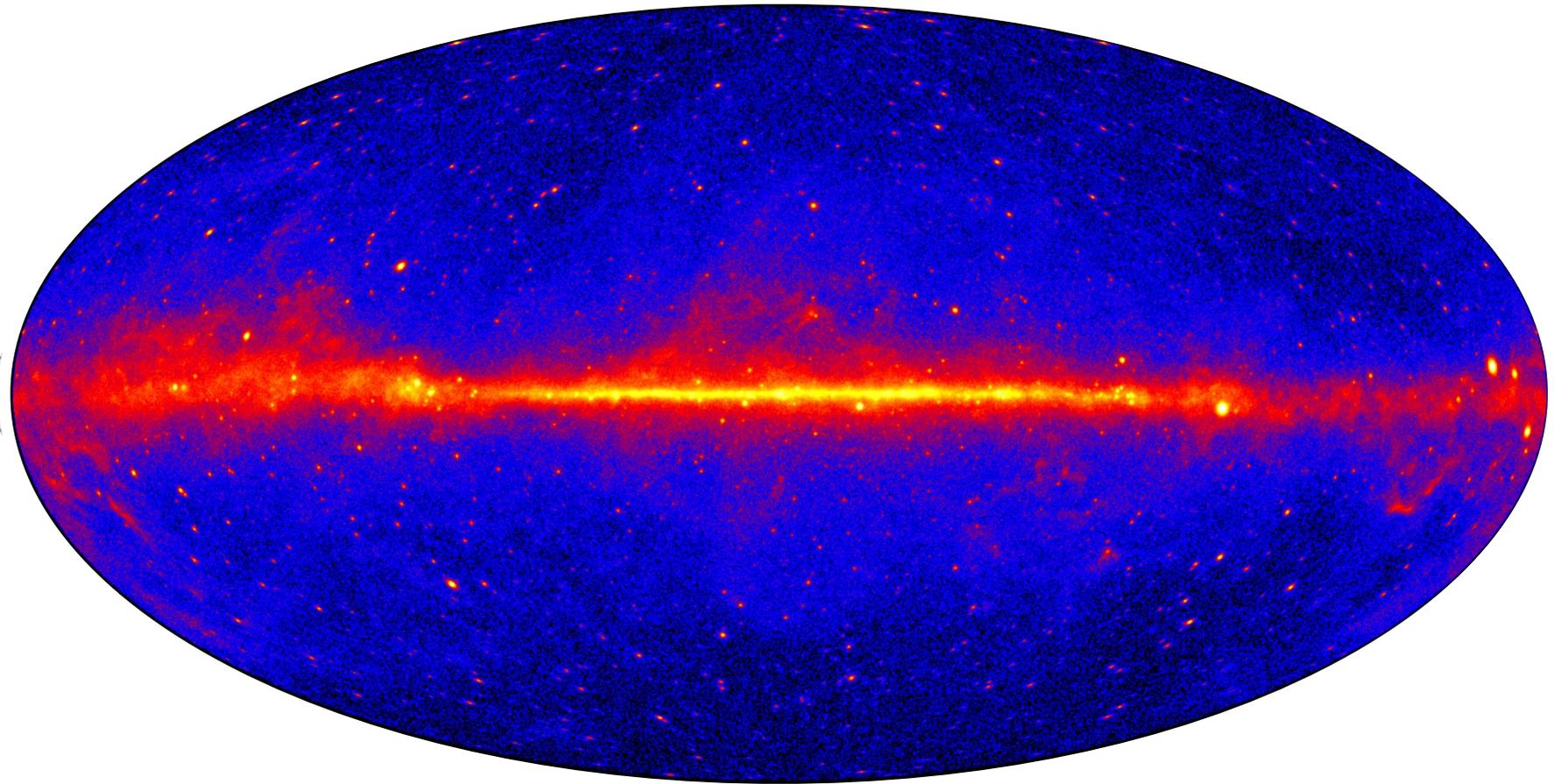


# The Galactic Center Excess: An Overview

Mariangela Lisanti  
Princeton University

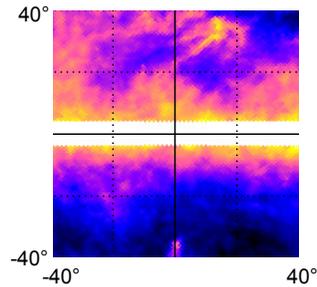
# Touring the Gamma-Ray Sky



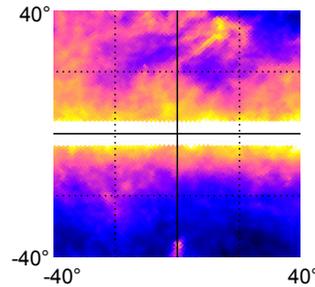
# Diffuse Gamma Rays

High-energy  $\gamma$ -rays produced through propagation of cosmic rays in the Galaxy

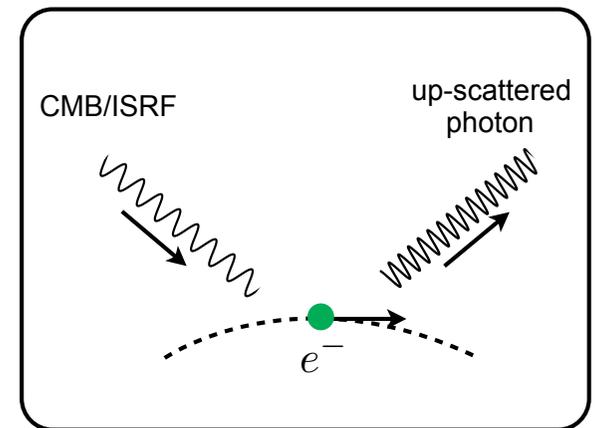
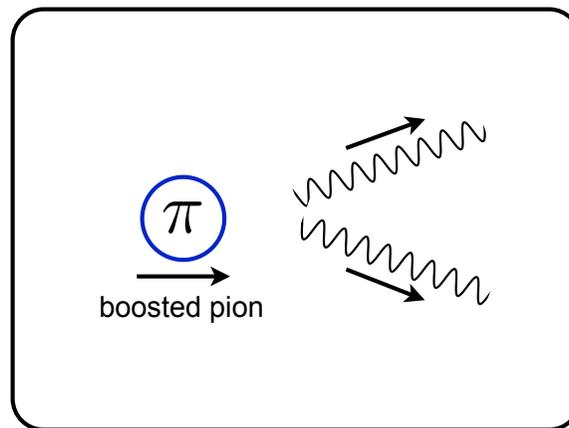
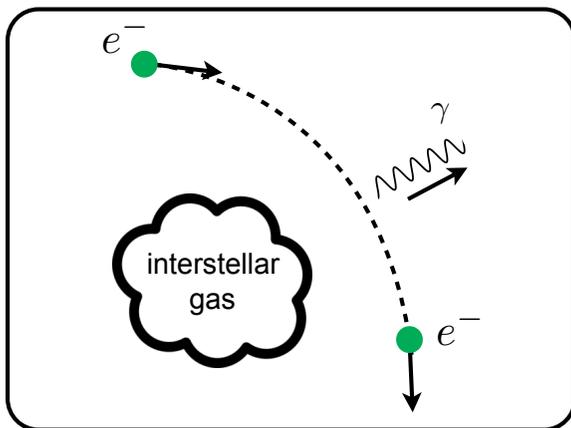
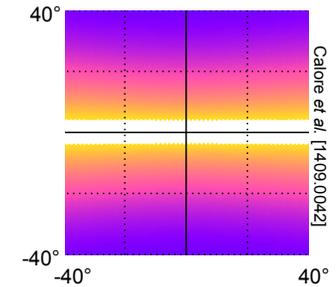
## Bremsstrahlung



## Pion Emission



## Inverse Compton

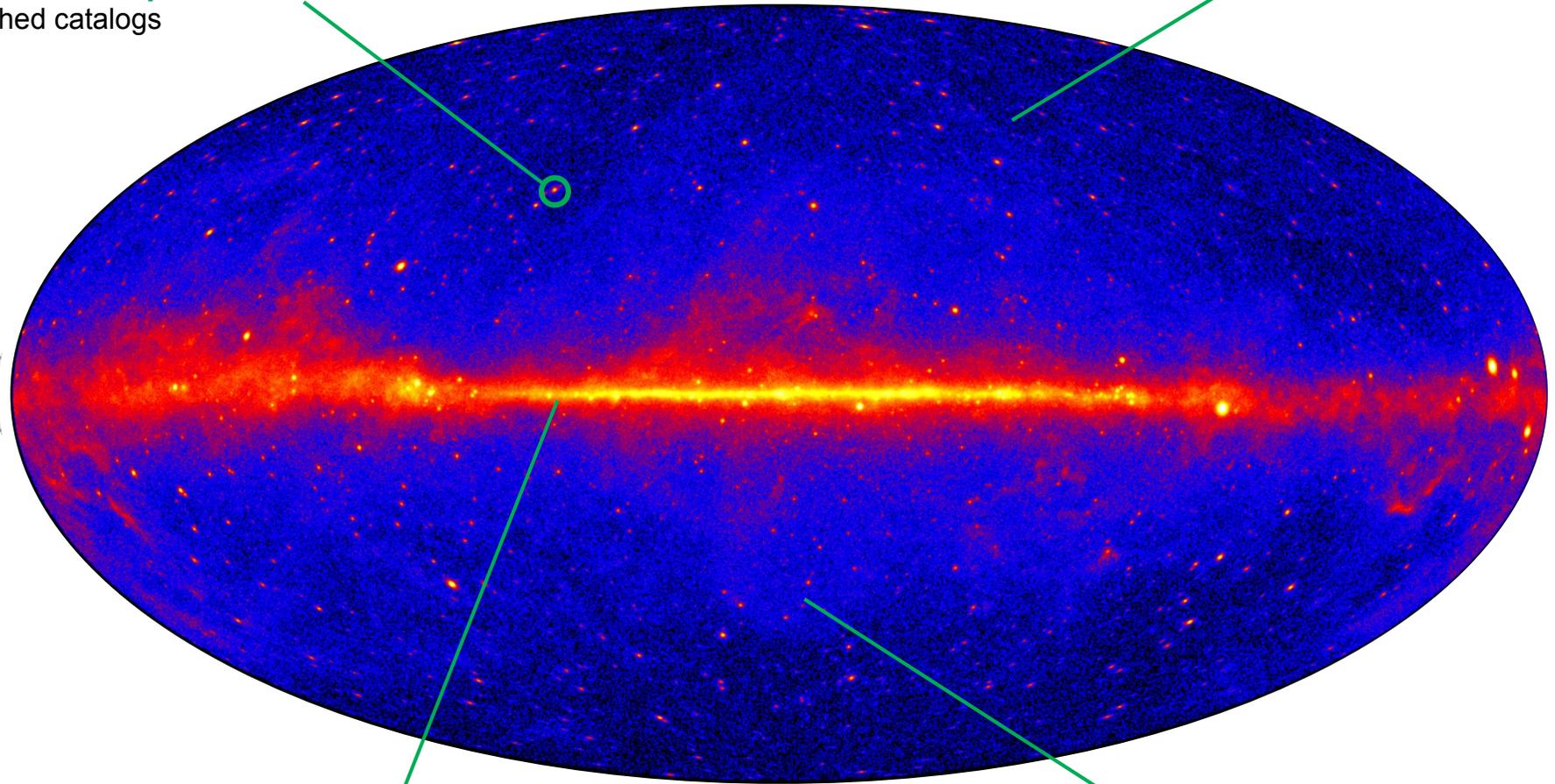


# Touring the Gamma-Ray Sky

Resolved point source

published catalogs

Extragalactic Background



Galactic plane

dominated by diffuse emission

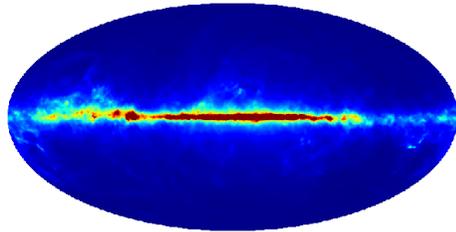
Fermi bubbles

# The Templates

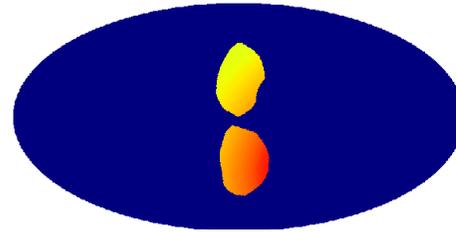
Each component contributing to the gamma-ray emission is modeled as a 'template'

The fitting procedure determines how much flux is attributed to each template

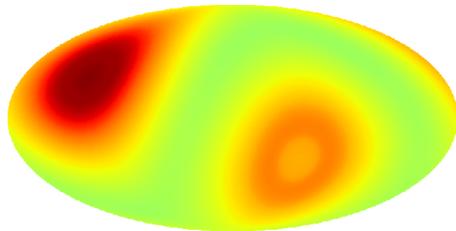
Galactic Diffuse Emission



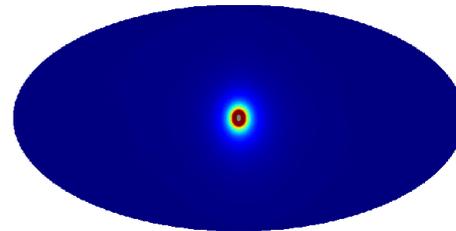
Fermi Bubbles



Extragalactic (Isotropic)



Dark Matter (NFW)



Inherent uncertainties due to assumptions about the spatial distributions (as well as number) of templates that are included in the analysis

# Where to Look for Dark Matter

The photon flux for dark matter annihilation is given by

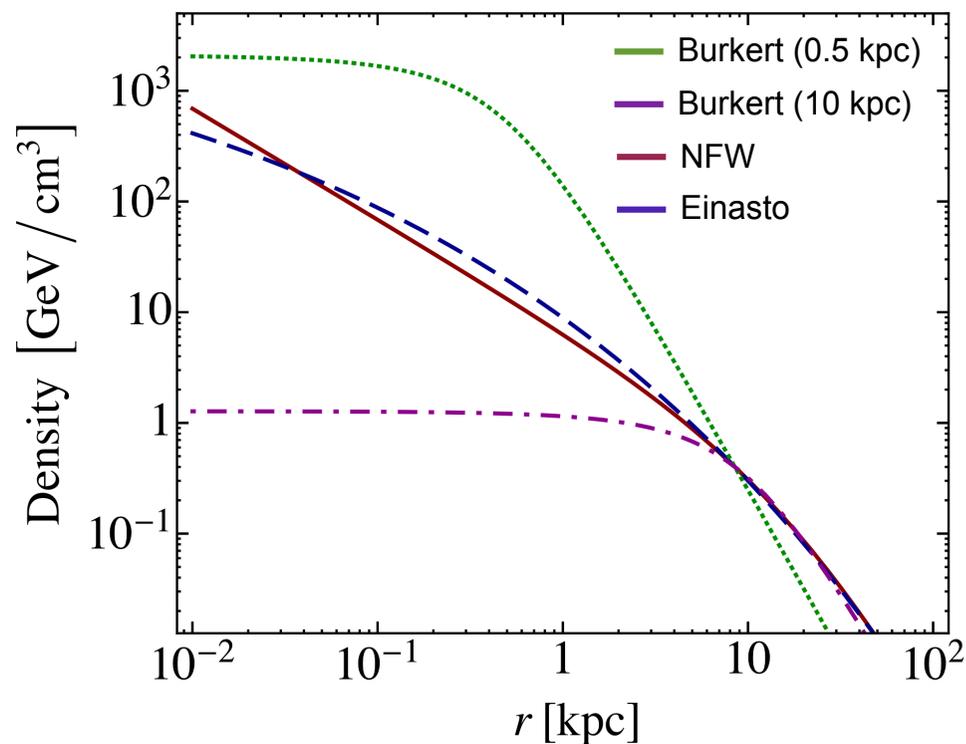
$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho[r(\ell, \psi)]^2$$

particle physics
J-factor

J-factor depends on the dark matter density profile

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

Best to look for dark matter annihilation at centers of galaxies, where density is highest



# The Galactic Center

# GeV Photon Excess

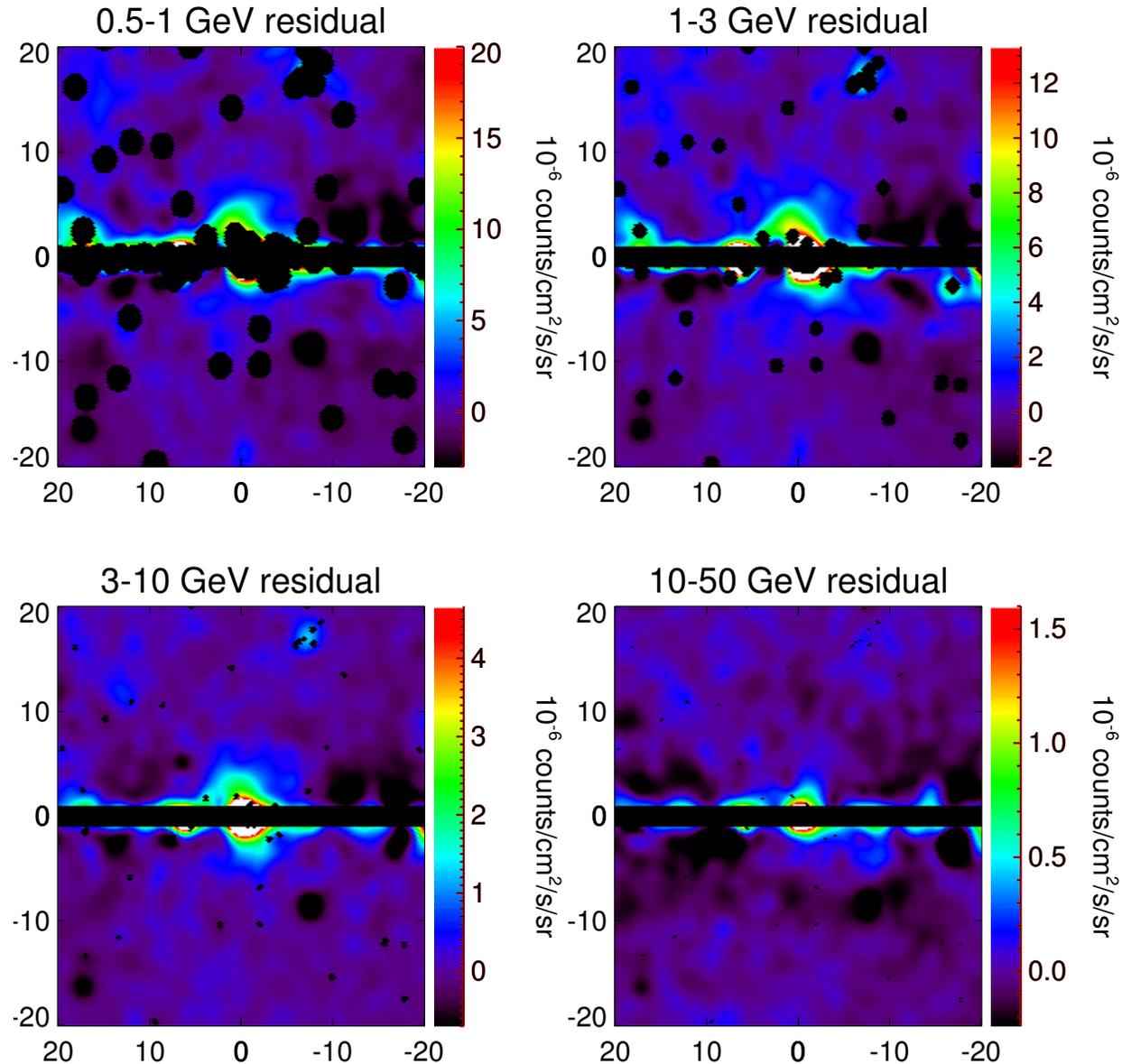
Spherically symmetric gamma-ray excess in the Inner Galaxy

Extends out  $10^\circ$  ( $\sim 5000$  lyr) from the center of Galaxy

Constitutes  $\sim 10\%$  total flux

High statistical significance

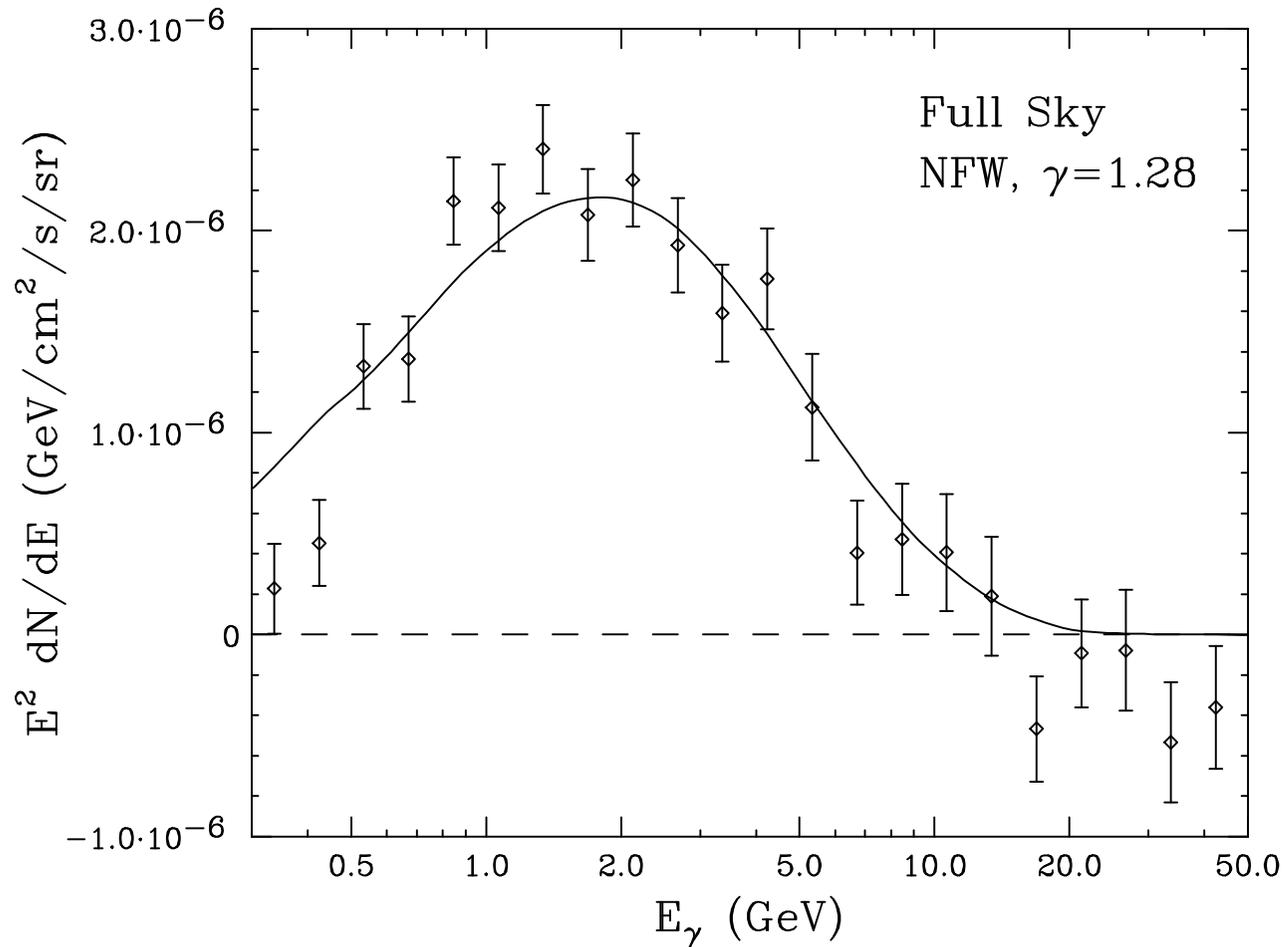
Goodenough and Hooper [0910.2998]  
Hooper and Goodenough [1010.2752]  
Boyarsky, Malyshev, Ruchayskiy [1012.5839]  
Hooper and Linden [1110.0006]  
Abazajian and Kaplinghat [1207.6047]  
Gordon and Macias [1306.5725]  
Abazajian *et al.* [1402.4090]  
Daylan *et al.* [1402.6703]  
Calore, Cholis, and Weniger [1409.0042]  
*Fermi* Collaboration [1511.02938, 1704.03910]



Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, and Slatyer [1402.6703]

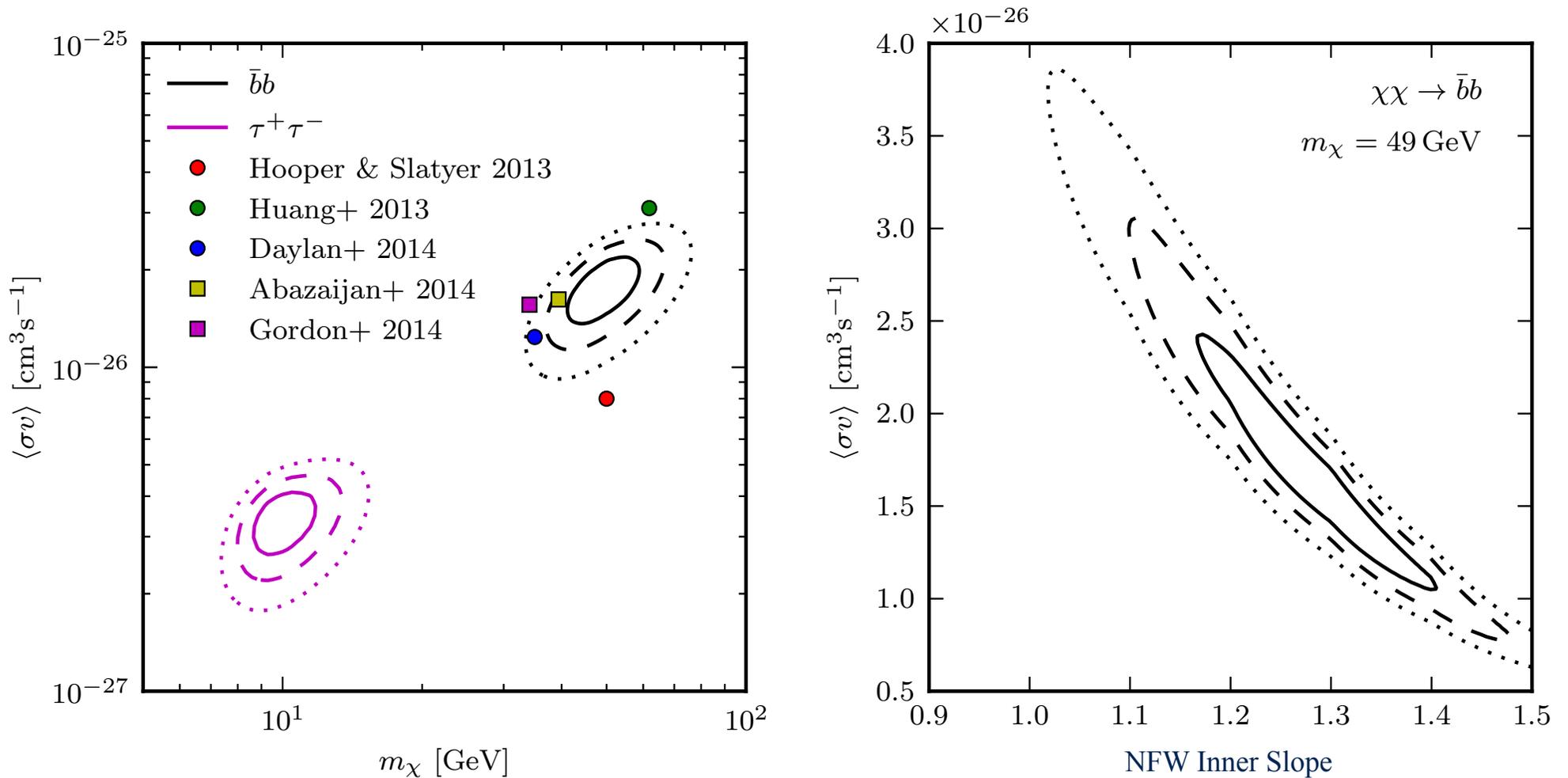
# GeV Photon Excess

Spatial morphology and energy spectrum of excess is consistent with dark matter expectation



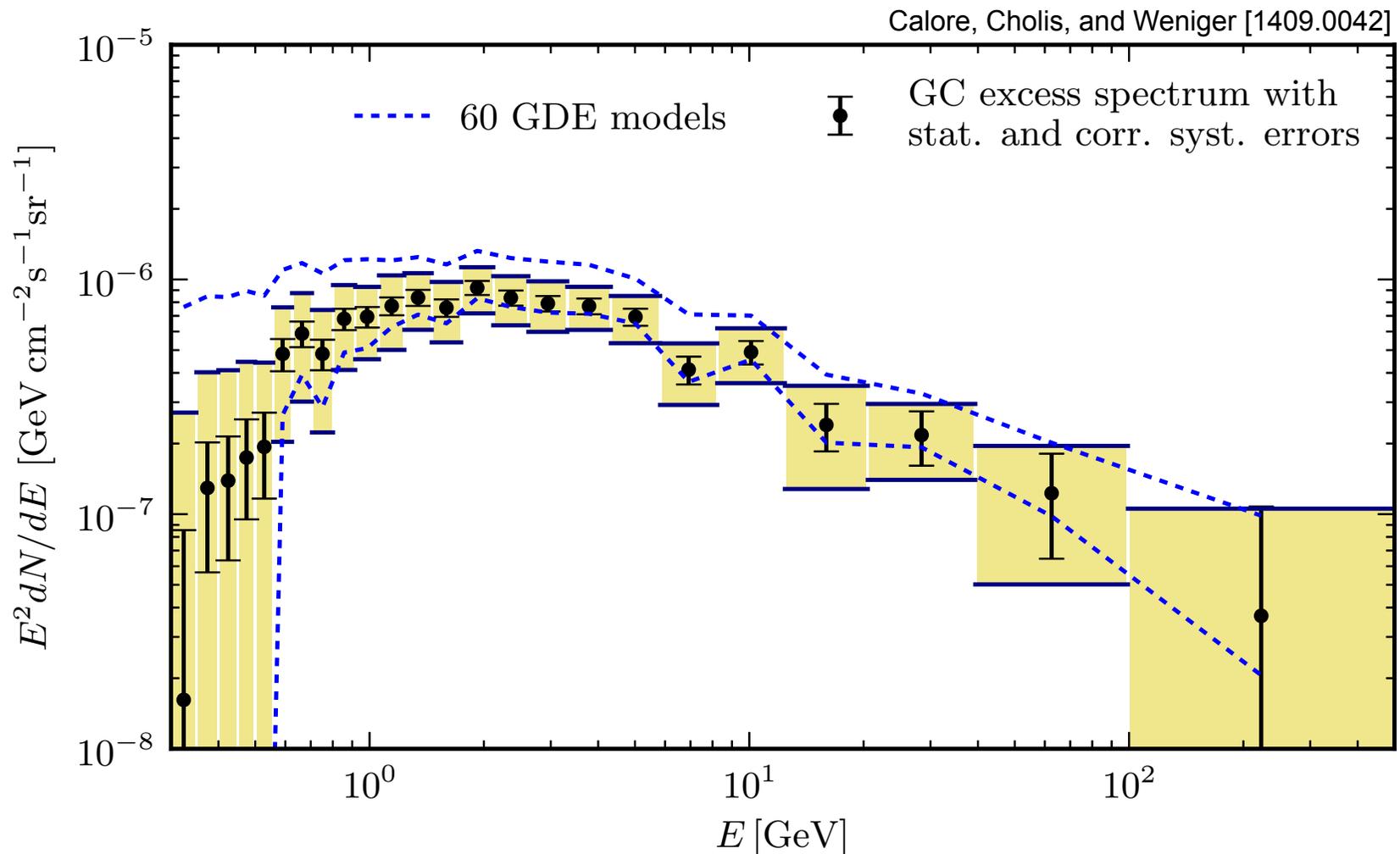
# GeV Photon Excess

Spatial morphology and energy spectrum of excess is consistent with dark matter expectation



# Diffuse Foreground Uncertainty

Evidence for excess emission is robust to variations in the models of Galactic diffuse emission, at least within Galprop framework

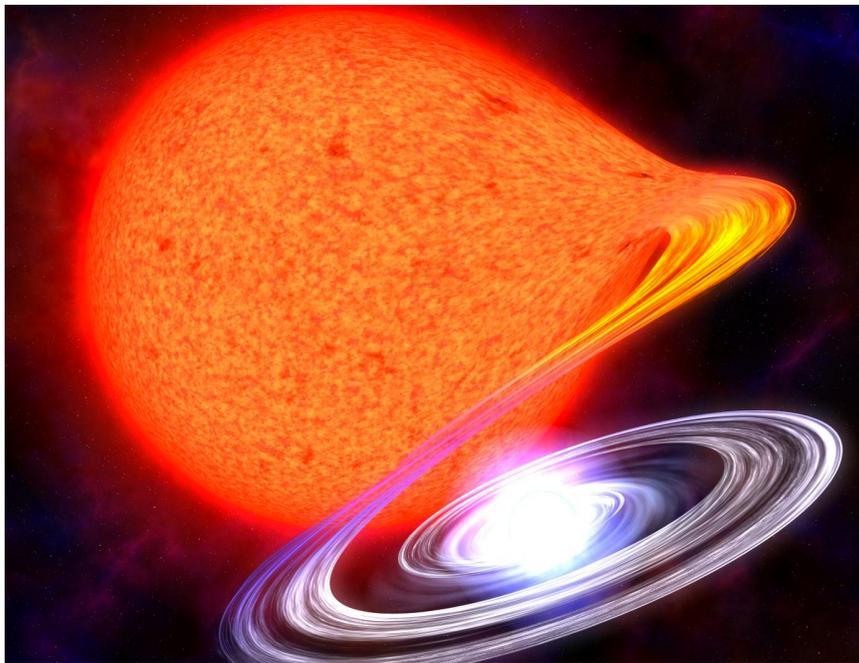


# Unresolved Sources

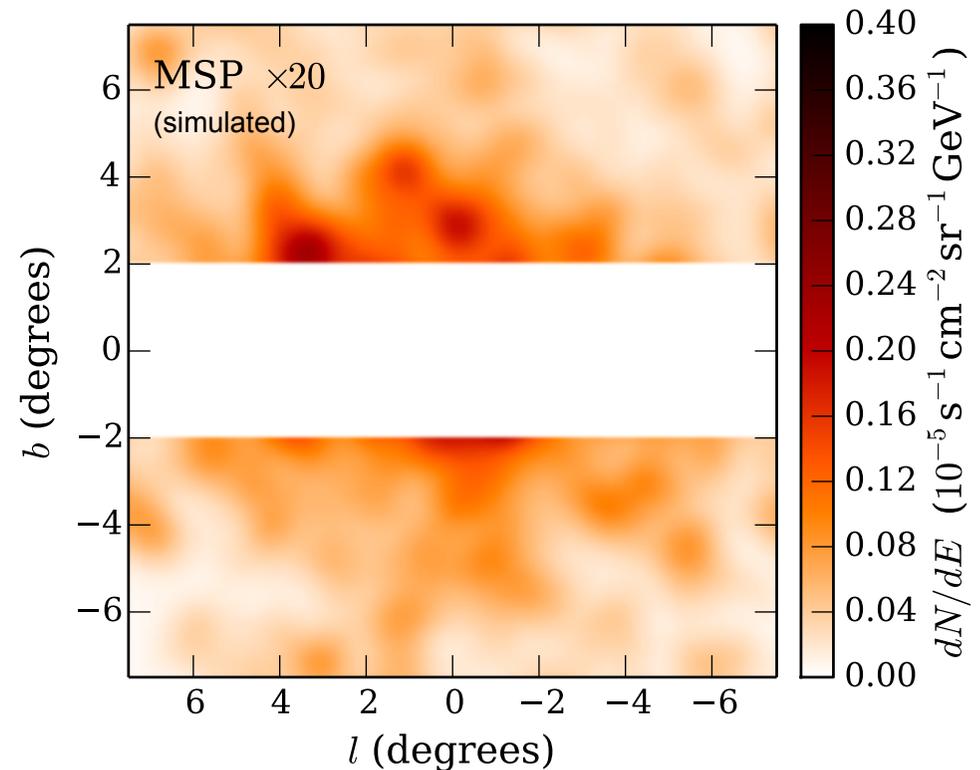
GeV Excess could also be explained by a population of unresolved sources just below *Fermi*'s detection threshold

Rapidly-spinning neutron stars, called millisecond pulsars, are potential candidates

Abazajian [1011.4275]



<https://apatruno.files.wordpress.com/2013/09/binarystarcataclysm.jpg>

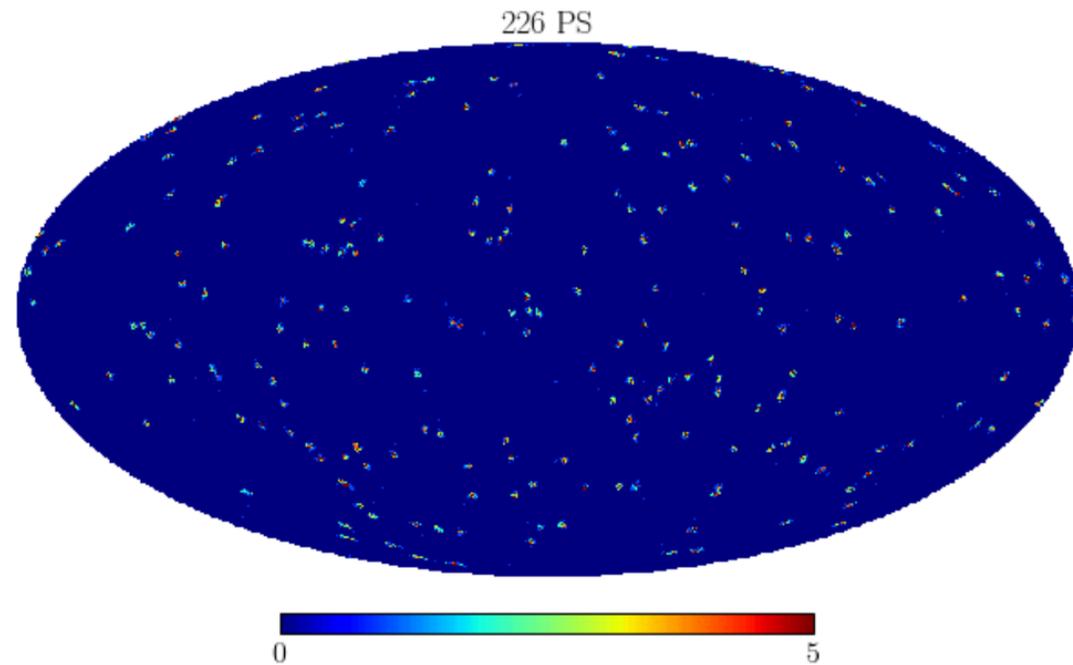
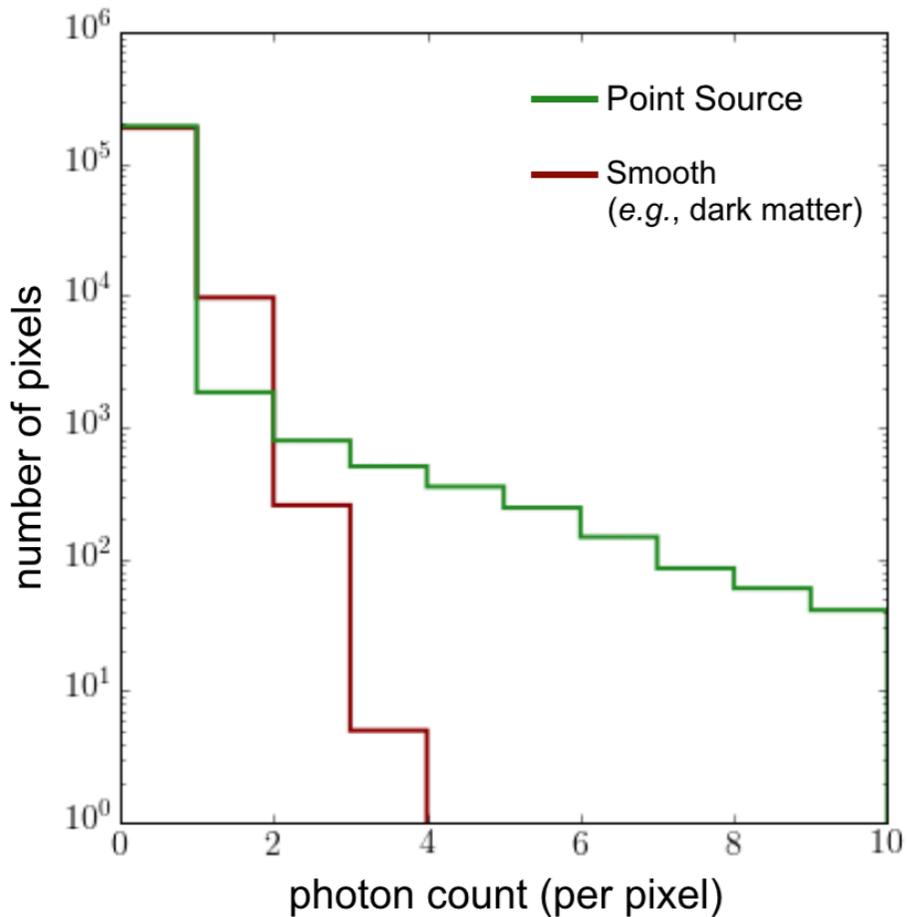


O'Leary *et al.* [1601.05797]

# Photon Statistics

Apply image processing techniques to distinguish dark matter from unresolved astrophysical sources

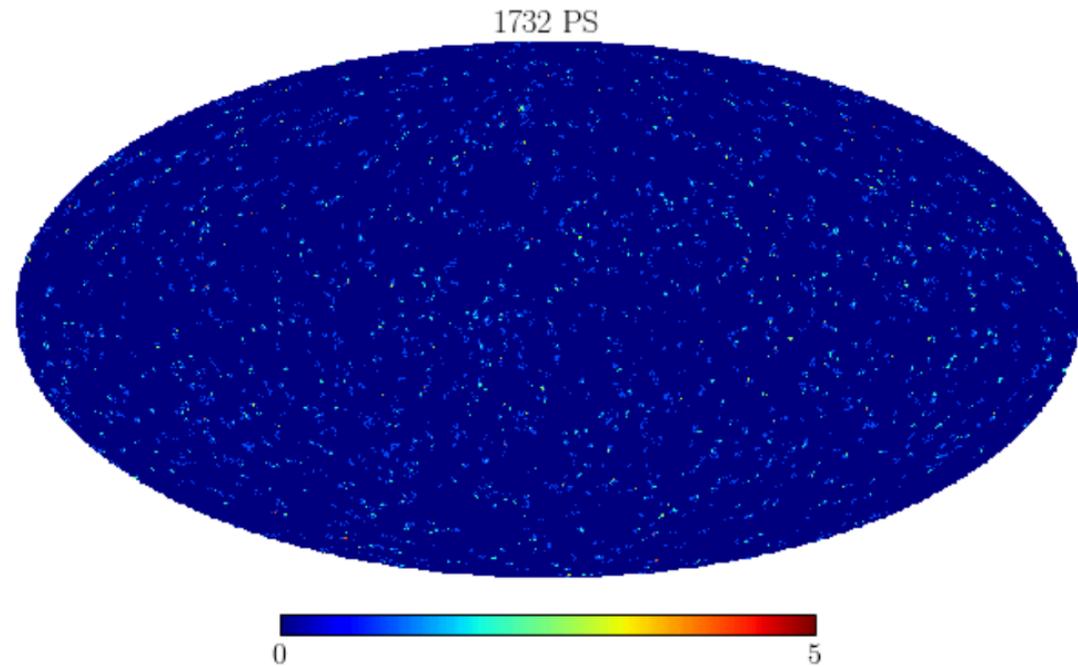
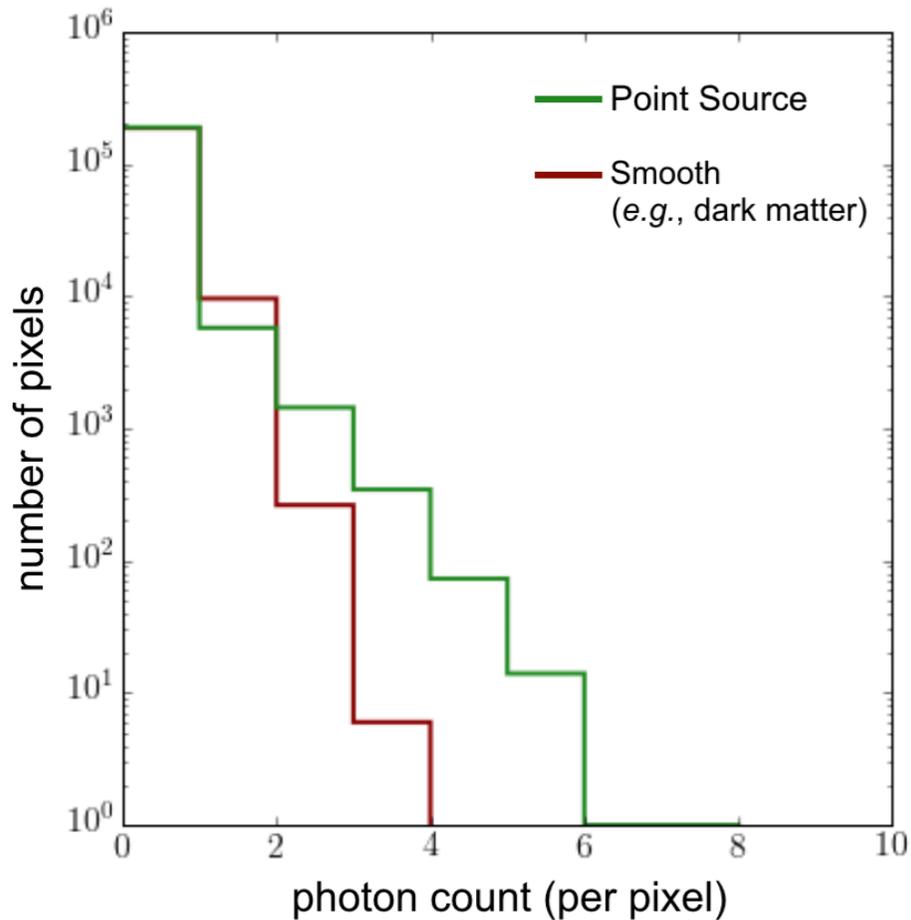
Malyshev and Hogg [1104.0010]; Lee, Lisanti, and Safdi [1412.6099]



# Photon Statistics

Apply image processing techniques to distinguish dark matter from unresolved astrophysical sources

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



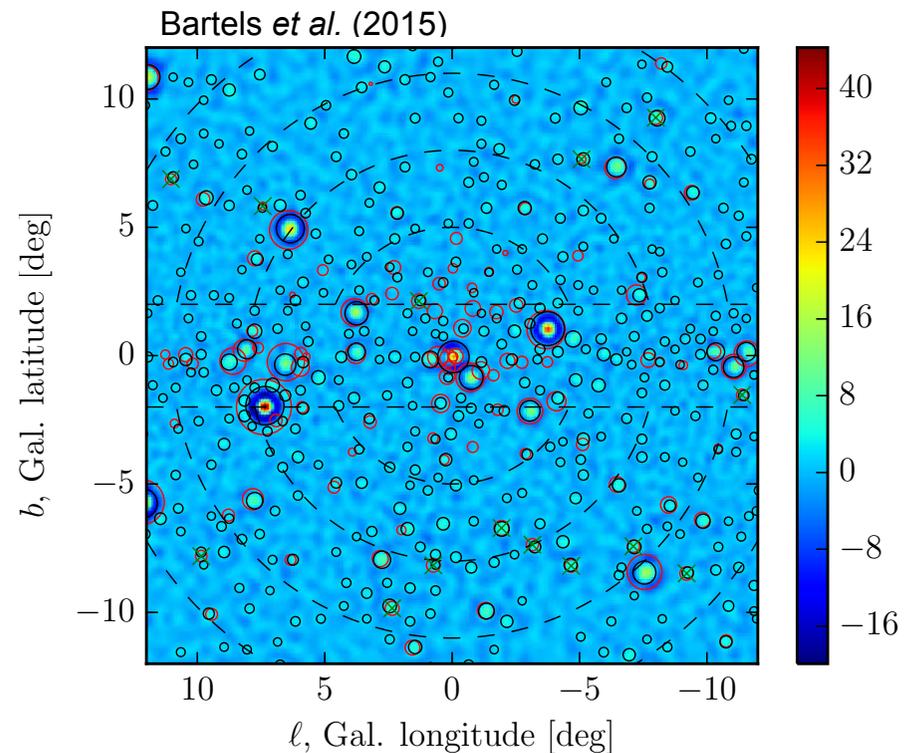
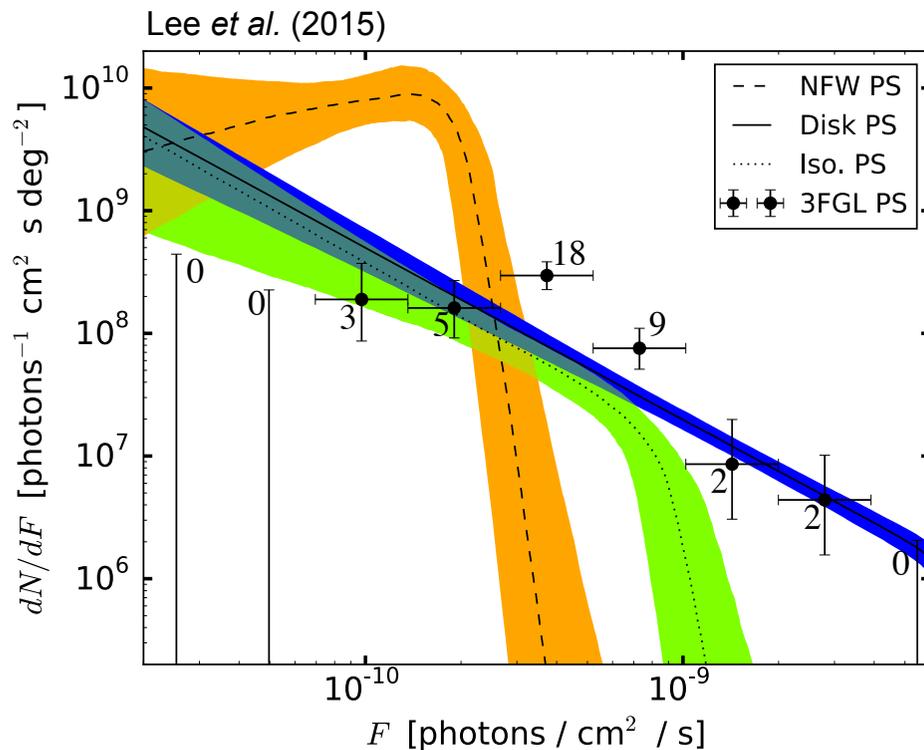
# Inner Galaxy Analysis

Study of photon statistics in the Inner Galaxy provides strong evidence for a population of unresolved astrophysical sources

Lee, Lisanti, Safdi, Slatyer, and Xue [1506.05124]

Complimentary study using wavelet methods found similar results

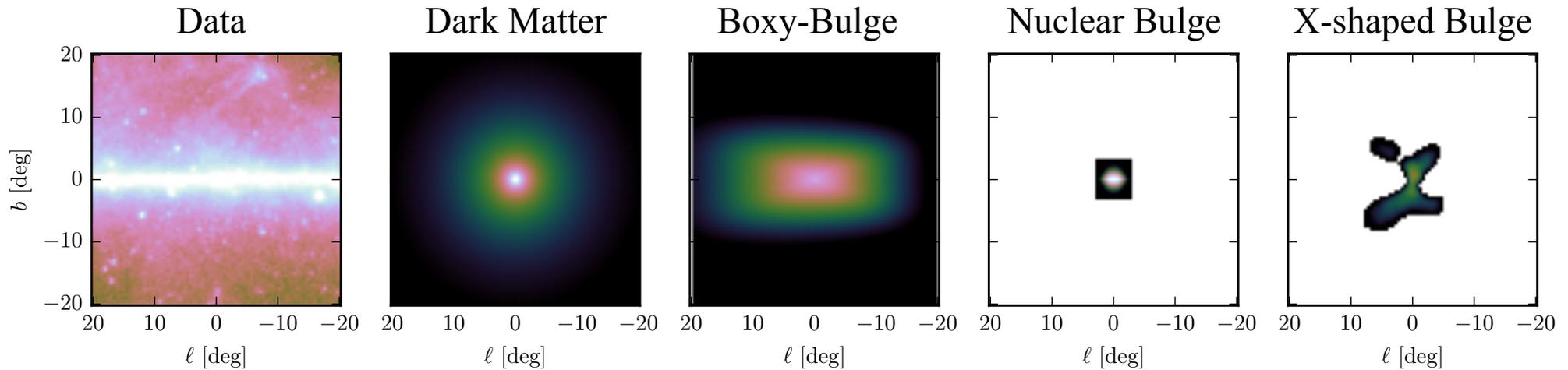
Bartels, Krishnamurthy, and Weniger [1506.05104]



# Stellar Bulge

GeV Excess may better trace the stellar bulge rather than dark matter emission

Macias *et al.* [1507.05616]; Bartels *et al.* [1711.04778]



Bartels *et al.* [1711.04778]

This weakens the argument that the morphology of the excess is consistent with dark matter and strengthens the hypothesis that the excess has a stellar origin

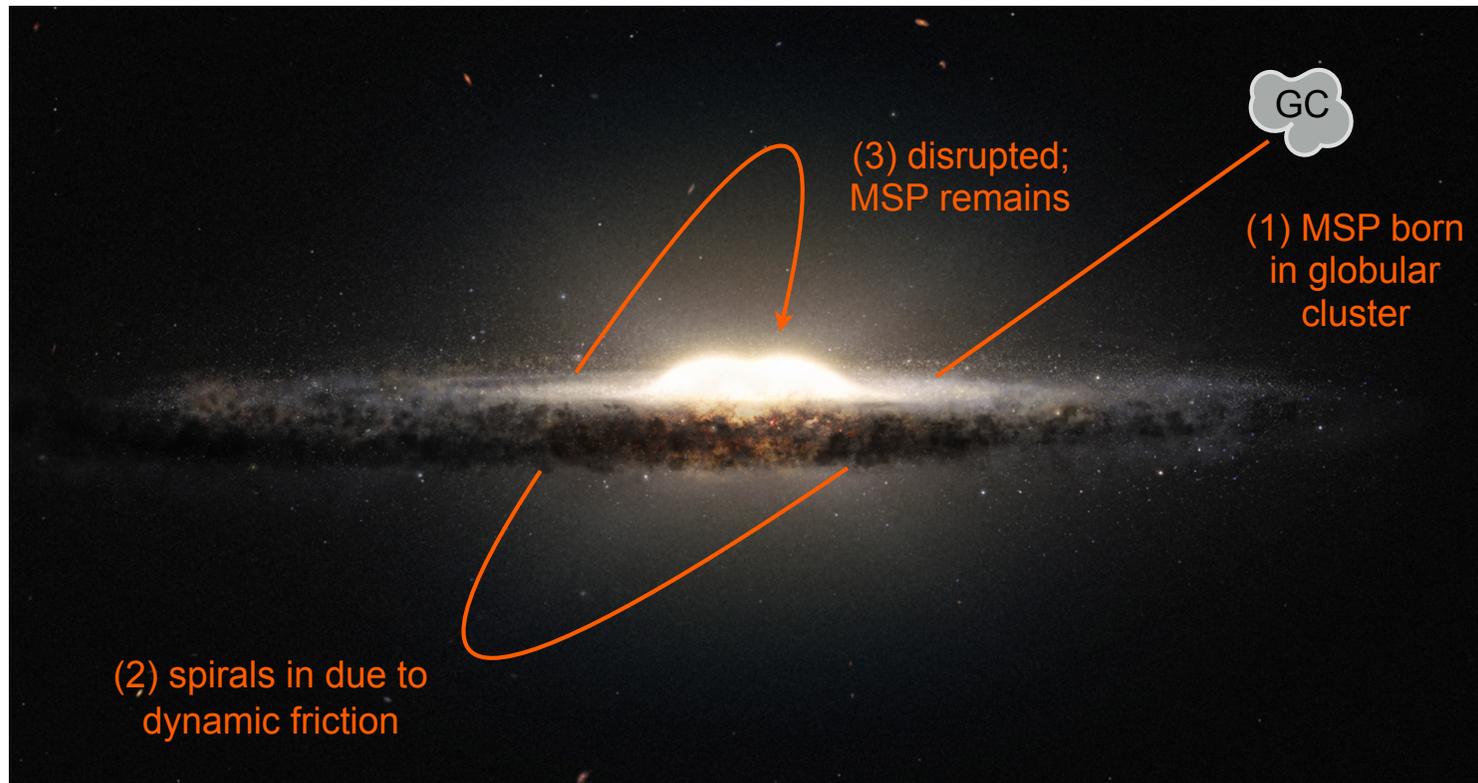
# Millisecond Pulsars

MSPs may have been dumped in Inner Galaxy by disrupted globular clusters

Brandt and Kocsis [1507.05616]; see also Hooper and Linden [1606.09250] for summary of challenges

In the coming few years, targeted and large-area radio surveys will be able to detect individual millisecond pulsars if they exist in the Inner Galaxy

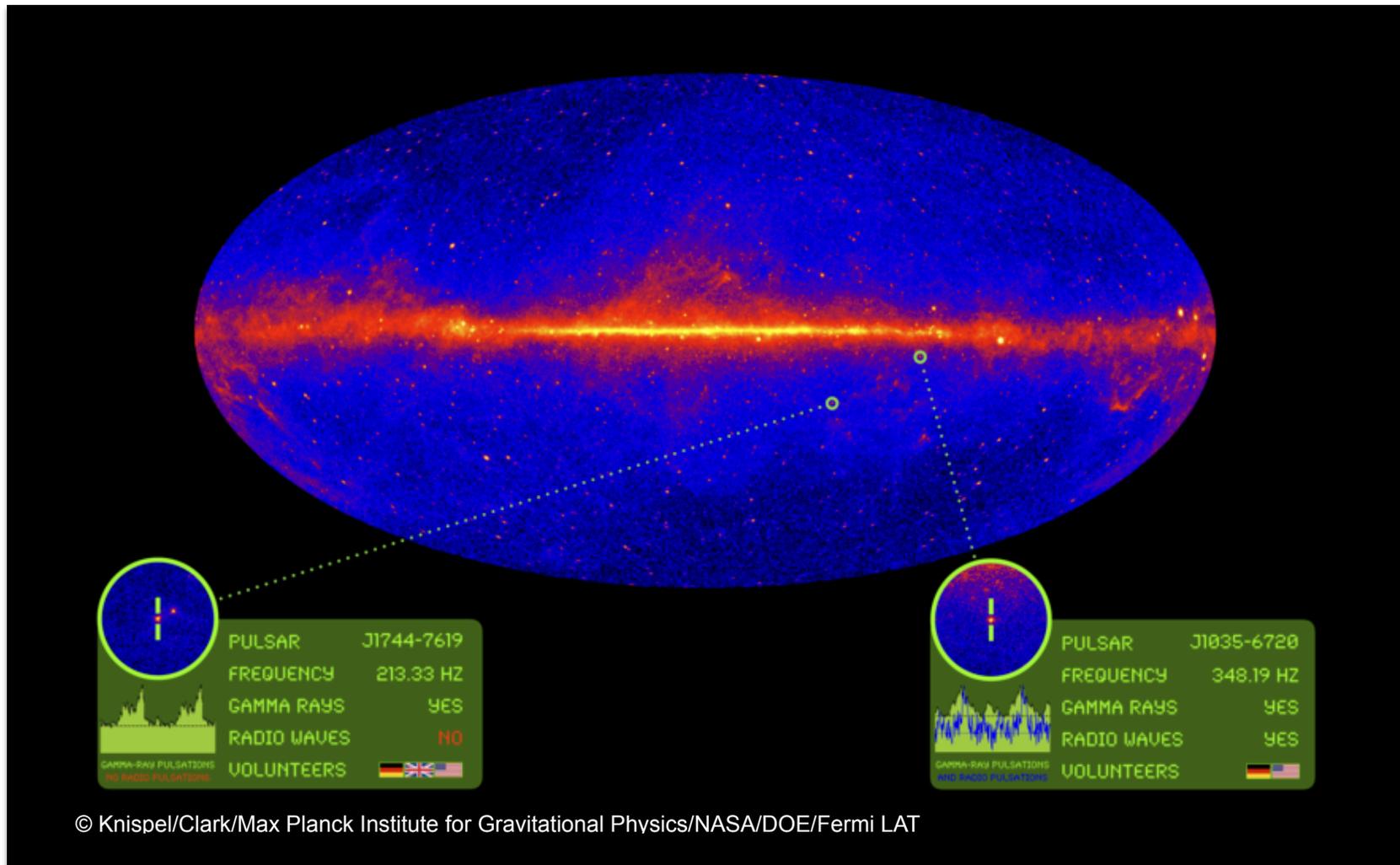
Calore *et al.* [1512.06825]



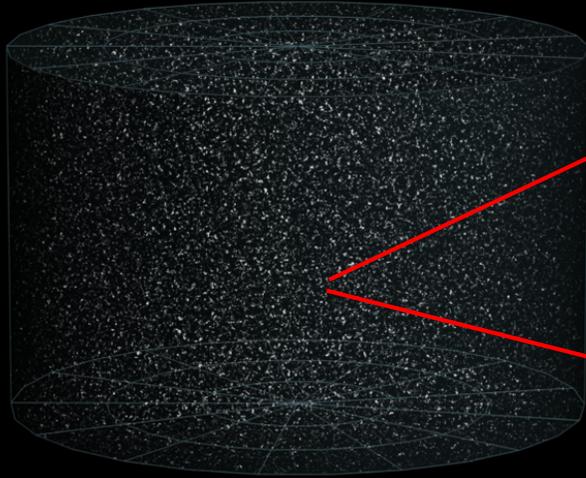
# Einstein@Home MSP

First detection of radio-quiet gamma-ray MSP using Einstein@Home network

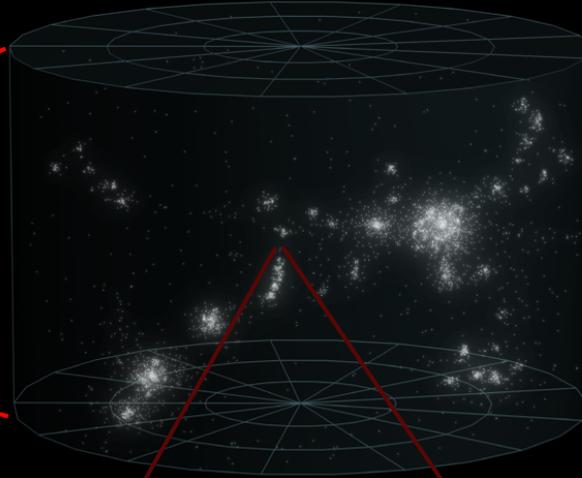
Clark *et al.* [1803.06885]



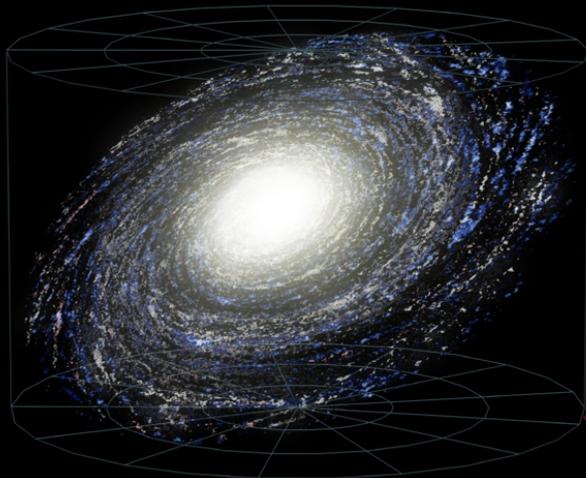
Observable Universe



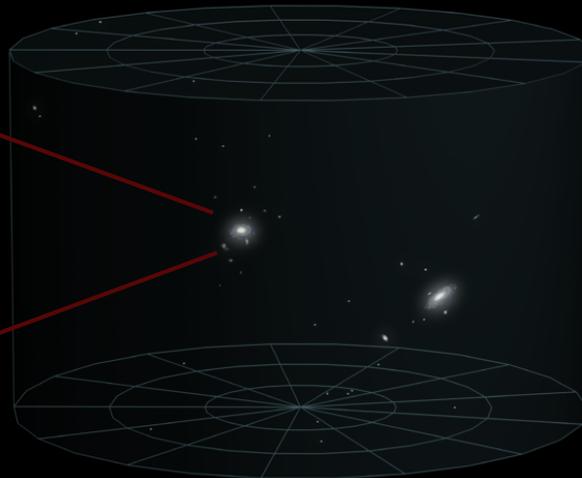
Virgo Supercluster



Milky Way



Local Galactic Group



# Looking Elsewhere

If the GeV Excess is a true dark matter signal, then we should expect to see hints/detections in other astrophysical targets

Dwarf galaxies and galaxy groups are promising options

## Dwarf Galaxies

Relatively 'clean' systems;  
foregrounds better under control

Uncertainties in density  
distribution: core v. cusp

About 50 known to date

## Galaxy Groups

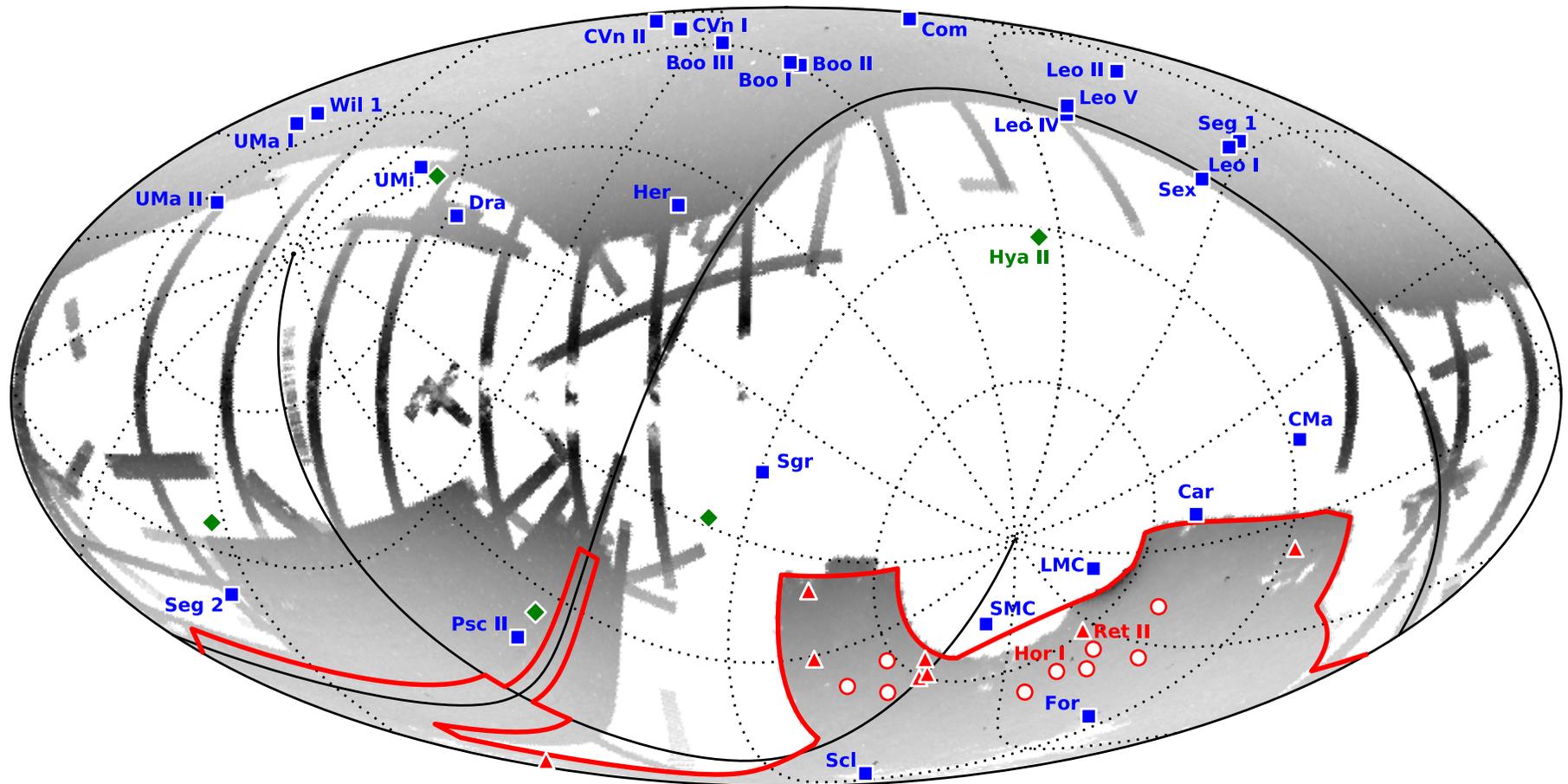
Cosmic-ray emission from known  
astrophysical processes

Dark matter signal can be boosted  
due to substructure—also,  
difficult to model

In the thousands...

# Dwarf Galaxies

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



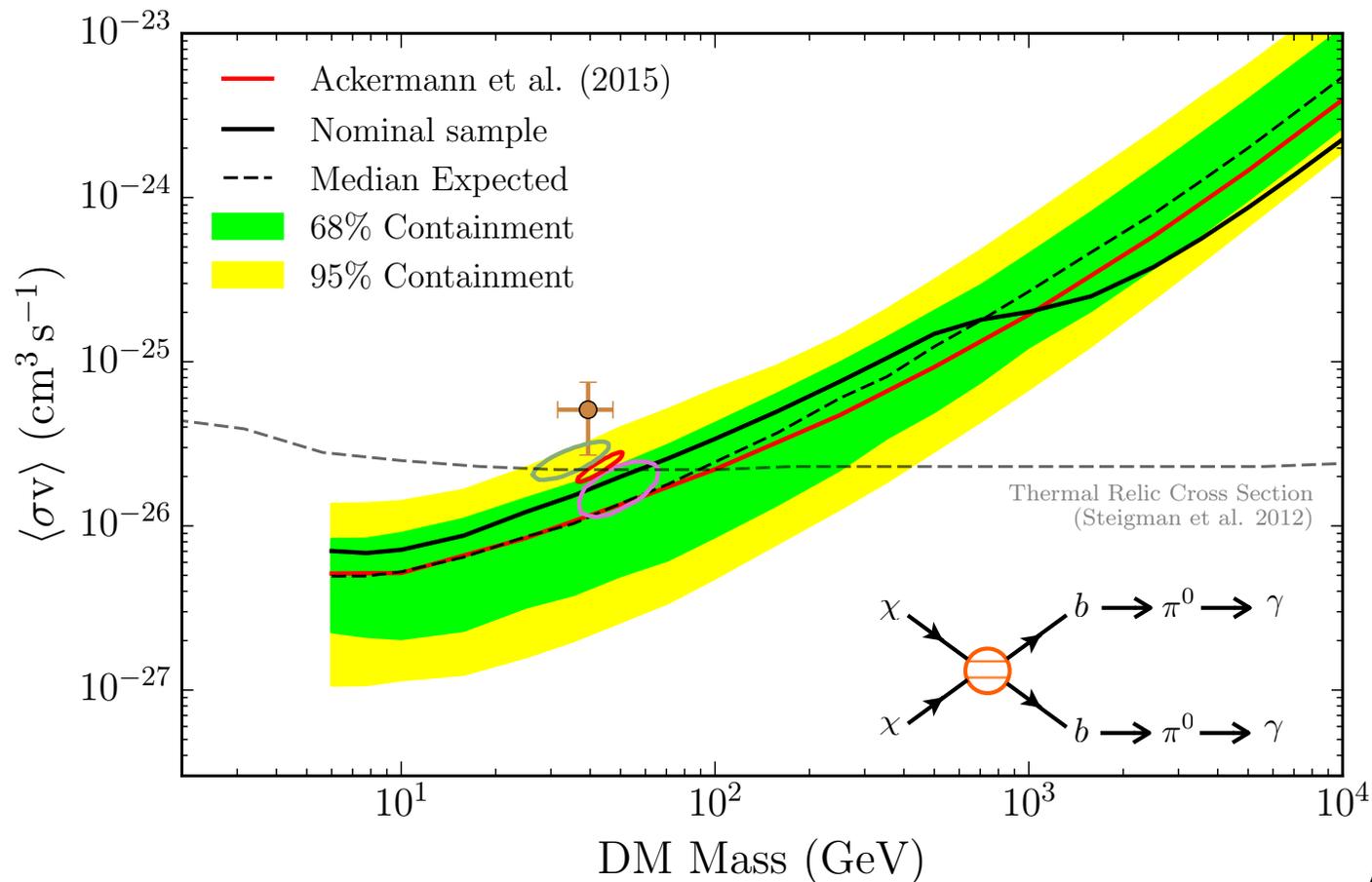
■ Known satellites before 2015

○ ▲ ◆ New Candidates

# Dwarf Galaxies

Six years of data from *Fermi* LAT used to search for gamma-ray emission from 45 dwarf spheroidal candidates

Observations are becoming sensitive to thermal weak-scale dark matter



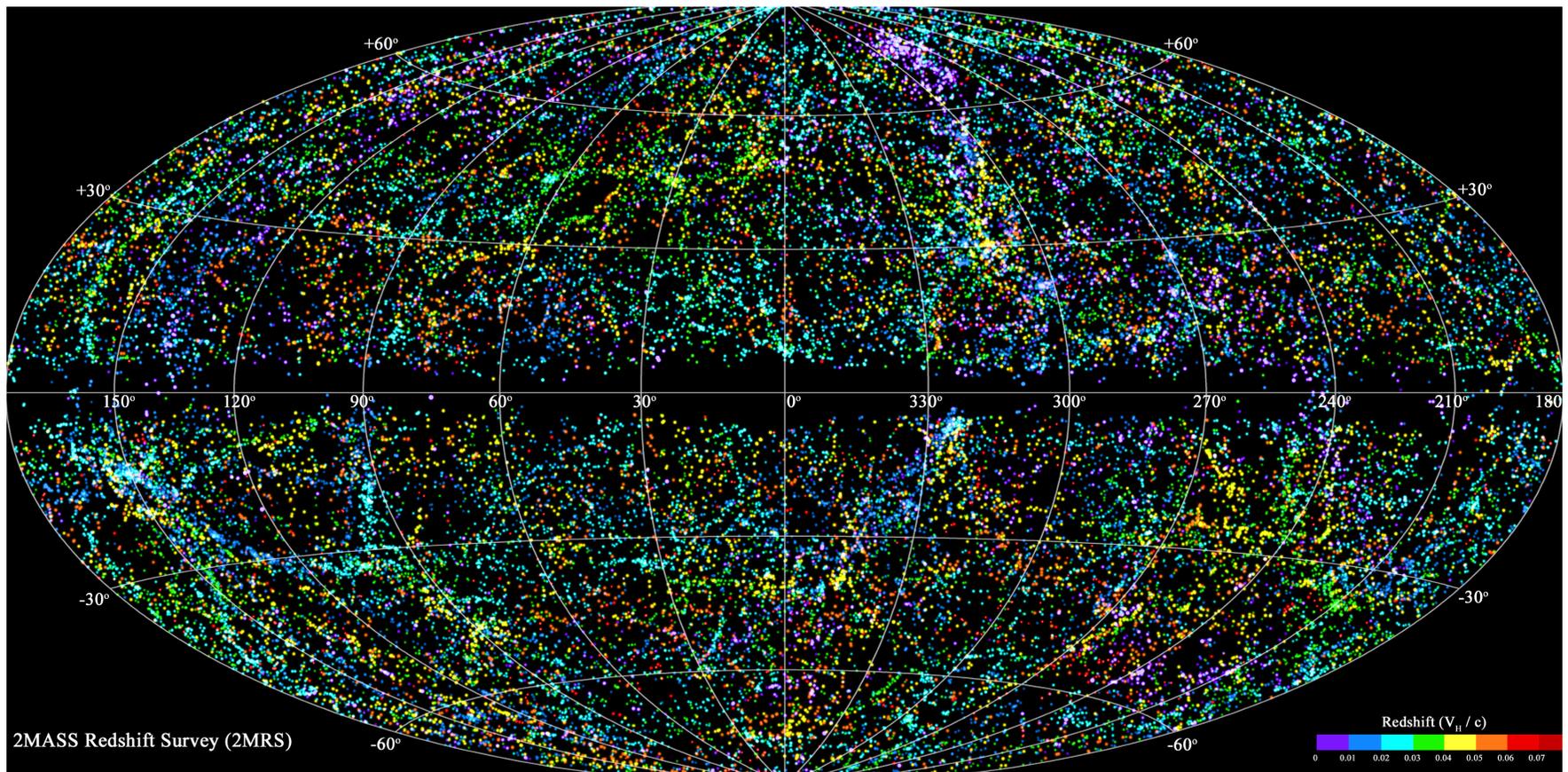
# From a Group Catalog...

2MASS Redshift Survey is a nearly all-sky near-infrared survey that samples 45,000 galaxies up to redshifts of  $z \sim 0.03$

Bilicki et al. [1311.5246]; Huchra et al. [1108.0669]

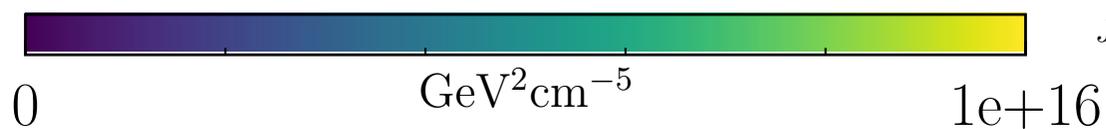
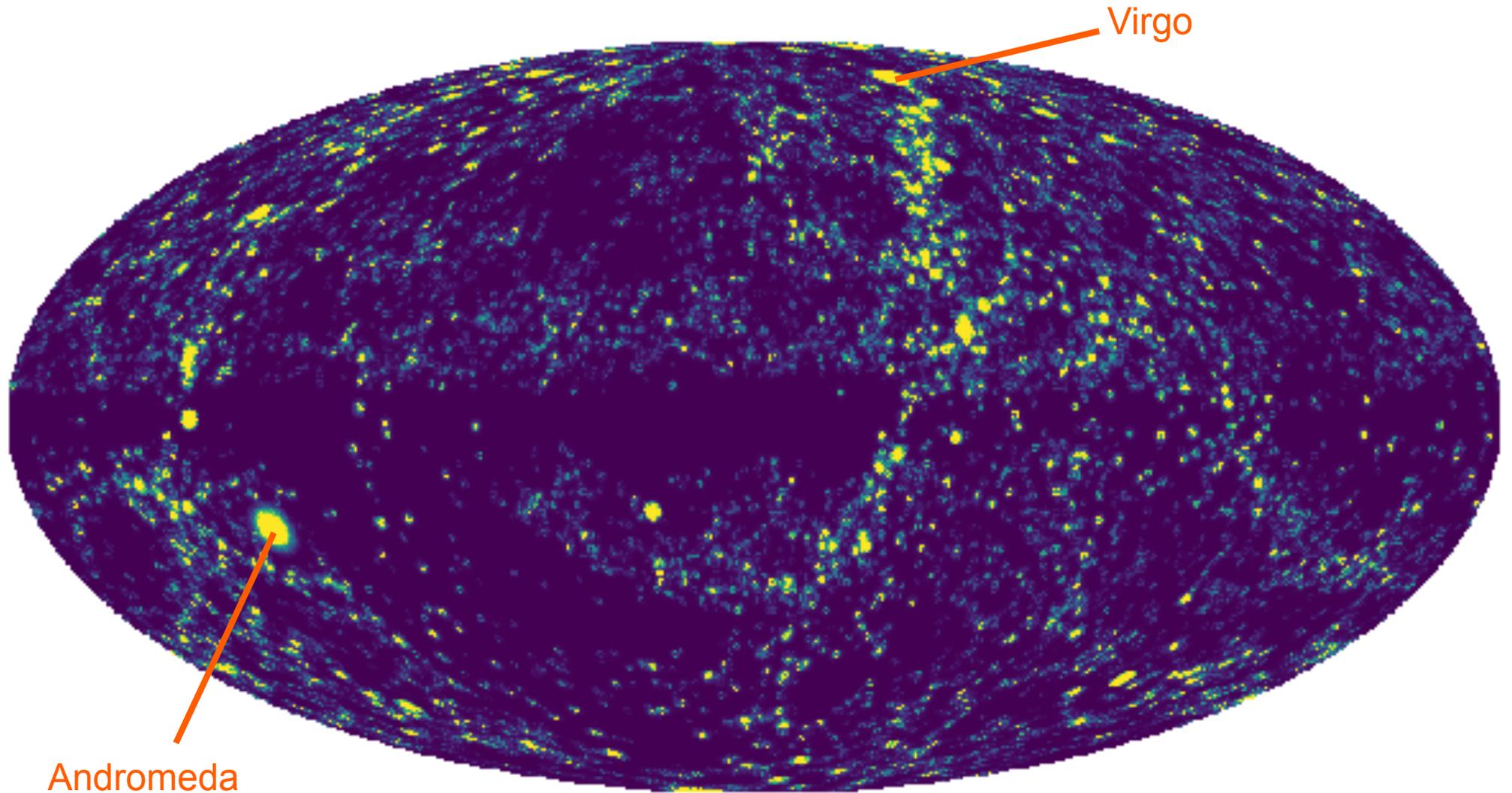
Recent catalogs identify groups of nearby galaxies and their associated halo properties

Tully [1503.03134]; Lu et al. [1607.03982]; Kourkchi and Tully [1705.08068]



# ...to a Dark Matter Sky Map

Lisanti, Mishra-Sharma, Rodd, Safdi, and Wechsler [1709.00416]  
Lisanti, Mishra-Sharma, Rodd, and Safdi [1708.09385]

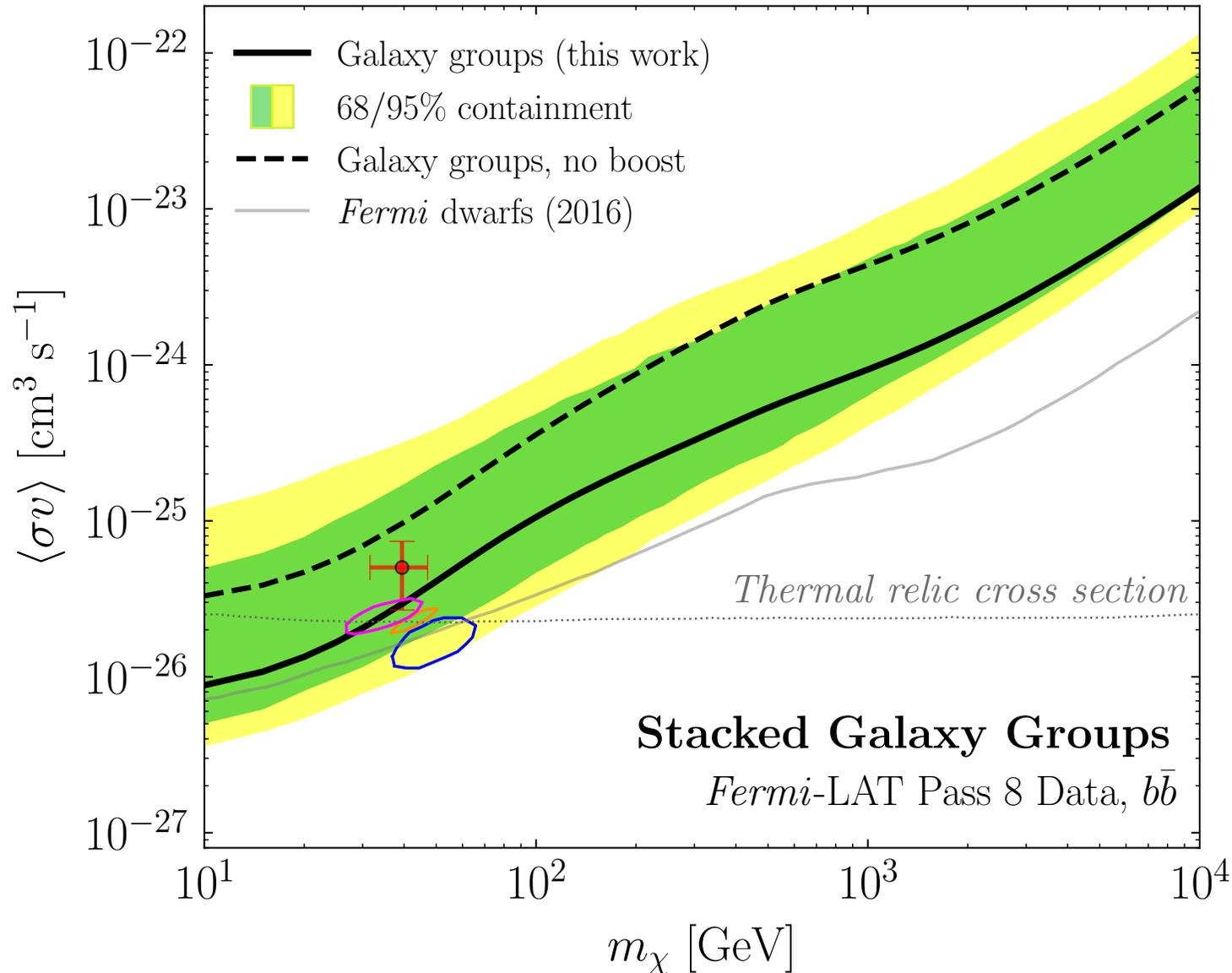


$$J \sim (1 + \text{boost}) \int \rho_{\text{NFW}}^2 dl d\Omega$$

# Galaxy Group Limit

Lisanti, Mishra-Sharma, Rodd, Safdi, and Wechsler [1709.00416]

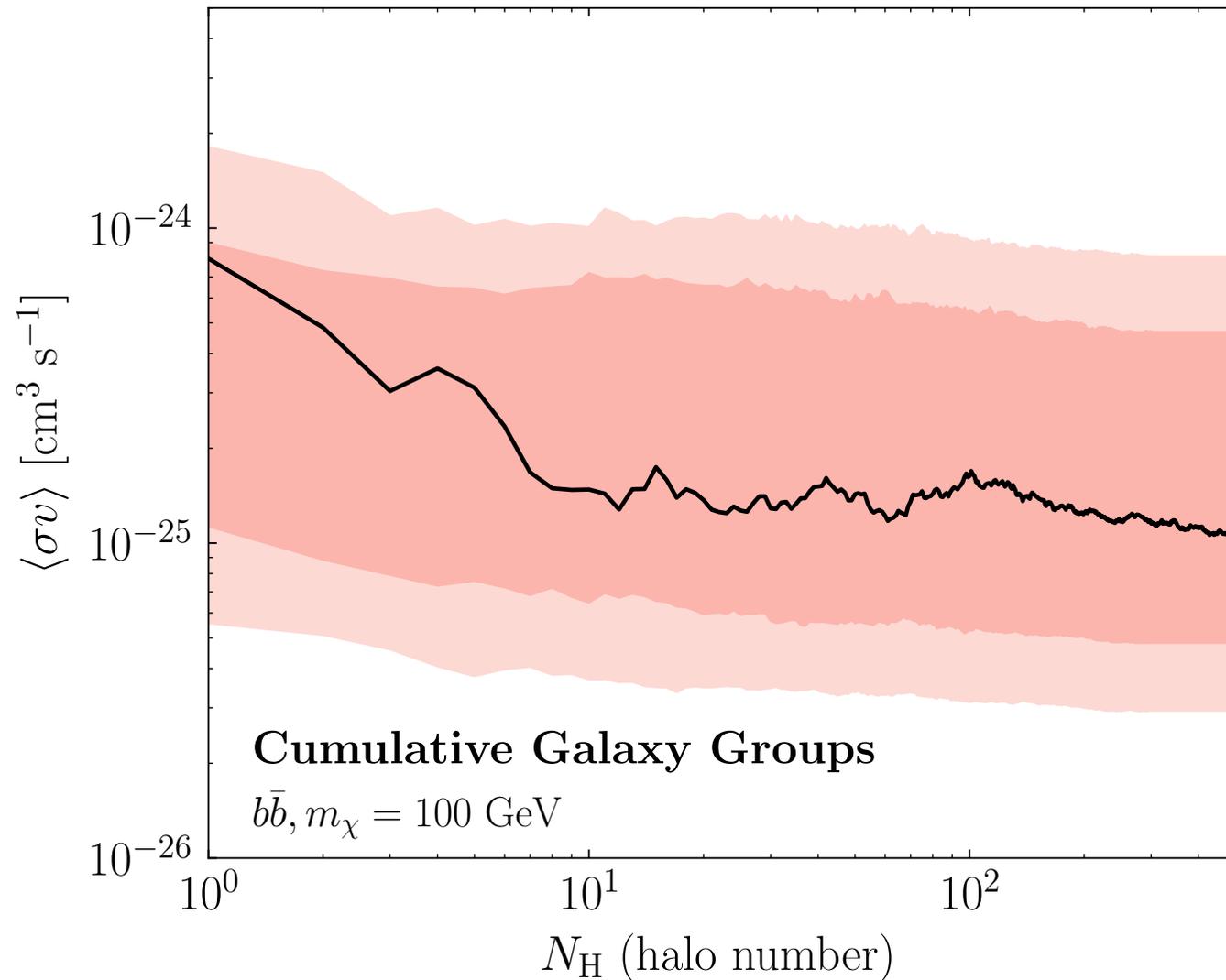
Lisanti, Mishra-Sharma, Rodd, and Safdi [1708.09385]



# Effect of Stacking

Order of magnitude gain in the limit achieved by stacking the galaxy groups

The brightest galaxy cluster does not dominate the bounds



# Returning to the Milky Way...

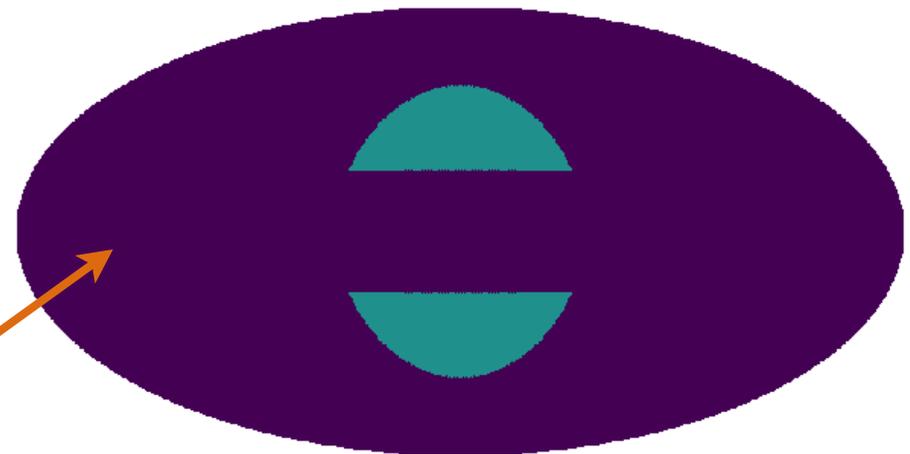
What if we look for dark matter annihilation in the Milky Way halo, but away from the Galactic Center?

A comparison of the J-factors shows that the signal can still be brighter than that expected for dwarfs or galaxy groups

## J-factor Comparison

$$J = \int ds d\Omega \rho^2(s, \Omega)$$

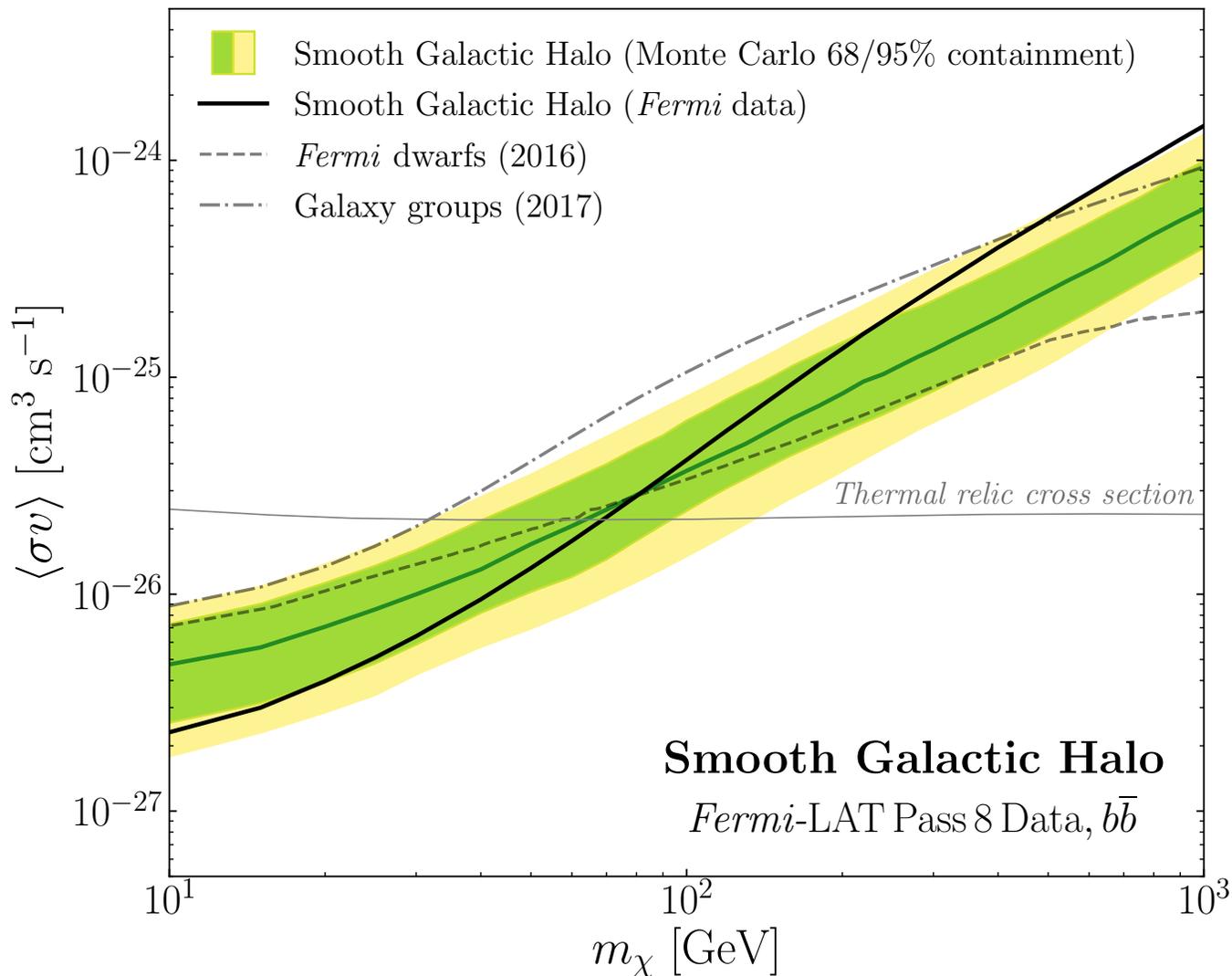
Dwarf Galaxy	$\sim 10^{19} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}$
Brightest Groups	$\sim 10^{19} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}$
Milky Way (20°x20°)	$\sim 10^{23} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}$
Milky Way (ROI)	$\sim 10^{22} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}$



# Smooth Milky Way Halo

Chang, Lisanti, and Mishra-Sharma [1804.xxxxx]

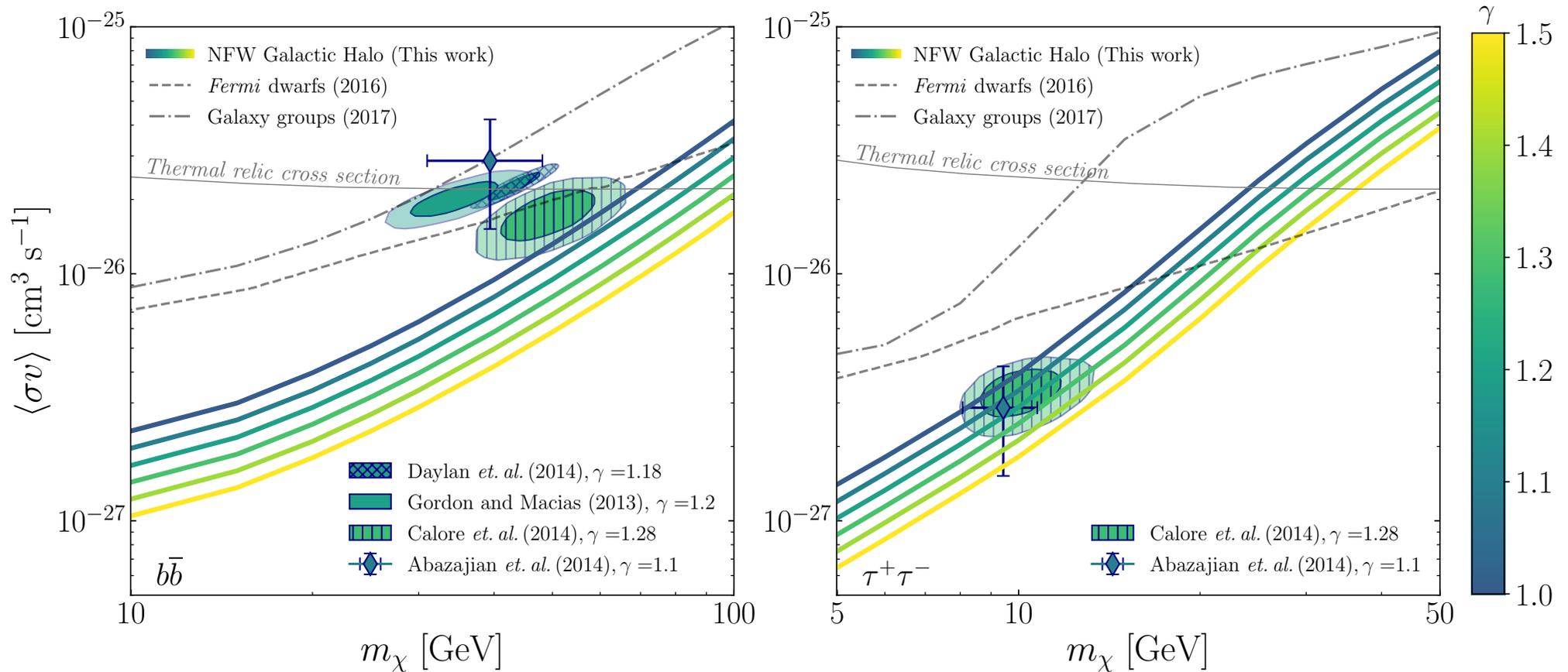
The strongest limits on annihilating dark matter below masses of  $\sim 70$  GeV



# Implications for GeV Excess

Chang, Lisanti, and Mishra-Sharma [1804.xxxxx]

We exclude the b-channel interpretation of the GeV Excess  
and constrain the tau-channel for the first time



# Conclusions

Abundance of evidence for an excess of GeV gamma-rays in the Galactic Center

Photon statistics and spatial morphology strongly suggest a stellar origin  
as opposed to emission from dark matter annihilation

Dark matter interpretation remains in tension with limits from dwarfs and groups

New search for annihilation in the Milky Way halo at high latitudes  
excludes the b-channel interpretation of the Excess, and puts the tau-channel  
interpretation in tension

Back Up Slides

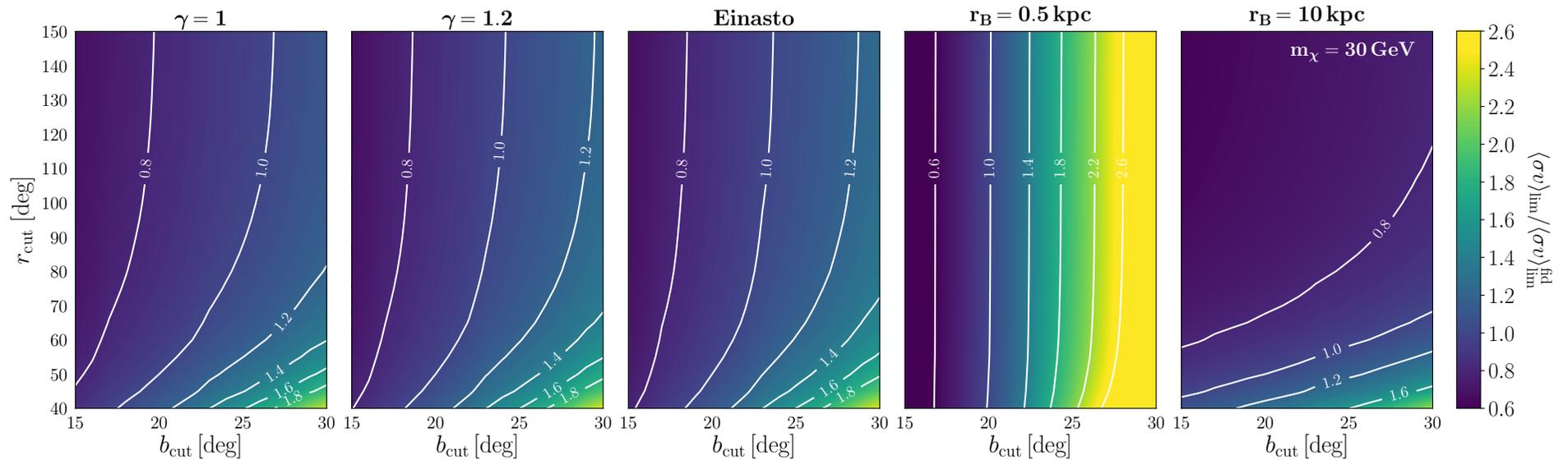


FIG. S1. Sensitivity projections for a 30 GeV dark matter particle annihilating to  $b\bar{b}$  for different regions of interest, which are defined by latitude ( $|b| > b_{\text{cut}}$ ) and radial ( $r < r_{\text{cut}}$ ) cuts. The projected limit,  $\langle\sigma v\rangle_{\text{lim}}$ , is compared to the limit for the fiducial region,  $\langle\sigma v\rangle_{\text{fid}}$ , which corresponds to  $|b| > 20^\circ$  and  $r < 50^\circ$ . The contours indicate the ratio of these two cross sections. The projections are provided for different dark matter density profiles: (left to right) generalized NFW with inner-slope  $\gamma = 1, 1.2$ , Einasto, and Burkert with  $\sim 0.5$  and  $10$  kpc core.

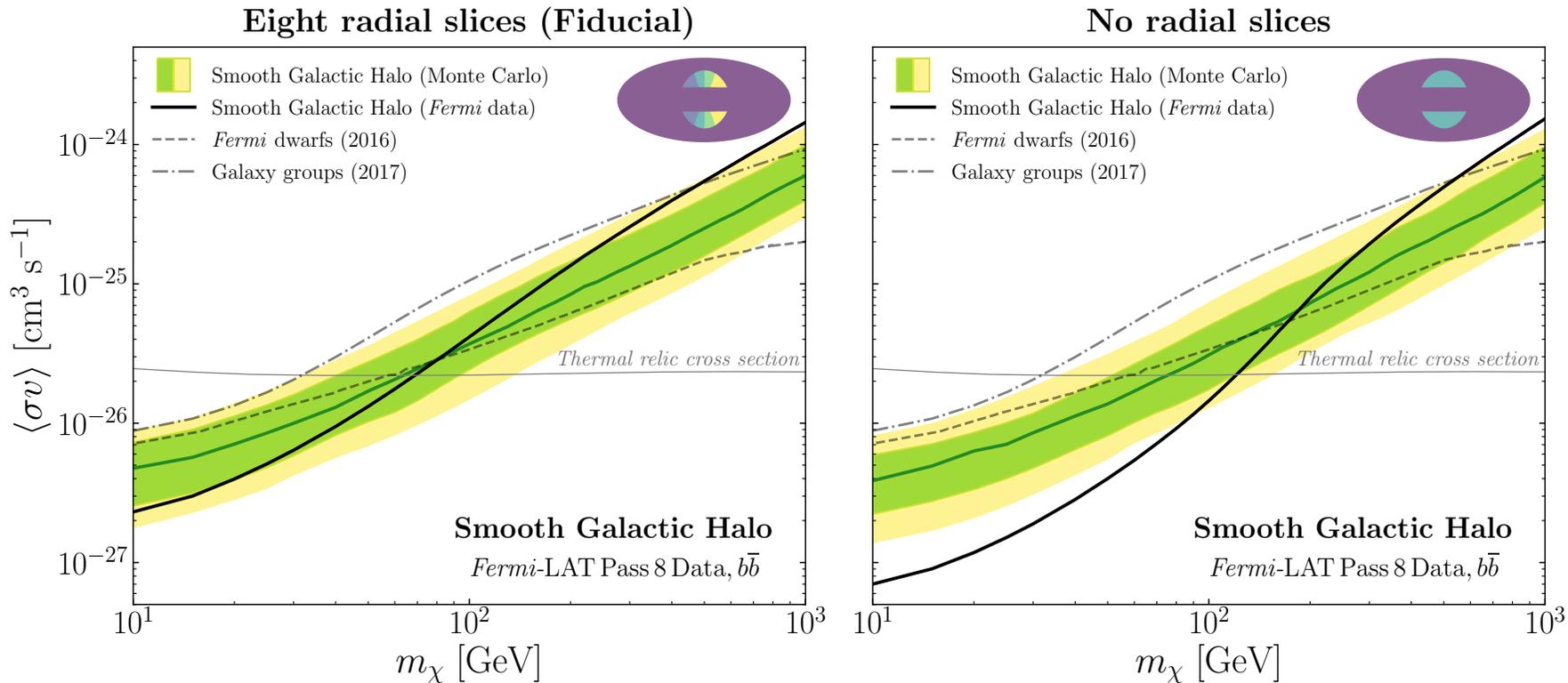


FIG. S2. (Left) Reproduction of Fig. 1 of the *Letter*, included here for convenience. (Right) The corresponding limits when the p6v11 template is not divided into eight radial slices whose normalizations float independently in the fitting procedure. For each panel, the inset depicts the regions over which the p6v11 template is allowed to float.

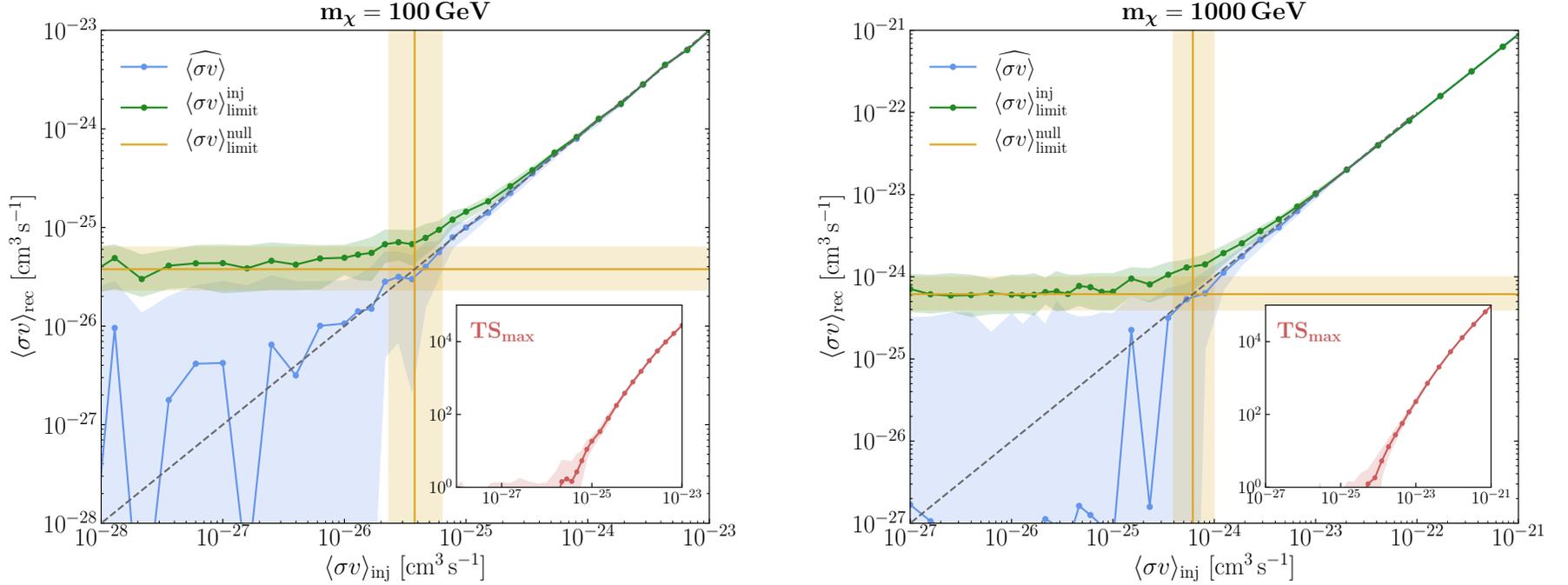


FIG. S3. Signal injection tests on Monte Carlo simulations for a 100 (left) and 1000 (right) GeV DM particle annihilating to  $b\bar{b}$ . In each panel, the gold line corresponds to the limit  $\langle\sigma v\rangle_{\text{limit}}^{\text{null}}$  obtained when no signal is injected into the simulated data. The green line corresponds to the cross section,  $\langle\sigma v\rangle_{\text{limit}}^{\text{inj}}$ , that is recovered for a given injected cross section  $\langle\sigma v\rangle_{\text{inj}}$ , when  $TS = -2.71$ . The blue line corresponds to the recovered cross section  $\widehat{\langle\sigma v\rangle}$  that is associated with the maximum test statistic,  $TS_{\text{max}}$  (plotted in the inset). Each line represents the median value over 50 simulated maps, and each band corresponds to 68% containment.

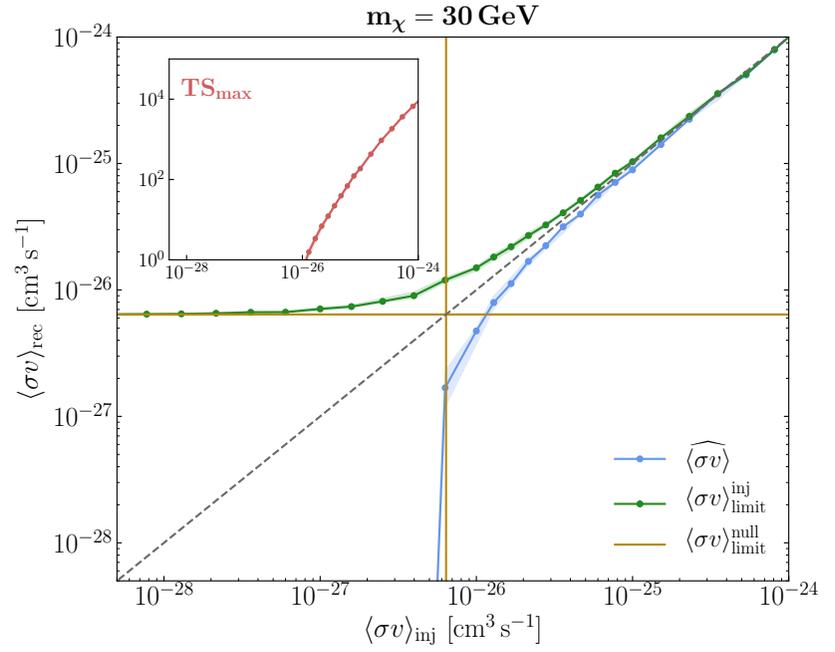
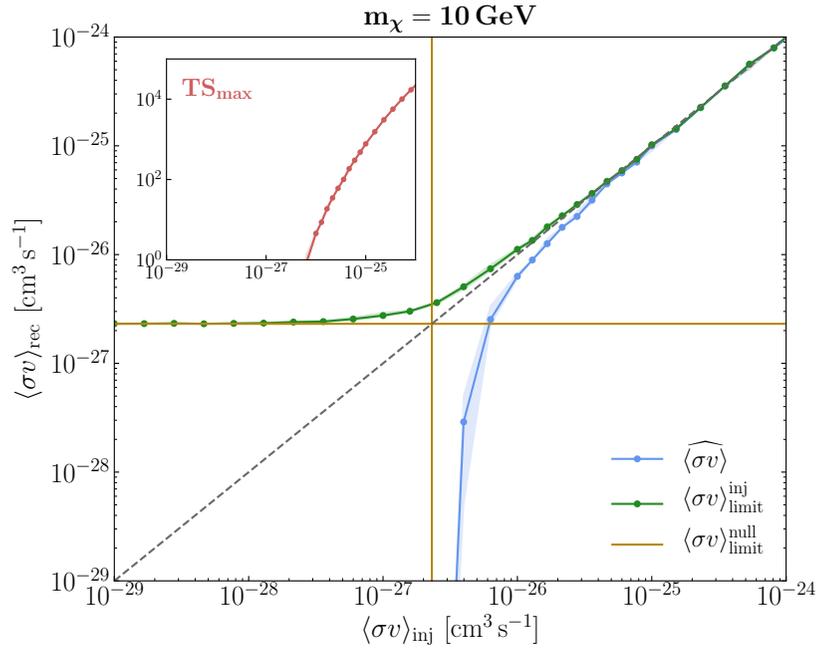


FIG. S4. The same as Fig. S3, except for signal injected on data. The left(right) panel corresponds to a 10(30) GeV DM mass. Each line represents the median value over 10 simulated maps, and each band corresponds to 68% containment.

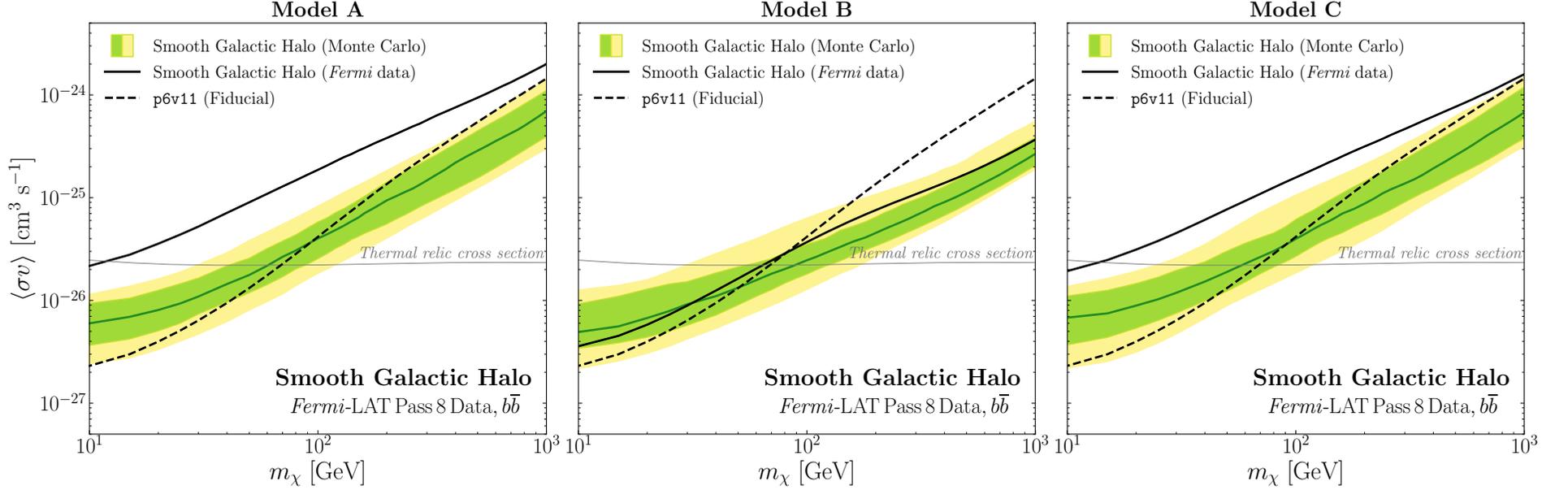


FIG. S5. Similar to Fig. 1 of the *Letter*, except using the Model A, B, and C foreground models (left, middle, and right panel, respectively) as provided by the *Fermi*-LAT Collaboration [8]. Note that the foreground templates are still divided into eight radial slices, as in the fiducial study, but the normalizations of the inverse-Compton and  $\pi^0$ +Brehmstrahlung templates are allowed to float independently. The fiducial limit obtained using the p6v11 foreground model is shown by the dashed black line for comparison. The excesses in the Model A and C studies are well-understood in terms of the source populations included in these models; see text for further discussion.

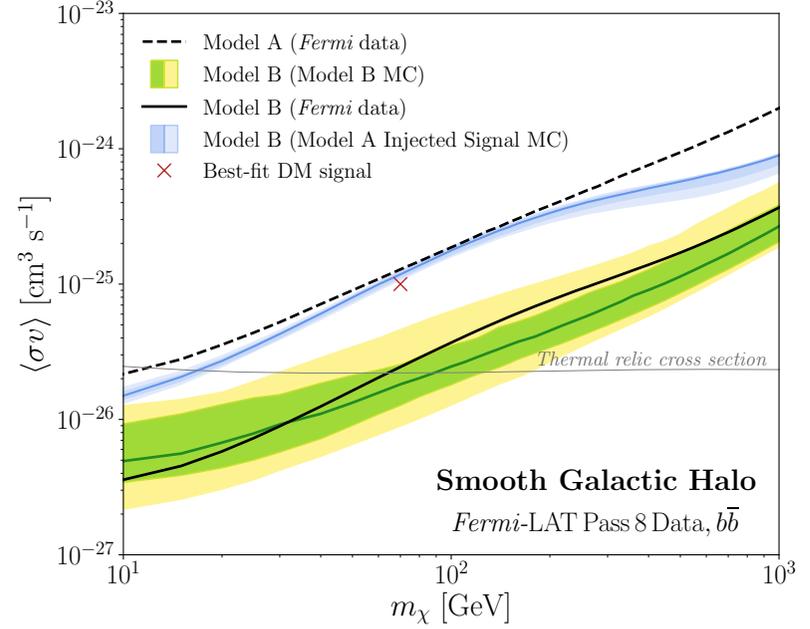
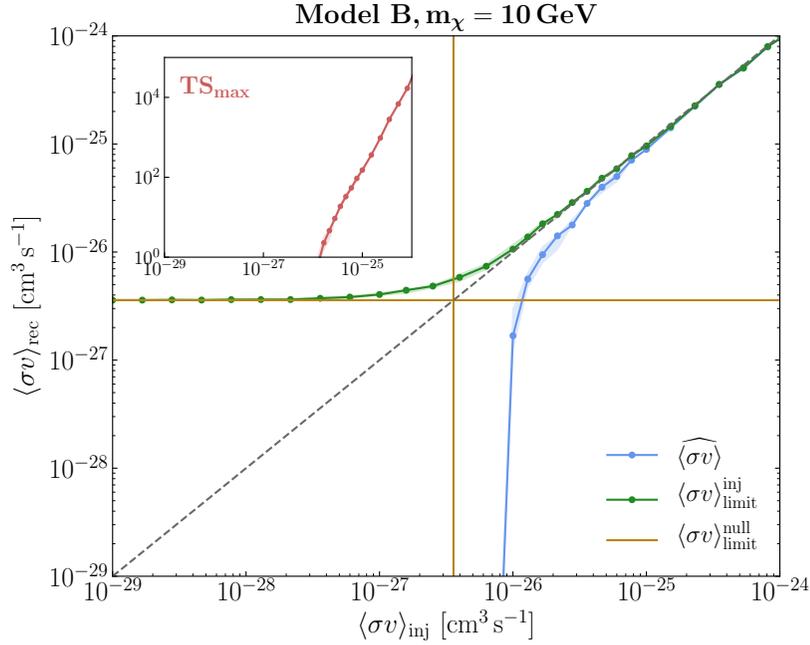


FIG. S6. (Left) Signal injection test on data using the Model B foreground template, assuming  $m_{\chi} = 10$  GeV. Format as in Fig. S4. (Right) Results obtained by creating 10 simulated sky maps using the best-fit Model A template normalizations and injecting the best-fit DM signal (indicated by the red cross) consistent with the excess observed in the Model A limit (dashed black line). The dark(light) blue bands show the resulting 68(95)% containment for the limits obtained when analyzing the simulated sky maps using the Model B templates. The excess observed in the Model A study would be picked up as a signal with  $TS \sim 9$ ; given the similarities between Models A and C, we expect the same to be true for the Model C excess. The origin of the additional gamma-ray flux picked up in the Model A and C studies is therefore most likely related to the modeling of the IC component, as discussed in the text. Note that we include the original Model B limit (solid black line) and Monte Carlo expectation (green/yellow bands) for comparison.

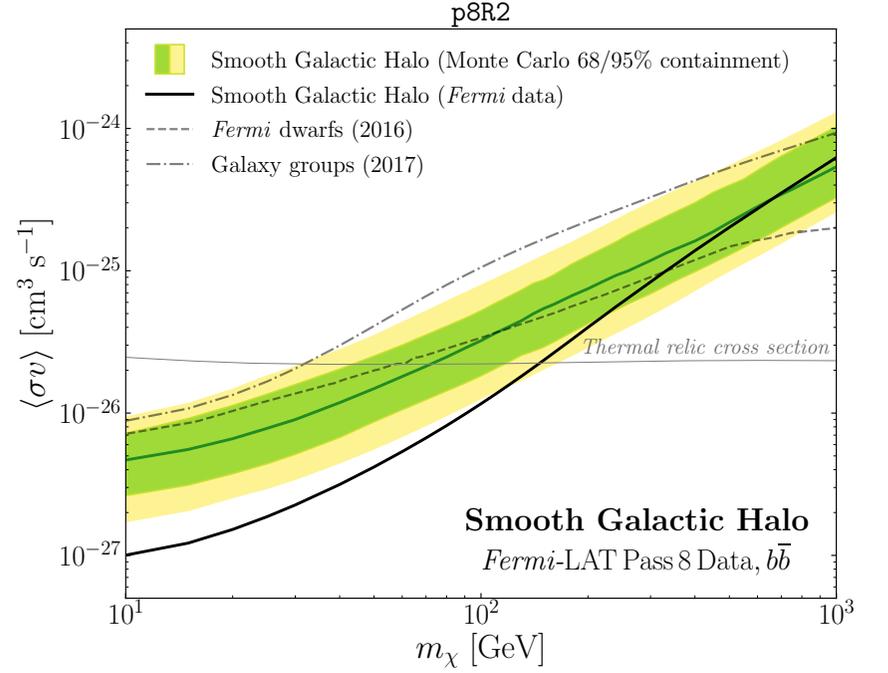
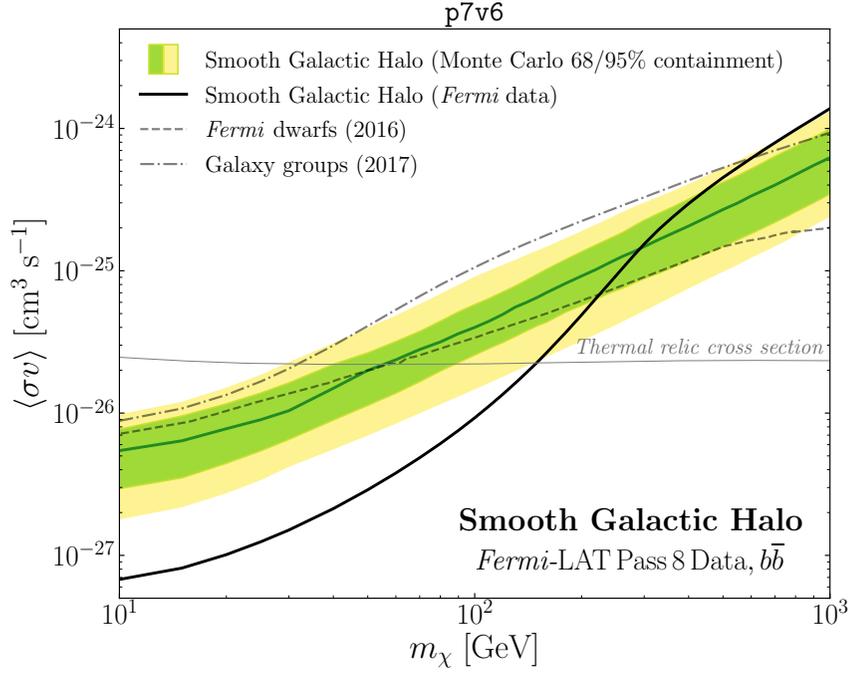


FIG. S7. Similar to Fig. 1 of the *Letter*, except using the p7v6 and p8R2 foreground models (left and right panel, respectively) [51]. We only include these results for illustration as both of these foreground models are not appropriate for studies of diffuse DM signals, as discussed in the text.

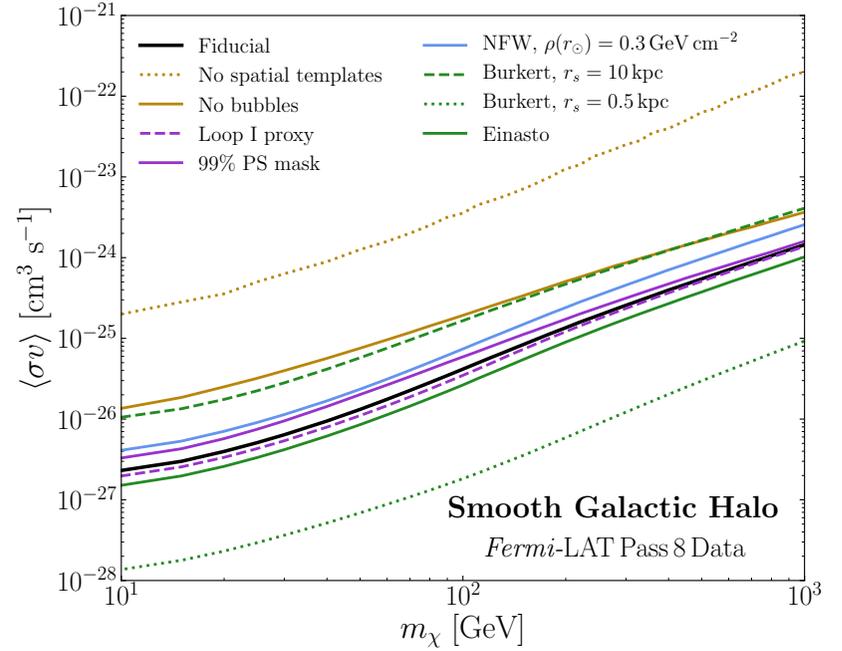
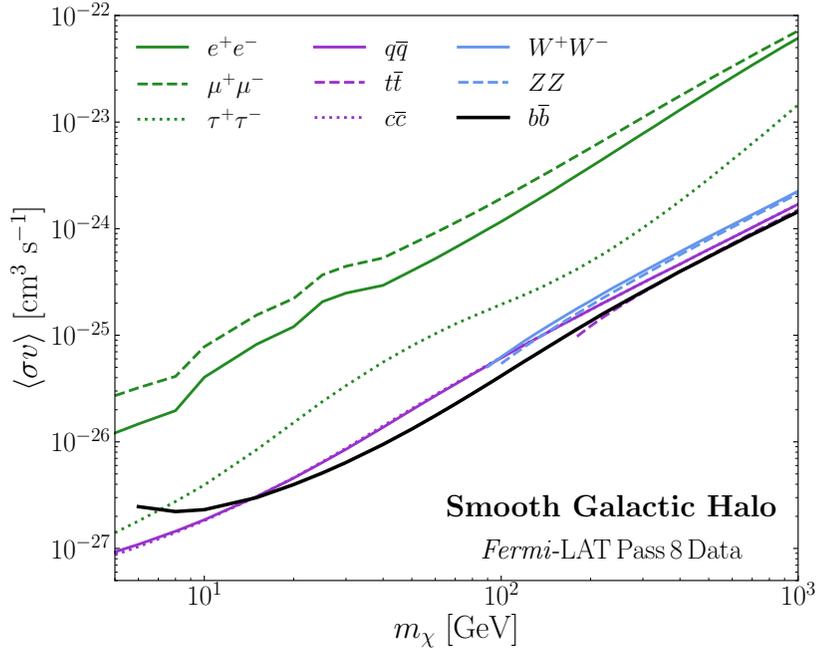


FIG. S8. (Left) The 95% confidence limit on dark matter of mass,  $m_\chi$ , annihilating with cross section,  $\langle\sigma v\rangle$ , in the smooth Galactic Halo. The limits are obtained following the fiducial analysis procedure described in the *Letter*, but varying over the annihilation channel. (Right) The 95% confidence limits associated with variations to the fiducial analysis, as labeled in the legend and described in the text.