Evidence for unresolved point sources in the GeV gamma-ray excess

Tracy Slatyer
based on arXiv:1506.05124 (submitted to Science)
with Samuel Lee, Mariangela Lisanti, Ben Safdi and Wei Xue

Accurate Astrophysics, Correct Cosmology
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Outline

- BACKGROUND: a primer on the GeV gamma-ray excess
  - Properties that suggest a dark matter origin
  - Astrophysical alternatives
- METHOD: template fitting for models with non-Poissonian statistics
- RESULTS: evidence for a (peculiar?) point source population largely responsible for the excess

The GeV gamma-ray excess

- Excess of ~1-3 GeV gamma rays in the (extended) central region of the Milky Way, spatially concentrated at the Galactic Center, identified as a possible signature of dark matter annihilation.

- Discovered in public data from the Fermi Gamma-Ray Space Telescope

  - First in the Galactic Center (Goodenough & Hooper 09).

  - Later extending to higher latitudes (Hooper & TRS 13).

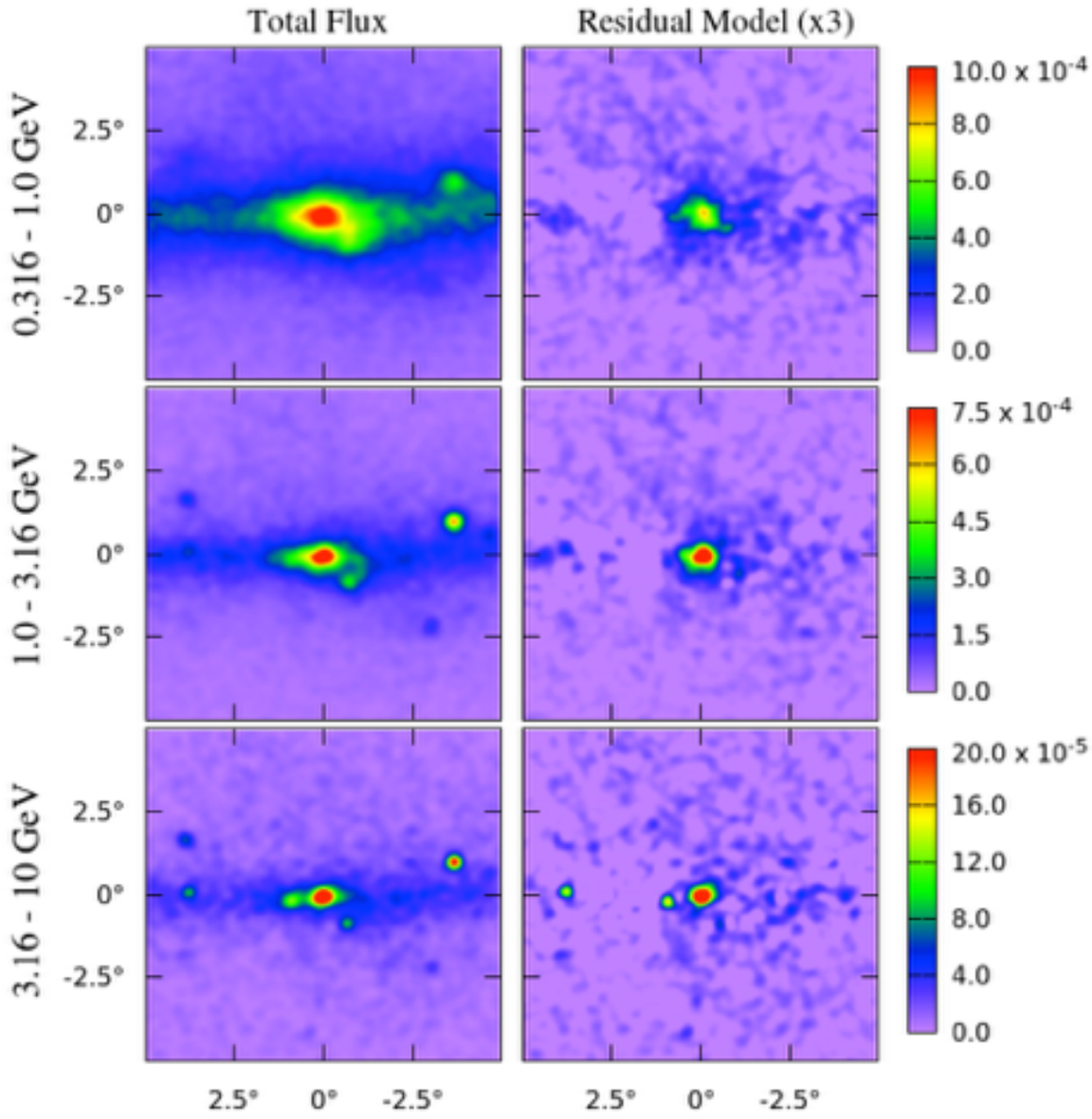
  - Existence and properties have been confirmed in both regions by multiple independent groups.

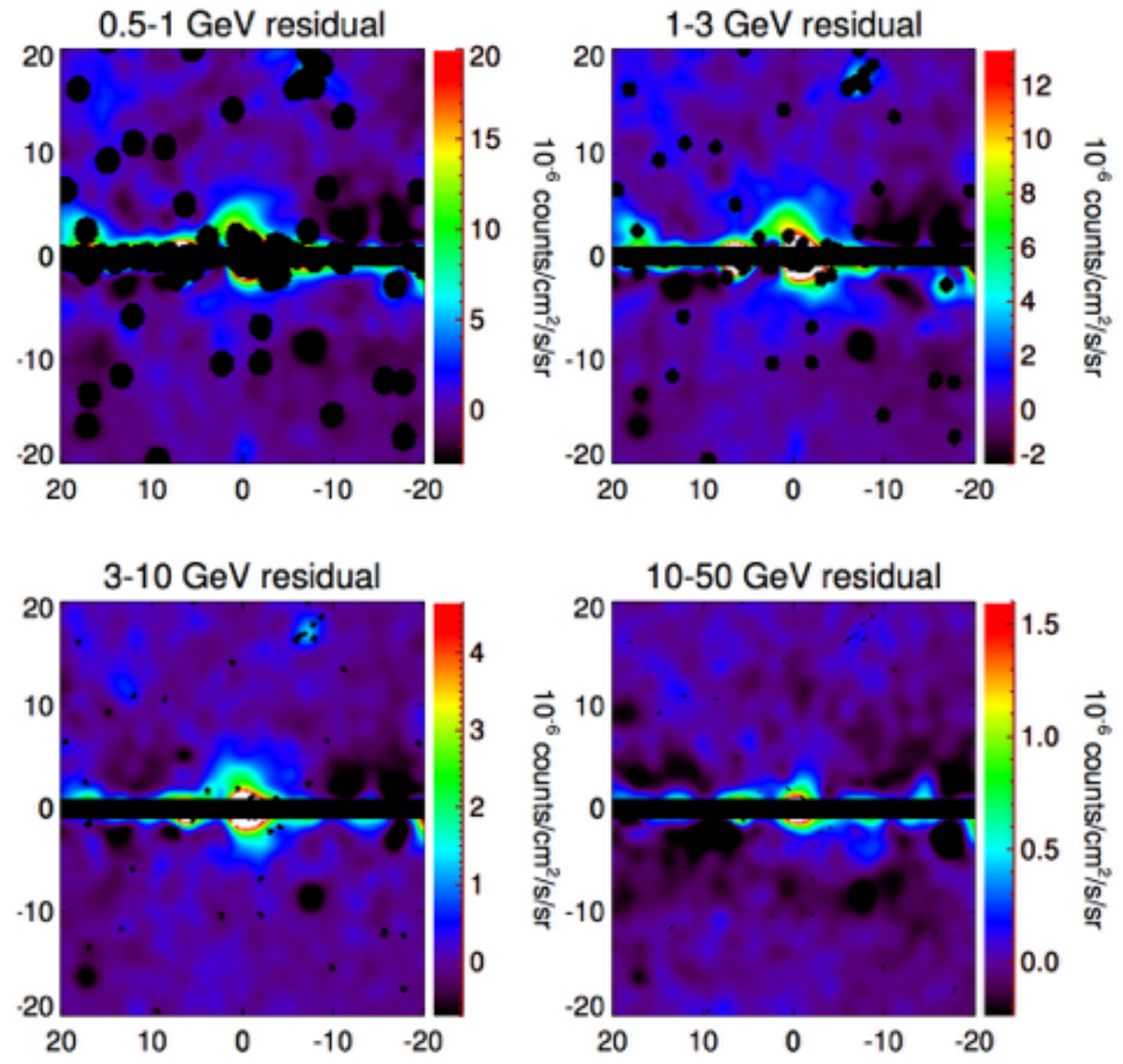
- Highly significant, not a statistical fluctuation.

  - Tens of thousands of photons

  - Can contribute up to ~30% of the total photon flux (at the peak of the excess, and near the Galactic Center)

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd & TRS ’14

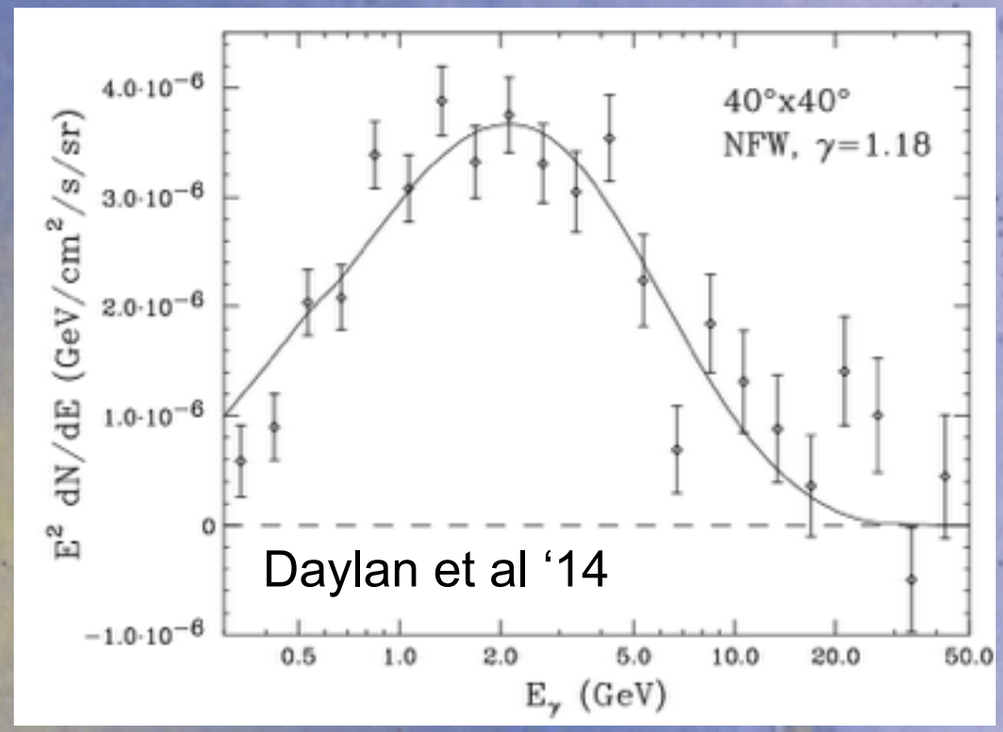


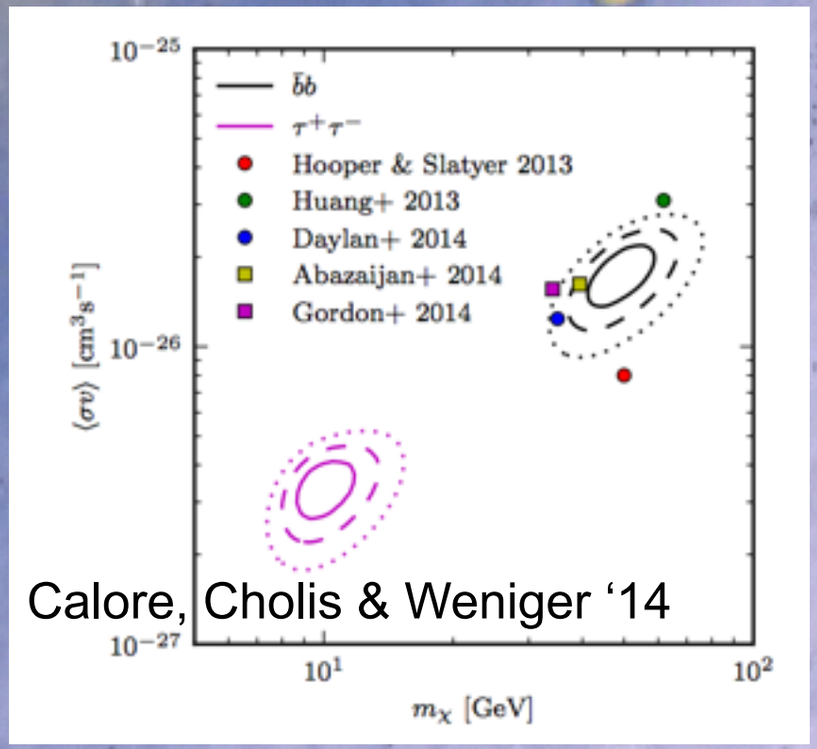


- Generally consistent with spherical symmetry around the Galactic Center (can exclude stretches by more than ~20% along the Galactic plane).
- Power-law slope (in inferred flux per unit volume, assuming spherical symmetry) ~ $r^{-2.2\text{-}2.8}$. If photons originate from DM annihilation (scaling as density squared), corresponds to a small-r DM density profile slightly steeper than standard Navarro-Frenk-White (NFW) profile, proportional to $r^{-1.1\text{-}1.4}$ (compared to 1/r for standard NFW).
- Appears centered on Sgr A*, the black hole at the center of the Milky Way.
- Extends out to at least 10 degrees (~1.5 kpc) from the GC.

Dark matter…

- Naturally explains:
  - The shape of the spectrum - well fit by fairly light DM (~100 GeV or less) annihilating to a range of Standard Model particles.
  - Apparent absence of spatial variation in the spectrum of the excess.
  - The ~spherical morphology of the signal.
  - The profile: steeply peaked at the Galactic Center but extending out to (at least) 10 degrees.
- Required annihilation cross section lines up with long-standing predictions for the “thermal relic” scenario.

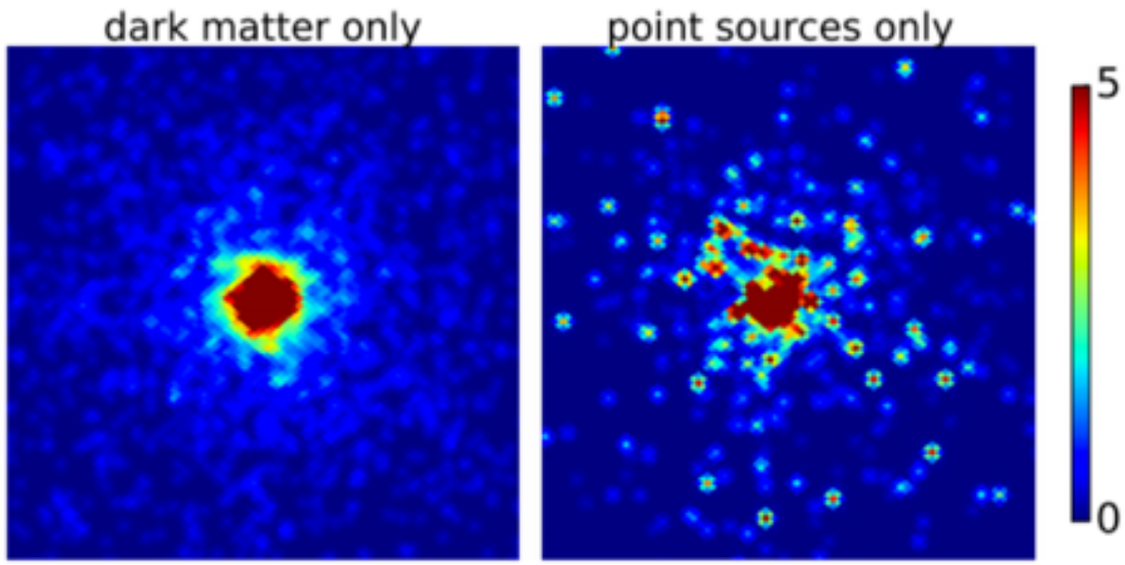




… or astrophysics?

- MILLISECOND PULSARS (first proposed by Abazajian 1011.4275):
  - Spectrum of observed MSPs matches excess well at energies > 1 GeV.
  - MSPs originate from binary systems, can naturally explain steep slope of profile.
  - BUT: sphericity unexpected, and required luminosity function different than inferred elsewhere in the Galaxy.
- COSMIC RAY OUTFLOWS:
  - Almost certainly have occurred in the past - but challenges in simultaneously matching morphology + spectrum for excess (Carlson & Profumo 1405.7685, Petrovic, Serpico & Zaharijas 1411.2980, Cholis et al 1506.05119).

Point sources vs diffuse emission



- Setting aside questions of theoretical plausibility, what can the data tell us?
- Central question: can we distinguish smooth diffuse emission from a population of point sources?
- The hope: spatial distribution of photons should be different (in detail) between these two cases.
- Of course, depends on luminosity function of sources. Very large number of very faint sources = diffuse emission.

Template fitting

- Model the photon counts (within some energy bin) as a linear combination of background and signal spatial templates $\mu_{p,l}$.
- Templates obtained by taking physical models or simple ansatzes, applying exposure and smoothing by Fermi point spread function (PSF).
- Given model (as a function of coefficients $\theta=\{\alpha_l\}$), overall likelihood is given by the product of the Poisson likelihoods for each (spatial) pixel.
- Maximize likelihood with respect to θ parameters (frequentist) or compute posterior probabilities (Bayesian).

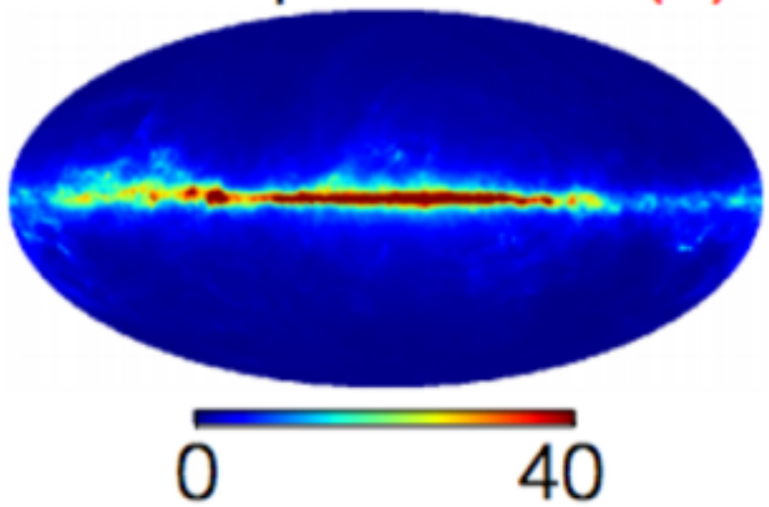
$$\mu_p = \sum_\ell \alpha_\ell \, \mu_{p,\ell} \qquad p_k^{(p)} = \frac{(\mu_p)^k \, e^{-\mu_p}}{k!}$$

$$p(d|\theta, \mathcal{M}) = \prod_p p_{n_p}^{(p)}(\theta)$$

d.o.f

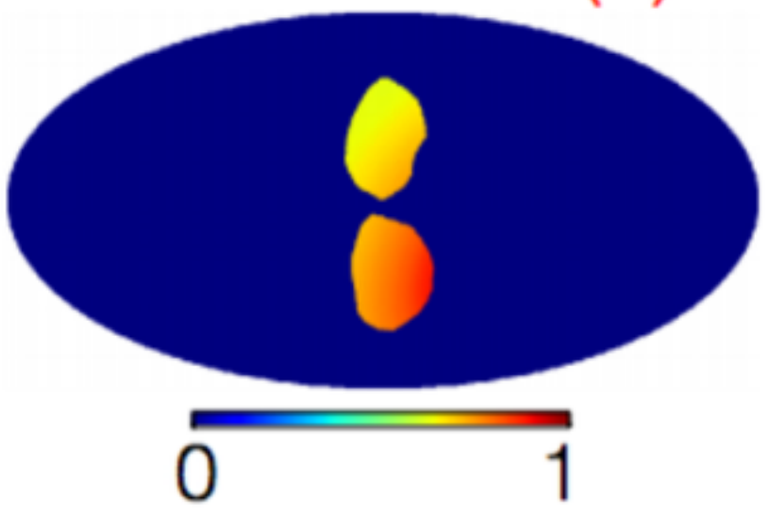
Fermi p6 diffuse (1)

$\mu_{p,1}$



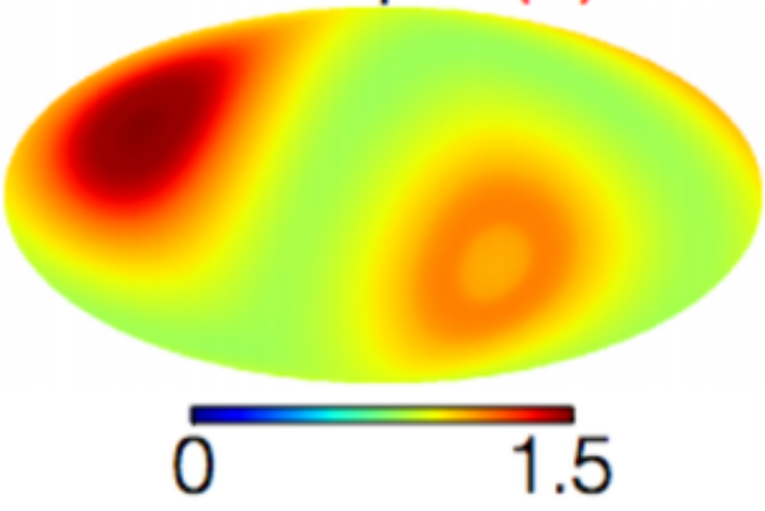
Fermi bubbles (1)

$\mu_{p,2}$



Isotropic (1)

$\mu_{p,3}$



Non-Poissonian templates

- Known sources - can model them, or mask their locations.
- Unknown sources - remain agnostic as to their location, create likelihood including non-Poissonian statistics for photon counts, i.e. Non-Poissonian Template Fitting (NPTF).
- Method worked out and applied to gamma-ray data by Malyshev & Hogg ’11, focusing on isotropically distributed PSs. Need to compute:

expected number of m-photon sources in a pixel

$$x_m = \frac{\Omega_{\rm pix}}{4\pi}\int_0^\infty dS \frac{dN}{dS}(S)\int df\,\rho(f)\frac{(fS)^m}{m!}e^{-fS}.$$

generating function for point source population

$$\sum_{k=0}^{\infty} p_k t^k = \exp\left[\sum_{m=1}^{\infty} x_m (t^m - 1)\right] \equiv P(t)$$

For comparison, in Poisson case:

$$\mathcal{P}^{(p)}(t) = \exp[\mu_p(t-1)]$$

Overall generating function $\mathcal{P}^{(p)}(t)$ is given by product of generating functions for each template. Then:

pixel likelihood

$$p_k^{(p)} = \frac{1}{k!}\frac{d^k\mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

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Number of sources providing S counts, including position-dependent normalization

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Number of sources providing S counts, including position-dependent normalization

Poisson draw for actual number of photons, given f S expected

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Fitting procedure

- Use energy range ~2-12 GeV - good angular resolution (degrades at lower energies), includes peak of GeV excess.
- Use data with a quality cut to improve angular resolution.
- Use Fermi Pass 7 data up to December 2013 (results confirmed with both up-to-date Pass 7 and Pass 8 data, which have different event reconstruction pipelines).
- Where required, model source count function as a broken power law - four parameters, including overall normalization.

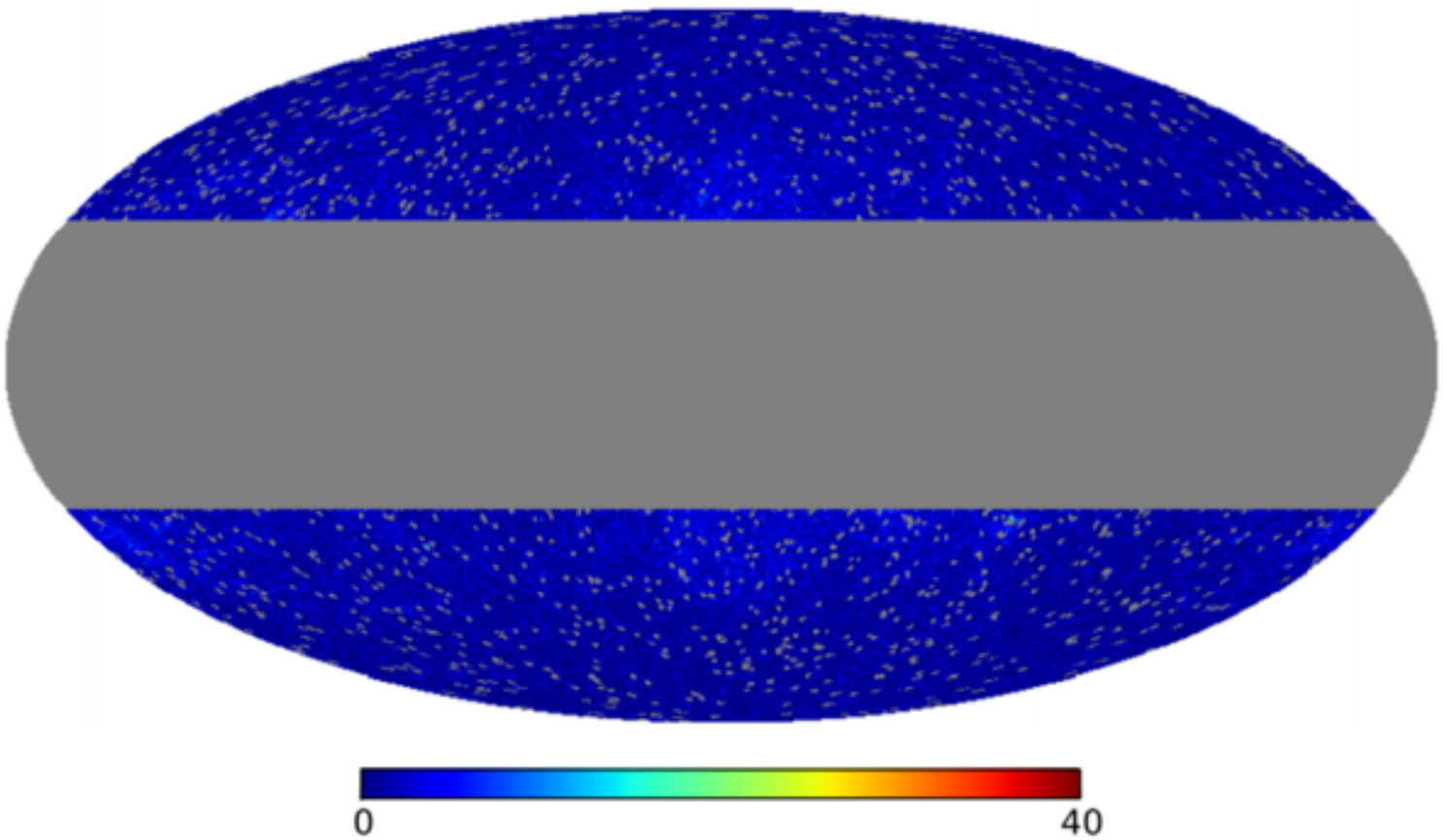
follows a spatial template

$$\frac{dN_p(S)}{dS} = A_p \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & S < S_b \end{cases}$$

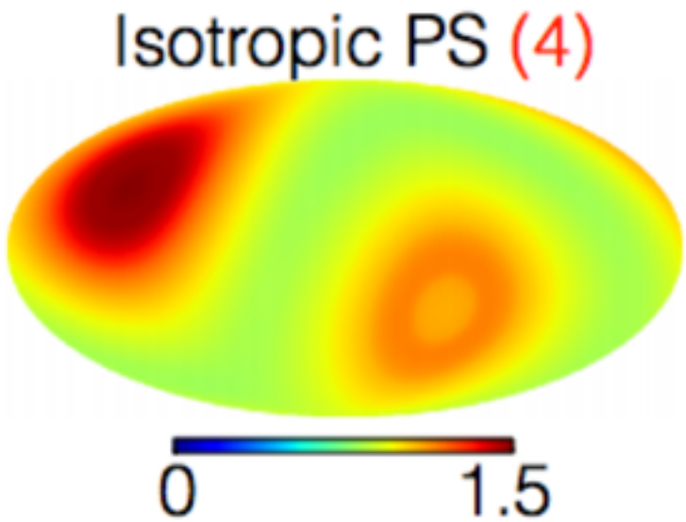
- Fits always include diffuse model, Fermi Bubbles and isotropic diffuse templates, + other templates as appropriate.
- In some analyses we mask the known point sources (based on the Fermi LAT 4-Year Point Source Catalog, 3FGL); where this is done, the mask radius is just under 1 degree (formally, 5σ where σ is the approximate Gaussian width of the PSF for the lowest-energy photons in the bin).

High-latitude analysis

mask region within 30 degrees of Galactic plane



add isotropic non-Poissonian point source template (4 d.o.f)

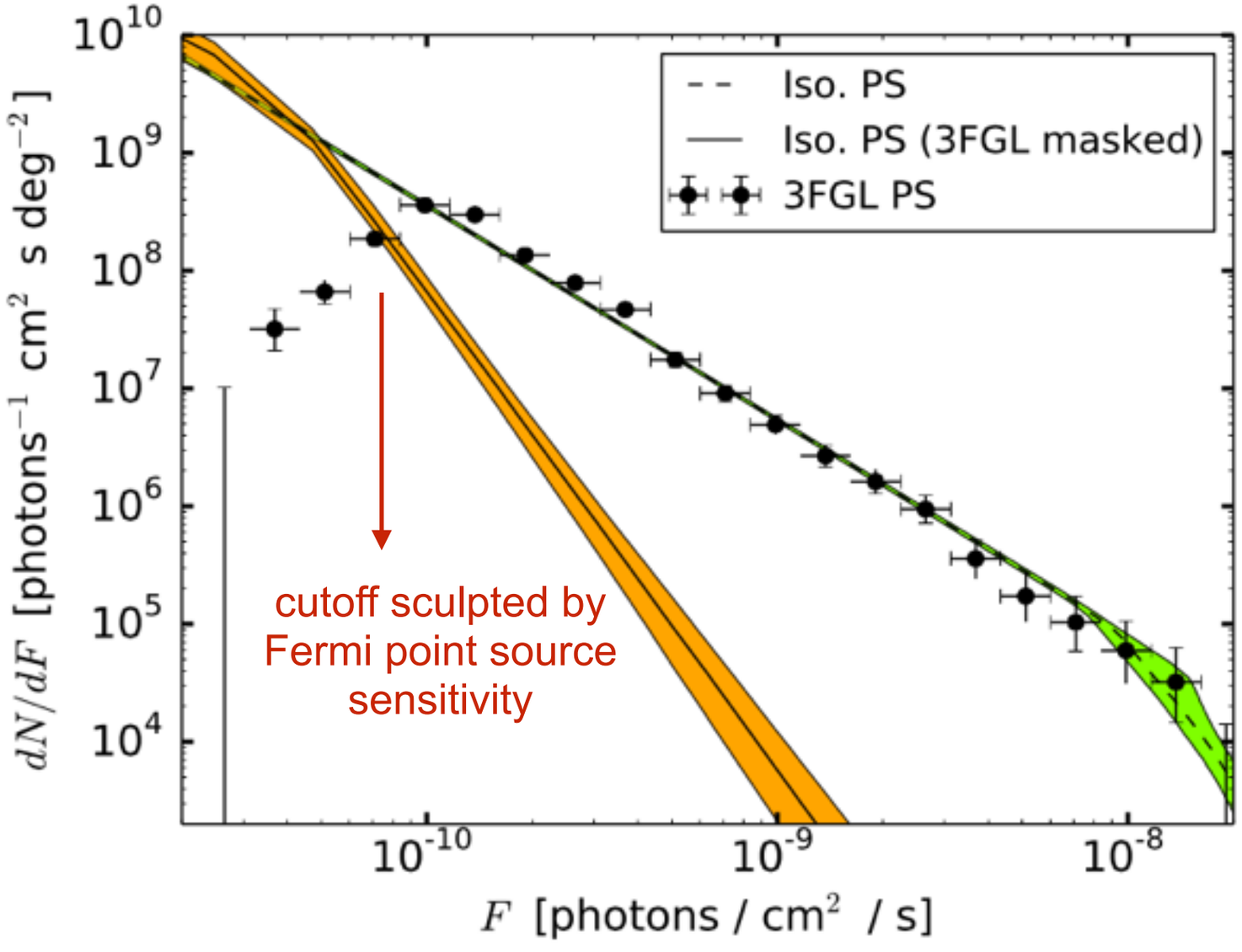


- Test method first at high latitude (|b| > 30°), searching for unresolved uniformly distributed (isotropic) sources.

- Previously studied by Malyshev & Hogg ’11 using a similar approach (unbinned likelihood rather than pixel-based likelihood); we find consistent results, also consistent with estimate of isotropic diffuse background from Ackermann et al 1410.3696.

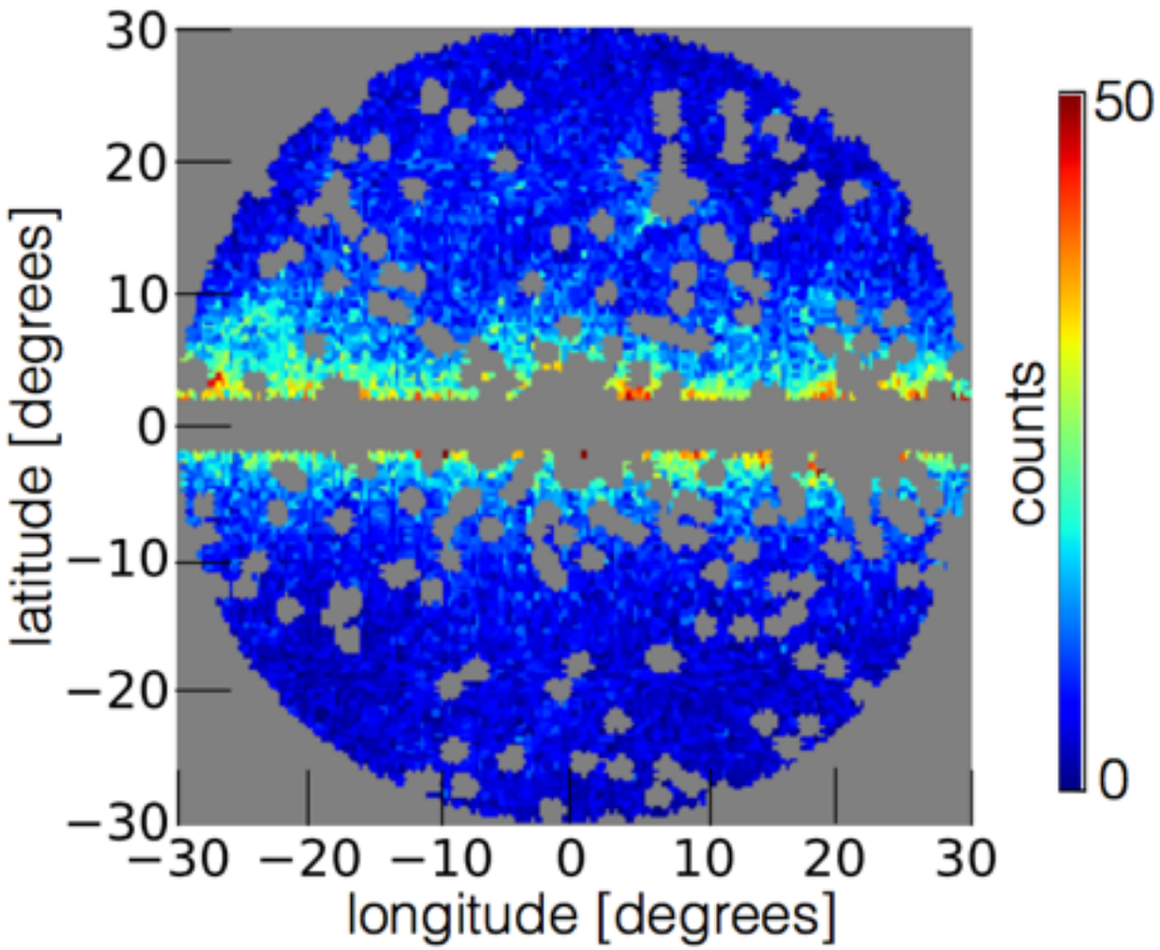
High-latitude results

- 3FGL PS = known sources in this region.
- Green line = reconstructed source count function without masking sources.
- Orange line = source count function when all known sources are masked.
- Low-luminosity slope of source count function is recovered even when all sources are masked.



Masked (unmasked) analysis finds that 47% (55%) of the isotropic gamma-ray background is due to (resolved and unresolved) point sources.

Inner Galaxy (IG) analysis

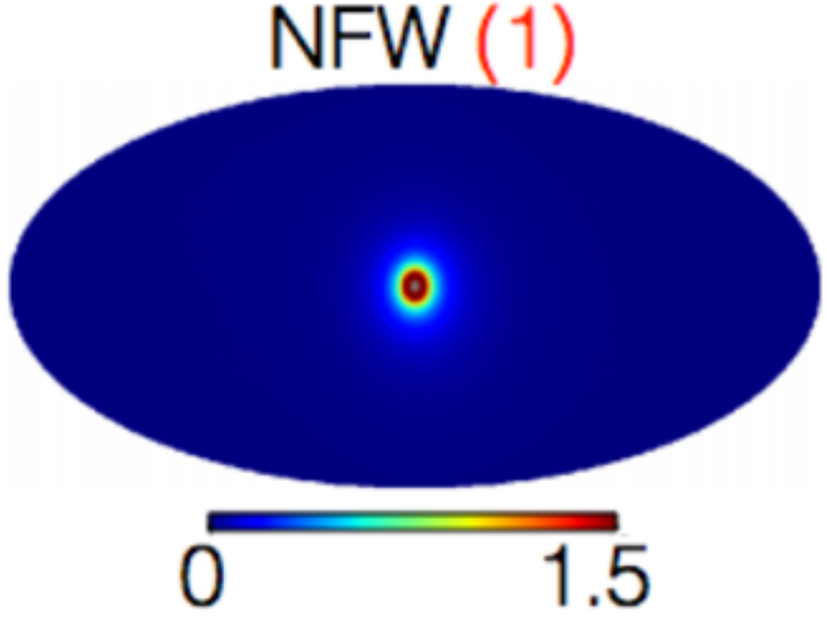


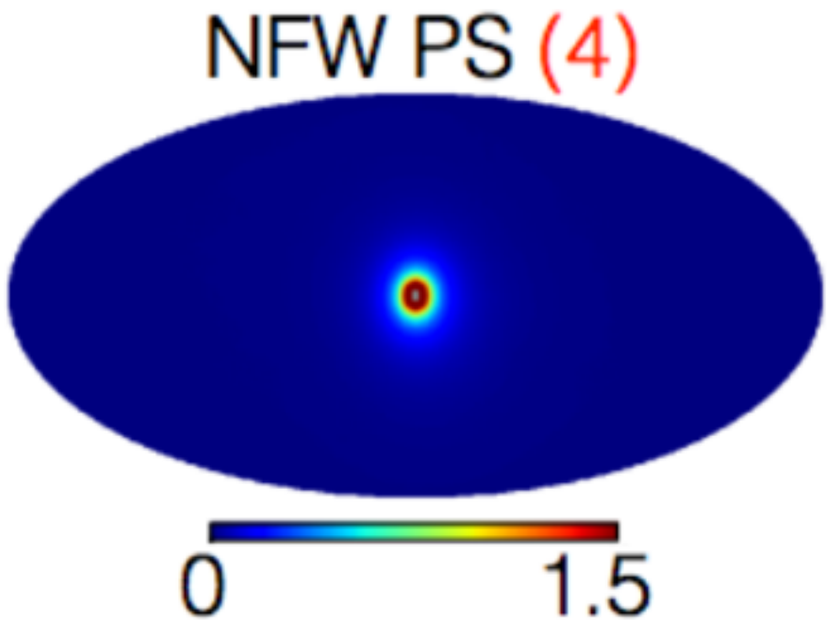
- Fit region is within 30 degree radius of Galactic Center, masking the region within 2 degrees of the plane.
- Results shown in terms of smaller region, within 10 degree radius of the center.

Signal templates

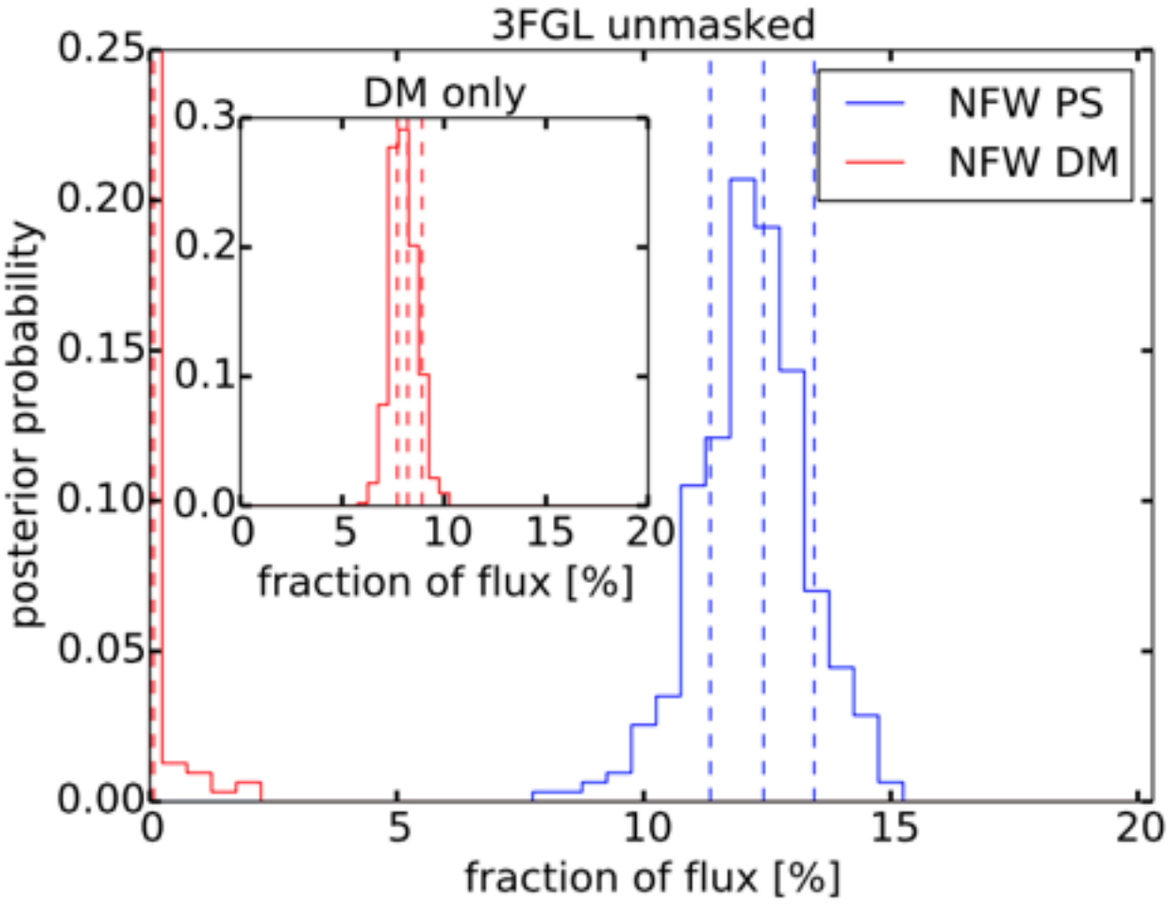
- In addition to high-latitude templates, include:
  - DM annihilation template corresponding to a modified NFW profile scaling as $r^{-1.25}$ at small r, squared and projected along the line of sight. Labeled “NFW DM”. 1 extra parameter (normalization).
  - Point source (PS) template with the same overall spatial distribution as “NFW DM” template, but non-Poissonian statistics. Labeled “NFW PS”. 4 extra parameters (normalization + source count function).

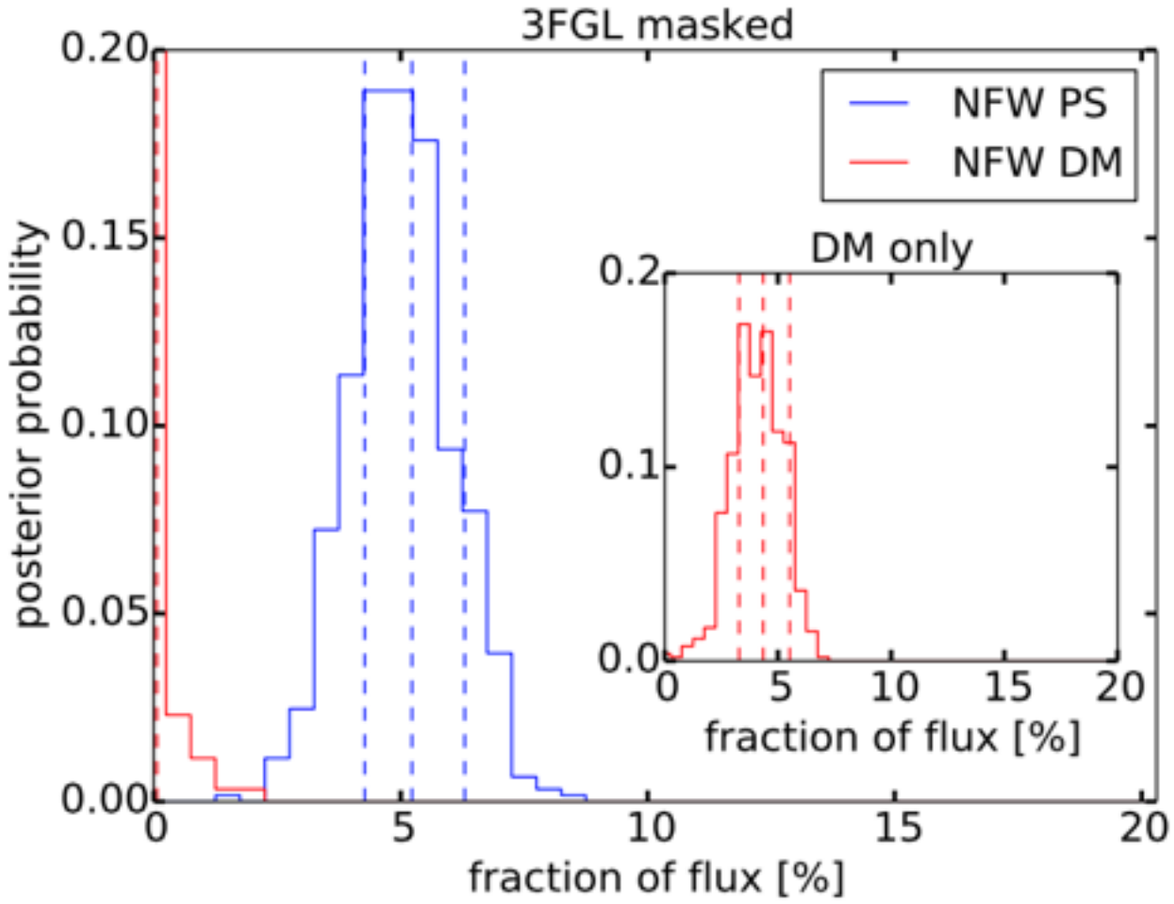
new templates





Inner Galaxy results

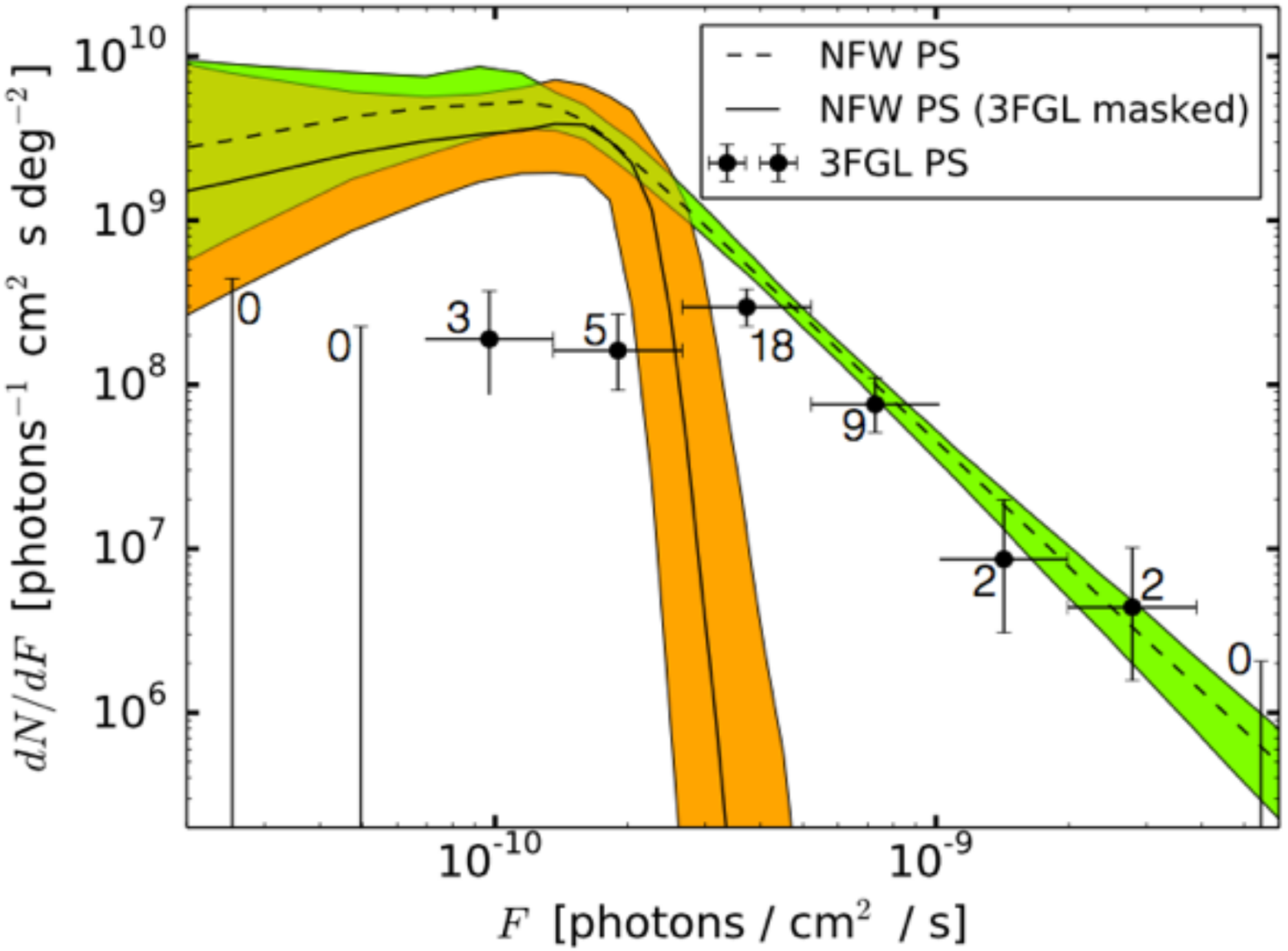




- Plots show flux fractions attributed to templates over region within 10 degrees of GC, more than 2 degrees from Galactic plane (including masked areas).
- First: include only NFW DM, not NFW PS - cross-check that we reproduce results from previous studies with Poissonian template fitting.
- Second: include both templates. NFW PS absorbs full flux otherwise attributed to NFW DM.

The source count function

- High-flux end of reconstructed source count function reproduces 3FGL sources (in unmasked analysis).
- Low-flux end prefers quite flat source count function (in dN/dF).
- Due to this flat source-count function, flux is strongly dominated by sources near threshold.
- Excess (in this region) can be explained by ~203^{+109}_{-68} PSs.
- Suggests O(1000) sources to explain the whole excess.
- Half the flux coming from PSs with above ~1.7×10^{-10} photons/cm^2/s (in this energy bin) - close to threshold!



$$F_b = \begin{cases} 1.48^{+0.41}_{-0.43} & \text{unmasked} \\ 2.16^{+0.64}_{-0.43} & \text{masked} \end{cases} \times 10^{-10} \text{ photons/cm}^2\text{/s}$$

$$n_2 = \begin{cases} -0.57^{+1.11}_{-0.85} & \text{unmasked} \\ -0.47^{+0.76}_{-0.93} & \text{masked} \end{cases}$$

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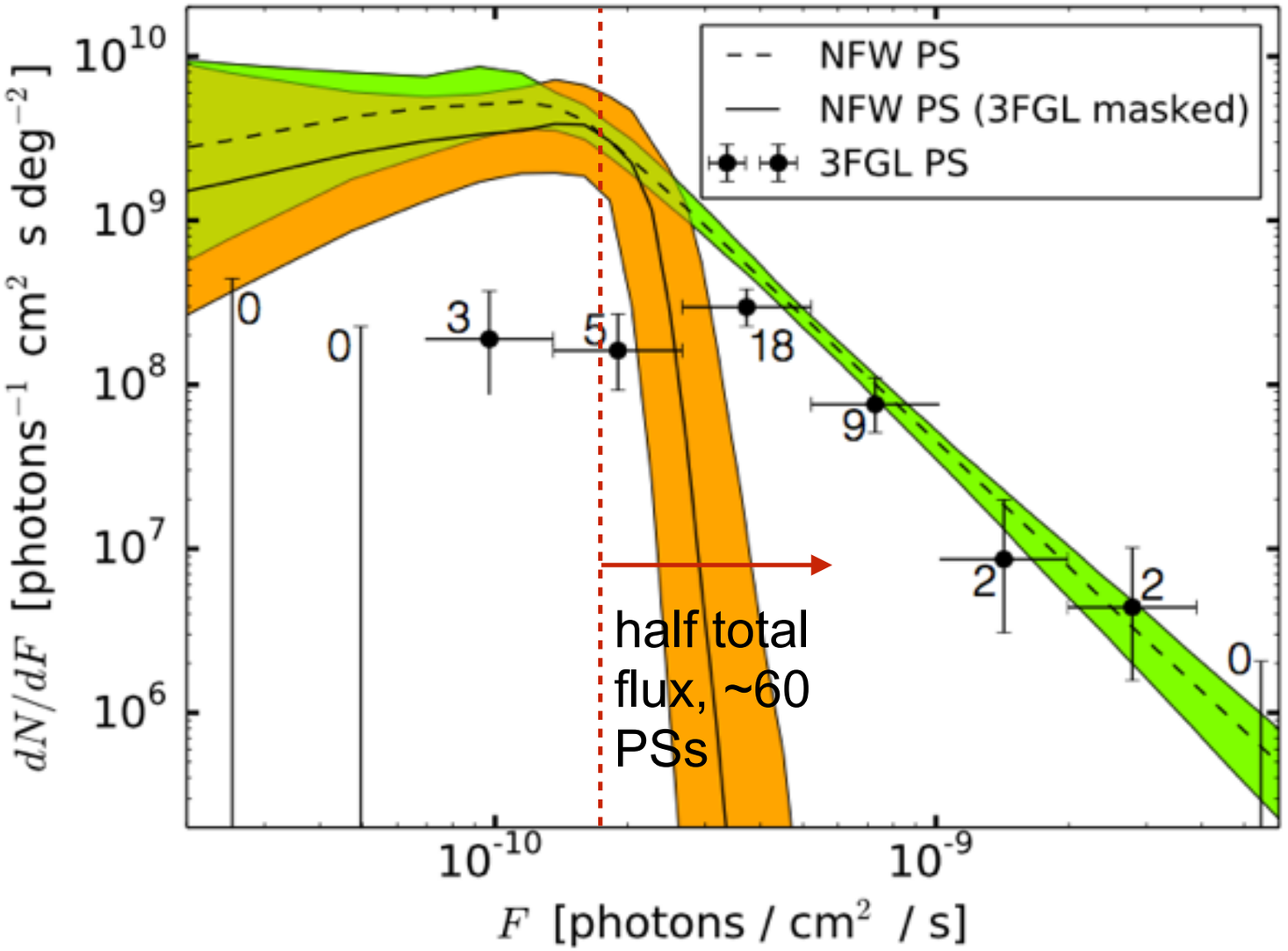

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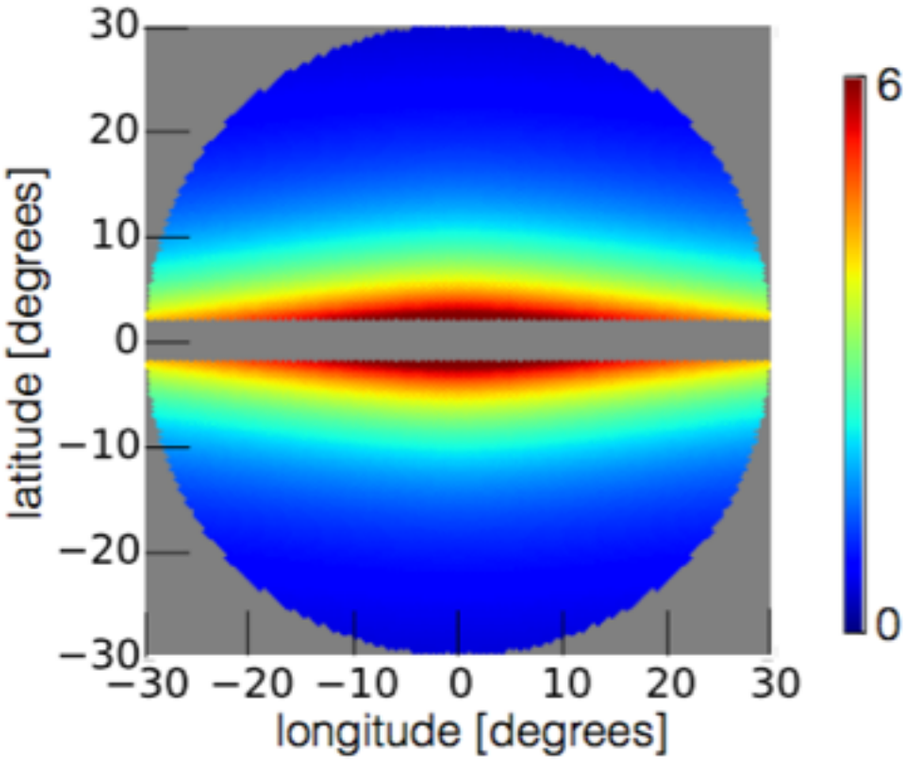
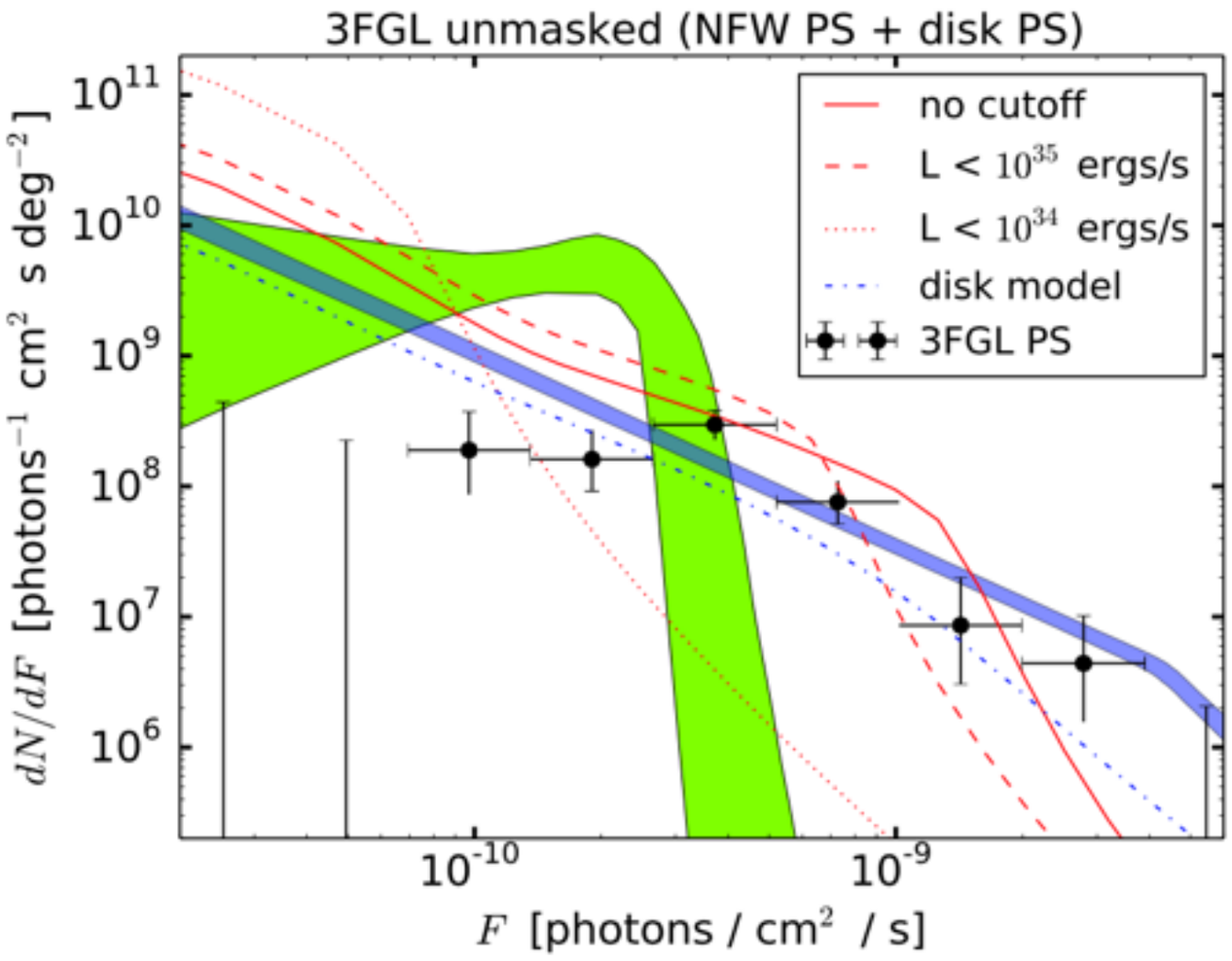
Adding disk PSs





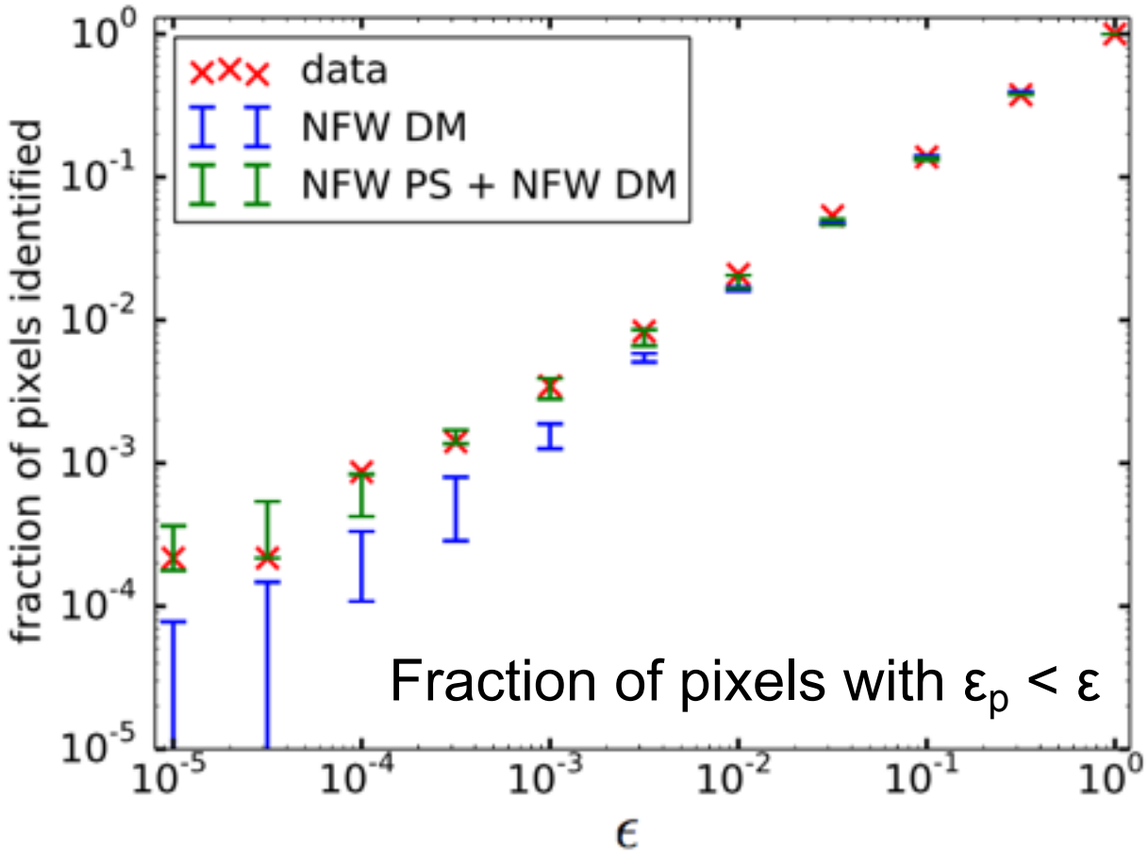
- Alternative to masking is to model 3FGL sources.
- First simple attempt: add a PS template corresponding to thick-disk distribution, consistent with distribution of observed pulsars.
- Thick-disk distribution largely absorbs known sources - NFW PS template appears to prefer a novel population peaked just below current detection threshold.
- Reconstructed source count function for disk population consistent with luminosity function of observed pulsars (blue line, from Cholis, Hooper & Linden 1407.5583) - new population appears more dominated by bright sources, albeit with large statistical uncertainties.

What drives the PS preference?

- Perform standard Poissonian template fit (including NFW DM) - take best-fit model μ_p, make map of ε_p = P(# observed photons > n_p) under this model. Here n_p is the actual observed number of photons in that pixel.

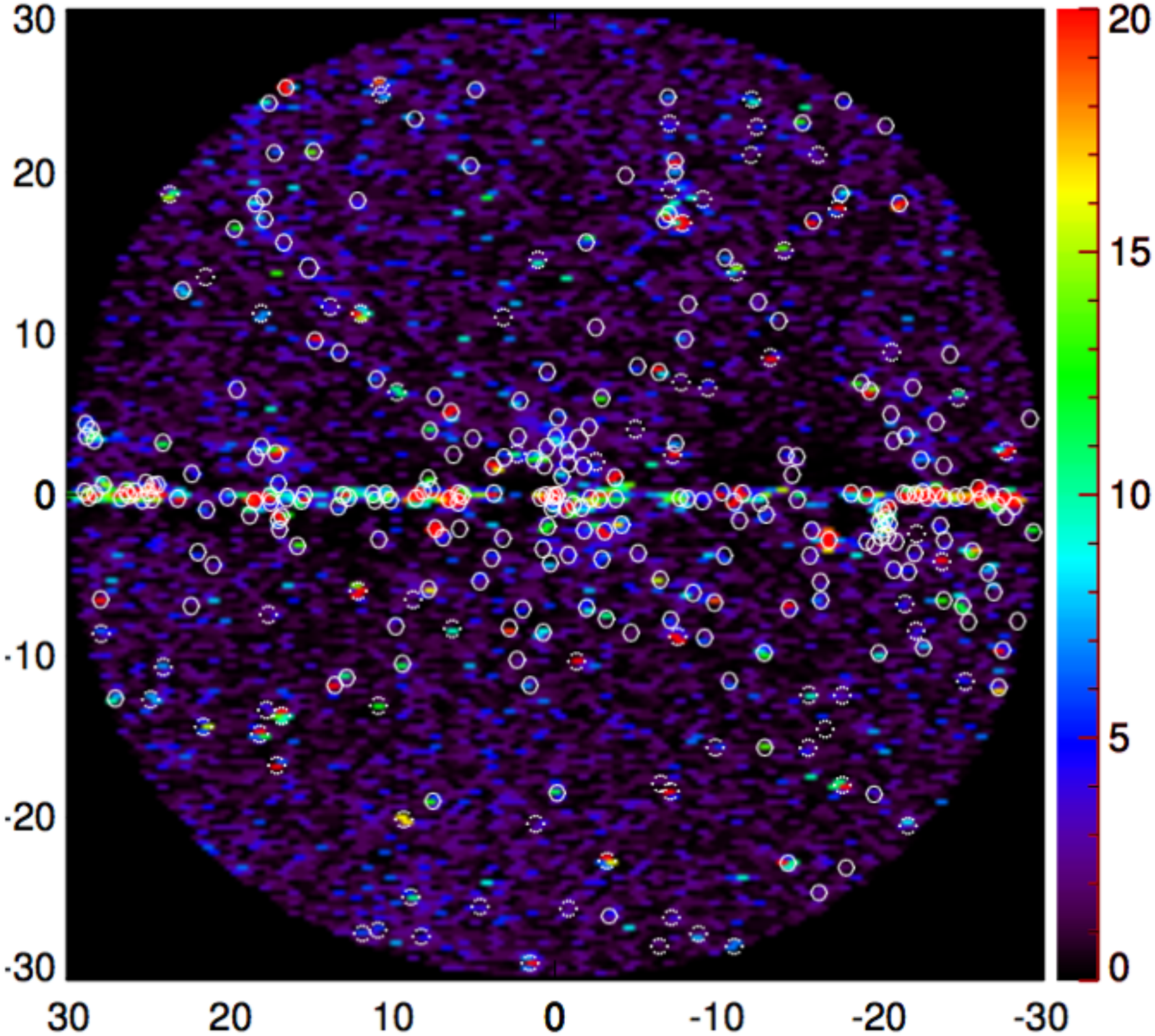
- Small ε_p corresponds to “hot pixels” - unusually bright relative to purely diffuse model.

- Fraction of pixels with small ε_p is a diagnostic for PS contribution - are there more than are expected from Poisson statistics?



Results shown for mock data with no NFW PSs and best-fit DM model (“NFW DM”), mock data including NFW PSs (“NFW PS + NFW DM”), and real data. In all cases template fit includes NFW DM but not NFW PS, with 3FGL mask.

Hot pixels and known PSs



Plot shows log ε_p^{-1}

Brighter points = more unlikely given best-fit purely Poissonian model

Circles = known (3FGL) sources, dotted circles are believed to be extragalactic

Model comparison

- We use the Bayes factor as our measure of preference for the NFW PS template.

- Bayes factor = ratio of Bayesian evidences for the model with and without including NFW PS:

$$B_{10} = \frac{p(d|\mathcal{M}_1)}{p(d|\mathcal{M}_0)} \qquad p(d|\mathcal{M}) = \int_{\Omega_{\mathcal{M}}} d\theta \, p(d|\theta, \mathcal{M}) p(\theta|\mathcal{M})$$

- In our masked analysis, non-zero NFW PS contribution is preferred with a Bayes factor ~ 10^7.

- Agrees reasonably well (within systematic uncertainties due to modeling of diffuse emission) with mock data created using best-fit reconstructed model.

Systematics

“There is no systematic way to address systematic uncertainties” - Licia Verde

- Spatially mismodeled background ..... Can affect source count function, flux fraction, but preference for PSs is consistent
- Spatially mismodeled signal ..... No effect
- Mismodeled angular resolution ..... Can change details of source count function
- Mismodeled source count function ..... Add more freedom - results consistent within uncertainties
- Simple “look elsewhere” - study of bright excess 30 degrees away from GC ..... No robust preference for point sources, i.e. this preference is not inevitable
- Halving the dataset - northern hemisphere vs southern hemisphere ..... Source count function and flux fraction consistent within uncertainties
- Increased dataset (from ~5.5 years to 7 years Pass 7 to 7 years Pass 8) ..... Bayes factor increases, results consistent within uncertainties

In progress

- Include multiple energy bins - more careful study of energy spectra.
- In-depth studies of NPTF method sensitivity and possible biases, using mock data.
- “Hot pixels” provide candidate point source locations, so:
  - Can new Pass 8 Fermi LAT data allow us to (significantly) detect the individual sources contributing to the excess?
  - Can we search for counterparts or correlations at other wavelengths or with other messengers (e.g. ICECUBE neutrinos), either in archival or new data?
  - What is the energy spectrum in these pixels, as a function of the ε parameter?
  - If new sources are detected, can we constrain the underlying spatial distribution from which these sources are drawn? (requires careful modeling of point source sensitivity as a function of position)

Conclusions

- Template fitting with non-Poissonian statistics provides a model-independent probe of pointlike structure in photon data.

- We estimate that point sources (resolved and unresolved) contribute roughly half the isotropic gamma-ray background at 2-12 GeV.

- We find a strong statistical preference for a novel unresolved point source population in the inner Galaxy, with a source count function dominated by sources near Fermi's current detection threshold.

- In the presence of such a population, a dominant contribution to the GeV excess from annihilation of a smooth dark matter component (or any similar smooth diffuse source) is disfavored.

BACKUP SLIDES

Generating functions

- Can express the probabilities in terms of generating functions:

$$p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\Big|_{t=0}$$

- For the Poisson case, generating function is simple:

$$\mathcal{P}^{(p)}(t) = \exp[\mu_p(t-1)]$$

- More generally, the total generating function for Poissonian + non-Poissonian templates is simply the product of the components:

$$\mathcal{P}^{(p)}(t) = \mathcal{D}^{(p)}(t) \cdot \mathcal{G}^{(p)}(t)$$

Generating functions (II)

- PSF can be included at the level of the generating function (Malyshev & Hogg 1104.0010).
- Effect is to reduce number of very bright and faint pixels, more pixels with intermediate brightness.

expected number of m-photon sources

determined by Monte Carlo, accounts for PSF

$$x_m = \frac{\Omega_{\rm pix}}{4\pi} \int_0^\infty dS \frac{dN}{dS}(S) \int df\, \rho(f) \frac{(fS)^m}{m!} e^{-fS}.$$

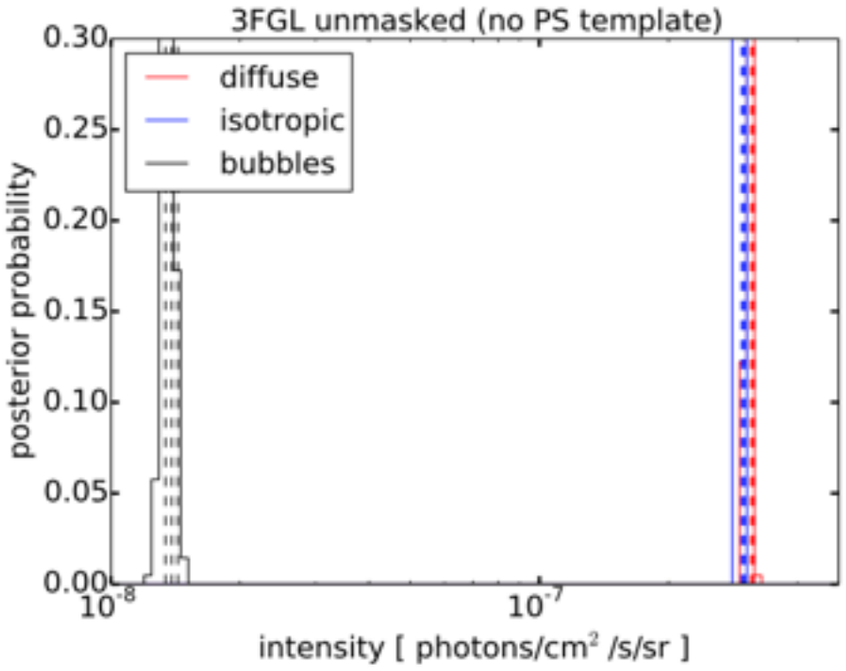
$$\sum_{k=0}^{\infty} p_k t^k = \exp\left[\sum_{m=1}^{\infty} x_m (t^m - 1)\right] \equiv P(t)$$

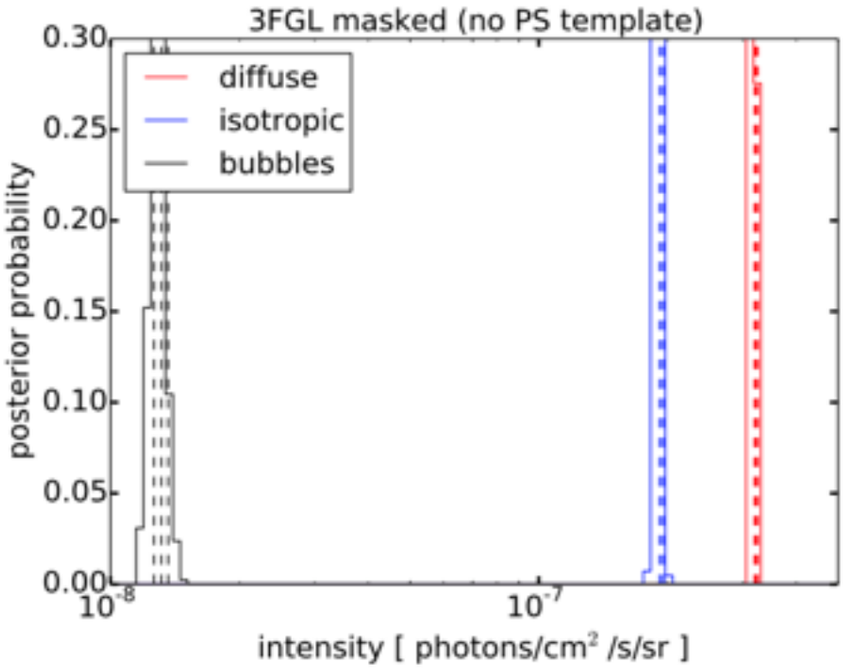
generating function for point source population

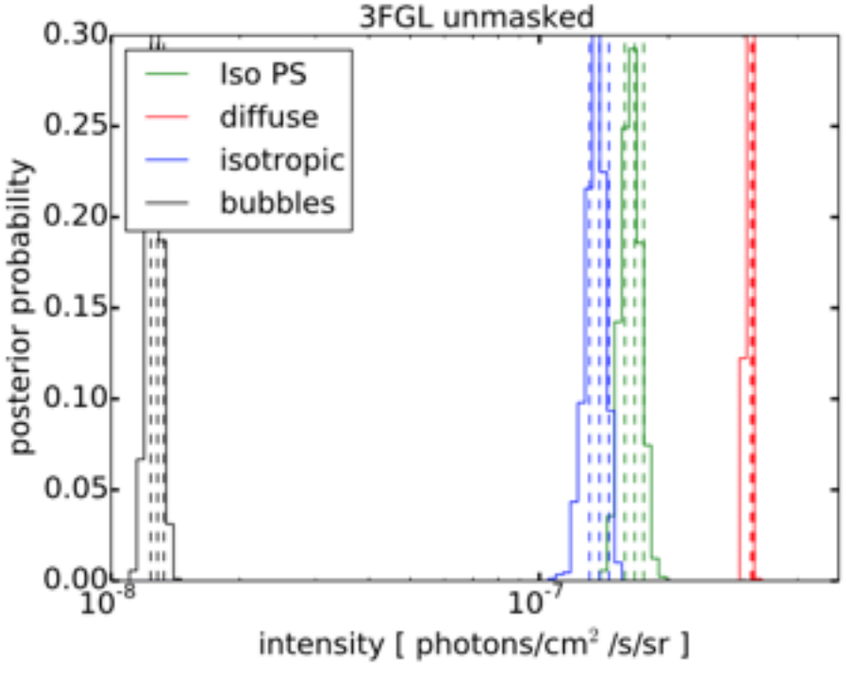
Priors

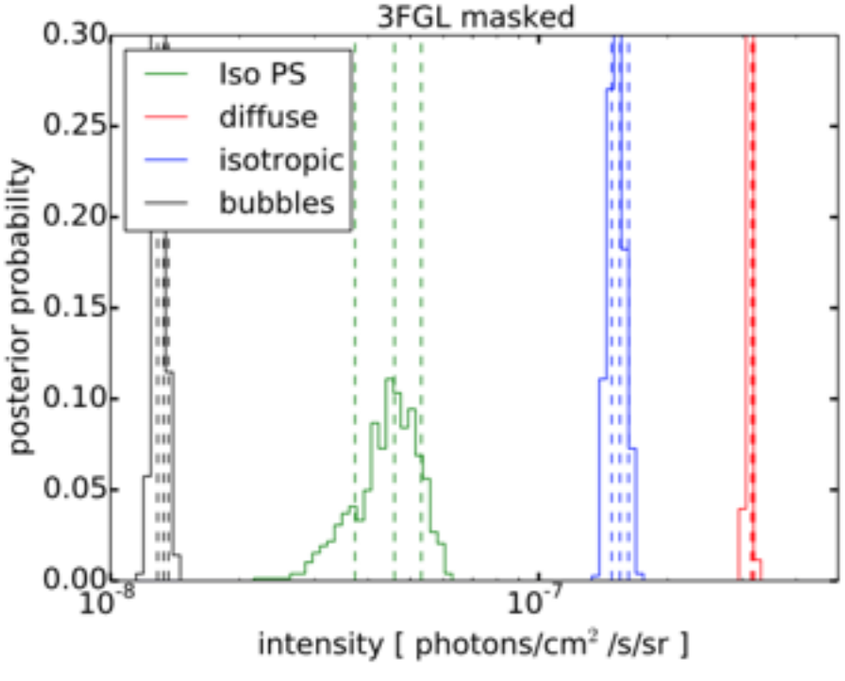
Parameter	Prior Ranges	
	High Latitude	Inner Galaxy
$A_{\rm iso}$	$[0, 10]$	20% of $A_{\rm iso}^{\rm HL}$
$A_{\rm diff}$	$[0, 10]$	20% of $A_{\rm diff}^{\rm HL}$
$A_{\rm bub}$	$[0, 10]$	20% of $A_{\rm bub}^{\rm HL}$
$\log_{10} A_{\rm NFW}$	$[-6, 6]$	$[-6, 6]$
$\log_{10} A_{\rm PS}$	$[-6, 6]$	$[-6, 6]$
S_b	$[0, k_{\rm max}]$	$[0, k_{\rm max}]$
n_1	$[2.05, 50]$	$[2.05, 50]$
n_2	$[-2, 1.95]$	$[-2, 1.95]$

Additional results for the high-latitude analysis

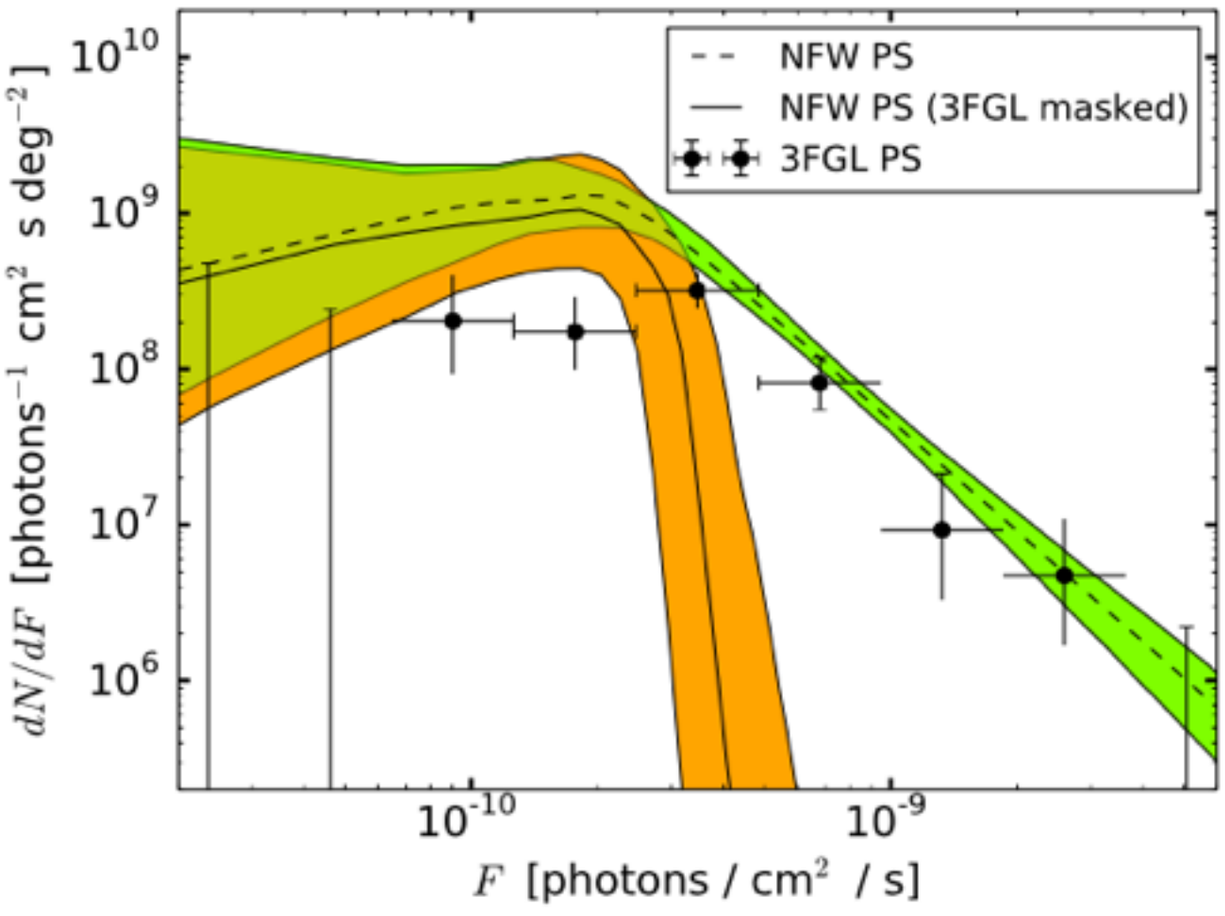


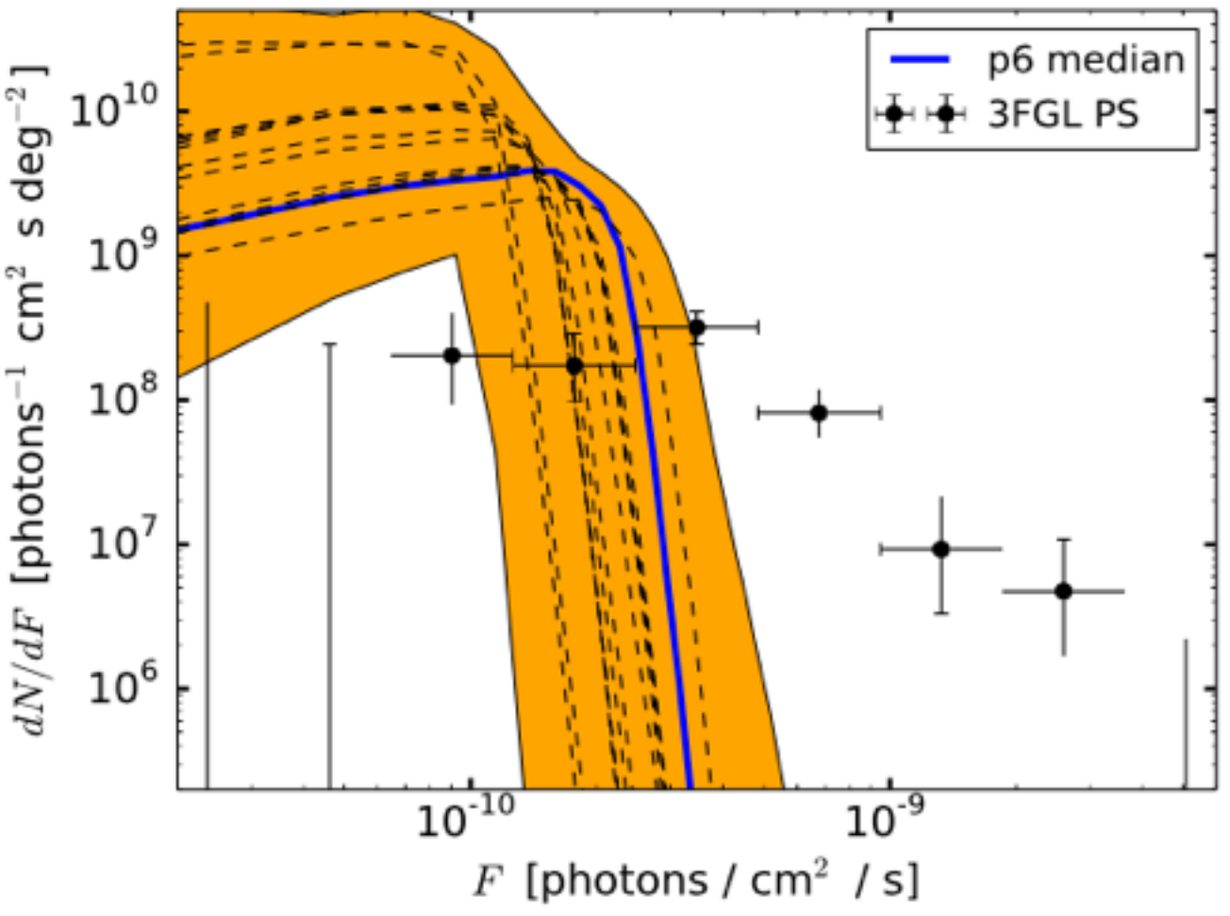






A different background model

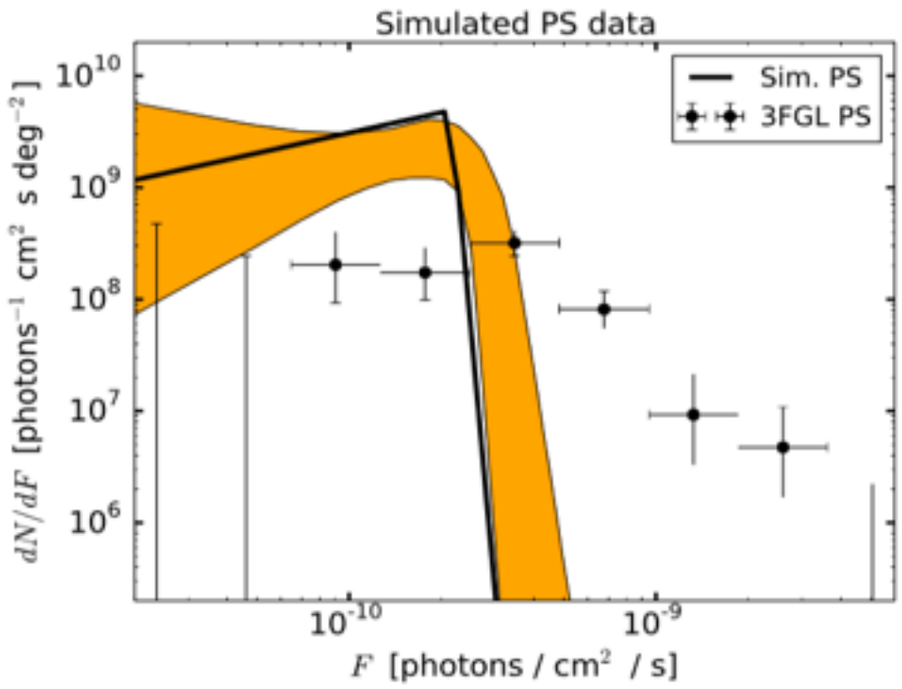


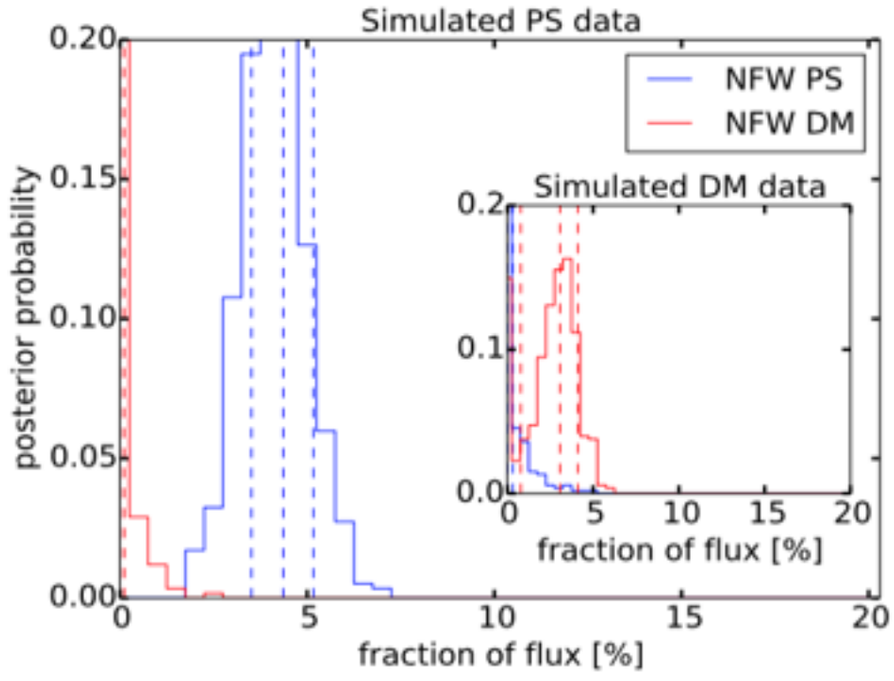


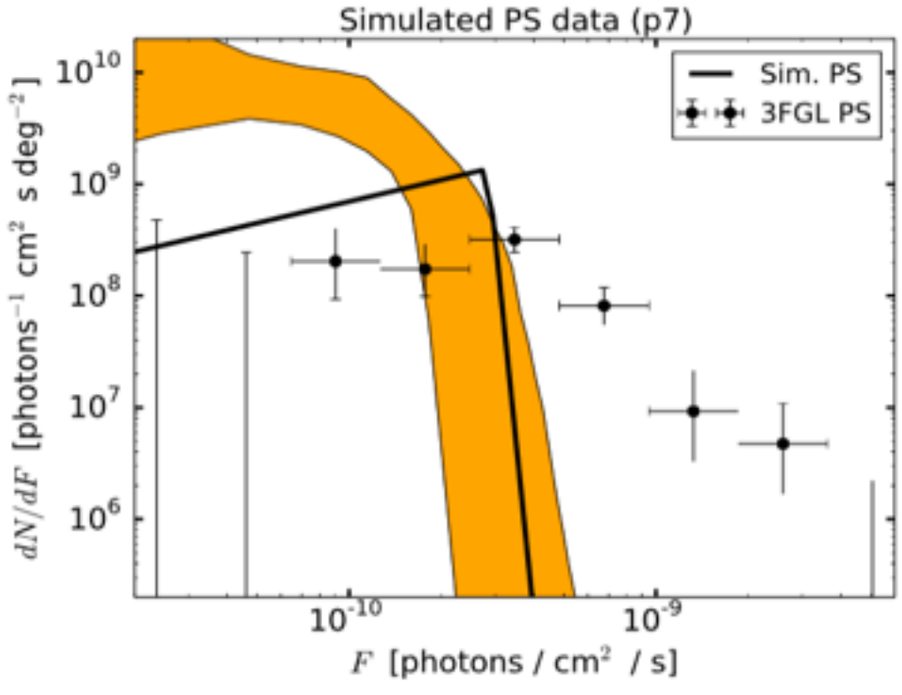
- Left panel: reconstructed source-count function for p7v6 Fermi diffuse model.
- Right panel: reconstructed source-count functions for 13 GALPROP-based diffuse models, with the 3FGL point sources masked.

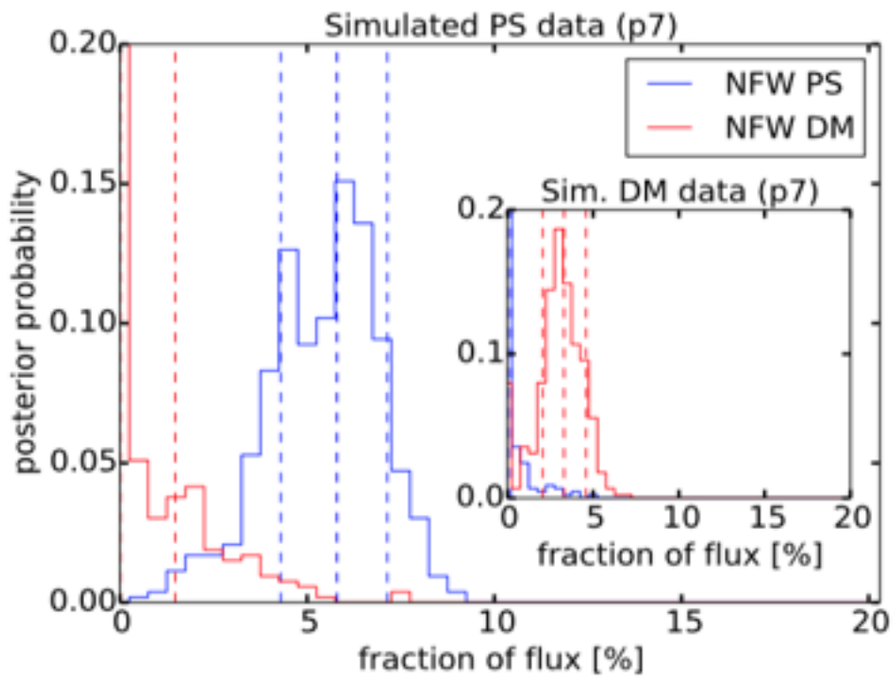
Mock data tests

- Upper panels: mock data generated and fitted with p6 model (and best-fit contributions from other templates).
- Lower panels: mock data generated with p7 model, fitted with p6 model.
- Insets: data generated with only DM component, no PSs.





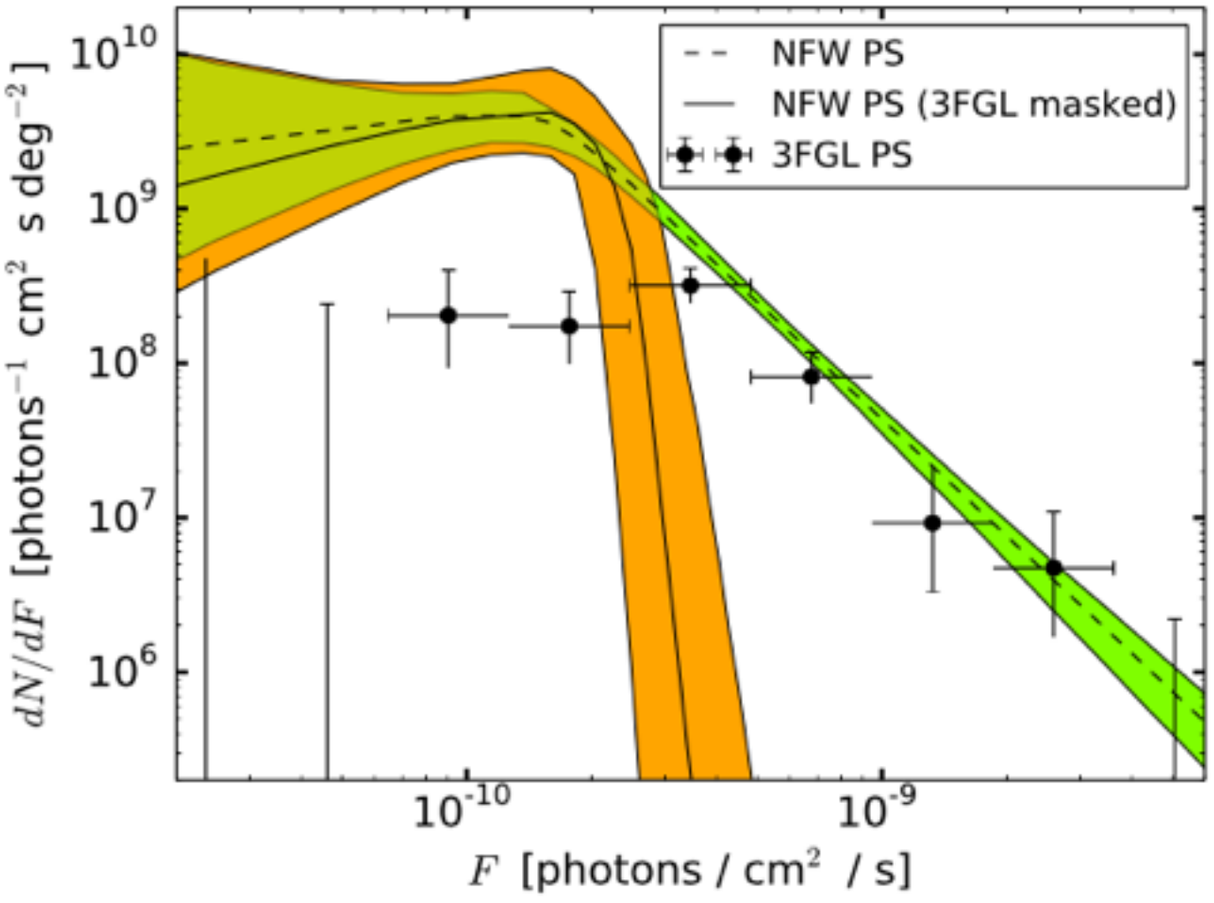


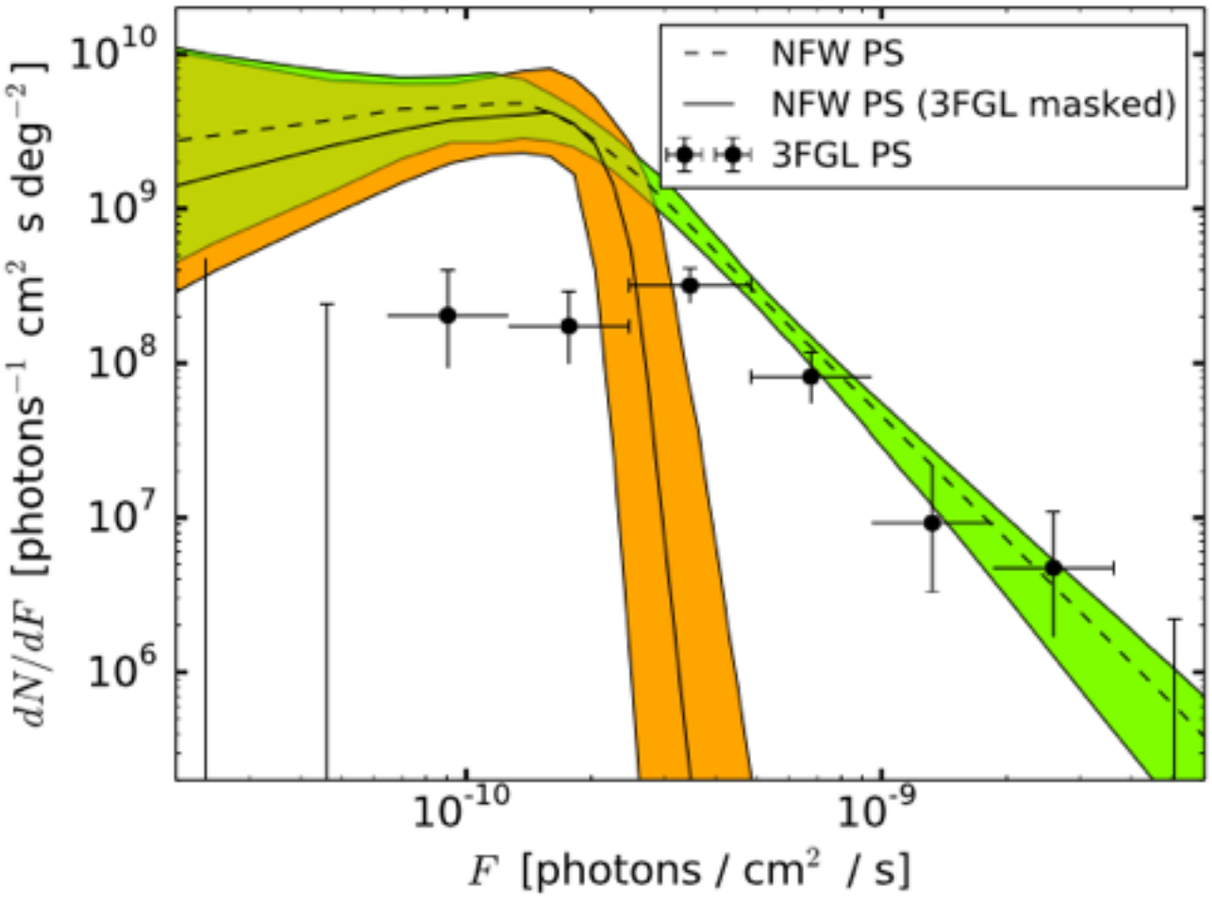


Mock data tests (II)

- Bayes factor in mock data (including PSs) is ~10^{10}, somewhat larger than in real data.
- Pipeline run again using 13 GALPROP-based diffuse models and p7 diffuse model to generate the simulated data; in all case fit is performed using default (p6) diffuse model. There is always a preference for PSs with Bayes factor ~10^{5}-10^{9}.
- That is, mismodeling the diffuse emission tends (if anything) to reduce the preference for point sources.
- We also tested mock data with half the excess attributed to PSs and half to DM - in this case, a non-zero PS contribution was favored with a Bayes factor of O(100), but the source count function could not be reliably reconstructed.

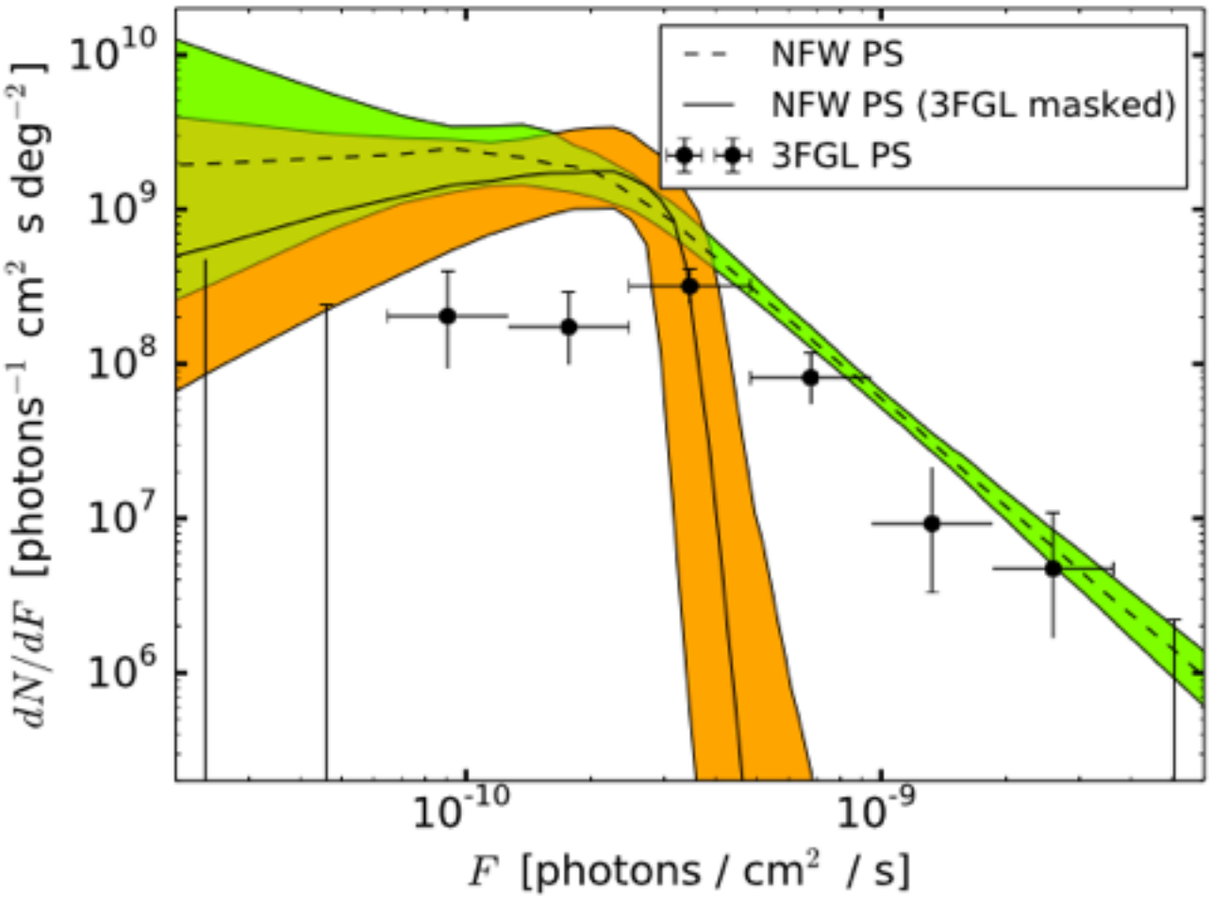
Changing the signal template

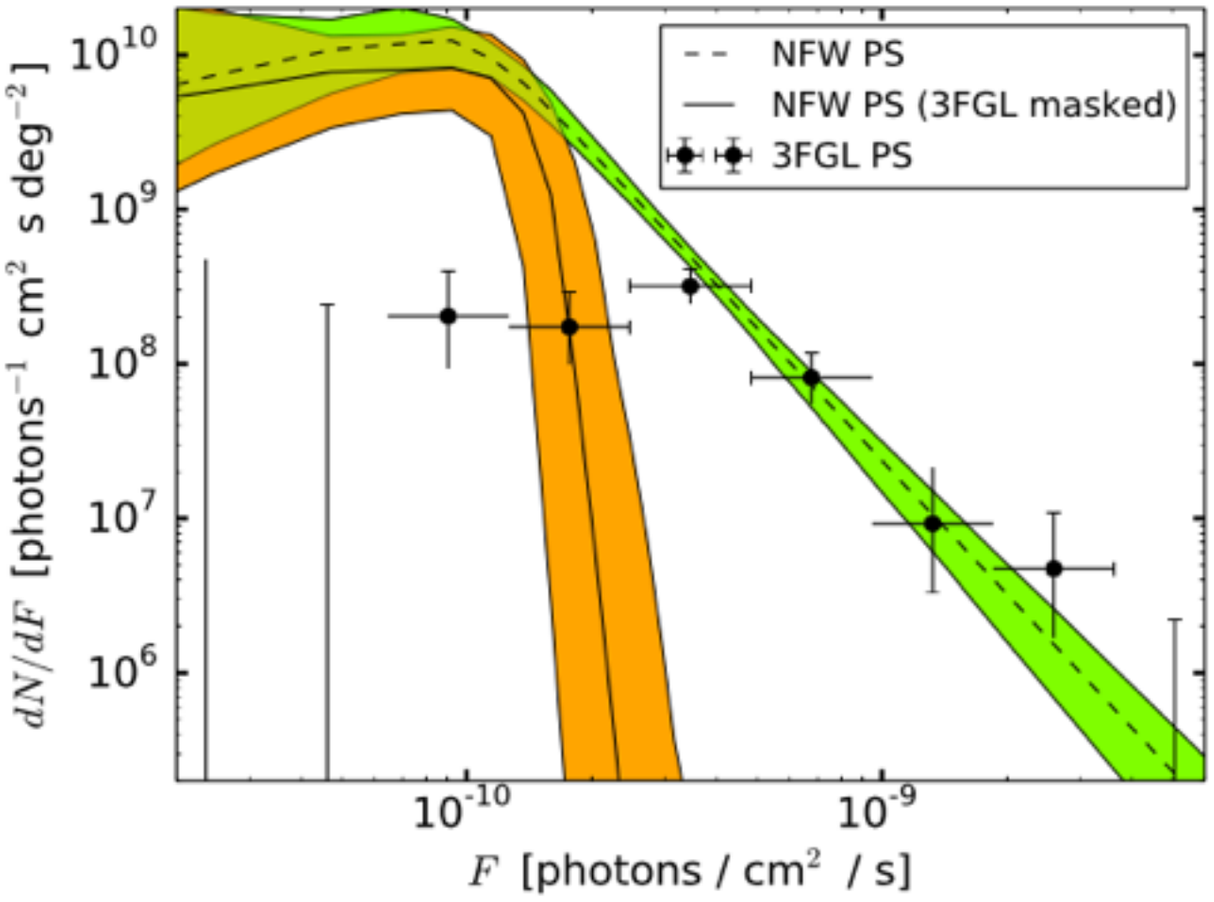




- Effect of changing the power-law slope of the NFW profile at small r to 1.1 (left) or 1.4 (right), rather than the default value of 1.25.

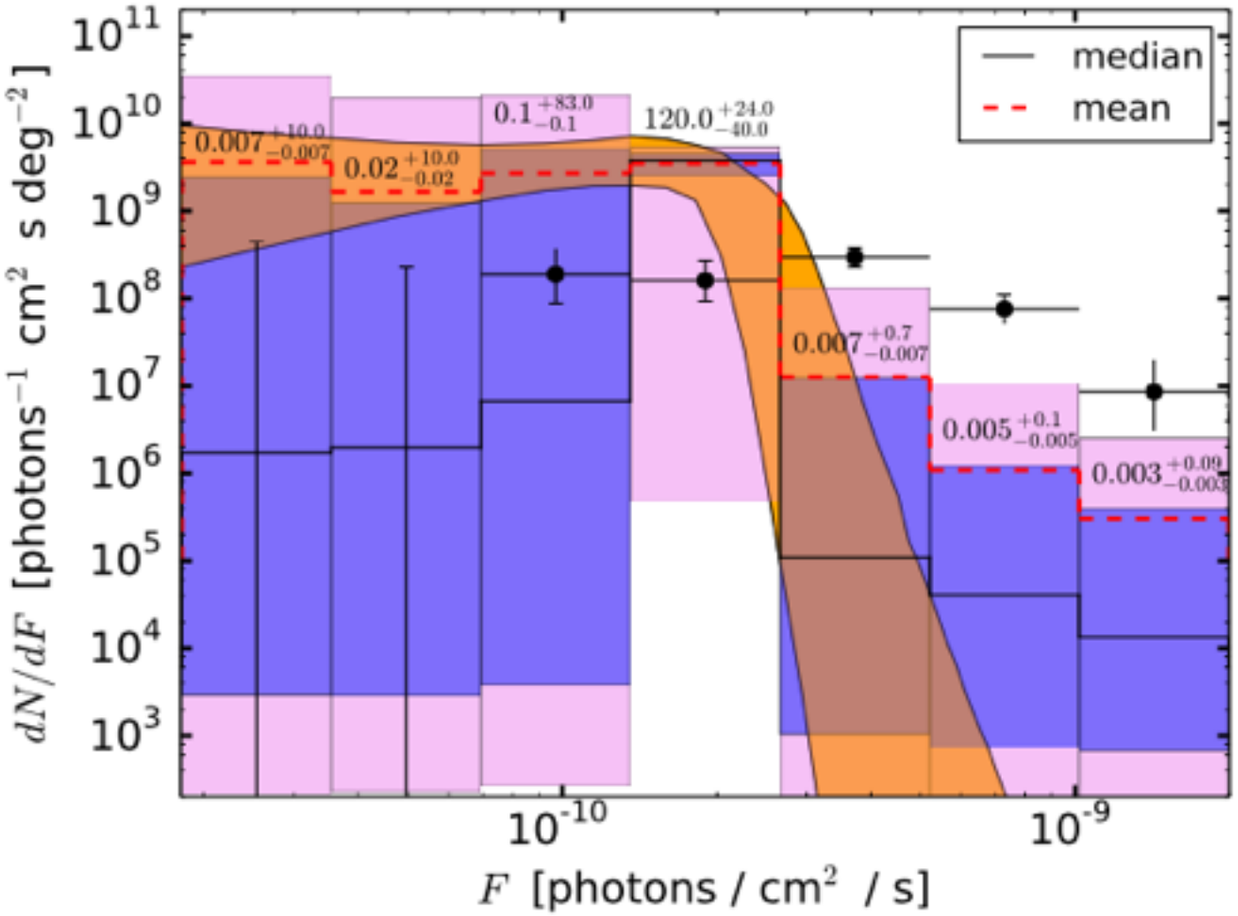
Mismodeling the PSF

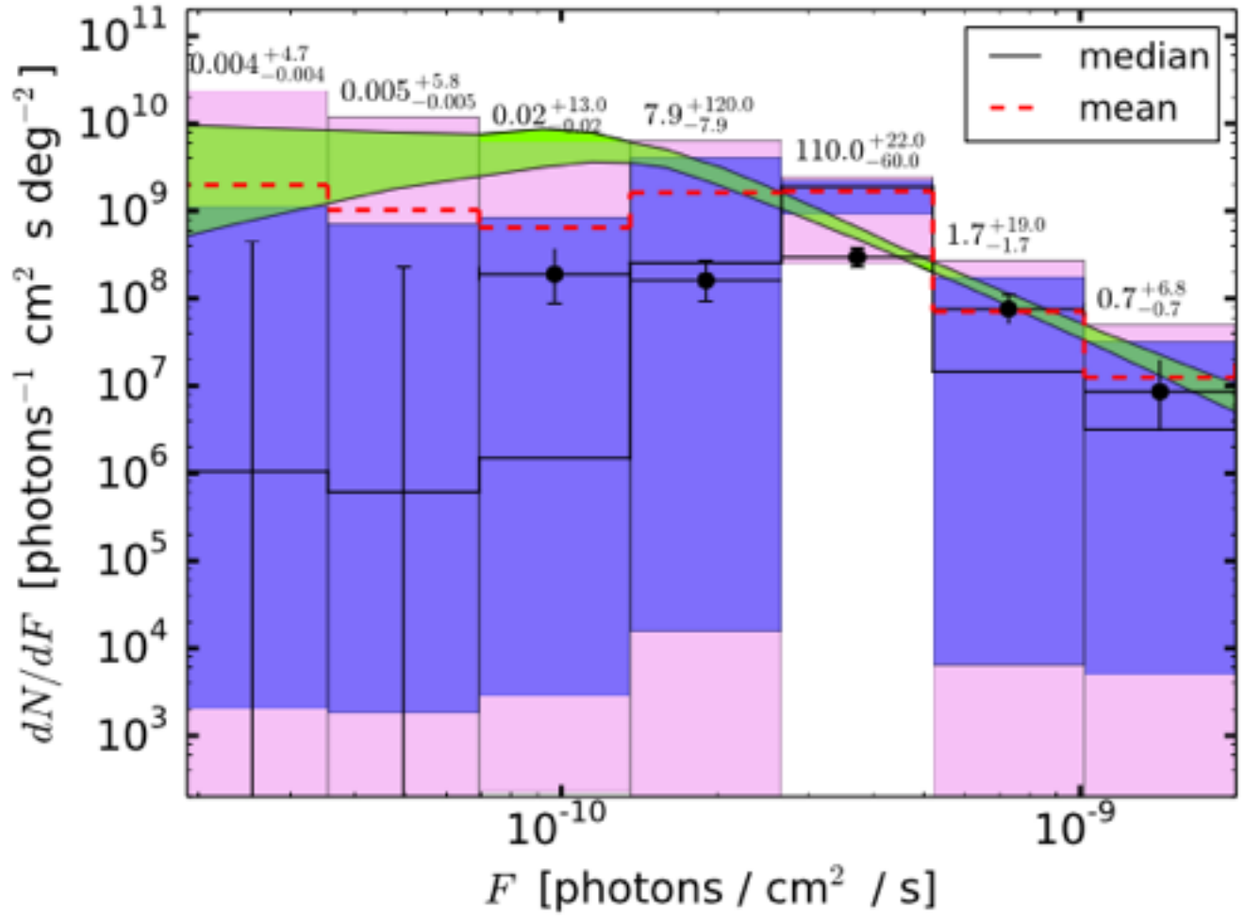




- Gaussian sigma for PSF set to 0.198 degrees (left) or 0.0492 degrees (right), in generating function formalism - these correspond to the estimated PSF at the lowest and highest energies in our bin.

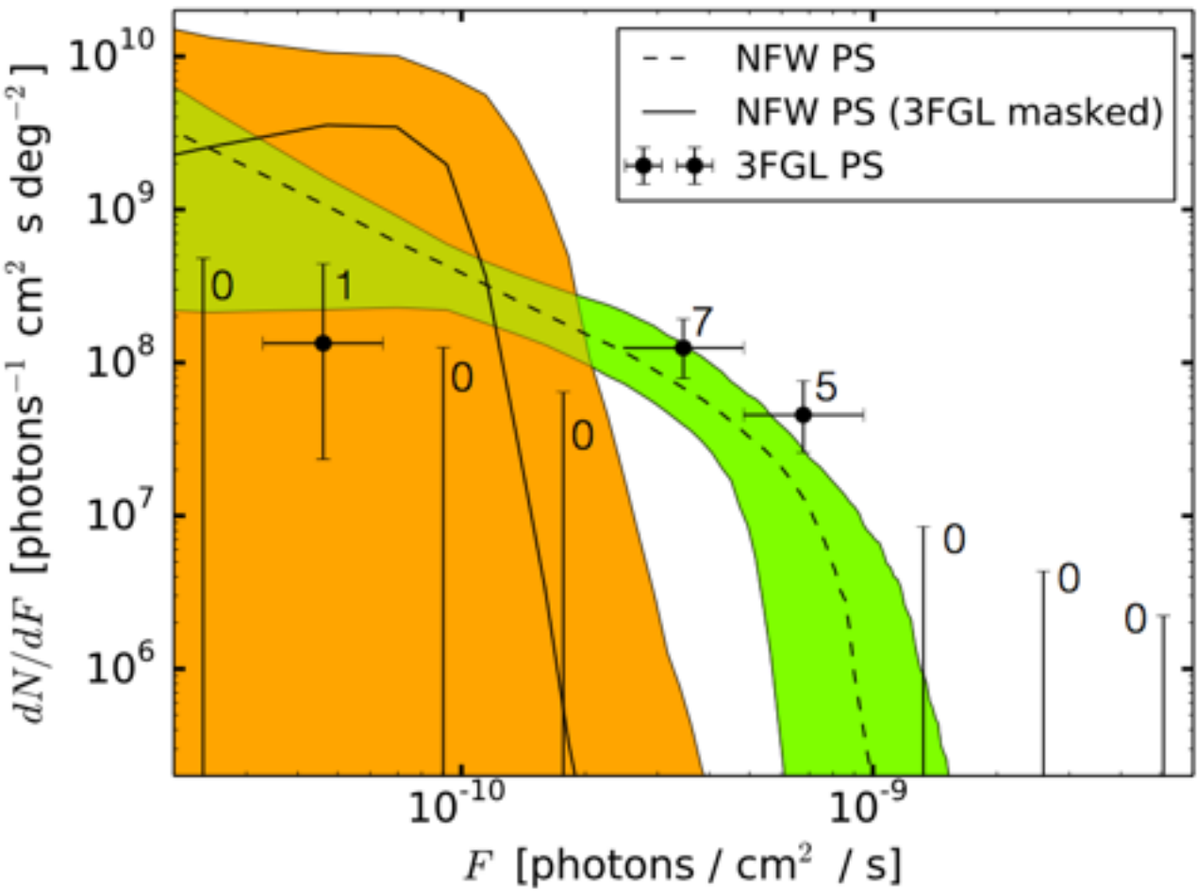
- We neglect non-Gaussian PSF tails in the generating function formalism (but include them properly in smoothing the diffuse background), but taking a much broader Gaussian PSF should largely capture the impact of mismodeled tails.

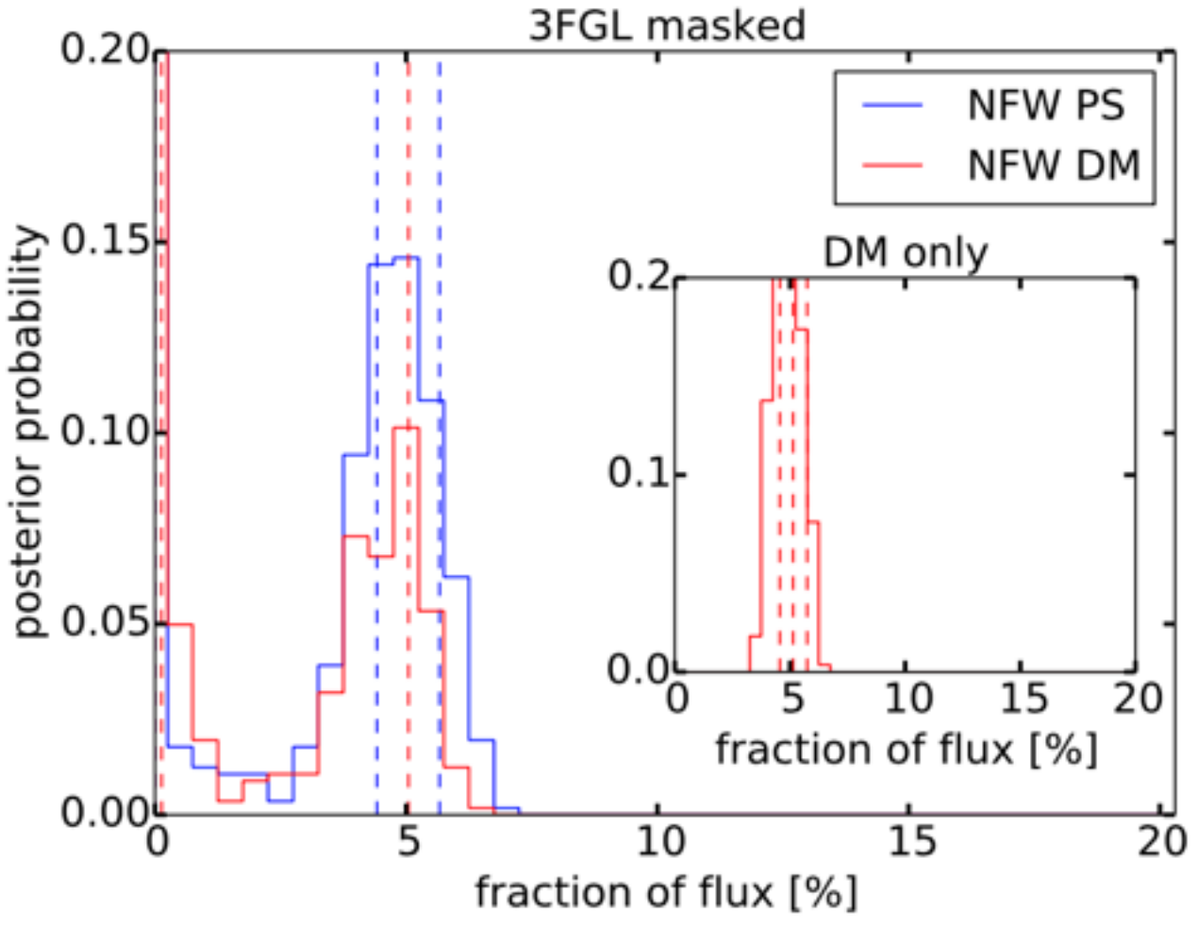




- Rather than modeling the source-count function as a broken power law, we can allow it to float independently bin-by-bin.
- Uncertainties are large (and highly correlated - not shown by error bars above), but results are consistent.
- Purple region shows 68% containment, pink region shows 95% containment, orange (green) regions are those attributed to NFW PS template in masked (unmasked) analyses.

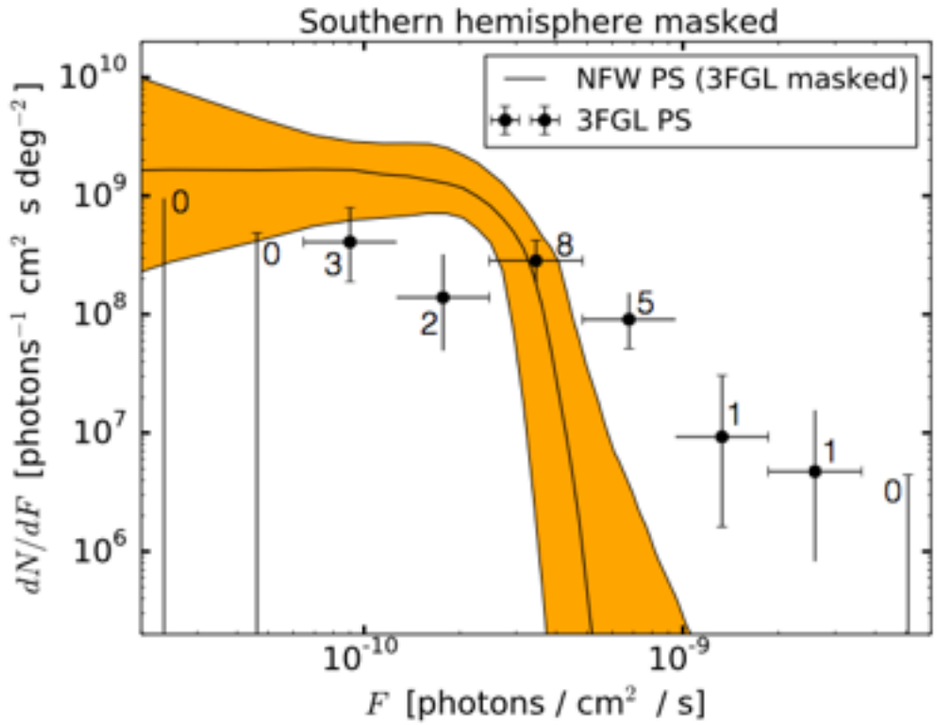
An alternate region

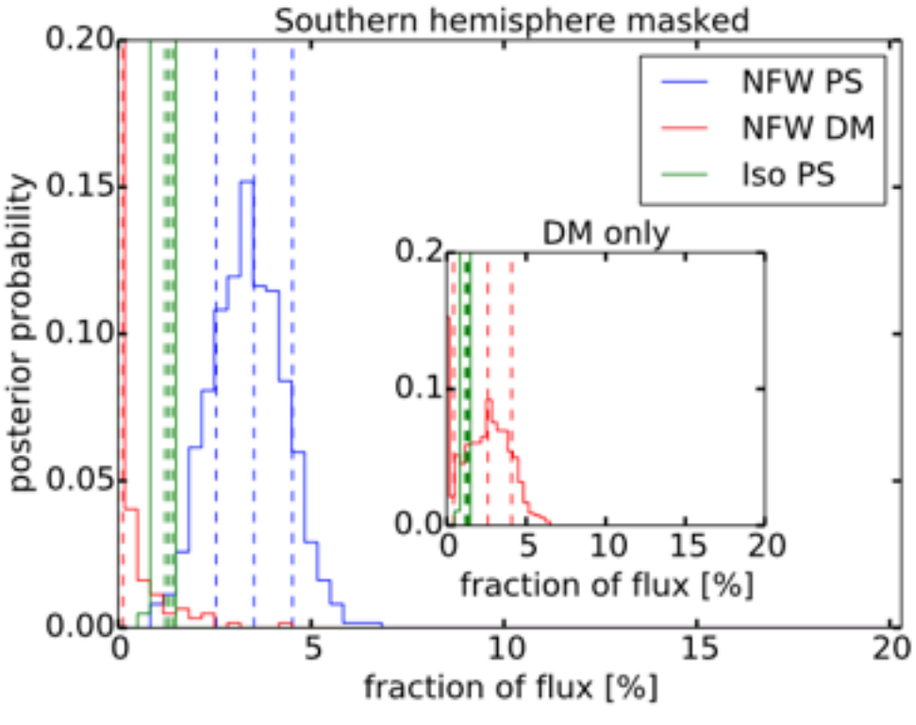


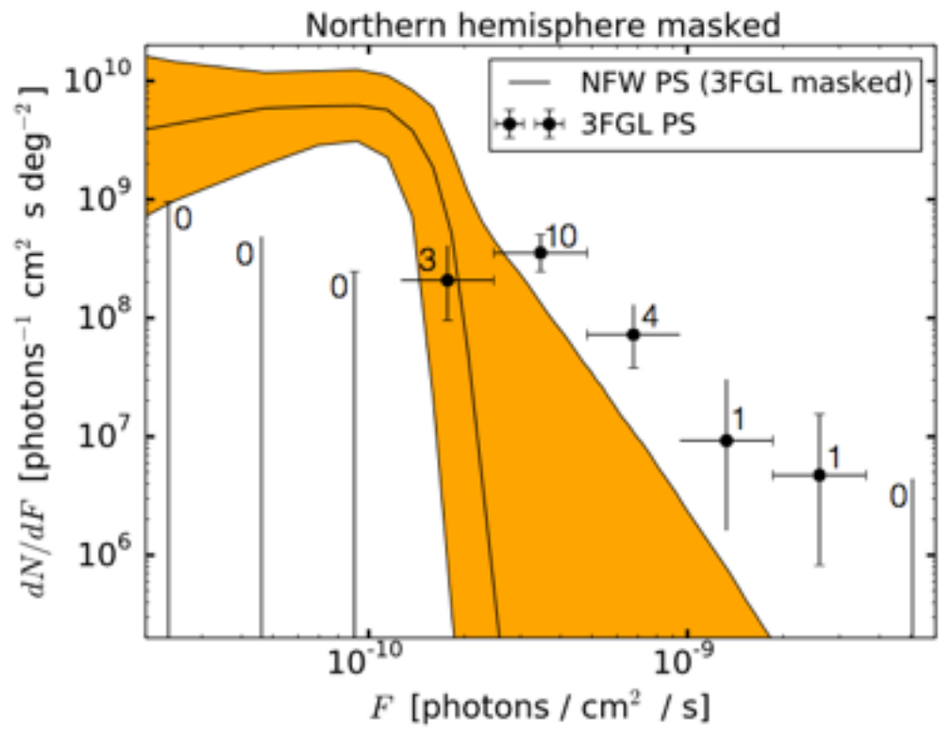


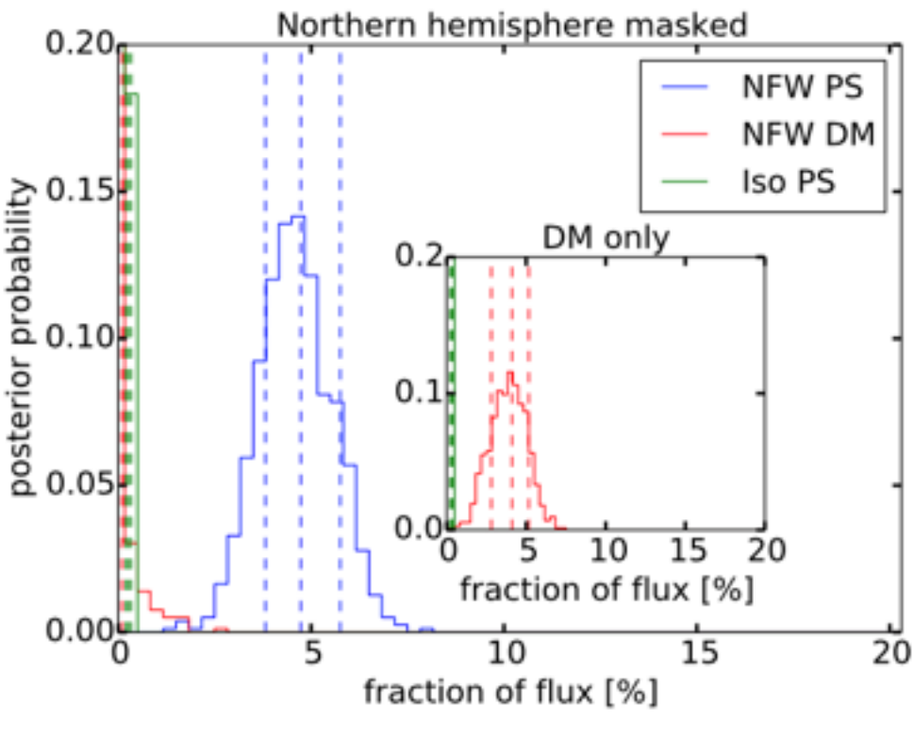
- There is a bright excess 30 degrees along the Galactic Plane from the Galactic Center, albeit with a soft spectrum.
- When the same analysis is repeated on this region in masked data, there is no significant preference for PSs over a diffuse signal.

North vs south

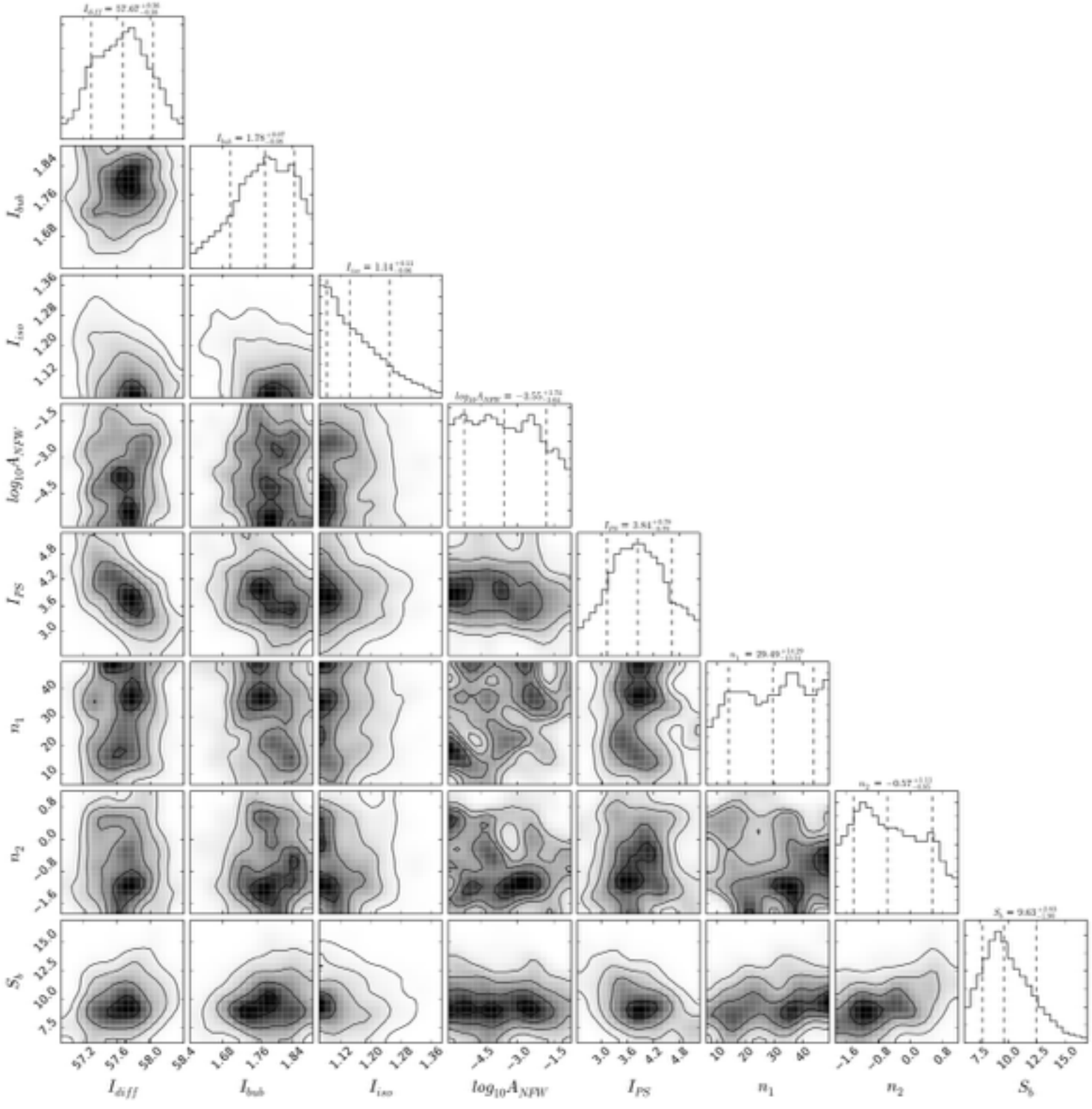






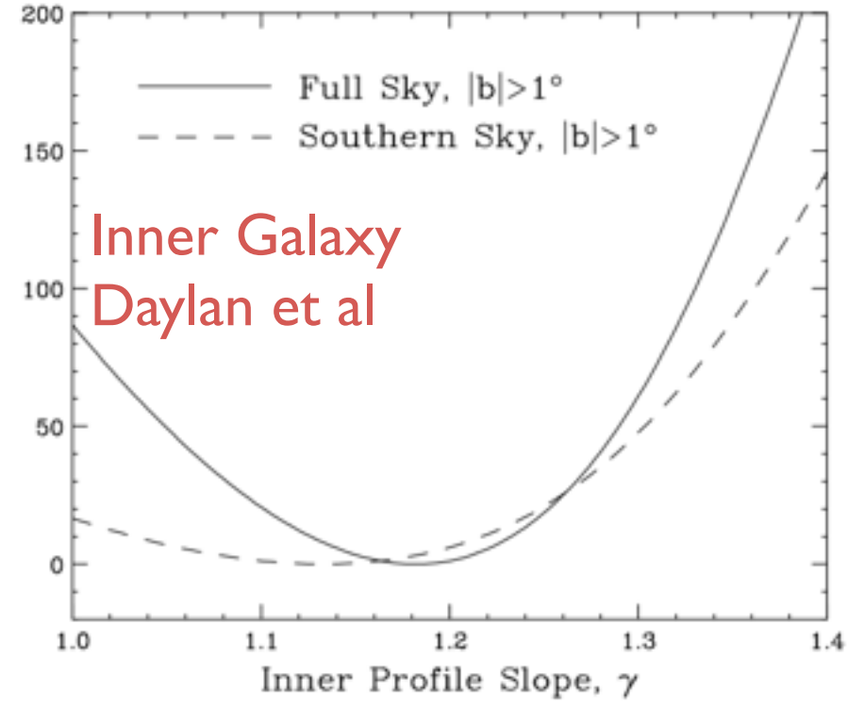


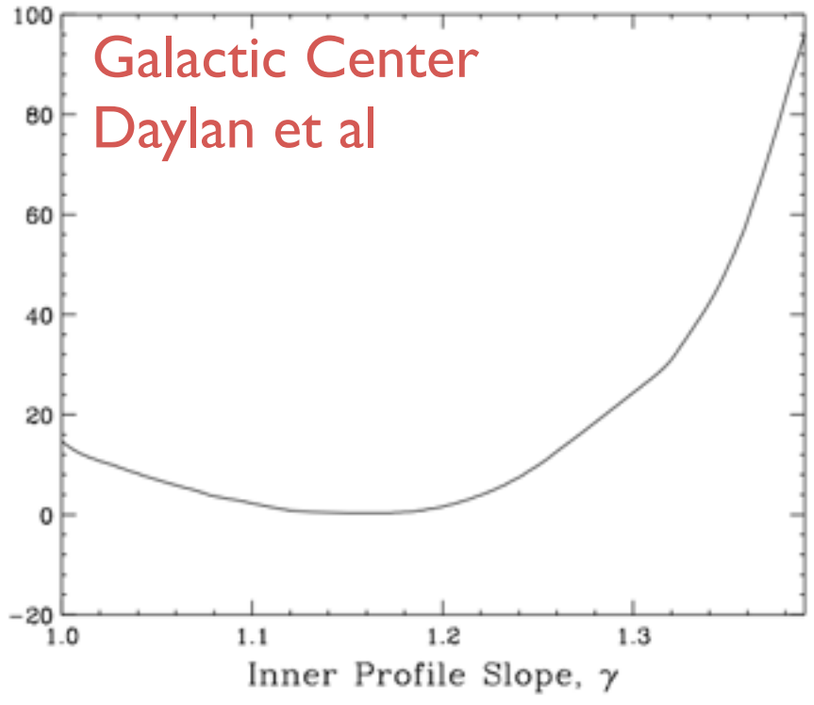
Triangle plot (masked IG)

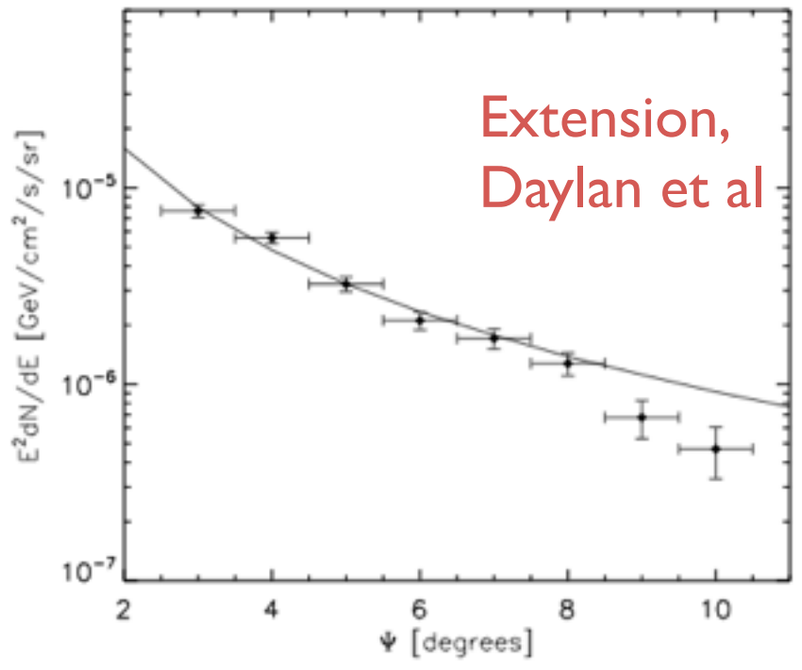


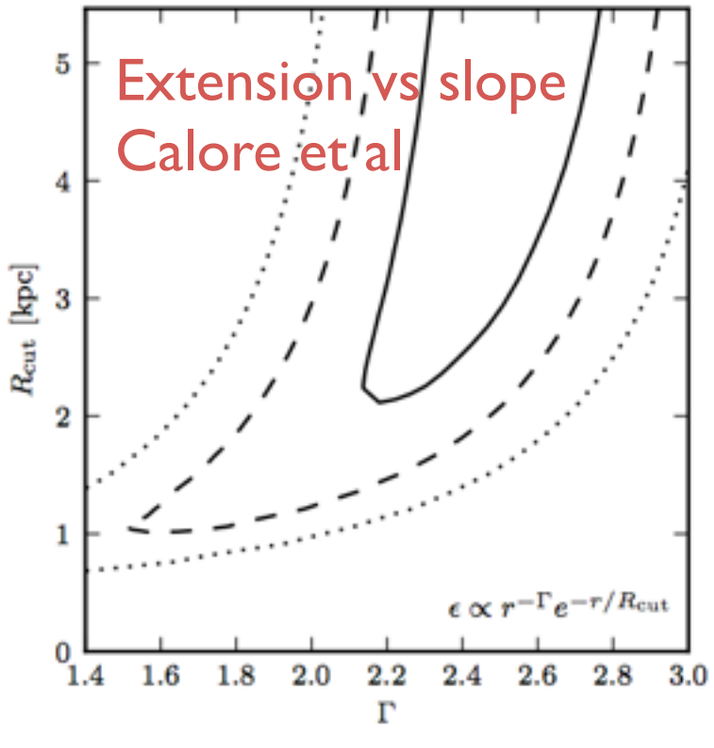
Properties of the GeV excess

Slope and extension









- Preferred power-law slope for power per unit volume (i.e. 2γ for annihilation from an NFW profile): ~2.2-2.4 (Galactic Center, Paper 1), ~2.2-2.6 (Inner Galaxy, Paper I), ~2.2-2.8 (CCW, syst. errors included)

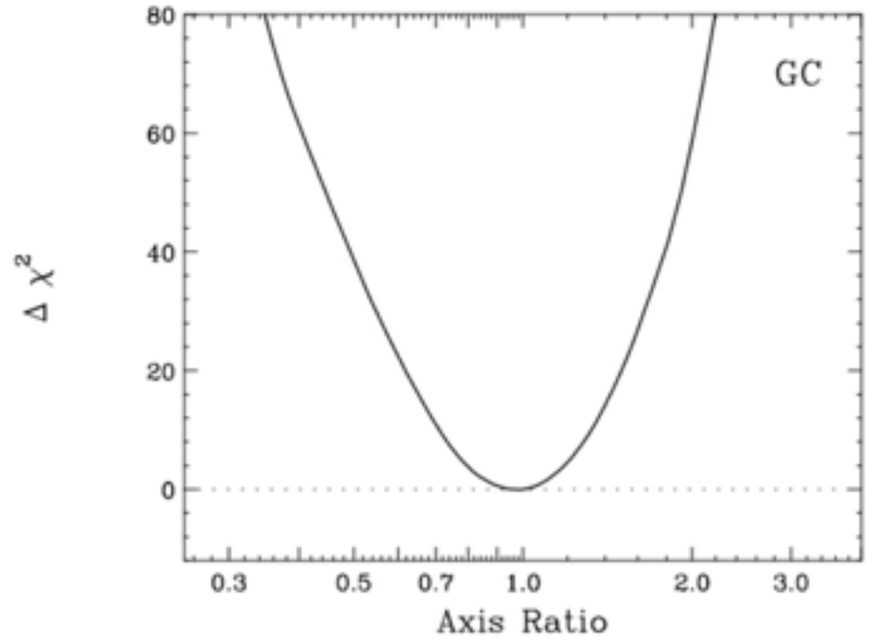
- Extends to ~10 degrees / 1.5 kpc.

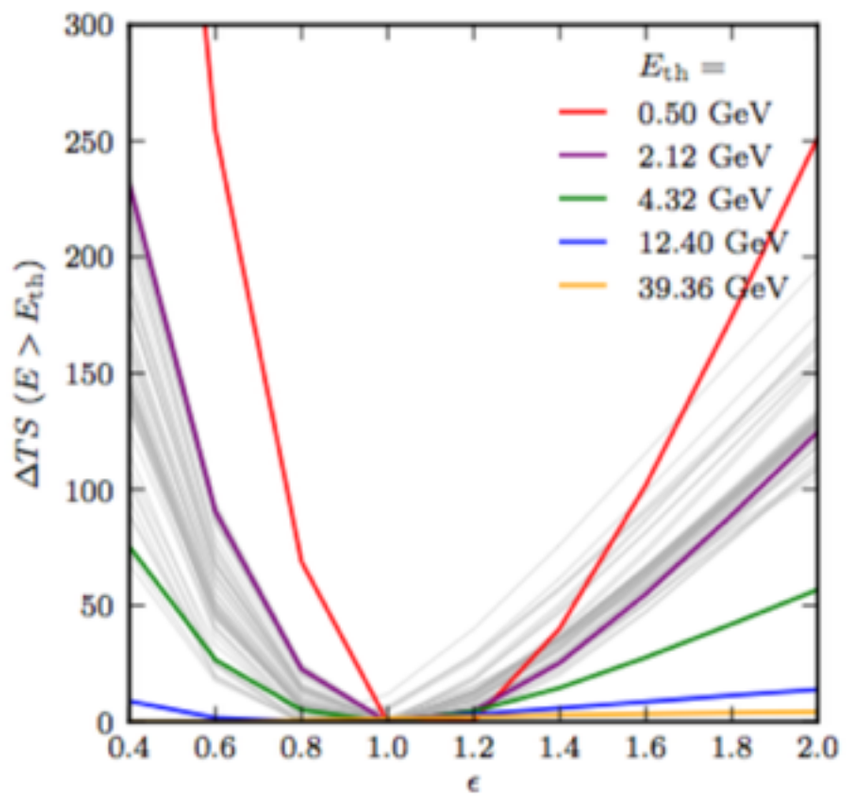
Sphericity

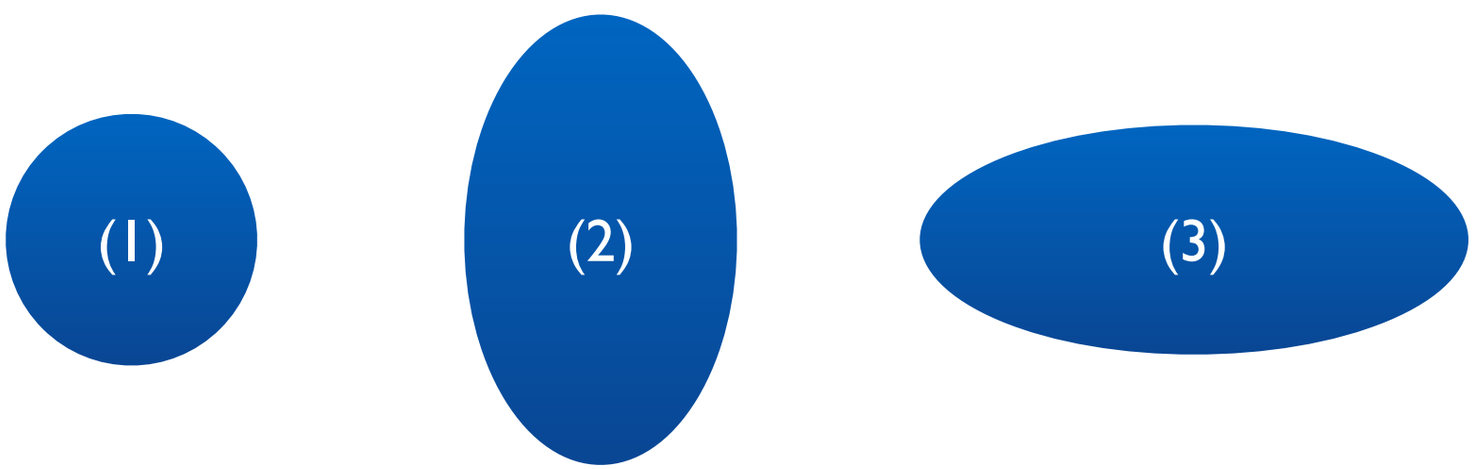
- Test: which provides a better fit to the data? (1) Circular template, (2) template stretched perpendicular to the Galactic plane, (3) template stretched along the Galactic plane?

- (3) would be a strong hint at an astrophysical origin. But data seem to prefer (1), disfavoring a stretch by a factor of more than 1.2.

- Top - Daylan et al, bottom - Calore et al.

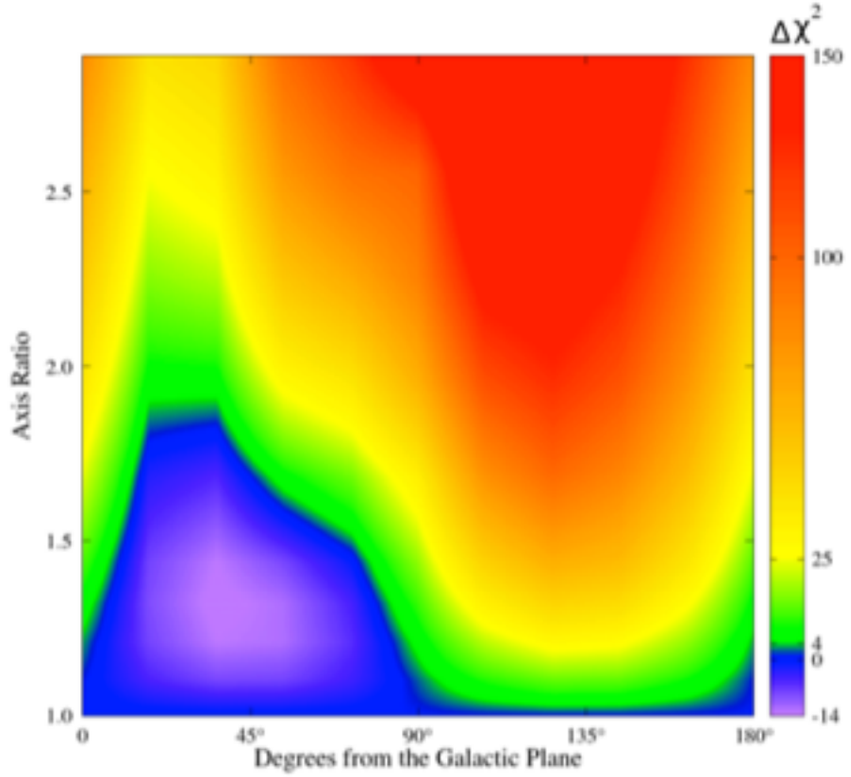




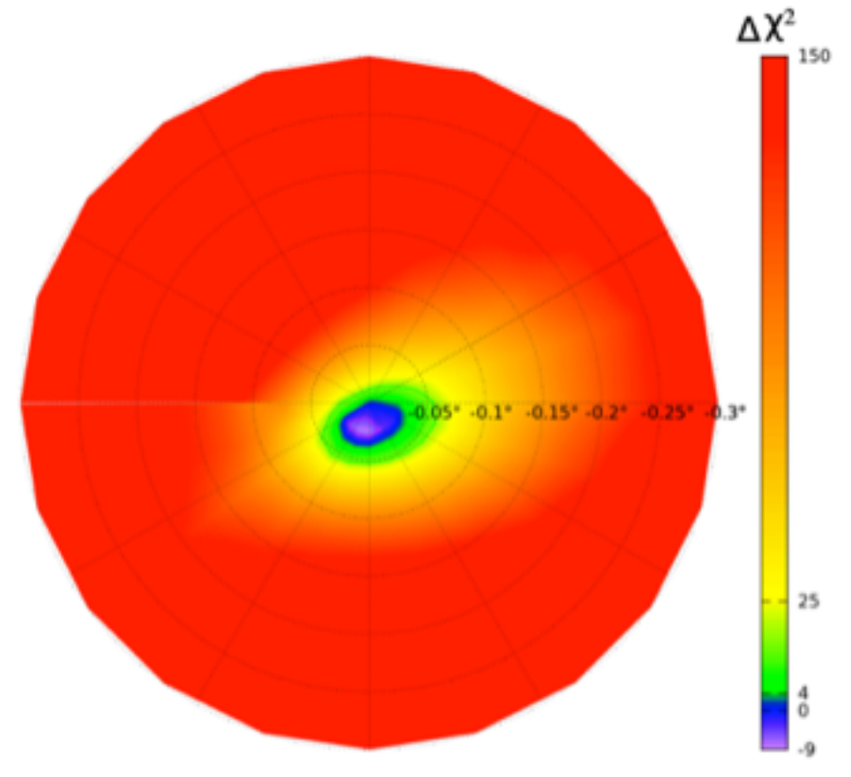


Orientation & centering

- More spatial tests (from Daylan et al):
- Stretch signal template along arbitrary angles to the Galactic plane.
- Move template so it is not centered on Galactic Center.



- Results: shift more than 0.05 degrees from the GC is disfavored at 95% confidence (from GC analysis - inner Galaxy analysis less sensitive).
- Mild preference for stretch factor of 1.3-1.4 at an angle ~35 degrees from the Galactic Plane, but not significant.

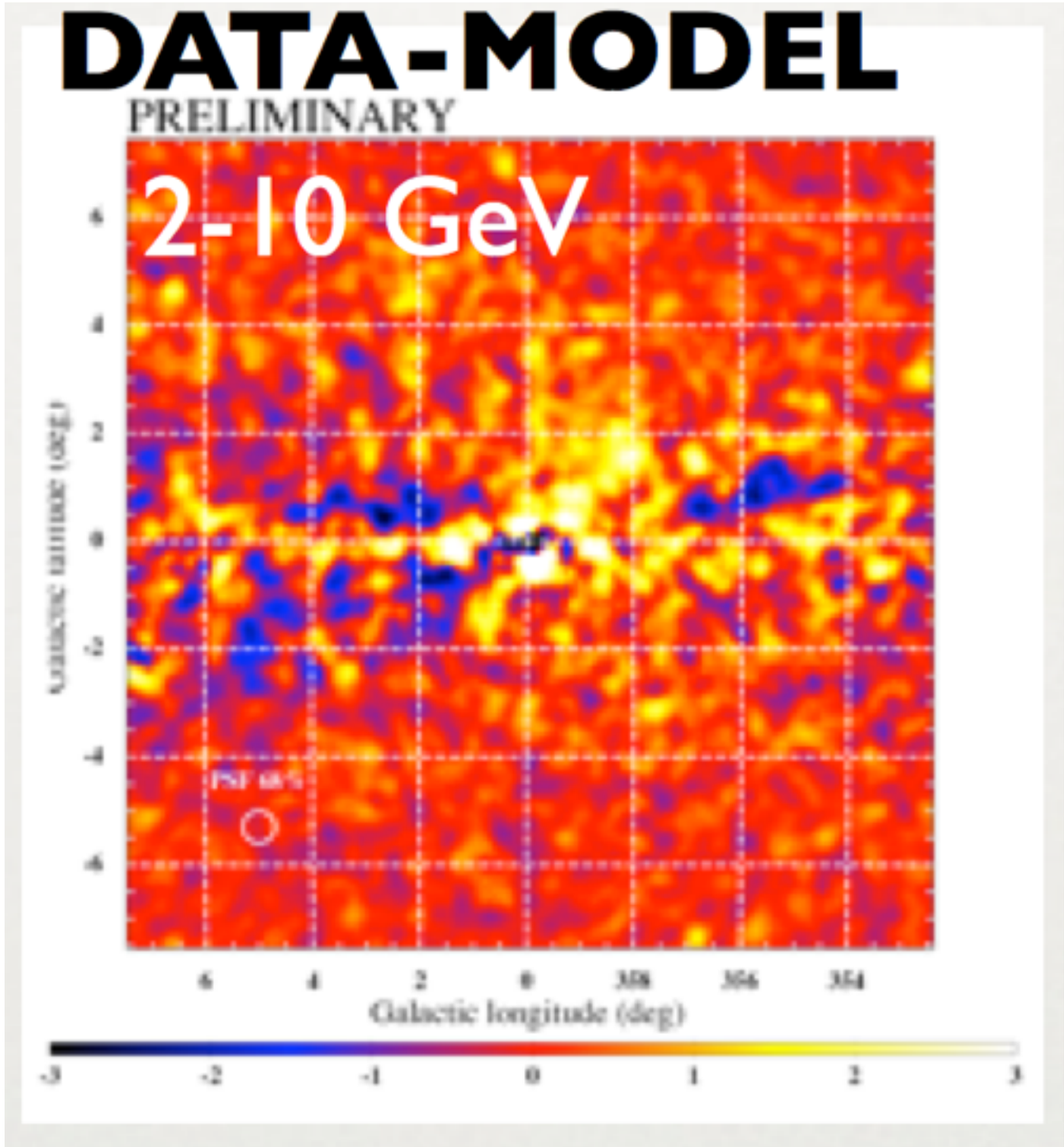


What does the Fermi Collaboration say?

- Talk presented by Simona Murgia at Fermi Symposium 20-24 October.

- “We find an enhancement approximately centered on the Galactic center with a spectrum that peaks in the GeV range, that persists across the models we have employed”

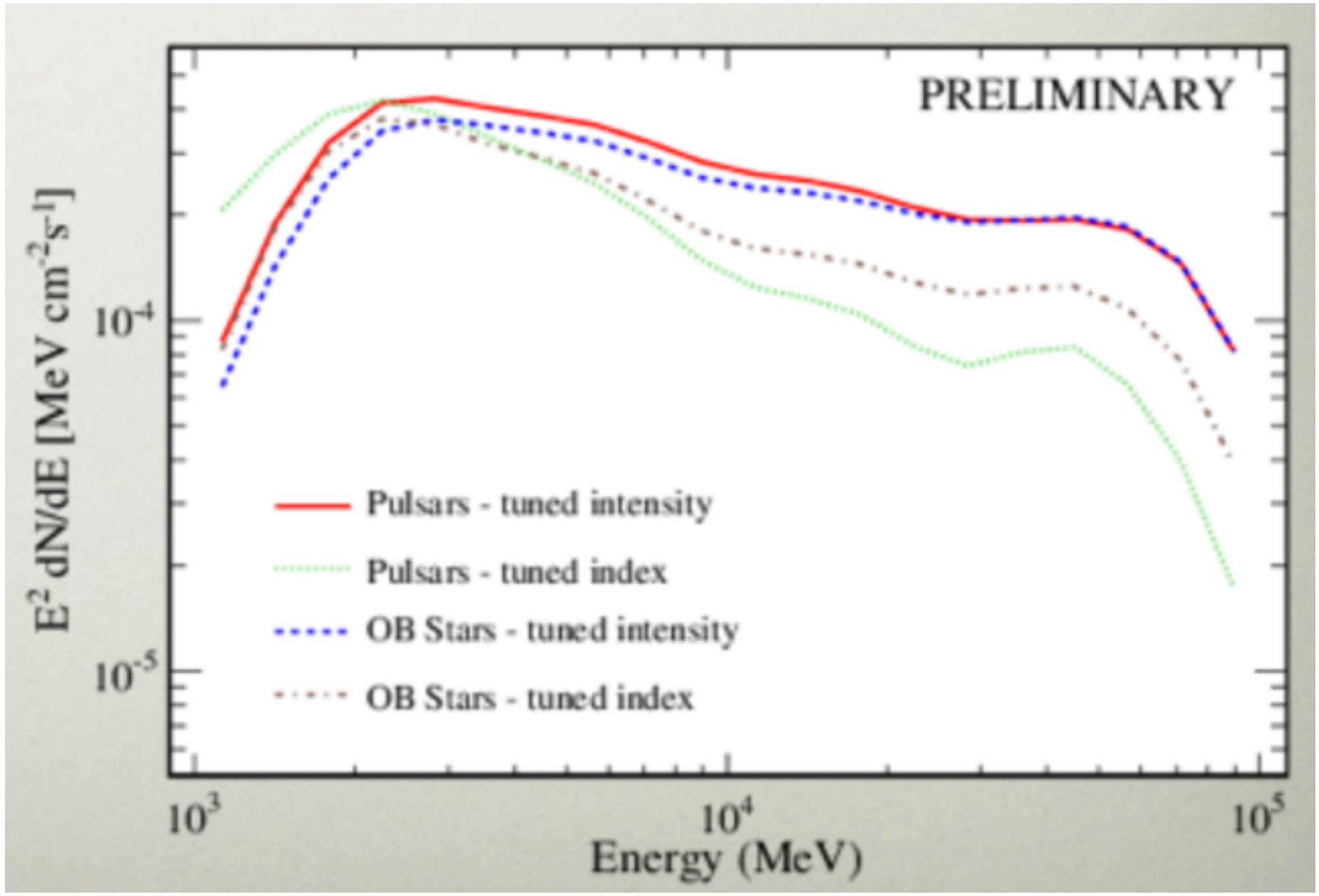
- “Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data- model agreement”



The spectrum from the Fermi Collaboration

- Two sets of source distributions ("pulsars" and "OB stars"). "Tuned index" models allow spectral indices of background to vary (rather than just intensity), provide better agreement with data.

- Spectrum of excess seems broadly consistent with other results (lower at ~1 GeV); tuned-intensity models lead to higher "signal" tails at large E, but are known to generically undersubtract data at high energies.



Talk presented by Simona Murgia at Fermi Symposium

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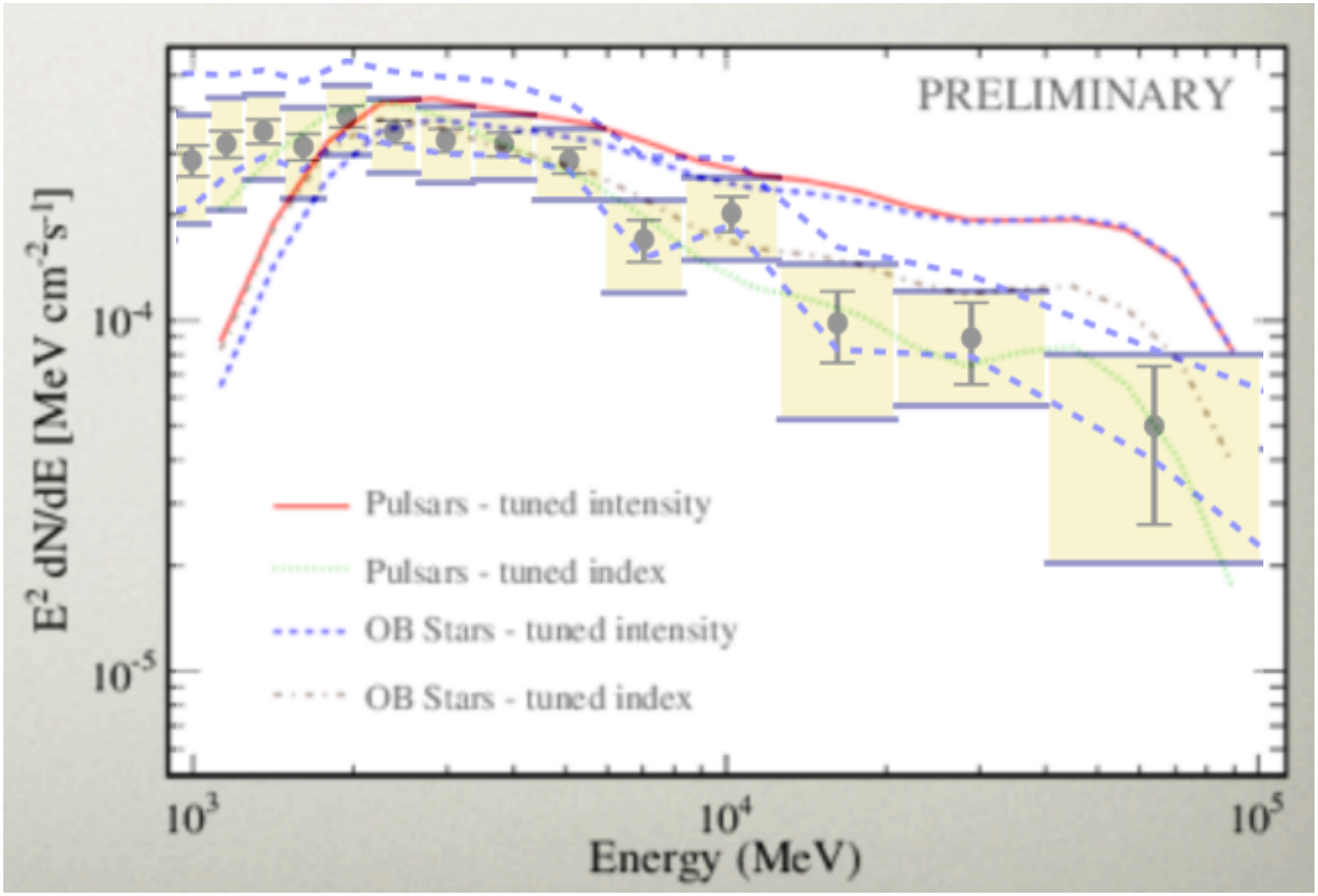
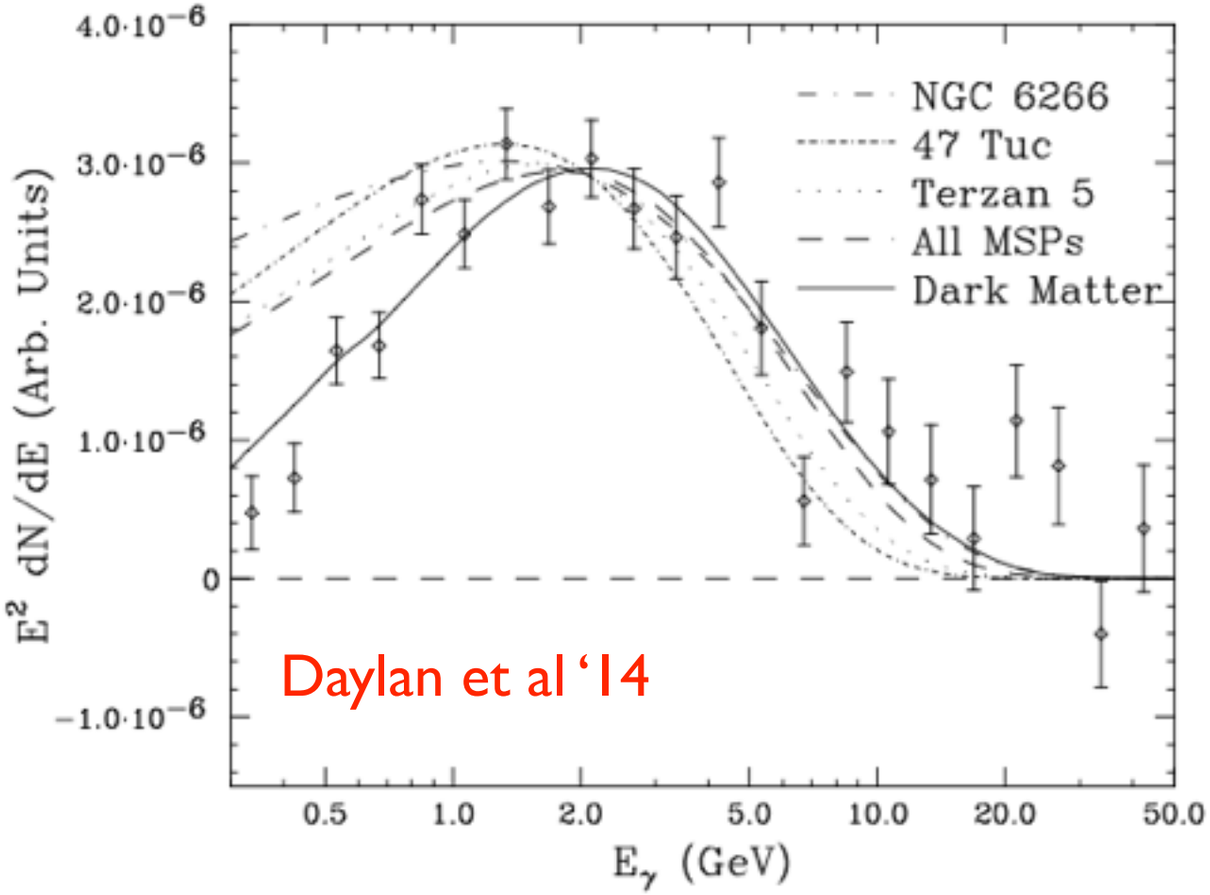
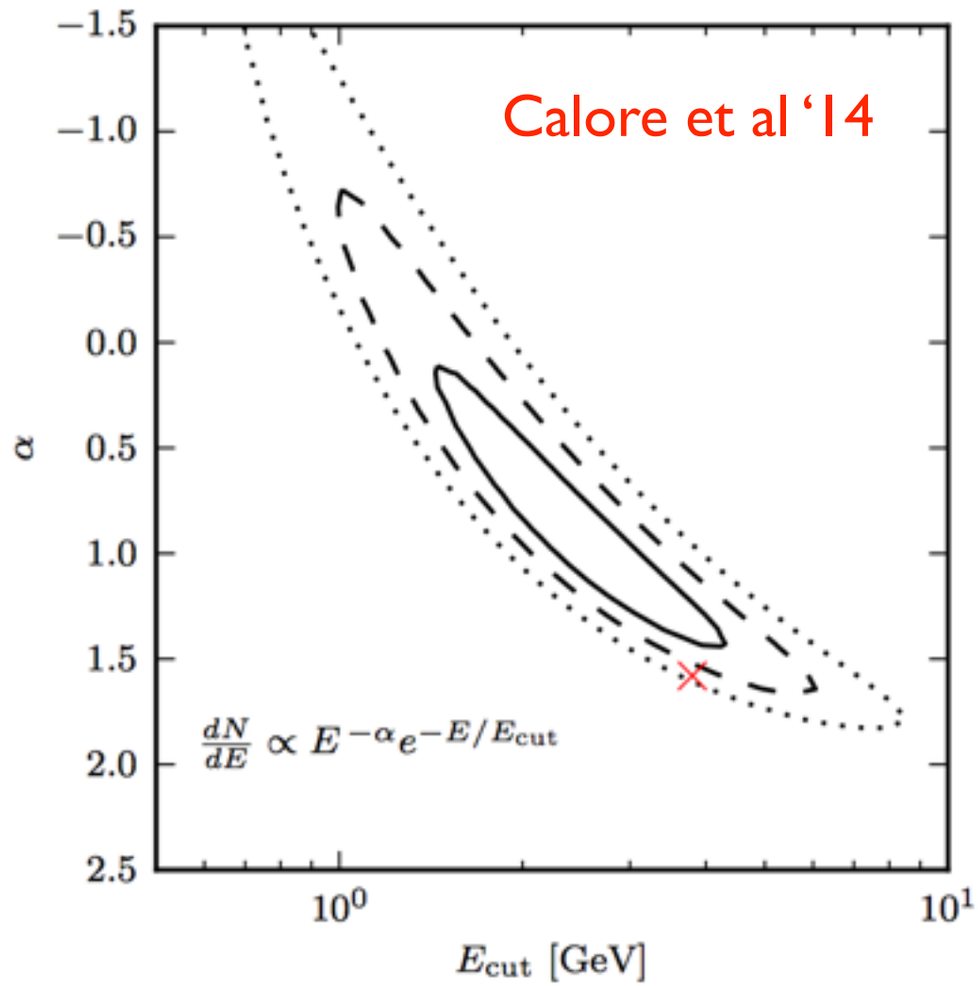


Talk presented by Simona Murgia at Fermi Symposium

The pulsar interpretation for the GeV excess

The pulsar spectrum

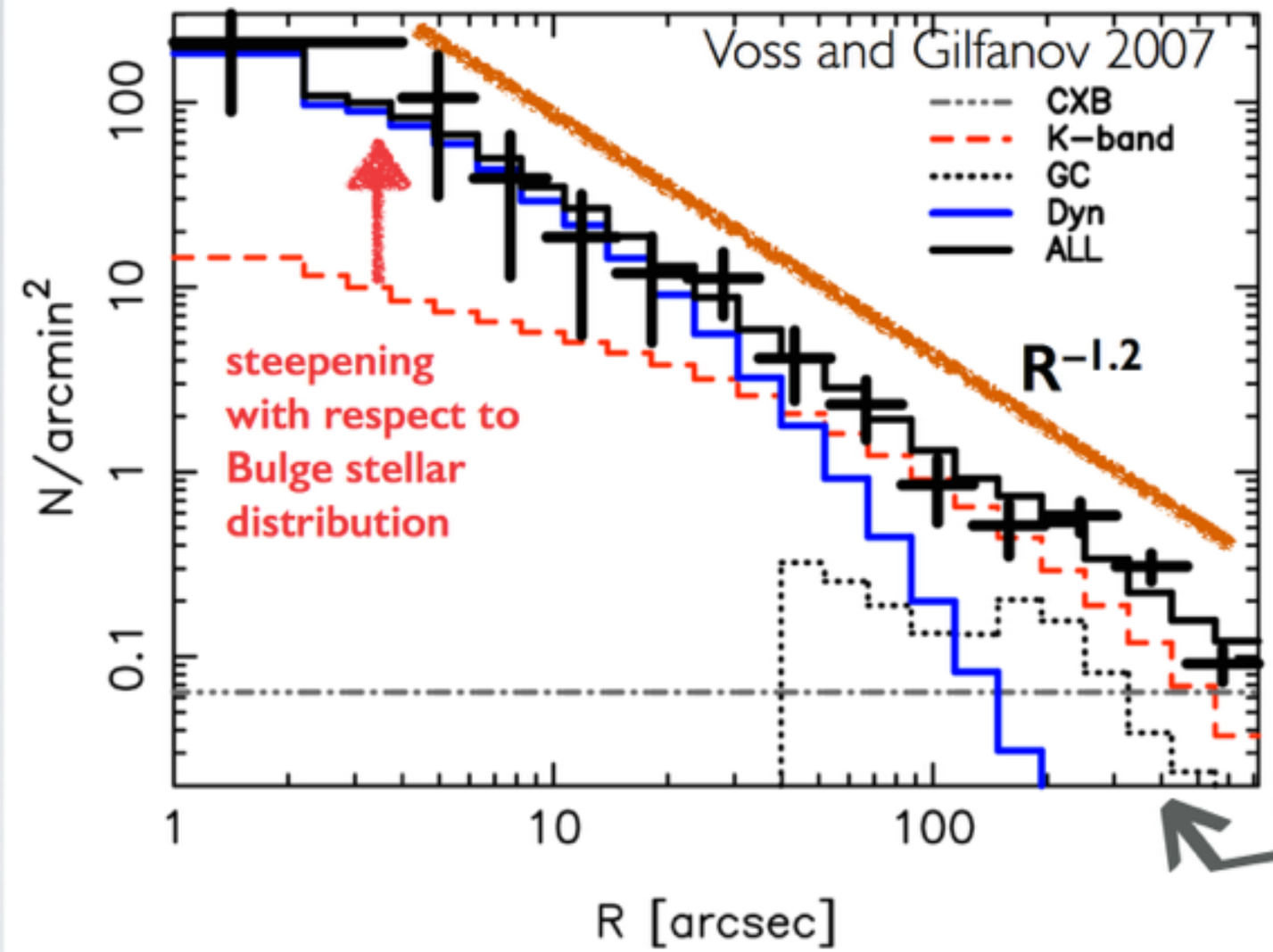




- Millisecond pulsars (MSPs) have an (observed) spectral cutoff at approximately the correct energy (~5-10 GeV).
- Low-energy spectrum of MSPs seems somewhat softer than signal (marginally compatible given CCW estimates on systematic uncertainties).
- Abundance estimates seem to predict fewer MSPs than required (e.g. 1305.0830, 1407.5625).

Spatial distribution of MSPs

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



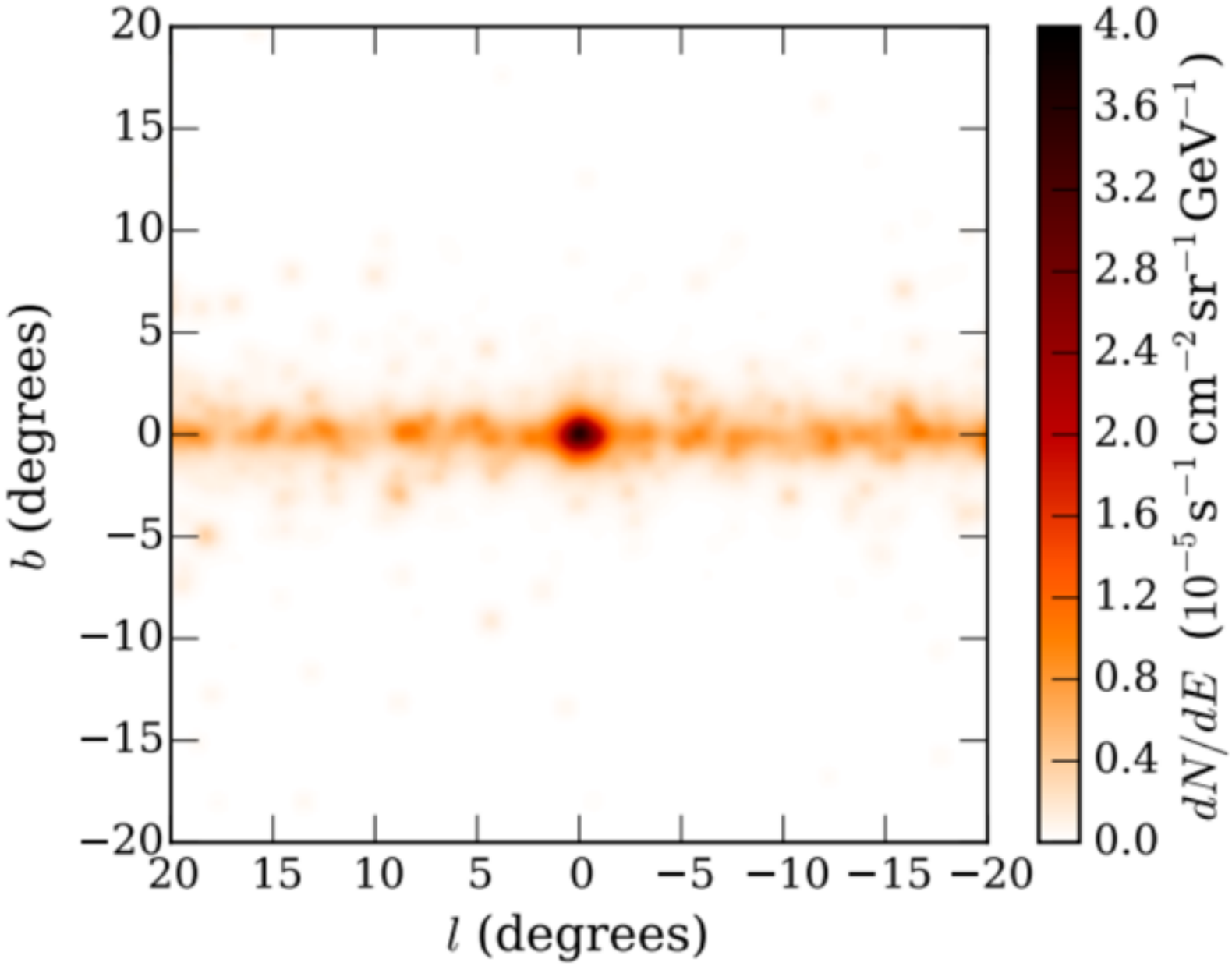
We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

400" towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

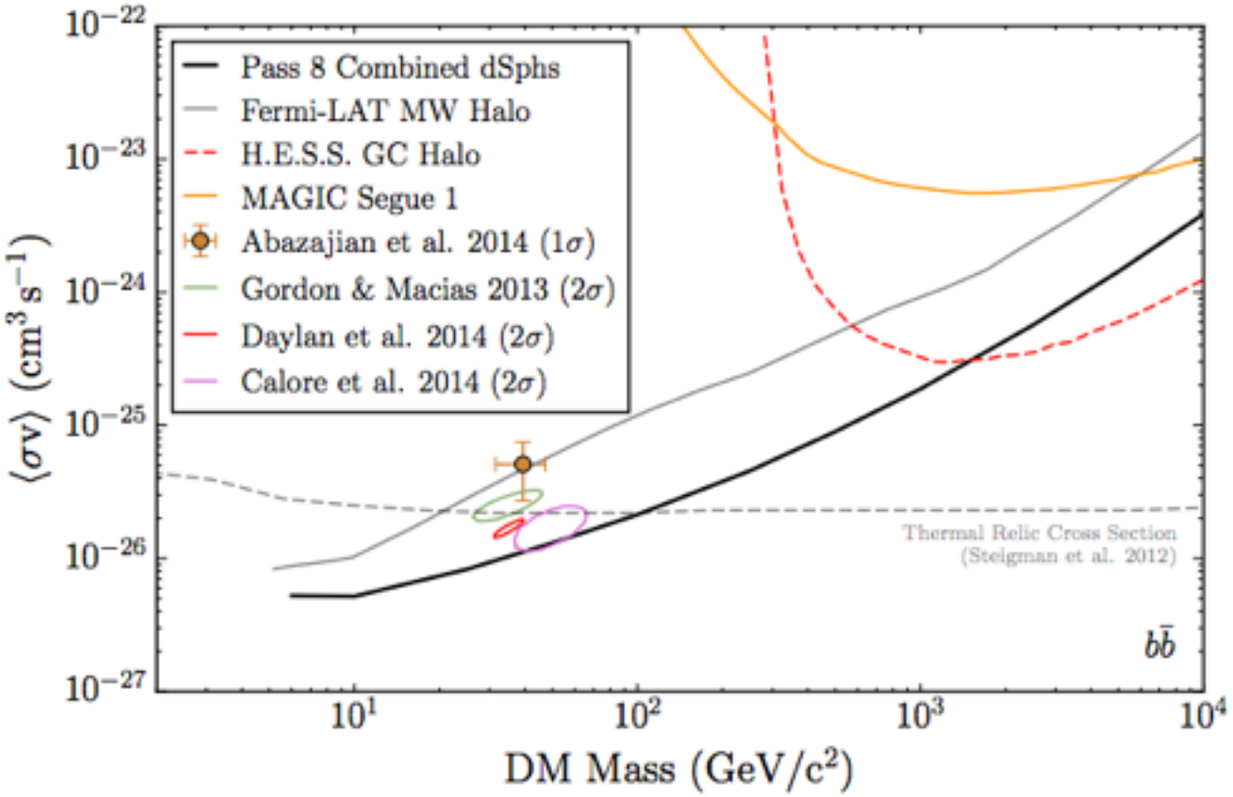
Sphericity?

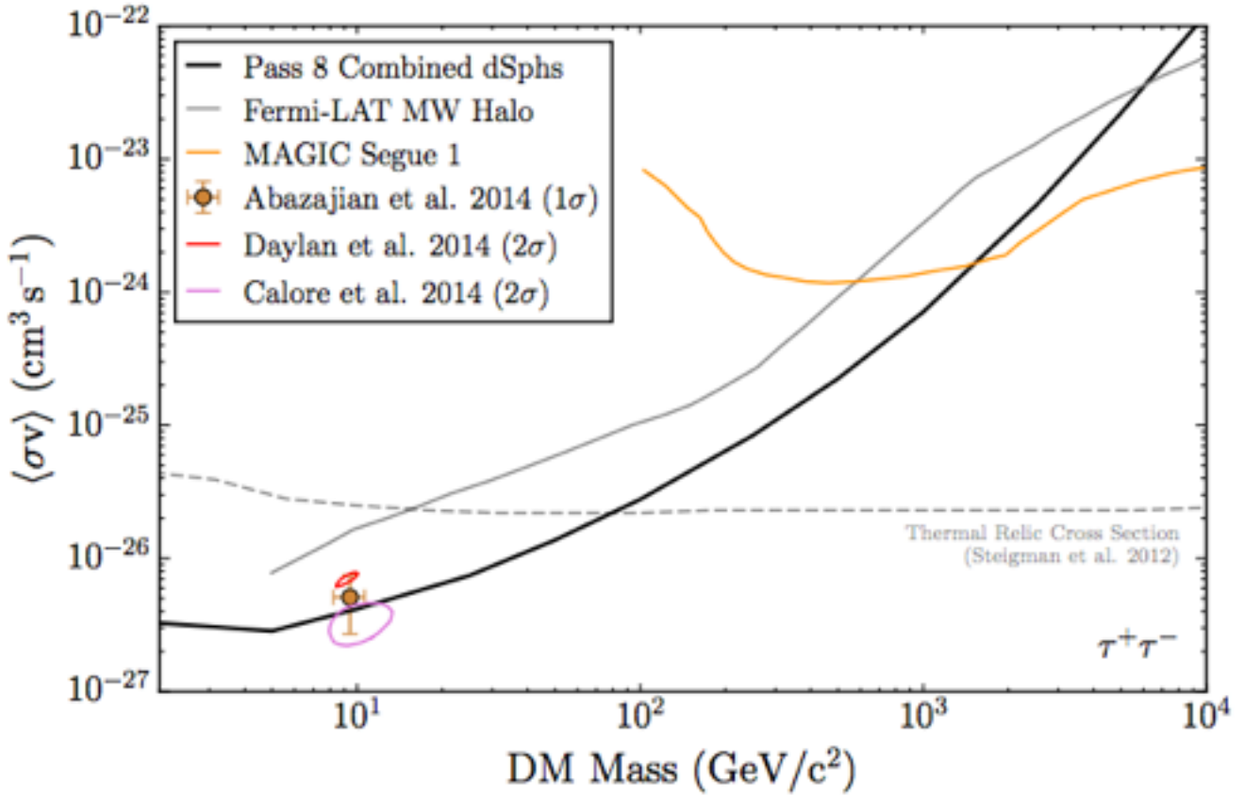
- Study of young pulsars by O'Leary, Kistler, Kerr and Dexter 1504.02477 - claims to reproduce morphology of excess.
- However, only angle-averaged profile is shown, sphericity is not tested explicitly.
- By eye, morphology appears much more disk-like than spherical, and disk pulsars are said to dominate outside inner few degrees.
- As found in earlier studies and confirmed in our current analysis, excess is absorbed by spherical population rather than a thick disk.



Indirect constraints on the GeV excess

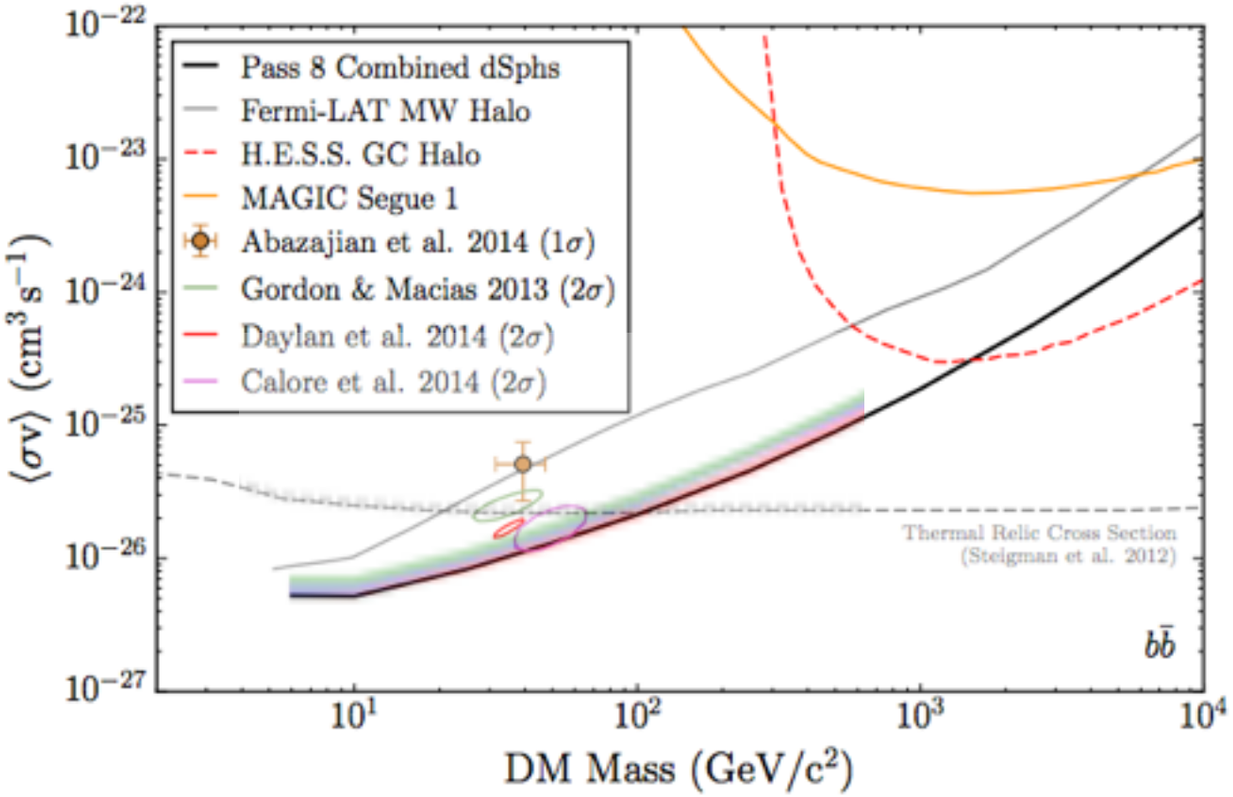
Dwarf galaxies

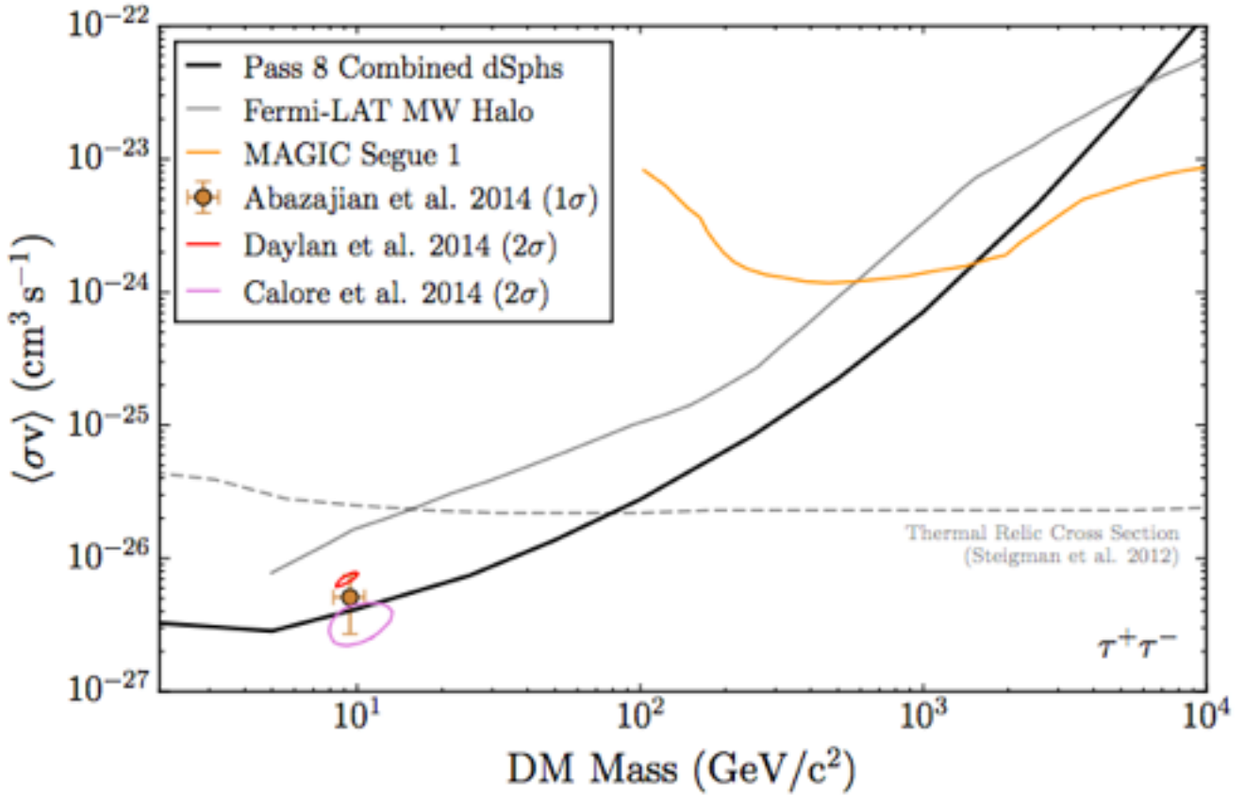




- Dwarf galaxies: DM-dominated systems, provide a clean independent test of DM-annihilation hypothesis.
- Currently provide best current limits on sub-TeV DM annihilating through most channels (Fermi Collaboration, 1503.02641).

Dwarf galaxies





- Dwarf galaxies: DM-dominated systems, provide a clean independent test of DM-annihilation hypothesis.
- Currently provide best current limits on sub-TeV DM annihilating through most channels (Fermi Collaboration, 1503.02641).

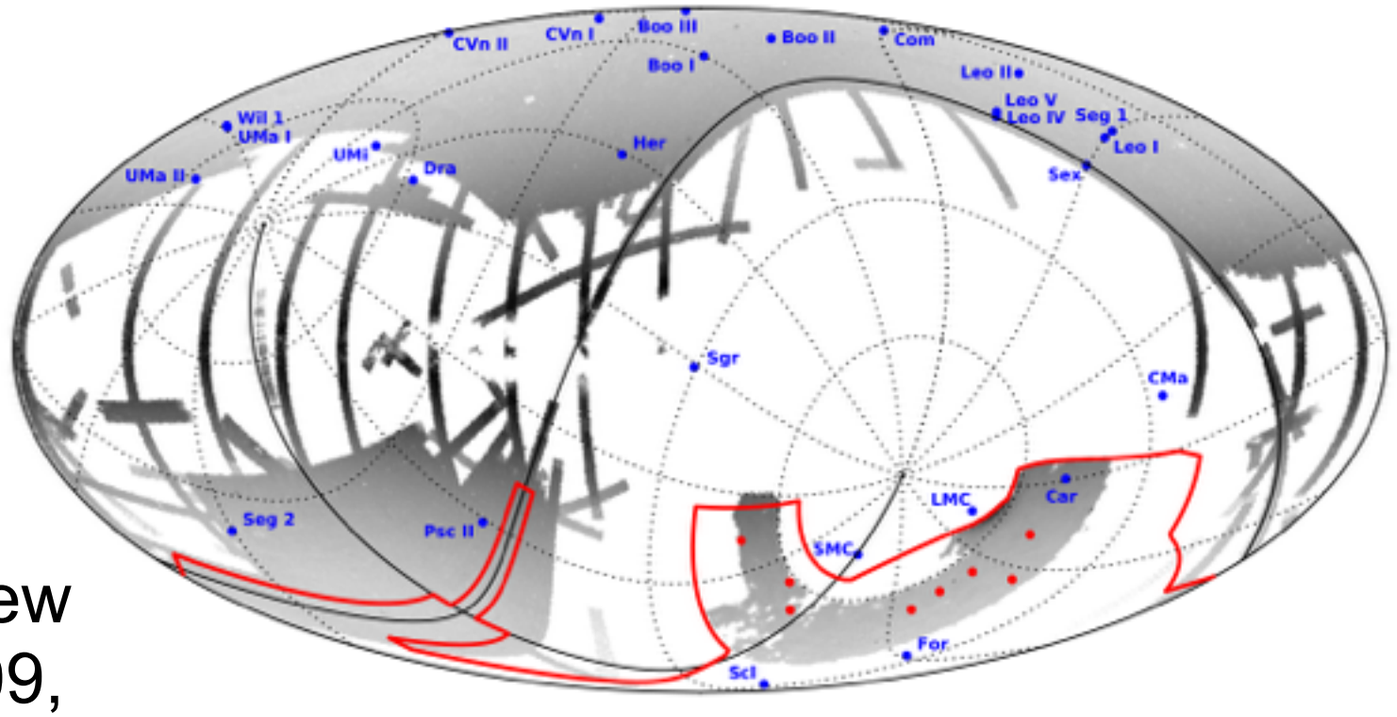
DES discovers new dwarf galaxies

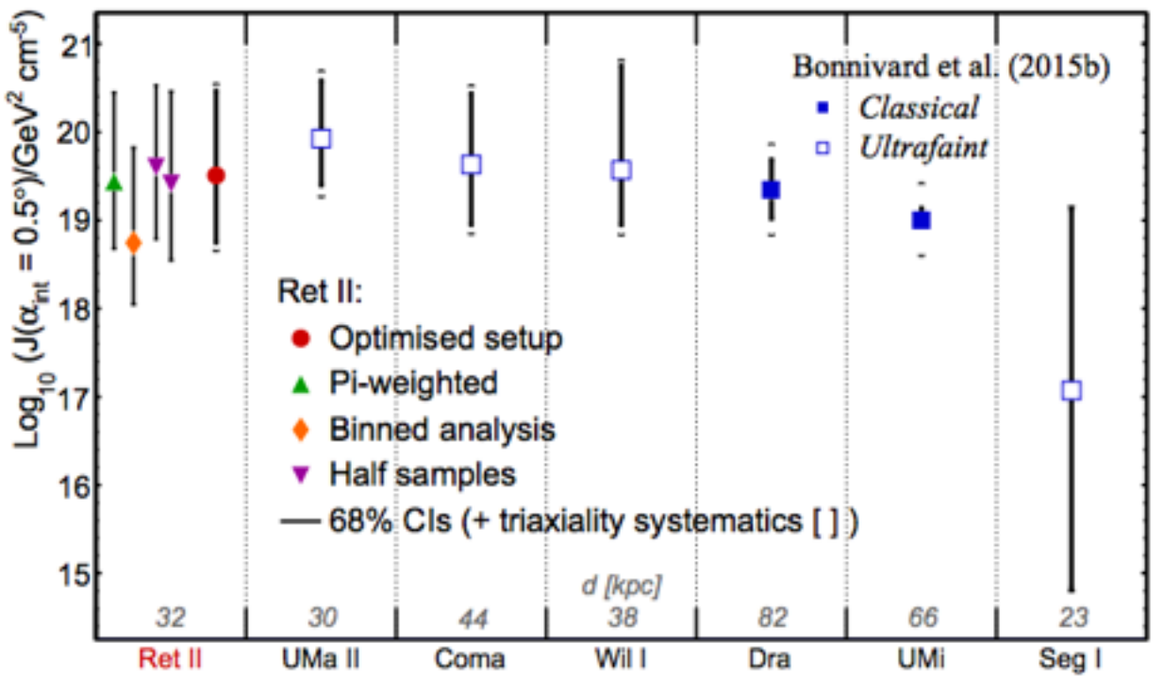
- Discovery of 8-9 new dwarf candidates in DES data in March (1503.02079, 1503.02584).

- More recently, kinematic studies were made of the DM content of “Reticulum II”, the closest of the new dwarfs (Bonnivard et al 1504.03309, Simon et al 1504.02889).

- Want to estimate “J-factor”, figure of merit for DM annihilation.

- Results are consistent within the (large) error bars, but Simon et al prefer a somewhat smaller value.





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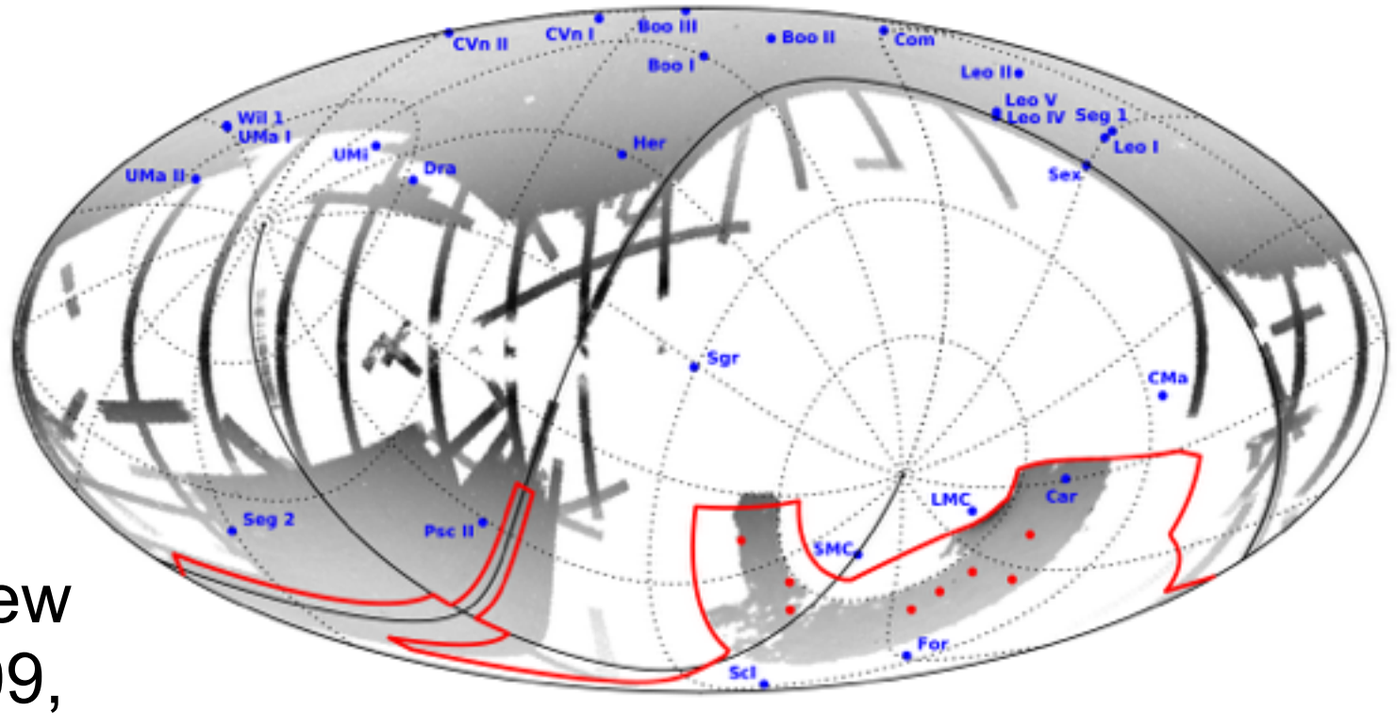
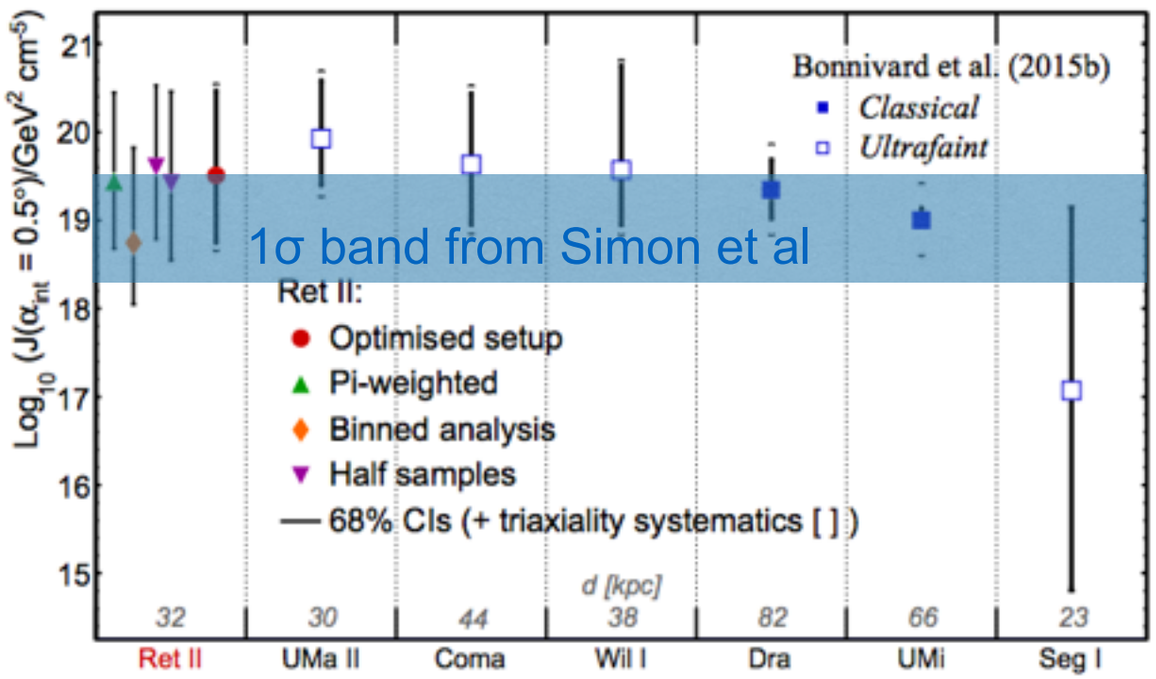




Reticulum II

- Recently discovered in DES data, ~30 kpc away. A gamma-ray excess is consistently seen, in the 2-10 GeV energy range.
- Significance debated, various groups find 2.2-3.7σ local significance depending on background modeling. (See talk by K. Bechtol for detailed discussion.)
- Global significance depends on J-factors for dwarves, and whether one scans over DM mass + annihilation channel.
- Within uncertainties, consistent with Galactic Center excess - but uncertainties are large.

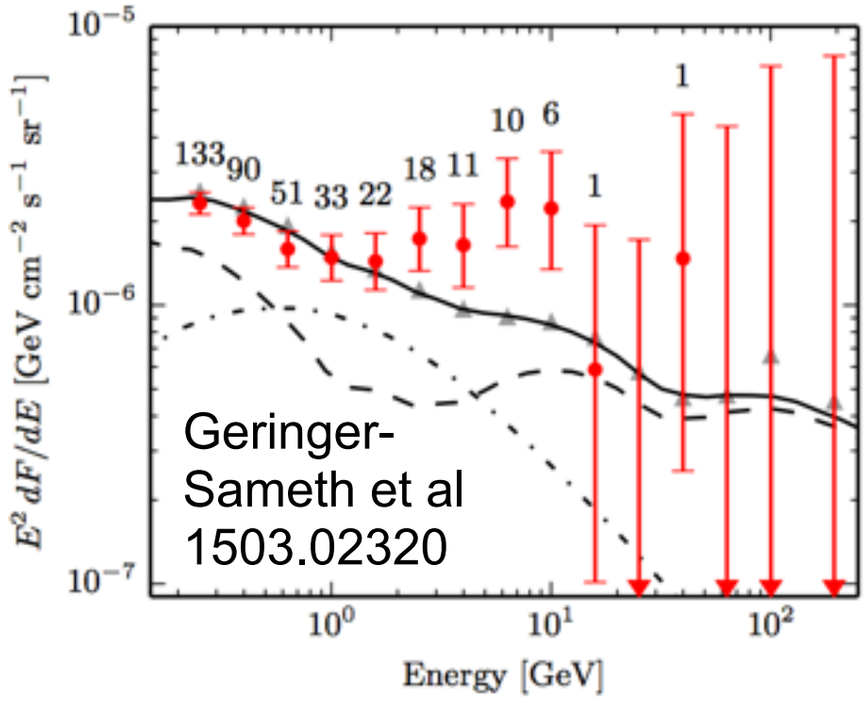
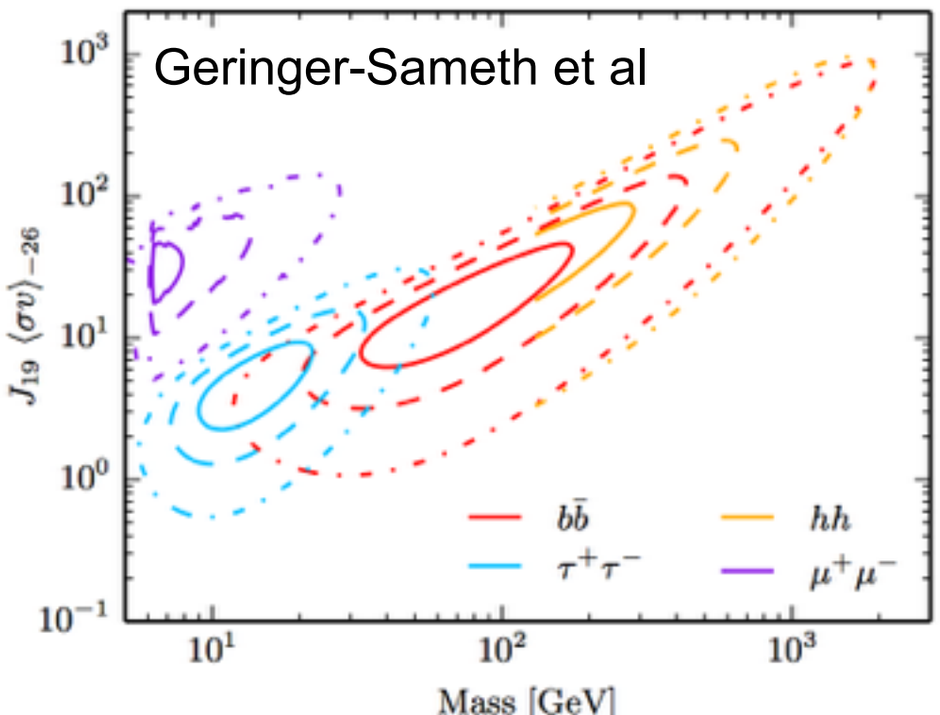
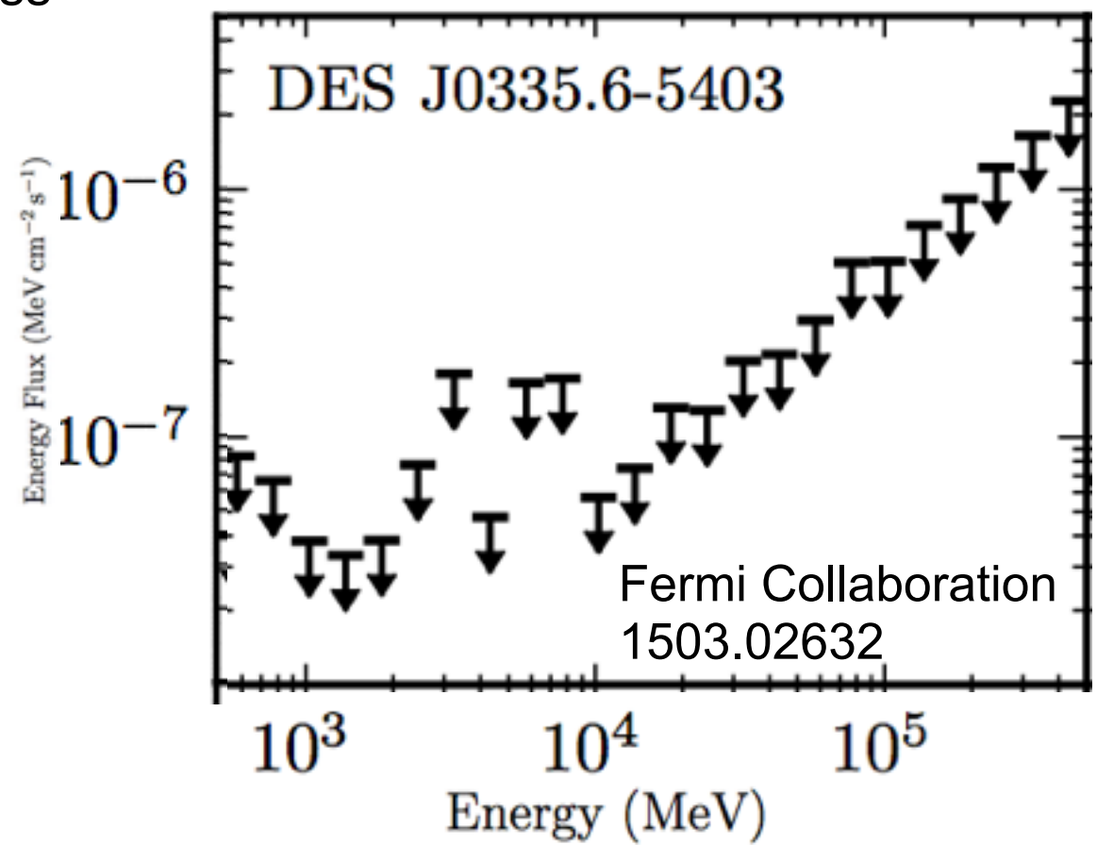


Figure takes a J-factor of $10^{19.5}$ GeV^2/cm^5 as found by 1504.03309*.

*Note however that this value has a 1-order-of-magnitude error bar.





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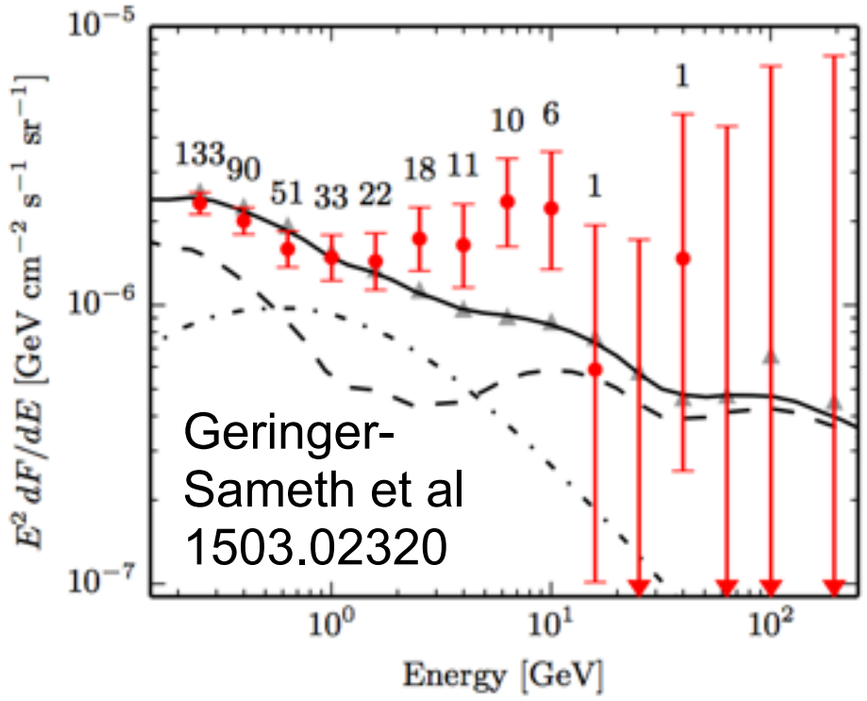

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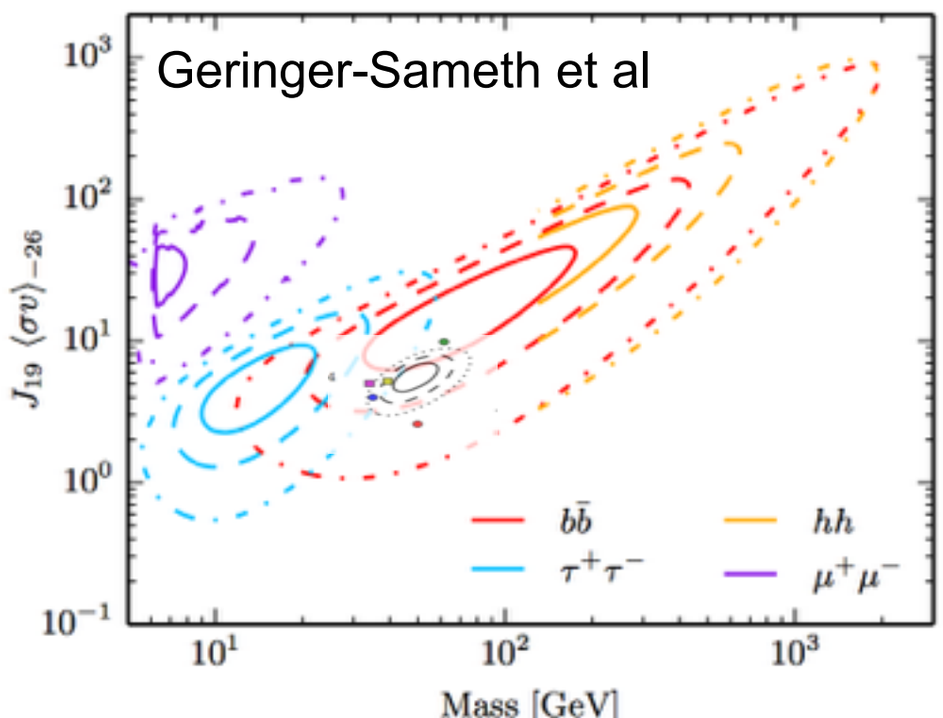
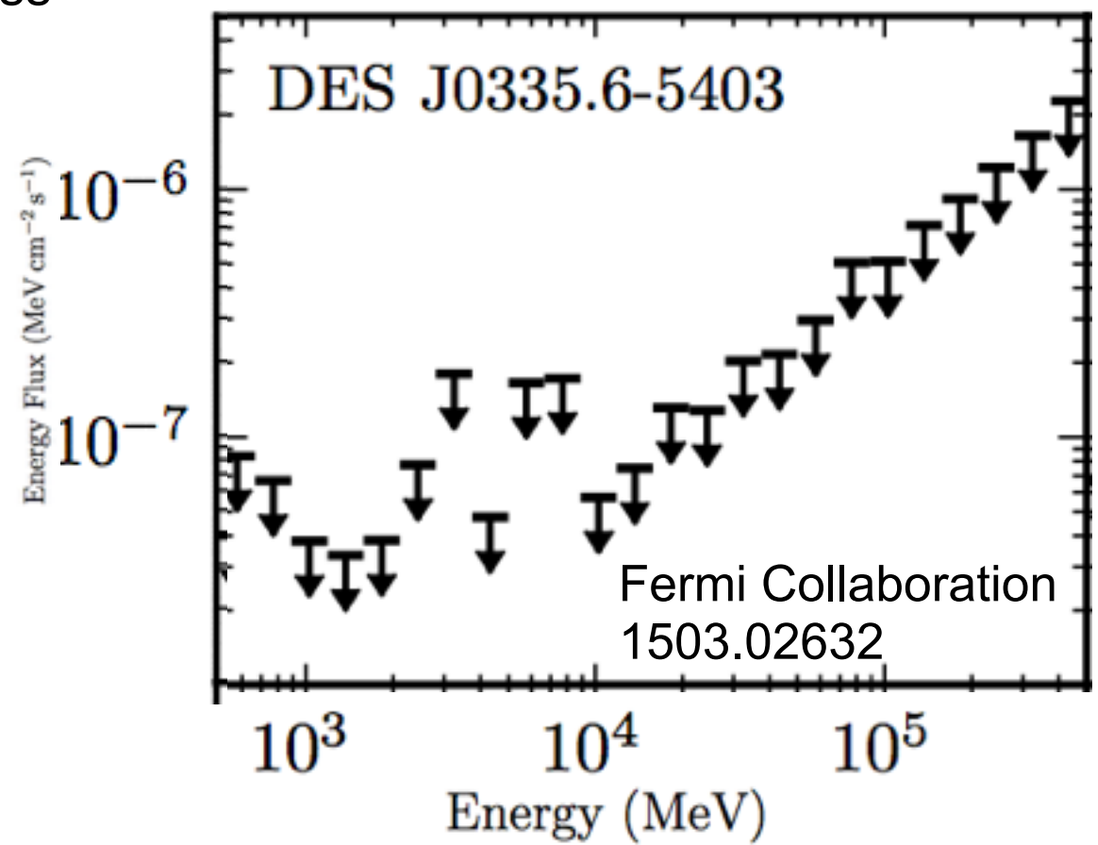
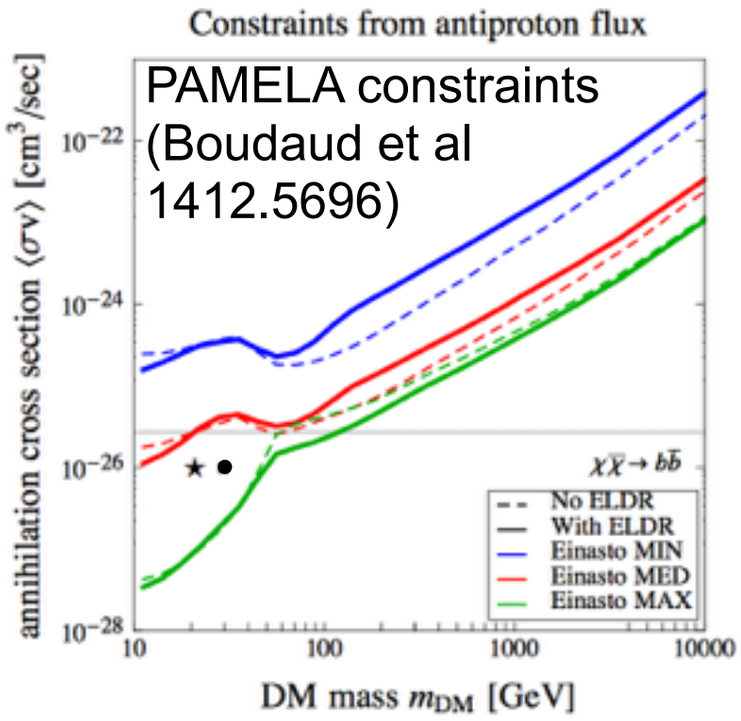
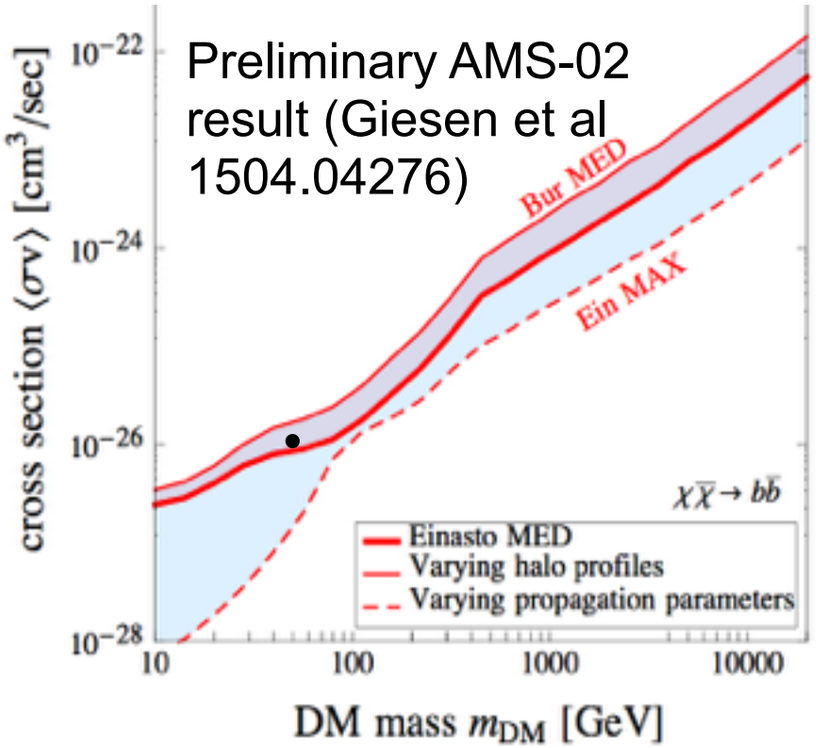
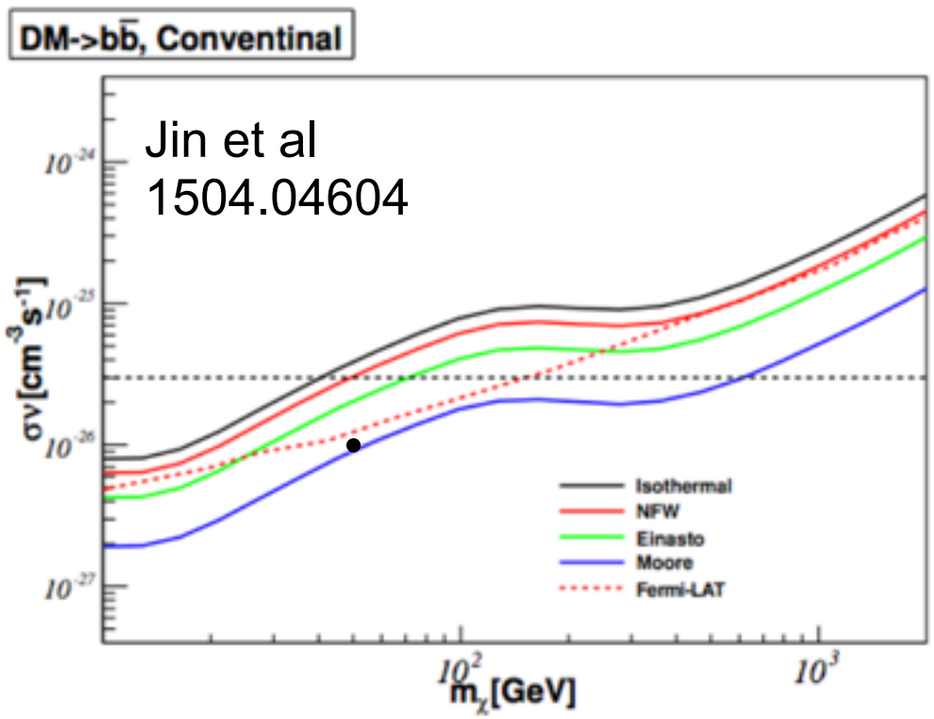




Constraining light dark matter with AMS-02







- Precision antiproton measurements give the hope of sensitivity to DM annihilating into hadronic channels.
- Large systematic uncertainties due to complex propagation effects (e.g. solar modulation, energy loss from tertiary particles, diffusive reacceleration). Incorporating all AMS-02 data may help constrain propagation models.
- Current estimates constrain thermal relic DM annihilating to b quarks below (very roughly) ~30-200 GeV, depending on DM density profile and propagation model.
- Also stringent limits from positron data on light DM annihilating to leptonic channels.