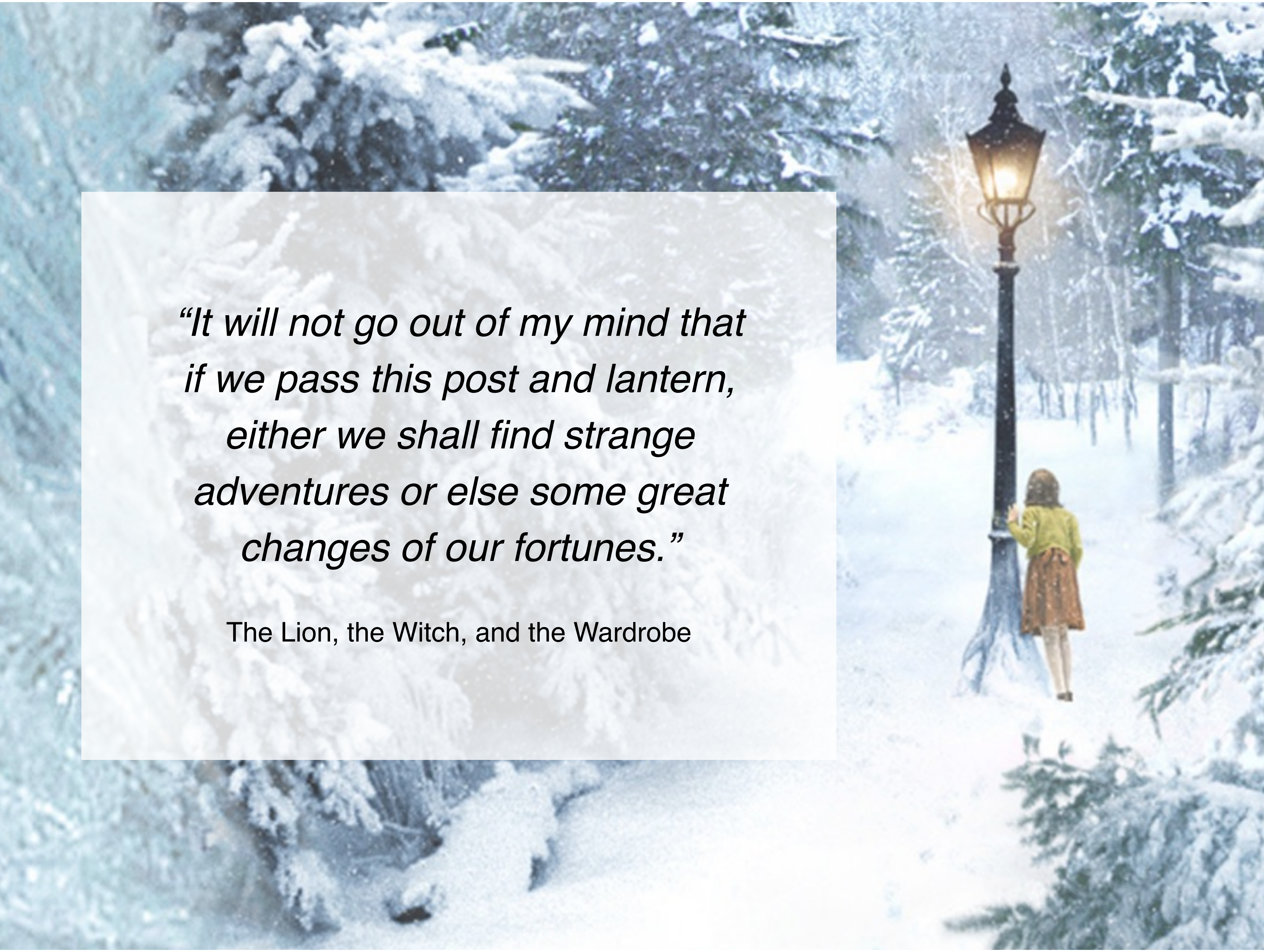
The Search for Dark Matter

Current Status & Future Prospects

Mariangela Lisanti
Princeton University

SUSY Conference—August 24, 2015



“It will not go out of my mind that if we pass this post and lantern, either we shall find strange adventures or else some great changes of our fortunes.”

The Lion, the Witch, and the Wardrobe

The Lamp Post

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

WIMP paradigm relies on a few basic assumptions:

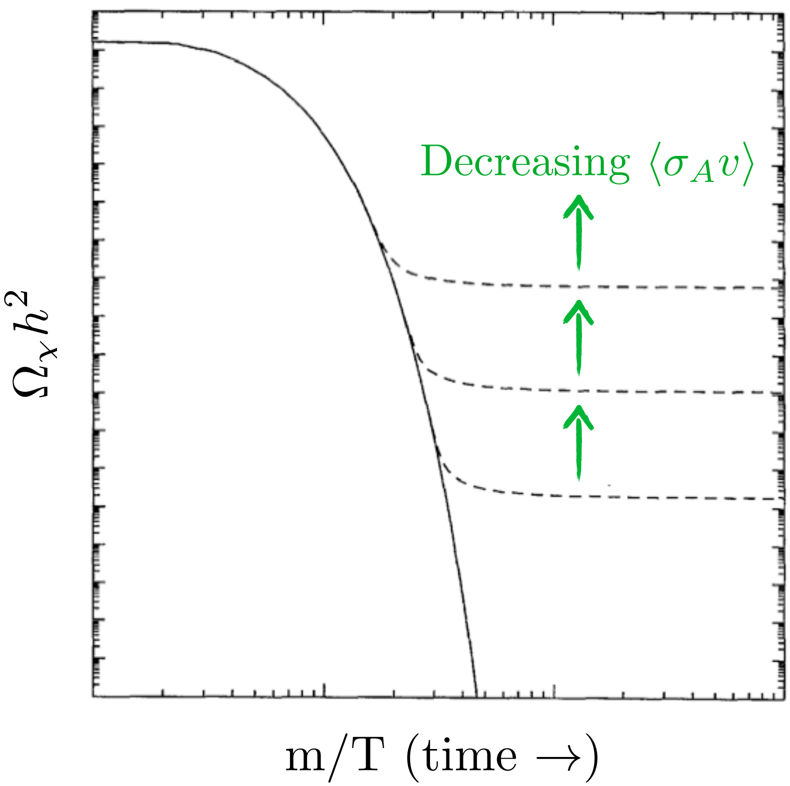
Single Particle

Weakly Interacting

Mass ~$10^{2\text{-}3}$ GeV

The Lamp Post

Dark matter is in thermal equilibrium in early Universe, until its interactions "freeze-out"



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

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

Planck + WMAP:

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

Three Vignettes

Direct Detection

Collider Searches

Indirect Detection

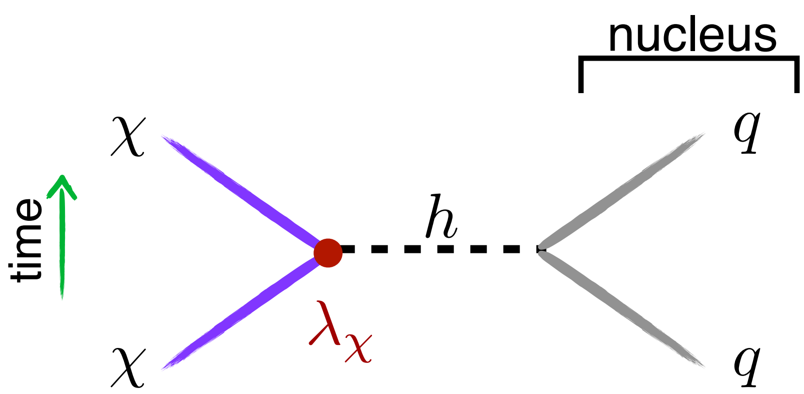
Three Vignettes

	Current Status	Future Prospects
Direct Detection		
Collider Searches		
Indirect Detection		

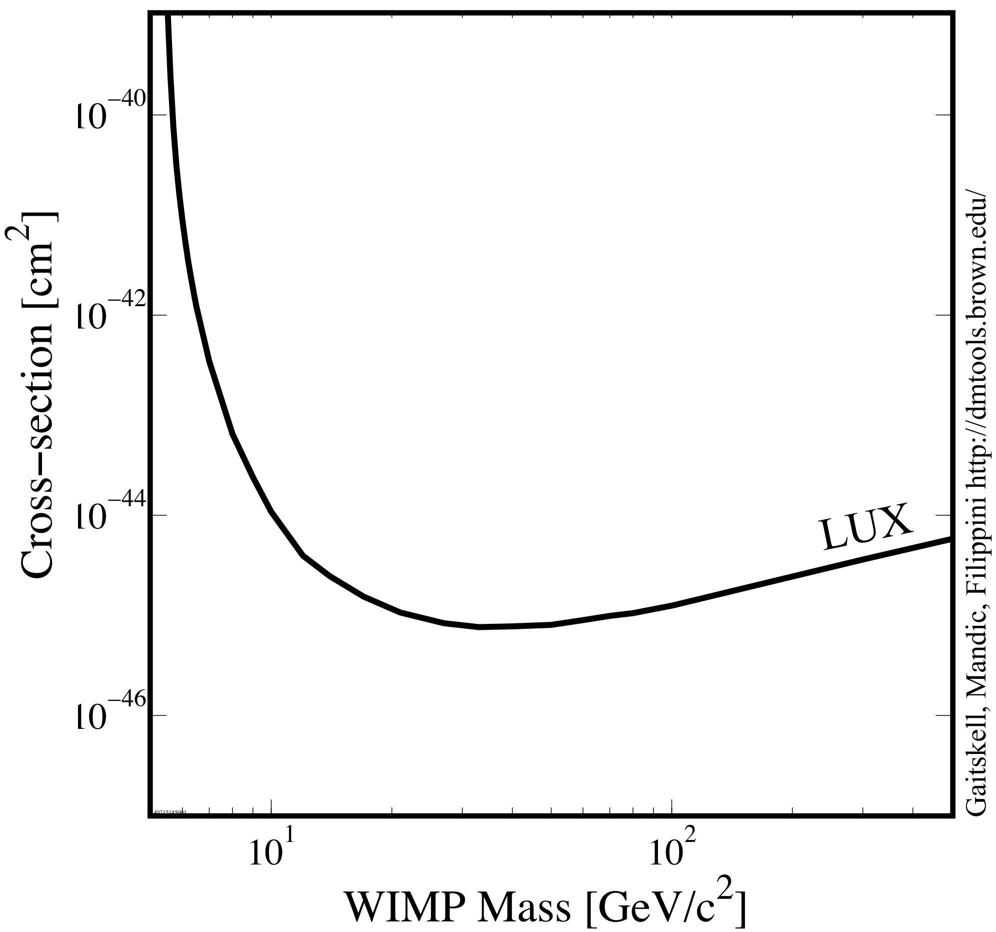
Higgs Exchange

Dark matter scattering off nuclei in underground detector

Spin-independent interaction due to Higgs exchange



$$\sigma_{\chi N \to \chi N} \simeq 10^{-45}\ \lambda_\chi^2 \quad \mathrm{cm}^2$$

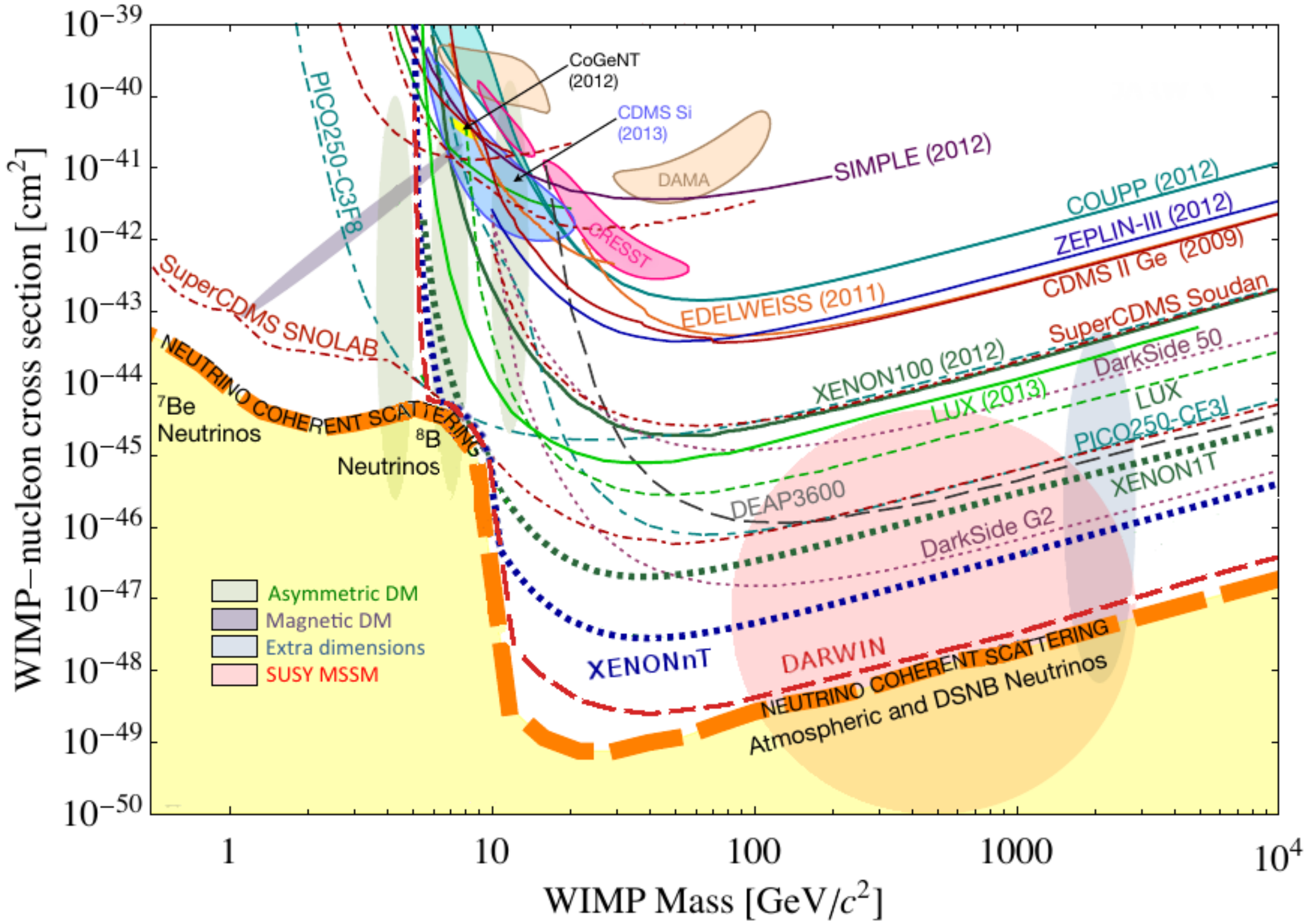


LUX Collaboration [1310.8214]

Next Frontiers

MeV to GeV masses

Weaker interactions



Questions to Explore

New model frameworks needed?

e.g., WIMPless, Asymmetric, SIMP dark matter

Feng and Kumar [0803.4196], Nussinov [Phys. Lett. B]; Kaplan, Luty, and Zurek [0901.4117]; Hochberg, Kuflik, Volansky, and Wacker [1402.5143]

New experimental strategies needed?

e.g., dark-matter-electron scattering

Essig, Mardon, Volansky [1108.5383]; Graham, Kaplan, Rajendran, Walters [1203.2531], Essig *et al.* [1206.2644]; Lee, **ML**, Safdi, Sharma [to appear]

Changes to standard phenomenology?

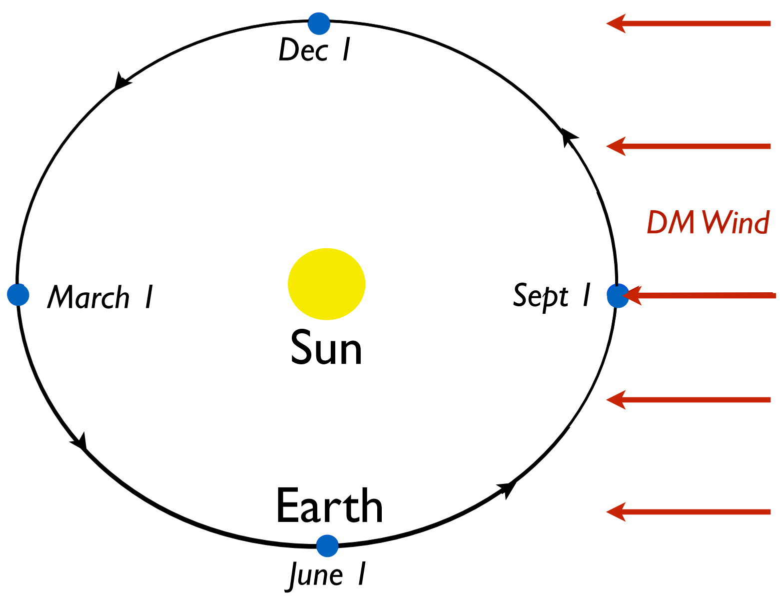
e.g., gravitational focusing and effects on modulation phase

Lee, **ML**, Peter, and Safdi [1308.1953]

Annual Modulation

Standard Modulation Picture

Maximum scattering rate in June, when Earth travels into 'wind'

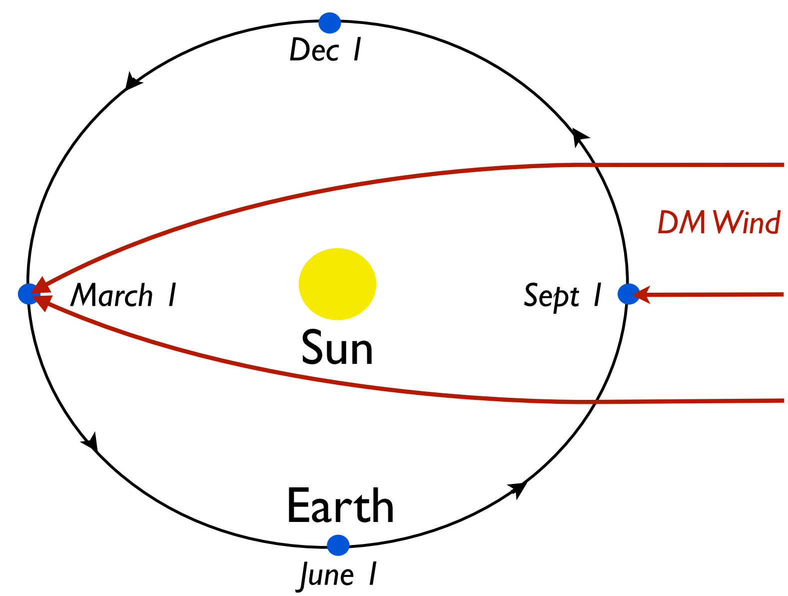


Drukier, Freese, and Spergel [PRD]
Review: Freese, **ML**, Savage [1209.3339]

With Gravitational Focusing

Sun's potential deflects incoming, unbound dark matter particles

Shifts the phase of the modulation



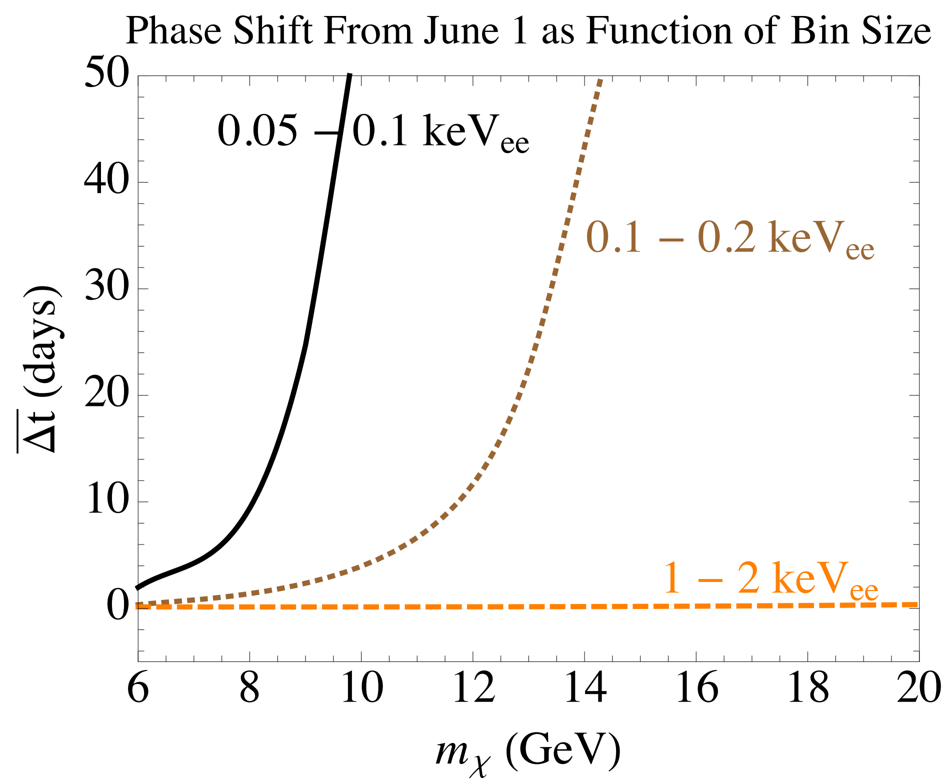
Griest, PRD 1988.
Alenazi and Gondolo [astro-ph/0608390]
Lee, **ML**, Peter, and Safdi [1308.1953]

Example: SABRE

Proposed experiment using ultra-high purity NaI(Tl) crystals

Depending on threshold energy, the phase of a modulation signal can be affected by gravitational focusing

SABRE



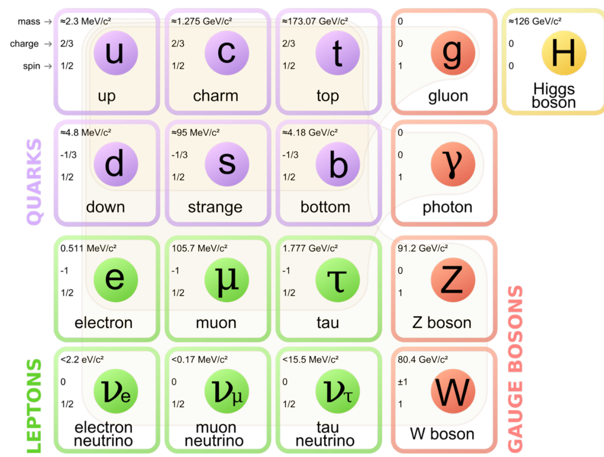
Shields, Xu, Calaprice [Phys. Procedia]

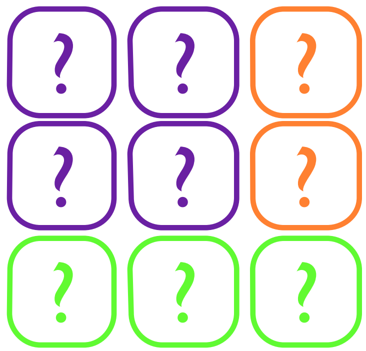
Three Vignettes

	Current Status	Future Prospects
Direct Detection	Probing Higgs-exchange region	Exploring MeV-GeV dark matter
Collider Searches		
Indirect Detection		

Minimal Scenario

Visible Sector

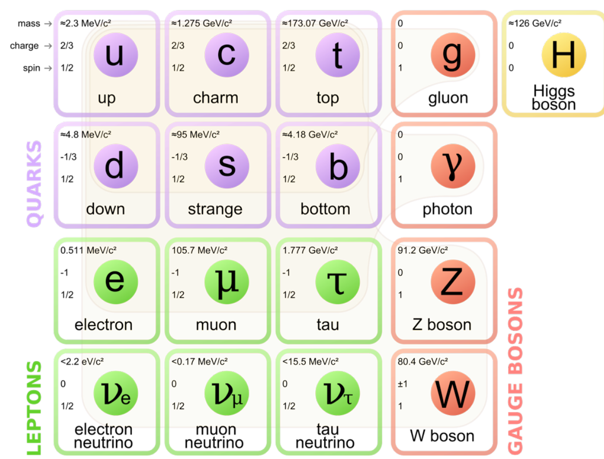




$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

Minimal Scenario

Visible Sector



$\tilde{g}$

$\tilde{t}$

$\chi^{\pm}$

χ

Minimal model
(susy-inspired)

$$SU_c(3) \times SU_L(2) \times U_Y(1)$$

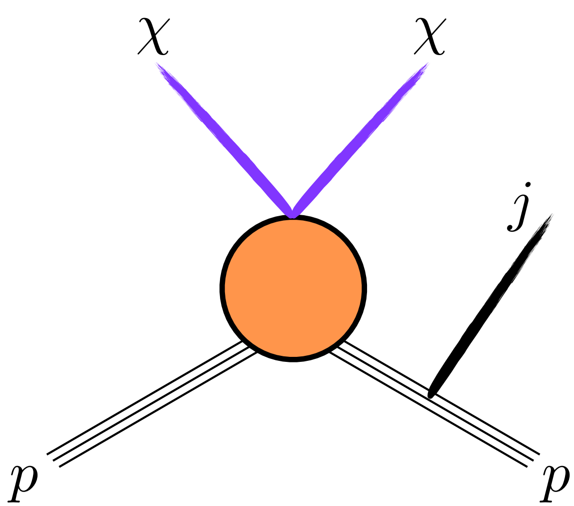
Monojet Searches

Dark matter can be directly produced in LHC collisions

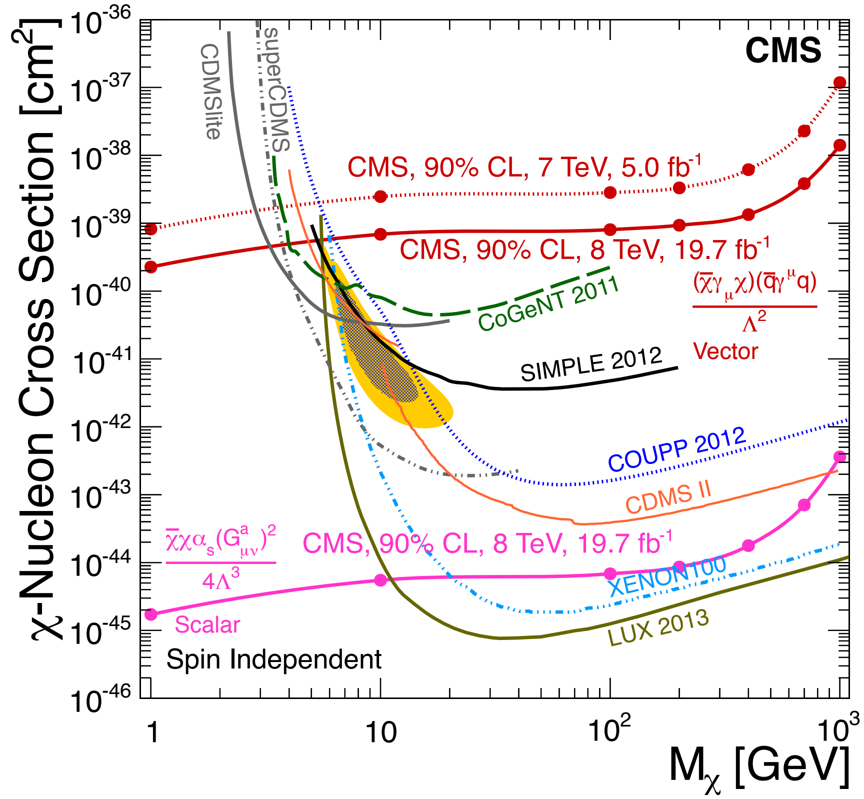
Monojet searches are particularly relevant:

Fox, Harnik, Kopp, Tsai [1109.4398]

Rajaraman, Shepherd, Tait, Wijangco [1108.1196]



1 jet + missing energy



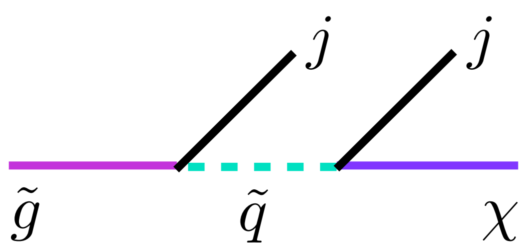
CMS Collaboration [1408.3583]

Colored Particle Production

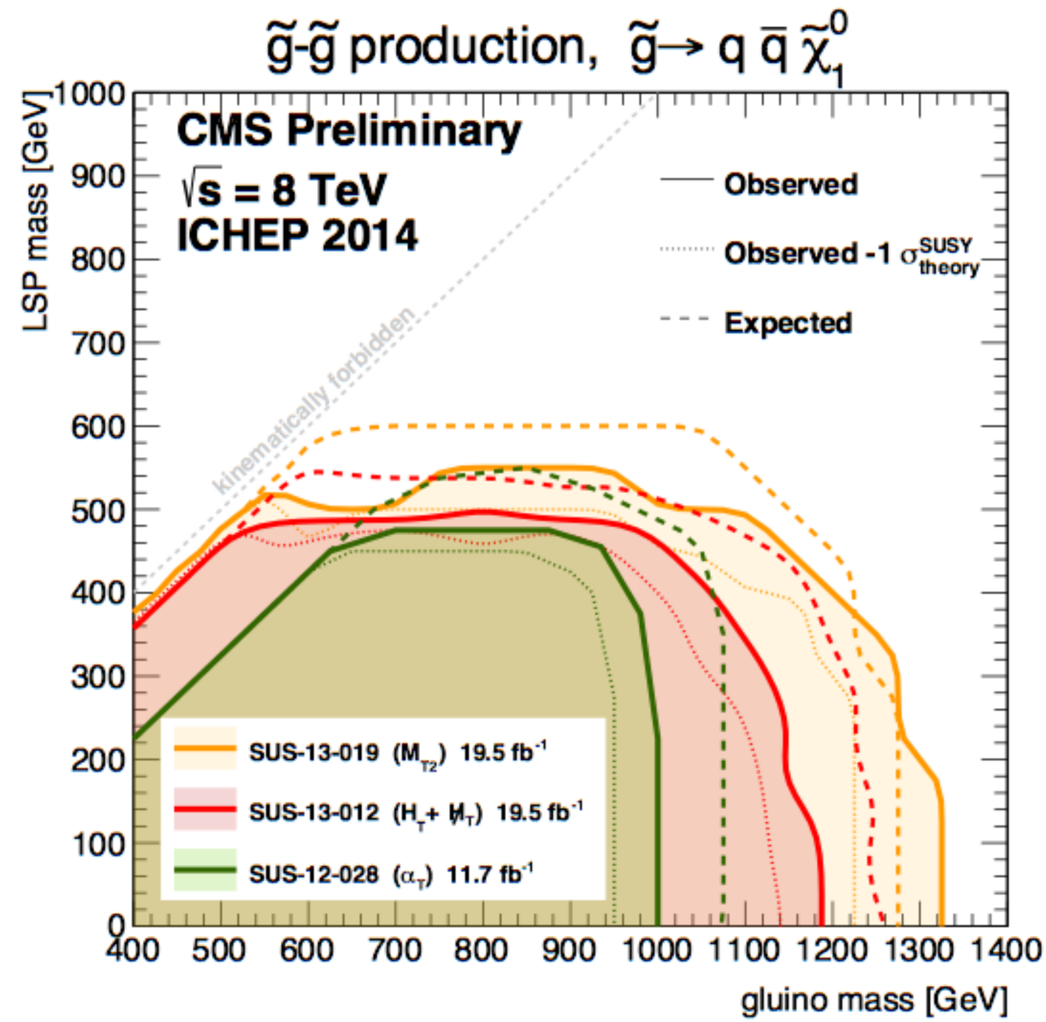
Dark matter can also be produced in decays of new colored particles

Takes advantage of large colored production cross section

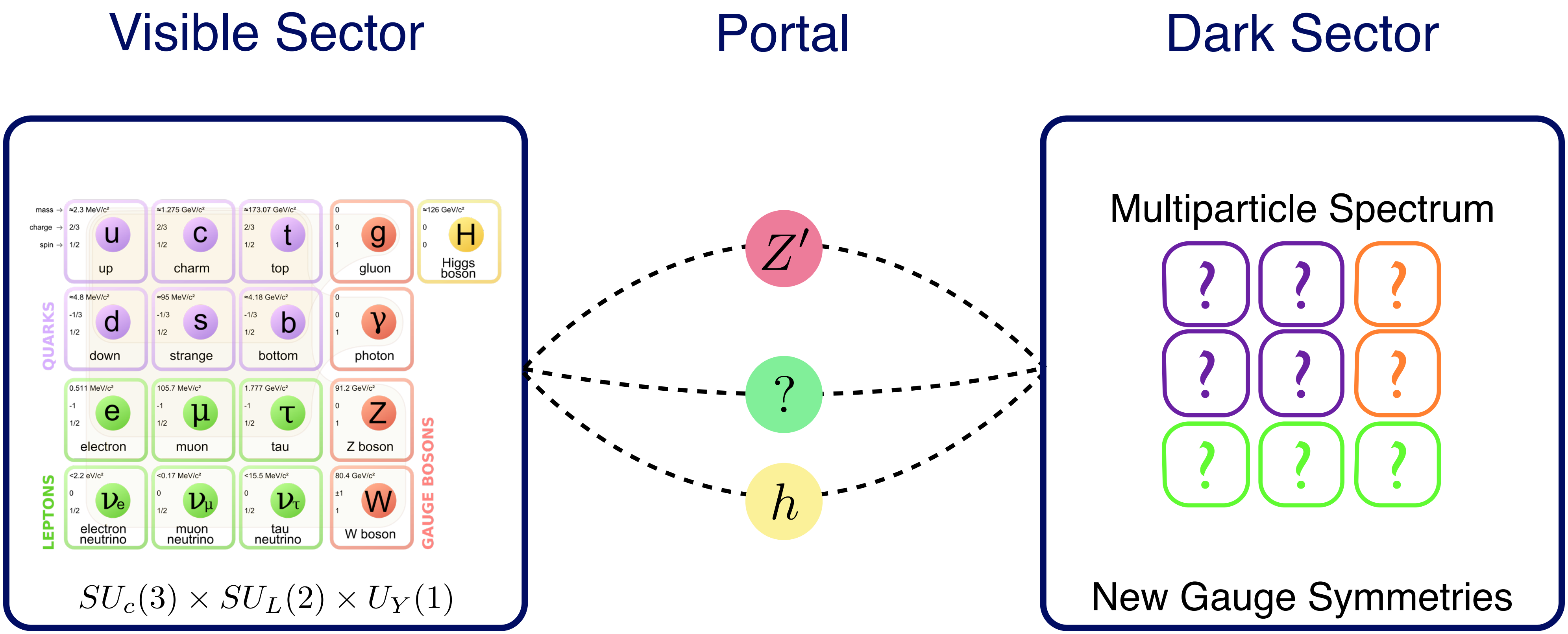
Events typically have several jets and missing energy



4 jets + missing energy



Hidden Dark Sector



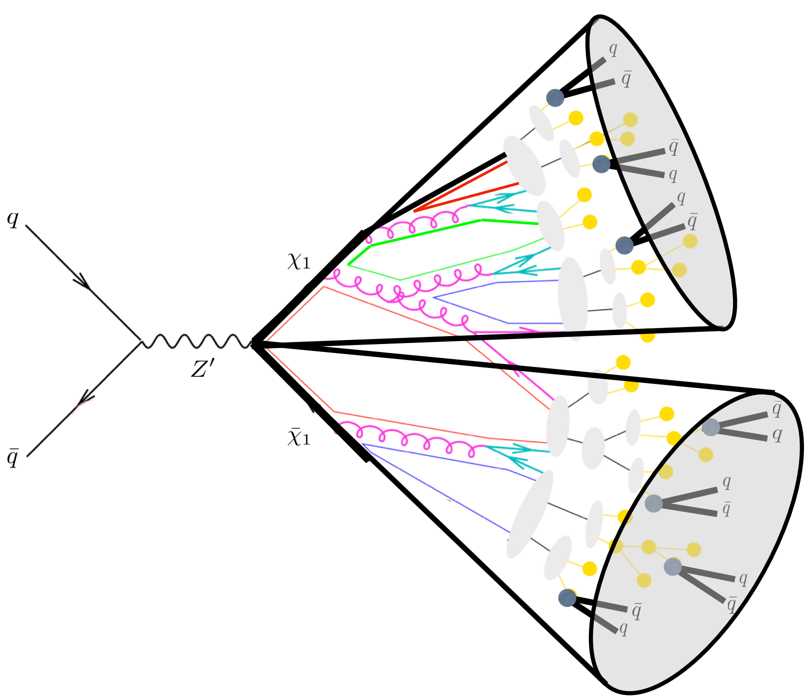
For instance: Hidden Valley Models, Higgs Portal Models

e.g., Strassler and Zurek [hep-ph/0604261, hep-ph/0605193];
Strassler [hep-ph/0607160]; Patt and Wilczek [hep-ph/0605188]; …

New Observables

Non-minimal dark sectors may result in complicated final states with many particles, displaced vertices, unusual tracks, …

Some of these final states may require fundamentally different search strategies at the LHC



Example: Semi-Visible Jets

Jets that contain both visible hadronic states, interspersed with stable neutral particles

Cohen, **ML**, Lou [1503.00009]

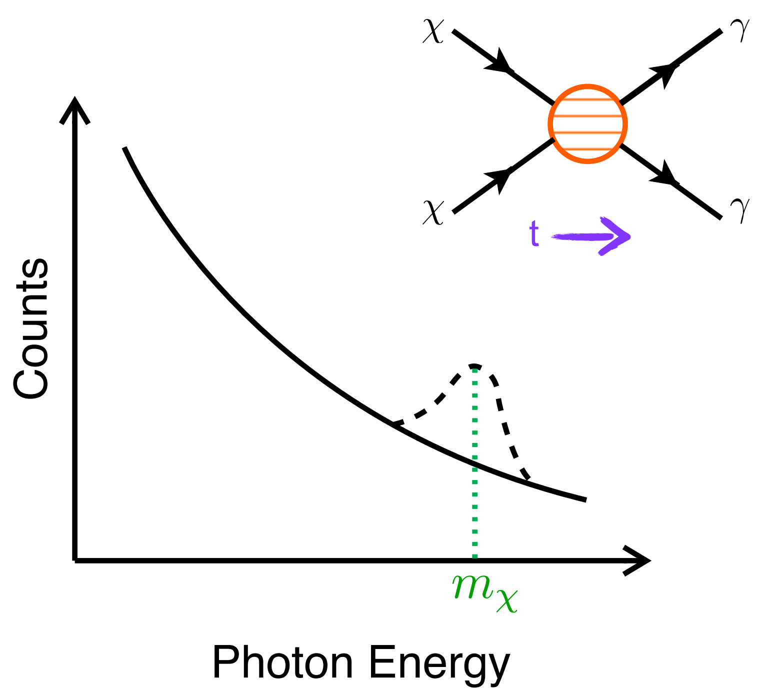
Three Vignettes

	Current Status	Future Prospects
Direct Detection	Probing Higgs-exchange region	Exploring MeV-GeV dark matter
Collider Searches	Missing energy searches	Probing non-minimal dark sectors
Indirect Detection		

Dark Matter Annihilation

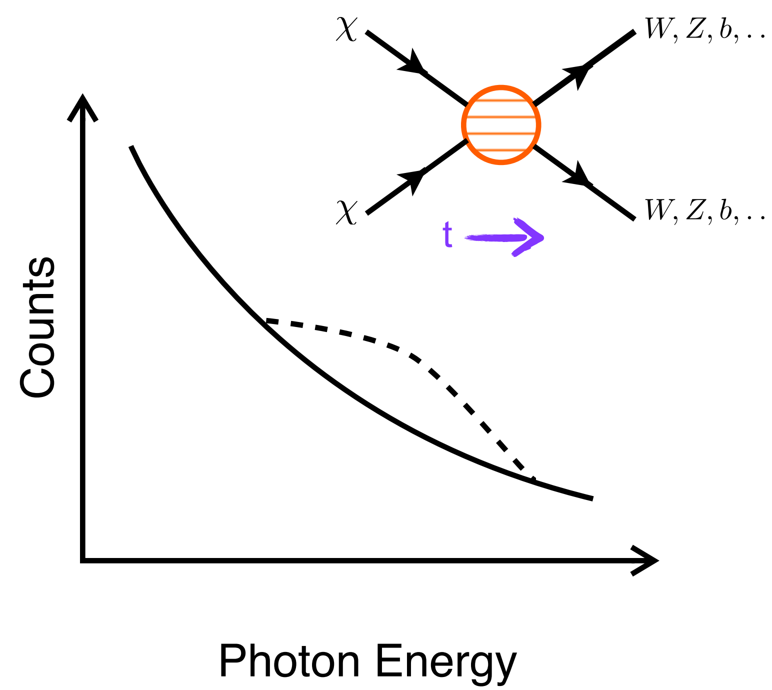
Monochromatic Photons

Direct decay to photons,
a line in photon energy spectrum



Continuum Photons

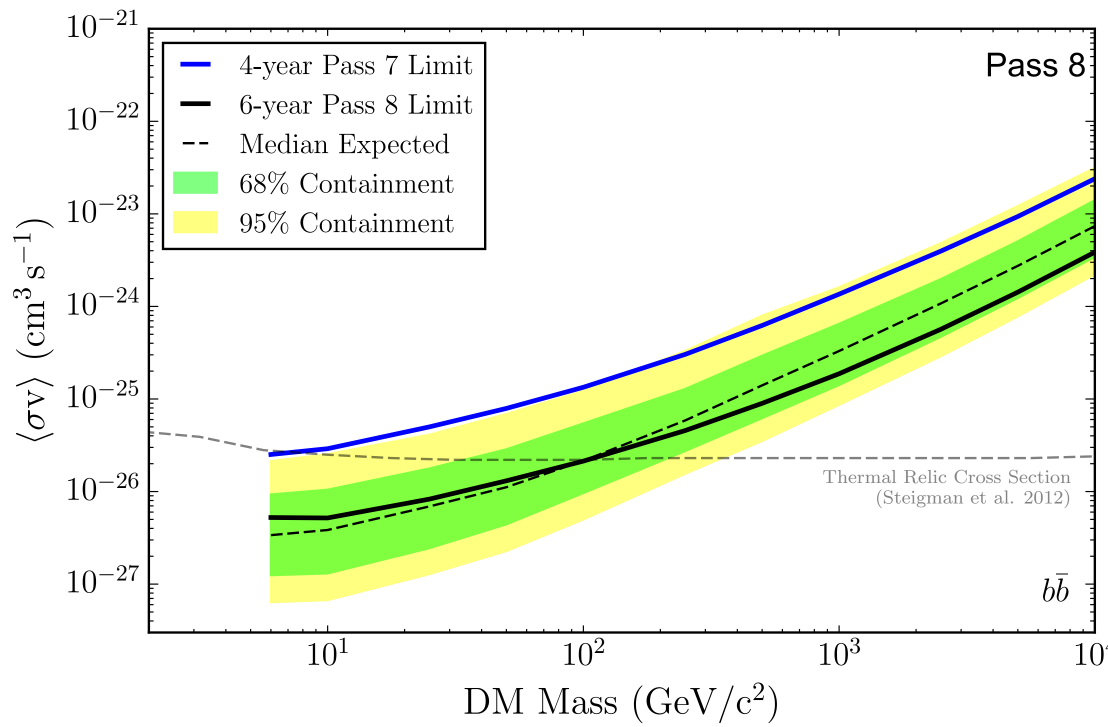
Annihilation to Standard Model final
states that shower into photons



Dwarf Galaxies

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

Current limits probes thermal relic annihilation cross sections for weak-scale dark matter



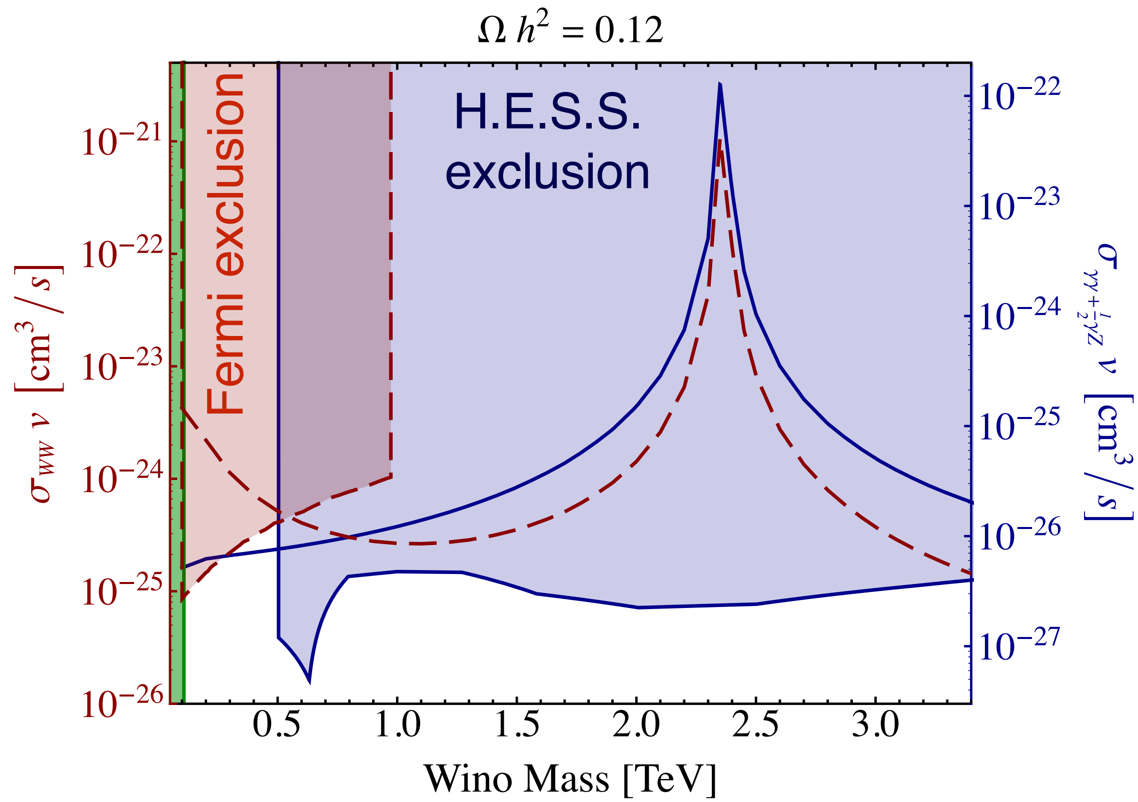
Ackermann *et al.* [1503.02641]

Heavy Relics

Limits from Cherenkov telescopes complement those from Fermi

Increased sensitivity to TeV-scale thermal relics

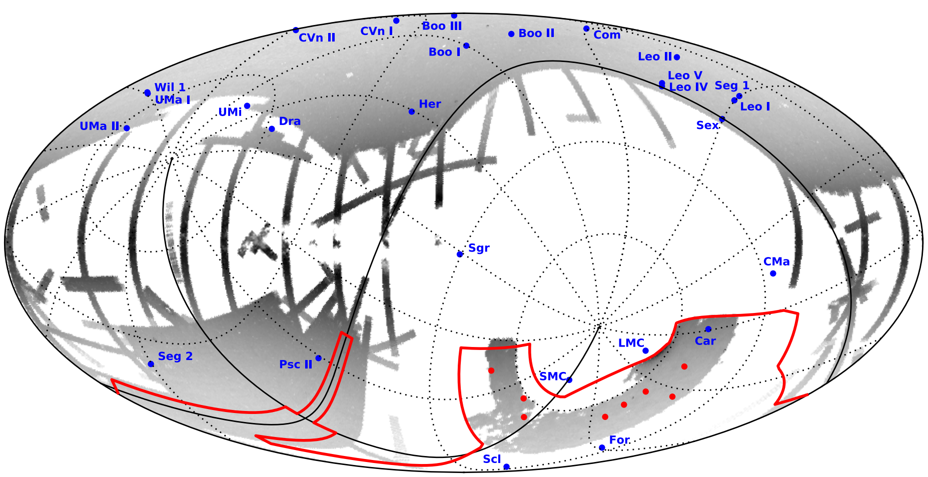
Example: Tight constraints on wino dark matter from H.E.S.S.



H.E.S.S. Collaboration [1301.1173]
Cohen, **ML**, Pierce, Slatyer [1307.4082]

New Targets

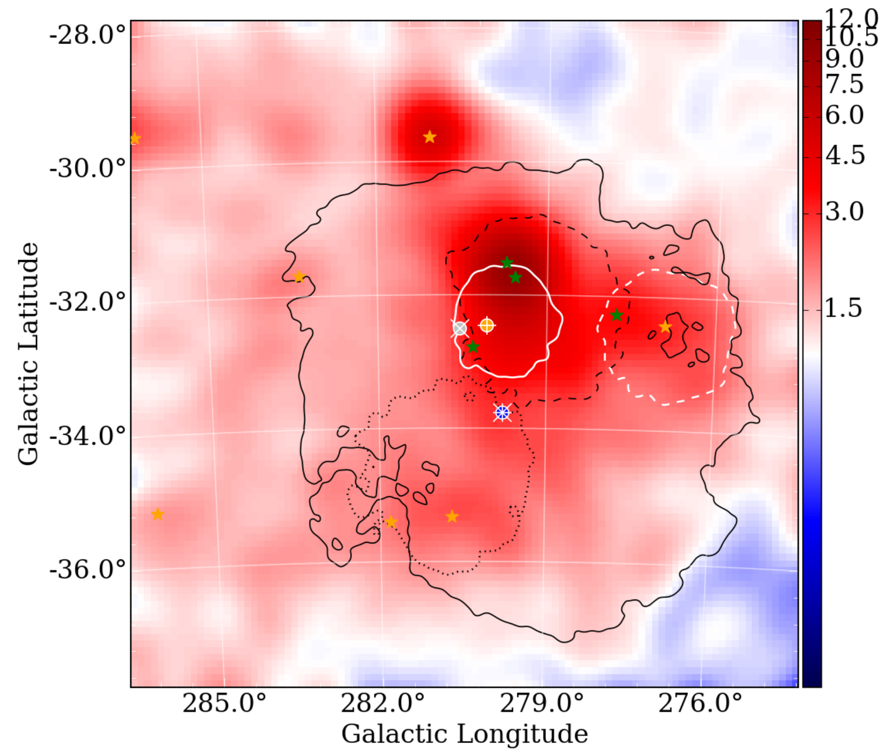
Evidence for 8 new dwarf candidates from Dark Energy Survey



● Known satellite galaxies ● DES candidates

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

Annihilation constraints from the Large Magellanic Cloud



Buckley *et al.,* [1502.01020]

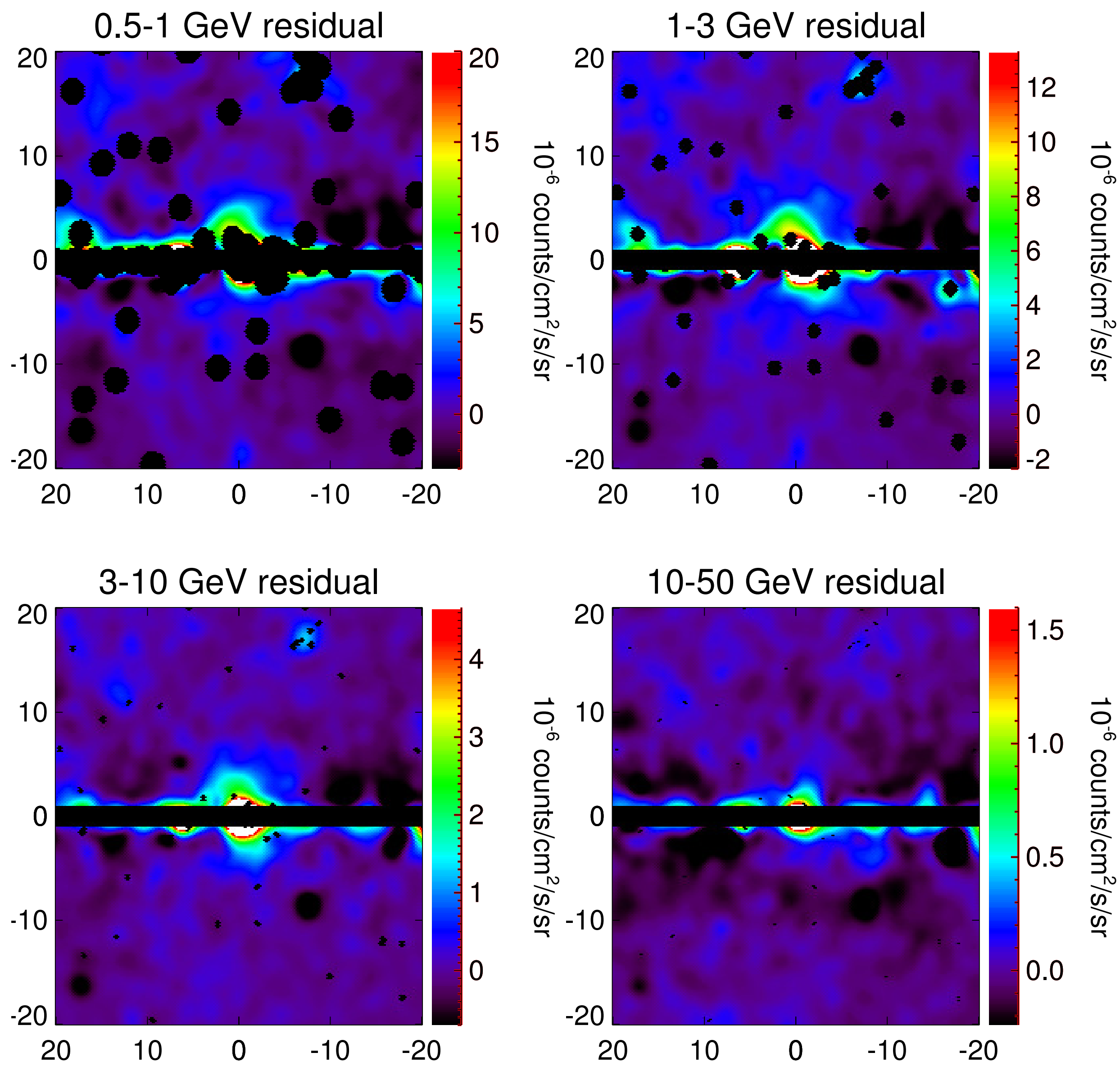
Galactic Center

Excess of GeV photons at the Galactic Center and Inner Galaxy ($\lesssim 10^\circ$)

High statistical significance

Energy spectrum consistent with dark matter signal

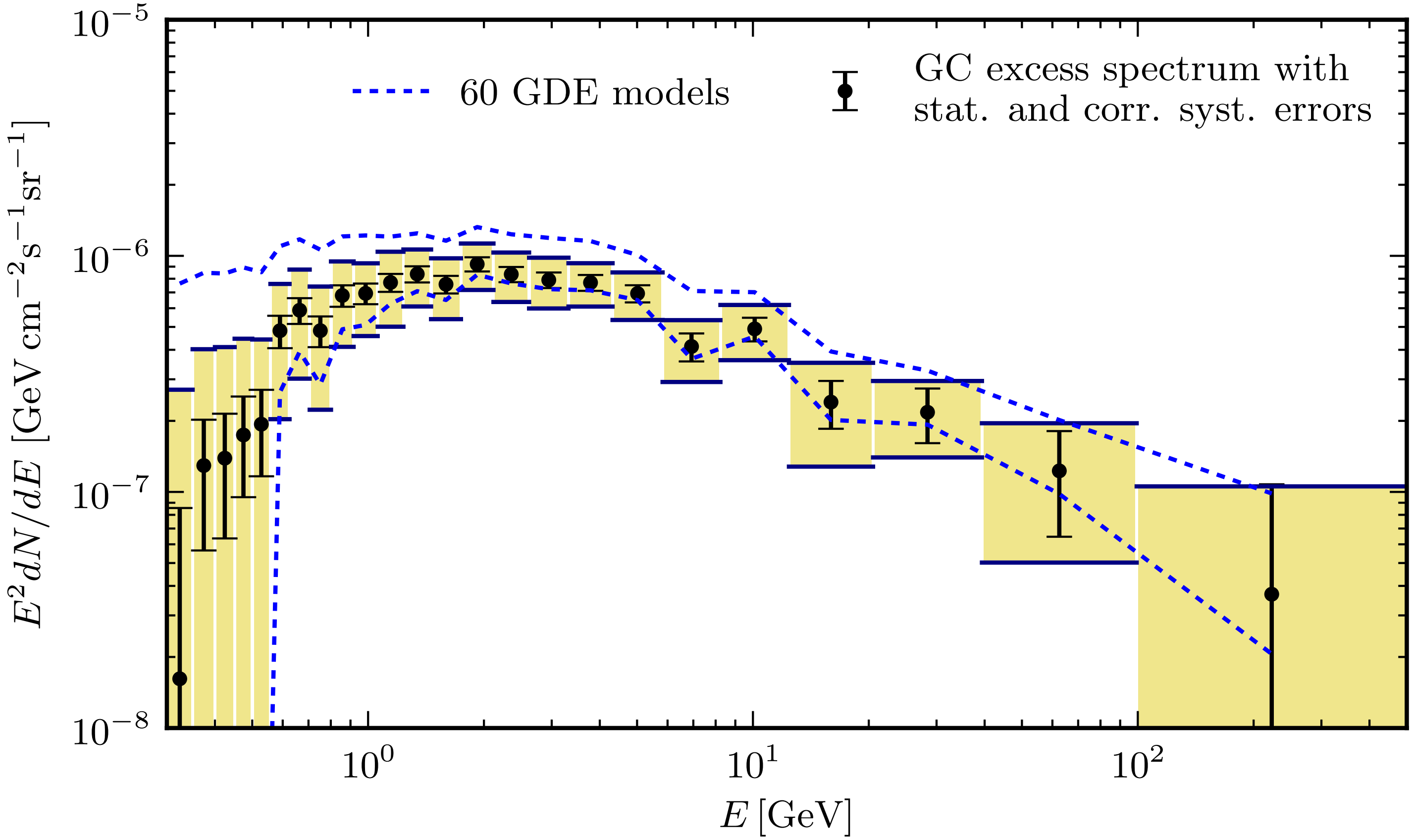
Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian *et al.* [1402.4090]
Daylan *et al.* [1402.6703]
Calore, Cholis, and Weniger [1409.0042]



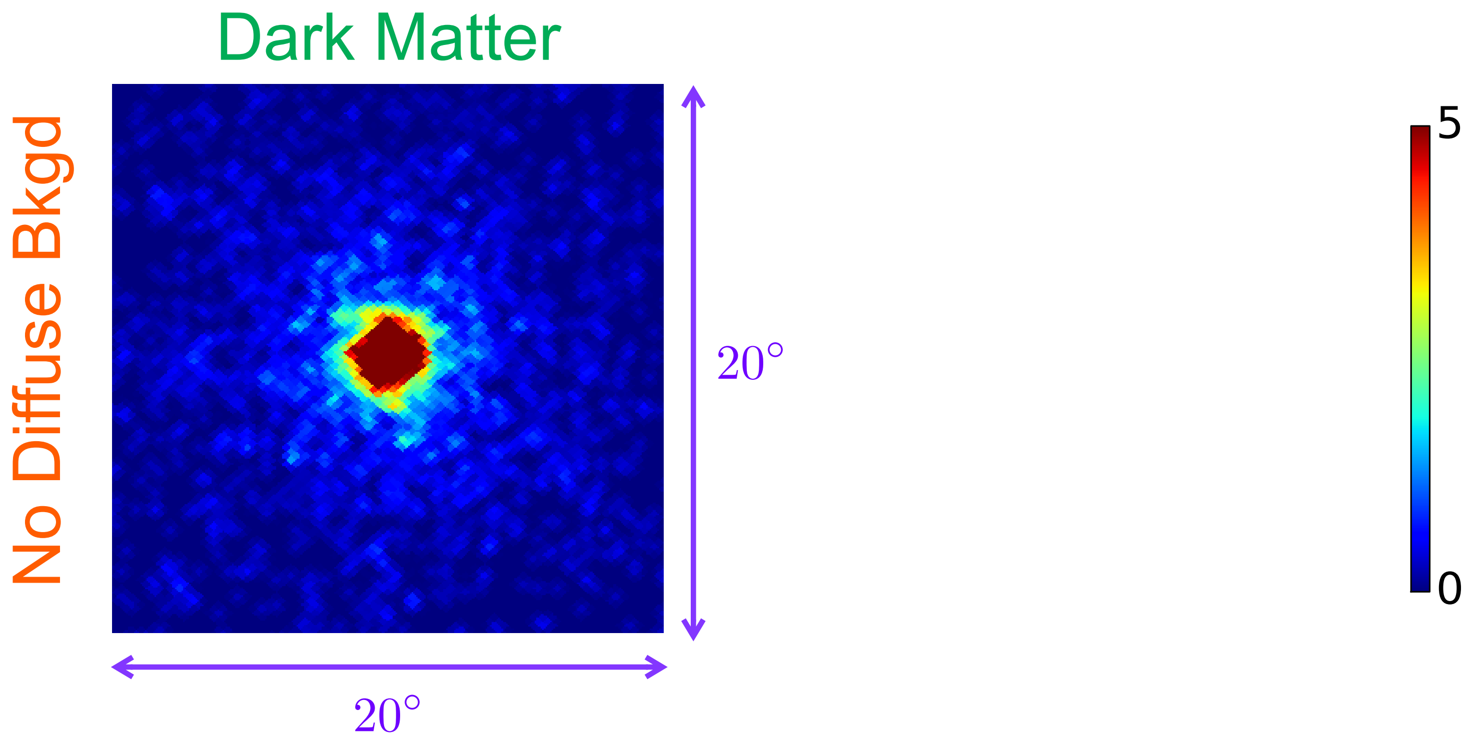
Daylan *et al.* [1402.6703]

Diffuse Background

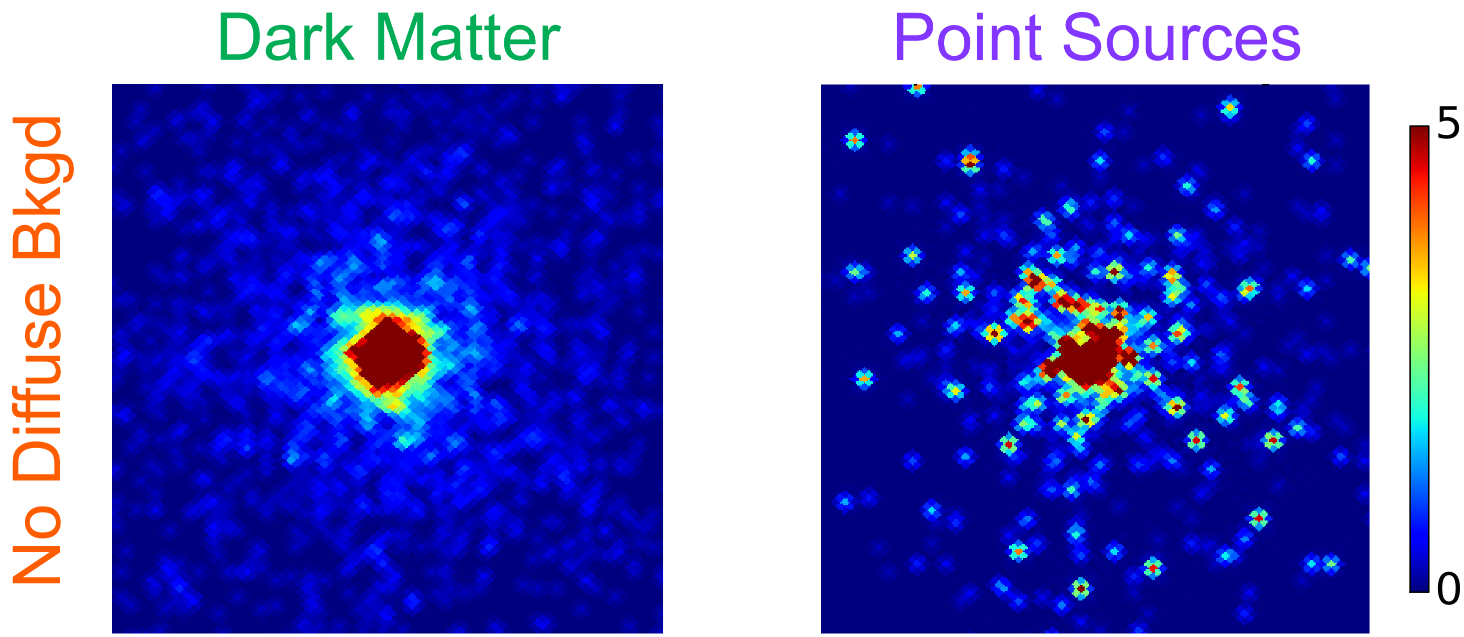
Evidence for excess emission appears to be robust even under uncertainties in diffuse emission models



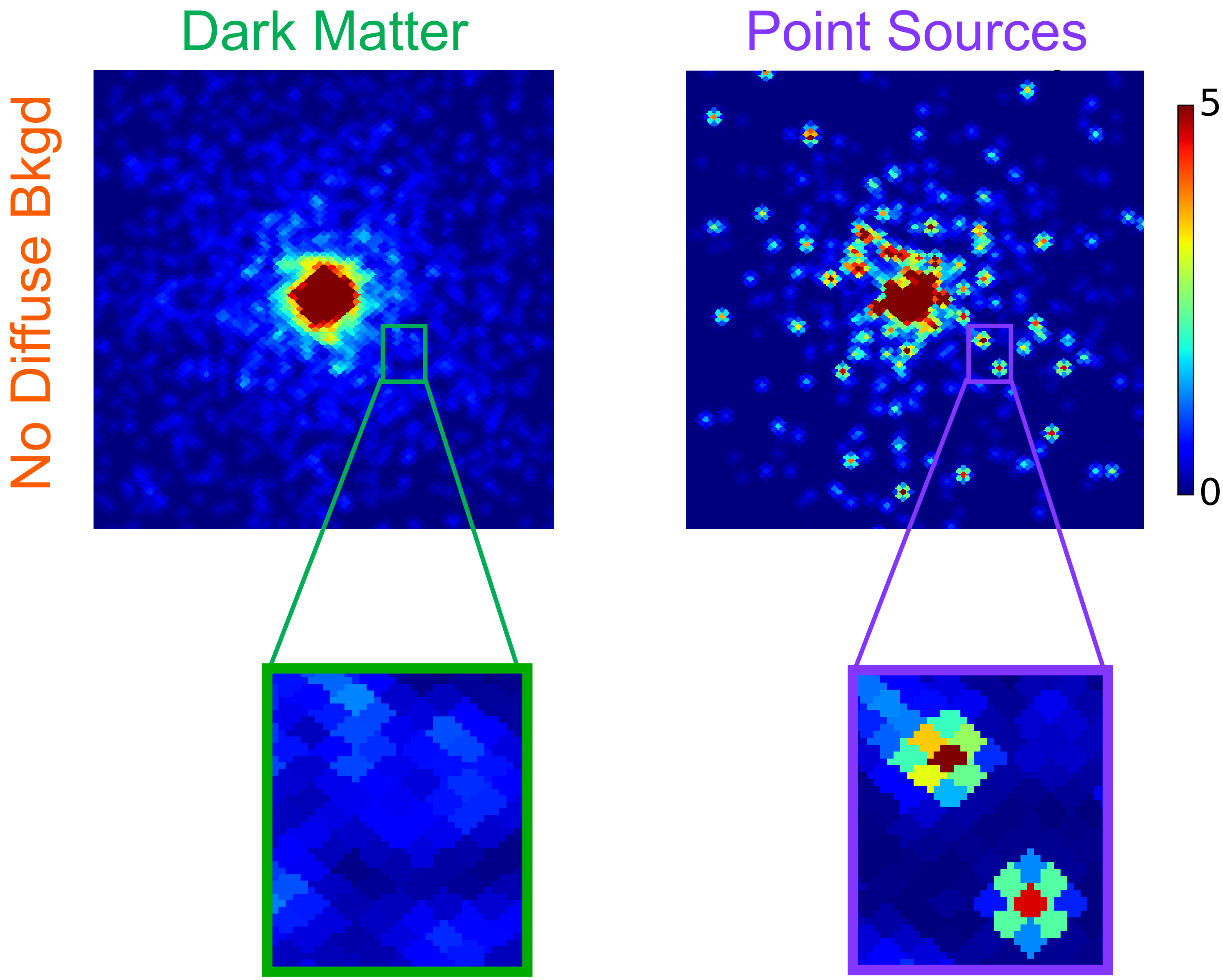
Calore, Cholis, and Weniger [1409.0042]



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

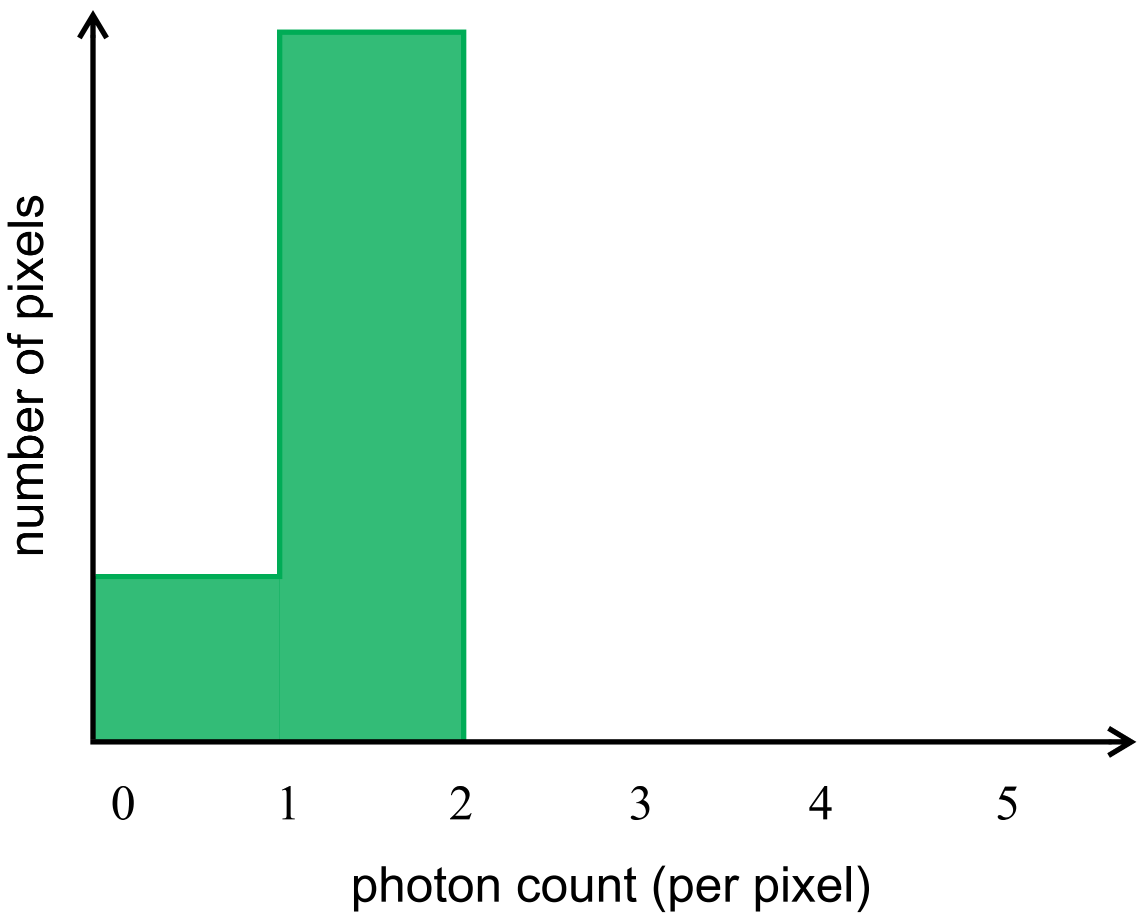


Malyshev and Hogg [1104.0010]; Lee, **ML**, Safdi [1412.6099]

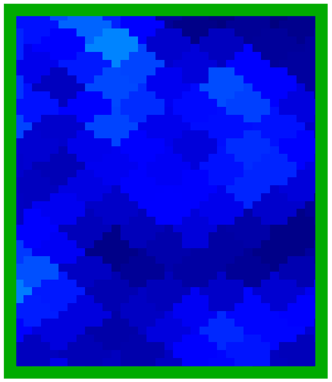


Malyshev and Hogg [1104.0010]; Lee, **ML**, Safdi [1412.6099]

Photon Counts

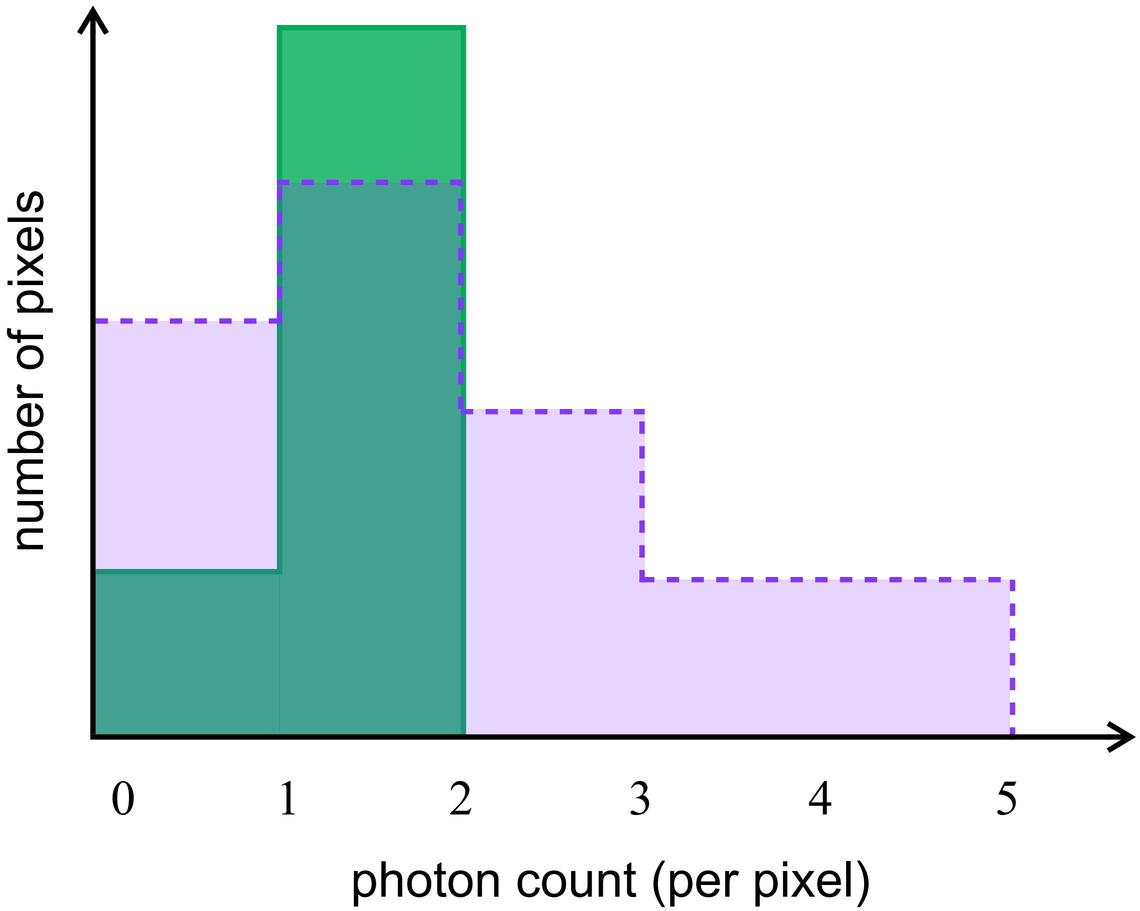


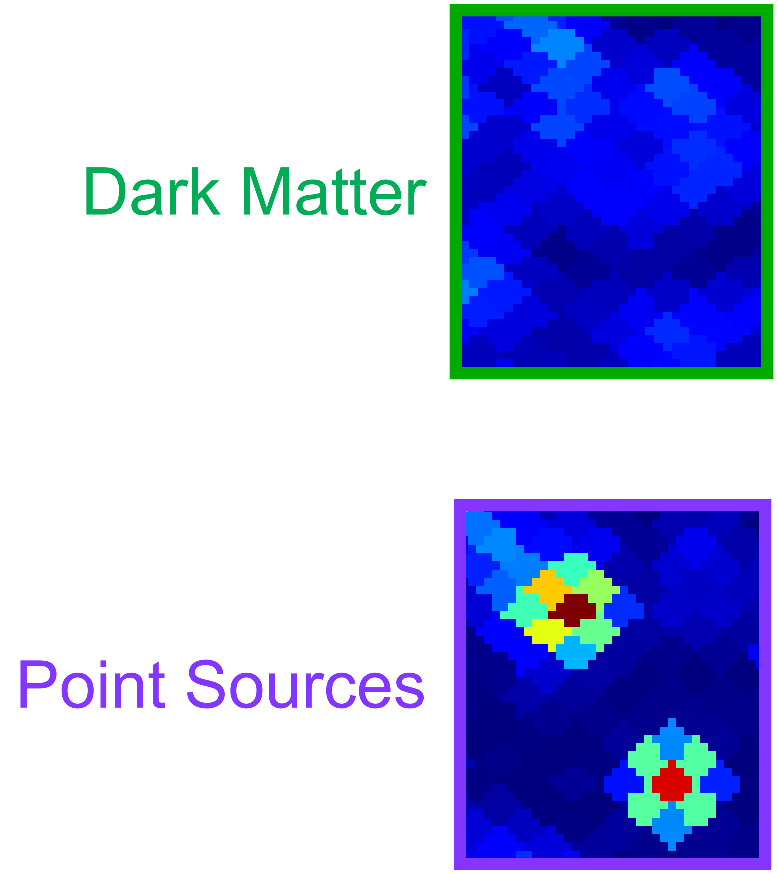
Dark Matter



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

Photon Counts



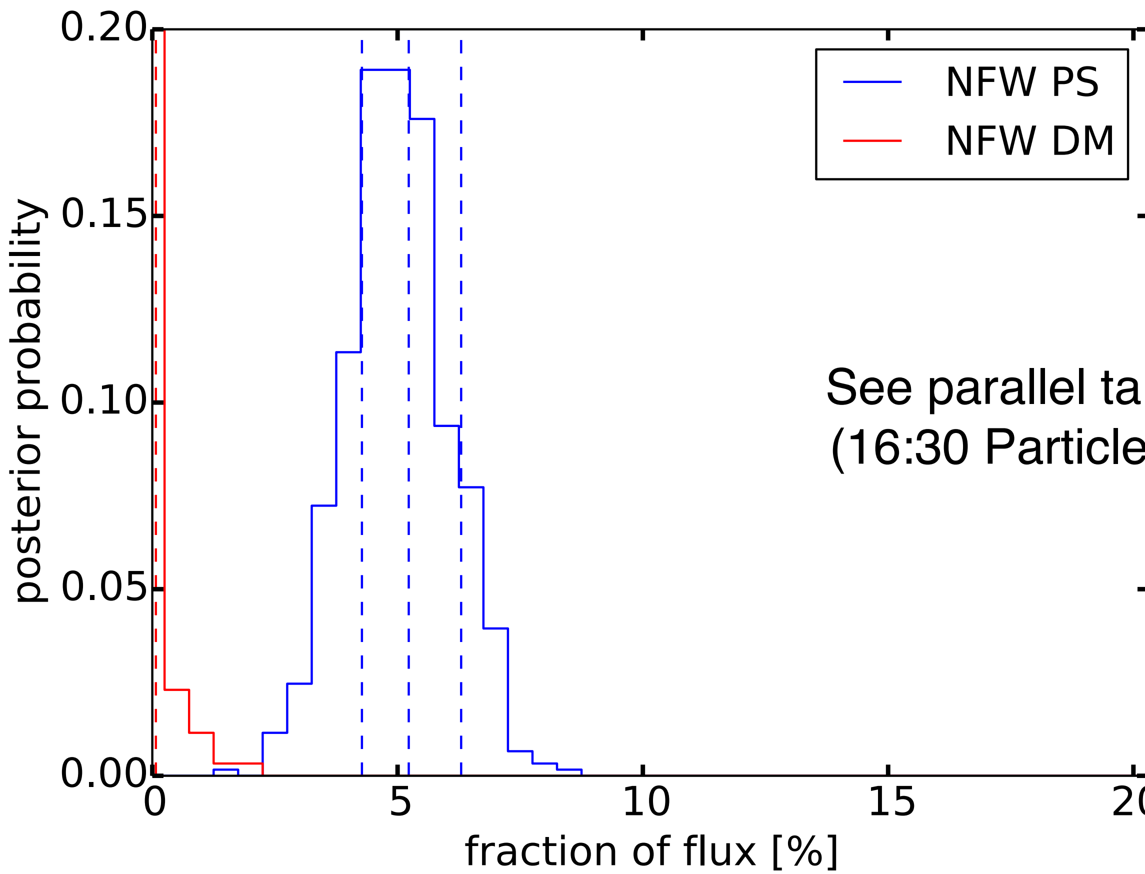


Malyshev and Hogg [1104.0010]; Lee, **ML**, Safdi [1412.6099]

Unresolved Point Sources

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



See parallel talk by B. Safdi
(16:30 Particle Cosmology)

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

Three Vignettes

	Current Status	Future Prospects
Direct Detection	Probing Higgs-exchange region	Exploring MeV-GeV dark matter
Collider Searches	Missing energy searches	Probing non-minimal dark sectors
Indirect Detection	Probing weak-scale annihilation cross sections	Clarifying GC anomaly

Current experiments are testing the WIMP paradigm and have set impressive constraints

Any anomalies under the WIMP “lamp post” must be carefully evaluated

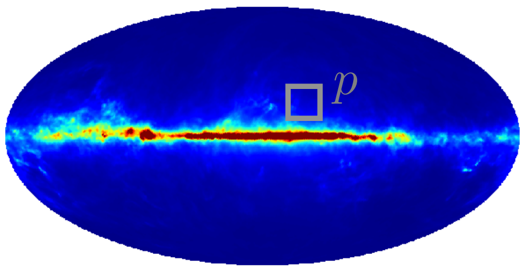
Necessary to think about the next targets of model exploration, especially if new experimental strategies are required

Backup Slides

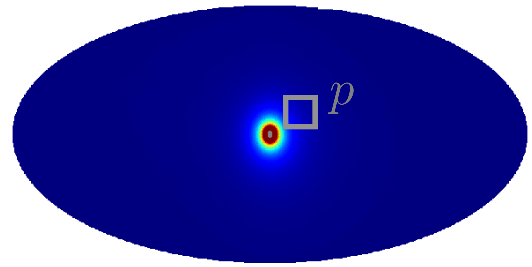
Standard Template Analysis

Spatial Templates

diffuse background



NFW dark matter



Expected number of photons in pixel *p*

$$\mu_p = \mu_{\mathrm{p,diff}} + \mu_{\mathrm{p,DM}}$$

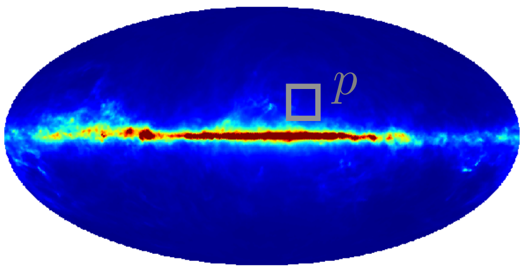
Probability of observing *k* photons in pixel *p*

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

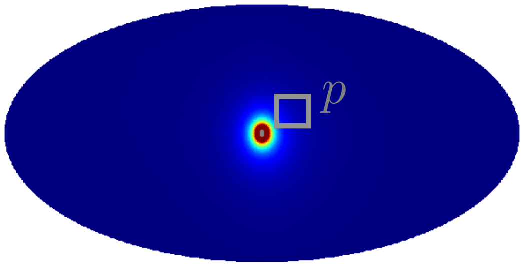
Non-Poissonian Template Fit

Spatial Templates

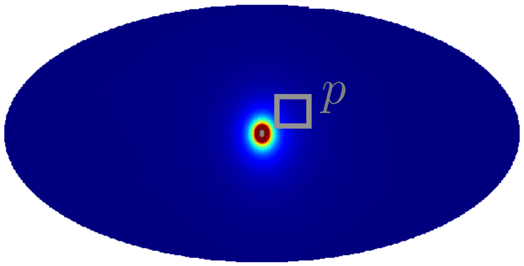
diffuse background



NFW dark matter



NFW point sources



Poisson (diffuse background, NFW dark matter) — Non-Poissonian (NFW point sources)

Total Generating Function

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

Probability of observing *k* photons in pixel *p*

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

Lee, Lisanti, Safdi [1412.6099]
Malyshev and Hogg [1104.0010]

Bayesian Approach

We use Bayesian methods to find the posterior distributions for the free parameters in the model

e.g., normalization of dark matter and point-source components

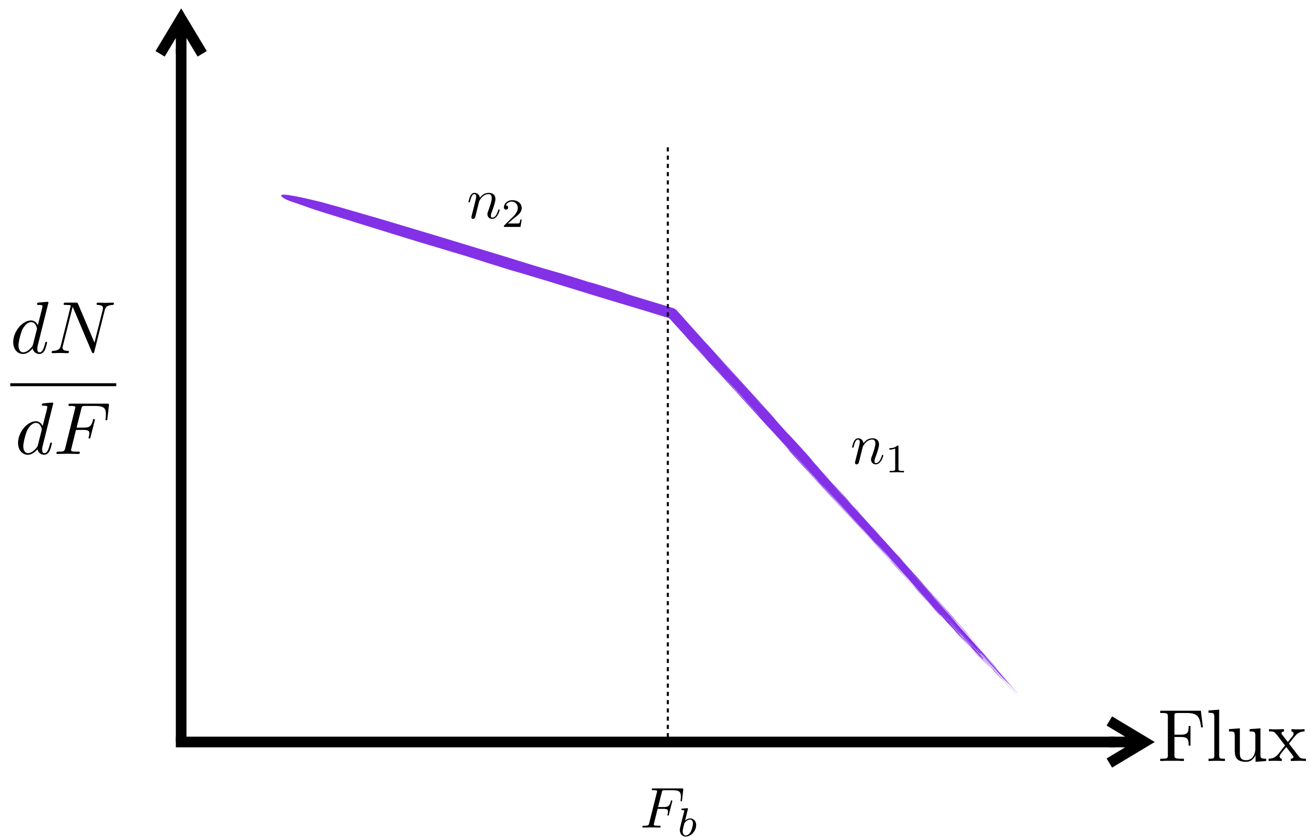
This allows us to reconstruct the source-count function for the point sources, assumed to be a double-power law:

$$\frac{dN}{dF} = A \begin{cases} \left(\frac{F}{F_b}\right)^{-n_1} & F \geq F_b \\ \left(\frac{F}{F_b}\right)^{-n_2} & F < F_b \end{cases}$$

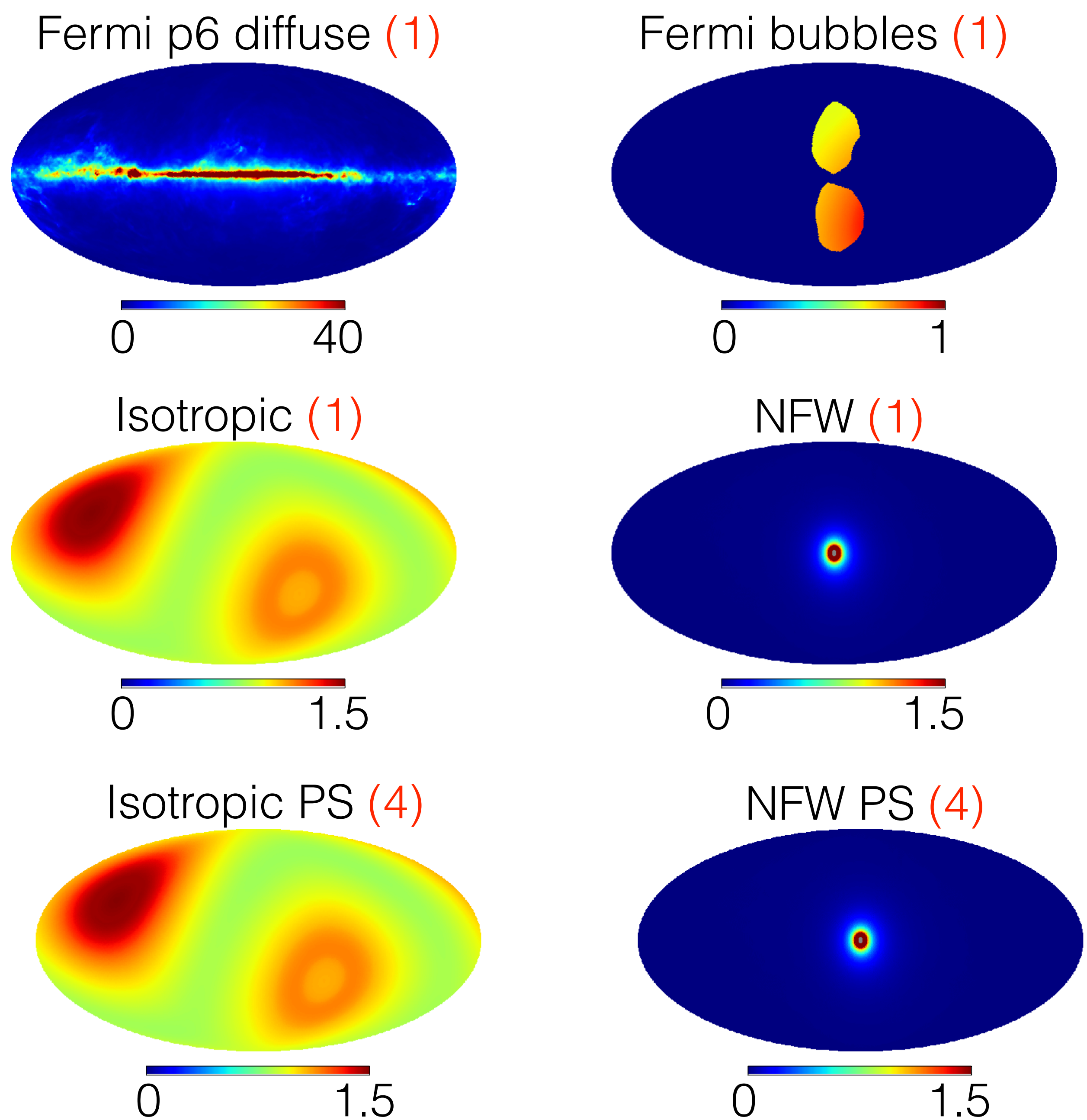
Source-Count Function

Number of sources in a given pixel with a flux between *F* and *F*+*dF*

Four free parameters: A, F_b, n_1, n_2



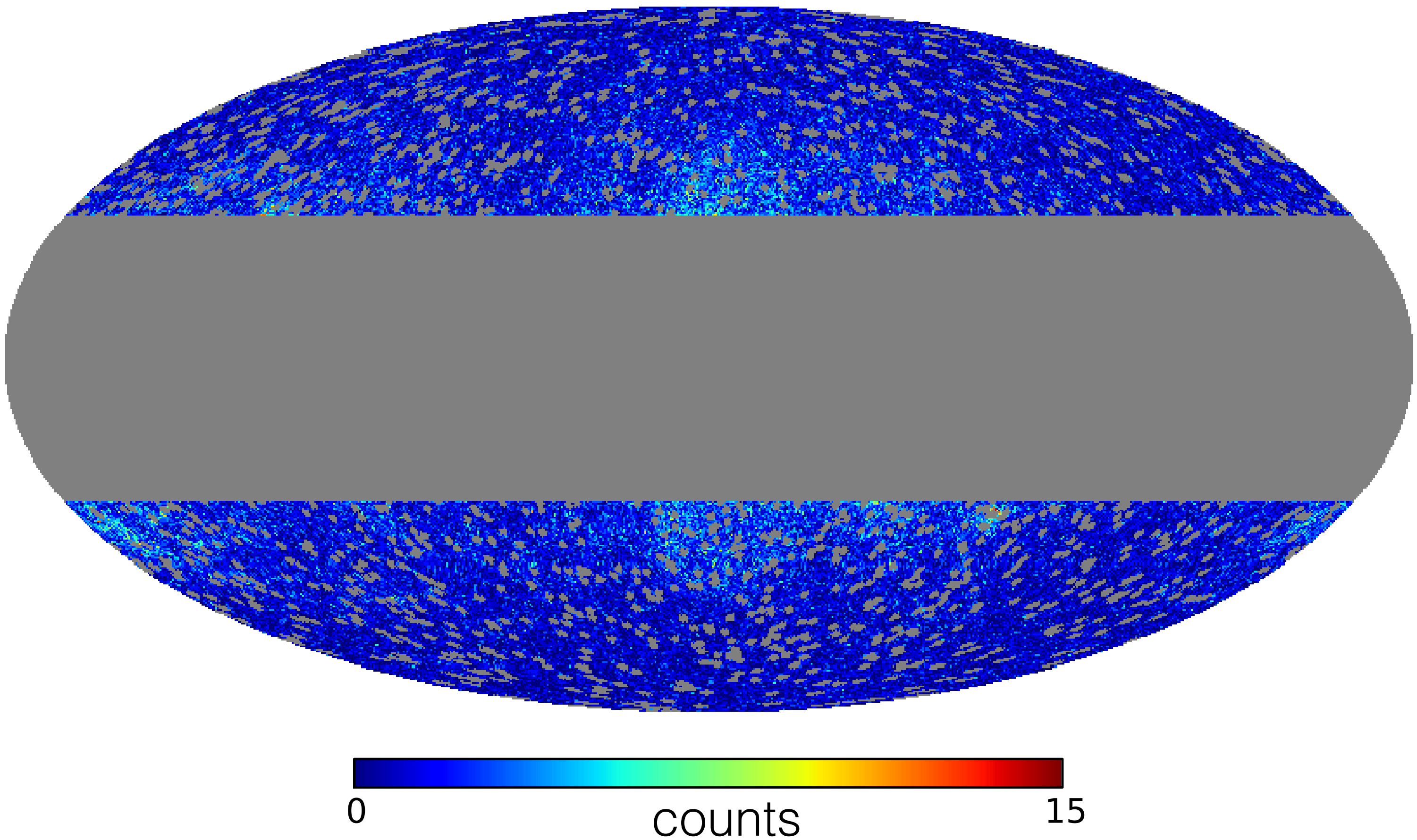
The Templates



High-Latitude Analysis

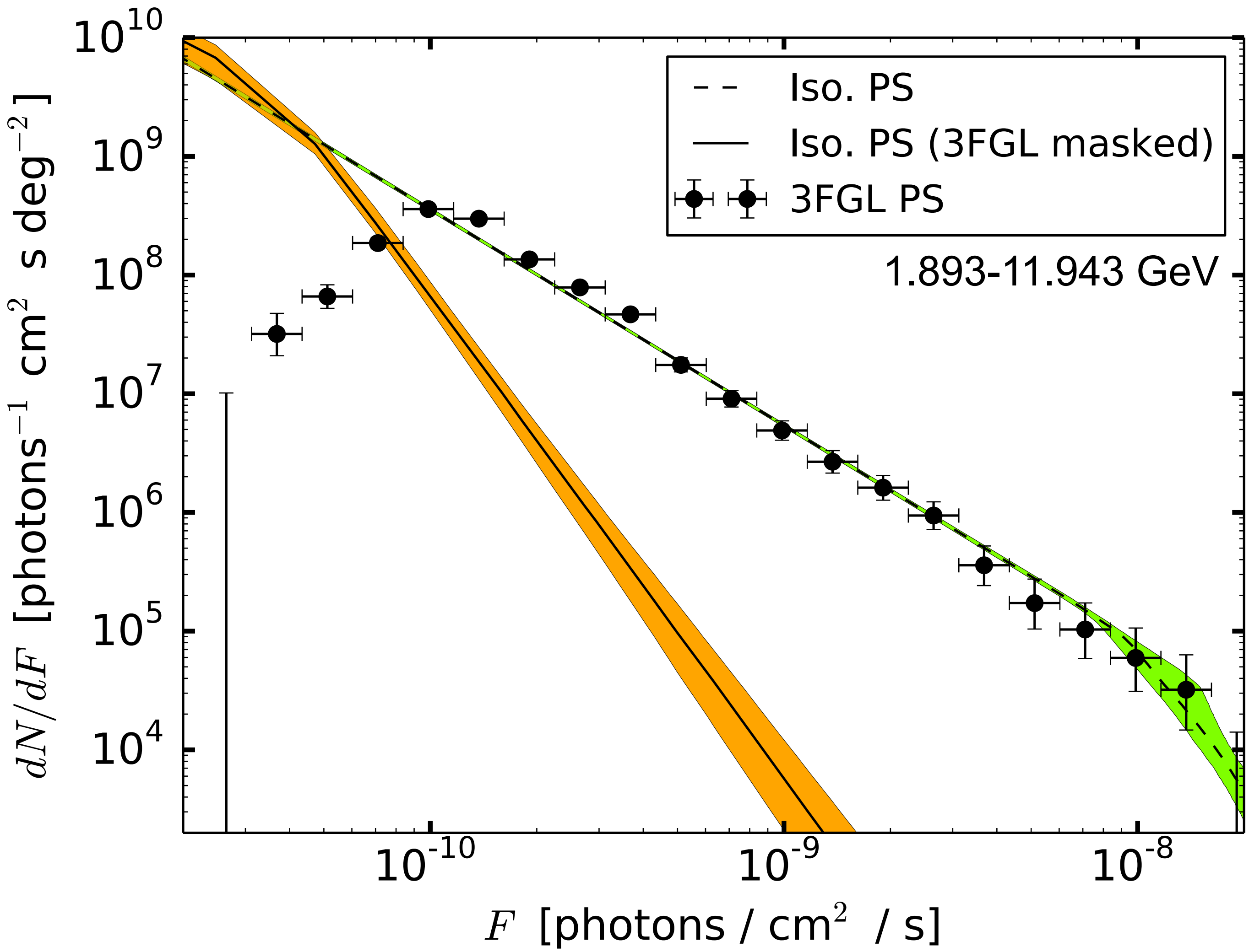
Mask all 3FGL point sources [1501.02003] with 5σ containment
HEALPIX *nside* = 128 (N_{pix} = 196,608)

Start by doing analysis at high latitudes (|b|>30°) where the diffuse background contribution is better under control



High-Latitude Analysis

Running the fit on data with masked 3FGL sources suggests presence of unresolved PSs below *Fermi* threshold



Templates:
diffuse
isotropic
bubbles
isotropic PS

Consistency

Can obtain an estimate for the intensity of the isotropic gamma-ray background

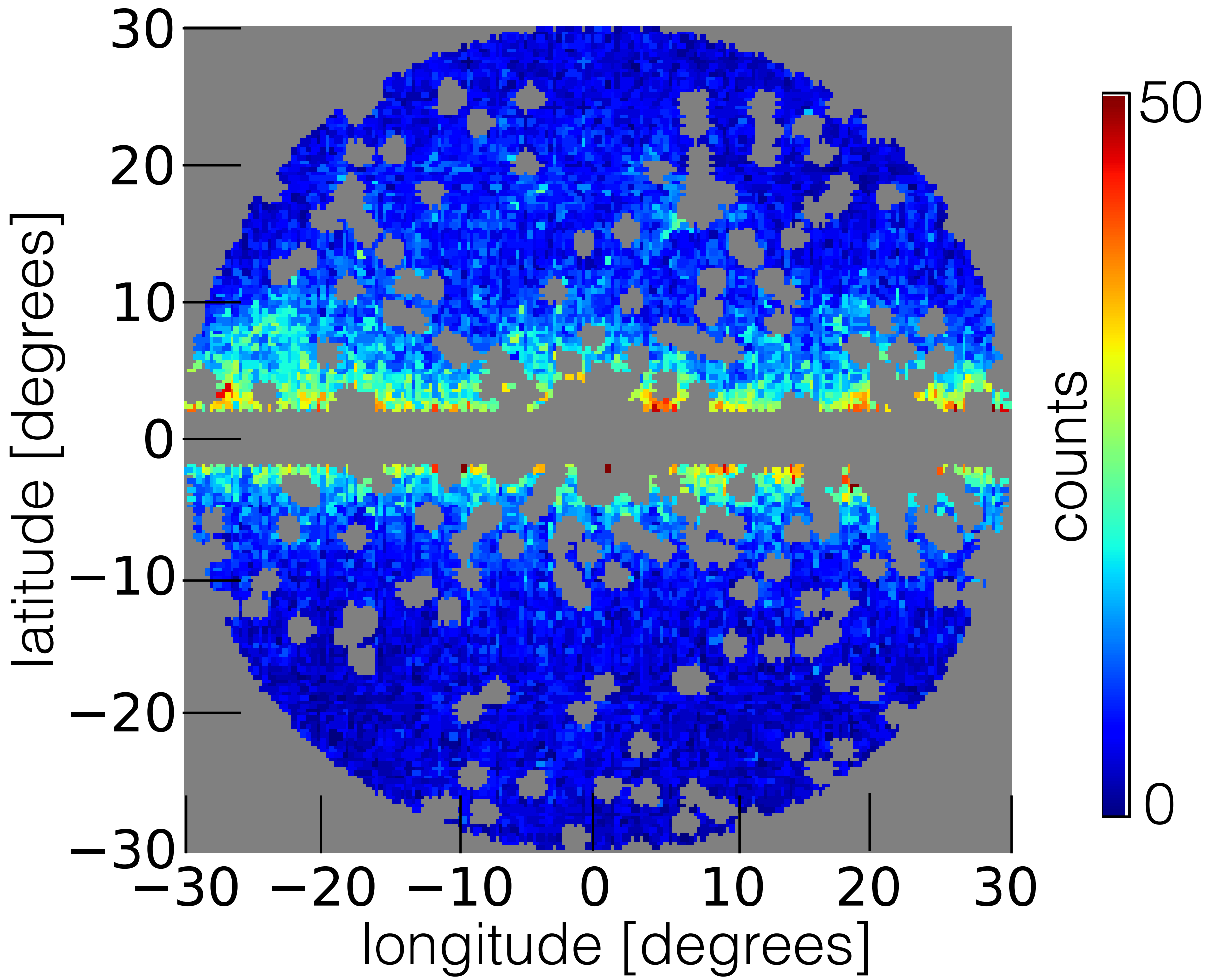
Consistent with results from [1410.3696]

Can obtain fraction of extragalactic background that is due to resolved/unresolved point sources

Consistent with results from [1003.0895, 1104.0010]

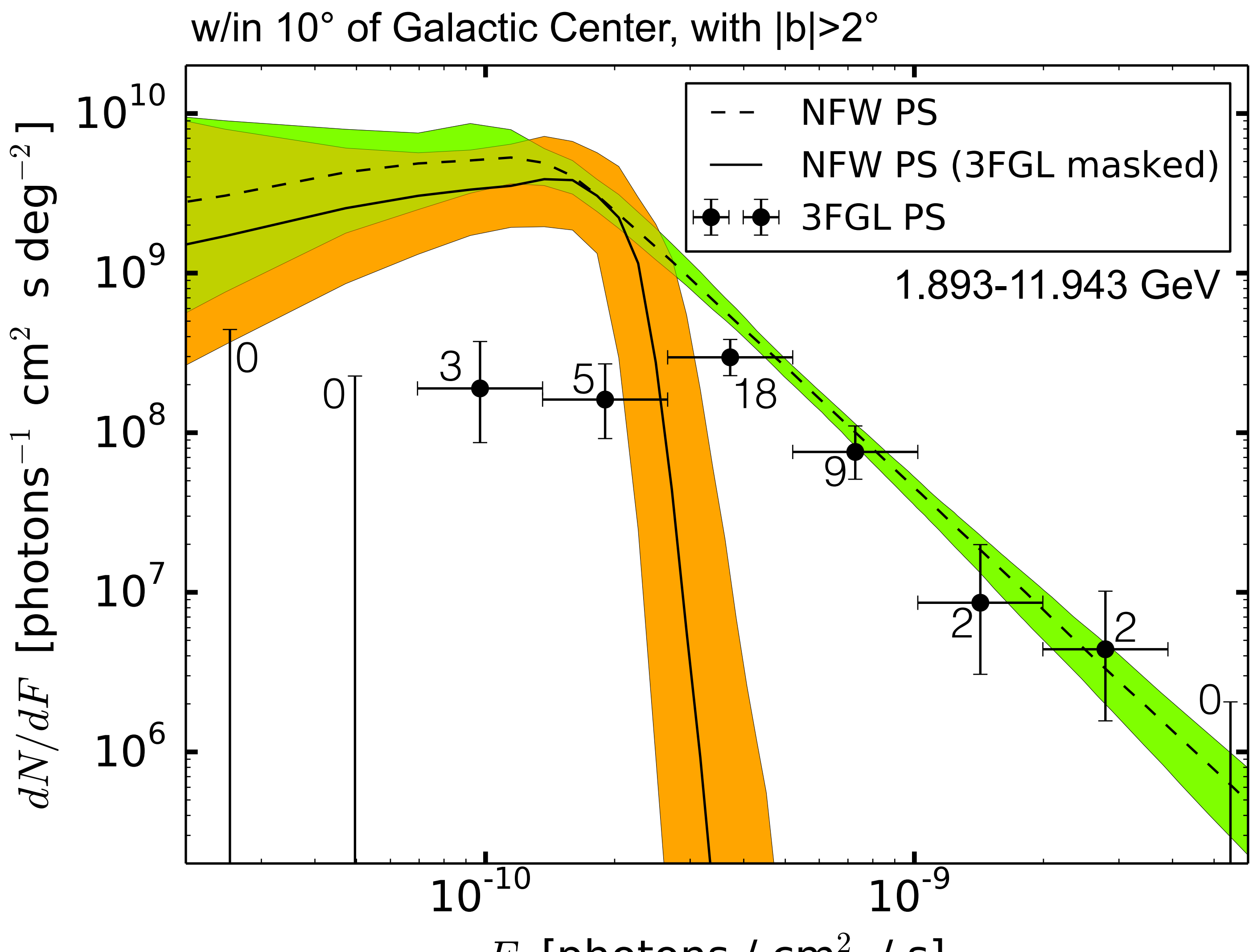
Inner Galaxy Analysis

Next, we repeat the analysis in the Inner Galaxy ...



Inner Galaxy Analysis

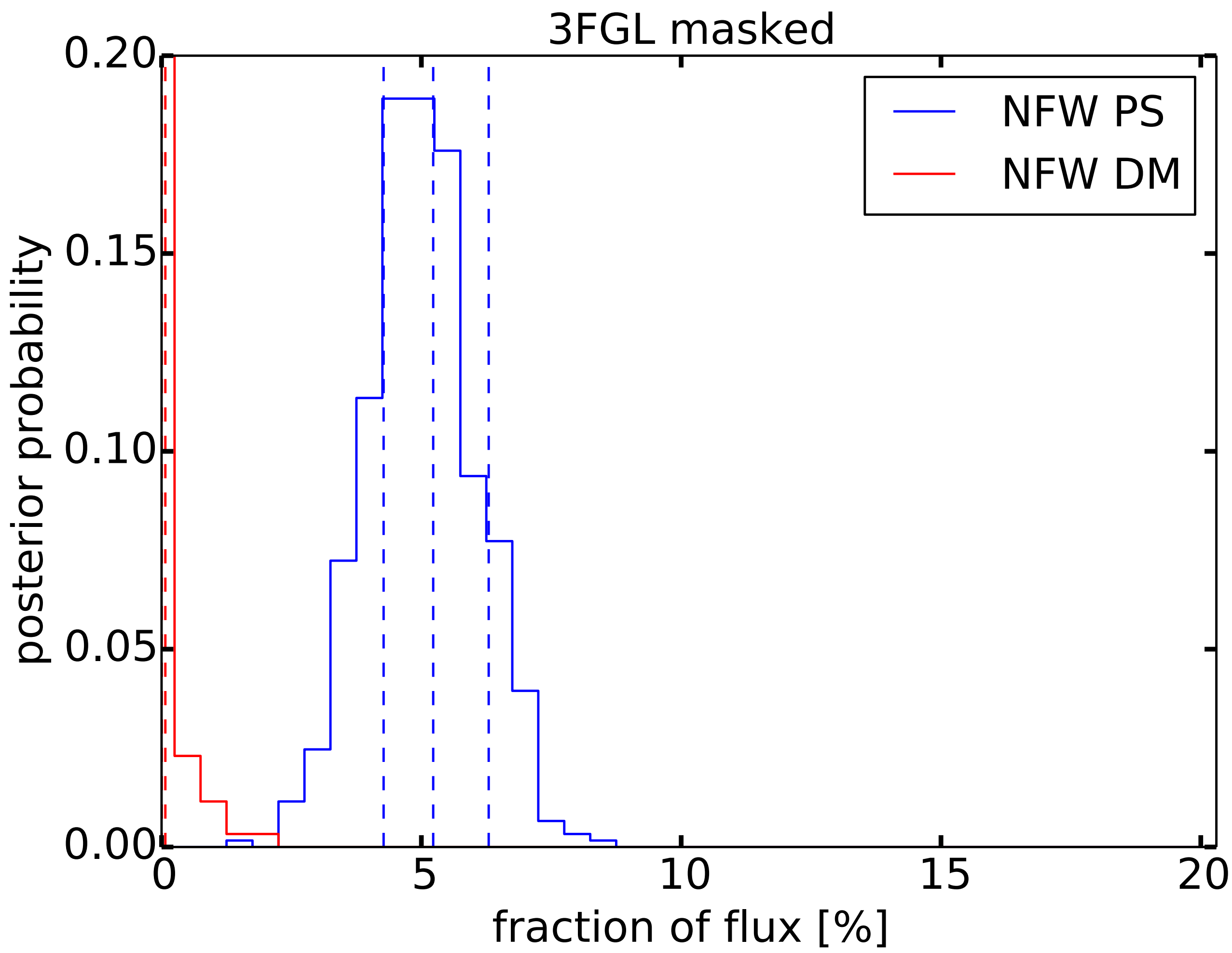
Evidence for a population of unresolved point sources below the Fermi detection threshold



Templates:
- diffuse
- isotropic
- bubbles
- isotropic PS
- NFW DM
- NFW PS

Inner Galaxy Analysis

Excess flux in the Inner Galaxy is entirely absorbed by the NFW PS template



Relevant Numbers

Strong preference for an additional point source template:

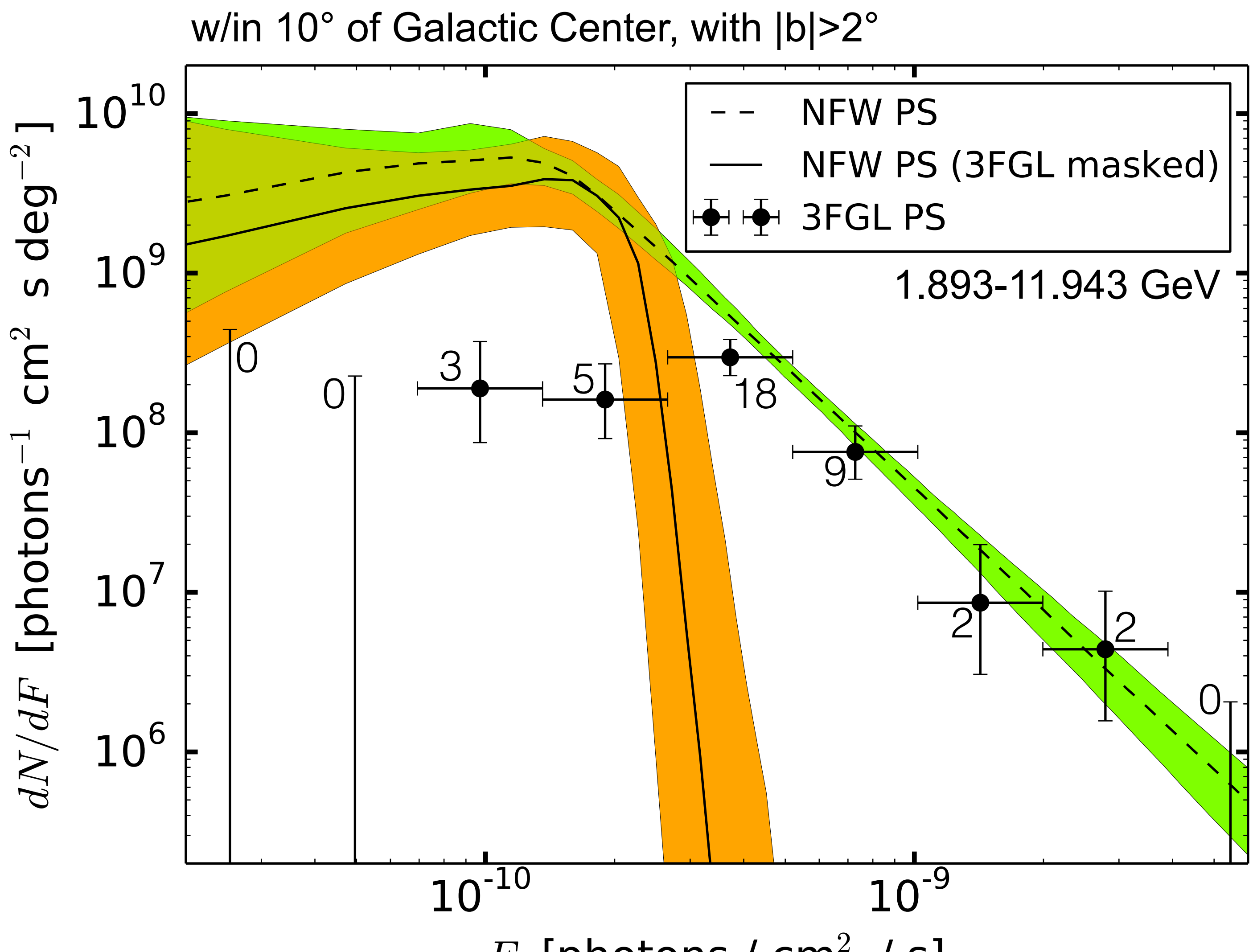
$$\text{Bayes Factor} = \frac{\text{Likelihood}\left[\text{NFW DM} + \text{NFW PS}\right]}{\text{Likelihood}\left[\text{NFW DM}\right]} \sim 10^7$$

Predict population of sources directly below detection threshold:

62^{+21}_{-19} sources to explain half of excess

203^{+109}_{-68} sources to explain all of excess
CAUTION: extrapolation of source-count function to low fluxes

Inner Galaxy Analysis



Templates:
diffuse
isotropic
bubbles
isotropic PS
NFW DM
NFW PS

Numerous Cross Checks

Check north/south asymmetry

Vary inner slope of NFW profile

Vary the diffuse model

Vary size of region of interest

Vary priors and check convergence

Study other excesses along the Galactic plane

Vary the point-spread function

Introduce diffuse-correlated point-source template

Identify most non-Poissonian pixels

Simulated data tests

⋮

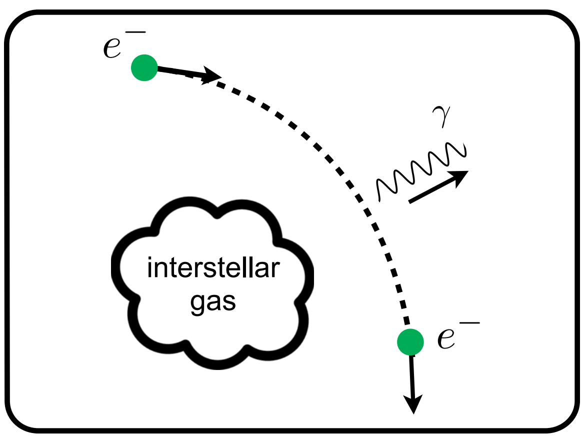
Diffuse Background

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

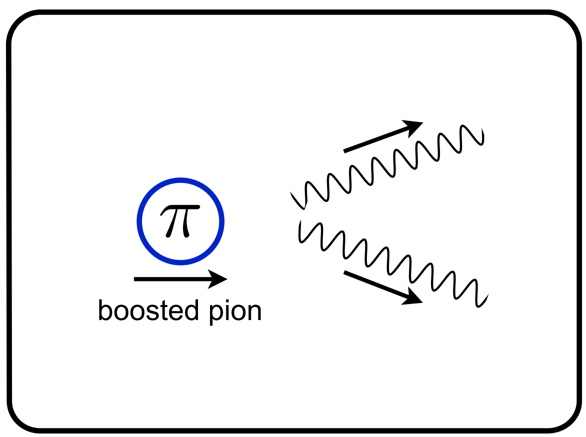
Depends on location of cosmic-ray sources and on the gas distribution

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

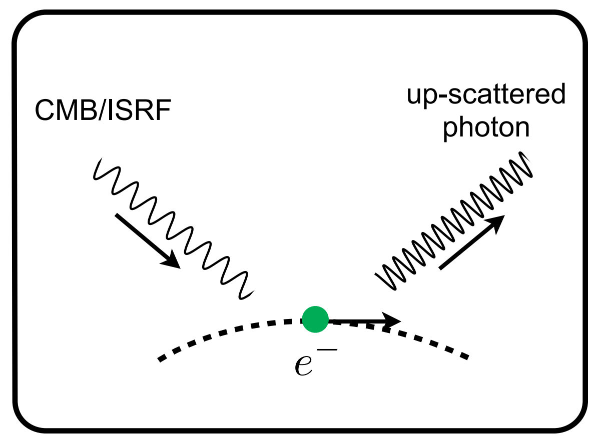
Bremsstrahlung



Pion Emission



Inverse Compton

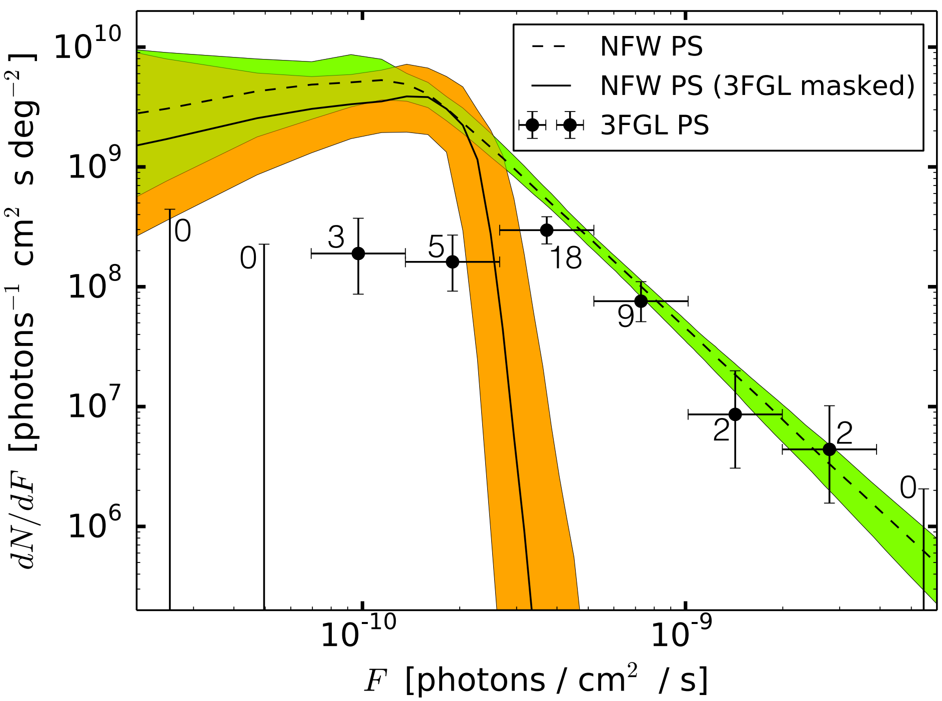


1. Varying the Diffuse Model

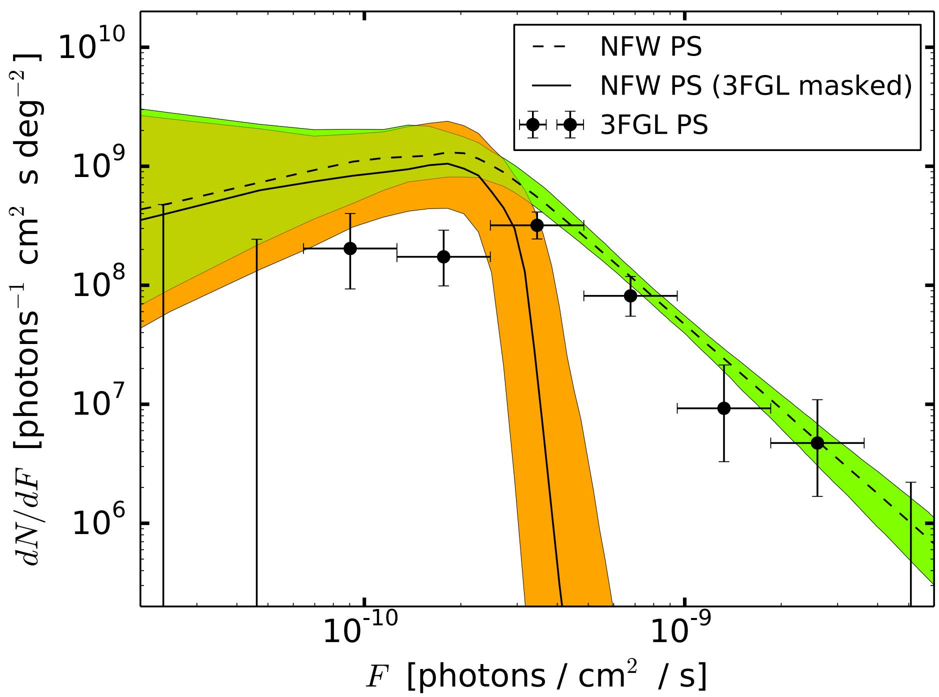
Evidence of new unresolved point sources robust to changing from p6v11 to p7v6 diffuse model

Number of projected sources decreases with p7v6, consistent with previous analyses that find reduced flux using this model

p6v11



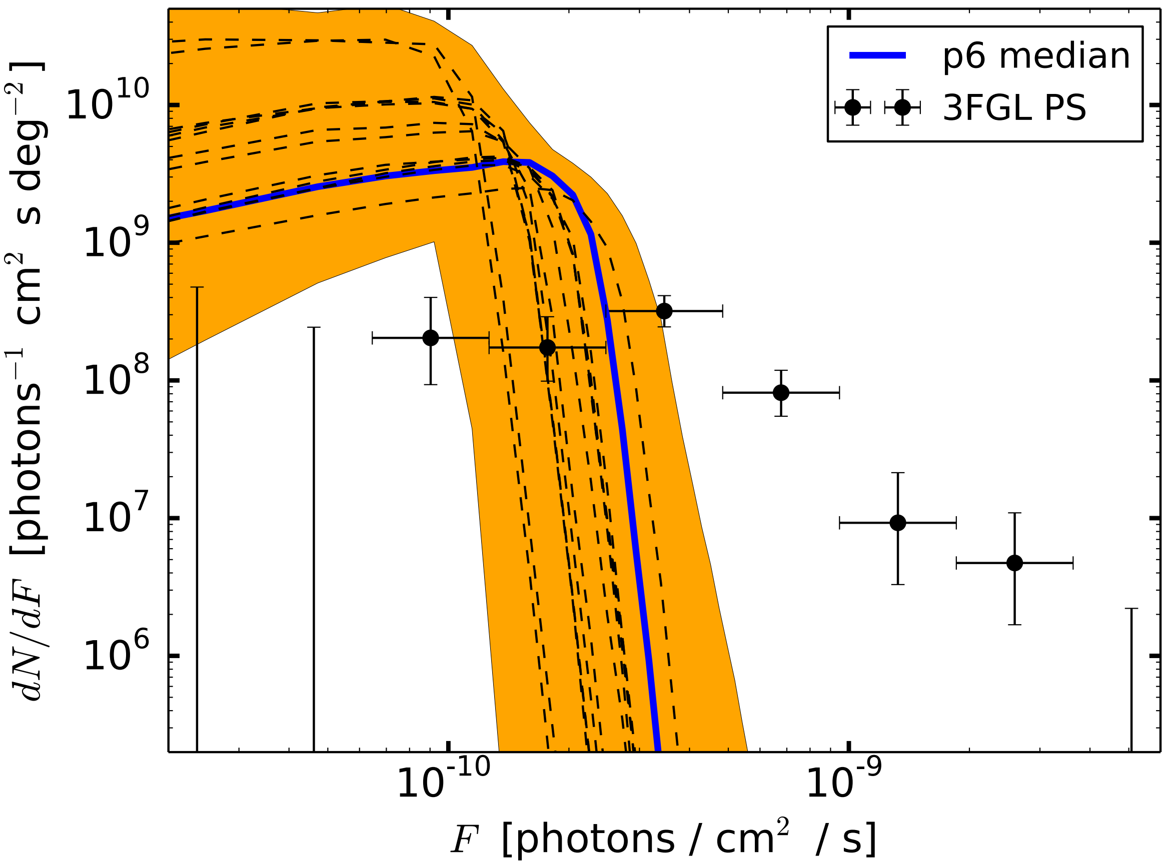
p7v6



1. Varying the Diffuse Model

Study 13 additional models chosen to span variations in the diffuse model parameters

Bayes factors in preference for PS template are 10^6-10^9 for all scenarios

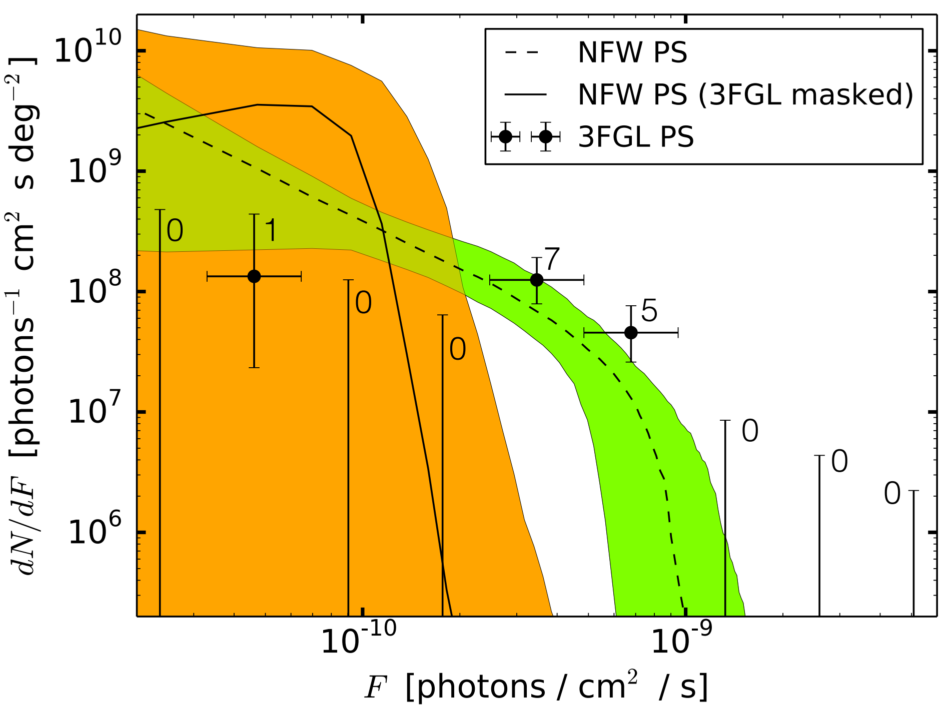


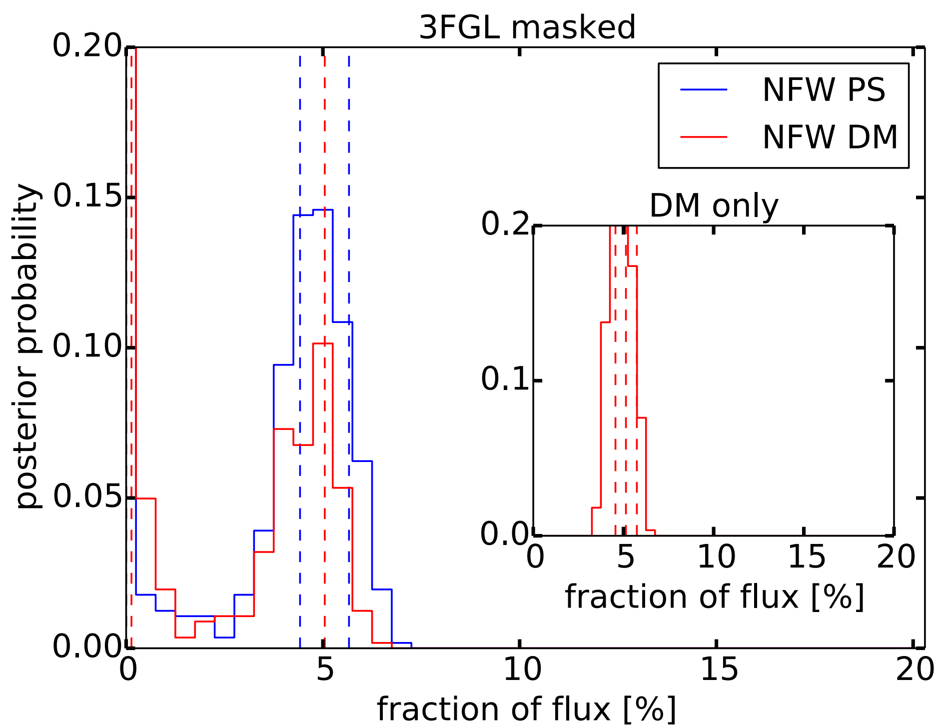
2. Scan Along the Plane

Other bright excesses along the plane; most significant at l=30°

Residual emission at l=30° is similar to that at Galactic Center, but softer energy spectrum

No evidence for PS component at l=30°

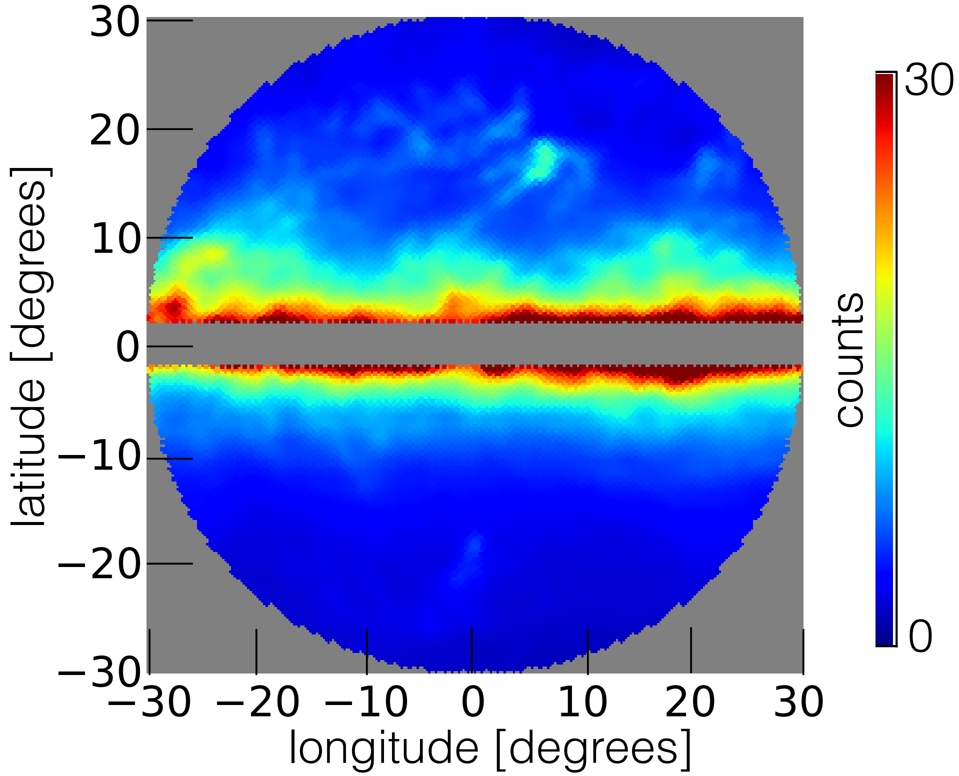




3. Diffuse-Correlated PSs

Can the preference for unresolved PSs be driven by localized substructure in the diffuse background that is not captured by the background model?

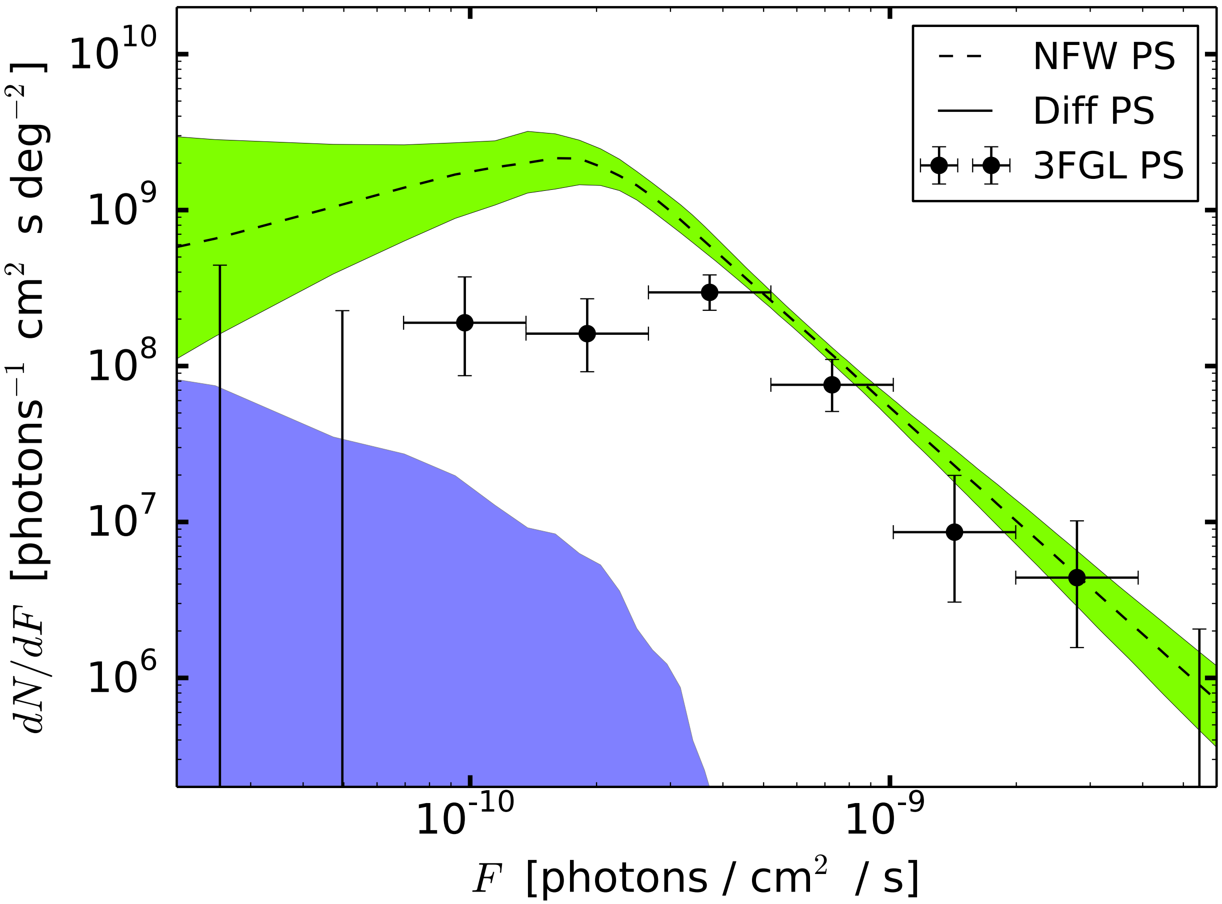
Introduce a new PS template that traces the diffuse model



3. Diffuse-Correlated PSs

Diffuse-correlated PS template does not absorb much flux

Suggests that spatial morphology of PSs not consistent with diffuse background



Many Open Questions

The source-count function we recover has unexpected features

Compare to expectations based on luminosity function derived from observed MSPs in nearby field of Milky Way

Cholis, Hooper, Linden [1407.5583, 1407.5625]