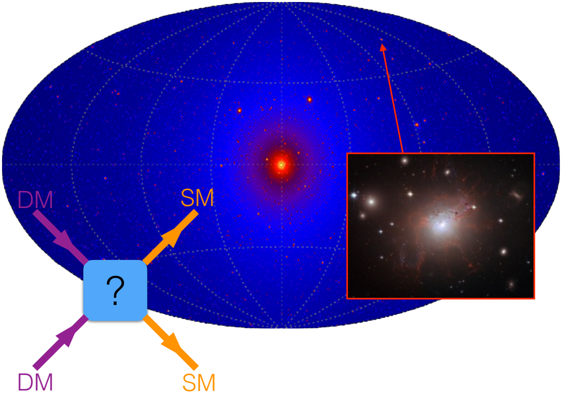
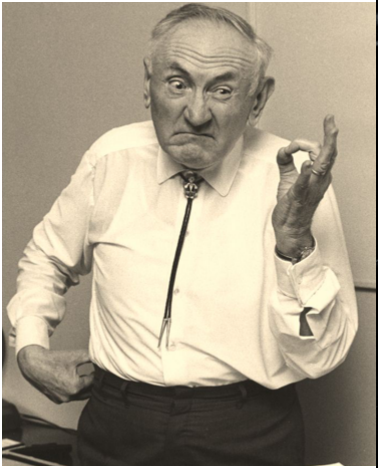
A search for dark-matter annihilation in galaxy groups



Ben Safdi

Massachusetts Institute of Technology

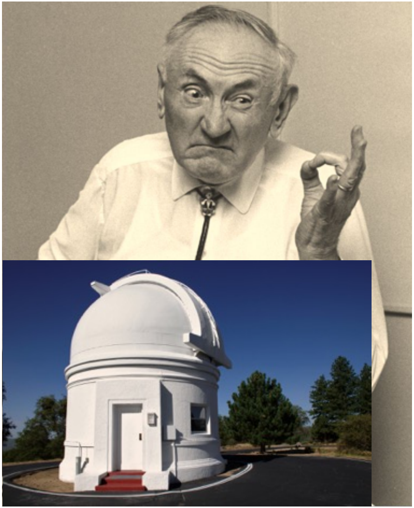
Dark matter exists!



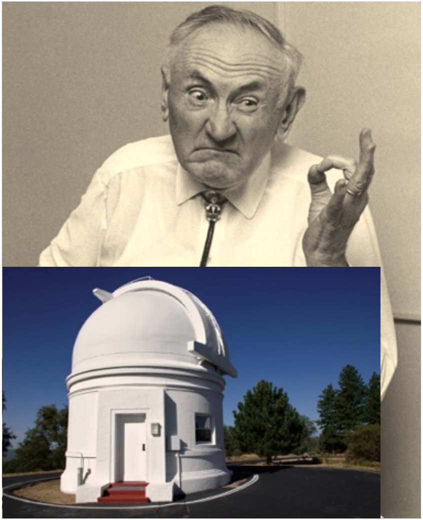
We just don't know **what** it is ...

Coma Cluster of Galaxies

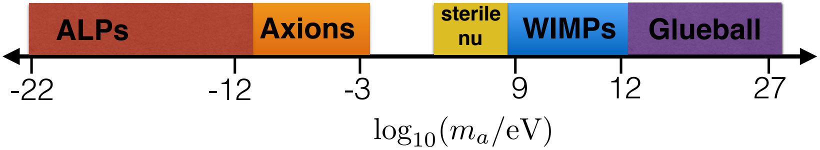
Coma: 1933 to today

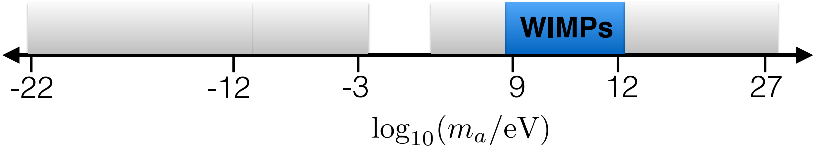


Coma: 1933 to today

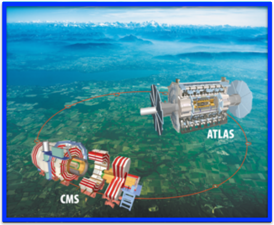


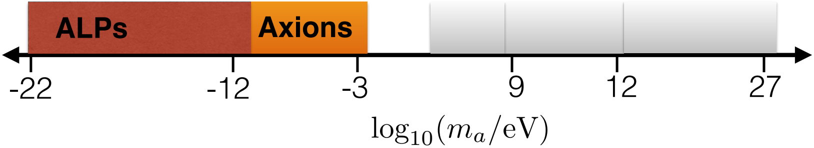
Fermi (NASA)


ALPs
Axions
sterile nu
WIMPs
Glueball
-22
-12
-3
9
12
27
$\log_{10}(m_a/\mathrm{eV})$



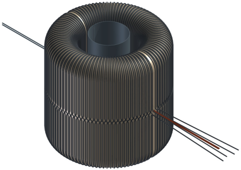
Fermi (NASA)





From Theory...

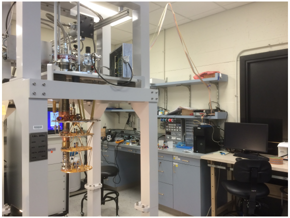
- **Phys. Rev. Lett.**, 117, 141801 (2016): Yoni Kahn, **B.S.**, Jesse Thaler



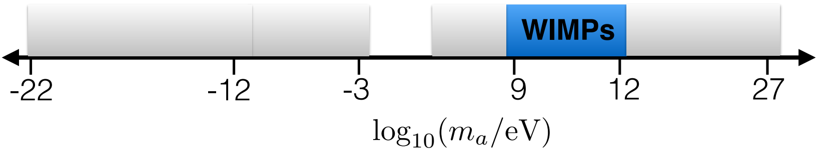
- Ultimate goal: Detect axion dark matter from GUT-scale solution to strong-CP problem

...to Experiment

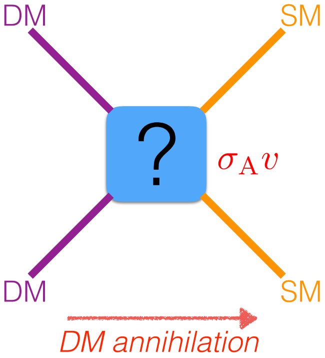
- ABRACADABRA-10 cm

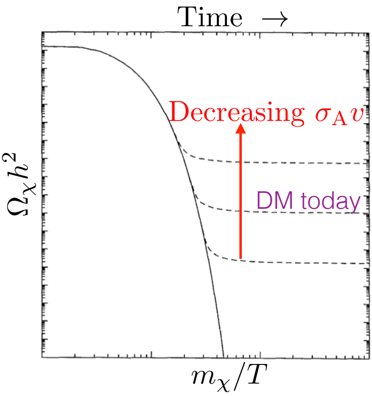


- The team: J. Conrad, J. Formaggio, S. Heine, J. Minervini, J. Ouellet, K. Perez, A. Radovinsky, D. Winklehner, L. Winslow, . . .
- **Funded by the NSF, data soon!**


WIMPs
-22
-12
-3
9
12
27
$\log_{10}(m_a/\mathrm{eV})$

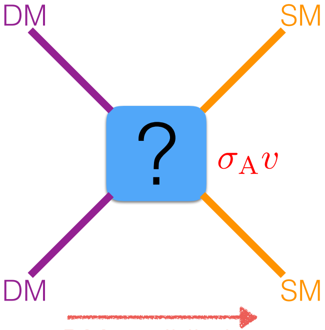
Relic abundance of thermal dark matter

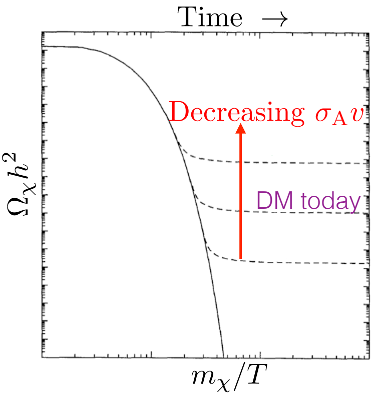




- $\Omega_\chi h^2 = 0.1199 \pm 0.0027$ (Planck + WMAP)

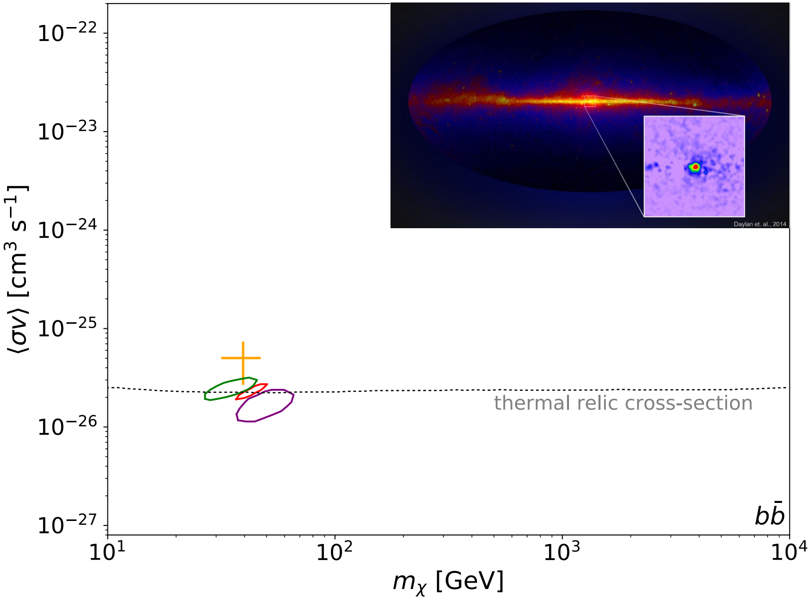
Relic abundance of thermal dark matter





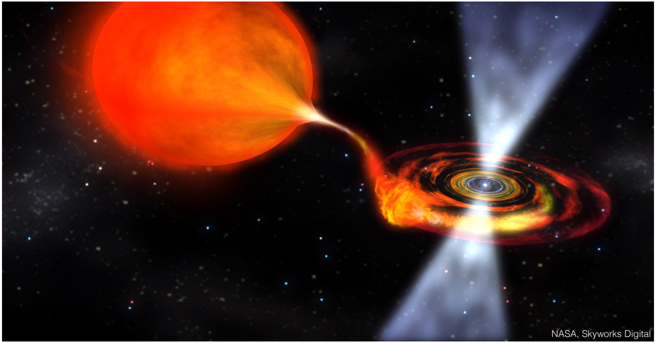
- $\Omega_\chi h^2 = 0.1199 \pm 0.0027$ (Planck + WMAP)
- $\Omega_\chi h^2 \approx 0.1 \times \frac{3 \times 10^{-26}\ \text{cm}^3/\text{s}}{\langle \sigma_A v \rangle}$ (DM freezeout)

Hints of dark matter annihilation in *Fermi* data?



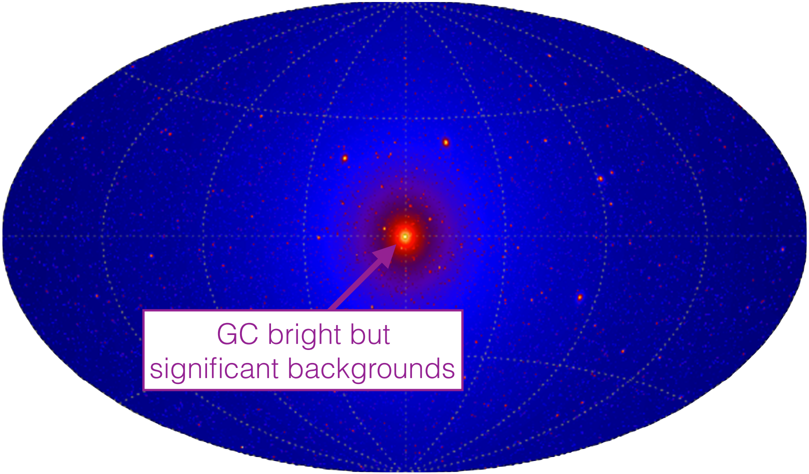
Daylan et. al., 2014, Abazajian et. al. 2014, Gordon et. al. 2014; Calore et. al. 2014

Excess may also arise from dim Point Sources



- Non Poissonian Template Fit (NPTF)
  - *JCAP* 2015: S. Lee, M. Lisanti, **B. S.**
  - *Phys. Rev. Lett.* 2016: S. Lee, M. Lisanti, **B. S.**, T. Slatyer, W. Xue
  - PRD 2016: T. Linden, N. Rodd, **B.S.**, T. Slatyer
  - Astrophys. J. 2016: M. Lisanti, S.M. Sharma, L. Necib, **B.S.**
  - 1612.03173: S.M. Sharma, N. Rodd, **B.S.**
- Wavelets: *Phys. Rev. Lett.* 2016: (R. Bartels, S. Krishnamurthy, C. Weniger)
- Population study: *Fermi* 2017: (1705.00009)
- MSP model: Astrophys. J. 2015: T. Brandt, B. Kocsis

Milky Way Center: largest gamma-ray flux from DM

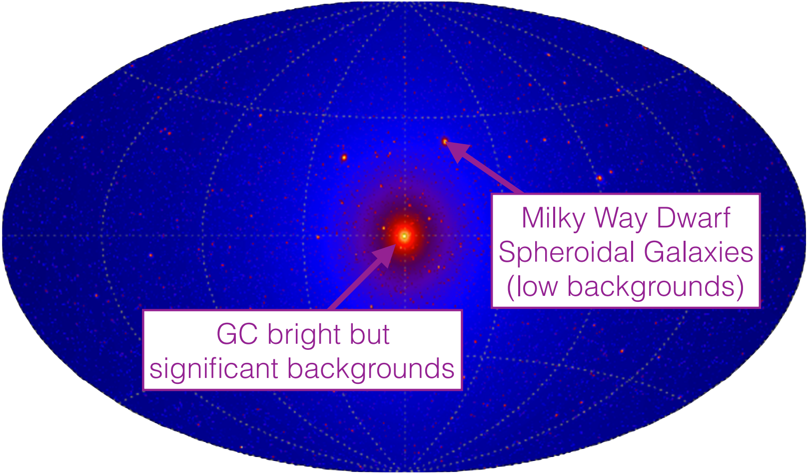


- DM-induced flux $\propto$ to L.O.S. integral of DM density:

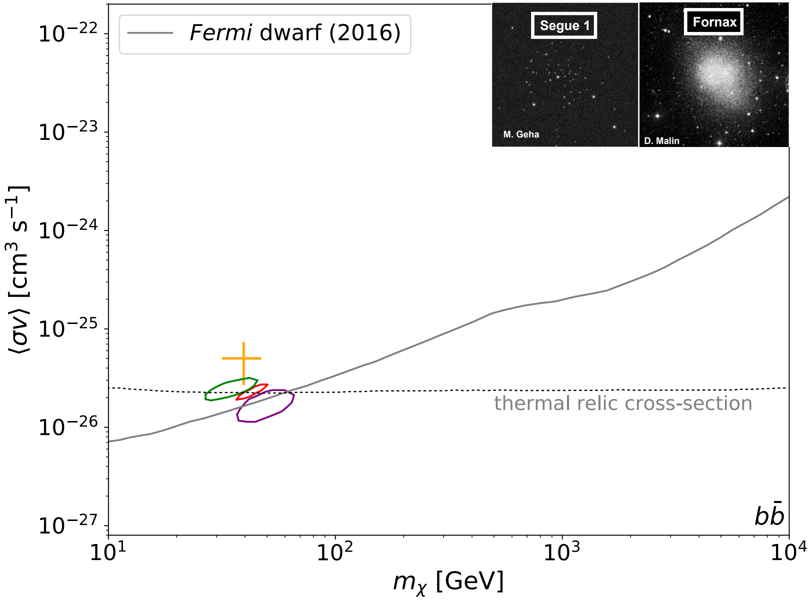
$$\Phi_{\mathrm{DM}} \sim J \equiv \int d\ell \, \rho^2_{\mathrm{DM}}$$

L. Pieri et. al., PRD 2011

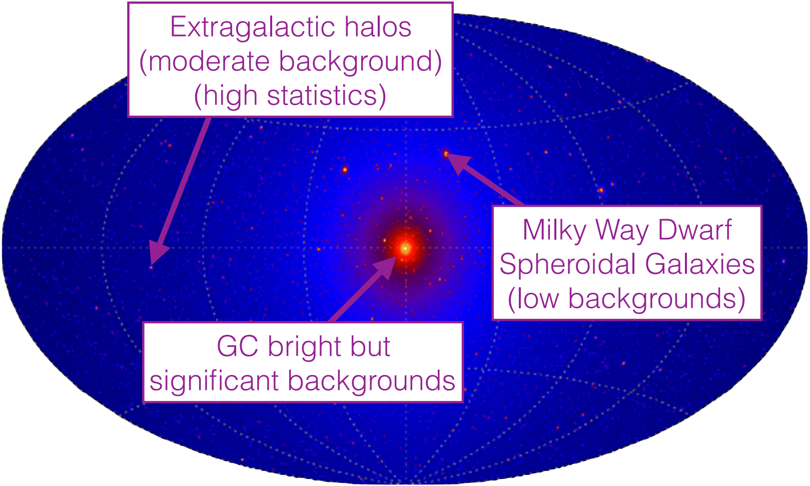
Milky Way Dwarf Spheroidal Satellites (dSphs)



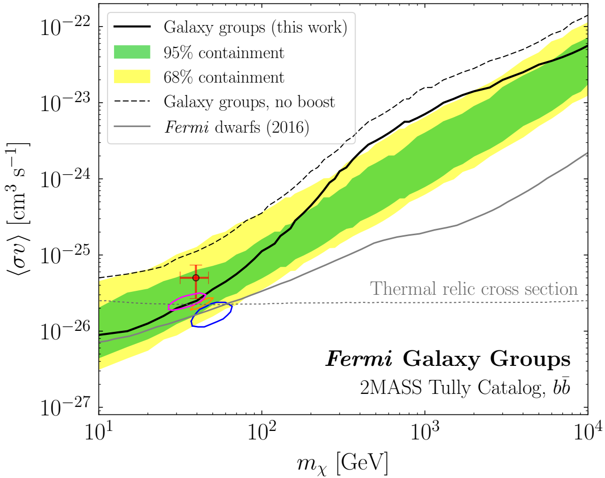
Milky Way Dwarf Spheroidal Satellites (dSphs)



Extragalactic Halos



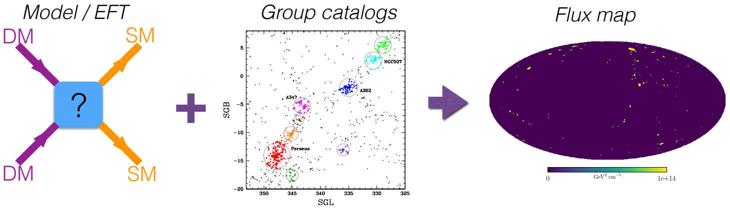
Extragalactic Halos: stacked limit ($N_H = 100$)



- *Real data:* M. Lisanti, S.M. Sharma, N. Rodd, **B.S.**, 170x.xxxxx
- *Simulated data:* M. Lisanti, S.M. Sharma, N. Rodd, **B.S.**, R. Wechsler, 170x.xxxxx

DM annihilation with group catalogs

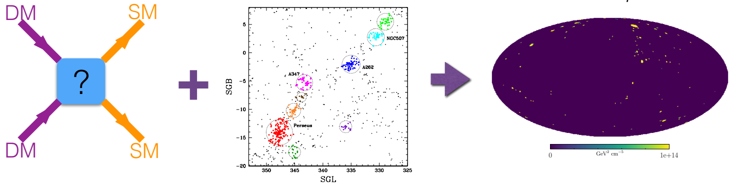
- 1. DM model + group catalog → gamma-ray flux map



DM annihilation with group catalogs

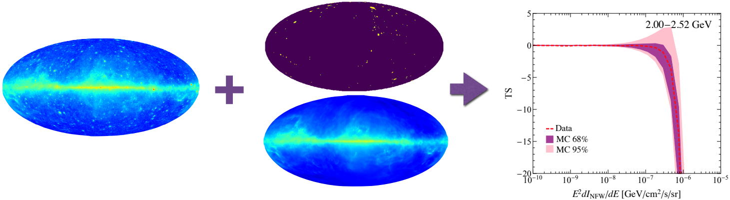
- 1. DM model + group catalog $\rightarrow$ gamma-ray flux map

Model / EFT *Group catalogs* *Flux map*

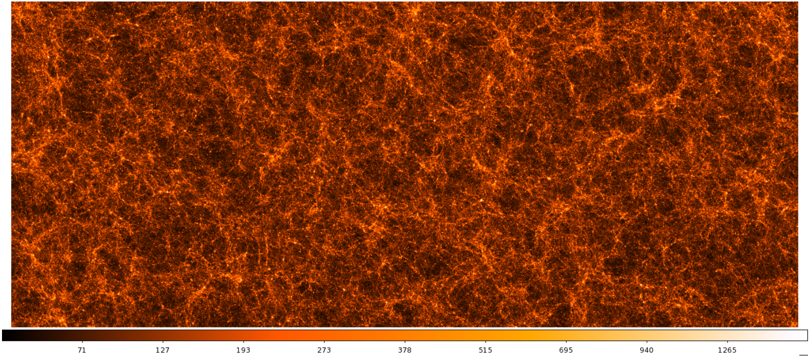


- 2. How do we search for that flux in *Fermi* data?

Fermi Data *Background + Signal Templates* *Likelihood Profiles*

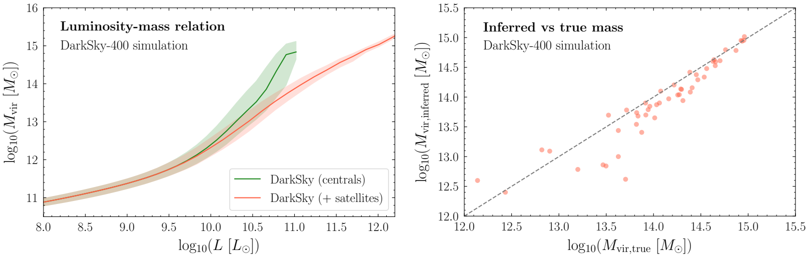


DarkSky (2014) N-body simulation



- 4096^3 particles, $m \sim 7.6 \times 10^7\ M_\odot$
- 400 Mpc h^{-1} per-side box, $z \leq 93$
- galaxy-halo connection: populate with galaxies
- Halo catalog generated with `Rockstar` group finder

DarkSky: galaxy-halo connection



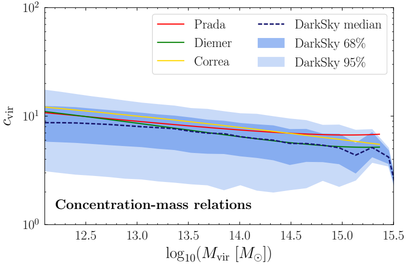
- J-factor depends on $M_{\rm vir}$, c, $b_{\rm sh}(M_{\rm vir})$, and z:

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

- Navarro-Frenk-White (NFW) profile:

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

DarkSky: concentration-mass relation

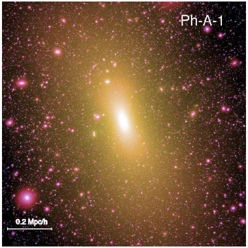


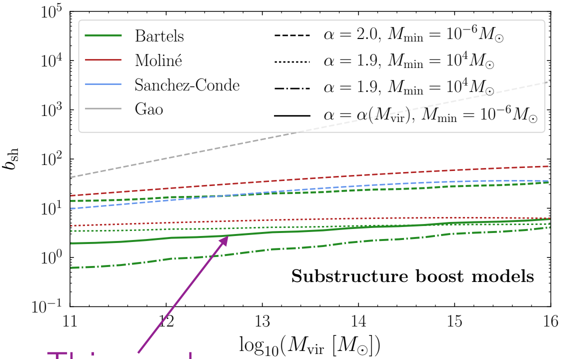
- J-factor depends on M_{vir}, c, $b_{\mathsf{sh}}(M_{\mathsf{vir}})$, and z:

$$J = (1 + b_{\mathsf{sh}}(M_{\mathsf{vir}})) \int \rho^2_{\mathsf{NFW}}(s, \Omega) ds d\Omega$$

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

Boost factor from DM sub-halos





This work

- J-factor depends on $M_{\rm vir}$, c, $b_{\rm sh}(M_{\rm vir})$, and z:

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

Boost factor from DM sub-halos

- Boost-factor given by integral over sub-halo population $dN/dm \sim m^{-1.9}$ (for field halos)

$$b_{\mathsf{sh}}(M_{\mathsf{vir}}) = \frac{1}{L_{\mathsf{host}}(M_{\mathsf{vir}})} \int dm \frac{dN}{dm} L_{\mathsf{sh}}(m)$$

Boost factor from DM sub-halos

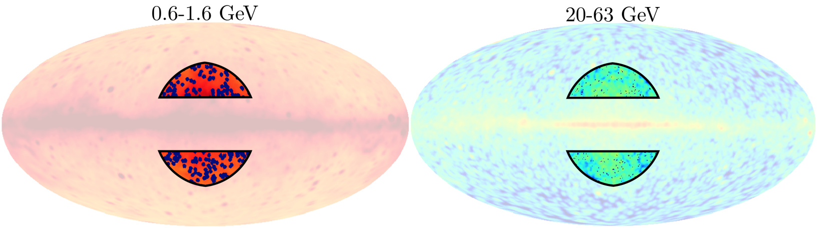
- Boost-factor given by integral over sub-halo population $dN/dm \sim m^{-1.9}$ (for field halos)

$$b_{\text{sh}}(M_{\text{vir}}) = \frac{1}{L_{\text{host}}(M_{\text{vir}})} \int dm \frac{dN}{dm} L_{\text{sh}}(m)$$

- Sub-halo luminosity $L_{\text{sh}}(m)$

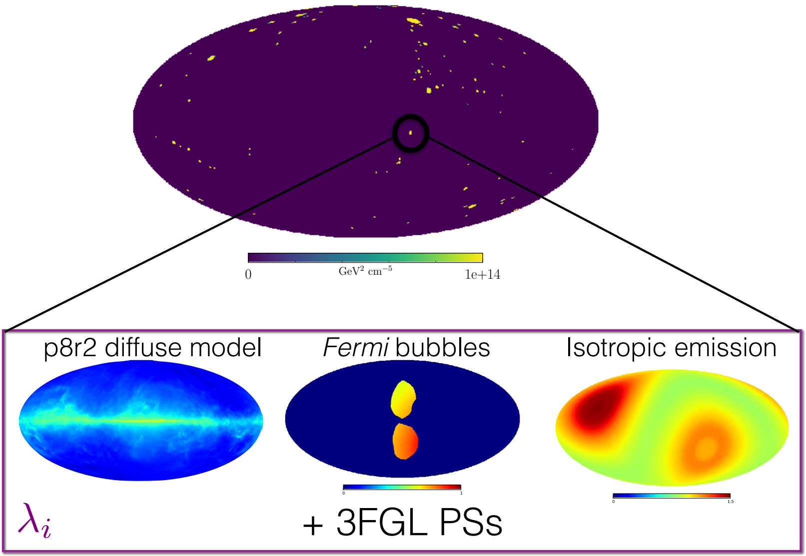
$$L_{\text{sh}}(m) \sim m\, c^3$$

Step 2: *Fermi* data selection

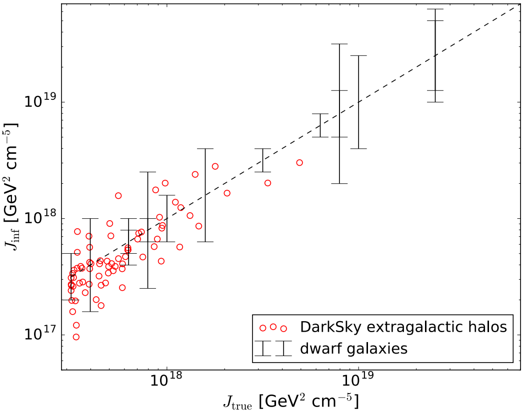


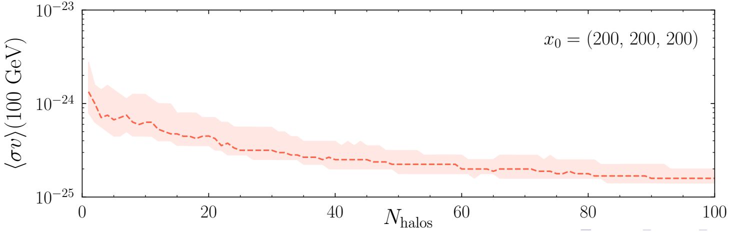
- 40 log-spaced bins between 200 MeV - 2 TeV
- 423 weeks Pass 8 UltracleanVeto
- mask: large-scale structures, $|b| \leq 5^{\circ}$

Profile likelihood in 10° halo ROIs

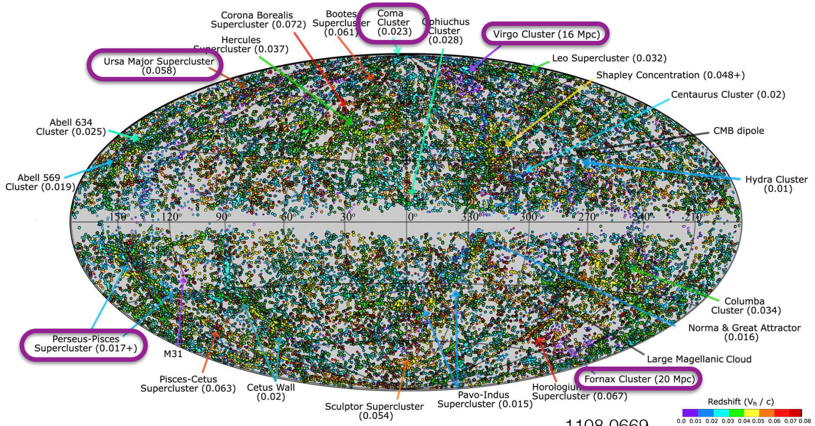


DarkSky: top ∼100 halos





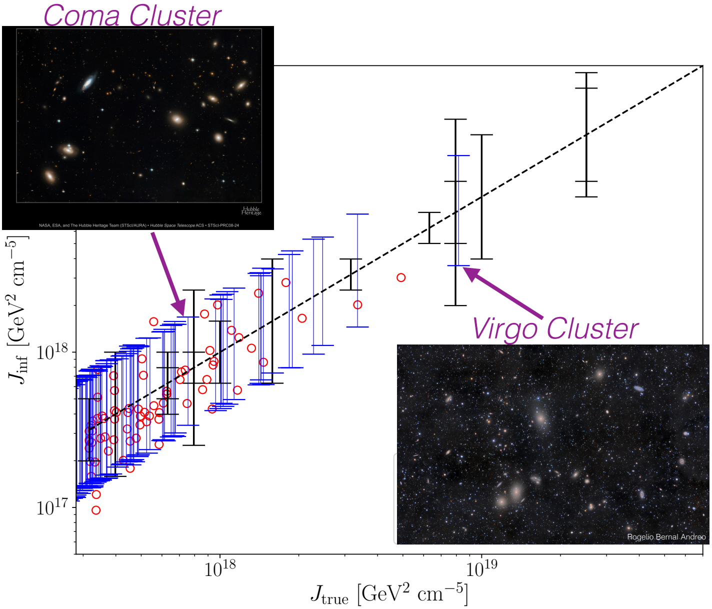
Real data: 2MASS redshift survey



1108.0669

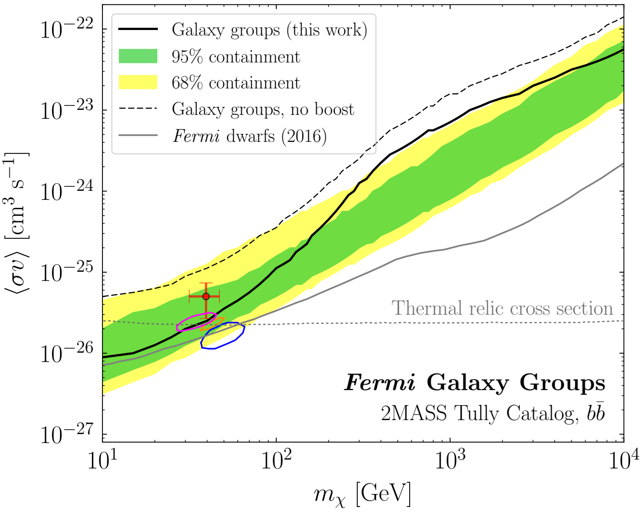
- 2MASS: 1997 - 2001 infrared survey ($K_s \leq 13.5$ mag)
- 2011: spectroscopic followup survey (CFA)
- 44,599 2MASS galaxies with $K_s \leq 11.75$ mag
- Tully 2015: group catalog

DarkSky N-body simulation vs real data



Real Data limit consistent with DarkSky

- Remove handful of halos with large cosmic-ray emission (TS > 5, $\sigma_A v > 10 \times$ best indiv. limit)

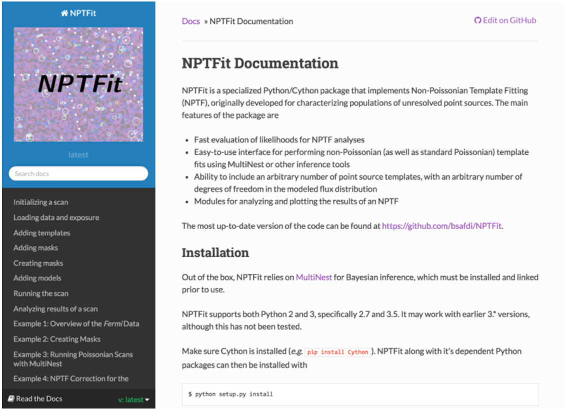


Extragalactic annihilation summary

- First systematic search for DM annihilation from extragalactic halos
- *Fermi* future: combines datasets (*e.g.*, *Fermi* data + galaxy group catalogs, DES for dSphs)
  - Combined EG + dSphs with Alex Drlica-Wagner in the works
- In progress: *Fermi* data + galaxy group catalogs for astrophysical source
- Galaxy-group J-factor catalog (to be released) likely useful elsewhere (e.g., HAWC, NuSTAR, . . .)
- WIMP DM is on the run: may detect soon, but should take seriously alternate proposals (*e.g.*, axions, heavy DM, $\cdots$)

Template fitting code available

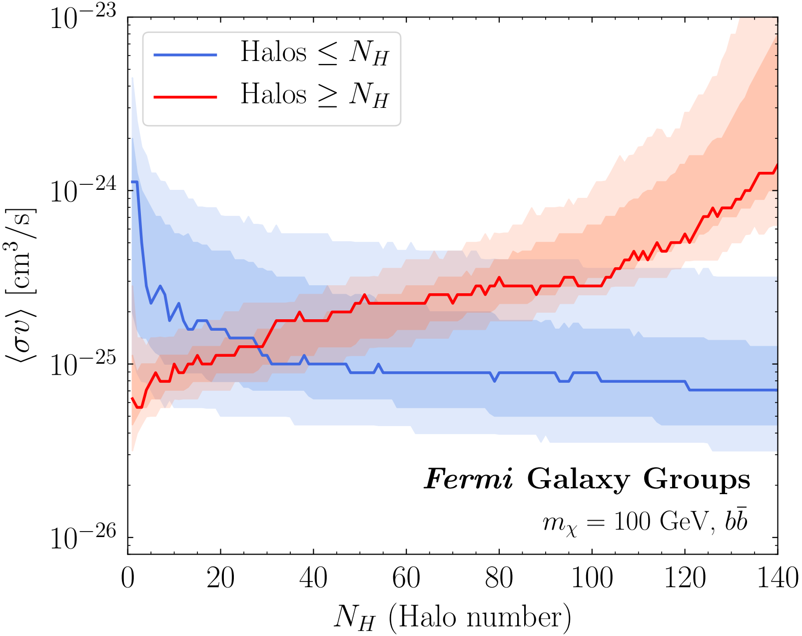
- https://github.com/bsafdi/NPTFit: S. M.-Sharma, N. Rodd, **B.S.**, 1612.03173. Open-source code for performing template analysis



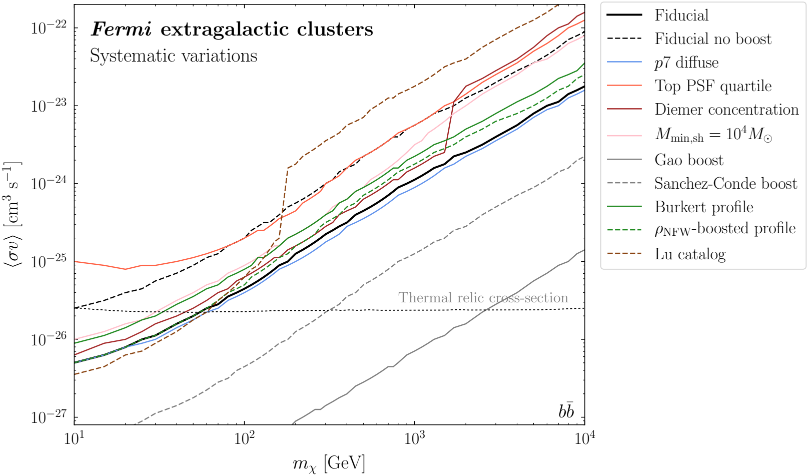
Questions?

Extragalactic backup

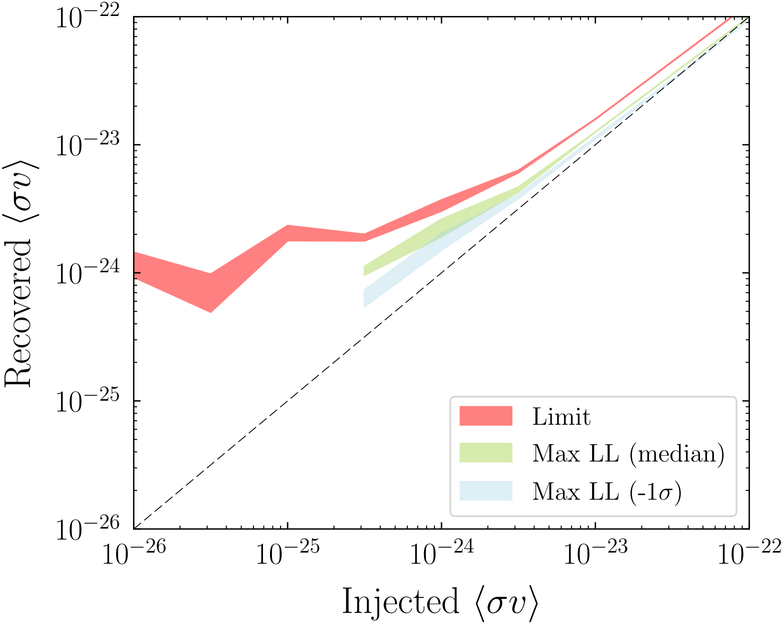
Top few halos dominate limit



Systematics



Recover Injected with DarkSky

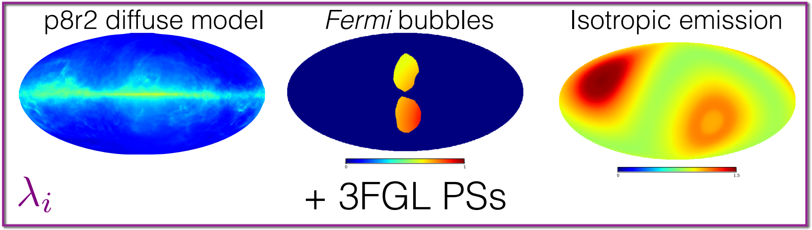


Poissonian template fit: stacking halos halo

- Sum log-likelihood ($p_h(d|\psi_{\text{DM}})$) of individual halos

$$\log p(d|\psi_{\text{DM}}) = \sum_h \log p_h(d|\psi_{\text{DM}})$$

- Construct likelihood profiles for σv at fixed m_{DM}



WIMP Indirect Detection

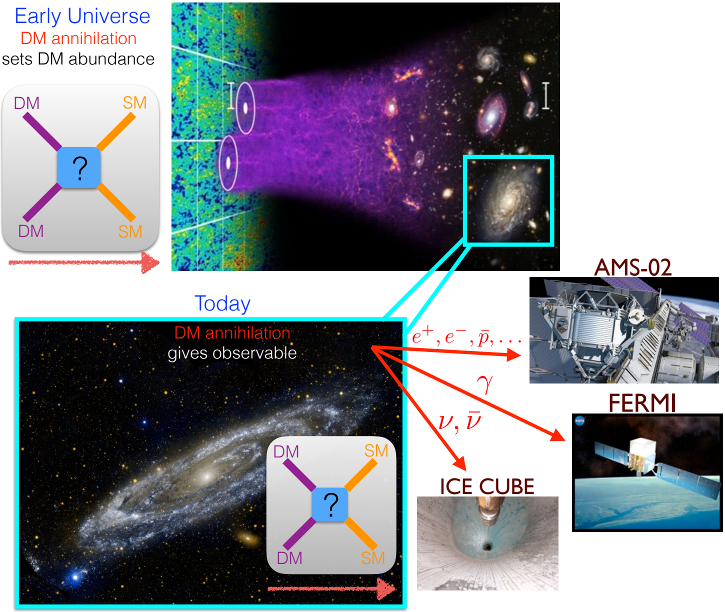
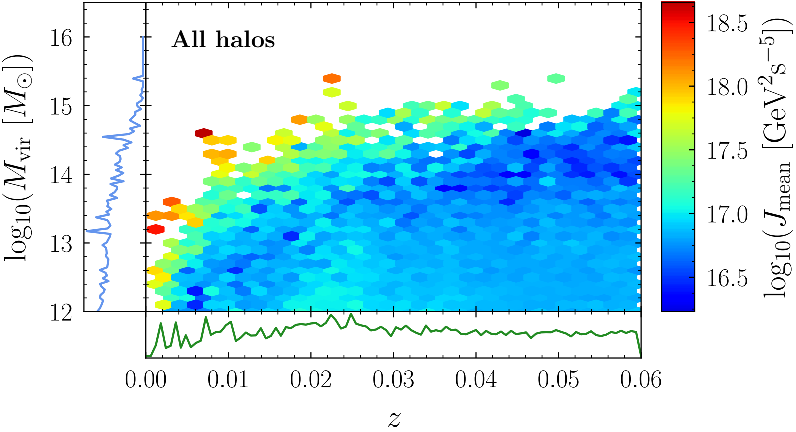


Image credits: AMS, Fermi, IceCube, NASA, *Scitechdaily*

DarkSky: compute J-factors for halos



Poissonian template fit: individual halo

- Model params.: $\theta = \{\psi_{\mathrm{DM}}, \lambda_{nuisance}\}$ ($\psi_{\mathrm{DM}} = \{m_{\mathrm{DM}}, \sigma_A v\}$)

Poissonian template fit: individual halo

- Model params.: $\theta = \{\psi_{\text{DM}}, \lambda_{nuisance}\}$ ($\psi_{\text{DM}} = \{m_{\text{DM}}, \sigma_A v\}$)
- Likelihood in energy bin i with pixelated data $d_i = \{n_i^p\}_p$:

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

Poissonian template fit: individual halo

- Model params.: $\theta = \{\psi_{\text{DM}}, \lambda_{nuisance}\}$ ($\psi_{\text{DM}} = \{m_{\text{DM}}, \sigma_A v\}$)
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- maximize over nuisance parameters: $\lambda = (\{\lambda_i\}, J)$

$$\log p(d|\psi_{\text{DM}}) = \max_J \left(\sum_{i=0}^{39} \max_{\lambda_i} \log p_i(d_i|\theta) - \frac{(\log J - \log \bar{J})^2}{2\sigma^2_{\log J}} \right)$$

Poissonian template fit: individual halo

- Model params.: $\theta = \{\psi_{\text{DM}}, \lambda_{nuisance}\}$ ($\psi_{\text{DM}} = \{m_{\text{DM}}, \sigma_A v\}$)
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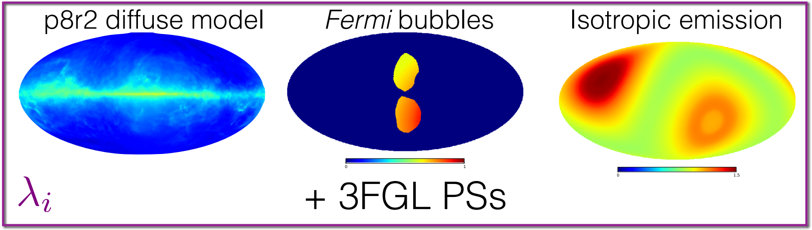
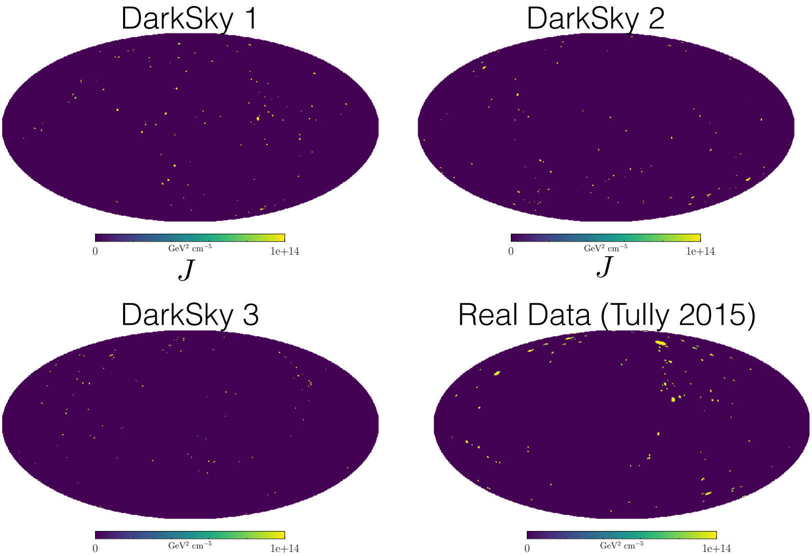
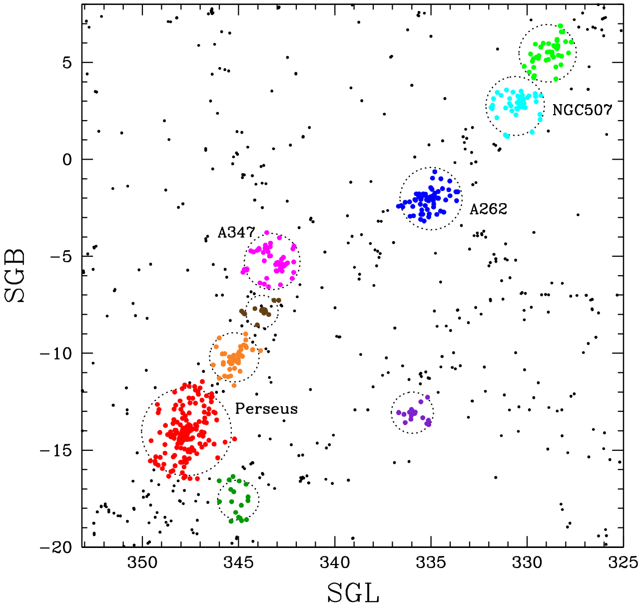


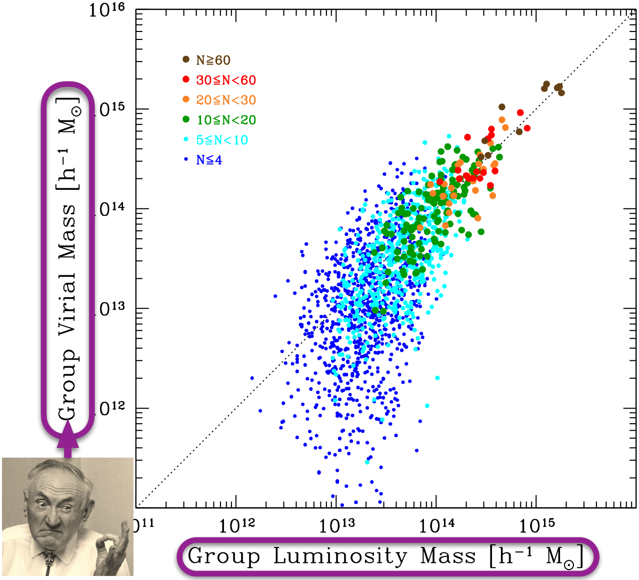
DarkSky N-body simulation vs real data



Real data: 2MASS group catalog (Tully 2015)



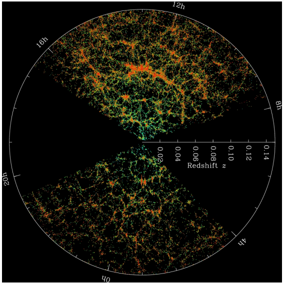
Real data: 2MASS group catalog (Tully 2015)

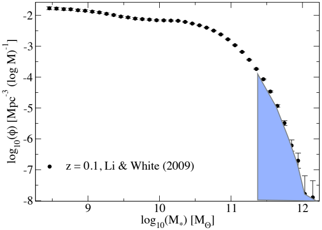


More accurate: we use this

DarkSky (2016): mock galaxy catalog

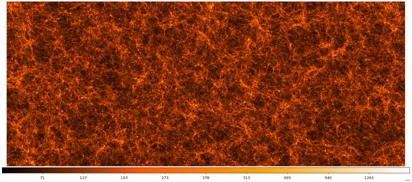
Stellar Mass

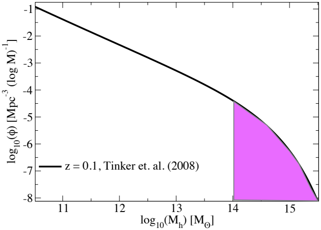




Galaxy Surveys (SDSS)

Dark Matter Mass





Simulations

Boost factor from DM sub-halos

- Boost-factor given by integral over sub-halo population $dN/dm \sim m^{-1.9}$ (for field halos)

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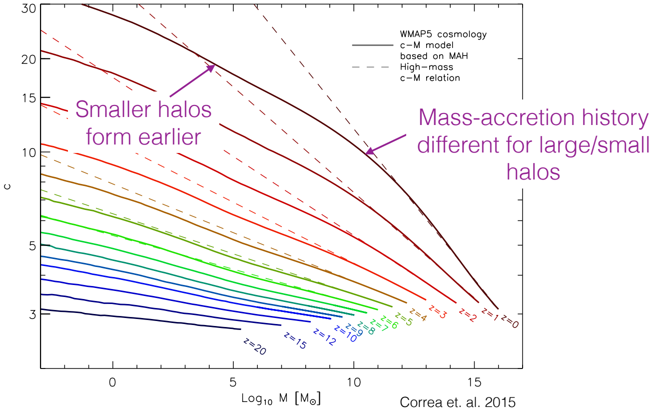
- Kinetic decoupling depends on elastic-scattering with SM

$$T_{\text{kd}} \sim 50 \left(\frac{m_{\chi}}{50 \text{ GeV}} \right)^{3/4} \text{ MeV}$$

Boost factor: importance of $c(M)$, dN/dM



Correa et. al. 2015

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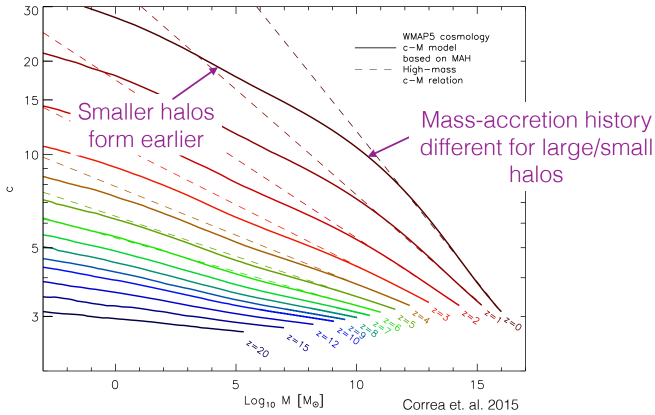

- $c(M)$ steepens at low m from tidal stripping
- dN/dM hardens at low m from tidal stripping
  - Low-mass halos tidally stripped (Bartels et. al. 2015)

DarkSky: top ∼100 halos