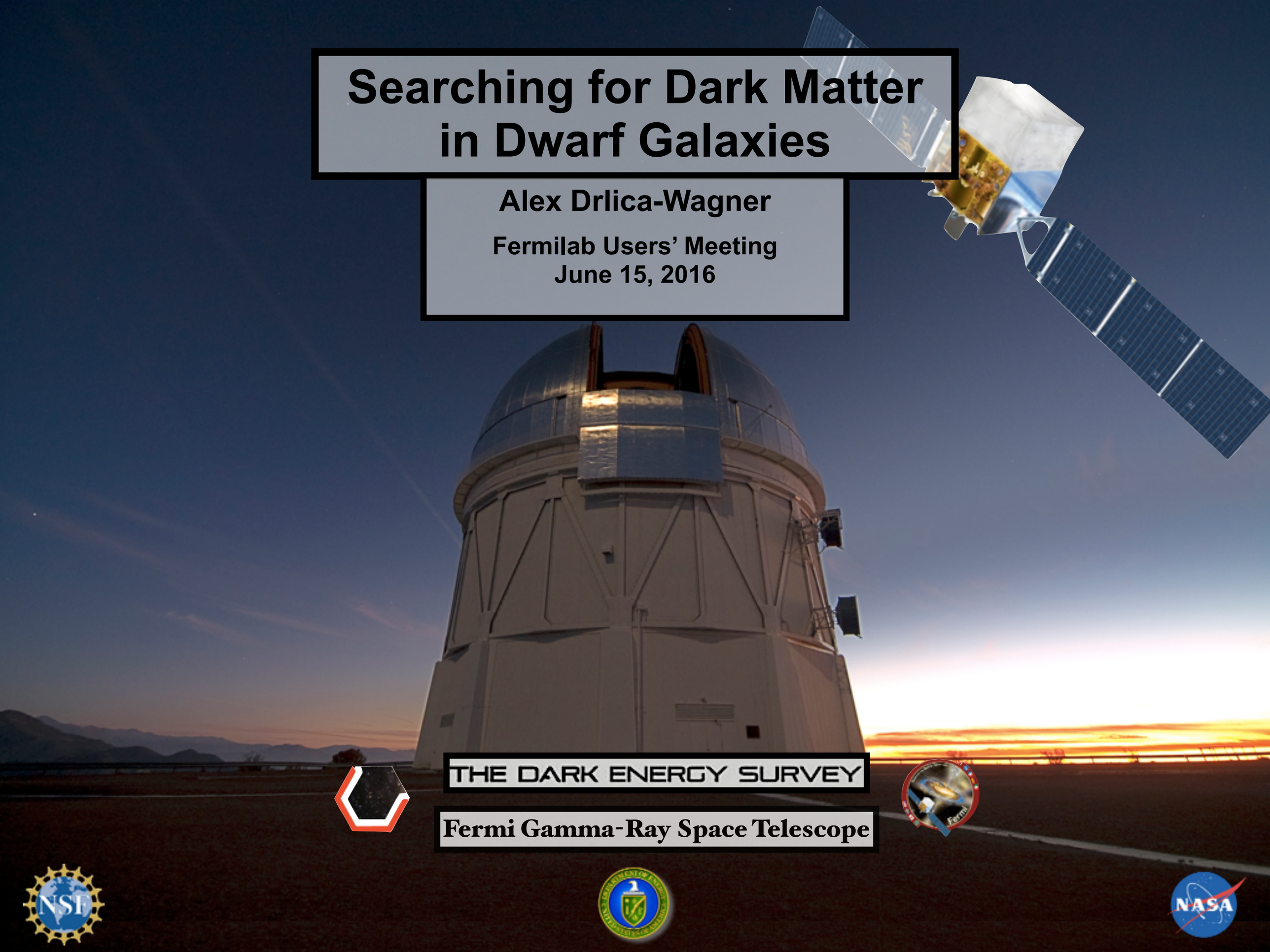
Searching for Dark Matter in Dwarf Galaxies

Alex Drlica-Wagner

Fermilab Users' Meeting
June 15, 2016



THE DARK ENERGY SURVEY

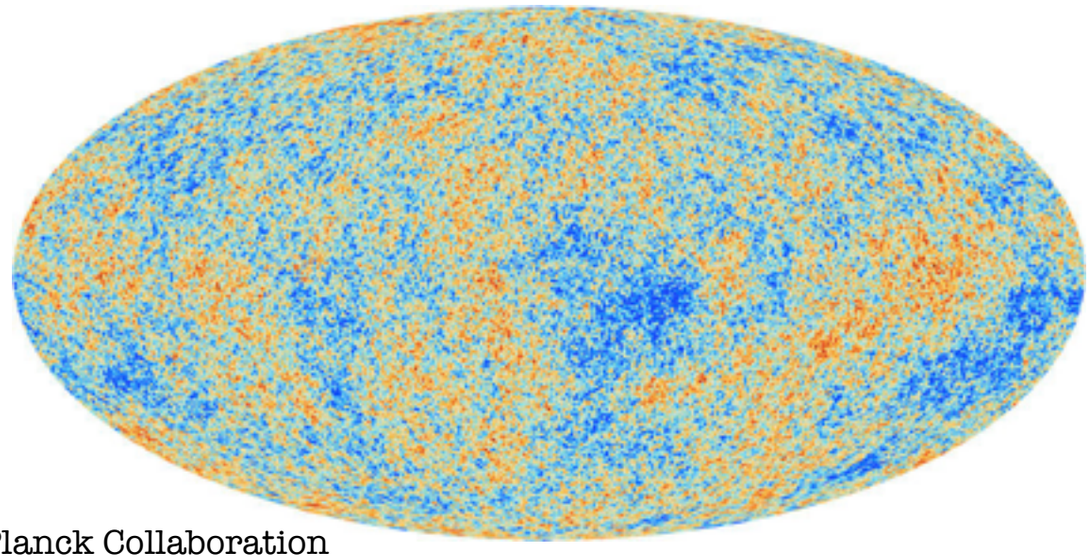
Fermi Gamma-Ray Space Telescope

- ❖ Dark Matter & Indirect Detection
  - ❖ Dark Matter in the Galactic Center
  - ❖ Dark Matter in Dwarf Galaxies
- ❖ Finding New Dwarf Galaxies

- **Dark Matter & Indirect Detection**
  - **Dark Matter in the Galactic Center**
  - **Dark Matter in Dwarf Galaxies**
- **Finding New Dwarf Galaxies**

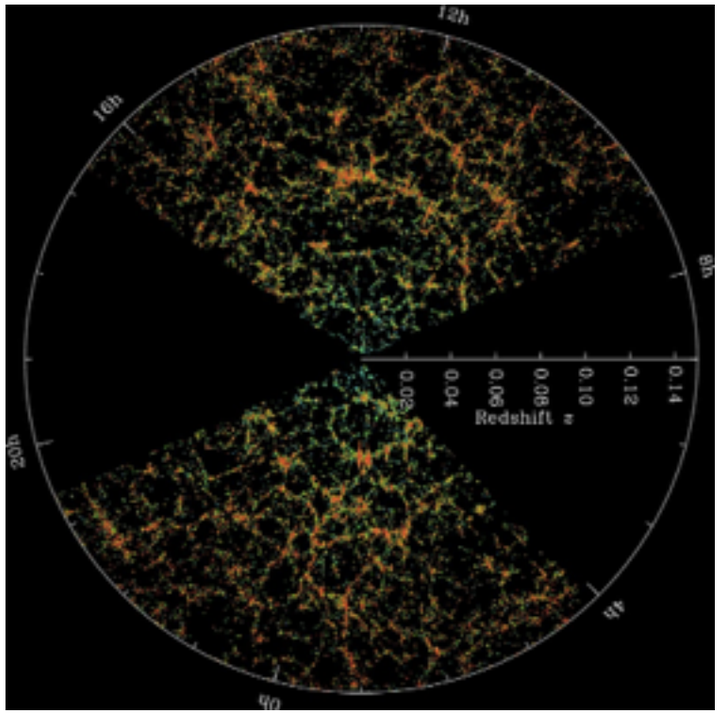
Dark Matter

Cosmic Microwave Background



Planck Collaboration

Large Scale Structure

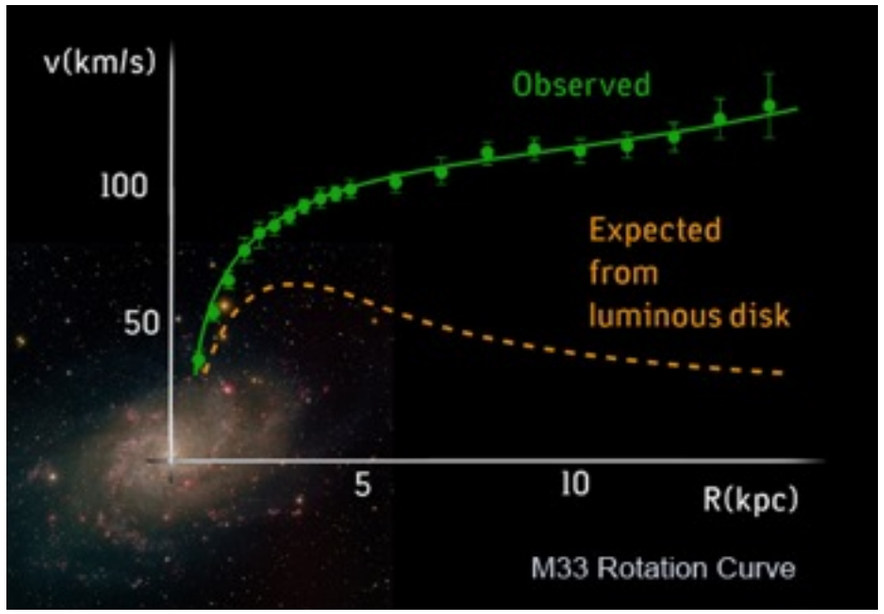


M. Blanton and SDSS Collaboration

Colliding Clusters

Bullet Cluster (Markevitch & Clowe, 2006)

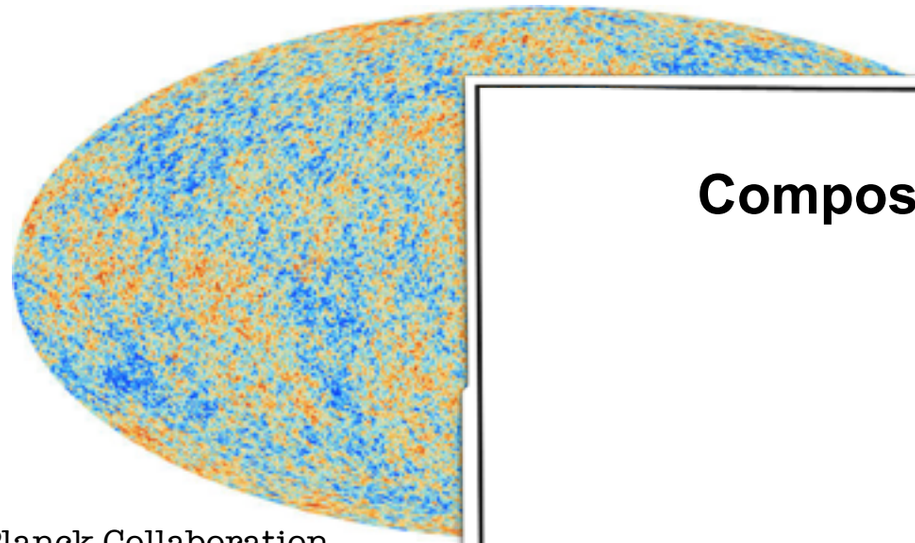
Galaxy Rotation Curves



NOAO, AURA, NSF, T.A. Rector

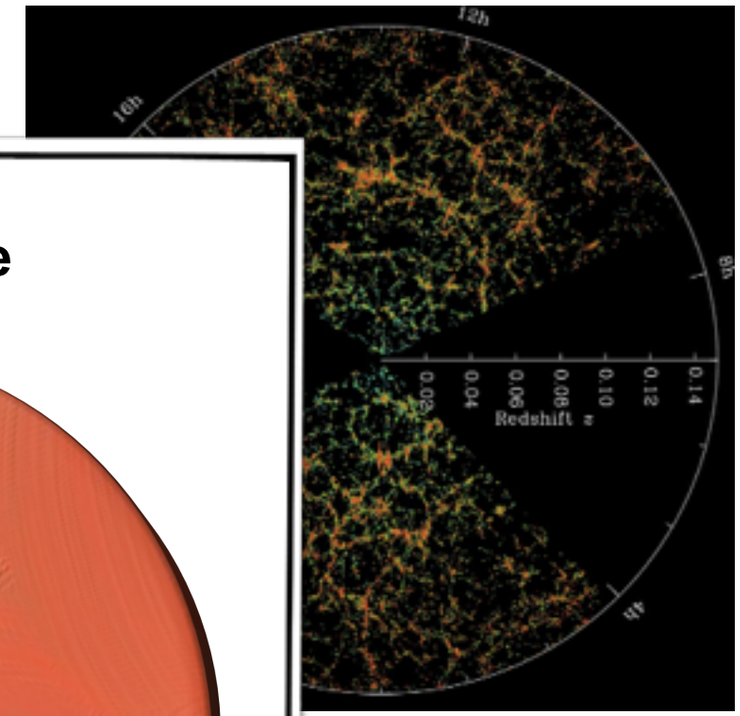
Dark Matter

Cosmic Microwave Background



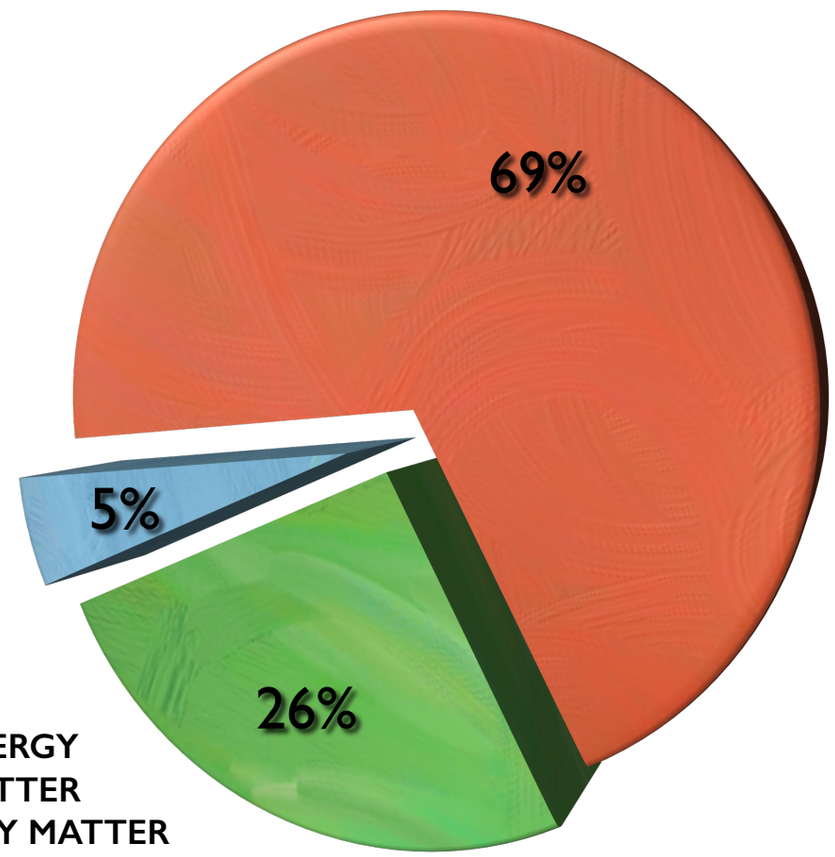
Planck Collaboration

Large Scale Structure

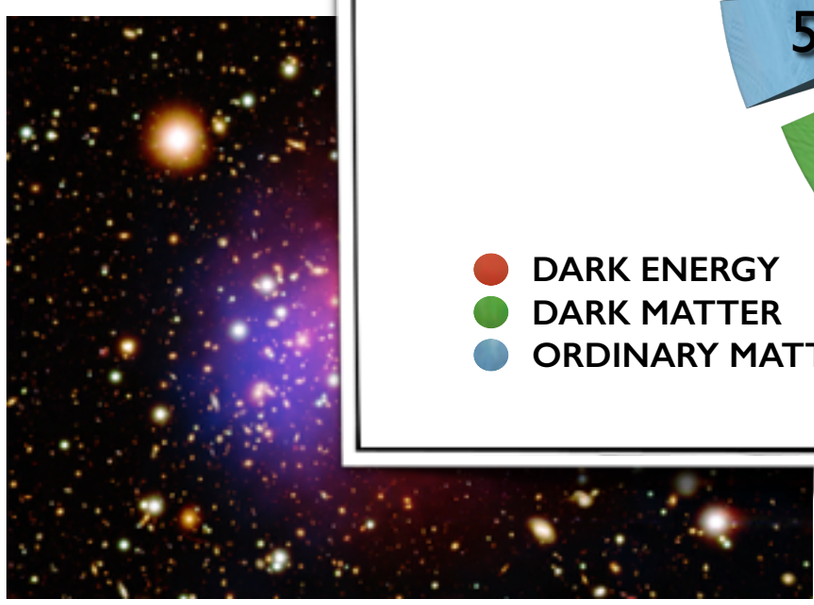


nd SDSS Collaboration

Composition of the Universe



Collidi



Bullet Cluster (Markevitch & Clowe, 2006)

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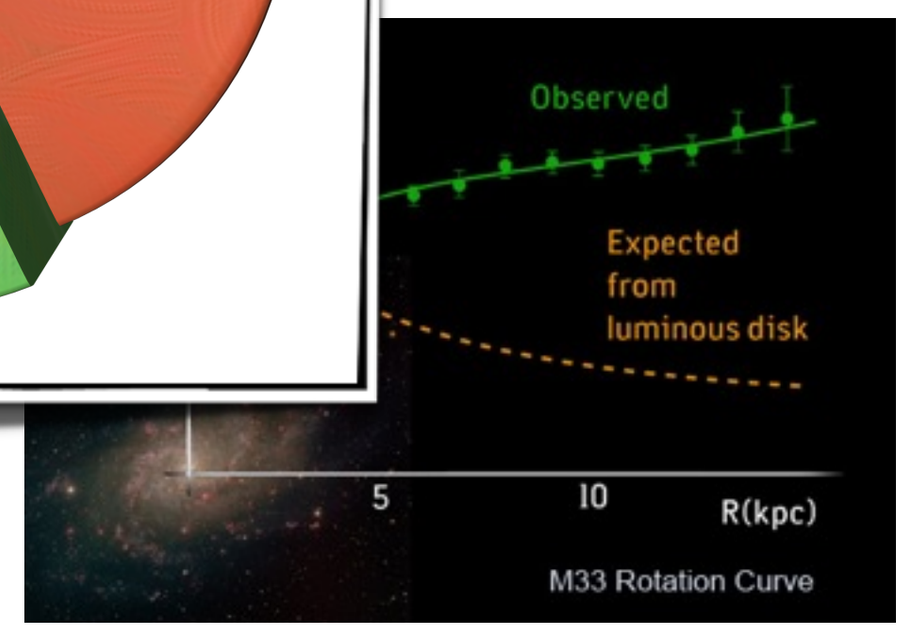


NOAO, AURA, NSF, T.A. Rector

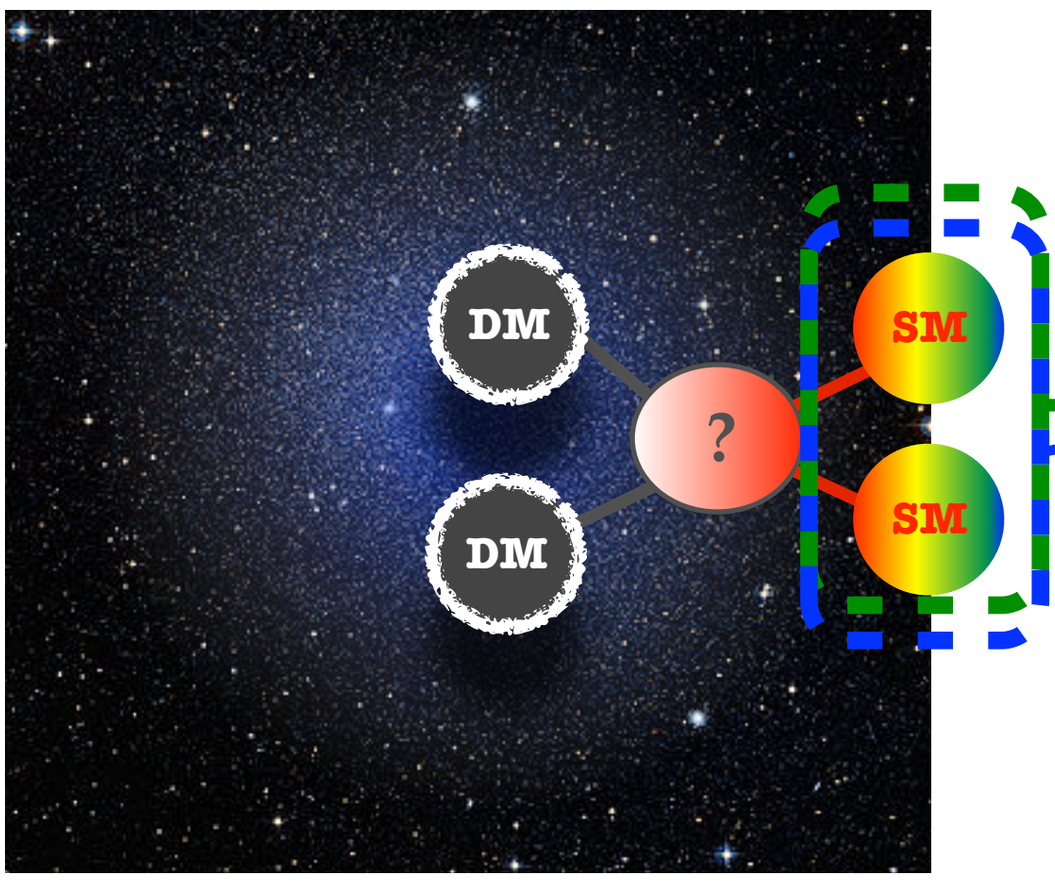
Indirect Detection

Dark Matter Distribution

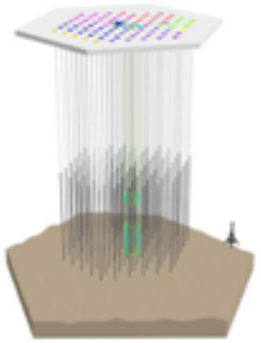
Particle Propagation

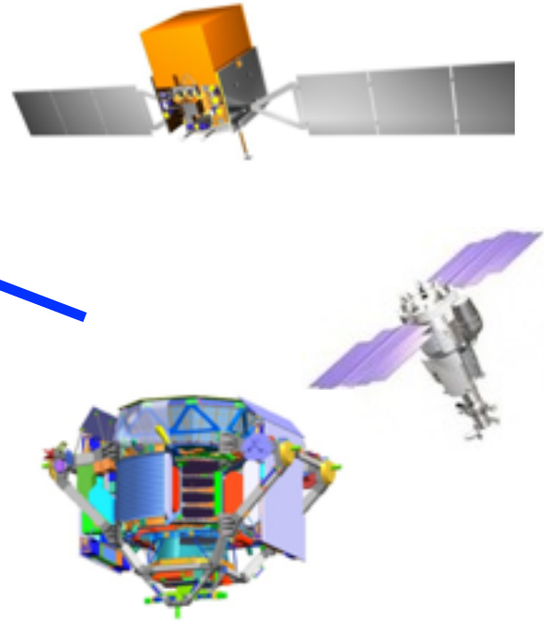
Particle Detection

Dark Matter Annihilation



Neutral Particles
(γ, ν)



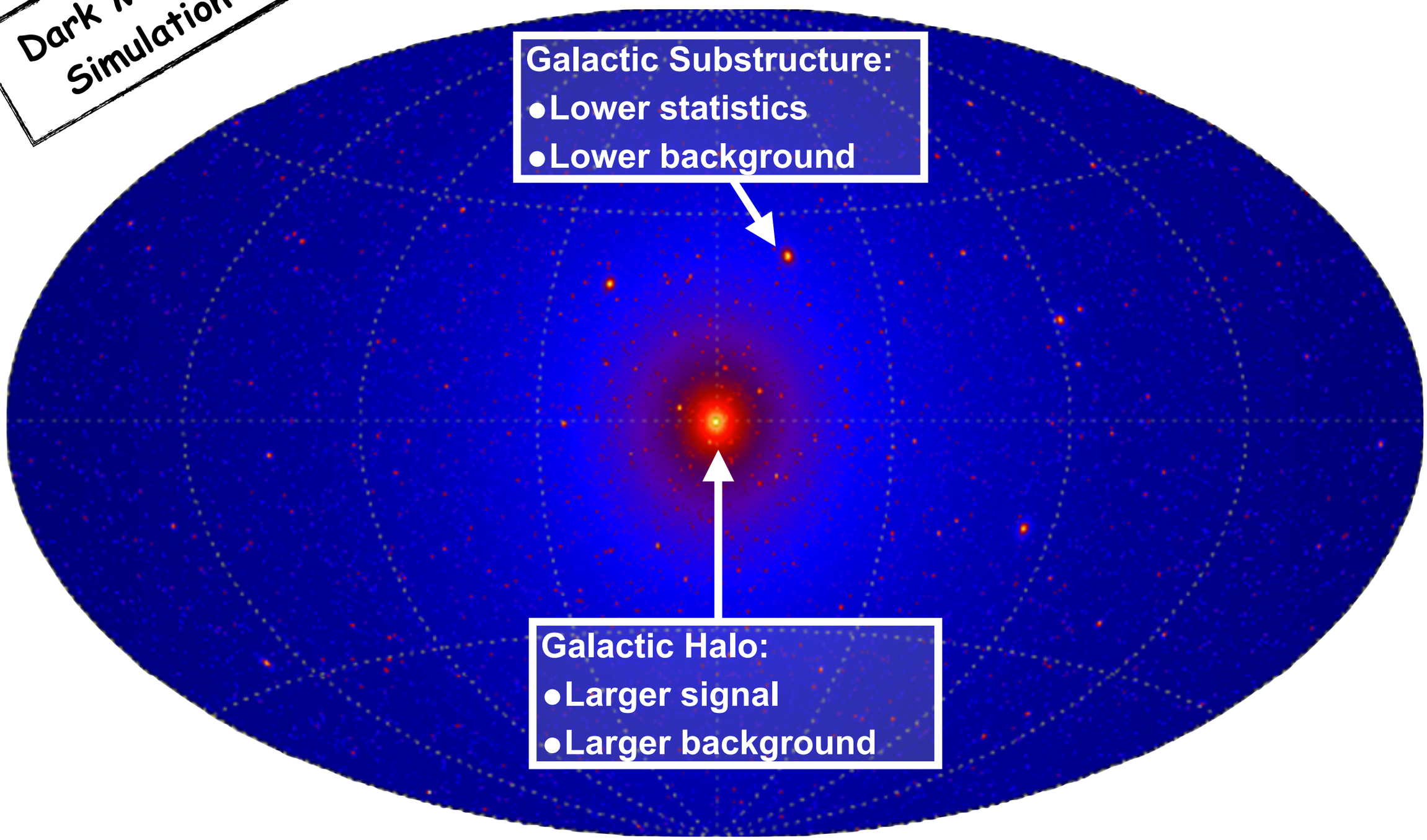


Charged Particles
$(e^{\pm}, p^{\pm}, etc.)$

Dark Matter Distribution

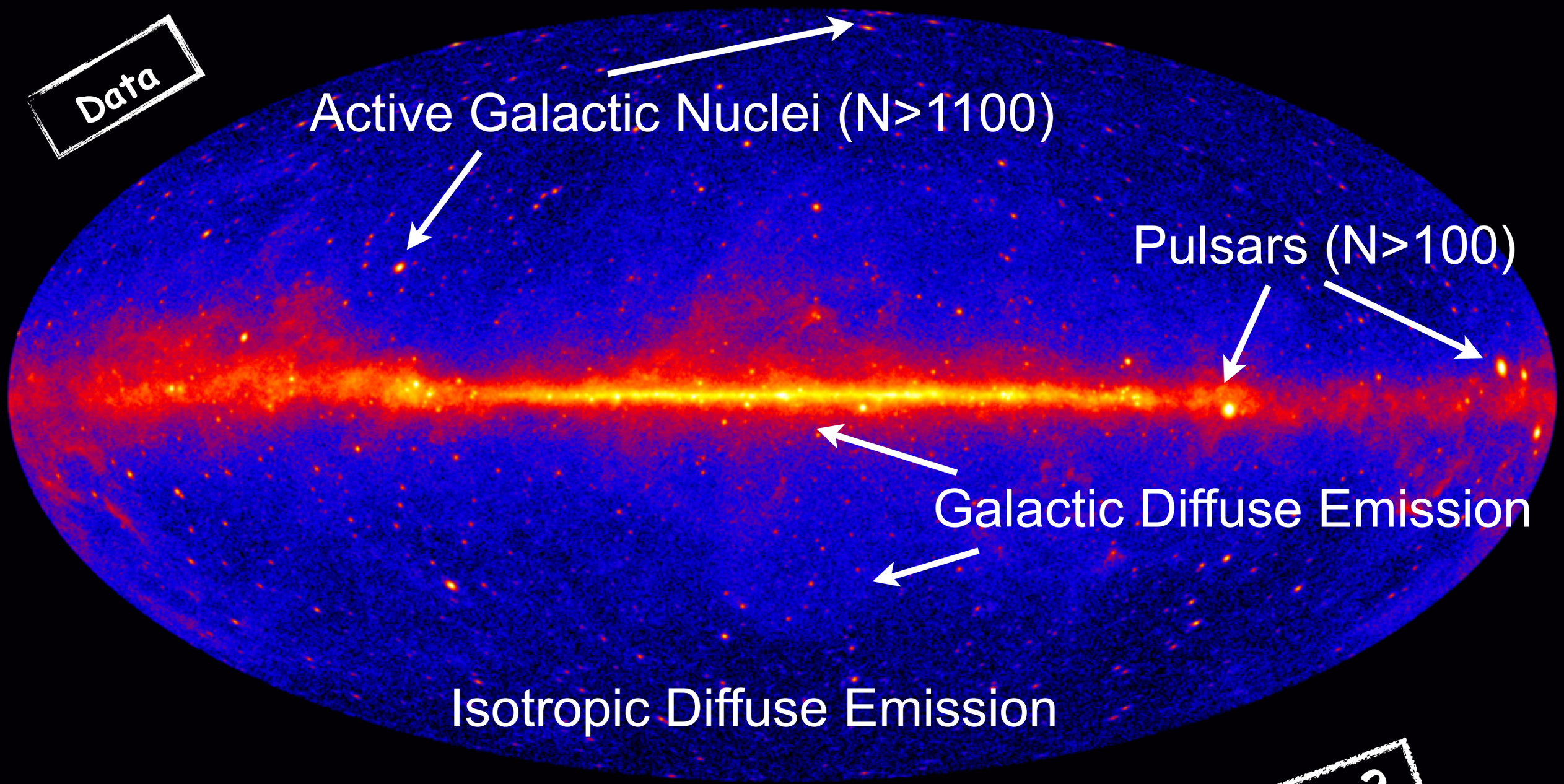
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

Dark Matter Simulation



Pieri et al. Phys Rev D83, 023518 (2011)

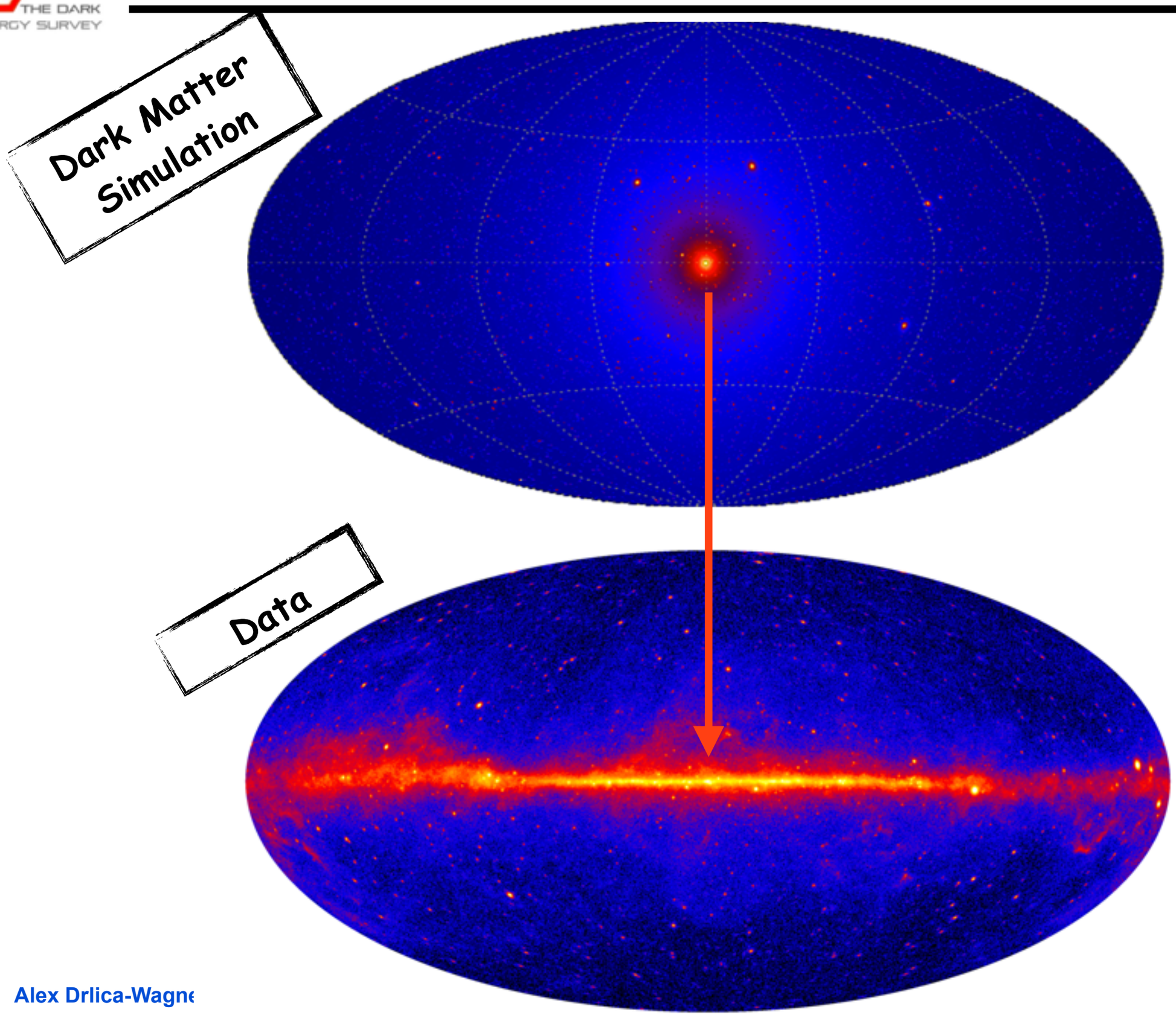
Gamma-Ray Data ($E\gamma$ > 1 GeV)



+ a lot of additional astrophysics … + Dark Matter?

- Dark Matter & Indirect Detection
  - **Dark Matter in the Galactic Center**
  - Dark Matter in Dwarf Galaxies
- Finding New Dwarf Galaxies

The Galactic Center



The Galactic Center

The Galactic Center is an appealing target for dark matter searches

- Rich in dark matter
- Relatively nearby

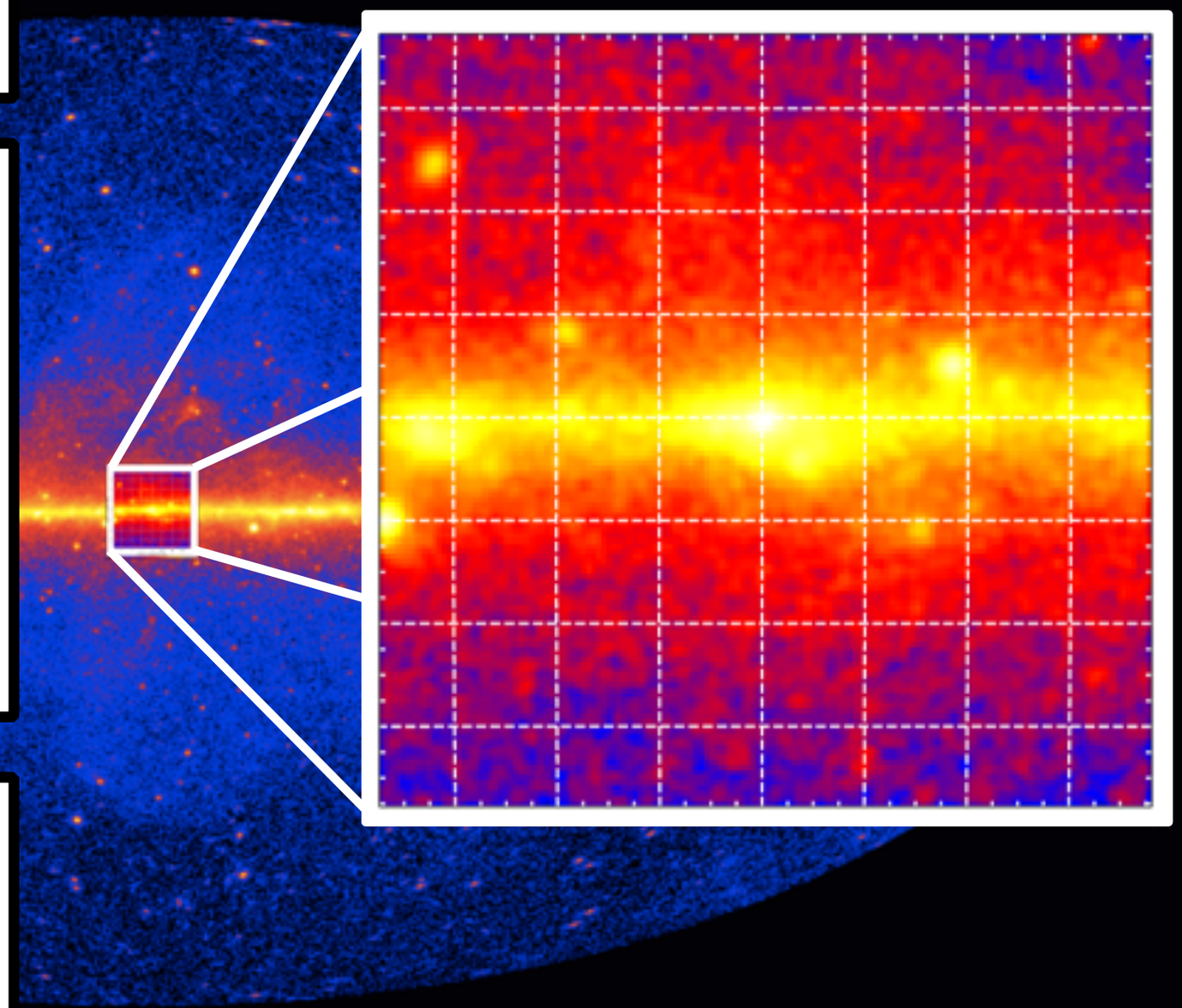
However, the Galactic Center is astrophysically complicated

- Diffuse emission from cosmic-ray interactions with Galactic gas and dust
- Densely populated by astrophysical sources (e.g., pulsars, SNR), which are detected in other wavelengths (e.g., radio, X-ray, TeV)

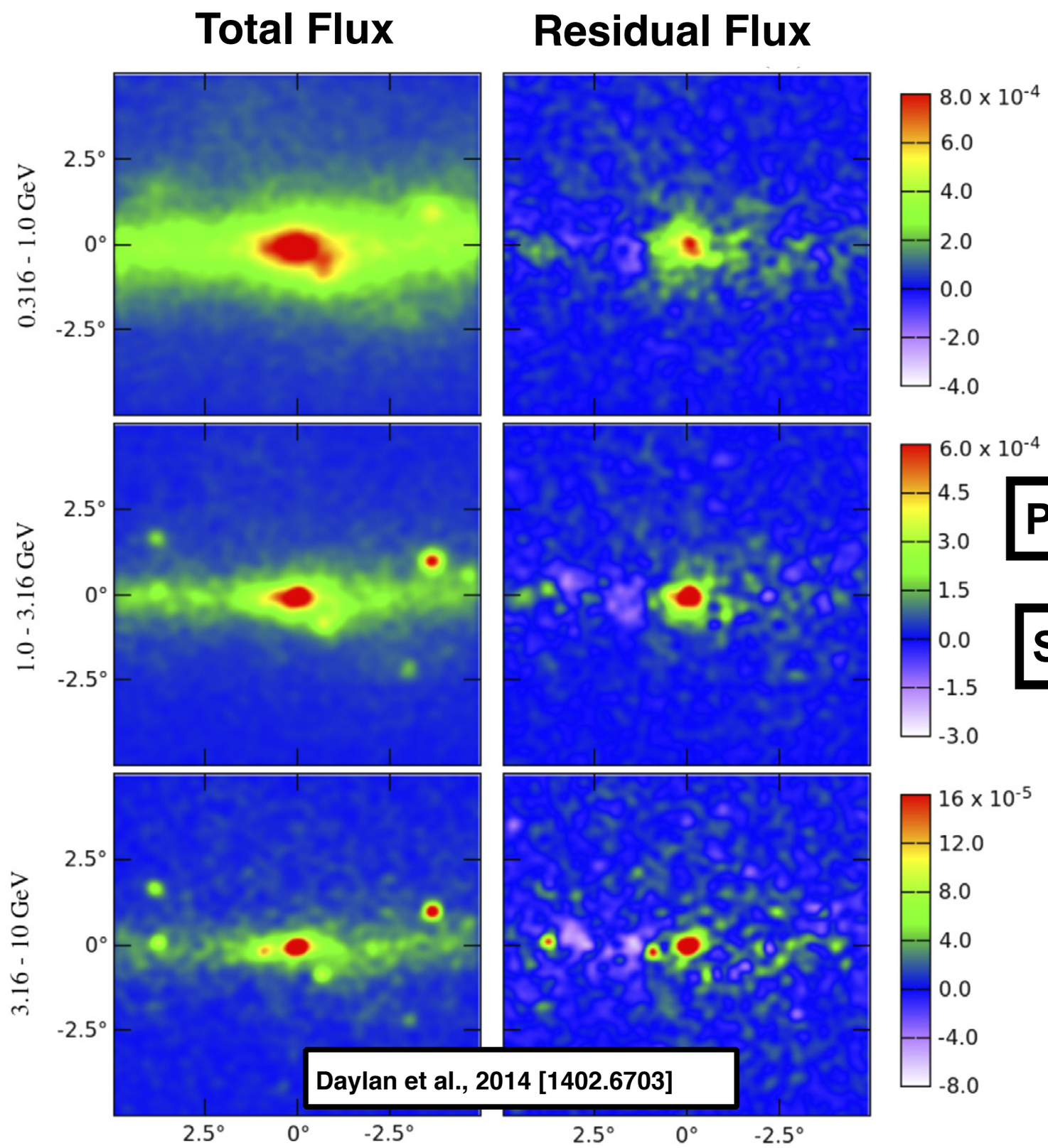
Topic of extensive recent research (much led here at Fermilab)…

- Hooper & Linden (2011); Boyarski et al. (2011); Abazajian & Kaplinghat (2012); Gordon & Macias (2013); Huang et al. (2013); Abazajian et al. (2014); Daylan et al. (2014); Calore et al. (2014); Lee et al. (2015); Bartels et al. (2015) Ajello et al. (2015); etc.

Gamma-ray Data ($E\gamma > 1$ GeV)



The Galactic Center

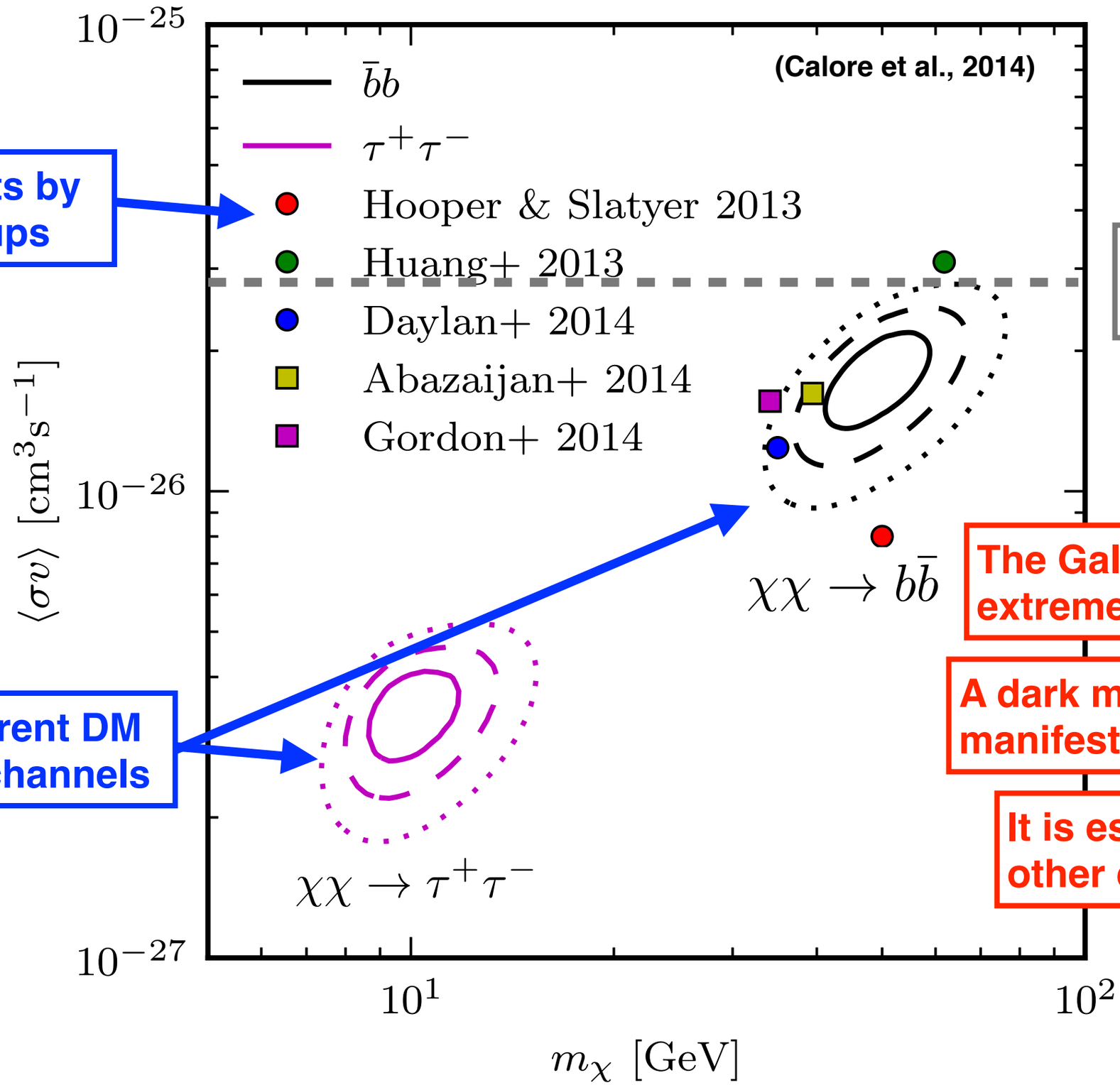


Peaks at a few GeV

Spatially extended

Daylan et al., 2014 [1402.6703]

The Galactic Center



Measurements by different groups

Thermal Relic Cross Section

Assume different DM annihilation channels

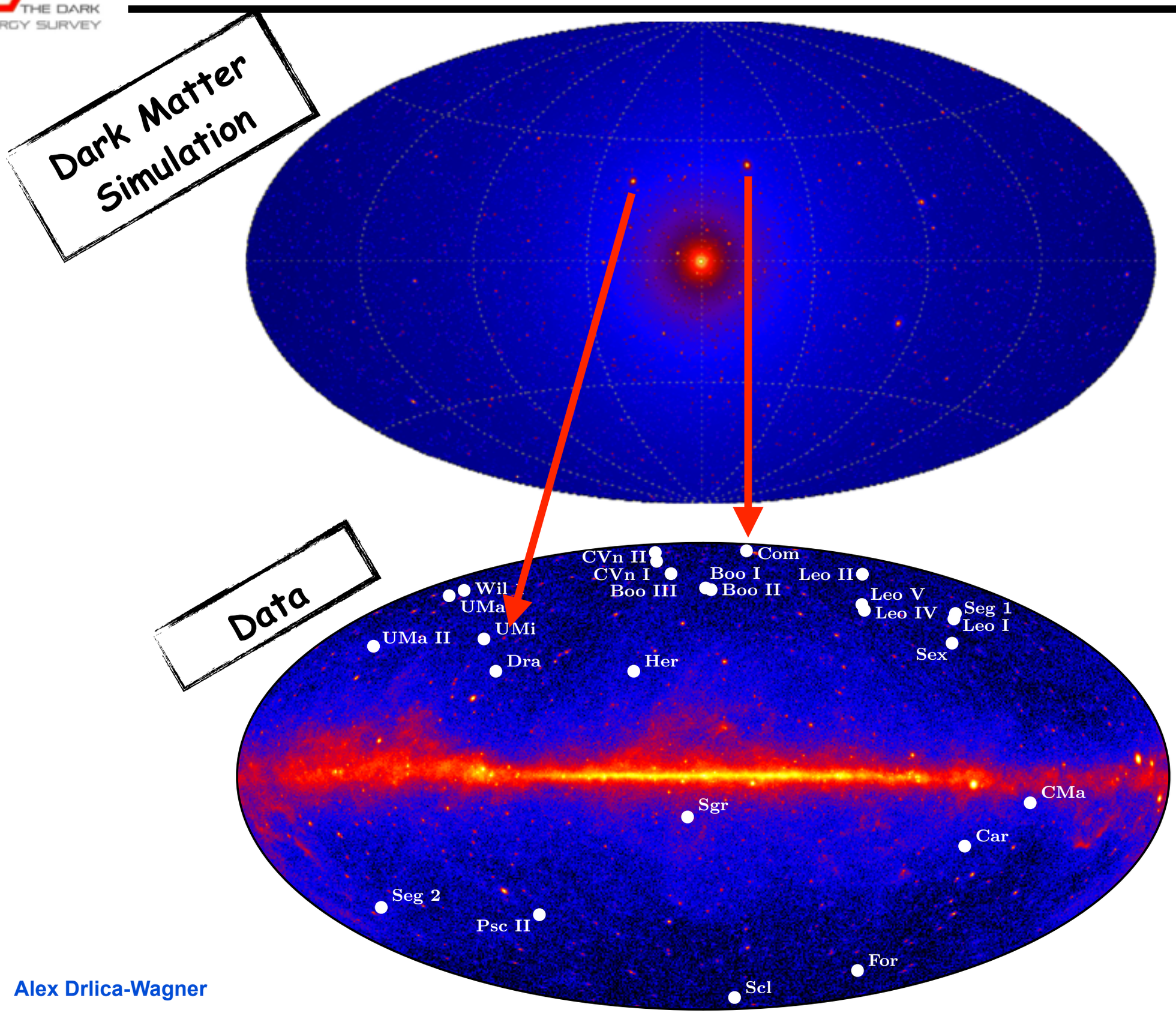
The Galactic Center is an extremely complicated region

A dark matter signal should manifest itself in other regions

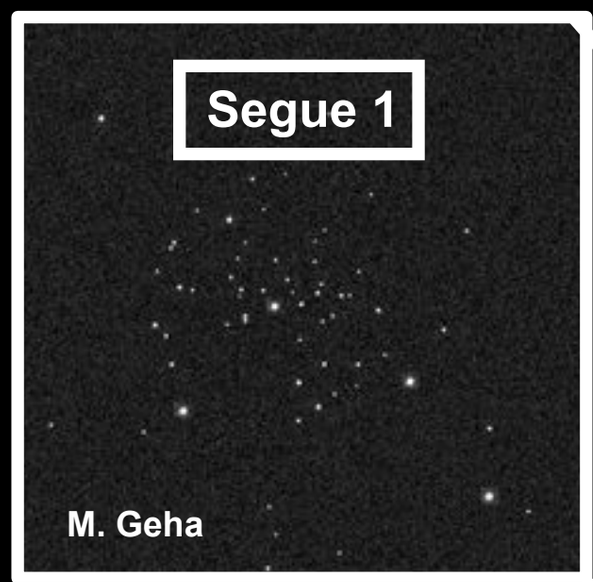
It is essential to investigate other dark matter targets

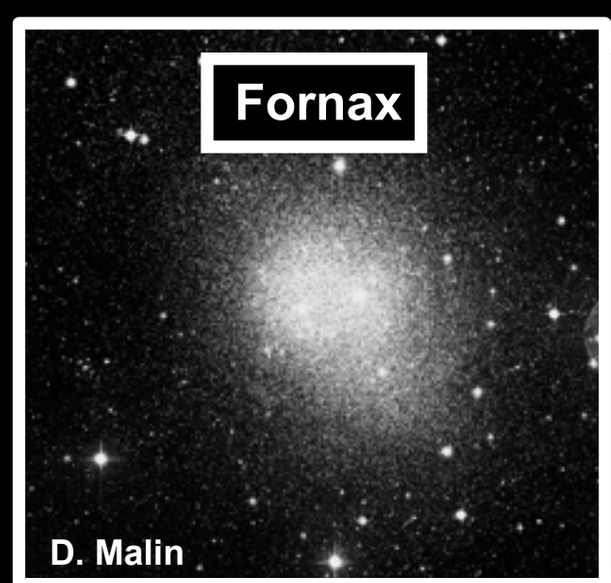
- ❖ Dark Matter & Indirect Detection
- ❖ Dark Matter in the Galactic Center
- ❖ Dark Matter in Dwarf Galaxies
- ❖ Finding New Dwarf Galaxies

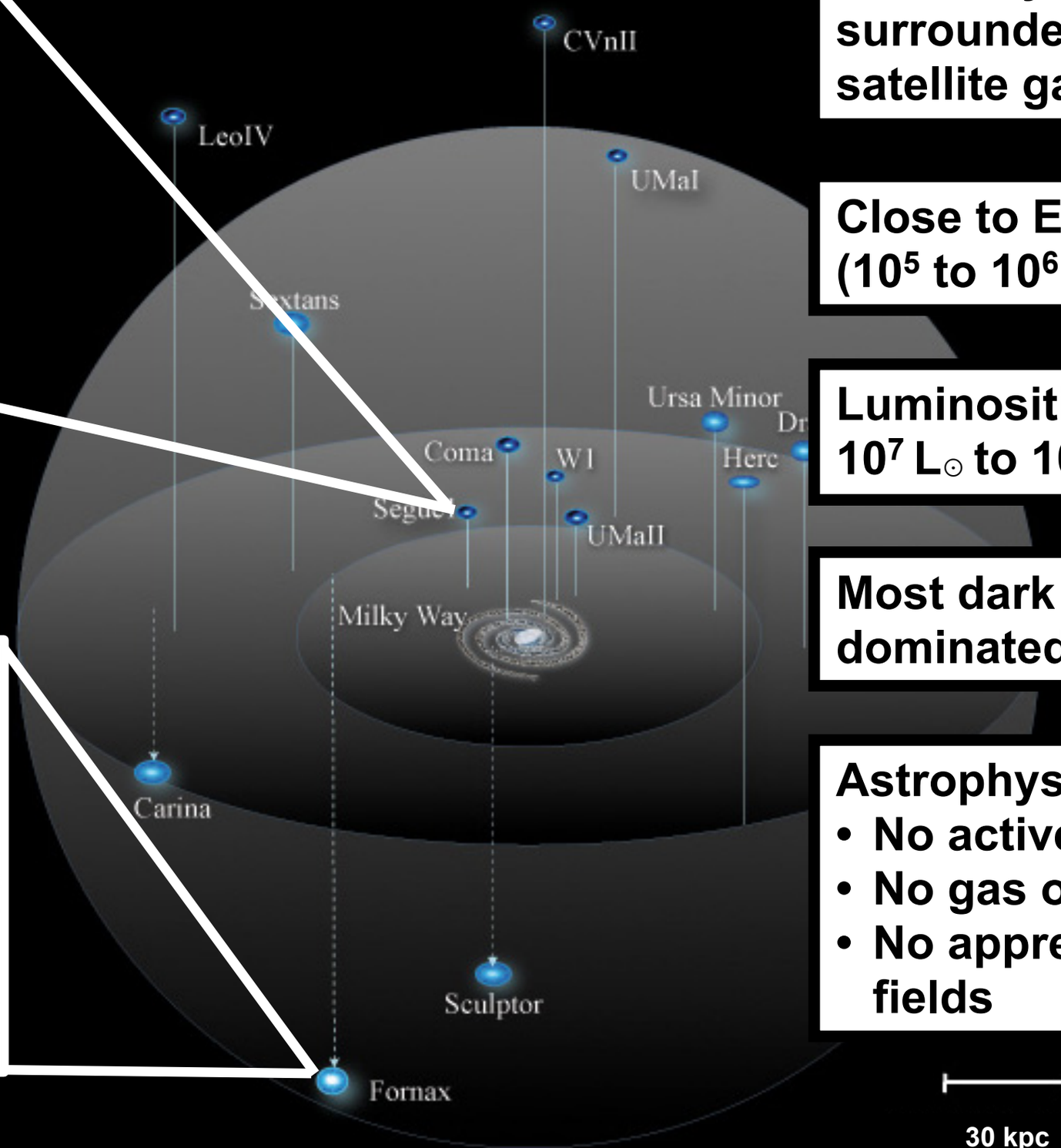
Milky Way Satellite Galaxies



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

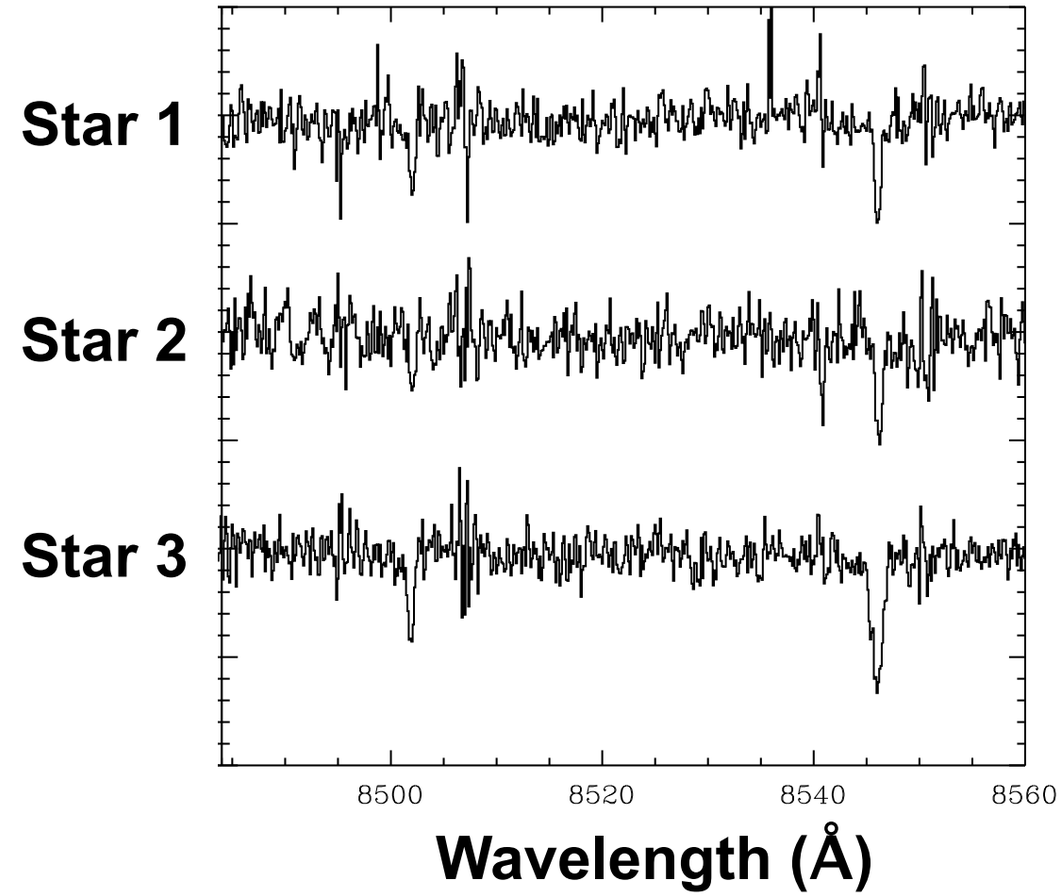
Astrophysically simple
- **No active star formation**
- **No gas or dust**
- **No appreciable magnetic fields**

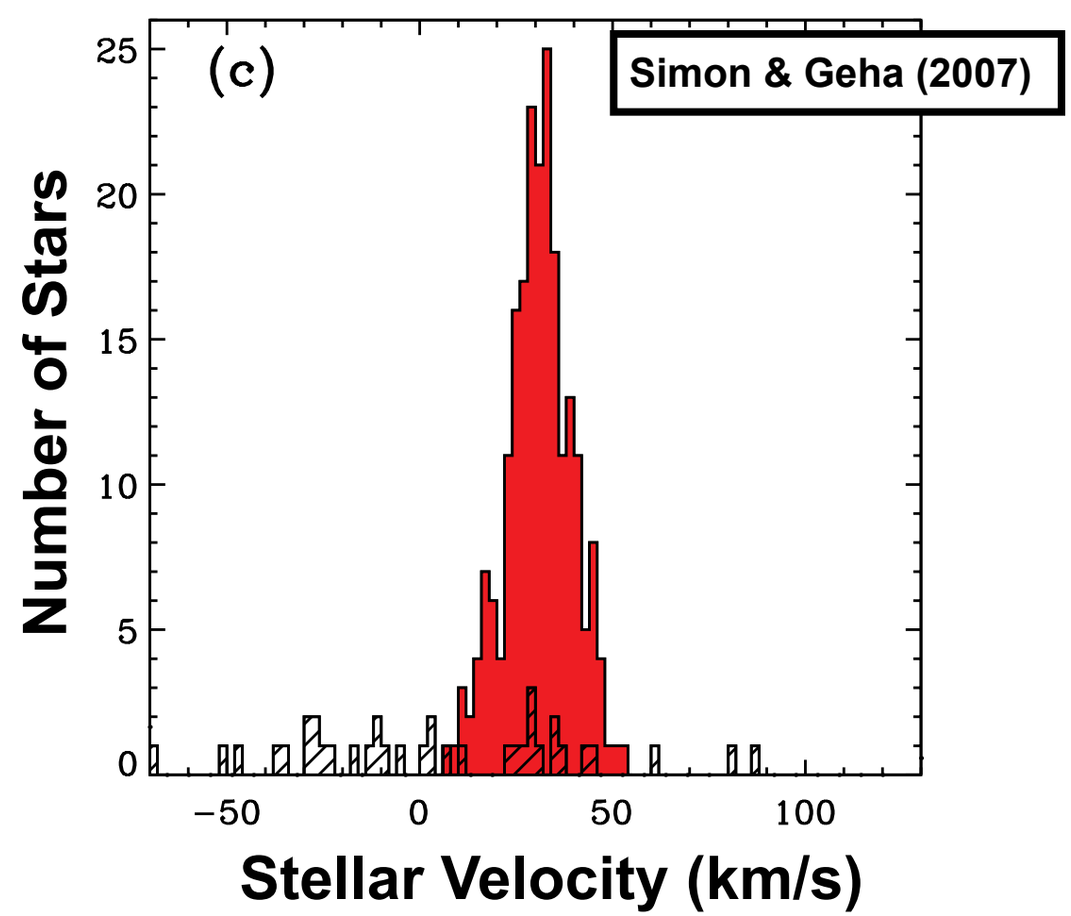
(Bullock, Geha, Powell)

Dark Matter Content (J-Factor)

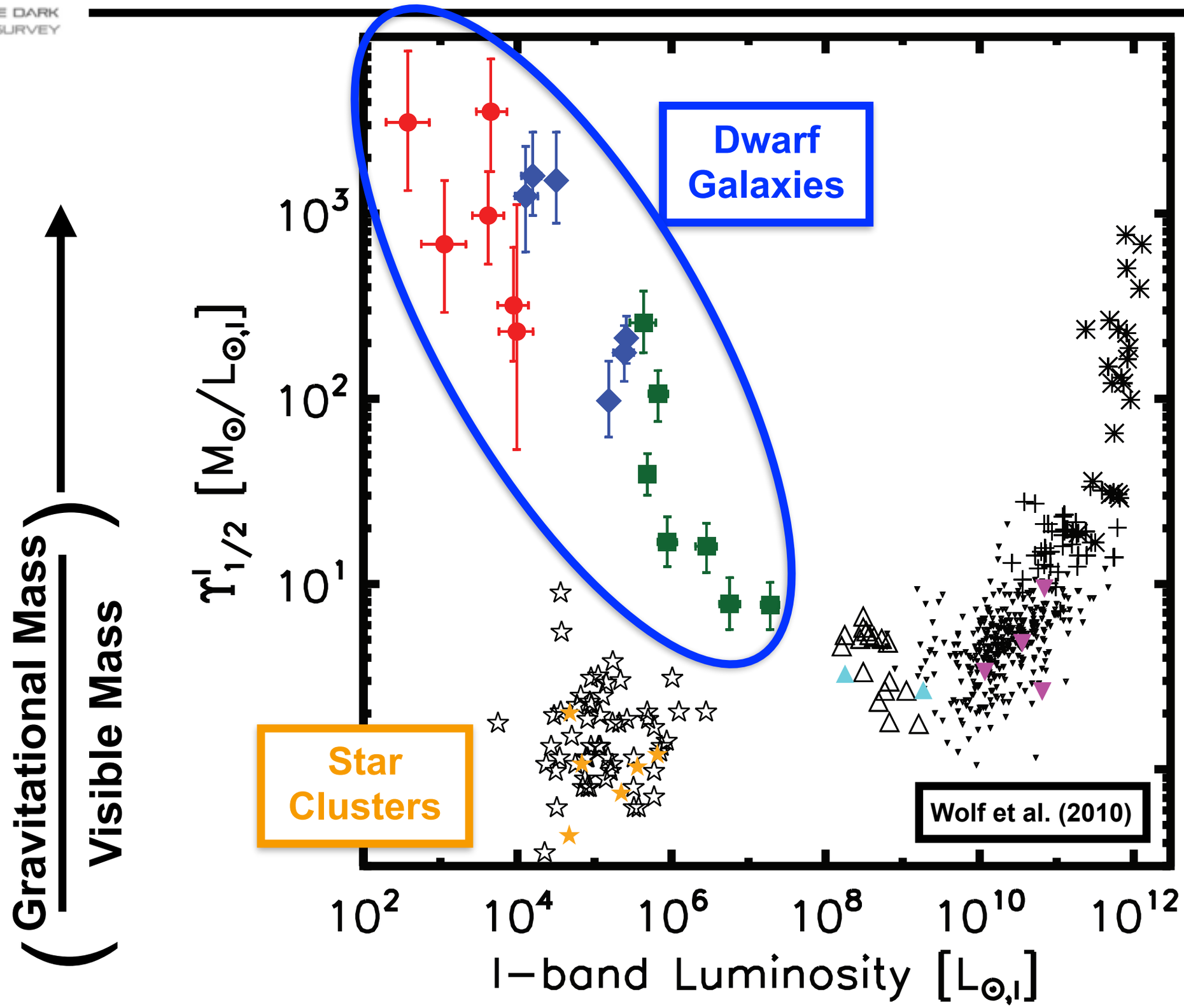
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

- The dark matter content of dwarf galaxies can be determined from the velocities of their stars
- Measure the Doppler shift of atomic lines in stellar spectra
  - Bright dwarf galaxies: velocities for thousands of stars
  - Faint dwarf galaxies: velocities for fewer than one hundred stars
- A large dispersion of stellar velocities requires a large gravitational binding force





Milky Way Satellite Galaxies

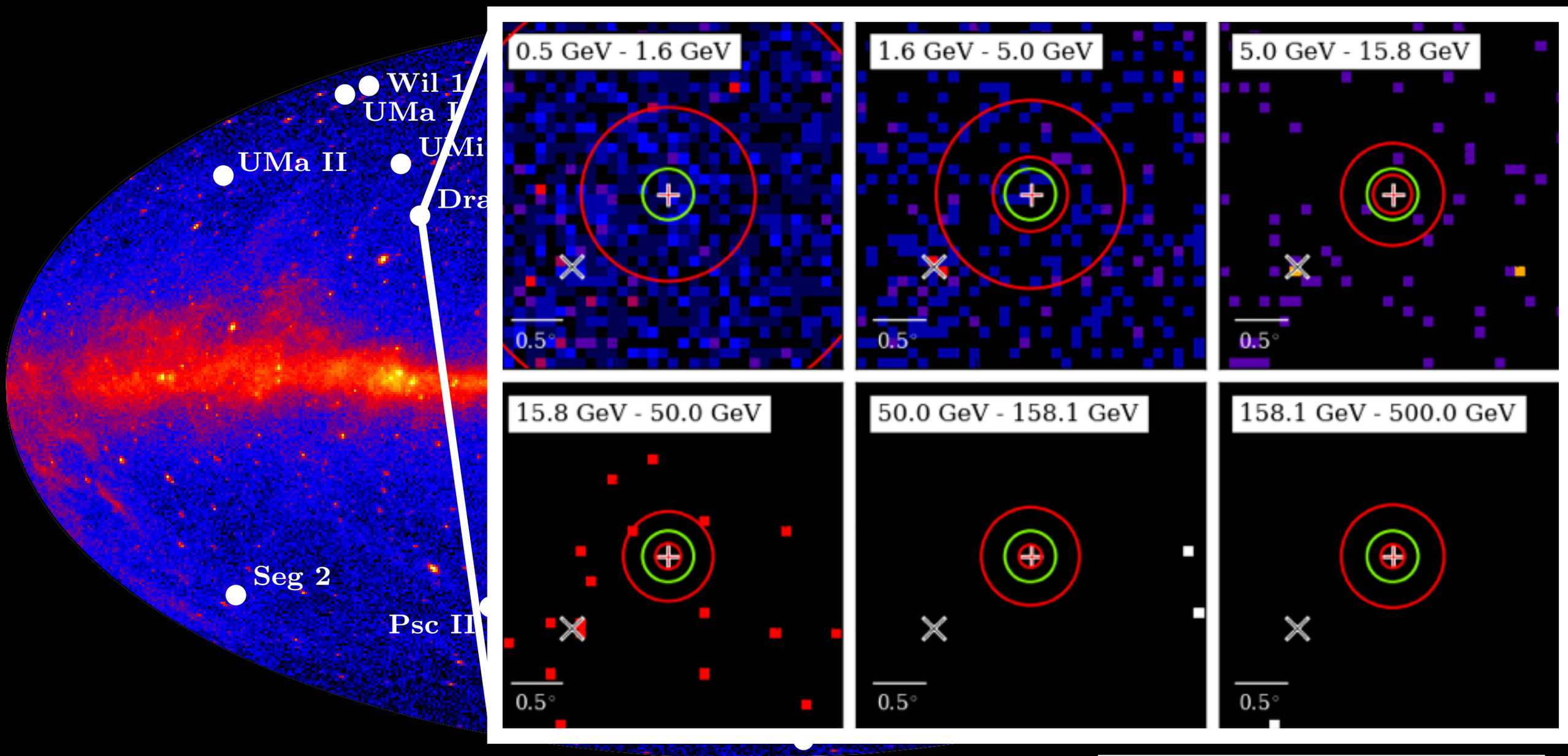


$$\left(\frac{\text{Gravitational Mass}}{\text{Visible Mass}}\right)$$

"Brightness" →

Milky Way Satellite Galaxies

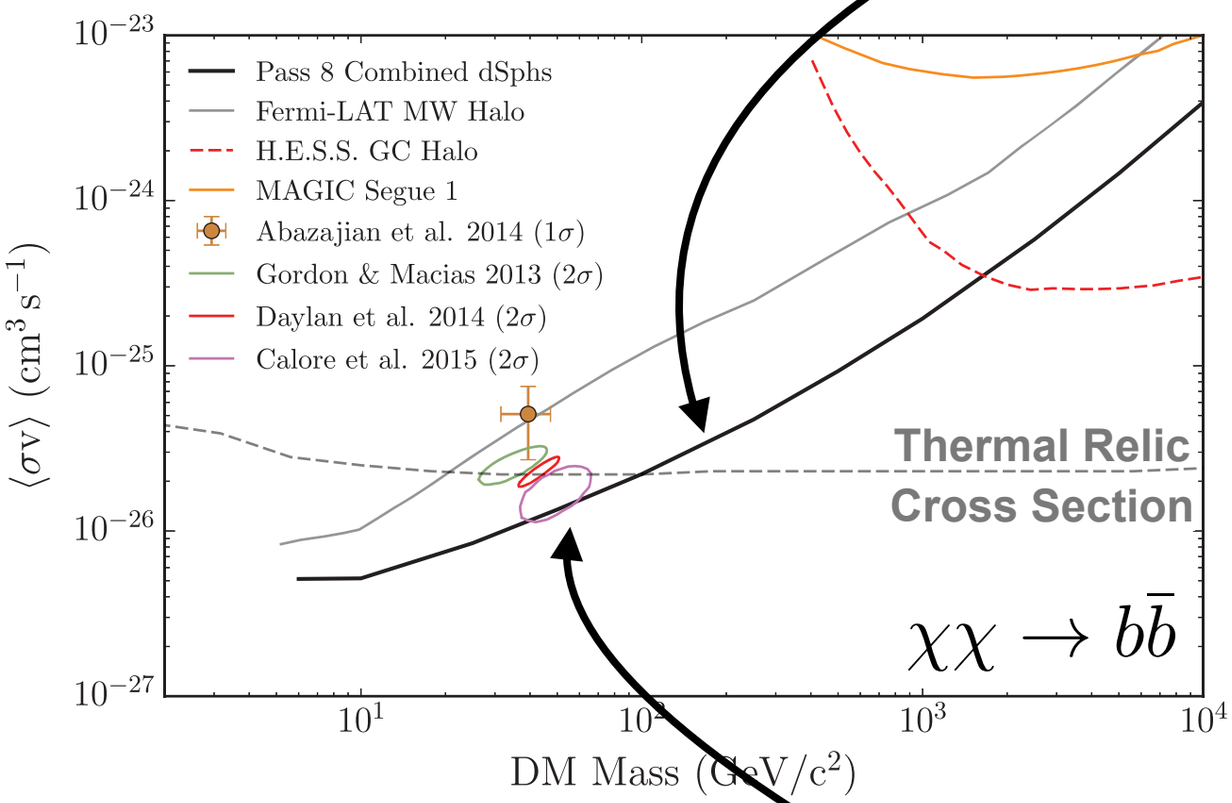
Draco Dwarf Galaxy (0.5 GeV < Eγ < 500 GeV)

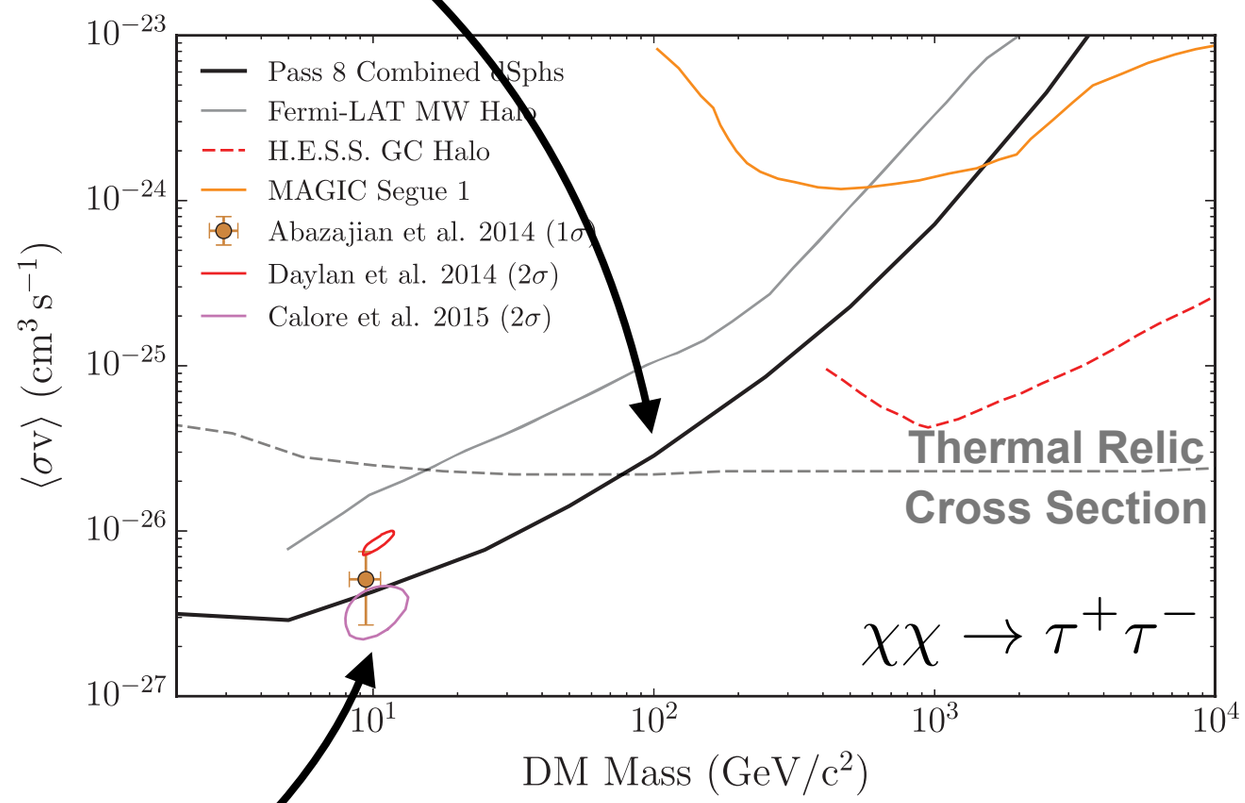


— Dark Matter Halo Size
— LAT Resolution (68%/95%)

Dwarf Galaxy Constraints

Combined upper limits from observations of 15 dwarf galaxies





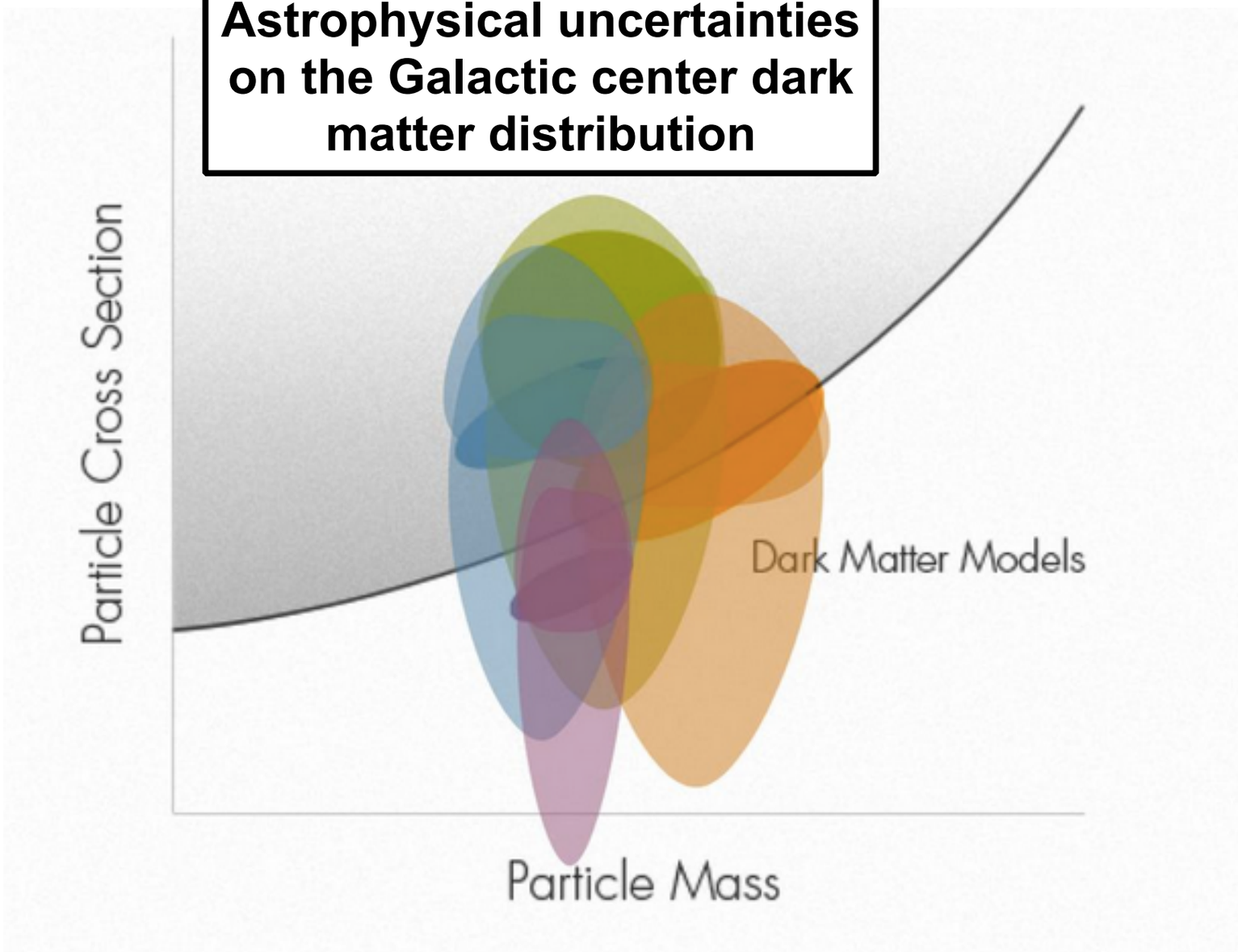
Dark matter interpretations of the Galactic Center excess

Ackermann et al. 2015 (1503.02641)

Galactic Center Comparison

CARTOON

Astrophysical uncertainties on the Galactic center dark matter distribution

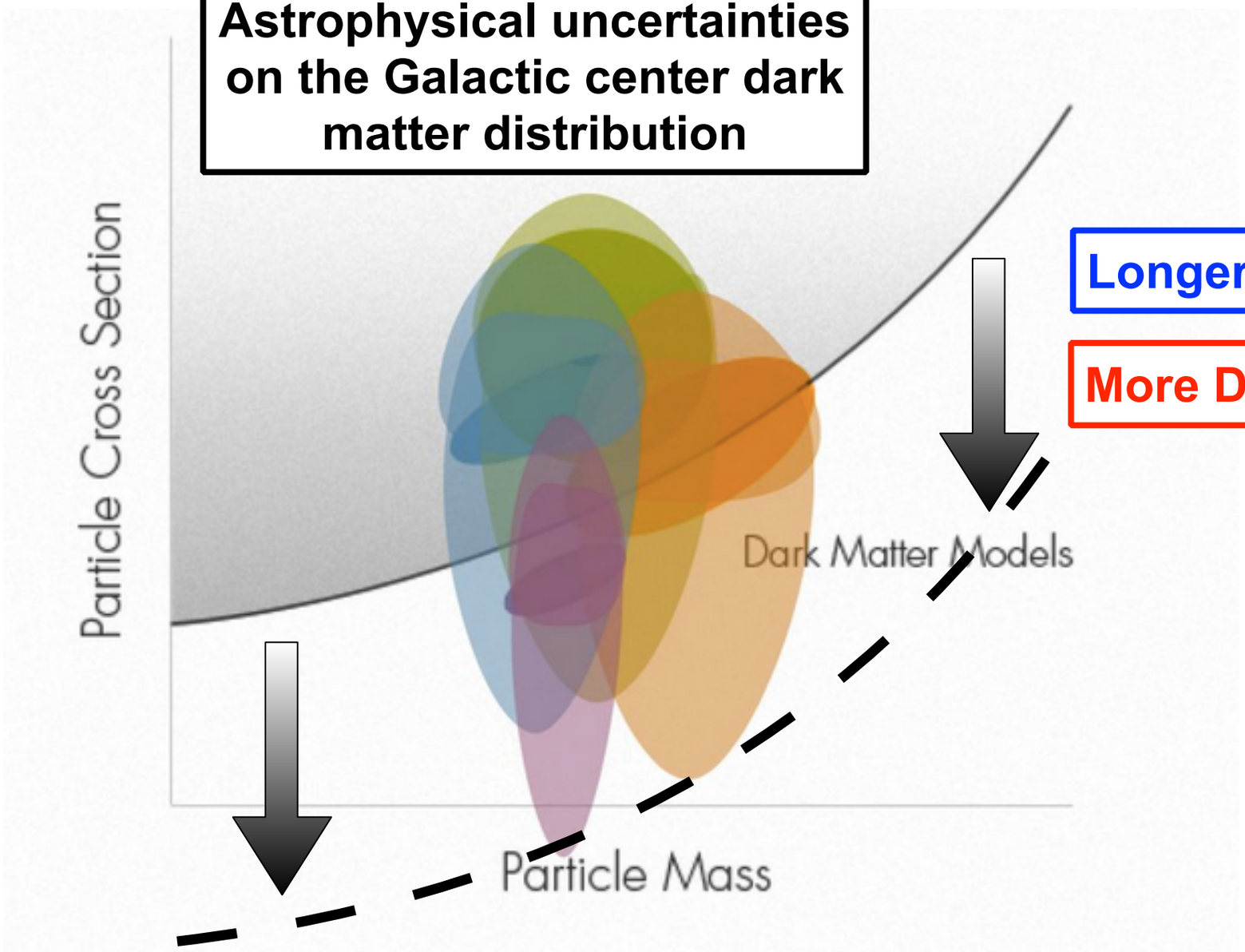


Quanta Magazine & Kev Abazajian

Galactic Center Comparison

CARTOON

Astrophysical uncertainties on the Galactic center dark matter distribution



Longer Exposure

More Dwarf Galaxies

Quanta Magazine & Kev Abazajian

- Dark Matter & Indirect Detection
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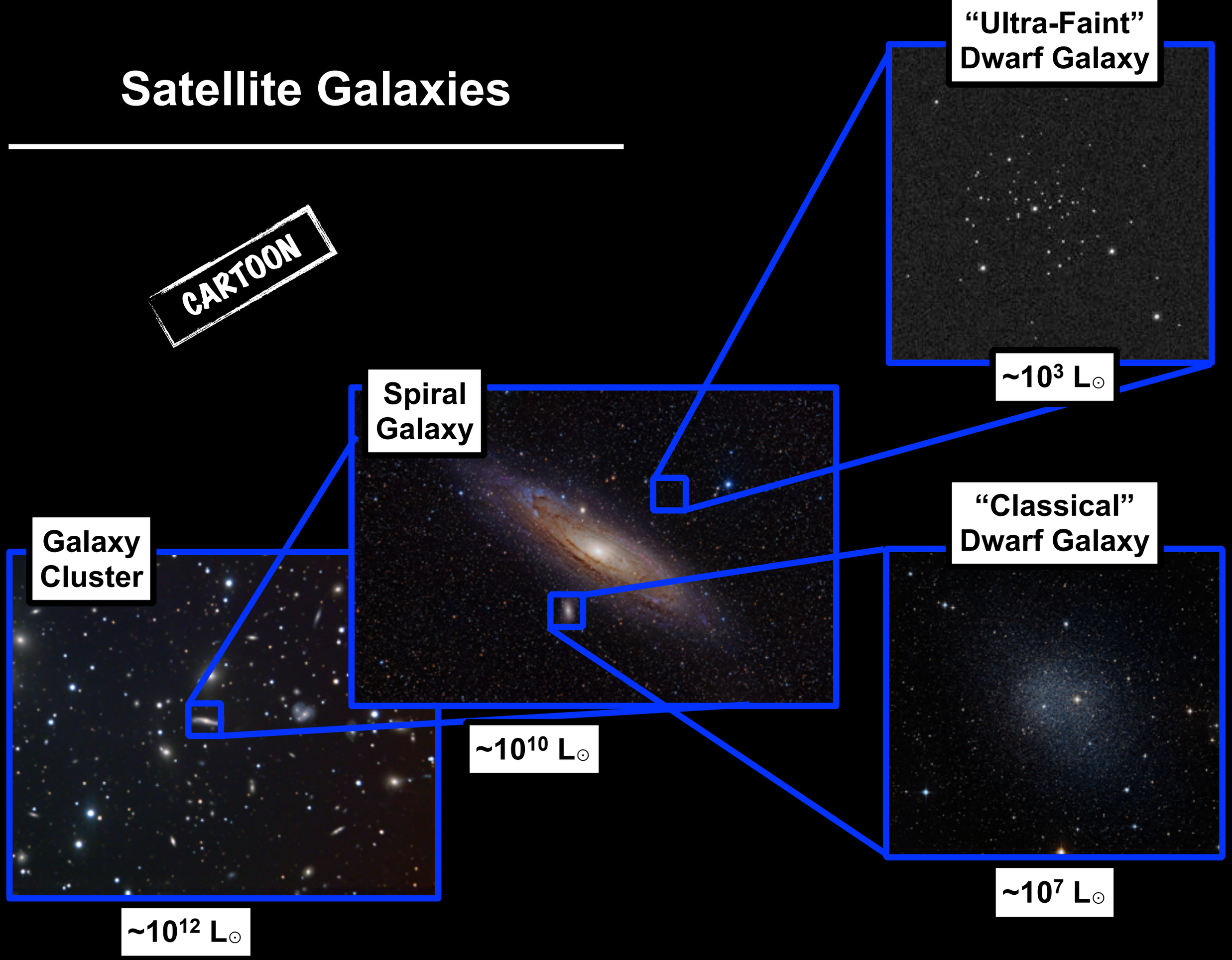
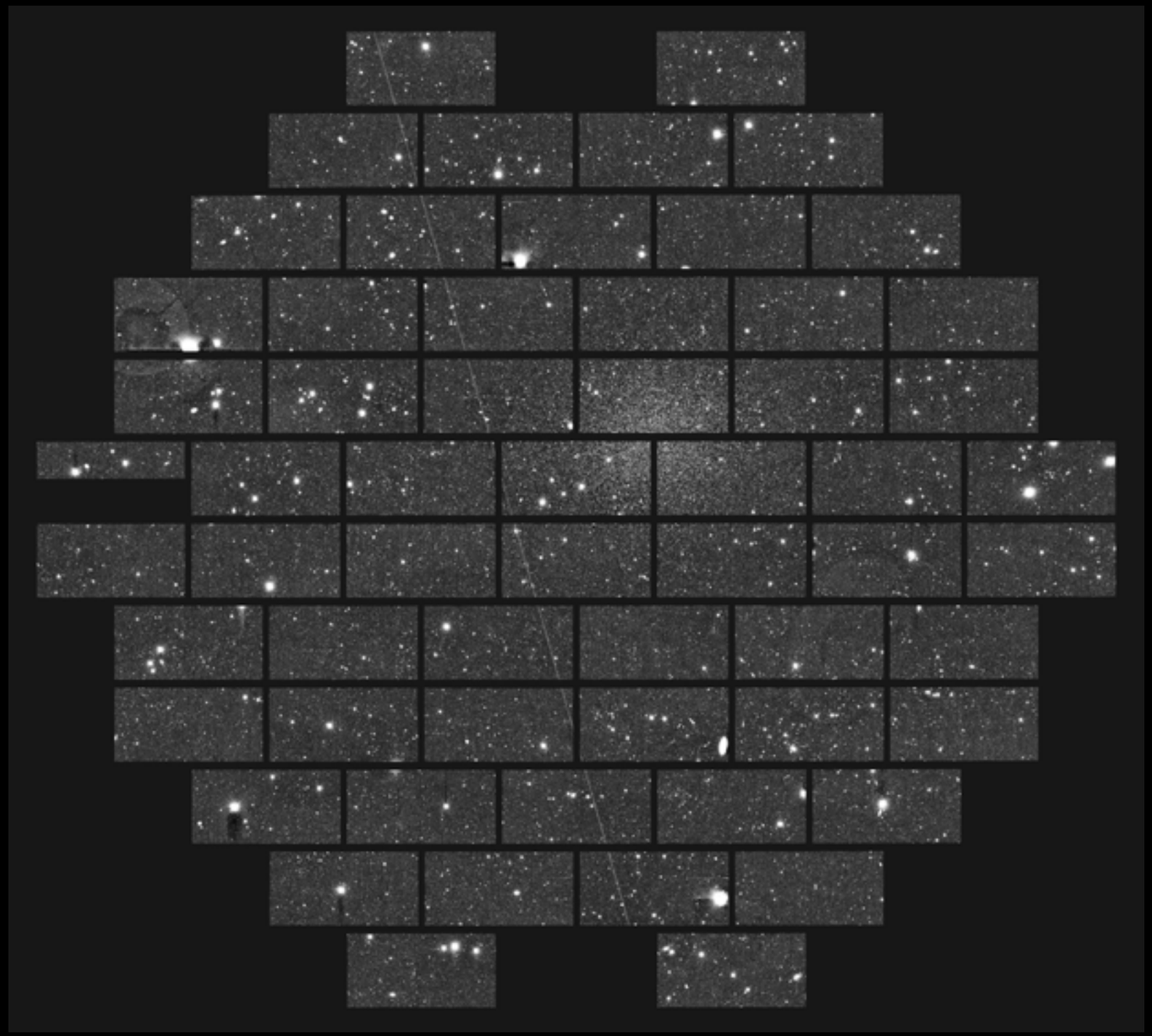
Satellite Galaxies



Dark Energy Camera (DECam) Image



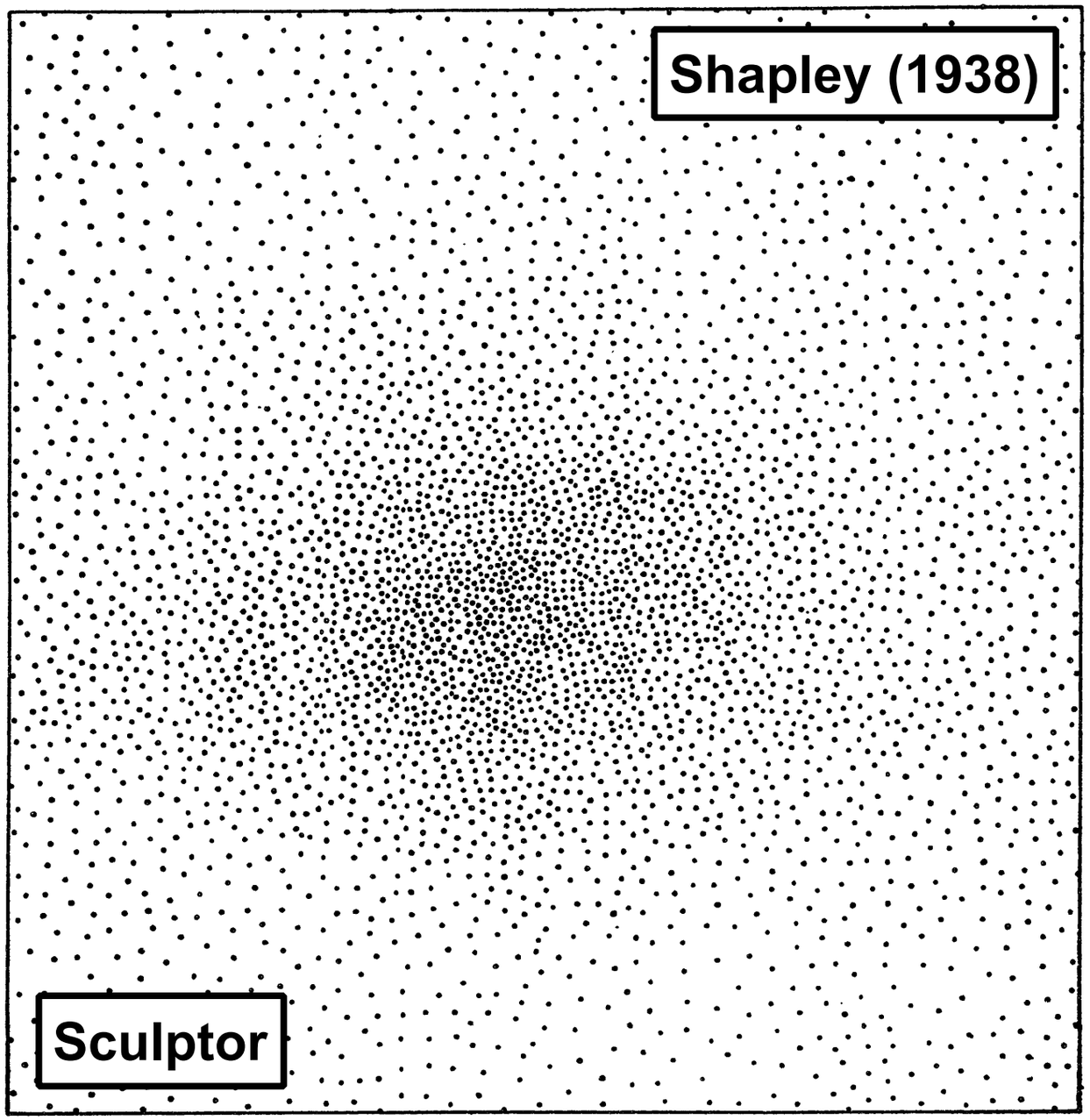
Finding Milky Way Satellite Galaxies

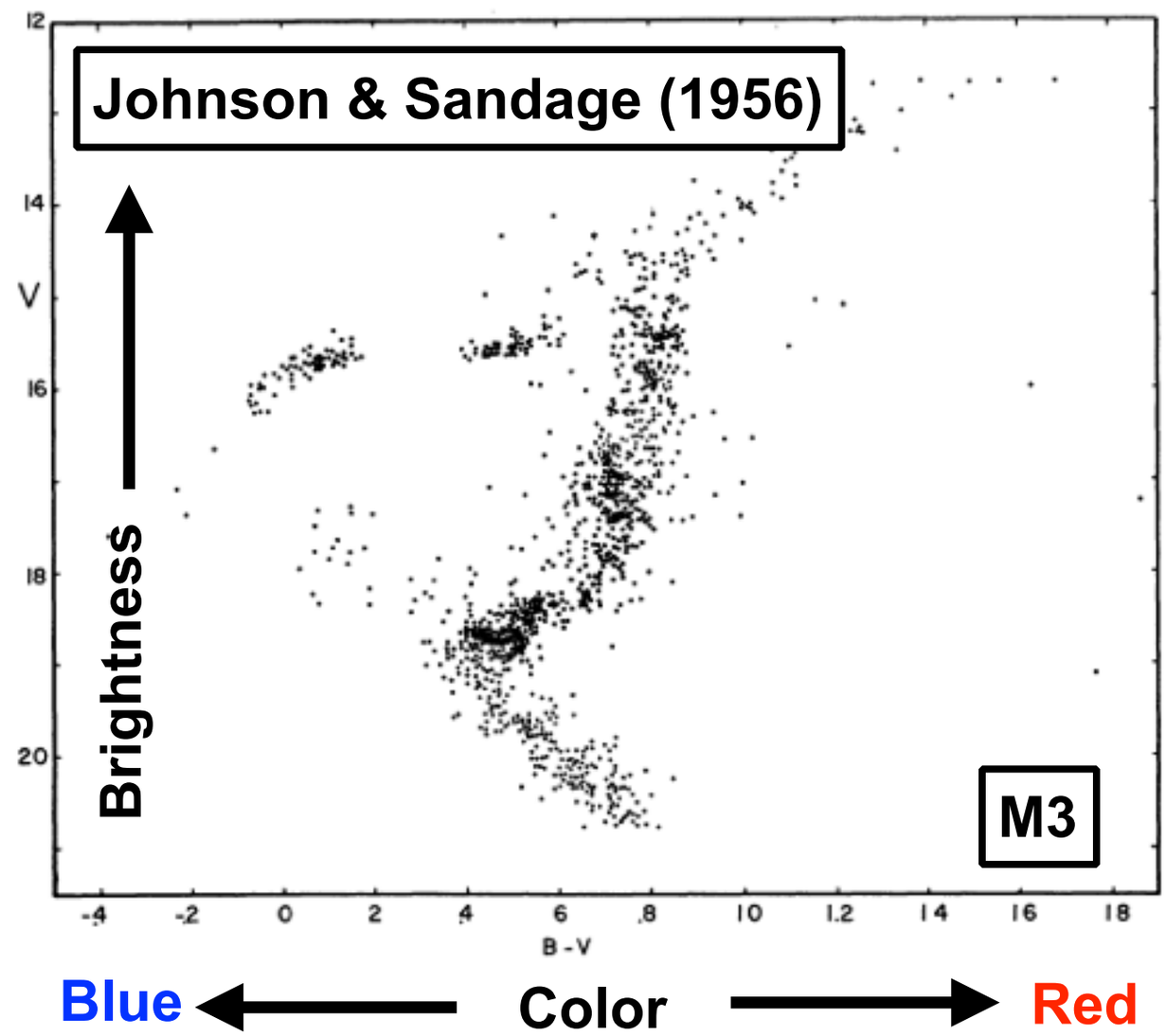
Detectors Drive Discoveries

Naked Eye

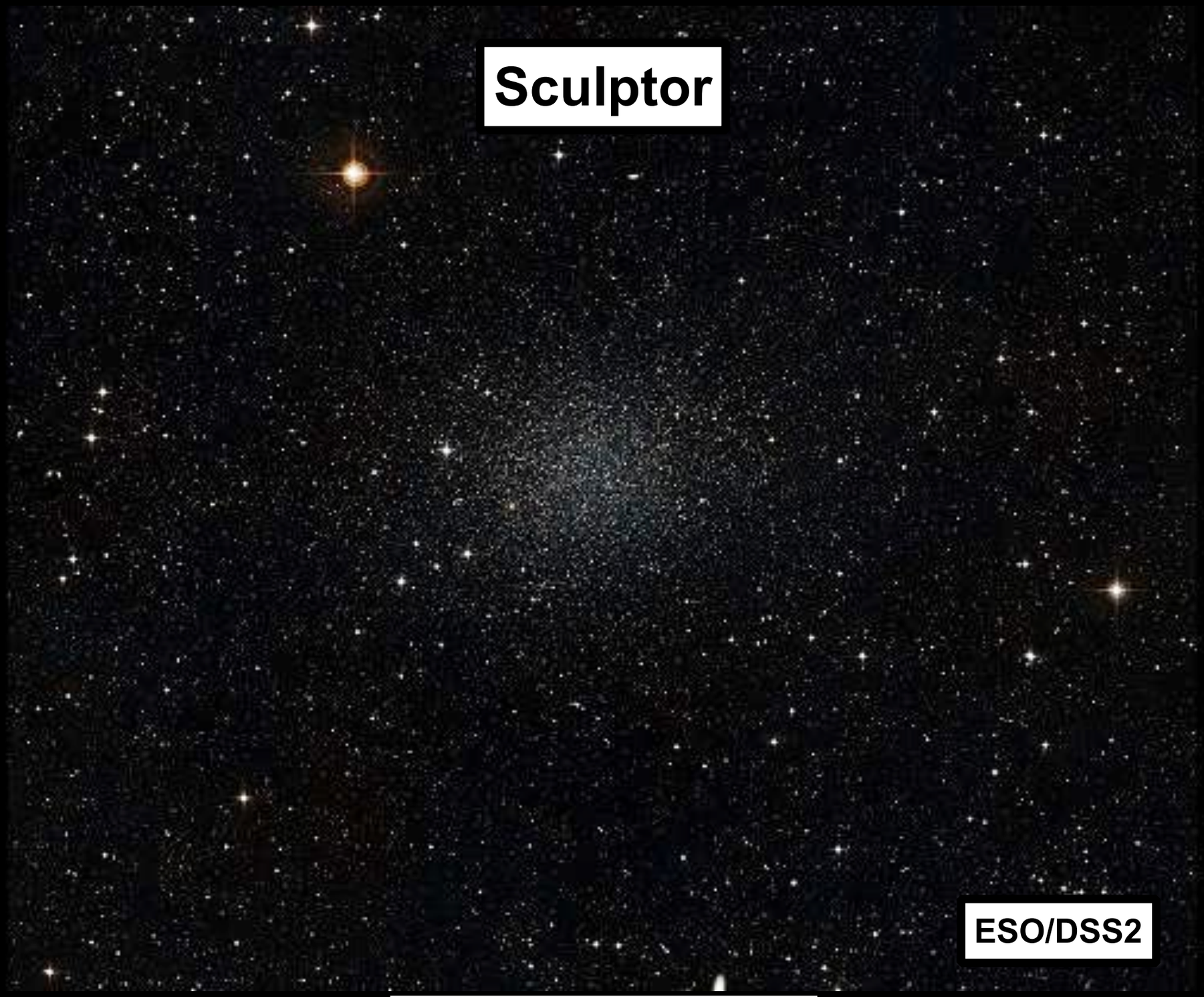
Visual Searches

- **First objects discovered by visual scans of photographic plates**



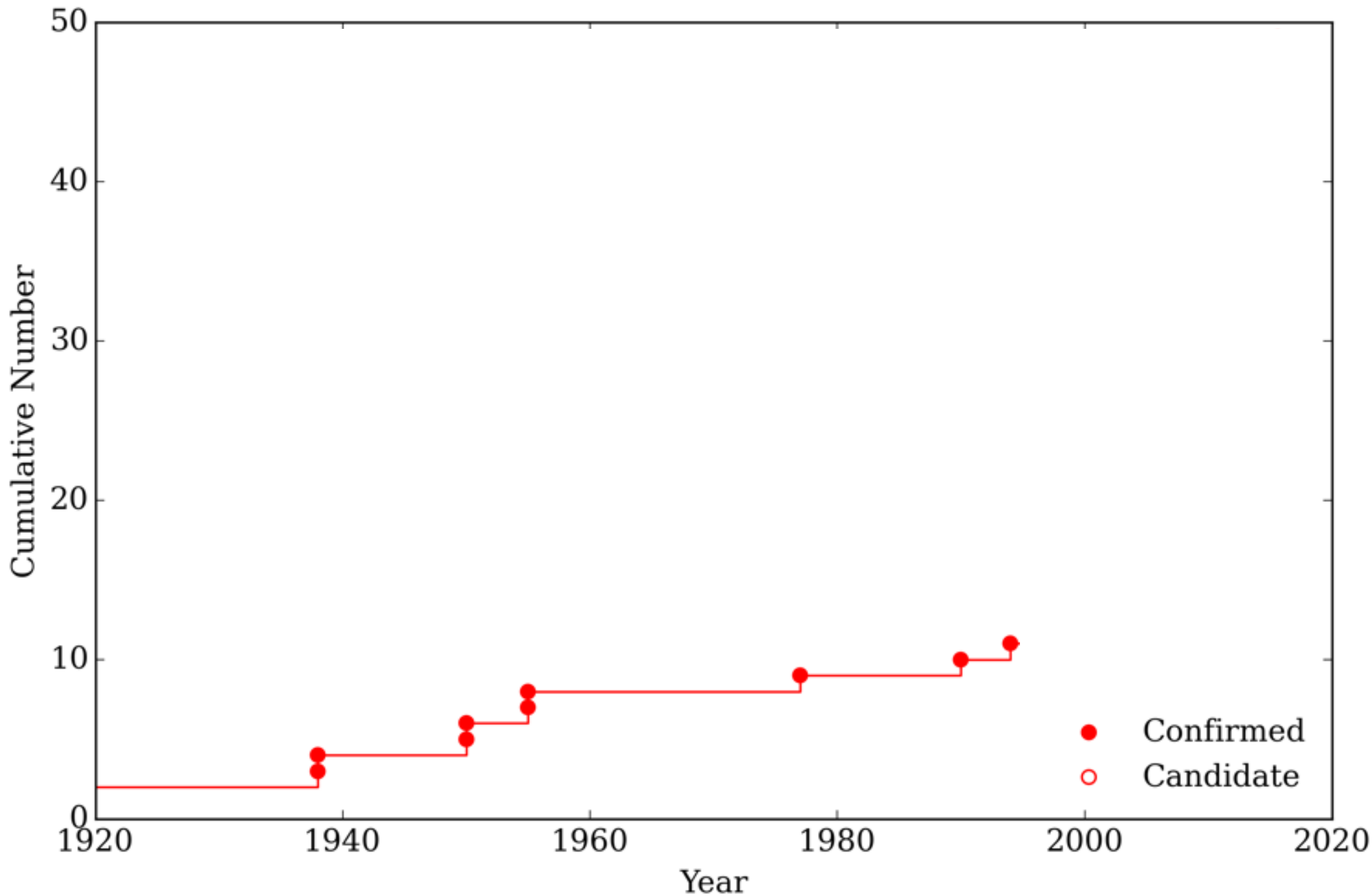


24-inch Telescope Photographic Plates



1.2m Telescope
Photographic Plates

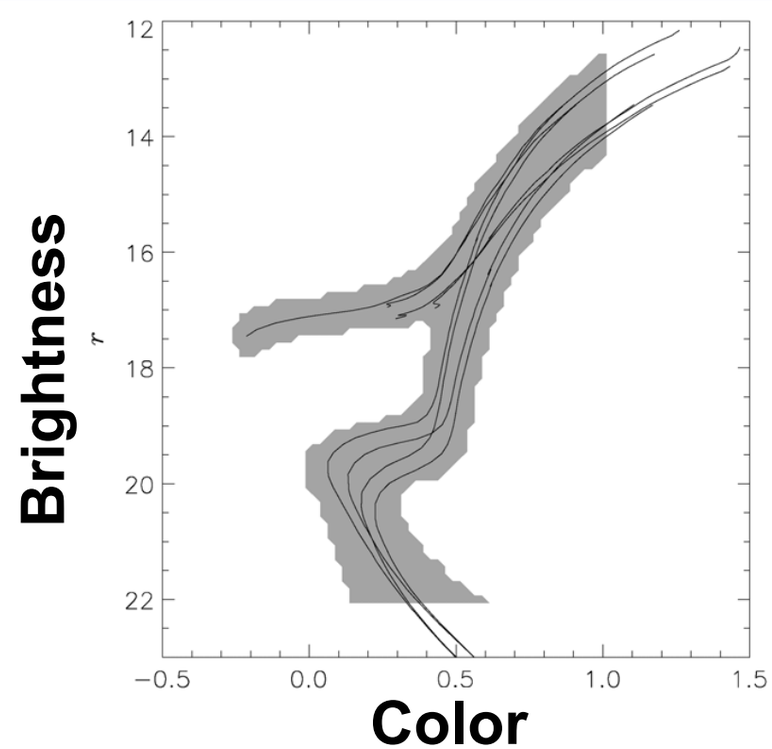
Discovery Timeline

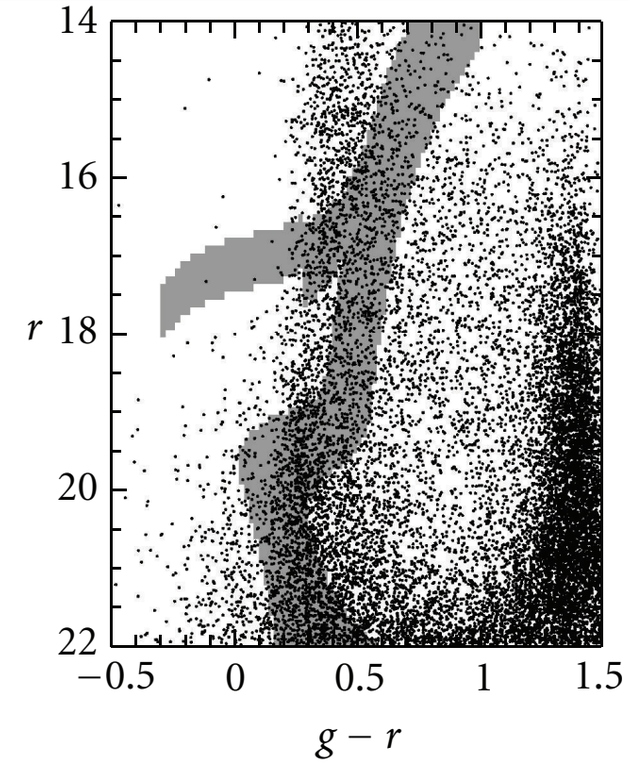


Matched-Filter Searches

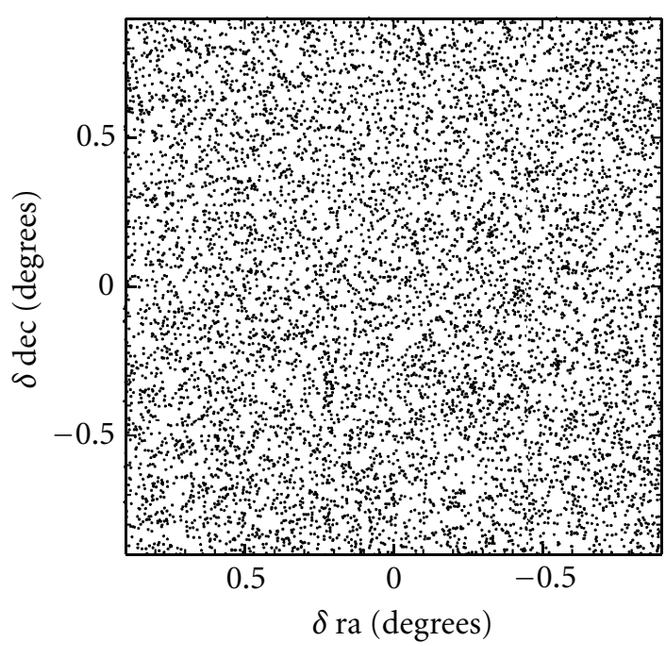
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

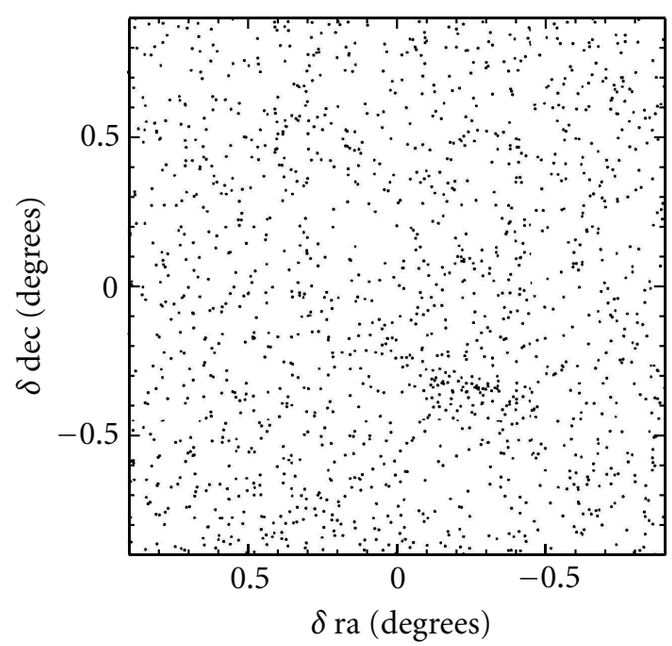
Color-Brightness Domain

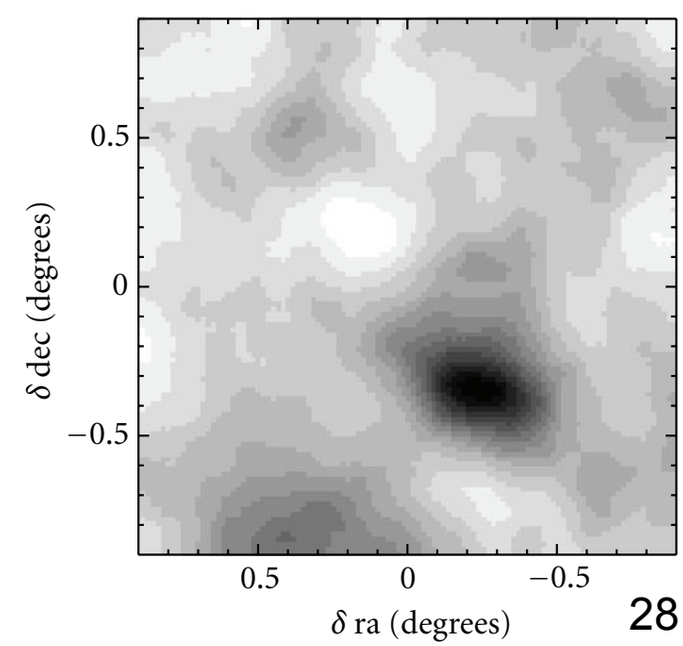


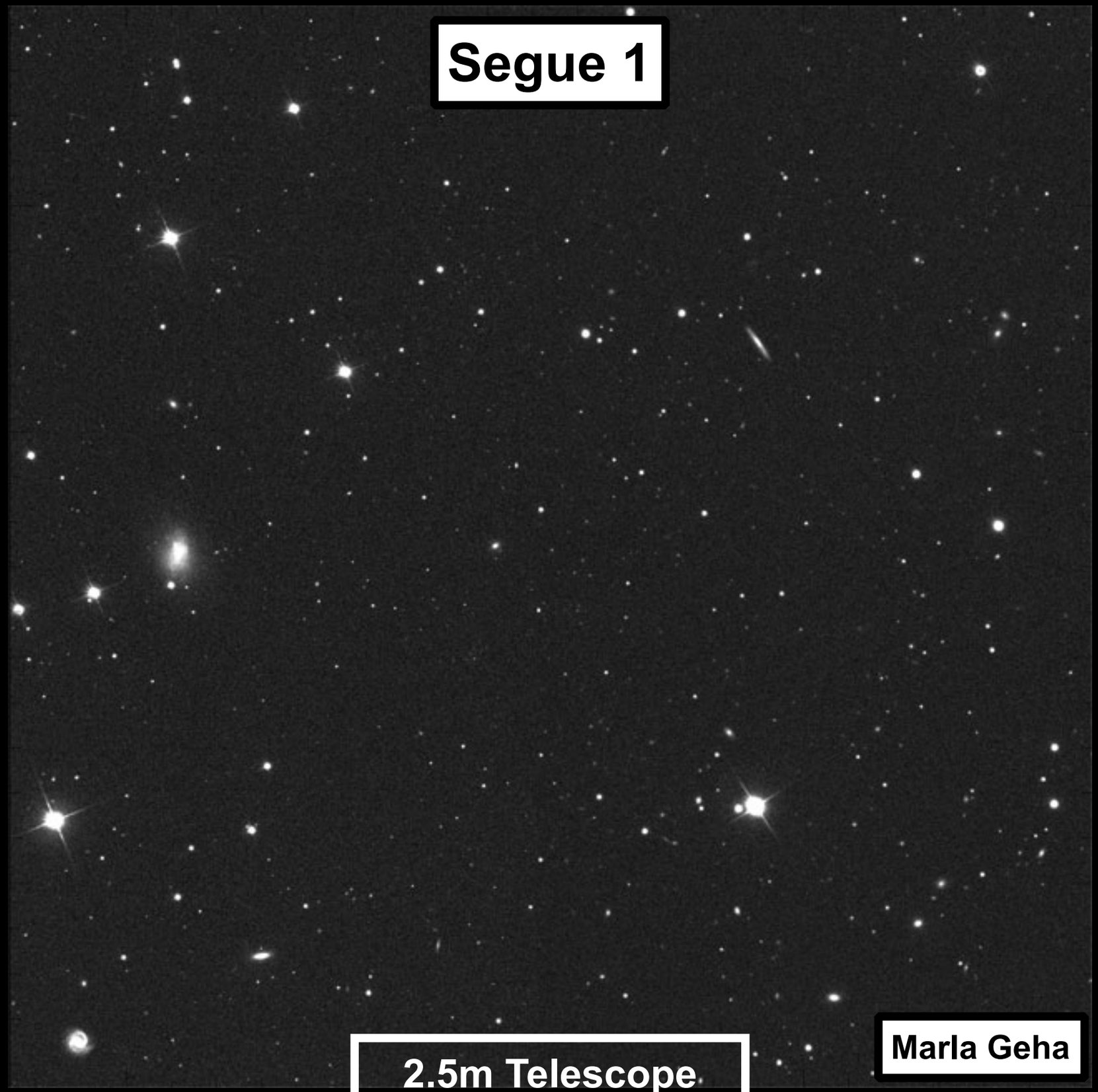


Spatial Domain

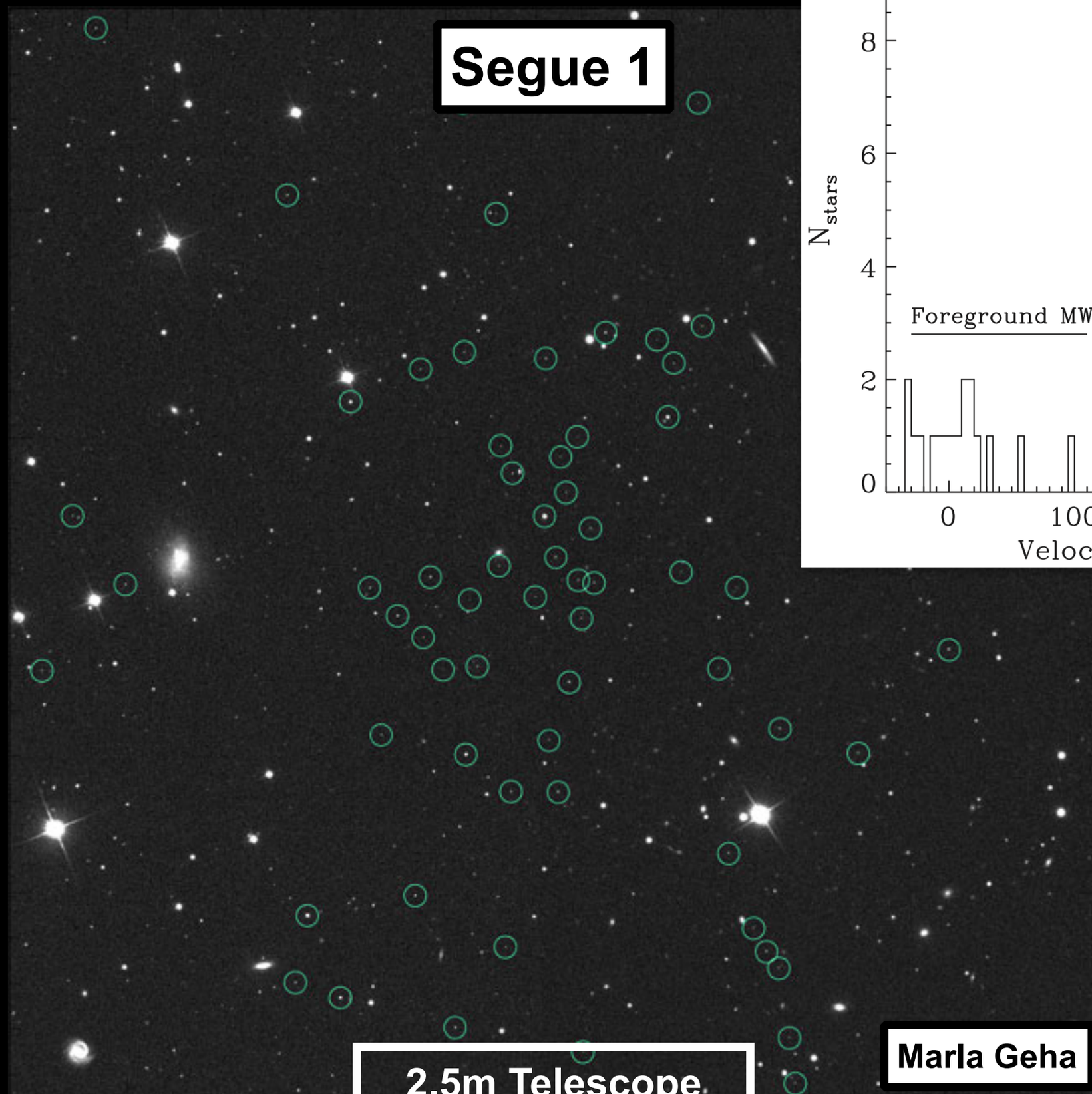


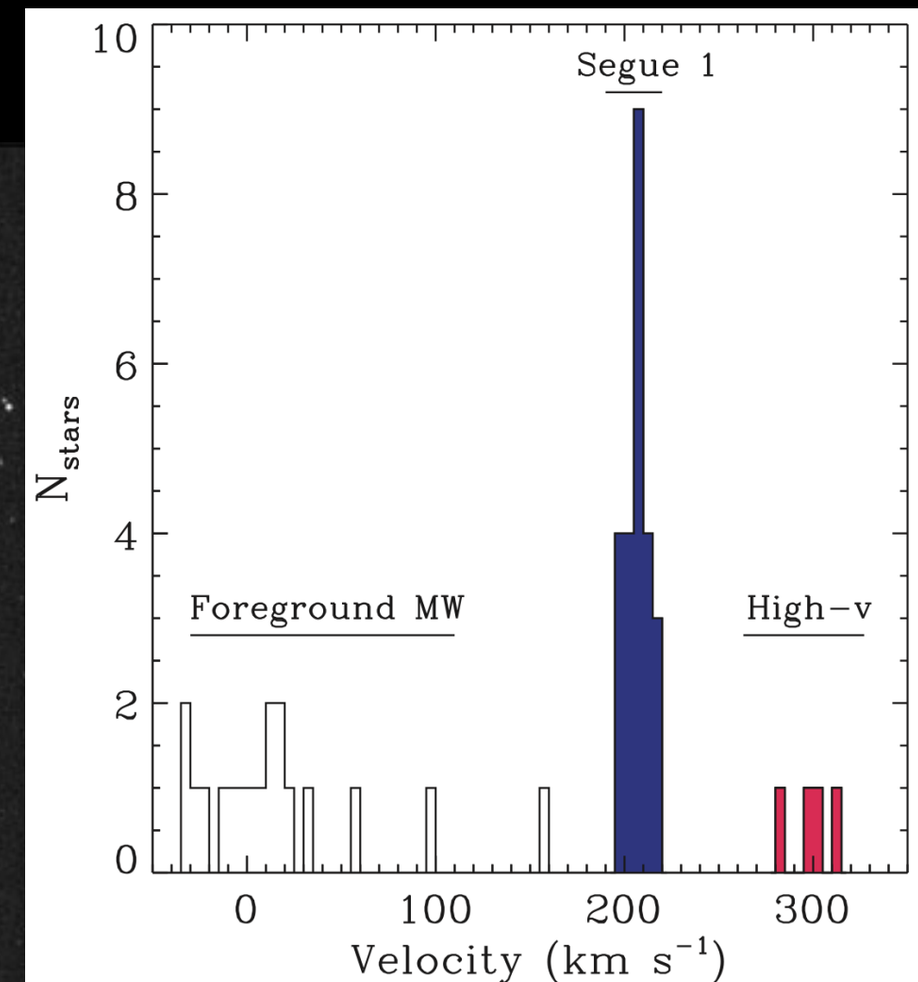






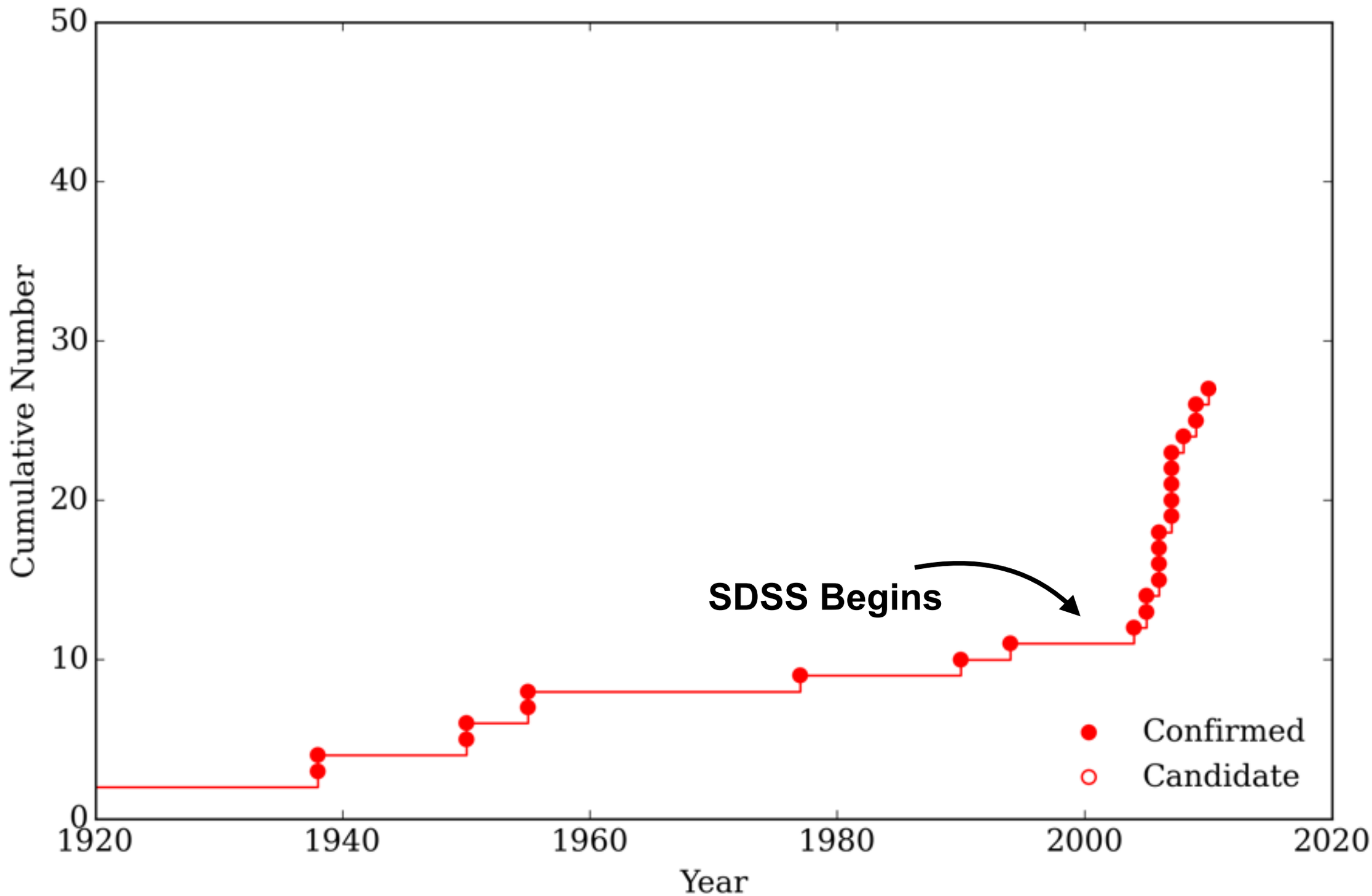
2.5m Telescope
SDSS CCD Camera



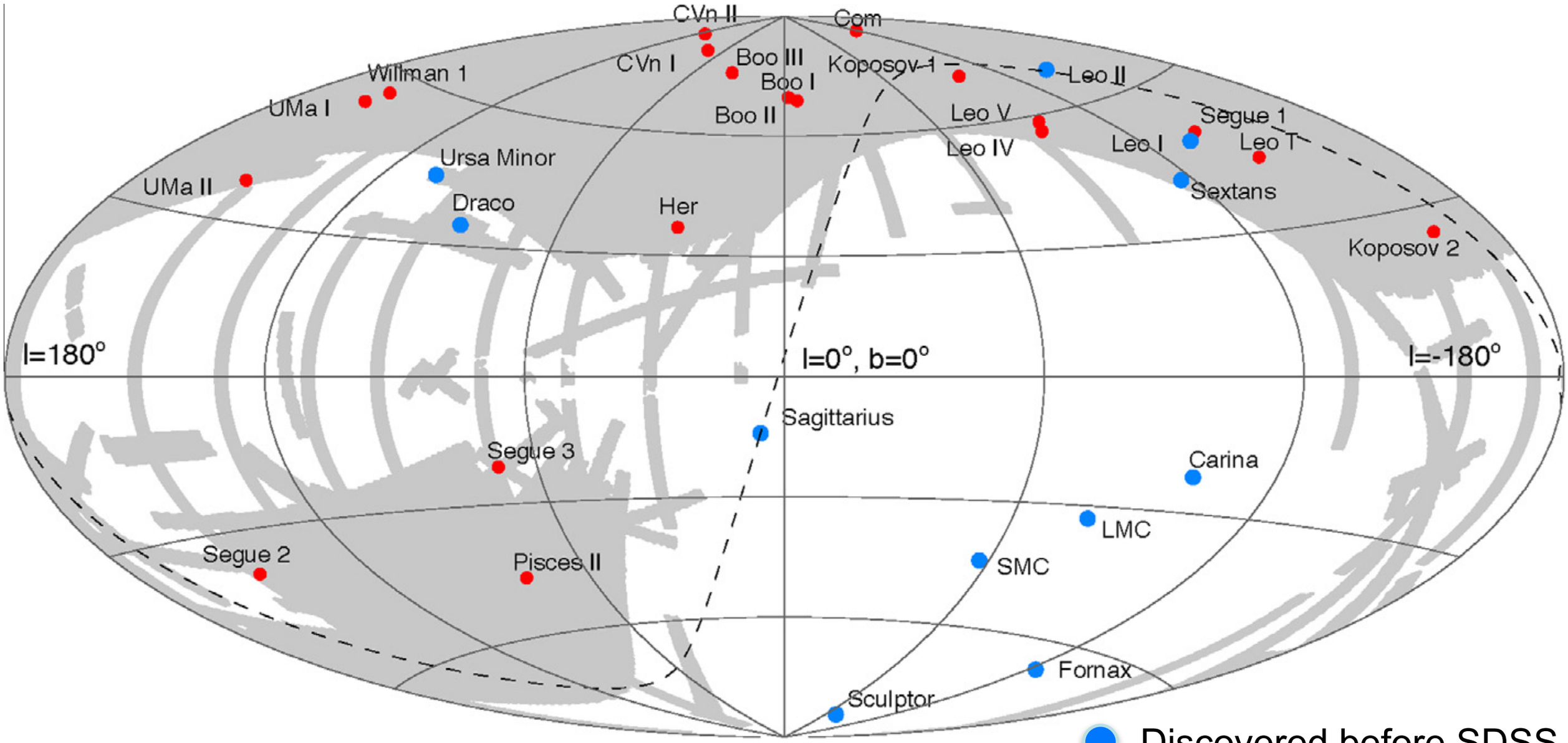


2.5m Telescope
SDSS CCD Camera

Discovery Timeline



SDSS DR10



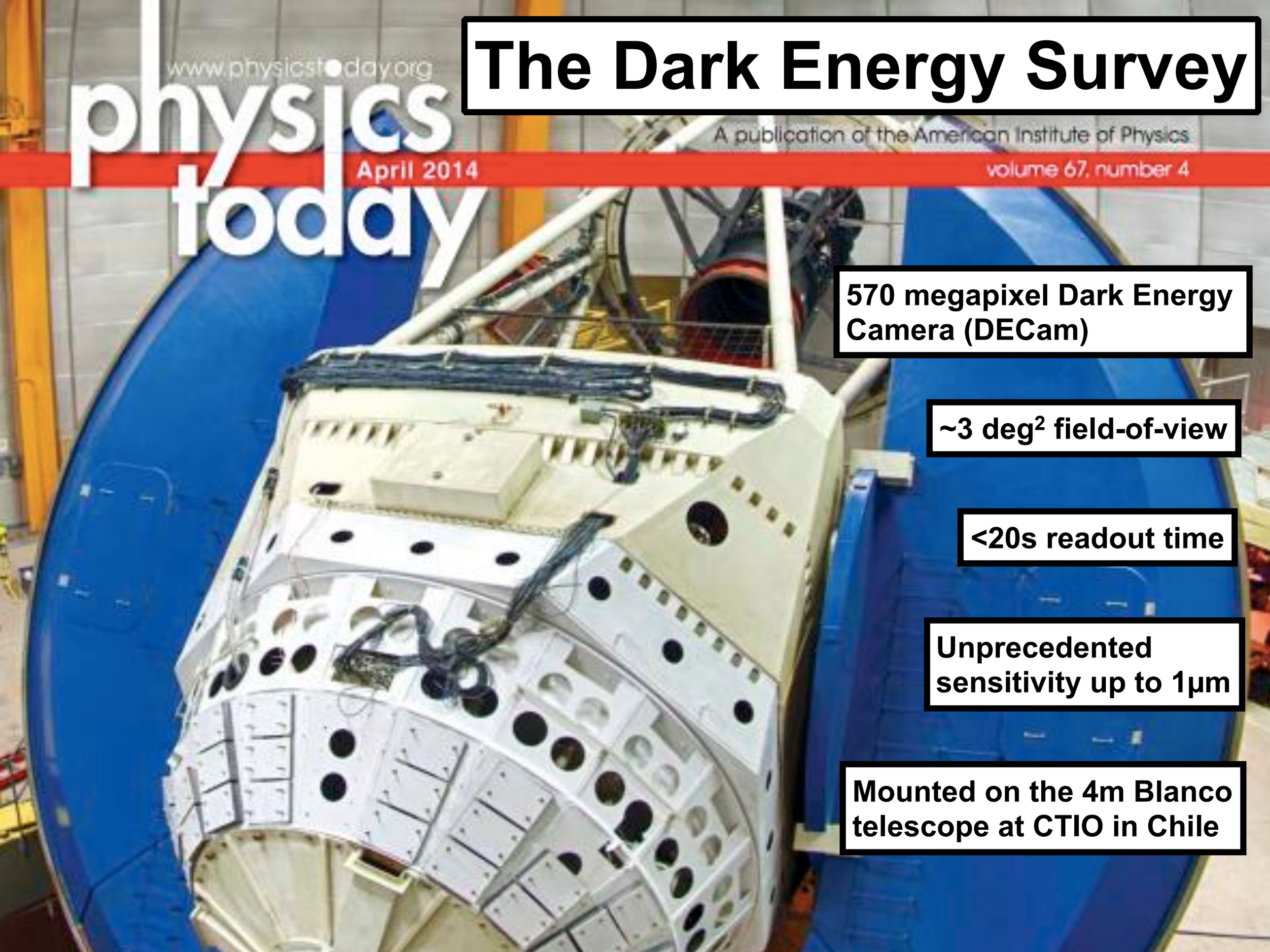
Sky Covered by SDSS

Discovered before SDSS (classical dwarfs)

Discovered with SDSS (ultra-faint dwarfs)

(Belokurov 2013)

The Dark Energy Survey



570 megapixel Dark Energy Camera (DECam)

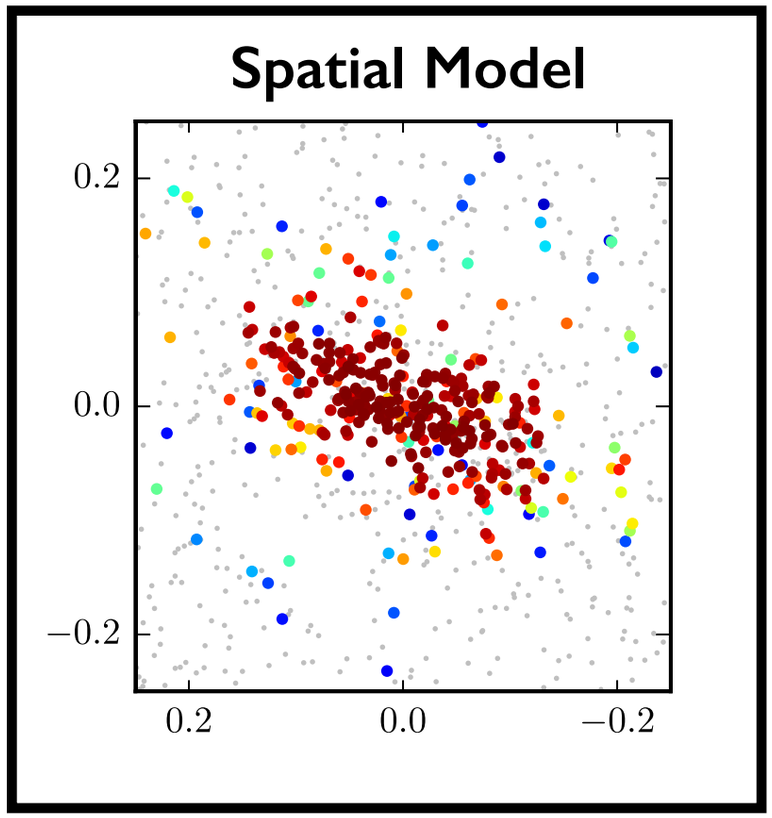
~3 deg^2 field-of-view

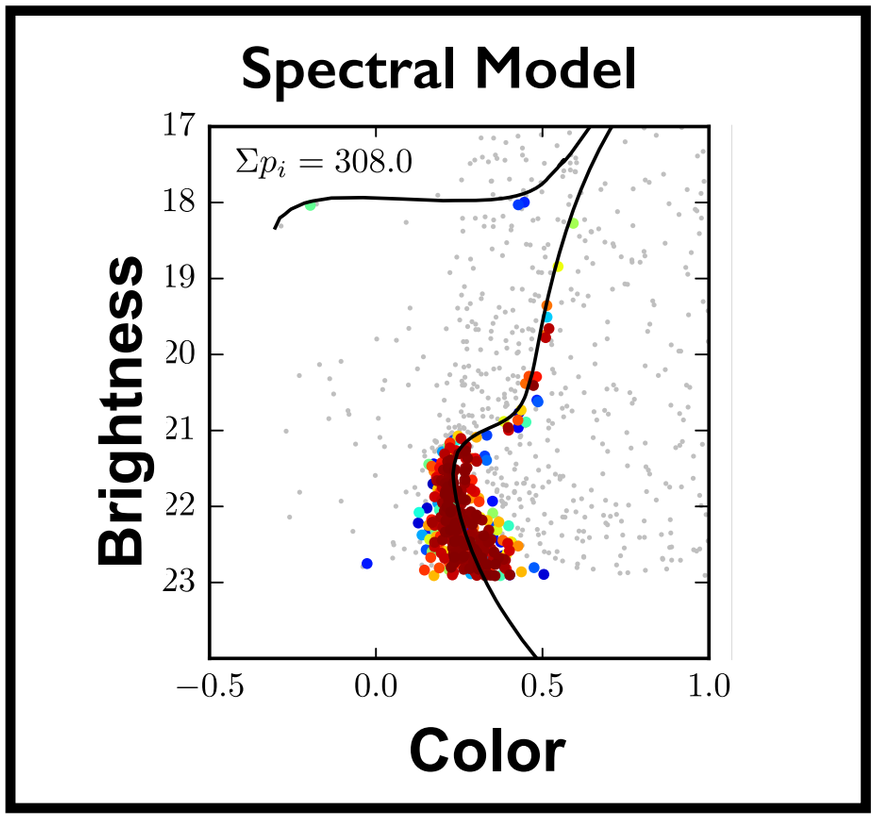
<20s readout time

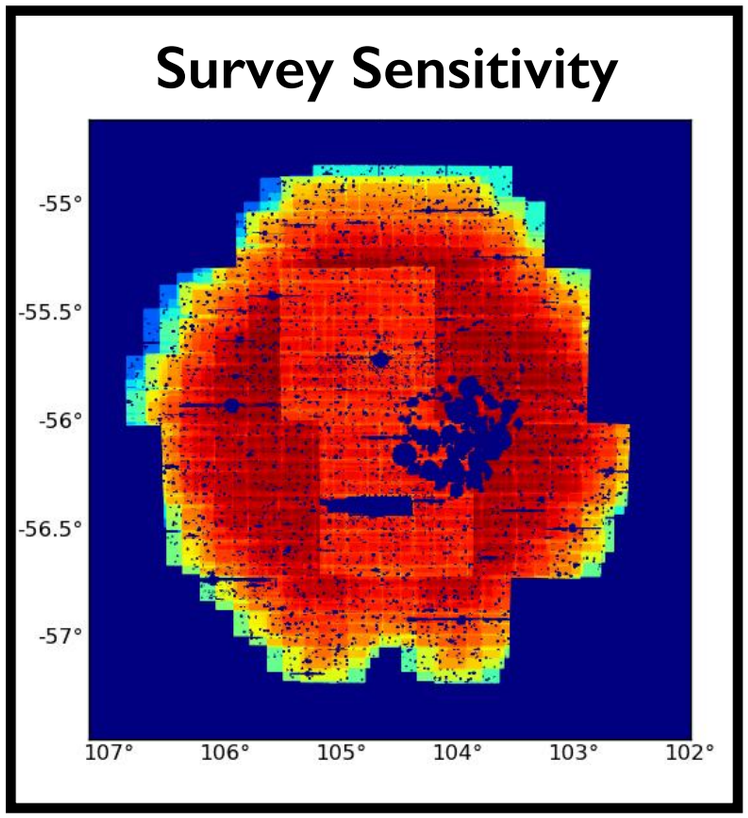
Unprecedented sensitivity up to 1μm

Mounted on the 4m Blanco telescope at CTIO in Chile

Maximum-Likelihood Searches







$$p_i = \frac{\lambda u_i}{\lambda u_i + b_i}$$

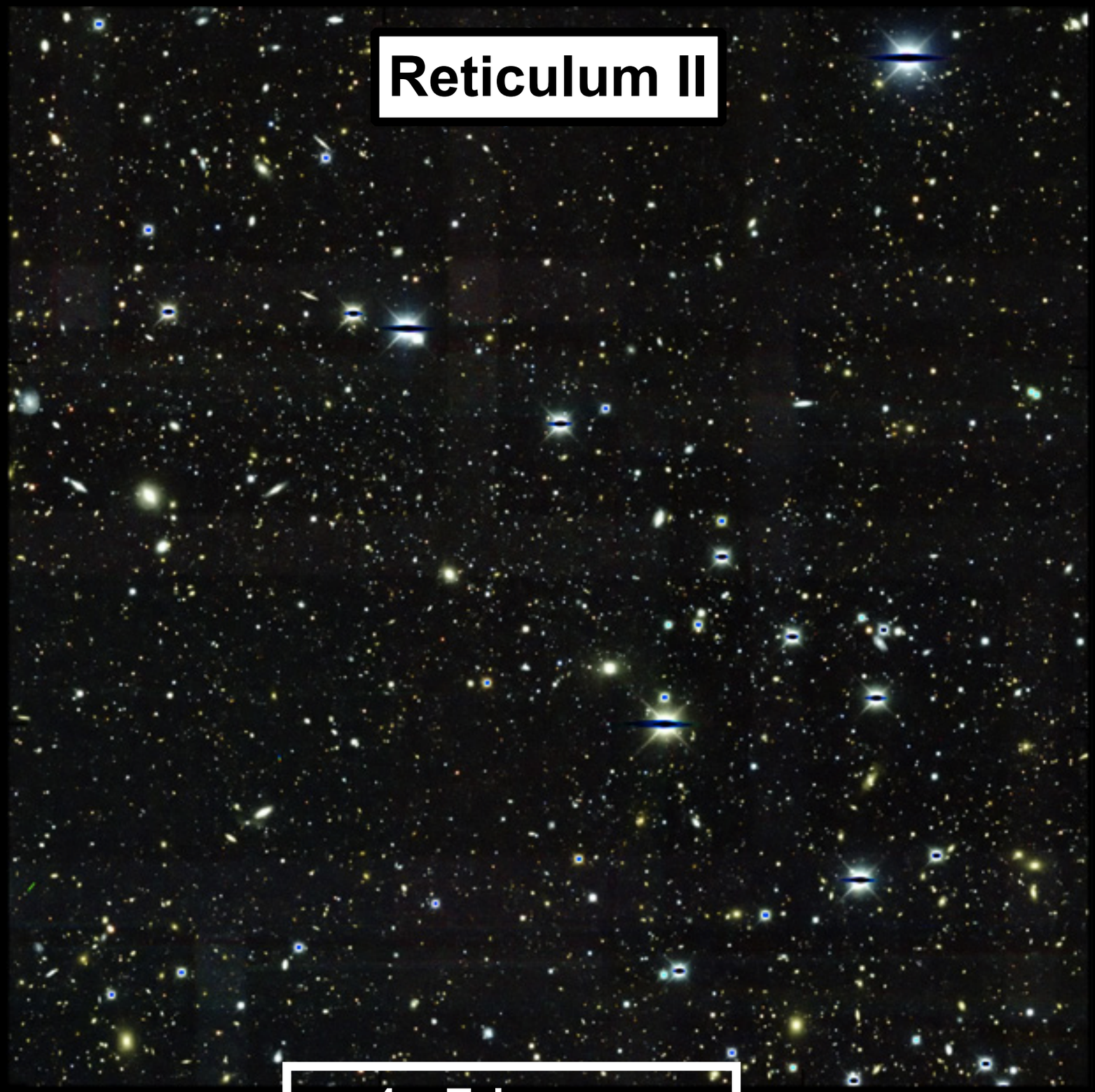
$$\lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i$$

$$\log L = -\sum_{i \in \text{Stars}} \log(1 - p_i) - f\lambda$$

A likelihood analysis to simultaneously combines spatial and spectral information

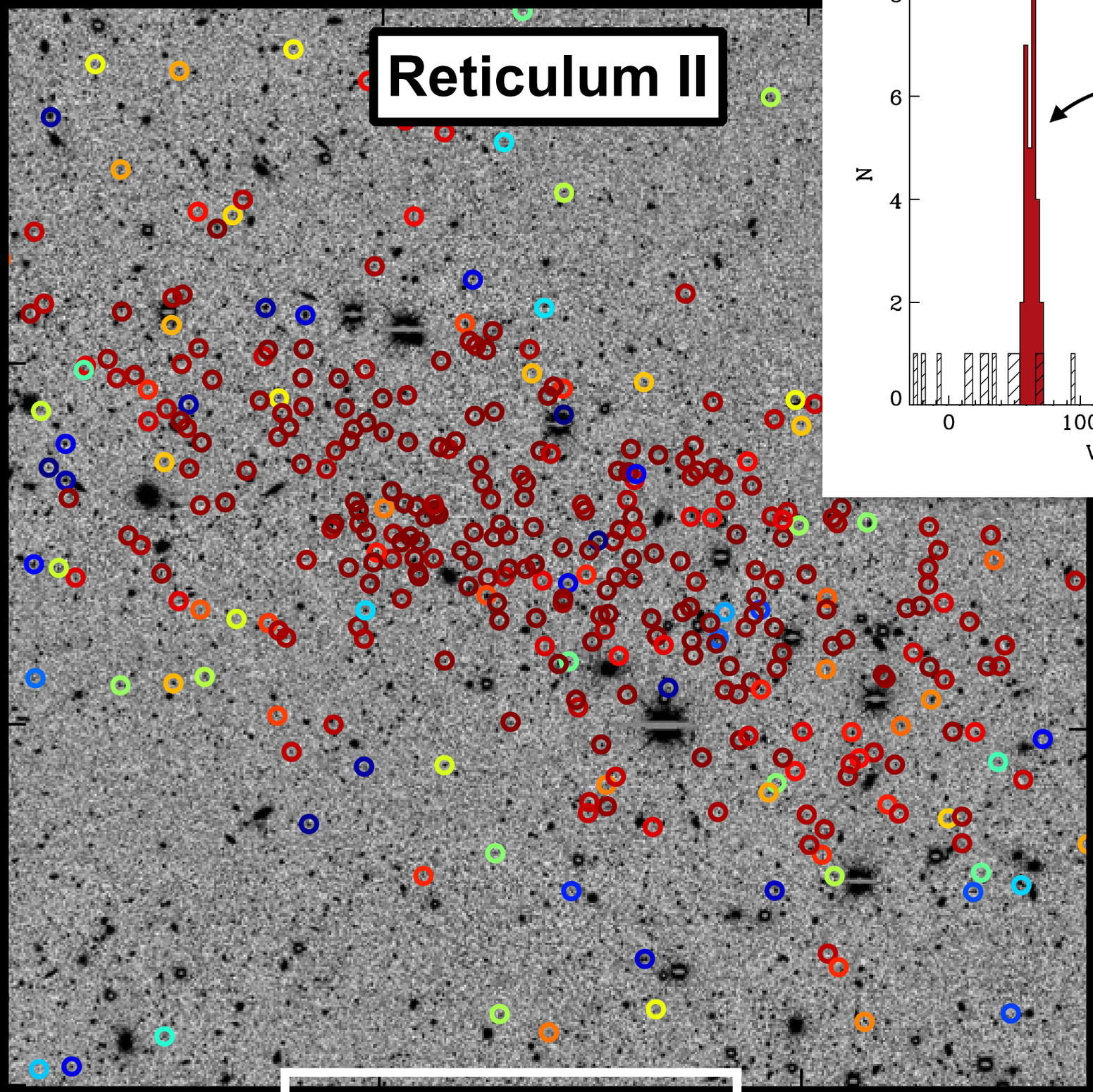
u_i = sig prob
b_i = bkg prob
λ = normalization = number of stars
f = observable fraction

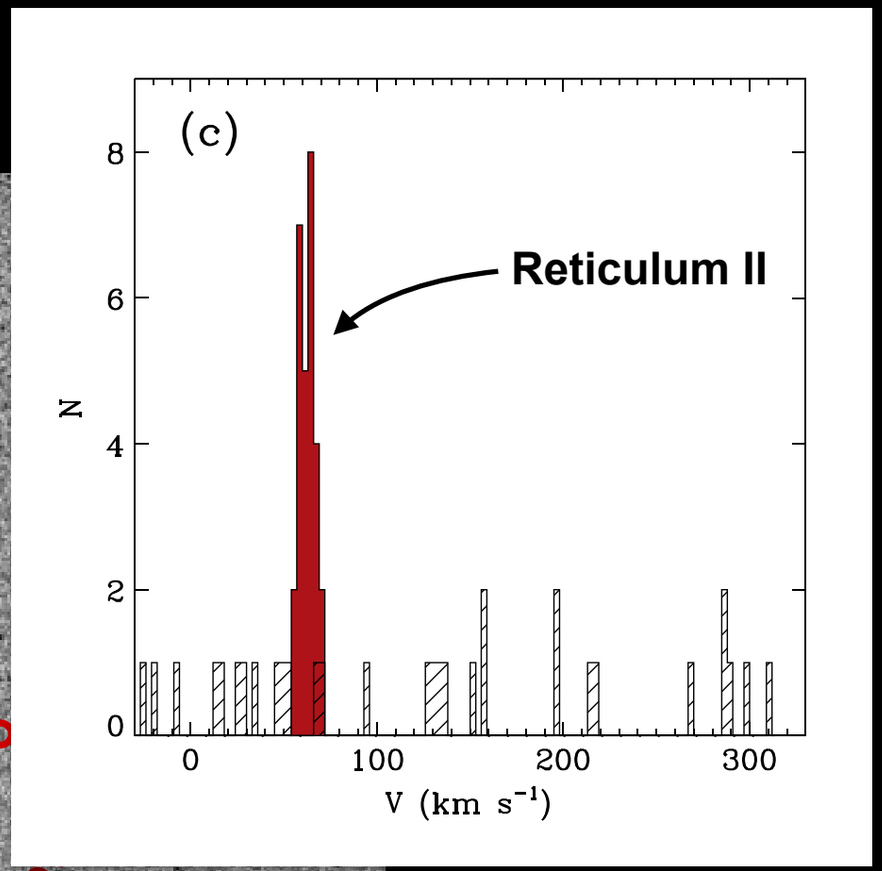
This approach naturally yields a membership probability for each star; important for spectroscopy



4m Telescope
DECam CCD Camera

DES Collaboration

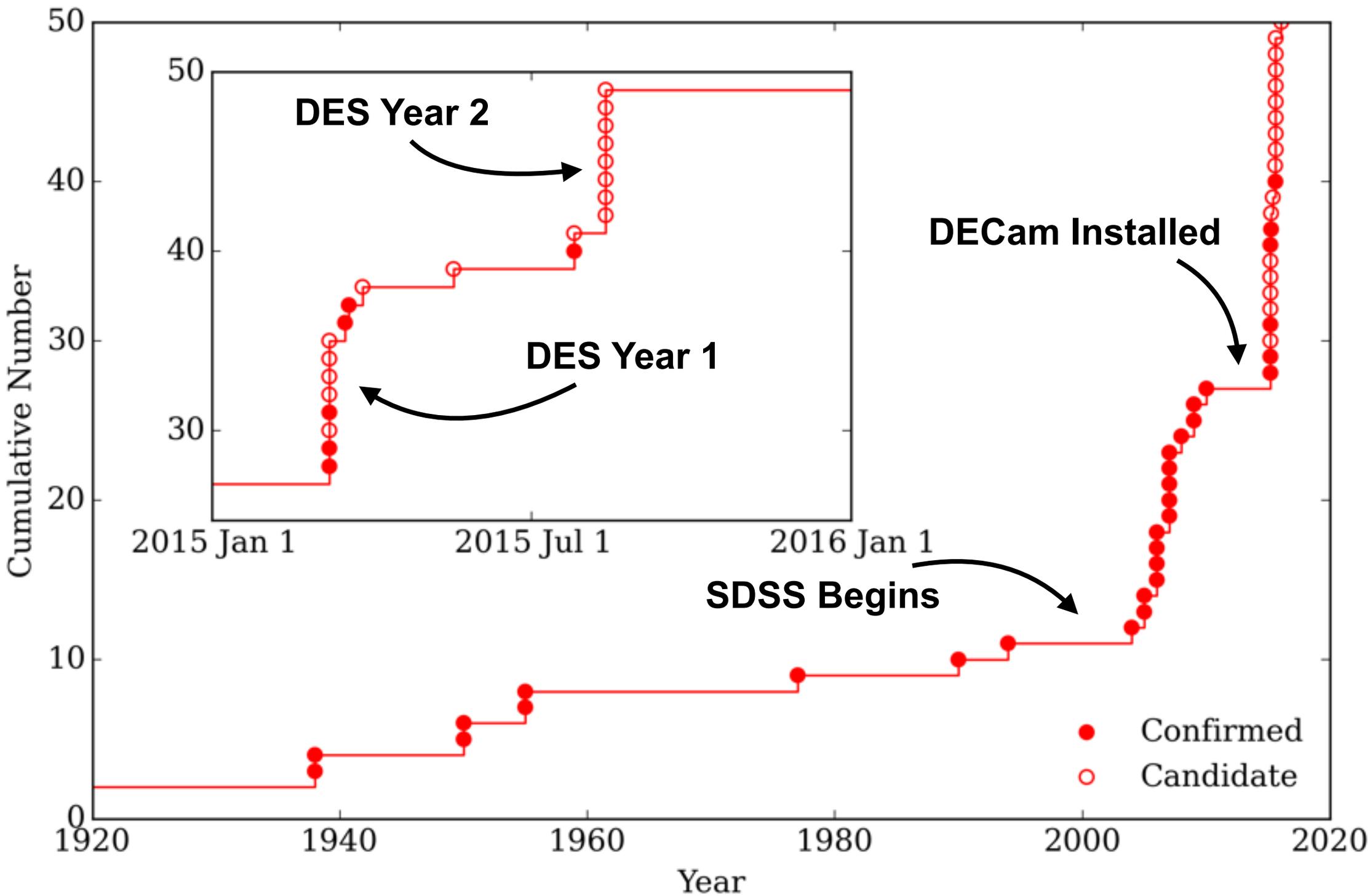




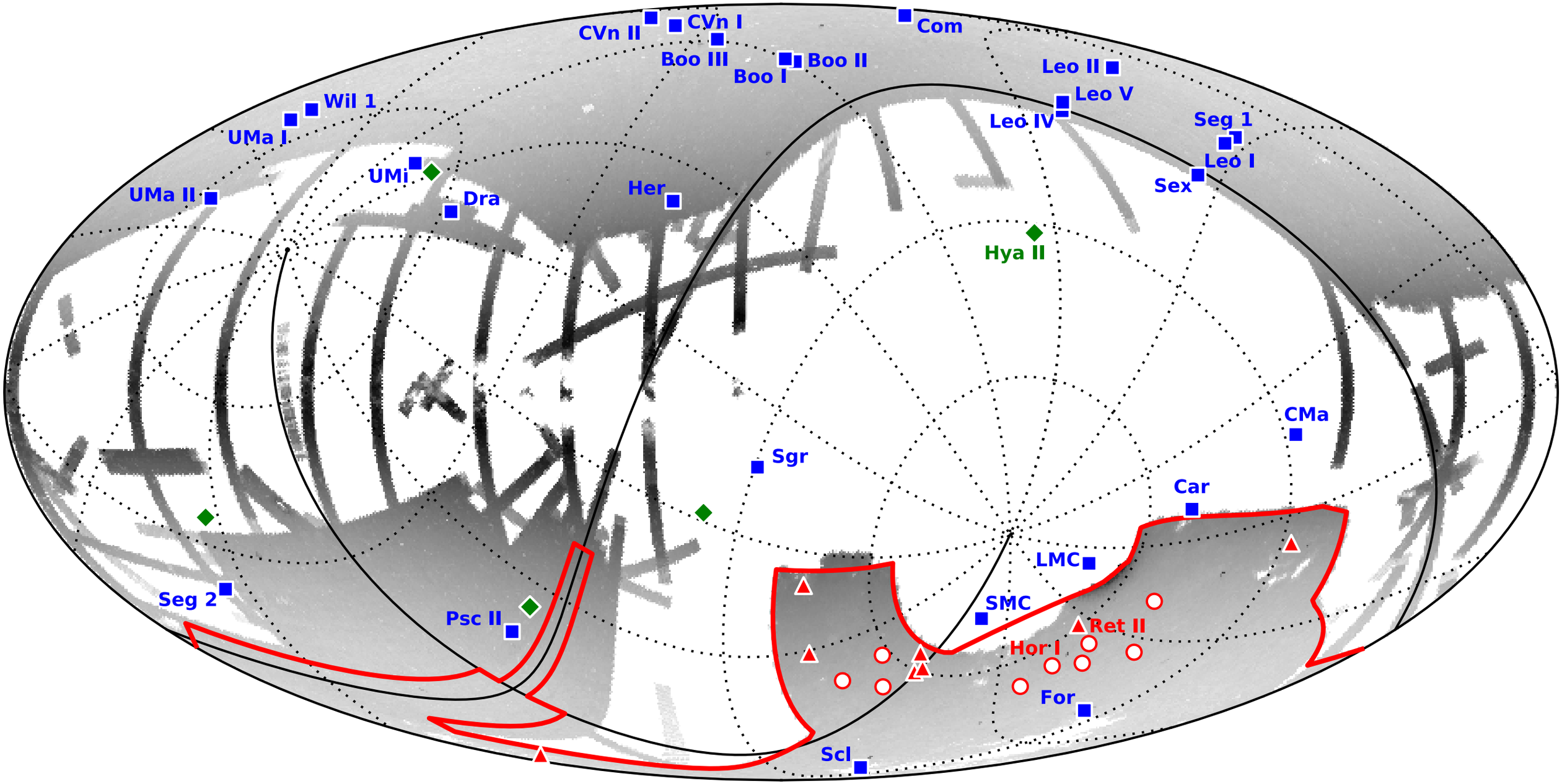
4m Telescope
DECam CCD Camera

DES Collaboration

Discovery Timeline



SDSS DR10 + DES Y2

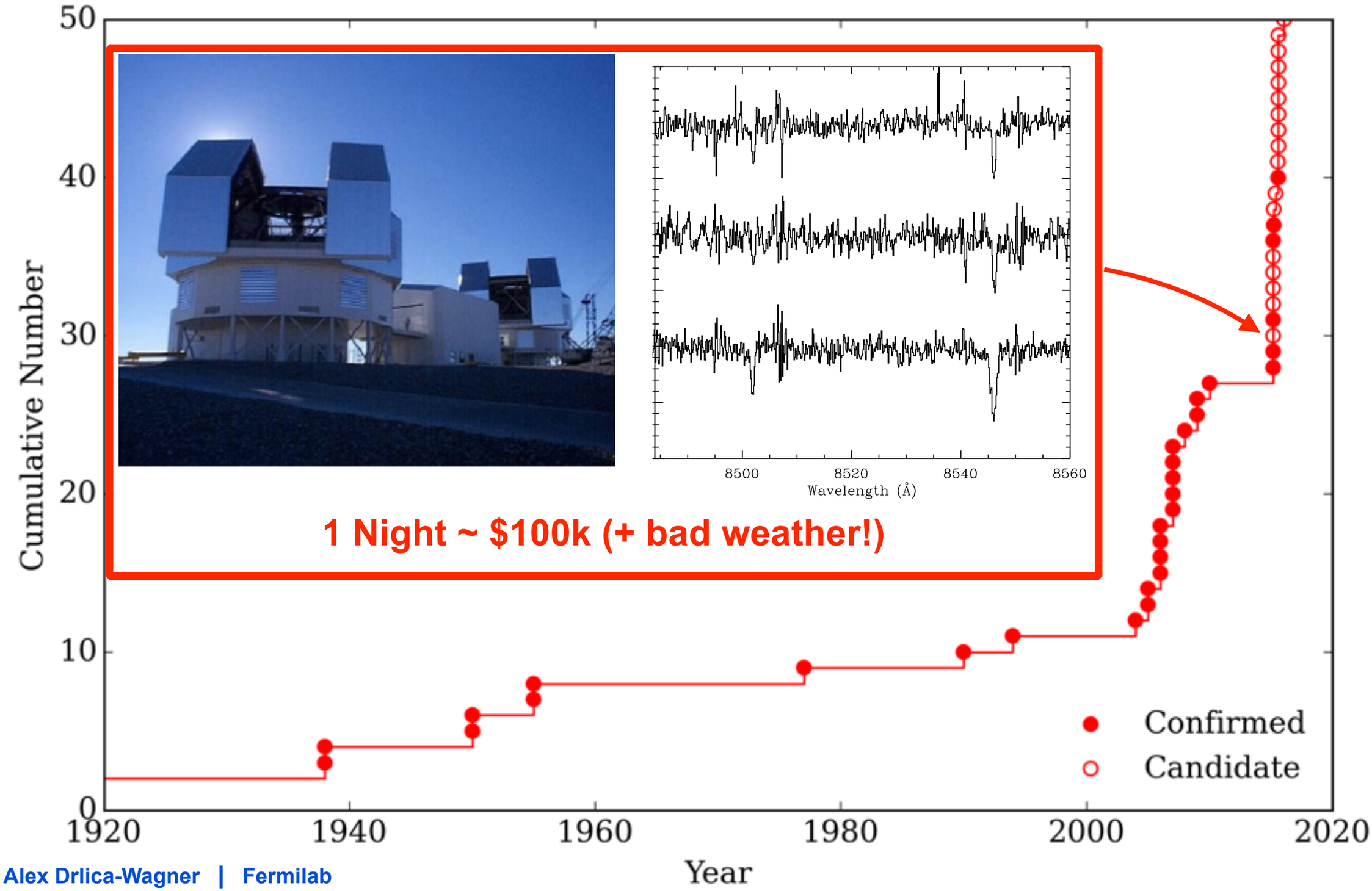


Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

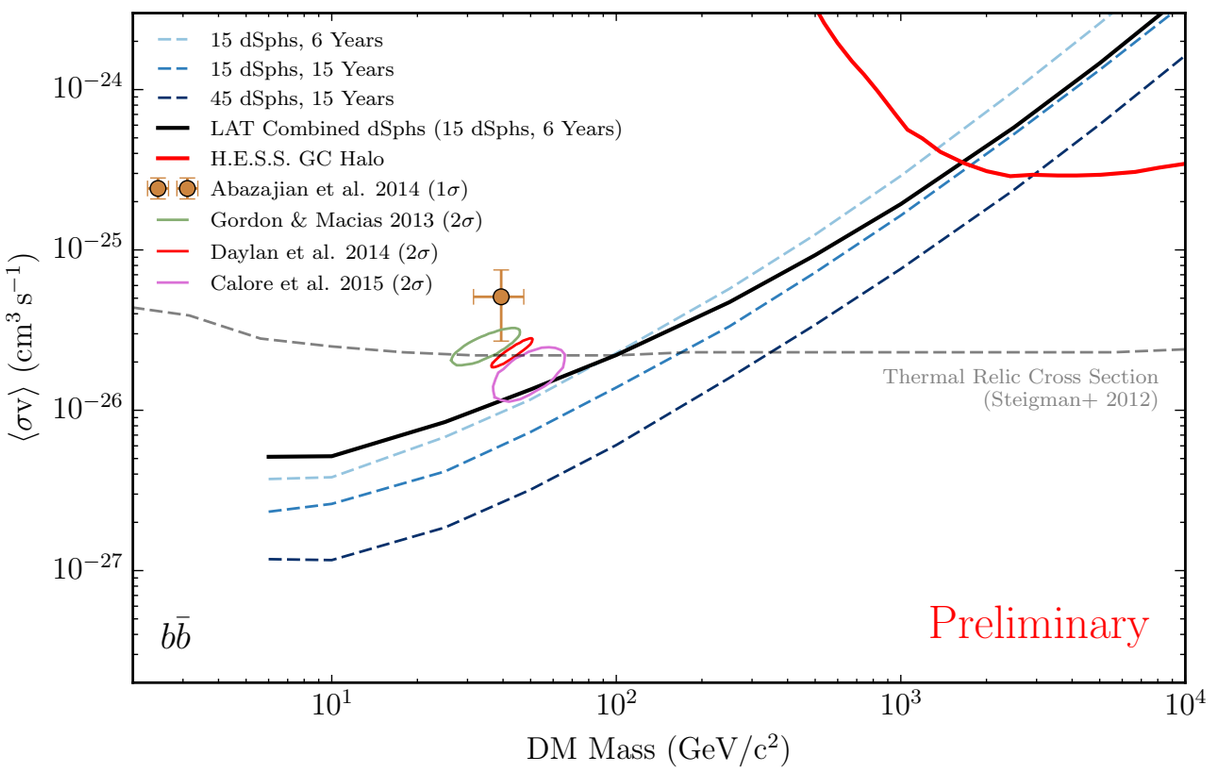
Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

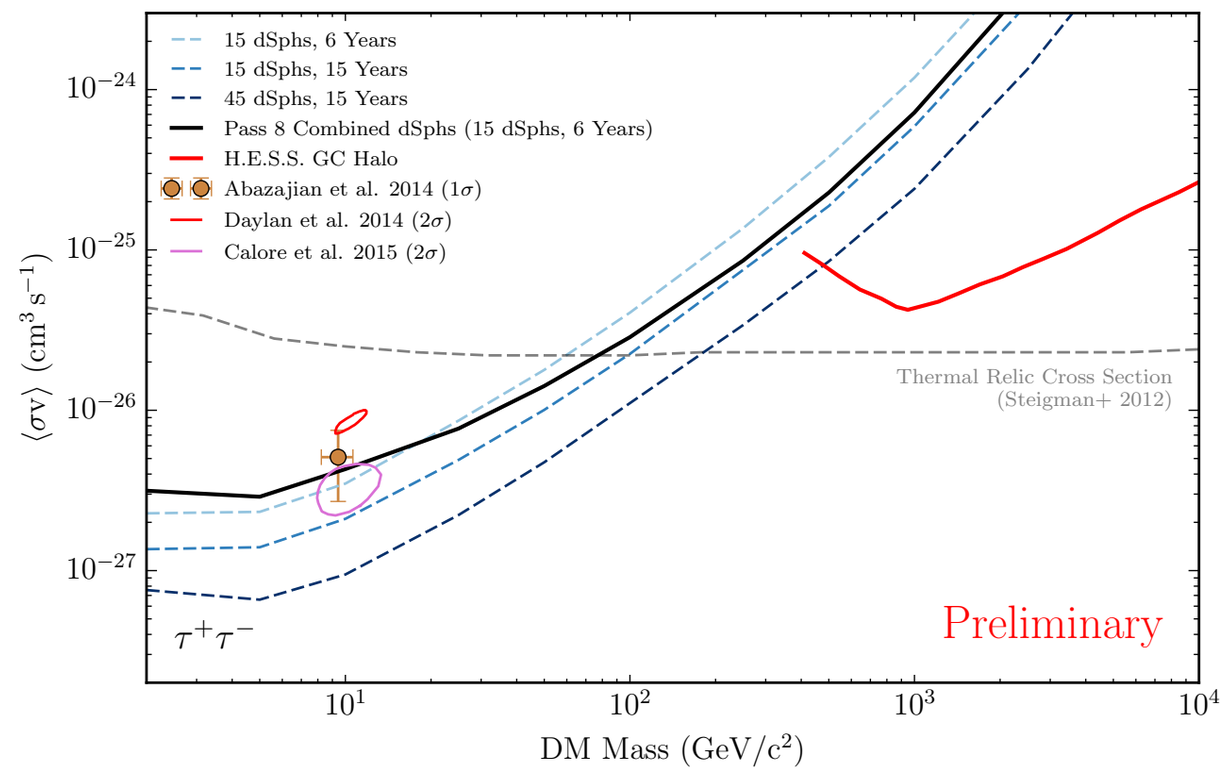
DES Collaboration, ApJ 813, 109 (2015)

Discovery Timeline



Looking Forward





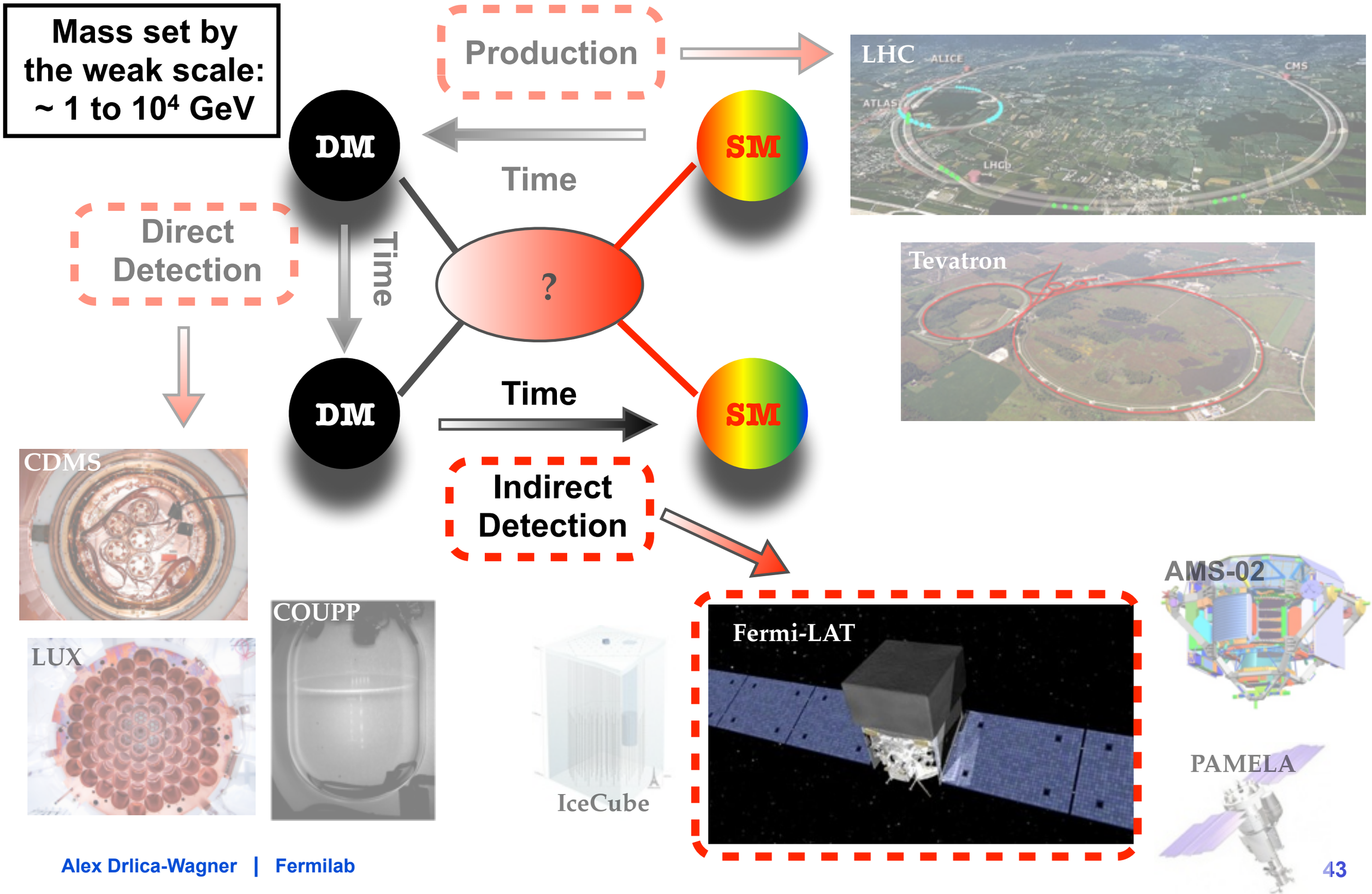
Conclusions

- The nature of dark matter is one of the most important questions in fundamental physics.
- Indirect detection is an important and complimentary search technique
  - The gamma-ray excess at the Galactic center is enticing, but it's interpretation is limited by background systematics
  - Dwarf galaxies are signal limited and provide an important consistency check on dark matter interpretations of the Galactic center
- DECam and DES have revolutionized the discovery of Milky Way dwarf galaxies in the southern hemisphere
- The future of dwarf galaxy discovery is extremely promising
  - DECam will eventually cover the entire southern sky
  - LSST will expand the search to the outer limits of the Milky Way
- Observations of dwarf galaxies should be able to definitively confirm or refute a dark matter origin for the Galactic center gamma-ray excess.

Backup Slides

Particle Dark Matter

Mass set by the weak scale: ~ 1 to 10^4 GeV

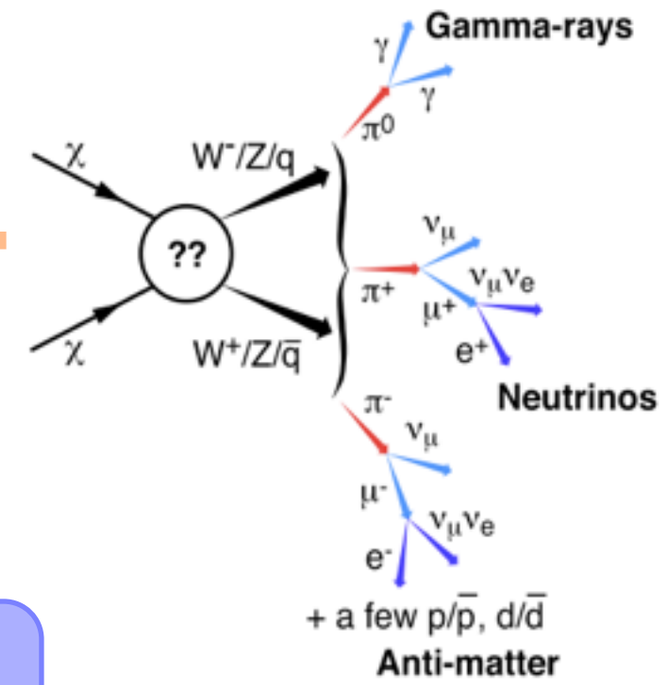


Indirect Detection

Gamma-ray Flux
(signal in data)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi}\frac{\langle \sigma_{\rm ann} v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$$

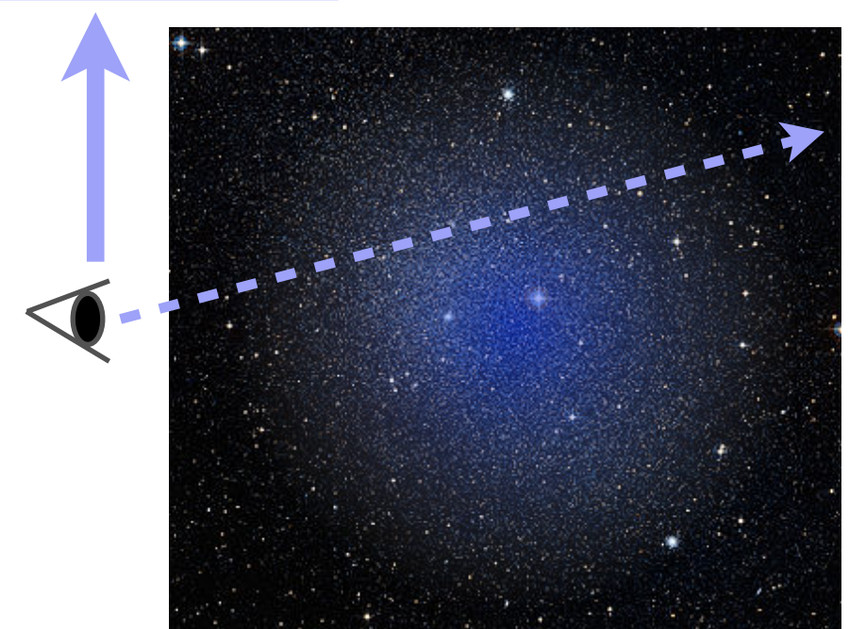
Particle Physics
(photons per annihilation)



$$\times$$

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

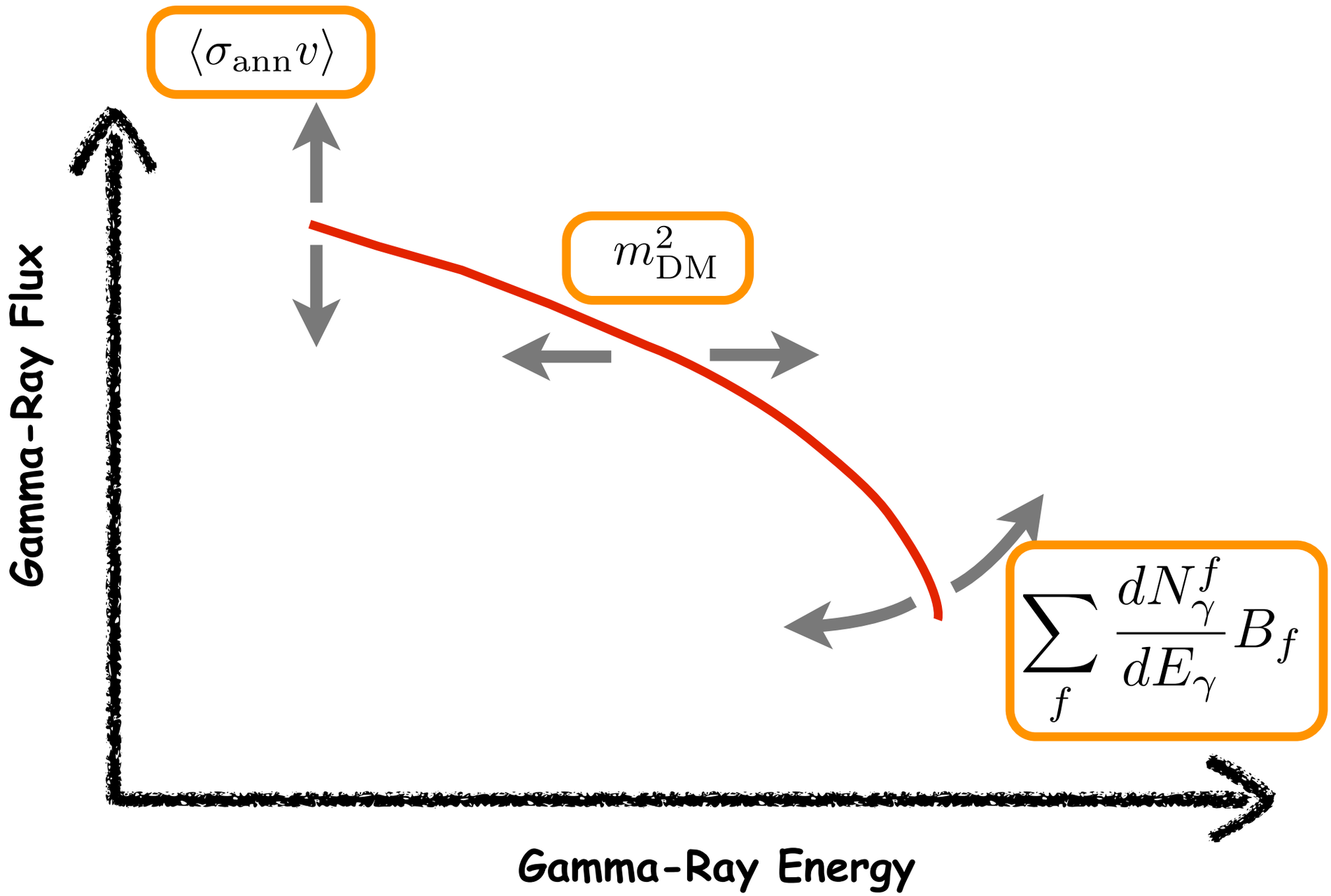
Dark Matter Distribution
("J-factor")
(line-of-sight integral)



Gamma-ray Spectrum

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

CARTOON



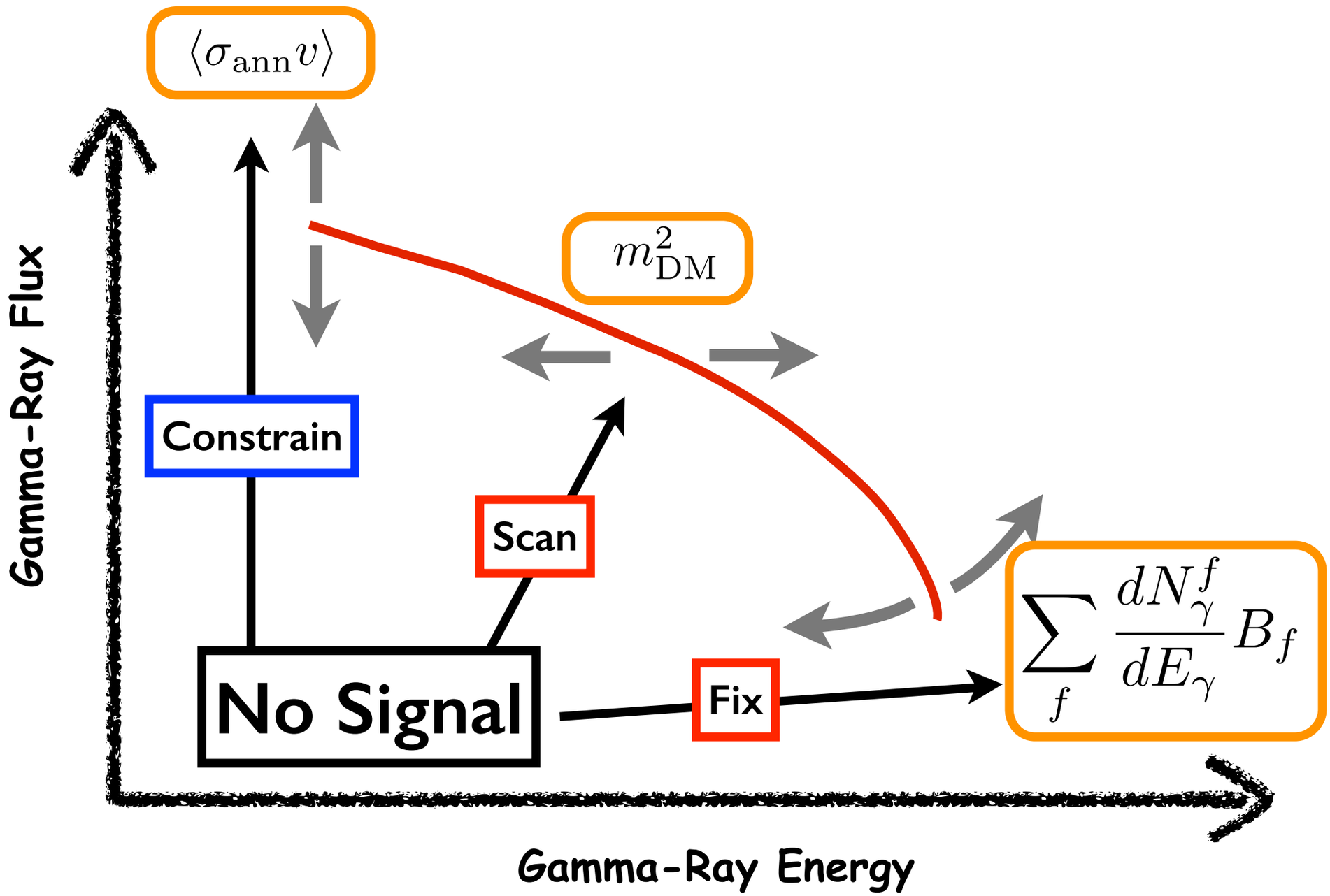
Gamma-ray Spectrum

Thermal Relic Cross Section

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$\frac{1}{4\pi}\frac{\langle \sigma_{\mathrm{ann}} v\rangle}{2m_{\mathrm{DM}}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$$

CARTOON



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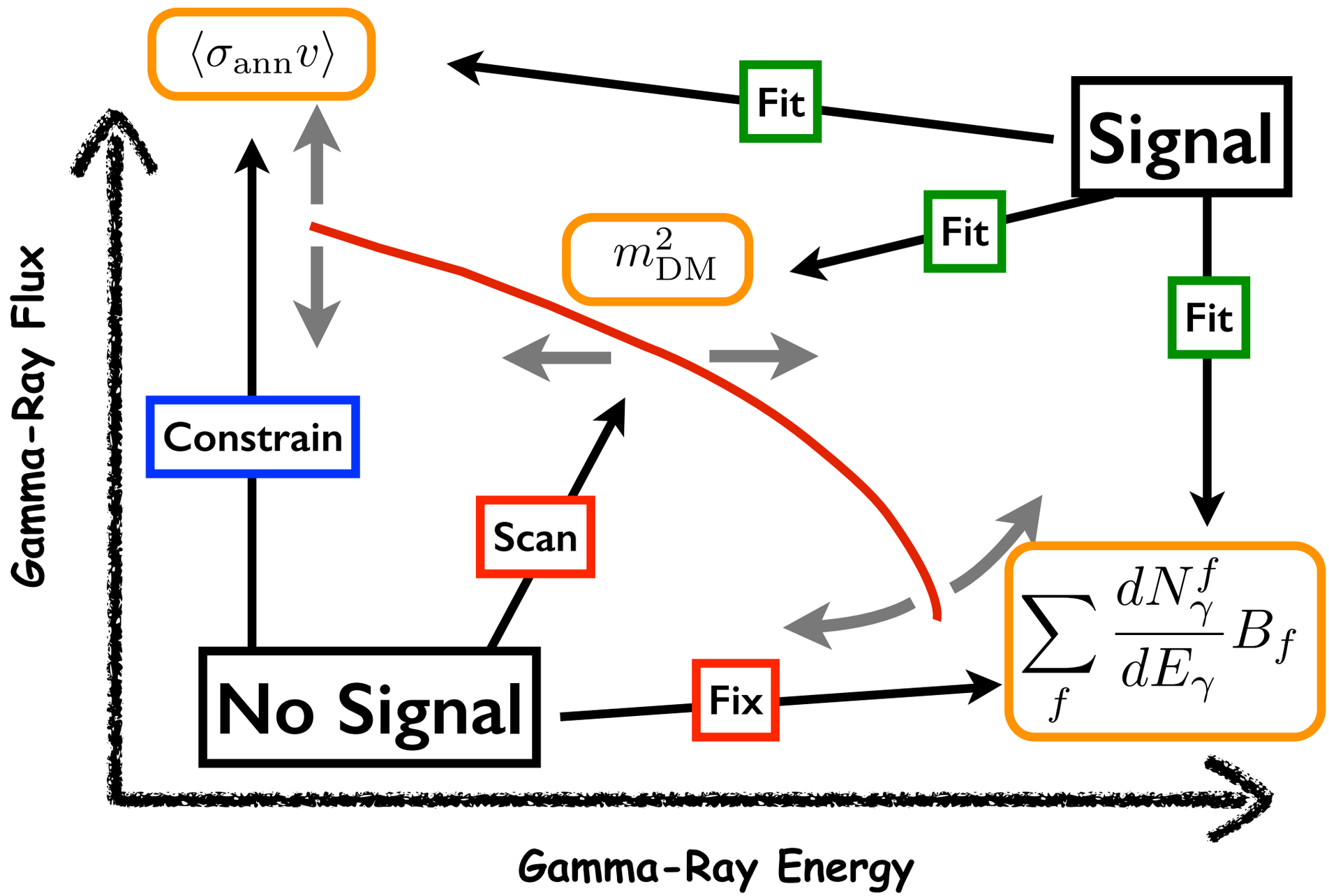
CARTOON

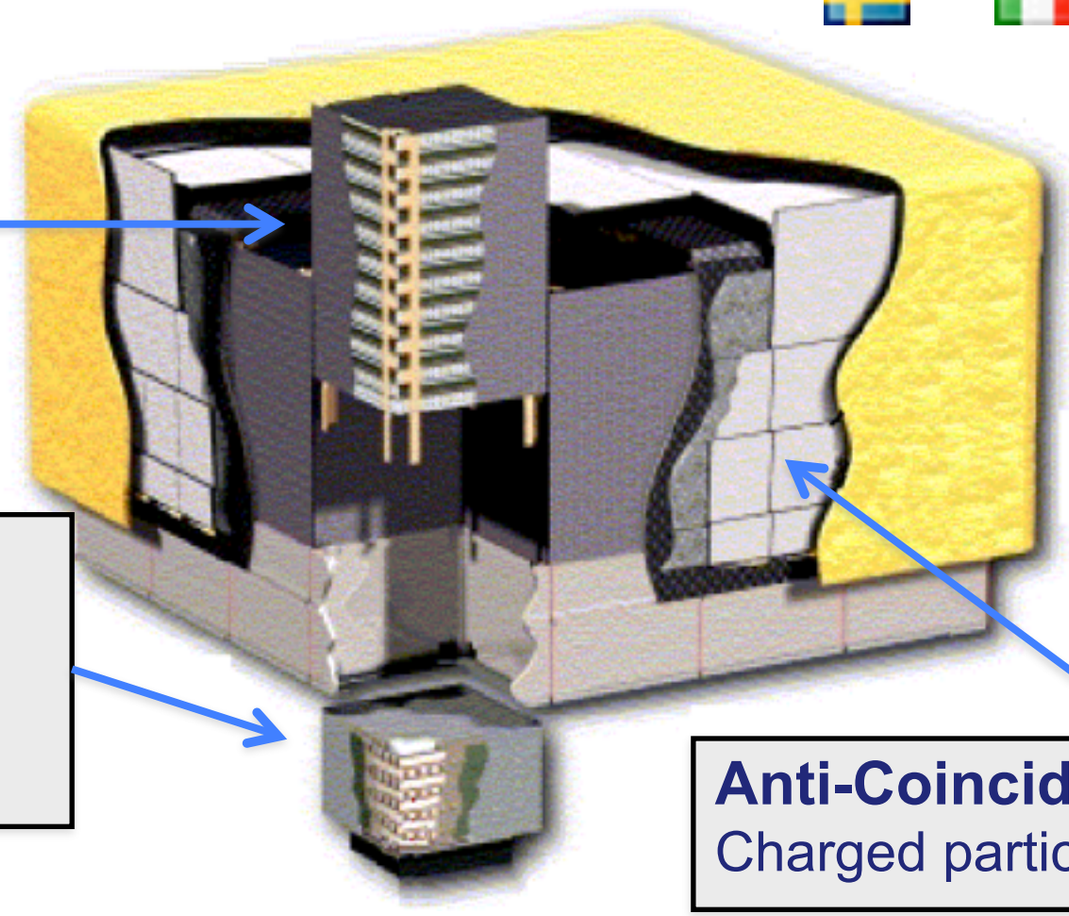


The Fermi Large Area Telescope

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM vs. hadron separation



No Magnet

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

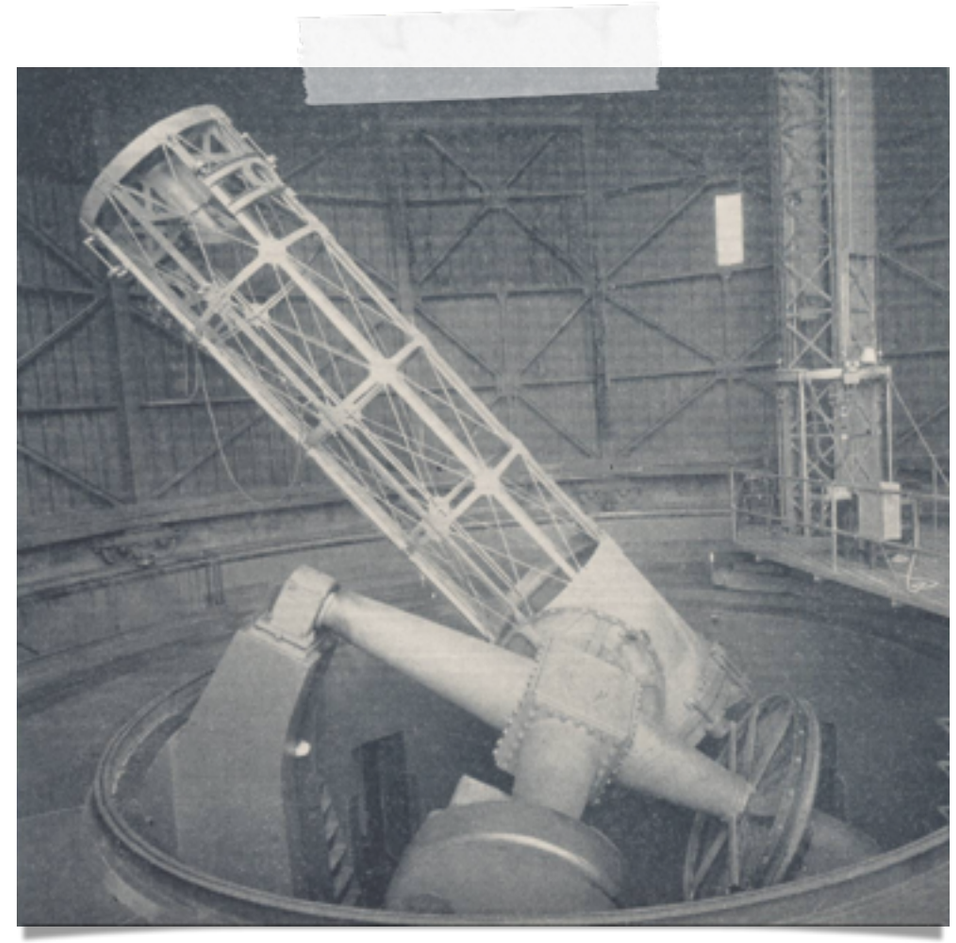
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
The LAT observes the whole sky every 3 hours (2.5 sr FOV)

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

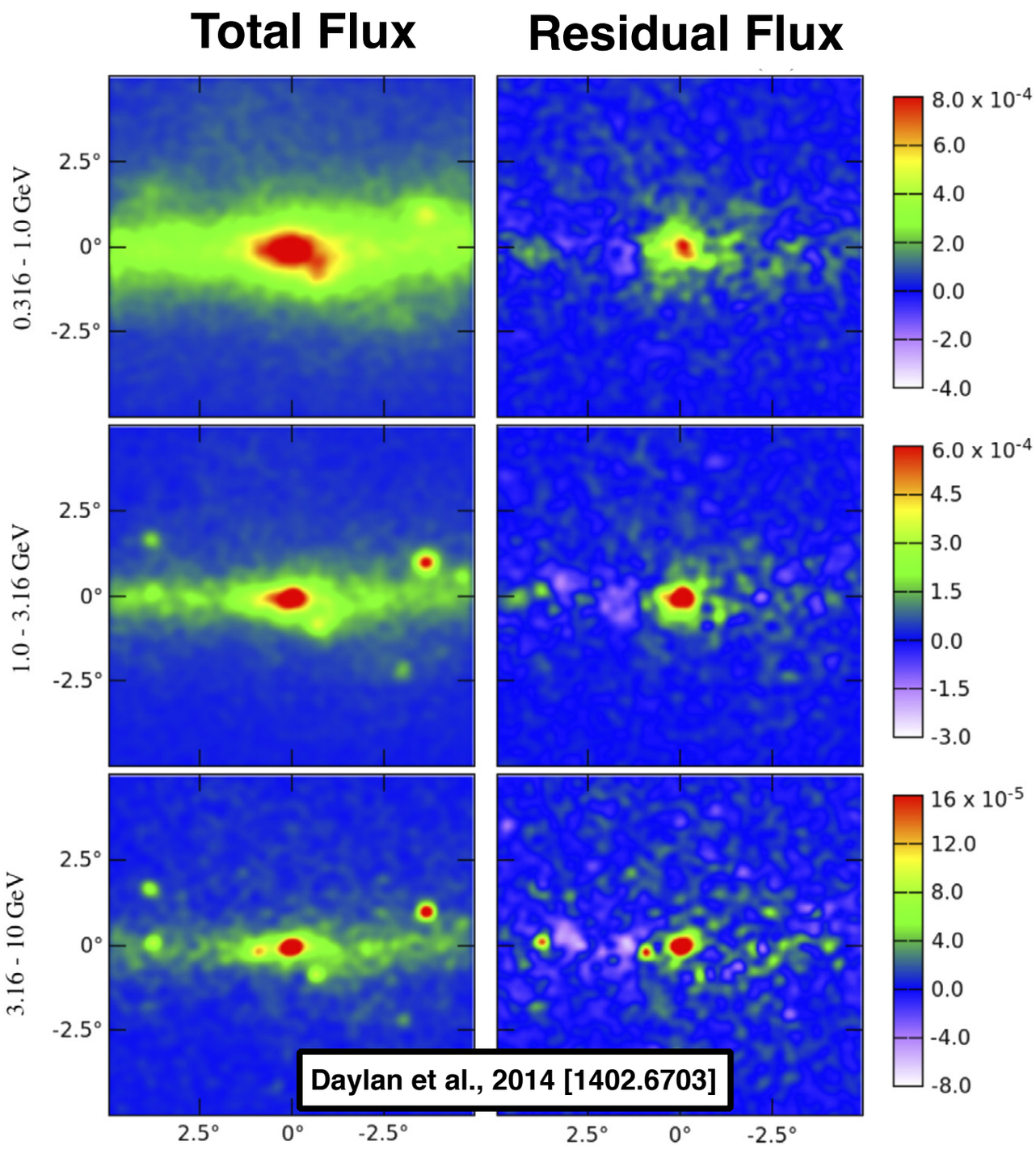
Visual Searches

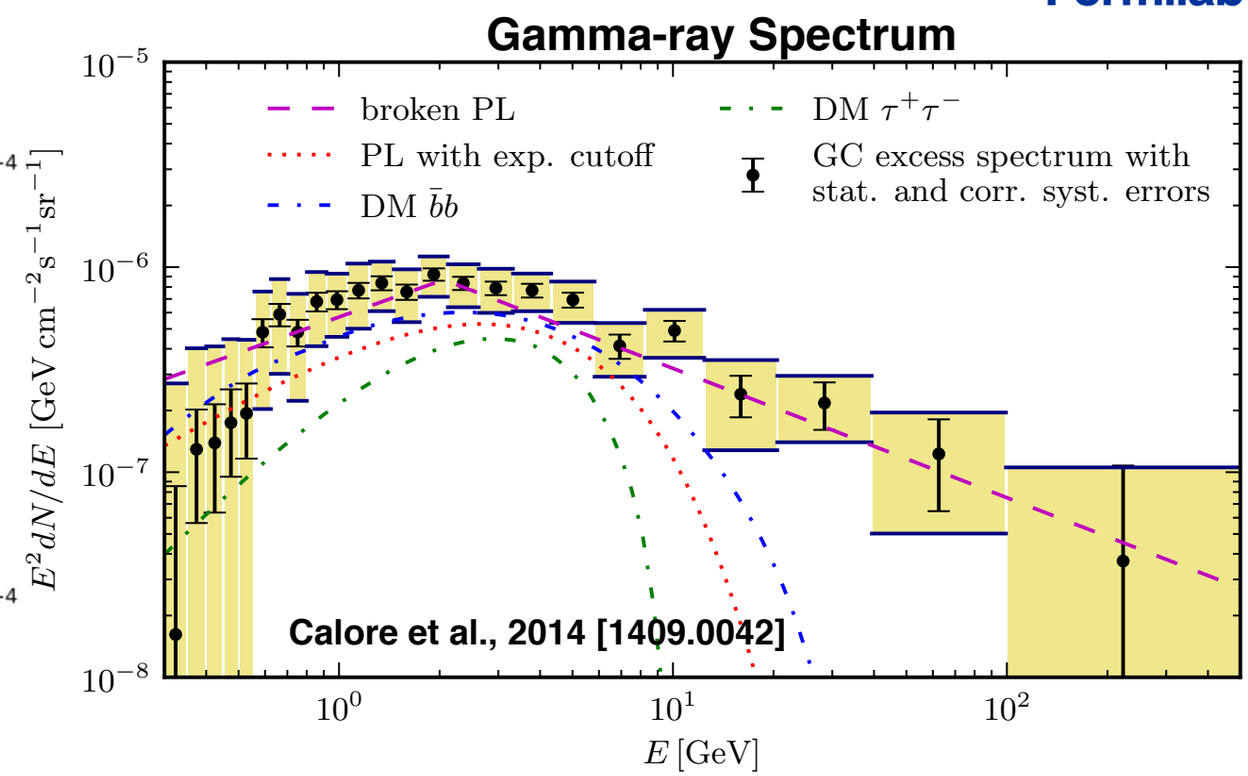
24-inch Bruce Refractor

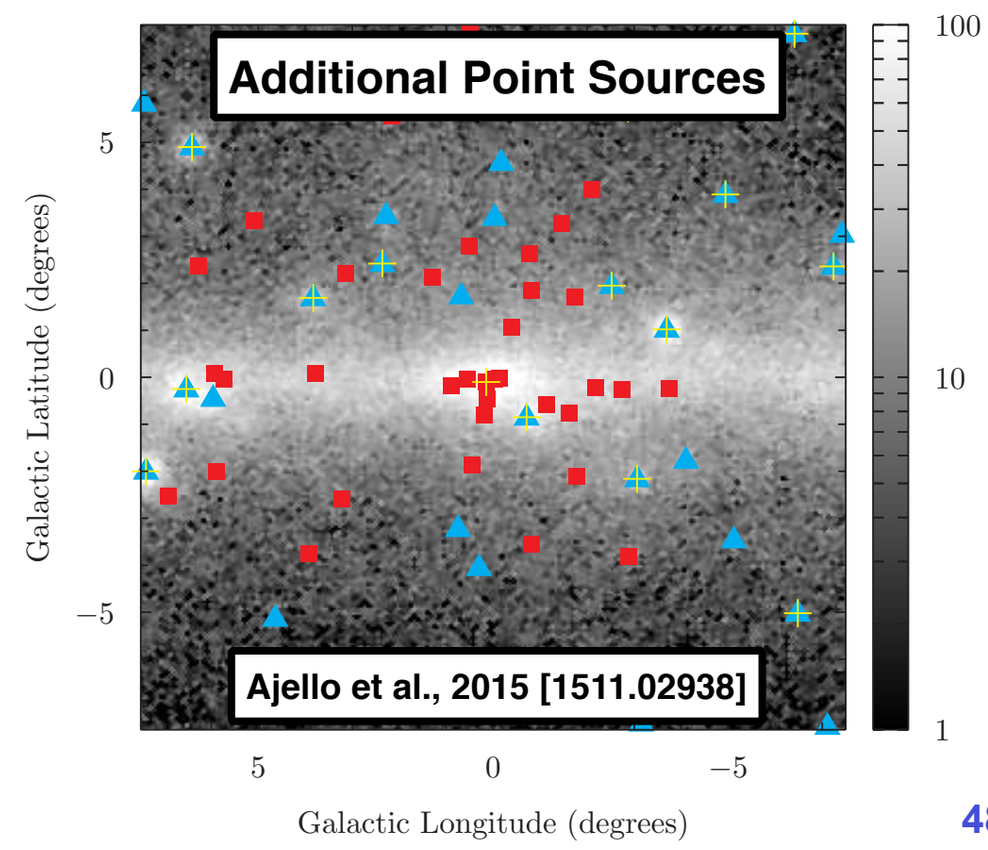


60-inch Rockefeller Reflector

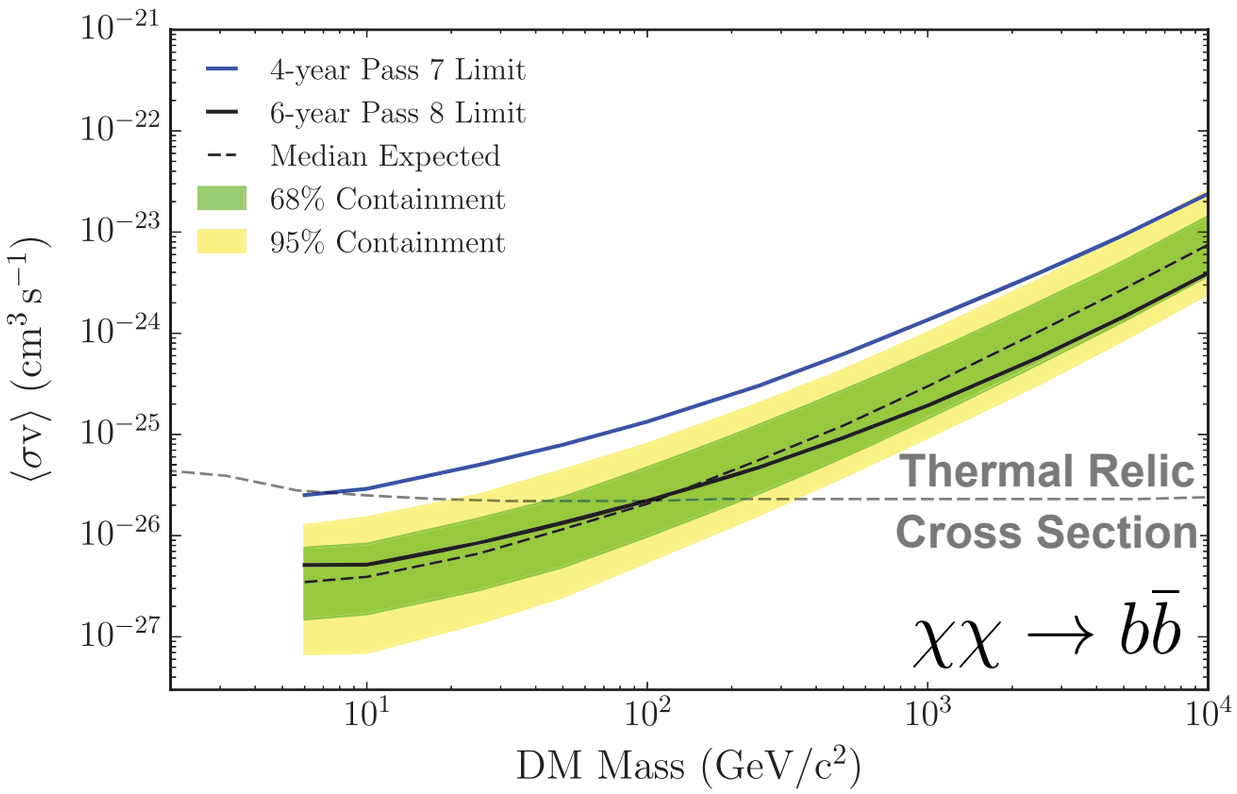
The Galactic Center

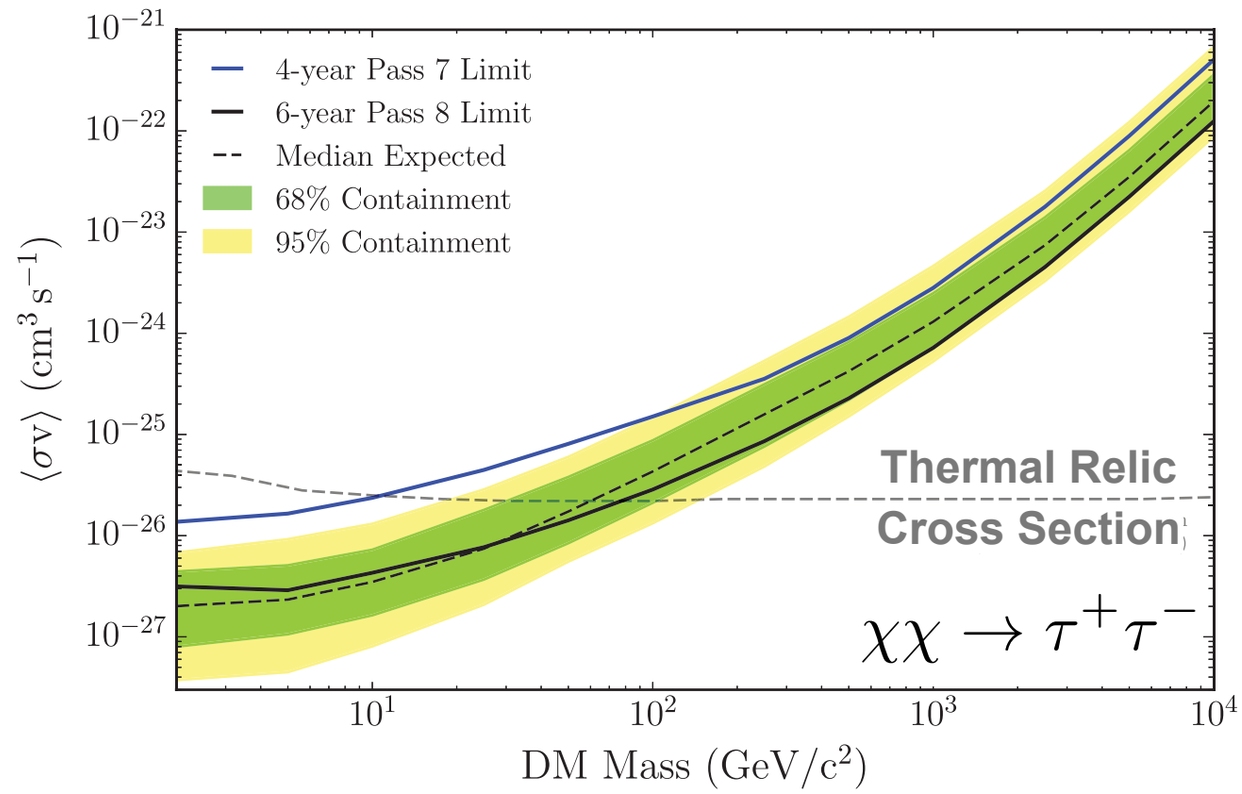






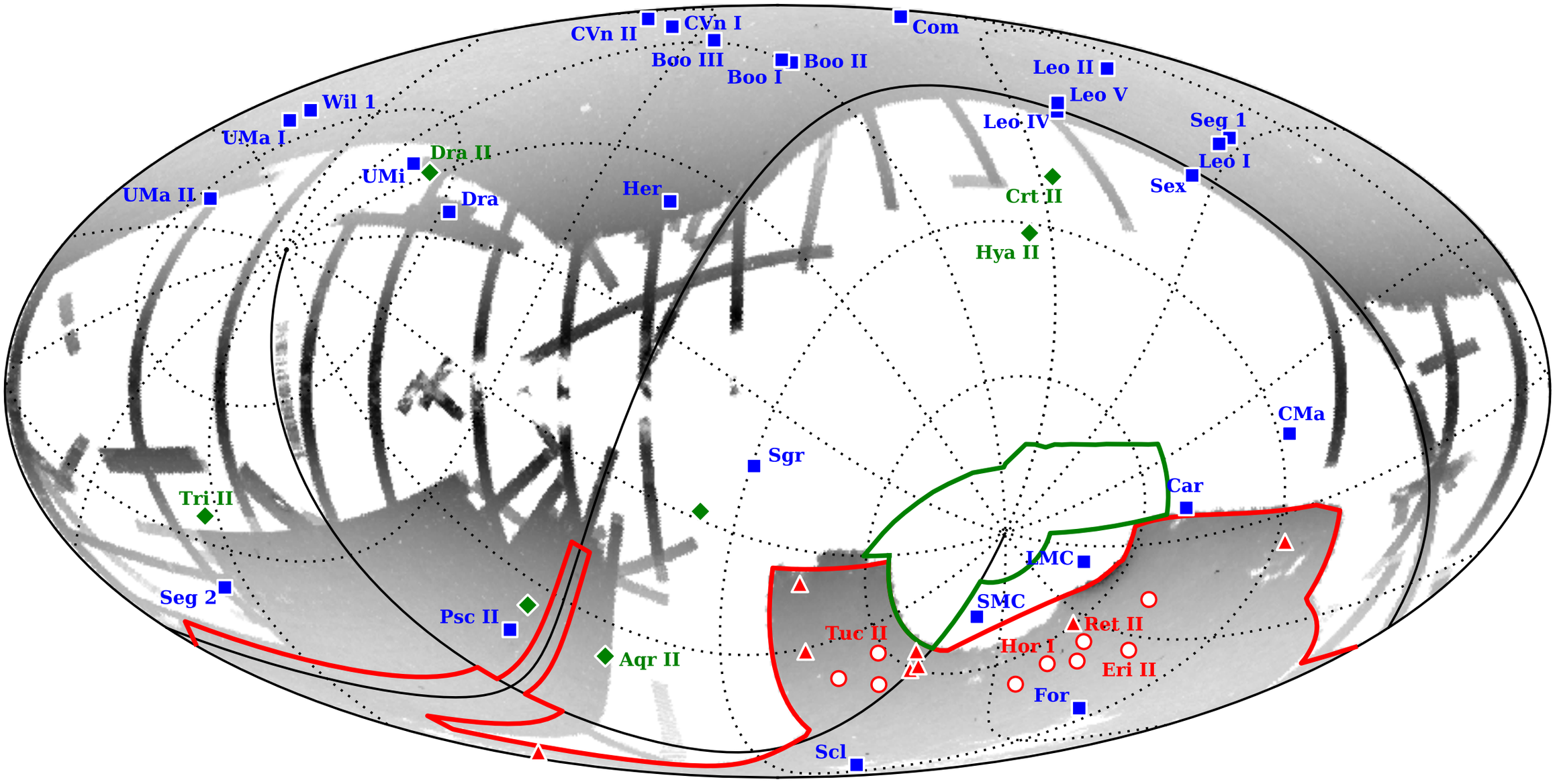
Dwarf Galaxy Constraints



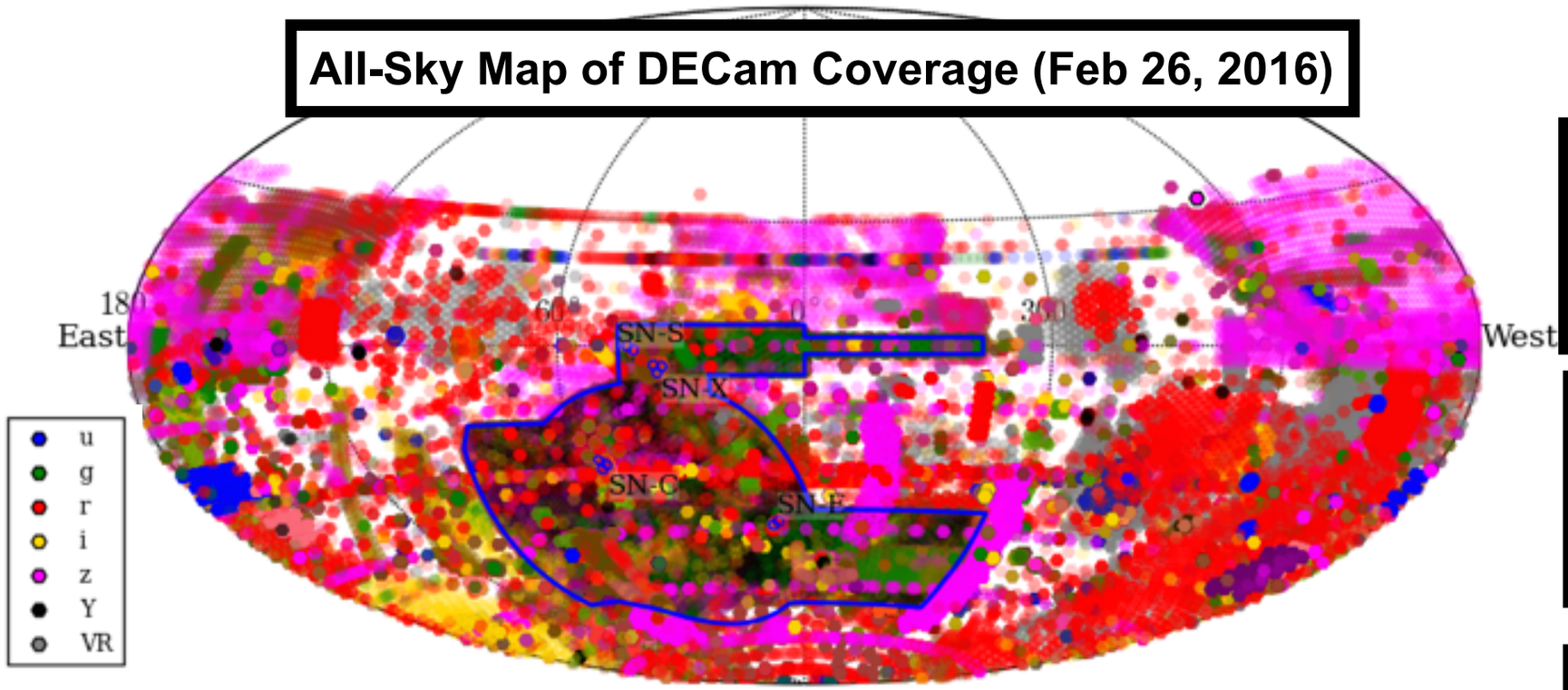


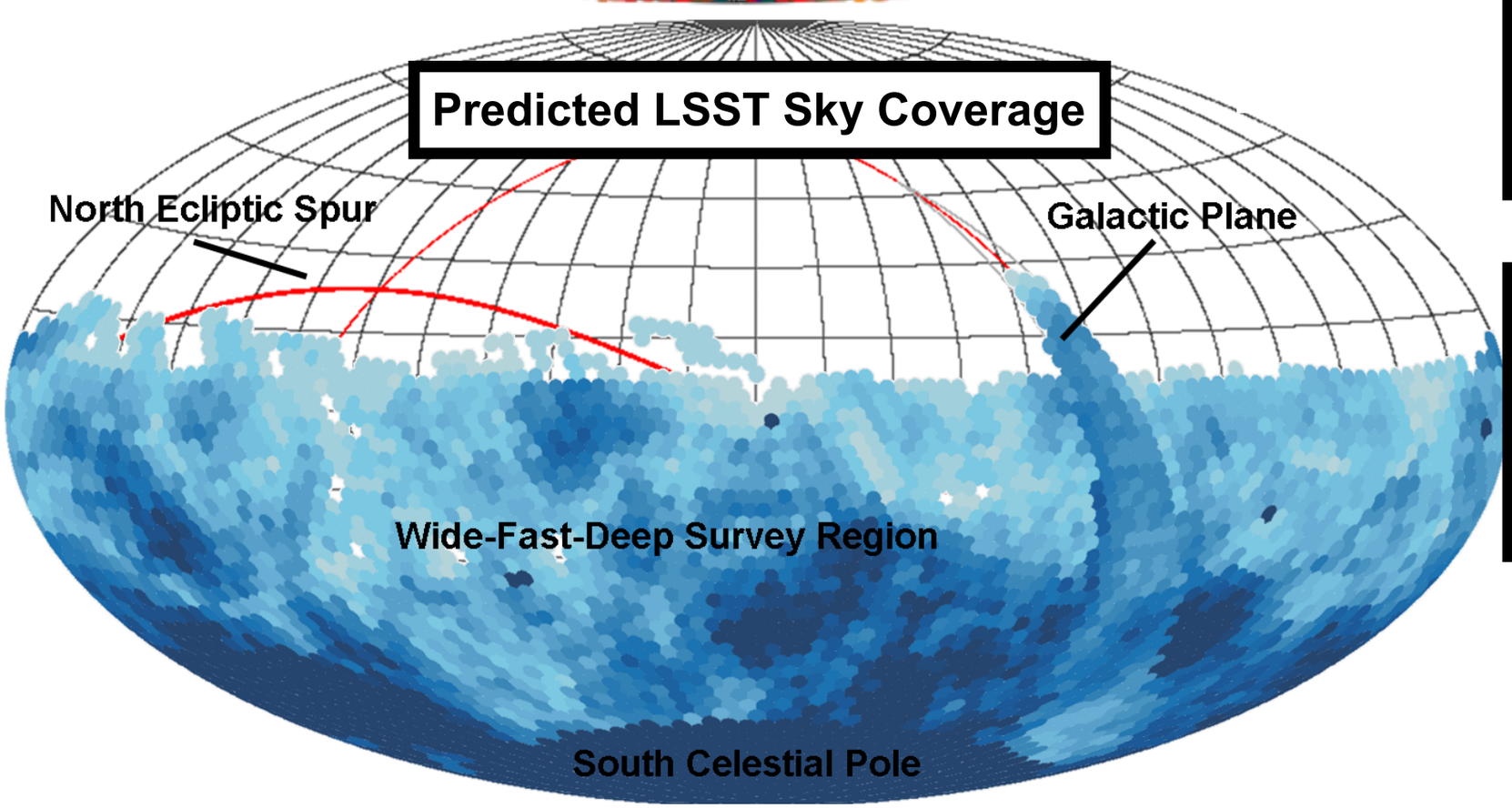
Ackermann et al. 2015 (1503.02641)

Magellanic Satellites Survey



Future Discoveries





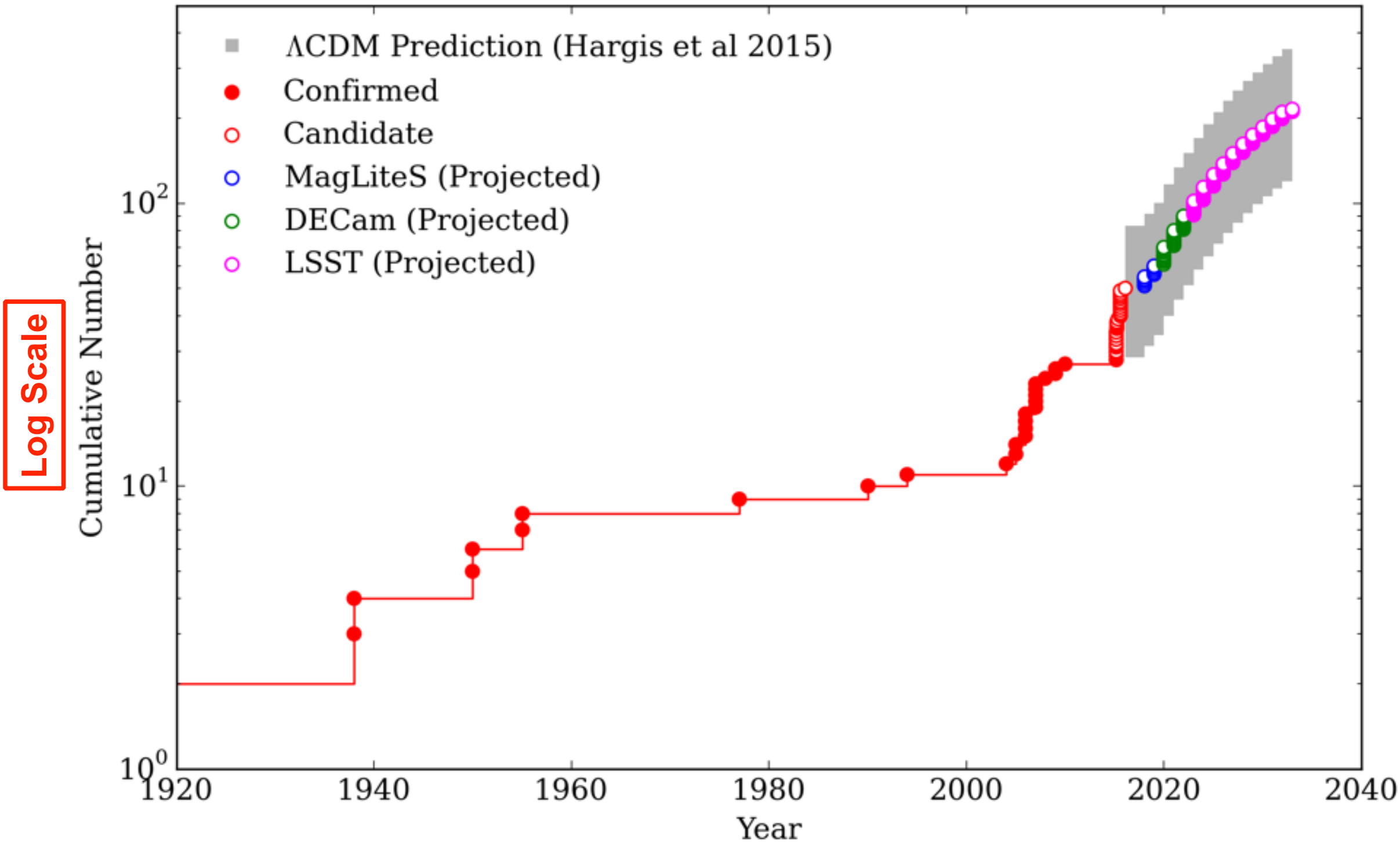
DES only observes 1/6th of the sky accessible to DECam

Only 1/3 of the exposures taken with DECam are part of DES

Only 1/3 of the exposures taken with DECam are part of DES

LSST will cover the entire southern sky and be a factor of 10 more sensitive

Projected Timeline



Search for Gamma Rays

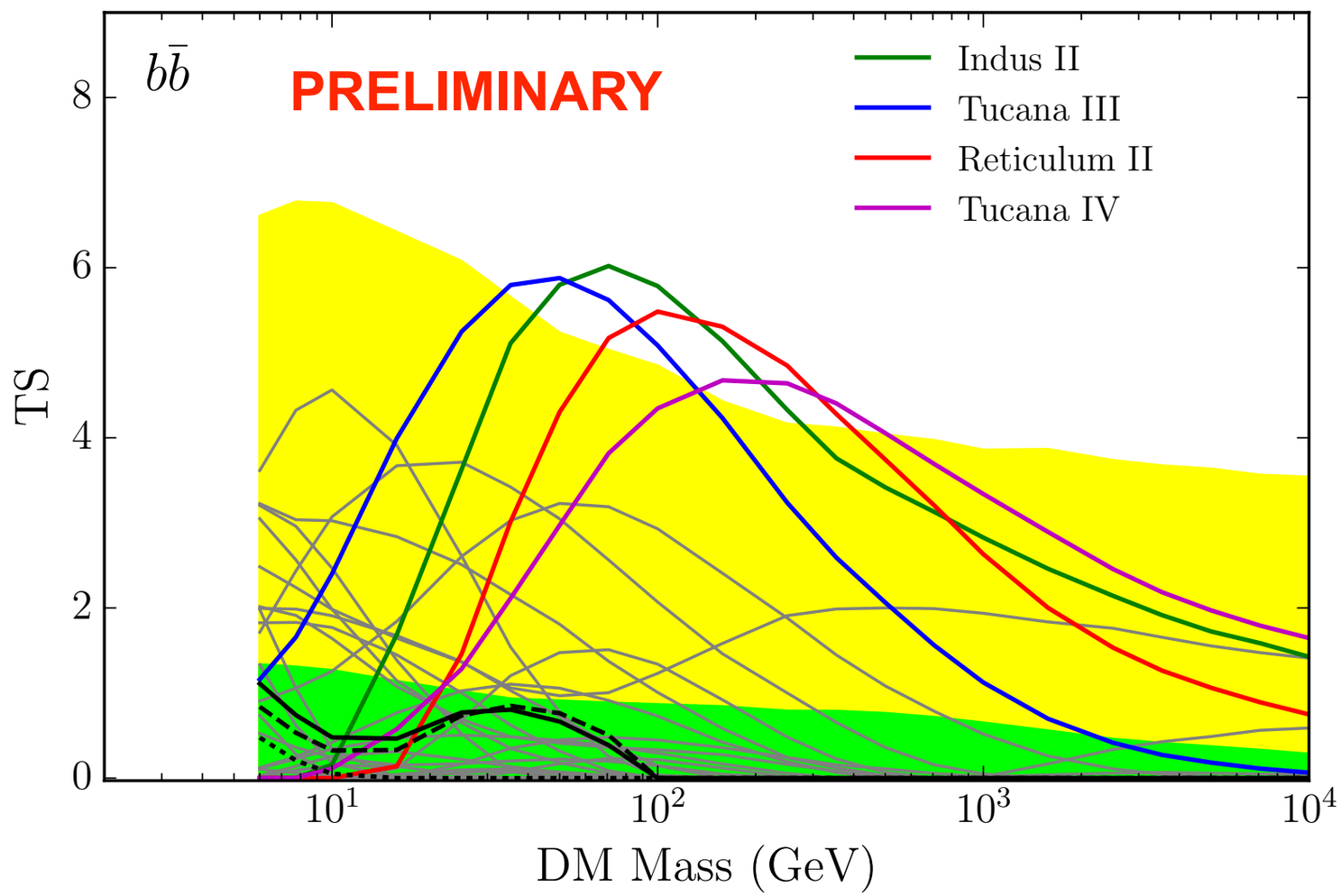
Target 45 confirmed and candidate dSphs

Four targets show ~2 sigma (local) gamma-ray excesses

Two of these targets are nearby: Ret II and Tuc III (D < 35 kpc)

Composite analysis depends on J-factor and uncertainty

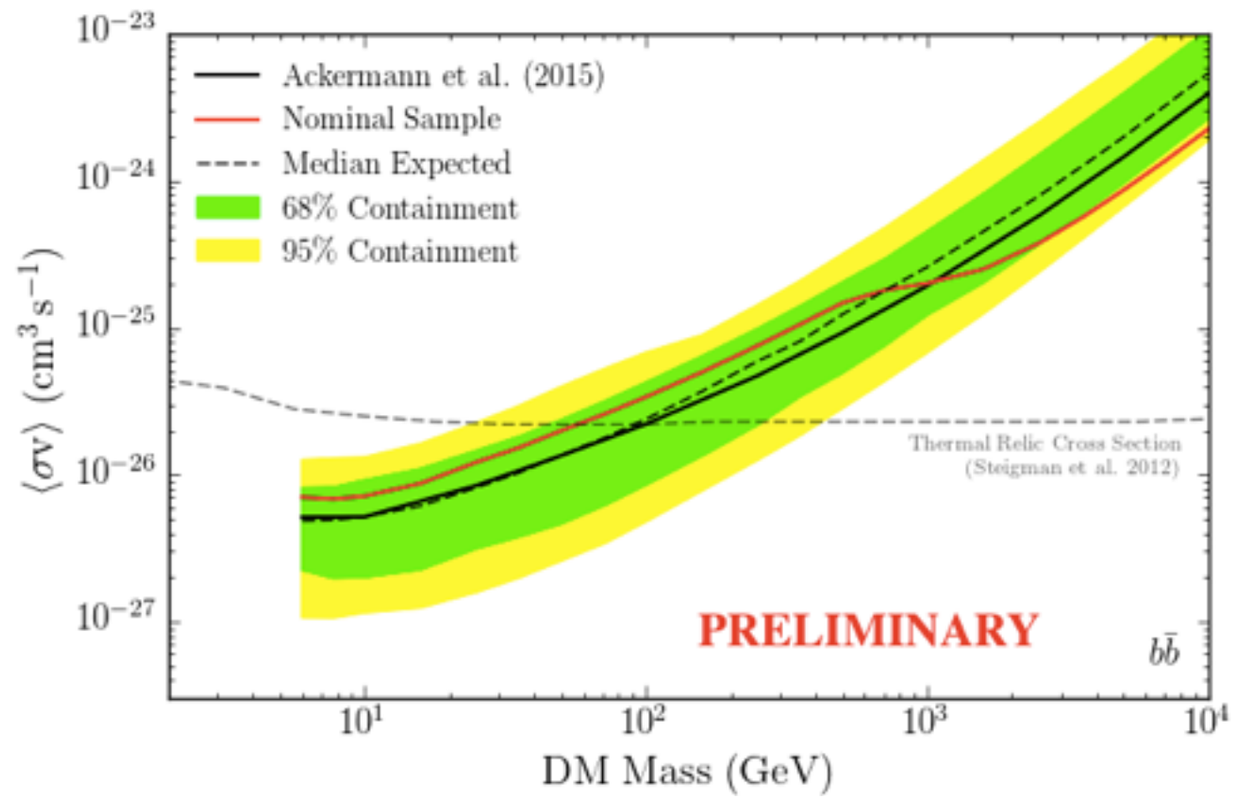
Can we predict the J-factors of these objects?

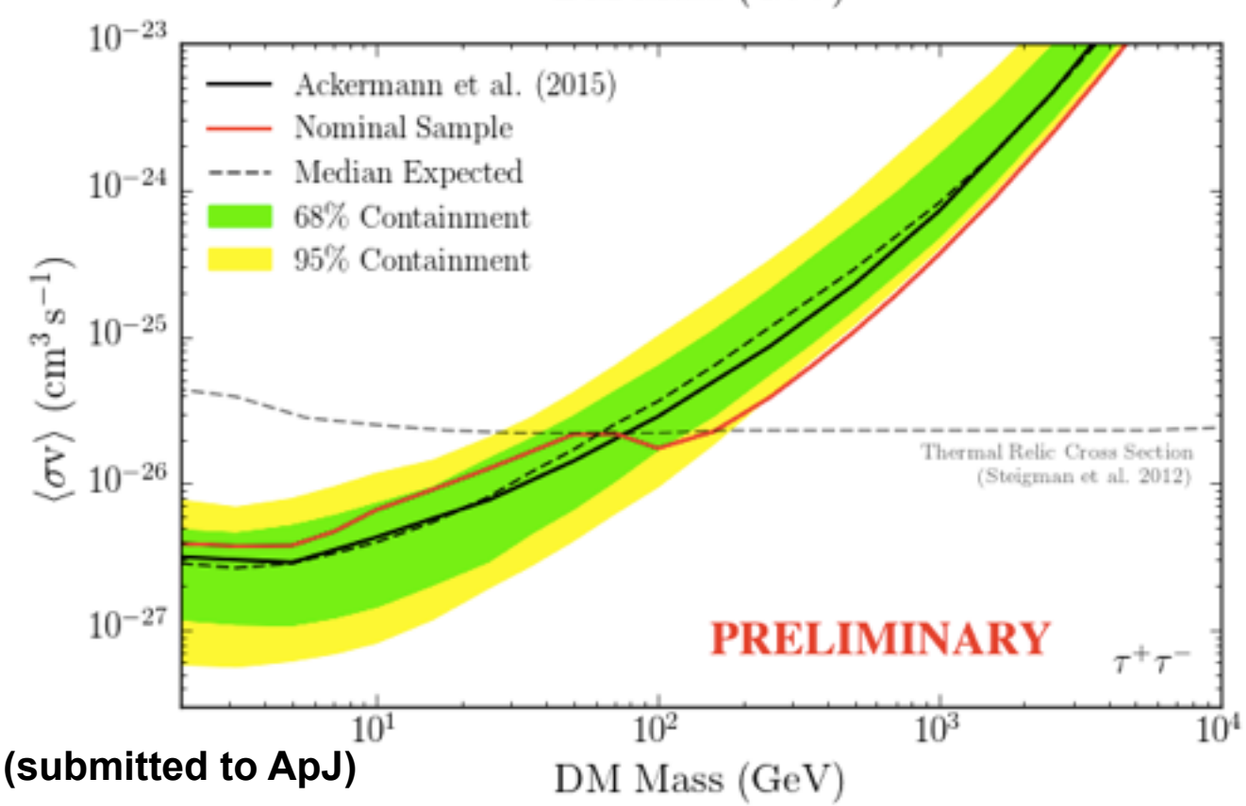


LAT & DES Collaborations (submitted to ApJ)

Combined Analysis
Confirmed and Candidate dSphs

- Spectroscopy is expensive (in both person and telescope time)
- We can predict J-factors assuming the new systems are dark-matter-dominated dSphs:
  1. New systems are dark-matter-dominated dwarf galaxies
  2. Dwarf galaxies inhabit dark matter halos of similar mass (e.g., Strigari et al. 2008)
  3. The distance to each target is determined from photometry
- Predict a J-factor uncertainty of 0.6 dex (Geringer-Sameth et al. 2015), to combine the full population
- The most significant excess from the combined analysis is < 1σ (depends on J-factors)





LAT & DES Collaborations (submitted to ApJ)