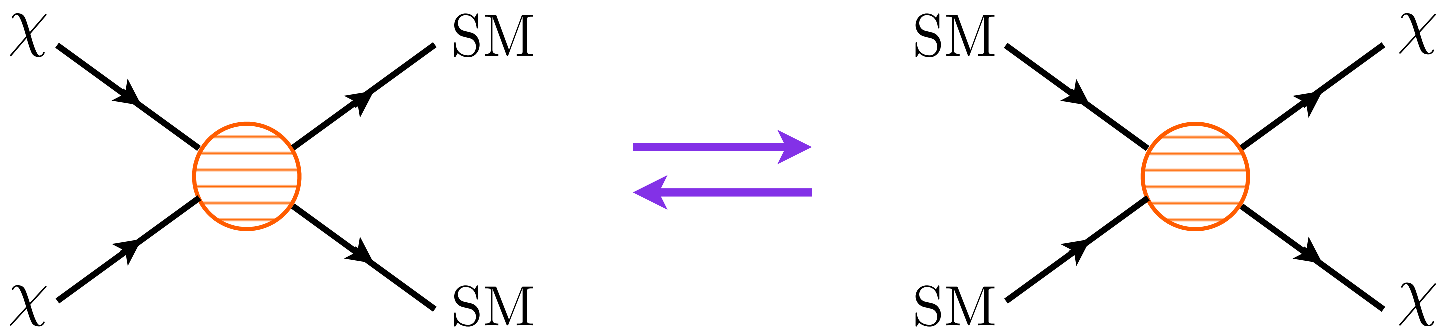
Indirect Detection of Dark Matter

Mariangela Lisanti
Princeton University

Thermal Dark Matter

Dark matter is in equilibrium in the early Universe



As temperature cools, eventually

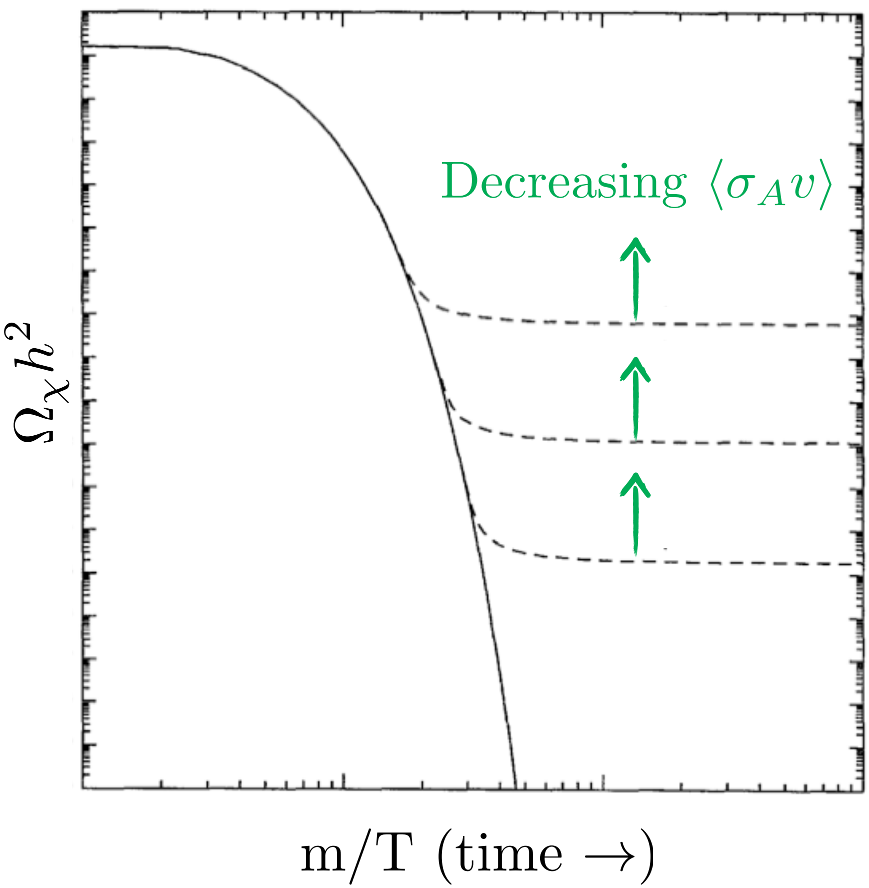
$$n_\chi \langle \sigma_A v \rangle \sim H$$

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:

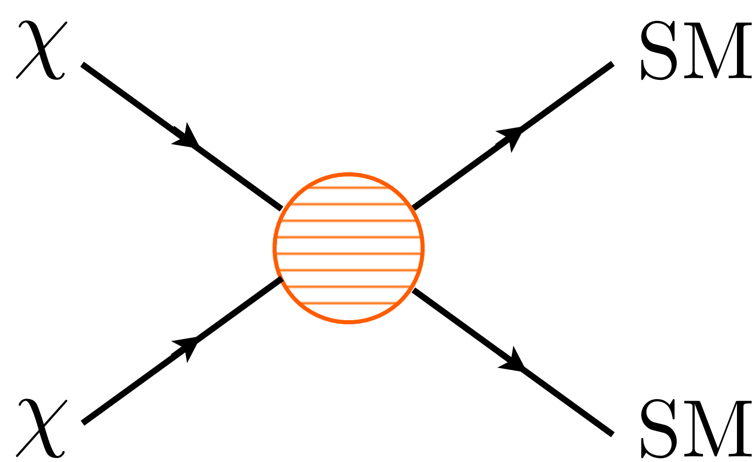
$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

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

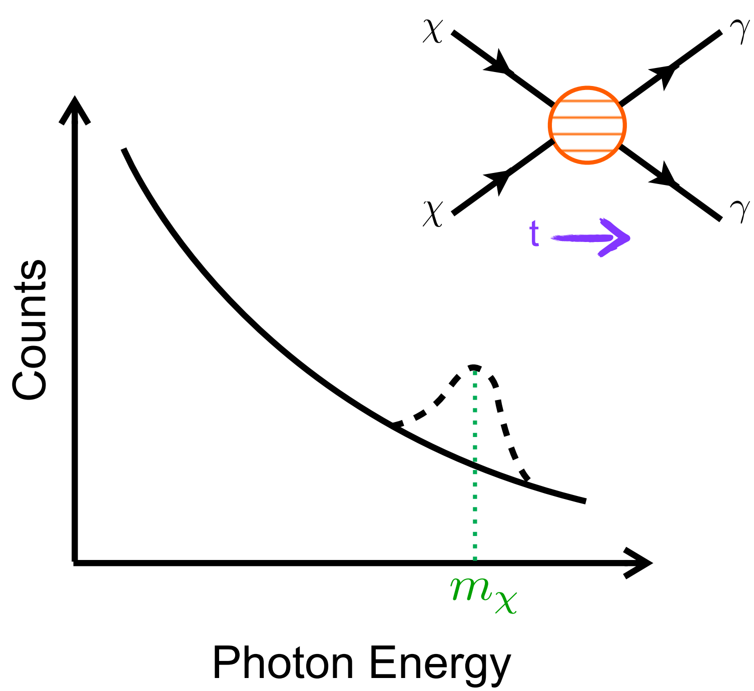
Sensitive to energies from 20 MeV to > 300 GeV

Scans over the whole sky every three hours

Indirect Detection

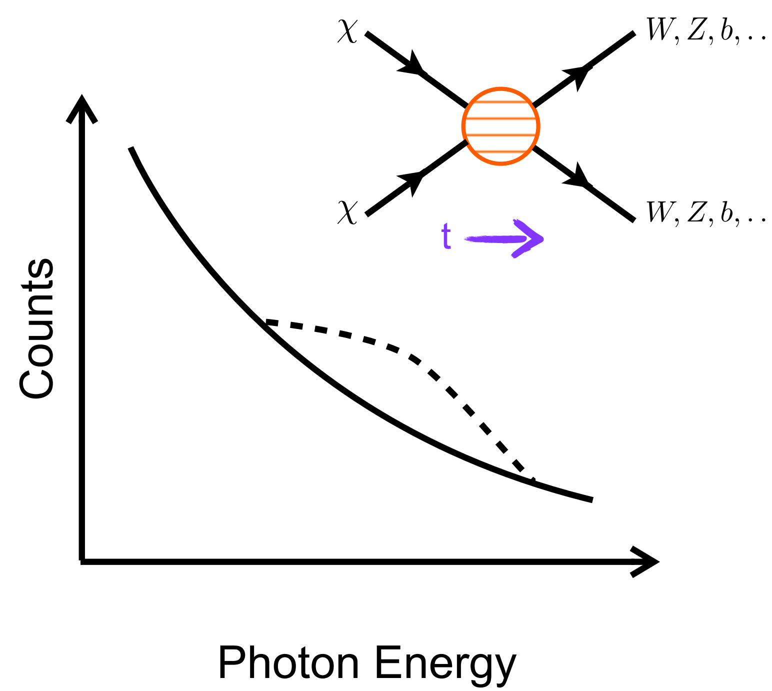
Monochromatic Photons

Direct annihilation to photons, a line in photon energy spectrum



Continuum Photons

Annihilation to SM final states that shower into photons



Photon Flux

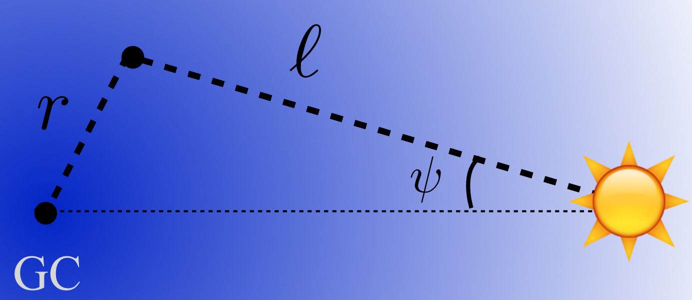
The intensity profile for dark matter annihilation is given by

annihilation cross section

dark matter density

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

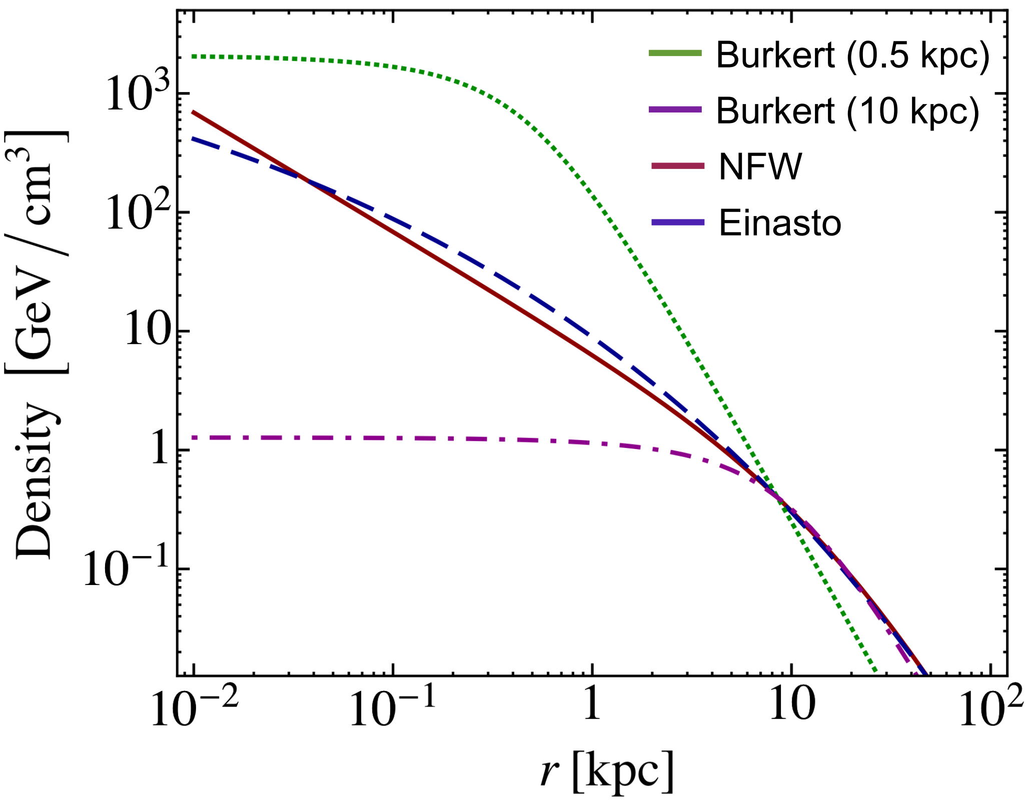
photon energy spectrum



J-Factor

Astrophysical uncertainties are absorbed by the "J-factor"

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



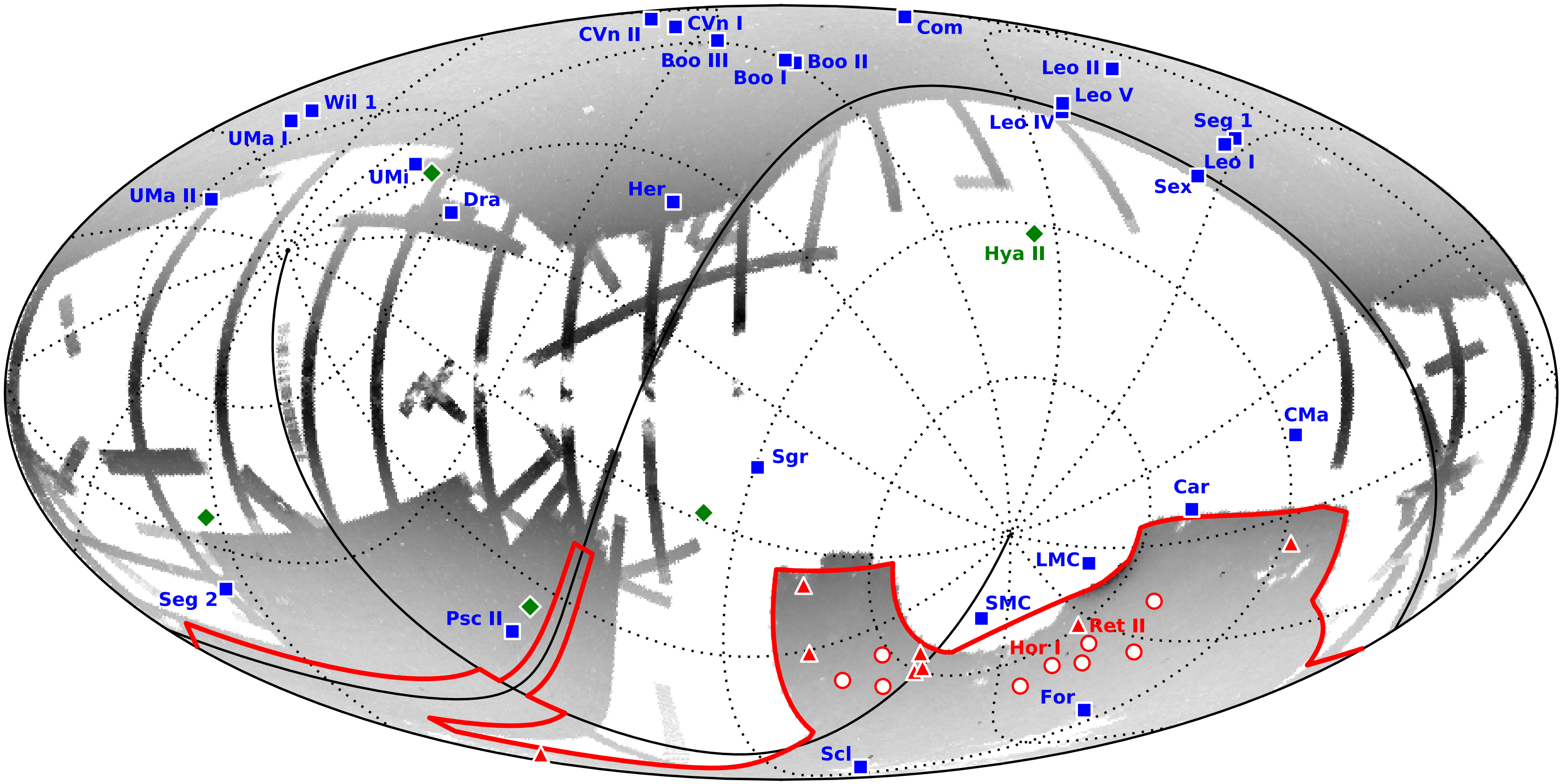
Generalized NFW Profile

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

Most dense regions at the centers of dark-matter halos

Dwarf Galaxies

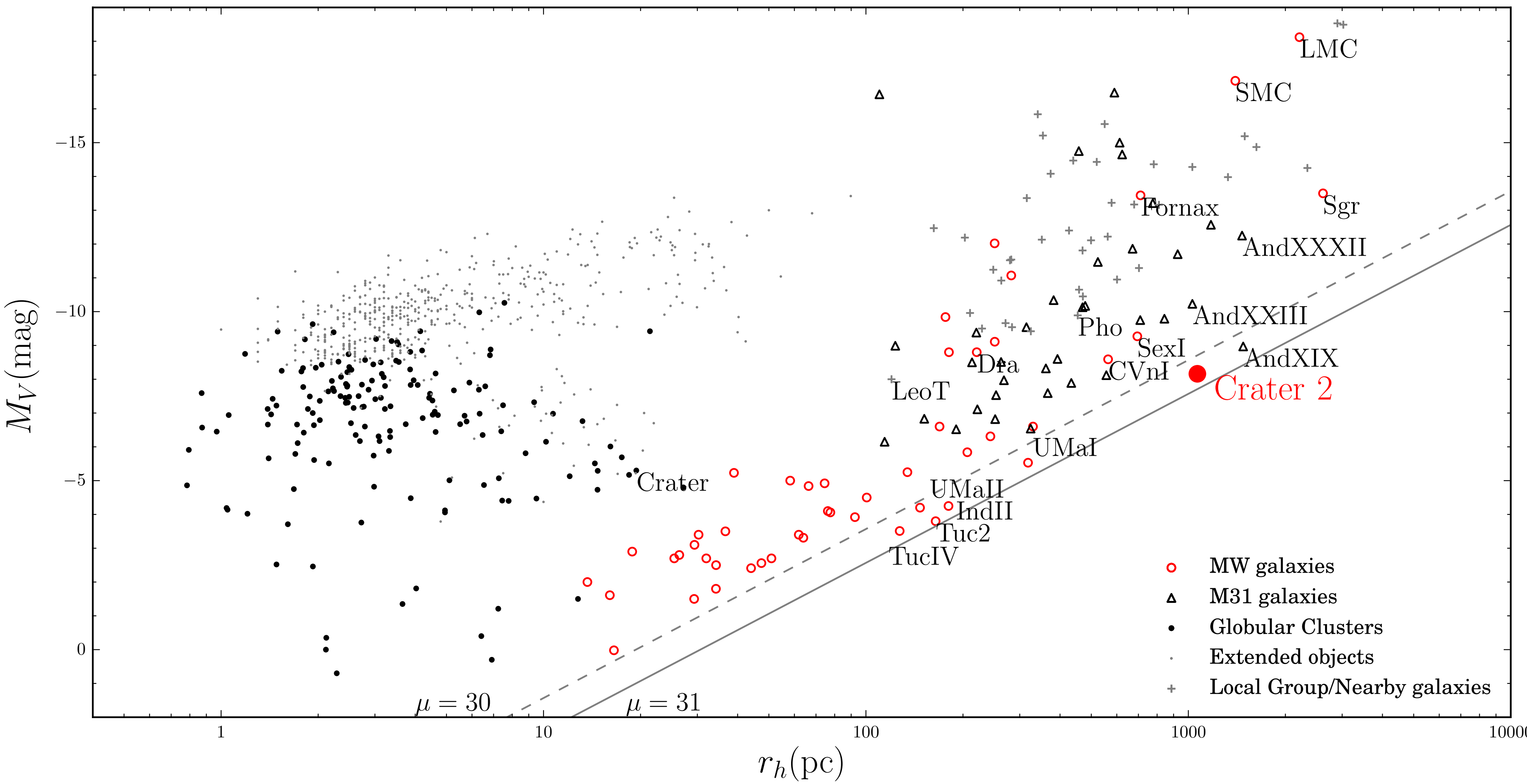
These faint galaxies are dark-matter dominated and thus excellent targets for annihilation searches



Drlica-Wagner *et al.* [1508.03622]

Crater 2

The fourth largest Milky Way satellite (after the SMC, LMC, & Sgr) was only recently discovered!

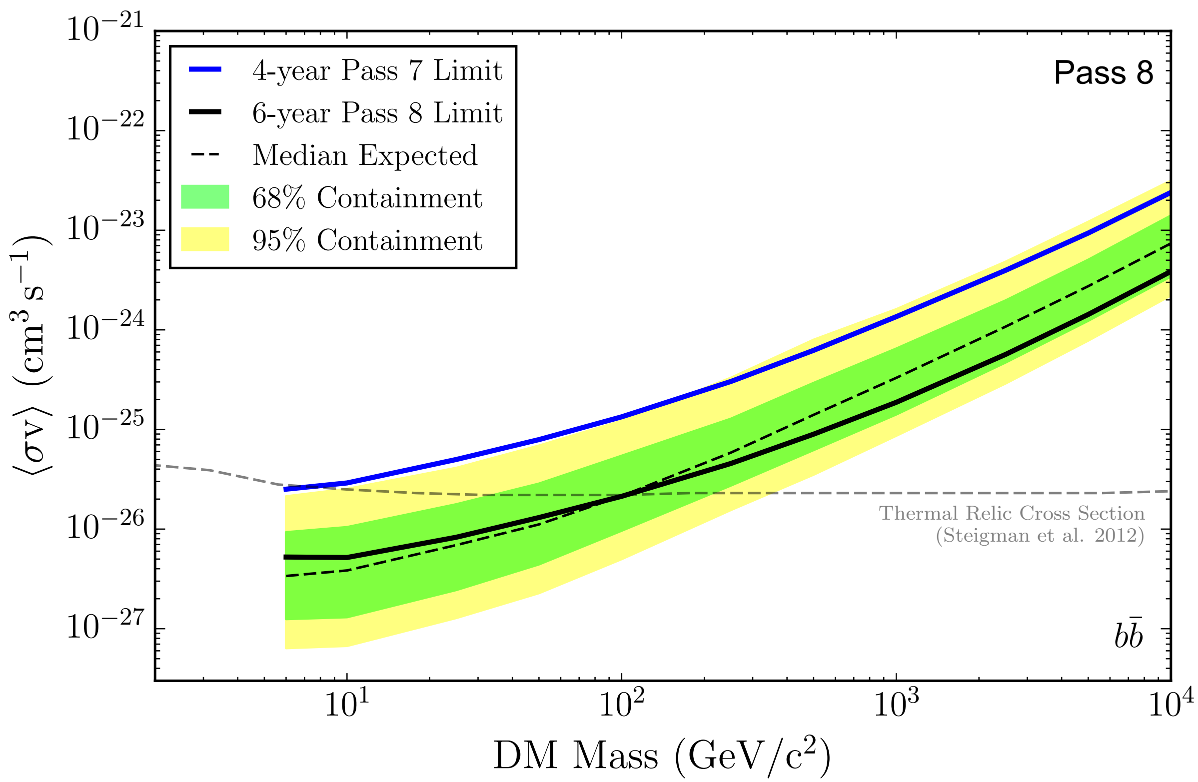


Torrealba *et al.* [1601.07178]

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)

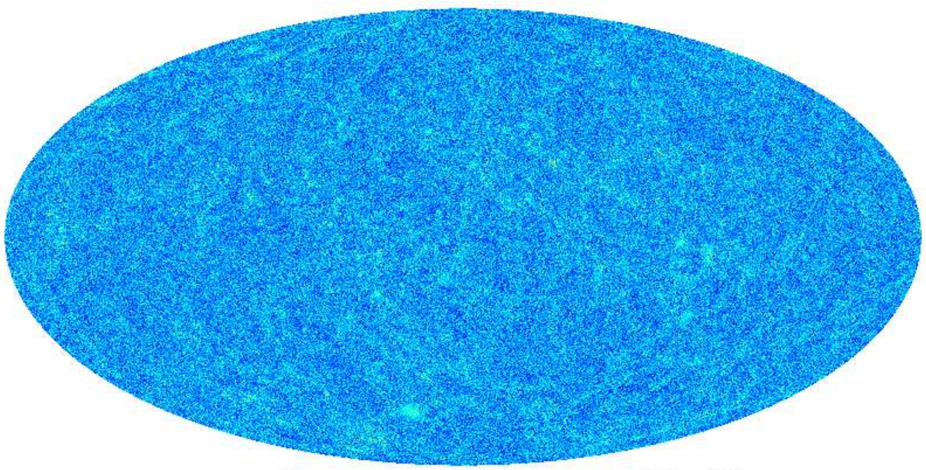


Ackermann *et al.* [1503.02641]

Isotropic Background

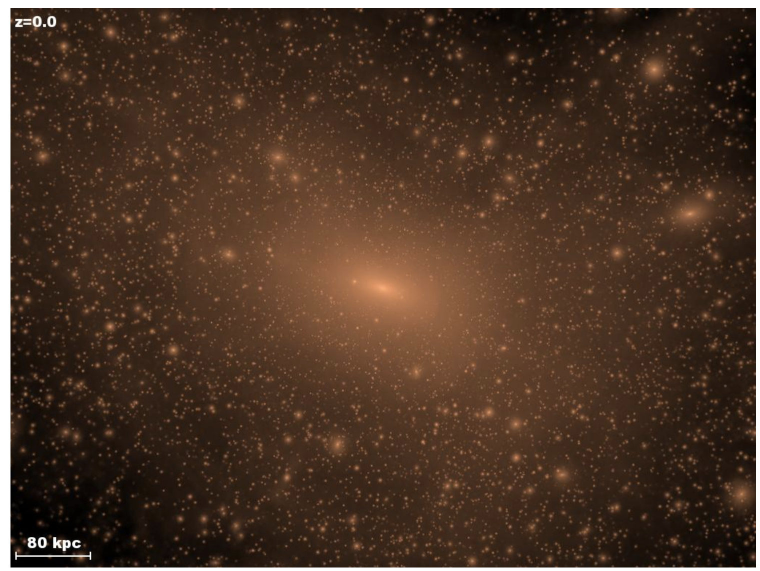
Unresolved gamma-ray emission at high-latitudes can arise from dark matter annihilation in:

Extragalactic Halos



Zavala, Springel, Boylan-Kolchin [0908.2428]

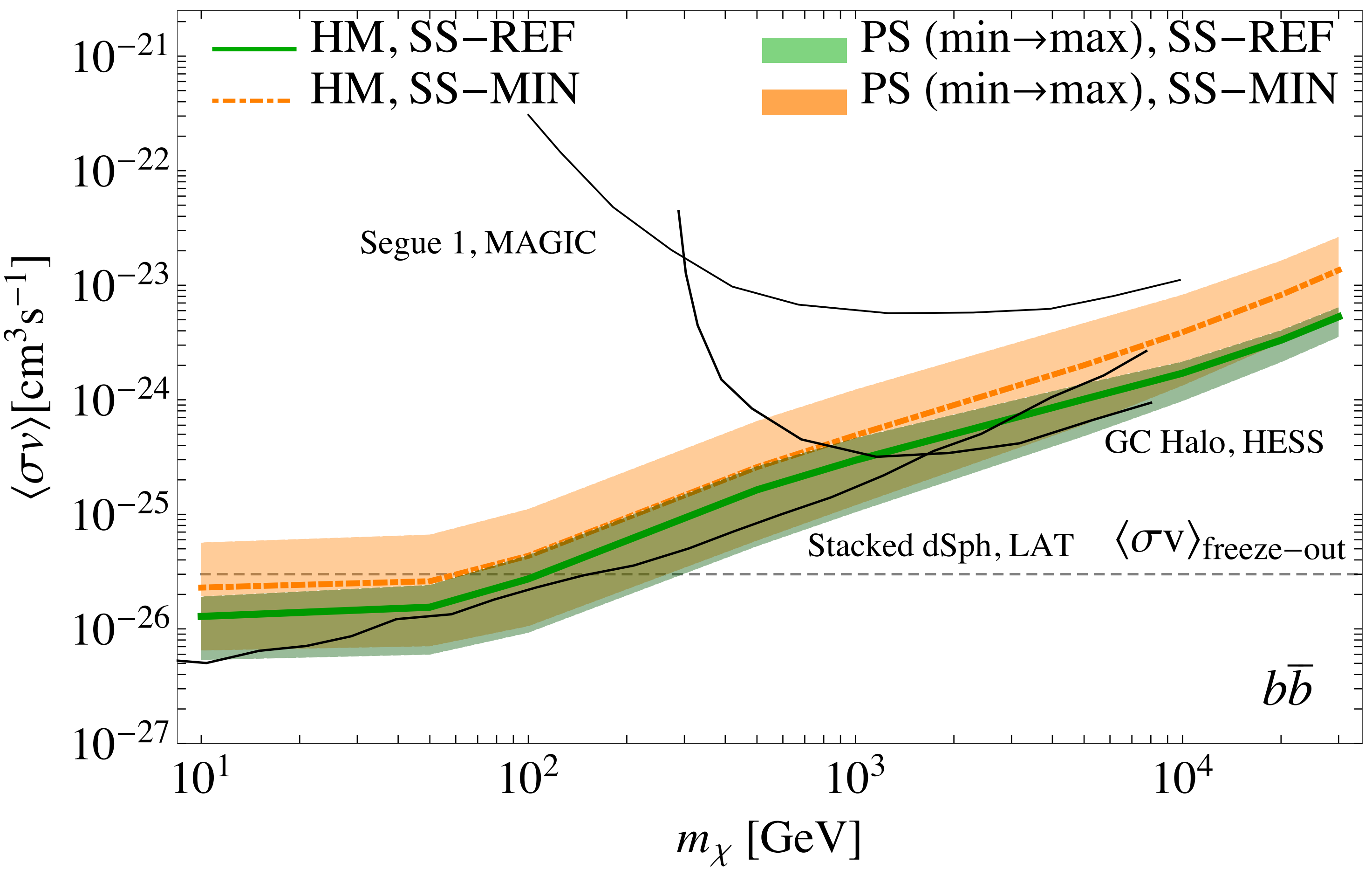
The Milky Way



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

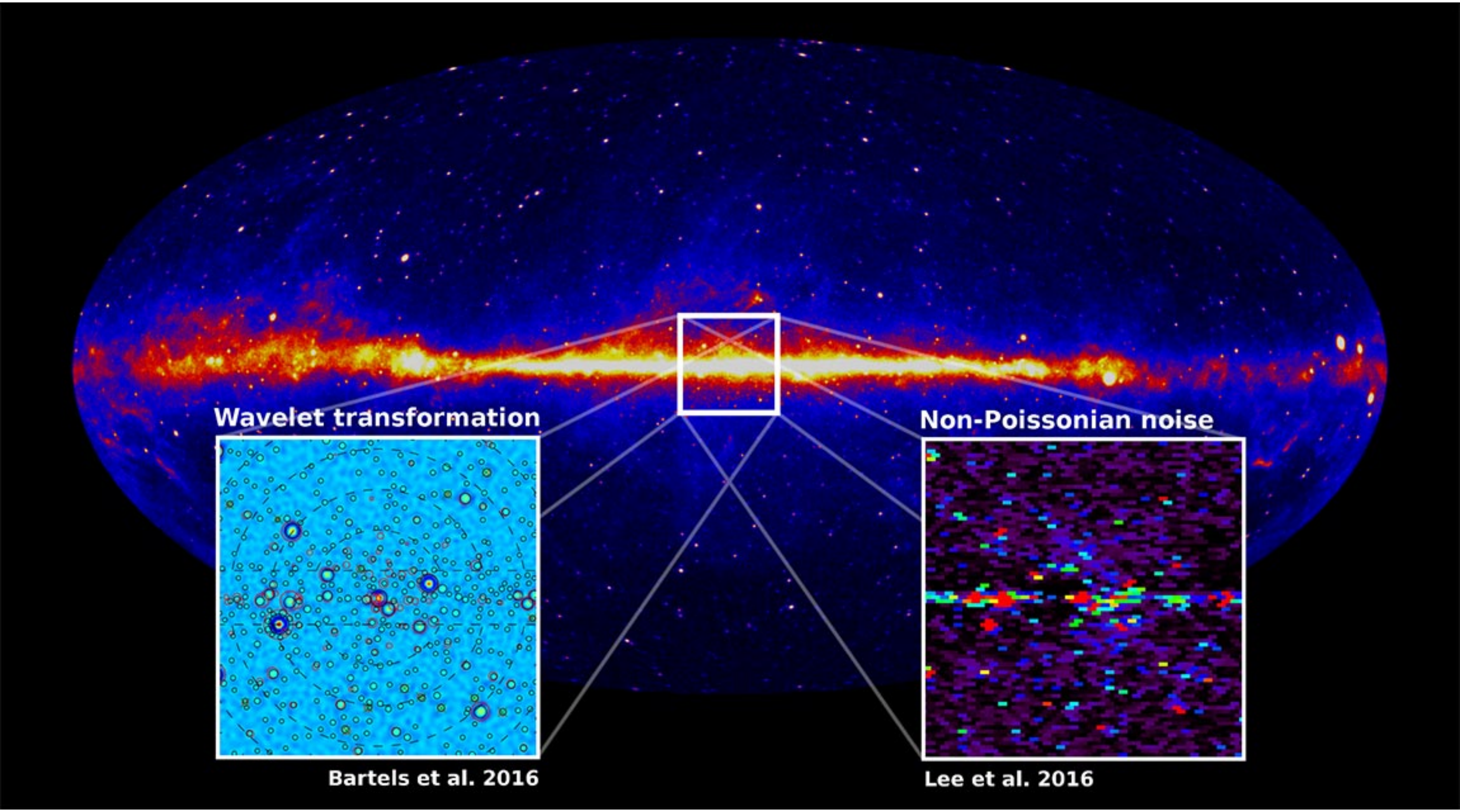
Isotropic Background

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



Ackermann *et al.* [1501.05464]

Galactic Center

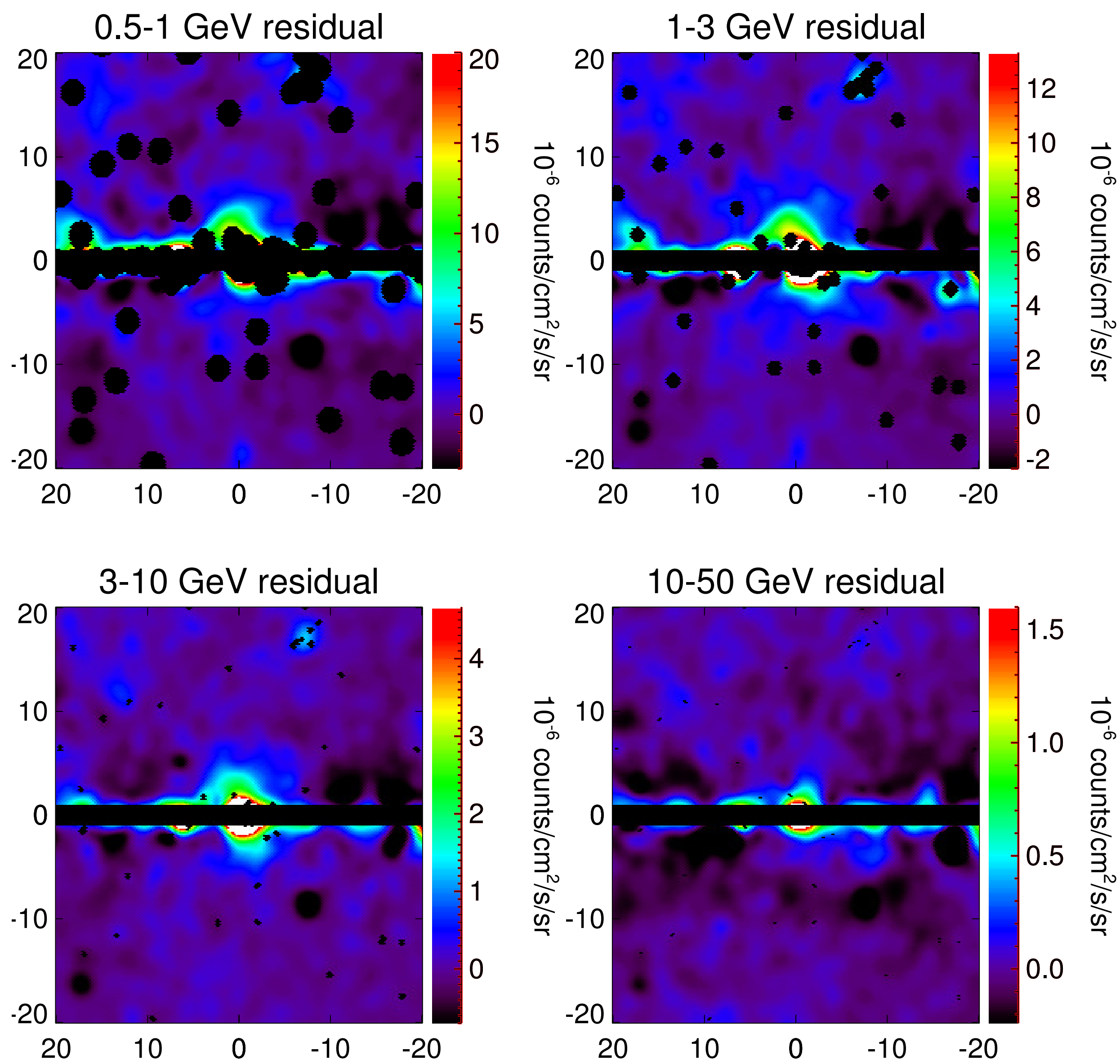


GeV Photon Excess

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

Constitutes ~10% total flux

High statistical significance



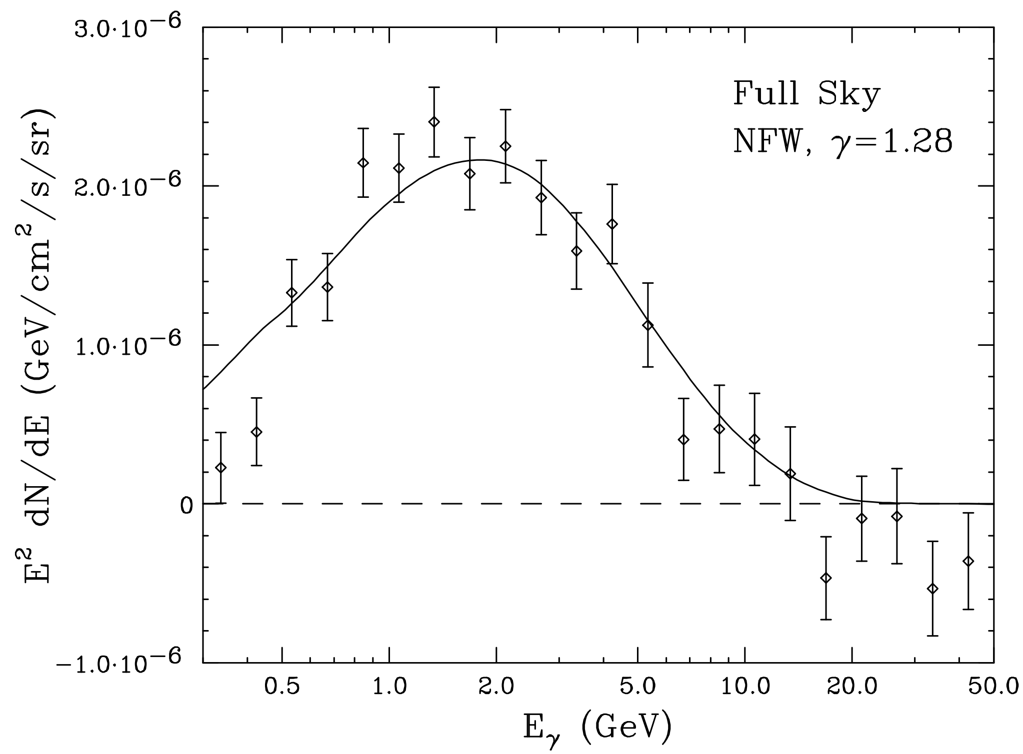
Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian *et al.* [1402.4090]
Daylan *et al.* [1402.6703]
Calore, Cholis, and Weniger [1409.0042]
Fermi Collaboration [1511.02938]

Daylan *et al.* [1402.6703]

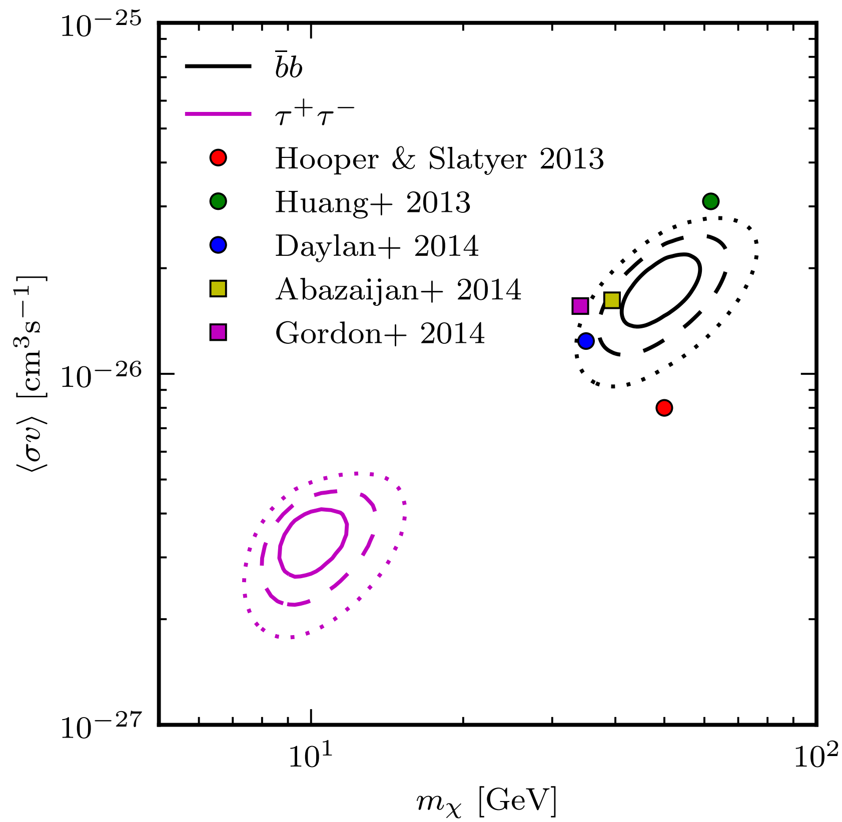
The Signal

Approximately spherically symmetric, centered on Sgr A*

Energy spectrum is well-fit by dark matter



Daylan *et al.* [1402.6703]



Calore, Cholis, & Weniger [1409.0042]

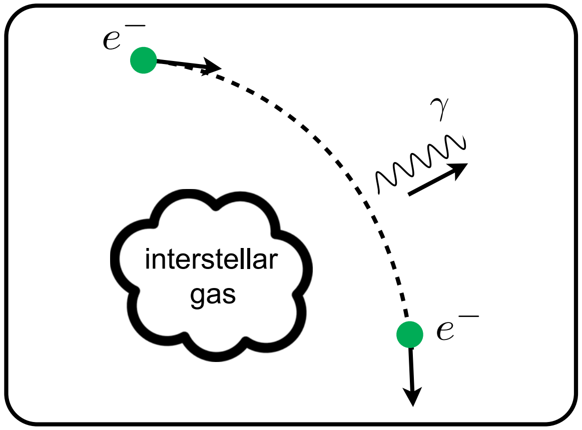
Diffuse Background

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

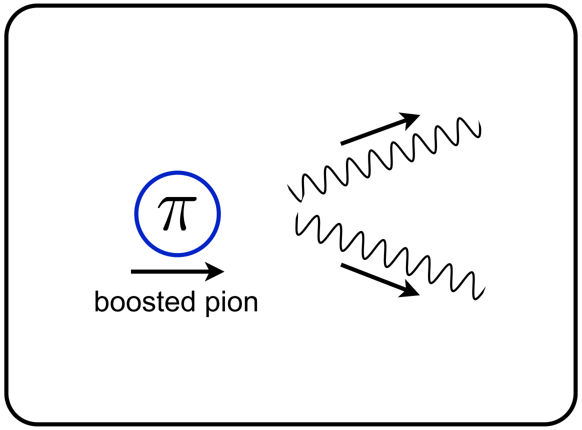
Depends on location of cosmic-ray sources and on the gas distribution

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

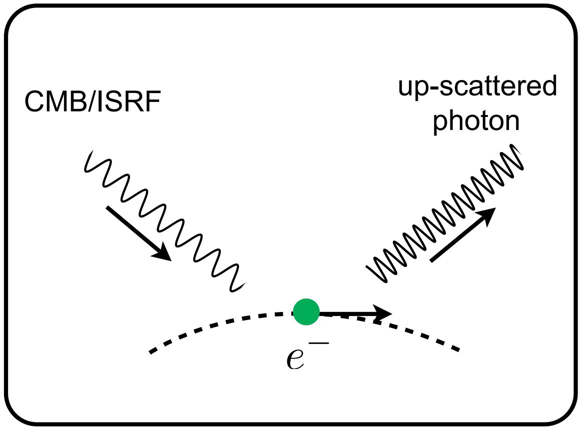
Bremsstrahlung



Pion Emission

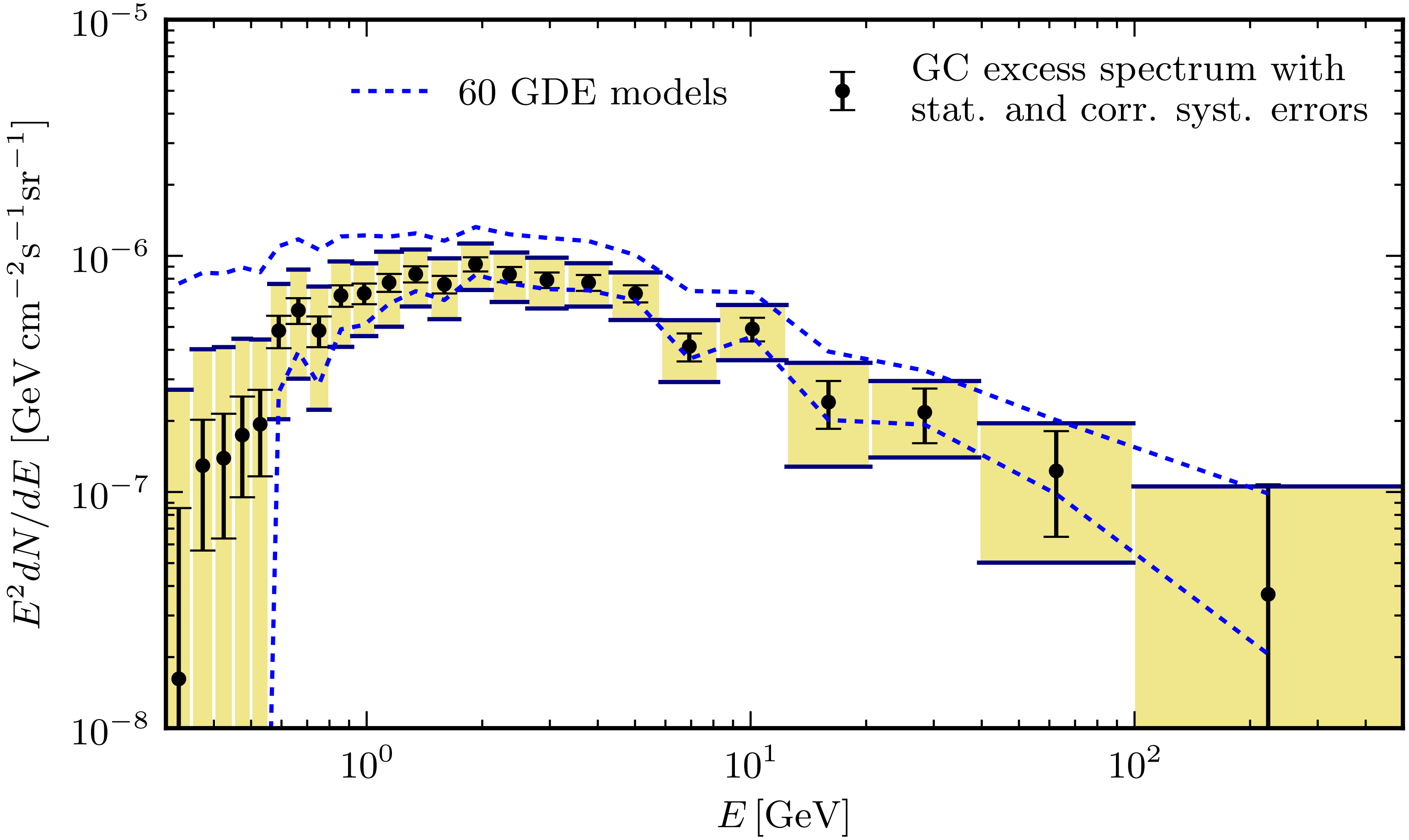


Inverse Compton



Diffuse Background

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



Calore, Cholis, and Weniger [1409.0042]

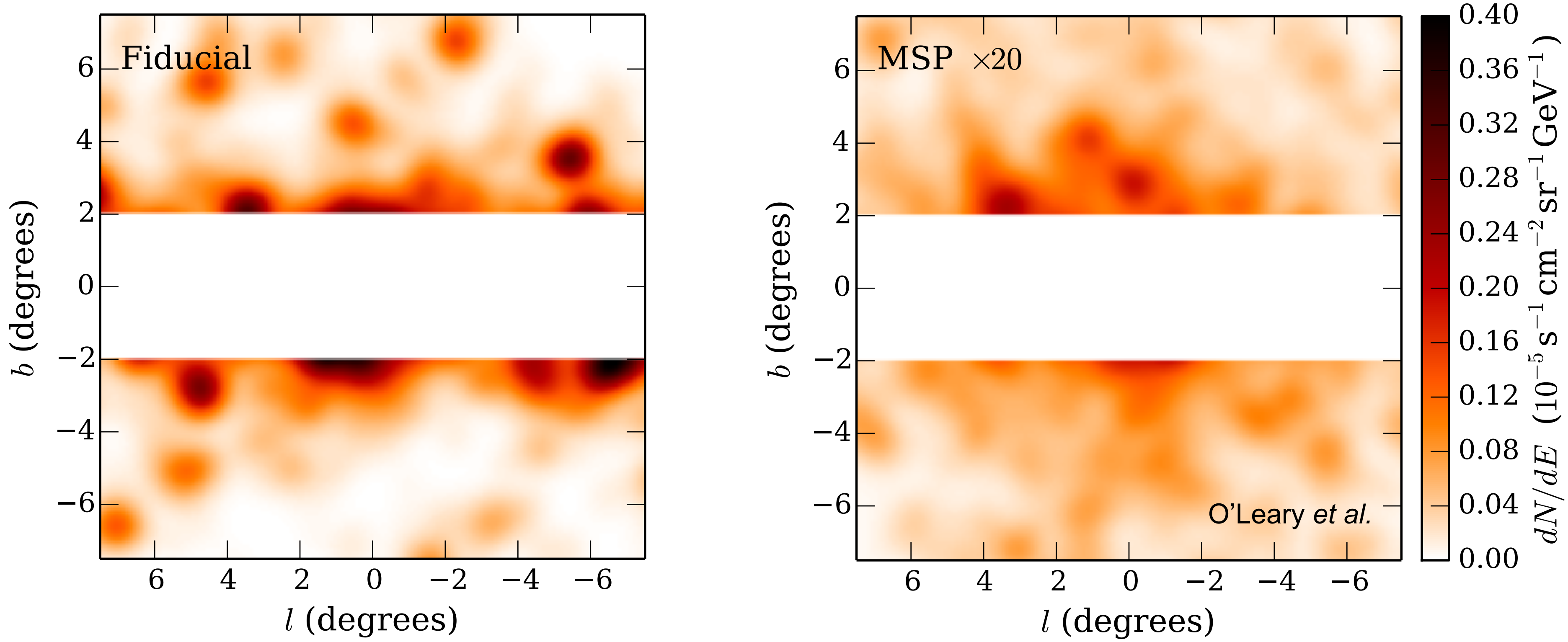
Astrophysical Sources

Unresolved young and millisecond pulsars can potentially mimic a dark-matter signal

Hooper *et al.* [1305.0830]; Cholis, Hooper, Linden [1407.5583, 1407.5625]
Brandt and Kocsis [1507.05616]; O'Leary *et al.* [1601.05797]

Young Pulsars

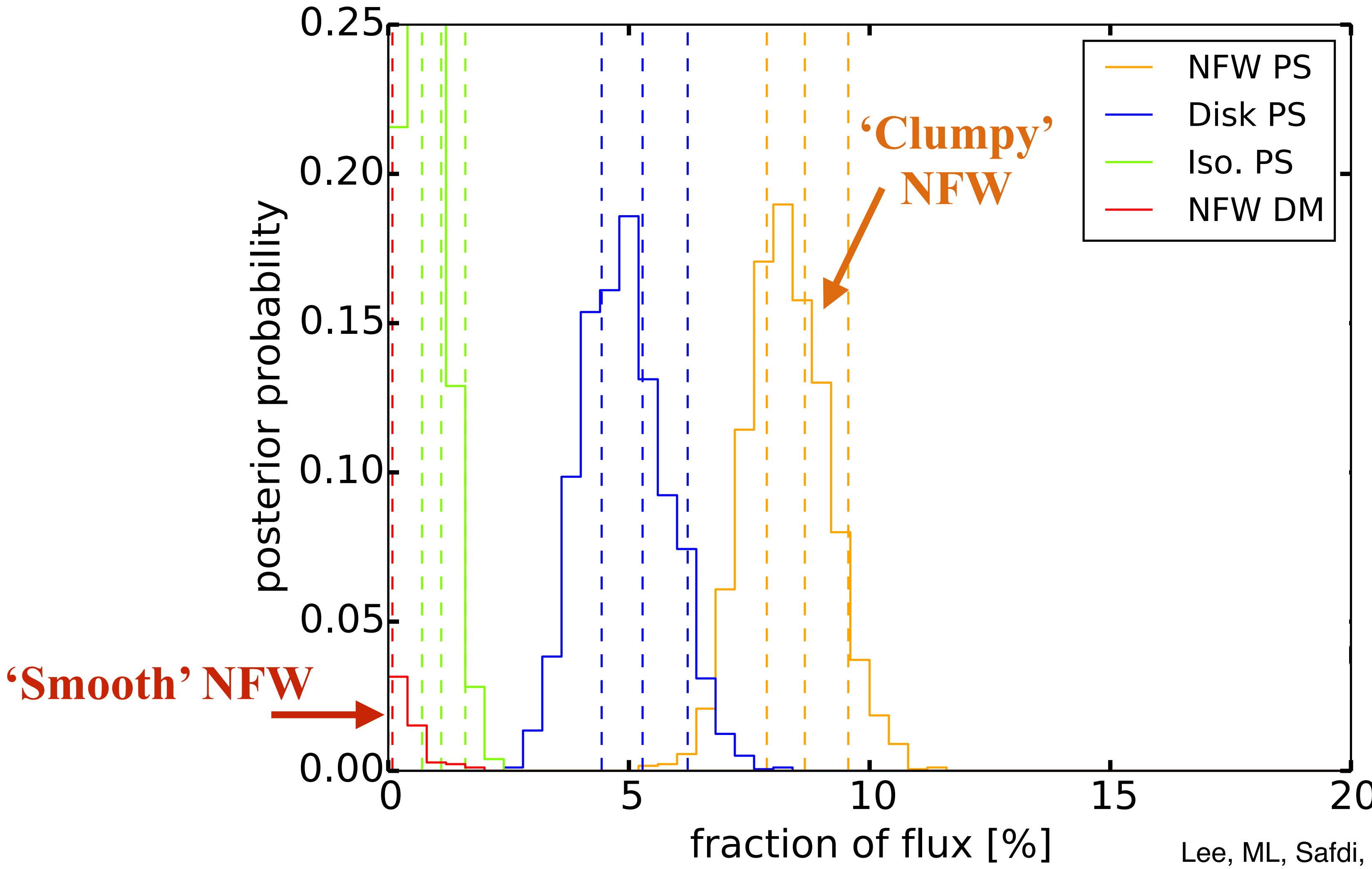
Millisecond Pulsars



Inner Galaxy Analysis

Photon count statistics can distinguish point sources from dark matter

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



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

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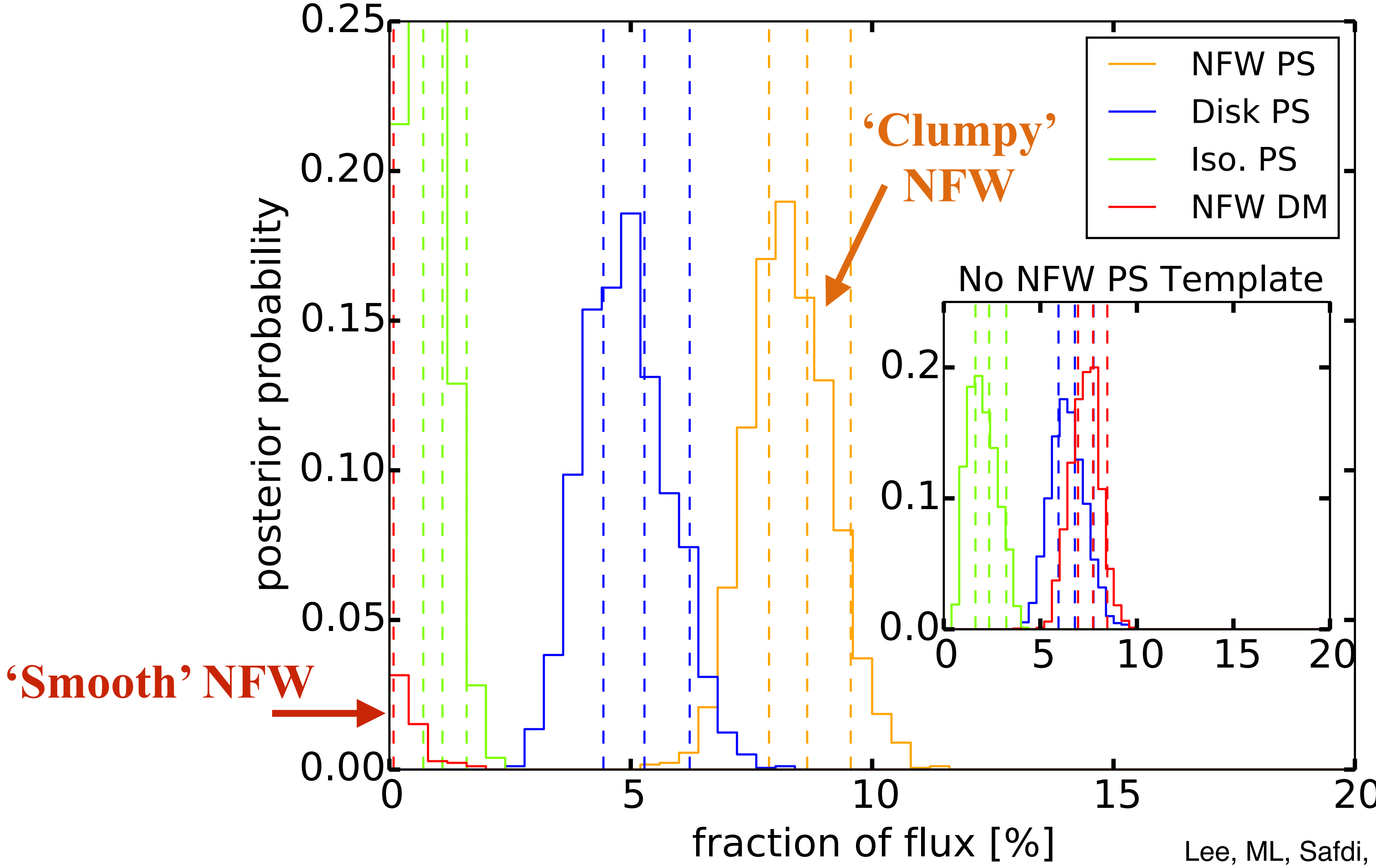

Lee, ML, Safdi, Slatyer, Xue [1506.05124]
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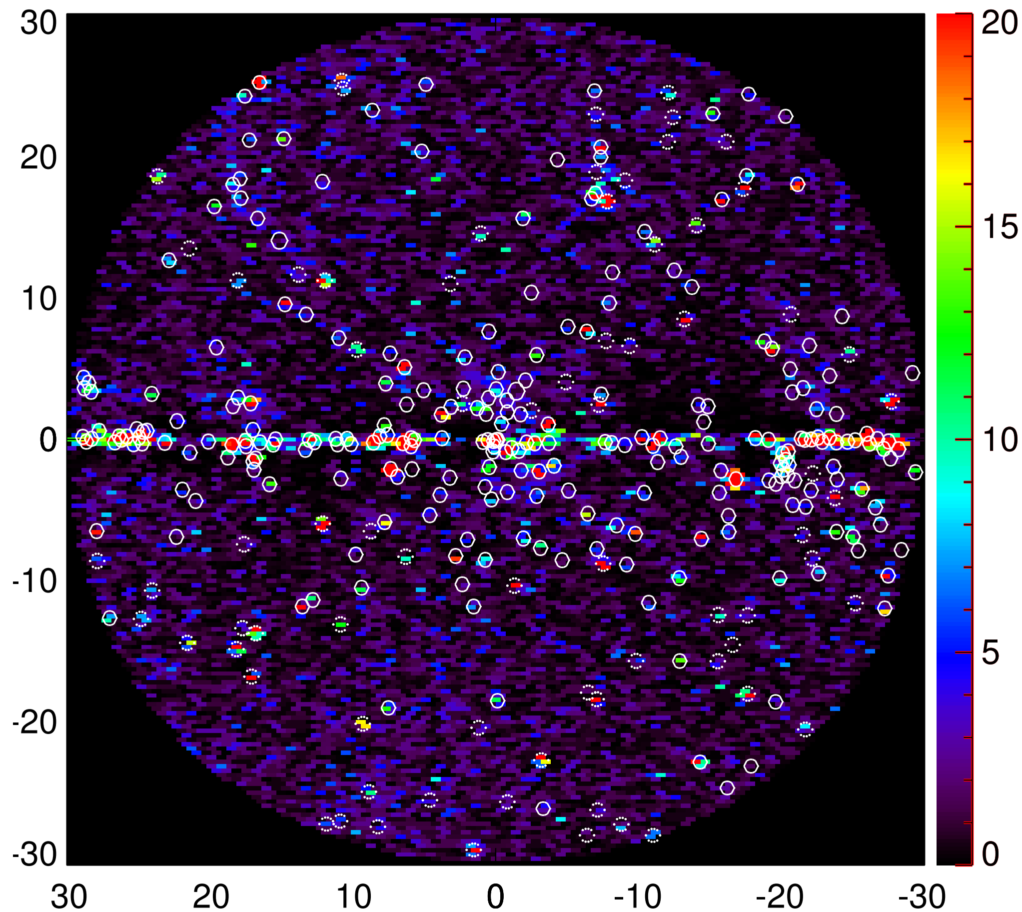
What are these point sources?

We can identify the most likely regions in the Inner Galaxy that contain these unresolved sources
…a critical step for multi-wavelength follow-up studies



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

Indirect Detection: Challenges

Astrophysical backgrounds = Large Systematic Uncertainties

Challenging to model theoretically
(e.g., cosmic ray diffusion)

New surprises as experimental sensitivities continue to improve
(e.g., millisecond pulsars)

How will we ever know that we have discovered dark matter?

Signal detection in more than one target

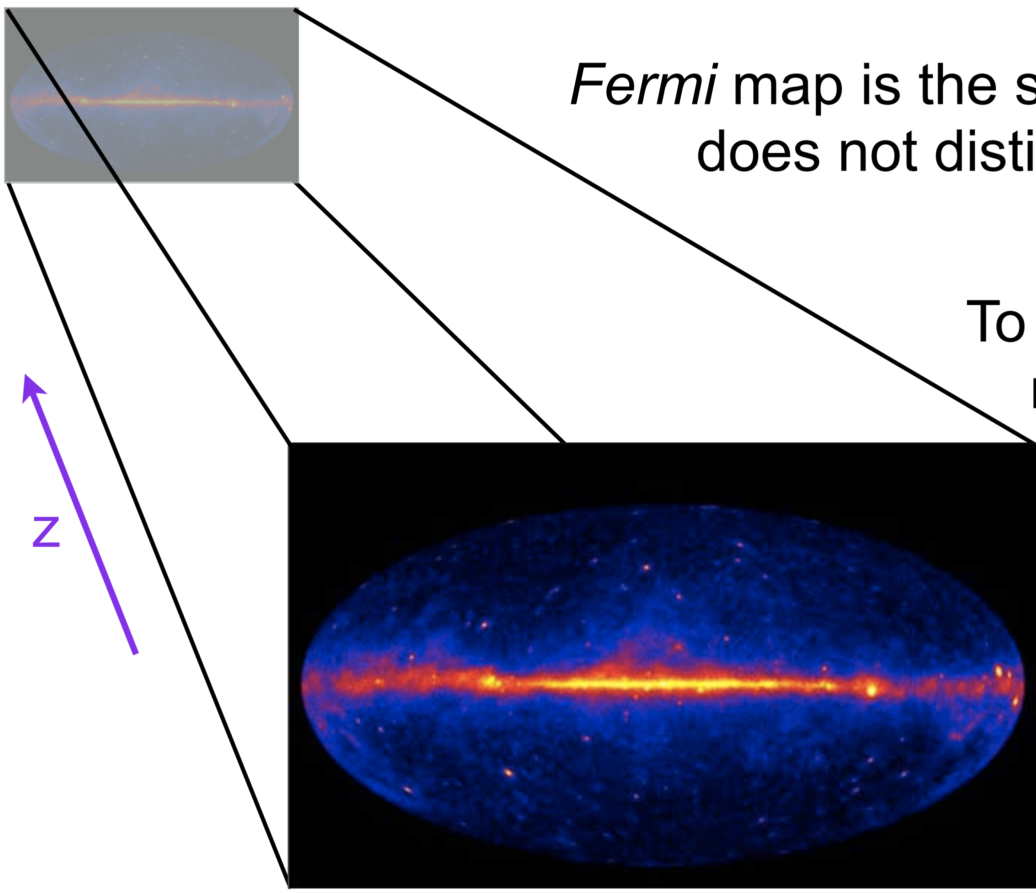
Correlate gamma-ray signal with large-scale structure that traces the DM signal

ML, Mishra-Sharma, Rodd, Safdi [in progress]

The Redshift Axis

Different classes of astrophysical sources are expected to dominate at different redshifts

e.g., SFGs at z~2 and dark matter at z≲0.3



Fermi map is the sum total of all these contributions, and does not distinguish redshift of origin for γ-rays

To select out individual components, *Fermi* must be correlated with maps that are associated with a given redshift

Ando *et al.* [1312.4403]
Xia *et al.* [1503.05918]
Cuoco *et al.* [1506.01030]

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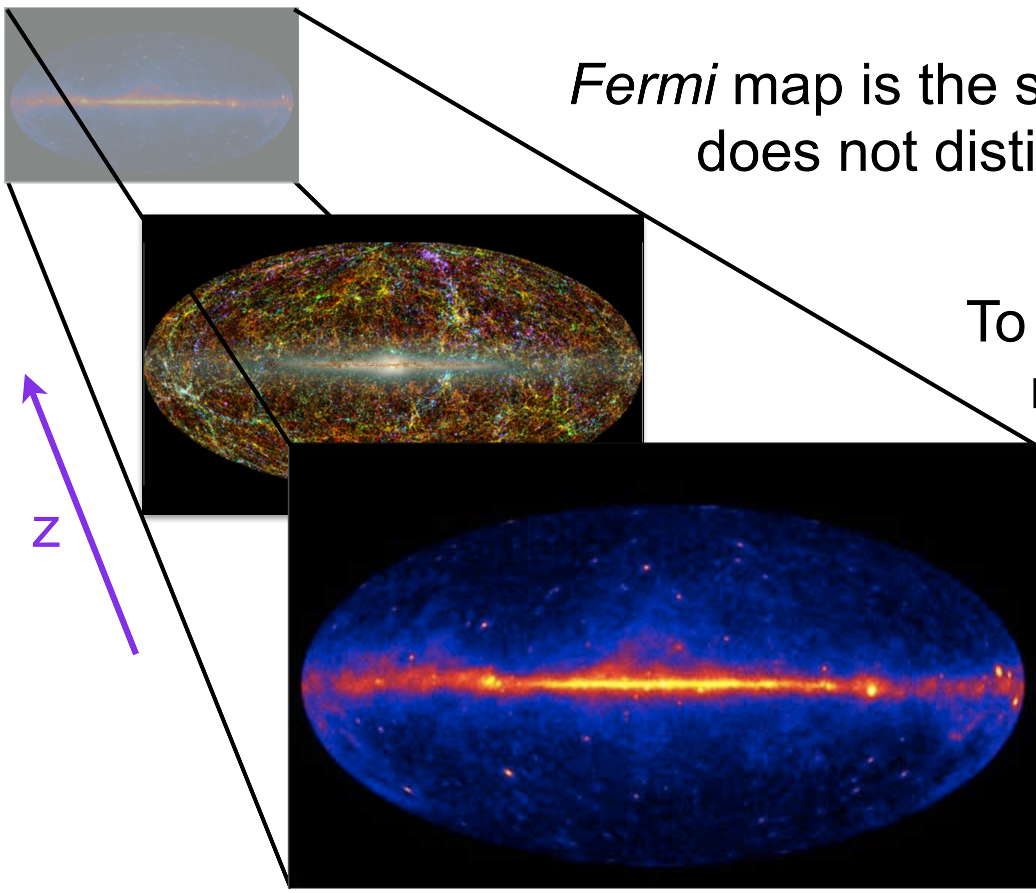

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Xia *et al.* [1503.05918]
Cuoco *et al.* [1506.01030]

Both the LHC and indirect detection experiments are sensitive to WIMPs, but have separate advantages

LHC	Indirect
More challenging to detect dark matter that only interacts leptonically	Sensitive to all dark-matter interactions with Standard Model
Controlled environment	Challenging systematic uncertainties; Uncertainties in halo profiles
Strongly interacting DM can look a lot like QCD	No sensitivity if DM annihilation is absent today (e.g., asymmetric DM)
Better for lighter dark matter	May be the only option for TeV-scale dark matter

Wino Dark Matter

The neutralino is the dark matter in many supersymmetric models

The neutralino is a Majorana fermion and SM singlet

$$\chi = c_1 \widetilde{B} + c_2 \widetilde{W} + c_3 \widetilde{H}_u^0 + c_4 \widetilde{H}_d^0$$

gauginos higgsinos

Comes along with a SM triplet

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gauginos higgsinos

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$$\chi^{\pm} = a_1 \widetilde{W}^{\pm} + a_2 \widetilde{H}^{\pm}$$

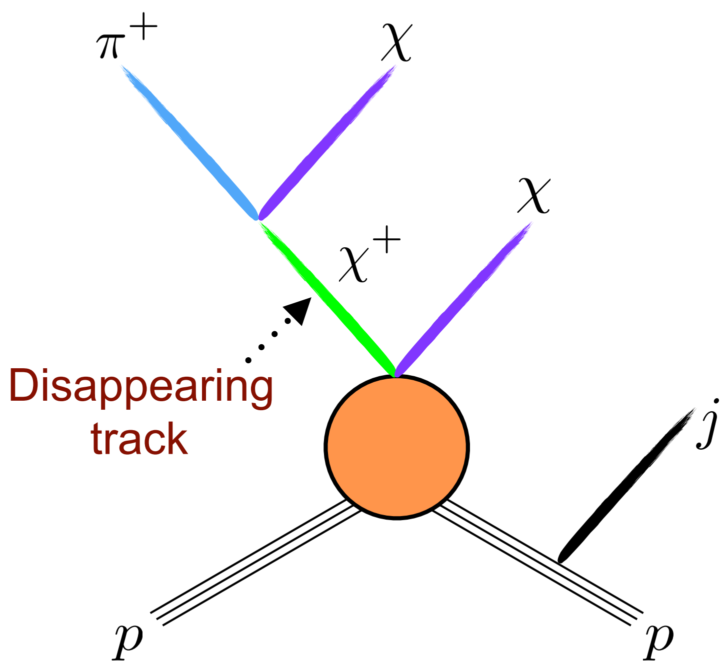
Neutral and charged states are nearly degenerate in mass

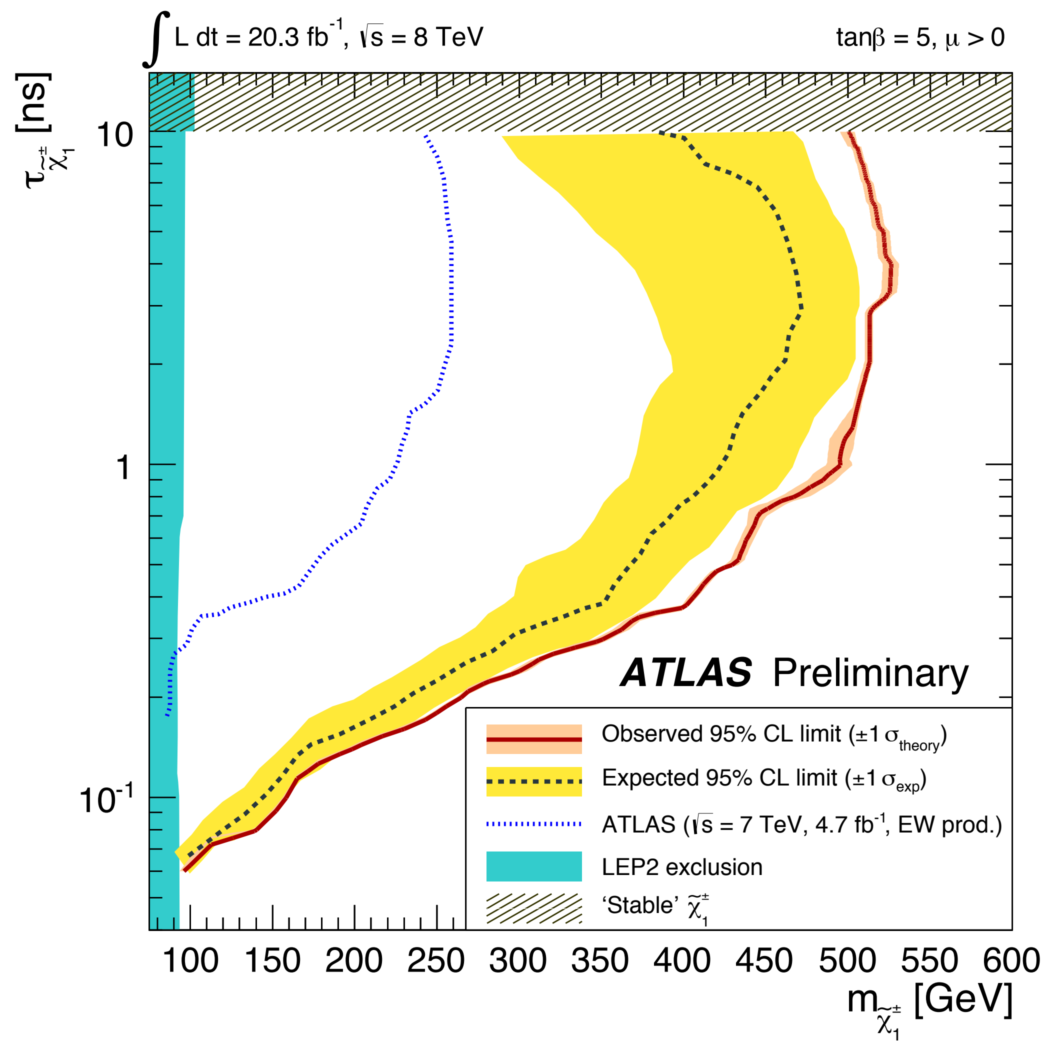
$$M_{\chi^{\pm}} - M_{\chi} \simeq 0.16 \text{ GeV}$$

Winos do not couple to Higgs — direct detection challenging

LHC limits

Searches for disappearing charged tracks probe winos up to ~few hundred GeV





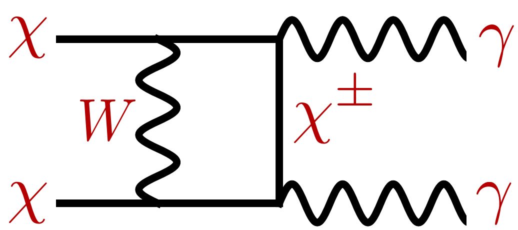
ATLAS-CONF-2013-069

Thermal Winos

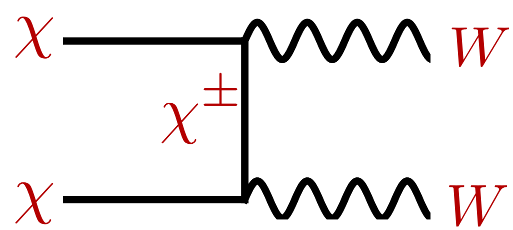
~3.1 TeV winos can constitute all of the dark matter density

Wino annihilation gives both a line and continuum signature

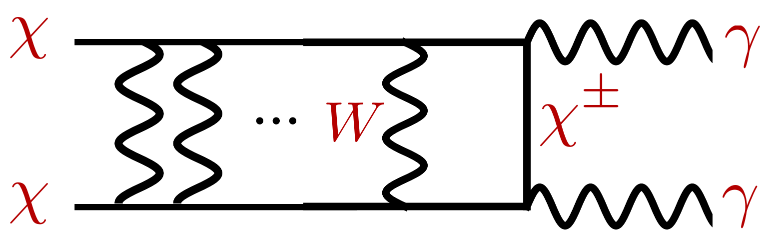
Photon Line



Continuum Photons



Sommerfeld enhancement in annihilation cross section at TeV masses



H.E.S.S.

High Energy Stereoscopic System

Ground-based telescope array that measures high-energy photons from Cherenkov showers in the atmosphere

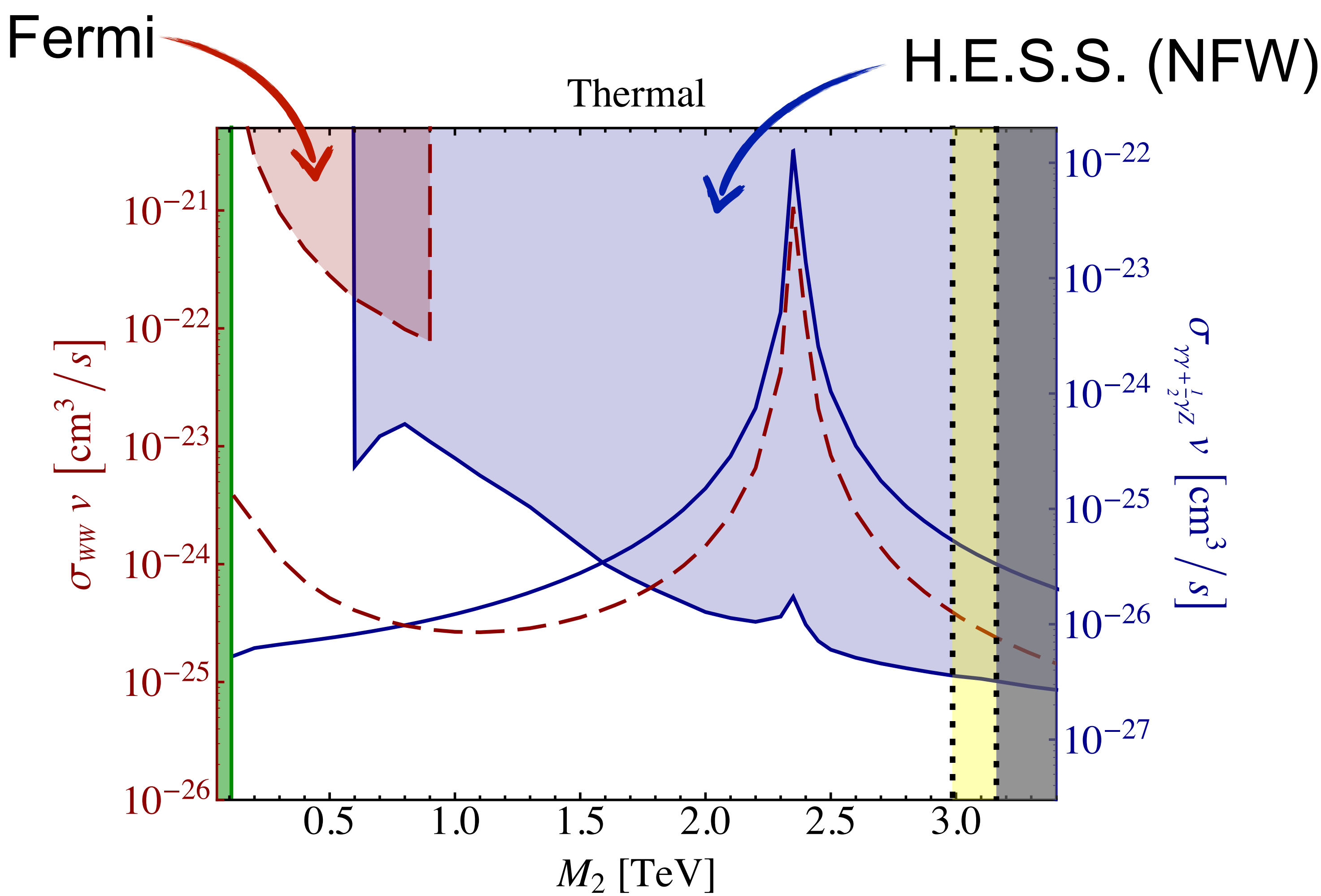
Search for γ-ray lines within 1˚ of GC

600 GeV < M_{χ} < 24 TeV

HESS Collaboration [1301.1173]

Wino Exclusions

H.E.S.S. can exclude thermal wino dark matter for most dark-matter density profiles



Cohen, ML, Pierce, Slatyer [1307.4082]
Fan and Reece [1307.4400]

Summary

Indirect detection searches provide an excellent way to test the thermal dark matter hypothesis

Fermi observations becoming sensitive to weak-scale, thermal dark matter

Indirect detection complementary to LHC searches; pros/cons in either case, however indirect detection may be the only option for some TeV-scale candidates