Residuals in the Inner Galaxy and the case of an unresolved population of Millisecond Pulsars

Discuss the excess:

(convince you the excess is real AND relatively well understood)

Hooper & Goodenough: (arXiv:1010.2752), Linden & Hooper (1110.0006), Abazajian & Kaplinghat (1207.6047), Hooper & Slatyer (1302.6589), Gordon & Macias (1306.5725), Huang, Urbano & Xue (1307.6862)

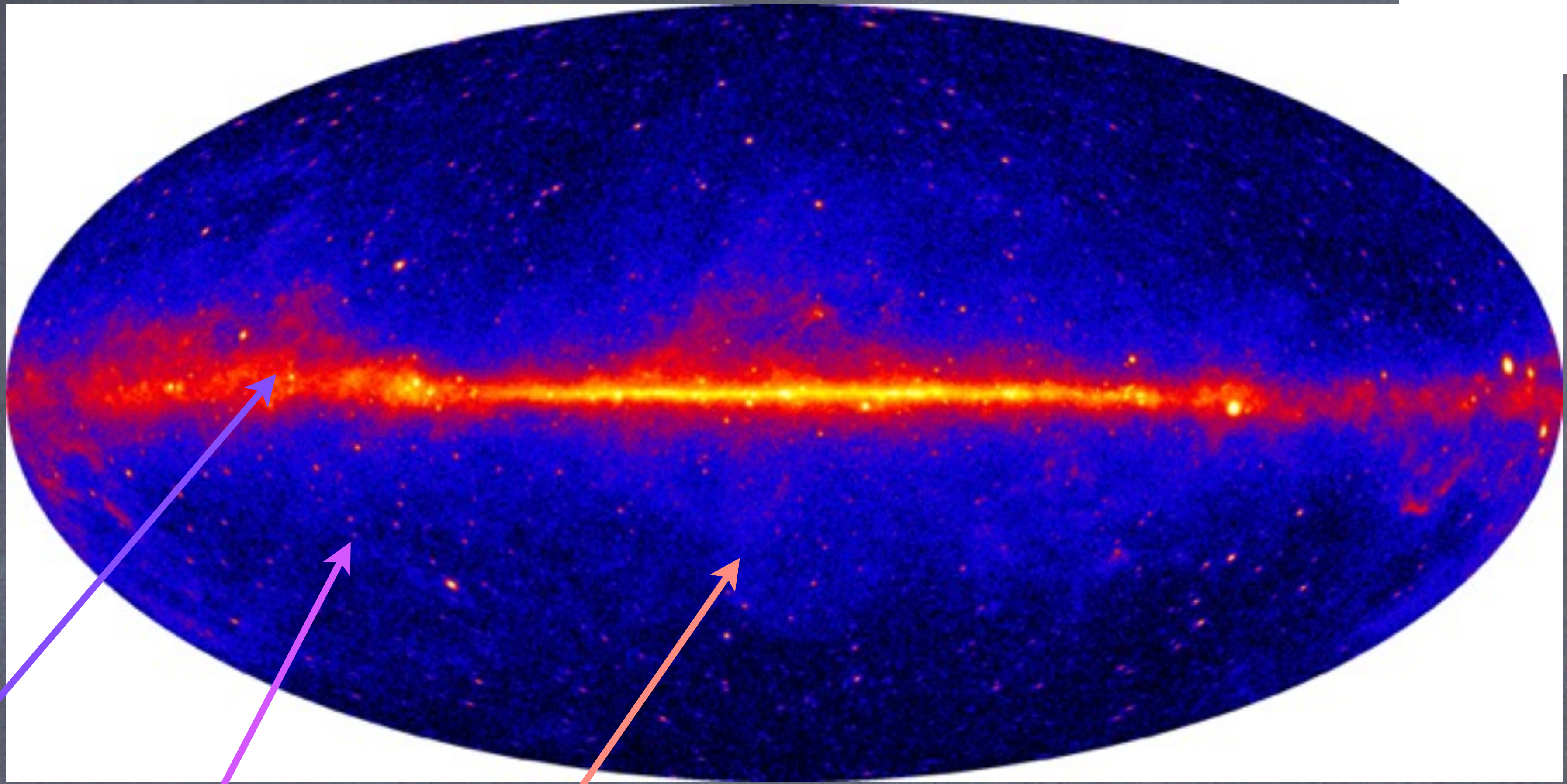
Discuss the interpretations:

Dark Matter VS Pulsars (0:-1)

Hooper, Cholis, Linden, Siegal-Gaskins & Slatyer (1305.0830), Gordon & Macias (1306.5725)

Ilias Cholis, Trieste, 10/10/2013

The Fermi-LAT Gamma-ray SKY



Known sources for the observed gamma-rays are:

i)Galactic Diffuse: decay of pi0s (and other mesons) from pp (NN) collisions (CR nuclei inelastic collisions with ISM gas), bremsstrahlung radiation off CR e, Inverse Compton scattering (ICS): up-scattering of CMB and IR, optical photons from CR e

ii)from point sources (galactic or extra galactic) (1873 detected in the first 2 years)

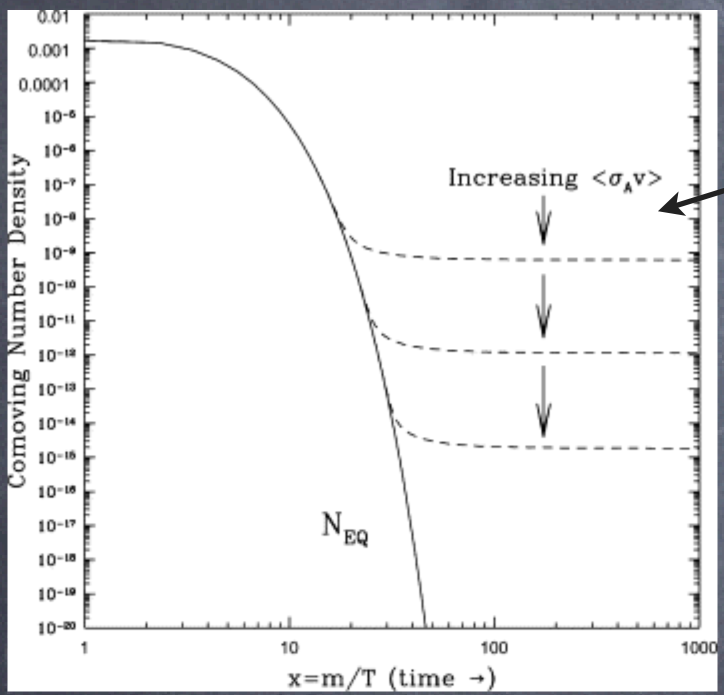
iii)Extragalactic Isotropic

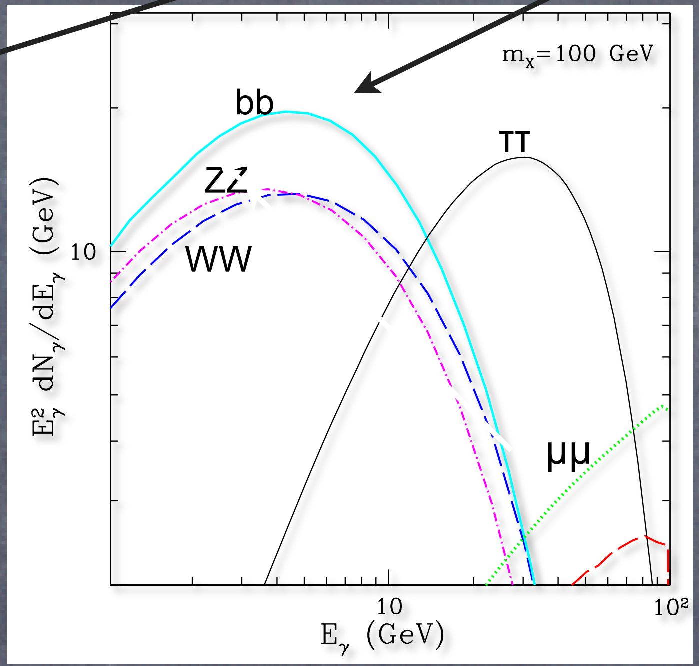
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

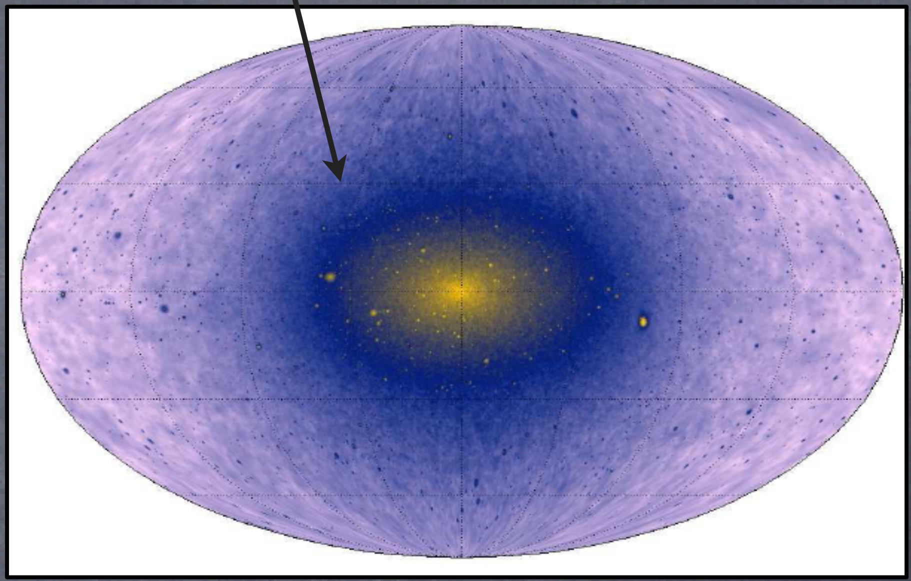
iv)misidentified CRs (isotropic dew to diffusion of CRs in the Galaxy)

BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe: $$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\,m^2_\chi} dl d\Omega$$

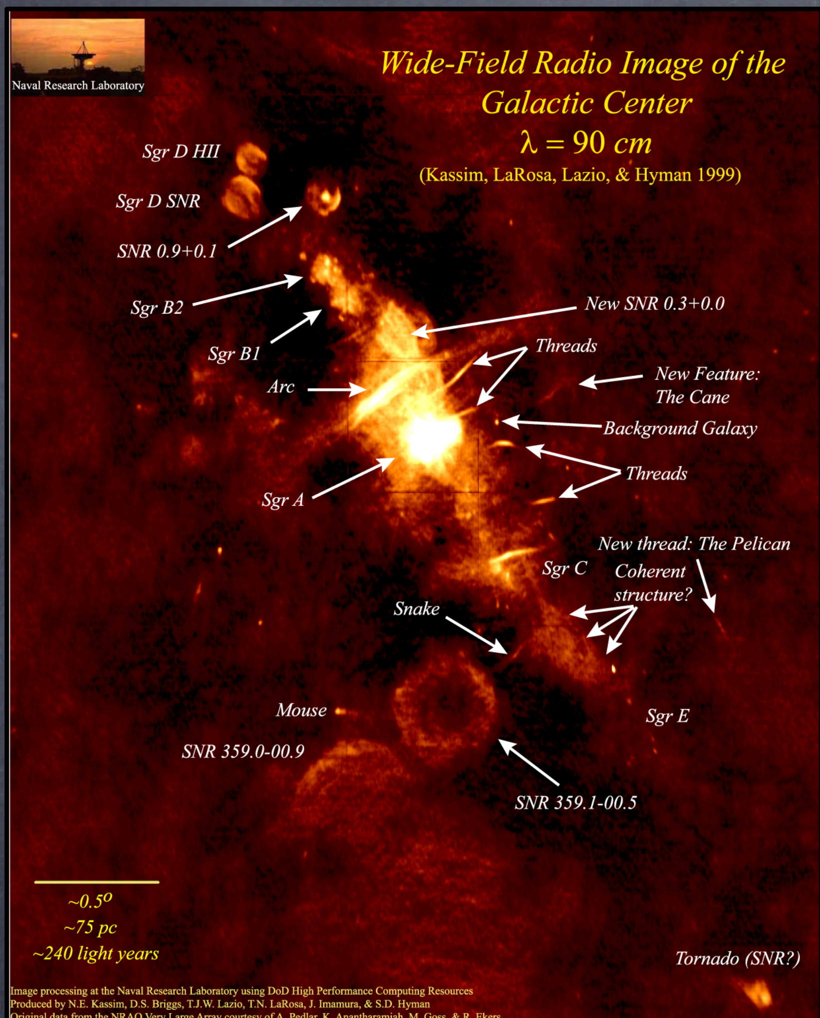






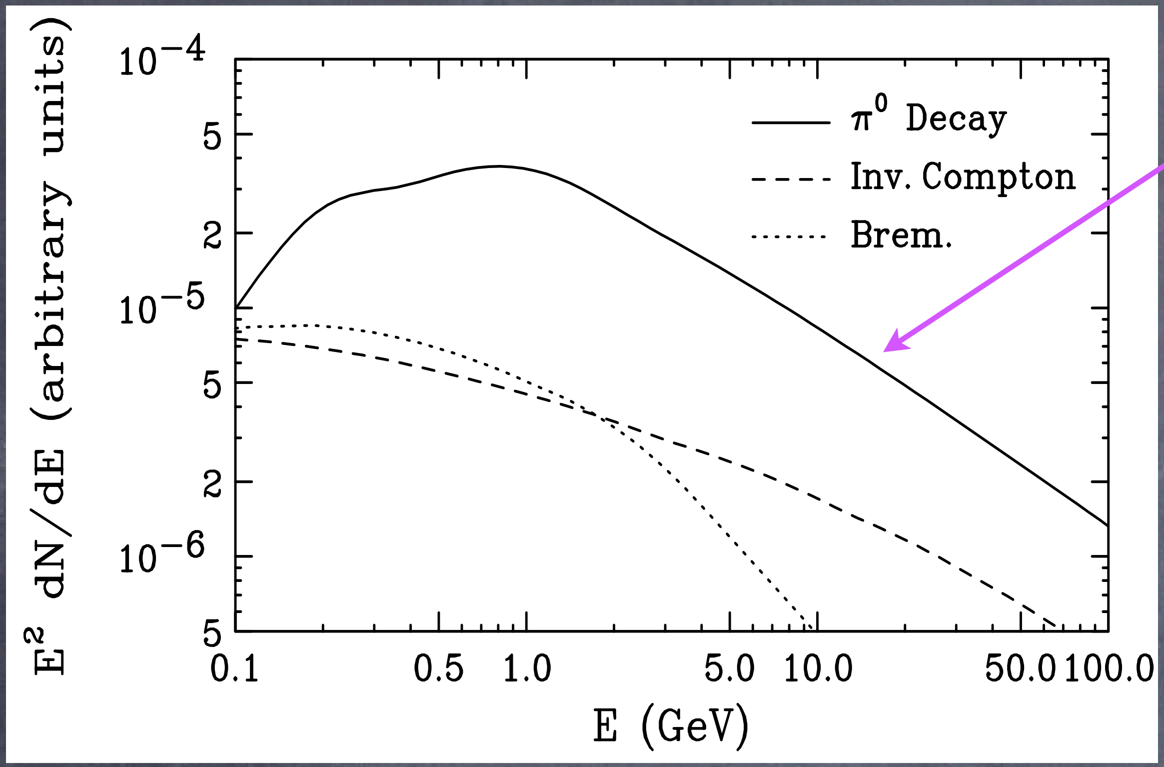
- Hardening of a spectrum without a clear cut-off localized in a certain region (Fermi haze->Fermi bubbles)
- Hardening of a spectrum with a clear cut-off: 10-50 GeV DM claims towards the Galactic Center (GC) inner few degrees
- Line or lines

One of the most likely targets is the GC (though backgrounds also peak), others are the known substructure (dSphs) or Galaxy clusters



- The region of the galactic center is complex with uncertainties in the gas and the CR distribution
- A DM annihilation signal also peaks with significant uncertainties though on the DM distribution
- Take advantage of multi-wavelength searches, different gamma-ray spectra and distinctively different morphologies between the backgrounds and a DM signal

On the gamma-ray backgrounds from the inner galaxy

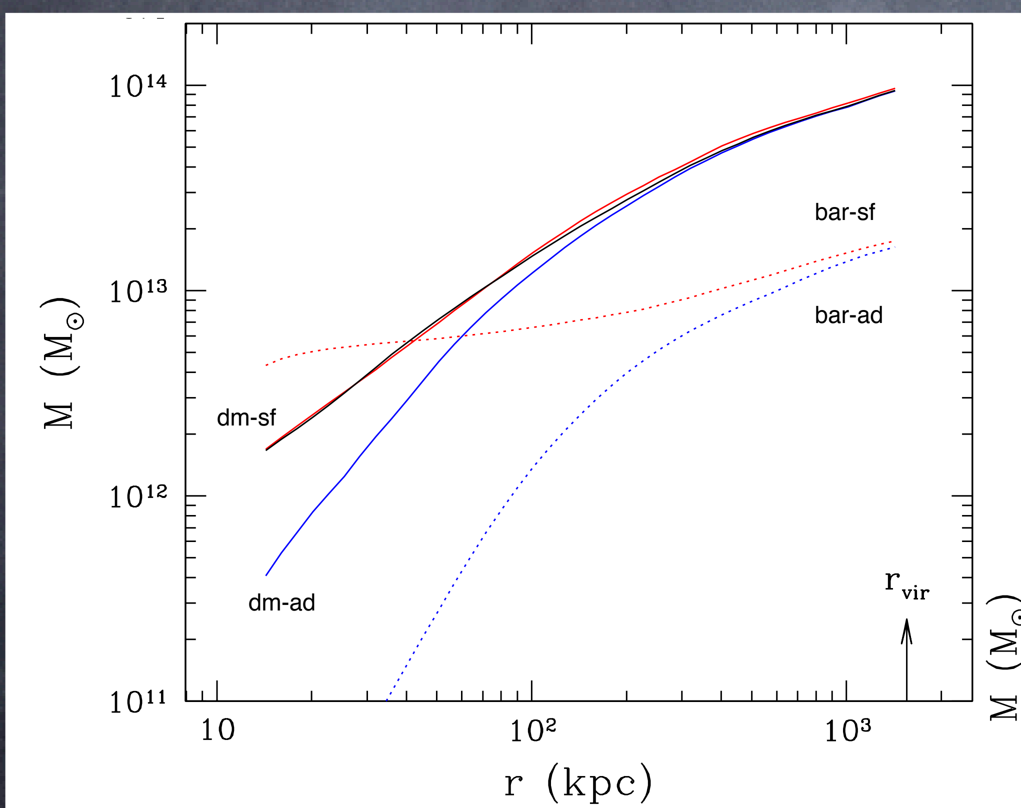


- Spectrally the galactic diffuse gamma-ray components can be modeled. In addition we can model their morphology on the galactic sky
- Extended sources can also be modeled (morphologically and spectrally)and subtracted (yet with some uncertainties related to the mechanism producing their signal)
- Point sources can either be resolved or unresolved extragalactic sources (AGNs, Star forming or starburst galaxies etc). But are isotropic and thus can not contribute significantly to an excess in the inner galaxy. Misidentified GeV scale CRs are also isotropic due to diffusion.
- Galactic point sources that can give strong gamma-ray signals in the GeV range include SNRs in the inner part of the Galaxy and pulsars (more later on that, but keep that last point in mind).

On the DM distribution in the inner galaxy

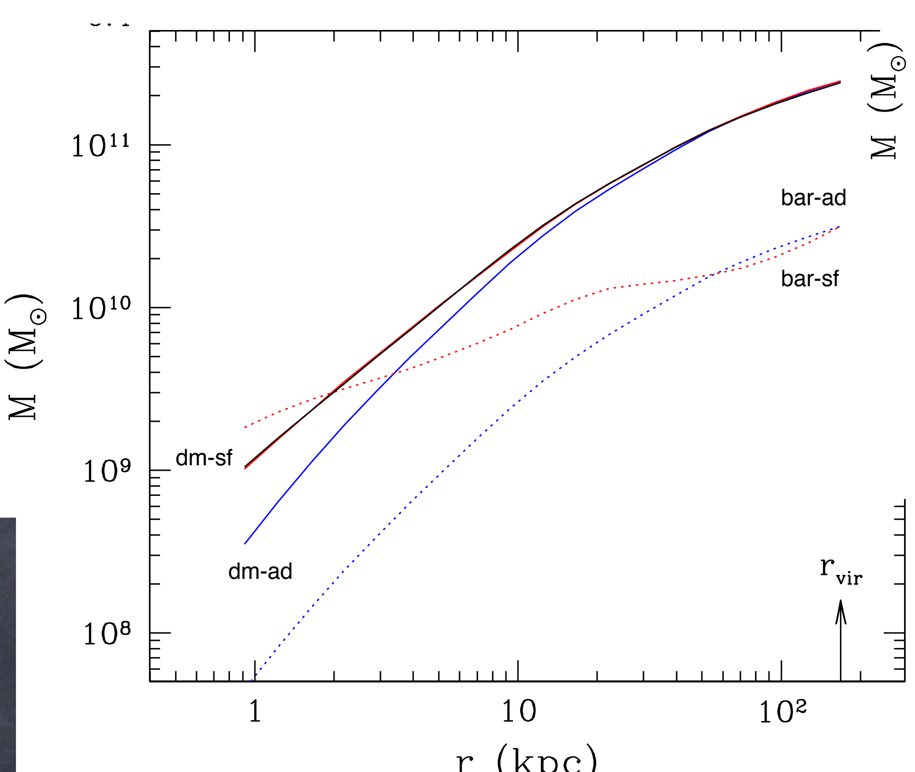
From hydrodynamical simulations there are suggestions from different groups in favor of contraction in the Milky-Way like halos with an inner slope gamma from 1.0 up to 1.5.
Yet there still are groups suggesting flattening of the halo profile if baryonic feedback processes are efficient.
Assuming NFW-like profile with some uncertainty in the inner slope is the way to treat any search for a signal of DM from the inner galaxy.

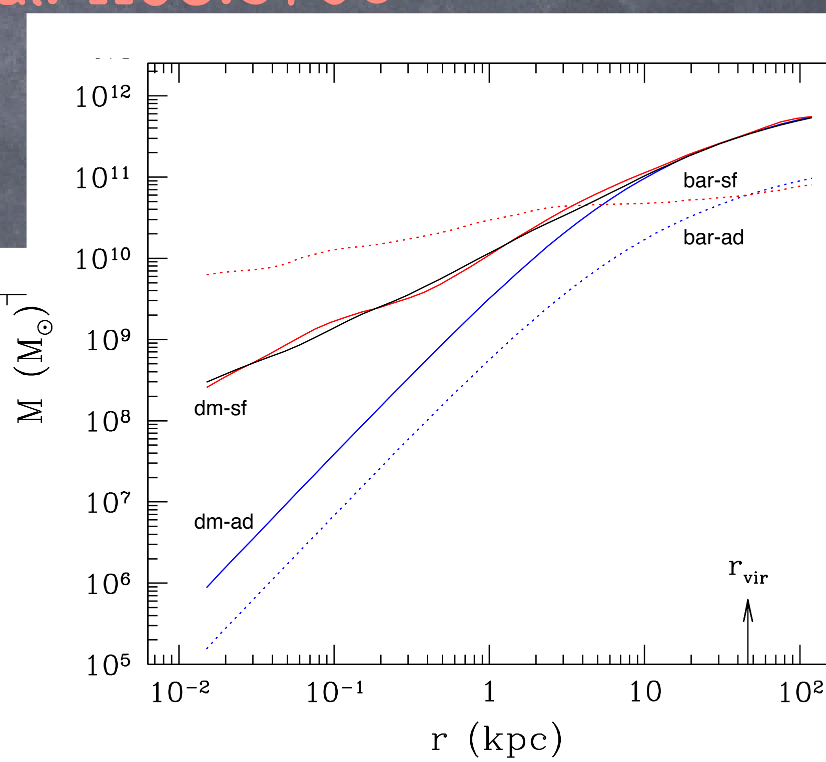
Gnedin et al. 1108.5736



Nagai 2006 ApJ 650, 538

Gottglober et al. 1005.2687



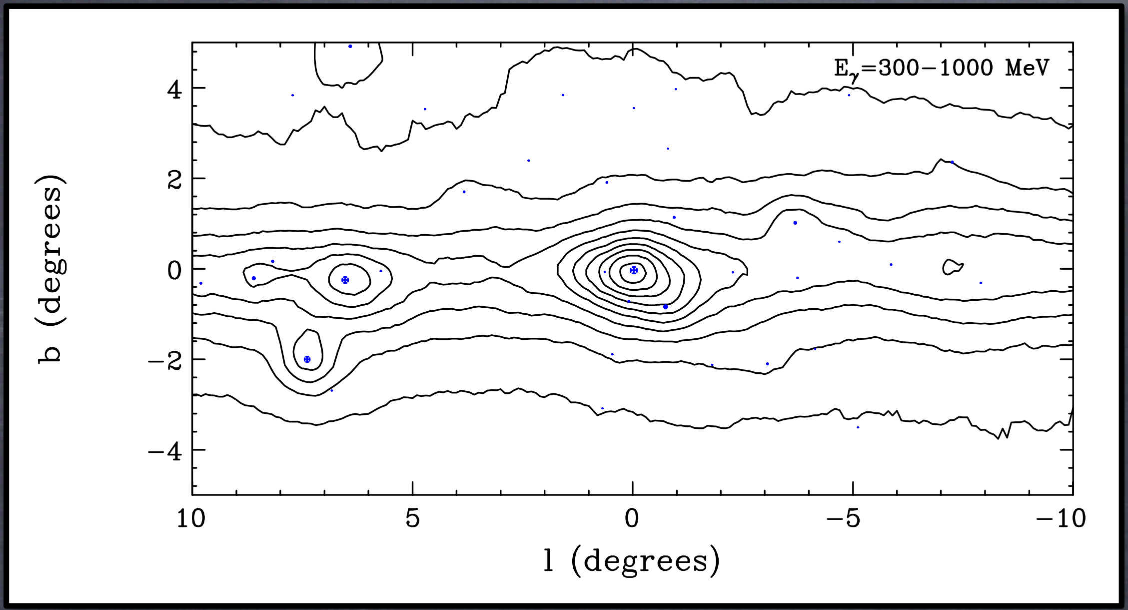


Levine at al. 2008 ApJ 678, 154

Looking for excesses in the inner galaxy

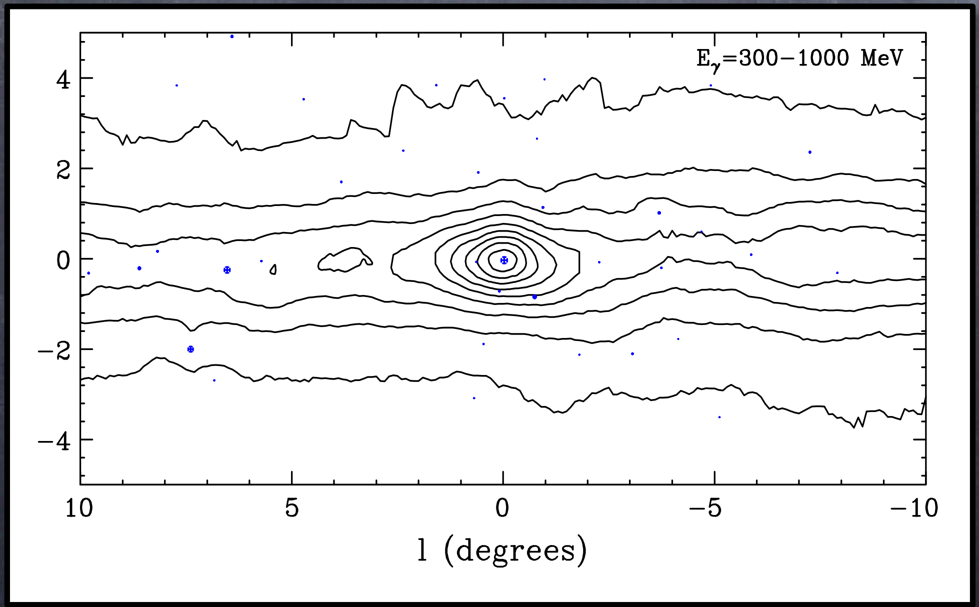
Hooper&Linden 1110.0006

Smoothed Raw gamma-ray map



− POINT SOURCES (2yr catalogue)

−



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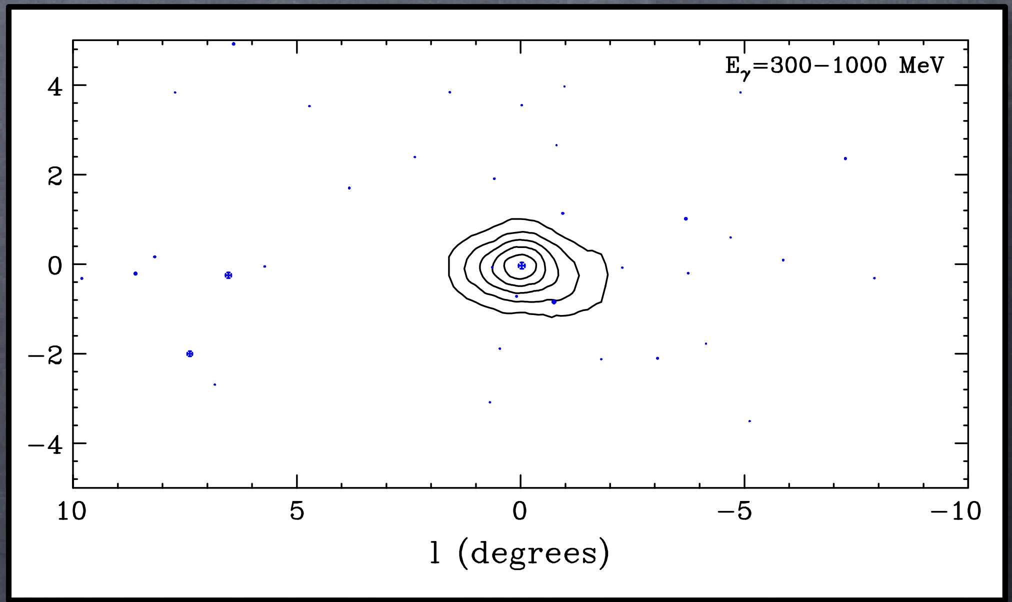
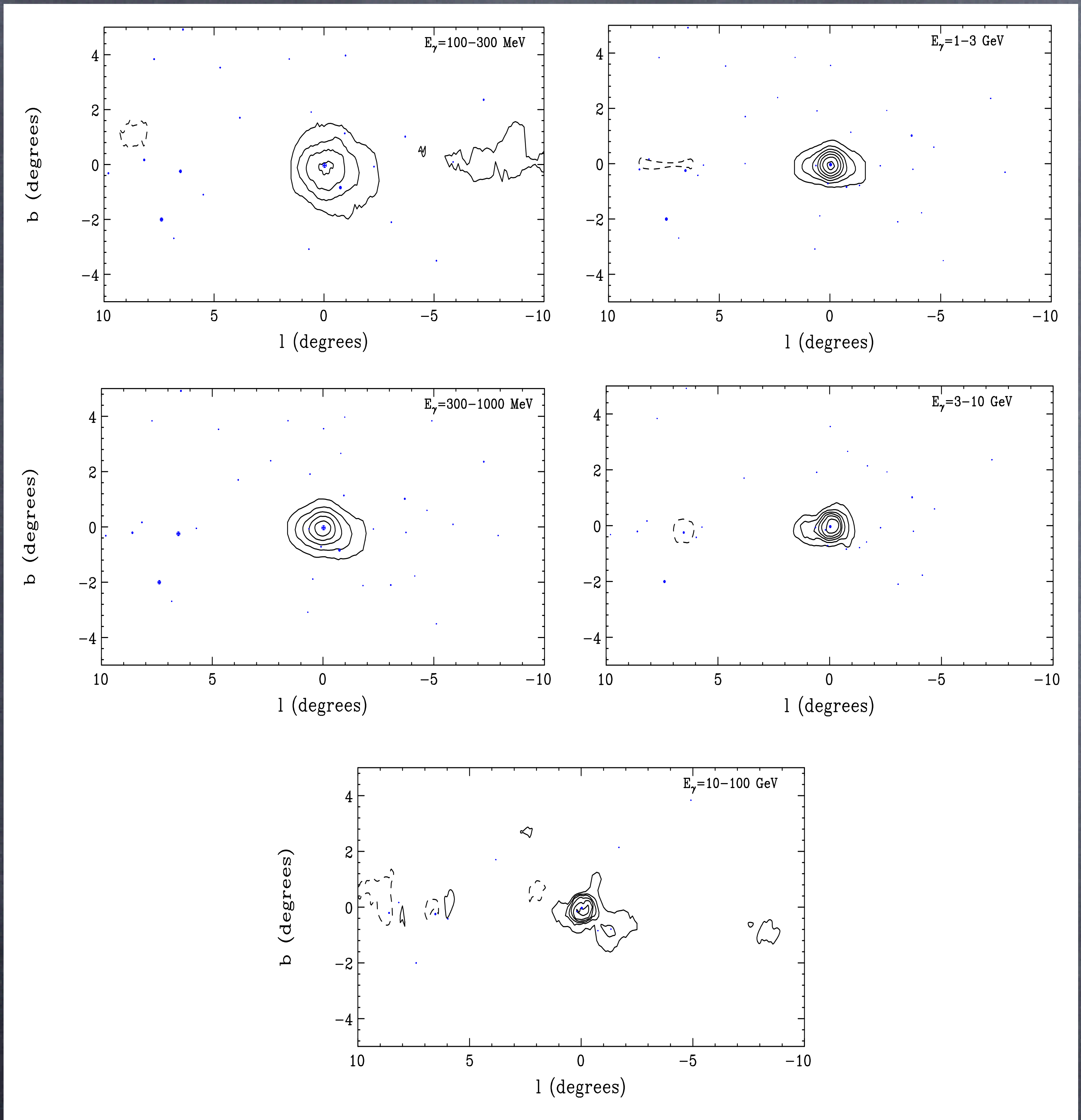


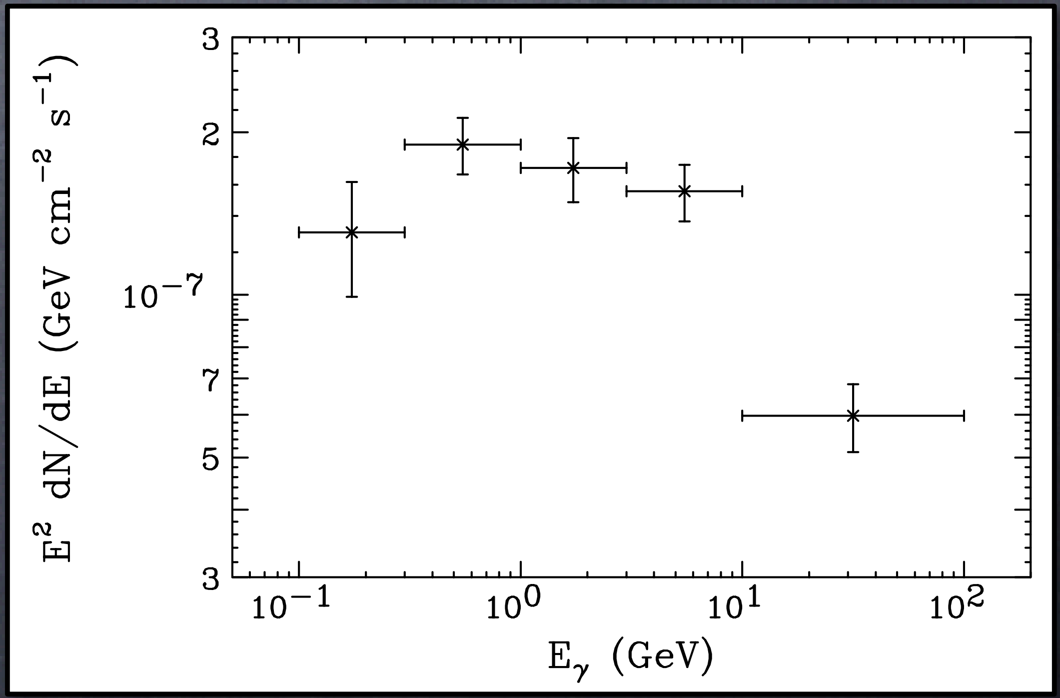
Model for Galactic Diffuse Emission

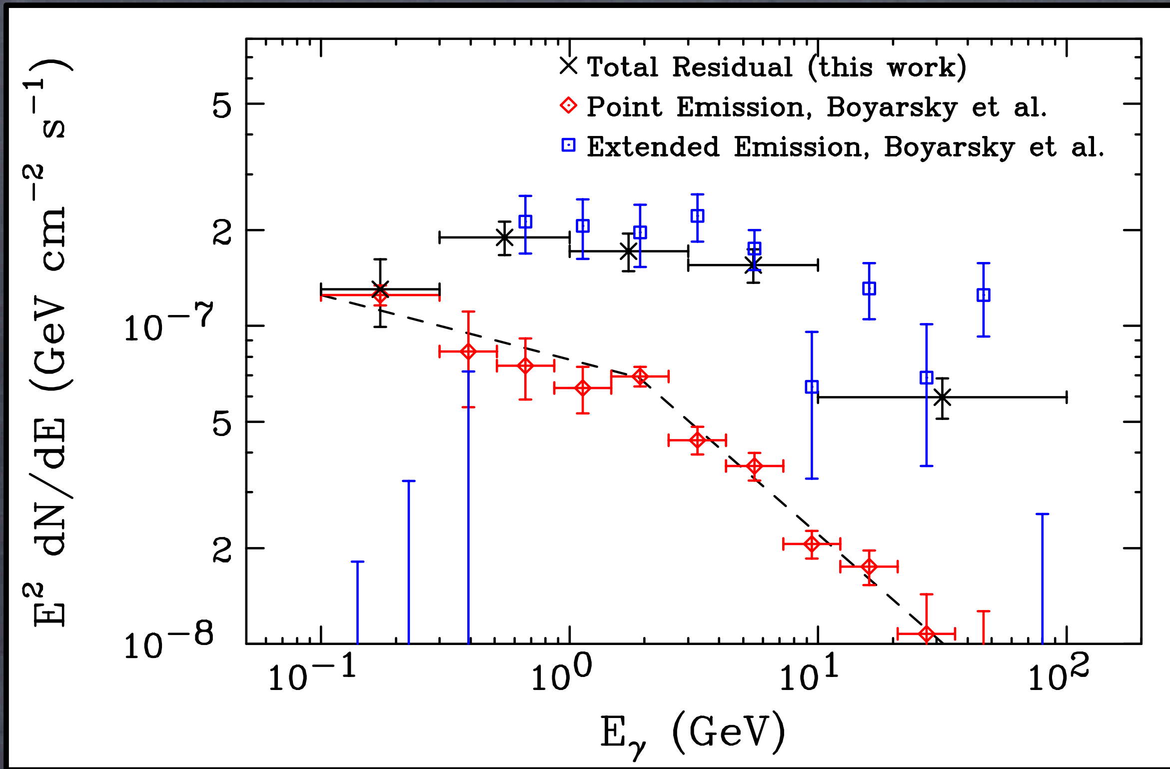
Excess Difuse Emission

Repeating the exercise in different energies



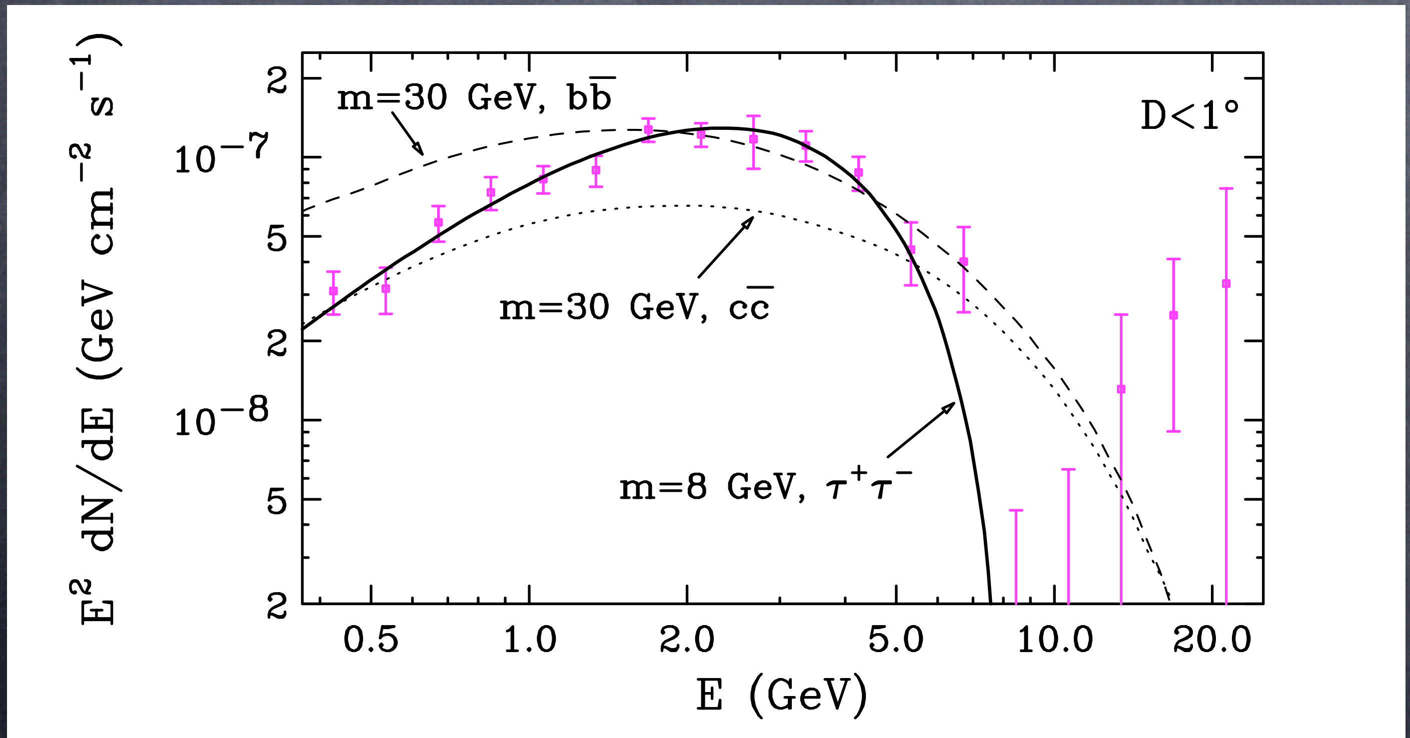
- A clear excess emission in the galactic center emerges
- 90% of the total emission in the inner few degrees is removed
- Residuals not related to the galactic center (GC) are up to ~5% as bright as the GC residual
- Excess emission cuts-off at ~10 GeV





Only a small fraction of the emission can be associated to the TeV point source emission in the GC

Similar results with earlier study: Hooper & Goodenough: (arXiv:1010.2752)



Statements

FROM a Talk of mine in 2010 at SISSA

Using the Fermi gamma-ray data and modeling the background they suggest a signal from DM annihilation seen in the inner 1.25° ~175pc.

arXiv:1010.2752	arXiv:0910.2998
DM mass : 7.3-9.2 GeV	25-30 GeV
DM profile : ~NFW with $\rho \propto r^{-1.34\pm0.04}$	$\rho \propto r^{-1.1}$
$\langle\sigma v\rangle = 3.3 \times 10^{-27} - 1.5 \times 10^{-26}\ cm^3/s$	$\sim 9 \times 10^{-26}\ cm^3/s$
annihilates predominantly to: $\tau^+\tau^-$	$b\bar{b}$

$$\Phi_\gamma(E_\gamma, \psi) = \frac{dN_\gamma}{dE_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_X^2}\int_{\rm los}\rho^2(r)dl$$

Comment:

Background gamma-ray estimates dominate the result

Non-Dan Hooper related groups on the inner 1-2 degrees

Abazajian & Kaplinghat (1207.6047)

- Different method: isotropic and galactic diffuse gamma-ray components are modeled using the Fermi tools. So are the point sources
- The excess is found at a significance level of Delta(ln(L)) =400 in log likelihood difference
- The morphology of the excess is confirmed, the spectrum is similar
- Suggestive of the fact that the excess is not just the result of mis-subtraction of somewhat well understood backgrounds

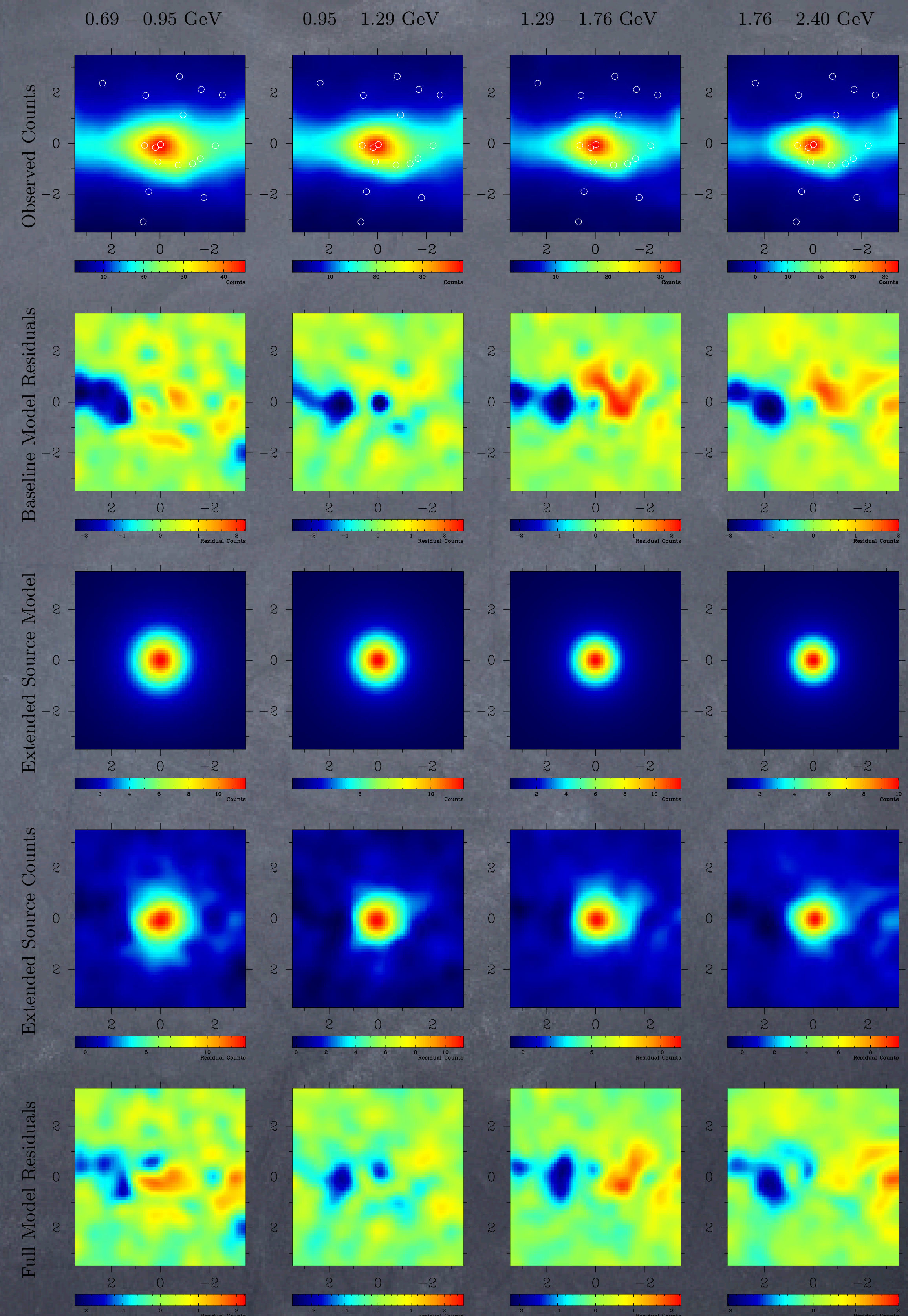
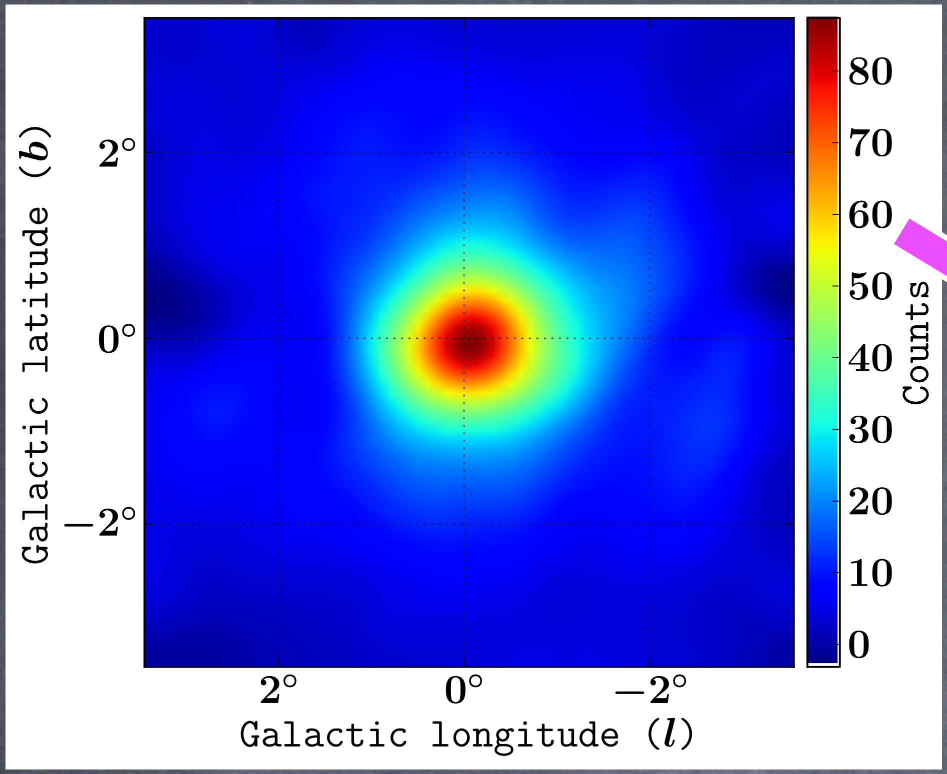
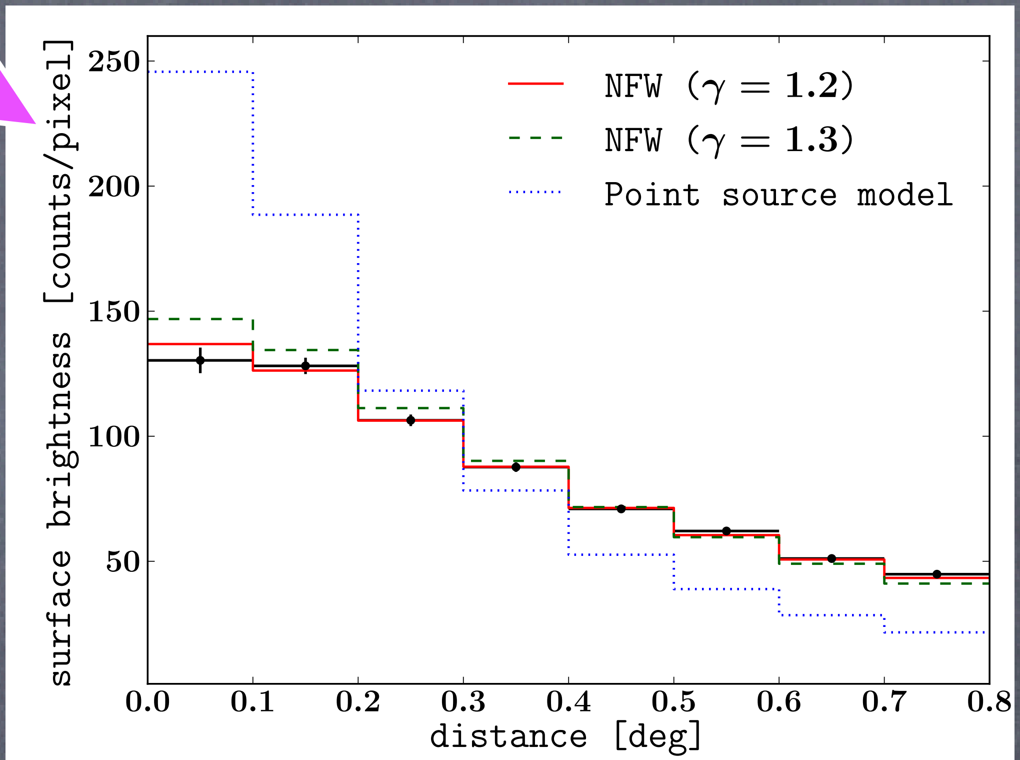


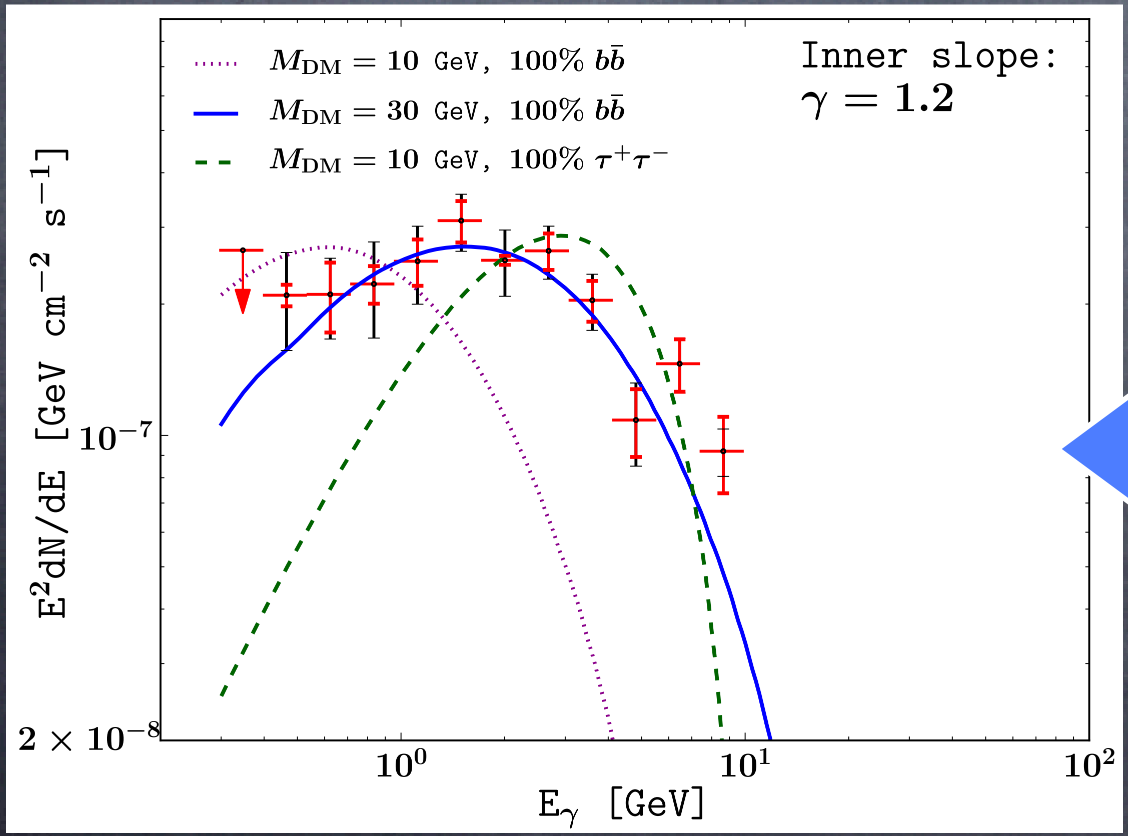
FIG. 1. Shown in the top row are photon counts in four energy bins that have significant evidence for an extended source with a spectrum, morphology, and rate consistent with a 30 GeV mass WIMP annihilating to $b\bar{b}$-quarks in the $7^\circ \times 7^\circ$ region about the GC. This row shows the 17 2FGL point sources in the ROI as circles. The second row shows the residuals for the fit to the region varying all the sources in the 2FGL catalog as well as the amplitudes of Galactic diffuse and isotropic diffuse models. The presence of an extended source and oversubraction of the central point sources are visible here. The third row shows the best fit model counts for 30 GeV WIMP annihilating to $b\bar{b}$-quarks. The fourth row is the residual emission for this model without subtracting the extended component. The fifth row contains the residuals when the extended component is also subtracted. The maps have been filtered with a Gaussian of width $\sigma = 0.3^\circ$.

Gordon & Macias (1306.5725)



Morphology is cuspy





Spectrum has a sharp cut-off

A different way of seeing the level of agreement between individual results

Let's Consider as an example the case of DM annihilation into taus, b-quarks or combinations :

Gordon & Macias (1306.5725)

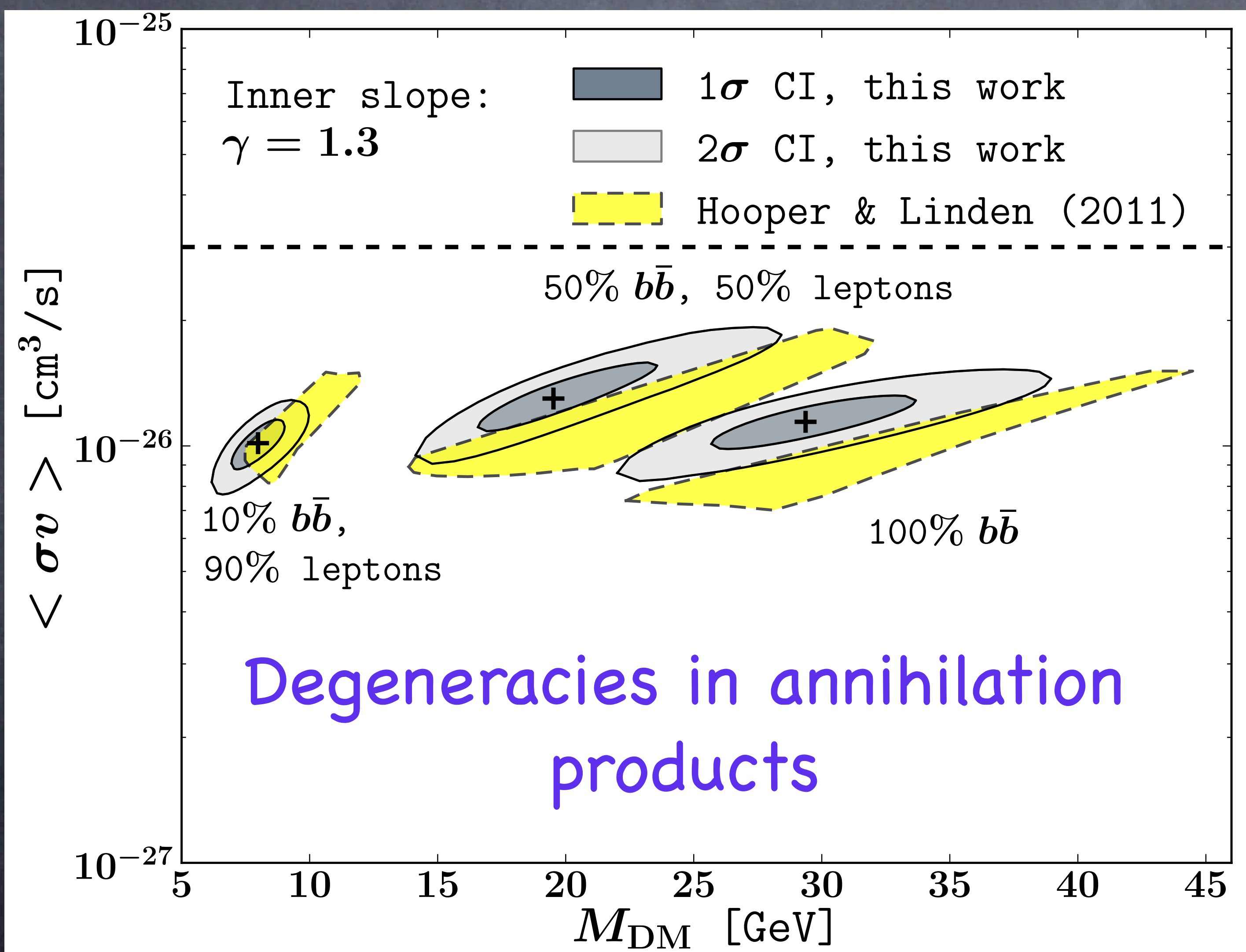


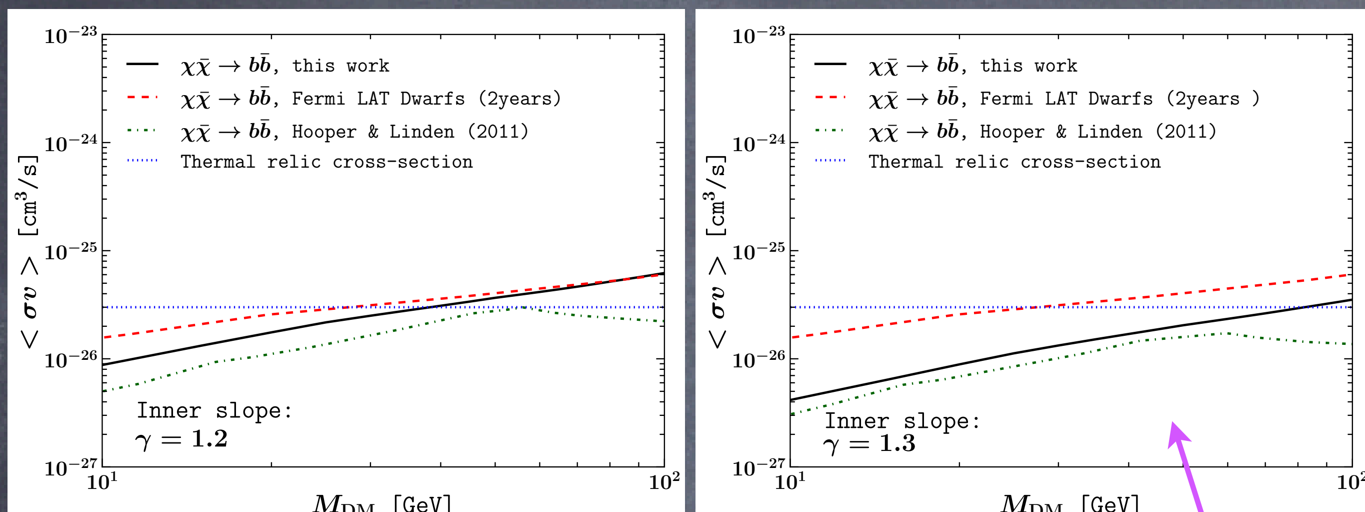
TABLE II. The best-fit $\mathrm{TS}_{\approx}$, negative log likelihoods, and $\Delta \ln \mathcal{L}$ from the baseline, for specific dark matter channel models, using the $\alpha\beta\gamma$ profile (Eq. 2.1) with $\alpha = 1, \beta = 3, \gamma = 1.2$.

channel, m_χ	$\mathrm{TS}_{\approx}$	$-\ln \mathcal{L}$	$\Delta \ln \mathcal{L}$
$b\bar{b}$, 10 GeV	2385.7	139913.6	156.5
$b\bar{b}$, 30 GeV	3460.3	139658.3	411.8
$b\bar{b}$, 100 GeV	1303.1	139881.1	189.0
$b\bar{b}$, 300 GeV	229.4	140056.6	13.5
$b\bar{b}$, 1 TeV	25.5	140108.2	−38.0
$b\bar{b}$, 2.5 TeV	7.6	140114.2	−44.0
$\tau^+\tau^-$, 10 GeV	1628.7	139787.7	282.5
$\tau^+\tau^-$, 30 GeV	232.7	140055.9	14.2
$\tau^+\tau^-$, 100 GeV	4.10	140113.4	−43.3

Abazajian & Kaplinghat (1207.6047)

The excess signals from different analyses, agree within a factor of less than 2 in terms of either suggested DM mass or in terms of suggested cross-section.

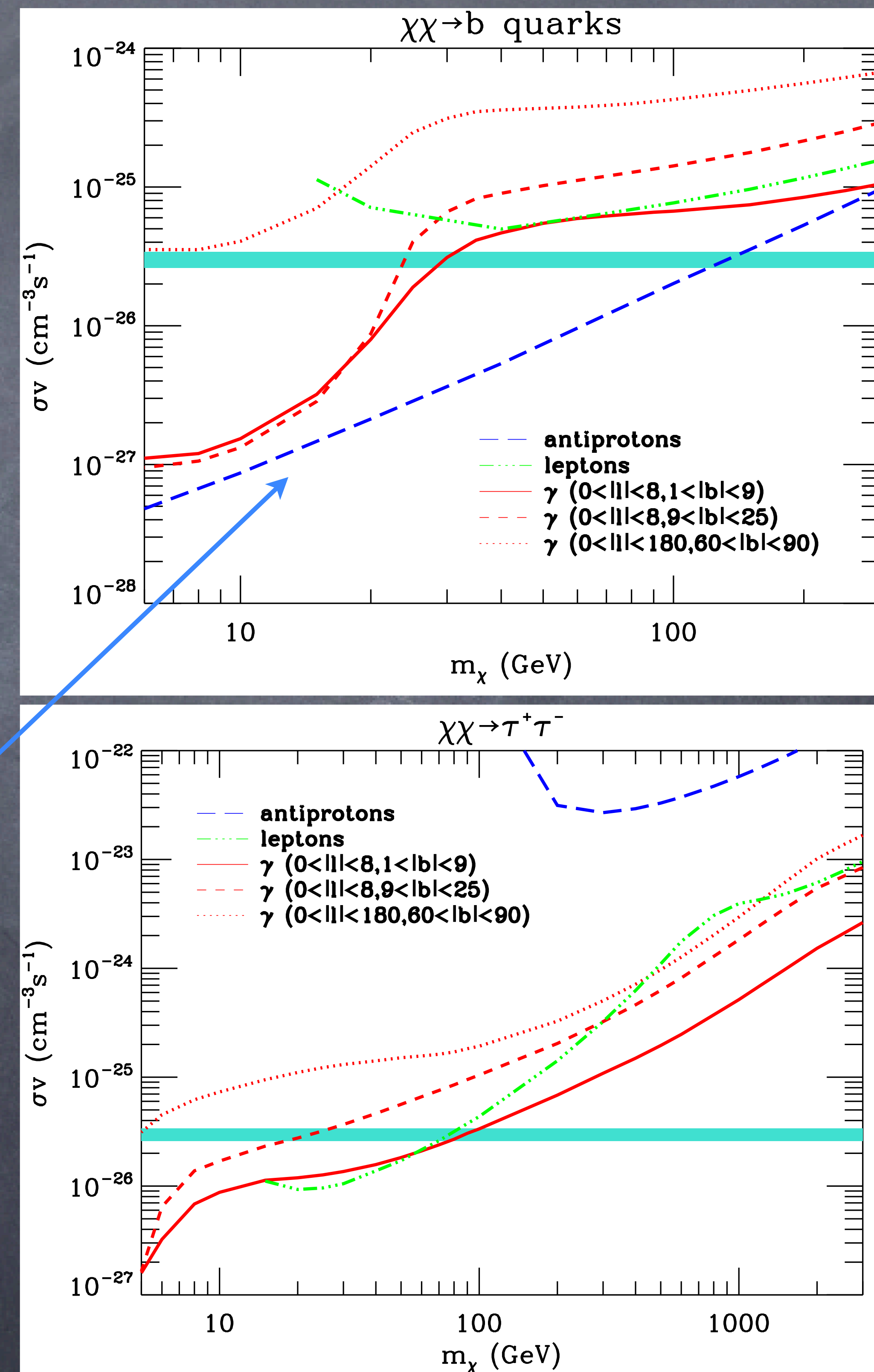
The amplitude of the signal is in general agreement with constraints from other indirect probes: Dwarf spheroidal galaxies, antiprotons, gamma-rays from other regions of the galactic sky



Gordon & Macias (1306.5725)

Derived limits form the same inner few degrees region are stronger than those from dwarf spheroidal galaxies

Antiprotons can still give stronger limits for b-quarks by a factor of ~2.



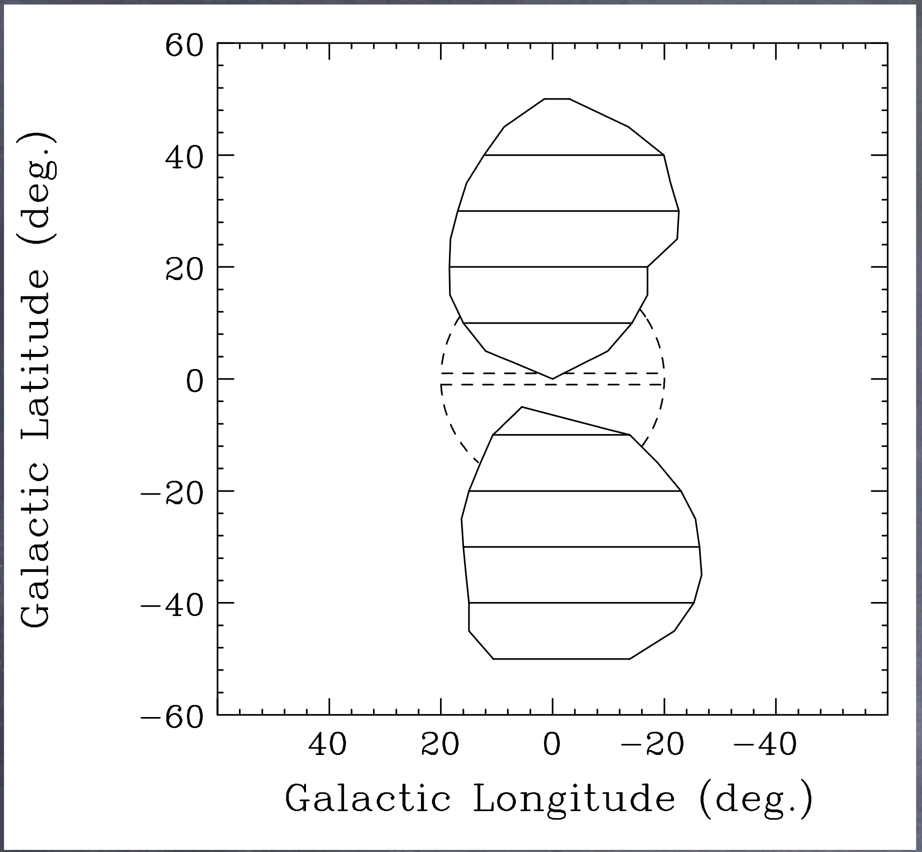
Tavakoli, IC, Evoli, Ullio (1308.4135)

Going to High Latitudes

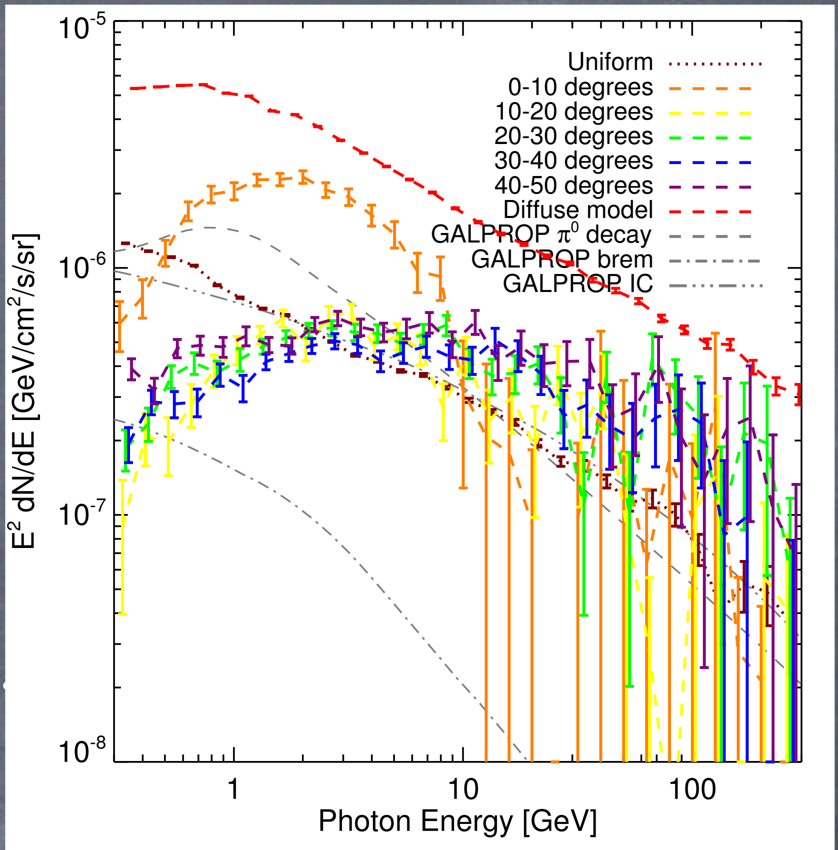
For a DM signal you want to look outside the galactic disk but still just above the galactic center (also dSph galaxies can be an alternative target)

Advantages of going outside the inner few degrees:
i) if a DM signal: you have a prediction on how the spectrum should look (same shape) and how its normalization should be (contacted NFW)
ii) Different region on the galactic sky suffer from different uncertainties in the background models: In the inner part of the Galaxy point source subtraction is a very important uncertainty, the gas density is also an important uncertainty and also the radiation field is an other. At higher latitudes : Fermi Bubbles, possibly unknown gas (unaccounted for in spectral line observations). Also propagation assumptions on the CRs may differ significantly between different regions of the Galaxy (due to strong winds outflows or magnetic fields causing anisotropic and preferential diffusion).

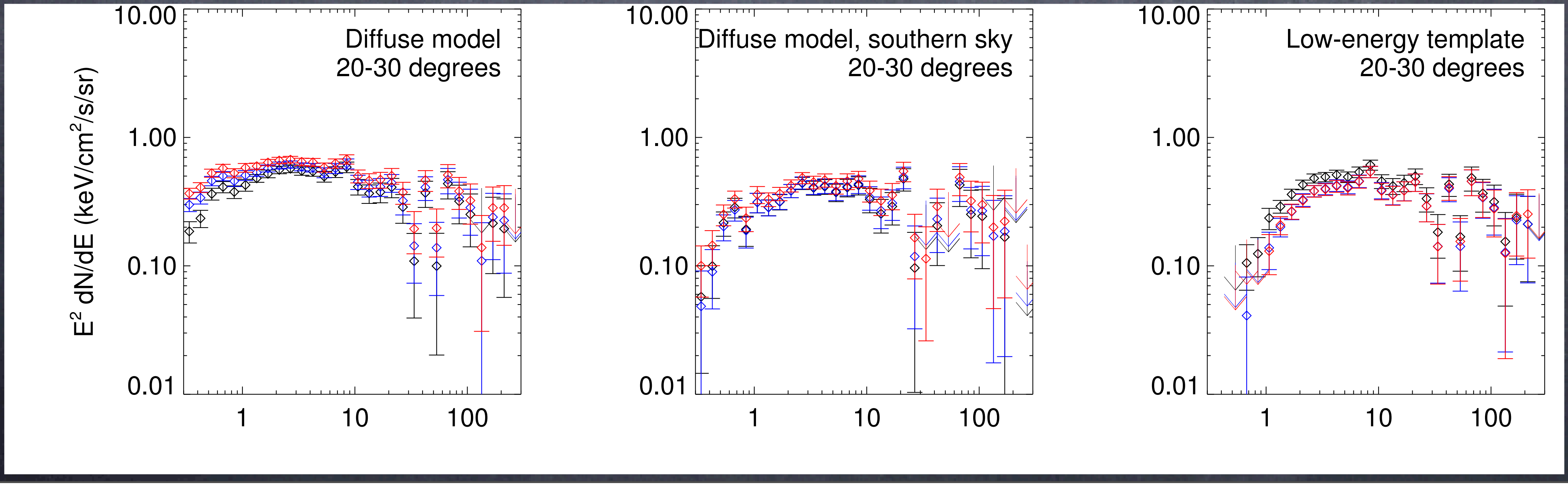
Hooper & Slatyer
1302.6589



Search for residuals at higher latitudes accounting for the Fermi bubbles. Account for diffuse gamma rays (isotropic and galactic). Account for p.s. Residuals can be retrieved.

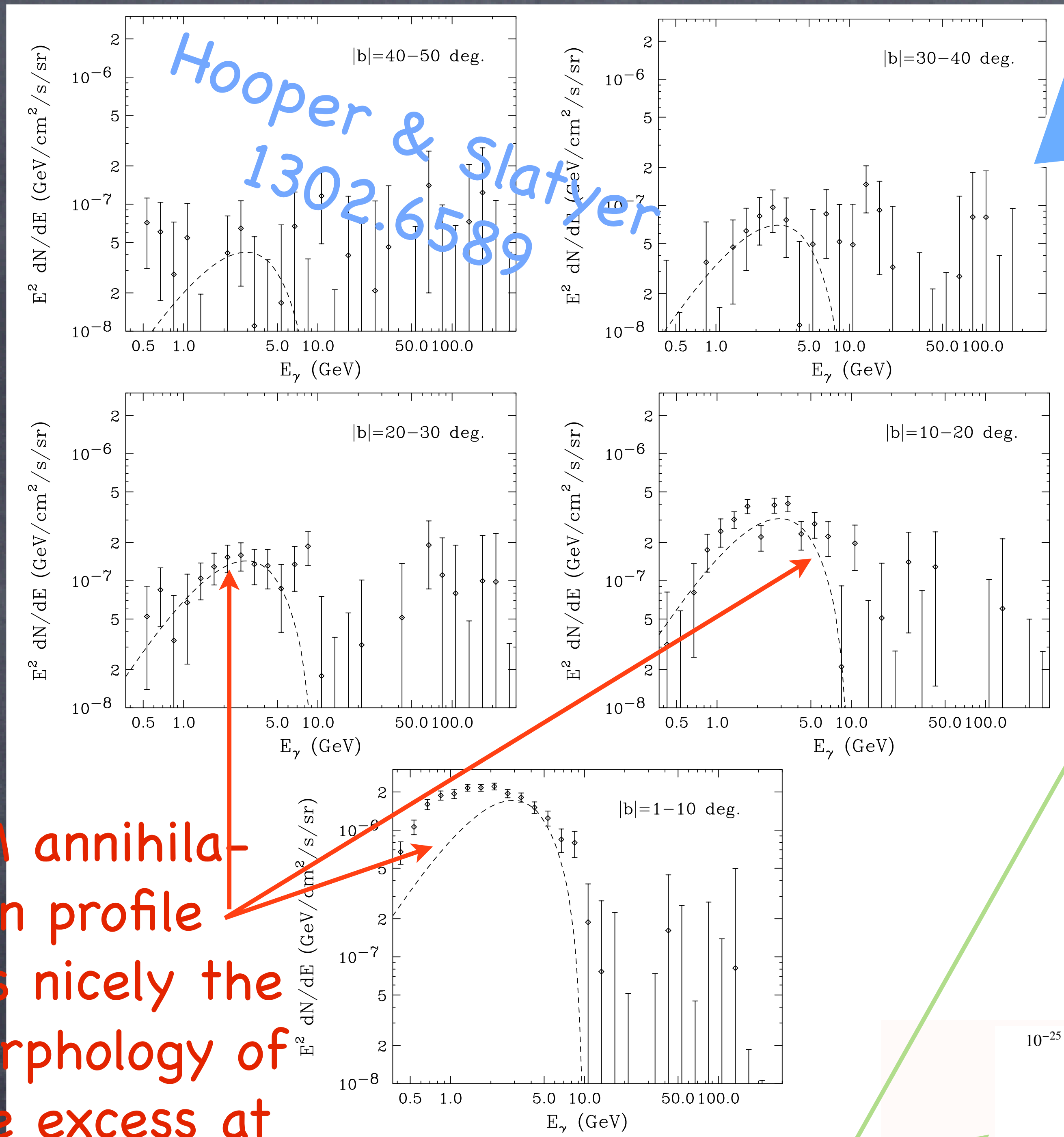


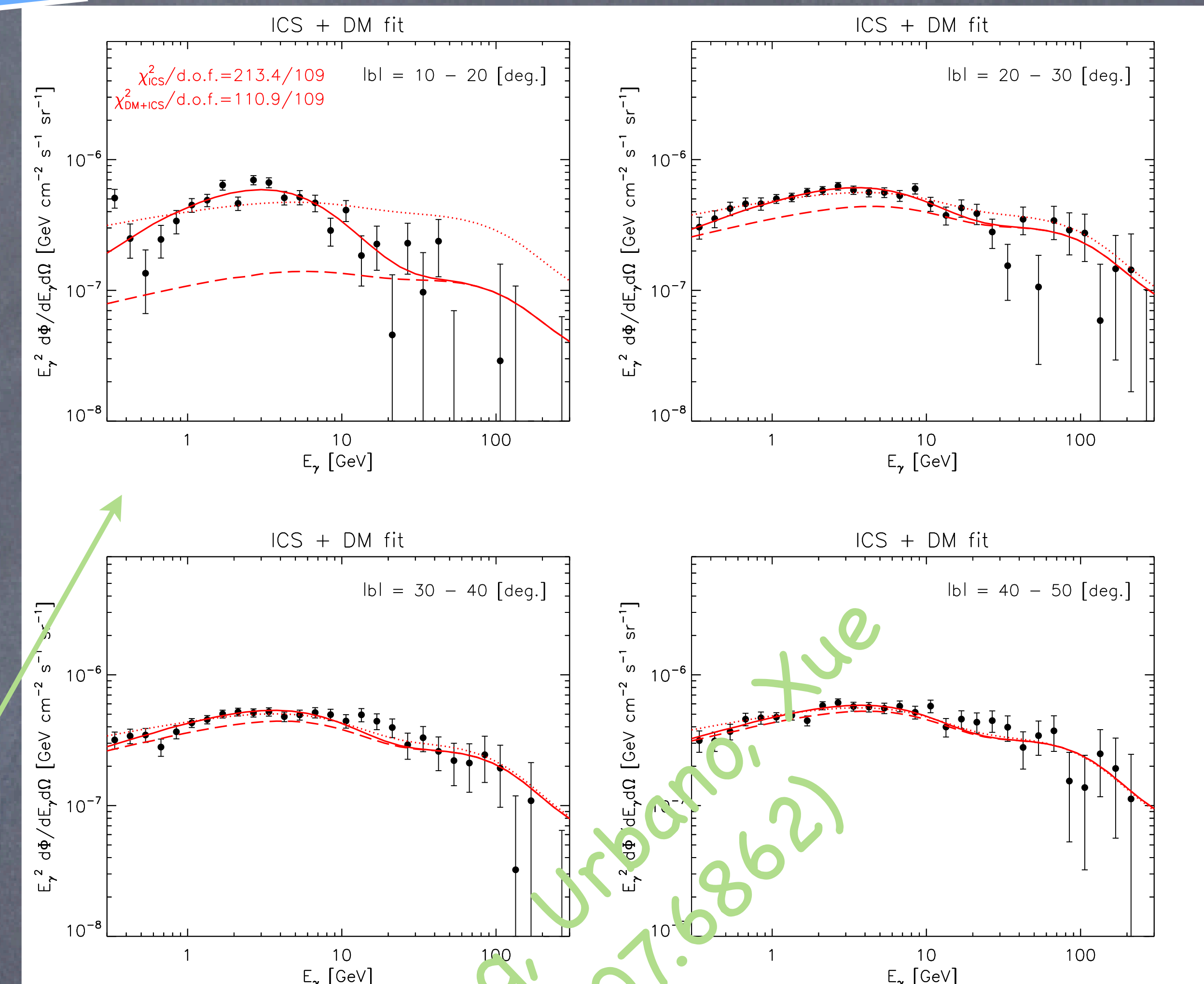
Most important uncertainties remain to be the ones associated to the diffuse model assumptions: AN EXAMPLE:



Residuals in different parts of the galactic sky

Hooper & Slatyer 1302.6589





DM annihilation profile fits nicely the morphology of the excess at high latitudes

Similar results at high latitudes from independent group

Huang, Urbano, Xue (1307.6862)

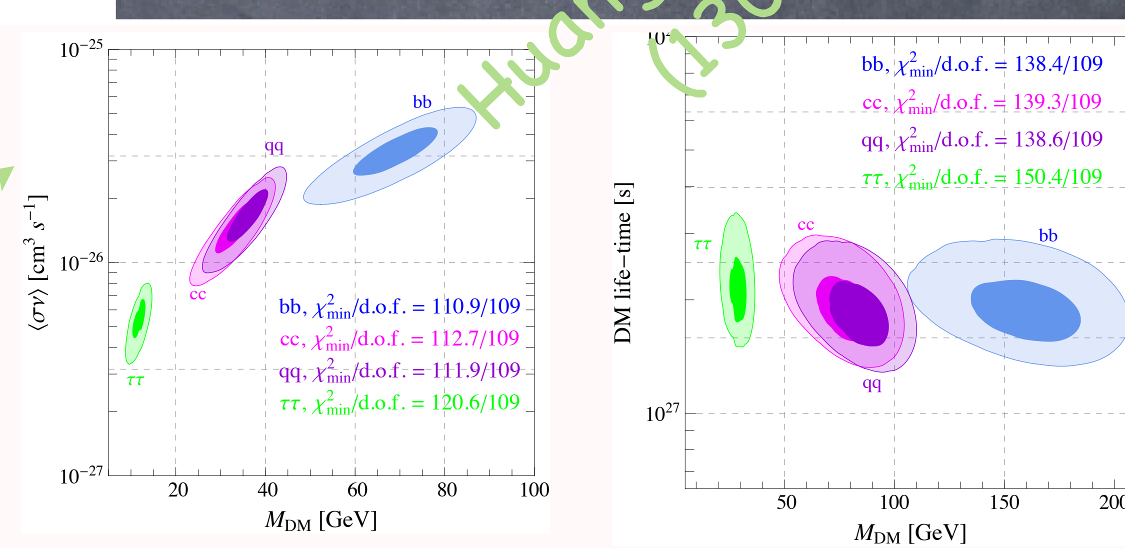


Figure 9: *Confidence regions (99% C.L. and 68% C.L.) for the annihilating (left panel) and decaying (right panel) DM component in the analysis of the Fermi bubbles spectrum (see text for details).*

A non-DM interpretation: Millisecond Pulsars (MSPs)?

How about a collection of Unresolved MSPs ?

Consider a large population of unresolved points sources distributed throughout the inner 100 parsecs of the Galaxy could produce the observed signal, Most likely scenario ~10^3 millisecond pulsars.

Why MSPs? : The observed spectra of Fermi's observed MSPs are qualitatively similar to that from the extended emission from the Galactic Center.

Still the Galactic Center emission appears to have a significantly harder spectral index below ~1-2 GeV

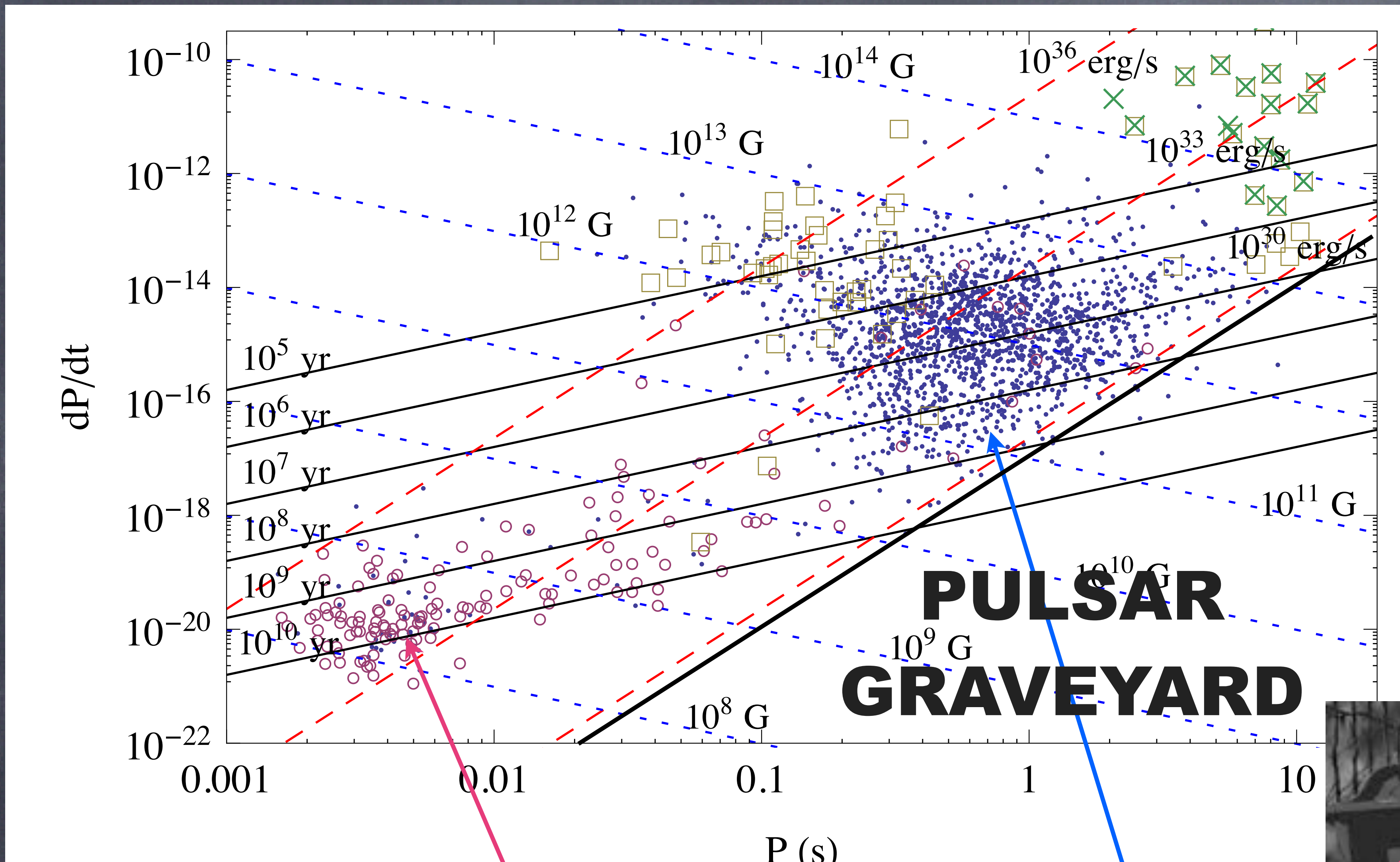
Also suggested the morphology in the inner few degrees of the observed flux implies a very concentrated distribution of sources ($F \propto r^{-2.6}$), while the observed stellar distribution is much more shallow ($n_{star} \propto r^{-1.25}$)
Yet, MSPs are born as a result of star-star interactions, so in that environment they may have been formed over the last many Gyrs at a preferable rate (and distribution).

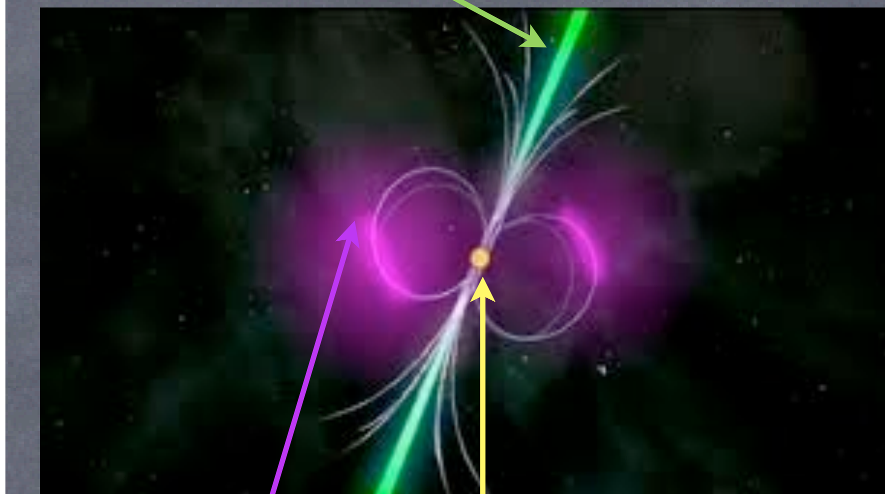
Within the inner 2 degrees BOTH DM annihilation and MSPs ARE VIABLE

A bit about Pulsars in General

Basic model assumed Magnetic dipole radiation (n=3)

$$\tau = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$





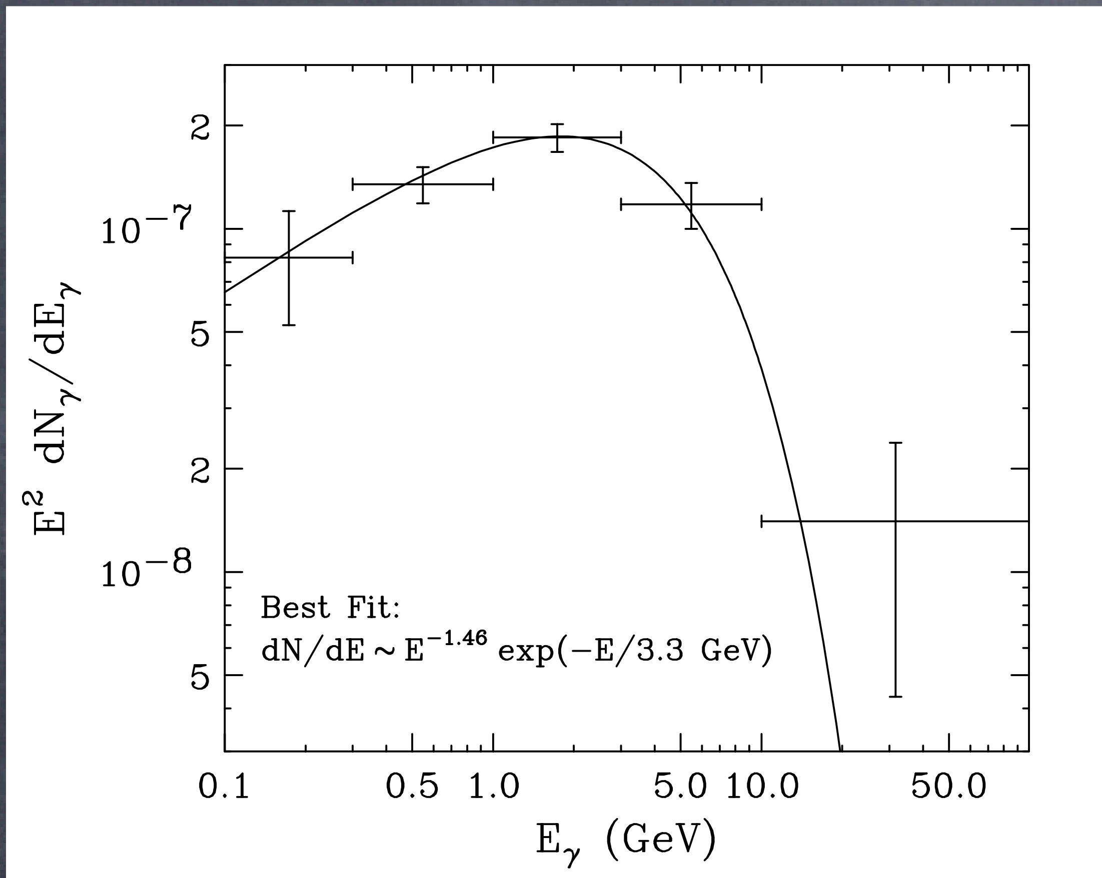
Spinning Up of a normal pulsar (with a period of seconds) to a milli-second ("zombie") pulsar: NEED A COMPANION

$$\dot{E} = -\frac{B_s^2 R_s^6 \Omega^4}{6c^3} \approx 10^{31} B_{12}^2 R_{10}^6 P^{-4}\ \mathrm{erg\ s^{-1}}$$

$$\dot{P} = 3.3 \times 10^{-15}\,(B/10^{12}\,\mathrm{G})^2\,(P/0.3\,\mathrm{s})^{-1}$$

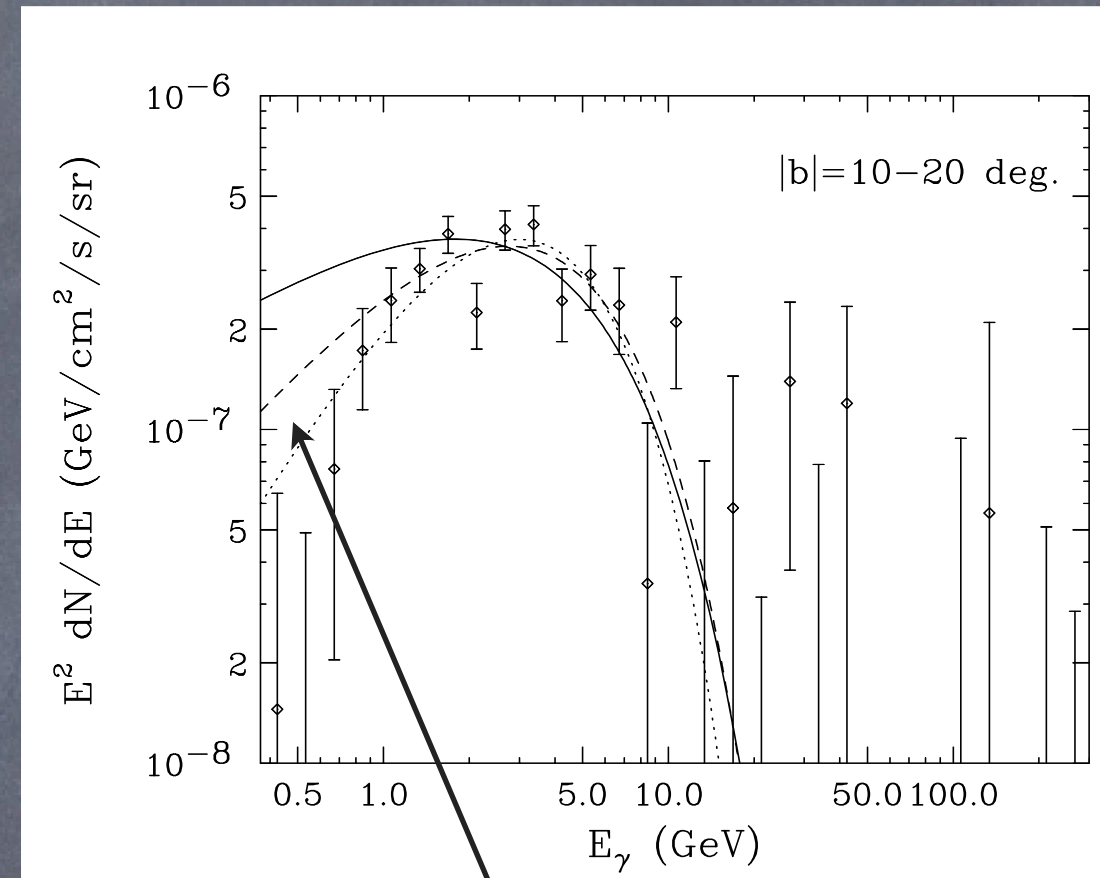
Spectral Arguments

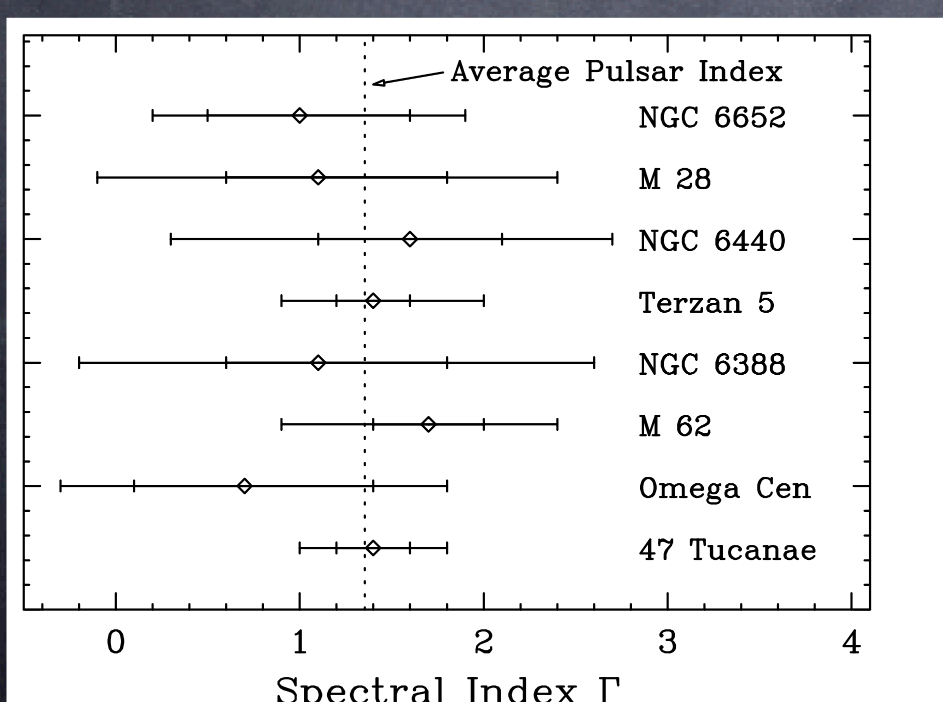
Known MSPs (37 from Fermi)



VS

Gamma-Residual



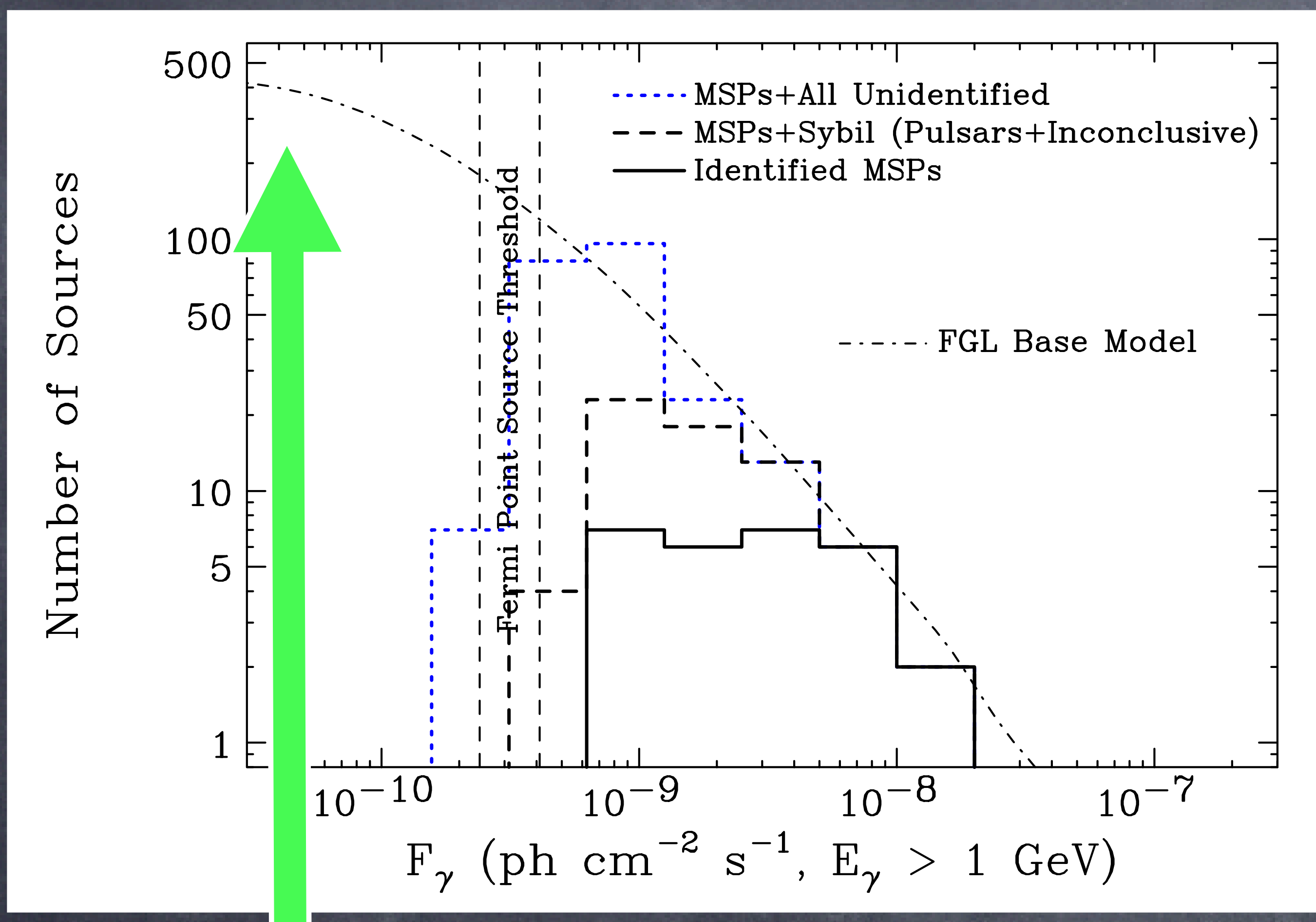


If we change the power-law to E^-1 (Ecut=2.75 GeV), E-^0.5 (Ecut=2.0 GeV) we can get a better fit to the excess. BUT excluded from the data on the left at (at least) 99.8% CL.

Hooper, IC, Linden, Siegal-Gaskins, Slatyer (1305.0830) PRD accept.

"We should have seen them elsewhere" arguments

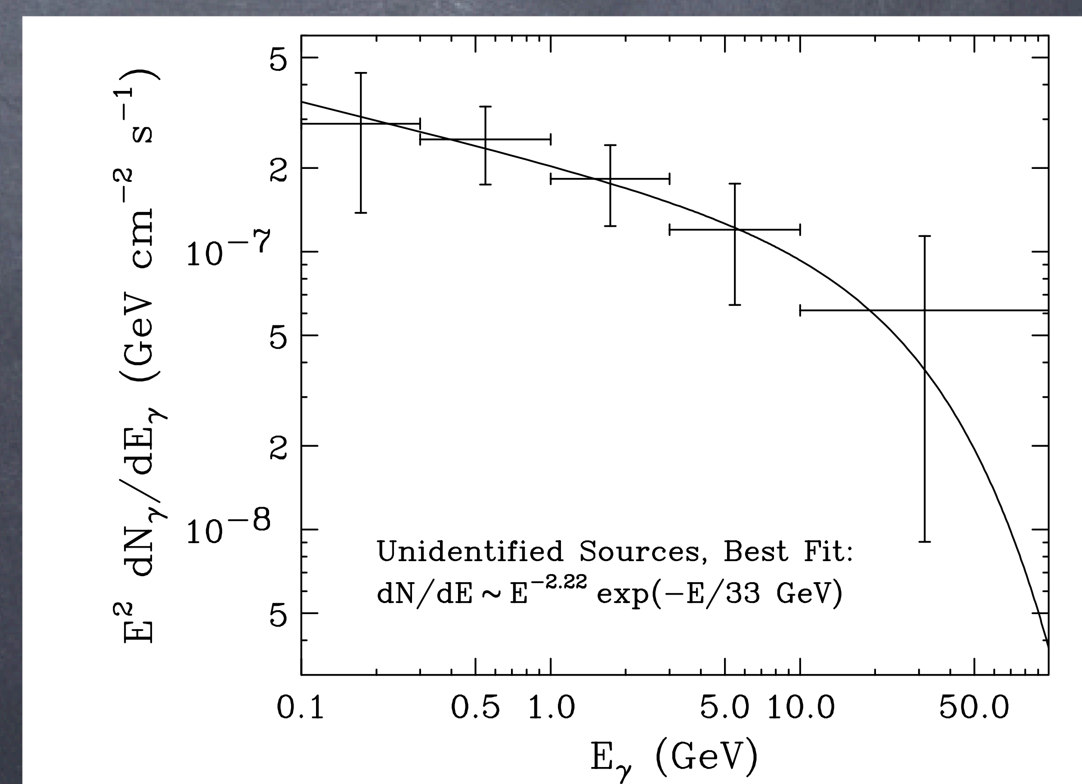
$n(r,z) \propto \exp(-r^2/2\sigma_r^2)\,\exp(-|z|/\langle|z|\rangle)$: spatial distribution in the Galaxy



:Based on some reference assumptions on the MSP spatial and B-field distribution, that still over-predict the number of dimmer but observable sources

As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

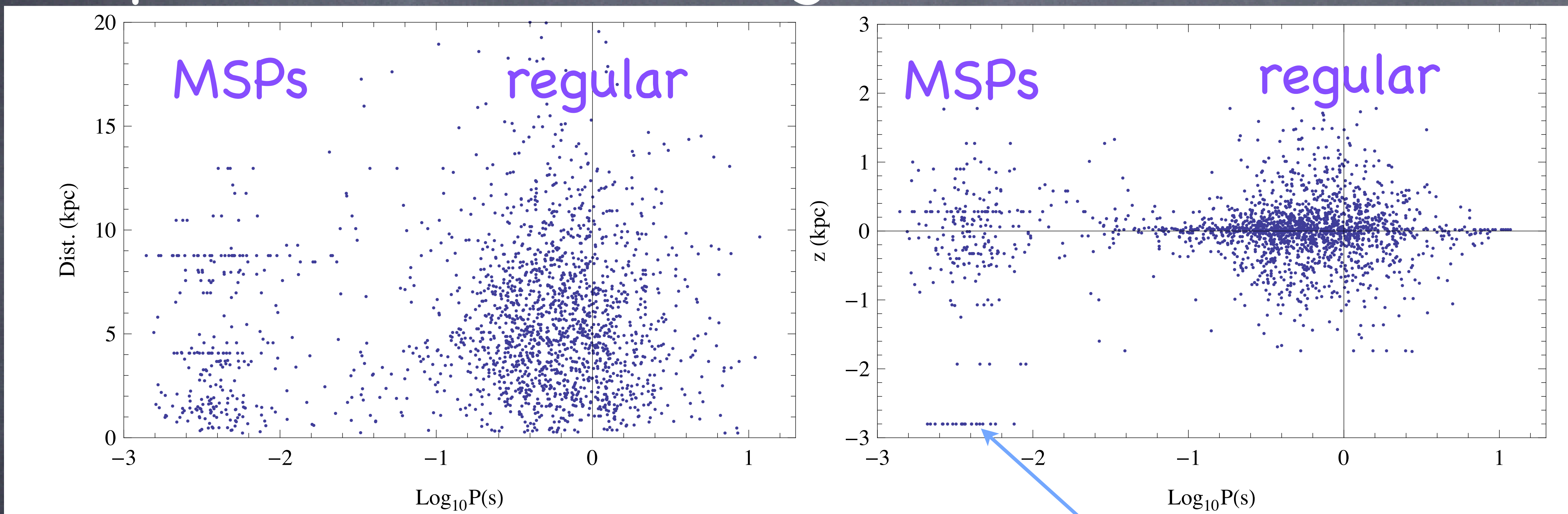
Fermi unresolved p.s. above |b|>10: Disagrees with the excess spectrum. They are dominated by the AGN sample



What is the information on their location

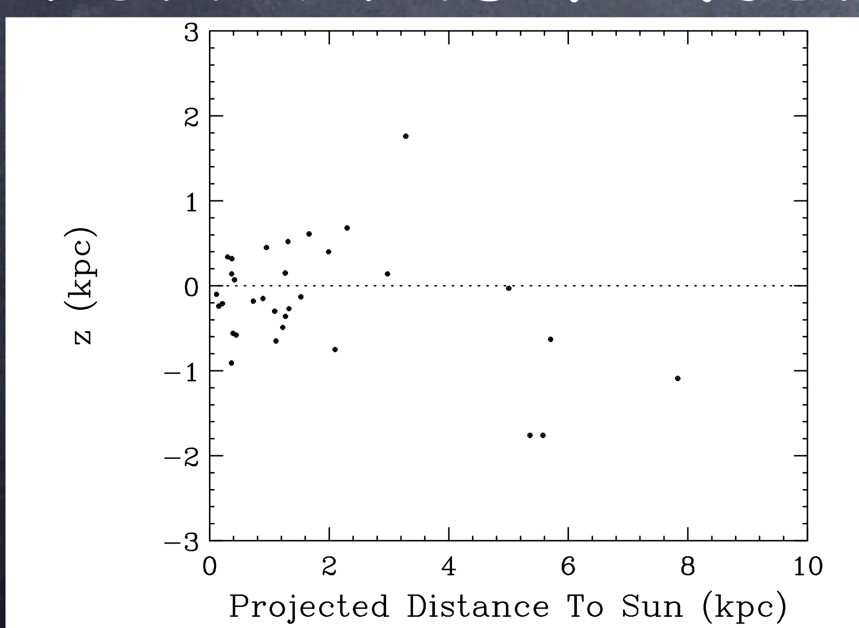
MSPs have a characteristic time of Gyrs and kick velocities ~10 km/s Will travel ~1 kpc inside the Galaxy. Thus a non Glob Clust. population not be very concentrated.

ALL pulsars (ATNF catalogue)

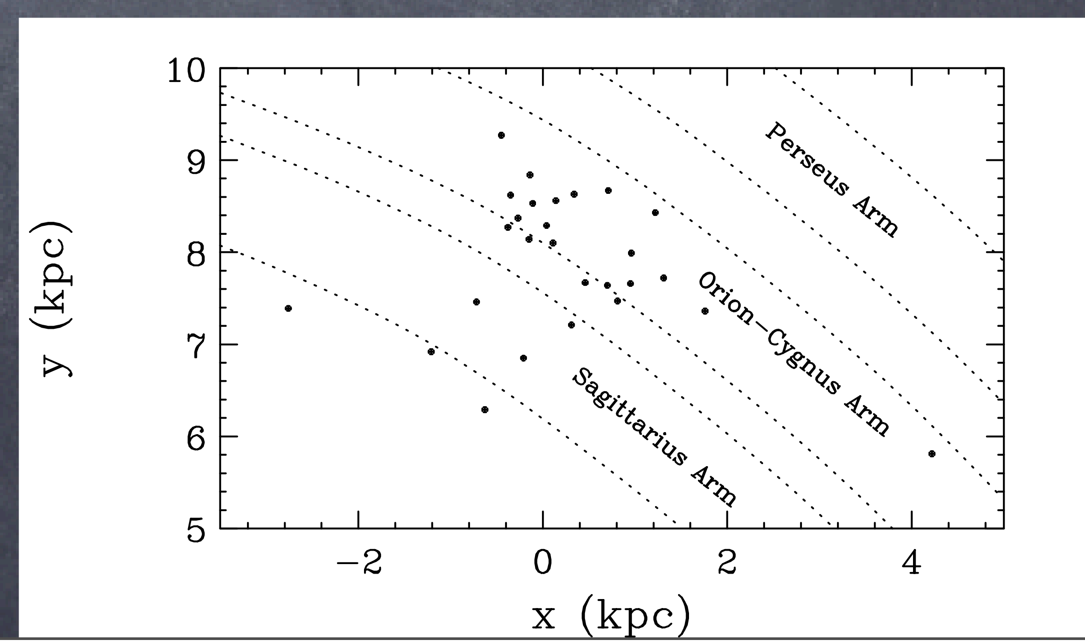


Globular cluster MSPs

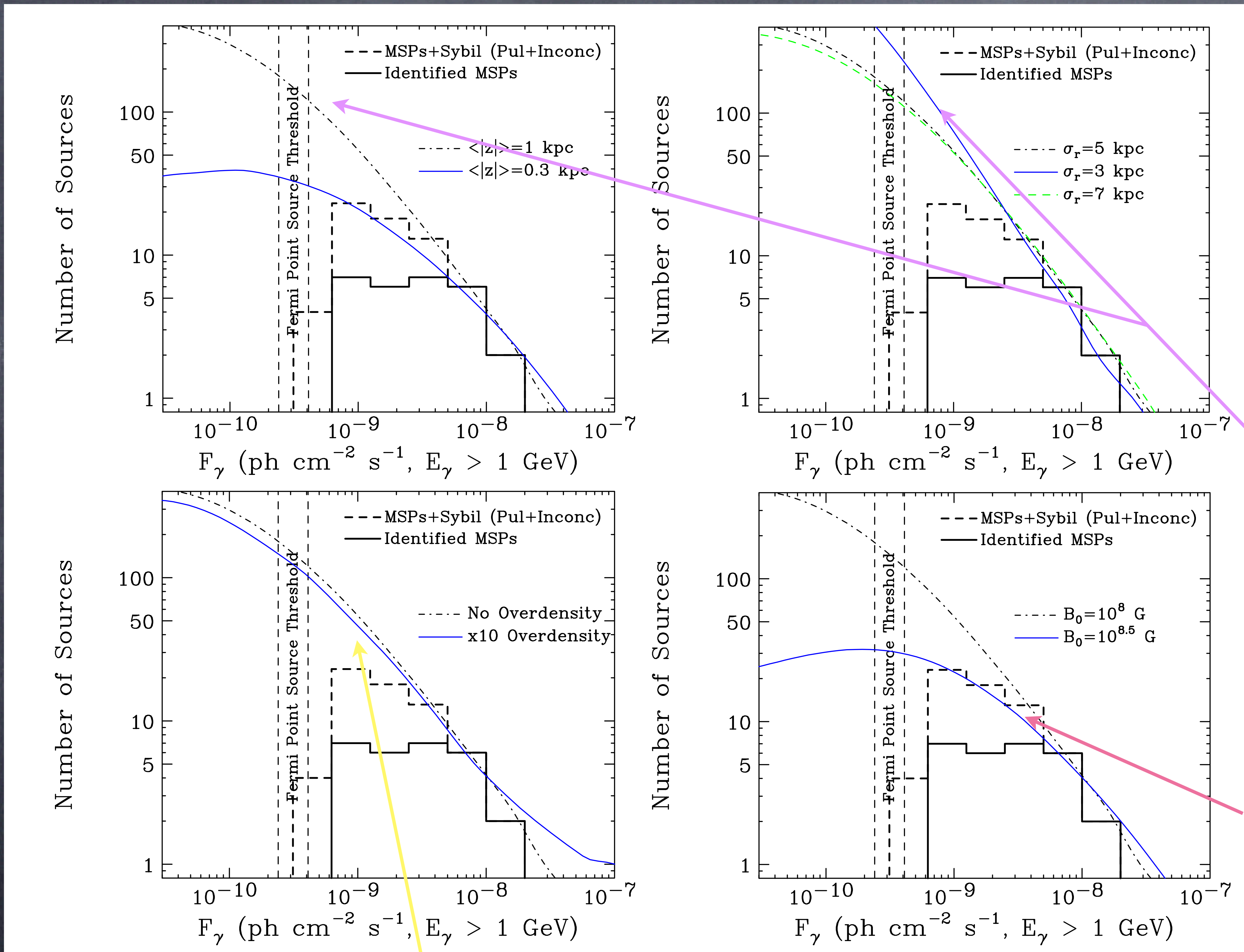
Fermi MS Pulsars (37<)



In gamma -rays they are close by.



Varying the distribution assumptions

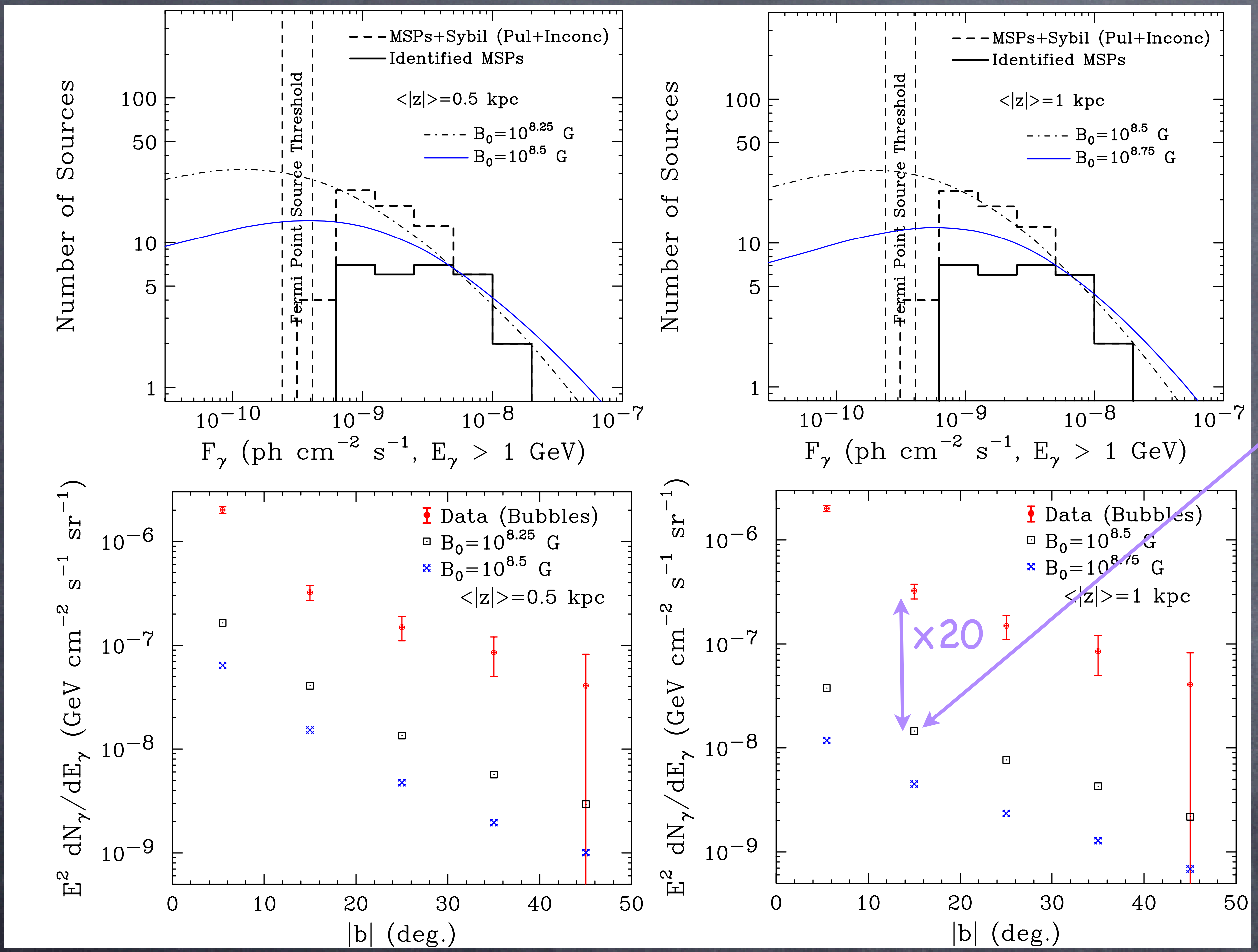


Models that would give enough MSPs in the inner 2 kpc over-predict the number of MSPs that should have already been observed by LAT at locations closer to the Earth

Preferred B-field assumptions do not give a dim MSP population

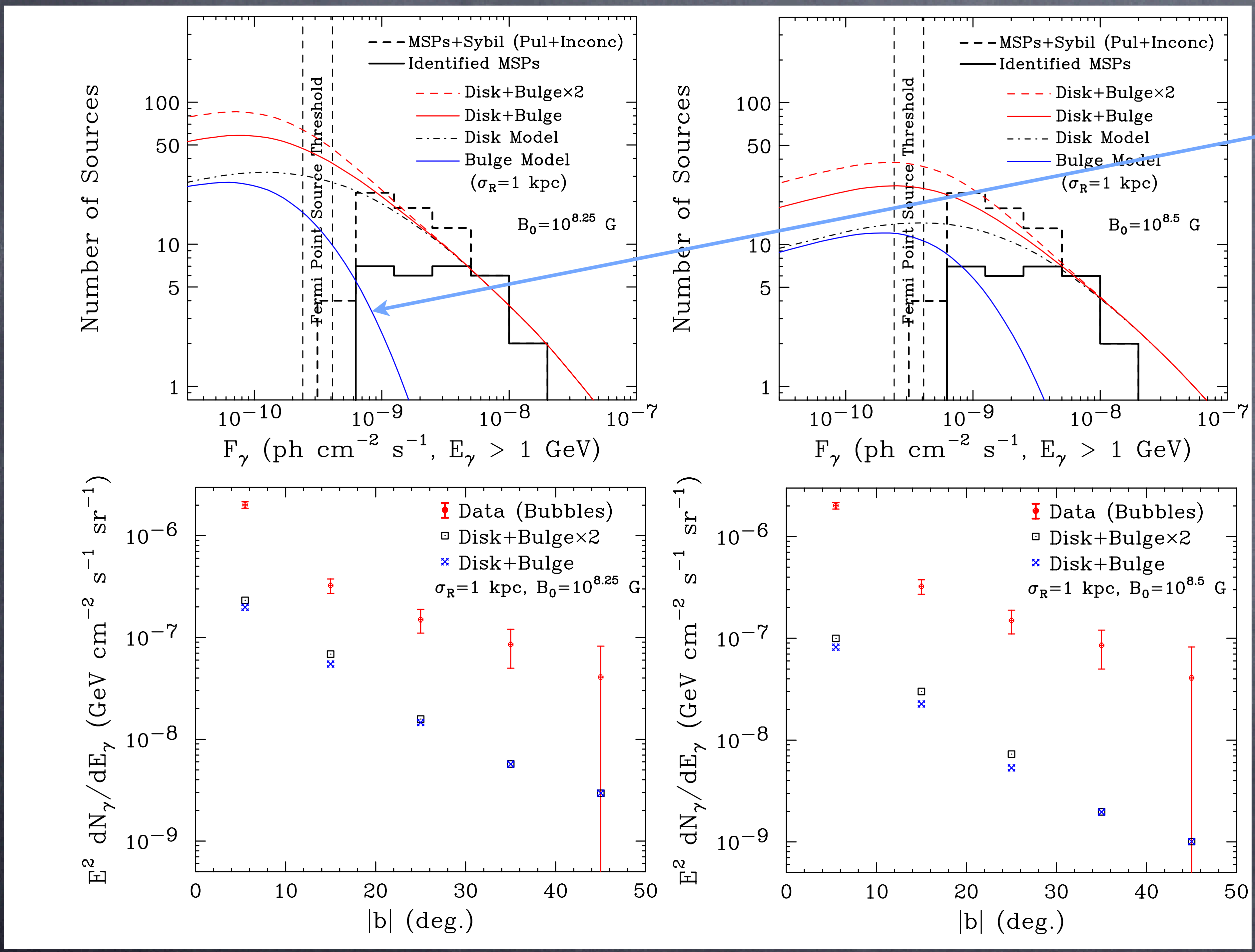
Being in at a local overdensity/underdensity can not affect much the results

Assumptions that agree with everything



MSP models that are consistent with the observed (suggested) population can give only 5-10% of the observed diffuse emission in the inner 2kpc of the Galaxy.

Adding a bulge (but staying in agreement with observations)



Having a bulge can result in adding dim MSPs (since there are no local MSPs from the bulge). Yet that does not help much, especially above |b|>20 where the bulge population can not contribute.

Rough approx. for Bulge MSP distr. :

$$n(R) \propto \exp(-R^2/\sigma_R^2)$$

Questions for further discussion…

- How well have we probed the relevant uncertainties? Are the different methods used to probe the excess signal in the inner few degrees and at higher latitudes DIFFERENT/ ORTHOGONAL (to quote Meng and Gabi) ENOUGH?

- How well do we understand the diffusion/propagation of CRs in the inner part? (to quote Carmelo, Paolo and Pasquale)

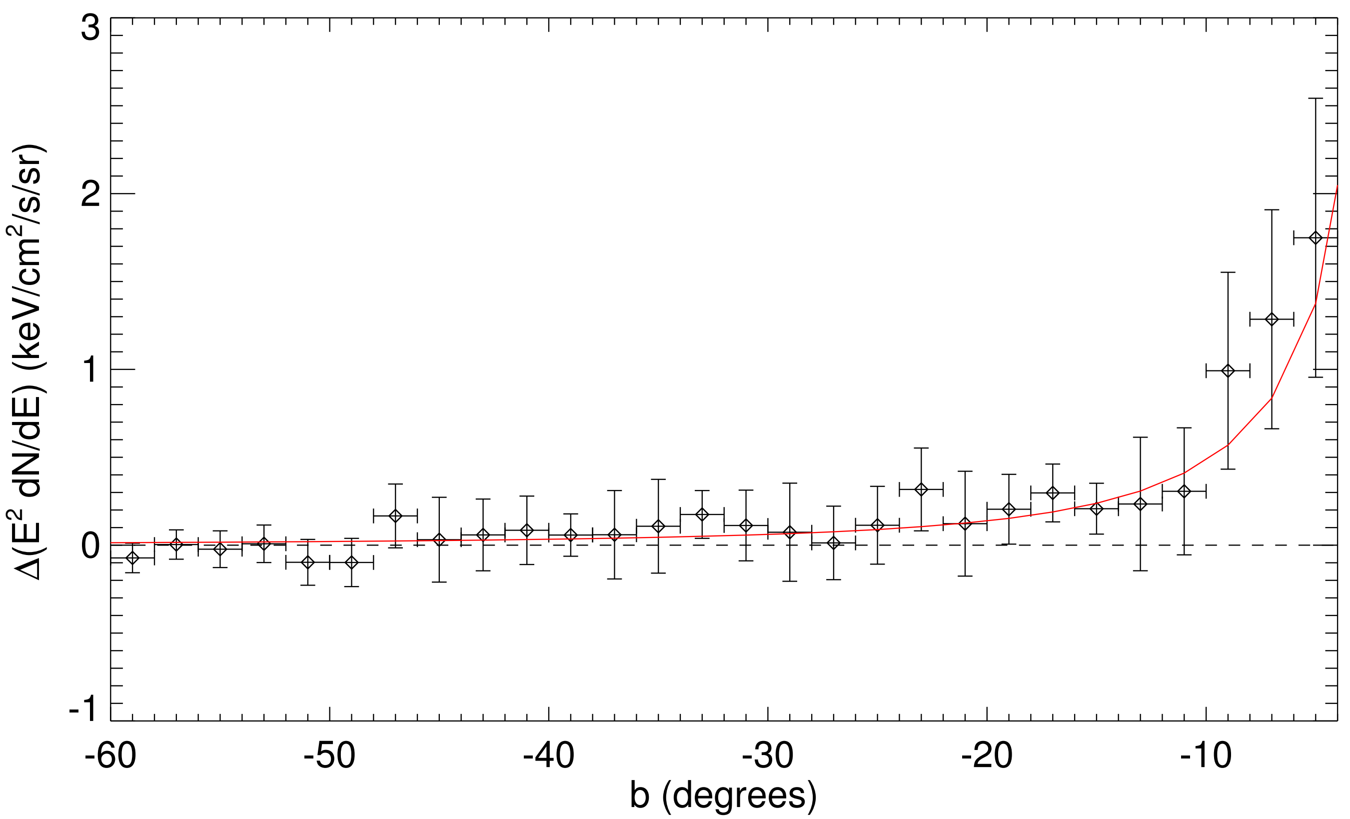
- Can we build up a new distribution of sources in the inner 1-2 kpc that have the right properties but are not close by to us? How would we see them? (to quote Christoph)

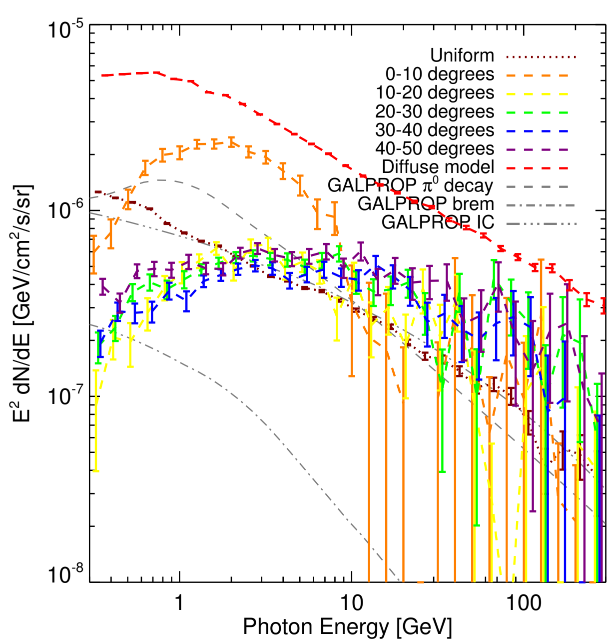
- How about dSphs? (Dan is "enthusiastic" about the recent Fermi results)

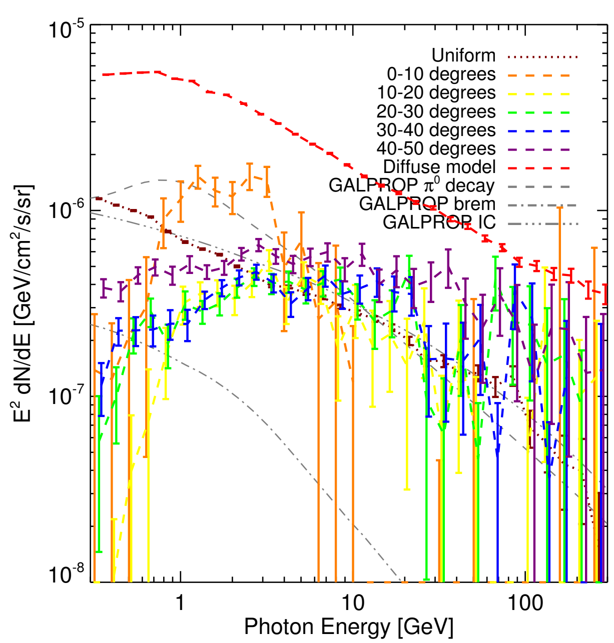
- How about galaxy clusters? (I am not optimistic yet due to large contamination from both background and foreground emission)

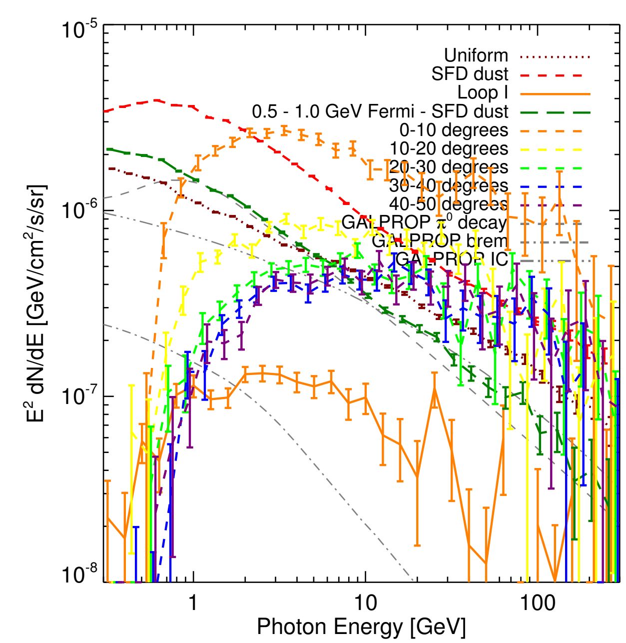
Thank you!

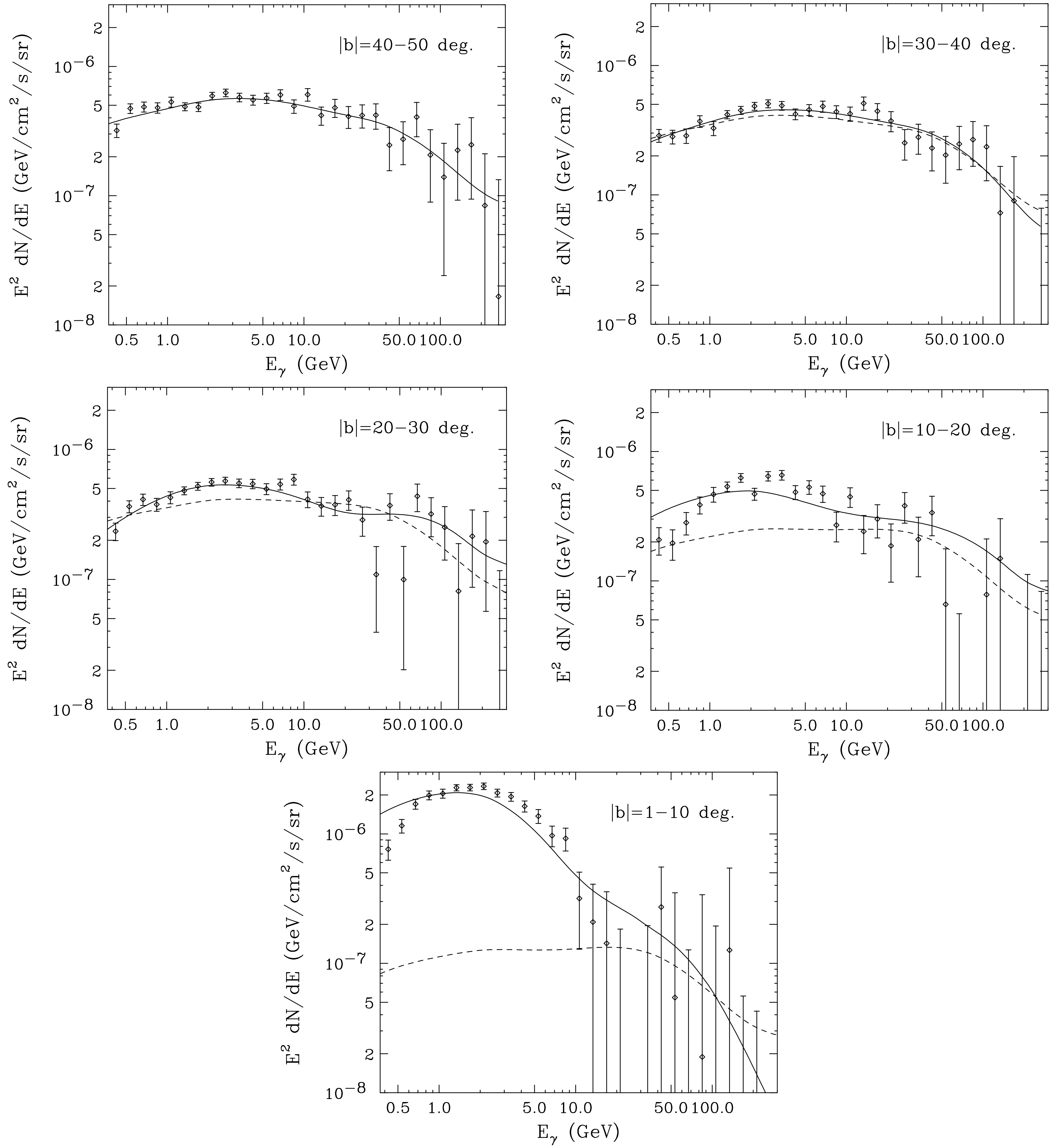
Additional Slides

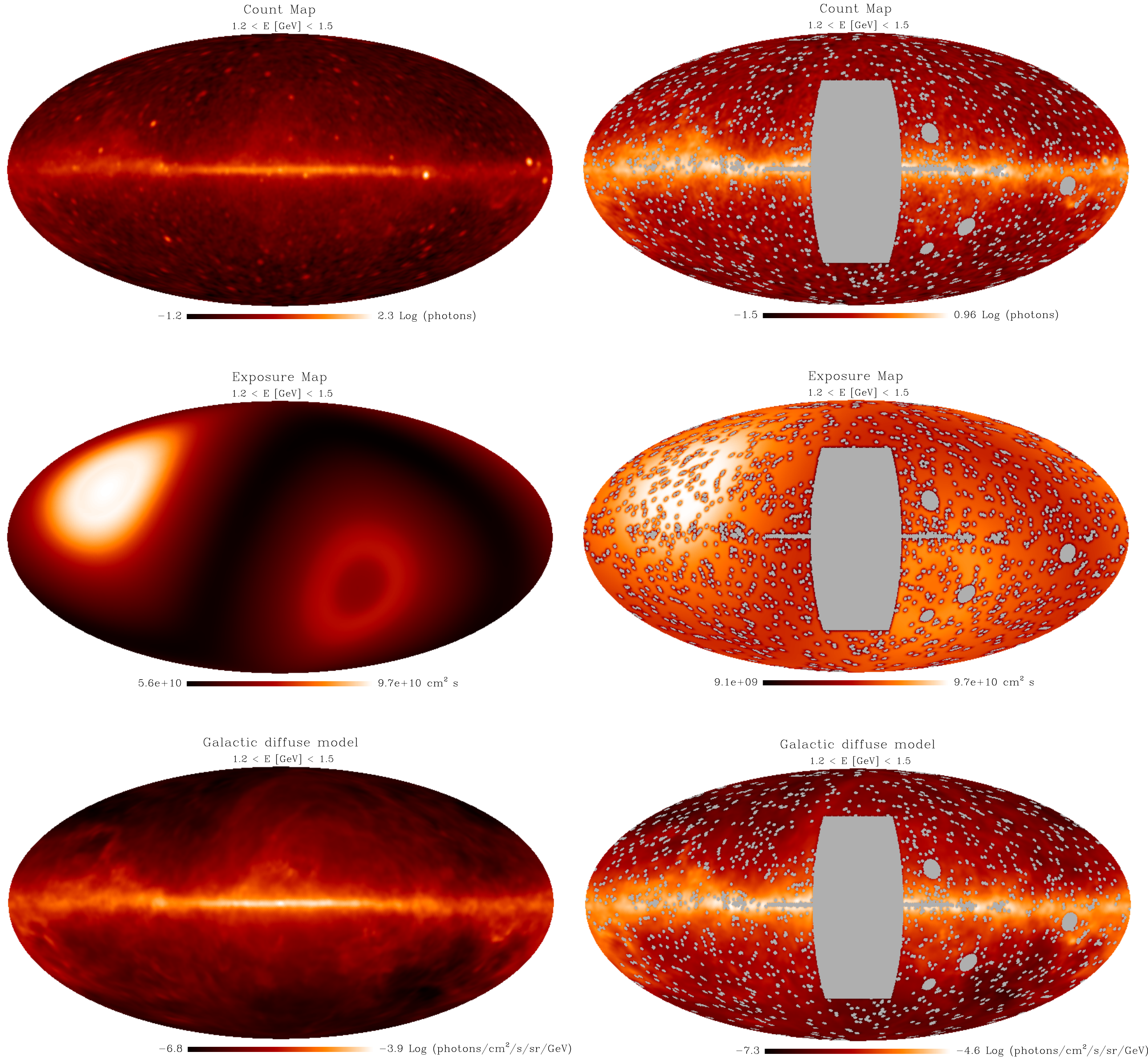




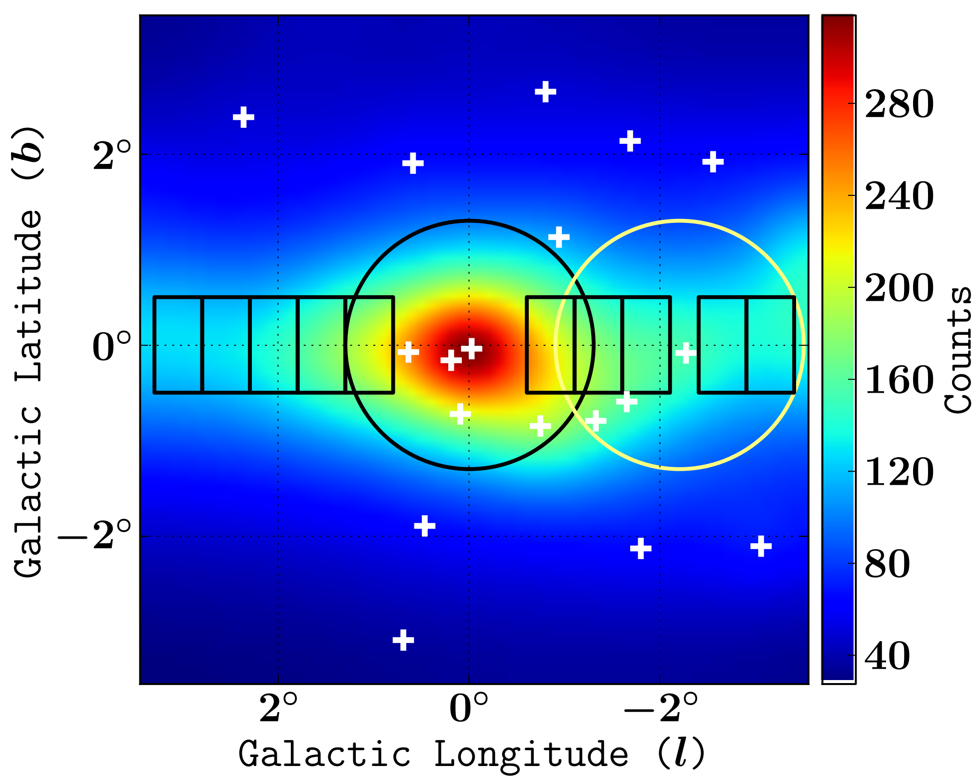





|b|=40−50 deg.
|b|=30−40 deg.
|b|=20−30 deg.
|b|=10−20 deg.
|b|=1−10 deg.
E² dN/dE (GeV/cm²/s/sr)
E_γ (GeV)
10⁻⁶
10⁻⁷
10⁻⁸
0.5 1.0 5.0 10.0 50.0 100.0


Count Map
1.2 < E [GeV] < 1.5
−1.2
2.3 Log (photons)
Count Map
1.2 < E [GeV] < 1.5
−1.5
0.96 Log (photons)
Exposure Map
1.2 < E [GeV] < 1.5
5.6e+10
9.7e+10 cm² s
Exposure Map
1.2 < E [GeV] < 1.5
9.1e+09
9.7e+10 cm² s
Galactic diffuse model
1.2 < E [GeV] < 1.5
−6.8
−3.9 Log (photons/cm²/s/sr/GeV)
Galactic diffuse model
1.2 < E [GeV] < 1.5
−7.3
−4.6 Log (photons/cm²/s/sr/GeV)

DM annihilation	$M_{\rm DM}$ $[GeV]$	$\langle \sigma v \rangle$ $[cm^3 s^{-1}]$	$\chi^2_{\rm min}$/d.o.f.
$b\bar{b}$	$61.8^{+6.9}_{-4.9}$	$3.30^{+0.69}_{-0.49} \times 10^{-26}$	110.9/109
$c\bar{c}$	$29.3^{+2.4}_{-3.4}$	$1.54^{+0.26}_{-0.30} \times 10^{-26}$	112.7/109
$q\bar{q}$	$32.0^{+2.6}_{-3.8}$	$1.73^{+0.30}_{-0.30} \times 10^{-26}$	111.9/109
$\tau^+\tau^-$	$10.6^{+0.5}_{-0.6}$	$5.63^{+0.58}_{-0.64} \times 10^{-27}$	120.6/109



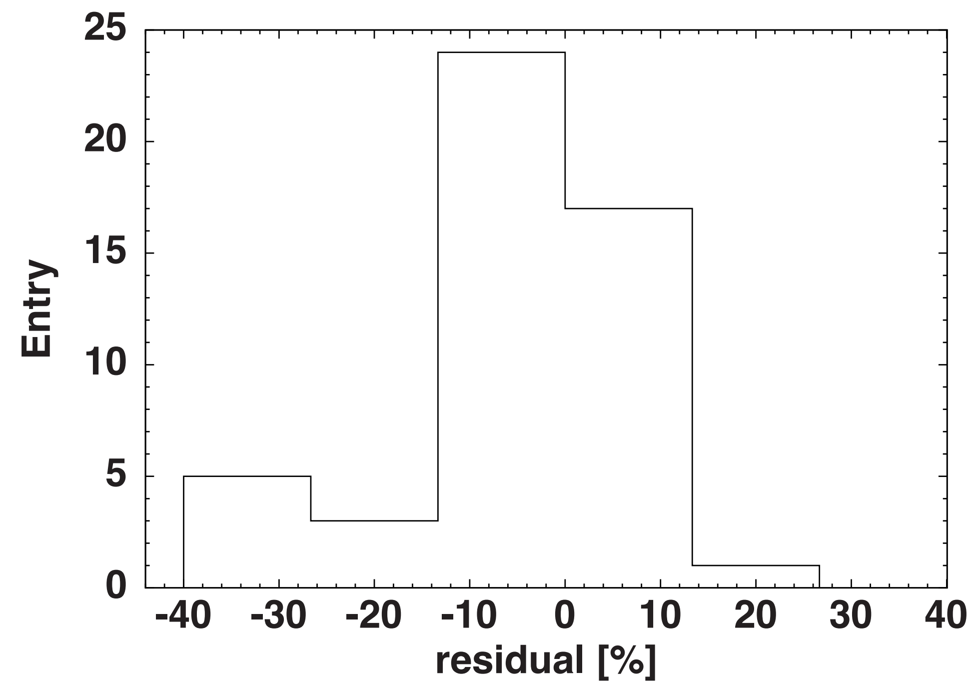


FIG. 6. (a) Counts map in the 0.3−100 GeV energy band smoothed with a Gaussian filter of radius $\sigma = 0.3°$. The black rectangles ($1.0° \times 0.5°$) highlight the regions selected for the examination of the spatial uncertainties in the Galactic diffuse background. The black and yellow circles show the regions where the flux of the file `gal_2yearp7v6_v0.fits` was varied to evaluate the effects of the spatial dispersion of the model. (b) Histogram of the fractional residuals for ten rectangular regions in five energy bands: 0.30−0.50 GeV, 0.50−0.80 GeV, 0.80−1.30 GeV, 1.3−10 GeV and 10−100 GeV. The residuals were calculated as (observed-model)/model, where we also subtracted the best fit fluxes of all the sources (except for the Galactic diffuse background source) from the observed counts map.