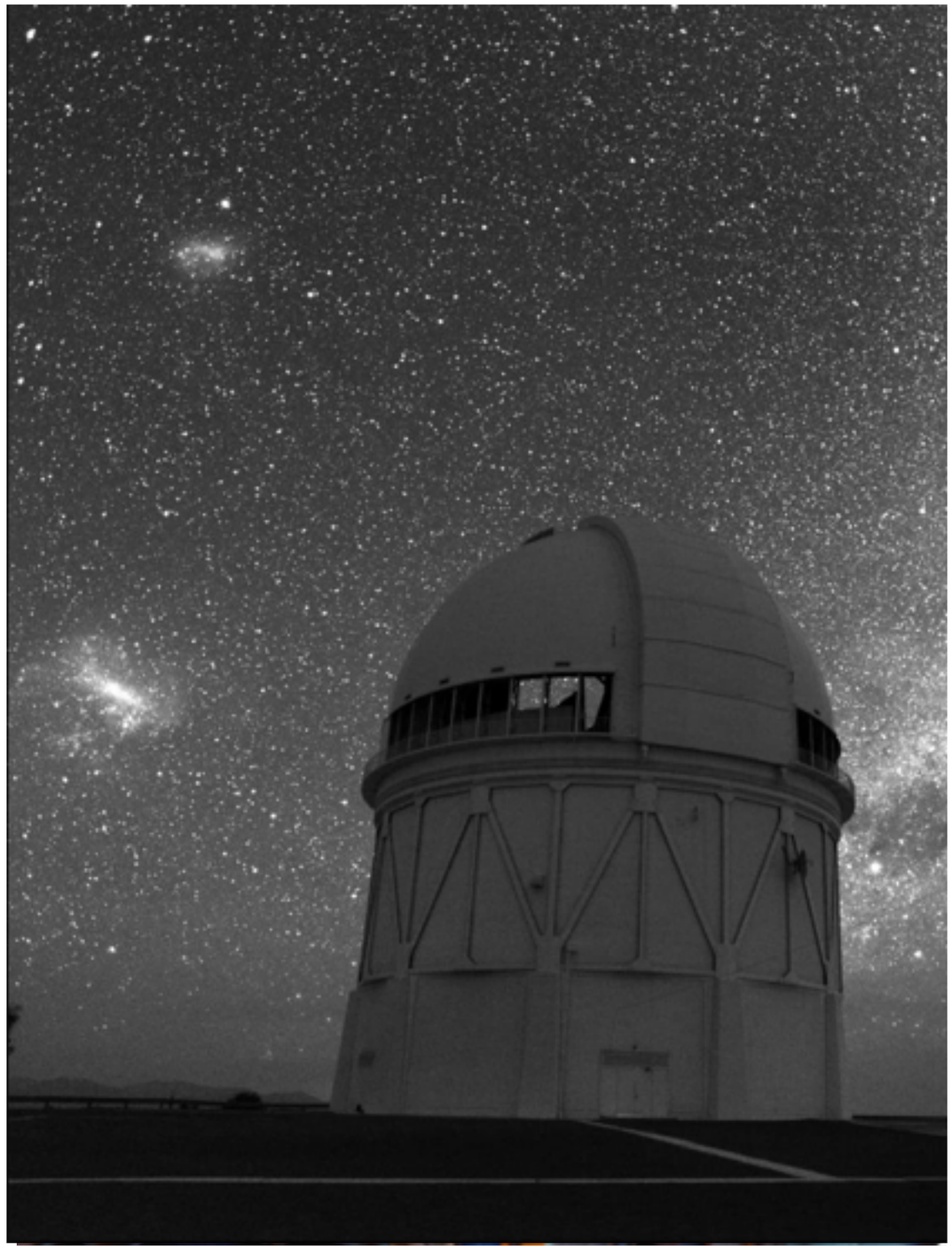
Searching for Milky Way Satellite Galaxies with the Dark Energy Survey

Alex Drlica-Wagner
on behalf of the
DES & Fermi-LAT Collaborations

Mitchell Workshop
May 19, 2015

Fermilab | Center for Particle Astrophysics



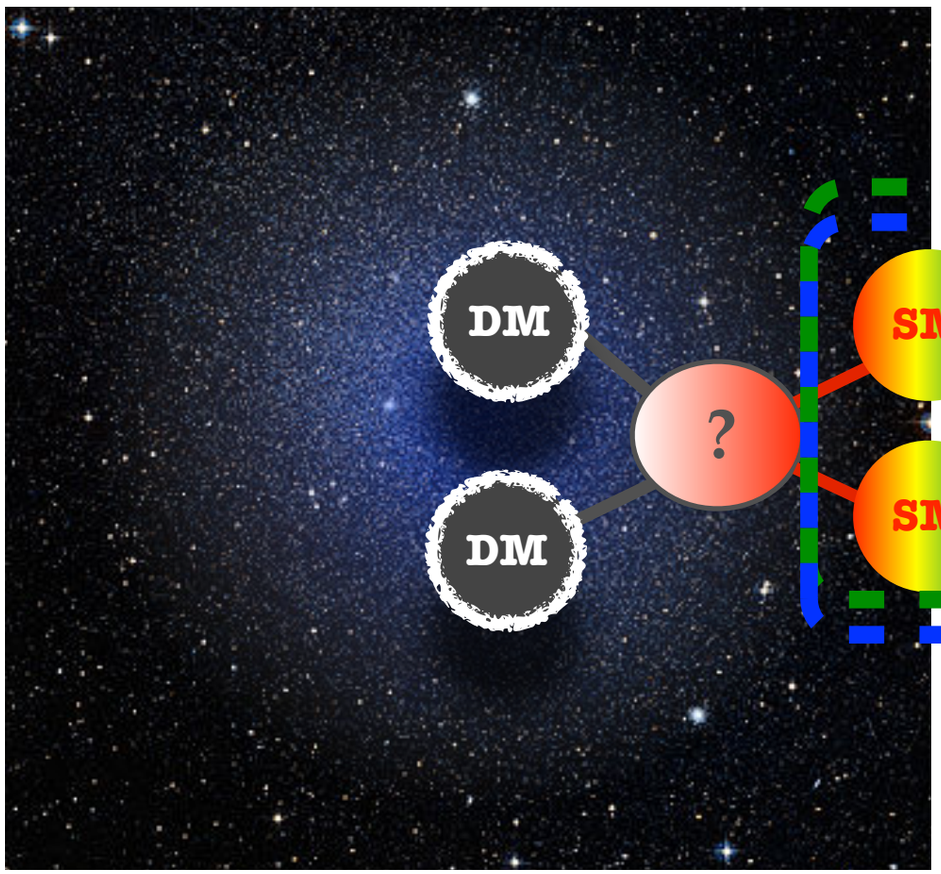
Indirect Detection of Dark Matter Annihilation

Dark Matter Distribution

Particle Propagation

Particle Detection

Dark Matter Annihilation

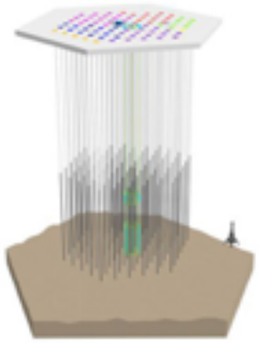


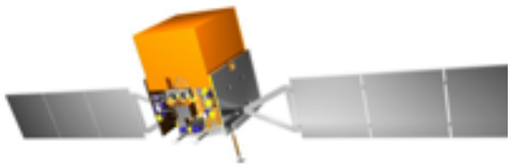
Neutral Particles

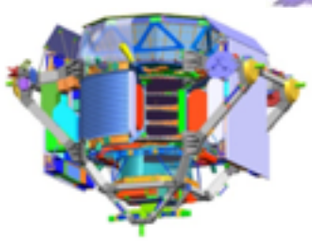
(γ, ν)

Charged Particles

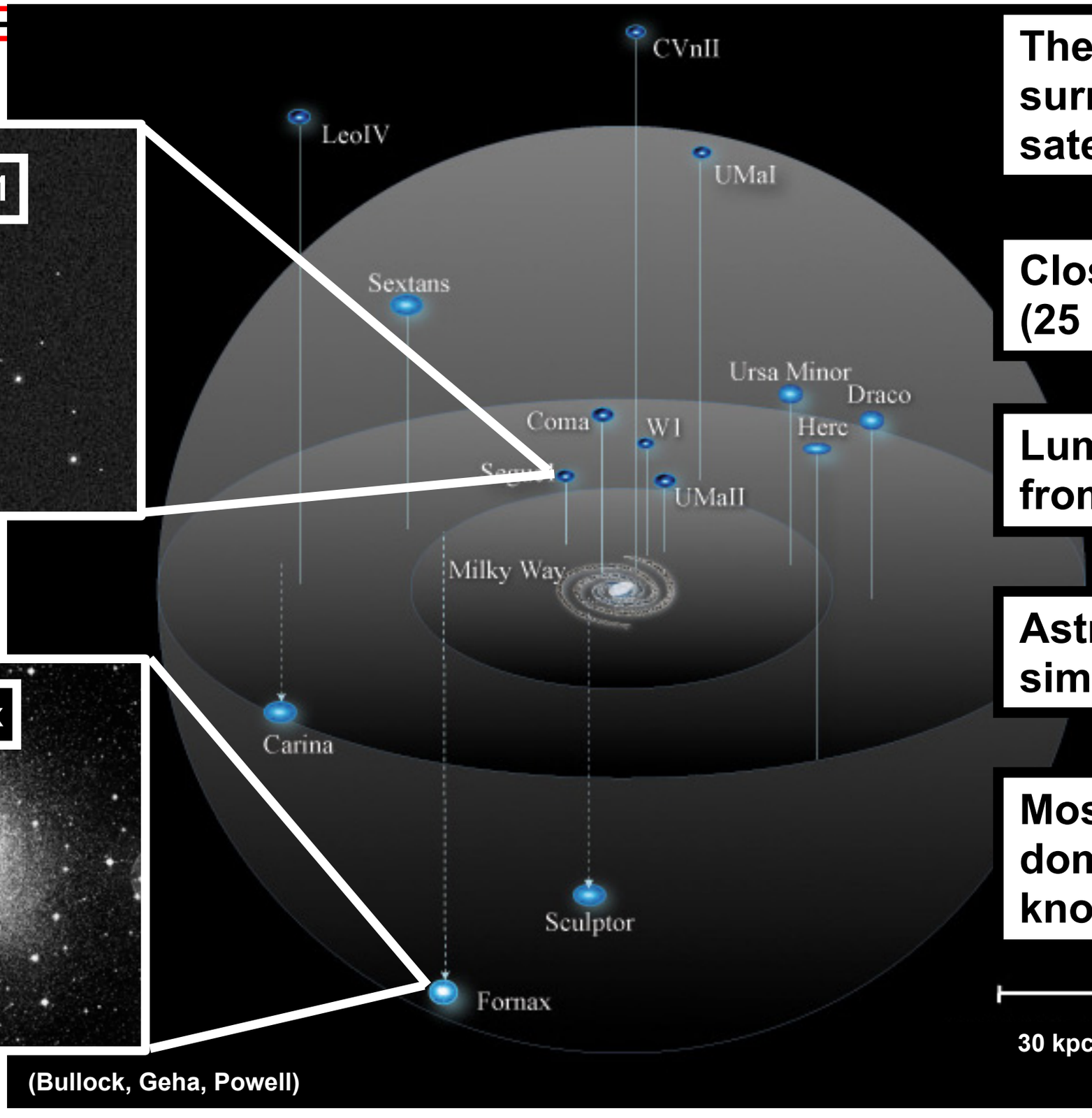
$(e^{\pm}, p^{\pm}, etc.)$

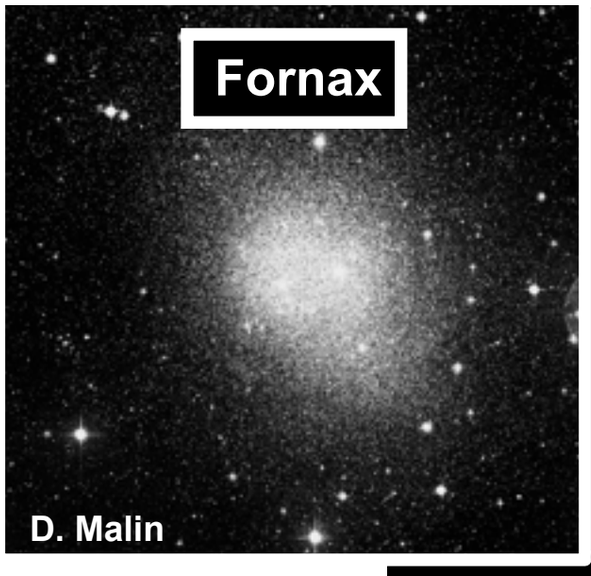






Milky Way Satellite Galaxies





(Bullock, Geha, Powell)

The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

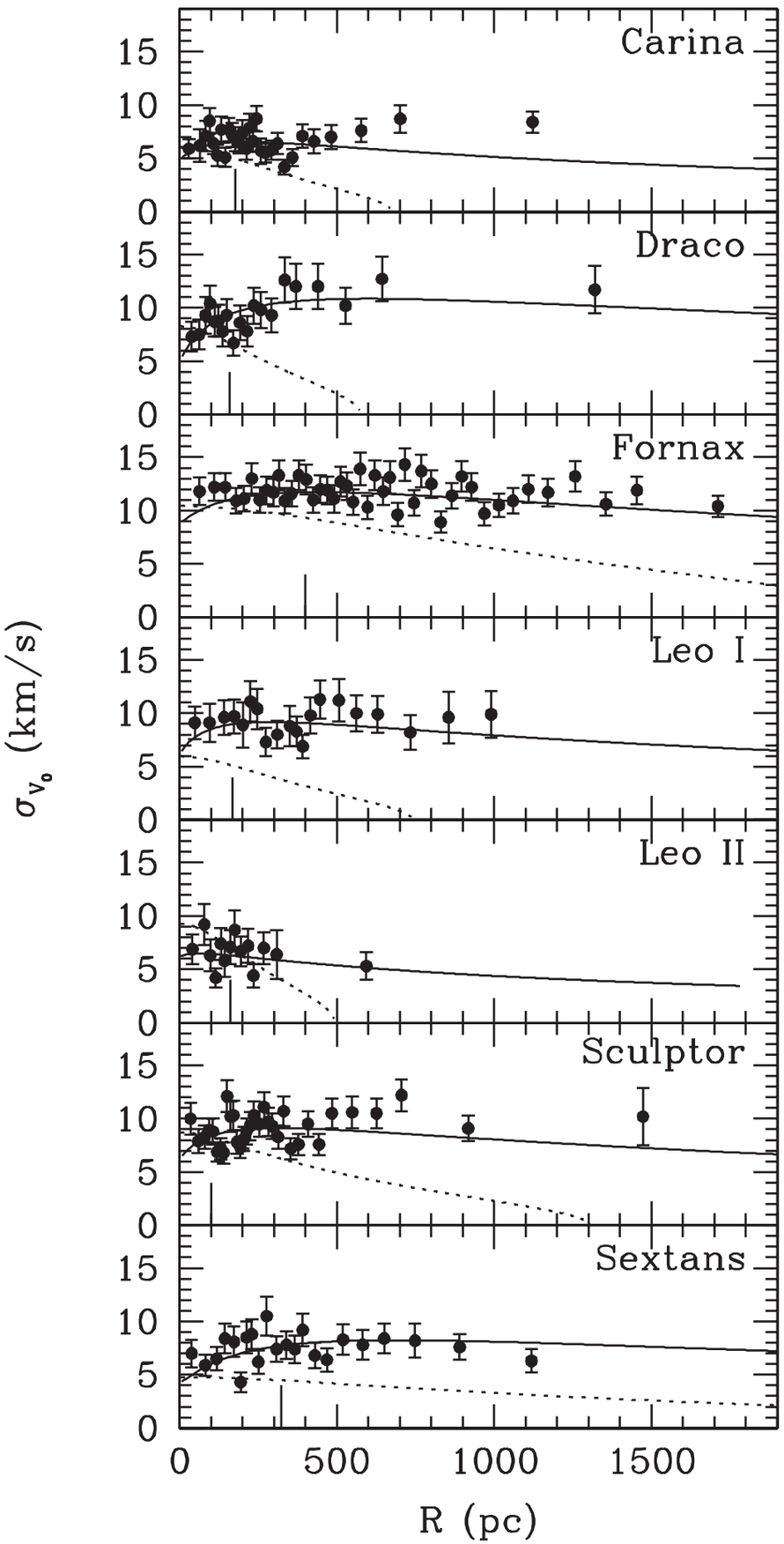
Luminosities range from 10^7 $L_\odot$ to 10^3 $L_\odot$

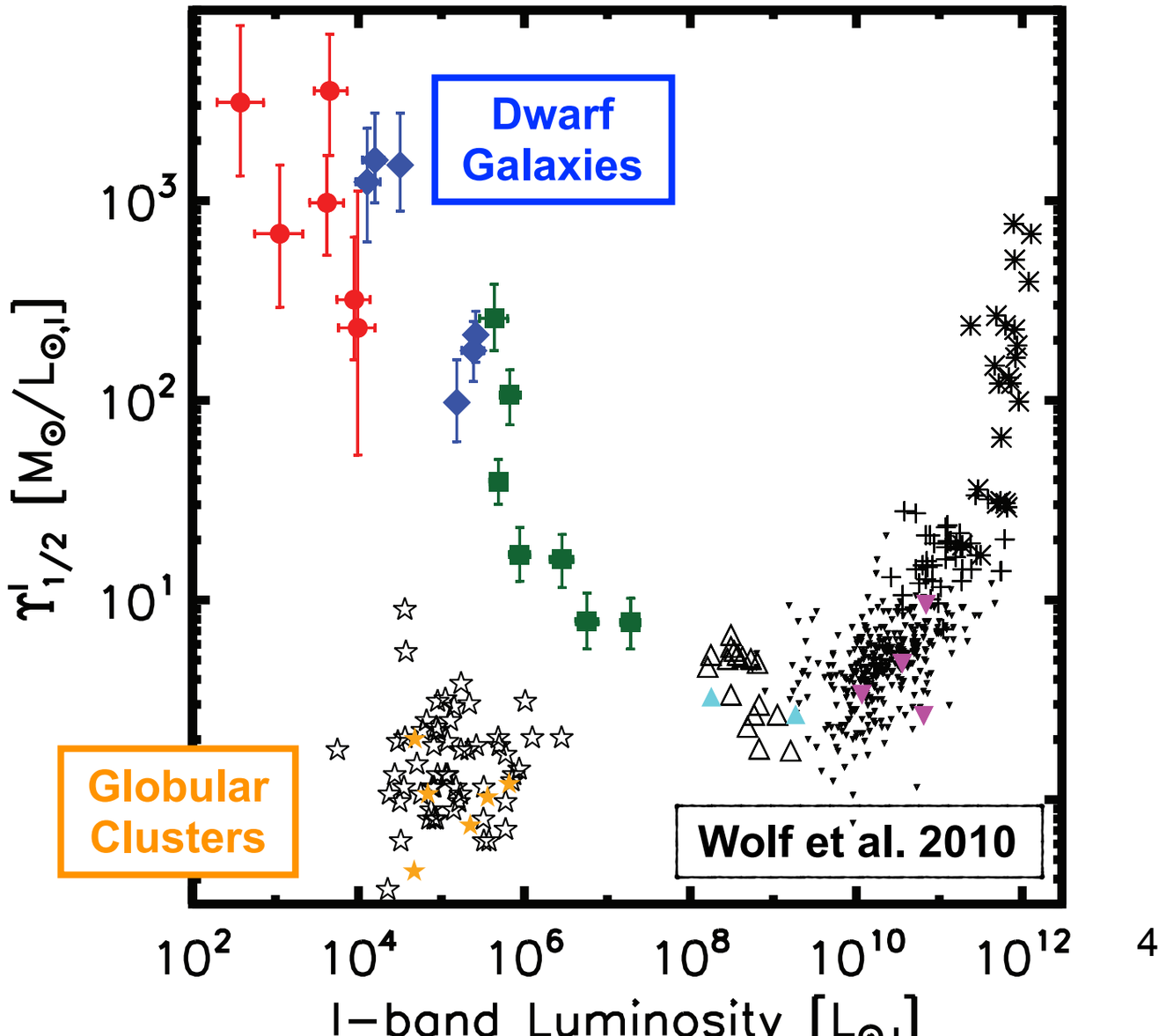
Astrophysically simple

Most dark matter dominated objects known

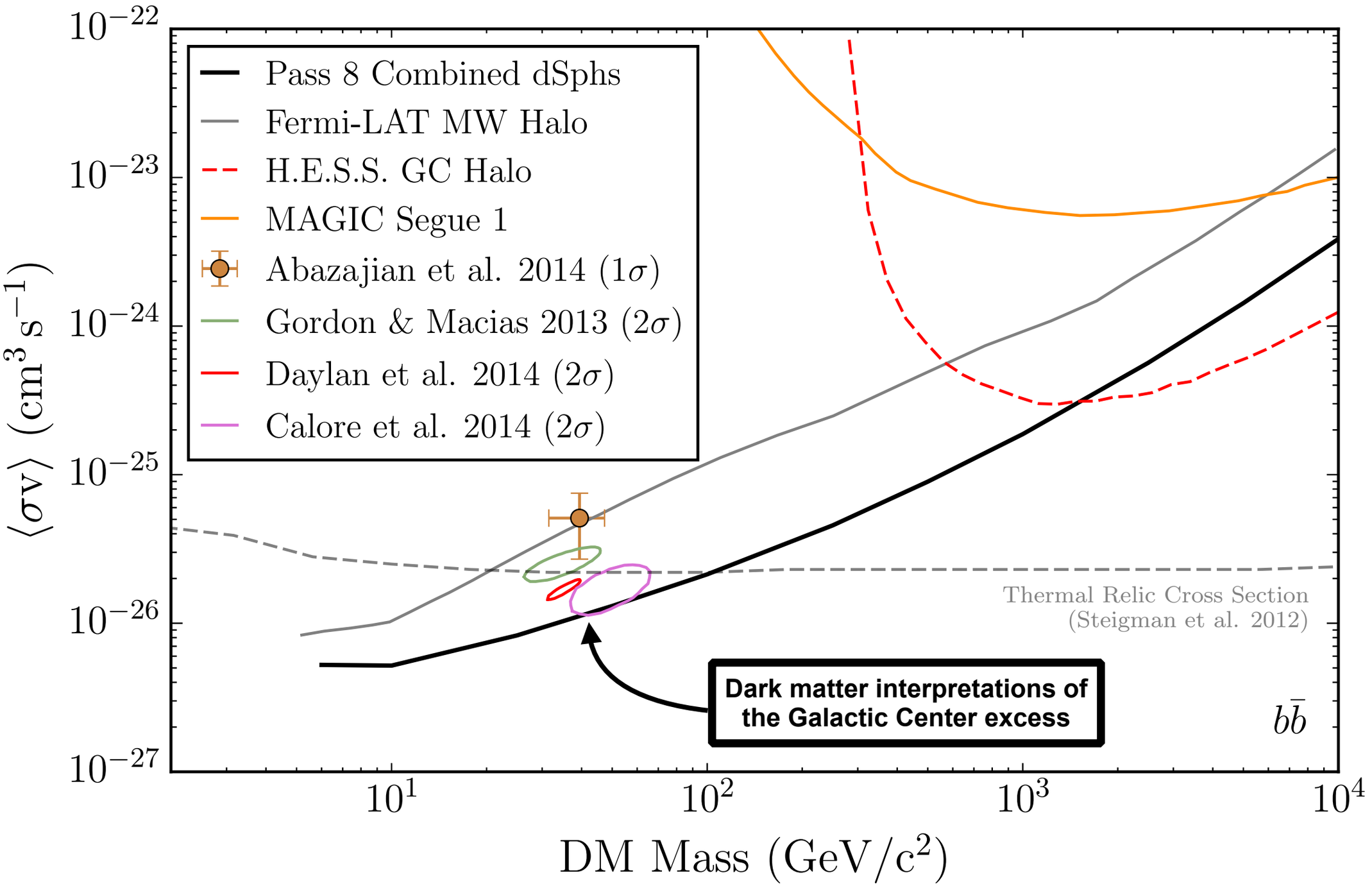
Dark Matter Dominated

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



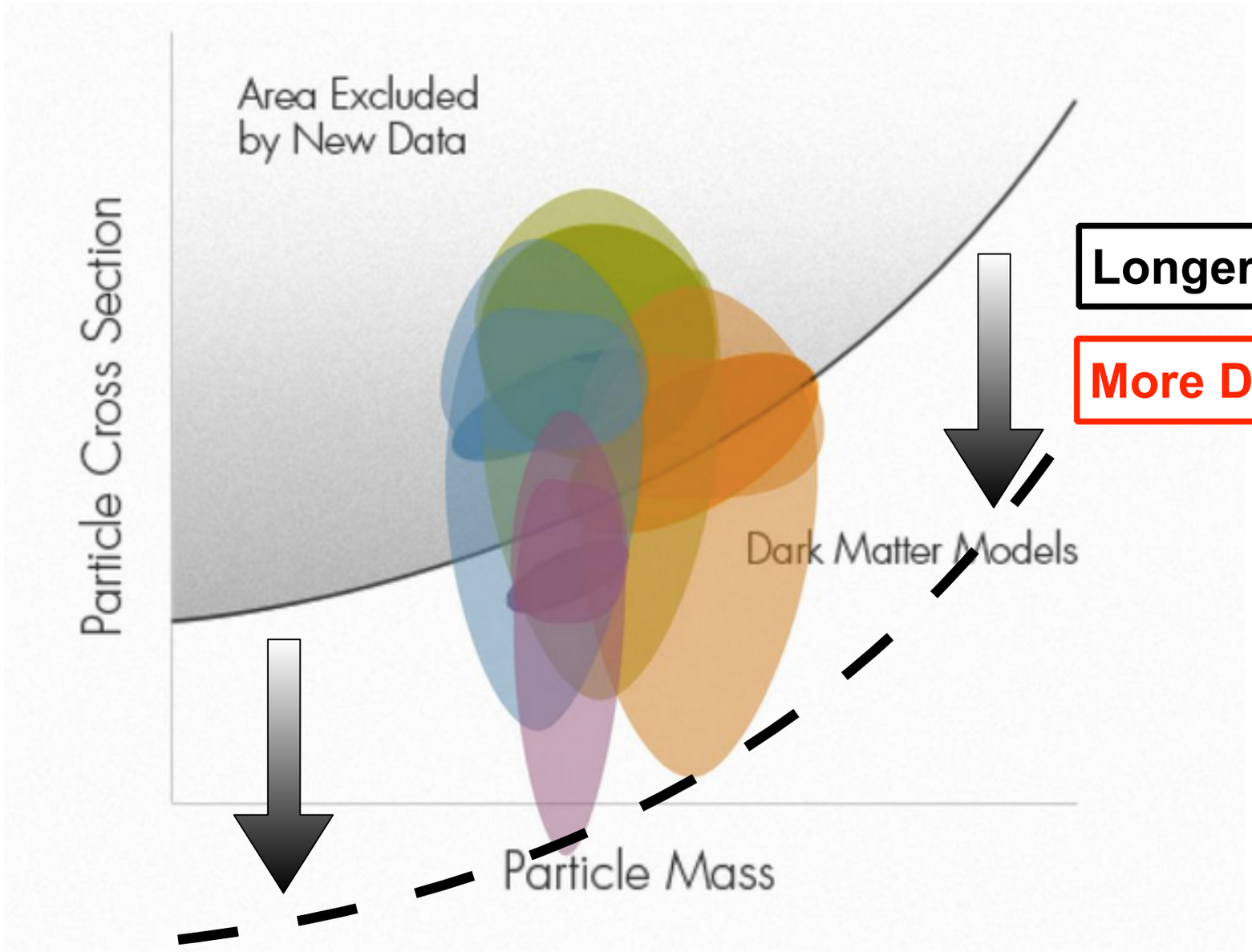


Galactic Center Comparison



Ackermann et al. 2015 (1503.02641)

Galactic Center Comparison



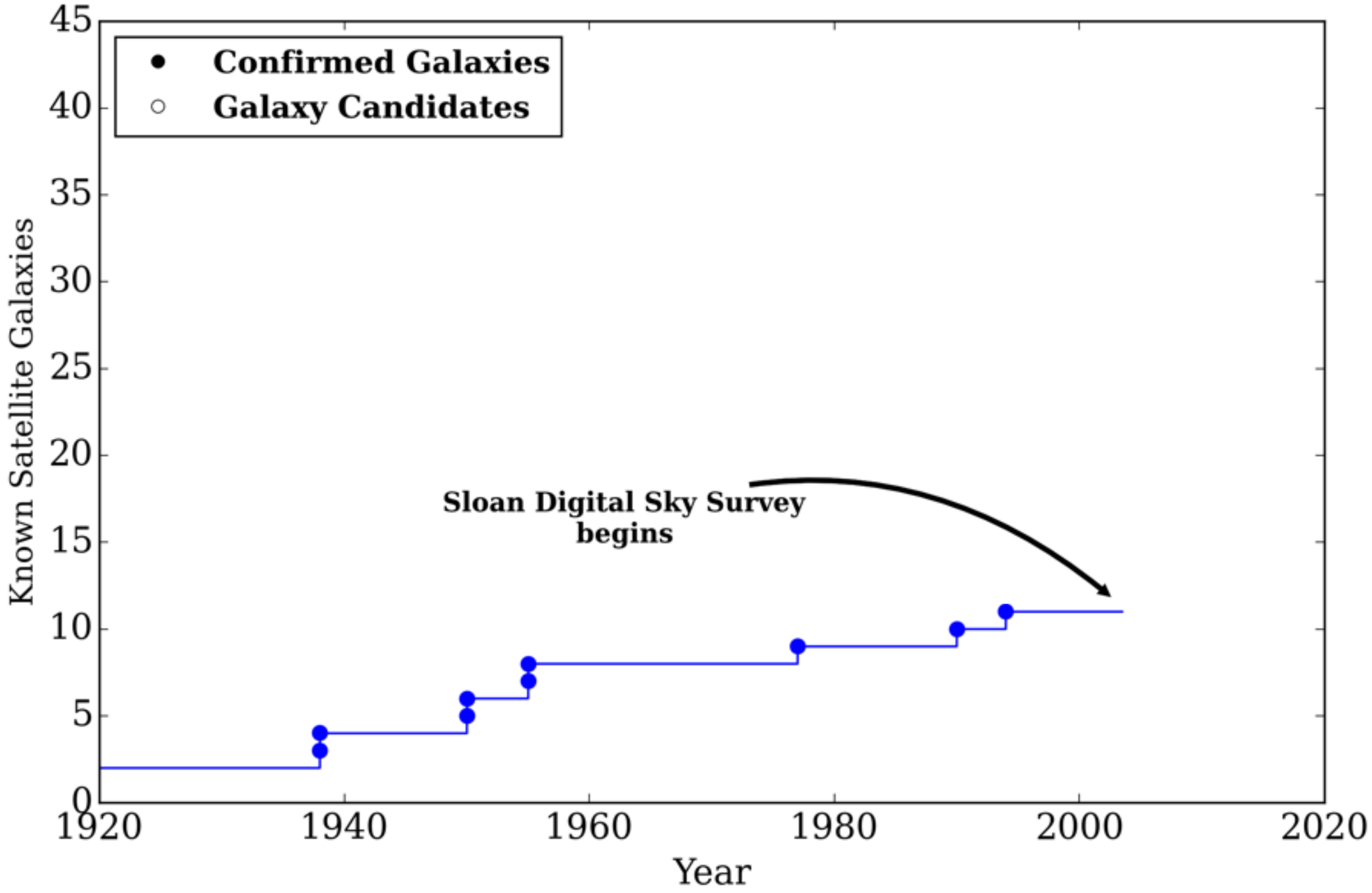
Kevork Abazajian @kevaba · Oct 25

@QuantaMagazine @nattyover I corrected the figure for the article to reflect the approx. halo density uncert to 2σ

1

Finding Milky Way Satellite Galaxies

Milky Way Satellite Galaxies Discovery Timeline



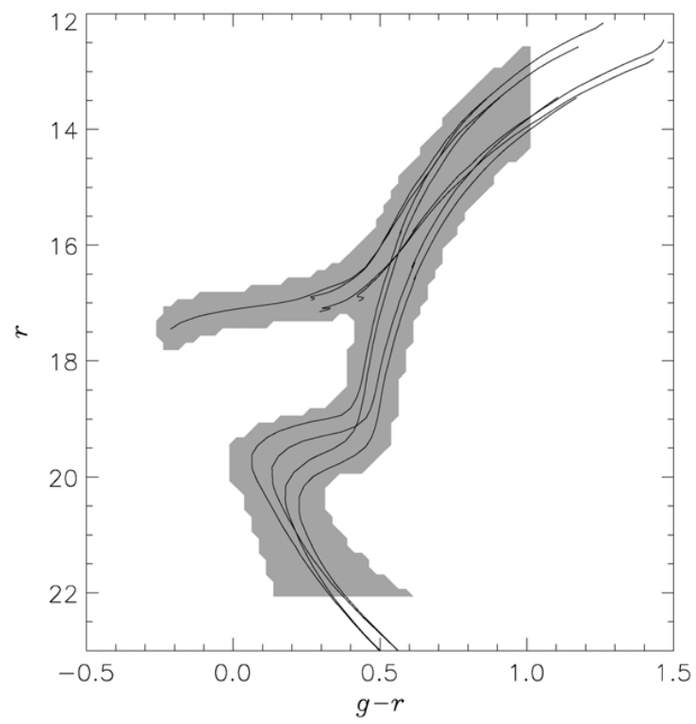
Finding Milky Way Satellite Galaxies

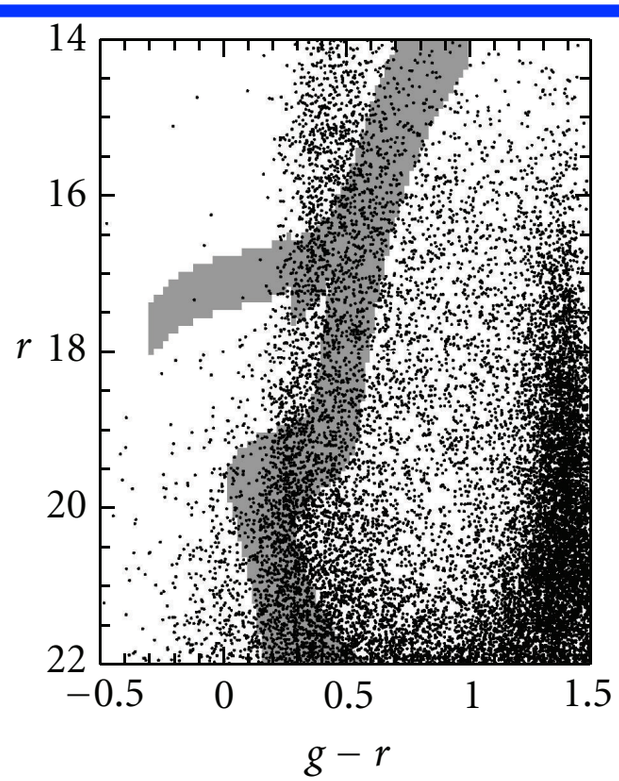
THE DARK ENERGY SURVEY

Fermilab

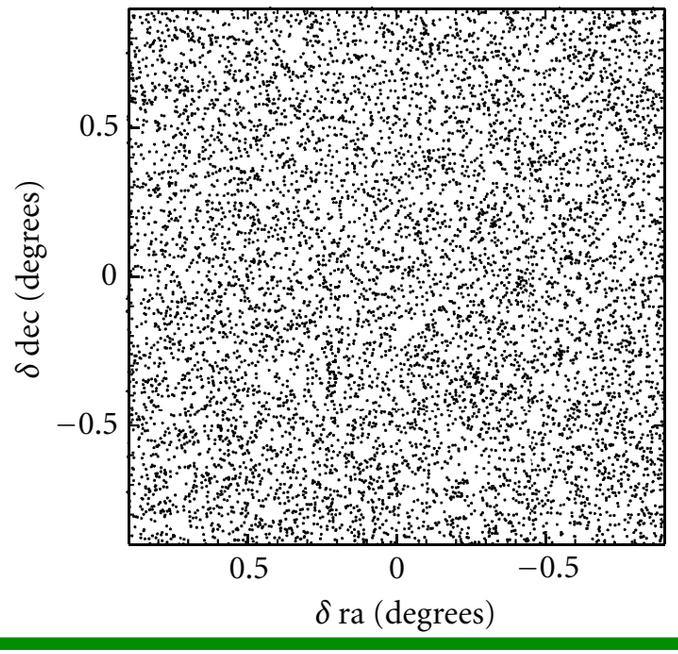
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

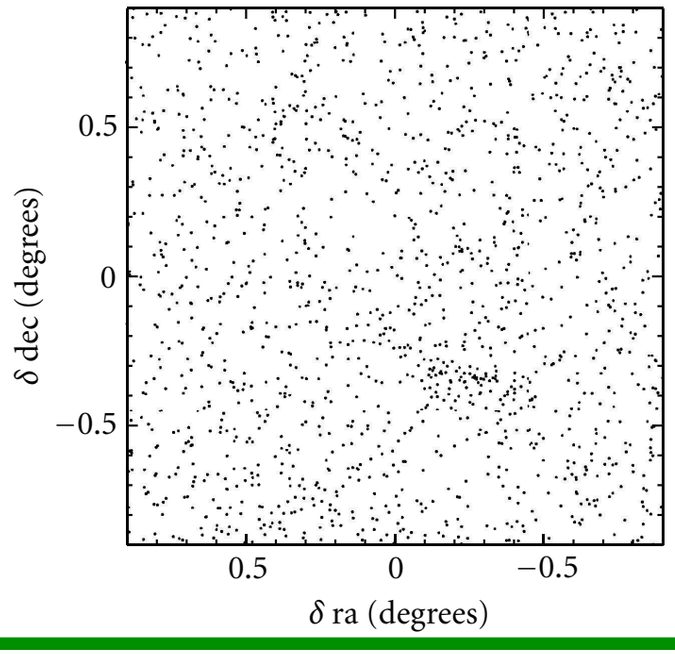
Color-Magnitude Domain

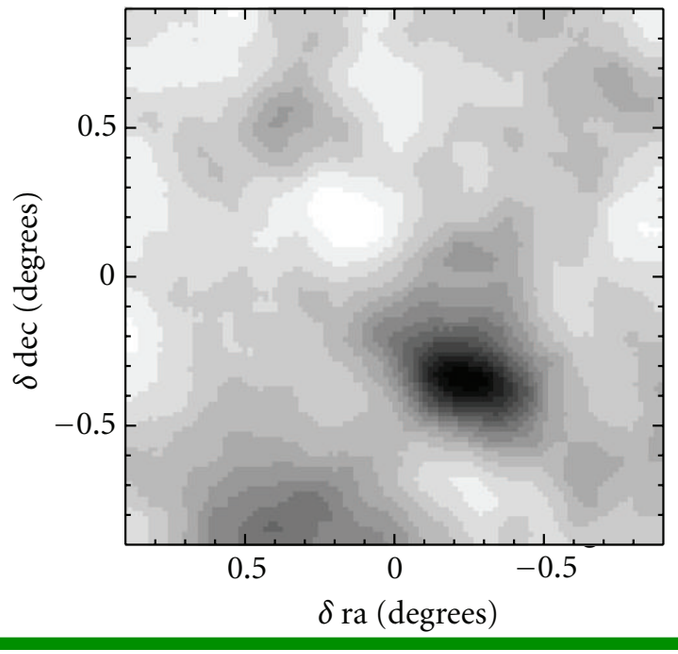




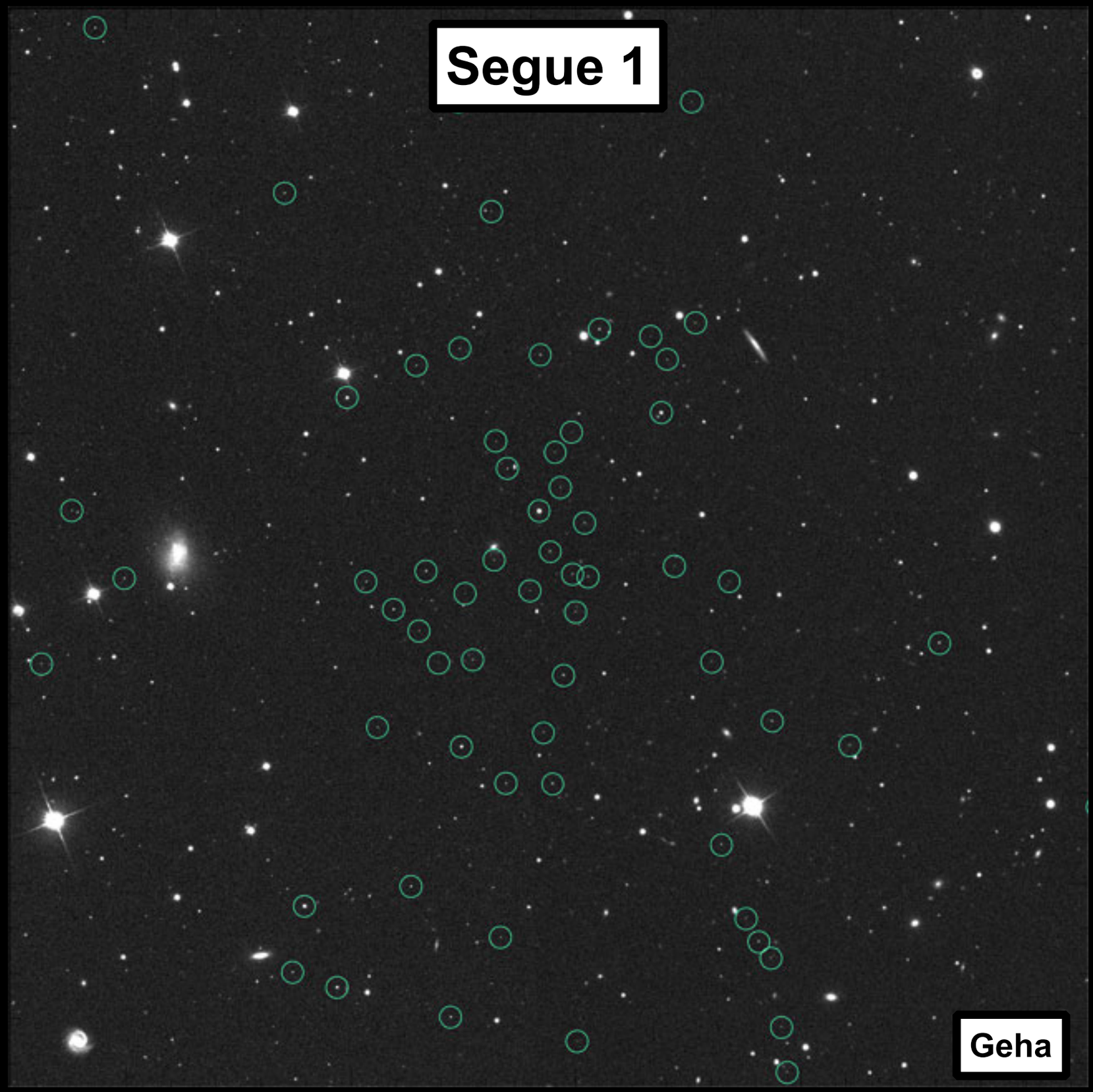
Spatial Domain



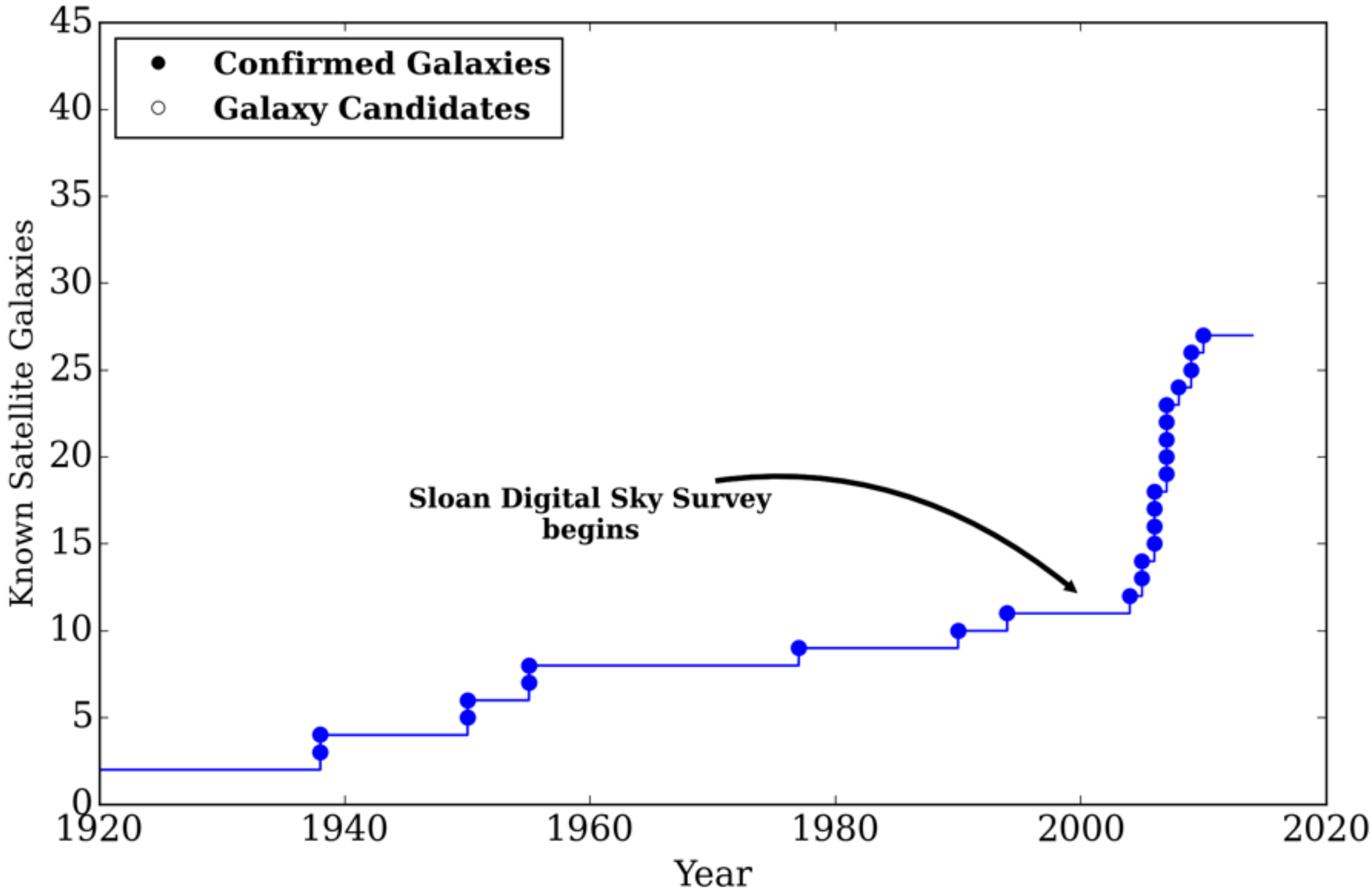




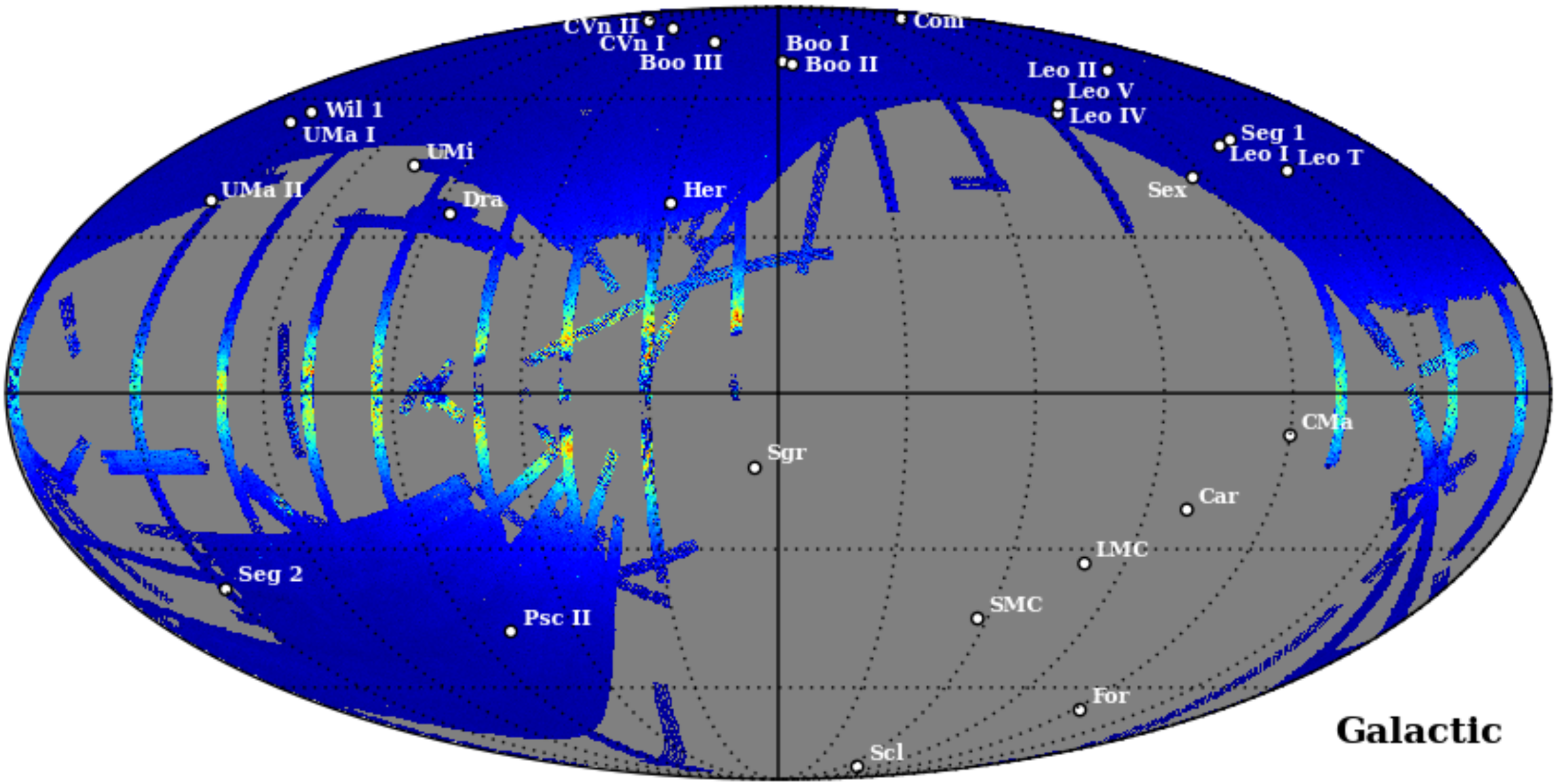

Segue 1
Geha


Segue 1
Geha

Milky Way Satellite Galaxies Discovery Timeline



SDSS DR10


CVn II
CVn I
Boo III
Com
Boo I
Boo II
Leo II
Leo V
Leo IV
Seg 1
Leo I
Leo T
Wil 1
UMa I
UMi
UMa II
Dra
Her
Sex
CMa
Sgr
Car
LMC
SMC
Seg 2
Psc II
For
Scl
Galactic

www.physicstoday.org

physics today

April 2014

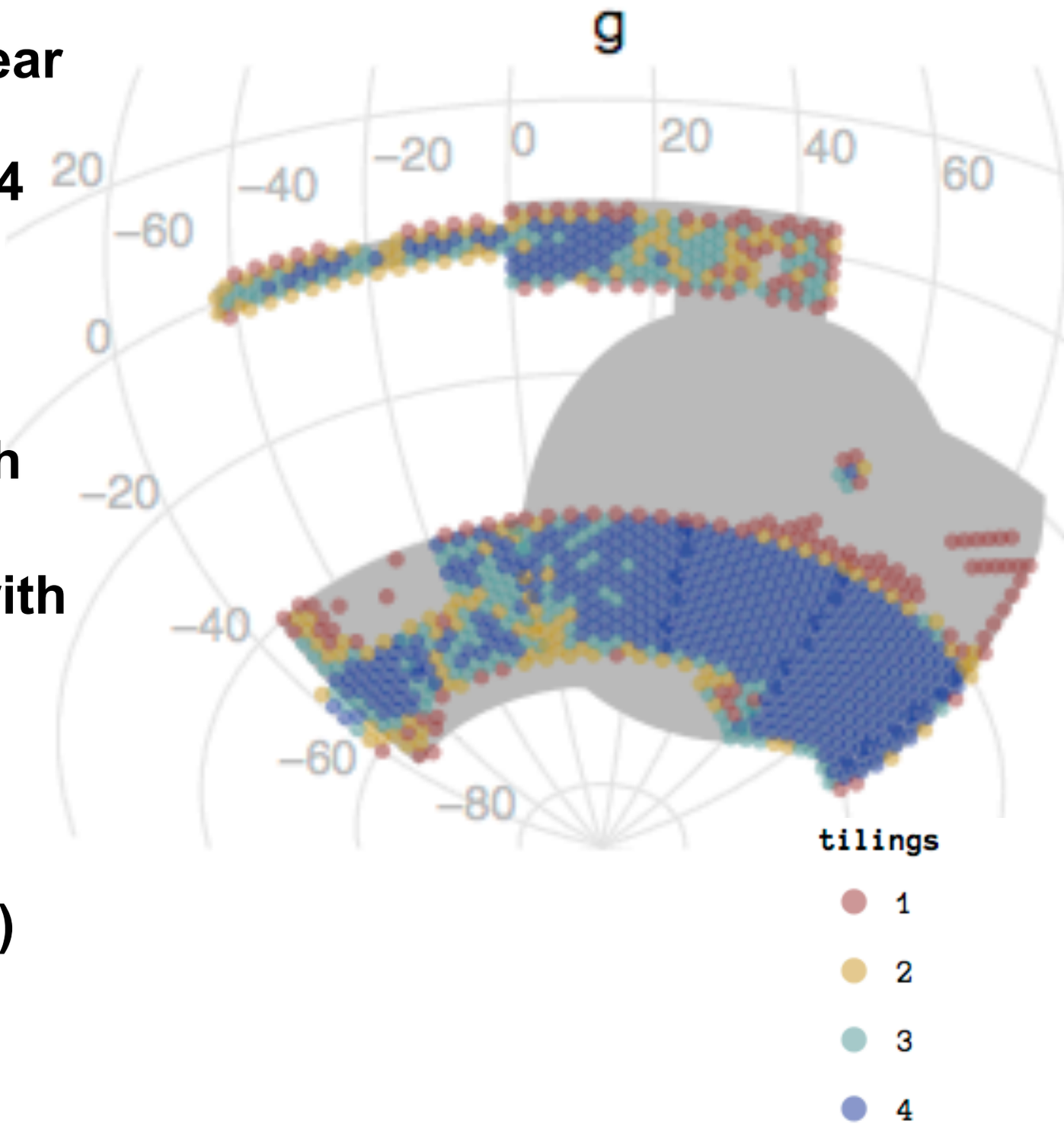
A publication of the American Institute of Physics

volume 67, number 4

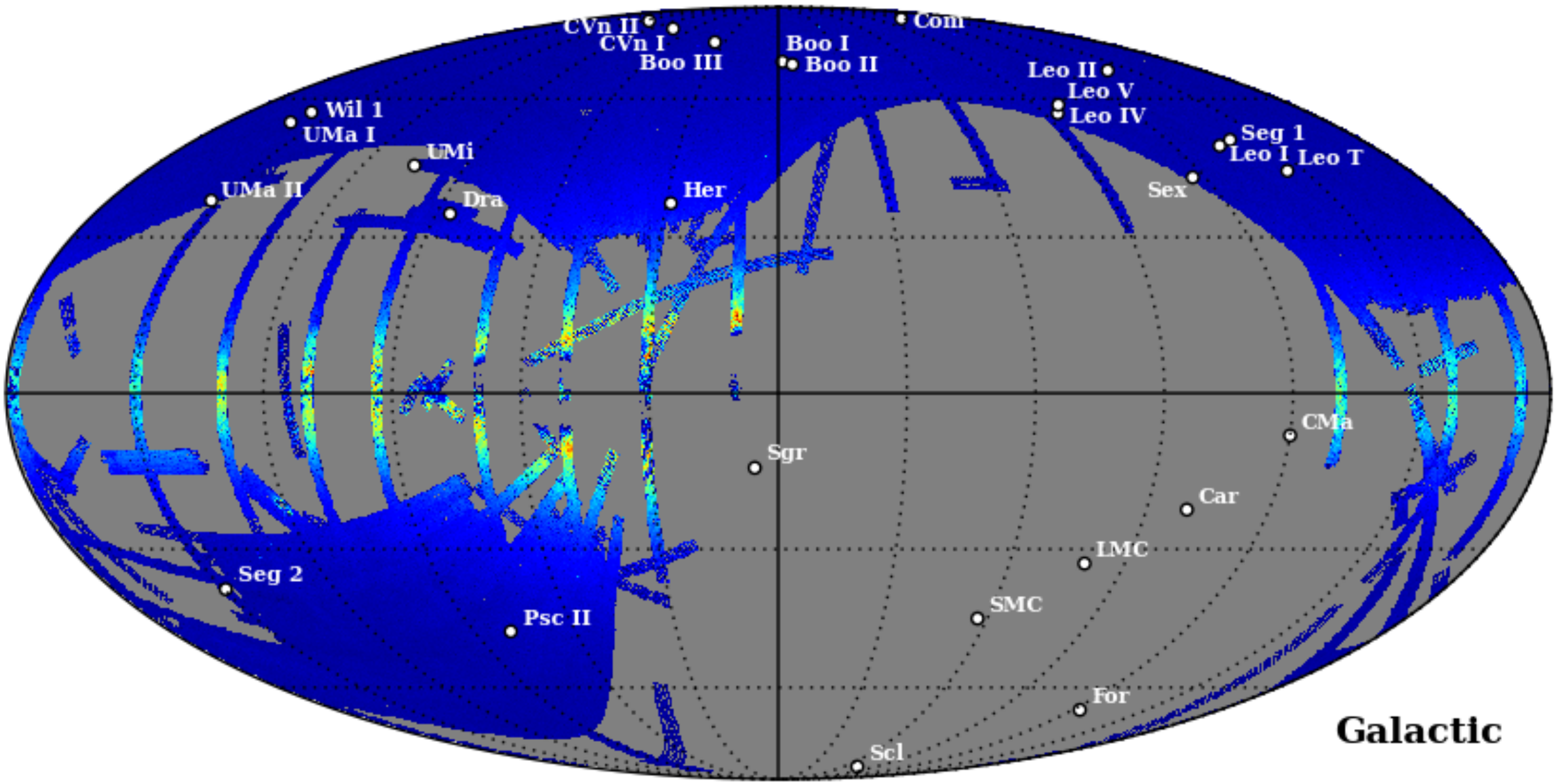
The Dark Energy Survey

DES Year-One (Y1A1)

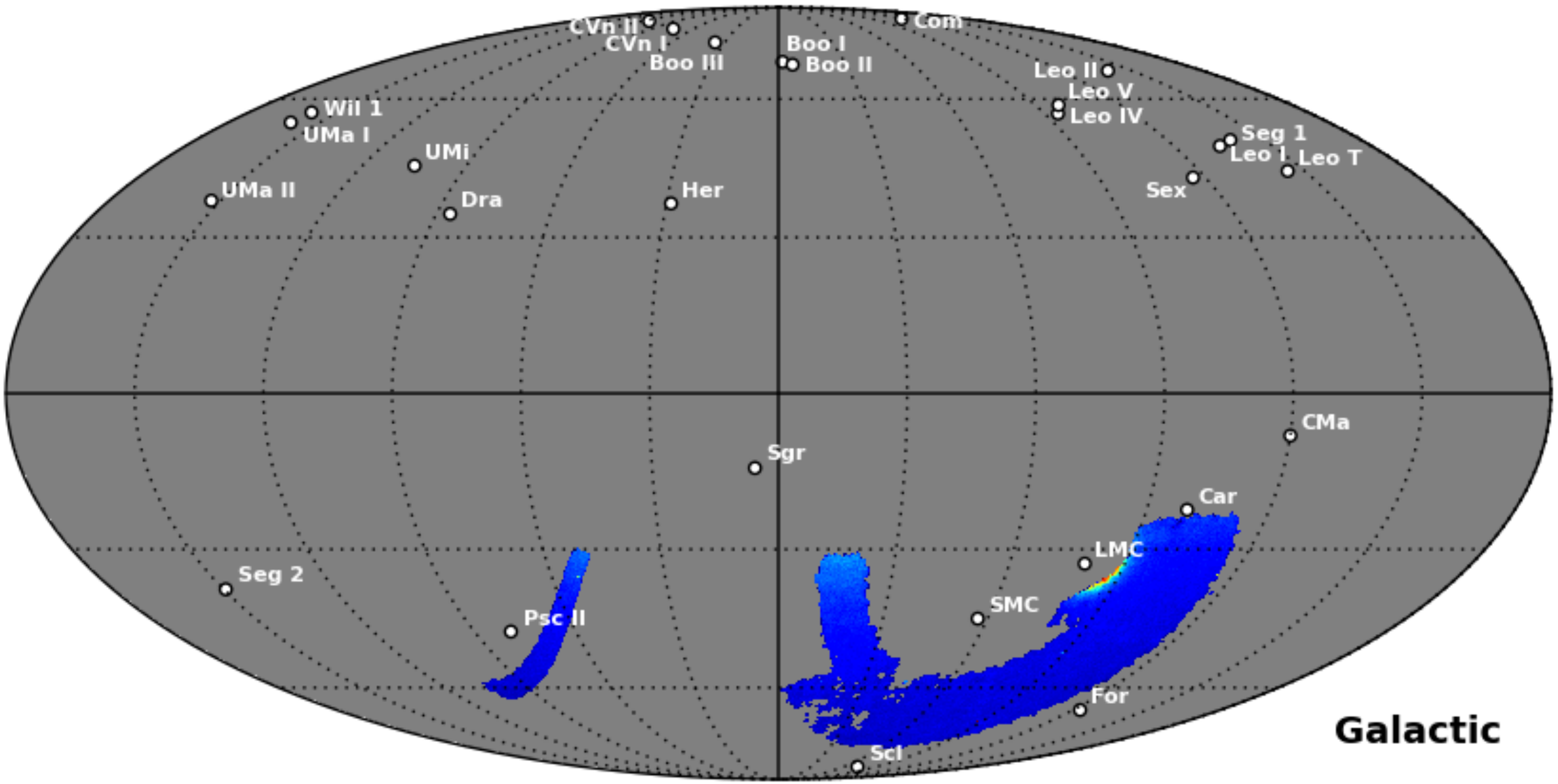
- **Imaging data from the first year of the survey:**
  August 2013 to February 2014
- **~12,000 science exposures**
- **Coadded image catalog covering ~1800 deg^2**
  - **~200 deg^2 overlapping with SDSS Stripe-82**
  - **~1600 deg^2 overlapping with the South Pole Telescope**
- **Stellar completeness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



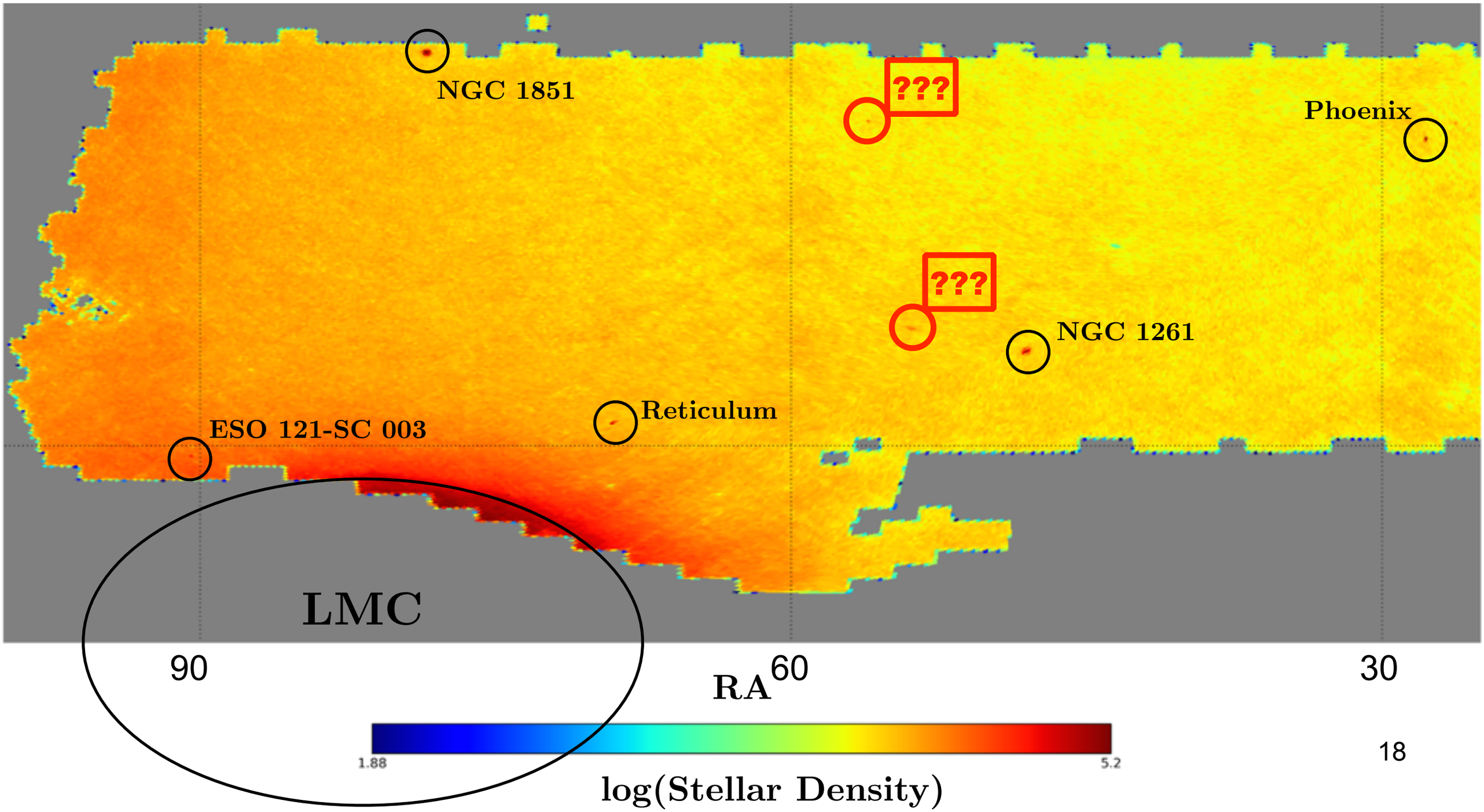
SDSS DR10


CVn II
CVn I
Boo III
Com
Boo I
Boo II
Leo II
Leo V
Leo IV
Seg 1
Leo I
Leo T
Wil 1
UMa I
UMi
UMa II
Dra
Her
Sex
CMa
Sgr
Car
LMC
Seg 2
Psc II
SMC
For
Scl
Galactic

DES Y1A1

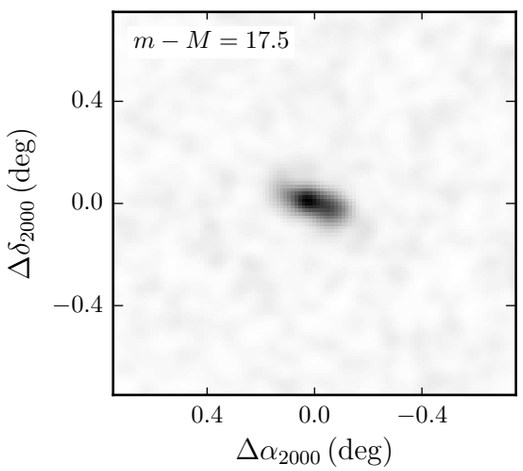

CVn II
CVn I
Boo III
Boo I
Boo II
Com
Leo II
Leo V
Leo IV
Wil 1
UMa I
UMi
Seg 1
Leo I
Leo T
UMa II
Dra
Her
Sex
CMa
Sgr
Car
LMC
Seg 2
Psc II
SMC
For
Scl
Galactic

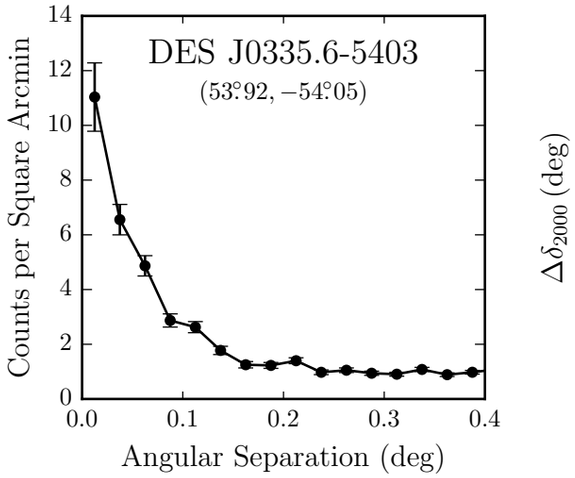
Y1A1: A First Look

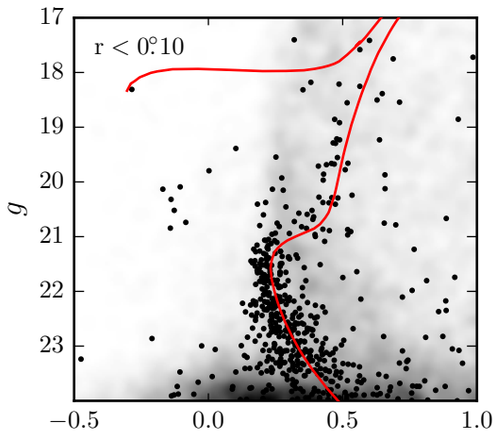


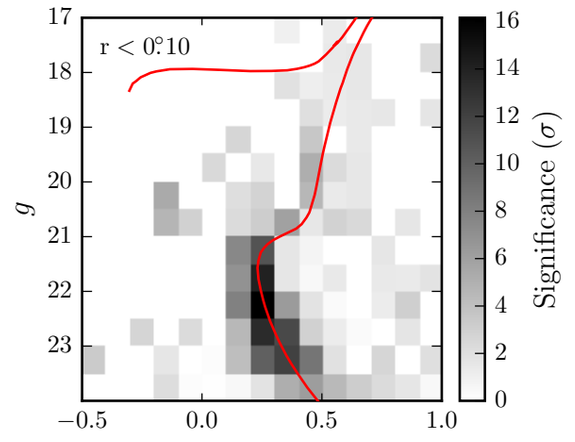
Y1A1: A First Look

Reticulum II (DES J0335.6-5403)

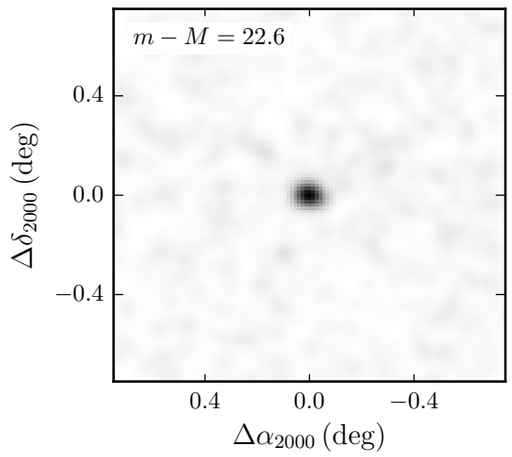


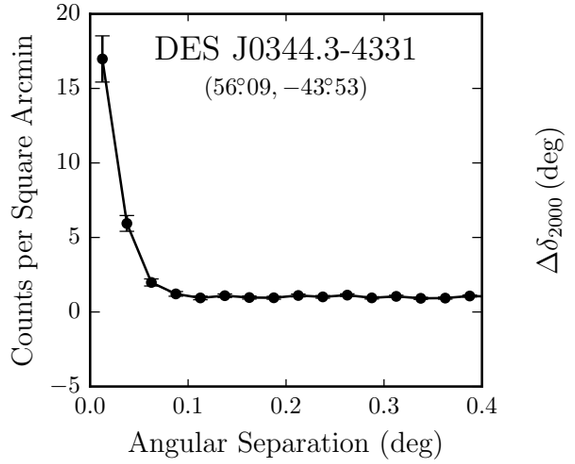


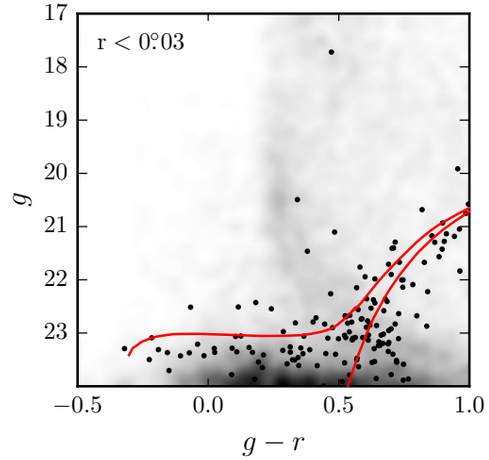


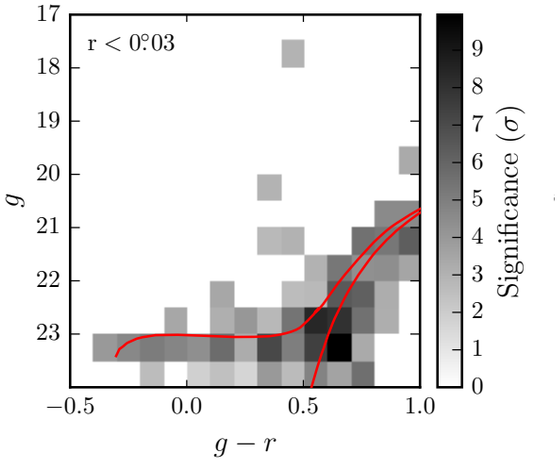


Eridanus II (DES J0344.3-4331)





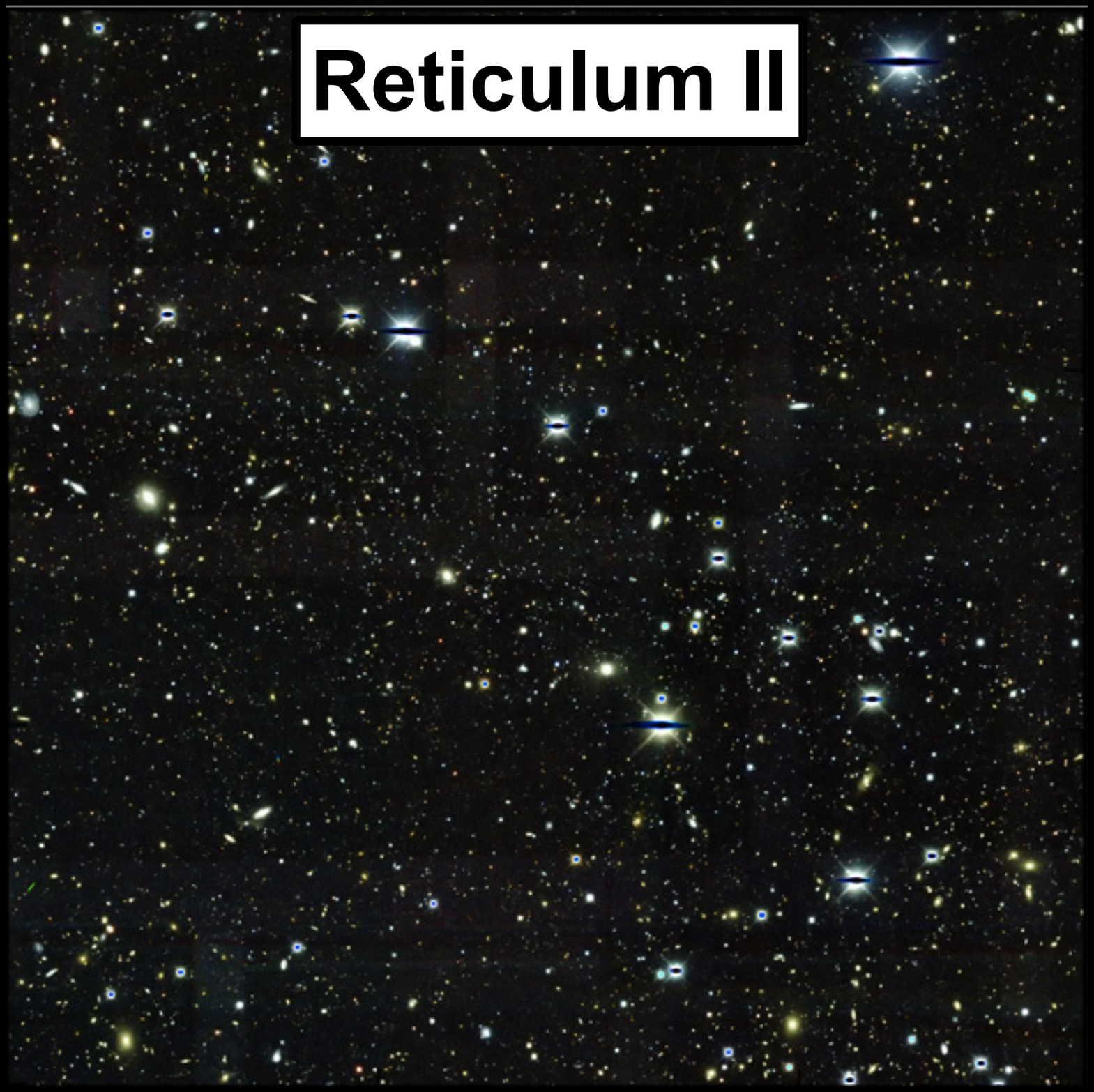




arXiv:1503.02584

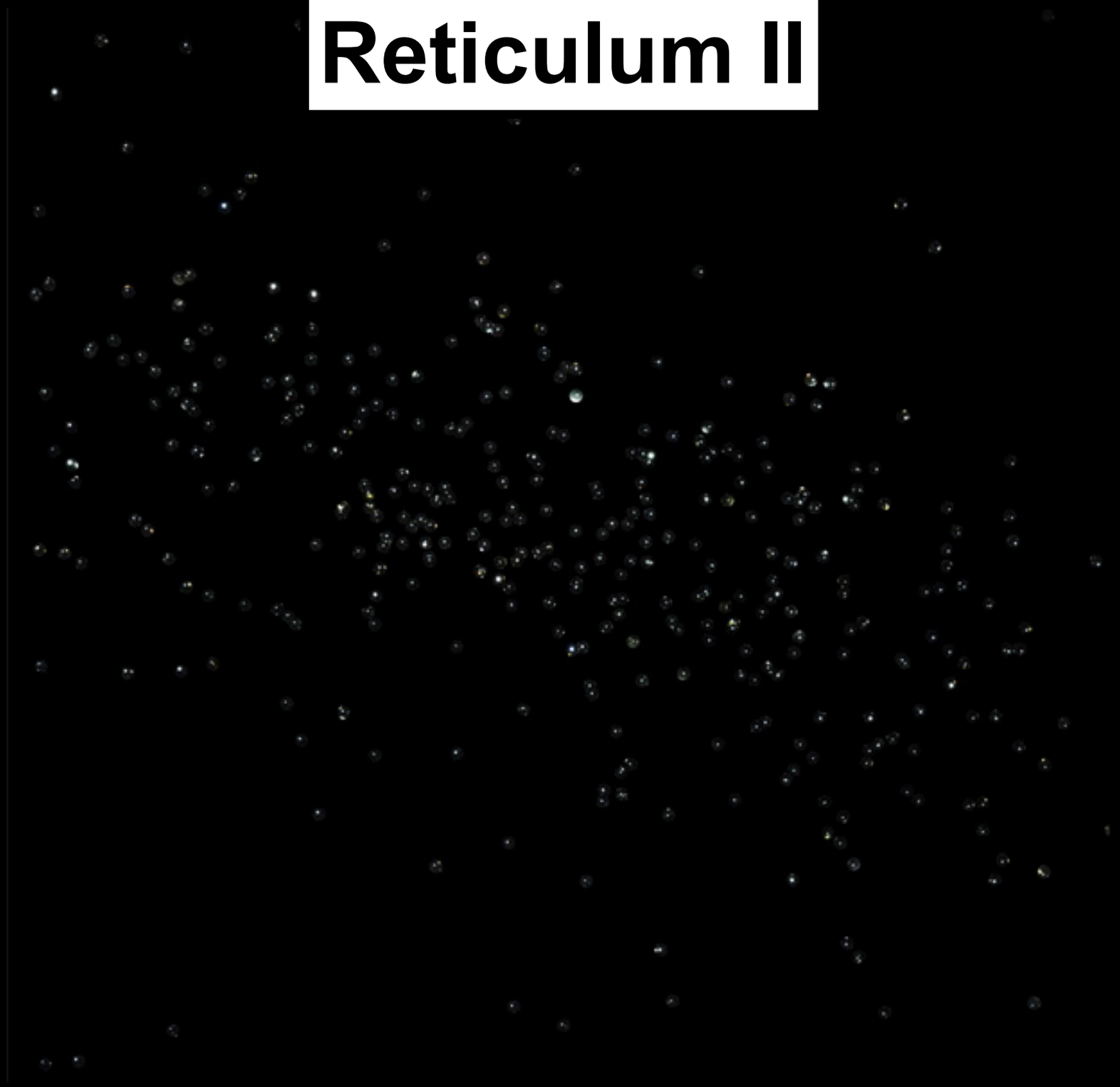
arXiv:1503.02079

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

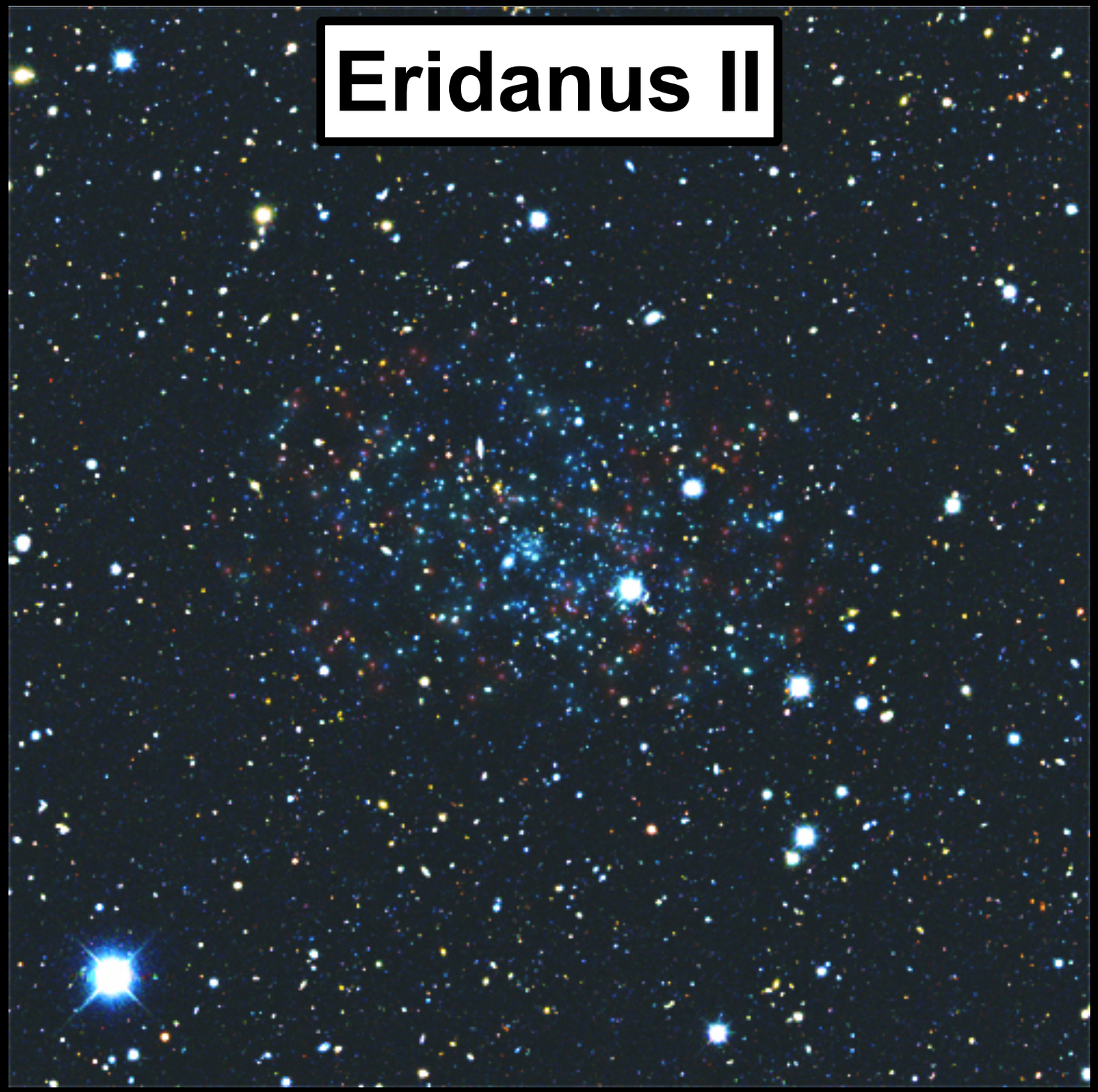


DES Collaboration

Reticulum II



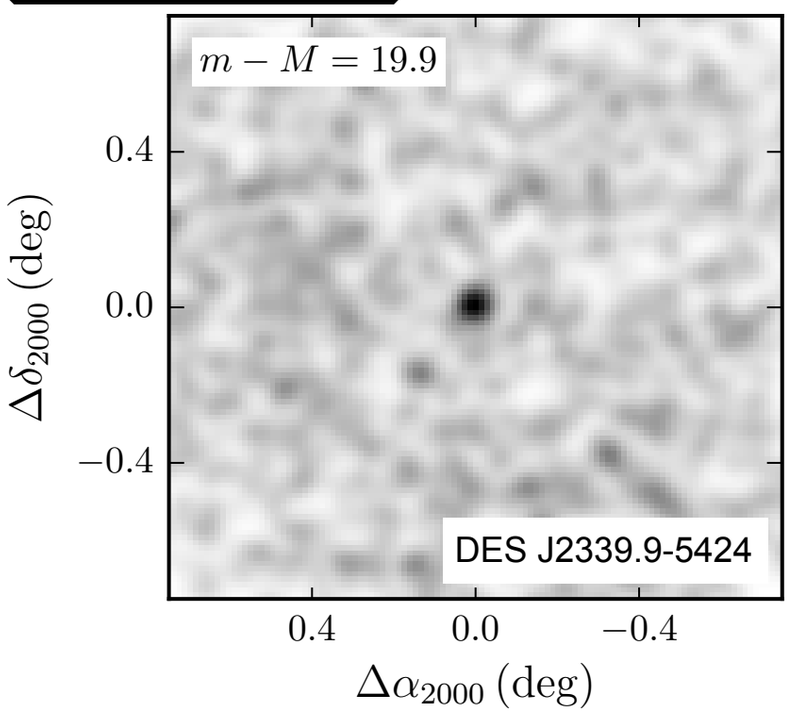
DES Collaboration

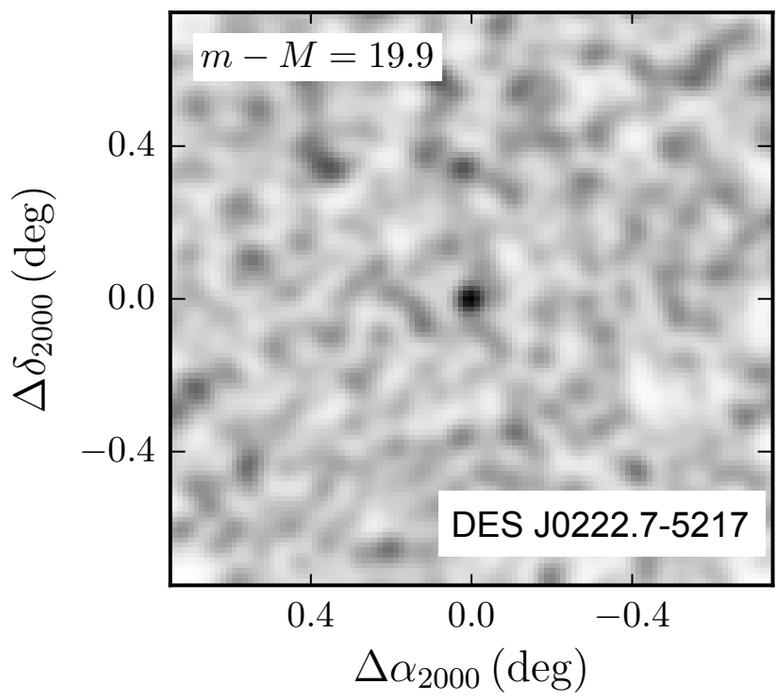


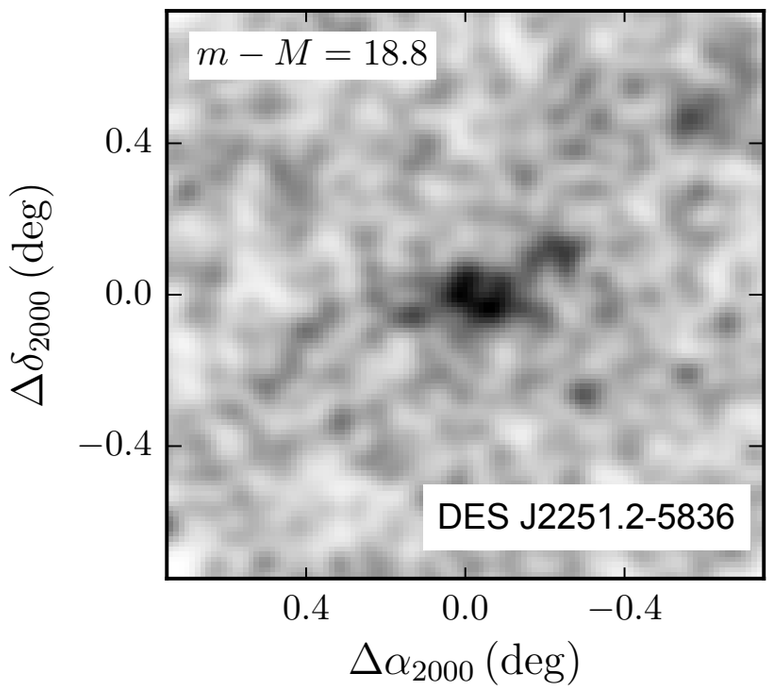
Belokurov & Koposov

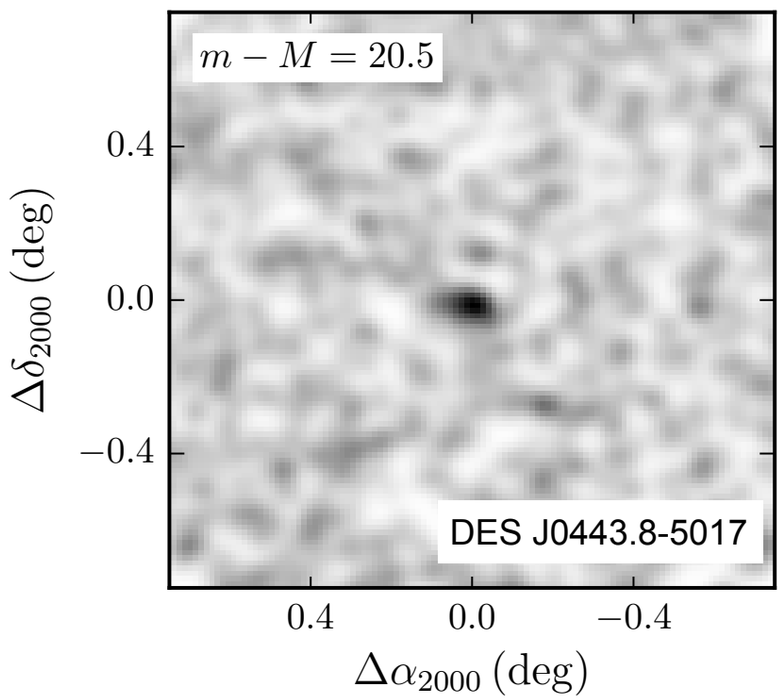
Additional Objects

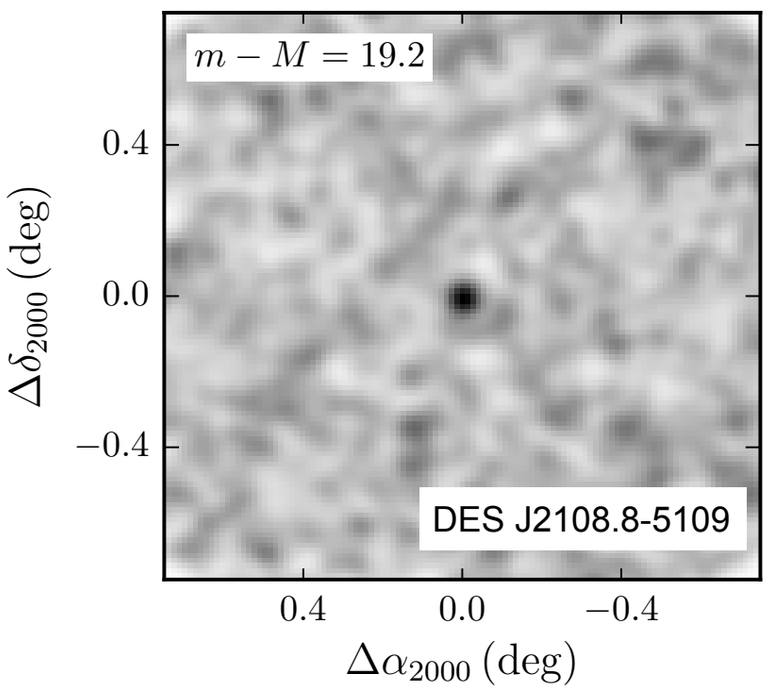
arXiv:1503.02584

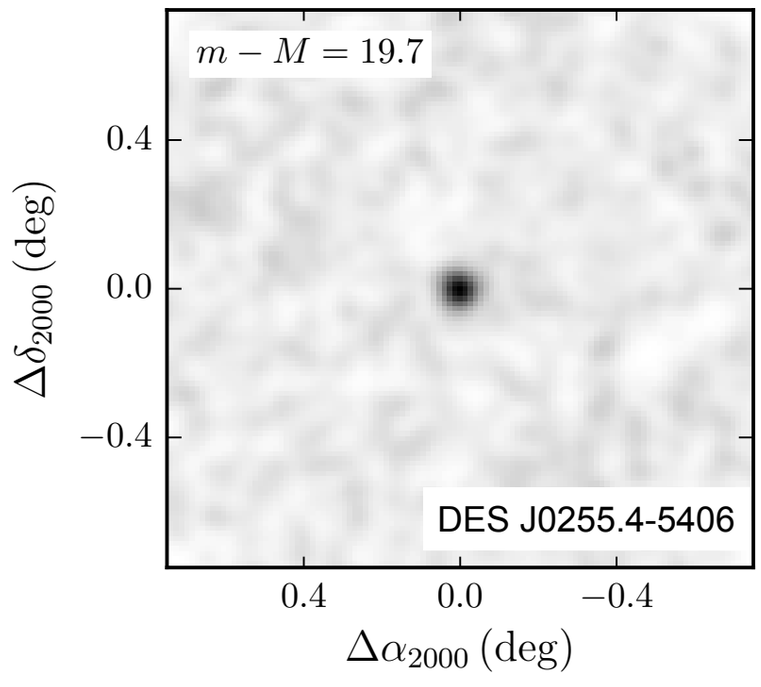




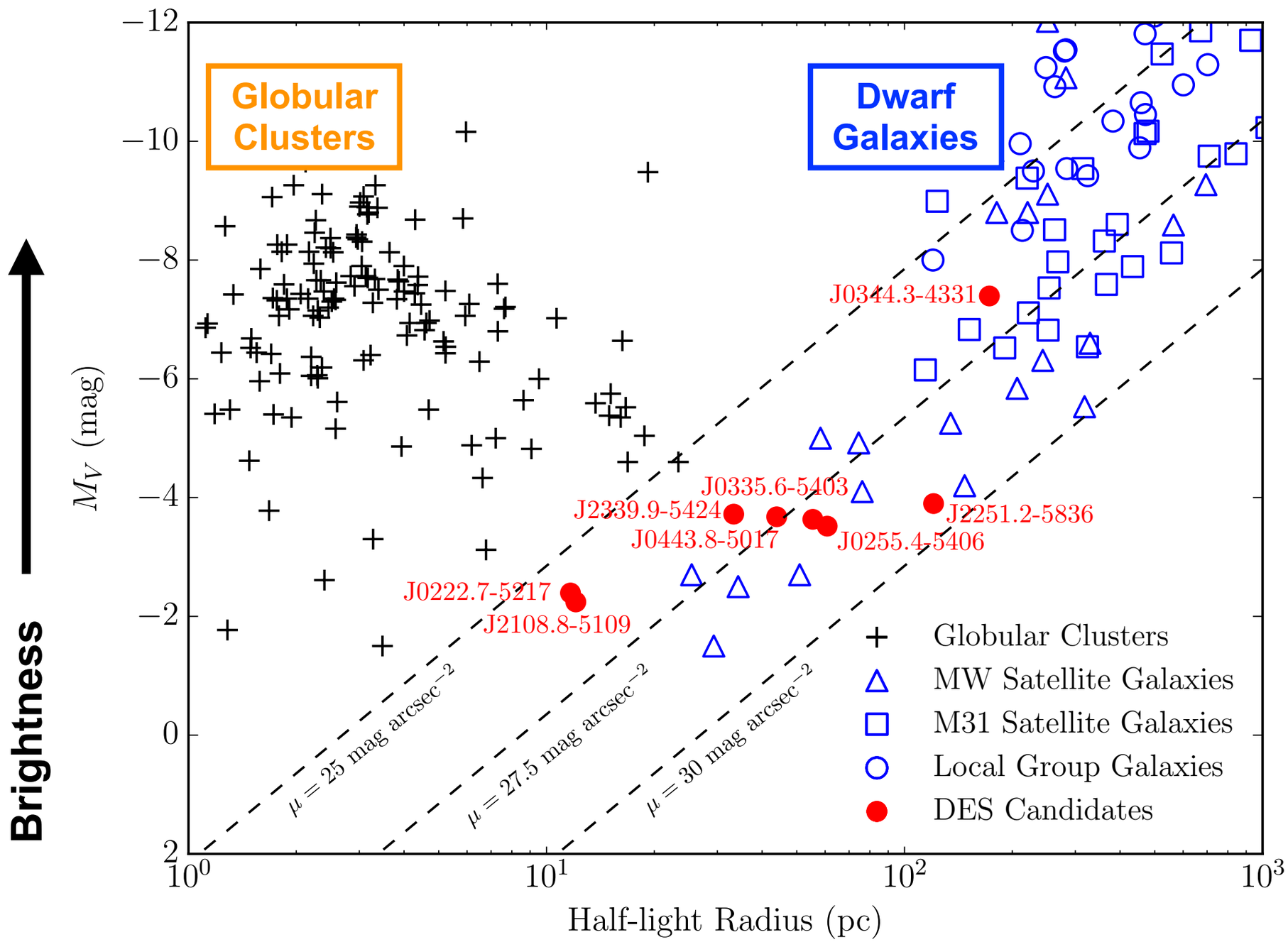






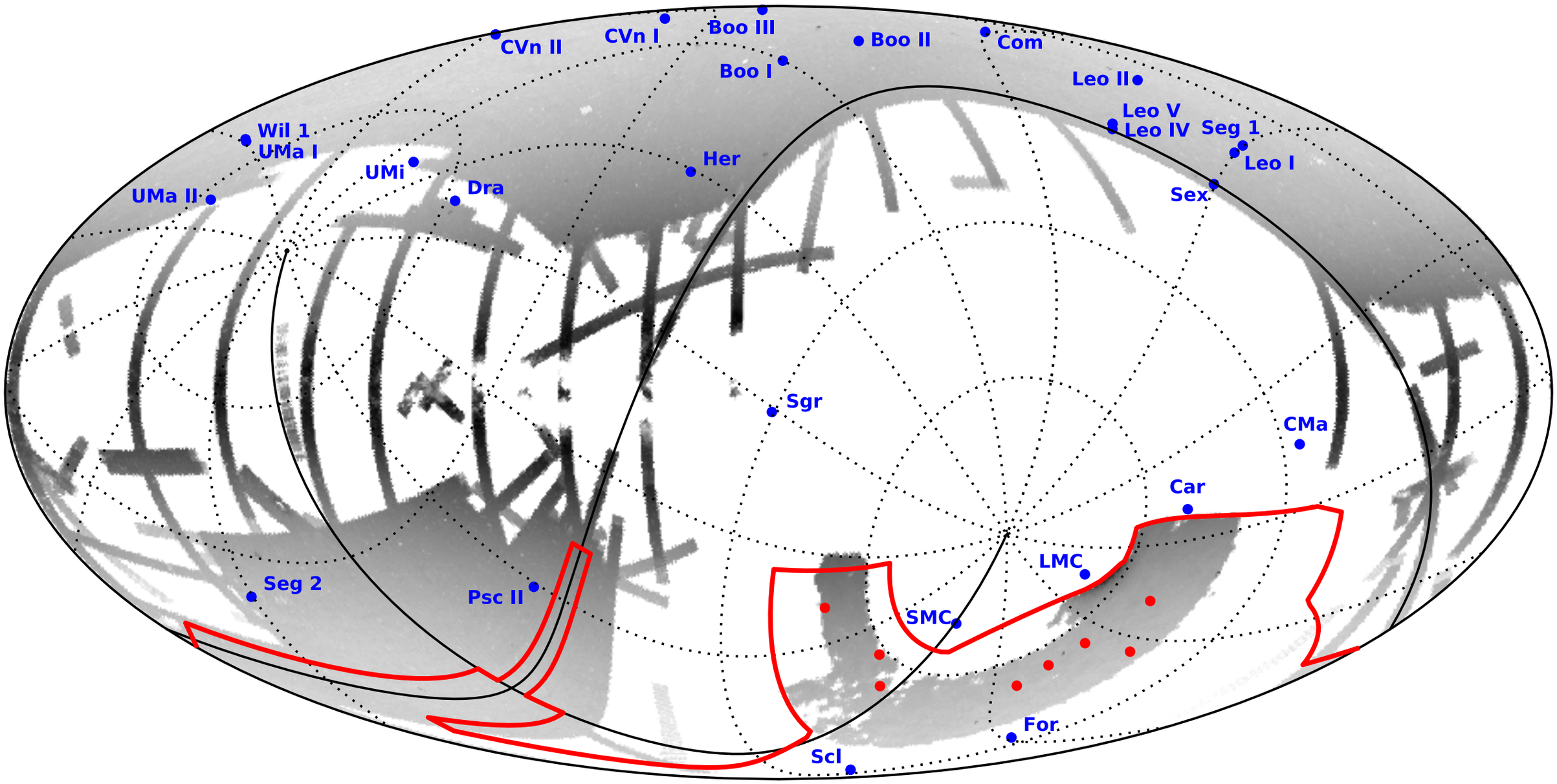


Dwarf Galaxies or Globular Clusters?



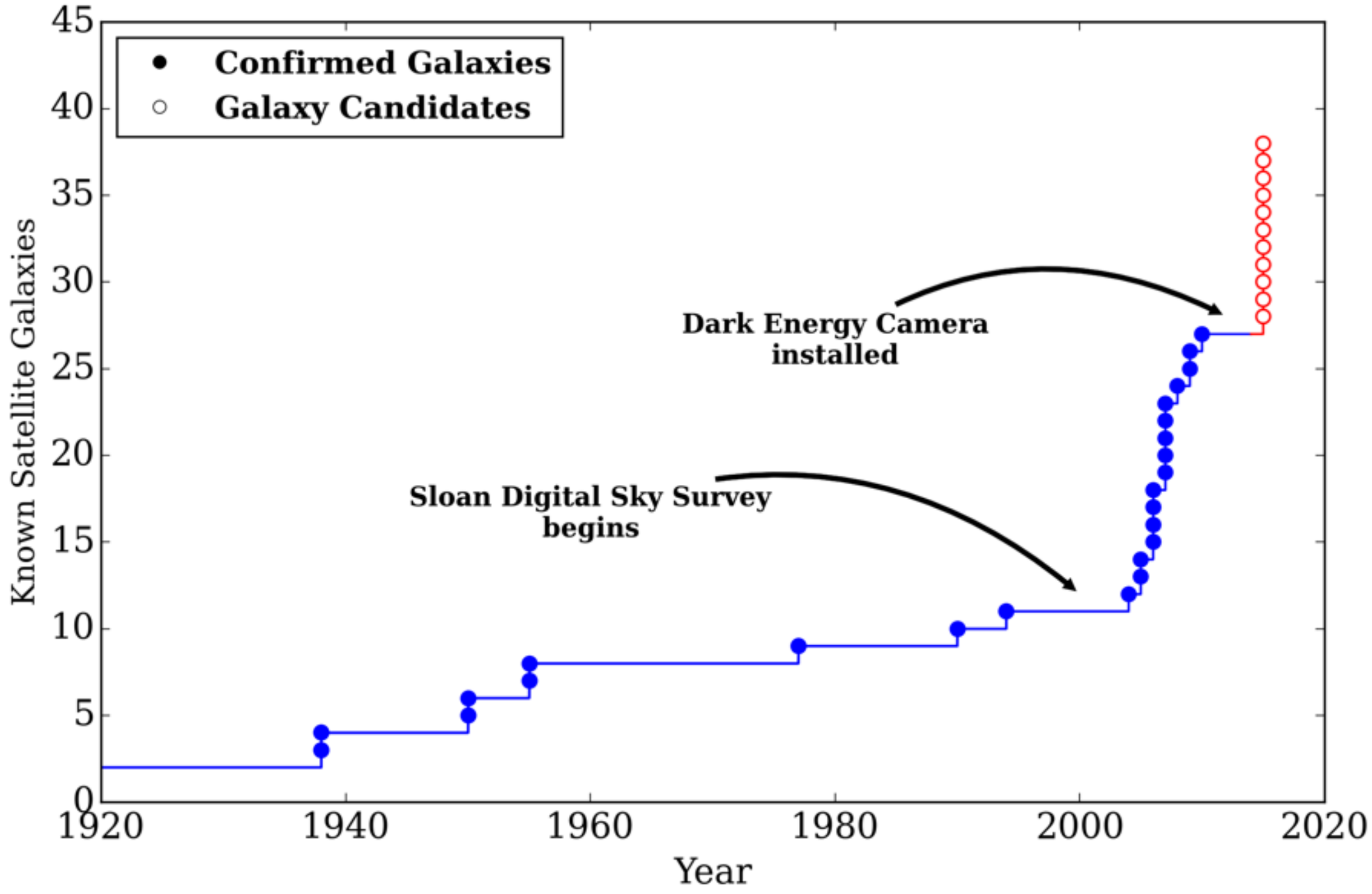
arXiv:1503.02584

Dwarf Galaxy Candidates

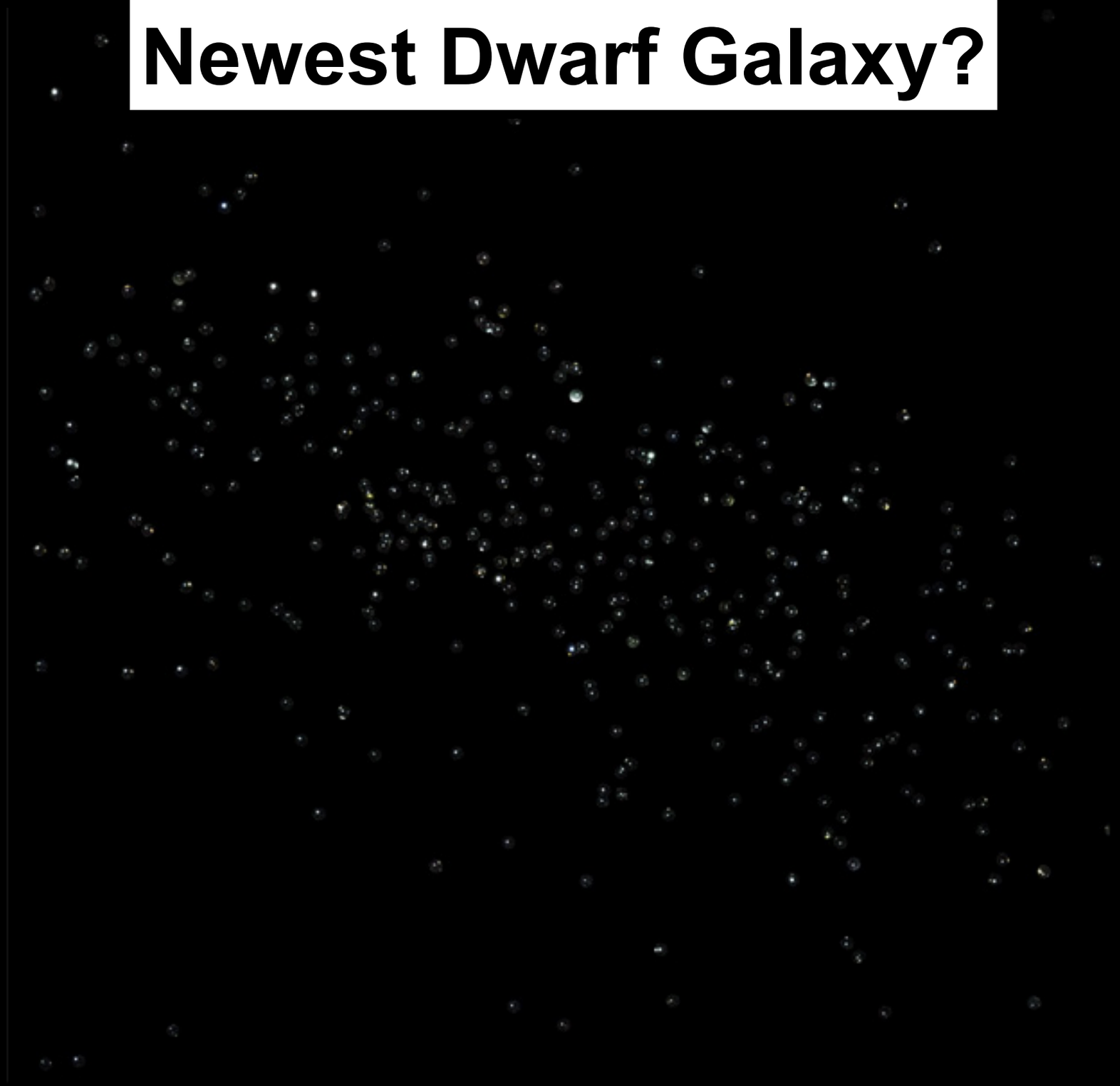


arXiv:1503.02584

Milky Way Satellite Galaxies Discovery Timeline



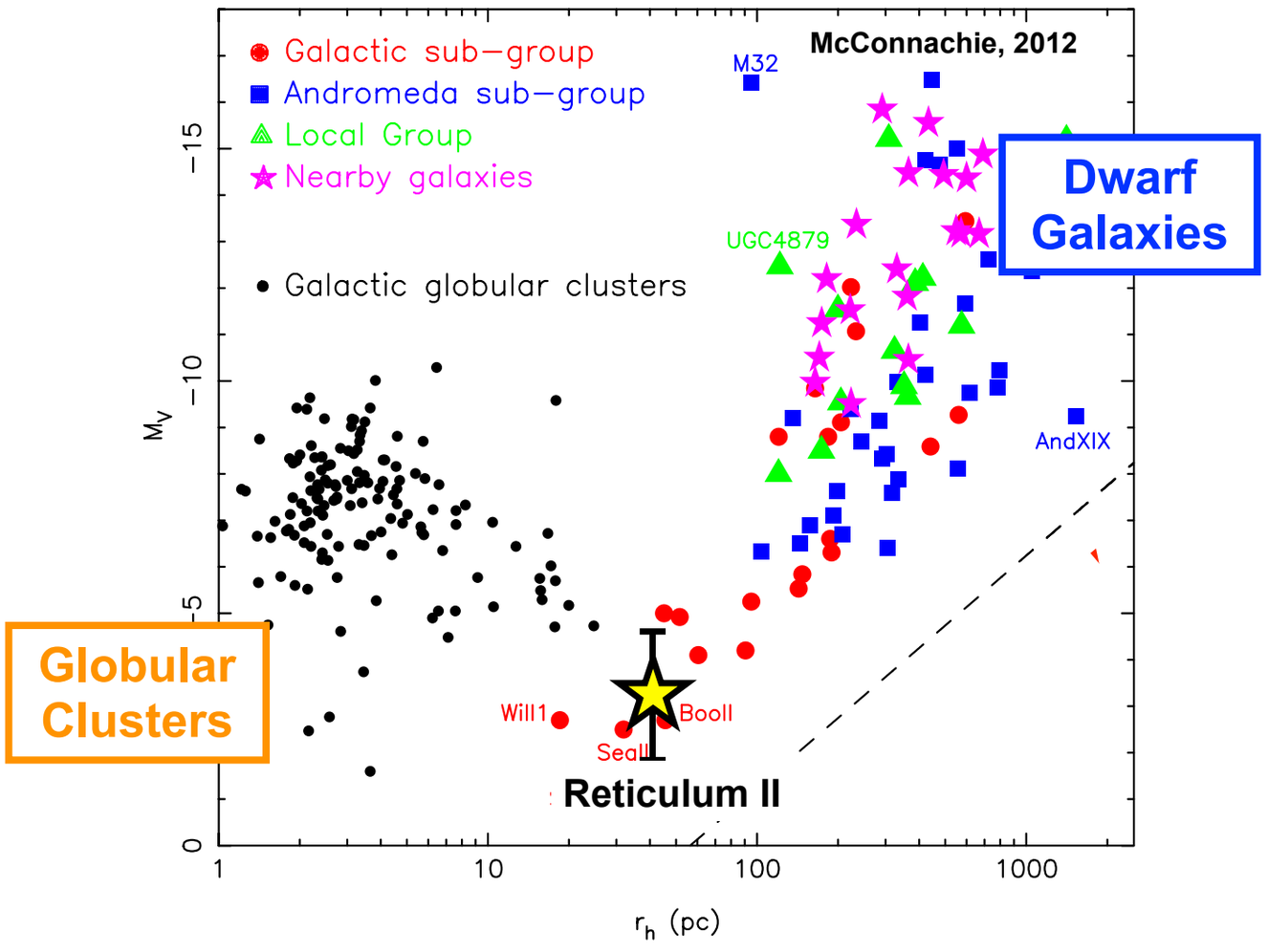
Reticulum II:
Newest Dwarf Galaxy?

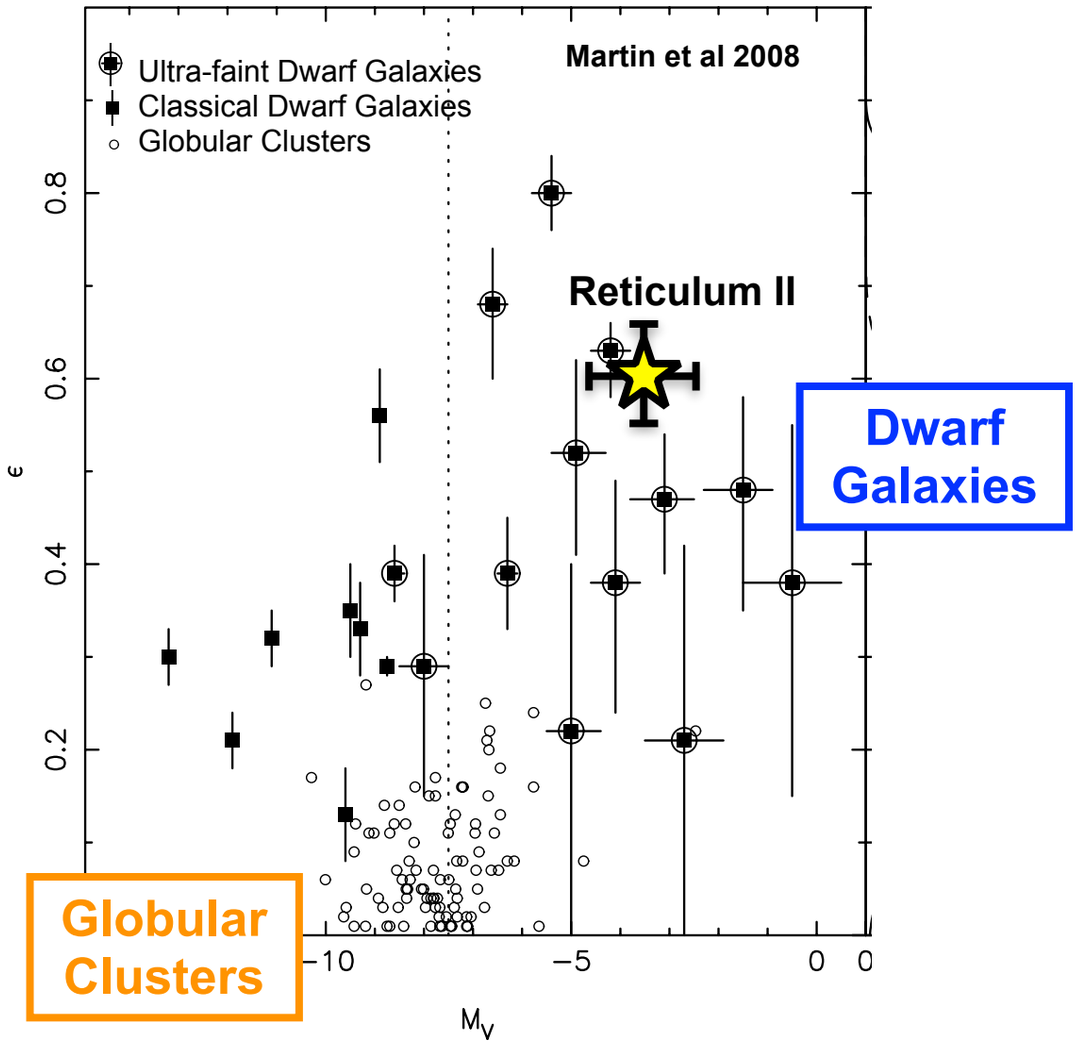


DES Collaboration

Reticulum II: Newest Dwarf Galaxy?

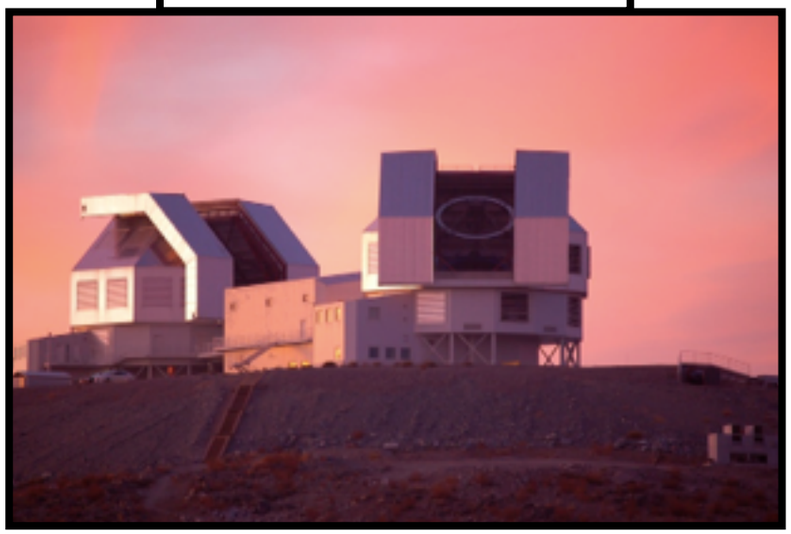
- Satellite galaxies tend to be more spatially extended and have a stronger correlation between size and luminosity.
- Satellite galaxies also tend to be more elliptical.
- Reticulum II is consistent with the population of satellite galaxies.
- Spectroscopy necessary to definitively distinguish satellite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





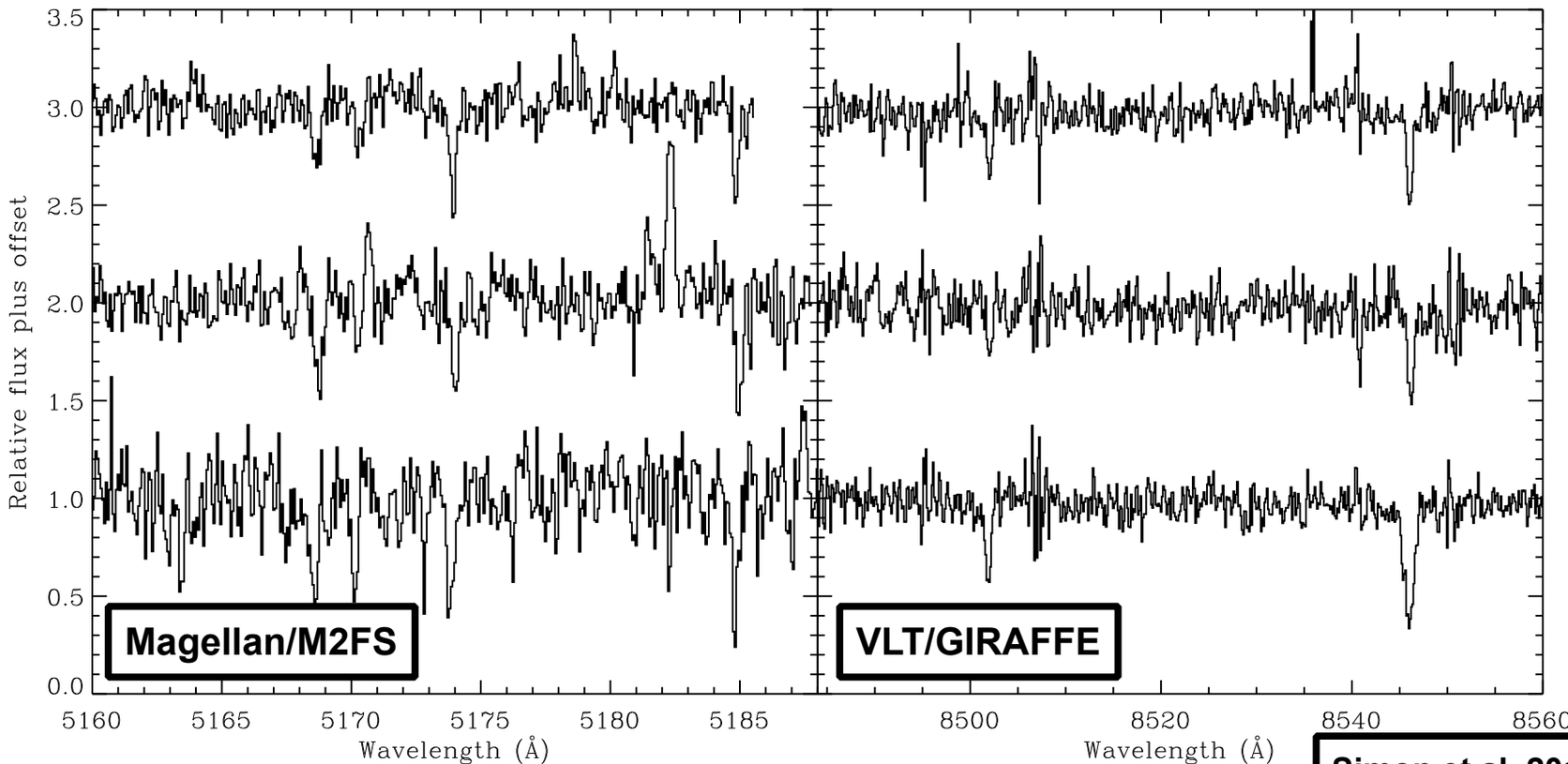
Reticulum II: Spectroscopy Campaign

Magellan/M2FS



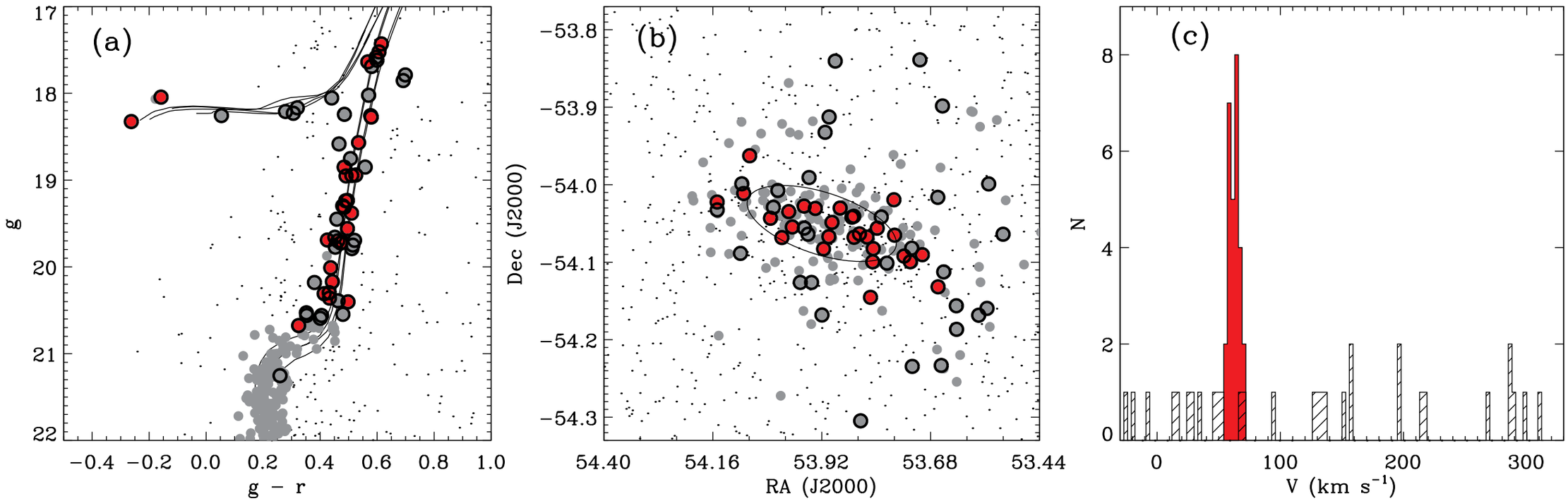
Gemini/GMOS

VLT/GIRAFFE



Simon et al. 2015 (DES Collaboration)

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**

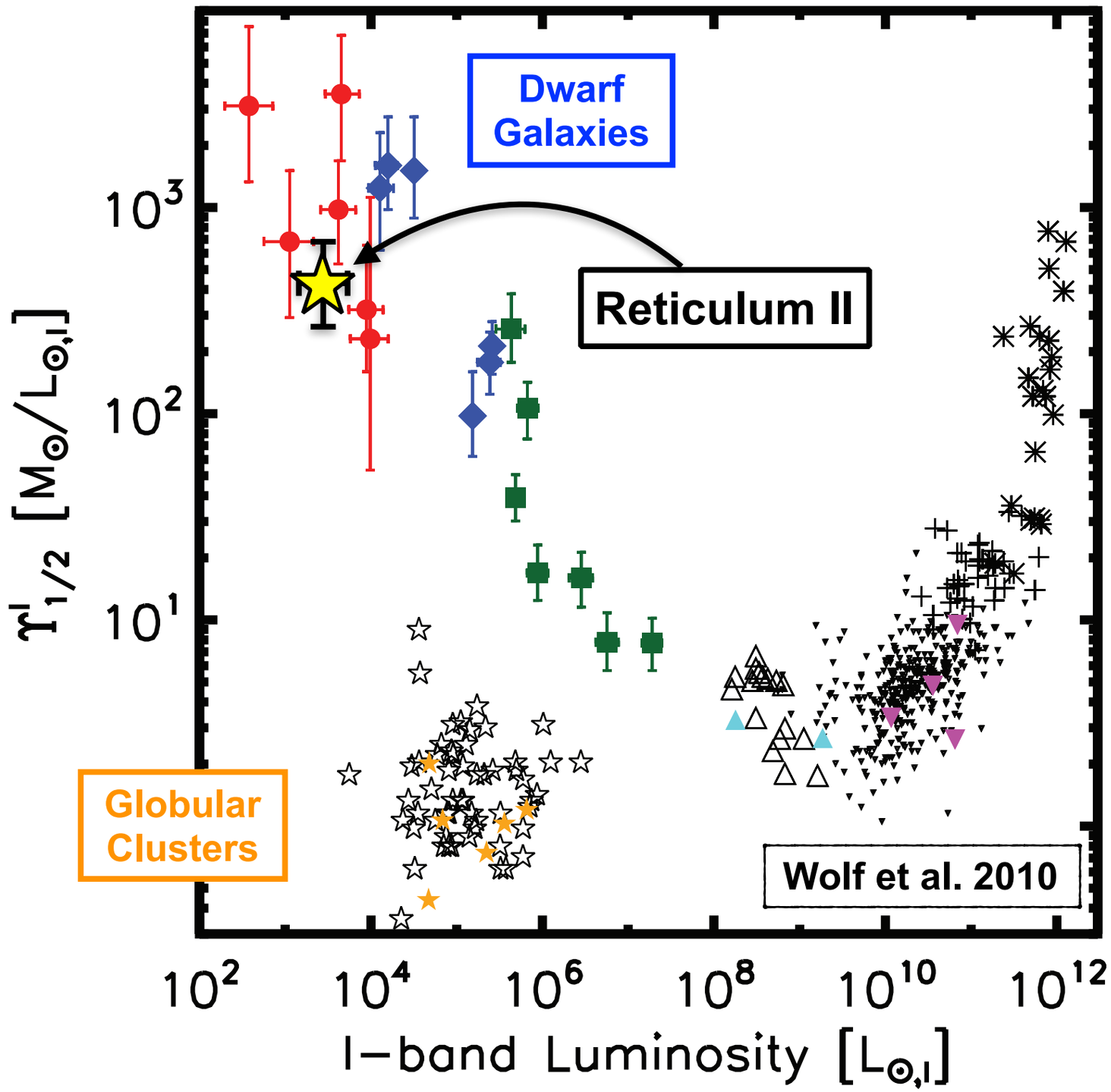
Systemic Velocity	$v = 62.8 \pm 0.5\,\mathrm{km\,s^{-1}}$
Velocity Dispersion	$\sigma_v = 3.3 \pm 0.7\,\mathrm{km\,s^{-1}}$
Metallicity	$[\mathrm{Fe/H}] = -2.65 \pm 0.07$
Metallicity Dispersion	$\sigma_{[\mathrm{Fe/H}]} = 0.28 \pm 0.09$
Dynamical Mass	$M_{1/2} = 5.6 \pm 2.4 \times 10^5\,\mathrm{M_\odot}$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

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

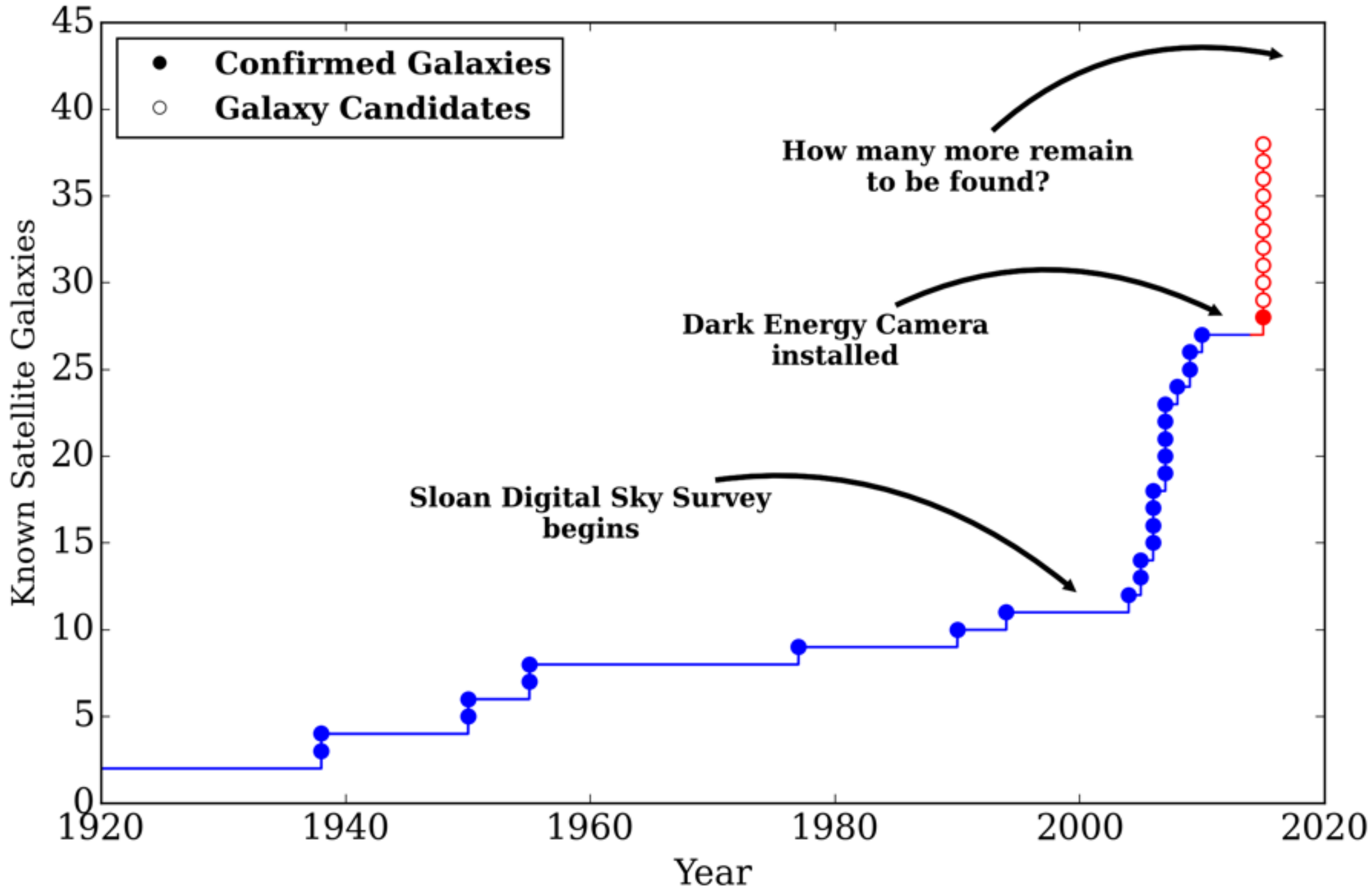
arXiv:1504.02889

arXiv:1504.03309

Reticulum II: Ultra-faint Dwarf Galaxy



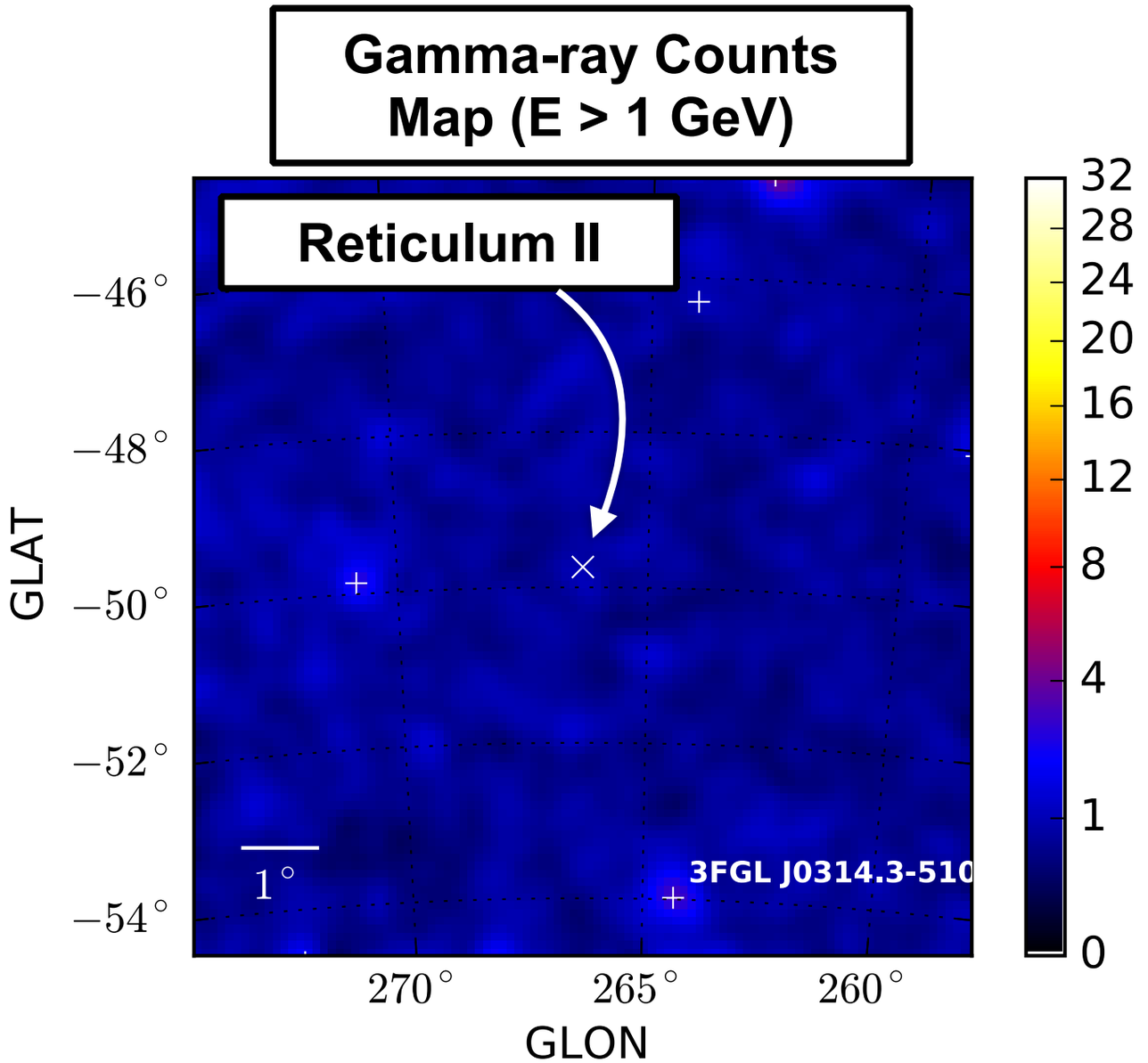
Milky Way Satellite Galaxies Discovery Timeline



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: individual p-value = 0.06 (1.5σ)
  - Geringer-Sameth+, Pass 7: individual p-value = 0.01 (2.3σ)

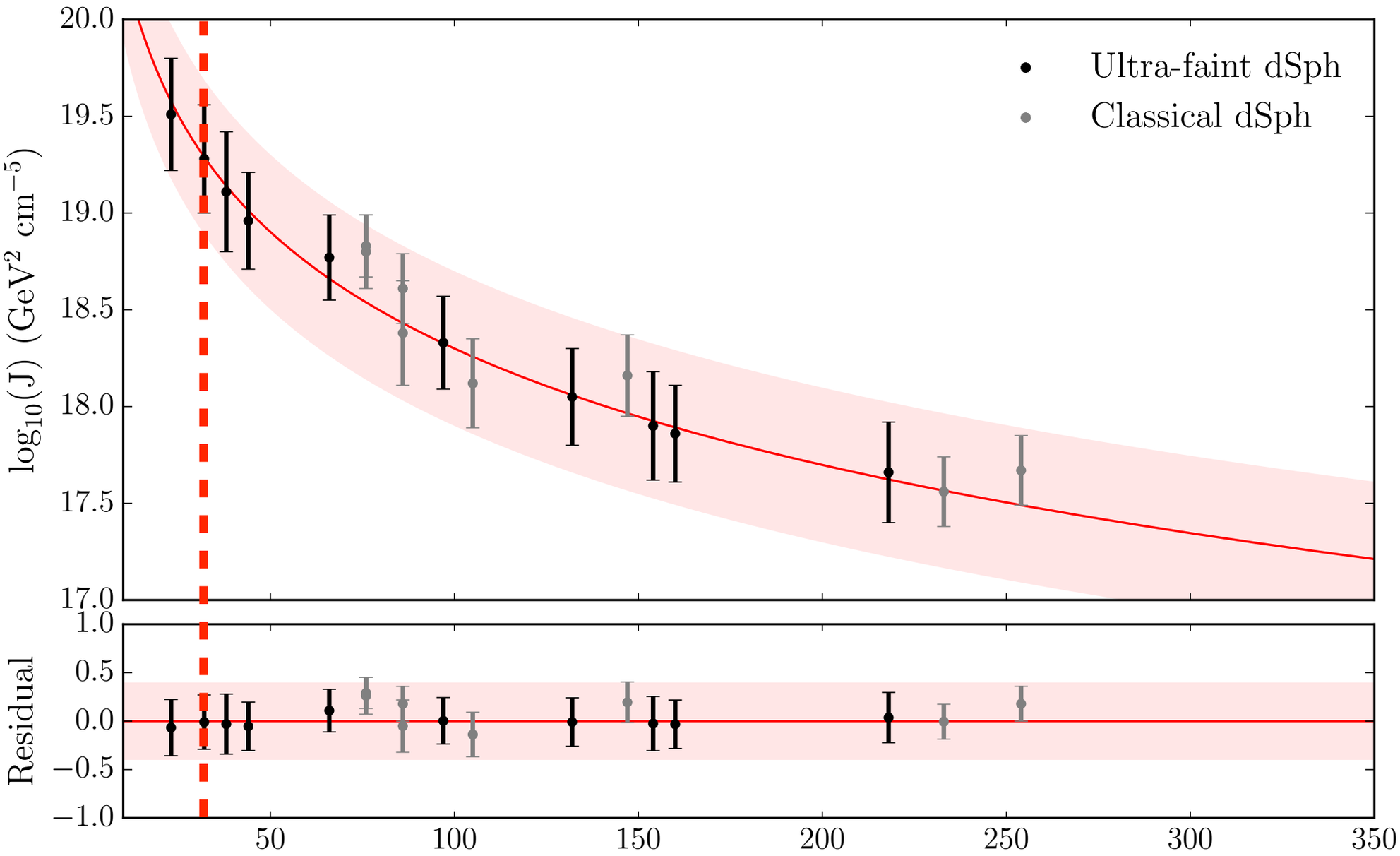
- How does the expected dark matter annihilation signal from Reticulum II compare to other dwarf galaxies?



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

arXiv:1503.02632 arXiv:1503.02320

Dark Matter Searches in Gamma Rays



arXiv:1503.02632

Dark Matter Searches in Gamma Rays

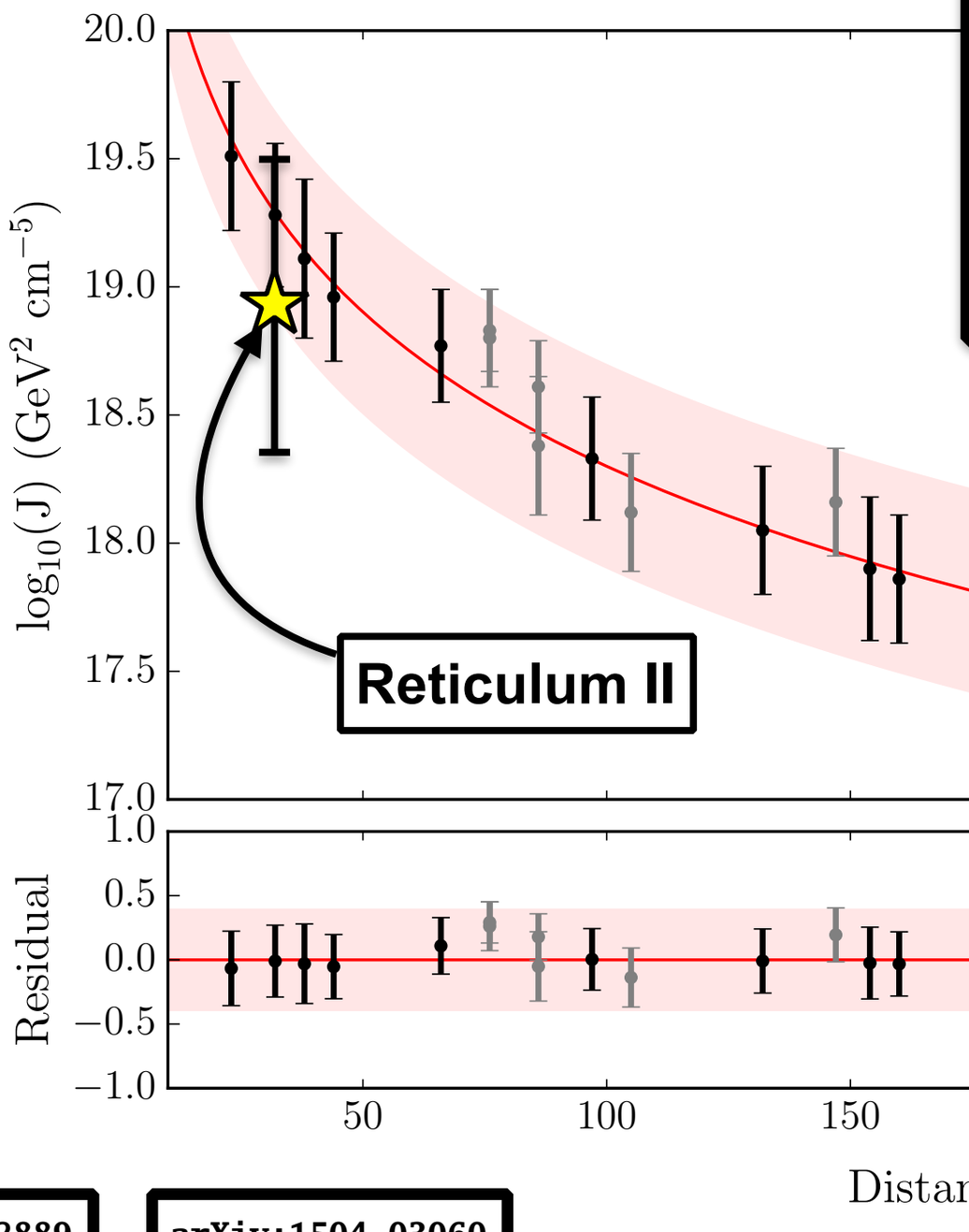


Table 1. Reticulum II

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

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.

arXiv:1504.02889

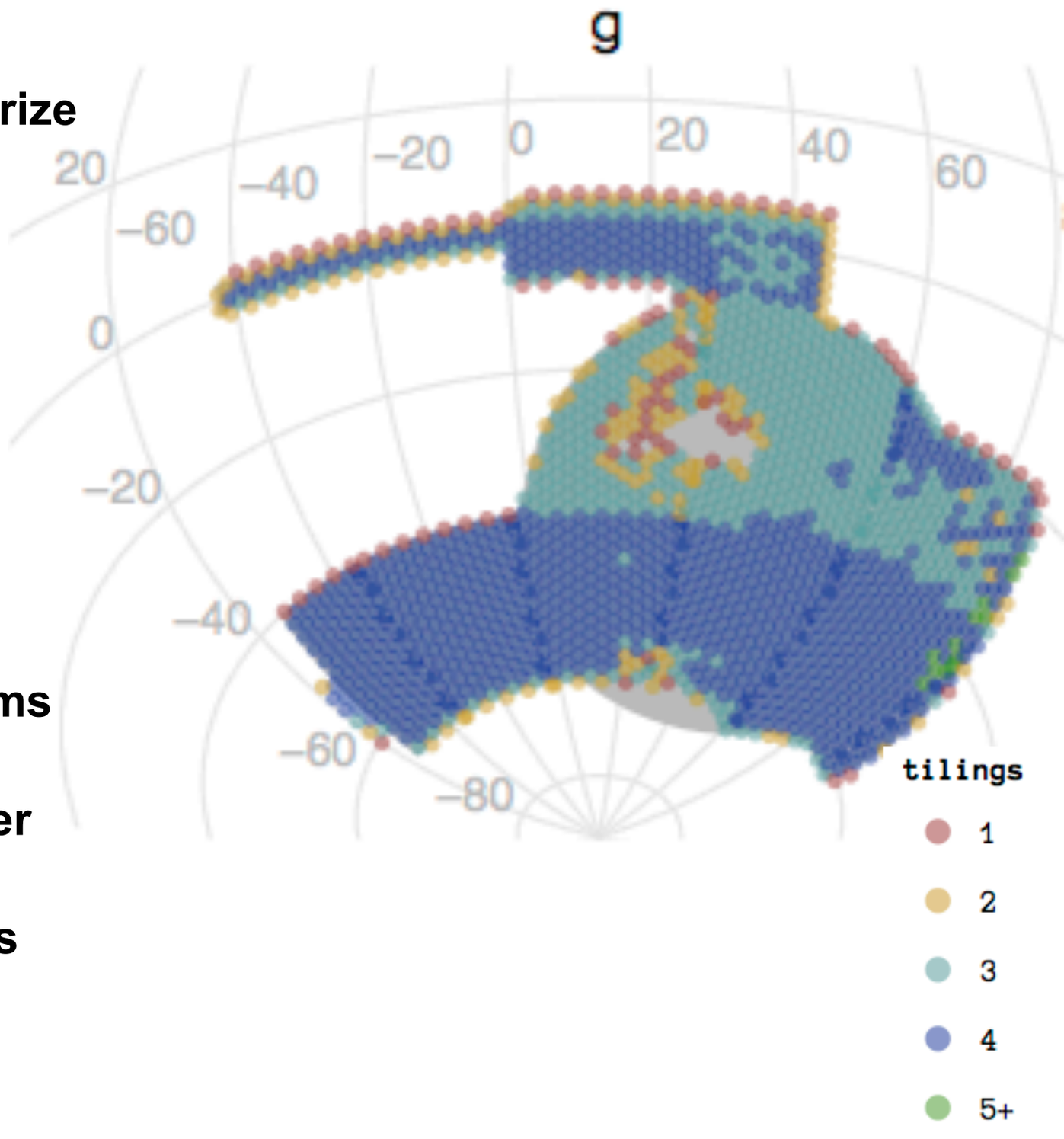
arXiv:1504.03060

Looking Forward

- **A large spectroscopic campaign is necessary to classify and characterize the newly discovered systems**

- **Future sky coverage:**
  - **DES Y2: >4,000 deg^2**
  - **DES Y3+: 5,000 deg^2 (and greater sensitivity)**
  - **LSST: 10,000 deg^2 (and much greater sensitivity)**

- **Increased sensitivity: stellar systems with larger spatial extent**
  - **Do galaxies extend to even lower surface brightness?**
  - **Nearby ultra-faint dwarf galaxies can be very spatially extended.**



Backup Slides

Finding Milky Way Satellite Galaxies

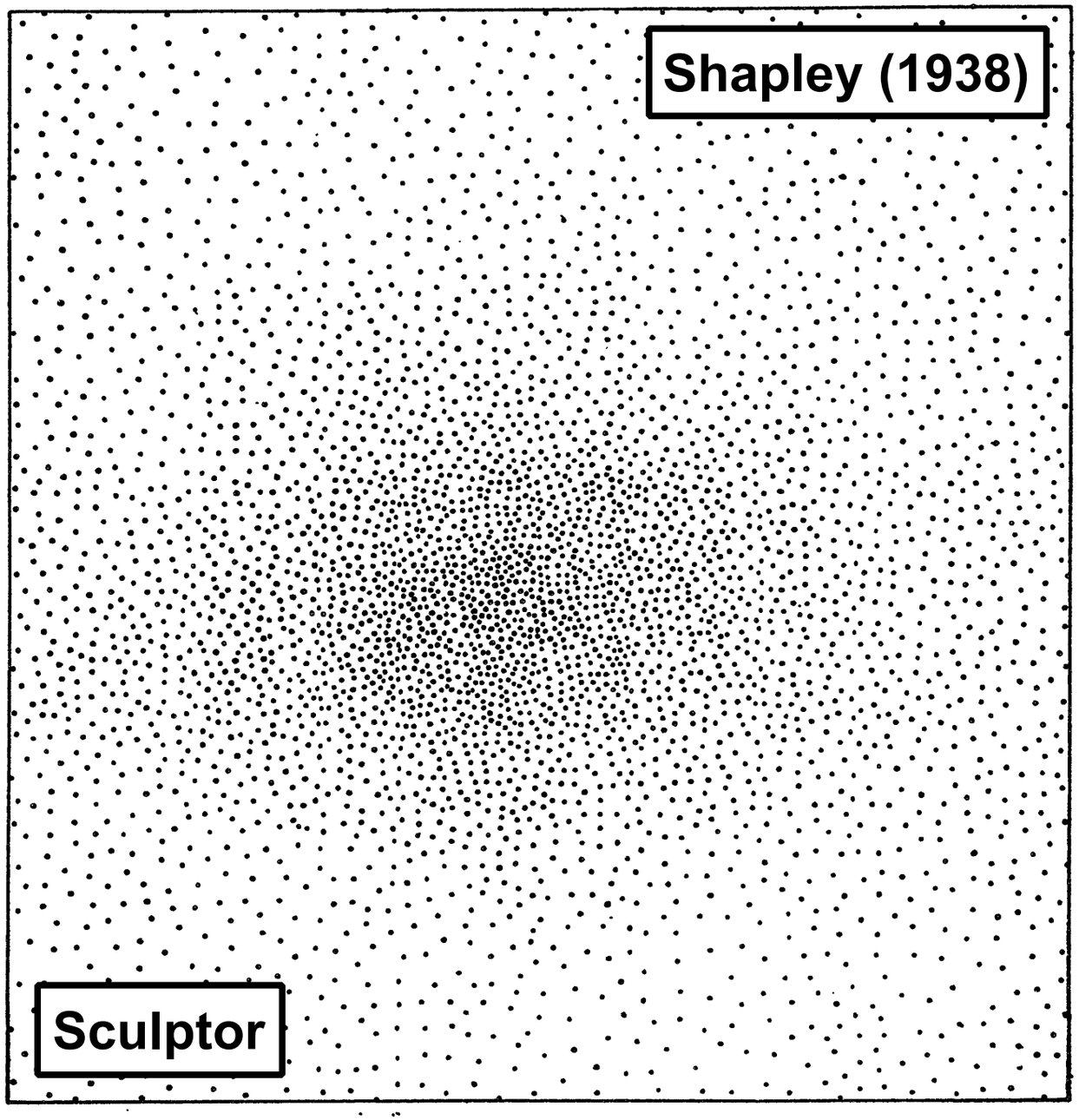


FIGURE 2.– DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

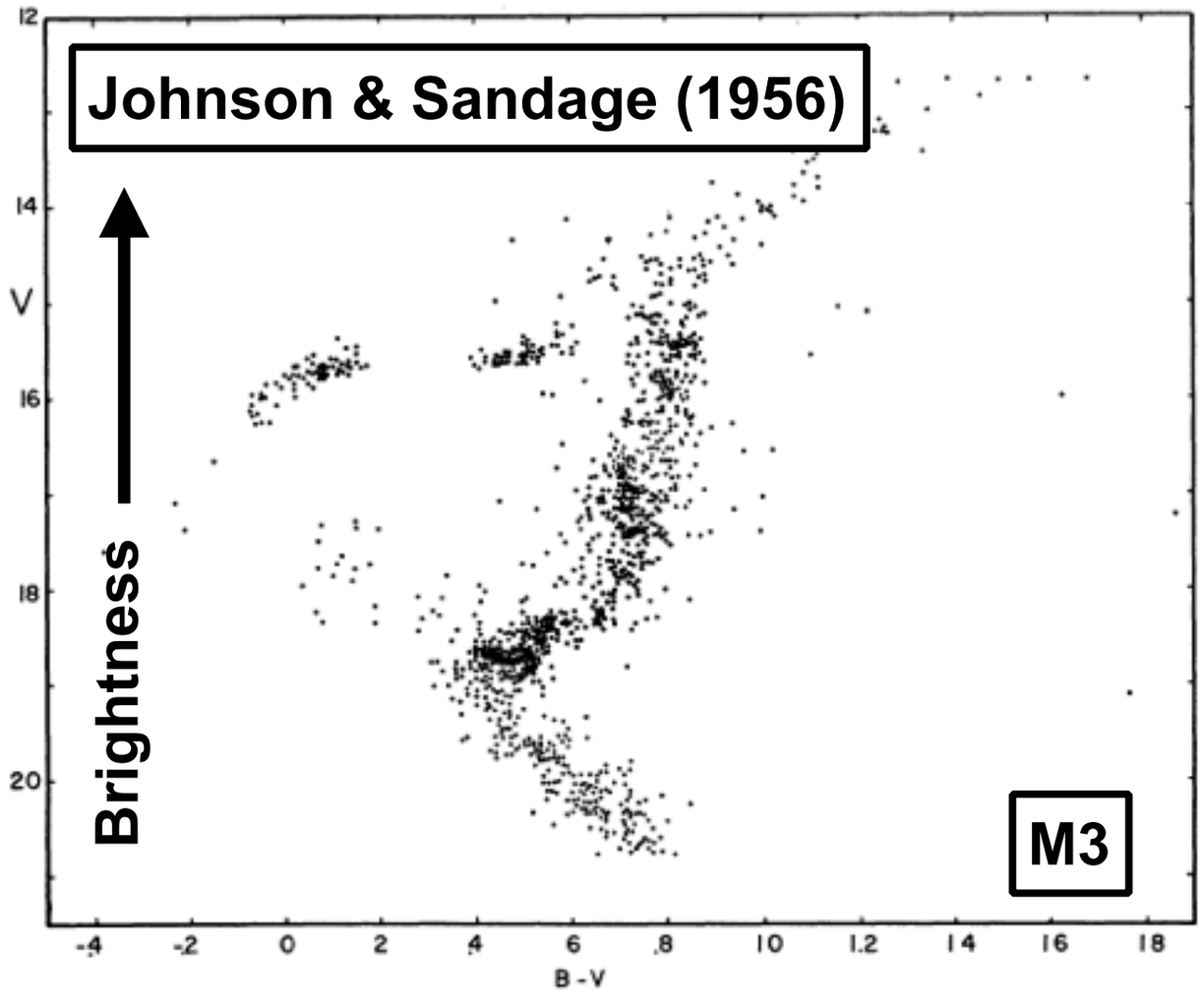
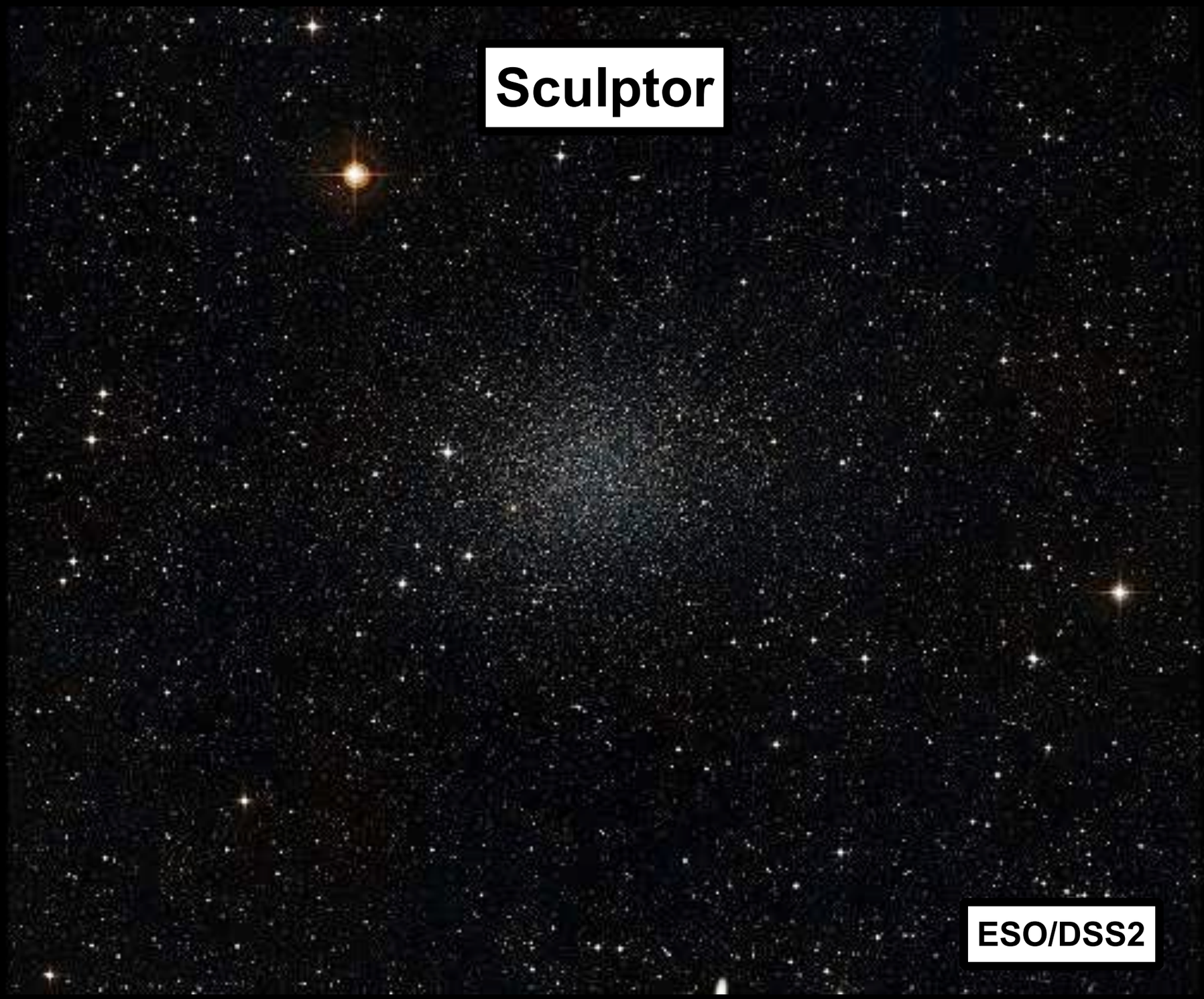


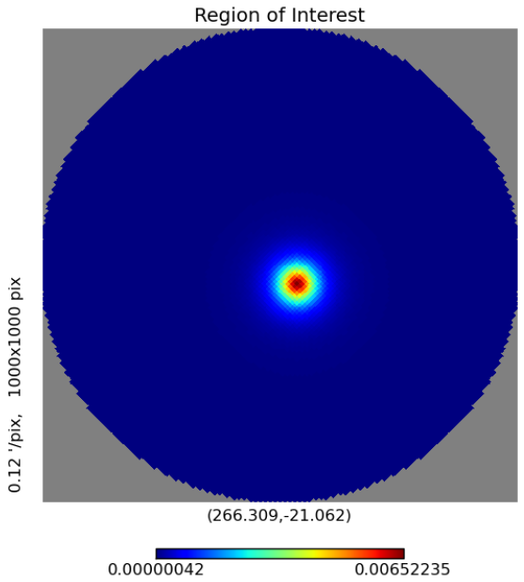
FIG. 5.—Color-magnitude diagram for M3 stars in the arguments V and $B - V$

"Redness" →

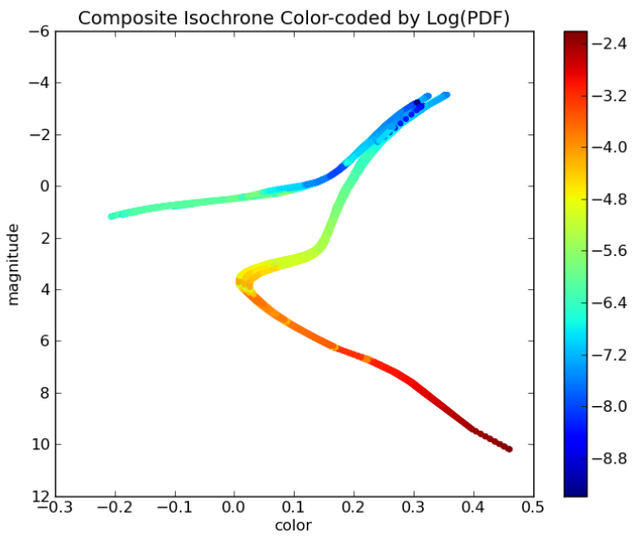

Sculptor
ESO/DSS2

Maximum Likelihood Analysis

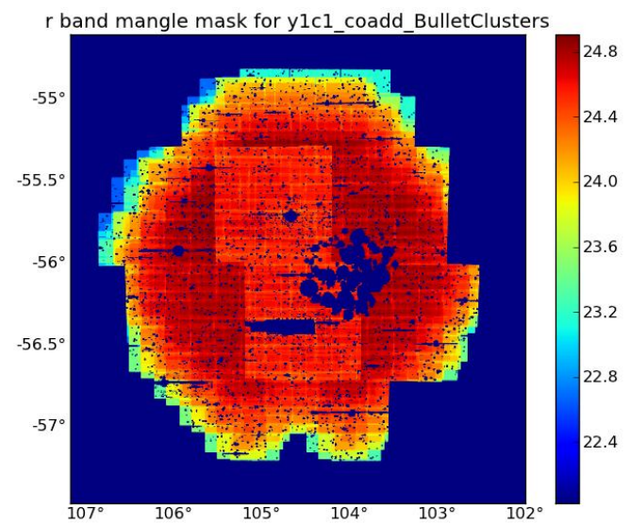
Spatial Model



"Spectral" Model



"Exposure"



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

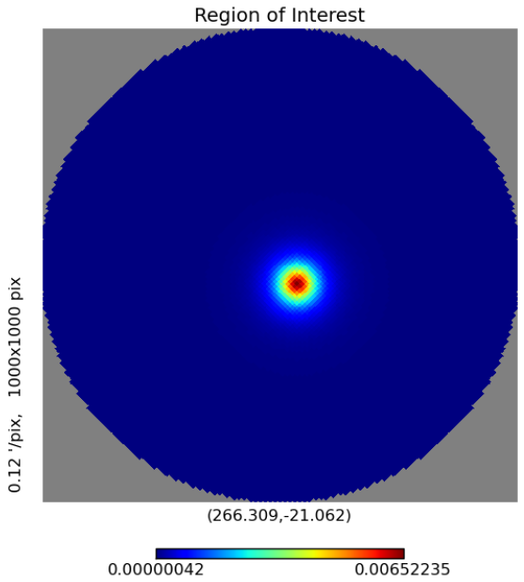
Richness: $\lambda = \frac{1}{f} \sum_{i \in \text{Stars}} p_i$ **(λ = normalization = number of stars)**

(f = observable fraction)

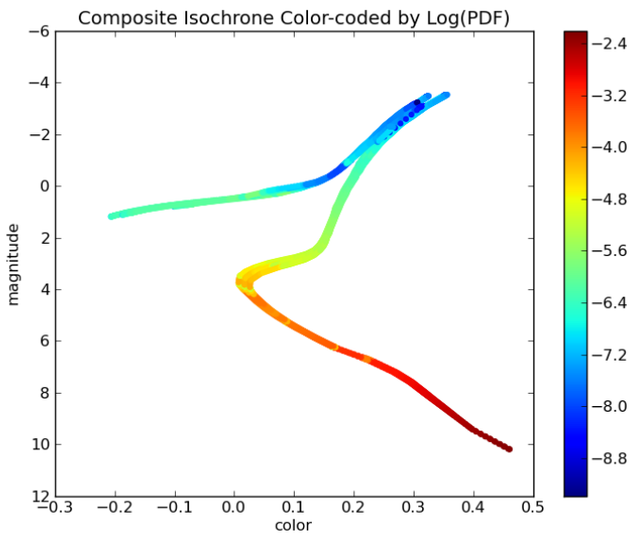
Log Likelihood: $\log L = -\sum_{i \in \text{Stars}} \log(1 - p_i) - f\lambda$

Maximum Likelihood Analysis

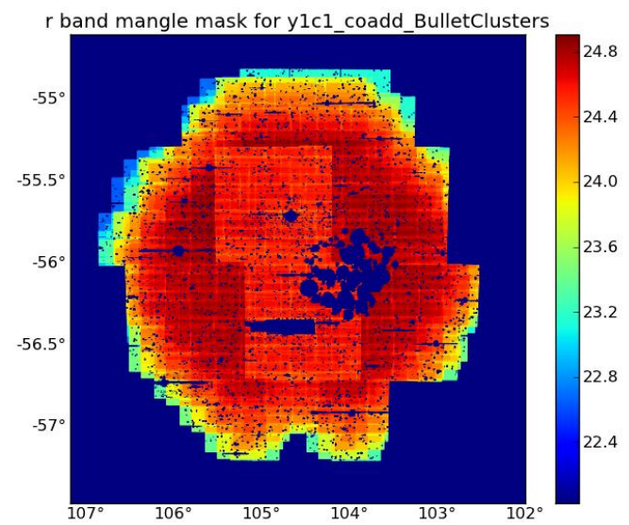
Spatial Model



"Spectral" Model



"Exposure"



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

Important for spectroscopic follow up observations

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

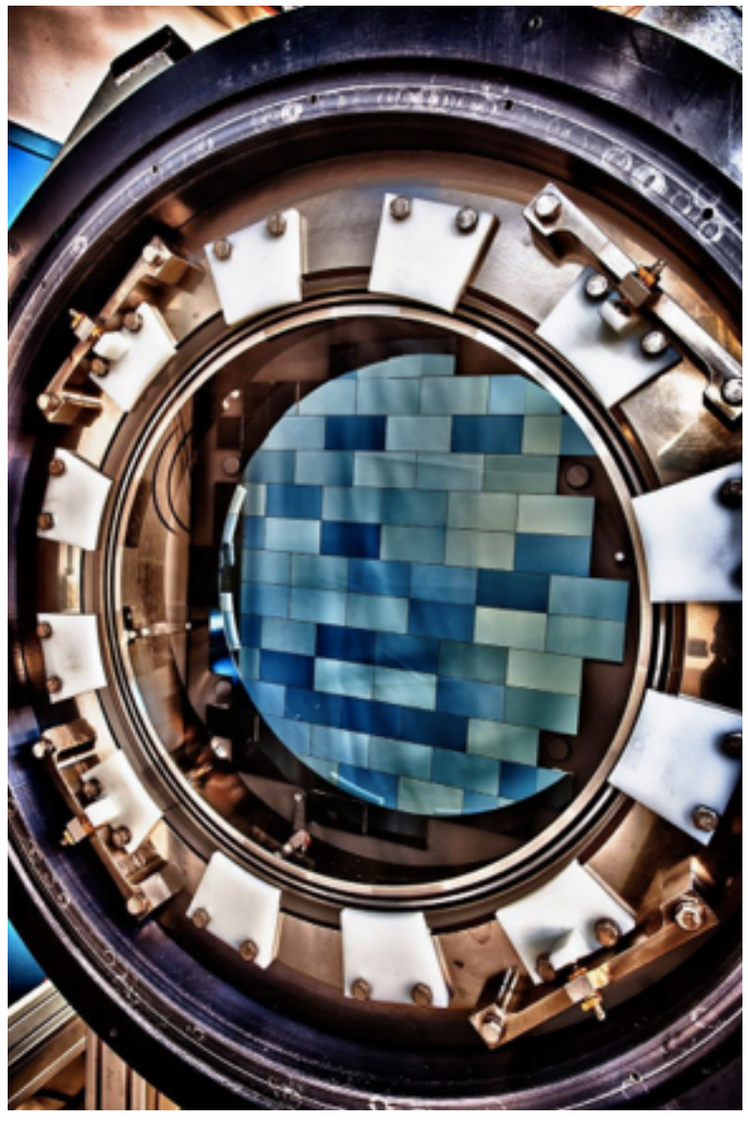
(λ = normalization = number of stars)

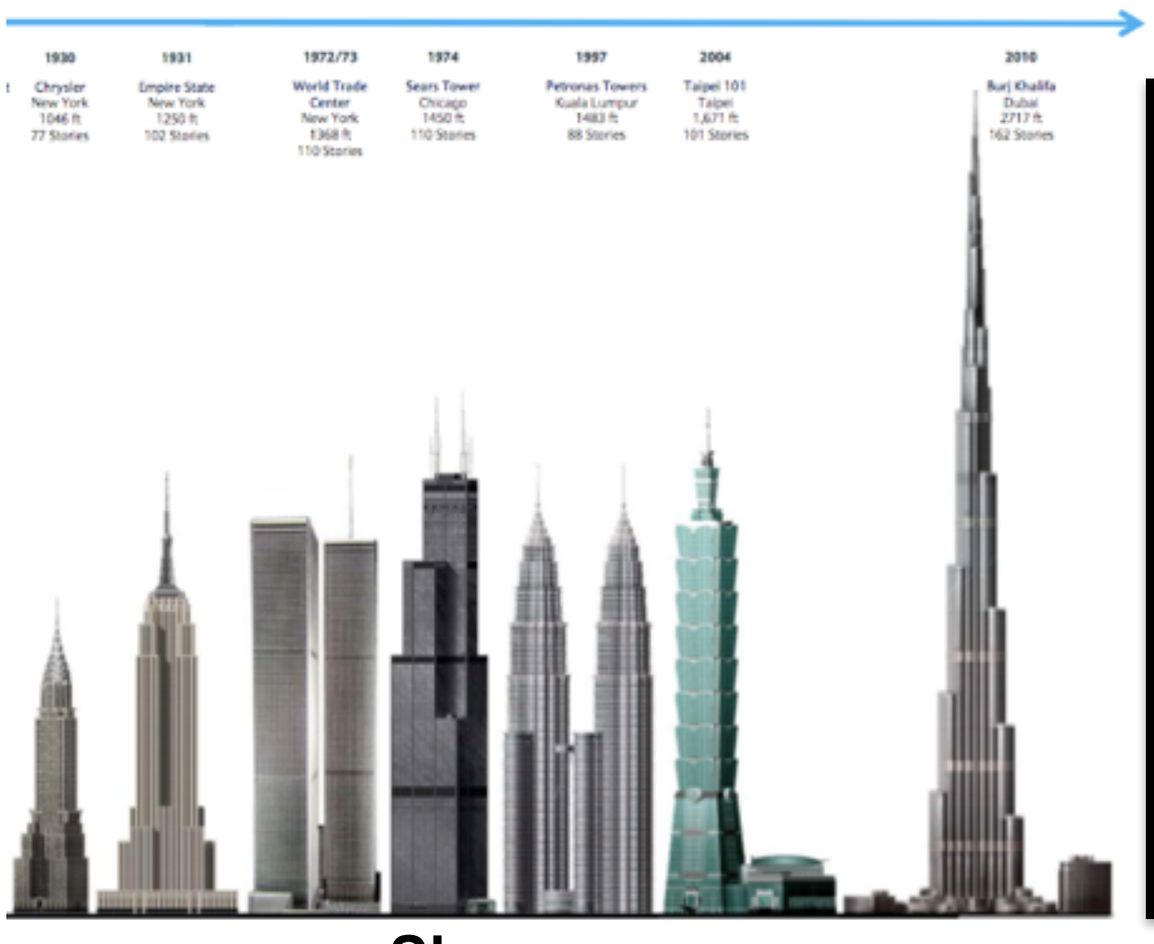
(f = observable fraction)

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

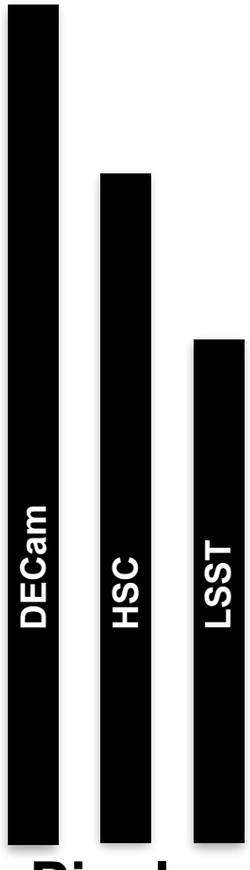
Dark Energy Camera (DECam)

- 570 megapixel camera
- < 20s readout time
- ~3 deg^2 field-of-view
- Unprecedented sensitivity





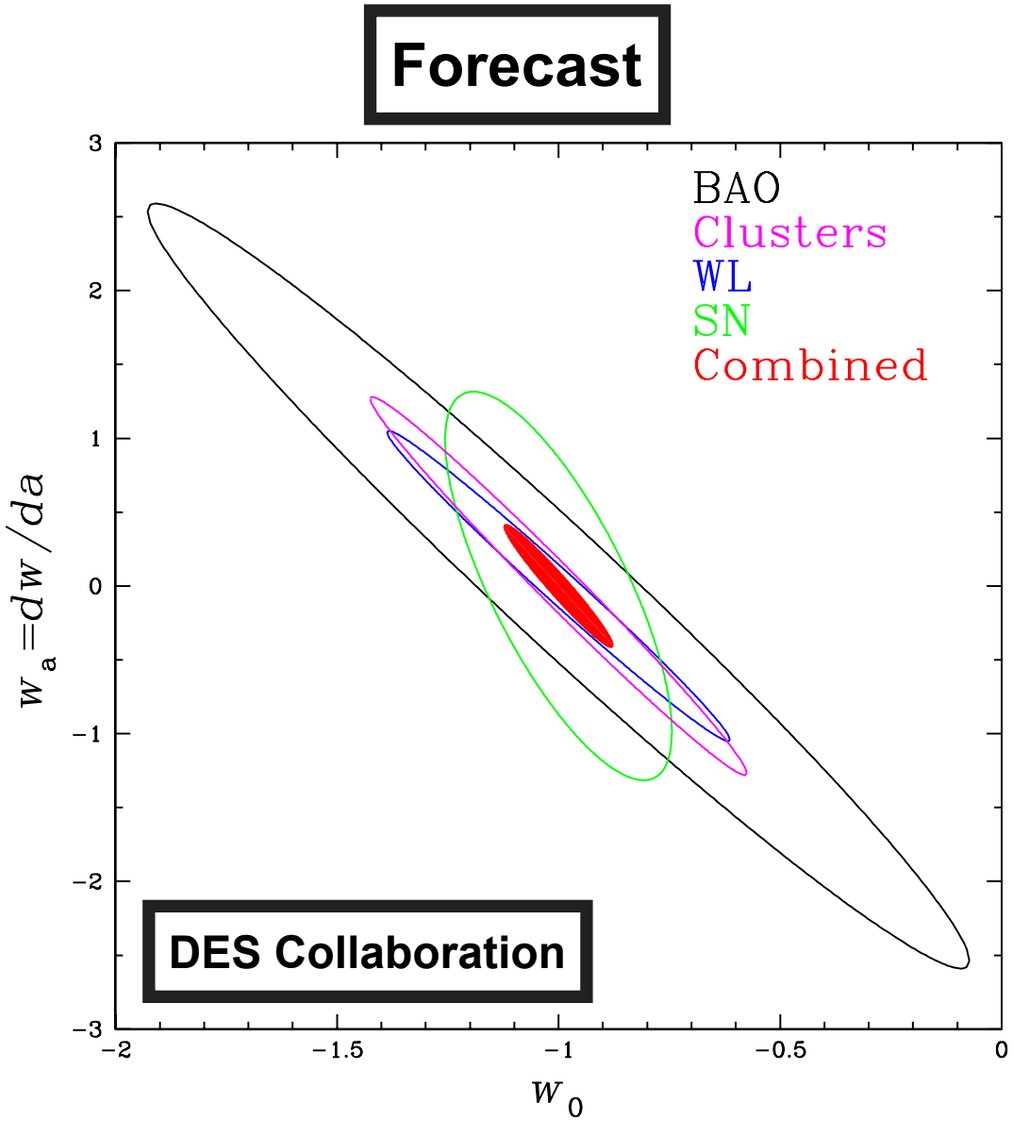
Skyscrapers



Pixels

The Dark Energy Survey (DES)

- **Fist full of fives:**
  - **525 nights over 5 years**
  - **5,000 deg^2**
  - **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

Dwarf Galaxy Candidates (continued…)

THE DARK ENERGY SURVEY

Fermilab

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. Ibata[1], Hans-Walter Rix[2], Edouard J. Bernard[3], Eric F. Bell[4], Branimir Sesar[2], Annette M. N. Ferguson[3], Edward F. Schlafly[2], Colin T. Slater[4], William S. Burgett[5], Kenneth C. Chambers[6], Heather Flewelling[6], Klaus A. Hodapp[6], Nicholas Kaiser[6], Rolf-Peter Kudritzki[6], Robert H. Lupton[7], Eugene A. Magnier[6], Nigel Metcalfe[8], Jeffrey S. Morgan[6], Paul A. Price[7], John L. Tonry[6], Richard J. Wainscoat[6], Christopher Waters[6]

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

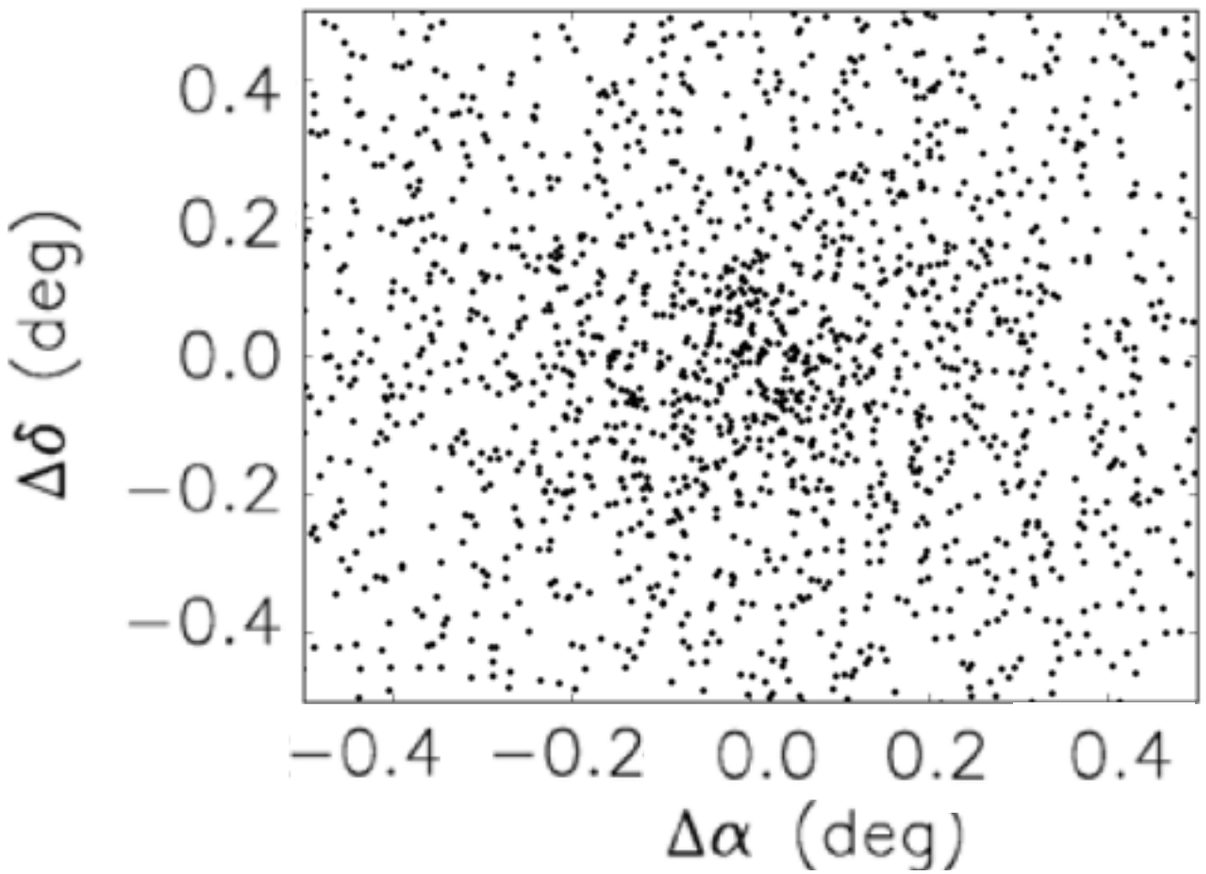
HYDRA II: A FAINT AND COMPACT MILKY WAY DWARF GALAXY FOUND IN THE SURVEY OF THE MAGELLANIC STELLAR HISTORY

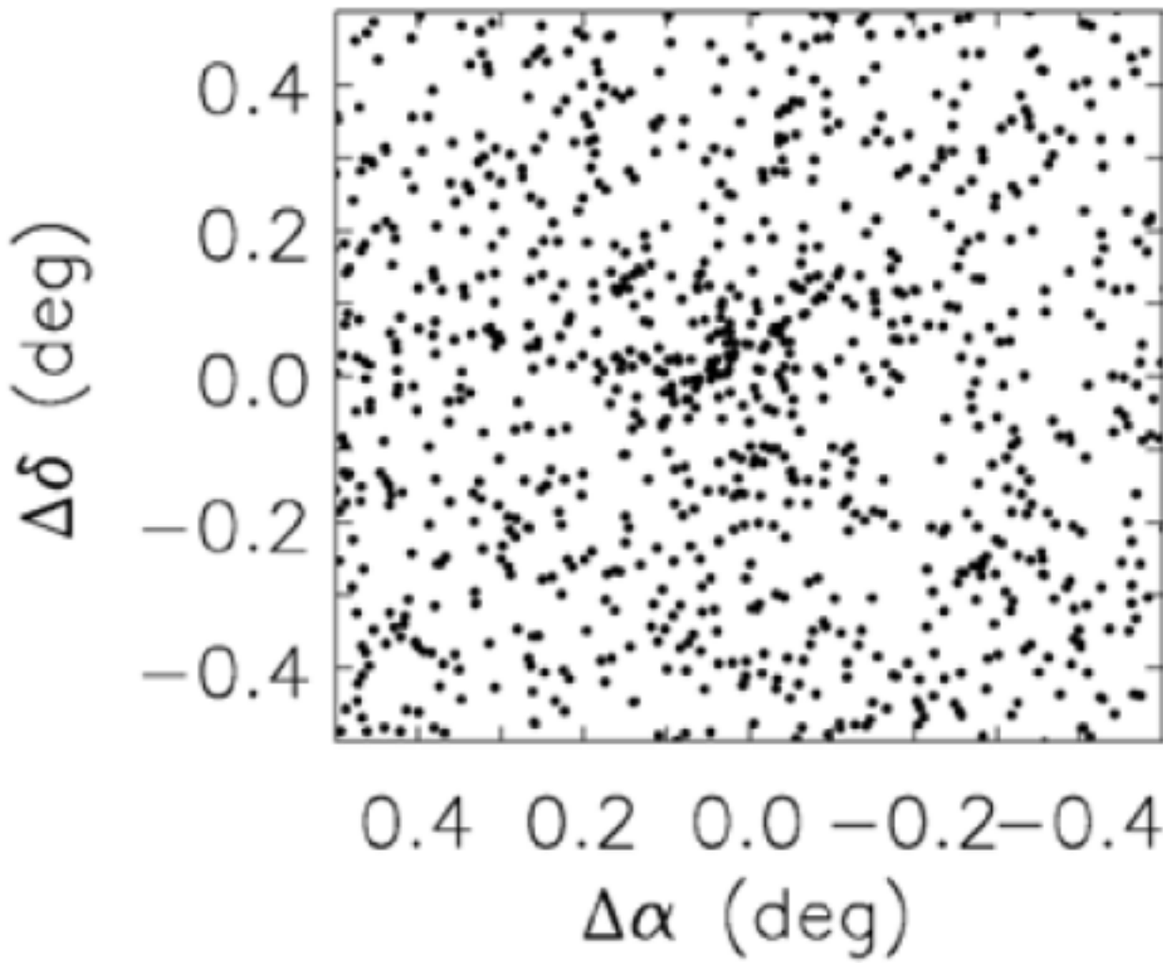
Nicolas F. Martin[1,2], David L. Nidever[3], Gurtina Besla[4], Knut Olsen[5], Alistair R. Walker[6], A. Katherina Vivas[6], Robert A. Gruendl[7,8], Catherine C. Kaleida[5,6], Ricardo R. Muñoz[9,25], Robert D. Blum[5], Abhijit Saha[5], Blair C. Conn[10], Eric F. Bell[3], You-Hua Chu[11,8], Maria-Rosa L. Cioni[12,13,14], Thomas J. L. de Boer[15], Carme Gallart[16,17], Shoko Jin[18], Andrea Kunder[13], Steven R. Majewski[19], David Martinez-Delgado[20], Antonela Monachesi[21], Matteo Monelli[16,17], Lara Monteagudo[16,17], Noelia E. D. Noël[22], Edward W. Olszewski[4], Guy S. Stringfellow[23], Roeland P. van der Marel[24], Dennis Zaritsky[4]

Draft version April 3, 2015

DECam Data

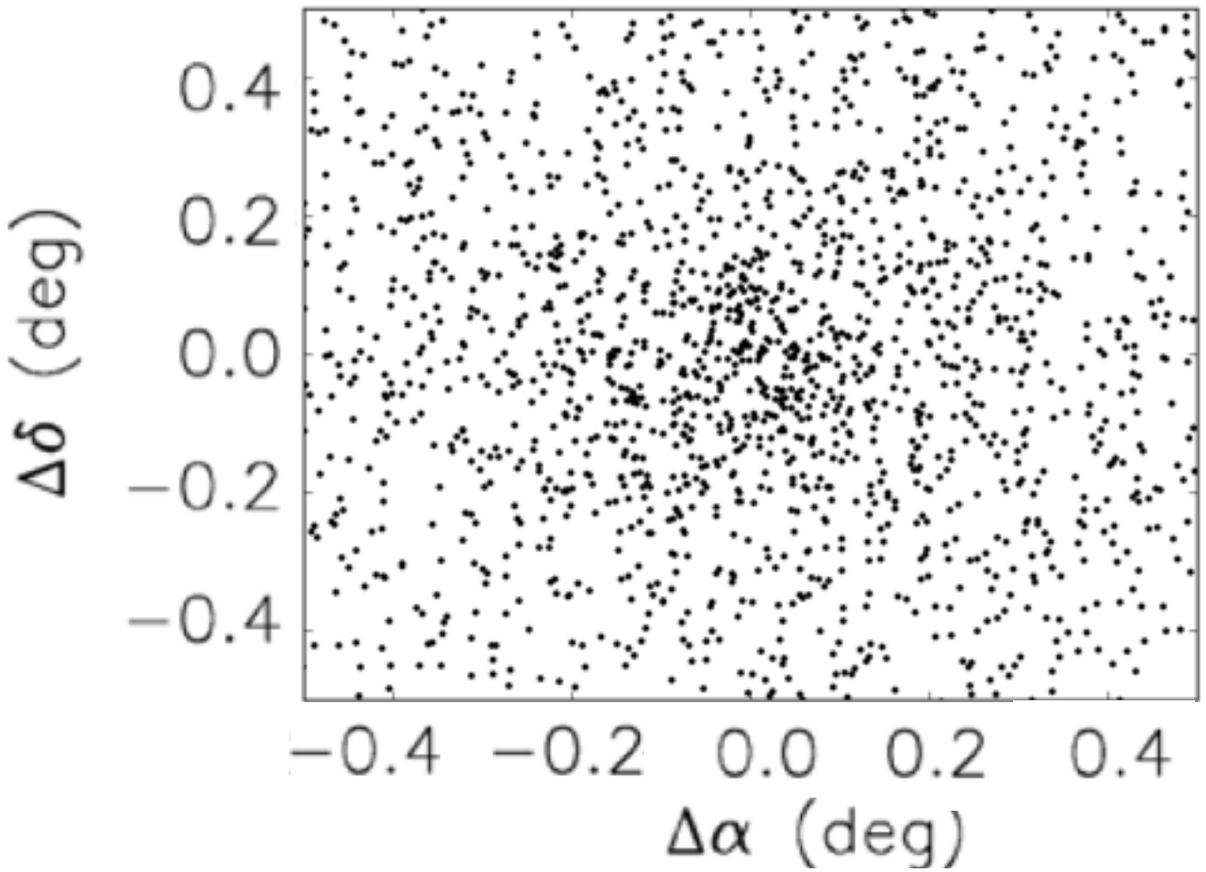
A Familiar Problem



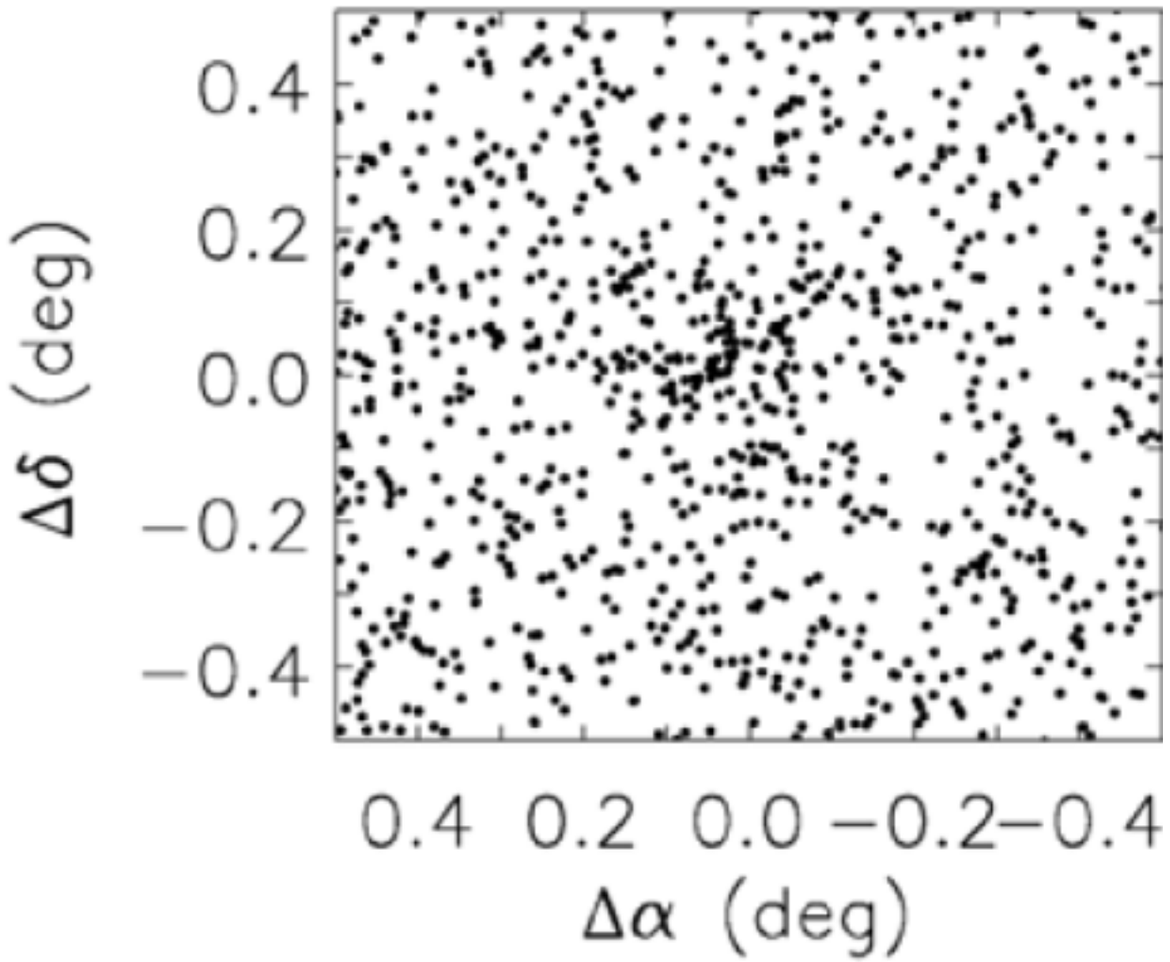


A Familiar Problem

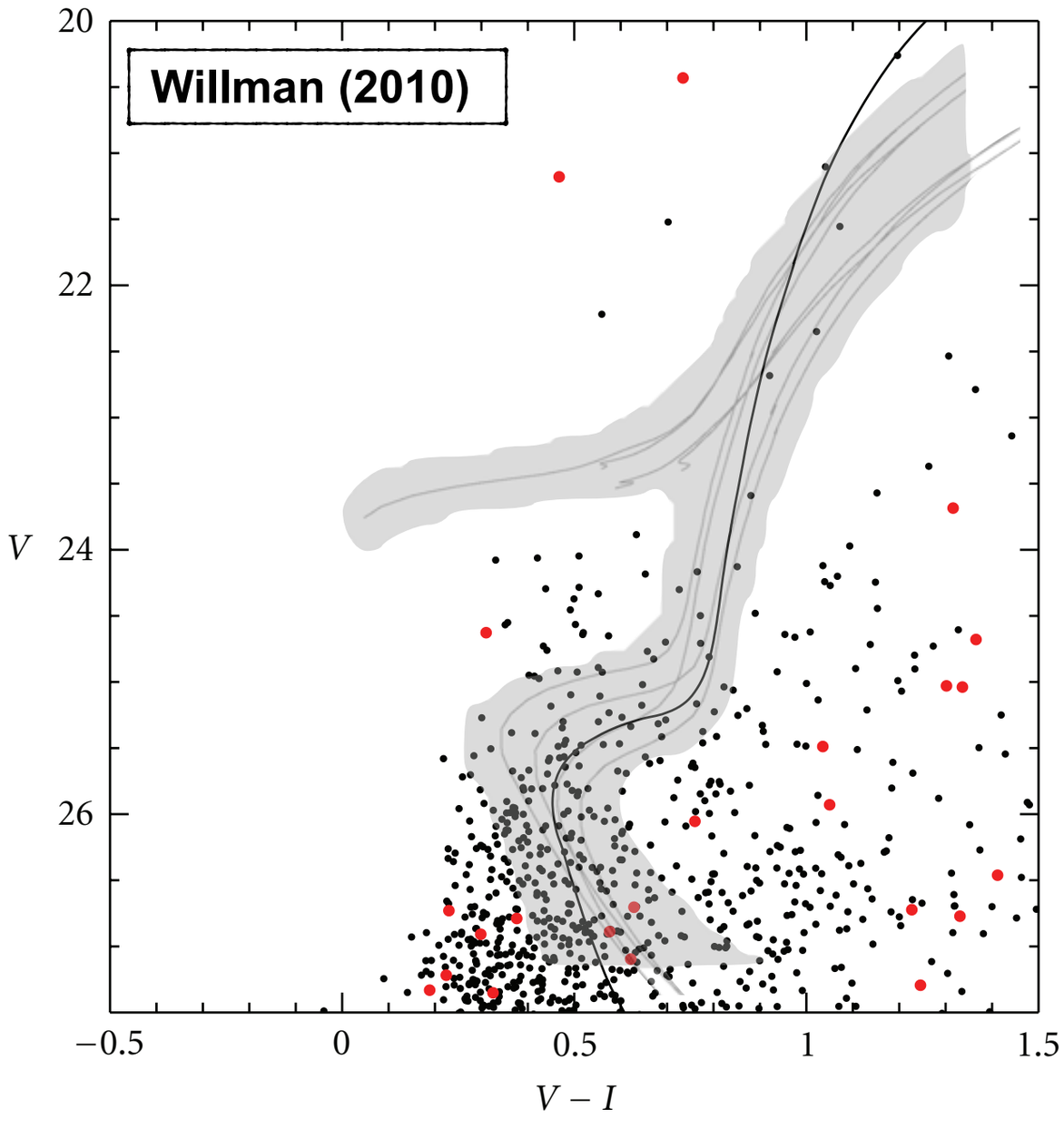
Gamma-ray Source (4C+21.35)



Dwarf Galaxy (Coma Berenices)



Upcoming Challenges



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

• Stellar sources in the HUDF

• Galaxies with fwhm < 0.8 arcsec in the HUDF

Galaxy more abundant than stars a faint magnitudes.

Require better star-galaxy separation

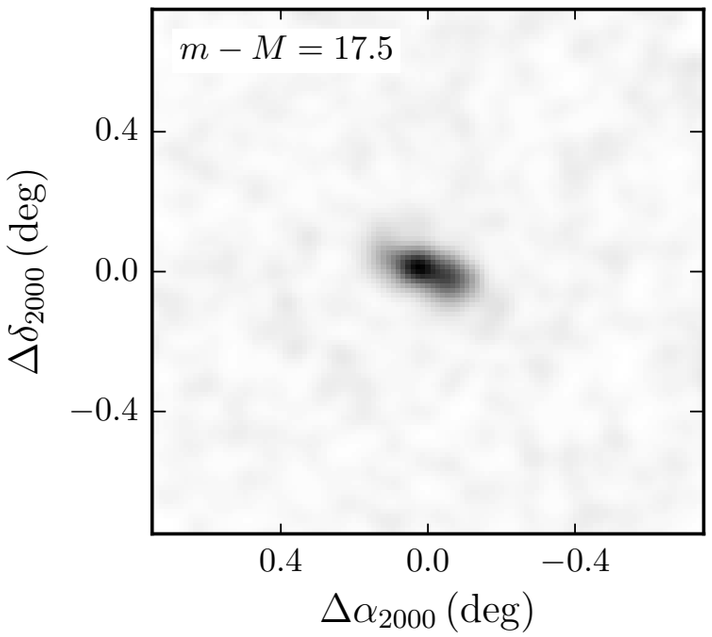
More sensitive and robust search techniques

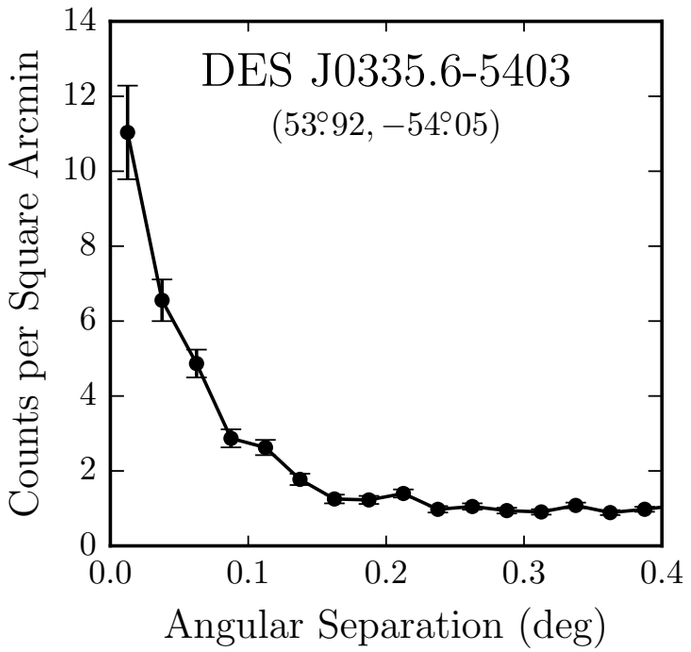
Small, well characterized signal in a strong, structured background.

Reticulum II: Newest Dwarf Galaxy?

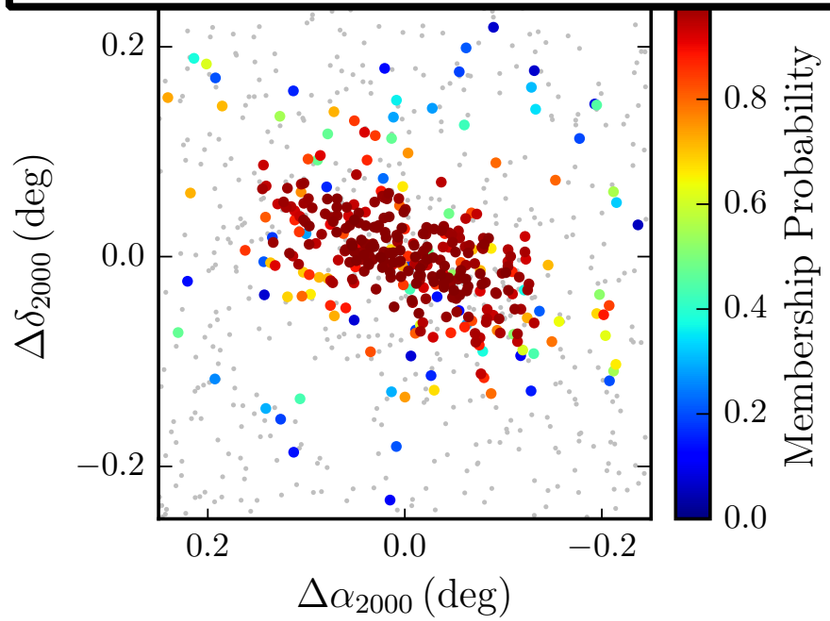
THE DARK ENERGY SURVEY

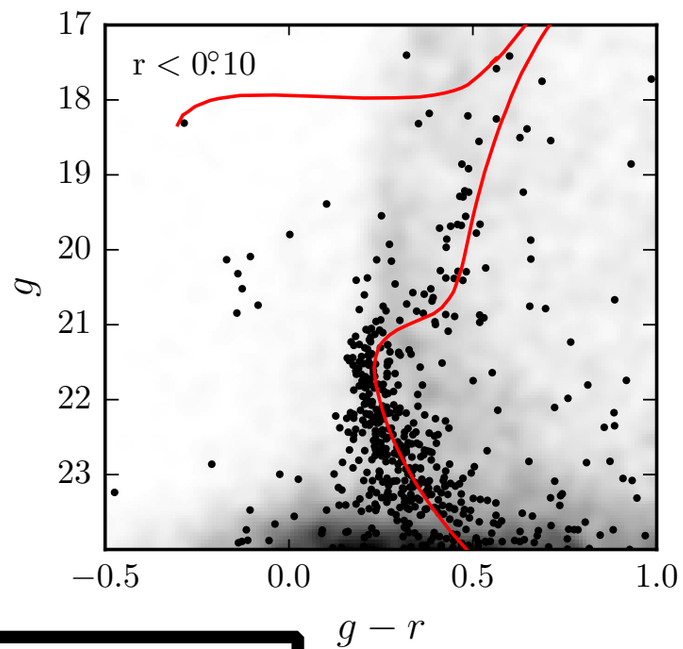
Fermilab

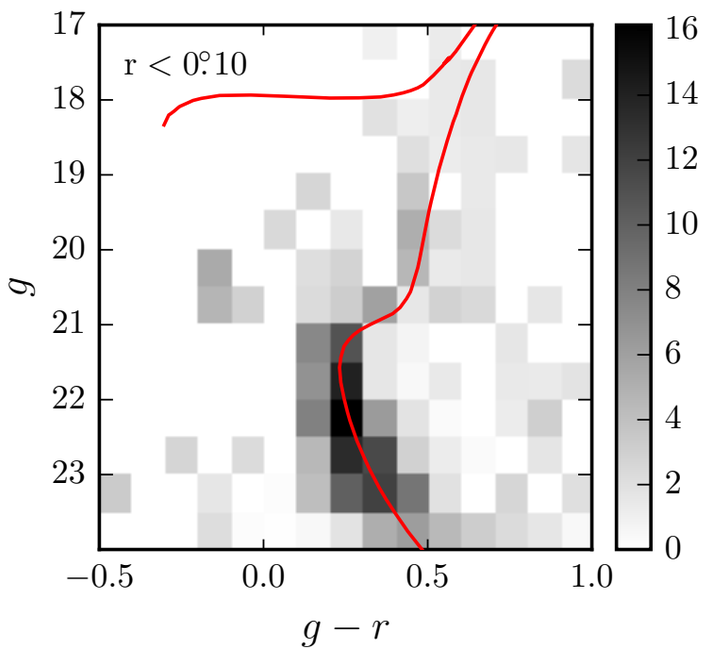


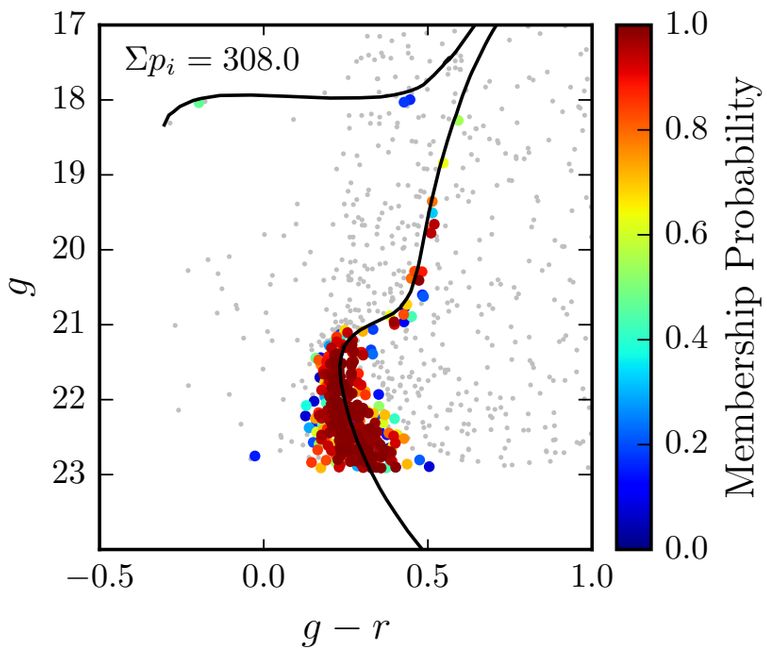


Membership probabilities will play an important role targeting spectroscopy









arXiv:1503.02584

Looking Forward

- A large-scale spectroscopy campaign will be necessary to classify and characterize newly discovered systems
- Future sky coverage:
  - DES Y2: >4,000 deg^2
  - DES Y3+: 5,000 deg^2 (and greater sensitivity)
  - LSST: 10,000 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?