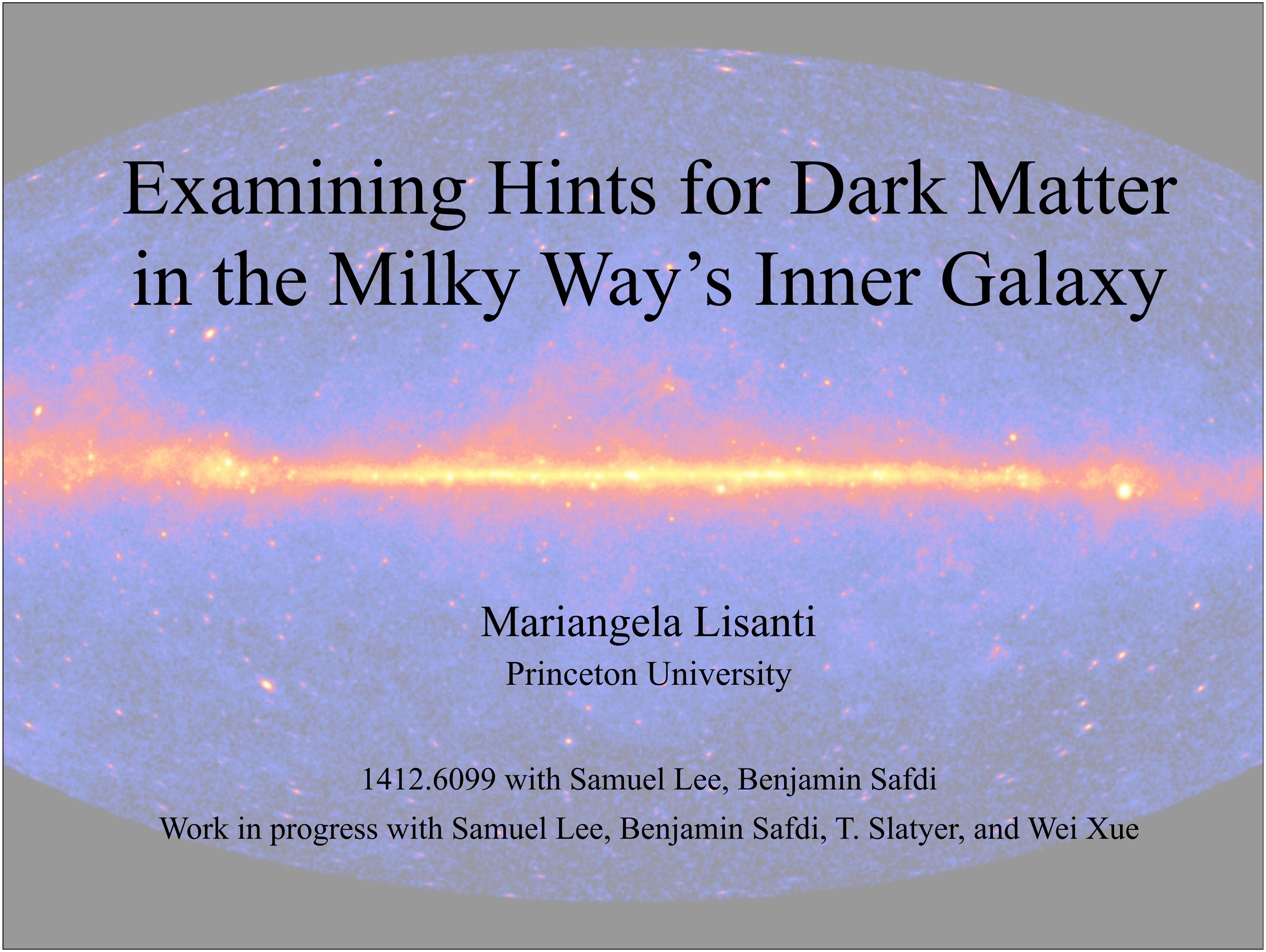


Examining Hints for Dark Matter in the Milky Way's Inner Galaxy

Mariangela Lisanti

Princeton University

1412.6099 with Samuel Lee, Benjamin Safdi

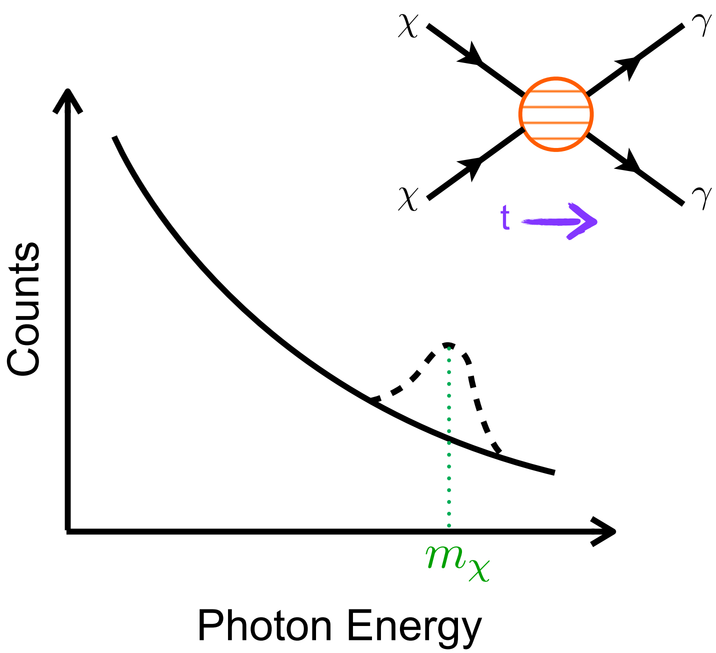
Work in progress with Samuel Lee, Benjamin Safdi, T. Slatyer, and Wei Xue

Indirect Detection

Indirect detection is a promising avenue for dark matter discovery

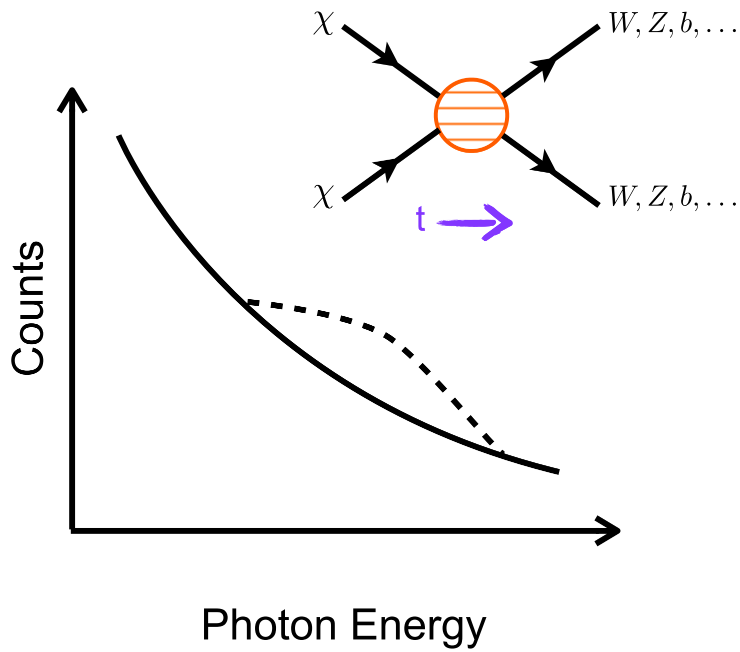
Monochromatic Photons

Direct decay to photons,
a line in photon energy spectrum



Continuum Photons

Annihilation to SM final states that
shower into photons



Fermi LAT

Today, the *Fermi* LAT is one of the best probes of high-energy gamma rays from dark matter annihilation

http://fermi.gsfc.nasa.gov/

Launched June 11, 2008

Sensitive to energies from 20 MeV to > 300 GeV

Scans over the whole sky every three hours

Outline

Current Status:

The Galactic Center Excess

Two Hypotheses:

Dark Matter and Point Sources

Distinguishing the Hypotheses:

Photon Count Statistics

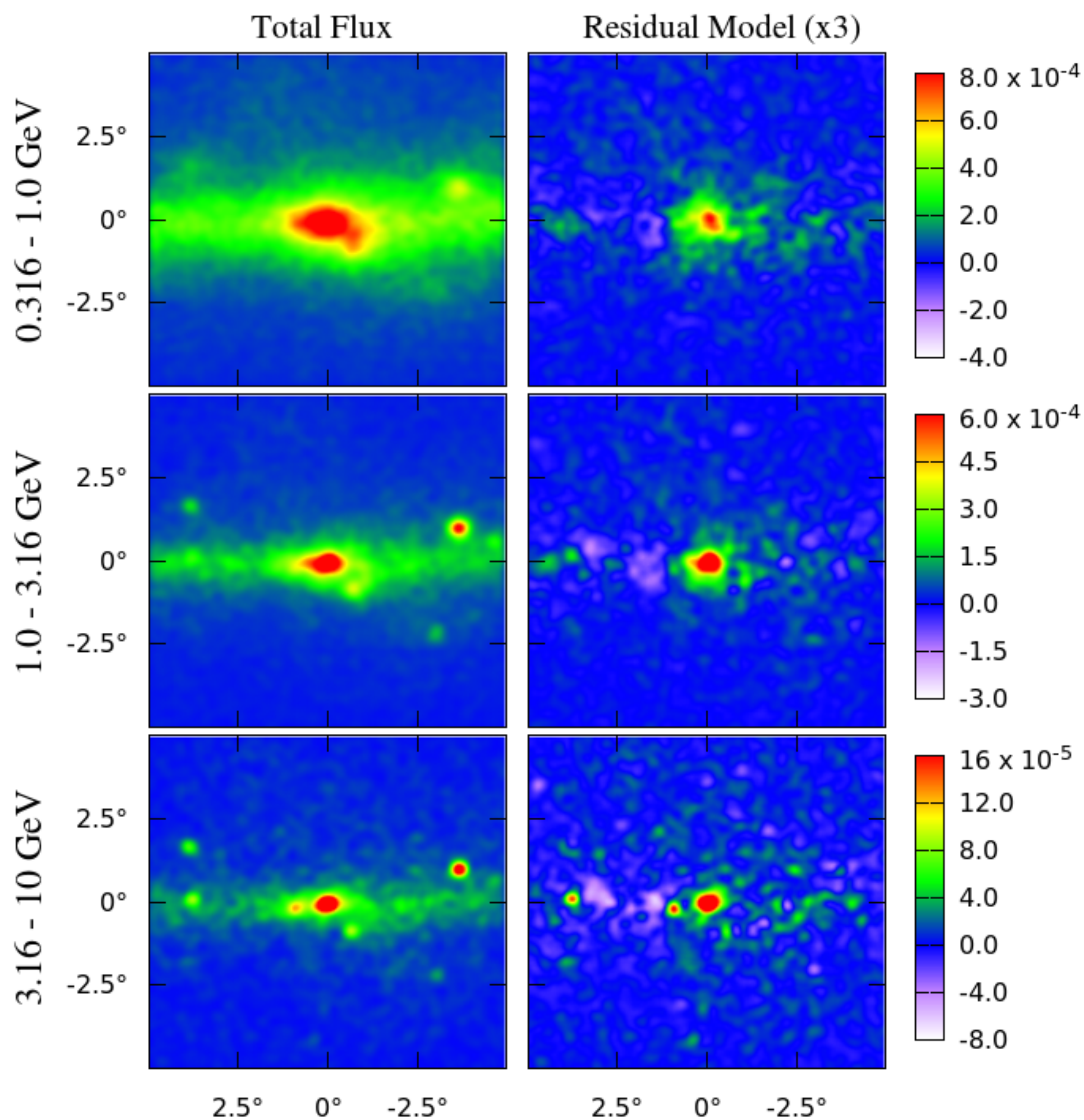
GeV Photon Excess

Observed at the Galactic Center and Inner Galaxy (≲ 10°)

Constitutes ~10% total flux

High statistical significance

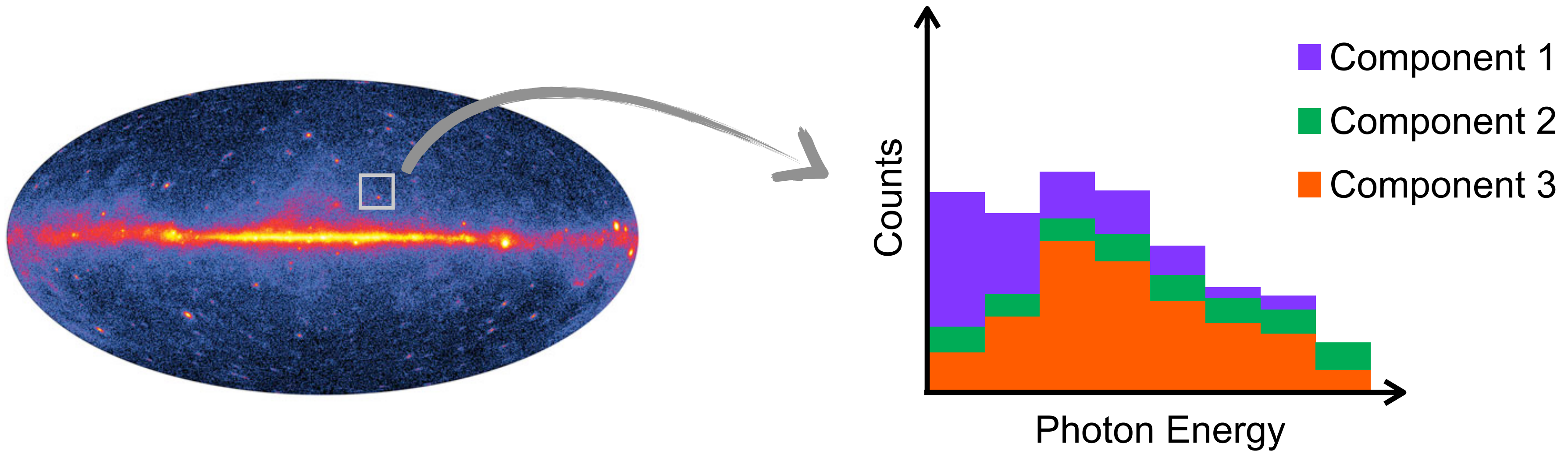
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian *et al.* [1402.4090]
Daylan *et al.* [1402.6703]
Calore, Cholis, and Weniger [1409.0042]



Daylan *et al.* [1402.6703]

Template Analysis

For a given pixel, find the photon contribution of each component in each energy bin



Use spatial information of the different source components to determine whether they contribute in a given pixel

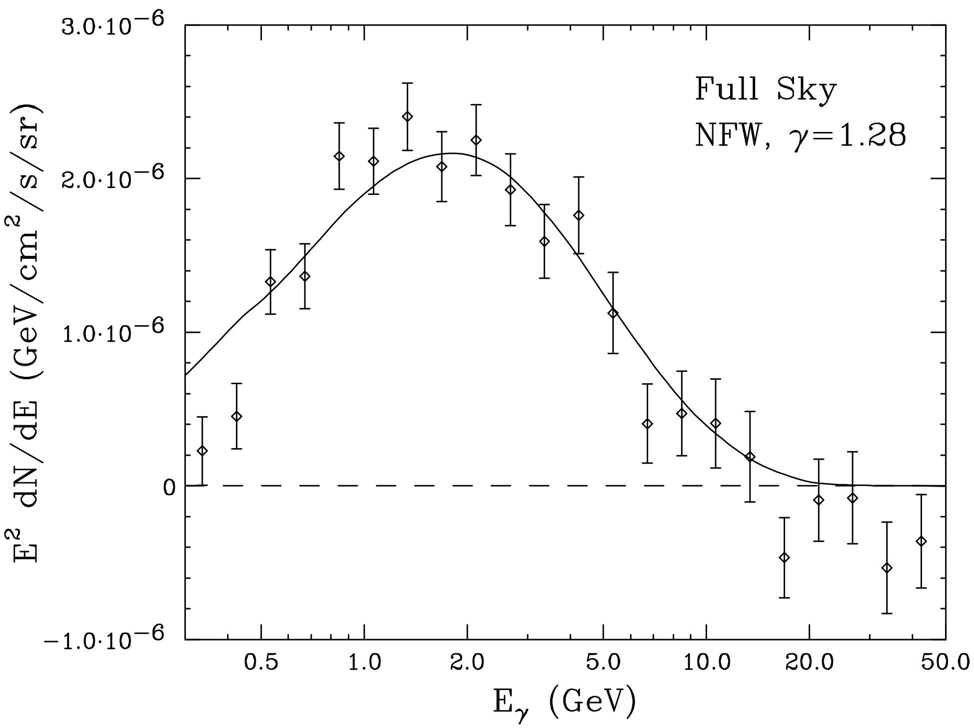
Likelihood maximization determines overall normalization of each component in the region of interest, for a given energy bin

The Signal

Approximately spherically symmetric, centered on Sgr A*

Flux fall off radially as ~ $r^{-(2.2-2.6)}$

Extends up to 10° off the plane



Daylan *et al.* [1402.6703]

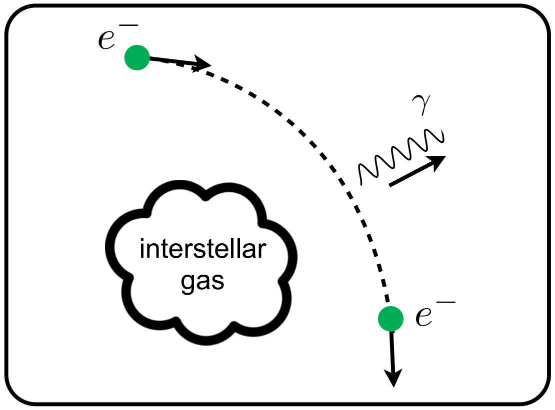
Diffuse Background

High-energy γ-rays produced from cosmic rays propagating in the Galaxy

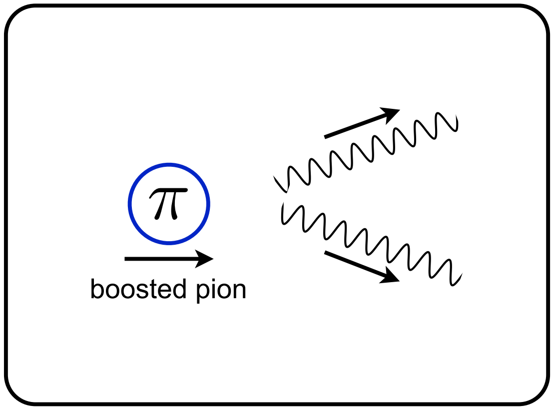
Depends on location of cosmic-ray sources and on the gas distribution

Modeling of diffuse emission in the Inner Galaxy is uncertain;
local measurements do not set very tight constraints in that region

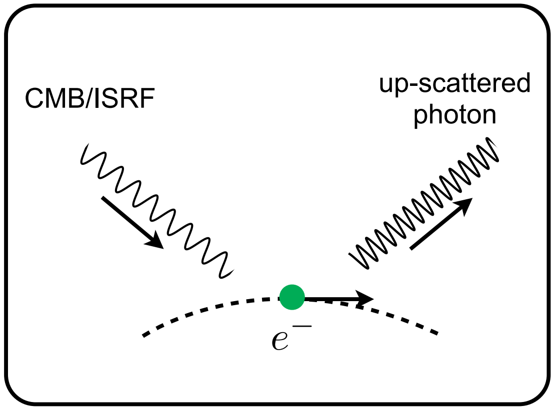
Bremsstrahlung



Pion Emission

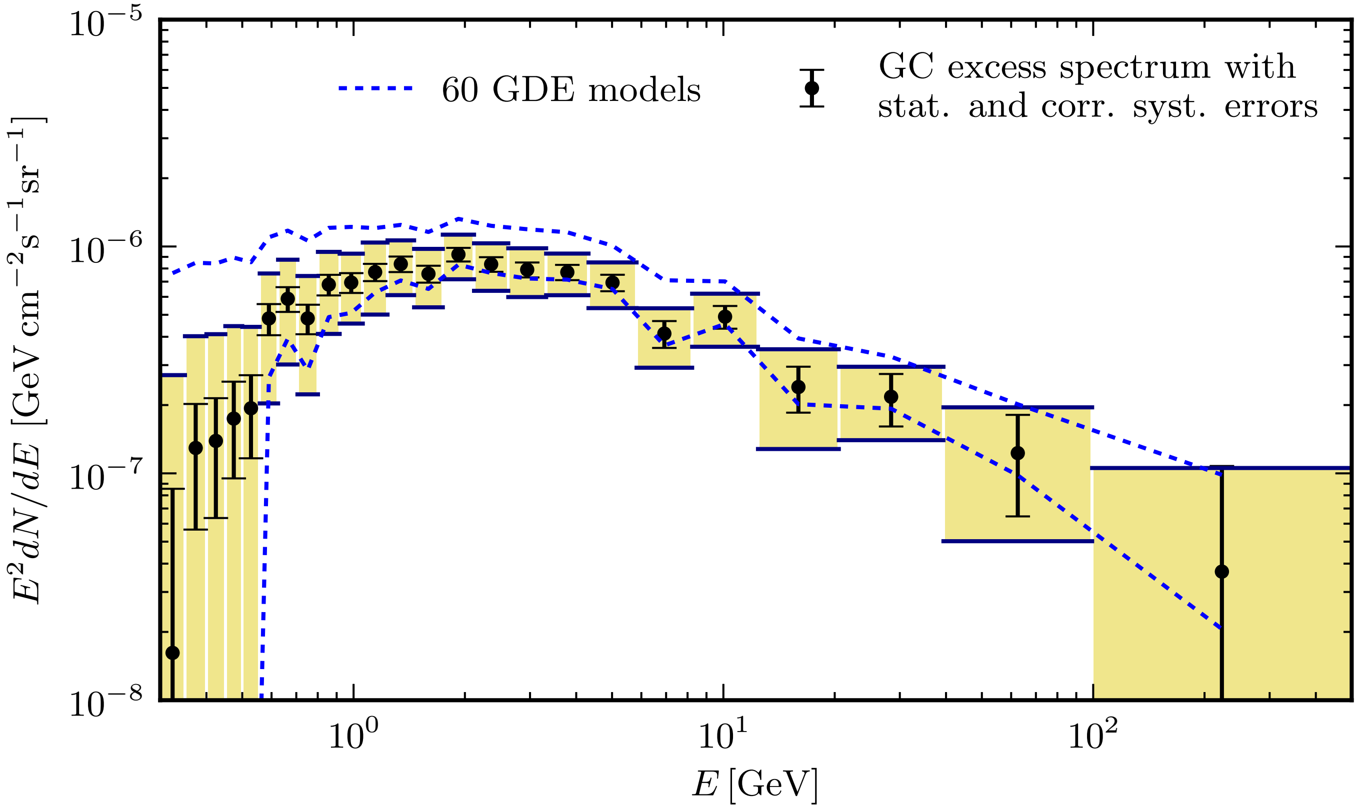


Inverse Compton



Diffuse Background

Evidence for excess emission appears to be robust even under uncertainties in diffuse emission models



Calore, Cholis, and Weniger [1409.0042]

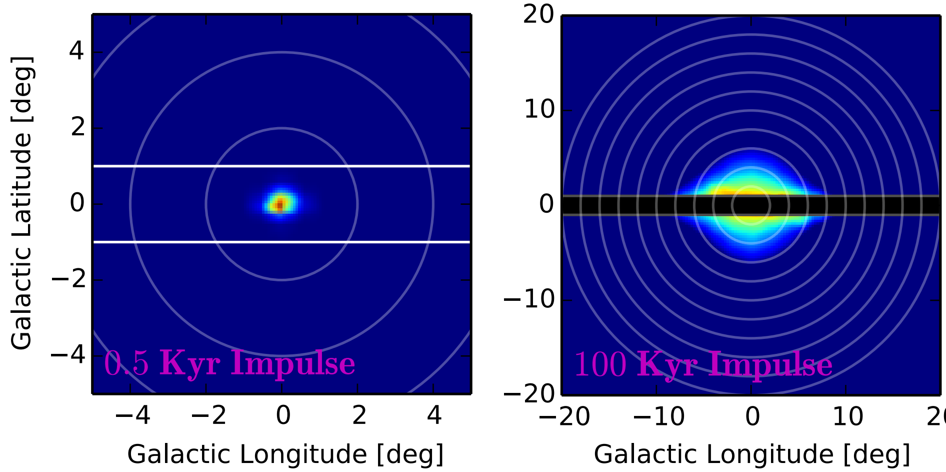
New Injection Sources

Example 1

New population of cosmic-ray protons injected at the GC

Correlated with gas distribution -- spatial morphology?

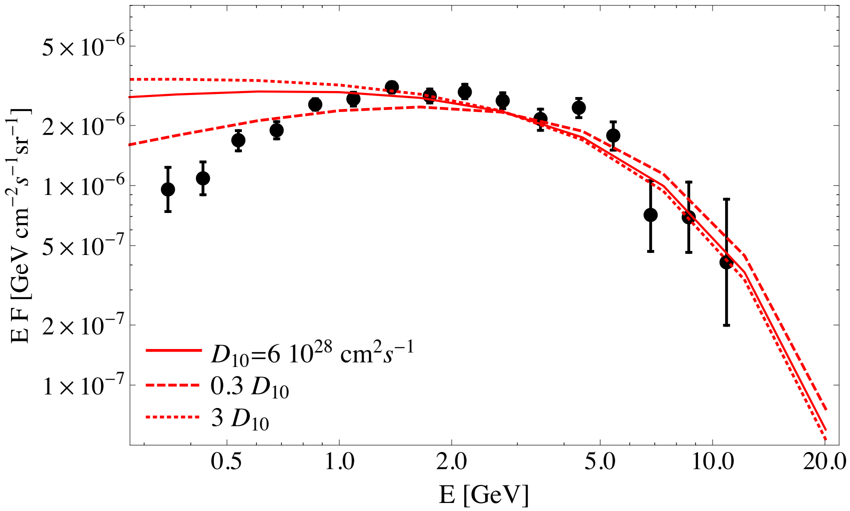
Carlson and Profumo [1405.7685]



Example 2

Inverse Compton emission off high-energy electrons injected with $10^{52\text{-}53}$ ergs of energy about 10^6 years ago

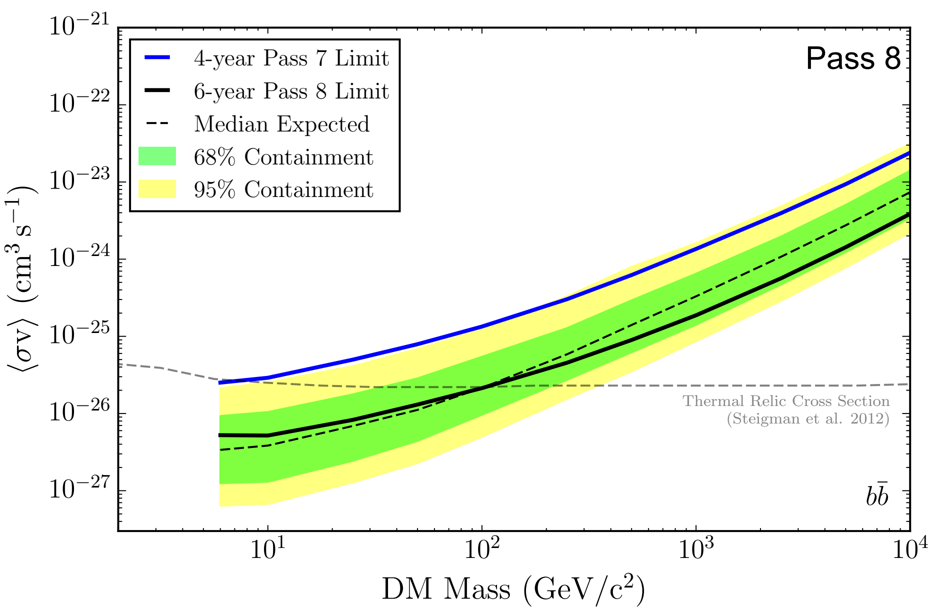
Petrovic, Serpico, Zaharijas [1405.7928]

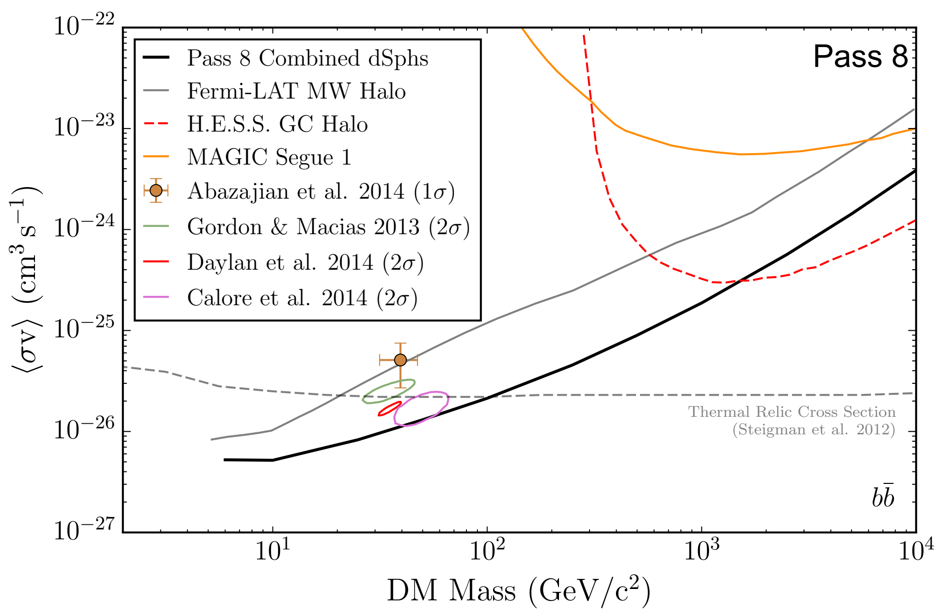


Dwarf Galaxies

Six years of data from *Fermi* LAT used to search for gamma-ray emission from 15 dwarf spheroidal satellite galaxies

Constraints fall below the thermal relic cross section for dark matter masses less than ~100 GeV (bb annihilation channel)



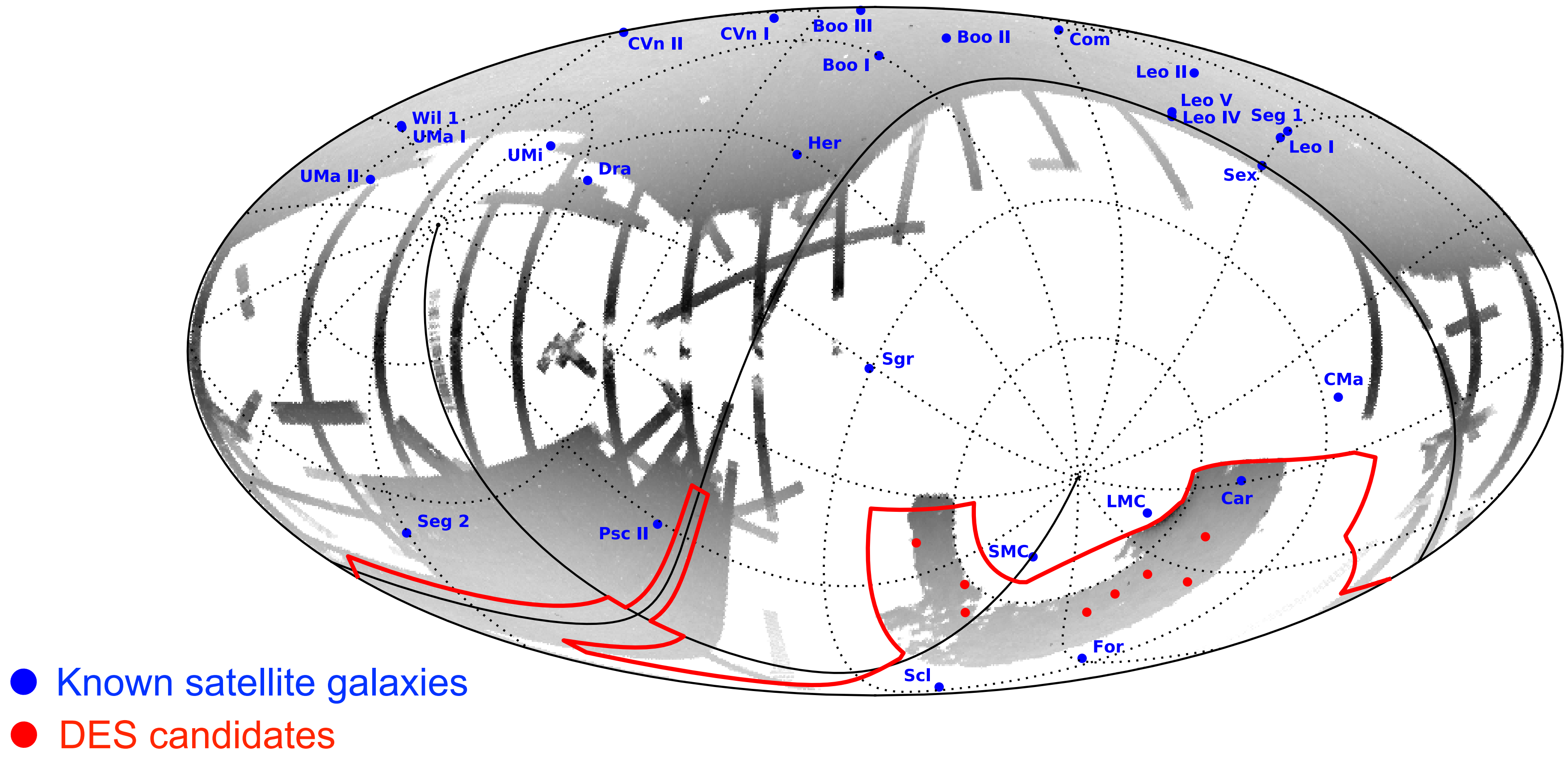


Ackermann *et al.* [1503.02641]

New Dwarf Candidates

Evidence for 8 new dwarf candidates from Dark Energy Survey

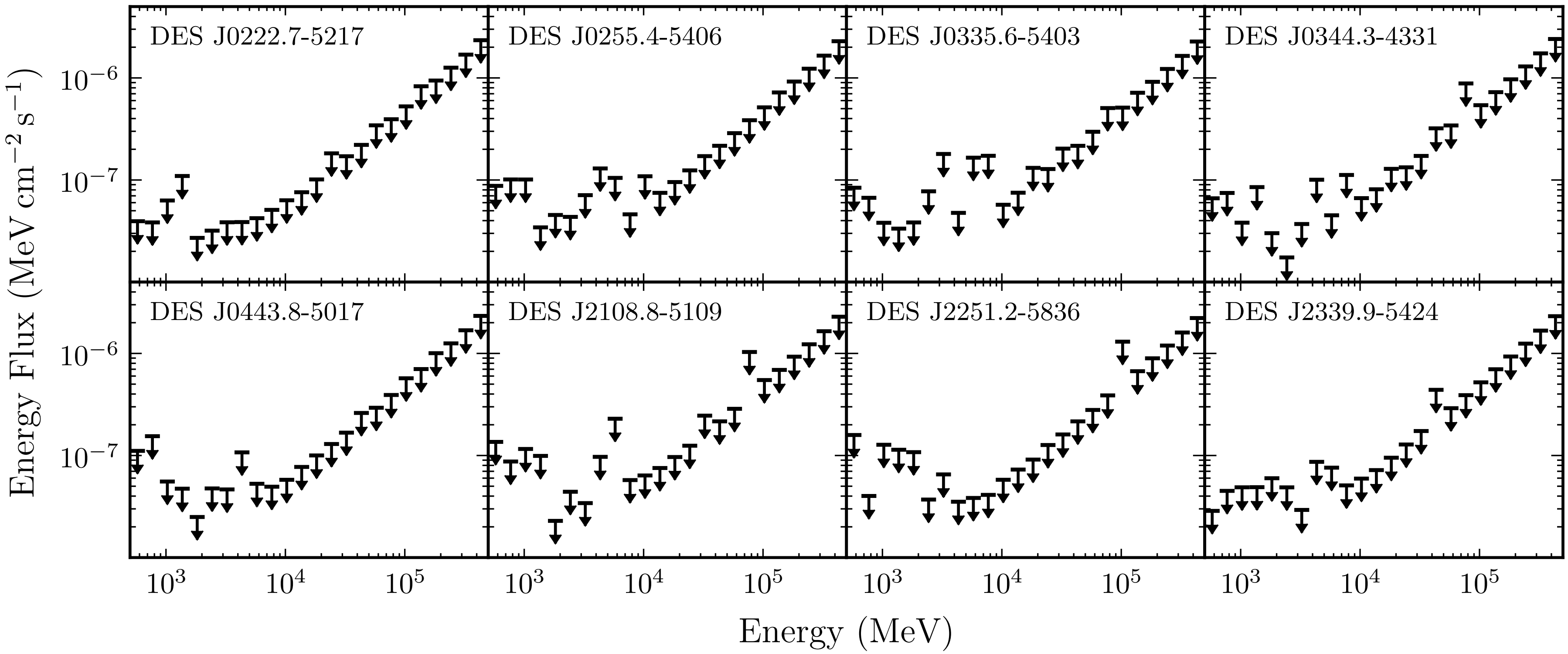
These stellar overdensities range in heliocentric distance from 30-300 kpc



Bechtol *et al.* [1503.02584]; Koposov *et al.* [1503.02079].

Excess in Reticulum?

Analysis of Pass 8 data from *Fermi* Collaboration yields
no significant excess

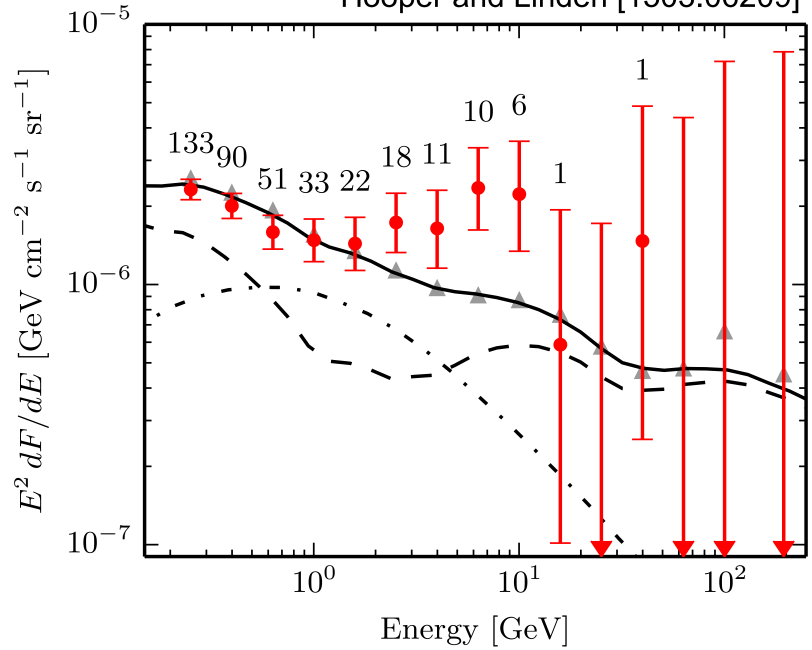


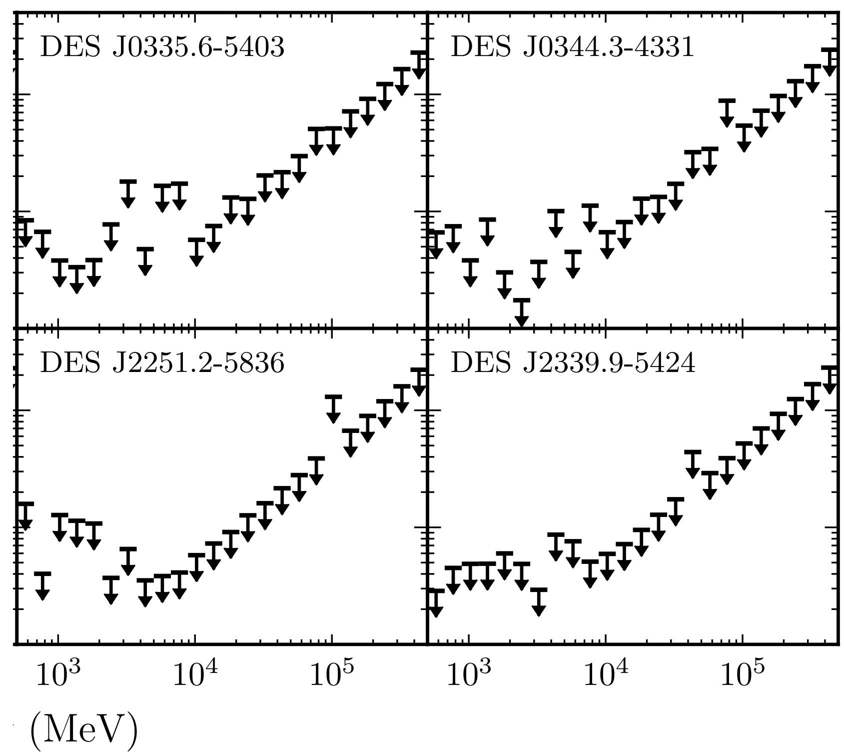
A. Drlica-Wagner *et al.* [1503.02632]

Excess in Reticulum?

Analysis of Pass 8 data from *Fermi* Collaboration yields no significant excess

A. Geringer-Sameth *et al.* [1503.02320]
Hooper and Linden [1503.06209]





A. Drlica-Wagner *et al.* [1503.02632]

Outline

Current Status:

The Galactic Center Excess

Two Hypotheses:

Dark Matter and Point Sources

Distinguishing the Hypotheses:

Photon Count Statistics

Best-Fit Dark Matter

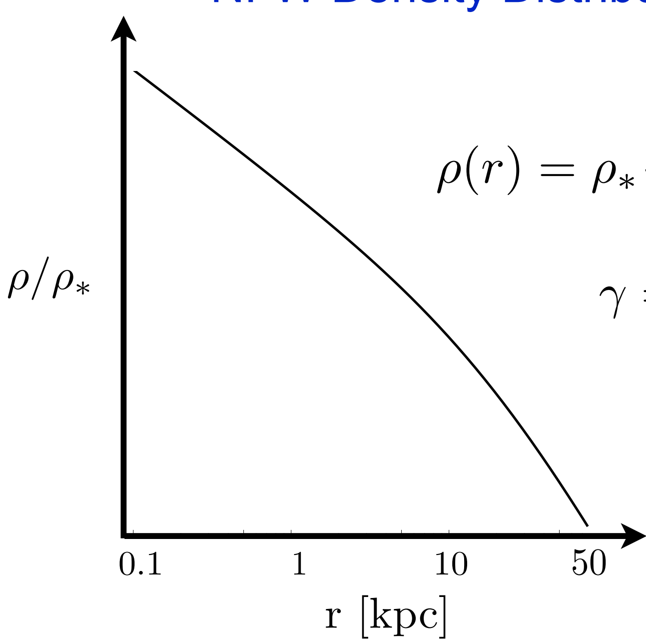
The intensity profile for dark matter annihilation is given by

annihilation cross section — dark matter density

$$\Phi(E,\psi) = \frac{\sigma v}{8\pi m_\chi^2}\frac{dN_\gamma}{dE}\int d\ell\,\rho[r(\ell,\psi)]^2$$

photon energy spectrum

NFW Density Distribution

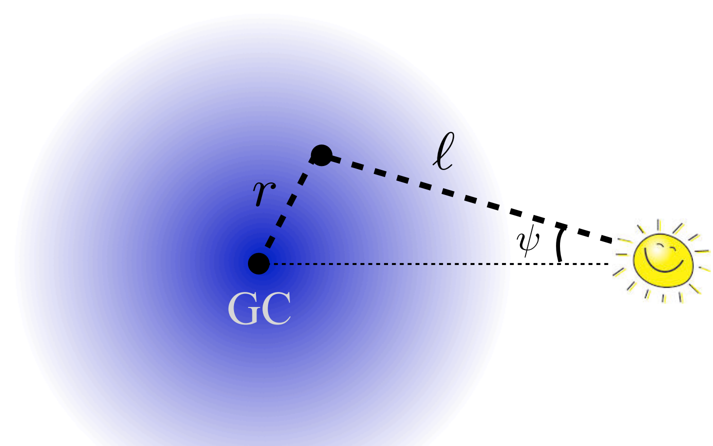


$$\rho(r) = \rho_* \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

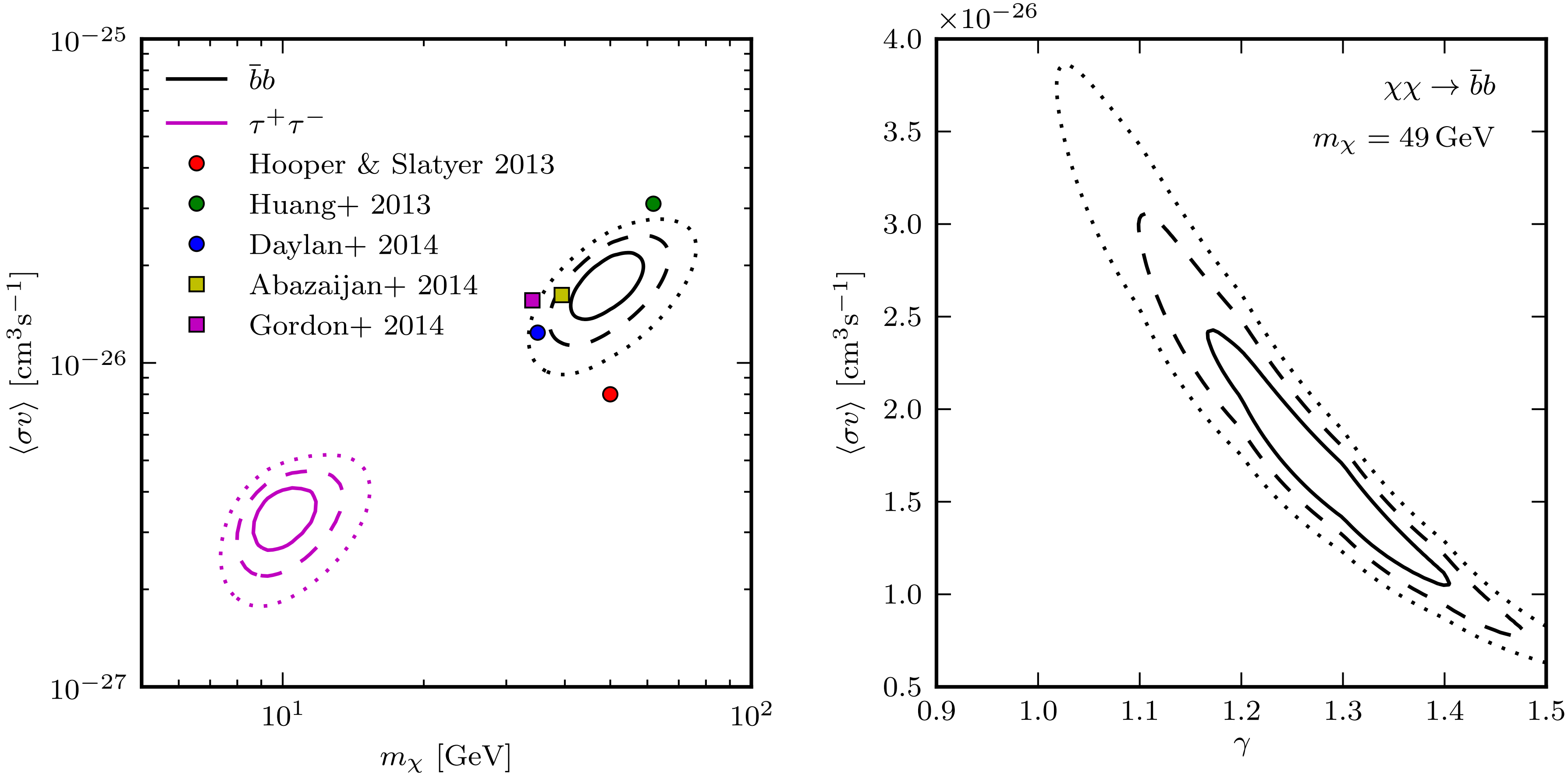
$$\gamma = 1.25$$

Intensity Profile

$$\Phi \propto \psi^{1-2\gamma}$$



Best-Fit Dark Matter



Calore, Cholis, & Weniger [1409.0042]

Best-Fit Point Sources

Normalized number density of point-source population is

$$n(r) \propto r^{-\delta}$$

Observed density profile is proportional to line-of-sight integral

$$\int d\ell \; n\left[r(\ell, \psi)\right] \propto \psi^{1-\delta}$$

To explain the excess, we take

$$\delta \approx 2.5$$

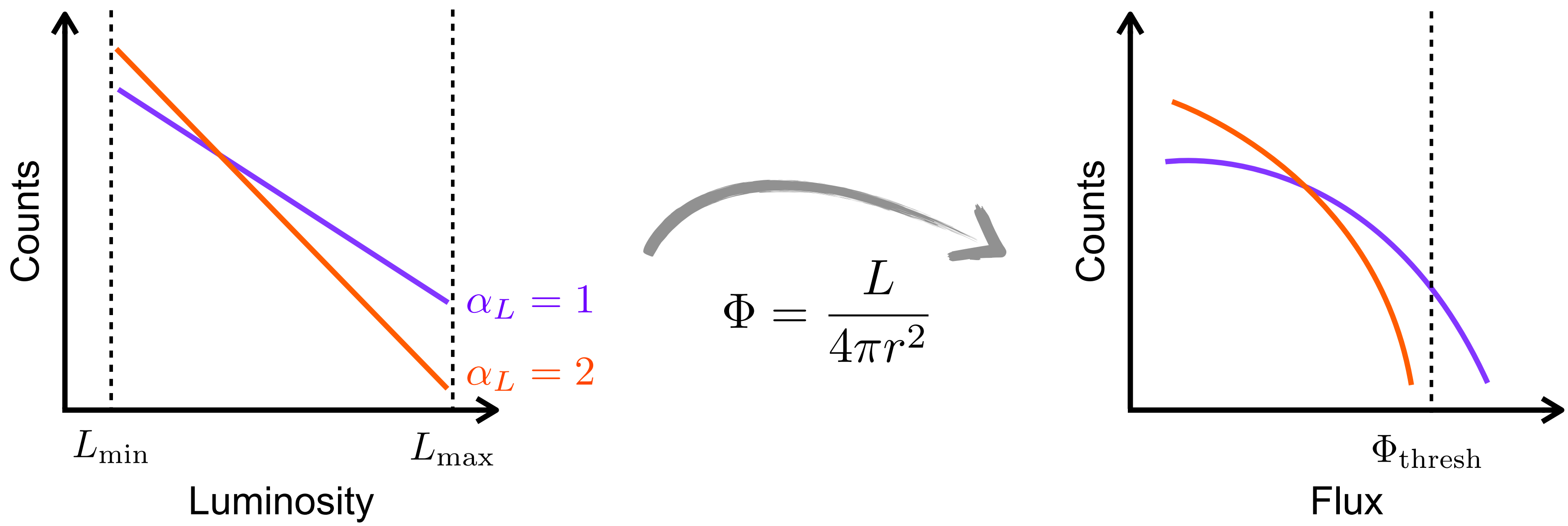
Best-Fit Point Sources

Point-source emission is specified by the luminosity function

$$\frac{dN}{dL} \propto L^{-\alpha_L} \qquad \alpha_L \sim 1\text{-}2$$

Analysis depends on shape of luminosity function near L_{max} cutoff

⇒ Can't over-predict sources above Fermi's point-source flux threshold

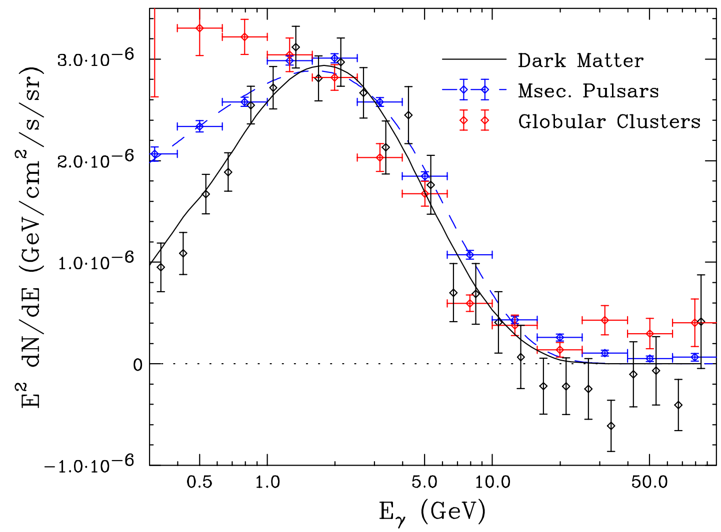


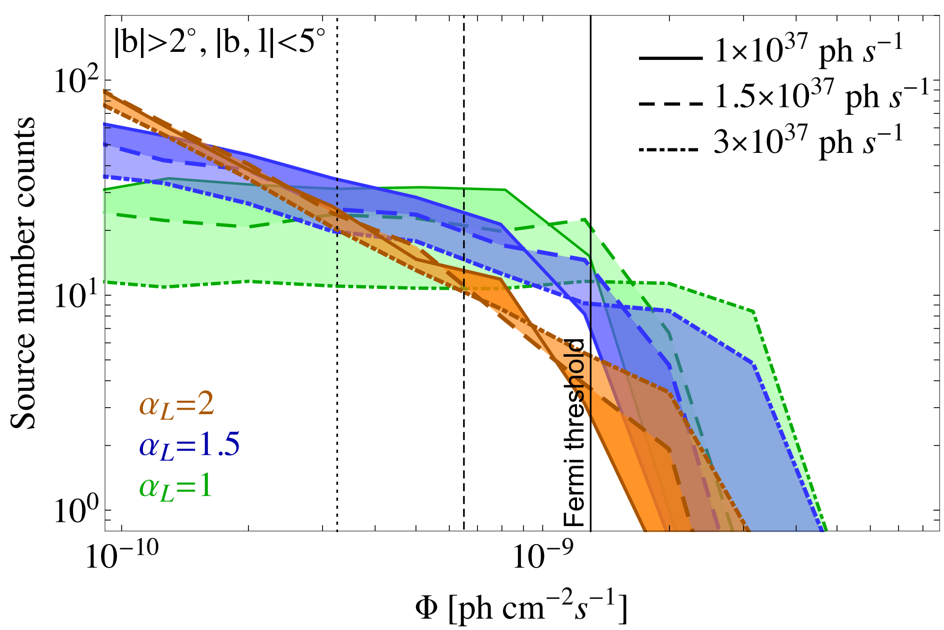
Best-Fit Point Sources

Derive luminosity function from observed nearby millisecond pulsars

$$\alpha_L \simeq 1$$

Cholis, Hooper, Linden [1407.5583, 1407.5625]

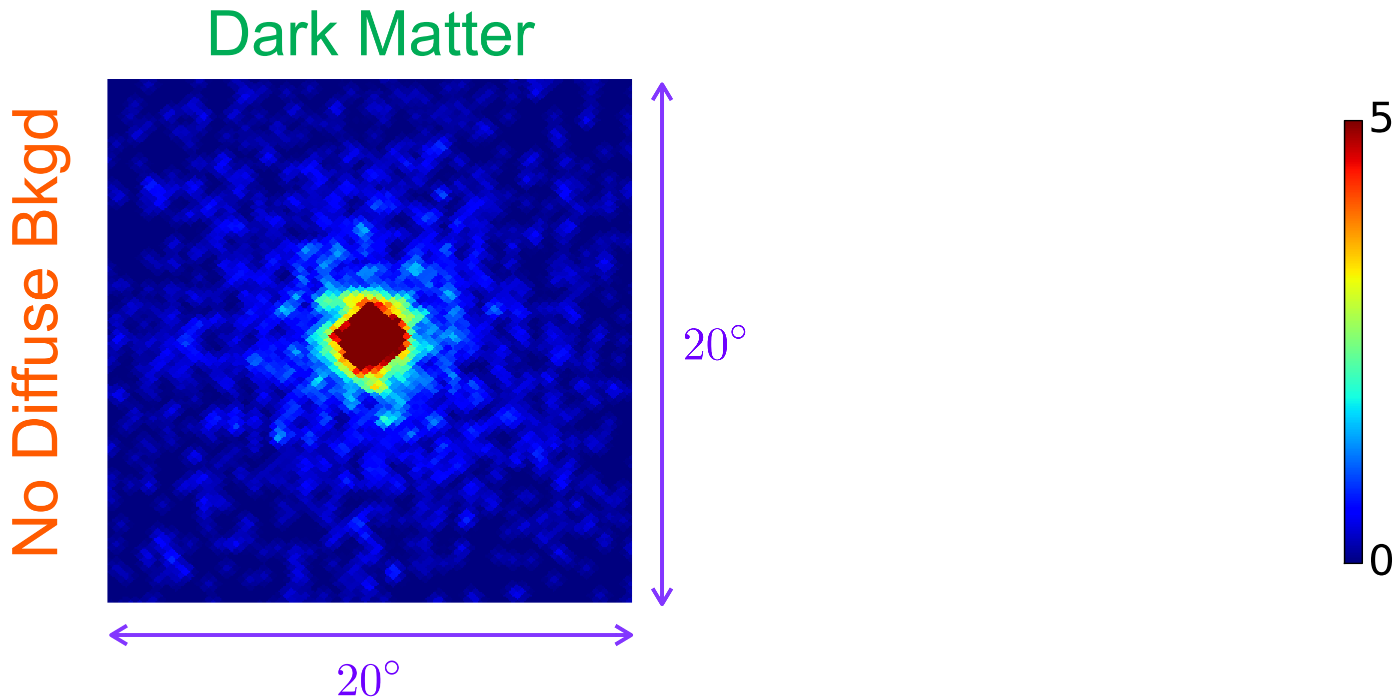


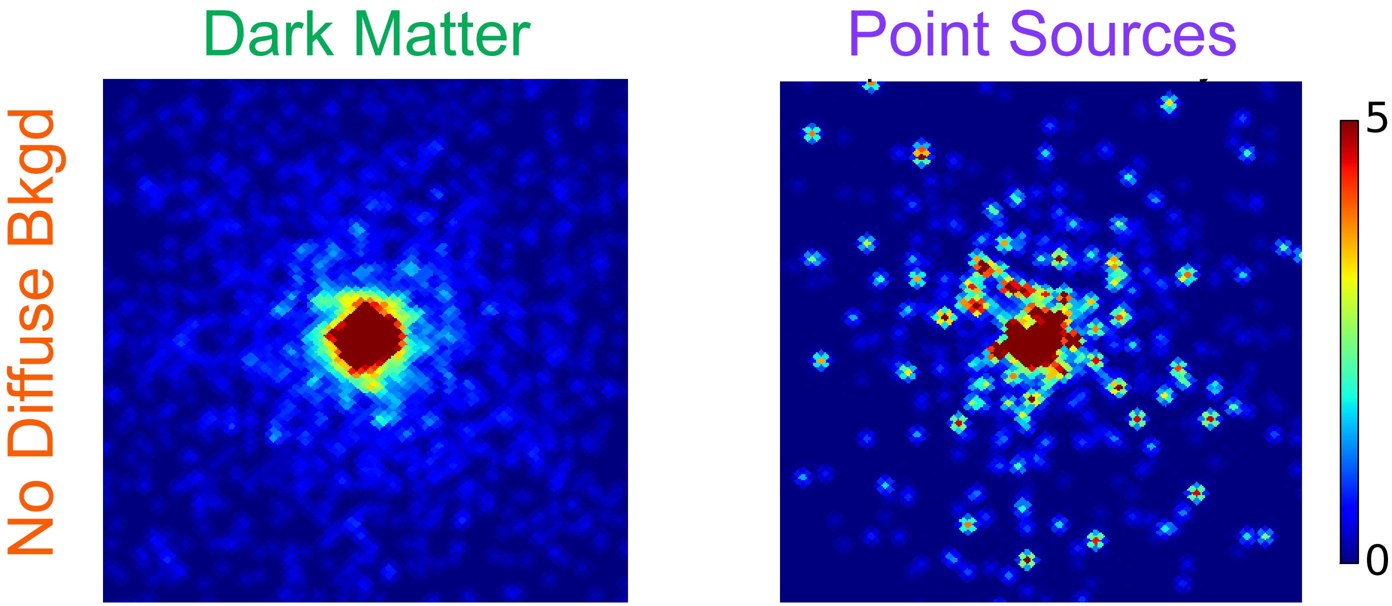


We remain agnostic to details of point-source population

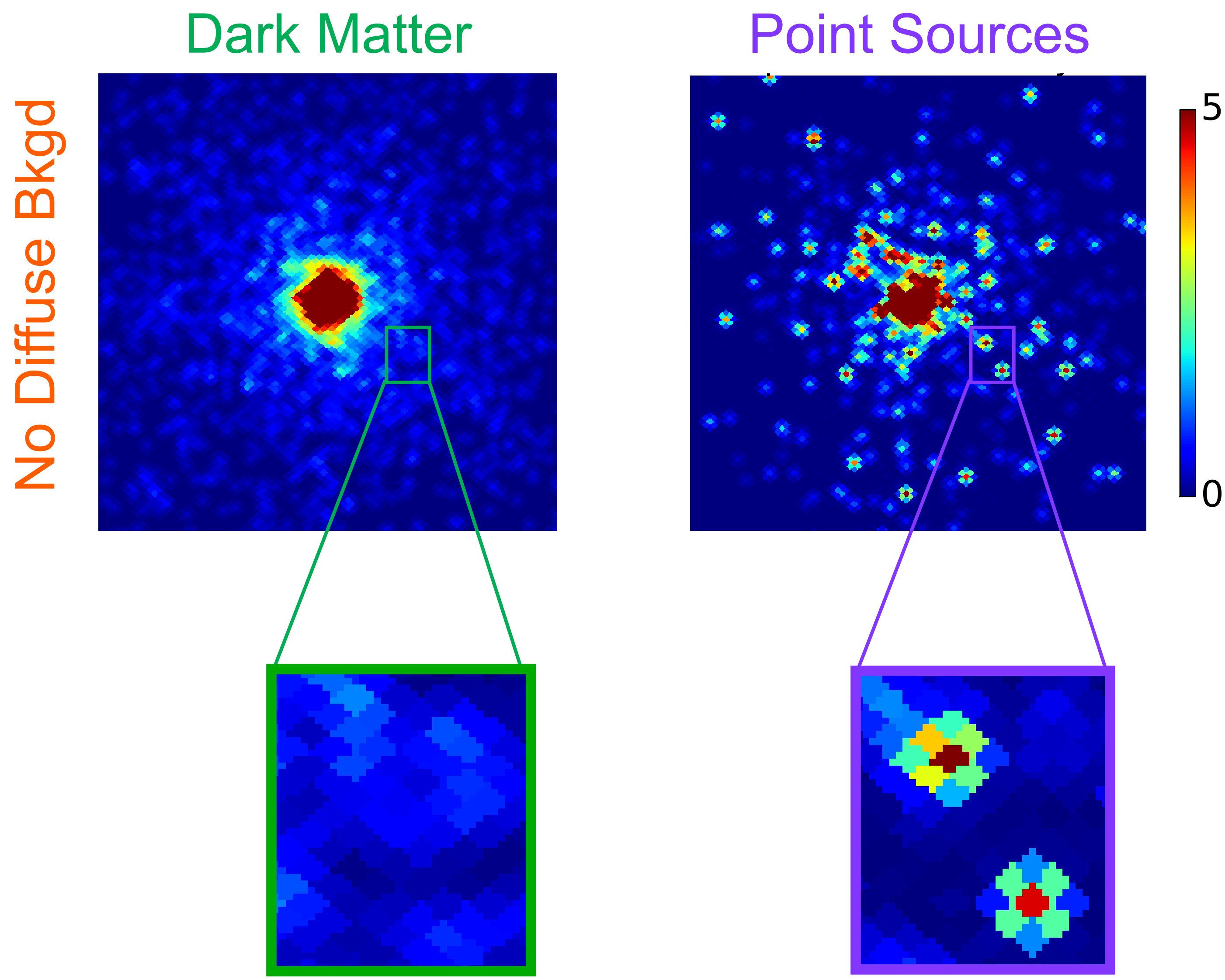
Parametrize model in terms of a few physical parameters

Petrovic, Serpico, and Zaharijas [1411.2980]

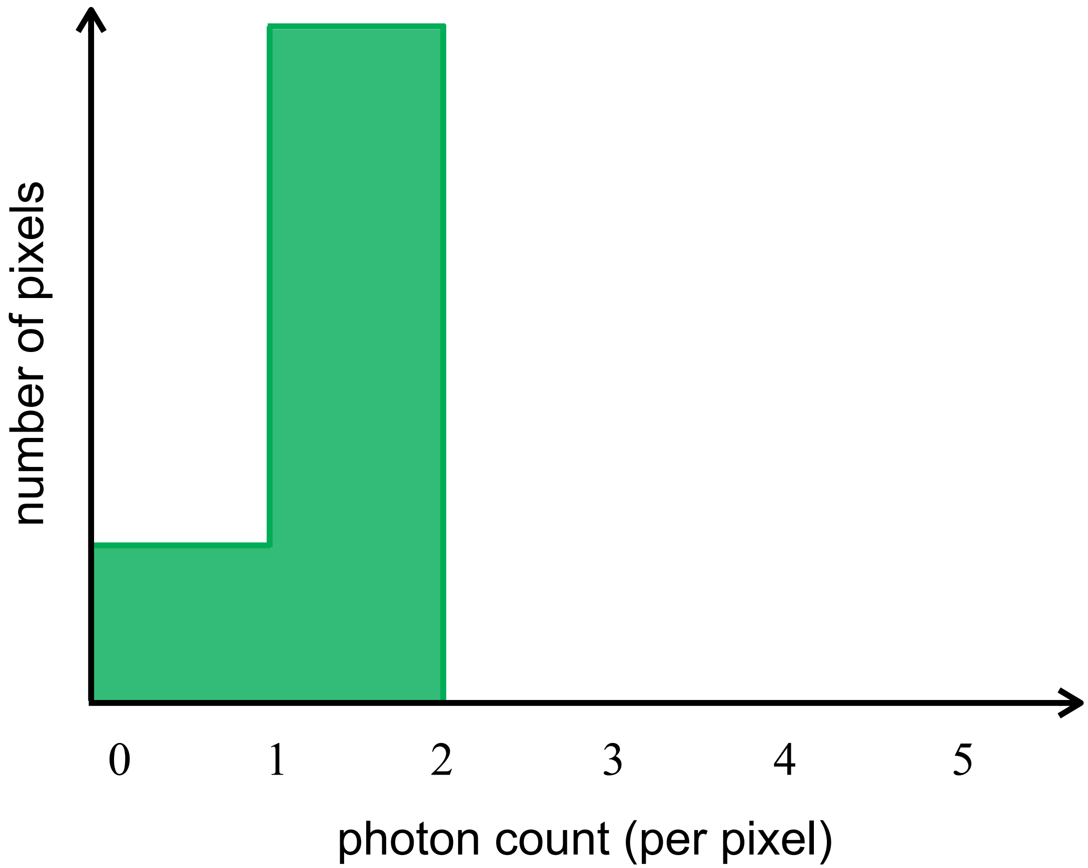

Dark Matter
No Diffuse Bkgd
20°
20°
5
0



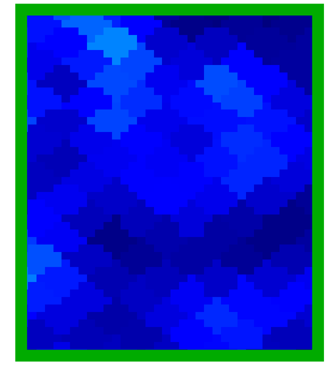
Dark Matter
Point Sources
No Diffuse Bkgd
5
0


Dark Matter
Point Sources
No Diffuse Bkgd
5
0

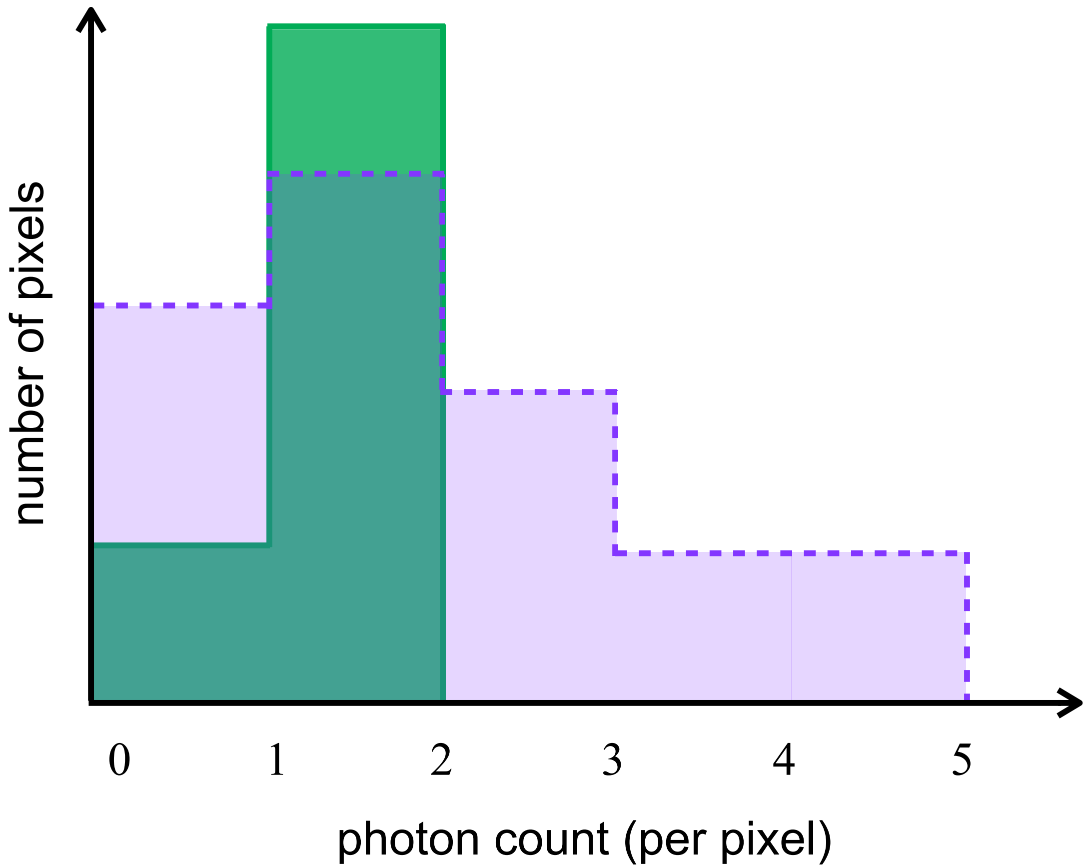
Photon Counts



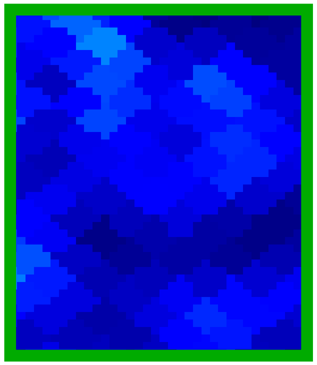
Dark Matter



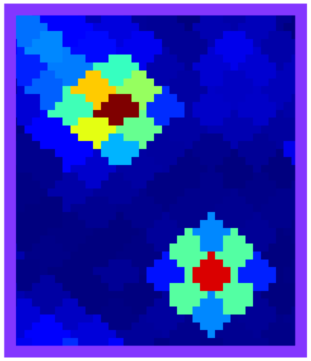
Photon Counts

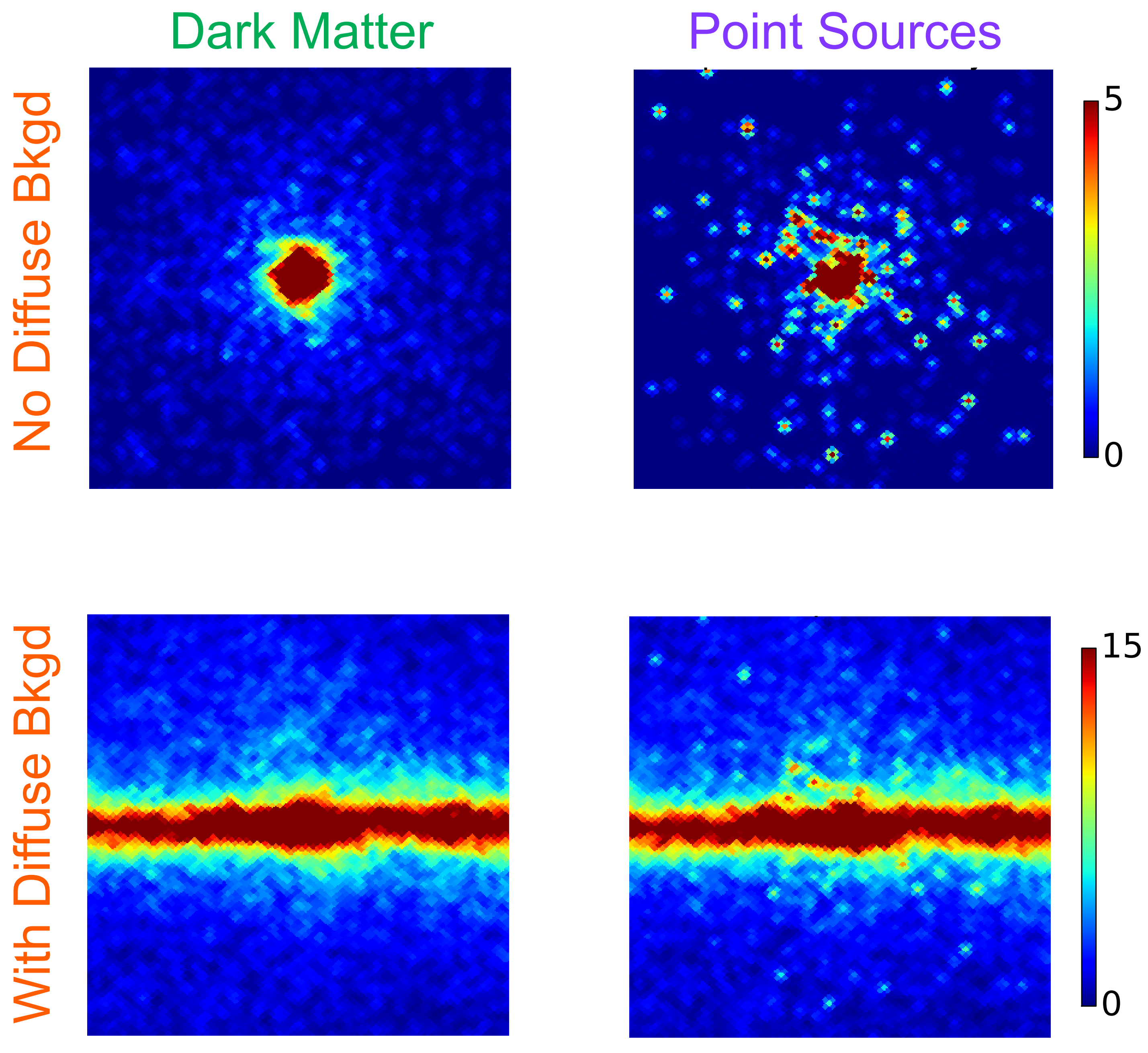


Dark Matter



Point Sources





Dark Matter
Point Sources
No Diffuse Bkgd
With Diffuse Bkgd
5
0
15
0

Outline

Current Status:

The Galactic Center Excess

Two Hypotheses:

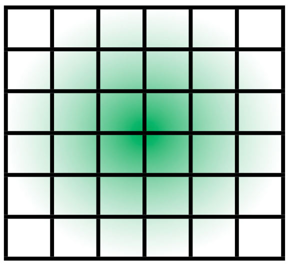
Dark Matter and Point Sources

Distinguishing the Hypotheses:

Photon Count Statistics

The Flux PDF

Intensity distribution of source determines photon counts per pixel



collection of N_{pix} pixels

n_k is number of pixels with *k* photons

$$p_k = \frac{n_k}{N_{\rm pix}} = \text{flux PDF}$$

Generating function analytically determines flux PDF

Generating Function

$$\mathcal{P}(t) = \sum_{k=0}^{\infty} p_k \, t^k$$

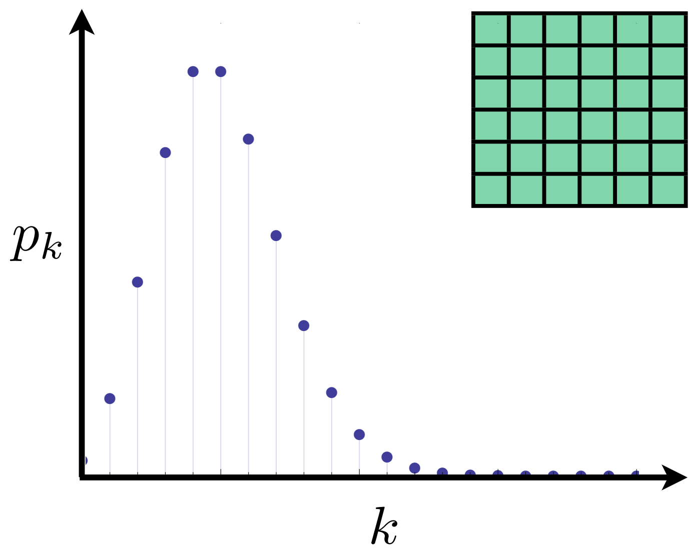
Flux PDF

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

t = auxiliary variable

Uniform Diffuse Emission

Example: photons from diffuse emission that is uniform in the ROI



Poisson distribution gives probability of finding *k* photons in a given pixel

$$p_k = \frac{x^k}{k!} e^{-x}$$

x = mean # of photons/pixel

Generating function reproduces Poisson distribution

Generating Function

$$\mathcal{P}(t) = \exp\left[x\left(t-1\right)\right]$$

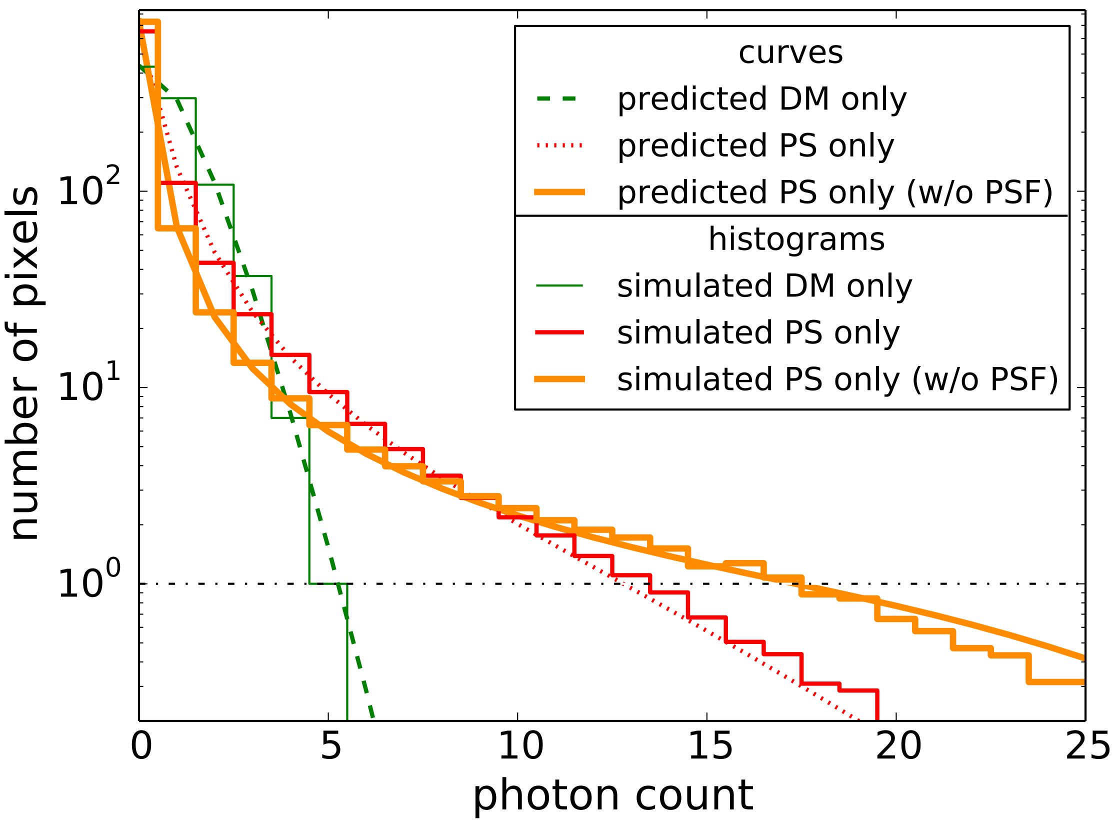
Flux PDF

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

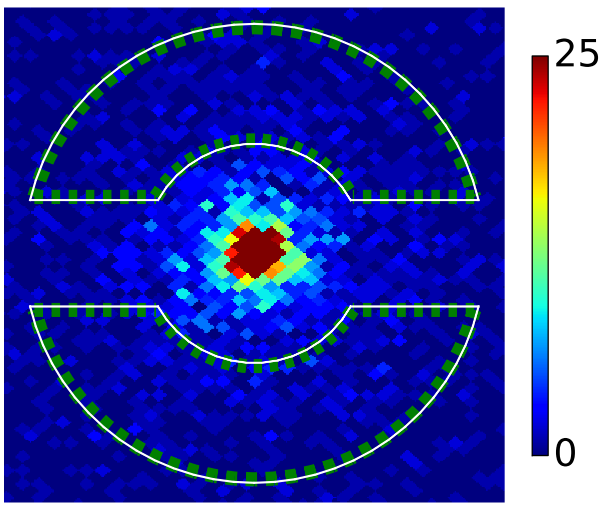
Dark Matter-Only

DM annihilation results in spatially varying, non-uniform diffuse emission

Flux PDF is more complicated than simple Poissonian



Intensity Profile

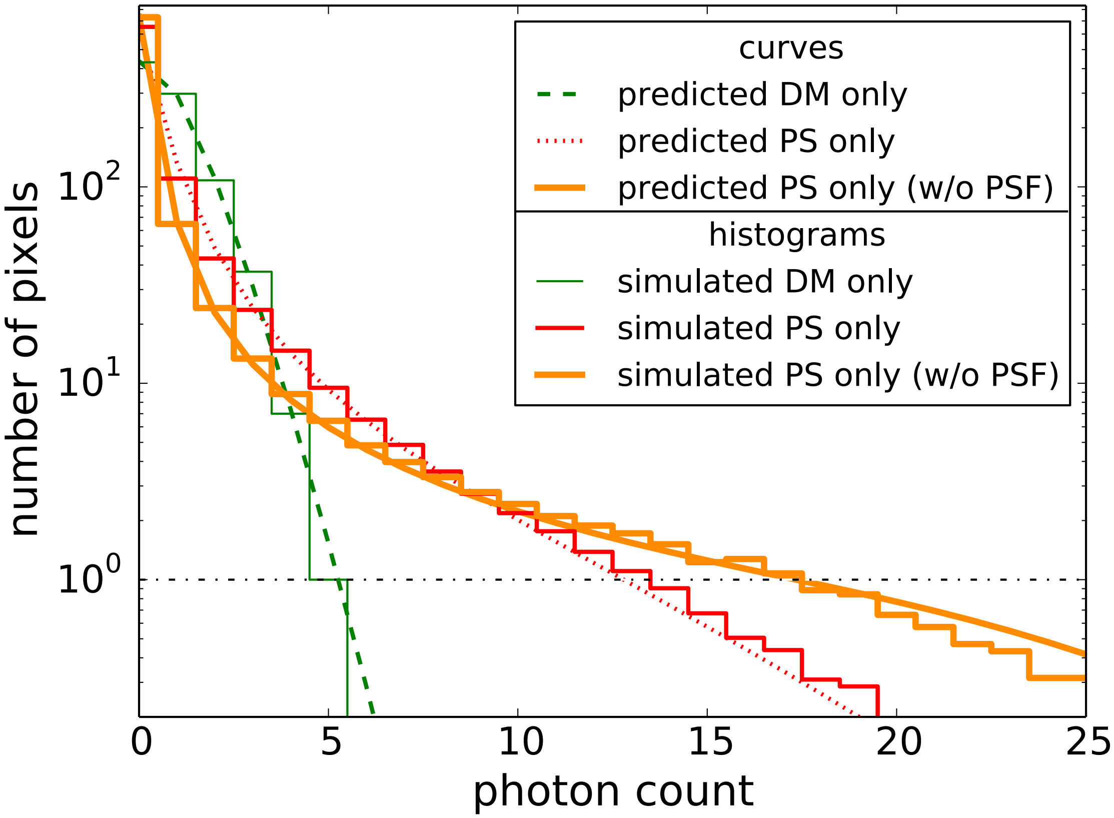


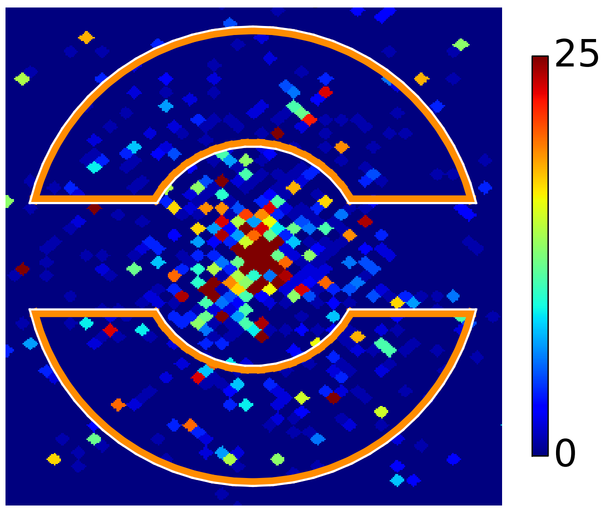
Best-fit DM parameters
NFW profile with γ=1.26

Point Source-Only

Flux PDF for point source emission is also not Poissonian

p_k should be larger at both small and large k, relative to DM case

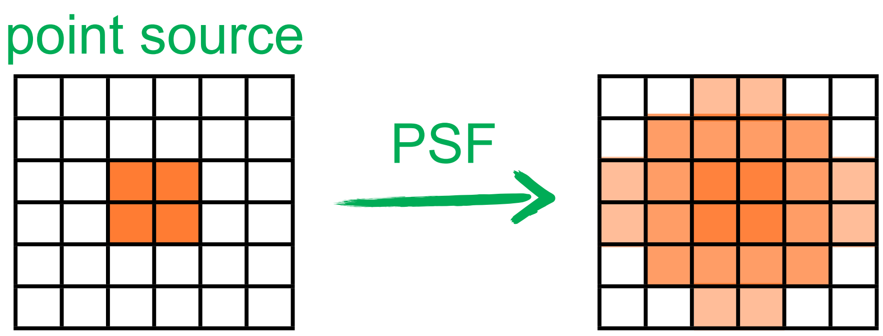




Best-fit point-source parameters

Point-Spread Function (PSF)

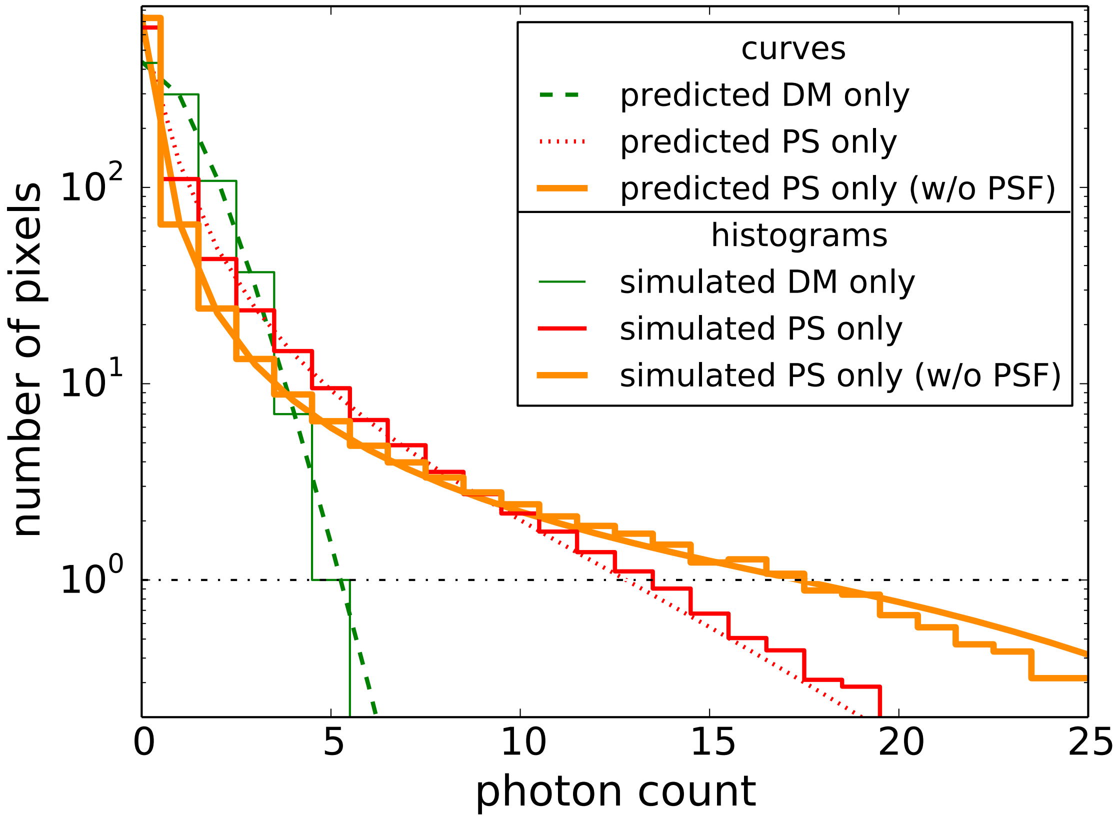
A finite PSF redistributes flux from a point source over multiple pixels



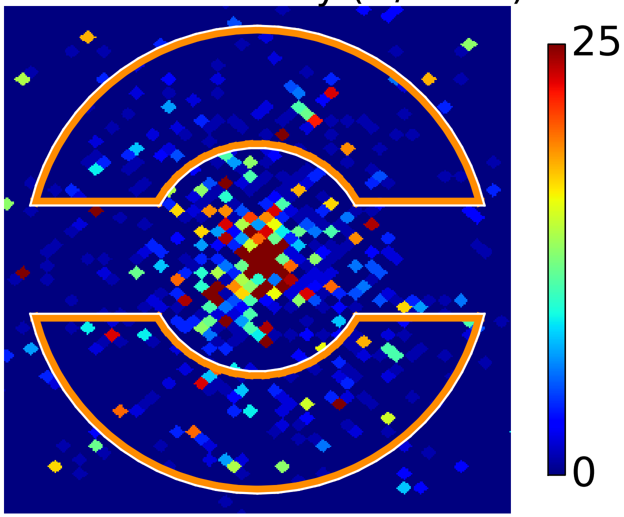
Assuming a Gaussian PSF with σ=0.18˚,

most pixels contain less than 60% of the flux from the point source

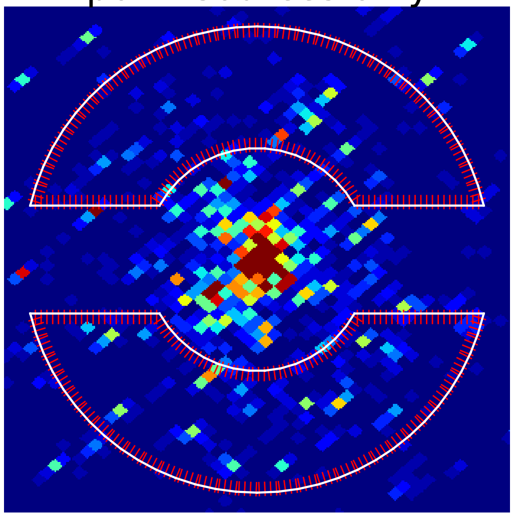
Point Sources w/PSF



point sources only (w/o PSF)



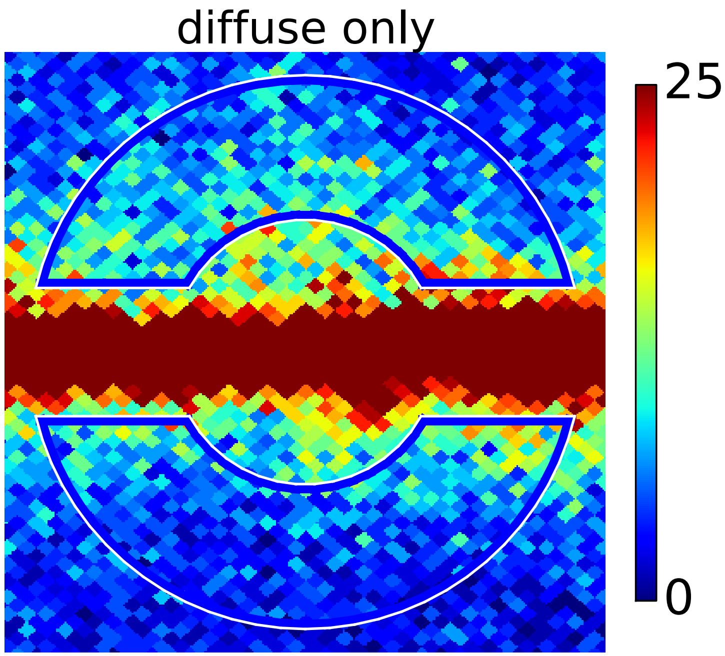
point sources only



Diffuse Background

Diffuse background model contains a Galactic component

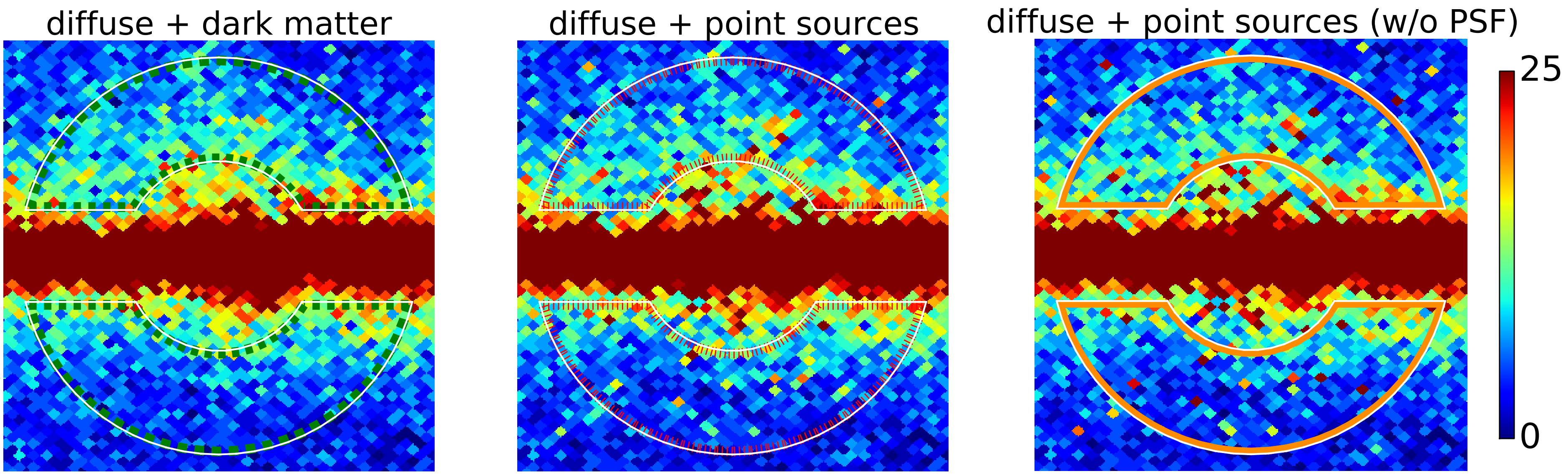
Generated using default parameters in GALPROP



Diffuse Background

Challenging to distinguish the DM and point source scenarios by eye once diffuse background is included

Requires a careful statistical analysis



Total Flux PDF

Inner Galaxy contains contributions from Galactic diffuse emission, and (potentially) dark matter or point sources

Total generating function is the product of the generating functions for each of these sources

Generating Function

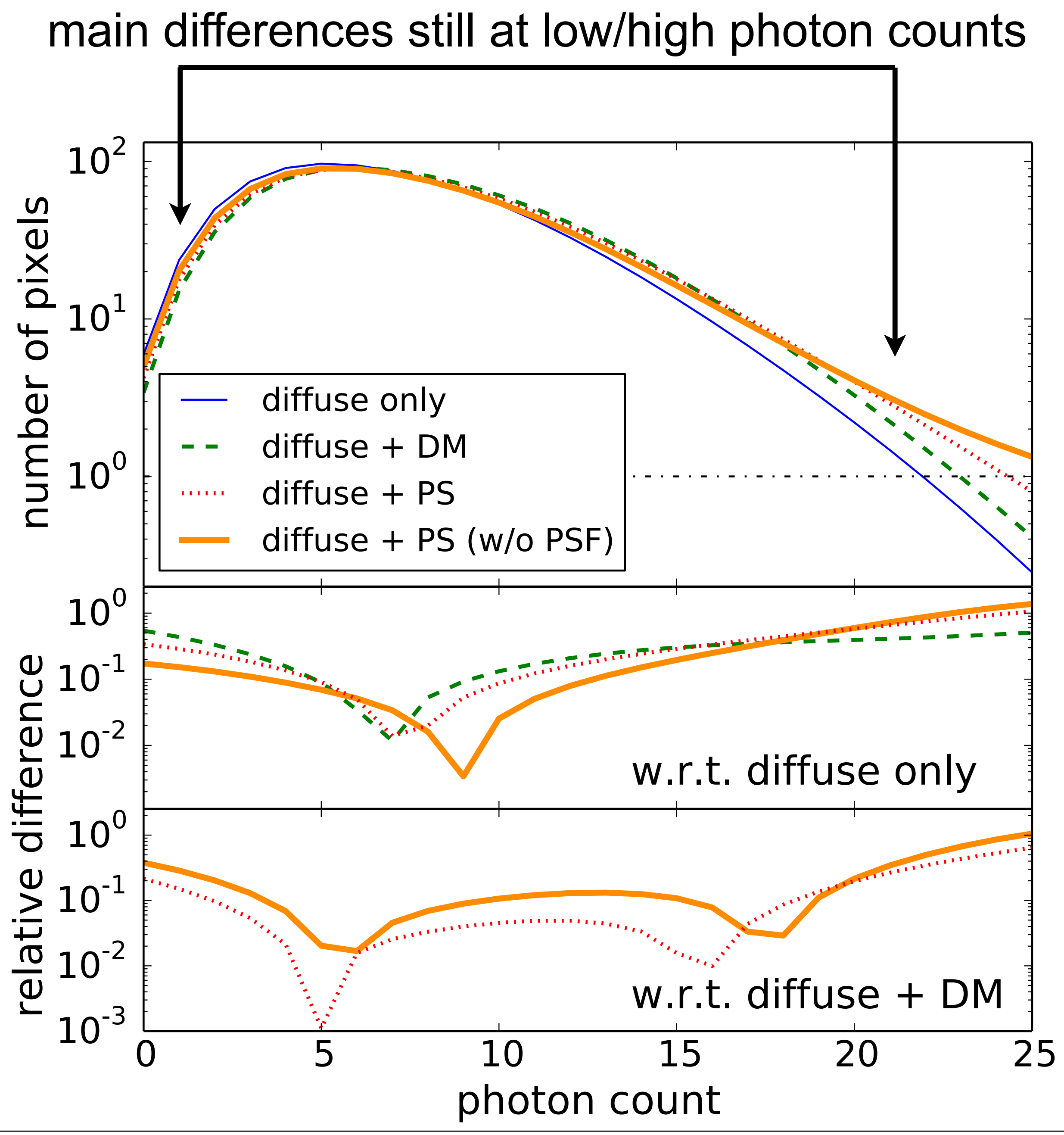
$$\mathcal{P}(t) = G_{\mathrm{DM}}(t) \times G_{\mathrm{Bkgd}}(t)$$

t = auxiliary variable

Flux PDF

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

Total Flux PDF



The Likelihood Function

Model 1

Dark Matter + Diffuse

vs.

Model 2

Point Source + Diffuse

Bayesian evidence for a given model is given by prior-weighted average of the likelihood

Likelihood

$$p(d|\theta, \mathcal{M}) = \prod_{k=0}^{k_{\max}} \frac{[p_k(\theta) N_{\rm pix}]^{n_k}}{n_k!} e^{-p_k(\theta) N_{\rm pix}}$$

Bayesian Evidence

$$p(d|\mathcal{M}) = \int_{\Omega_\mathcal{M}} d\theta \, p(d|\theta, \mathcal{M}) p(\theta|\mathcal{M})$$

Prior

Model Comparison

Model 1

vs.

Model 2

Model 1: Dark Matter + Diffuse

$$\mathrm{NFW},\ \gamma = 1.26$$

$$m_\chi = 35\ \mathrm{GeV}, b\bar{b}$$

1 free parameter: normalization

Model 2: Point Source + Diffuse

$$\mathrm{NFW},\ \gamma = 1.26$$

$$dN/dL \propto L^{-1.4}\ , L_{\max}$$

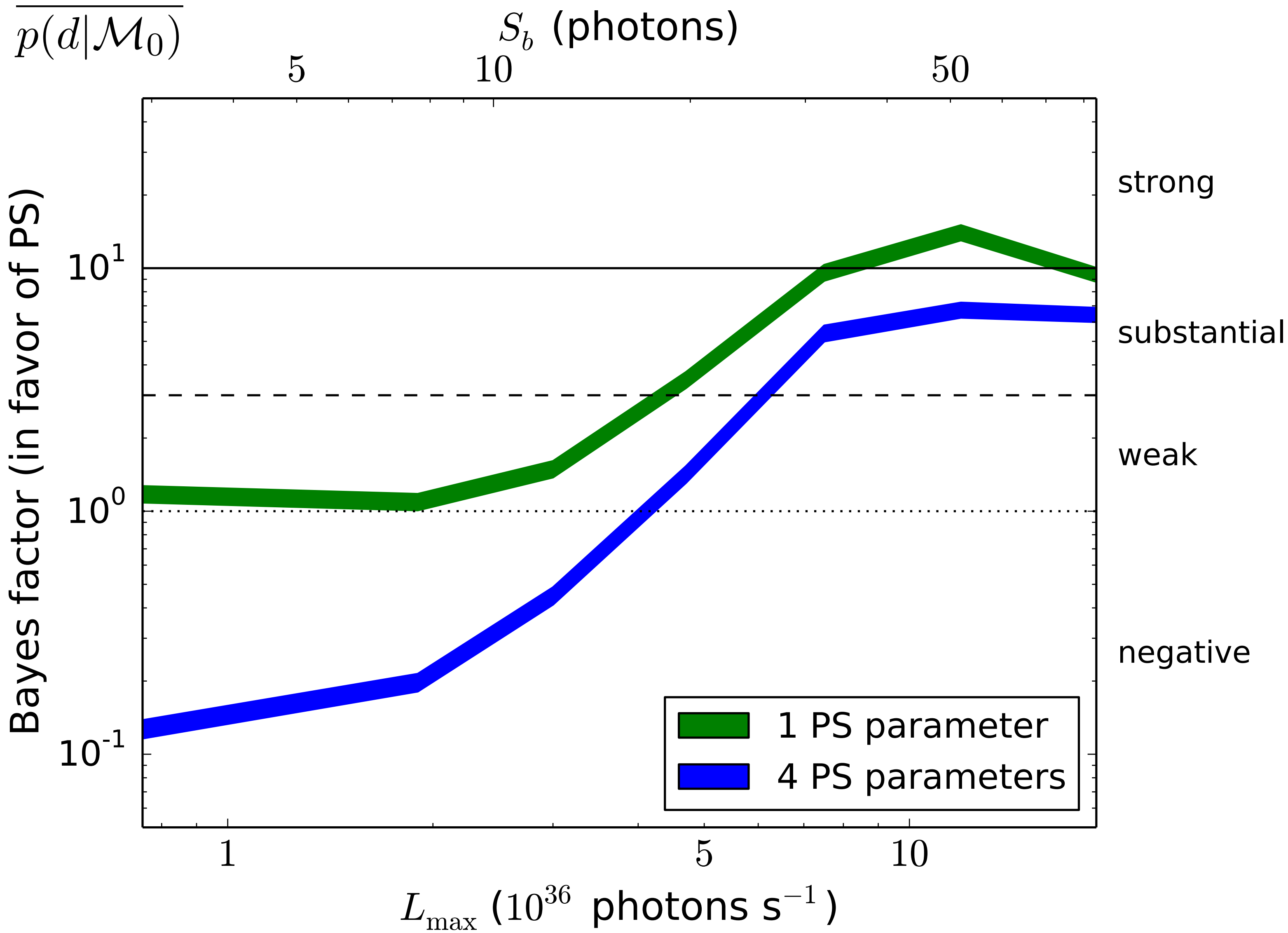
$$\frac{dN}{dS} = A \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & , \ S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & , \ S < S_b \end{cases}$$

1 free parameter: A

4 free parameters: A, S_b, n_1, n_2

Bayes Factor

$$B_{10} = \frac{p(d|\mathcal{M}_1)}{p(d|\mathcal{M}_0)}$$



Conclusions

GeV Excess at the Galactic Center is a potentially interesting dark matter signal, but other explanations must be explored

The use of photon count statistics provides a concrete way to determine whether the photon distribution is non-Poissonian

The photon count procedure may be used to distinguish between dark matter and point-source models