The Search for Dark Matter in the Gamma-Ray Sky

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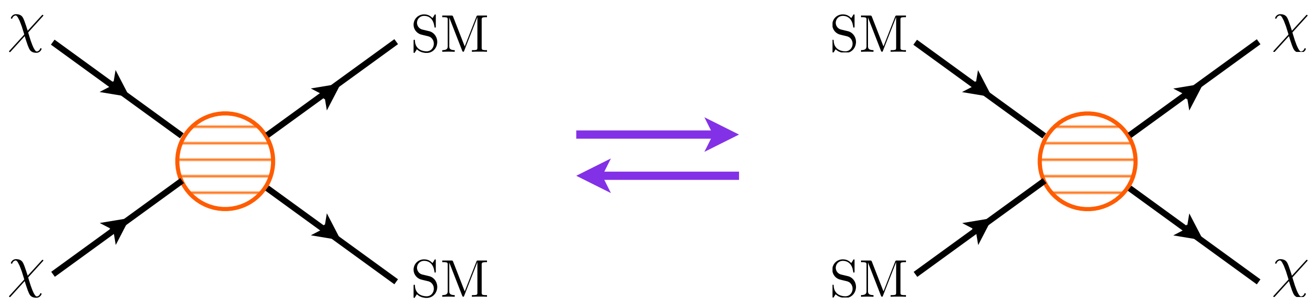
Thermal Dark Matter

Dark matter is in equilibrium in the early Universe



As temperature cools, eventually

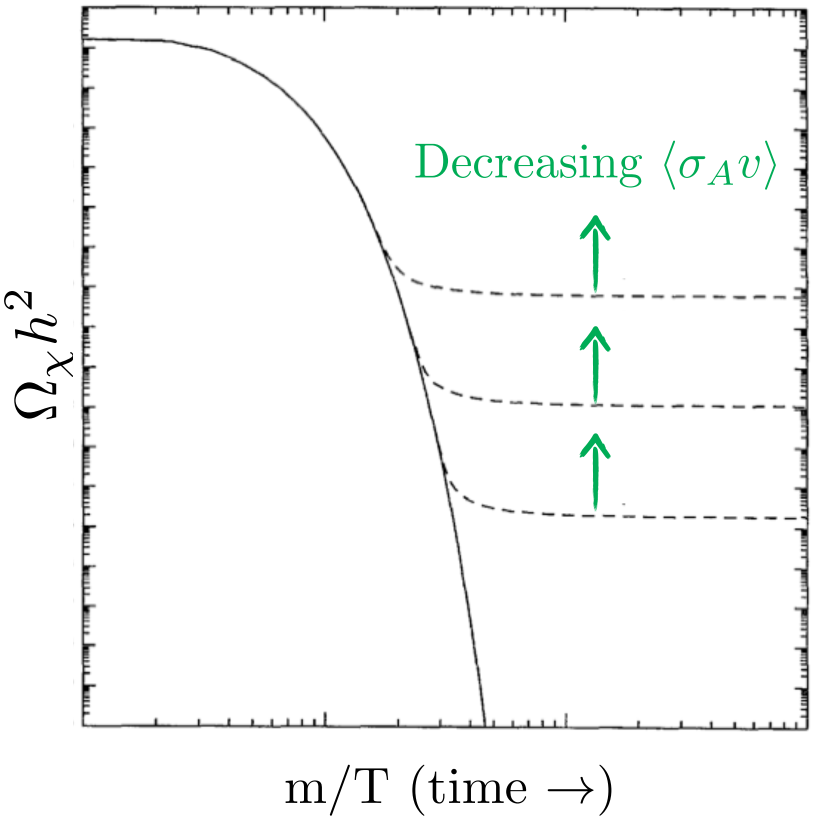
$$\underbrace{n_\chi \langle \sigma_{\rm A} v \rangle}_{\text{dark matter annihilation rate}} \sim \underbrace{\mathrm{H}}_{\text{Hubble rate}}$$

Dark matter stops annihilating and falls out of equilibrium

Relic abundance for dark matter is thus established

WIMP Paradigm

Weakly interacting particle with mass ~100 GeV to 1 TeV
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:

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

Planck Collaboration [1303.5076]

WIMPs provide a lamppost to guide searches for dark matter

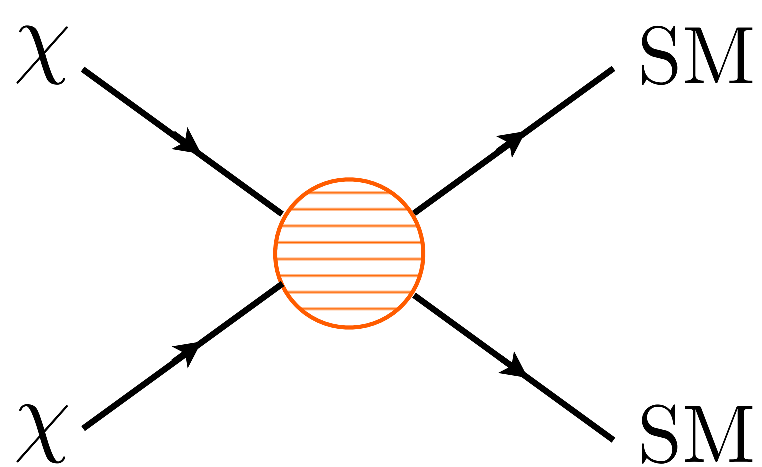
(Important to keep in mind that many other possibilities are theoretically viable)

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

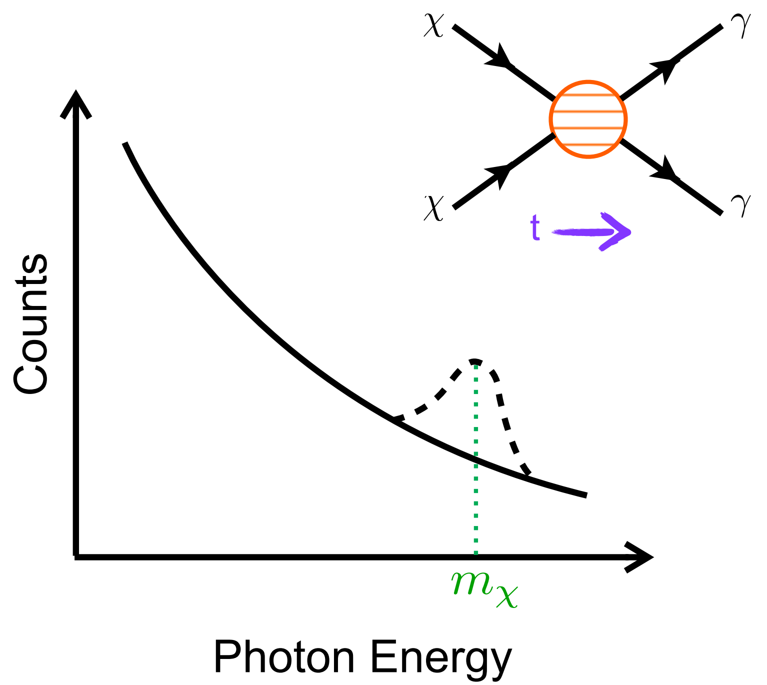
Searching for high-energy gamma rays from dark matter annihilation is the most direct way to probe the thermal hypothesis



Indirect Detection

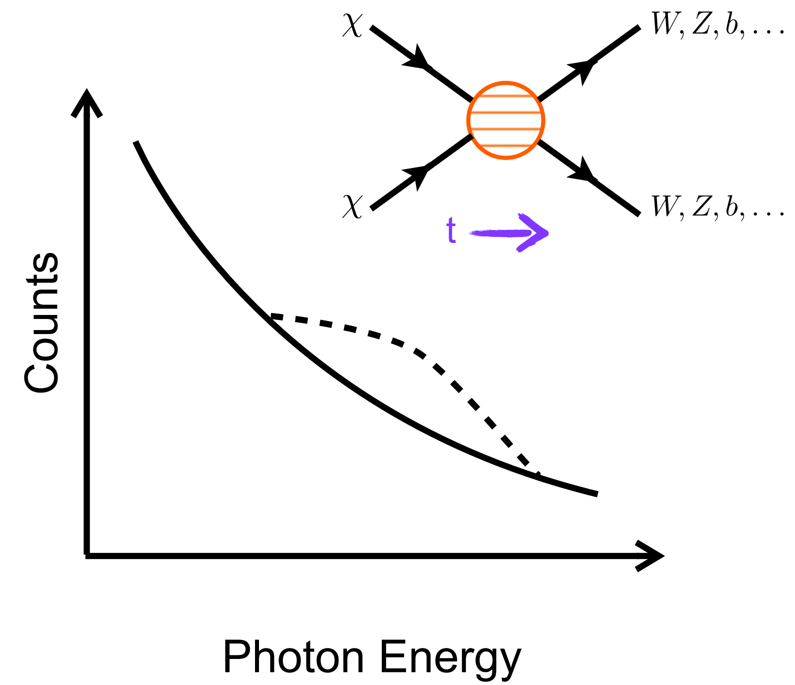
Monochromatic Photons

Direct annihilation to photons,
a line in photon energy spectrum



Continuum Photons

Annihilation to Standard Model
states that shower into photons



Annihilation Flux

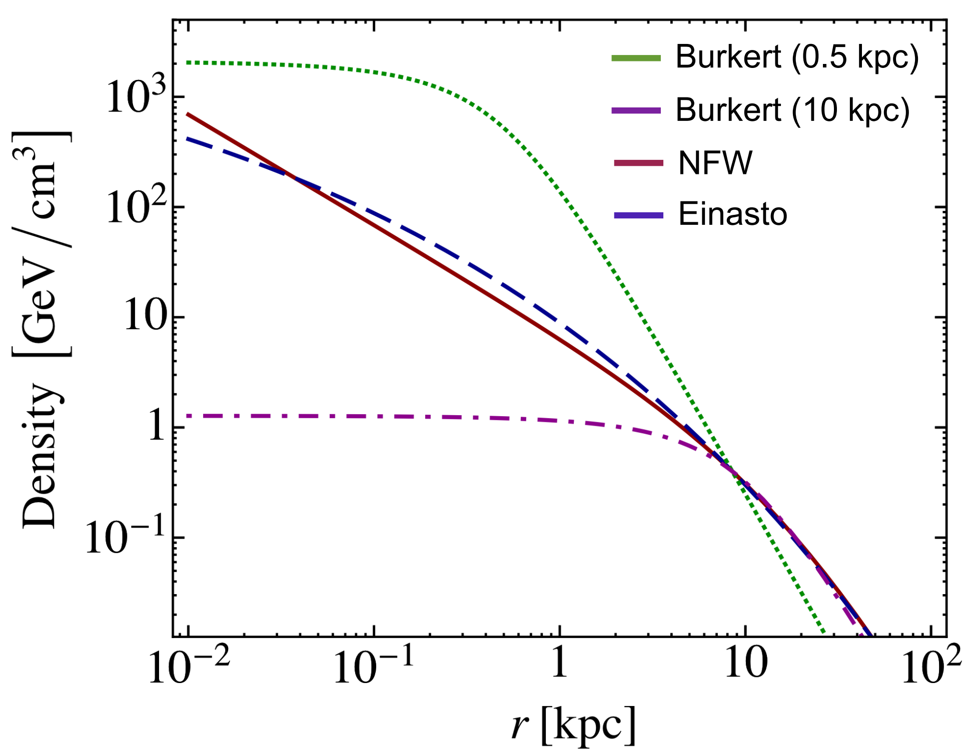
The photon flux for dark matter annihilation is given by

$$\Phi(E,\psi) = \underbrace{\frac{\sigma_{\rm A} v}{8\pi m_\chi^2}\frac{dN_\gamma}{dE}}_{\text{particle physics}} \underbrace{\int d\ell\, \rho\left[r(\ell,\psi)\right]^2}_{\text{J-factor}}$$

J-factor depends on the dark matter density profile

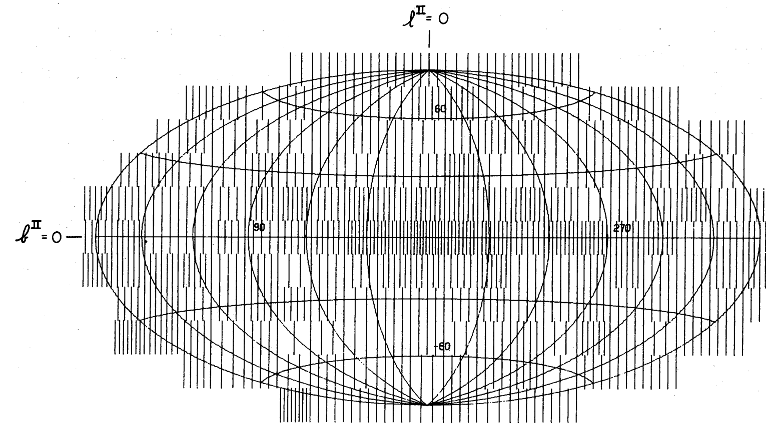
$$\rho_{\rm NFW}(r) \propto \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

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



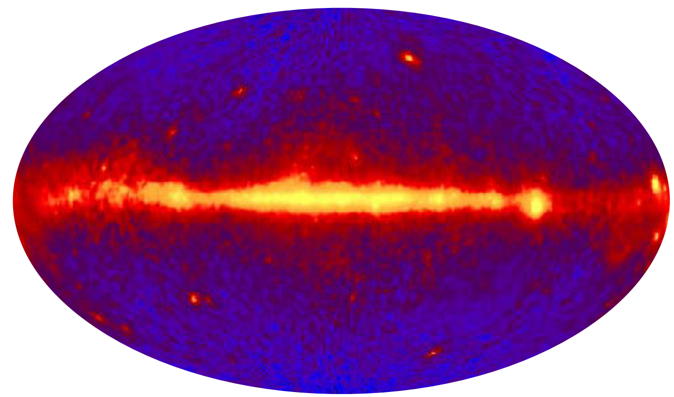
The Sky in Gamma Rays

OSO-3 (1967-1968)
> 50 MeV

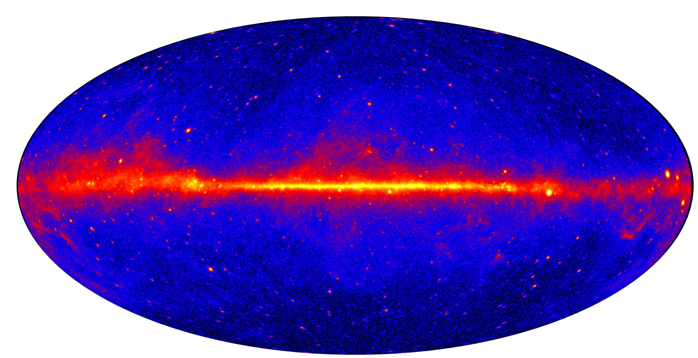


(not shown)

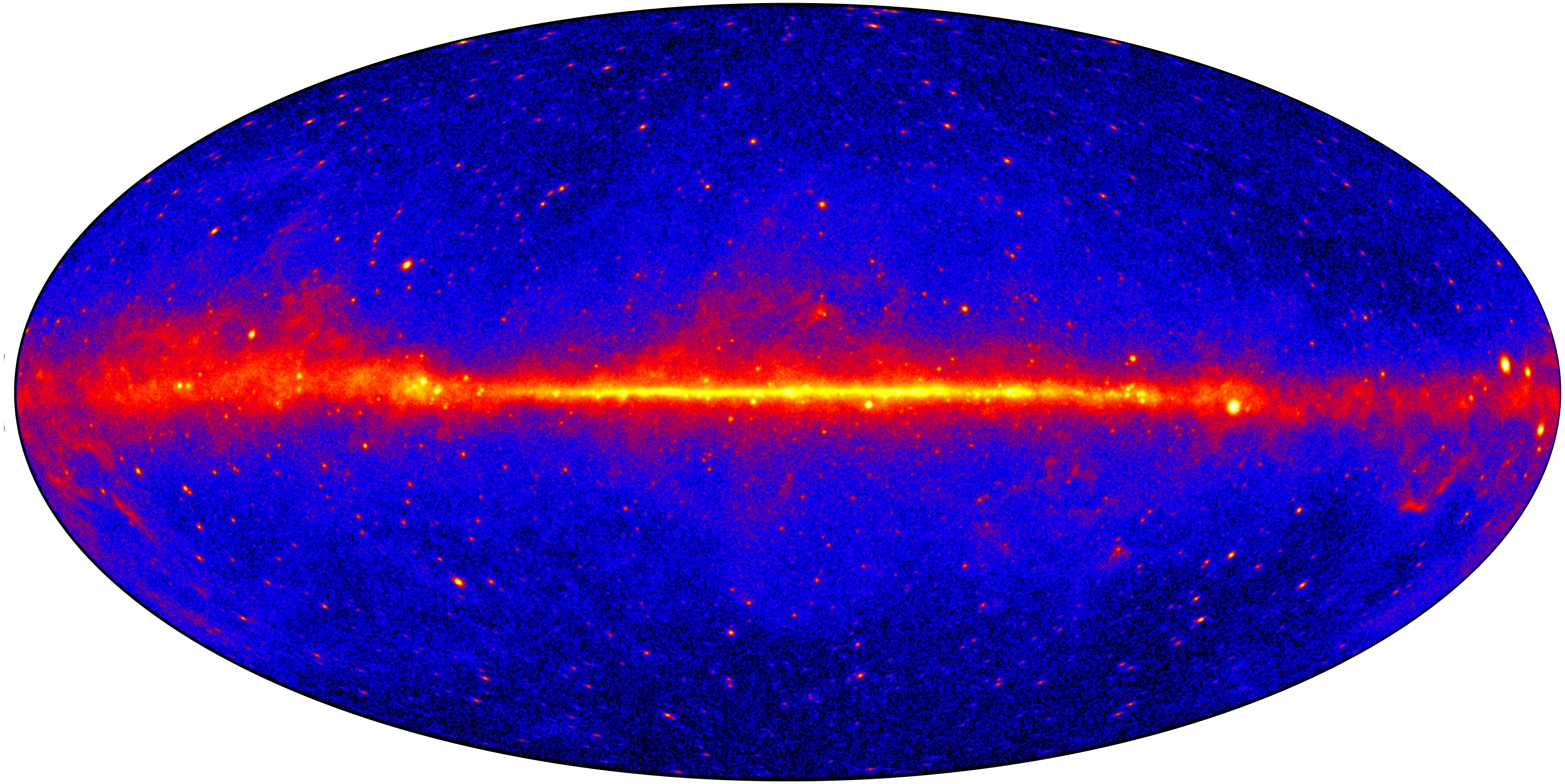
EGRET (1991-2000)
30 MeV - 30 GeV



Fermi LAT (2008-)
20 MeV - 300 GeV



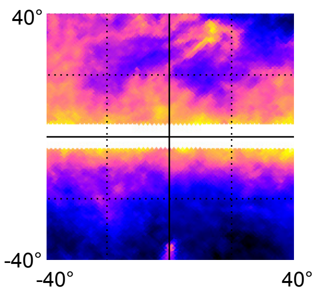
Touring the Gamma-Ray Sky

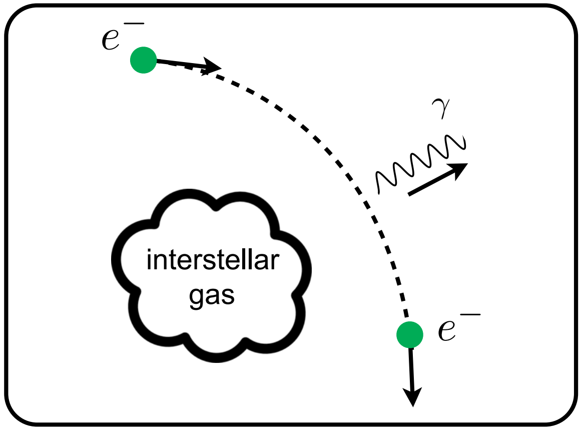


Diffuse Gamma Rays

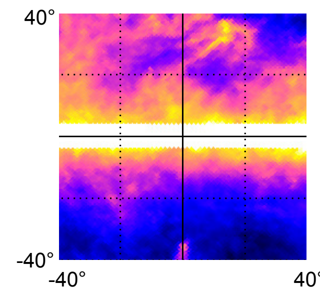
High-energy γ-rays produced through propagation of cosmic rays in the Galaxy

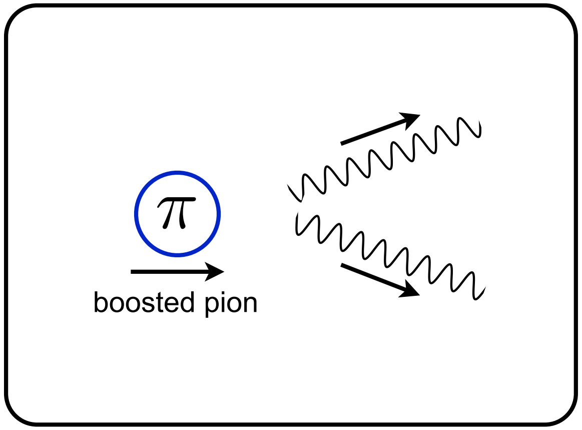
Bremsstrahlung



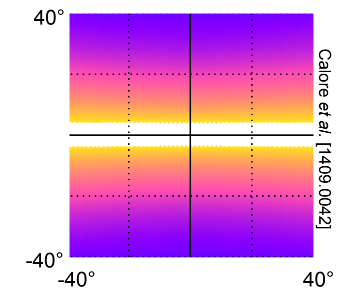


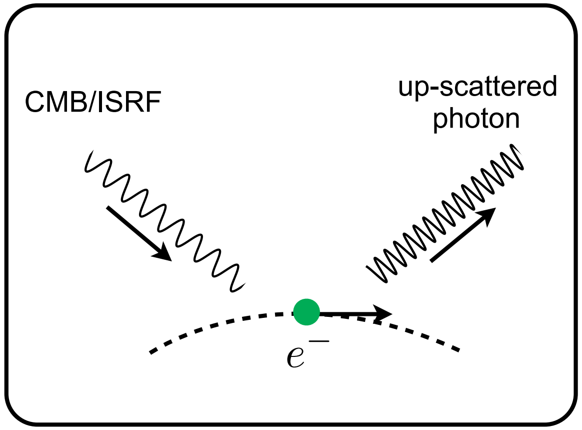
Pion Emission



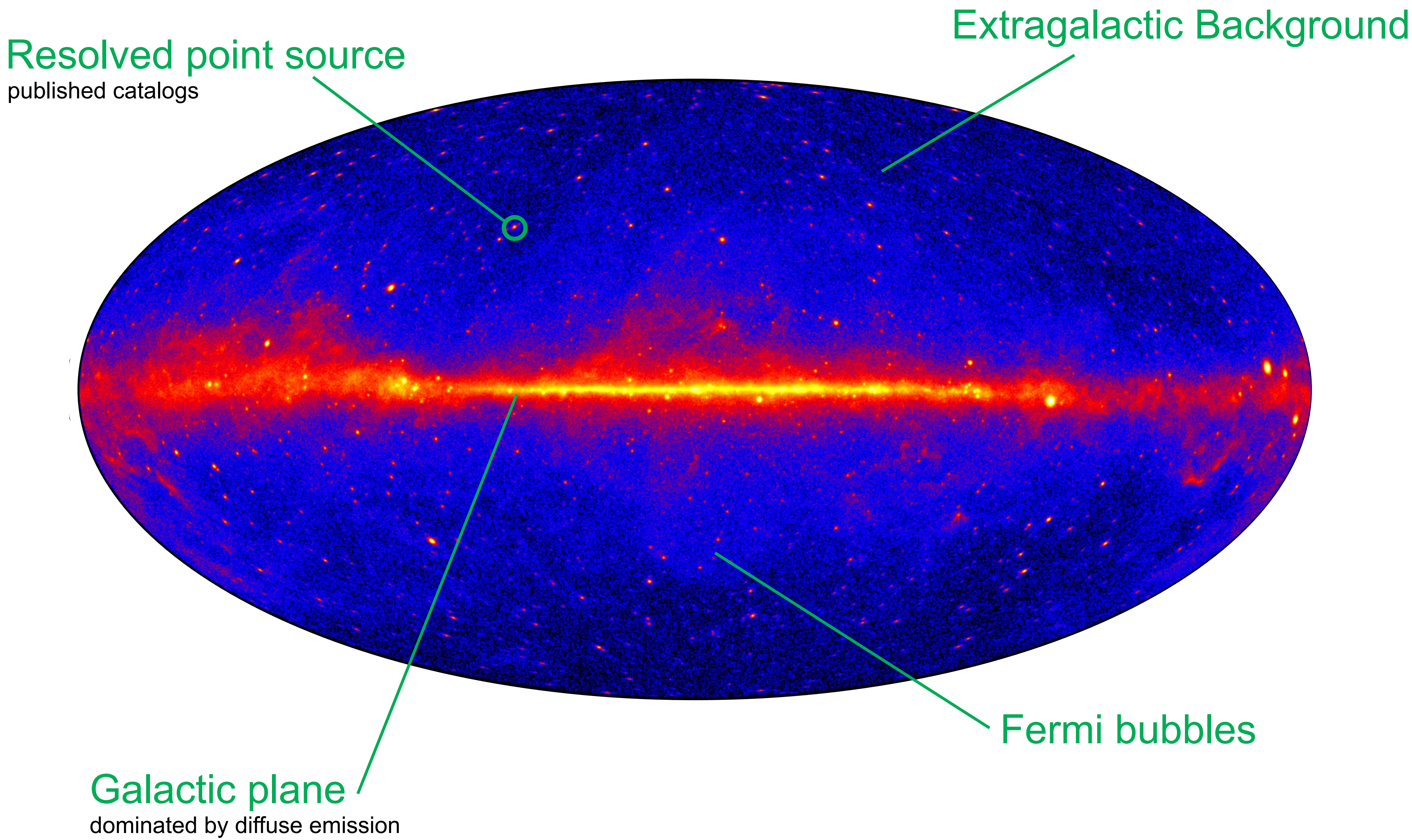


Inverse Compton

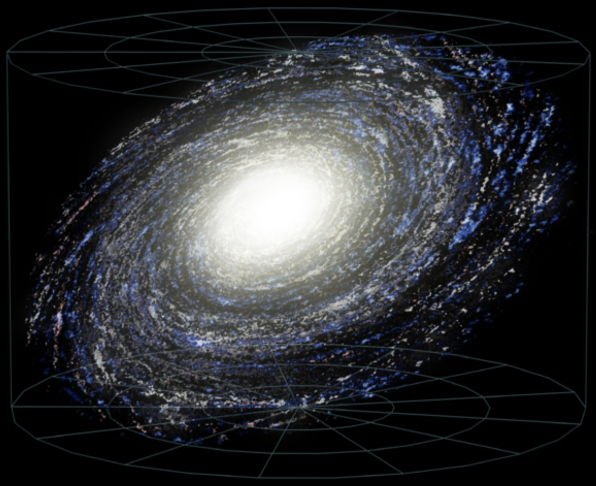




Touring the Gamma-Ray Sky



Milky Way



Simulations: Andrew Z. Colvin

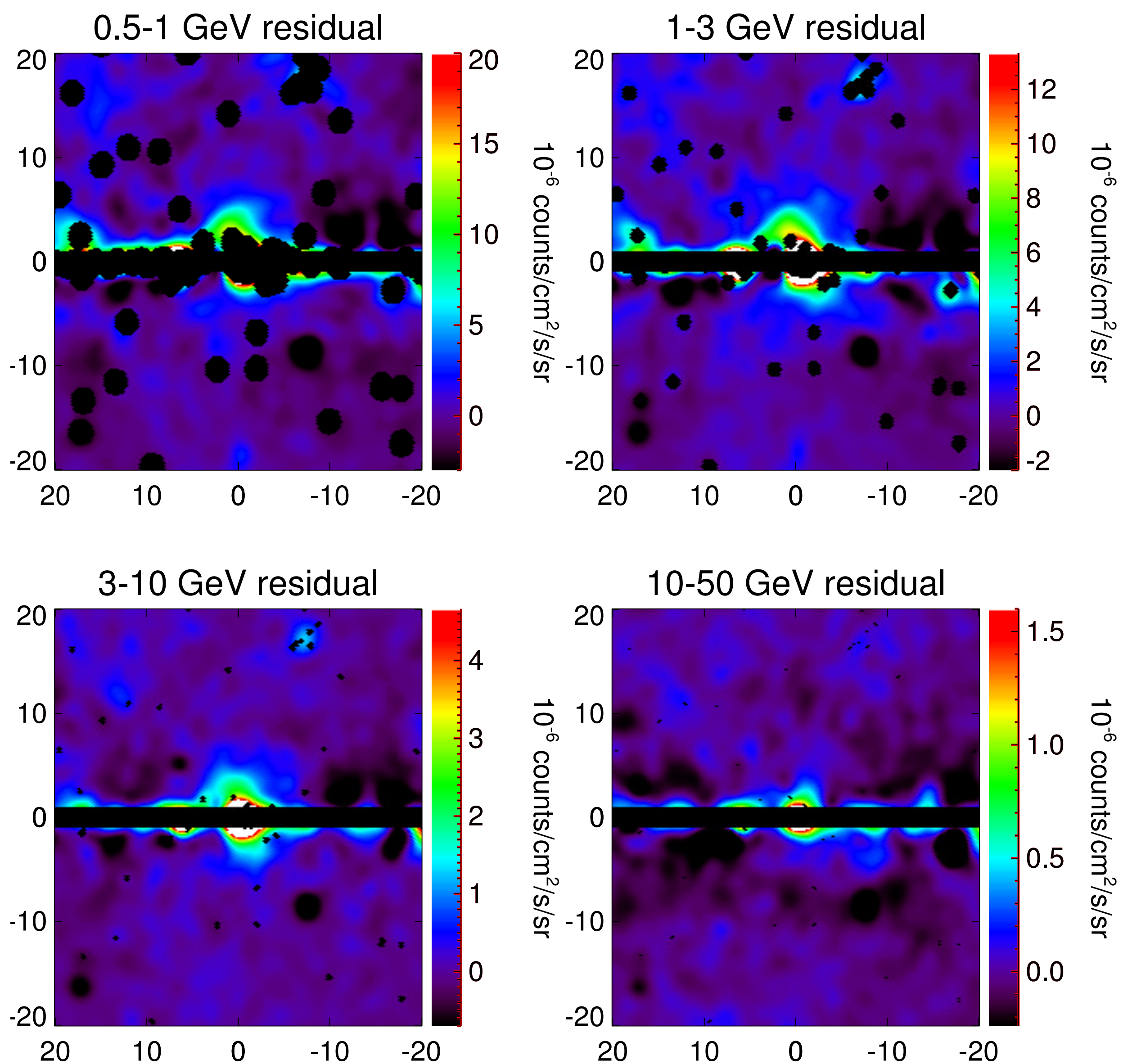
GeV Photon Excess

Spherically symmetric gamma-ray excess in the Inner Galaxy

Extends out 10˚ (~5000 lyr) from the center of Galaxy

Constitutes ~10% total flux

High statistical significance



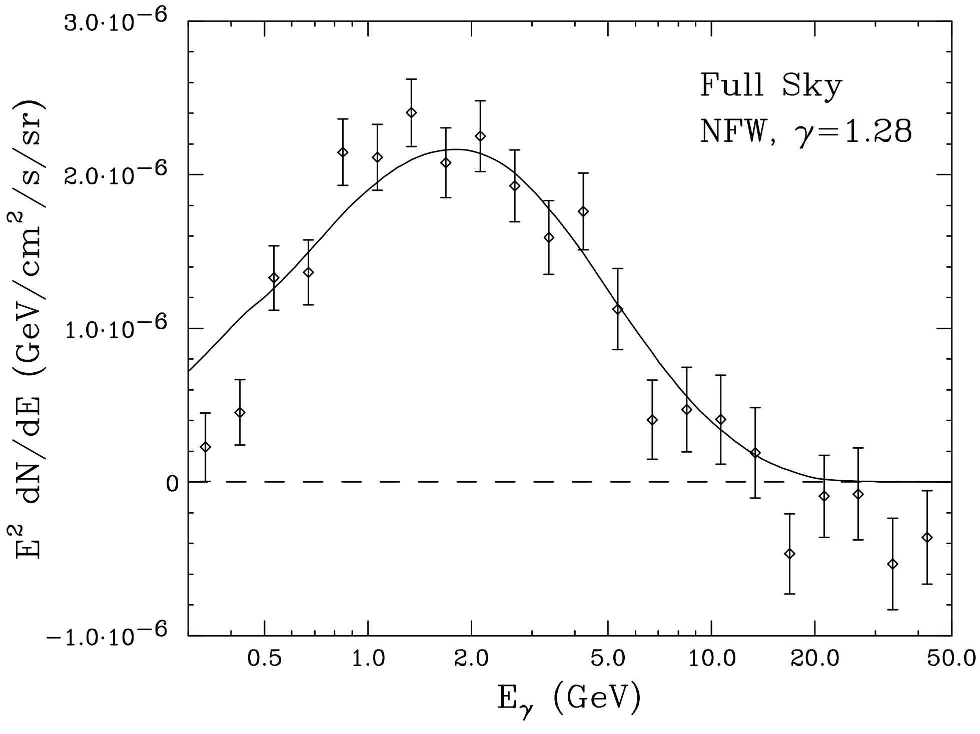
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, and Slatyer [1402.6703]

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]

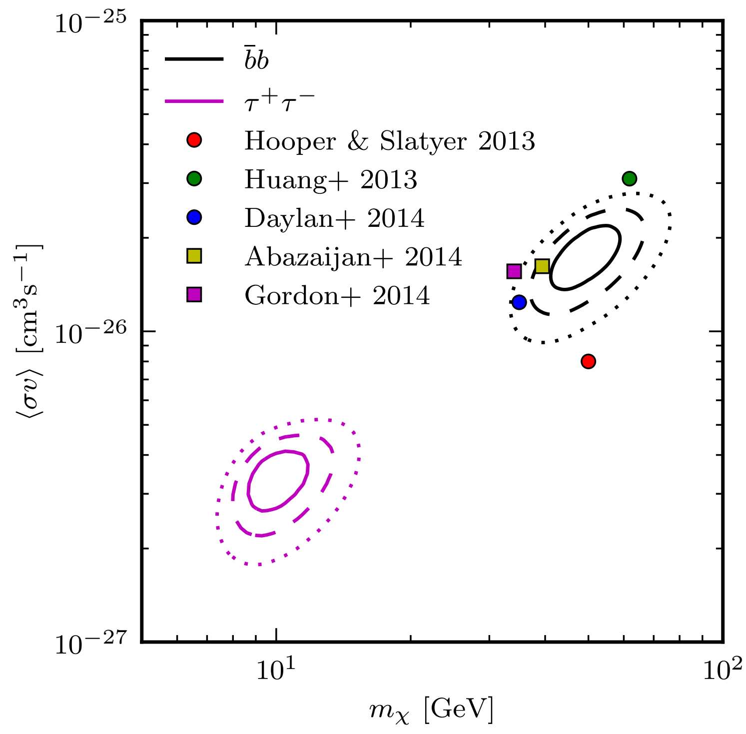
GeV Photon Excess

Spatial morphology and energy spectrum may be consistent with dark matter expectation

GeV excess appears to be robust to changes in diffuse-emission modeling



Daylan *et al.* [1402.6703]



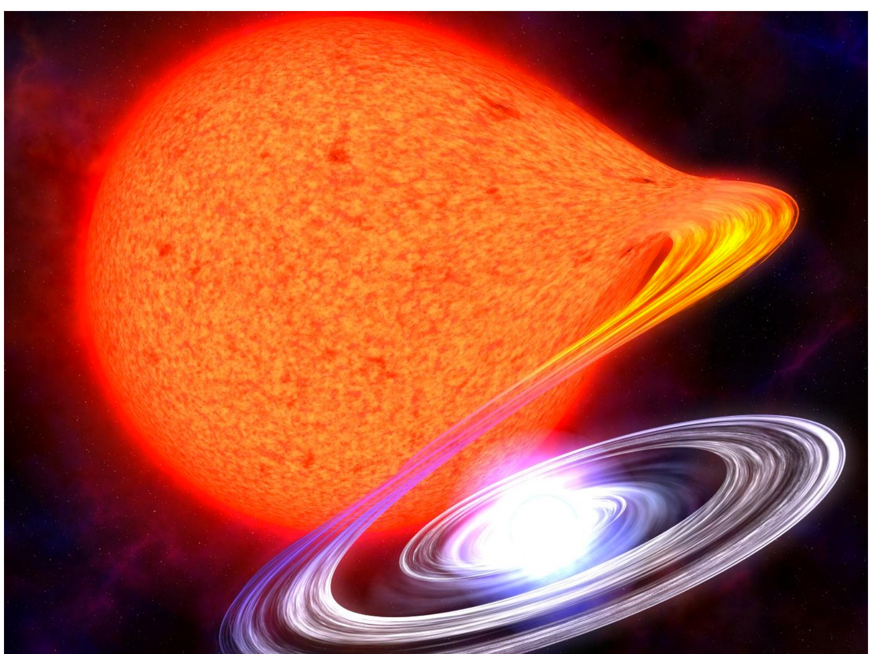
Calore, Cholis, & Weniger [1409.0042]

Unresolved Sources

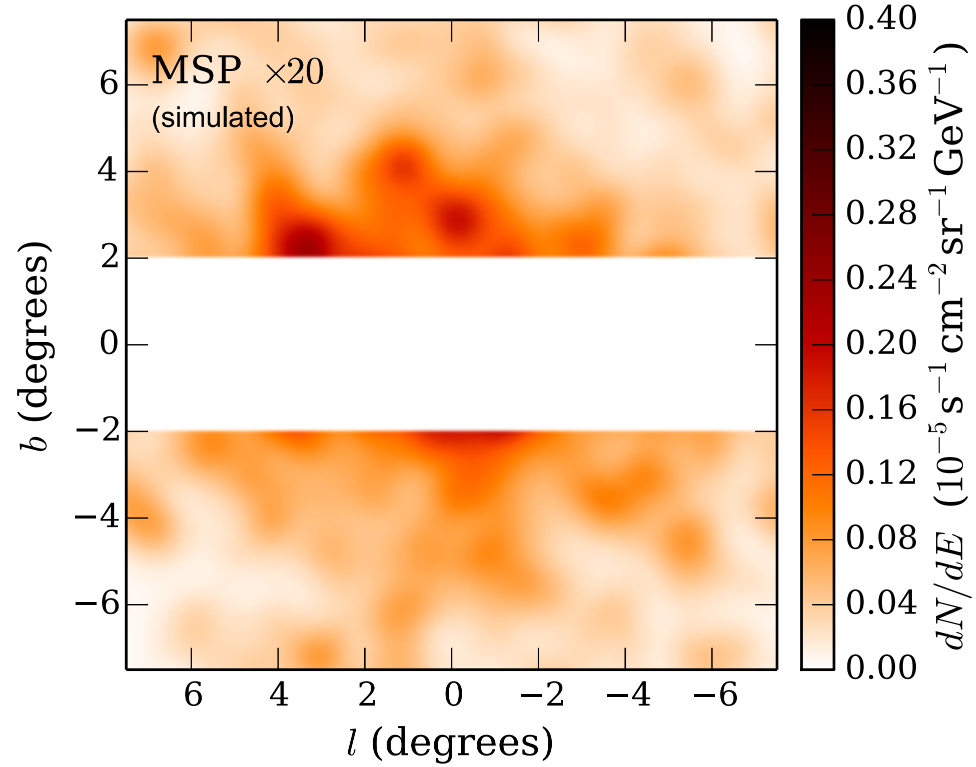
GeV excess could also be explained by a population of unresolved sources just below *Fermi*'s detection threshold

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

Abazajian [1011.4275]



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

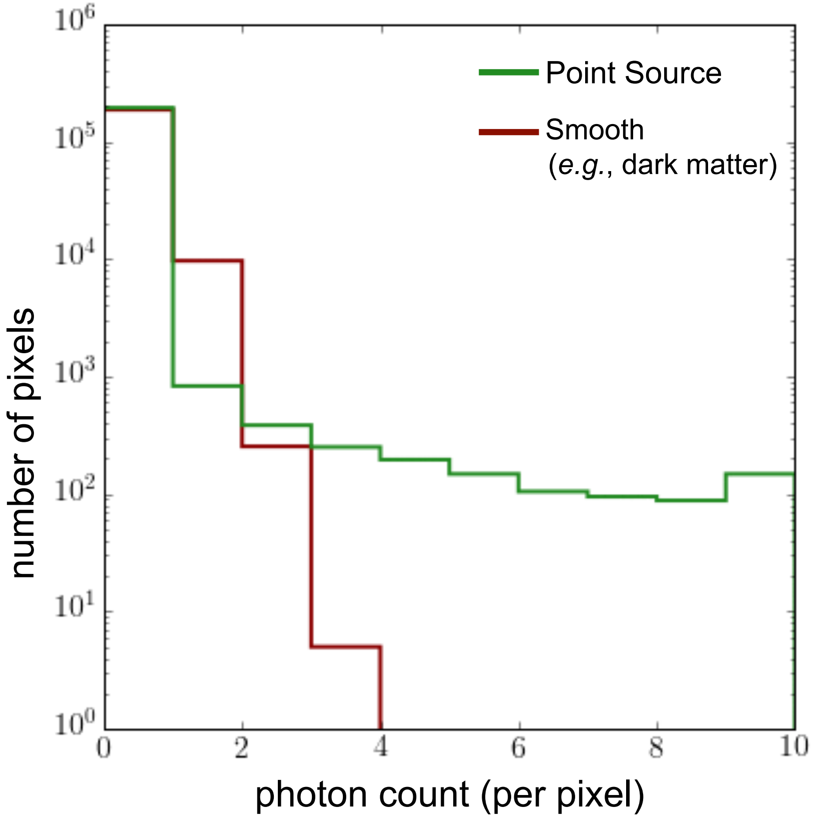


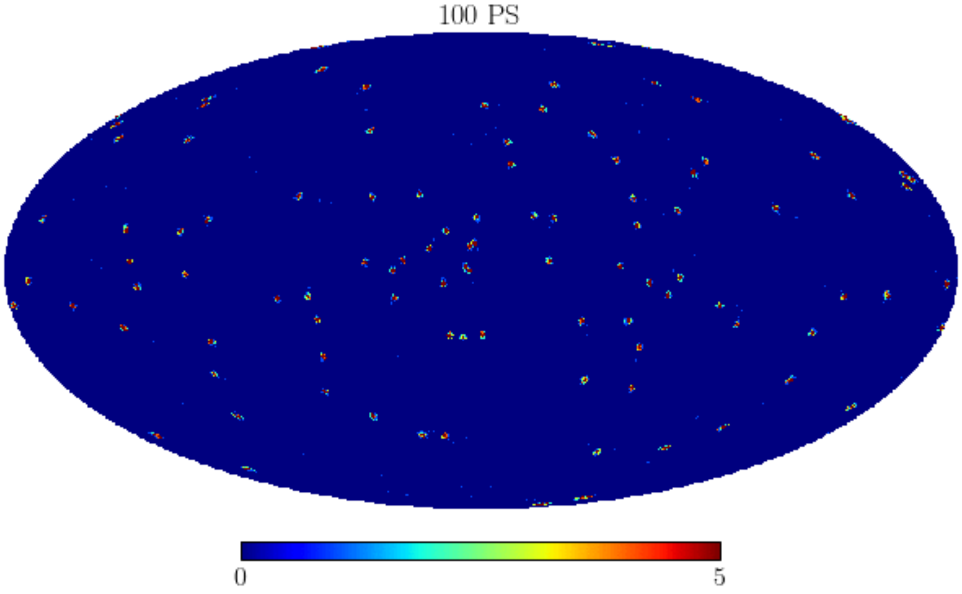
O'Leary *et al.* [1601.05797]

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]





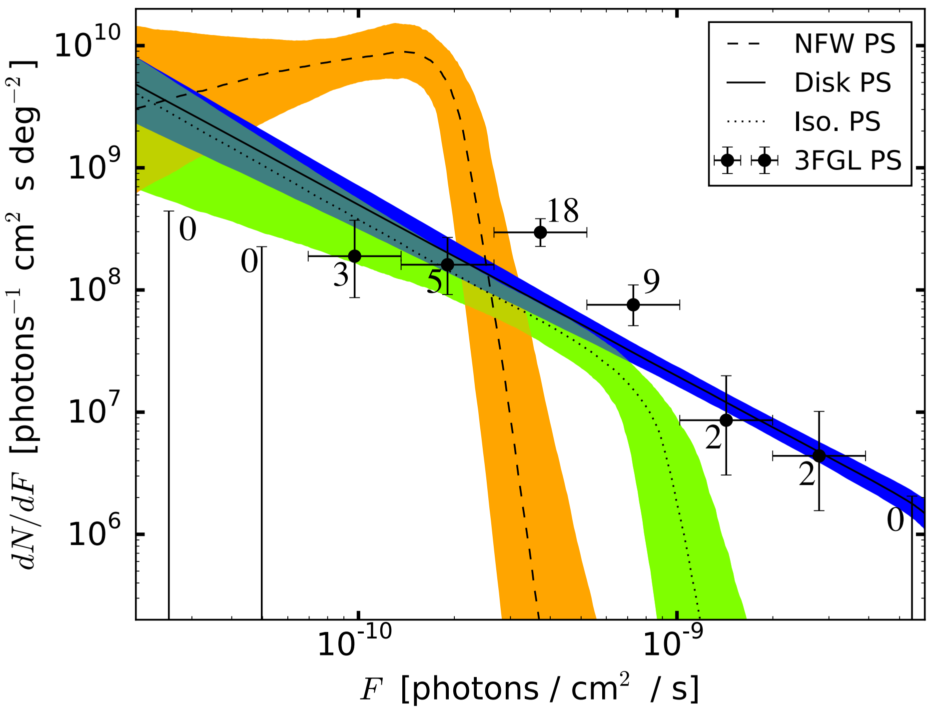
Inner Galaxy Analysis

Evidence for unresolved sources in the Galactic Center that can account for the GeV excess

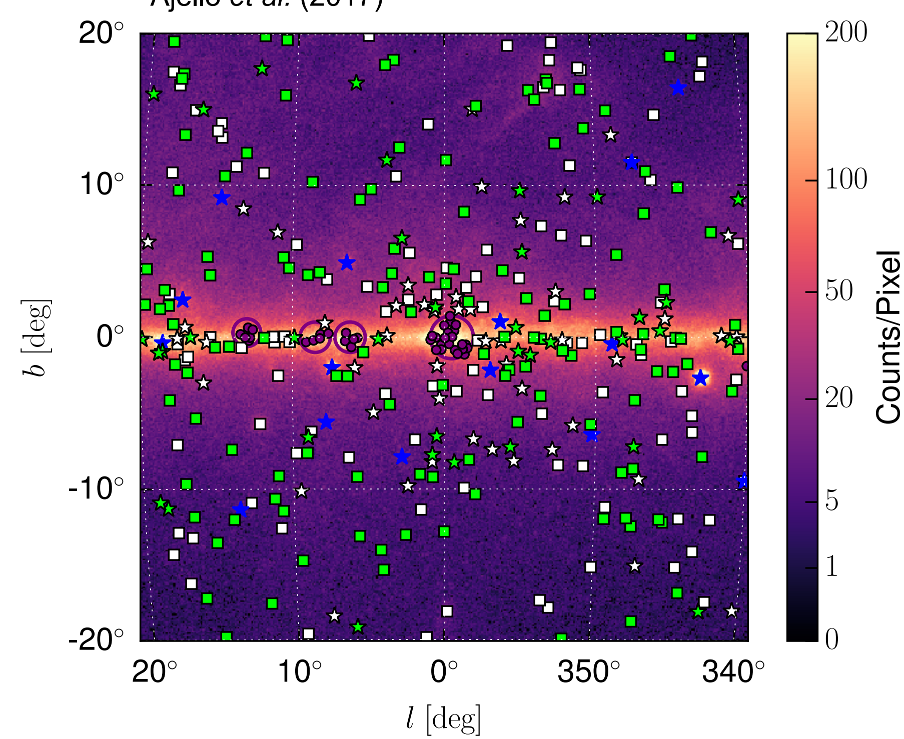
Lee, Lisanti, Safdi, Slatyer, and Xue [1506.05124]

Complimentary study using wavelet methods (Bartels 2016) found similar results; findings supported by recent *Fermi* analysis (Ajello 2017)

Lee *et al.* (2015)



Ajello *et al.* (2017)



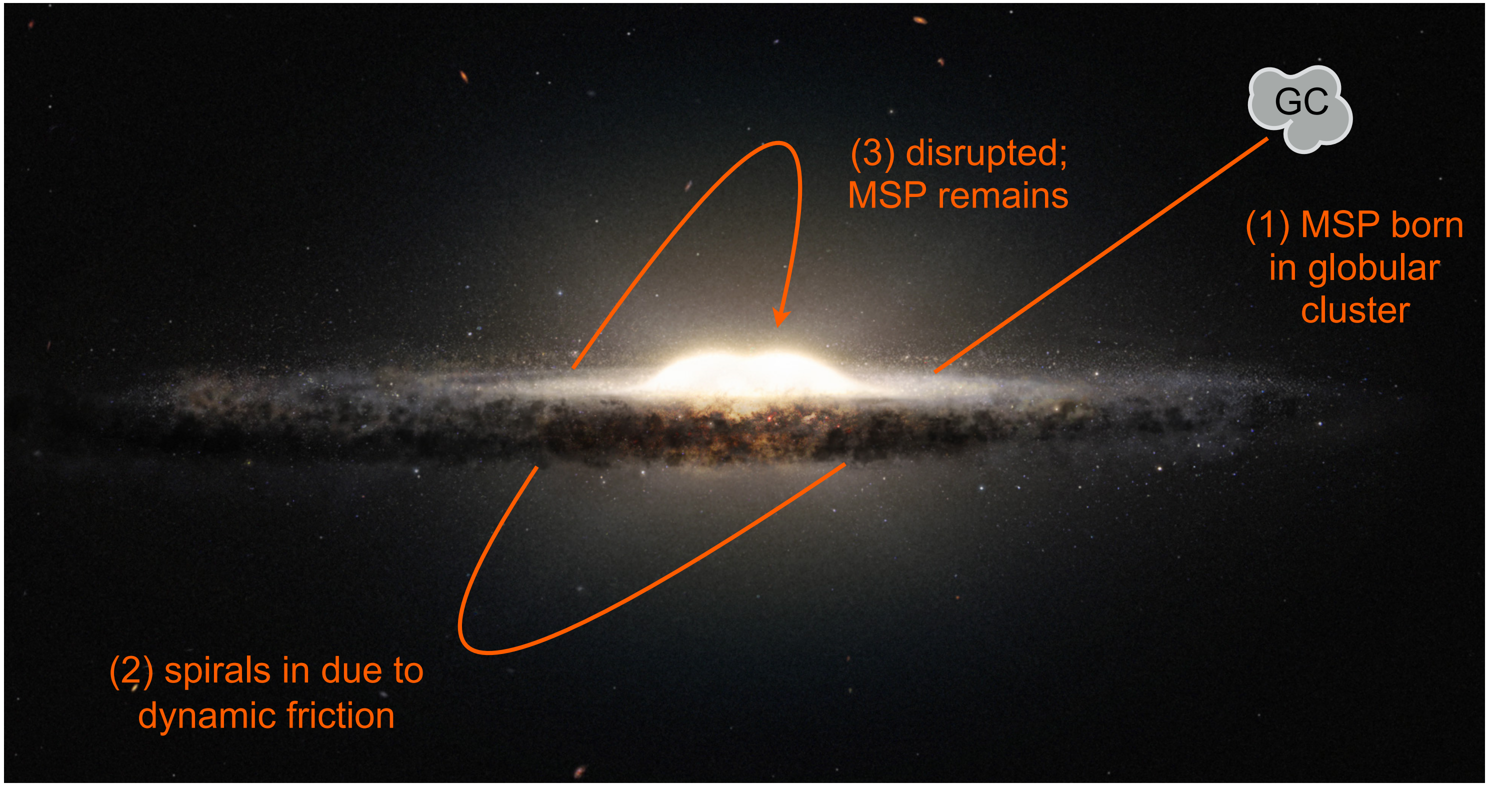
Millisecond Pulsars

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

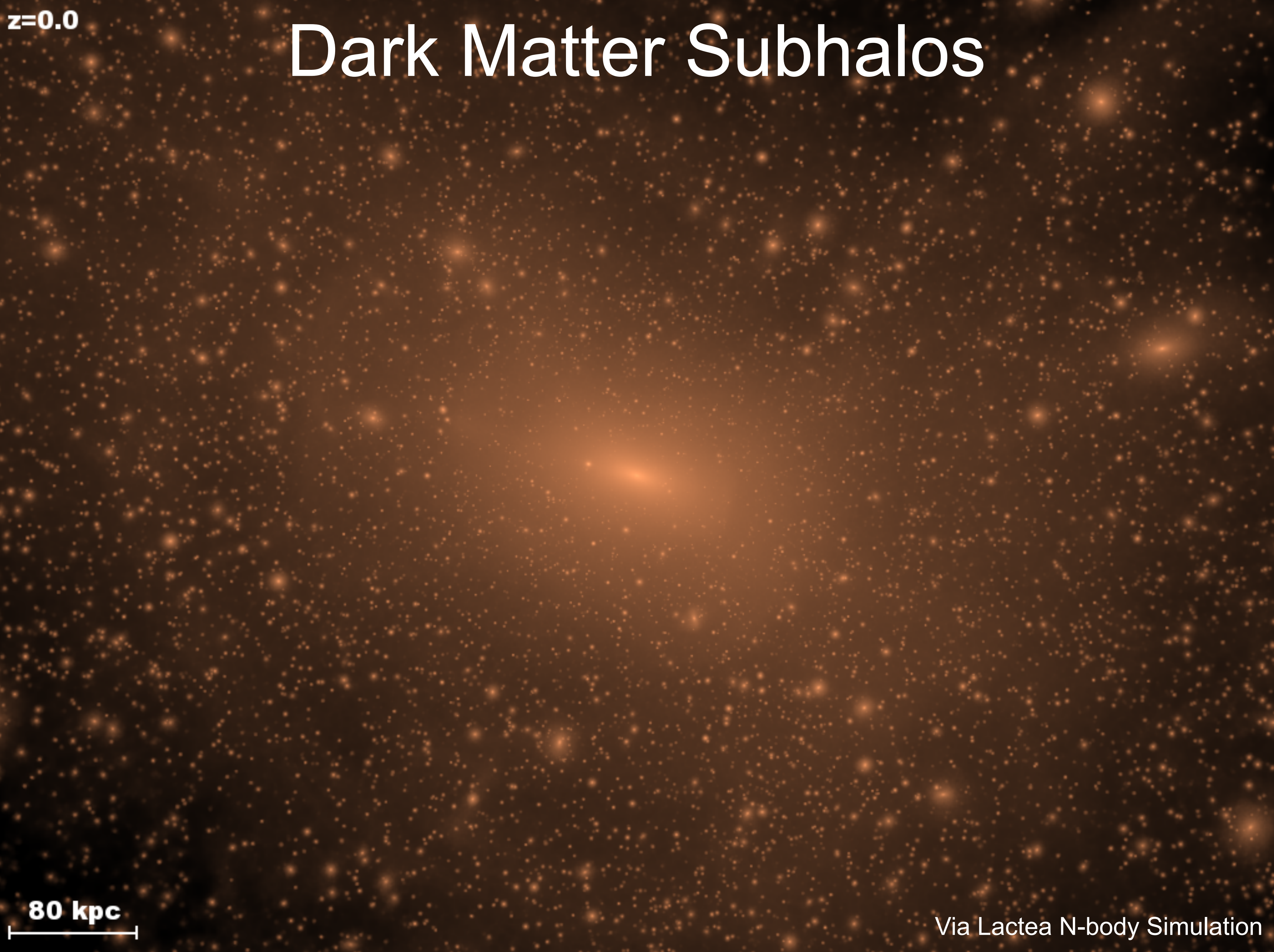
In the coming few years, targeted and large-area radio surveys will be able to detect individual millisecond pulsars if they exist in the Inner Galaxy

Calore *et al.* [1512.06825]



ESO/NASA/JPL-Caltech/M. Kornmesser/R. Hurt

Dark Matter Subhalos



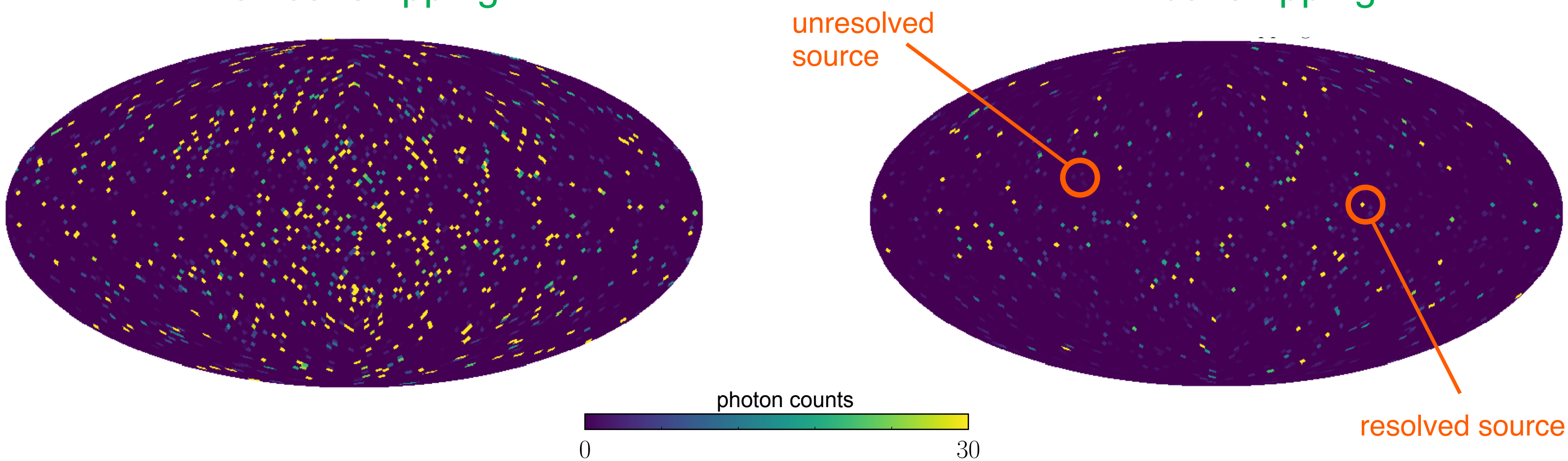
Dark Matter Subhalos

See parallel session talk by Laura Chang

Hierarchical structure formation leads to substructure within large halos

Predicted Subhalo Flux in Milky Way

no tidal stripping | with tidal stripping

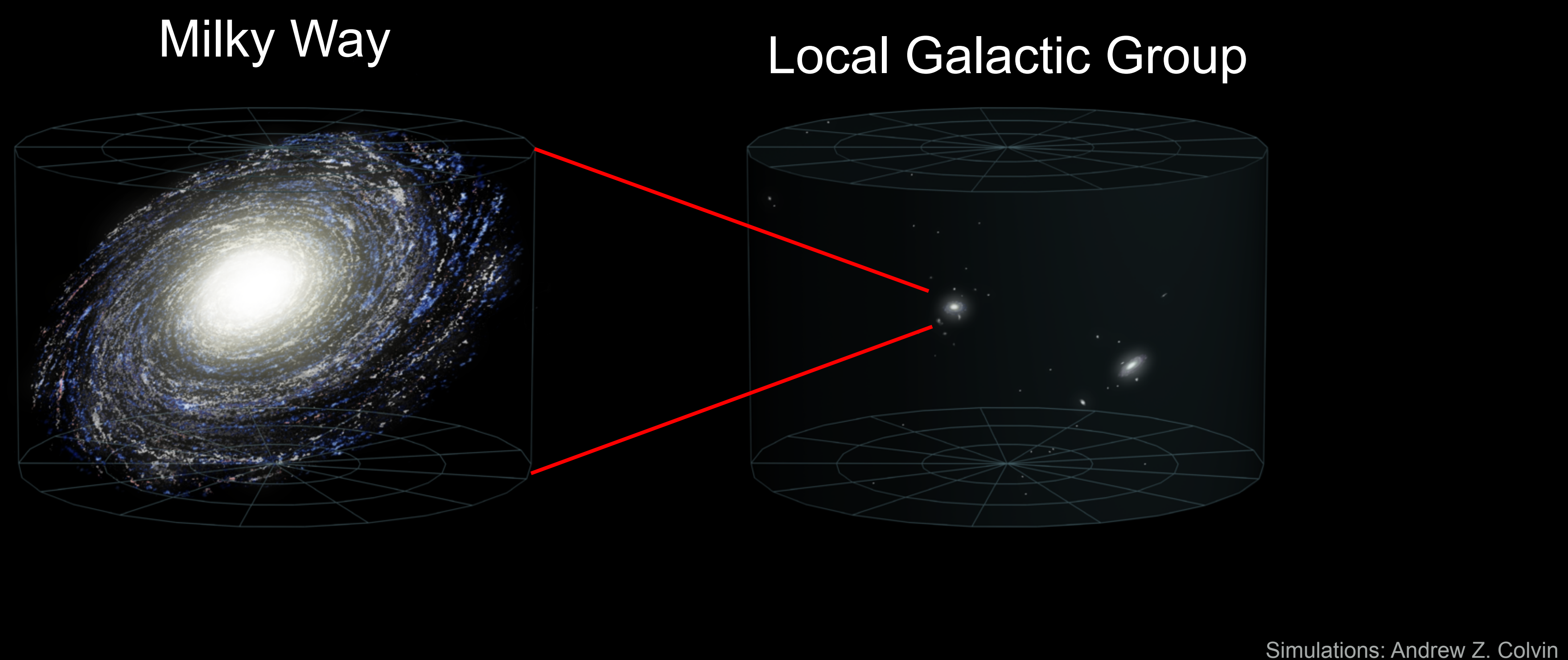


Require that the number of bright subhalos do not over-predict the number of resolved sources observed by *Fermi*

Schoonenberg *et al.* [1601.06781]; Bertoni *et al.* [1602.07303]; Hooper and Witte [1610.07587]; Calore *et al.* [1611.03503]; Wang *et al.* [1611.05135]; Liang *et al.* [1703.07078]

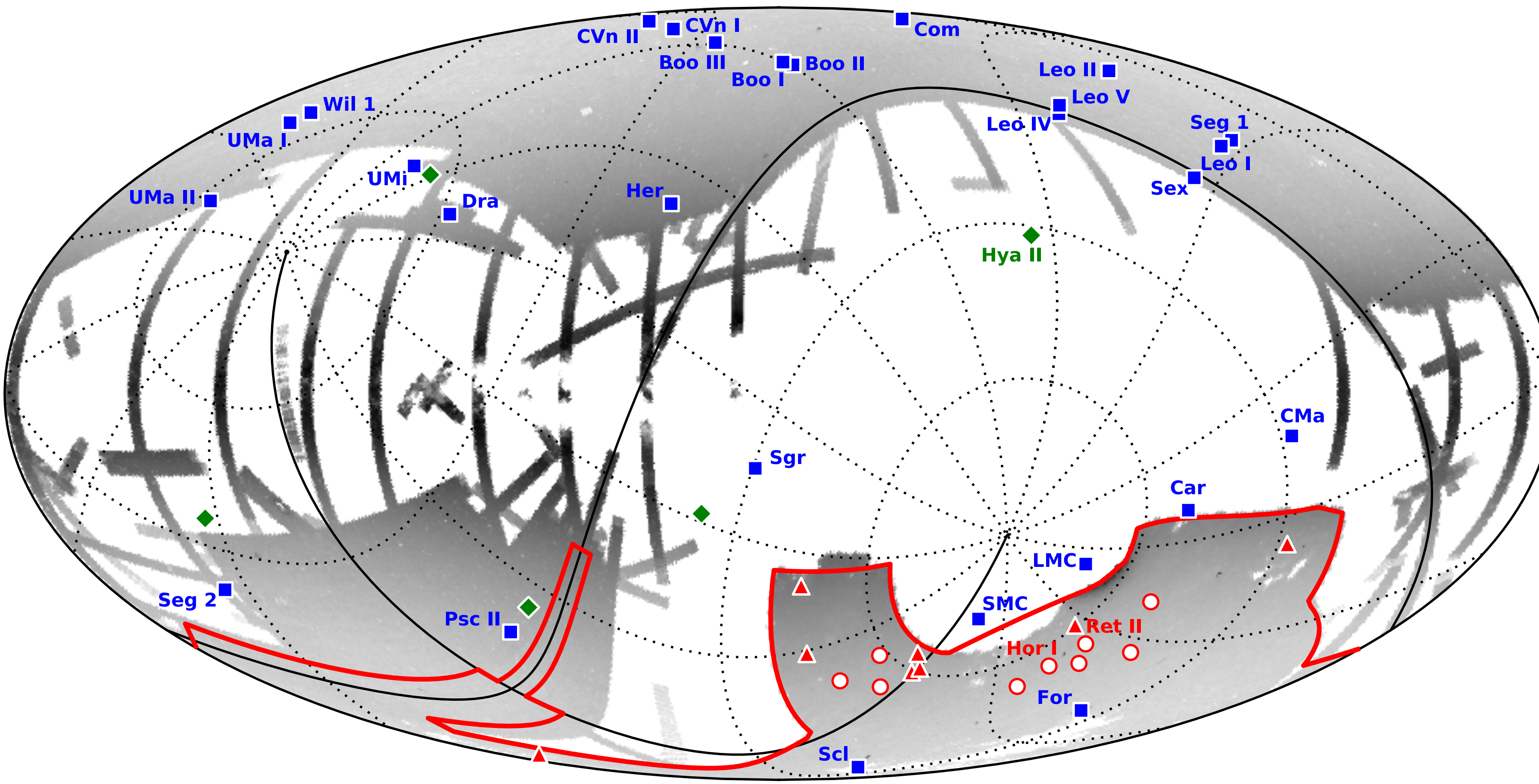
Can also search for a population of unresolved subhalos using photon statistics

Lee *et al.* [0810.1284]; Chang, Lisanti, and Mishra-Sharma [in progress]


Milky Way
Local Galactic Group
Simulations: Andrew Z. Colvin

Dwarf Galaxies

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



Known satellites before 2015

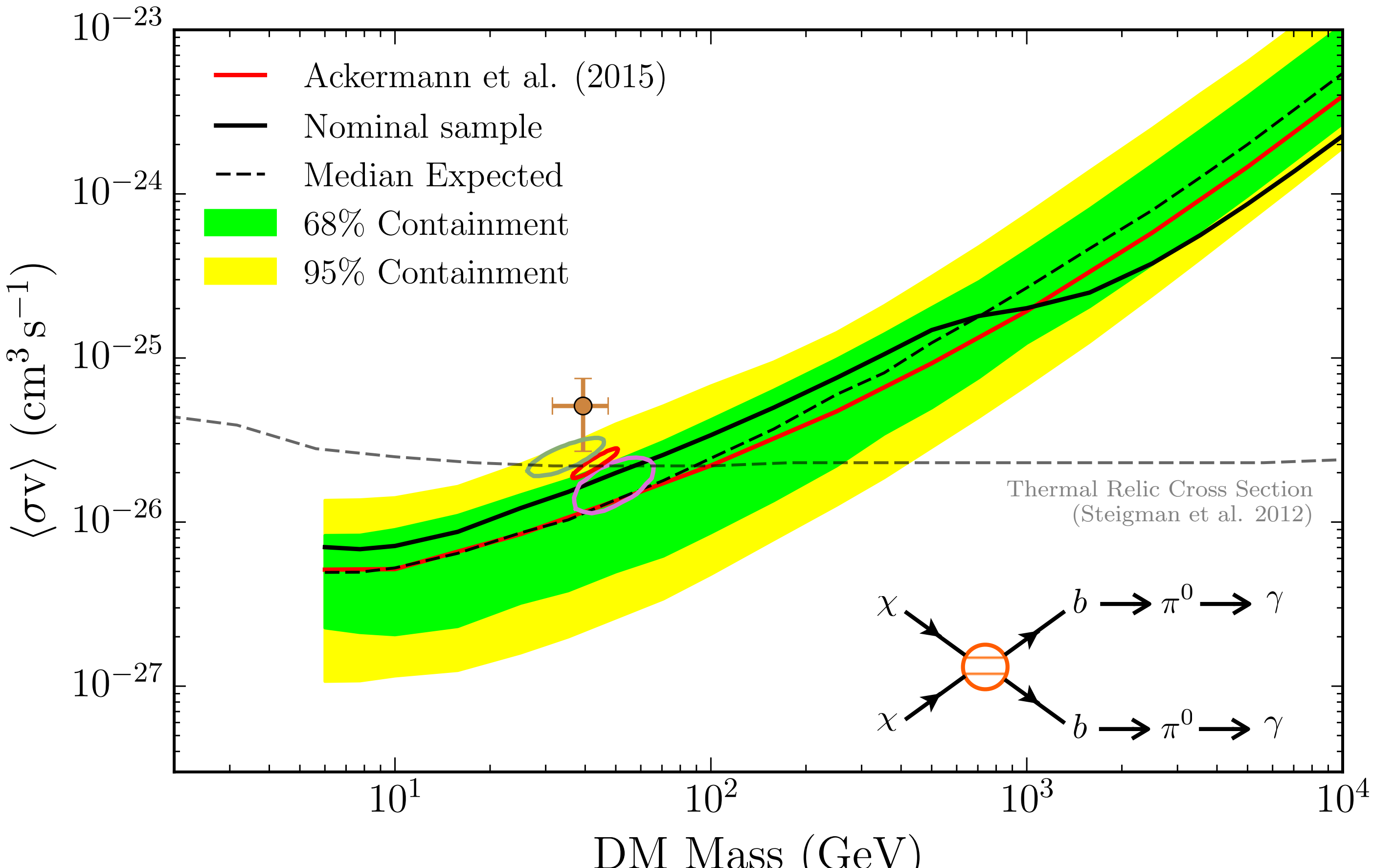
New Candidates

Drlica-Wagner *et al.* [1508.03622]

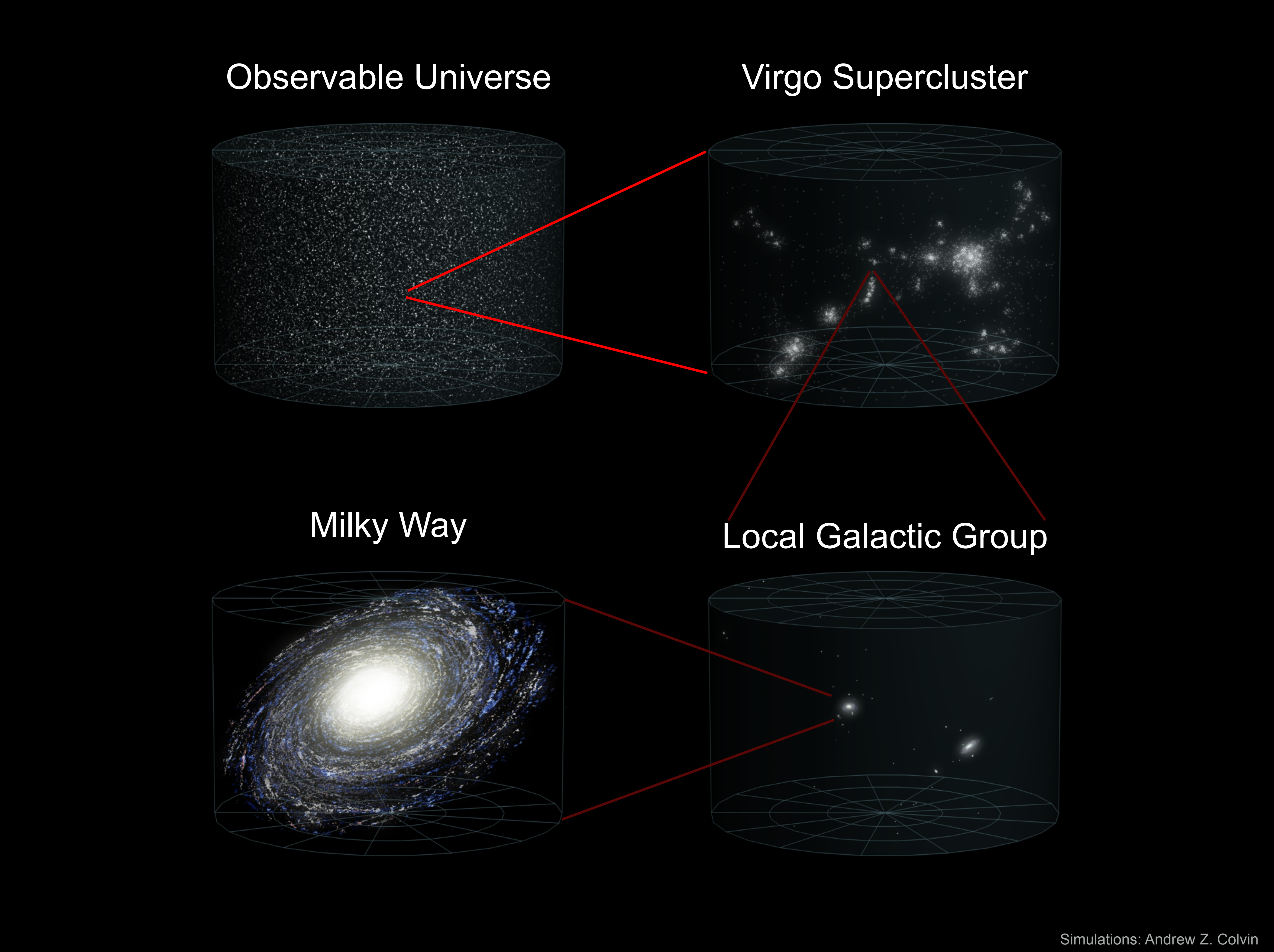
Dwarf Galaxies

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



Albert *et al.* [1611.03184]


Observable Universe
Virgo Supercluster
Milky Way
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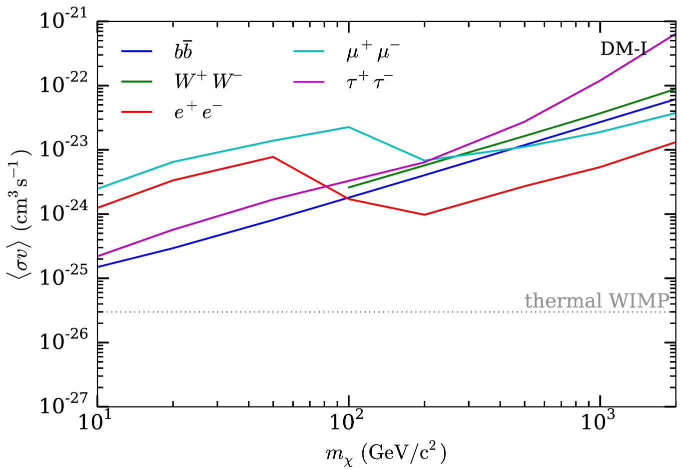
Extragalactic Dark Matter

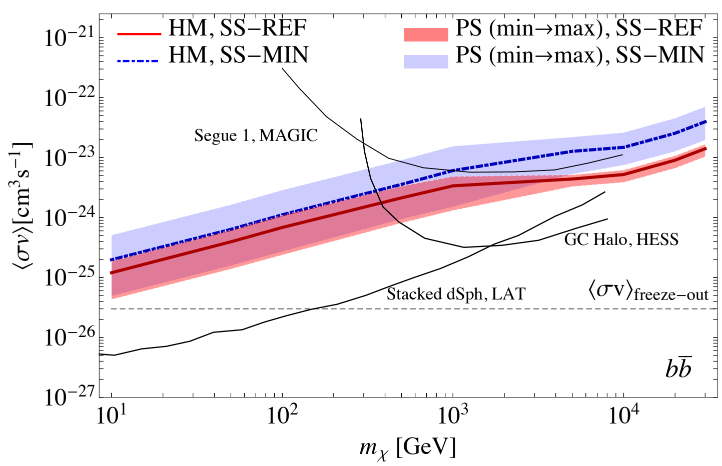
Breadth of searches currently targeting signals from extragalactic halos

Cluster Analysis



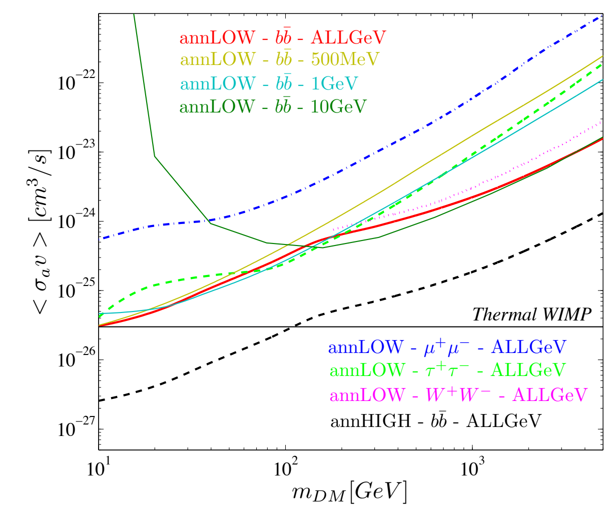
Ackermann *et al.* [1510.00004]

Isotropic Gamma-Ray Background



Ackermann *et al.* [1501.05464]

Cross Correlation Studies



Regis *et al.* [1503.05922]

Dark Matter Sky Maps

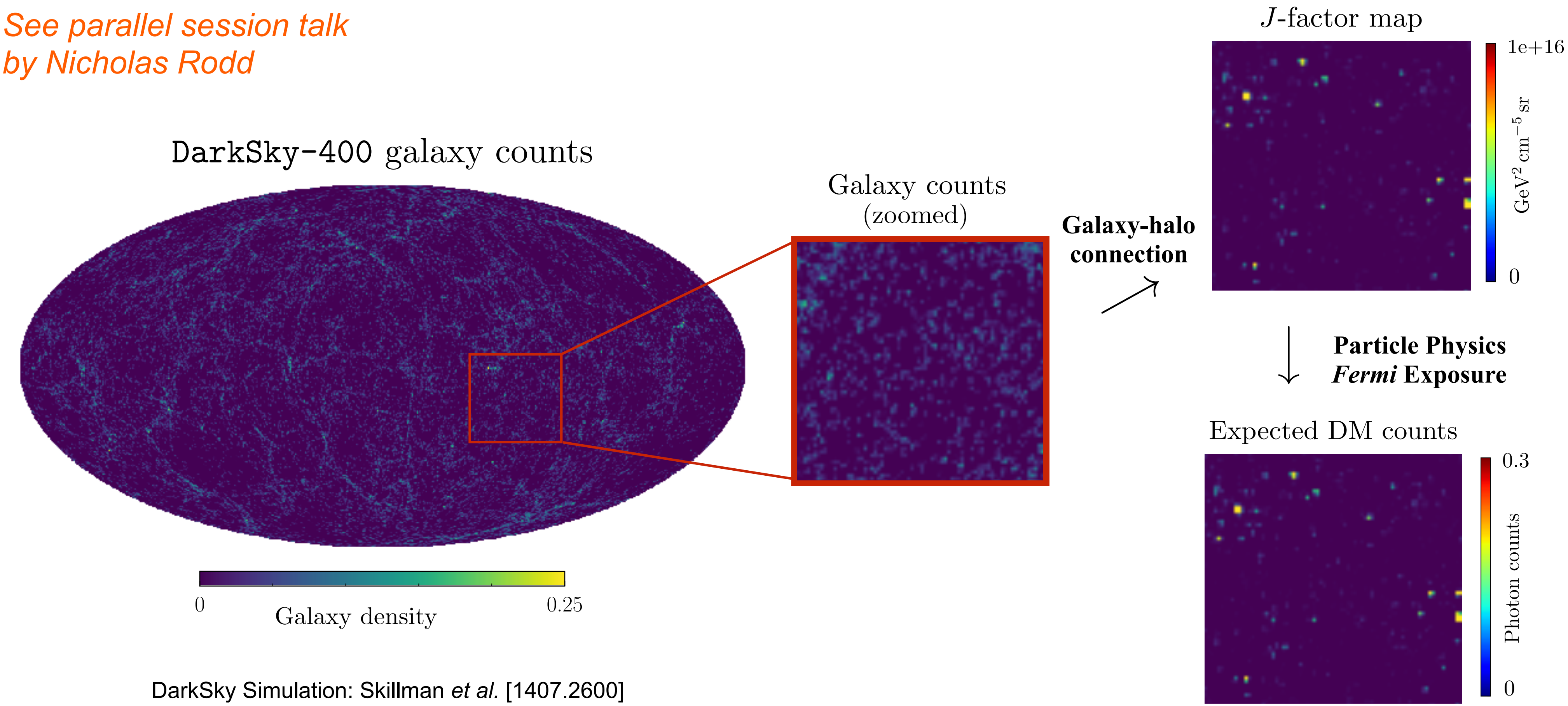
Lisanti, Mishra-Sharma, Rodd, and Safdi [in preparation]

Create an all-sky map that traces the 'hot spots' for dark matter annihilation

Galaxy-halo connection allows one to build this map in a deterministic fashion

Galaxy luminosity → Halo mass → Halo concentration

See parallel session talk by Nicholas Rodd



DarkSky Simulation: Skillman *et al.* [1407.2600]

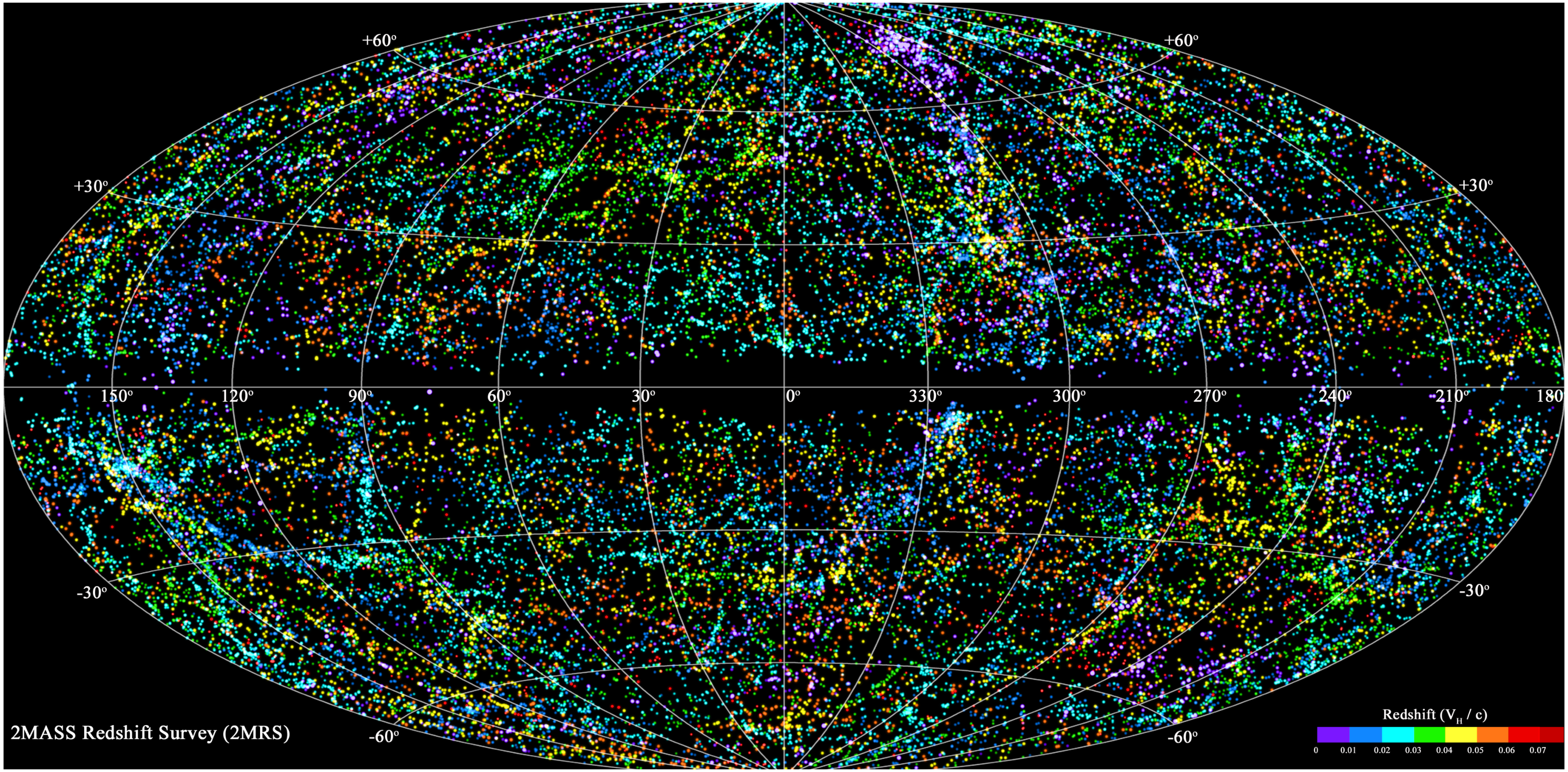
From a Group Catalog…

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

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

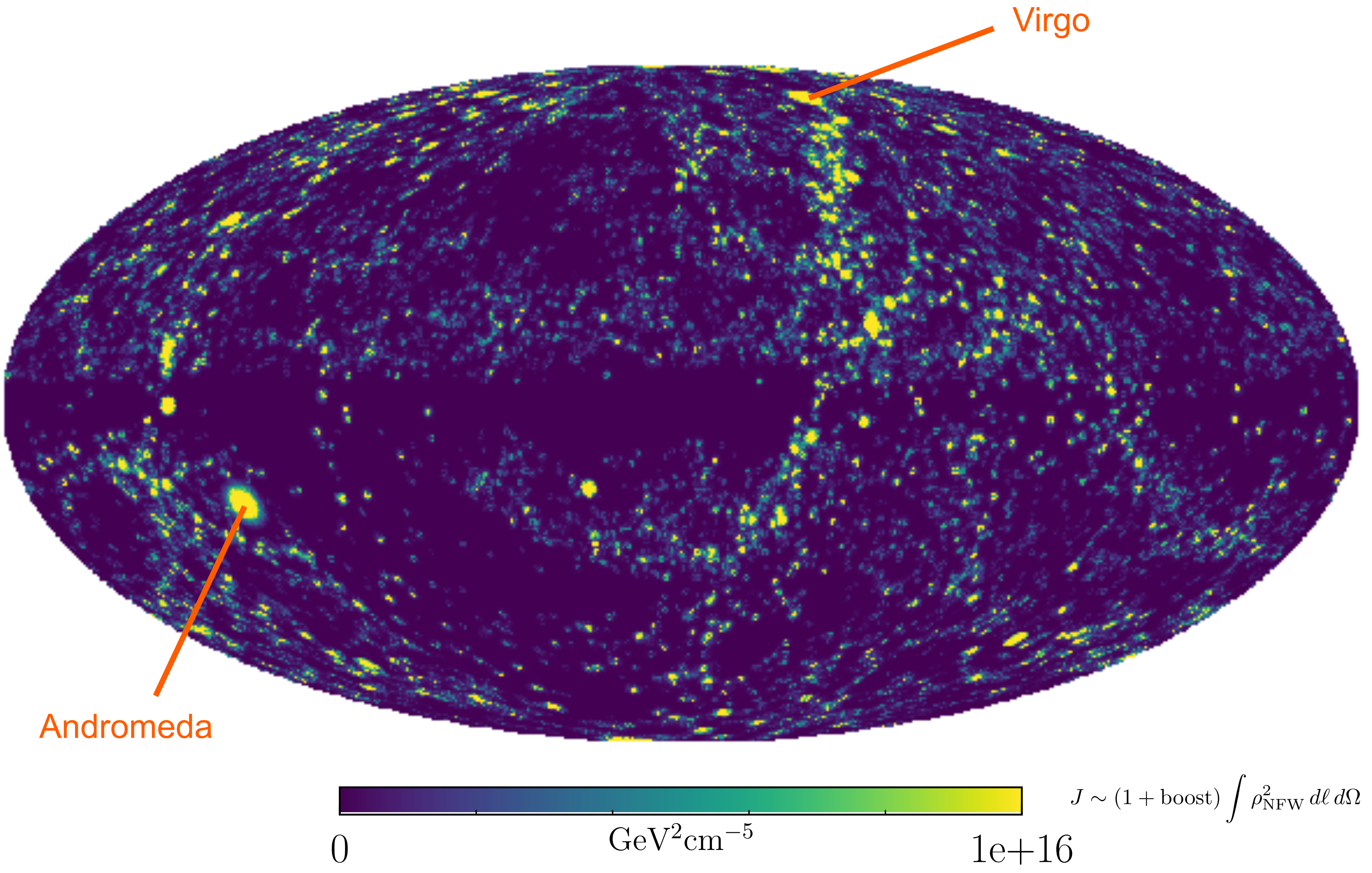
Recent catalogs identify groups of nearby galaxies and their associated halo properties

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



…to a Dark Matter Sky Map

Lisanti, Mishra-Sharma, Rodd, and Safdi [in preparation]

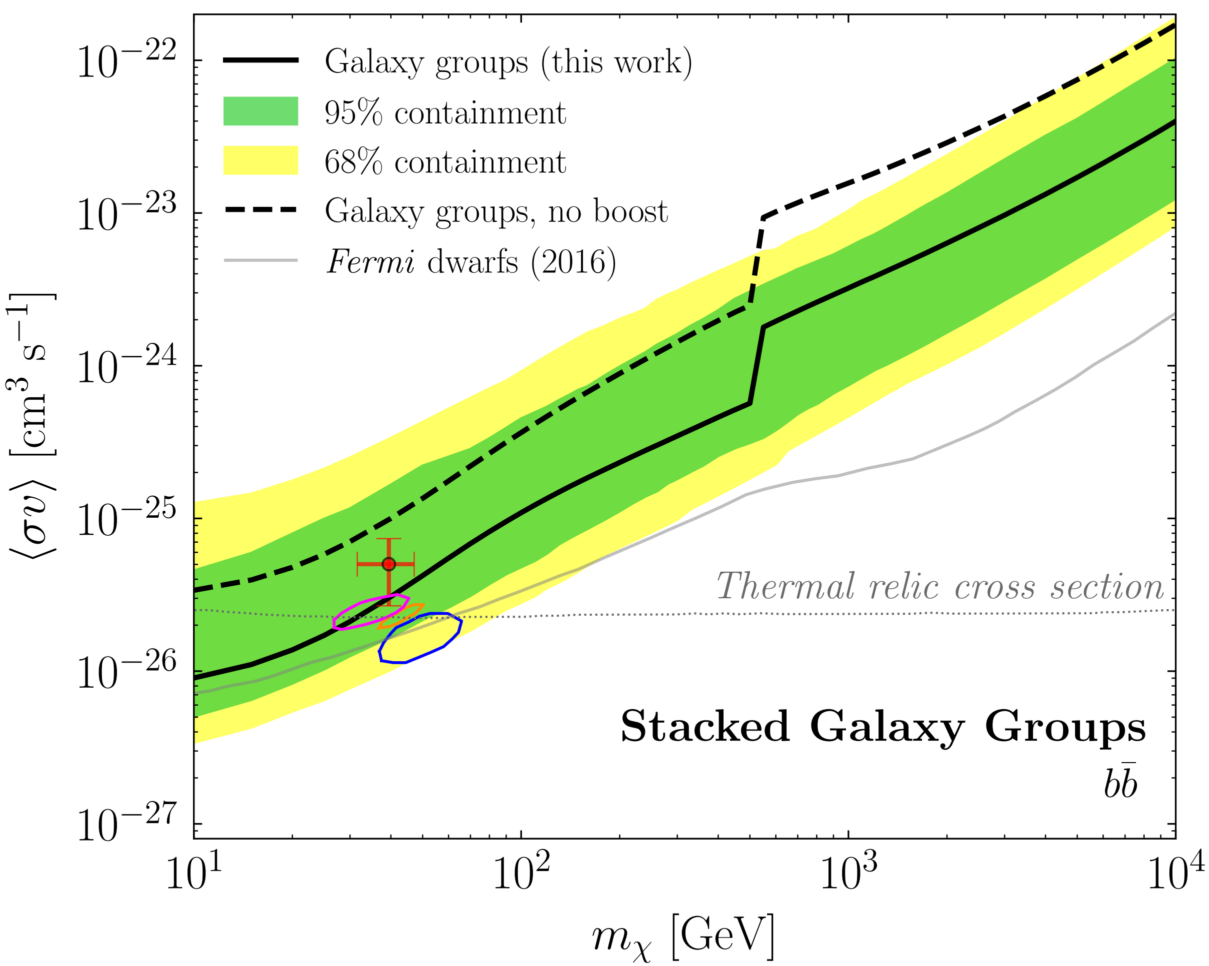


Galaxy Group Limit

Lisanti, Mishra-Sharma, Rodd, and Safdi [in preparation]

Stacked analysis of ~500 brightest galaxy groups out to z ~ 0.03

Limits are competitive with dwarf galaxies and put dark matter interpretation of GeV excess further into tension



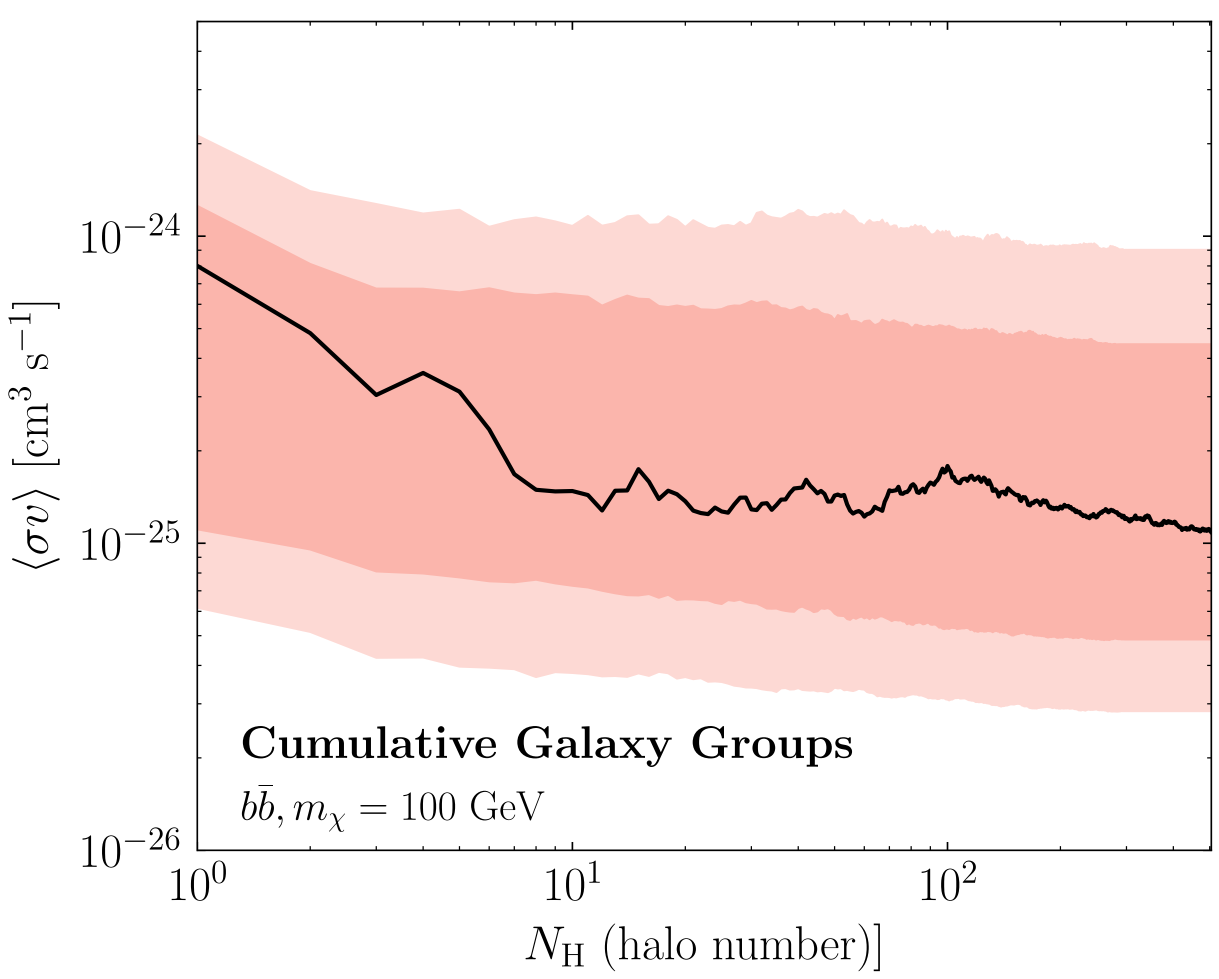
See parallel session talk by Siddharth Mishra-Sharma

Galaxy Group Limit

Lisanti, Mishra-Sharma, Rodd, and Safdi [in preparation]

Largest gain in the stacking comes from the ~10 brightest halos in the catalog

Virgo, NGC0253, NGC3031, Centaurus, NGC1399, NGC4594, IC1613, NGC4736, NGC4565, Hydra



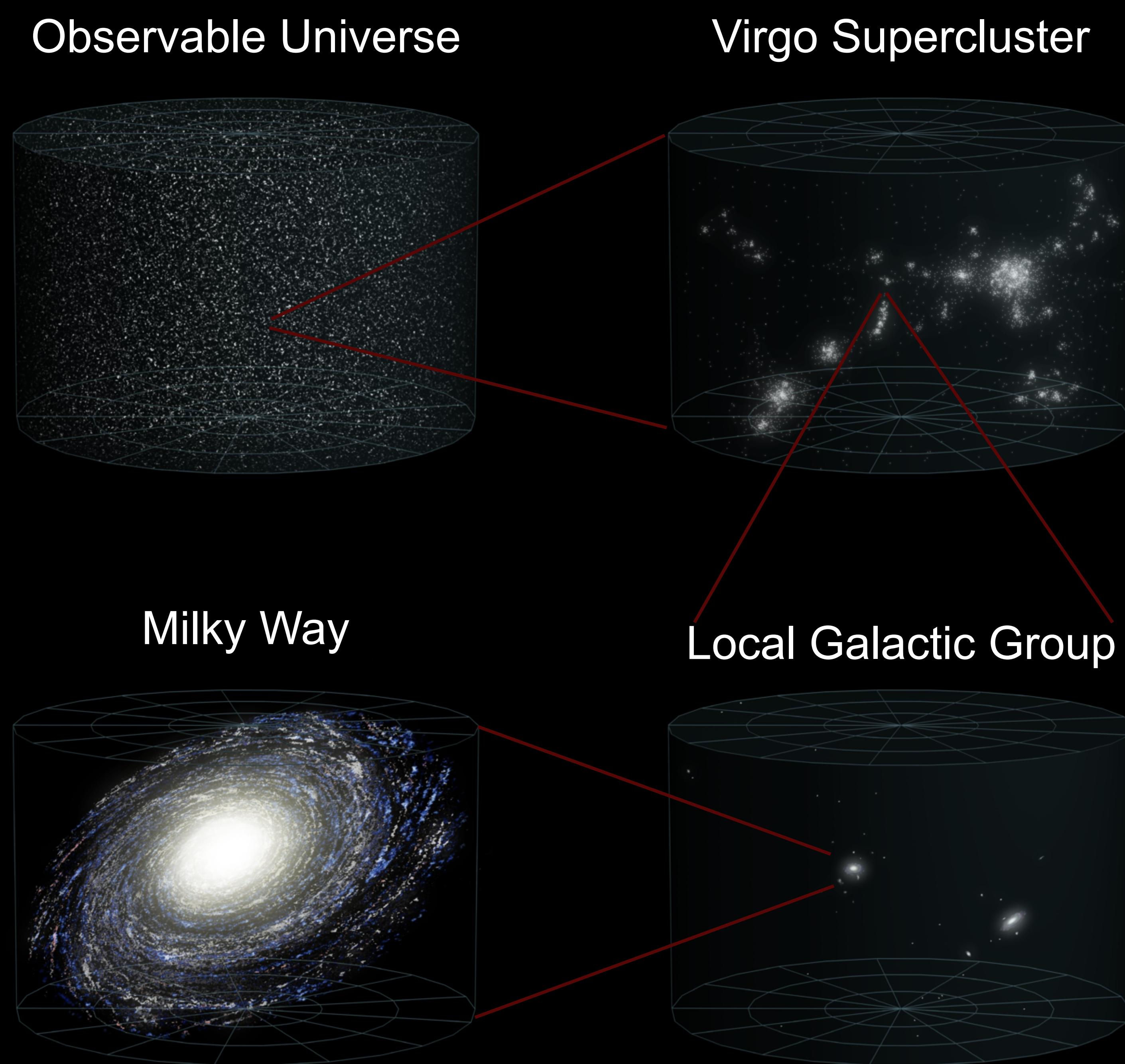
Public Catalog

Lisanti, Mishra-Sharma, Rodd, and Safdi [in preparation]

Our work provides a new catalog of extragalactic dark matter targets

This catalog will be publicly available and will include J-factors, masses, concentrations, and boost factors for each target

Name	$\log_{10} J$ [GeV^2 cm^{-5} sr]	$\log_{10} M_{\rm vir}$ [$M_\odot$]	$z \times 10^{-3}$	ℓ [deg]	b [deg]	$\log_{10} c_{\rm vir}$	$b_{\rm sh}$	$\theta_{\rm vir}$	$\mathrm{TS}_{\rm max}$
Andromeda	19.79	12.44	0.17	121.51	-21.79	1.04	2.64	28.26	3.01
Virgo	19.12	14.66	3.58	283.78	74.49	0.80	4.53	7.36	1.05
NGC5128	18.90	12.95	0.82	307.88	17.08	0.99	3.14	8.63	0.00
NGC0253	18.76	12.78	0.79	98.24	-87.89	1.01	2.90	7.85	0.57
Maffei 1	18.69	12.69	0.78	136.23	-0.44	1.02	2.81	7.42	6.83
NGC 6822	18.59	10.71	0.11	25.34	-18.40	1.18	1.70	11.69	21.17
NGC3031	18.59	12.63	0.83	141.88	40.87	1.02	2.76	6.71	0.00
Centaurus	18.35	14.62	8.44	302.22	21.65	0.81	4.50	3.06	5.21
NGC1399	18.31	13.87	4.11	236.62	-53.88	0.89	3.87	3.50	38.77
IC0356	18.27	13.57	3.14	138.06	12.70	0.93	3.51	3.65	0.00
NGC4594	18.27	13.36	2.56	299.01	51.30	0.95	3.36	3.81	0.00
Norma	18.18	15.10	17.07	325.29	-7.21	0.75	5.17	2.20	1.56
IC 1613	18.17	10.66	0.17	129.74	-60.58	1.18	1.67	7.31	0.00
Perseus	18.14	15.08	17.62	150.58	-13.26	0.75	5.16	2.10	0.00


Observable Universe
Virgo Supercluster
Milky Way
Local Galactic Group

Back Up Slides

Galaxy Group Selection

Some clusters emit gamma-rays because of standard cosmic-ray processes

We exclude galaxies with residuals that are inconsistent with dark matter

A galaxy group is excluded if it…

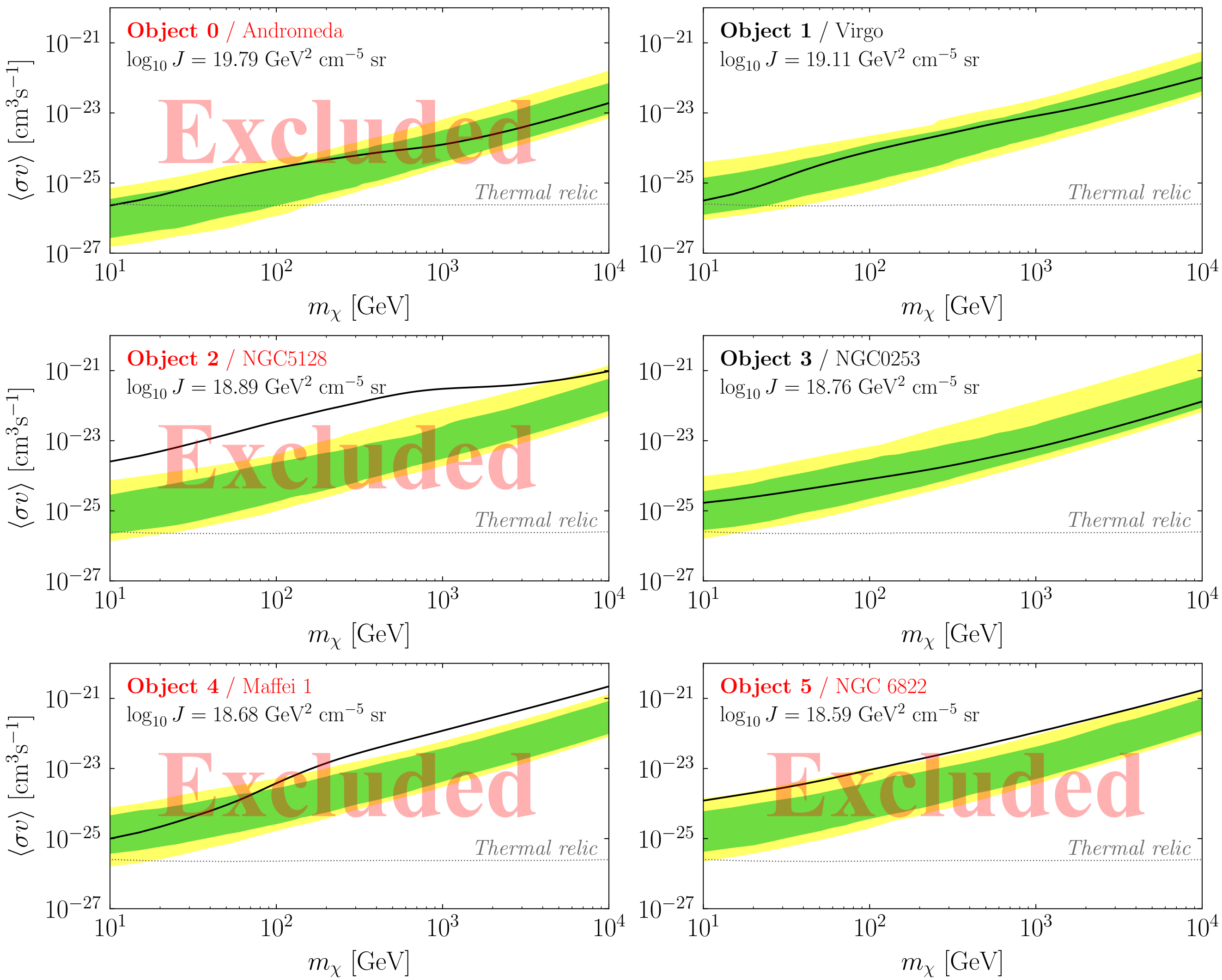
- is located near the galactic plane
- overlaps with another halo
- has a significant 3σ gamma-ray excess
  and
  this excess is strongly excluded by dark matter limits set by other galaxy groups

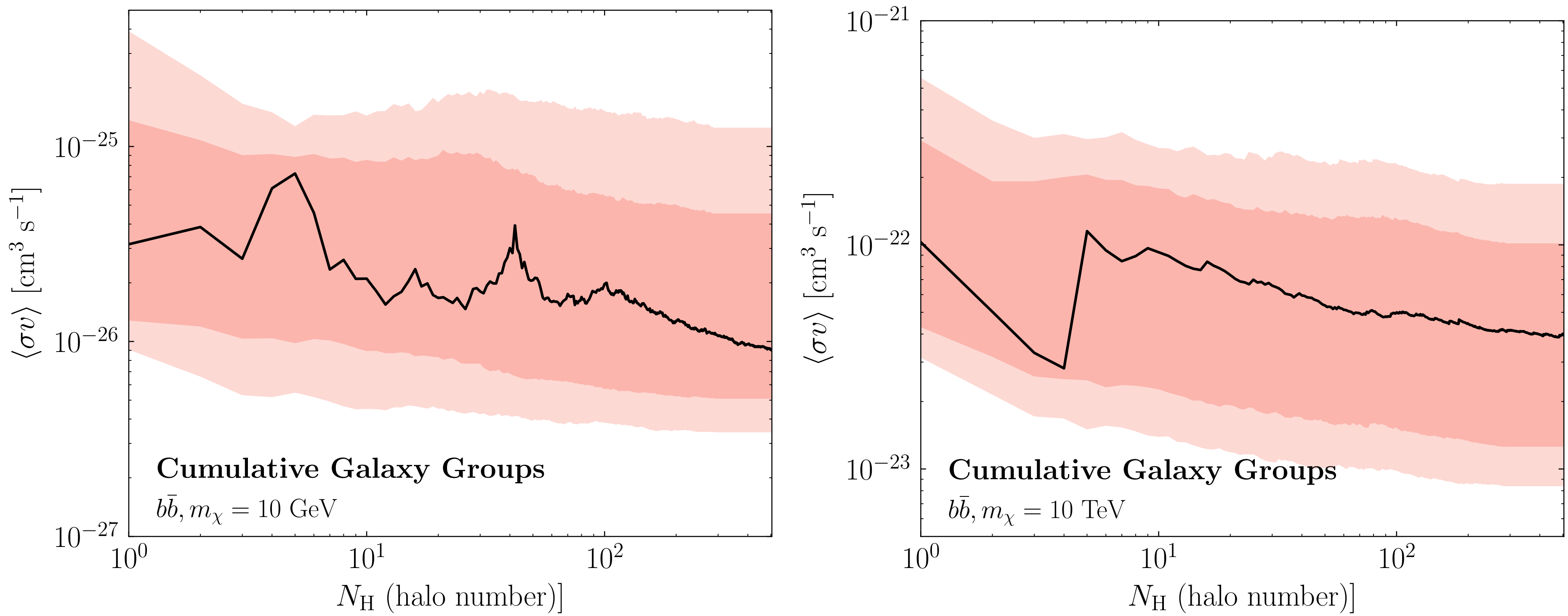
We performed extensive tests to ensure that an actual signal would not be excluded by these requirements

Galaxy Group Selection

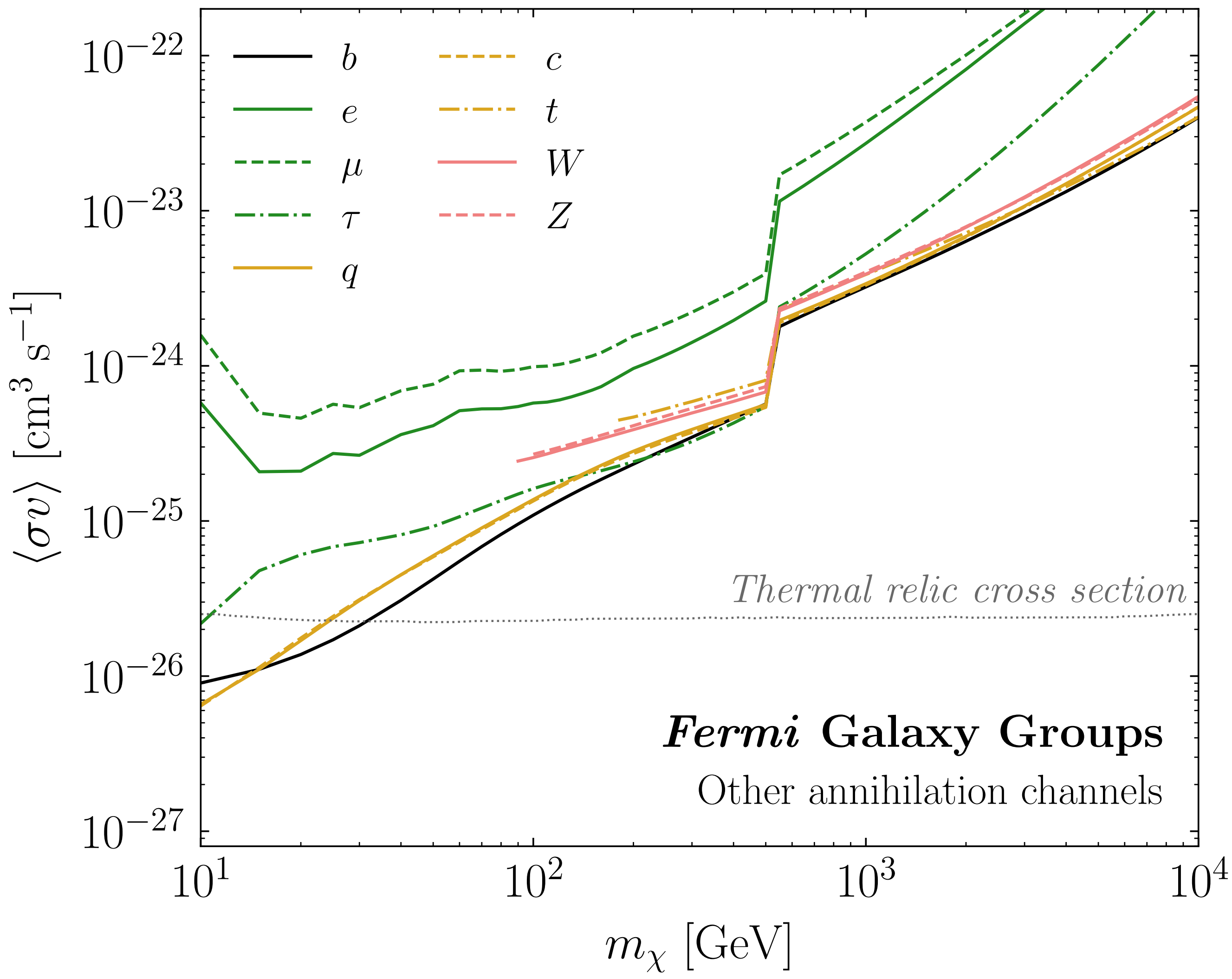
Starting from 1000 galaxy groups, about 400 pass the selection criteria

Example: Top 6 Halos, Ranked by J-factor

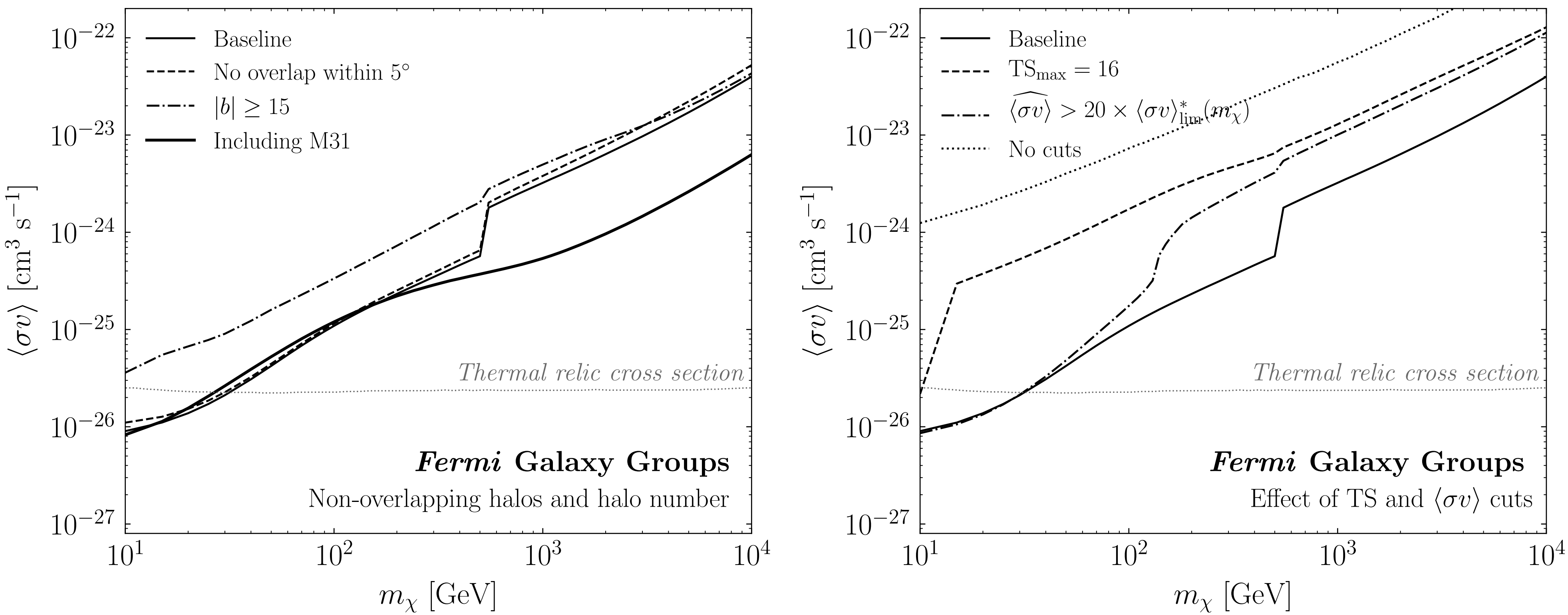




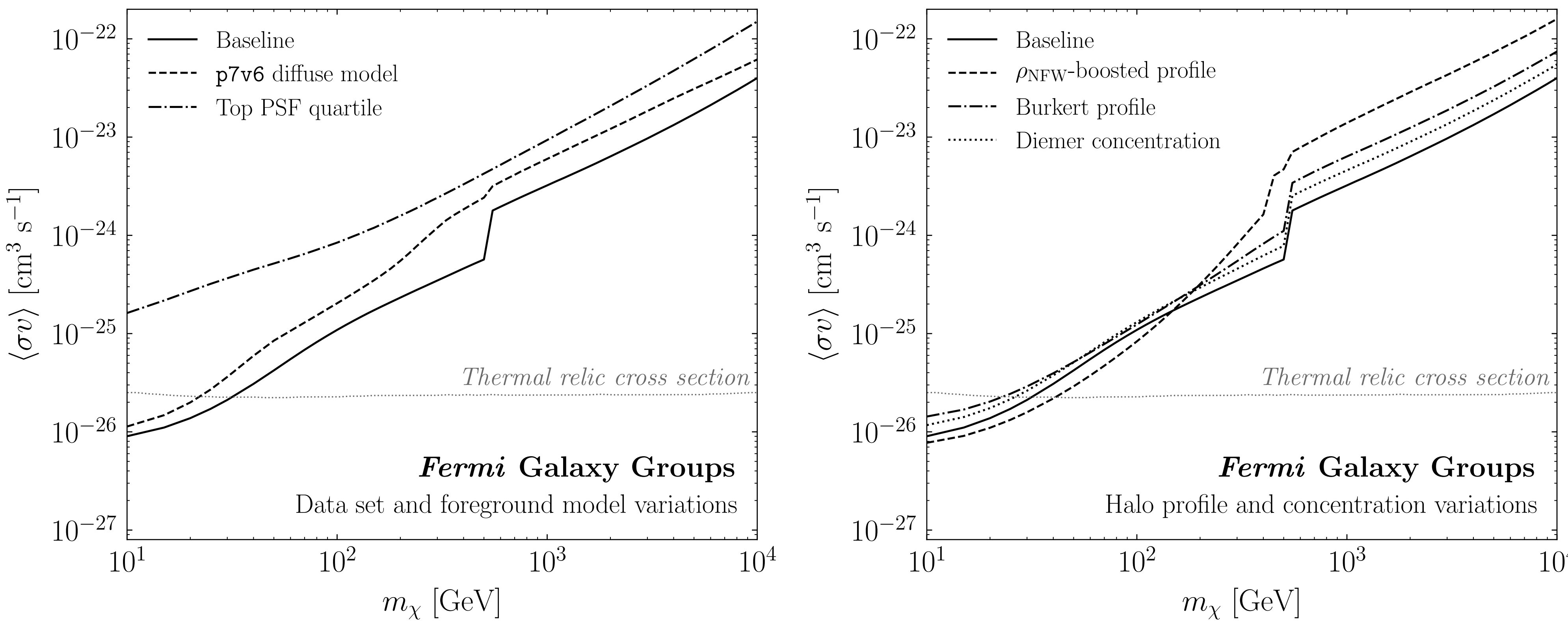
10^{-25}
10^{-26}
10^{-27}
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
Cumulative Galaxy Groups
$b\bar{b}, m_\chi = 10$ GeV
10^0
10^1
10^2
$N_{\rm H}$ (halo number)]
10^{-21}
10^{-22}
10^{-23}
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
Cumulative Galaxy Groups
$b\bar{b}, m_\chi = 10$ TeV
10^0
10^1
10^2
$N_{\rm H}$ (halo number)]



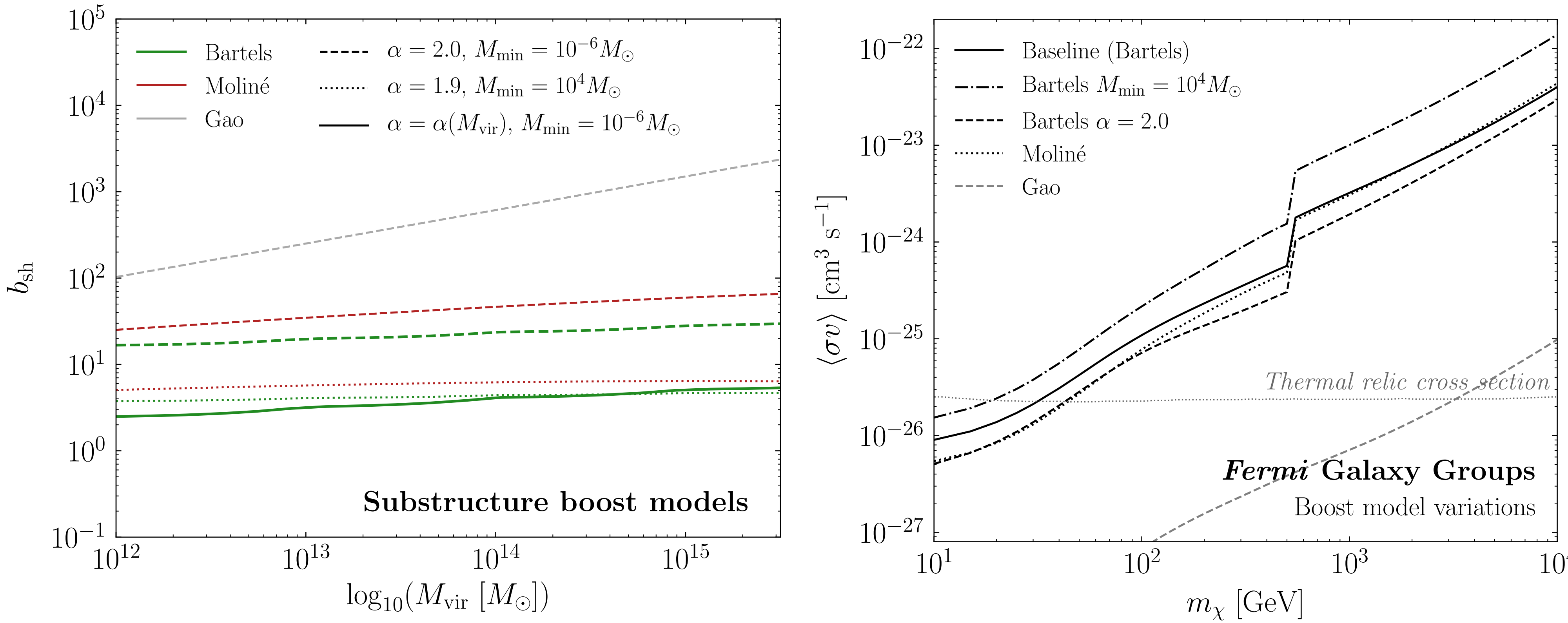
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
10^1
10^2
10^3
10^4
m_χ [GeV]
b
e
μ
τ
q
c
t
W
Z
Thermal relic cross section
***Fermi* Galaxy Groups**
Other annihilation channels



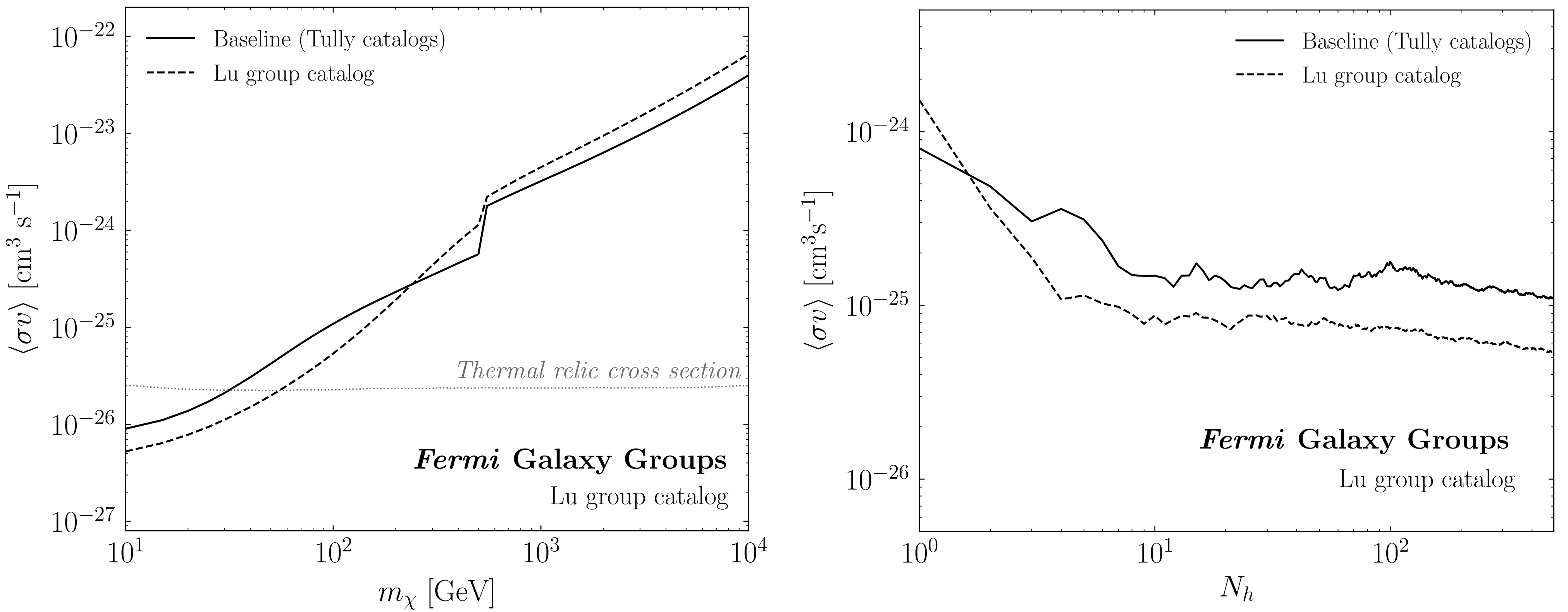
Baseline
No overlap within 5°
$|b| \geq 15$
Including M31
Thermal relic cross section
Fermi Galaxy Groups
Non-overlapping halos and halo number
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]
Baseline
$\mathrm{TS}_{\max} = 16$
$\widehat{\langle \sigma v \rangle} > 20 \times \langle \sigma v \rangle^*_{\lim}(m_\chi)$
No cuts
Thermal relic cross section
Fermi Galaxy Groups
Effect of TS and $\langle \sigma v \rangle$ cuts
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]



Baseline
p7v6 diffuse model
Top PSF quartile
Thermal relic cross section
Fermi Galaxy Groups
Data set and foreground model variations
⟨σv⟩ [cm^3 s^{-1}]
m_χ [GeV]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4
Baseline
$\rho_{\rm NFW}$-boosted profile
Burkert profile
Diemer concentration
Thermal relic cross section
Fermi Galaxy Groups
Halo profile and concentration variations
⟨σv⟩ [cm^3 s^{-1}]
m_χ [GeV]



Bartels
Moliné
Gao
$\alpha = 2.0,\ M_{\rm min} = 10^{-6} M_\odot$
$\alpha = 1.9,\ M_{\rm min} = 10^{4} M_\odot$
$\alpha = \alpha(M_{\rm vir}),\ M_{\rm min} = 10^{-6} M_\odot$
Substructure boost models
$b_{\rm sh}$
$\log_{10}(M_{\rm vir}\ [M_\odot])$
Baseline (Bartels)
Bartels $M_{\rm min} = 10^4 M_\odot$
Bartels $\alpha = 2.0$
Moliné
Gao
Thermal relic cross section
Fermi Galaxy Groups
Boost model variations
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]



Baseline (Tully catalogs)
Lu group catalog
Thermal relic cross section
Fermi Galaxy Groups
Lu group catalog
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
m_χ [GeV]
Baseline (Tully catalogs)
Lu group catalog
Fermi Galaxy Groups
Lu group catalog
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
N_h