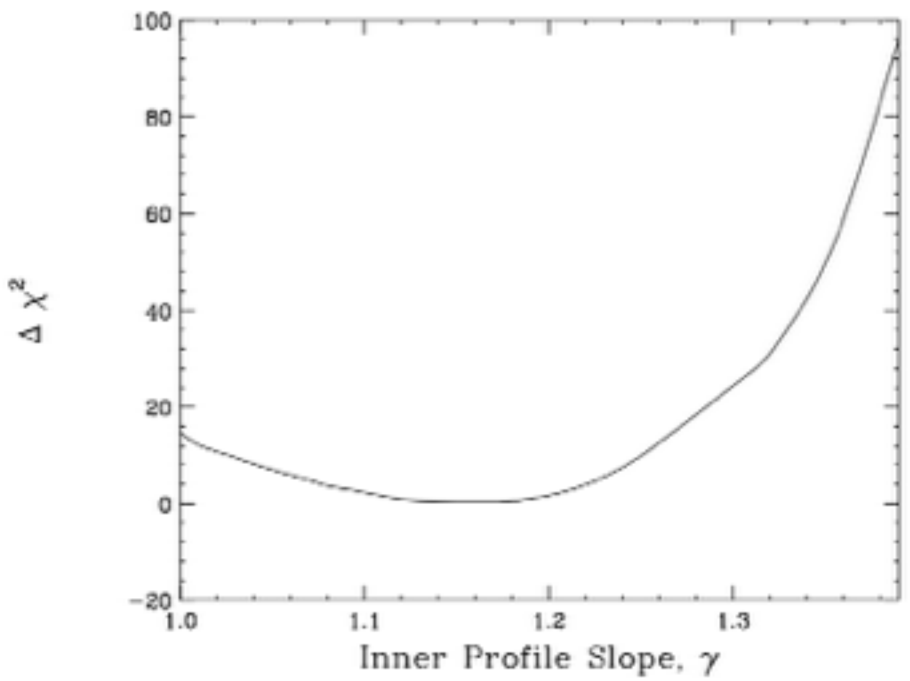



FIG. 8: The value of $\Delta\chi^2$ as a function of the inner slope of the dark matter halo profile, $\gamma$, as found in our Galactic Center likelihood analysis. The best-fit value is somewhat shallower than found in our analysis of the larger Inner Galaxy region, favoring $\gamma \sim 1.17$ (rather than $\gamma \simeq 1.26$).

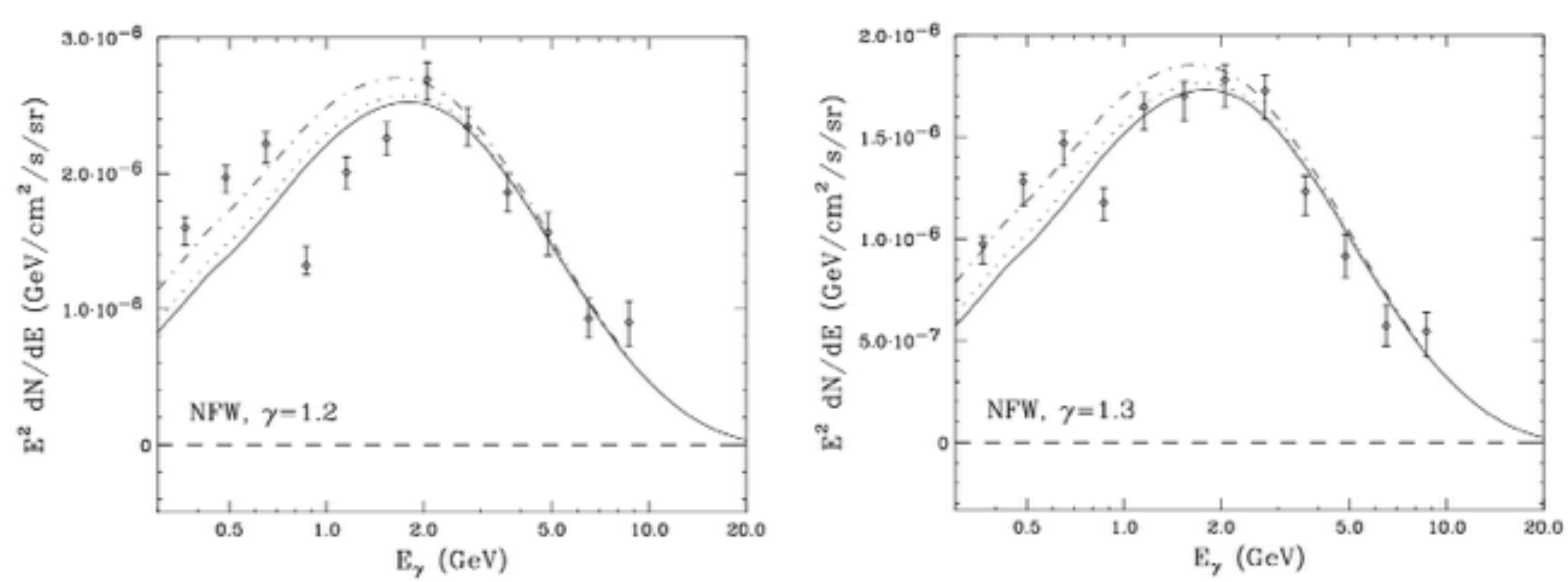
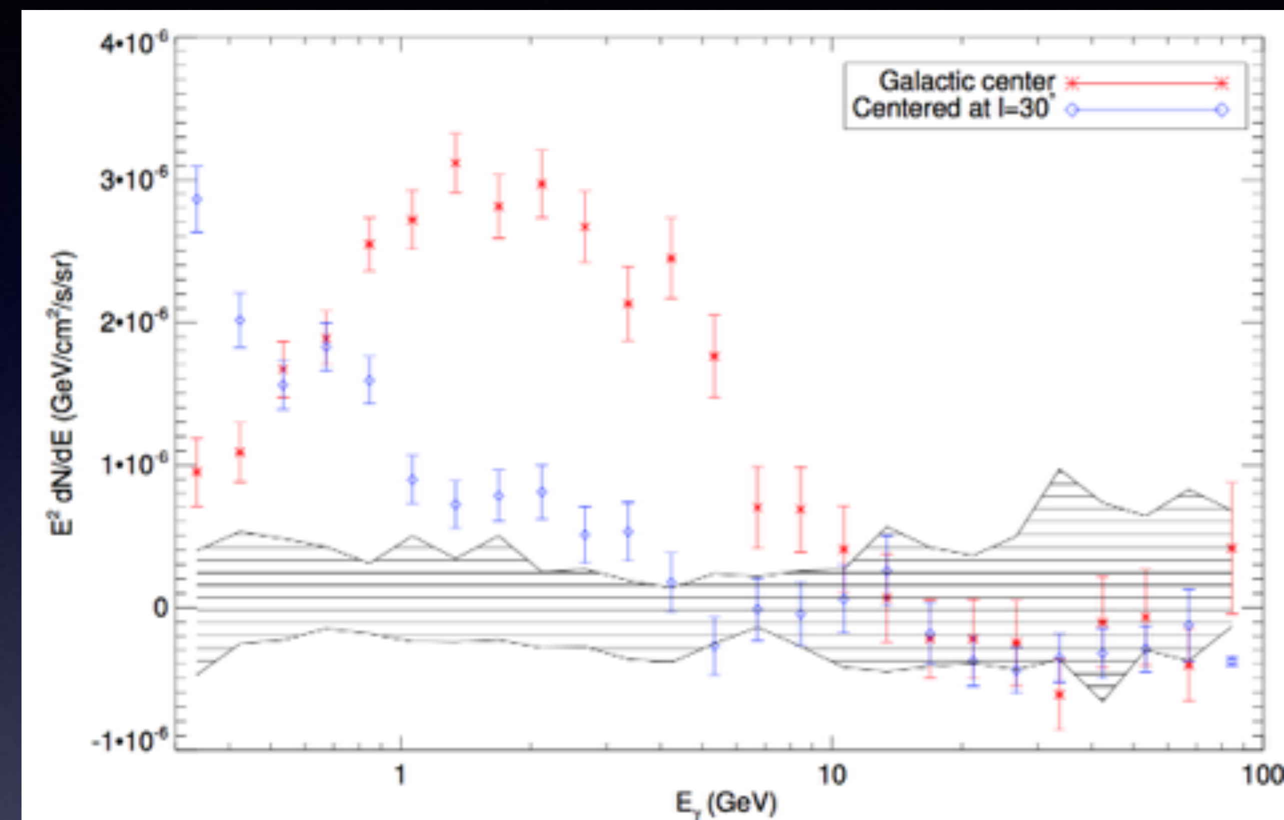


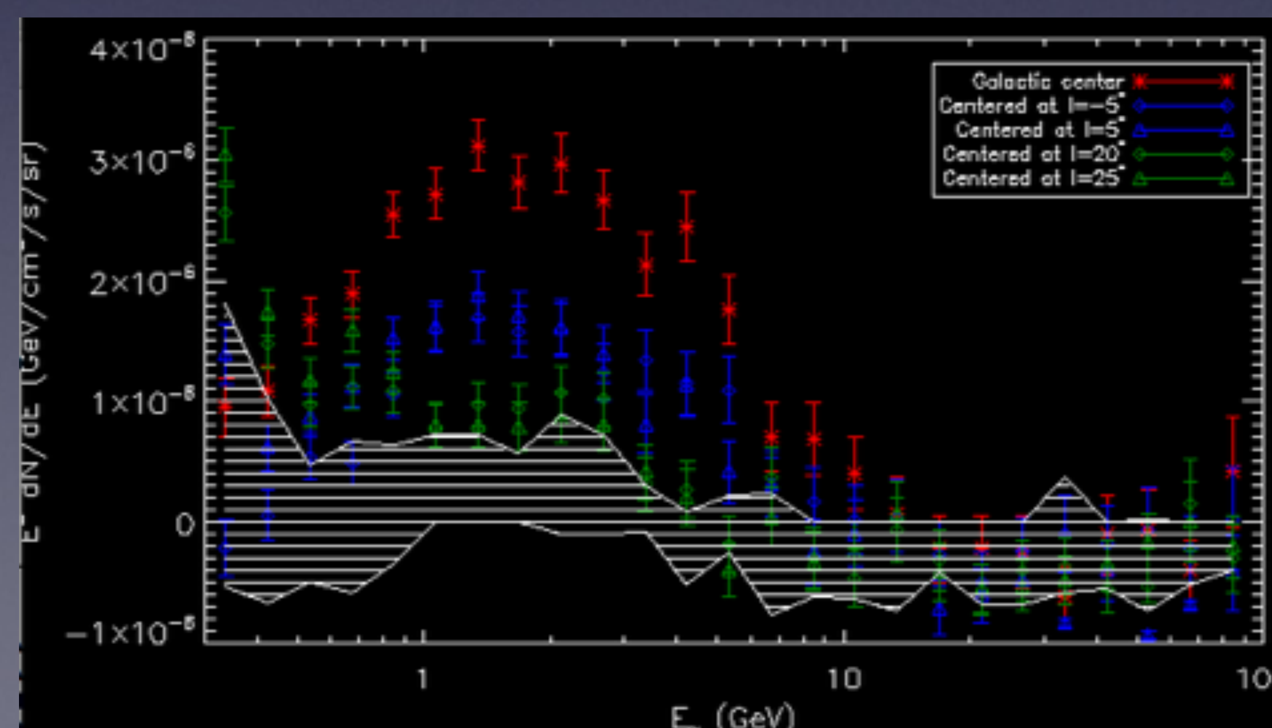

FIG. 7: The spectrum of the dark matter component derived in our Galactic Center analysis, for a template corresponding to an NFW halo profile with an inner slope of $\gamma = 1.2$ (left) or 1.3 (right), normalized to the flux at an angle of 5° from the Galactic Center. We caution that significant and difficult to estimate systematic uncertainties exist in this determination, especially at energies below ~1 GeV. Shown for comparison (solid line) is the spectrum predicted from a 35.25 GeV dark matter particle annihilating to $b\bar{b}$ with a cross section of $\sigma v = 2.15 \times 10^{-26}$ cm$^3$/s $\times [(0.3\,\mathrm{GeV/cm^3})/\rho_{\mathrm{local}}]^2$ (left) or $\sigma v = 1.0 \times 10^{-26}$ cm$^3$/s $\times [(0.3\,\mathrm{GeV/cm^3})/\rho_{\mathrm{local}}]^2$ (right). The dot-dash and dotted curves include an estimated contribution from bremsstrahlung, as shown in the right frame of Fig. 2.

- Preferred NFW slope is 1.1-1.2, a little shallower than inner Galaxy.
- Preferred DM models to fit data are similar.

# Residual disk emission

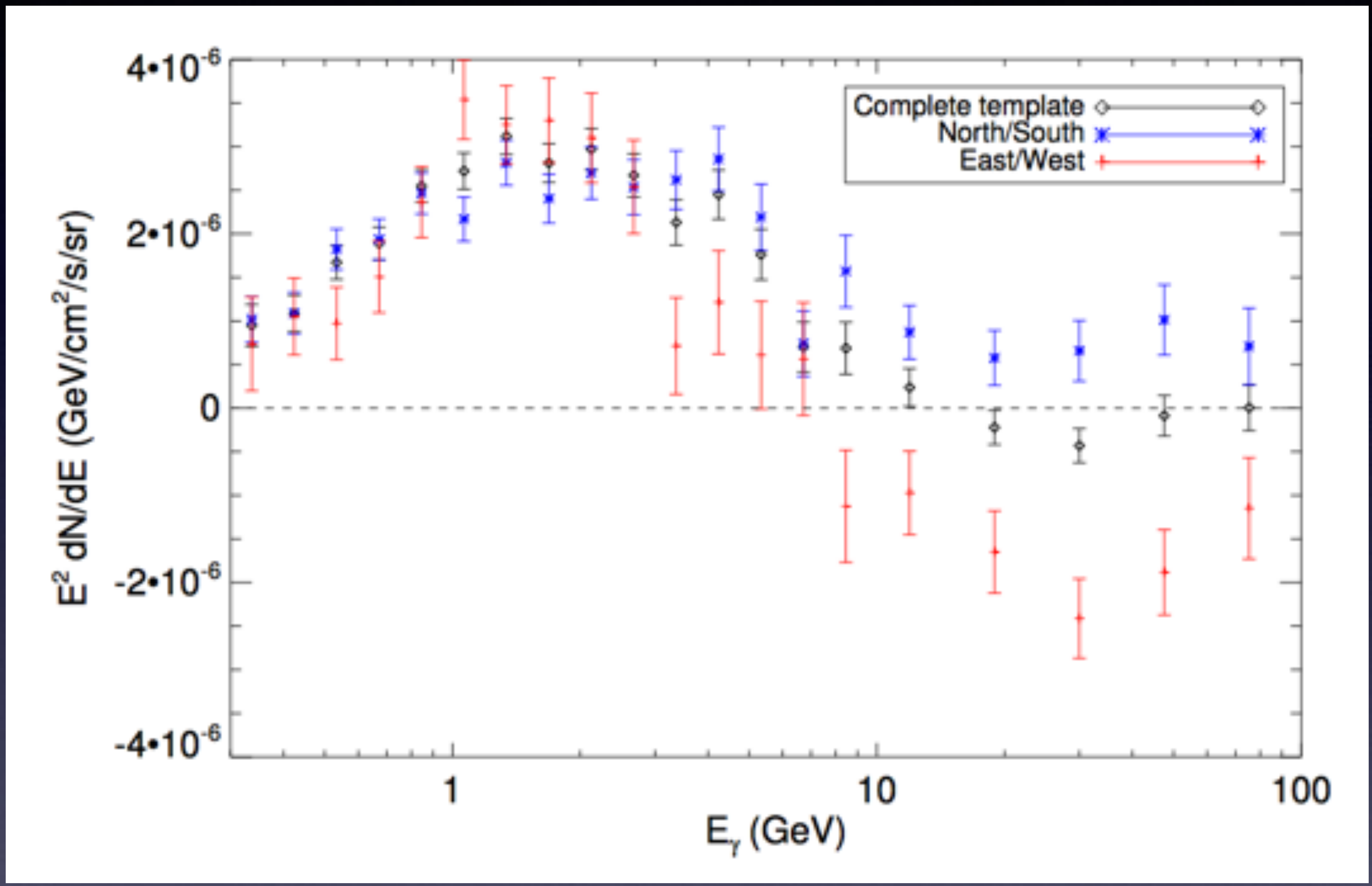
- Simple look-elsewhere test: do we see this spectral feature elsewhere along the plane?
- Shift DM-like template in 30 degree steps along the Galactic plane, check correlated emission. (Lower panel: 5 degree steps within the inner 60 degrees.)
- We find one example of a substantial signal with a soft spectrum unlike the bump (around l~20-30 degrees), the other sample points show very little emission.

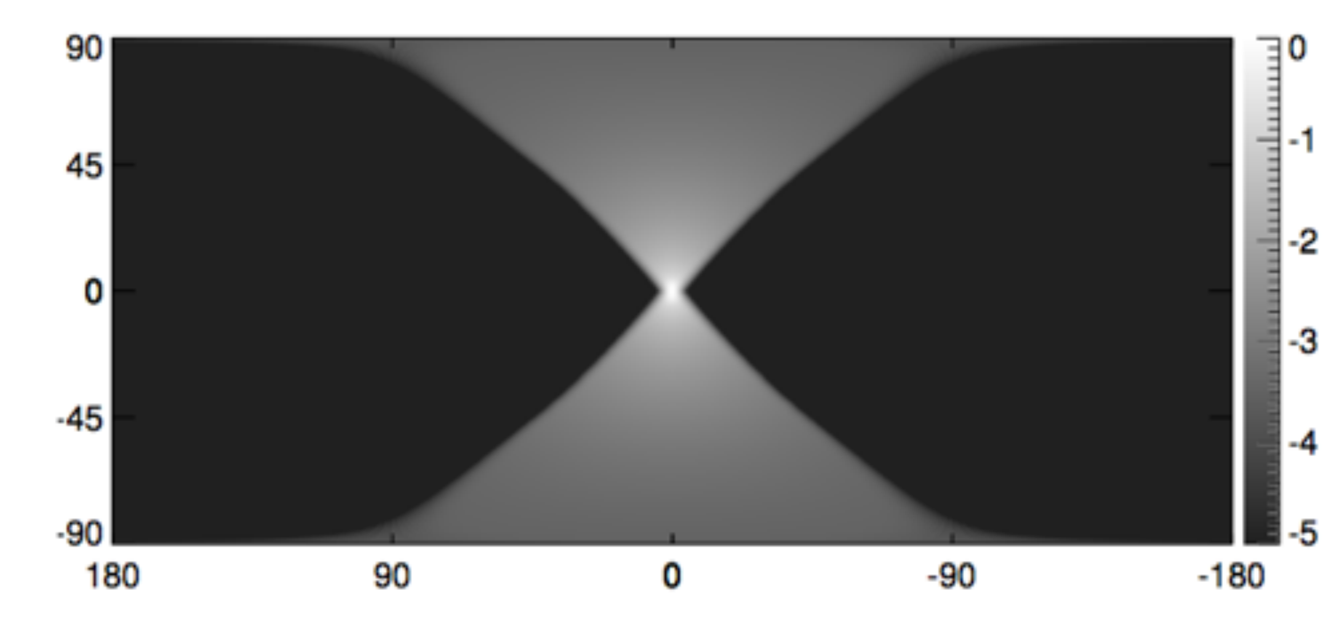


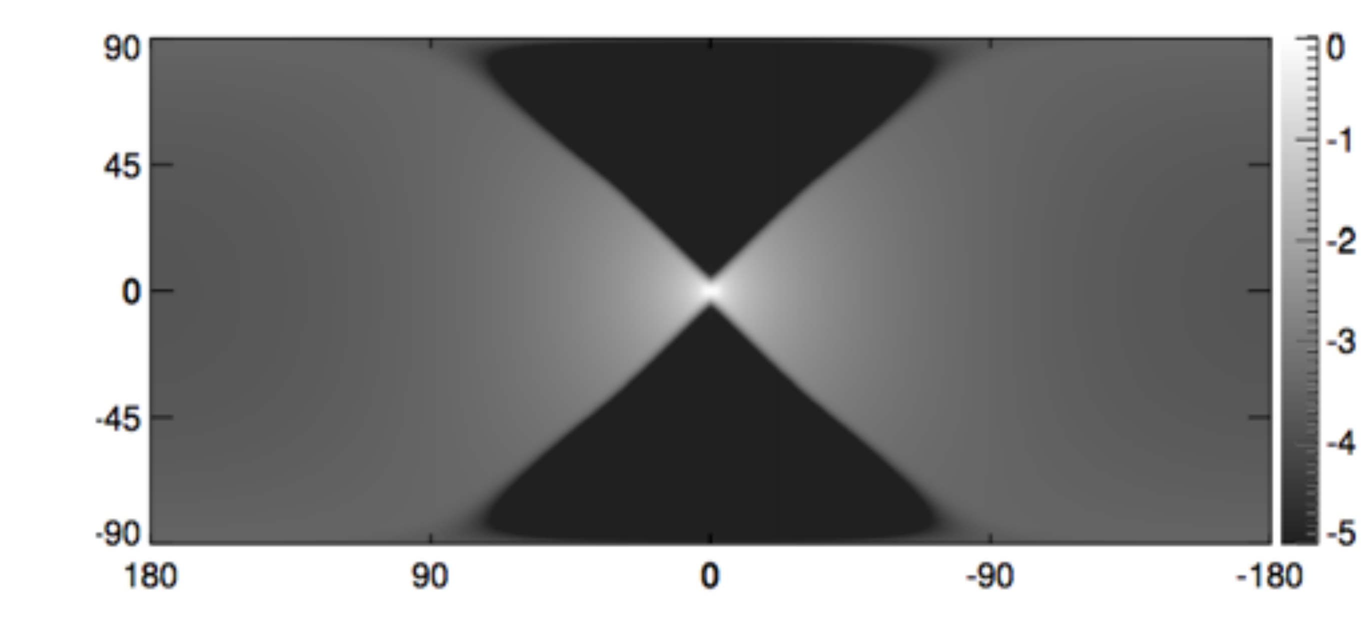



# Symmetry about the GC

- Previous attempts to test e.g. presence of signal outside Bubbles suffered from large contamination by Galactic plane spectrum.
- CTBCORE cuts alleviate this problem.



# Sphericity

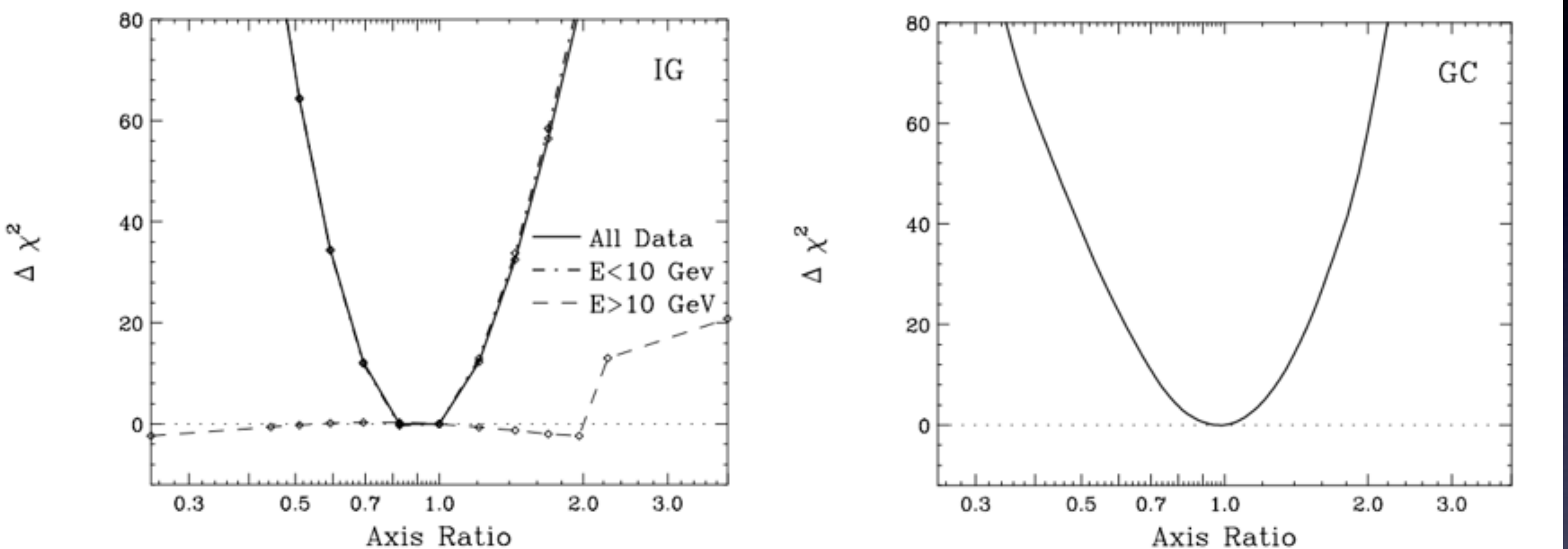



FIG. 10: The change in the quality of the fit, as performed in Sec. IV's Inner Galaxy analysis (left frame) and Sec. V's Galactic Center analysis (right frame), when breaking our assumption of spherical symmetry for the dark matter template. The axis ratio is defined such that values less than one are elongated along the Galactic Plane, whereas values greater than one are elongated with Galactic latitude. The fit strongly prefers a morphology for the anomalous component that is approximately spherically symmetric, with an axis ratio near unity.

- More generally, take NFW profile, stretch it along l or b. Test delta log likelihood for fit with stretched vs unstretched profile.
- In both IG and GC, can exclude axis ratio > 1.2 along plane, best-fit at axis ratio 1.

# Orientation & centering

- Some mild evidence for a preference for elongation (axis ratio ~1.3) along an axis rotated 35 degrees from the Galactic plane.
- Test of centering constrains center to be within 0.05° of Sgr A*.

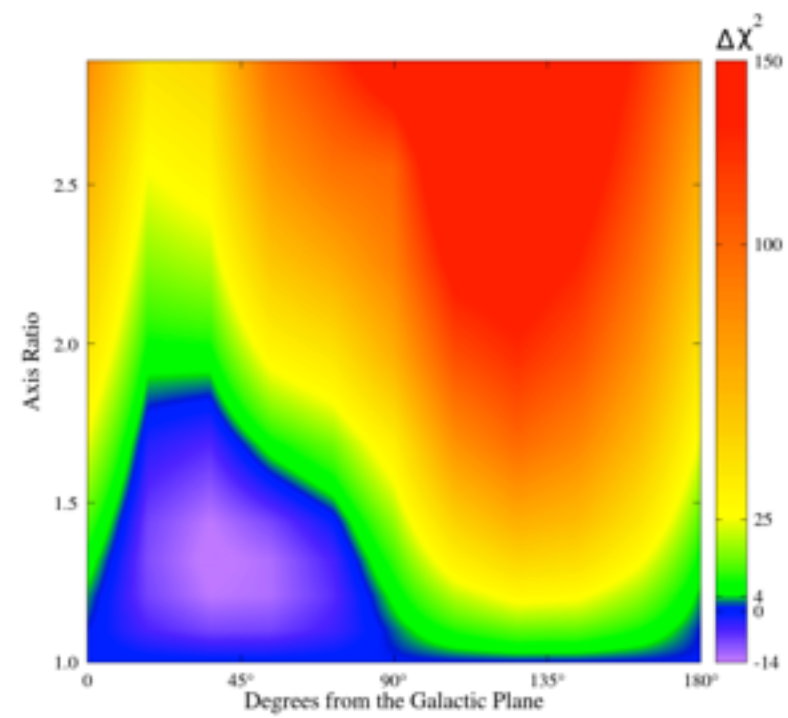



FIG. 11: The change in the quality of the fit in our Galactic Center analysis, for a dark matter template that is elongated along an arbitrary orientation (x-axis) and with an arbitrary axis ratio (y-axis). As shown in Fig. 10, the fit worsens if the this template is significantly stretched either along or perpendicular to the direction of the Galactic Plane (corresponding to 0° or 90° on the x-axis, respectively). A mild statistical preference, however, is found for a morphology with an axis ratio of ~1.3-1.4 elongated along an axis rotated ~35° counterclockwise from the Galactic Plane.

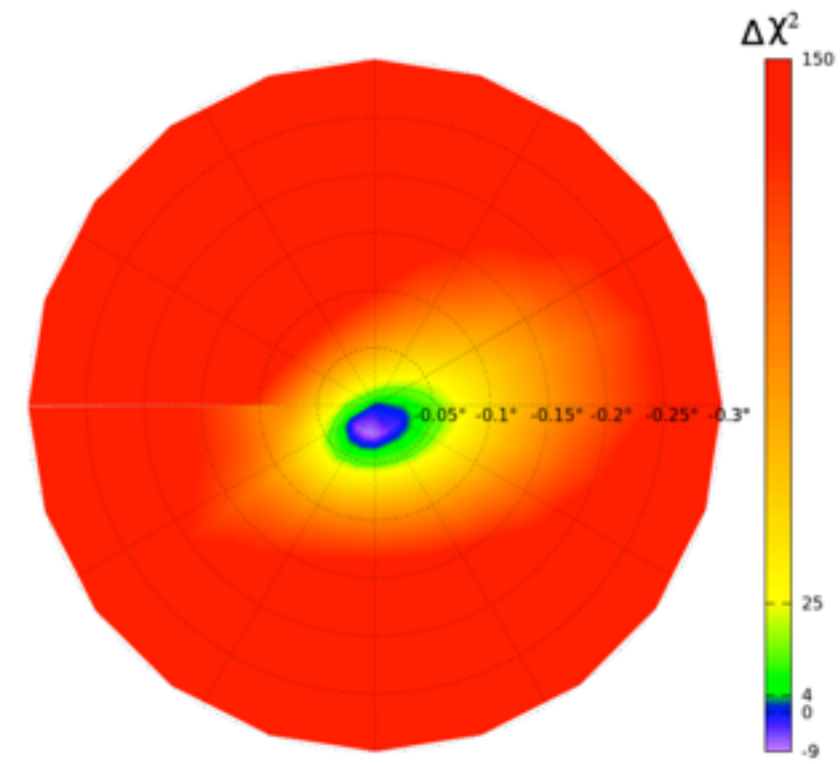



FIG. 12: To test whether the excess emission is centered around the dynamical center of the Milky Way (Sgr A*), we plot the $\Delta\chi^2$ of the fit found in our Galactic Center analysis, as a function of the center of our dark matter template. The fit clearly prefers this template to be centered within ~0.05° degrees of the location of Sgr A*.

# Extension of the excess

- Instead of putting in a DM-like template for the emission by hand, model the emission as a series of concentric rings with the same spectrum (extracted from the inner Galaxy analysis) and allow the amplitude of each ring to vary independently.
- The signal is detected out to 10 degrees from the Galactic center.
- Prefers a steeper profile than earlier fits, γ ~ 1.4 (could be due to steepening of slope at larger r, or diffuse background mis-subtraction).

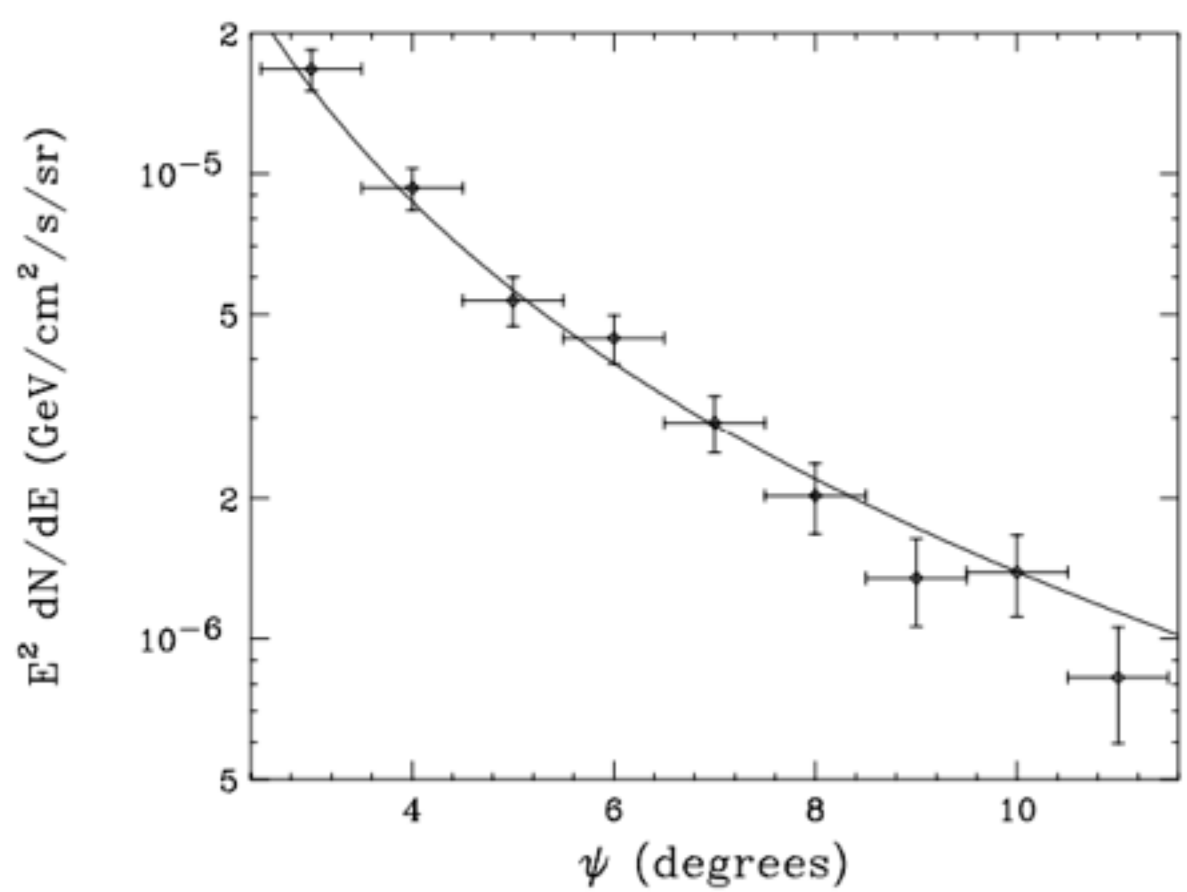
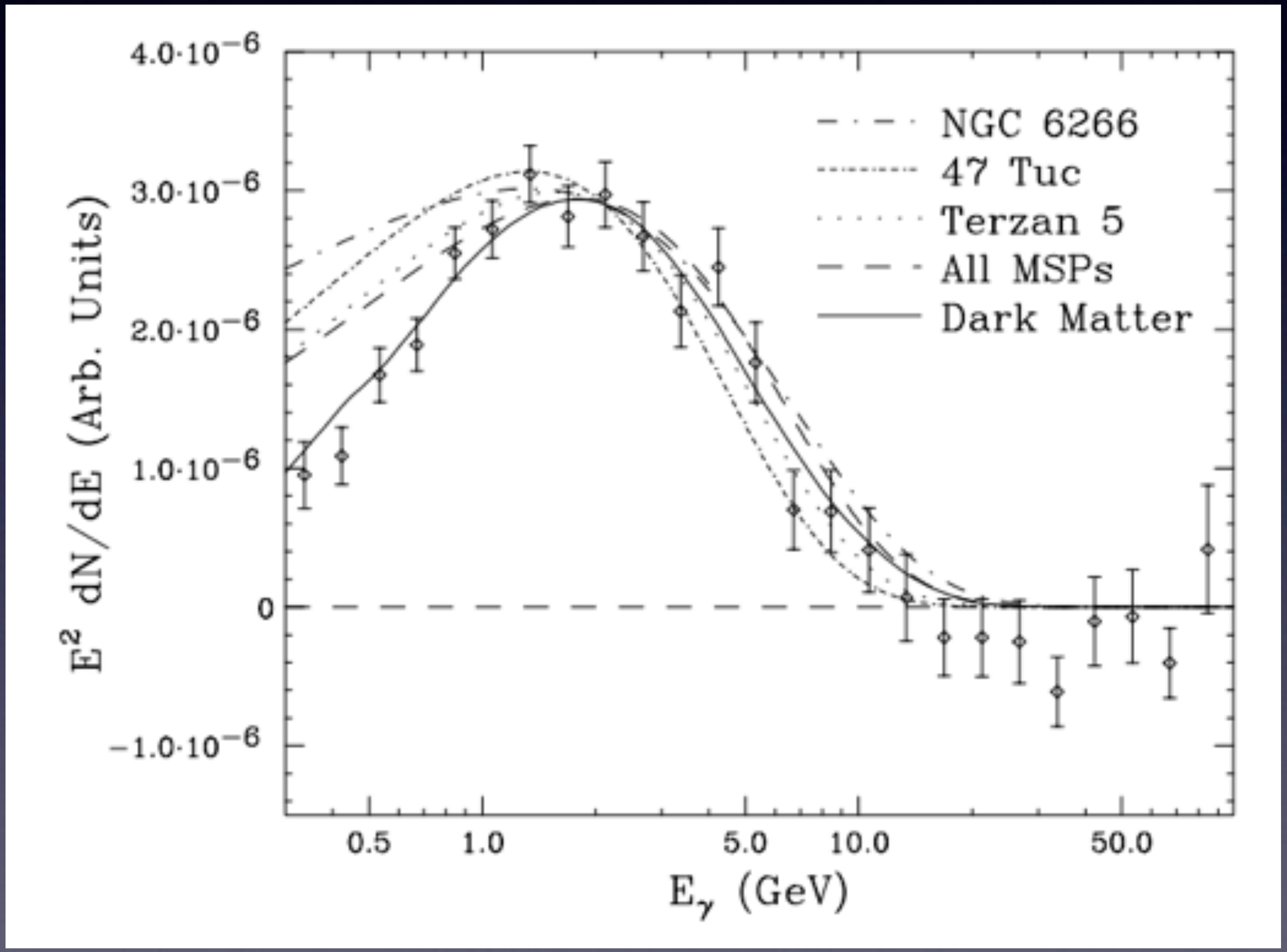


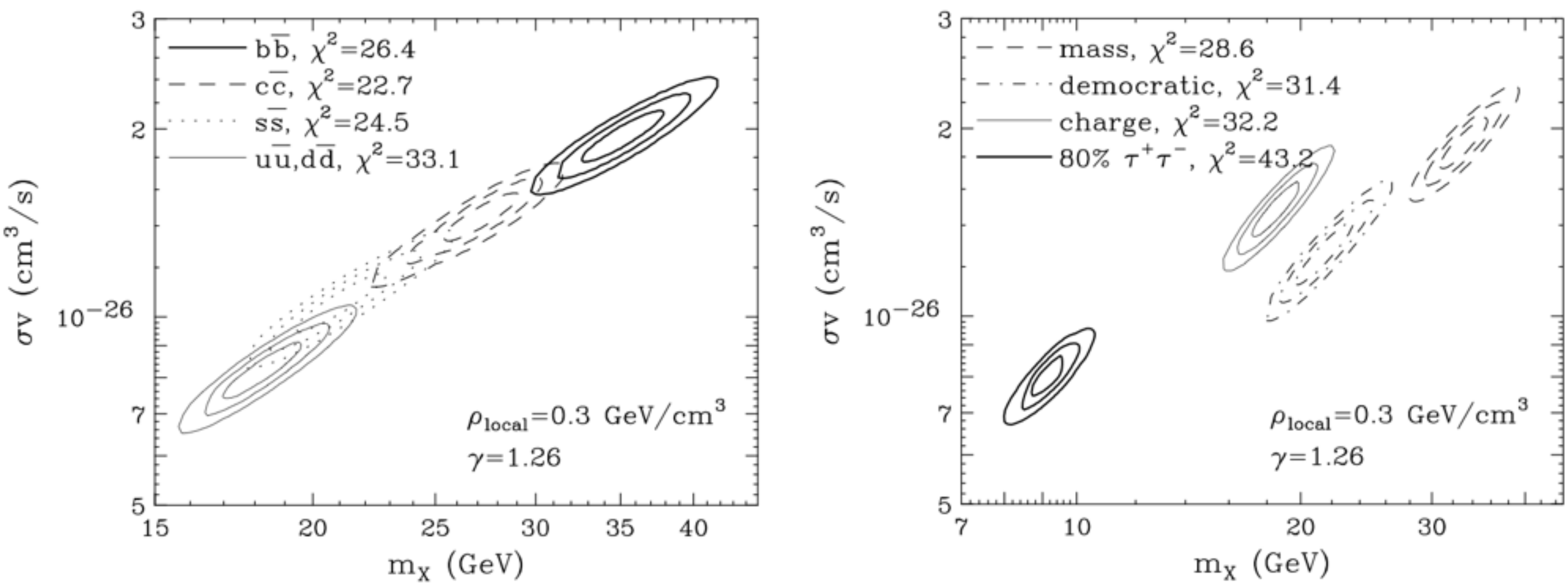

FIG. 13: To constrain the degree to which the gamma-ray excess is spatially extended, we have repeated our Inner Galaxy analysis, replacing the dark matter template with a series of concentric ring templates centered around the Galactic Center. The dark-matter-like emission is clearly and consistently present in each ring template out to ∼12°, beyond which systematic and statistical limitations make such determinations difficult. For comparison, we also show the predictions for a generalized NFW profile with $\gamma = 1.4$.

# What else could it be?

- The sphericity of the excess, improvement with angular resolution cuts and lack of correlation with the gas (see also 1312.6671, 1402.4090) disfavors a simple mismodeling of the diffuse emission.
- Most widely discussed candidate is millisecond pulsars - their observed gamma-ray spectrum cuts off at the right energy.
- Would need thousands of pulsars, each one too faint to be detected individually. (Requires an intrinsically fainter luminosity function than disk millisecond pulsars, 1305.0830.)
- Sphericity and extension of signal are challenges for this interpretation - can they be satisfied?

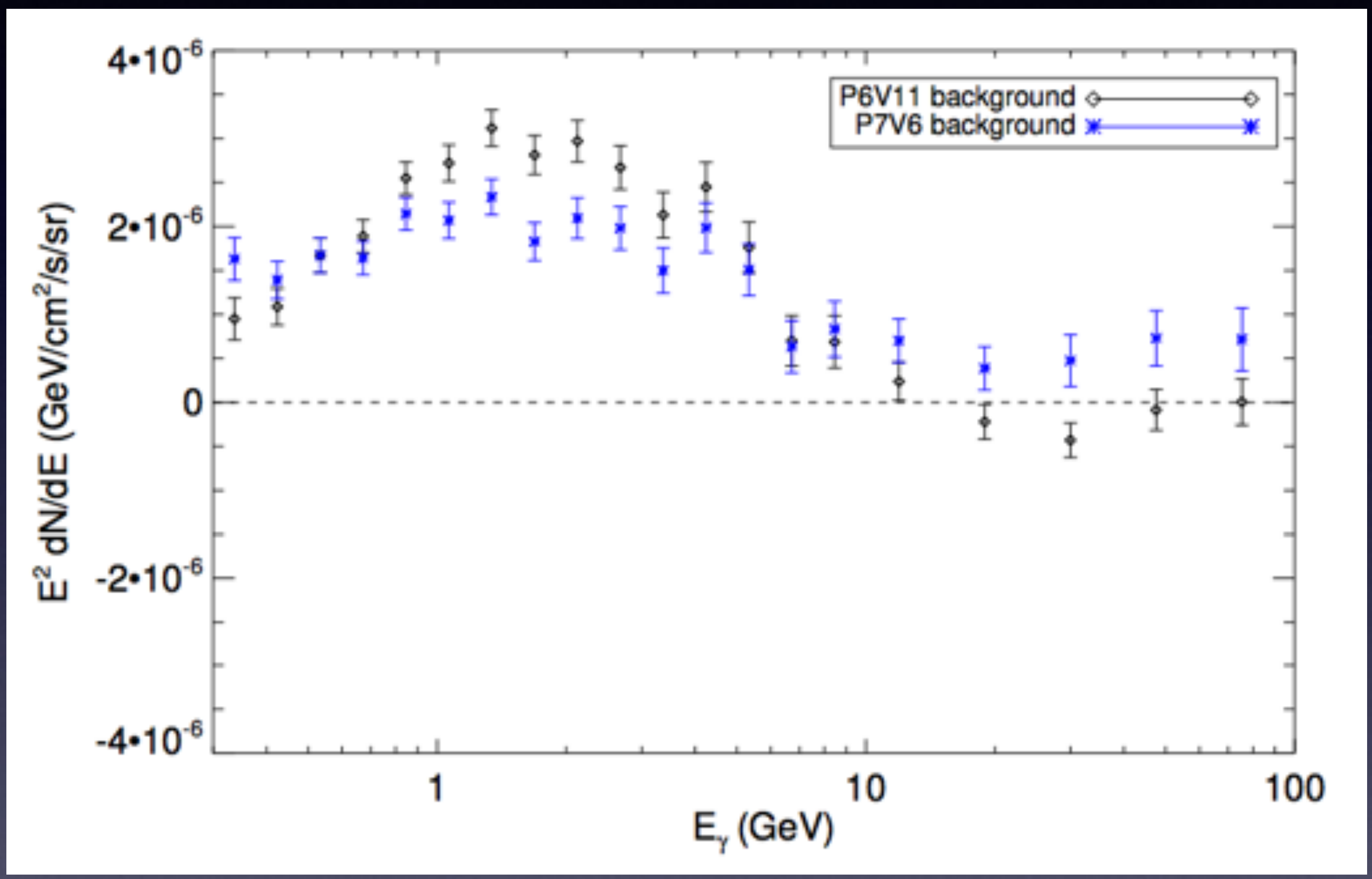


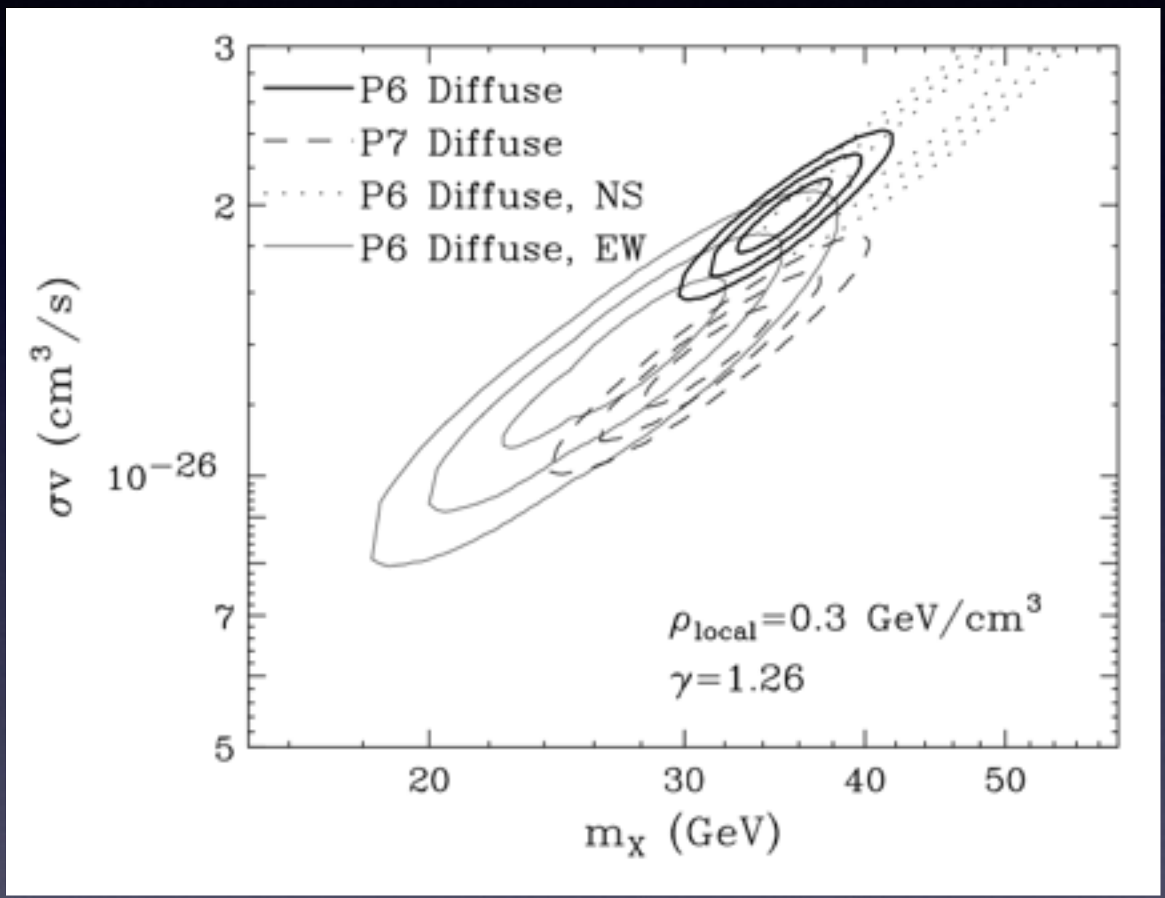
# DM analysis by annihilation final state




- Preferred cross section ~$10^{-26}$ cm$^3$/s, ~15-50 GeV DM annihilating to quarks or mixed final states.

# Systematic uncertainty from the diffuse background



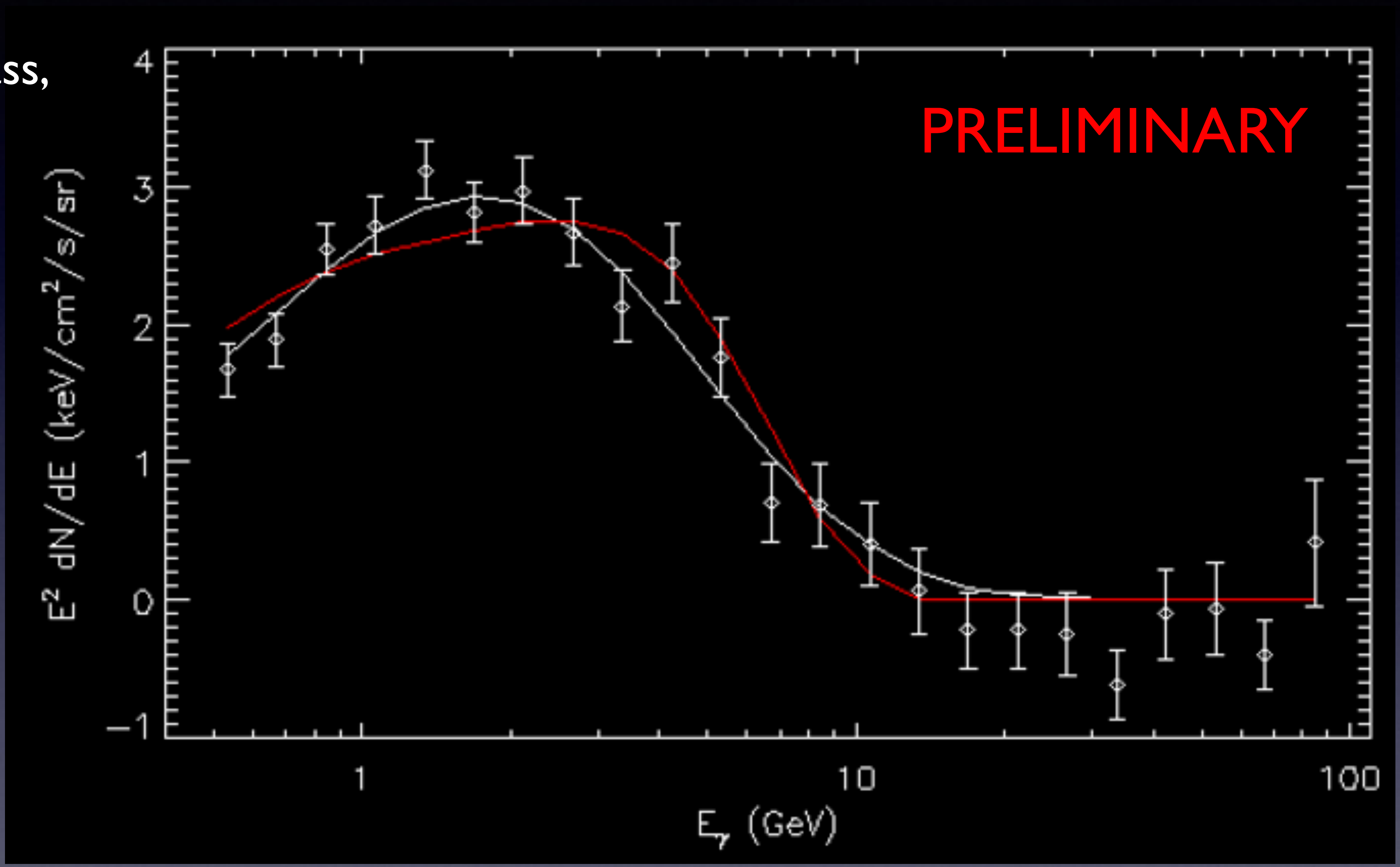

- Can try changing the diffuse model, and using the results from the "north/south" and "east/west" slicings shown earlier (which divide the signal template into regions lying mostly within the Fermi Bubbles and regions overlapping the Galactic plane).
- The resulting curves give some estimate of systematic uncertainties (although note our default model has a much better log likelihood than the alternative diffuse model).

# ~10 GeV DM?

Example: float cross section, mass, branching ratio to b's vs tau's

White curve: best fit, 100% to b's, 34.7 GeV, 2 x $10^{-26}$ $cm^3/s$, $\Delta\chi^2$ = 23.4 over 23 error bars (10.7 over 13 error bars below 10 GeV)

Red curve: 32% to b's, 68% to taus, 11.3 GeV, 1 x $10^{-26}$ $cm^3/s$, $\Delta\chi^2$ = 34.7 over 23 error bars (22.7 over 13 error bars below 10 GeV)




- There are degeneracies between the DM mass, annihilation cross section and branching ratio to quarks vs tau-rich final states - lower DM masses require a lower cross section and harder spectrum, favoring a higher branching ratio to taus vs quarks.
- Our fit prefers slightly heavier DM annihilating to quarks, but degeneracies in the spectrum mean the preferred branching ratio is quite sensitive to the modeling of the diffuse background.

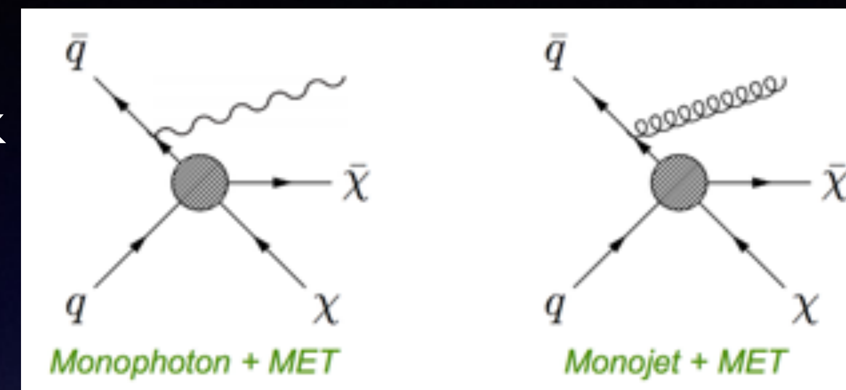
# Model-building challenges

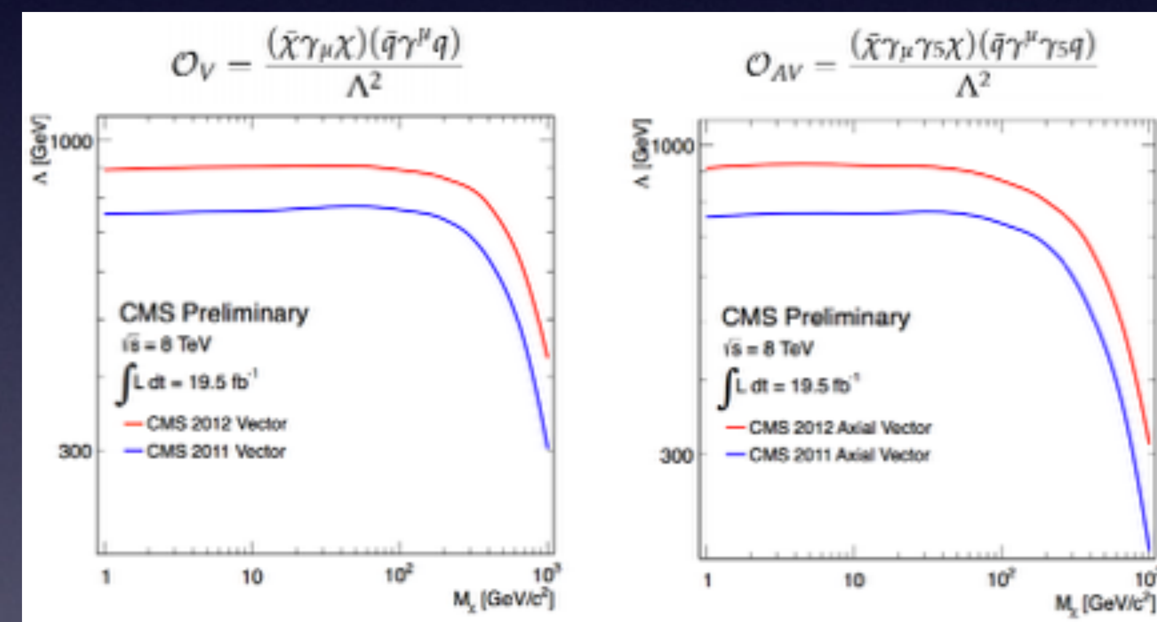
- Direct detection is very sensitive in this mass range, why haven't we seen it?
  - Annihilation may be resonant
  - Direct detection may be dominantly spin-dependent or otherwise suppressed (although in many models, upcoming direct detection experiments have sensitivity anyway)
  - Annihilation may be 2->4 and the intermediate particles may have small couplings to the SM
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values
  - Nonetheless, substantial classes of simplified models can be ruled out.

# Collider searches

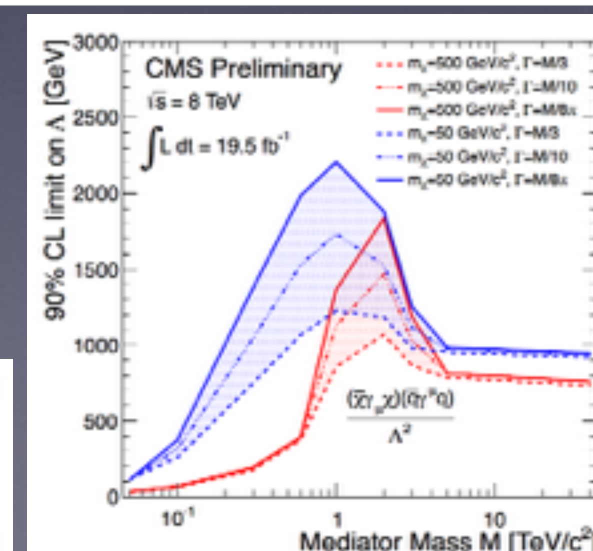
- Whatever the dark matter is, if it couples to Standard Model particles, it could potentially be produced at the LHC and appear as missing energy.
- (somewhat) model-independent searches, look for a photon or jet recoiling against missing energy.
- Can place model-independent bounds if we assume a heavy mediator coupling the dark matter to the Standard Model (integrating out the mediator).
- Beyond this effective field theory approach, we can constrain "simplified models" where the DM couples to a scalar/vector/fermionic mediator.

Taken from Feb 2014 talk by Steven Worm here at Fermilab




CMS EXO-12-048



# Effective field theory…

(a) Operators for Dirac fermion DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| D1 | $\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$ | 7 | SI |
| D2 | $\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$ | 7 | N/A |
| D3 | $\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| D4 | $\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| D5 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | 6 | SI |
| D6 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | 6 | N/A |
| D7 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | N/A |
| D8 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | SD |
| D9 | $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | 6 | SD |
| D10 | $\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$ | 6 | N/A |
| D11 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | SI |
| D12 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | N/A |
| D13 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |
| D14 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |

(b) Operators for Complex scalar DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| C1 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$ | 6 | SI |
| C2 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$ | 6 | N/A |
| C3 | $\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$ | 6 | SI |
| C4 | $\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$ | 6 | N/A |
| C5 | $\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$ | 6 | SI |
| C6 | $\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 6 | N/A |

Study couplings to hadronic states only

Alves et al
1403.5027

# Effective field theory…

(a) Operators for Dirac fermion DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| | | | |
| D2 | $\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$ | 7 | N/A |
| D3 | $\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| D4 | $\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| | | | |
| D6 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | 6 | N/A |
| D7 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | N/A |
| D8 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | SD |
| D9 | $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | 6 | SD |
| D10 | $\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$ | 6 | N/A |
| | | | |
| D12 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | N/A |
| D13 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |
| D14 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |

(b) Operators for Complex scalar DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| | | | |
| C2 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$ | 6 | N/A |
| | | | |
| C4 | $\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$ | 6 | N/A |
| | | | |
| C6 | $\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 6 | N/A |

ruled out by DD

Study couplings to
hadronic states only

Alves et al
1403.5027

# Effective field theory…

(a) Operators for Dirac fermion DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| D2 | $\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$ | 7 | N/A |
| D4 | $\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| D7 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | N/A |
| D10 | $\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$ | 6 | N/A |
| D12 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$ | 7 | N/A |
| D14 | $\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 7 | N/A |

(b) Operators for Complex scalar DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| C2 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$ | 6 | N/A |
| C6 | $\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 6 | N/A |

ruled out by DD

cannot fit signal

Study couplings to hadronic states only

Alves et al 1403.5027

# Effective field theory…

(a) Operators for Dirac fermion DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| D2 | $\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$ | 7 | N/A |
| D4 | $\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$ | 7 | N/A |
| D7 | $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$ | 6 | N/A |

(b) Operators for Complex scalar DM

| Name | Operator | Dimension | SI/SD |
|---|---|---|---|
| C2 | $\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$ | 6 | N/A |
| C6 | $\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$ | 6 | N/A |

ruled out by DD

cannot fit signal

ruled out by LHC

Study couplings to
hadronic states only

Alves et al
1403.5027

# … and beyond

Berlin et al 1404.0022 (simplified models)

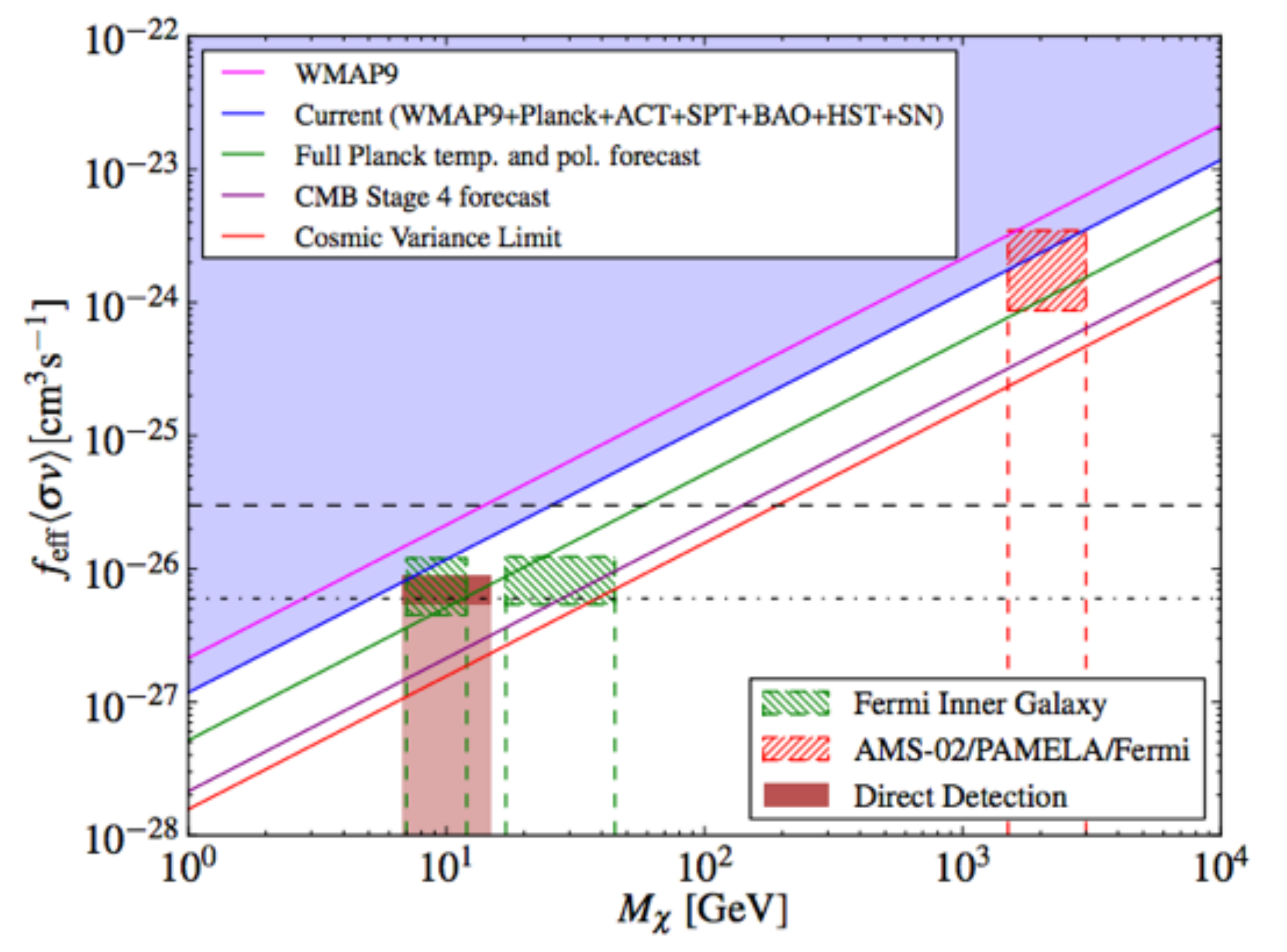
| *Model Number* | *DM* | *Mediator* | *Interactions* | Elastic Scattering | Near Future Reach? Direct | LHC |
|---|---|---|---|---|---|---|
| 1 | Dirac Fermion | Spin-0 | $\bar{\chi}\gamma^5\chi$, $\bar{f}f$ | $\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar) | No | Maybe |
| 1 | Majorana Fermion | Spin-0 | $\bar{\chi}\gamma^5\chi$, $\bar{f}f$ | $\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar) | No | Maybe |
| 2 | Dirac Fermion | Spin-0 | $\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$ | Never | Maybe |
| 2 | Majorana Fermion | Spin-0 | $\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$ | Never | Maybe |
| 3 | Dirac Fermion | Spin-1 | $\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$ | $\sigma_{\rm SI} \sim$ loop (vector) | Yes | Maybe |
| 4 | Dirac Fermion | Spin-1 | $\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$ | $\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$ | Never | Maybe |
| 5 | Dirac Fermion | Spin-1 | $\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$ | $\sigma_{\rm SD} \sim 1$ | Yes | Maybe |
| 5 | Majorana Fermion | Spin-1 | $\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$ | $\sigma_{\rm SD} \sim 1$ | Yes | Maybe |
| 6 | Complex Scalar | Spin-0 | $\phi^\dagger\phi$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q/2m_n)^2$ | No | Maybe |
| 6 | Real Scalar | Spin-0 | $\phi^2$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q/2m_n)^2$ | No | Maybe |
| 6 | Complex Vector | Spin-0 | $B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q/2m_n)^2$ | No | Maybe |
| 6 | Real Vector | Spin-0 | $B_\mu B^\mu$, $\bar{f}\gamma^5 f$ | $\sigma_{\rm SD} \sim (q/2m_n)^2$ | No | Maybe |
| 7 | Dirac Fermion | Spin-0 ($t$-ch.) | $\bar{\chi}(1 \pm \gamma^5)b$ | $\sigma_{\rm SI} \sim$ loop (vector) | Yes | Yes |
| 7 | Dirac Fermion | Spin-1 ($t$-ch.) | $\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$ | $\sigma_{\rm SI} \sim$ loop (vector) | Yes | Yes |
| 8 | Complex Vector | Spin-1/2 ($t$-ch.) | $X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$ | $\sigma_{\rm SI} \sim$ loop (vector) | Yes | Yes |
| 8 | Real Vector | Spin-1/2 ($t$-ch.) | $X_\mu\gamma^\mu(1 \pm \gamma^5)b$ | $\sigma_{\rm SI} \sim$ loop (vector) | Yes | Yes |

# Other indirect searches

- Best way to exclude astrophysical explanations would be an independent signal. Indirect searches provide the most model-independent probes. This signal is not currently constrained by any indirect search, but some are close.

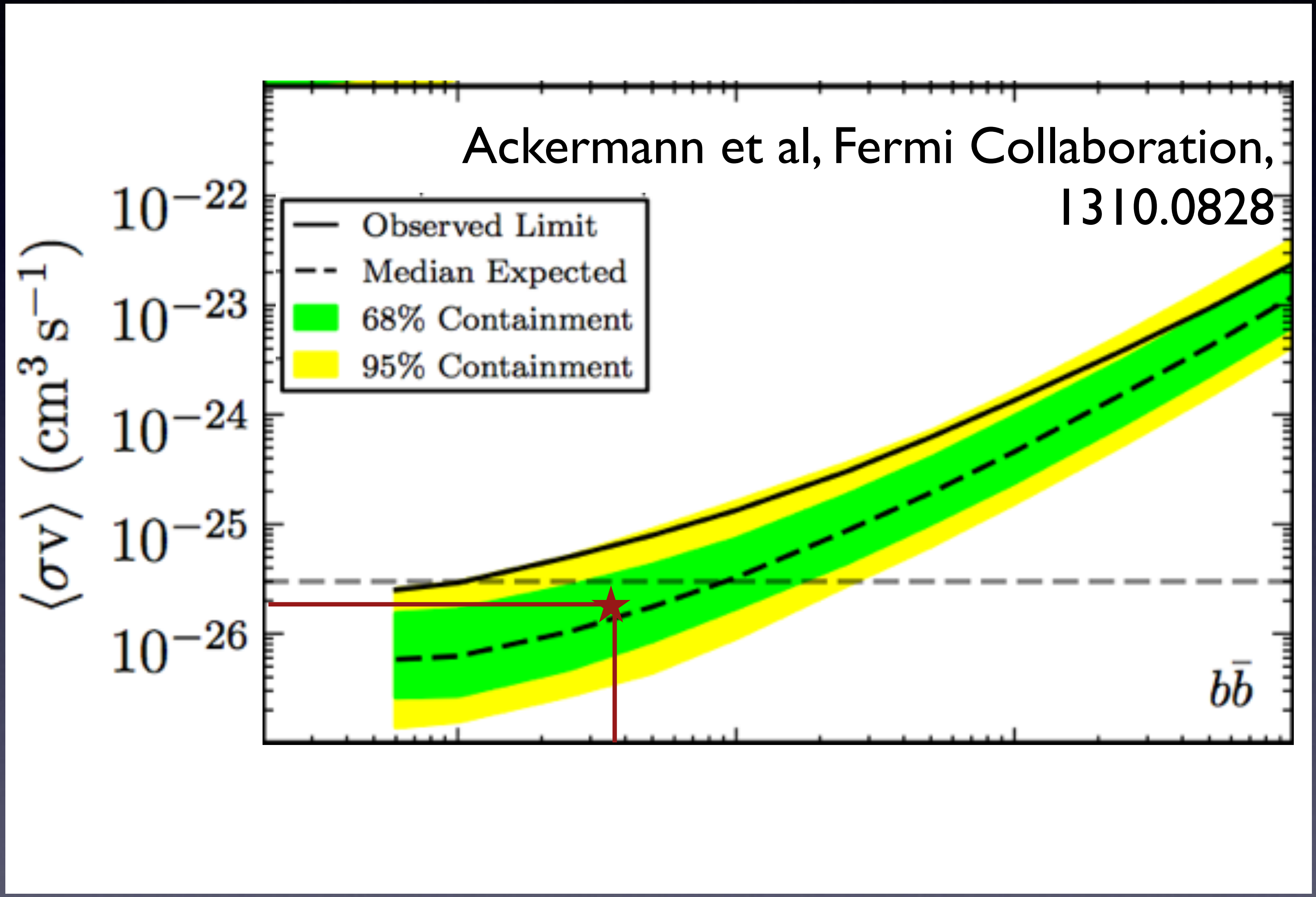
Madhavacheril, Sehgal & TRS 1310.3815

- CMB: when polarization data is released, Planck will have sensitivity to 10 GeV thermal relic DM independent of final state (via changes to ionization history from annihilation). Not yet sensitive to ~30-40 GeV DM annihilating to quarks - CMB Stage IV experiments will probe this region.



# Dwarf galaxies

- There is an existing search by the Fermi Collaboration for gamma-rays in the Milky Way dwarf spheroidals from DM annihilation.
- Current bounds are within a factor of a few of this signal - and actually see a small excess, although not statistically significant.



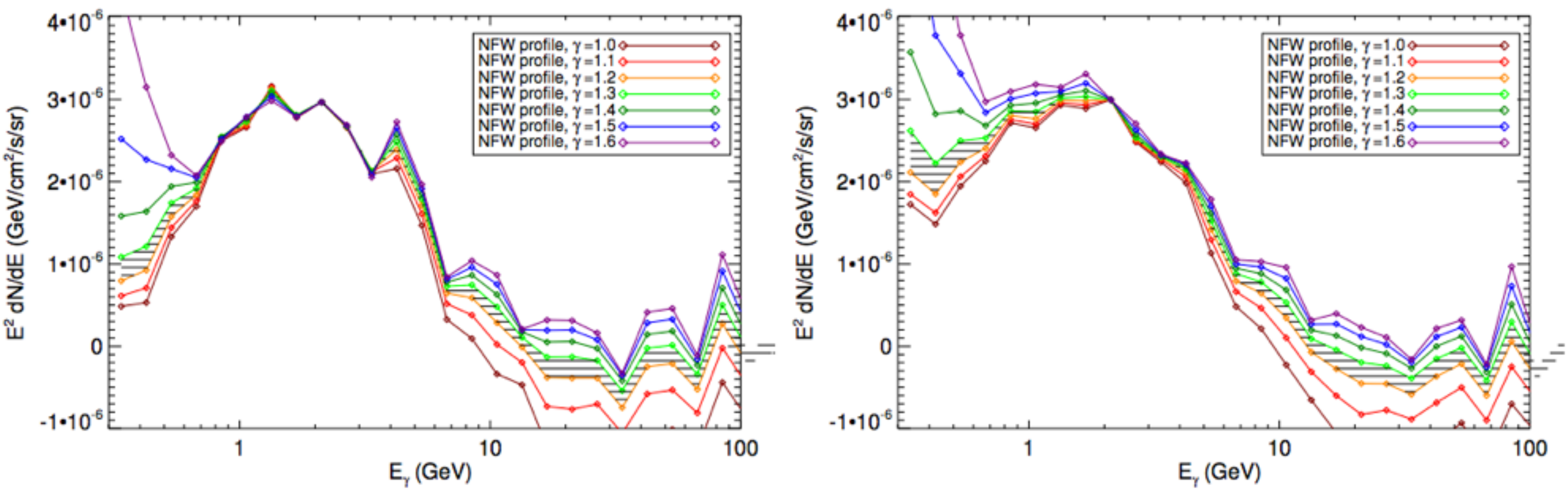

- Future dwarf sensitivity depends on whether more dwarfs are found - unfortunately no good news from PANSTARRS on this front.

# The claim

- After fitting for modeled backgrounds, we detect a broad-spectrum gamma-ray excess in the Galactic Center and inner Galaxy, with the following properties:
  - Peaking at ~1-2 GeV in $E^2 dN/dE$, consistent morphology between 0.5 GeV and 10 GeV.
  - Consistent with spherical symmetry about the GC; we can exclude axis ratios larger than ~1.2 along the Galactic plane. (Mild hint of extension along an axis 35 degrees off the plane, with axis ratio ~1.3).
  - When modeled by a squared, projected NFW profile, prefers a density profile with small-r power-law slope ~1.1-1.2 in the Galactic Center analysis, 1.2-1.3 in the inner Galaxy analysis (hints of steepening at larger radii).
  - Centered on Sgr A* to within 0.05 degrees.
  - Detected out to 10 degrees from the GC.
  - Spectrum well described by 20-50 GeV DM annihilating to (mostly) quarks with a ~thermal relic annihilation cross section.

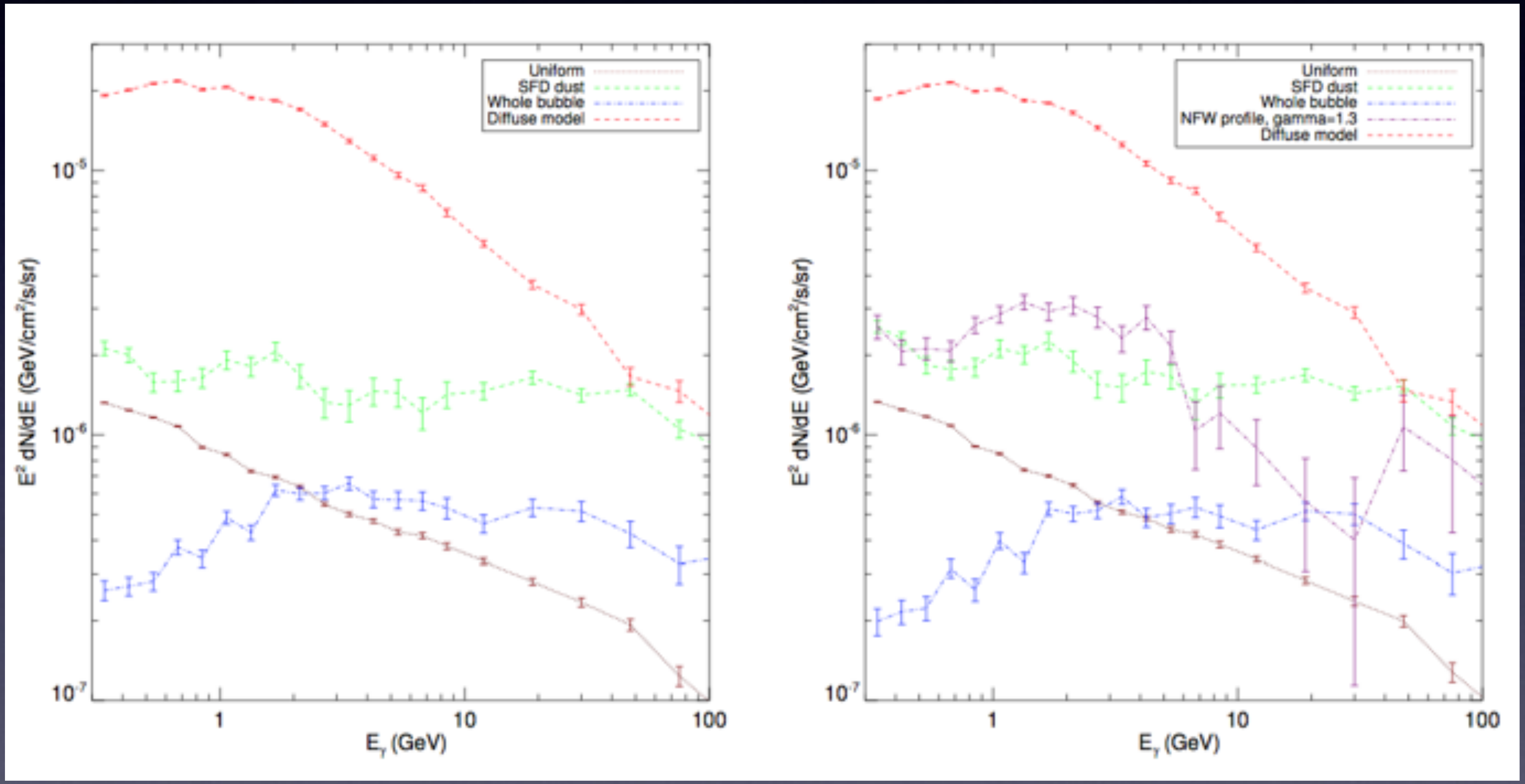
# BONUS SLIDES

# Dependence of spectrum on morphology



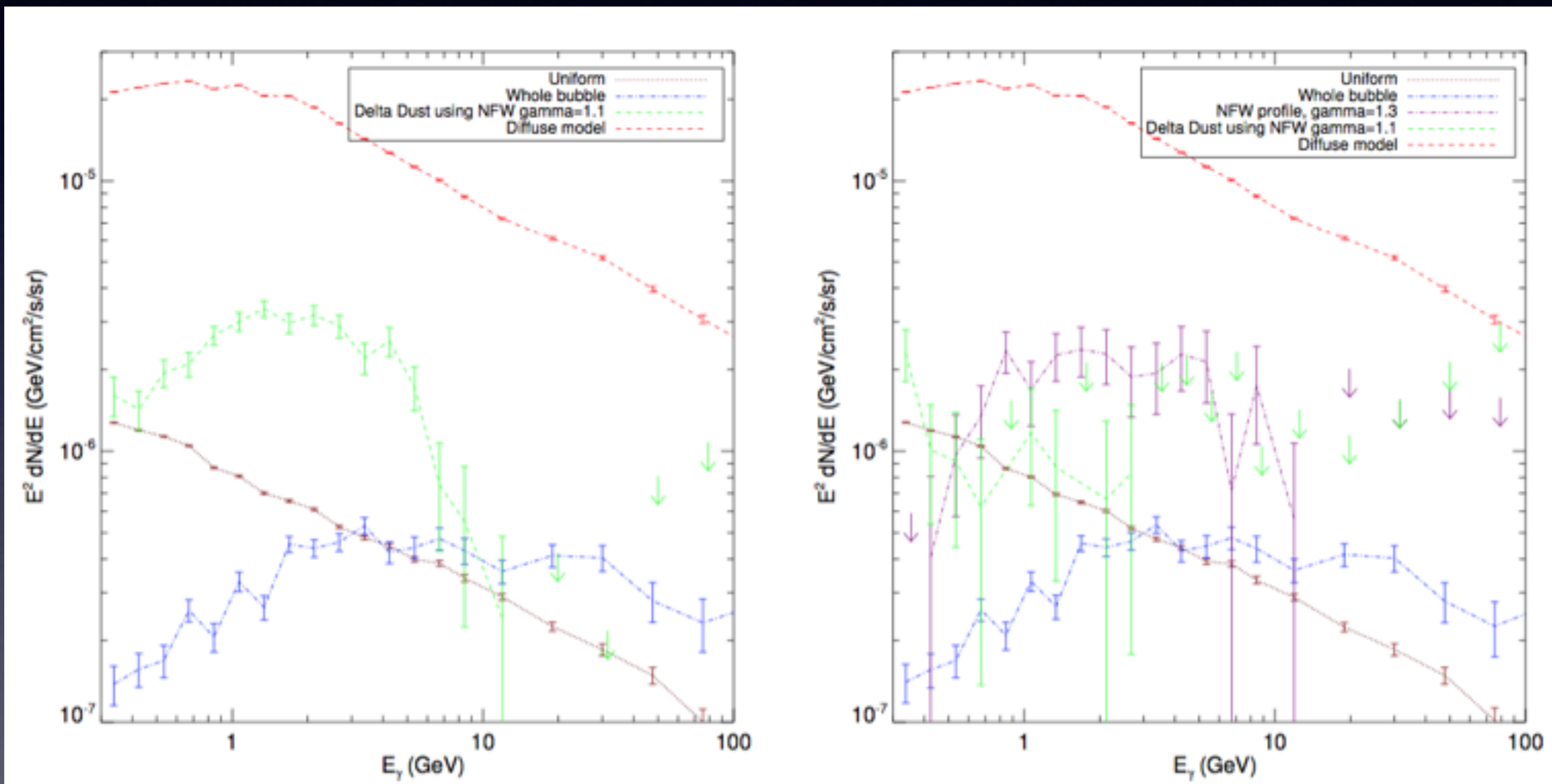

- Above ~600 MeV, even putting in quite a "wrong" spatial morphology (much steeper or shallower than the best-fit value) does not significantly change the reconstructed spectrum.
- Left panel: with CTBCORE cut, right panel: before CTBCORE cut.

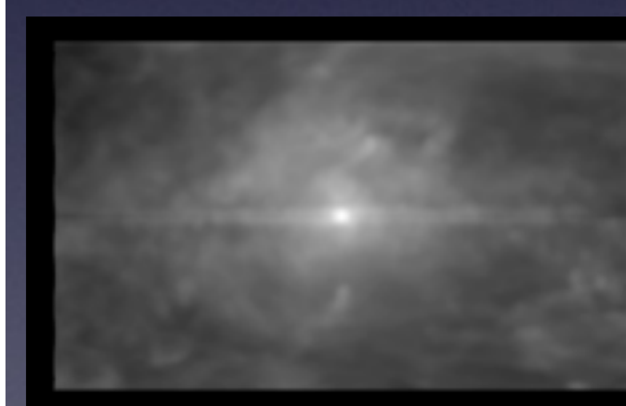
# Is the signal correlated with the gas?




- First test: add another template for the gas (traced by the dust) in addition to the Fermi diffuse model.
- Fit still strongly prefers DM-like template, although finds a non-negligible coefficient for the extra gas component.

# Is the signal correlated with the gas? (II)



- Modulate the dust map to try to make it look as DM-like as possible - stretch to achieve approximate spherical symmetry, modulate to give correct slope toward the inner Galaxy.
- Fit will correlate the bump with resulting template, but still prefers smooth DM-like template if allowed.

# A simple model for Galactic gamma rays

Good maps!

:-)

Roughly constant across the Galaxy; assume constant

gas density x cosmic ray proton density

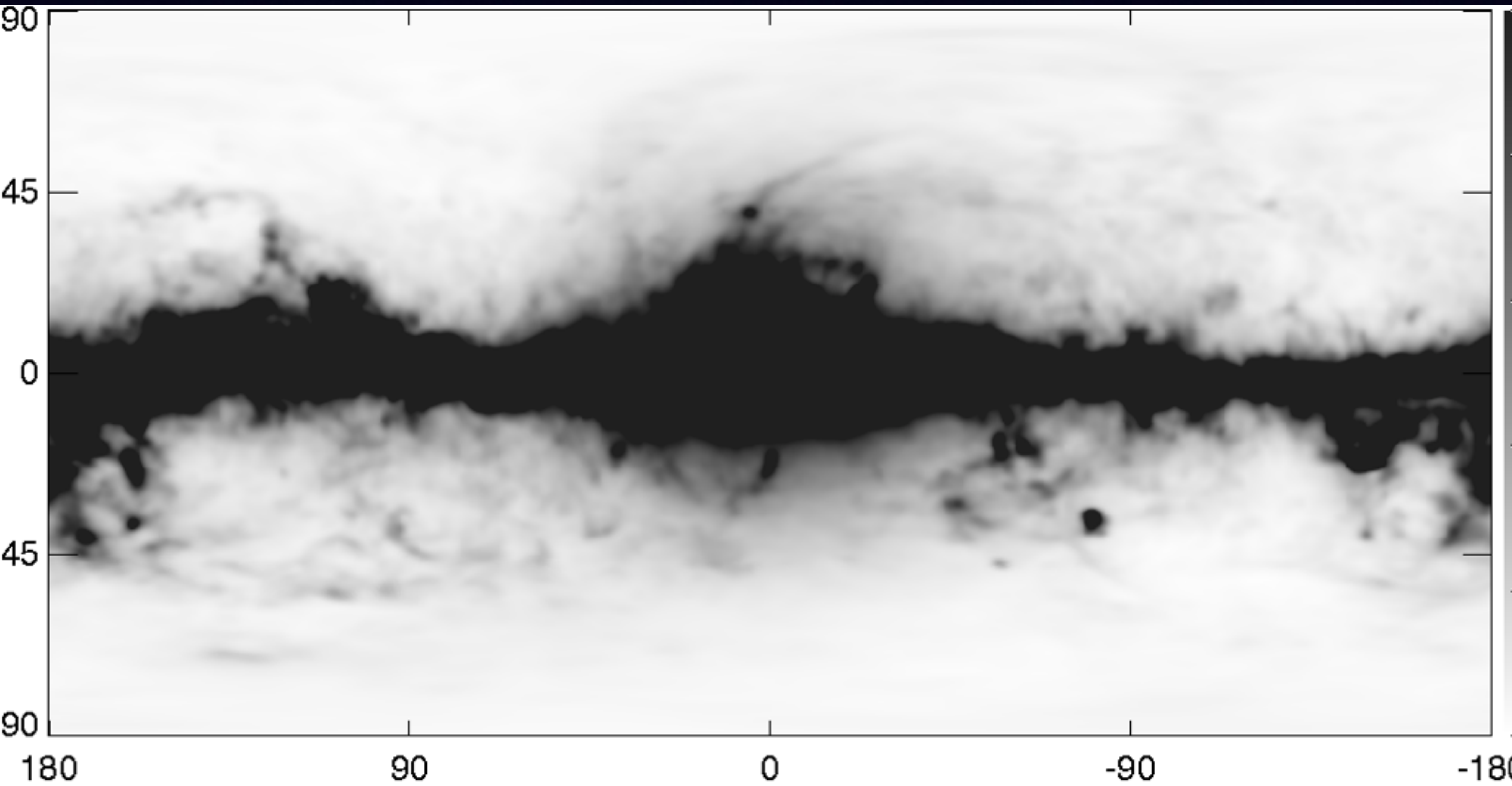
+ gas density x cosmic ray electron density

Always subdominant; neglect

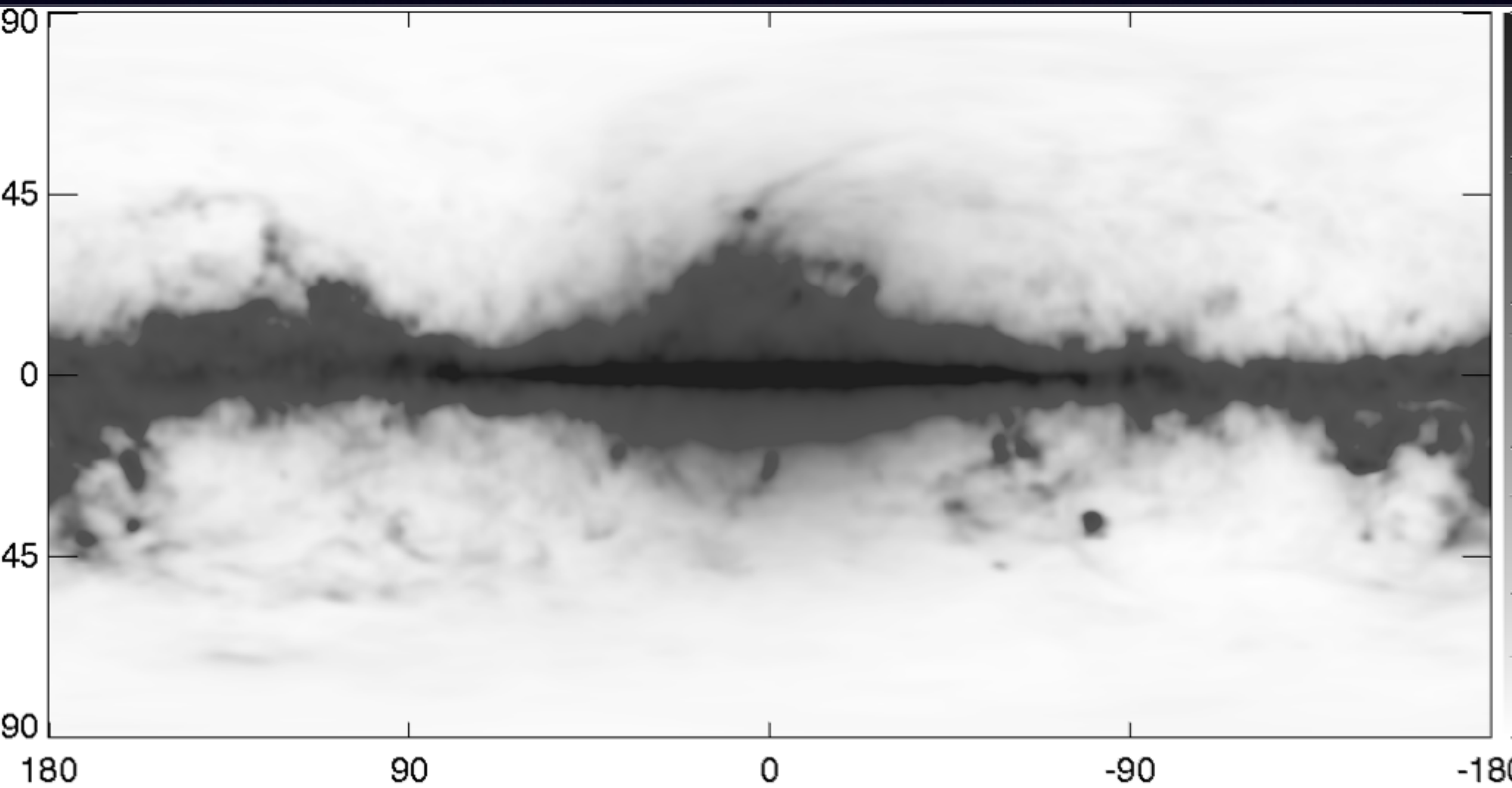
+ photon density x cosmic ray electron density

Should follow disk, where stars + supernovae are concentrated - put in some simple disk-like profile

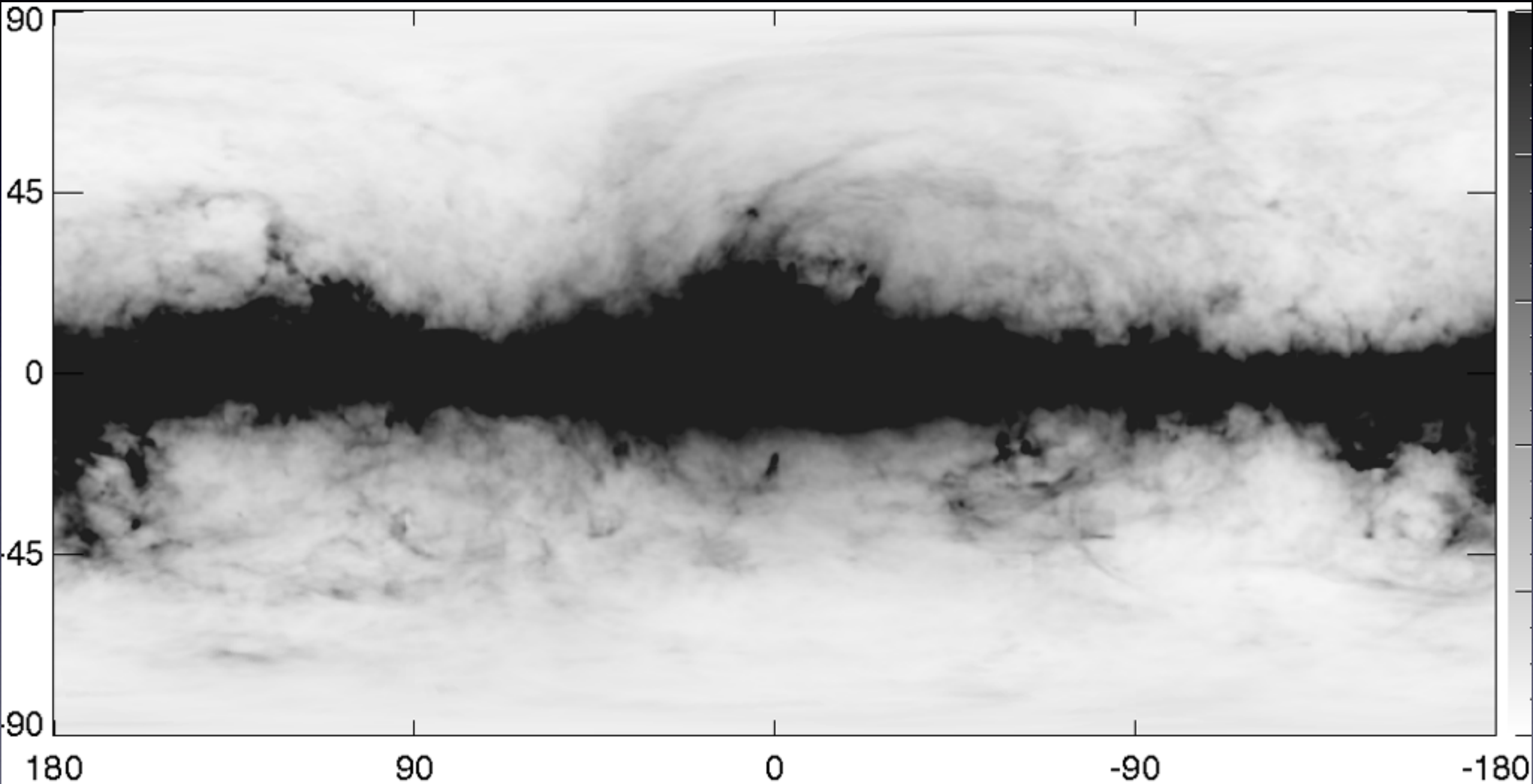
# Simple model of the (expected) gamma rays



# Simple model of the (expected) gamma rays

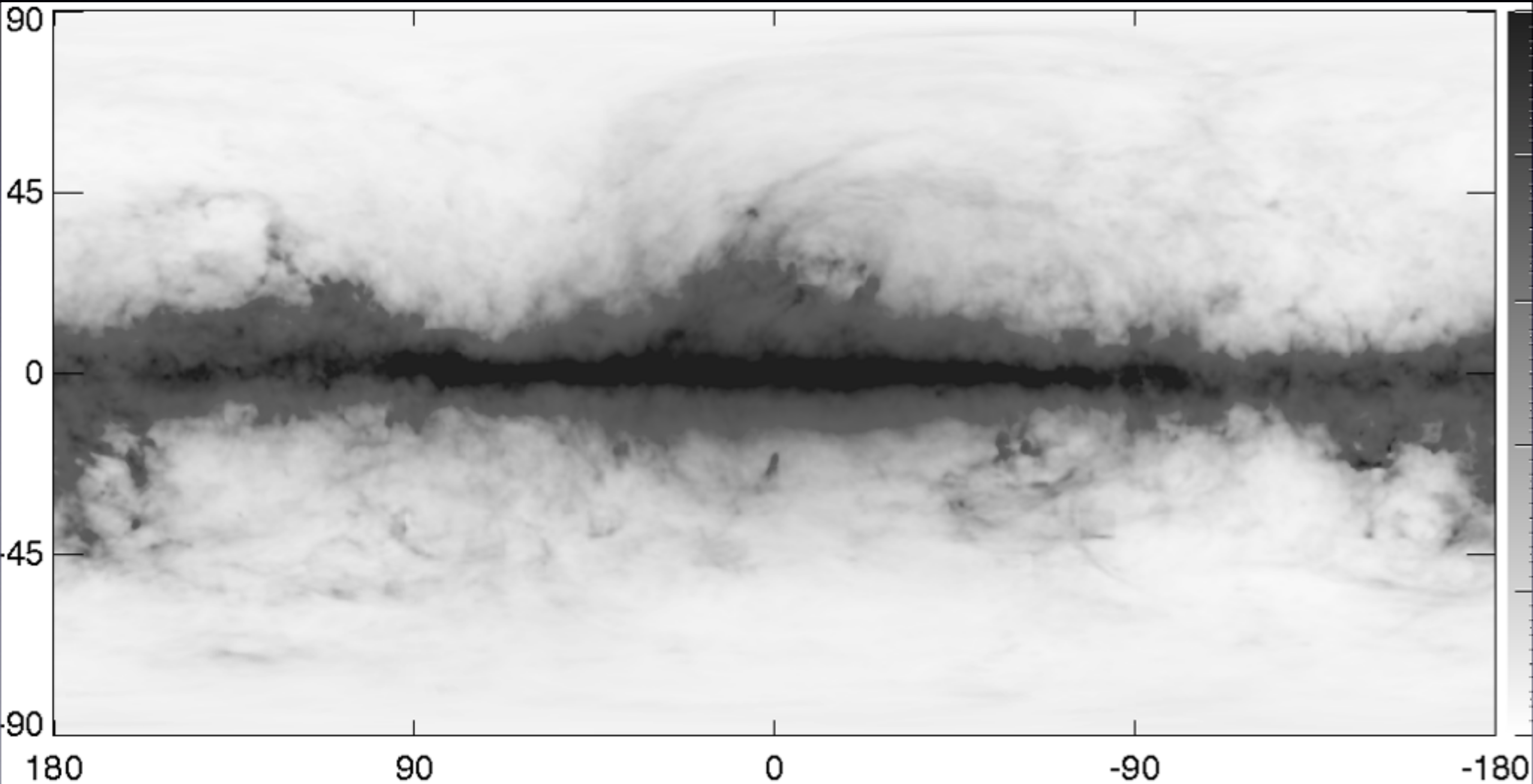


# A more detailed model




- The Fermi LAT Collaboration provides an estimate for the gamma rays based on a complete physical model of the Galaxy.

# A more detailed model

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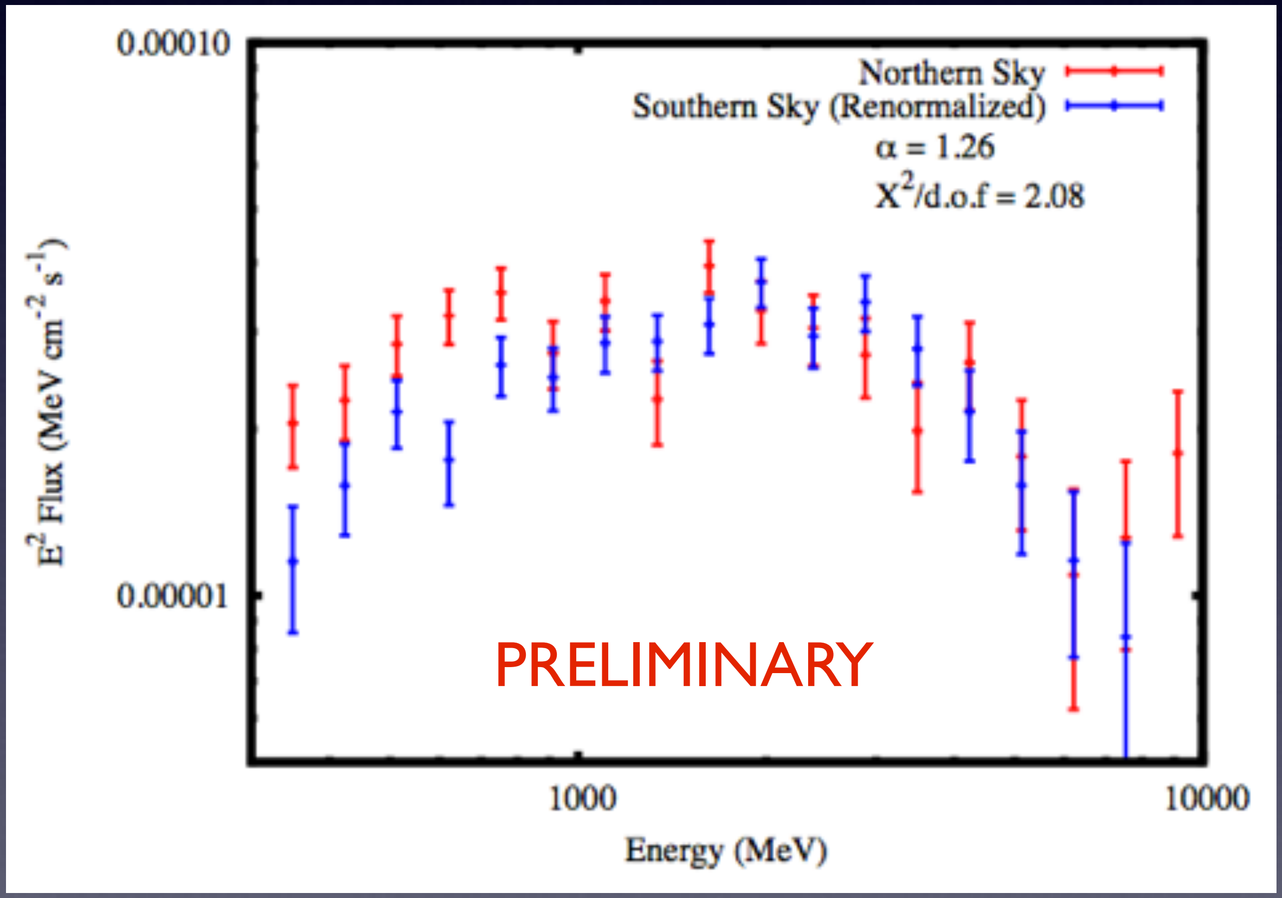
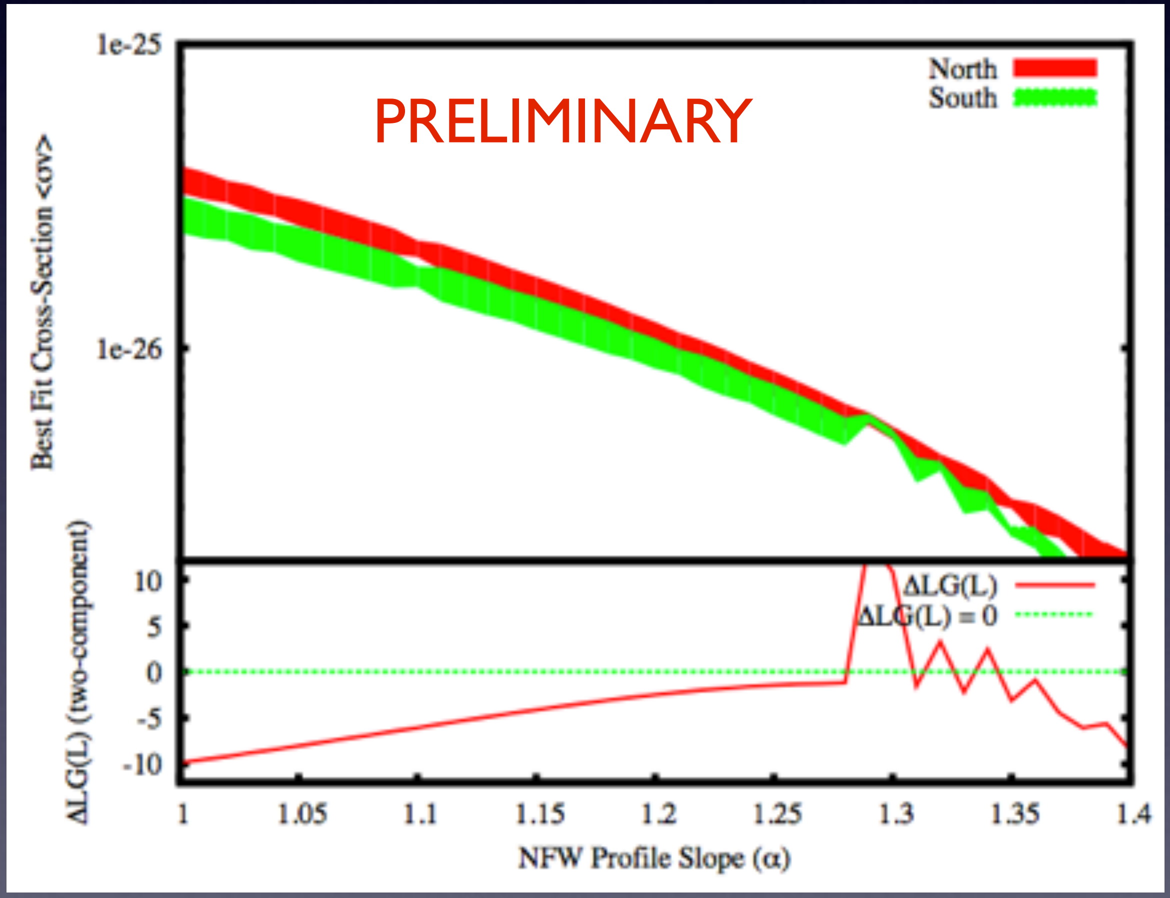
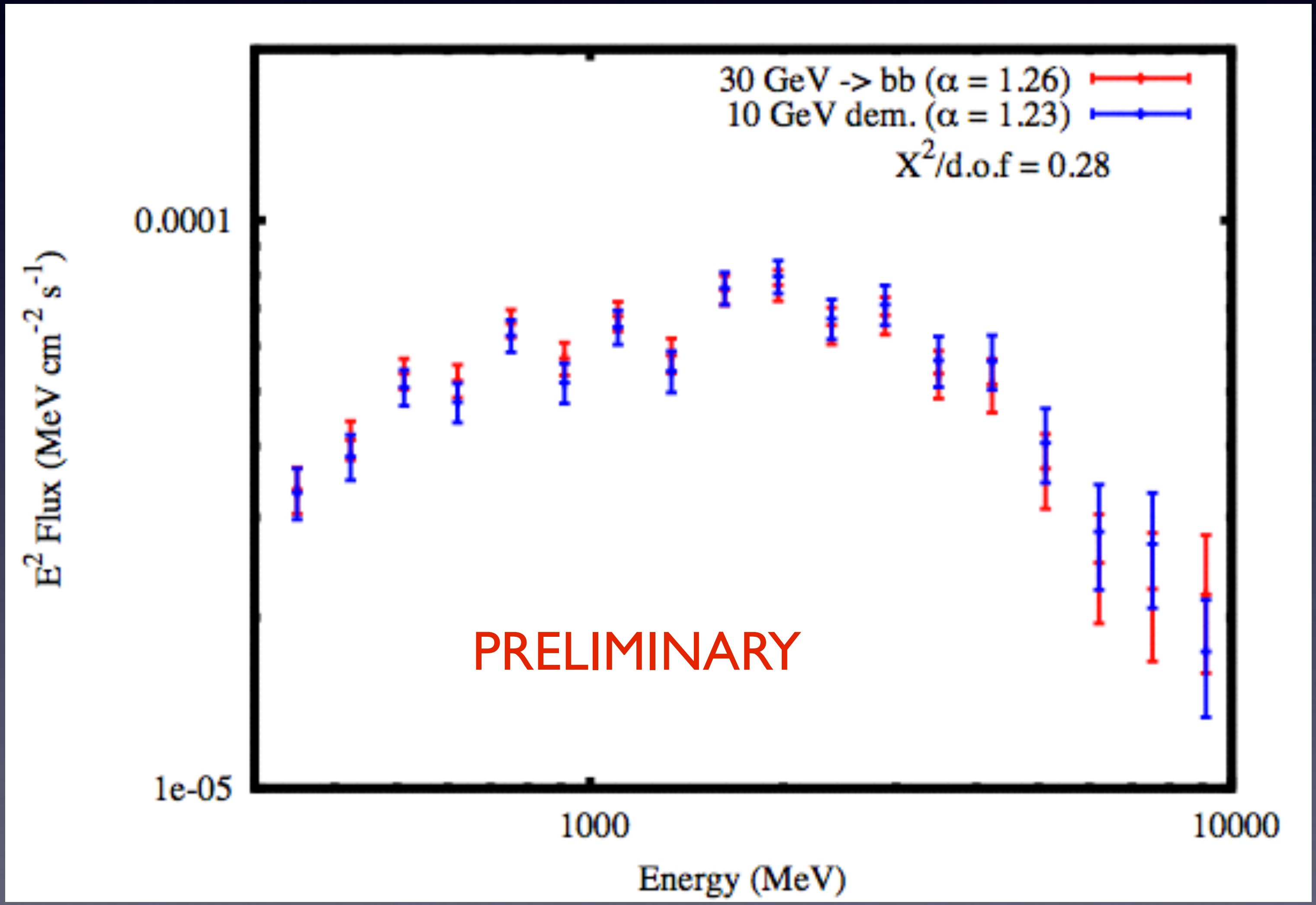
# North-south symmetry in the GC

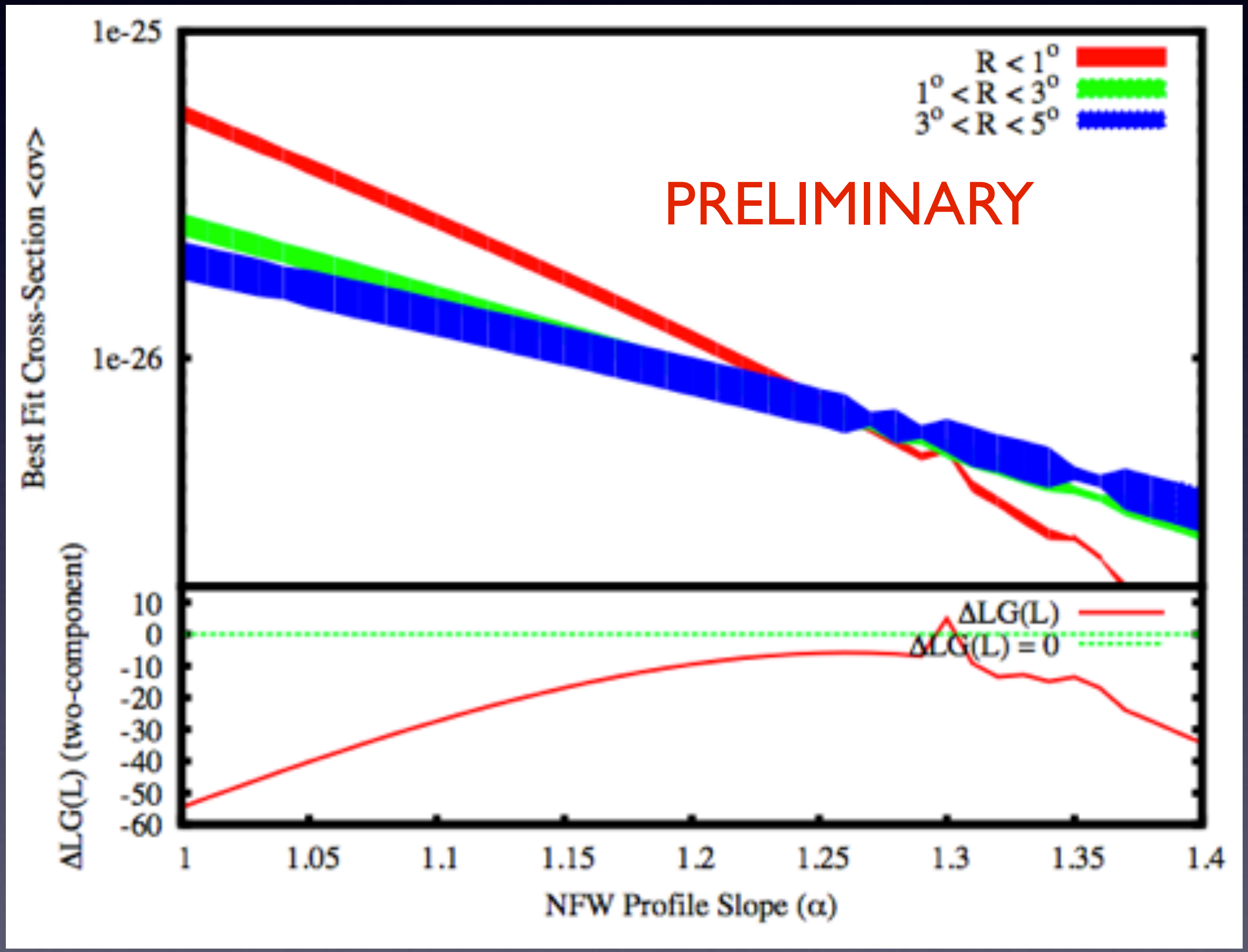


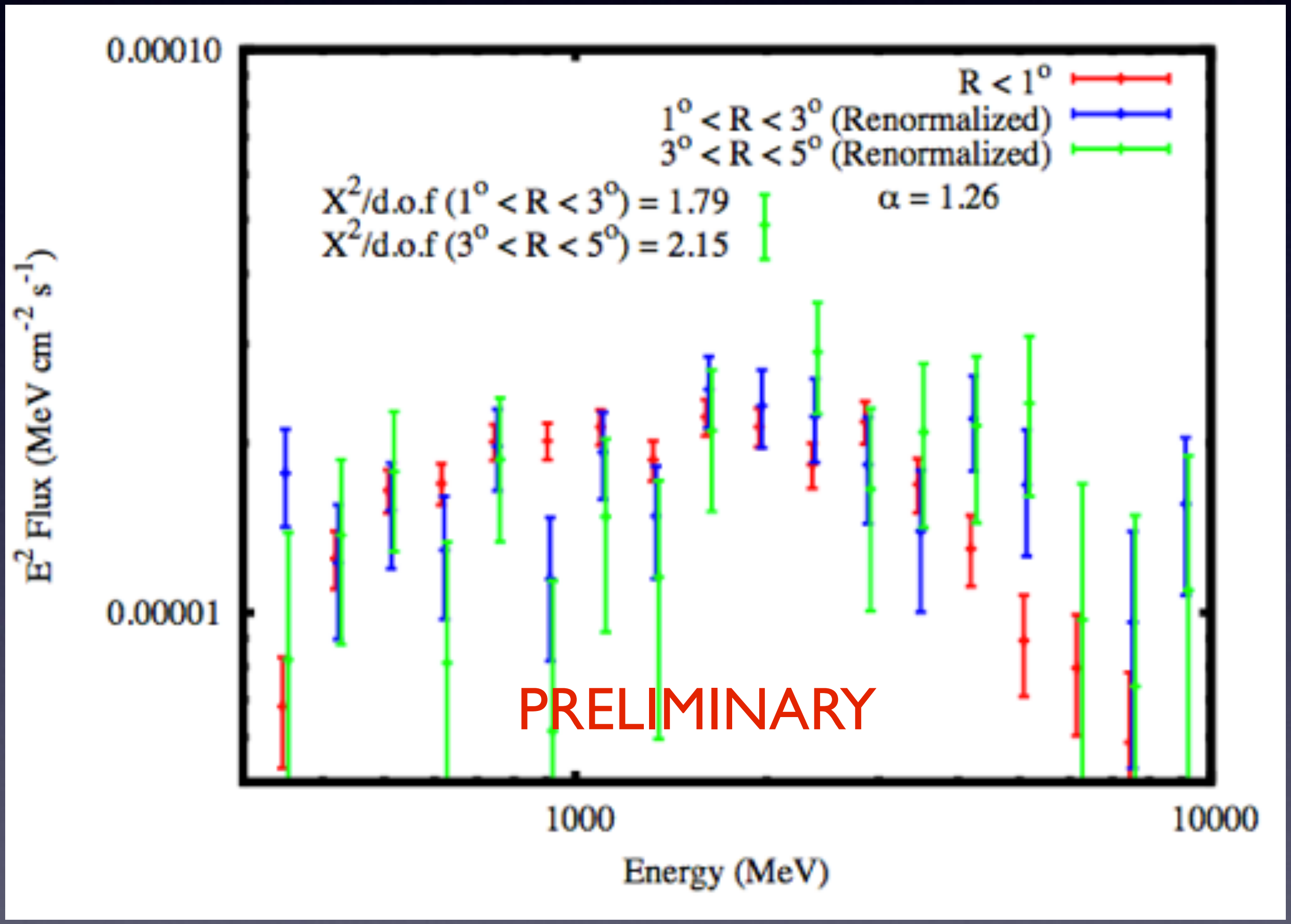



# The GC spectrum

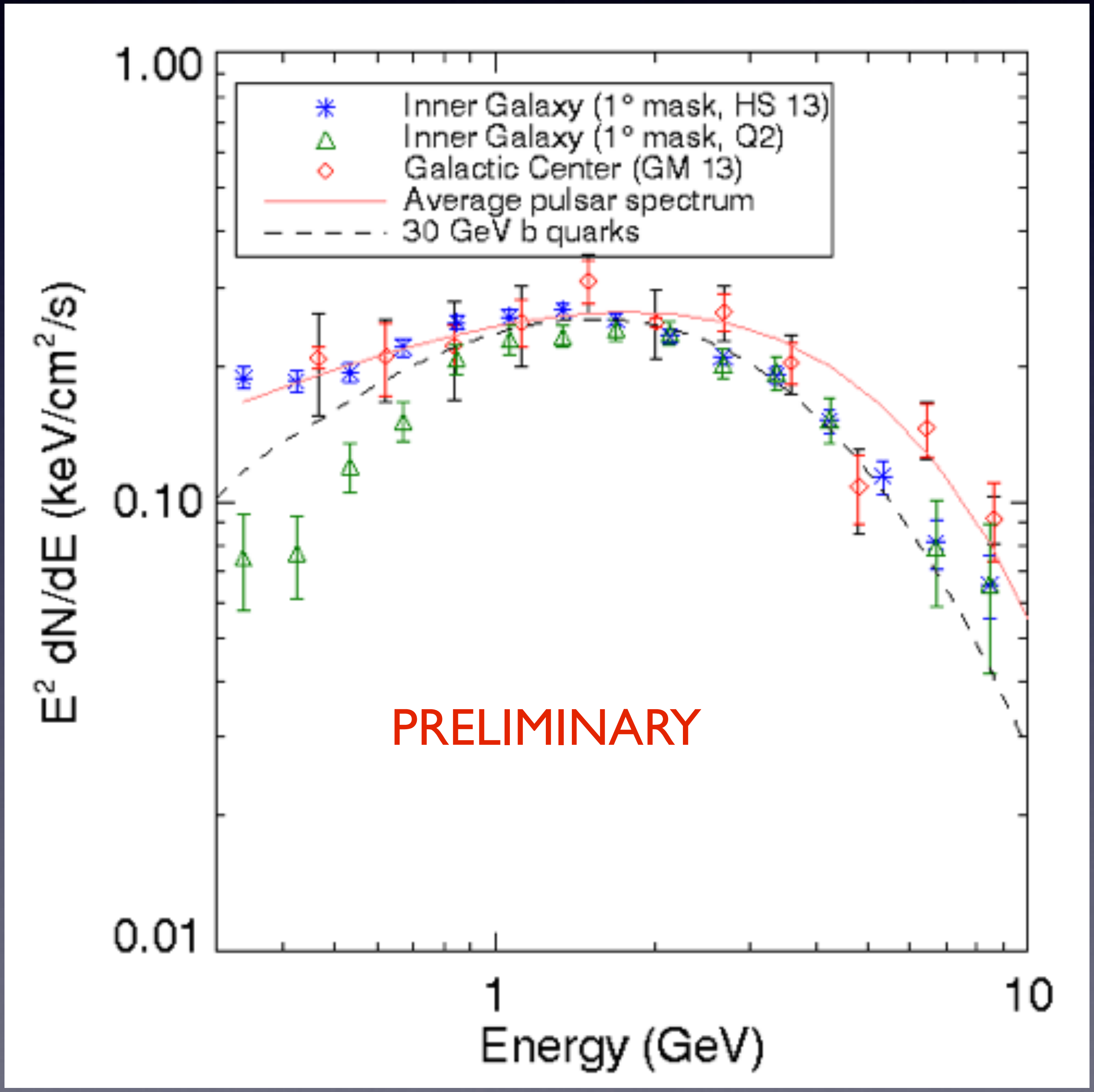


# Moving away from the GC

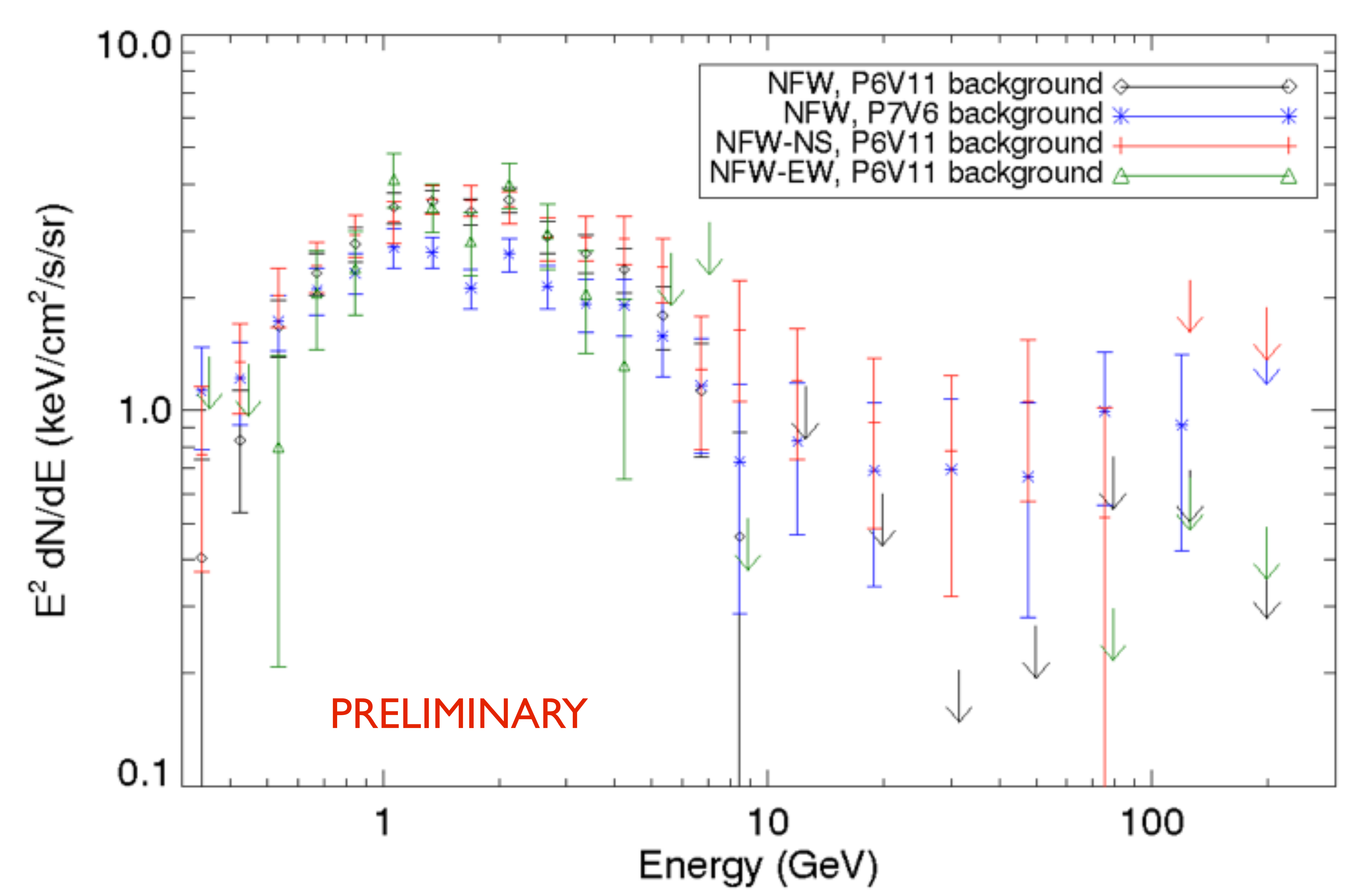


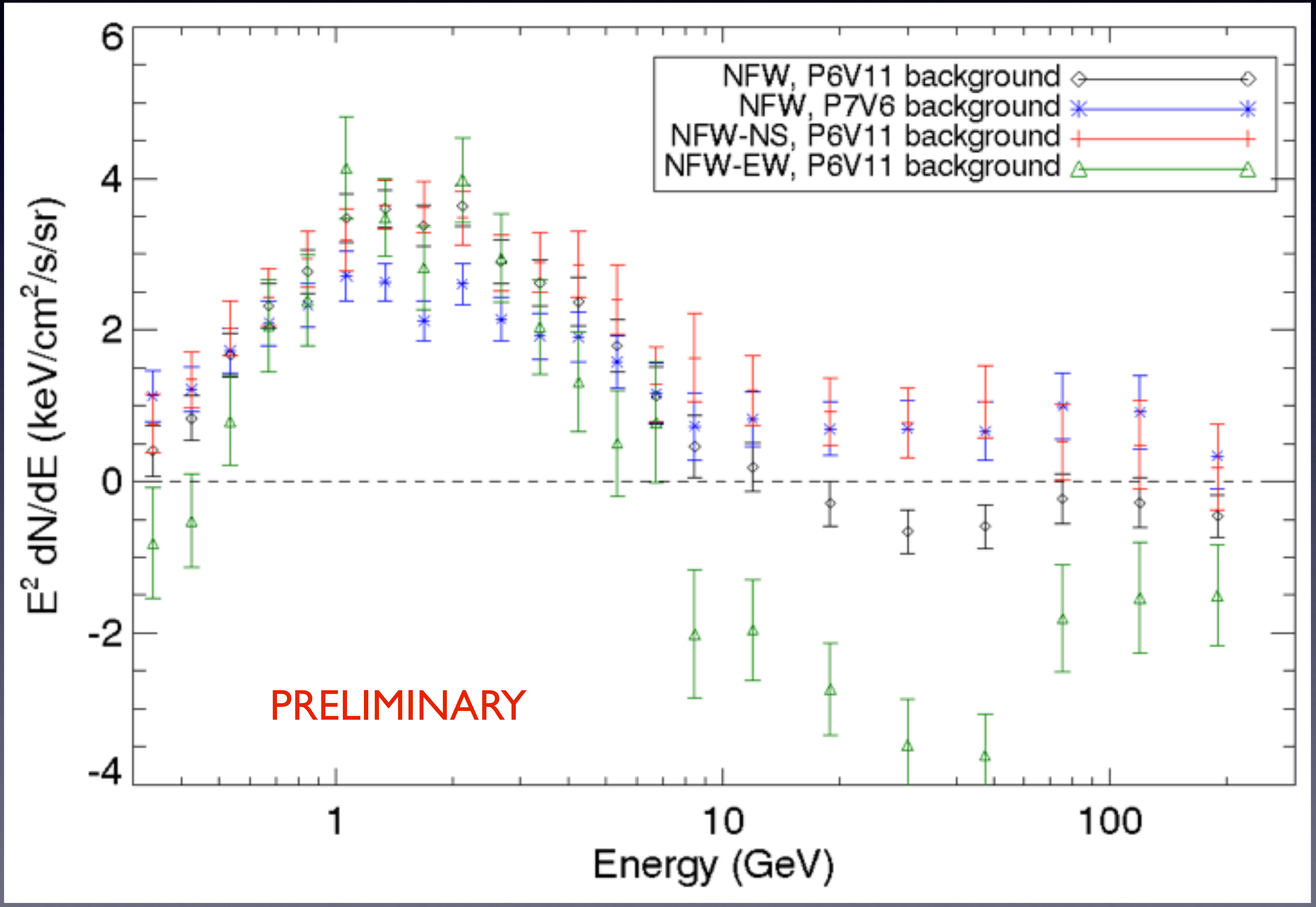
# Impact of the CTBCORE cut (Q2)



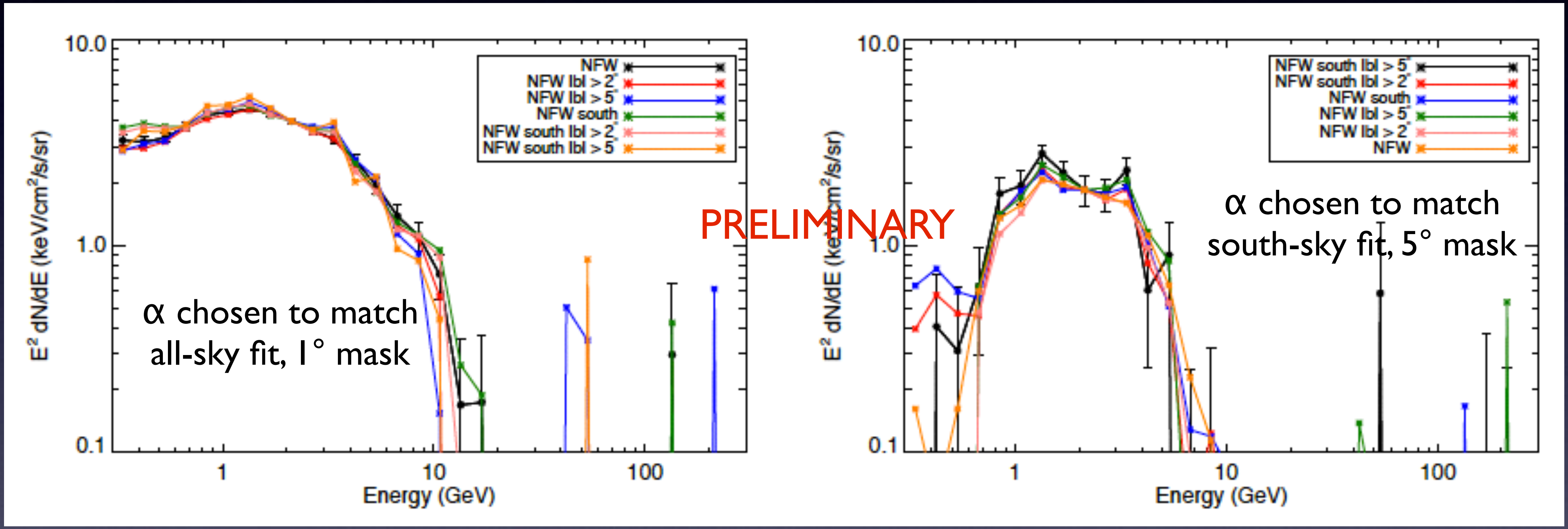
# Spherical symmetry & background modeling



# High-energy mismodeling



# Diffuse background mis-subtraction (pre-CTBCORE)



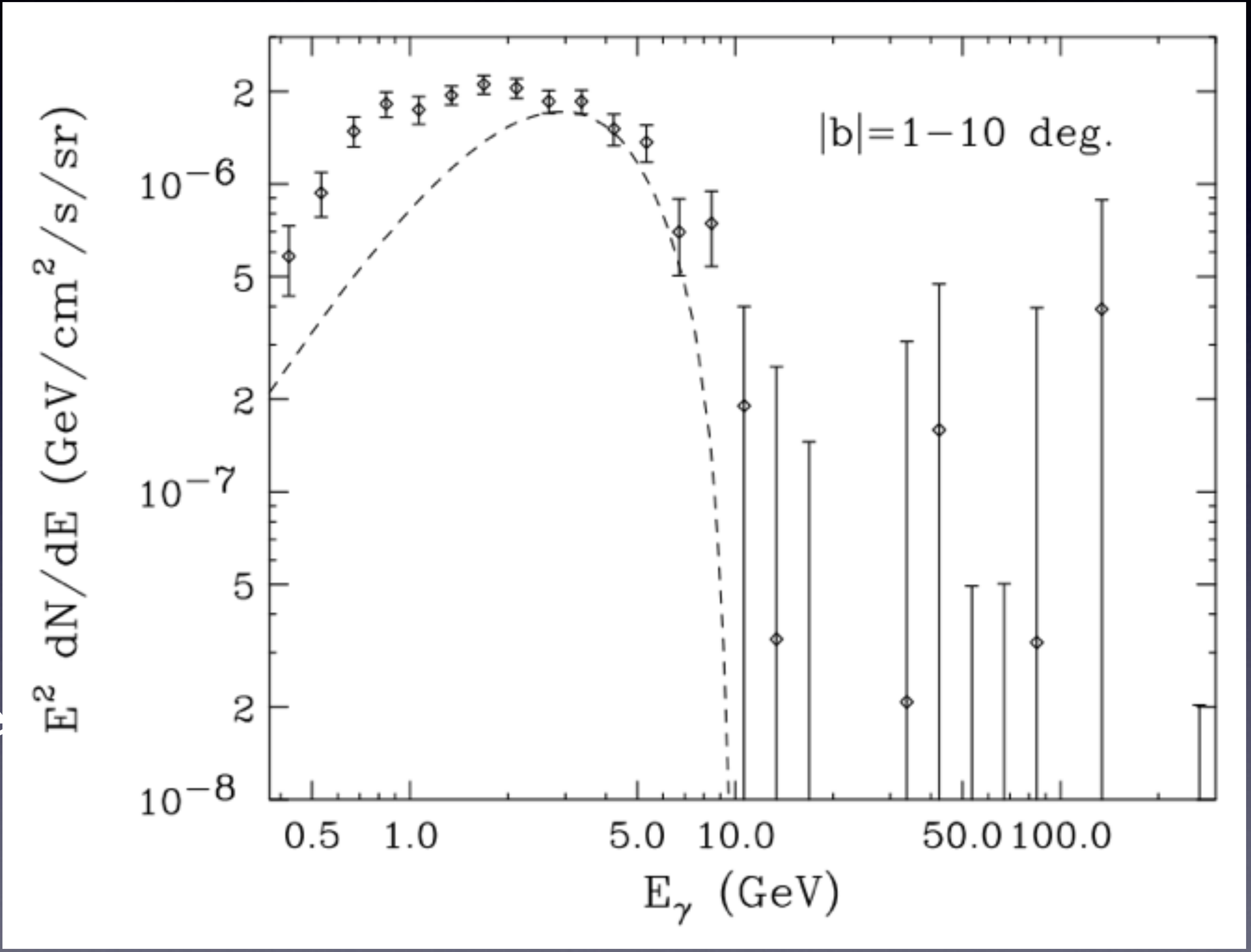

- It turns out that the spectra extracted from all our fits are members of the same one-parameter family of curves, related by:

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

- 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

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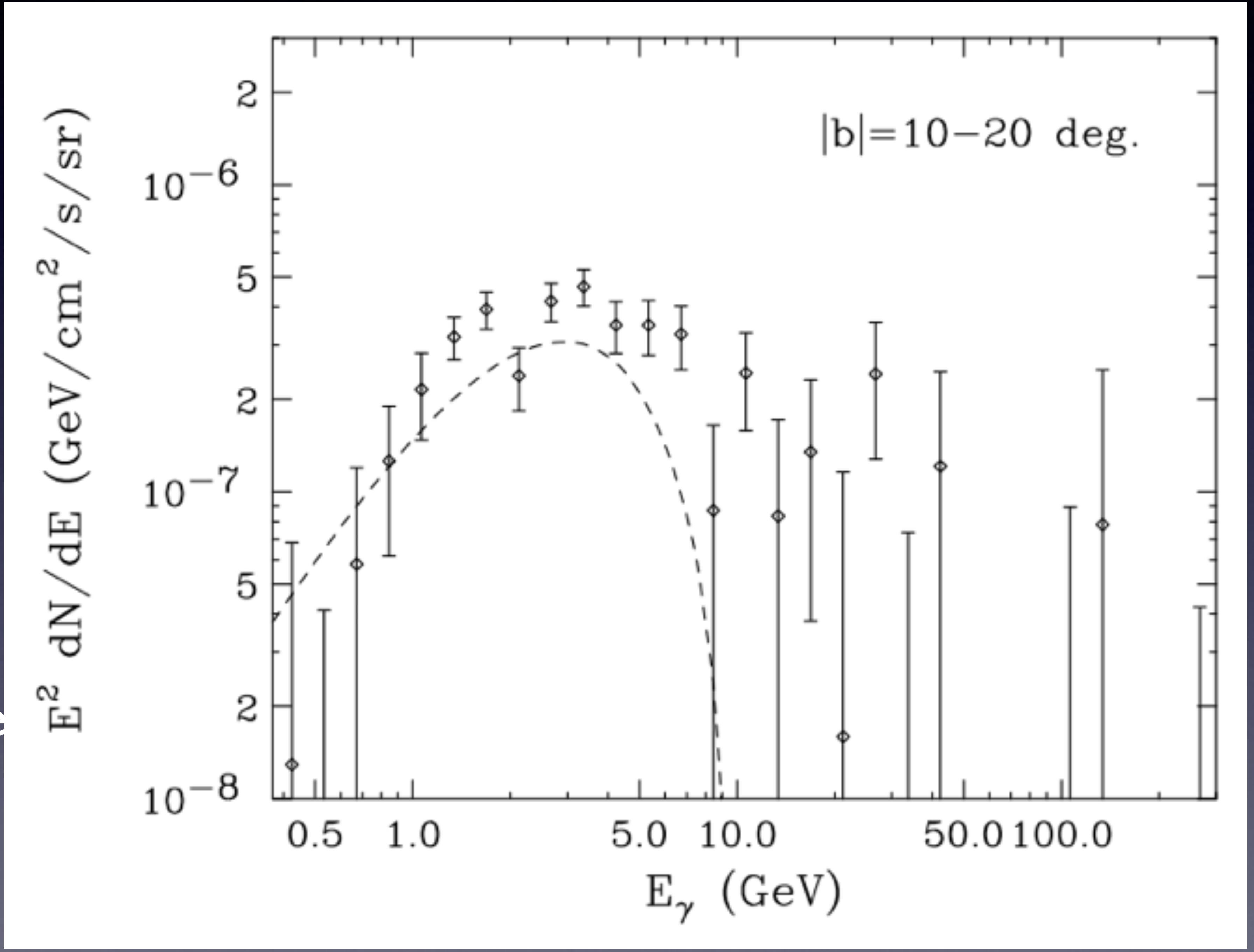


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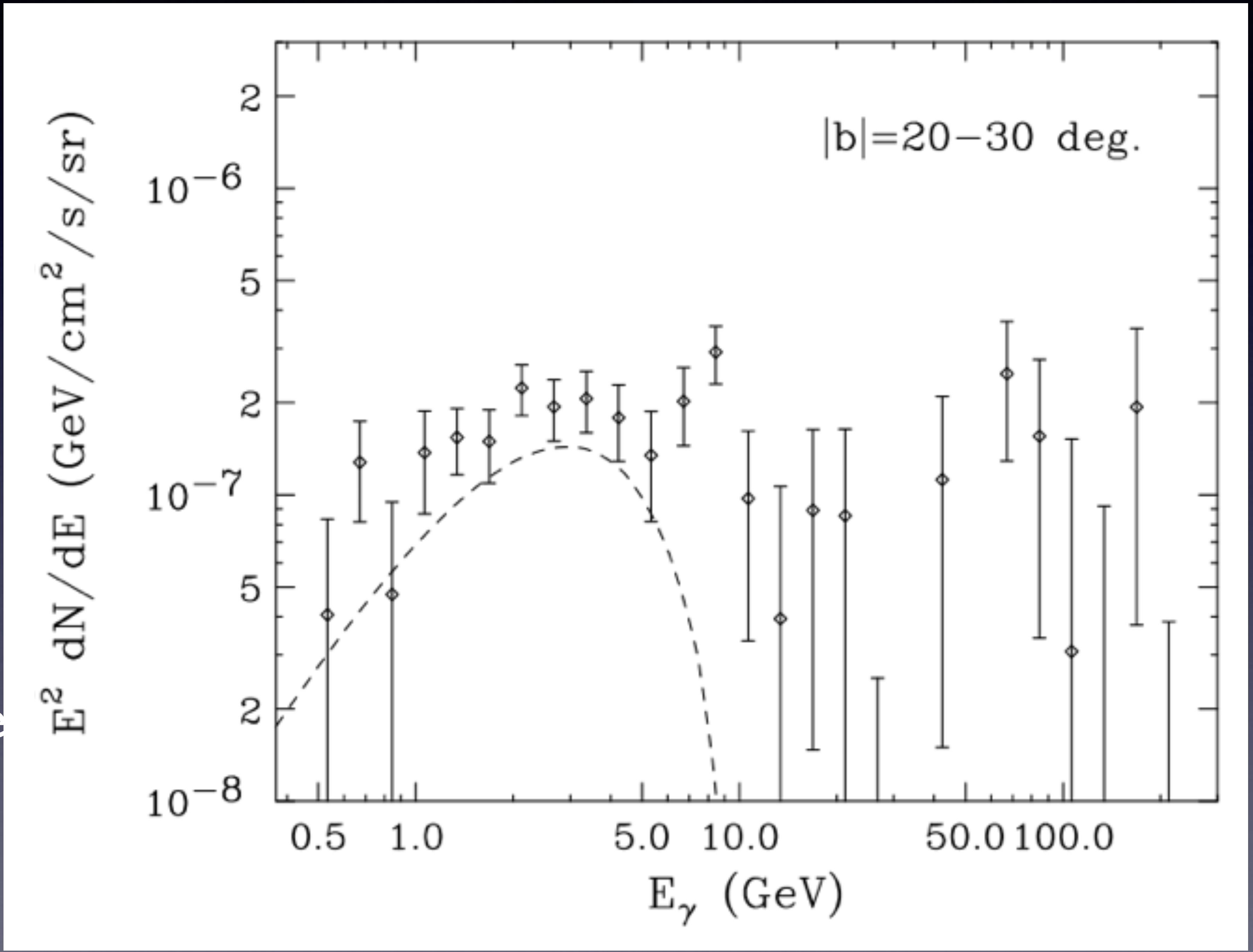


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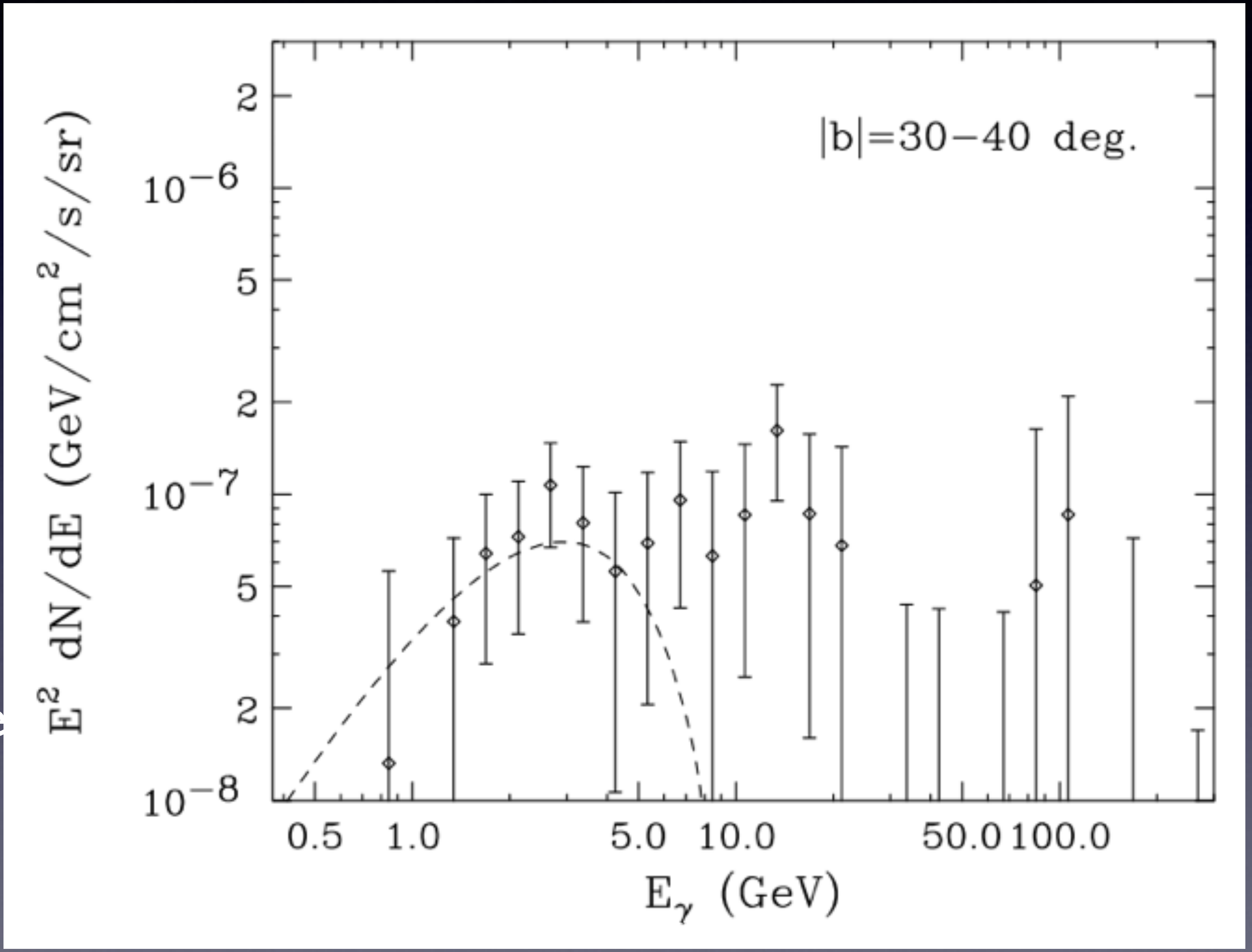


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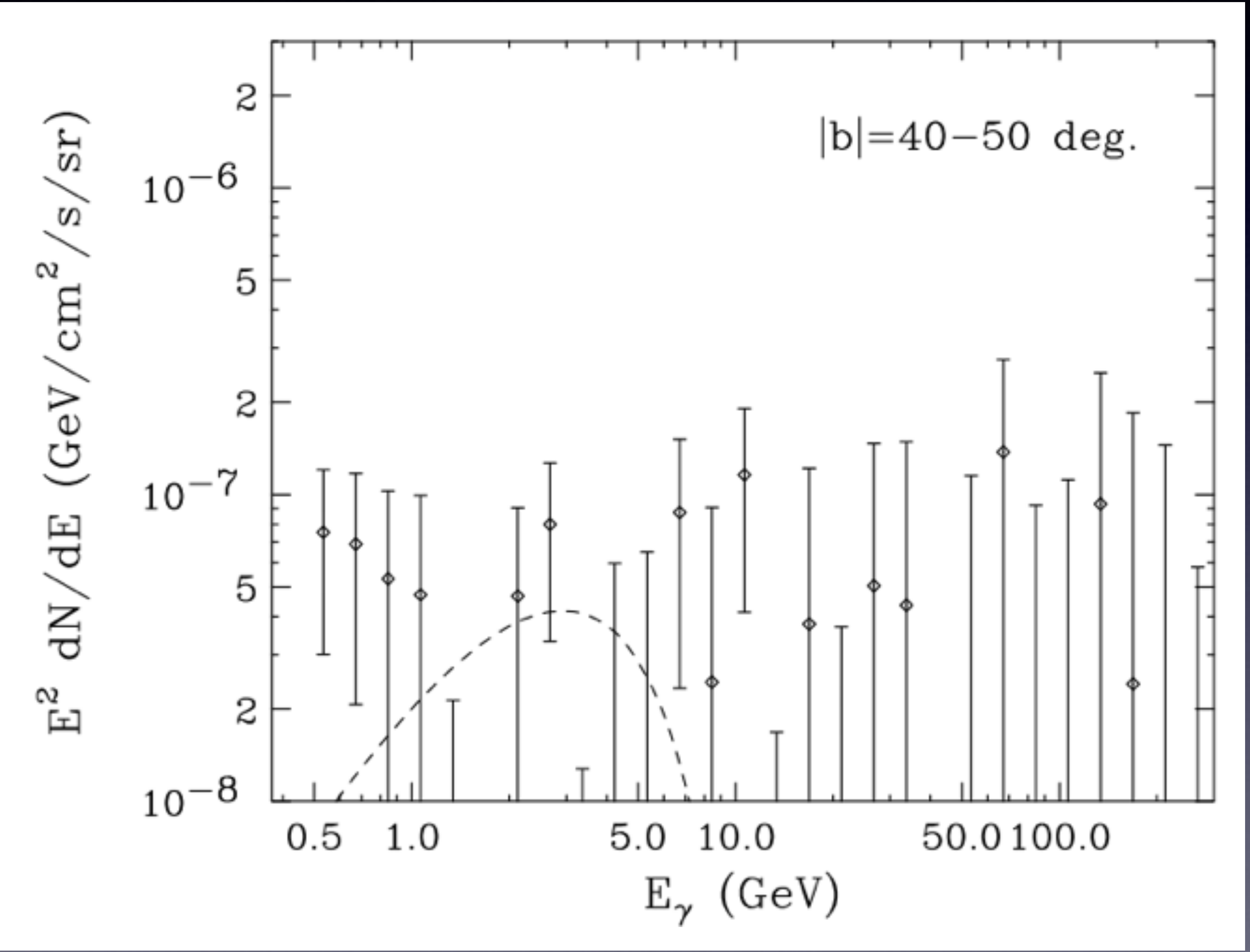


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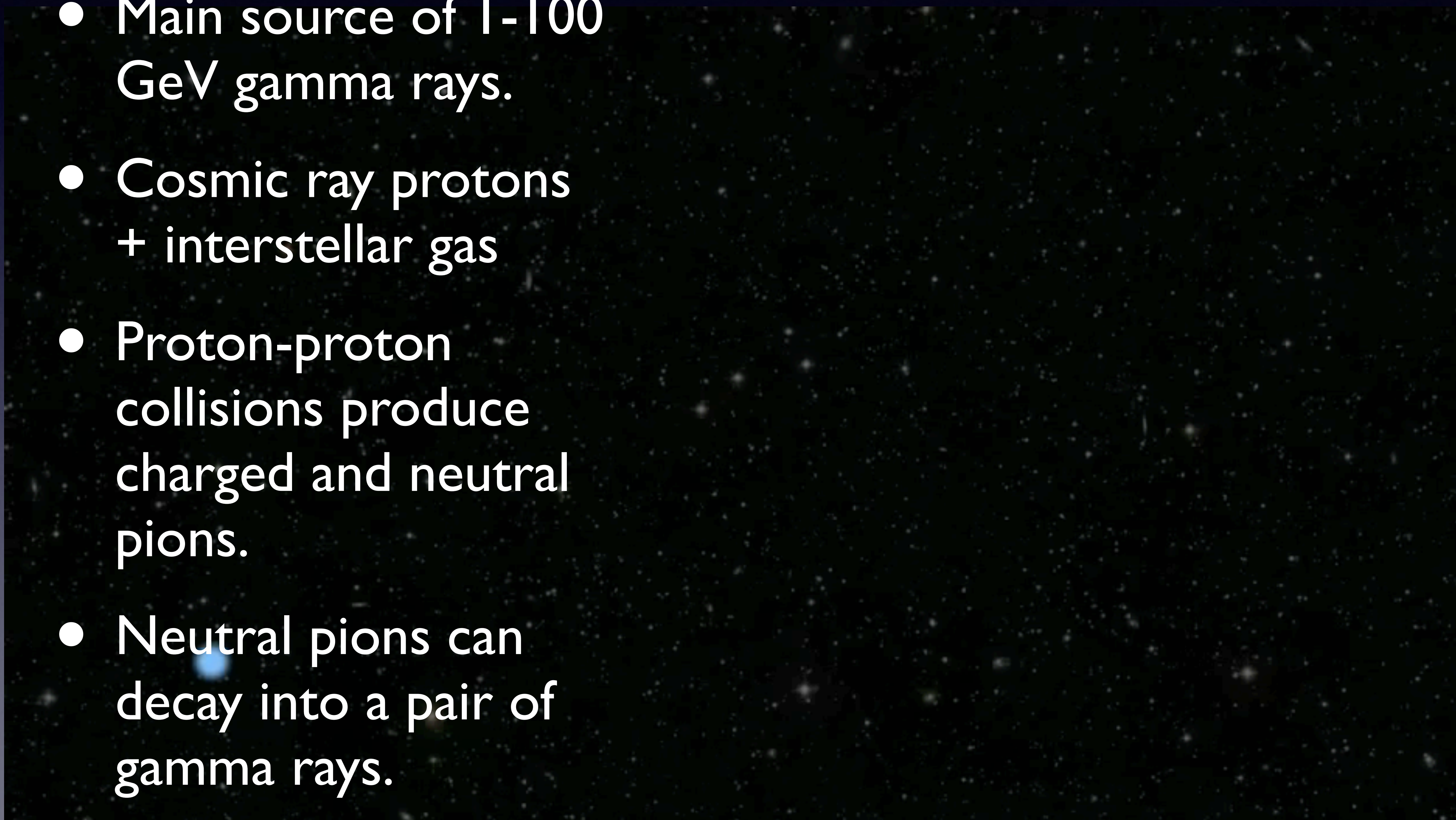
# Gammas from pion production

Video credit: NASA



- Main source of 1-100 GeV gamma rays.
- Cosmic ray protons + interstellar gas
- Proton-proton collisions produce charged and neutral pions.
- Neutral pions can decay into a pair of gamma rays.

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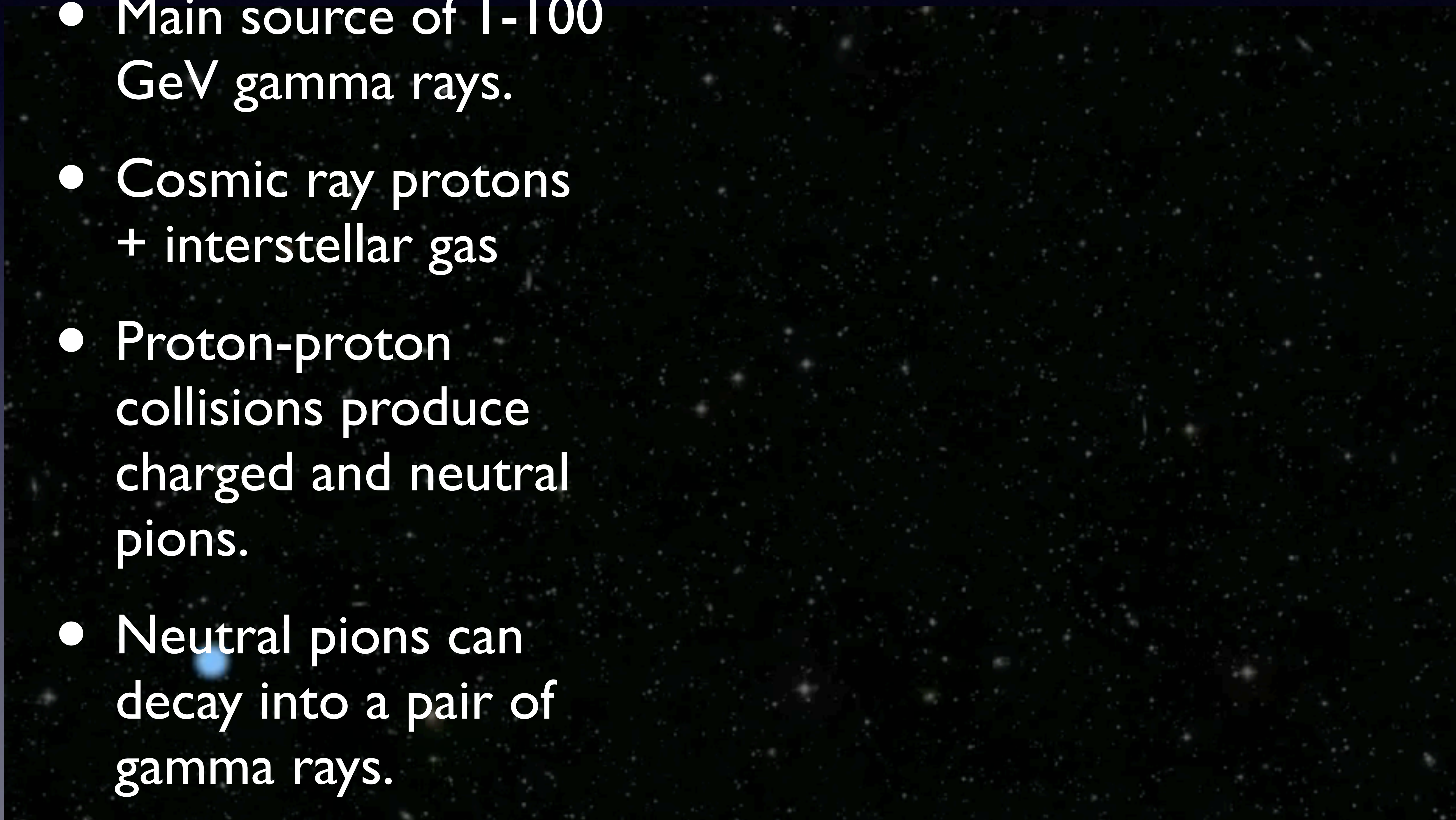

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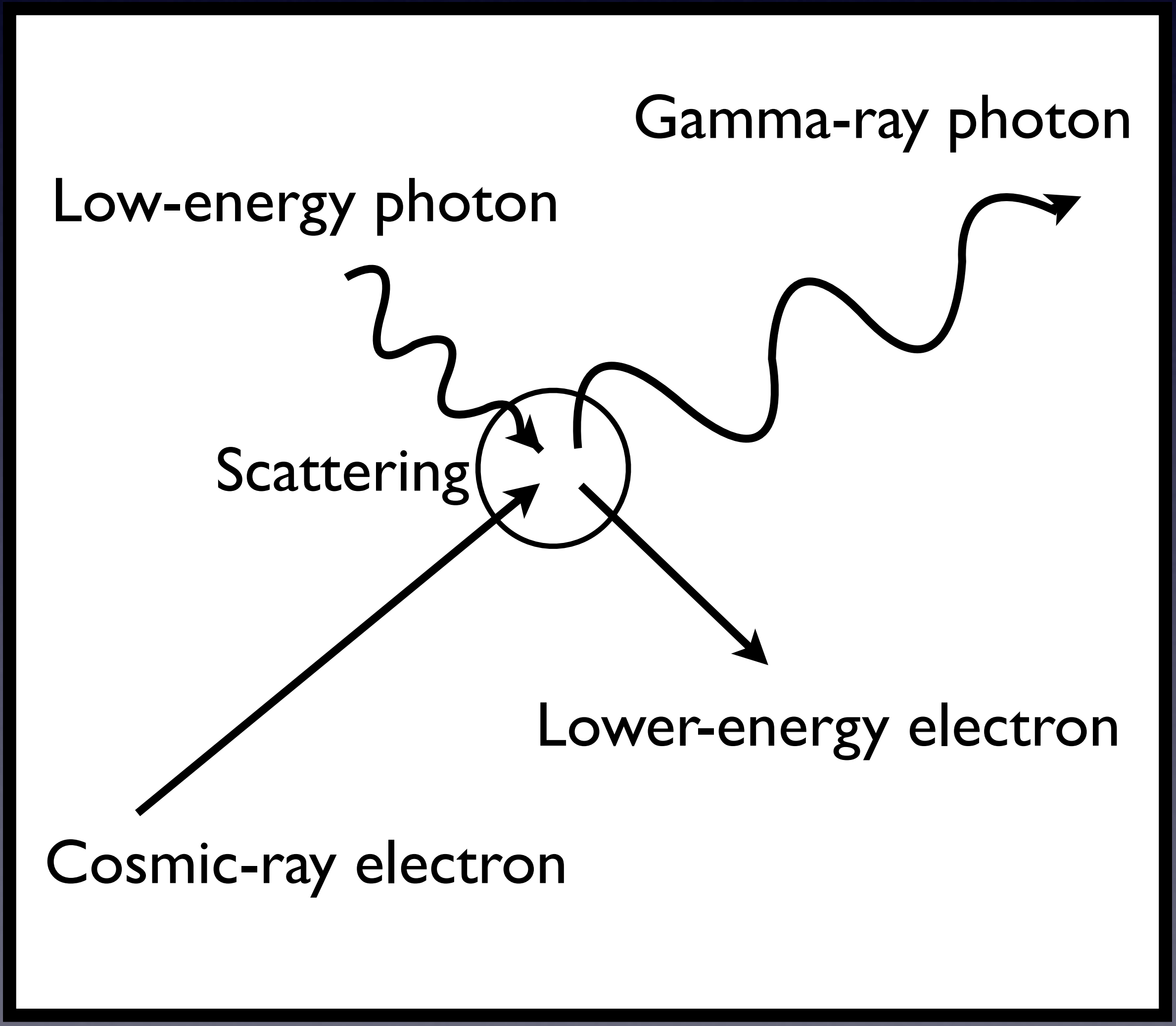
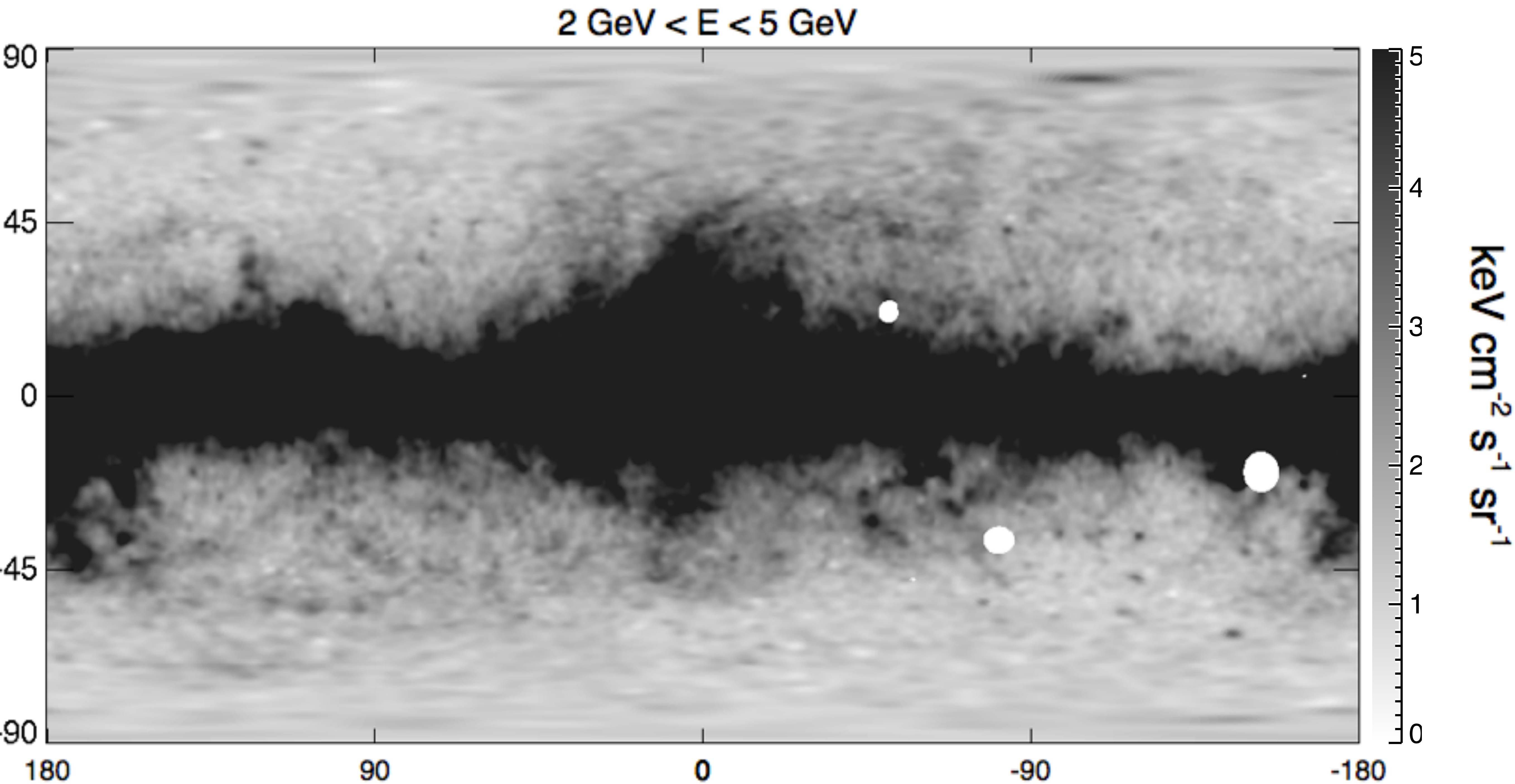
- Neutral pions can decay into a pair of gamma rays.

# Inverse Compton scattering (ICS)

- High-energy electron scatters on low-energy photon, transfers energy to it.
- Converts a starlight/infrared/microwave photon into a gamma ray.



Data - Fermi model



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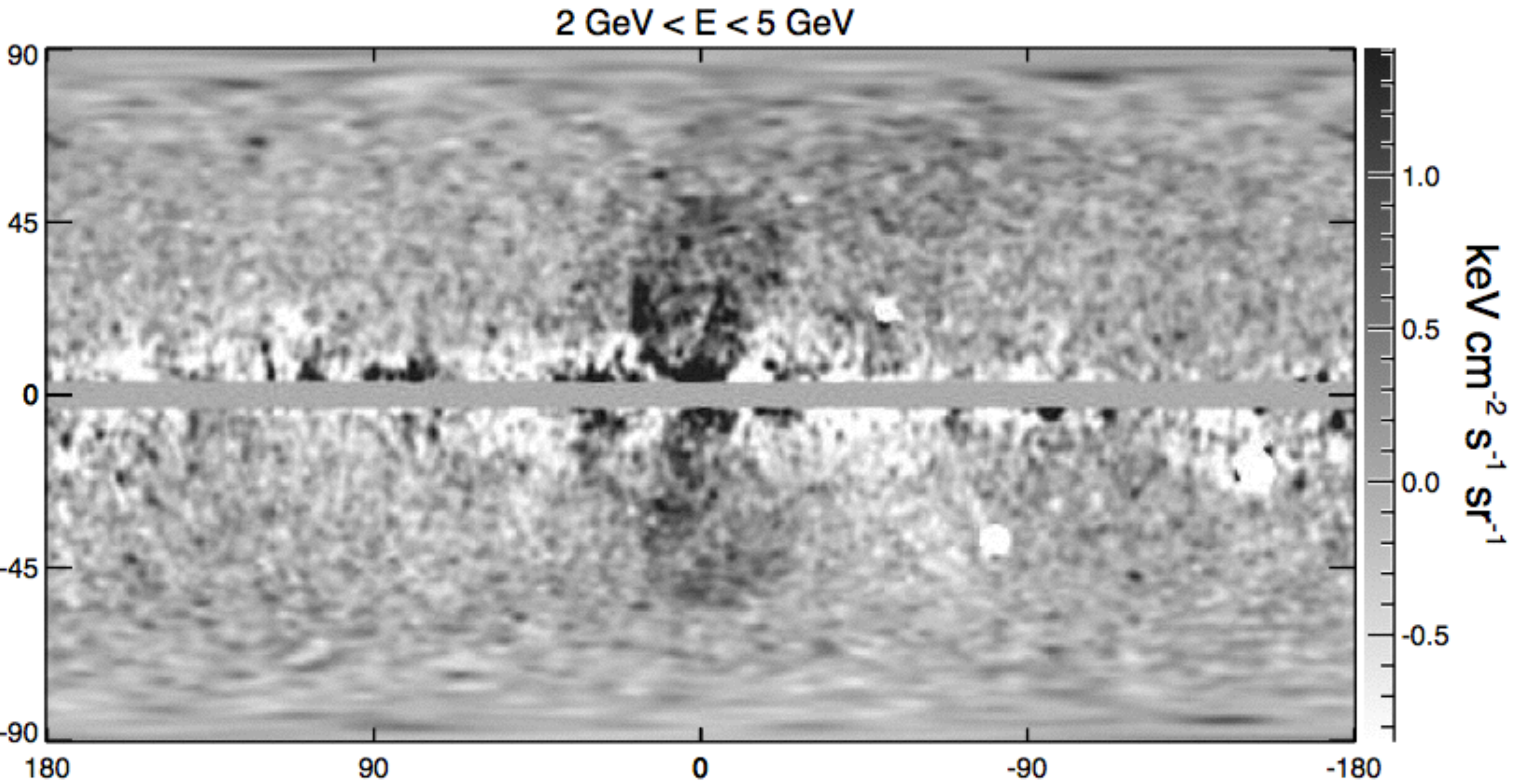

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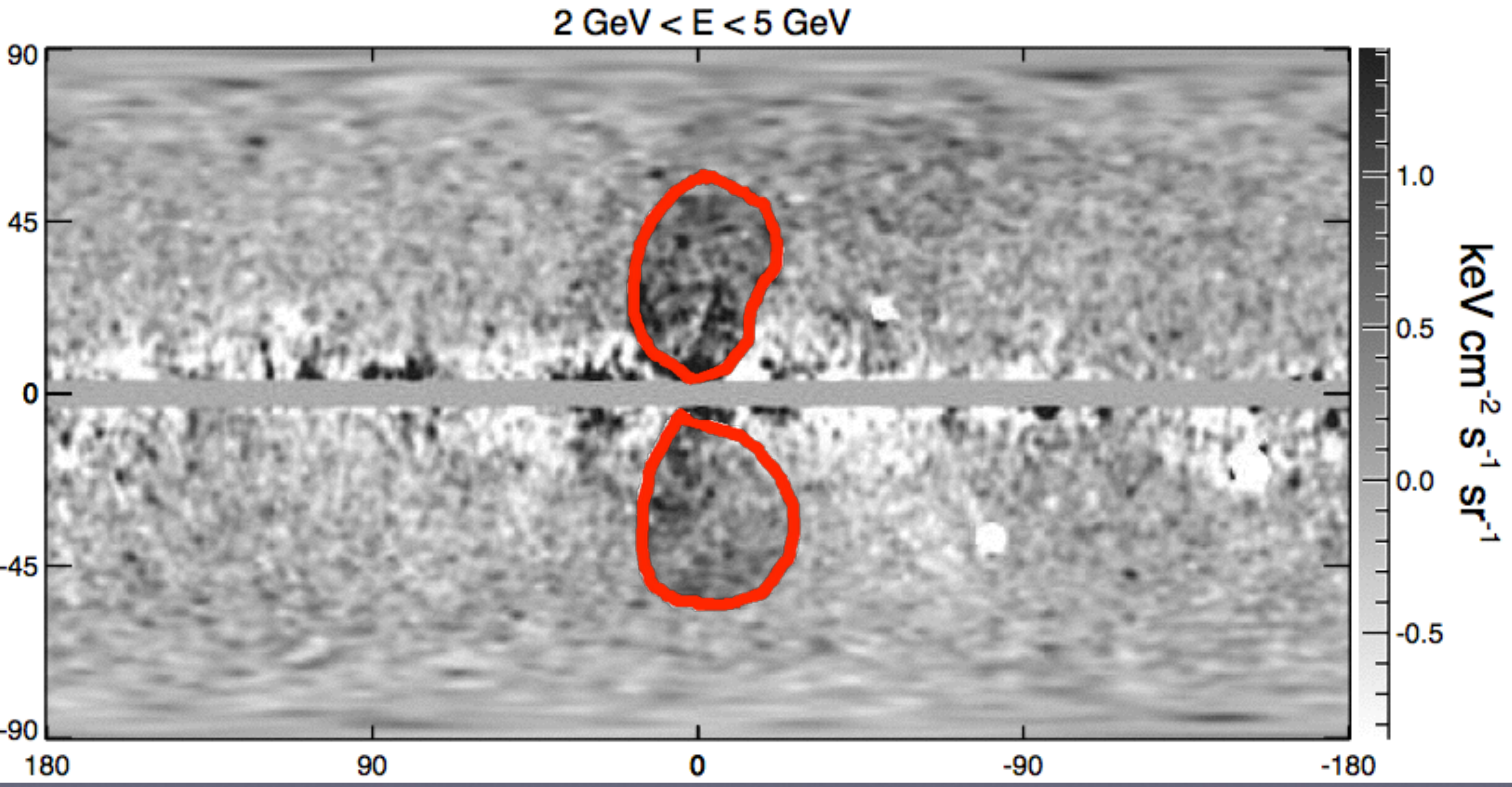


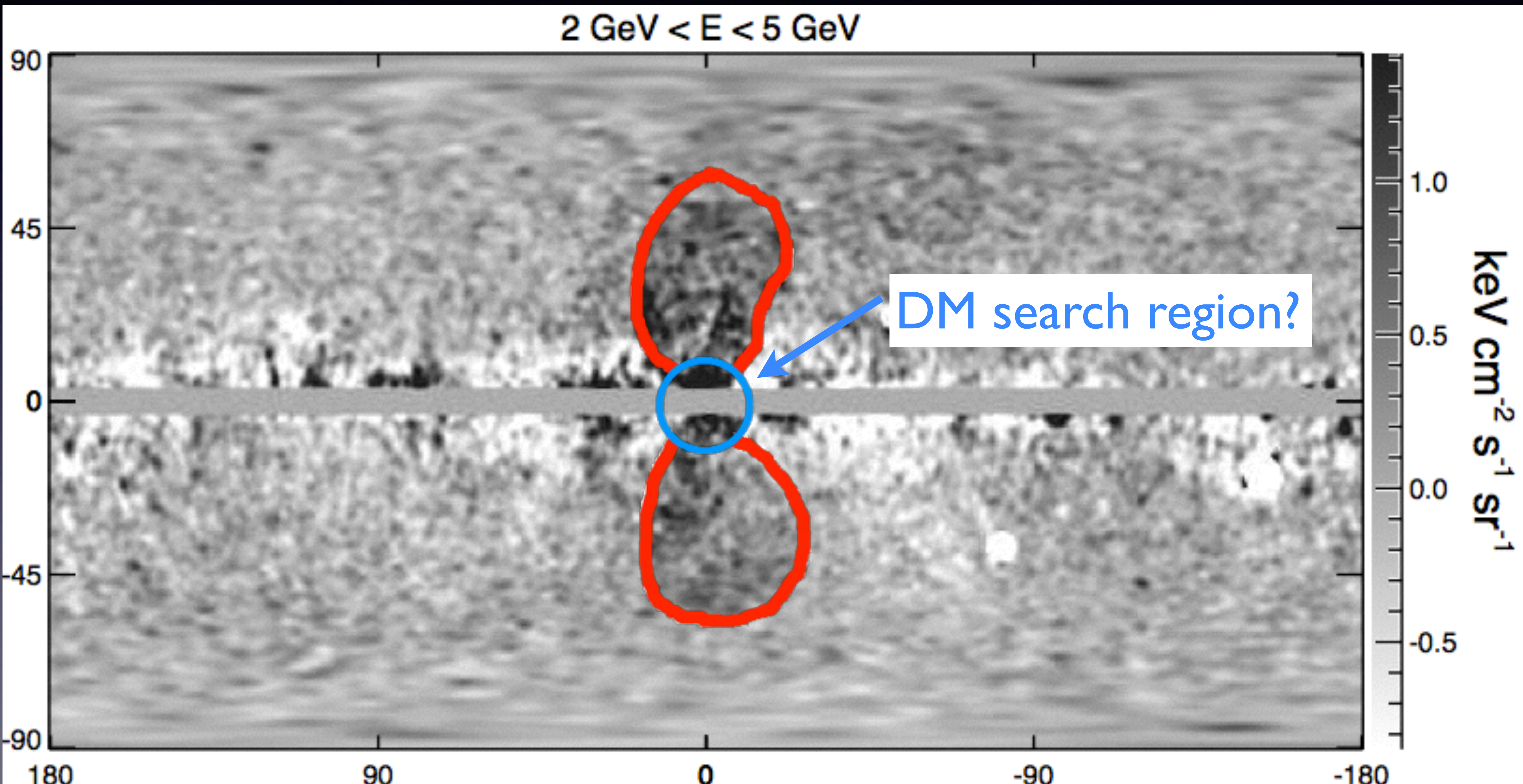
# The “Fermi Bubbles”

- Giant, double-lobed structure centered at the Galactic Center, extending ~50 degrees to the north and south.
- Bright in 1-100 GeV gamma rays.
- May be a relic of activity of the black hole at the Galactic Center in the last 1-10 million years, or supernovae in the inner Galaxy over a much longer timescale.
- Now also observed in X-ray and microwaves.
- Many puzzling features and their origin is still an open question.
- Discovered in 2010 by Finkbeiner, Su (now a Pappalardo Fellow) and TRS (Rossi Prize awarded 2014).

# Extracting a spectrum

- We want to know the spectrum of each component - how many photons are associated with the gas / IC / Bubbles at each energy.
- Follow a "template fitting" procedure:
  - Bin the photons in energy.
  - Model the sky in each bin as a linear combination of the different spatial templates.
  - Solve for the best-fit coefficients (using a pixelized likelihood method).

# The inner Galaxy



# The interstellar medium (dust/gas)