Galactic and extragalactic searches for dark matter annihilation

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Princeton University

Based on:

M. Lisanti, **SM**, N. Rodd and B. Safdi [1708.09385]

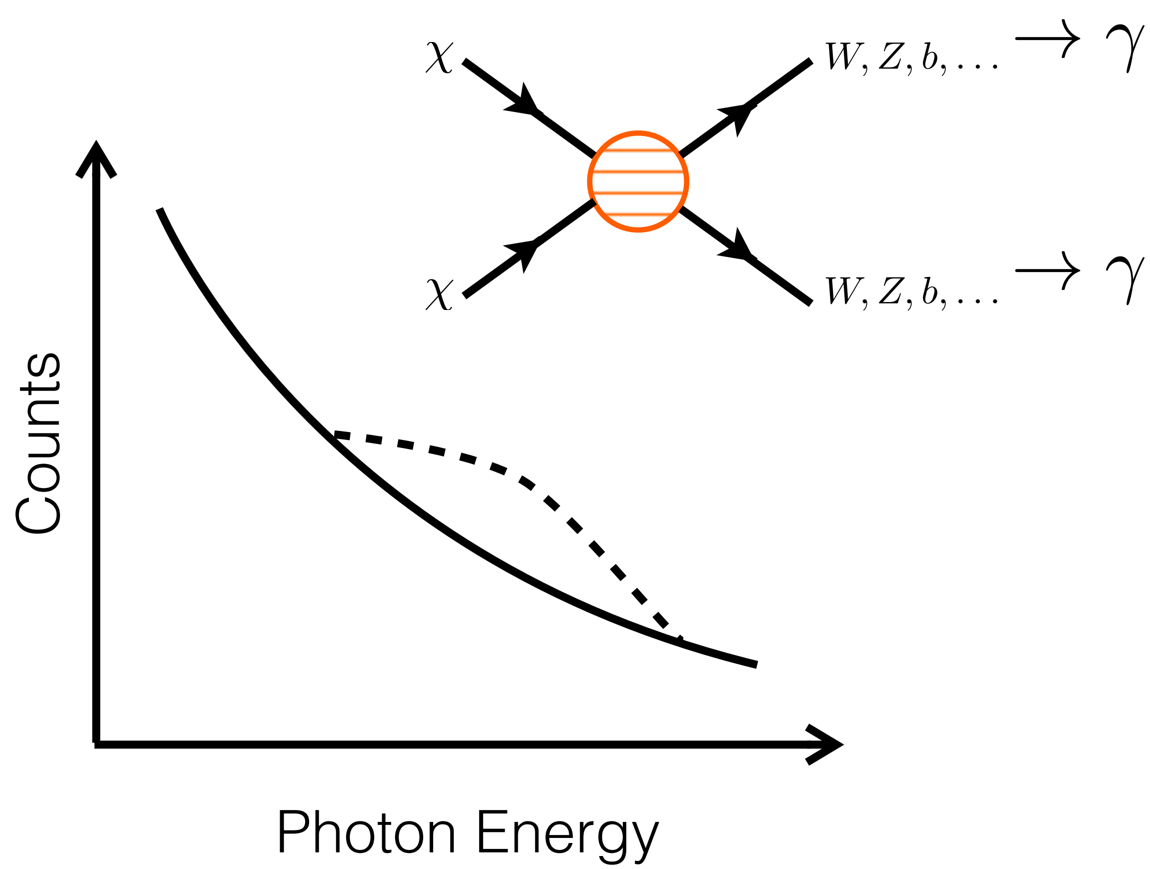
M. Lisanti, **SM**, N. Rodd, B. Safdi and R. Wechsler [1709.00416]

L. Chang, M. Lisanti, **SM** [1804.04132]

30th Recontres de Blois
Blois, France
June 5, 2018

PRINCETON UNIVERSITY

Dark matter annihilation today



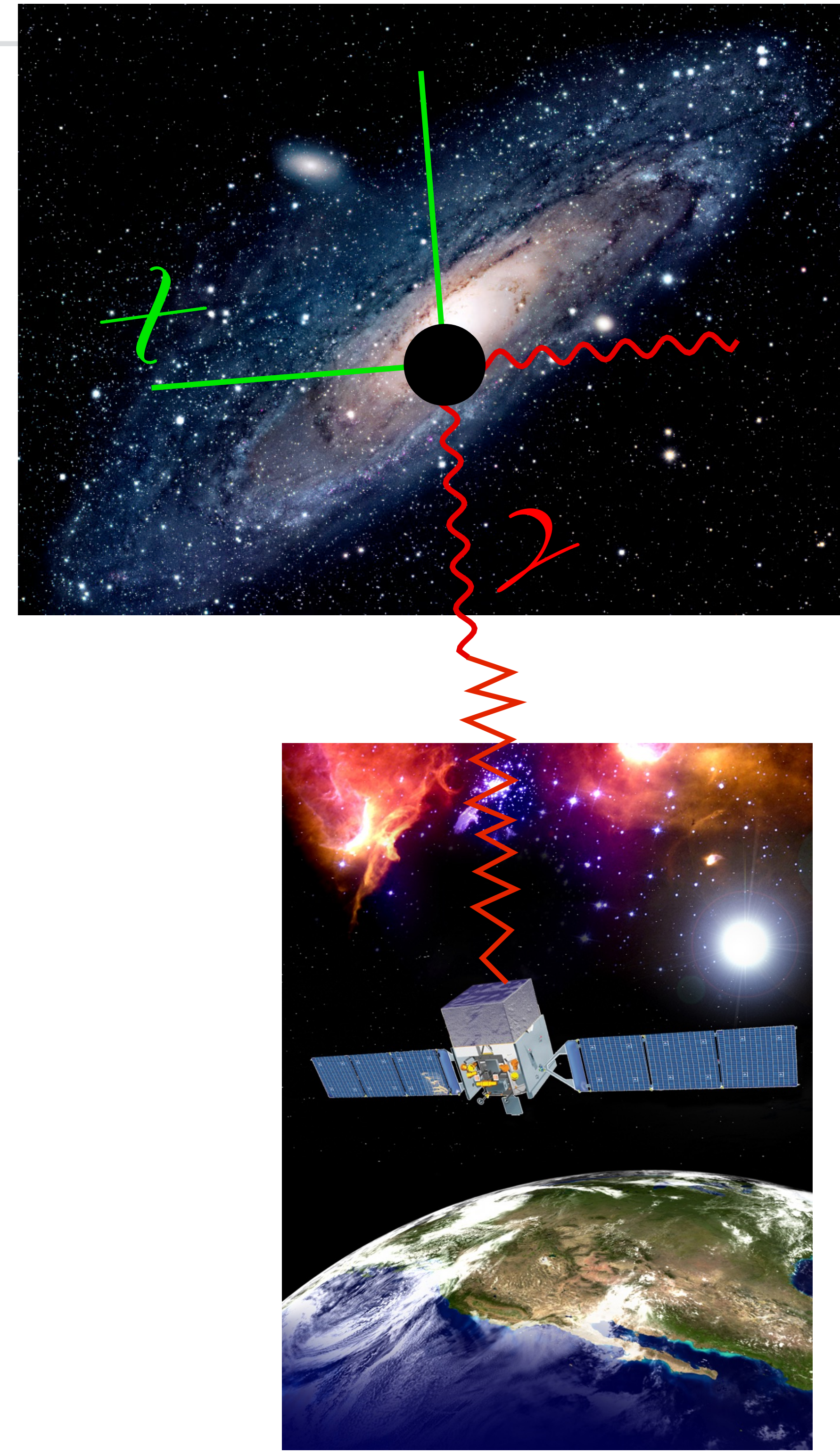
- Dark matter (DM) particles may annihilate to standard model (SM) with subsequent production of photons
- Would enhance gamma-rays from DM rich regions

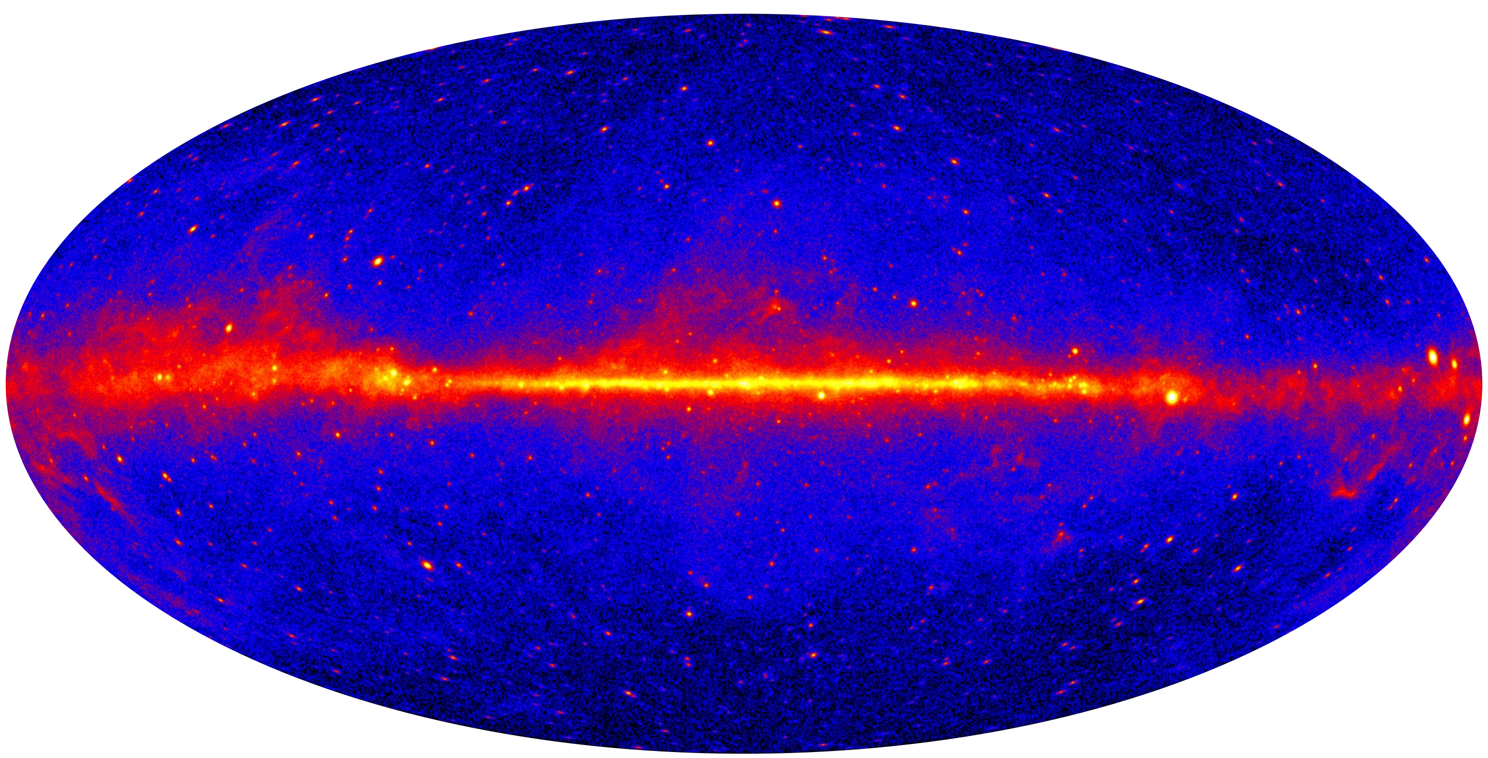
The photon flux for dark matter annihilation is given by

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\text{J-factor}}\ .$$

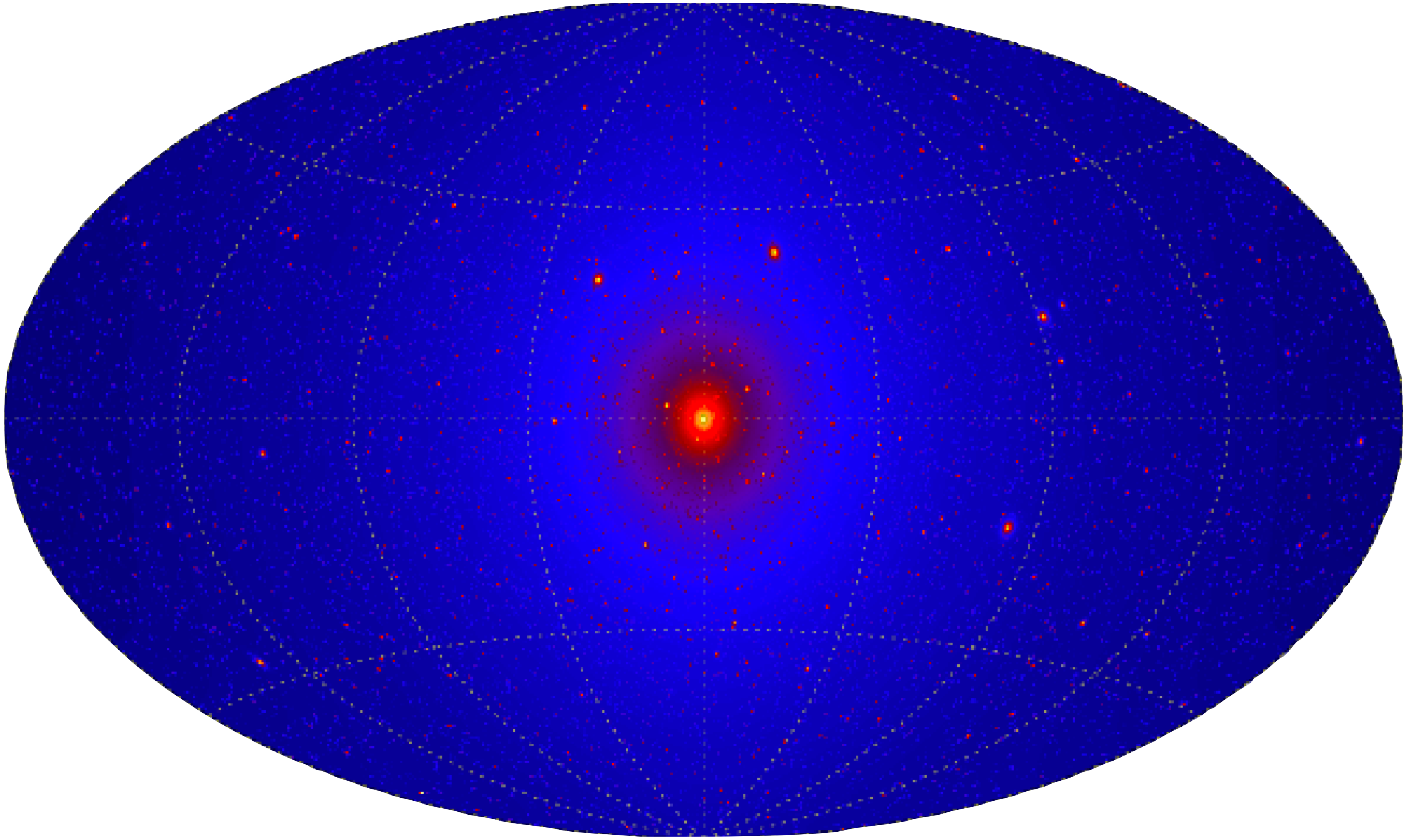
The *Fermi* gamma-ray sky

- **Fermi Large Area Telescope (LAT):** pair-conversion telescope consisting of layers of tungsten and silicon on top of a calorimeter
- **Sensitive to EW scale thermal DM!**





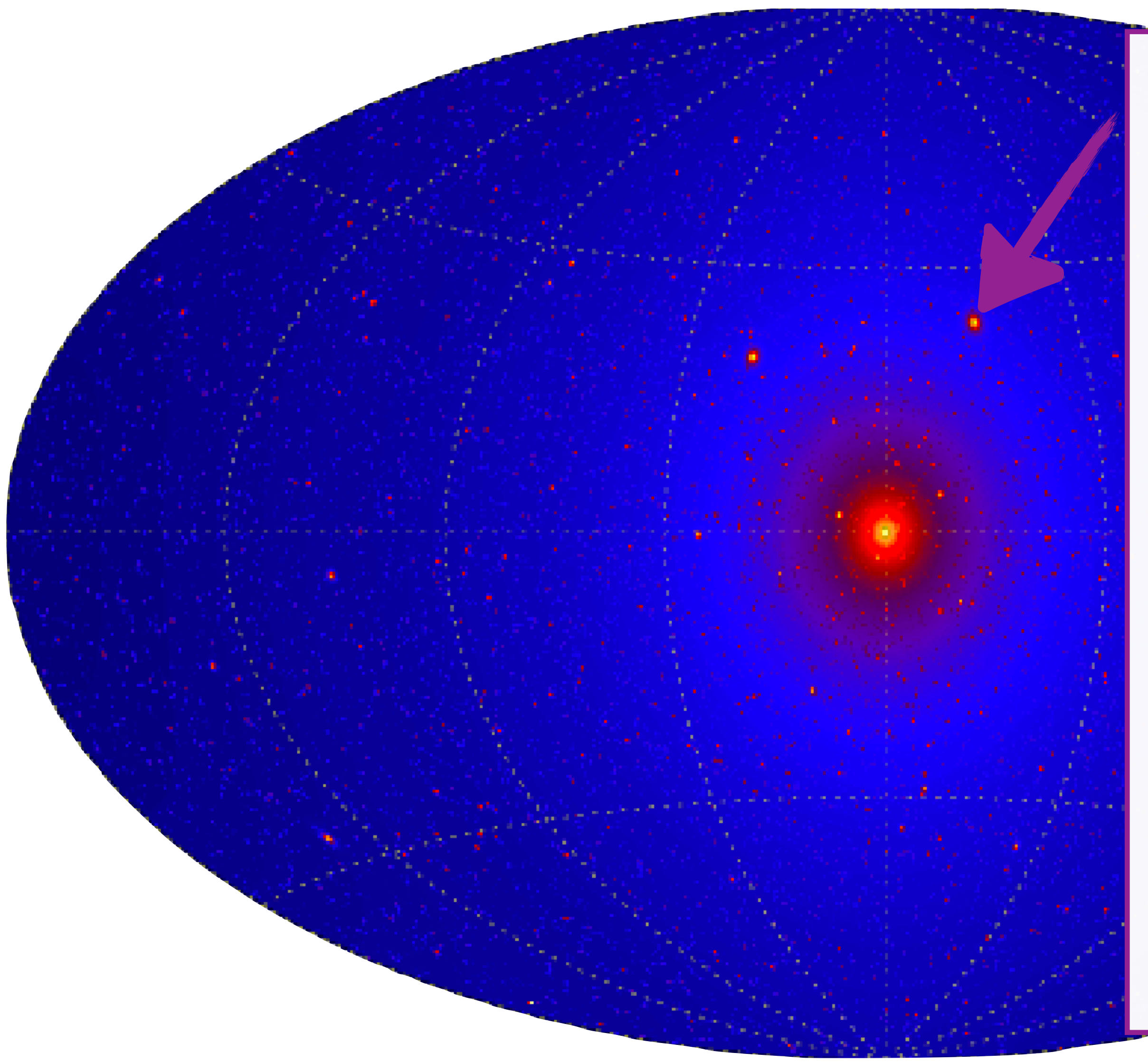
Where should we look?



$$\Phi_{\rm DM} \propto J \sim \int ds\, \rho^2$$

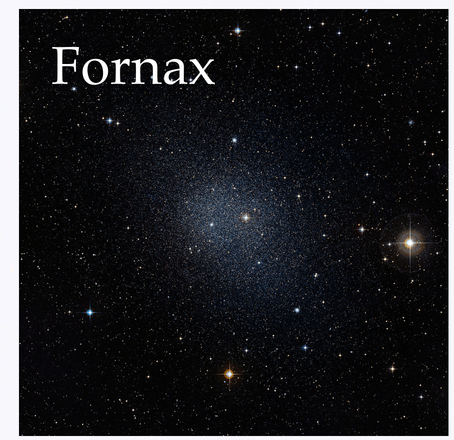
Image taken from [0908.0195]

Where should we look?



Milky Way Dwarfs

- Dark matter dominated
- Many discovered recently



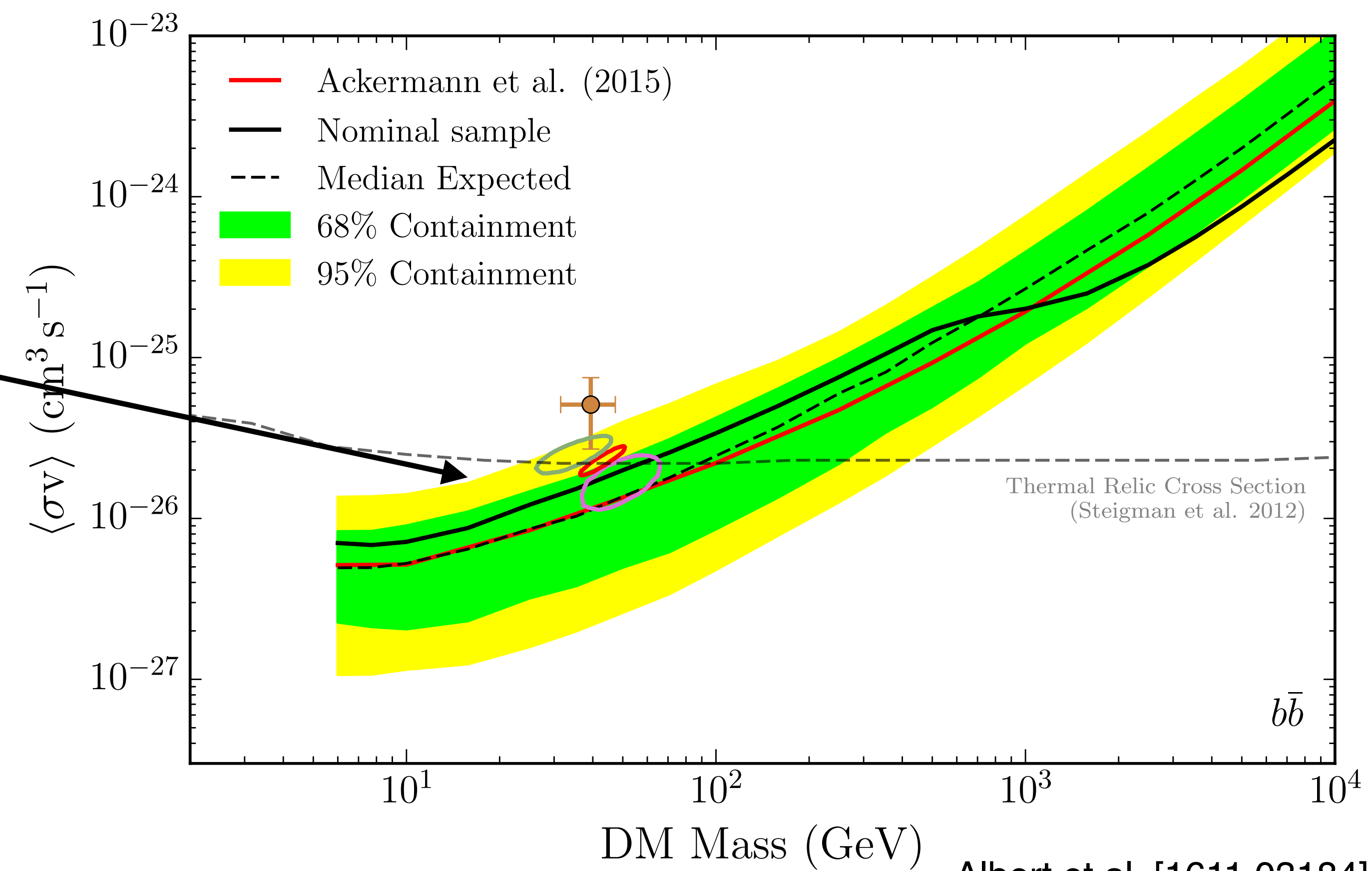
See *Fermi*-LAT Collaboration:
[1310.0828,1503.02641,1611.03184]

$$\Phi_{\mathrm{DM}} \propto J \sim \int ds\, \rho^2$$

Image taken from [0908.0195]

Dark matter in the Local Group: dwarf galaxies

Observations are becoming sensitive to thermal weak-scale dark matter



Albert et al. [1611.03184]

Dark matter in the Local Group: dwarf galaxies

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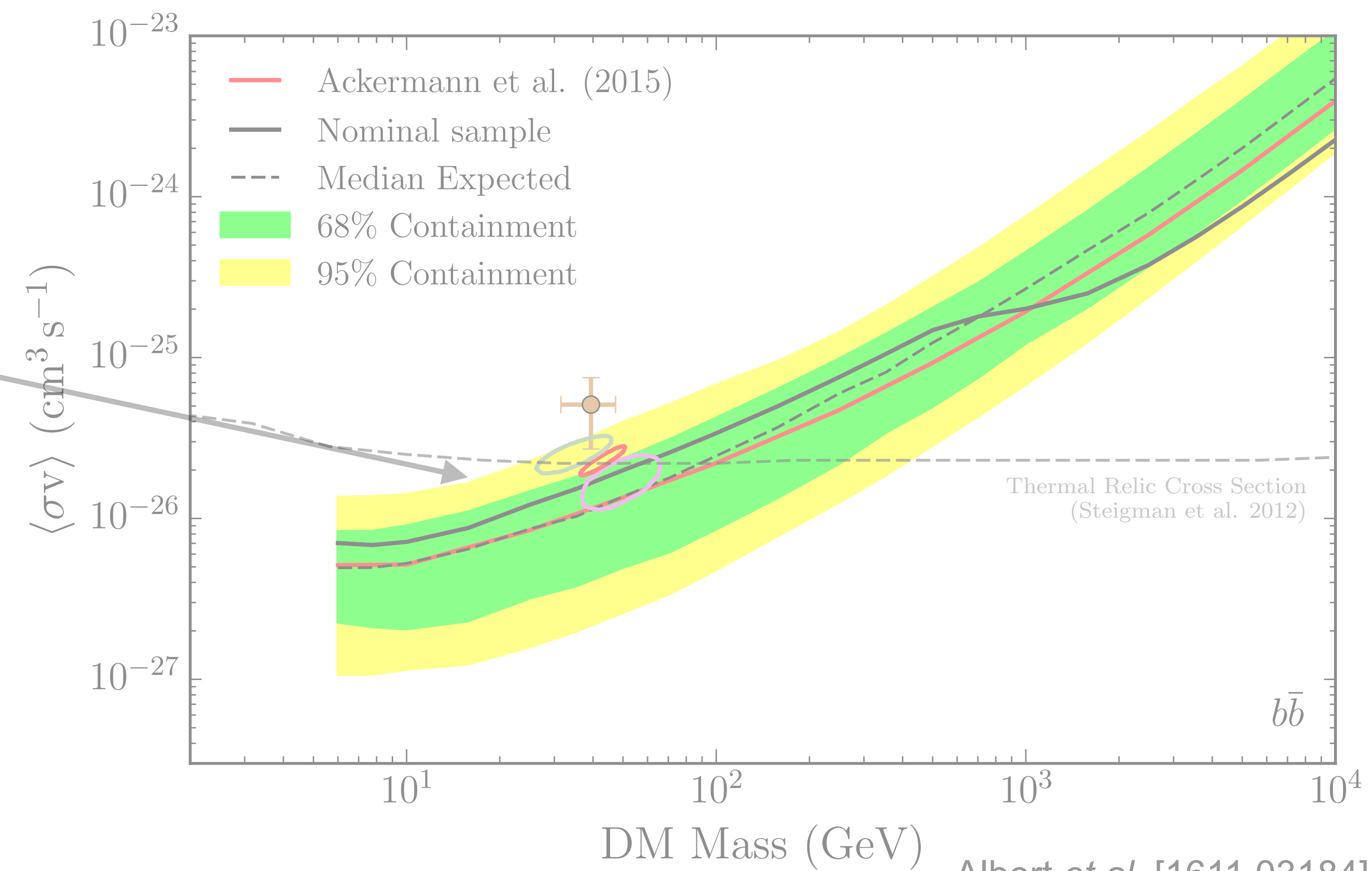

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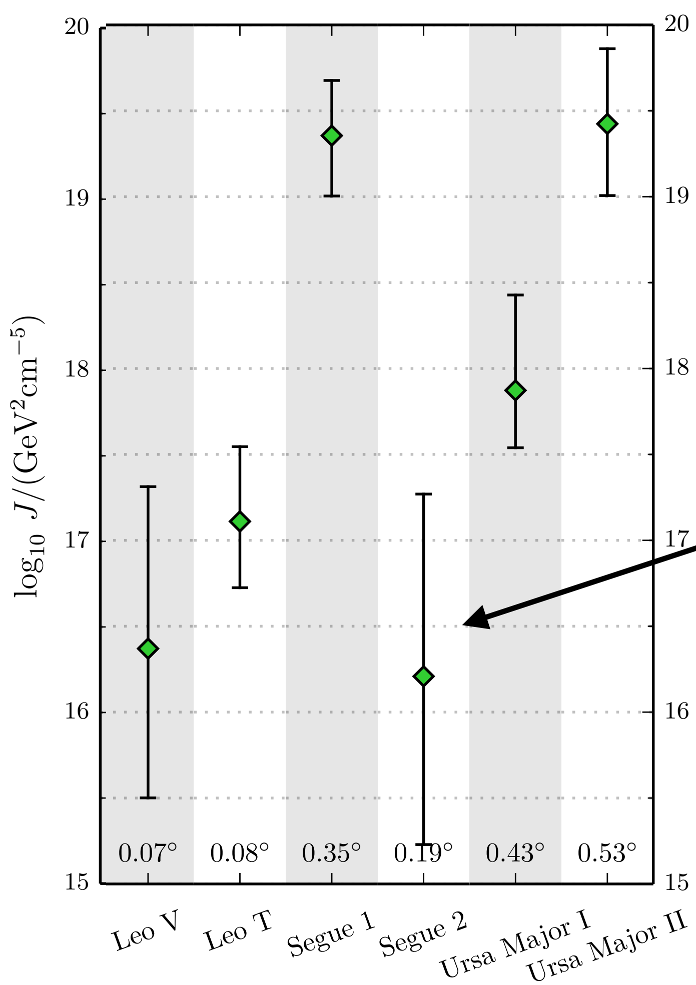
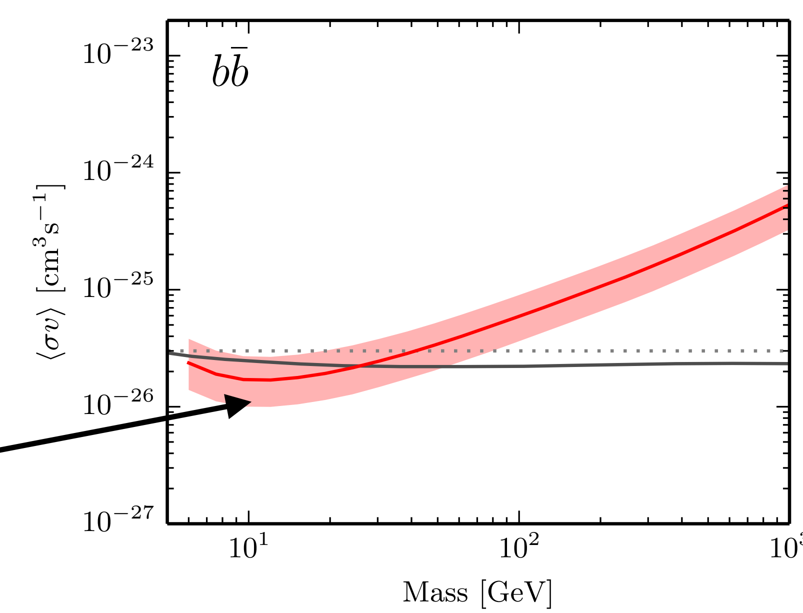


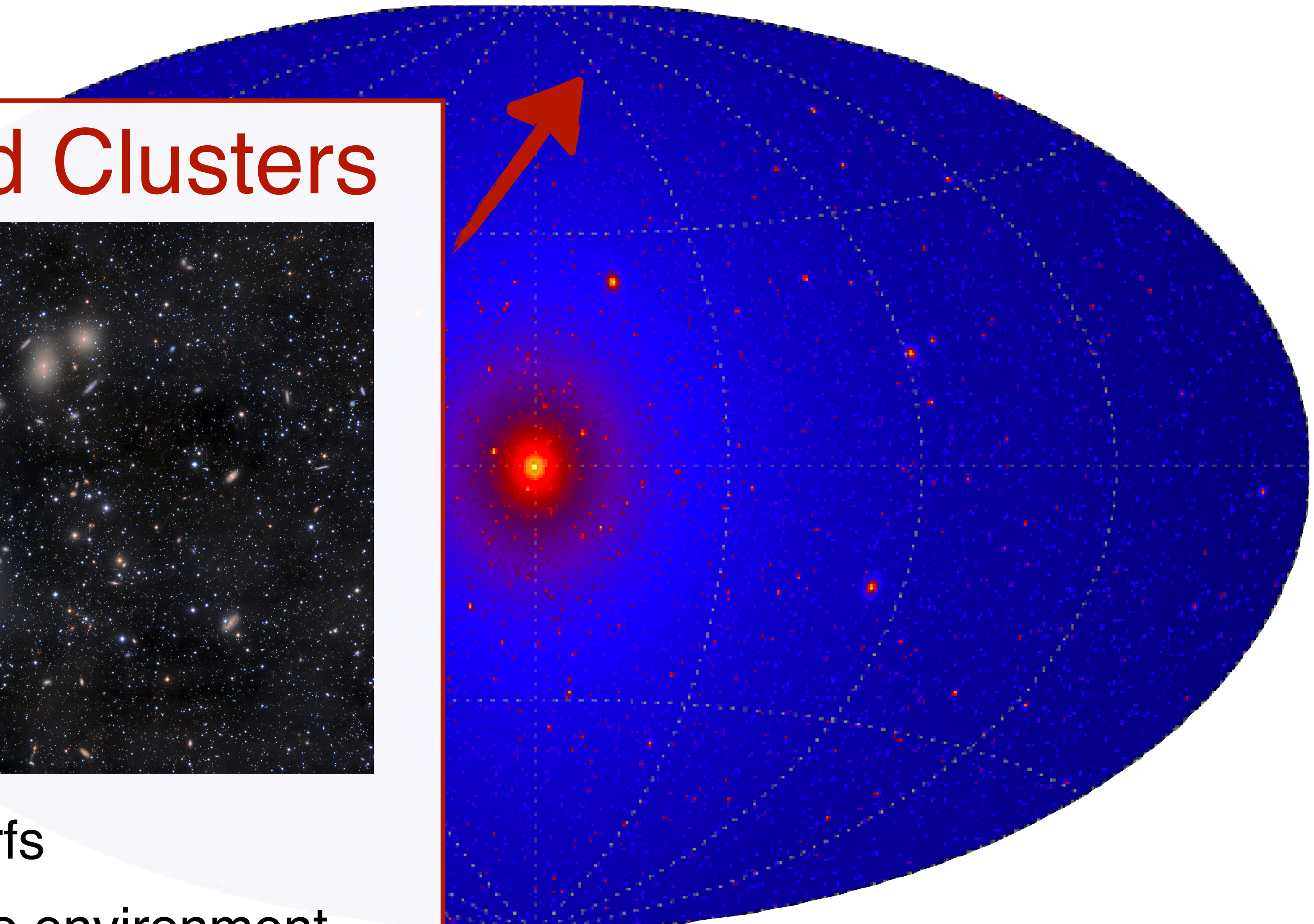
Large uncertainties remain

Assumptions can have a big effect on sensitivity



Geringer-Sameth *et al.* [1410.2242]

Where should we look?



Galaxies and Clusters

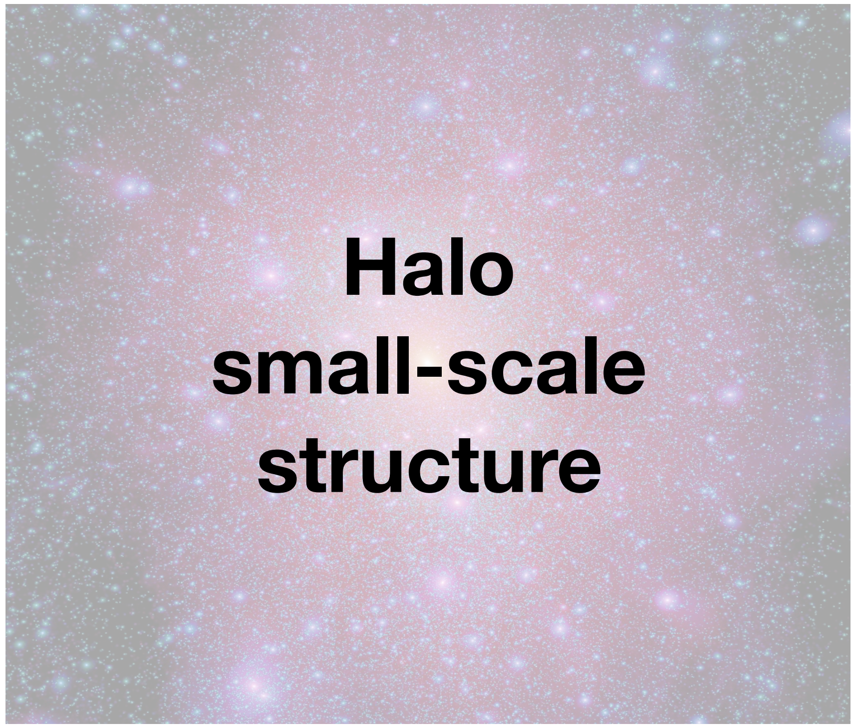
- Dimmer than dwarfs
- Hard to model halo environment

$$\Phi_{\rm DM} \propto J \sim \int ds\, \rho^2$$

Image taken from [0908.0195]

Extragalactic DM

We take advantage of recent progress in understanding…

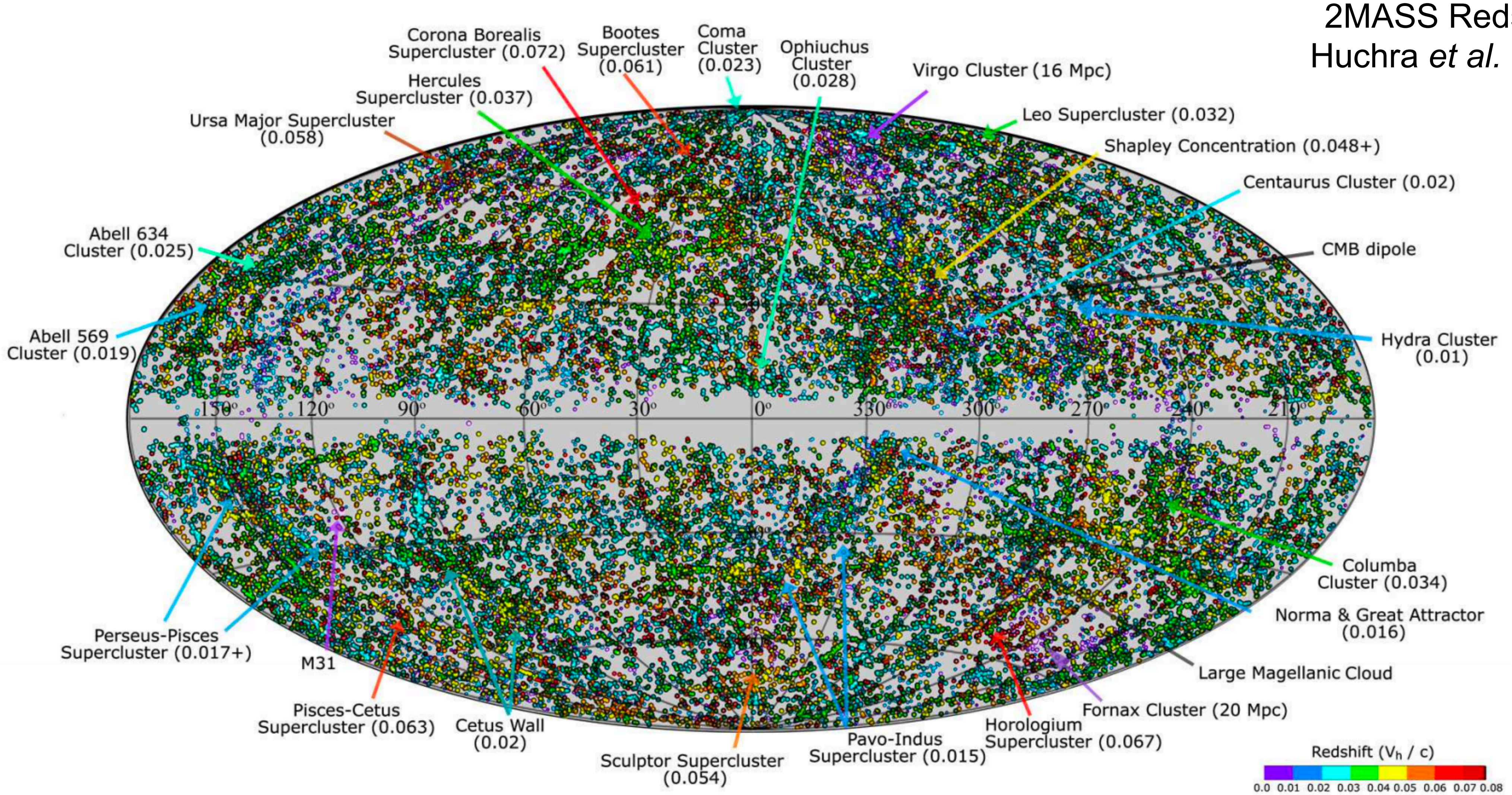


… to model galaxy clusters and groups as annihilation targets

Building a map of extragalactic DM

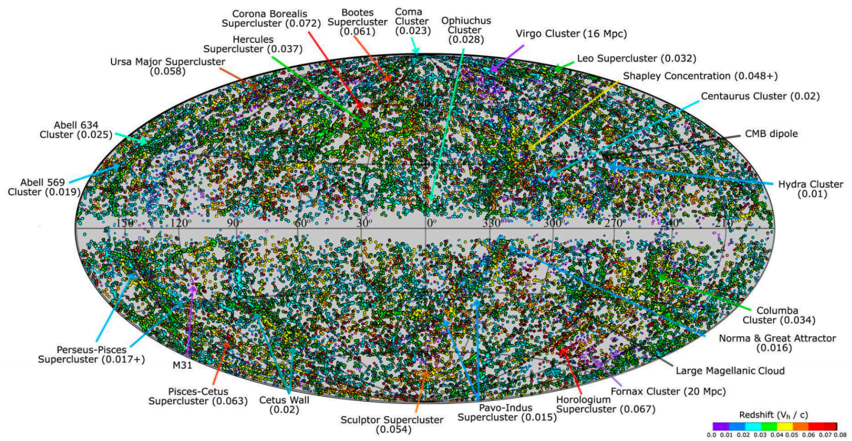
Starting point: a catalog of galaxies, e.g. 2MASS

2MASS Redshift Survey
Huchra *et al.* [1108.0669]



How do we go from galaxies to DM?

Building a map of extragalactic DM



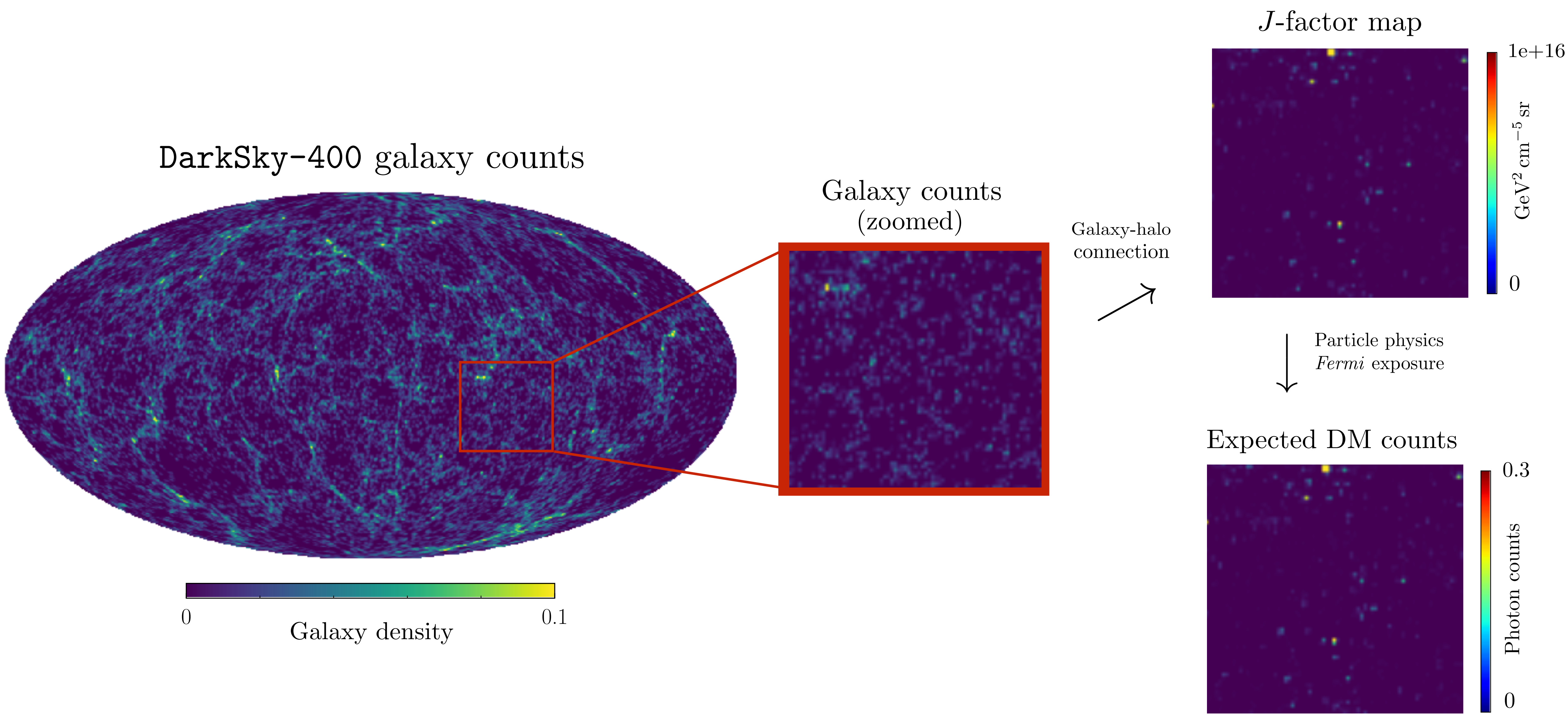
$$J = (1 + b_{\rm sh}) \int \rho^2 (s, \Omega)\, ds d\Omega$$

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}, \quad c_{\rm vir} \equiv r_{\rm vir}/r_s$$

$$\Rightarrow J \sim (1 + {\color{red} b_{\rm sh}}) \frac{{\color{red} M_{\rm vir} c_{\rm vir}^3}}{d_A^2[{\color{red} z}]} \rho_c$$

Model all 4 for every galaxy group

Building a map of extragalactic DM



4096^3 particles; 400 Mpc/*h* box;
Skillman *et al.* 1407.2600;
darksky.slac.stanford.edu

Use DarkSky *N*-body simulation and galaxy catalog as testing ground

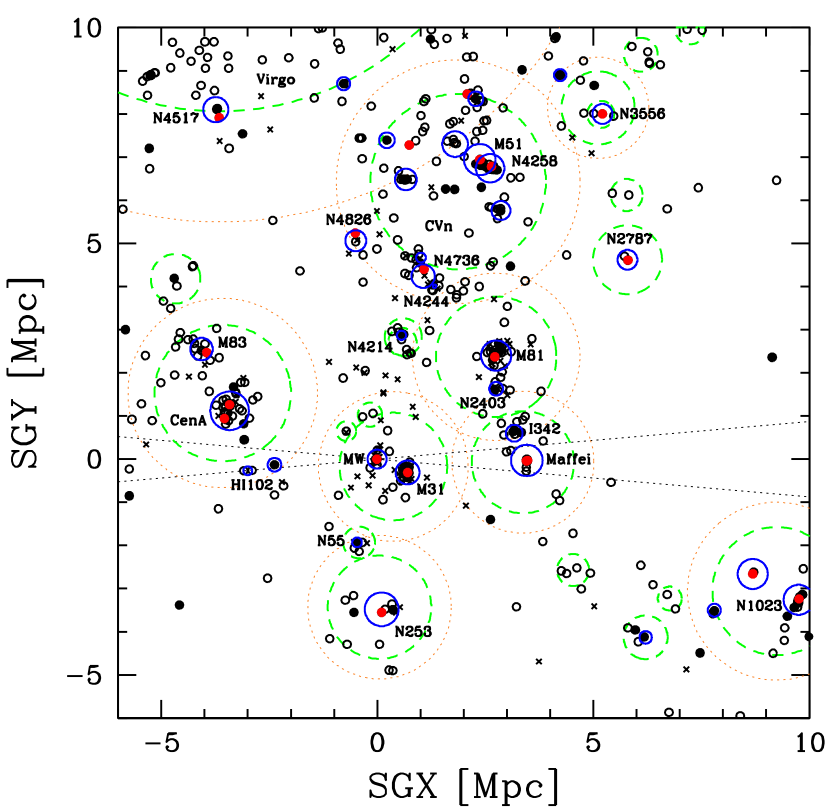
Galaxy group catalogs

Main catalog: Kourkchi and Tully [1705.08068]

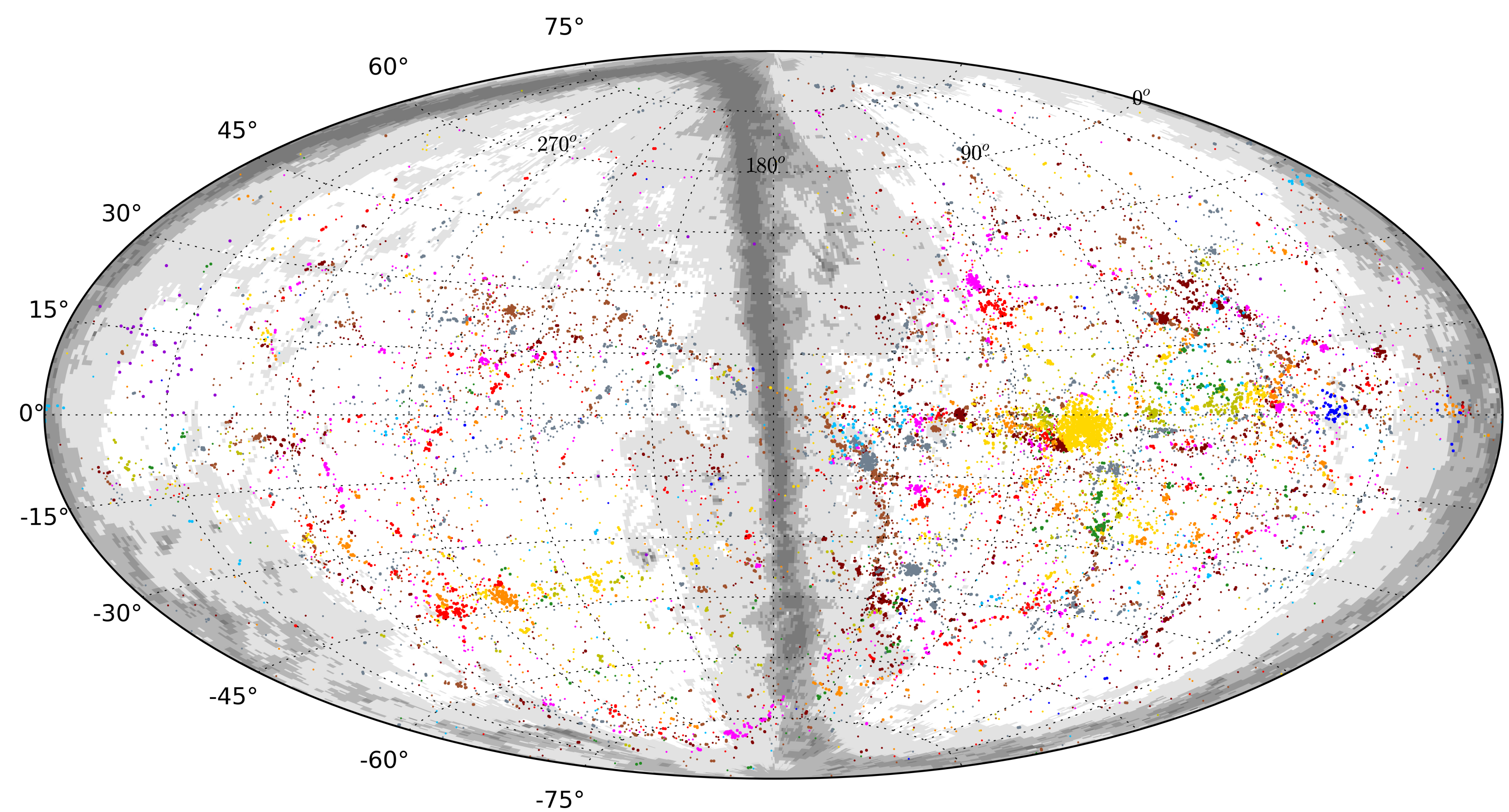
$$z \lesssim 0.01$$

Based on several nearby galaxy catalogs
(2MASS, LEDA, NED, CosmicFlow3…)

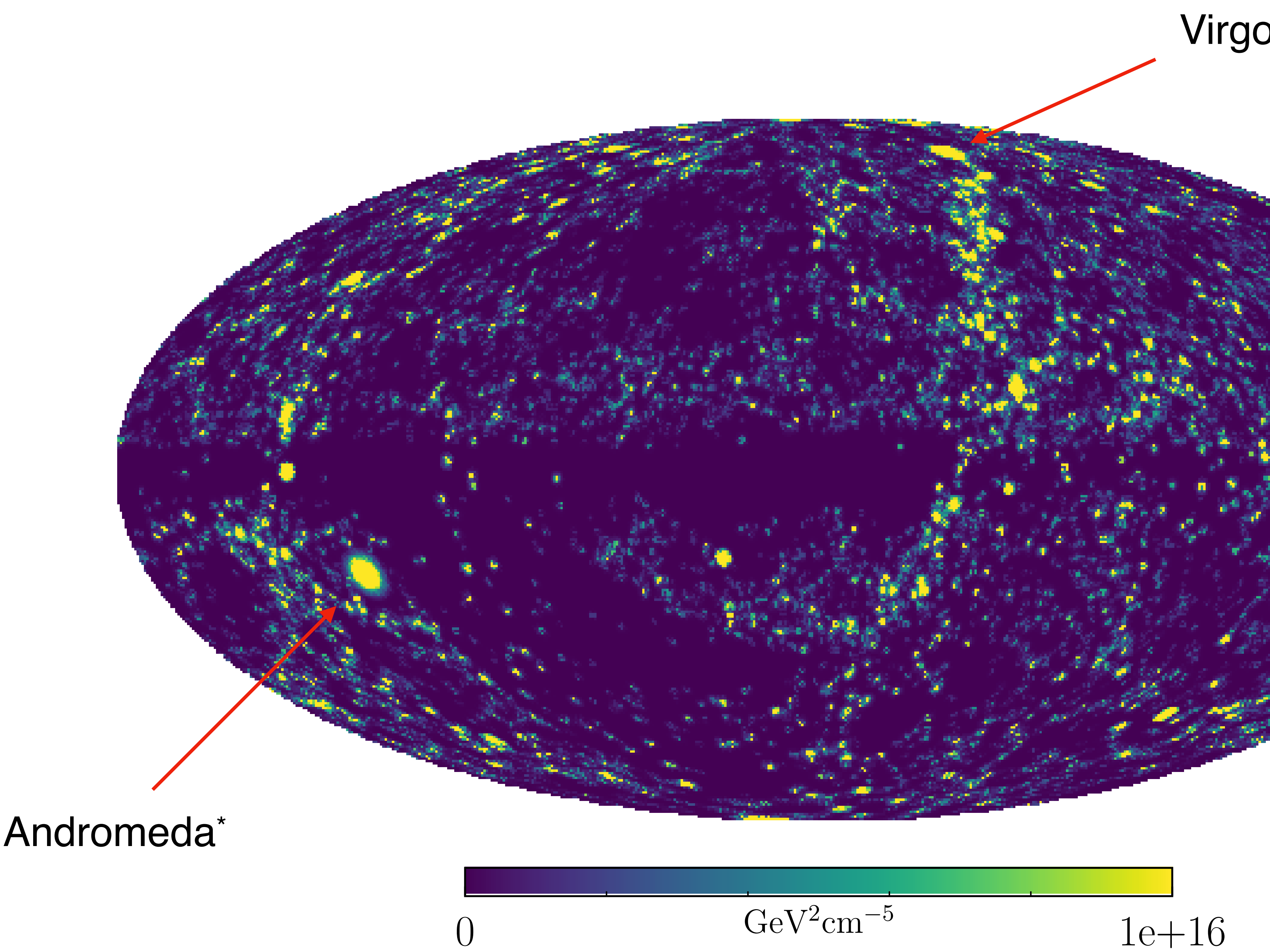
Nearby galaxies and groups



All groups



Full sky *J*-factor map



* Not included in analysis

Extragalactic dark matter targets catalog

https://github.com/bsafdi/DMCat

Send catalogs through our pipeline to obtain table of **DM properties:**

J-factor **Halo mass** **Concentration** **Substructure boost**

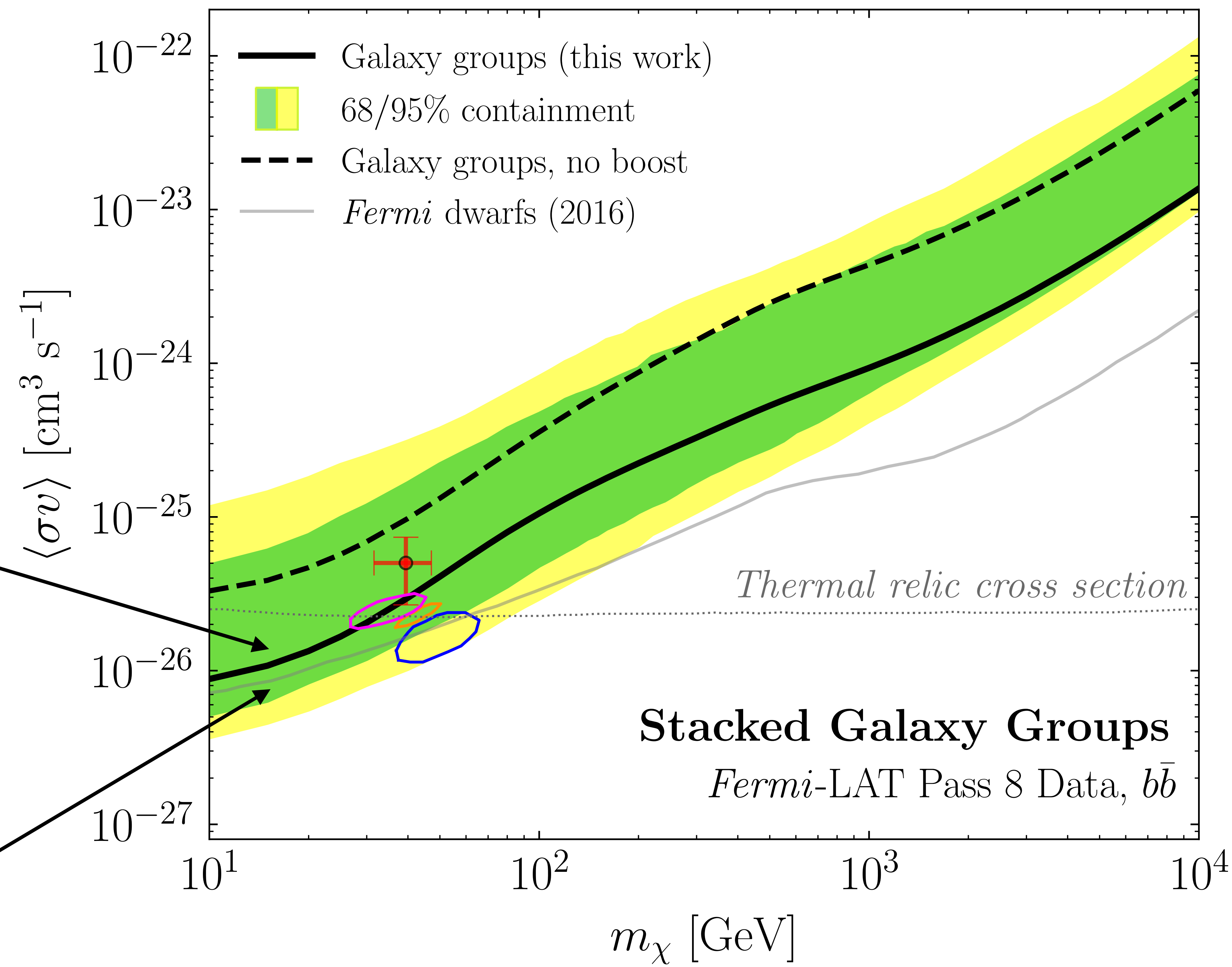
Bartels and Ando [1507.08656]

Name	$\log_{10} J$ [GeV^2 cm^{-5} sr]	$\log_{10} M_{\rm vir}$ [$M_\odot$]	$z \times 10^{-3}$	ℓ [deg]	b [deg]	$\log_{10} c_{\rm vir}$	$\theta_{\rm s}$ [deg]	$b_{\rm sh}$	$\mathrm{TS}_{\rm max}$
Andromeda	19.79±0.36	12.4±0.12	0.17	121.51	-21.79	1.04±0.17	2.57	2.64	2.92
NGC4472/Virgo	19.11±0.35	14.6±0.14	3.58	283.94	74.52	0.80±0.18	1.16	4.53	1.04
NGC5128	18.89±0.37	12.9±0.12	0.82	307.88	17.08	0.99±0.17	0.88	3.14	0.00
NGC0253	18.76±0.37	12.7±0.12	0.79	98.24	-87.89	1.00±0.17	0.77	2.90	0.63
Maffei 1	18.68±0.37	12.6±0.12	0.78	136.23	-0.44	1.01±0.17	0.71	2.81	7.26
NGC6822	18.59±0.37	10.7±0.10	0.11	25.34	-18.40	1.17±0.17	0.77	1.70	16.65
NGC3031	18.58±0.36	12.6±0.12	0.83	141.88	40.87	1.02±0.17	0.64	2.76	0.00
NGC4696/Centaurus	18.34±0.35	14.6±0.14	8.44	302.22	21.65	0.80±0.18	0.48	4.50	6.60
NGC1399	18.31±0.37	13.8±0.13	4.11	236.62	-53.88	0.89±0.17	0.45	3.87	0.72
IC0356	18.27±0.36	13.5±0.13	3.14	138.06	12.70	0.92±0.17	0.43	3.51	0.02
NGC4594	18.26±0.35	13.3±0.13	2.56	299.01	51.30	0.94±0.17	0.43	3.36	0.00

Stacked clusters: DM annihilation limit

Galaxy groups

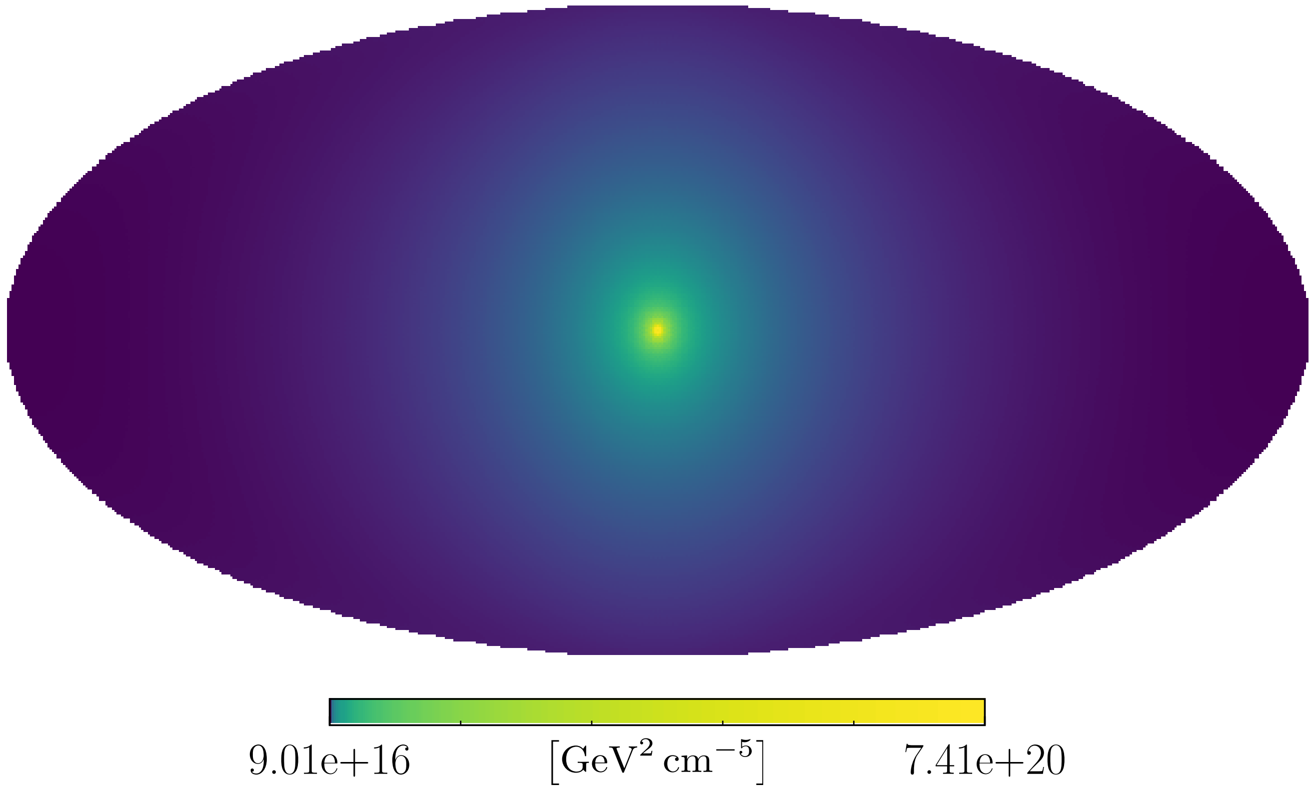
Fermi dwarfs



Lisanti, **SM**, Rodd and Safdi **[1708.09385]**

Where should we look? Galactic DM

Dark matter annihilation signal from **smooth Galactic halo**



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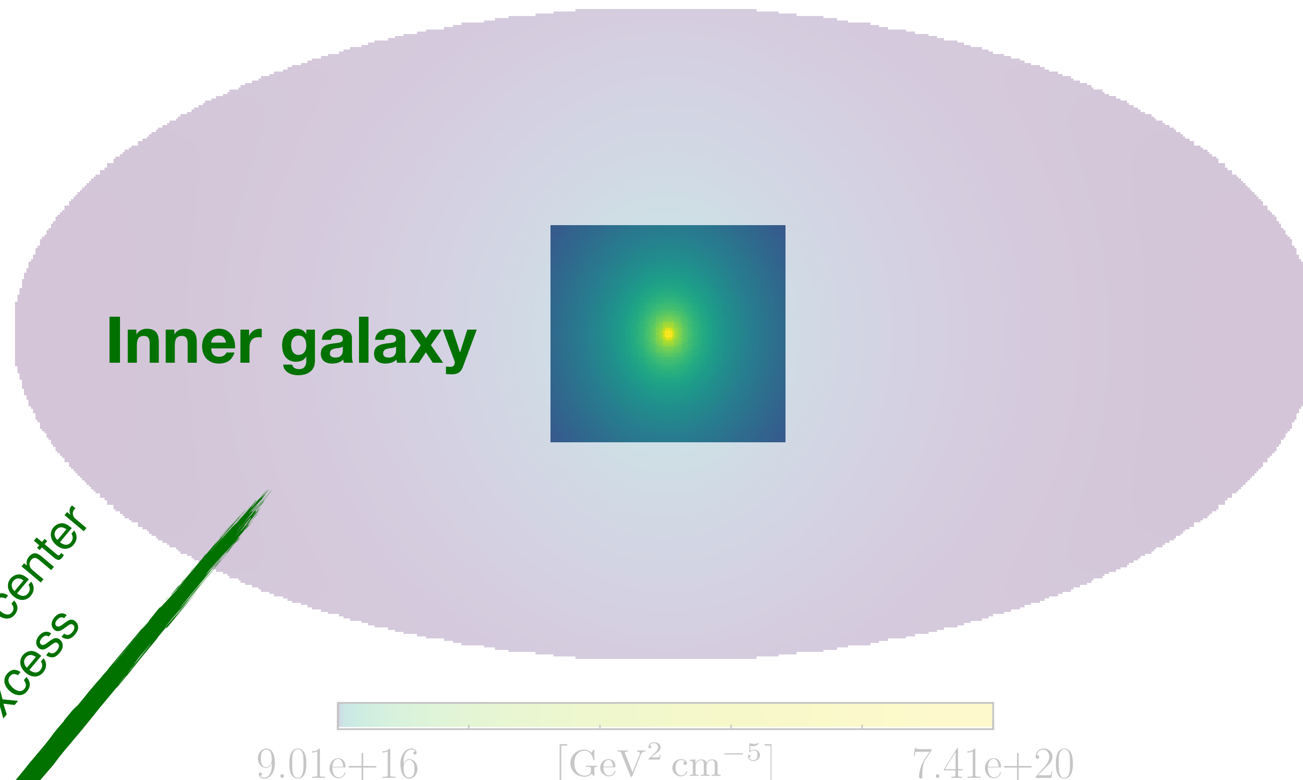
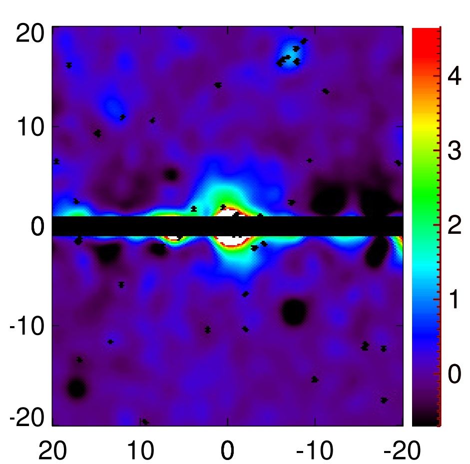
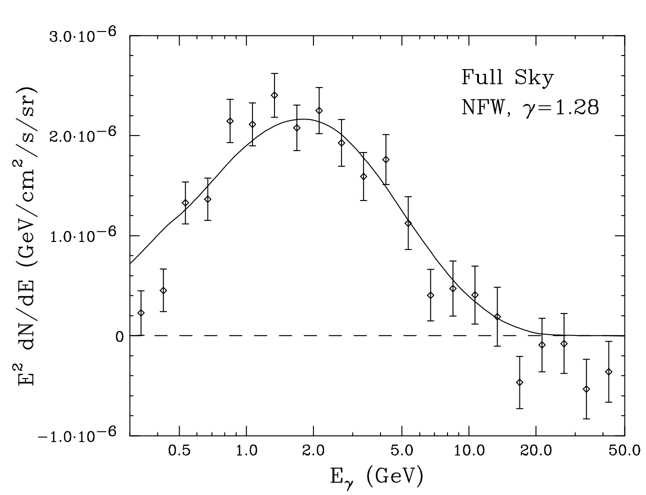


Galactic center excess





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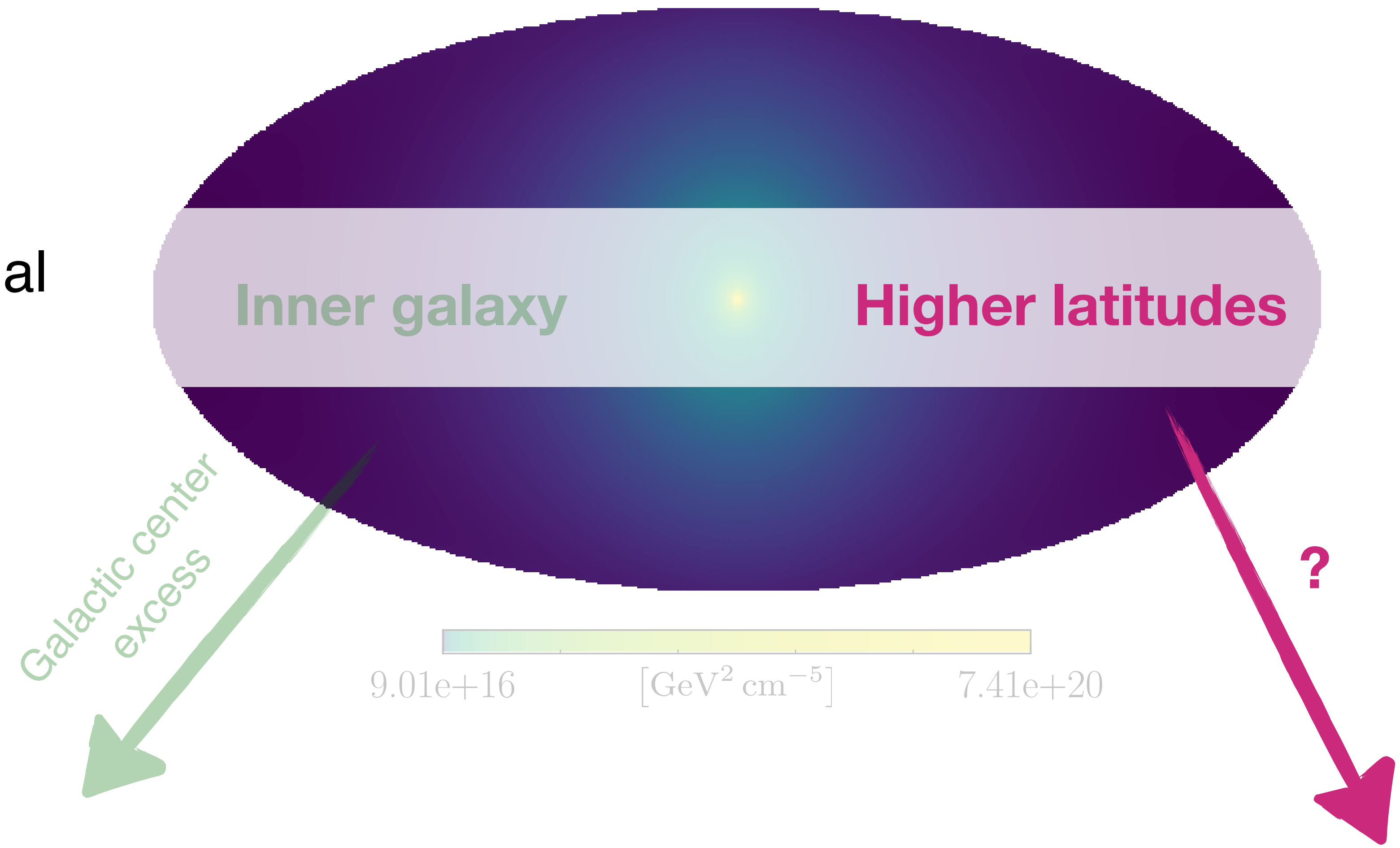
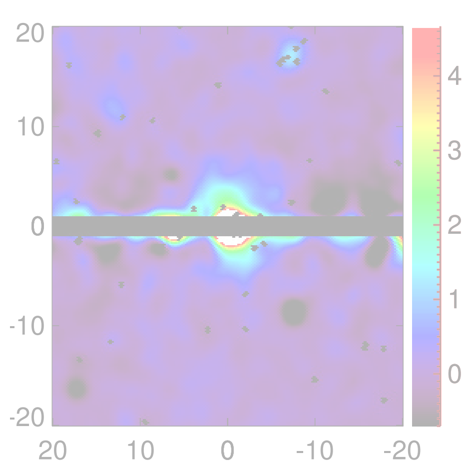
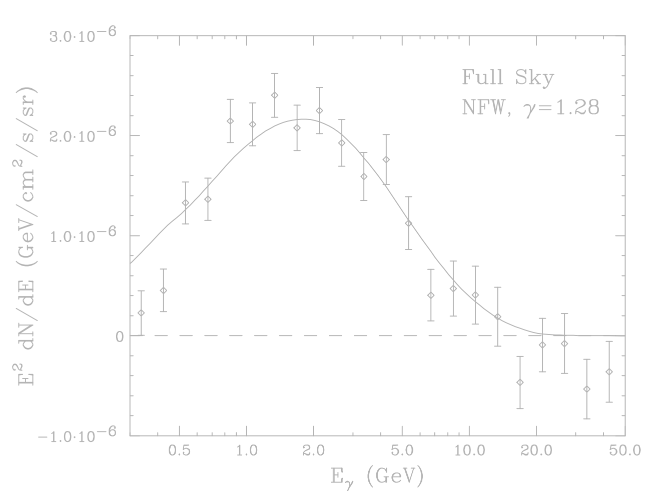
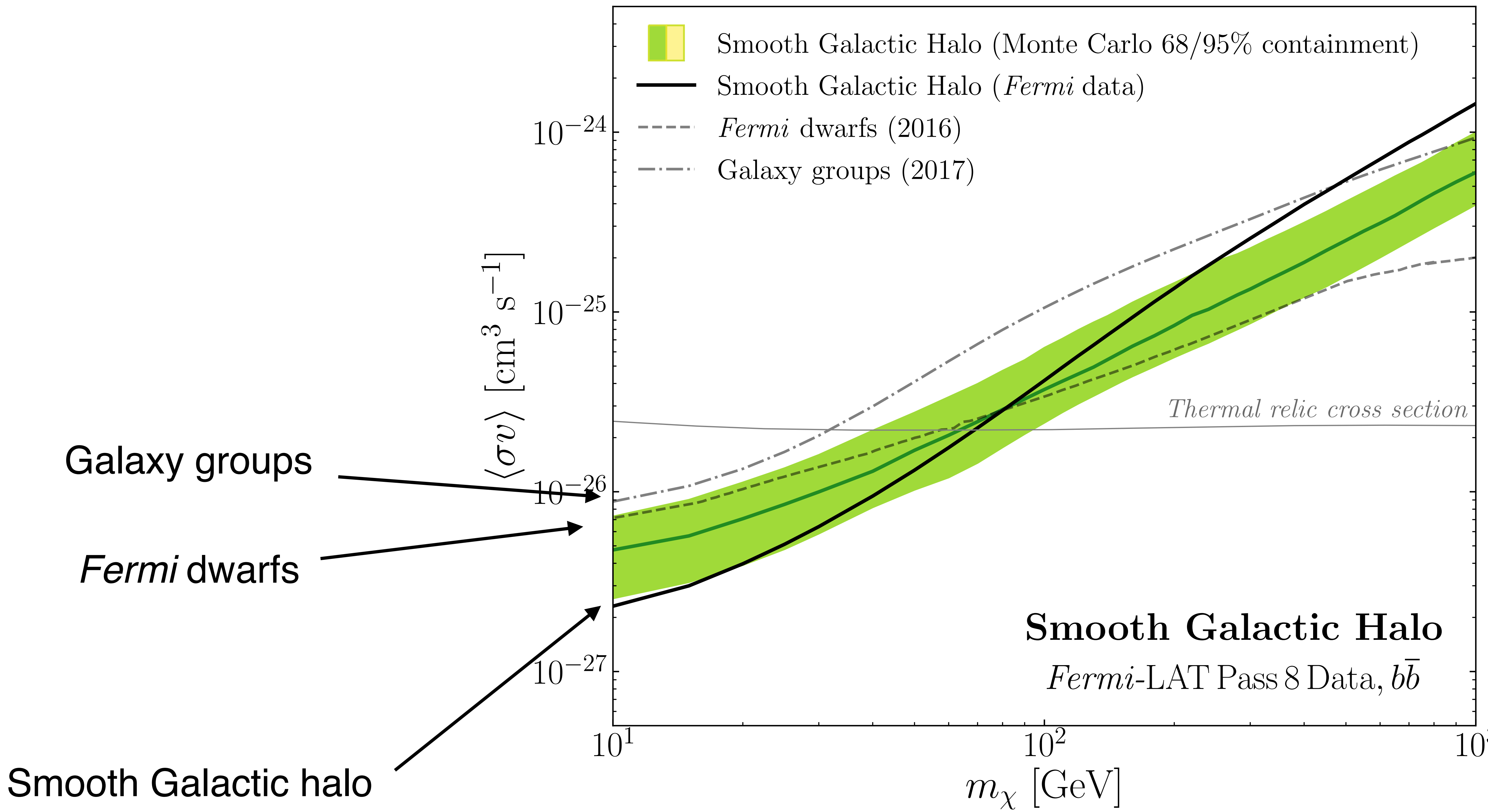






- Requires careful understanding of systematics over large region of sky
- Can potentially **directly probe Galactic center excess**

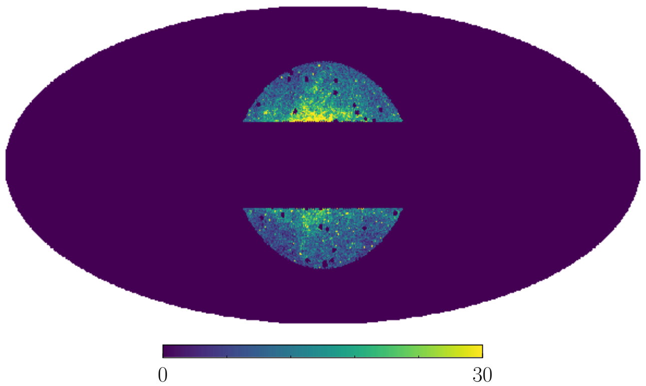
Galactic DM annihilation limit



Chang, Lisanti, **SM** **[1804.04132]**

Galactic DM: confronting diffuse foregrounds

- Look at **smaller regions of the sky**

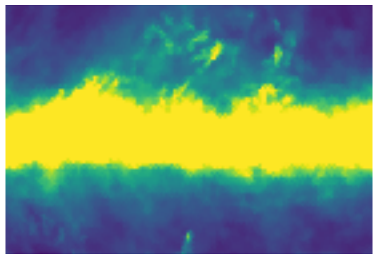


Smaller region of interest

- **Allow diffuse background more freedom** by floating independently in radial slices

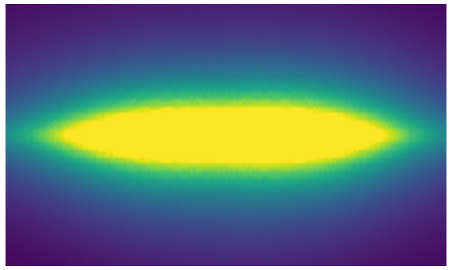
Sub-regions for diffuse background

- Consider **different diffuse models**, floating different sub-components of diffuse background separately



Brem + Pion decay

+



Inverse Compton (IC)

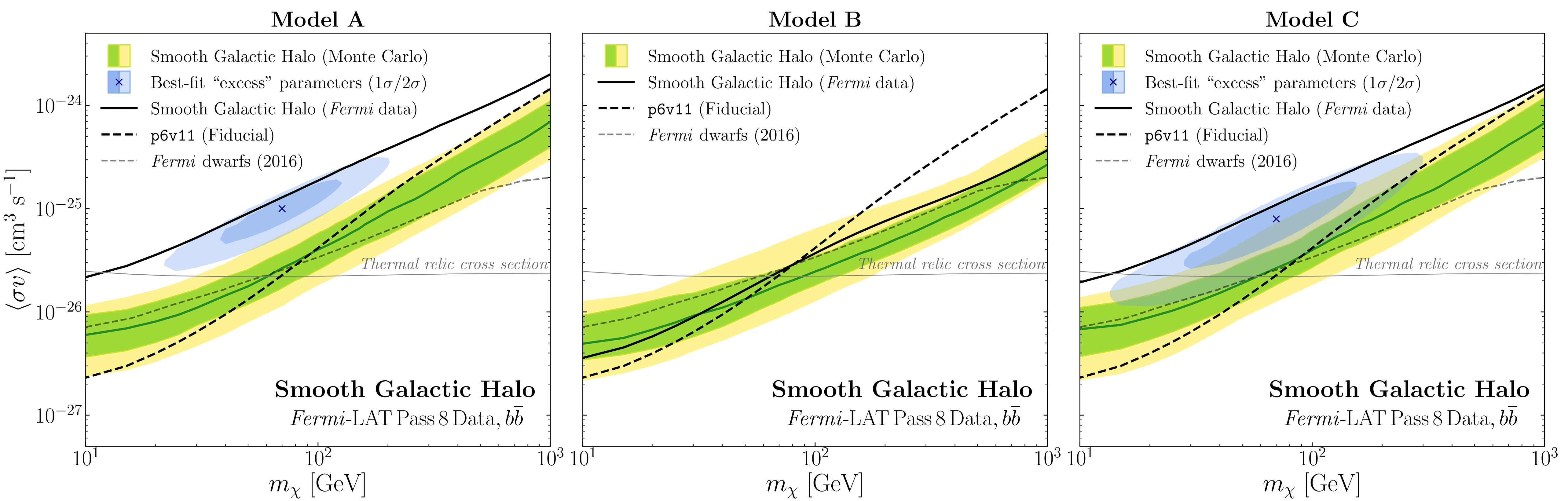
Galactic DM: confronting diffuse foregrounds

Consider different diffuse models from Ackermann et al [1410.3696]:

Baseline

Better diffuse modeling in inner halo

Better diffuse modeling in outer halo



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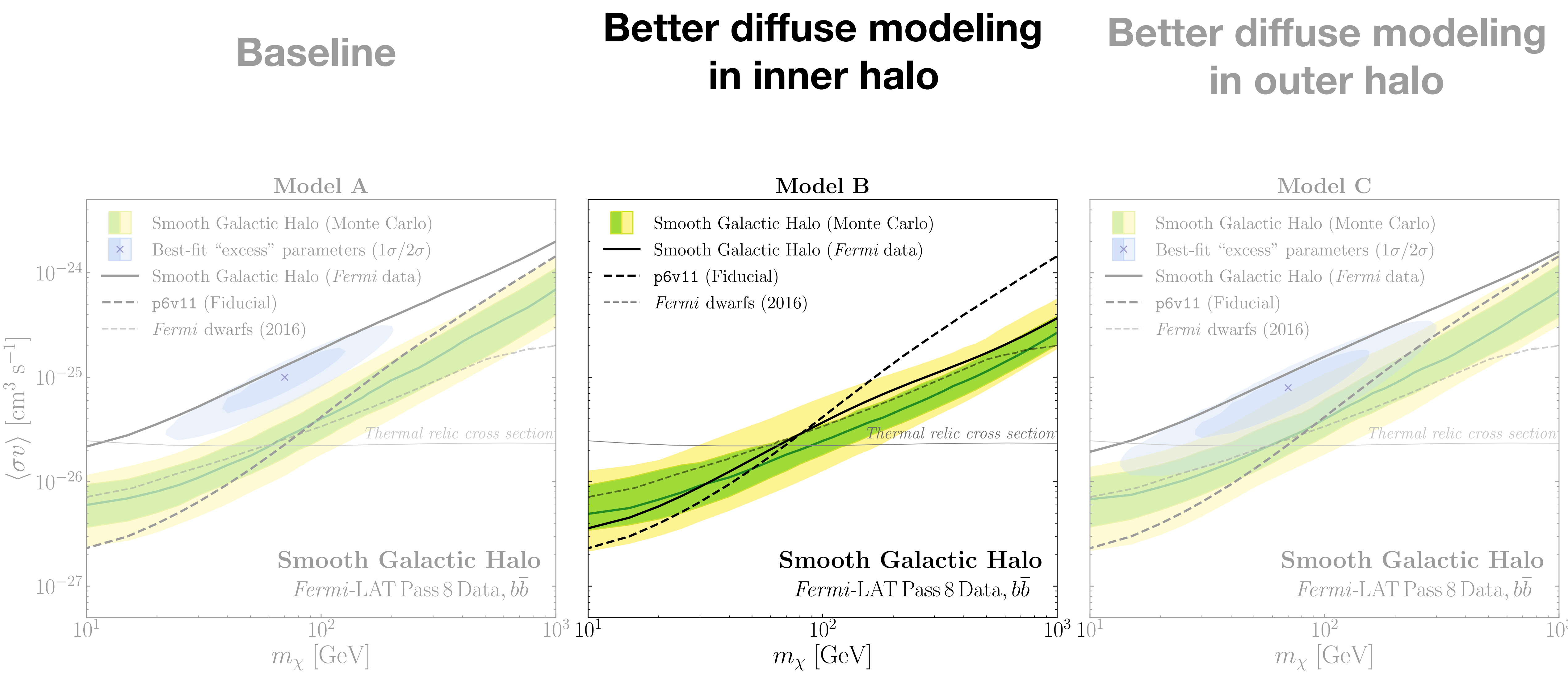
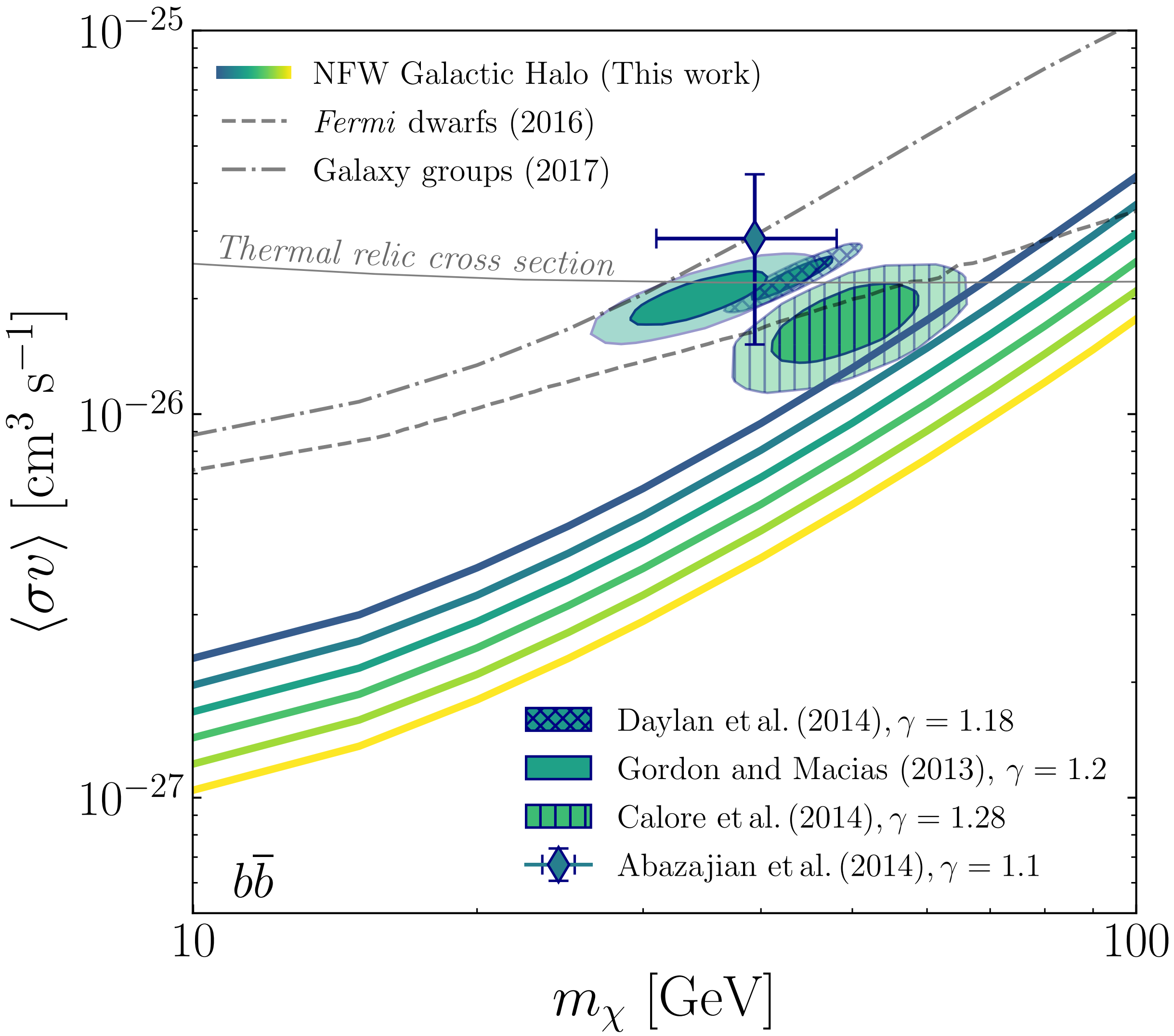


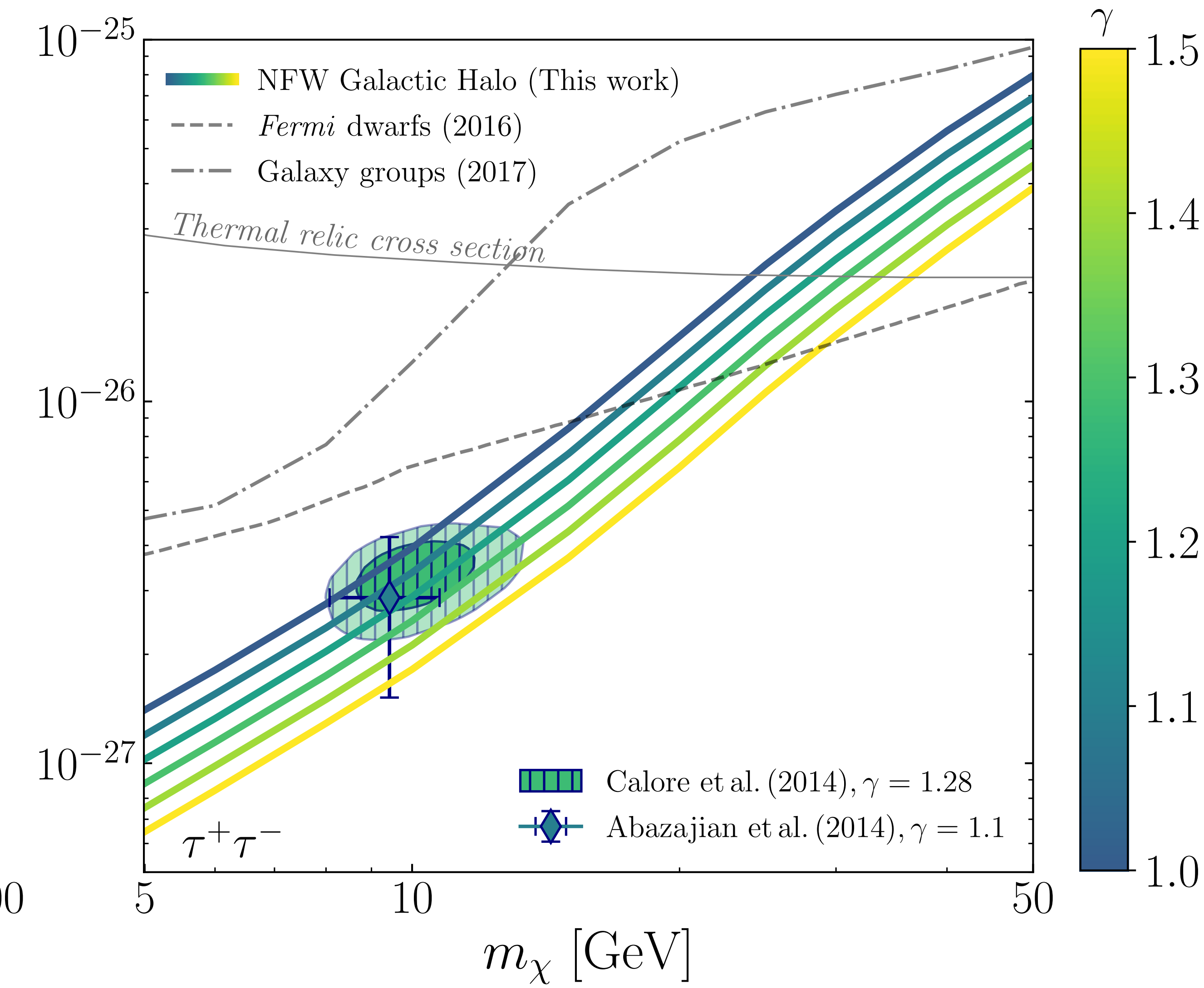
Can understand variations in terms of modeling of IC component

Implications for the Galactic Center excess

$b\bar{b}$ interpretation robustly excluded

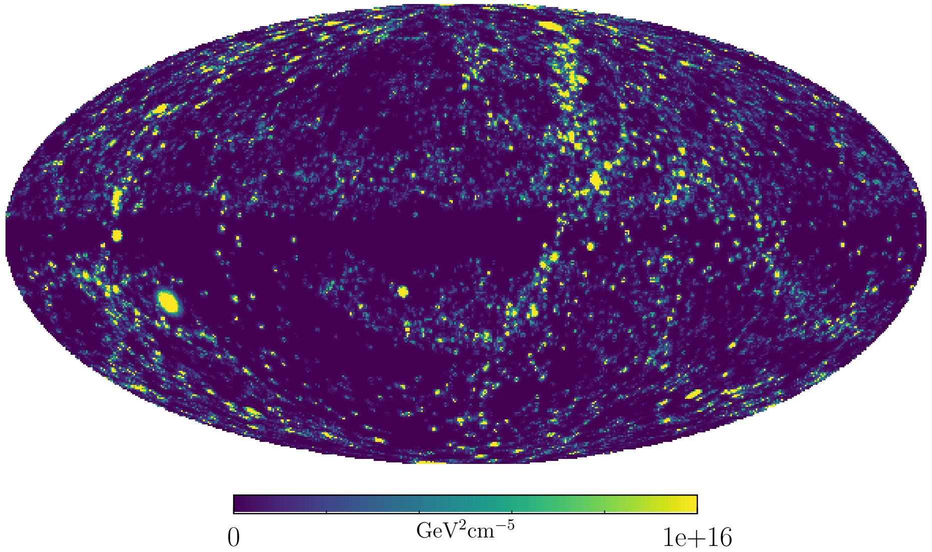


$\tau^+\tau^-$ interpretation under tension for the first time

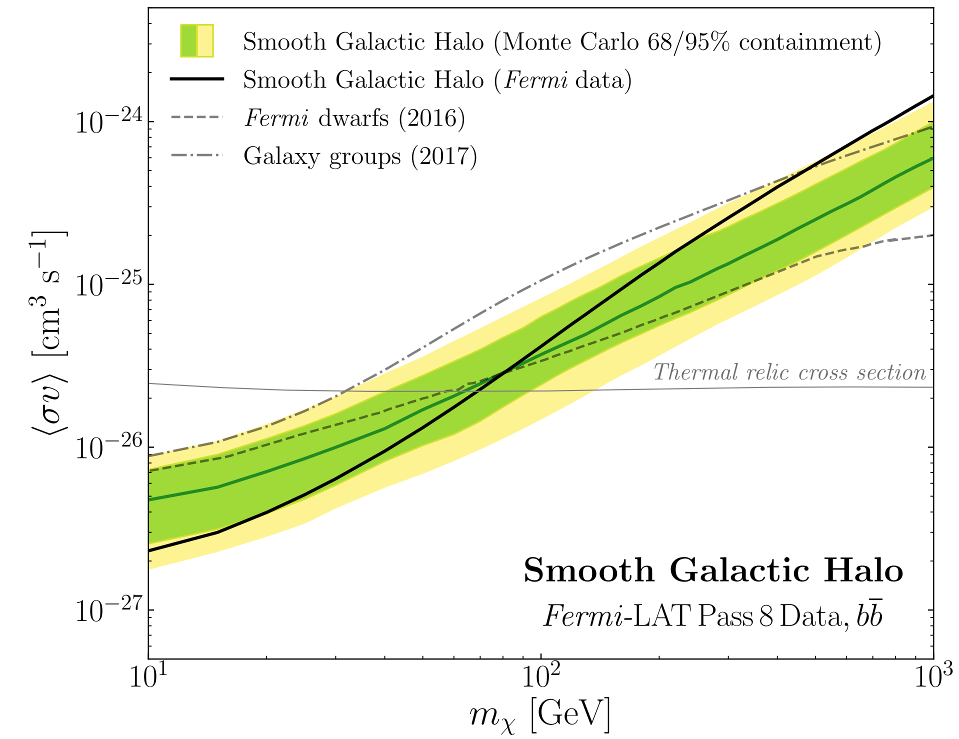


Conclusions

We construct a **map of extragalactic DM** in the local universe



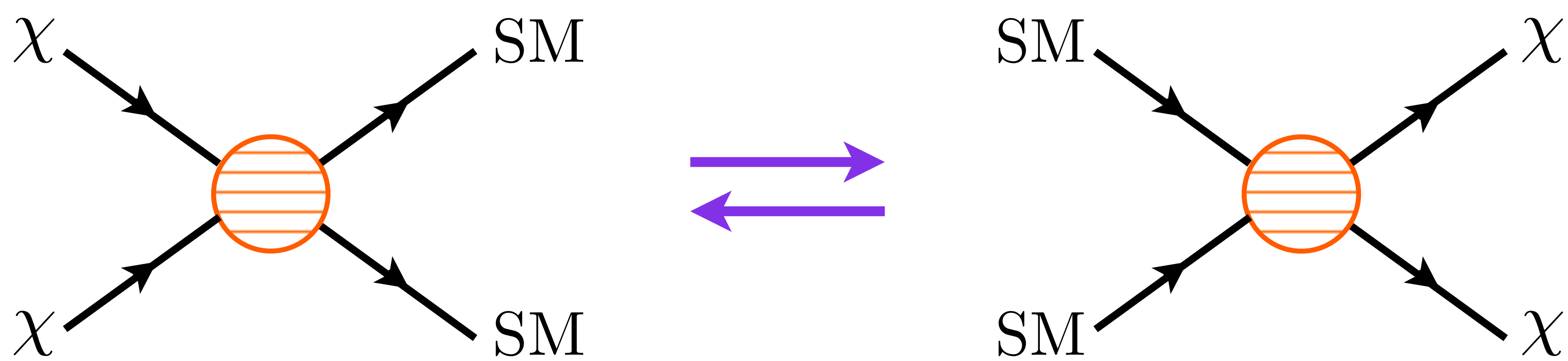
Using galaxy groups and the smooth Galactic halo, we obtain **tight bounds on annihilating DM**, complementing existing bounds from dwarfs



Backup

Thermal dark matter and WIMPs

Dark matter was in equilibrium with SM in the early Universe



As universe cools, eventually

$$\underbrace{n_\chi \langle \sigma_A v \rangle}_{\text{dark matter annihilation rate}} \sim \underbrace{H}_{\text{Hubble rate}}$$

Dark matter stops annihilating and falls out of equilibrium

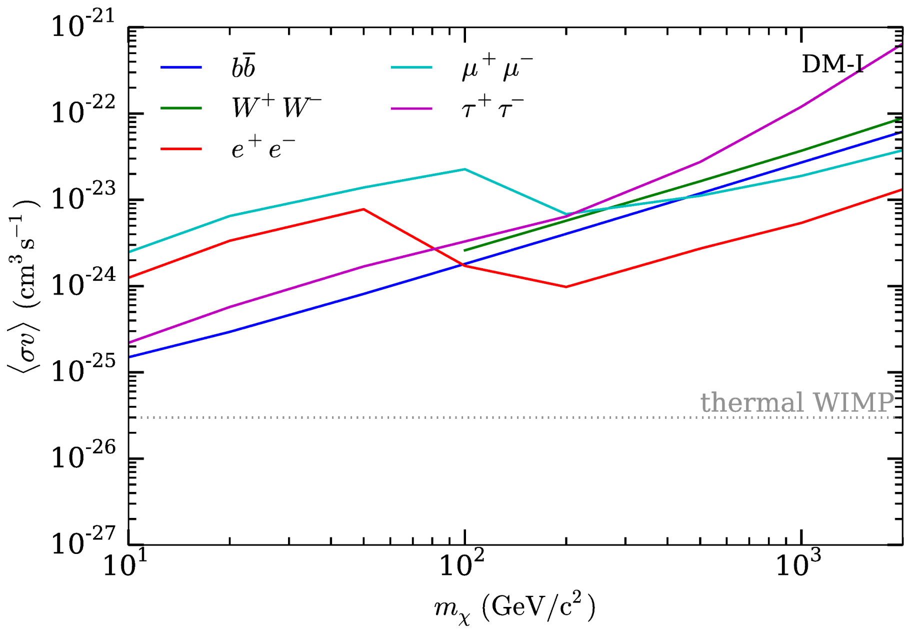
Relic abundance for dark matter is thus established

Weakly interacting particles of masses O(10 GeV -1 TeV) give observed relic density

Extragalactic DM searches

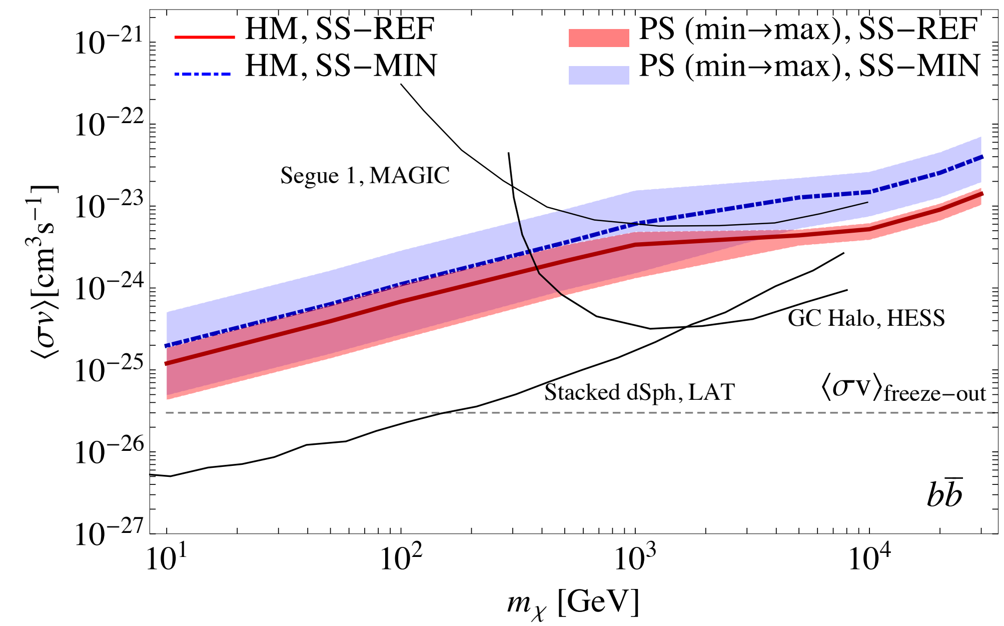
Breadth of searches targeting DM from extragalactic halos

Individual clusters



Ackermann *et al.* [1510.00004]

Total DM intensity



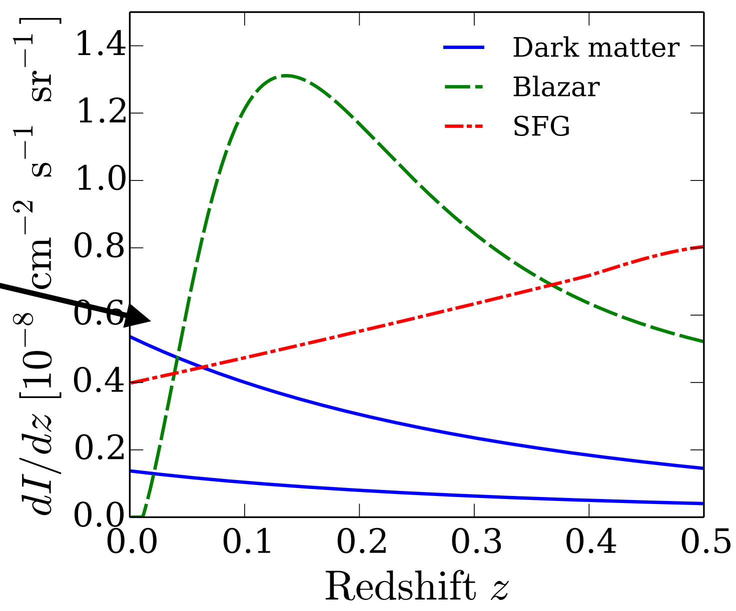
Ackermann *et al.* [1501.05464]

Generally not sensitive to thermal cross sections

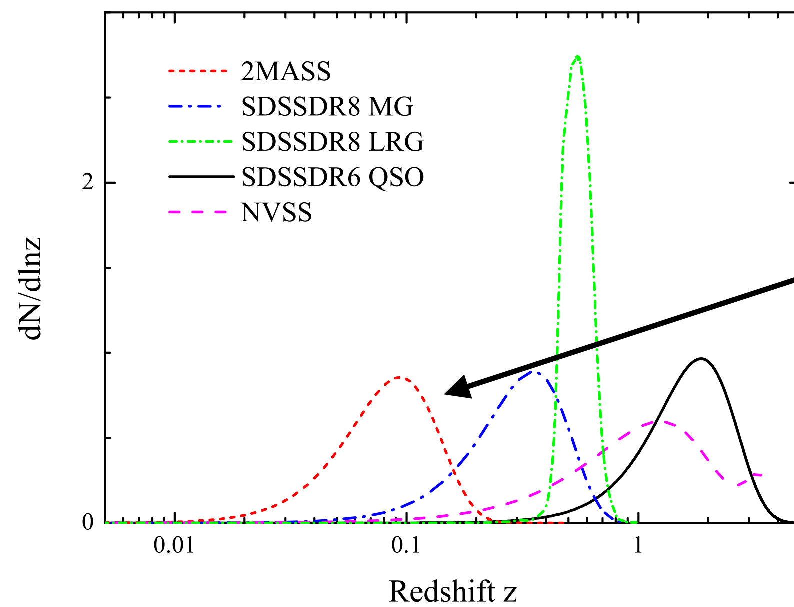
Extragalactic DM searches: redshift dependence

DM intensity peaks at **smaller redshifts**

Ando *et al.* [1407.8502]



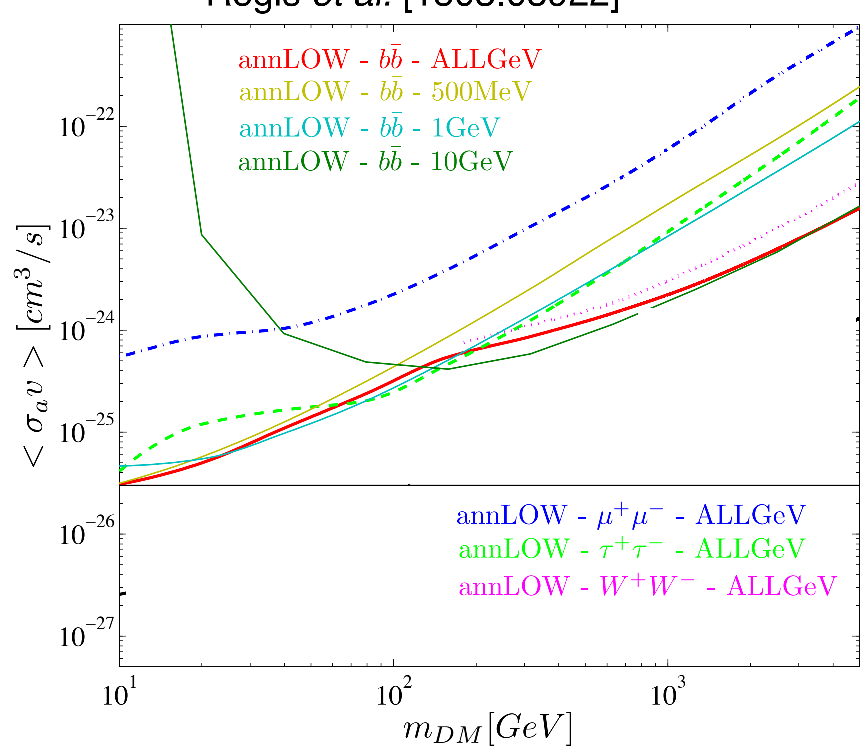
Xia *et al.* [1503.05918]



Expected to preferentially correlate with **nearby galaxies**

Cross-correlation of DM with nearby galaxy catalog

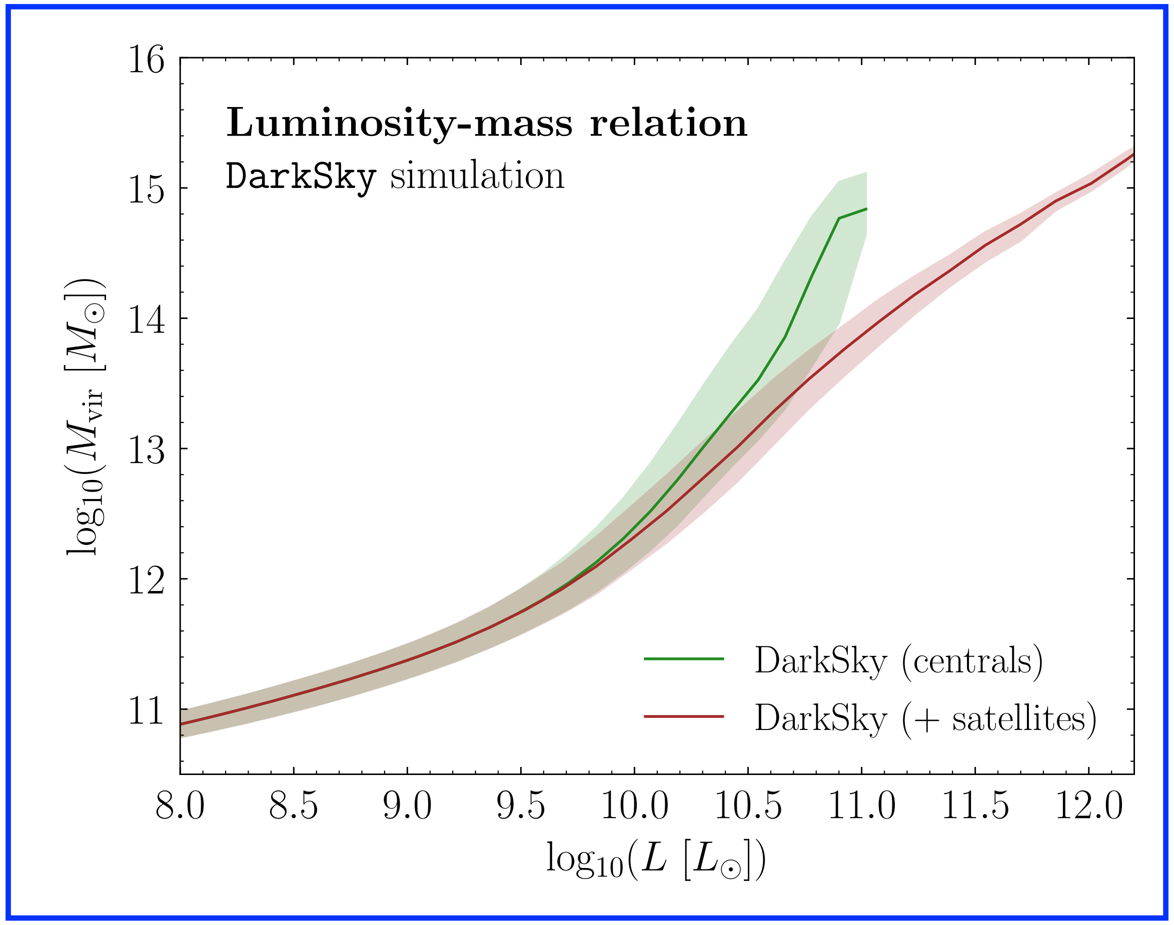
Regis *et al.* [1503.05922]

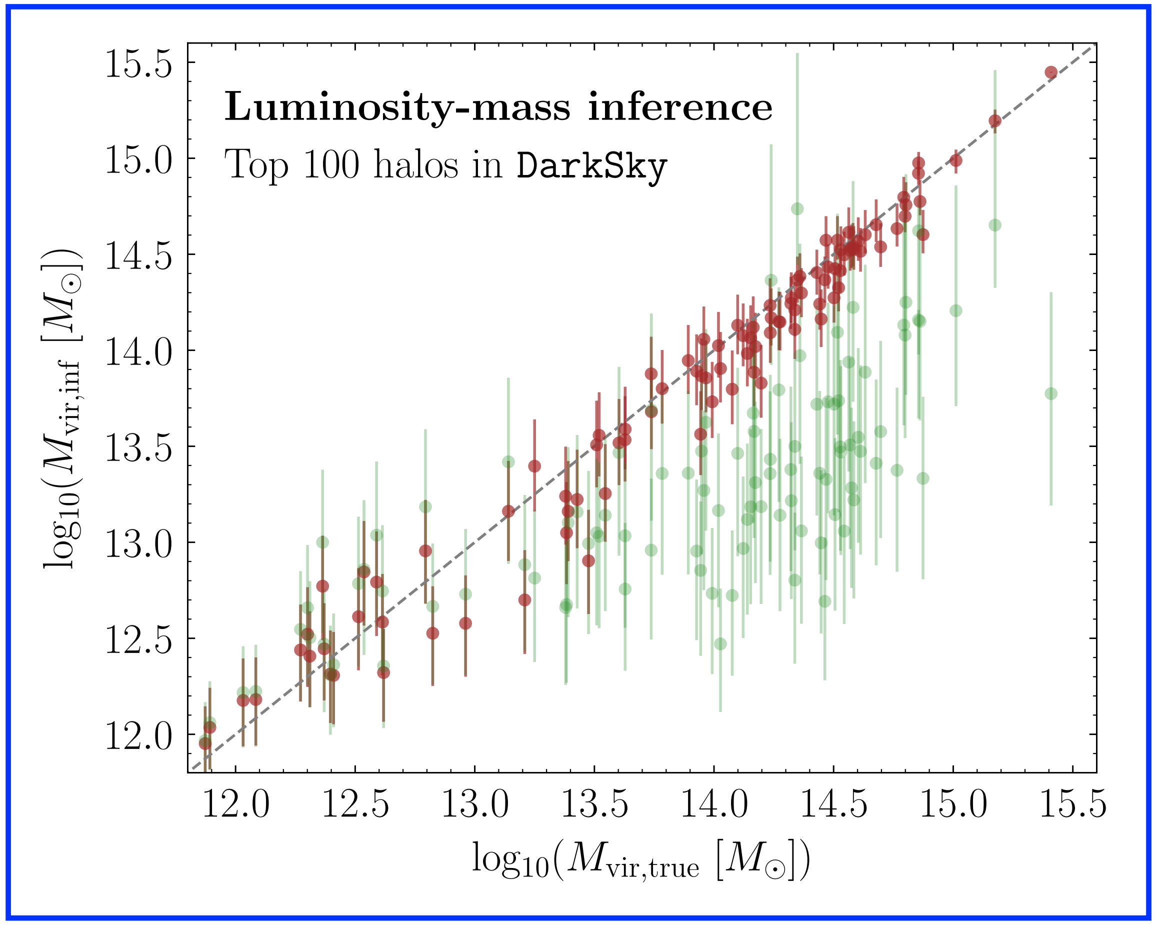


Allows us to **isolate DM** and **distinguish from astrophysics**

Building a map of extragalactic DM: **halo mass**

$$J \sim (1 + b_{\rm sh}) \frac{M_{\rm vir} c_{\rm vir}^3}{d_A^2[z]} \rho_c$$

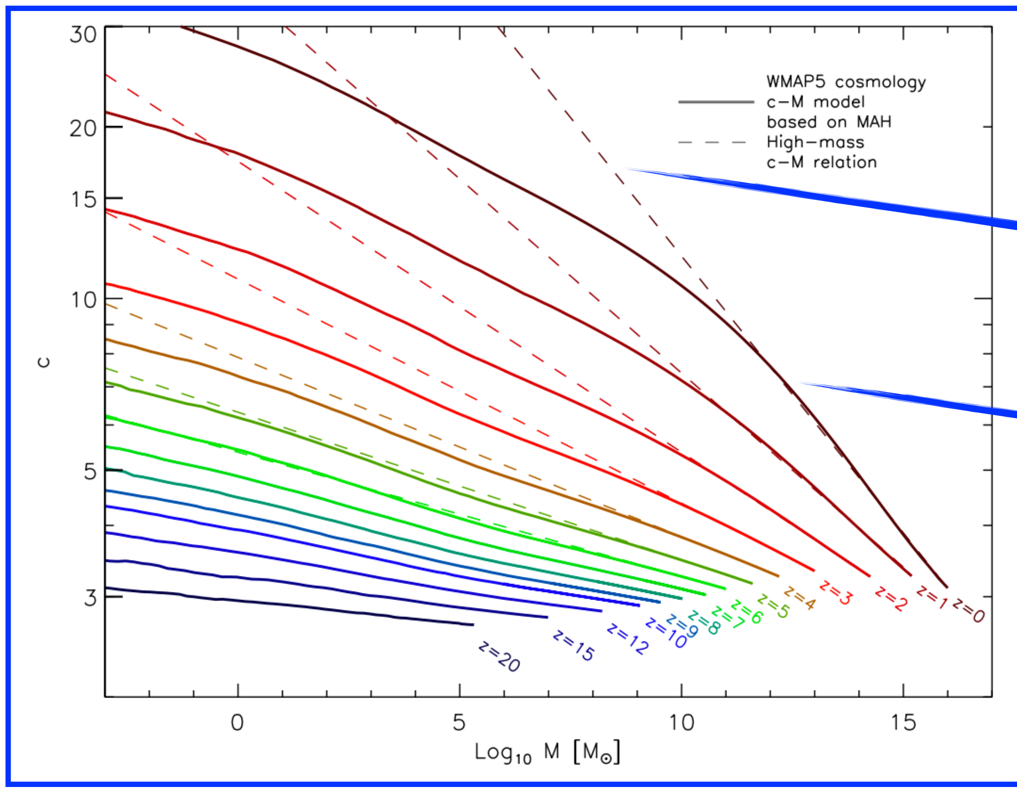




Infer halo mass from total group luminosity

Building a map of extragalactic DM: **substructure**

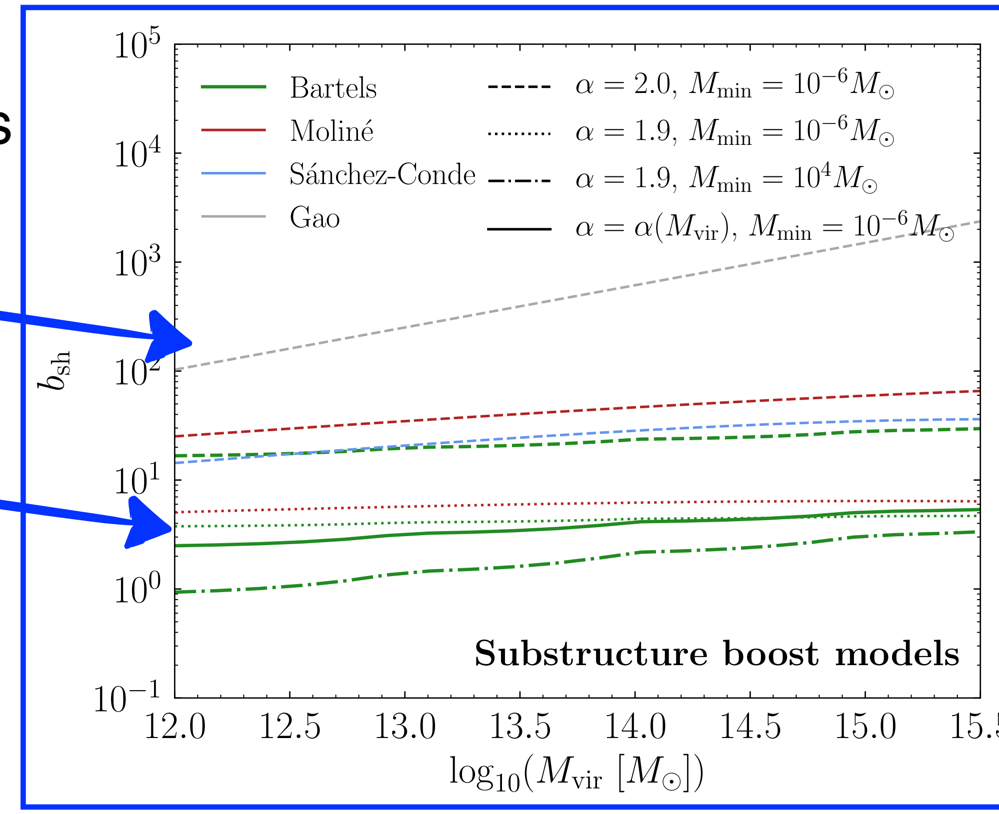
$$J \sim (1 + b_{\rm sh}) \frac{M_{\rm vir} c_{\rm vir}^3}{d_A^2[z]} \rho_c$$



Correa *et al.* [1502.00391]

Much larger boosts now disfavoured

Our boost



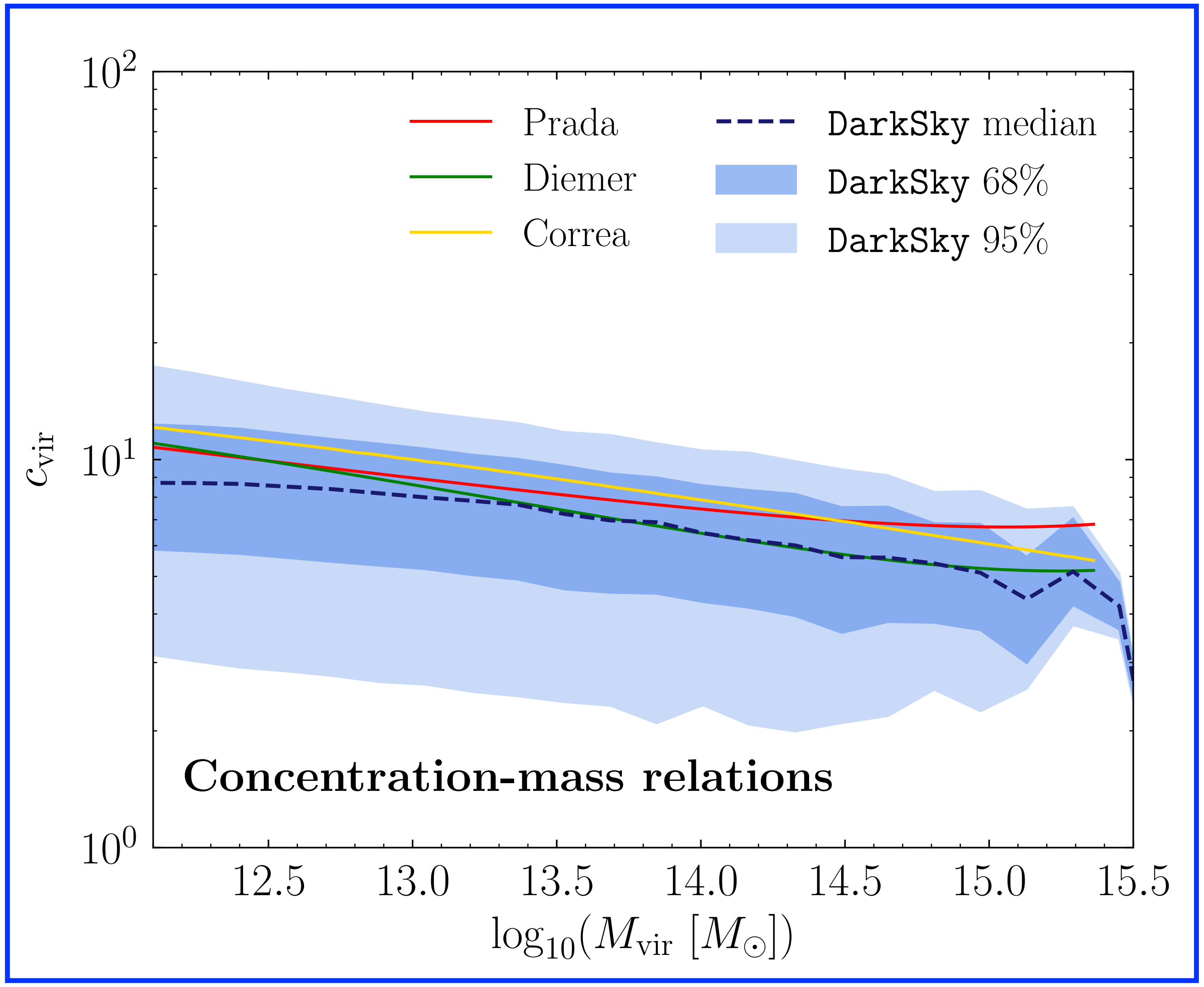
Use conservative assumptions about substructure enhancement

- Tidal stripping of subhalos
- Flattening of c-M relation at low subhalo masses
- Difference in concentration between host halos and subhalos

Building a map of extragalactic DM: **concentration**

$$J \sim (1 + b_{\rm sh}) \frac{M_{\rm vir} c_{\rm vir}^3}{d_A^2[z]} \rho_c$$

$$c_{\rm vir} \equiv r_{\rm vir}/r_s$$



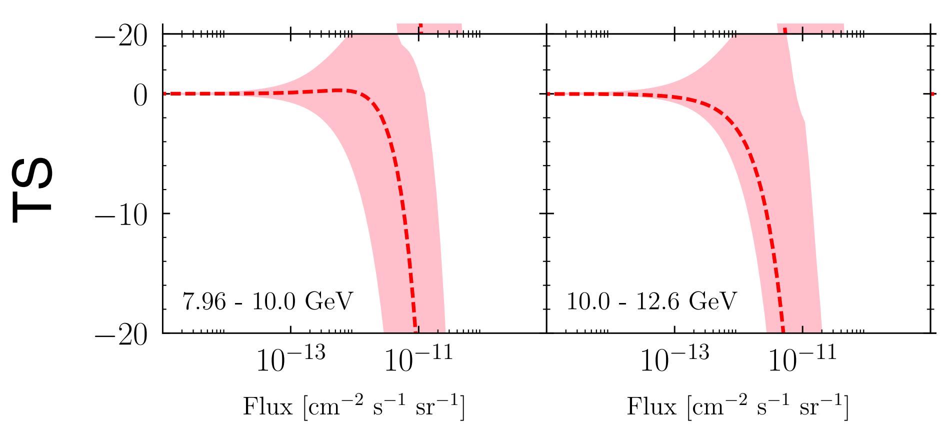
Infer concentration from concentration-mass relation

Correa *et al.* [1502.00391]

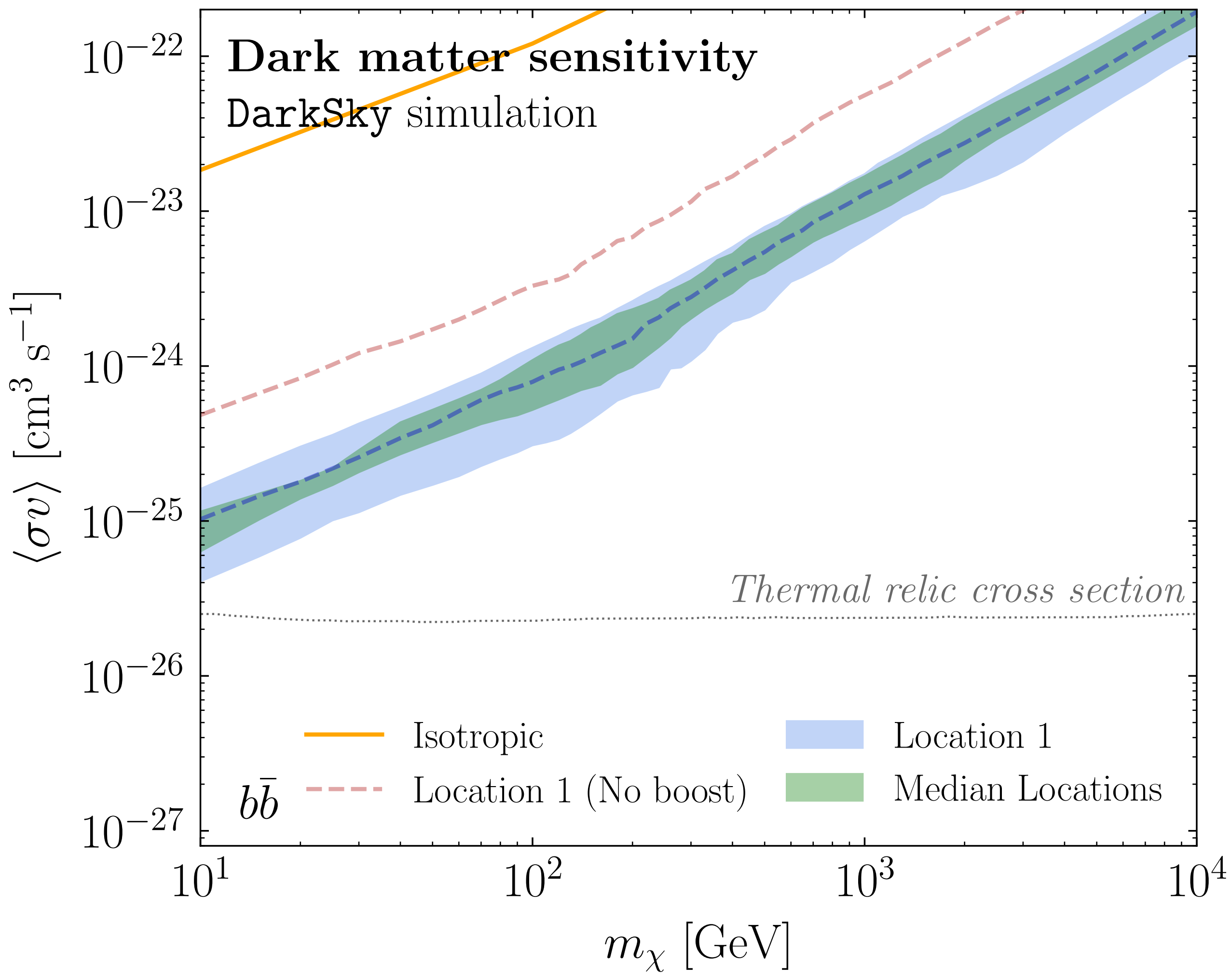
Data analysis: stacking procedure

Basic ingredients of analysis procedure:

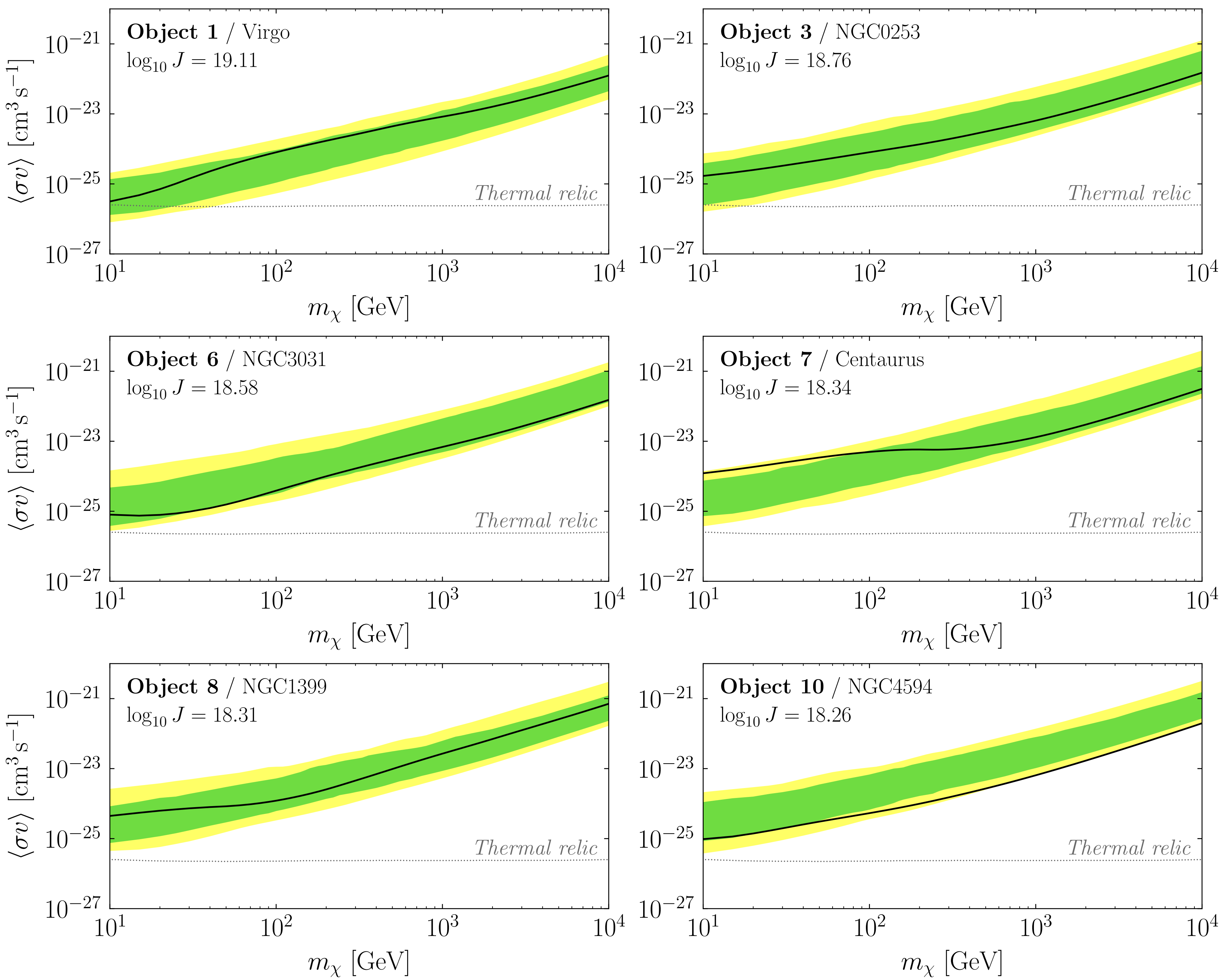
- Use profile likelihoods
- Radius 10° ROI
- Marginalize over:
  - Resolved point sources
  - Isotropic point sources
  - Diffuse background
- Marginalize over J-factor uncertainty



Statistical procedure validate using DarkSky simulation



Individual region of interest (ROI) analyses



Stacking groups together = better sensitivity

Halo selection

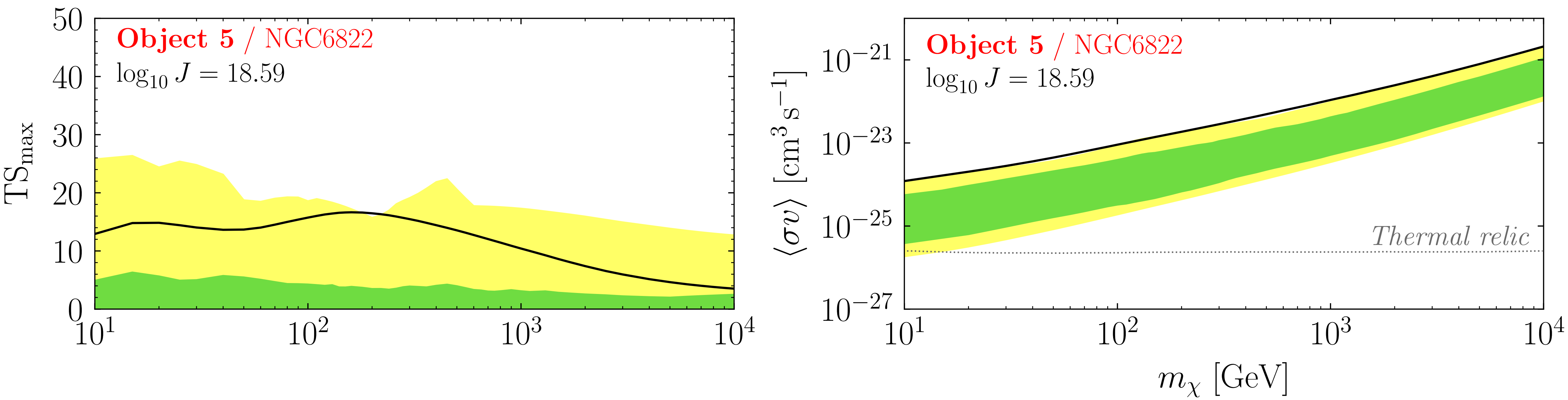
To minimize contamination from **astrophysical sources** and **foreground mismodeling**, require:

1. Top 1000 halos
2. $|b| > 20^\circ$
3. No overlapping halos to within 2°
4. Significance < 3σ and and not excluded to within a factor of 10 in $\langle \sigma v \rangle$ by another halo

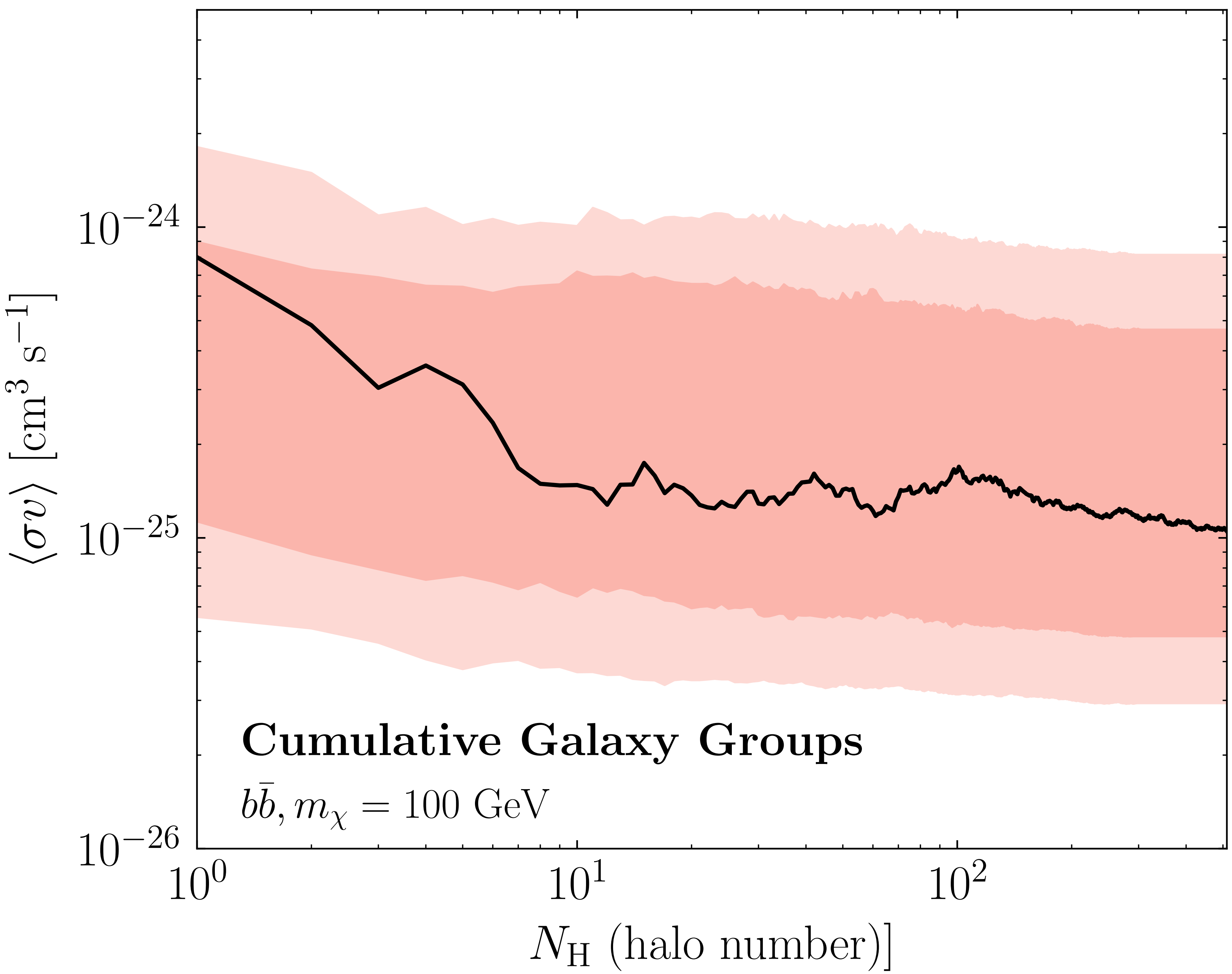
Tested on MC!

~500 halos passing selection

Example of excluded object:

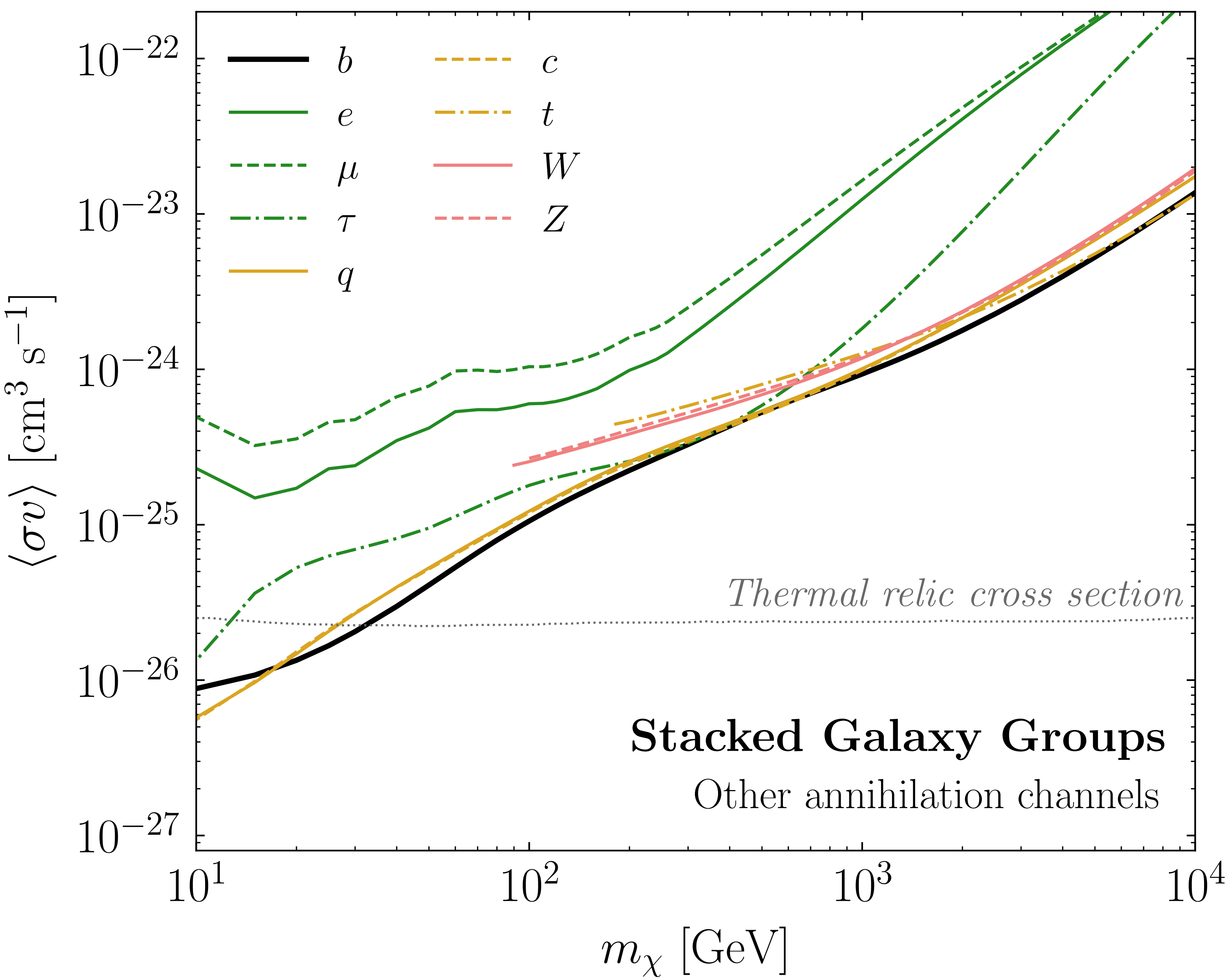


Effect of stacking



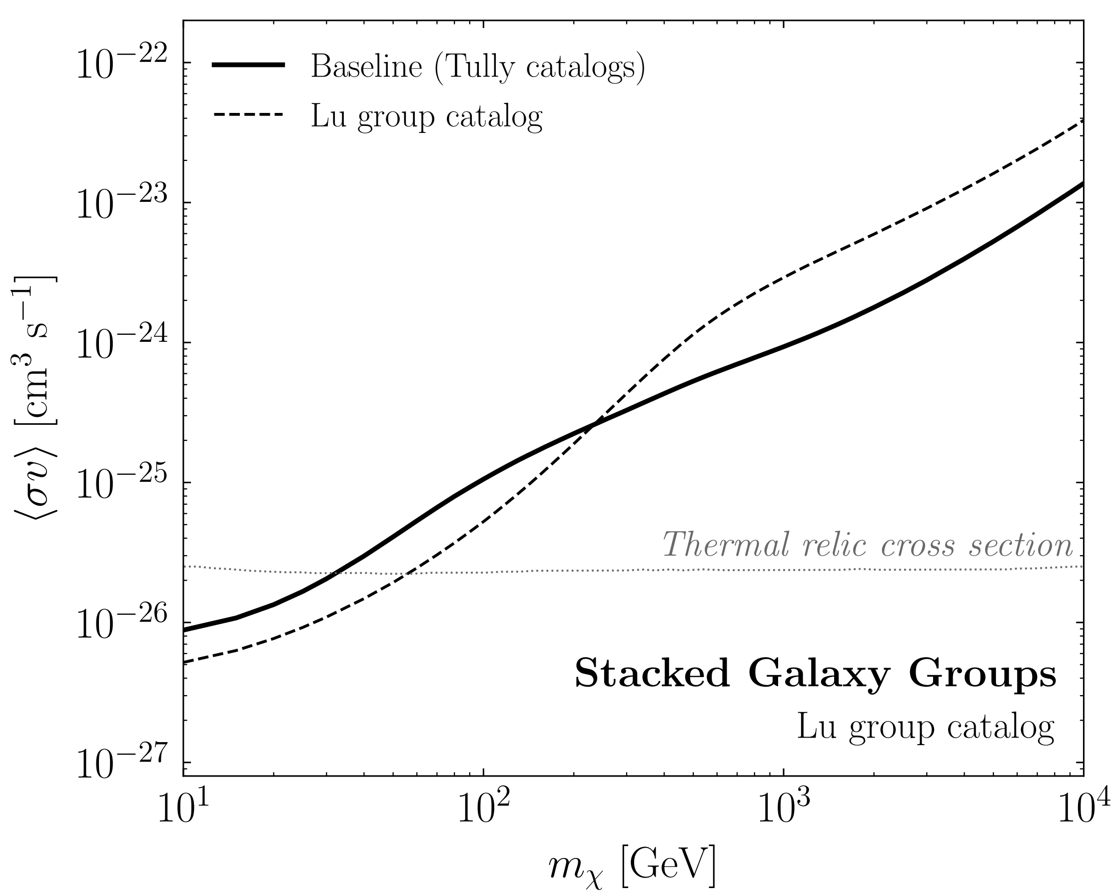
Stacking halos provides an ~order of magnitude improvement!

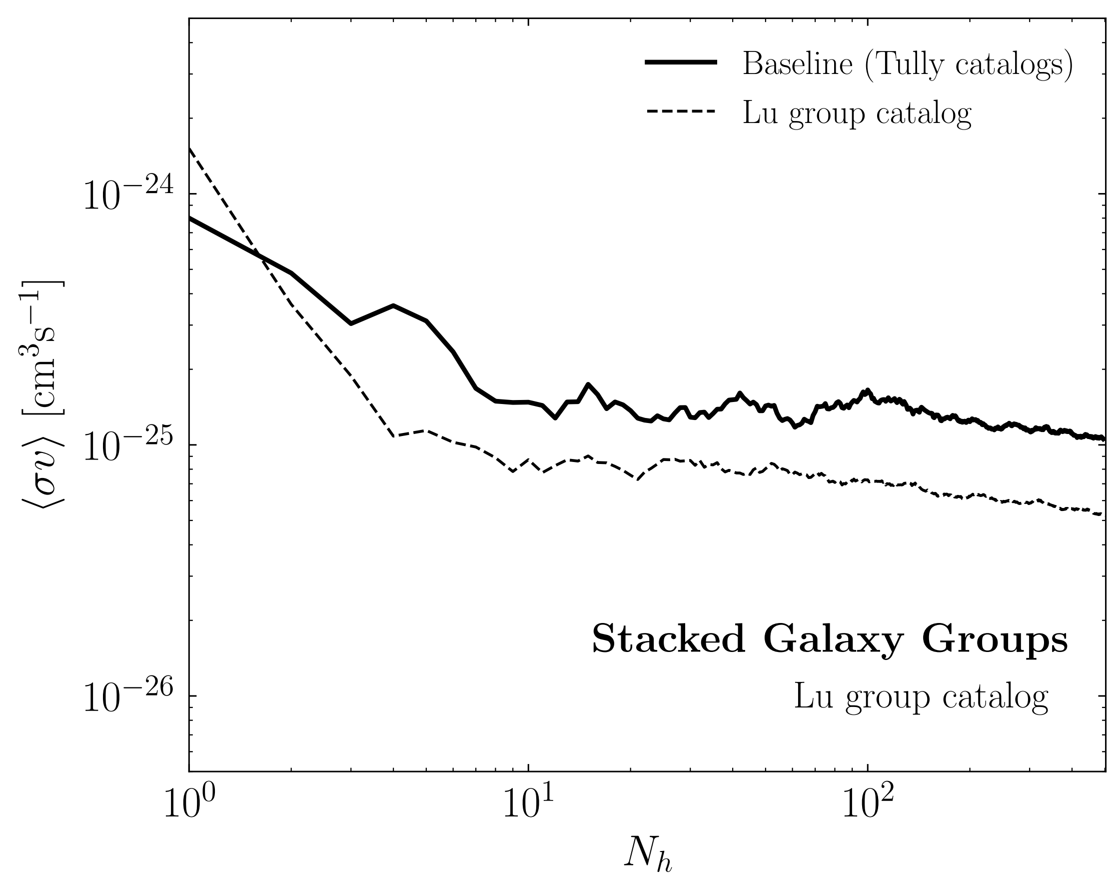
Other annihilation channels



Systematic variations: group catalogs

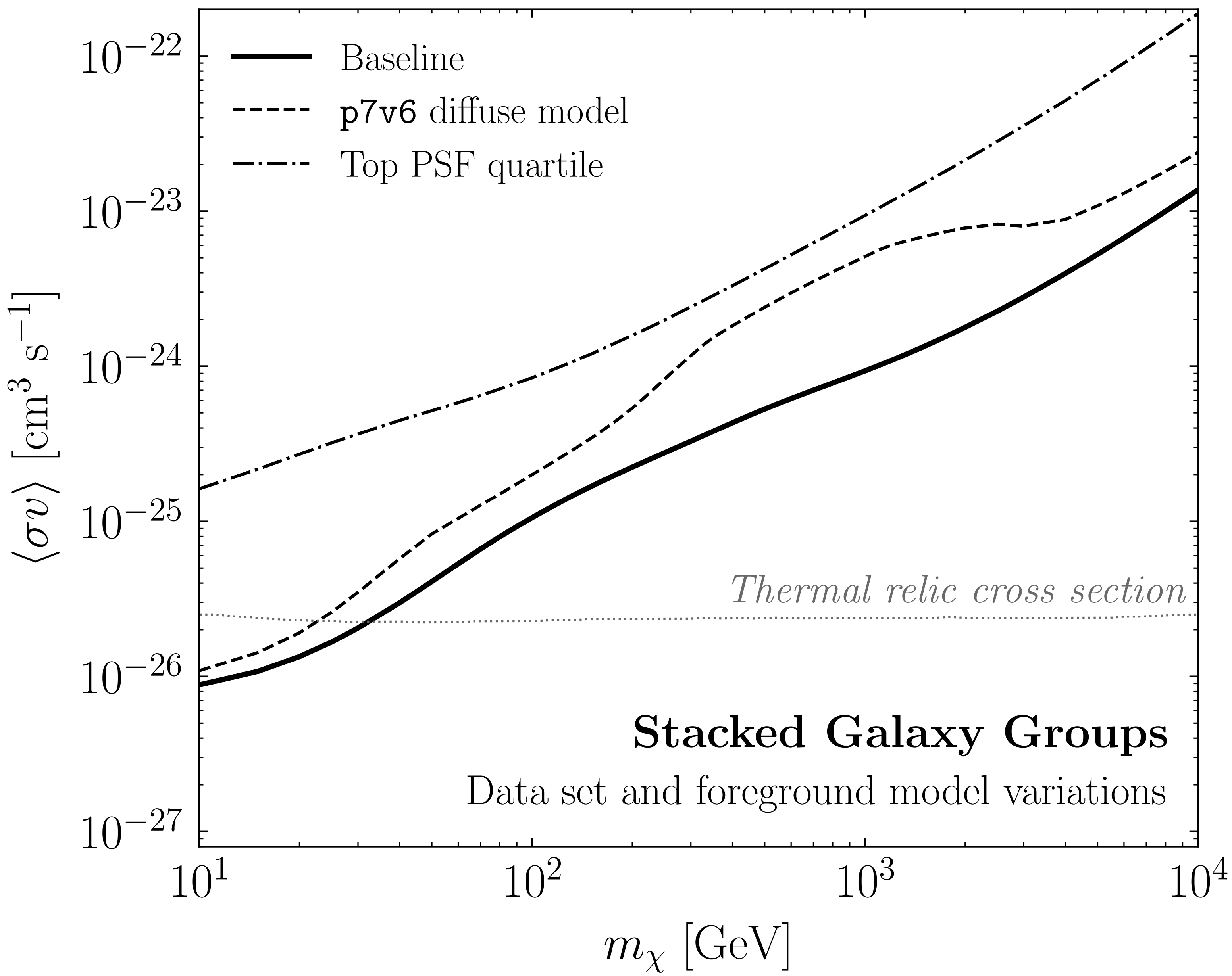
- Use Lu et al. group catalog [1607.03982]
- Independent group-finding algorithm
- Galaxies from 2MASS Redshift Survey



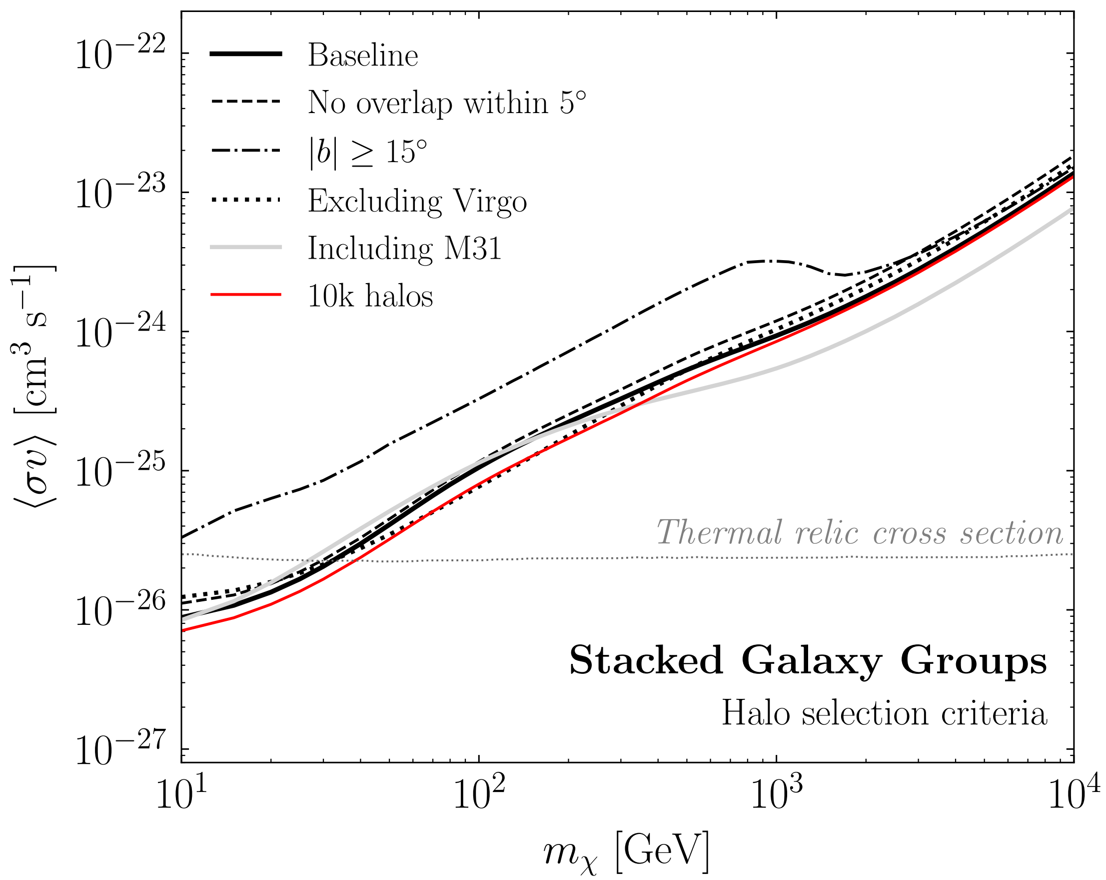


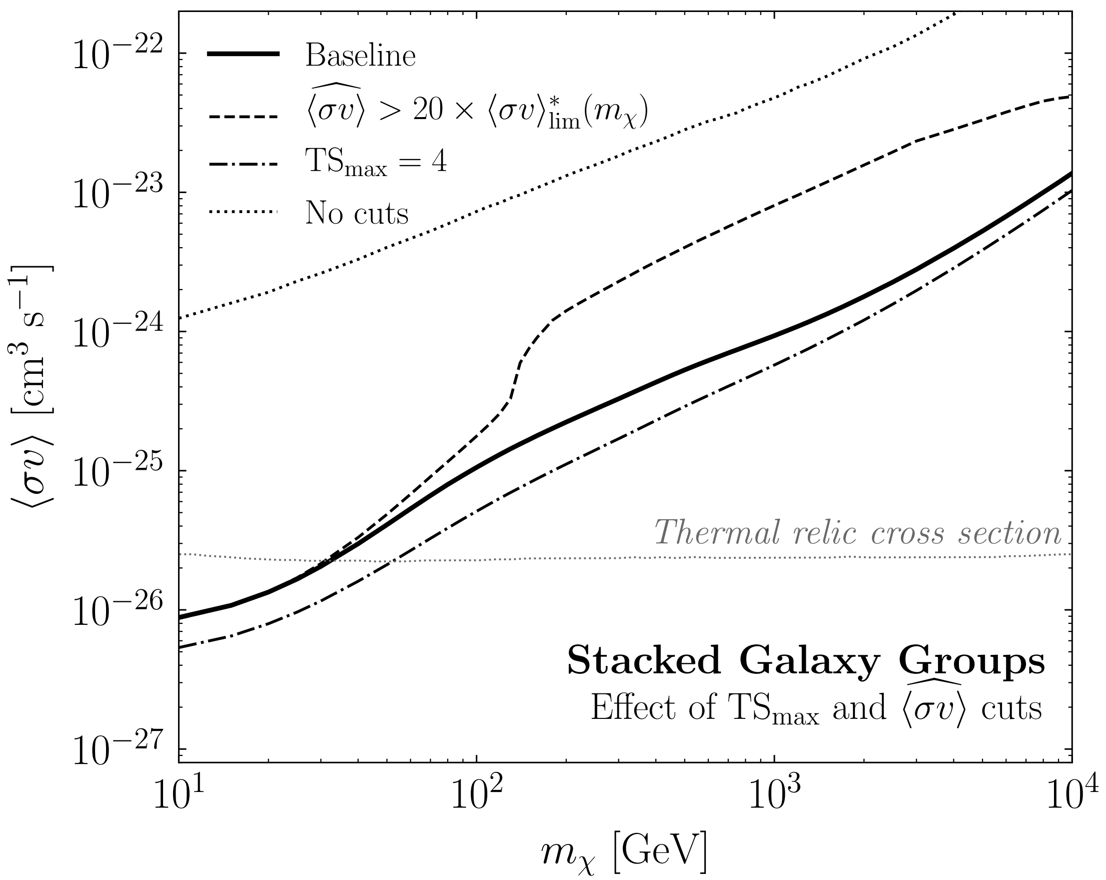
Similar limit!

Dataset systematics



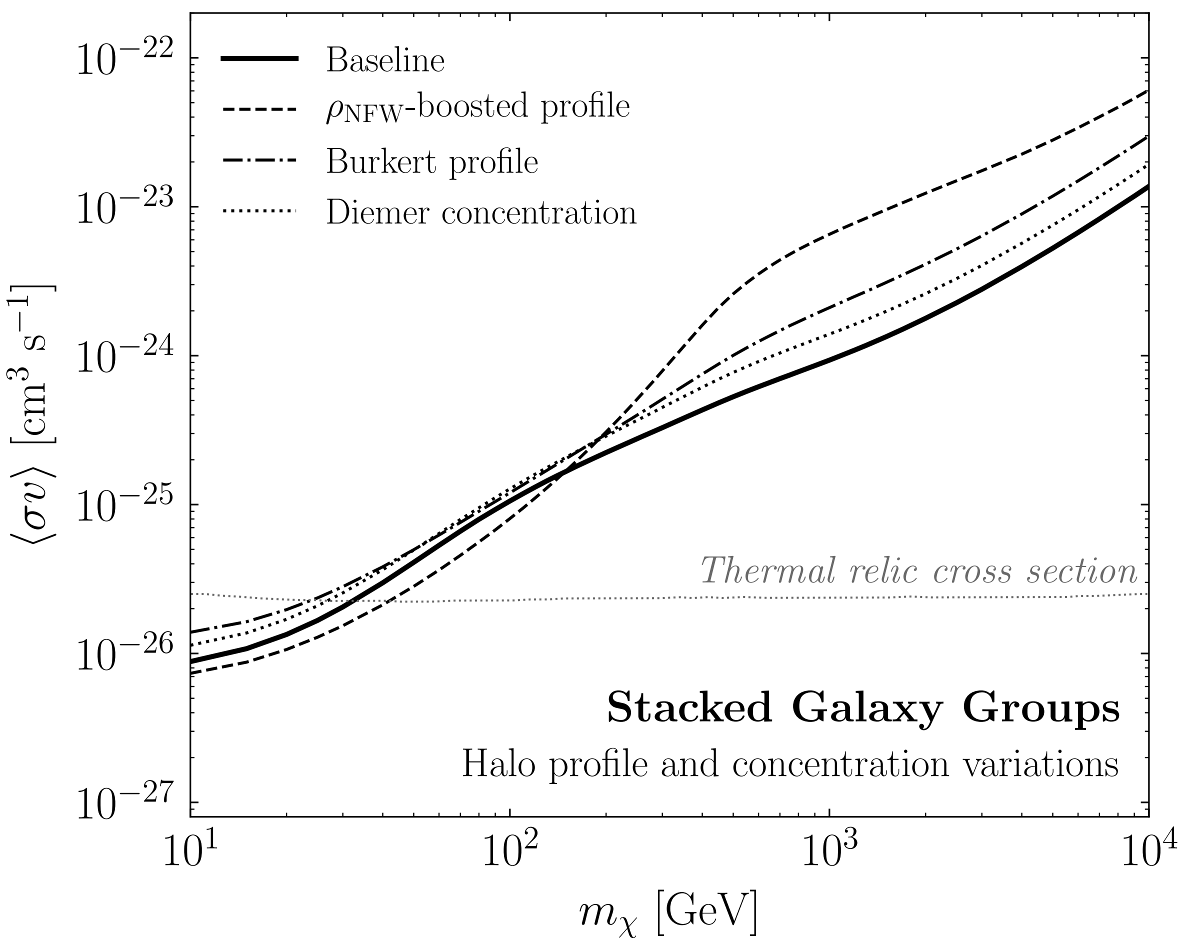
Selection systematics



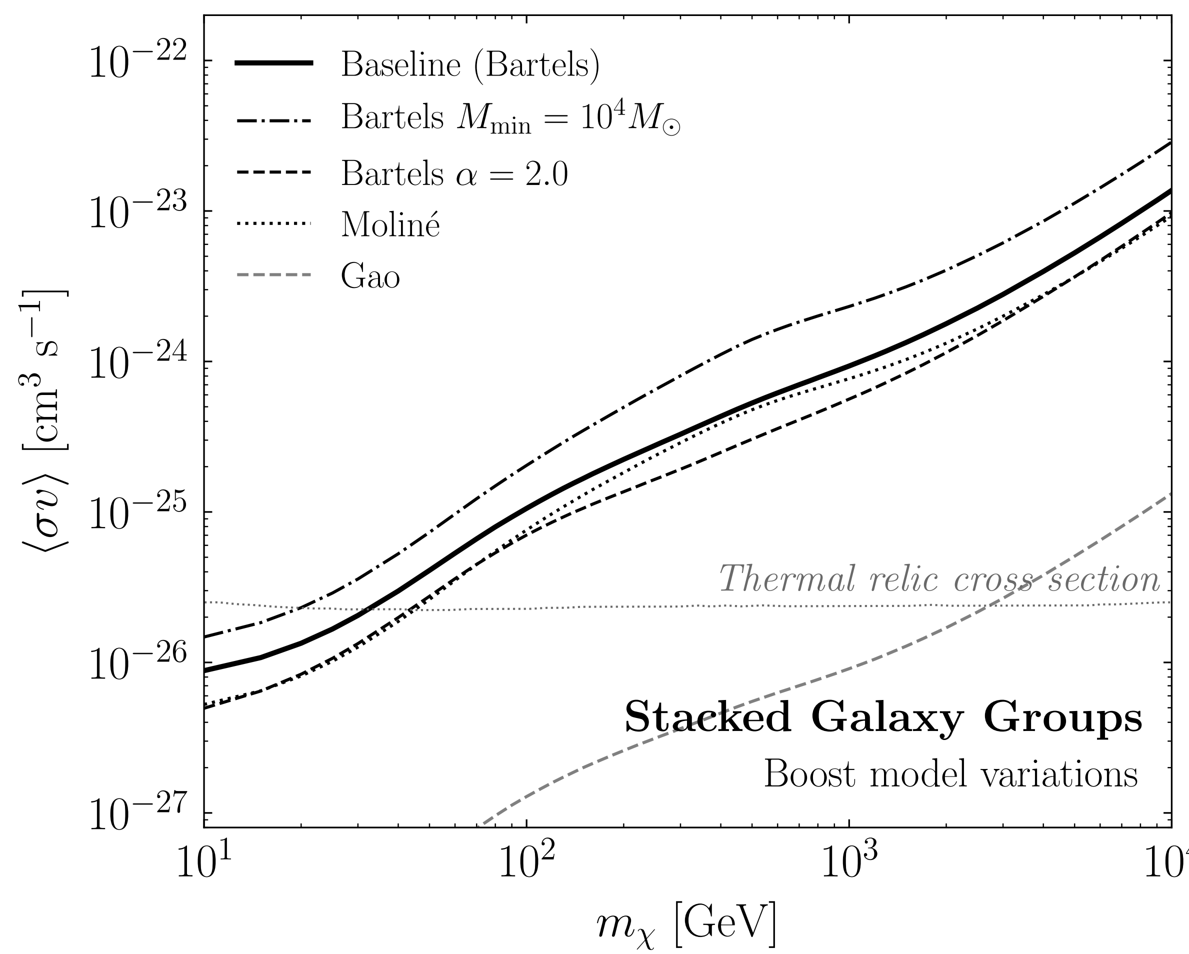


Systematic variations: profile/conc/boost

Effect of DM profile/concentration



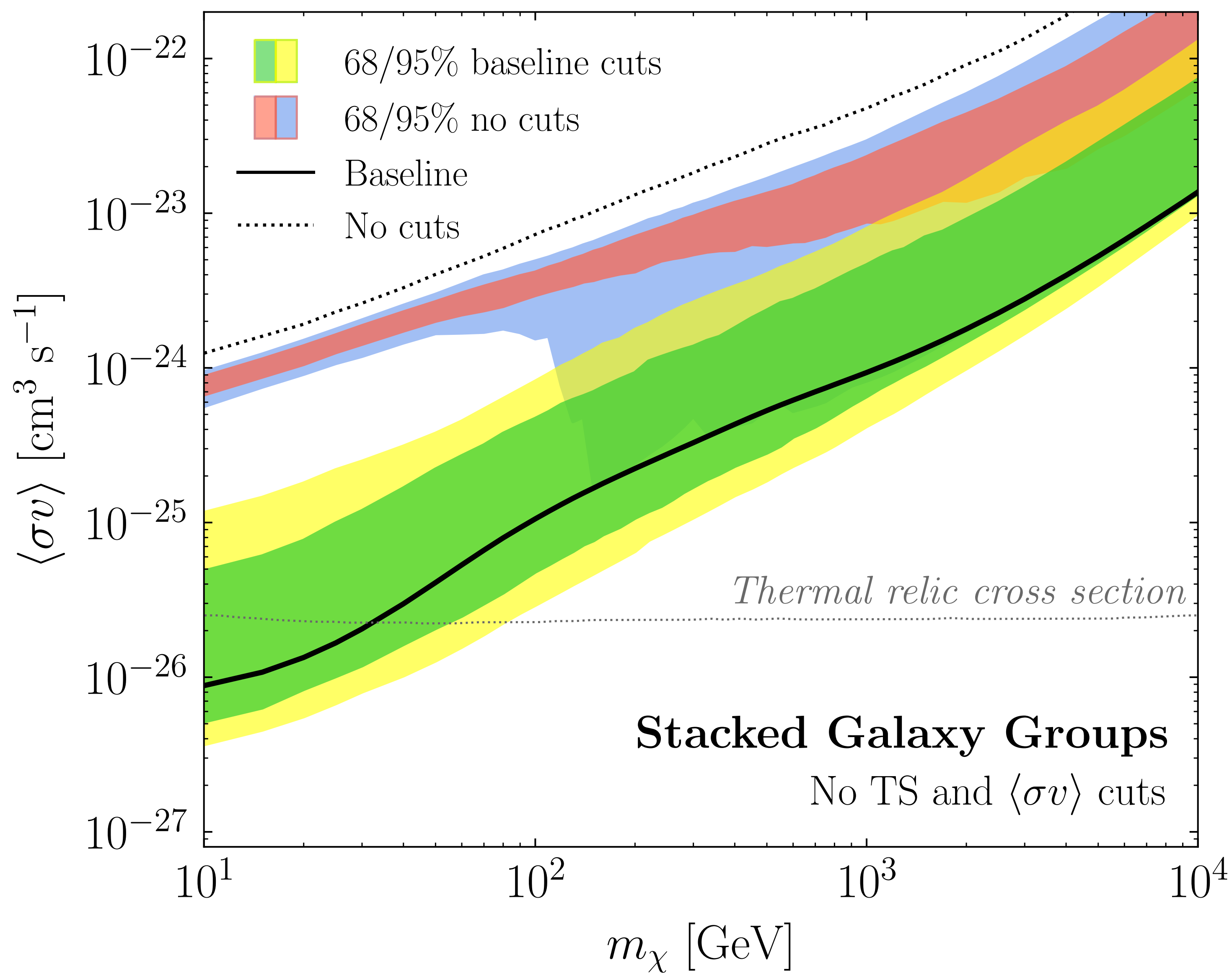
Effect of boost model



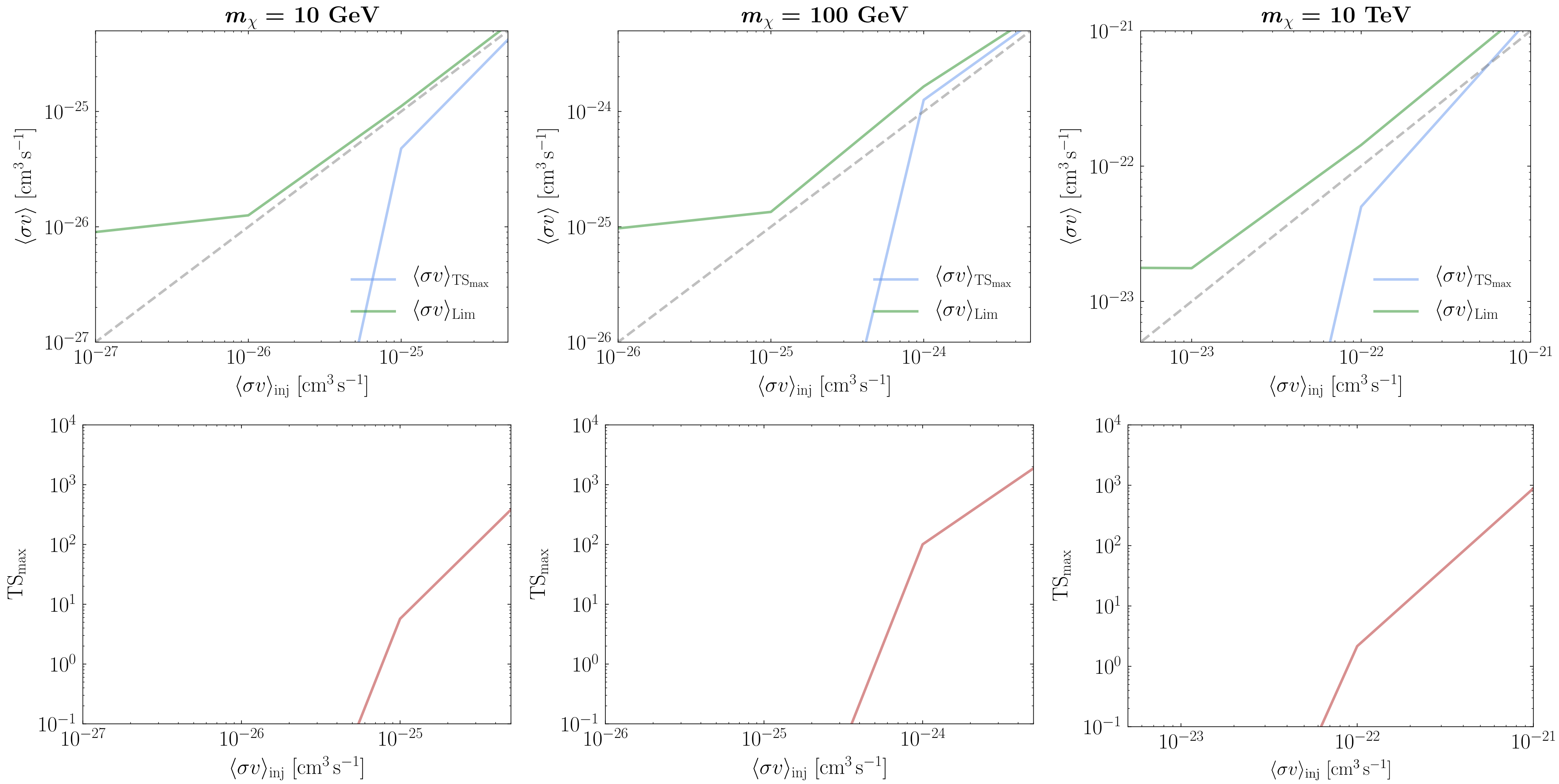
J-factor scaling

$$
\begin{aligned}
J_{\rm NFW} &= (1 + b_{\rm sh}[M_{\rm vir}]) \int ds d\Omega \, \rho^2_{\rm NFW}(s, \Omega) \\
&\approx (1 + b_{\rm sh}[M_{\rm vir}]) \, \frac{1}{d_A^2[z]} \int_V dV' \rho^2_{\rm NFW}(r') \\
&= (1 + b_{\rm sh}[M_{\rm vir}]) \, \frac{M_{\rm vir} c^3_{\rm vir} \rho_c \Delta_c[z]}{9 d_A^2[z]} \\
&\times \left[1 - \frac{1}{(1 + c_{\rm vir})^3}\right] \left[\ln\left(1 + c_{\rm vir}\right) - \frac{c_{\rm vir}}{1 + c_{\rm vir}}\right]^{-2} \\
&\sim (1 + b_{\rm sh}) \frac{M_{\rm vir} c^3_{\rm vir}}{d_A^2[z]}
\end{aligned}
$$

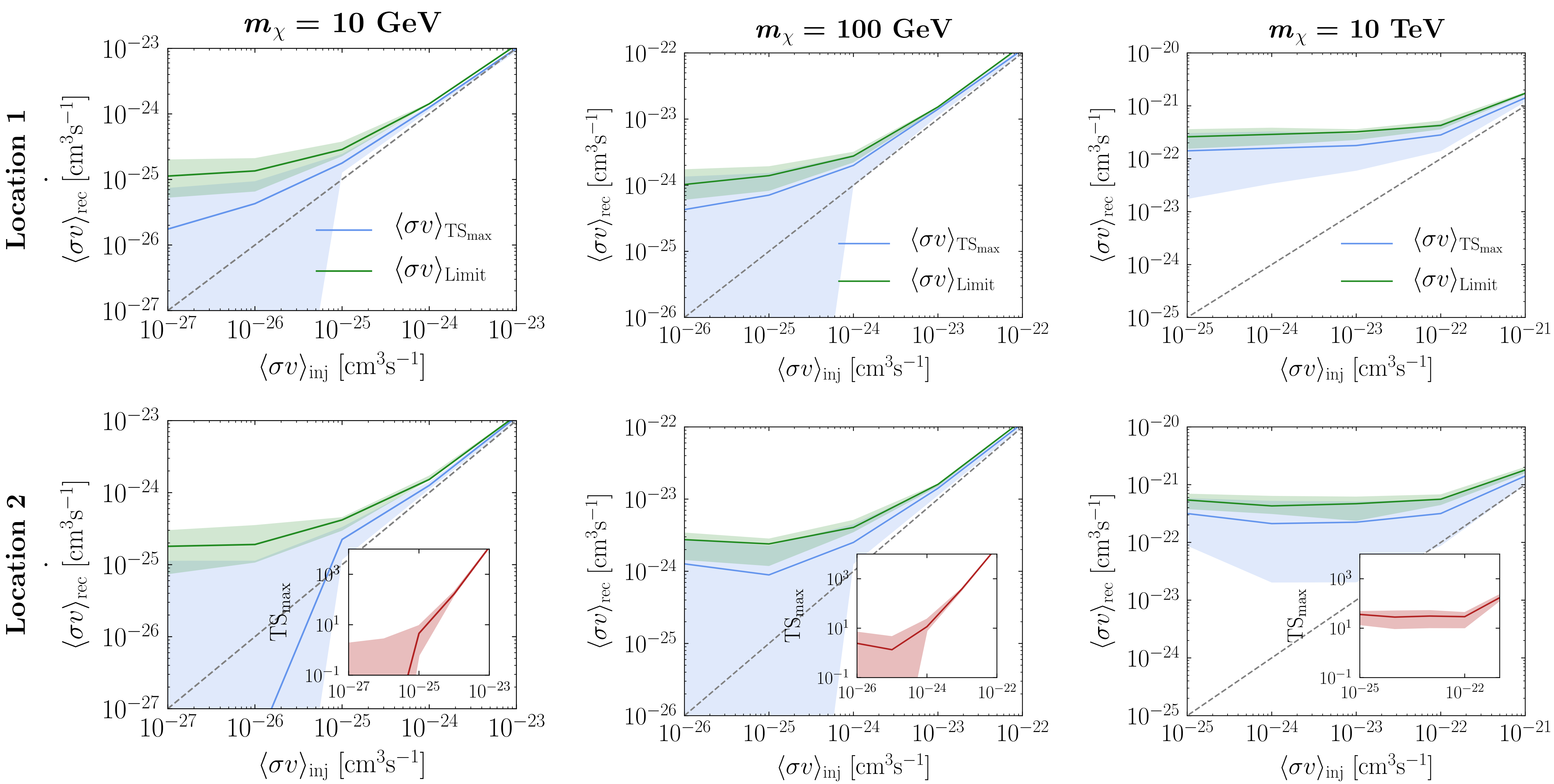
No cuts with MC



Injected signal on data



Injected signal on MC



DM profile likelihood

- Bin the data in energy (i) and spatial pixels (p): $\{l, b, E\} \Rightarrow n_i^p$
- Describe with model parameters: $\theta = \{\psi_{\rm DM}, \lambda_{\rm nuisance}\}$
- Construct the Poisson likelihood in each energy bin *i*

$$p_i(d_i|\theta_i) = \prod_p \frac{\mu_i^p(\theta_i)^{n_i^p} e^{-\mu_i^p(\theta_i)}}{n_i^p!}$$

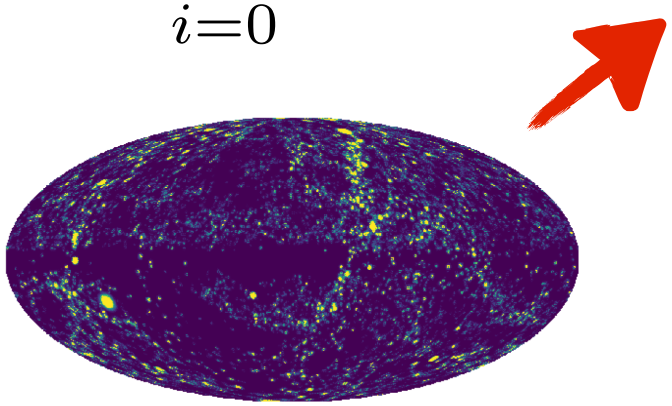
- Eliminate the nuisance parameters by profile likelihood

$$\log p_i(d_i|\psi_i) = \max_{\lambda_i} \log p_i(d_i|\theta_i)$$

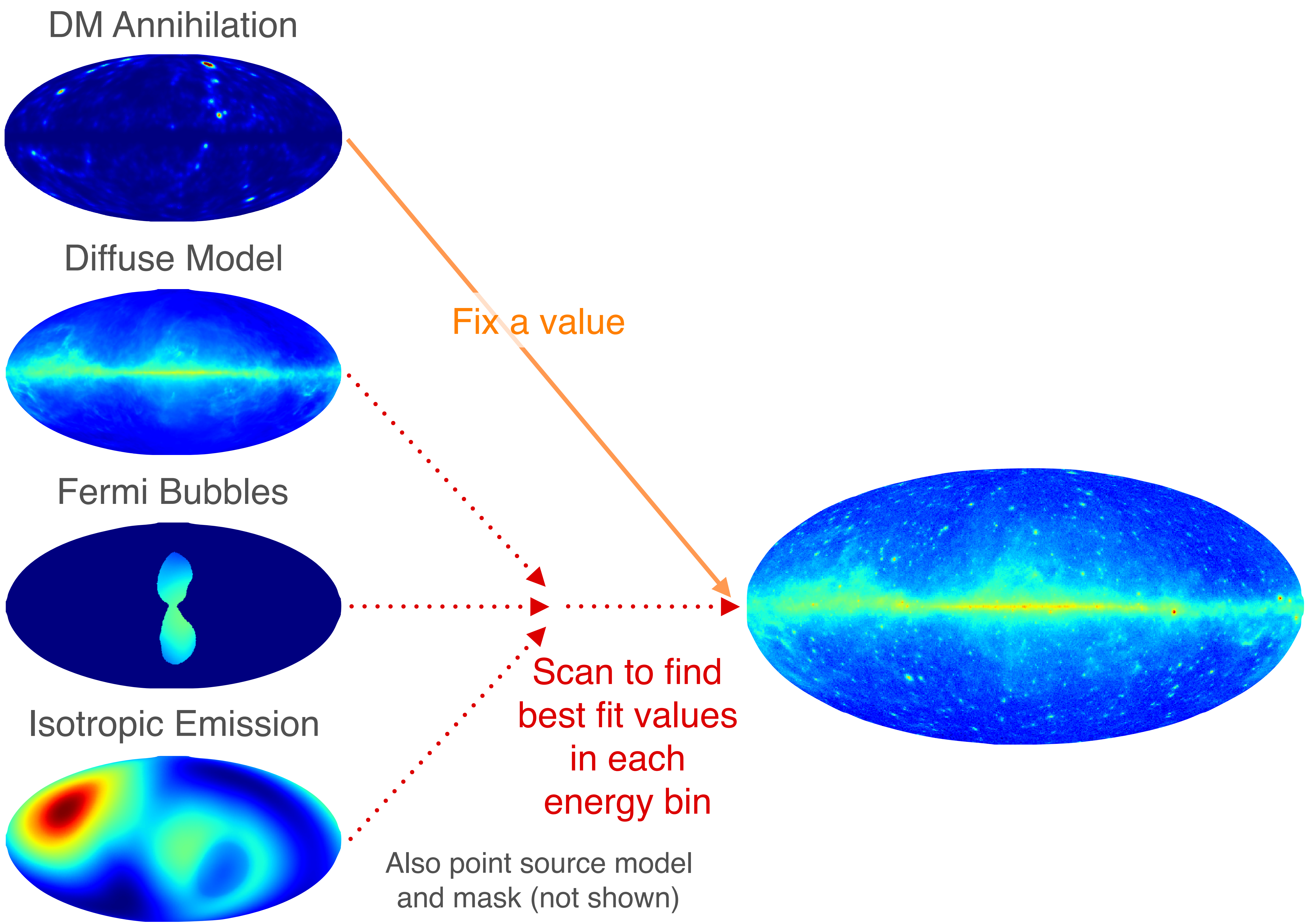
- Likelihood of a model depends on the injected galactic and extragalactic flux

$$\log p\,(d|\mathcal{M}, \{\langle\sigma v\rangle, m_{\rm DM}\}) = \sum_{i=0}^{39} \log p_i\,\left(d_i|I^i_{\rm cat}\right)$$

- From this define a TS, from which limits can be set
- Implement analysis using NPTFit [1612.03173]

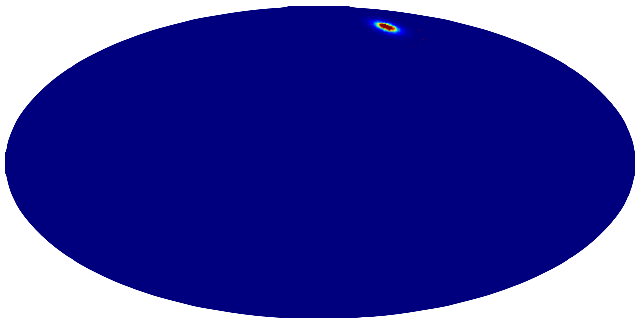


Profile likelihoods

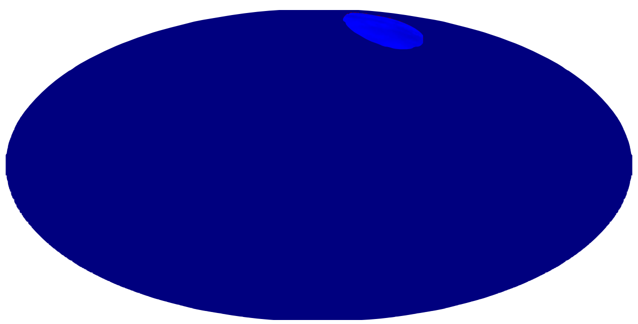


Profile likelihoods

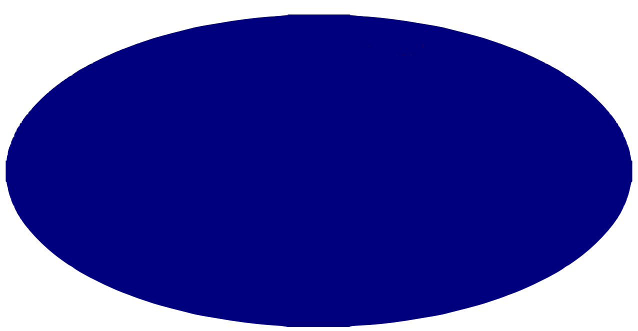
DM Annihilation



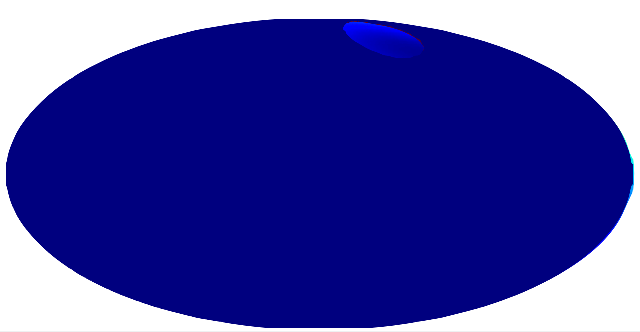
Diffuse Model



Fermi Bubbles

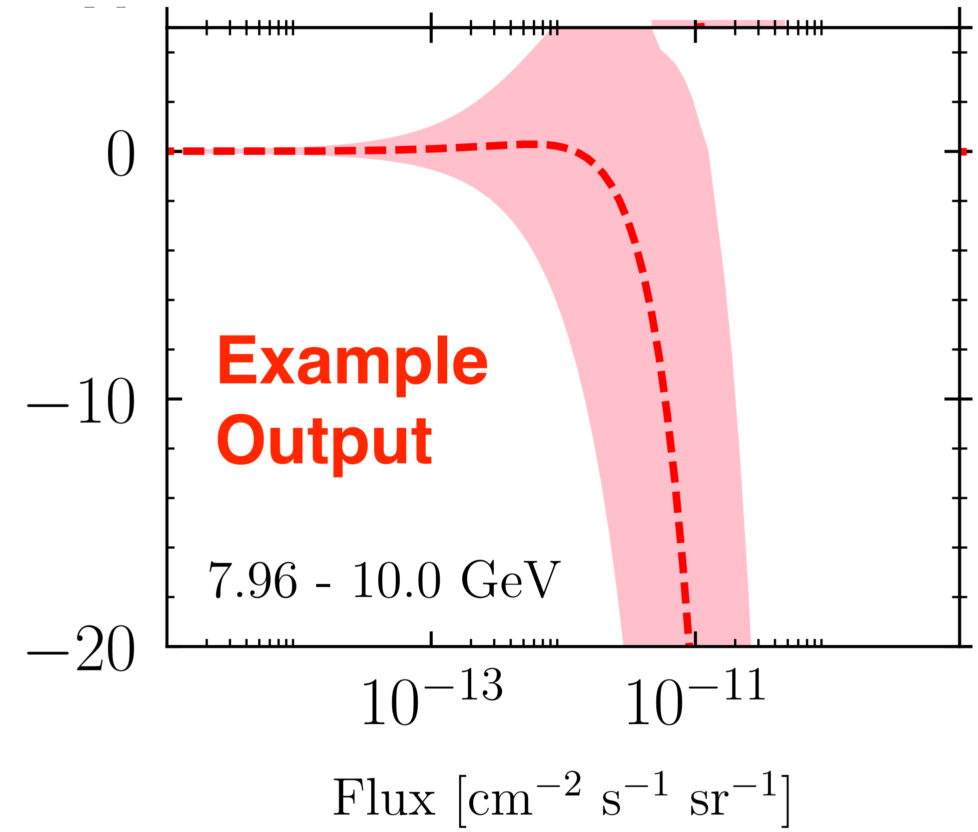


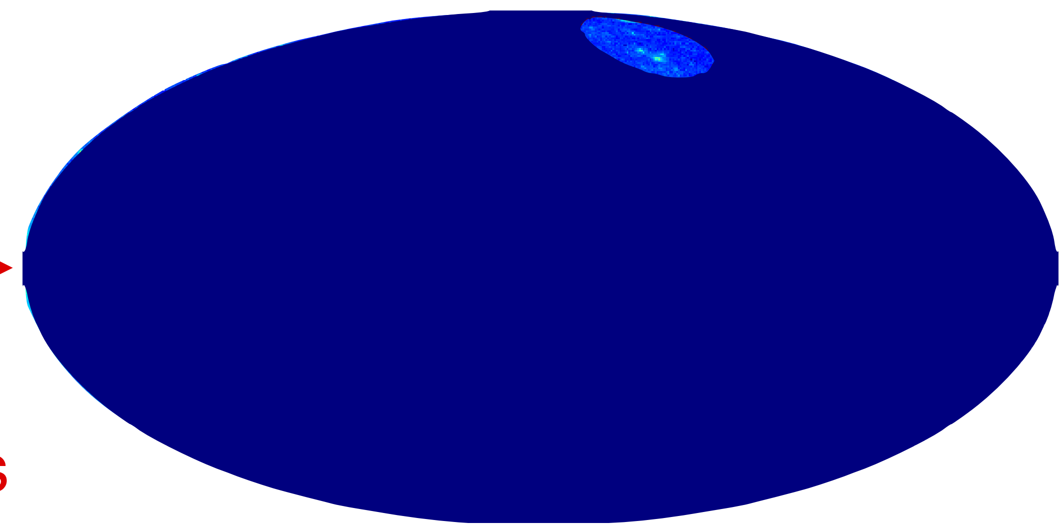
Isotropic Emission



Fix a value

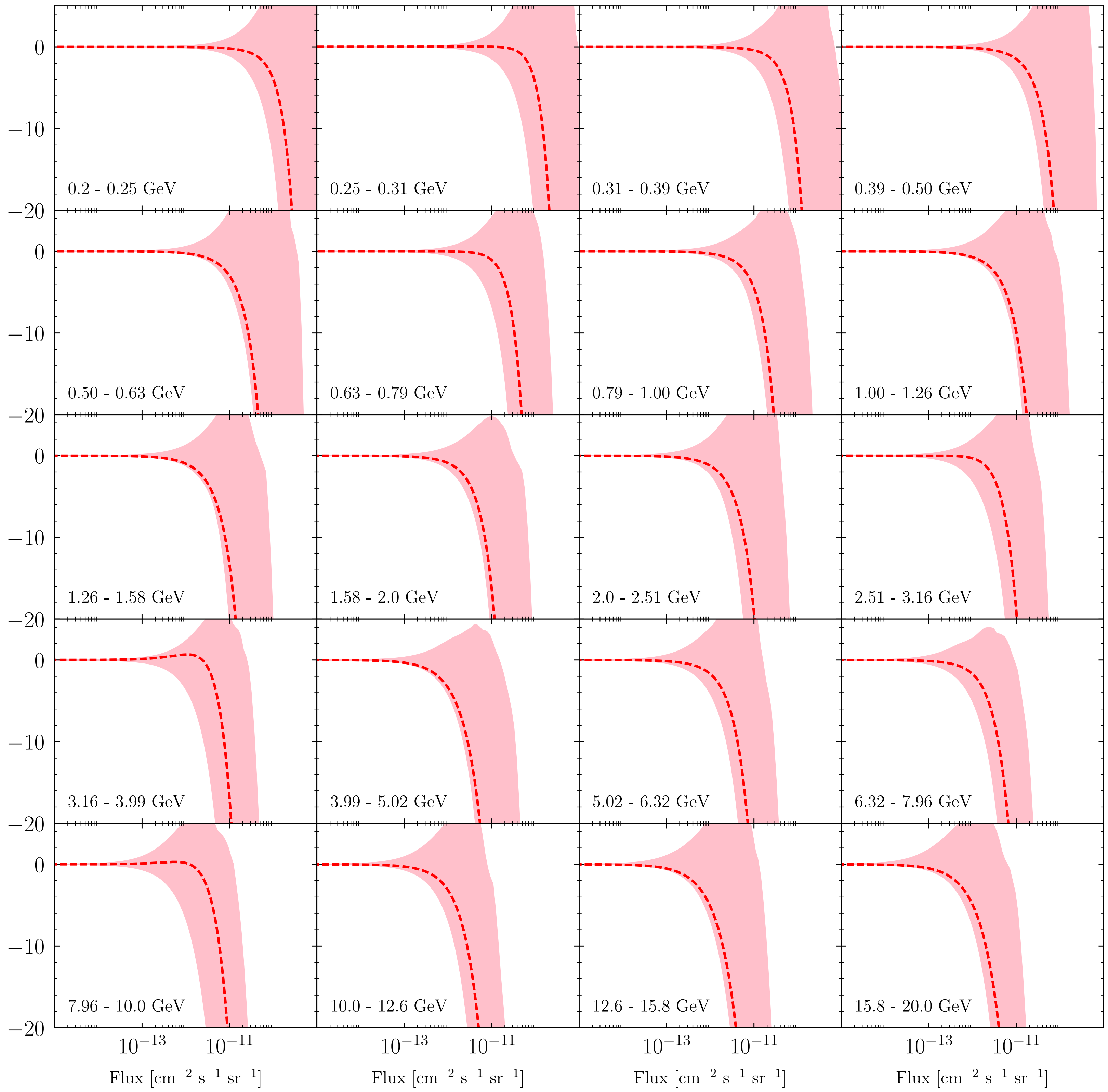
Scan to find best fit values in each energy bin





Also point source model and mask (not shown)

DM profile likelihood



Distance determination

arXiv:1605.01765v1

COSMICFLOWS-3

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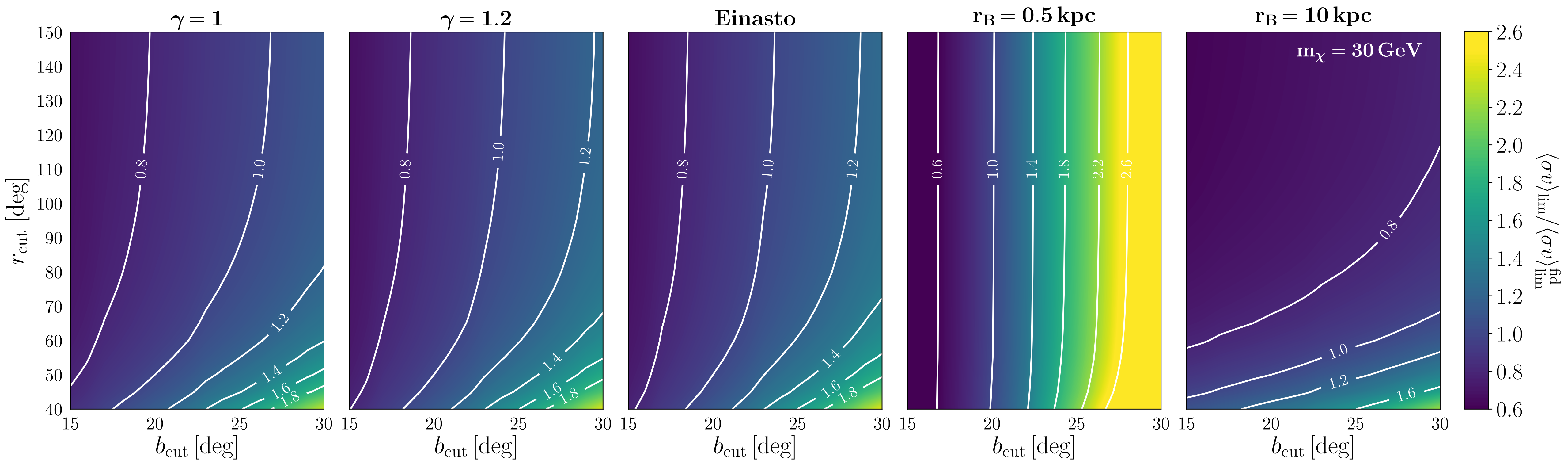
ABSTRACT

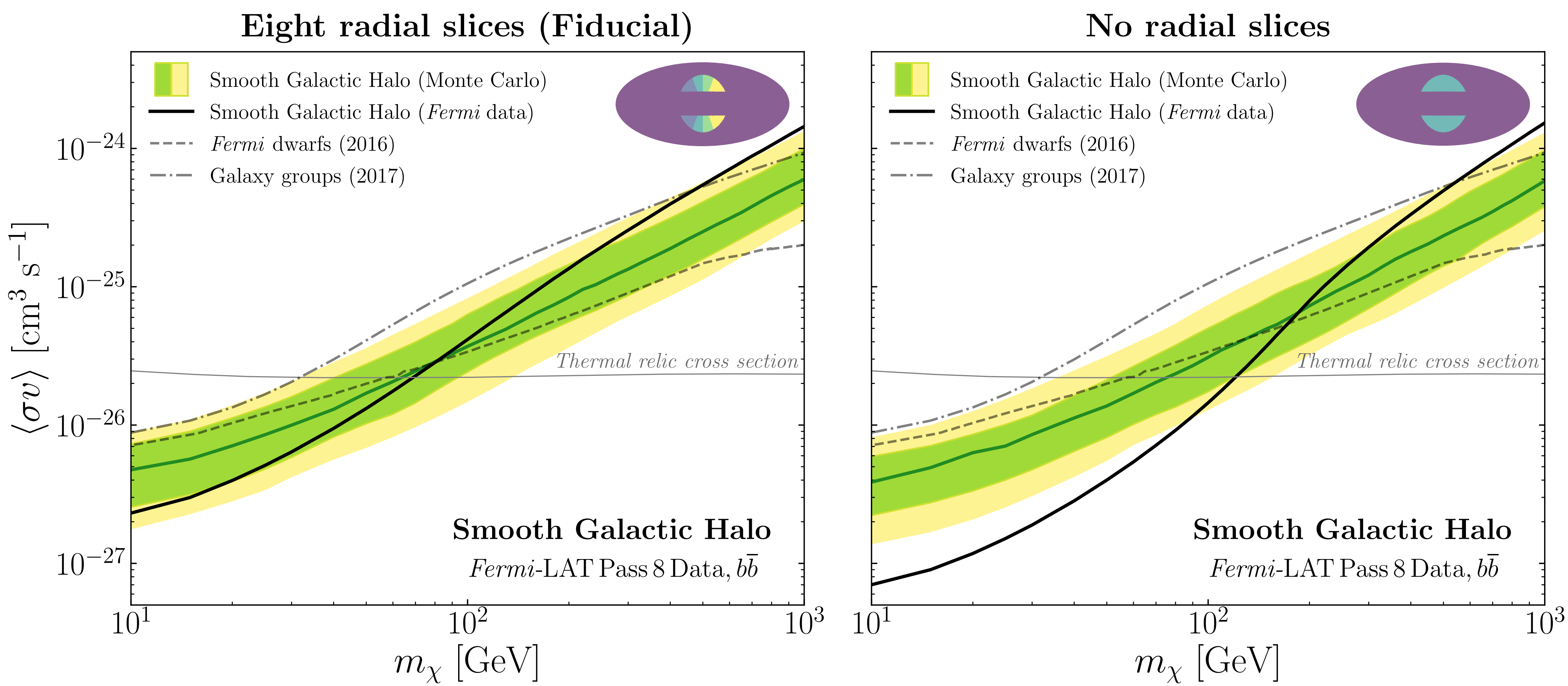
The *Cosmicflows* database of galaxy distances that in the 2nd edition contained 8,188 entries is now expanded to 17,669 entries. The major additions are 2,257 distances that we have derived from the correlation between galaxy rotation and luminosity with photometry at 3.6 μm obtained with *Spitzer Space Telescope* and 8,885 distances based on the Fundamental Plane methodology from the 6dFGS collaboration. There are minor augmentations to the Tip of the Red Giant Branch and Type I*a* supernova compilations. A zero point calibration of the supernova luminosities give a value for the Hubble Constant of $76.2 \pm 3.4 \pm 2.7$ ($\pm$ rand. $\pm$ sys.) km s^{-1} Mpc^{-1}. Alternatively, a restriction on the peculiar velocity monopole term representing global infall/outflow implies $H_0 = 75 \pm 2$ km s^{-1} Mpc^{-1}.

Key words: large scale structure of universe — galaxies: distances and redshifts

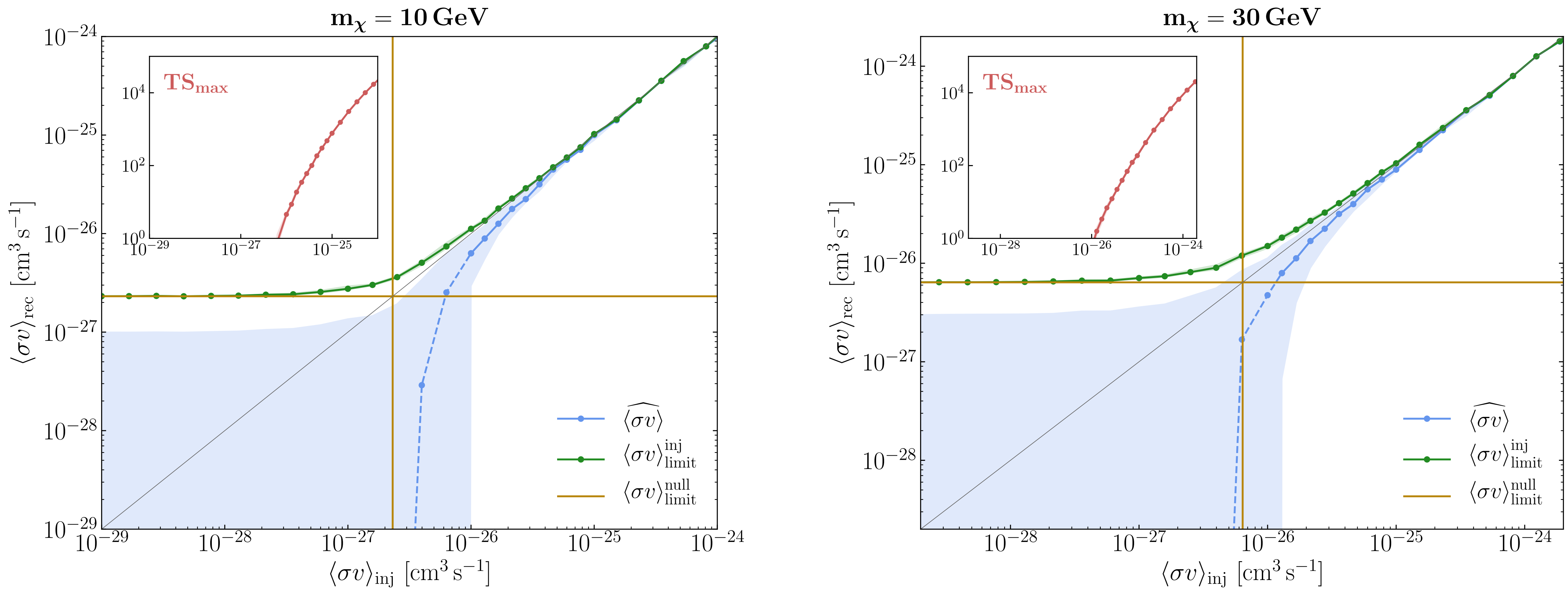
Asimov tests with Galactic halo templates



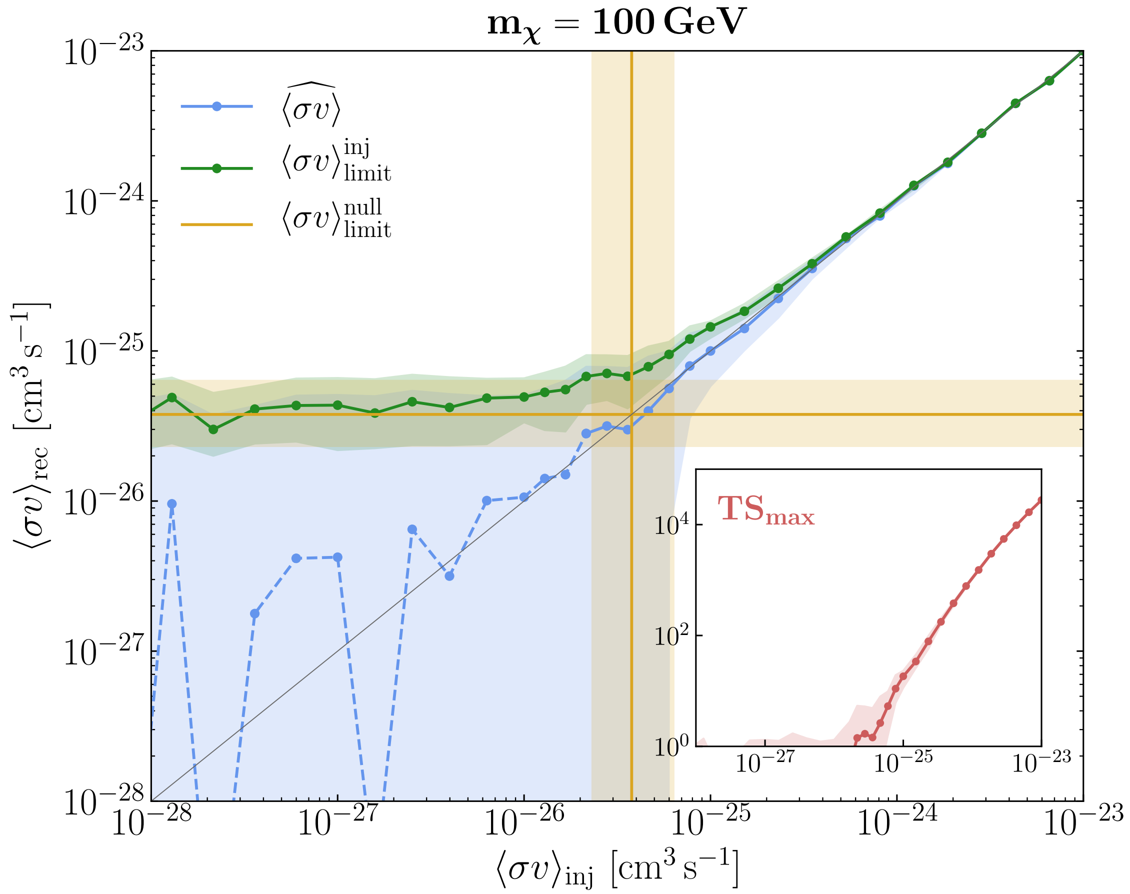
Galactic DM: Importance of radial slicing

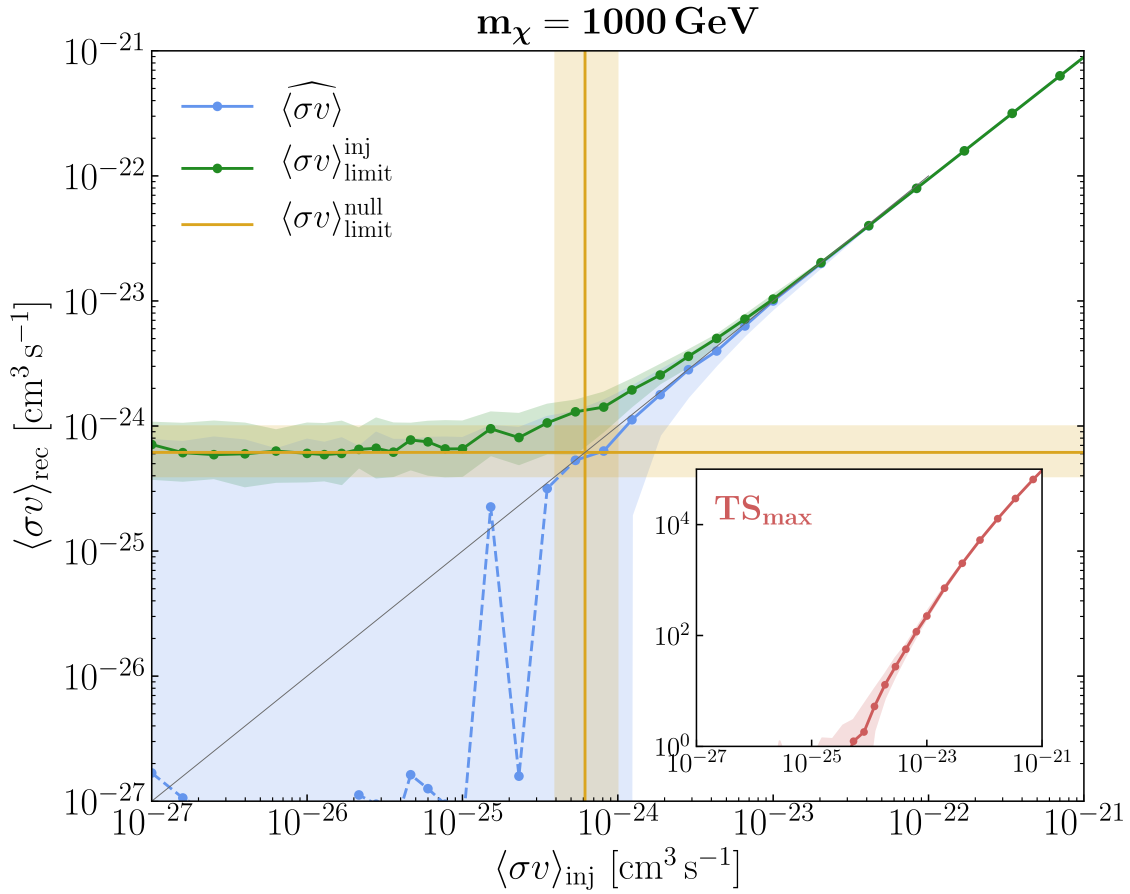


Injected signal on data

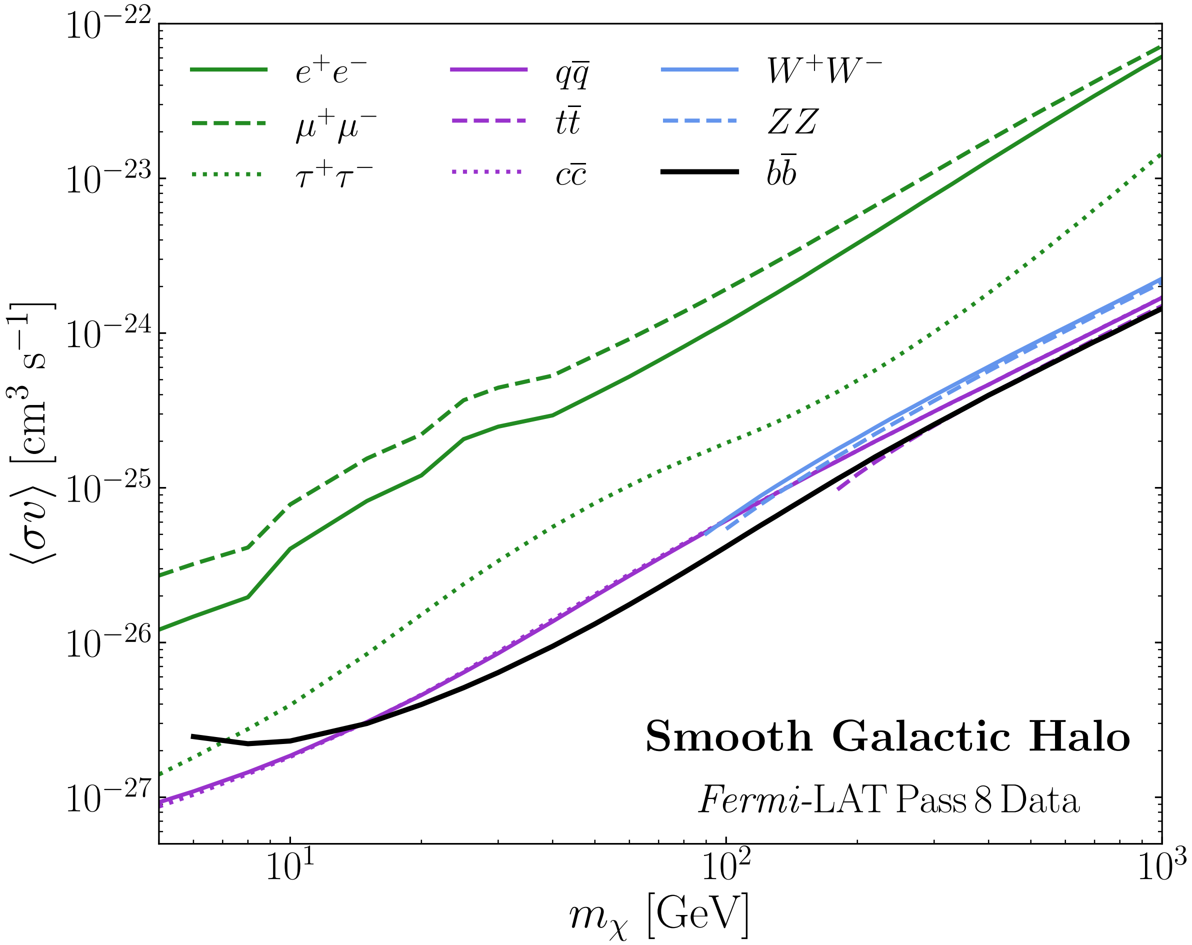


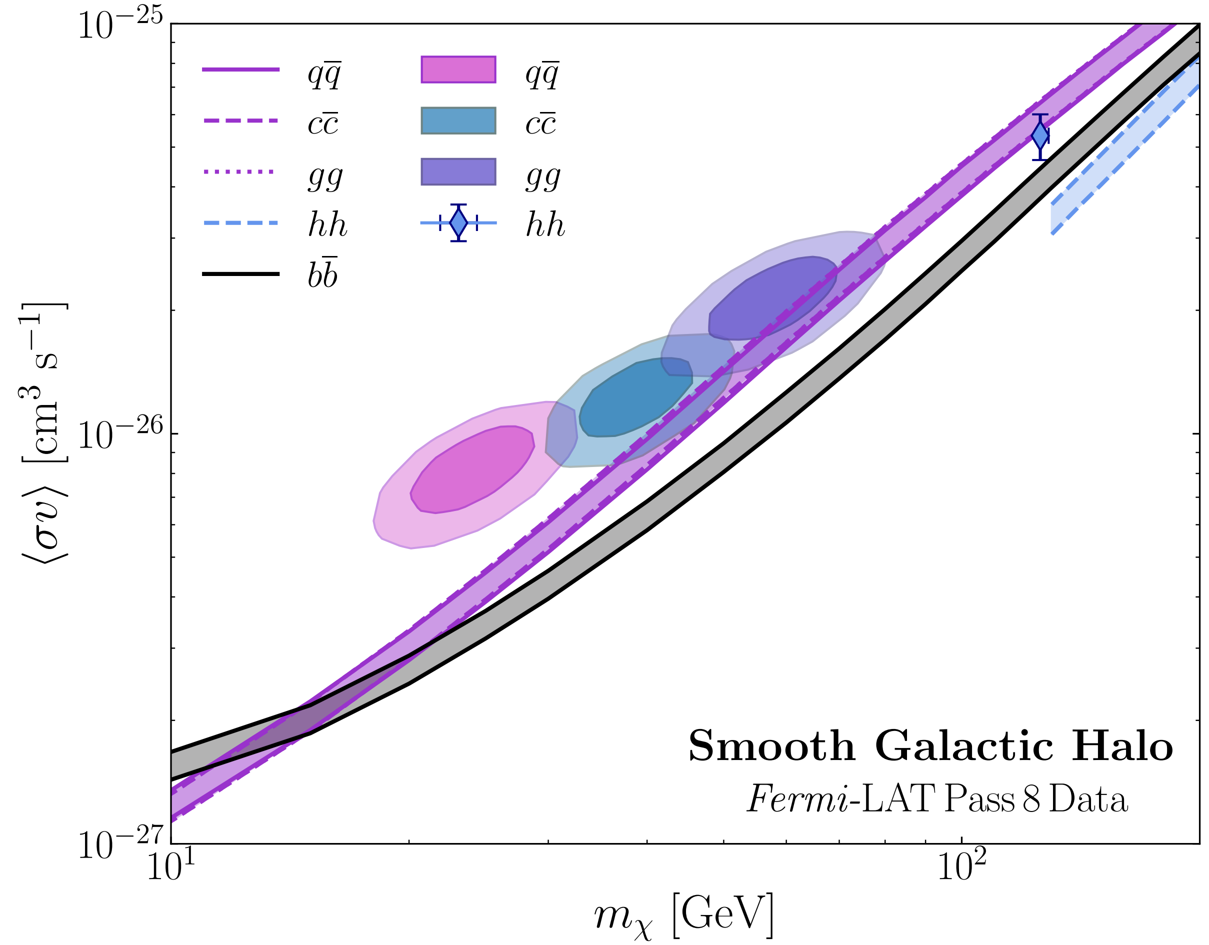
Injected signal on MC





Galactic DM: other annihilation channels





Galactic DM: systematic variations