Fermilab

Searching for Dark Matter in Dwarf Galaxies

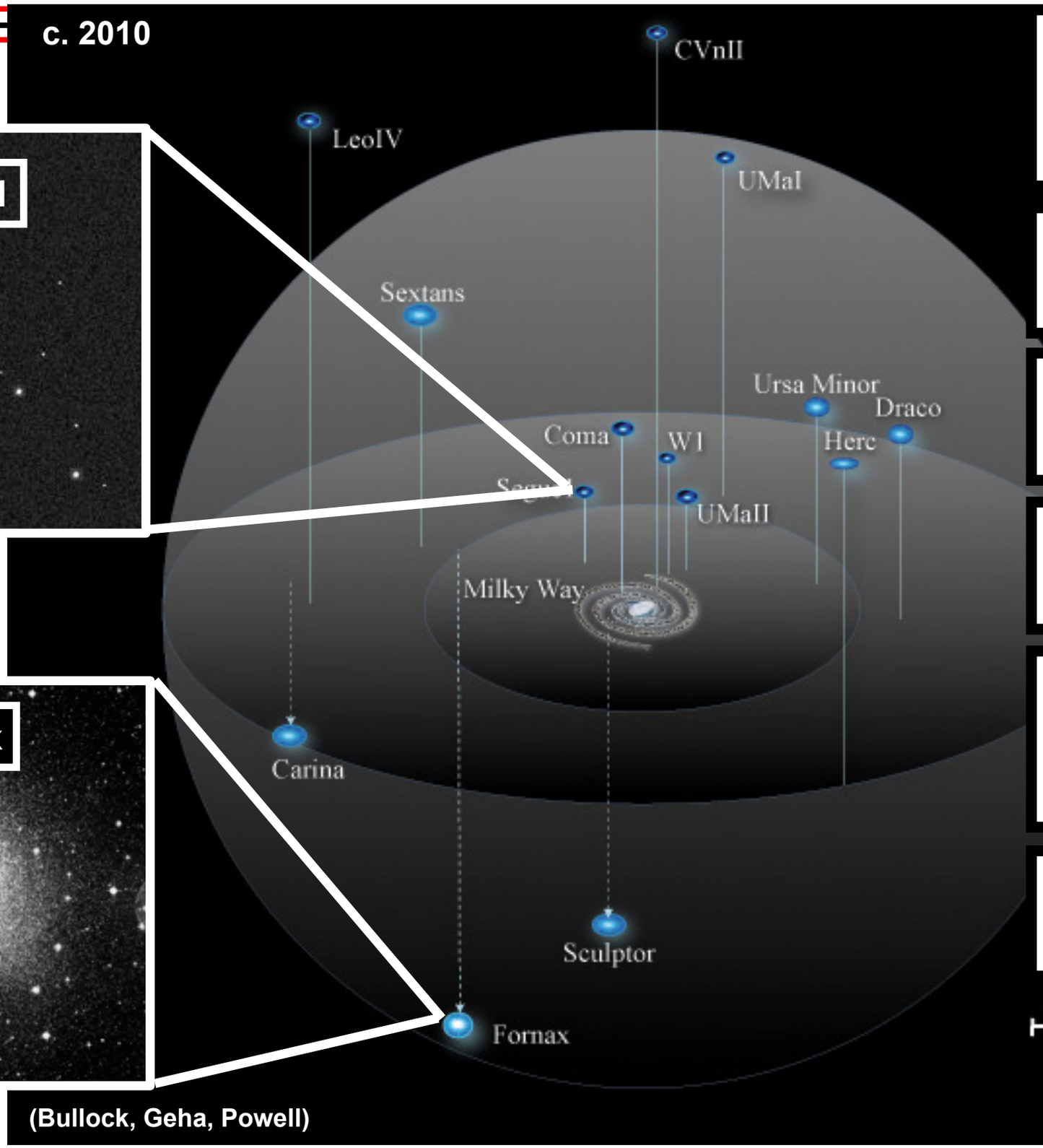
Alex Drlica-Wagner

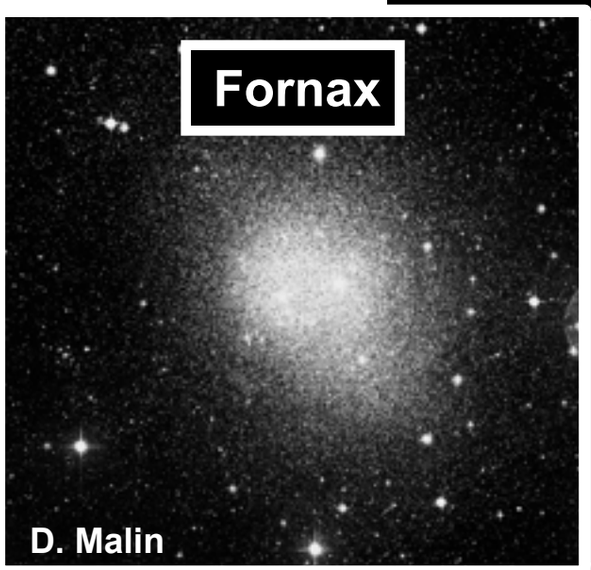
on behalf of the
Fermi-LAT and DES Collaborations

ICHEP 2016
August 5th, 2016

Fermilab | Center for Particle Astrophysics

Milky Way 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 simple

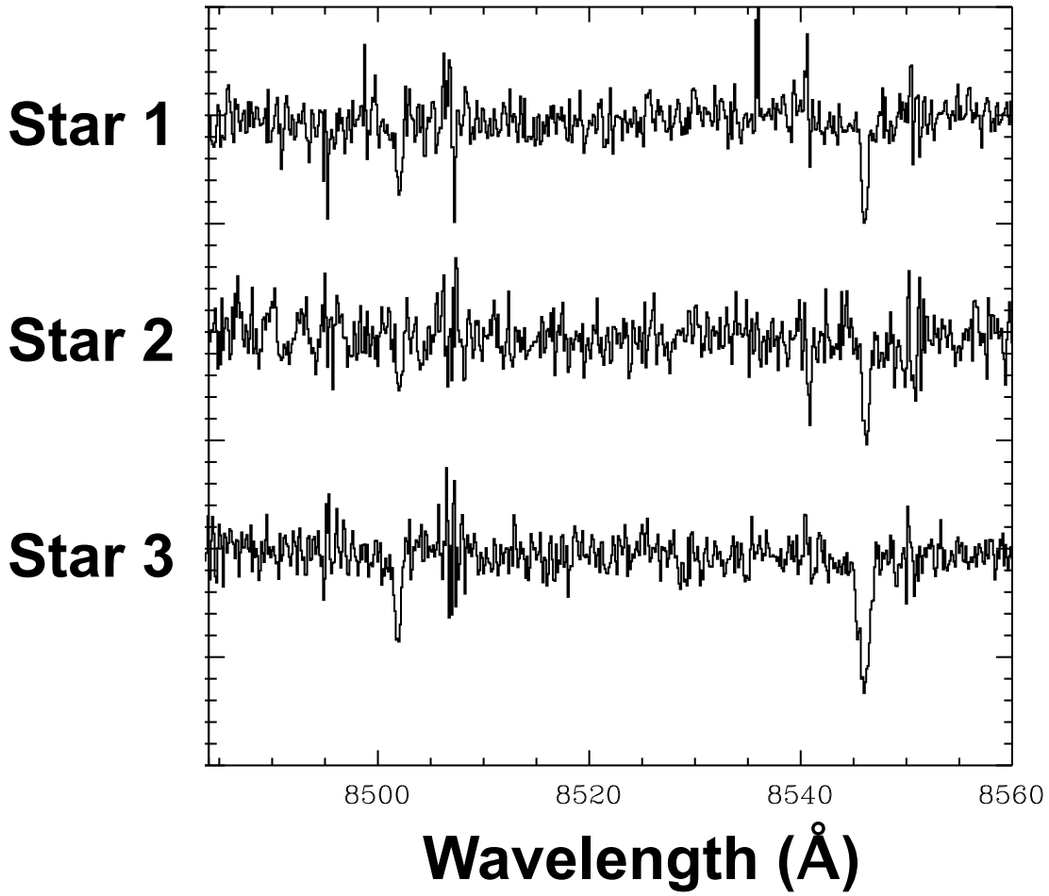
Most dark matter dominated objects known

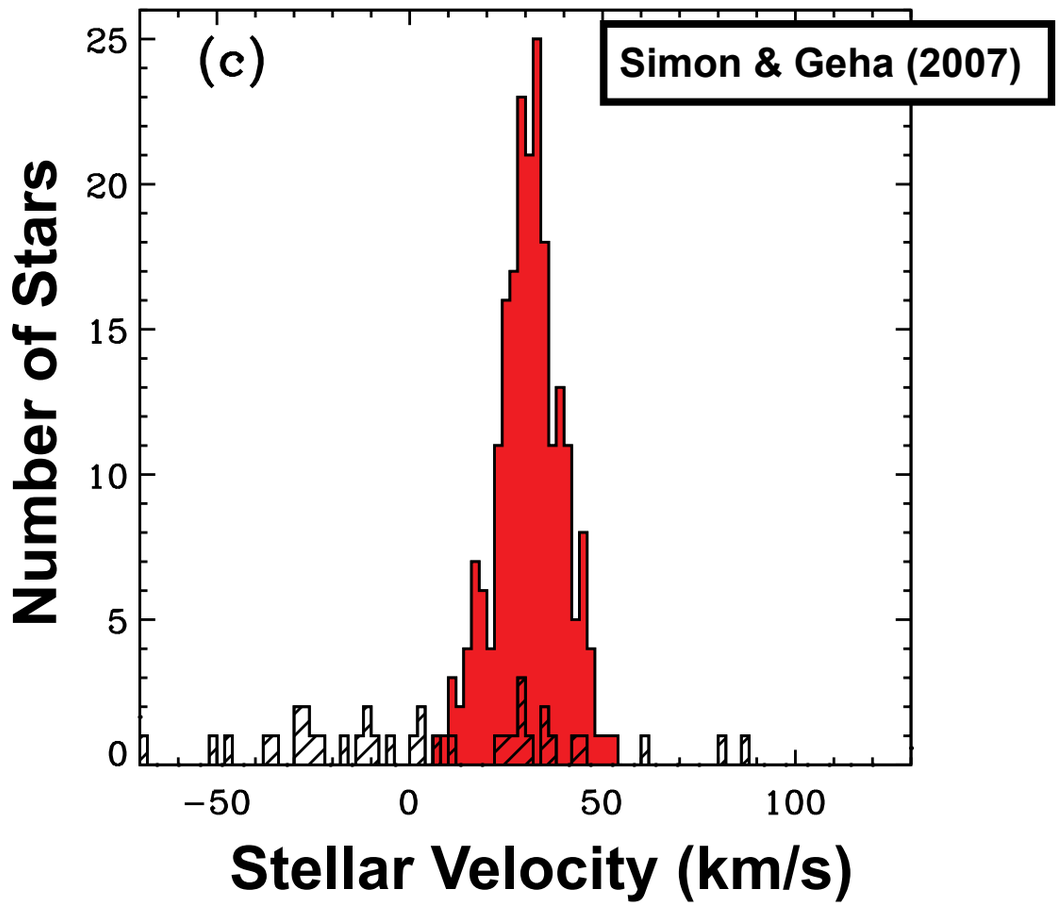
Birth of near-field cosmology

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**





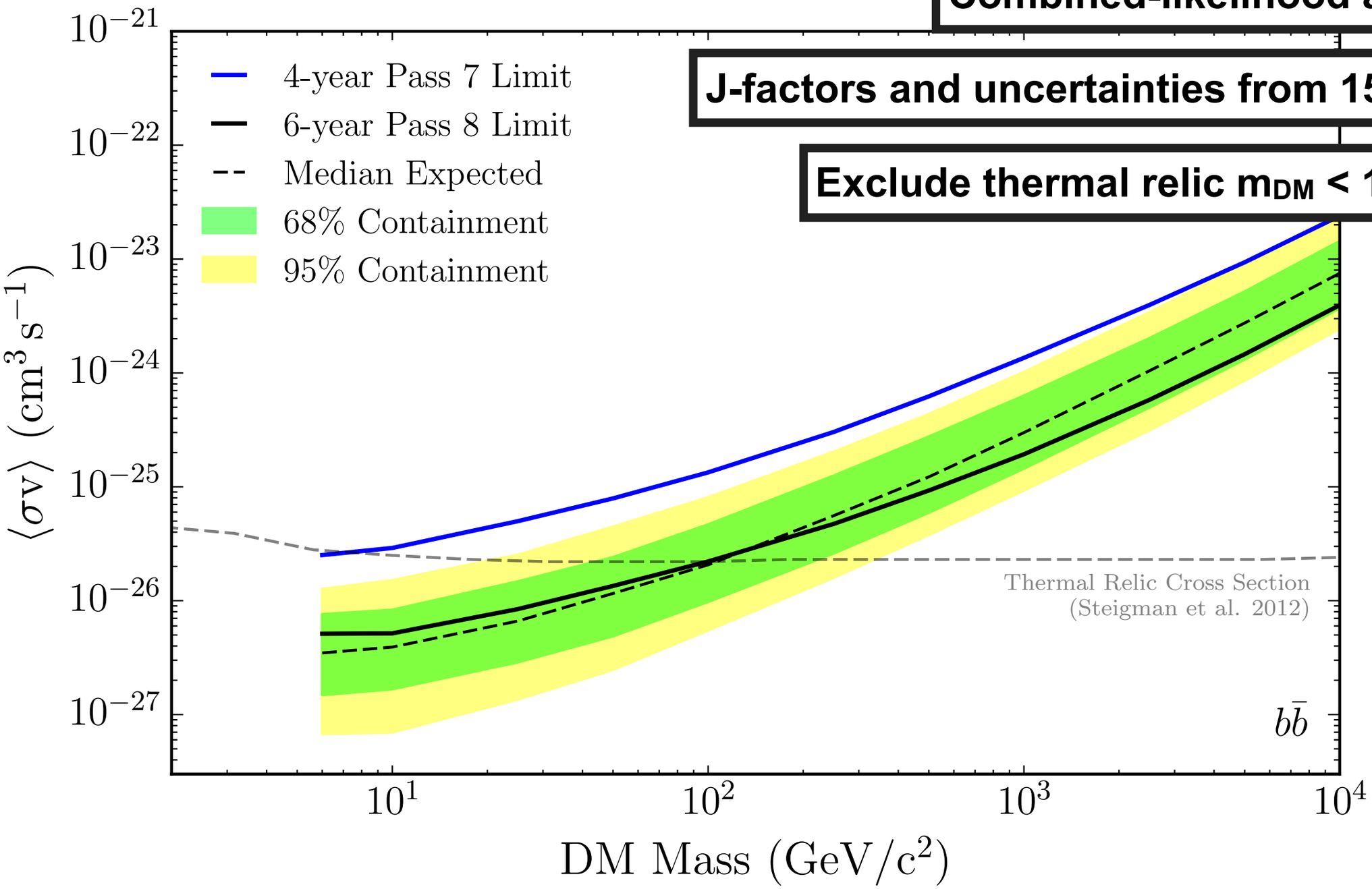
Pass 8 Analysis

6 Years of Pass 8 data: improved PSF

Combined-likelihood analysis

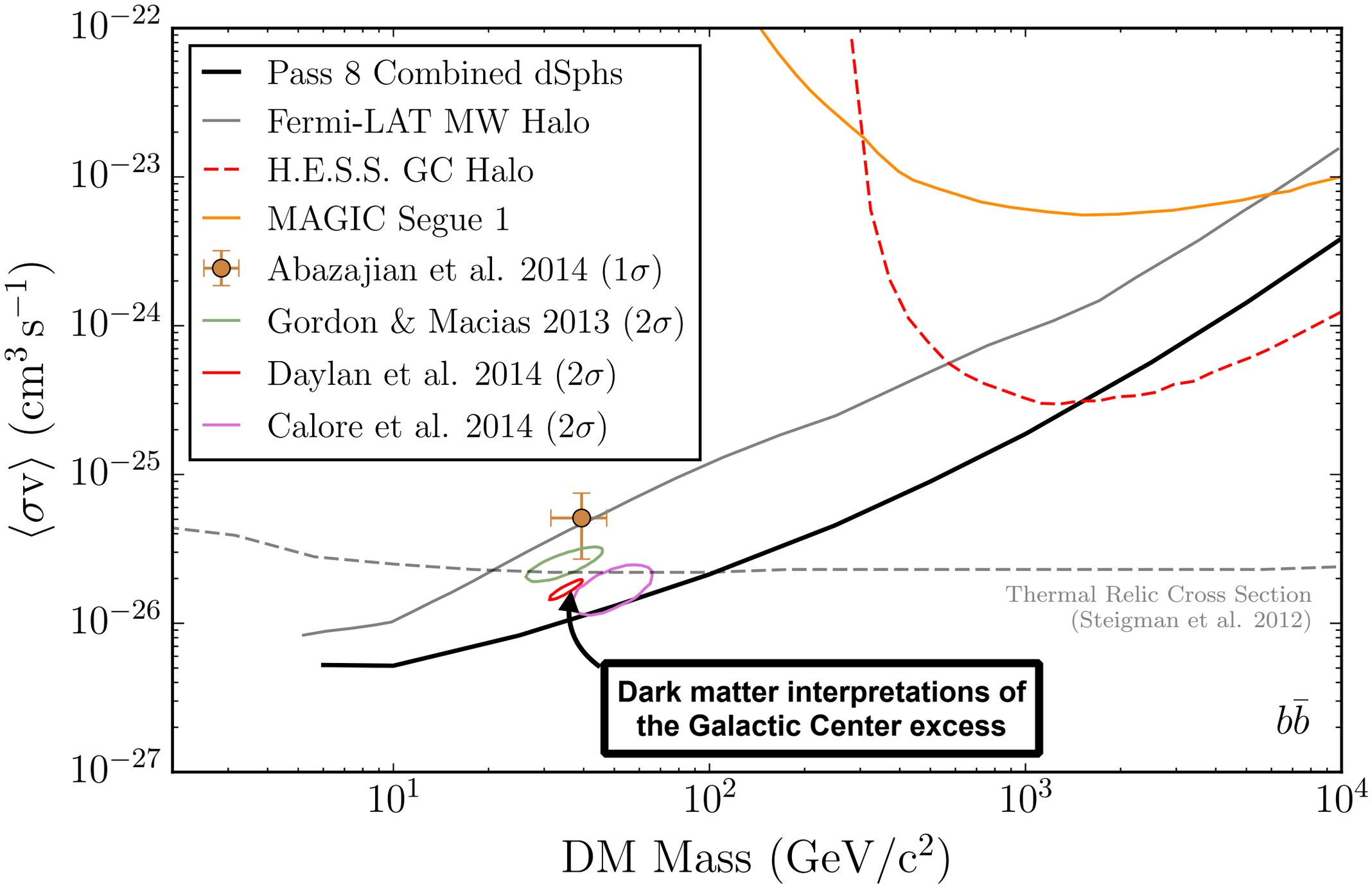
J-factors and uncertainties from 15 dSphs

Exclude thermal relic m_{DM} < 100 GeV



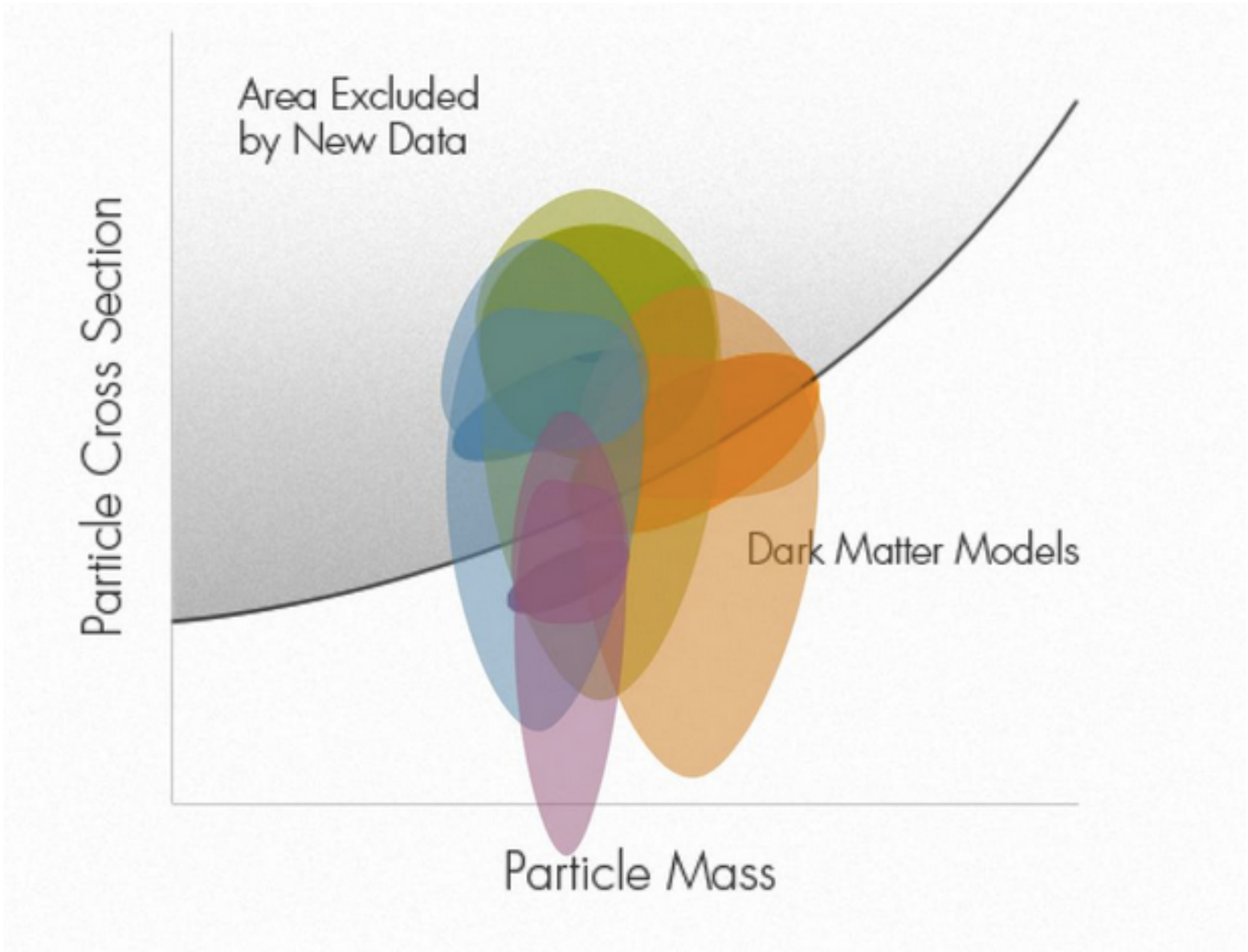
Ackermann et al. PRL 115, 231301 (2015)

Galactic Center Comparison



Ackermann et al. 2015 [1503.02641]

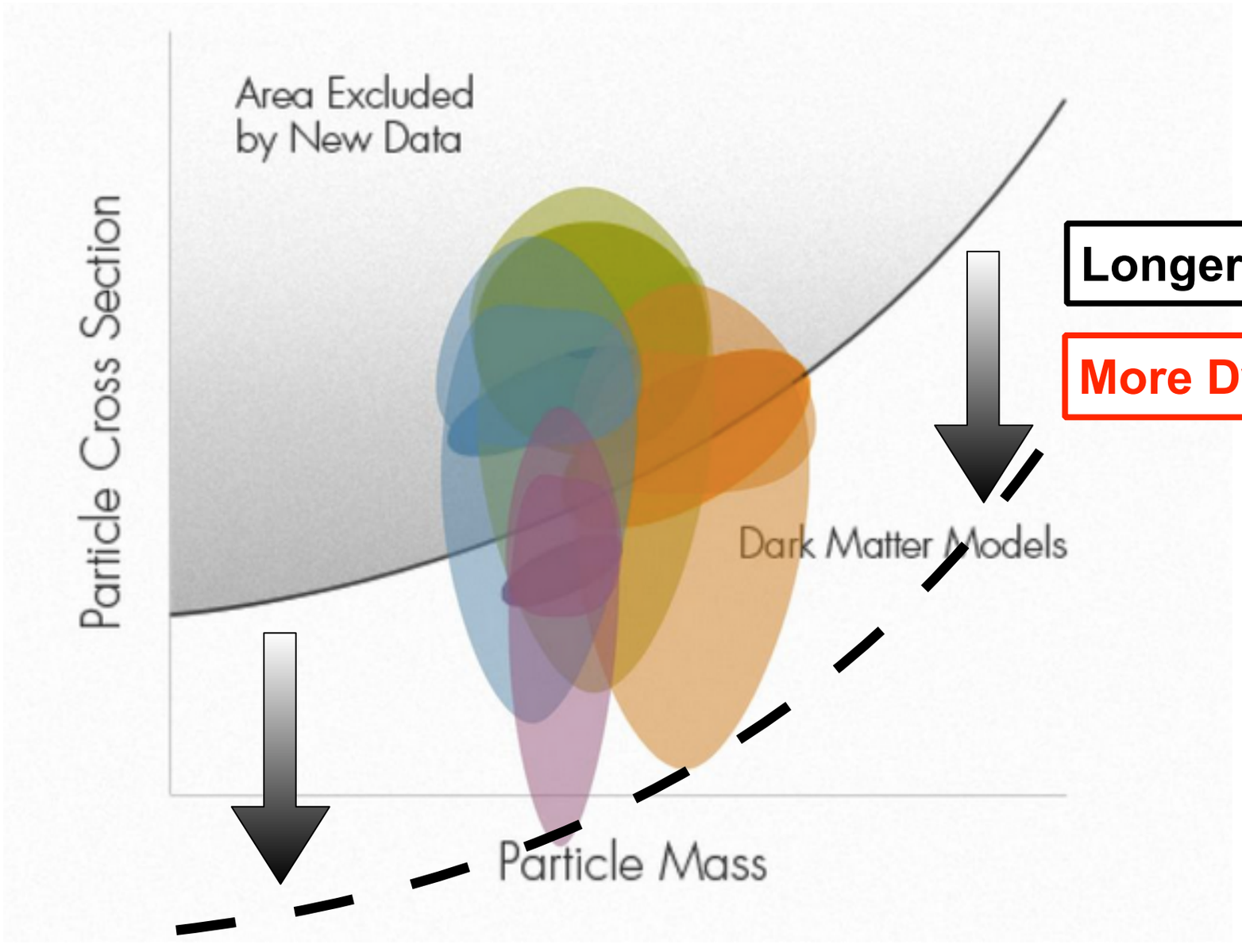
Galactic Center Comparison



Kevork Abazajian @kevaba · Oct 25
@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

1

Galactic Center Comparison



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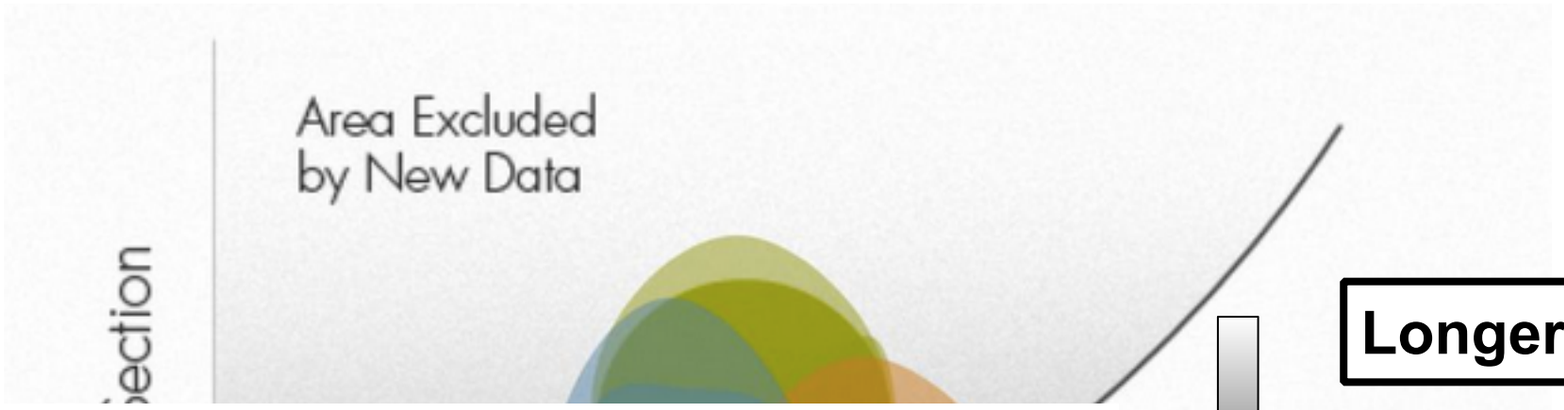
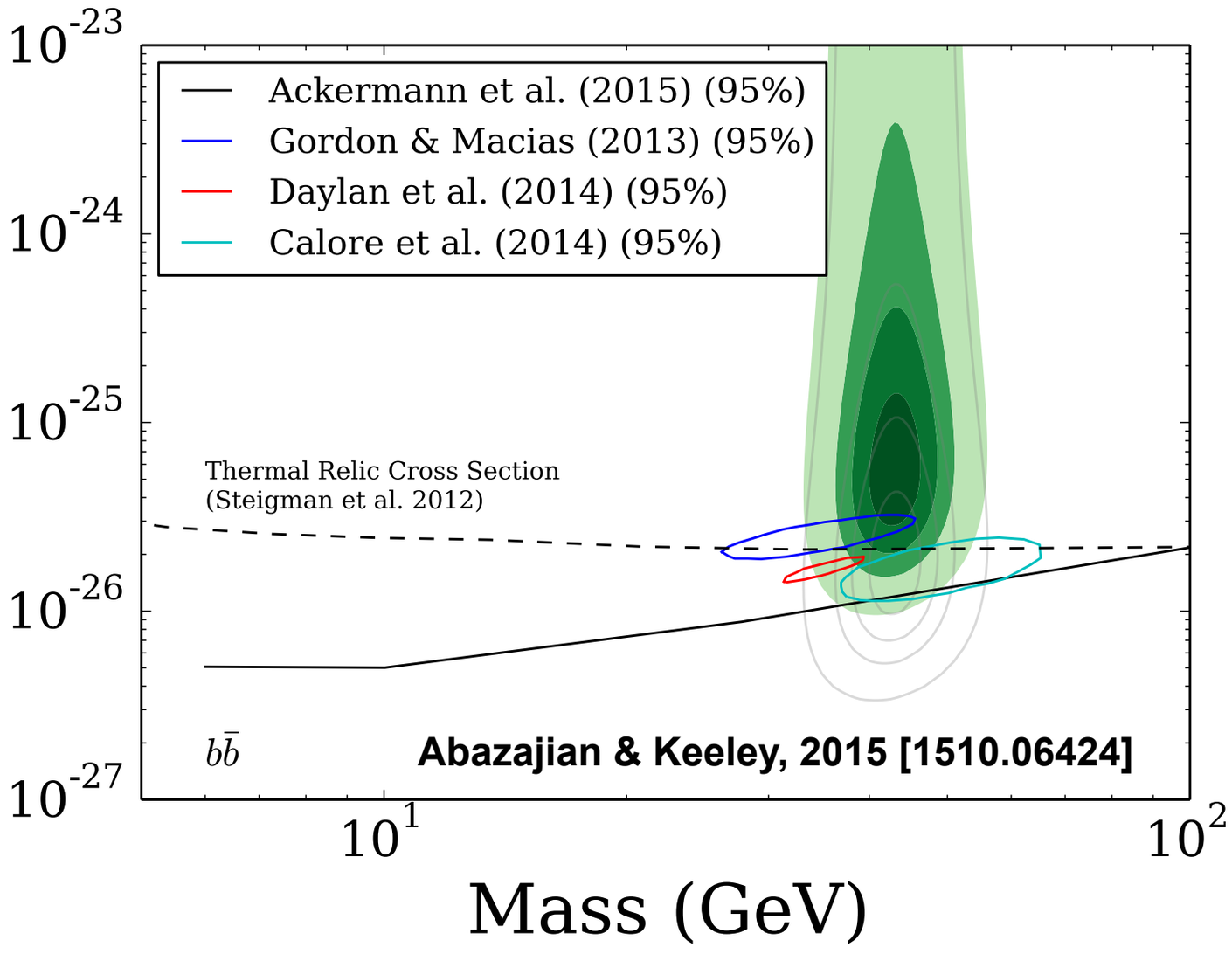
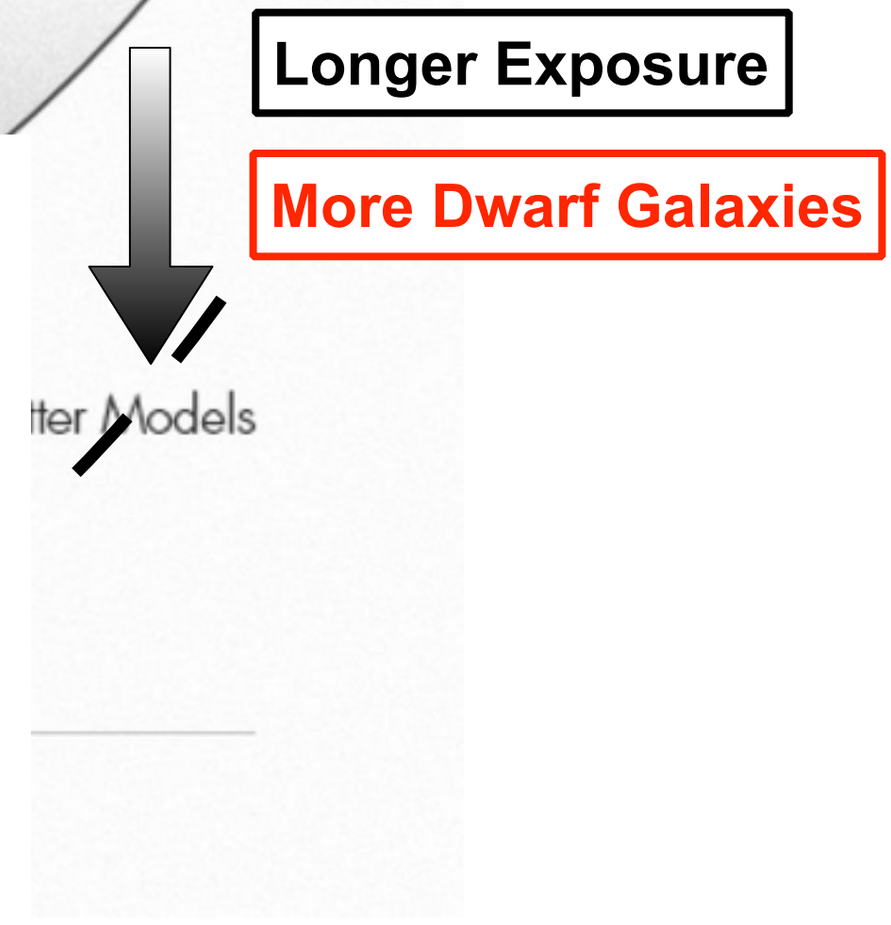






Finding Milky Way Satellite Galaxies

Detectors Drive Discoveries

Naked Eye

Finding Milky Way Satellite Galaxies

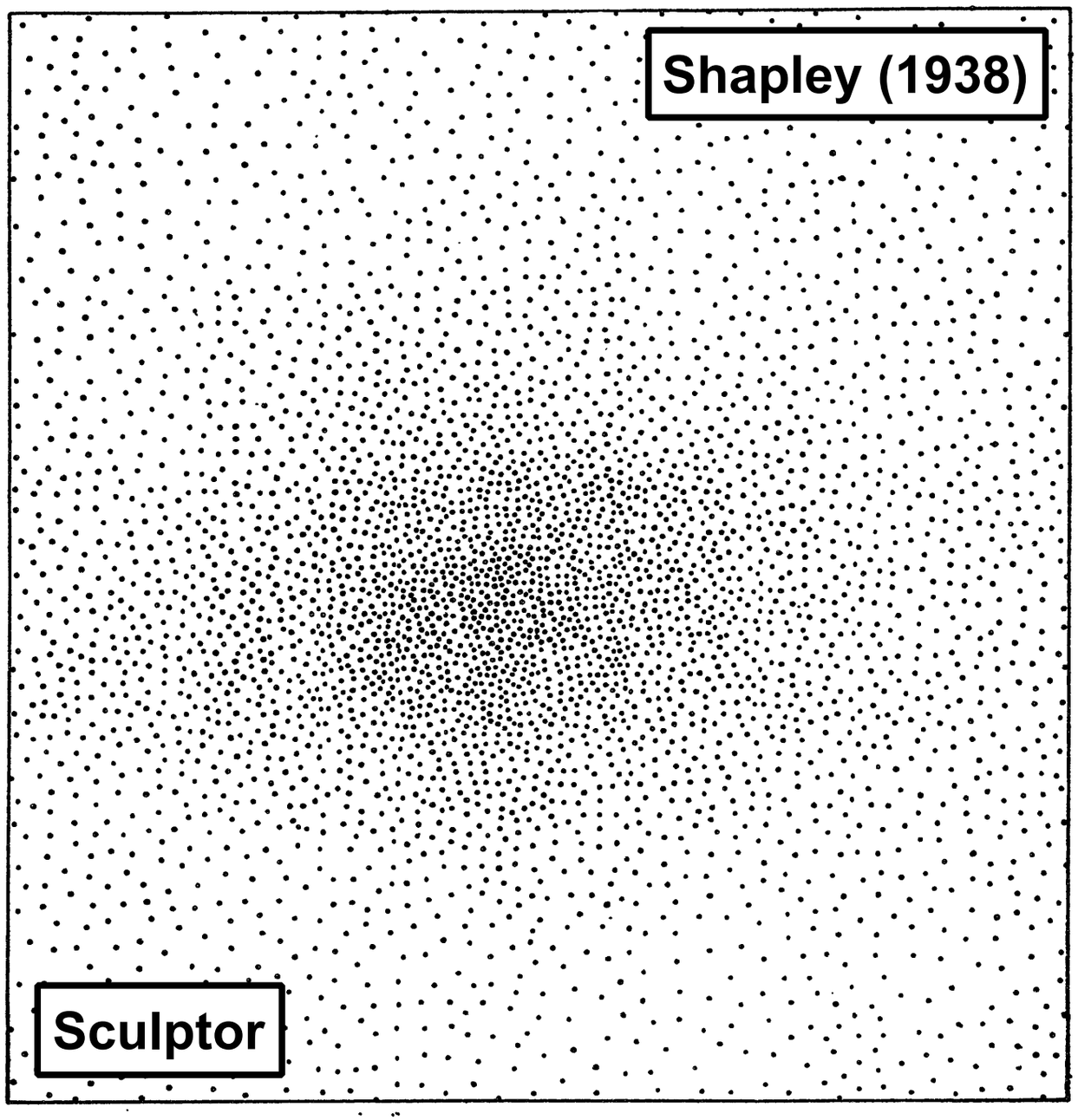


FIGURE 2.– DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

Population of old and metal-poor stars

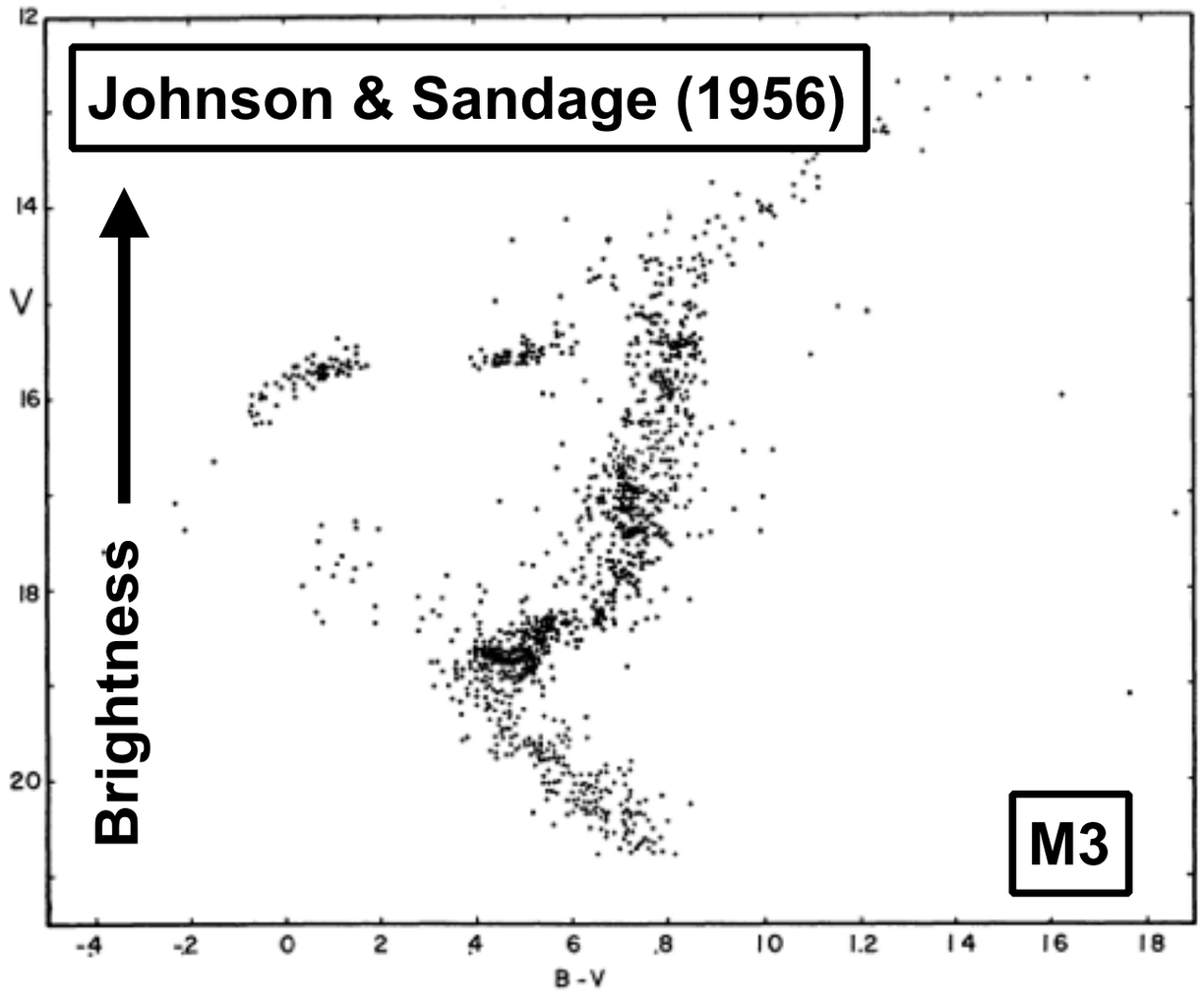
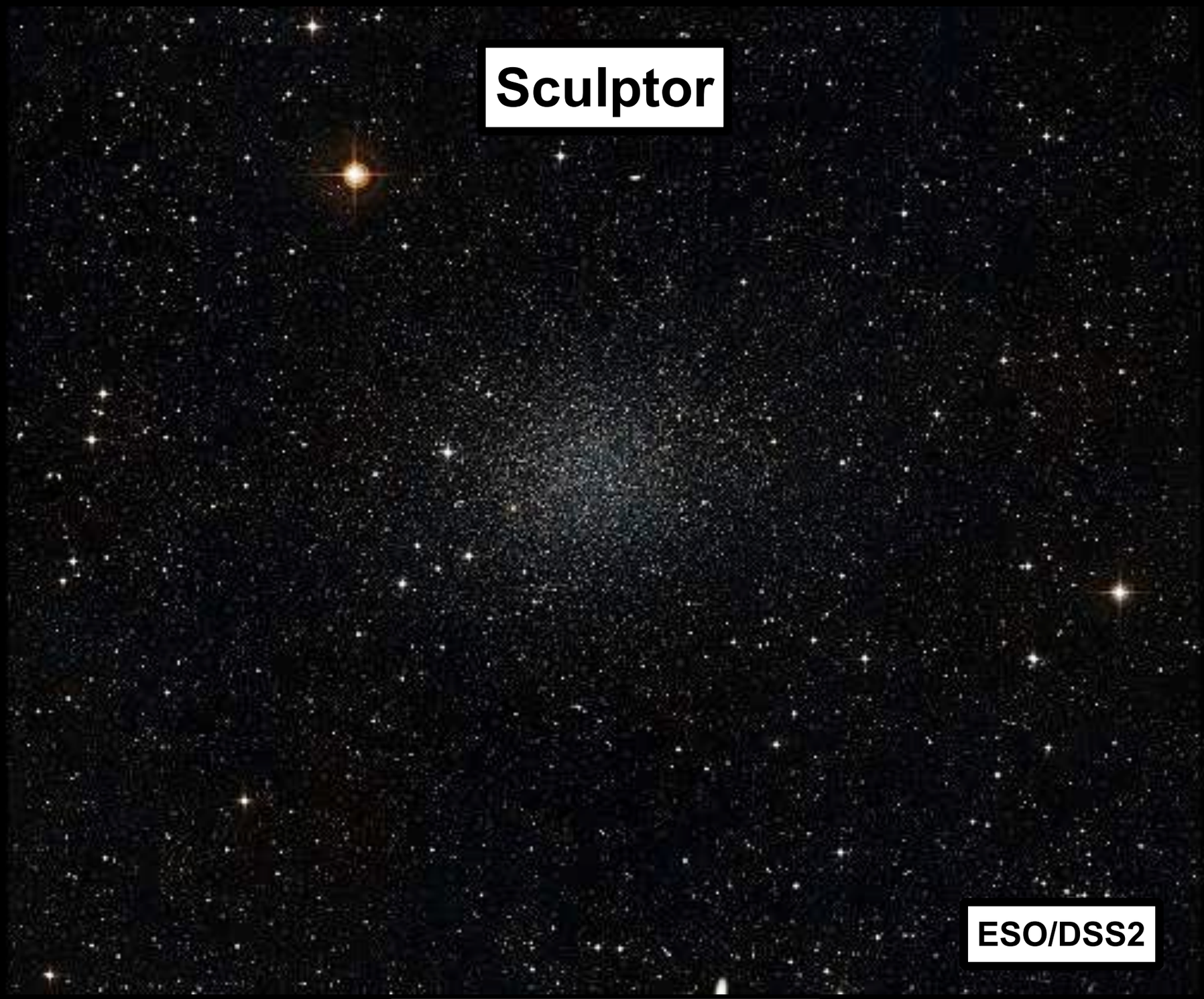


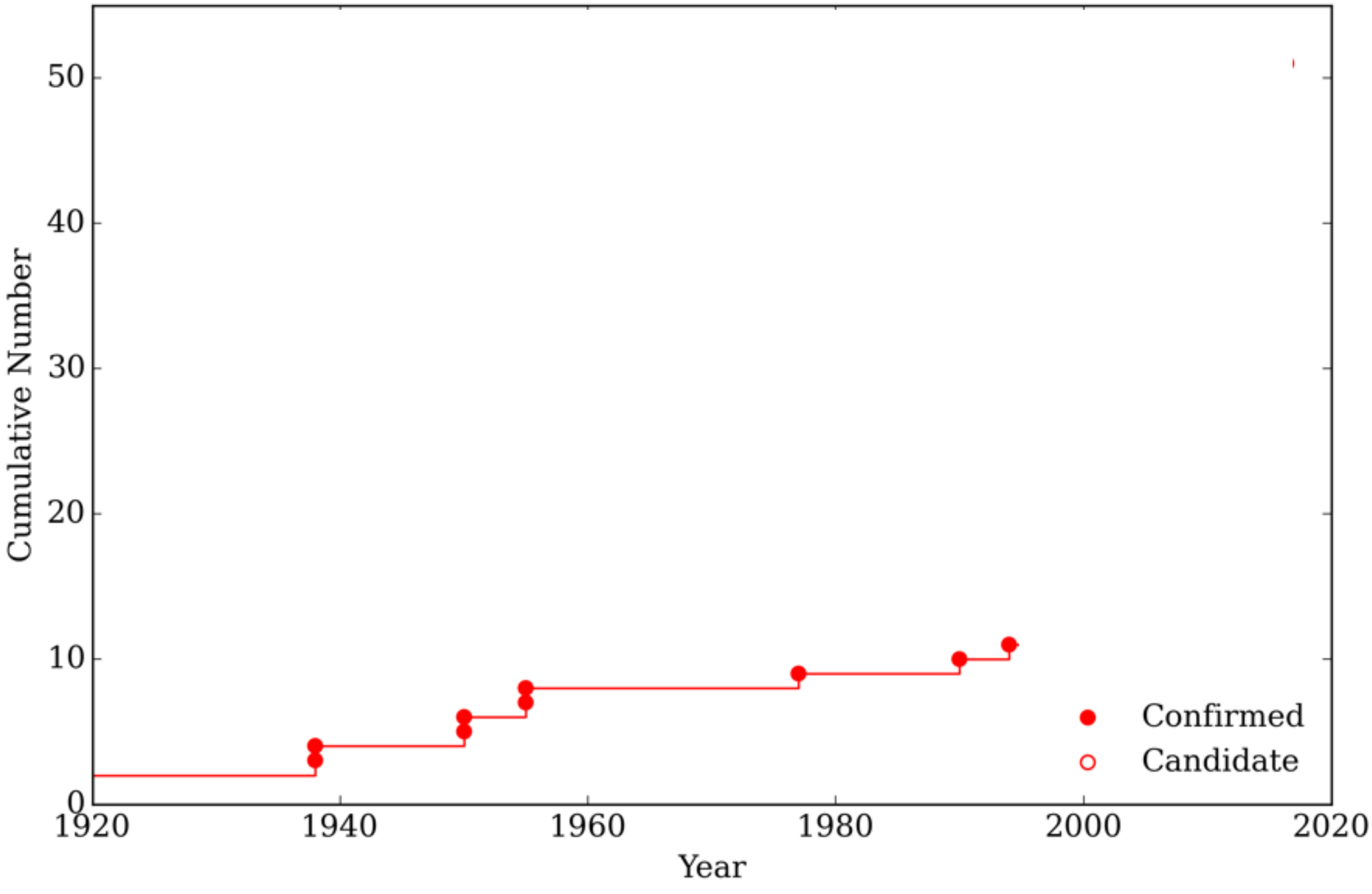
FIG. 5.—Color-magnitude diagram for M3 stars in the arguments V and $B - V$

"Redness" →



1.2m Telescope
Photographic Plates

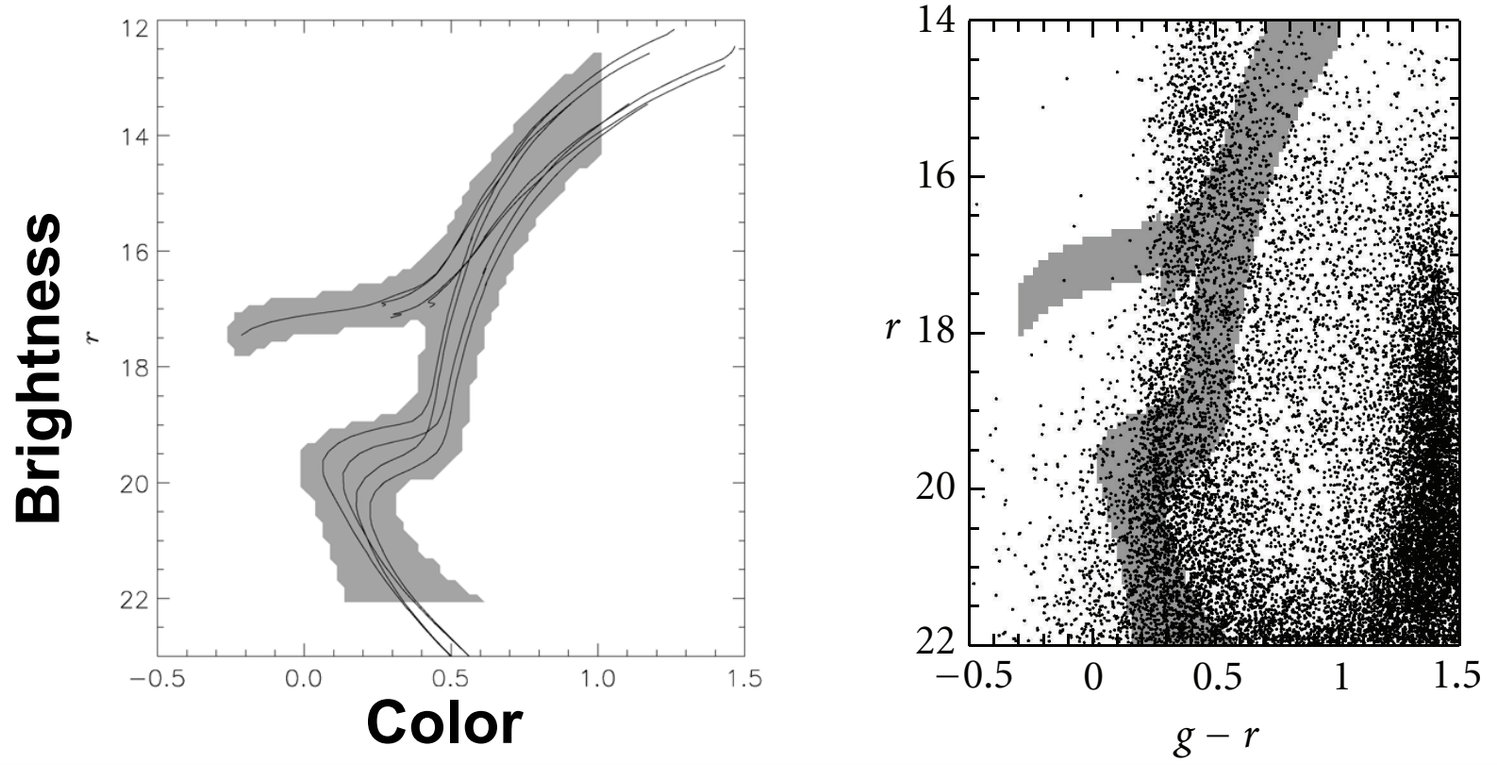
Discovery Timeline



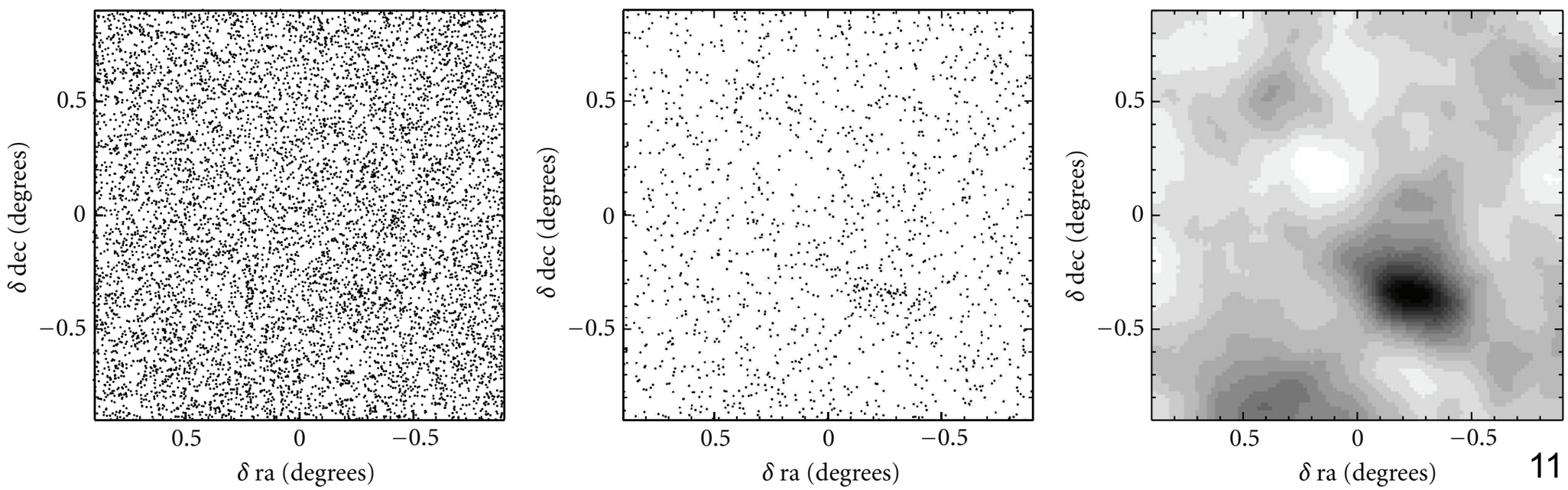
Finding Milky Way Satellite Galaxies

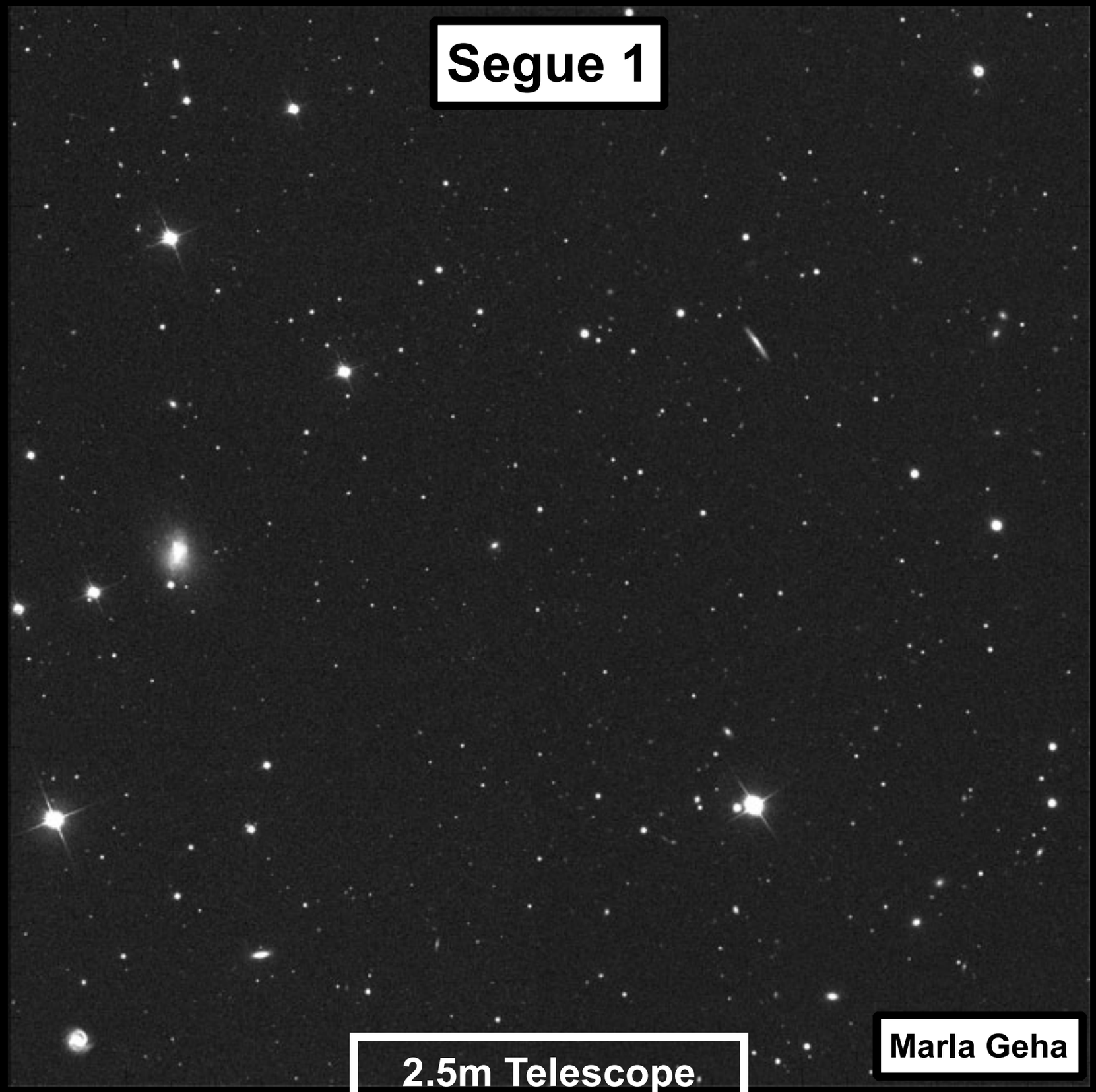
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

Color-Brightness Domain

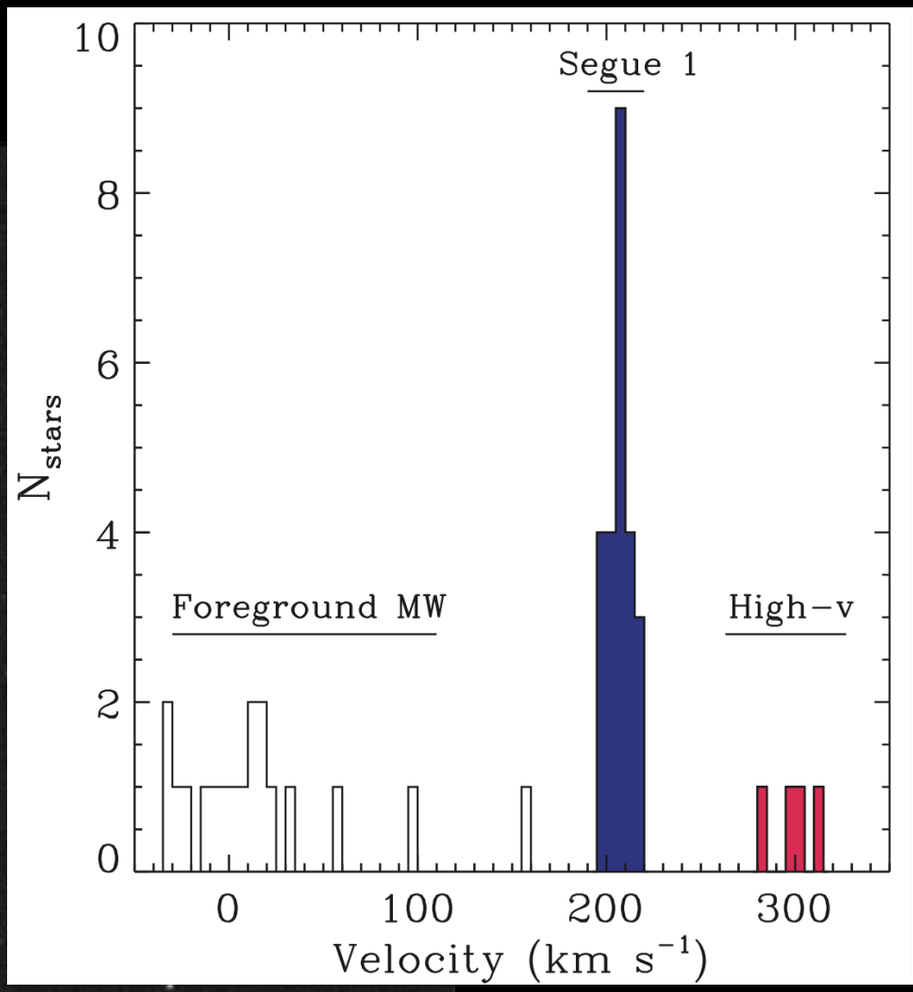


Spatial Domain




Segue 1
2.5m Telescope
SDSS CCD Camera
Marla Geha

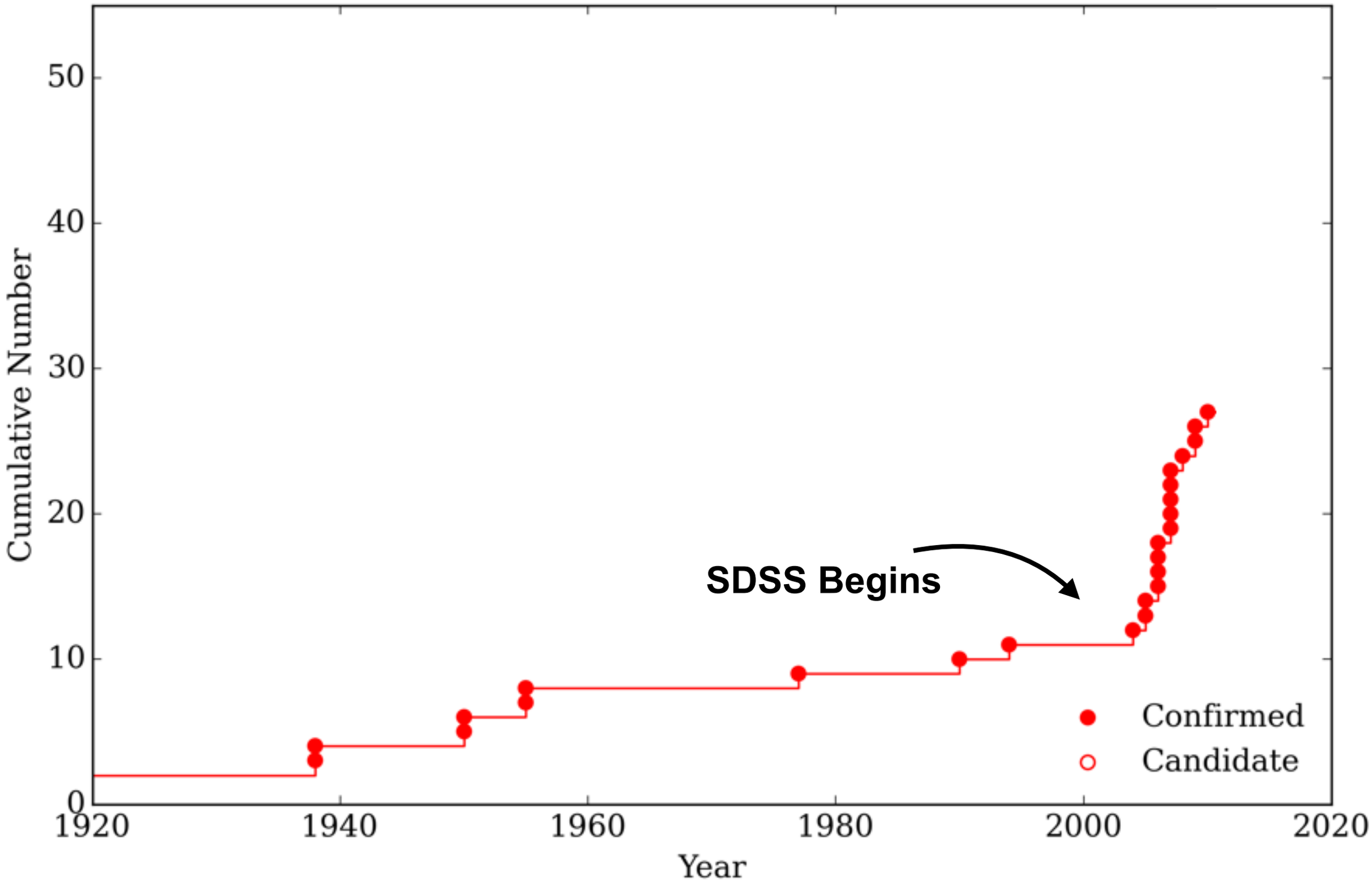
Segue 1



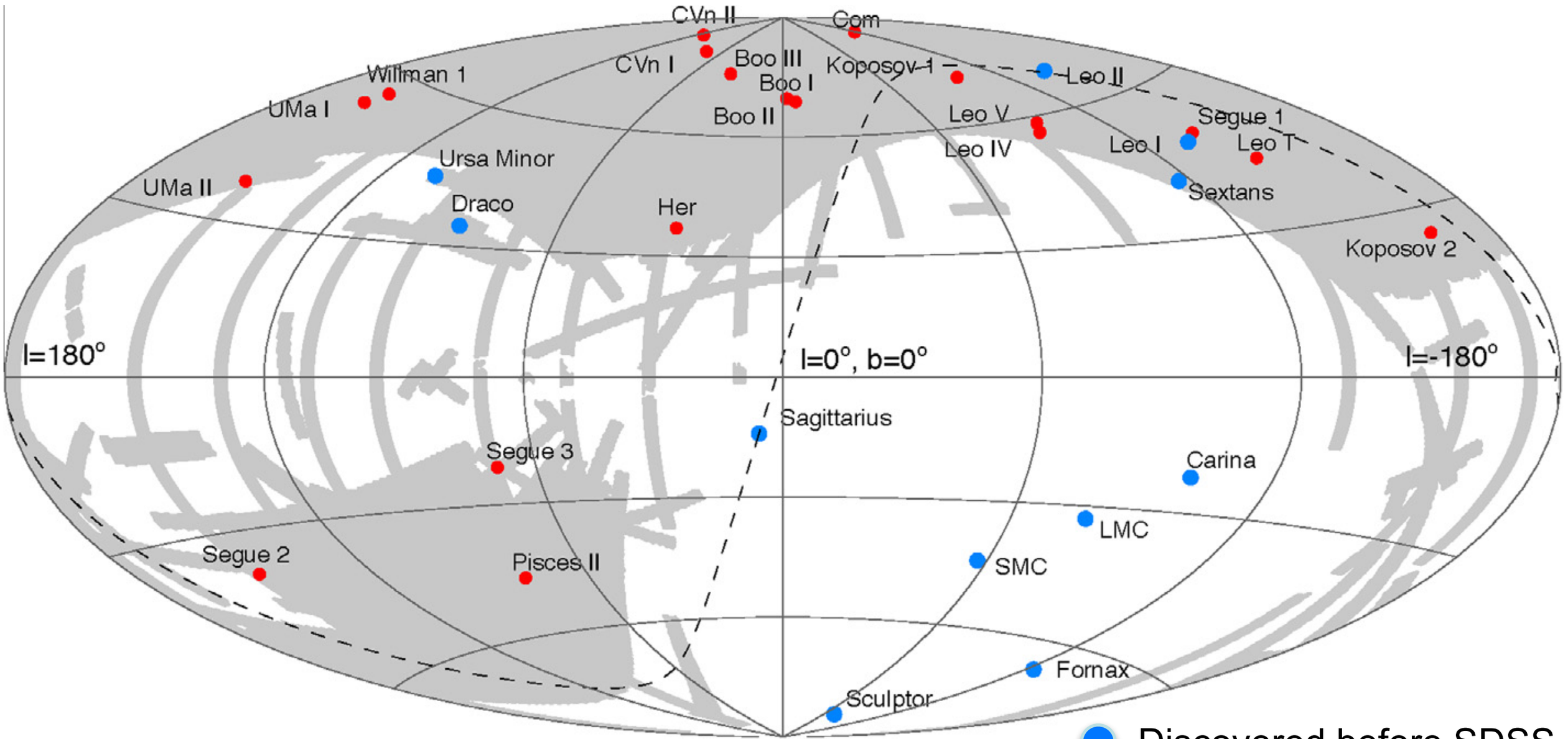
2.5m Telescope
SDSS CCD Camera

Marla Geha

Discovery Timeline



SDSS DR10



Sky Coverage of SDSS

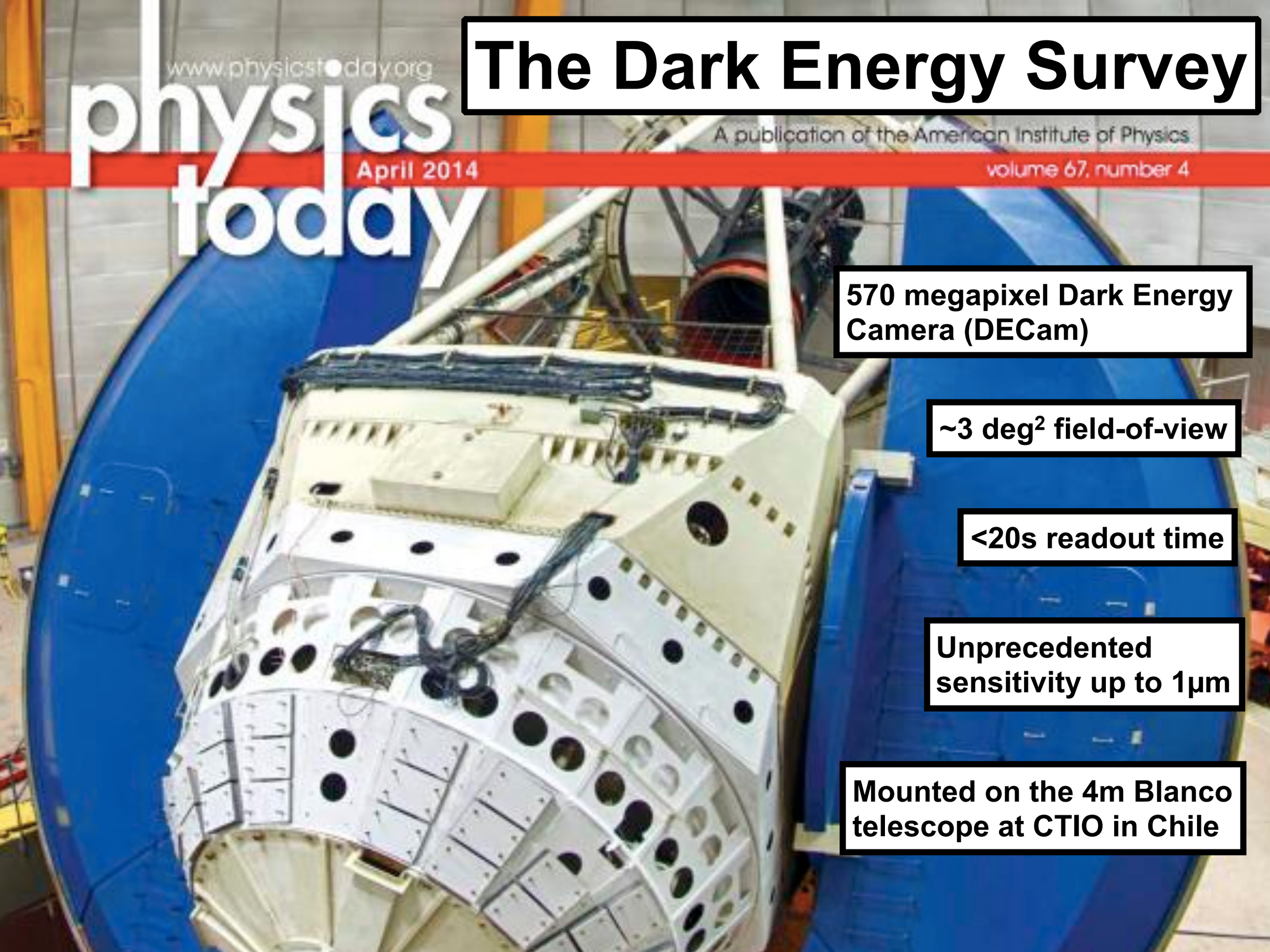
Discovered before SDSS (classical dwarfs)

Discovered with SDSS (ultra-faint dwarfs)

Belokurov, 2013

www.physicstoday.org
physics today
April 2014
A publication of the American Institute of Physics
volume 67, number 4

The Dark Energy Survey



570 megapixel Dark Energy Camera (DECam)

~3 deg^2 field-of-view

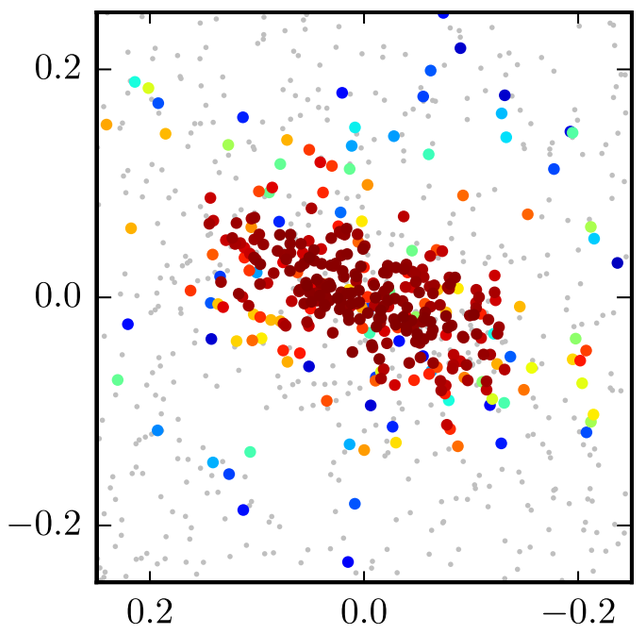
<20s readout time

Unprecedented sensitivity up to 1μm

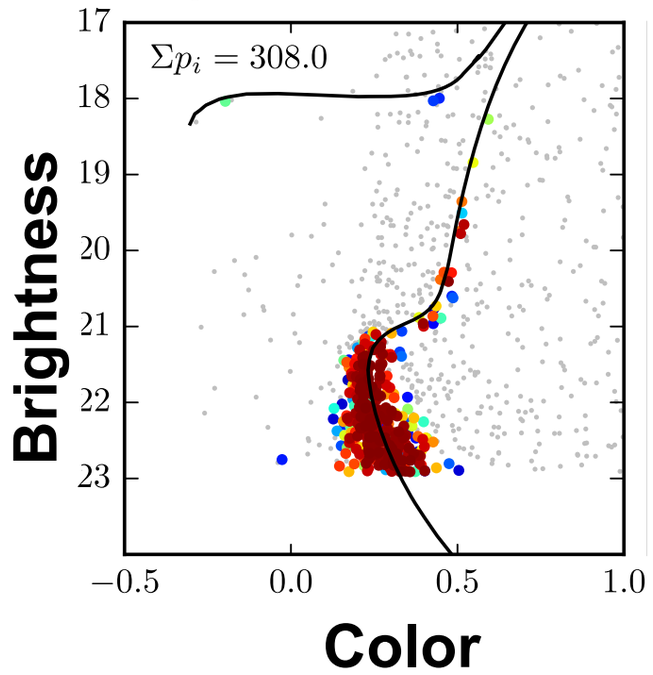
Mounted on the 4m Blanco telescope at CTIO in Chile

Maximum-Likelihood Searches

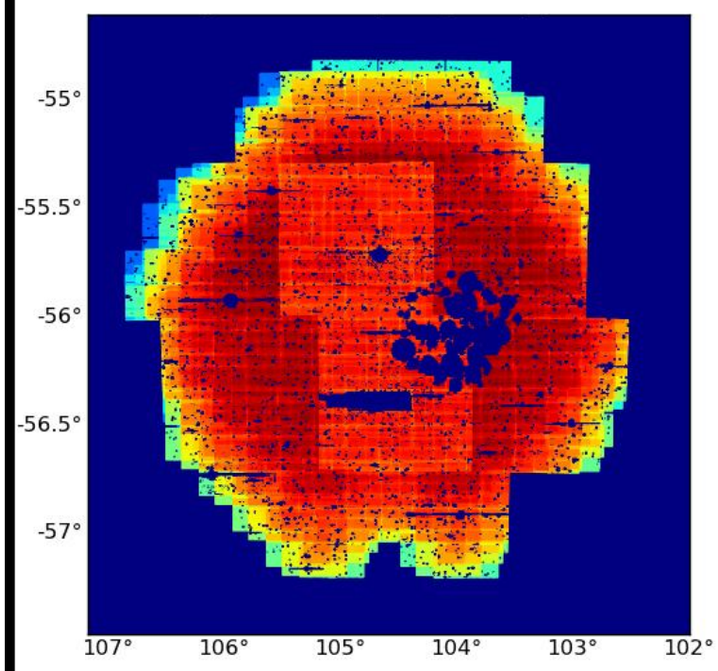
Spatial Model



Spectral Model



Survey Sensitivity



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

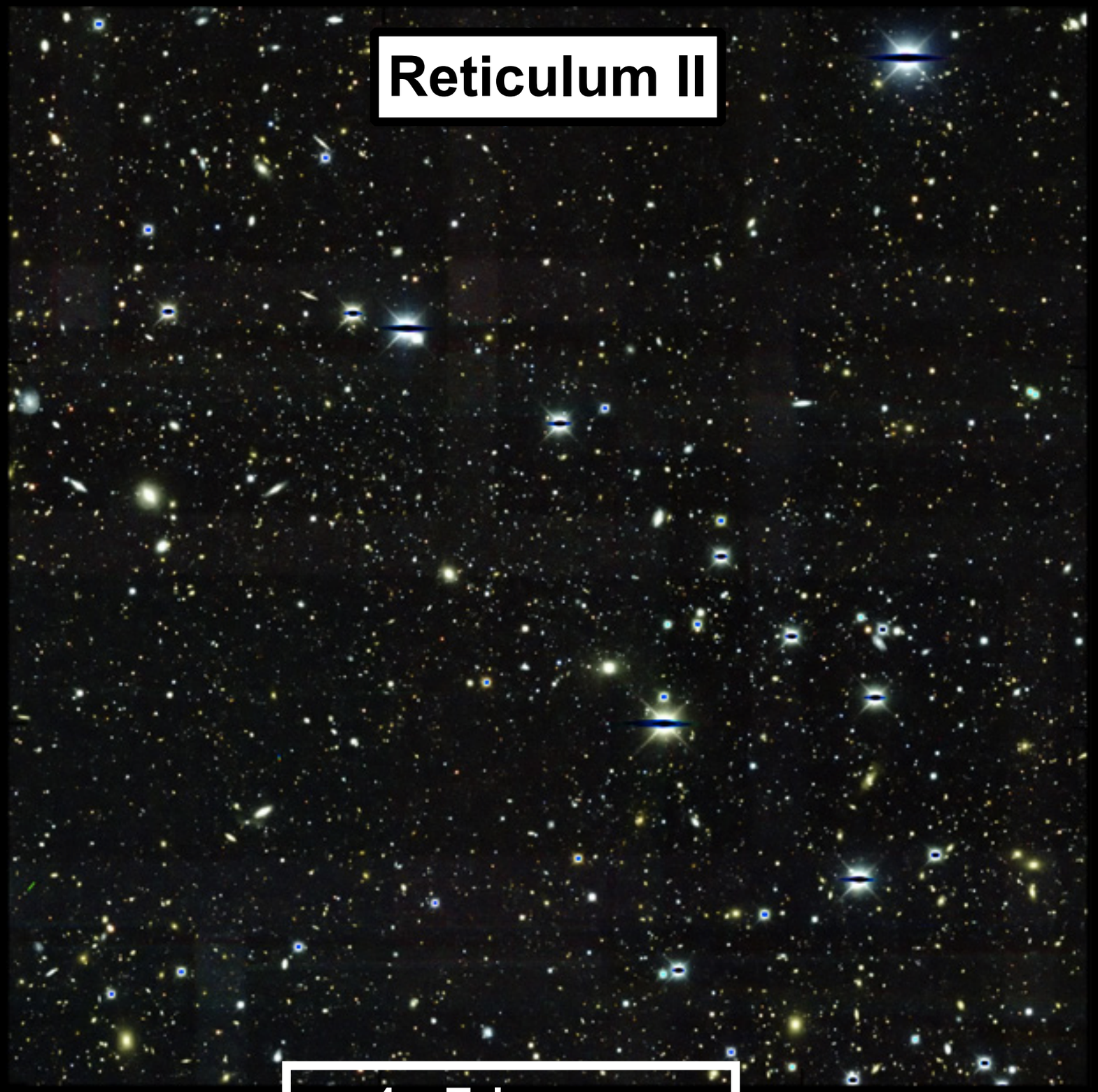
$$\lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i$$

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

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

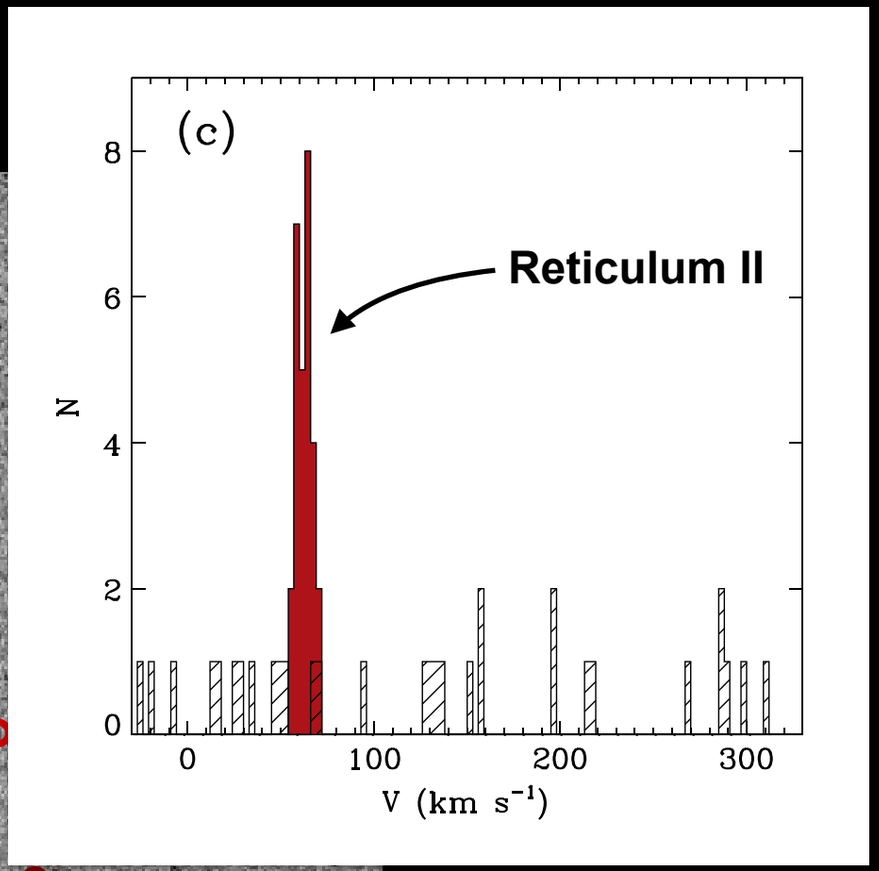
This approach naturally yields a membership probability for each star; important for spectroscopy



4m Telescope
DECam CCD Camera

DES Collaboration

Reticulum II



4m Telescope
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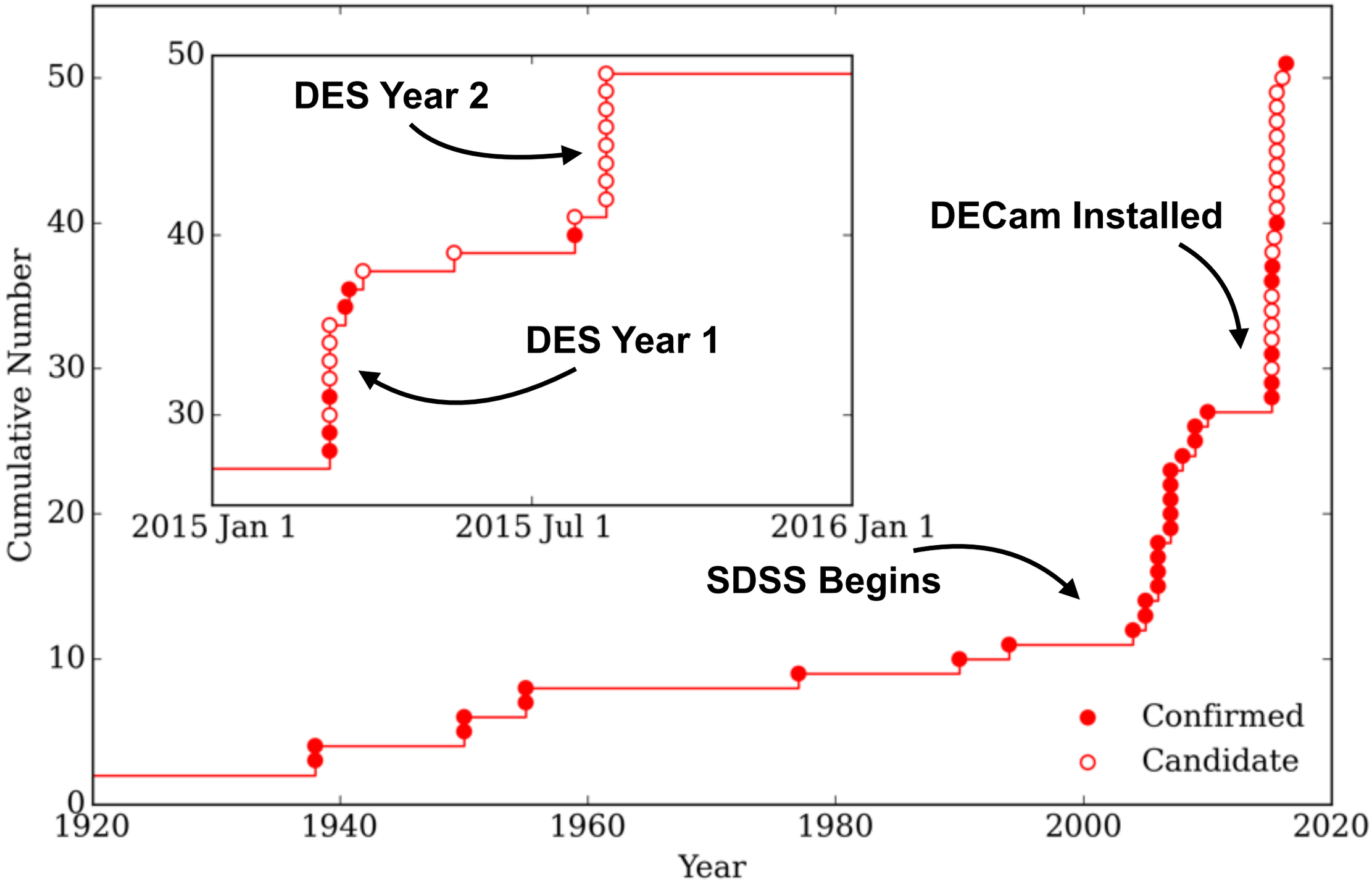
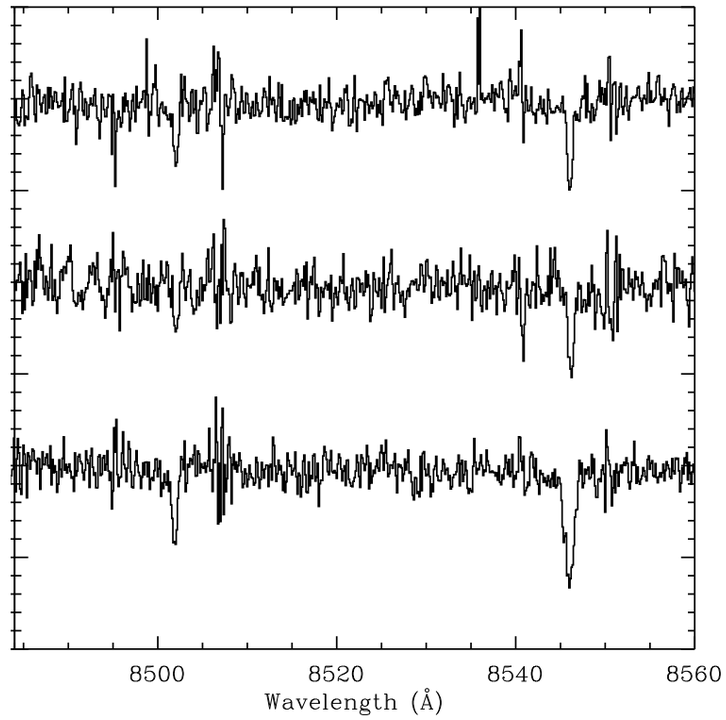
DES Collaboration

Discovery Timeline

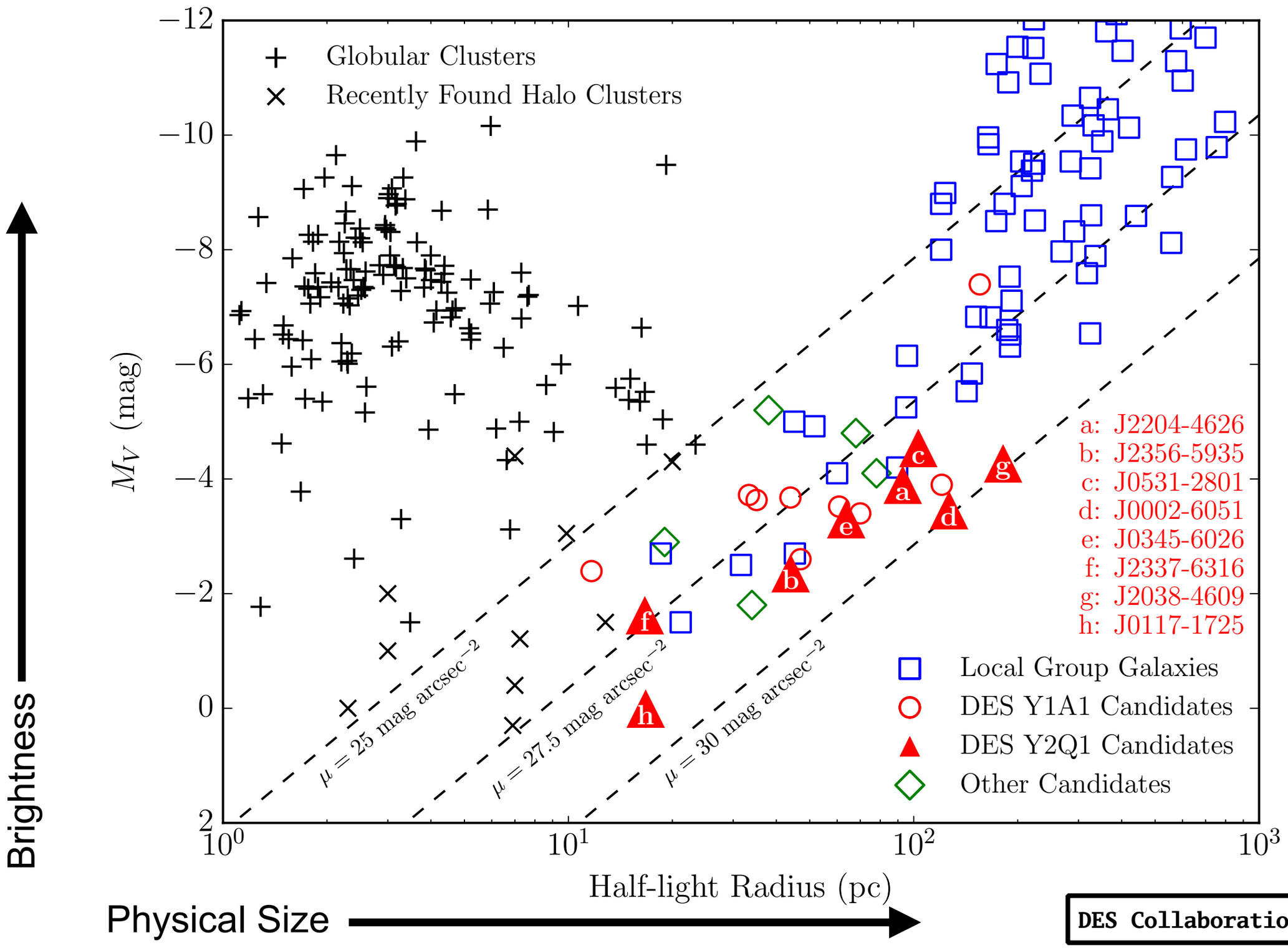


Discovery Timeline



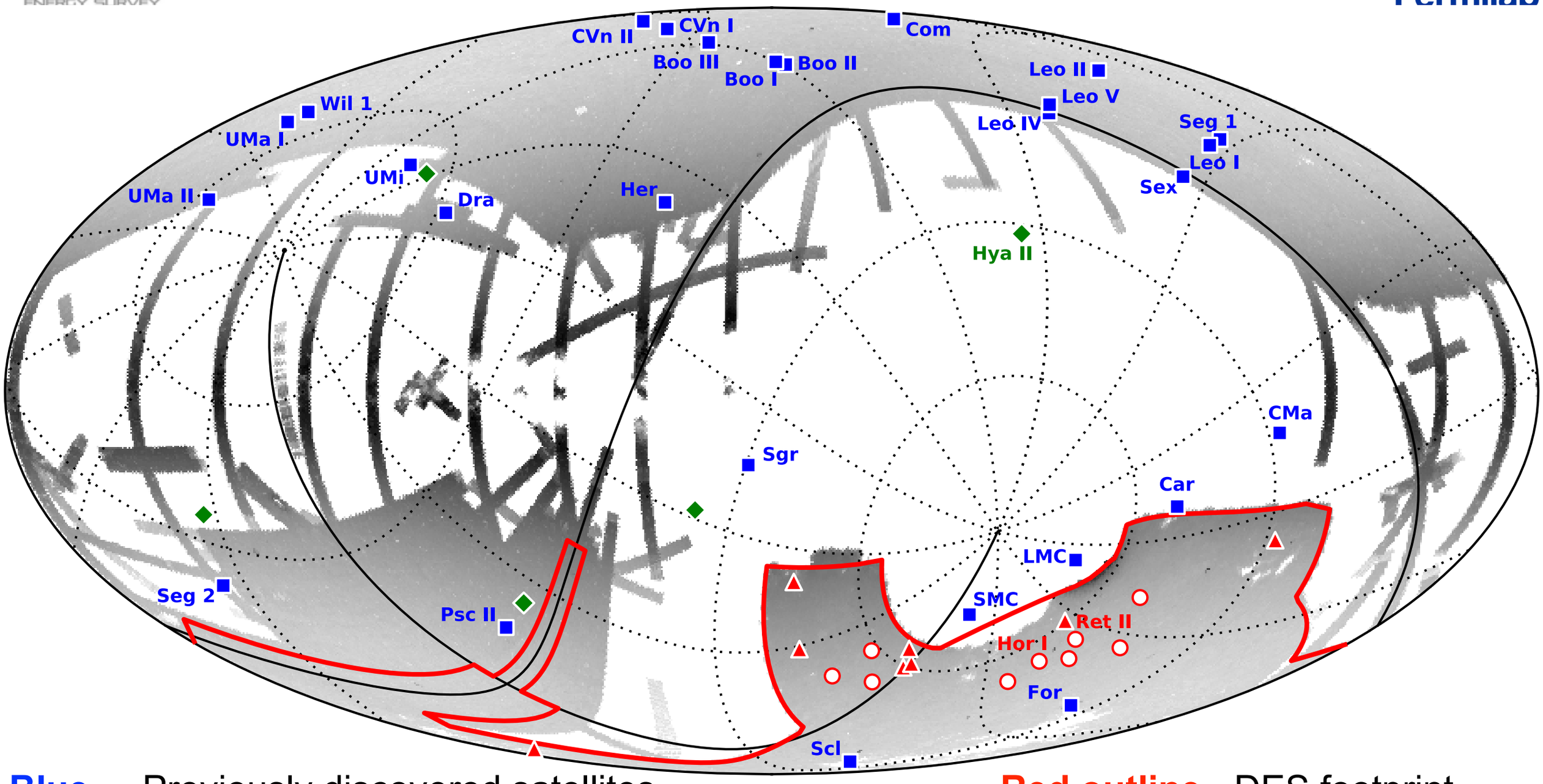
1 Night ~ $100k (+ bad weather!)

Dwarf Galaxies or Star Clusters?



DES Collaboration [1503.02584]

SDSS DR10 + DES Y2

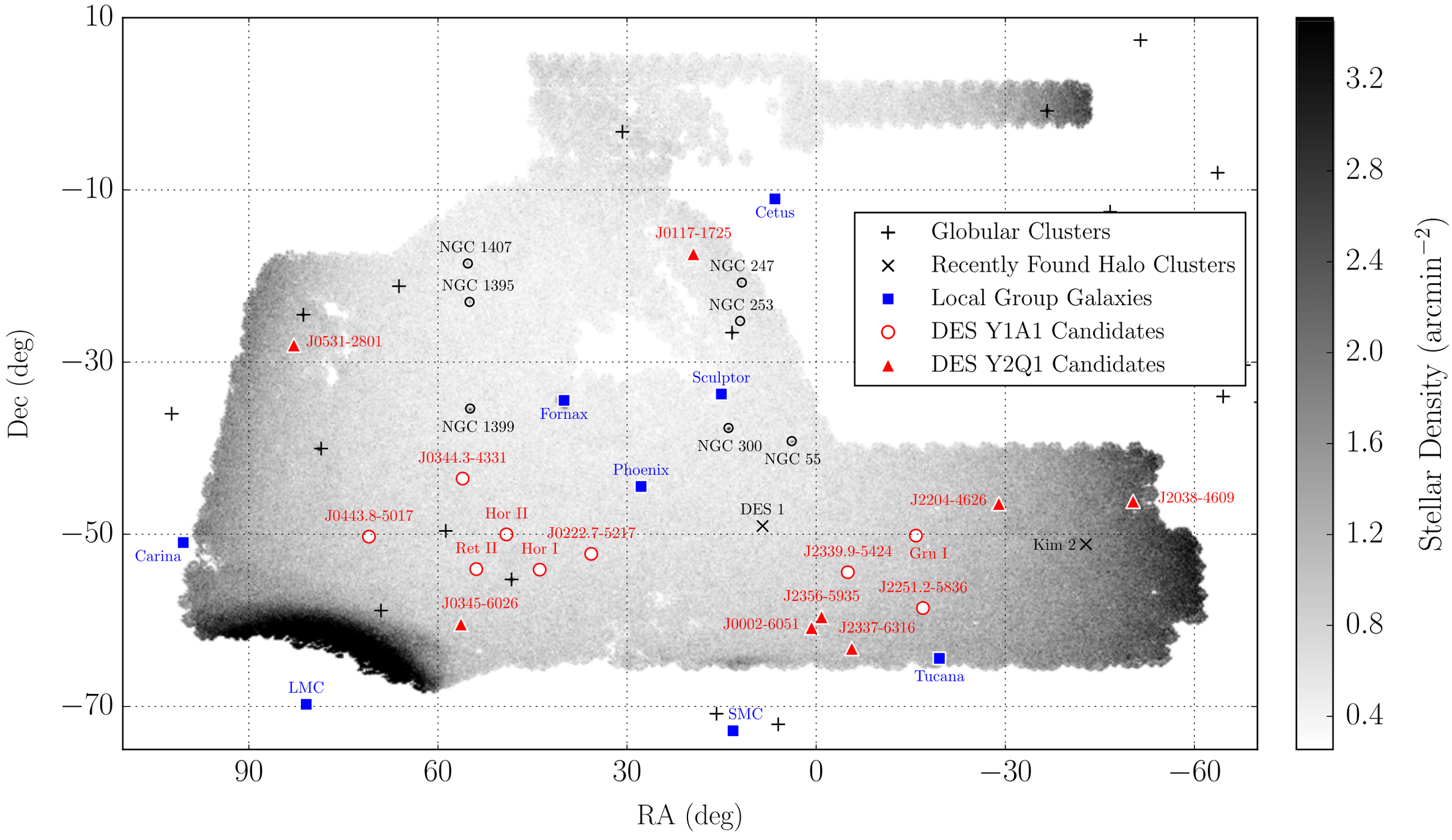


Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

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

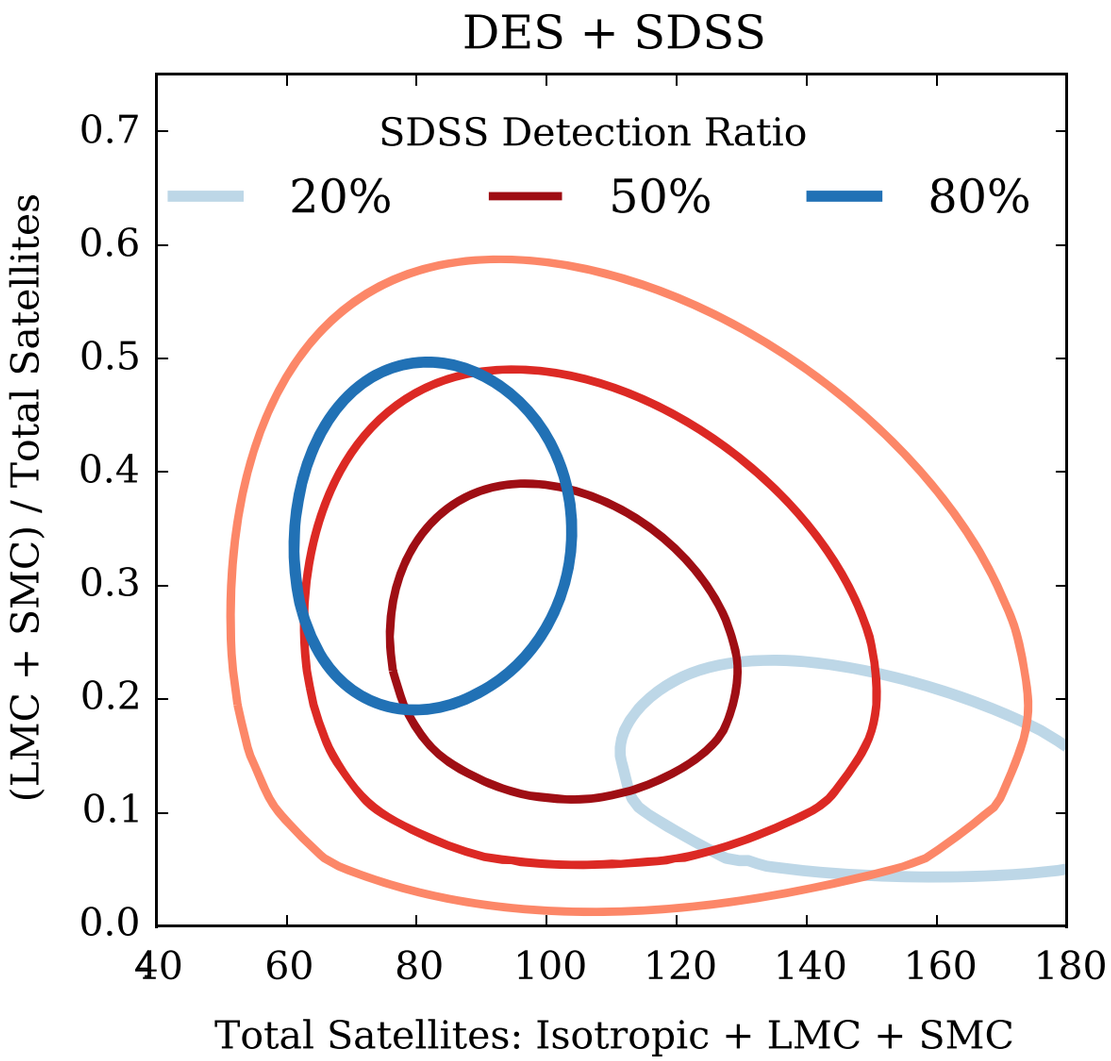
DES Collaboration [1503.02584]

DES Satellites



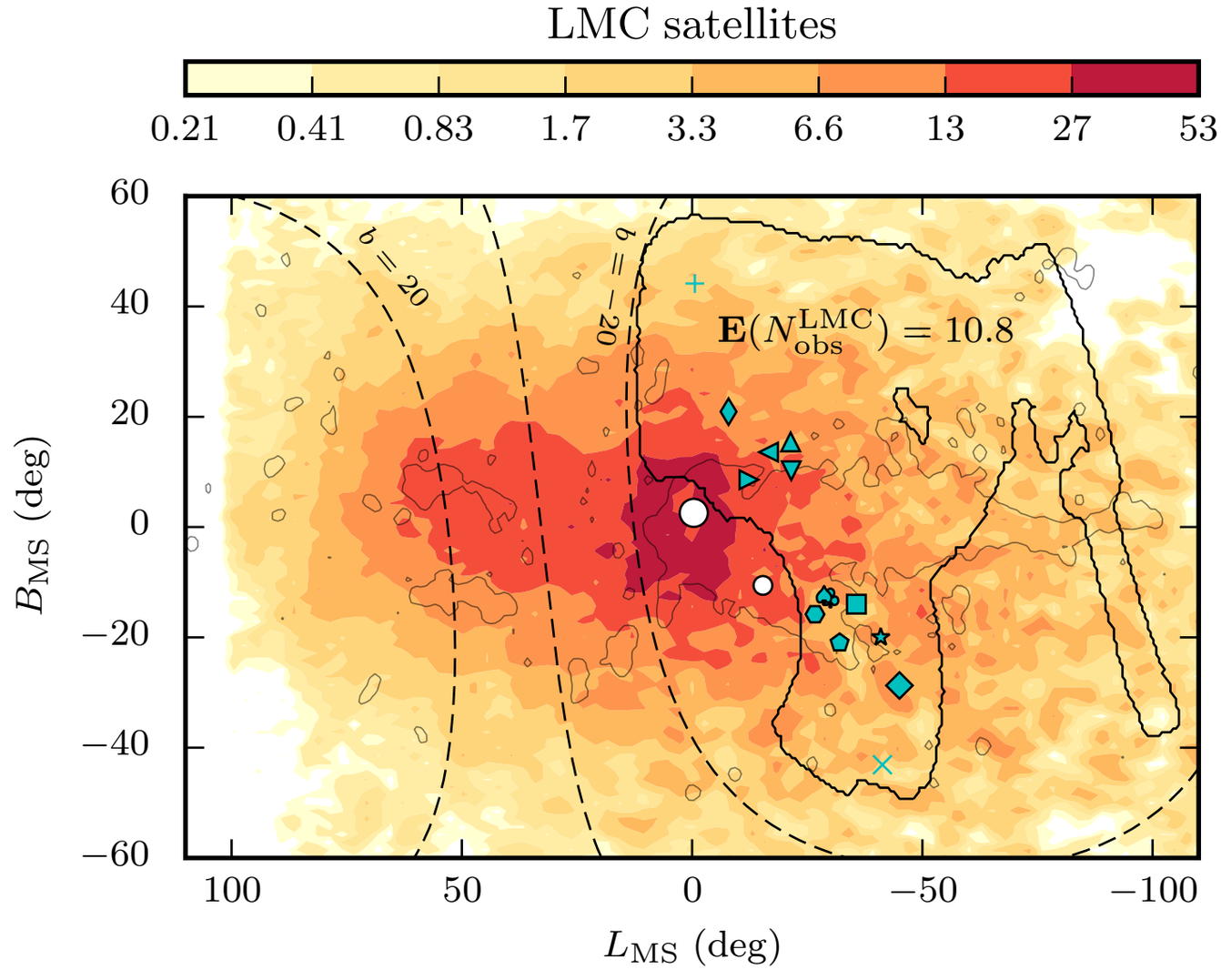
Magellanic Satellites?

With DES sensitivity expect 100+ satellites over the entire sky



DES Collaboration [1503.02584]

30+ of these satellites contributed by the LMC/SMC

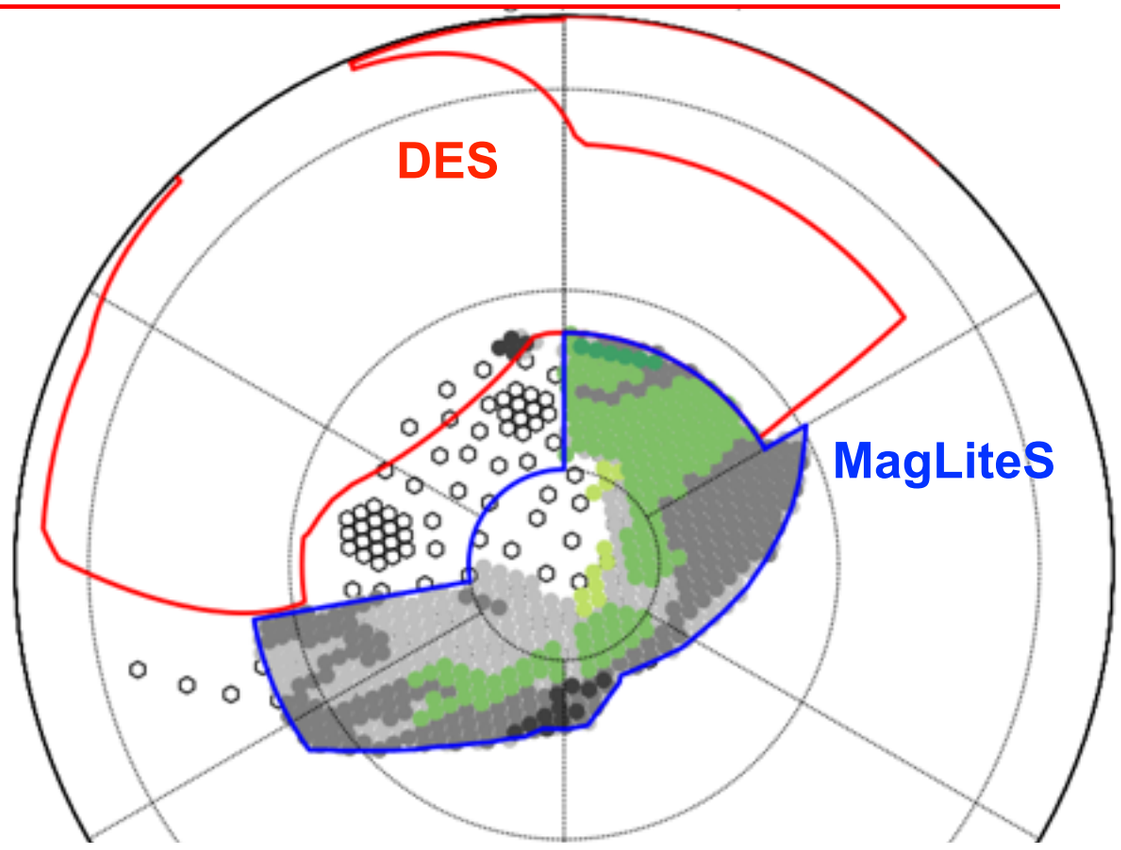


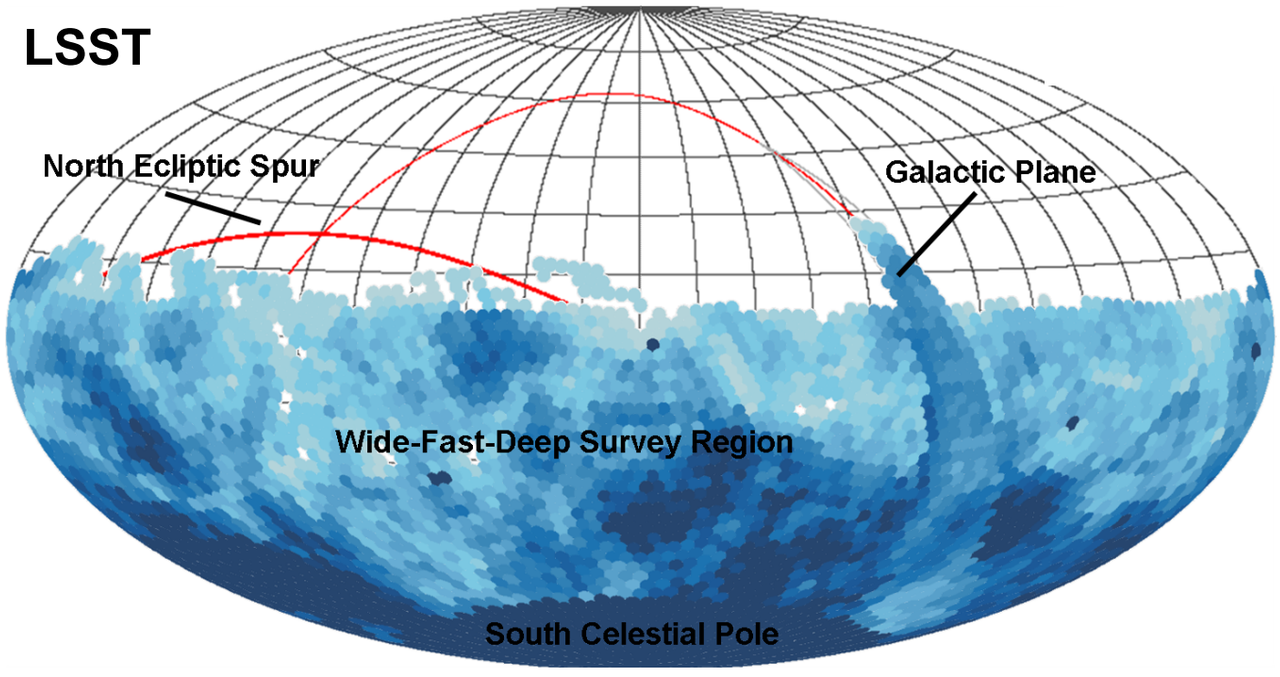
Jethwa et al [1603.04420]

Looking Forward

- A large spectroscopic campaign is underway to classify and characterize newly discovered systems
- Future sky coverage:
  - DES Y3+: a few hundred deg^2, better data reduction, greater sensitivity
  - Additional DECam observations outside of DES (e.g., MagLiteS)
  - LSST: 20,000 deg^2 (and much greater sensitivity)

- Increased sensitivity: fainter systems with large angular sizes
  - Do galaxies extend to even lower surface brightness?
  - Are there very nearby ultra-faint dwarf galaxies?





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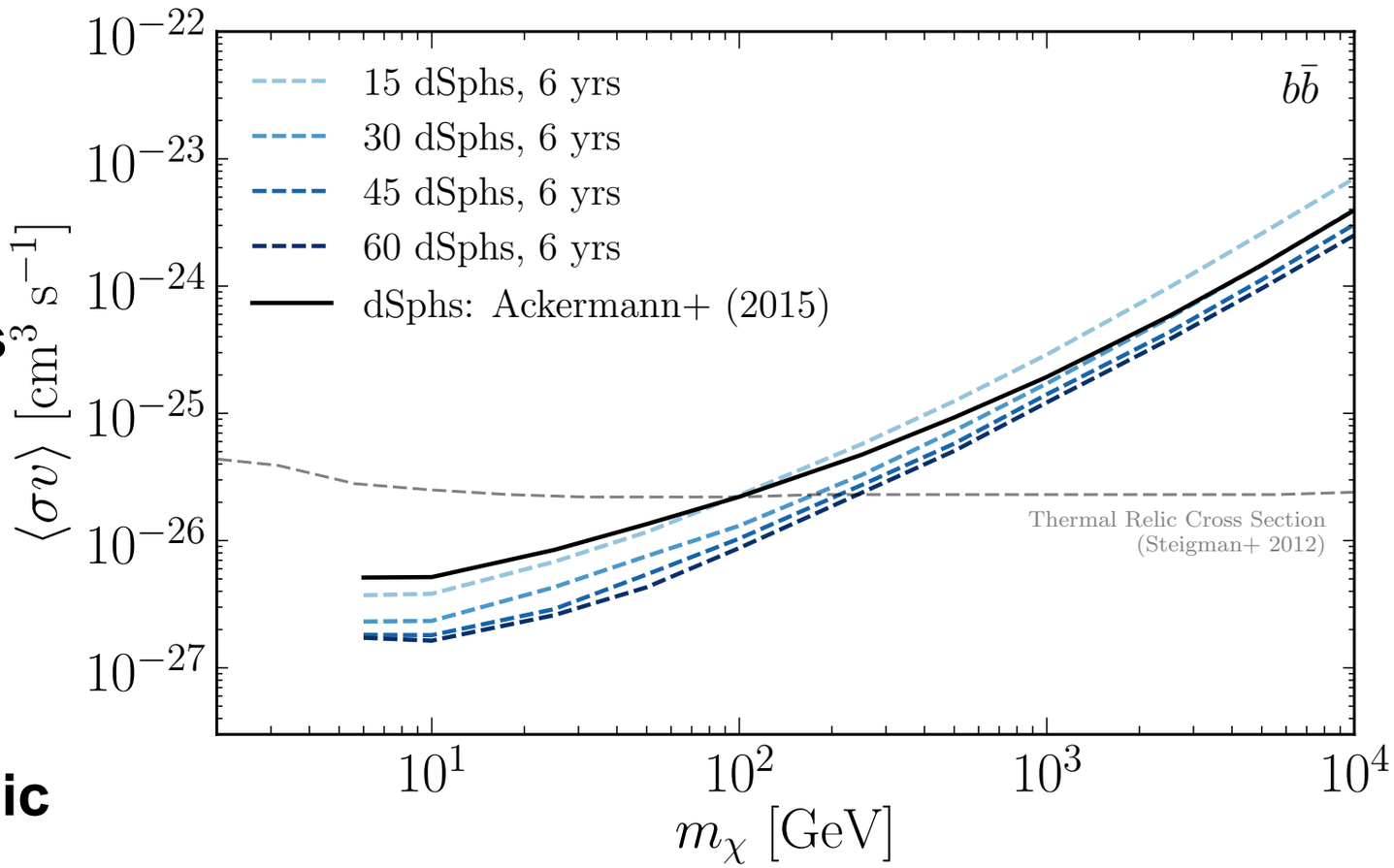
  - Additional DECam observations outside of DES (e.g., MagLiteS)
  - LSST: 20,000 deg² (and much greater sensitivity)
- The LAT continues to survey the entire gamma-ray sky
  - Expect sensitivity to thermal relic DM with a mass up to 400 GeV
  - Dwarfs will provide a sensitive test of DM interpretations of the Galactic Center excess



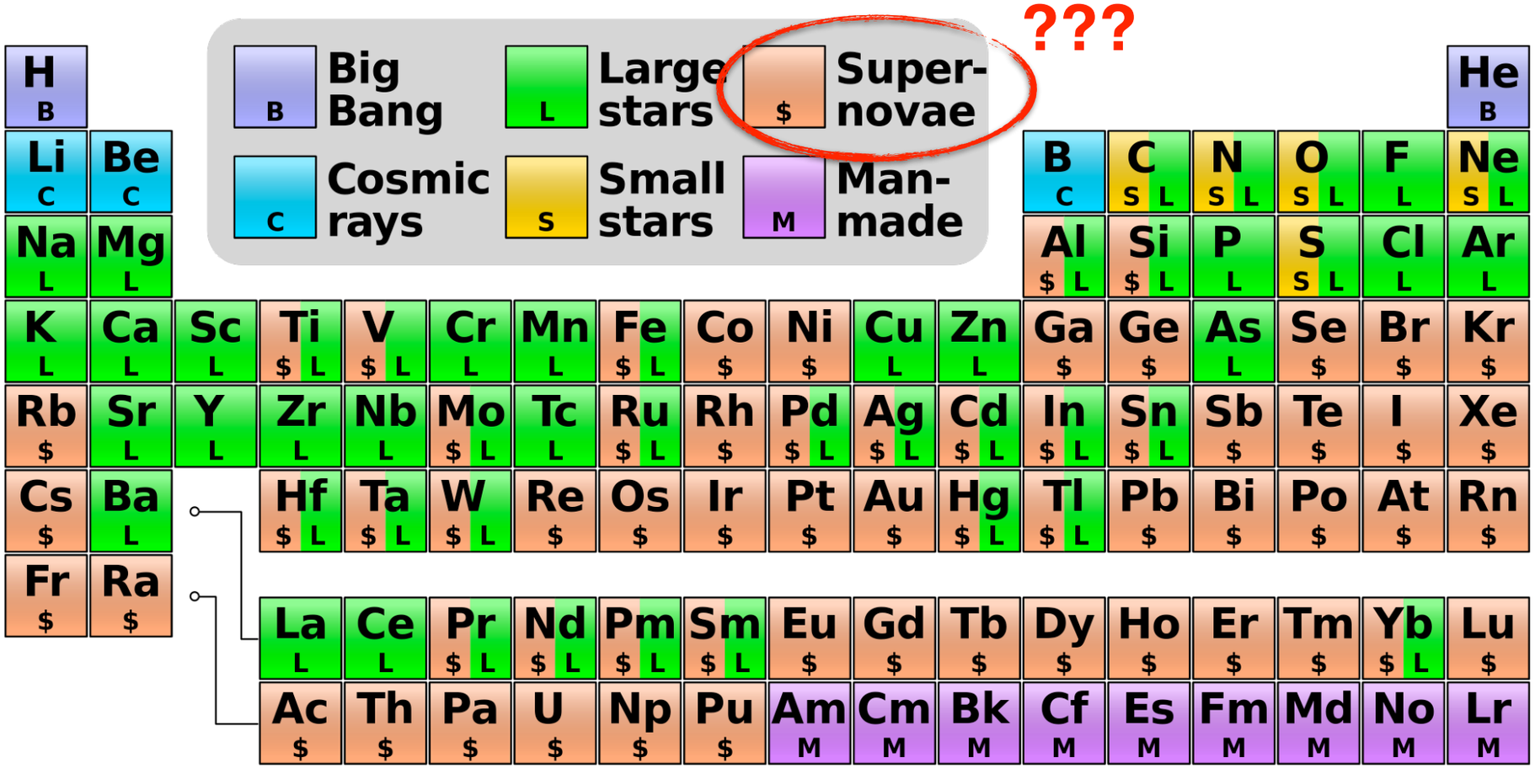
Charles et al. [1605.02016]

Backup Slides

Reticulum II and the Origin of Heavy Elements

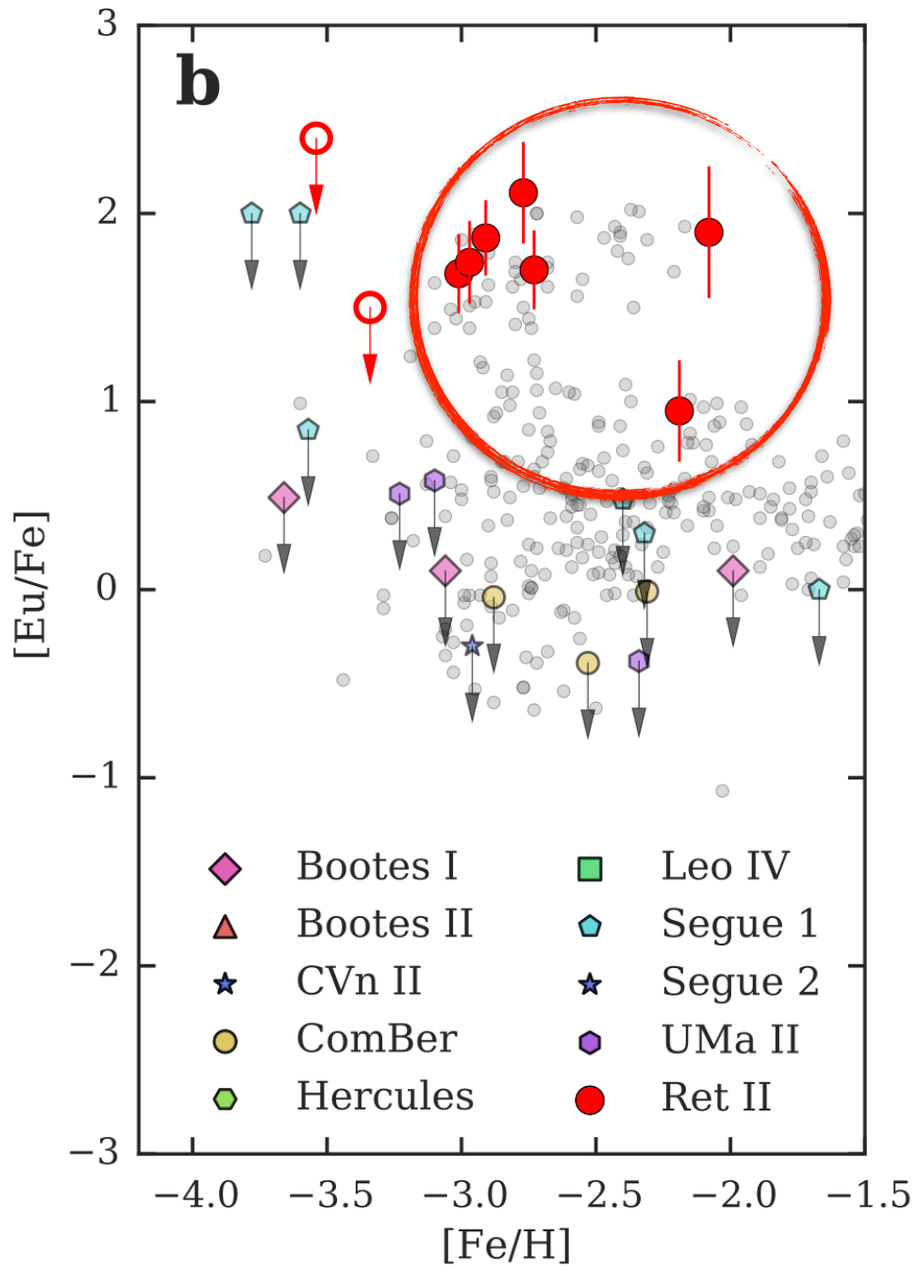
Rapid absorption of free neutrons during explosive event
Possible sites: core-collapse SNe, neutron star mergers

Observed excess of r-process elements in Ret II relative to other ultra-faint dwarfs (by factor >100) suggests enrichment by a single (rare) event
→ Consistent with neutron star merger hypothesis

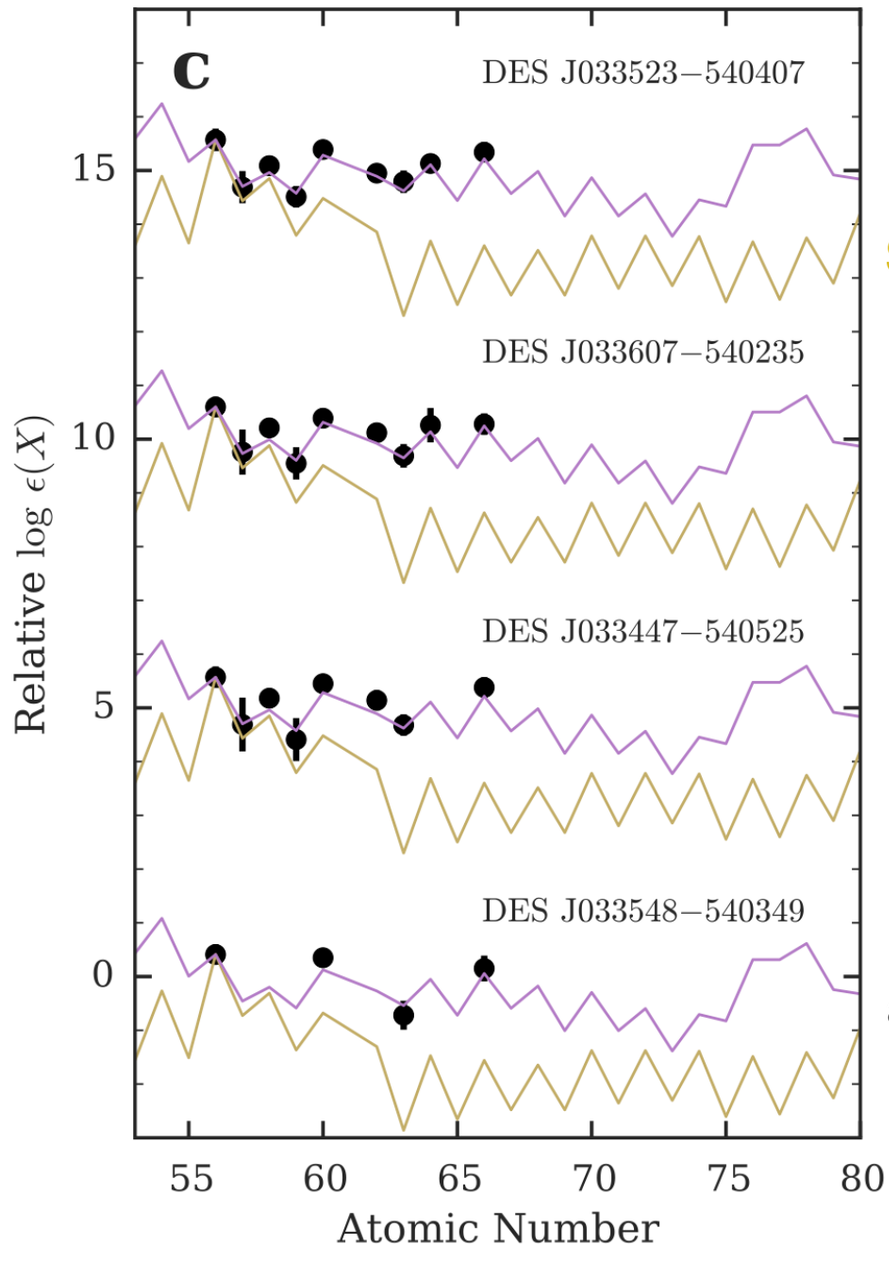


Reticulum II and the Origin of Heavy Elements

Using europium as representative r-process element



Neutron-capture abundance patterns for 4 brightest Ret II stars



r-process
s-process

Ji et al. 2015
arXiv:1512.01558

Gamma-ray Emission Towards Reticulum II

Most significant gamma-ray excess for DES Y1 targets peaks at 2 to 10 GeV and is associated with the nearby object Reticulum II

	LAT Data Set	Local Significance	Post-trials for DM mass and annihilation channel
Fermi-LAT + DES	Pass 8	2.2 σ	1.65 σ
Geringer-Sameth et al.	Pass 7	2.8 σ	2.3 σ
Geringer-Sameth et al.	Pass 8	2.0 σ	1.6 σ
Hooper & Linden	Pass 7	3.2 σ	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

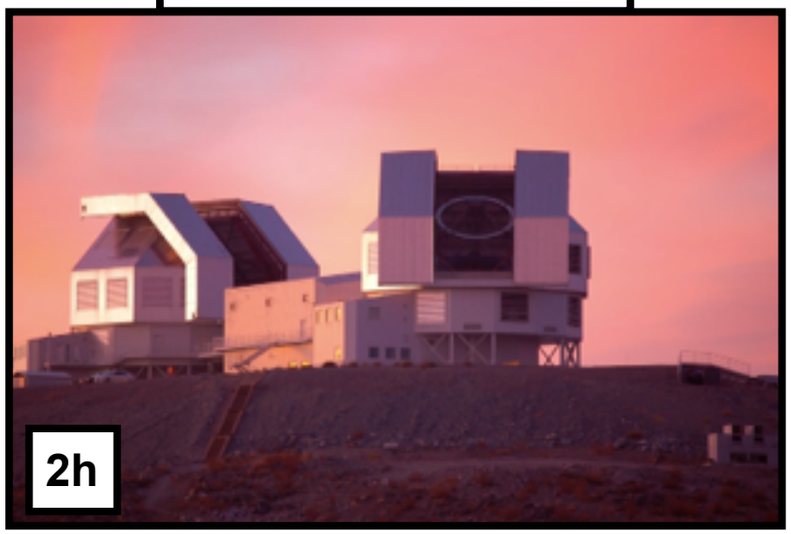
Geringer-Sameth et al. 2015
arXiv:1503.02320

Hooper & Linden
arXiv:1503.06209

Consistency with a DM interpretation depends on the J-factor of Reticulum II relative to other dSphs

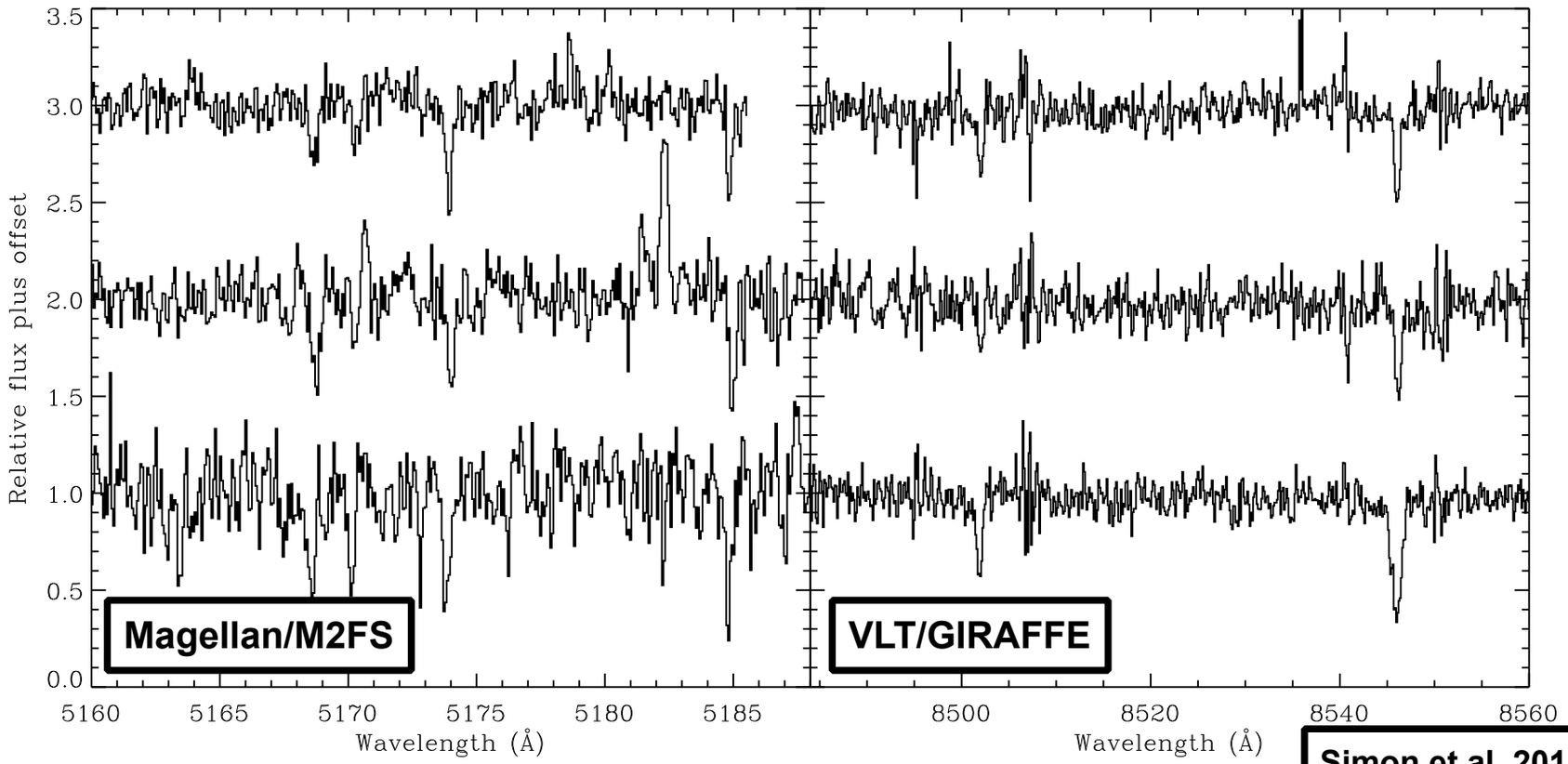
Reticulum II: Spectroscopy Campaign

Magellan/M2FS



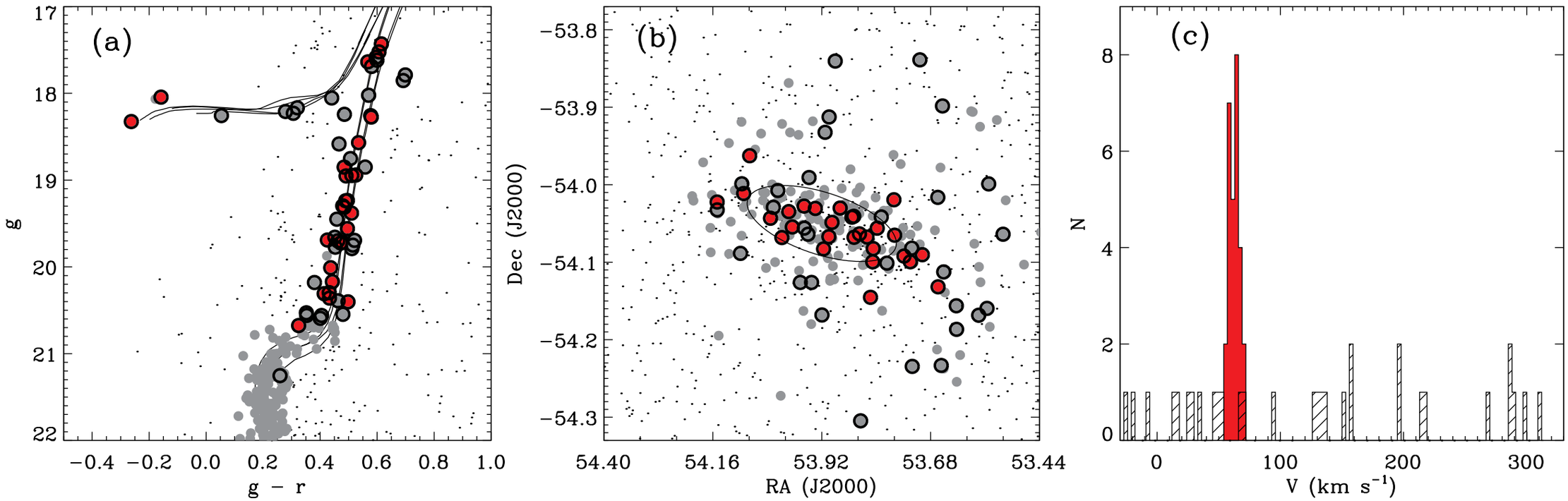
Gemini/GMOS

VLT/GIRAFFE



Simon et al. 2015 (DES Collaboration)

Reticulum II: New Dwarf Galaxy



- **Velocity peak indicative of a gravitationally bound object**
- **Dynamical mass calculated from the width of the velocity dispersion (width of the velocity peak)**
- **Metallicity spread also indicative of deep gravitational potential**
- **Every measured characteristic of Reticulum II is consistent with the known population of dwarf galaxies**

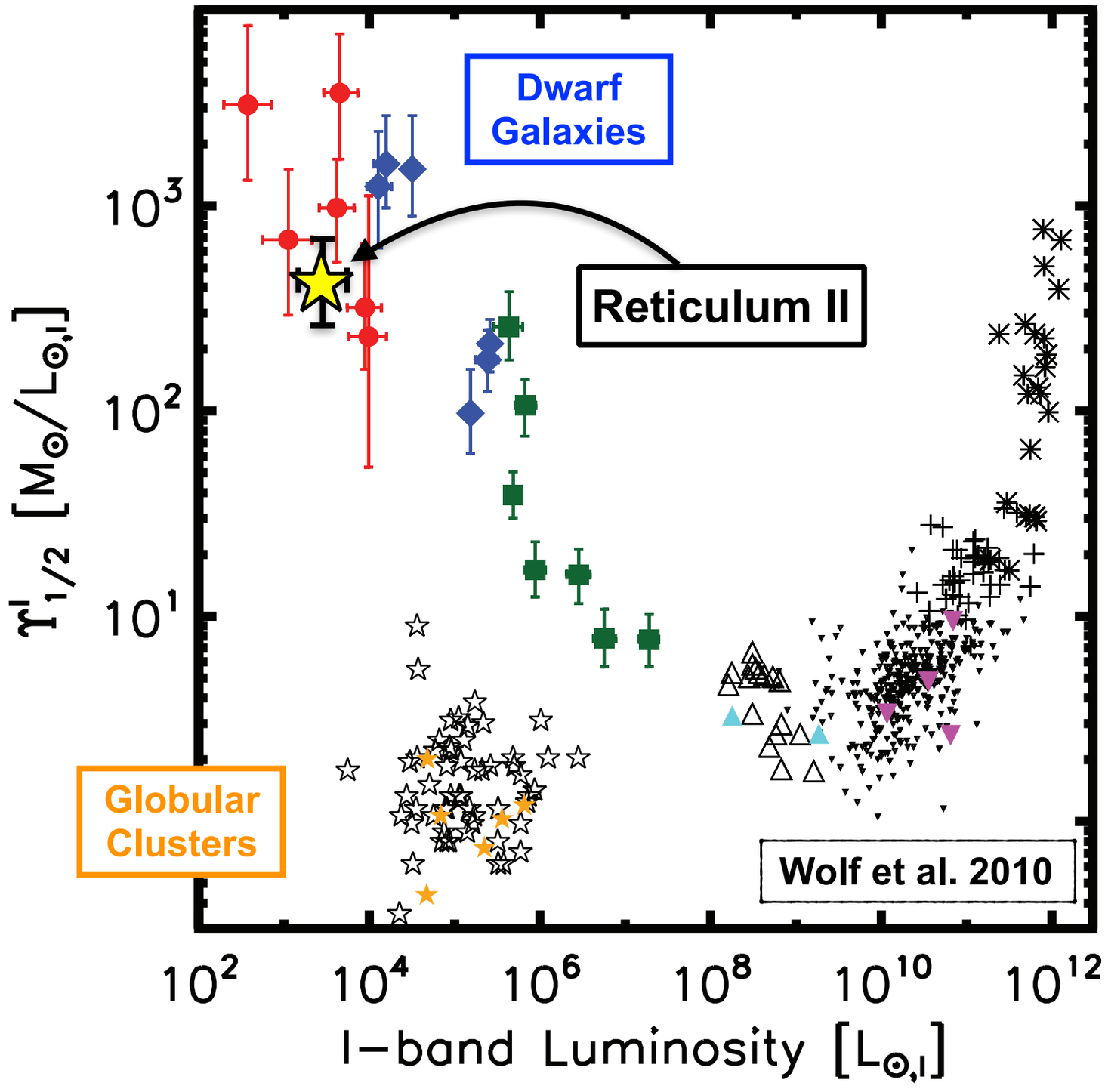
Simon et al. 2015 [1504.02889]

Walker et al. 2015 [1504.03309]

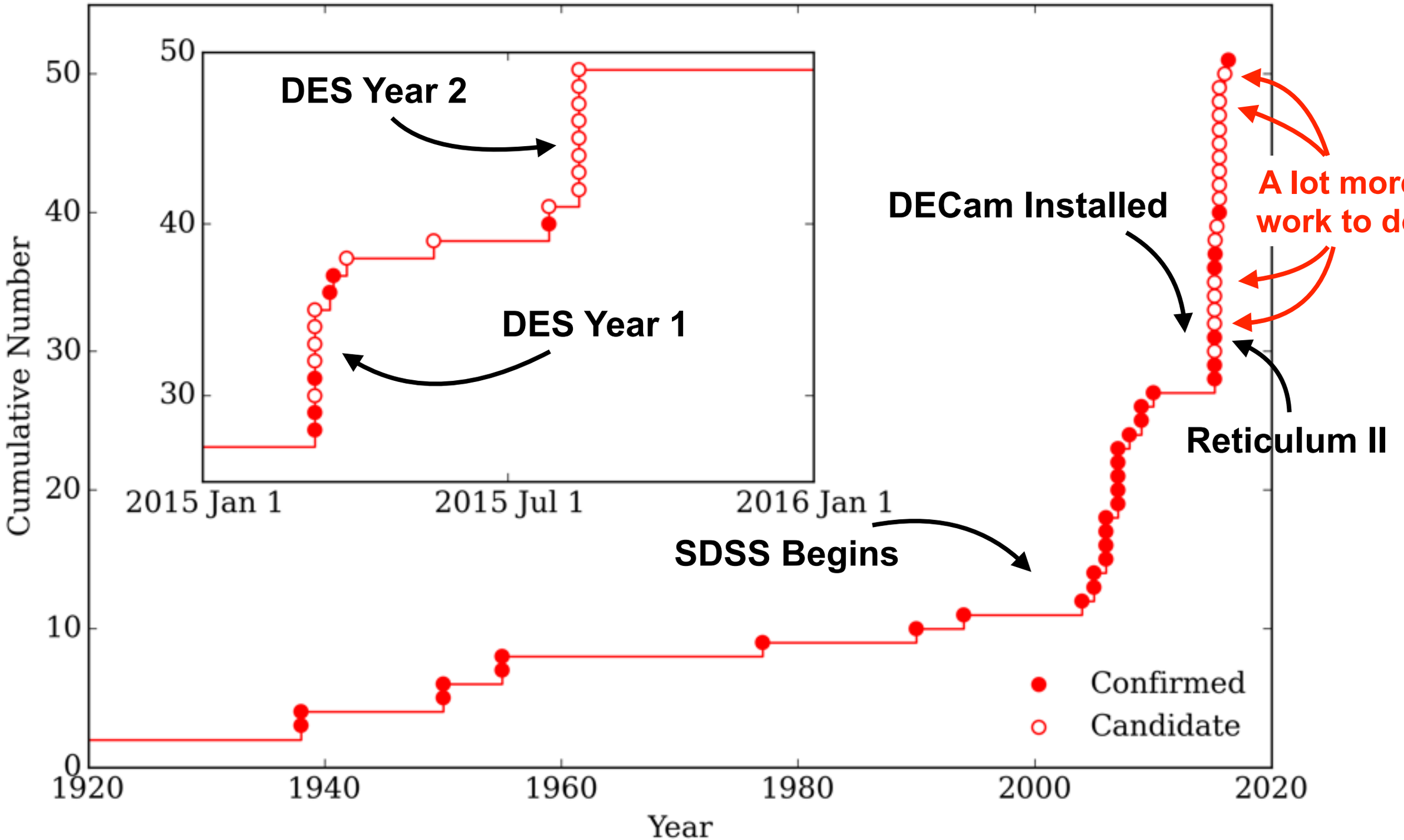
Koposov et al. 2015 [1504.07916]

Quantity	Value
Systemic Velocity	$v = 62.8 \pm 0.5\,\mathrm{km\,s^{-1}}$
Velocity Dispersion	$\sigma_v = 3.3 \pm 0.7\,\mathrm{km\,s^{-1}}$
Metallicity	$[\mathrm{Fe/H}] = -2.65 \pm 0.07$
Metallicity Dispersion	$\sigma_{[\mathrm{Fe/H}]} = 0.28 \pm 0.09$
Dynamical Mass	$M_{1/2} = 5.6 \pm 2.4 \times 10^5\,\mathrm{M_\odot}$
Mass-to-Light Ratio	$M/L = 470 \pm 210\,\mathrm{M_\odot}/\,\mathrm{L_\odot}$

Reticulum II: New Dwarf Galaxy

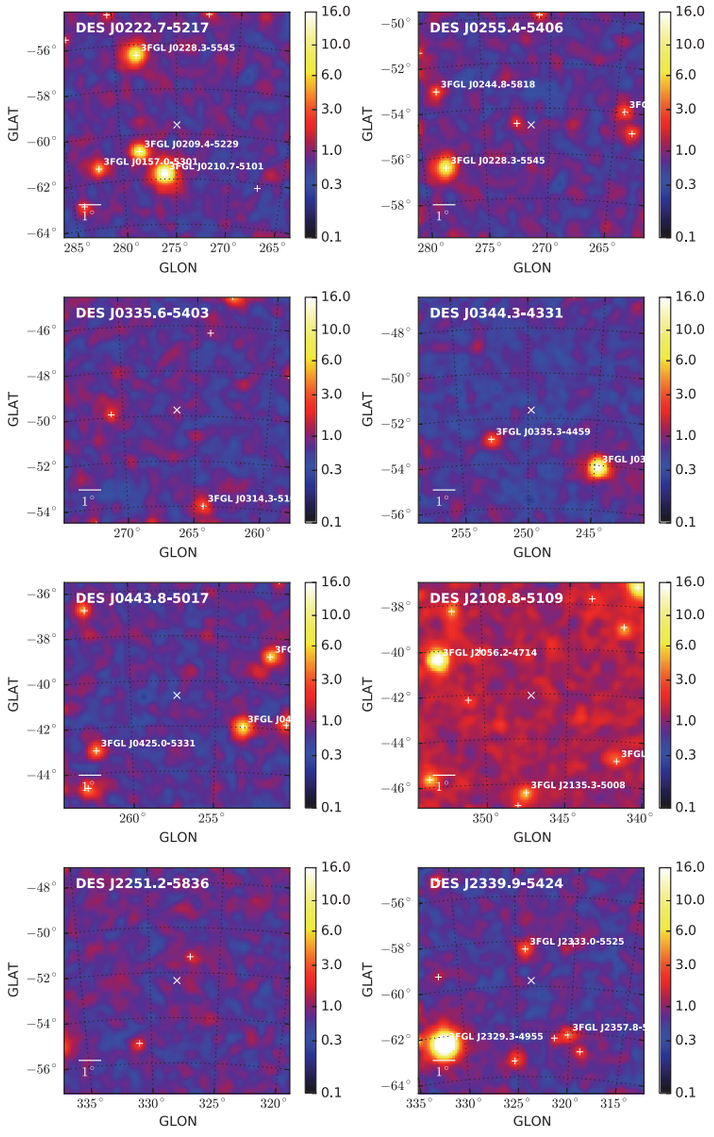


Discovery Timeline



Search for Dark Matter

Search Fermi-LAT data for gamma-rays from dark matter annihilation



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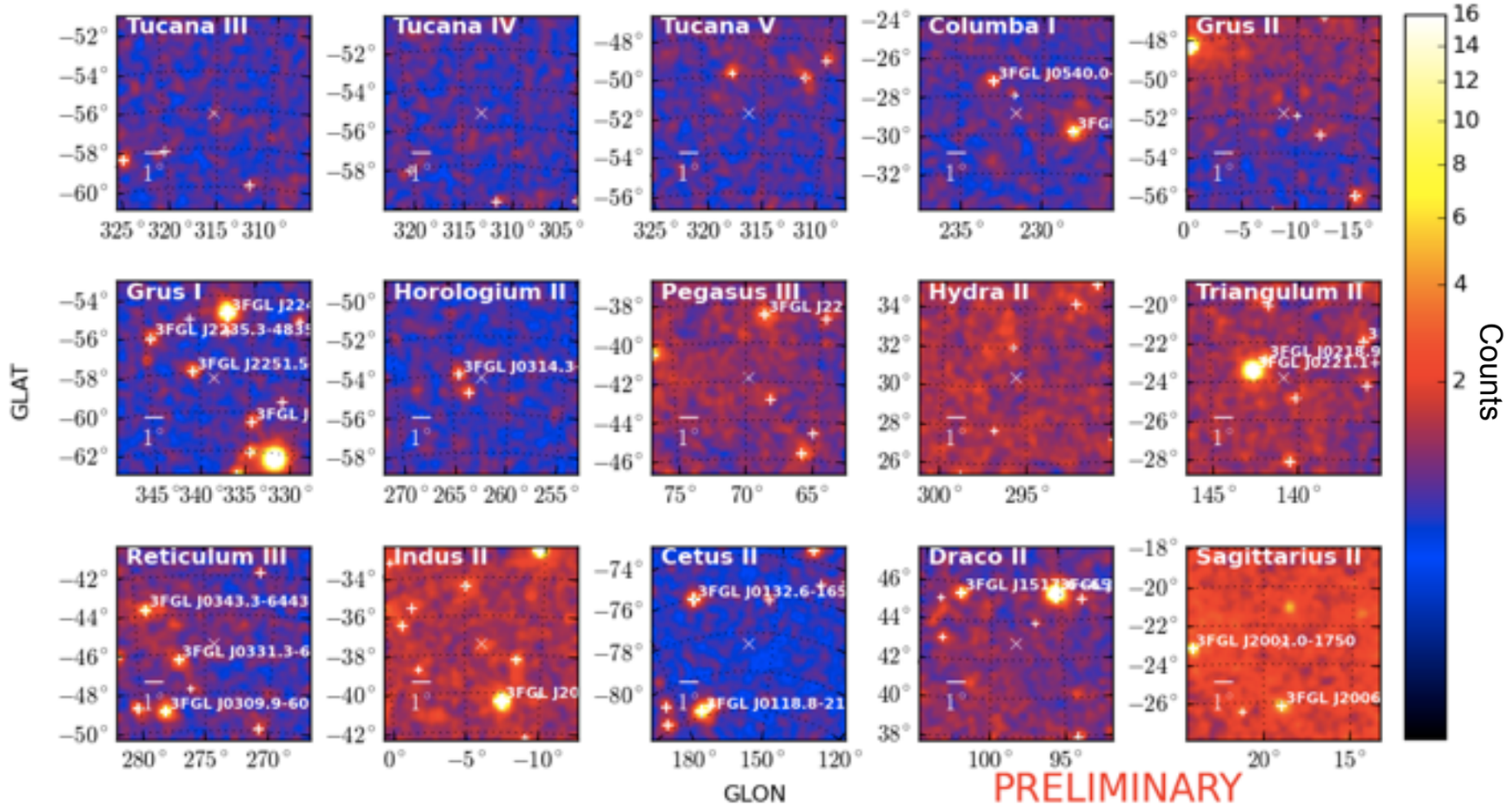

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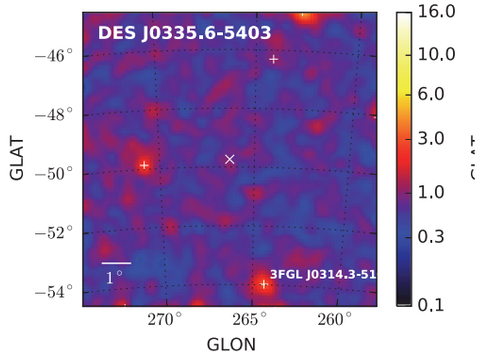
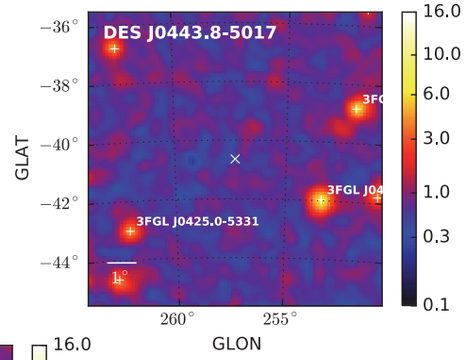
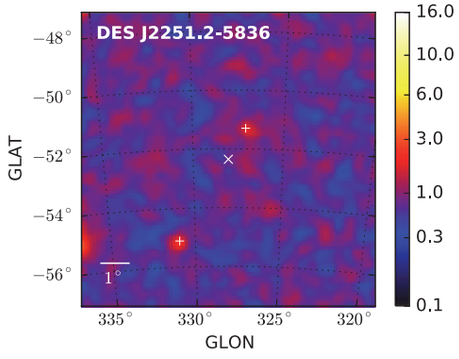
23 other dSphs…

ADW et al. ApJ 809 L4 (2015)

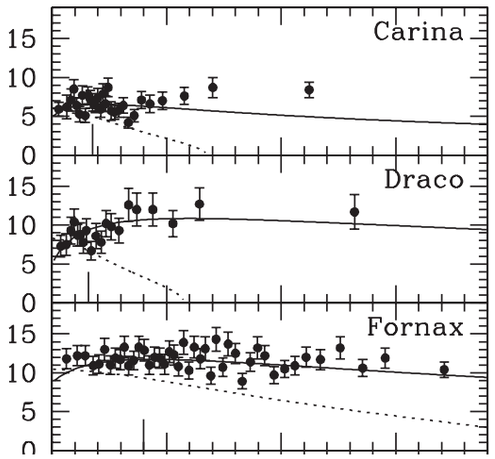
Search for Gamma Rays







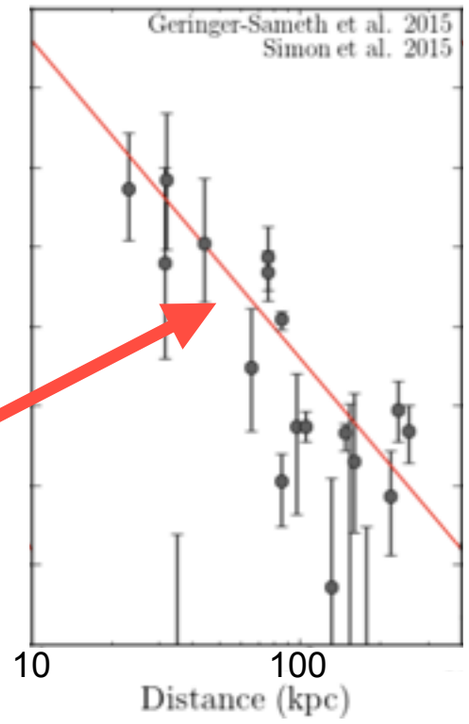
Walker et al. (2007)

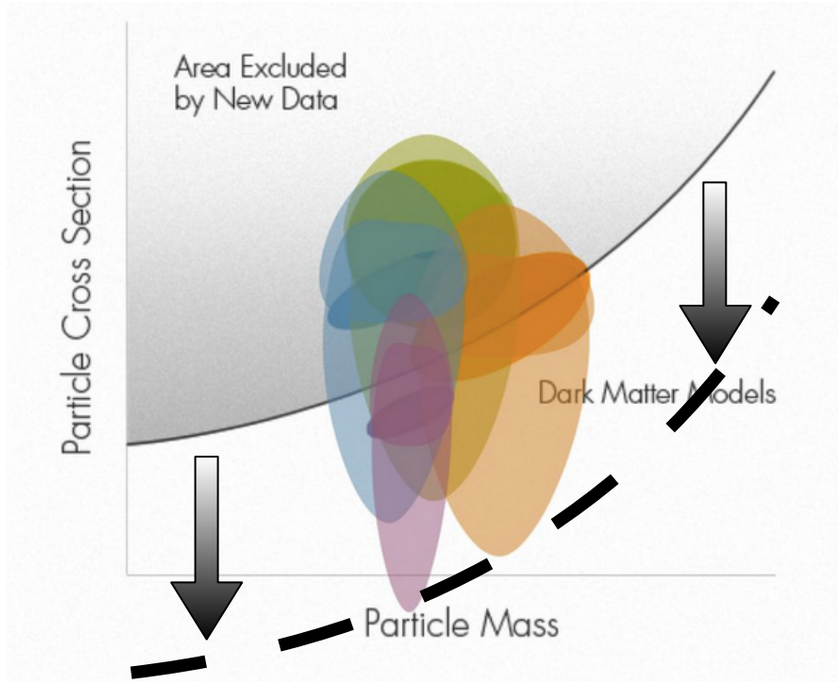


What we'd like

DM Content

What we have…

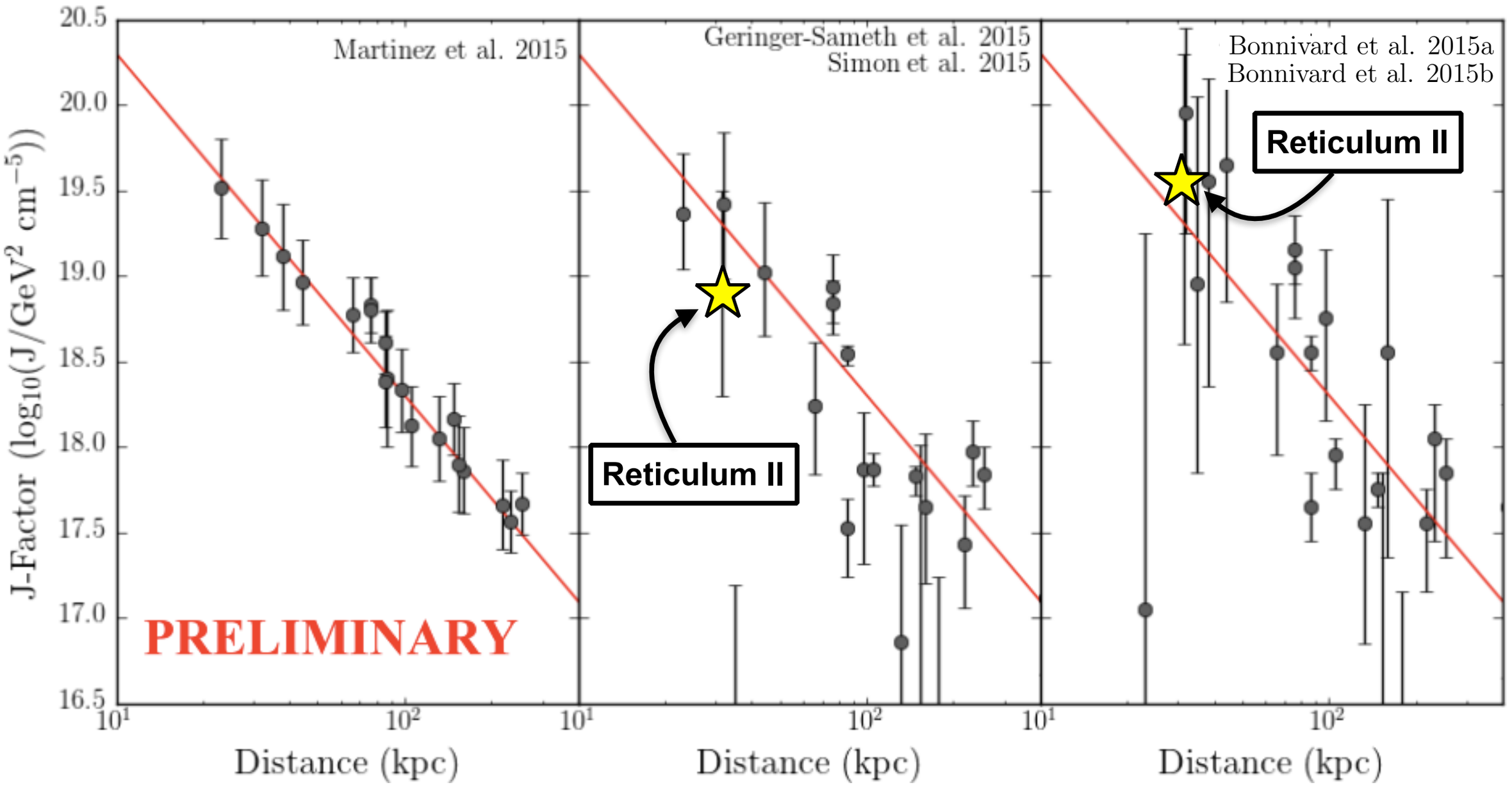




Kevork Abazajian @kevaba · Oct 25
@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

1

J-Factor Scaling



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**