Discovery of Milky Way Dwarf Galaxies in the Dark Energy Survey

Ting Li
on behalf of the DES Collaborations
Milky Way Working Group

Department of Physics and Astronomy
Texas A&M University
APS DFP2015
Aug 4, Ann Arbor

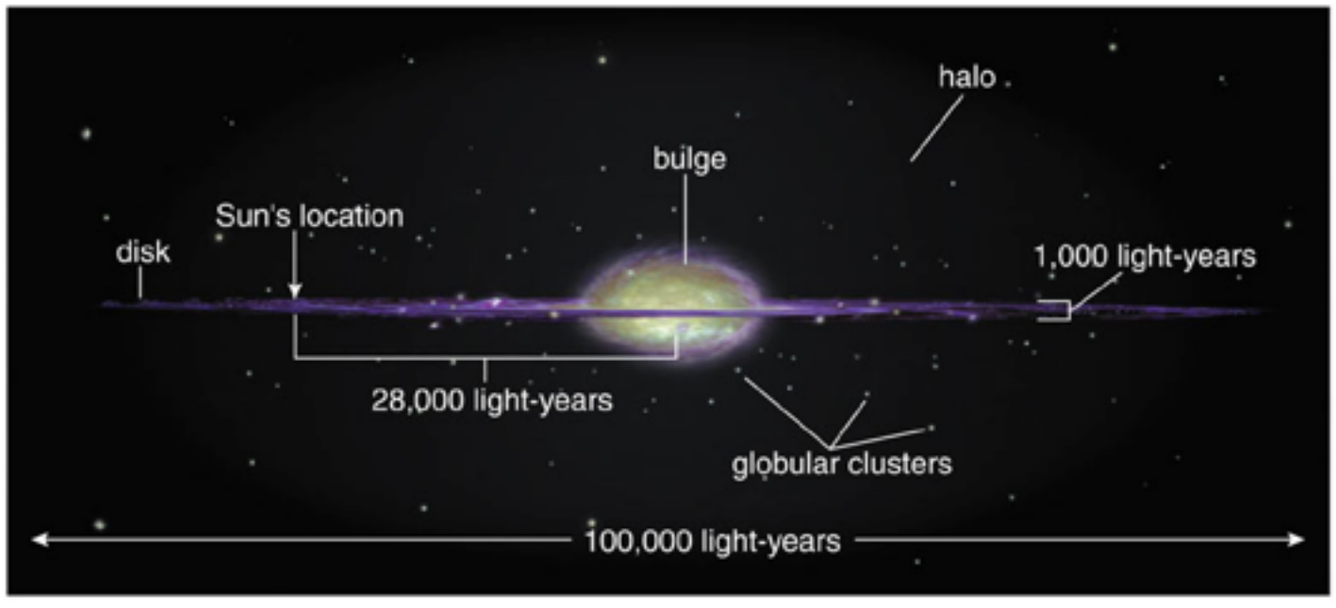
Credit: Reidar Hahn, Yuanyuan Zhang

The formation of Milky Way

- **ELS Monolithic Collapse Model (top-down)**

  Eggen, Lynden-Bell and Sandage 1962

  Milky Way formed from the rapid collapse of a large proto-galactic nebula



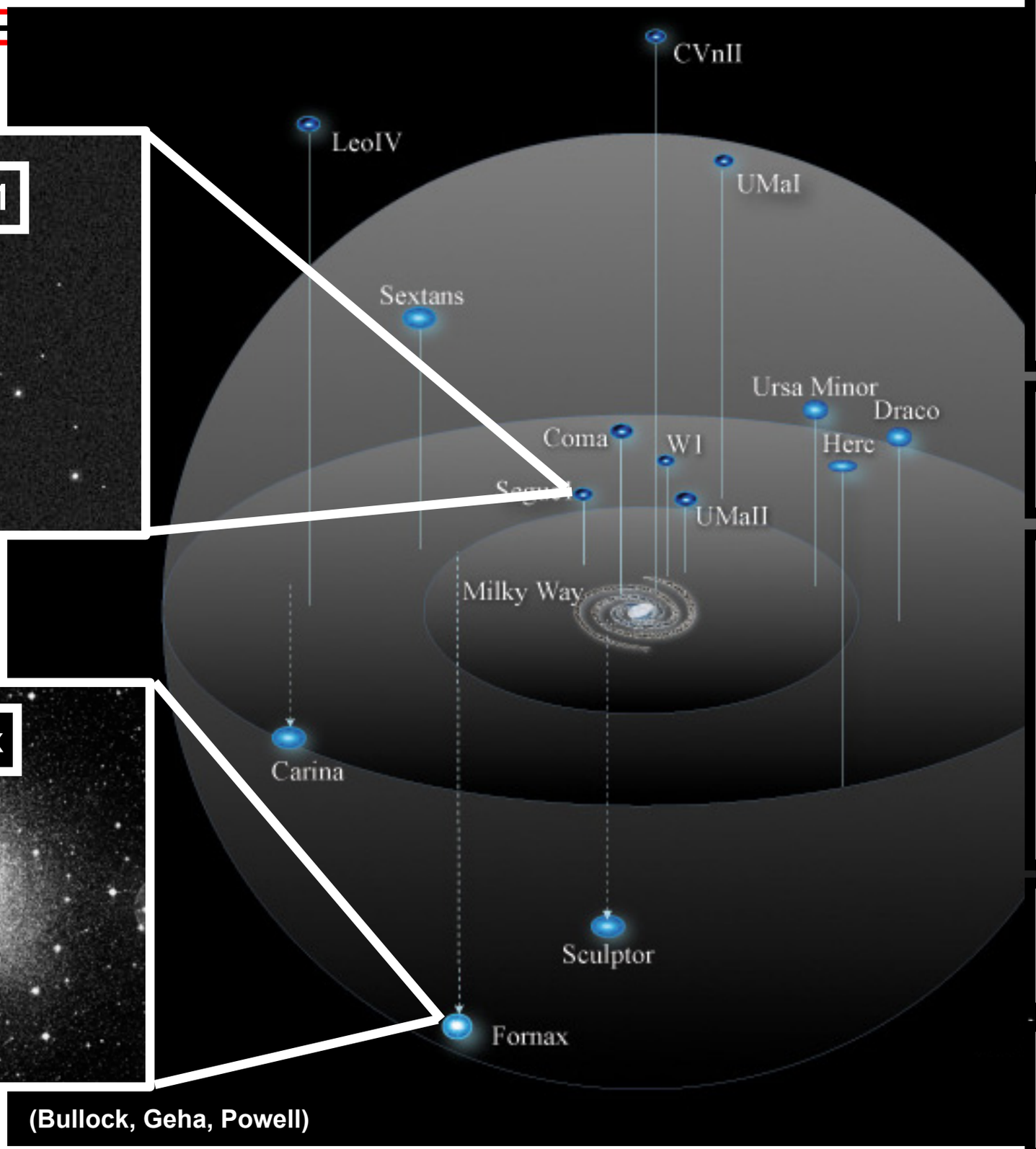
- **SZ Merger and Accretion Model (bottom-up)**

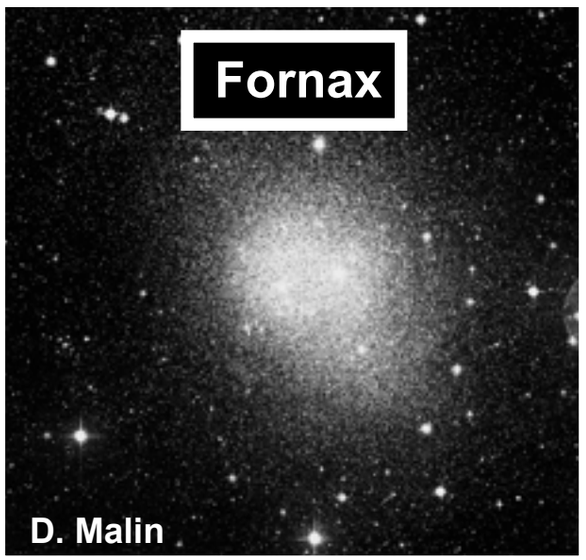
  Searle & Zinn 1978

  Galaxies are built up from merging or accreting smaller fragments

  N-body simulations under ΛCDM context

Milky Way Satellite Galaxies





(Bullock, Geha, Powell)

The Milky Way is surrounded by small satellite galaxies

Distances ranges from 25 kpc to a few hundred kpc

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

The stars are moving too fast to be explained by visible mass
——— dark matter dominated

Astrophysically simple and clean

Birth of near-field cosmology

Dwarf Galaxies as Cosmological Probes

- Missing Satellites Problem?
  - CDM simulations predict thousands of dark matter substructures
  - Only dozens of dwarf galaxies are found
- "Too big to fail" Problem?
  - Circular velocities of known dwarf galaxies are significantly smaller than predicted by simulations.
- Density profile of dark matter halo
  - cusp vs core problem
- Gamma rays from dark matter annihilation
  - Study the property of dark matter particles

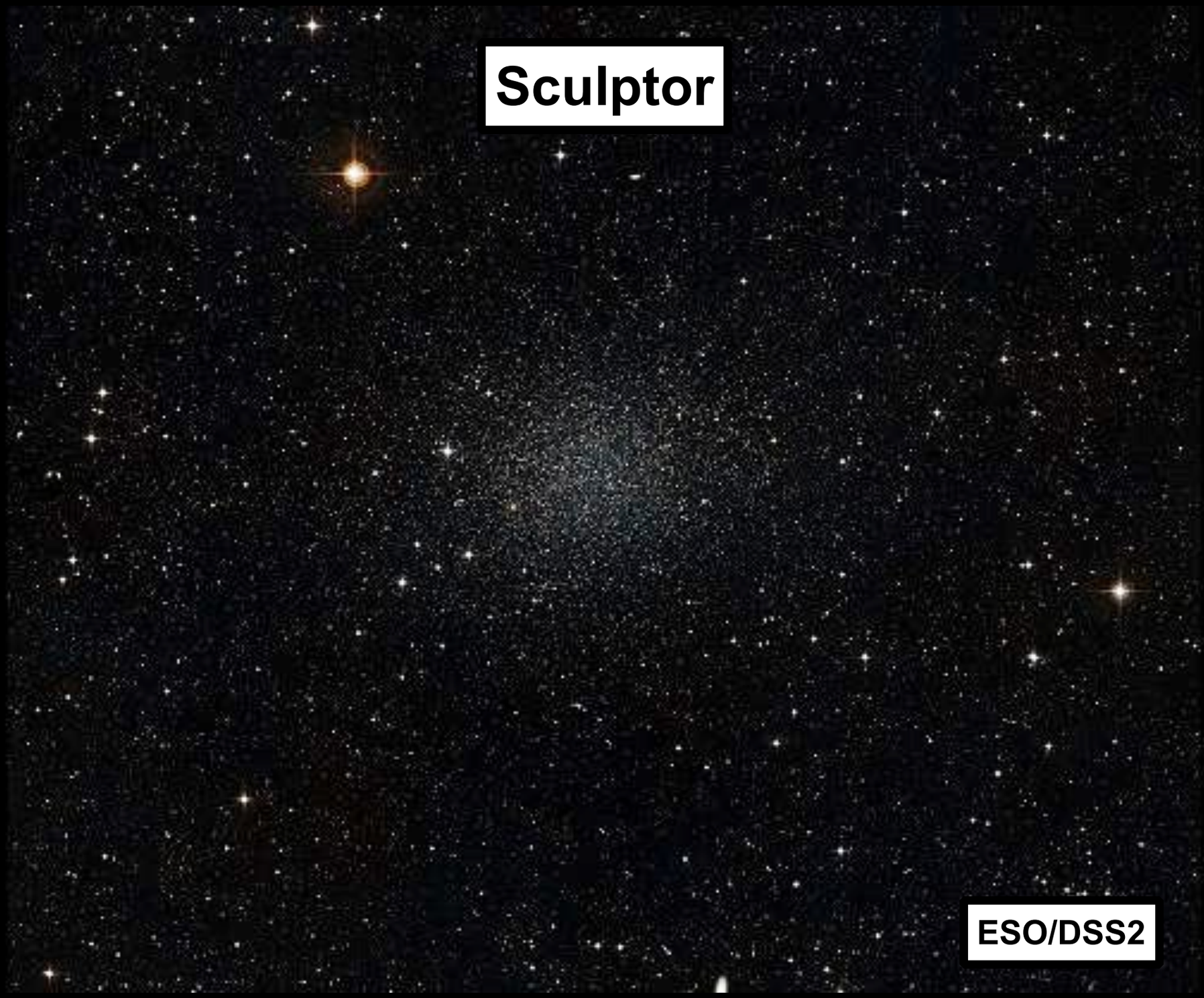
- Cold dark matter?
- Warm dark matter?
- Self-interacting dark matter?
- Or other?

z=0.0

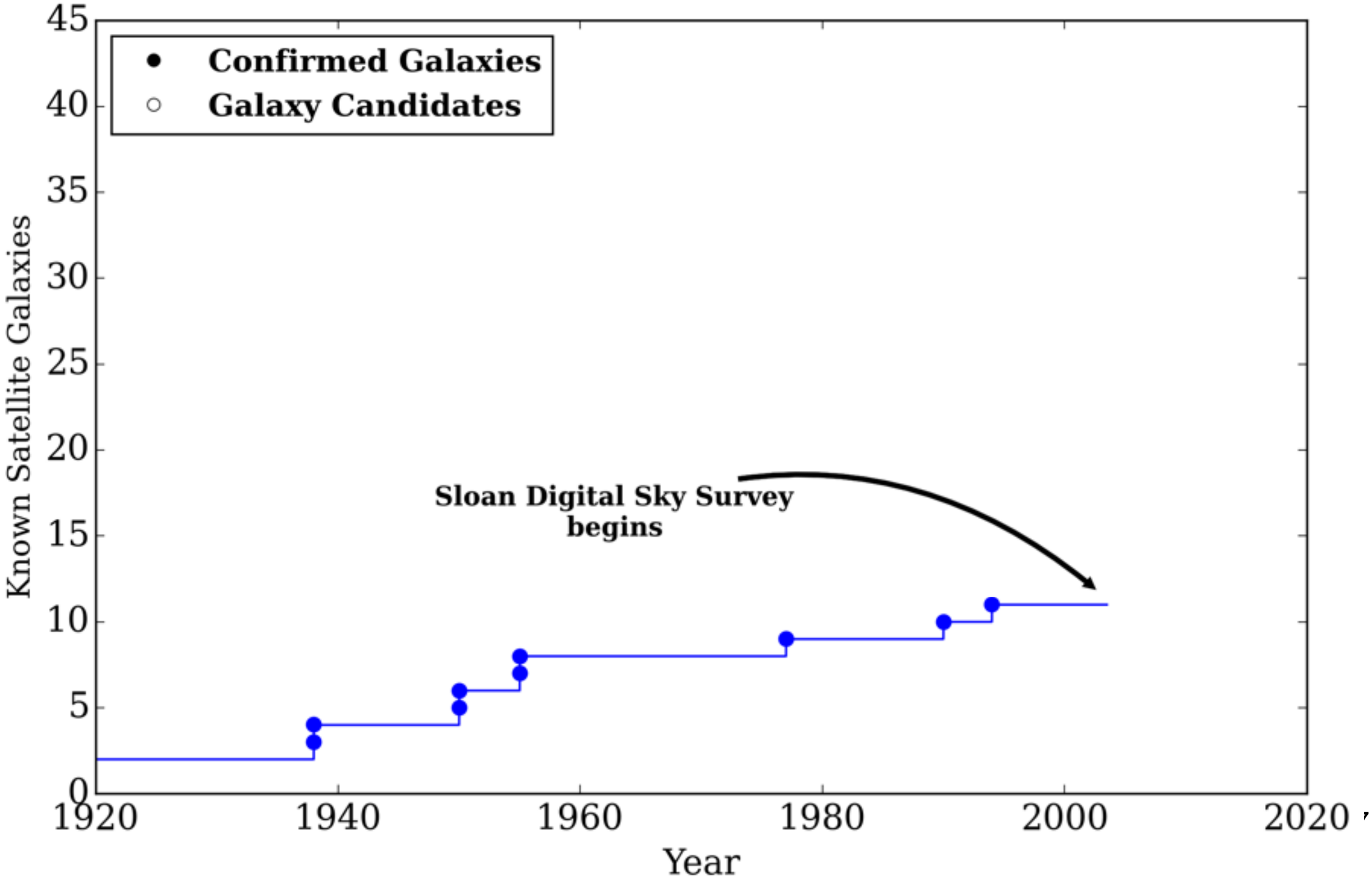
Finding Milky Way Satellite Galaxies

80 kpc

Classical Dwarf Spheroidal Galaxies (dSph)



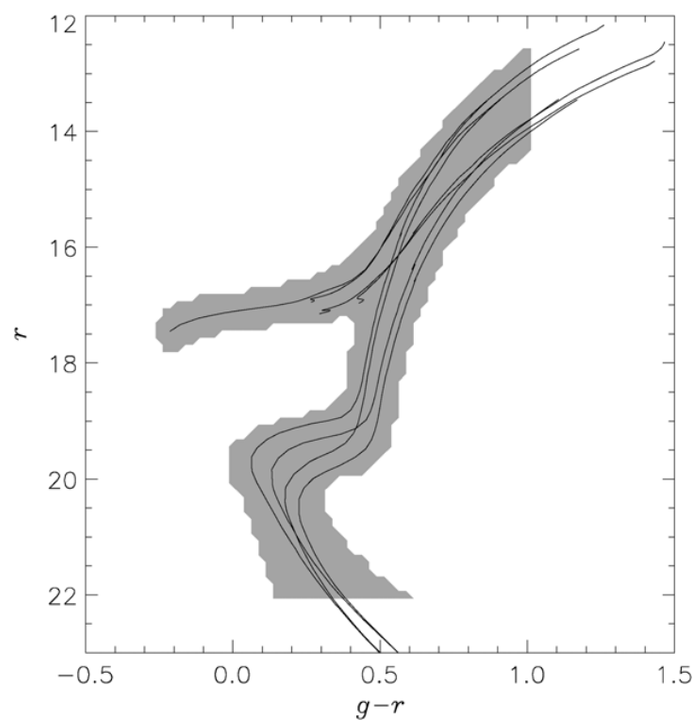
Milky Way Satellite Galaxies Discovery Timeline

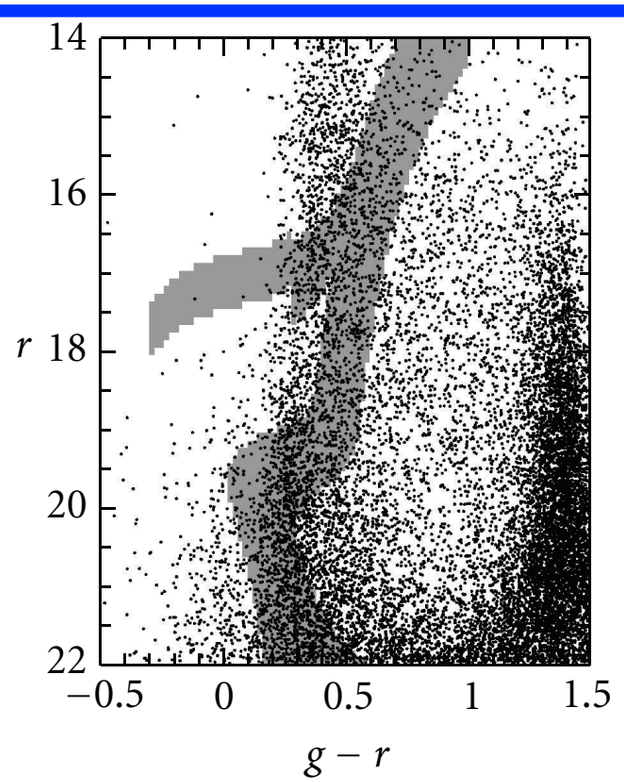


Finding Milky Way Satellite Galaxies

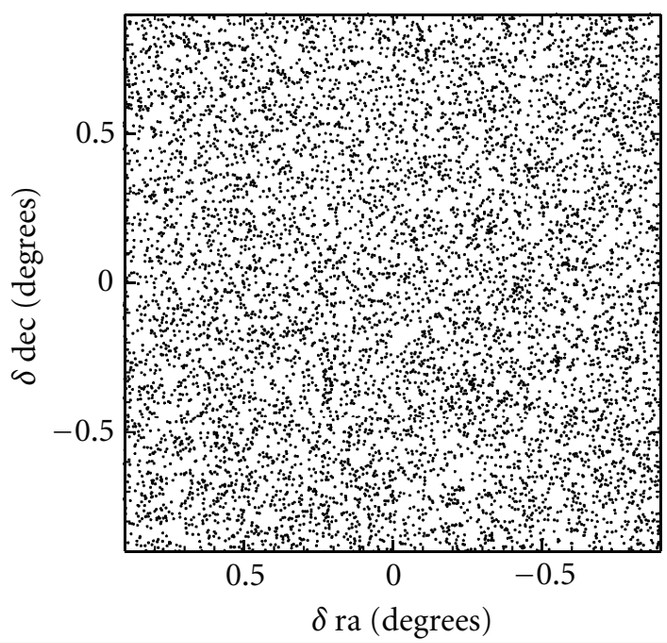
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

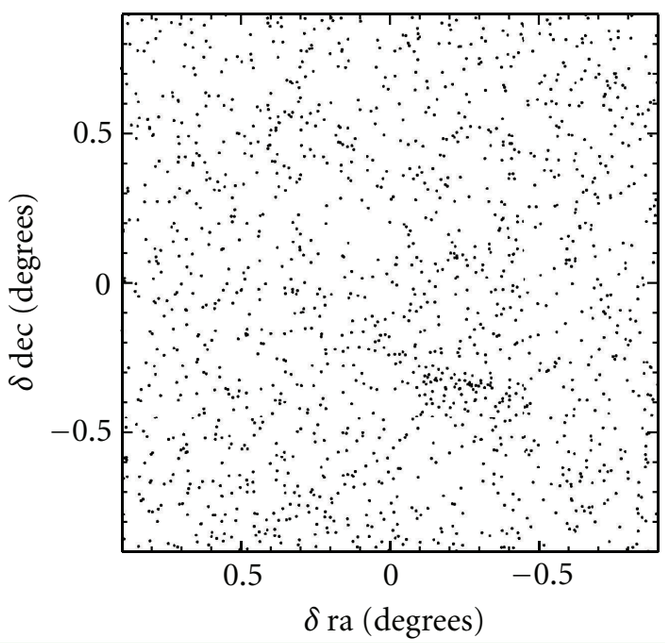
Color-Magnitude Domain

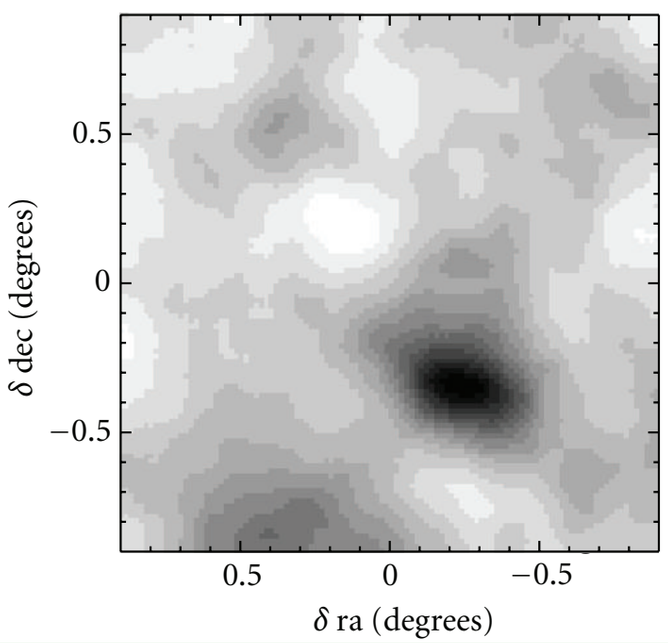




Spatial Domain

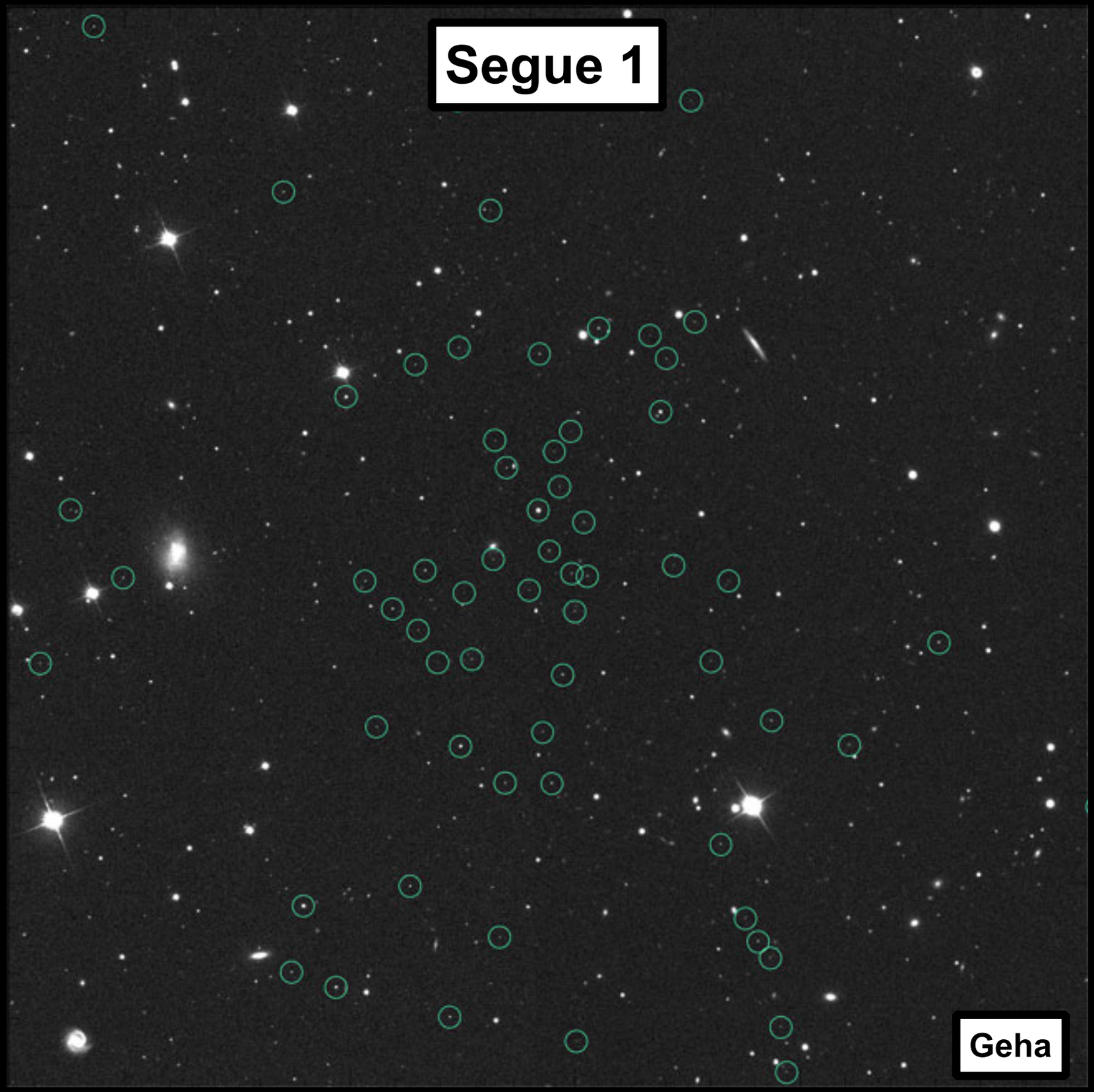




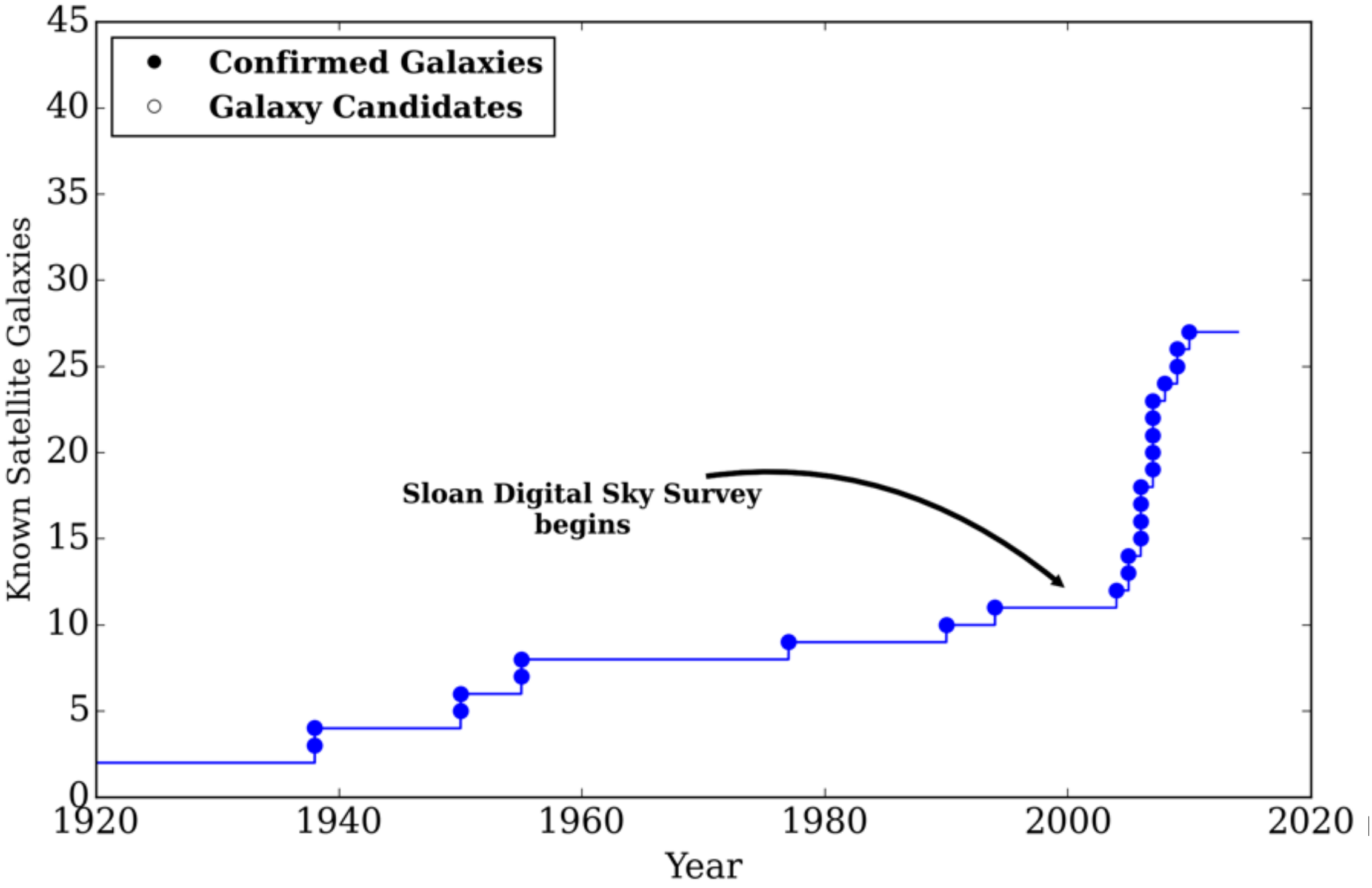


Ultra-Faint Dwarf Galaxies

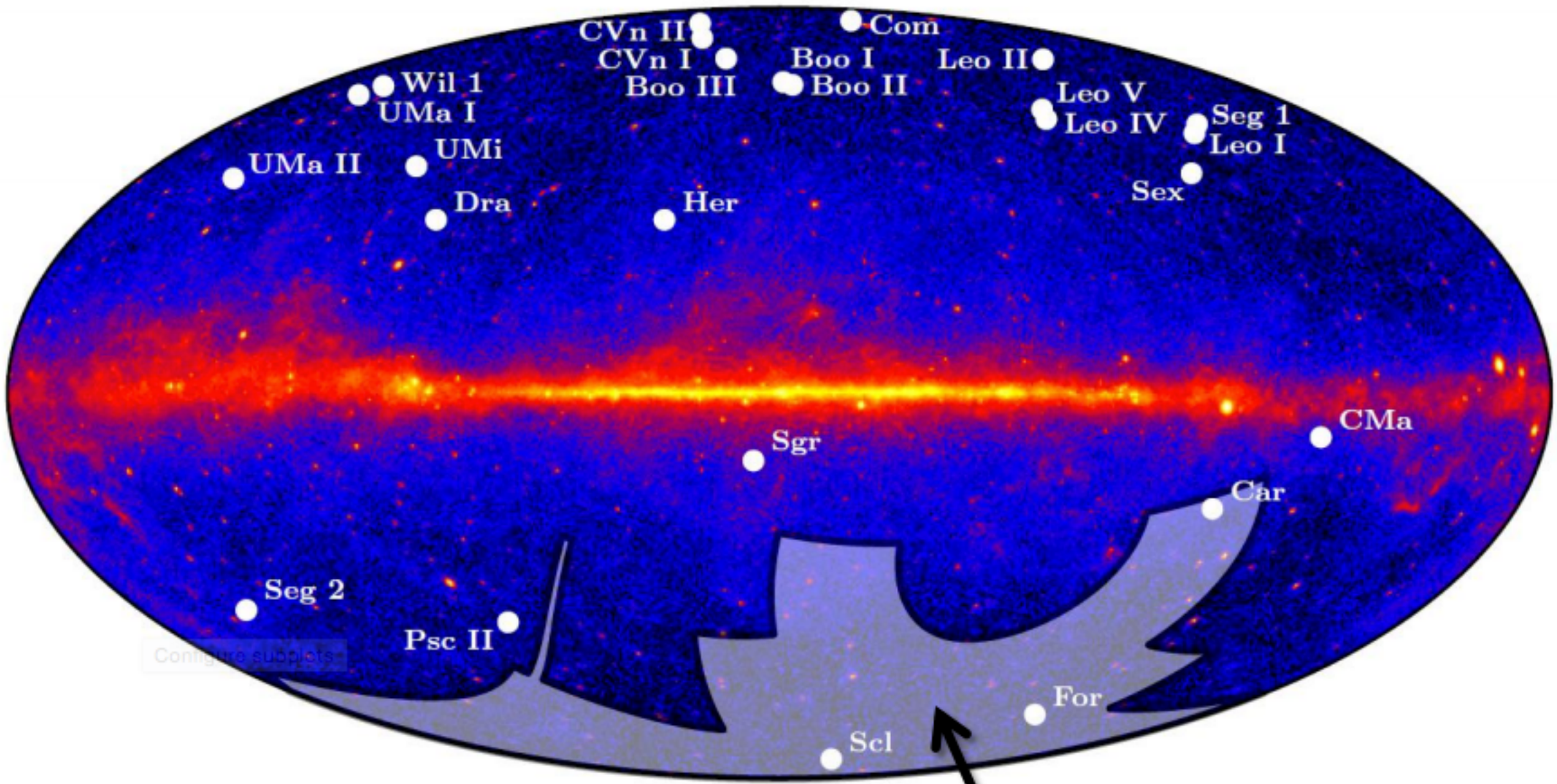
Ultra-Faint Dwarf Galaxies



Milky Way Satellite Galaxies Discovery Timeline



Known Milky Way Satellites after SDSS



- **What will DES discover?**

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

The Dark Energy Survey

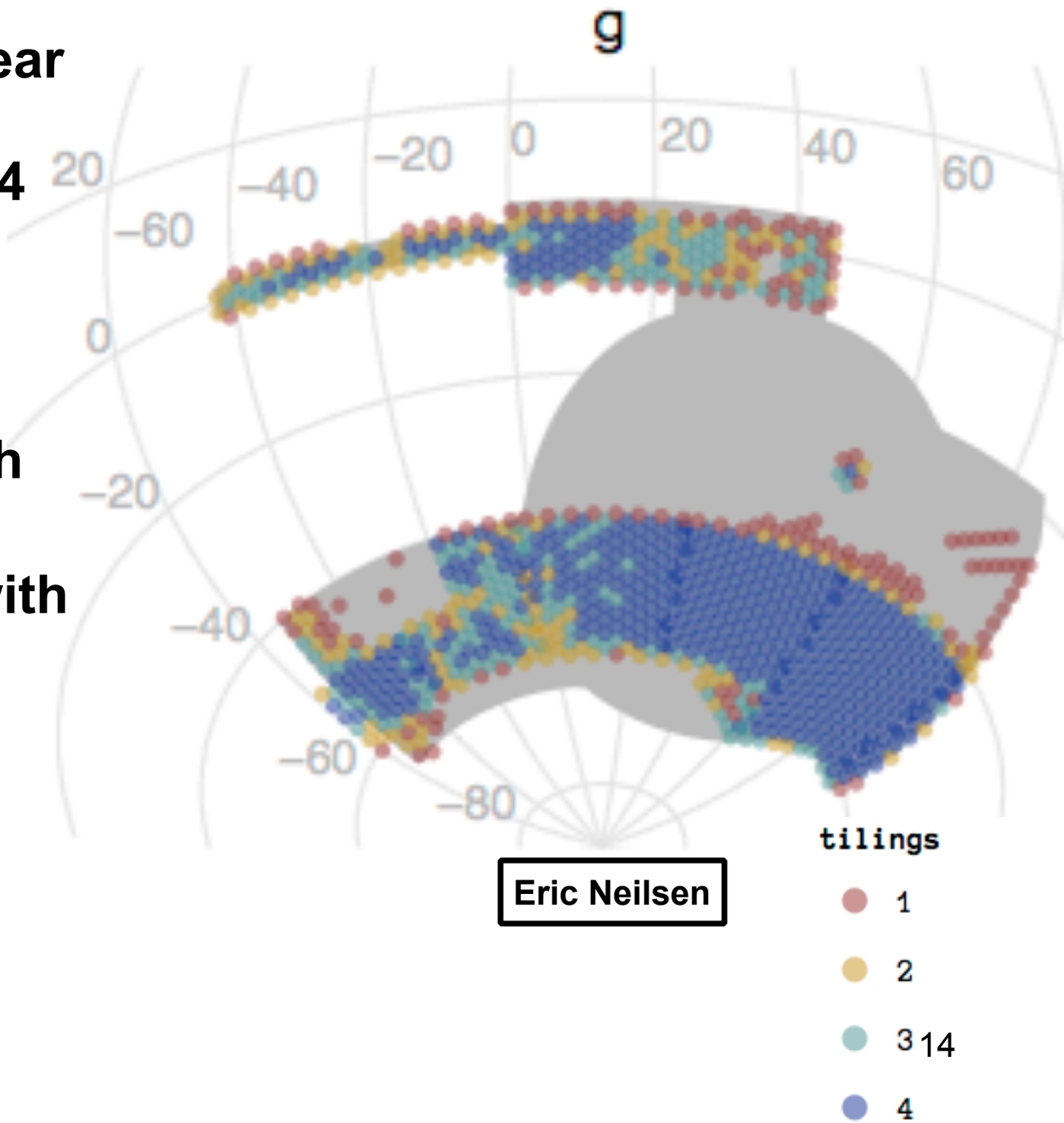
5 year survey over 525 nights
5 filters: g,r,i,z,Y
~5,000 sq. degree
~24th mag in g-band with 10 tiling

DES Year-One (Y1A1)

- **Imaging data from the first year of the survey:**
  August 2013 to February 2014

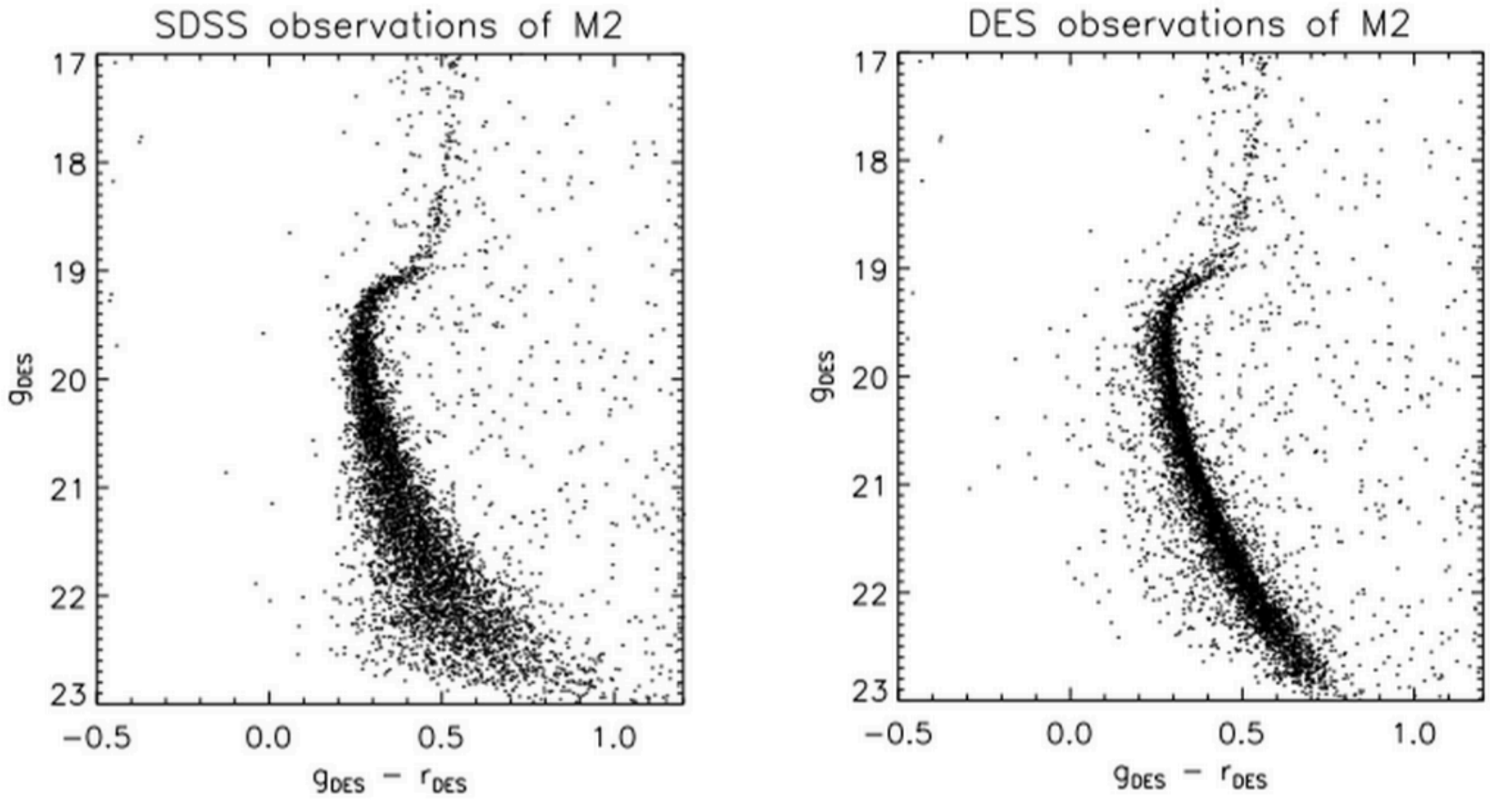
- **Coadded image catalog covering ~1800 deg^2**
  - **~200 deg^2 overlapping with SDSS Stripe-82**
  - **~1600 deg^2 overlapping with the South Pole Telescope**

- **Stellar completeness >50% down to g,r ~ 23**



DES Year 1 vs. SDSS on Messier 2

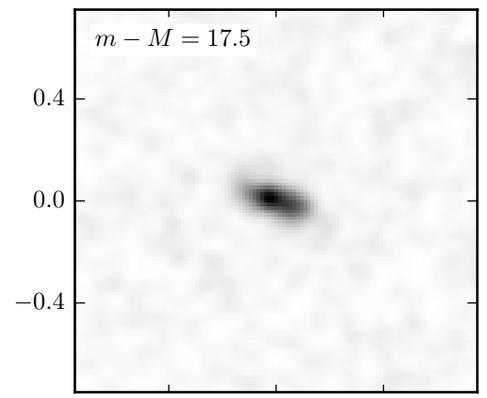
- **A dramatic improvement in the photometric precision with Blanco+DECam!**

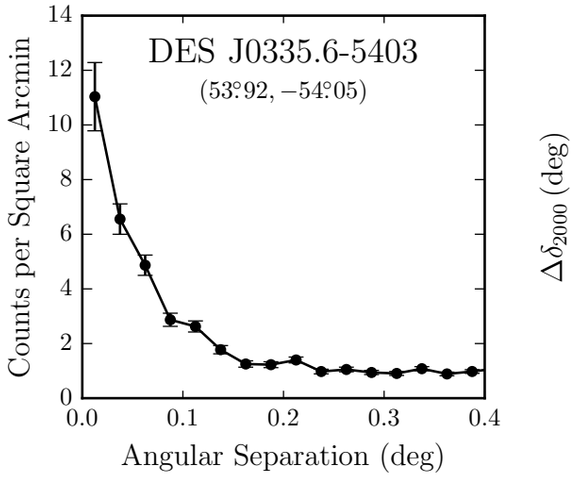


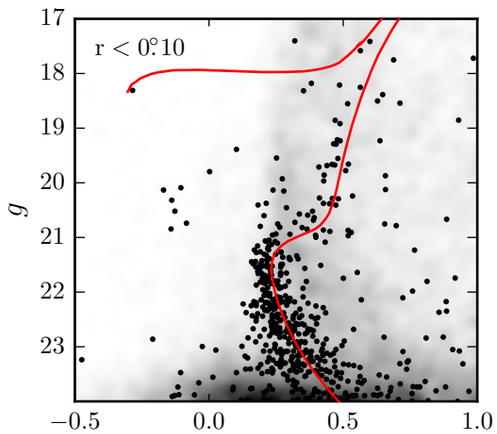
And this is just Year 1—deeper, more precise photometry will be produced throughout the five-year survey

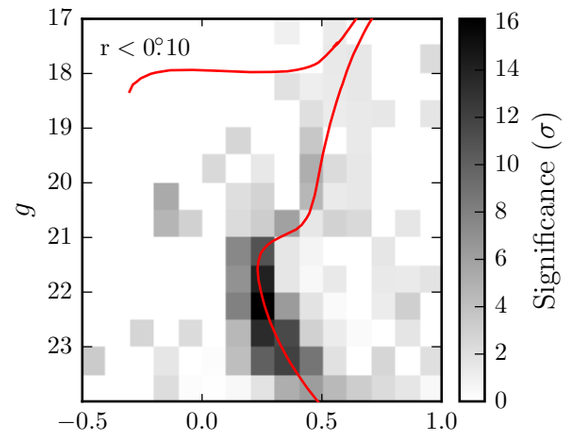
Y1A1: A First Look

Reticulum II (DES J0335.6-5403)

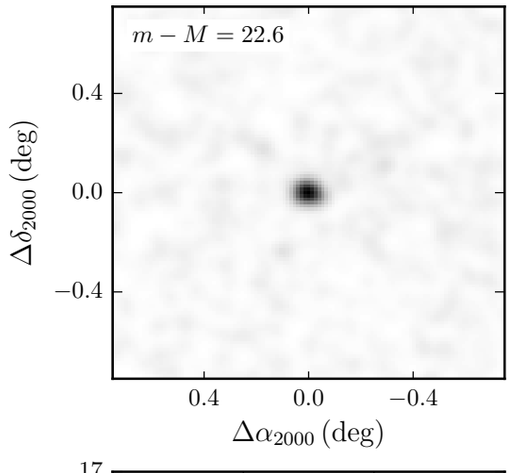


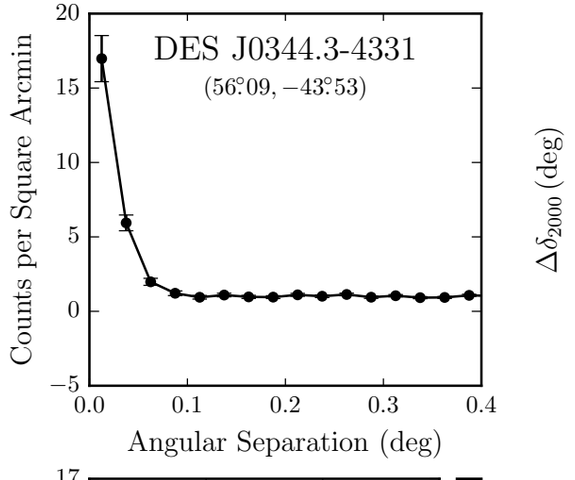


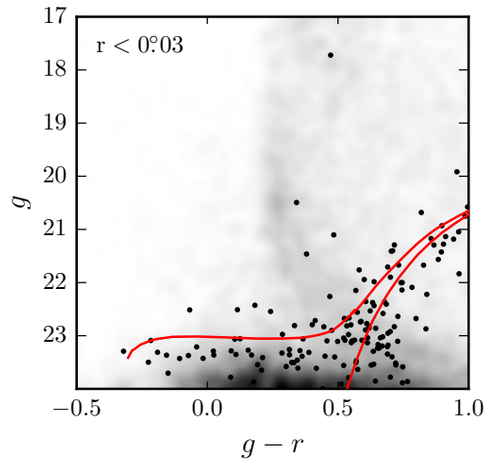


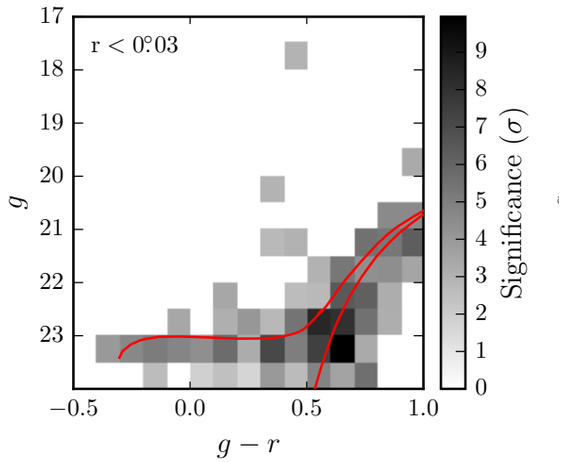


Eridanus II (DES J0344.3-4331)





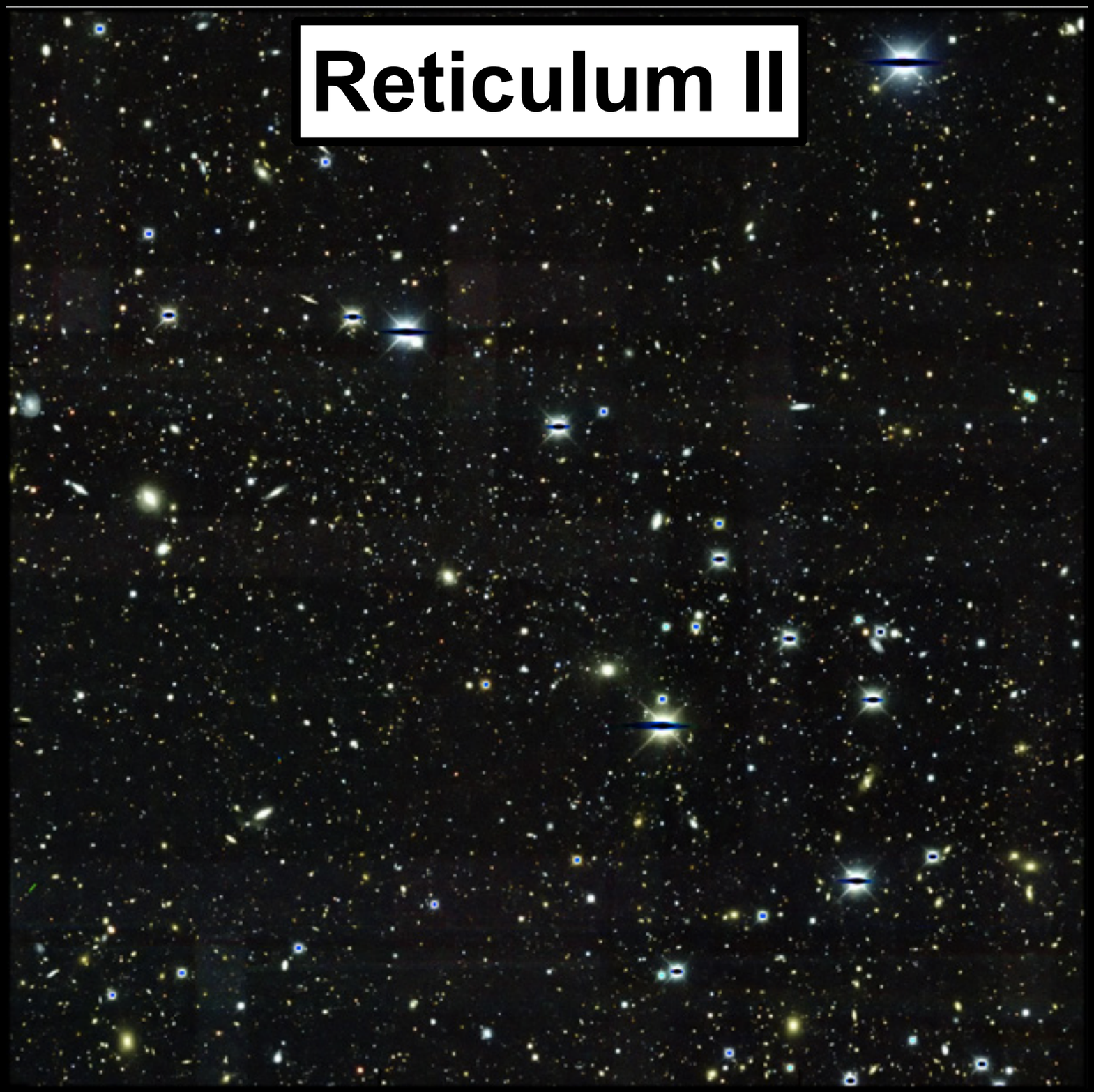




arXiv:1503.02584

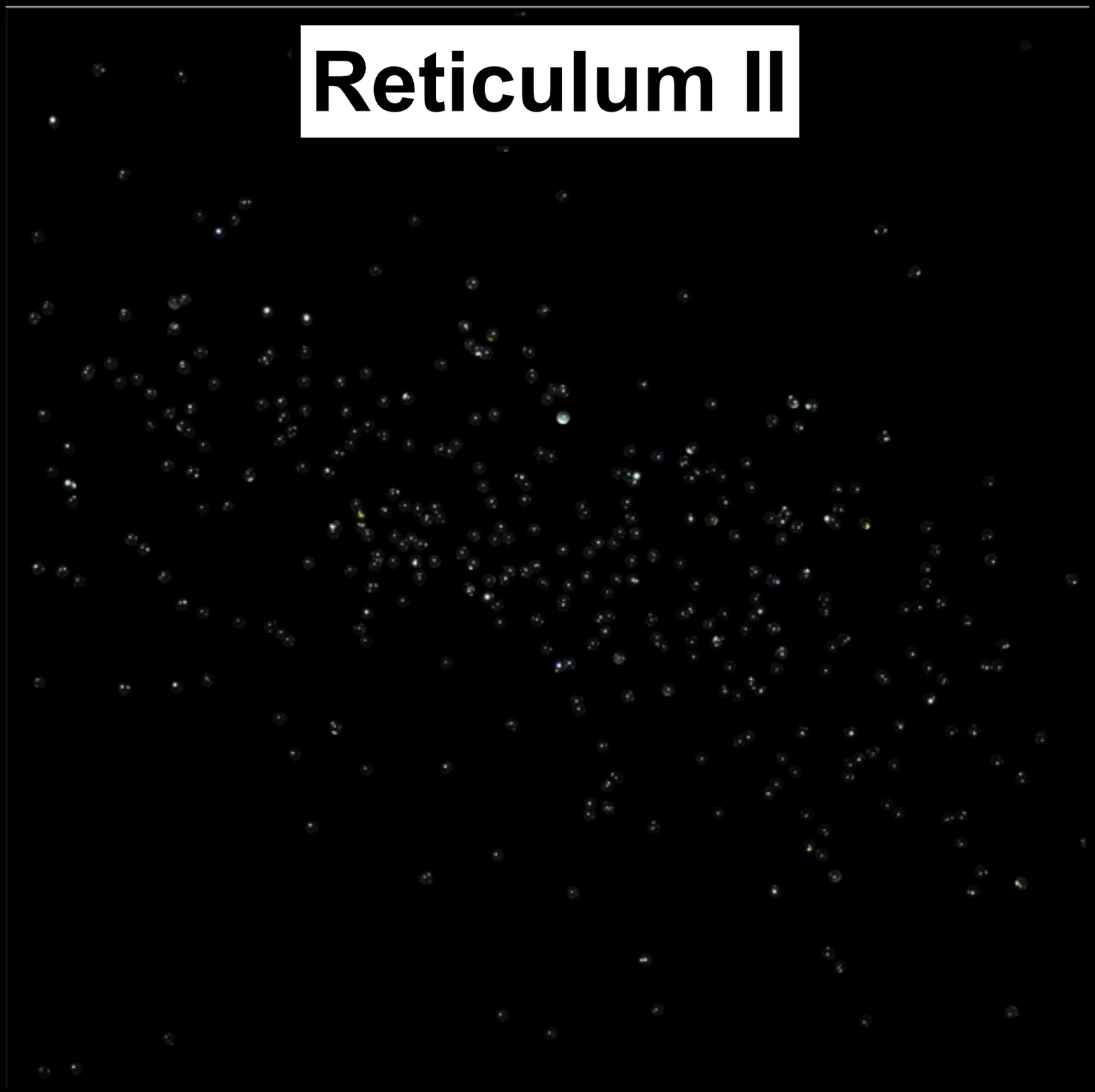
arXiv:1503.02079

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



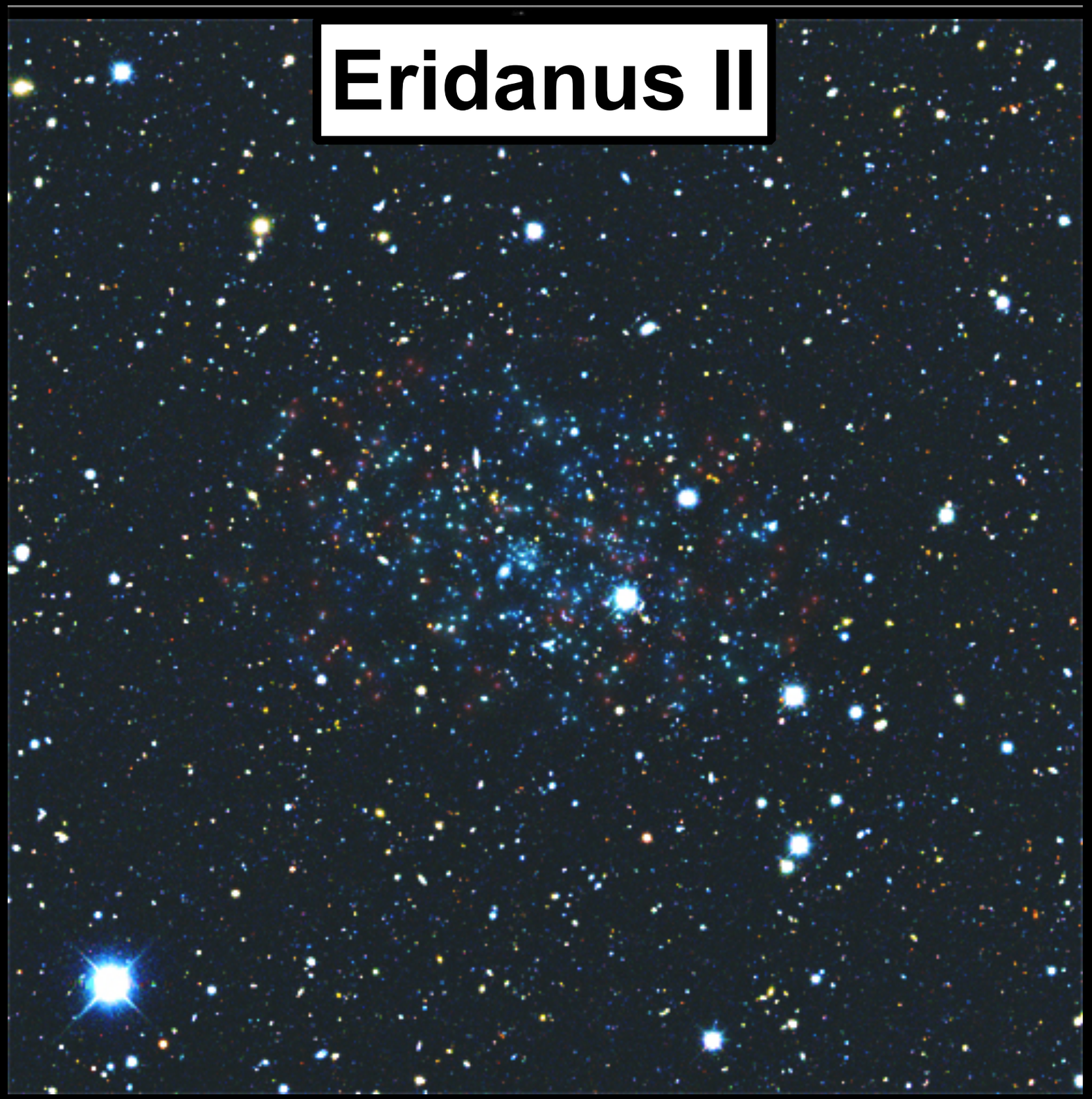
DES Collaboration

Reticulum II



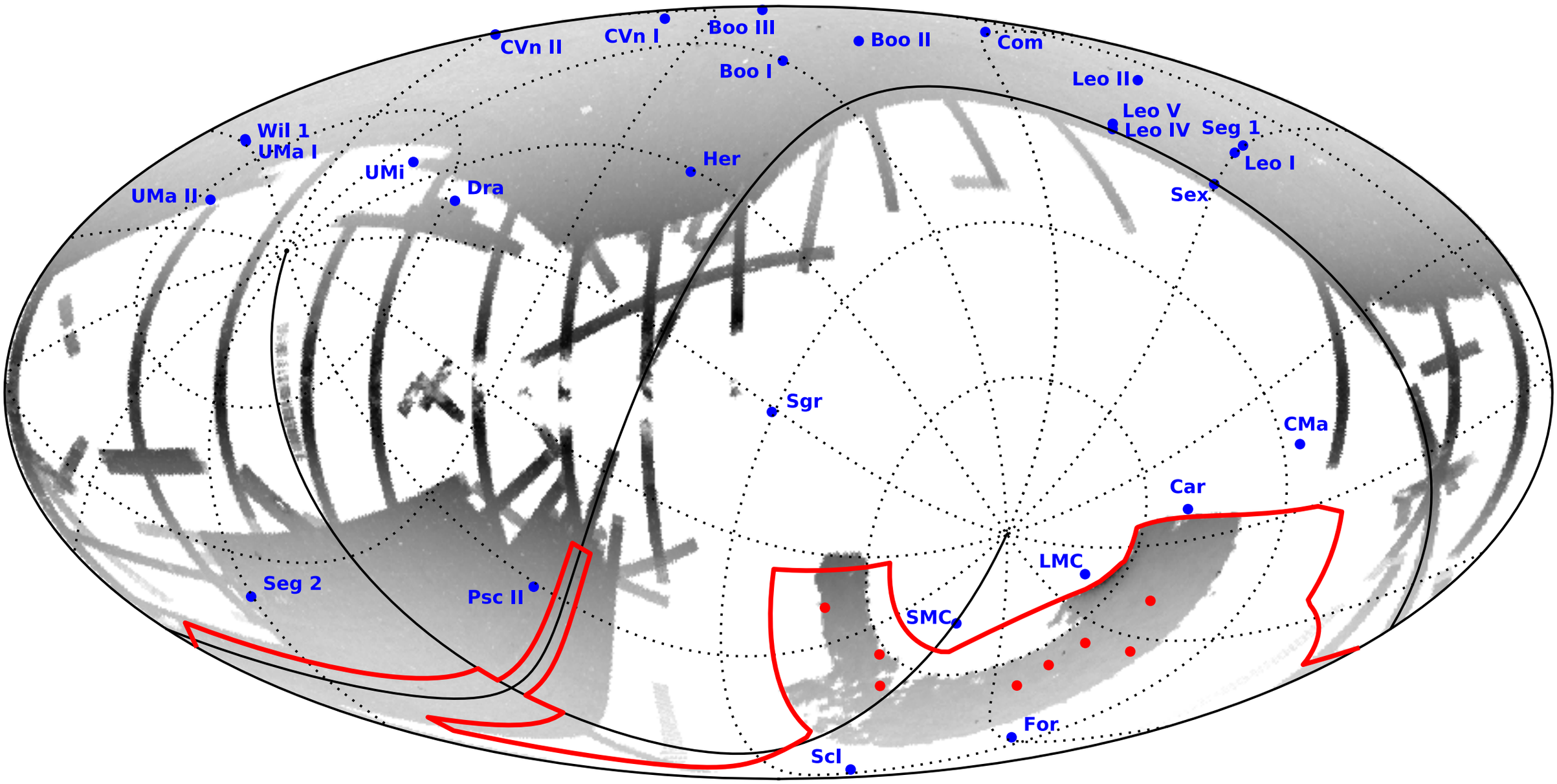
DES Collaboration

Eridanus II



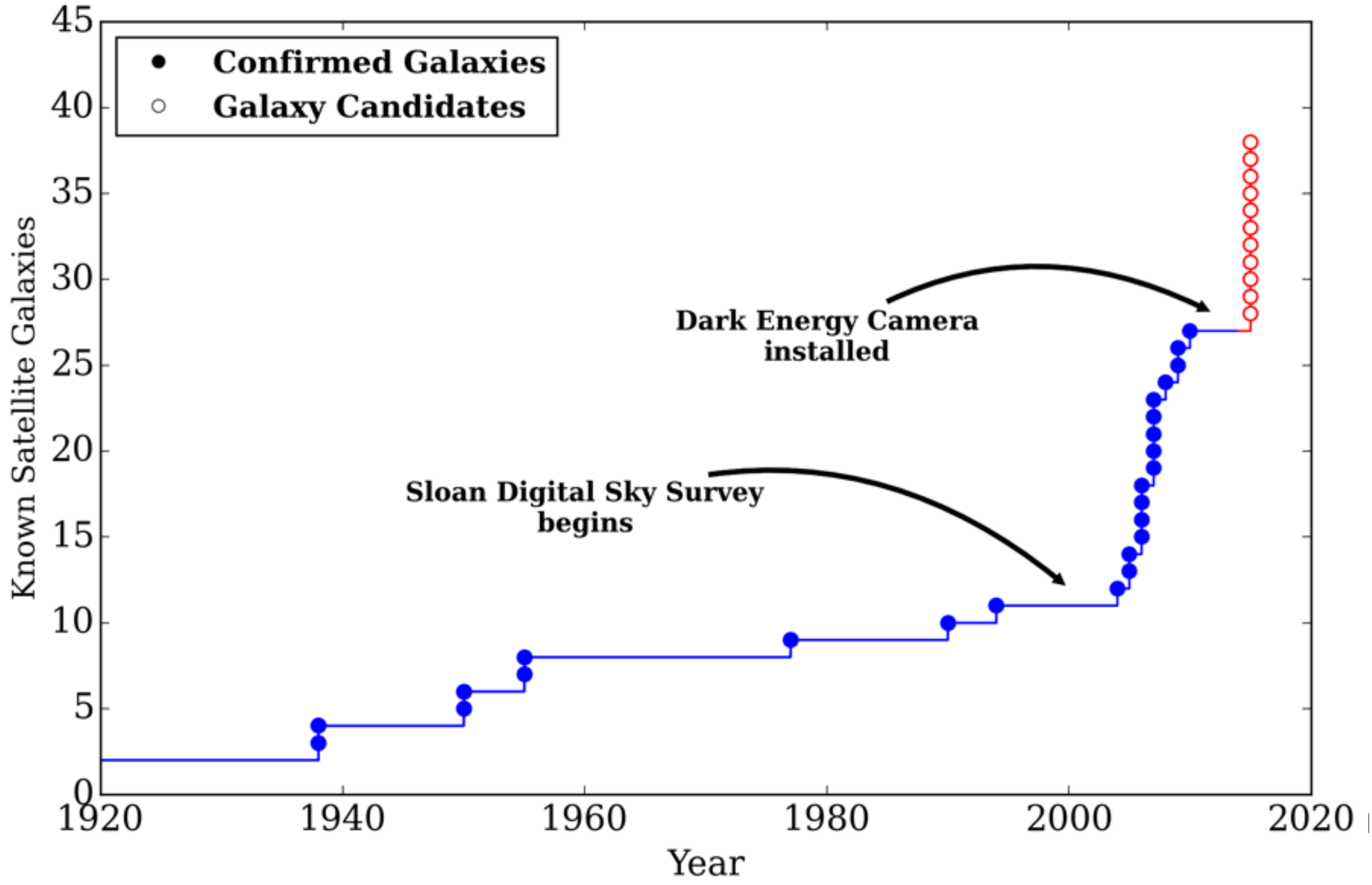
Belokurov & Koposov

Dwarf Galaxy Candidates



arXiv:1503.02584

Milky Way Satellite Galaxies Discovery Timeline



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

DES Data

(Dated: March 10, 2015)
Draft version March 10, 2015

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

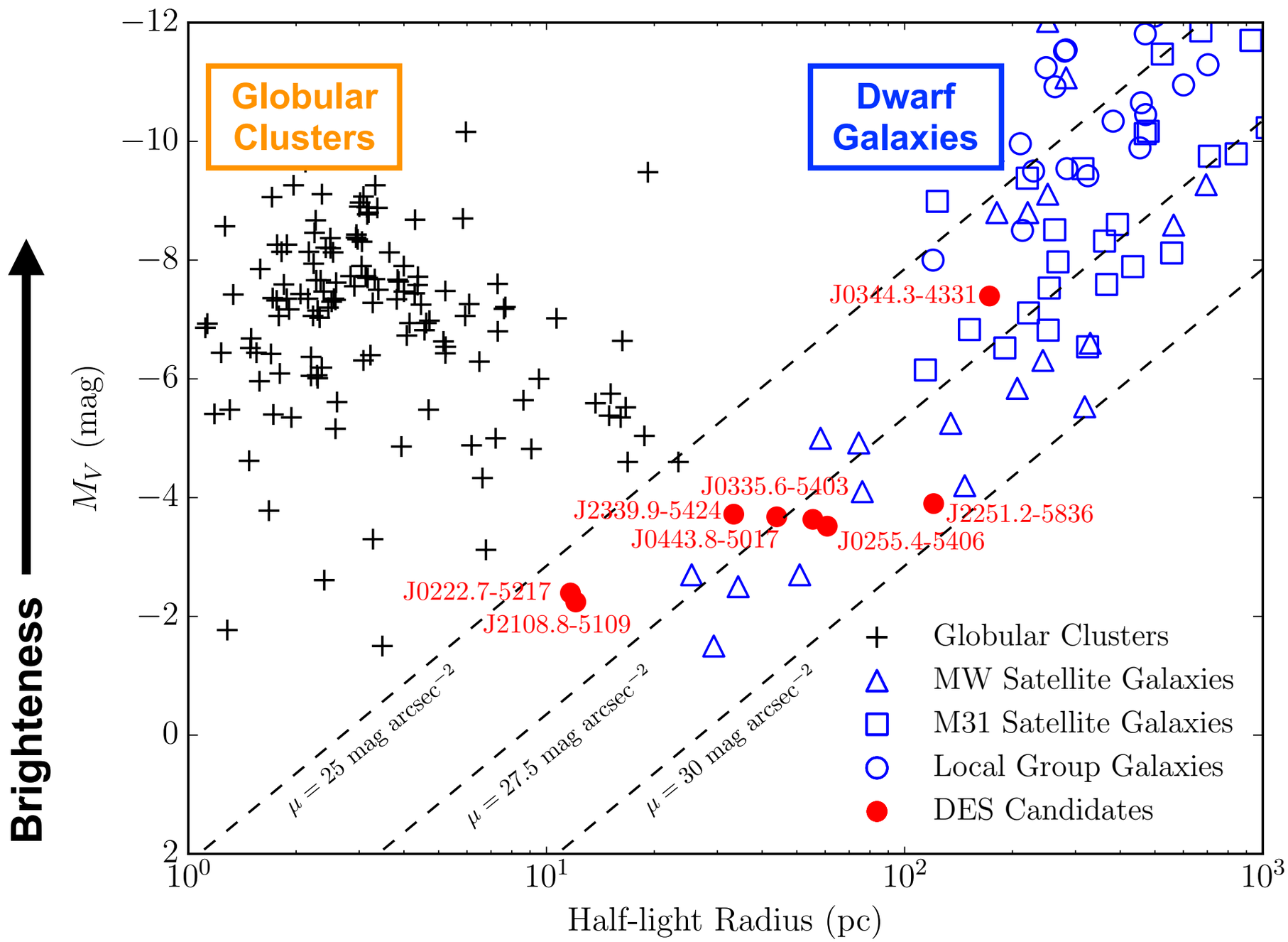
HYDRA II: A FAINT AND COMPACT MILKY WAY DWARF GALAXY FOUND IN THE SURVEY OF THE MAGELLANIC STELLAR HISTORY

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

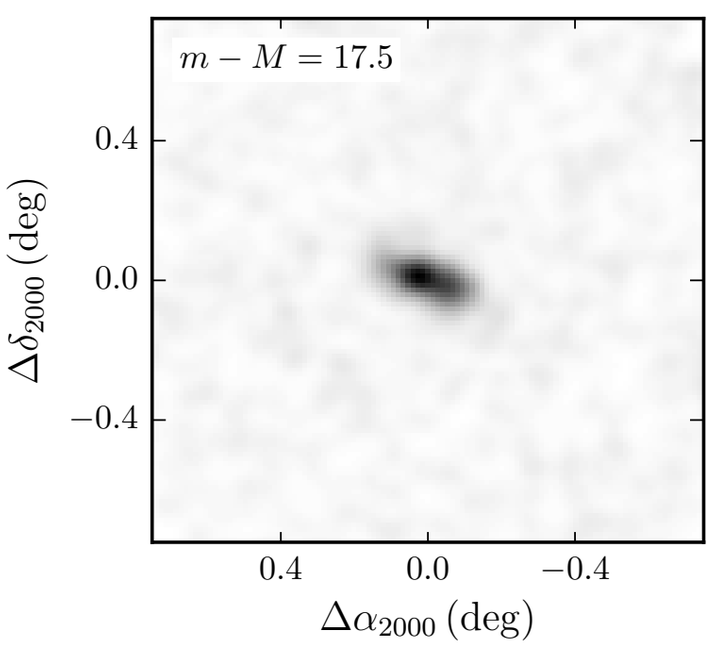
Dwarf Galaxies or Globular Clusters?

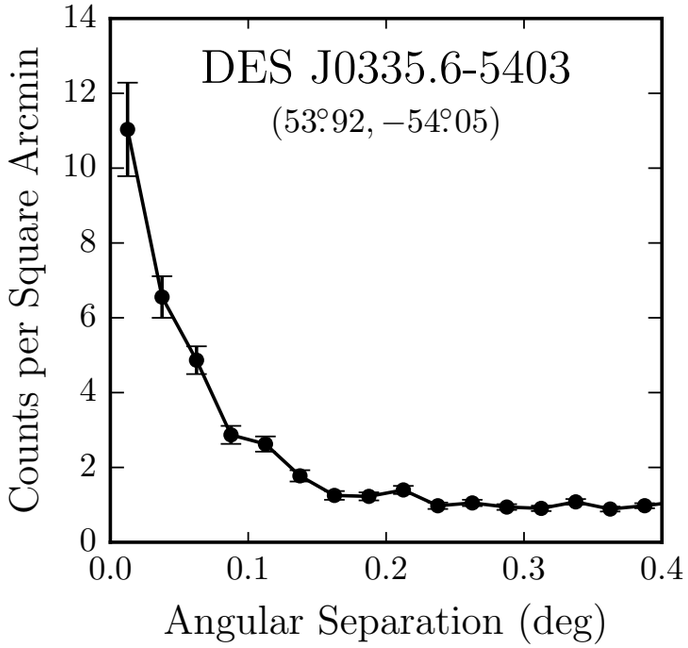


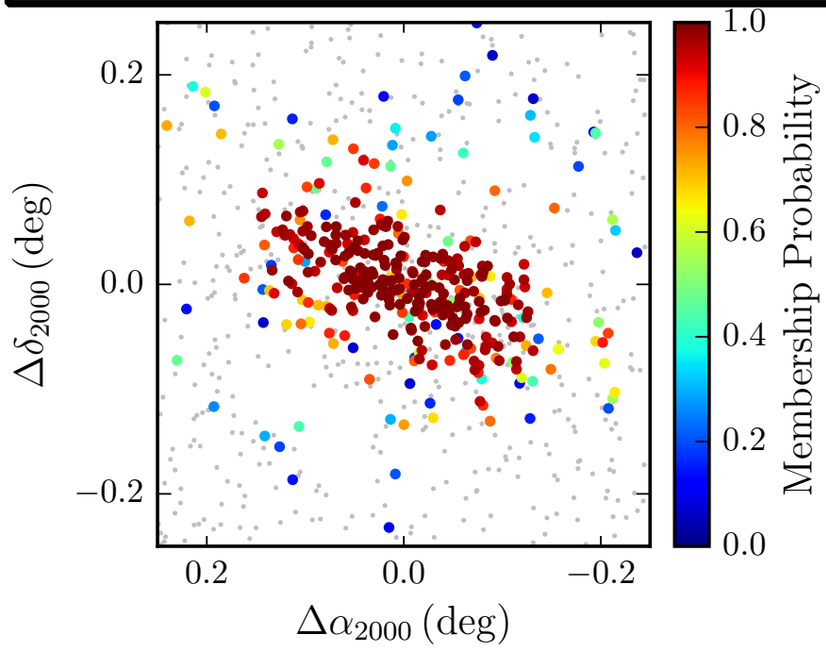
arXiv:1503.02584

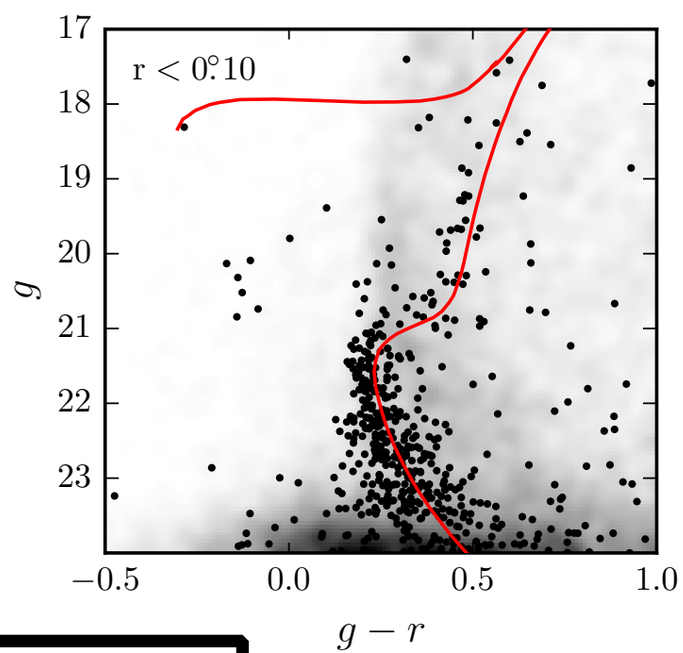
Reticulum II: Newest Dwarf Galaxy?

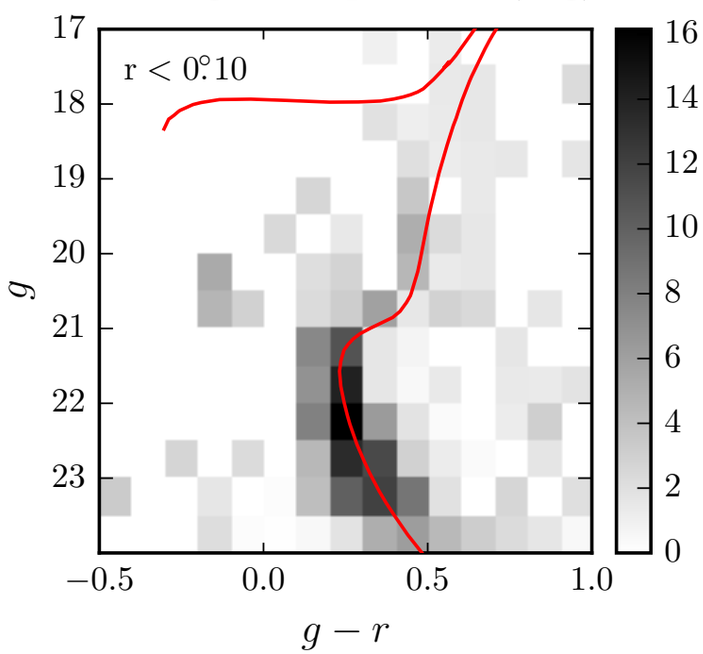
Membership probabilities will play an important role targeting spectroscopy

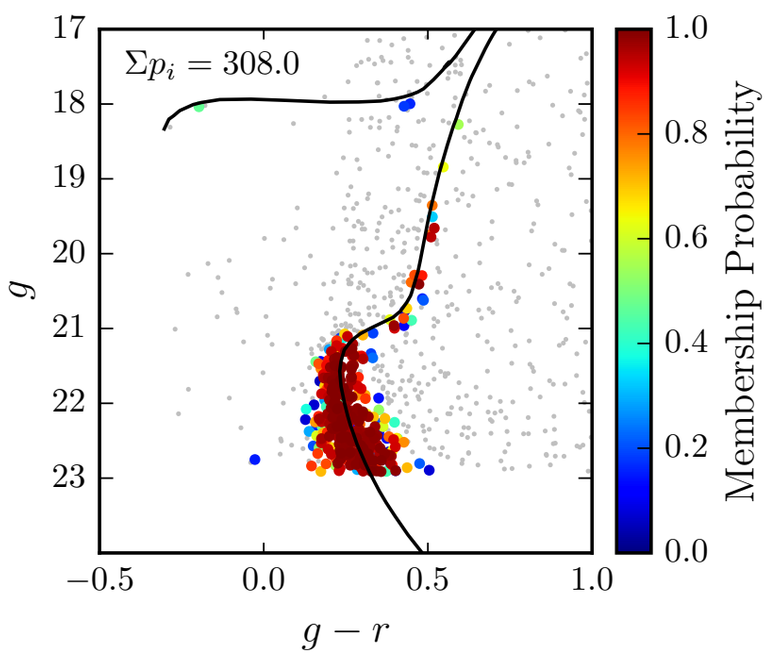












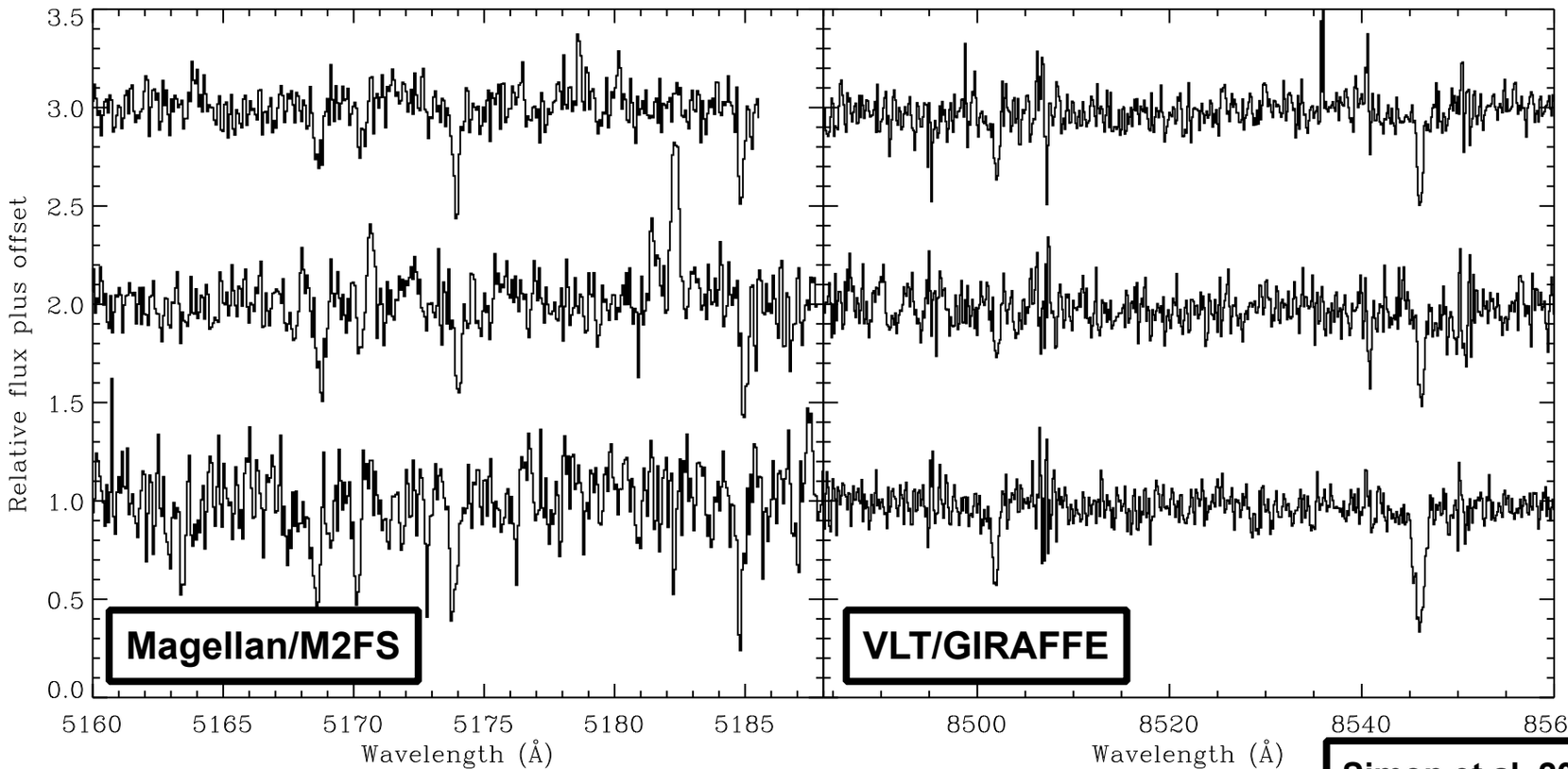
arXiv:1503.02584

Reticulum II: Spectroscopy Campaign

Magellan/M2FS

Gemini/GMOS

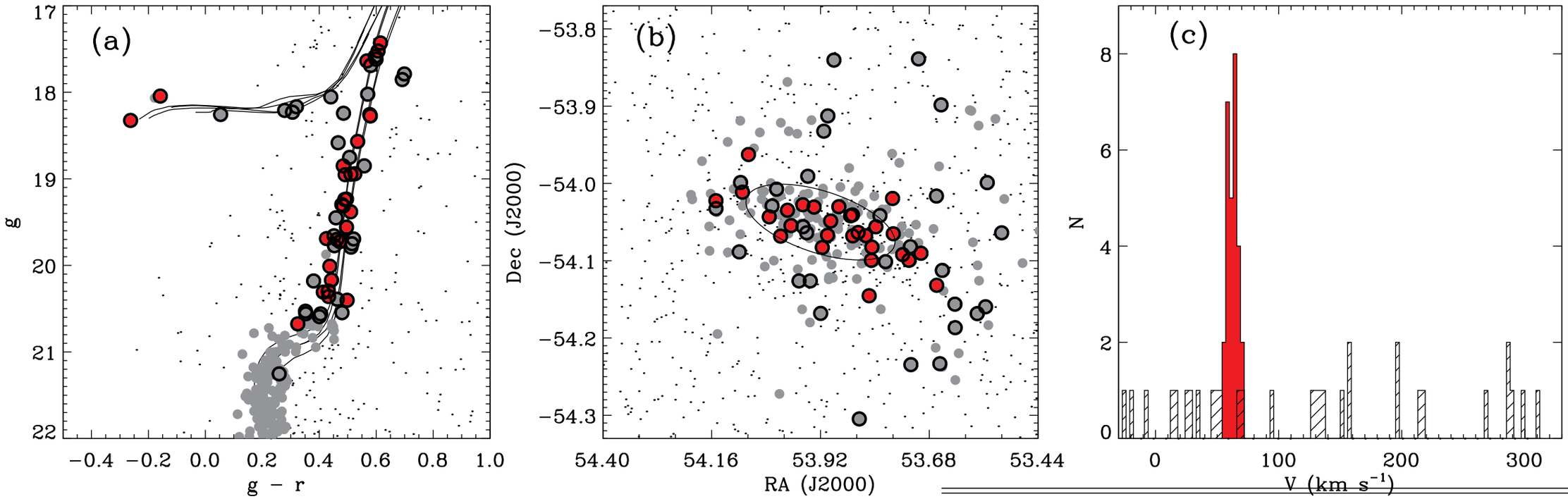
VLT/GIRAFFE



arXiv:1504.02889

Simon et al. 2015 (DES Collaboration)

Reticulum II: Newest Dwarf Galaxy



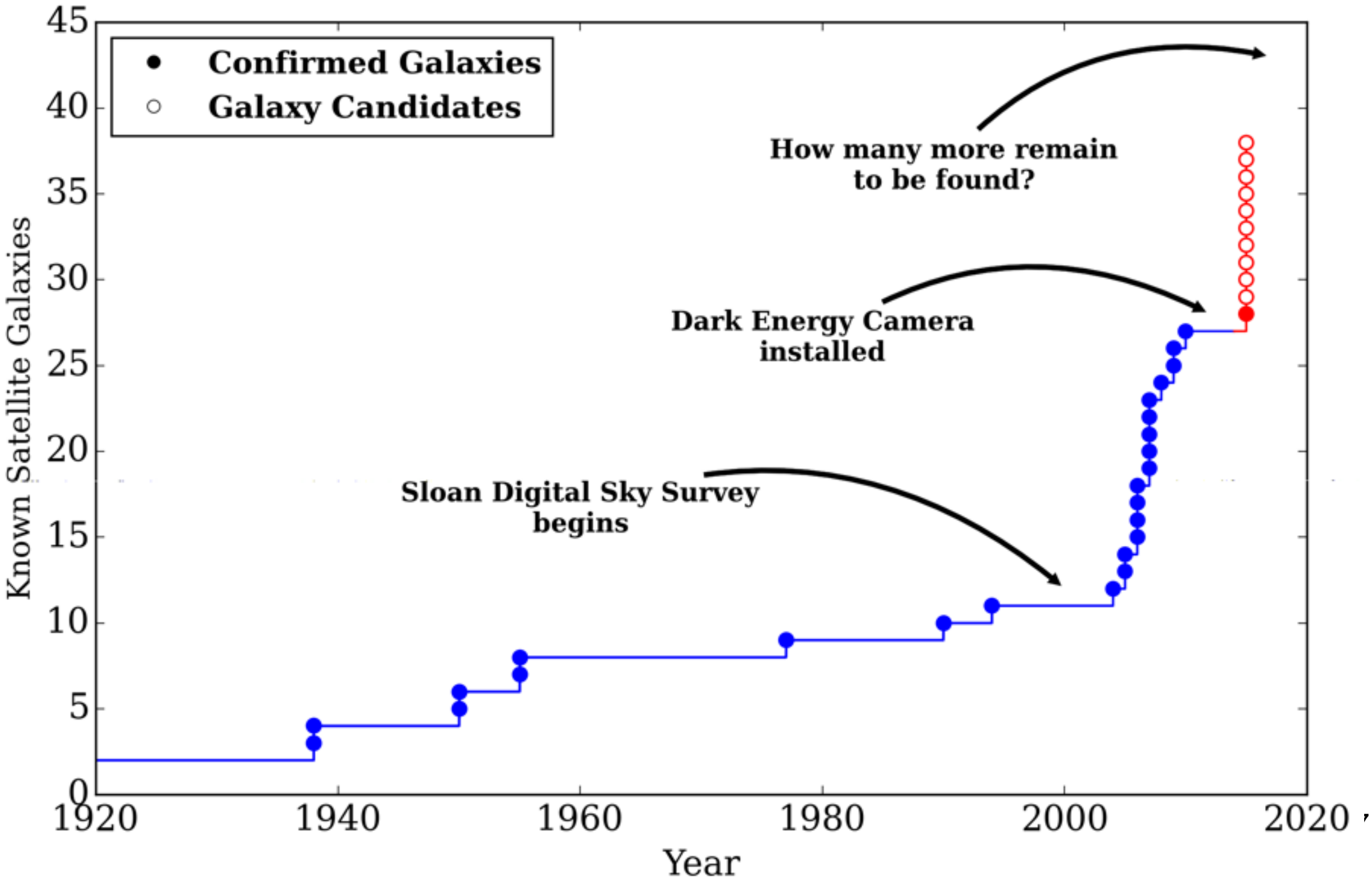
- **Velocity peak indicative of a gravitationally bound object**
- **Dynamical mass calculated from the width of the velocity dispersion**
- **Every measured characteristic of Reticulum is consistent with the known population of dwarf galaxies**

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	$M/L = 470 \pm 210\,\mathrm{M_\odot}/\,\mathrm{L_\odot}$

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

arXiv:1504.02889 **arXiv:1504.03060** **arXiv:1504.07916**

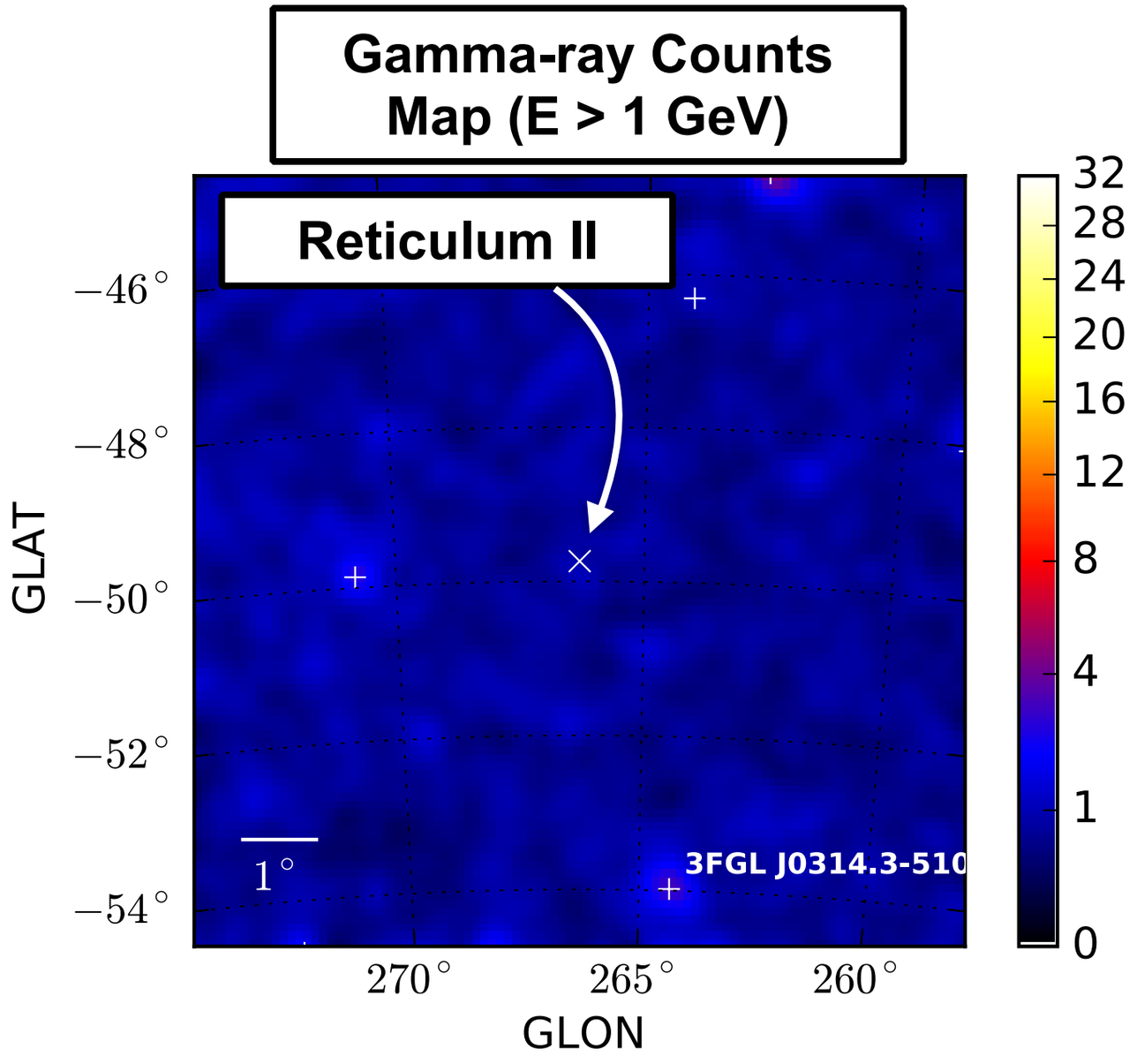
Milky Way Satellite Galaxies Discovery Timeline



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, Pass 8: local pvalue = 0.06 (1.5σ)
  - Geringer-Sameth+, Pass 7: local pvalue = 0.01 (2.3σ)

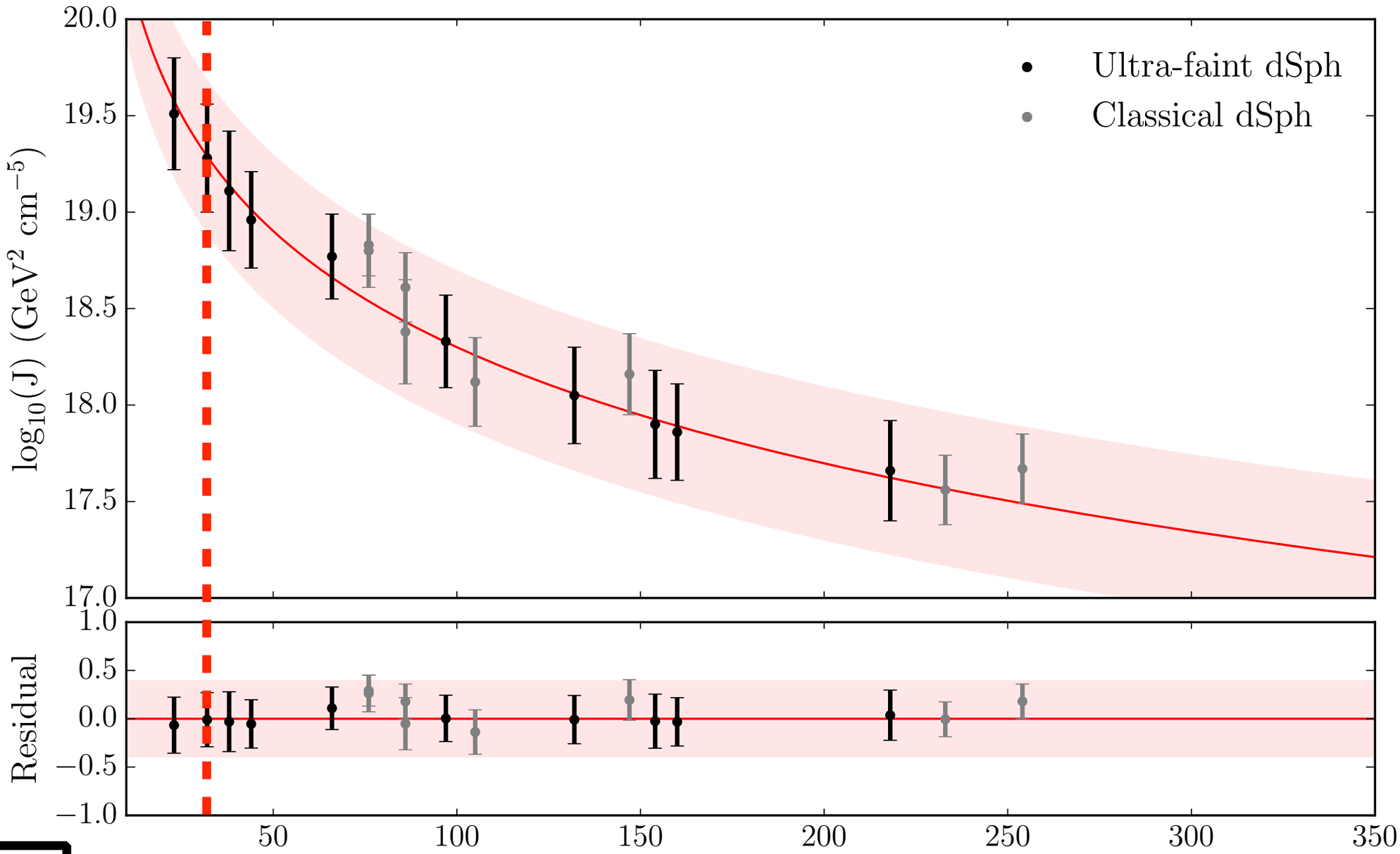
- How does the expected dark matter annihilation signal from Reticulum II compare to other dwarf galaxies?



Drlica-Wagner et al. (2015)
(LAT & DES Collaboration)
(see also Geringer-Sameth et al. 2015)

arXiv:1503.02632 arXiv:1503.02320

Dark Matter Searches in Gamma Rays



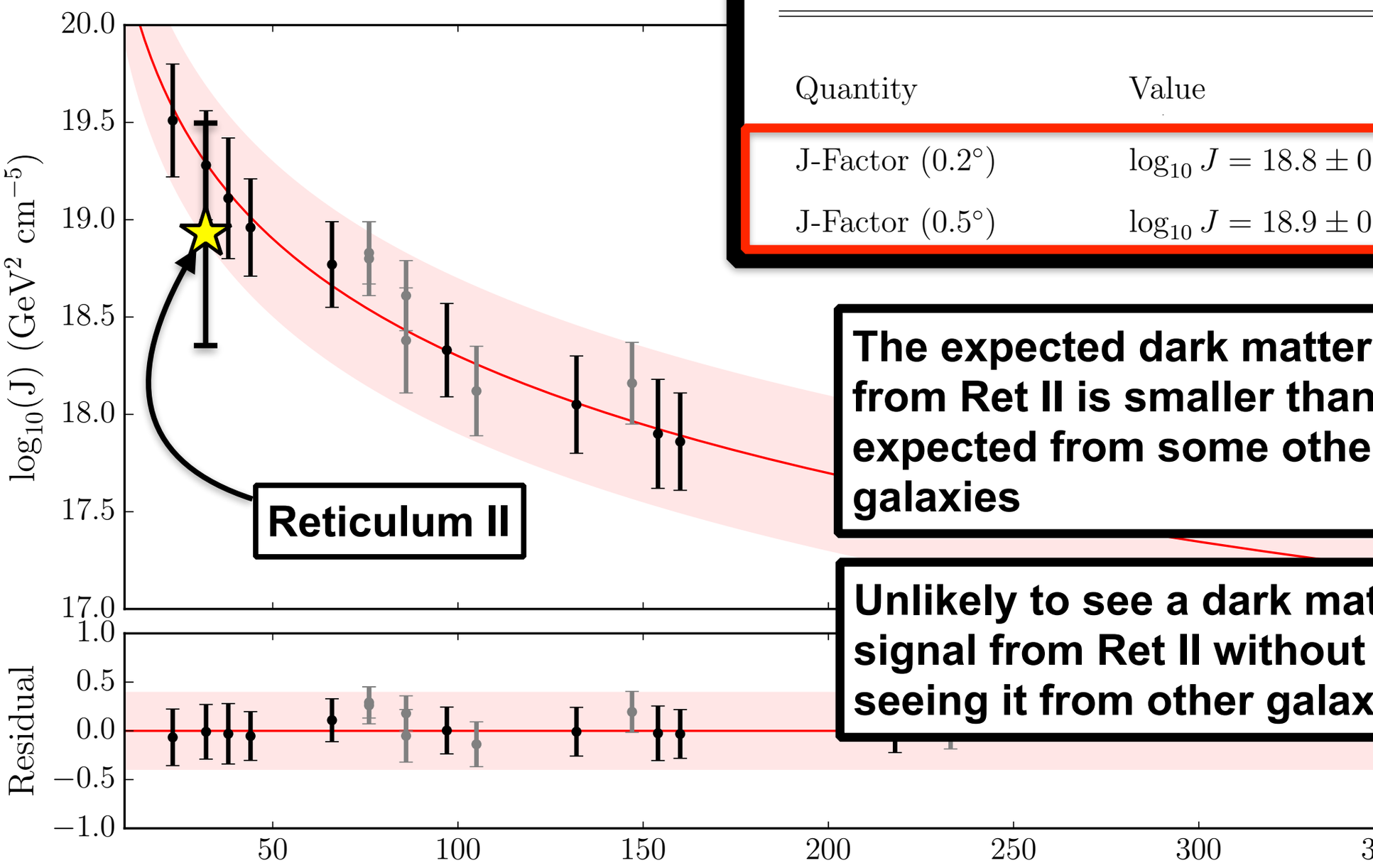
arXiv:1503.02632

Drlica-Wagner et al. (2015) (LAT & DES Collaboration)

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°)	$\log_{10} J = 18.9 \pm 0.6\,\mathrm{GeV^2\,cm^{-5}}$



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.

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

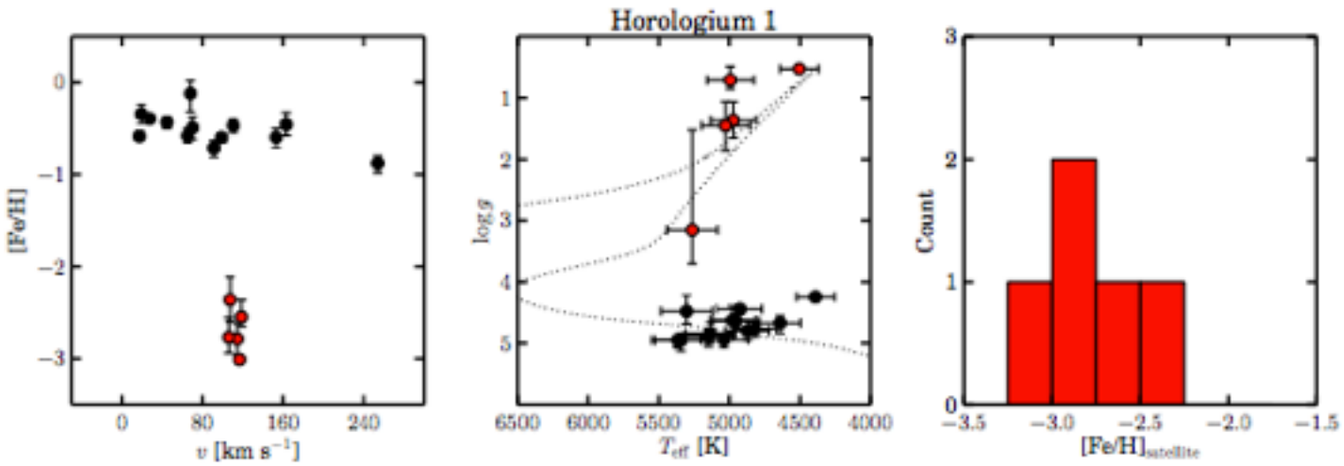
arXiv:1504.02889

arXiv:1504.03309

More Confirmed Dwarf Galaxies

KINEMATICS AND CHEMISTRY OF RECENTLY DISCOVERED RETICULUM 2 AND HOROLOGIUM 1 DWARF GALAXIES

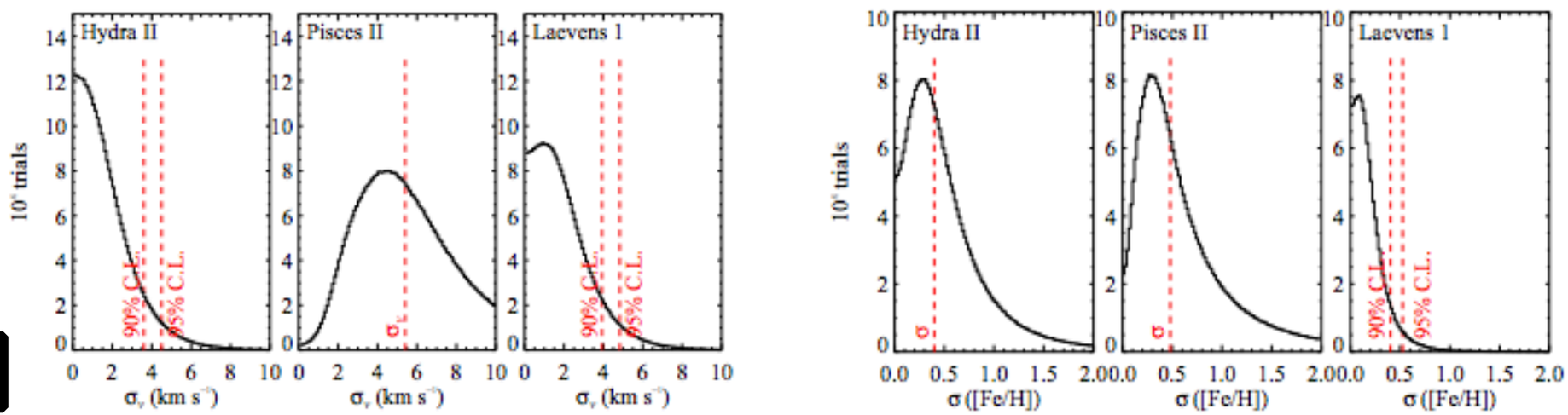
Sergey E. Koposov,[1] Andrew R. Casey,[1] Vasily Belokurov,[1] James R. Lewis,[1] Gerard Gilmore,[1] Clare Worley,[1] Anna Hourihane,[1] T. Bensby,[2] A. Bragaglia,[3] M. Bergemann,[4] G. Carraro,[5] E. Flaccomio,[6] U. Heiter,[7] V. Hill,[8] P. Jofre,[1] P. de Laverny,[8] L. Monaco,[9] L. Sbordone,[10,11] Š. Mikolaitis,[12] and N. Ryde[2]



arXiv:1504.07916

SPECTROSCOPIC CONFIRMATION OF THE DWARF GALAXIES HYDRA II AND PISCES II AND THE GLOBULAR CLUSTER LAEVENS 1

Evan N. Kirby[1], Joshua D. Simon[2], Judith G. Cohen[1]



arXiv:1506.01021

Looking Forward

- More spectroscopic follow-ups on the dwarf galaxy candidates
  - Magellan
  - VLT
  - AAT
- Y2 data are coming! Total sky coverage >4,000 deg^2

  —— Find MORE candidates!
- Y3 observing starts TODAY!
- Dwarf galaxy is not the only interesting science in Milky Way working group. More results coming soon!

Summary

- **Dwarf Galaxies are important cosmological probes for studying dark matter**

- **More ultra faint dwarf galaxy candidates have been discovered using DECam**

- **Coordinating follow-up**
  - **Spectroscopic confirmation**
  - **Obtaining dynamical mass and J-factors**
  - **Fermi-LAT collaborations**

- **More results coming from the DES Y2+**