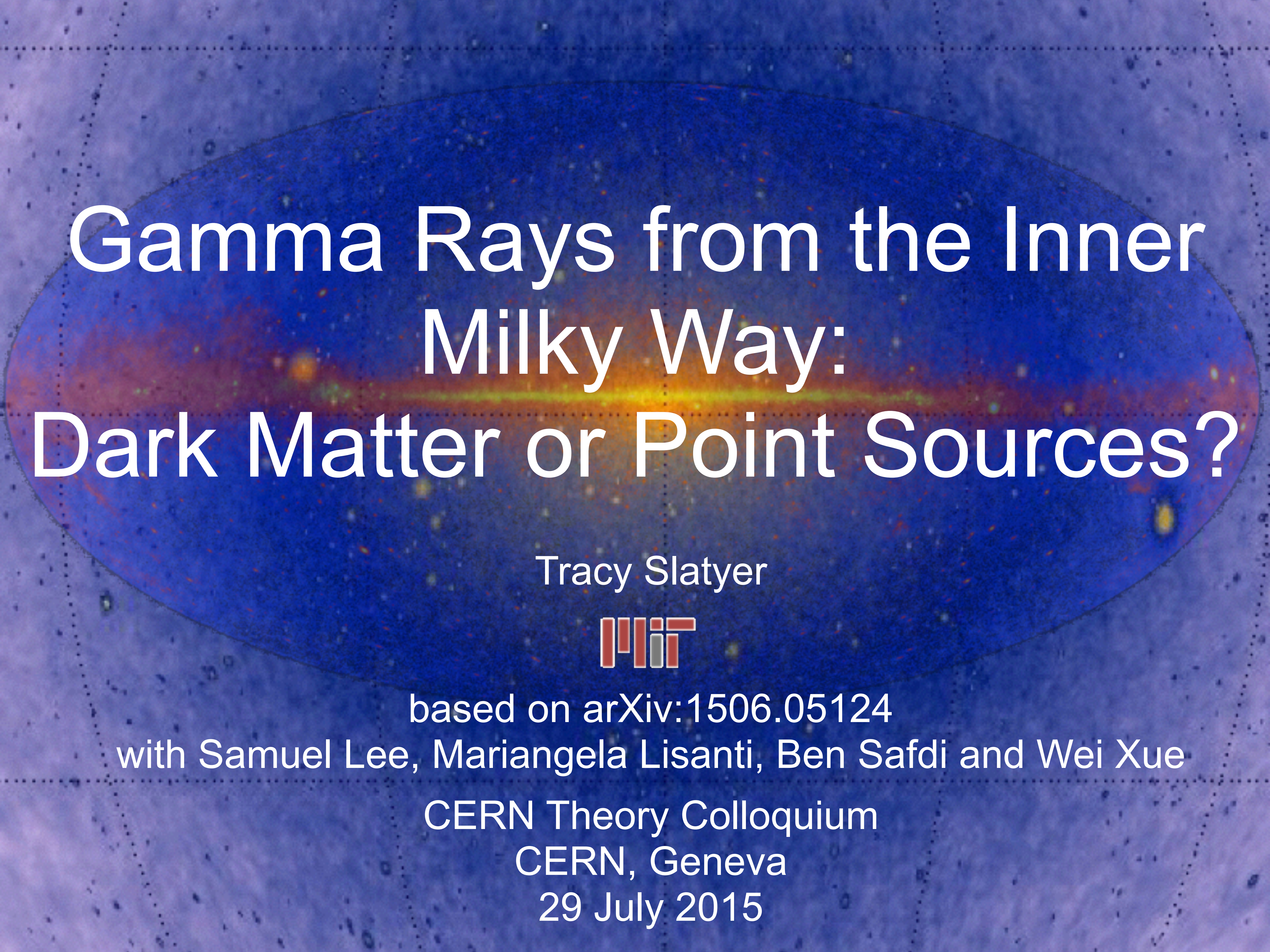


Gamma Rays from the Inner Milky Way: Dark Matter or Point Sources?

Tracy Slatyer

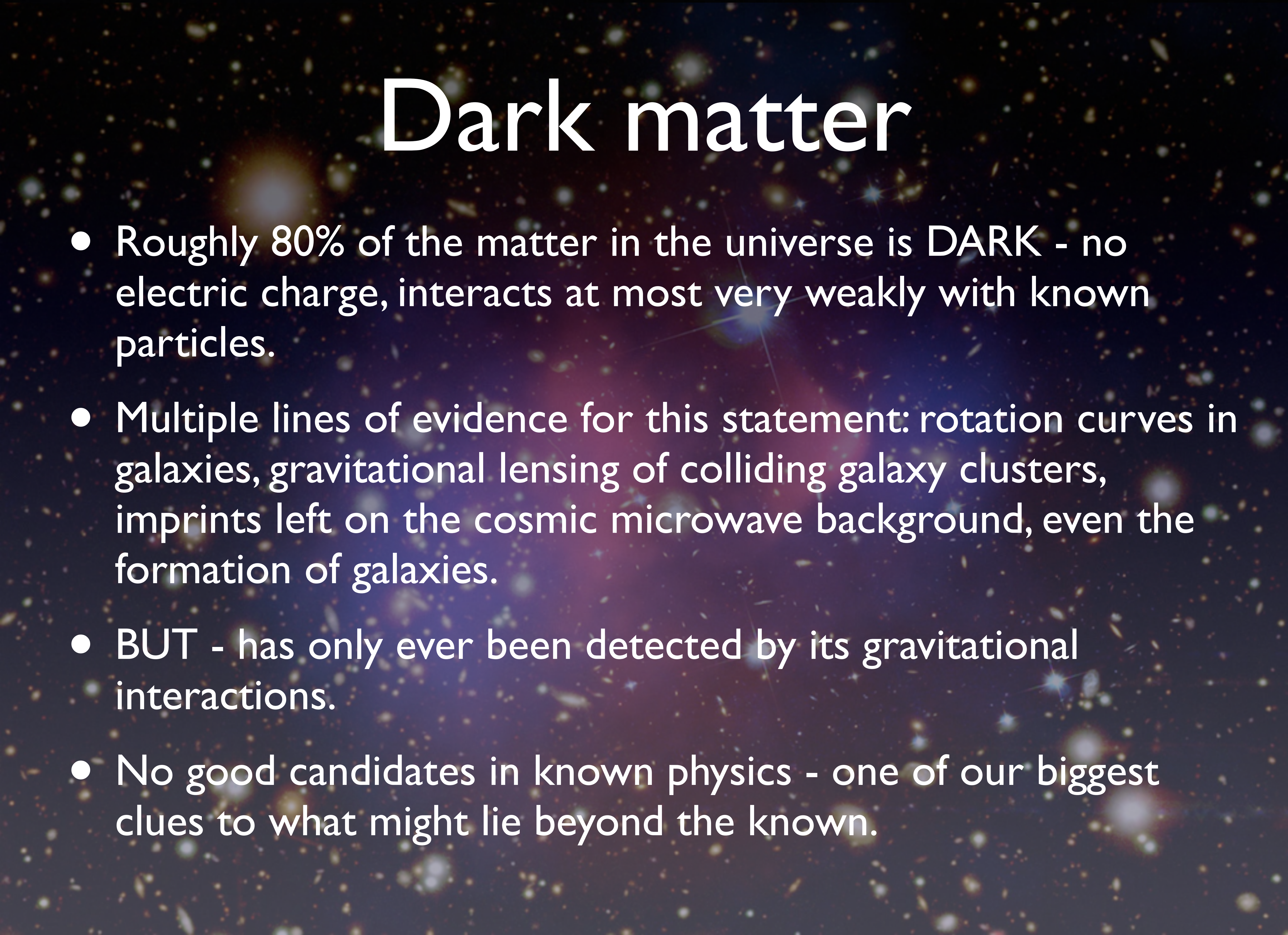
based on arXiv:1506.05124
with Samuel Lee, Mariangela Lisanti, Ben Safdi and Wei Xue

CERN Theory Colloquium
CERN, Geneva
29 July 2015

Outline

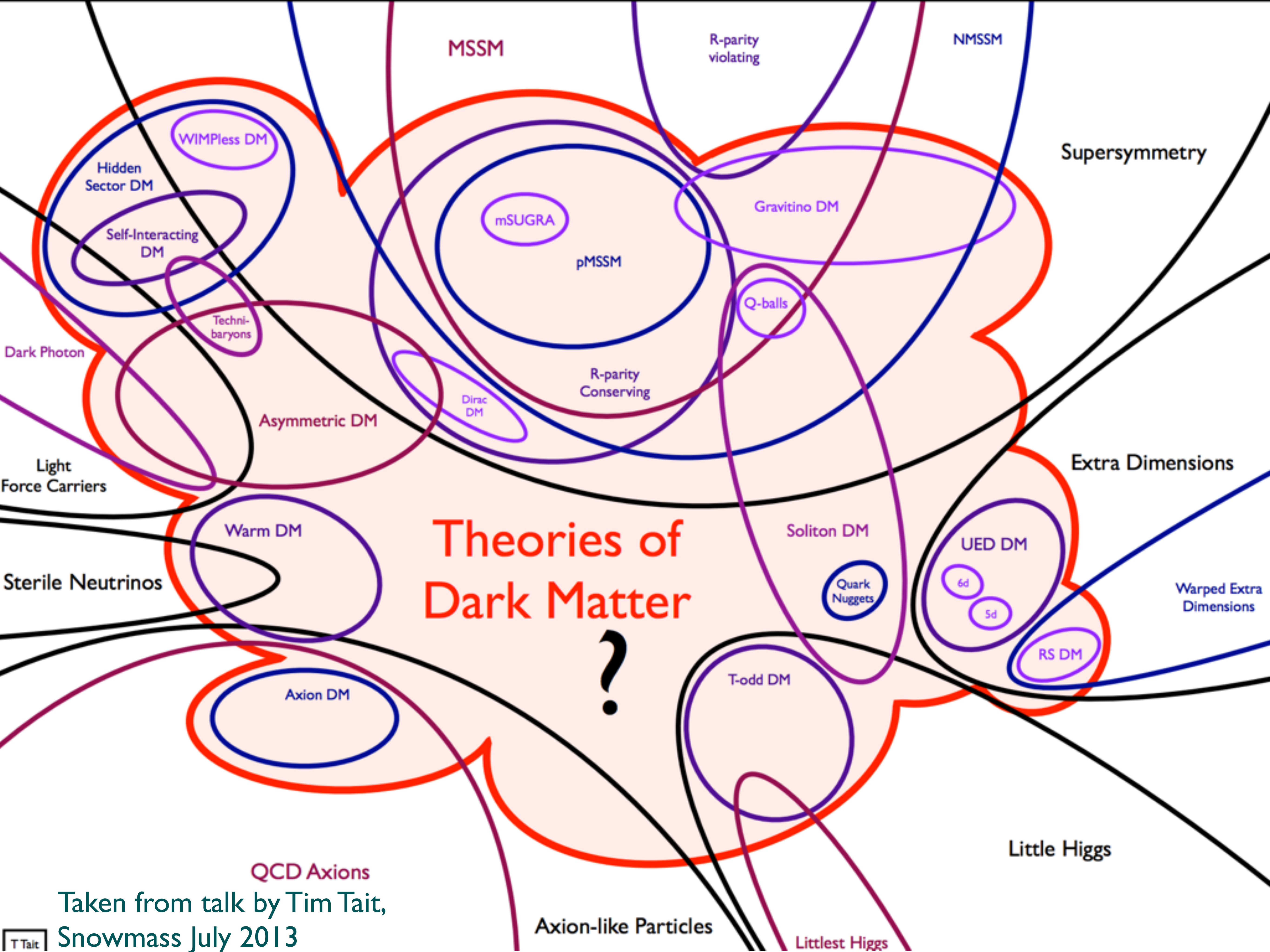
- BACKGROUND: a primer on the GeV gamma-ray excess.
  - How to search for dark matter in gamma rays.
  - The excess, its properties, and the case for dark matter.
  - Astrophysical alternatives, and their challenges.
- WHAT MORE CAN THE DATA TELL US? A new analysis technique to search for unresolved point sources using photon statistics.
- HINTS FOR NOVEL ASTROPHYSICS? Evidence for a (peculiar?) point source population largely responsible for the excess.

Searching for Light from Dark Matter



Dark matter

- Roughly 80% of the matter in the universe is DARK - no electric charge, interacts at most very weakly with known particles.
- Multiple lines of evidence for this statement: rotation curves in galaxies, gravitational lensing of colliding galaxy clusters, imprints left on the cosmic microwave background, even the formation of galaxies.
- BUT - has only ever been detected by its gravitational interactions.
- No good candidates in known physics - one of our biggest clues to what might lie beyond the known.



Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

Hidden Sector DM

WIMPless DM

Self-Interacting DM

Techni-baryons

Dark Photon

Asymmetric DM

Light Force Carriers

mSUGRA

pMSSM

R-parity Conserving

Dirac DM

Gravitino DM

Q-balls

Soliton DM

Quark Nuggets

Extra Dimensions

UED DM

6d

5d

RS DM

Warped Extra Dimensions

Sterile Neutrinos

Warm DM

Axion DM

T-odd DM

Little Higgs

Littlest Higgs

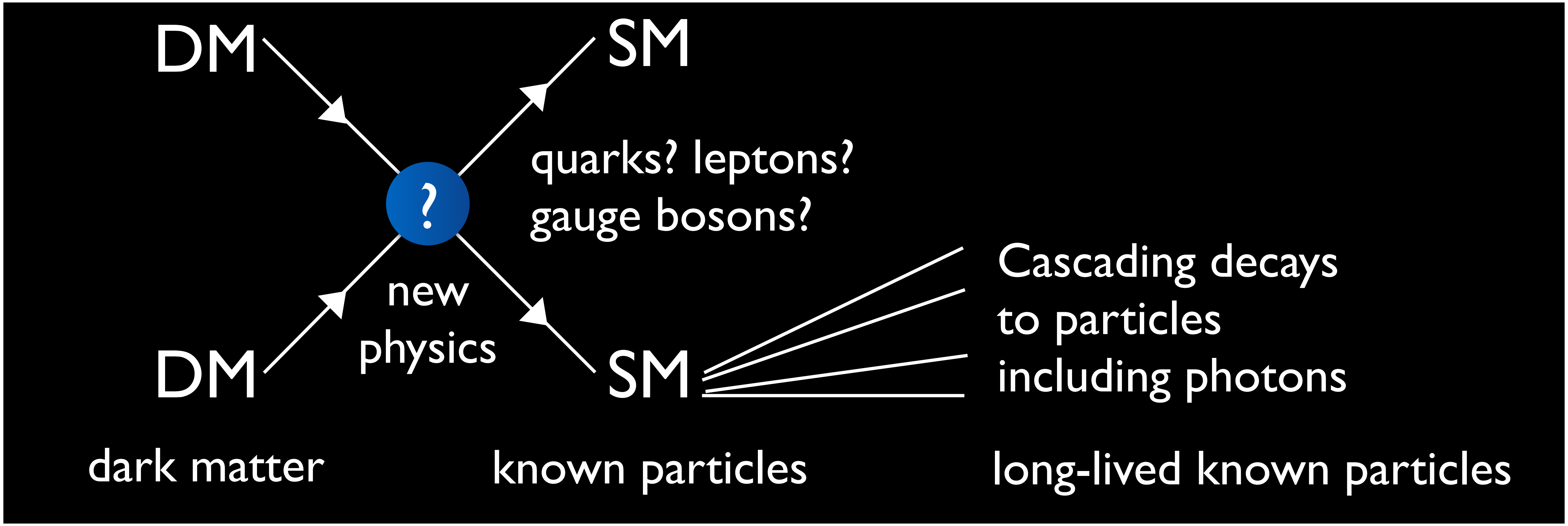
QCD Axions

Axion-like Particles

T Tait

Taken from talk by Tim Tait, Snowmass July 2013

What are we looking for?

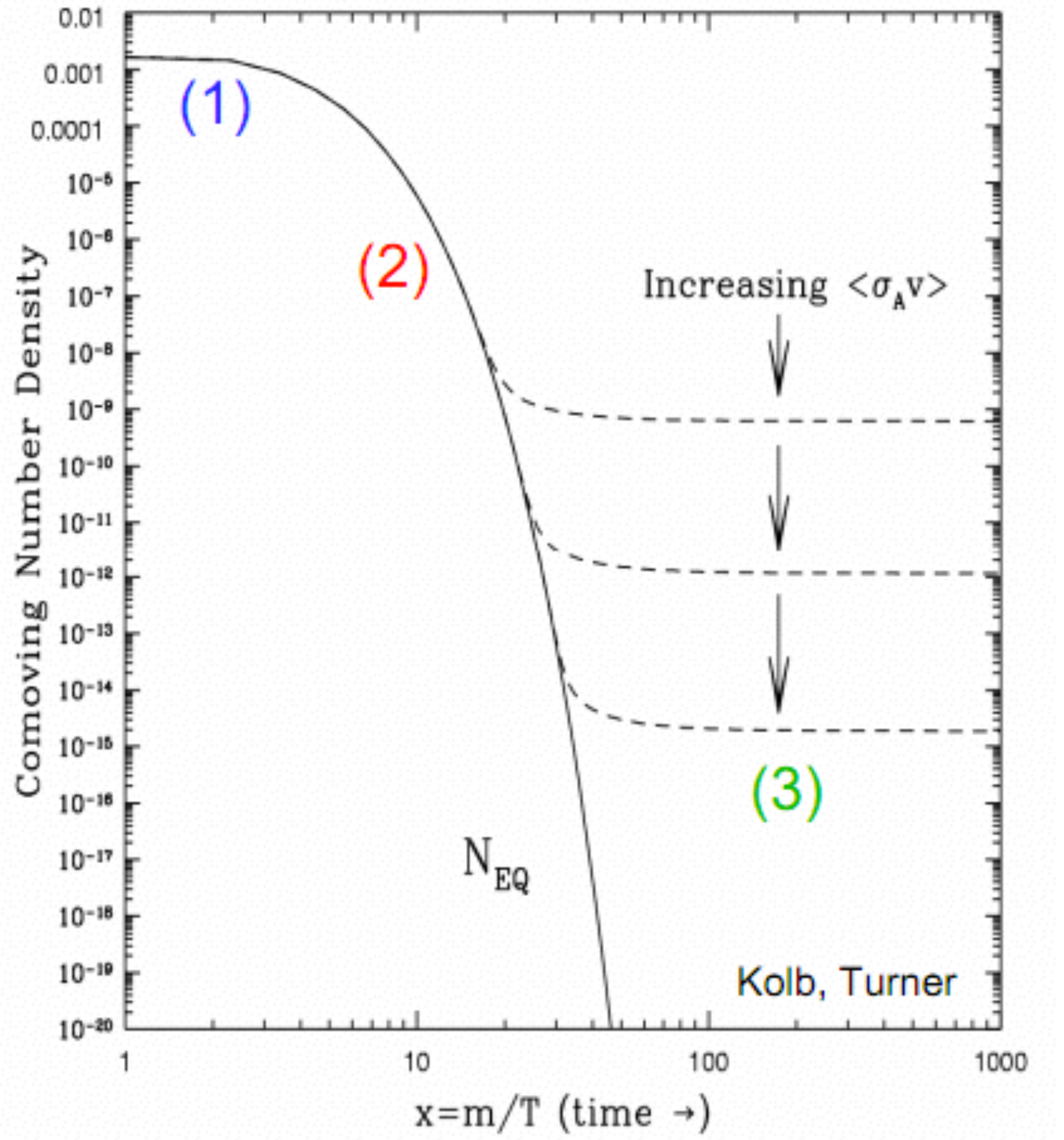


- Dark matter is dark - does not interact directly with photons
- But if DM annihilates to known particles, the decays of these particles can produce gamma rays
- Spectrum of gamma rays depends on mass of DM, intermediate Standard Model states

How large a signal?

- Many possible models for DM, with different signal rates.
- One simple and very popular class of scenarios is thermal relic dark matter:
- Annihilation in the early universe depletes the primordial abundance of dark matter
- Late-time abundance set by early annihilation rate - higher annihilation rate means less DM left over
- CMB experiments measure late-time abundance to percent-level precision ⇒

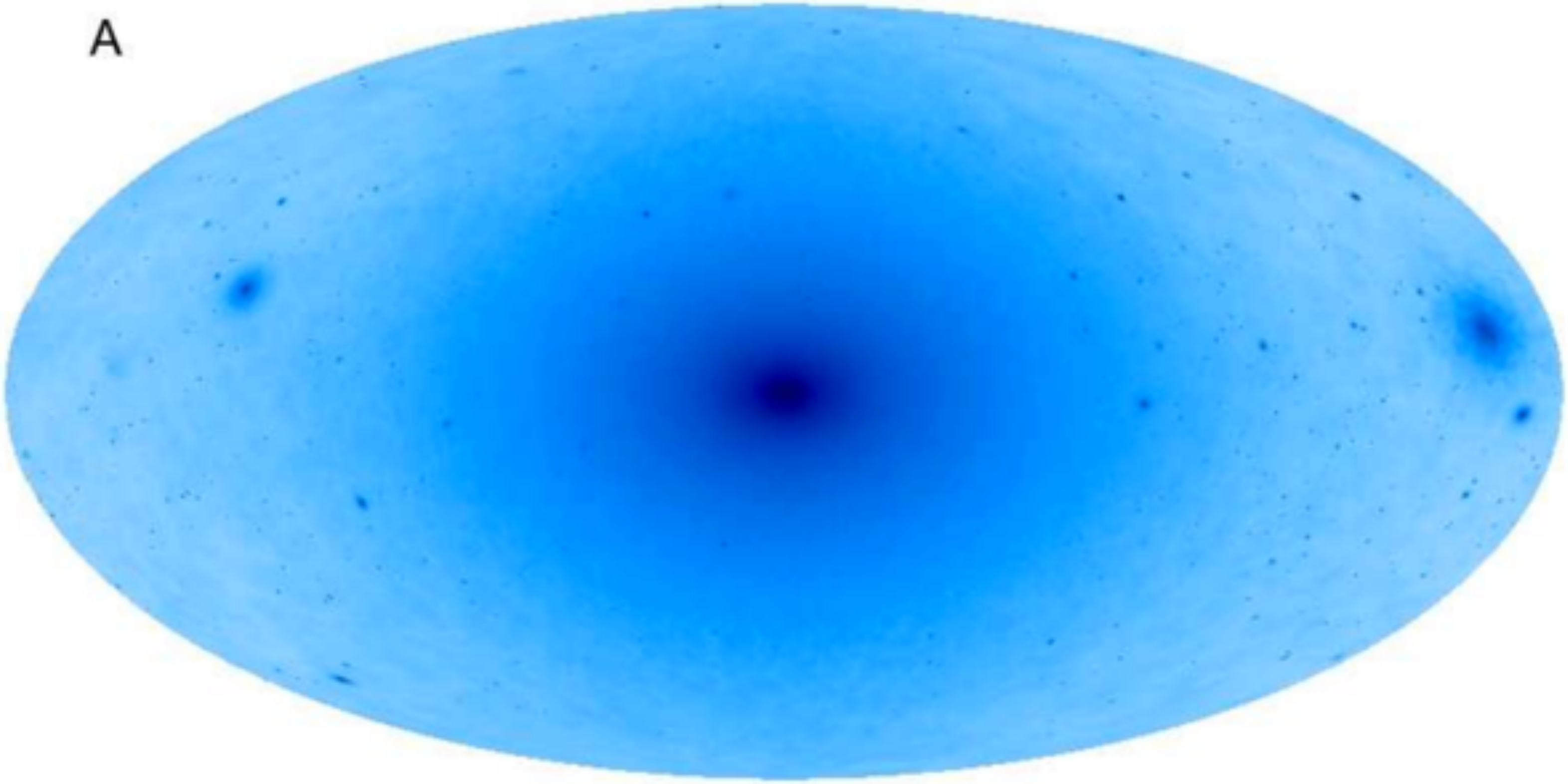
  infer annihilation rate



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

Where to look?

- Rotation curves: DM should have a roughly spherical distribution - “halo”, not “disk”.
- Density rises toward the Galactic Center
- Annihilation rate (if 2-body) scales as density squared
- In simulations, density ~ described by classic Navarro-Frenk-White (NFW) profile.



Surface brightness from DM annihilation in the Galaxy as seen from Earth in the Via Lactea II simulation (Kuhlen et al 2009)

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

Most uncertain parameter is small-r slope γ.

For classic NFW, γ=1.

For Milky Way, R_s ~ 20 kpc.

What are the backgrounds?

- The Galaxy is a sea of high energy cosmic rays.

- Diffuse gamma-ray emission at these energies dominated by:

  - Cosmic-ray protons striking the gas (~traces the gas distribution, largest contribution)

  - Cosmic-ray electrons scattering visible light to high energies

  - Unresolved point sources of gamma rays (pulsars, supernova remnants, etc)

  - The Fermi Bubbles (large diffuse gamma-ray structures of unknown origin, possibly relics of a transient event in the Galactic Center)

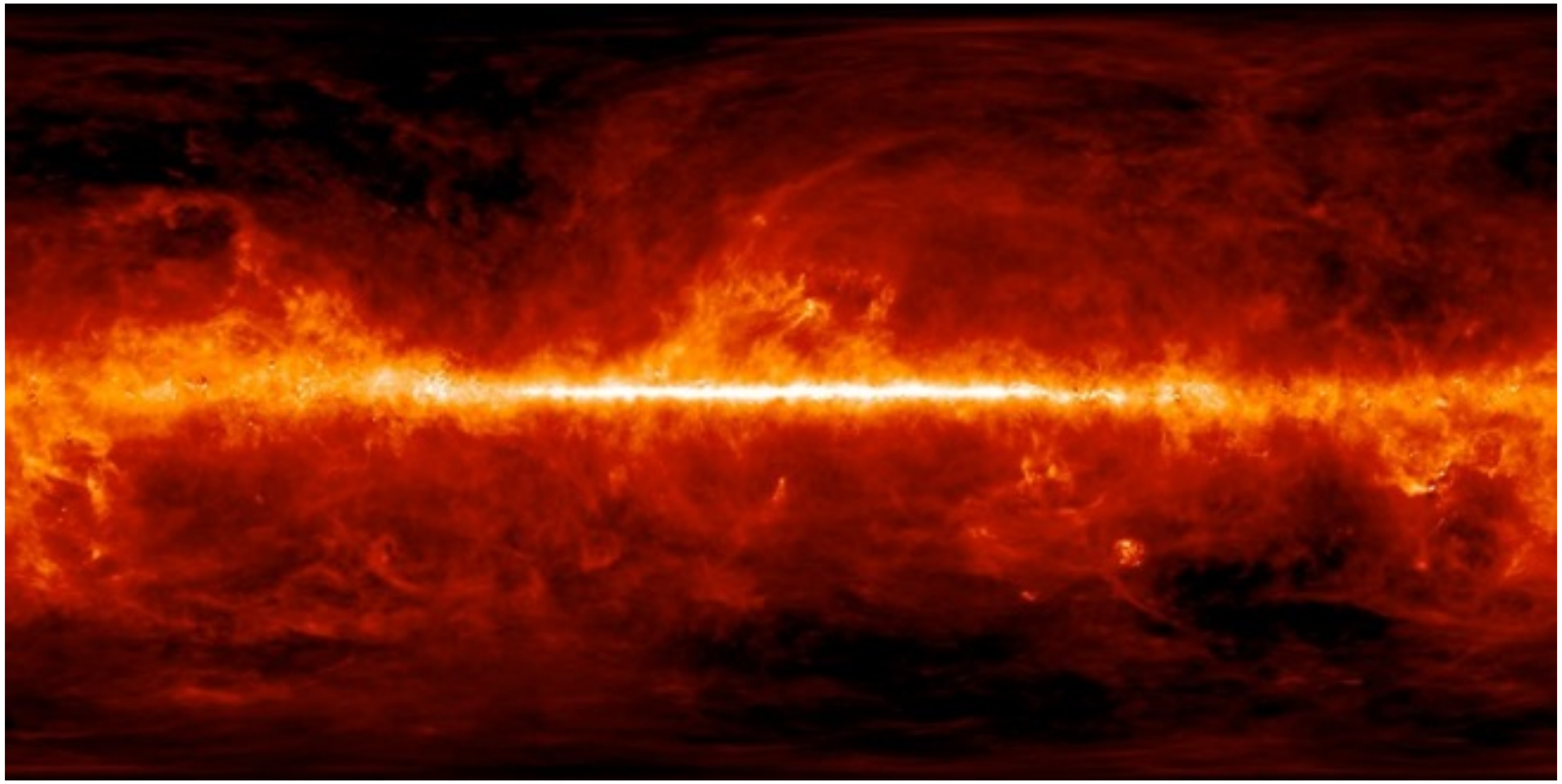


Image of the Galactic gas distribution - note it is brightest along the disk

- Backgrounds are NOT fully understood.

- Deviations must be assessed carefully - many only indicate e.g. a slight mismodeling of the interstellar gas.

- Available diffuse models are generally fitted to a subset of the data, and assume steady-state conditions.

The GeV Gamma-Ray Excess

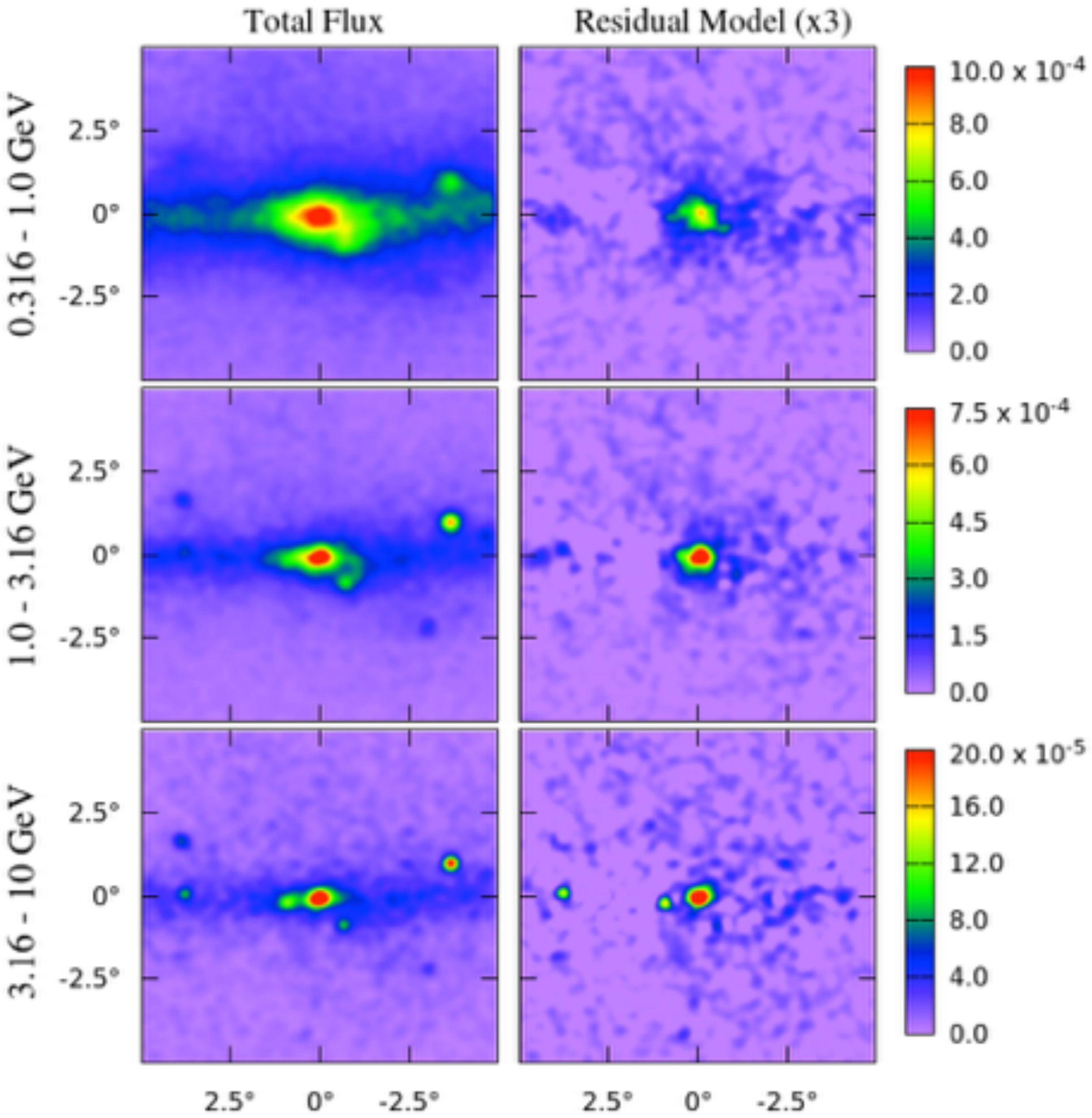
The Fermi Gamma-Ray Space Telescope

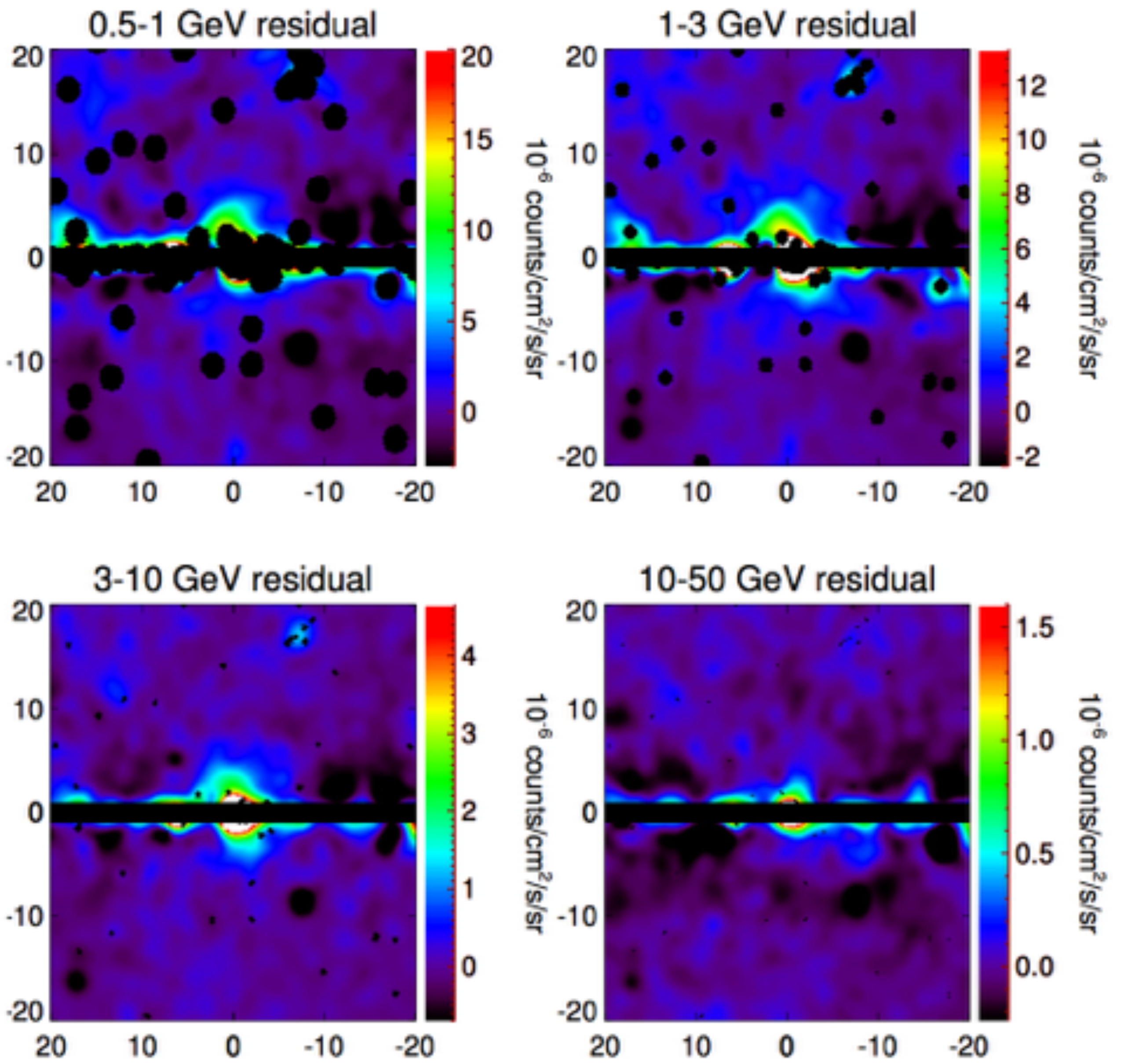
- Launched successfully from Cape Canaveral on 11 June 2008.
- Now in low-Earth orbit, 340 mile altitude.
- Scans the entire sky every two orbits (~3 hours).
- Sensitive to gamma-rays from tens of MeV up to several TeV.
- All data is public.

The GeV gamma-ray excess

- Excess of ~1-3 GeV gamma rays.
- Spatially concentrated in the Galactic Center, extended throughout the central region of the Milky Way, with consistent spectrum.
- Discovered in public data from the Fermi Gamma-Ray Space Telescope - first in the Galactic Center by Goodenough & Hooper 09, extended counterpart found by Hooper & TRS 13. Independently confirmed in both regions.
- Highly significant - not a statistical fluke. Tens of thousands of photons, ~1/3 of the total flux at Galactic Center and peak energy.

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

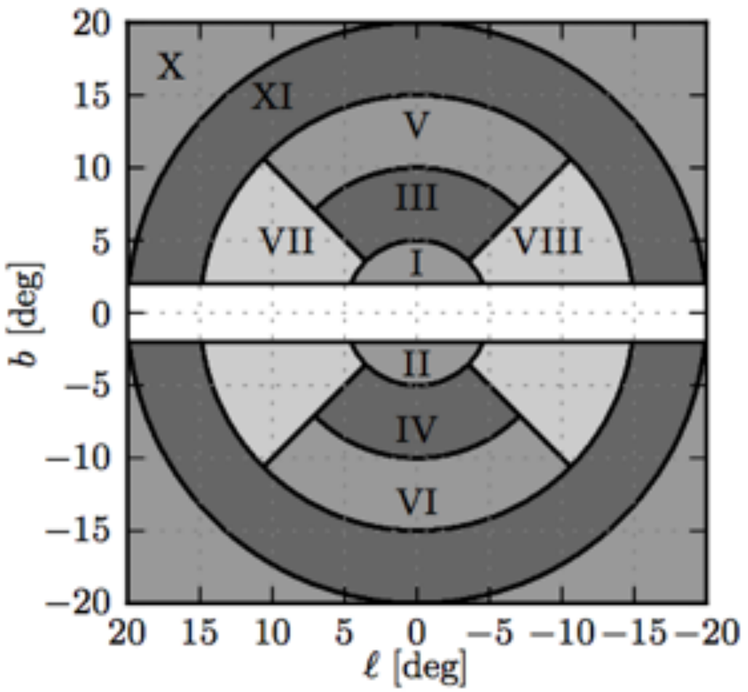




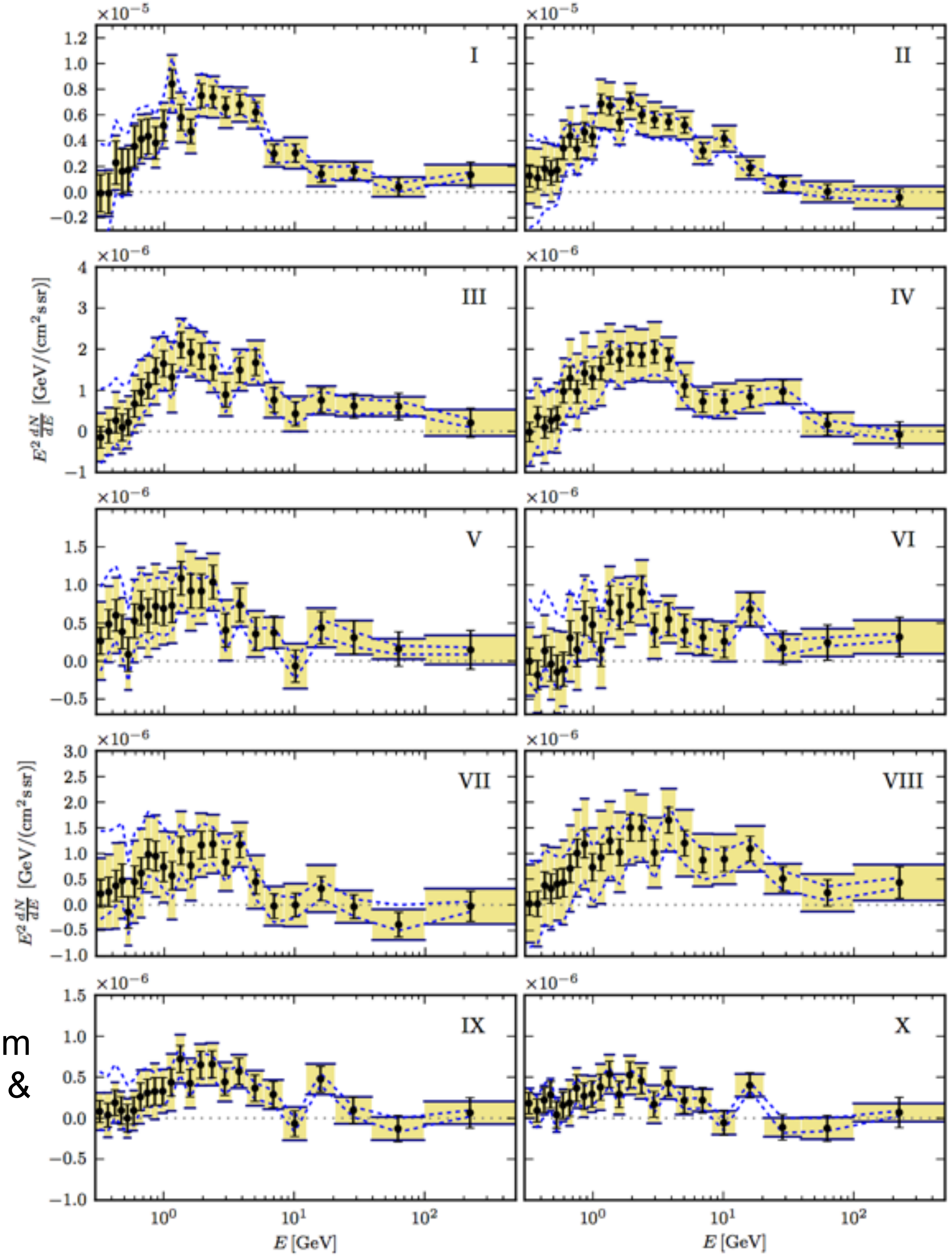
- Does not trace Galactic disk - roughly spherically symmetric.
- Appears centered on Sgr A*, the black hole at the center of the Milky Way.
- Rises steeply toward center, as ~ $r^{-2.2-2.8}$ (r = distance from center).
- Extends out to at least 10 degrees (~1.5 kpc) from the GC.

A symmetric signal

- Can rule out a stretch along the Galactic plane of more than 20% at 95% confidence.
- Excess exhibits high degree of symmetry.



Plots taken from Calore, Cholis & Weniger '14



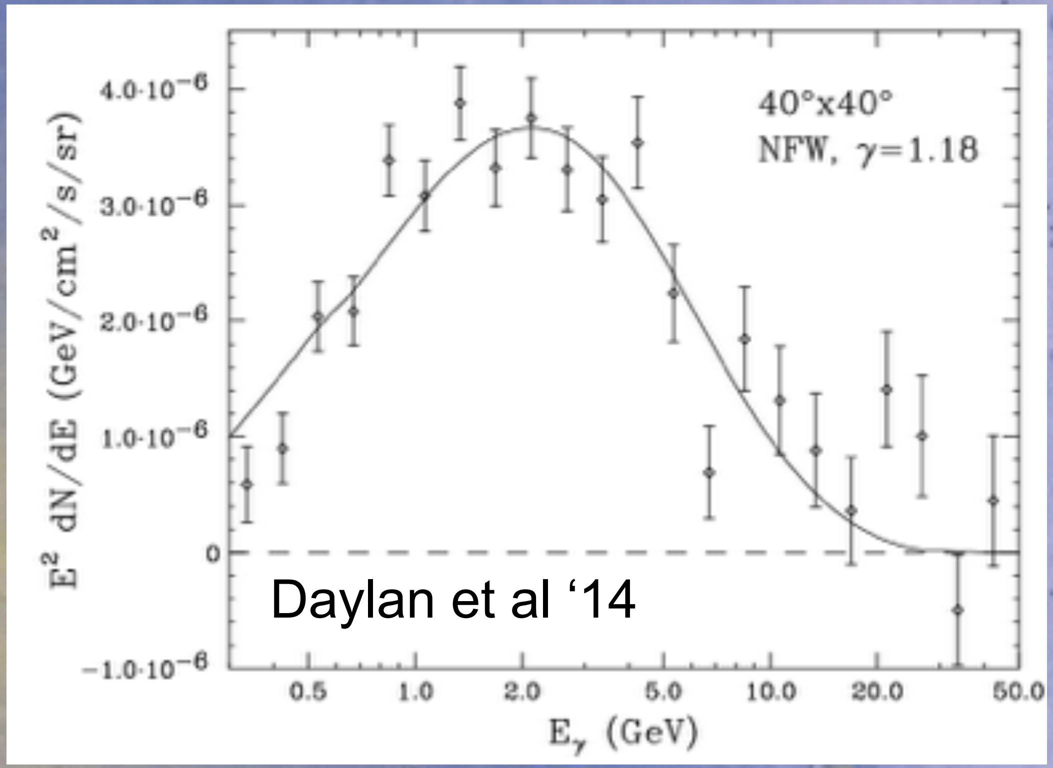
Hypotheses

- Dark matter annihilation. (Particle theorist: 😀)
- “Conventional” astrophysics (i.e. not requiring physics beyond the Standard Model):
  - A new population of stars or other point sources - most discussed candidate is <u>millisecond pulsars</u>.
  - A new diffuse background - most discussed candidate is an <u>outflow or burst</u> from the Galactic Center.

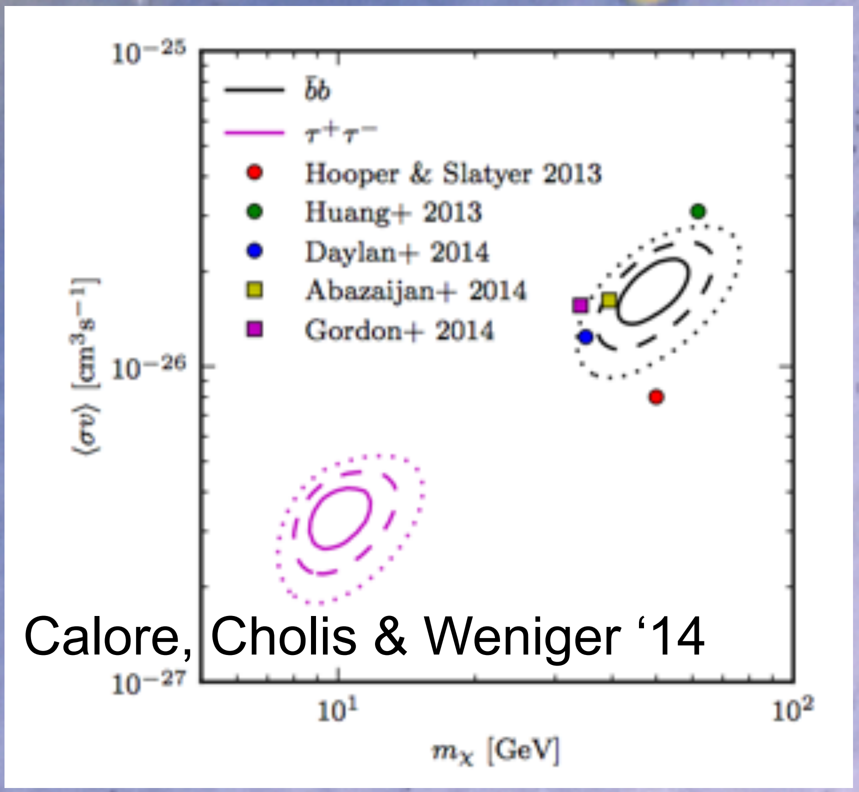
(Particle theorist: 😕 Astrophysicist: 😀)

Dark matter explains:

- The shape of the spectrum - well fit by fairly light DM (~100 GeV or less) annihilating to a range of Standard Model particles.
- The ~spherical morphology of the signal.
- The signal size - required rate matches thermal relic.
- The profile: resembles slightly steepened NFW profile (squared).
- The spatial invariance of the photon energy spectrum.



Daylan et al '14



Calore, Cholis & Weniger '14

If this is dark matter…

- Direct detection is very sensitive in this mass range, why haven’t we seen it?
  - Annihilation may be resonant.
  - Direct detection may be dominantly spin-dependent or otherwise suppressed.
  - Annihilation may be 2 → 4 and the intermediate particles may have small couplings to the SM.
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values.
  - Nonetheless, substantial classes of simplified models can be ruled out.
  - There are existence proofs of UV-complete models that satisfy all constraints.
- Also interesting limits from dwarf galaxies, AMS-02 positrons+antiprotons - but not yet able to probe the parameter space in depth. (Also a hint of possible counterpart signal from Reticulum II dwarf, but significance is much debated.)

Millisecond pulsars (MSPs)

Signal arises from a large population of fast-spinning old pulsars, each too faint to resolve individually as a point source.

PRO:

Spectrum of observed MSPs matches excess well at energies above 1 GeV.

MSPs originate from binary systems, can naturally explain steep slope of profile.

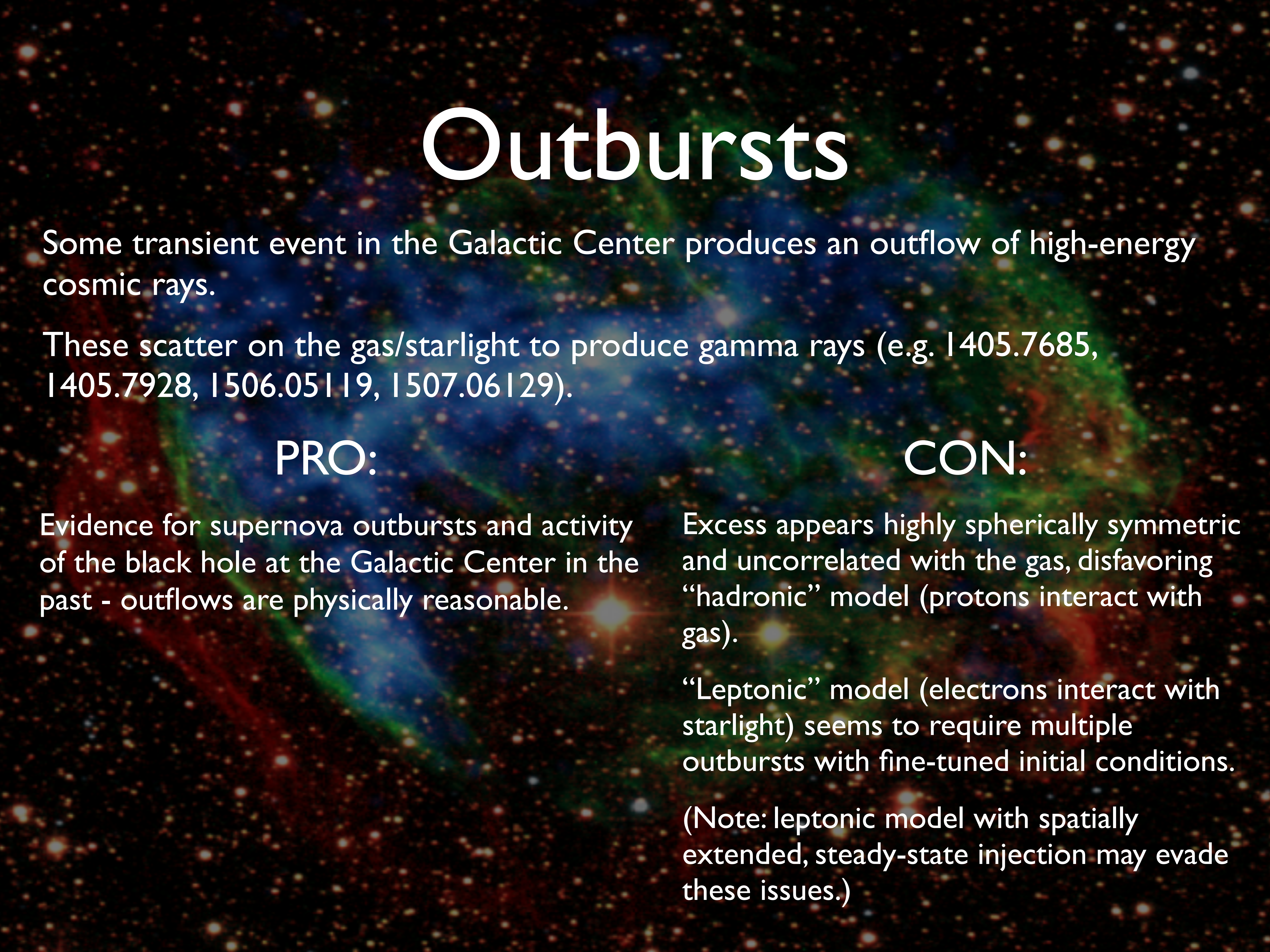
Measurements of X-ray binaries in Andromeda Galaxy suggest steep slope can extend out to ~10 degrees from GC.

CON:

Known MSP populations are not abundant enough to make signal, + wrong distribution.

A new population would need to be systematically fainter than pulsars elsewhere in the Galaxy.

Mild disagreement between low-energy spectrum of excess and known pulsars.



Outbursts

Some transient event in the Galactic Center produces an outflow of high-energy cosmic rays.

These scatter on the gas/starlight to produce gamma rays (e.g. 1405.7685, 1405.7928, 1506.05119, 1507.06129).

PRO:

Evidence for supernova outbursts and activity of the black hole at the Galactic Center in the past - outflows are physically reasonable.

CON:

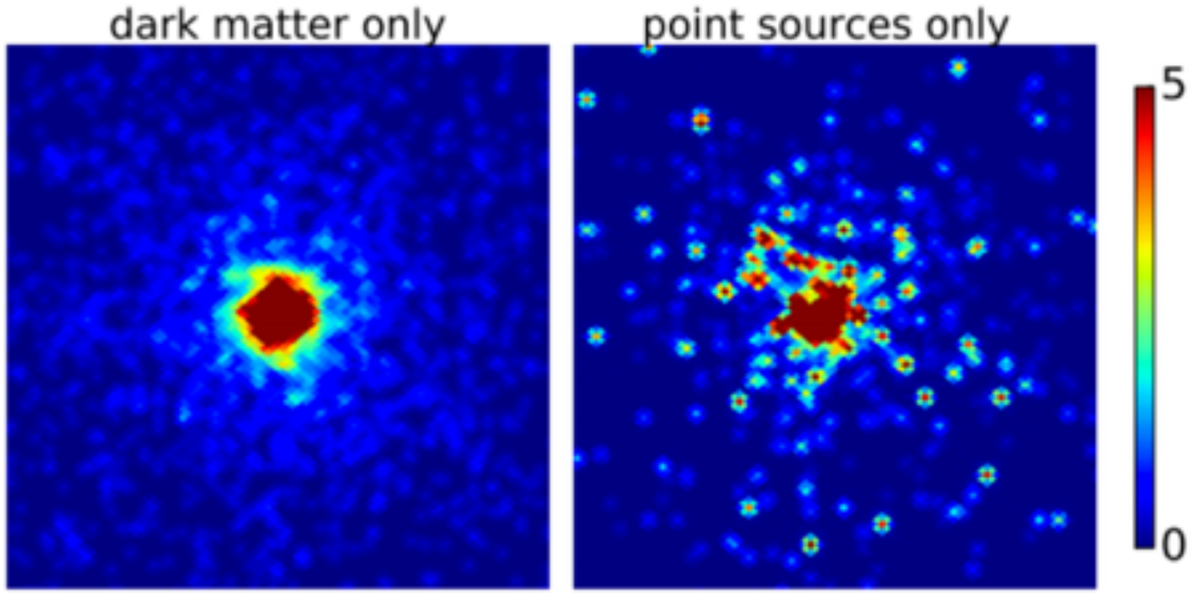
Excess appears highly spherically symmetric and uncorrelated with the gas, disfavoring "hadronic" model (protons interact with gas).

"Leptonic" model (electrons interact with starlight) seems to require multiple outbursts with fine-tuned initial conditions.

(Note: leptonic model with spatially extended, steady-state injection may evade these issues.)

What Can We Learn From Photon Statistics?

Point sources vs diffuse emission



- Theoretical plausibility of models is important to study, but can be <u>hard to assess</u>.

- What can the <u>data</u> tell us?

- Want to distinguish smooth diffuse emission from a population of point sources, using detailed spatial distribution of photons.

Template fitting

- Photon counts = linear combination of background and signal spatial templates $\mu_{p,l}$.
- Given model (as a function of coefficients $\theta=\{\alpha_l\}$), overall likelihood = product of Poisson pixel likelihoods.
- Maximize likelihood with respect to θ parameters (frequentist) or compute posterior probabilities (Bayesian).

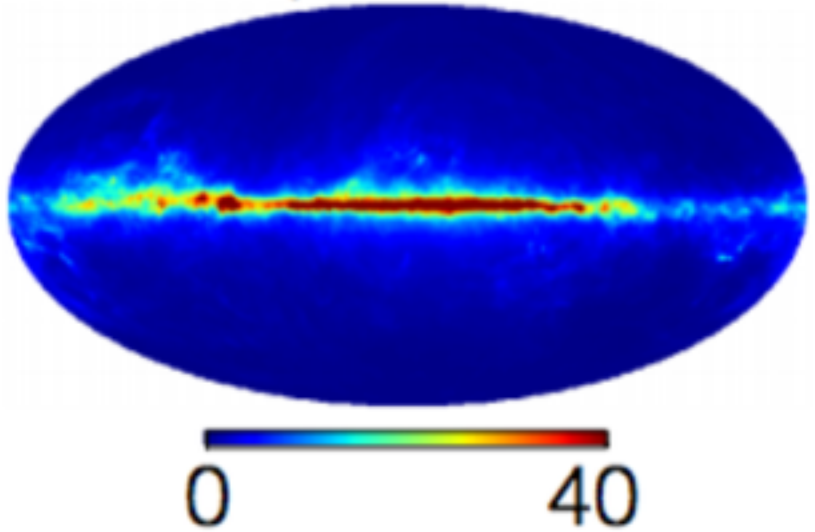
$$\mu_p = \sum_\ell \alpha_\ell \, \mu_{p,\ell}$$

$$p_k^{(p)} = \frac{(\mu_p)^k \; e^{-\mu_p}}{k!}$$

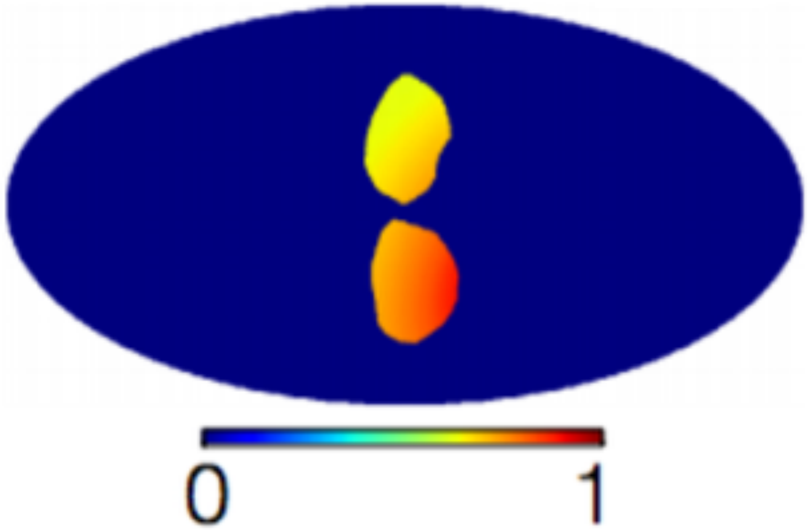
$$p(d|\theta,\mathcal{M}) = \prod_p p_{n_p}^{(p)}(\theta)$$

- Basic background model consists of three templates:

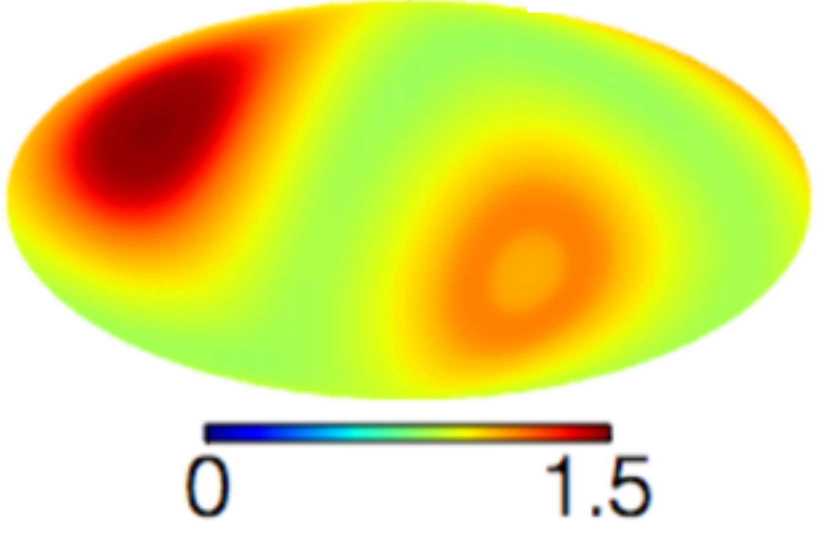
Fermi p6 diffuse $\mu_{p,1}$

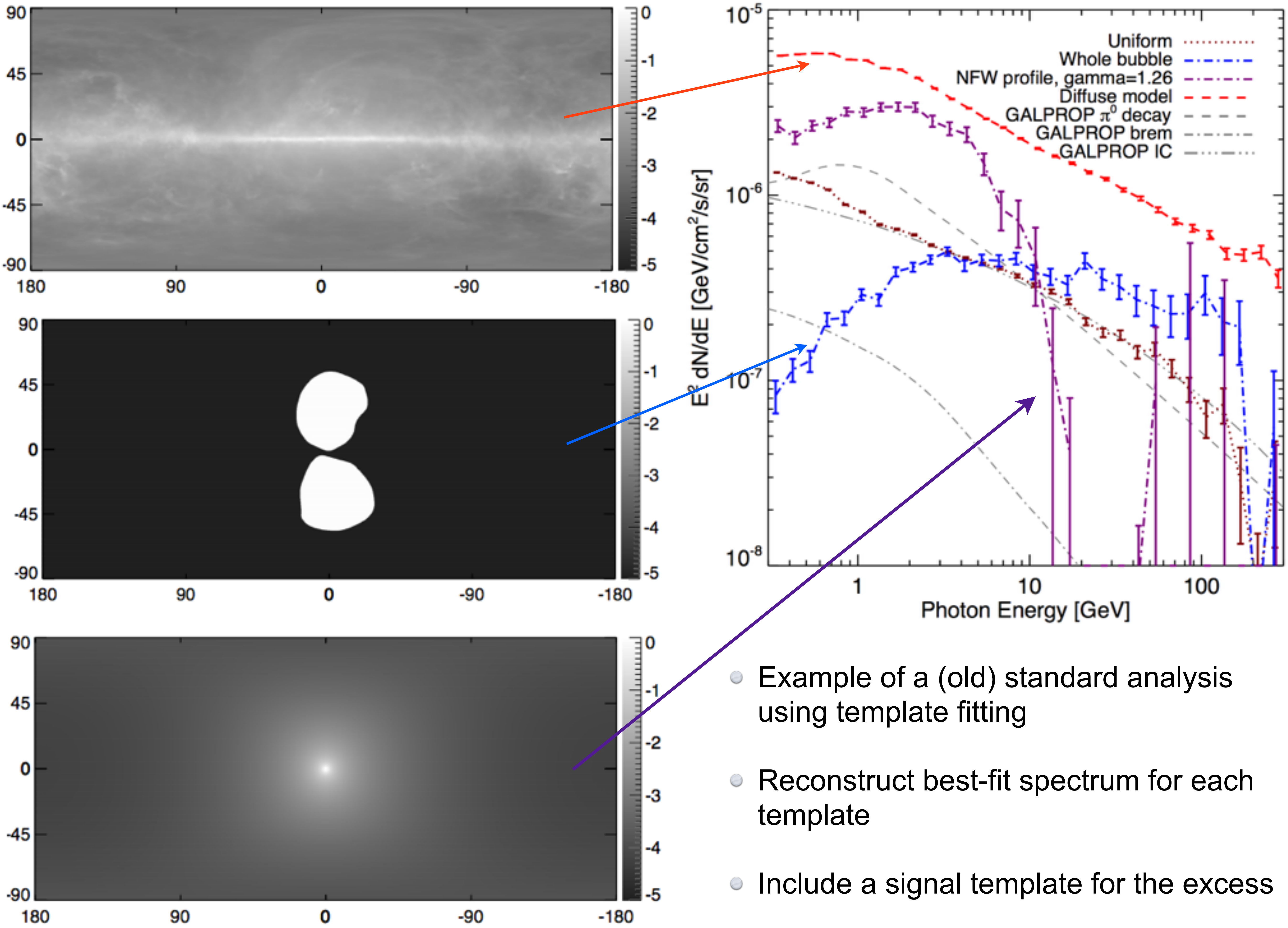


Fermi bubbles $\mu_{p,2}$



Isotropic $\mu_{p,3}$





- Example of a (old) standard analysis using template fitting
- Reconstruct best-fit spectrum for each template
- Include a signal template for the excess

What about point sources?

- Known sources - can include them in the model, or cut out (mask) their locations.

- Unknown sources?

Our answer - treat as source of non-Poissonian statistics

(Malyshev & Hogg ’11, Lee, Lisanti & Safdi ’14)

An example

I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

Case 1: diffuse emission, Poissonian statistics

$P(12 \text{ photons}) = 10^{12} e^{-10}/12! \sim 0.1$

Likewise $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

Case 2: population of rare sources.

Expect 100 photons/source, 0.1 sources/pixel - same expected # of photons

$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12} e^{-100}/12! \sim 10^{-29}$, $P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

Non-Poissonian statistics

- Easiest to recast probabilities in terms of generating functions:

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

- Then total generating function for sum of model components = product of component generating functions.

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

from non-Poissonian piece

from Poisson likelihood

generating function for point source population

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

expected number of m-photon sources

source count function

determined by Monte Carlo, accounts for finite angular resolution

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

Statistics for a PS population are defined by source count function - # of sources with a given brightness.

Non-Poissonian template fitting

- Can now add new templates to our model, which allow non-Poissonian statistics.

- 3 extra degrees of freedom for each such template, to describe source count function (parameterized as broken power law):

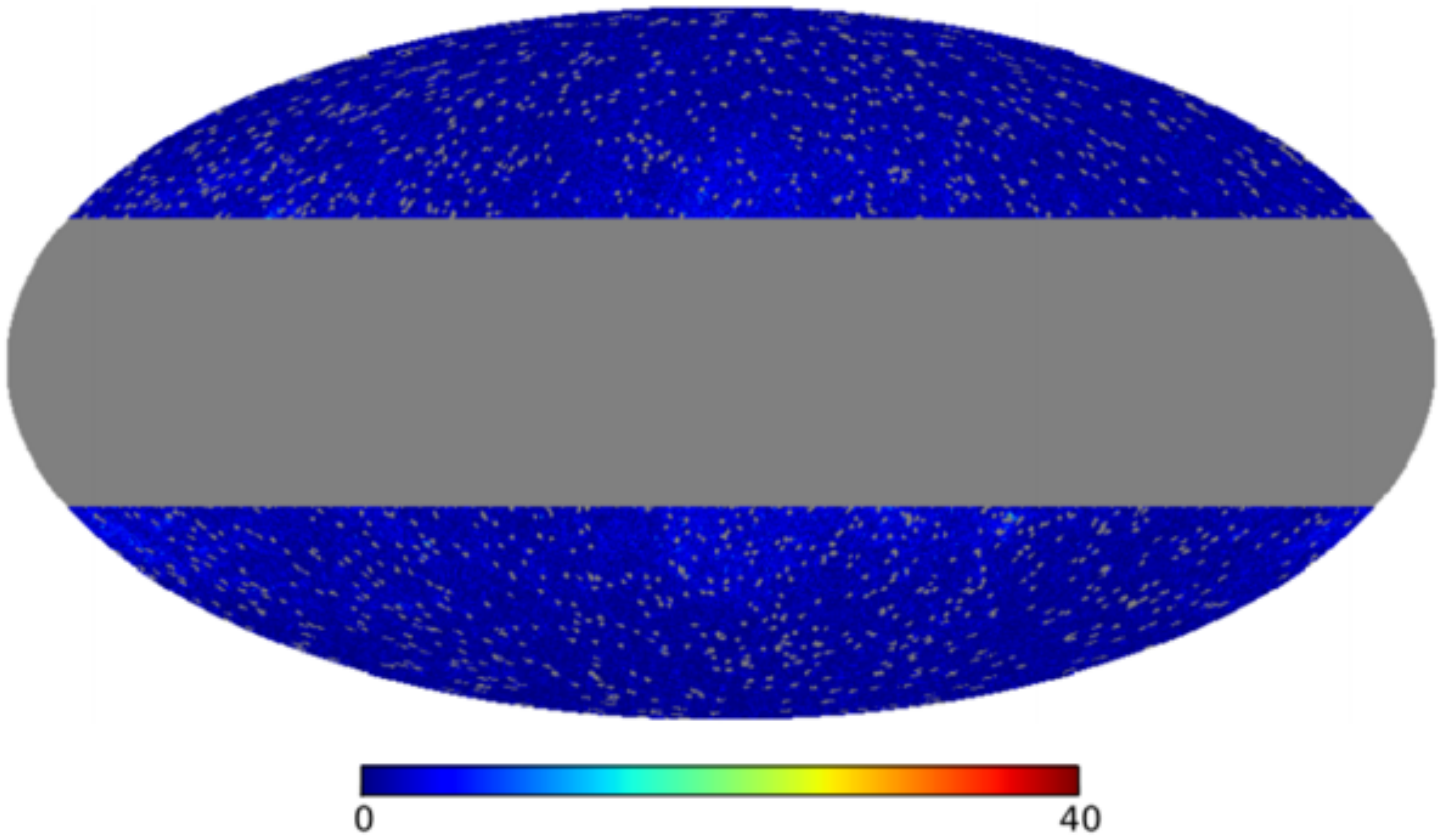
$$\frac{dN_p(S)}{dS} = \overset{\text{follows a spatial template}}{\overset{\downarrow}{A_p}} \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & S < S_b \end{cases}$$

- Source count function assumed constant over sky, but overall normalization can vary pixel to pixel - allows non-trivial spatial dependence of point source population.

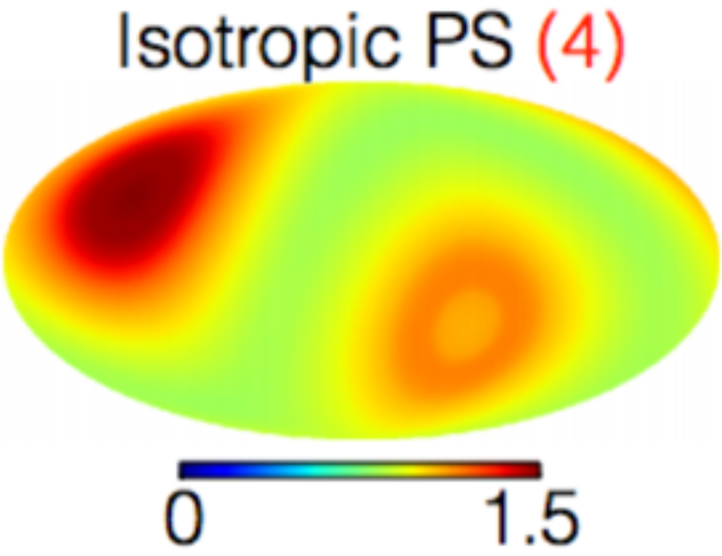
- For now, restrict to a single broad energy bin (2-12 GeV) - no extraction of spectrum.

High-latitude analysis

mask region within 30 degrees of Galactic plane



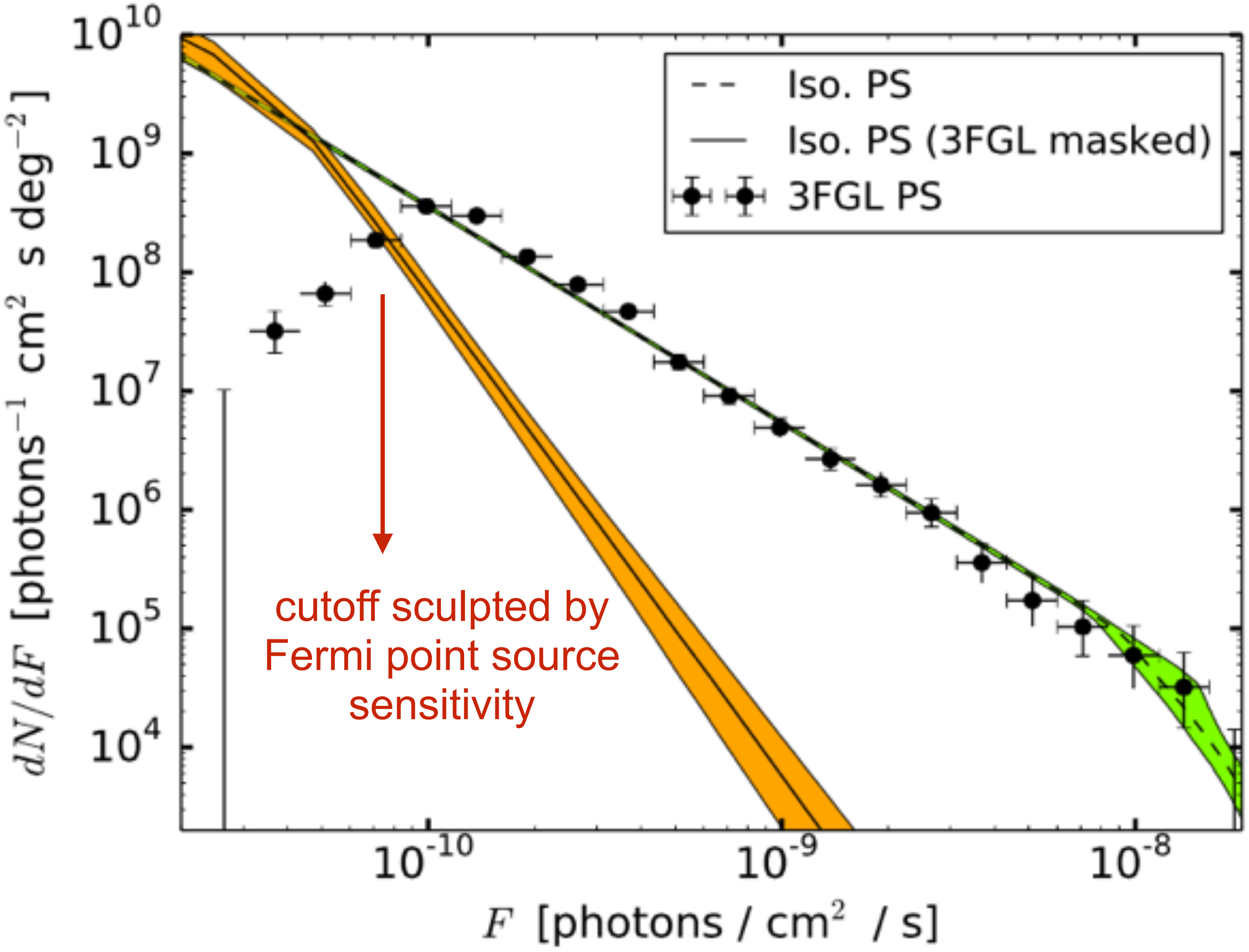
add isotropic non-Poissonian point source template (4 d.o.f)


Isotropic PS (4)

- Test method first at high latitude (|b| > 30°), searching for unresolved isotropically distributed sources.
- We find results consistent with Malyshev & Hogg ’11, Ackermann et al 1410.3696.

High-latitude results

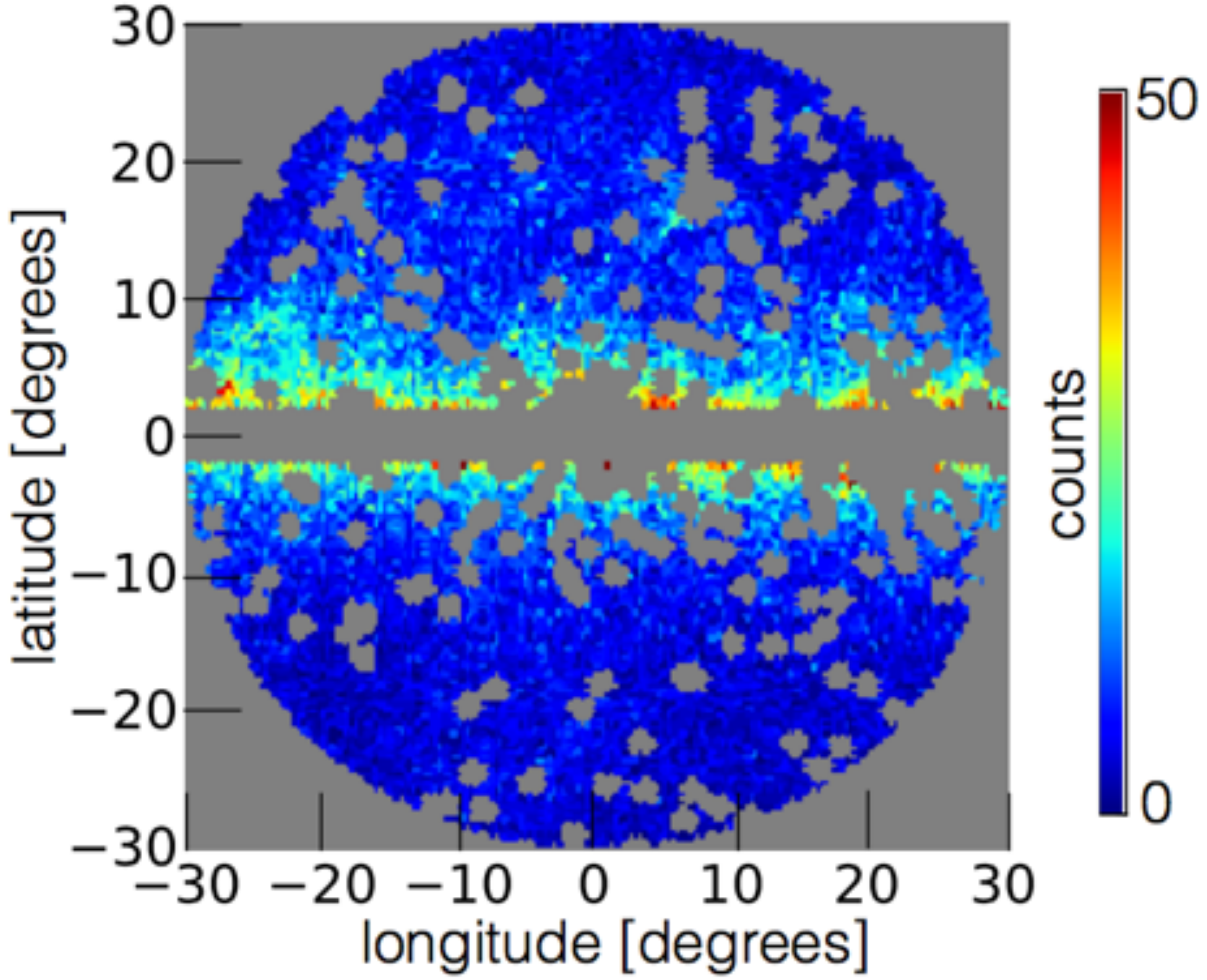
- 3FGL PS = known sources in this region.
- Green line = reconstructed source count function without masking sources.
- Orange line = source count function when all known sources are masked (within 1 degree).
- Low-luminosity slope of source count function is recovered even when all sources are masked.



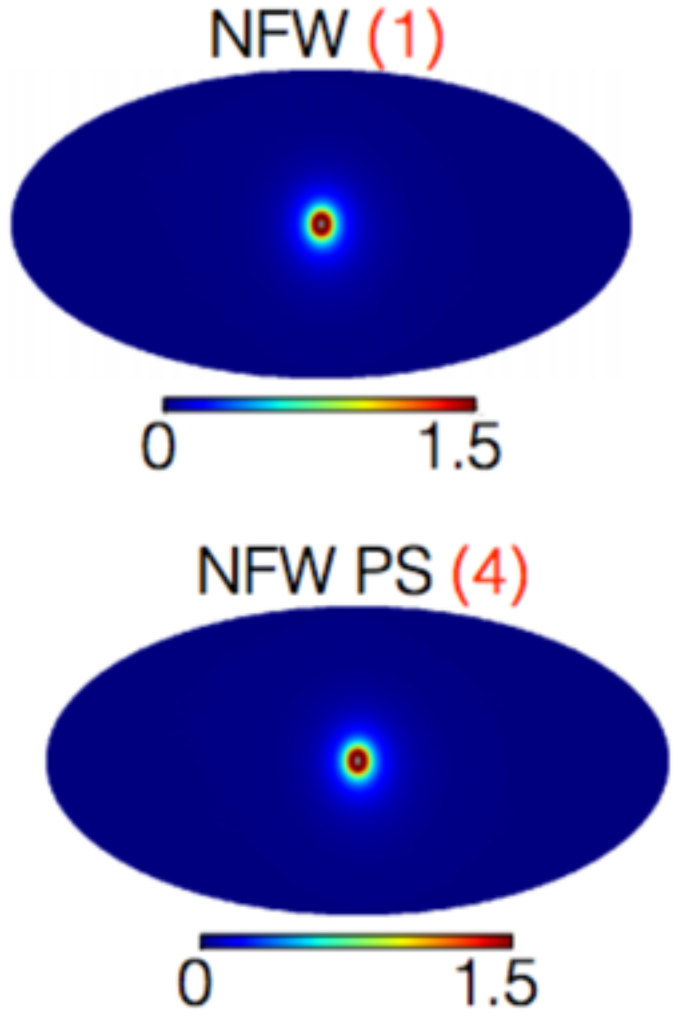
cutoff sculpted by Fermi point source sensitivity

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

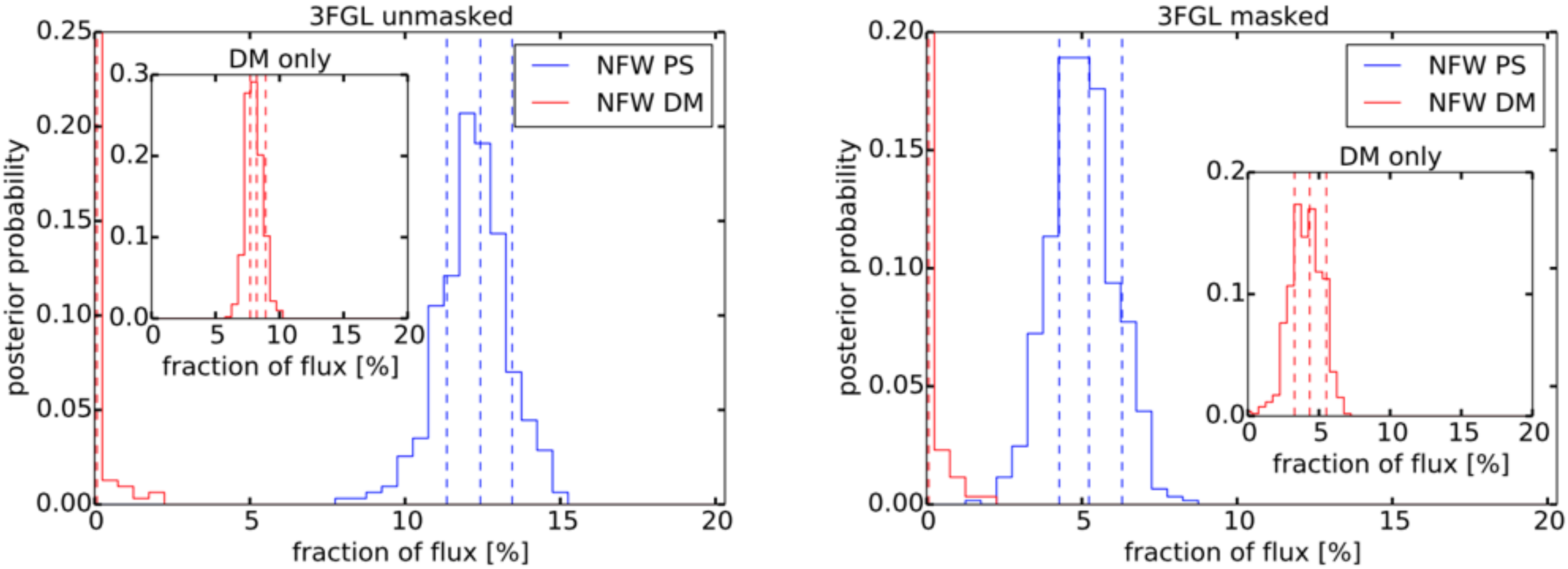


new templates



- Fit region is within 30 degree radius of Galactic Center, masking the region within 2 degrees of the plane.
- Add two new templates, both chosen to match the overall morphology of the excess.
    - Poissonian = “NFW DM” (1 degree of freedom, overall normalization)
    - Non-Poissonian = “NFW PS” (4 degrees of freedom, from source count function)

Inner Galaxy results



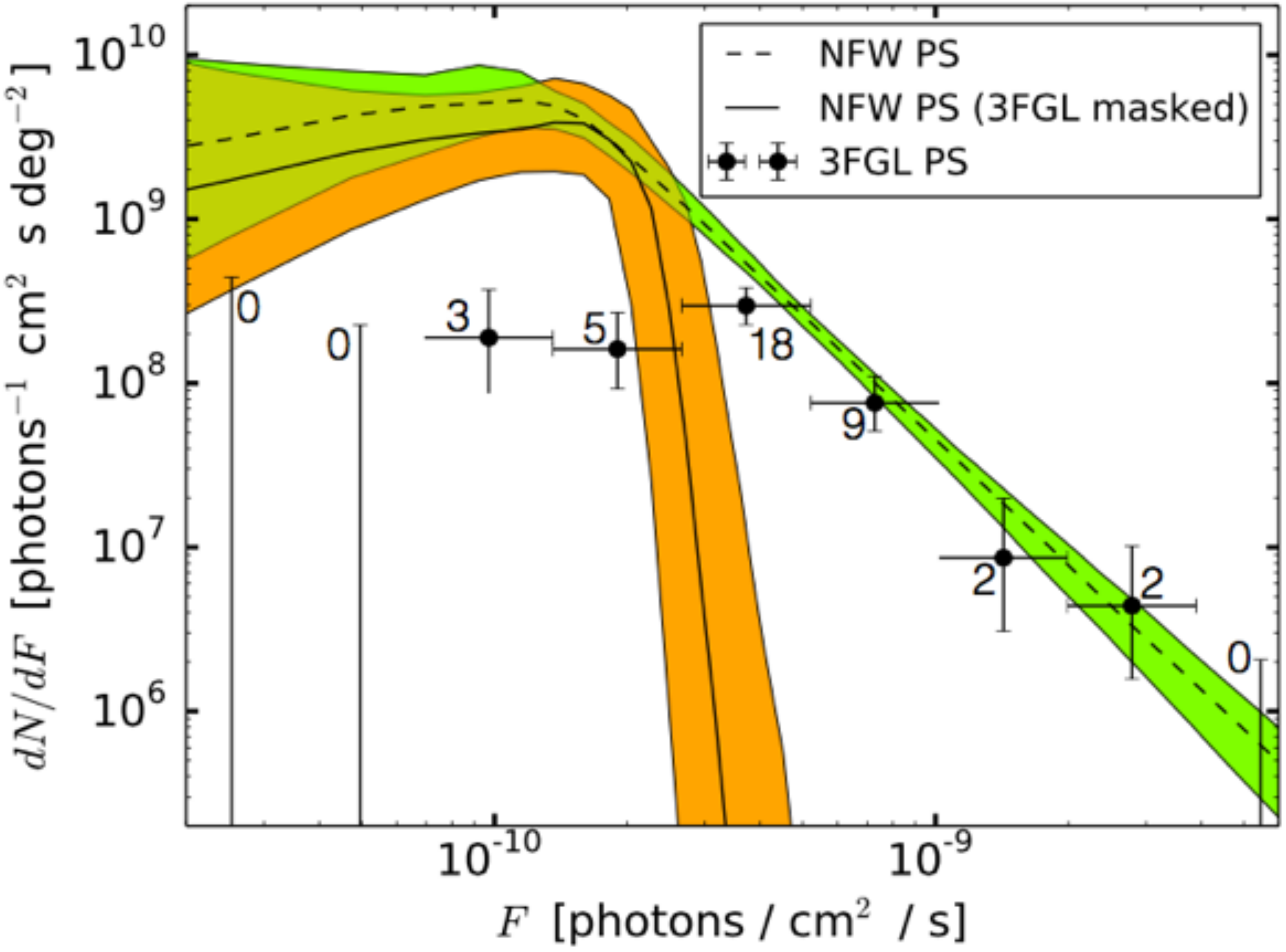
- Plots show flux fractions attributed to templates over region within 10 degrees of GC, more than 2 degrees from Galactic plane (including masked areas).

- 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. <u>NFW PS absorbs full flux otherwise attributed to NFW DM</u>.

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!

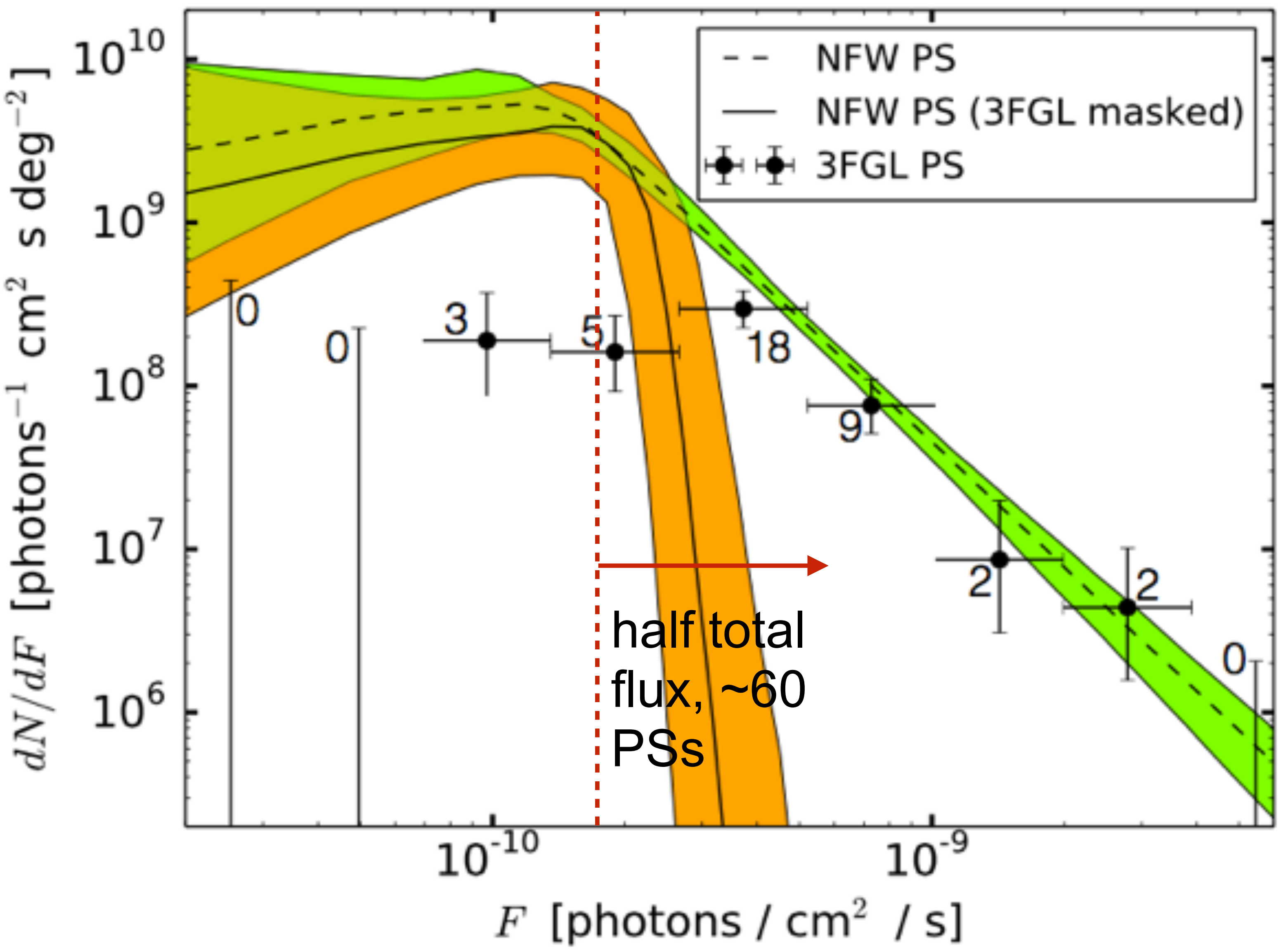


$$F_b = \begin{cases} 1.48^{+0.41}_{-0.43} & \text{unmasked} \\ 2.16^{+0.64}_{-0.43} & \text{masked} \end{cases} \times 10^{-10}\ \mathrm{photons/cm^2/s}$$

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

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!

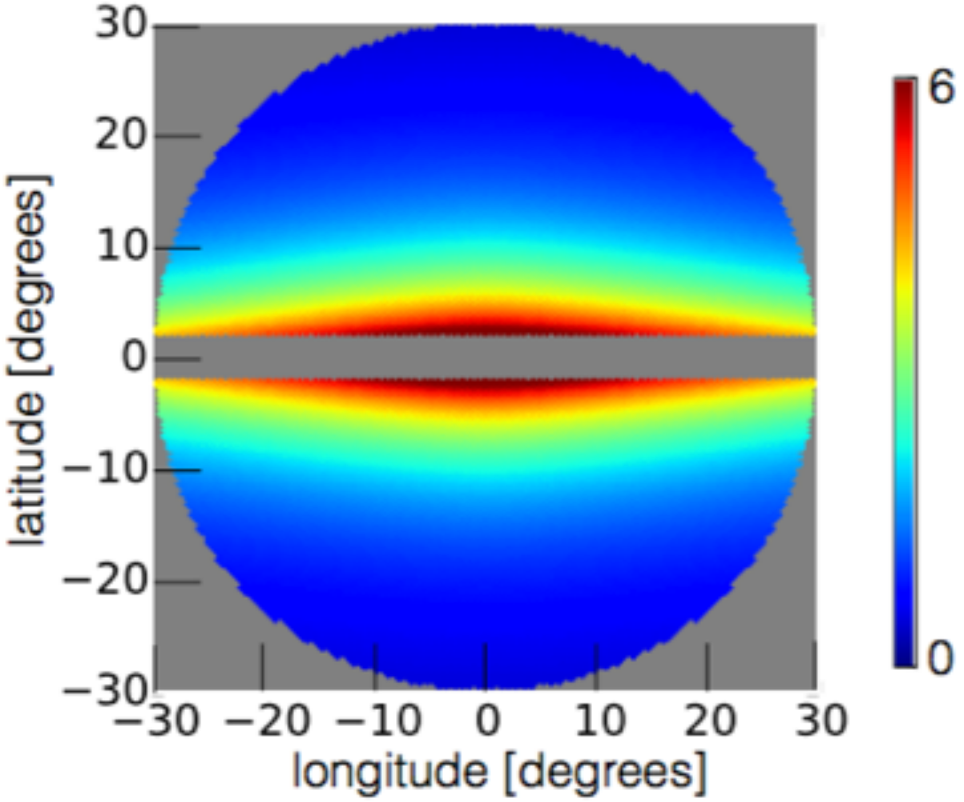


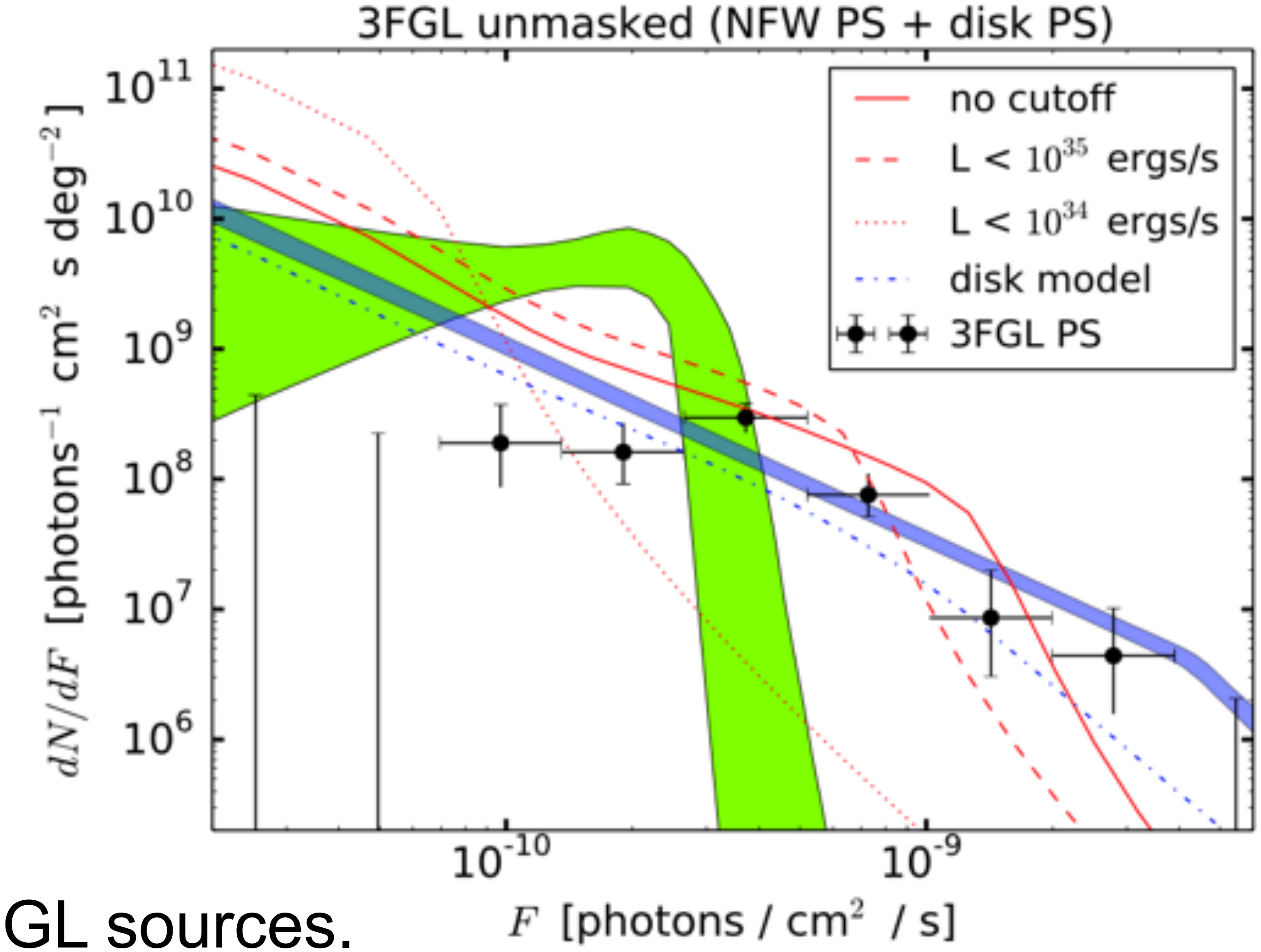
half total flux, ~60 PSs

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

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

Adding disk point sources





- 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 <u>novel</u> population peaked just below current detection threshold.

Model comparison

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

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

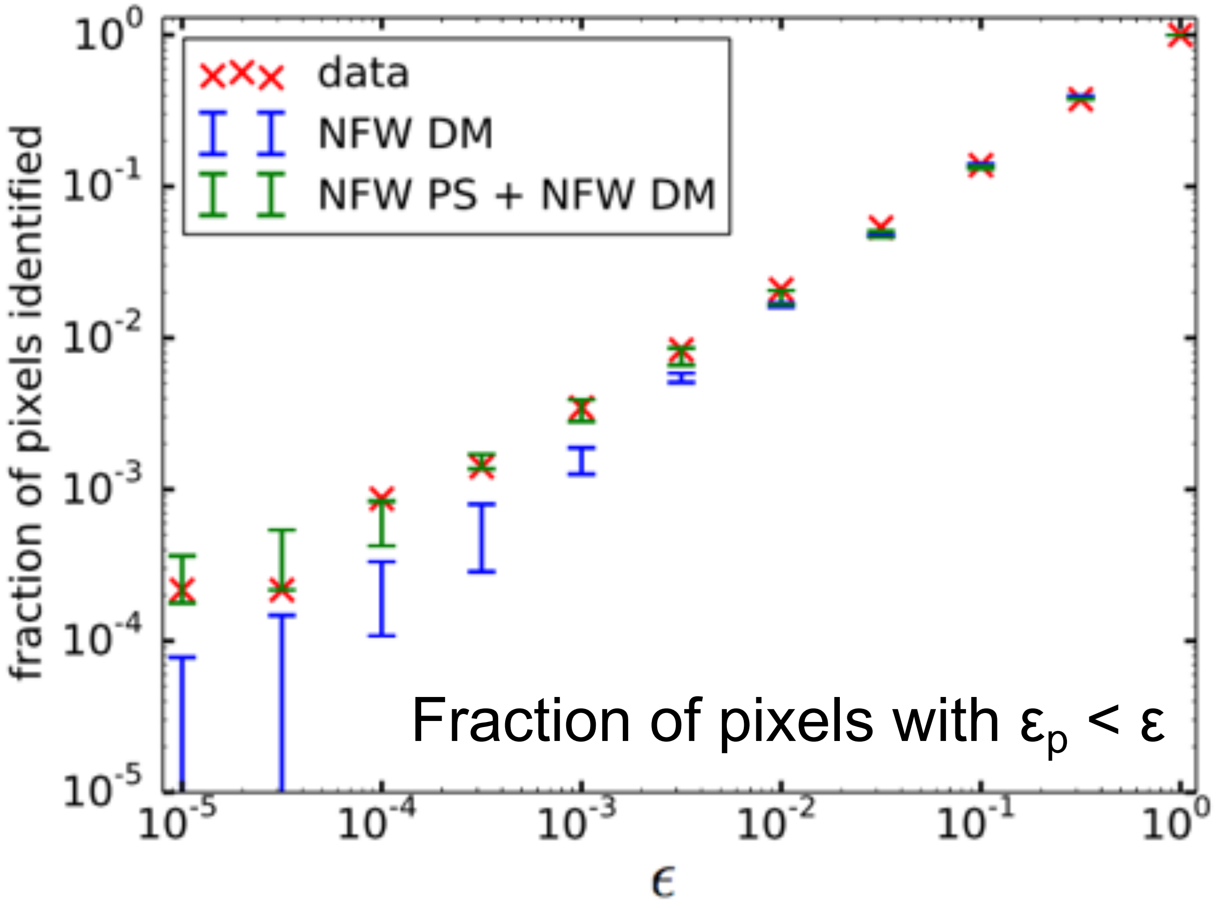
$$B_{10} = \frac{p(d|\mathcal{M}_1)}{p(d|\mathcal{M}_0)} \qquad p(d|\mathcal{M}) = \int_{\Omega_{\mathcal{M}}} d\theta \, p(d|\theta, \mathcal{M}) p(\theta|\mathcal{M})$$

- In our masked analysis, non-zero NFW PS contribution is preferred with a Bayes factor ~ 10^7. Strong statistical preference (but this number does not include systematics).

  - Very rough frequentist analogy: Bayes factor ~ likelihood ratio (- correction for extra degrees of freedom), test statistic (TS) ~ 2 ln L ~ 2 ln(Bayes factor) ~ 32, number of sigma ~ √TS ~ 5-6. (Or more simply, 1 - 10^{-7} CL ~ 5.3 sigma.)

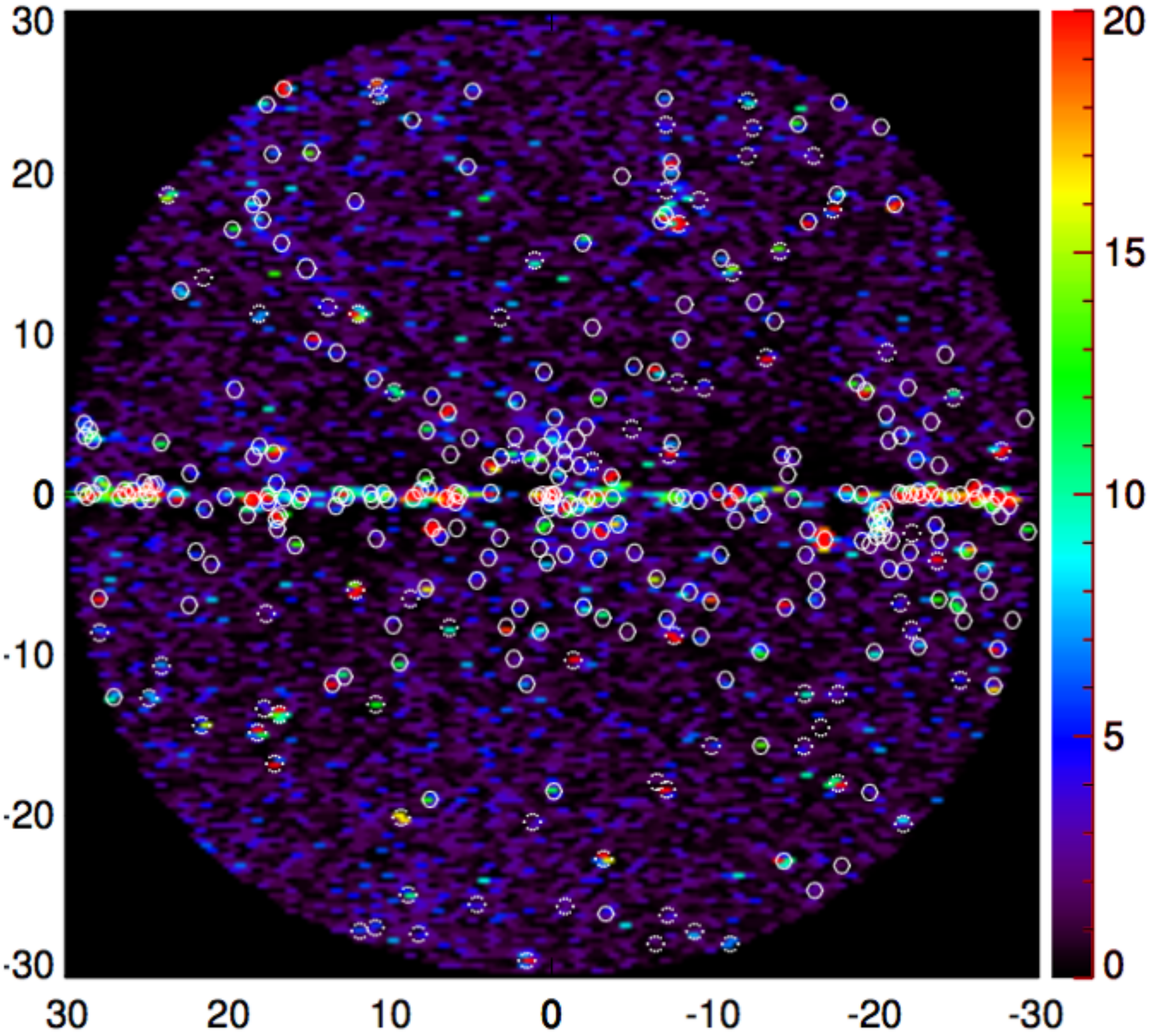
What drives the PS preference?

- Preference for non-Poissonian statistics driven by presence of more bright/faint pixels than expected.
- Can show this explicitly by computing # of outlier ("hot" or "cold") pixels, comparing to Poisson expectations.
- n_p = actual observed number of photons in a given pixel, define $\epsilon_p = P(\#\text{ photons} > n_p)$ under model with only Poissonian statistics (including DM template).
- 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 degree to which pixels are outliers with respect to Poissonian-only background model (log ϵ_p^{-1}).

Such "hot pixels" are potential point source candidates.

Including unmasked data, we recover many known sources.

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

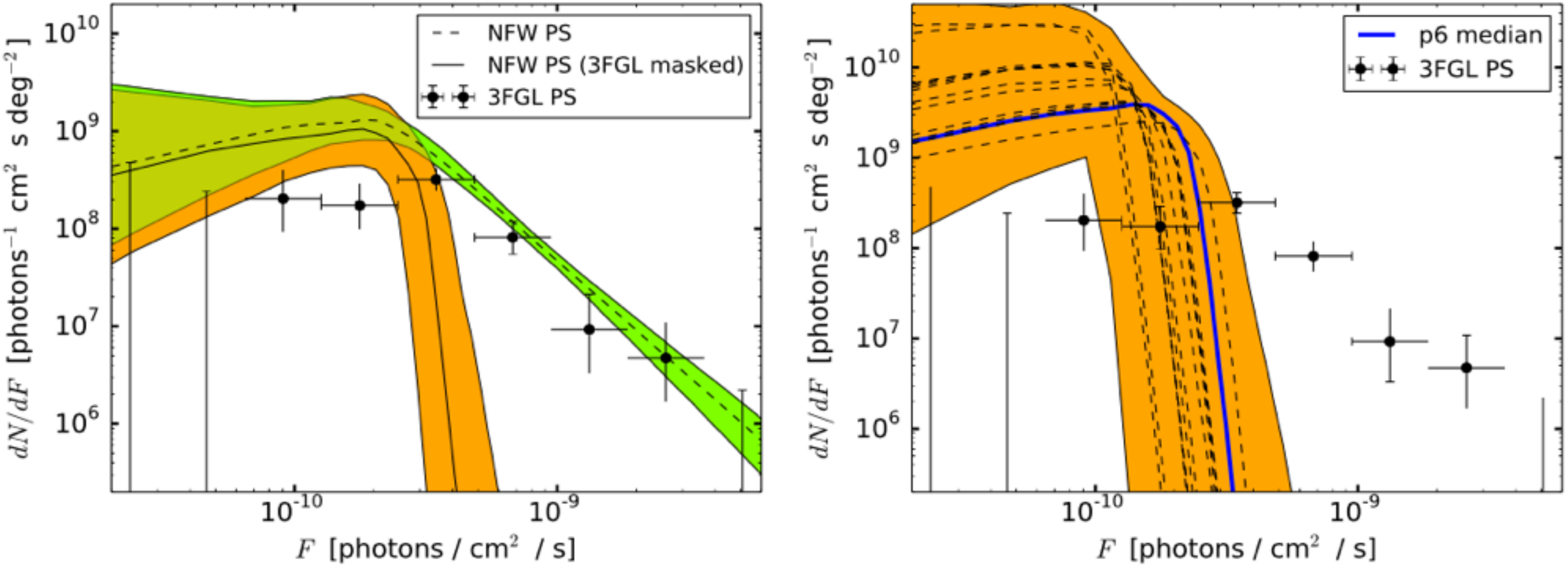
How Robust Is The Analysis?

Systematics

It is always possible there is a subtle effect we have missed. The quoted Bayes factor does not account for systematic effects. We continue to search for biases. So far we have tested the impact of:

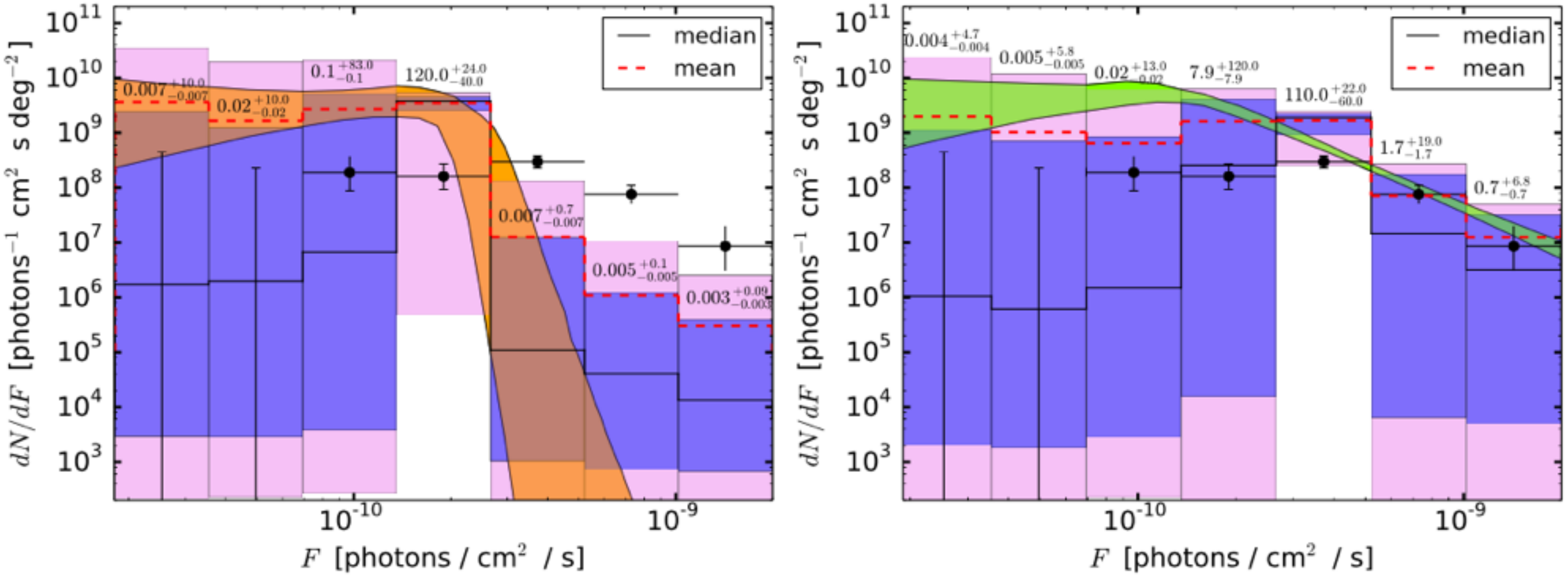
Spatially mismodeled background	Can affect details of source count function, flux fraction, but strong preference for PSs is consistent
Spatially mismodeled signal	No effect within our tests
Mismodeled angular resolution	Can change details of source count function, but not conclusions
Mismodeled source count function	Have tried adding more freedom - results consistent within uncertainties
Simple “look elsewhere” - study of bright excess 30 degrees away from GC	No robust preference for point sources elsewhere, 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

A different background model



- Left panel: reconstructed source-count function for p7v6 Fermi diffuse model.
- Right panel: reconstructed source-count functions for 13 alternate GALPROP-based diffuse models, with the 3FGL point sources masked (for these models we also allow the gas-correlated and inverse Compton scattering templates to vary independently).

Changing the source count function



- 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.
- The result seems to be driven almost entirely by the bin immediately below the estimated detection threshold - others consistent with zero in masked analysis.

What Could The Point Sources Be?

Properties

- If we take the data at face value, we now have evidence for a population that is:
  - With a spectrum peaked at 1-3 GeV.
  - Sharply rising toward the Galactic Center.
  - Spherically symmetric.
  - With a characteristic luminosity scale around 10^{34} erg/s (at energies > 1 GeV).
- How difficult is this to explain?

Properties

- If we take the data at face value, we now have evidence for a population that is:
  - With a spectrum peaked at 1-3 GeV.
  - Sharply rising toward the Galactic Center.
  - Spherically symmetric.
  - With a characteristic luminosity scale around 10^{34} erg/s (at energies > 1 GeV).
- How difficult is this to explain?

Most studies focus on pulsars for this reason

Properties

- If we take the data at face value, we now have evidence for a population that is:
  - With a spectrum peaked at 1-3 GeV.
  - Sharply rising toward the Galactic Center.
  - Spherically symmetric.
  - With a characteristic luminosity scale around 10^{34} erg/s (at energies > 1 GeV).
- How difficult is this to explain?

Most studies focus on pulsars for this reason

Can be natural for binary systems, or injections at the GC

Properties

- If we take the data at face value, we now have evidence for a population that is:
  - With a spectrum peaked at 1-3 GeV.
  - Sharply rising toward the Galactic Center.
  - Spherically symmetric.
  - With a characteristic luminosity scale around 10^{34} erg/s (at energies > 1 GeV).
- How difficult is this to explain?

Most studies focus on pulsars for this reason

Can be natural for binary systems, or injections at the GC

Generally challenging

Properties

- If we take the data at face value, we now have evidence for a population that is:
  - With a spectrum peaked at 1-3 GeV.

    Most studies focus on pulsars for this reason
  - Sharply rising toward the Galactic Center.

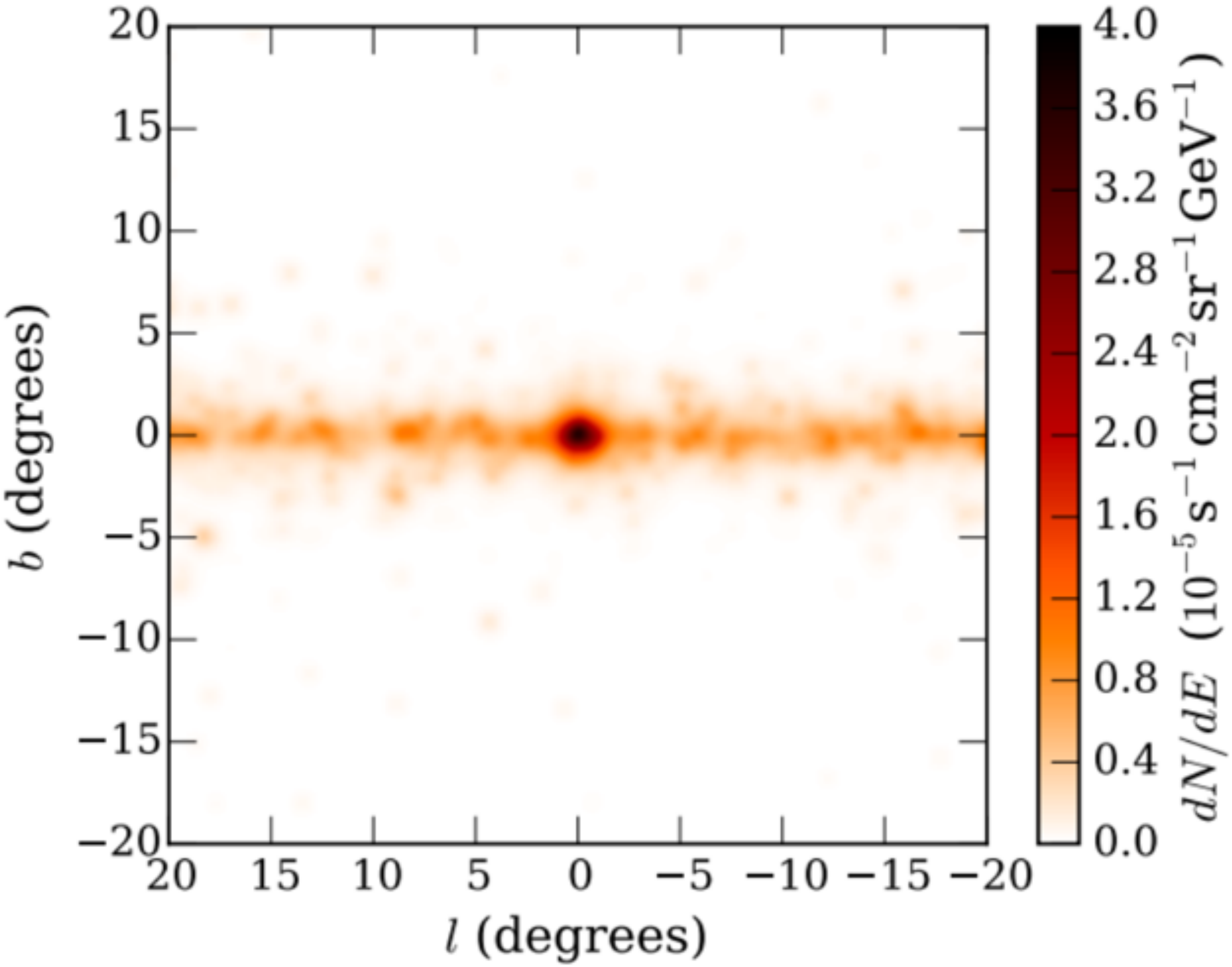
    Can be natural for binary systems, or injections at the GC
  - Spherically symmetric.

    Generally challenging
  - With a characteristic luminosity scale around 10^{34} erg/s (at energies > 1 GeV).

    ???
- How difficult is this to explain?

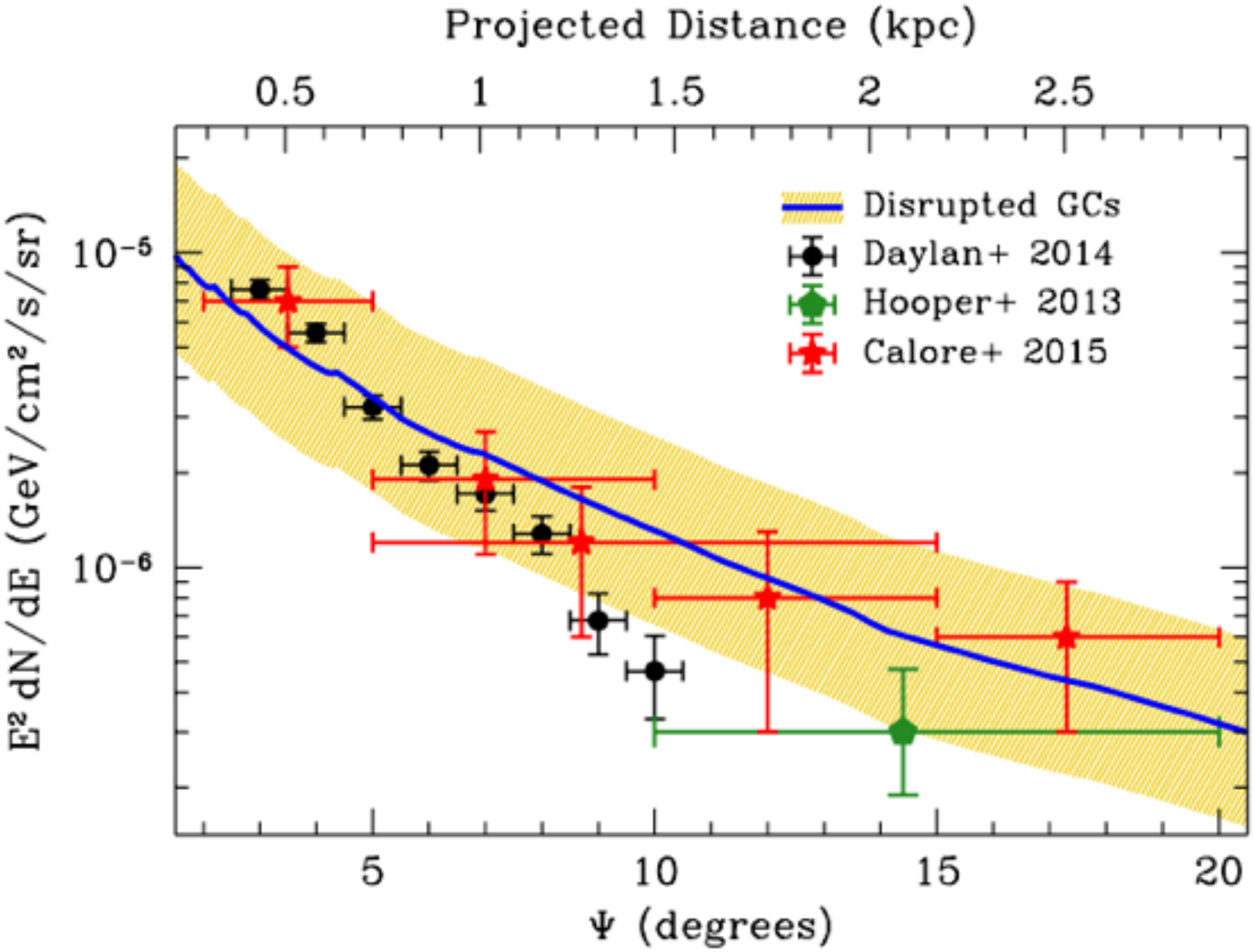
Young pulsars & sphericity

- 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, disk pulsars dominate outside inner few degrees.
- Excess is absorbed by spherical population rather than a thick disk.
- In contrast, known sources are better described by thick disk.



Pulsars from globular clusters

- Recent paper by Brandt & Kocsis 1507.05616 postulates disrupted globular clusters as source of MSPs.
- Idea: globular clusters spiral in toward Galactic Center due to dynamical friction. Tidal stripping spills MSPs (and other objects) from globular cluster into shell around the GC.
- Long-lived MSPs remain bright in gamma-rays after other traces (e.g. X-ray binaries) are gone.
- Globular cluster distribution is ~spherical, so resulting shell may also be spherical (not studied in depth).



- Good description of amplitude and radial fall-off of excess based on earlier model (Gnedin, Ostriker & Tremaine ’14) for dense Galactic nuclei, with no free parameters.

Where next?

- Include multiple energy bins - more careful study of energy spectra.
- Continue in-depth studies of NPTF method sensitivity and possible biases.
- Bright outlier pixels, relative to Poissonian-templates-only model, 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, either in archival or new data?
  - What is the energy spectrum in these pixels? How does removing them change the flux attributed to the excess?
  - If new sources are detected, can we constrain the underlying spatial distribution from which these sources are drawn?

Conclusions

- The GeV gamma-ray excess is a striking potential clue to novel (astro)physics; its detailed characterization has revealed several properties suggestive of dark matter annihilation.

- We have adapted template fitting methods to the case of non-Poissonian statistics, and applied them to Fermi gamma-ray data.

- 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, a flux sufficient to generate the entire observed GeV gamma-ray excess, and an unexpected (spherical) spatial morphology.

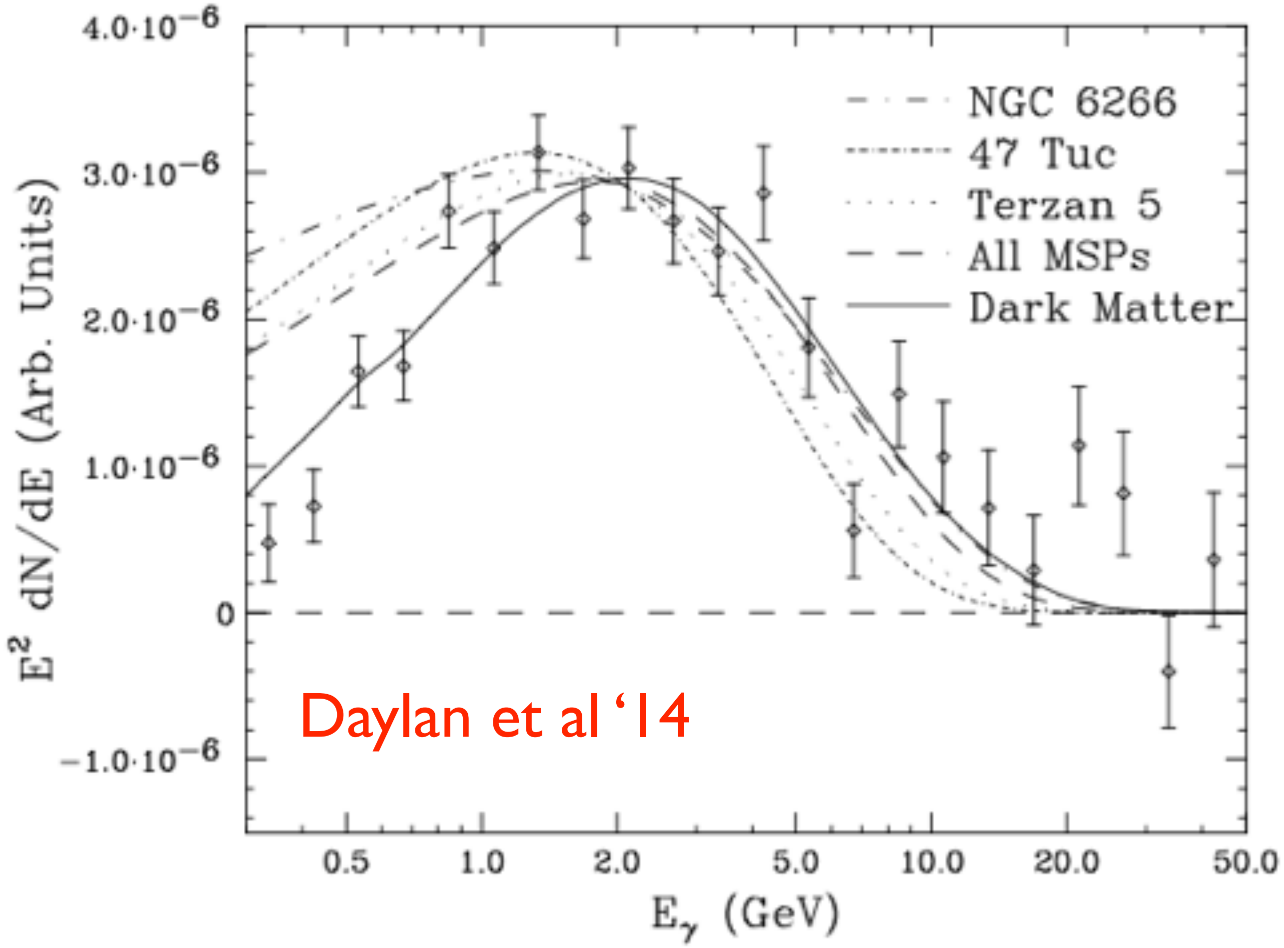
- If such a population is indeed present, there is no residual preference for a non-zero contribution to the GeV excess from dark matter annihilation.

- If the presence of such sources can be confirmed, it will solve the puzzle of the GeV excess, and open up studies of a novel gamma-ray point source population in the inner Galaxy.

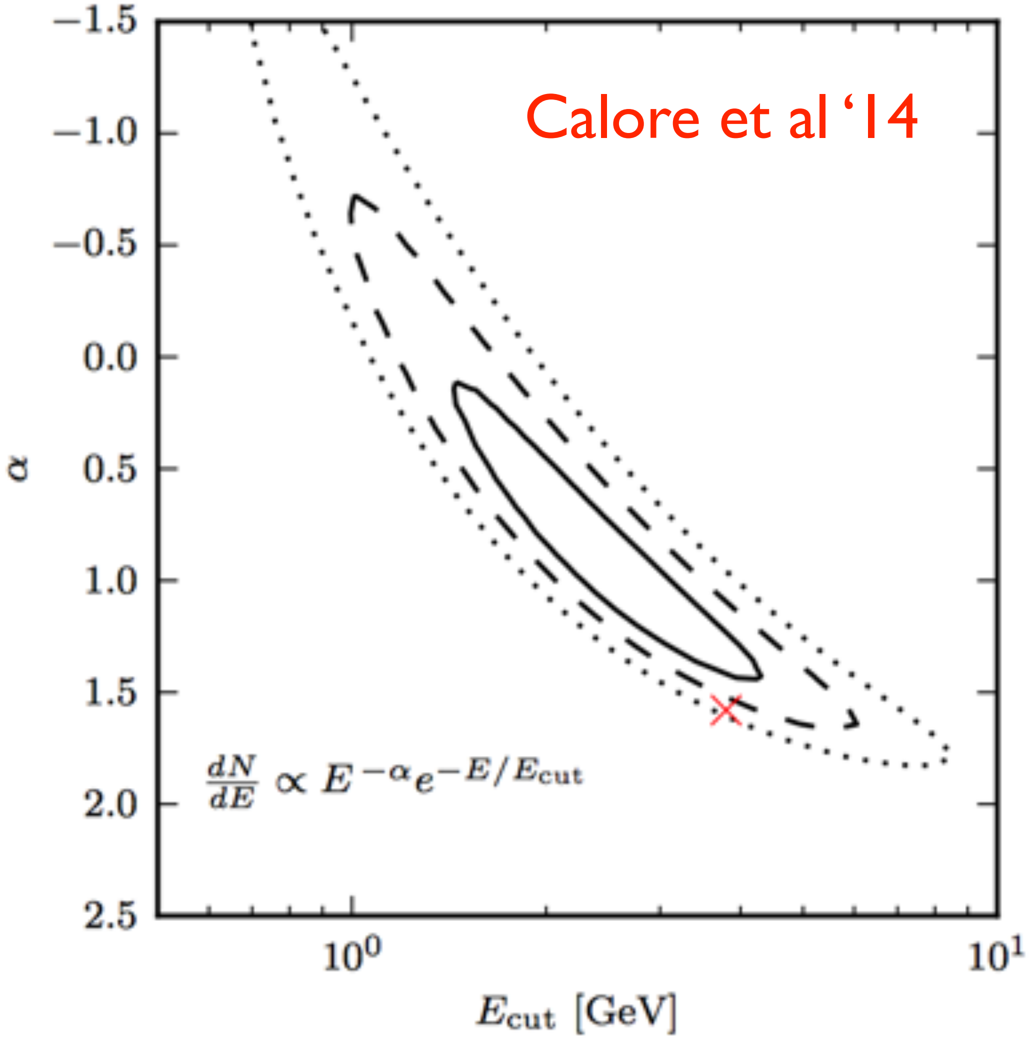
BACKUP SLIDES

Pulsar properties

The pulsar spectrum



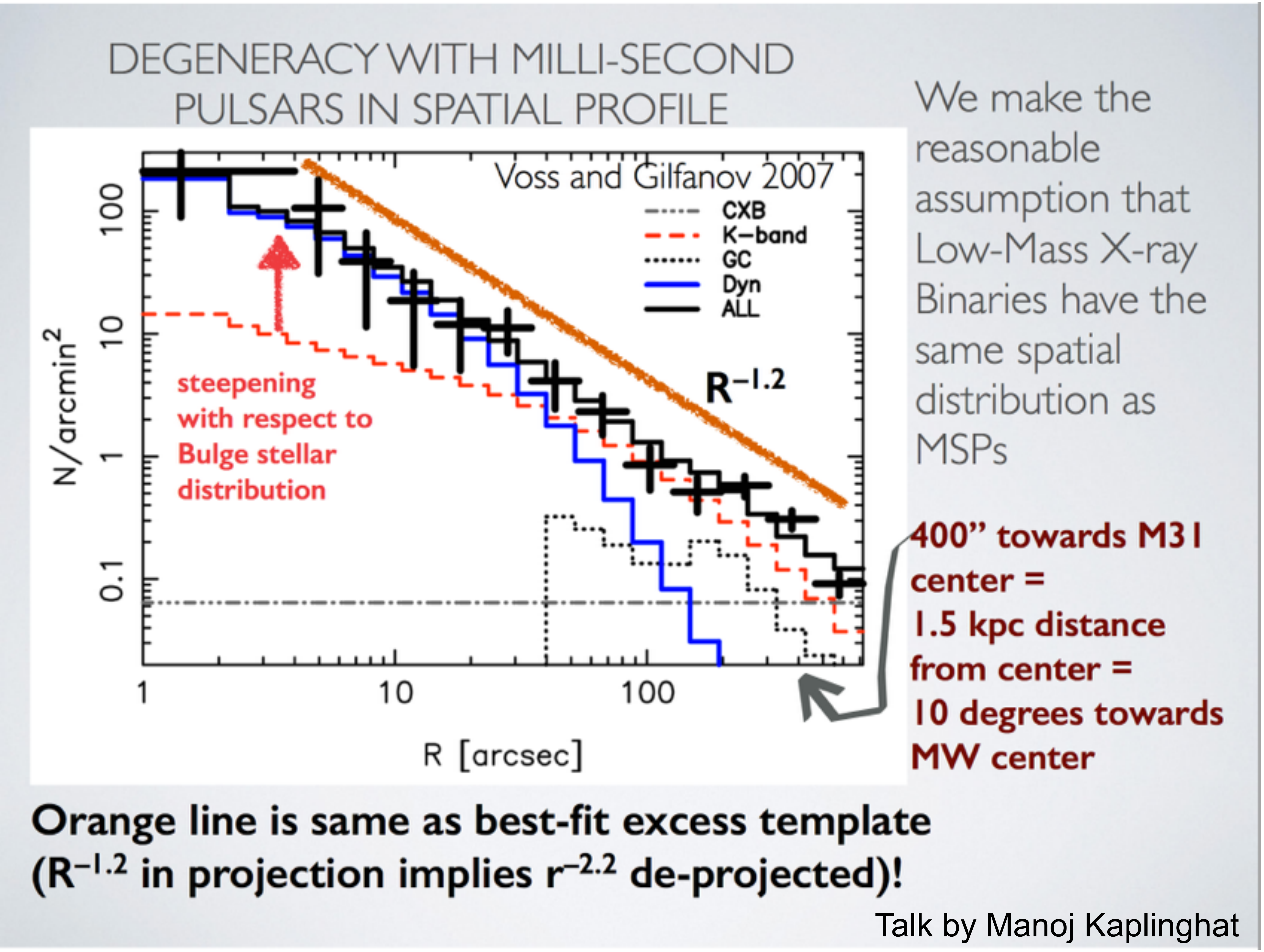
Daylan et al '14



Calore et al '14

- 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 (but compatible at 2 sigma, given estimates on systematic uncertainties).

Spatial distribution of LMXBs



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

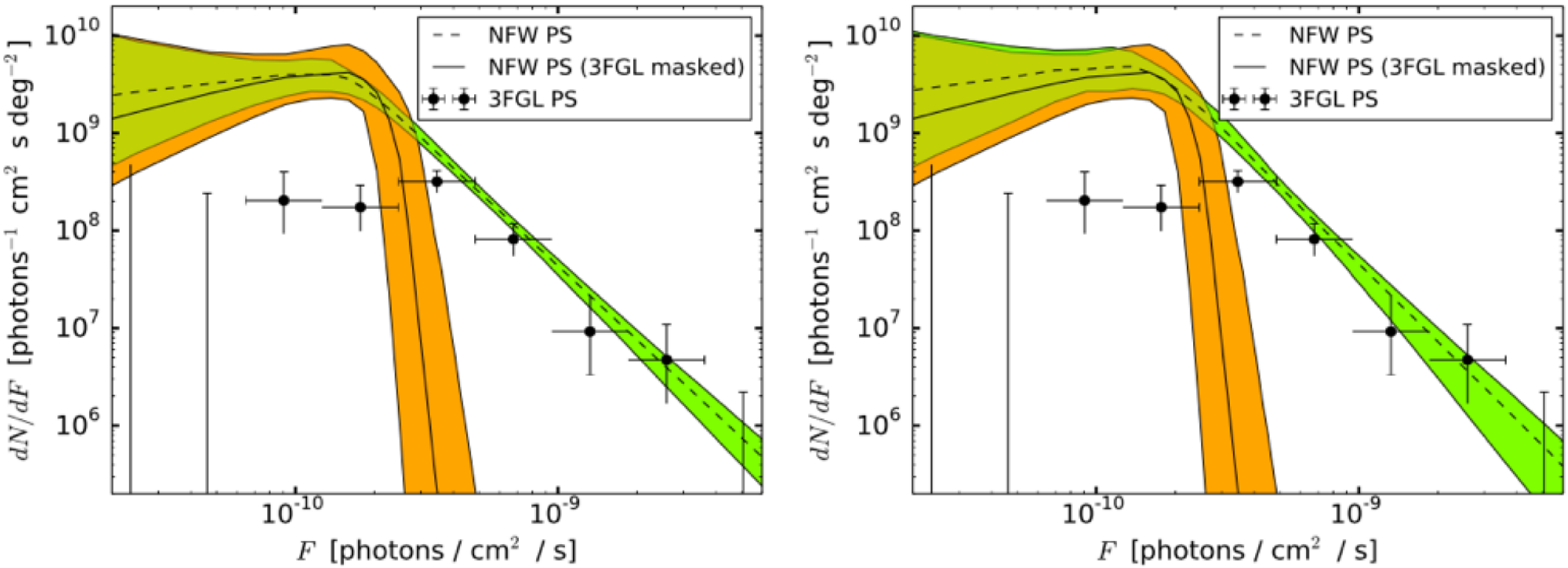
400" towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

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

Talk by Manoj Kaplinghat

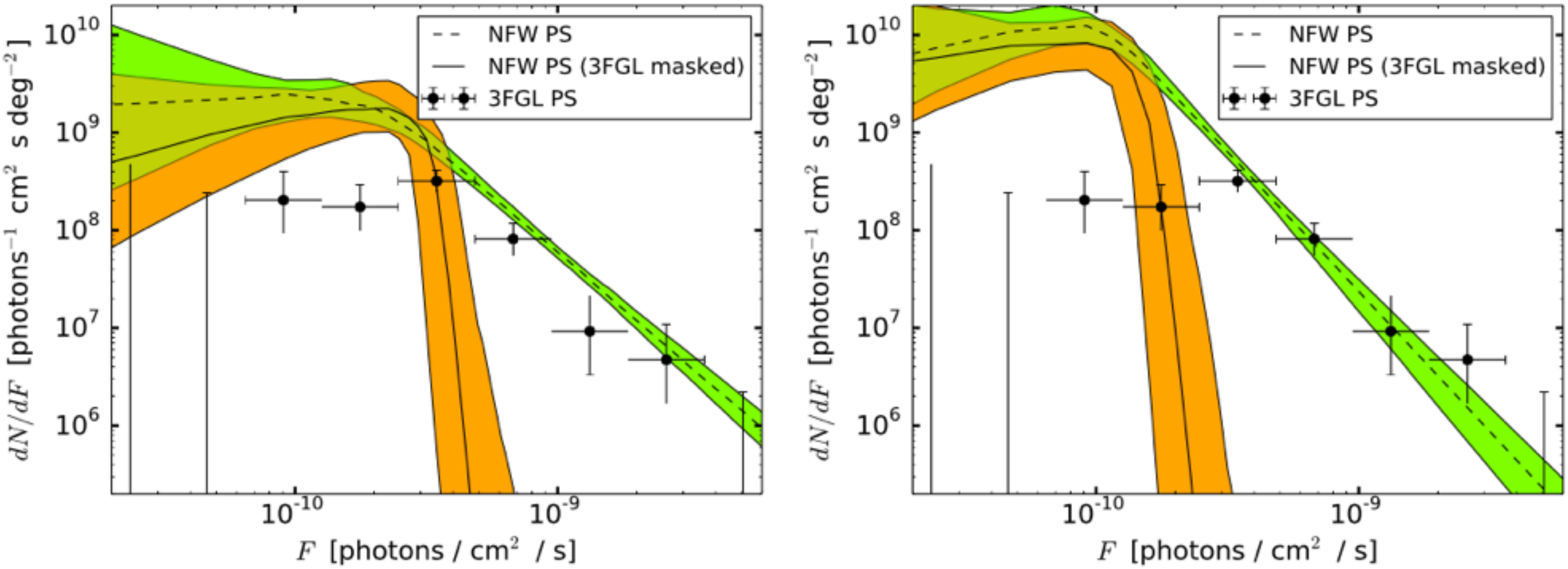
Cross-checks

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.

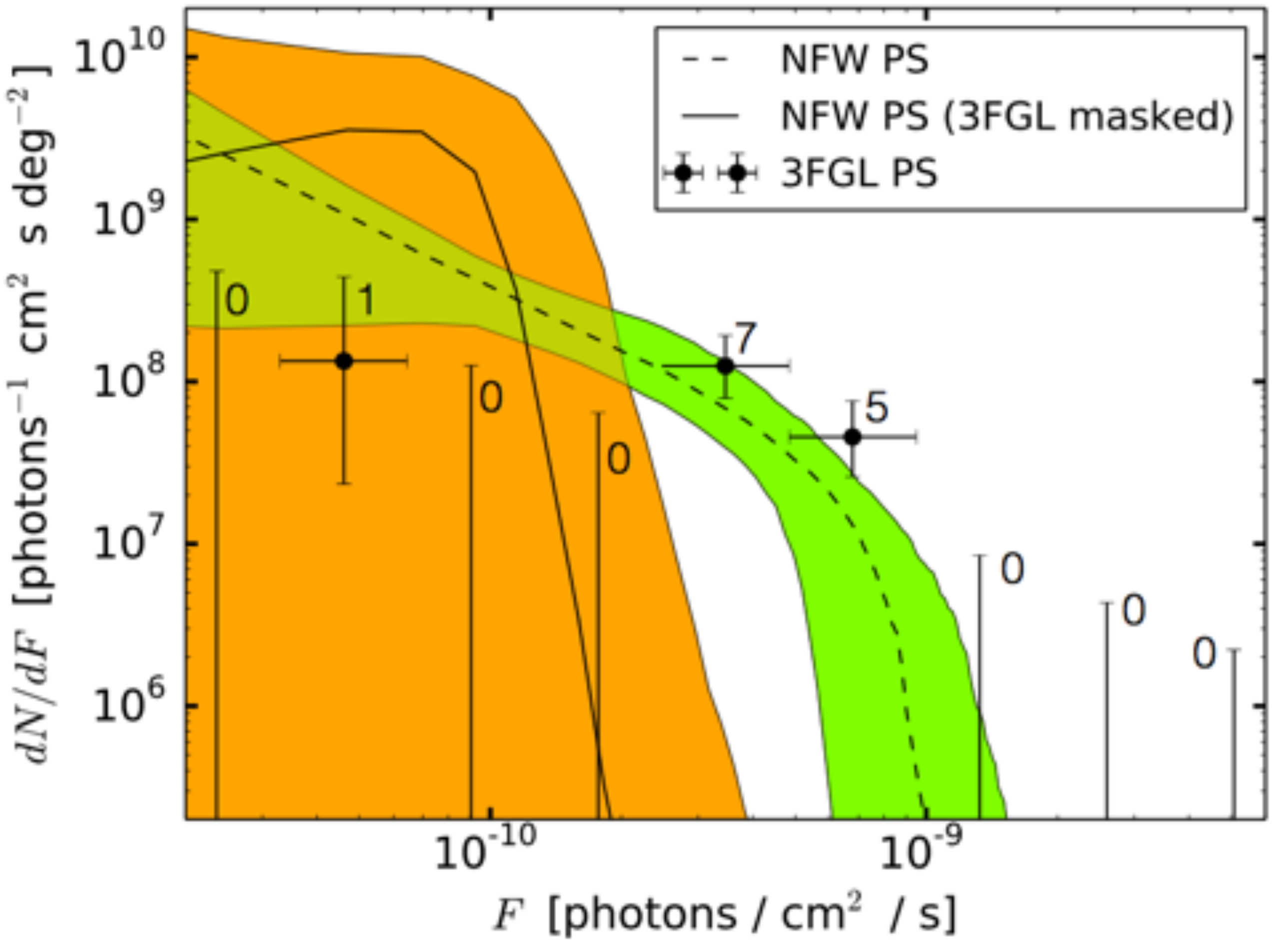
Changing the assumed PSF

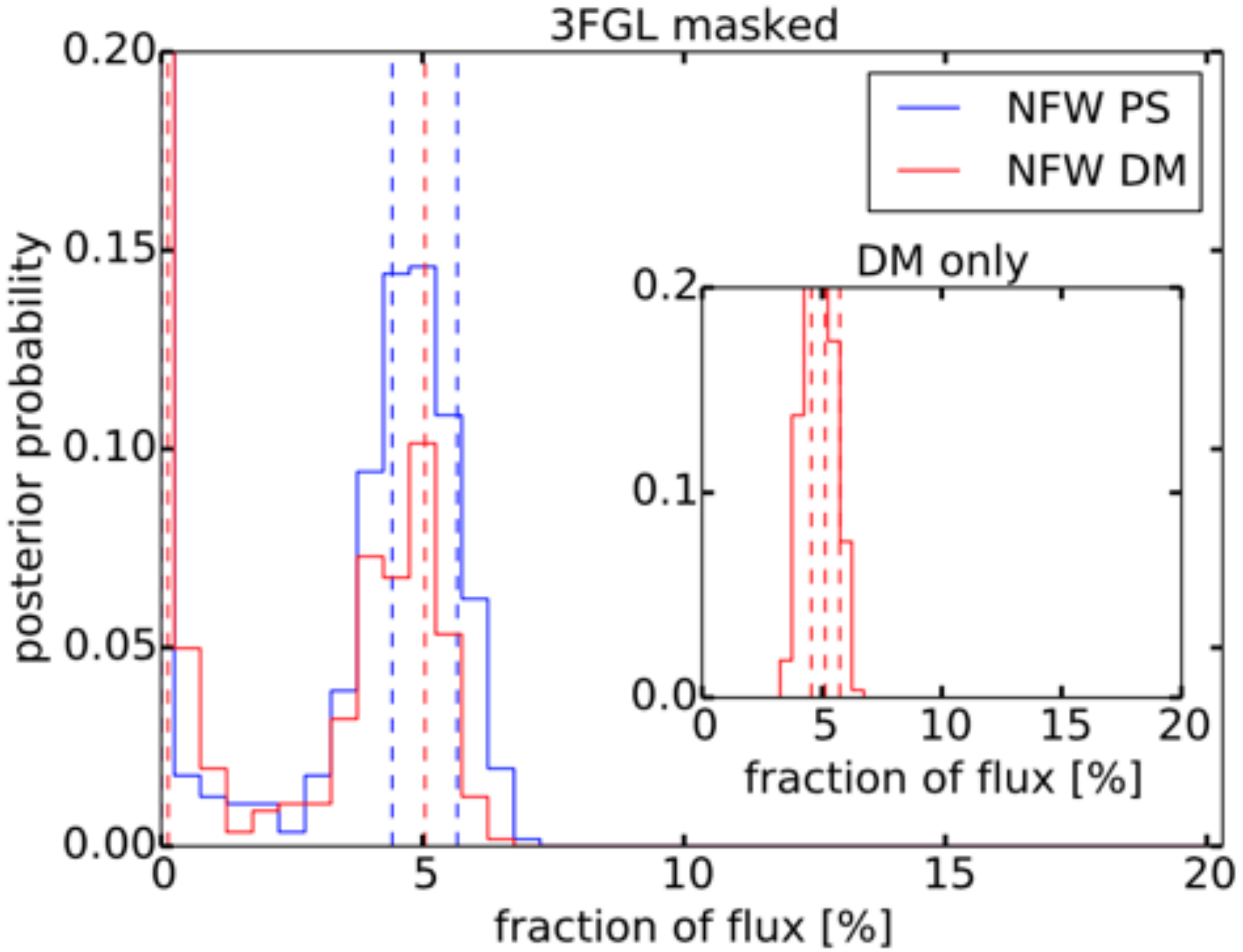


- Gaussian sigma for PSF set to 0.198 degrees (left) or 0.0492 degrees (right), in generating function formalism - these correspond to the estimated PSF at the lowest and highest energies in our bin.

- 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.

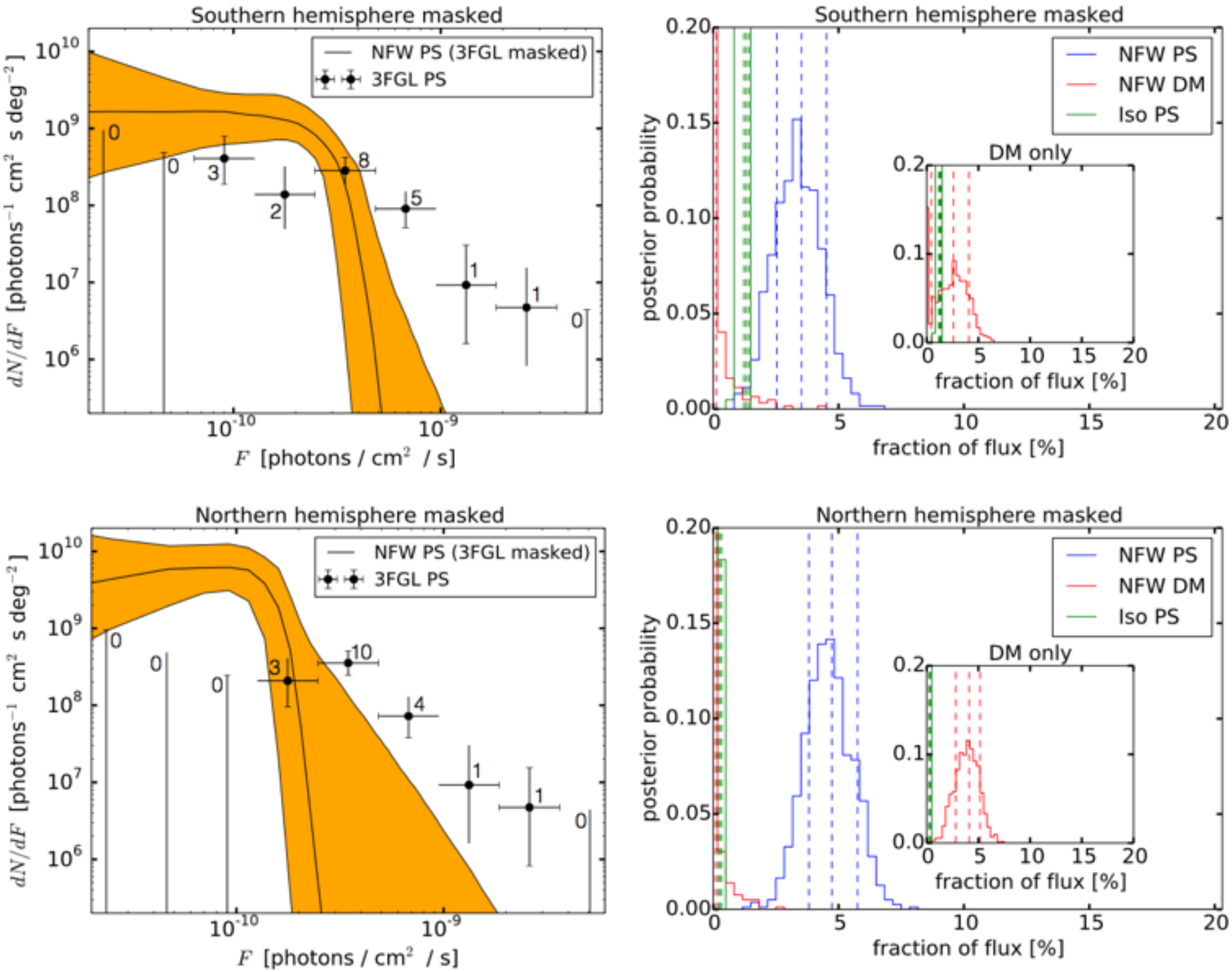
An alternate region





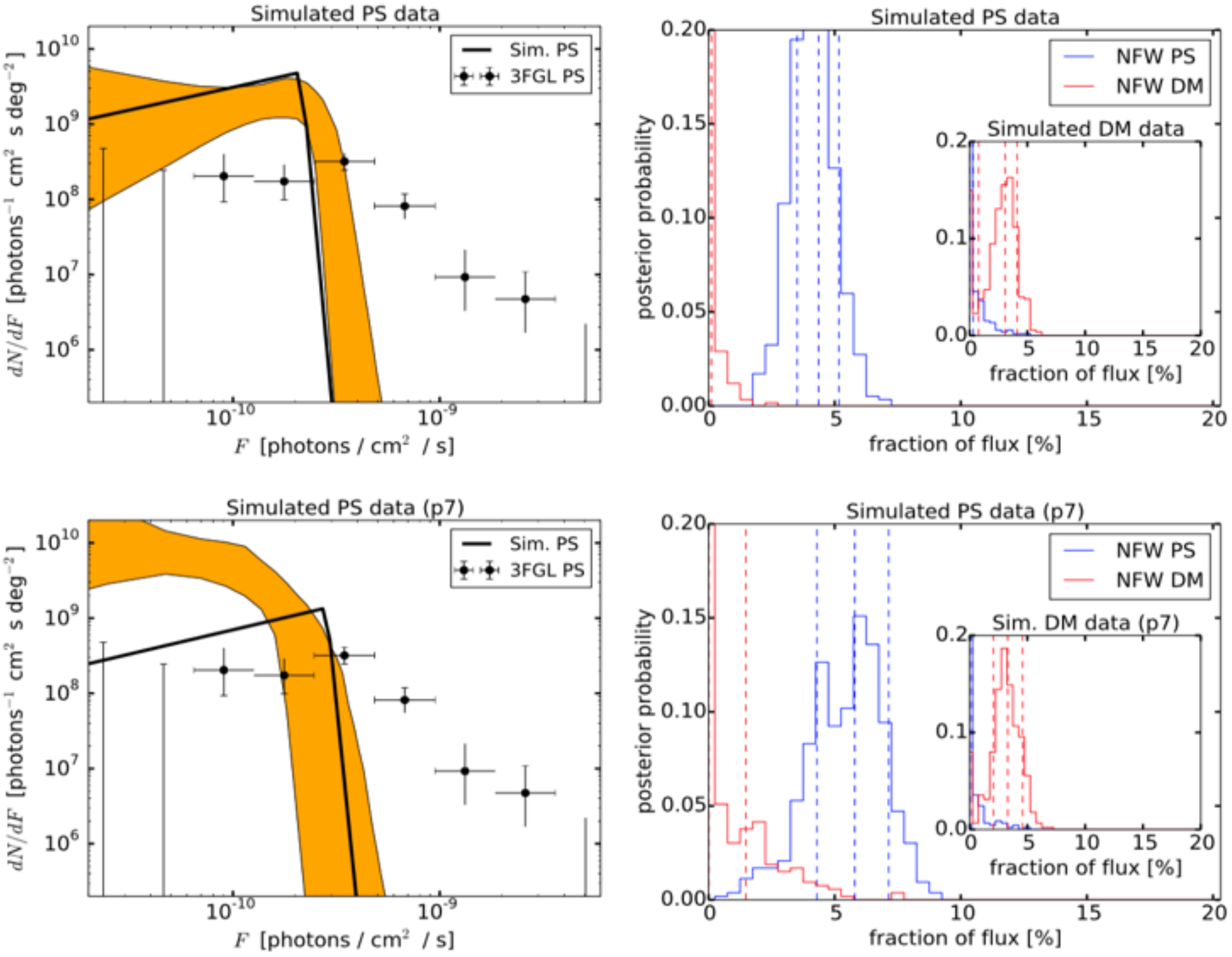
- There is a bright excess 30 degrees along the Galactic Plane from the Galactic Center, albeit with a soft spectrum.
- When the same analysis is repeated on this region in masked data, there is no significant preference for PSs over a diffuse signal (Bayes factor is O(1)).

North vs south



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.



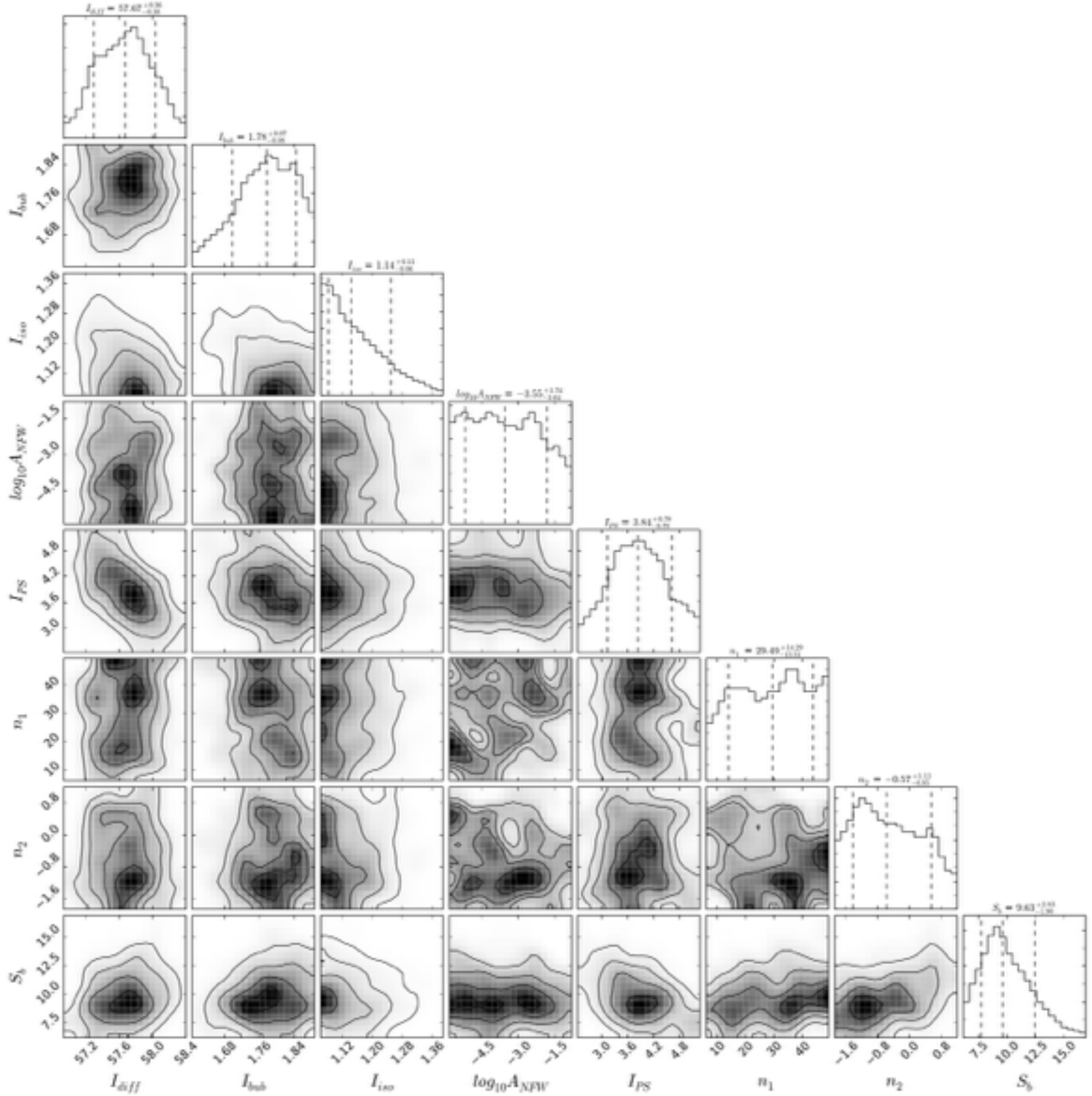
Mock data tests (II)

- 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 significance of 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.

Priors

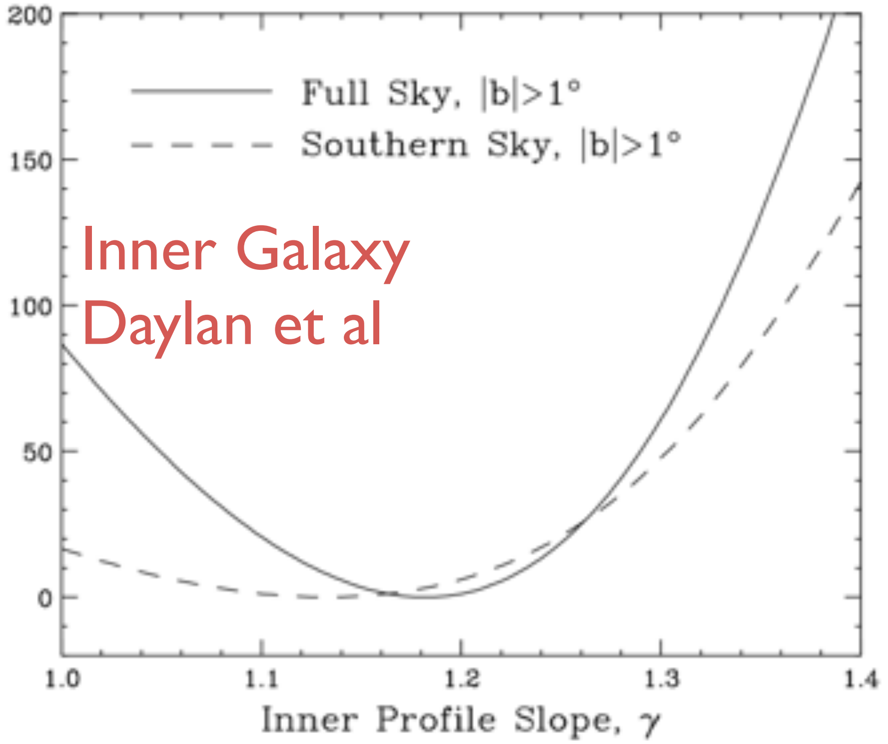
Parameter	Prior Ranges	
	High Latitude	Inner Galaxy
A_{iso}	$[0, 10]$	20% of $A_{\mathrm{iso}}^{\mathrm{HL}}$
A_{diff}	$[0, 10]$	20% of $A_{\mathrm{diff}}^{\mathrm{HL}}$
A_{bub}	$[0, 10]$	20% of $A_{\mathrm{bub}}^{\mathrm{HL}}$
$\log_{10} A_{\mathrm{NFW}}$	$[-6, 6]$	$[-6, 6]$
$\log_{10} A_{\mathrm{PS}}$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

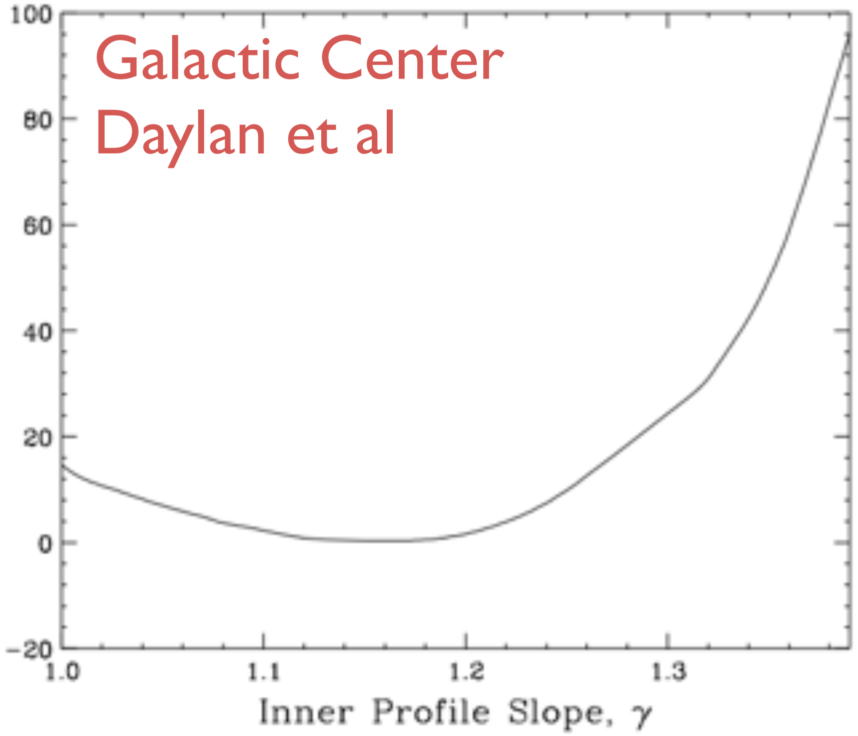
Triangle plot (masked IG)

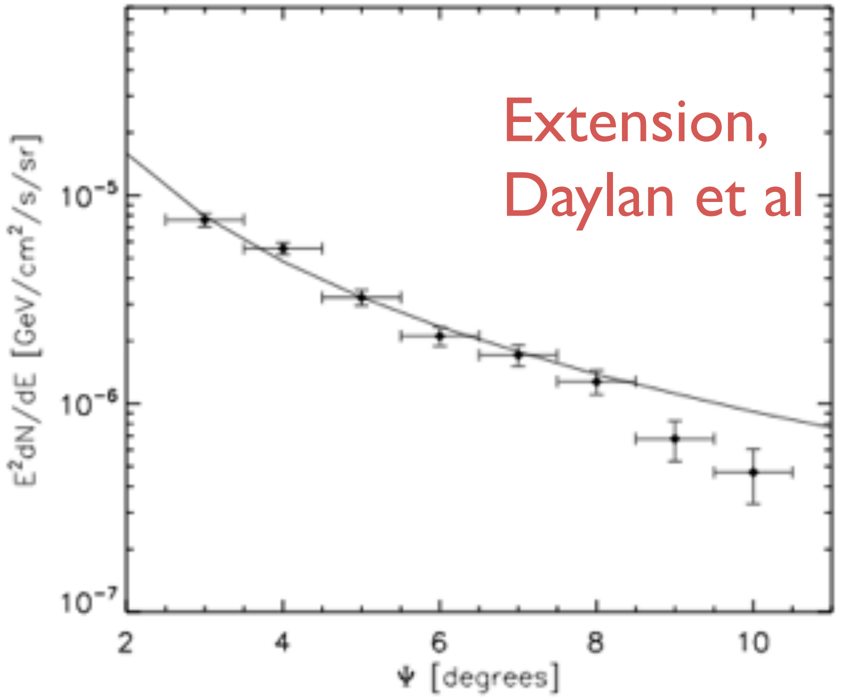


Properties of the GeV excess

Slope and extension

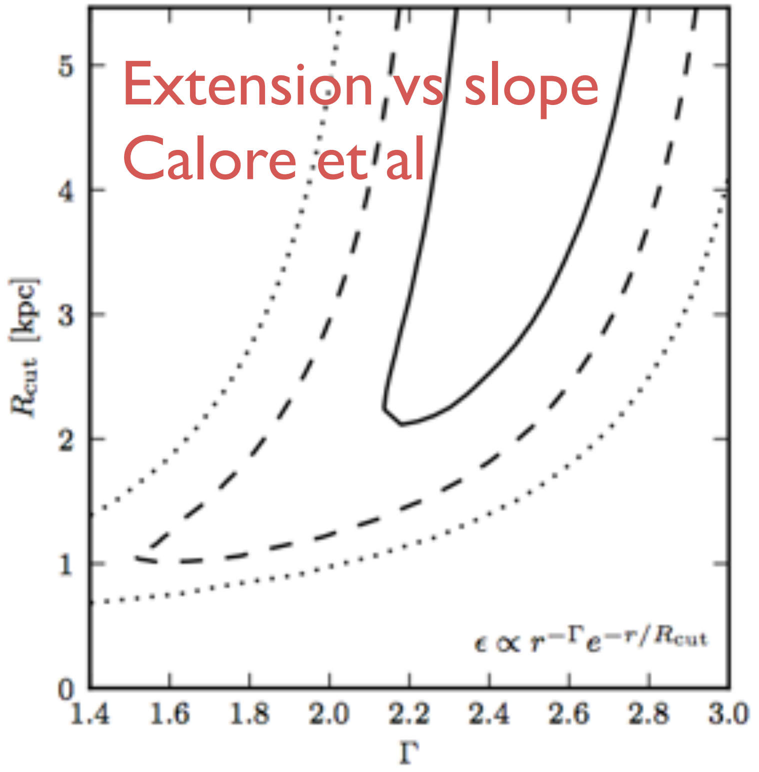

Inner Galaxy
Daylan et al


Galactic Center
Daylan et al


Extension,
Daylan et al

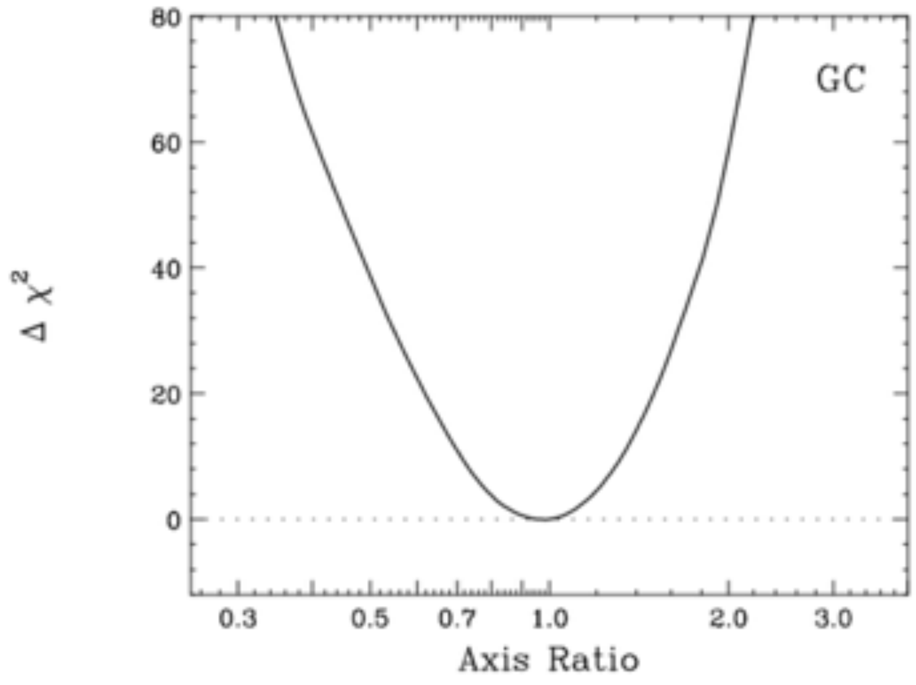
- Preferred power-law slope for power per unit volume (i.e. 2γ for annihilation from an NFW profile): ~2.2-2.4 (Galactic Center, Paper 1), ~2.2-2.6 (Inner Galaxy, Paper I), ~2.2-2.8 (CCW, syst. errors included)

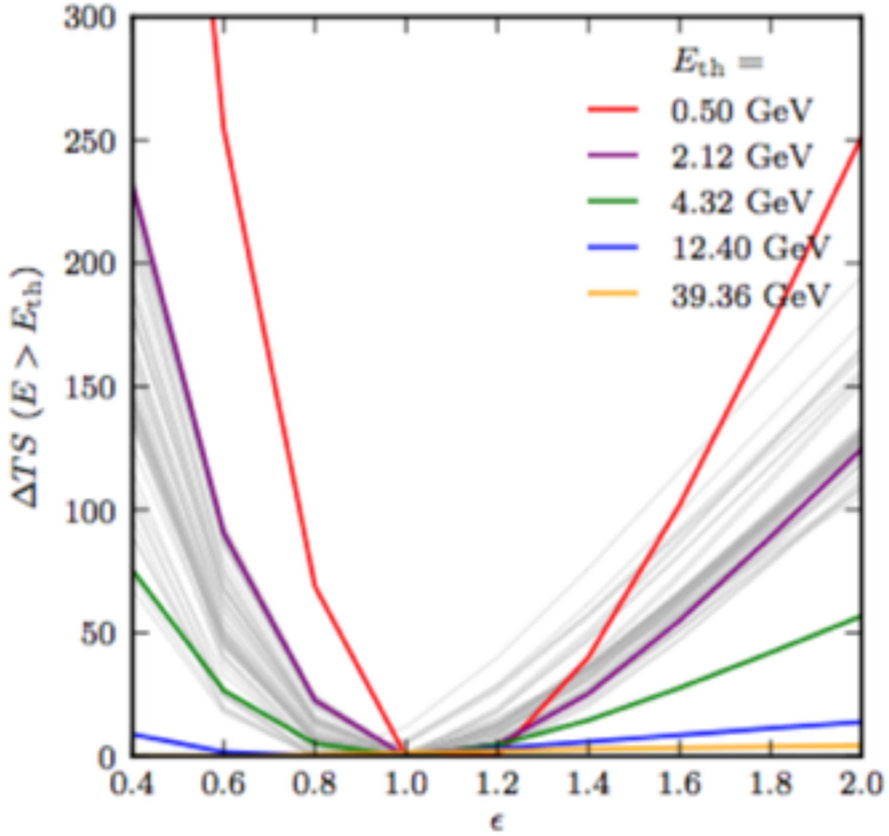
- Extends to ~10 degrees / 1.5 kpc.


Extension vs slope
Calore et al

Sphericity

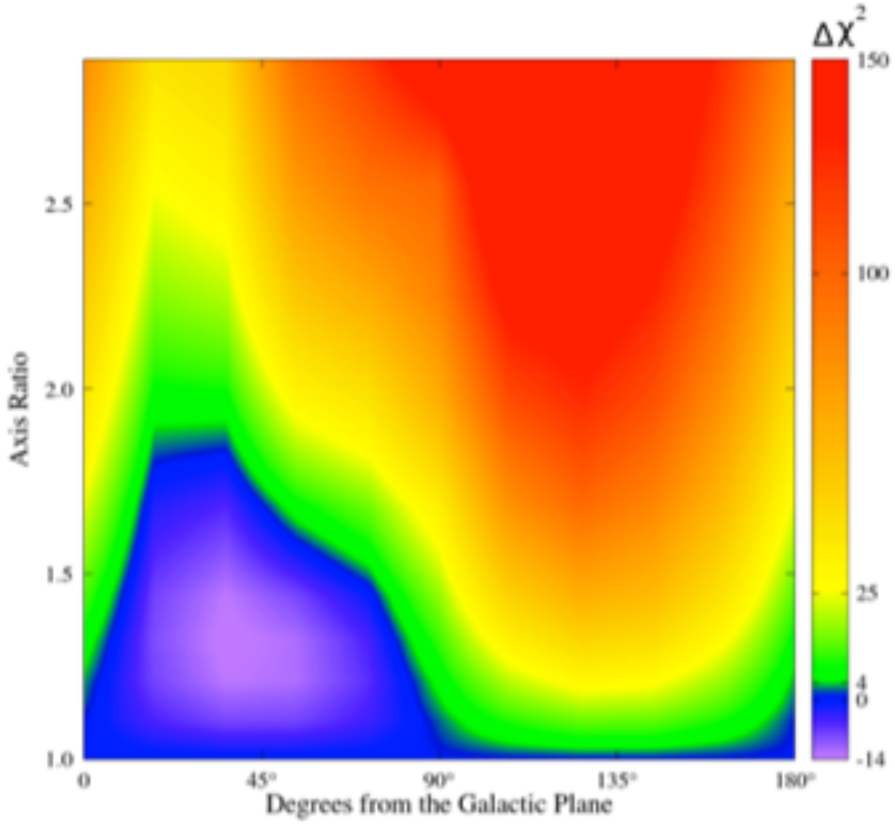
- Test: which provides a better fit to the data? (1) Circular template, (2) template stretched perpendicular to the Galactic plane, (3) template stretched along the Galactic plane?
- (3) would be a strong hint at an astrophysical origin. But data seem to prefer (1), disfavoring a stretch by a factor of more than 1.2.
- Top - Daylan et al, bottom - Calore et al.

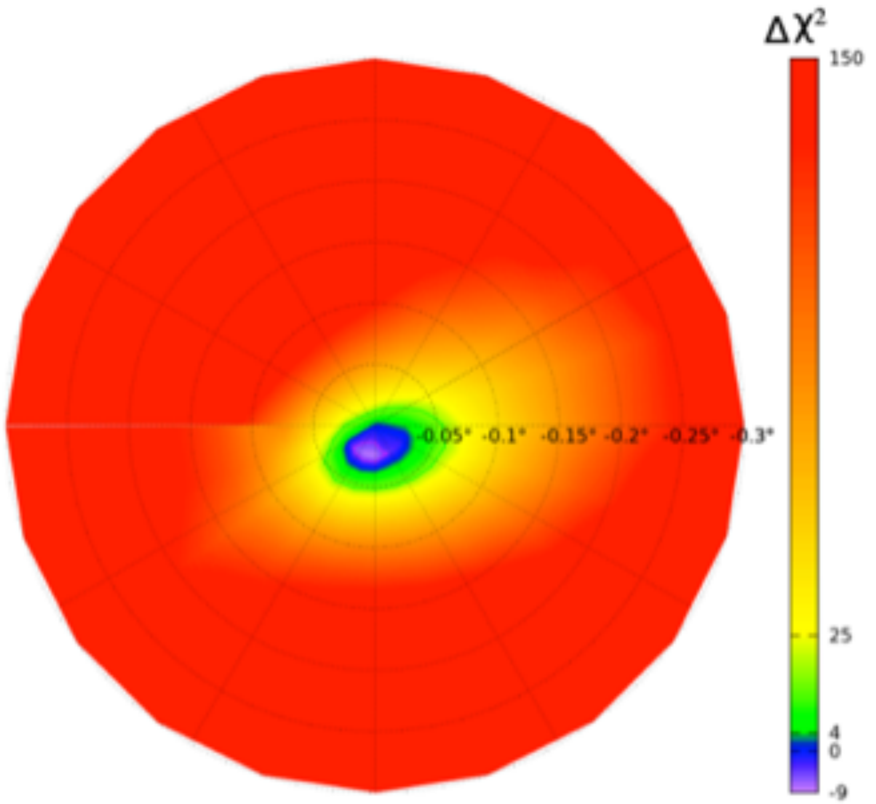




Orientation & centering

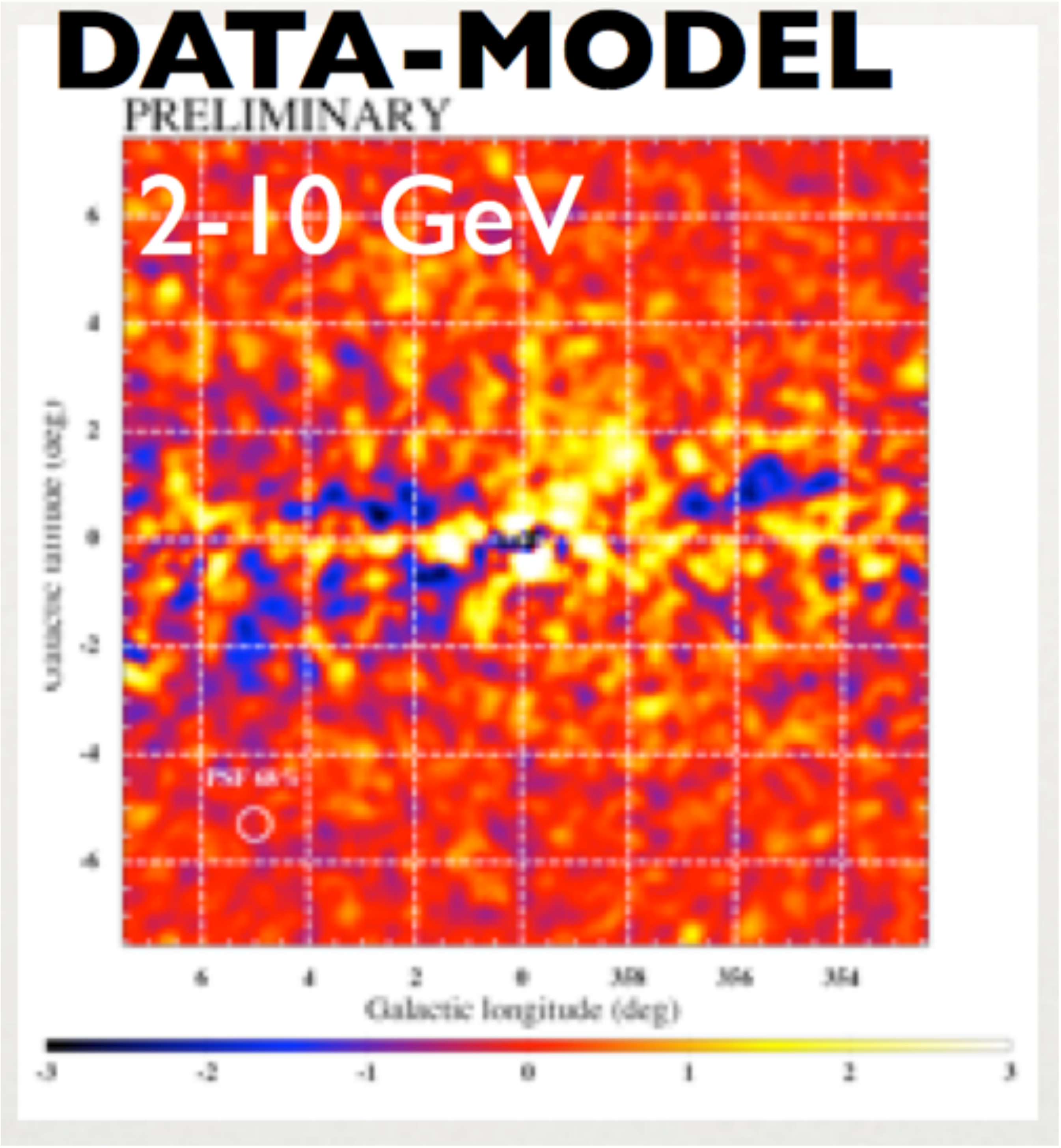
- More spatial tests (from Daylan et al):
- Stretch signal template along arbitrary angles to the Galactic plane.
- Move template so it is not centered on Galactic Center.
- Results: shift more than 0.05 degrees from the GC is disfavored at 95% confidence (from GC analysis - inner Galaxy analysis less 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?

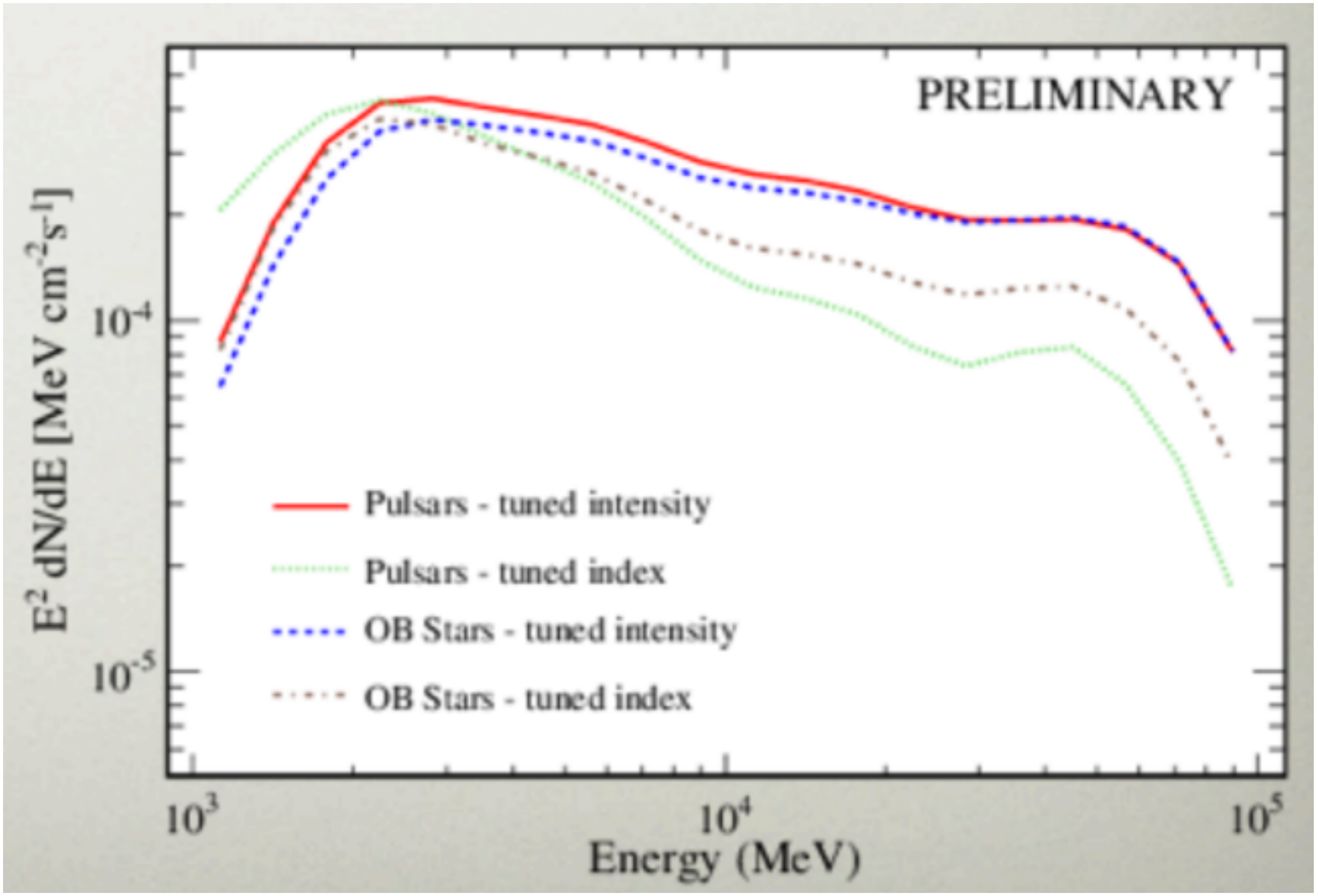
- Talk presented by Simona Murgia at Fermi Symposium 20-24 October.
- “We find an enhancement approximately centered on the Galactic center with a spectrum that peaks in the GeV range, that persists across the models we have employed”
- “Peaked profiles with long tails (NFW, NFW contracted) yield the 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.

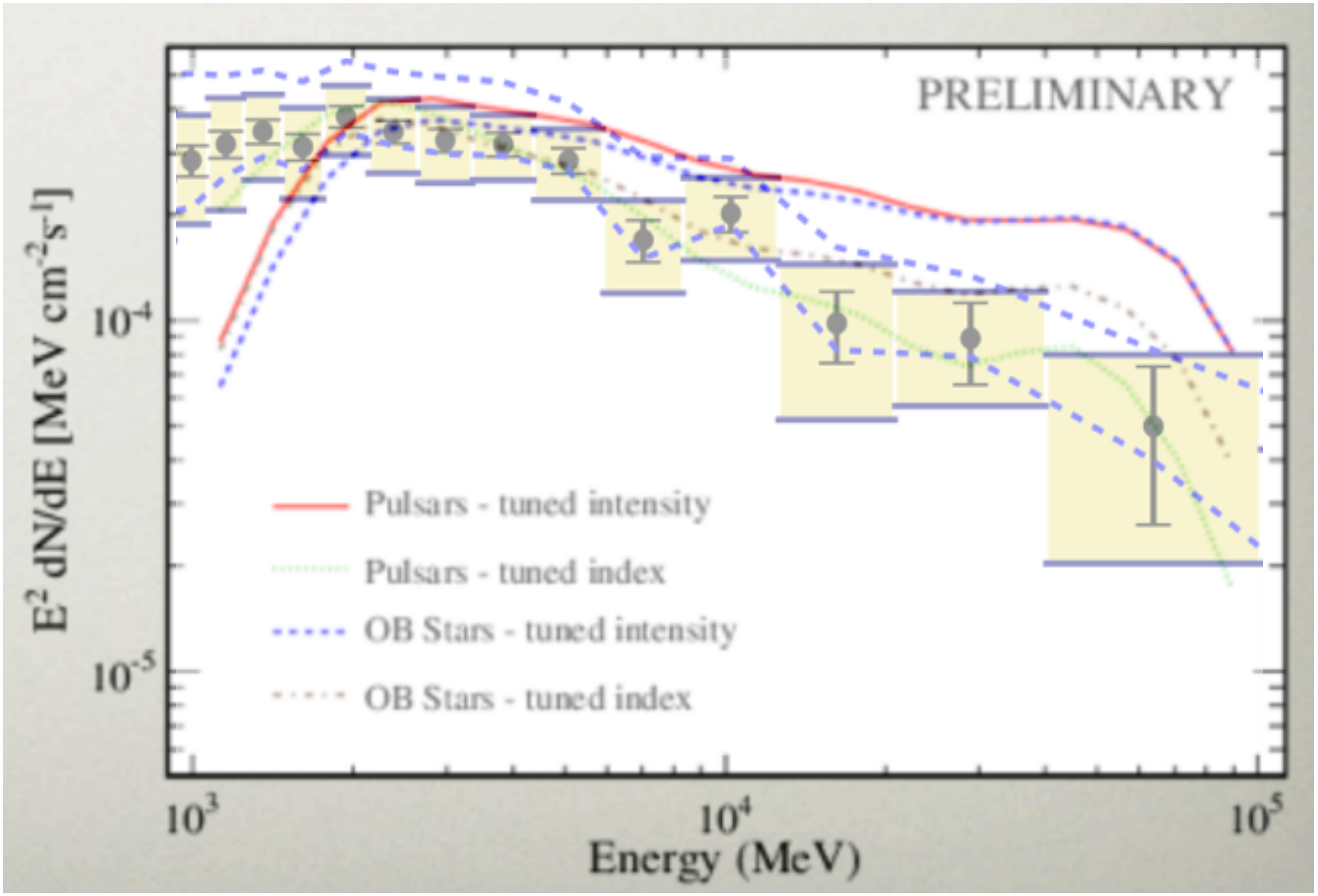
- Spectrum of excess seems broadly consistent with other results (lower at ~1 GeV); tuned-intensity models lead to higher “signal” tails at large E, but are known to generically undersubtract data at high energies.



Talk presented by Simona Murgia at Fermi Symposium

The spectrum from the Fermi Collaboration

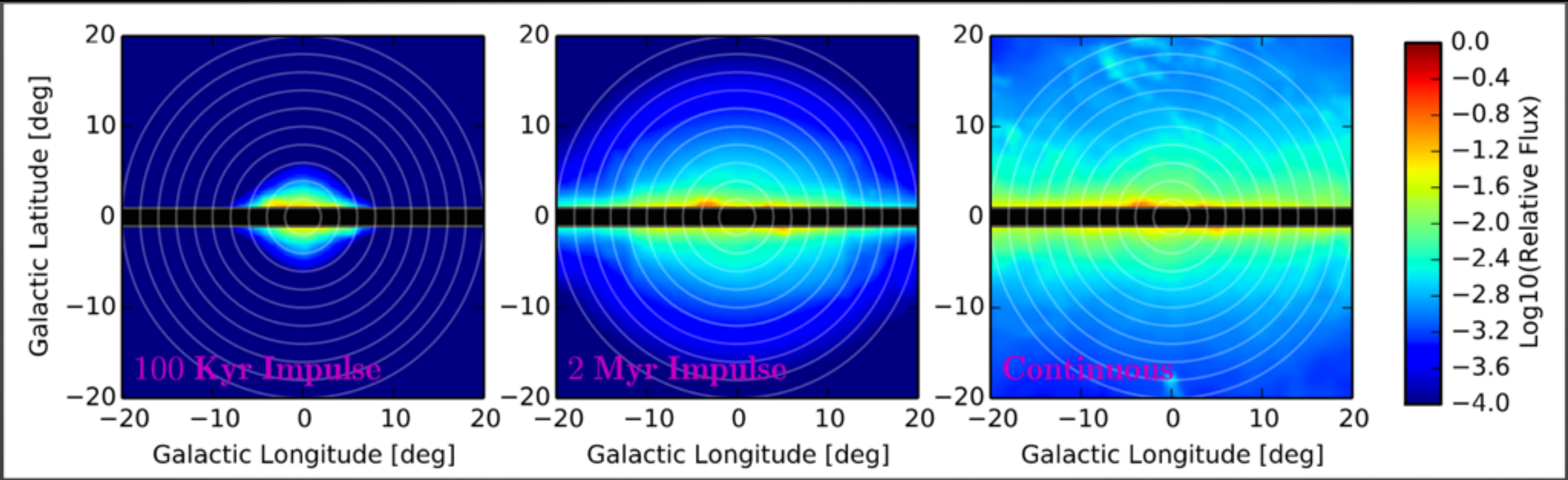
- Two sets of source distributions (“pulsars” and “OB stars”). “Tuned index” models allow spectral indices of background to vary (rather than just intensity), provide better agreement with data.
- Spectrum of excess seems broadly consistent with other results (lower at ~1 GeV); tuned-intensity models lead to higher “signal” tails at large E, but are known to generically undersubtract data at high energies.



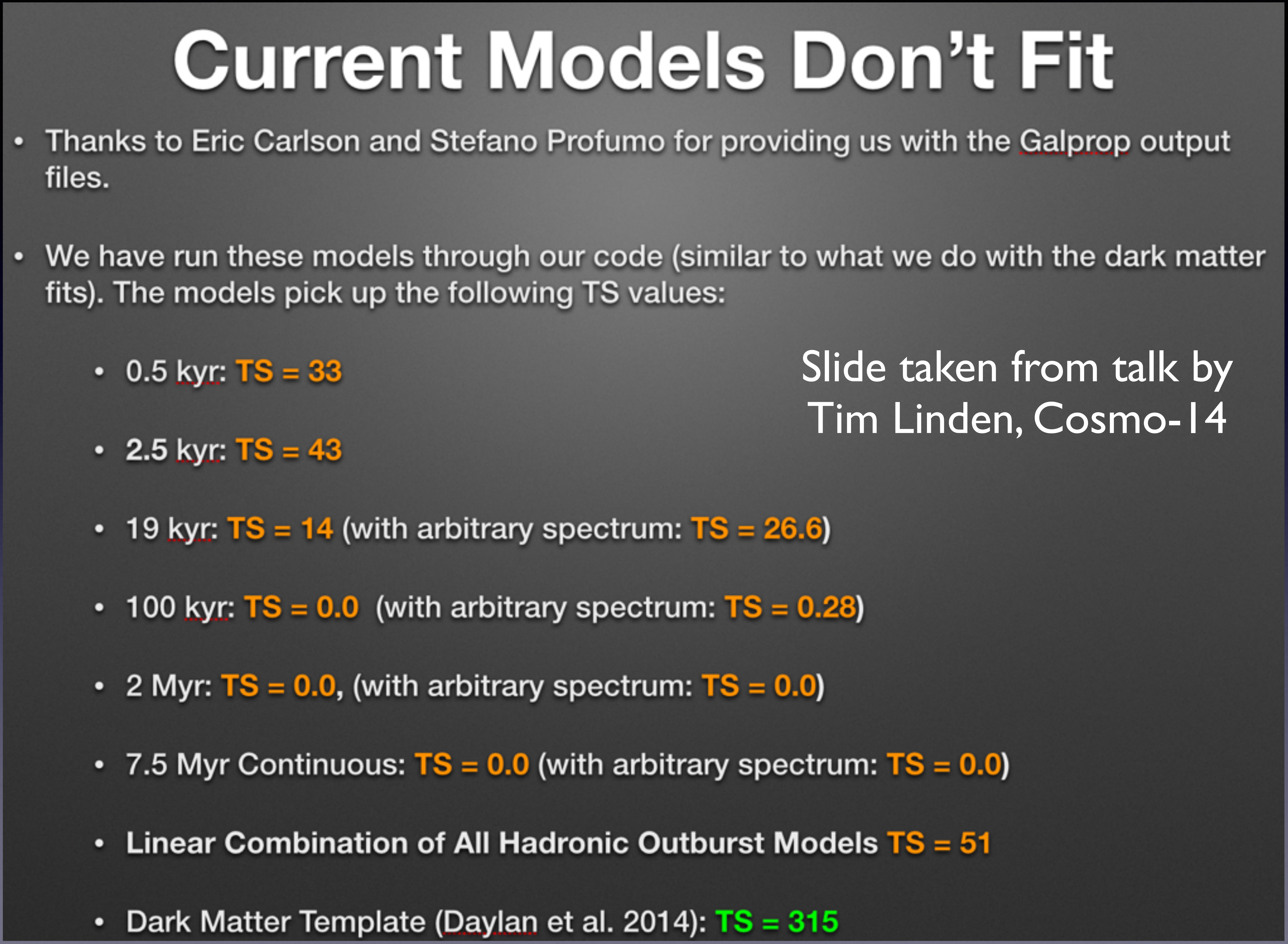
Talk presented by Simona Murgia at Fermi Symposium

Alternate explanations for the GeV excess

Hadronic outbursts



- Carlson & Profumo '14 proposed that an outflow of energetic protons from the Galactic Center could explain the excess.
- Transient event could perhaps give a sharp spectral feature and roughly spherical profile - however, best-fit to spectrum with a broken power law for the proton spectrum requires the index below the break to be -0.7 and above the break to be 17.35.
- Broken power laws common in astrophysics, but not such sharp breaks.



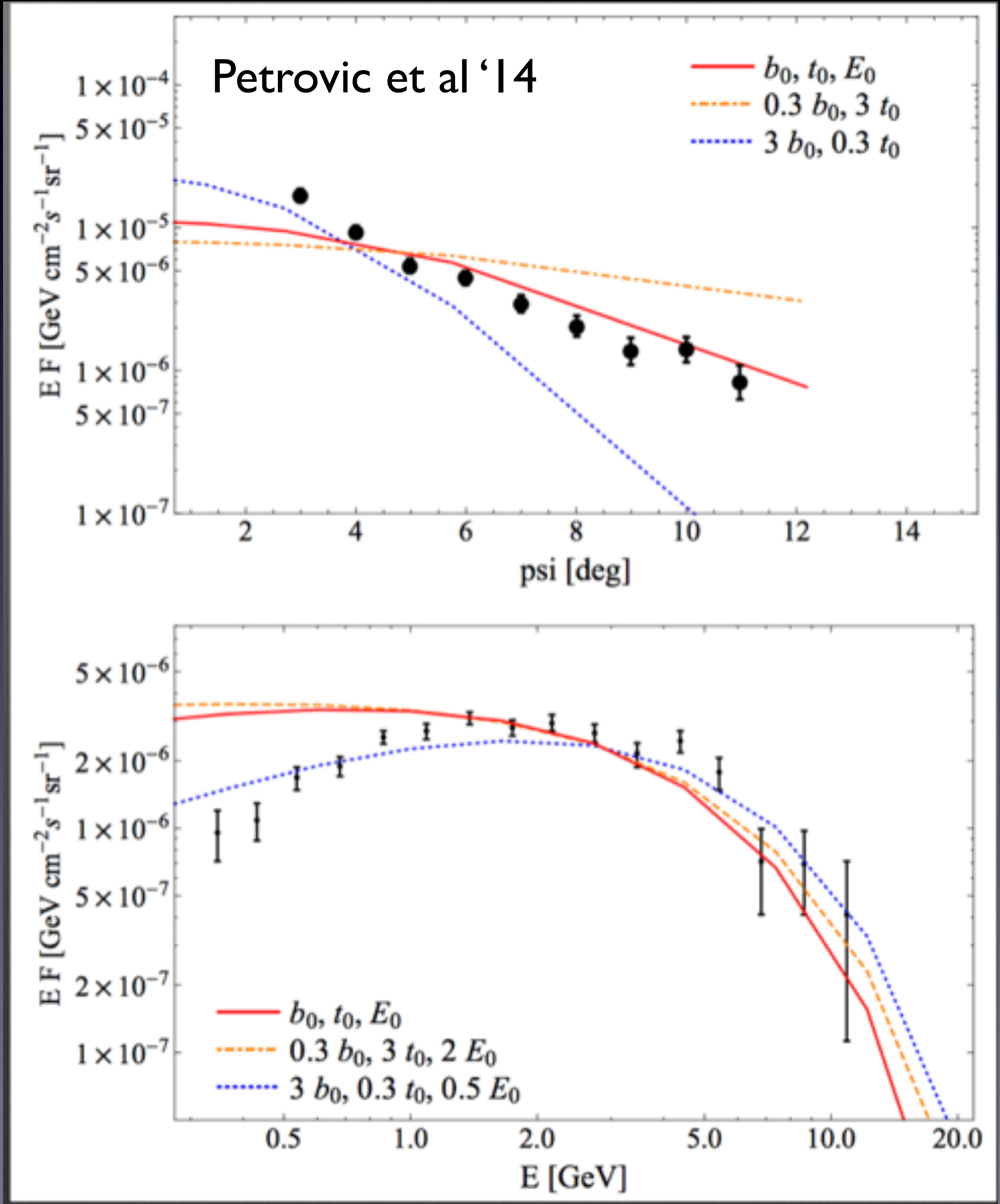
Current Models Don't Fit

- Thanks to Eric Carlson and Stefano Profumo for providing us with the Galprop output files.
- We have run these models through our code (similar to what we do with the dark matter fits). The models pick up the following TS values:
  - 0.5 kyr: **TS = 33**
  - 2.5 kyr: **TS = 43**
  - 19 kyr: **TS = 14** (with arbitrary spectrum: **TS = 26.6**)
  - 100 kyr: **TS = 0.0** (with arbitrary spectrum: **TS = 0.28**)
  - 2 Myr: **TS = 0.0**, (with arbitrary spectrum: **TS = 0.0**)
  - 7.5 Myr Continuous: **TS = 0.0** (with arbitrary spectrum: **TS = 0.0**)
  - **Linear Combination of All Hadronic Outburst Models TS = 51**
  - Dark Matter Template (Daylan et al. 2014): **TS = 315**

Slide taken from talk by
Tim Linden, Cosmo-14

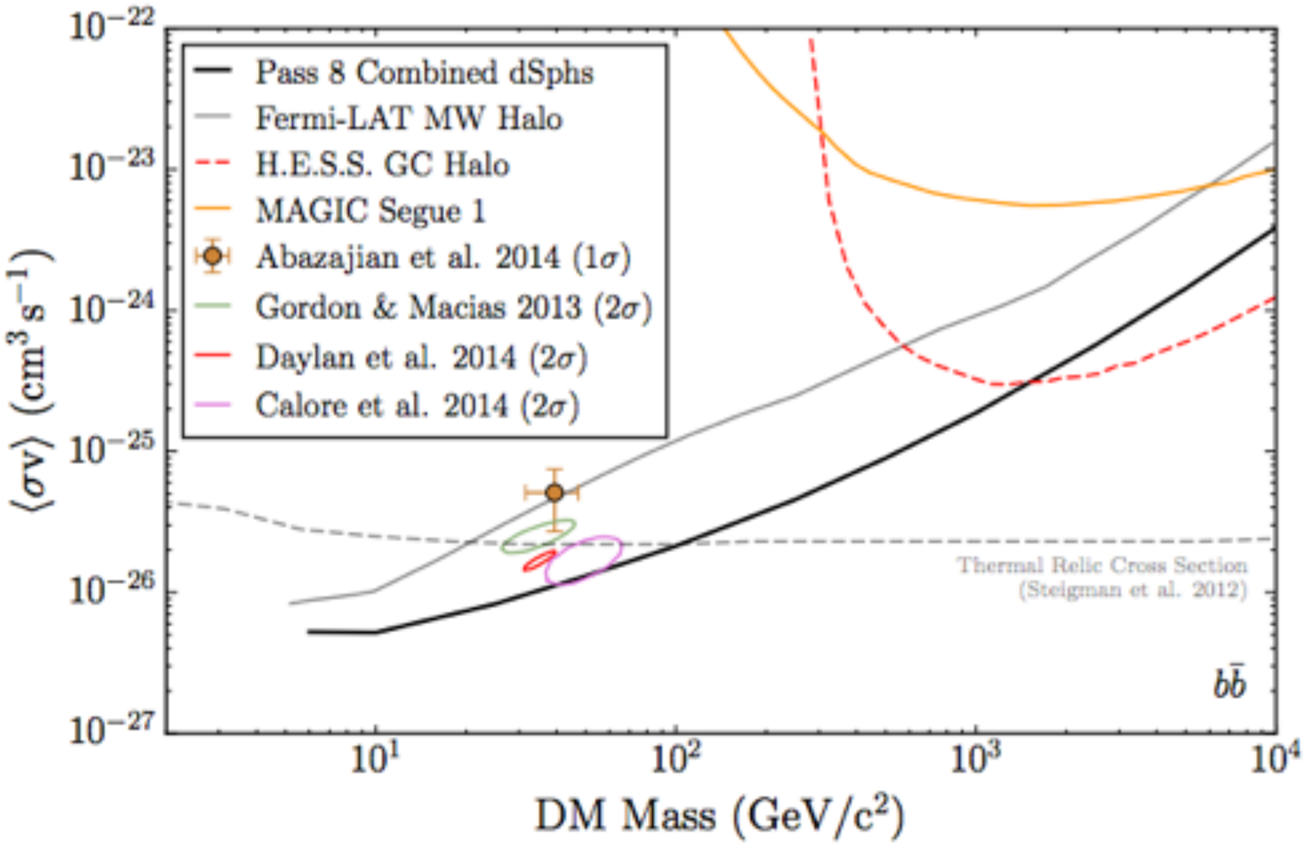
Leptonic outbursts

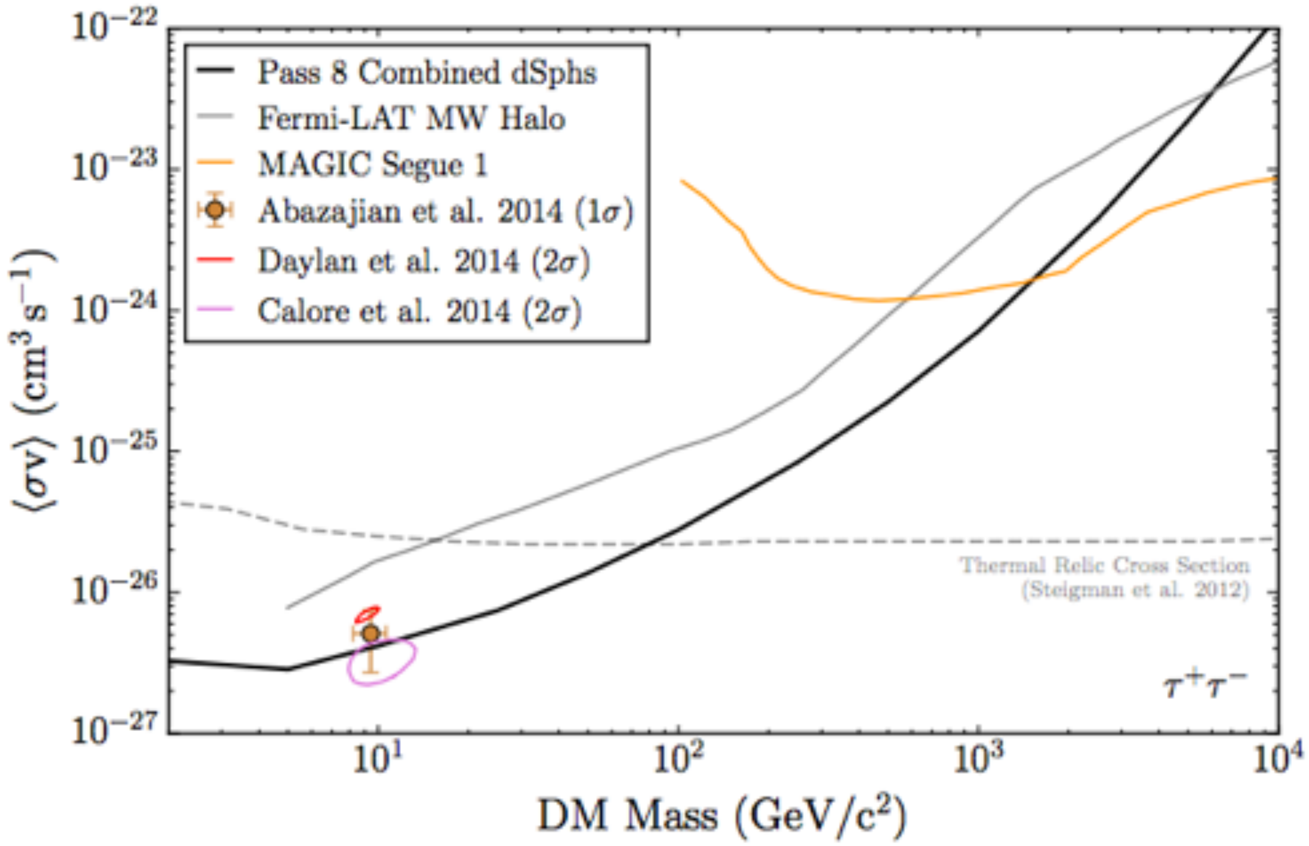
- CR electrons can produce gamma rays from ICS (or bremsstrahlung, but this would give gas-correlated emission)
- Electron cooling => difficult to produce the same hard spectrum over several degrees of sky.


Petrovic et al '14

The dark matter interpretation

Dwarf galaxies

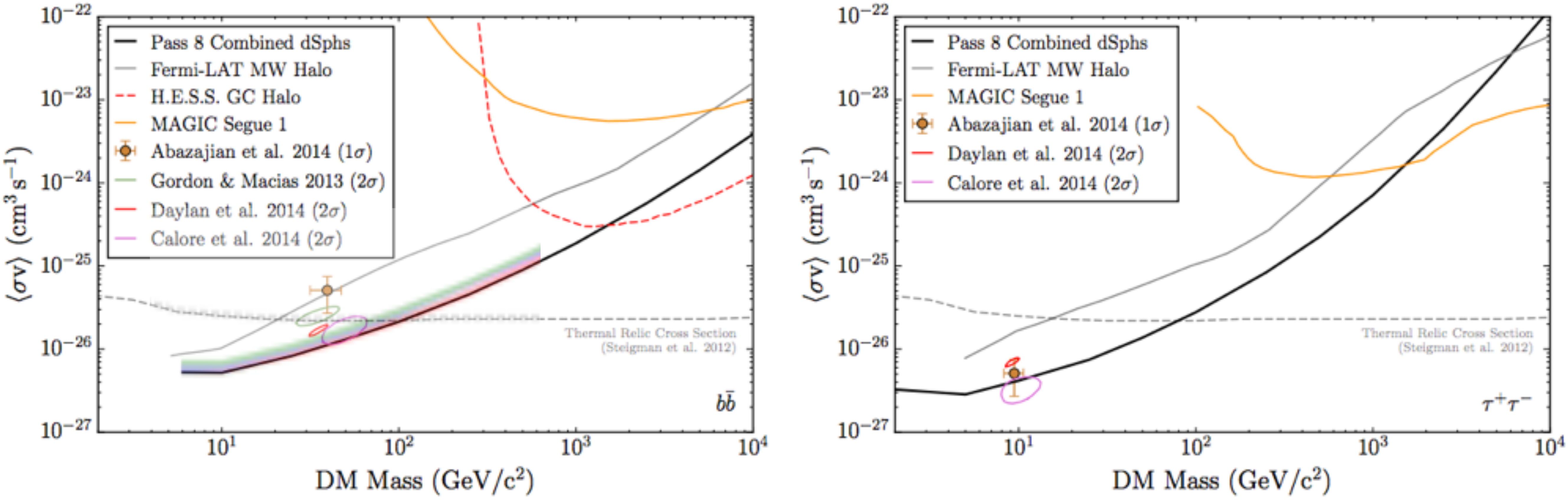




- Dwarf galaxies: DM-dominated systems, provide a clean independent test of DM-annihilation hypothesis.

- Currently provide best current limits on sub-TeV DM annihilating through most channels (Fermi Collaboration, 1503.02641).

Dwarf galaxies

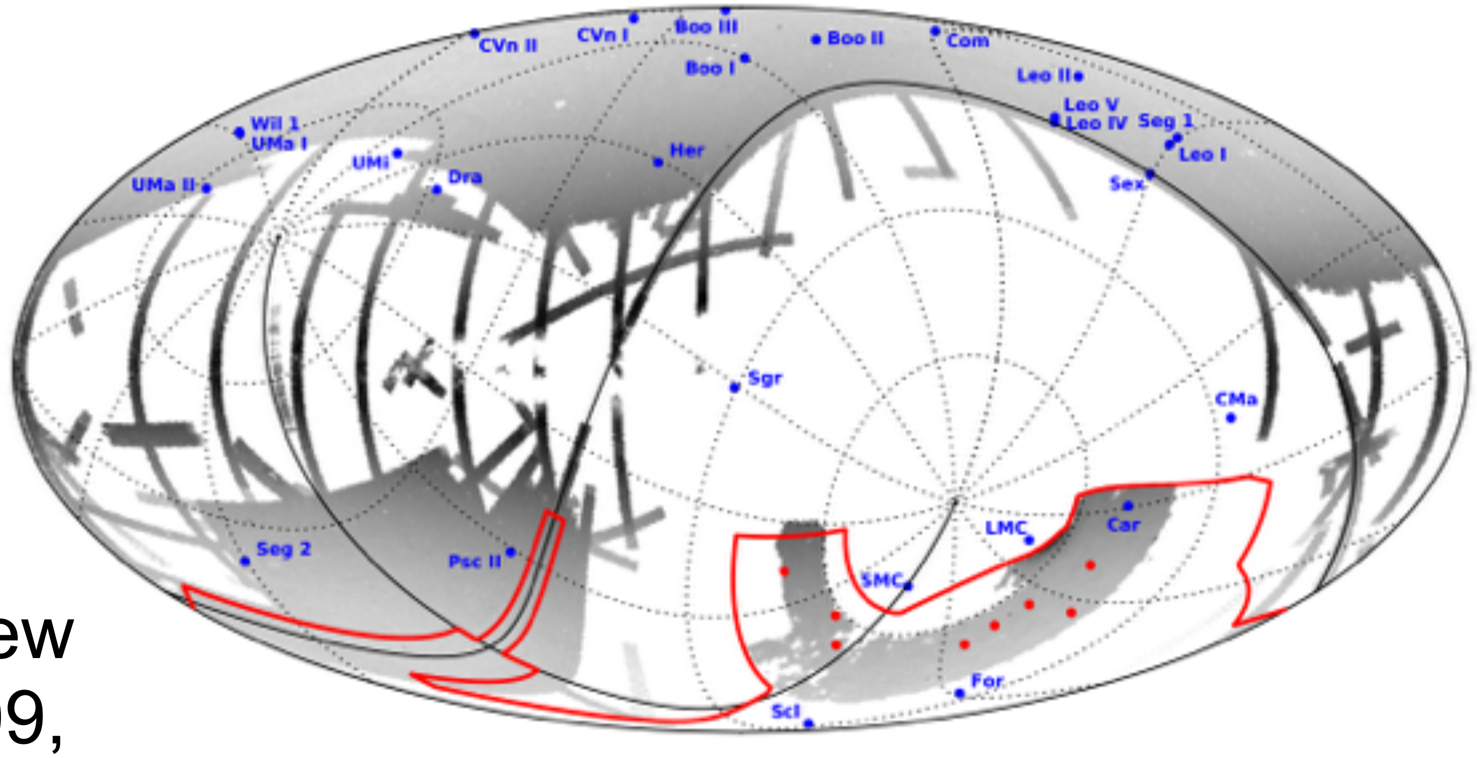


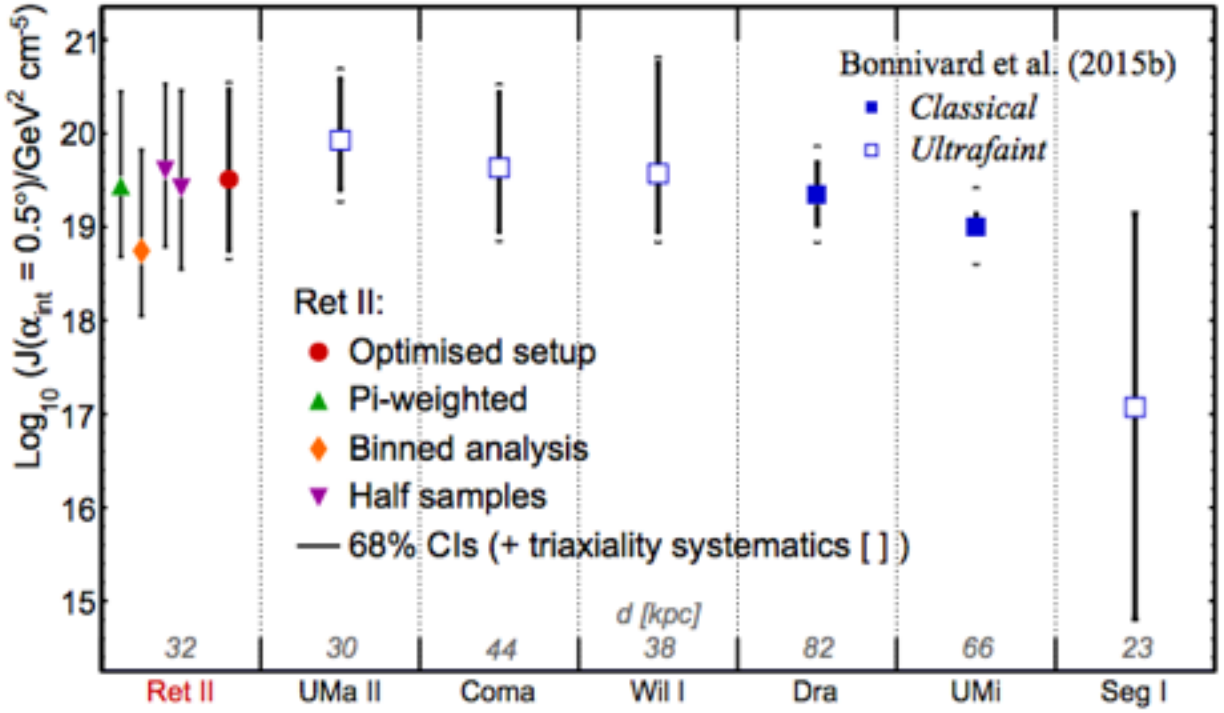
- Dwarf galaxies: DM-dominated systems, provide a clean independent test of DM-annihilation hypothesis.

- Currently provide best current limits on sub-TeV DM annihilating through most channels (Fermi Collaboration, 1503.02641).

DES discovers new dwarf galaxies

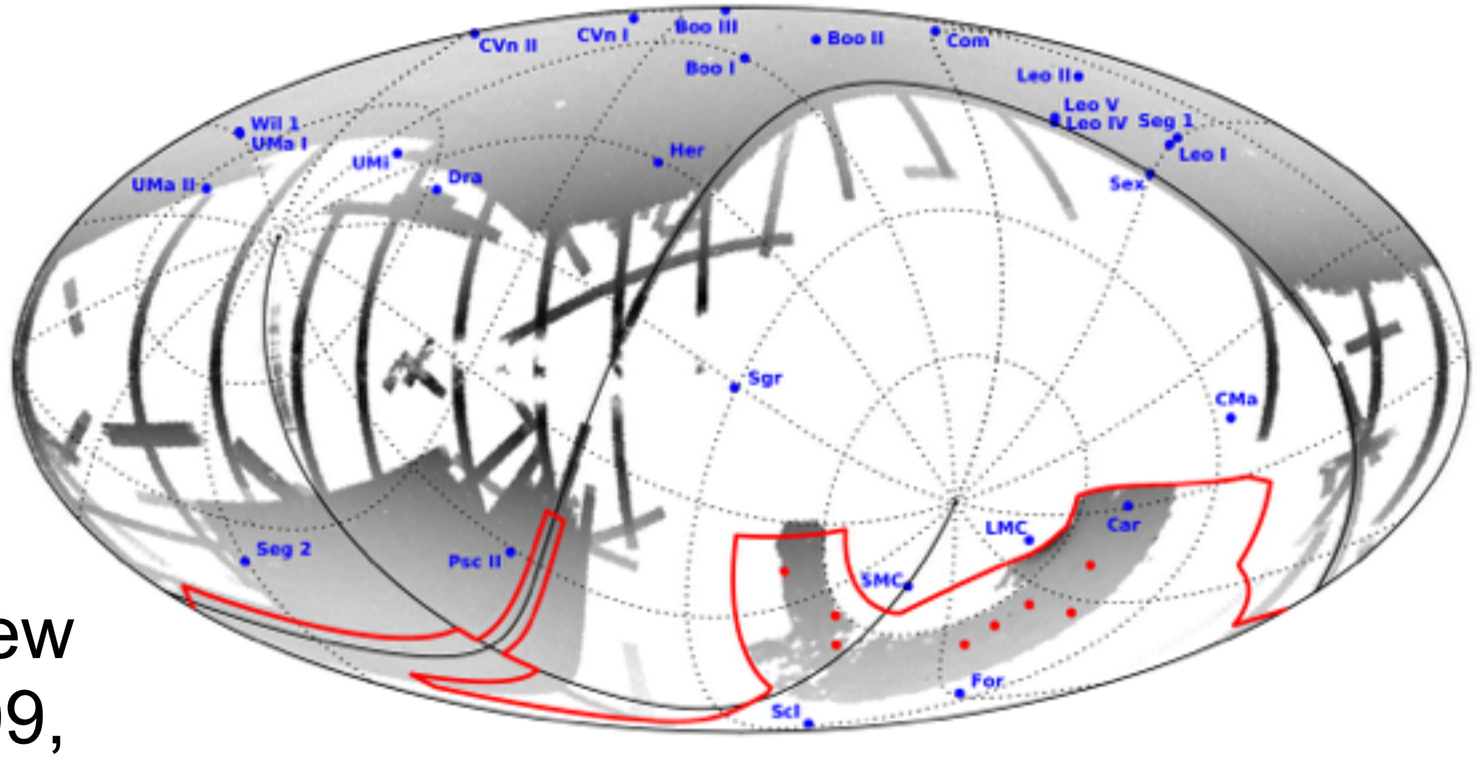
- Discovery of 8-9 new dwarf candidates in DES data in March (1503.02079, 1503.02584).
- More recently, kinematic studies were made of the DM content of “Reticulum II”, the closest of the new dwarfs (Bonnivard et al 1504.03309, Simon et al 1504.02889).
- Want to estimate “J-factor”, figure of merit for DM annihilation.
- Results are consistent within the (large) error bars, but Simon et al prefer a somewhat smaller value.

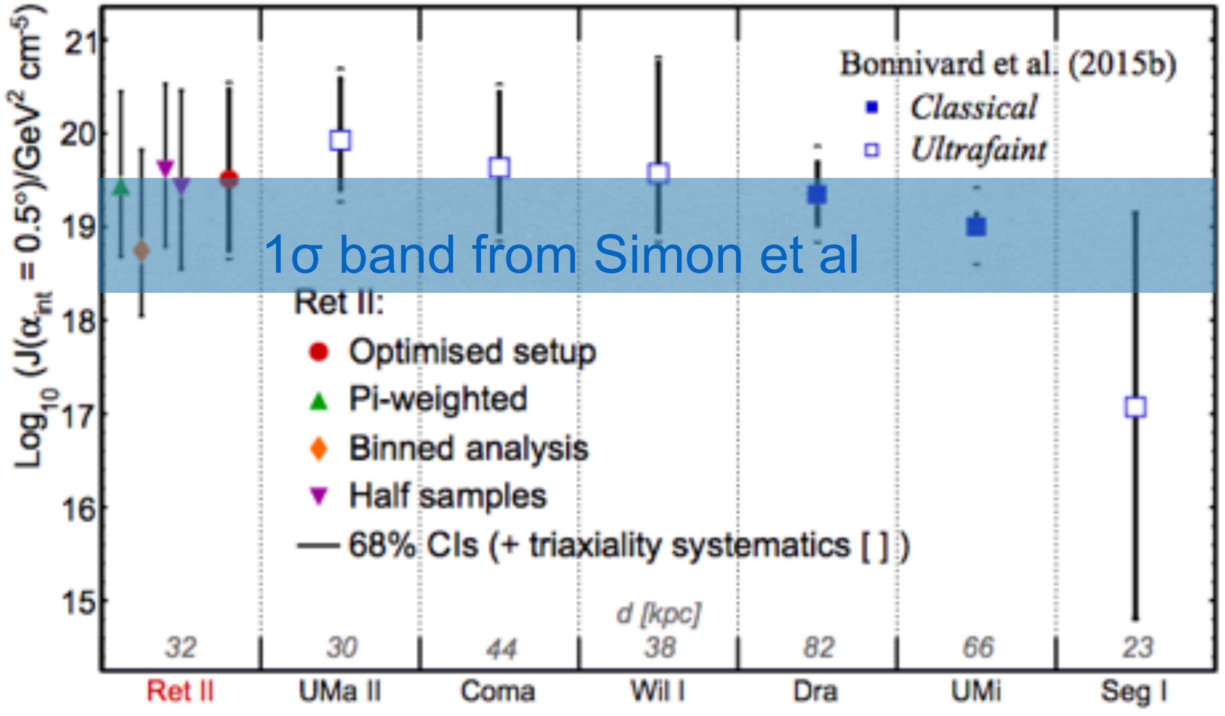




DES discovers new dwarf galaxies

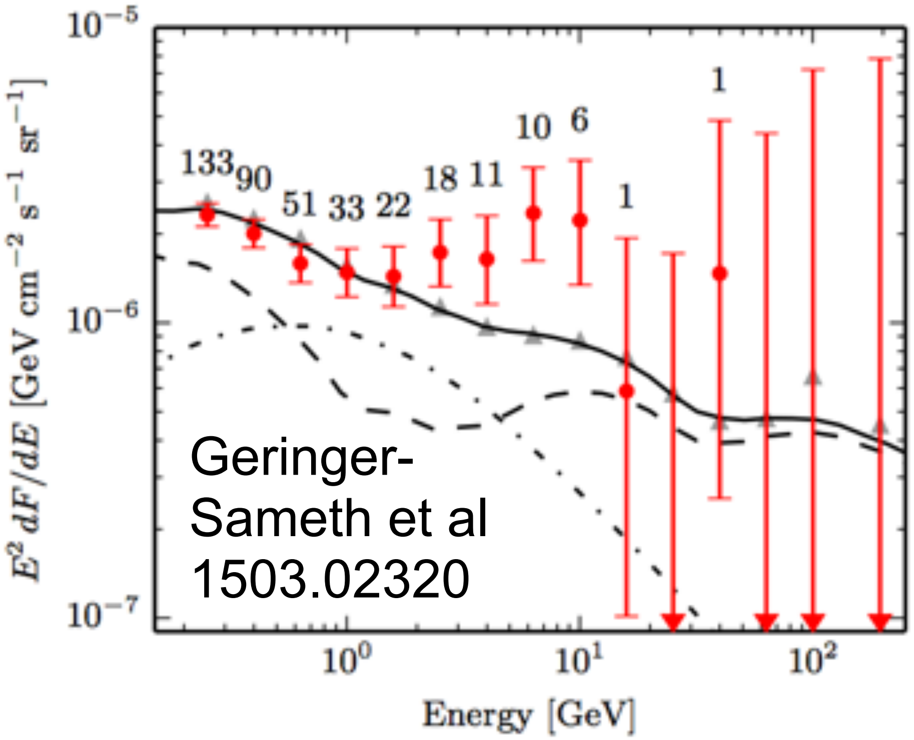
- Discovery of 8-9 new dwarf candidates in DES data in March (1503.02079, 1503.02584).
- More recently, kinematic studies were made of the DM content of “Reticulum II”, the closest of the new dwarfs (Bonnivard et al 1504.03309, Simon et al 1504.02889).
- Want to estimate “J-factor”, figure of merit for DM annihilation.
- Results are consistent within the (large) error bars, but Simon et al prefer a somewhat smaller value.





Reticulum II

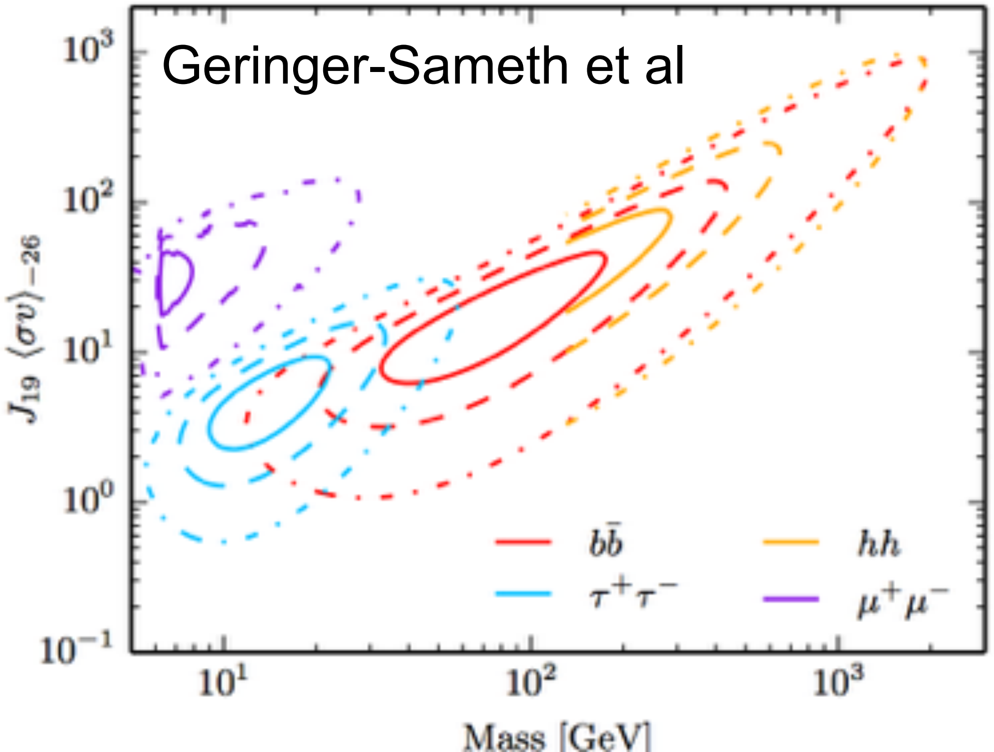
- Recently discovered in DES data, ~30 kpc away. A gamma-ray excess is consistently seen, in the 2-10 GeV energy range.
- Significance debated, various groups find 2.2-3.7σ local significance depending on background modeling. (See talk by K. Bechtol for detailed discussion.)
- Global significance depends 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.



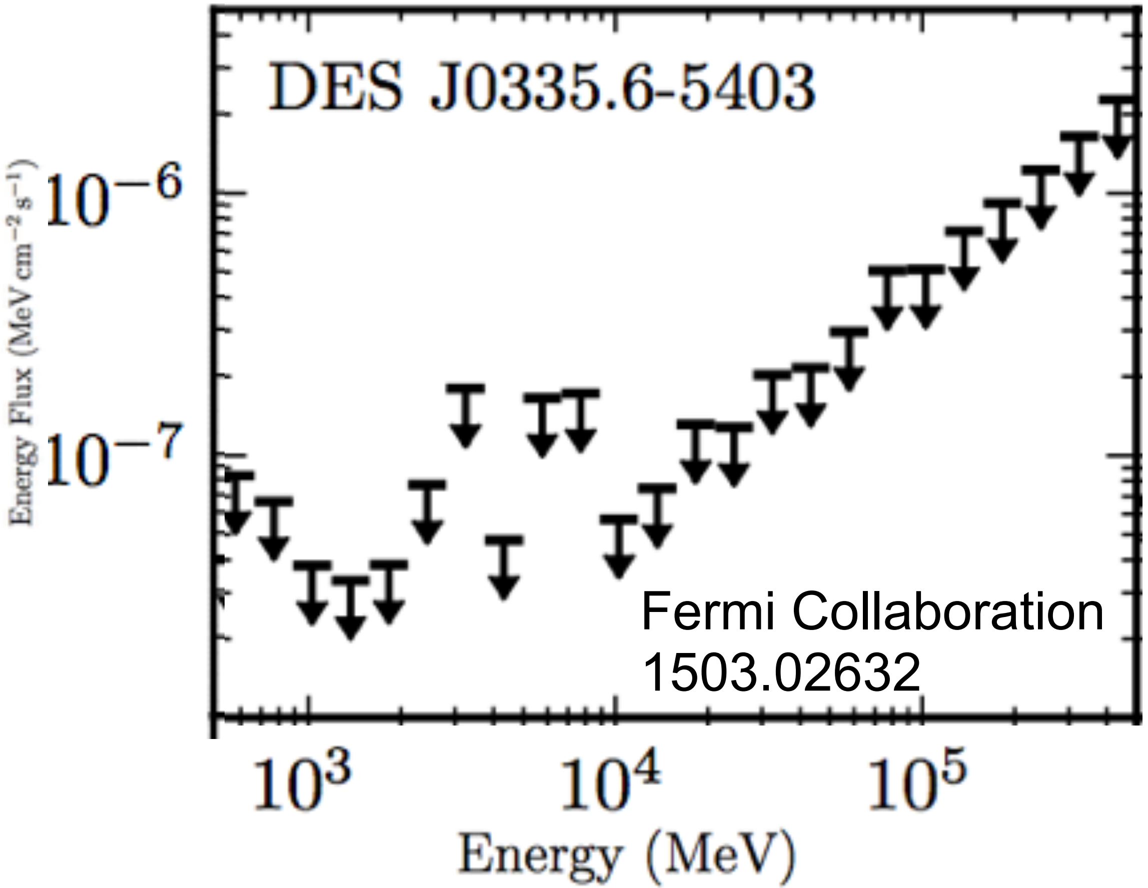
Geringer-Sameth et al 1503.02320

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.



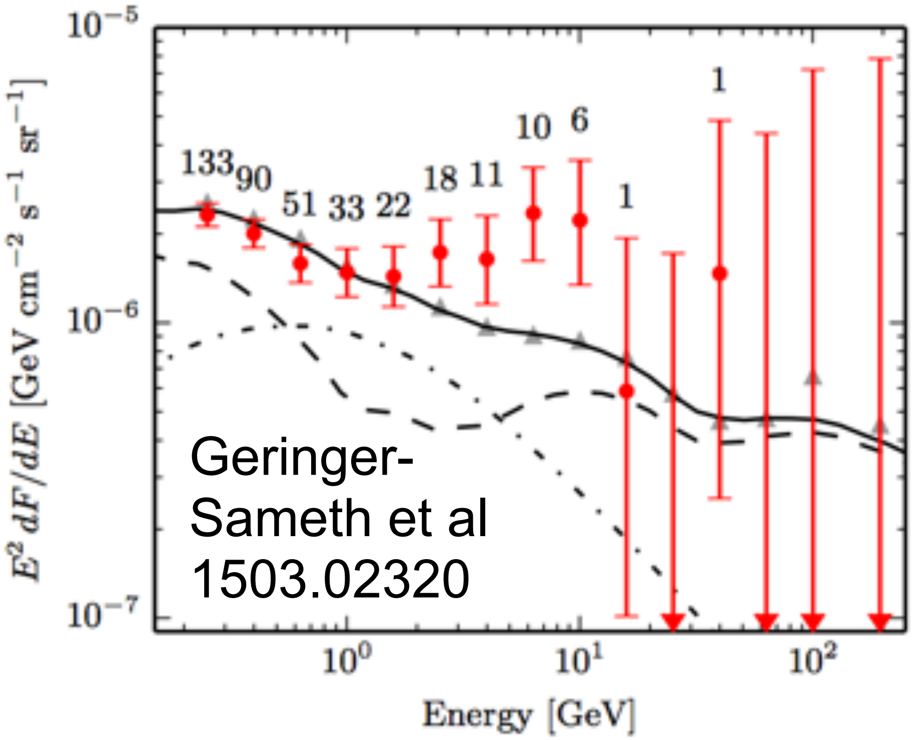
Geringer-Sameth et al



Fermi Collaboration 1503.02632

Reticulum II

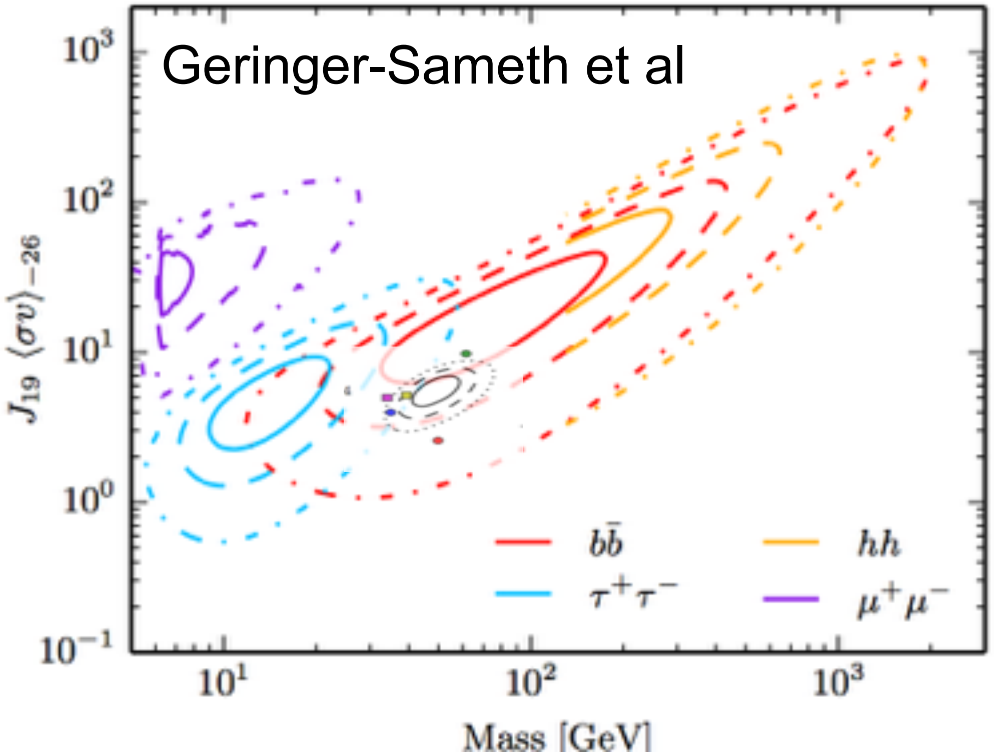
- Recently discovered in DES data, ~30 kpc away. A gamma-ray excess is consistently seen, in the 2-10 GeV energy range.
- Significance debated, various groups find 2.2-3.7σ local significance depending on background modeling. (See talk by K. Bechtol for detailed discussion.)
- Global significance depends 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.



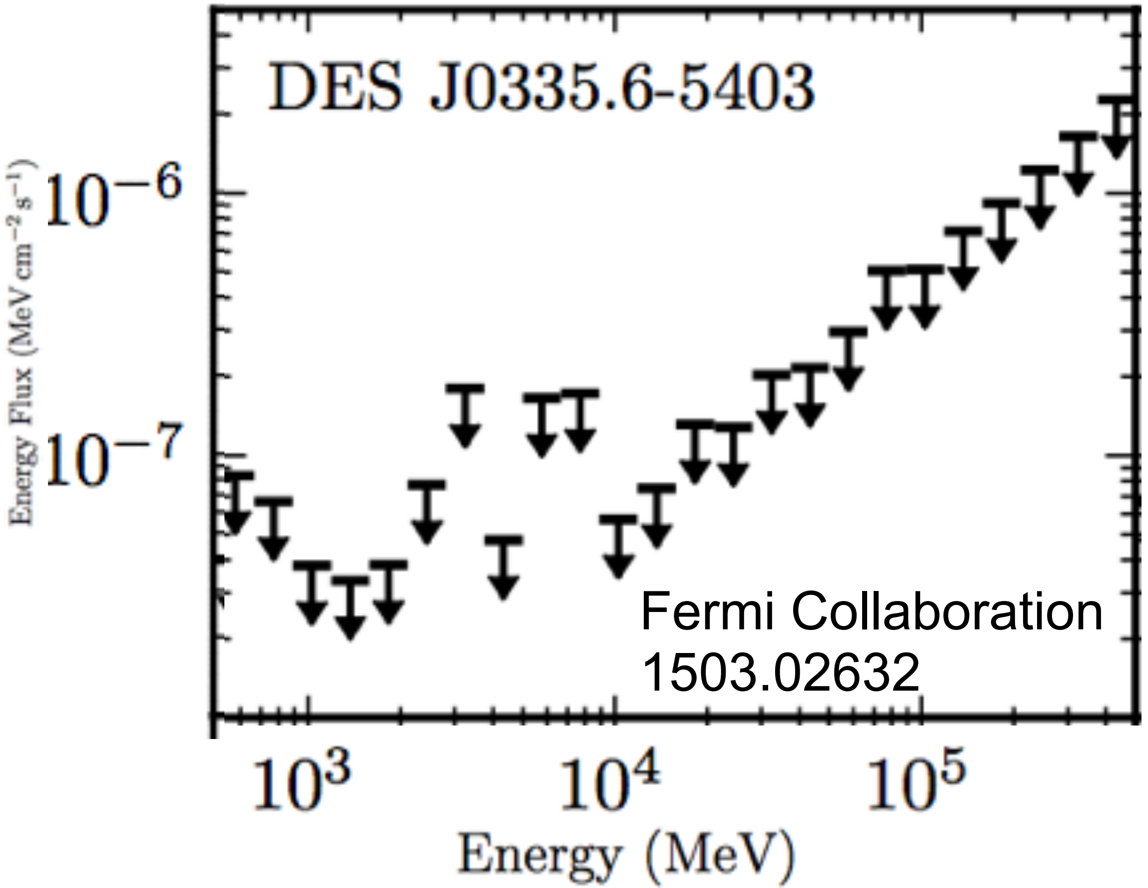
Geringer-Sameth et al 1503.02320

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.

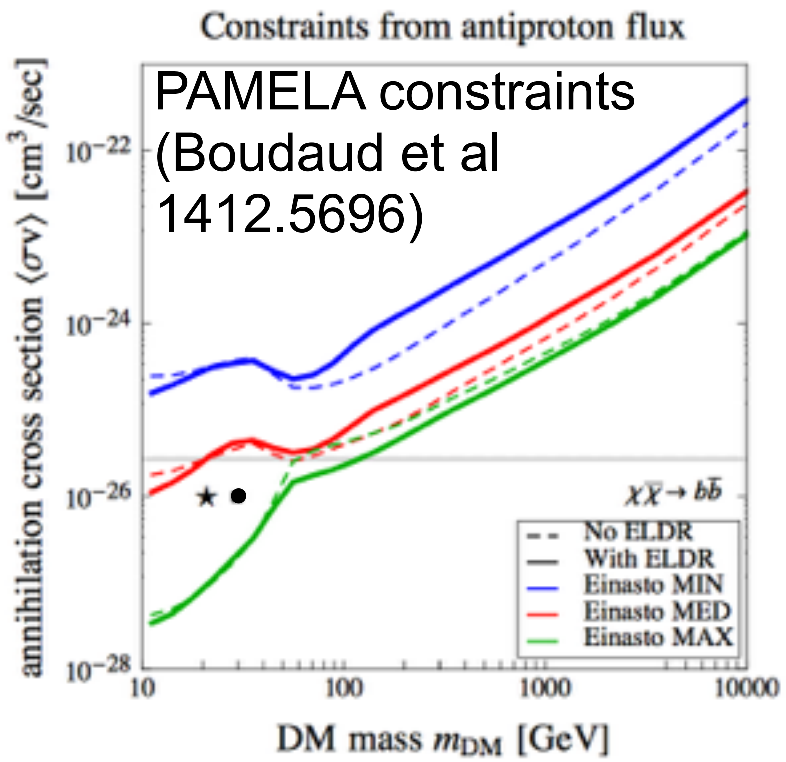


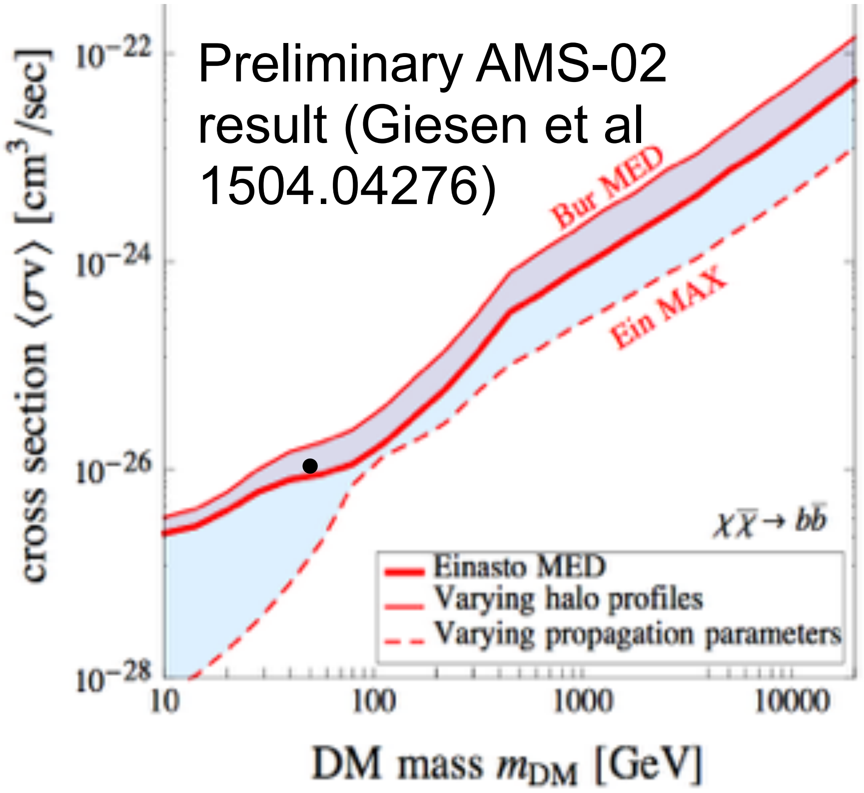
Geringer-Sameth et al

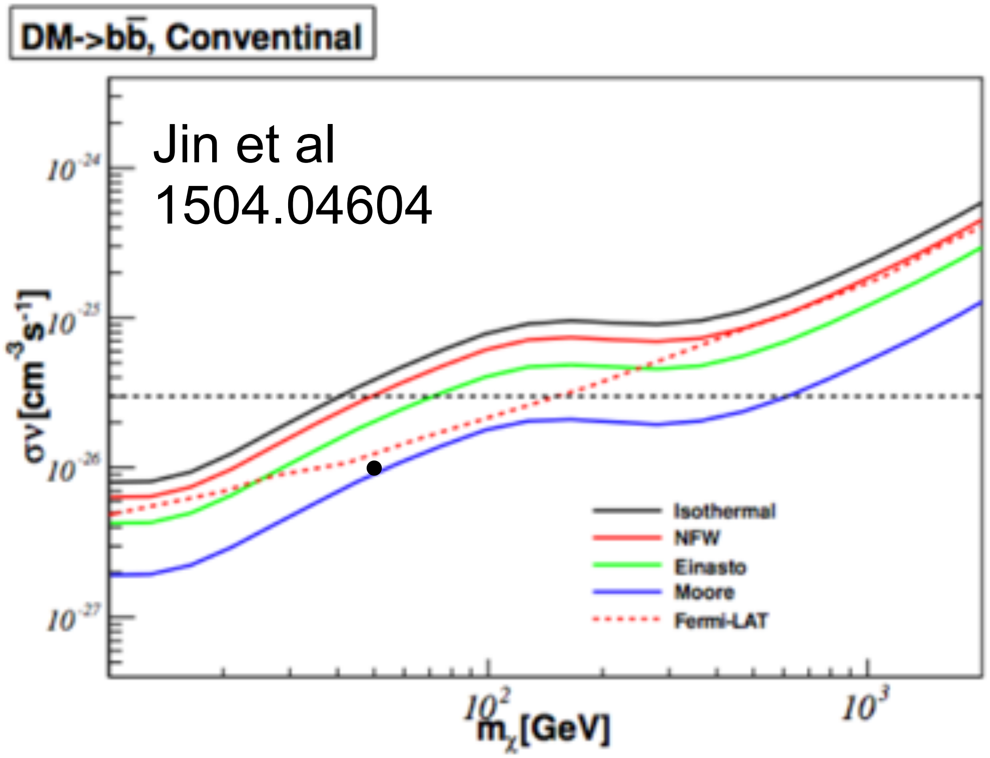


Fermi Collaboration 1503.02632

Constraining light dark matter with AMS-02


PAMELA constraints (Boudaud et al 1412.5696)

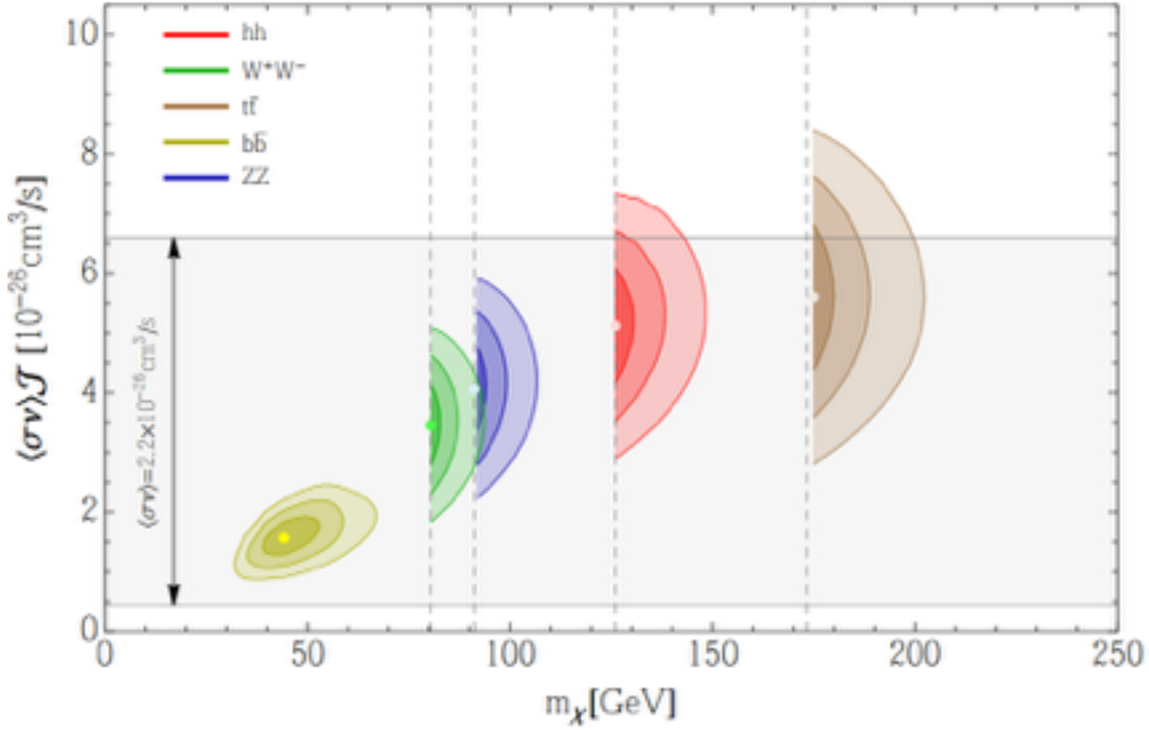

Preliminary AMS-02 result (Giesen et al 1504.04276)


Jin et al 1504.04604

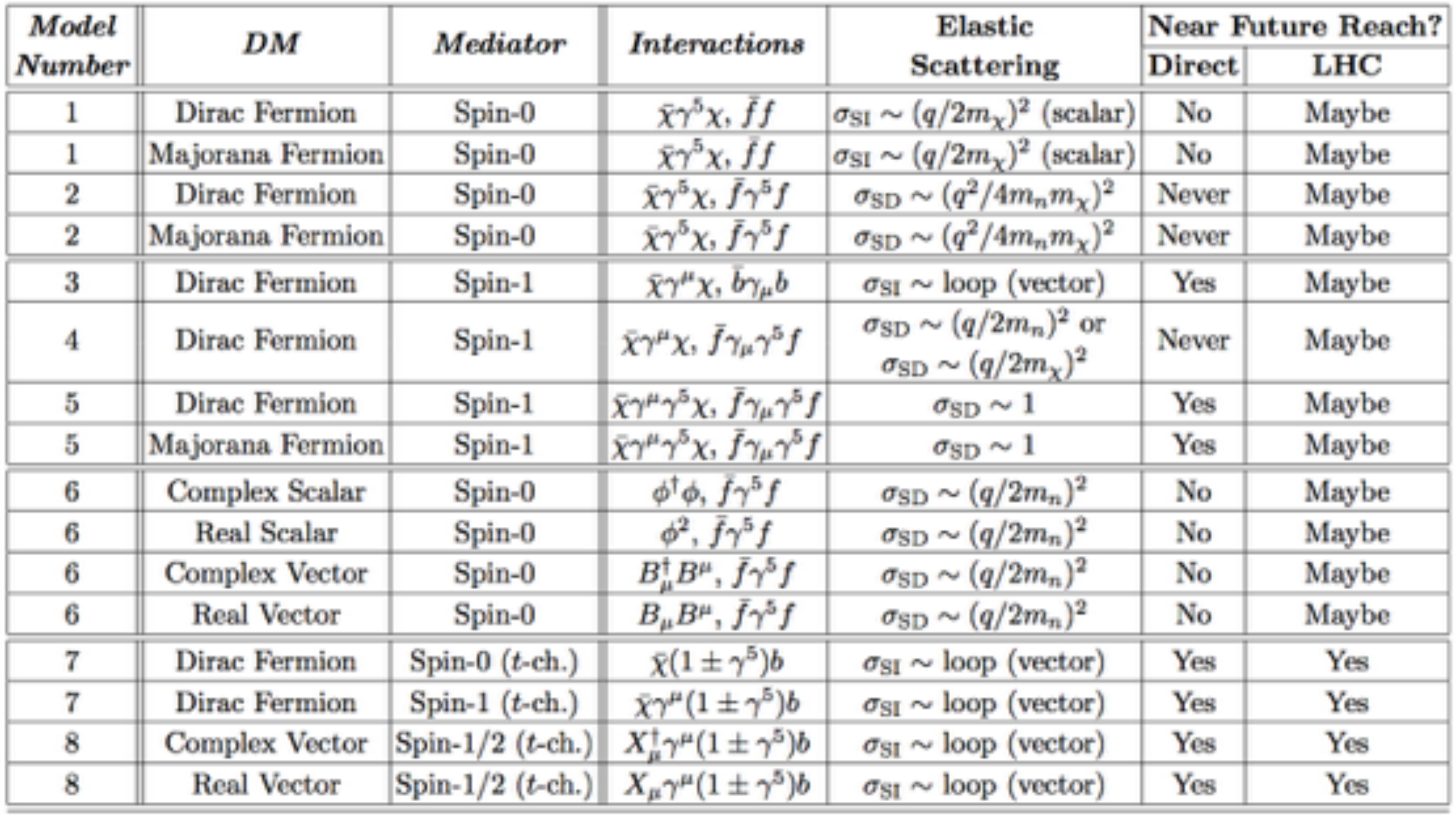
- Precision antiproton measurements give the hope of sensitivity to DM annihilating into hadronic channels.
- Large systematic uncertainties due to complex propagation effects (e.g. solar modulation, energy loss from tertiary particles, diffusive reacceleration). Incorporating all AMS-02 data may help 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.

Some theoretical studies

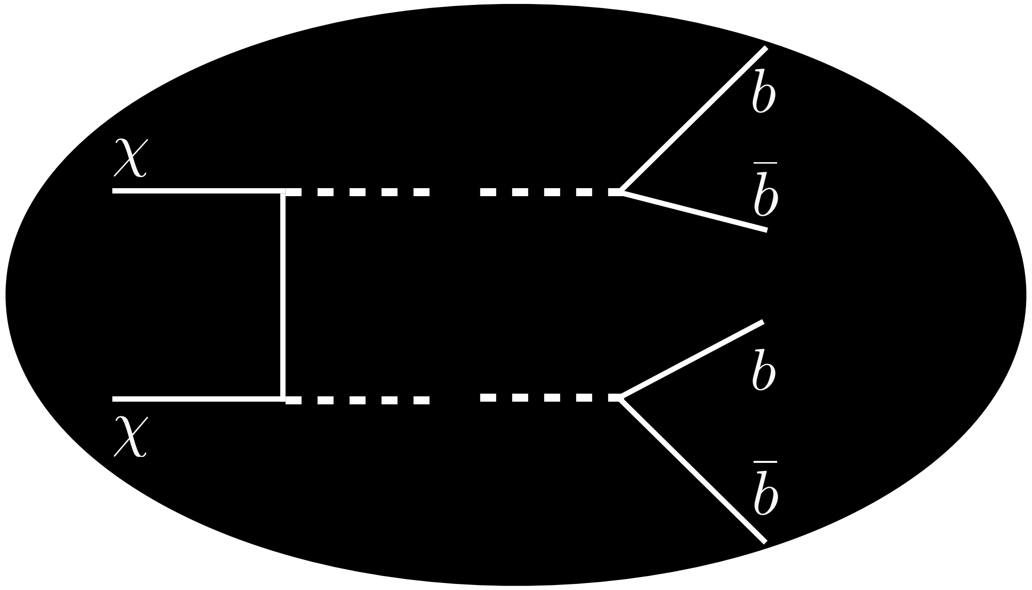
Agrawal et al 1411.2592 (high-mass DM)



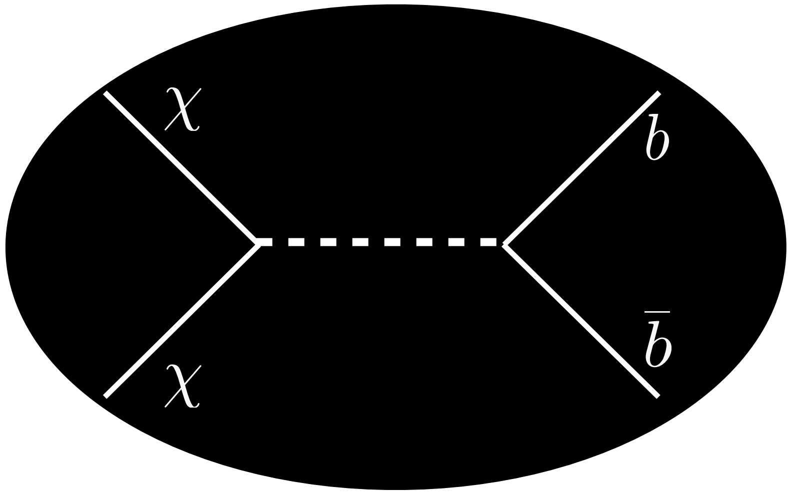
Berlin et al 1404.0022 (simplified models)



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



Annihilation to a new light state which subsequently decays to SM (e.g. 1405.0272, 1405.5204)



Annihilation through a pseudoscalar into b quarks ("coy DM", 1401.6458)

SUSY implementations discussed in e.g. 1406.6372, 1409.1573.

Very difficult in MSSM, can be done in NMSSM