fermi
Gamma-ray Space Telescope

Searches for Dark Matter Annihilation in Dwarf Spheroidal Galaxies with the Fermi-LAT

Alex Drlica-Wagner
on behalf of the
Fermi-LAT Collaboration

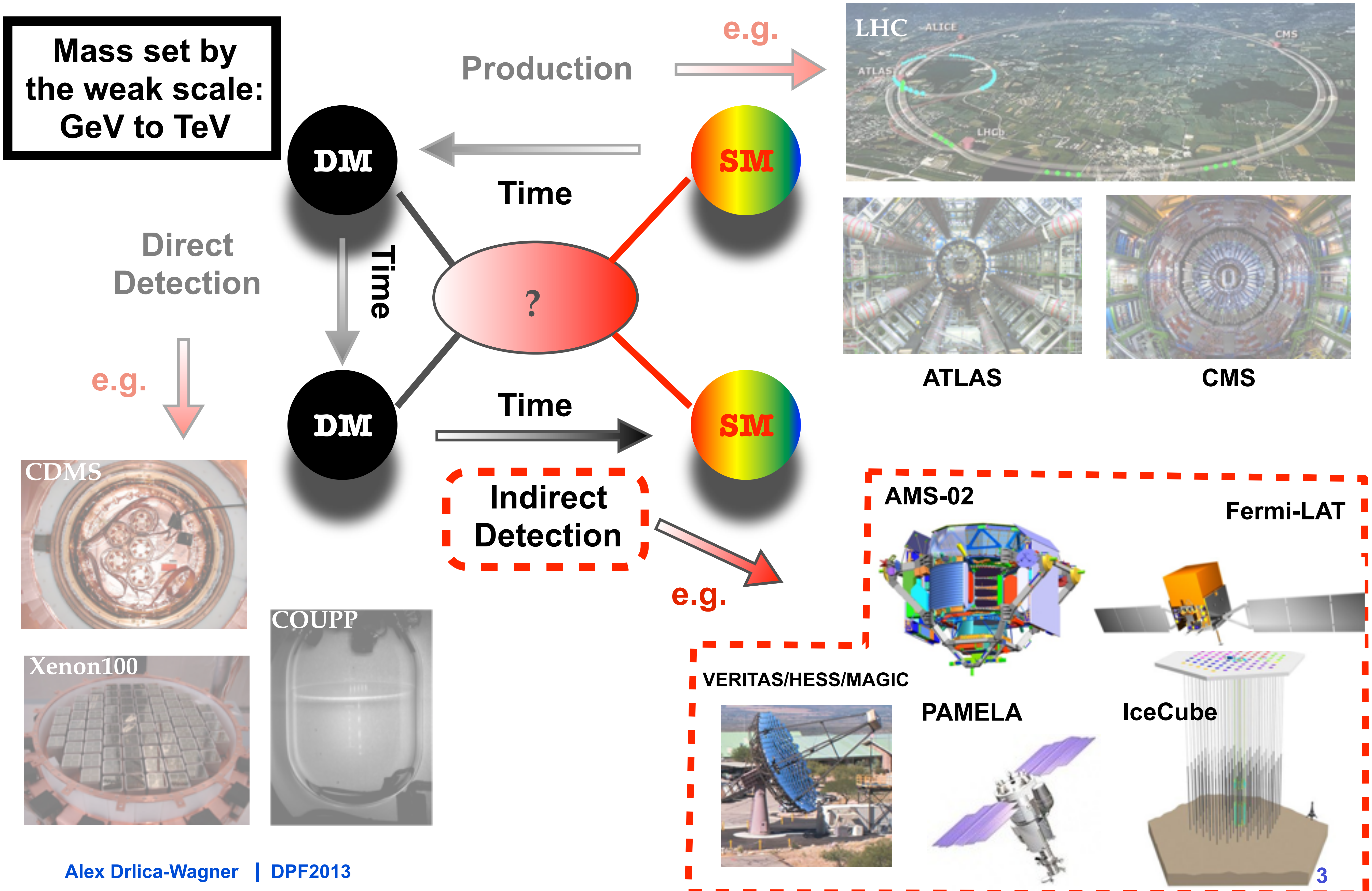
DPF 2013 Meeting
August 15th, 2013

SLAC KIPAC STANFORD UNIVERSITY

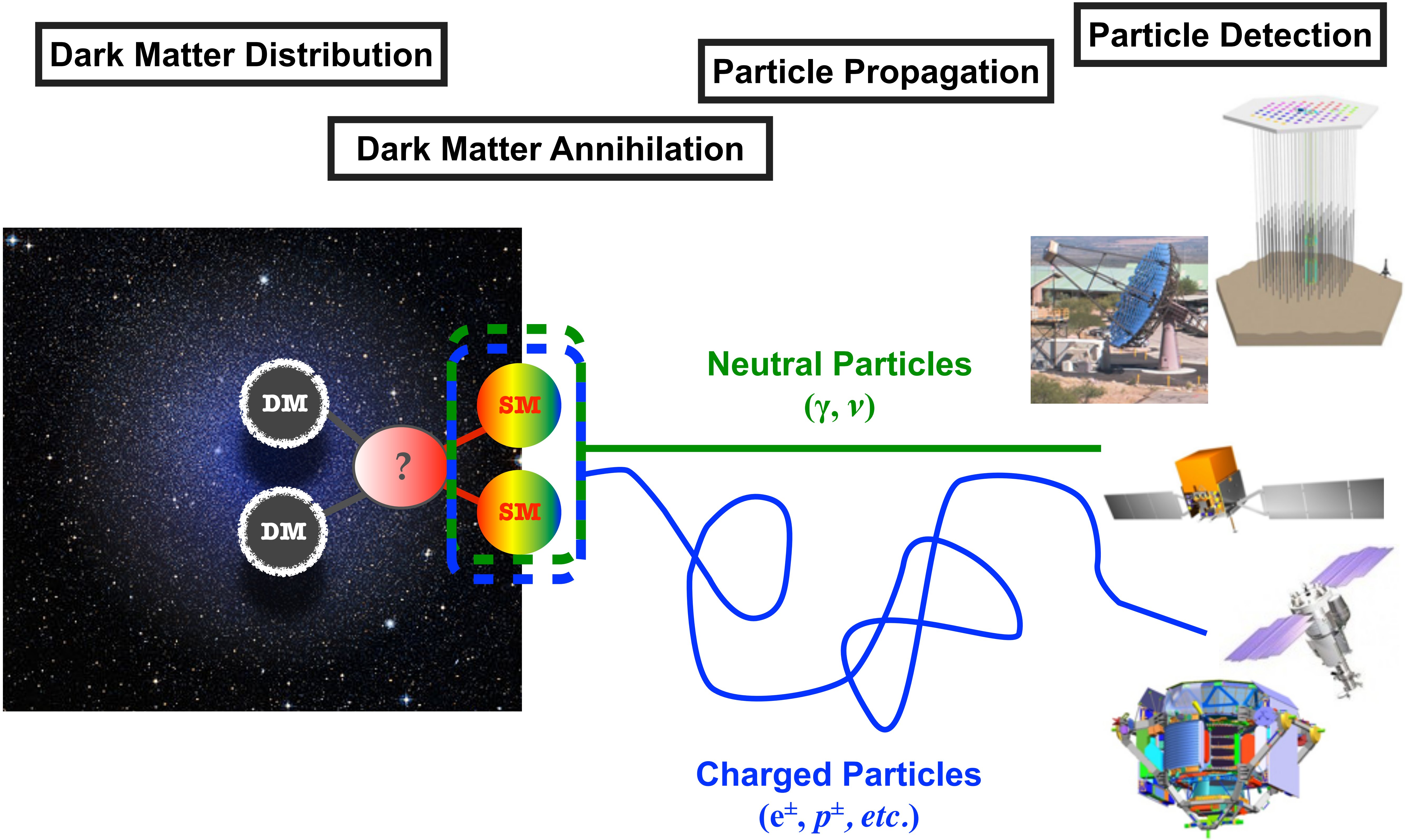
Results presented here are from Ph.D. dissertation (ref. [1])

Fermi-LAT Collaboration publication is forthcoming

Hunting for WIMPs



Indirect Detection



Indirect Detection

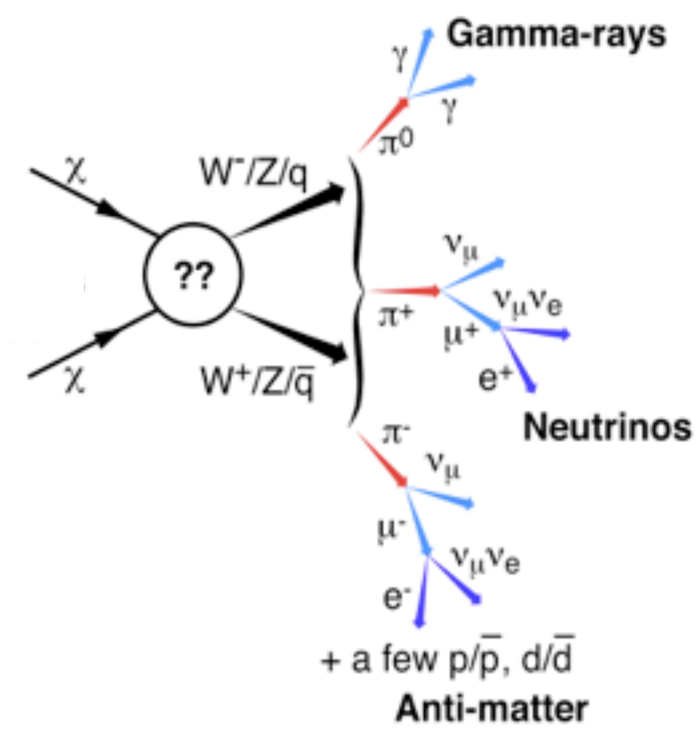
Gamma-Ray Flux
(signal in data)

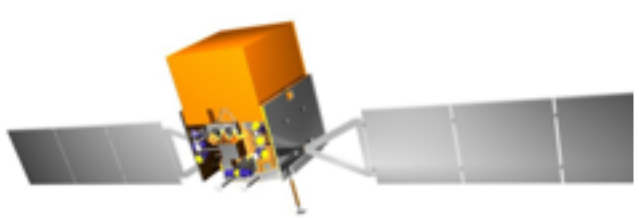
Particle Physics
(particles per annihilation)

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f$$

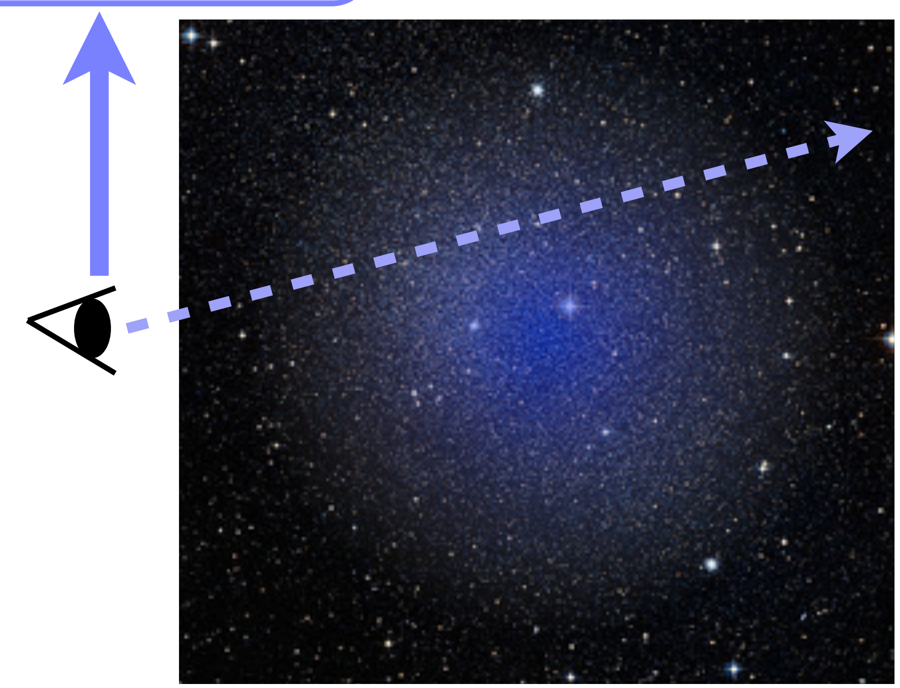
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

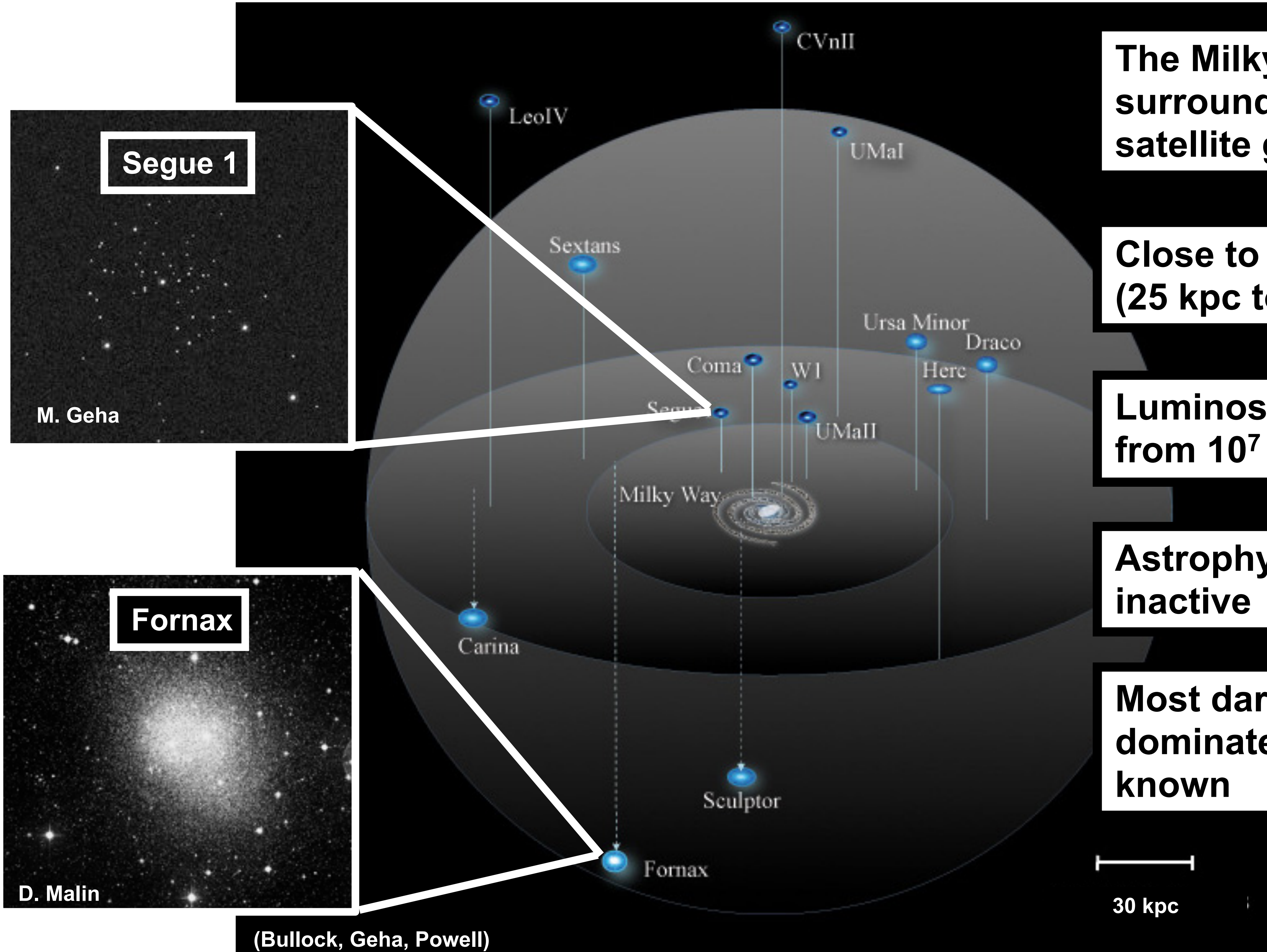




Dark Matter Distribution
(line-of-sight integral)



Dwarf Spheroidal Satellite Galaxies



(Bullock, Geha, Powell)

The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

Luminosities range from $10^7\ L_\odot$ to $10^3\ L_\odot$

Astrophysically inactive

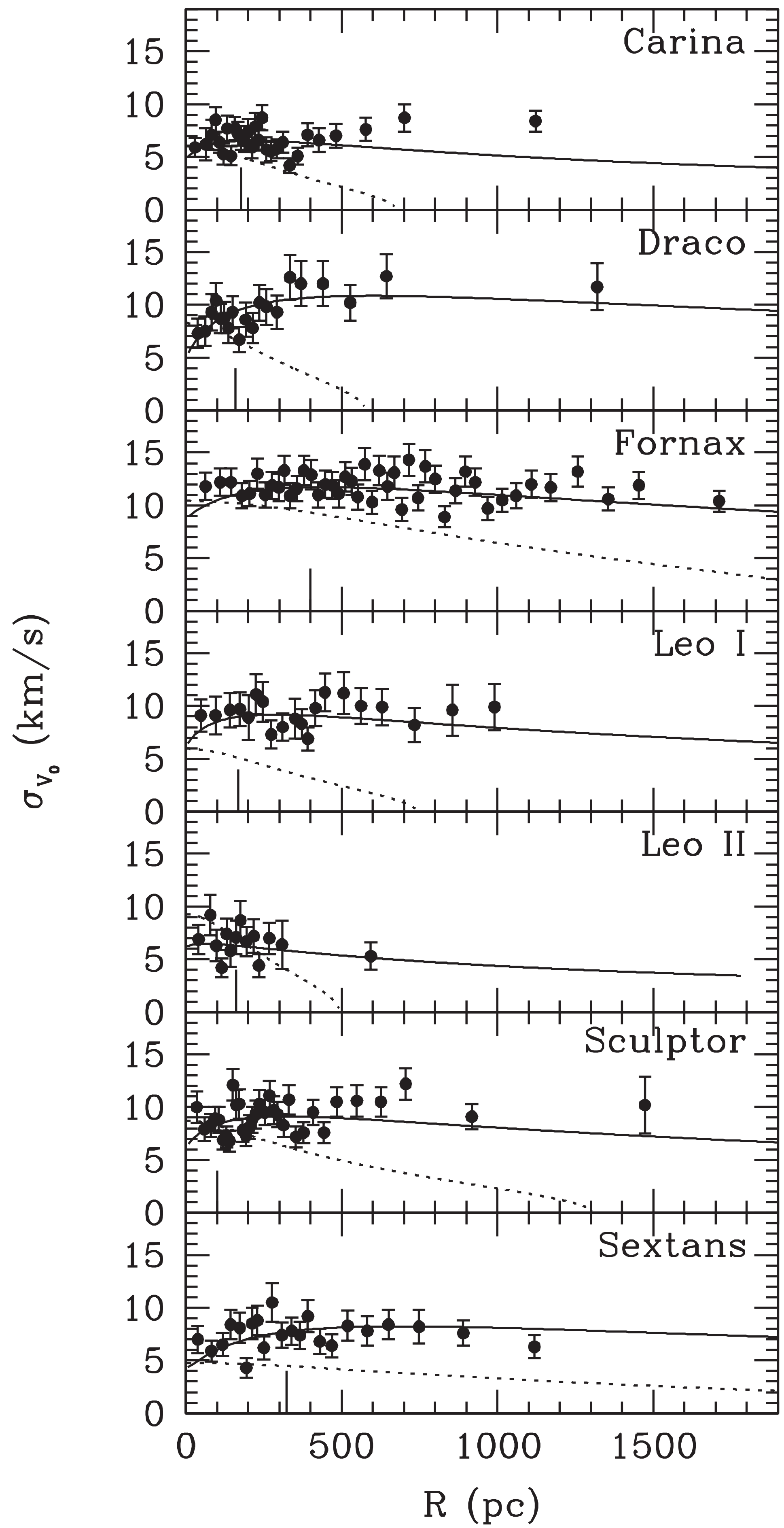
Most dark matter dominated objects known

Dark Matter Content

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

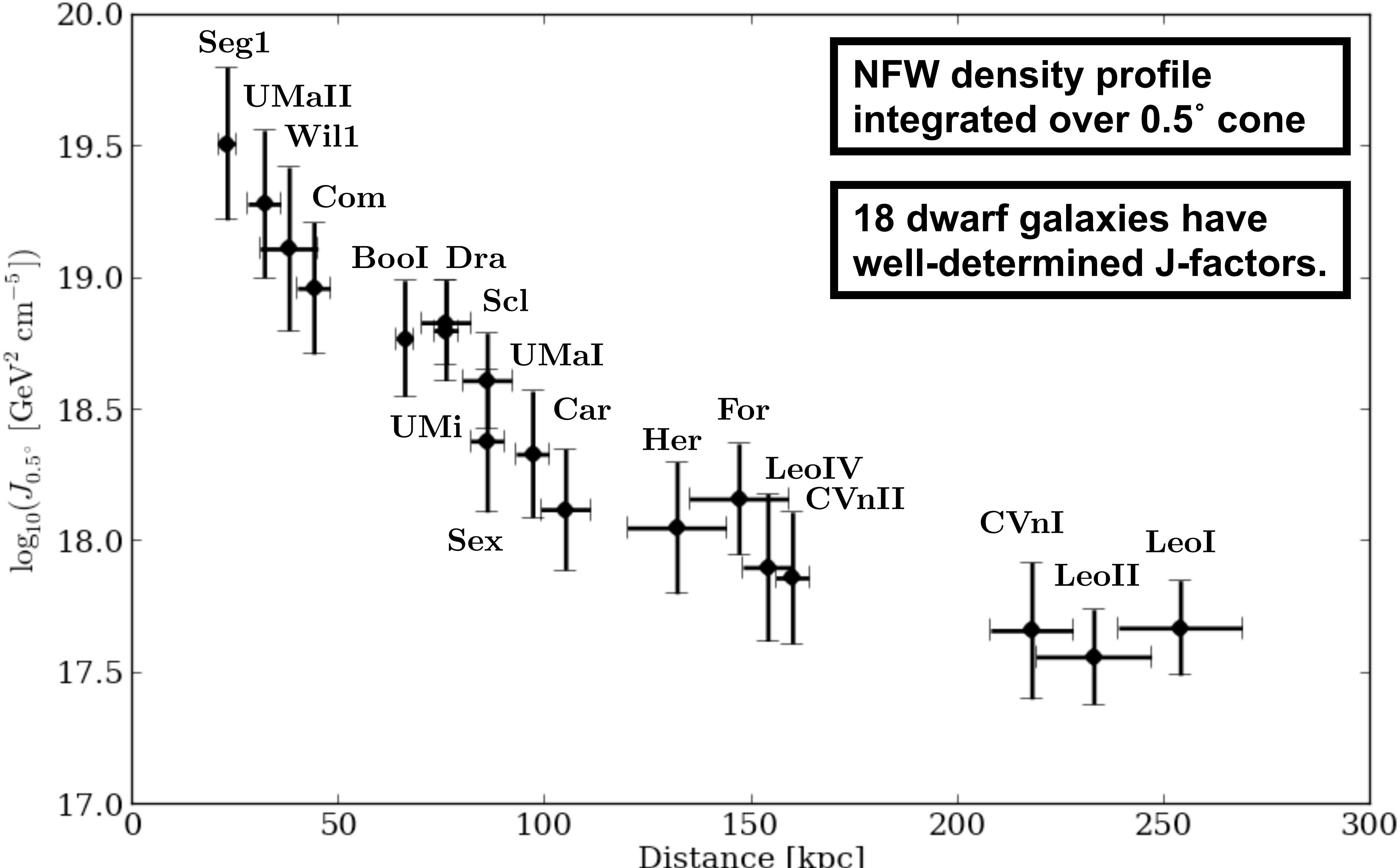
- **Dark matter content determined from stellar velocity dispersion**
  - **Classical dwarfs: spectra for several thousand stars**
  - **Ultra-faint dwarfs: spectra for fewer than 100 stars**
- **Fit stellar velocity distribution of each dwarf (assuming an NFW profile)**
- **Calculate the J-factor by integrating out to a radius of 0.5 deg (ref. [3])**
  - **Encloses the half-light radii of the dwarfs**
  - **Minimizes uncertainty in the J-factor**
  - **Large enough to be insensitive to the inner profile behavior (core vs. cusp)**
- **Include the J-factor uncertainty in the gamma-ray analysis**

Walker et al. 2007 (ref. [2])



J-Factors for 18 Dwarf Galaxies

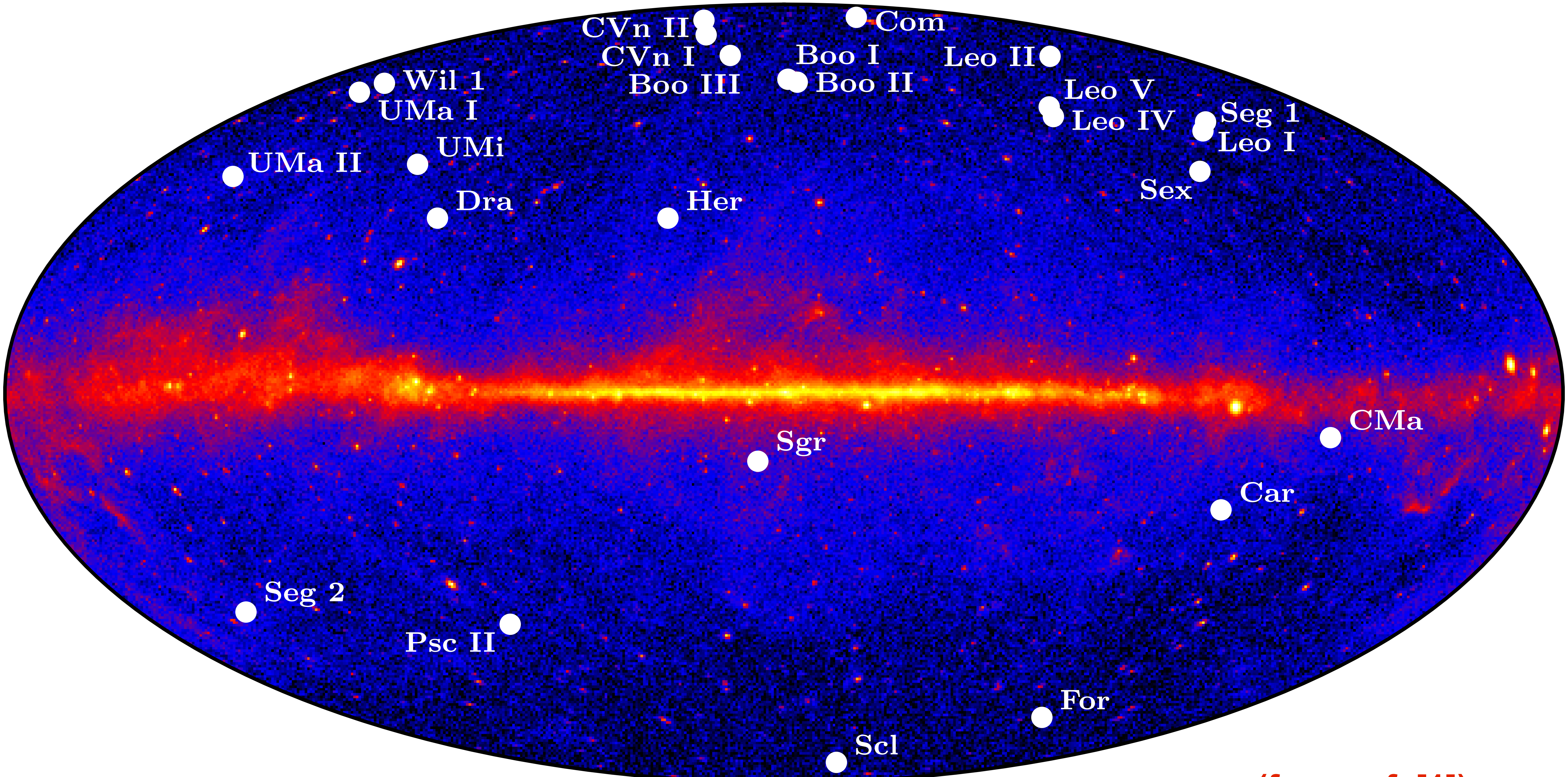
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



NFW density profile integrated over 0.5˚ cone

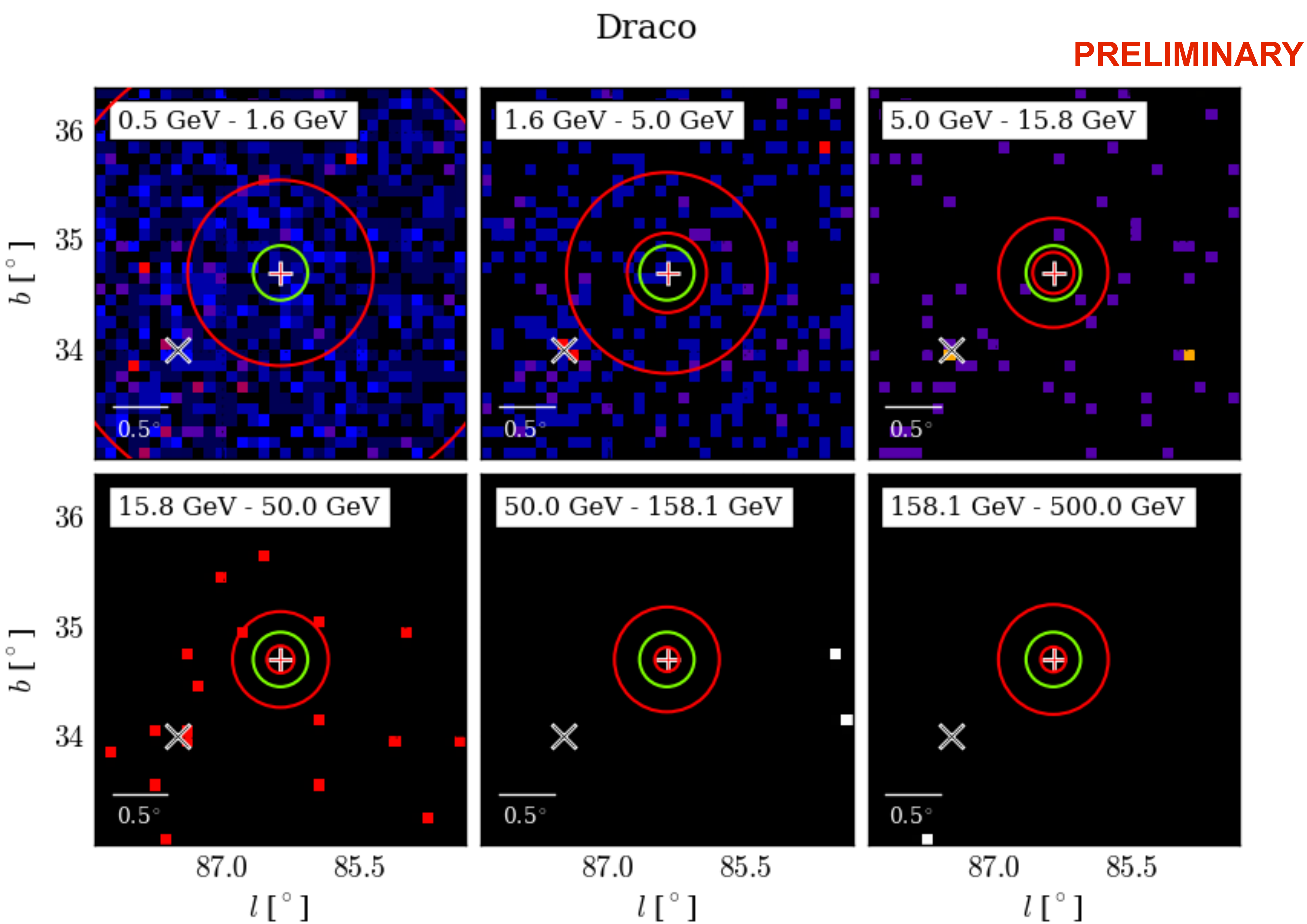
18 dwarf galaxies have well-determined J-factors.

Dwarf Spheroidal Galaxies

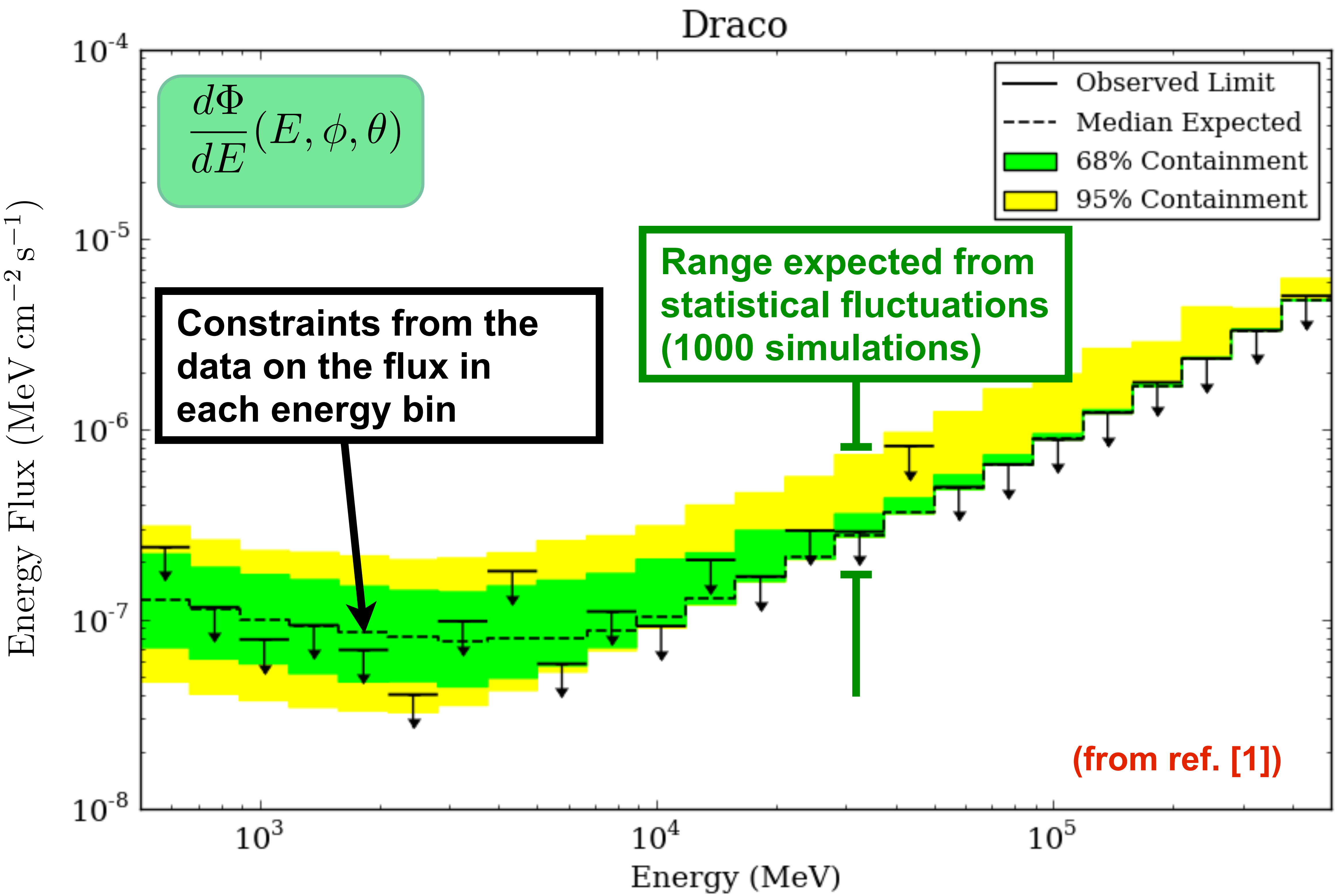


(from ref. [1])

LAT Count Maps

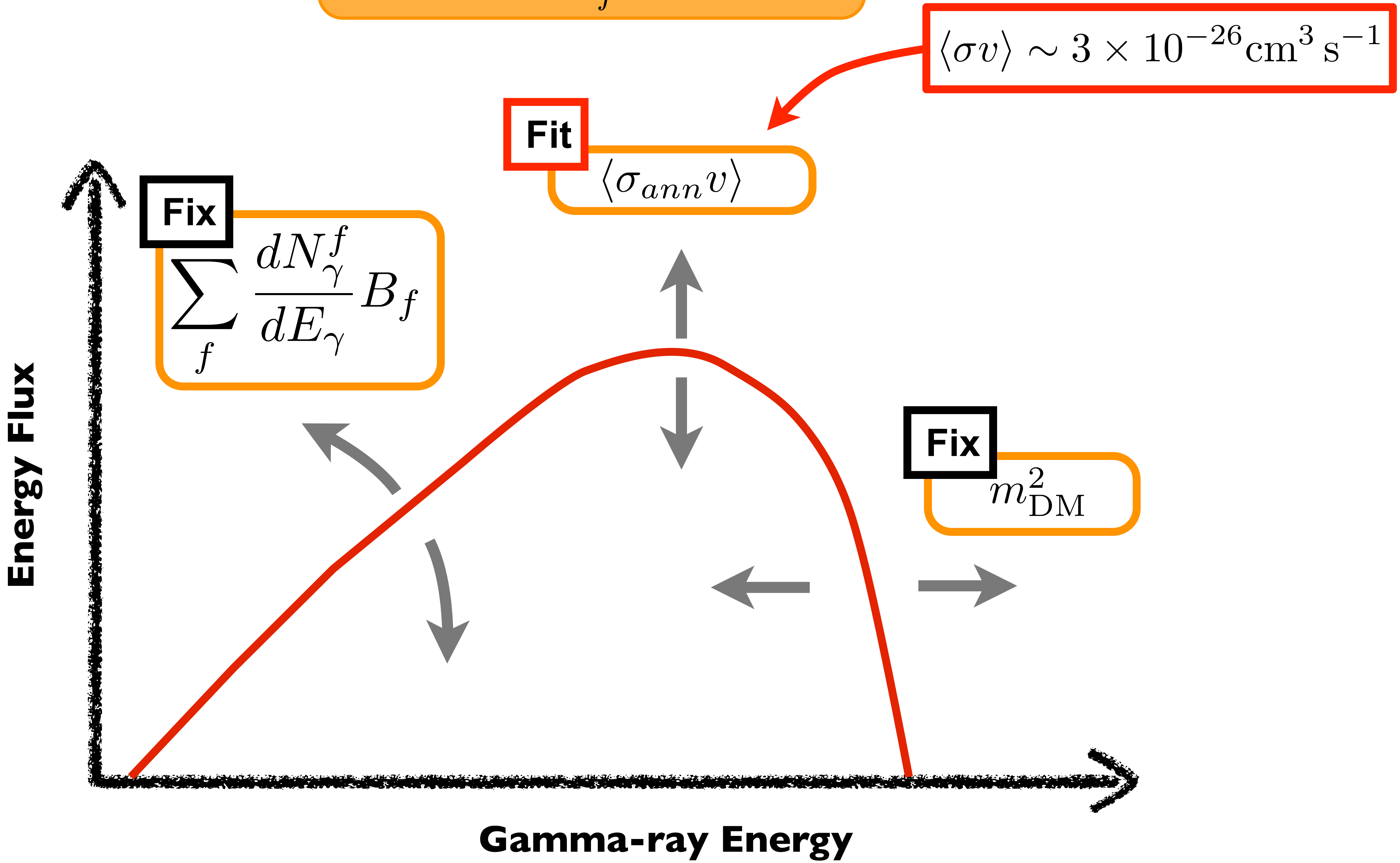


Differential Sensitivity



Particle Spectrum

$$\frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f$$



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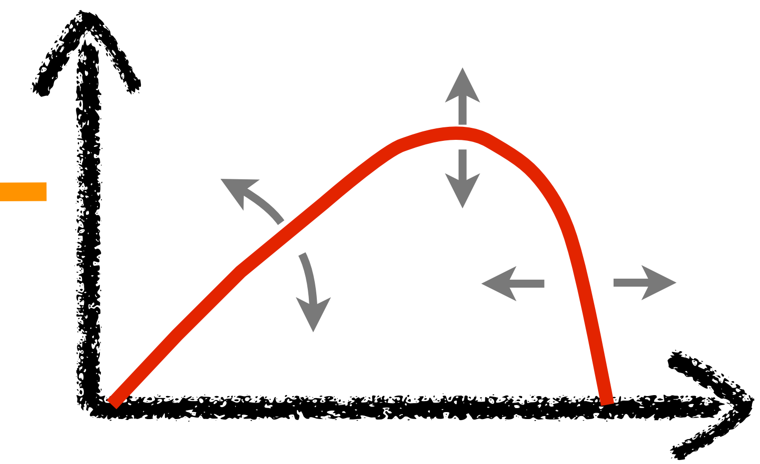
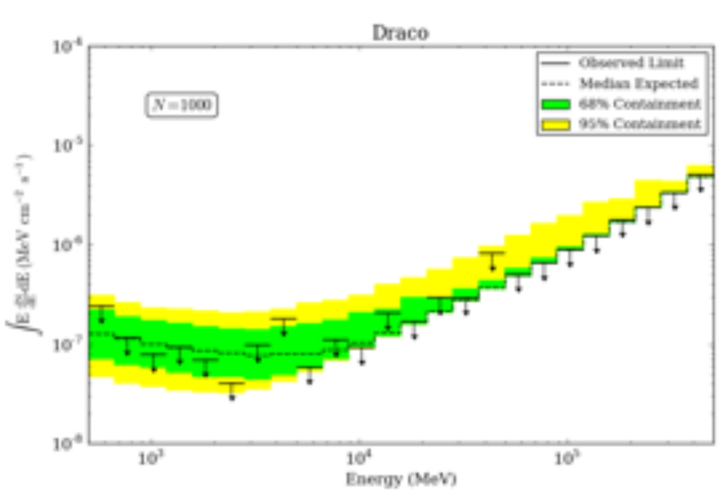


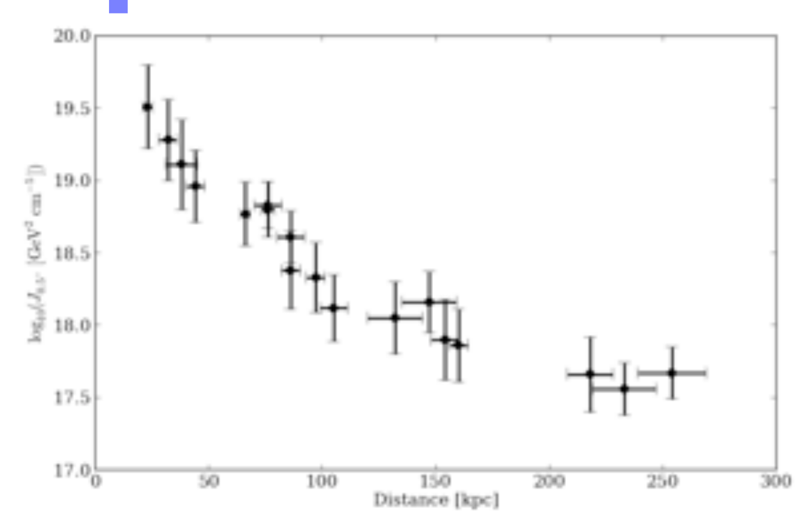
$$\times$$

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')$$



Dark Matter Distribution

(line-of-sight integral)



Joint Likelihood Analysis

- Assume same dark matter particle in all dwarf spheroidal galaxies
- Use all dwarf galaxies with well-determined J-factors in non-overlapping regions (N=15)
- Perform a combined likelihood analysis:
  - Predicted flux for each dwarf will depend on individual dark matter content (J-factor)
  - Include statistical uncertainties from stellar kinematic data.
  - Fit backgrounds independently
- Joint likelihood function:

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN^f}{dE}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

$$L(D\,|\,\mathbf{p_m},\{\mathbf{p_k}\}) = \prod_k L_k^{\rm LAT}(D_k\,|\,\mathbf{p_m},\mathbf{p_k}) \times \frac{1}{\ln(10)J_k\sqrt{2\pi}\sigma_k}e^{-(\log_{10}(J_k)-\overline{\log_{10}(J_k)})^2/2\sigma_k^2}$$

Shared by all dwarfs (dark matter particle parameters)

Fit for each dwarf (background sources)

Uncertainty in J-factor

Combined Limits at 95%CL

4 years of LAT data

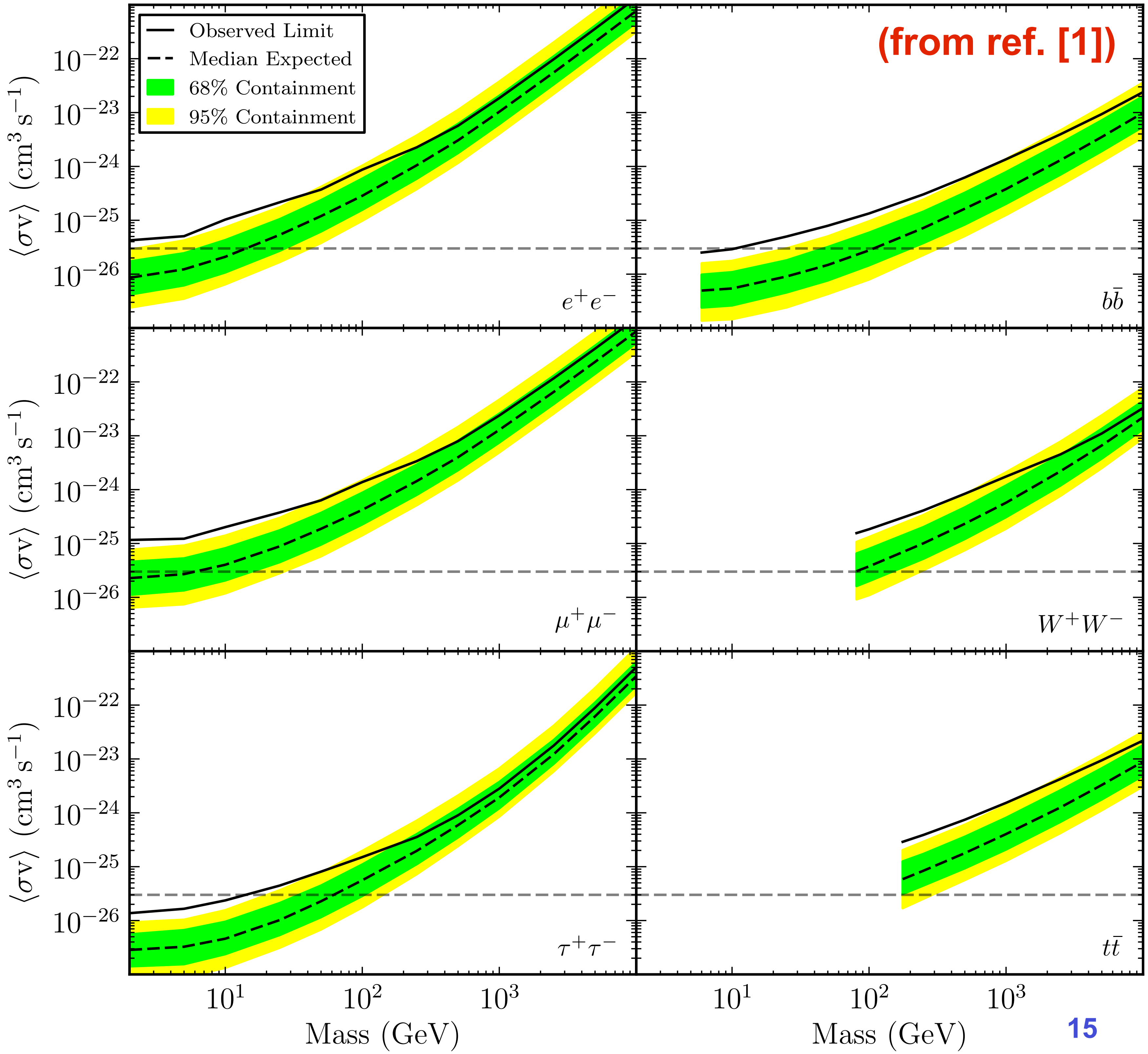
15 dwarf galaxies

Expected sensitivity calculated from 2000 sets of 15 realistic simulations

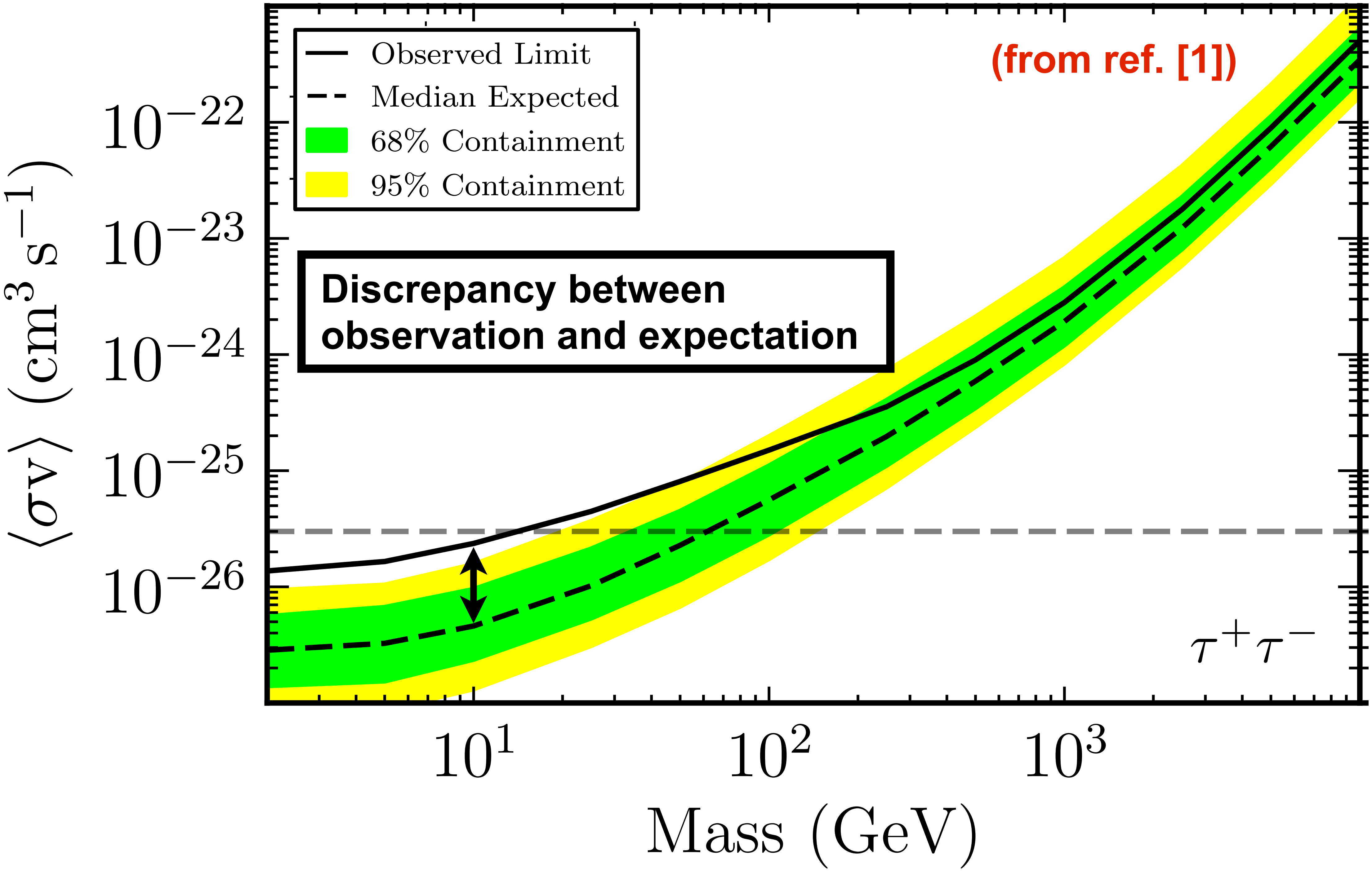
6 prototypical dark matter annihilation channels

Dark matter particle masses ranging from 2 GeV to 10 TeV (when kinematically allowed)

Simulations



Expected vs. Observed Limits



Combined Limits at 95%CL

Same observed limits

Expected sensitivity calculated from the data

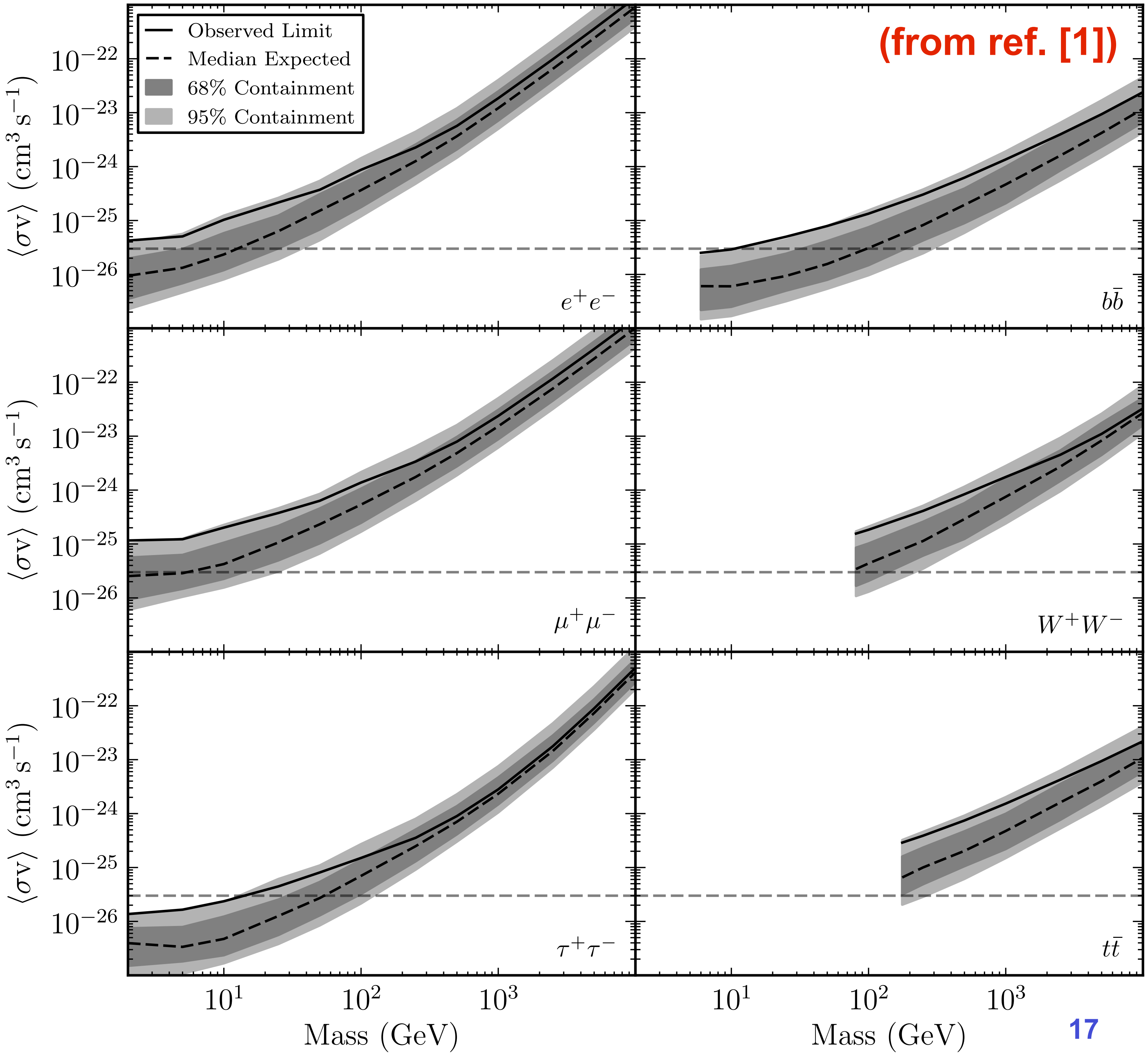
300 sets of 15 random sky locations

High-Galactic-latitude (|b|>20)

>1˚ from LAT catalog sources

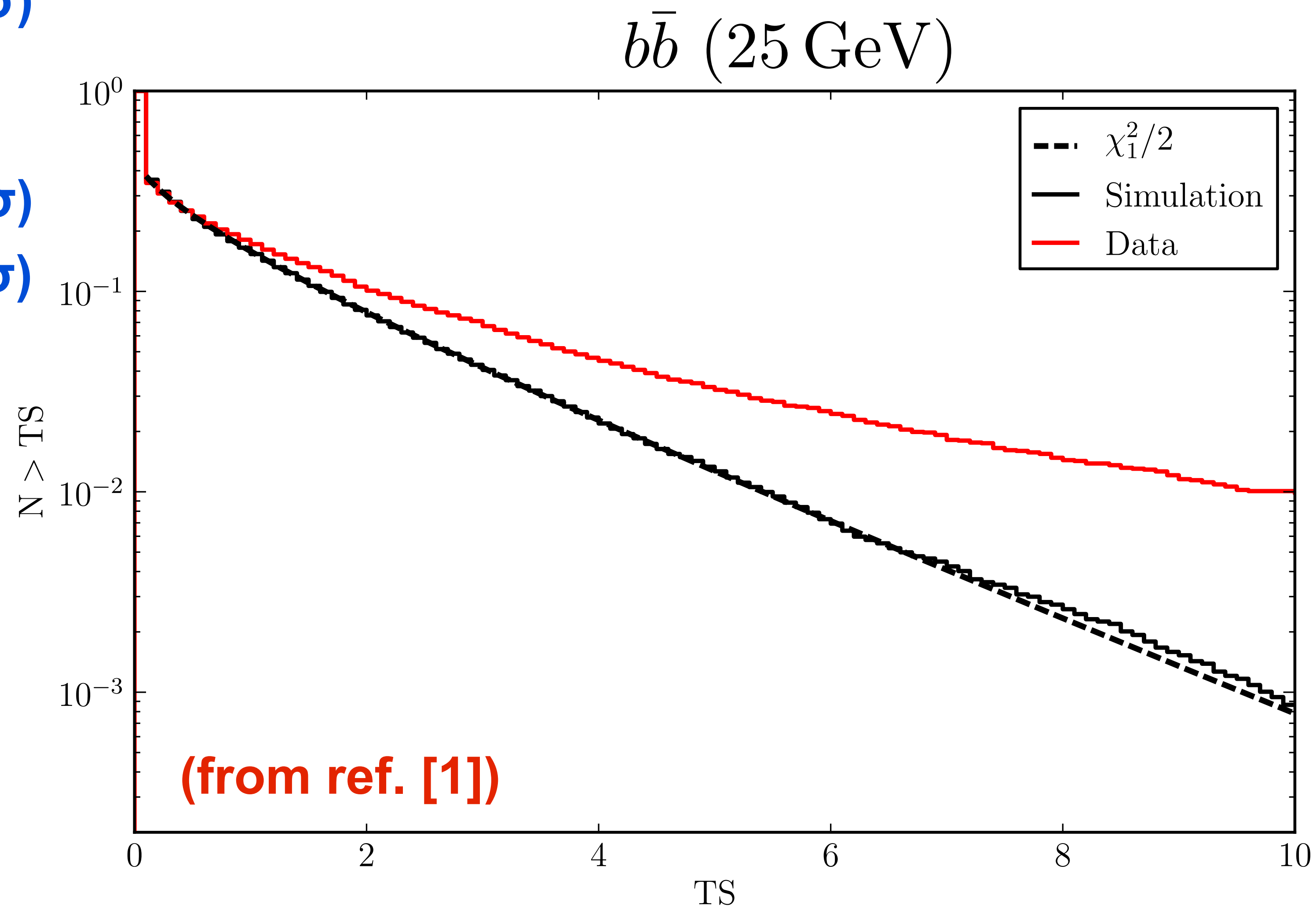
Reduces discrepancy between observations and expectations

Data



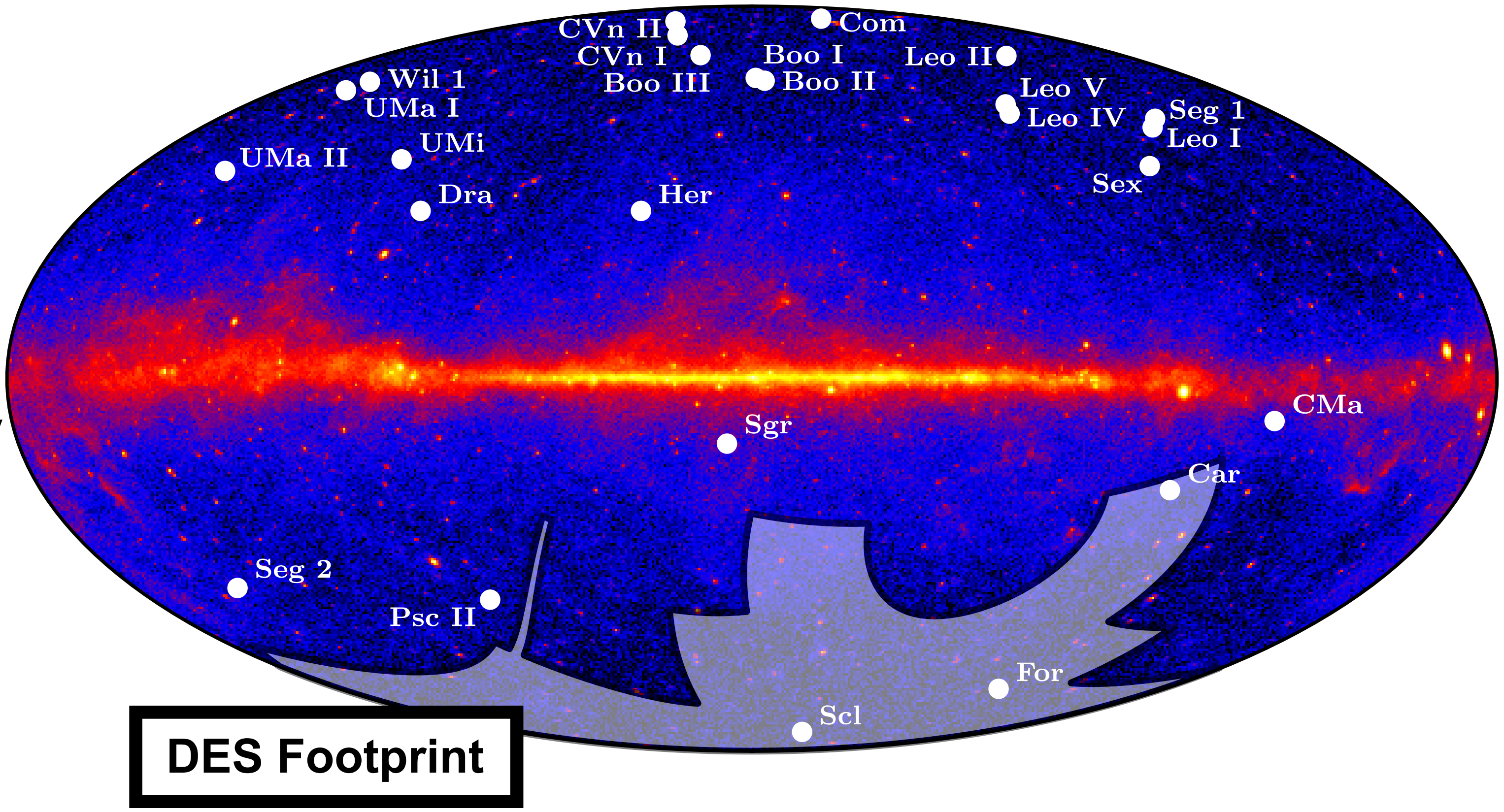
Statistical and Systematic Effects

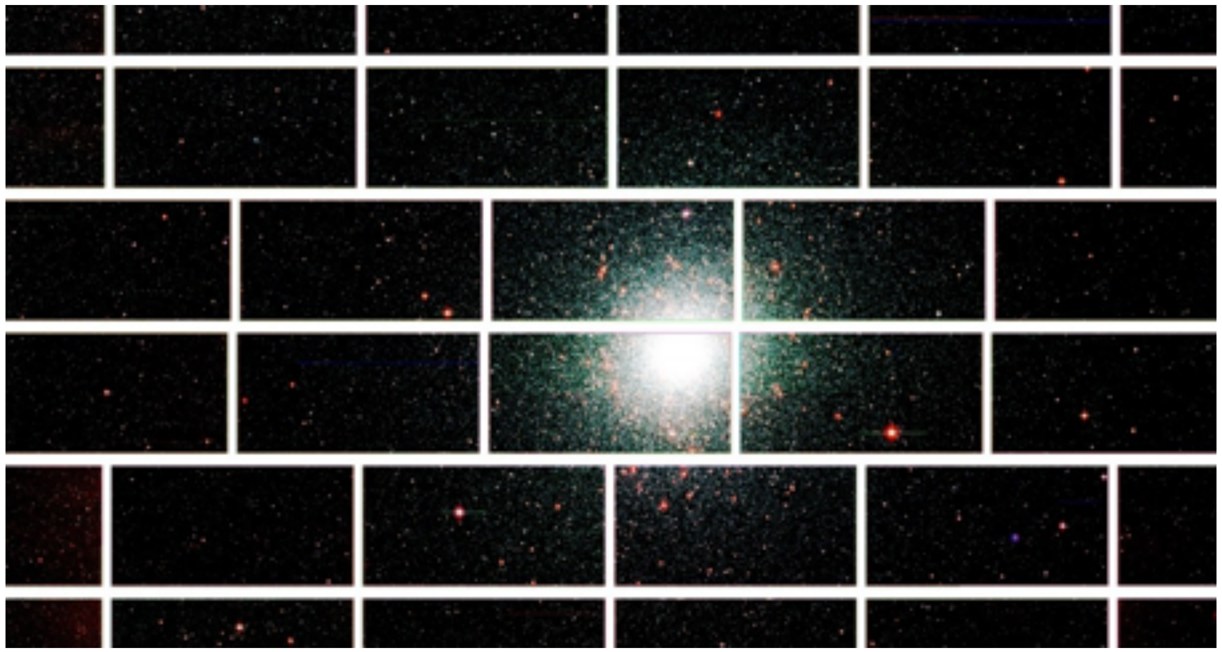
- **Distribution of TS values in the data does not follow asymptotic theorems**
- **Local significance:**
  - **Simulations: p-value = 1.6×10^{-3} (~2.9σ)**
- **Global significance:**
  - **Simulations: p-value = 2.4×10^{-2} (~2.0σ)**
  - **Data: p-value = 8.3×10^{-2} (~1.4σ)**
- **Confounding features of the data:**
  - **Unresolved background sources**
  - **Instrumental features**
  - **Imperfect modeling of the diffuse background**
- **Additional systematic uncertainties:**
  - **Instrument response (< 15%)**
  - **Diffuse backgrounds (< 10%)**
  - **Dark matter profile (< 20%)**



Finding More Dwarf Galaxies

- The number of known dSphs has doubled due to SDSS.
  - SDSS only covers ~25% of the sky
  - SDSS has a magnitude limit of ~22
- New wide-field surveys plan to greatly expand our coverage:
  - Pan-STARRS: ~75% of the sky from the north
  - Southern Sky Survey: ~75% of the sky from the south
  - DES: ~5000 deg^2 in the south (deeper)
  - LSST: ~50% of the sky (much deeper)
- Eventually hope to be complete for all bound dwarf galaxies ($L > 10^2 L_\odot$)
- Simulations predict hundreds of Milky Way satellite galaxies (ref. [4])



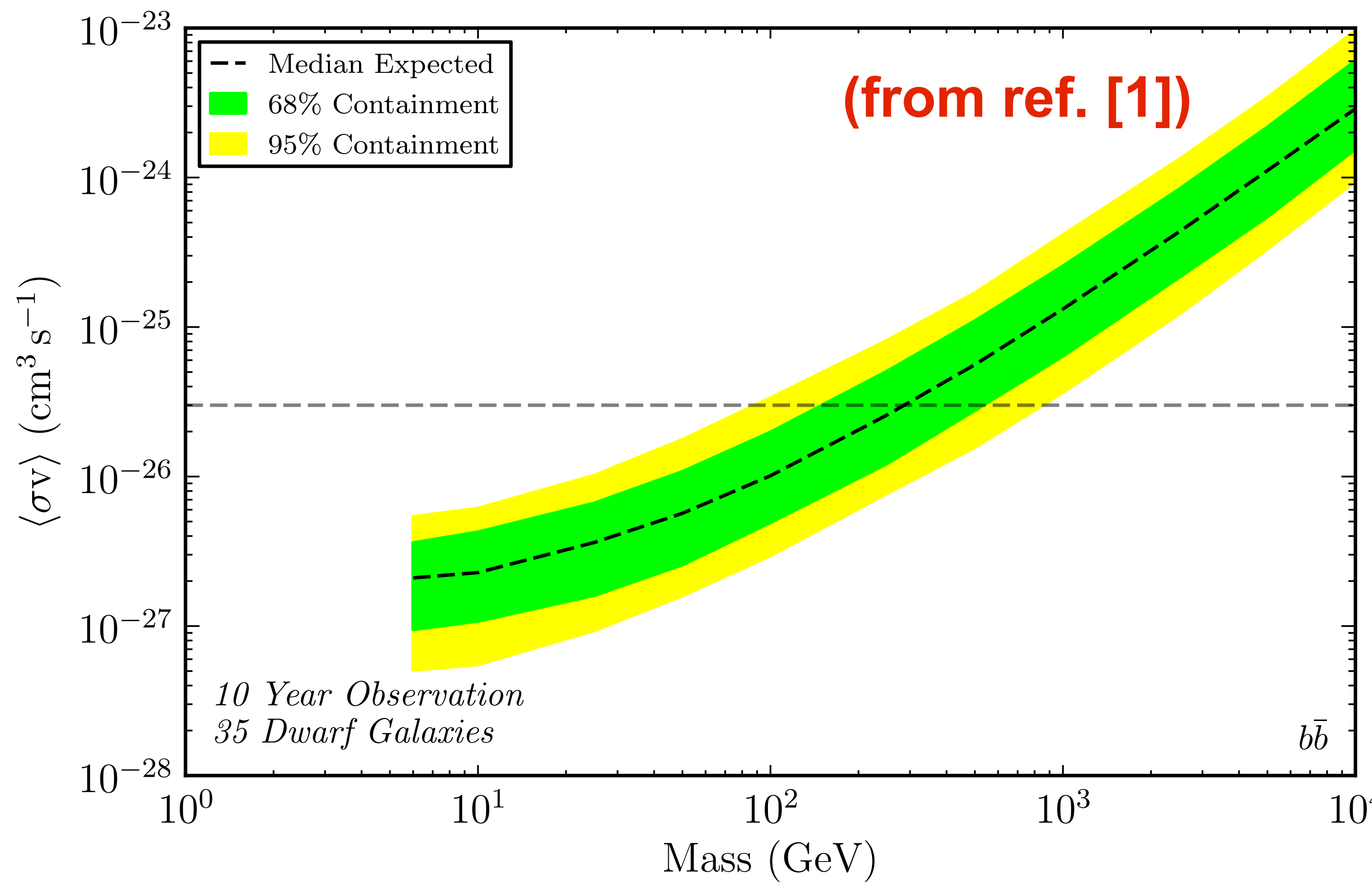


Globular Cluster 47 Tuc (DES Collaboration)

Finding More Dwarf Galaxies

- **Conservatively assume that upcoming surveys find 20 more dwarf galaxies.**
- **Assume that the characteristics of these new galaxies are similar to those recently discovered by SDSS.**
  - High Galactic Latitude
  - Comparable J-factors and uncertainties
- **Combine additional dwarfs with continued LAT operations.**
  - 10 years of LAT data taking
  - Current instrument performance
- **Expect sensitivity to the thermal relic cross section for dark matter particles with masses ~350 GeV**
- **Additional improvements to the LAT instrument...**

Only valid if systematics can be controlled

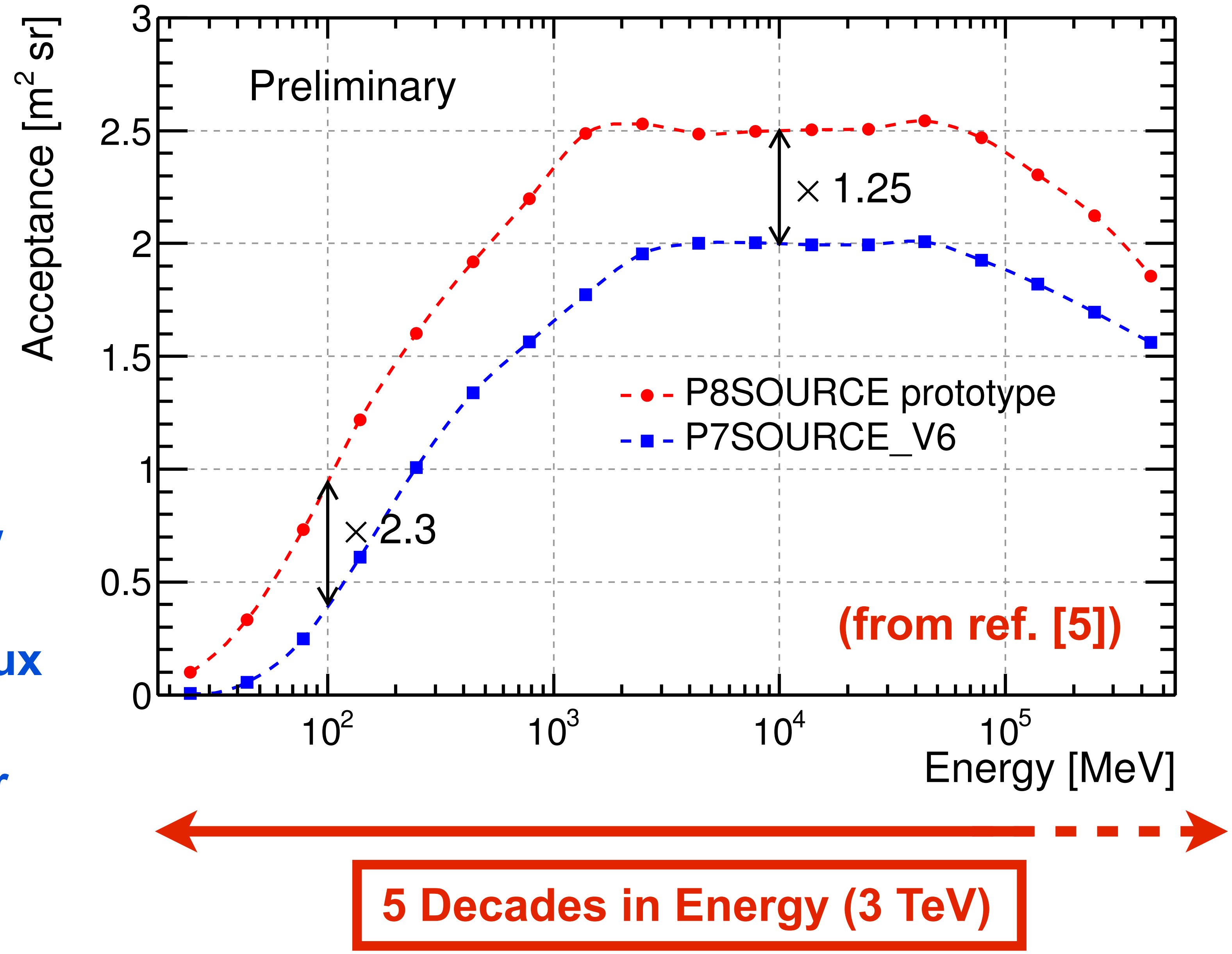


Doesn't include improvements to the LAT instrument

Pass8: Improved LAT Performance

- **Improvements to the LAT instrument performance:**
  - **Increased energy range**
  - **Increased effective area**
  - **Improved angular resolution**
  - **Better background rejection**
  - **New event classes**

- **Impacts for dark matter:**
  - **Energy Range <==> explore new high-mass parameter space**
  - **Effective Area <==> increased flux sensitivity**
  - **Angular Resolution <==> greater sensitivity to spatially extended sources**
  - **New Event Classes <==> check systematic effects in event selection**



References

1. Drlica-Wagner, A. “Searching for Dwarf Spheroidal Galaxies and other Galactic Dark Matter Substructures with the Fermi Large Area Telescope.” Stanford Ph.D. Thesis (2013)

2. Walker, M. et al. “Velocity Dispersions Profiles of Seven Dwarf Spheroidal Galaxies” Ap.J. 667:L53 (2007)

3. Martinez, G. et al. “Hierarchical Mass Modeling: An Improved Methodology to Robustly Determine Local Group Galaxy Properties.” In preparation, (2013)

4. Tollerud et al. “Hundreds of Milky Way satellites? Luminosity bias in the satellite luminosity function.” Ap.J. 668:227 (2008)

5. Atwood et al. “Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential” arXiv:1303.3514 (2012)