Gamma-ray jets & cocoons in the Milky Way

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Meng Su, MIT

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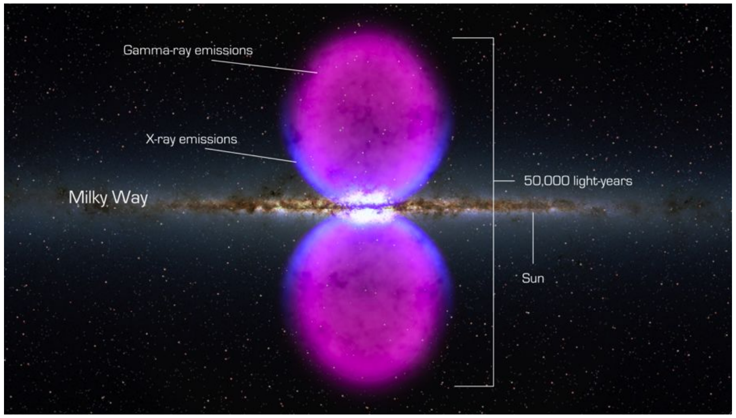
Monterey

Background:

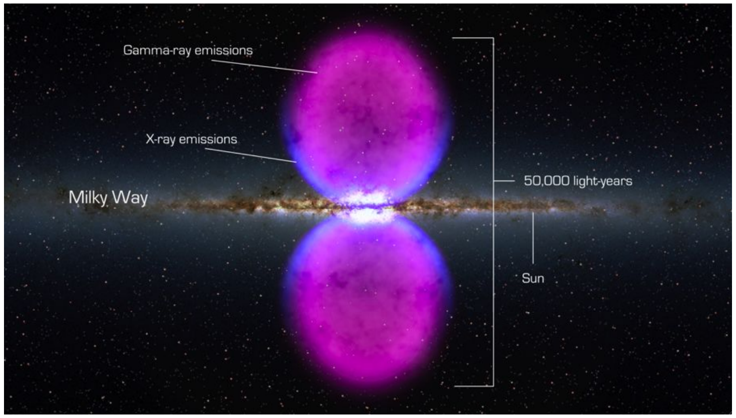
Based on a simple analysis of 1.6 years of *Fermi* data, we (Su, Slatyer, DPF) claimed in 2010 that there were “bubble” structures spanning ~ $|b| < 50$ deg and $|l| < 20$ deg.



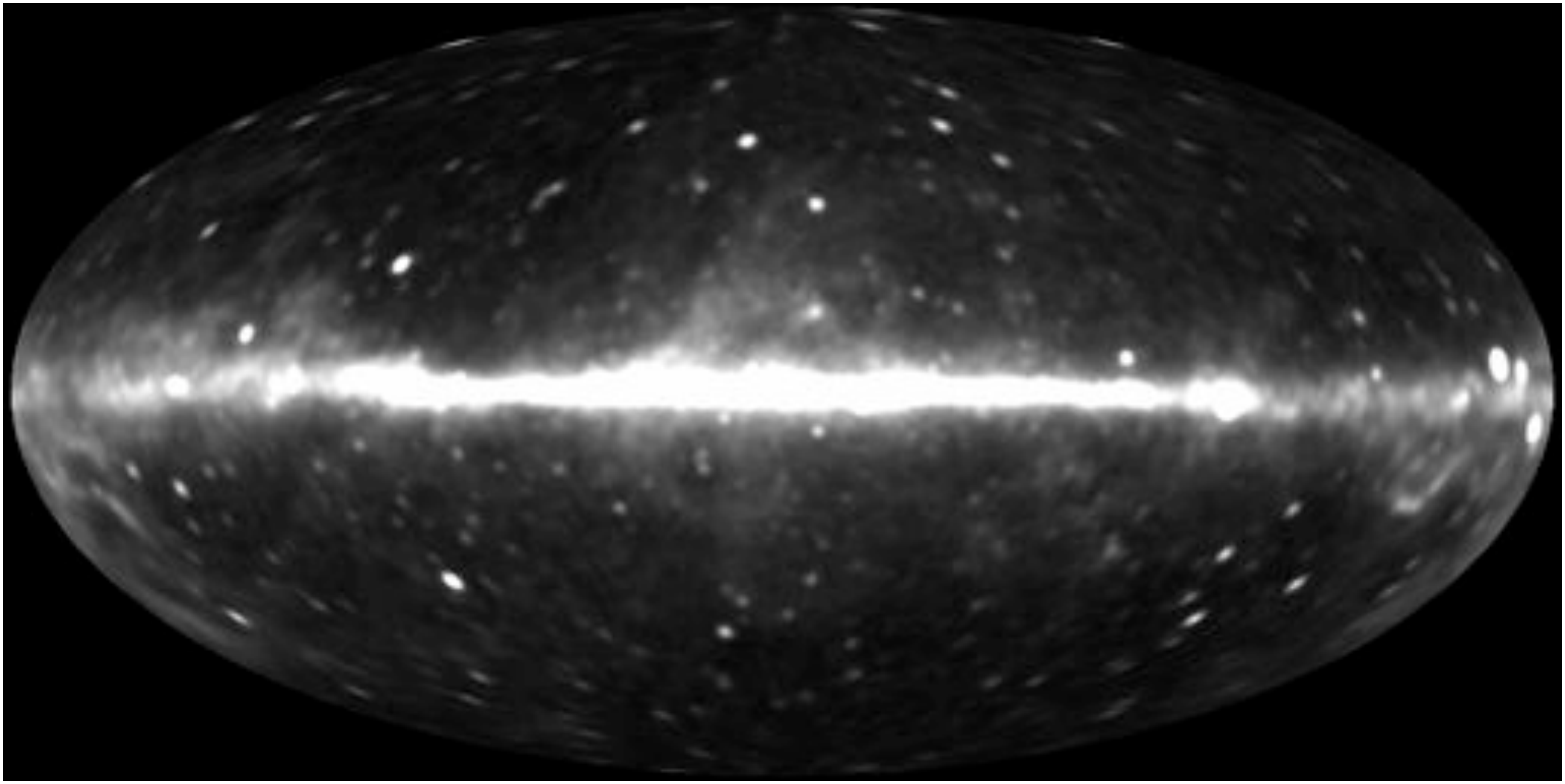
Background:

Based on a simple analysis of 1.6 years of *Fermi* data, we (Su, Slatyer, DPF) claimed in 2010 that there were "bubble" structures spanning ~ |b| < 50 deg and |l| < 20 deg.

Now with 3+ years of data, pass 7 events, and ULTRACLEAN event selection, we can see the structures more clearly, and can begin to investigate substructure.



Recall: *Fermi* bubbles processing steps:



Point sources / diffuse model / stretch

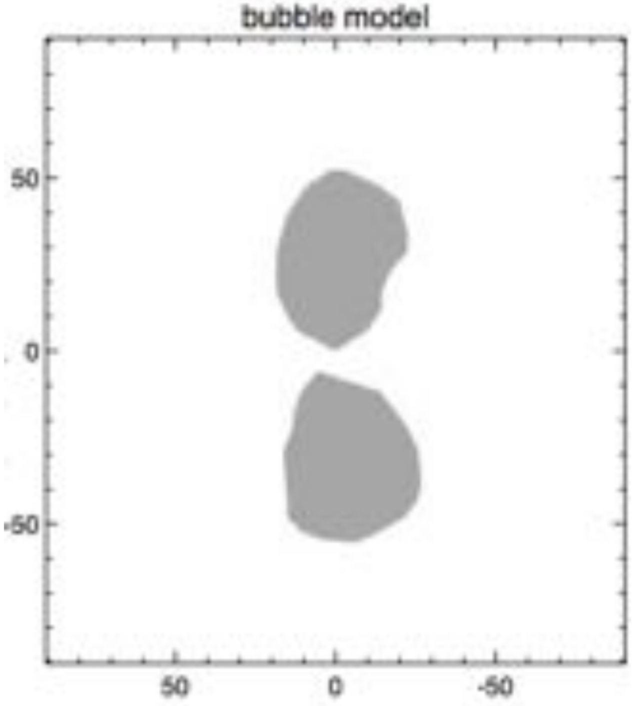
Processing details:

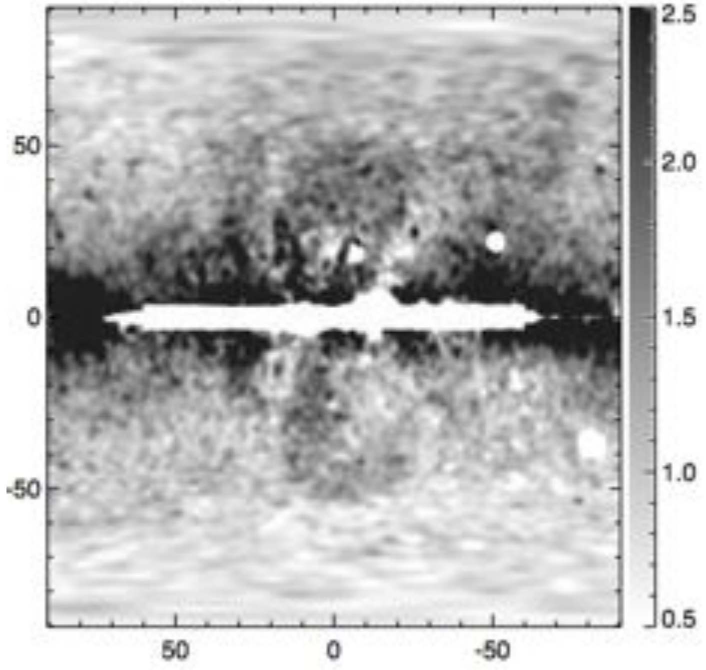
- Use Pass 7, 3 yr data, ultraclean events, bin to HEALPix maps
- Point sources - use Fermi 2nd year catalog (2FGL), in-flight PSF estimate
- Smooth to 1.5 or 2 degrees FWHM (spherical harmonic convolution)
- Diffuse model
  - Fermi diffuse model
    - Pros: based (in part) on physical model, sophisticated
    - Cons: not sure what is in it, or how various artifacts might be introduced.
  - Simple model with geometric templates
    - Pro: Easy to see what is going on
    - Con: might be too simple-minded

Simple templates...

Our previous work used a uniform intensity template for the Fermi bubbles.

This was correct to zeroth order.

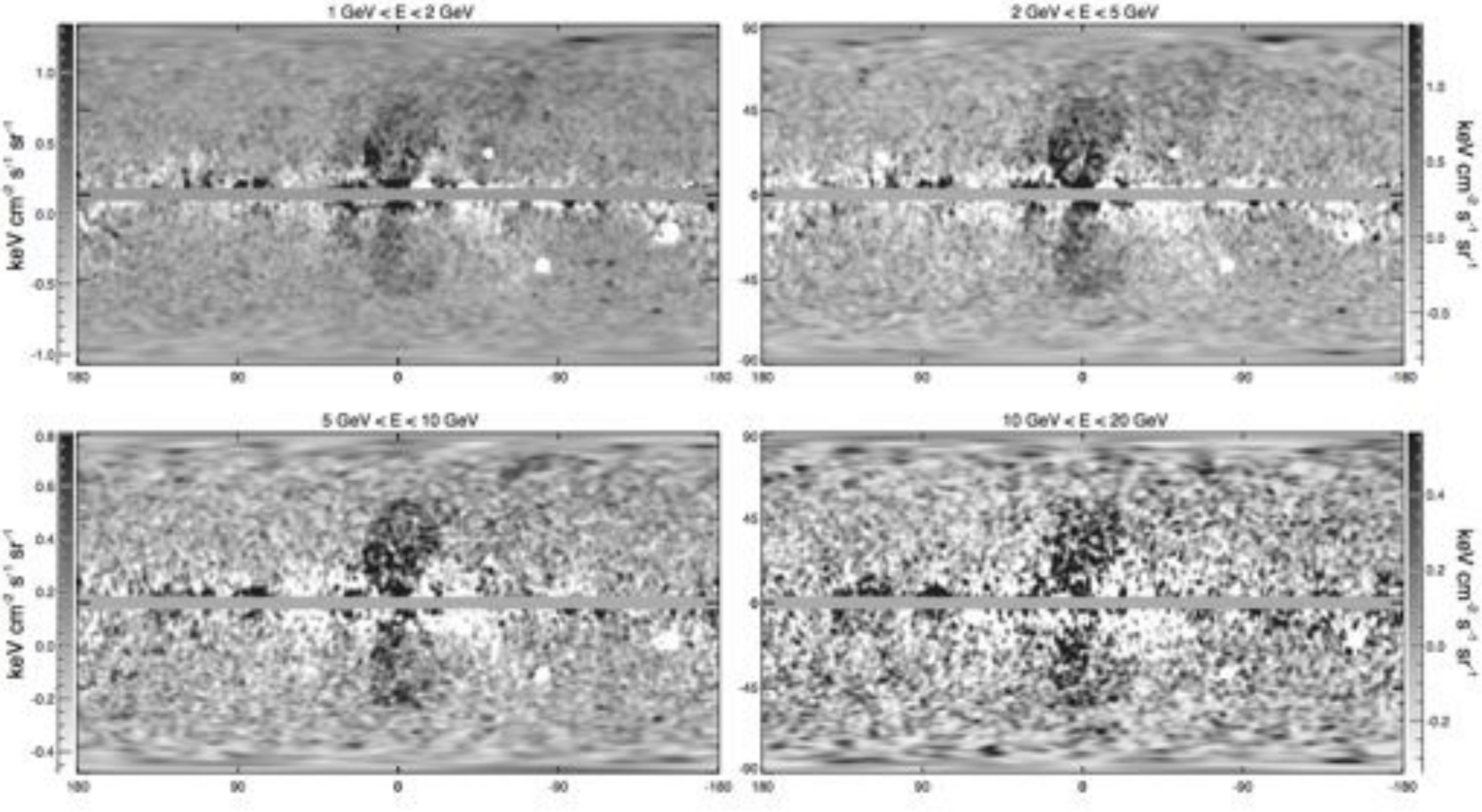




Su & Finkbeiner (2010)

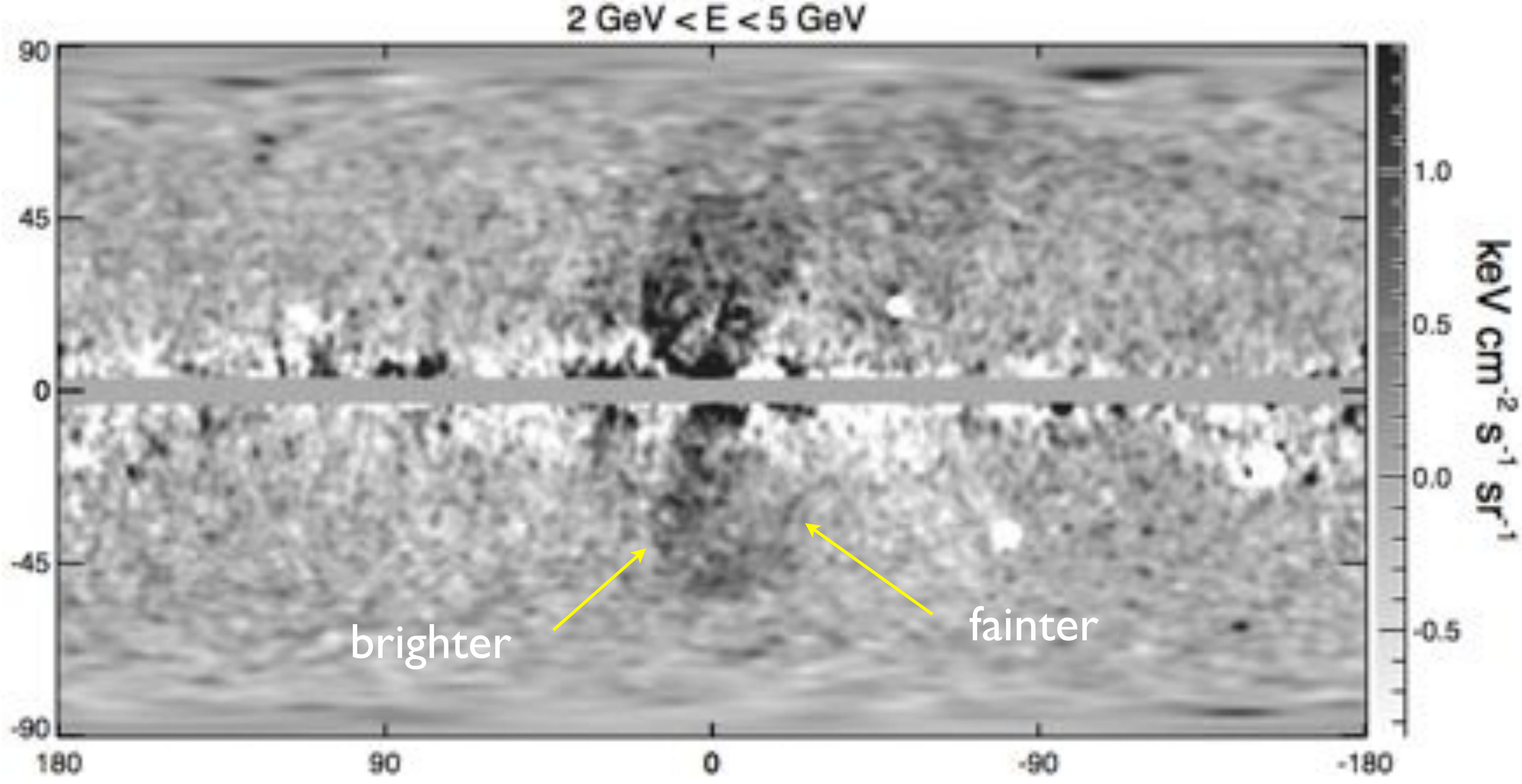
We also tried the Fermi diffuse model

Data minus Fermi diffuse model in 4 energy bins.   (1.6 yr data)



Su & Finkbeiner (2010)

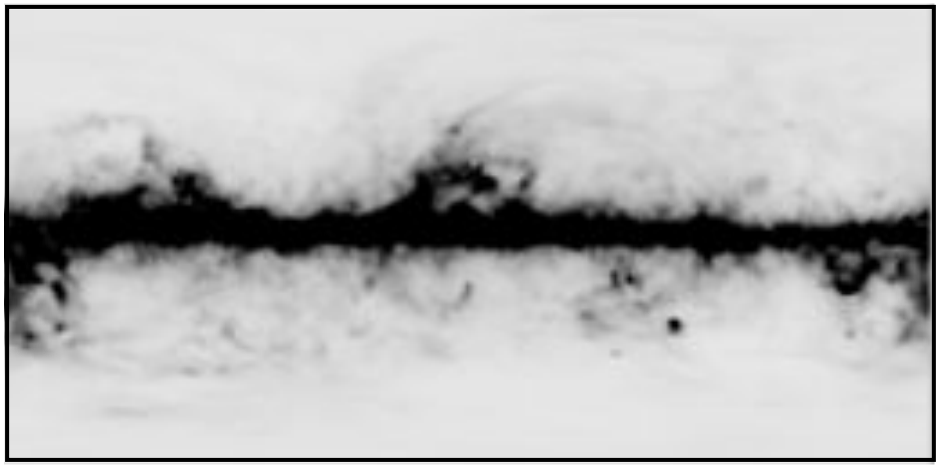
We always wondered why the left (east) part of the southern bubble was brighter, and if this was significant.

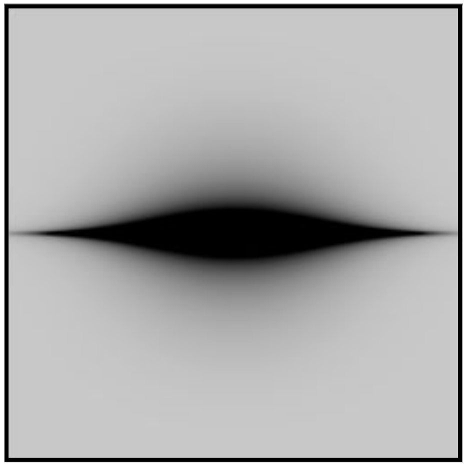


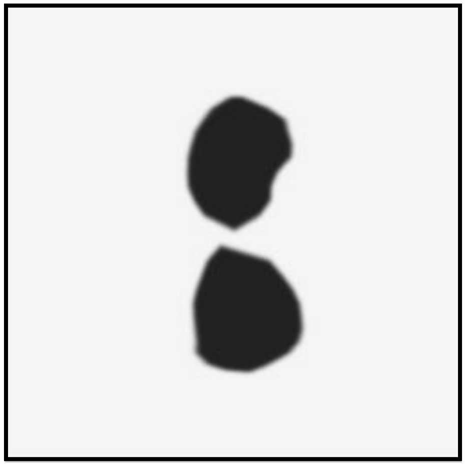
brighter

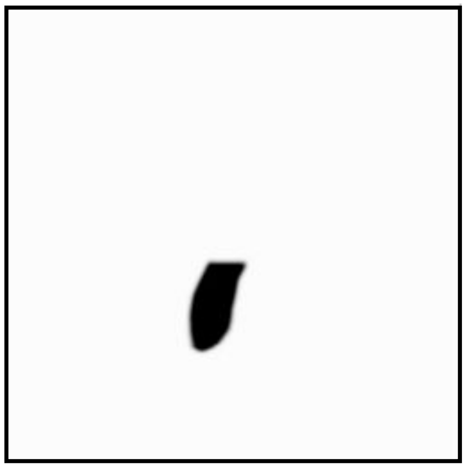
fainter

So we made another template...

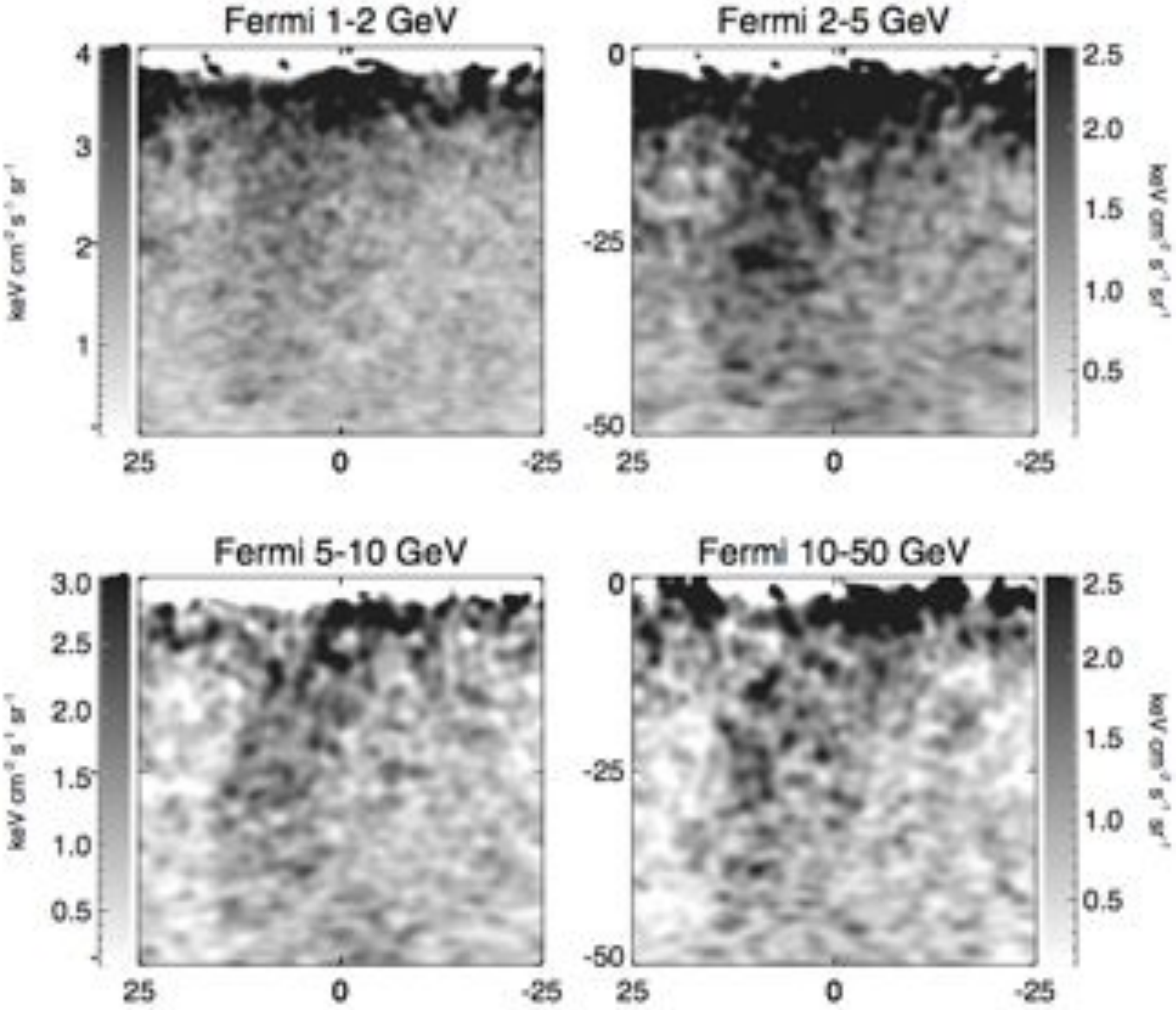

dust


disk


bubbles


cocoon

“Cocoon” feature on east (left) side of southern bubble

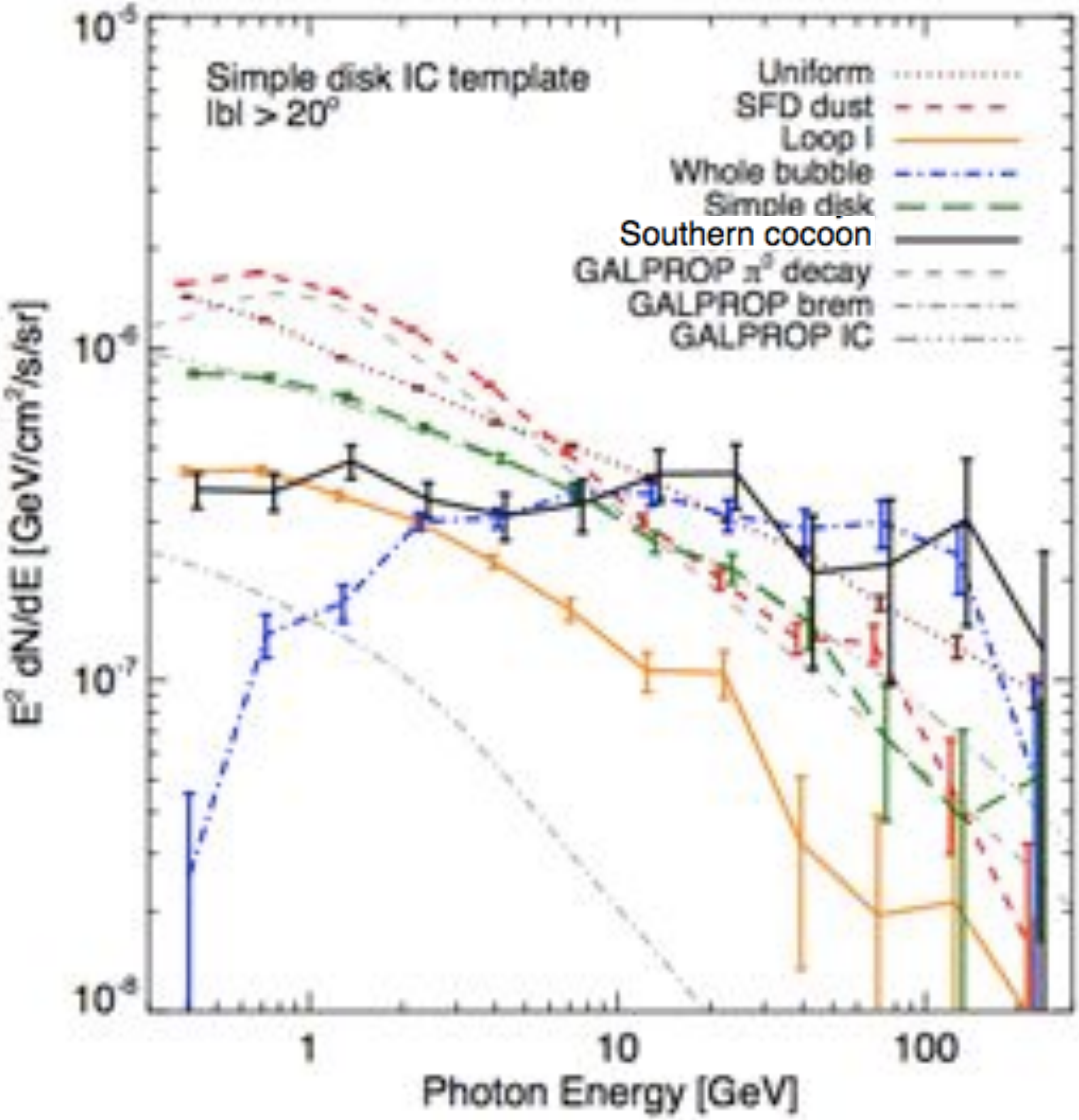


Su & Finkbeiner (2012)

The cocoon is detected as a distinct feature in
the multilinear regression at 12 sigma.

The spectrum is consistent with flat (in $E^2\, dN/dE$)
$L \sim 2\times10^{36}$ erg/sec for 1-100 GeV

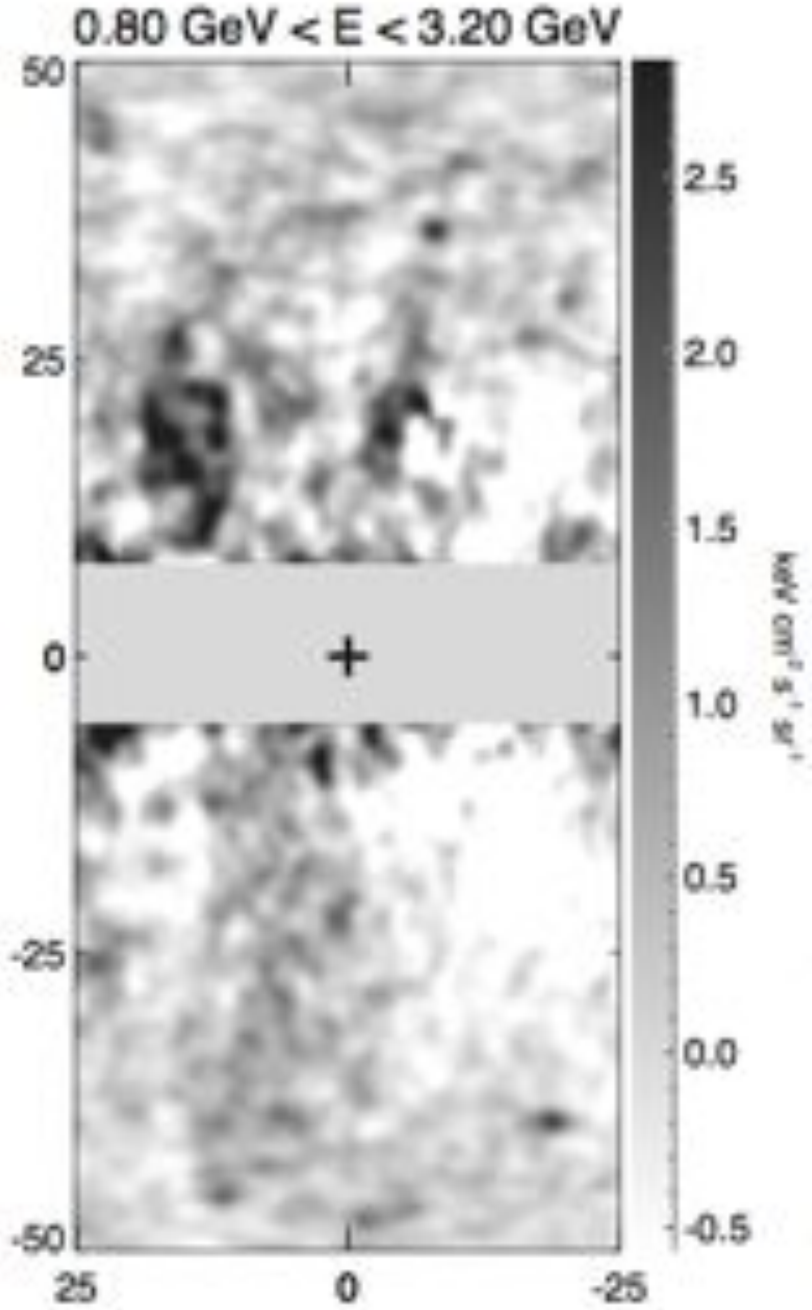
Su & Finkbeiner (2012)

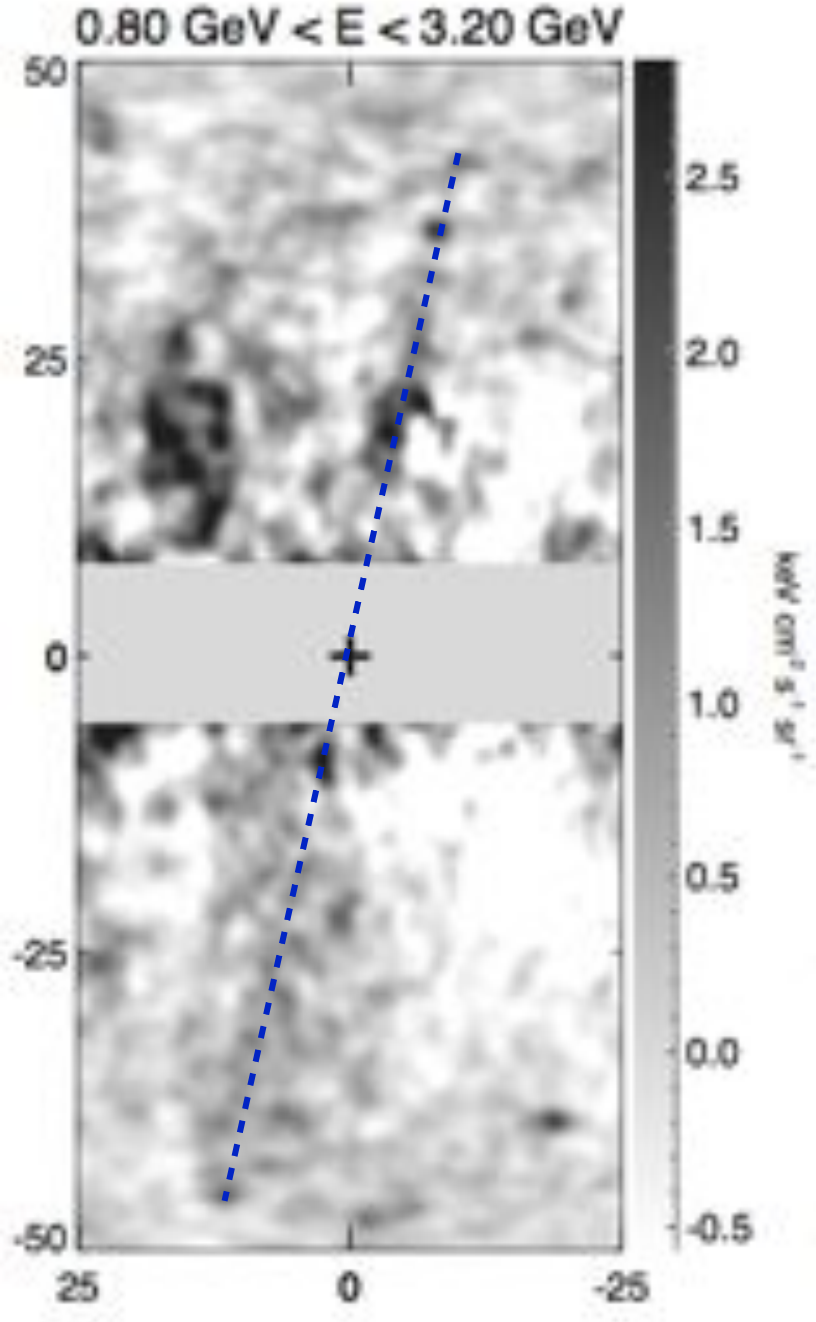


Su & Finkbeiner (2012)

It is tempting to imagine that this “cocoon” contains a jet, but the jet must be very faint.

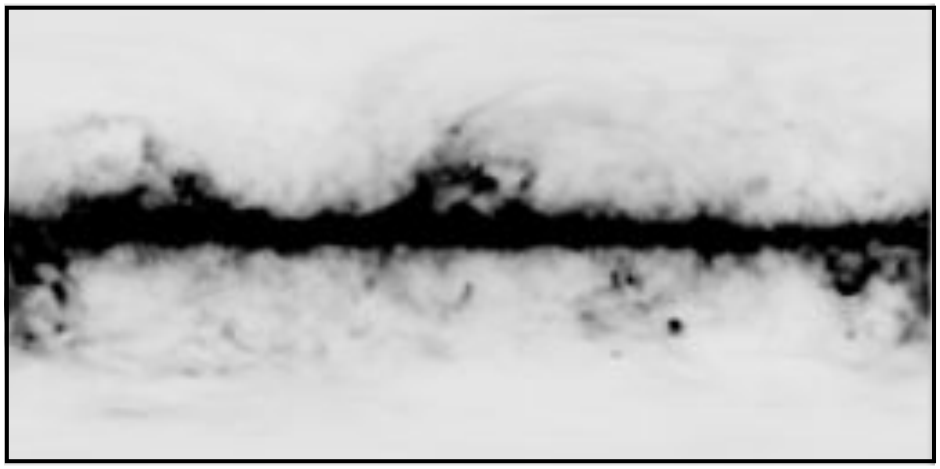
Let’s look more carefully at 90 arcmin maps, binning counts from 0.8 to 3.2 GeV, after subtracting the usual templates (but not the cocoon)...


0.80 GeV < E < 3.20 GeV
50
25
0
-25
-50
25
0
-25
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm⁻² s⁻¹ sr⁻¹

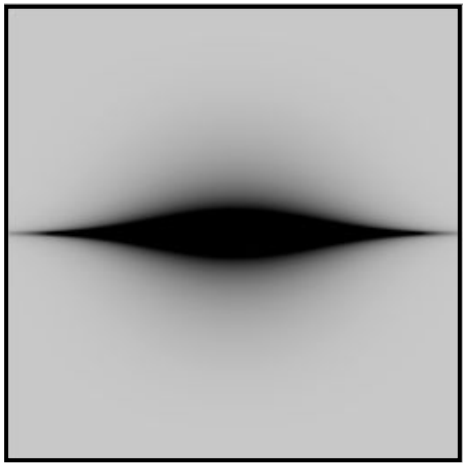

0.80 GeV < E < 3.20 GeV
50
25
0
-25
-50
25
0
-25
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
keV cm⁻² s⁻¹ sr⁻¹

So we made *yet* another template...

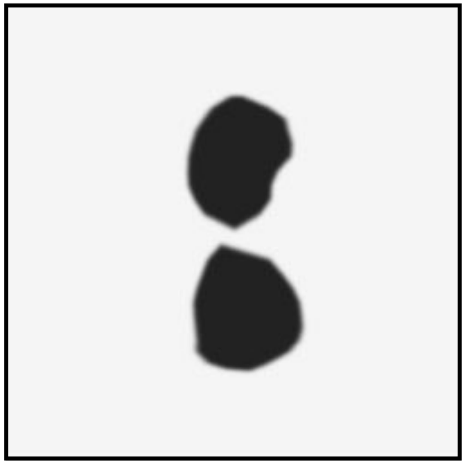
dust



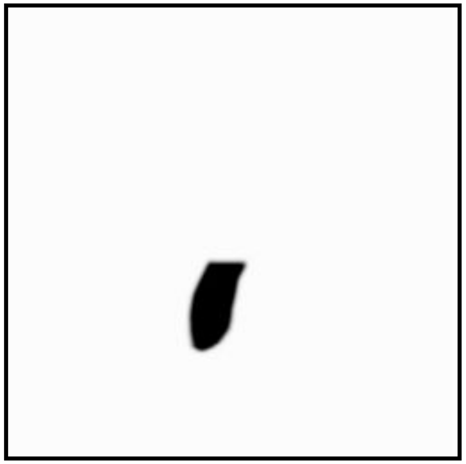
disk



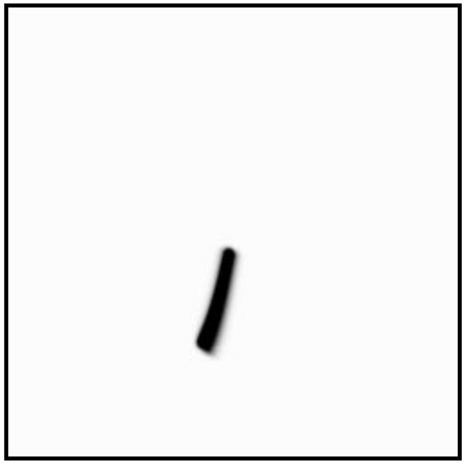
bubbles

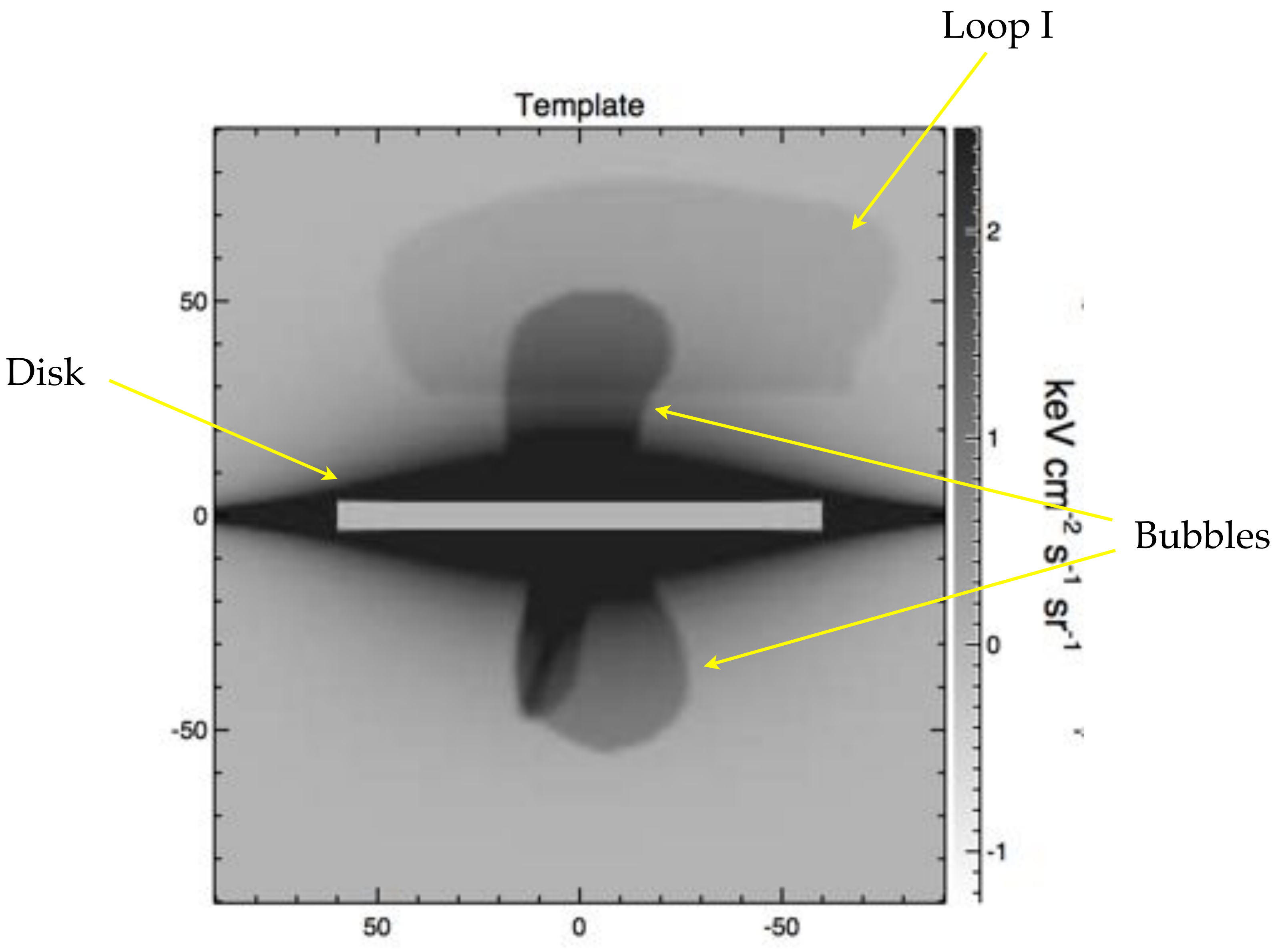


cocoon

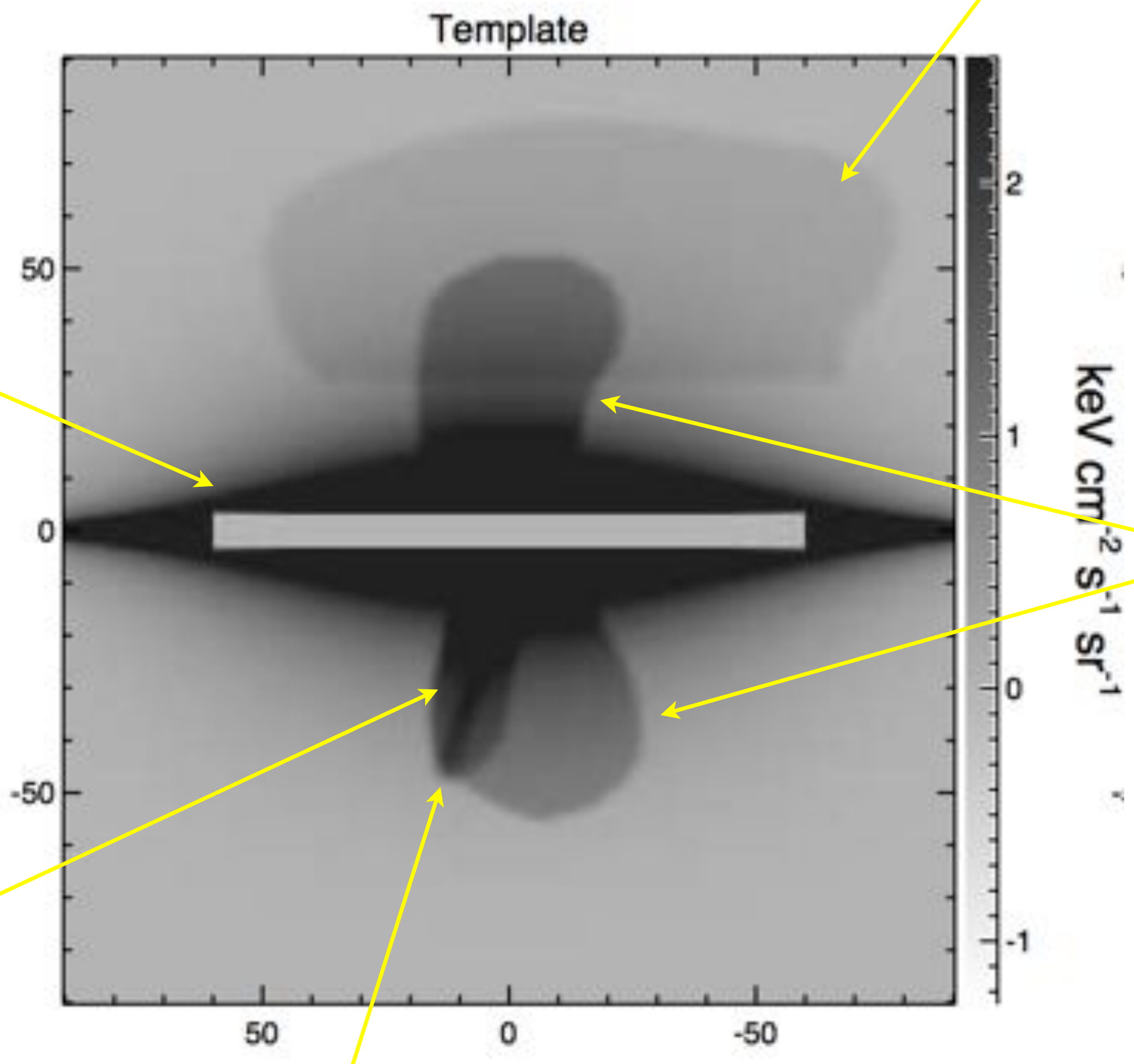


south jet





Su & Finkbeiner (2012)



Loop I

Disk

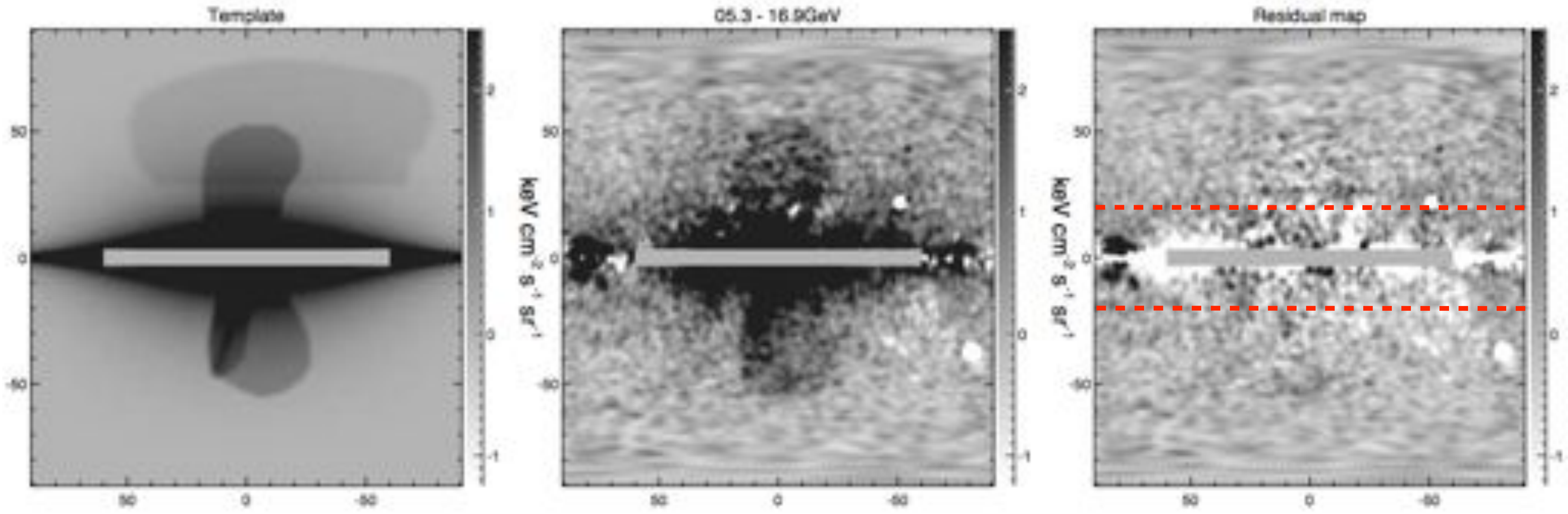
Bubbles

Cocoon

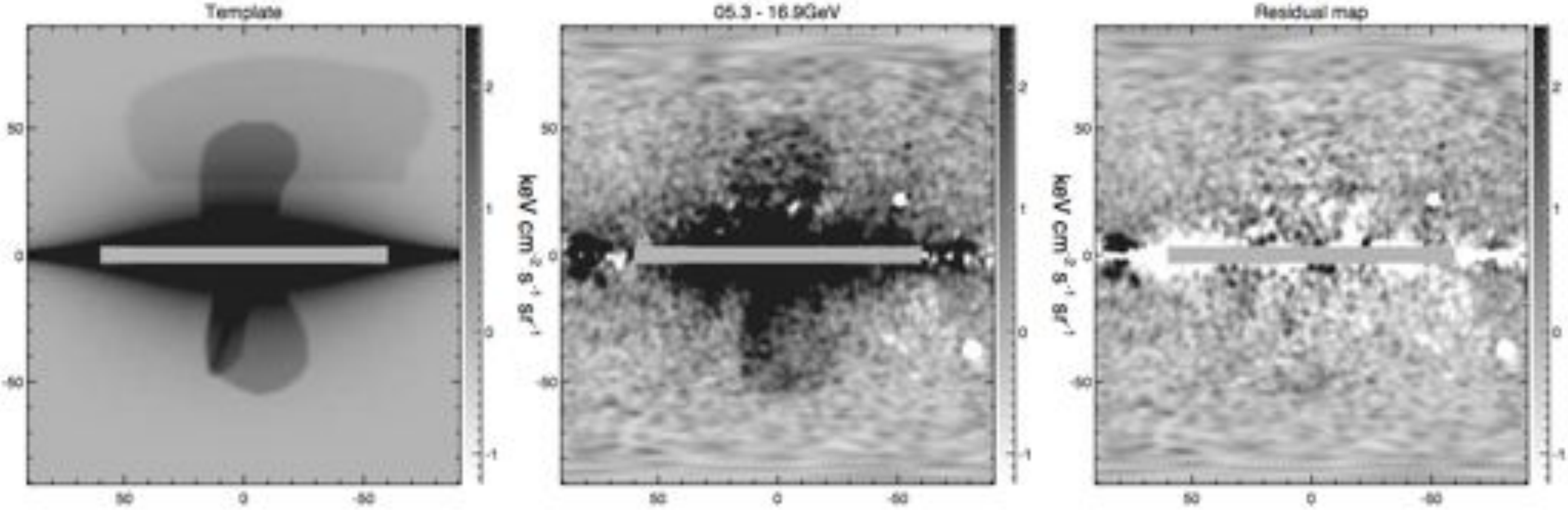
Jet

Su & Finkbeiner (2012)

Fit is done for $|b| > 20^{o}$



Su & Finkbeiner (2012)



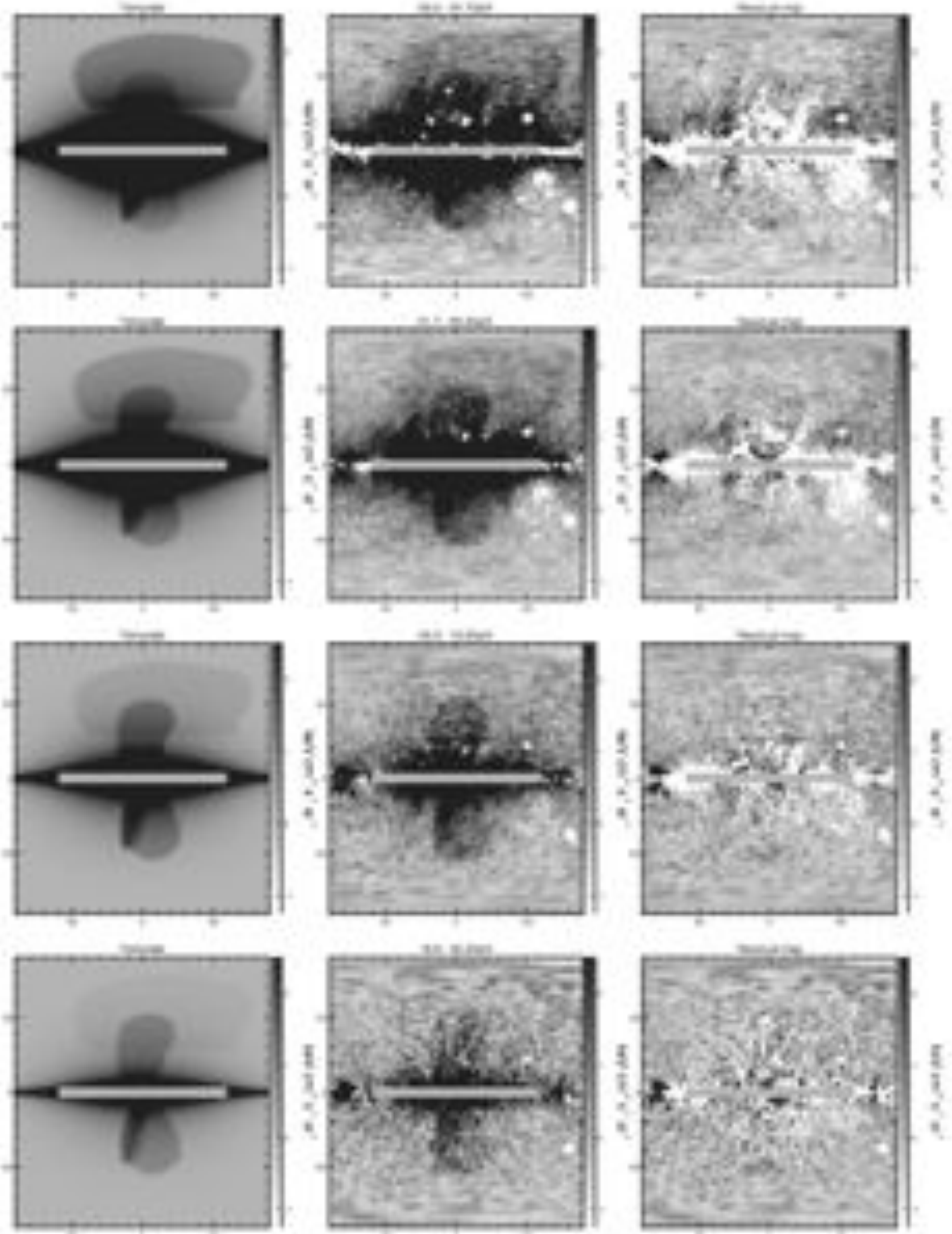
Template

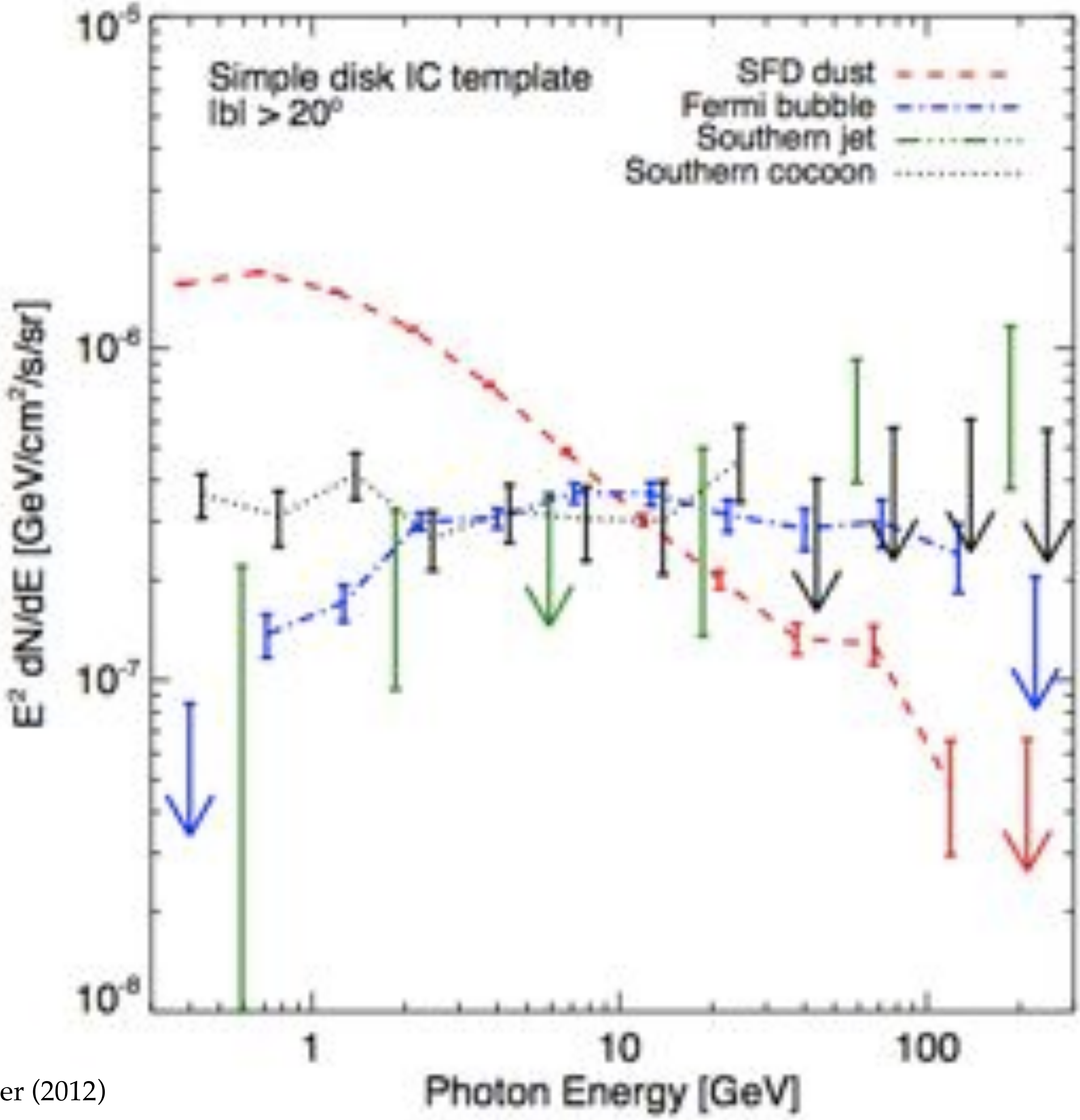
05.3 - 16.9GeV

Residual map

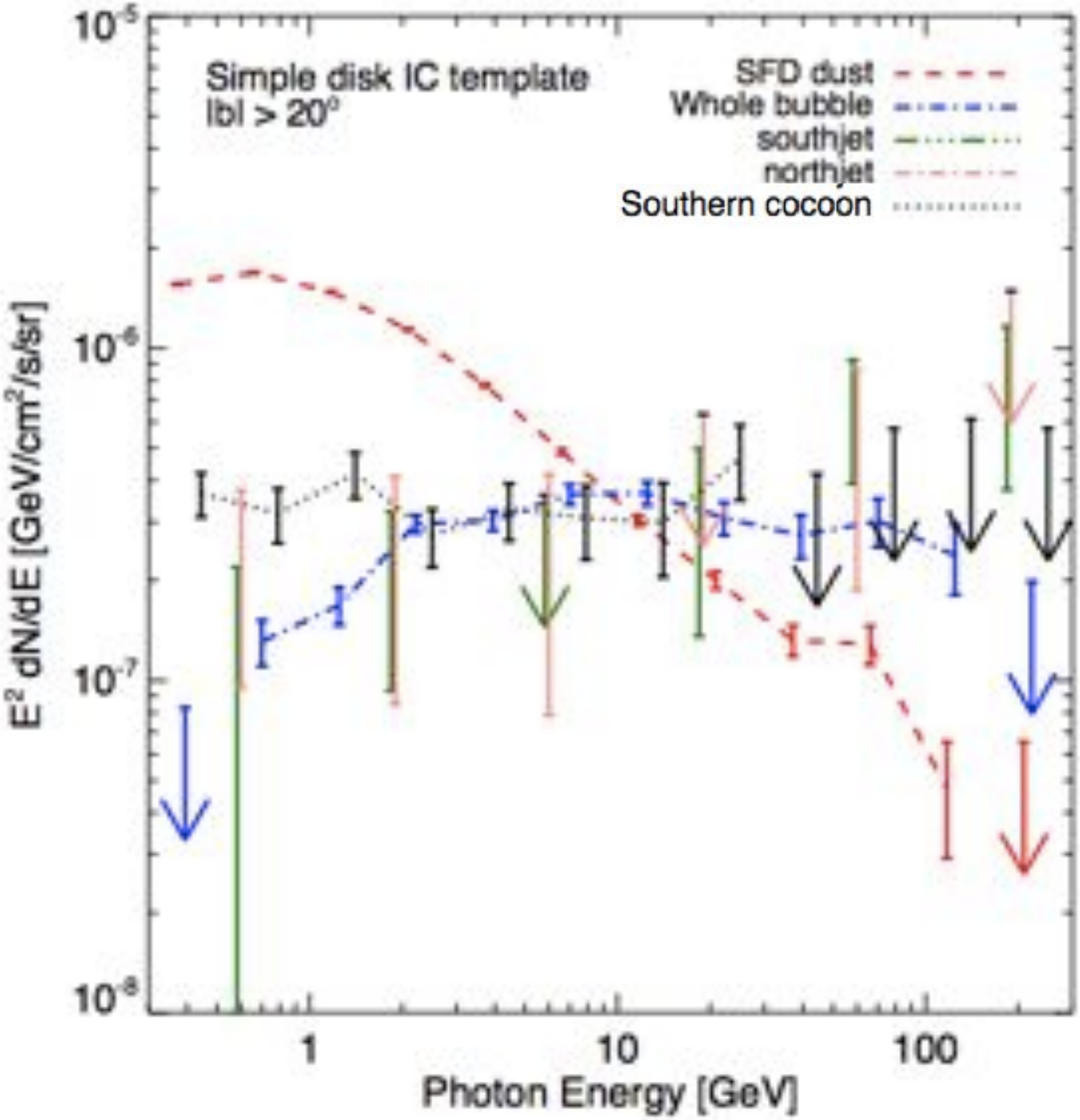
Now do this in each energy bin...

Su & Finkbeiner (2012)

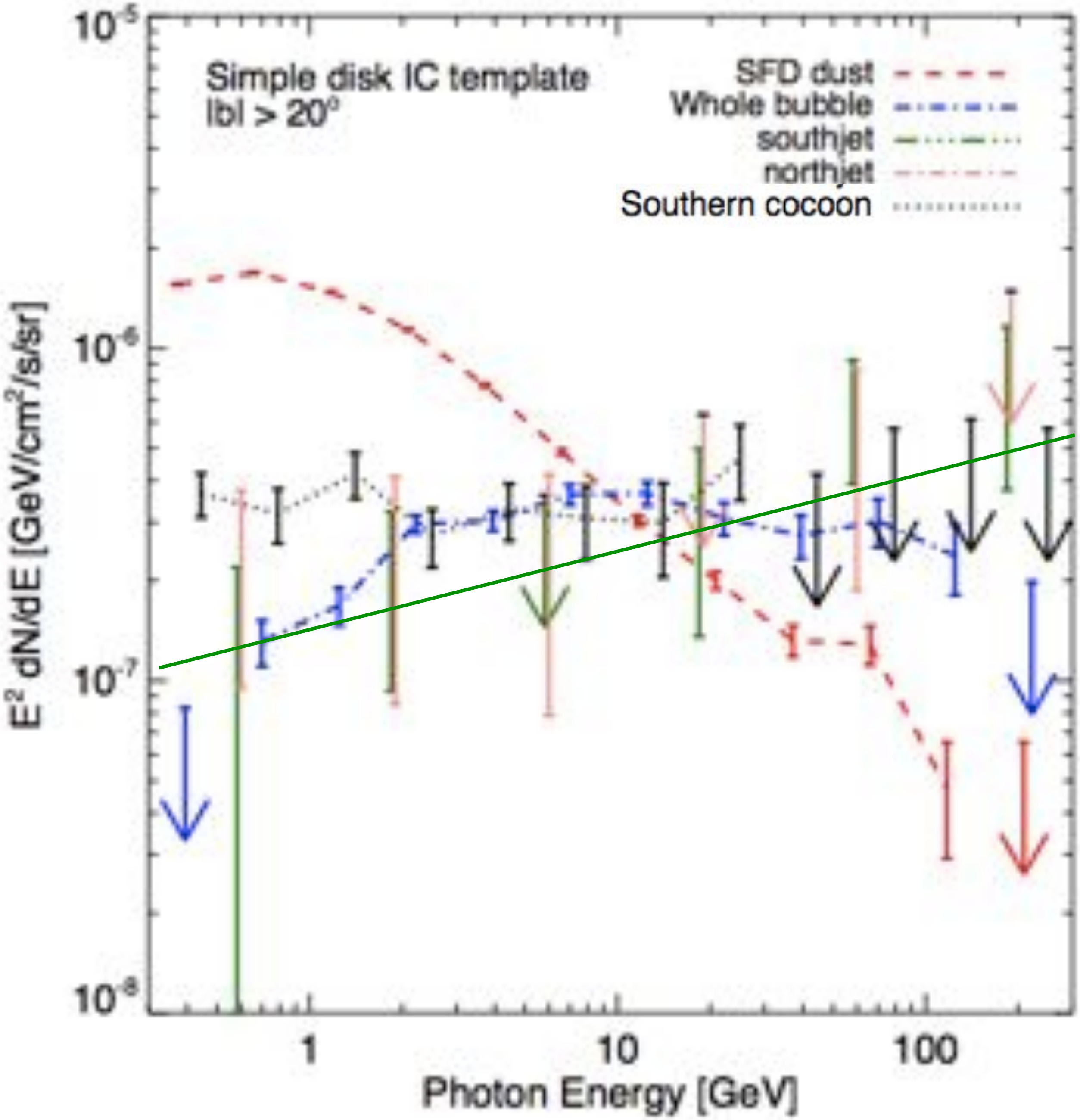




Su & Finkbeiner (2012)



Su & Finkbeiner (2012)



$E^2\ dN/dE \sim E^{0.2}$

Su & Finkbeiner (2012)

Significance (over 0.3-300 GeV):

- North jet: 3.1 sigma
- South jet: 4.1 sigma
- Jointly: 5.1 sigma

- Cocoon: 12 sigma

Conclusions

- With significance levels like these, some people would claim a discovery.
- We are calling this “evidence for” jets. We would like to see these confirmed at another wavelength.
- Future all-sky x-ray data (*eRosita*) and microwave data (*Planck*) may clarify the situation.
- See arXiv:1205.5852

Comments on the gamma-ray line(s):

There is serious concern about the excess of 130 GeV events in the limb photons.

We all agree this signal does not appear in the inner Galactic plane (the “inverse-ROI” region)

Need a hidden-variables theorem.

We (Weniger, Su, and I) have looked hard for some systematic (function of theta, phi, etc.) that could do this and have found nothing. (See Weniger’s talk)

We will keep looking...

II. Gamma-ray lines

The LAT has many ways to search for dark matter, e.g.:
- Emission from dwarf Galaxies
- Emission from the Galactic center
- **Line emission anywhere!**

II. Gamma-ray lines

No astrophysical process can make a gamma-ray line.

II. Gamma-ray lines

No astrophysical process can make a gamma-ray line.

“Cold ultrarelativistic pulsar winds as potential sources of galactic gamma-ray lines above 100 GeV”
F. Aharonian, D. Khangulyan, D. Malyshev

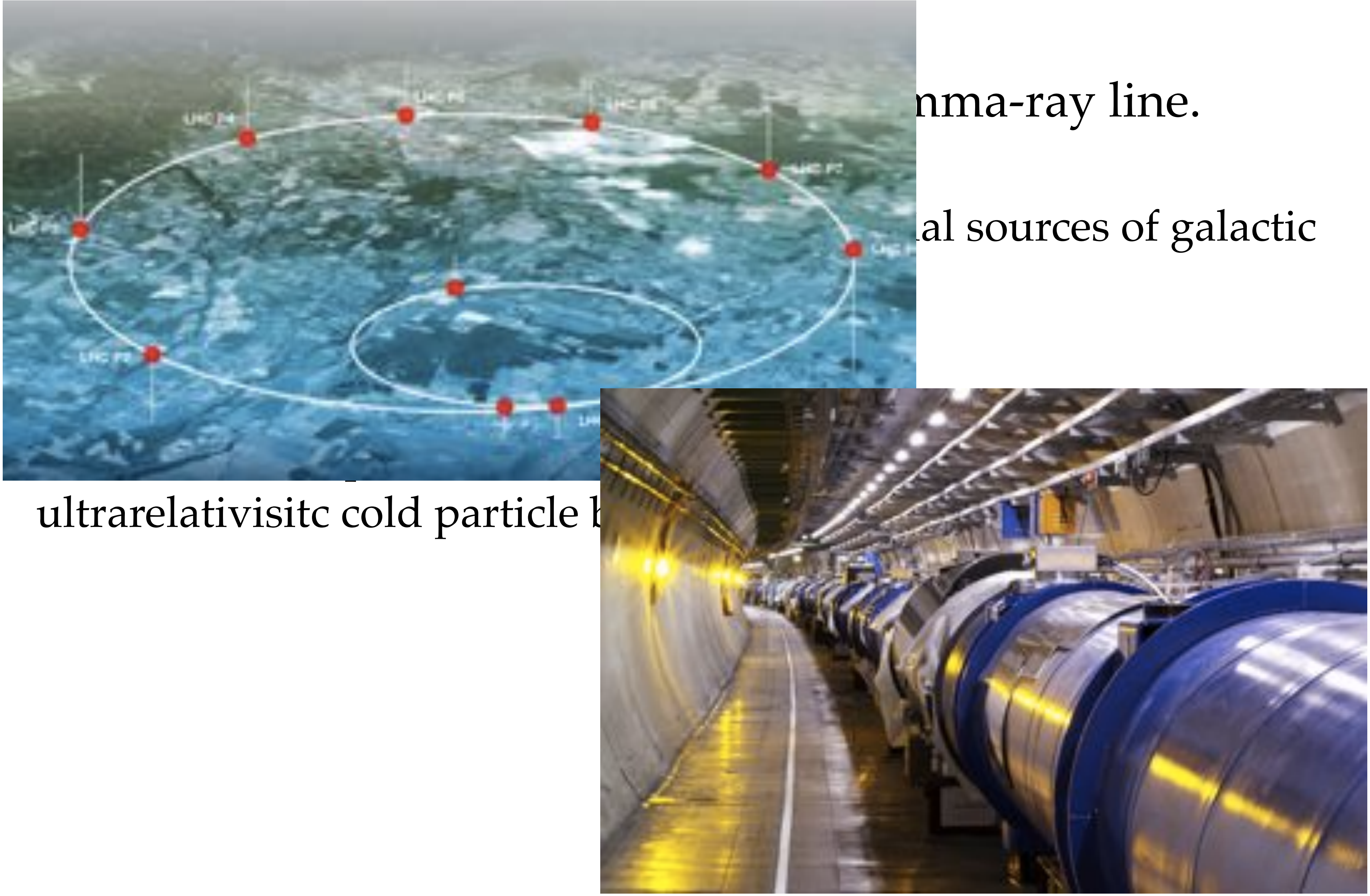
As an existence proof - there is at least one such source of ultrarelativisitc cold particle beams in the Galaxy:

II. Gamma-ray lines

nma-ray line.

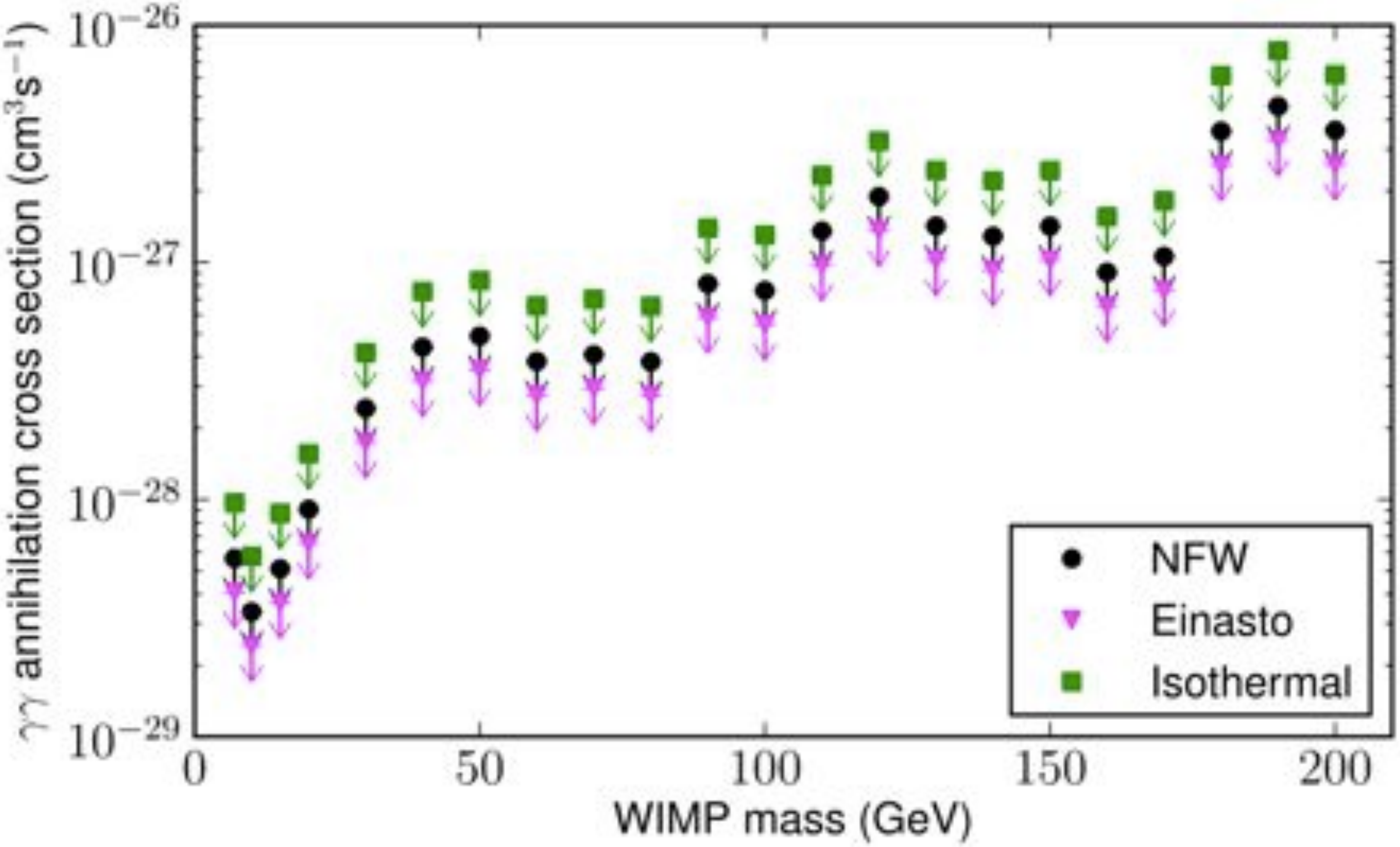
al sources of galactic

ultrarelativisitc cold particle b

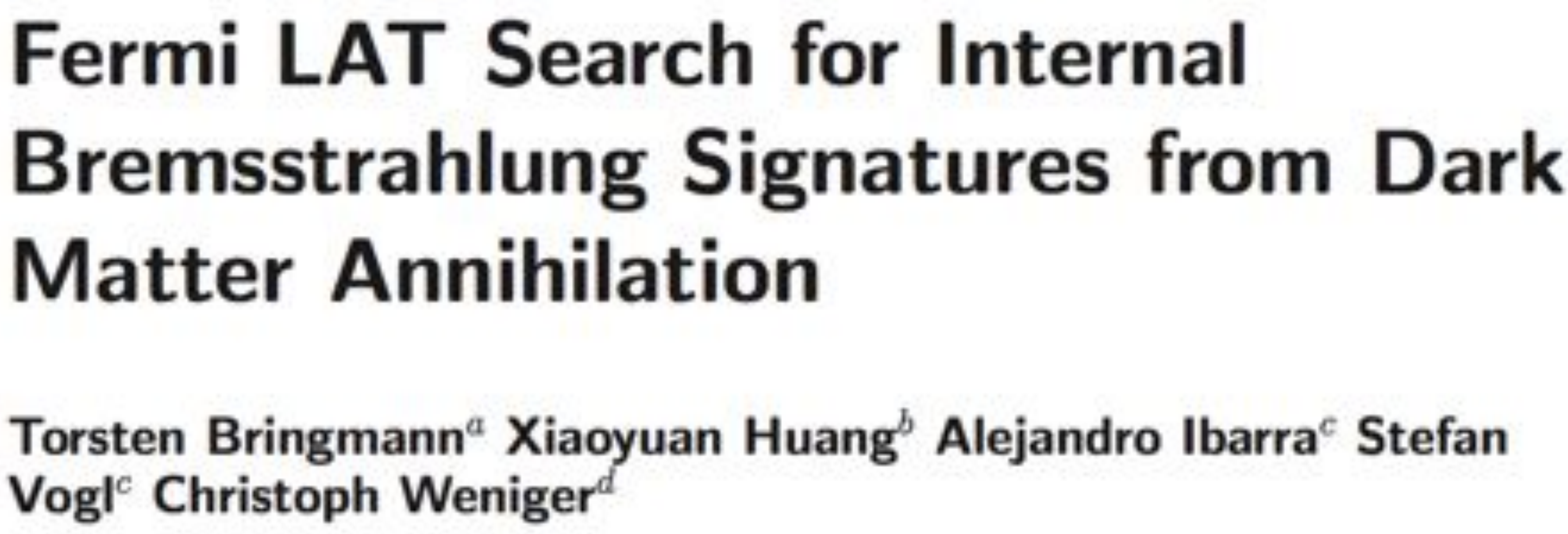


Best limits so far:

The LAT collaboration has a recent paper posted by Elliott Bloom (Ackermann et al., 1205.2739)



However, there have been hints of something at ~ 130 GeV

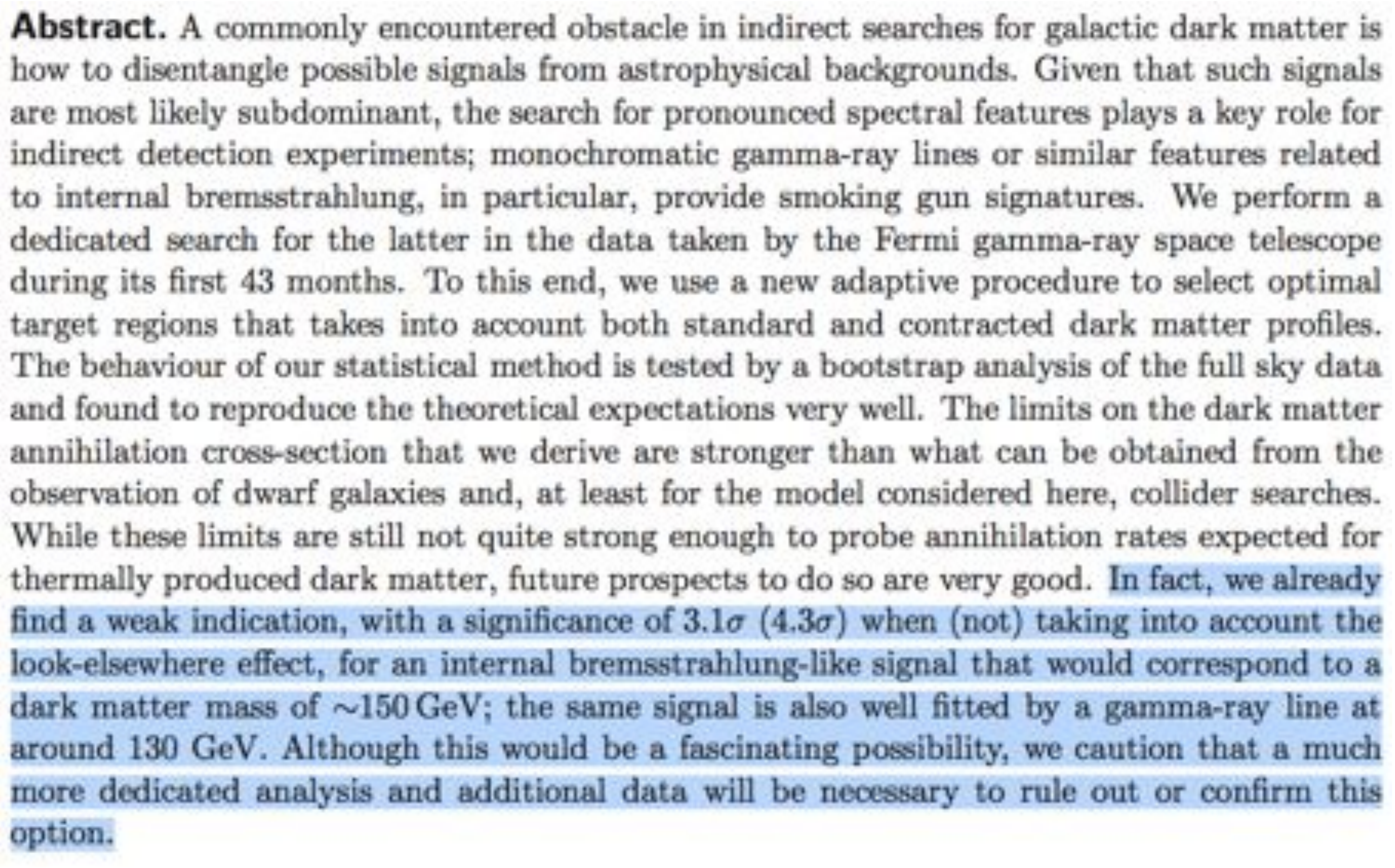


Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

Torsten Bringmann[a] Xiaoyuan Huang[b] Alejandro Ibarra[c] Stefan Vogl[c] Christoph Weniger[d]

(30 March, 2012)

Bringmann et al.:



Abstract. A commonly encountered obstacle in indirect searches for galactic dark matter is how to disentangle possible signals from astrophysical backgrounds. Given that such signals are most likely subdominant, the search for pronounced spectral features plays a key role for indirect detection experiments; monochromatic gamma-ray lines or similar features related to internal bremsstrahlung, in particular, provide smoking gun signatures. We perform a dedicated search for the latter in the data taken by the Fermi gamma-ray space telescope during its first 43 months. To this end, we use a new adaptive procedure to select optimal target regions that takes into account both standard and contracted dark matter profiles. The behaviour of our statistical method is tested by a bootstrap analysis of the full sky data and found to reproduce the theoretical expectations very well. The limits on the dark matter annihilation cross-section that we derive are stronger than what can be obtained from the observation of dwarf galaxies and, at least for the model considered here, collider searches. While these limits are still not quite strong enough to probe annihilation rates expected for thermally produced dark matter, future prospects to do so are very good. In fact, we already find a weak indication, with a significance of 3.1σ (4.3σ) when (not) taking into account the look-elsewhere effect, for an internal bremsstrahlung-like signal that would correspond to a dark matter mass of $\sim$150 GeV; the same signal is also well fitted by a gamma-ray line at around 130 GeV. Although this would be a fascinating possibility, we caution that a much more dedicated analysis and additional data will be necessary to rule out or confirm this option.

Bringmann et al.

Looking for internal bremsstrahlung:

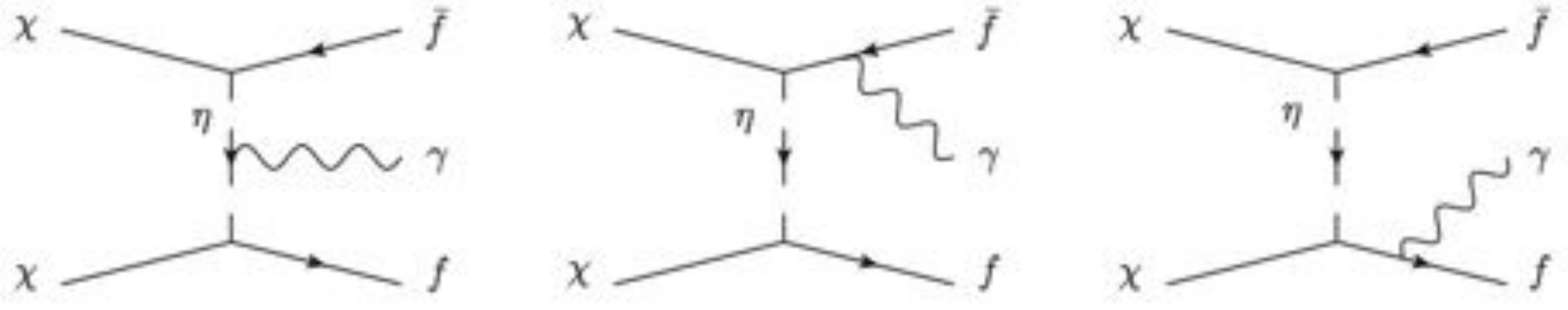
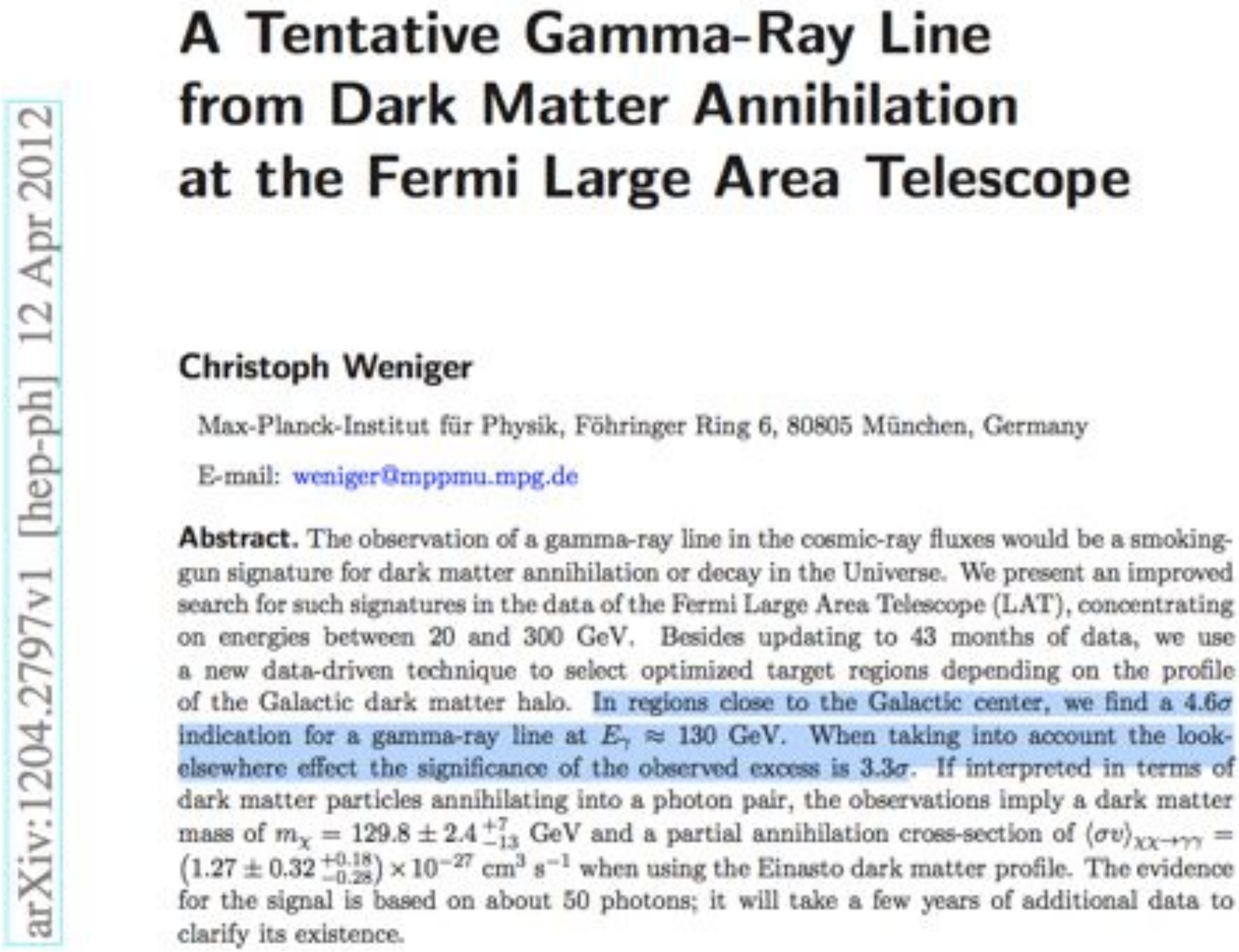


Figure 1. Feynman diagrams of the processes that contribute in leading order to the three-body annihilation cross-section and produce internal bremsstrahlung. The first diagram very roughly corresponds to VIB, the second and third to FSR (but note that these contributions can be properly defined and separated in a gauge-invariant way [19]).

Next, Christoph Weniger weighed in with a solo paper looking for a 130 GeV line:



arXiv:1204.2797v1 [hep-ph] 12 Apr 2012

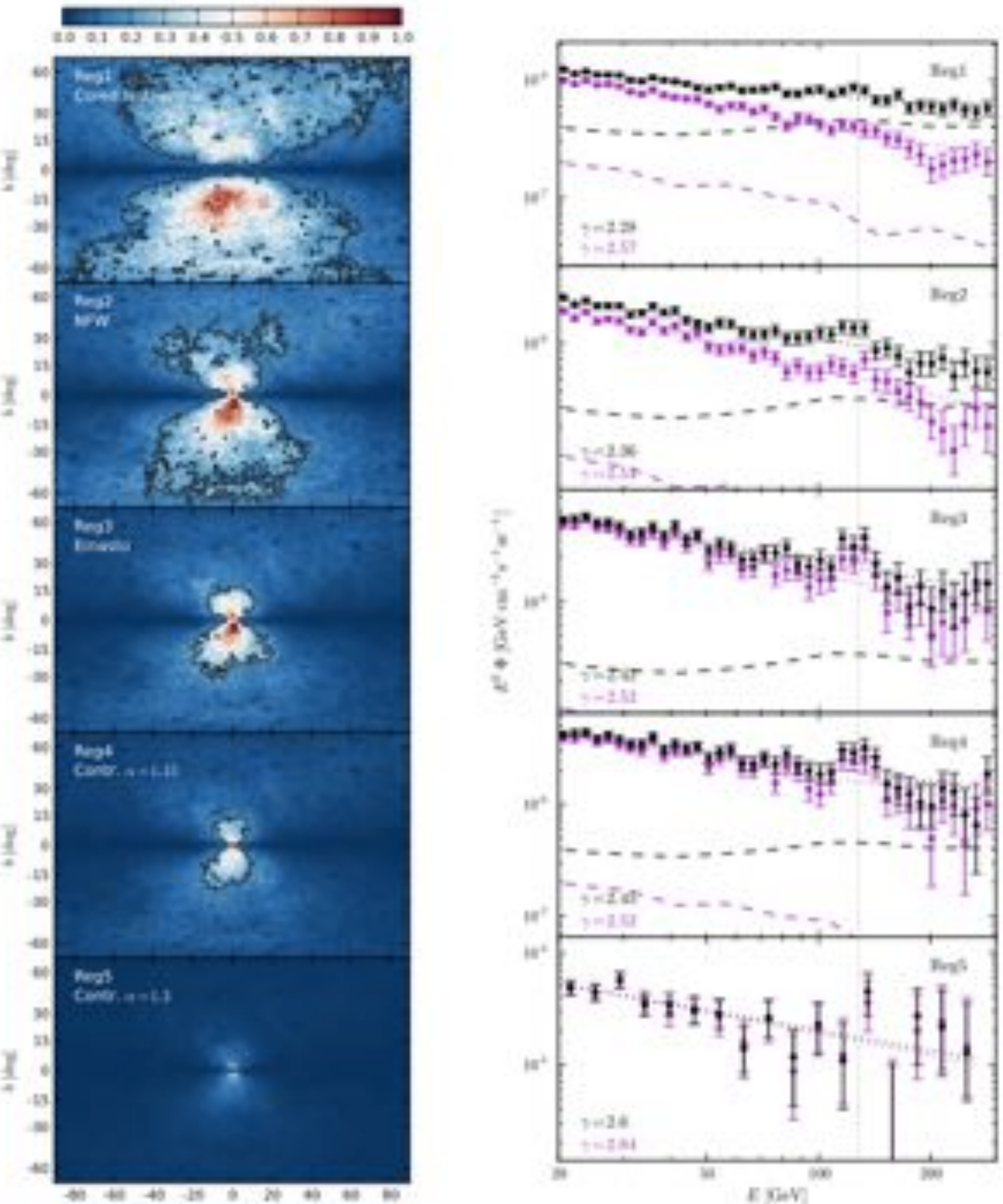
A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

Christoph Weniger

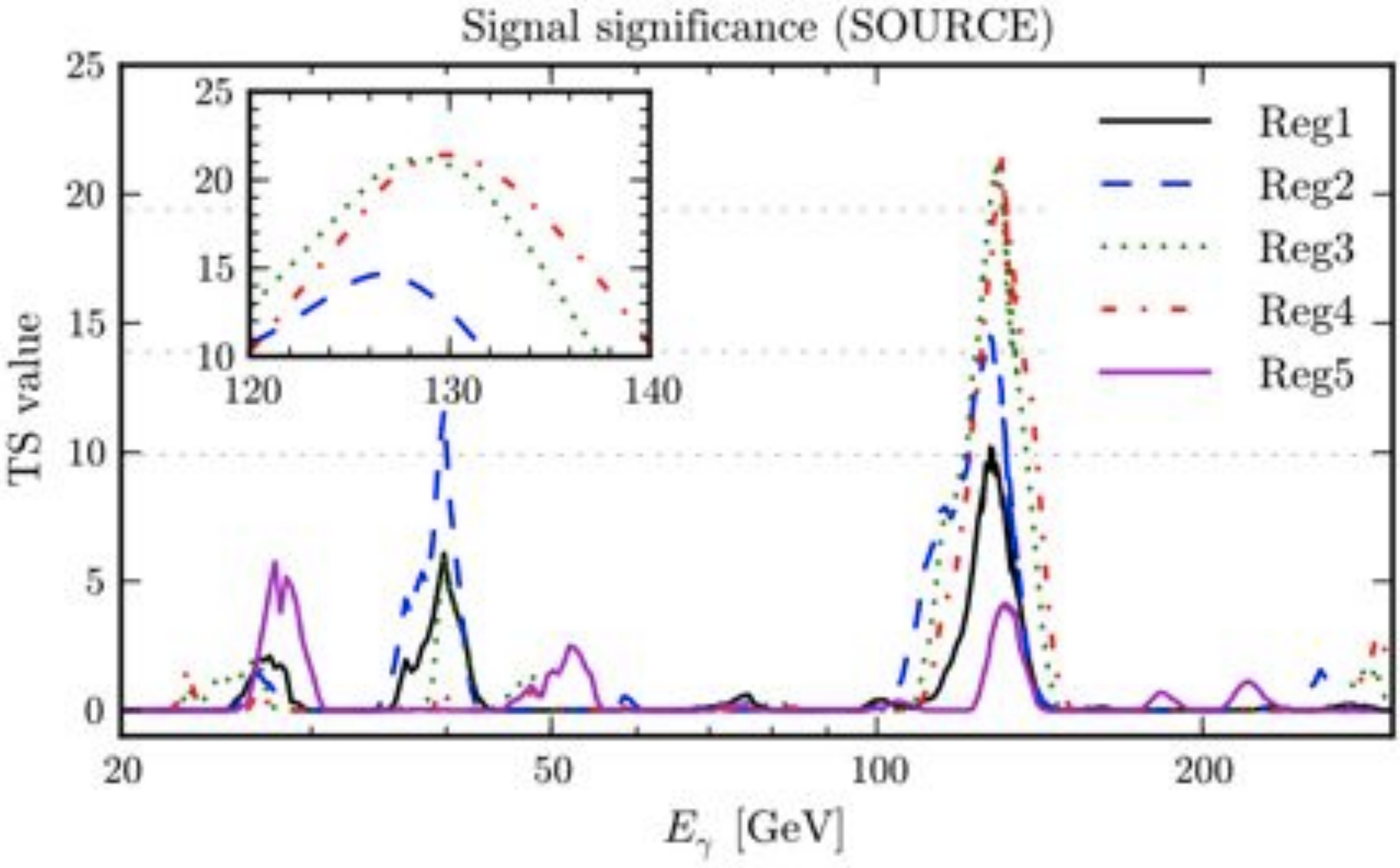
Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

E-mail: weniger@mppmu.mpg.de

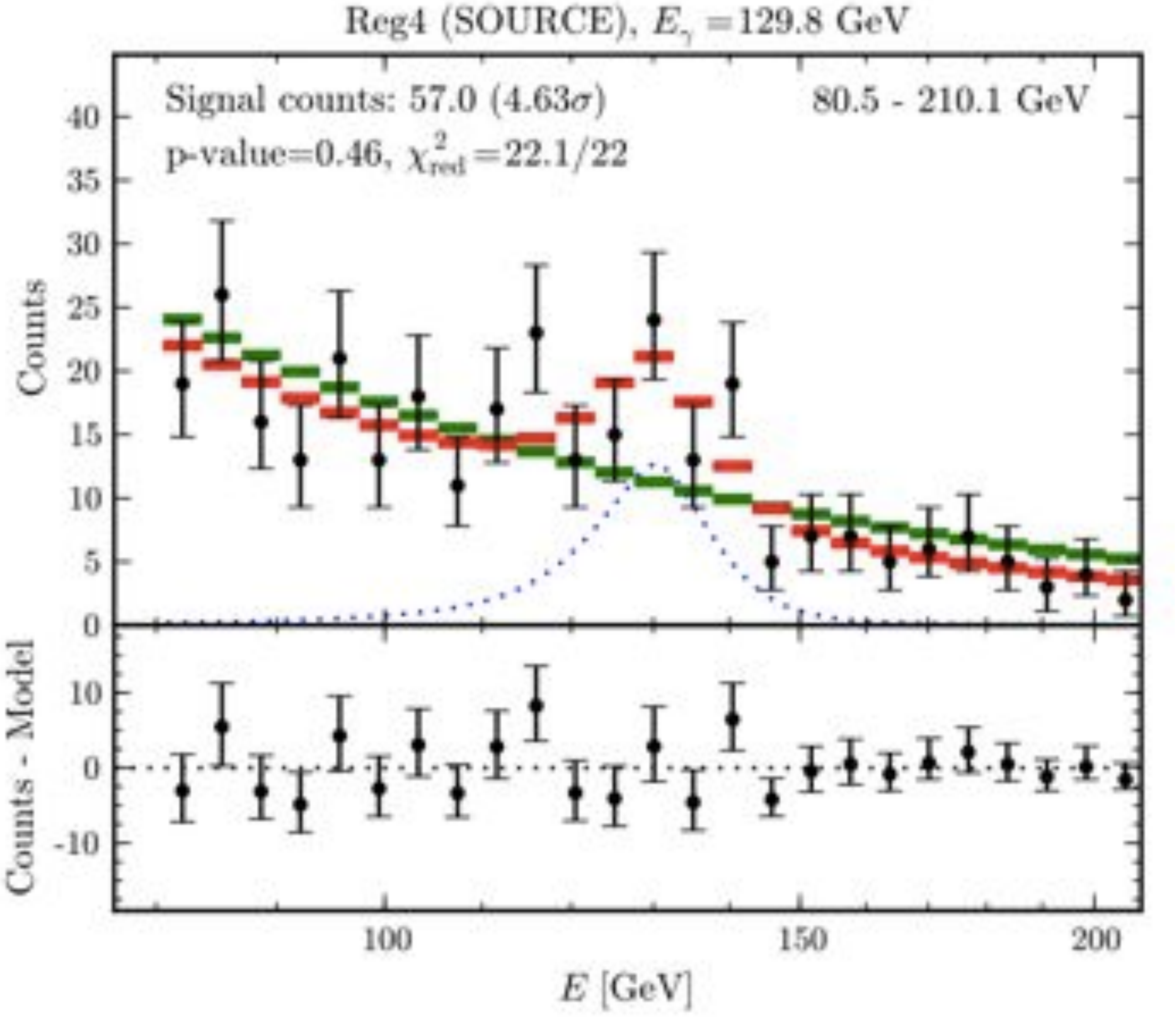
Abstract. The observation of a gamma-ray line in the cosmic-ray fluxes would be a smoking-gun signature for dark matter annihilation or decay in the Universe. We present an improved search for such signatures in the data of the Fermi Large Area Telescope (LAT), concentrating on energies between 20 and 300 GeV. Besides updating to 43 months of data, we use a new data-driven technique to select optimized target regions depending on the profile of the Galactic dark matter halo. In regions close to the Galactic center, we find a 4.6σ indication for a gamma-ray line at $E_\gamma \approx 130$ GeV. When taking into account the look-elsewhere effect the significance of the observed excess is 3.3σ. If interpreted in terms of dark matter particles annihilating into a photon pair, the observations imply a dark matter mass of $m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}$ GeV and a partial annihilation cross-section of $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$ when using the Einasto dark matter profile. The evidence for the signal is based on about 50 photons; it will take a few years of additional data to clarify its existence.


0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Reg1
Reg2
NFW
Reg3
Einasto
Reg4
Reg5
b [deg]
60
30
15
0
-15
-30
-60
-80 -60 -40 -20 0 20 40 60 80
l [deg]
$\gamma = 2.28$
$\gamma = 2.57$
$\gamma = 2.36$
$\gamma = 2.47$
$\gamma = 2.52$
$\gamma = 2.6$
$\gamma = 2.64$
$E^2\,\Phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
20
50
100
200
E [GeV]

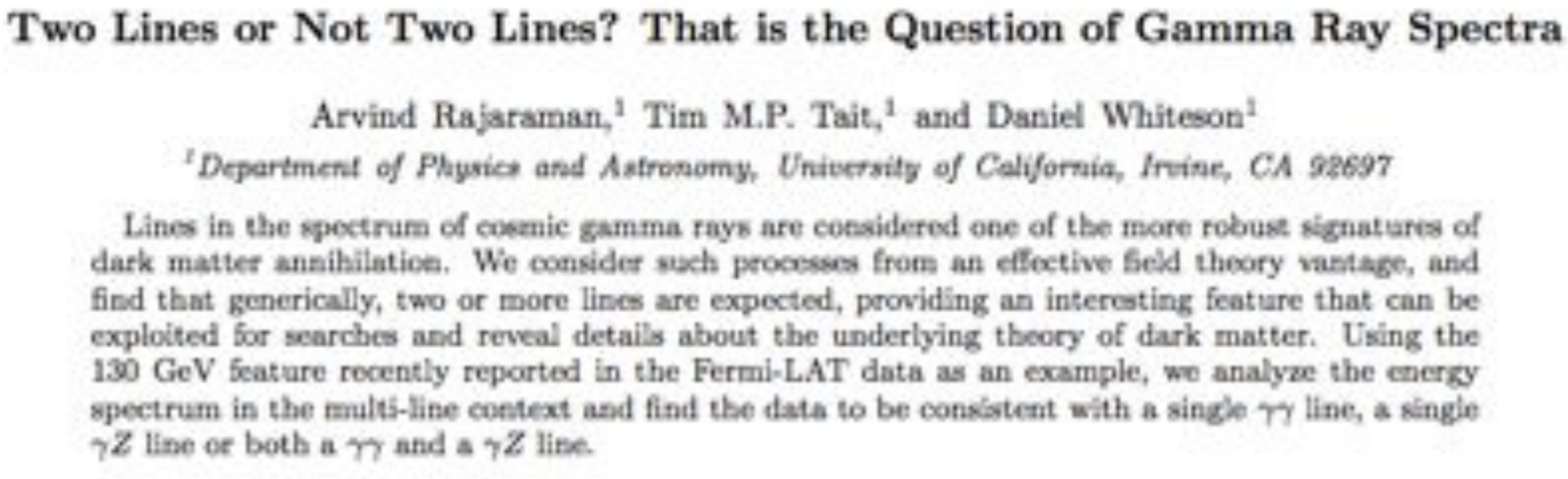
In fact, a line fits better than the VIB in Bringmann et al.



Tantalizing, but not real convincing yet...



This led the theorists to wonder if there is more than one line... (21 May, 1205.4723)



Two Lines or Not Two Lines? That is the Question of Gamma Ray Spectra

Arvind Rajaraman,[1] Tim M.P. Tait,[1] and Daniel Whiteson[1]

[1]Department of Physics and Astronomy, University of California, Irvine, CA 92697

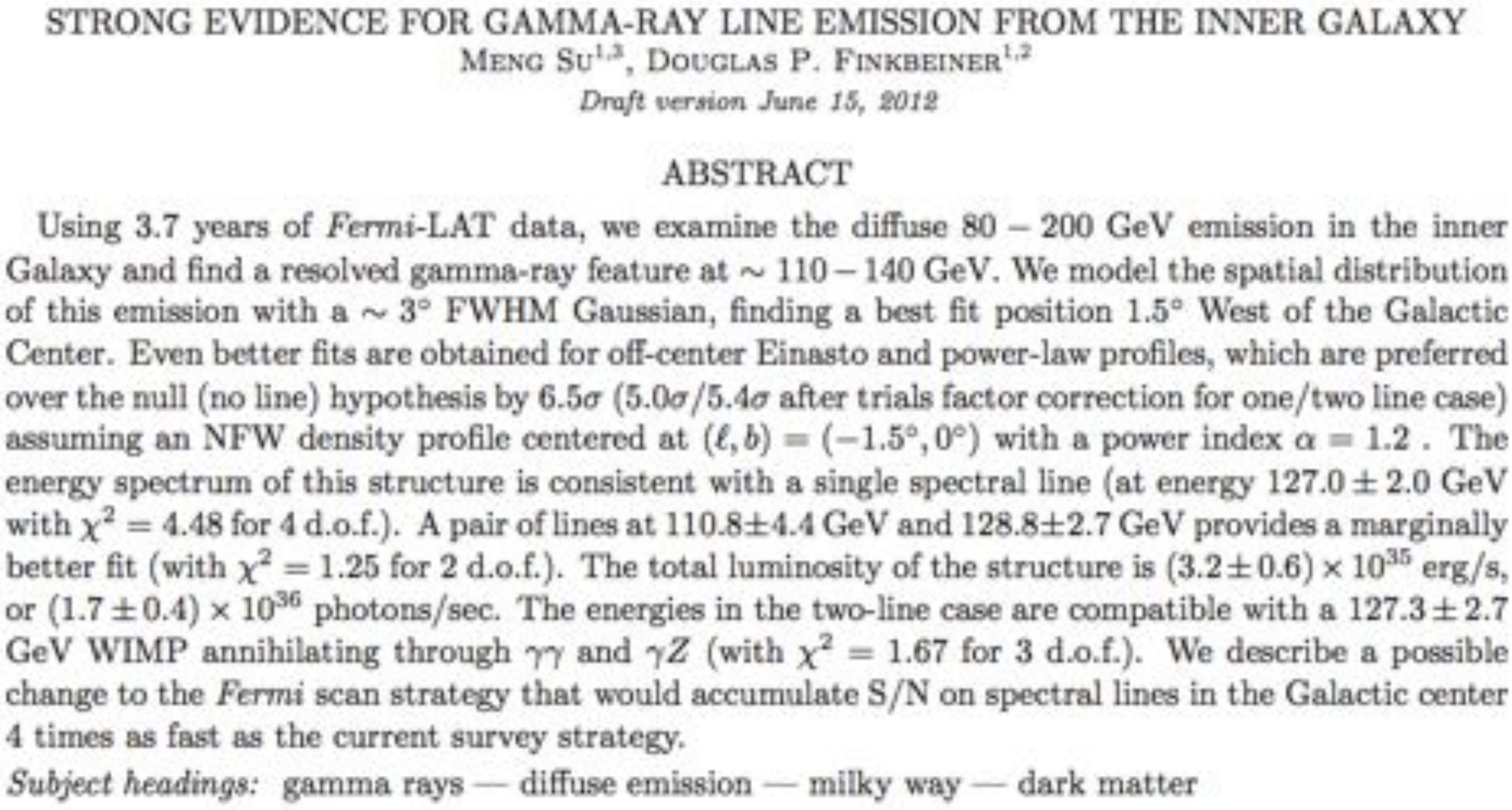
Lines in the spectrum of cosmic gamma rays are considered one of the more robust signatures of dark matter annihilation. We consider such processes from an effective field theory vantage, and find that generically, two or more lines are expected, providing an interesting feature that can be exploited for searches and reveal details about the underlying theory of dark matter. Using the 130 GeV feature recently reported in the Fermi-LAT data as an example, we analyze the energy spectrum in the multi-line context and find the data to be consistent with a single $\gamma\gamma$ line, a single γZ line or both a $\gamma\gamma$ and a γZ line.

$$E_\gamma = m_\chi \left(1 - \frac{m_X^2}{4m_\chi^2}\right)$$

Timeline of 130 GeV line:

- 12 April - Weniger (looks like a line at 130 GeV) (22 citations)
- 26 April - Profumo & Linden (is it the Fermi bubbles?)
- 10 May - Tempel et al., (No, it's not a bubble, could be DM)
- 21 May - Boyarsky (lots of blobs, probably not DM)
- 25 May - Acharya, Kane... (It's a Wino)
- 29 May - Bergstrom (reviews claims as part of larger review)
- 30 May - Jim Cline (two lines)
- 30 May - Buckley & Hooper (theoretical models)
- 5 June - Geringer-Sameth & Koushiappas (Line search in dwarfs)
- 7 June - Su & Finkbeiner (Off center 1.5 deg, Einasto, 6.5 sigma, use high energy-resolution events)
- 13 June - Weiner & Yavin (MiDM explains it)
- (*and 21 other papers...*)

Now for our paper:



STRONG EVIDENCE FOR GAMMA-RAY LINE EMISSION FROM THE INNER GALAXY

Meng Su[1,3], Douglas P. Finkbeiner[1,2]

Draft version June 15, 2012

ABSTRACT

Using 3.7 years of *Fermi*-LAT data, we examine the diffuse 80 – 200 GeV emission in the inner Galaxy and find a resolved gamma-ray feature at $\sim 110-140$ GeV. We model the spatial distribution of this emission with a $\sim 3°$ FWHM Gaussian, finding a best fit position 1.5° West of the Galactic Center. Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5σ ($5.0\sigma/5.4\sigma$ after trials factor correction for one/two line case) assuming an NFW density profile centered at $(\ell, b) = (-1.5°, 0°)$ with a power index $\alpha = 1.2$. The energy spectrum of this structure is consistent with a single spectral line (at energy 127.0 ± 2.0 GeV with $\chi^2 = 4.48$ for 4 d.o.f.). A pair of lines at 110.8 ± 4.4 GeV and 128.8 ± 2.7 GeV provides a marginally better fit (with $\chi^2 = 1.25$ for 2 d.o.f.). The total luminosity of the structure is $(3.2 \pm 0.6) \times 10^{35}$ erg/s, or $(1.7 \pm 0.4) \times 10^{36}$ photons/sec. The energies in the two-line case are compatible with a 127.3 ± 2.7 GeV WIMP annihilating through $\gamma\gamma$ and γZ (with $\chi^2 = 1.67$ for 3 d.o.f.). We describe a possible change to the *Fermi* scan strategy that would accumulate S/N on spectral lines in the Galactic center 4 times as fast as the current survey strategy.

Subject headings: gamma rays — diffuse emission — milky way — dark matter

A simple test: consider linear combinations of maps

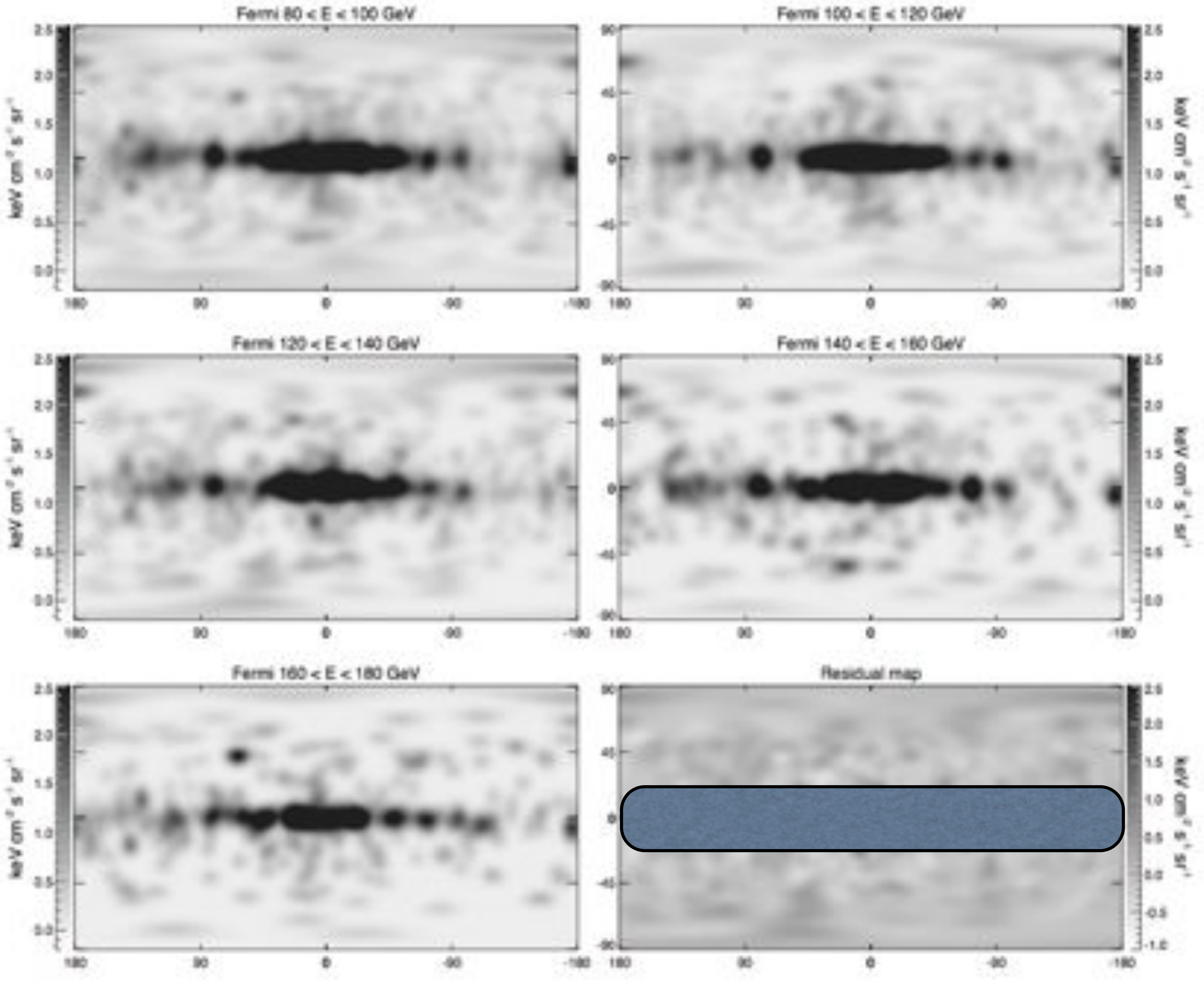


FIG. 3.— All-sky **CLEAN** 3.7 year maps in 5 energy bins, and a residual map (*lower right*). The residual map is the 120 − 140 GeV map minus a background estimate, taken to be the average of the other 4 maps where the average is computed in E^2dN/dE units. This simple

A simple test: consider linear combinations of maps

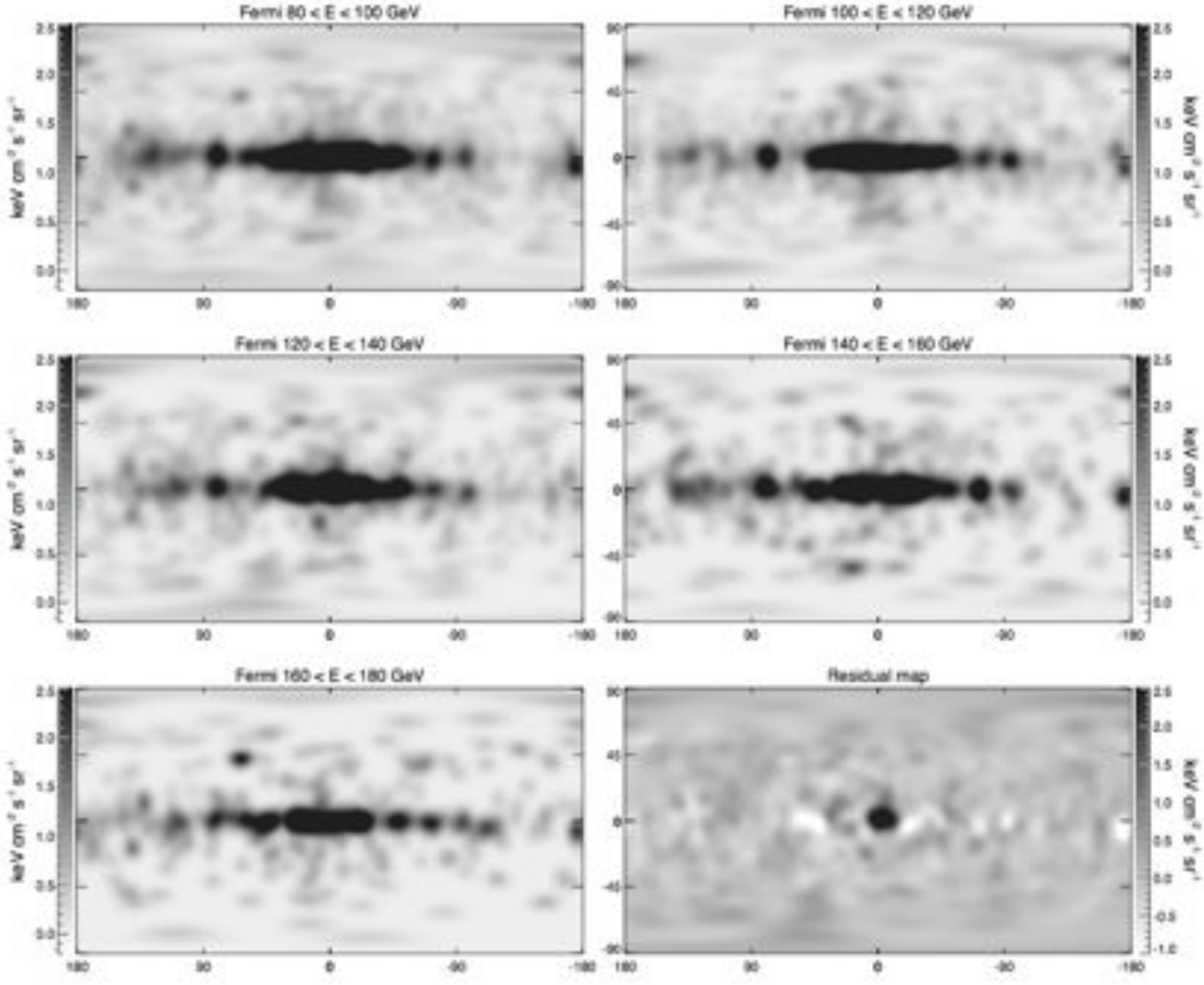


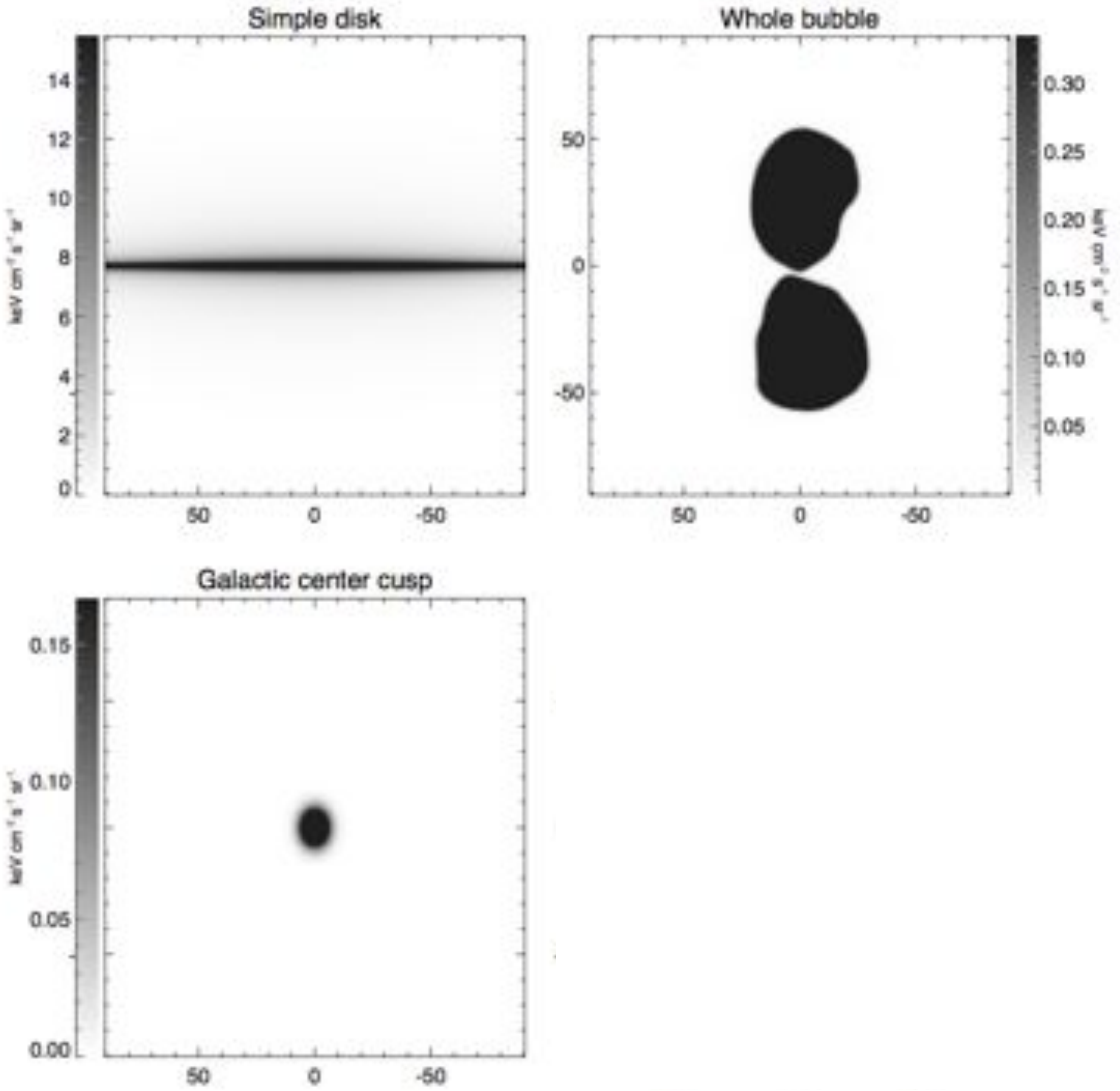
FIG. 3.— All-sky CLEAN 3.7 year maps in 5 energy bins, and a residual map (*lower right*). The residual map is the 120 − 140 GeV map minus a background estimate, taken to be the average of the other 4 maps where the average is computed in E^2dN/dE units. This simple

There is a blob in the Galactic center at ~ 130 GeV. How do extract its spectrum?

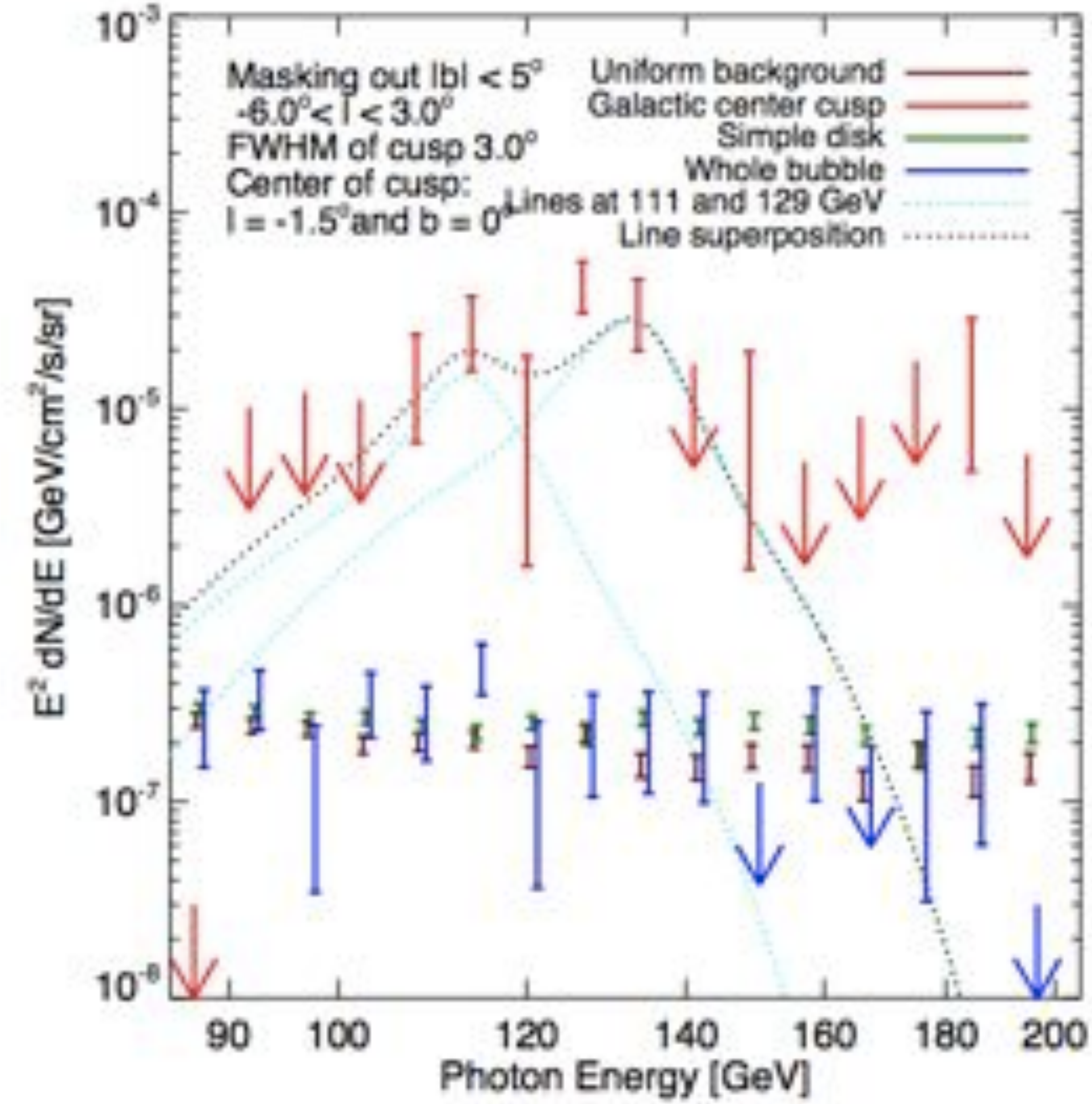
Make maps in each of 16 energy bins, assume that emission in each bin is a linear combination of template maps, and plot the template coefficients.

Coefficients are determined by maximizing the Poisson likelihood of observing the observed counts given the model.

Templates choice corresponds to hypothesis to be tested.


Simple disk
keV cm^{-2} s^{-1} sr^{-1}
0
2
4
6
8
10
12
14
50
0
-50
Whole bubble
50
0
-50
50
0
-50
keV cm^{-2} s^{-1} sr^{-1}
0.05
0.10
0.15
0.20
0.25
0.30
Galactic center cusp
keV cm^{-2} s^{-1} sr^{-1}
0.00
0.05
0.10
0.15
50
0
-50

Four-template fit (incl. uniform background)

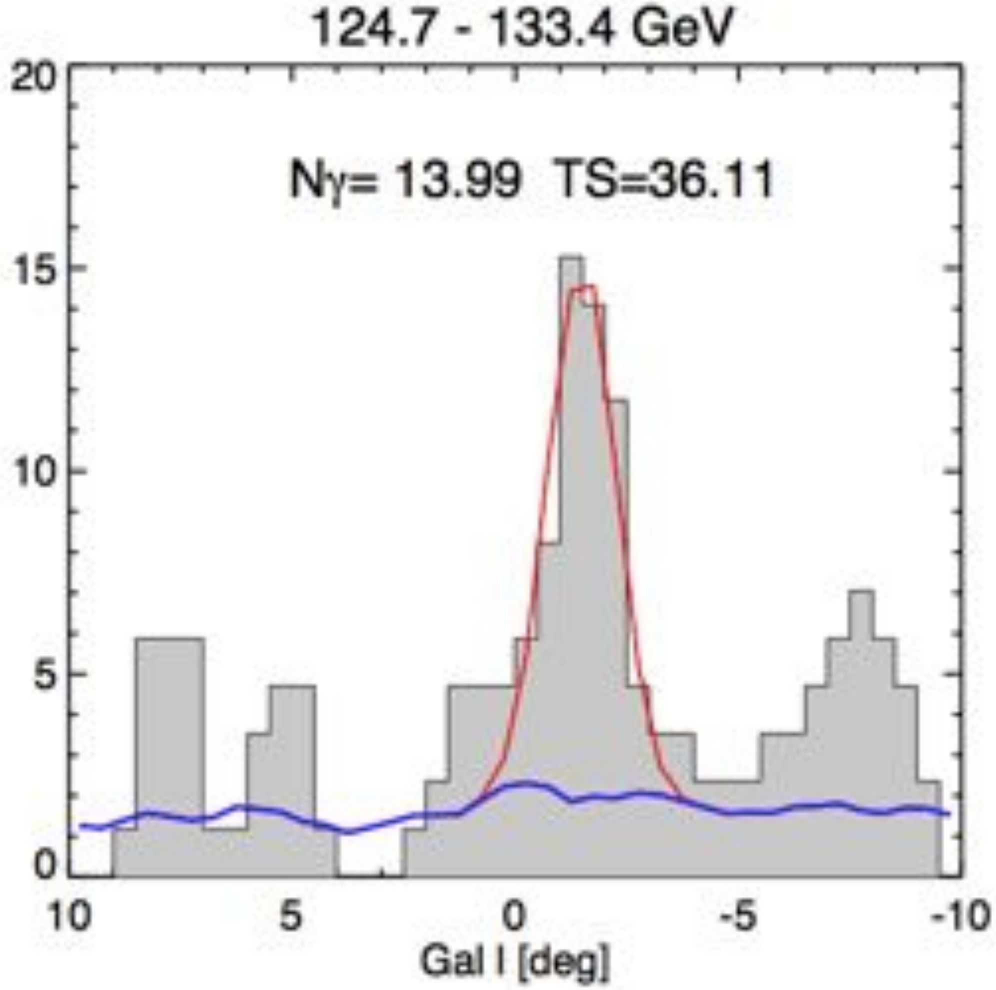


Uncertainty of each coefficient is determined from the curvature matrix of the likelihood surface.

The significance of the 110-140 GeV bins sums (in quadrature) to 6.5 sigma (local).

The fit prefers a line at 127 +/- 2 GeV
or (slightly better) two lines at 111 and 129 GeV.

There are very few photons, but we can project in Gal. longitude bins and look for a bump:



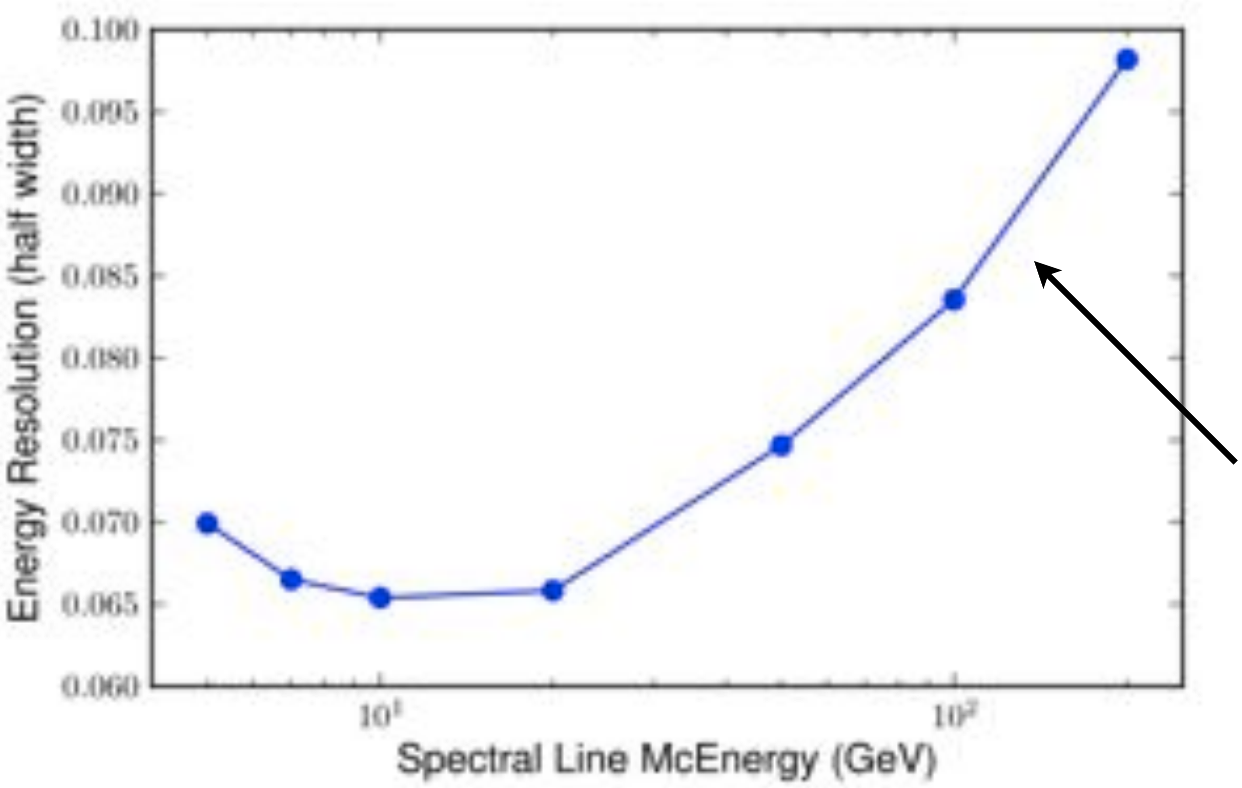
There is a bump... but offset by 1.5 deg in longitude. TS=36, which naively implies 6.0 sigma. Allowing for 3 new d.o.f., 5.25 sigma.

We can do better than this. The energy resolution of Fermi-LAT depends on incidence angle.

Events with higher incidence angle (> 40)
- have longer path length inside the calorimeter, and therefore
- have better energy resolution (factor of ~ 2 better)

Average resolution:

i.e. ~ sigma

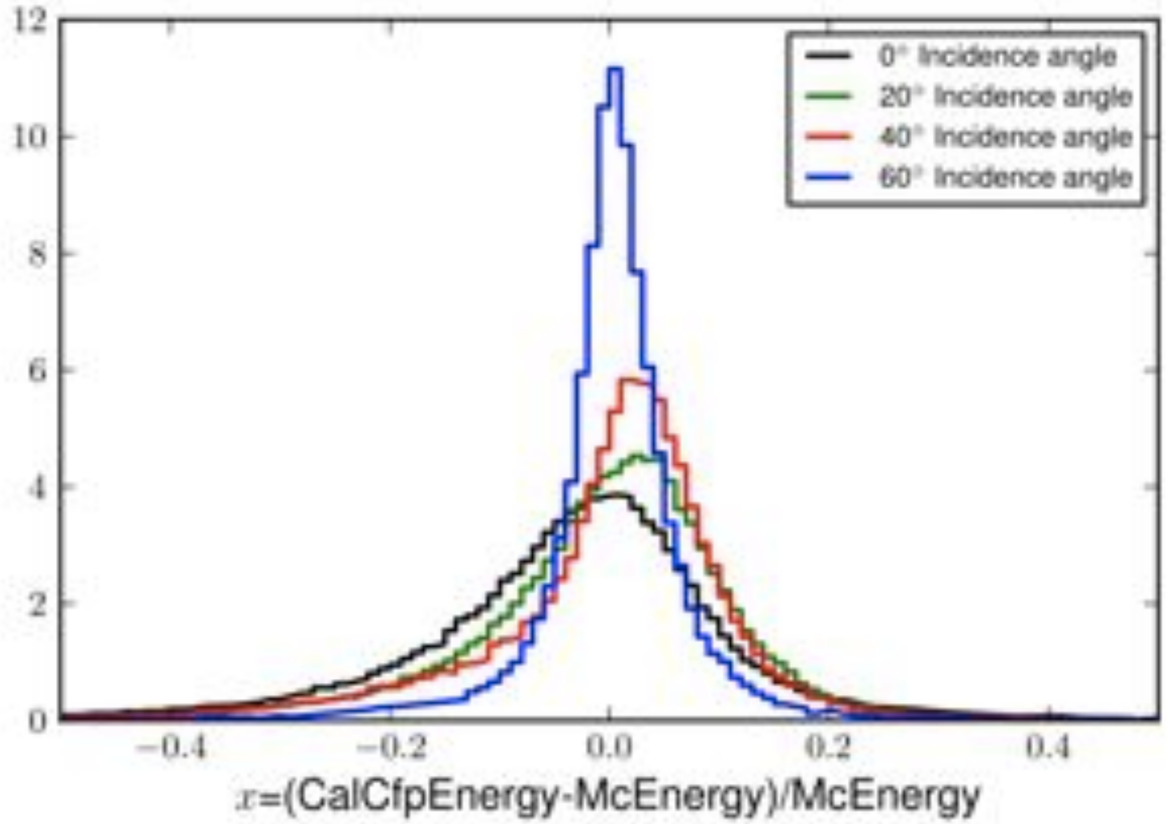


130 GeV

Figure 5.4: Energy resolution(68% energy dispersion containment half-windows) for MC spectral lines. The average 68% half-width is 7.5% ± 1.1%(1σ)

Y. Edmonds (thesis, 2011)

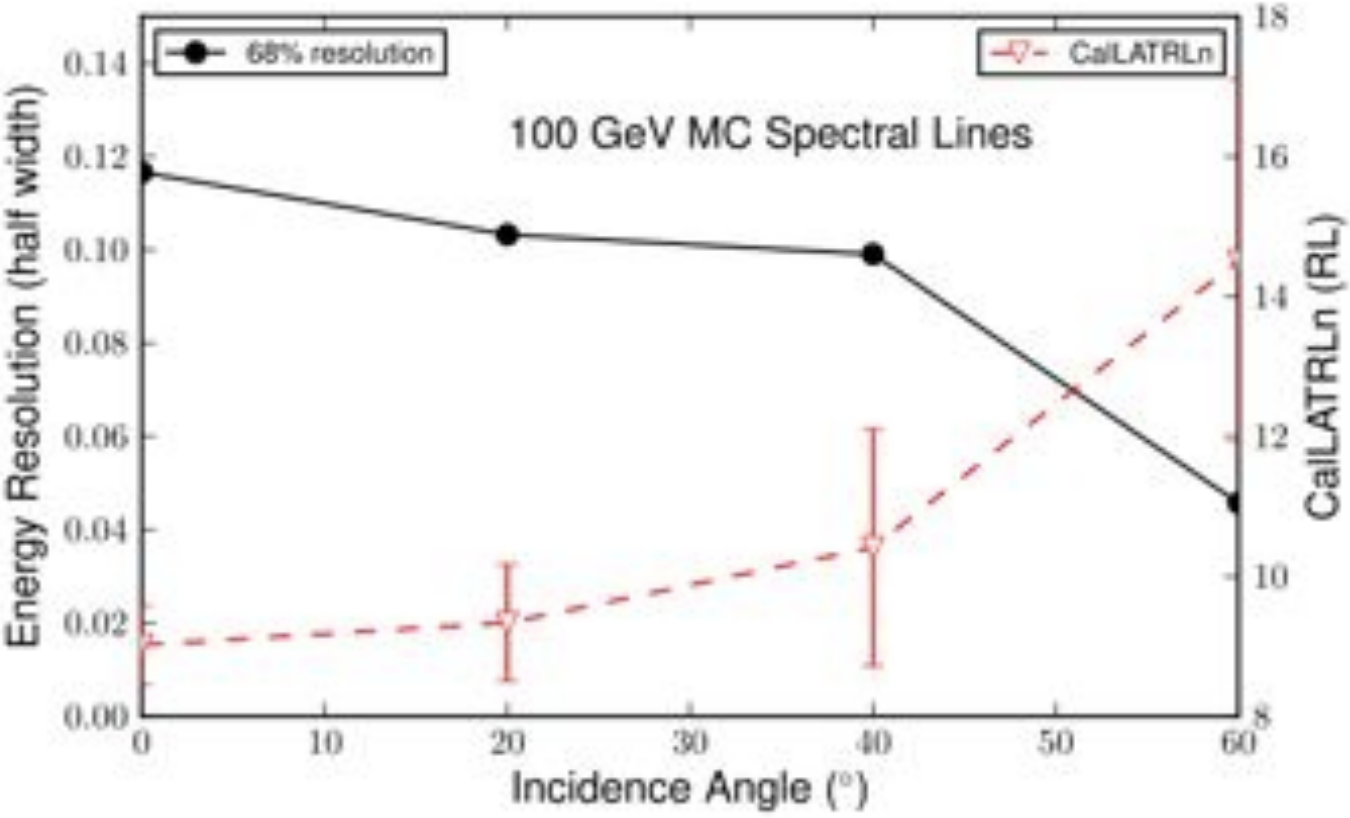
100 GeV line shape at various incidence angles



(a) Energy dispersion for MC 100 GeV spectral line at inclination of angles of 0°, 20°, 40°, and 60°. The histograms are normalized to an area of one

Y. Edmonds (thesis, 2011)

40-60 deg inclination events have much better energy resolution.

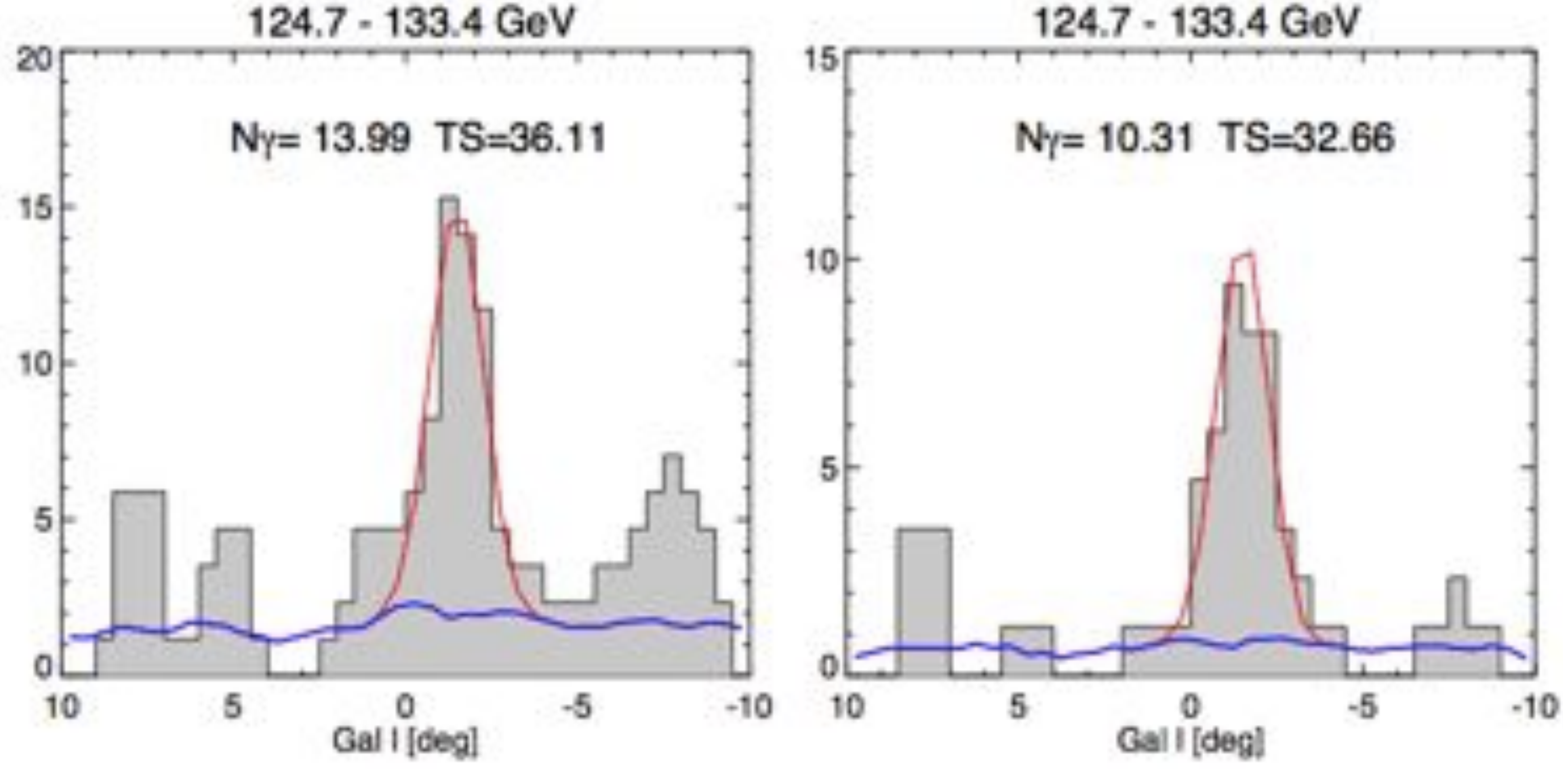


(b) 68% and 95% energy dispersion containment windows for a MC 100 GeV spectral line at various inclination angles.

Y. Edmonds (thesis, 2011)

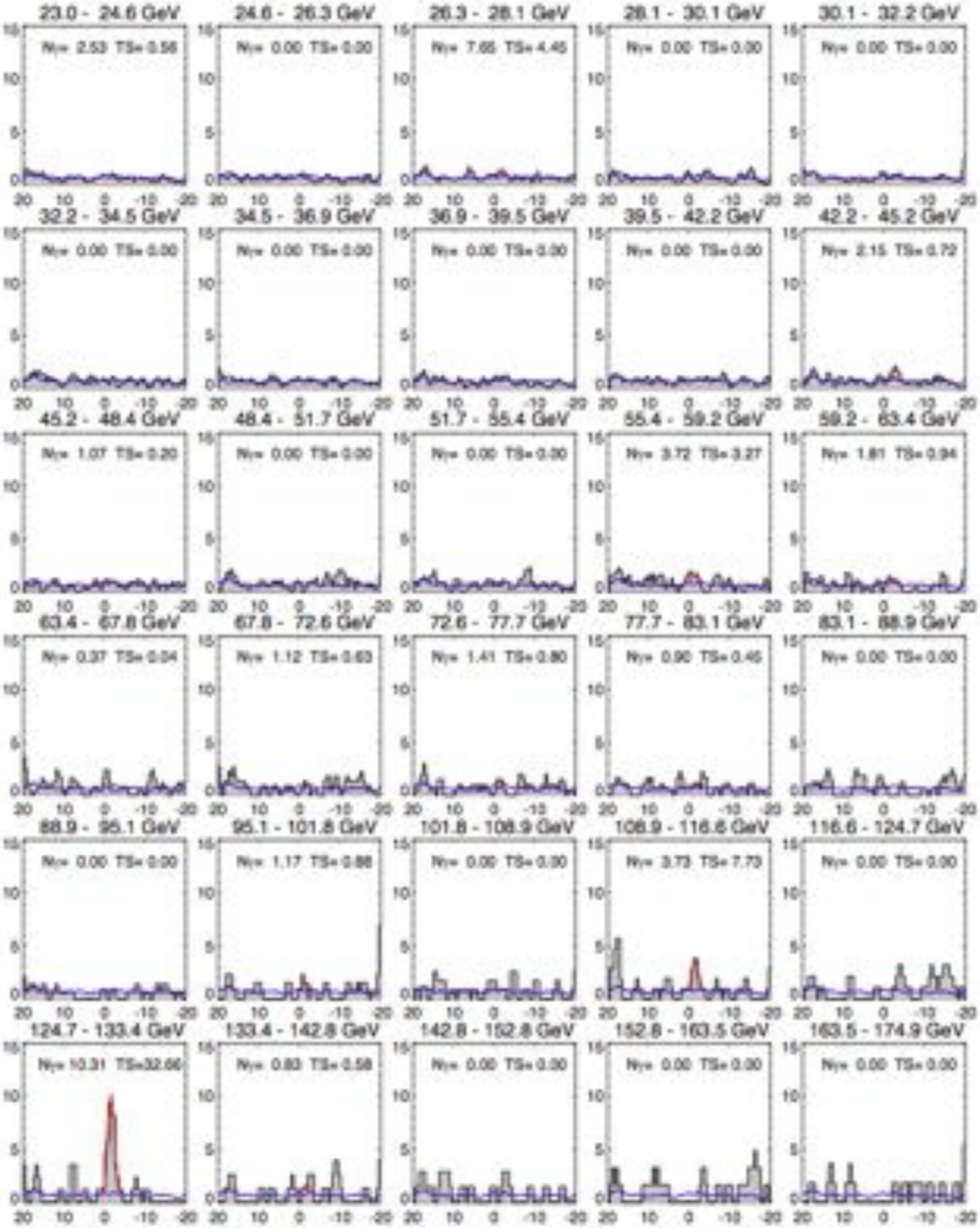
If we select events with better energy resolution, background is reduced.

Half as much data, almost the same significance!

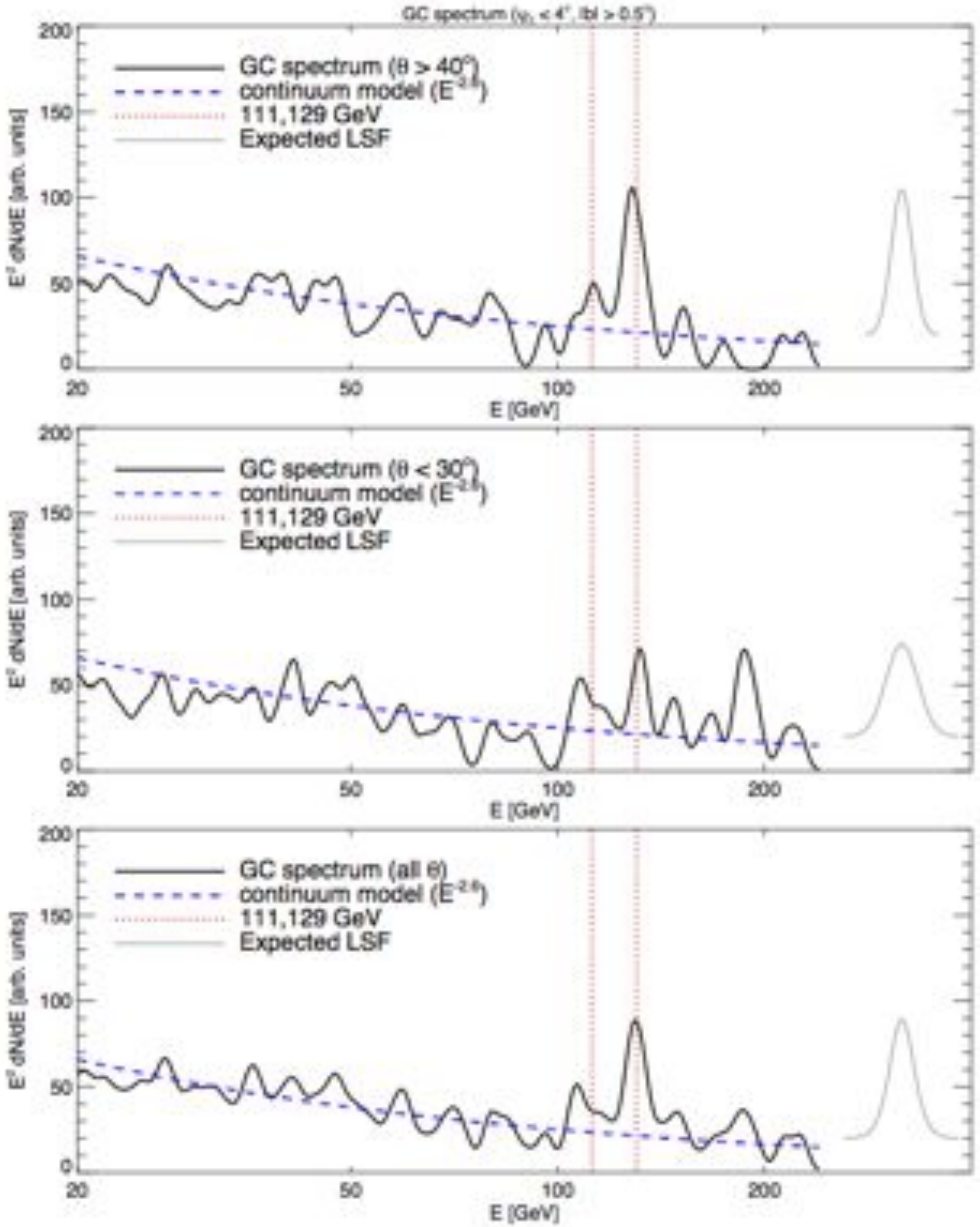


Background model generated by averaging 10-50 GeV assuming $dN/dE \sim E^{-2.6}$

See feature at 127 GeV, insignificant one at 113 GeV

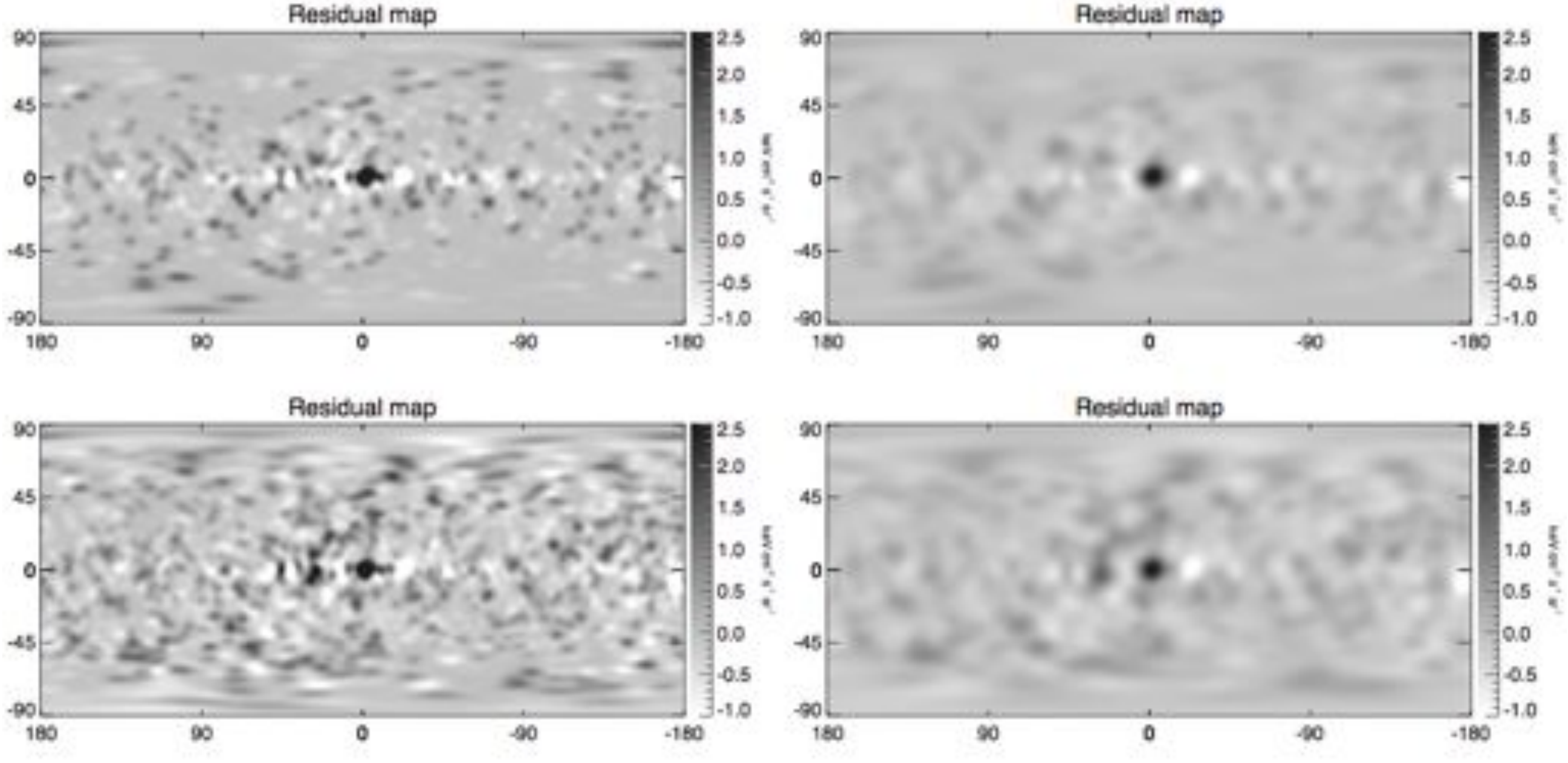


Now, what about the energy spectrum?



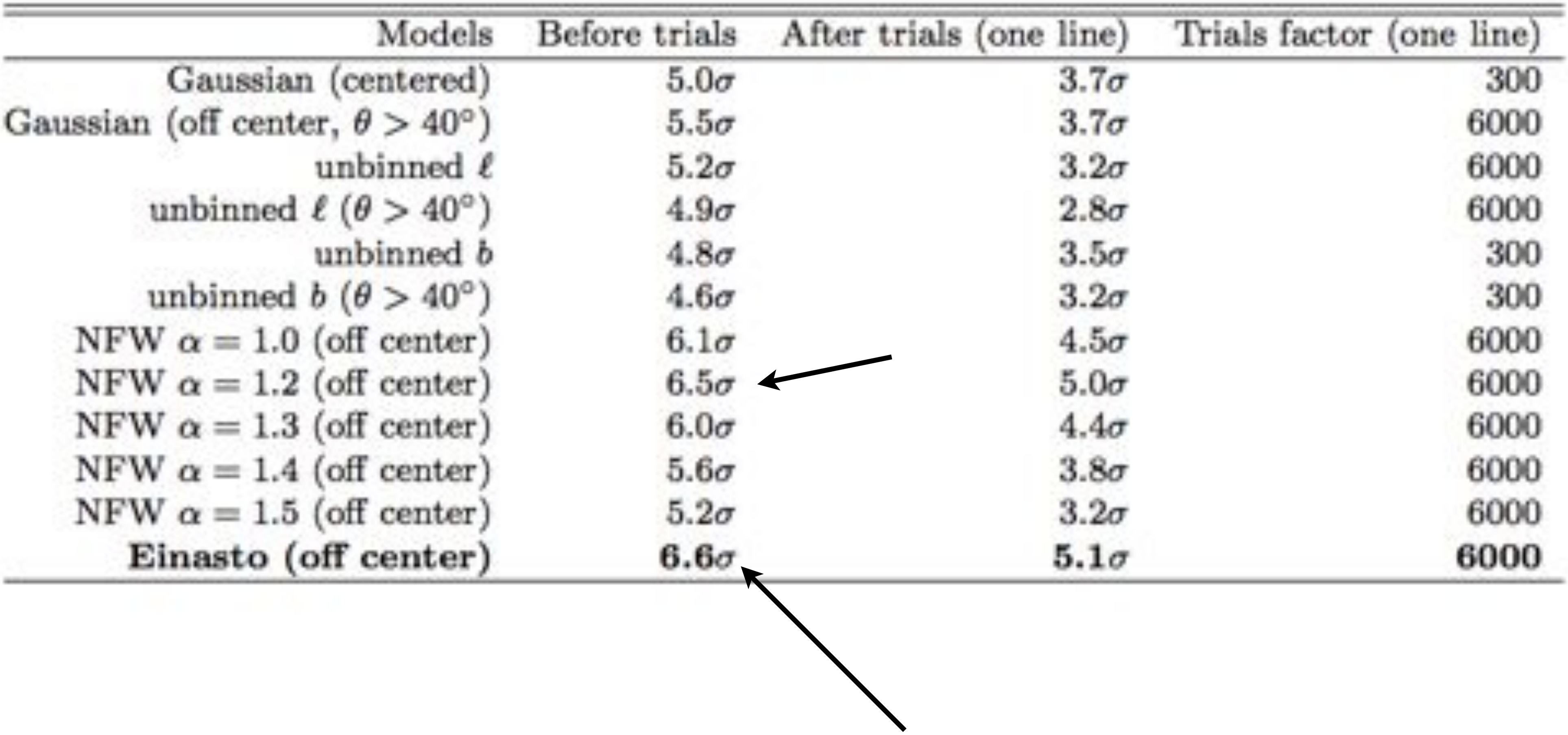
It looks more significant for events with better energy resolution, as it should for a true line signal.

Residual map even looks better with the subsample of events:



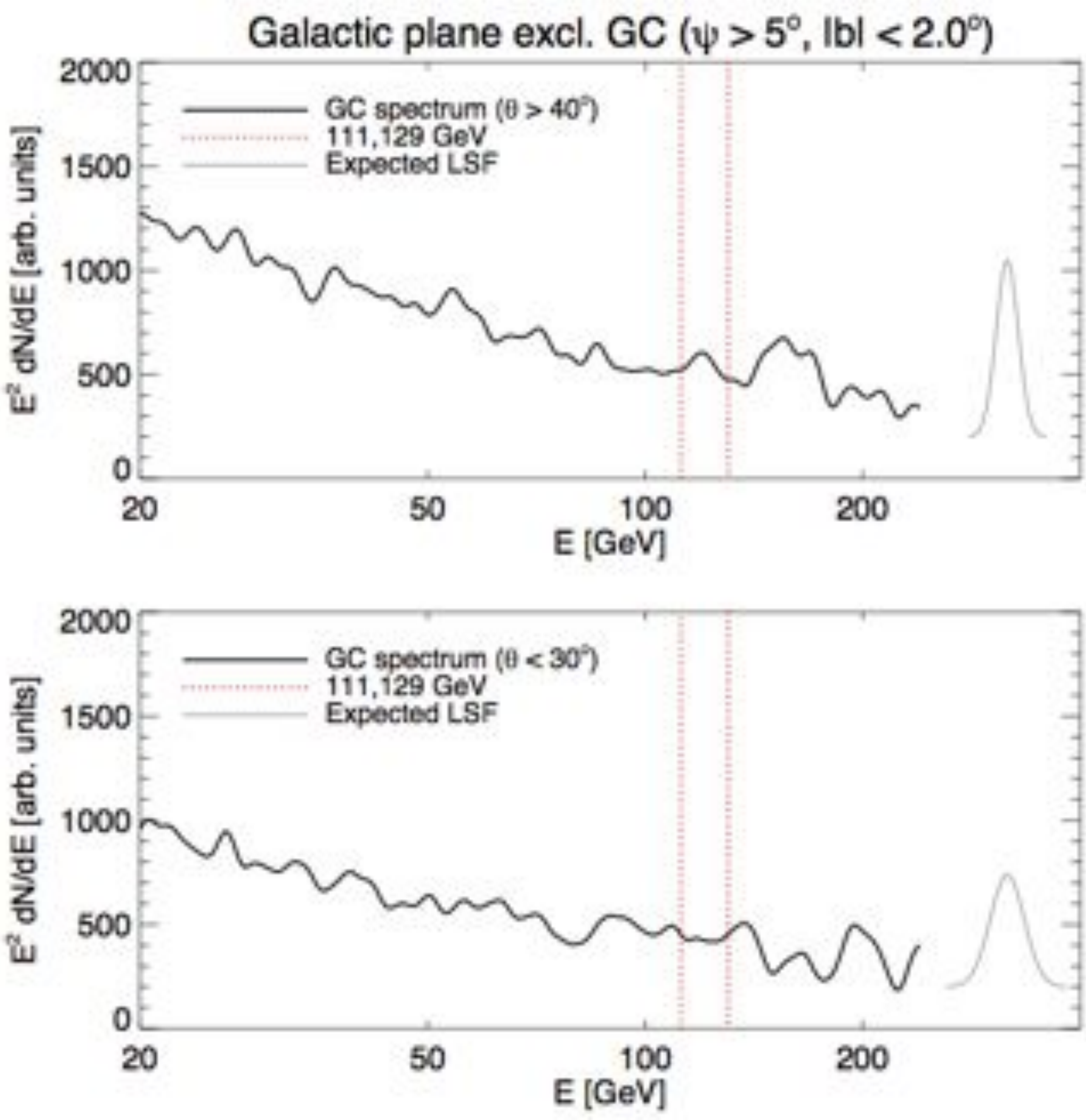
So, we have a blob (> 5 sigma local significance) but it is off center by 1.5 degrees.

We do the fit in many ways.
Off-center Einasto is the best.



Models	Before trials	After trials (one line)	Trials factor (one line)
Gaussian (centered)	5.0σ	3.7σ	300
Gaussian (off center, $\theta > 40°$)	5.5σ	3.7σ	6000
unbinned ℓ	5.2σ	3.2σ	6000
unbinned ℓ ($\theta > 40°$)	4.9σ	2.8σ	6000
unbinned b	4.8σ	3.5σ	300
unbinned b ($\theta > 40°$)	4.6σ	3.2σ	300
NFW $\alpha = 1.0$ (off center)	6.1σ	4.5σ	6000
NFW $\alpha = 1.2$ (off center)	6.5σ	5.0σ	6000
NFW $\alpha = 1.3$ (off center)	6.0σ	4.4σ	6000
NFW $\alpha = 1.4$ (off center)	5.6σ	3.8σ	6000
NFW $\alpha = 1.5$ (off center)	5.2σ	3.2σ	6000
Einasto (off center)	$\mathbf{6.6\sigma}$	$\mathbf{5.1\sigma}$	**6000**

Tests: We *do not* see the signal elsewhere in the Galactic plane:



Not a discovery yet.

- need more data (trials factors!)
- can change survey strategy to get it fast
- what is the cusp off center?
- are there two lines?

Doubling the data will address these questions...