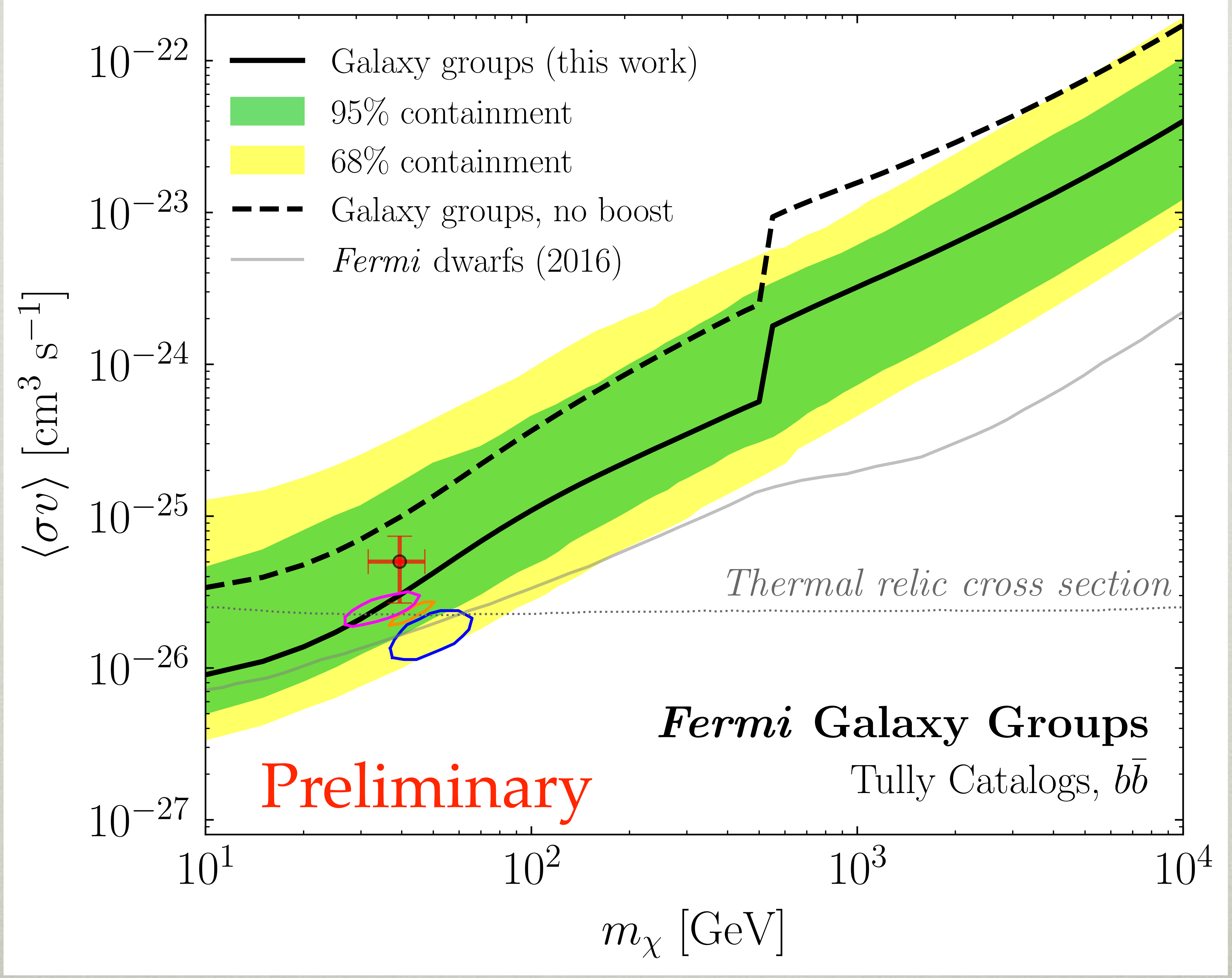
Searching for Dark Matter in Distant Galaxies

Nick Rodd

to appear (very soon!) w/ Mariangela Lisanti, Siddharth Mishra-Sharma, and Ben Safdi

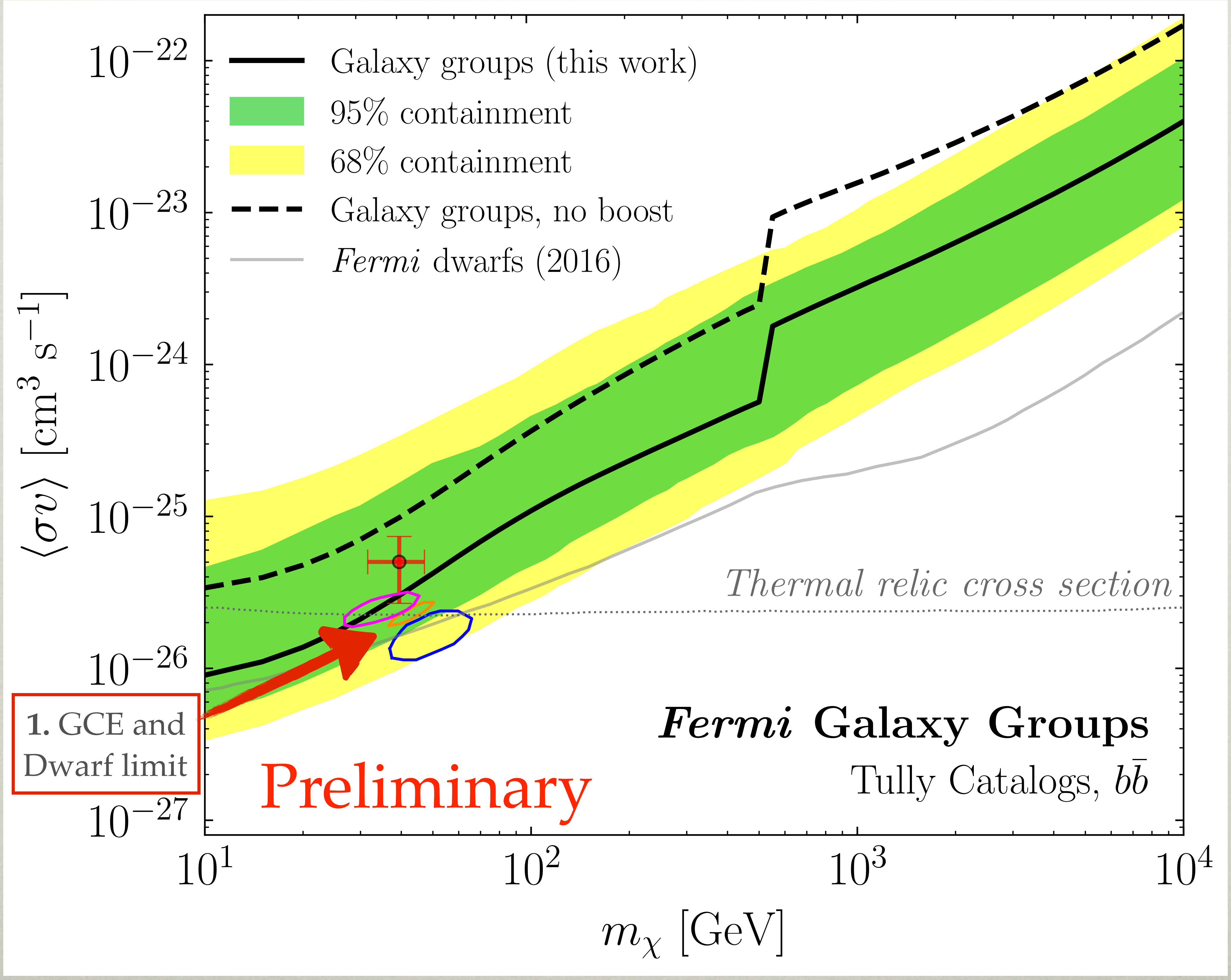
TeVPA
9 August 2017

Outline



Galaxy groups (this work)
95% containment
68% containment
Galaxy groups, no boost
Fermi dwarfs (2016)
Thermal relic cross section
Fermi Galaxy Groups
Tully Catalogs, $b\bar{b}$
Preliminary
$\langle \sigma v \rangle$ [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

Outline



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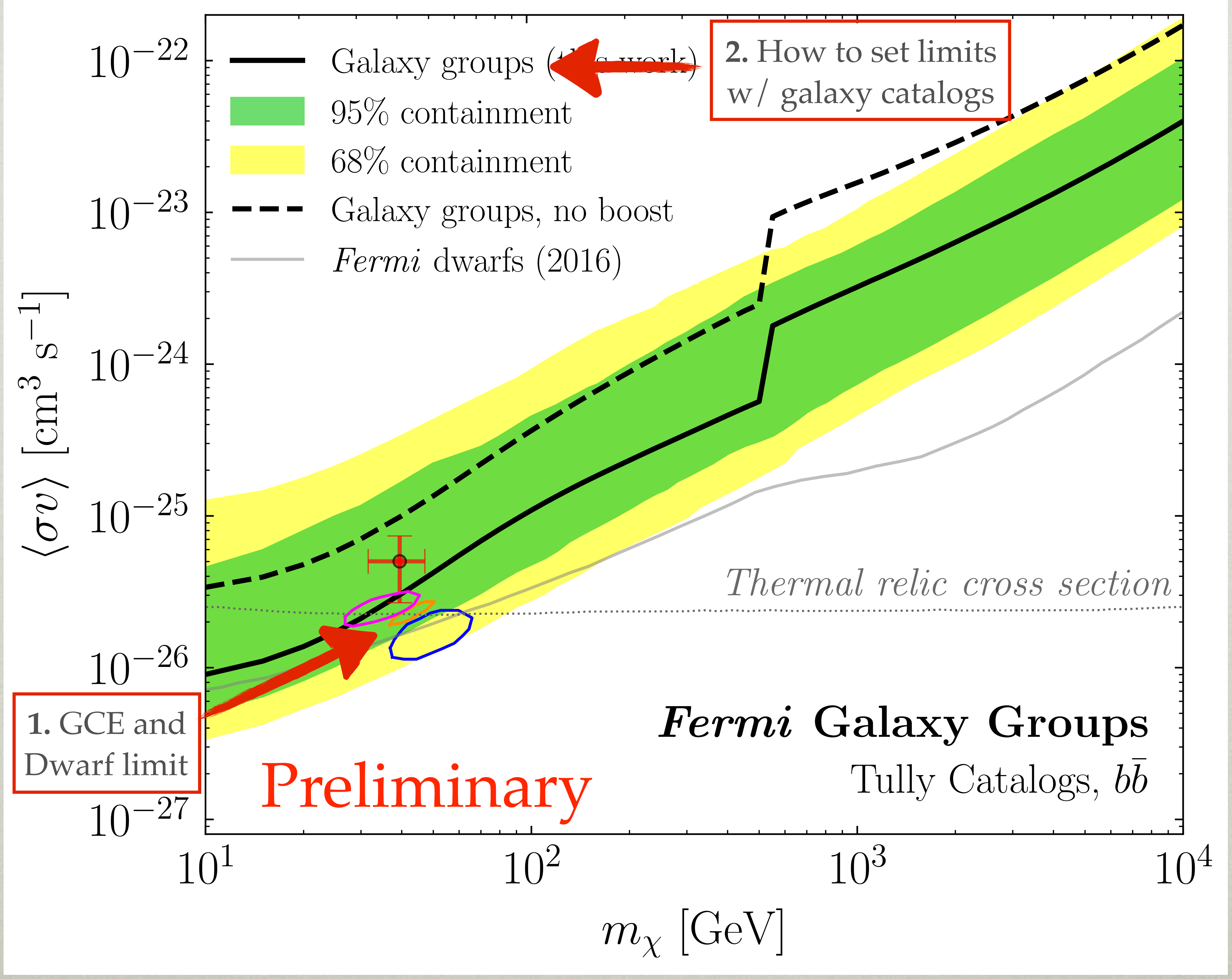

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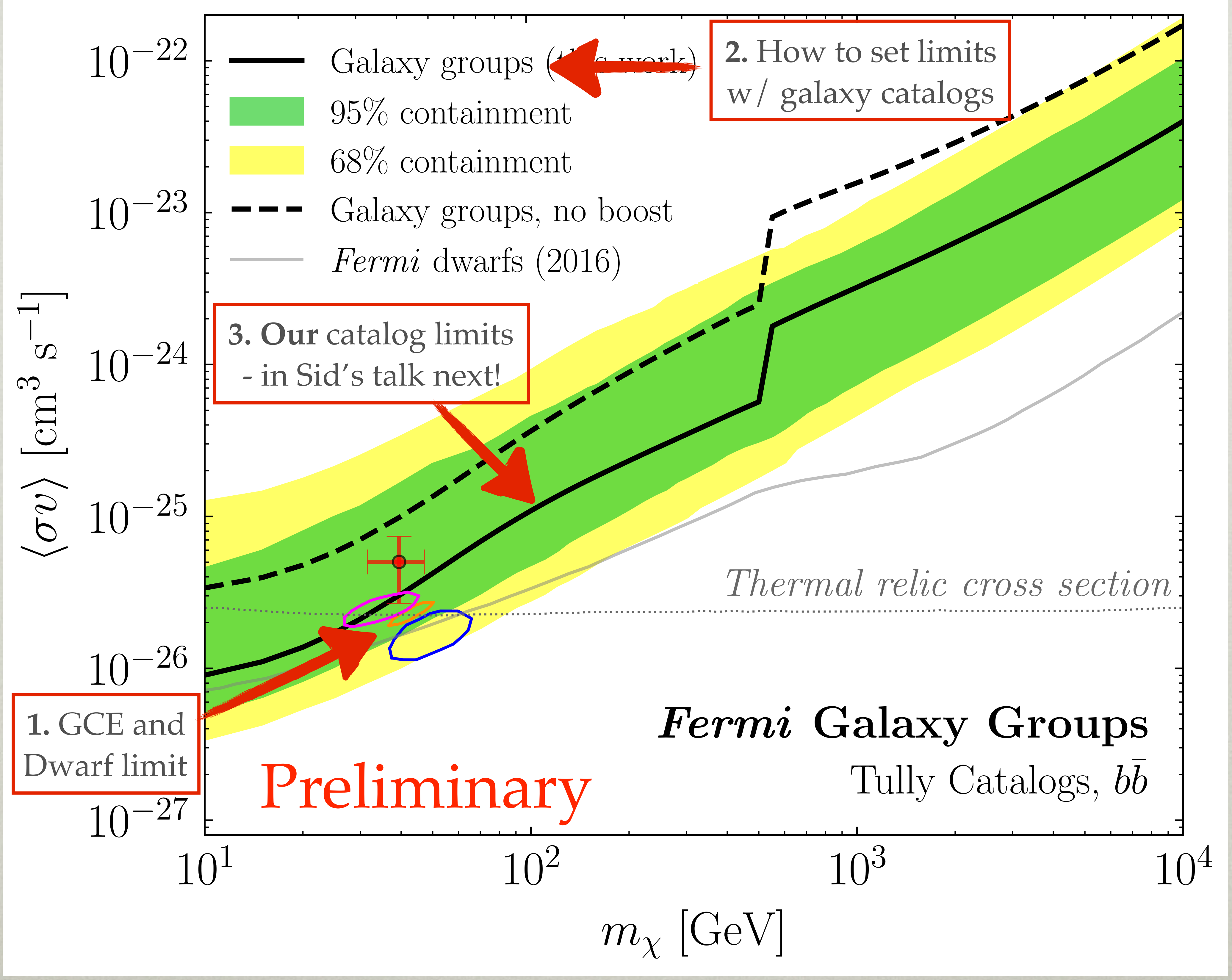

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2. How to set limits w/ galaxy catalogs
3. Our catalog limits - in Sid's talk next!
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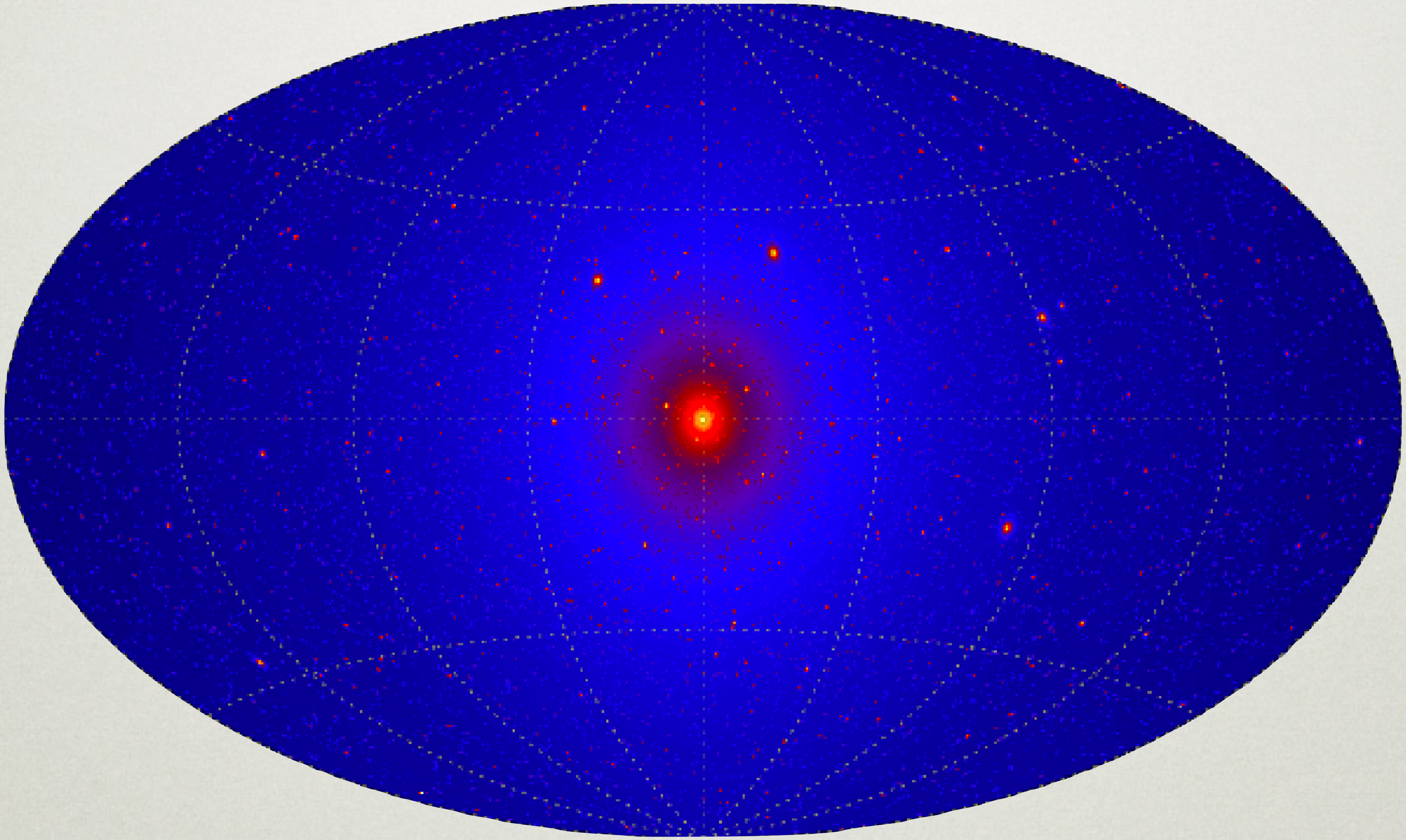
Where should we look?



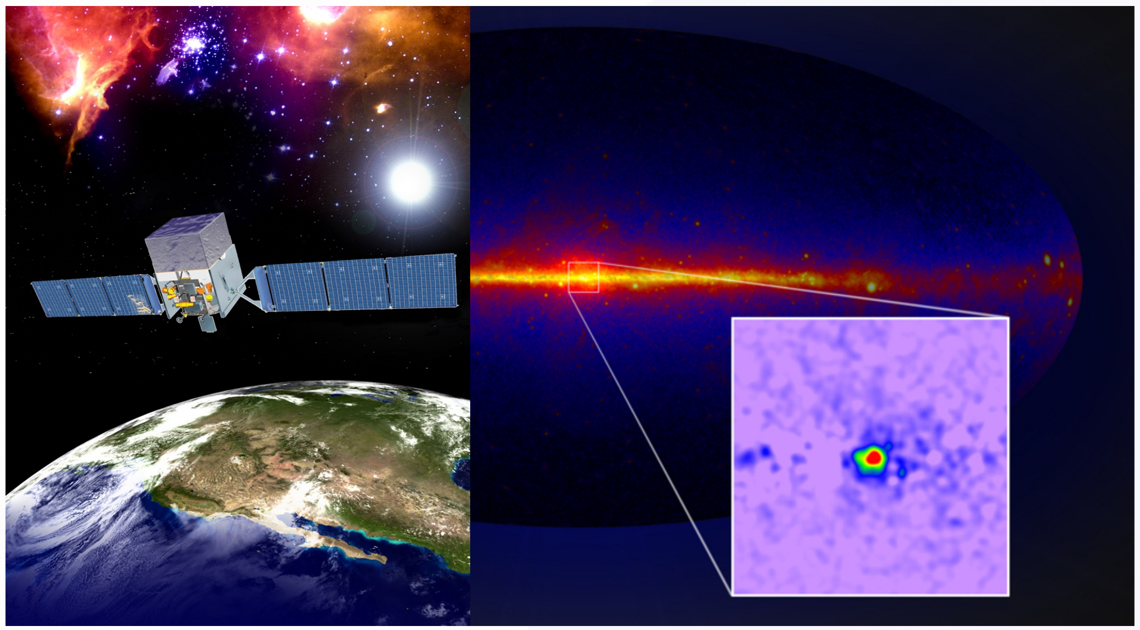
$$\Phi_{\rm DM} \propto J \sim \int ds\, \rho^2$$

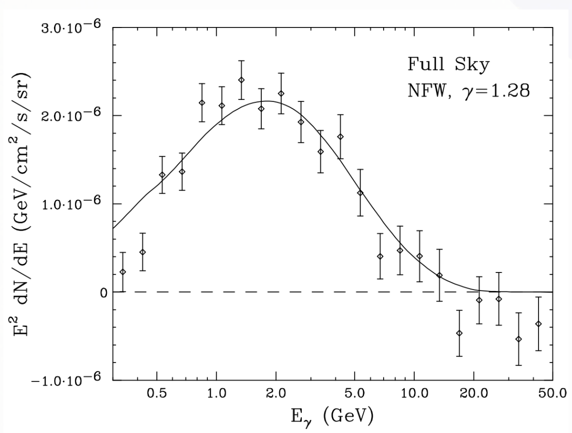
Image taken from 0908.0195

Where should we look?

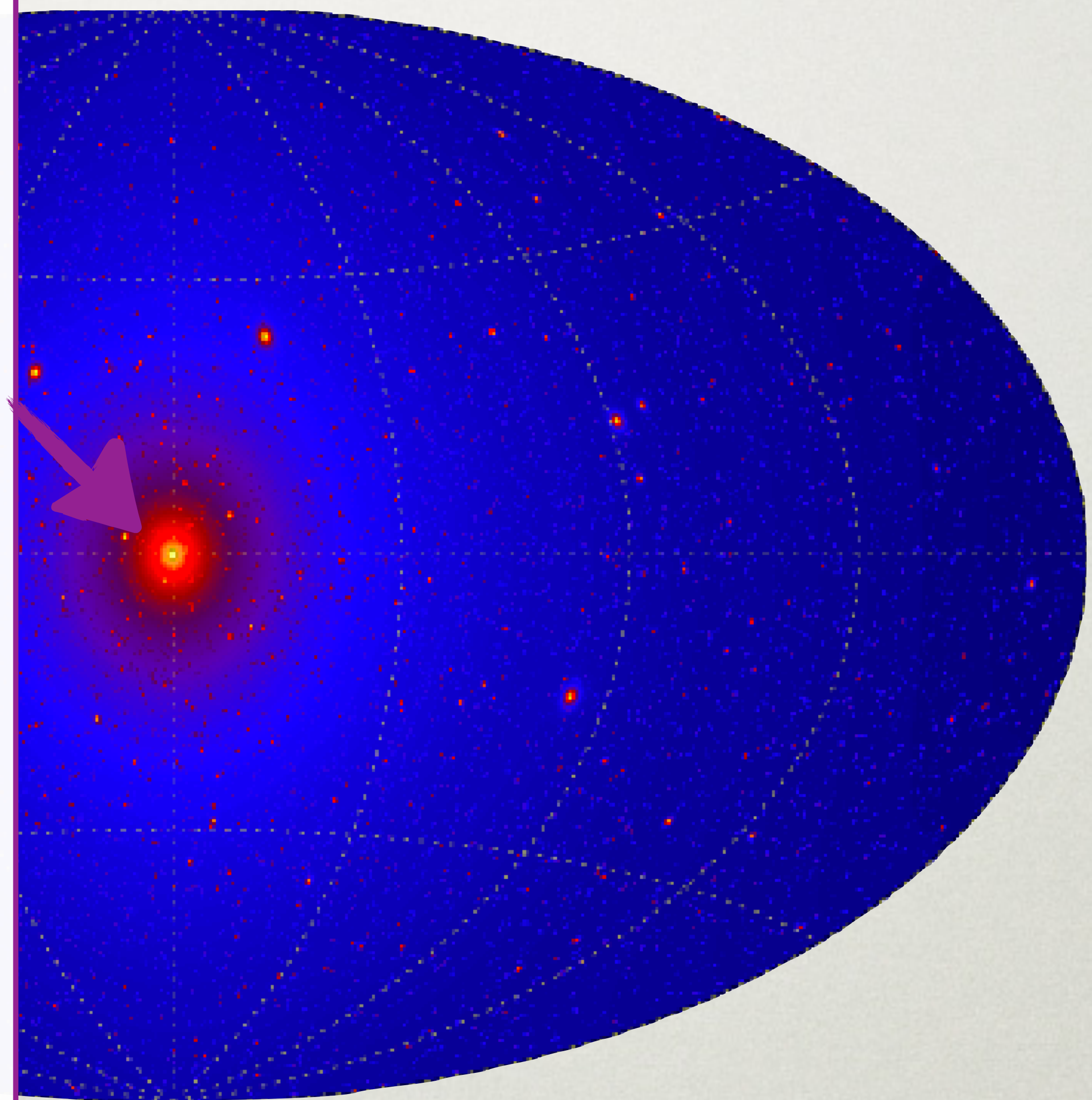
Galactic Center

- Bright but significant backgrounds
- An excess in the data!





NR et al (1402.6703)
See also **NR** et al (1604.01026) and many more!



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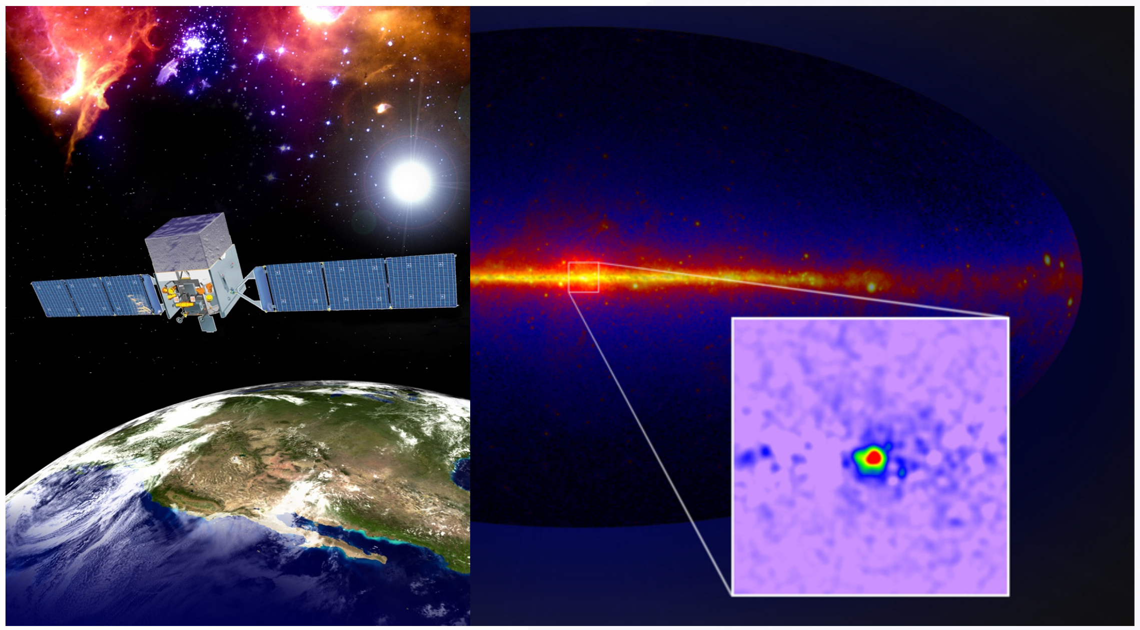

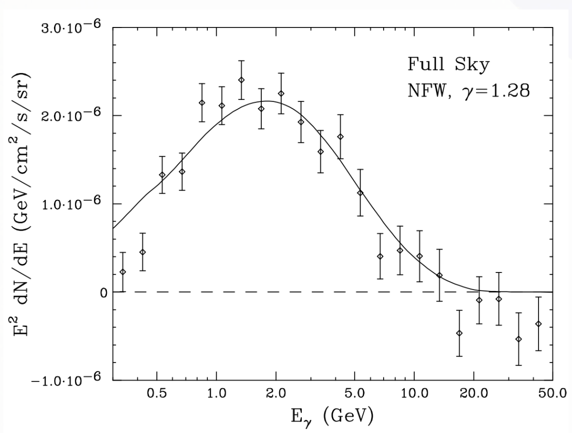

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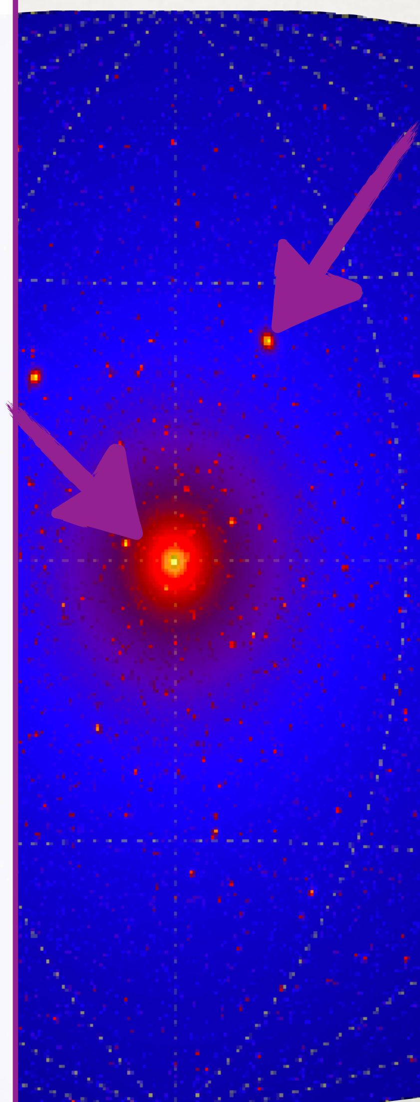
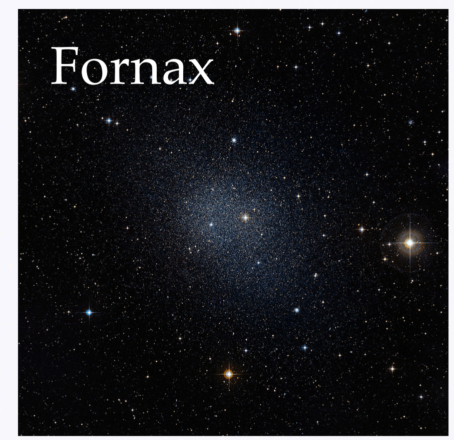


Milky Way Dwarfs

- Dim but low backgrounds
- Many discovered recently!



See Fermi-LAT Collaboration: 1310.0828, 1503.02641, 1611.03184

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

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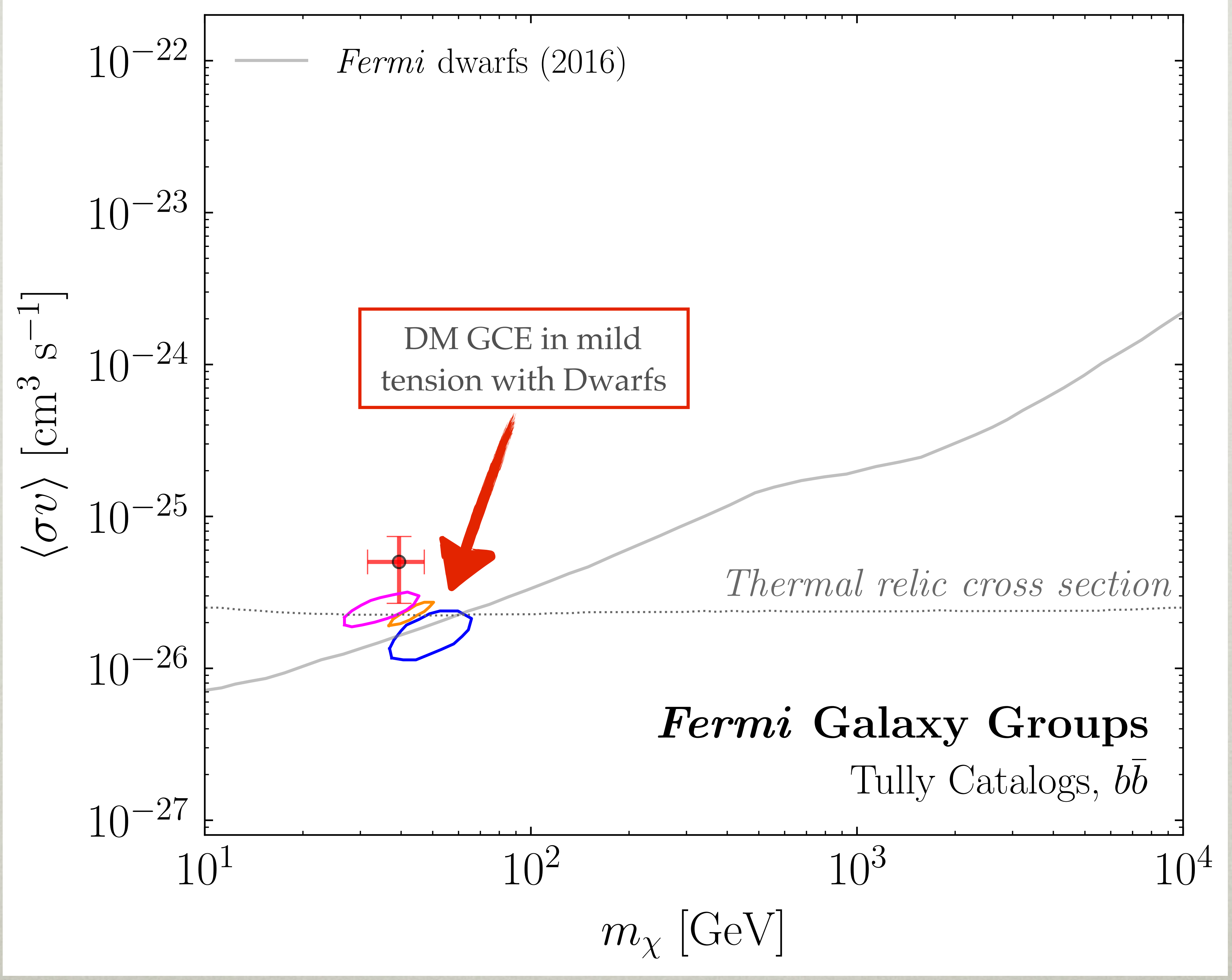

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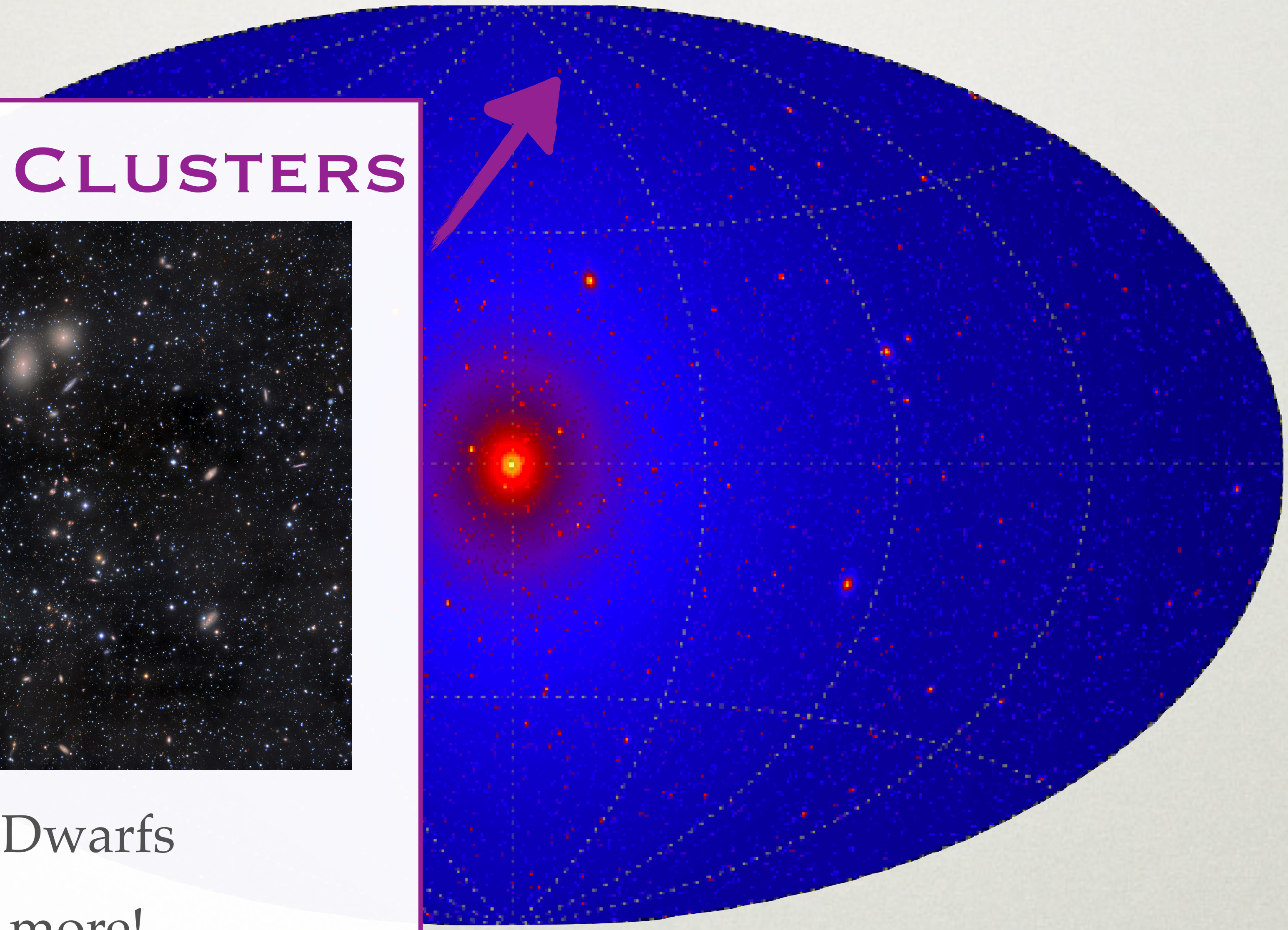


Galaxies and Clusters

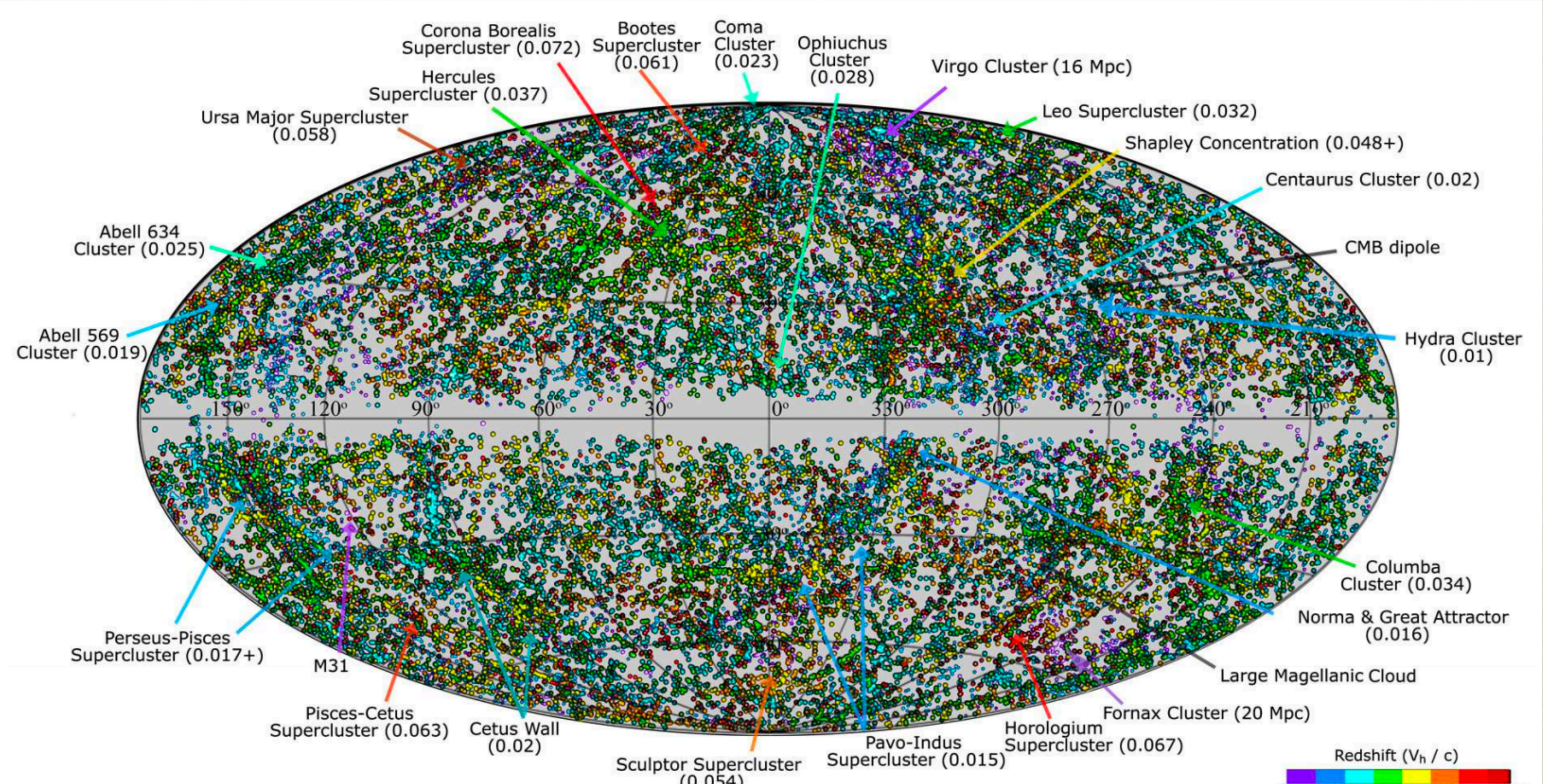
- Even dimmer than Dwarfs
- But there are many more!

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

Image taken from 0908.0195

Building a Map Of Extragalactic DM

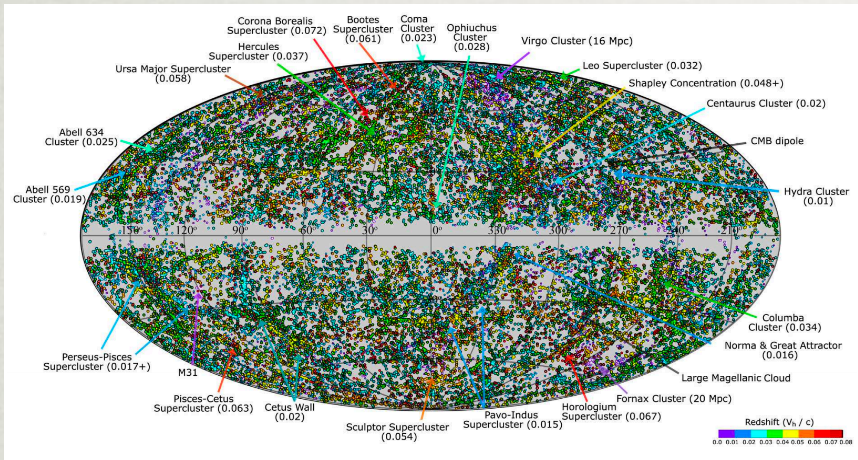
- **Starting point:** a catalog of galaxies, e.g. 2MASS



Huchra et al 1108.0669

- **Basic problem:** How do we go from galaxies to DM?

Building a Map Of Extragalactic DM



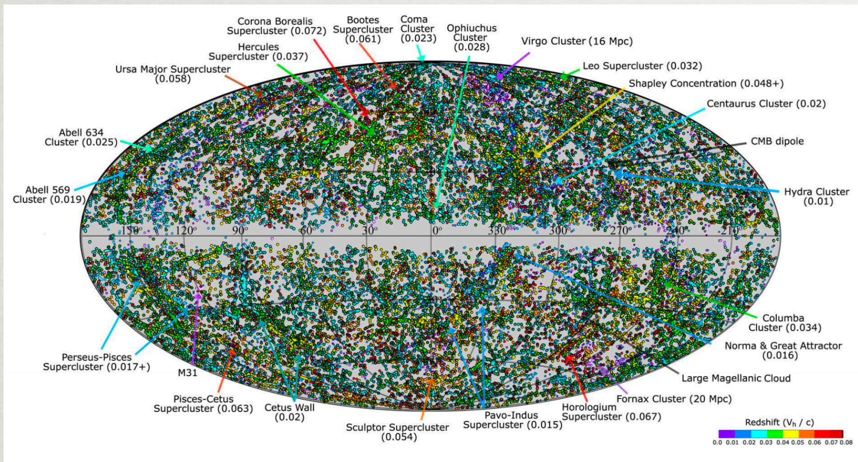
$$J = (1 + b_{\rm sh}) \int \rho^2 (s, \Omega)\, ds d\Omega$$

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

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

- Need all 4 for every galaxy
- z often well known, others less so

Building a Map Of Extragalactic DM



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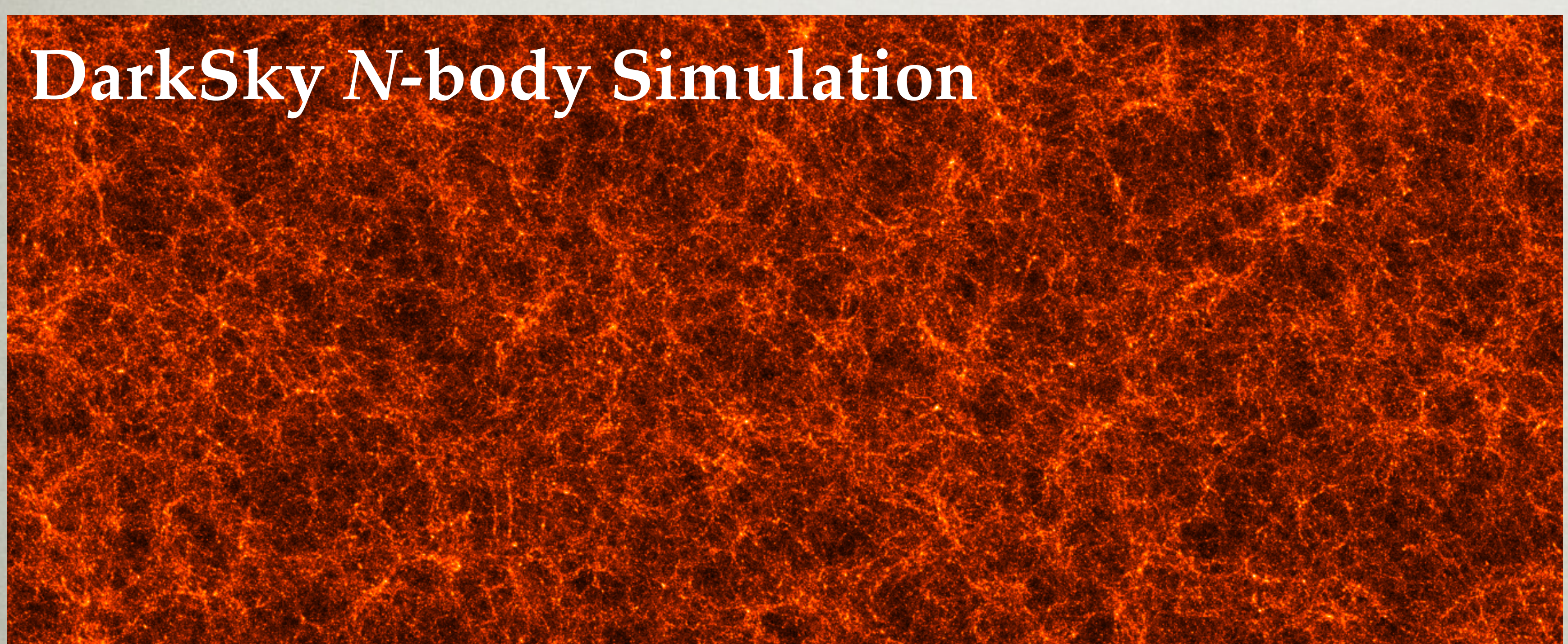
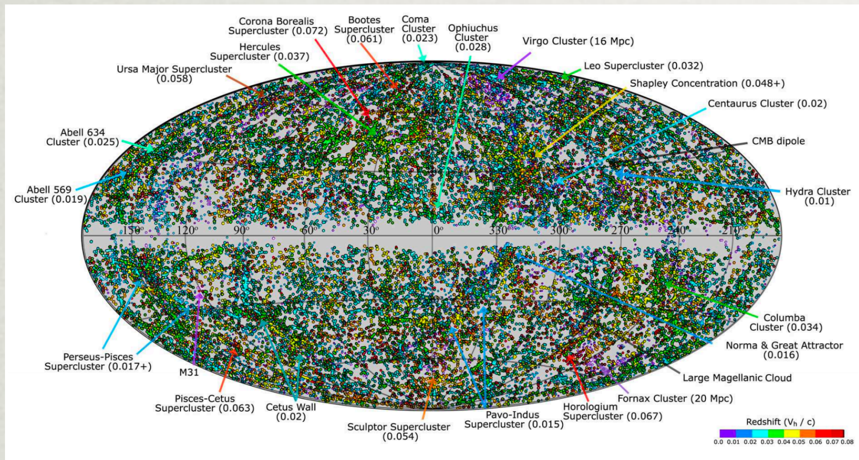


4096^3 particles; 400 Mpc/h box; $m \sim 7.6 \times 10^7 M_\odot$
Skillman et al 1407.2600;
darksky.slac.stanford.edu

Building a Map Of Extragalactic DM



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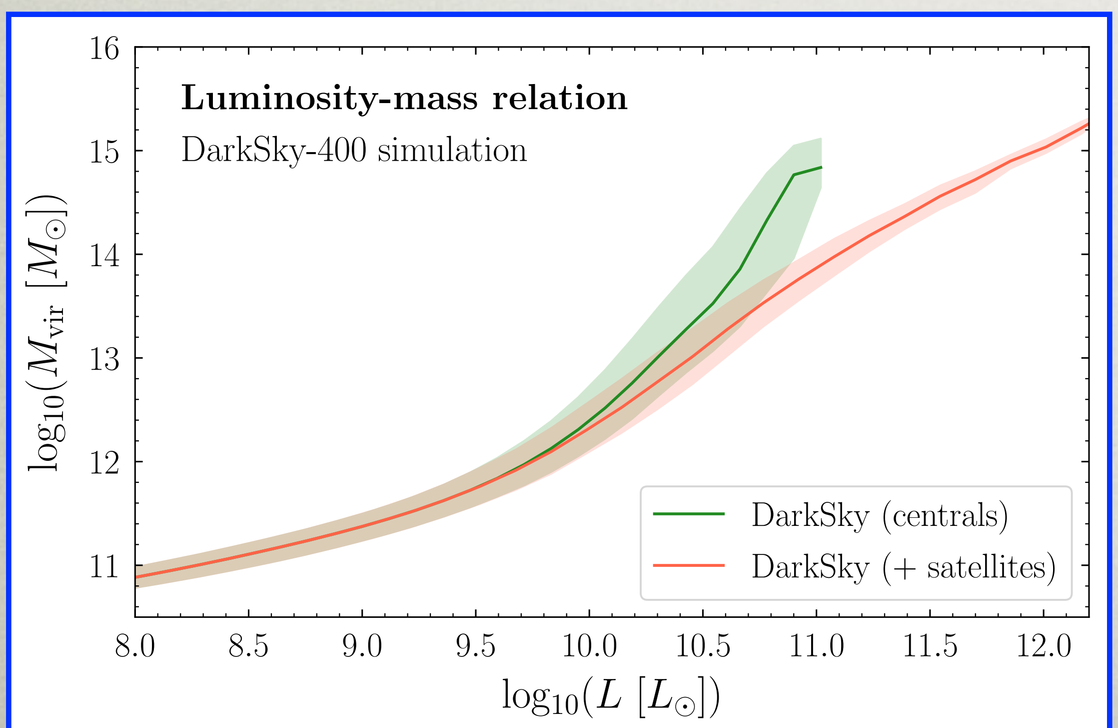

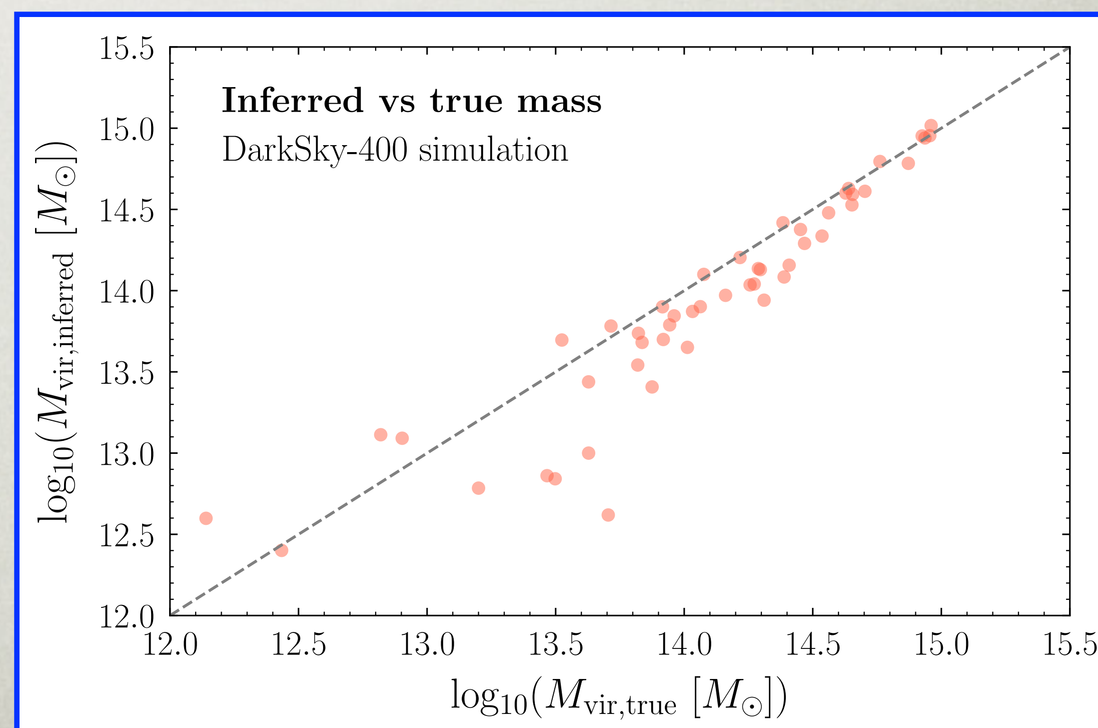

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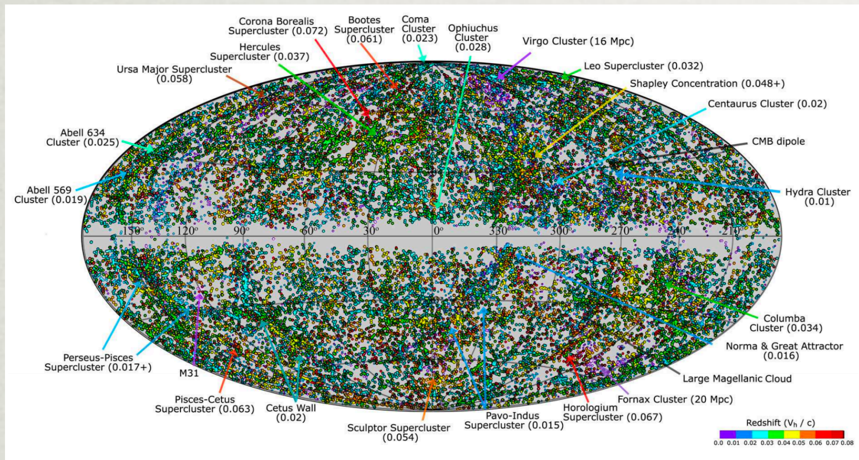

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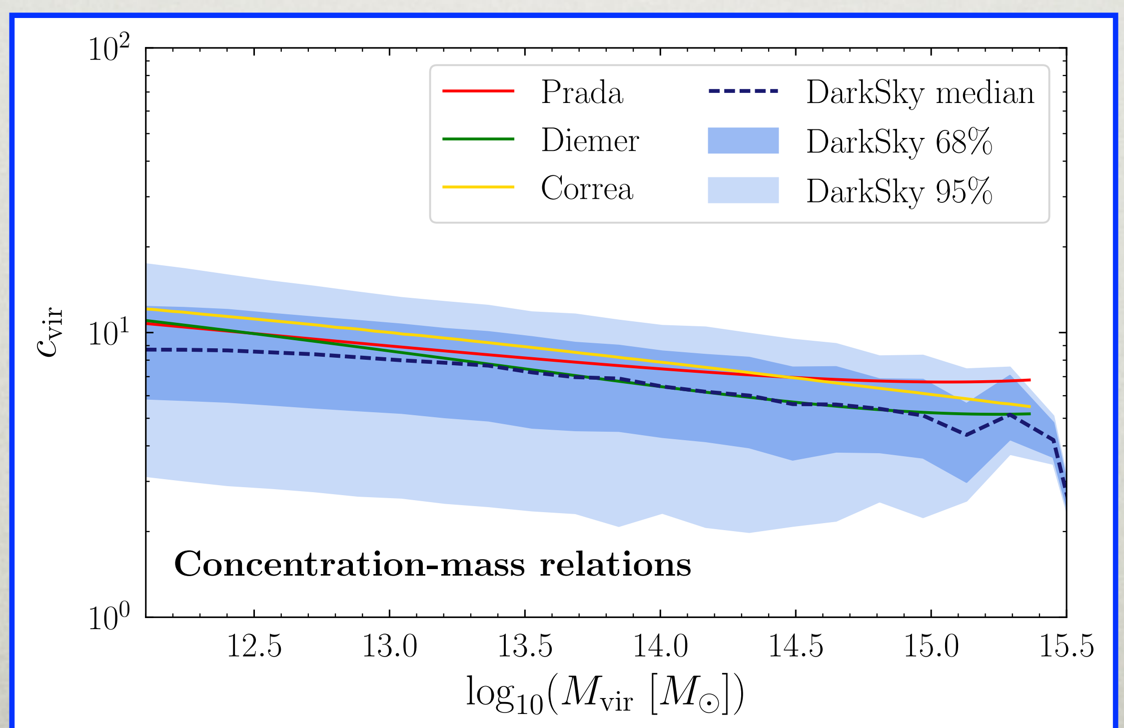

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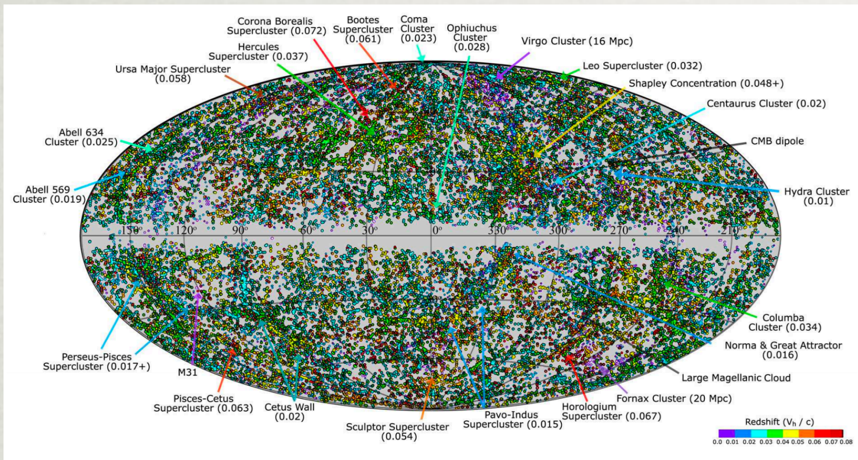

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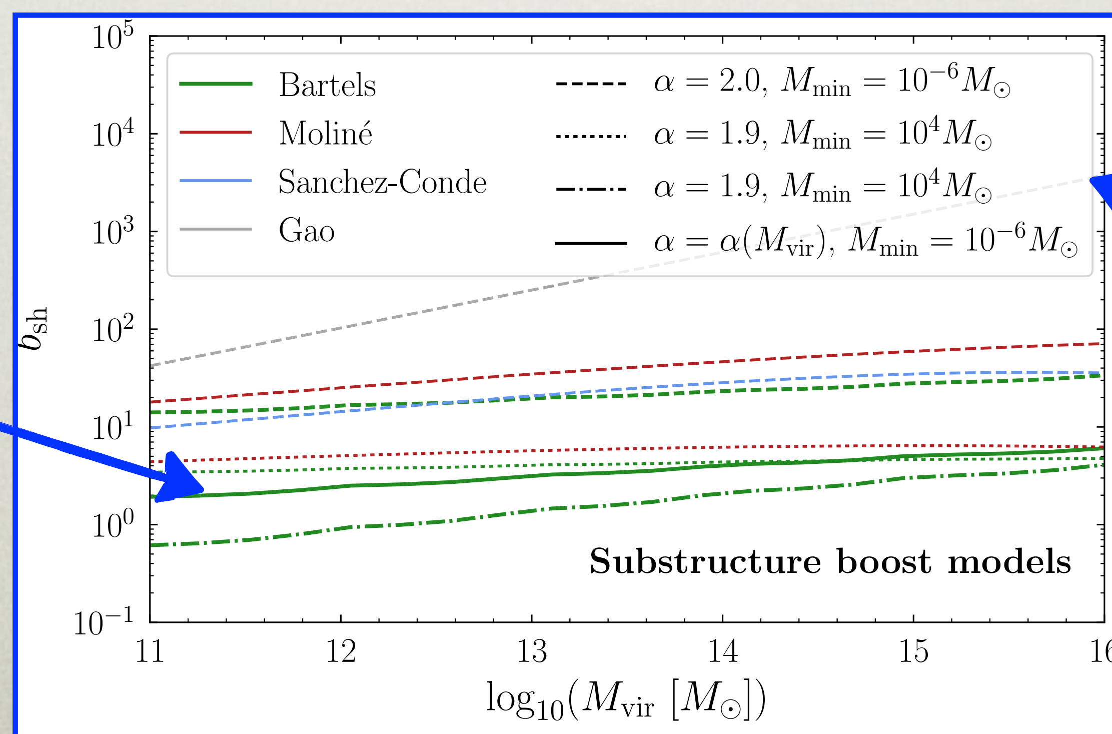
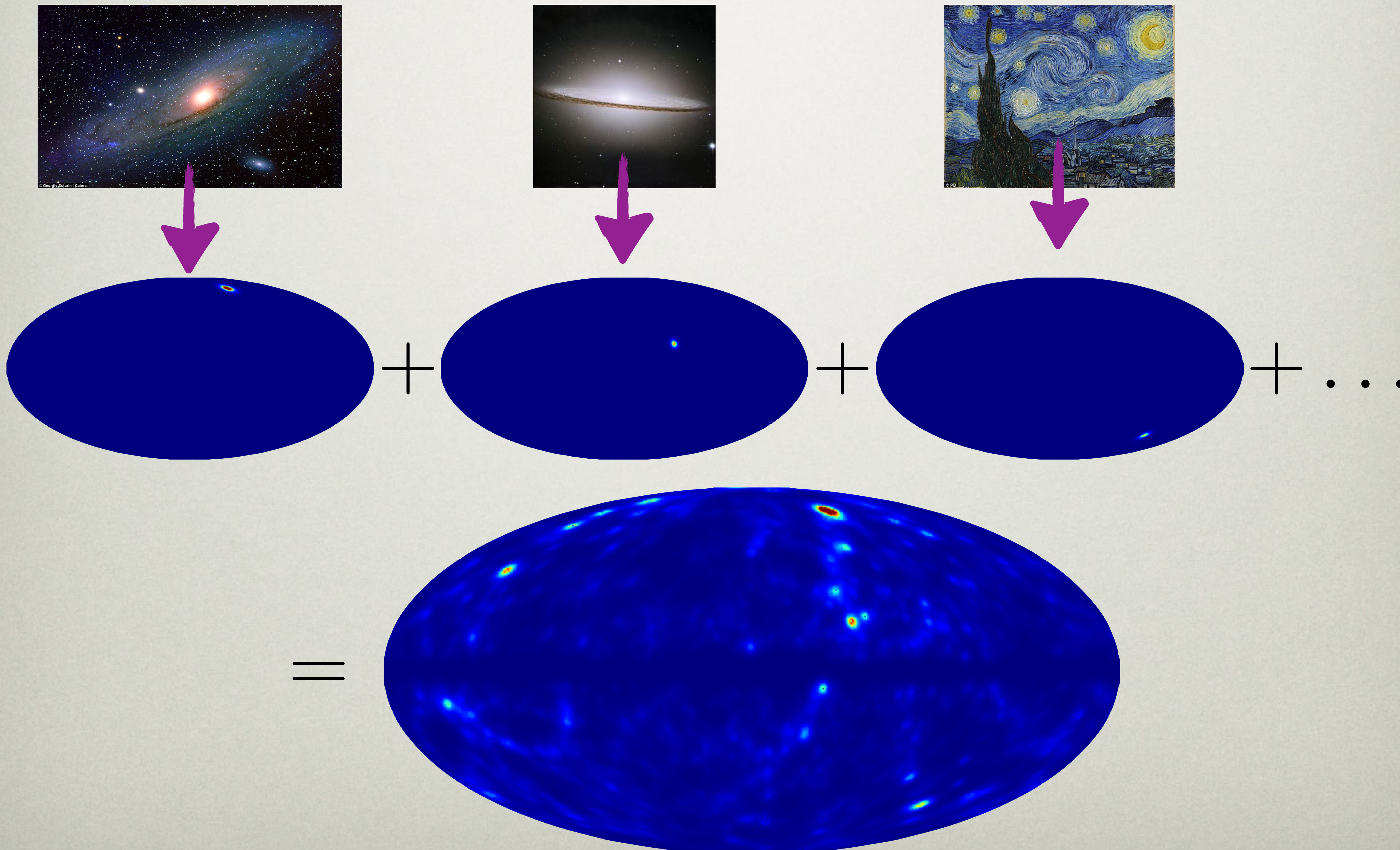
Boost model we use (1507.08656)



Much larger boosts now disfavoured (1107.1916)

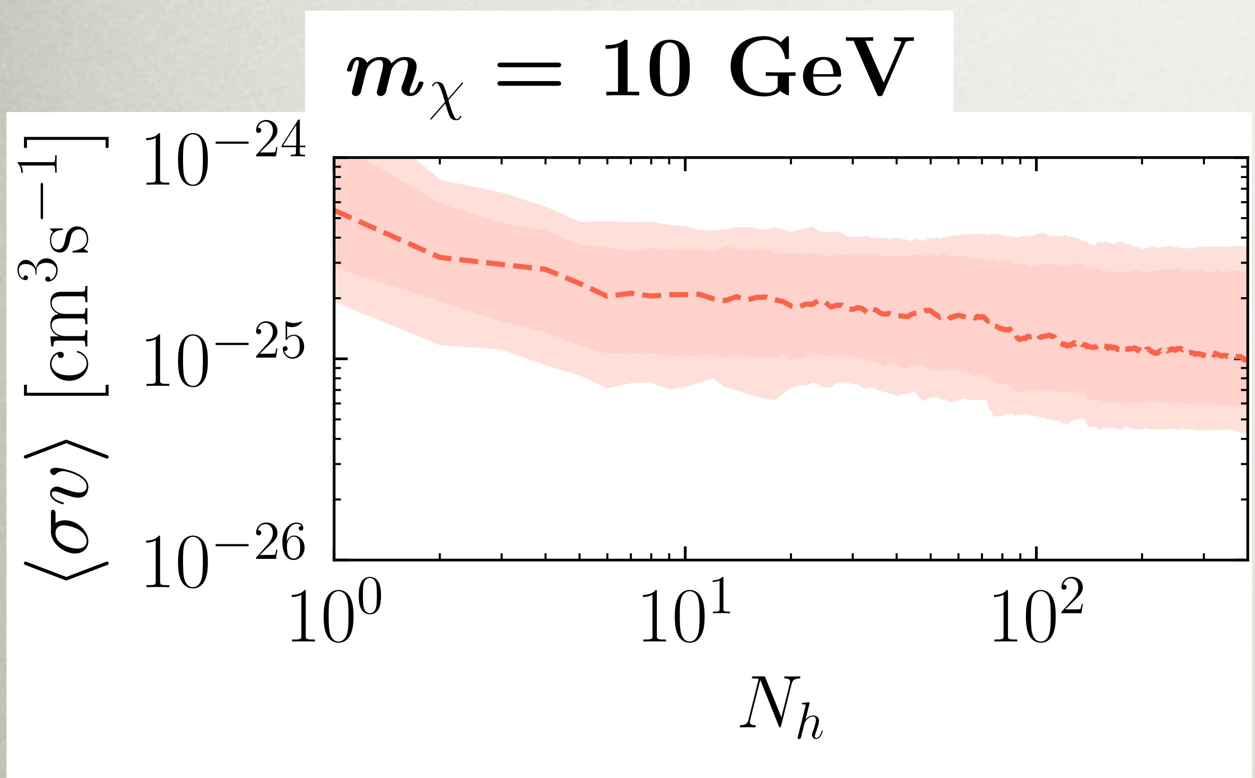
Building a Map Of Extragalactic DM

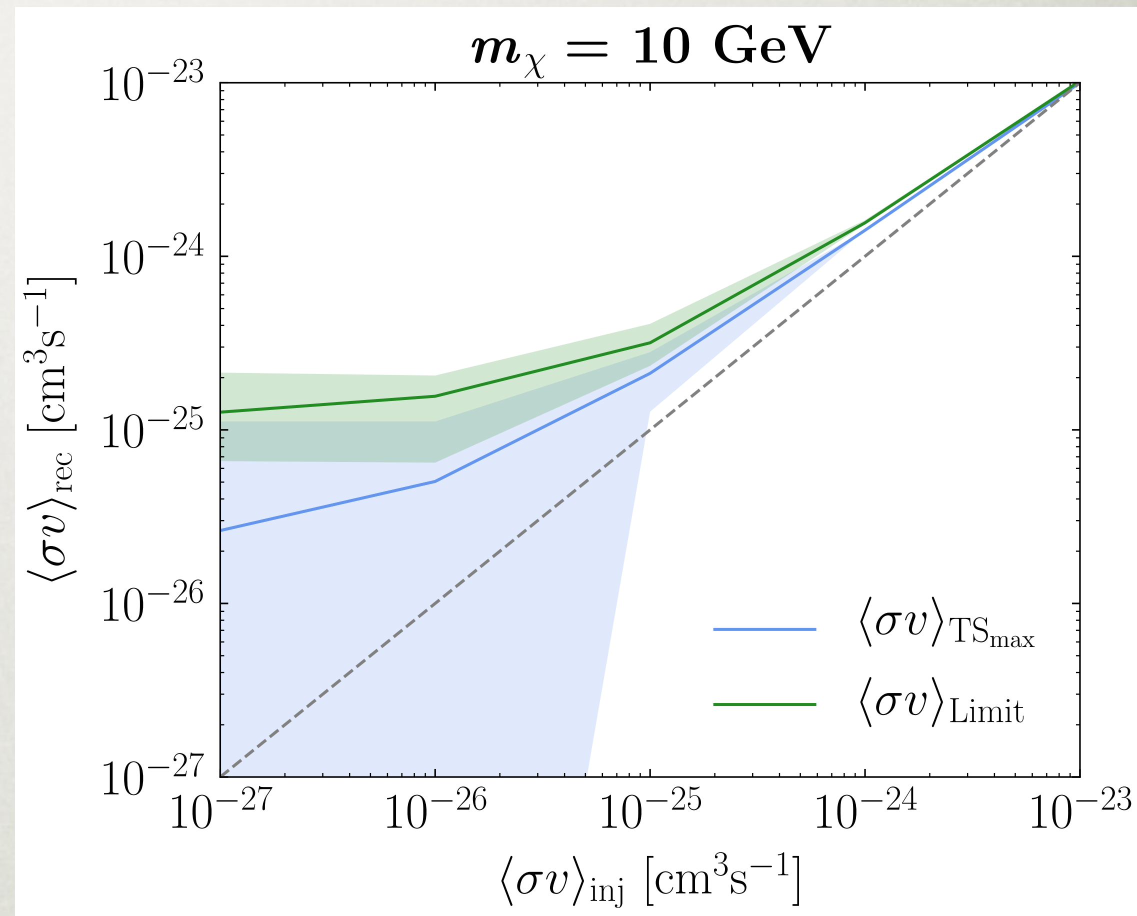
- Can now build up a full map of extragalactic DM



Building a Map Of Extragalactic DM

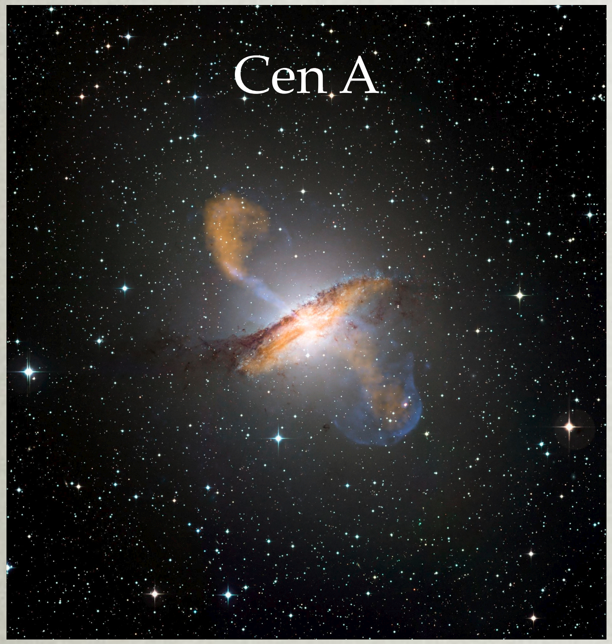
- Use these to perform a stacked template fit analysis:

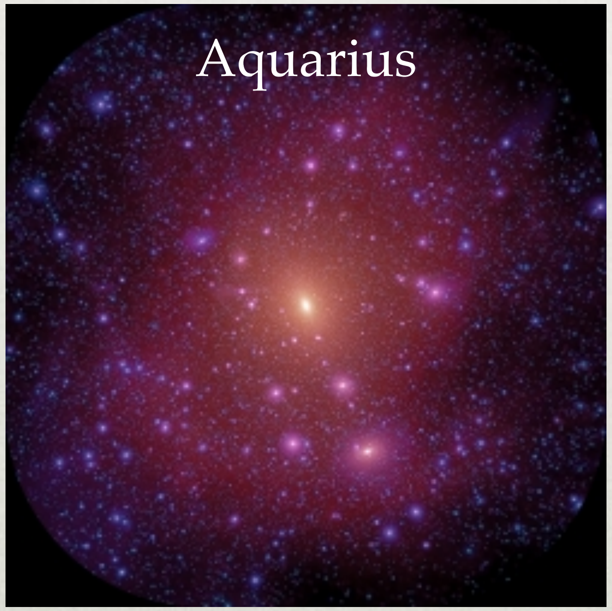


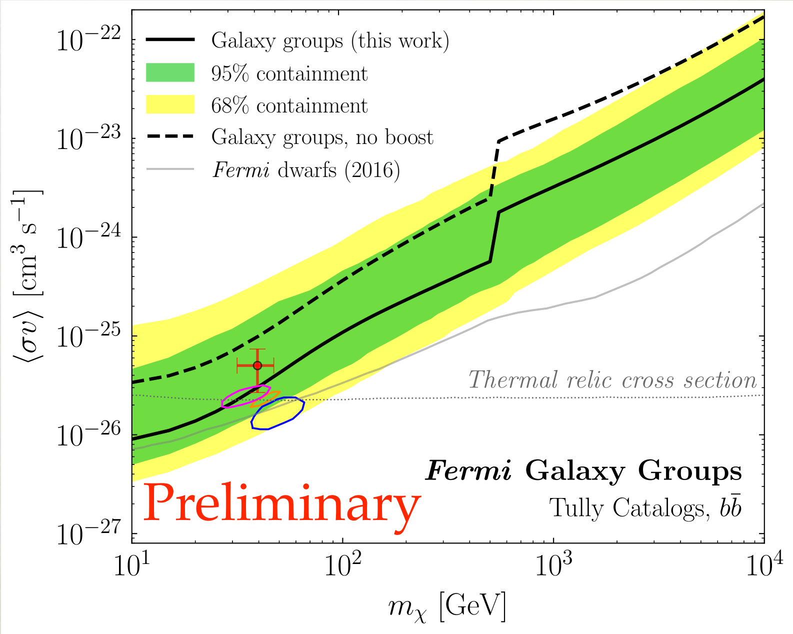


Conclusion

- Clusters are a powerful probe of DM annihilation
- I've shown how to go from galaxies, to a DM map, to a limit
- Sid will take over and show our application to the Fermi data







Backup Slides

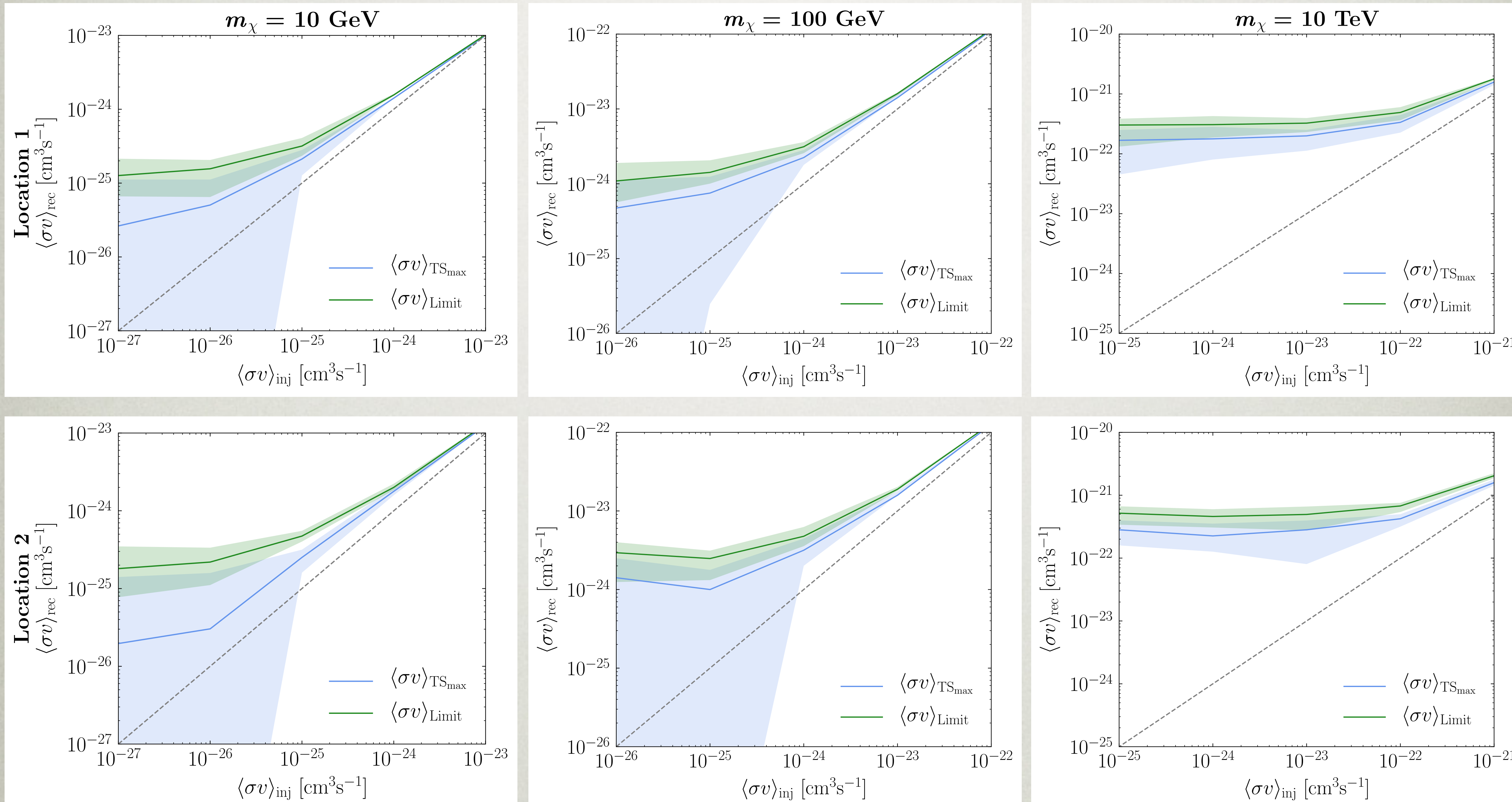
J-factor Scaling

- For extragalactic halos an excellent approximation is:

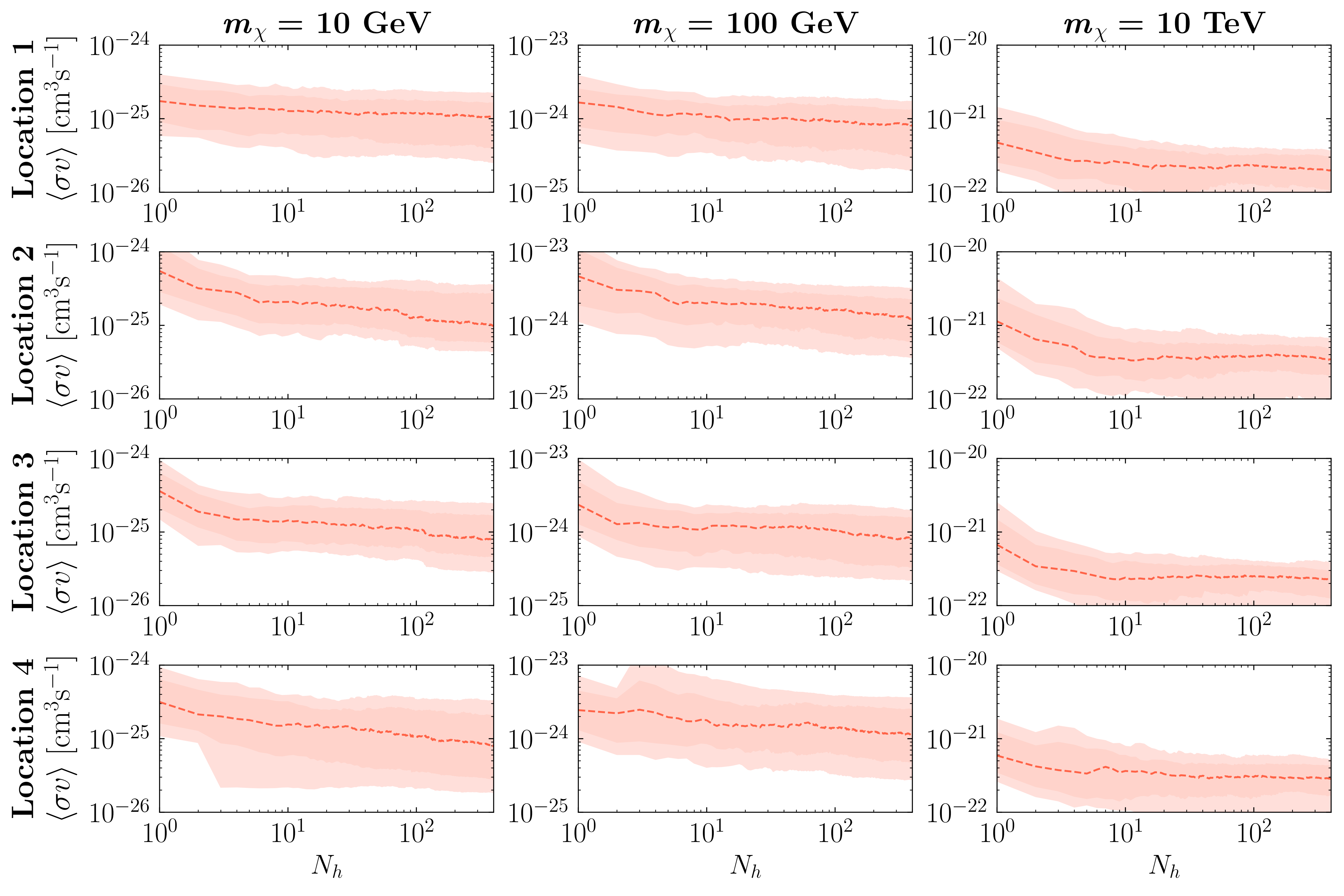
$$\begin{aligned} J_{\rm NFW} &= (1 + b_{\rm sh}[M_{\rm vir}]) \int ds d\Omega \, \rho^2_{\rm NFW}(s, \Omega) \\ &\approx (1 + b_{\rm sh}[M_{\rm vir}]) \, \frac{1}{d_A^2[z]} \int_V dV' \rho^2_{\rm NFW}(r') \\ &= (1 + b_{\rm sh}[M_{\rm vir}]) \, \frac{M_{\rm vir} c_{\rm vir}^3 \rho_c \Delta_c[z]}{9 d_A^2[z]}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

Same scaling holds for Burkert profile

Injected Signal

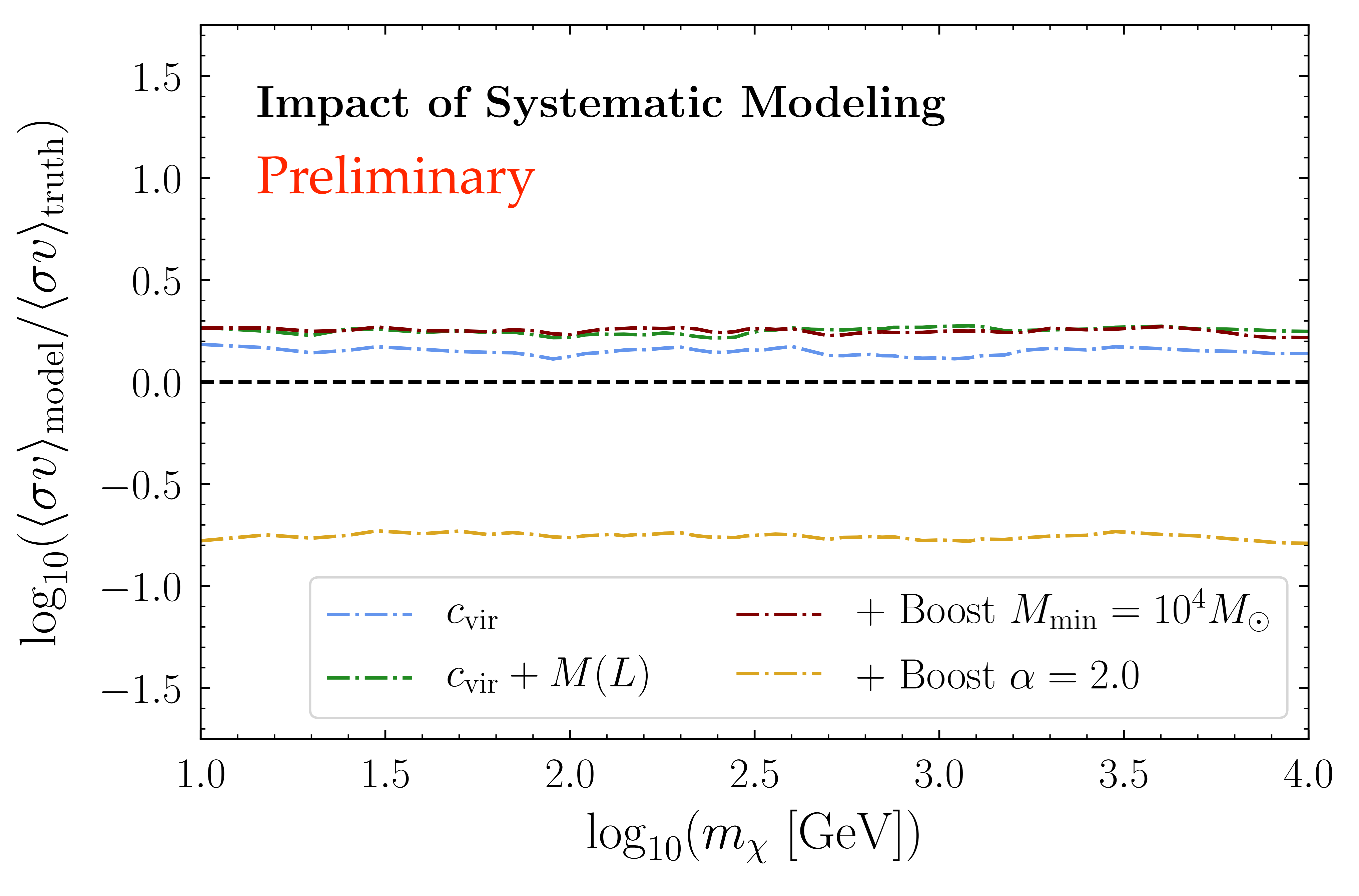


Elephants



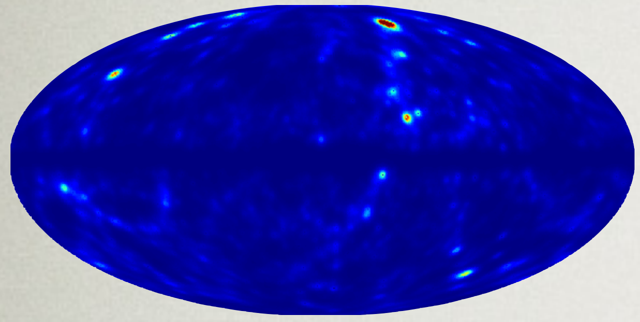
$m_\chi = 10$ GeV
$m_\chi = 100$ GeV
$m_\chi = 10$ TeV
Location 1
Location 2
Location 3
Location 4
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
N_h

Impact of Modelling

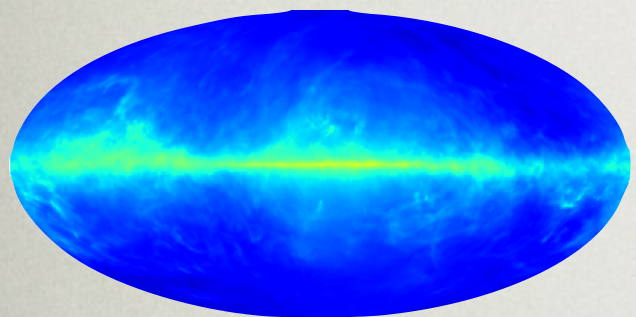


Template Fitting

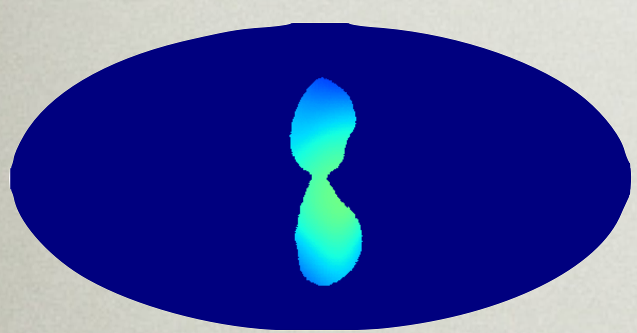
DM Annihilation



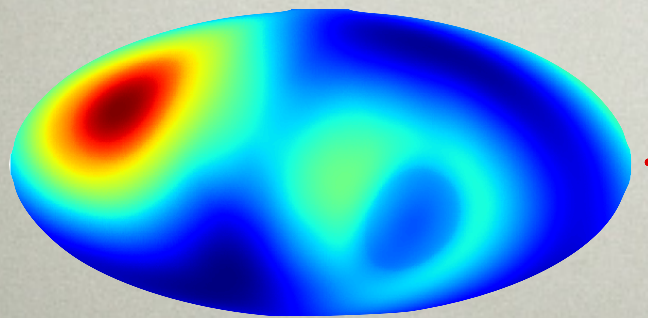
p7v6 Diffuse Model



Fermi Bubbles



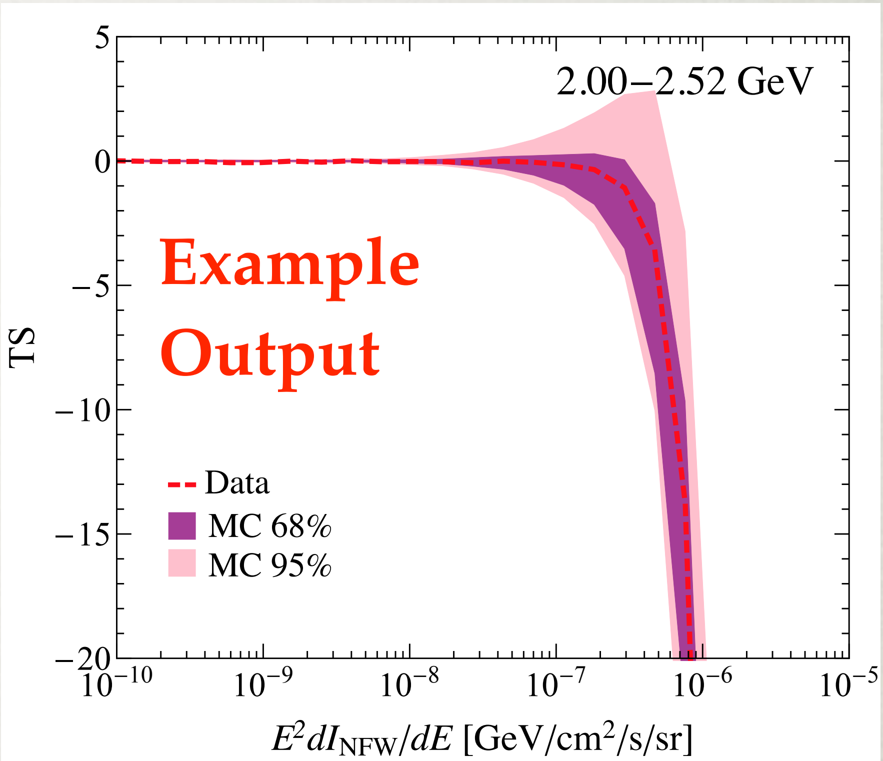
Isotropic Emission

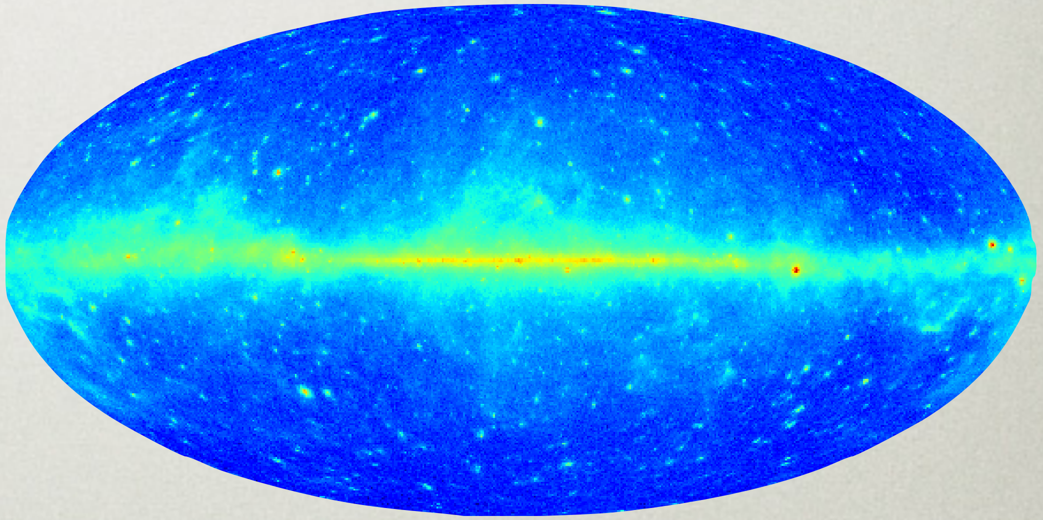


Fix a value

Scan to find best fit values in each energy bin

Also point source model and mask (not shown)





Simulated Fermi data
Fit implemented with NPTFit:
Rodd et al, Astron. J. 153 (2017) 253;
github.com/bsafdi/NPTFit/

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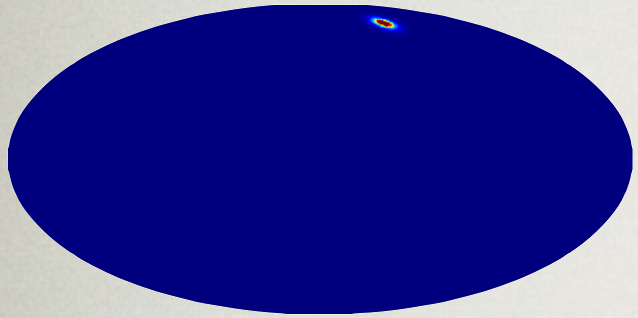

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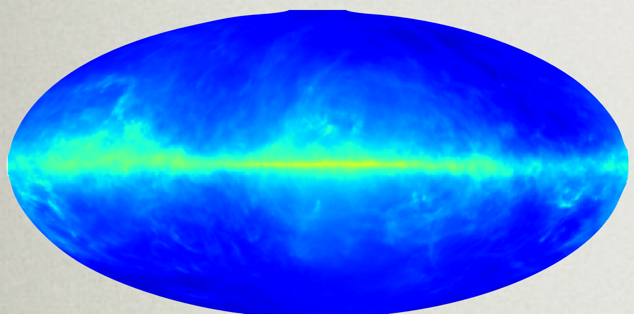

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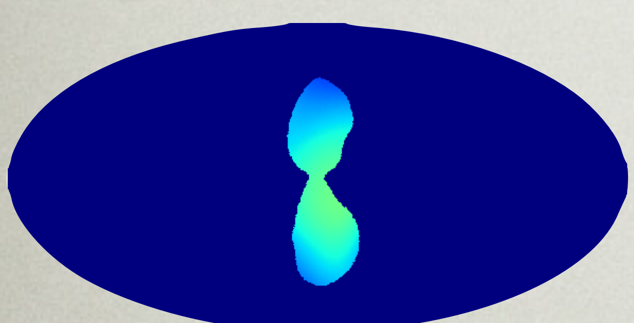

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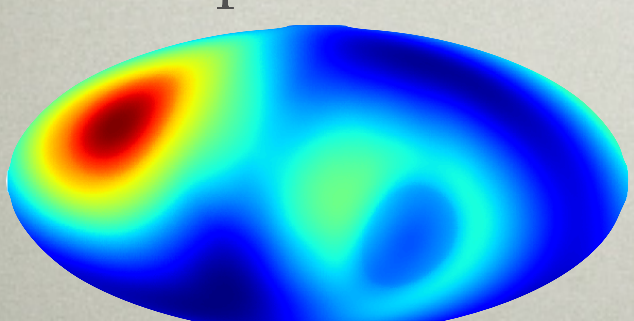

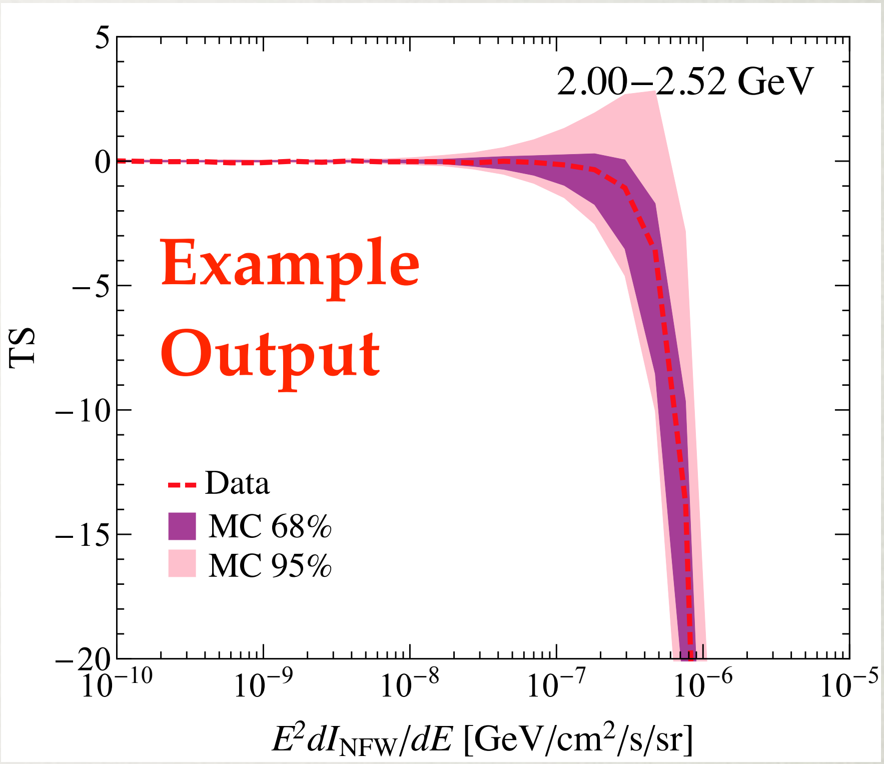

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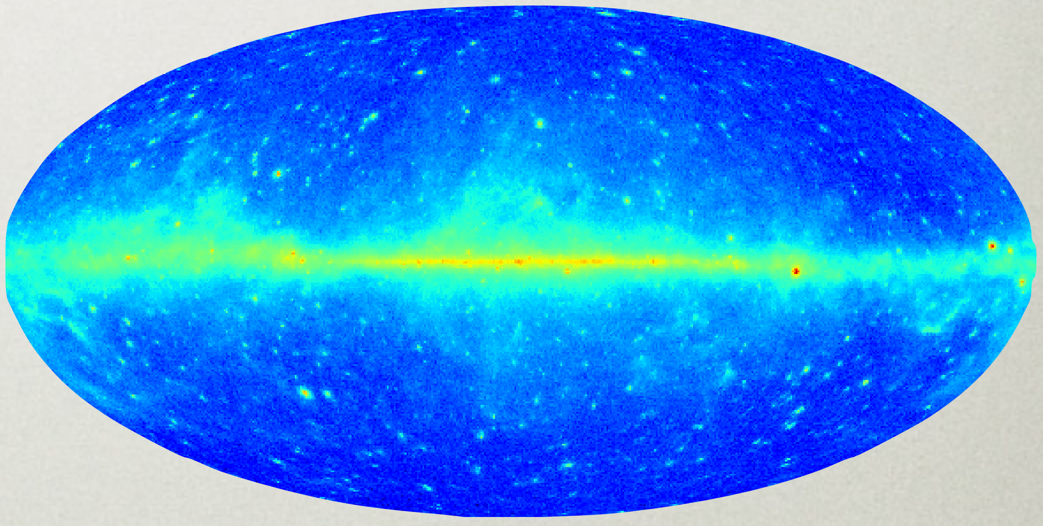

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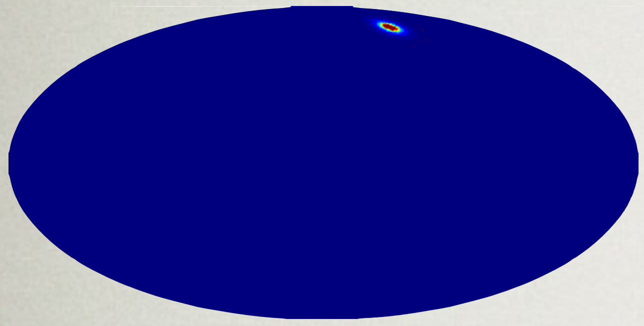

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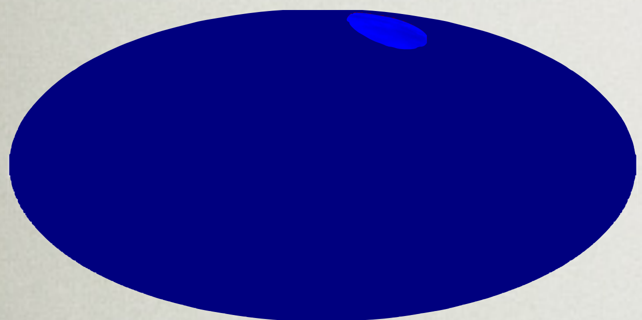

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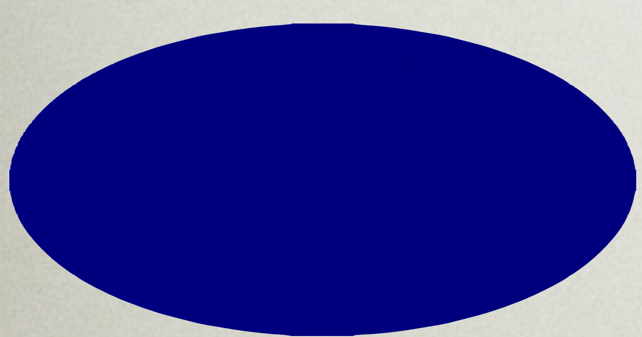

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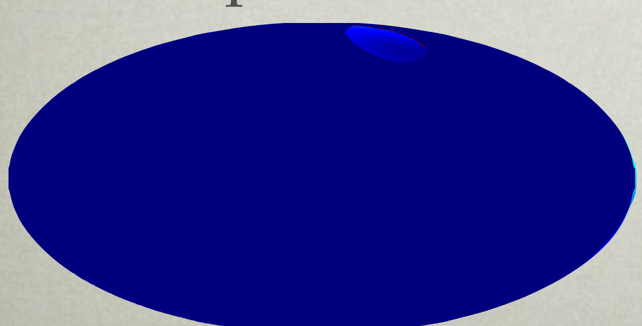

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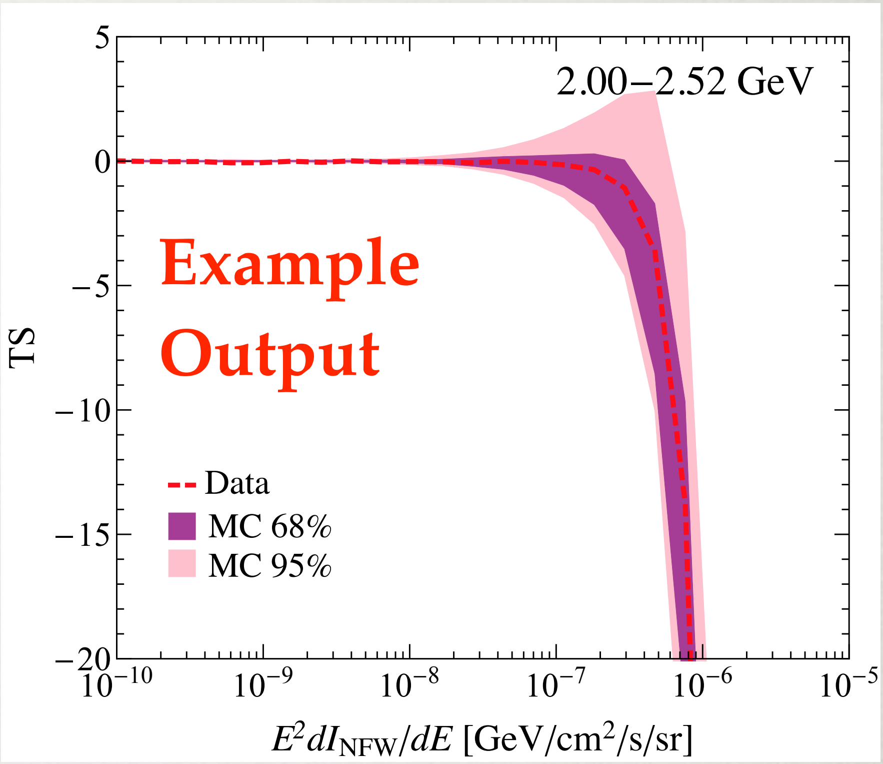

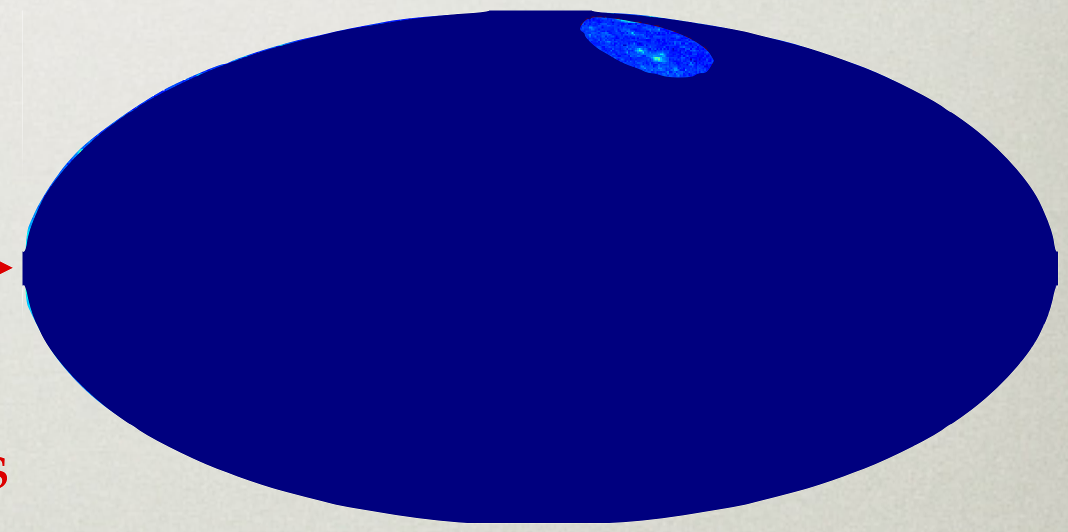

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Searching for Extragalactic DM

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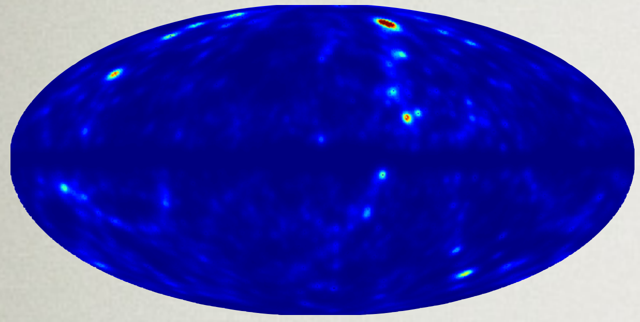

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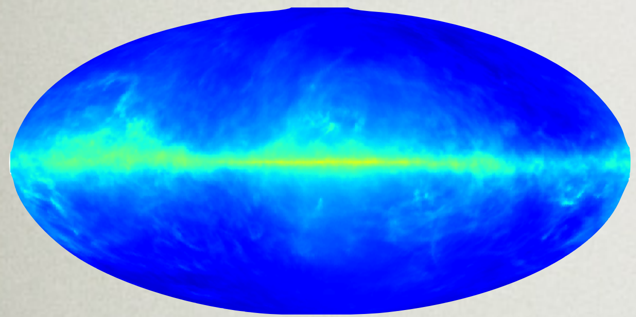

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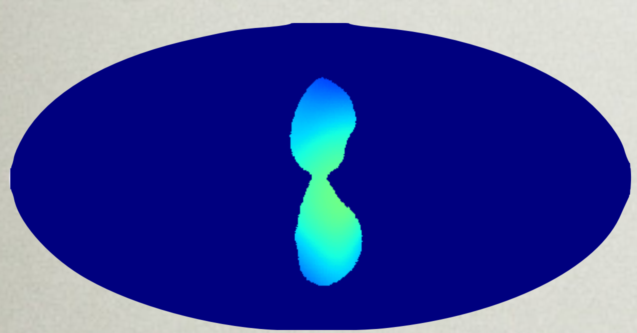
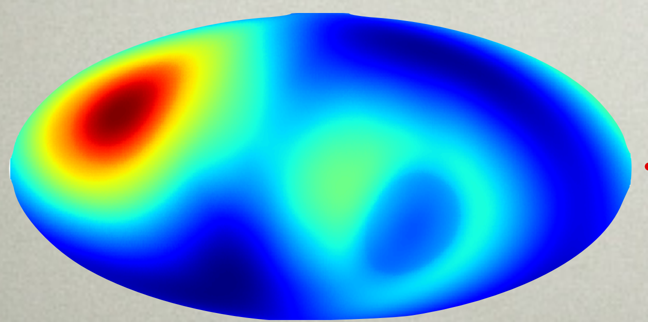
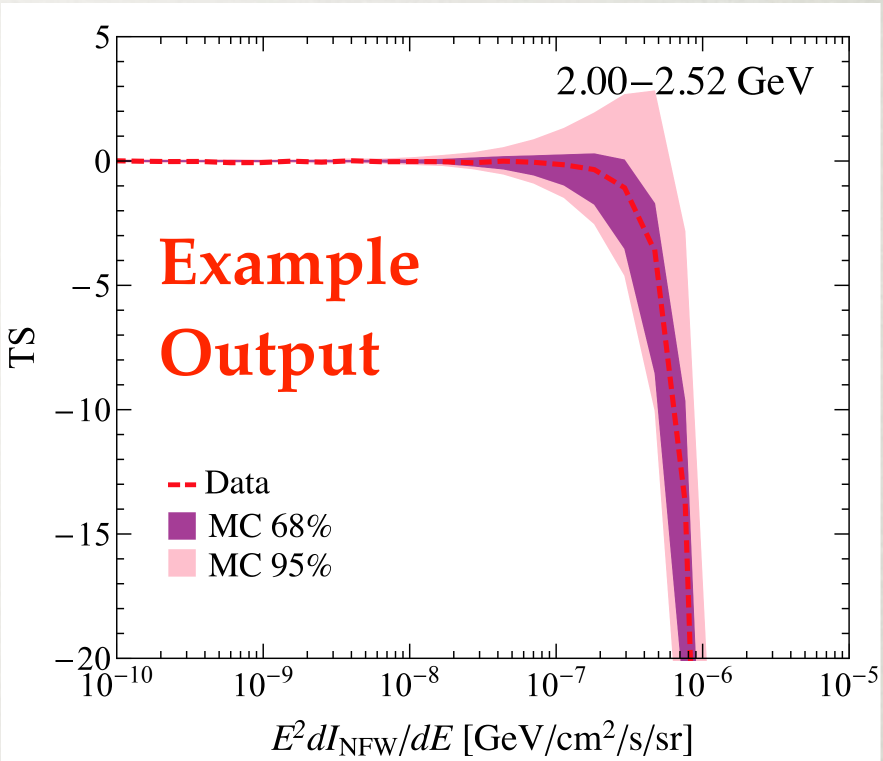


Isotropic Emission

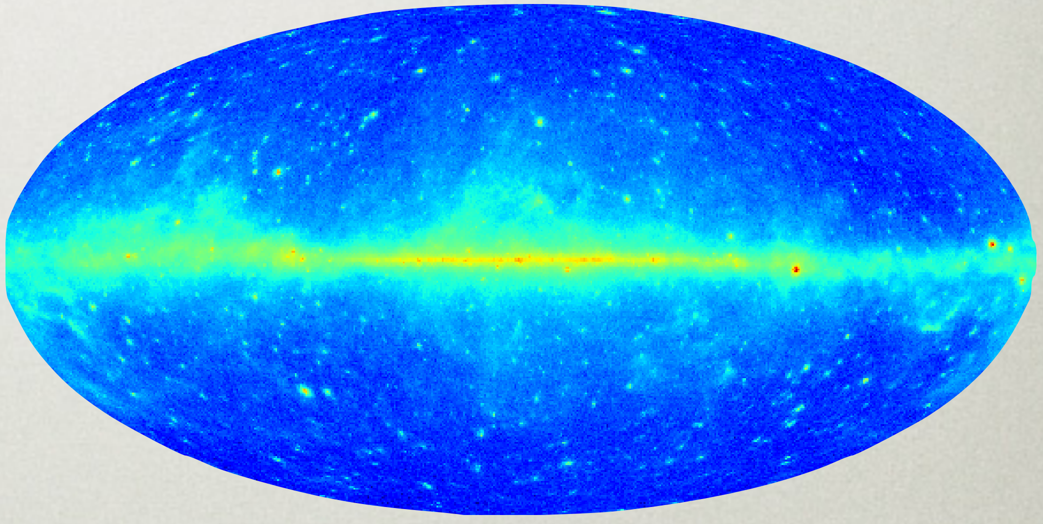


Fix a value



Scan to find best fit values in each energy bin

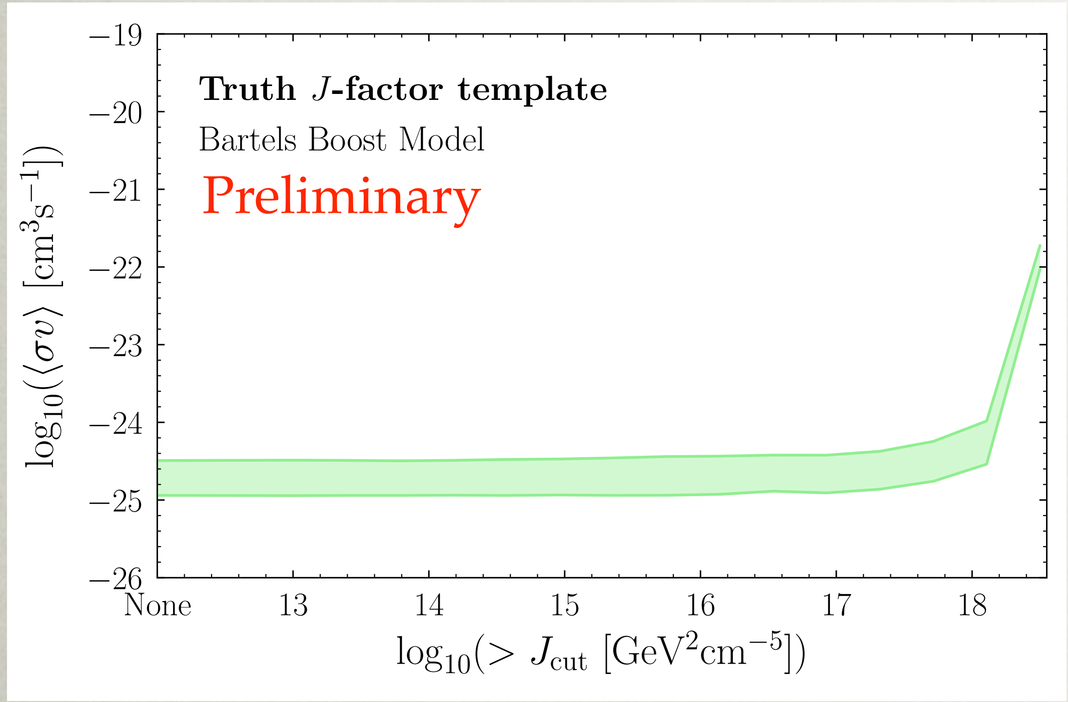
Also point source model and mask (not shown)

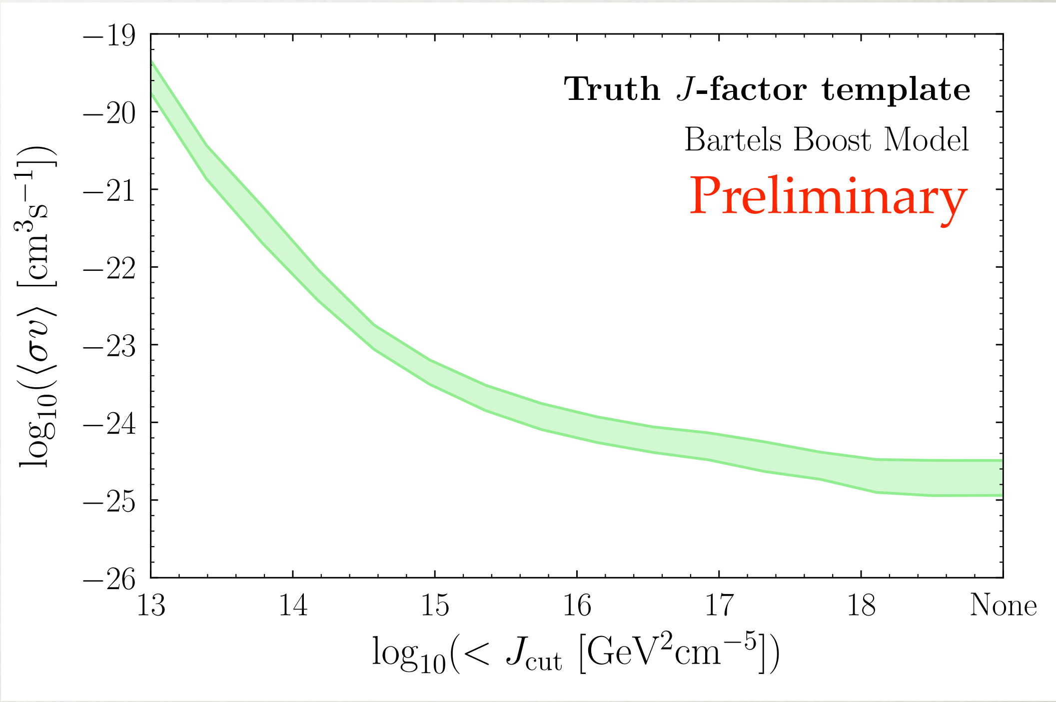


Simulated Fermi data
Fit implemented with NPTFit:
Rodd et al, Astron. J. 153 (2017) 253;
github.com/bsafdi/NPTFit/

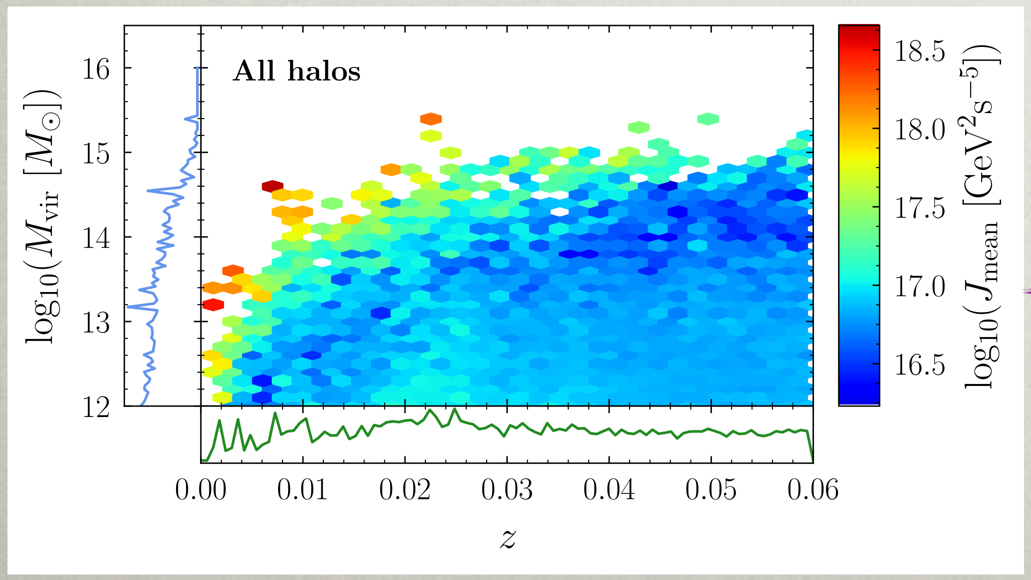
Searching for Extragalactic DM

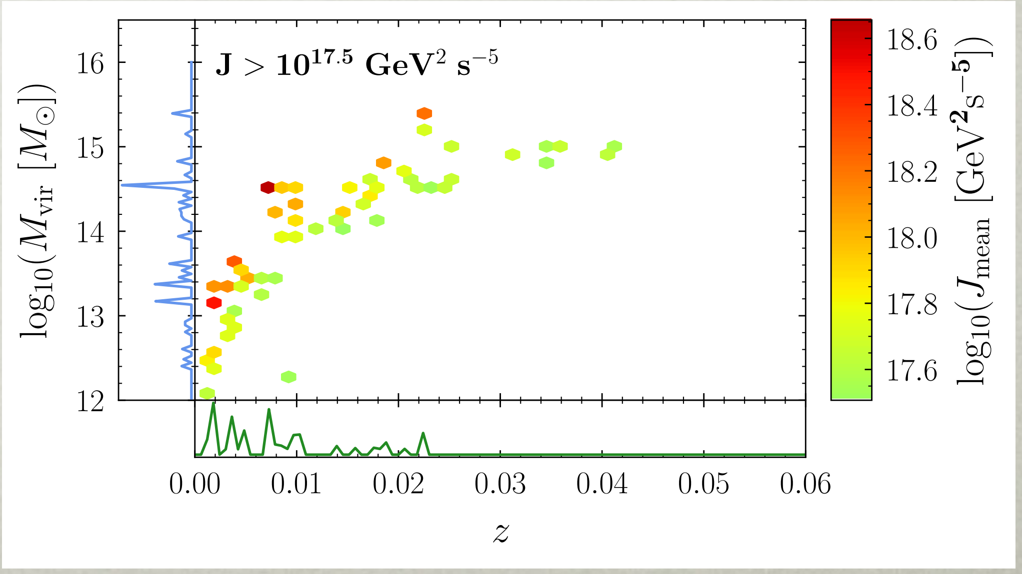
- Limit set in DarkSky + Fermi Monte Carlo on 100 GeV DM to bs



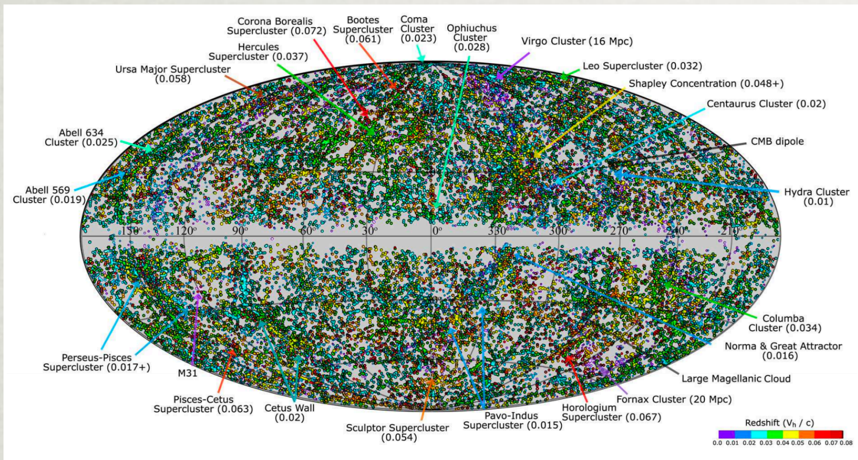


- Limit is dominated by the top ~ 100 halos when all added

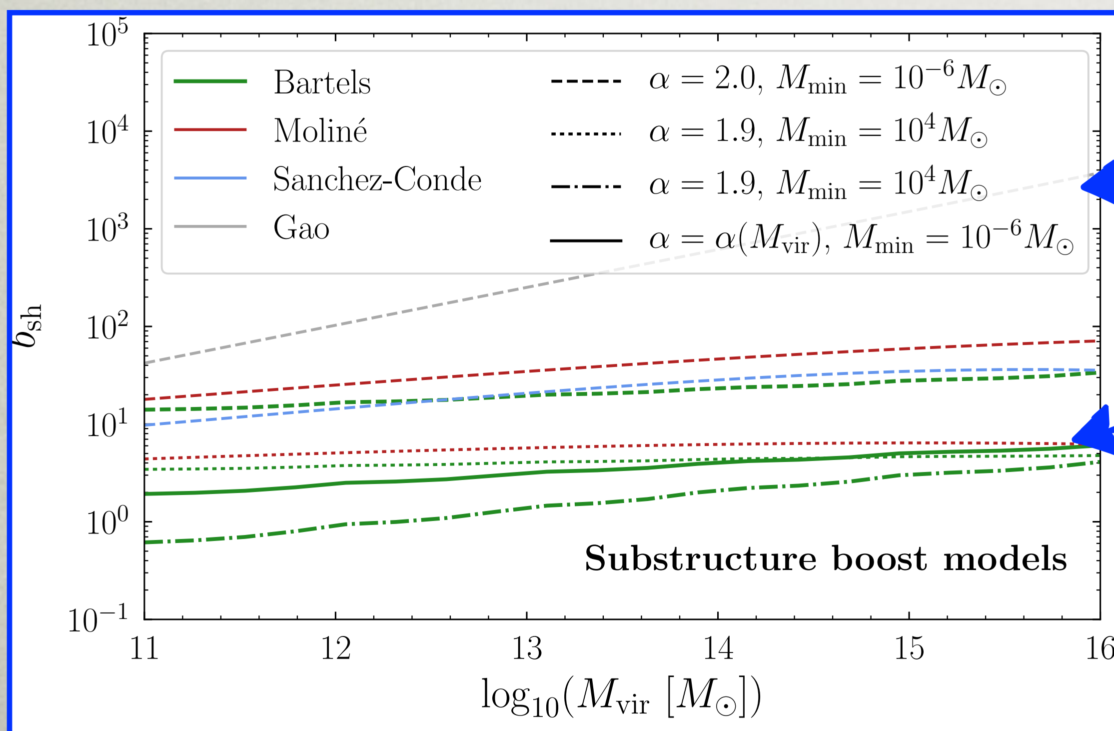


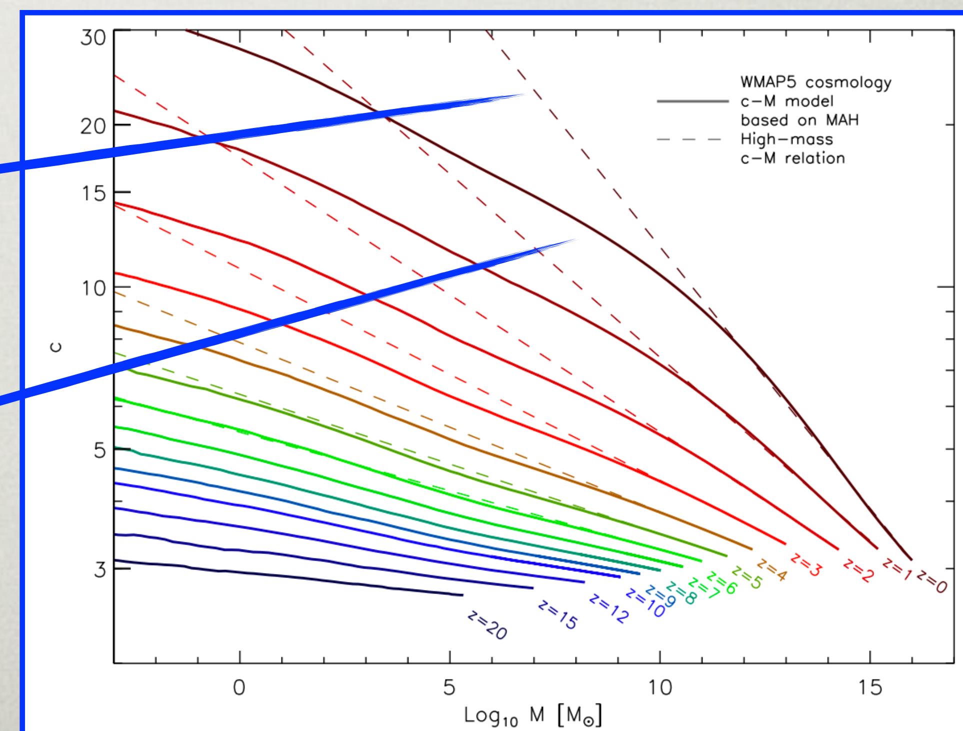


Building a Map Of Extragalactic DM



$$J \approx (1 + b_{\rm sh}) \, \frac{M_{\rm vir} c_{\rm vir}^3}{d(z)^2}$$





Plot from Correa et al; 1502.00391

Dark Matter at Fermi: 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*

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

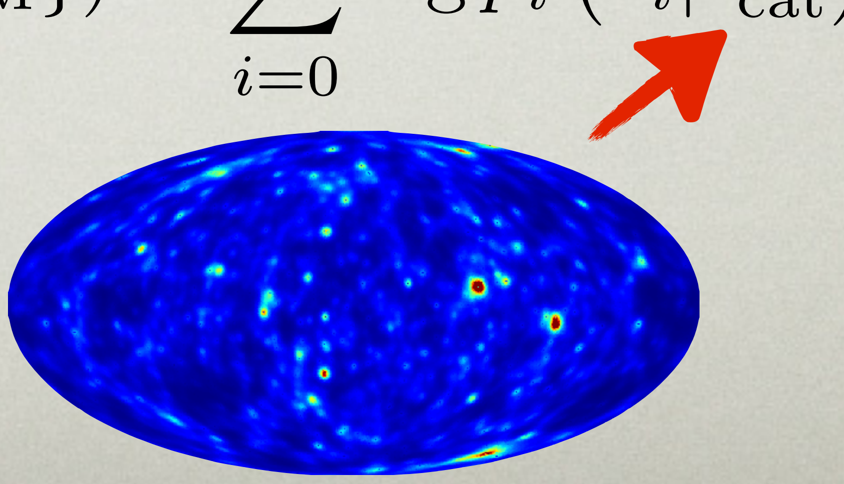
- Eliminate the nuisance parameters by profile likelihood

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

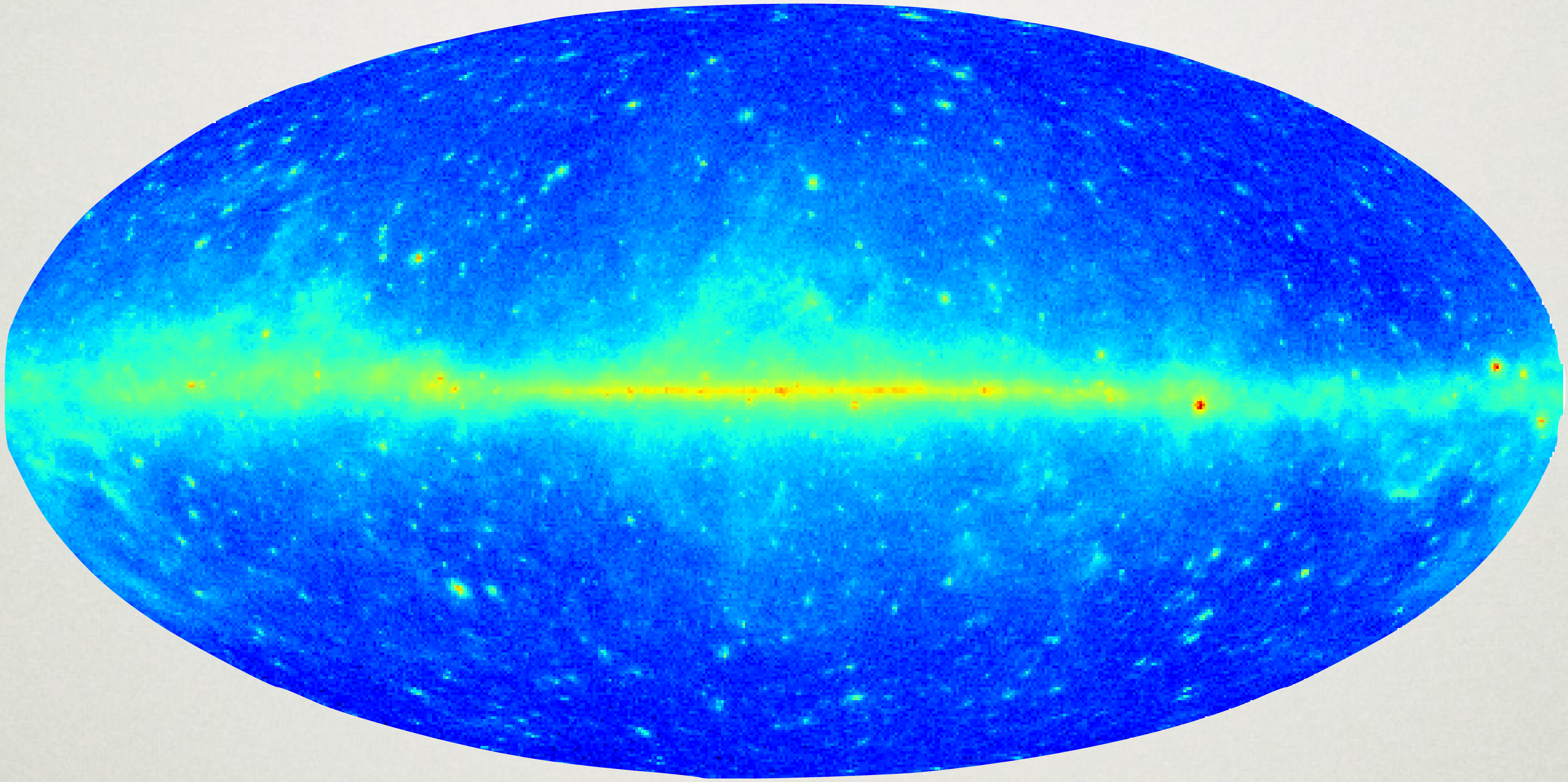
- Likelihood of a model depends on the injected galactic and extragalactic flux

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

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



Fermi Data Details



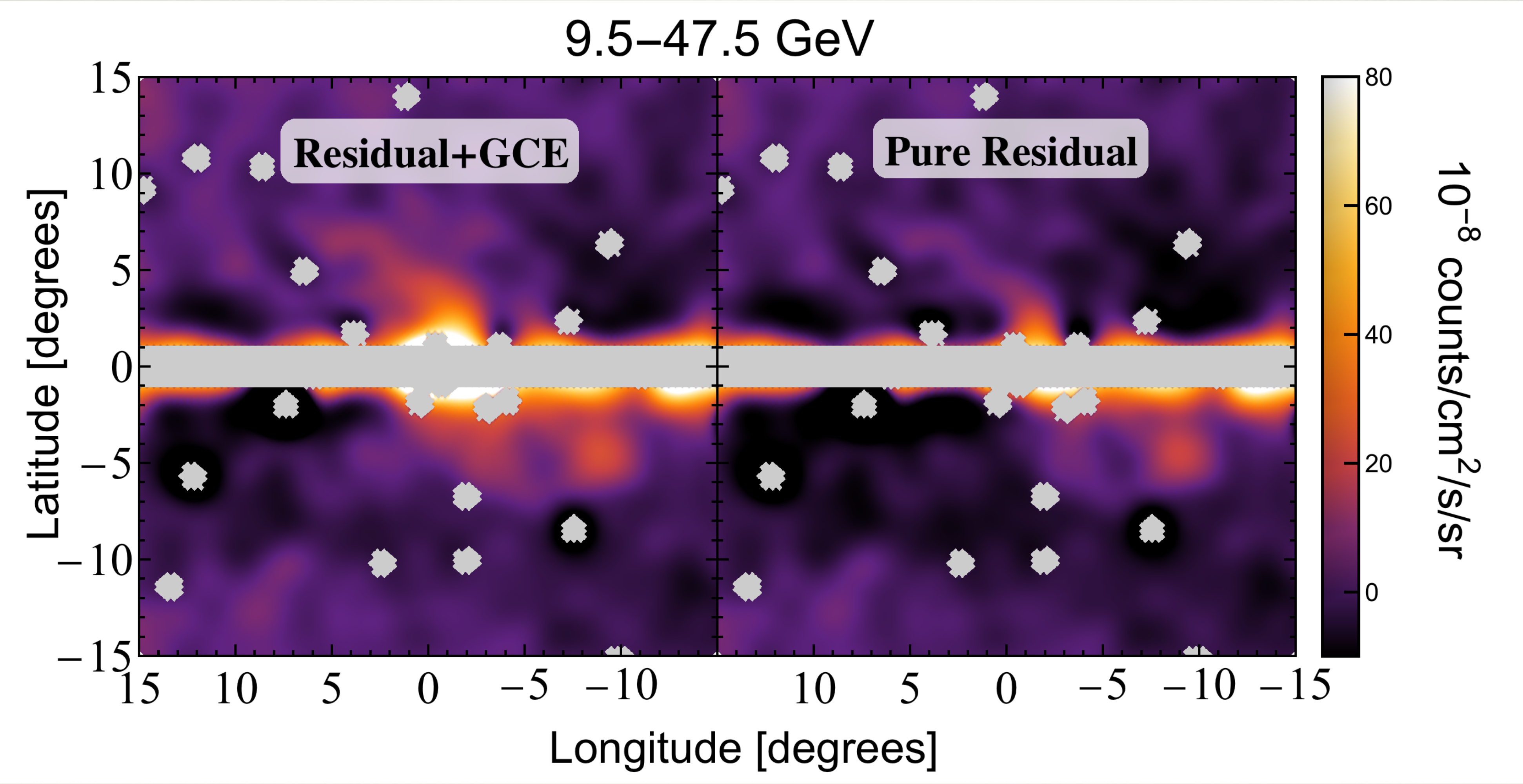
Simulated Monte Carlo base on:423 weeks of Fermi-LAT data

40 log spaced energy bins, from 200 MeV - 2 TeV

UltracleanVeto BestPSF

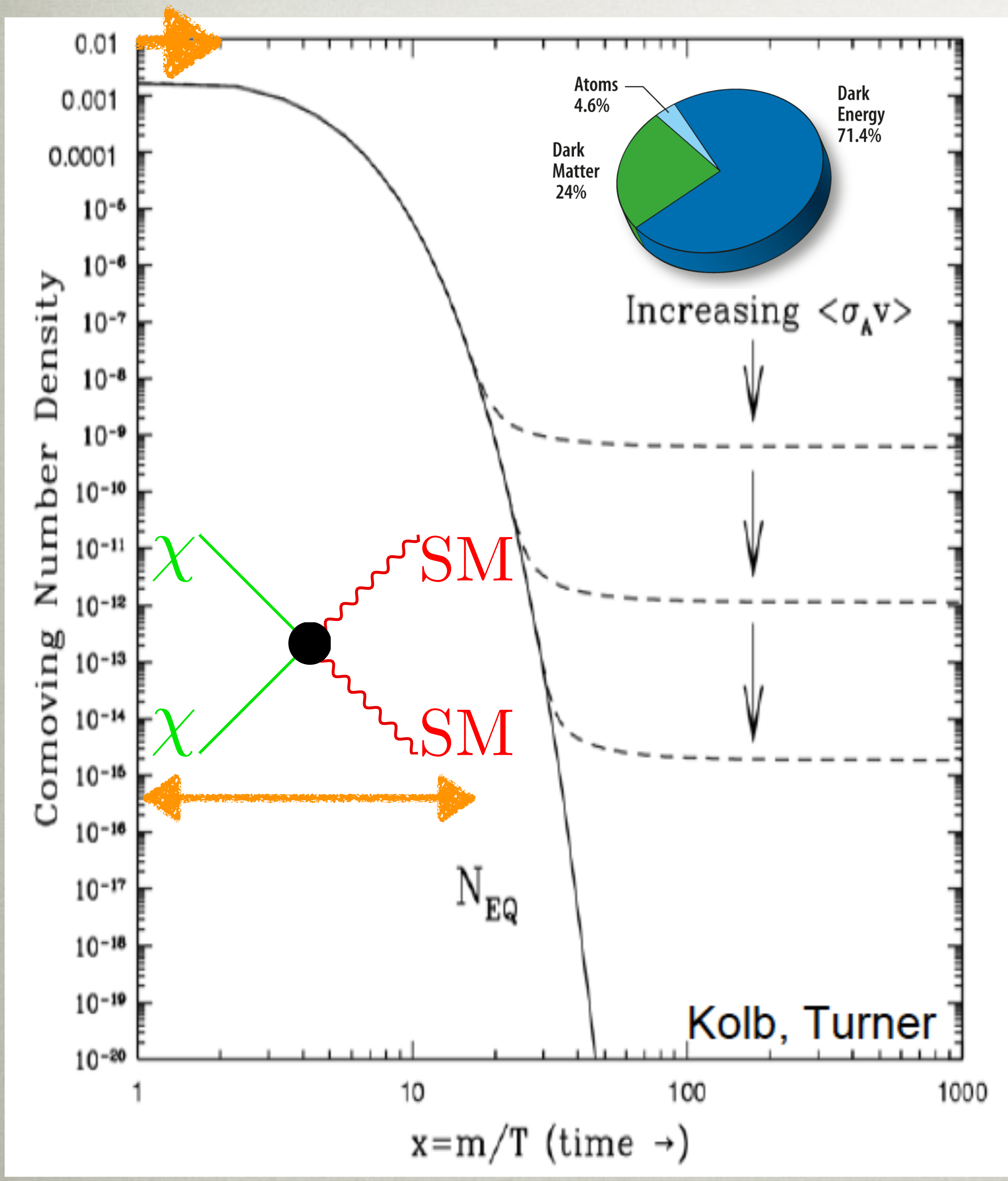
Background Mismodelling

- Models of the gamma ray sky do not explain the data to the level of Poisson noise, e.g. below for GCE from NR et al 1604.01026



- These issues are much more pronounced for larger ROIs
- As modelling of the sky improves, will be able to safely use larger ROIs and thereby more data

Wimp Miracle



Wimp Miracle

- We know the amount of DM
- If it was once in thermal EQ with SM, then:

$$\text{Amount of DM} \propto \frac{1}{\langle \sigma v \rangle}$$

- Putting in numbers find:

$$m_\chi \sim \text{EW} \; (\approx \text{TeV})$$

$$\langle \sigma v \rangle \sim 10^{-26} \; \text{cm}^3/s$$

- Suggestive, provides a benchmark!

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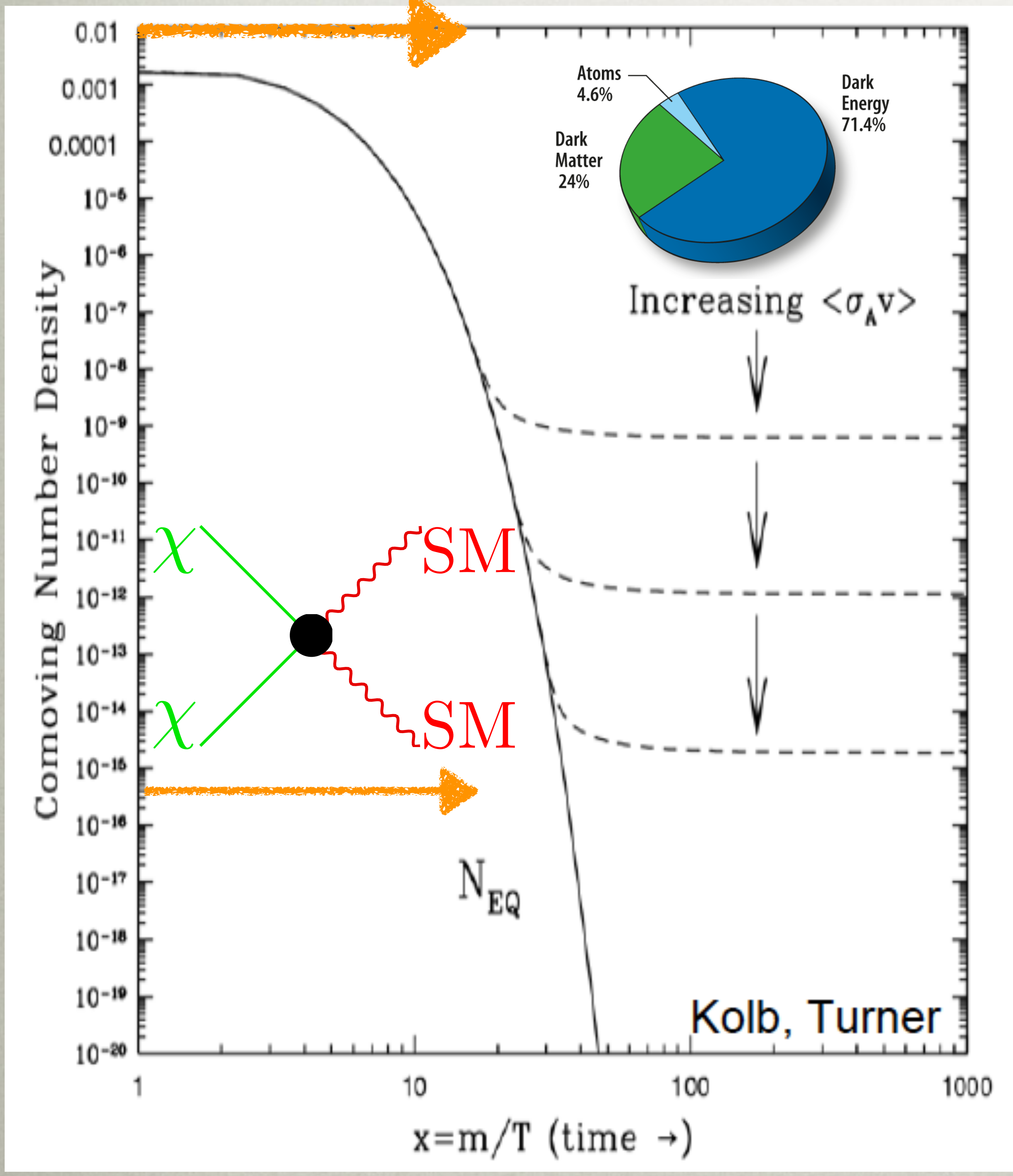

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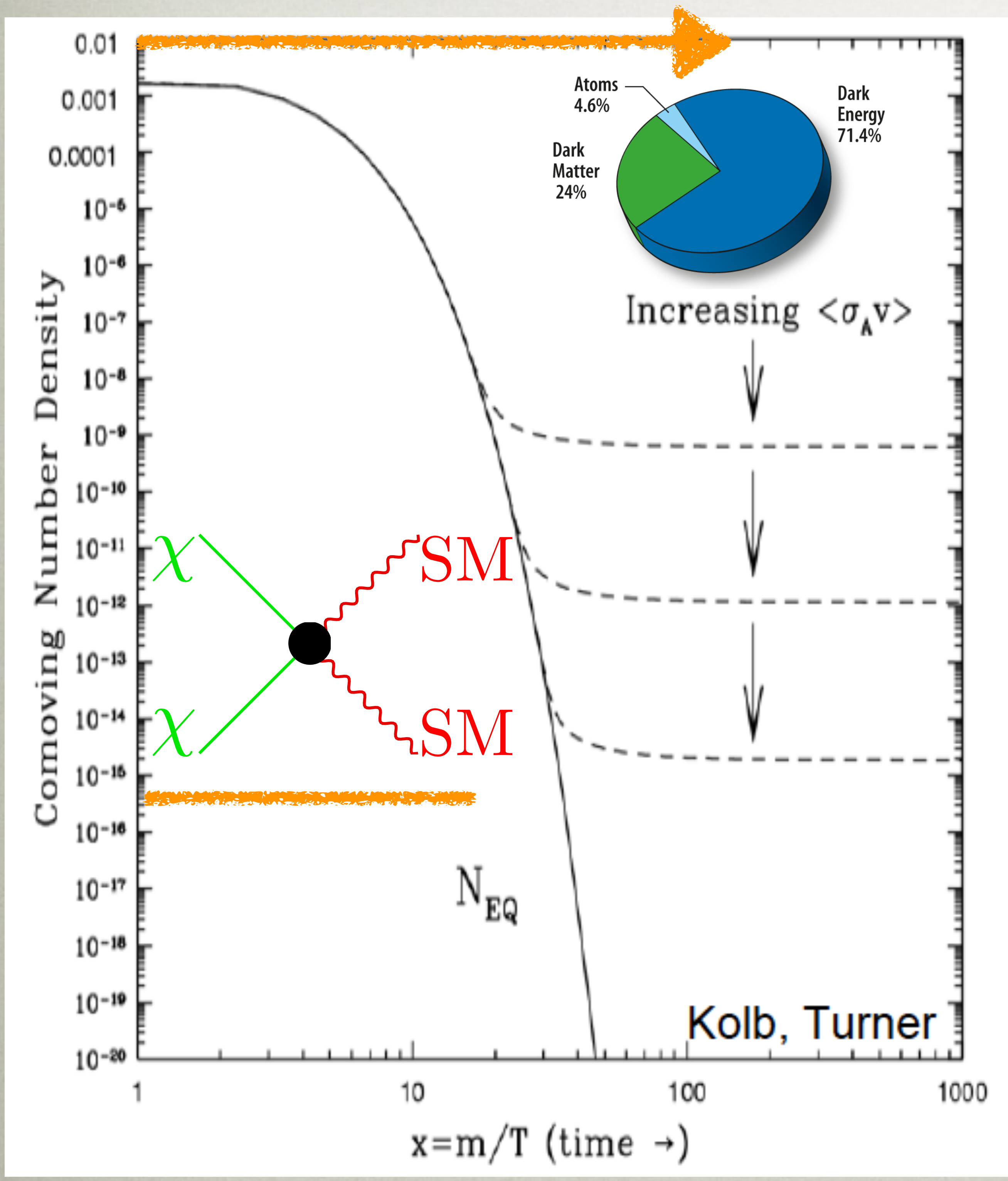

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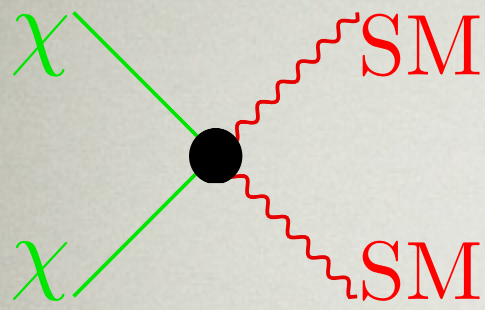
Where should we look?



$$\underbrace{\Phi(l,b)}_{\gamma/\text{cm}^2/s} = \underbrace{\frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{dN_\gamma}{dE}\, dE}_{\text{“Particle Physics Factor”}} \times \underbrace{\int_{\text{los}} \rho_{\text{DM}}^2(r)\, ds}_{\text{“}J\text{–Factor”}}$$

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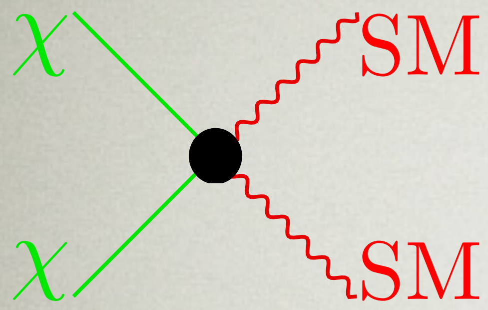

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$$\langle \sigma v \rangle = 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$m_\chi = 100\ \mathrm{GeV}$$

$$dN_\gamma/dE = 2\delta(E - m_\chi) \quad (\chi\chi \to \gamma\gamma)$$

$$\Rightarrow \mathrm{PP} \approx 10^{-31}\ \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}^2$$

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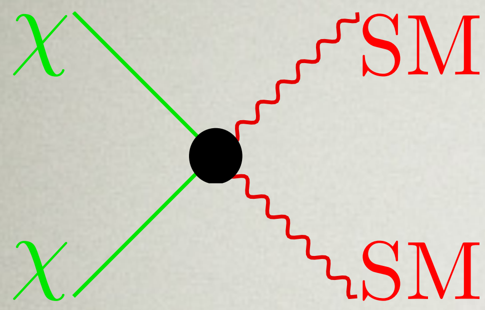

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e.g. Segue 1 :

$$J \approx 10^{20}\ \text{GeV}^2/\text{cm}^5$$

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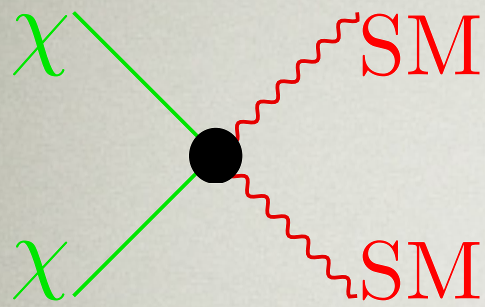

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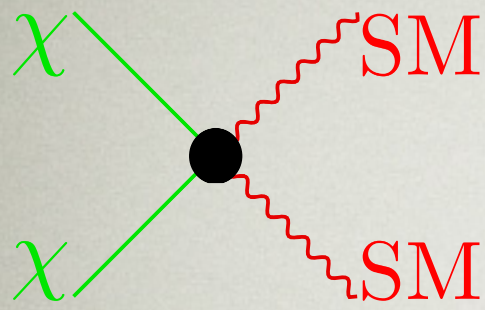

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e.g. Segue 1 :

$$J \approx 10^{20}\ \mathrm{GeV}^2/\mathrm{cm}^5$$

$$\Rightarrow \Phi \approx 10^{-11}\ \gamma/\mathrm{cm}^2/\mathrm{s}$$

If we had a 1m^2 space based telescope operate for 10 years:

$$(10^{-11}\ \gamma/\mathrm{cm}^2/\mathrm{s}) \times (10^4\ \mathrm{cm}^2) \times (10\times\pi\times10^7\ \mathrm{s}) \approx 30\ \gamma$$

Where should we look?

- **Fermi Large Area Telescope (LAT):** pair-conversion telescope consisting of layers of tungsten and silicon on top of a calorimeter
- Launched June 2008, still running
  - Narrowly avoided hitting a Soviet spy satellite in mid 2013
- Sensitive to EW scale thermal DM!
- **Rest of talk:** where should we point?