# Searching for Dark Matter Annihilation in Milky Way Satellite Galaxies

**Alex Drlica-Wagner**
**Fermilab**

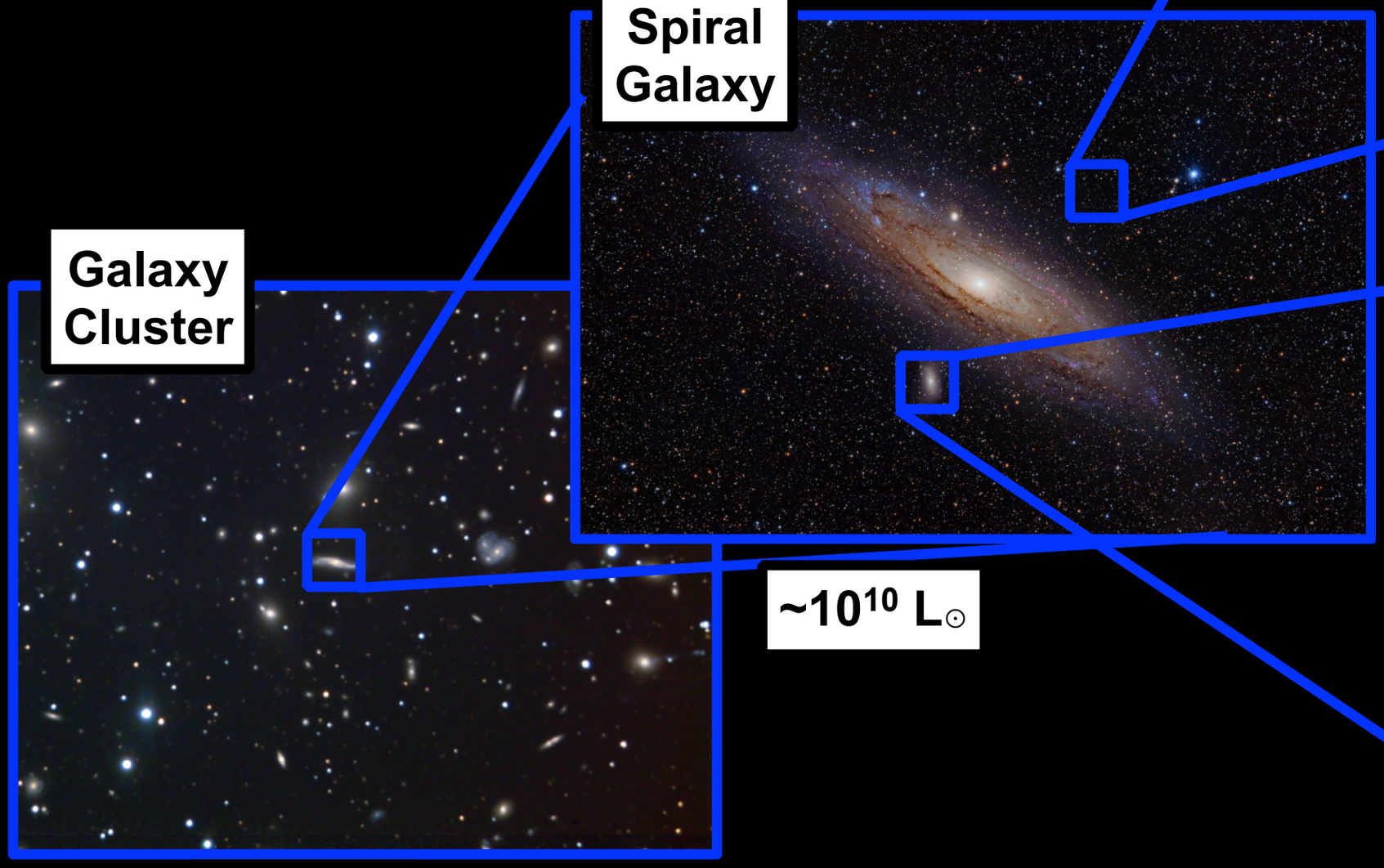
**TeVPA-2017**
**August 9, 2017**

THE DARK ENERGY SURVEY

**Fermi Gamma-Ray Space Telescope**

# Satellite Galaxies

CARTOON



# Milky Way Satellite Galaxies





**The Milky Way is surrounded by small satellite galaxies**

**Close to Earth ($10^5$ to $10^6$ ly)**

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

**Most dark matter dominated objects known**

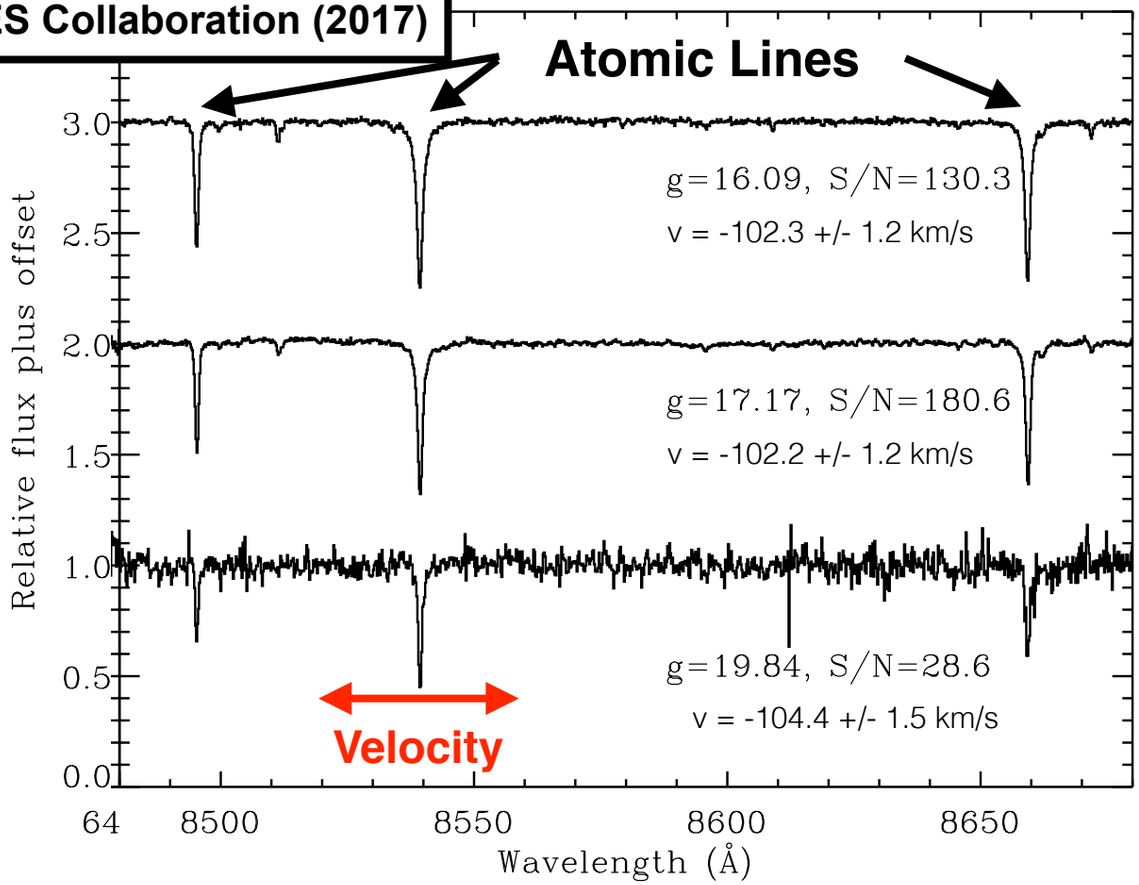
**Astrophysically simple**

30 kpc

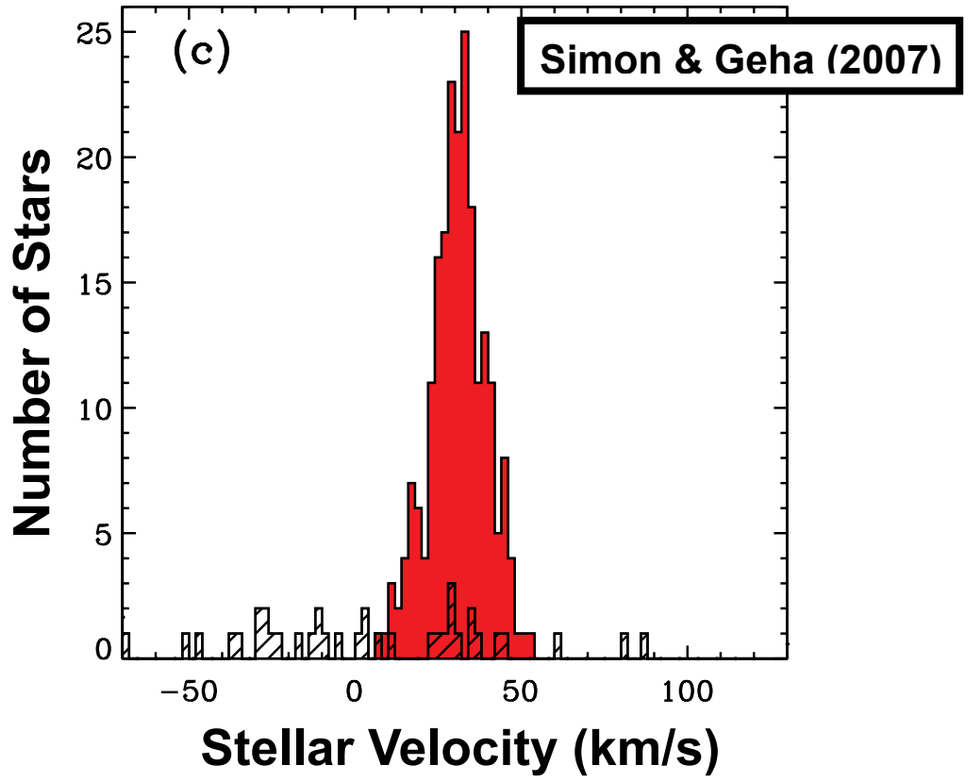
http://www.symmetrymagazine.org/article/our-galactic-neighborhood

# Dark Matter in Dwarf Galaxies

DES Collaboration (2017)



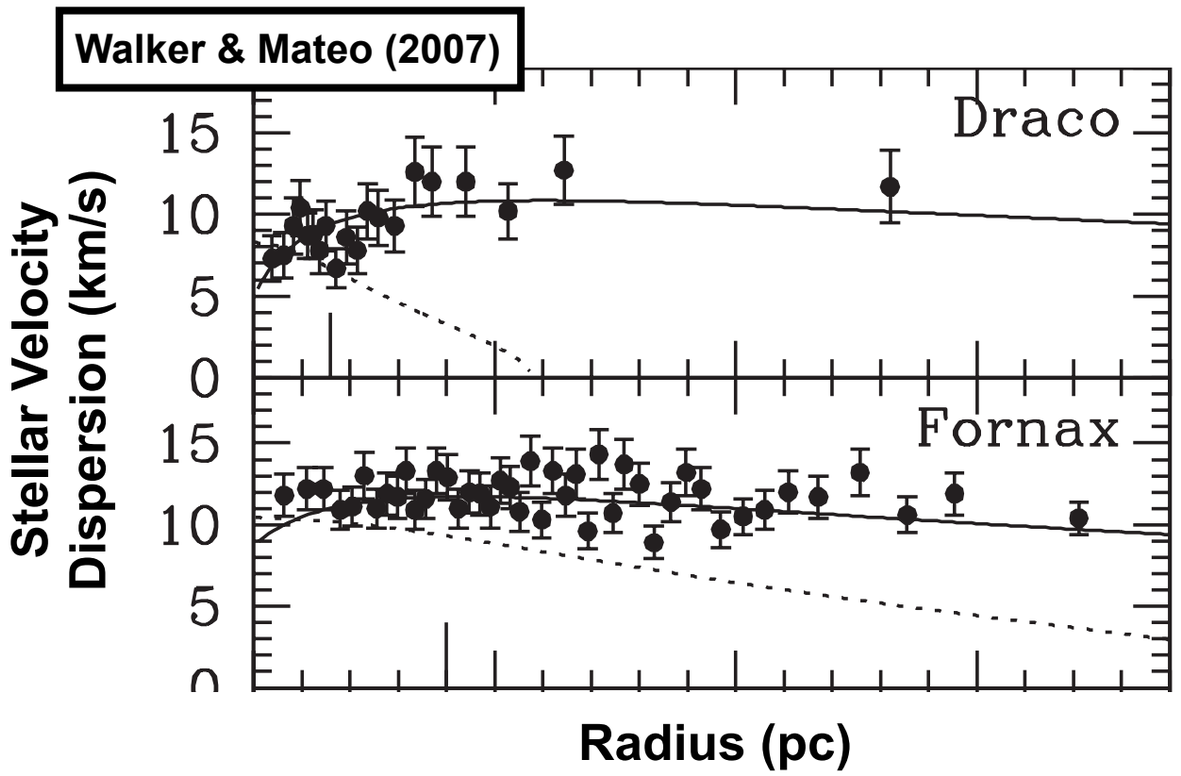

Simon & Geha (2007)



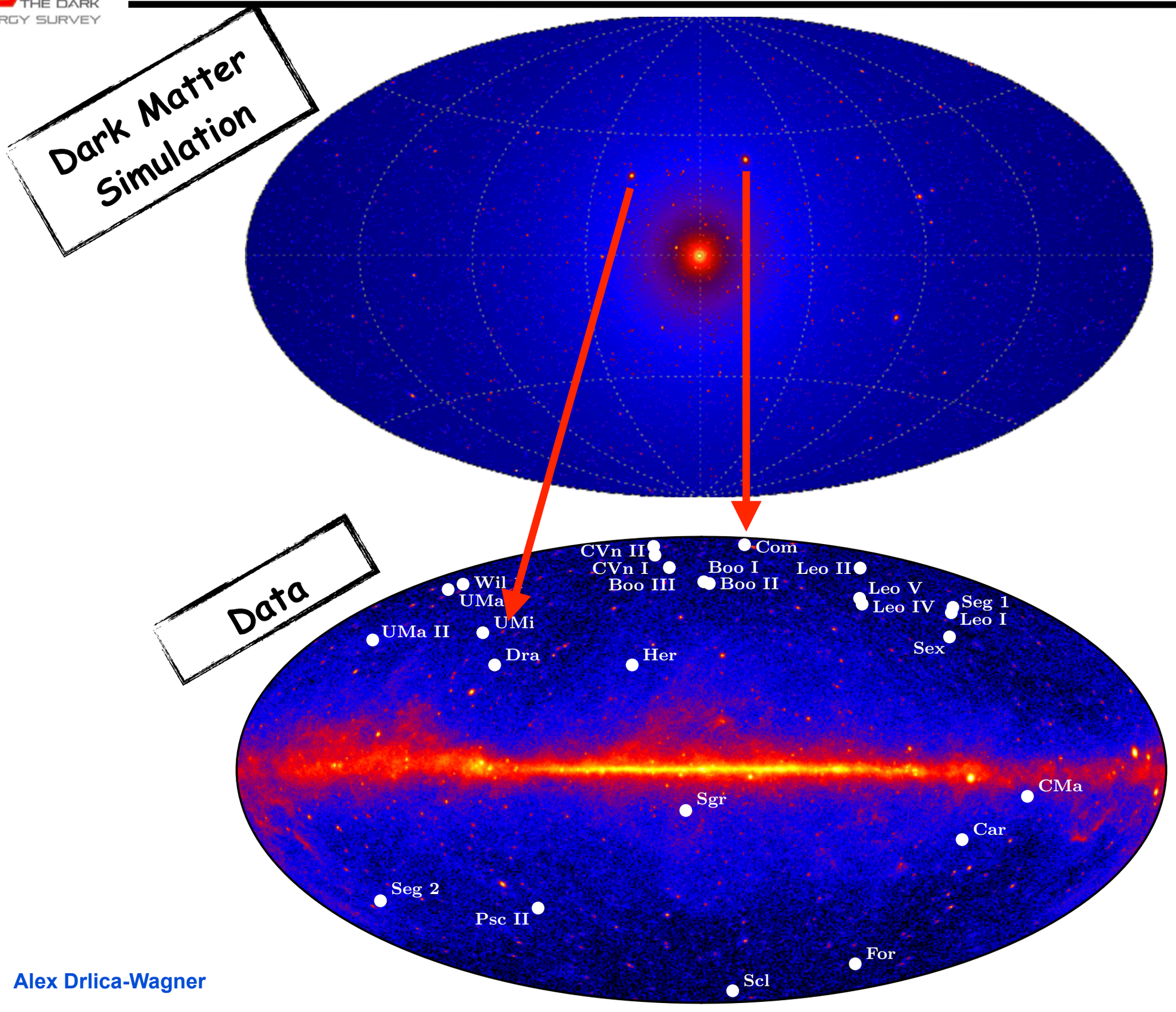

**Doppler shifts of atomic lines provide precise radial velocity measurements for stars**

**"Goldilocks" systems: enough stars to trace the gravitational potential, but not enough to alter it**

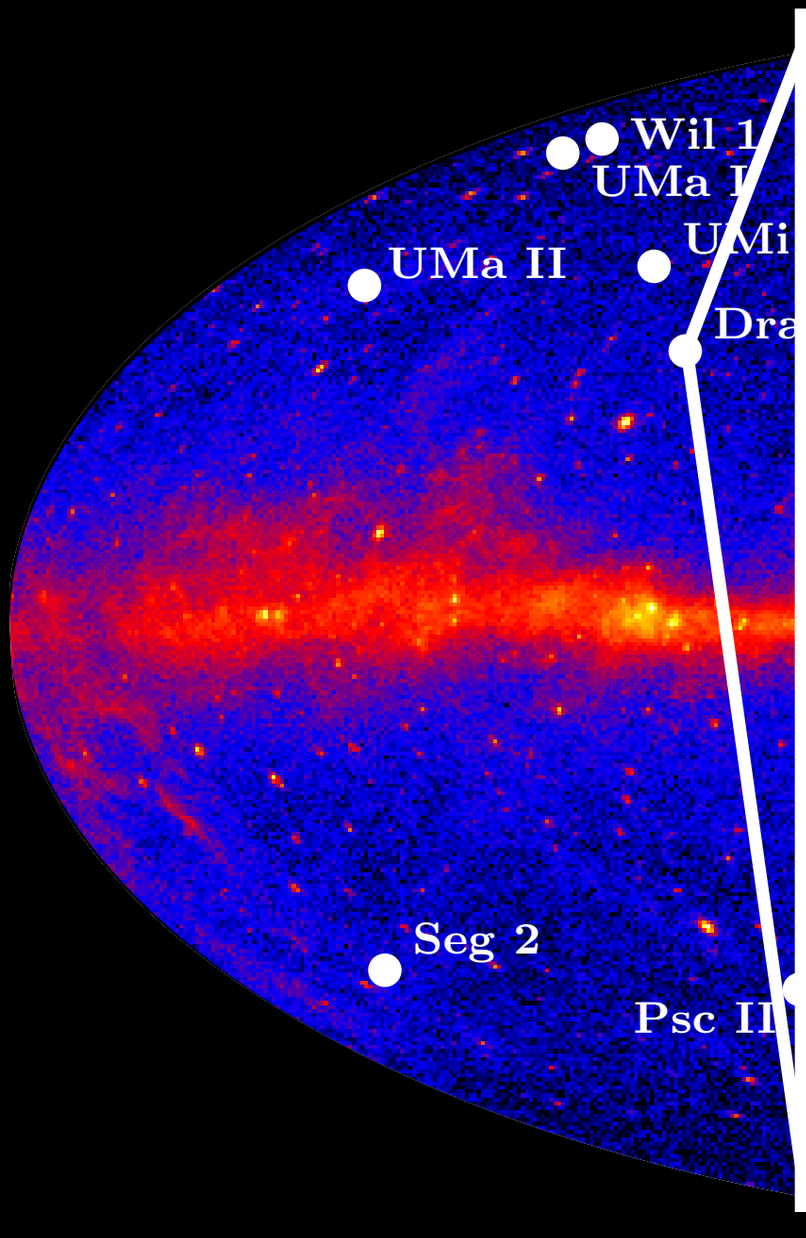
Walker & Mateo (2007)



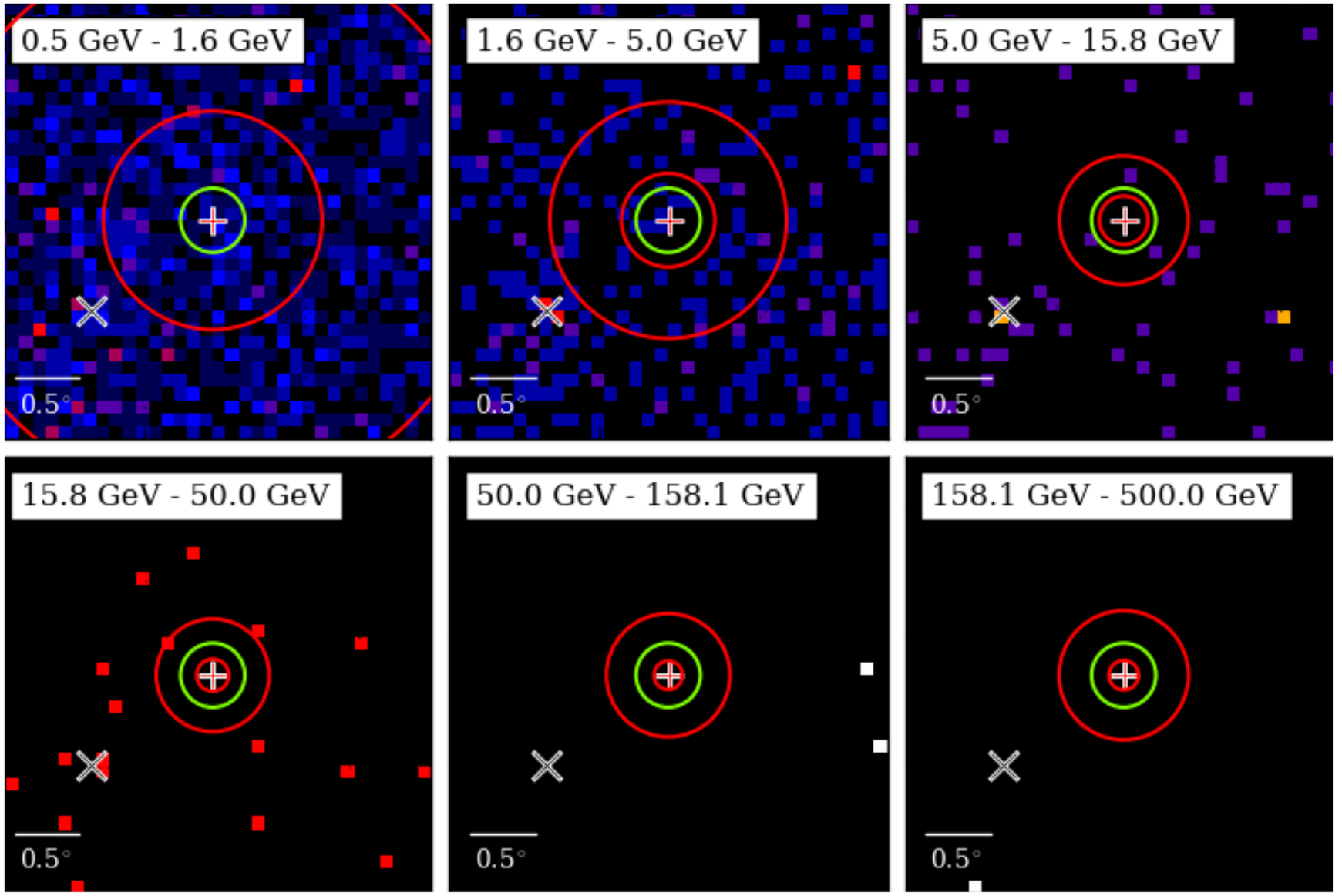
# Milky Way Satellite Galaxies



# Milky Way Satellite Galaxies



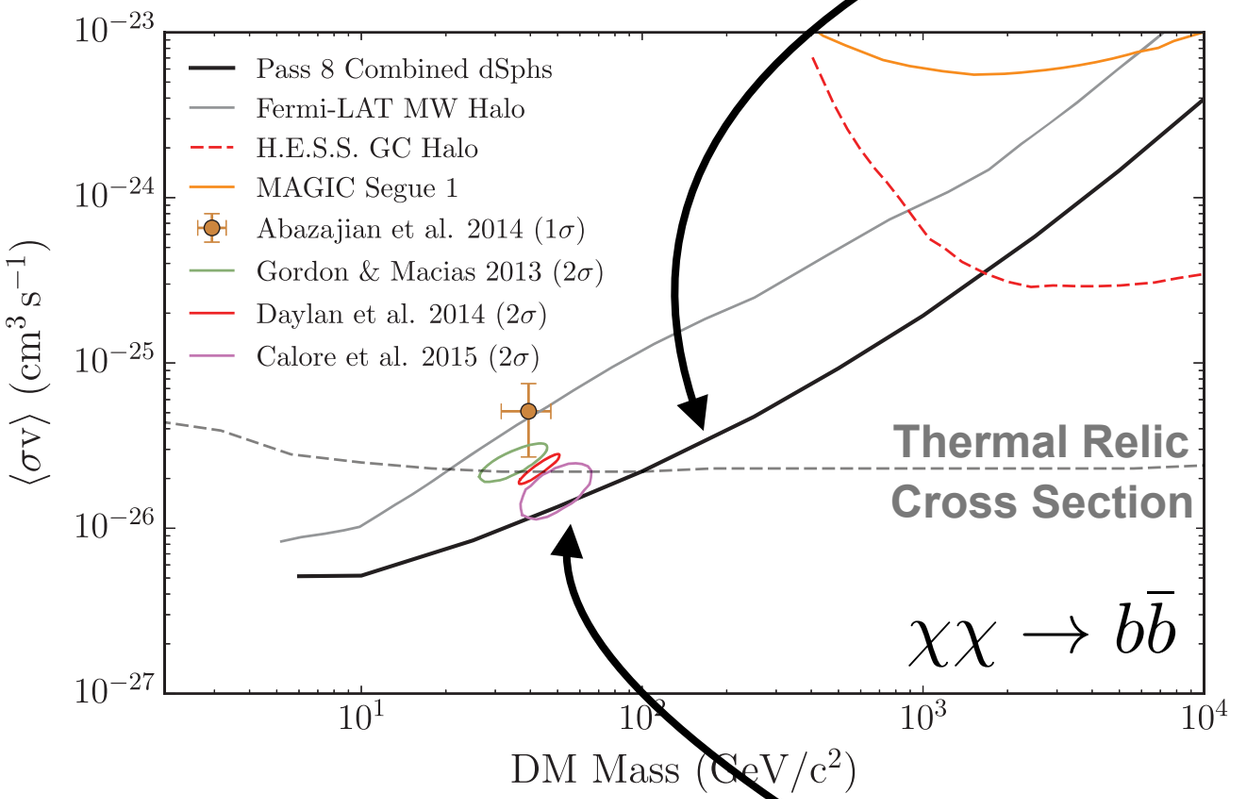

**Draco Dwarf Galaxy (0.5 GeV < Eγ < 500 GeV)**

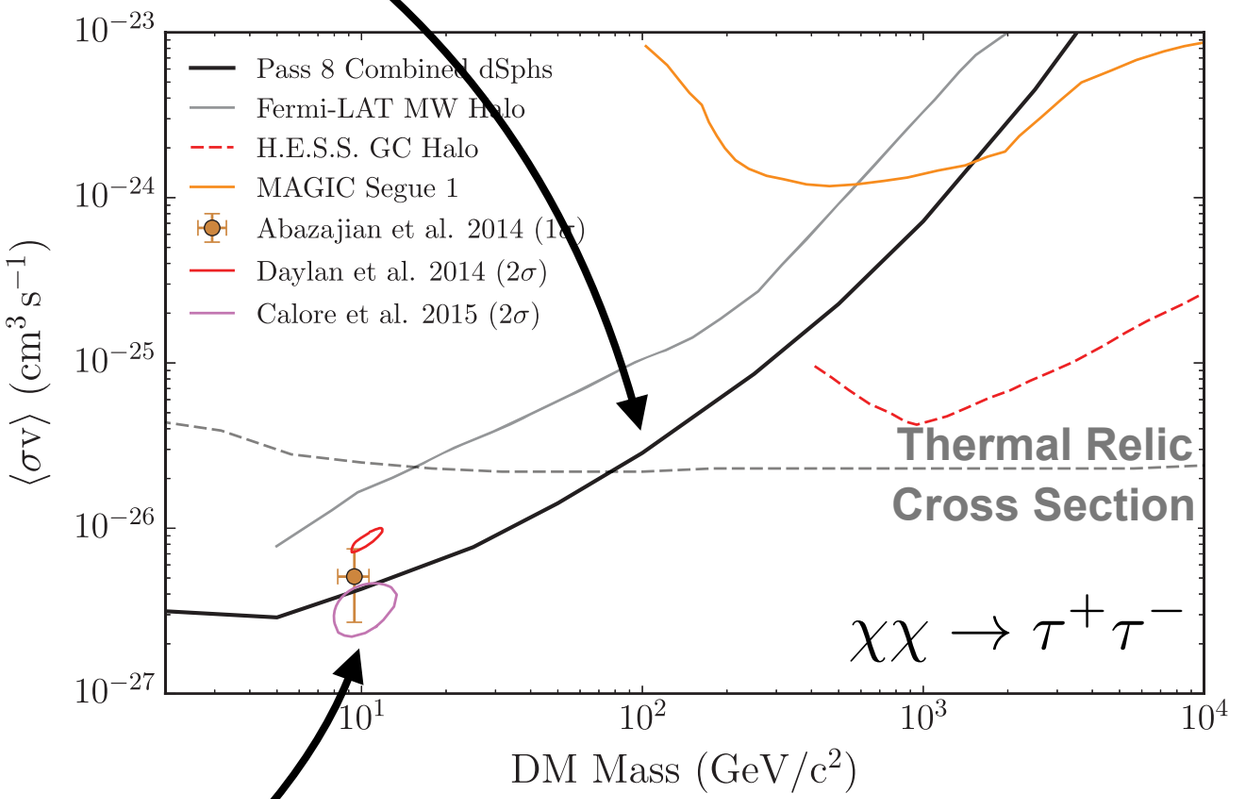



— Dark Matter Halo Size
— LAT Resolution (68%/95%)

# Dwarf Galaxy Constraints

**95% CL upper limits from combined observation of 15 dwarf galaxies**




**Dark matter interpretations of the Galactic Center excess**

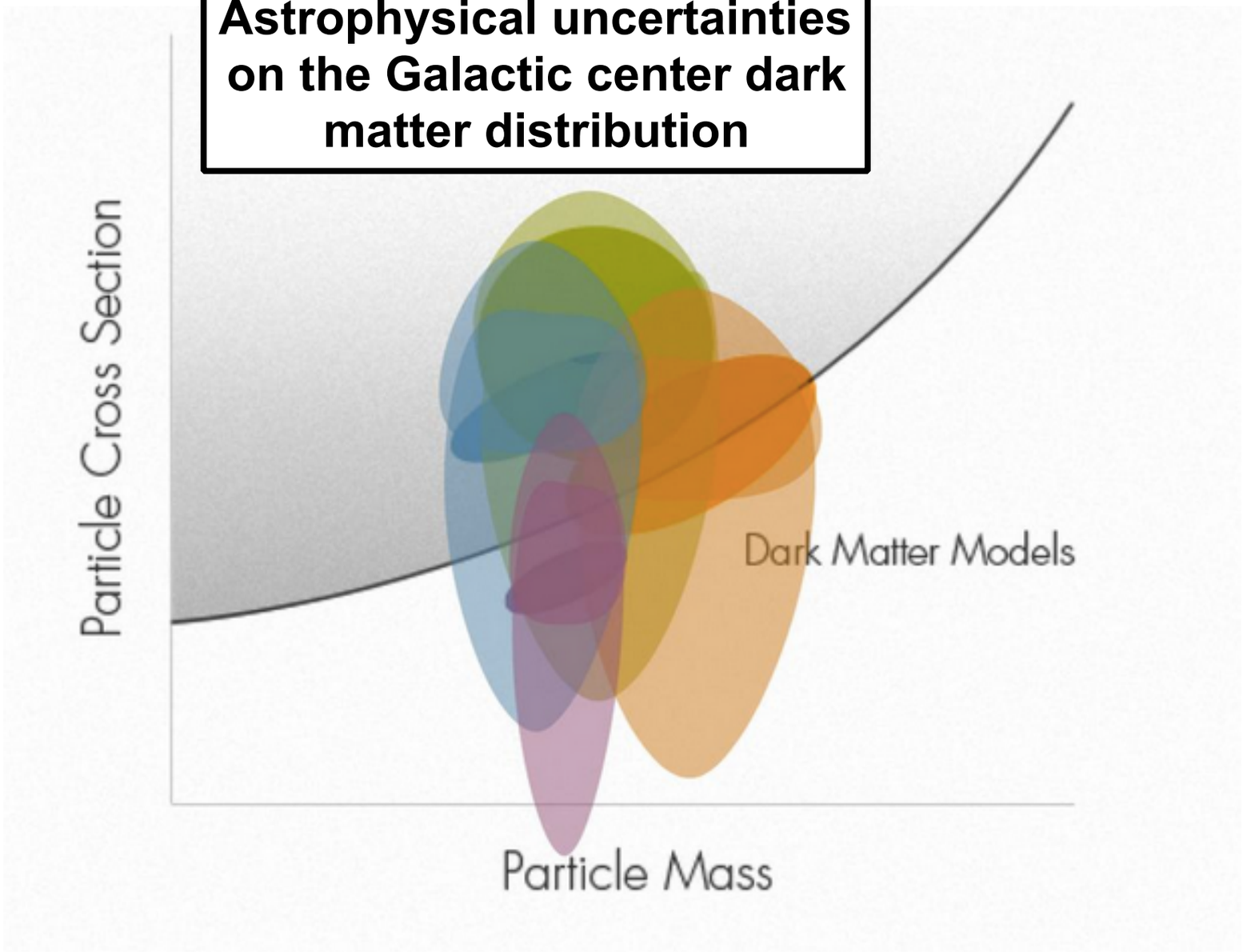


LAT Collaboration PRL 115, 231301 (2015)

# Galactic Center Comparison

CARTOON

**Astrophysical uncertainties on the Galactic center dark matter distribution**

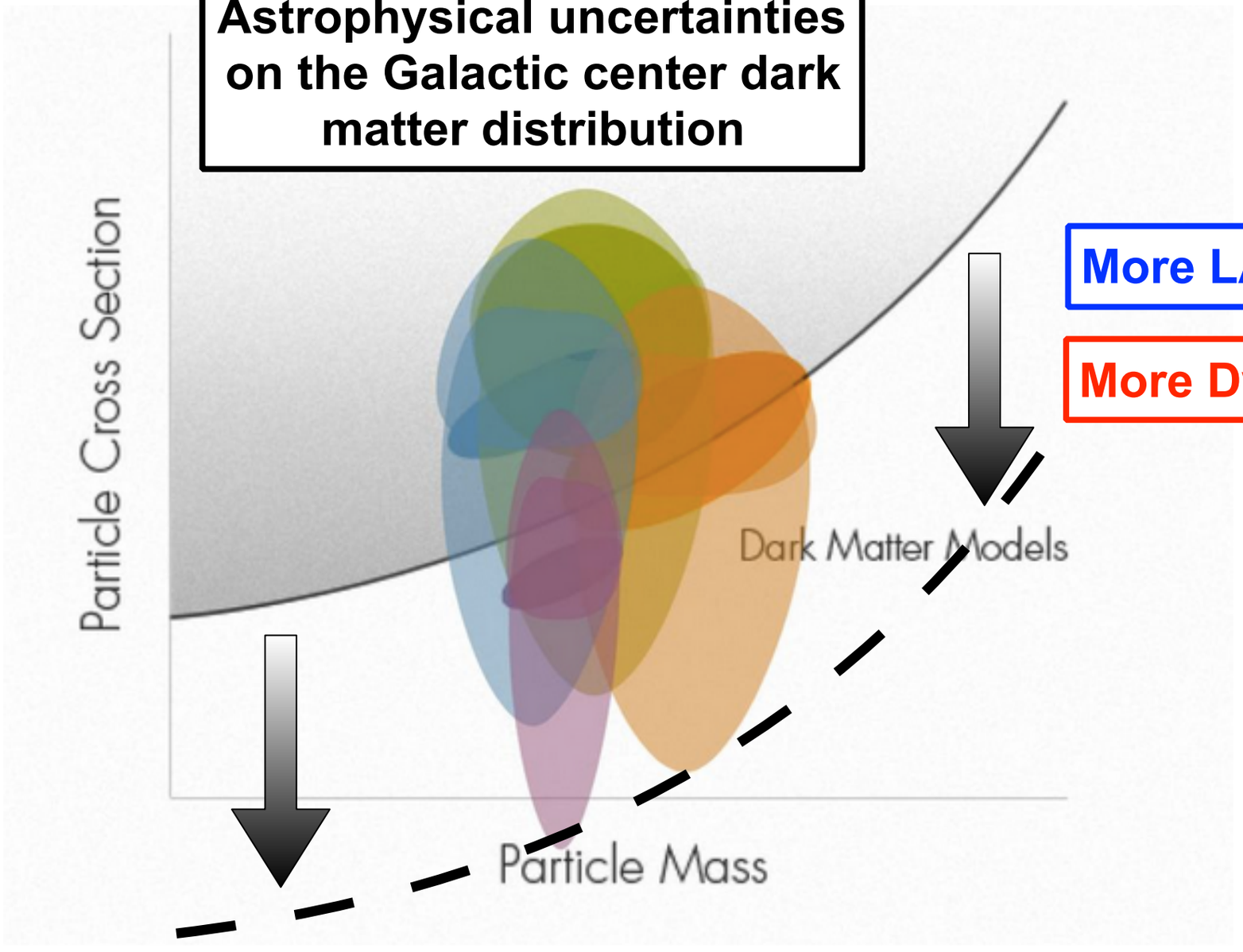



Quanta Magazine & Kev Abazajian

# Galactic Center Comparison

CARTOON

**Astrophysical uncertainties on the Galactic center dark matter distribution**

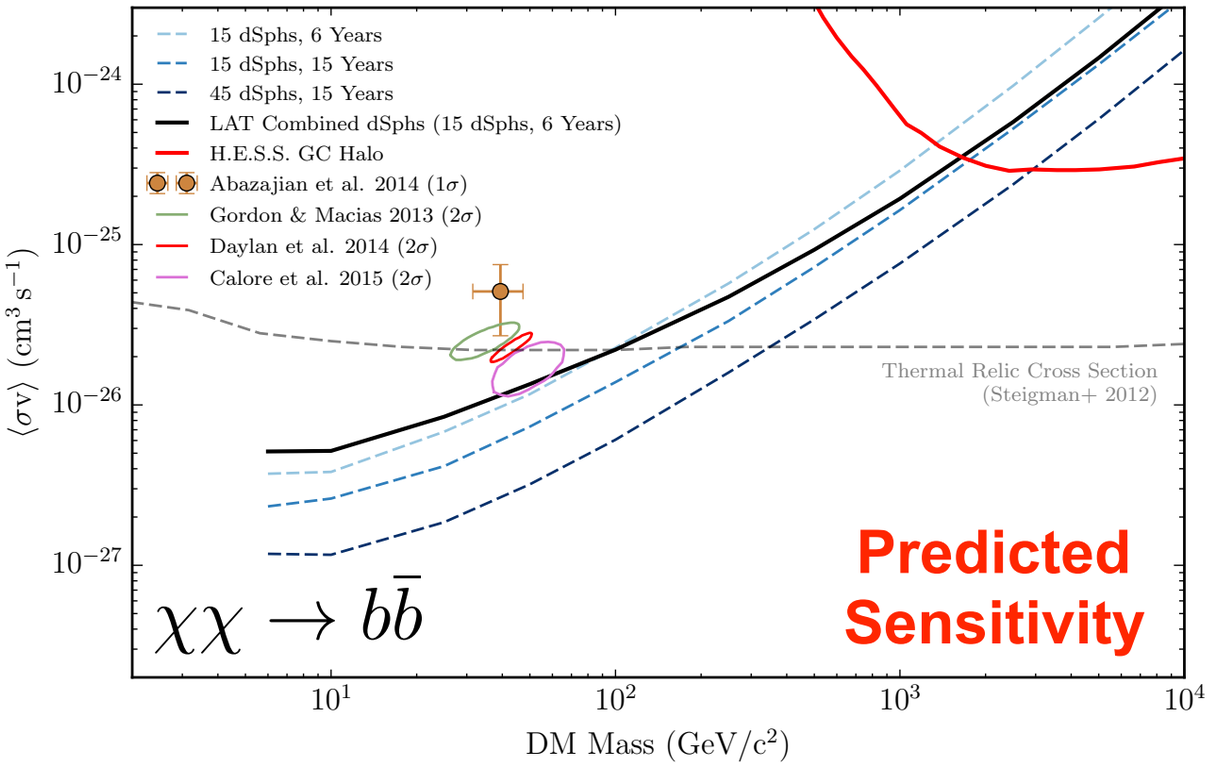


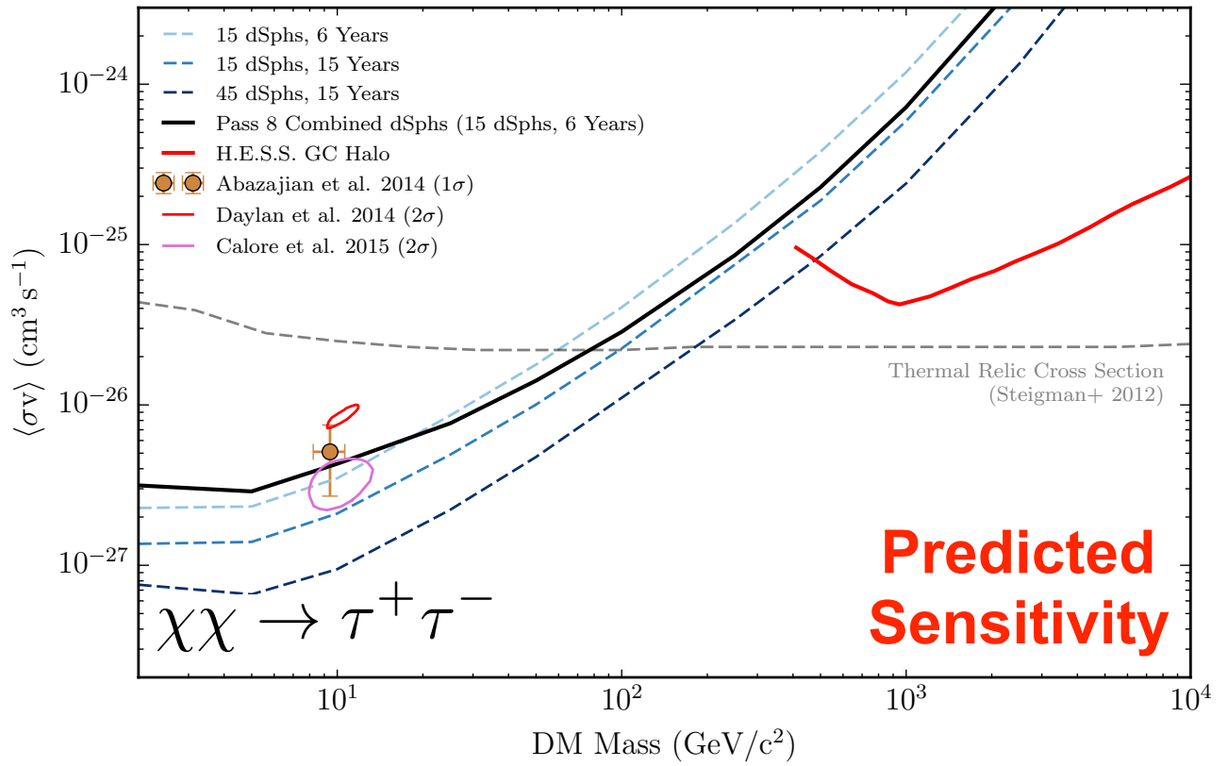

**More LAT Data**

**More Dwarf Galaxies**

**Quanta Magazine & Kev Abazajian**

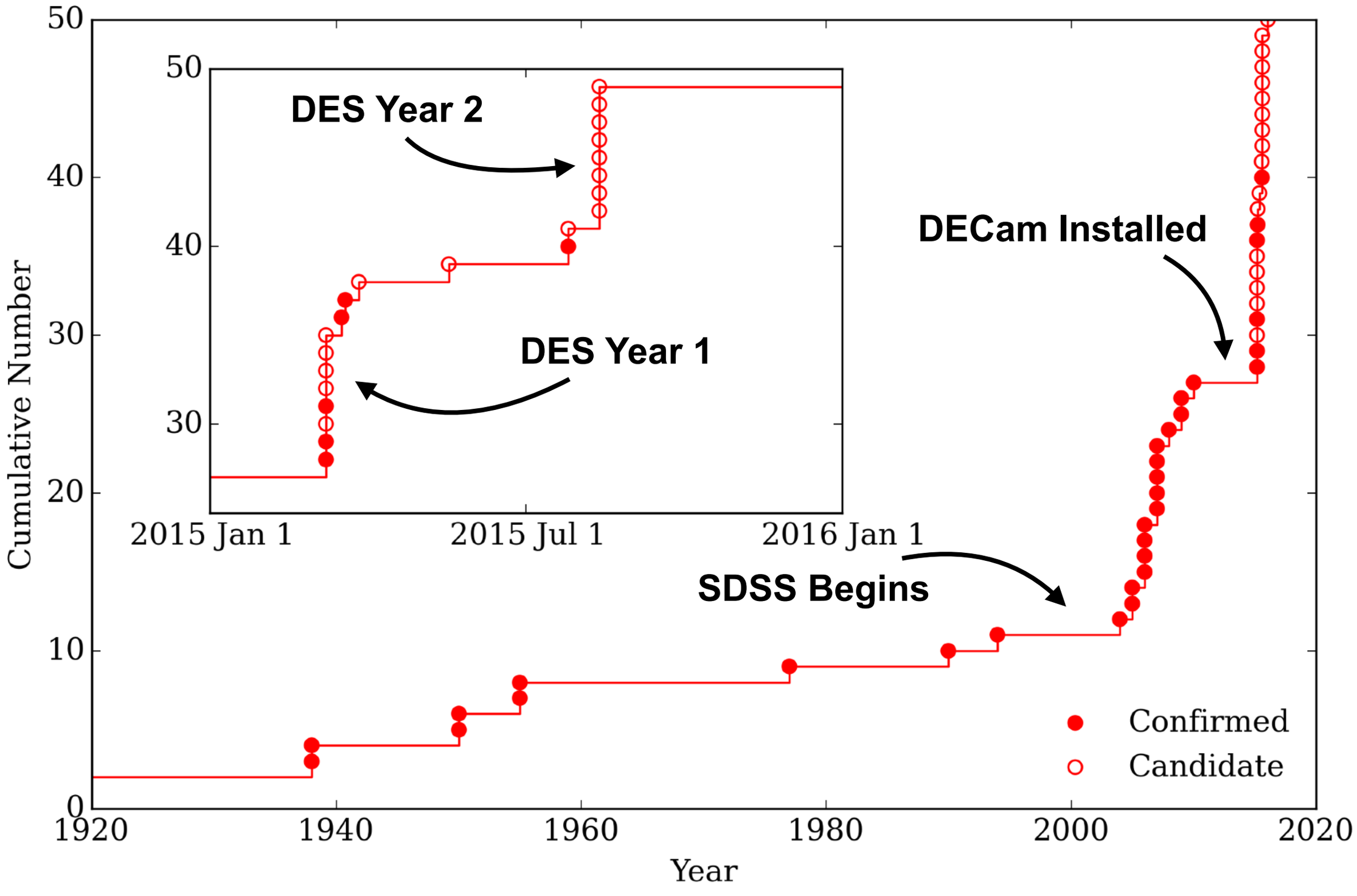
# Looking Forward



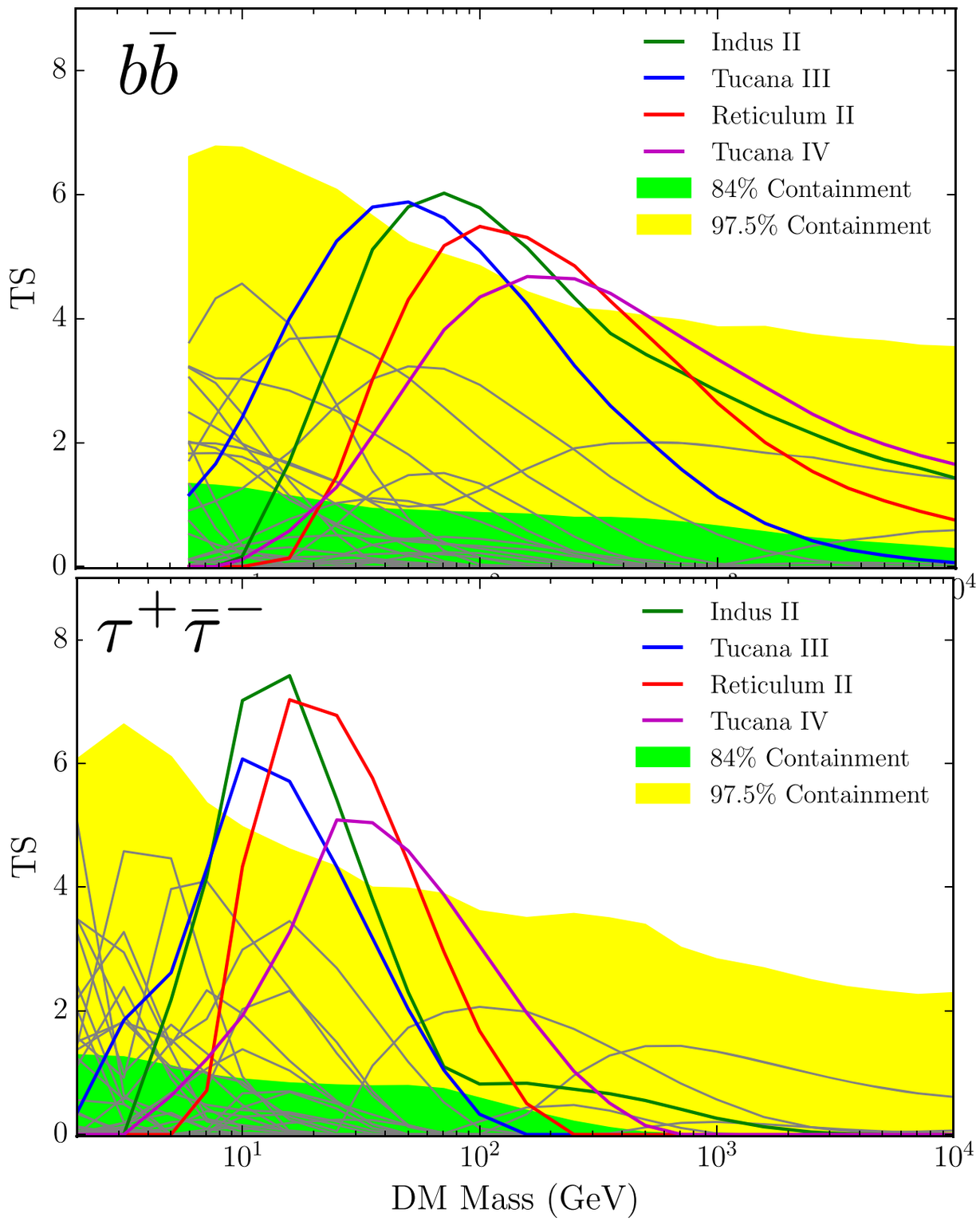




LAT Collaboration, Phys. Rep. 636, 1 (2016)

# Dwarf Galaxy Discovery Timeline



# Gamma-ray Observations




**Analyze 45 candidate and confirmed dwarf galaxies**

**Test for excess gamma-ray emission coincident with each individual target**

**Test Statistic:**

$$\mathrm{TS} = -2\Delta \log \mathcal{L}$$

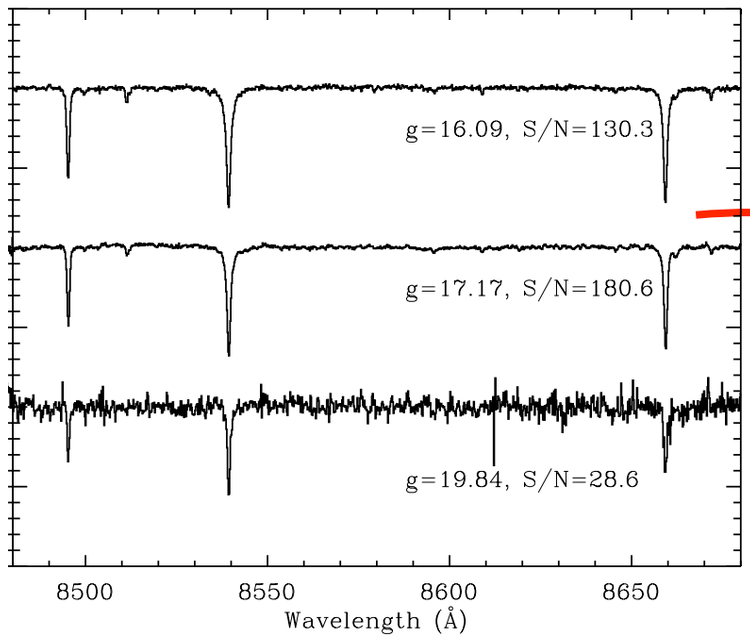
- **Find 4 targets with ~2σ local significance excesses**
- **Significance drops to ~1.6σ with a trials factor for mass and channel**
- **<< 1σ after including a trials factor from searching 45 locations**

**But dwarfs should not be weighted equally (i.e., different J-factors)…**



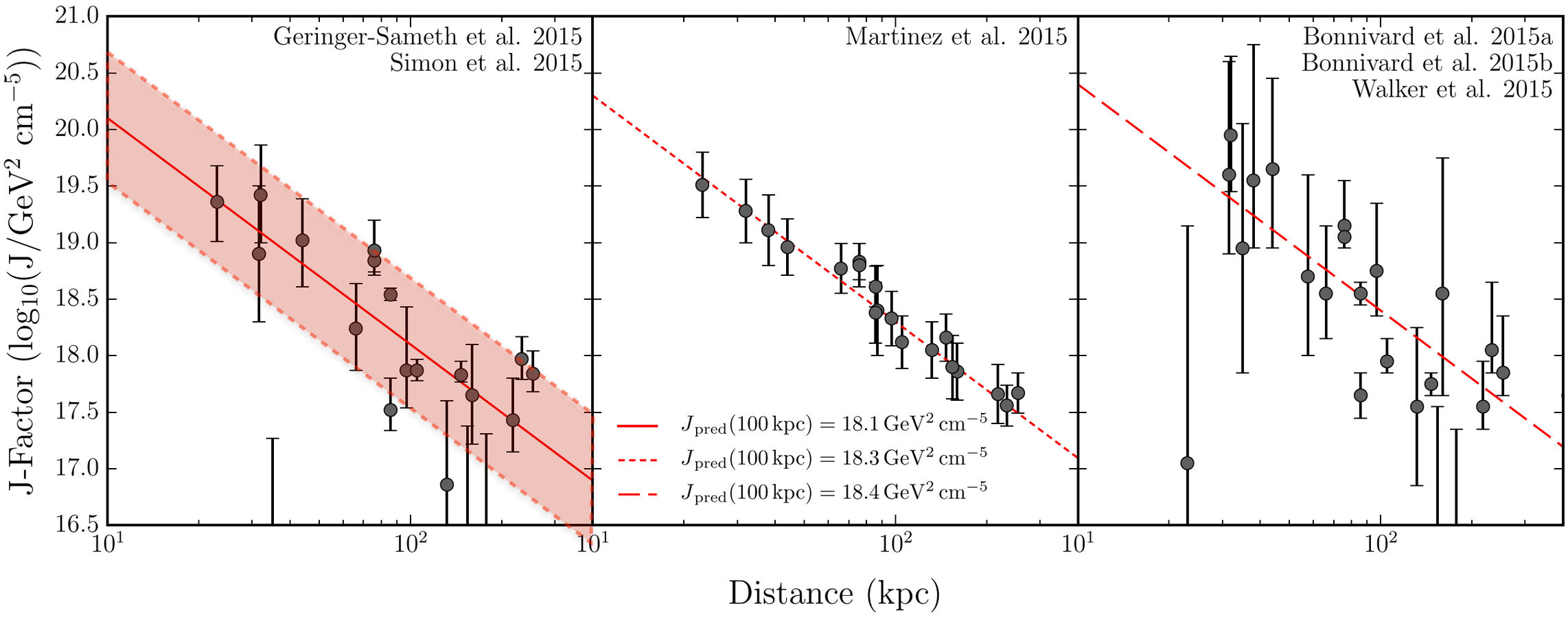
LAT & DES Collaborations, ApJ 834, 110 (2017)

# Discovery Timeline




**Several nights (+ bad weather!)**

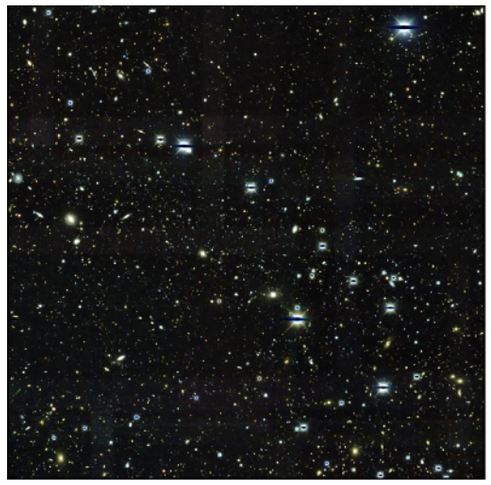
# Predicted J-factors

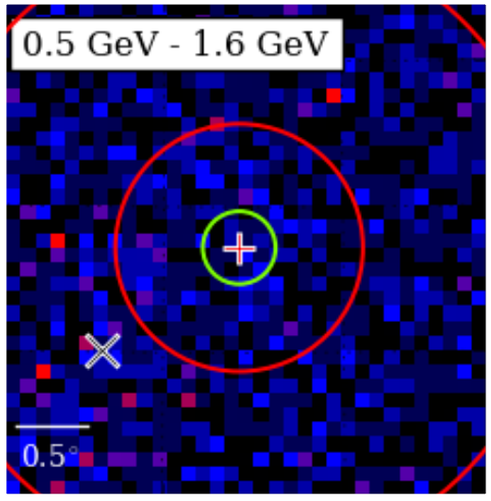



**Spectroscopic follow-up on ultra-faint dwarfs is difficult and expensive.**

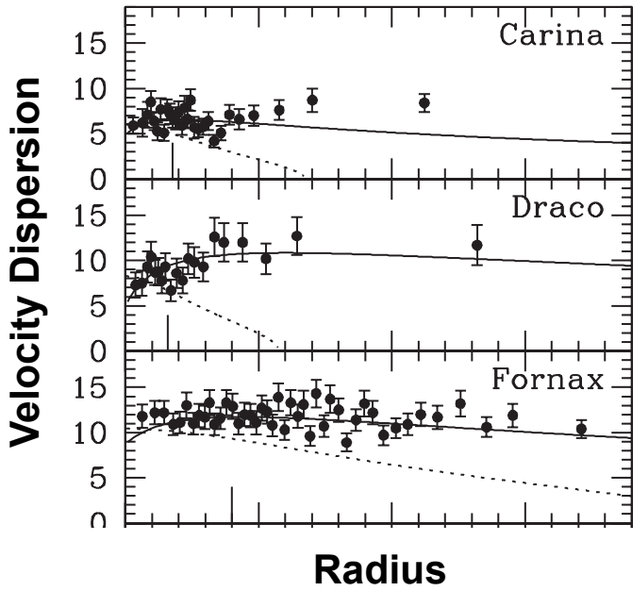
**J-factors can be estimated based on distance under the assumption that they are dark matter dominated.**

# Search for Gamma Rays



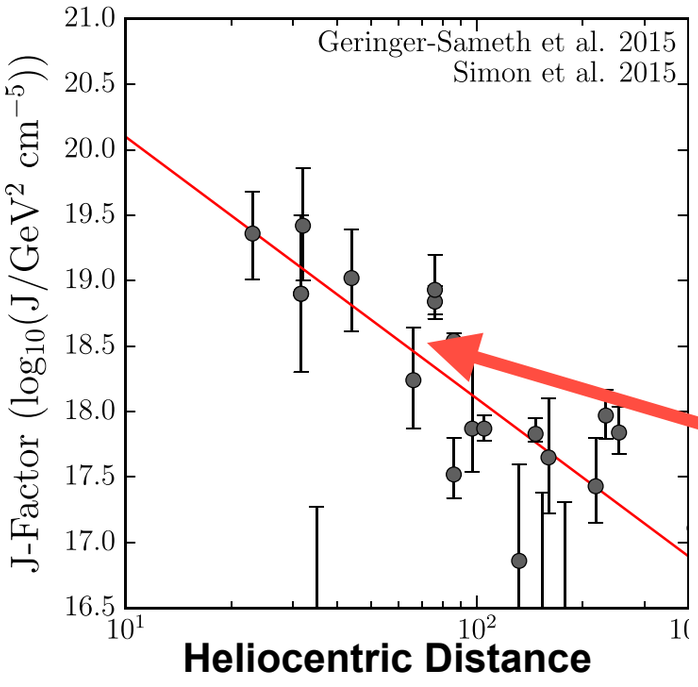


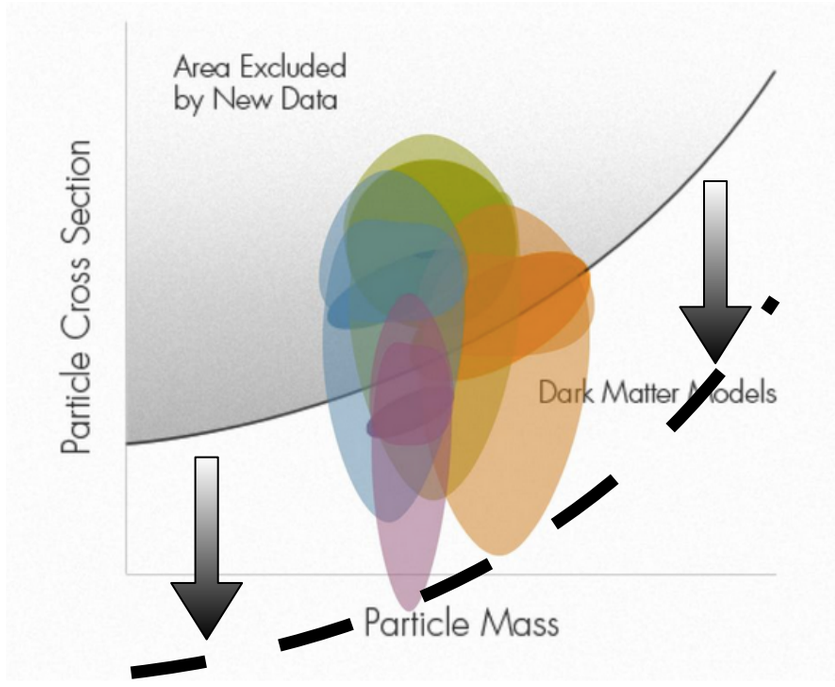

Walker et al. (2007)




**What we want…**

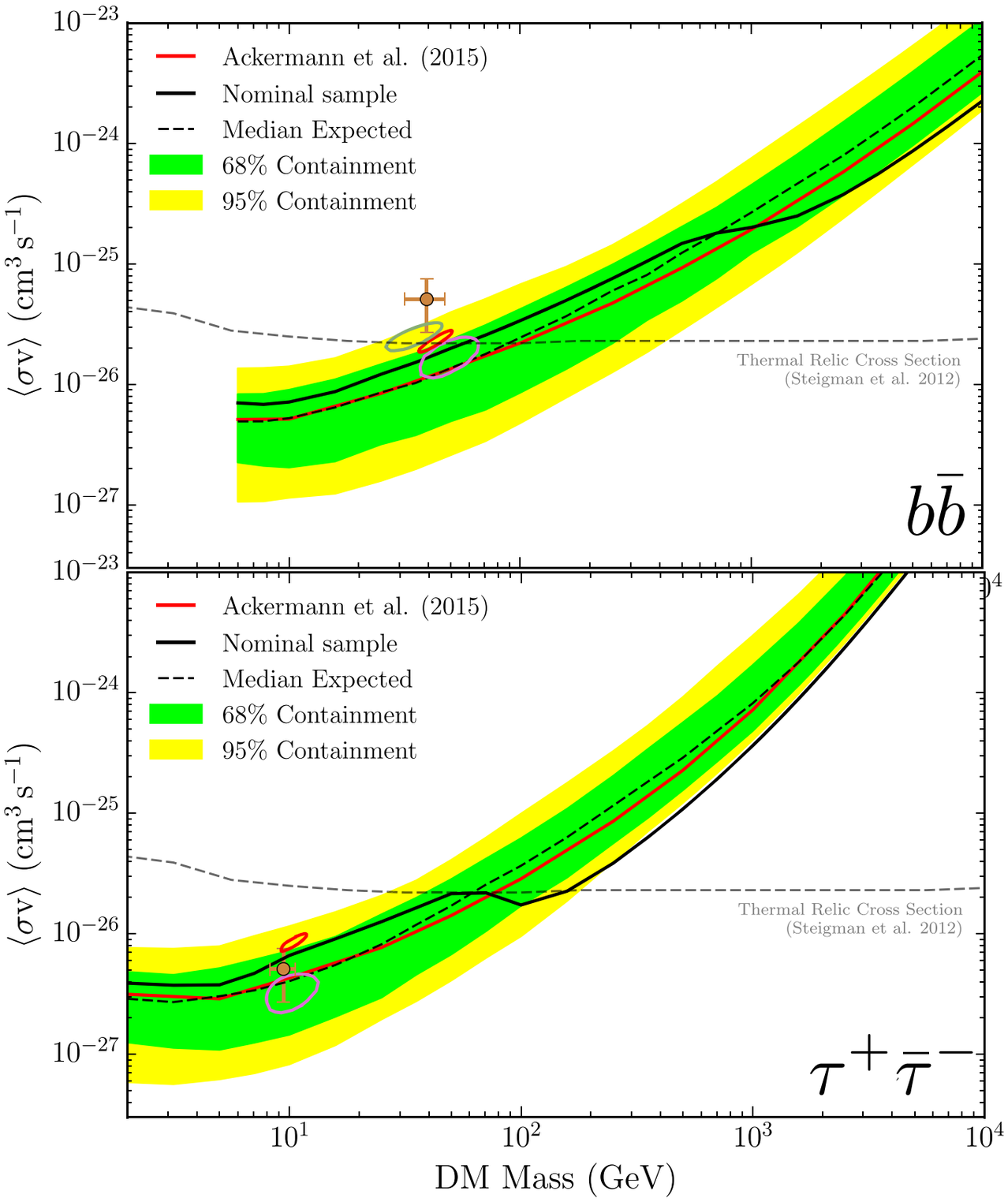
**DM Content**




**What we have…**

# Gamma-ray Observations




**Analyze 45 candidate and confirmed dwarf galaxies**

**Combine gamma-ray data weighted by expected/observed J-factor**

**Incorporate measurement uncertainty for targets with measured J-factors**

**Assume an uncertainty of 0.6 dex for targets without measured J-factors**

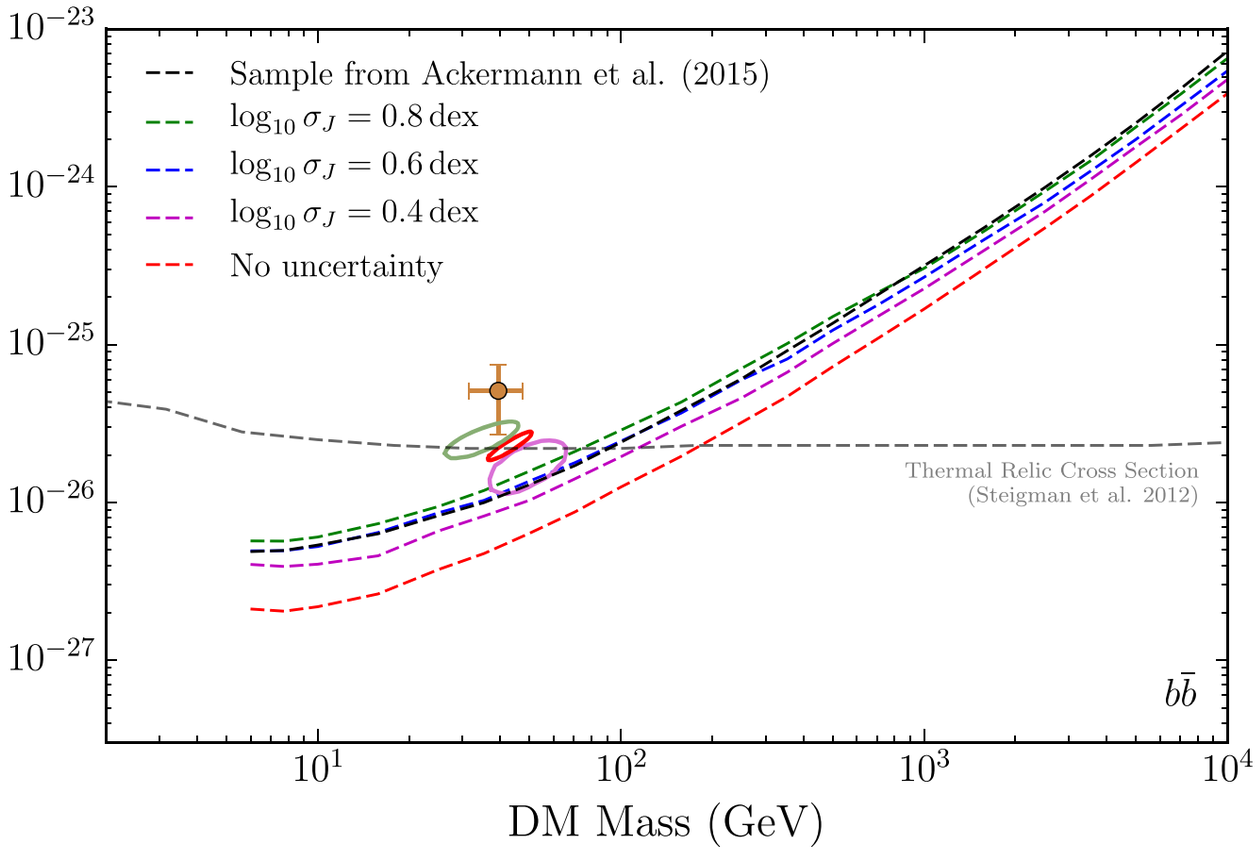
**Global significance ~1σ, accounting for mass and channel**

**This result should be thought of as "an informed estimate" until we have measured J-factors for all targets**



LAT & DES Collaborations, ApJ 834, 110 (2017)

# J-factor Uncertainties

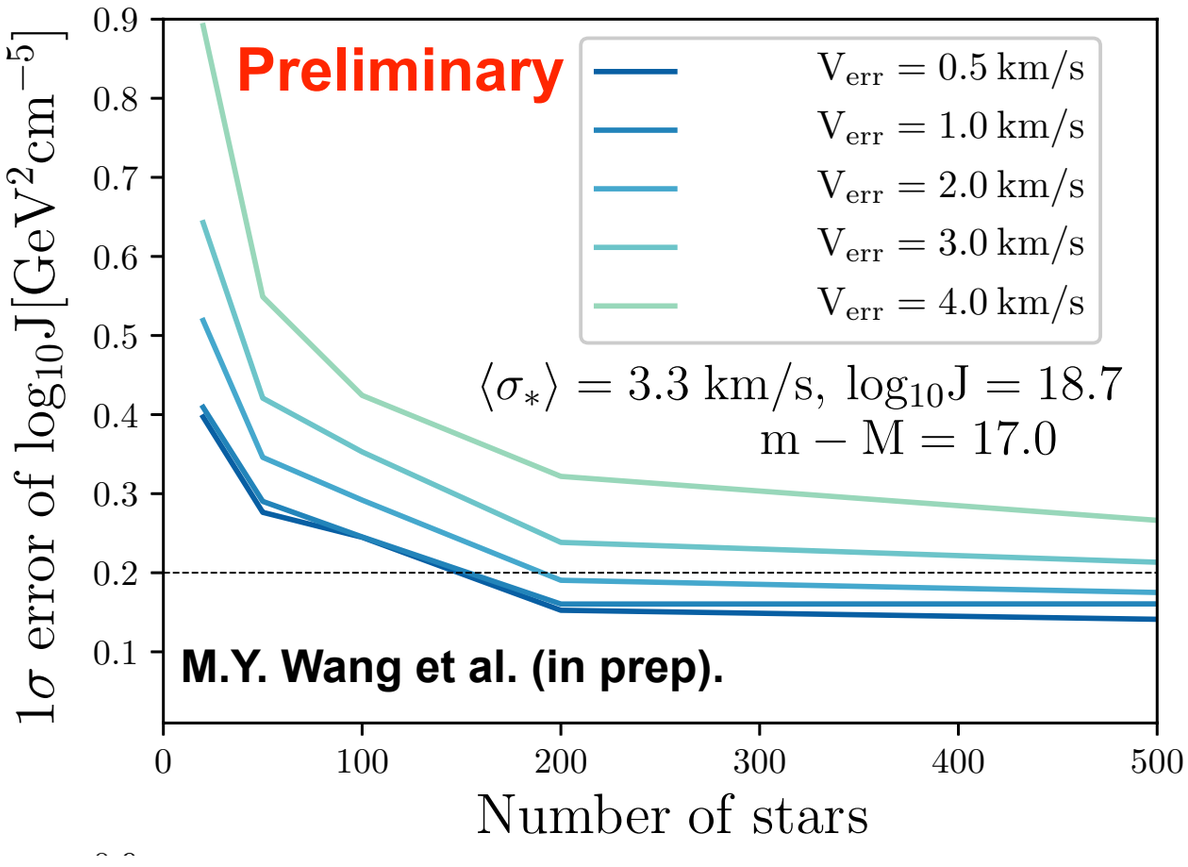



**The combined analysis includes J-factor uncertainty in the weighting scheme**

**Decreasing J-factor uncertainty can be a powerful way to improve sensitivity.**

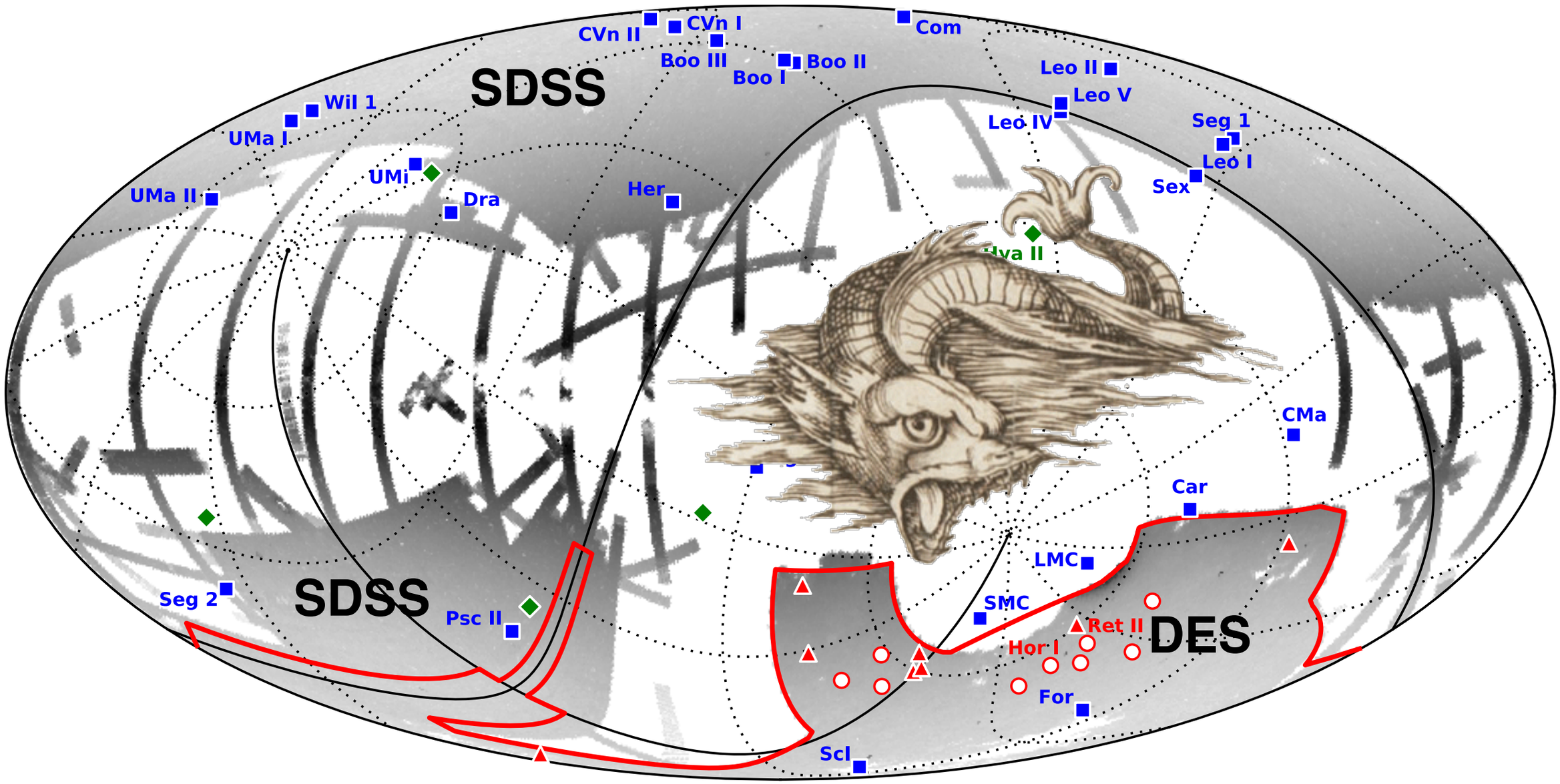
**For the faintest dwarfs it will not be possible to measure 100 stars with the current generation of telescopes.**

**The next generation of spectroscopic instruments must have sufficient stability and precision**




Alex Drlica-Wagner | Fermilab

# A Lot of Sky to Cover!

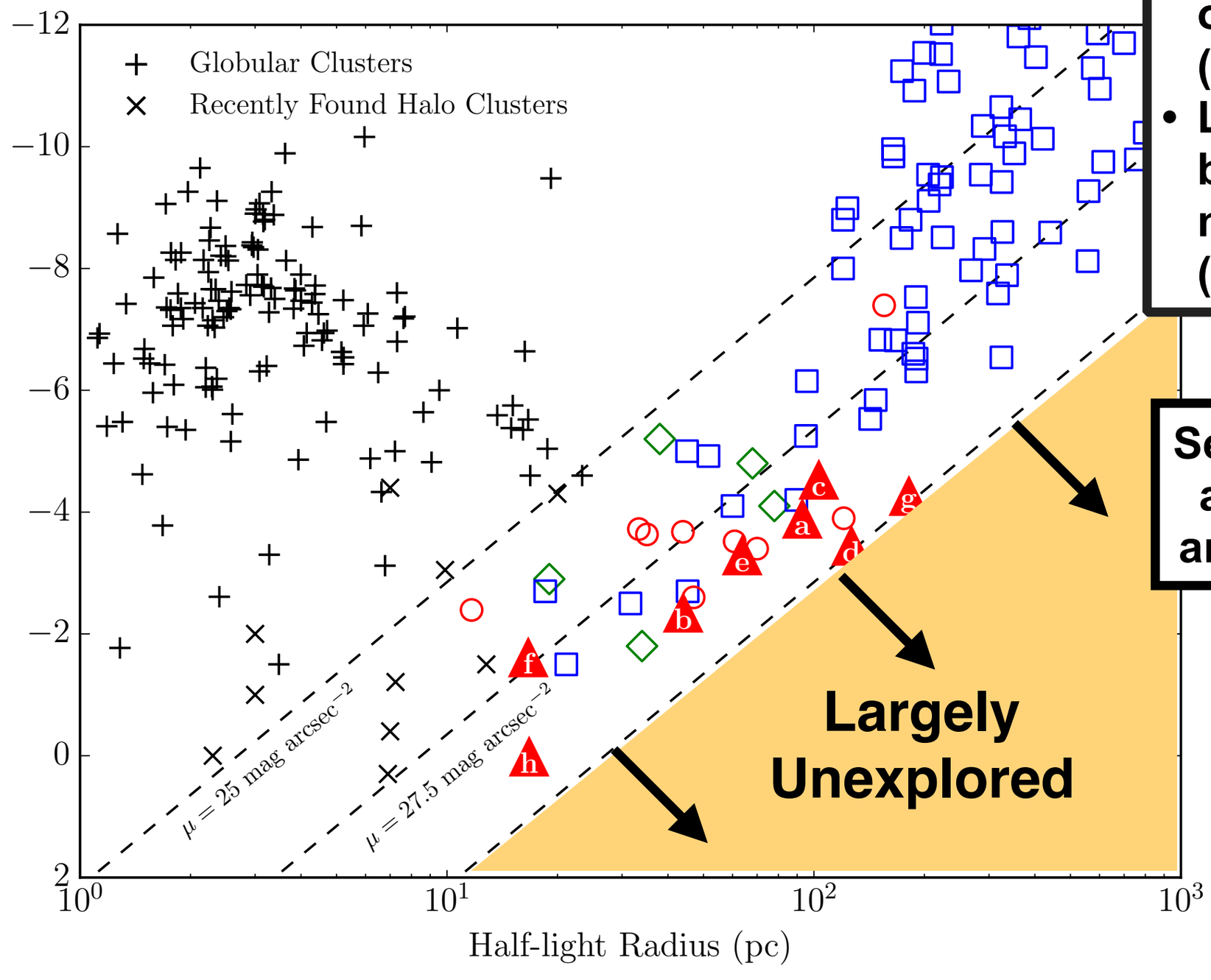



**Working to cover this area with DECam**
**Talk in Cosmology Session at 15:15**

# A Lot of Surface Brightness to Cover!

**Physical Size** →

**Brightness** ↑



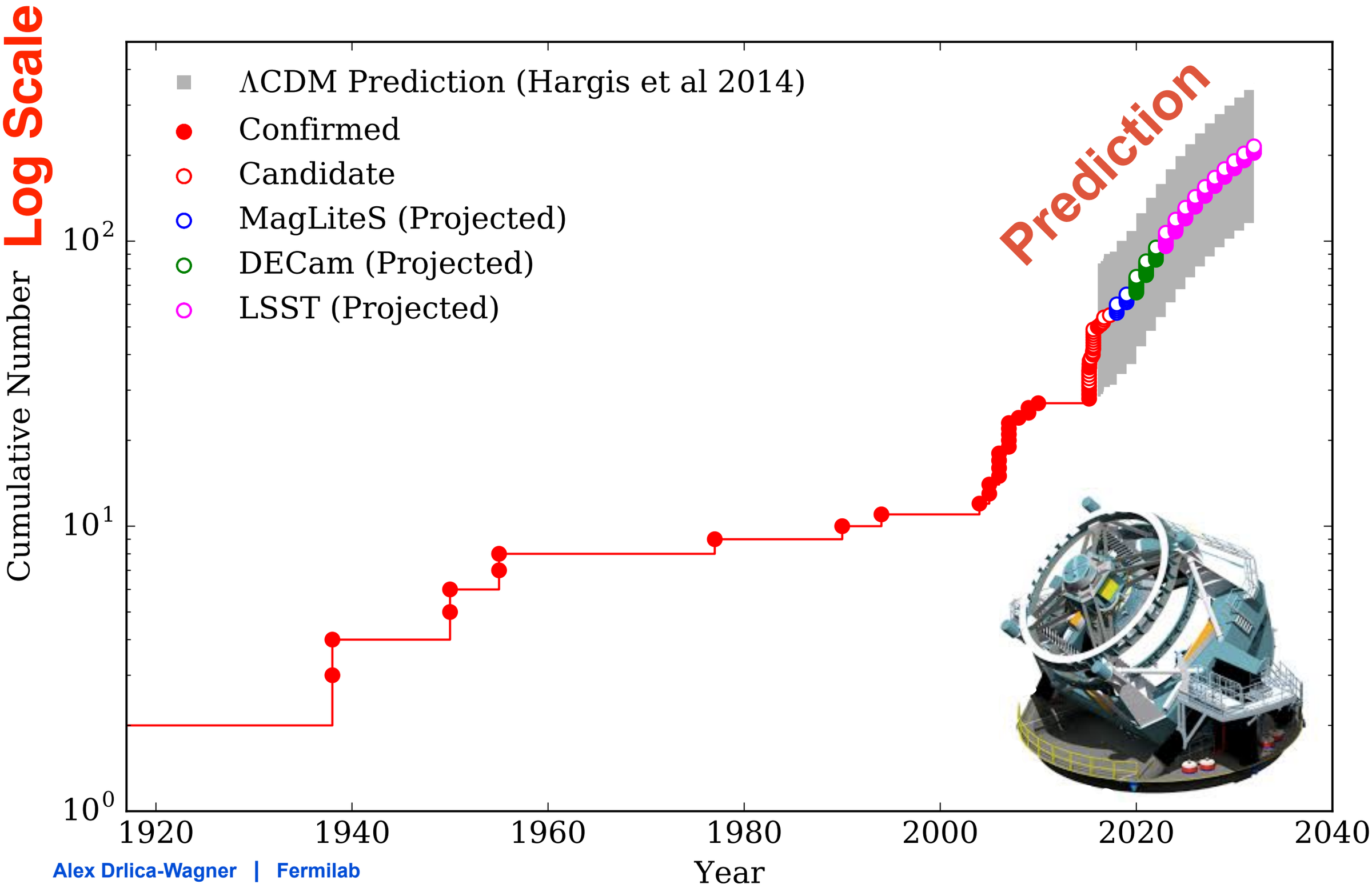

**Future surveys will find:**

- **Comparably bright objects farther away (missing satellites)**
- **Low surface brightness objects nearby (indirect detection)**

**Largely Unexplored**

**See Keith Bechtol's talk about upcoming DES analysis improvements**

# LSST is Coming!



# LSST is Coming!

# Backup Slides

# Gamma-ray Emission Towards Reticulum II

## Most significant gamma-ray excess for any new target found at gamma-ray energies between 2 to 10 GeV in the direction of Reticulum II

| | LAT Data Set | Local Significance | Post-trials for DM mass and annihilation channel |
|---|---|---|---|
| *Fermi*-LAT + DES | Pass 8 | 2.2 $\sigma$ | 1.65 $\sigma$ |
| Geringer-Sameth et al. | Pass 7 | 2.8 $\sigma$ | 2.3 $\sigma$ |
| Geringer-Sameth et al. | Pass 8 | 2.0 $\sigma$ | 1.6 $\sigma$ |
| Hooper & Linden | Pass 7 | 3.2 $\sigma$ | No trials, use best-fit from Galactic Center |

Also, possible blazar PMN J0335−5046 located ~0.1 deg away

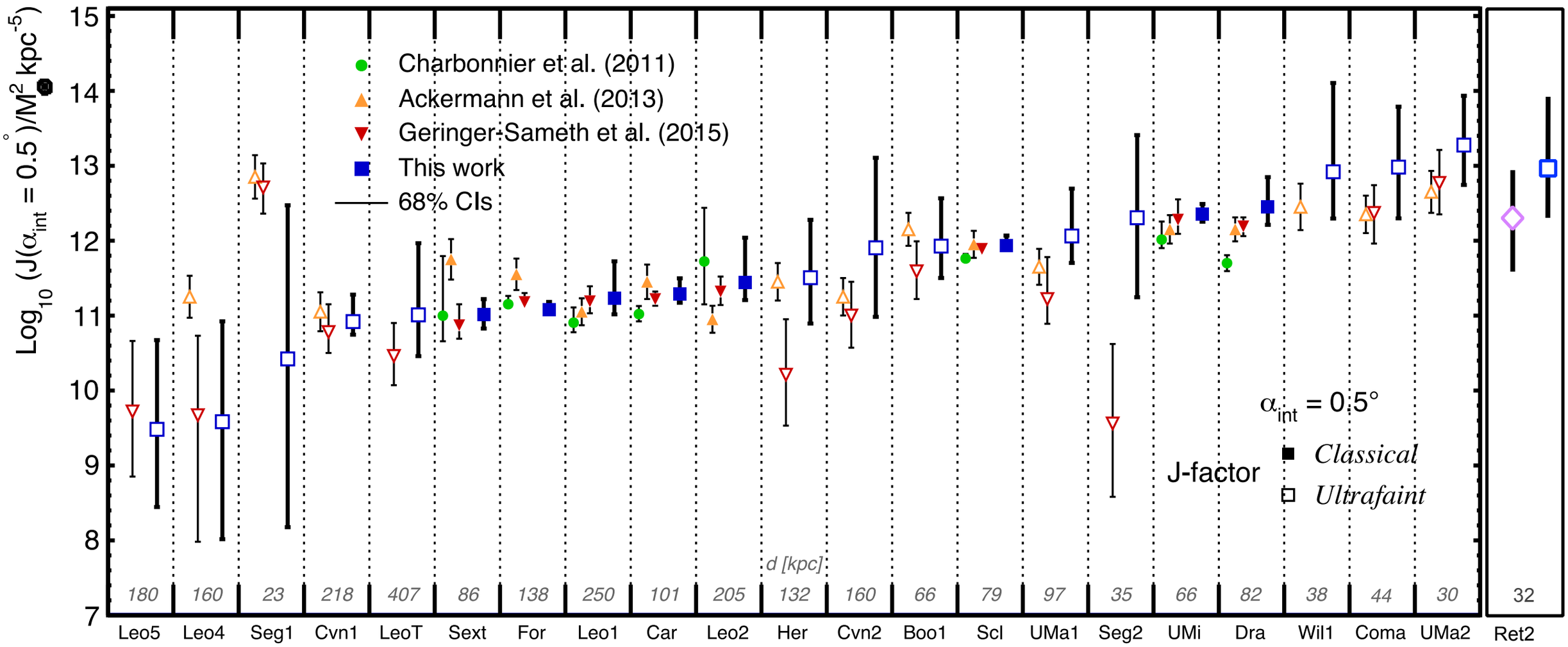
LAT & DES Collaborations
Drlica-Wagner et al. 2015
arXiv:1503.02632

Geringer-Sameth et al. 2015
arXiv:1503.02320

Hooper & Linden
arXiv:1503.06209

Consistency with dark matter interpretation depends in part on expected signal strength (i.e., “J-factor”) relative to other dSphs

# J-factor Estimates




**Bonnivard et al. MNRAS 849, 67 (2015)**

**Simon et al. ApJ 808, 95 (2015)**

**Bonnivard et al. ApJ 808, L36 (2015)**

# J-factor vs Gamma-ray Flux