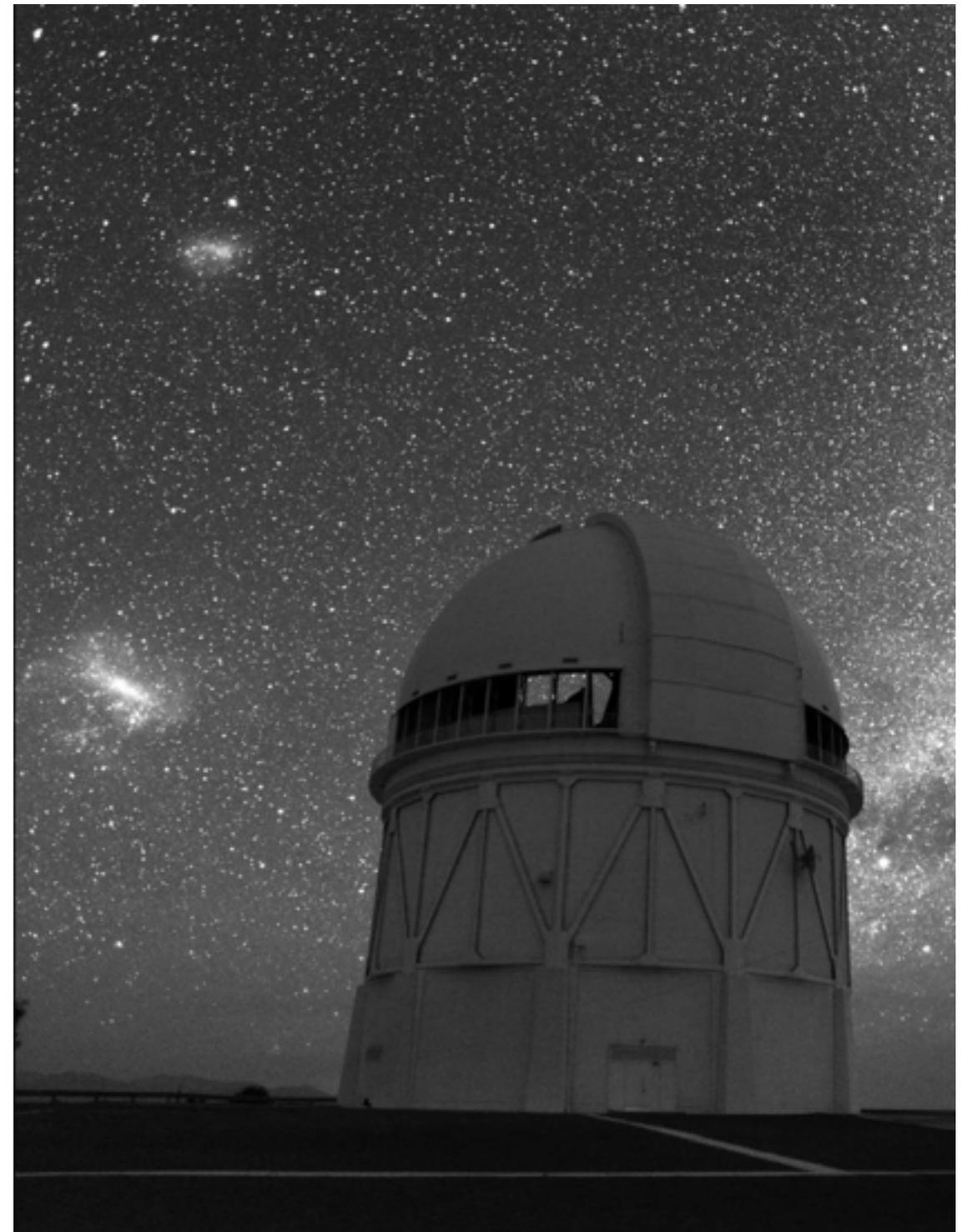

Searching for Milky Way Satellite Galaxies with the Dark Energy Survey

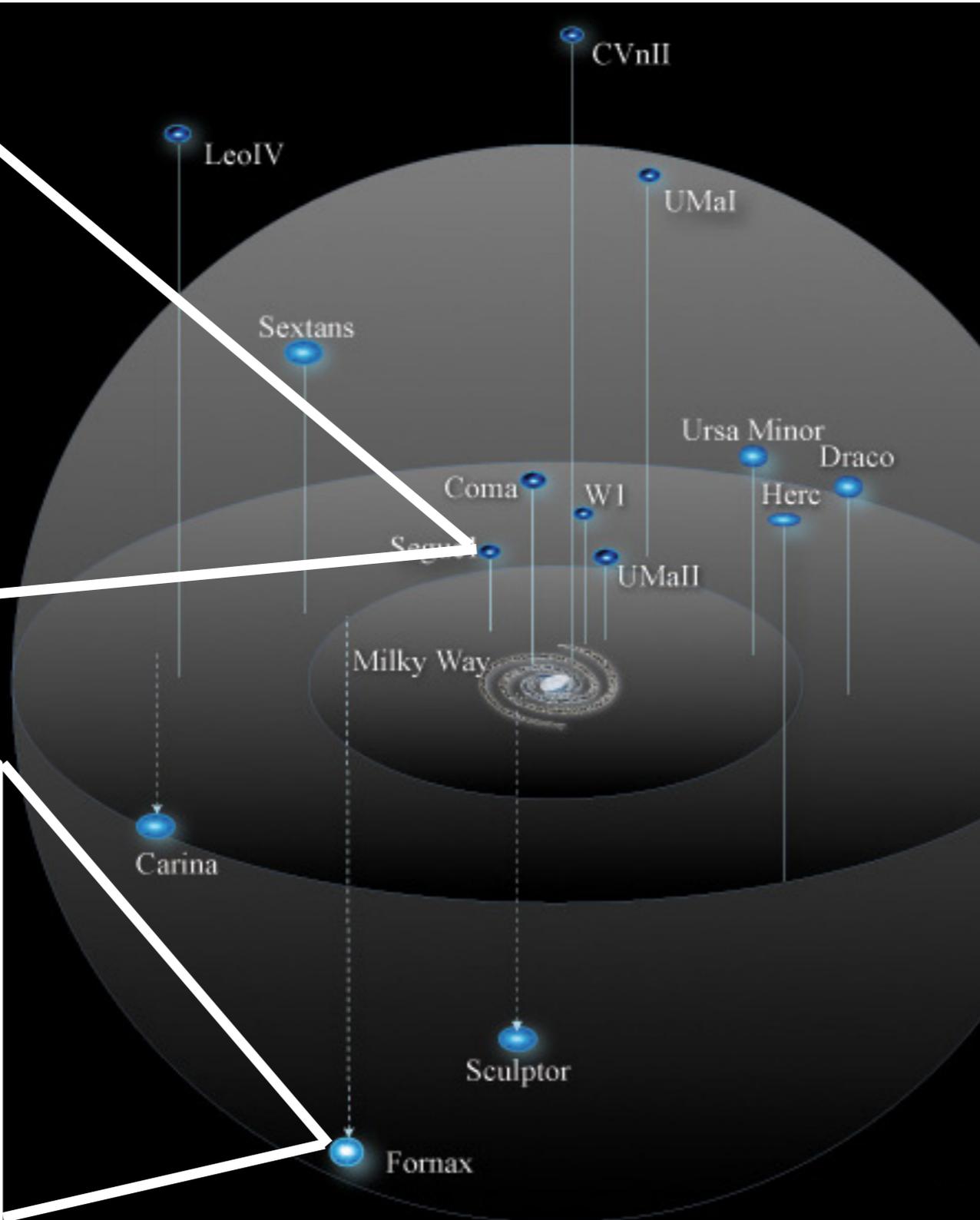
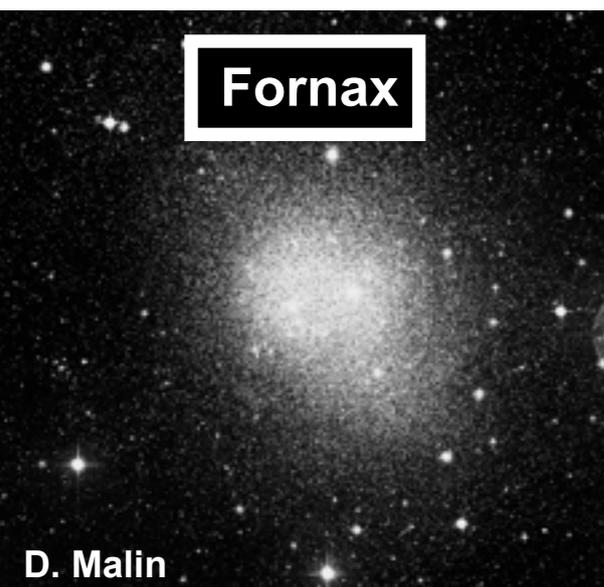
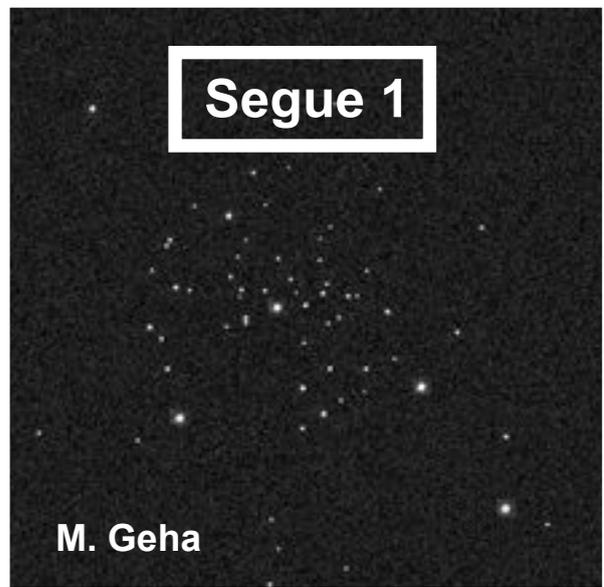
Alex Drlica-Wagner
on behalf of the DES Collaboration

WH7SW

Fermilab Wine & Cheese
April 24, 2015



Milky Way Satellite Galaxies



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

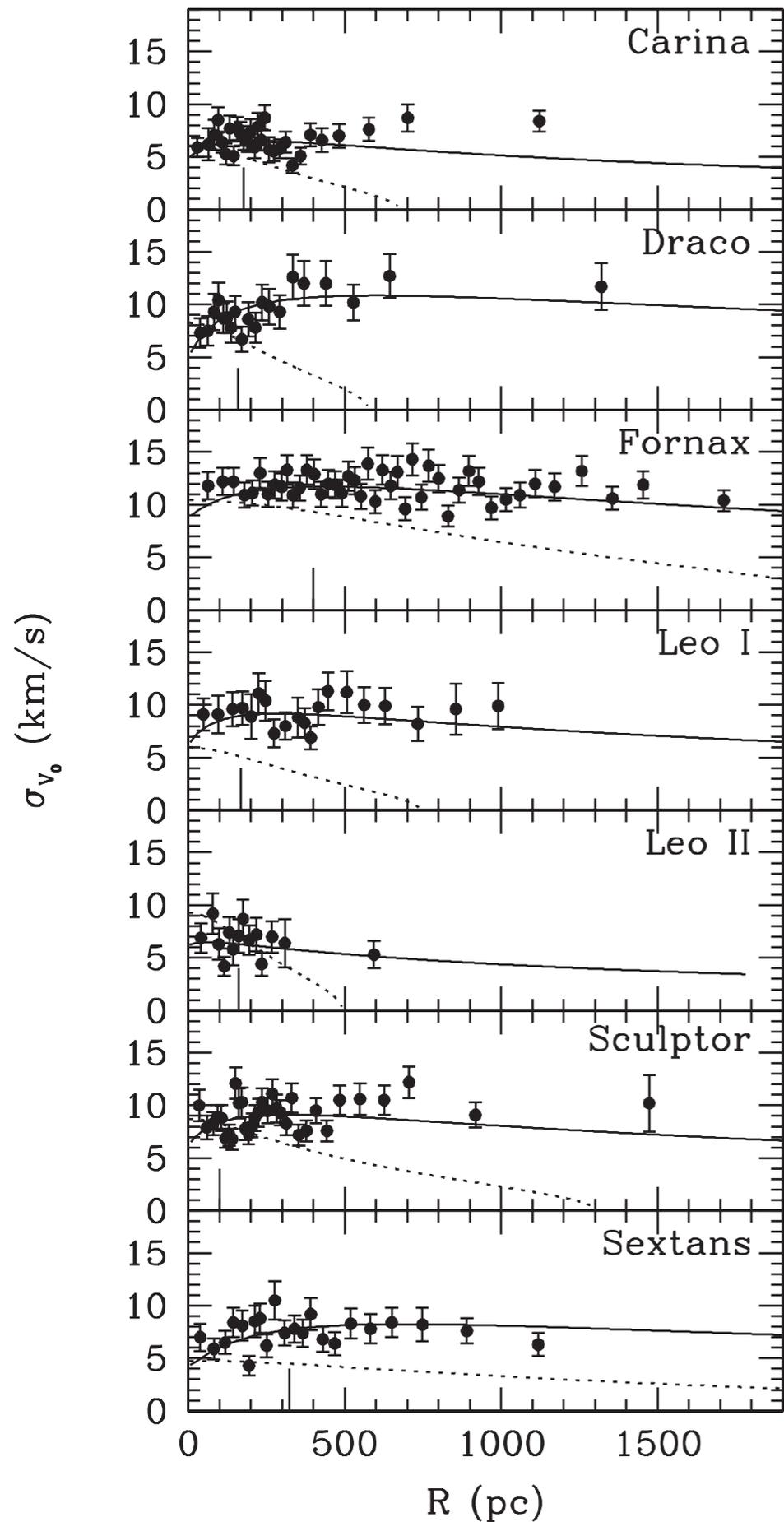
Most dark matter dominated objects known

Birth of near-field cosmology

30 kpc

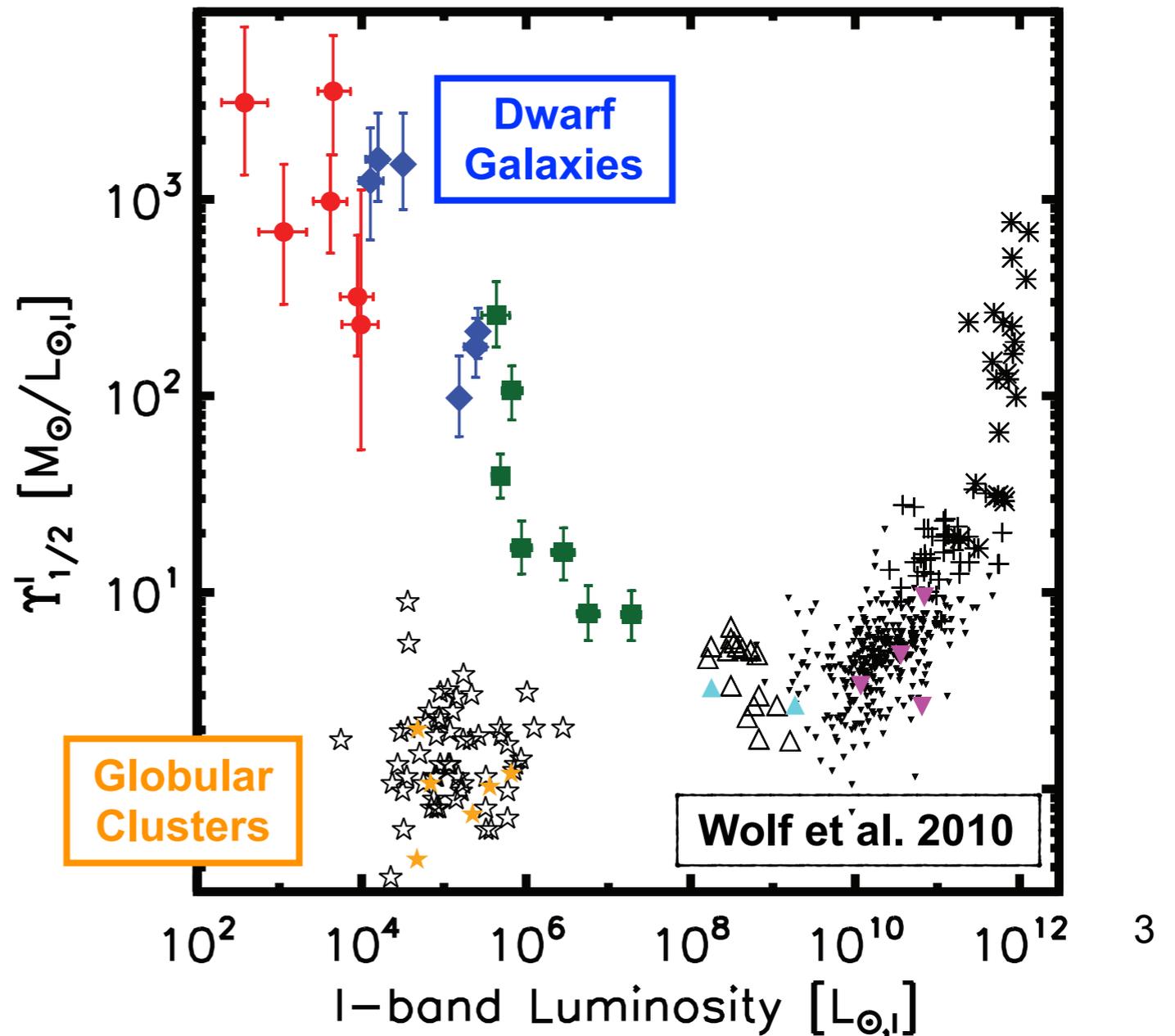
(Bullock, Geha, Powell)

Walker et al. 2007



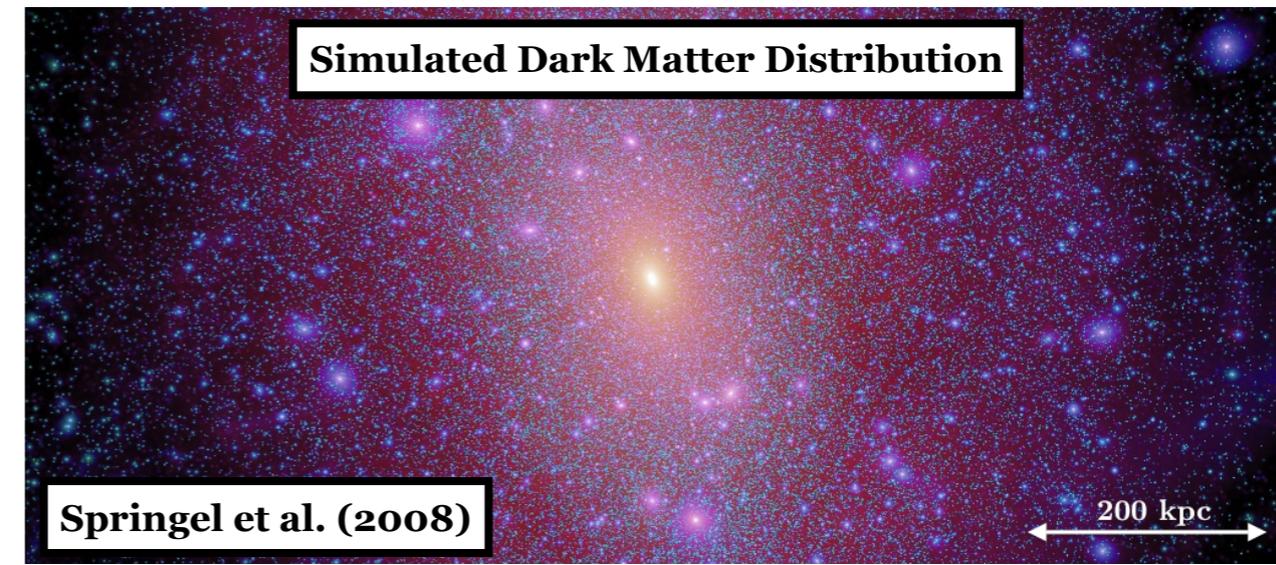
Dark Matter Dominated

The stars in dwarf galaxies are moving too fast to be explained by visible mass alone



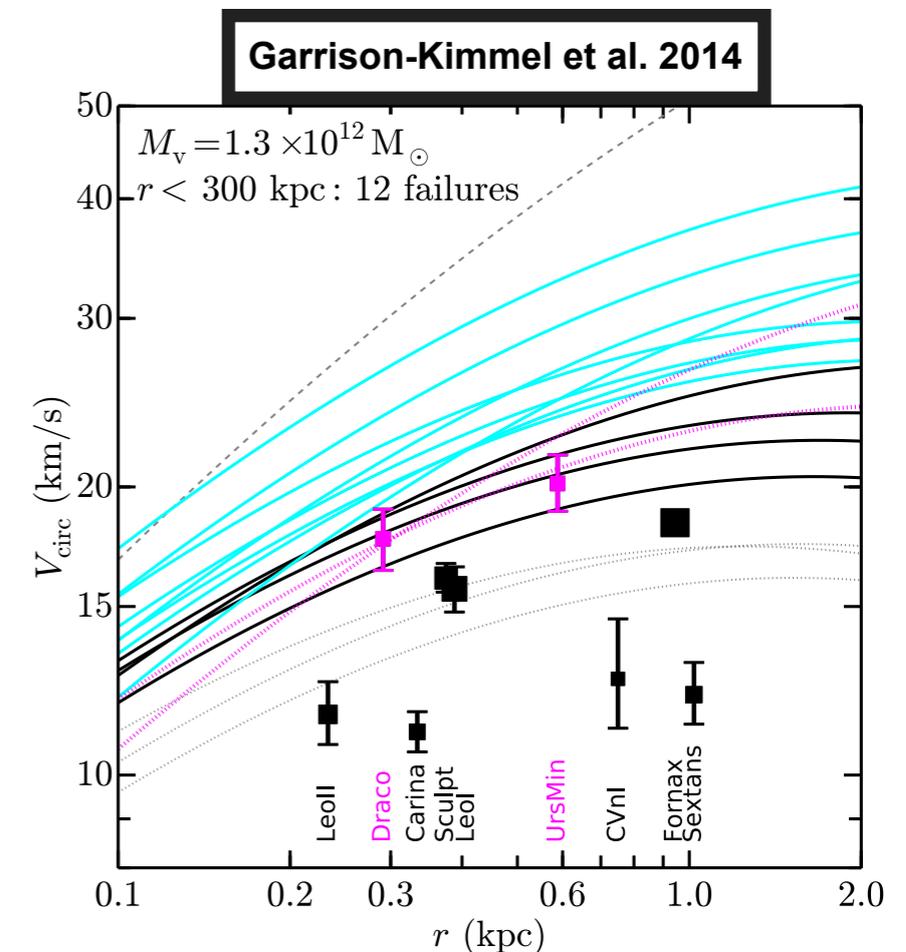
• Missing Satellites?

- CDM simulations predict thousands of dark matter substructures
- Only dozens of dwarf galaxies are found
- Tension reduced by better characterizing observational completeness and theoretical modeling of galaxy formation.



• Too big to fail?

- Expect dwarf galaxies to populate the most massive dark matter subhalos.
- Circular velocities of known dwarf galaxies are significantly smaller than predicted by simulations.
 - Baryonic effects in the cores of dwarf galaxies?
 - Warm dark matter? Self-interacting dark matter?



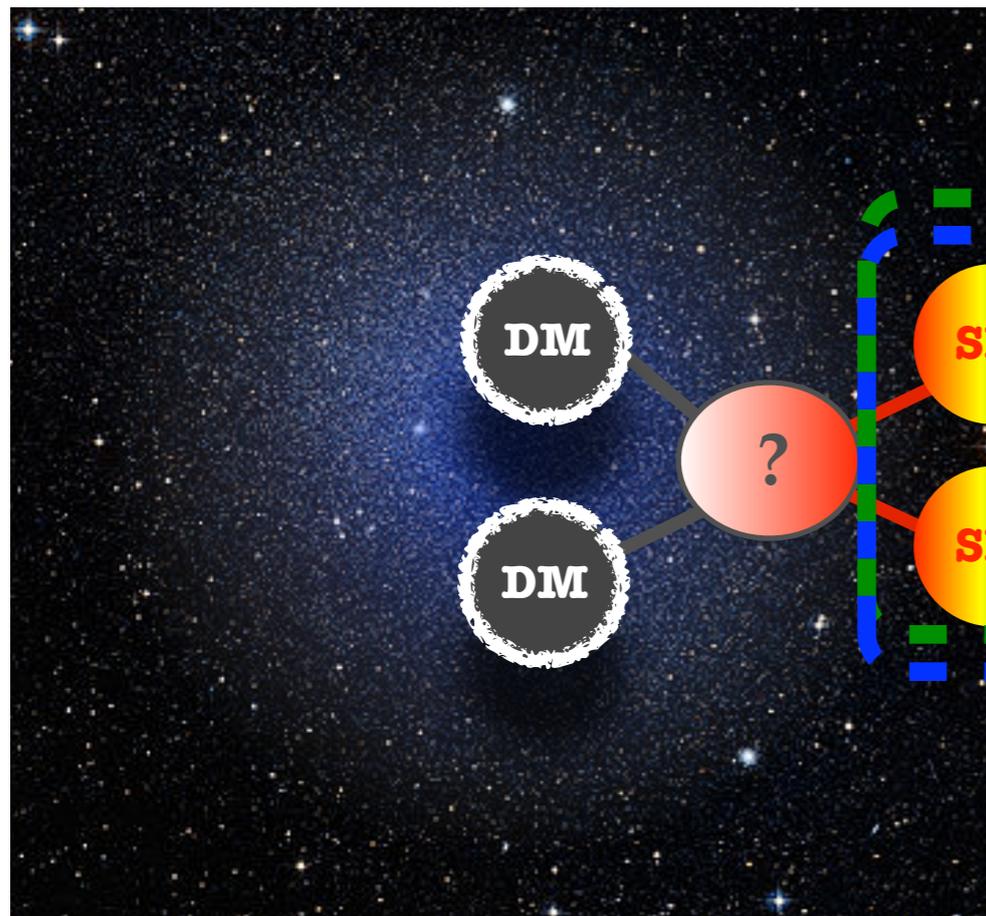
Indirect Detection of Dark Matter Annihilation

Dark Matter Distribution

Particle Propagation

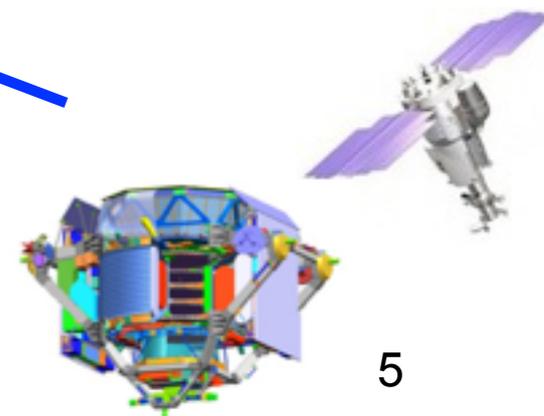
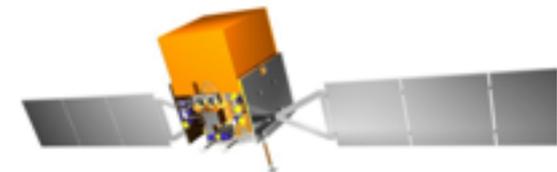
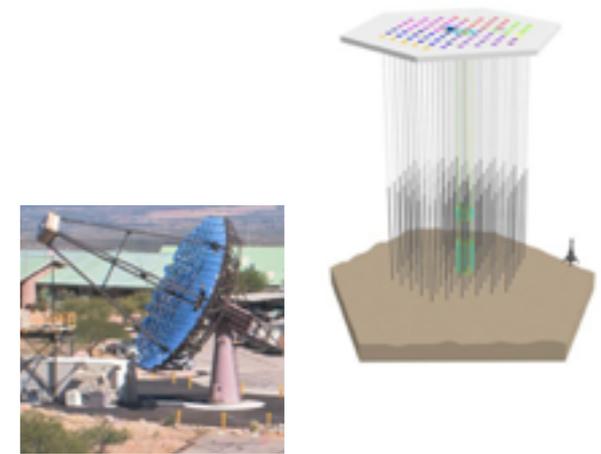
Particle Detection

Dark Matter Annihilation



Neutral Particles
(γ, ν)

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



Finding Milky Way Satellite Galaxies



Finding Milky Way Satellite Galaxies

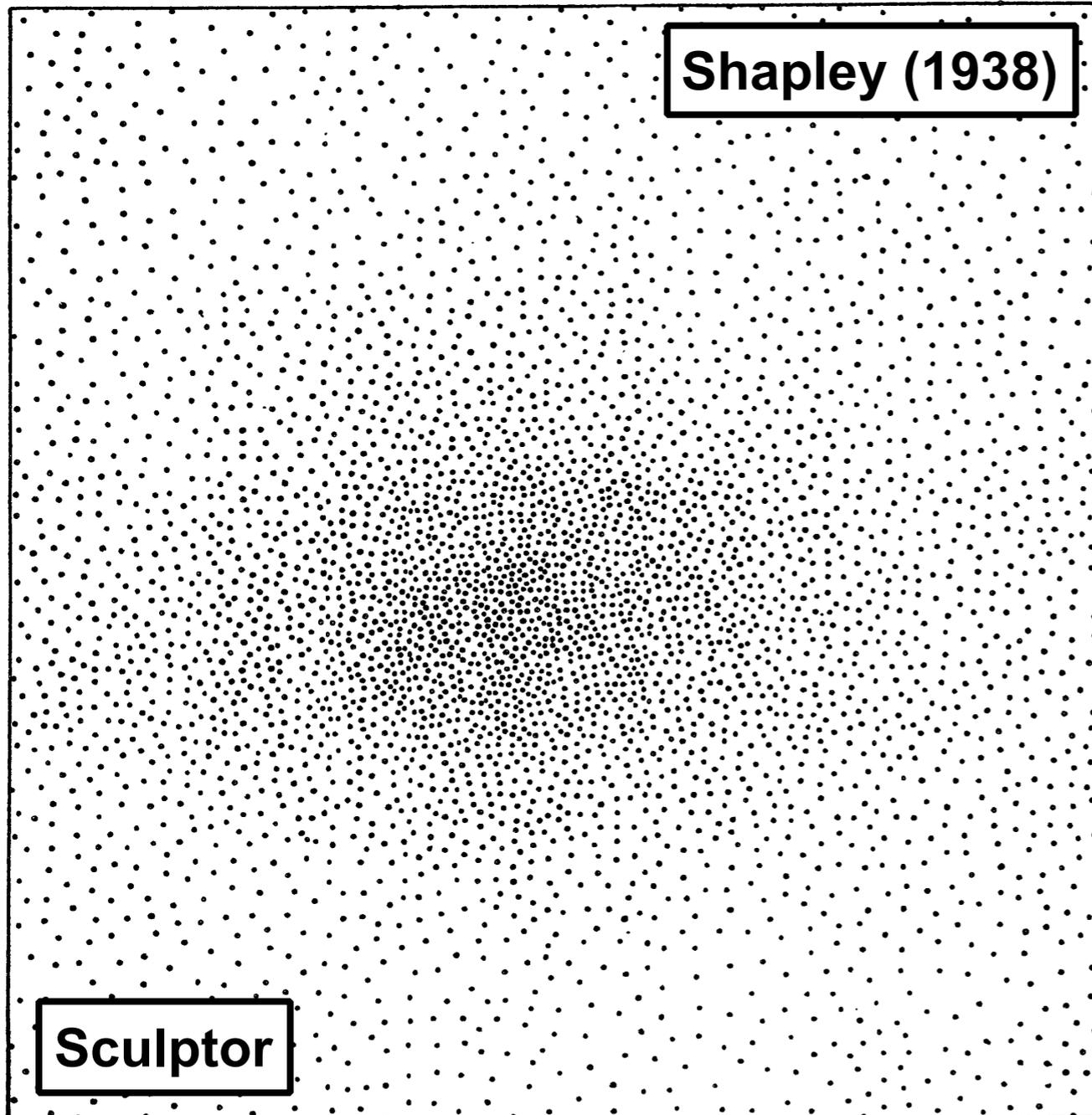


FIGURE 2.— DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

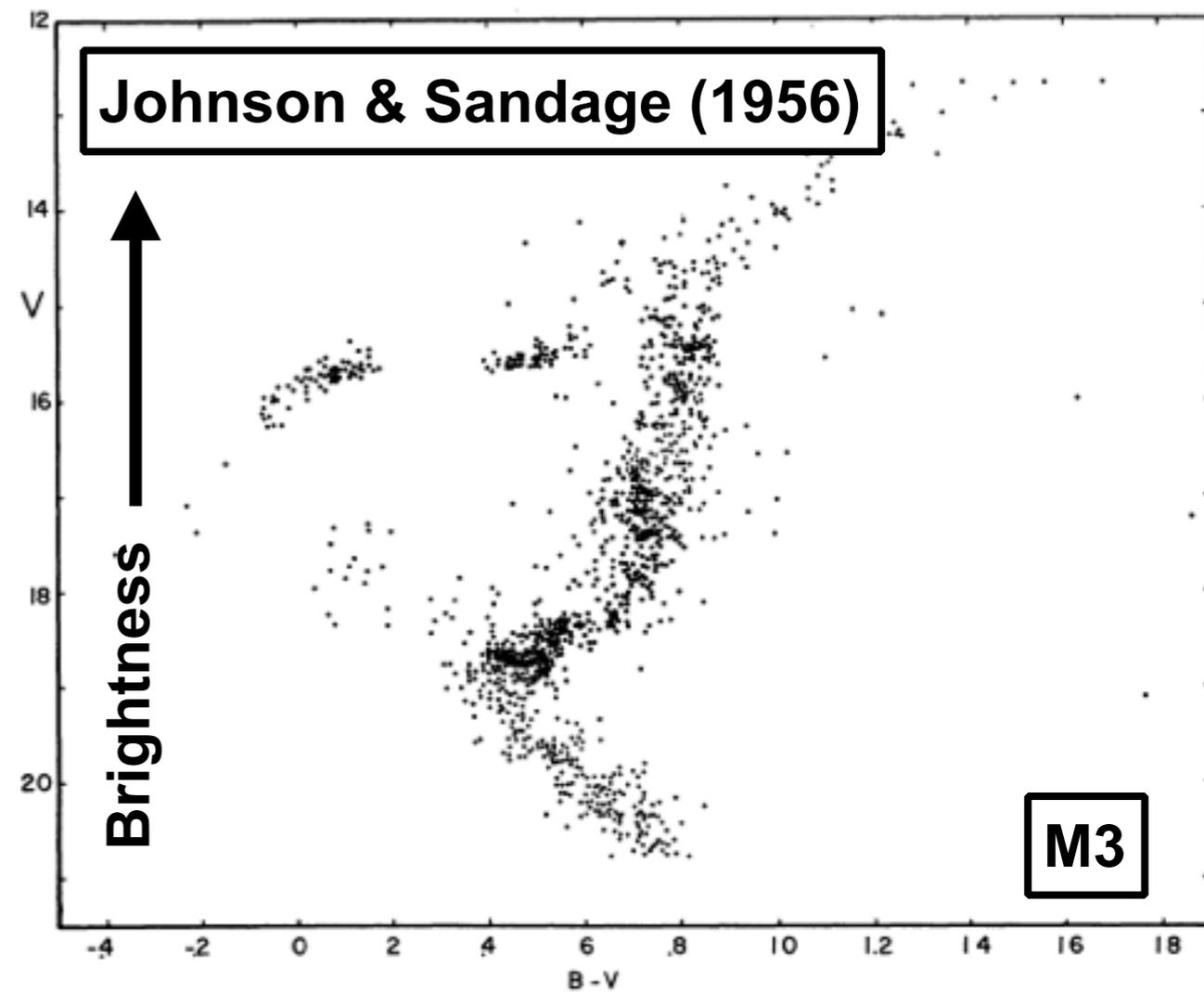
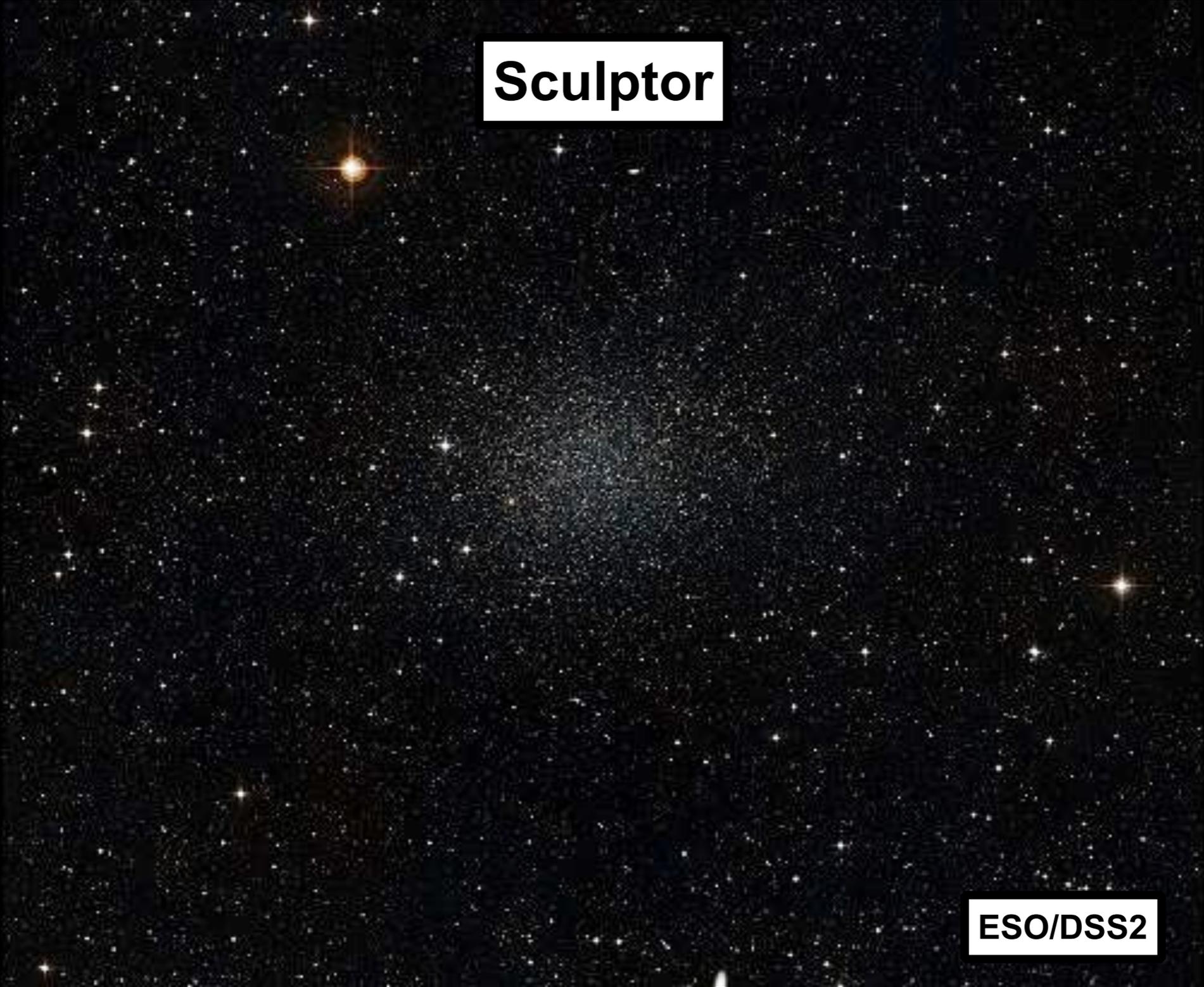


FIG. 5.—Color-magnitude diagram for M3 stars in the arguments V and $B - V$

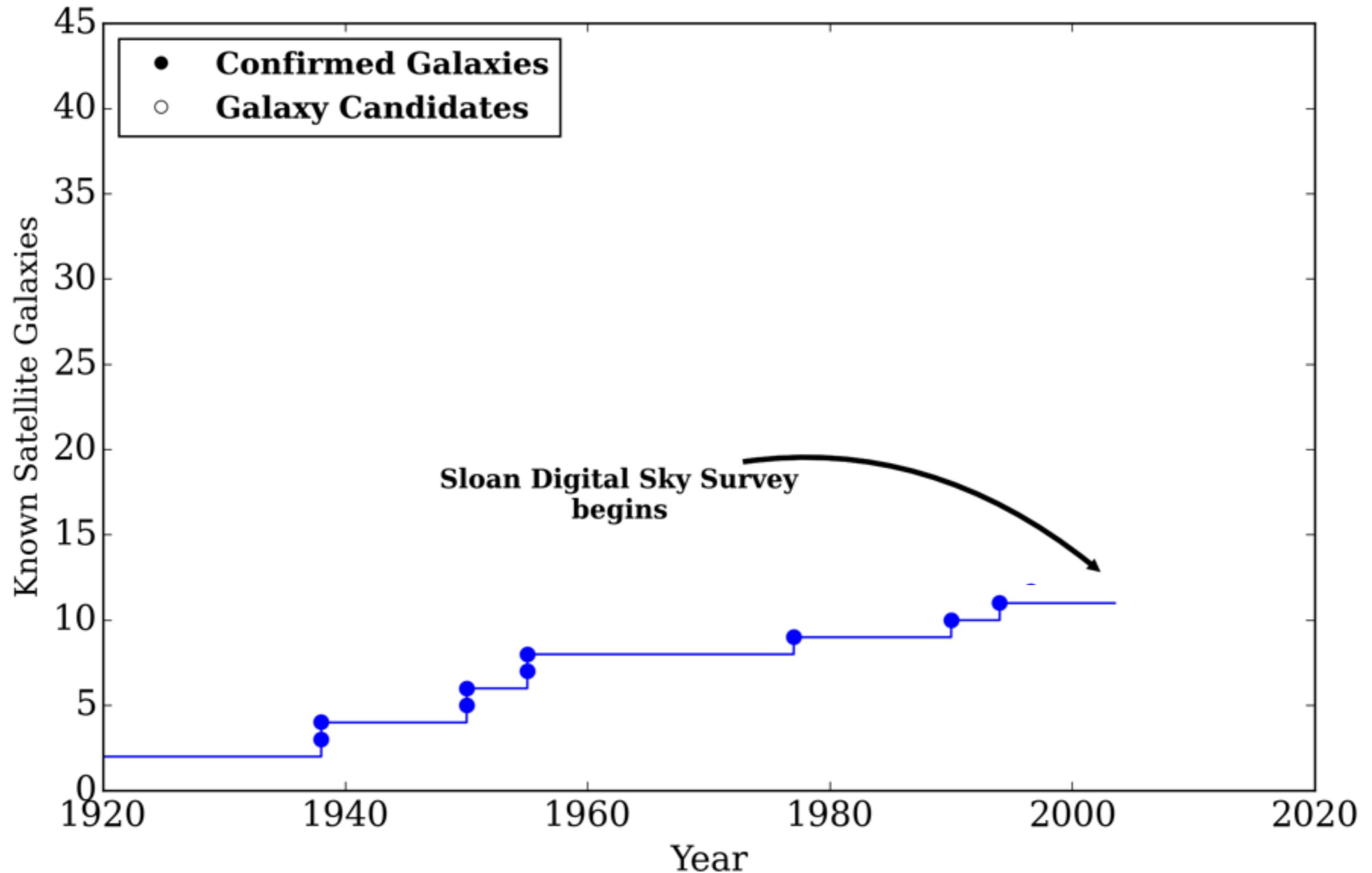
“Redness” →



Sculptor

ESO/DSS2

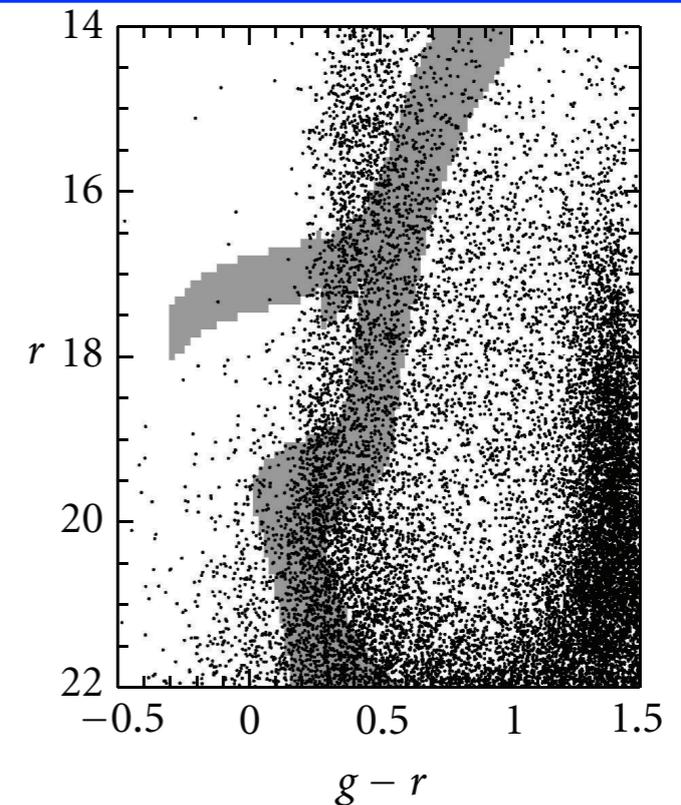
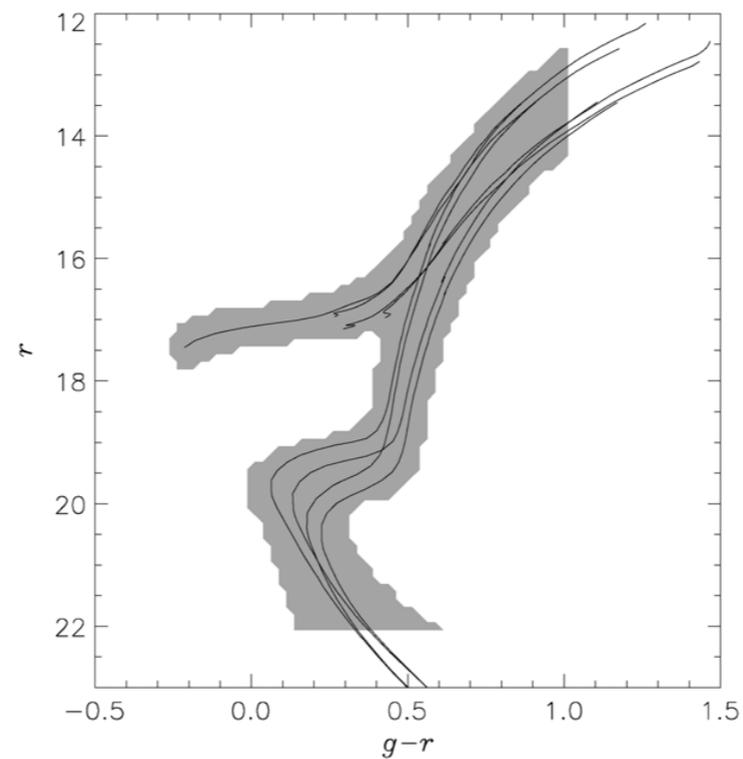
Milky Way Satellite Galaxies Discovery Timeline



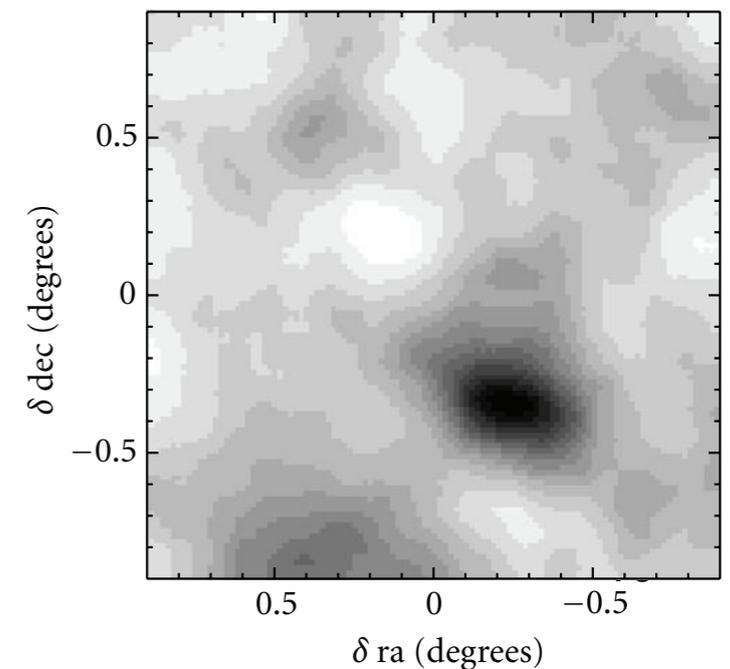
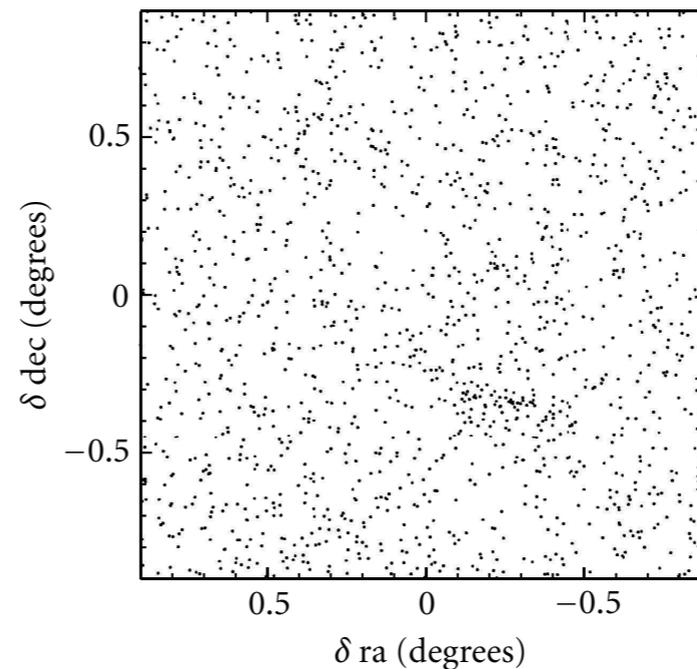
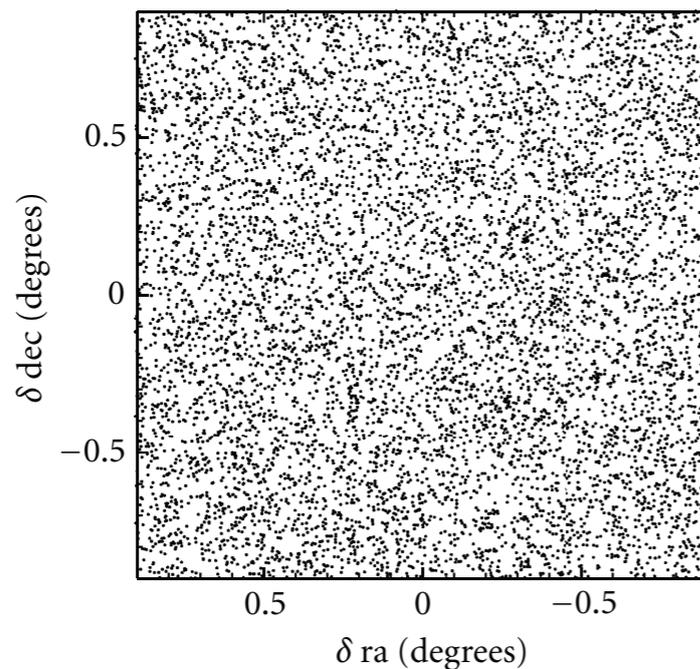
Finding Milky Way Satellite Galaxies

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

Color-Magnitude
Domain



Spatial
Domain



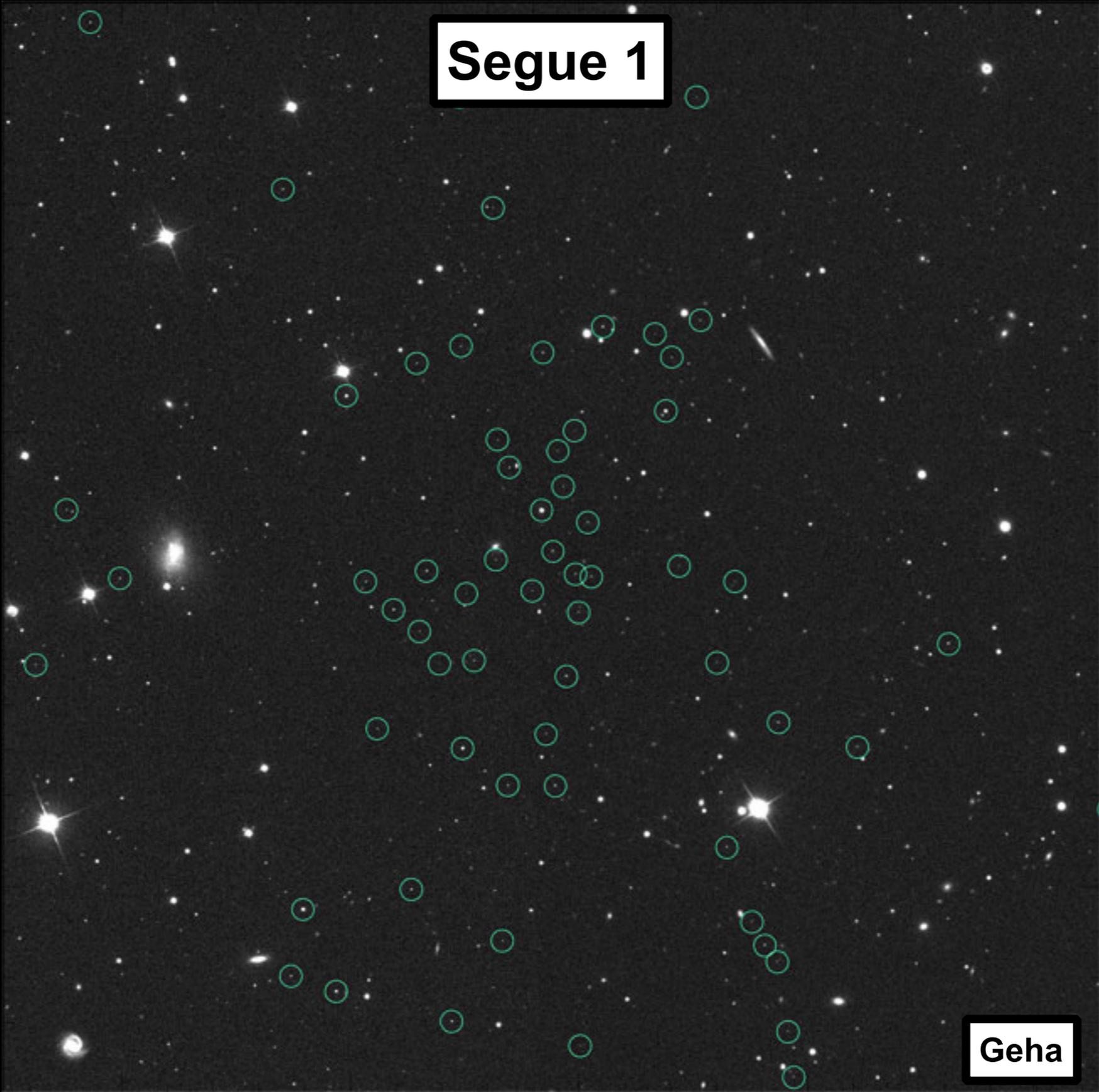
Segue 1

Geha

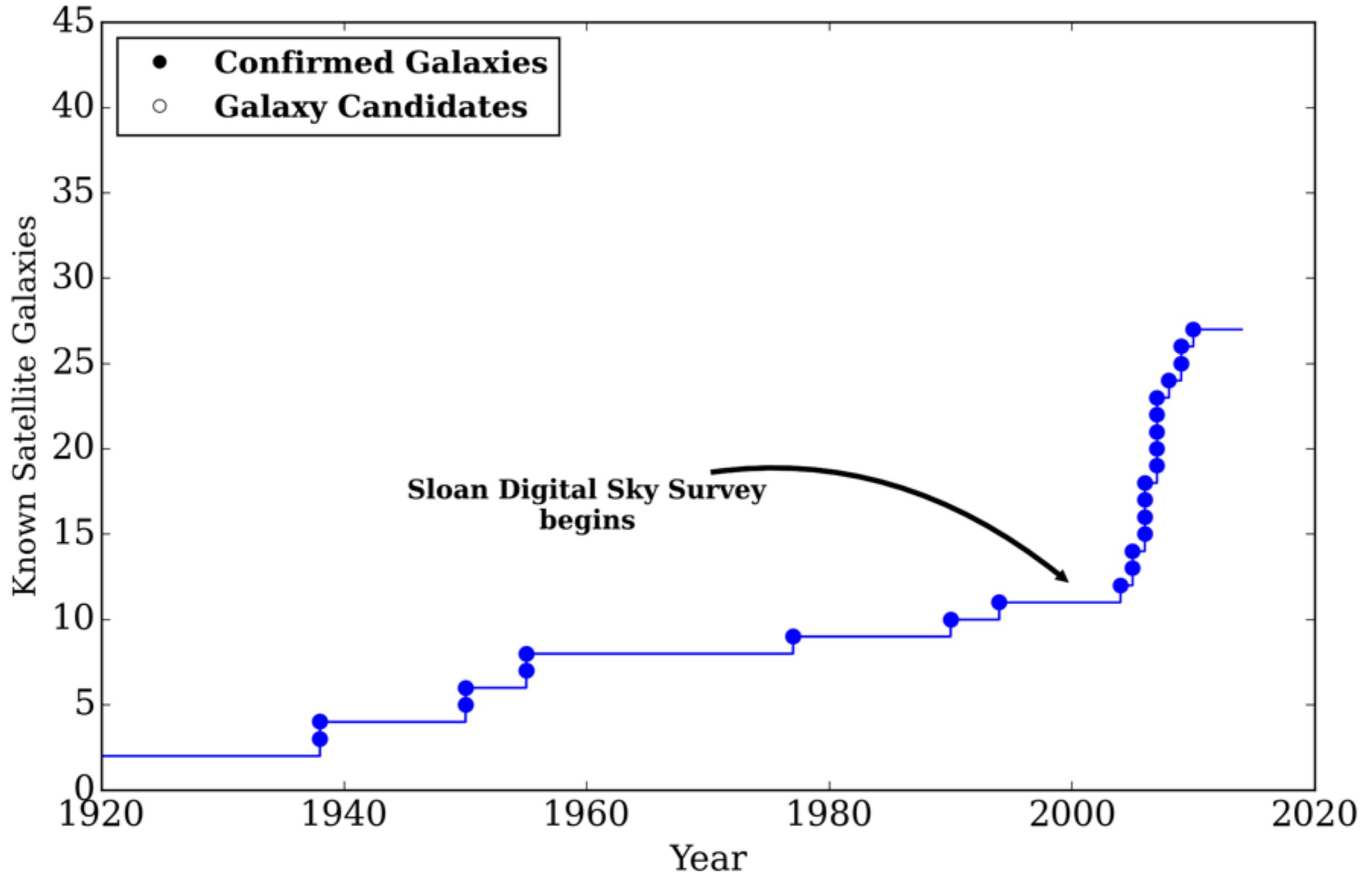


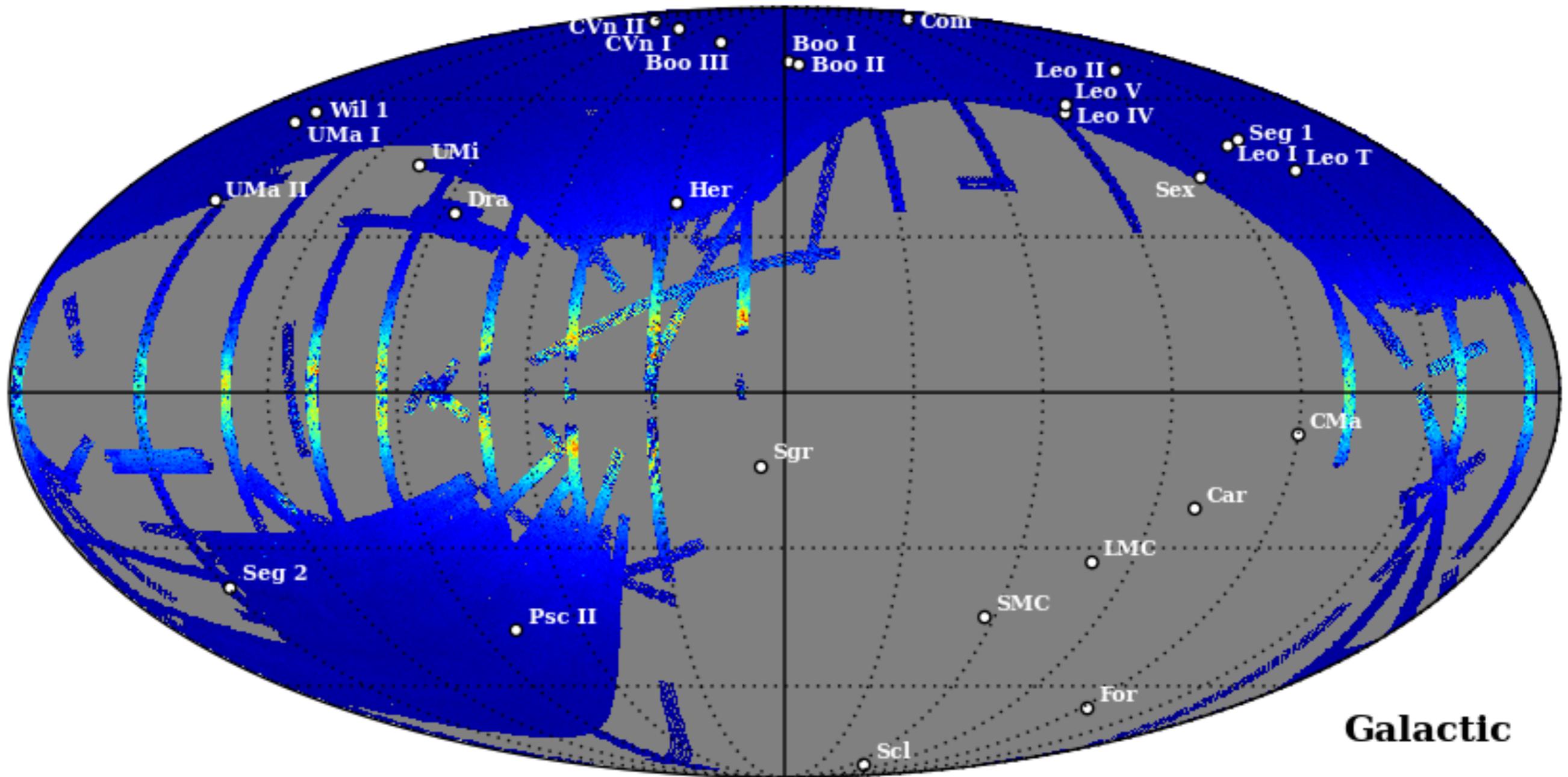
Segue 1

Geha

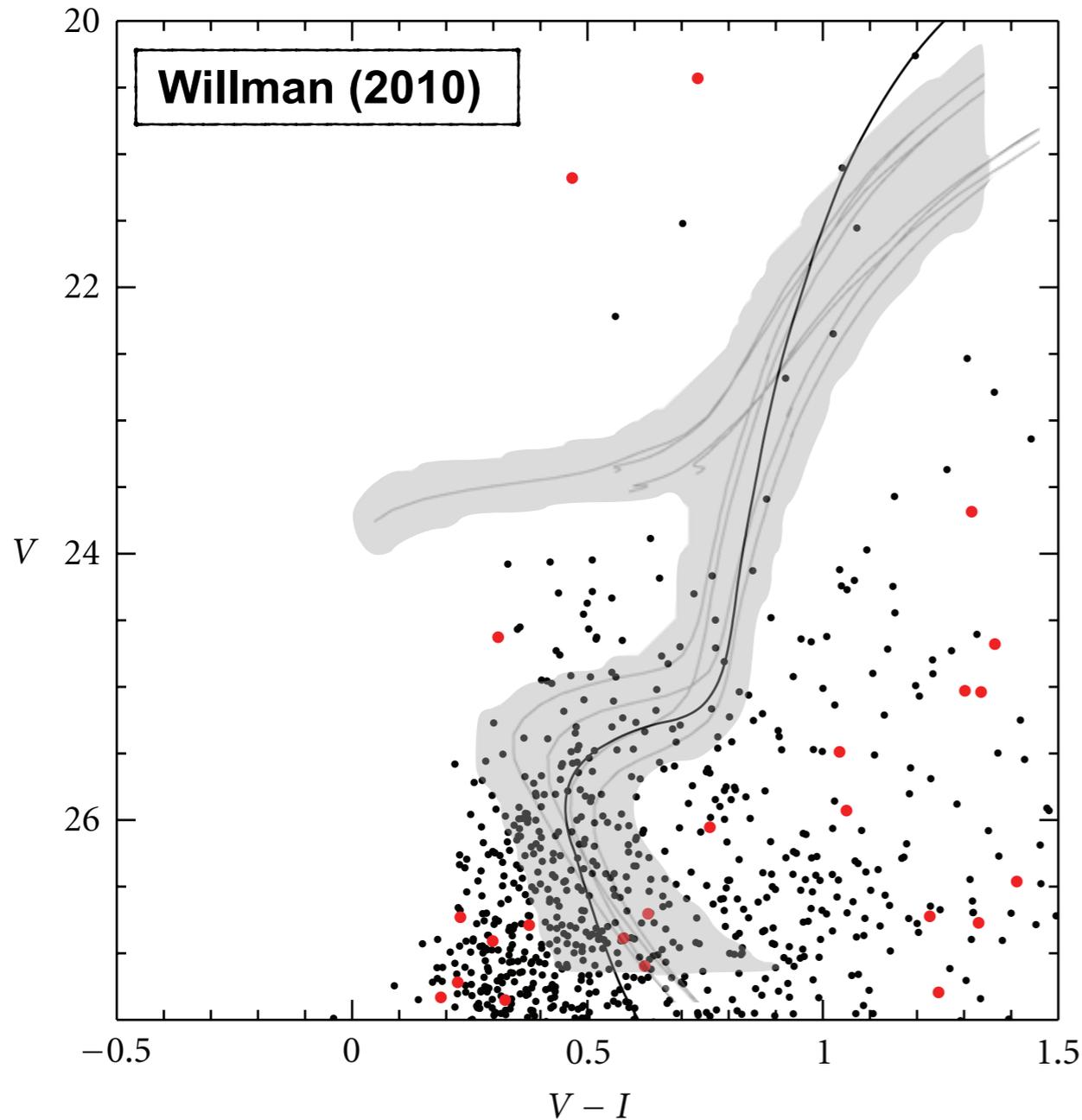


Milky Way Satellite Galaxies Discovery Timeline





Upcoming Challenges



Galaxy more abundant than stars a faint magnitudes.

Require better star-galaxy separation

More sensitive and robust search techniques

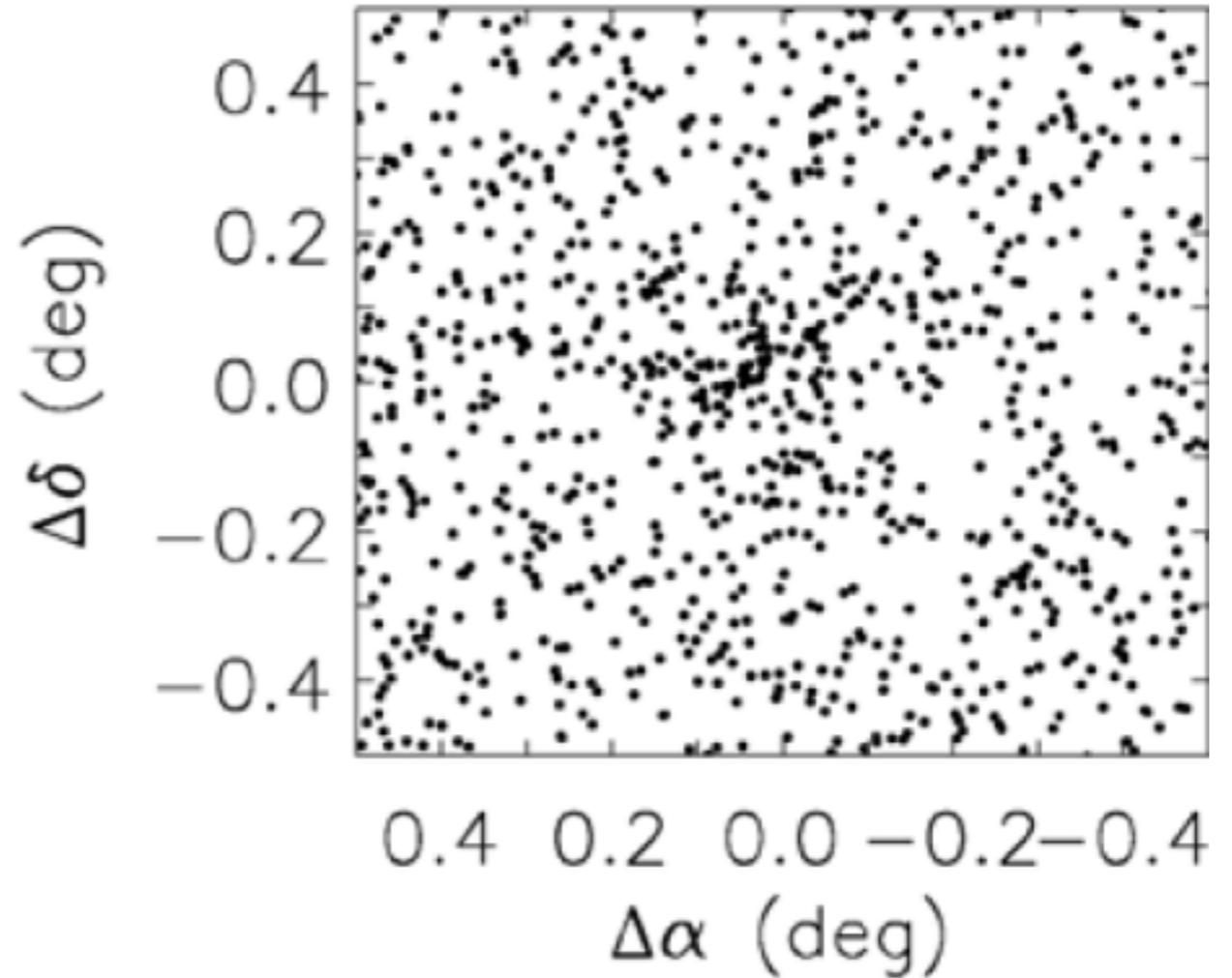
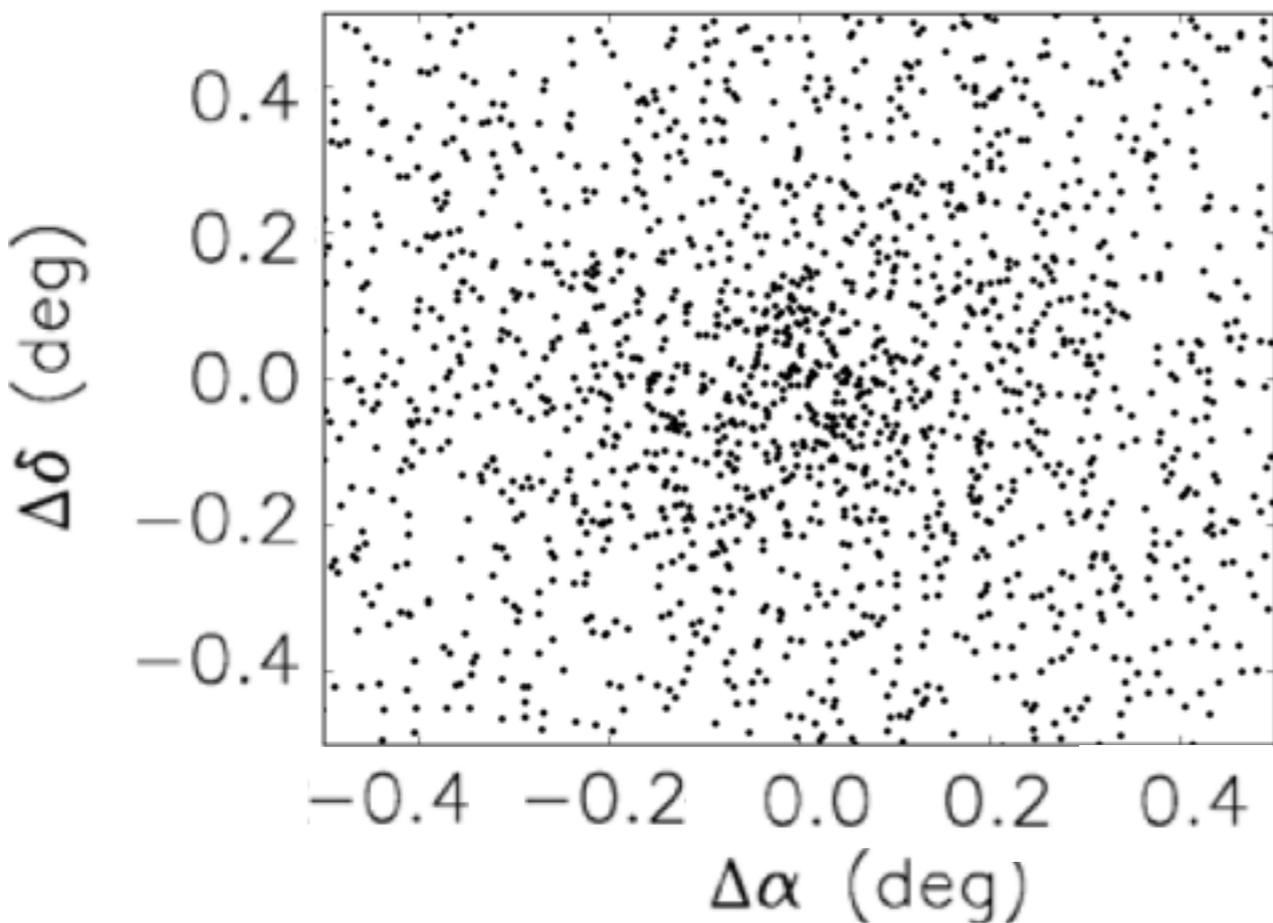
Small, well characterized signal in a strong, structured background.

— Dotter theoretical isochrone 300 kpc, 10 Gyr, $[Fe/H] = -2$

• Stellar sources in the HUDF

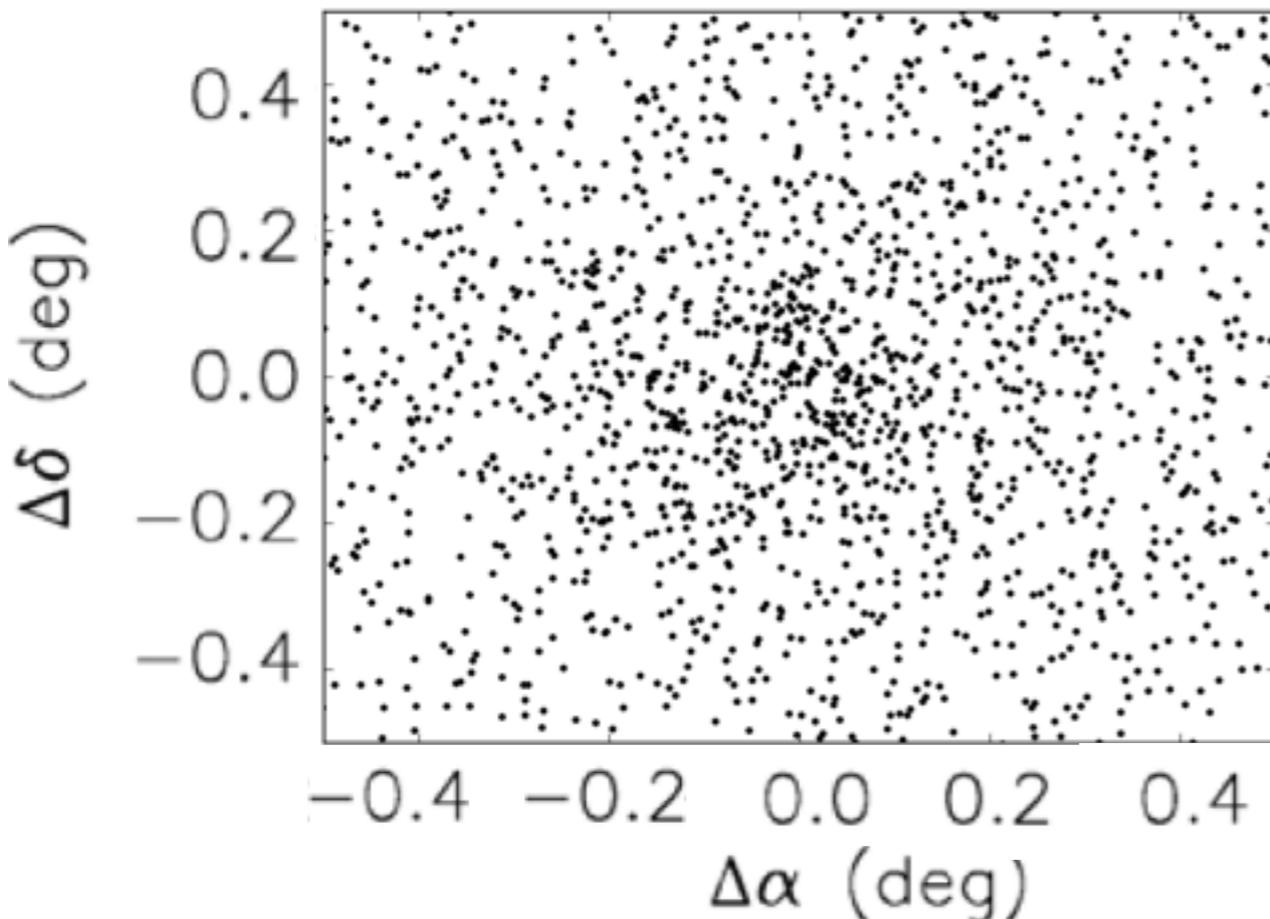
• Galaxies with $fwhm < 0.8$ arcsec in the HUDF

A Familiar Problem

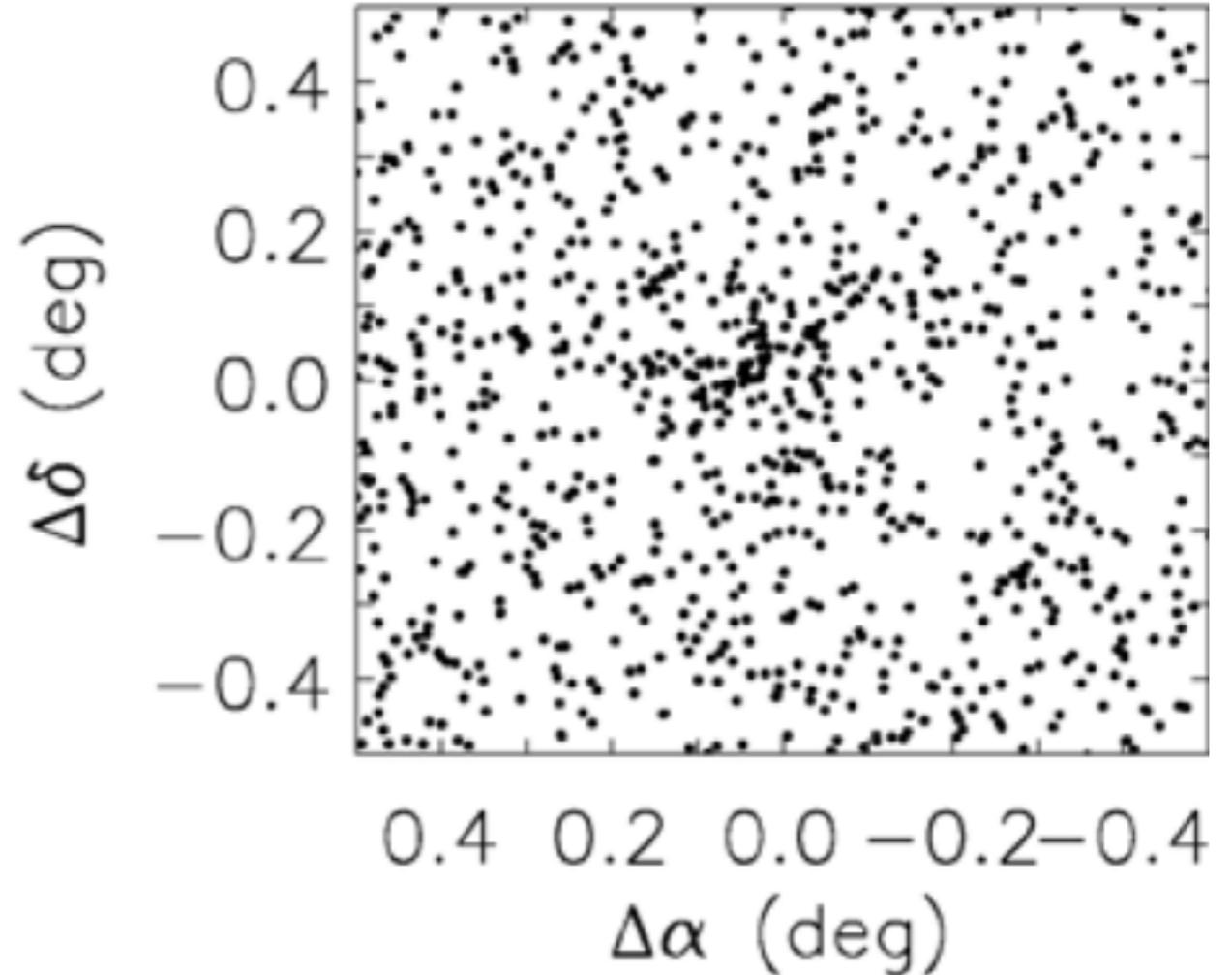


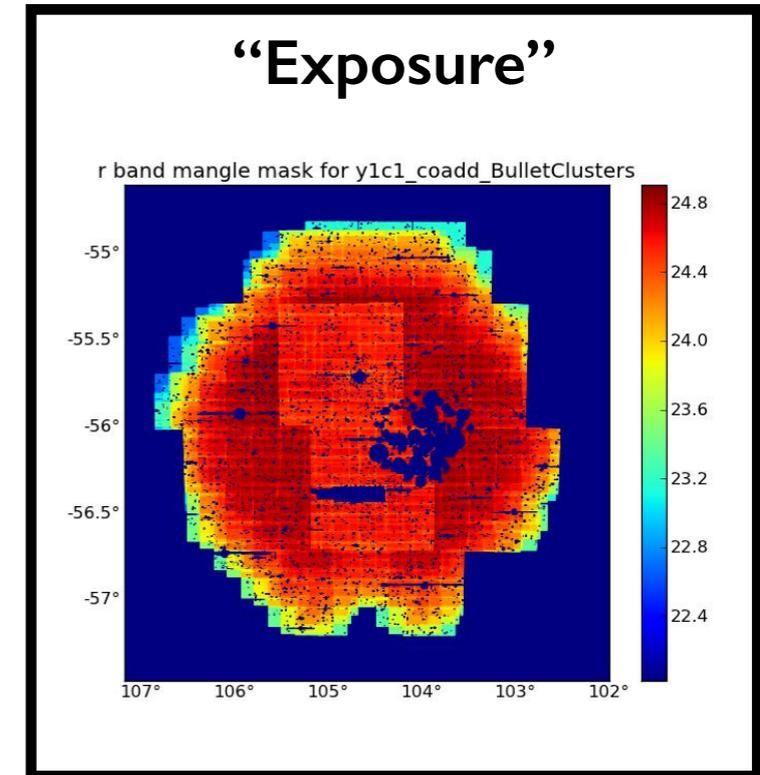
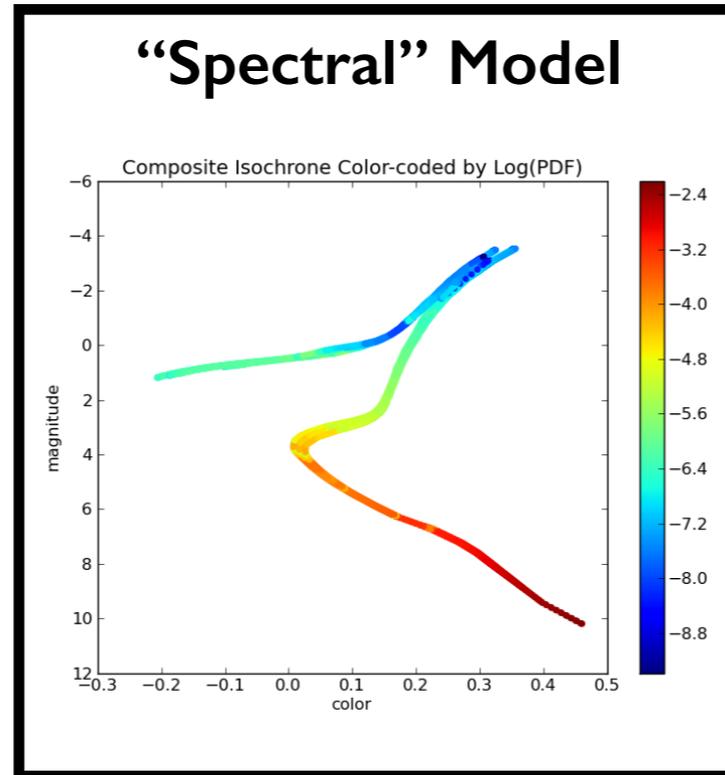
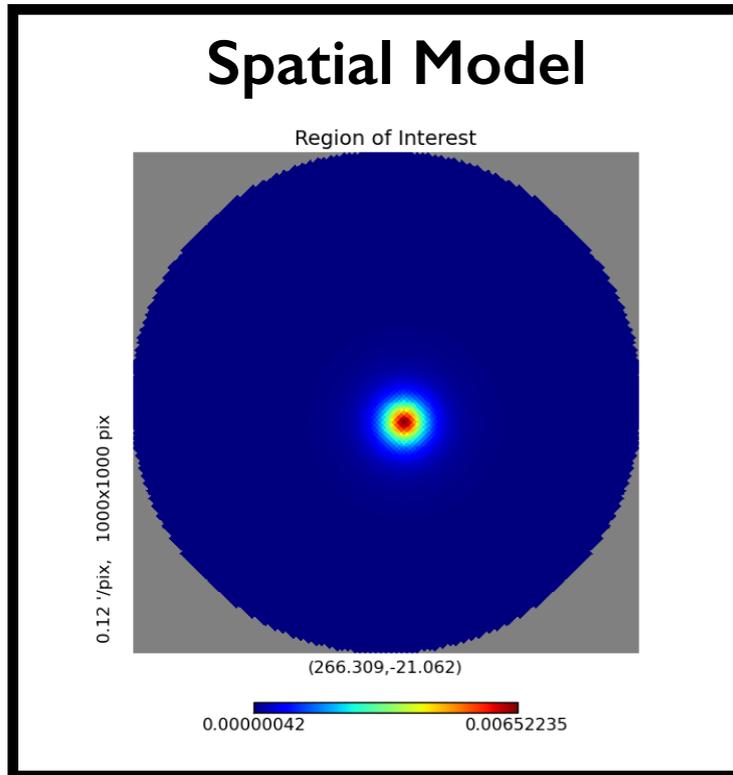
A Familiar Problem

**Gamma-ray Source
(4C+21.35)**



**Dwarf Galaxy
(Coma Berenices)**



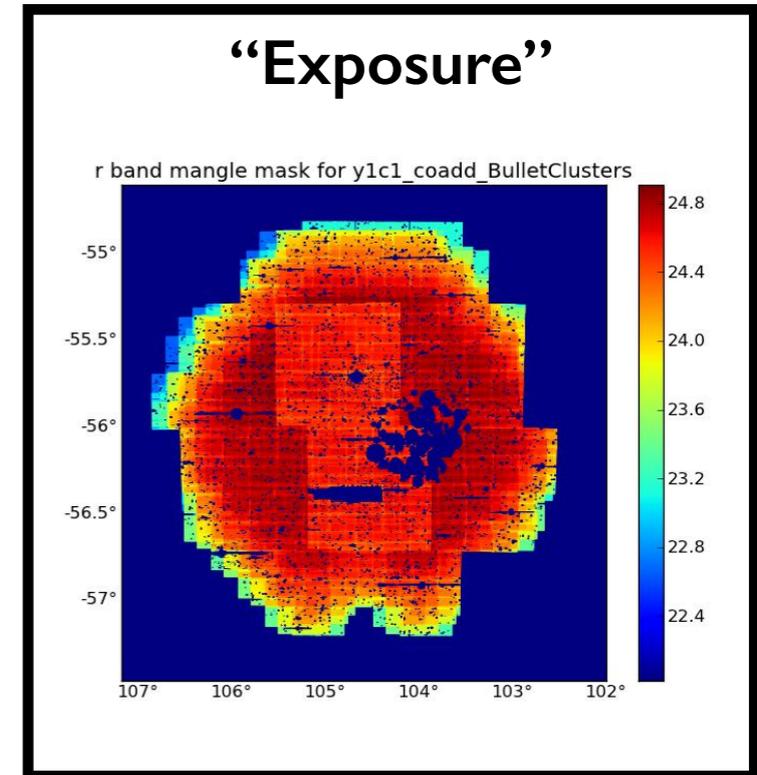
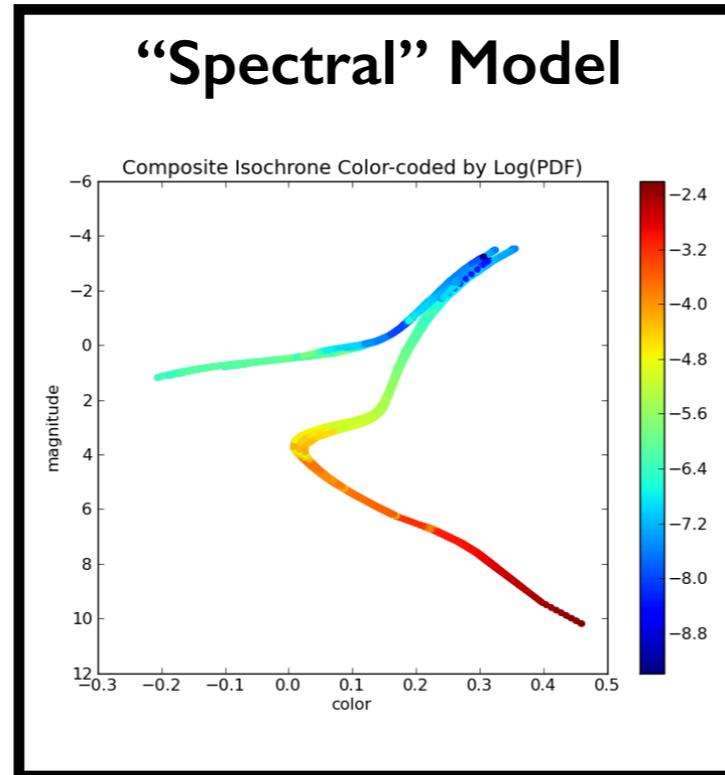
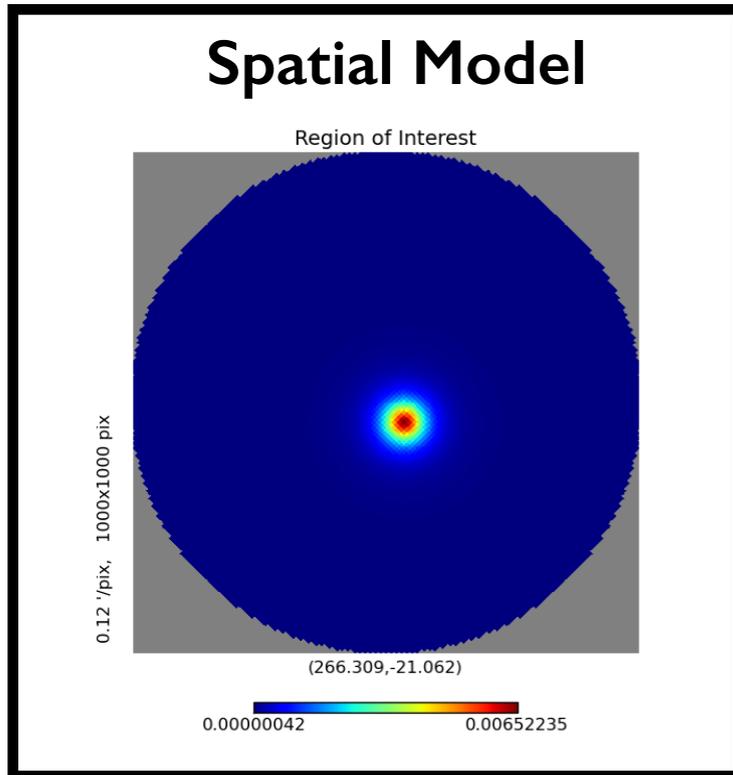


Membership Probability: $p_i = \frac{\lambda u_i}{\lambda u_i + b_i}$ ($u_i = \text{sig prob}, b_i = \text{bkg prob}$)

Richness: $\lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i$ ($\lambda = \text{normalization} = \text{number of stars}$)
 ($f = \text{observable fraction}$)

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

Maximum Likelihood Analysis



Membership Probability:
$$p_i = \frac{\lambda u_i}{\lambda u_i + b_i}$$

Important for spectroscopic follow up observations

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

(λ = normalization = number of stars)
(f = observable fraction)

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

www.physicstoday.org

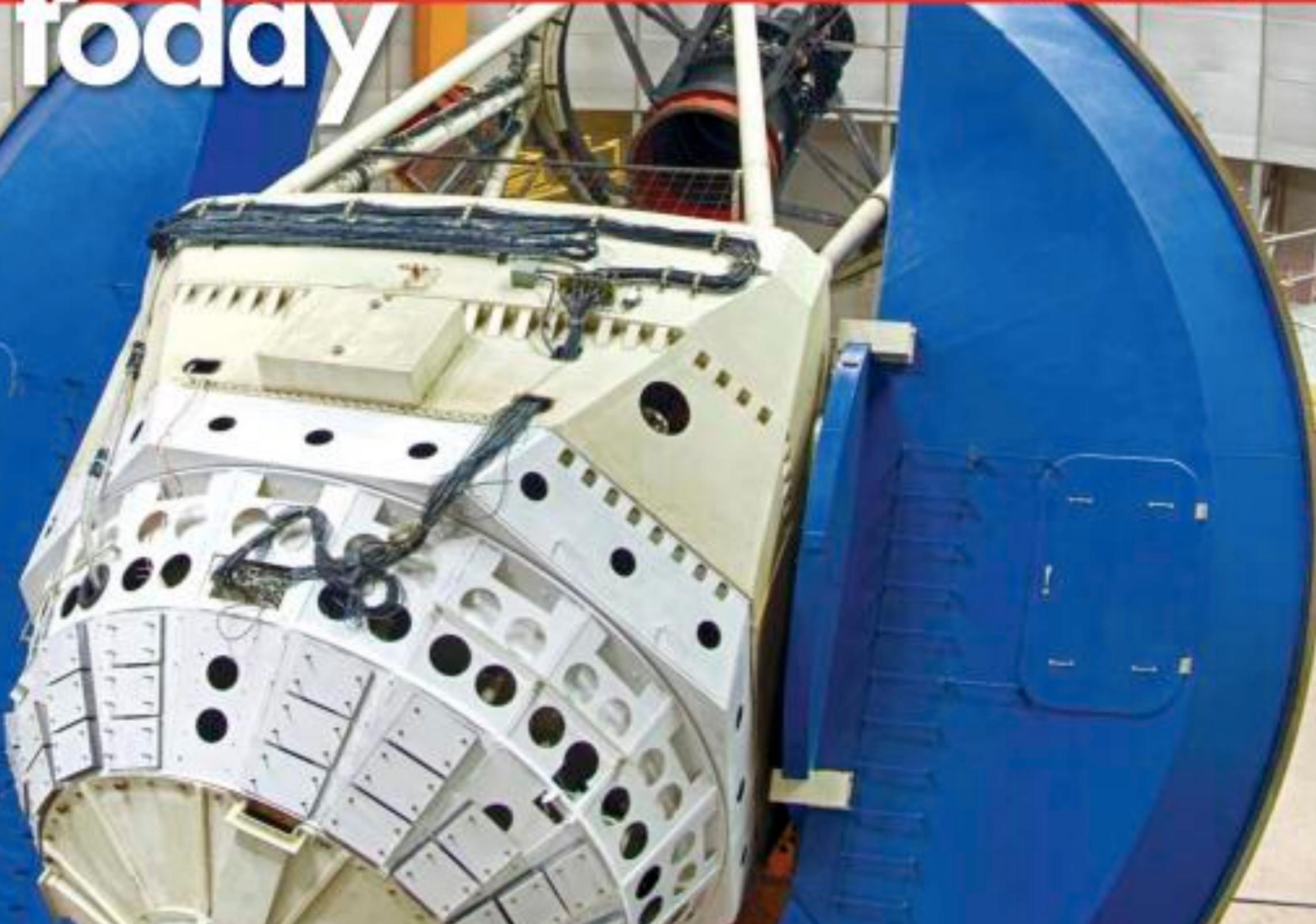
physics
today

April 2014

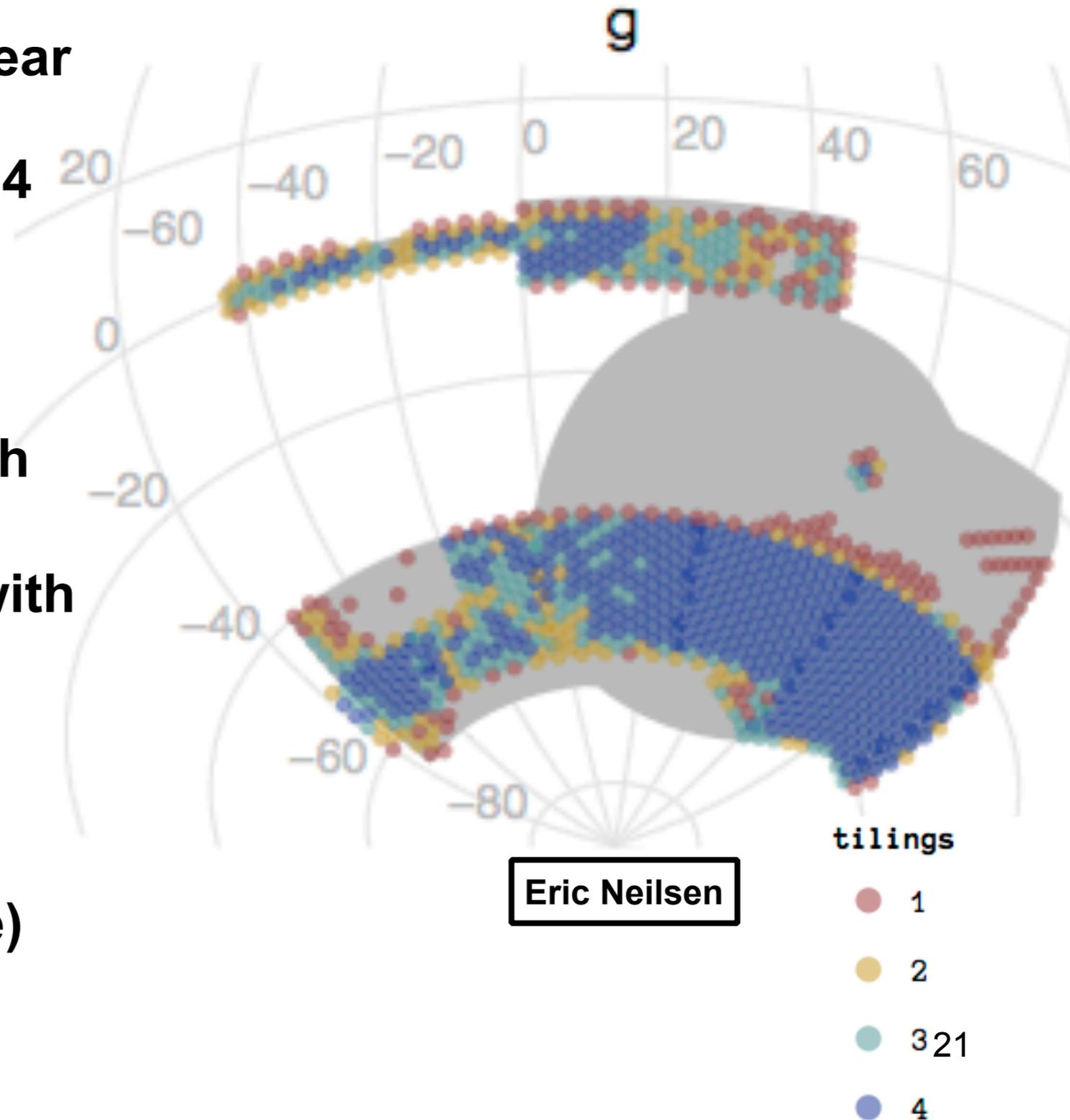
The Dark Energy Survey

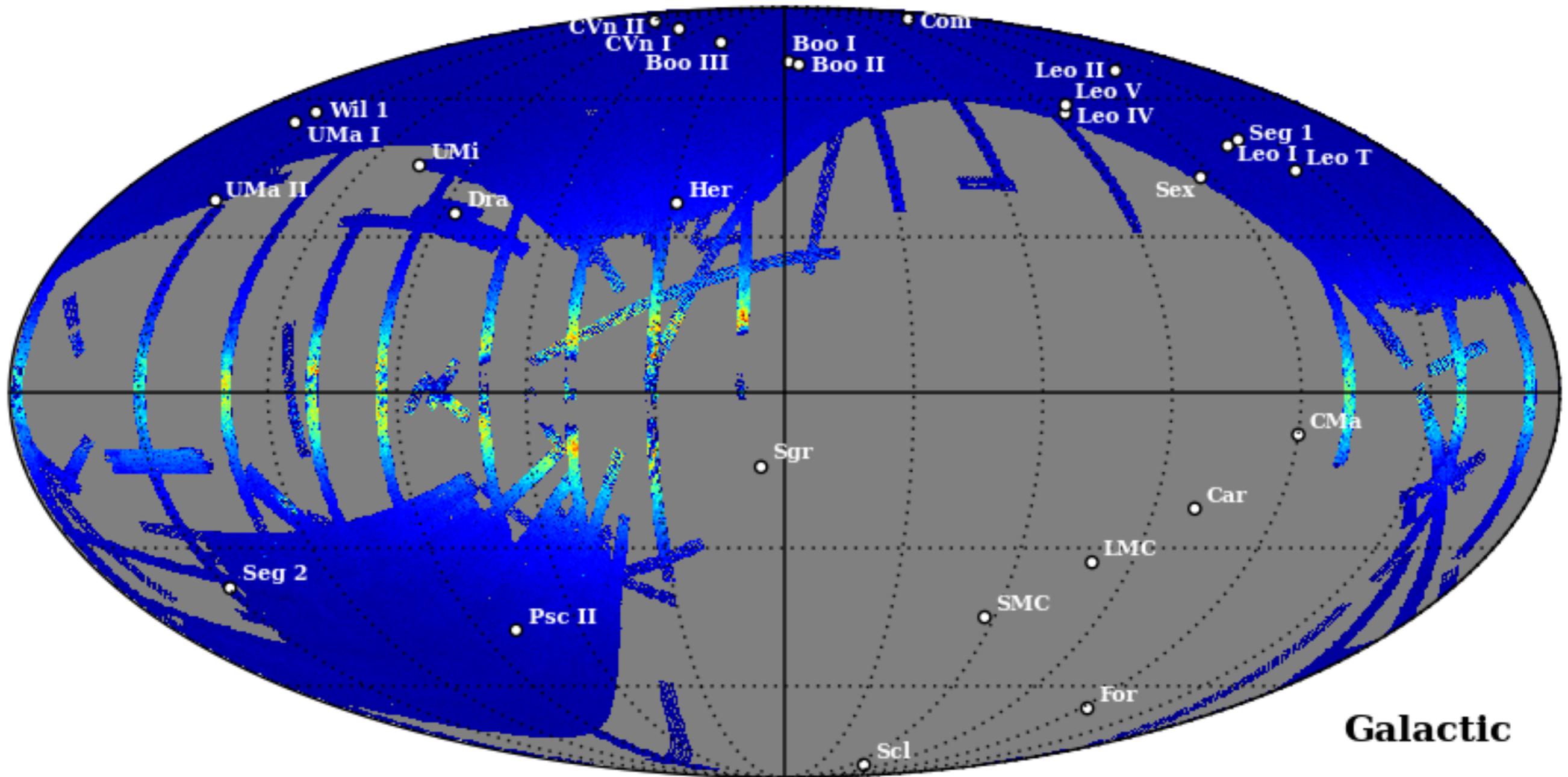
A publication of the American Institute of Physics

volume 67, number 4

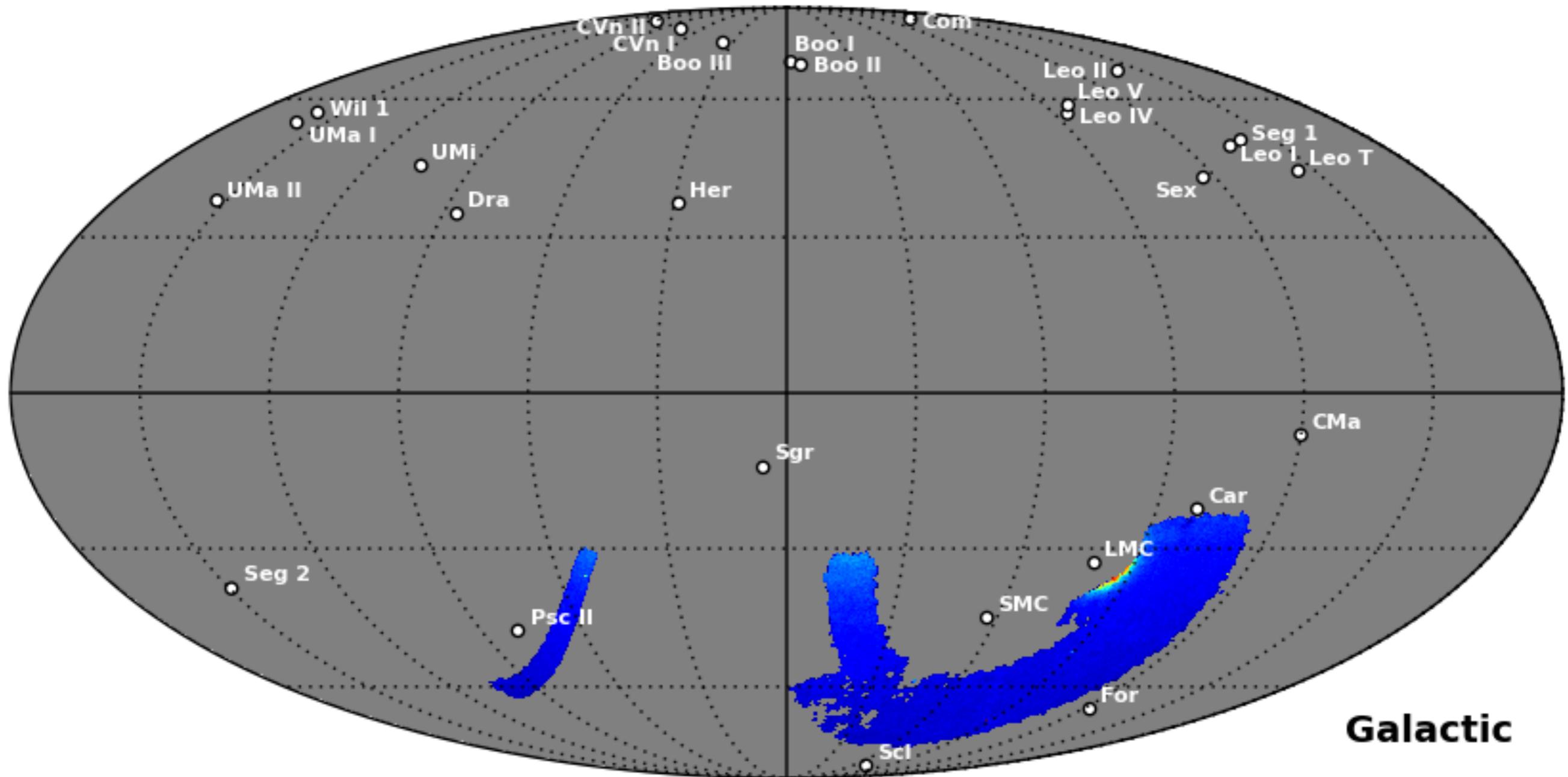


- Imaging data from the first year of the survey:
August 2013 to February 2014
- ~12,000 science exposures
- Coadded image catalog covering ~1800 deg²
 - ~200 deg² overlapping with SDSS Stripe-82
 - ~1600 deg² overlapping with the South Pole Telescope
- Stellar completeness >50% down to $g, r \sim 23$
- Calibration uncertainty:
2% (relative), 0.5% (absolute)

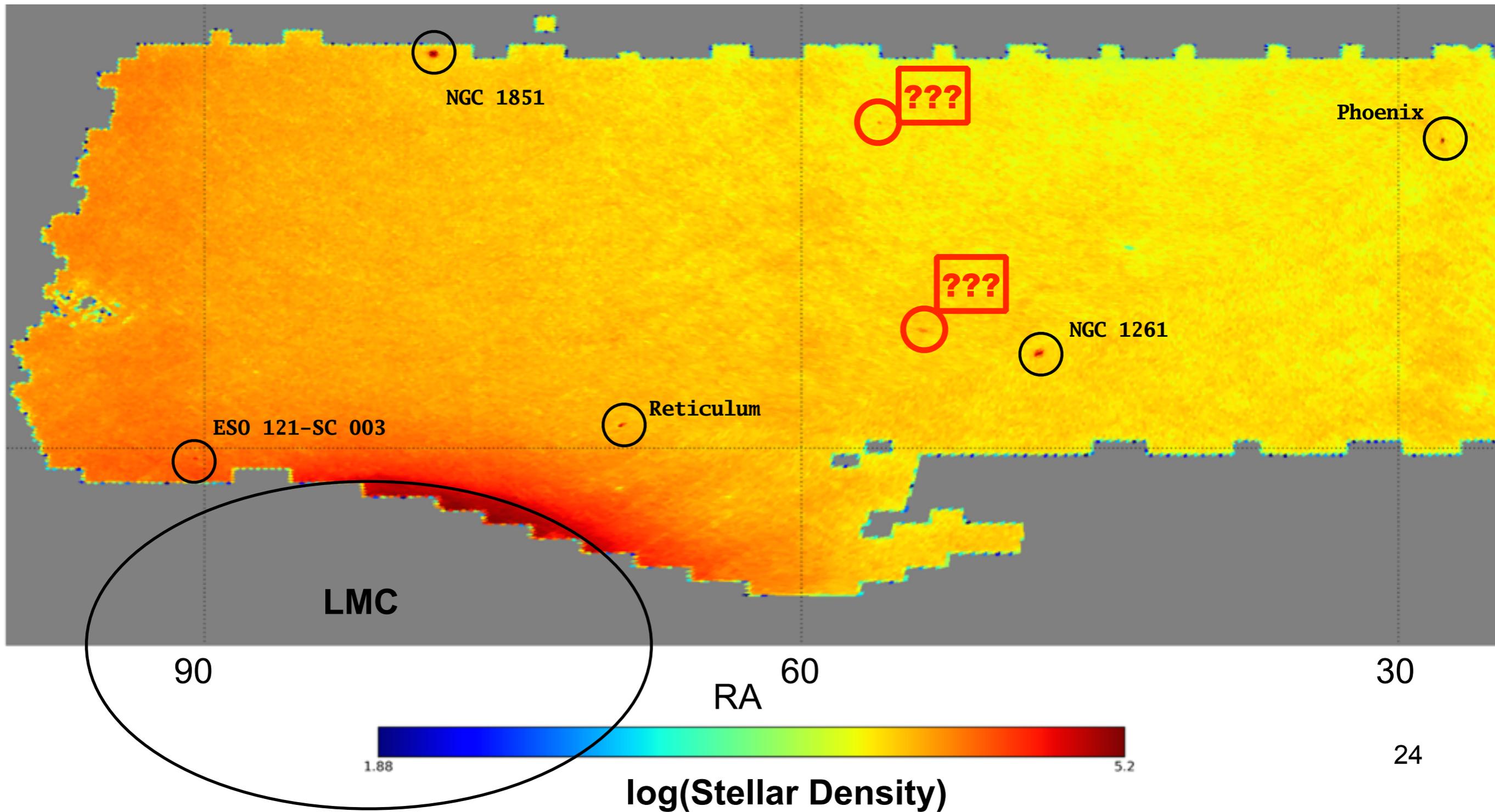




DES Y1A1



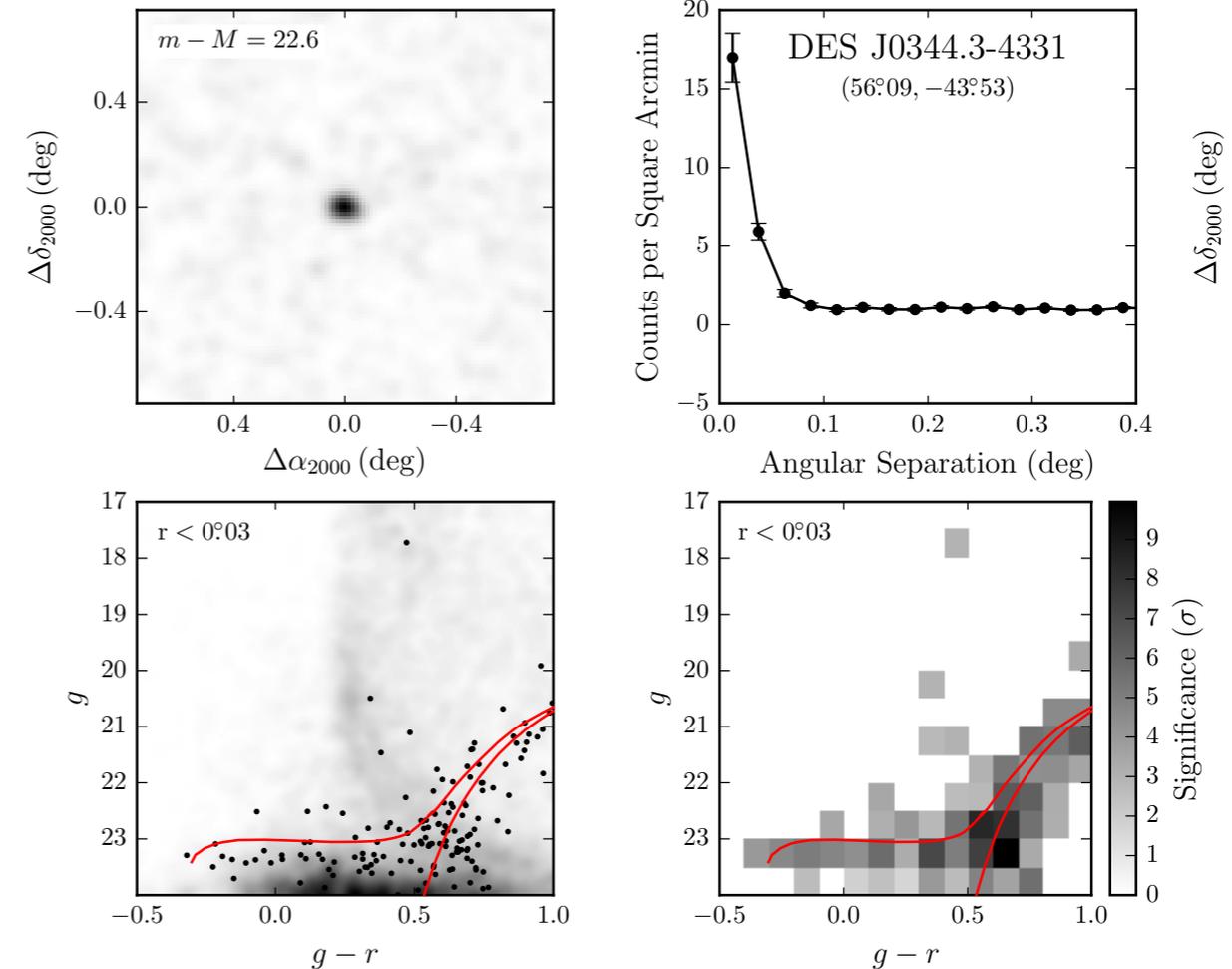
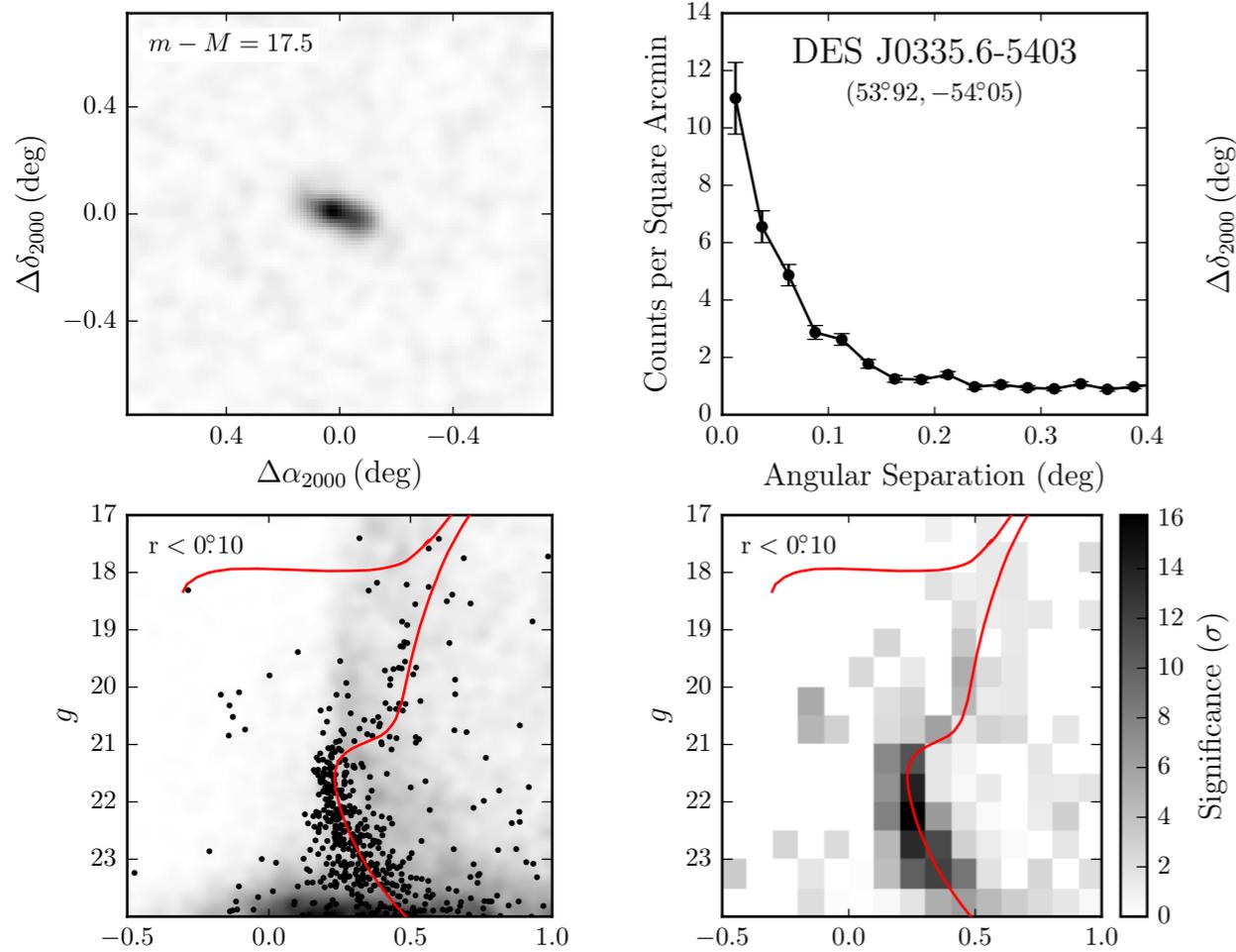
Y1A1: A First Look



Y1A1: A First Look

**Reticulum II
(DES J0335.6-5403)**

**Eridanus II
(DES J0344.3-4331)**

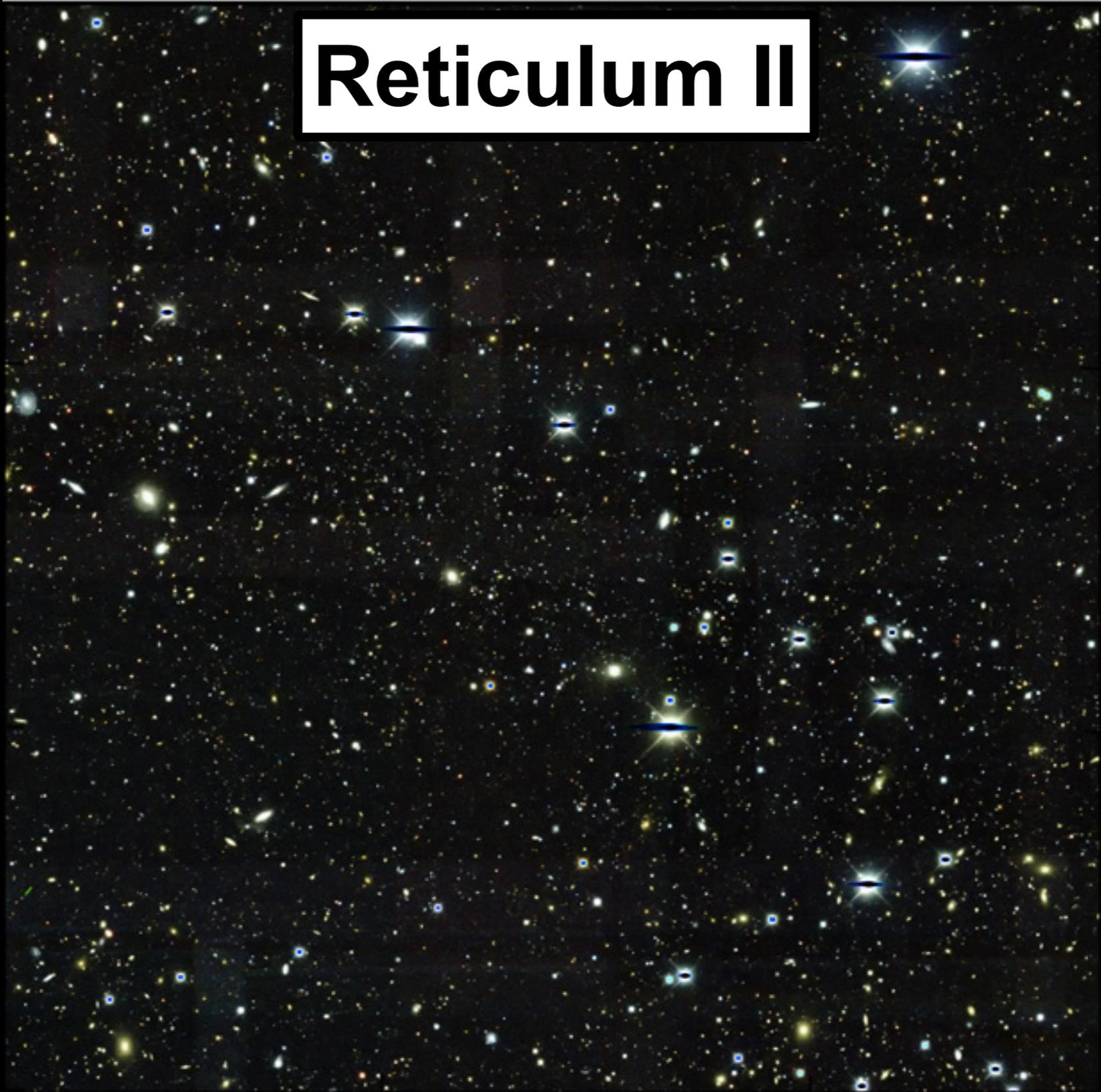


arXiv:1503.02584

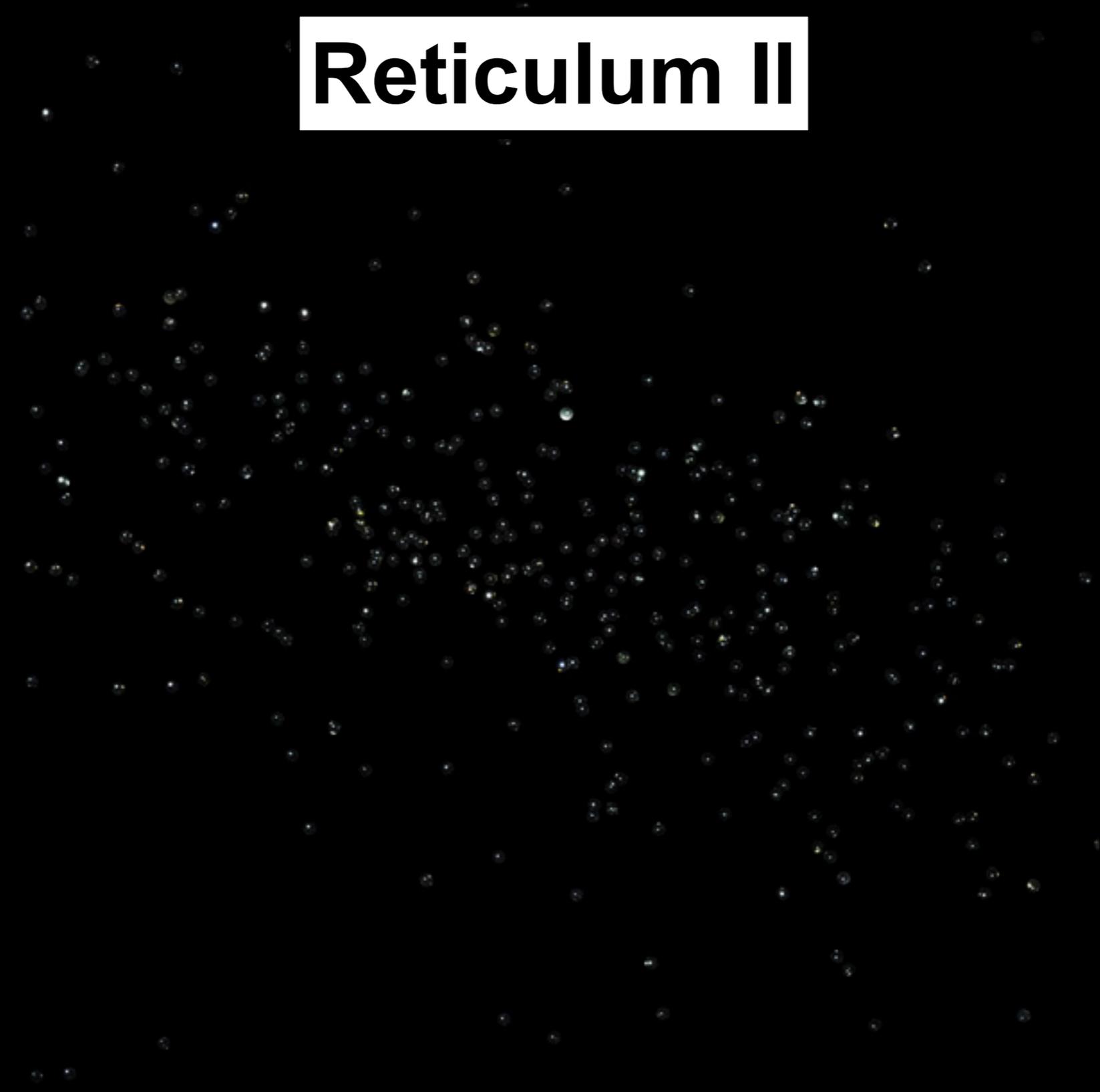
arXiv:1503.02079

**Bechtol et al. (2015) (DES Collaboration)
(see also Koposov et al. 2015)**

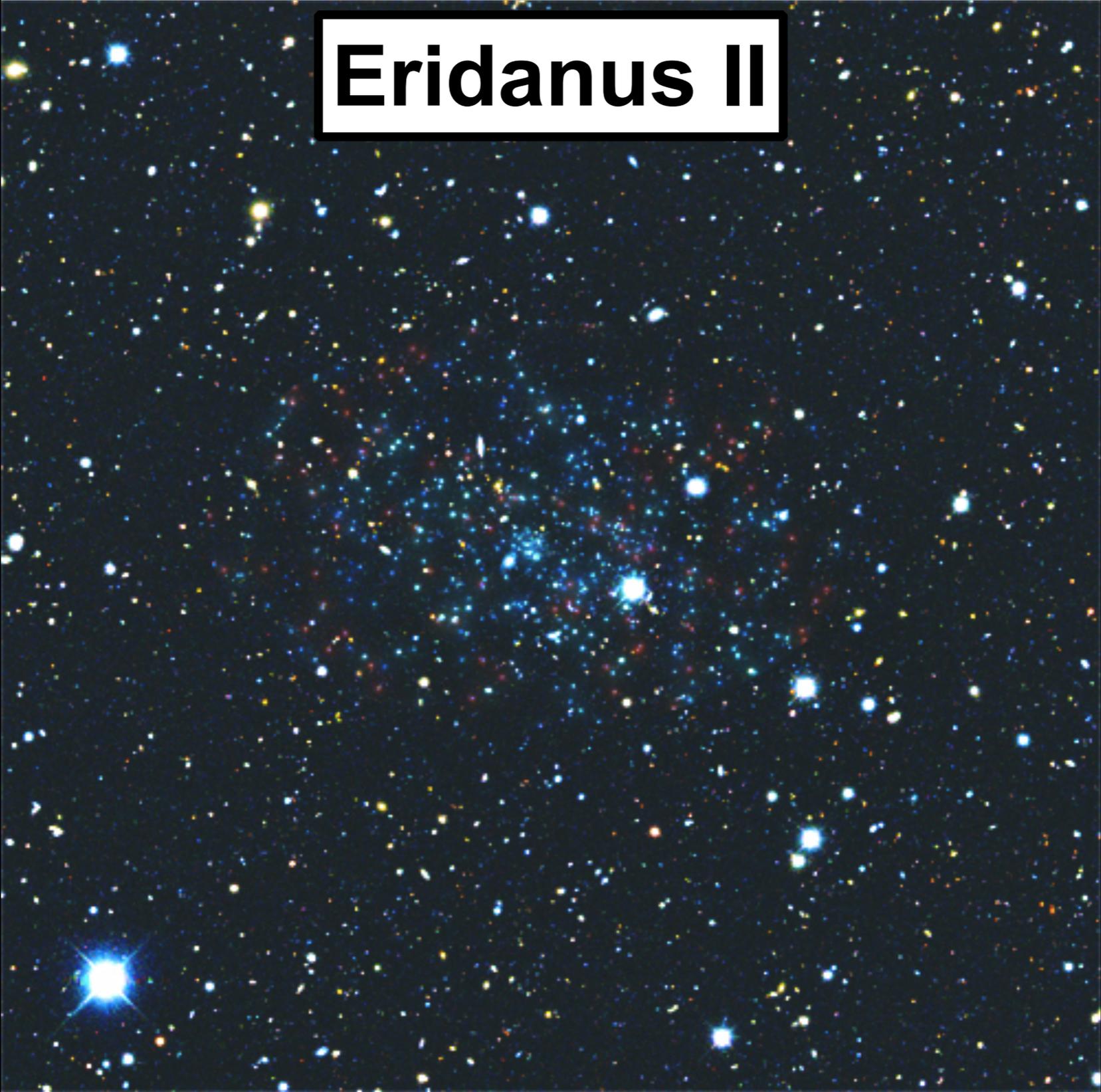
Reticulum II



Reticulum II

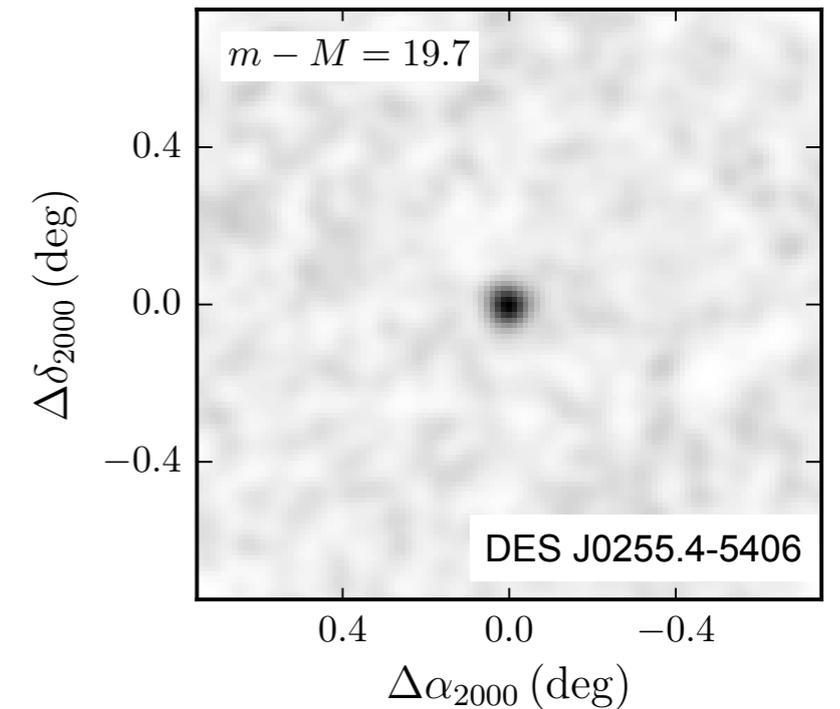
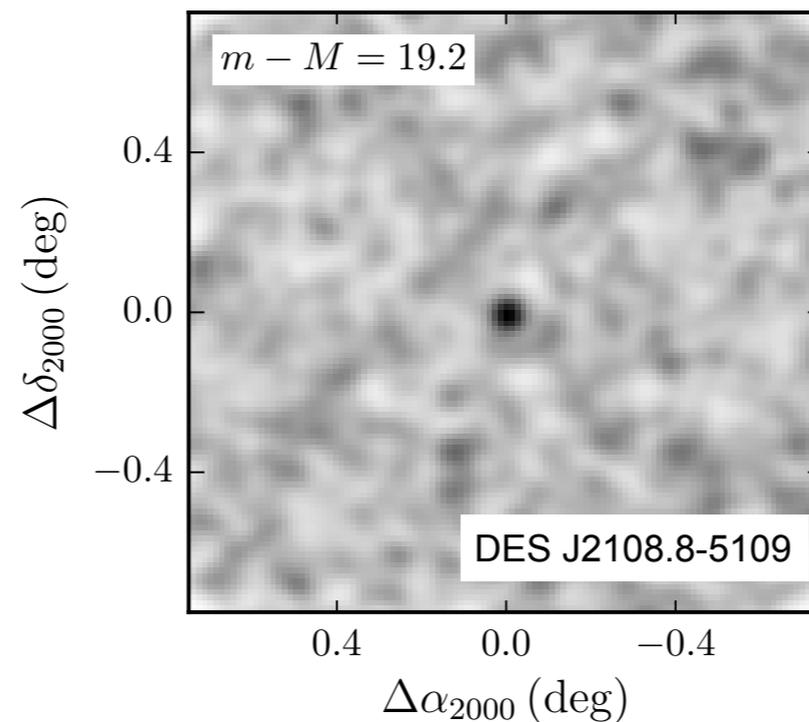
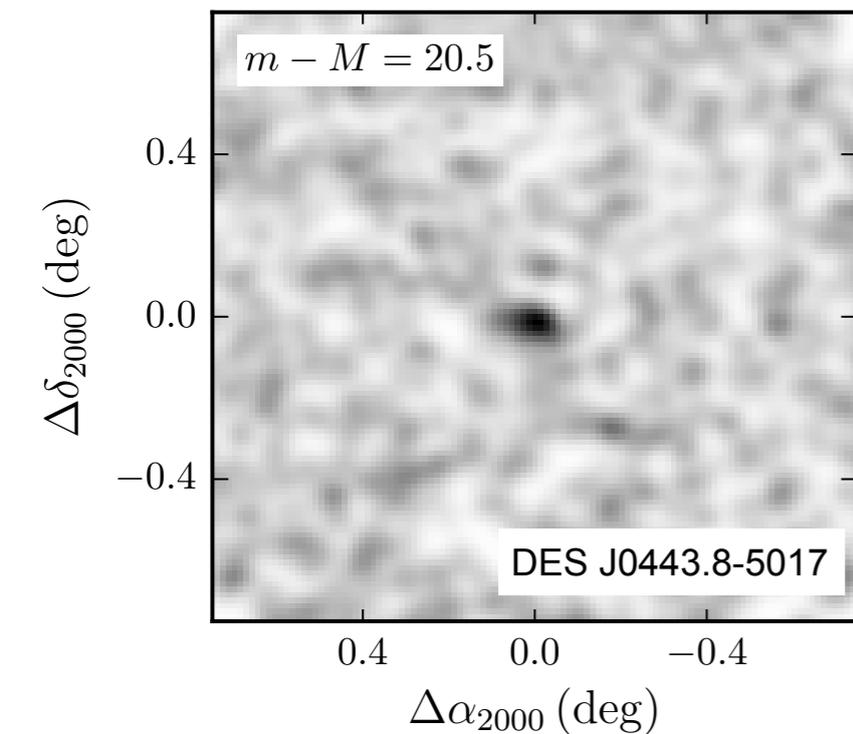
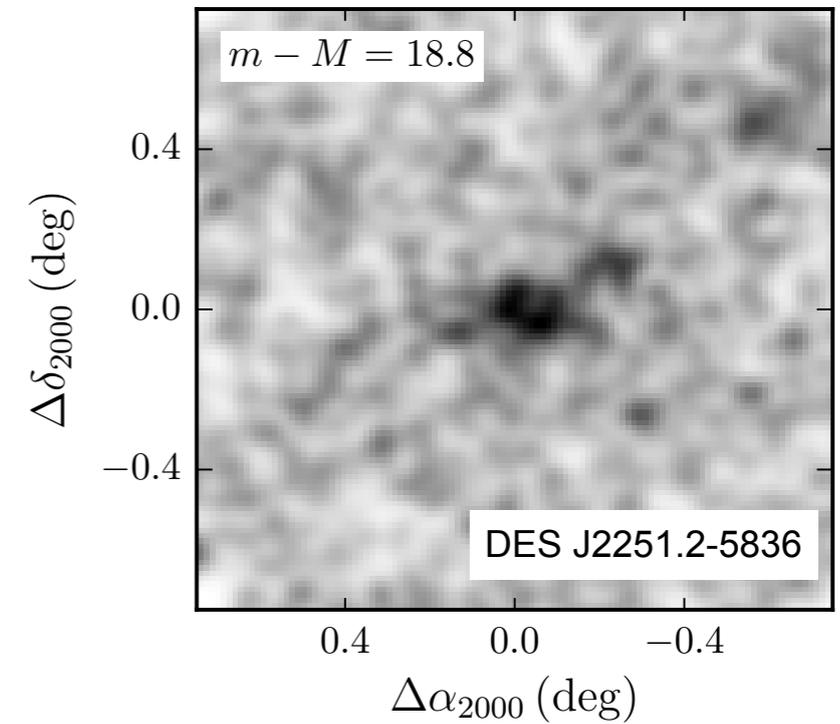
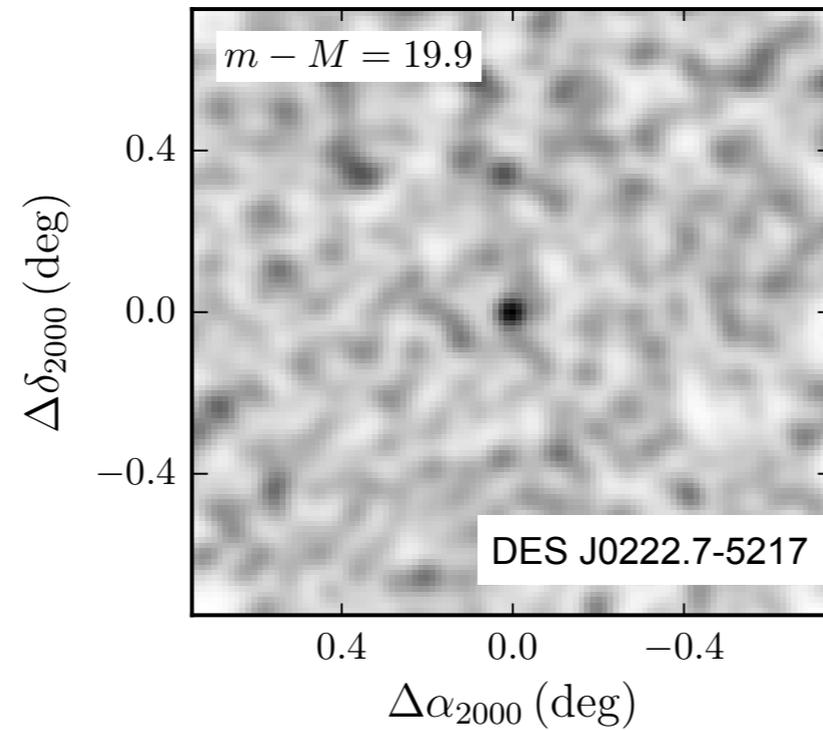
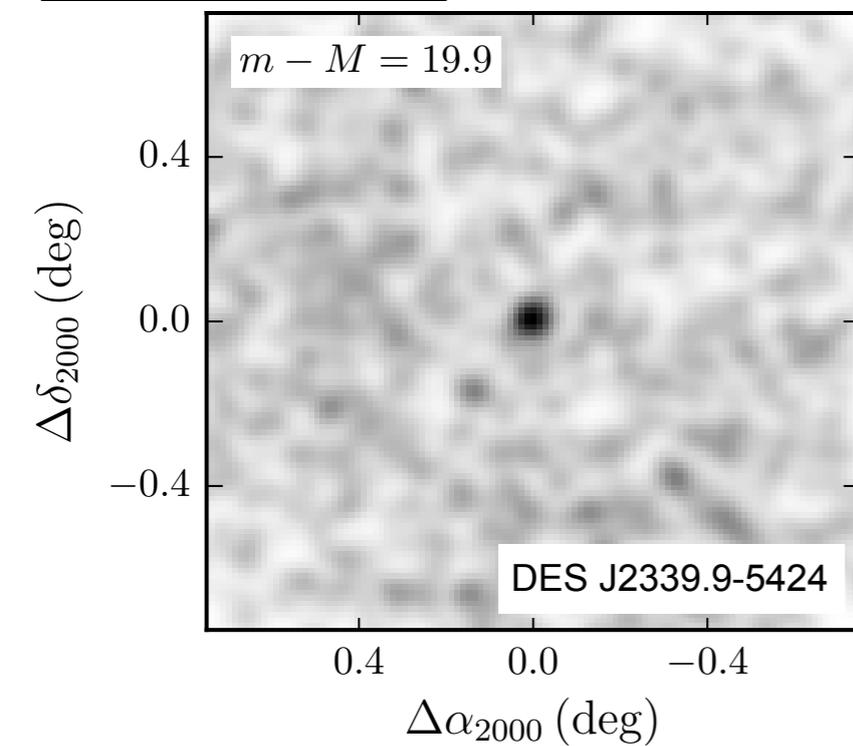


Eridanus II

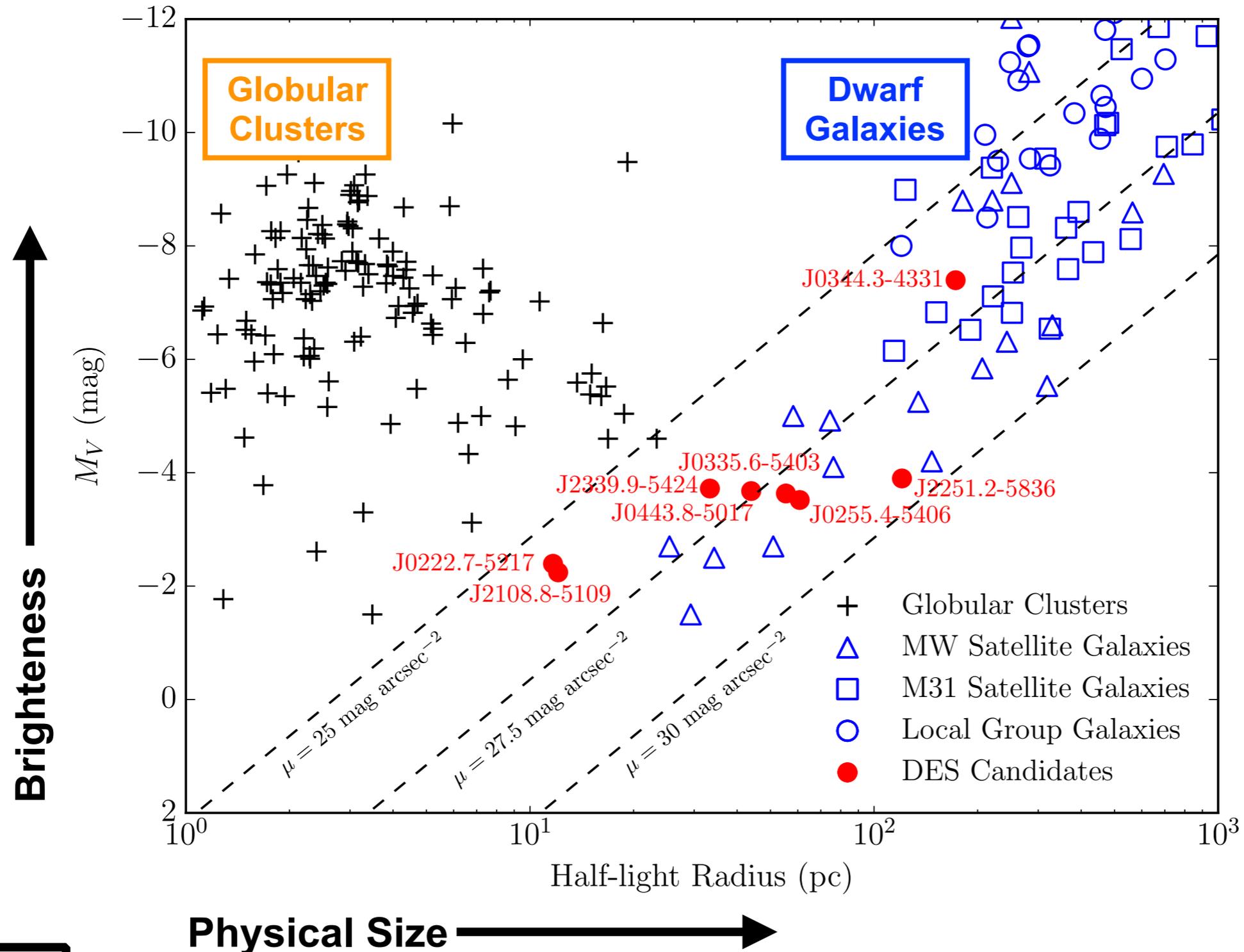


Additional Objects

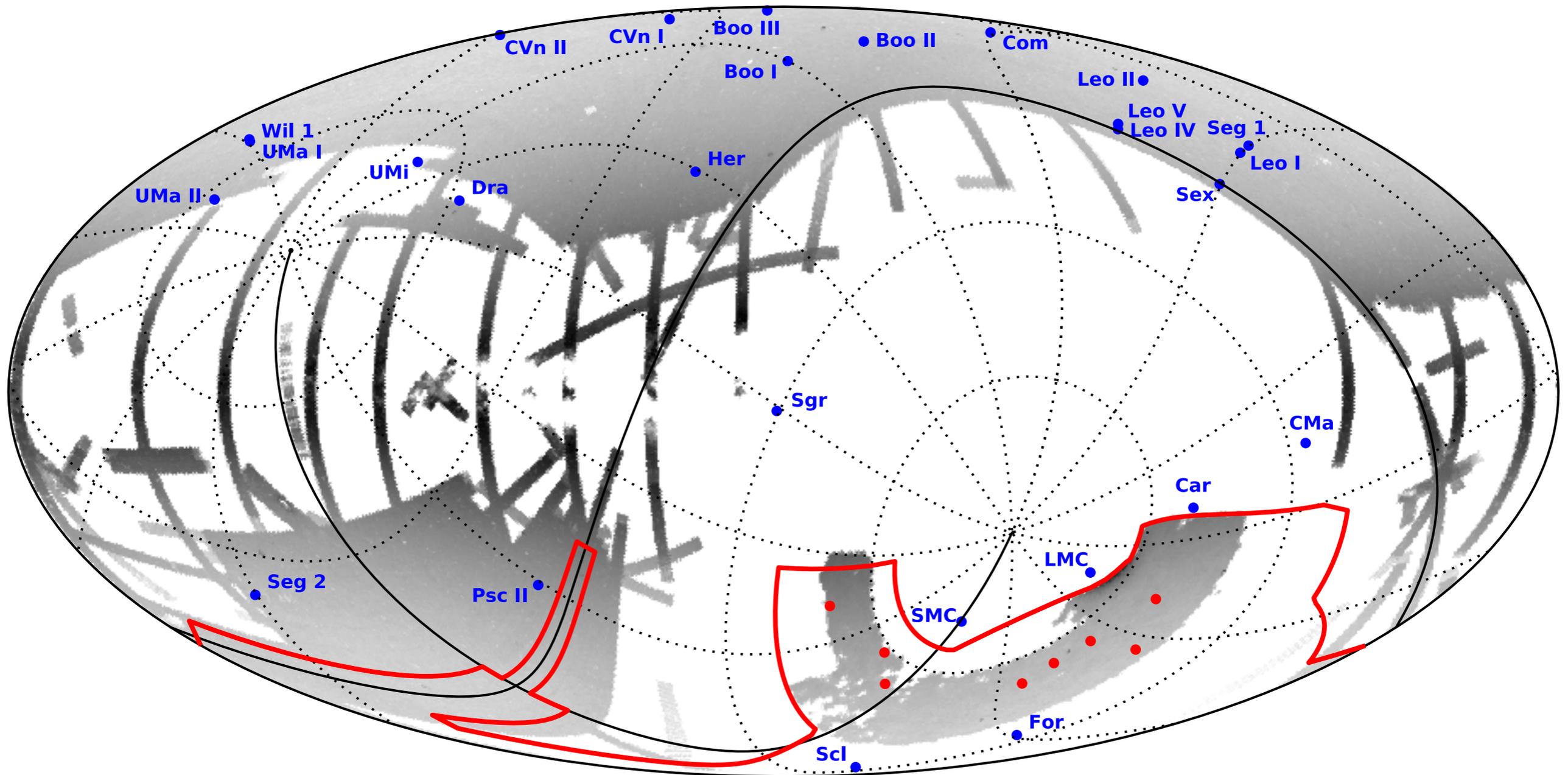
arXiv:1503.02584



Dwarf Galaxies or Globular Clusters?



Dwarf Galaxy Candidates



Dwarf Galaxy Candidates (continued...)

BEASTS OF THE SOUTHERN WILD. DISCOVERY OF A LARGE NUMBER OF ULTRA FAINT SATELLITES IN THE VICINITY OF THE MAGELLANIC CLOUDS.

SERGEY E. KOPOSOV, VASILY BELOKUROV, GABRIEL TORREALBA, AND N. WYN EVANS
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
(Dated: March 10, 2015)
Draft version March 10, 2015

DES Data

A NEW FAINT MILKY WAY SATELLITE DISCOVERED IN THE PAN-STARRS1 3π SURVEY

BENJAMIN P. M. LAEVENS^{1,2}, NICOLAS F. MARTIN^{1,2}, RODRIGO A. IBATA¹, HANS-WALTER RIX², EDOUARD J. BERNARD³,
ERIC F. BELL⁴, BRANIMIR SESAR², ANNETTE M. N. FERGUSON³, EDWARD F. SCHLAFLY², COLIN T. SLATER⁴, WILLIAM S.
BURGETT⁵, KENNETH C. CHAMBERS⁶, HEATHER FLEWELLING⁶, KLAUS A. HODAPP⁶, NICHOLAS KAISER⁶, ROLF-PETER
KUDRITZKI⁶, ROBERT H. LUPTON⁷, EUGENE A. MAGNIER⁶, NIGEL METCALFE⁸, JEFFREY S. MORGAN⁶, PAUL A. PRICE⁷,
JOHN L. TONRY⁶, RICHARD J. WAINSCOT⁶, CHRISTOPHER WATERS⁶
Draft version March 20, 2015

Pan-STARRS

A HERO'S DARK HORSE: DISCOVERY OF AN ULTRA-FAINT MILKY WAY SATELLITE IN PEGASUS

DONGWON KIM, HELMUT JERJEN, DOUGAL MACKEY, GARY S. DA COSTA, AND ANTONINO P. MILONE
Research School of Astronomy and Astrophysics, The Australian National University, Mt Stromlo Observatory, via Cotter Rd, Weston,
ACT 2611, Australia
Draft version March 31, 2015

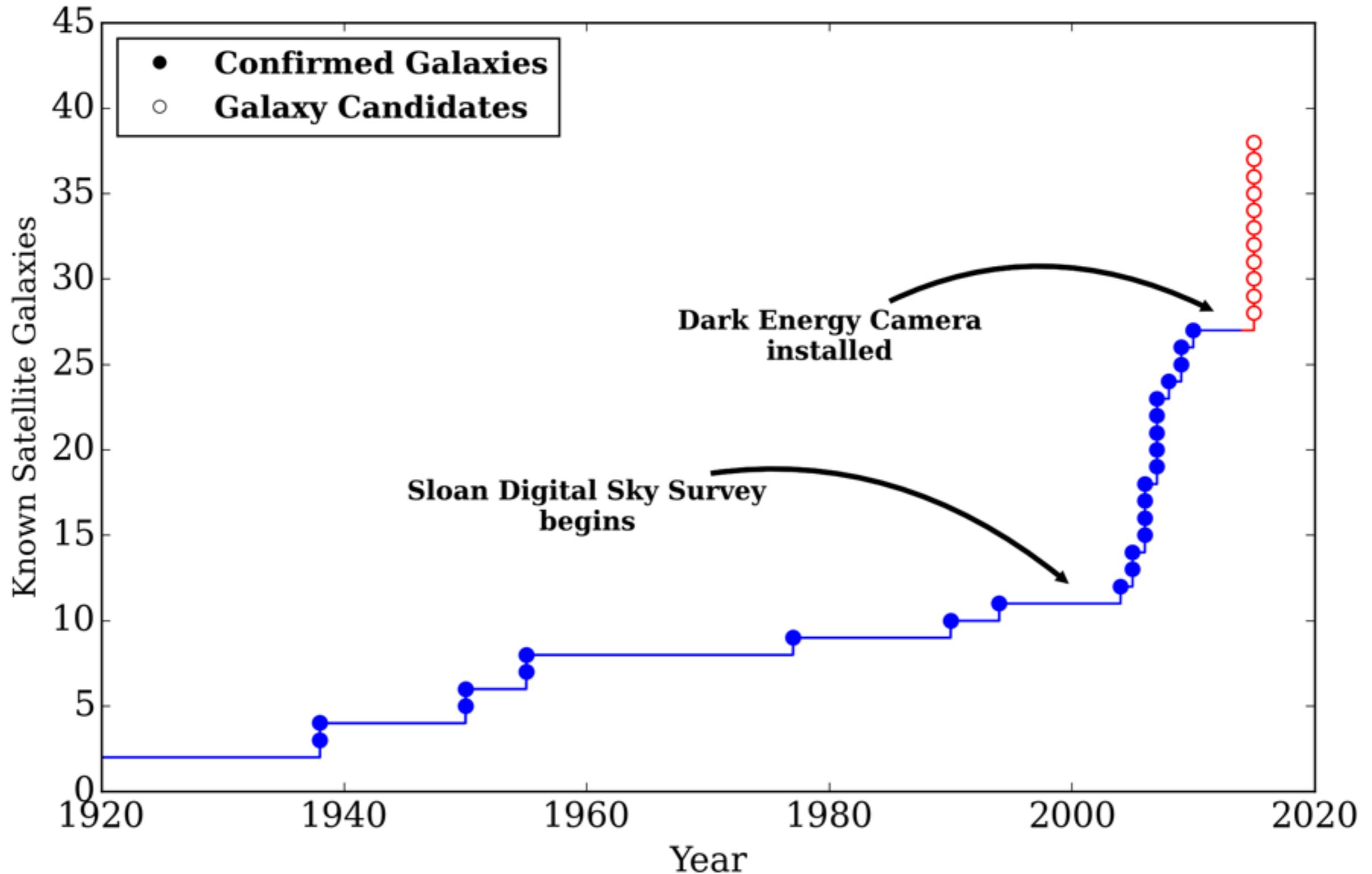
DECam Data

HYDRA II: A FAINT AND COMPACT MILKY WAY DWARF GALAXY FOUND IN THE SURVEY OF THE MAGELLANIC STELLAR HISTORY

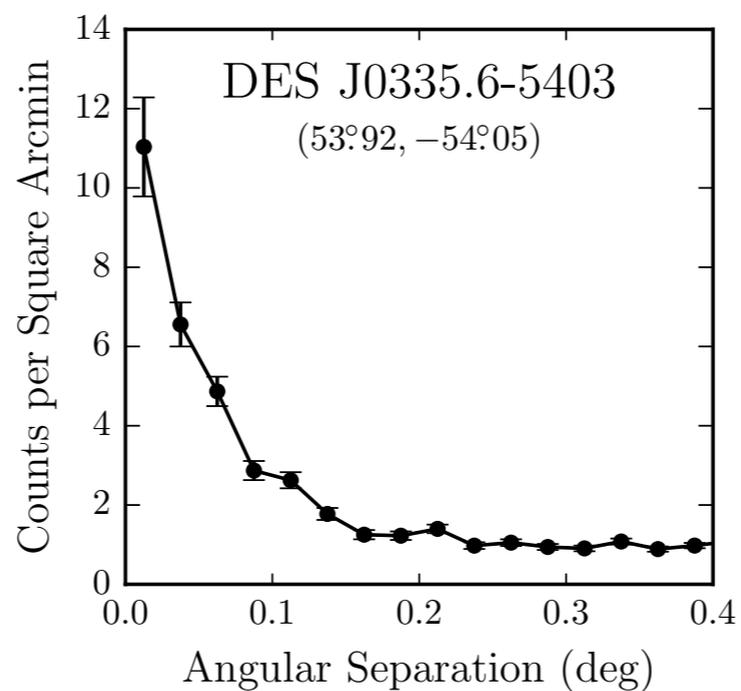
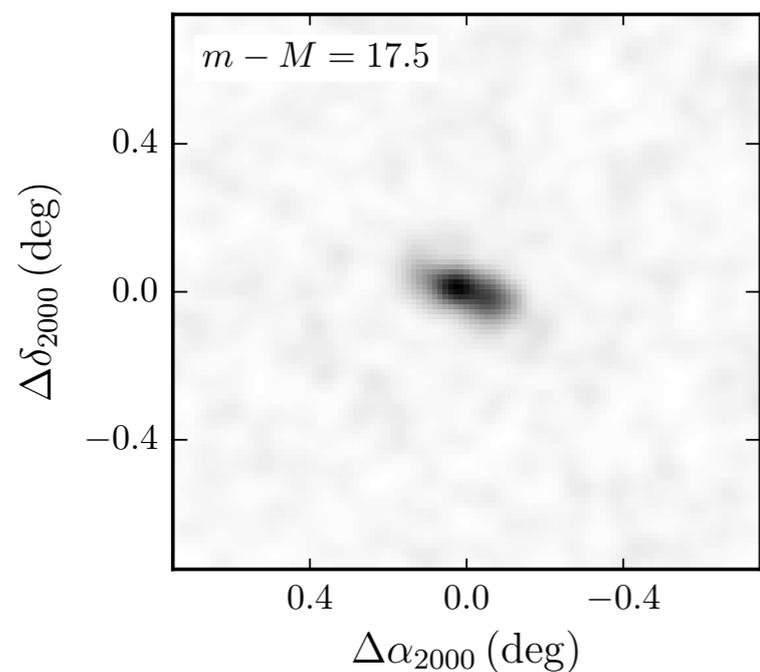
NICOLAS F. MARTIN^{1,2}, DAVID L. NIDEVER³, GURTINA BESLA⁴, KNUT OLSEN⁵, ALISTAIR R. WALKER⁶, A. KATHERINA
VIVAS⁶, ROBERT A. GRUENDL^{7,8}, CATHERINE C. KALEIDA^{5,6}, RICARDO R. MUÑOZ^{9,25}, ROBERT D. BLUM⁵, ABHIJIT SAHA⁵,
BLAIR C. CONN¹⁰, ERIC F. BELL³, YOU-HUA CHU^{11,8}, MARIA-ROSA L. CIONI^{12,13,14}, THOMAS J. L. DE BOER¹⁵, CARME
GALLART^{16,17}, SHOKO JIN¹⁸, ANDREA KUNDER¹³, STEVEN R. MAJEWSKI¹⁹, DAVID MARTINEZ-DELGADO²⁰, ANTONELA
MONACHESI²¹, MATTEO MONELLI^{16,17}, LARA MONTEAGUDO^{16,17}, NOELIA E. D. NOËL²², EDWARD W. OLSZEWSKI⁴, GUY S.
STRINGFELLOW²³, ROELAND P. VAN DER MAREL²⁴, DENNIS ZARITSKY⁴
Draft version April 3, 2015

DECam Data

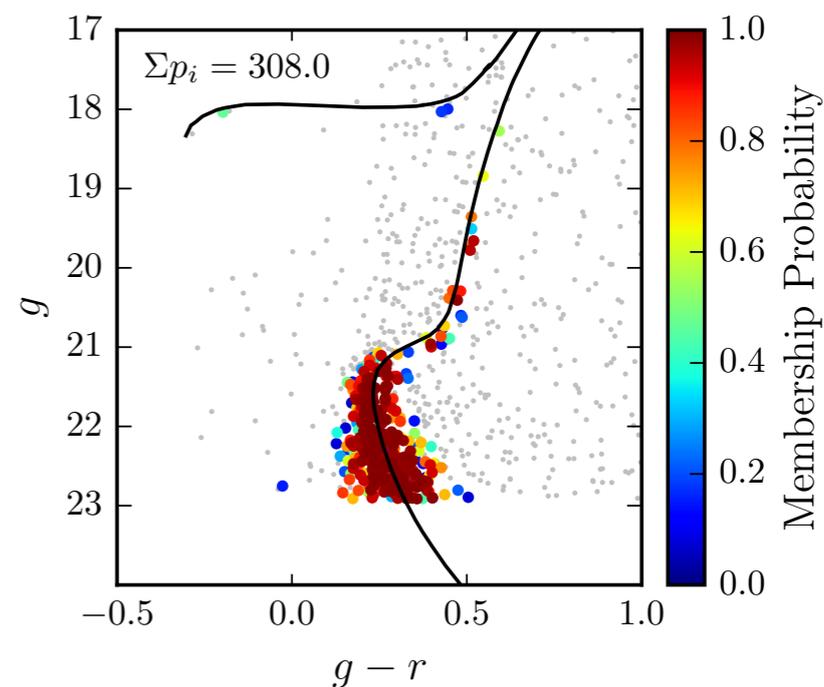
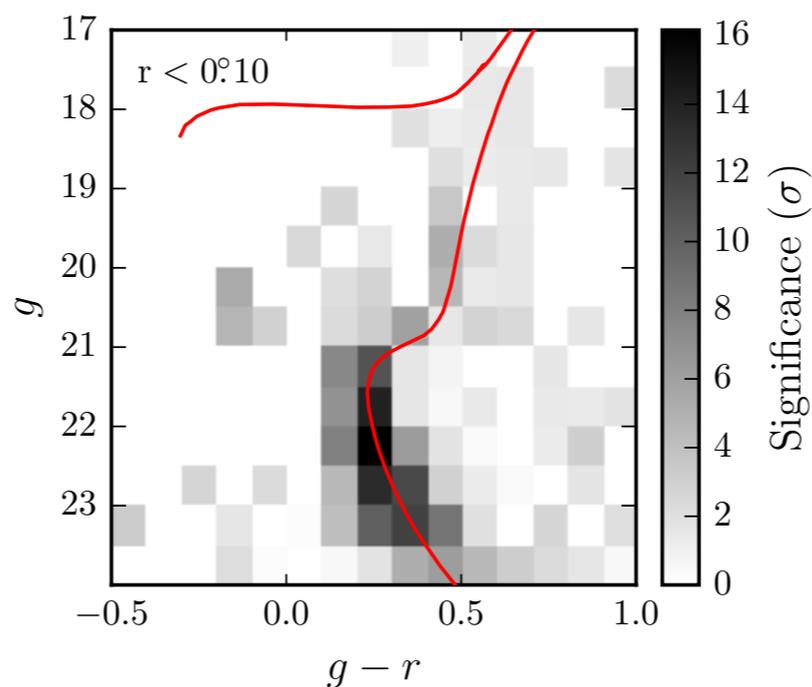
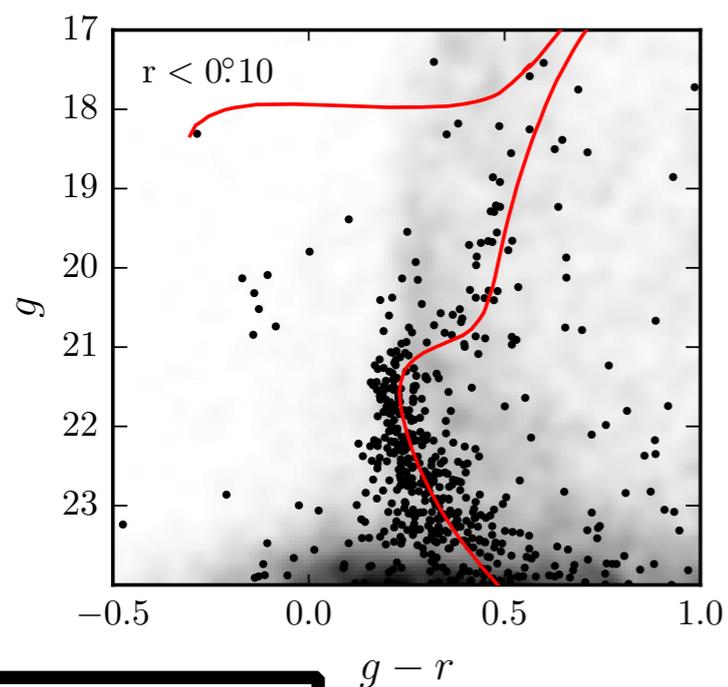
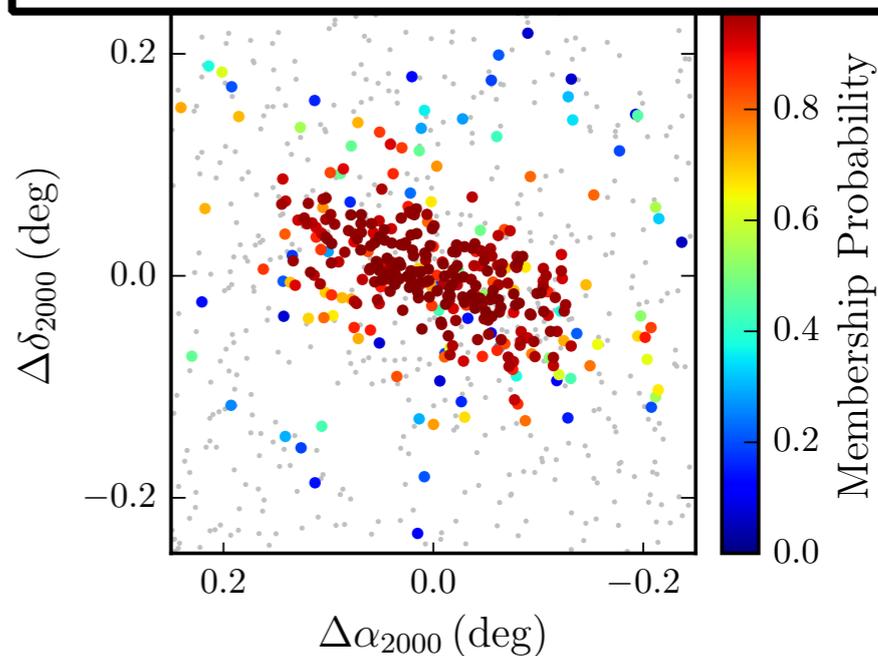
Milky Way Satellite Galaxies Discovery Timeline



Reticulum II: Newest Dwarf Galaxy?

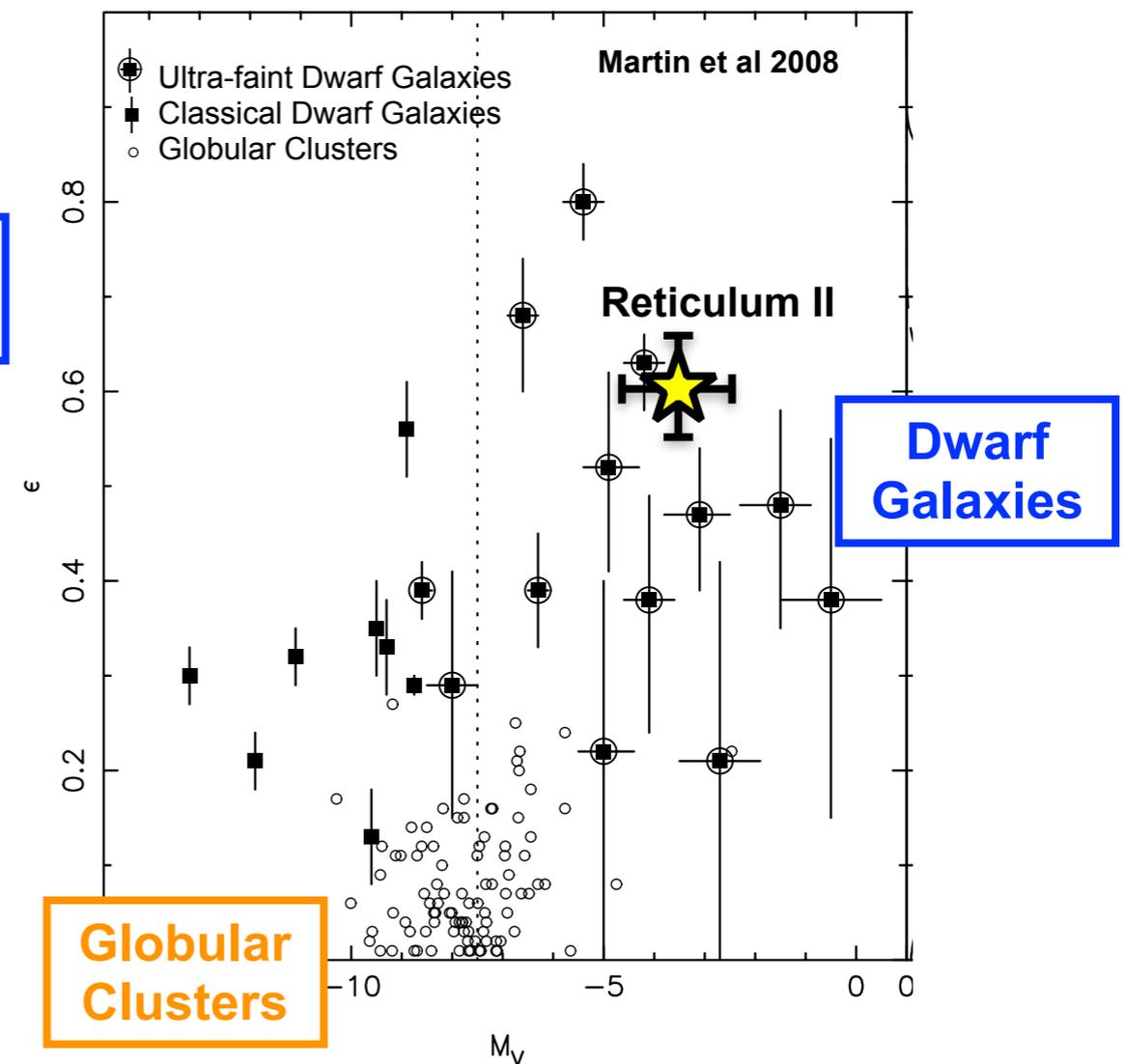
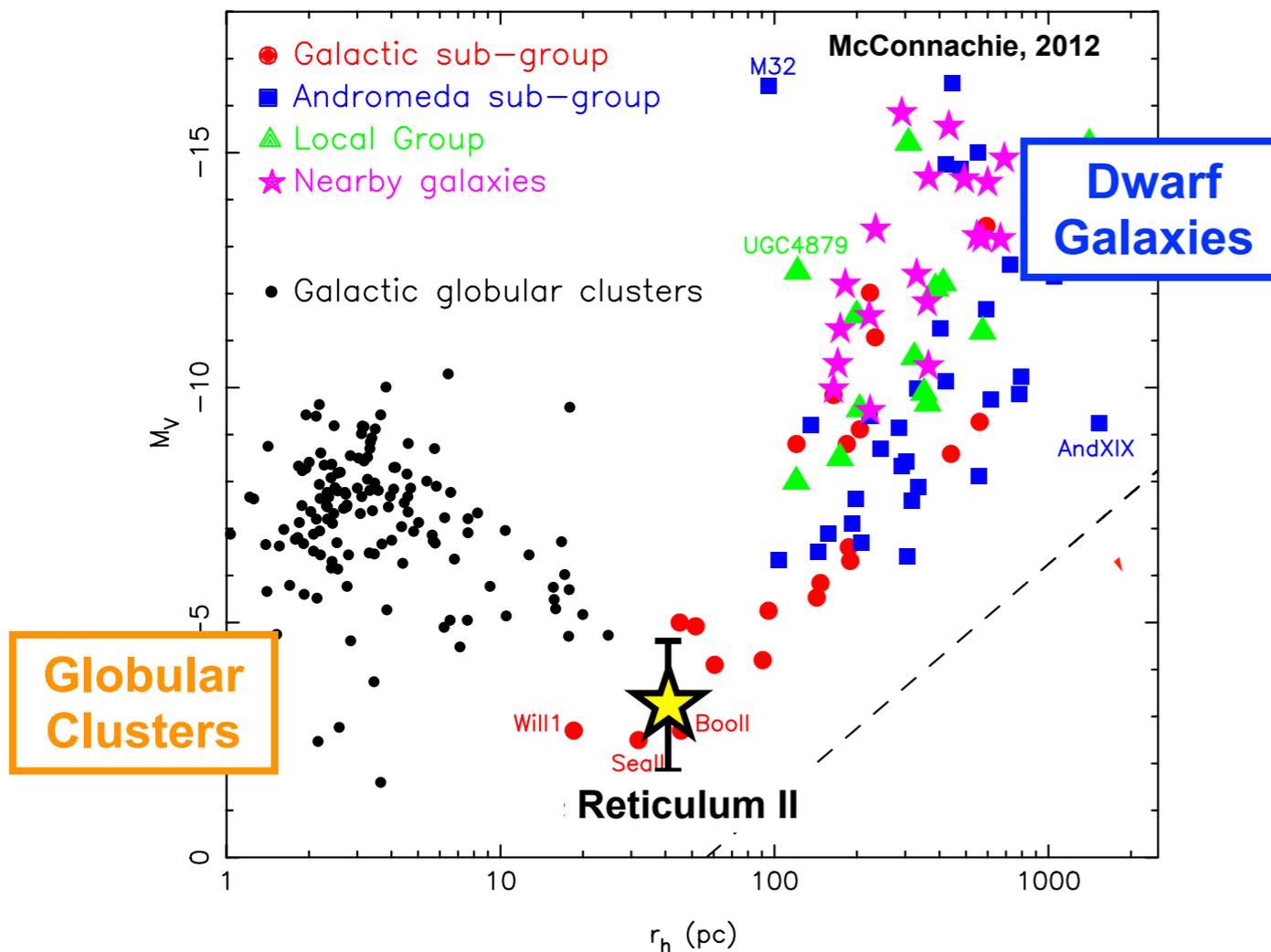


Membership probabilities will play an important role targeting spectroscopy



Reticulum II: Newest Dwarf Galaxy?

- Satellite galaxies tend to be **more spatially extended** and have a stronger **correlation between size and luminosity**.
- Satellite galaxies also tend to be **more elliptical**.
- Reticulum II is consistent with the population of satellite galaxies.
- **Spectroscopy necessary** to definitively distinguish satellite galaxies from globular clusters...



Reticulum II: Spectroscopy Campaign

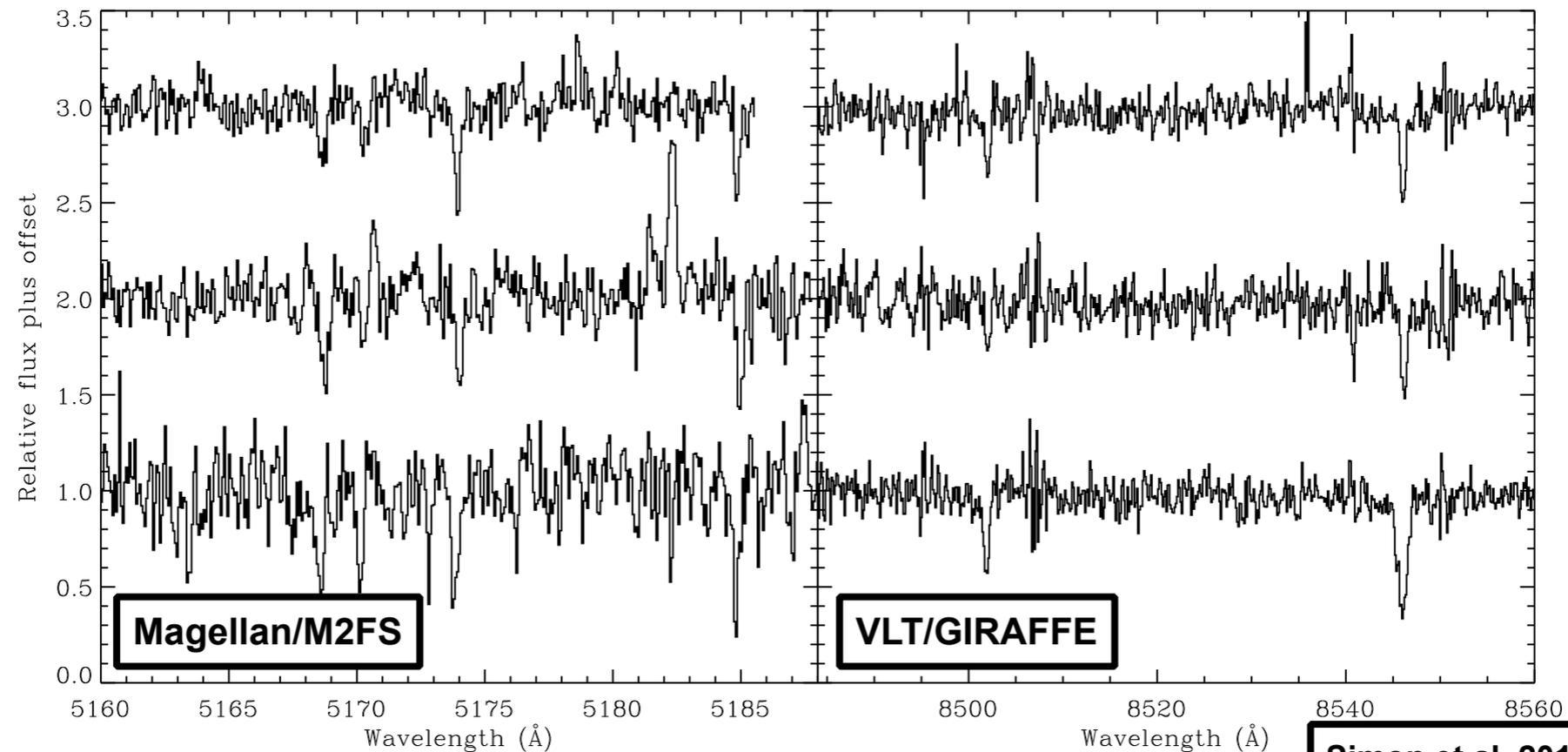
Magellan/M2FS



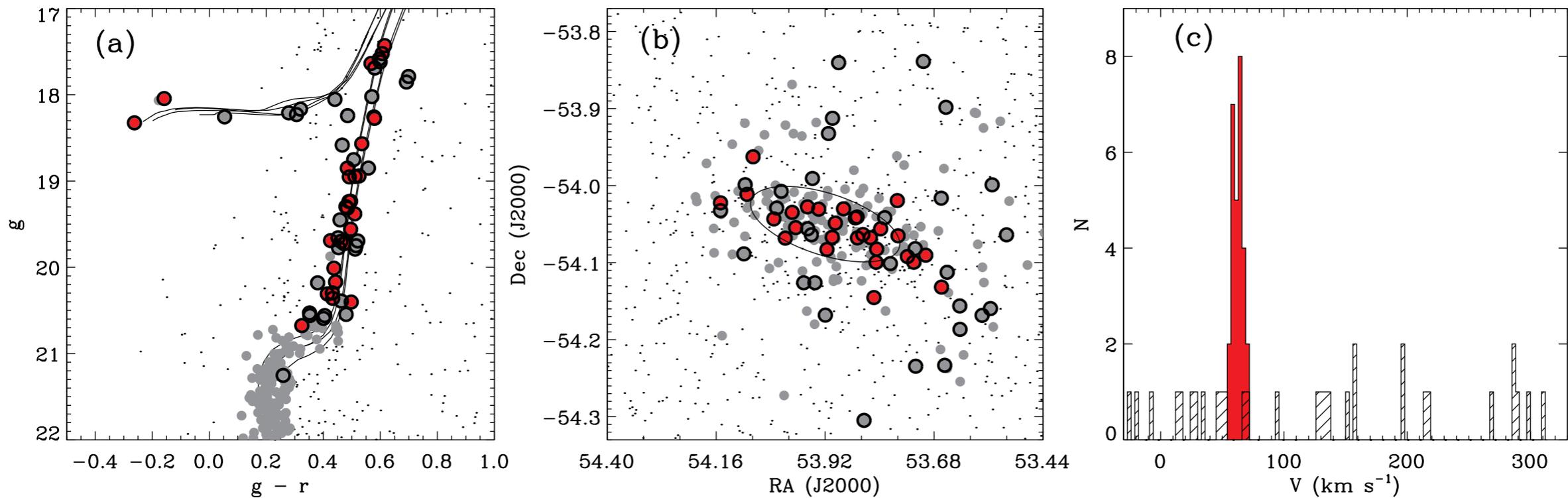
Gemini/GMOS



VLT/GIRAFFE



Reticulum II: Newest 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**

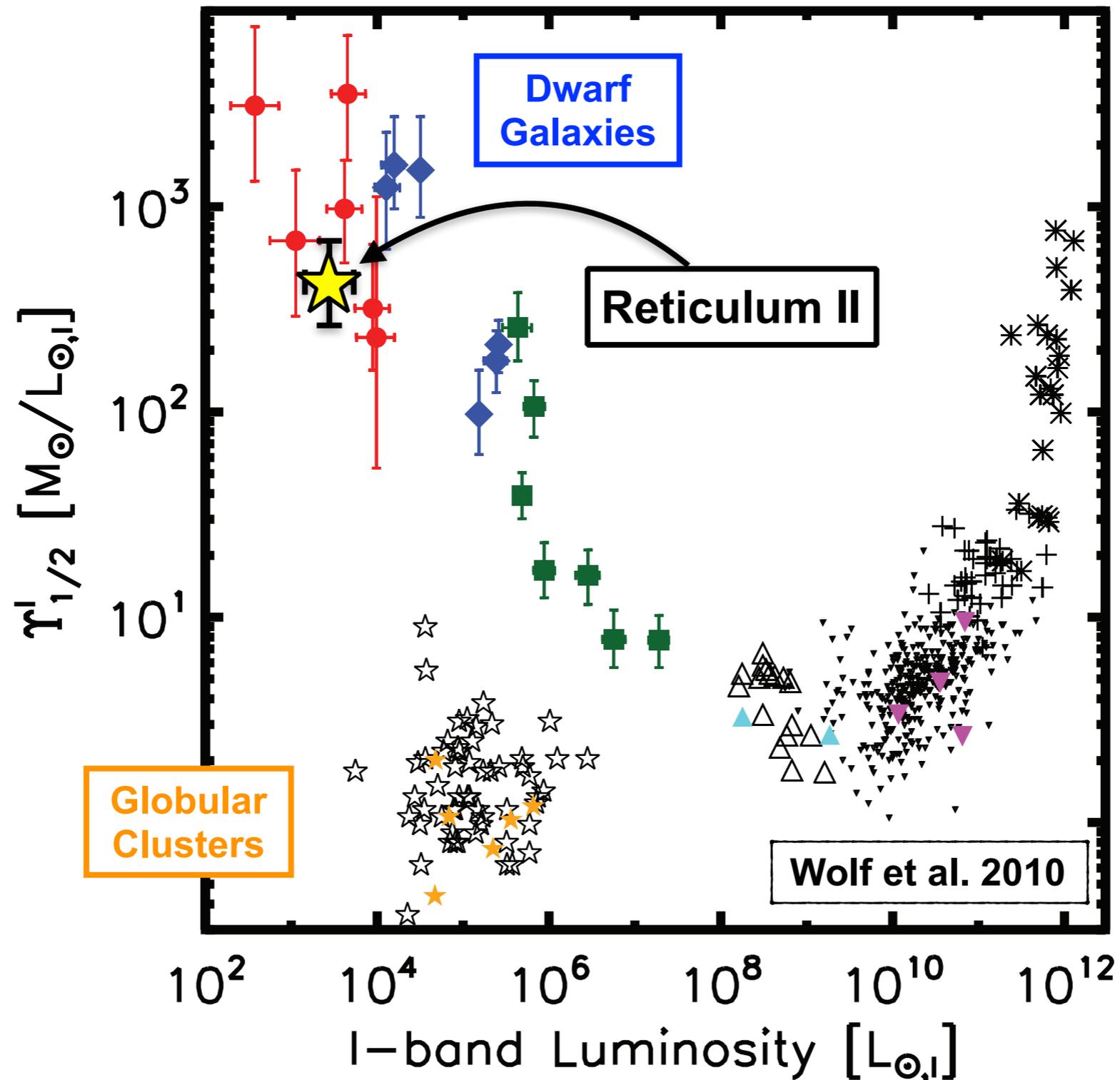
Simon et al. 2015 (DES Collaboration)
(see also Walker et al. 2015)

arXiv:1504.02889

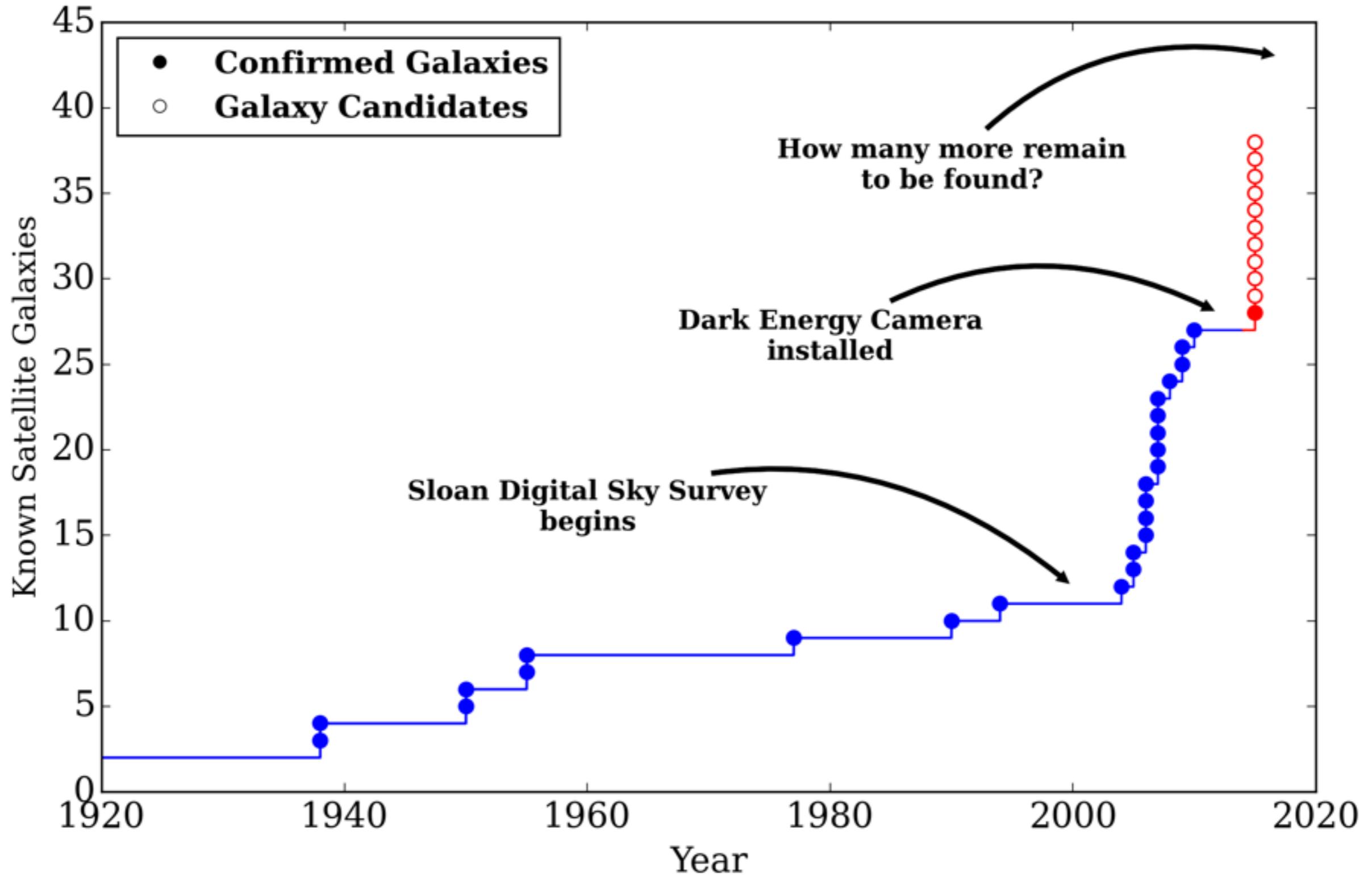
arXiv:1504.03309

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

Reticulum II: Ultra-faint Dwarf Galaxy

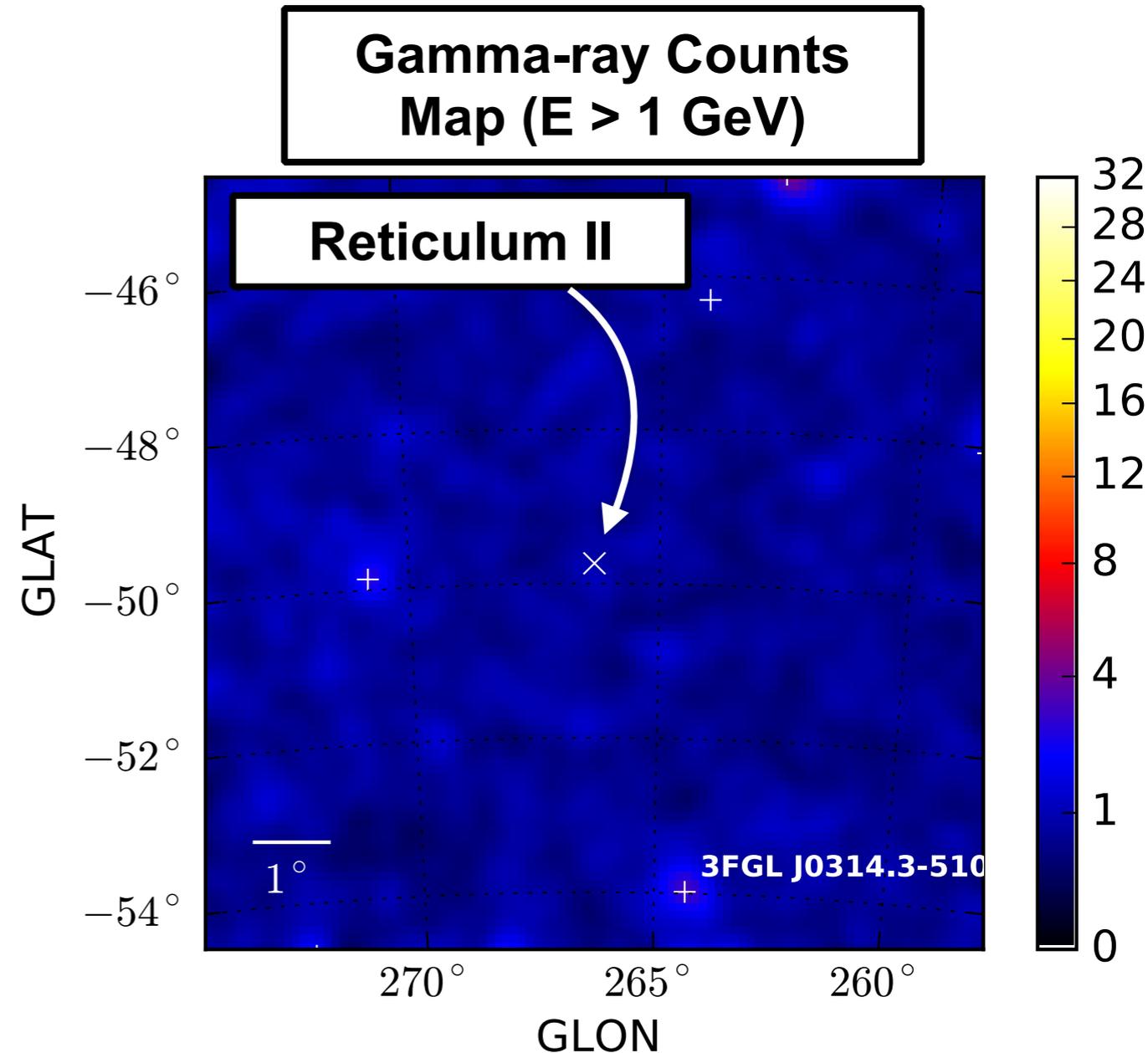


Milky Way Satellite Galaxies Discovery Timeline



Dark Matter Searches in Gamma Rays

- Search for discrete gamma-ray sources coincident with the DES dwarf galaxy candidates
- No significant gamma-ray sources detected over background
- Most significant excess coincident with Reticulum II
 - LAT Collaboration, Pass8: local pvalue = 0.06 (1.5σ)
 - Geringer-Sameth+, Pass 7: local pvalue = 0.01 (2.3σ)
- How does the expected dark matter annihilation signal from Reticulum II compare to other dwarf galaxies?

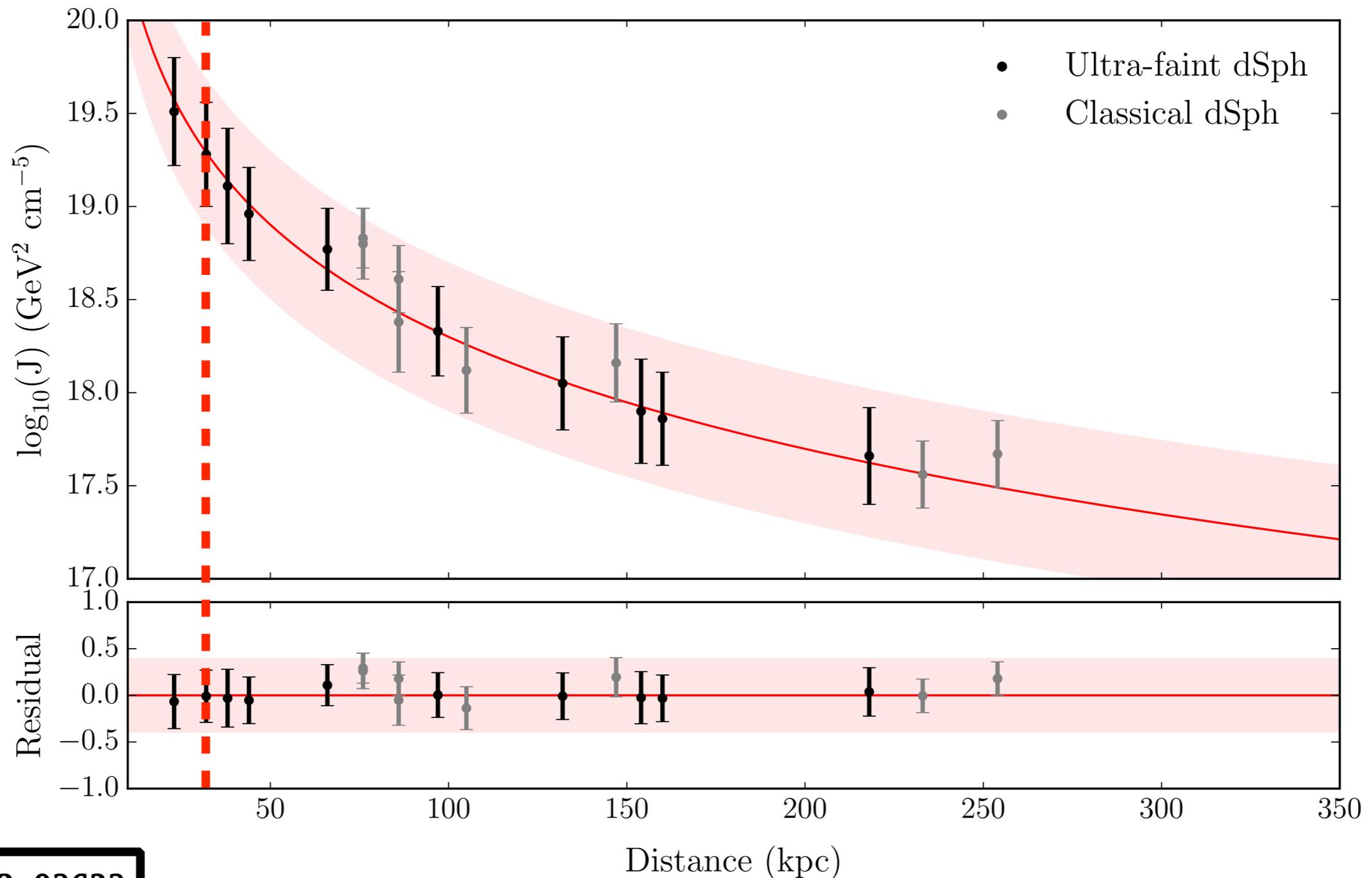


LAT & DES Collaborations
(see also Geringer-Sameth et al. 2015)

arXiv:1503.02632

arXiv:1503.02320

Dark Matter Searches in Gamma Rays



Dark Matter Searches in Gamma Rays

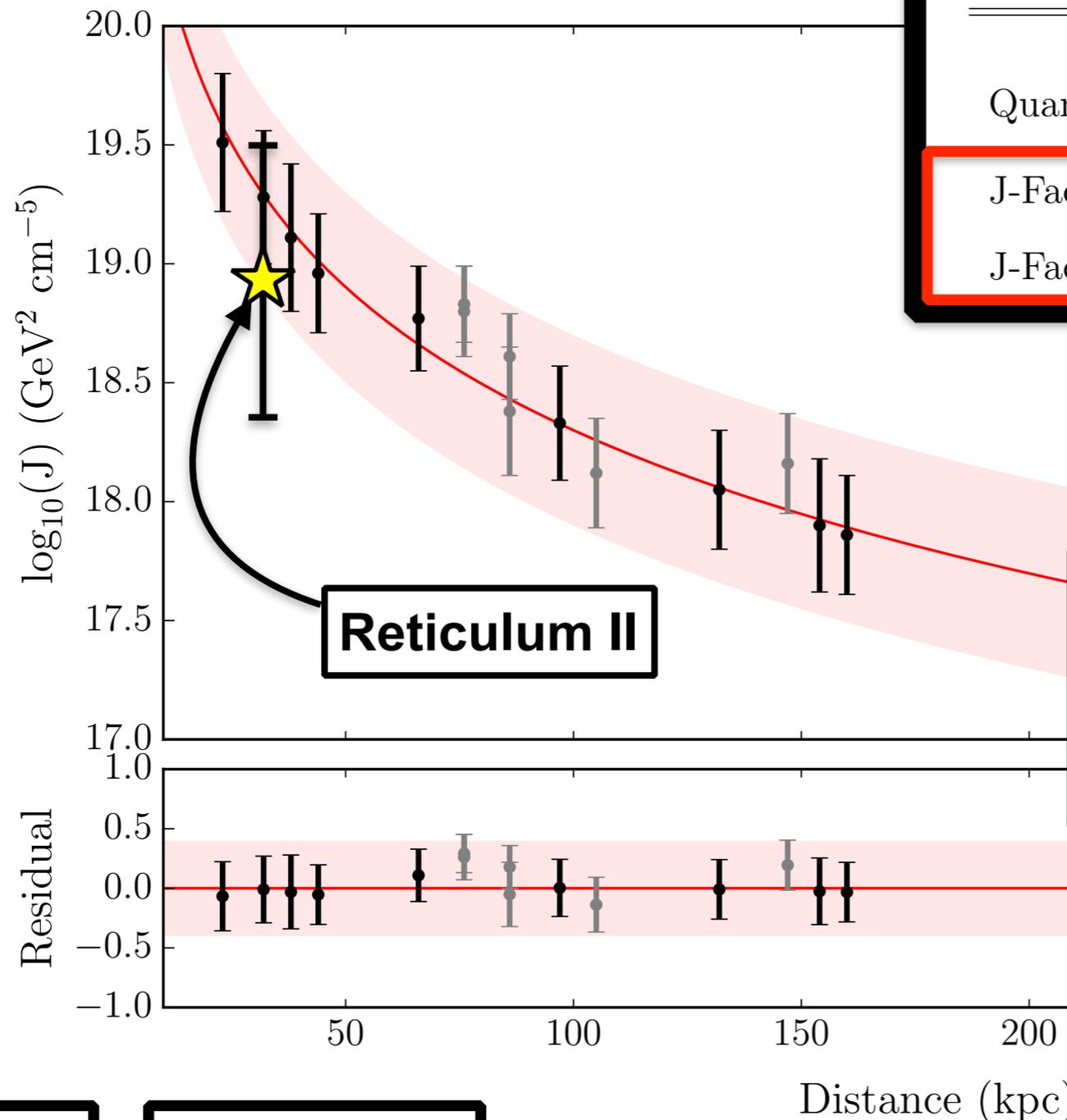


Table 1. Reticulum II

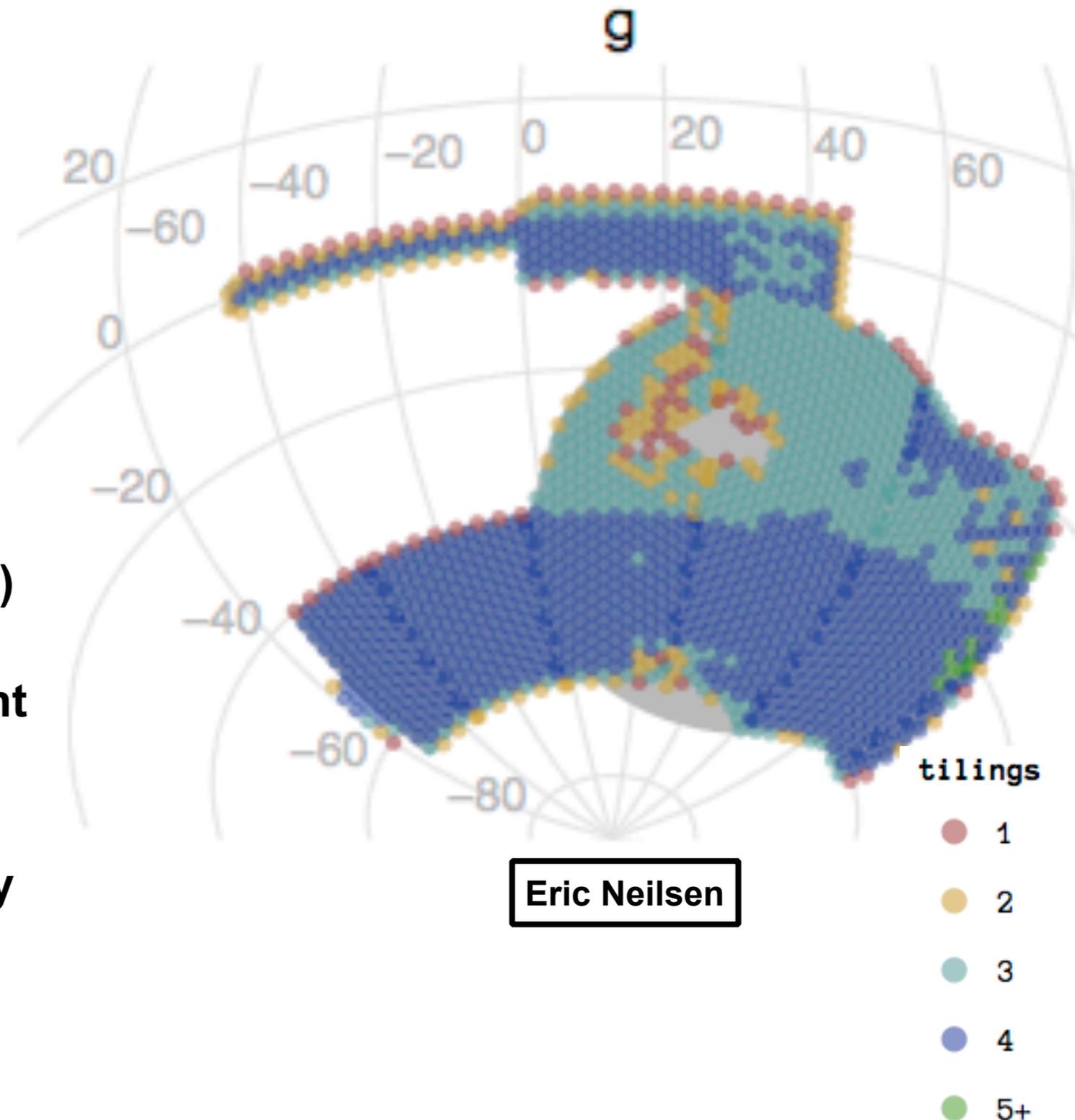
Quantity	Value
J-Factor (0.2°)	$\log_{10} J = 18.8 \pm 0.6 \text{ GeV}^2 \text{ cm}^{-5}$
J-Factor (0.5°)	$\log_{10} J = 18.9 \pm 0.6 \text{ GeV}^2 \text{ cm}^{-5}$

Some disagreement between groups about median J-factor...

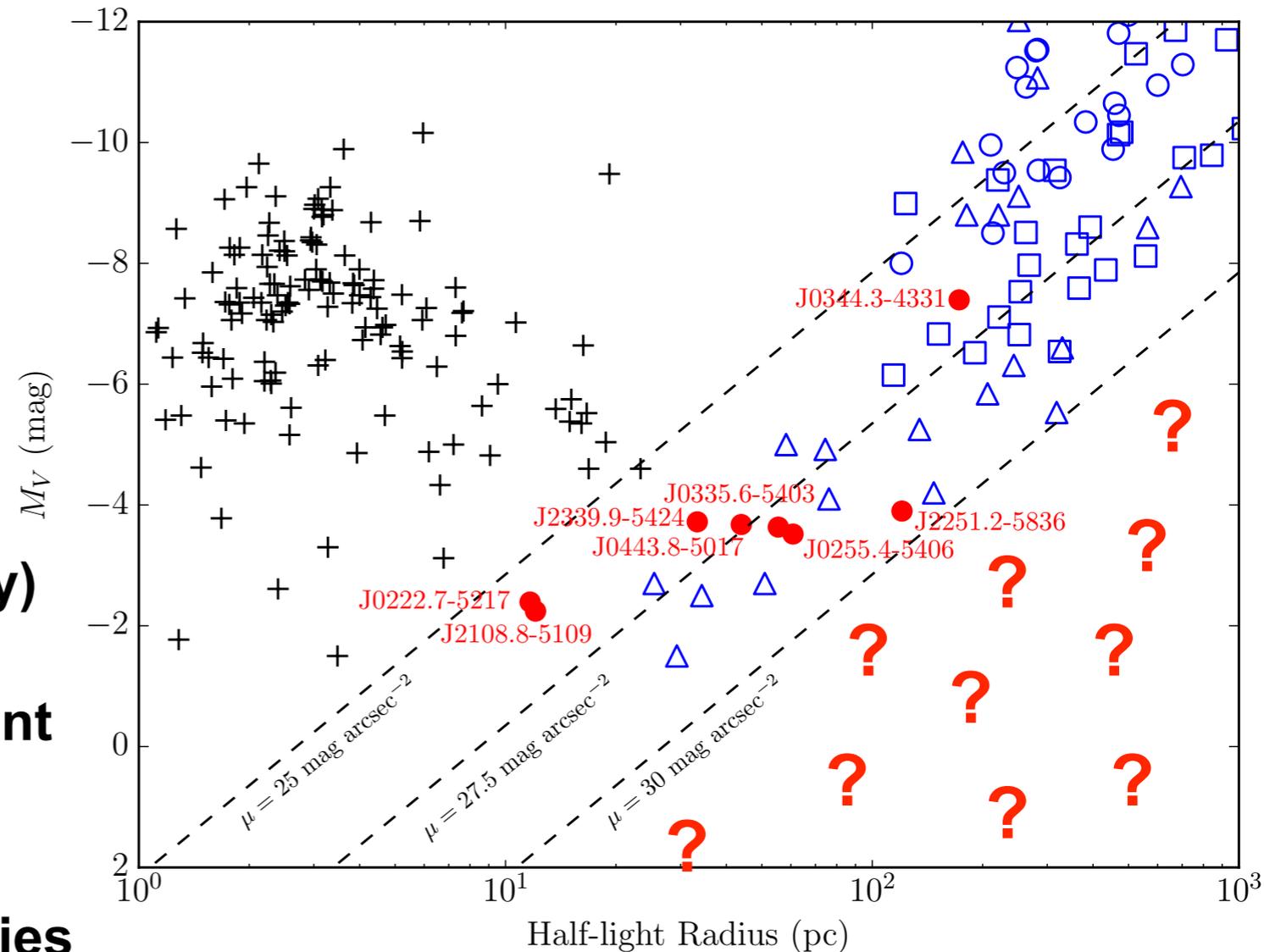
Groups agree that the expected dark matter signal from Ret II is smaller than that expected from some other dwarf galaxies

Unlikely to see a dark matter signal from Ret II without also seeing it from other galaxies.

- A large-scale spectroscopy campaign will be necessary to classify and characterize newly discovered systems
- Future sky coverage:
 - DES Y2: $>4,000 \text{ deg}^2$
 - DES Y3+: $5,000 \text{ deg}^2$ (and greater sensitivity)
 - LSST: $10,000 \text{ deg}^2$ (and much greater sensitivity)
- Increased sensitivity: stellar systems with larger spatial extent
 - Do galaxies extend to even lower surface brightness?
 - Ultra-faint dwarf galaxies very nearby will be very spatially extended.

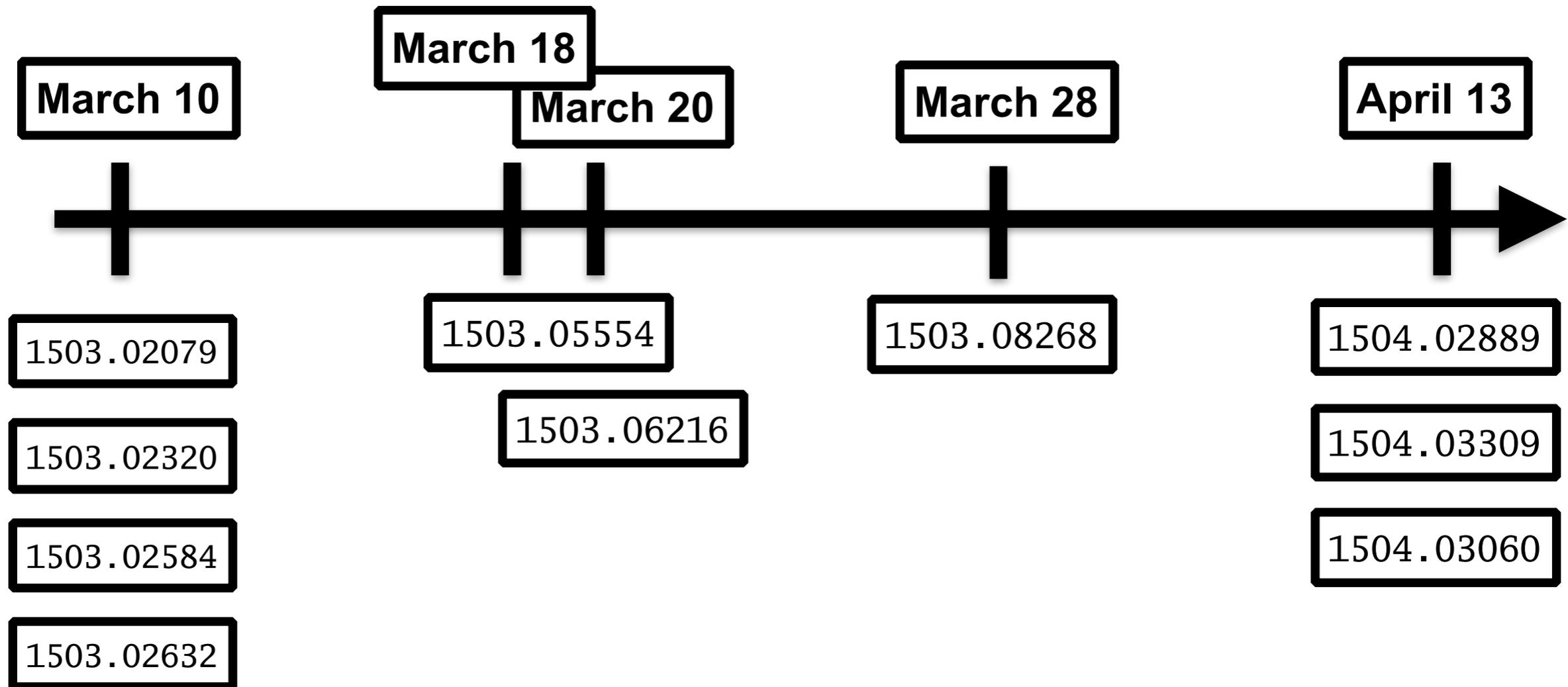


- A large-scale spectroscopy campaign will be necessary to classify and characterize newly discovered systems
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 - LSST: $10,000 \text{ deg}^2$ (and much greater sensitivity)
- Increased sensitivity: stellar systems with larger spatial extent
 - Are there ultra-faint dwarf galaxies very nearby?
 - Are there more distant galaxies with extremely low surface brightness?



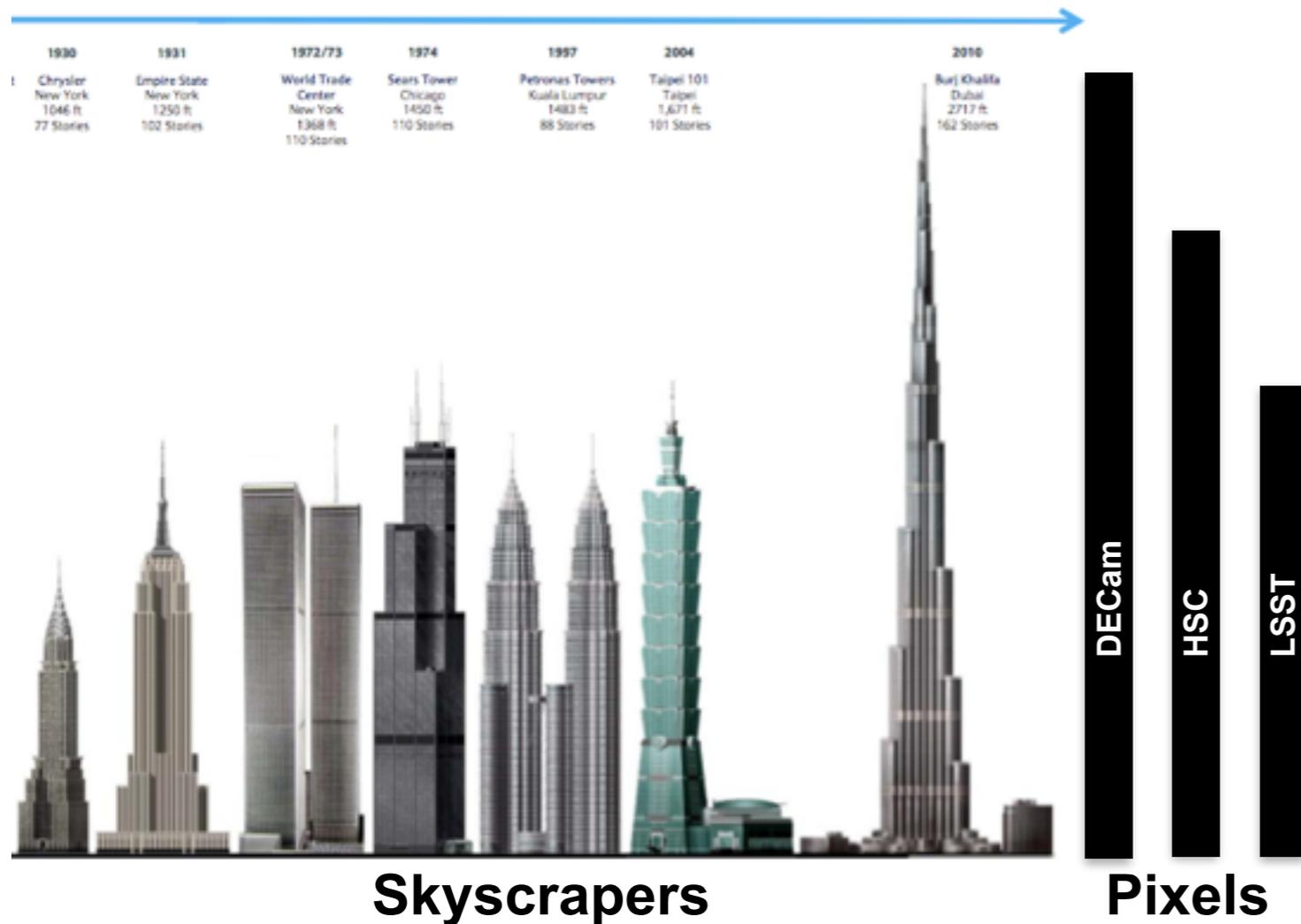
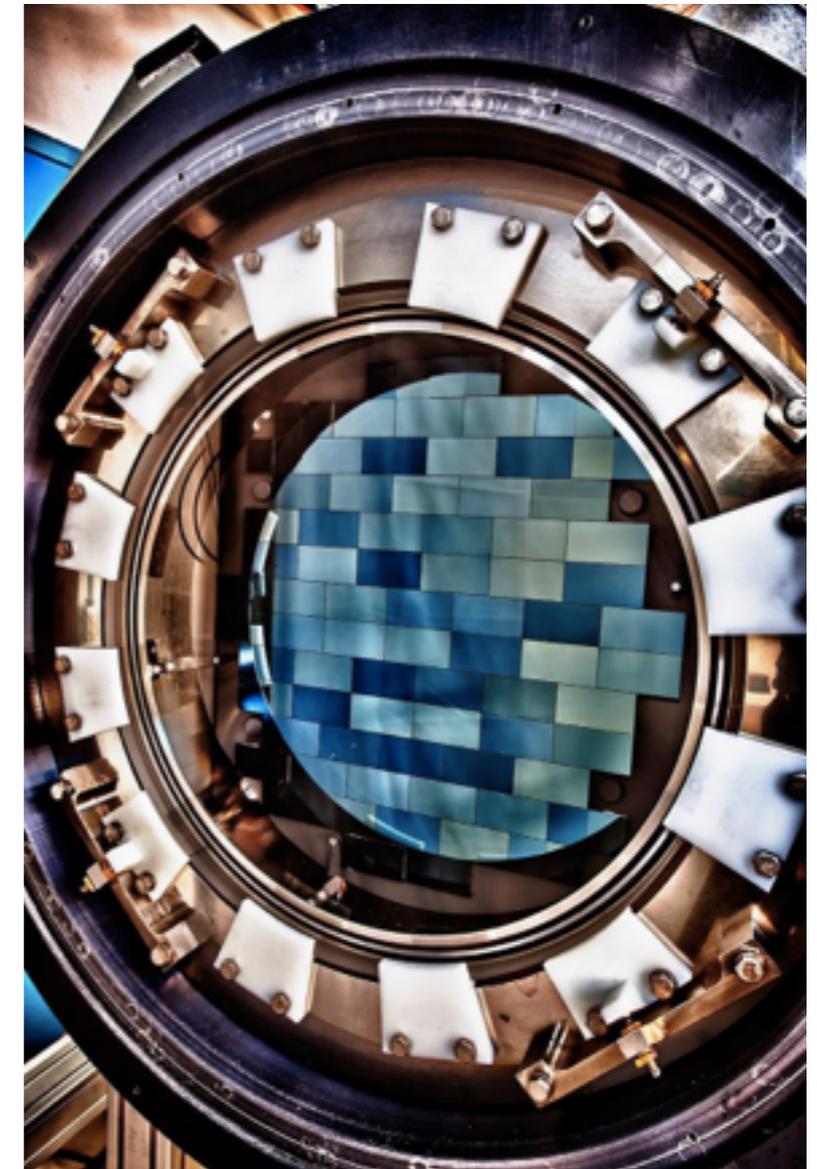
Backup Slides

Timeline

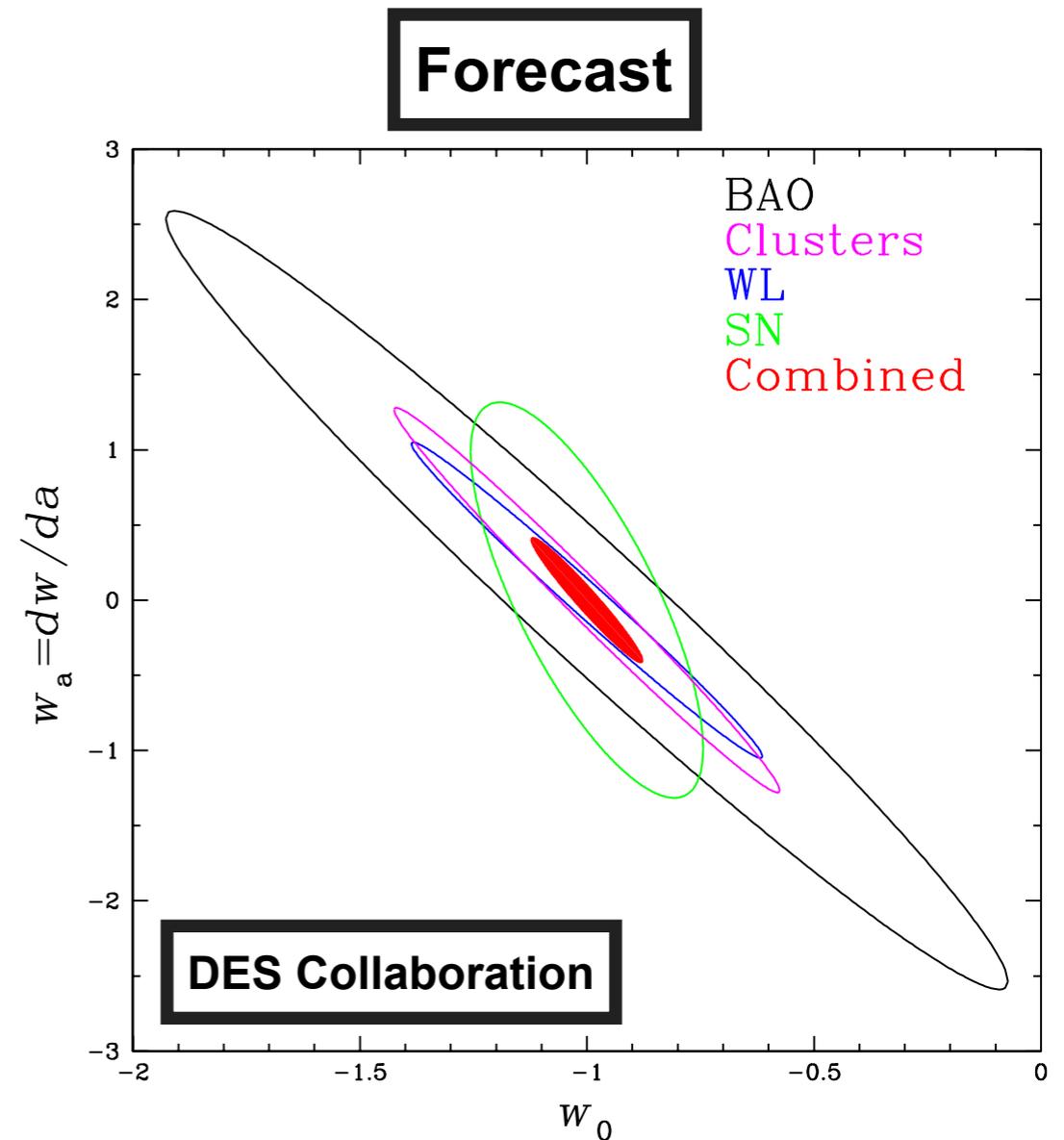


Dark Energy Camera (DECam)

- 570 megapixel camera
- < 20s readout time
- ~3 deg² field-of-view
- Unprecedented sensitivity



- **Fist full of fives:**
 - **525 nights over 5 years**
 - **5,000 deg²**
 - **5 filters: *g,r,i,z,Y***
- **Constrain the dark energy equation of state with:**
 - **Supernova**
 - **Weak Lensing**
 - **Large Scale Structure**
 - **Galaxy Clusters**
- **Unprecedented sensitivity can lead to unexpected discoveries...**



SESSION Y2
1:30PM Holiday 1