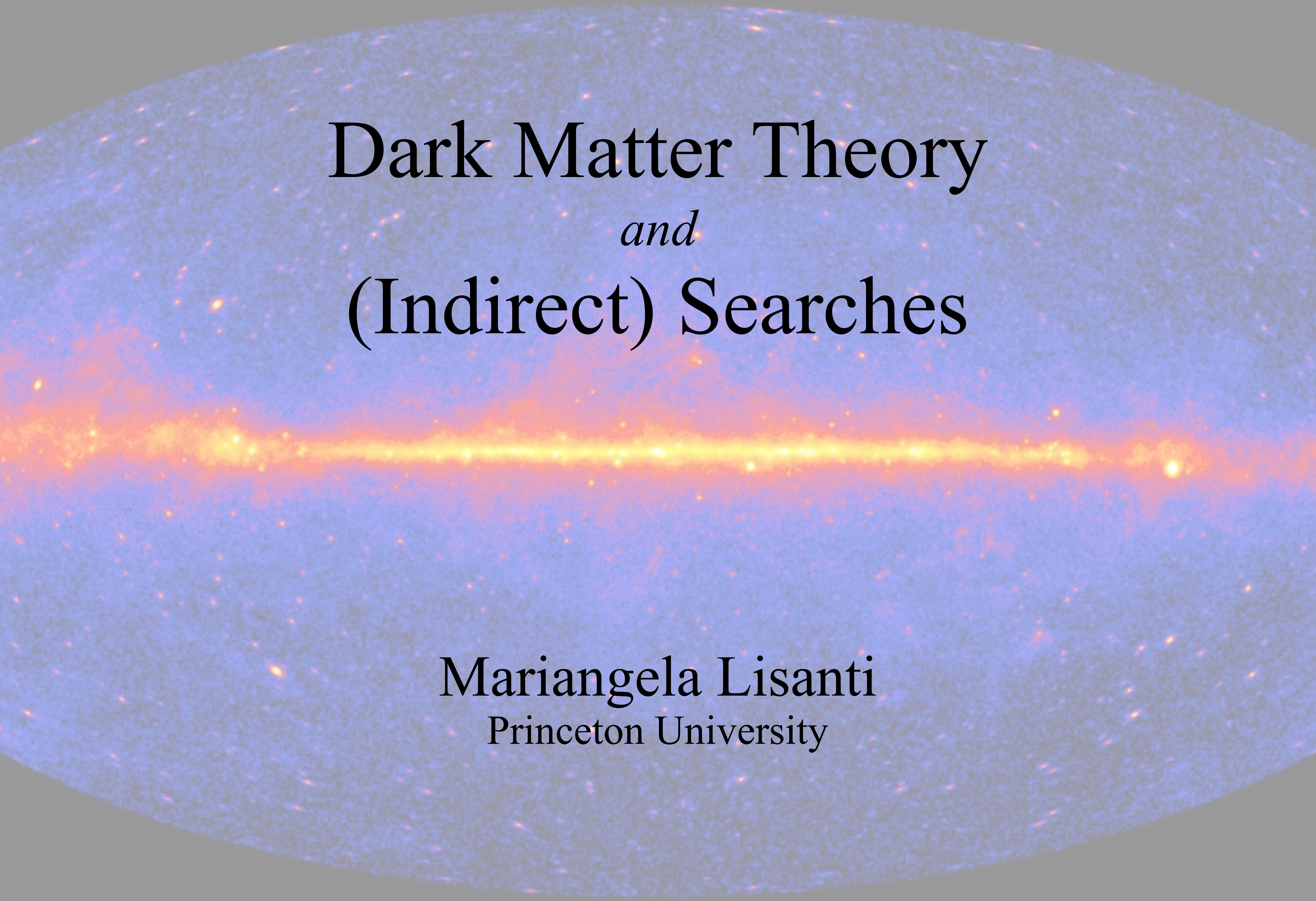


Dark Matter Theory

and

(Indirect) Searches

Mariangela Lisanti
Princeton University

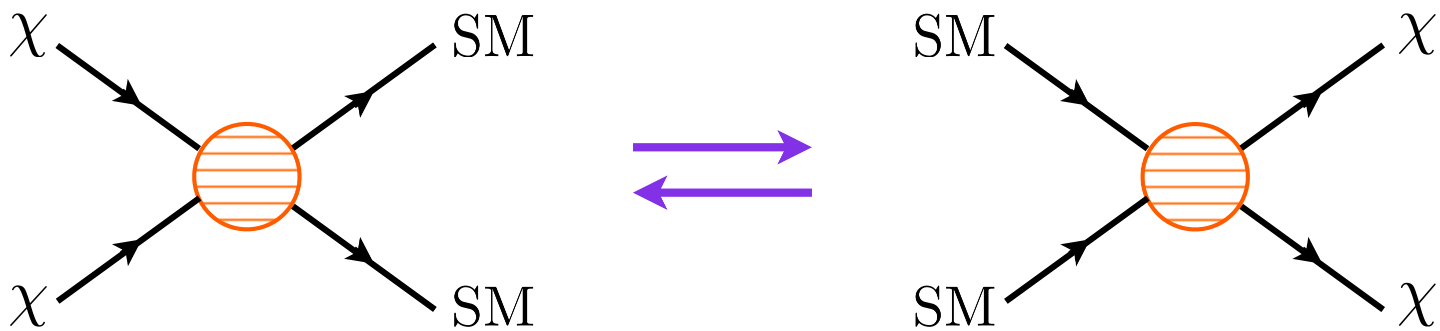
Strongest evidence for dark matter comes from its gravitational interactions with visible matter

Particle physics properties (e.g., mass, couplings) remain an open question

We can make educated guesses for the dark matter mass based on its interactions in the early Universe

Thermal Dark Matter

Dark matter is in equilibrium in the early Universe



As temperature cools, eventually

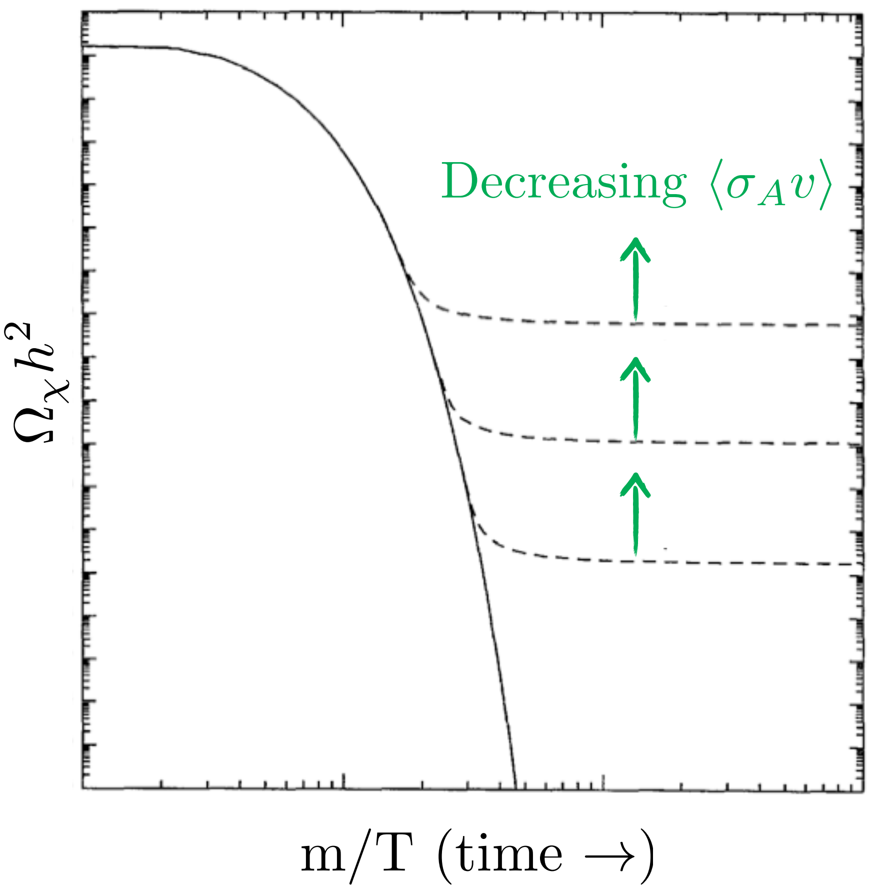
$$n_\chi \langle \sigma_{\rm A} v \rangle \sim \mathrm{H}$$

Dark matter stops annihilating and falls out of equilibrium

Relic abundance for dark matter is thus established

Thermal Dark Matter

Weakly interacting particle with mass ~$10^{2\text{-}3}$ GeV gives density observed today



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle}$$

$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

Planck + WMAP:

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

The Lamp Post

The WIMP paradigm has been the primary guide for the current dark matter experimental program

However, one does not have to do much to open up the parameter space for thermal dark matter

e.g., If the dark matter annihilates to a new, slightly heavier state

$$\chi\chi \to \phi\phi$$

then, the correct relic density can be obtained down to keV masses

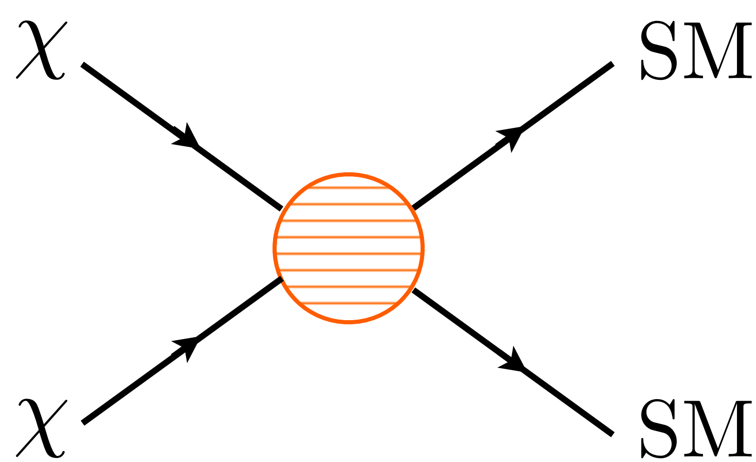
Griest and Seckel (1991); D'Agnolo and Ruderman [1505.07107]

WIMPs Today

Dark matter self-annihilations are rare today, but do occur

Increase chances of observing these rare events by looking in densest dark-matter regions of the sky

Searching for high-energy gamma rays from dark matter annihilation is the most direct way to probe the thermal hypothesis



Fermi LAT

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

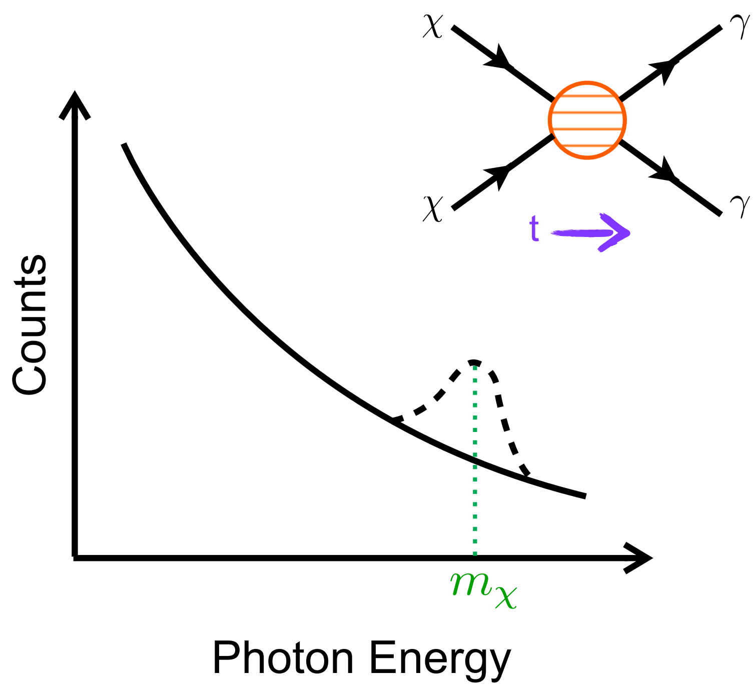
Sensitive to energies from 20 MeV to > 300 GeV

Scans over the whole sky every three hours

Indirect Detection

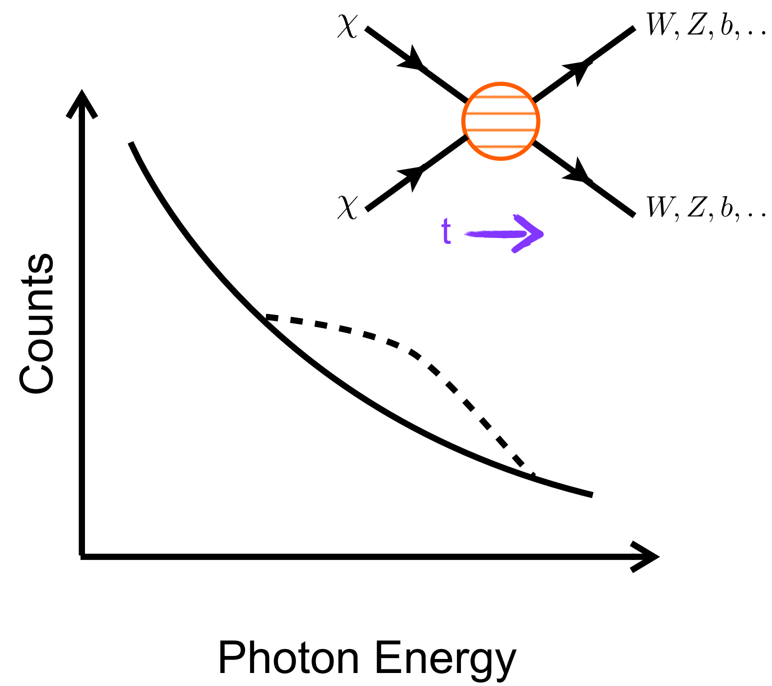
Monochromatic Photons

Direct annihilation to photons, a line in photon energy spectrum



Continuum Photons

Annihilation to SM final states that shower into photons



Photon Flux

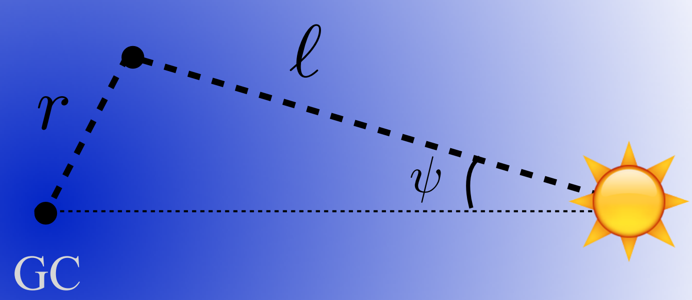
The intensity profile for dark matter annihilation is given by

$$\Phi(E,\psi) = \underbrace{\frac{\sigma_{\rm A} v}{8\pi m_\chi^2}}_{\text{annihilation cross section}} \underbrace{\frac{dN_\gamma}{dE}}_{\text{photon energy spectrum}} \int d\ell\, \underbrace{\rho\left[r(\ell,\psi)\right]^2}_{\text{dark matter density}}$$

annihilation cross section

dark matter density

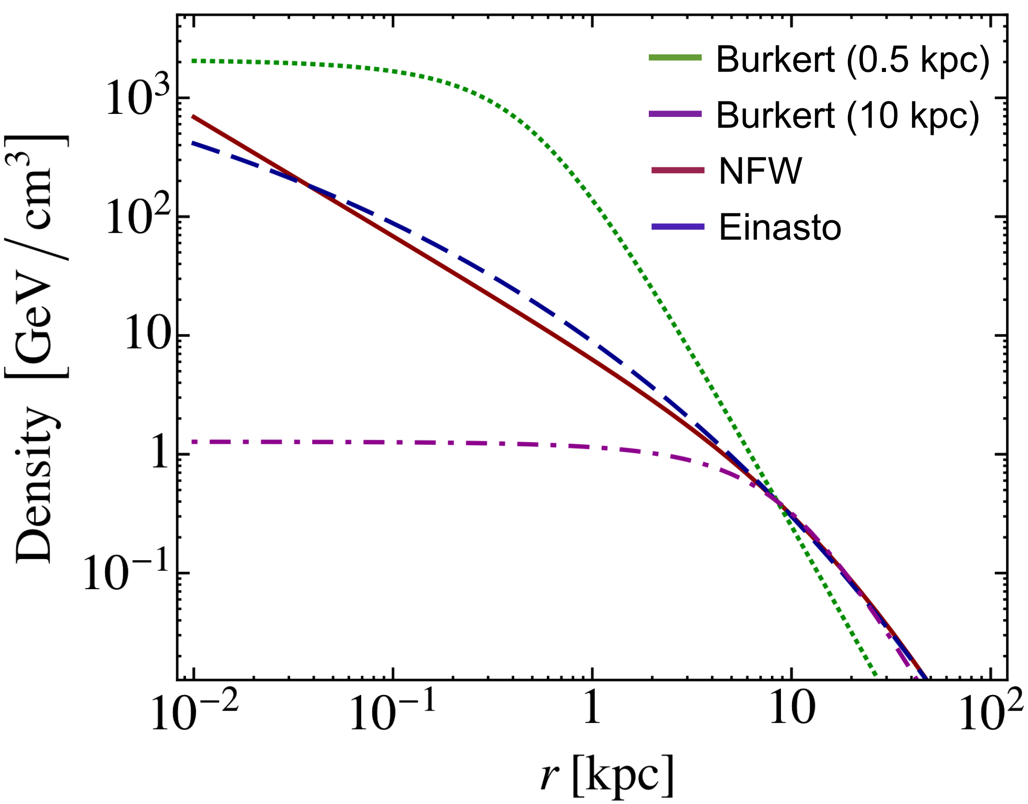
photon energy spectrum



J-Factor

Astrophysical uncertainties are absorbed by the "J-factor"

$$J \propto \int d\ell \, \rho[r(\ell, \psi)]^2$$



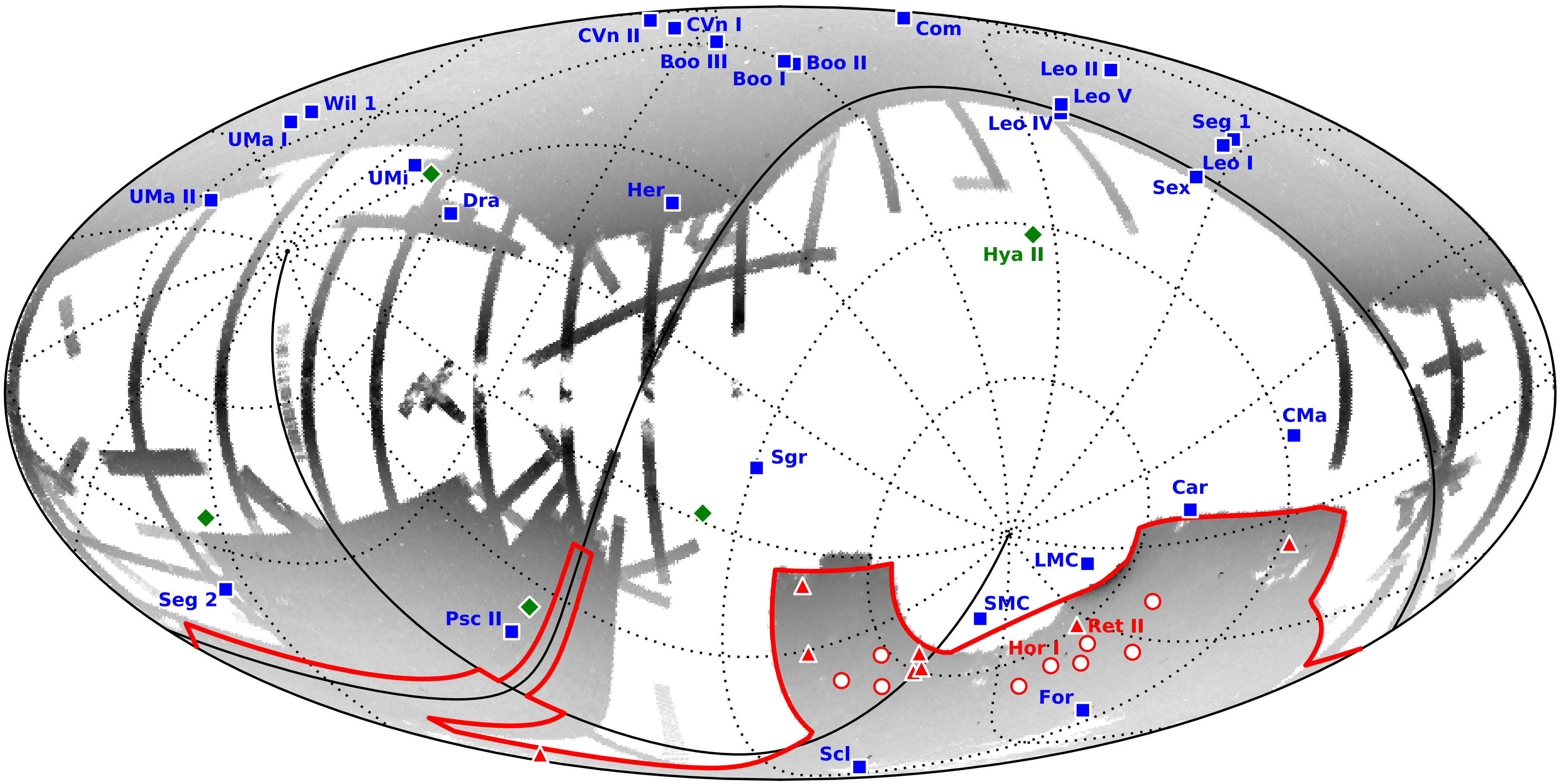
Generalized NFW Profile

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

Most dense regions at the centers of dark-matter halos

Dwarf Galaxies

These faint galaxies are dark-matter dominated and thus excellent targets for annihilation searches



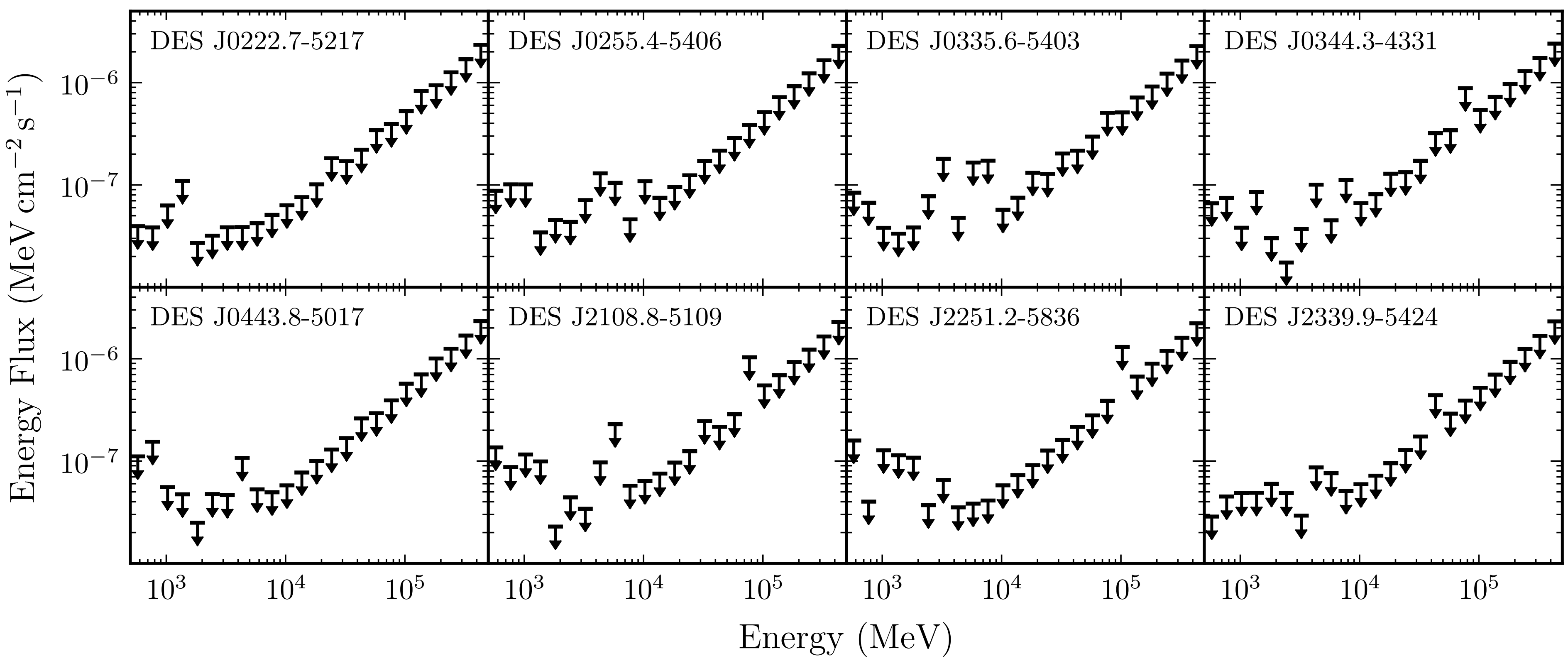
Known satellites before 2015

New Candidates

Drlica-Wagner *et al.* [1508.03622]

Excess in Reticulum?

Analysis of *Fermi* data yields no significant excesses in most candidates, though Reticulum still debated

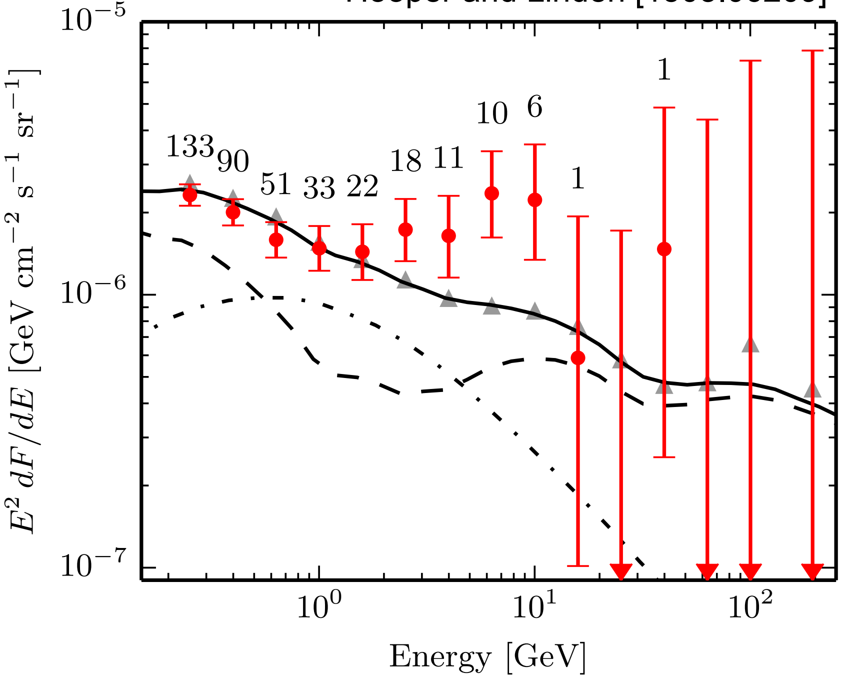


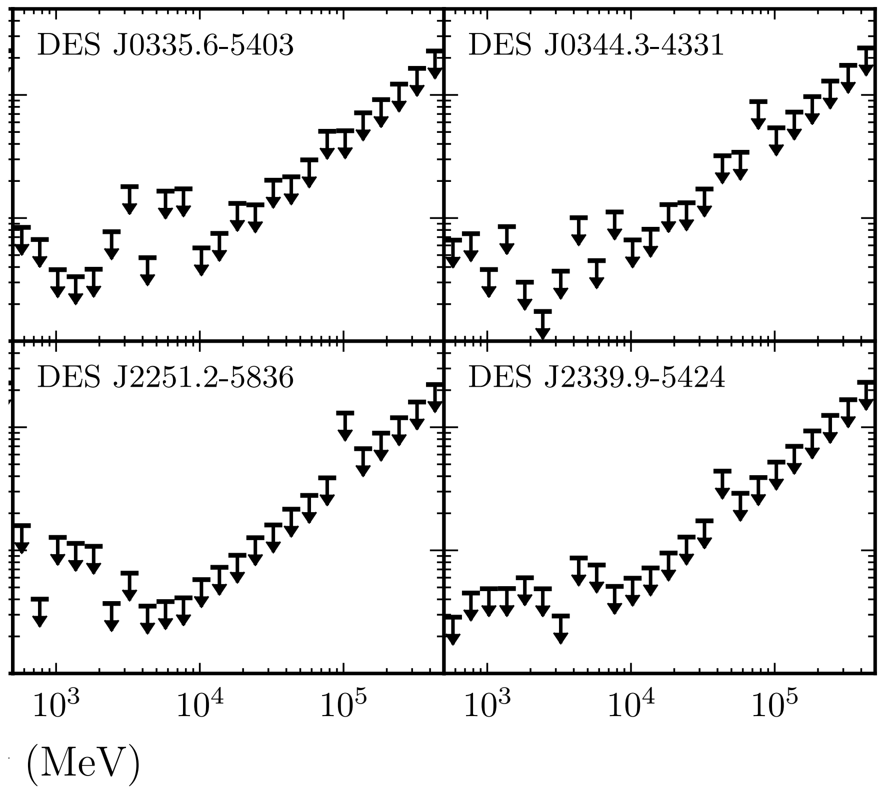
A. Drlica-Wagner *et al.* [1503.02632]

Excess in Reticulum?

Analysis of *Fermi* data yields no significant excesses in most candidates, though Reticulum still debated

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



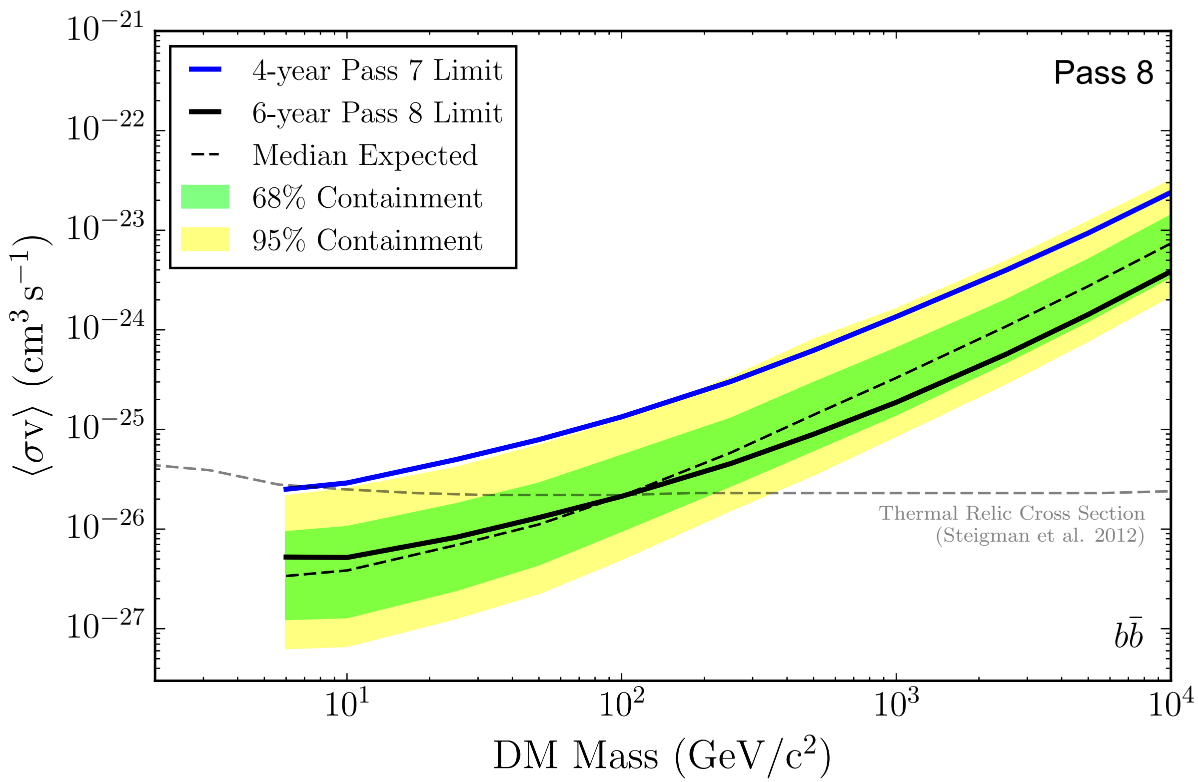


A. Drlica-Wagner *et al.* [1503.02632]

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)

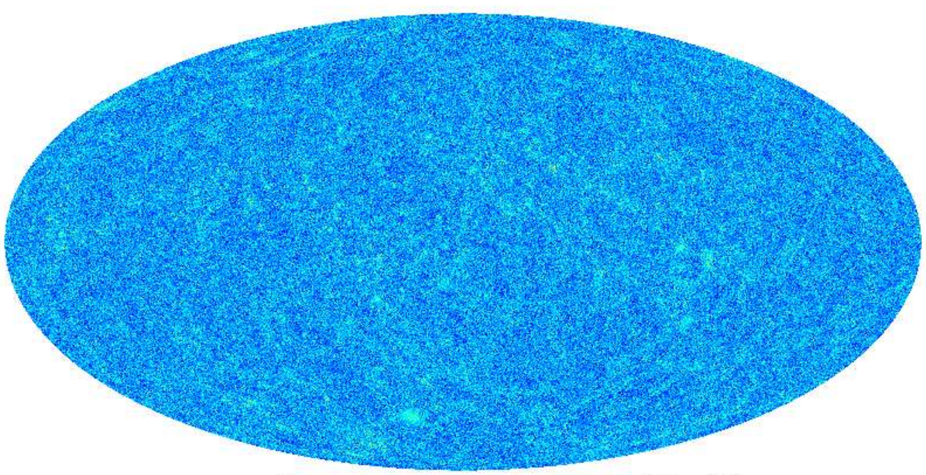


Ackermann *et al.* [1503.02641]

Isotropic Background

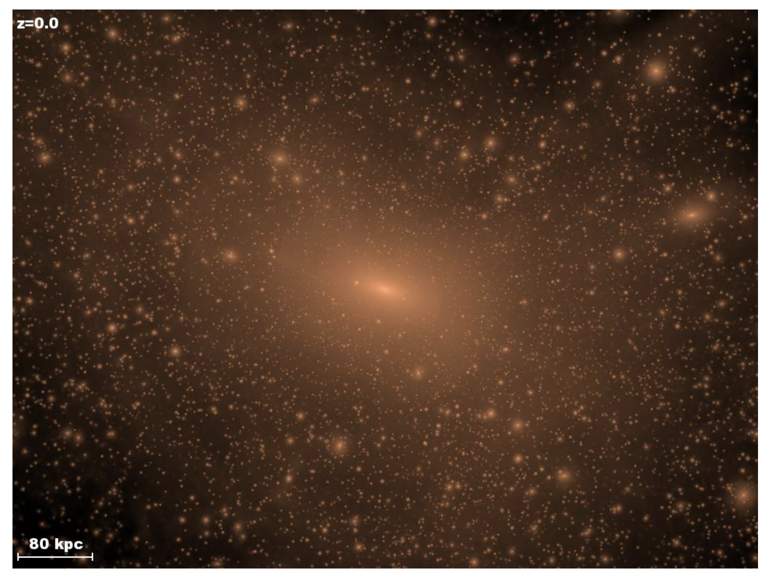
Unresolved gamma-ray emission at high-latitudes can arise from dark matter annihilation in:

Extragalactic Halos



Zavala, Springel, Boylan-Kolchin [0908.2428]

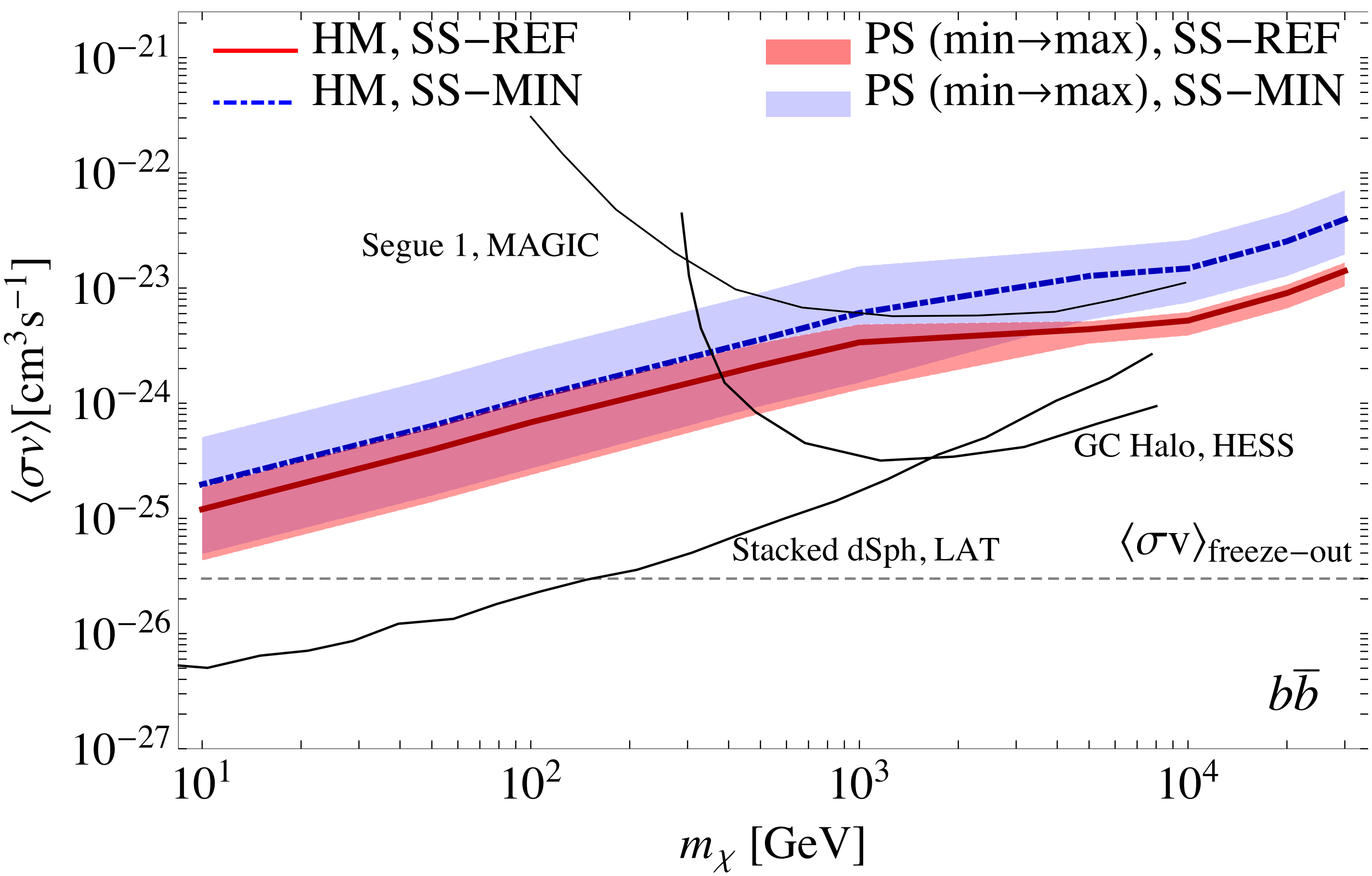
The Milky Way



http://www.ucolick.org/~diemand/vl/

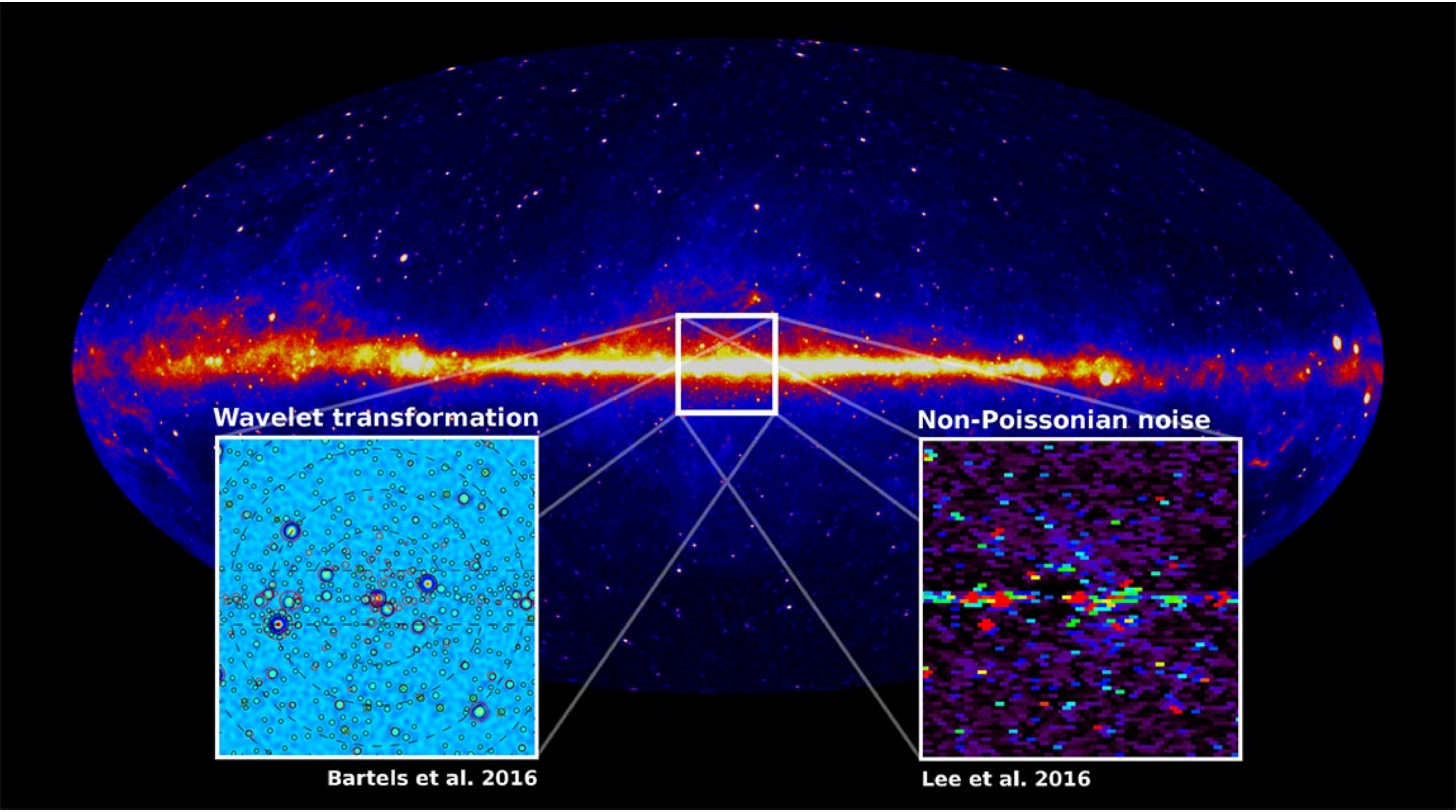
Isotropic Background

Fermi measurement of isotropic background can be converted into limits on dark-matter annihilation



Ackermann *et al.* [1501.05464]

Galactic Center



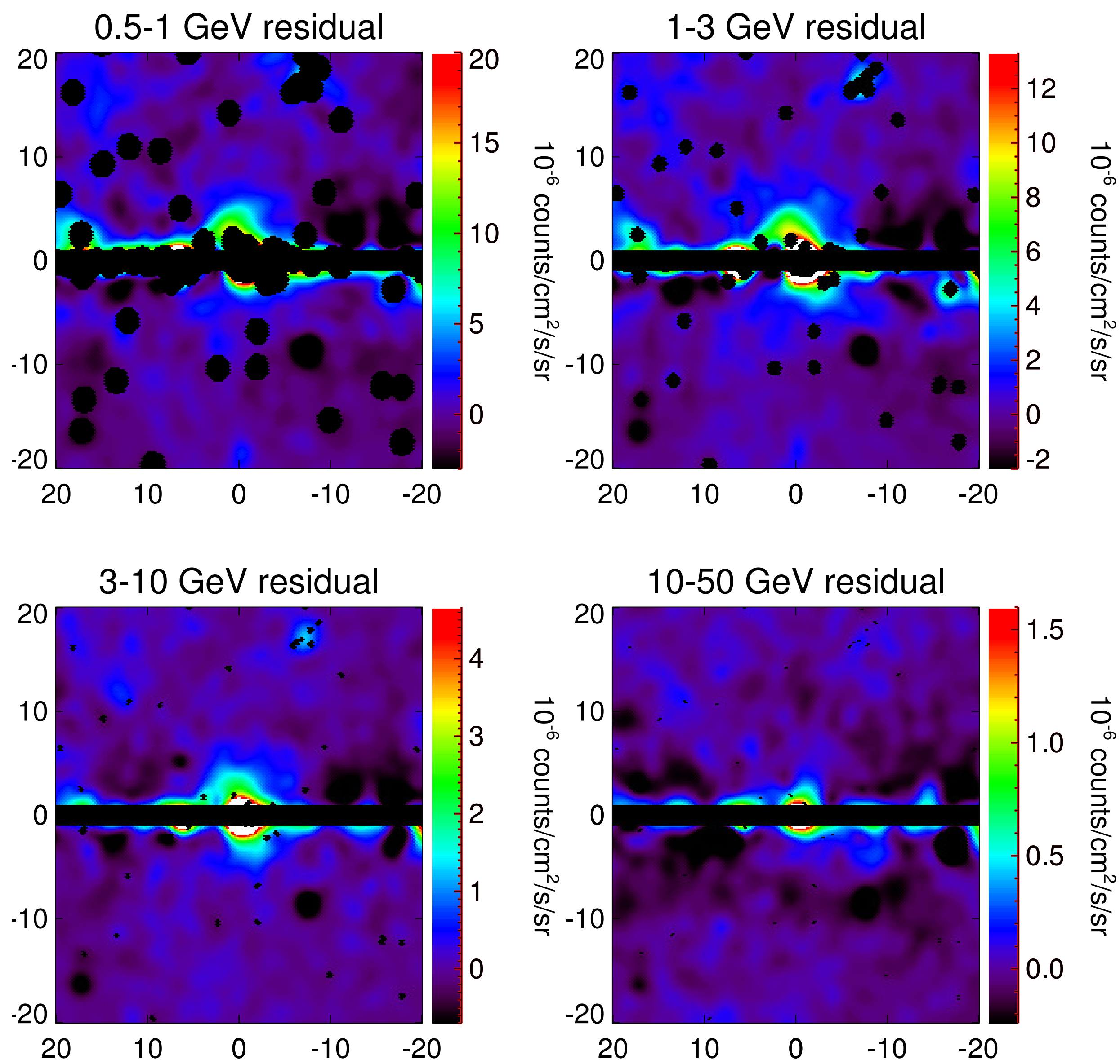
GeV Photon Excess

Observed at the Galactic Center and Inner Galaxy ($\lesssim 10^\circ$)

Constitutes ~10% total flux

High statistical significance

Goodenough and Hooper [0910.2998]
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]
Fermi Collaboration [1511.02938]



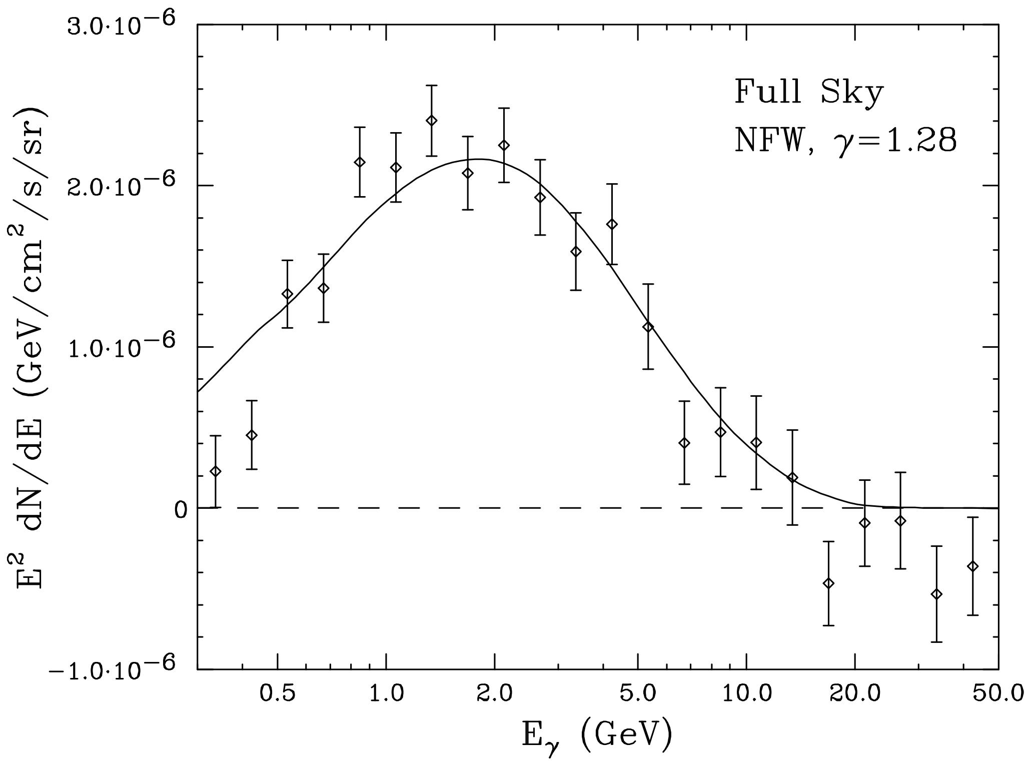
Daylan *et al.* [1402.6703]

The Signal

Approximately spherically symmetric, centered on Sgr A*

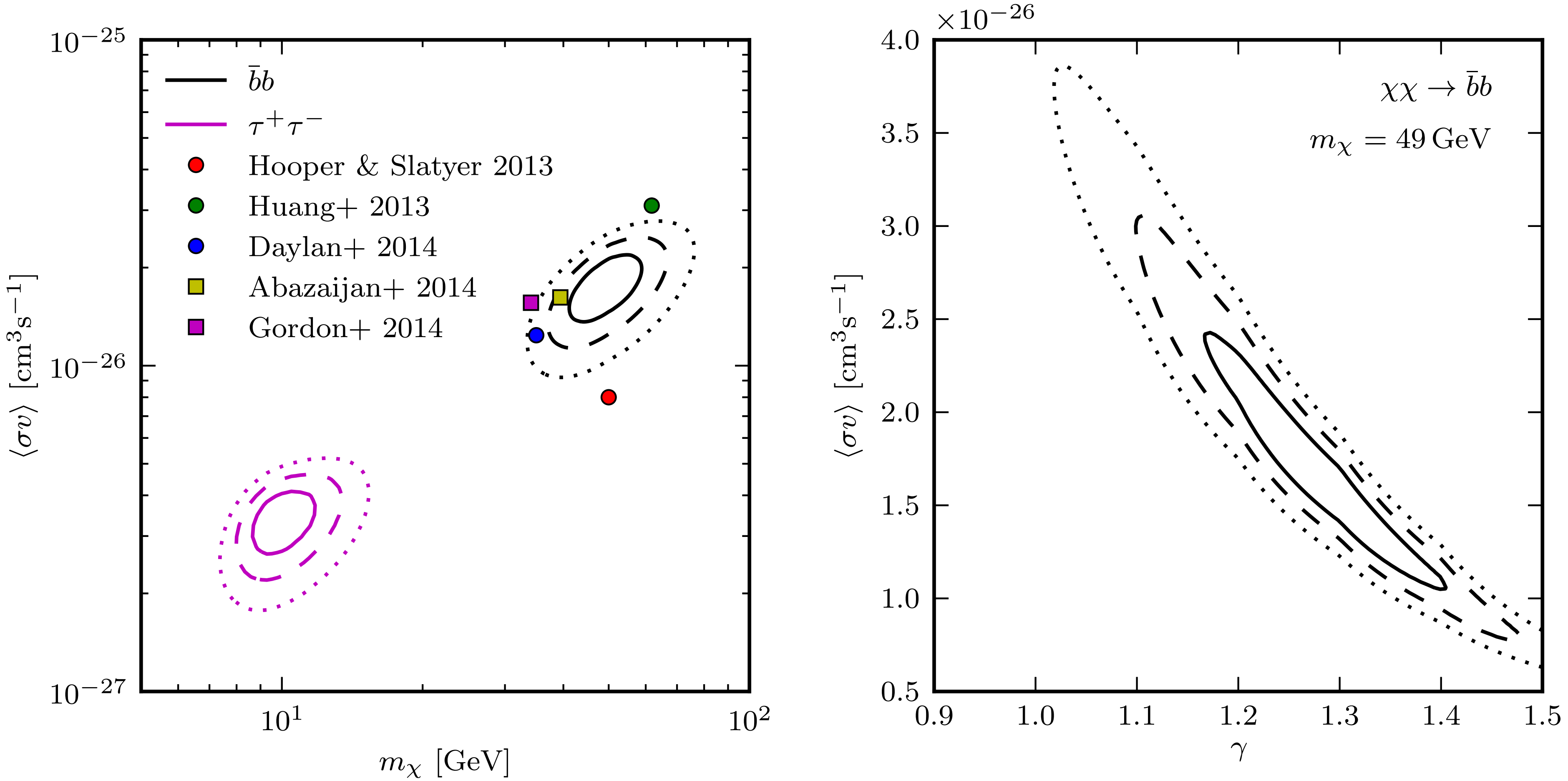
Flux falls off radially as ~ $r^{-(2.2\text{-}2.6)}$

Extends up to 10° off the plane



Daylan *et al.* [1402.6703]

Best-Fit Dark Matter



Calore, Cholis, & Weniger [1409.0042]

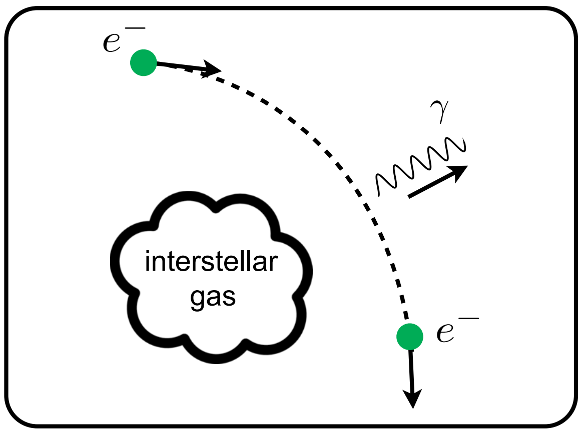
Diffuse Background

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

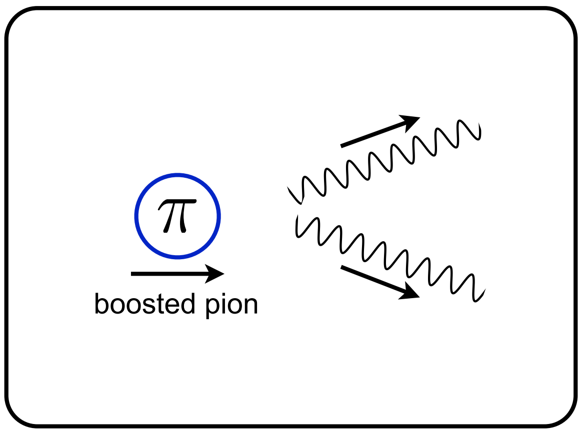
Depends on location of cosmic-ray sources and on the gas distribution

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

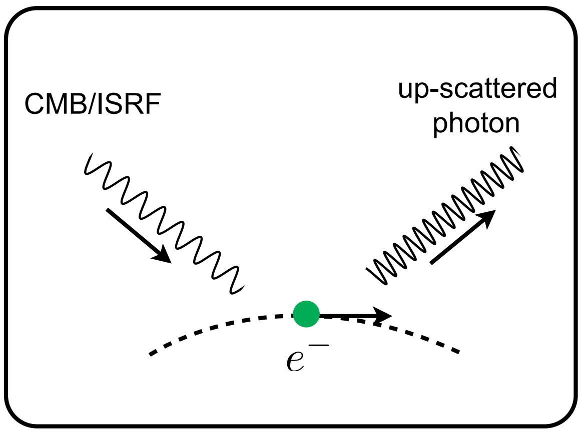
Bremsstrahlung



Pion Emission

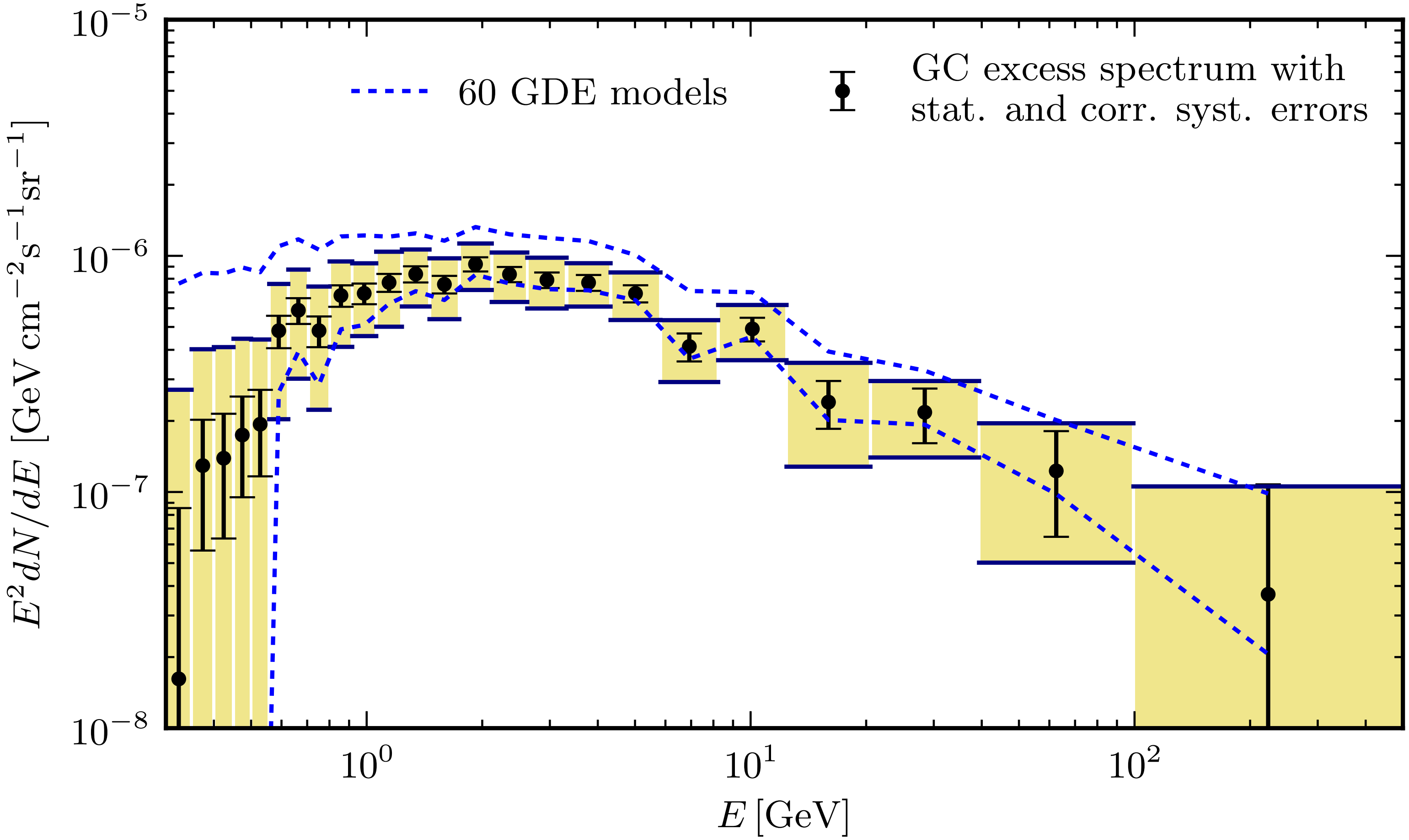


Inverse Compton



Diffuse Background

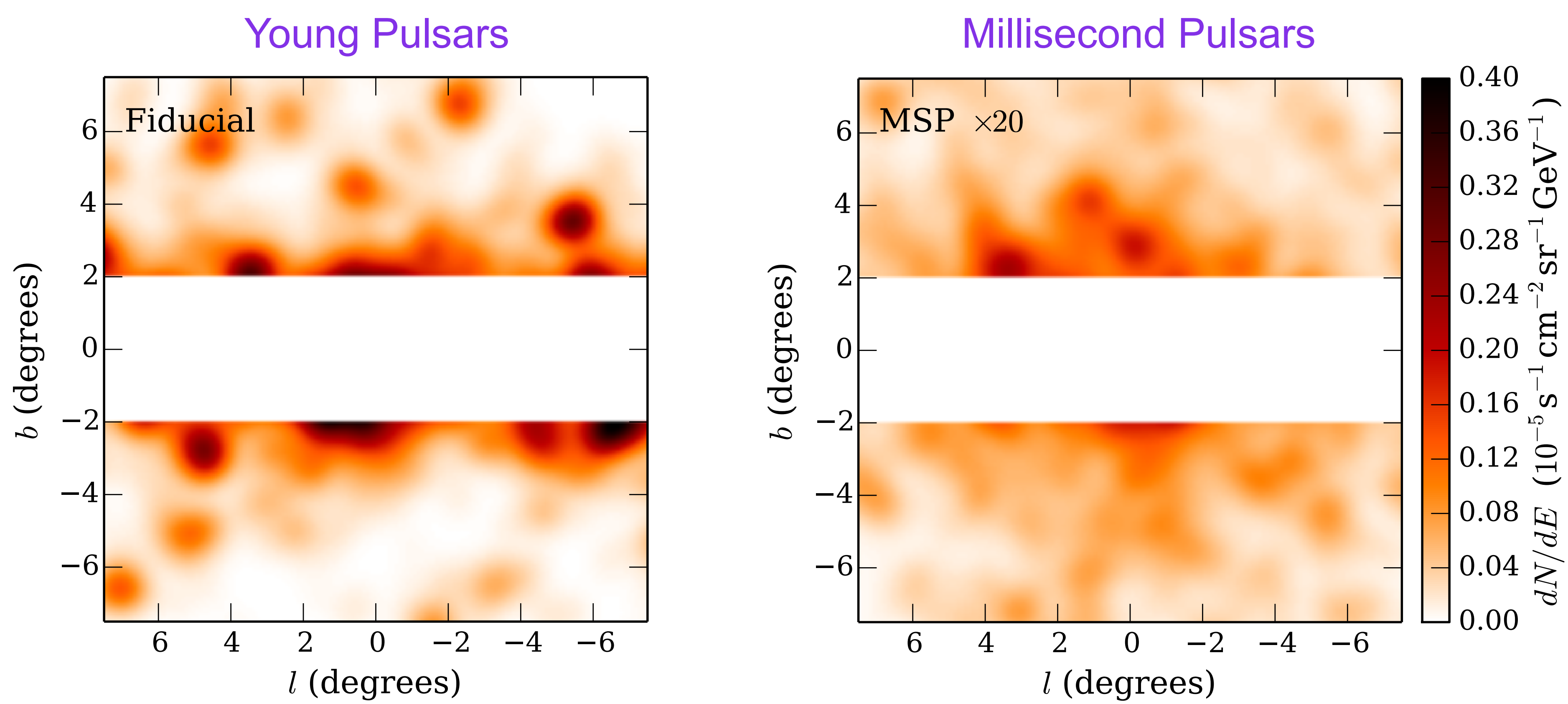
Evidence for excess emission may be robust even under uncertainties in diffuse emission models



Calore, Cholis, and Weniger [1409.0042]

Astrophysical Sources

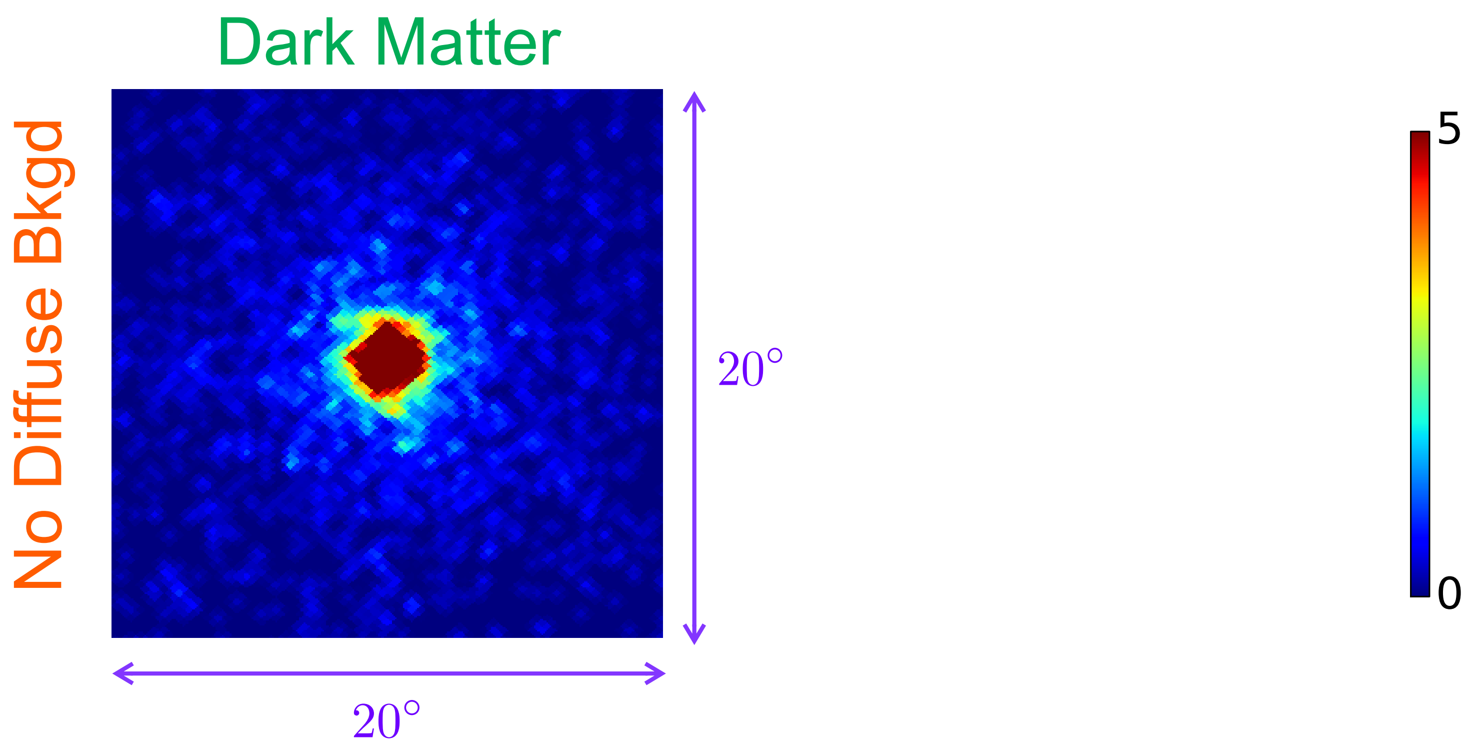
Unresolved young and millisecond pulsars may account for gamma-ray excess



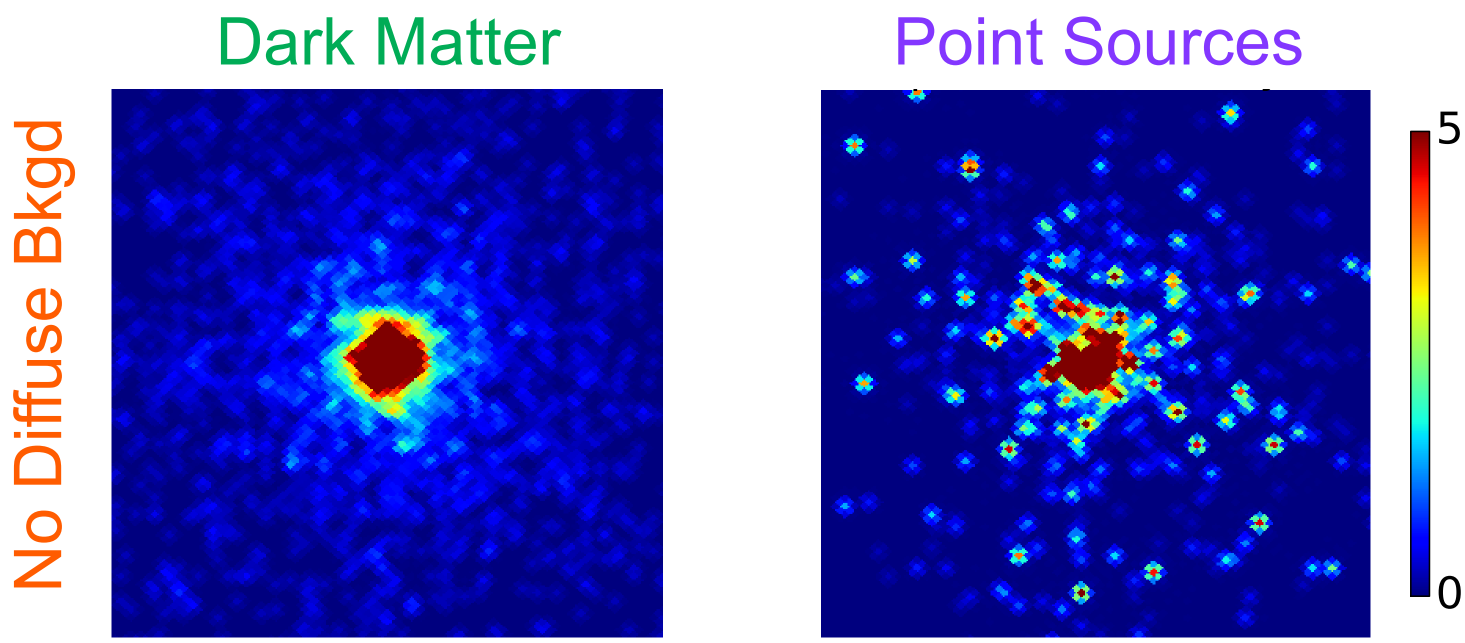
Hooper *et al.* [1305.0830]; Cholis, Hooper, Linden [1407.5583, 1407.5625]
Brandt and Kocsis [1507.0561]; O'Leary *et al.* [1601.05797]

Dark matter versus Astrophysical Sources

Can we improve discrimination power?



Malyshev and Hogg [1104.0010]
Lee, **ML**, Safdi [1412.6099]



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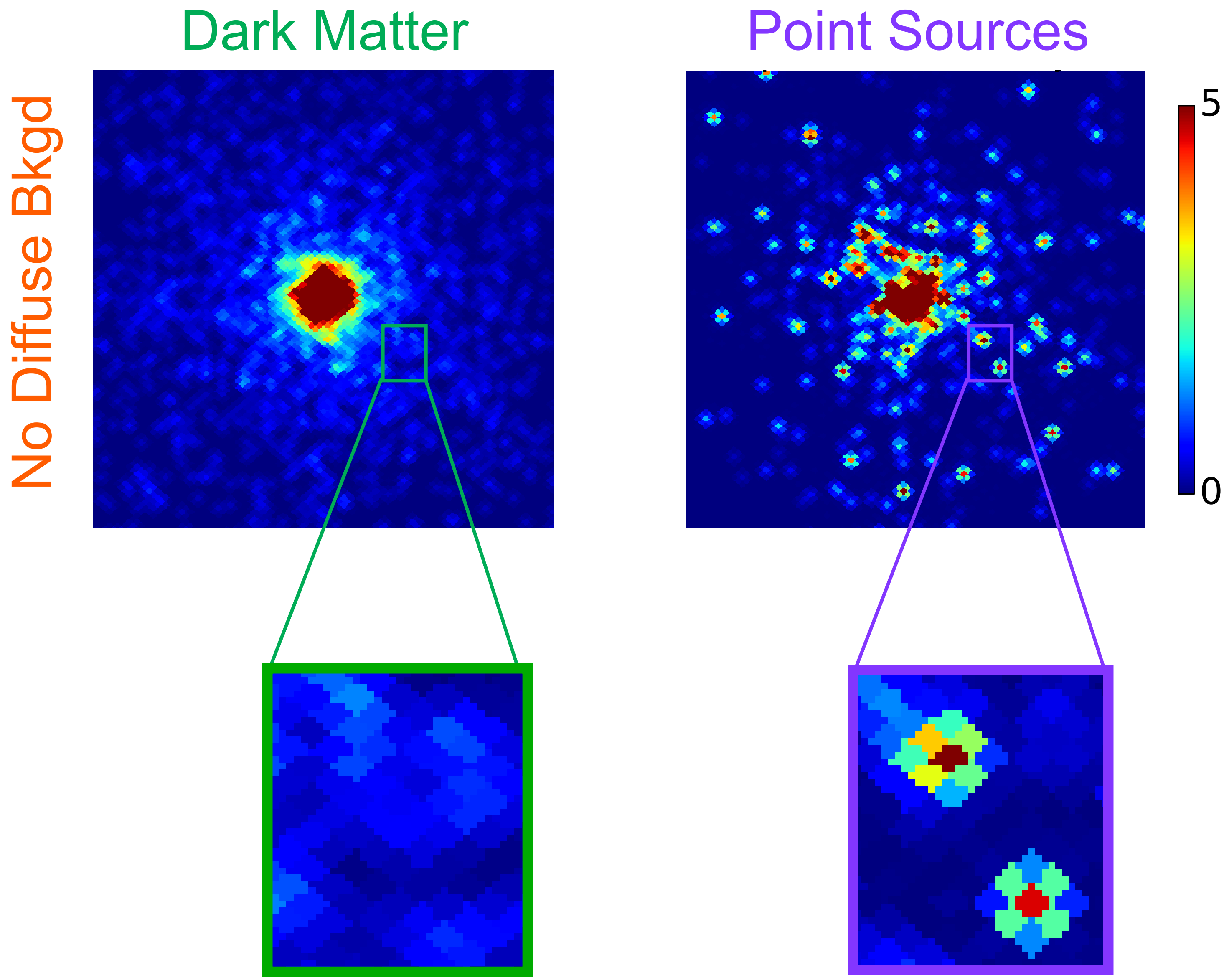
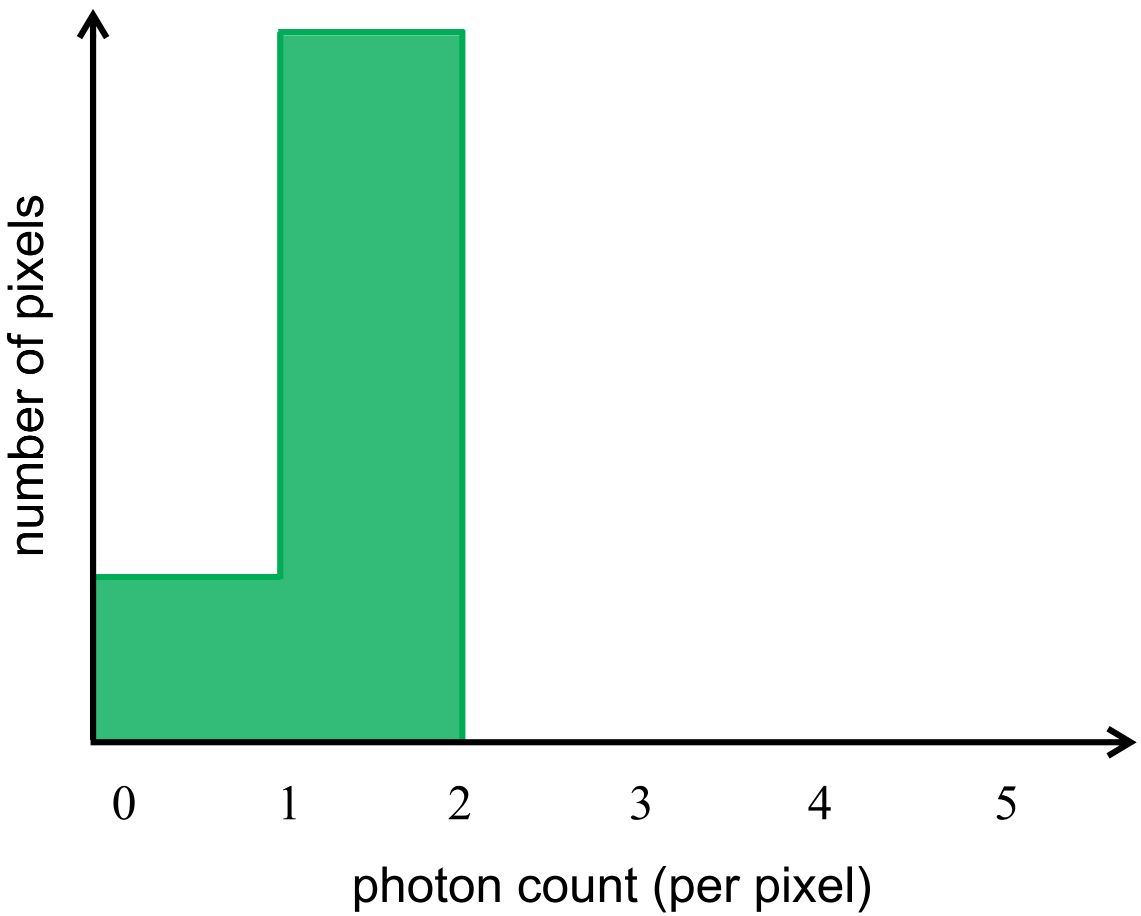
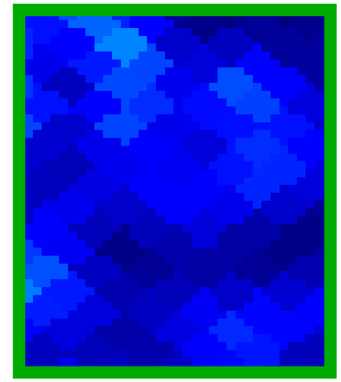


Malyshev and Hogg [1104.0010]
Lee, **ML**, Safdi [1412.6099]

Photon Counts

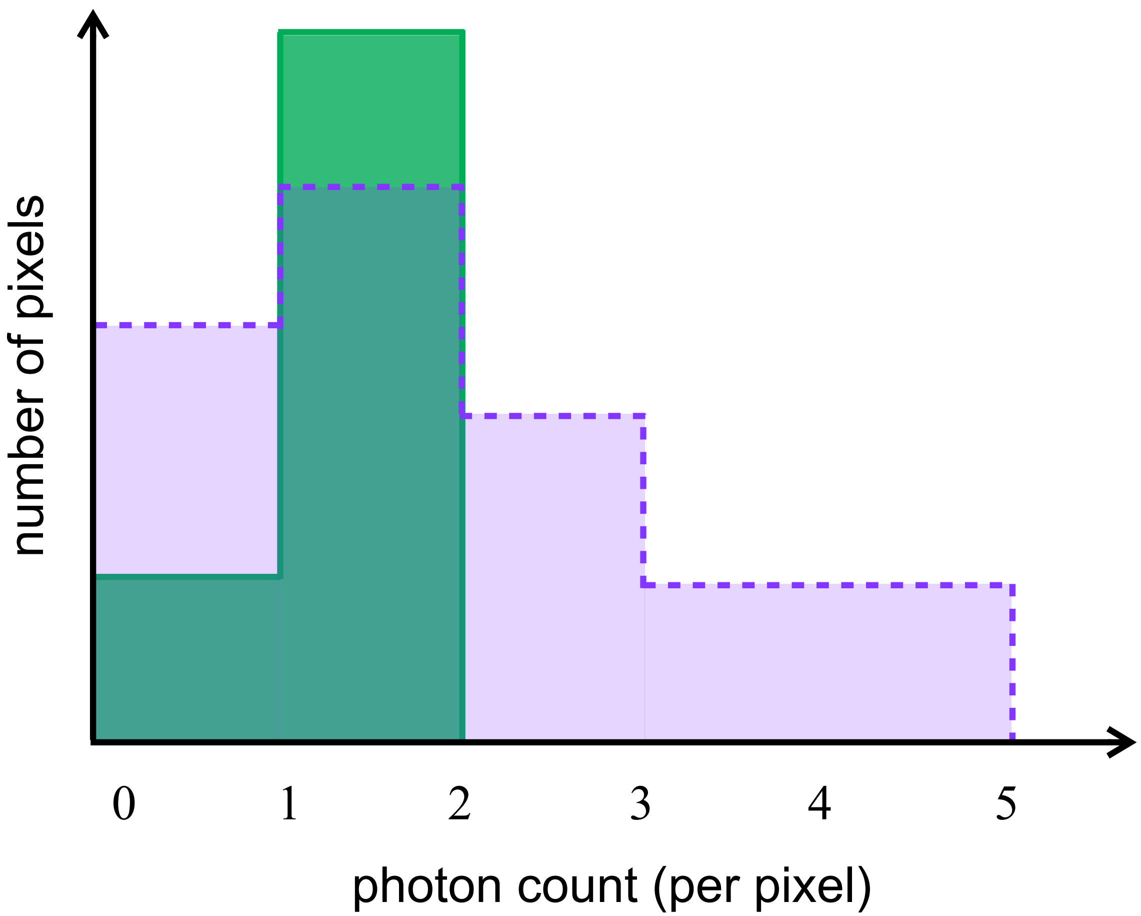


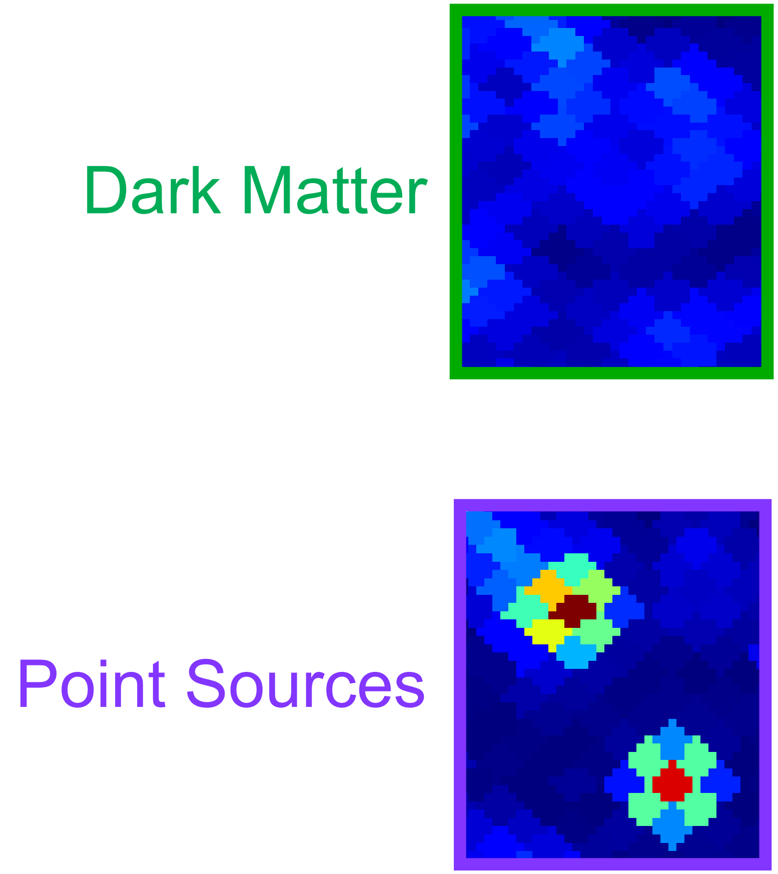
Dark Matter



Malyshev and Hogg [1104.0010]
Lee, **ML**, Safdi [1412.6099]

Photon Counts





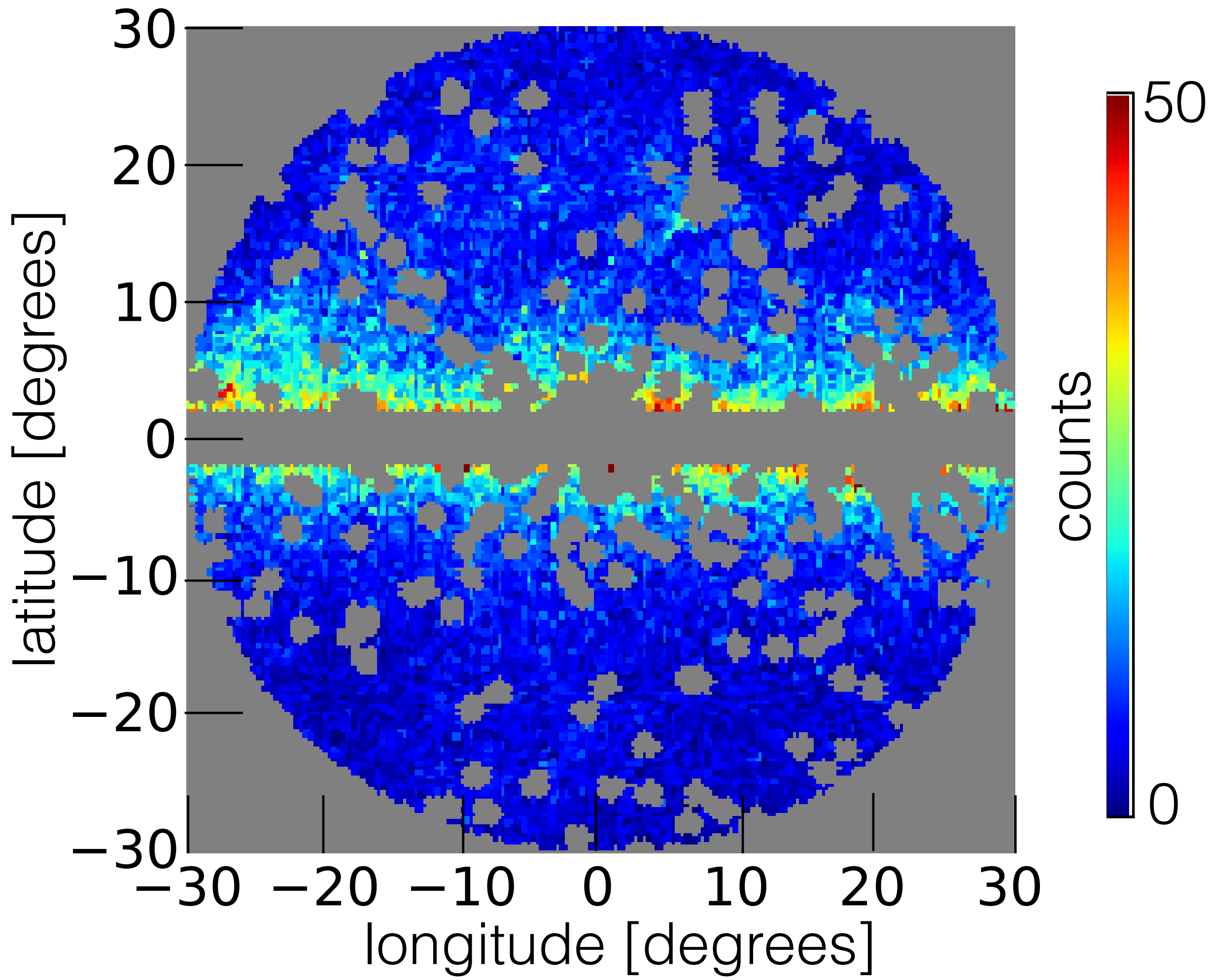
Malyshev and Hogg [1104.0010]
Lee, **ML**, Safdi [1412.6099]

Inner Galaxy Analysis

Lee, **ML**, Safdi, Slatyer, Xue [1506.05124]

Extended Pass 7 Reprocessed *Fermi* data (8/4/08-12/5/13)

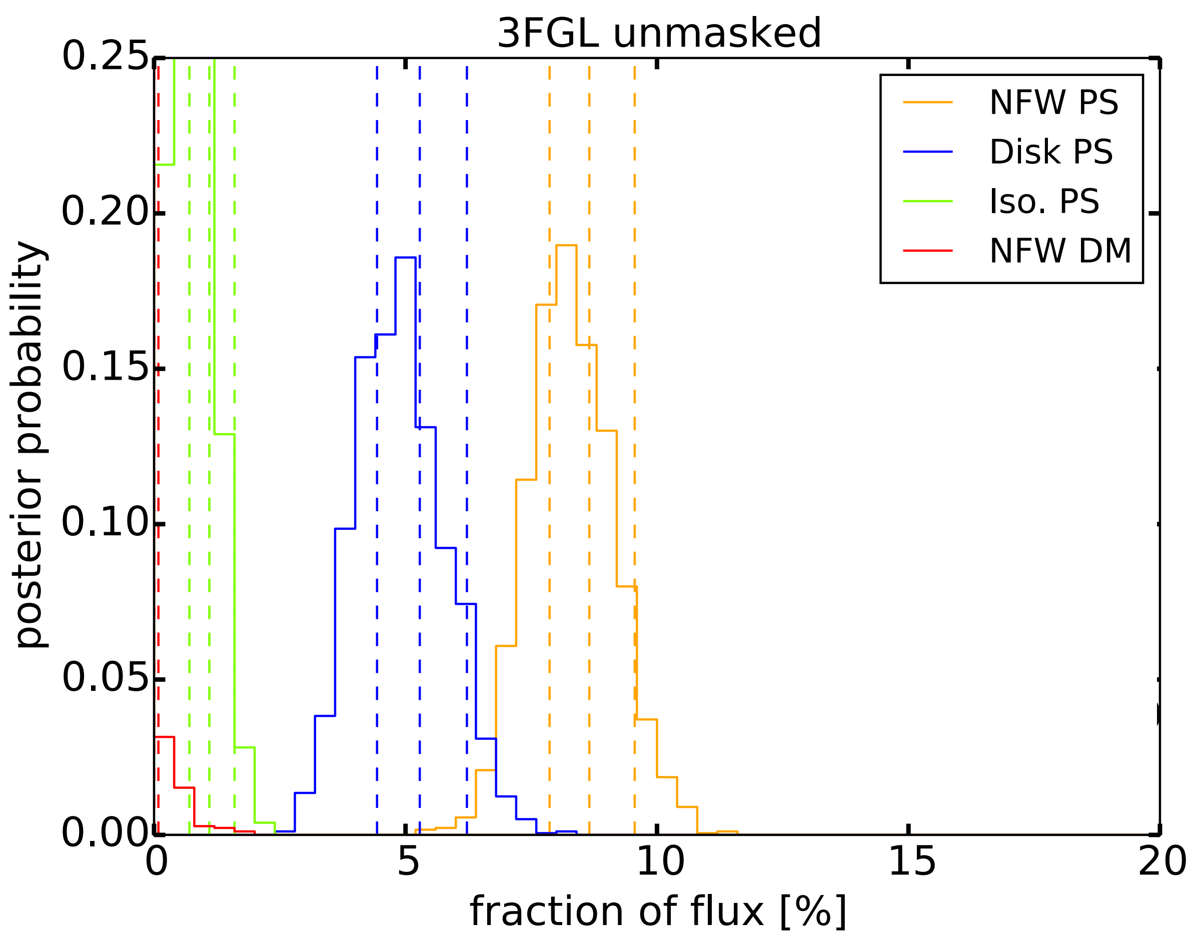
HEALPix pixelization with *nside* = 128



Inner Galaxy Analysis

Photon count statistics can distinguish point sources from dark matter

Excess flux in the Inner Galaxy can be entirely explained by a population of unresolved point sources



Lee, **ML**, Safdi, Slatyer, Xue [1506.05124]
Bartels, Krishnamurthy, Weniger [1506.05104]

What are these point sources?

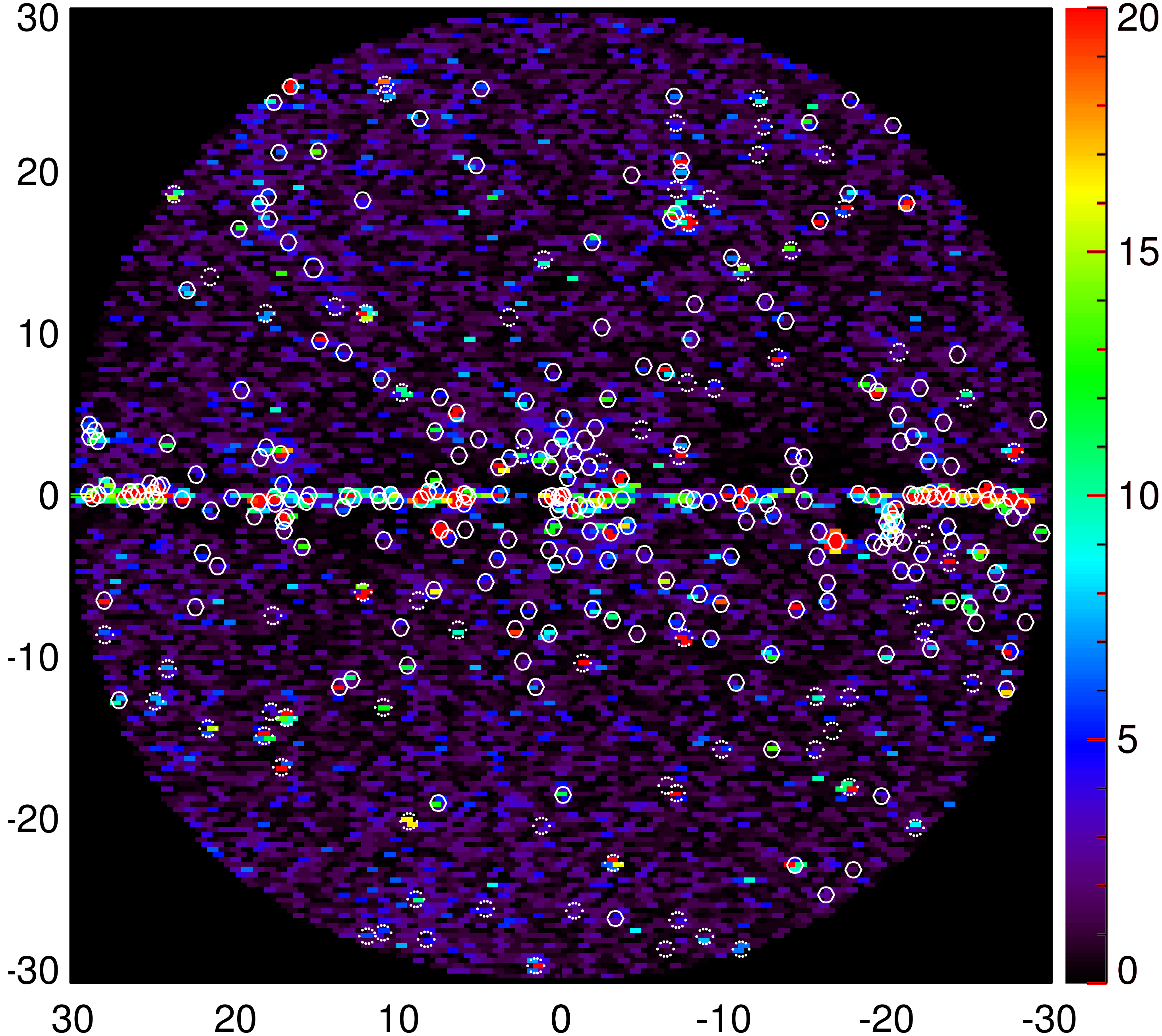
Our analysis is model-independent in that *any* sub-pixel structure is identified as a point source

So, what exactly is the nature of this point-source population?

Localized structure in the diffuse background?

Population of pulsars?

Dark matter substructure?



30
20
10
0
-10
-20
-30
30
20
10
0
-10
-20
-30
20
15
10
5
0

Isotropic Background

Presence of all-sky, diffuse gamma-ray emission has been known for decades, but its origin remains an open question

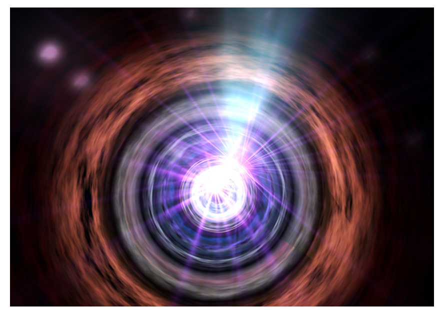
Star-Forming Galaxies (SFGs)

+

Misaligned AGN

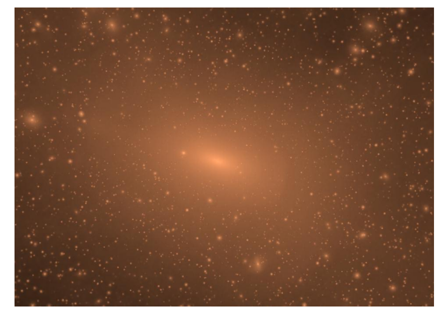
+

Blazars



+

Dark Matter?

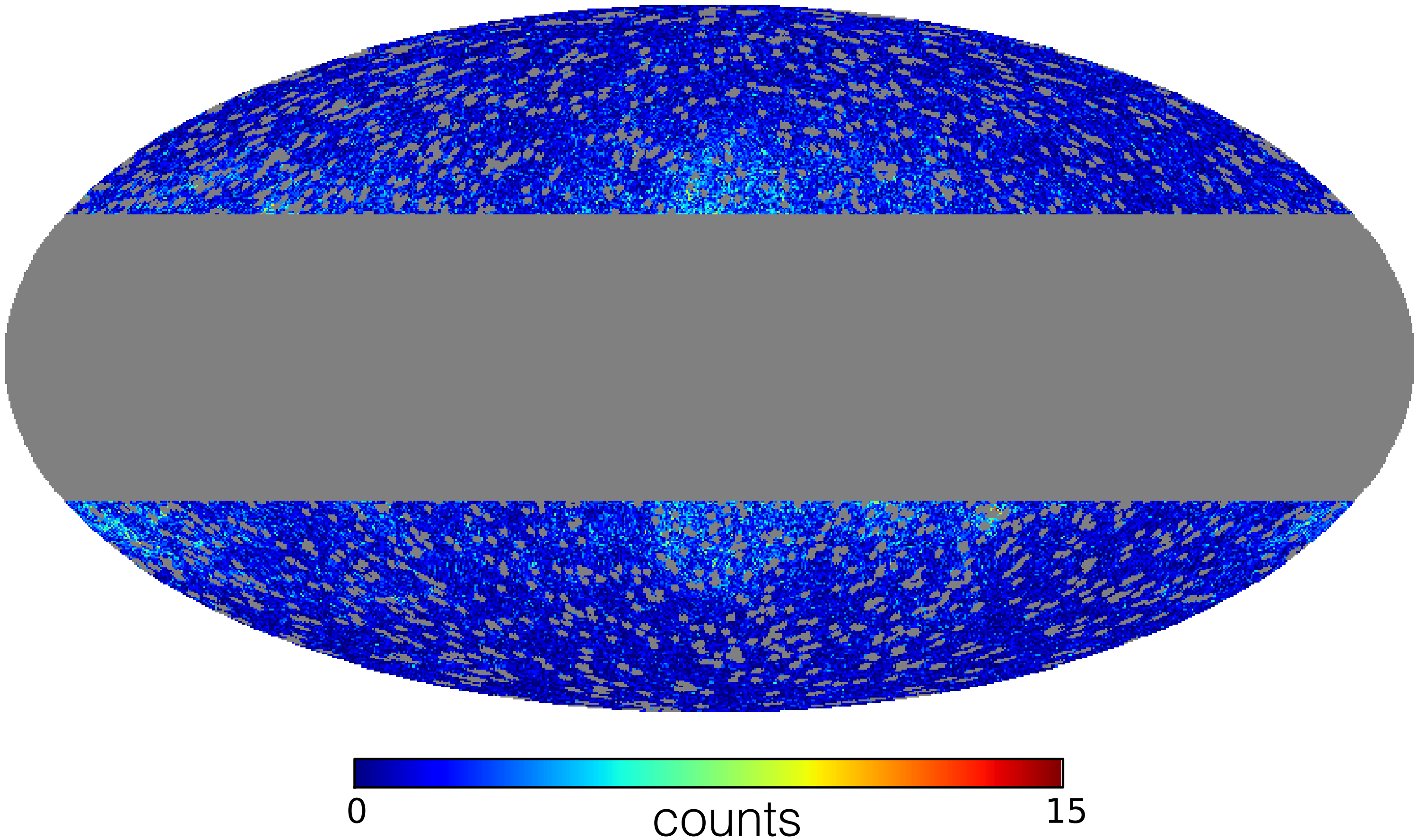


Potential wealth of information can be extracted from isotropic background if components are resolved

High-Latitude Analysis

ML, S. Mishra Sharma, L. Necib, B. Safdi [to appear]

Use photon statistics to characterize the population of unresolved point sources at high latitudes and understand implications for dark matter



Recent High-Latitude Studies: Zechlin *et al.* [1512.07190], Ackermann *et al.* [1508.04449]

Summary

Wide program of indirect searches currently looking for signals of dark matter annihilation

The biggest challenge is distinguishing a potential signal from the astrophysical backgrounds

Photon statistics has proved useful in the Inner Galaxy, where evidence suggests the presence of an unresolved point source population, disfavoring the dark matter interpretation

The wealth of gamma-ray data presently available is strong motivation to continue developing novel analysis methods that increase potential for dark matter discovery