

Searching for Milky Way Satellite Galaxies

Alex Drlica-Wagner
David N. Schramm Fellow
Fermilab

BAM 2017
September 6, 2017

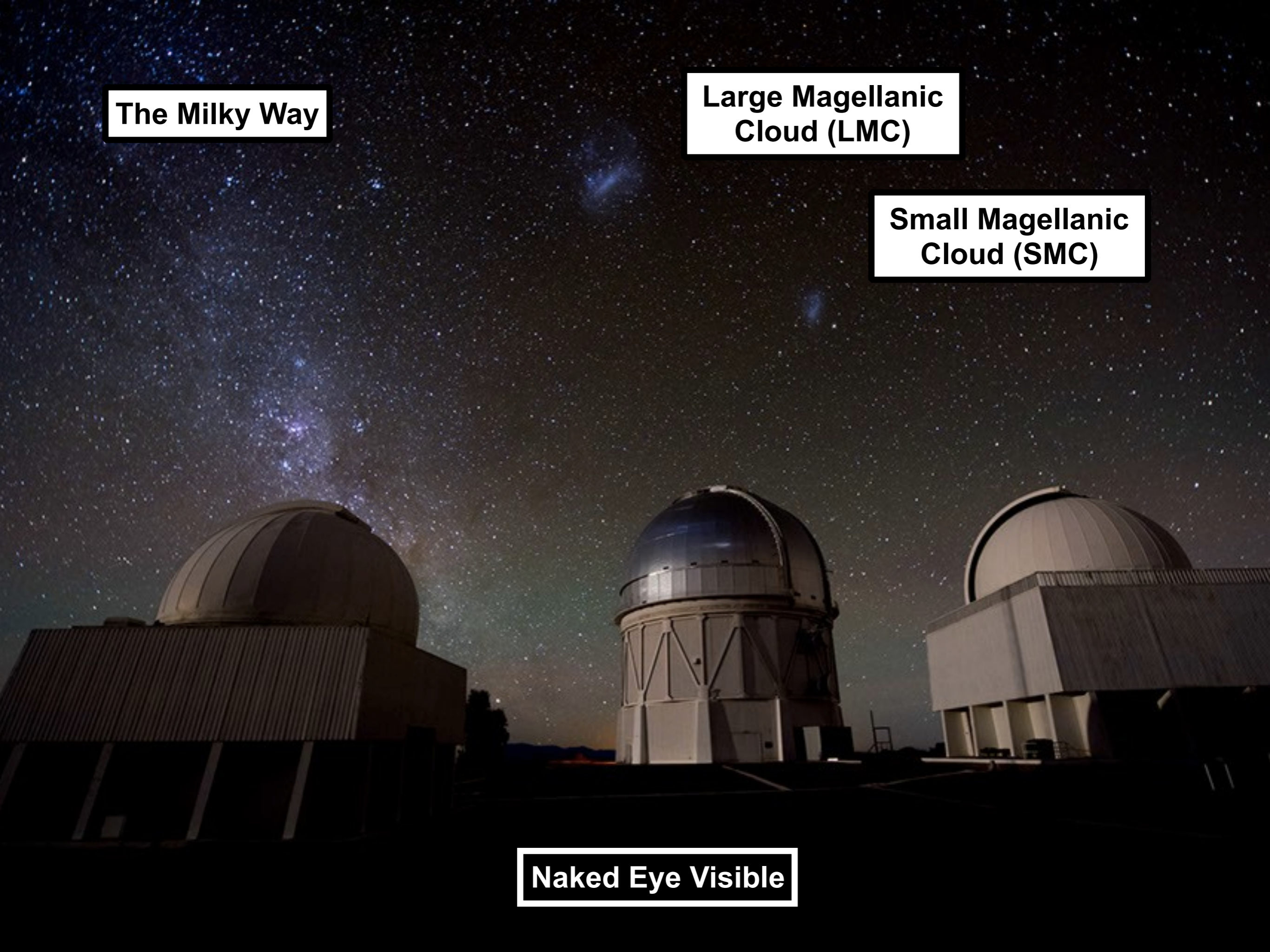


The Milky Way

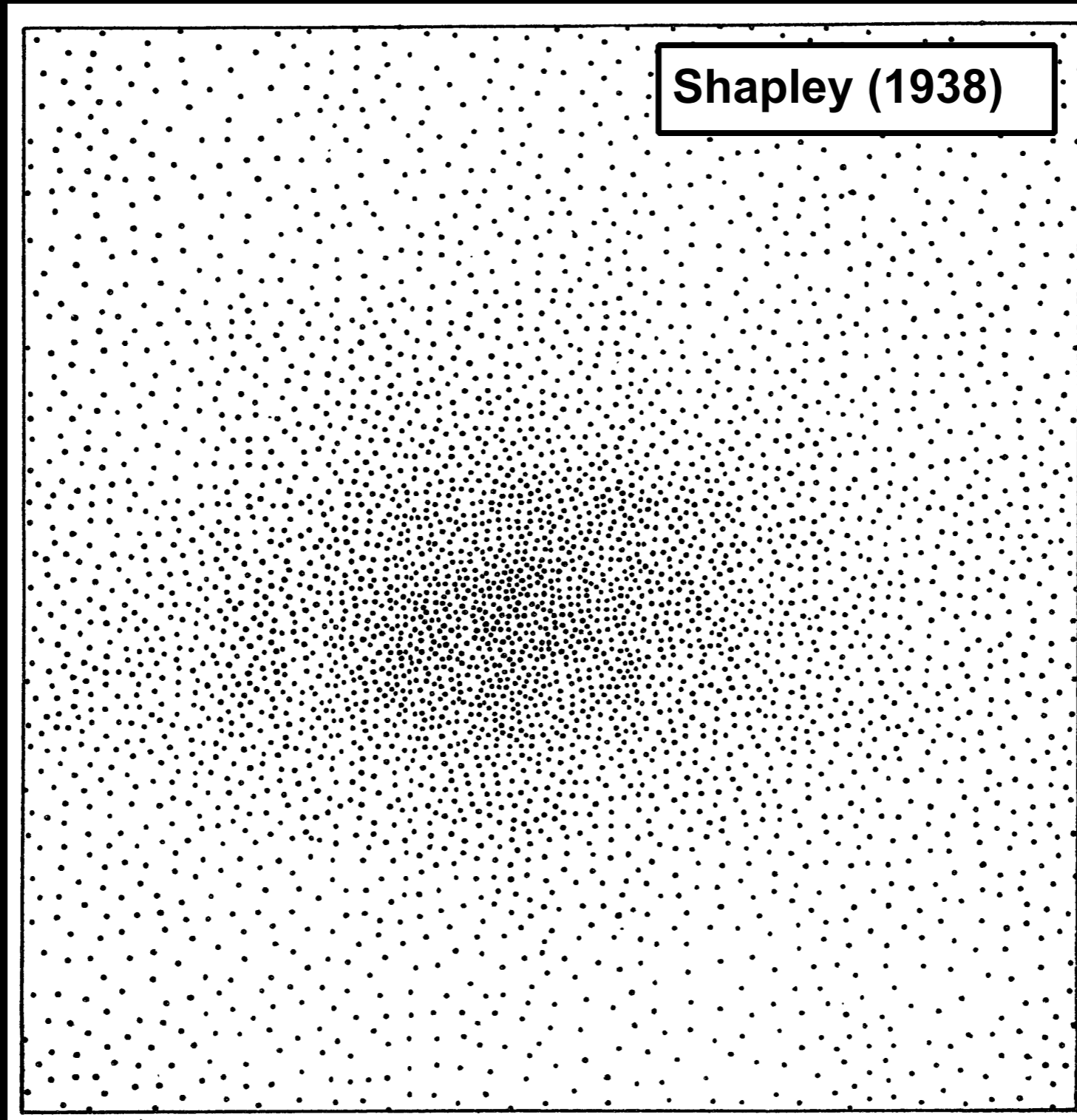
**Large Magellanic
Cloud (LMC)**

**Small Magellanic
Cloud (SMC)**

Naked Eye Visible



Sculptor Dwarf Galaxy



24-inch Telescope
Photographic Plates

Sculptor Dwarf Galaxy



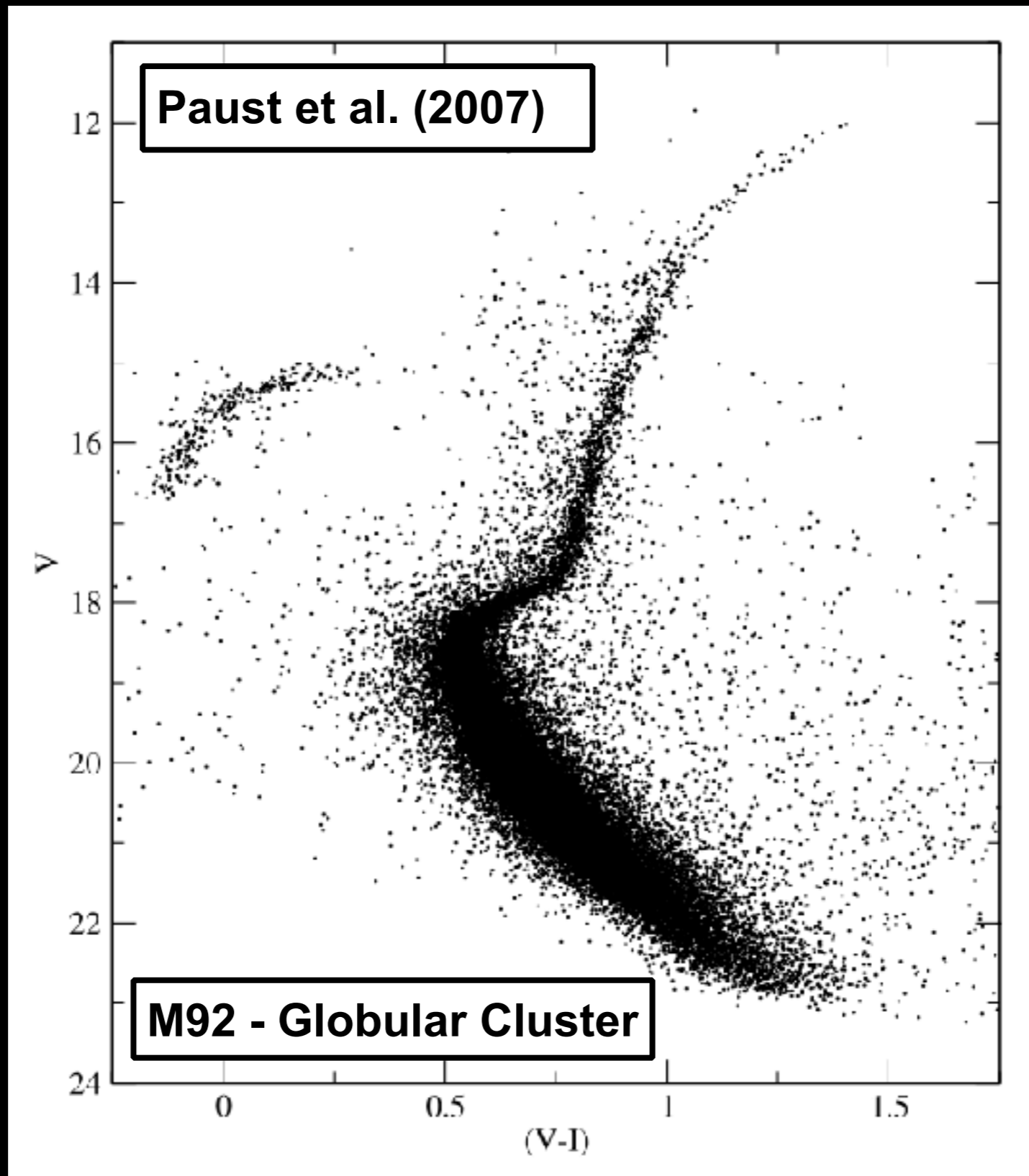
ESO/DSS2

1.2m Telescope
Photographic Plates



Fermilab

Brighter
↑
Magnitude
↓
Fainter

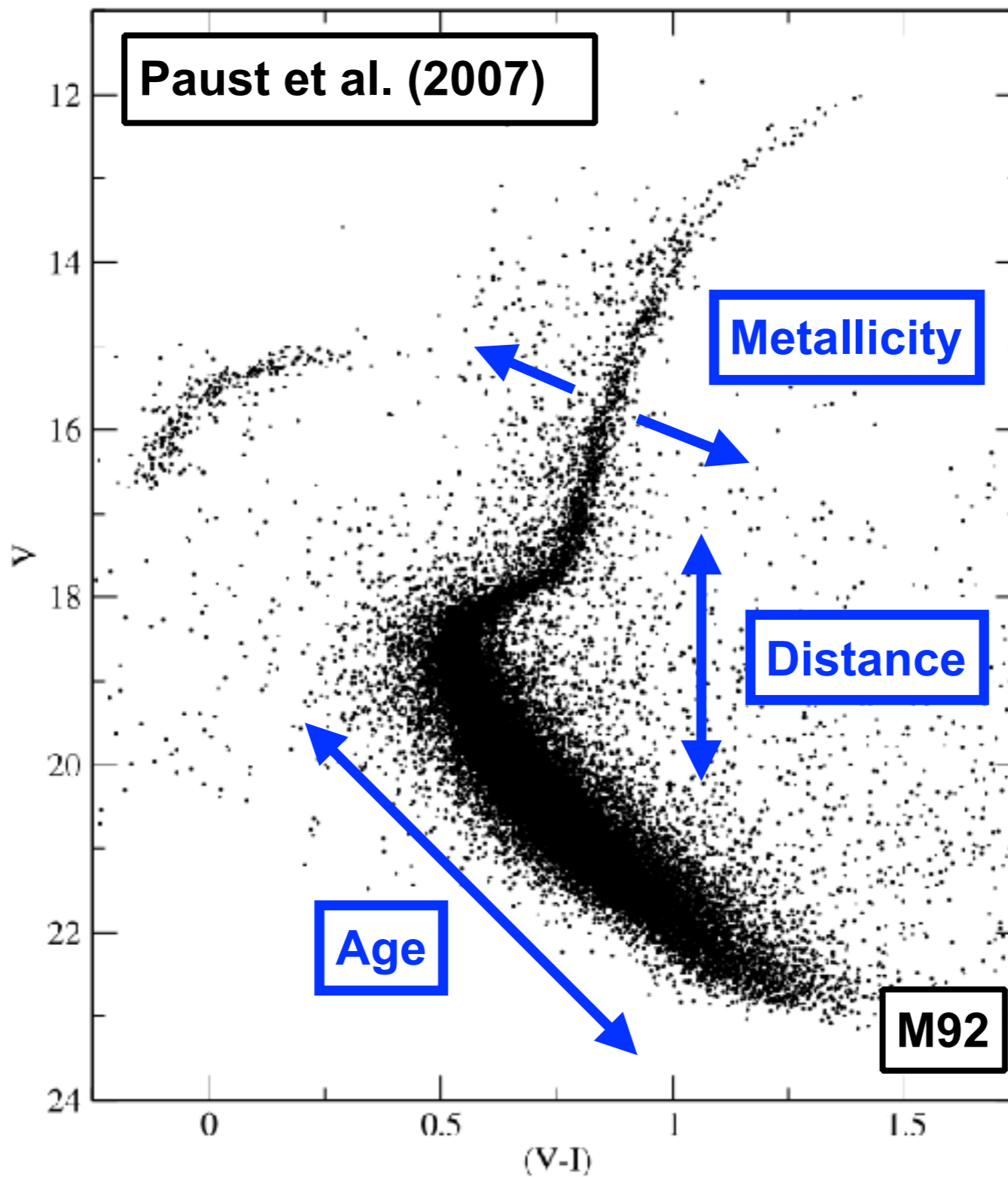


Bluer ← Color → Redder



Fermilab

Brighter
↑
Magnitude
↓
Fainter



Bluer

Redder

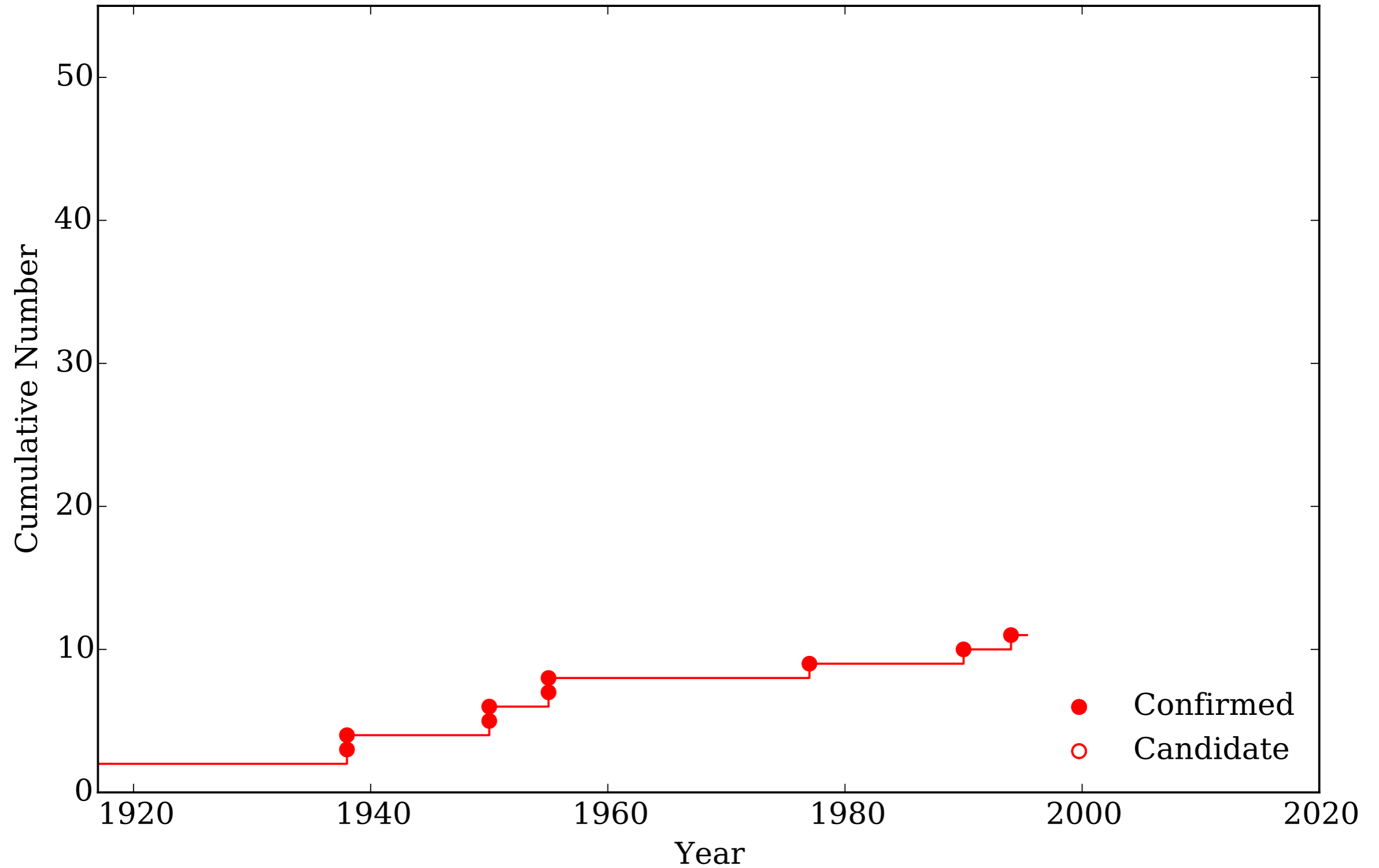
Measure:

- Age
- Metallicity
- Distance

NOTE: We can't measure dark matter content from photometry alone...

Spectroscopic campaign required!

Dwarf Galaxy Discovery Timeline

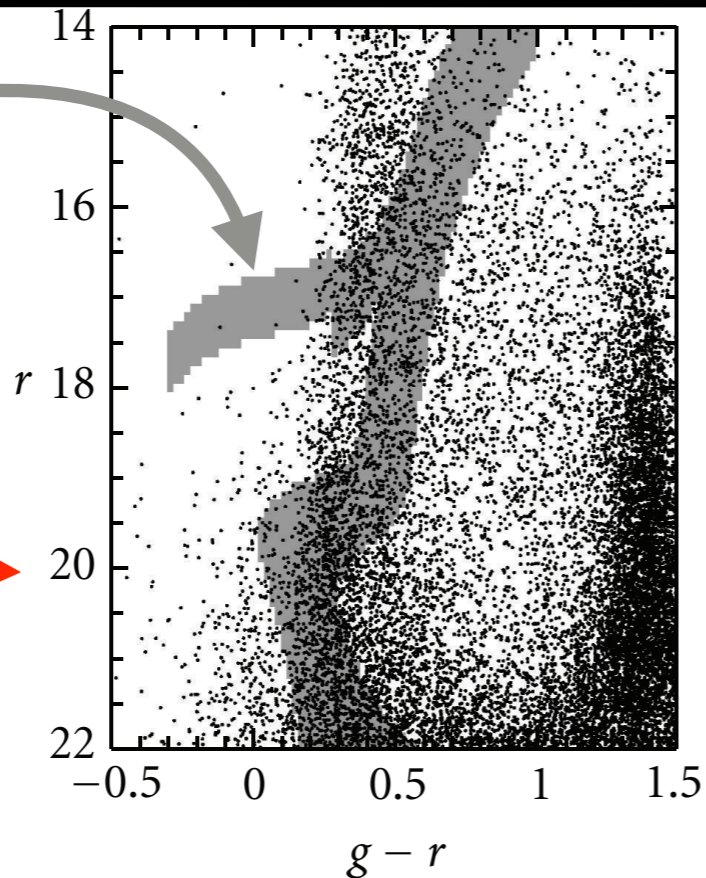


Matched-Filter Searches

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

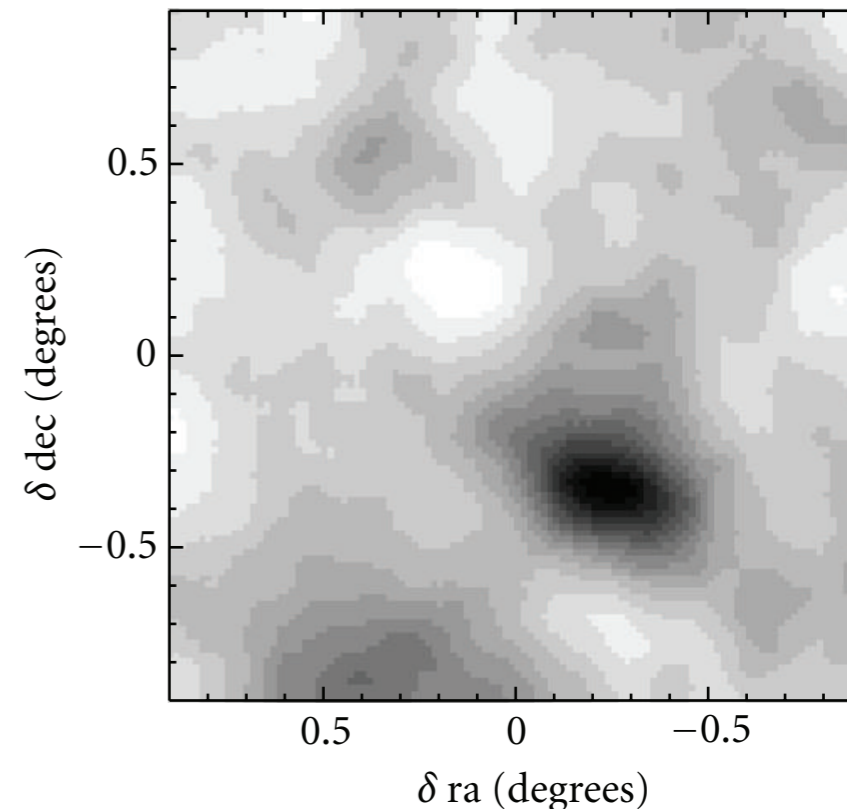
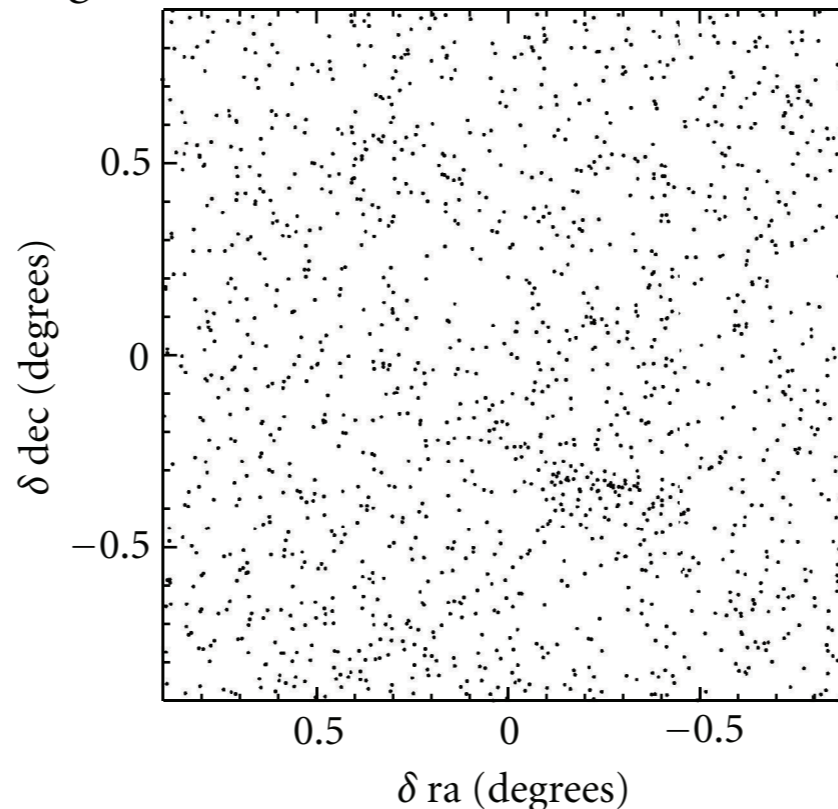
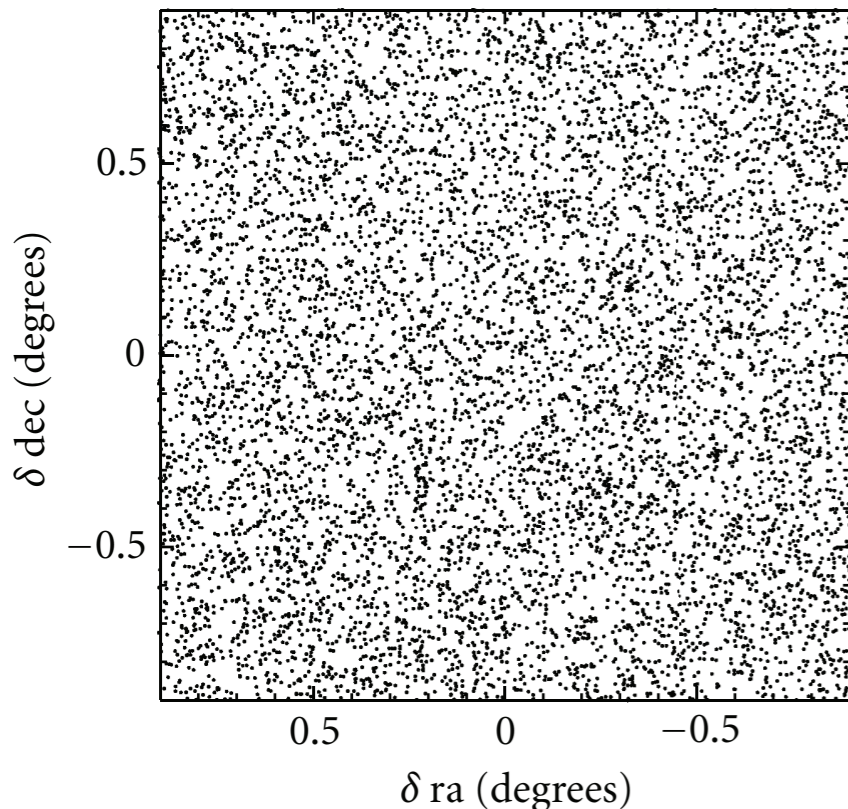
Stellar Isochrone

1) Start with a large catalog of stars



2) Apply a selection in color-magnitude space based on a stellar isochrone

3) Convolve with a spatial kernel

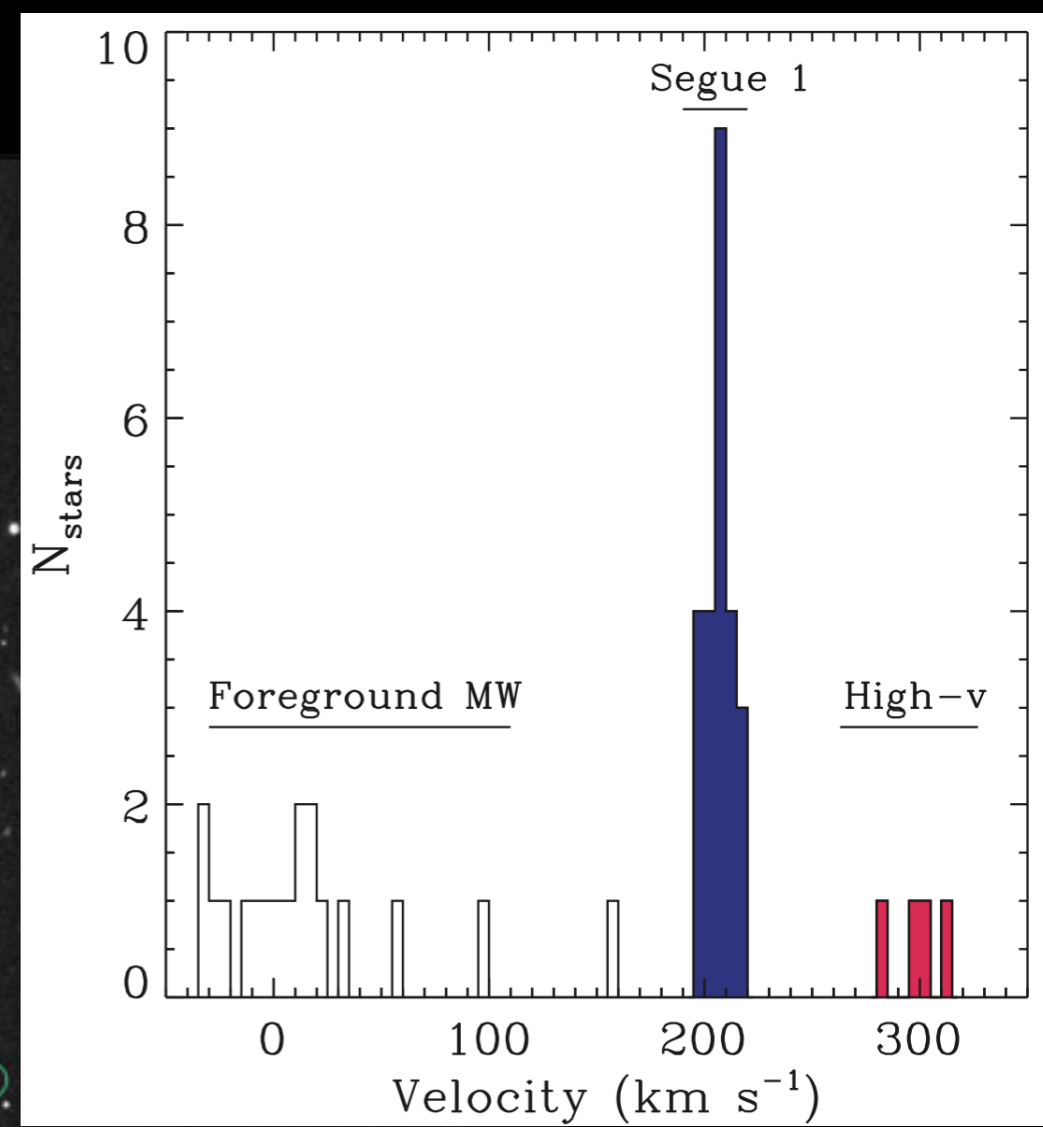
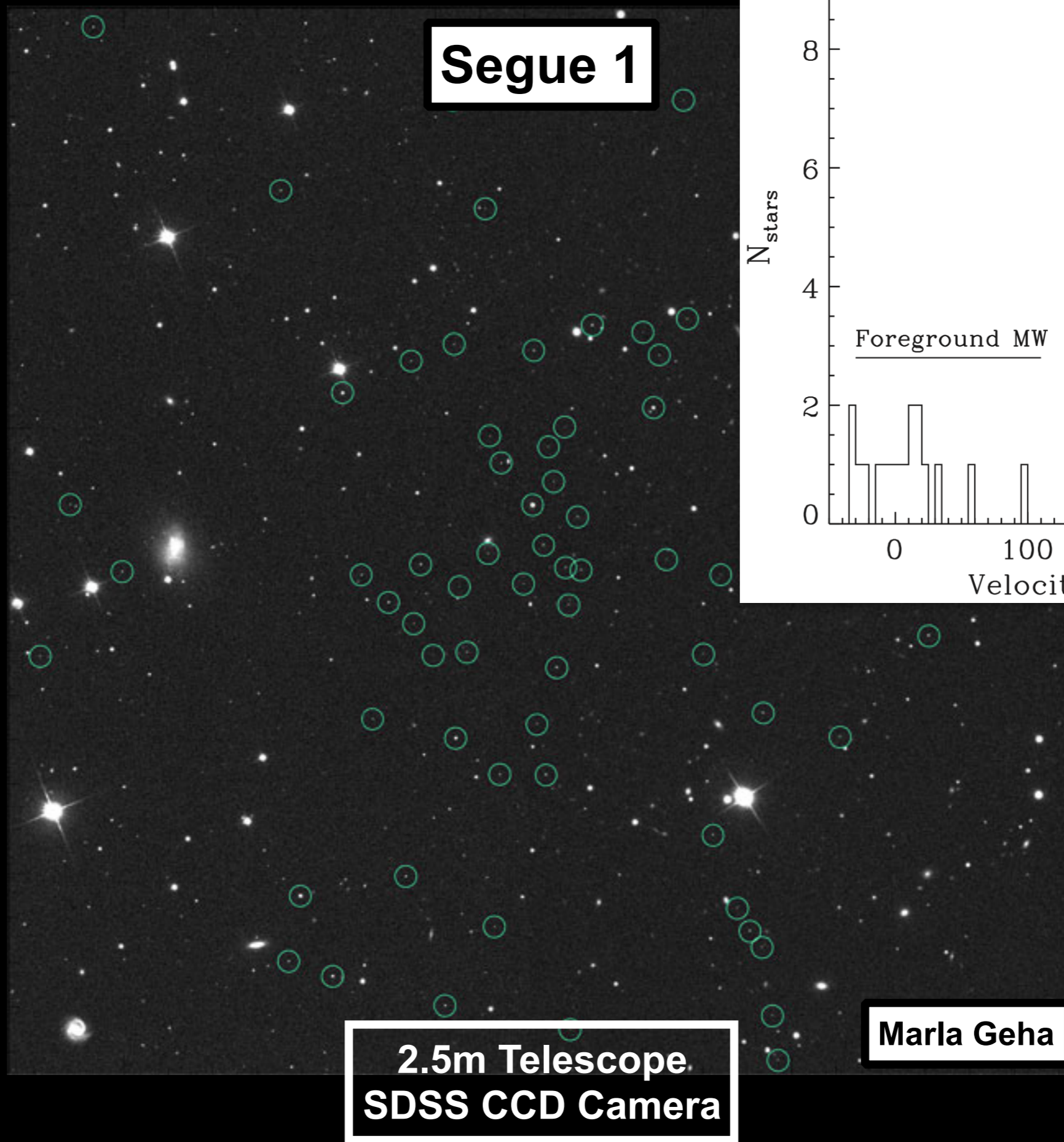




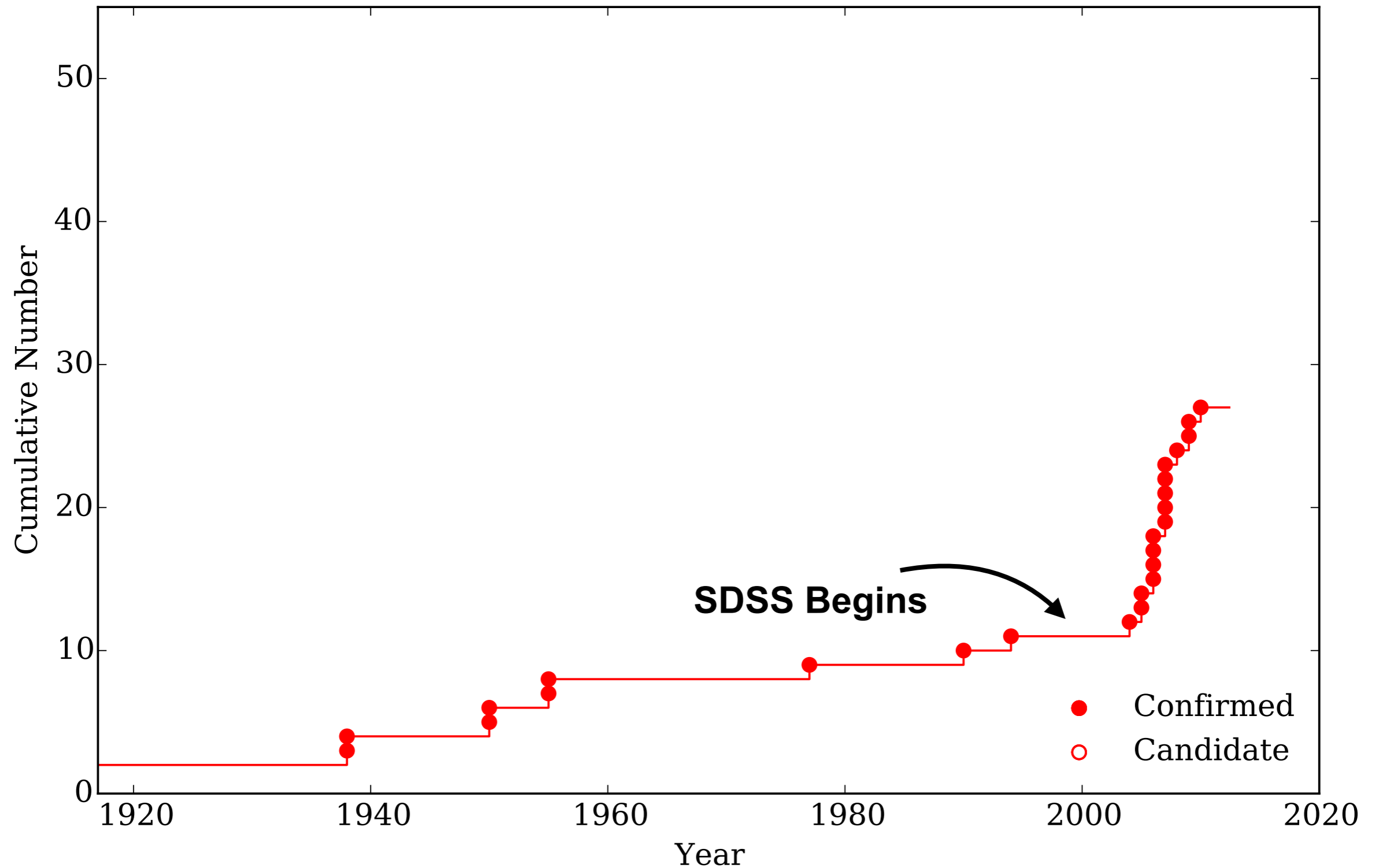
Segue 1

**2.5m Telescope
SDSS CCD Camera**

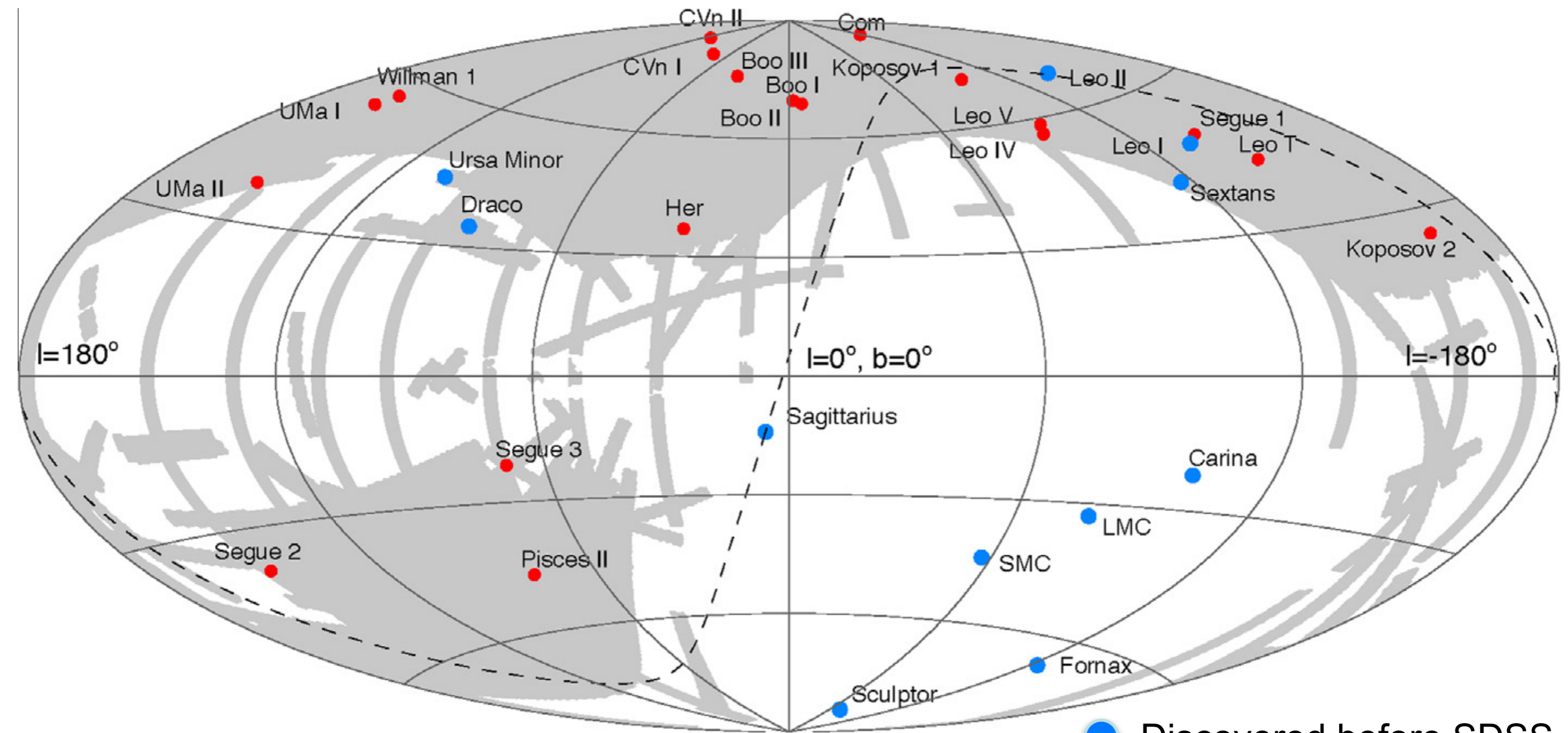
Marla Geha



Dwarf Galaxy Discovery Timeline



SDSS Sky Coverage

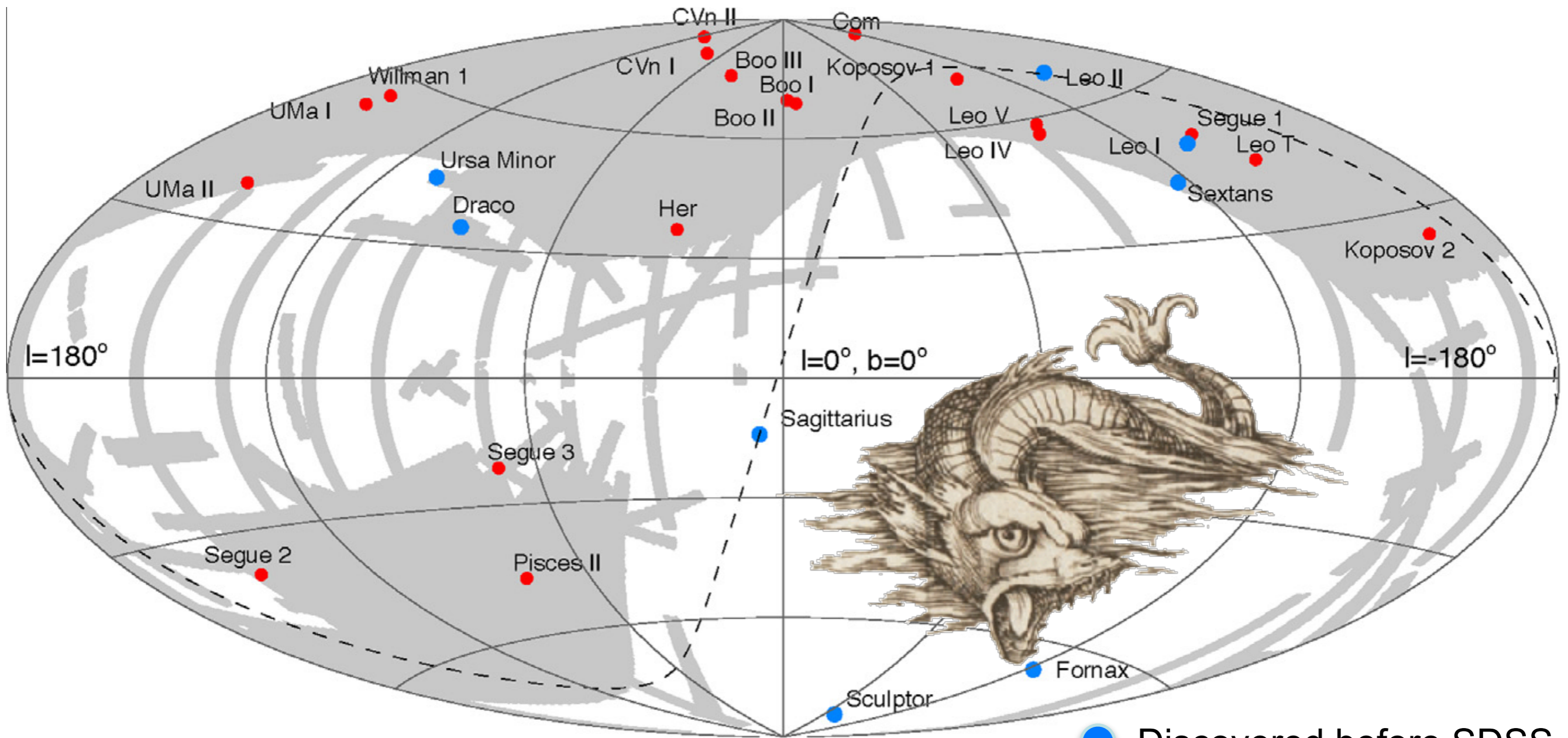


☐ Sky Covered by SDSS

- Discovered before SDSS (classical dwarfs)
- Discovered with SDSS (ultra-faint dwarfs)

(Belokurov 2013)

SDSS Sky Coverage



☐ Sky Covered by SDSS

- Discovered before SDSS (classical dwarfs)
- Discovered with SDSS (ultra-faint dwarfs)

(Belokurov 2013)

The Dark Energy Survey

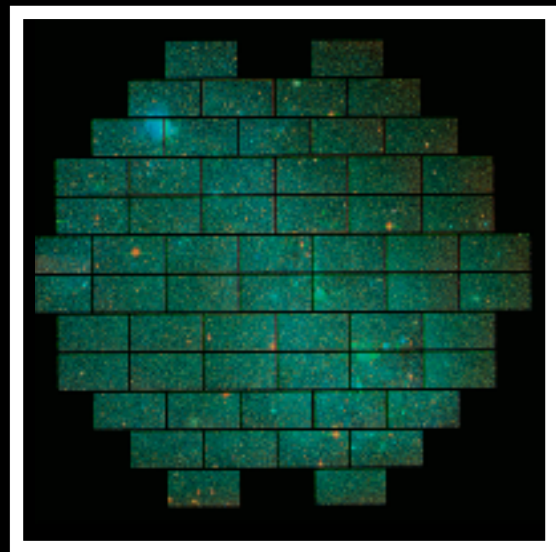
570 megapixel Dark Energy Camera (DECam)

~3 deg² field-of-view

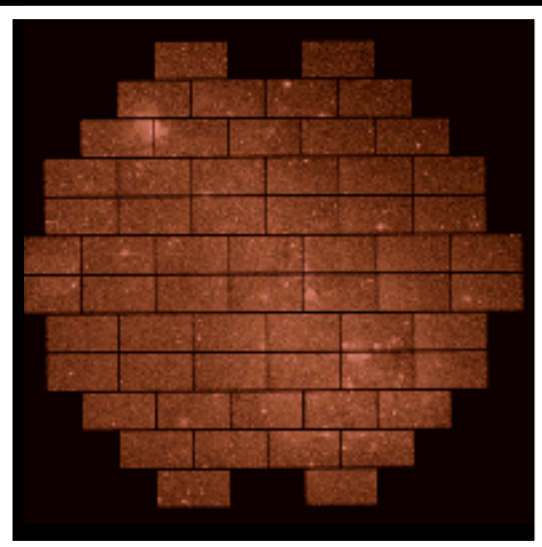
<20s readout time

Unprecedented sensitivity up to 1 μ m

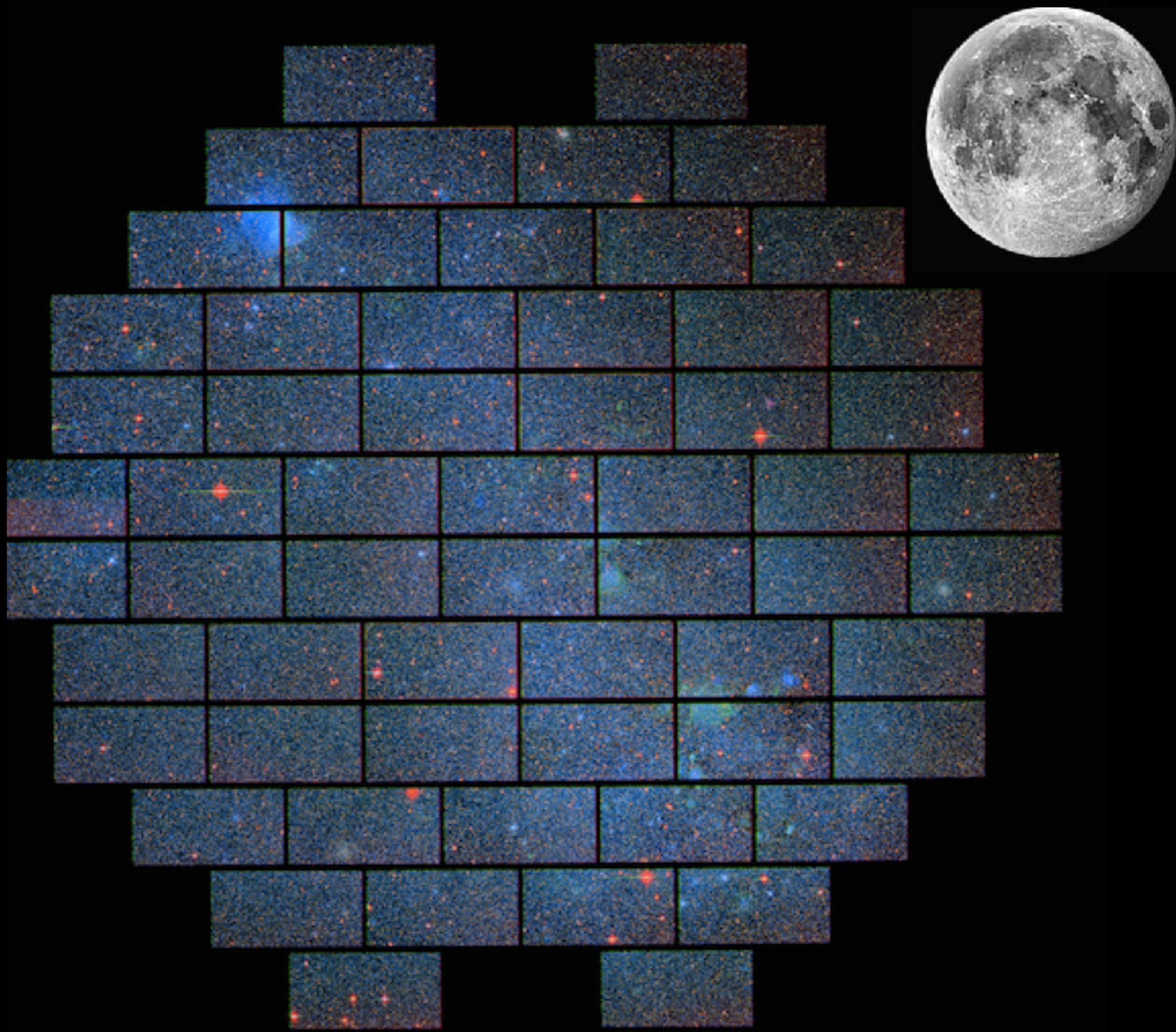
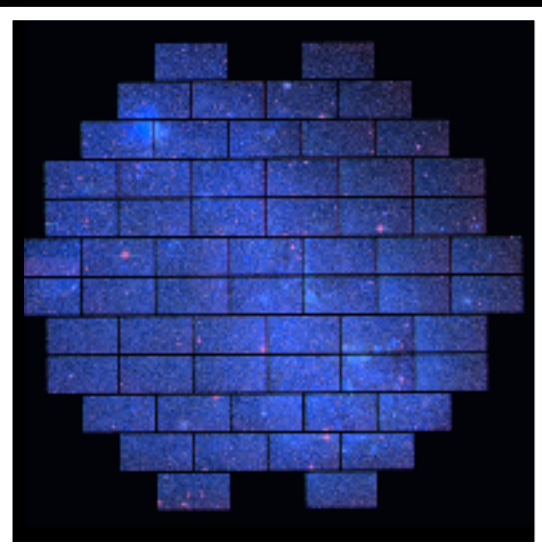
Mounted on the 4m Blanco telescope at CTIO in Chile

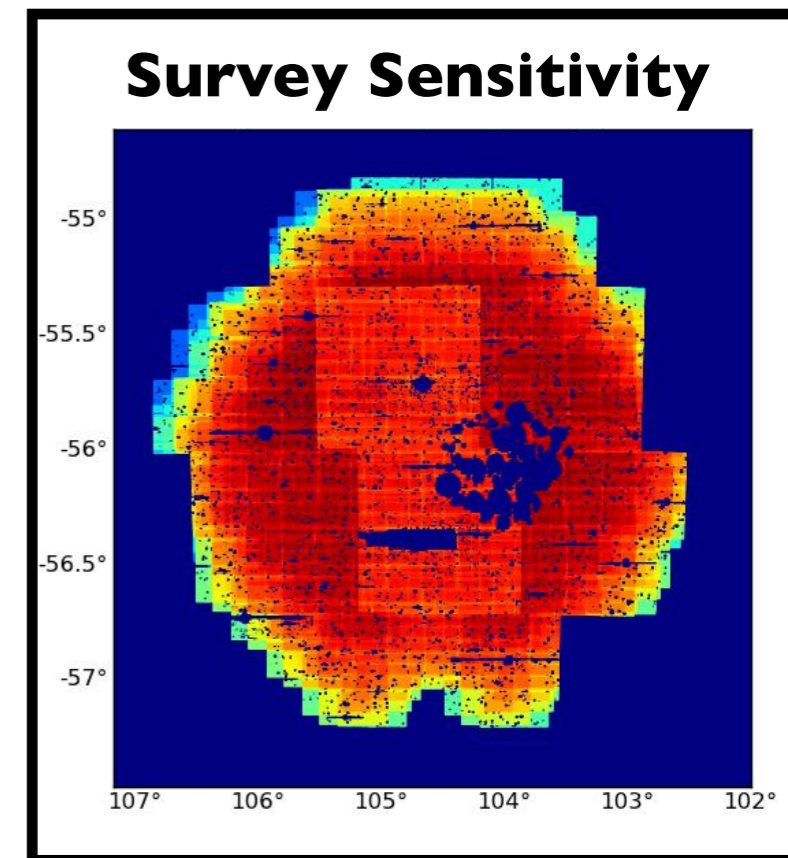
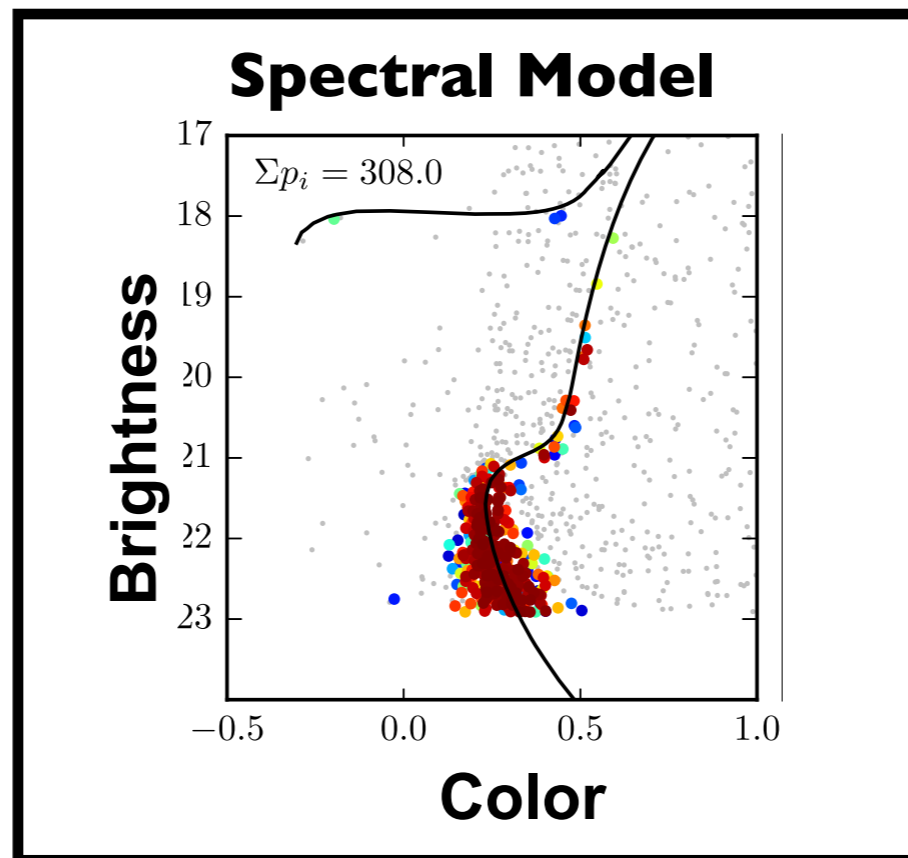
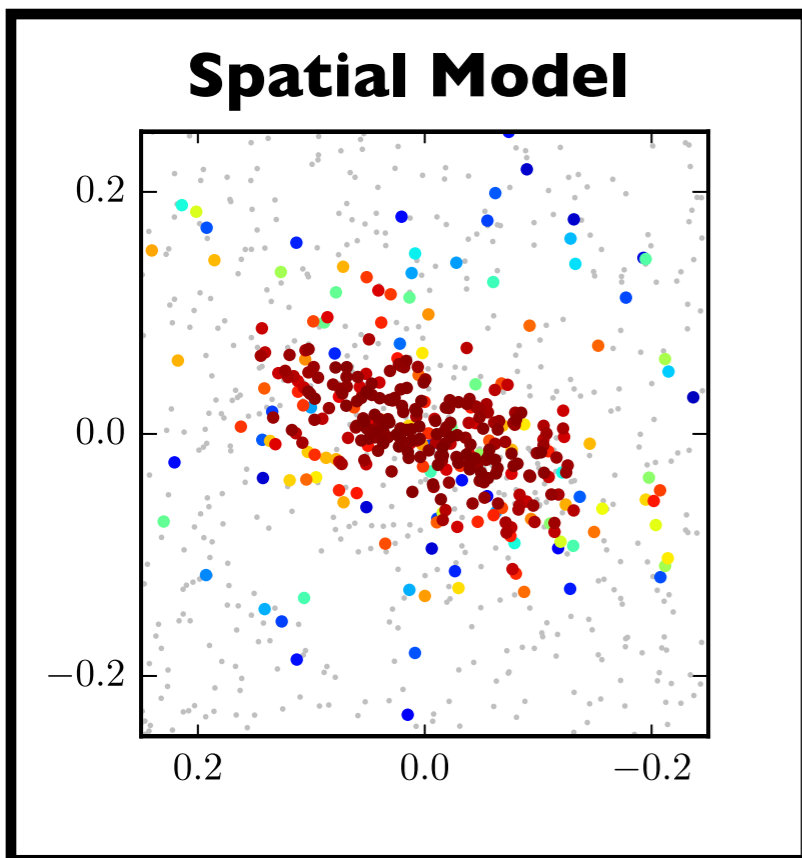


+



+





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

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

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

A likelihood analysis to simultaneously combine spatial and spectral information

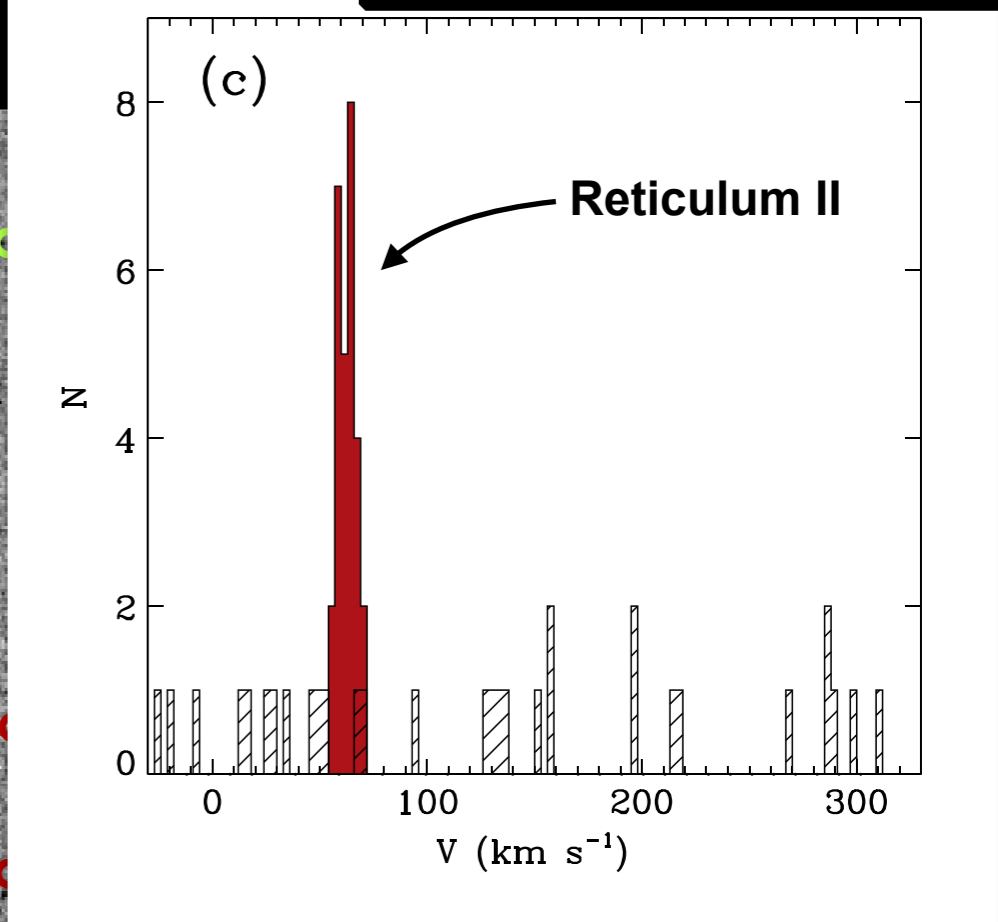
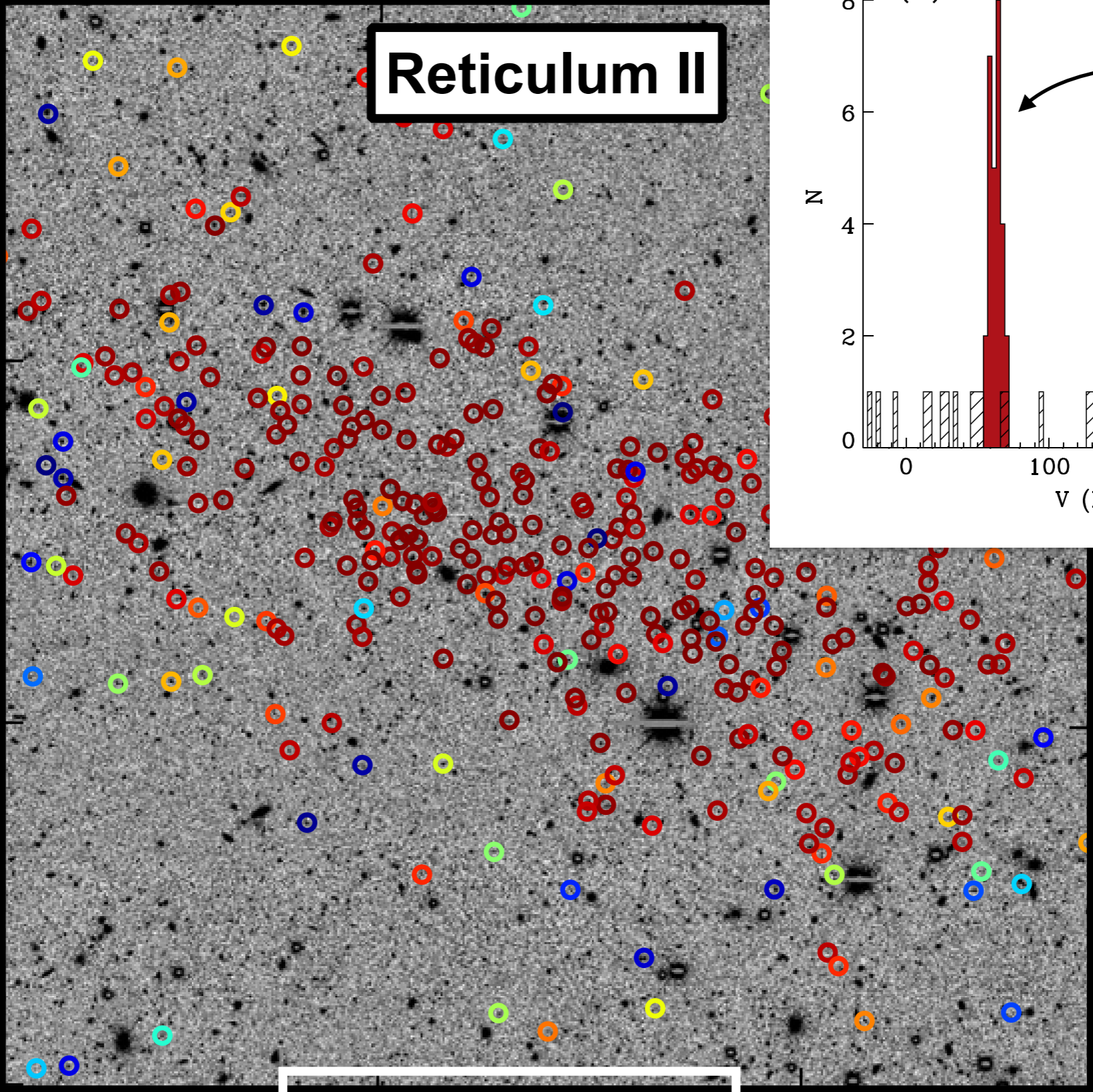
u_i = signal probability

b_i = background probability

λ = number of stars in the dwarf

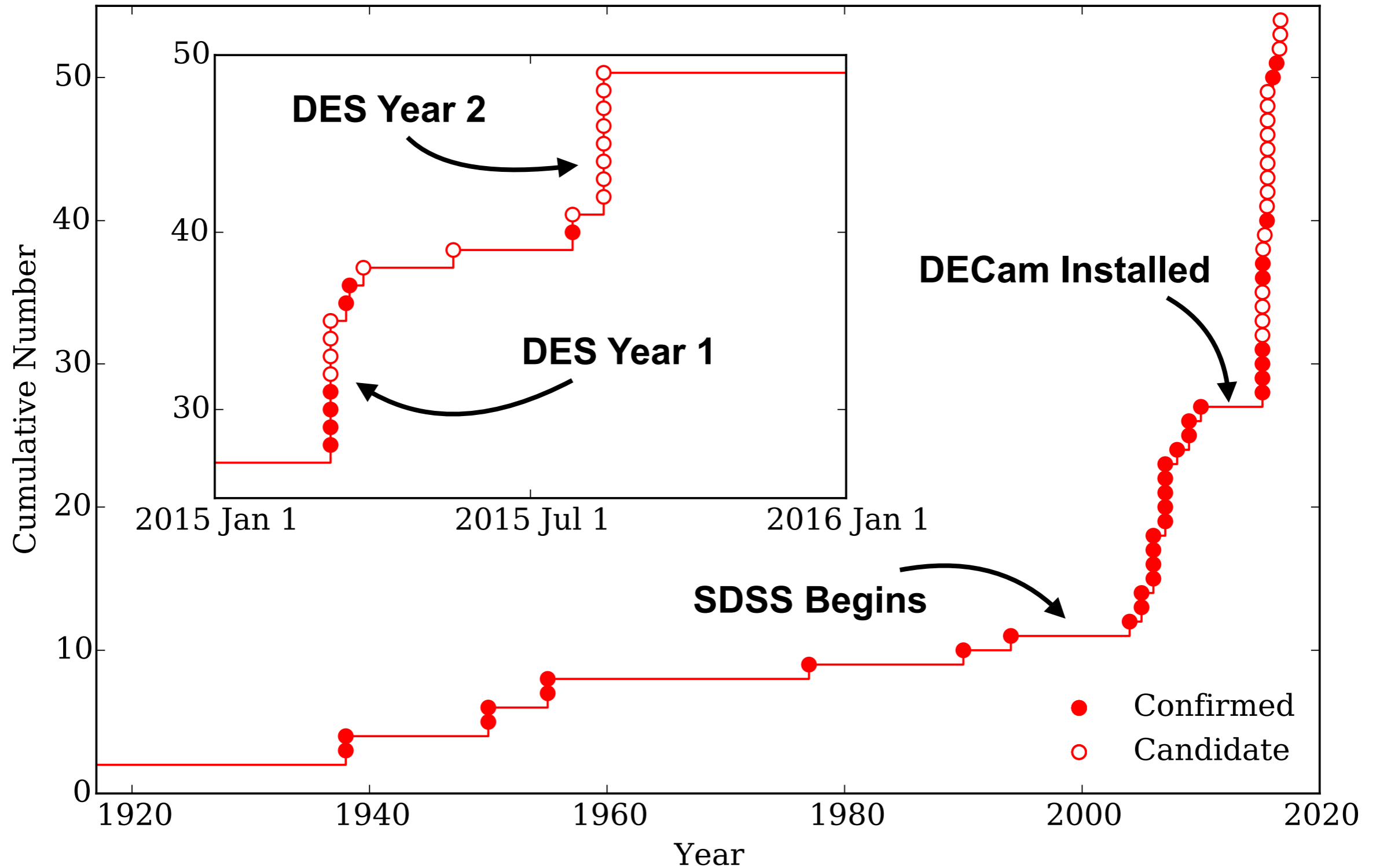
f = observable fraction of stars

This technique naturally yields a membership probability for each star; important for spectroscopic targeting

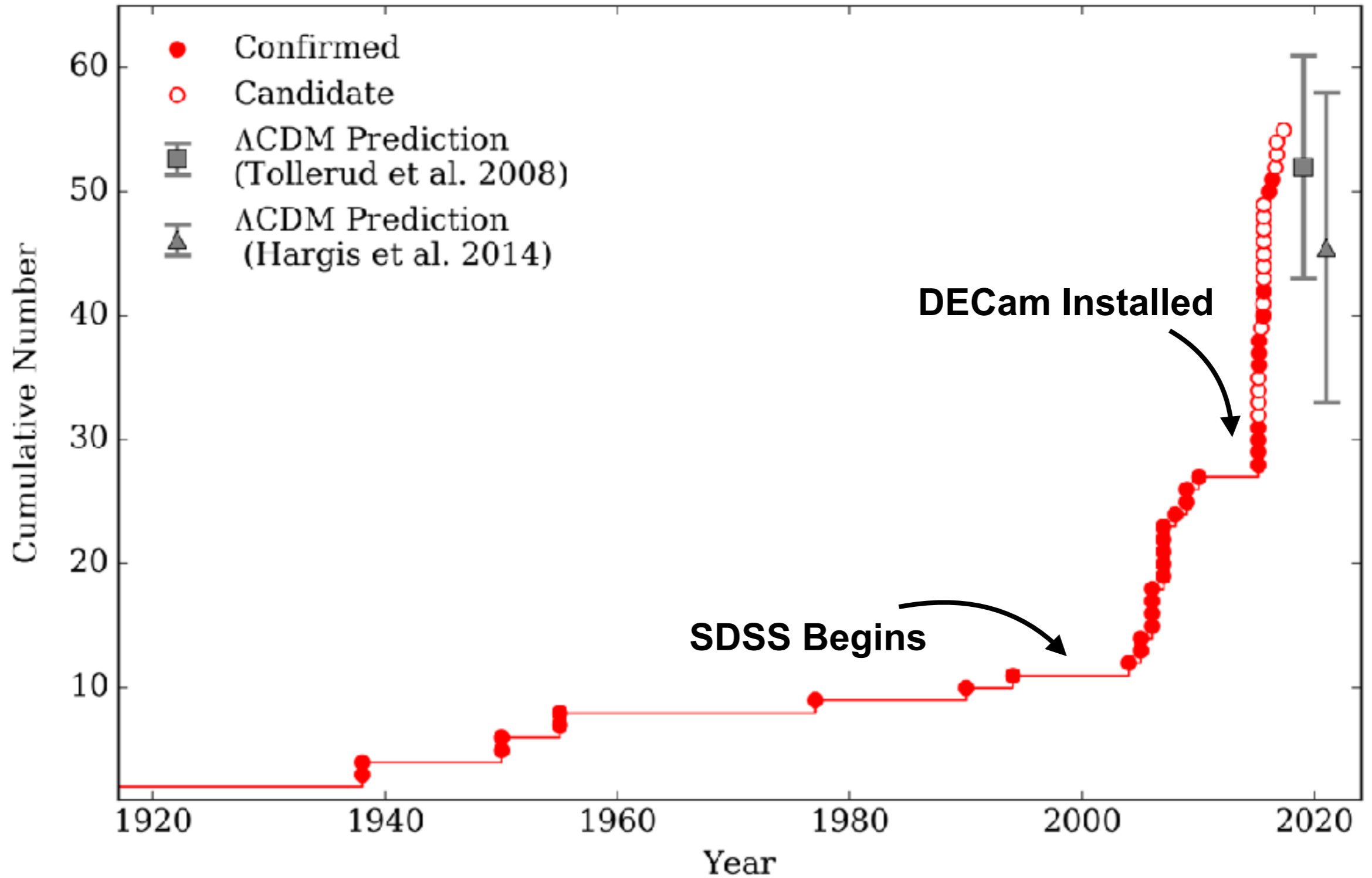


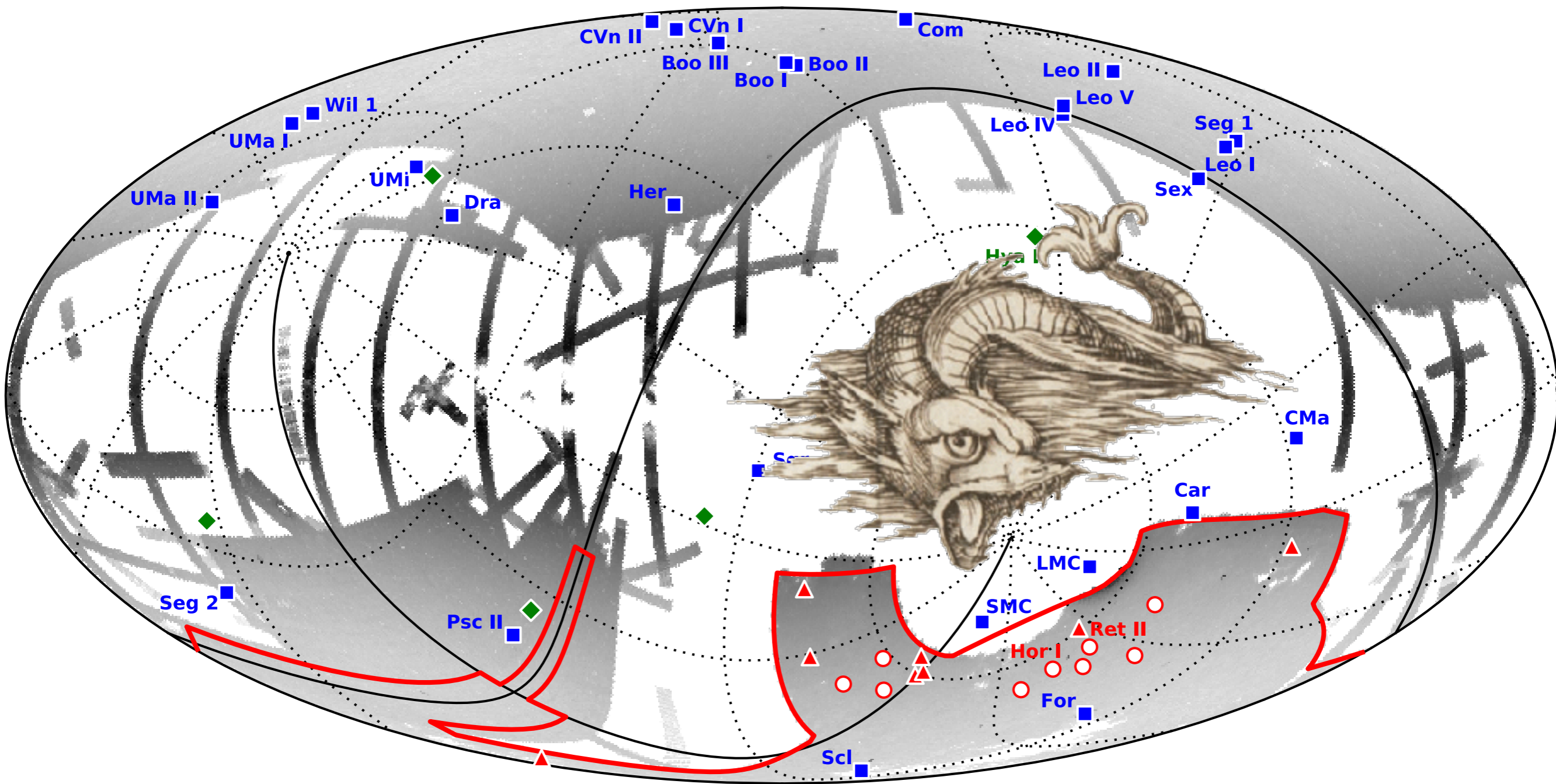
Colors correspond to the membership probability assigned to each star by the likelihood analysis

Dwarf Galaxy Discovery Timeline



Dwarf Galaxy Discovery Timeline





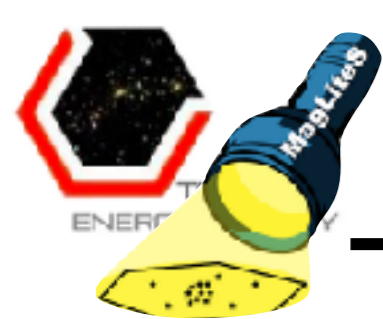
Blue - Previously discovered satellites

Green - Discovered in 2015 with PanSTARRS, SDSS, etc.

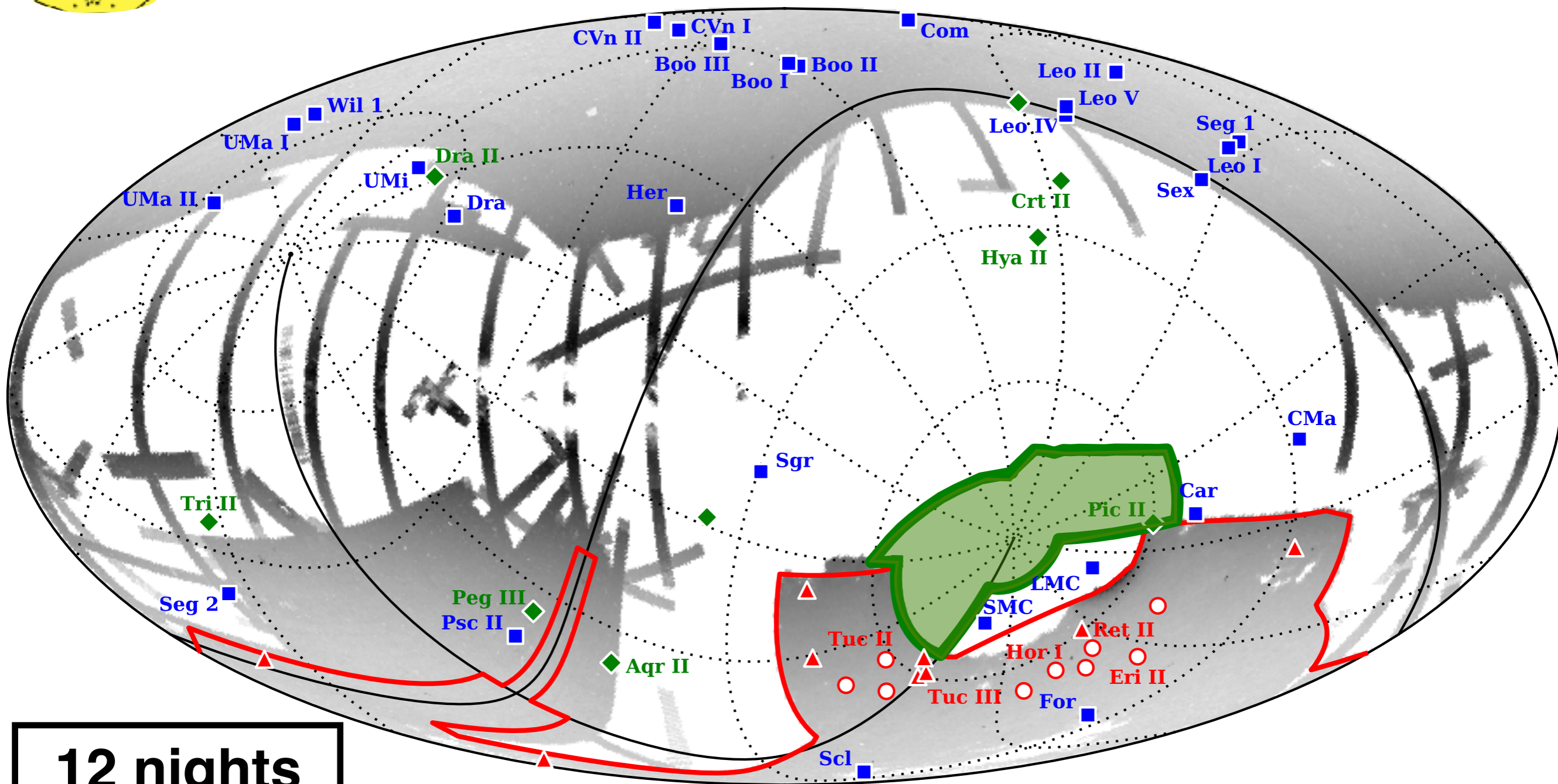
Red outline - DES footprint

Red circles - DES Y1 satellites

Red triangles - DES Y2 satellites



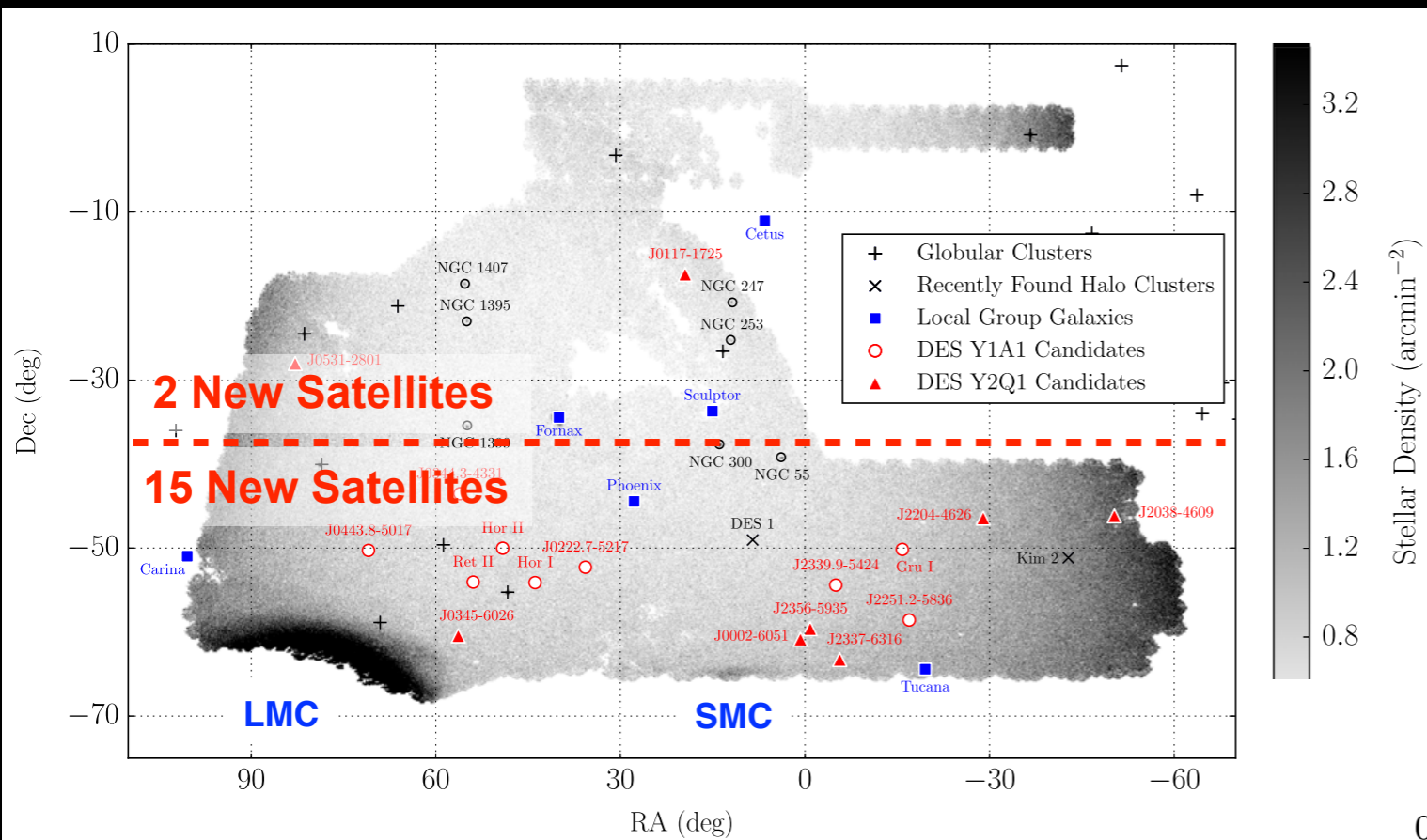
Magellanic Satellites Survey (MagLiteS)



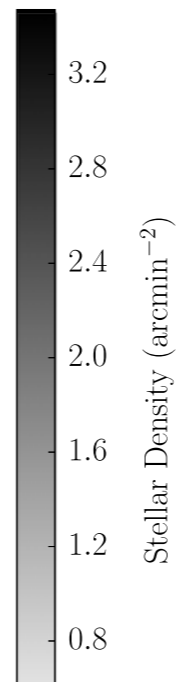
12 nights
~1300 deg²
3 tilings

Roughly comparable
in depth to the DES
Y2 satellite search

Satellites of the Magellanic Clouds?



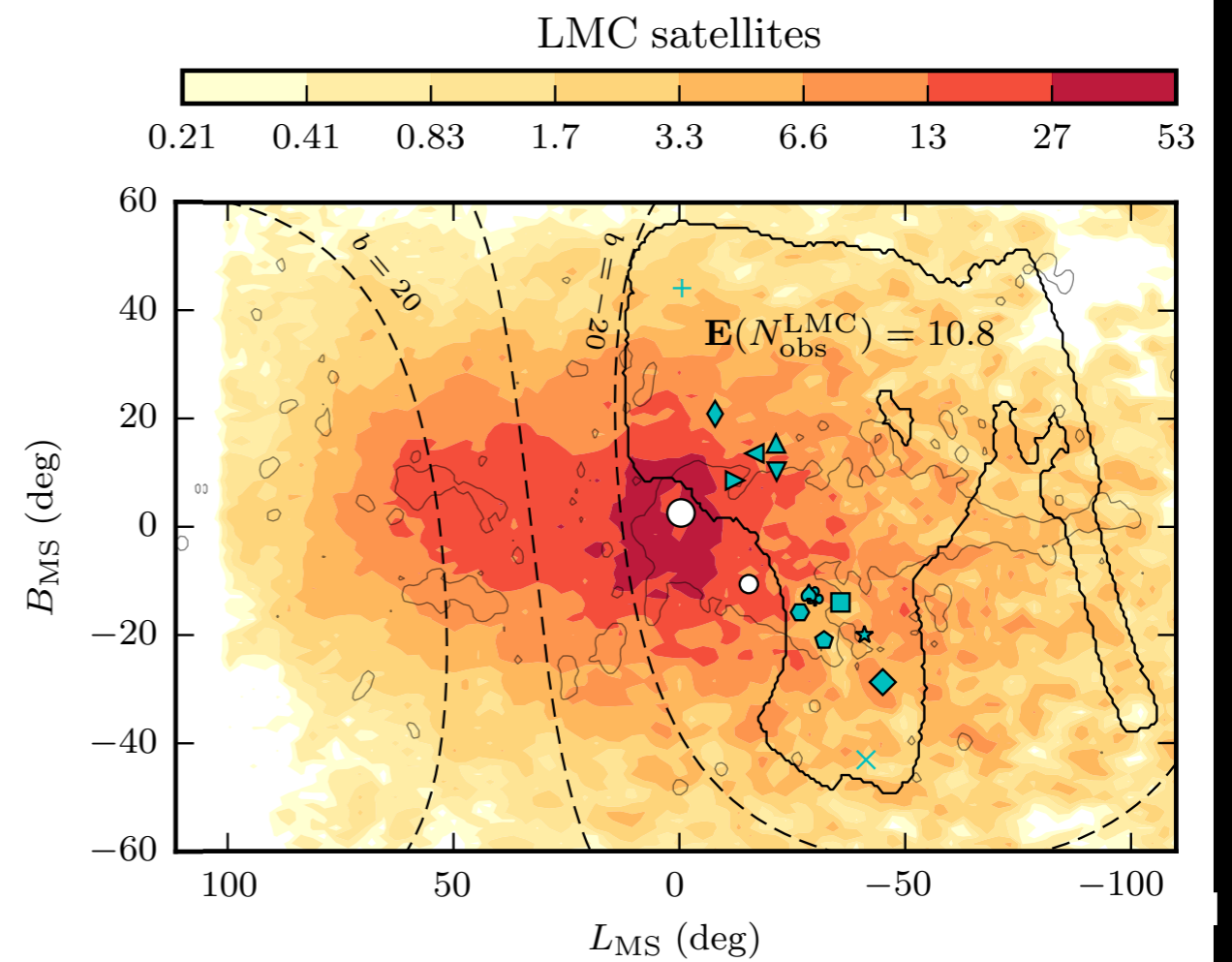
ADW et al. ApJ 813, 109 (2015)



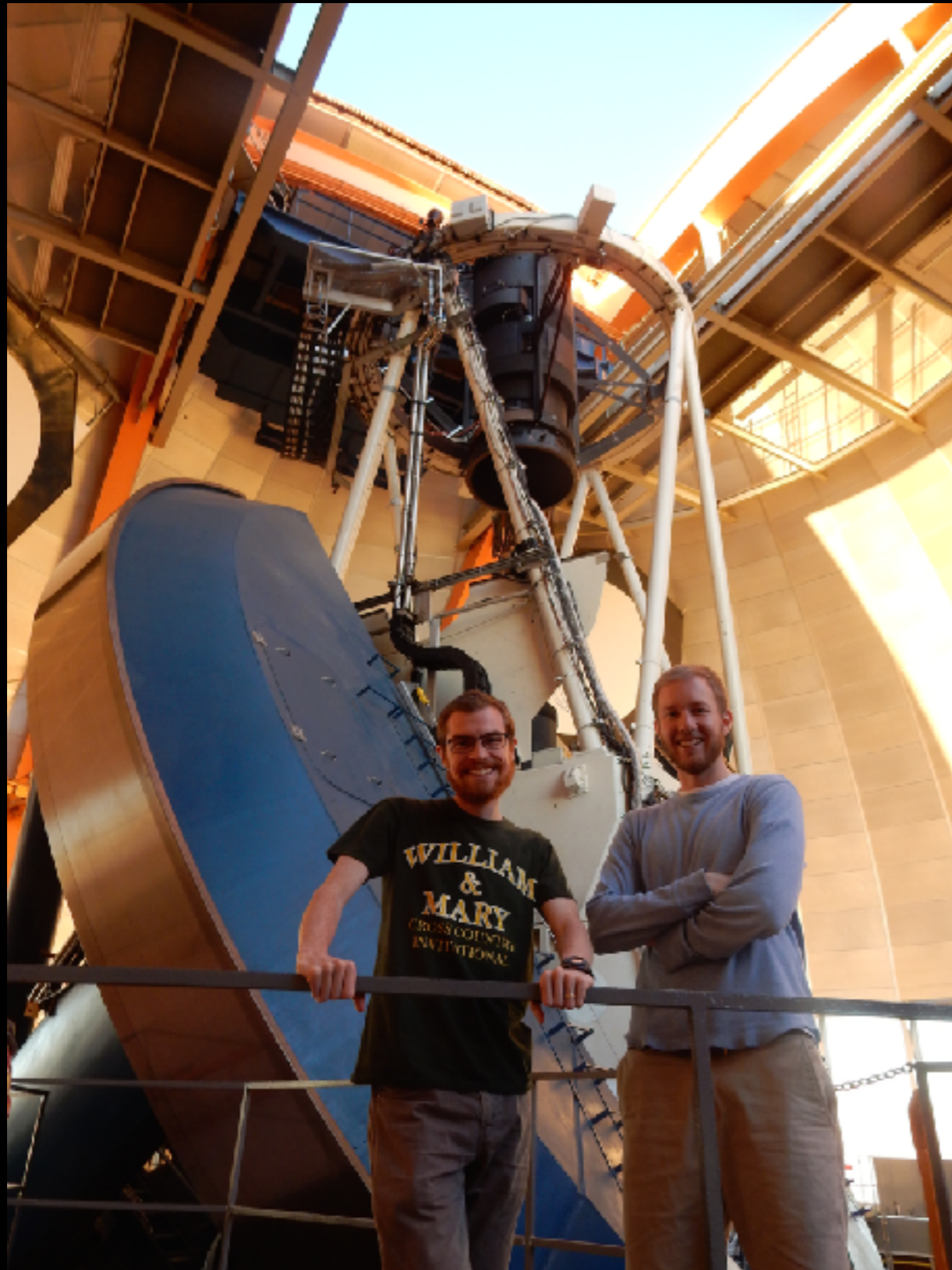
There is $\sim 3\sigma$ evidence that DES satellites are not isotropically distributed.

Jethwa et al. MNRAS 461, 2 (2016)

This anisotropy could be explained by an association with the Magellanic Clouds



Magellanic Satellites Survey



(MagLiteS)



**DECam Program for 12 nights
in 2016-2017**

PI: Keith Bechtol

Deputy PI: ADW

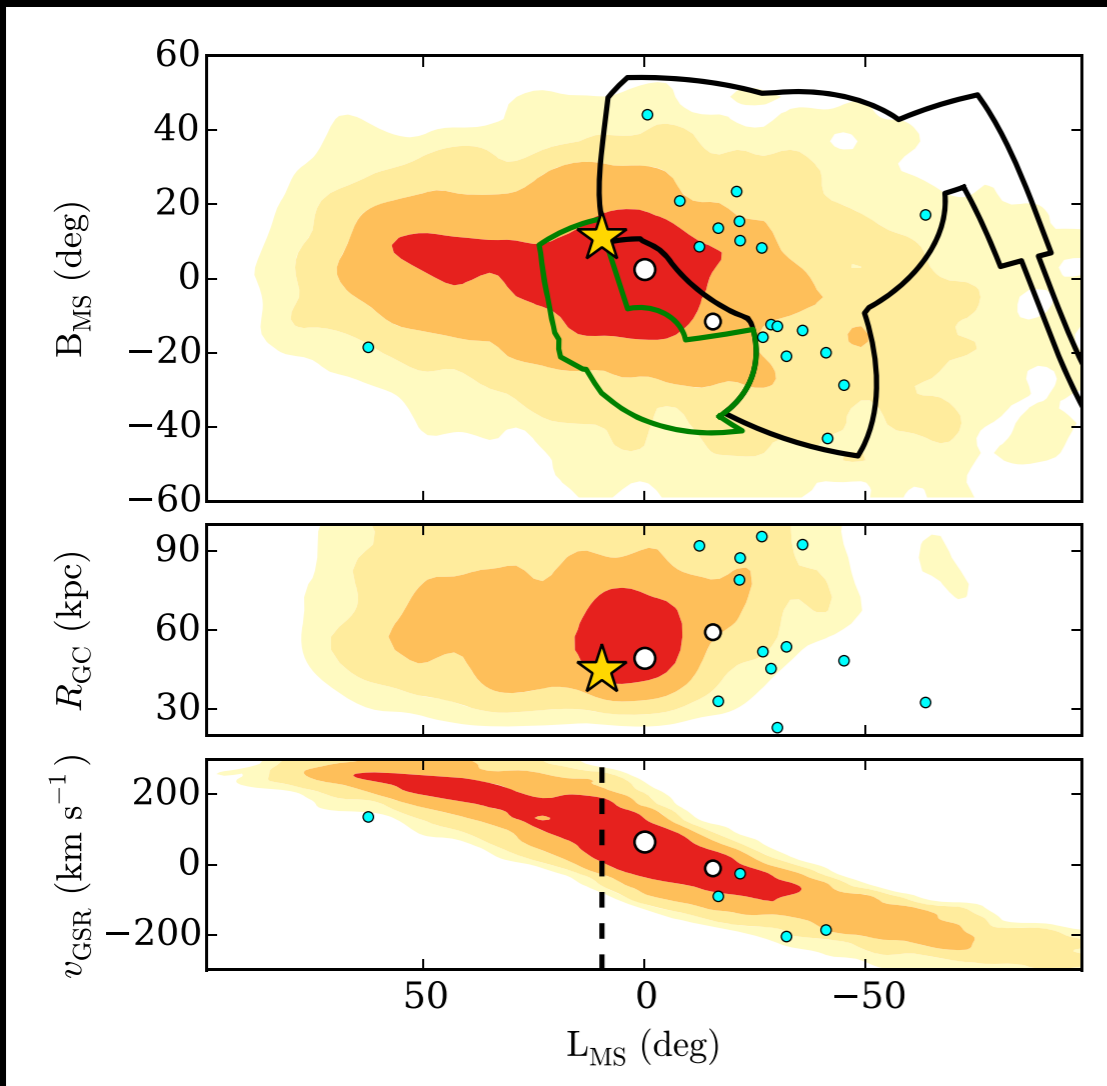
**Funding through the NASA
Guest Investigator Program**

PI: ADW

**Collaboration of ~45 members
across ~20 institutions**



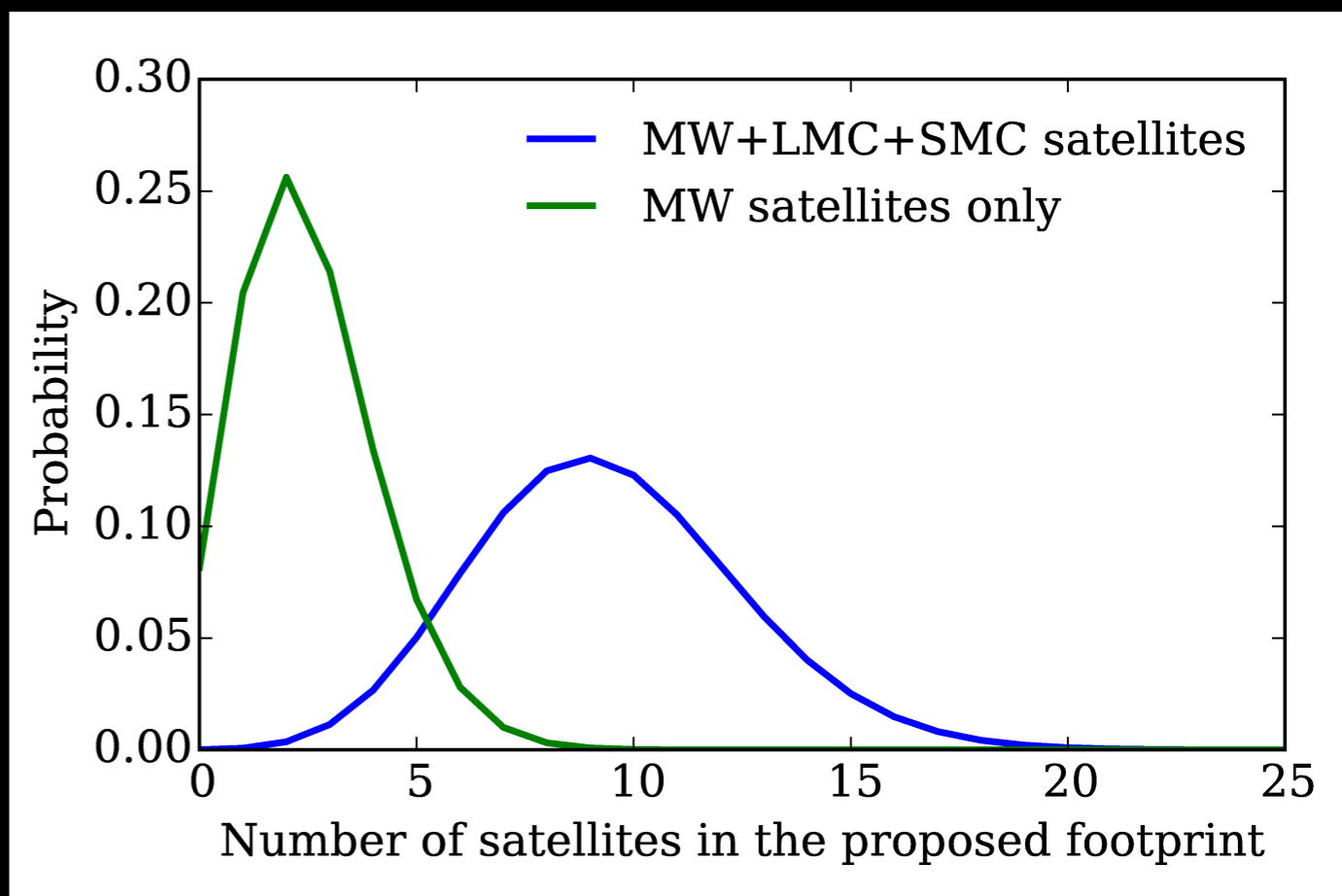
Satellites of the Magellanic Clouds?



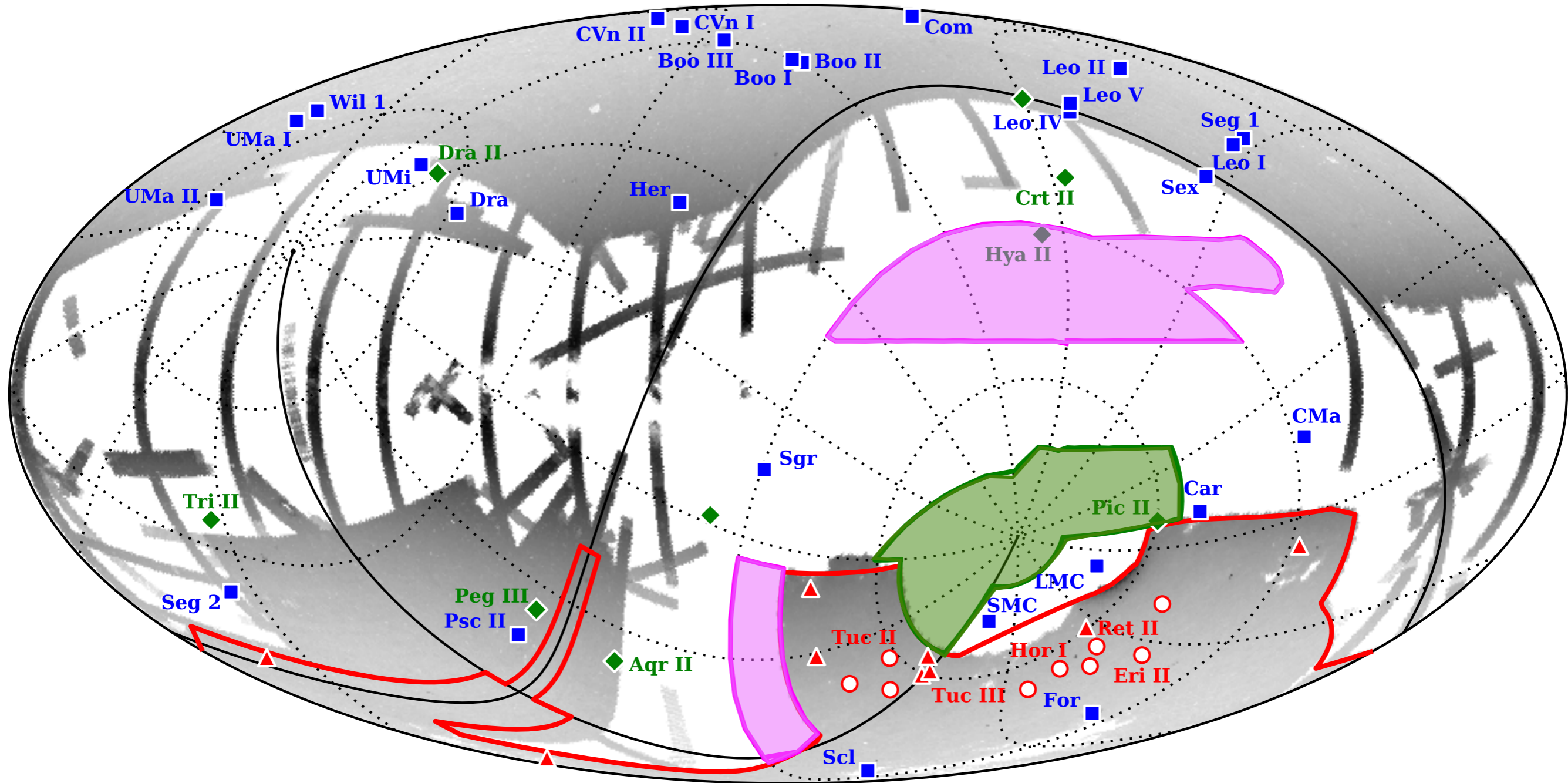
ADW et al. ApJL 833, 5, 2016

Simulations predict ~3 dwarf galaxies for an isotropic distribution and ~10 galaxies for a Magellanic Cloud association.

First quarter of MagLiteS:
1) One satellite that may still be bound to the LMC
2) Tight pair of satellites located close to the LMC...



Blanco Imaging of the Southern Sky (BLISS)



Blanco Imaging of the Southern Sky



**NOAO DECam Program for 12 nights in 2017A
Co-PIs: Soares-Santos & ADW**

3 Science Drivers:

- **Dwarf Galaxy Searches**
- **Gravitational Wave Follow-up**
- **Search for Planet 9**

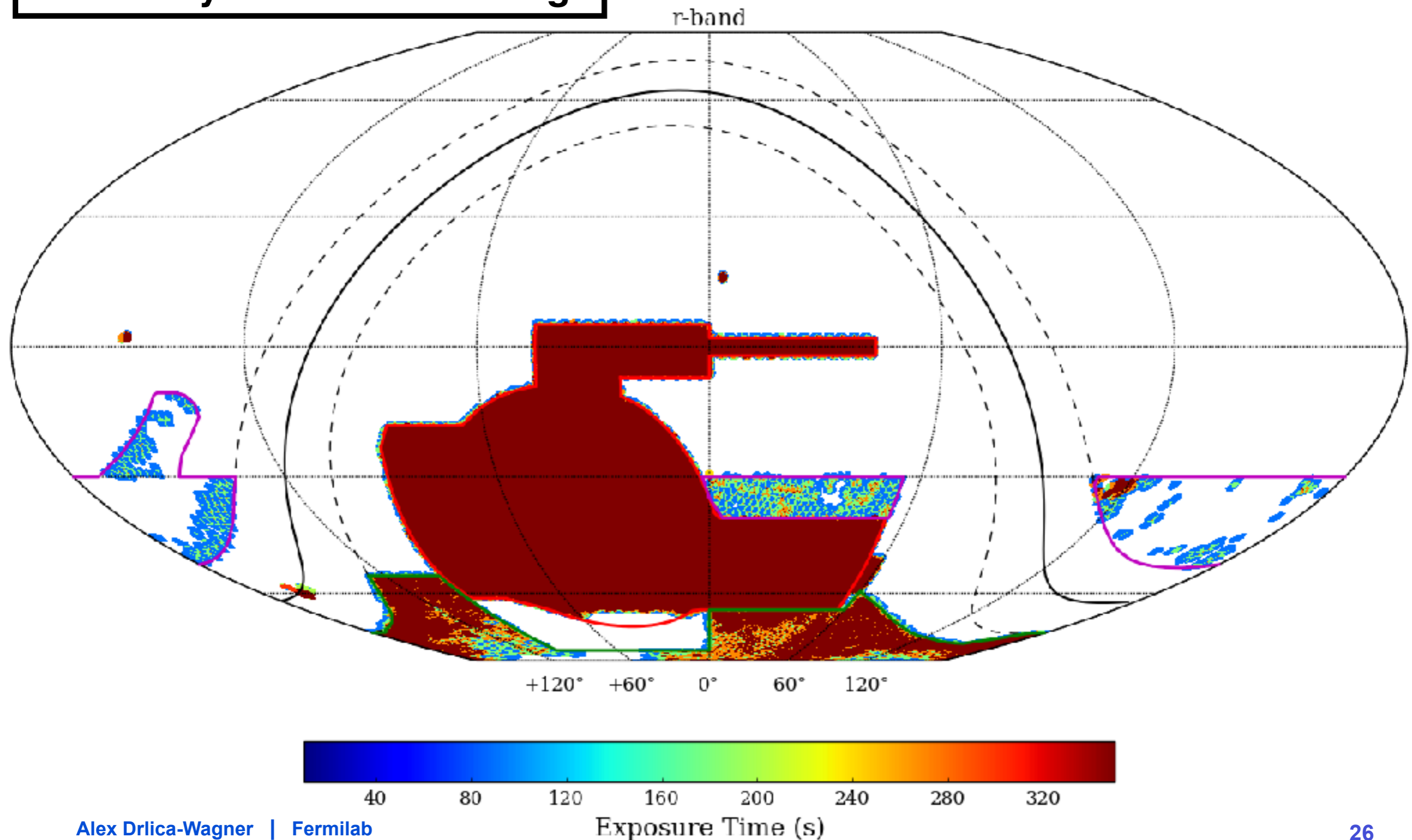
Collaboration of ~35 members across ~10 institutions

Cover ~2000 deg² in 2017; eventually cover the entire sky in g,r,i,z bands

First-year observations finished on Monday!

DES Sky Coverage

DES *only* covers ~5000 deg²

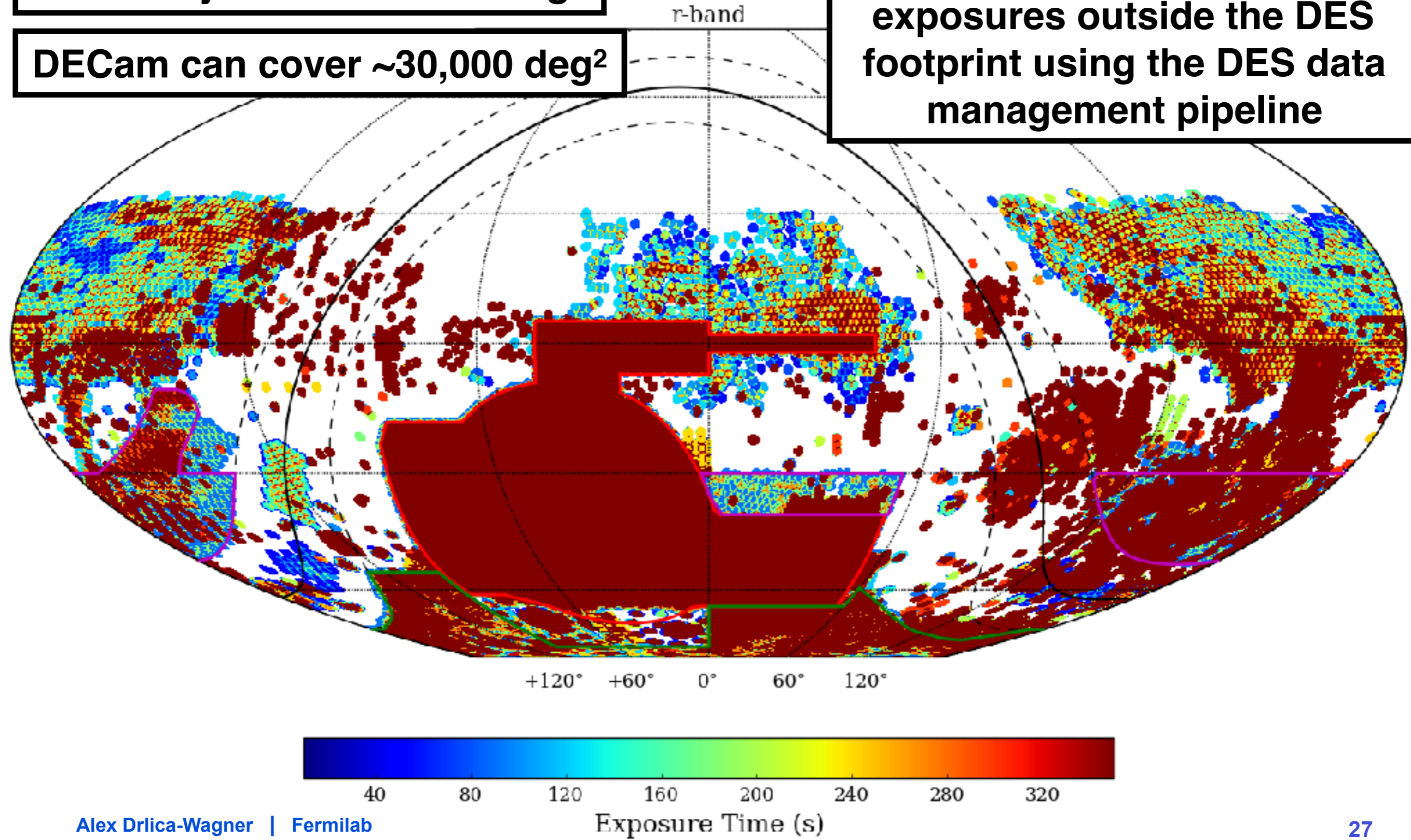


DECam Sky Coverage

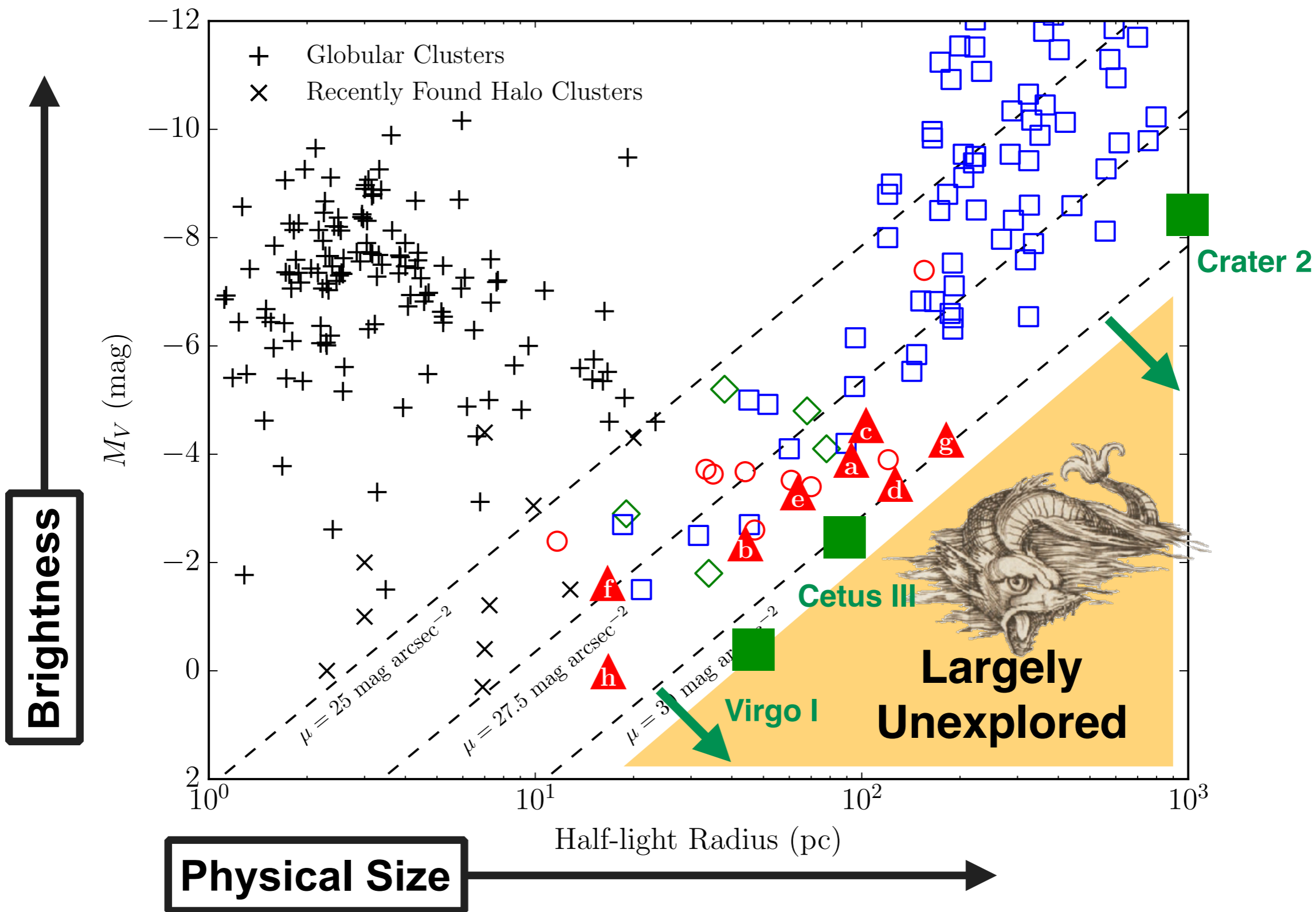
DES *only* covers ~5000 deg²

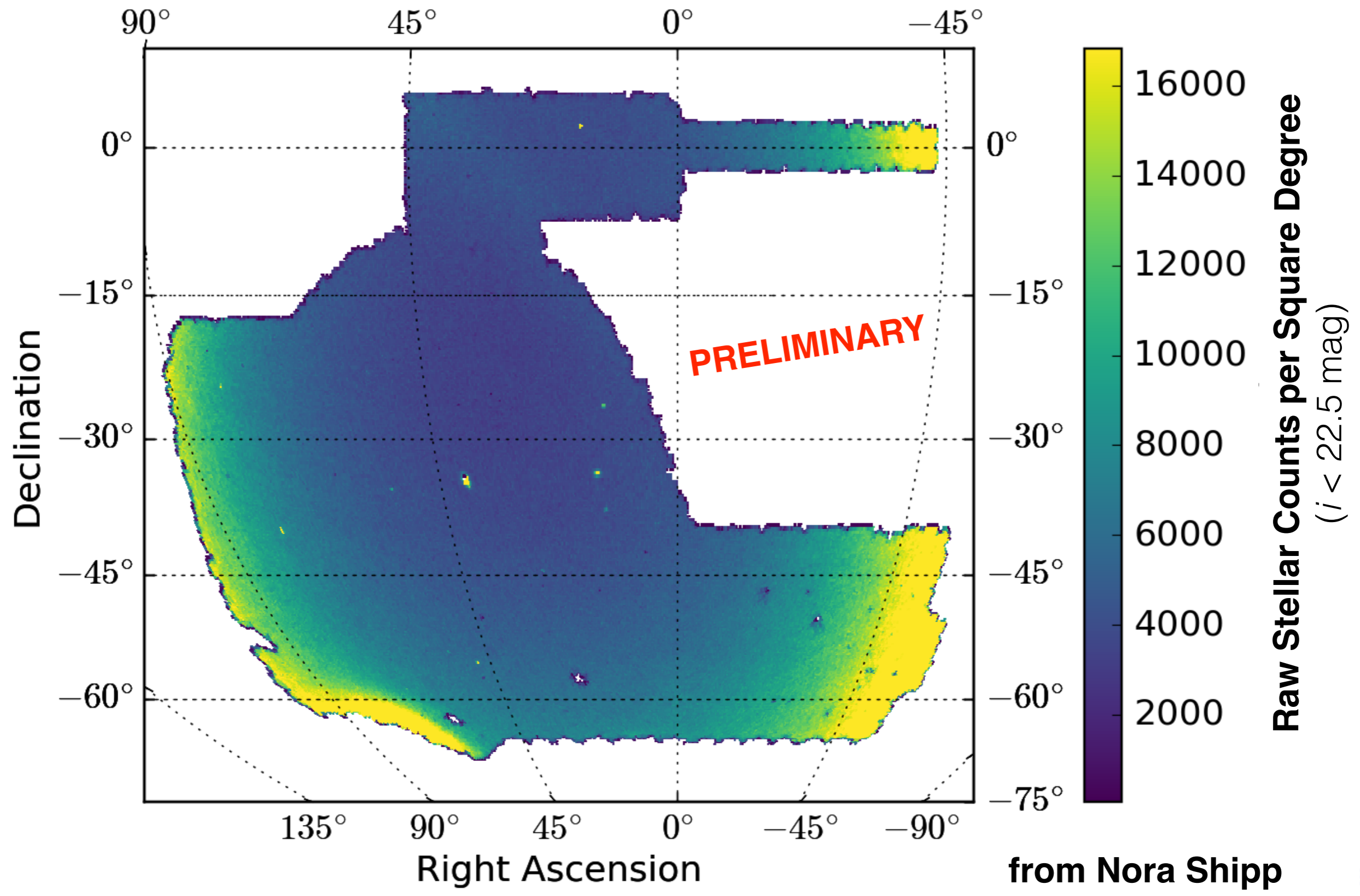
DECam can cover ~30,000 deg²

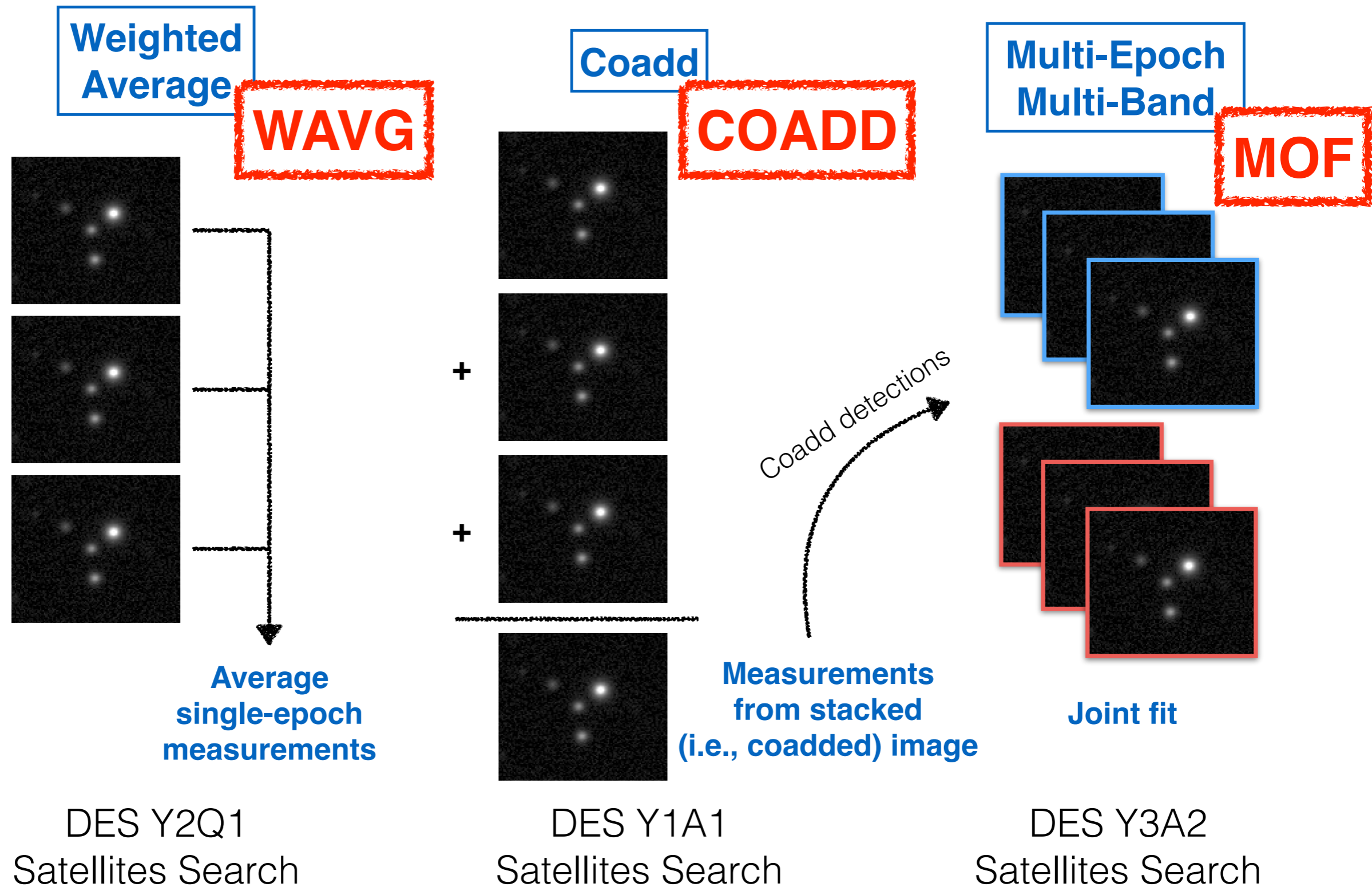
We have processed ~100k exposures outside the DES footprint using the DES data management pipeline

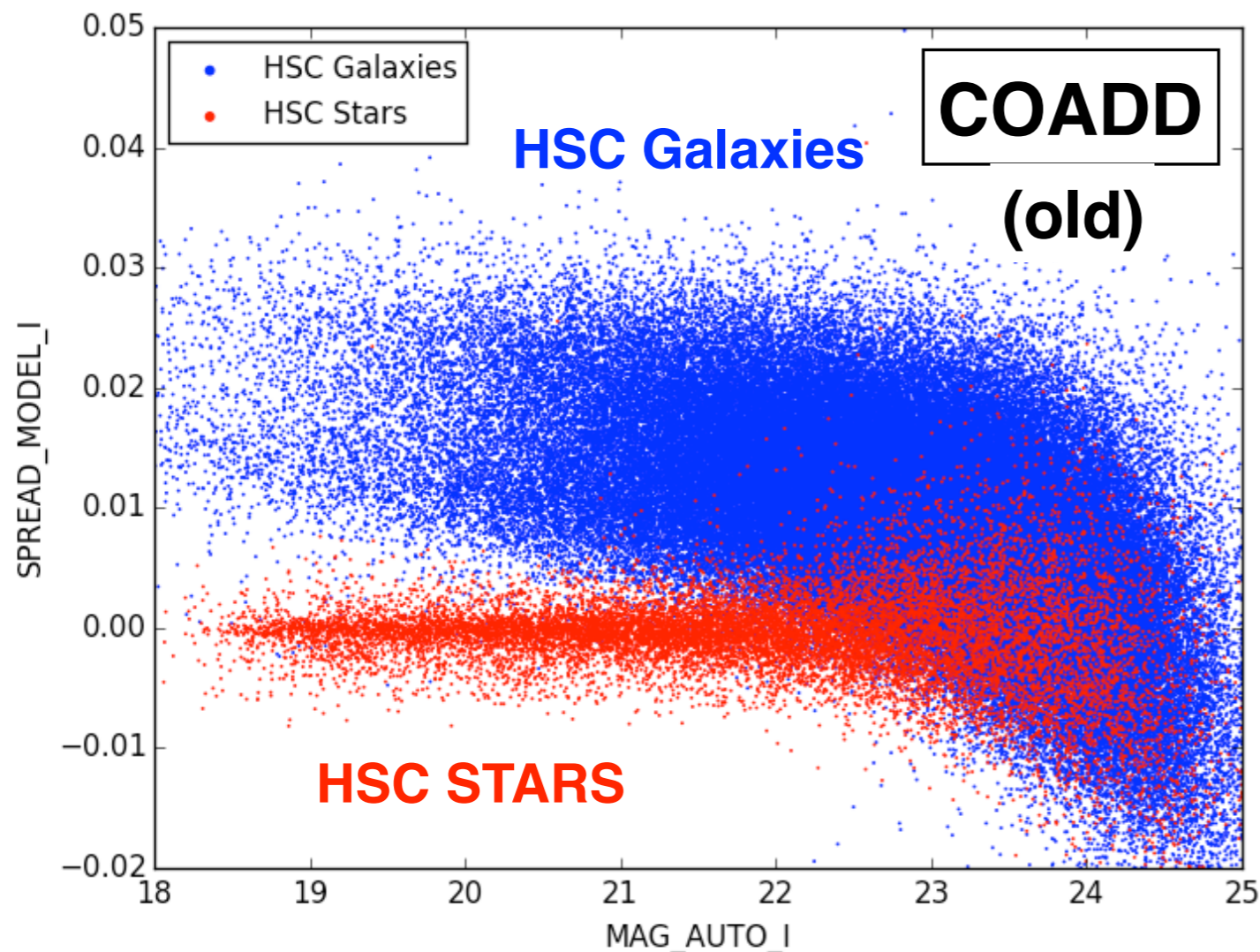


The Surface Brightness Frontier



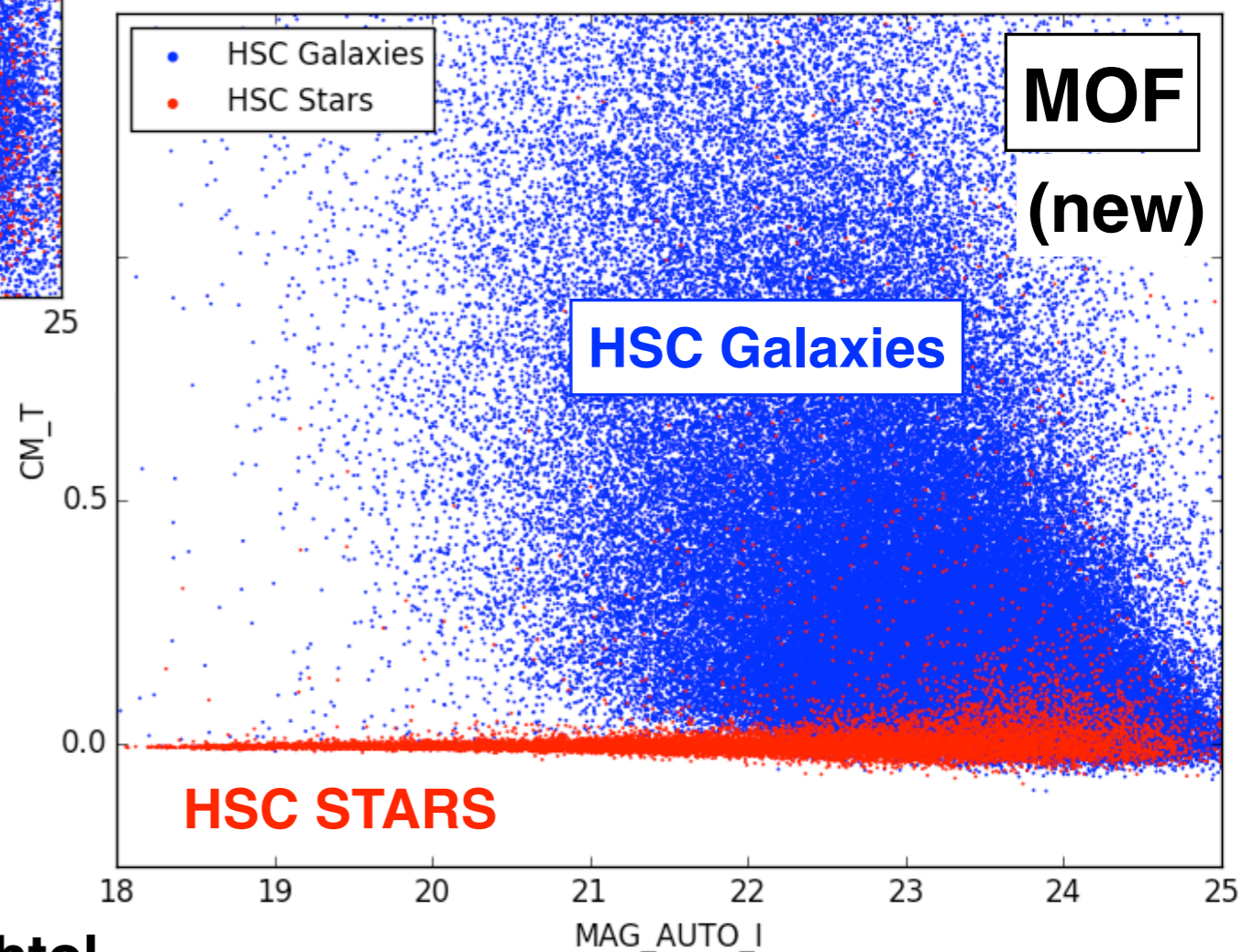






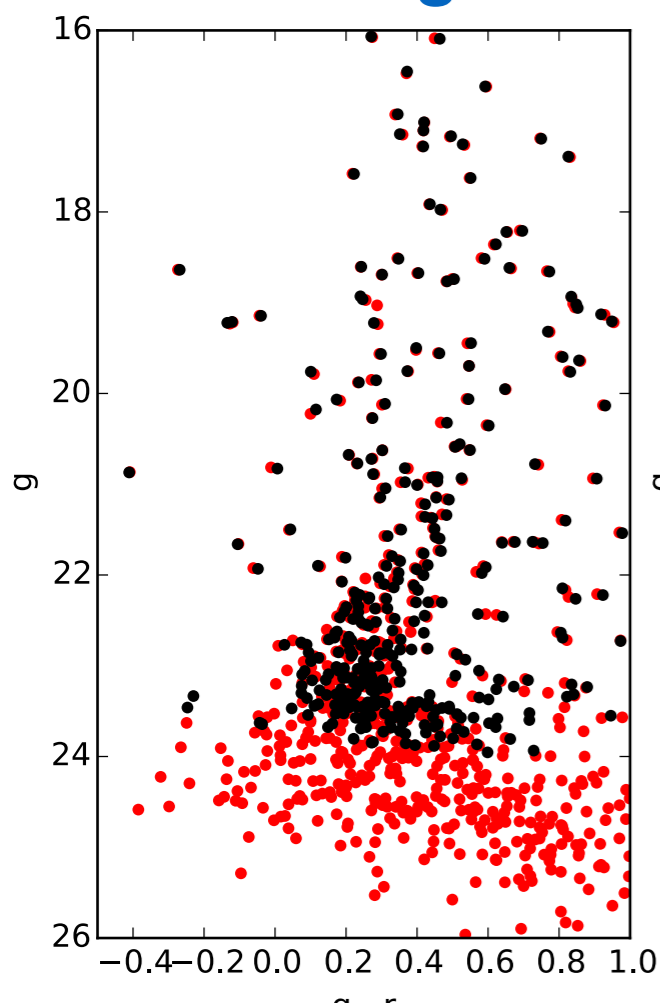
Modeling PSF from individual images yields large improvements in morphological measurements

HSC provides an unprecedented deep, wide-area, good-seeing training data set

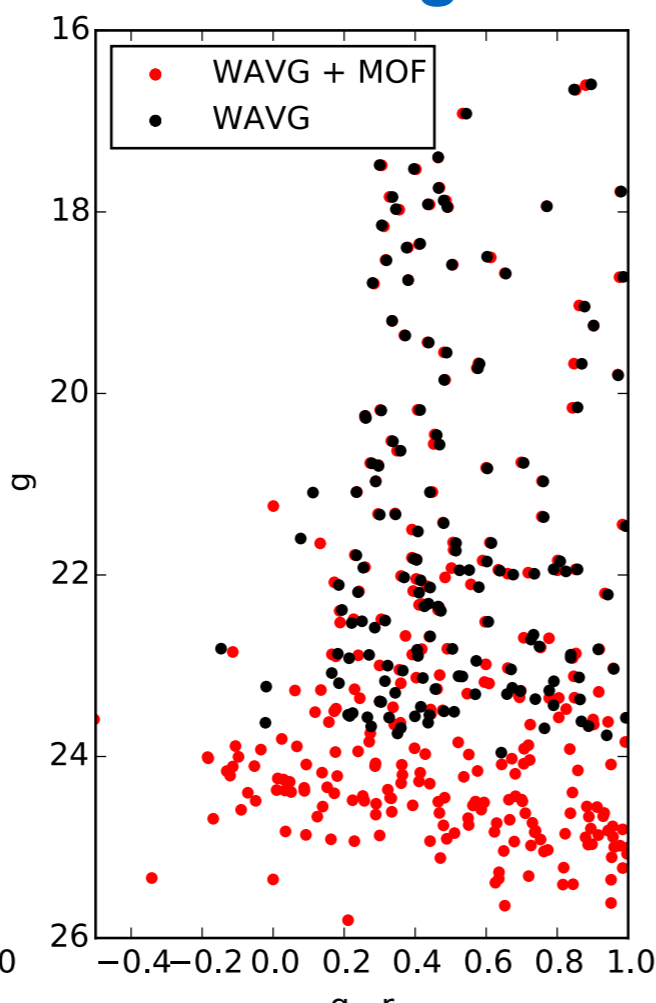


Example: Grus II ($M_V = -3.9$, $D = 53\text{kpc}$) discovered in DES Y2

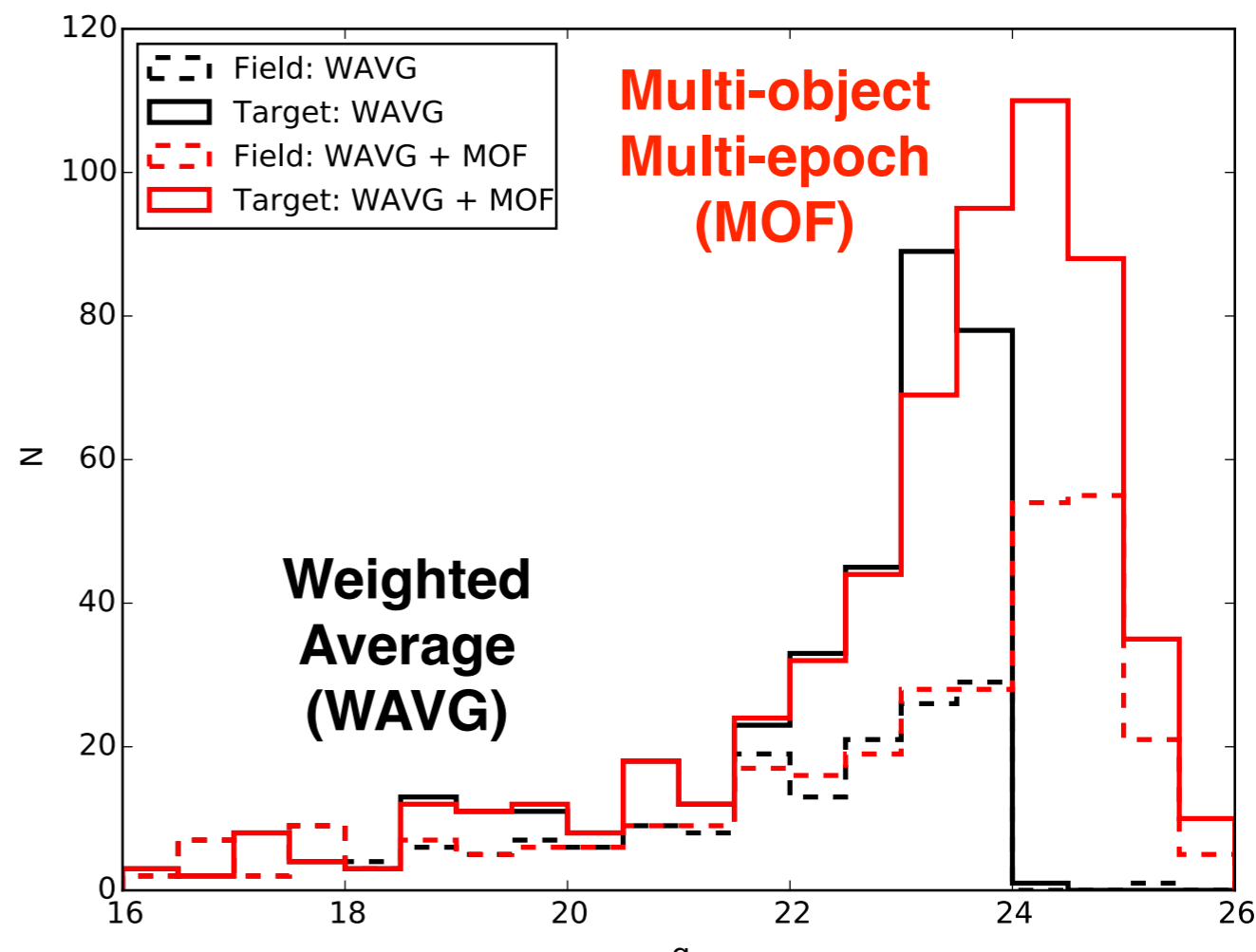
On-target



Off-target

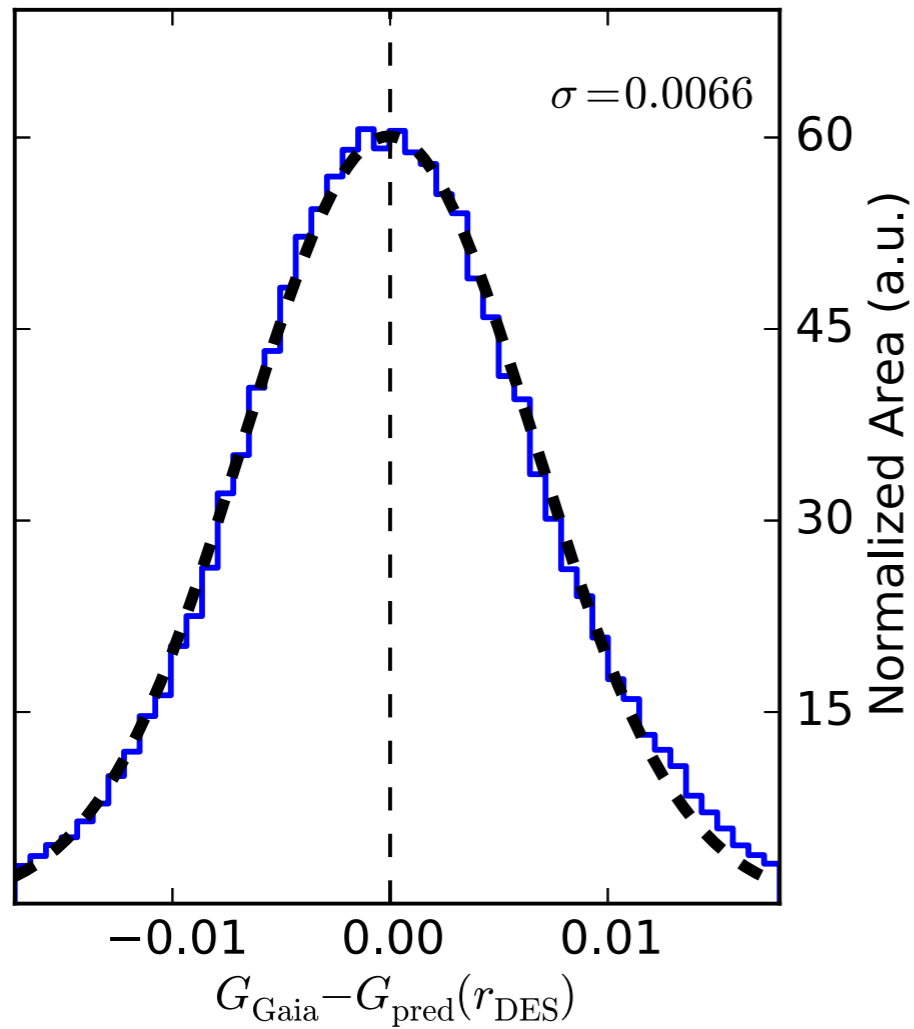


Flux distribution of *detected* stars



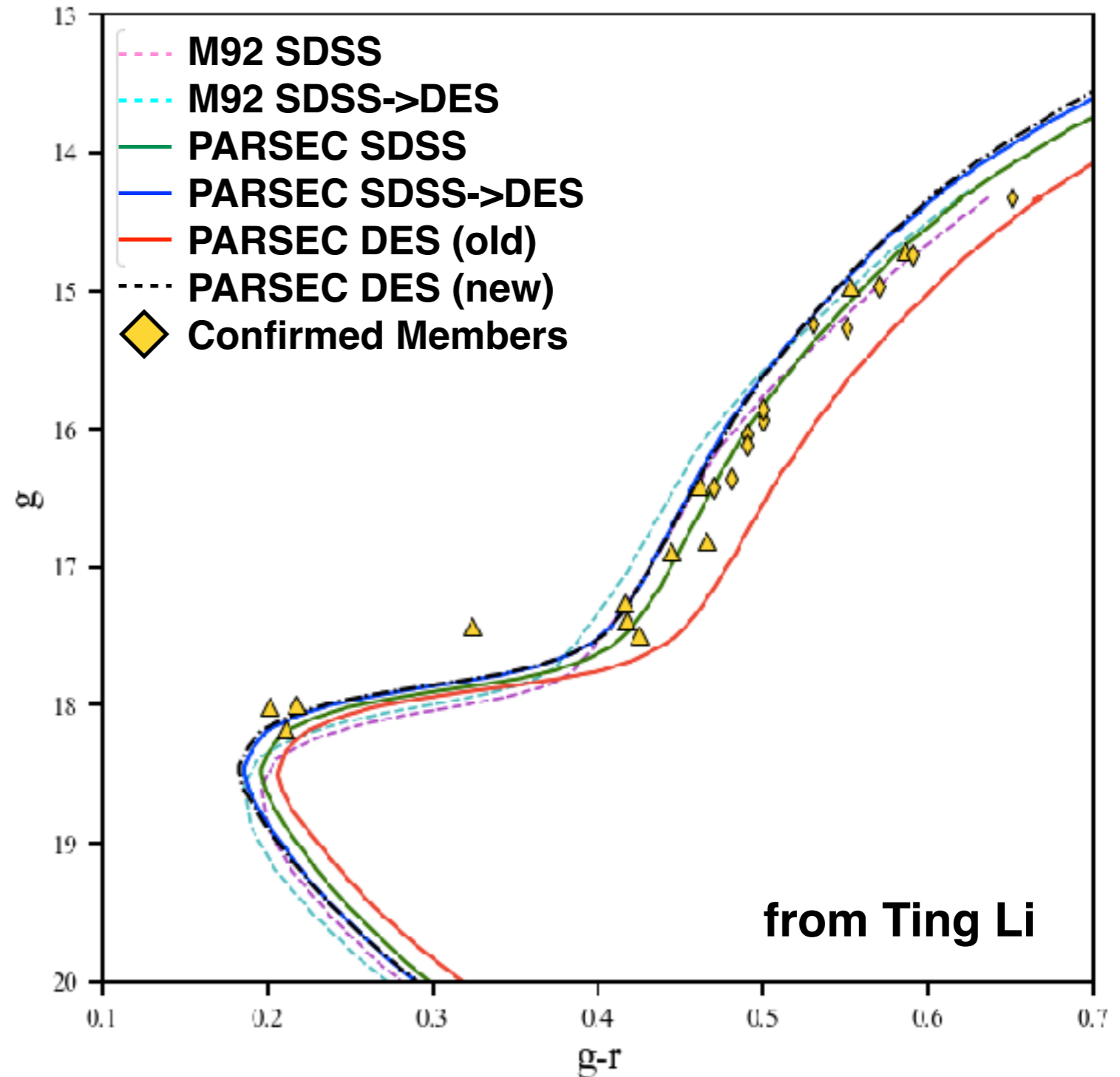
Detected at > 5 sigma using *only* the stars below the Y2 detection threshold!

0.0066 mag relative photometric calibration uncertainty



Burke et al. 2017

Updated filter throughput propagated to synthetic isochrones



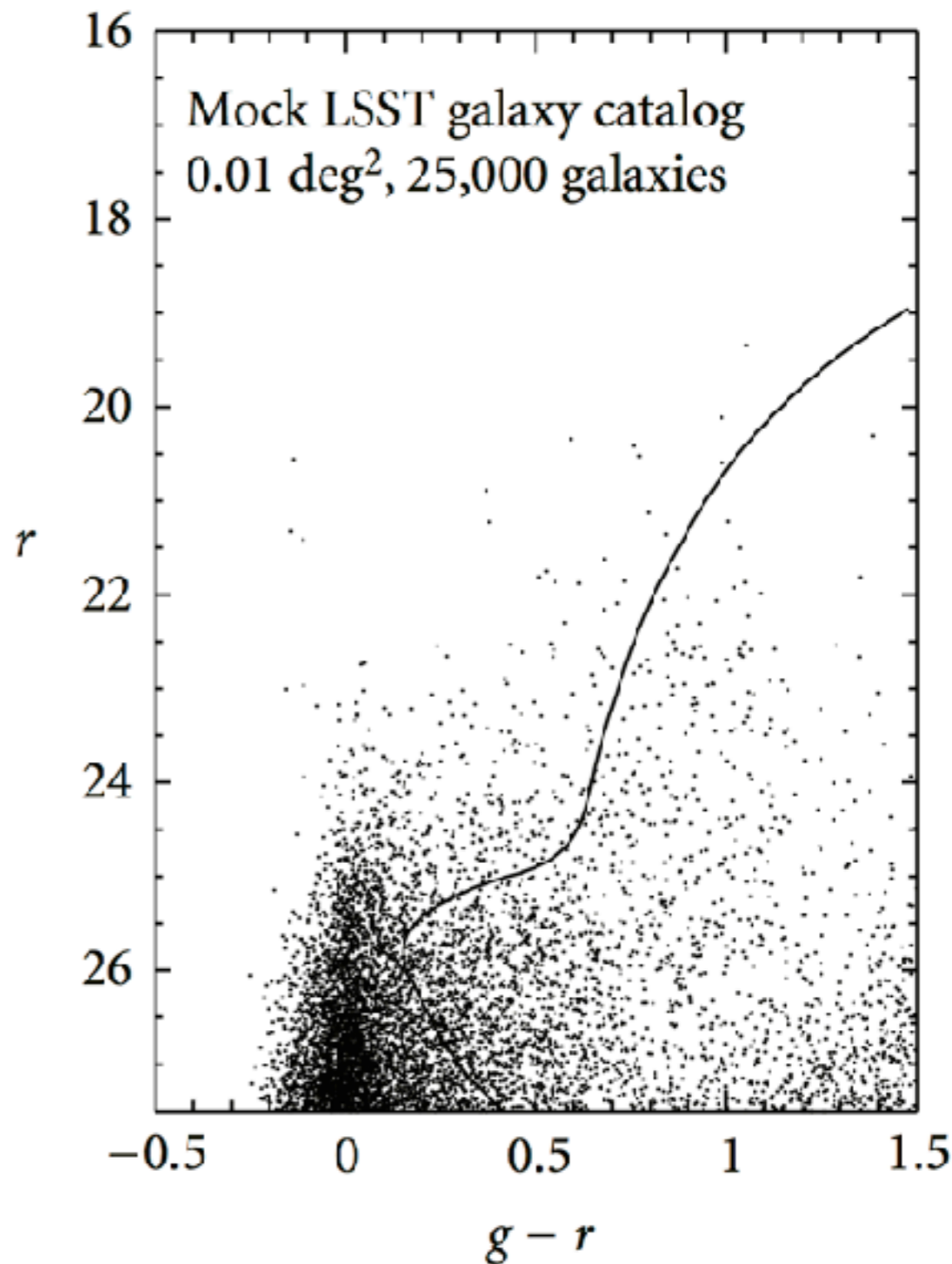
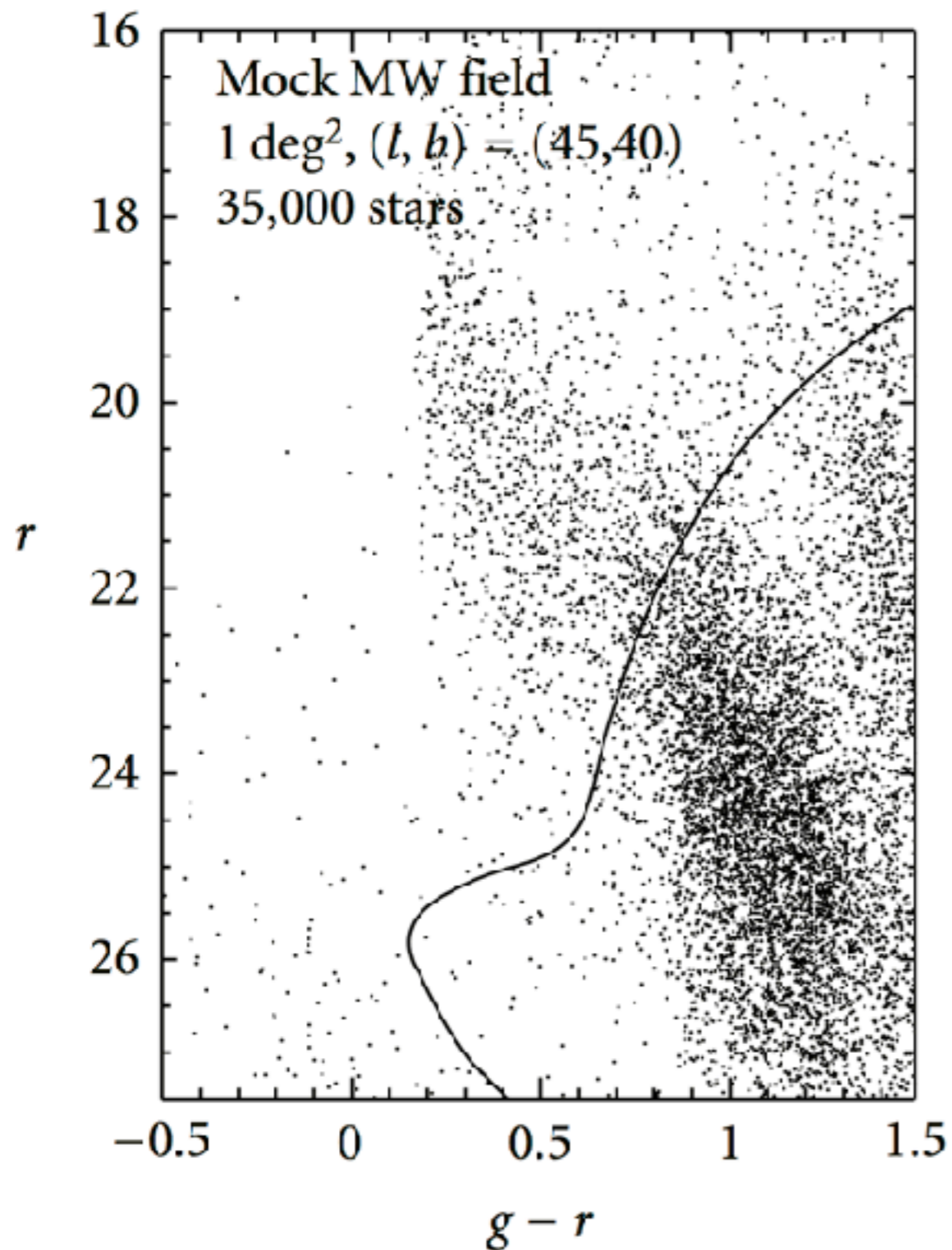
from Ting Li

LSST is Coming!

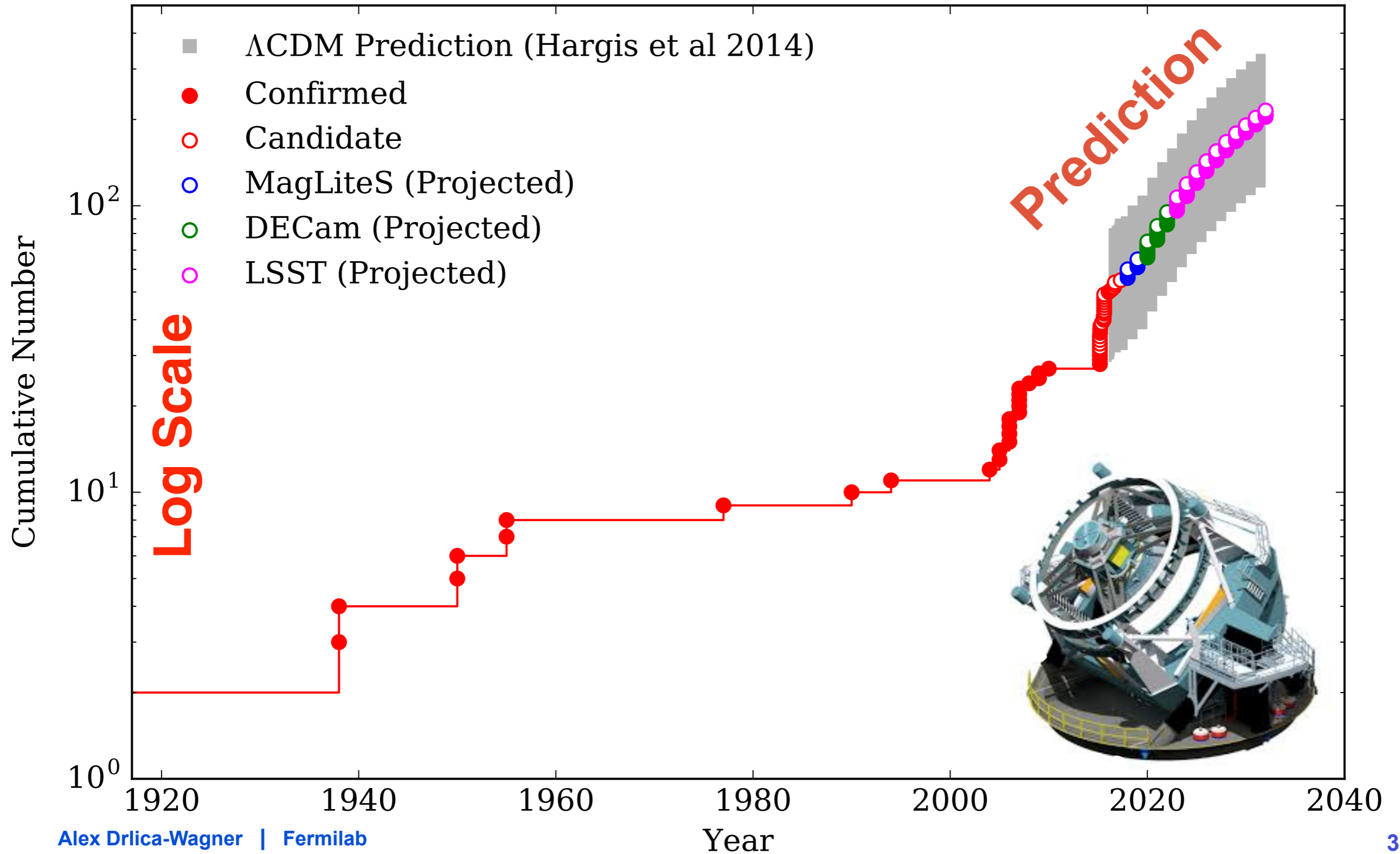


With Great Power Comes Great Responsibility

Background Galaxy Contamination!

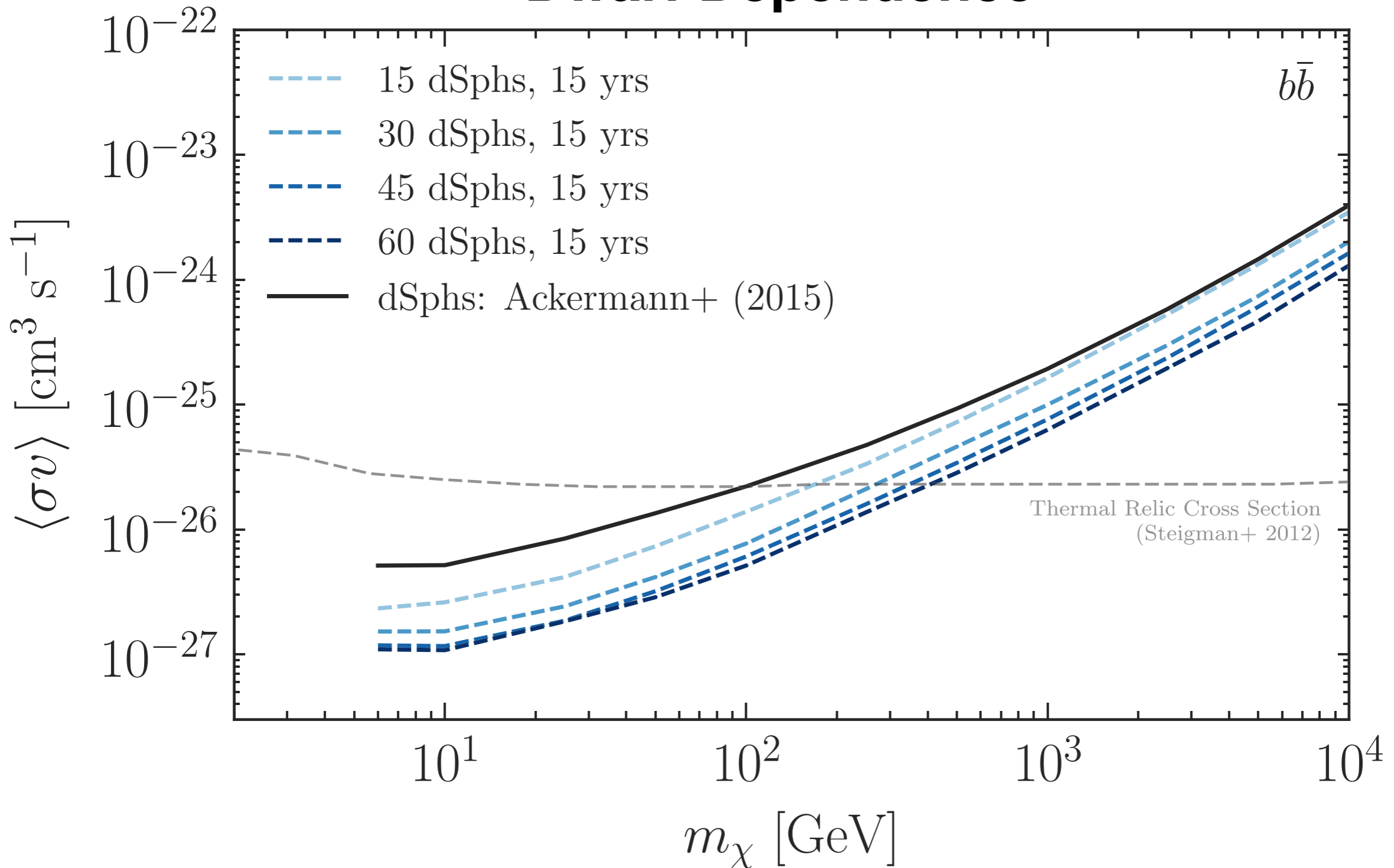


LSST is Coming!



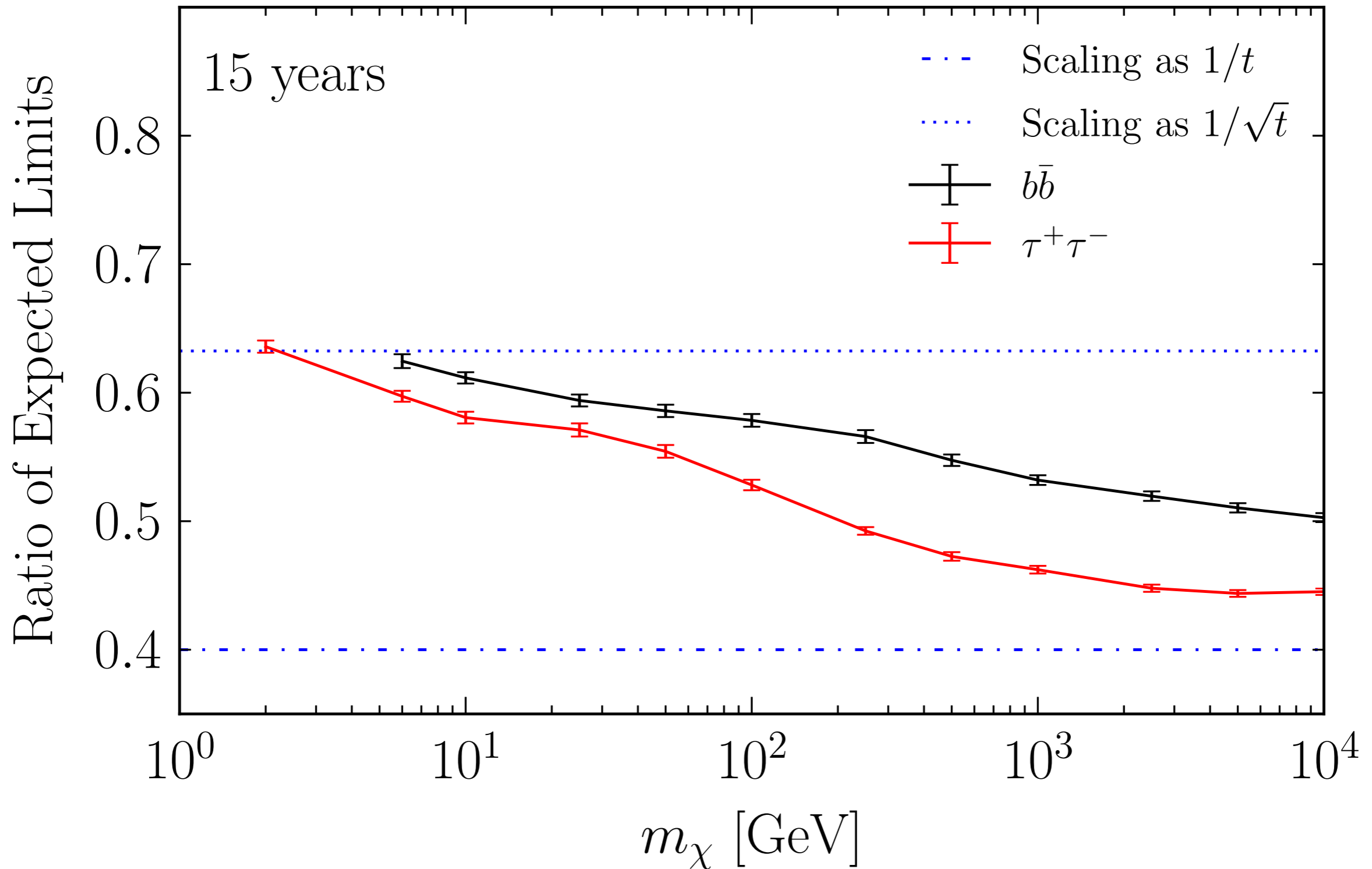
Expected Sensitivity to Dark Matter Annihilation

Dwarf Dependence



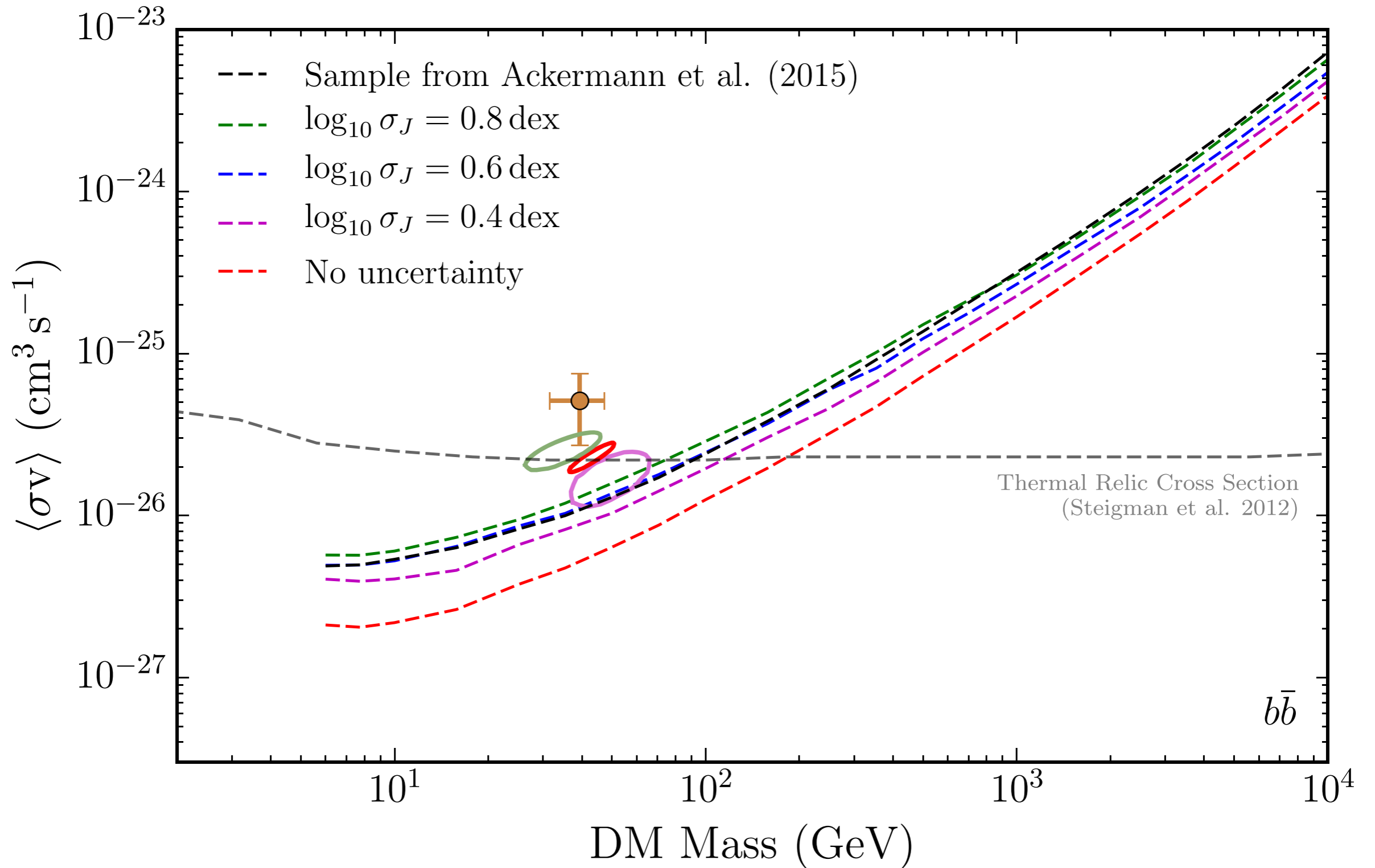
Expected Sensitivity to Dark Matter Annihilation

Background Dependence



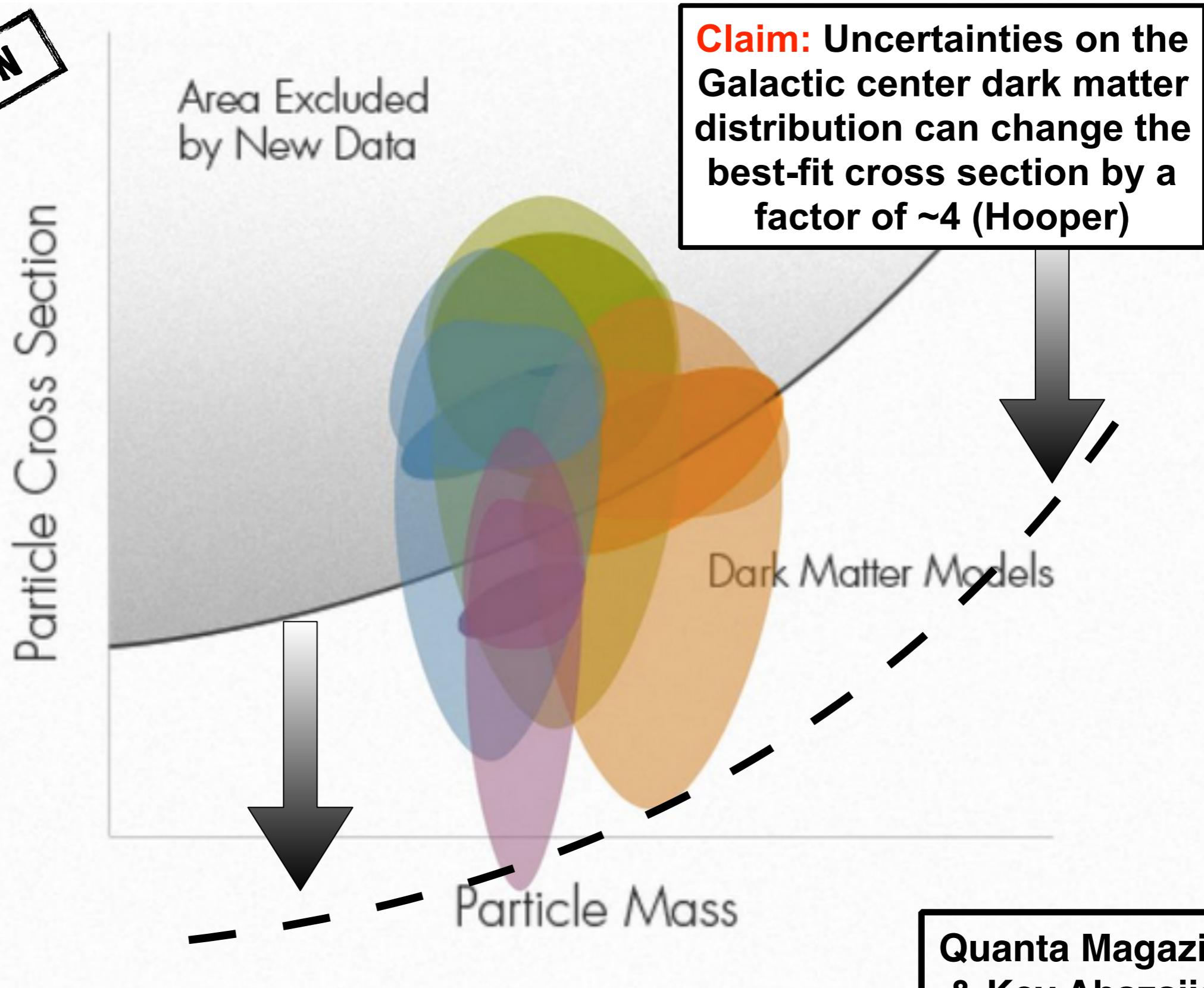
Expected Sensitivity to Dark Matter Annihilation

J-factor Dependence



Why Improvements are Important

CARTOON



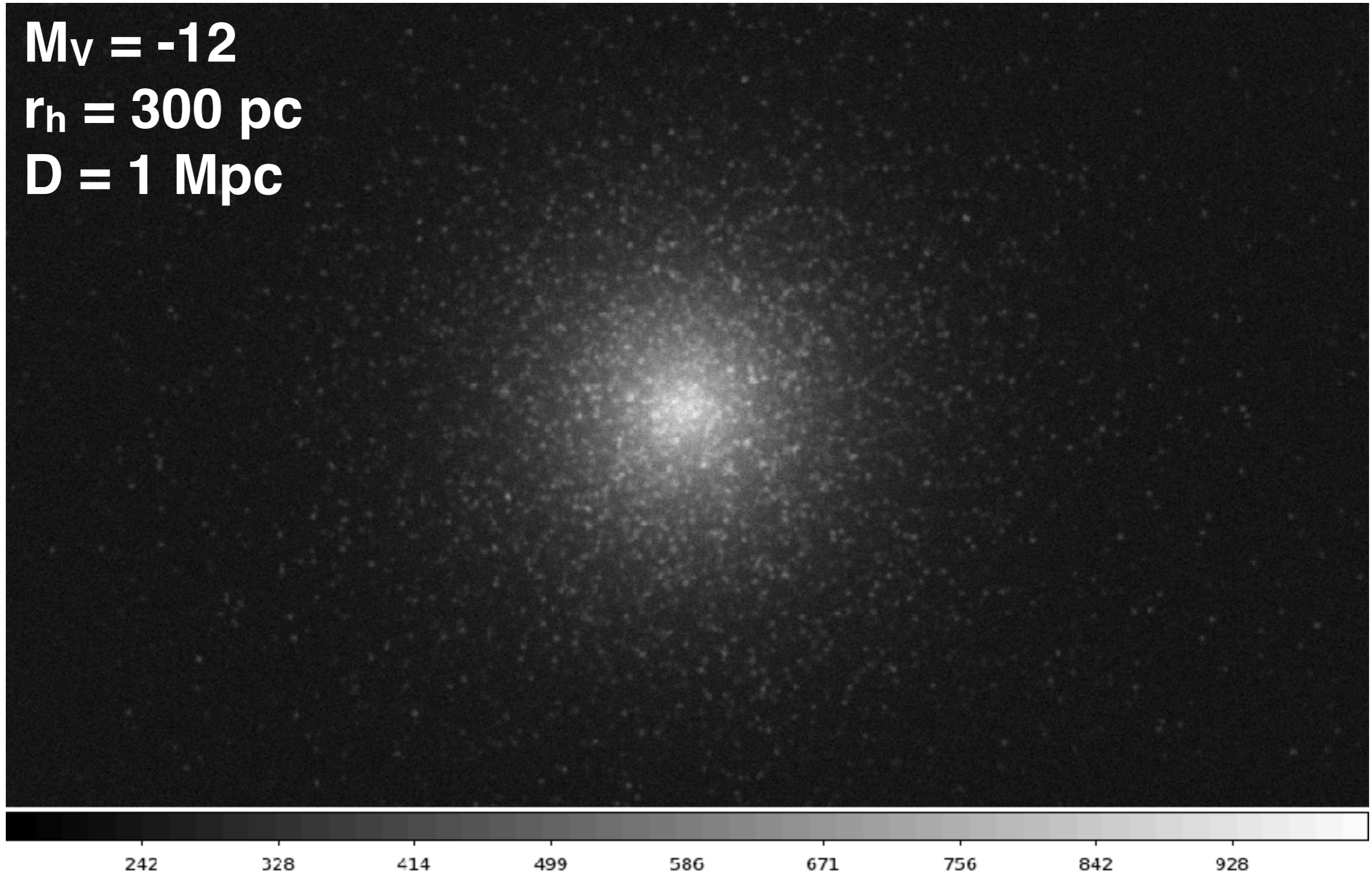
Claim: Uncertainties on the Galactic center dark matter distribution can change the best-fit cross section by a factor of ~ 4 (Hooper)

Quanta Magazine
& Kev Abazajian

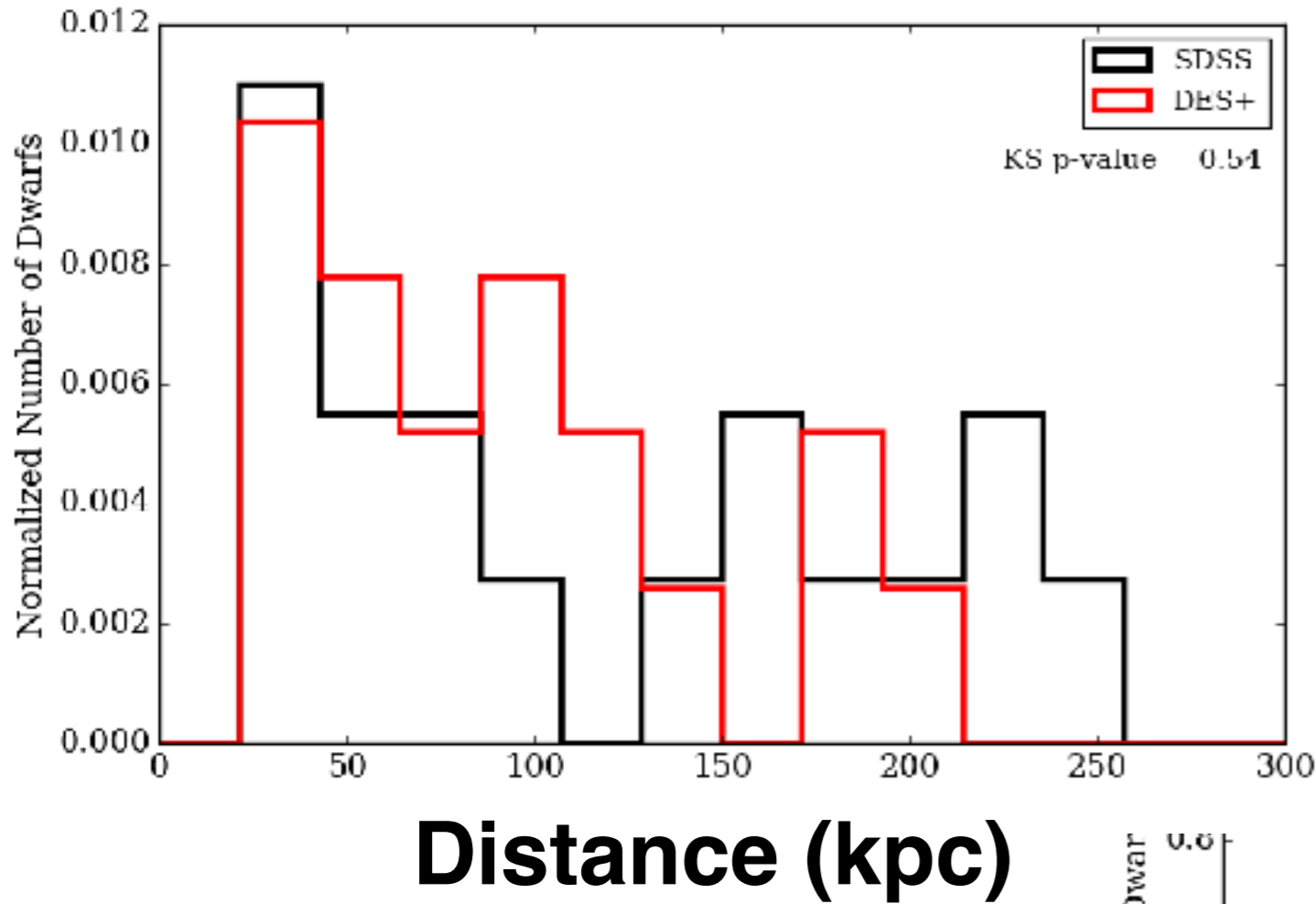
Backup Slides

Beyond the Milky Way!

$M_V = -12$
 $r_h = 300 \text{ pc}$
 $D = 1 \text{ Mpc}$



Are the DES Dwarfs like the SDSS Dwarfs?



Yes!

