Exploring Milky Way Halo Substructures with Large-Area Sky Surveys

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Lawrence Berkeley National Laboratory

Credit: Reidar Hahn, Yuanyuan Zhang

Overview

- **Milky Way Formation, Dwarf Galaxies, Halo Substructures**
- **The Dark Energy Survey (DES)**
- **Latest Milky Way Science Discoveries from DES**

Overview

- **Milky Way Formation, Dwarf Galaxies, Halo Substructures**
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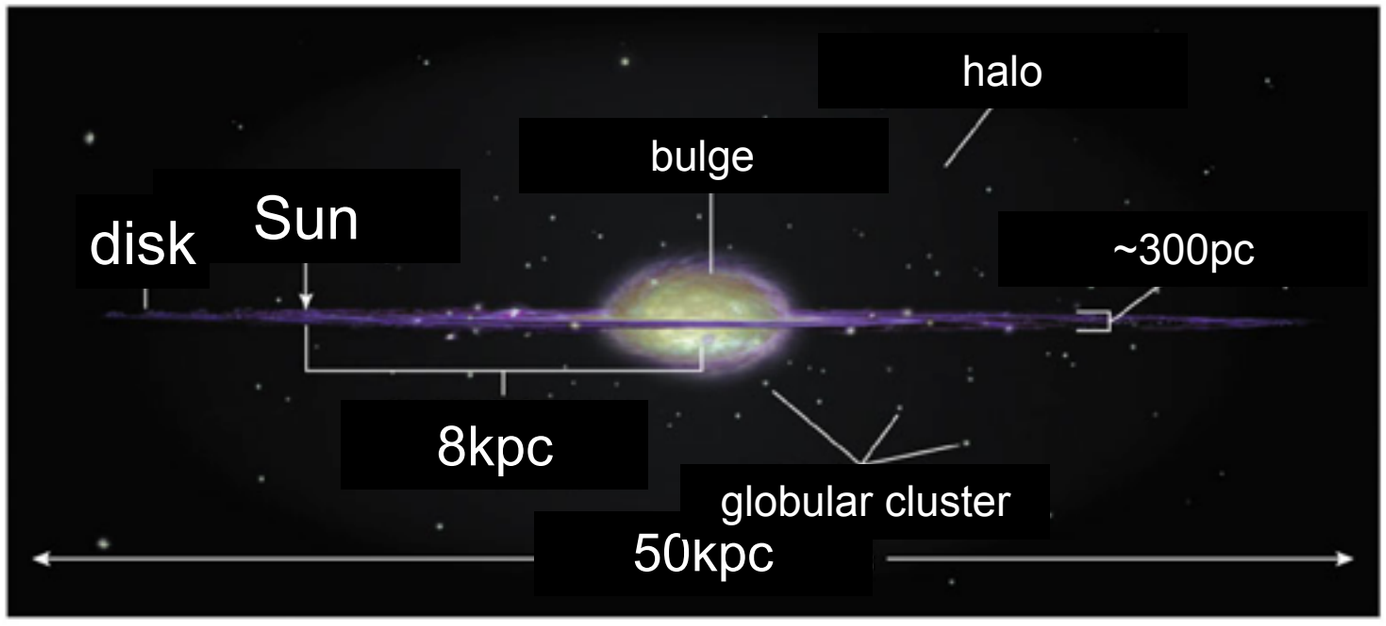
The Formation of Milky Way

- **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



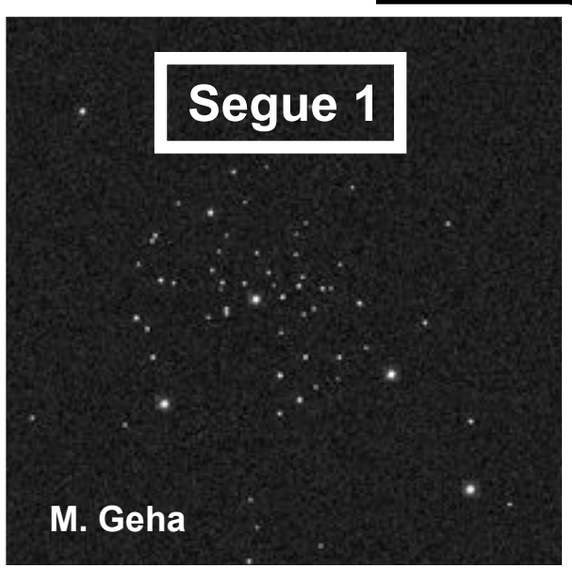
- **SZ Merger and Accretion Model (bottom-up)**

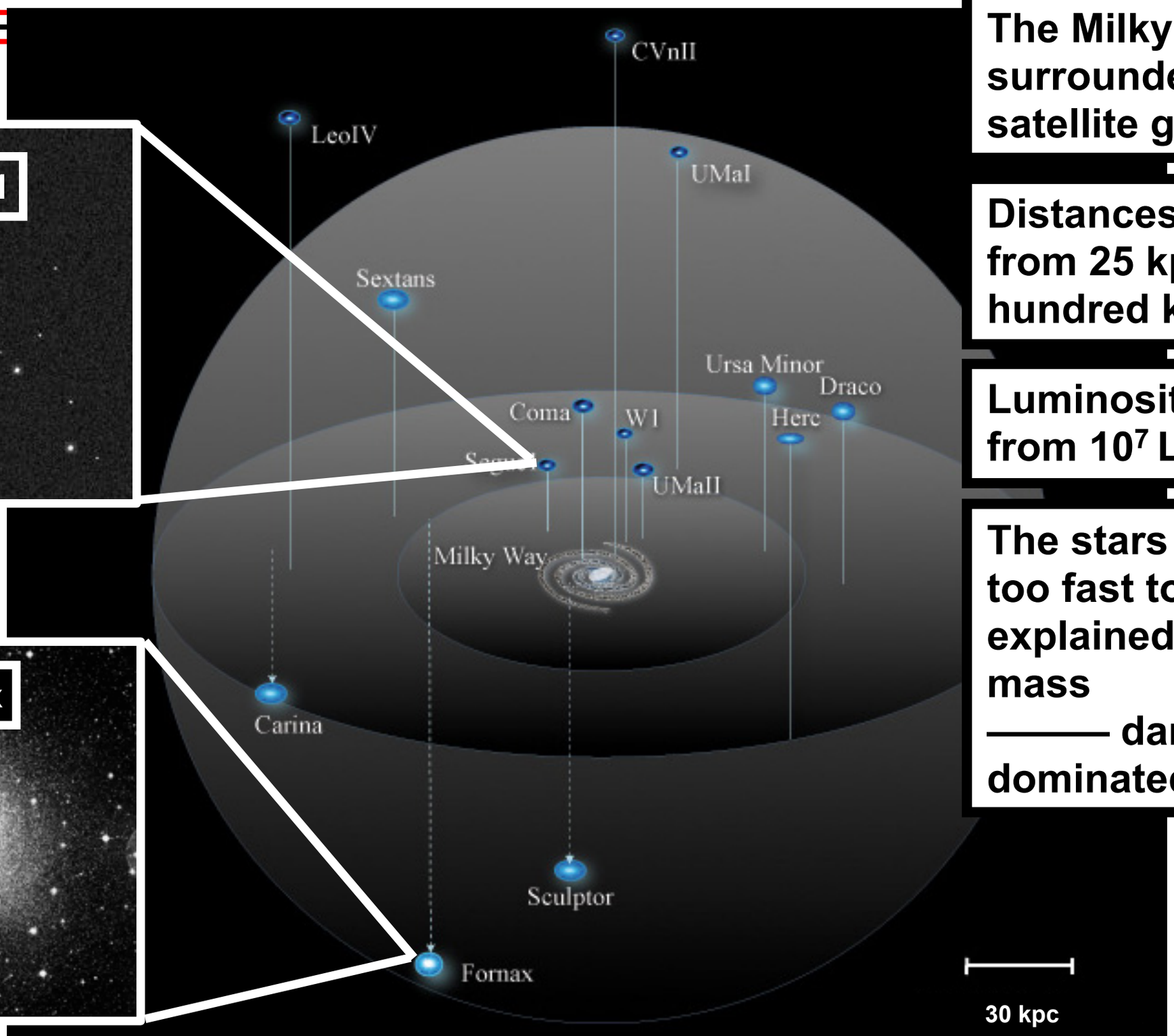
  Searle & Zinn 1978

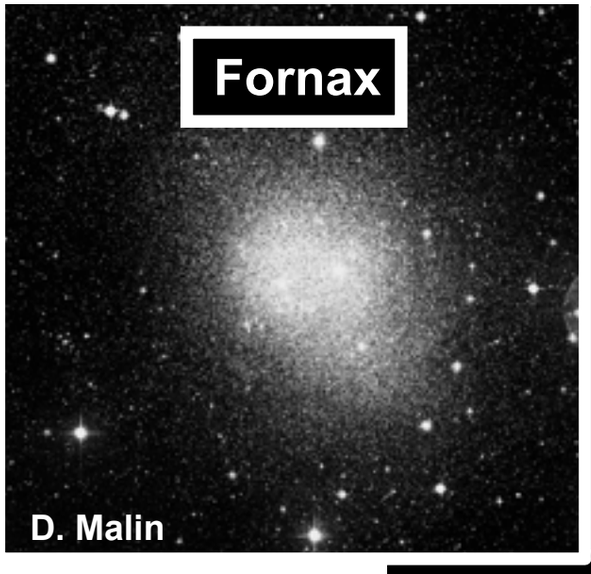
  Galaxies are built up from merging or accreting smaller fragments

  N-body simulations under ΛCDM context

Milky Way Satellite Galaxies







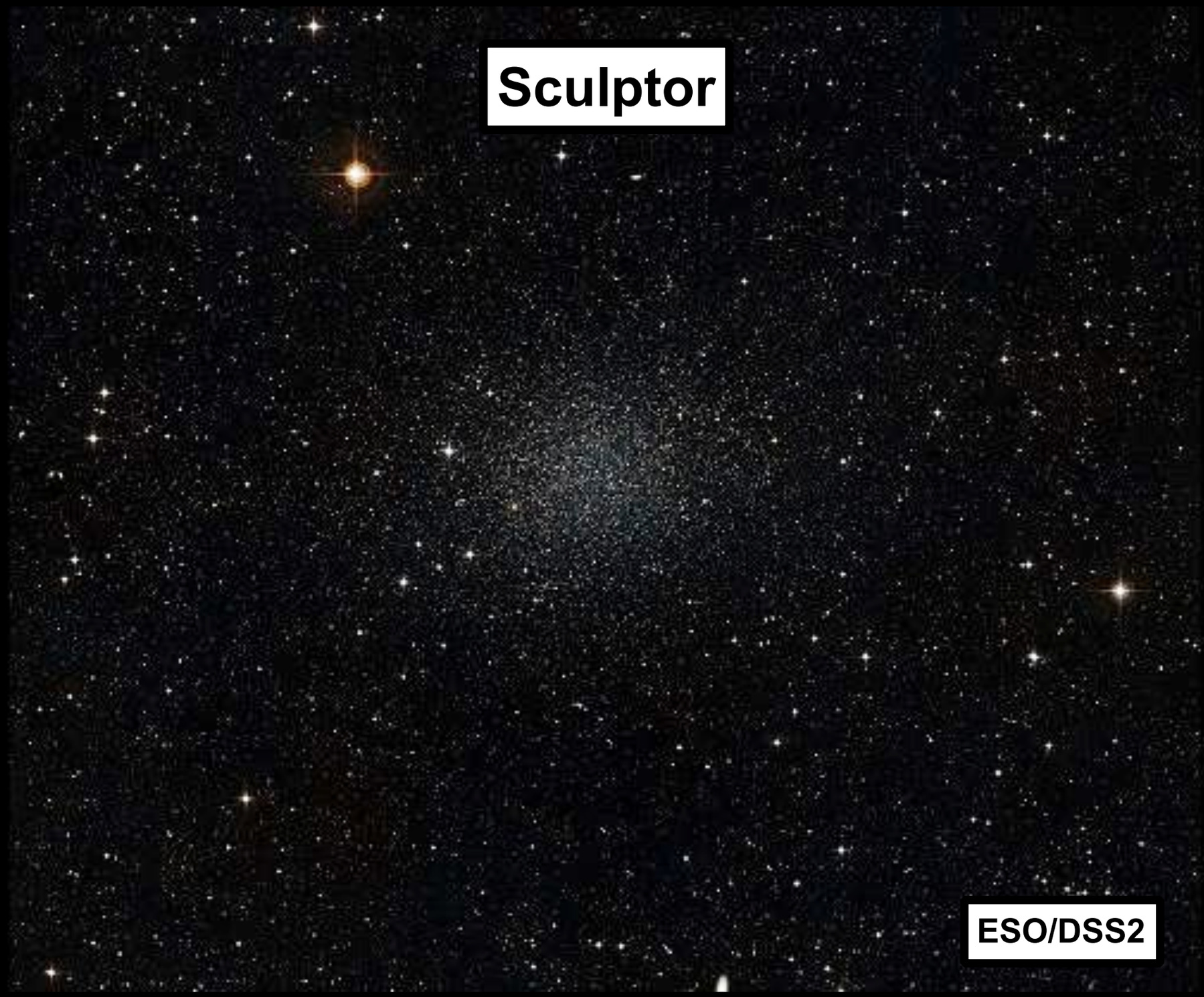
Credit: Bullock, Geha, Powell

The Milky Way is surrounded by small satellite galaxies

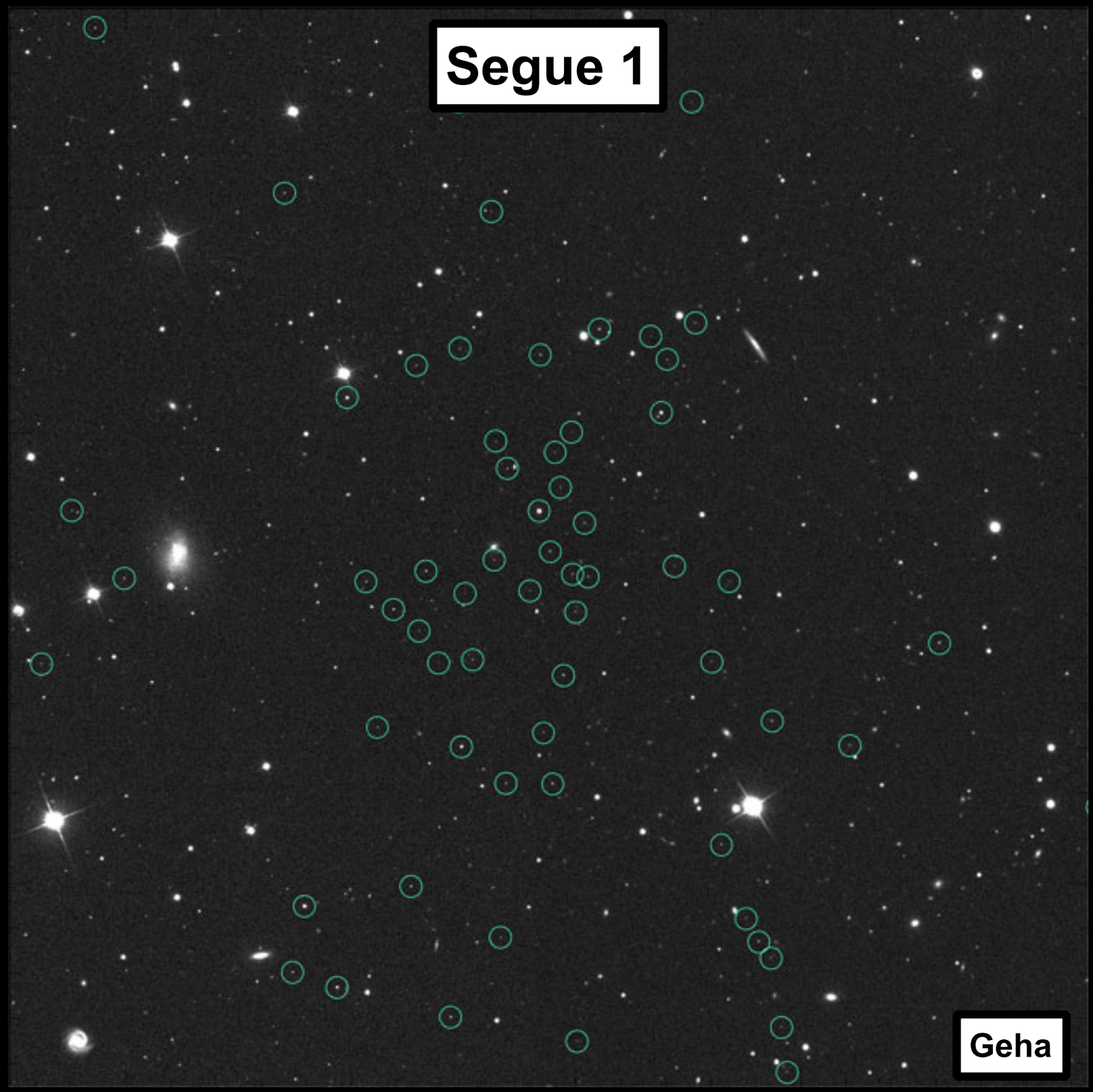
Distances ranges from 25 kpc to a few hundred kpc

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


Sculptor
ESO/DSS2


Segue 1
Geha


Segue 1
Geha

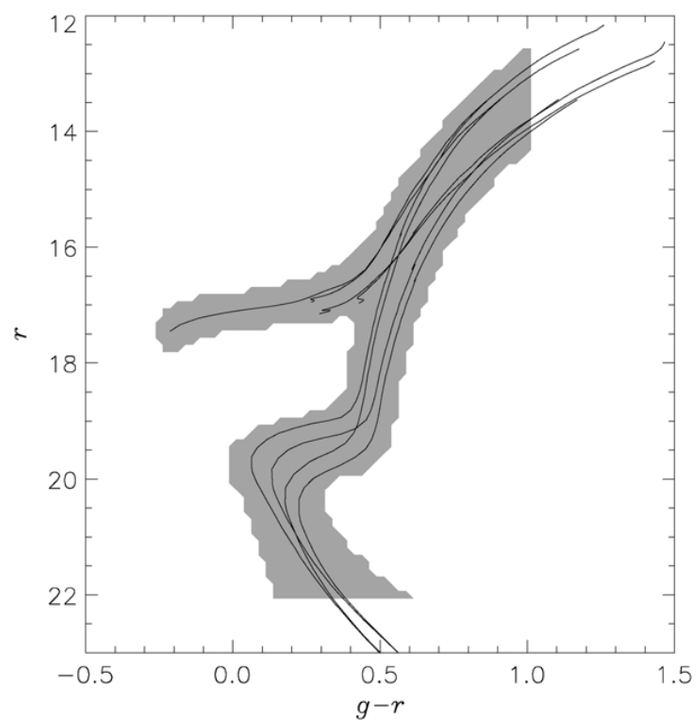
Finding Milky Way Satellite Galaxies

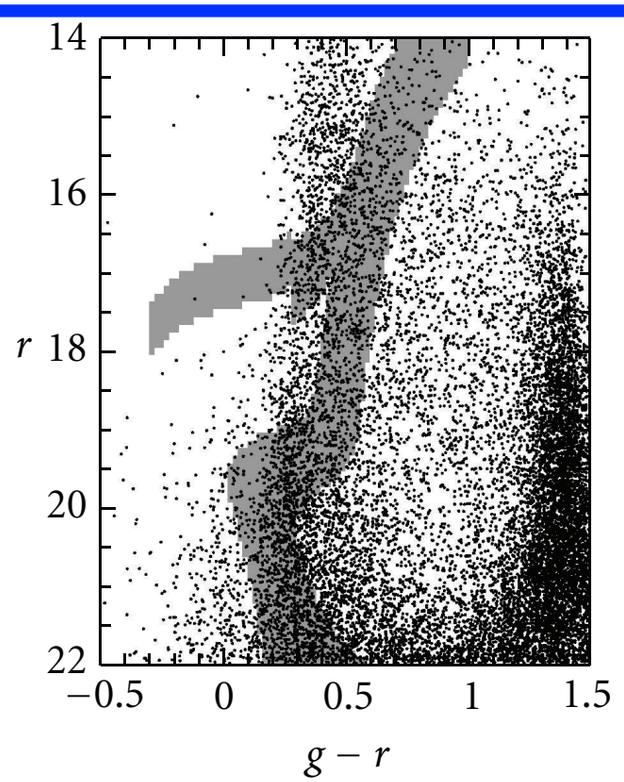
THE DARK ENERGY SURVEY

Fermilab

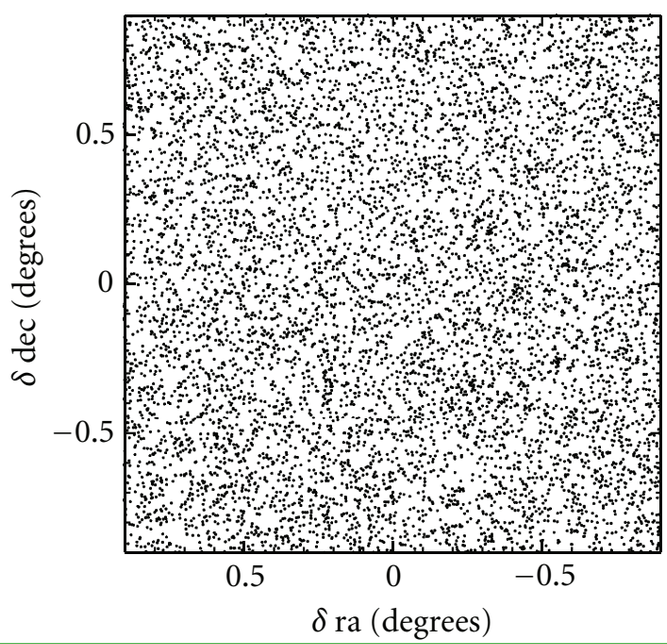
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

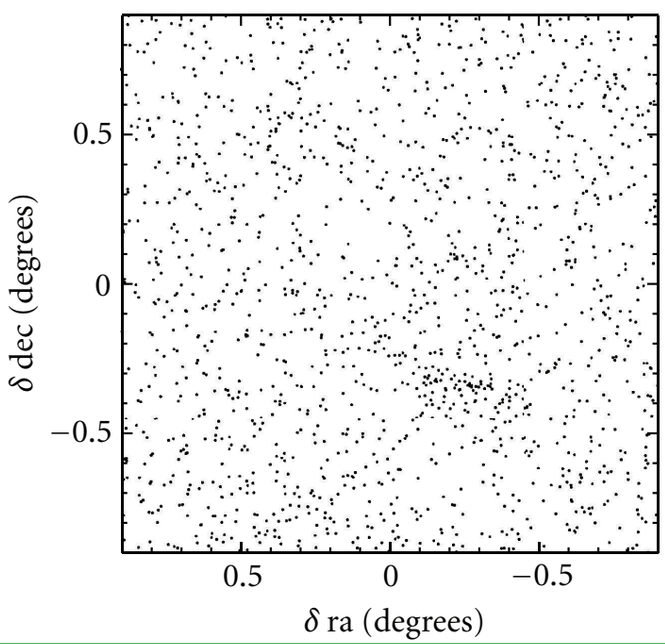
Color-Magnitude Domain

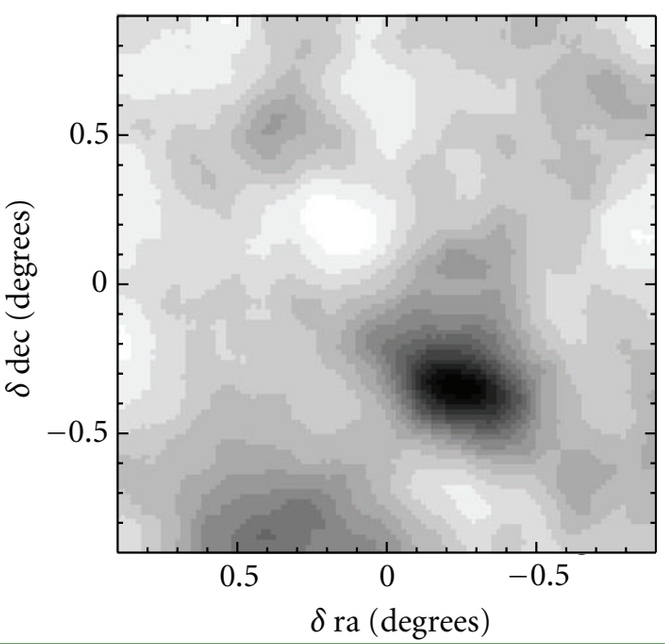




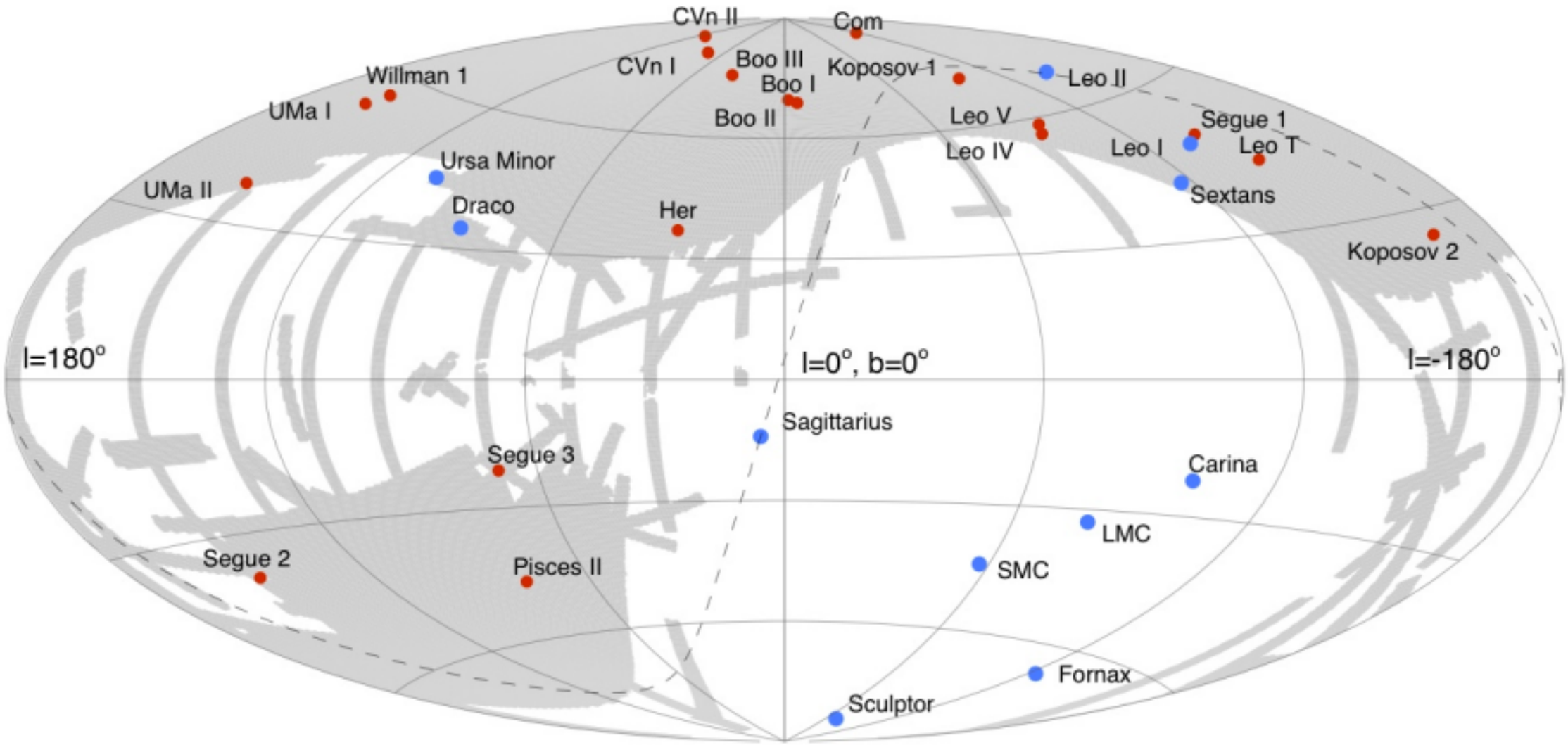
Spatial Domain







Known Dwarf Galaxies after SDSS



Belokurov 2013

Why studying the Milky Way dwarf galaxies

- A test of Lambda Cold Dark Matter (ΛCDM) Paradigm
  - Cold vs. Warm vs. Decay vs Self-interacting?

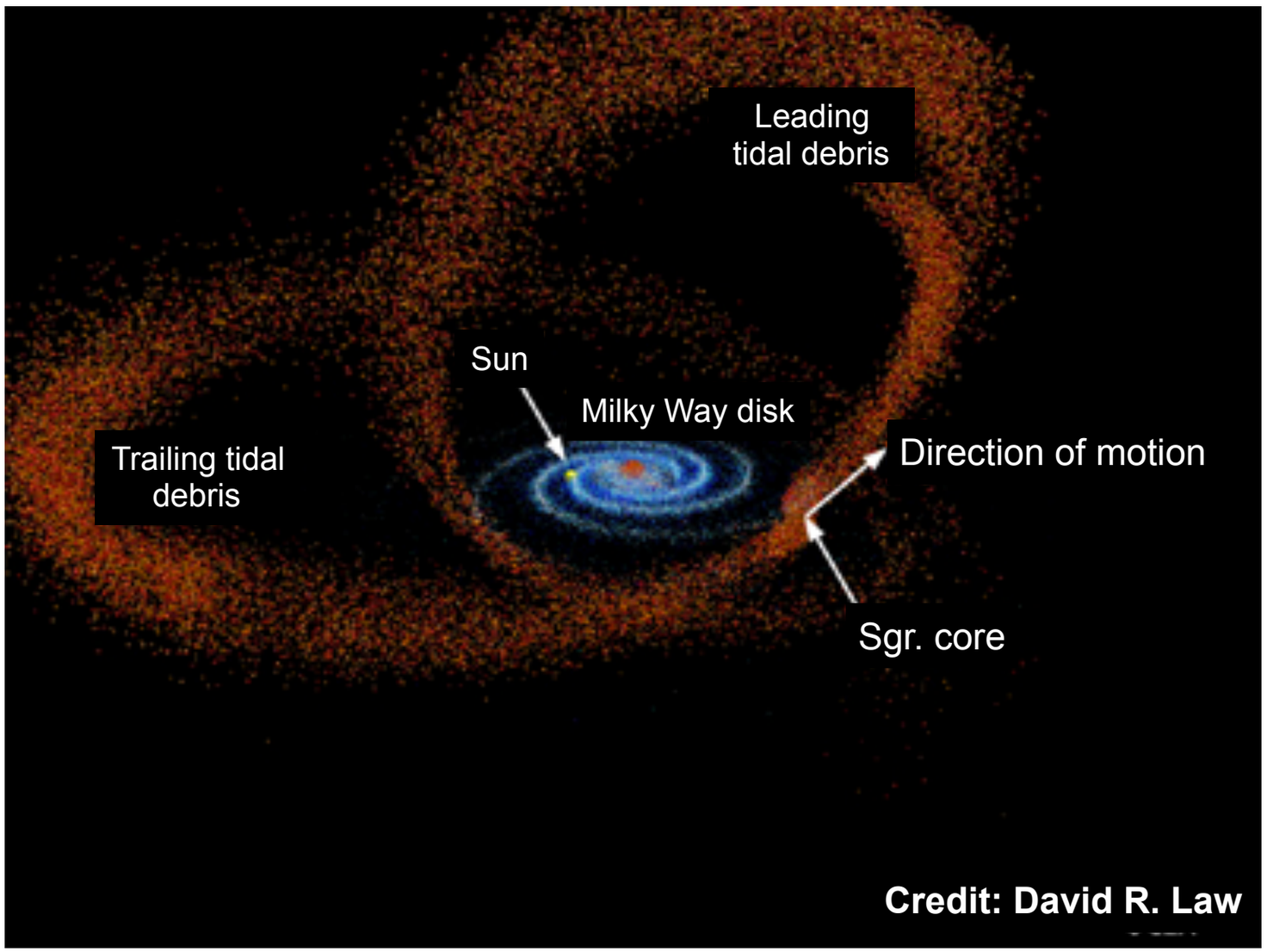
- Missing Satellites Problem?
  - CDM simulations predict thousands of dark matter substructures
  - Only dozens of dwarf galaxies are found

- Cusp/core Problem?
  - Simulations predict cuspy central density profiles, while observations suggest constant-density cores

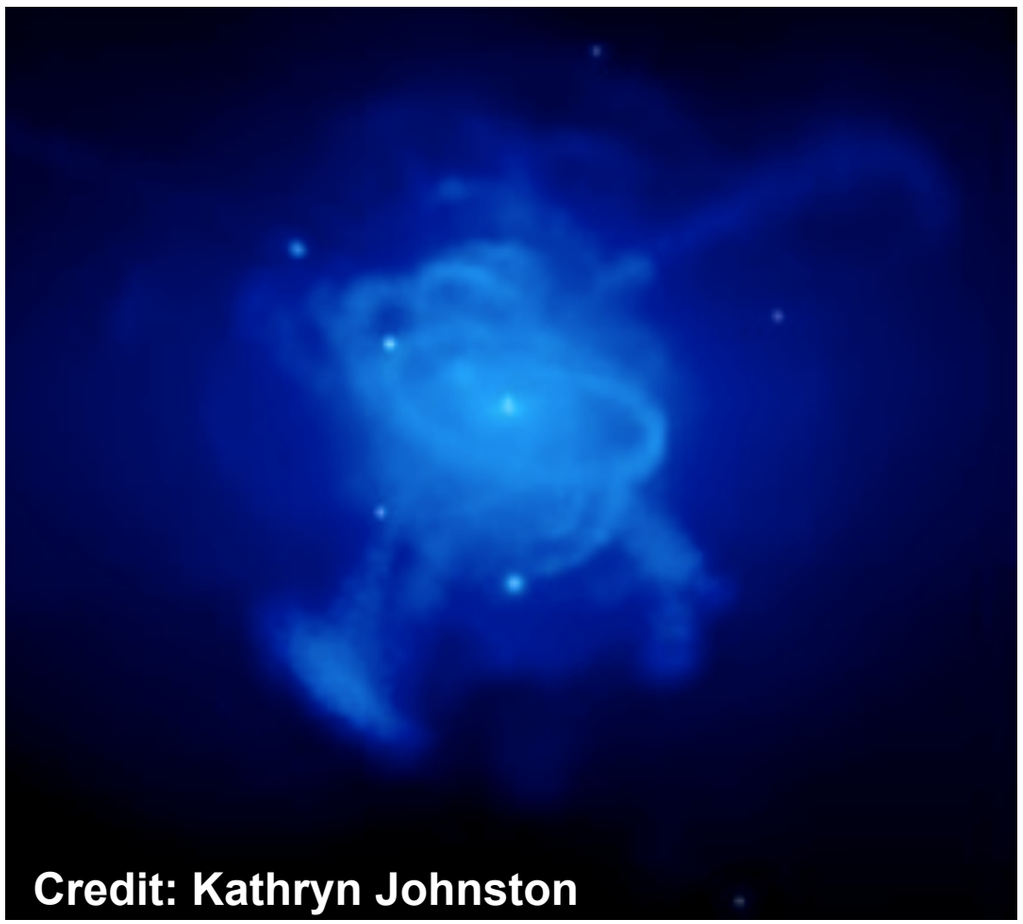
- Indirect Dark Matter Search
  - Clean — no astrophysical source
  - Dynamical mass from kinematics

Stellar Stream

- **Milky Way stellar halo is formed by accreting other galaxies.**

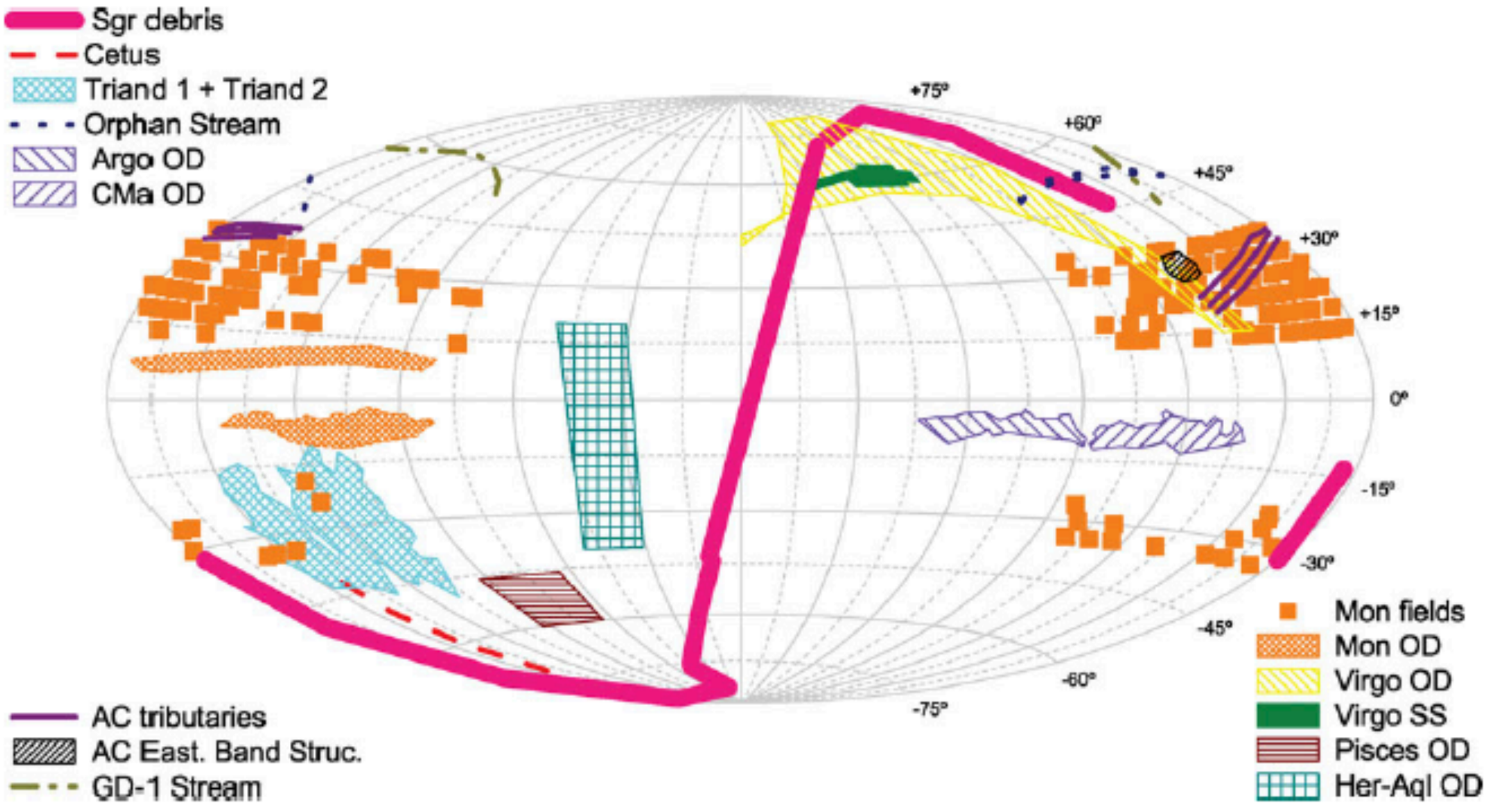


Credit: David R. Law



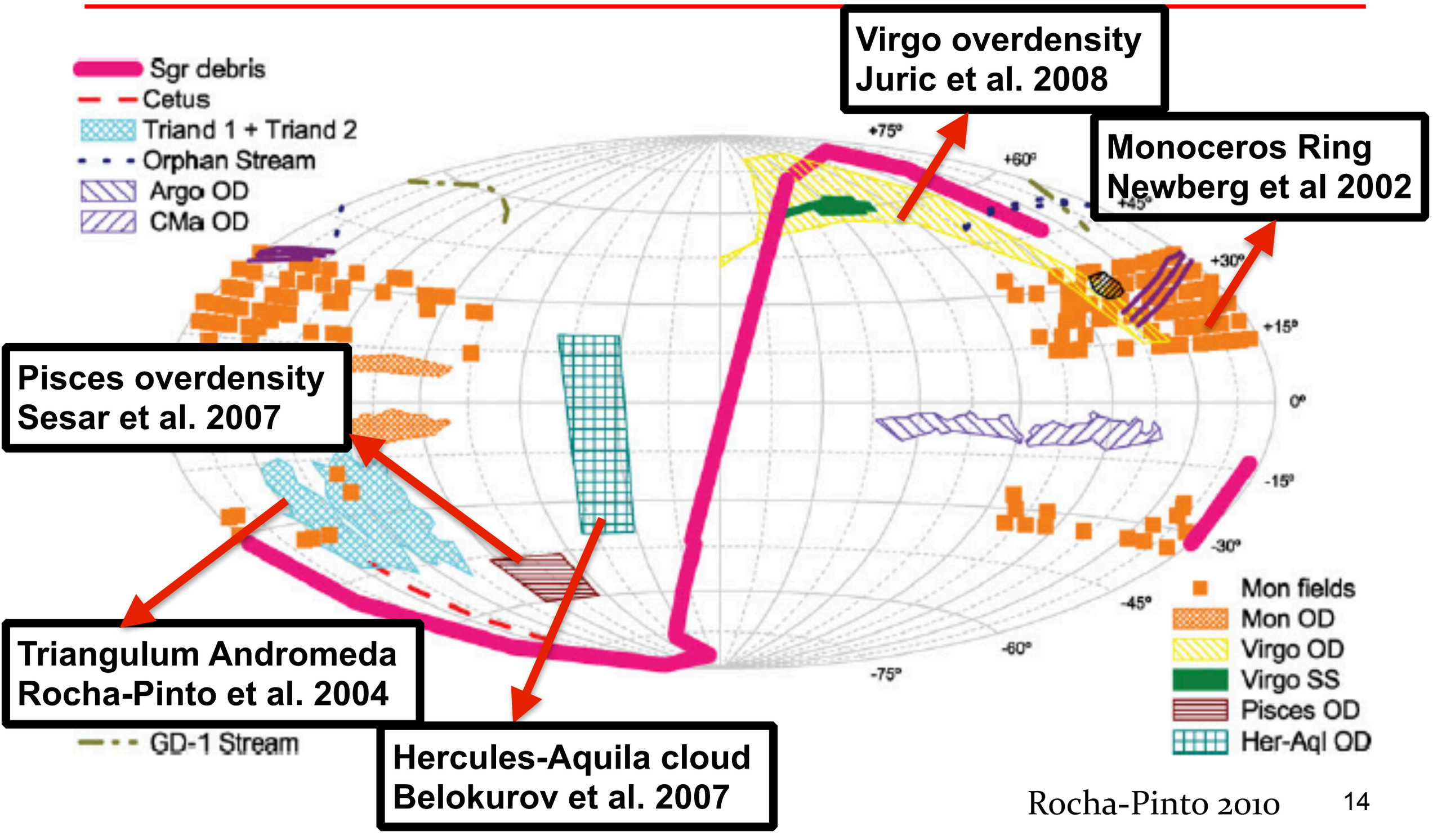
Credit: Kathryn Johnston

Known Diffuse Halo Substructures after SDSS



Rocha-Pinto 2010

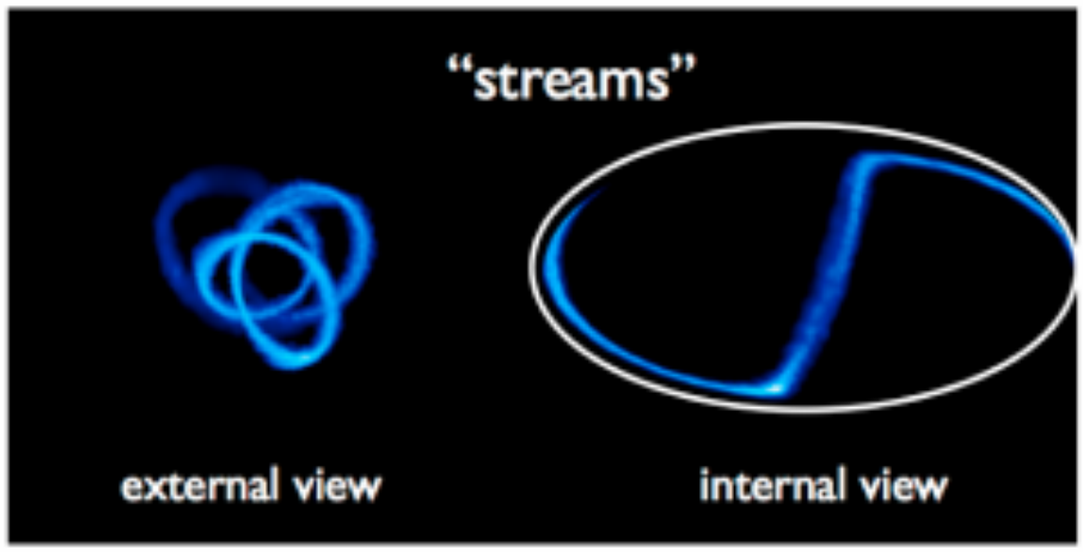
Known Diffuse Halo Substructures after SDSS

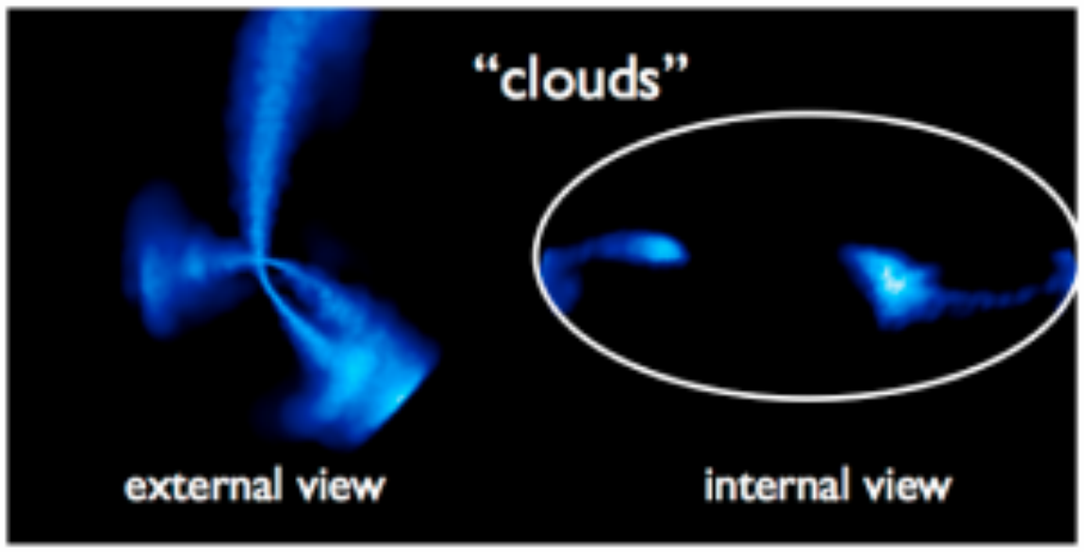


Rocha-Pinto 2010

Morphology of Tidal Debris

- Stellar Debris Streams
  - mildly eccentric orbit
- Stellar Debris Clouds
  - highly eccentric orbit





Johnston et al. 2008

Why Study the Milky Way Halo Substructure?

- **Hierarchical merging is predicted by ΛCDM.**
  - **What are the progenitors? How did the merging event happen?**
  - **Where is the thick disk from?**
  - **Inner halo vs. outer halo.**
  - **Halo formation: In Situ vs. Accretion vs. Kick out?**

- **Milky Way Dark Matter Potential**
  - **Distribution of Milky Way Dark Matter Halo, $1/r^2$?**
  - **Spherical vs. Triaxial?**

Overview

- Milky Way Formation, Dwarf Galaxies, Halo Substructures
- **The Dark Energy Survey (DES)**
- Latest Milky Way Science Discoveries from DES

Collaborators: Darren DePoy, Jennifer Marshall, Douglas Tucker, Gary Bernstein, Rick Kessler, Eli Rykoff, David Burke…. and the Dark Energy Survey Calibration Team

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

The Dark Energy Survey

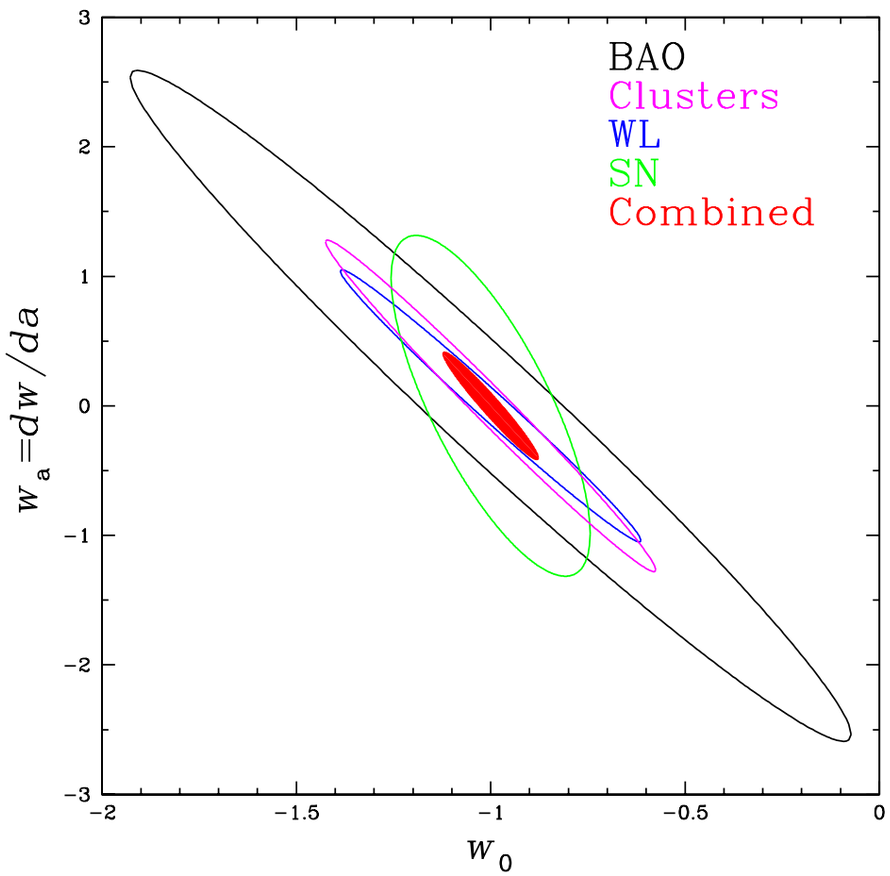
Dark Energy Camera (DECam)
Cerro Tololo Inter-American Observatory

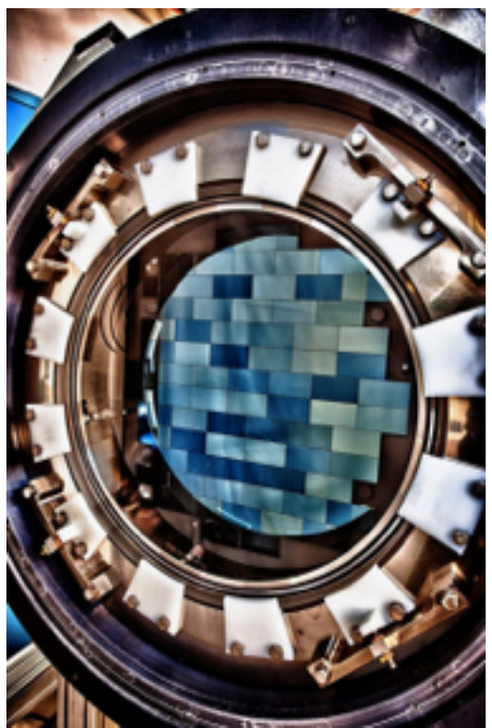
5 year survey over 525 nights
5 filters: g,r,i,z,Y
~5,000 sq. degree
~24th mag in g-band with 10 tiling

The Dark Energy Survey (DES)

- **Constrain the Dark Energy Equation of State with:**
  - **Supernova**
  - **Weak Lensing**
  - **Large Scale Structure**
  - **Galaxy Clusters**

Forecast

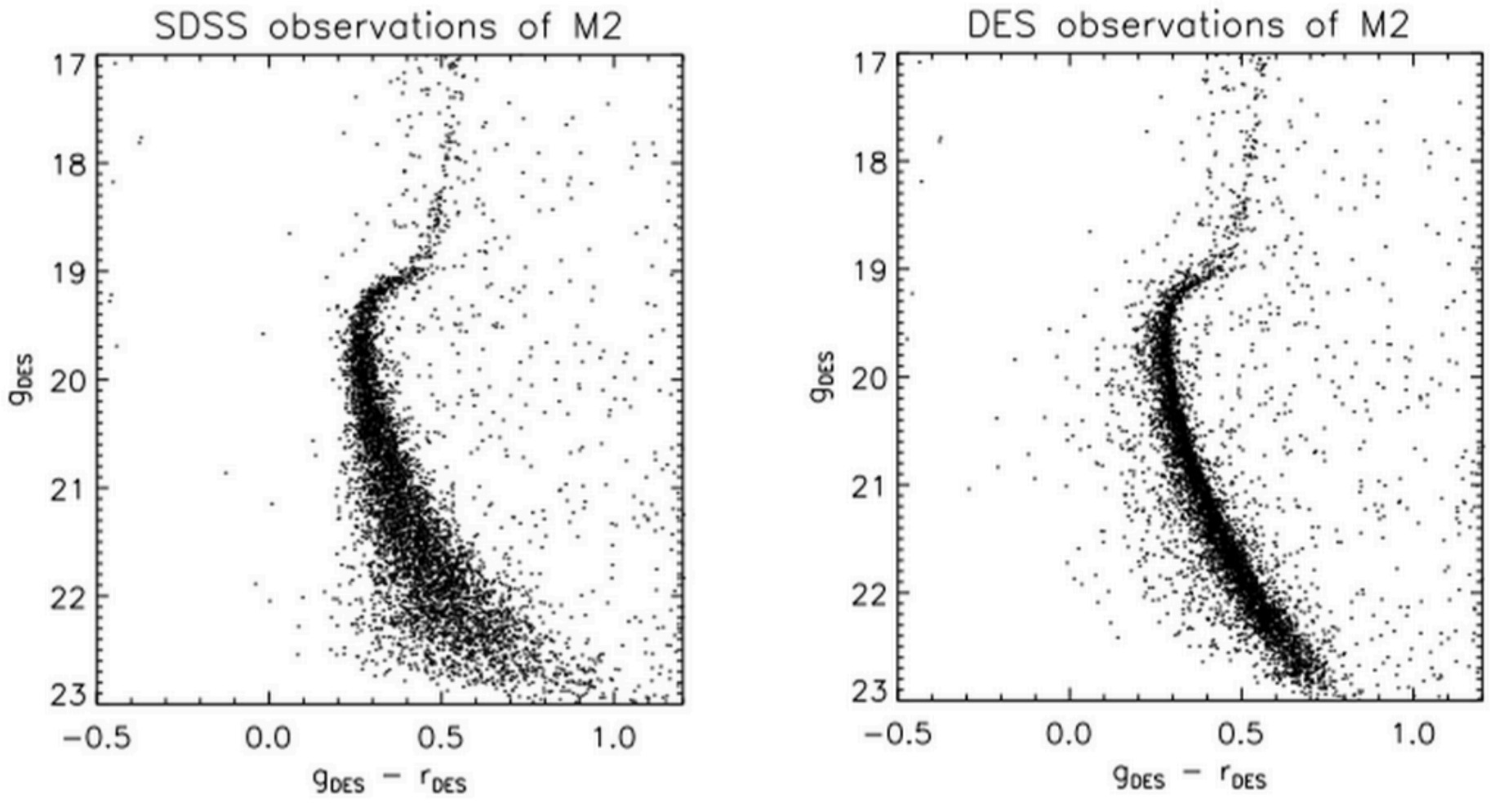




- **DECam**
  - **62 2k x 4k CCDs**
  - **570 megapixel camera**
  - **< 20s readout time**
  - **~3 deg^2 field-of-view**
  - **Unprecedented**

DES Year 1 vs. SDSS on Messier 2

- **A dramatic improvement in the photometric precision using Blanco+DECam.**

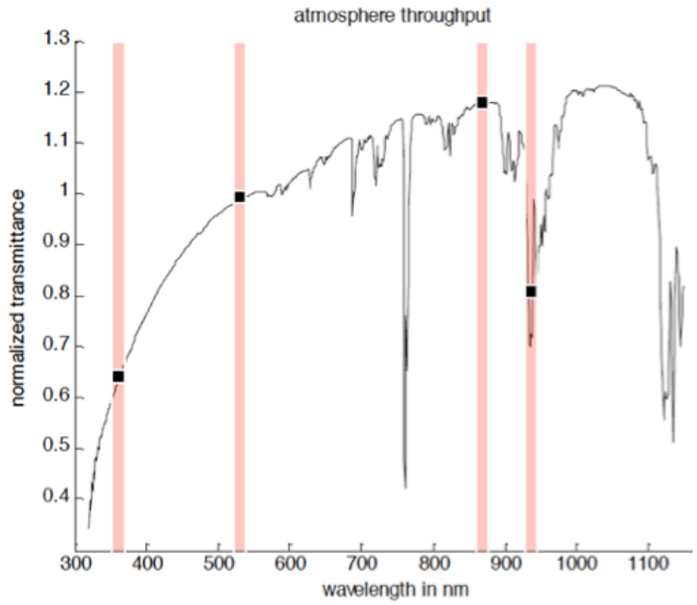


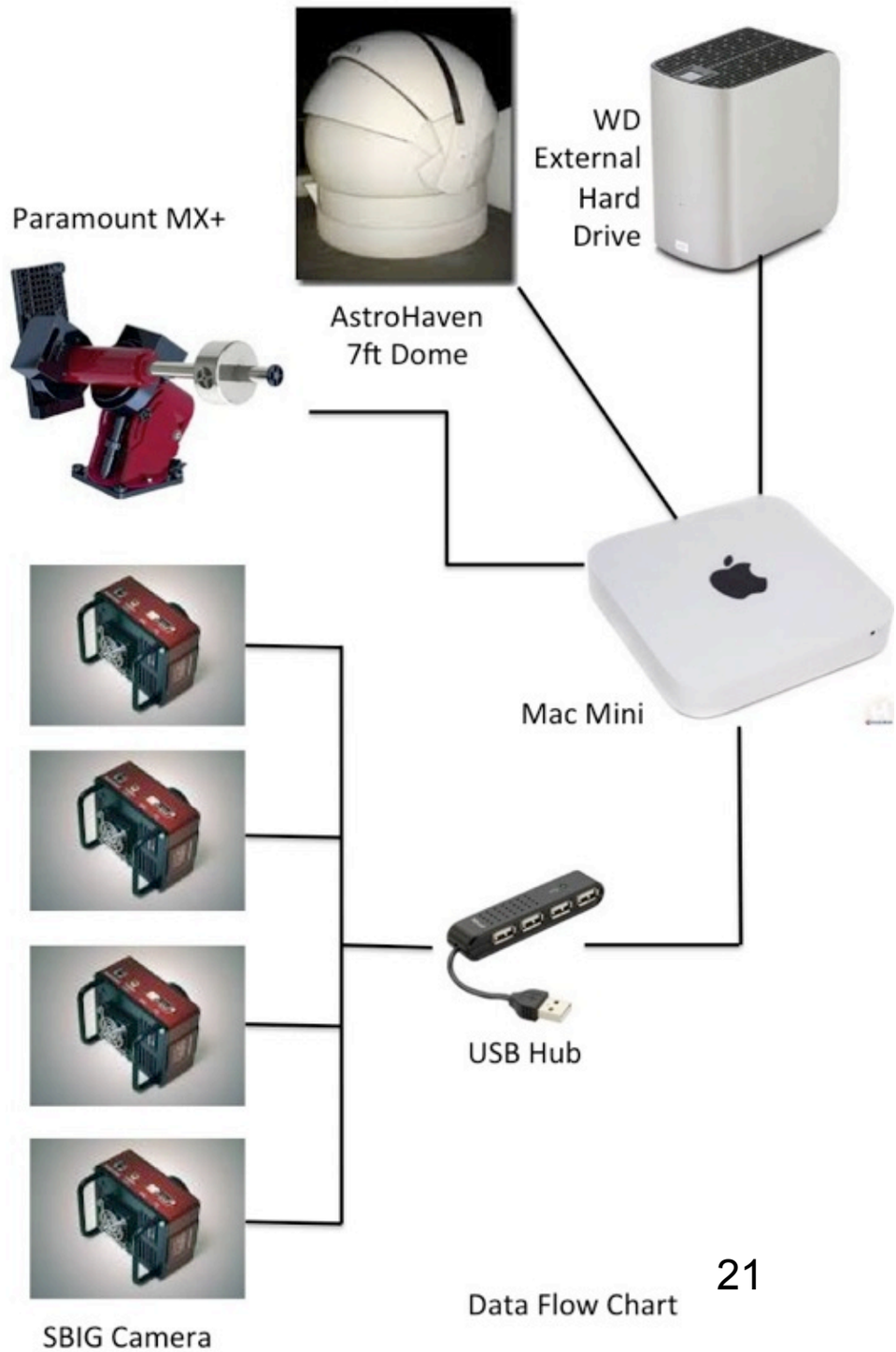
And this is just Year 1—deeper, more precise photometry will be produced throughout the five-year survey

aTmCam

Atmospheric Transmission Monitoring Camera

- **Robotic**
- **4 narrow-band filters**
- **Imager**





- **Purpose: derive and model the shape of atmospheric transmission**
- **Bonus: can also monitor the photometricity, but small FOV**

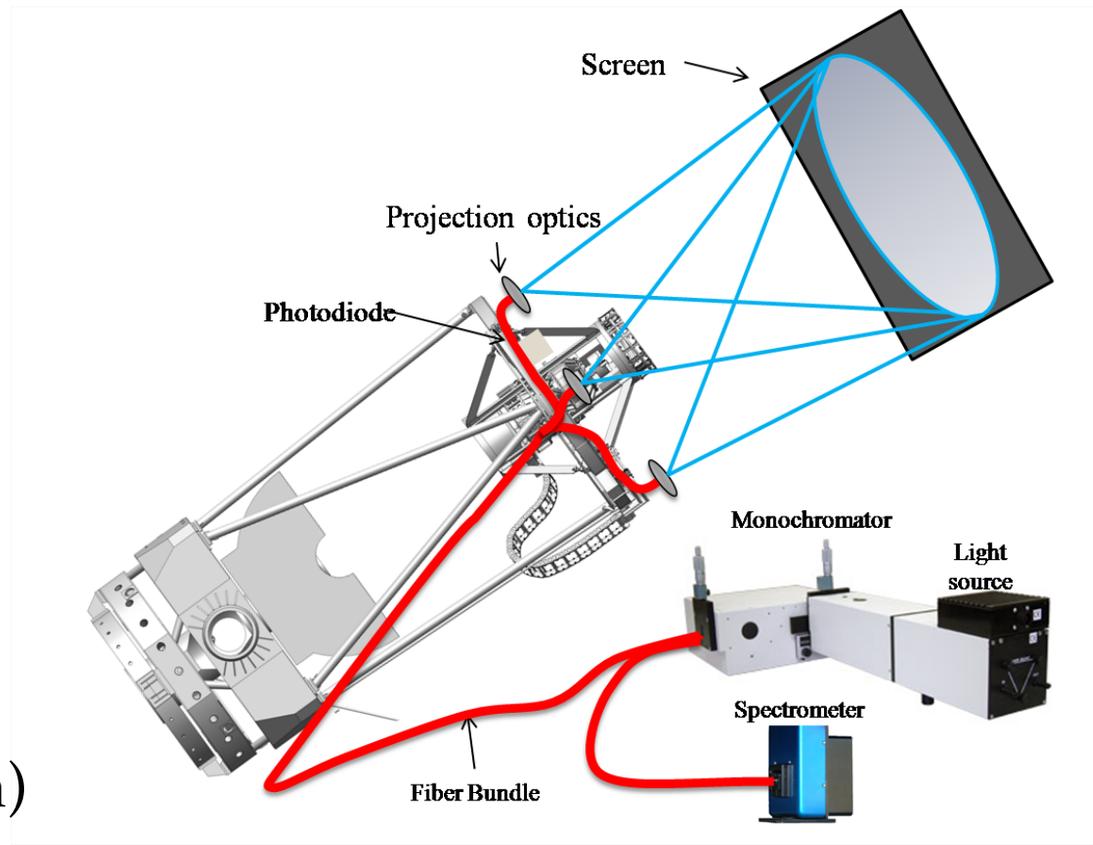
Li et al. 2012, 2014, SPIE

DECal

Spectroscopic Calibration System for DECam

- **Measure the instrument throughput vs. wavelength for every pixel on the CCD**
- **Monochromatic light: ~2nm width**
- **Scan during cloudy night (light leaks at Blanco)**
- **Out-of-band light inspection**

- **Instrument throughput vs. position on focal plane**
- **Instrument throughput vs. time**
- **Relative throughput — shape**



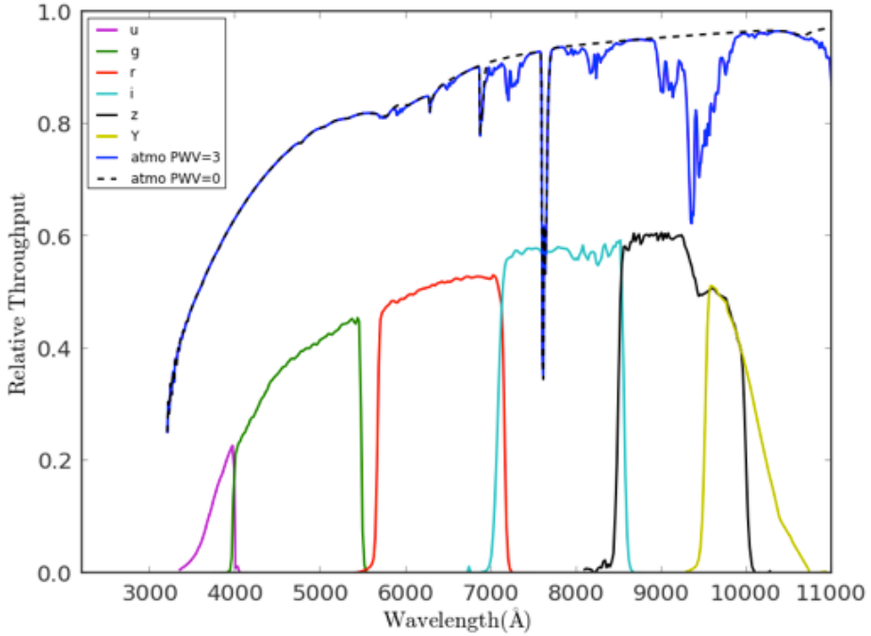
Marshall, Li + in prep (DES Collaboration)

Sub-1% Photometry with DES

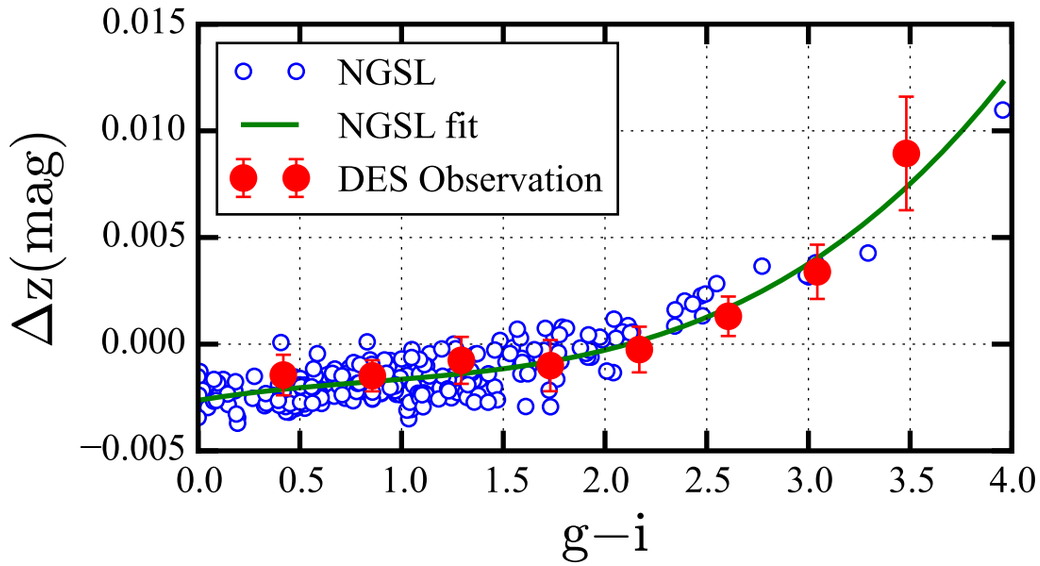
- **Auxiliary system to monitor the atmosphere and the instrument**

aTmCam measures the atmospheric throughput!

DES bandpasses & atmospheric throughput



Water vapor 3mm vs. 13 mm



Li et al. in prep (DES Collaboration)

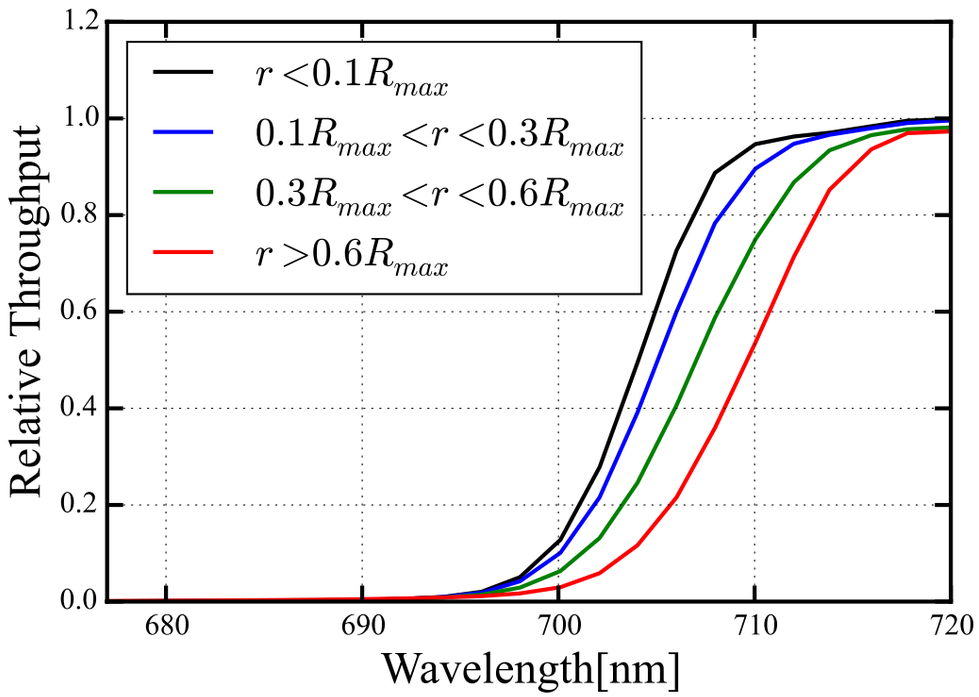
aTmCam Team: DePoy, Marshall, Li, Corona, Nagasawa, Mondrik, Allen, Prochaska

Sub-1% Photometry with DES

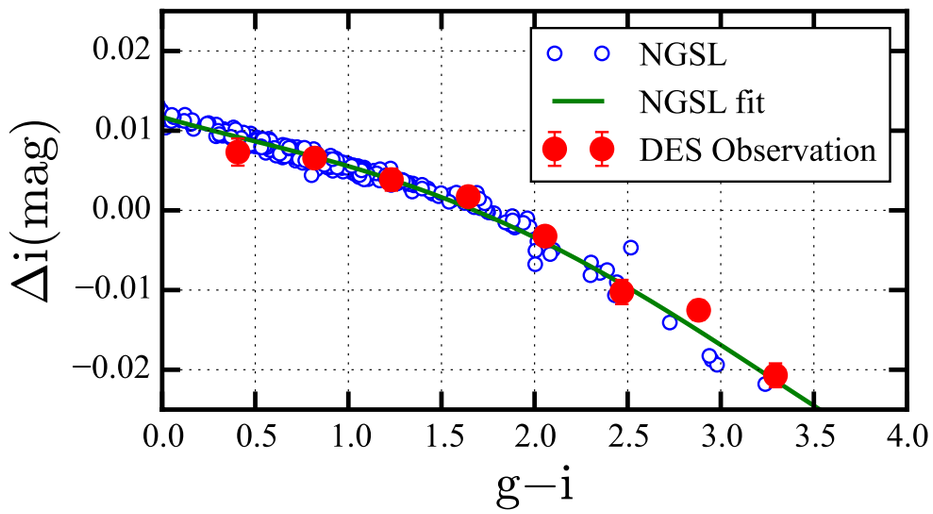
- **Auxiliary system to monitor the atmosphere and the instrument**

DECal measures the instrumental throughput!

DECal scan results in i-band



center vs. edge



Li et al. in prep (DES Collaboration)

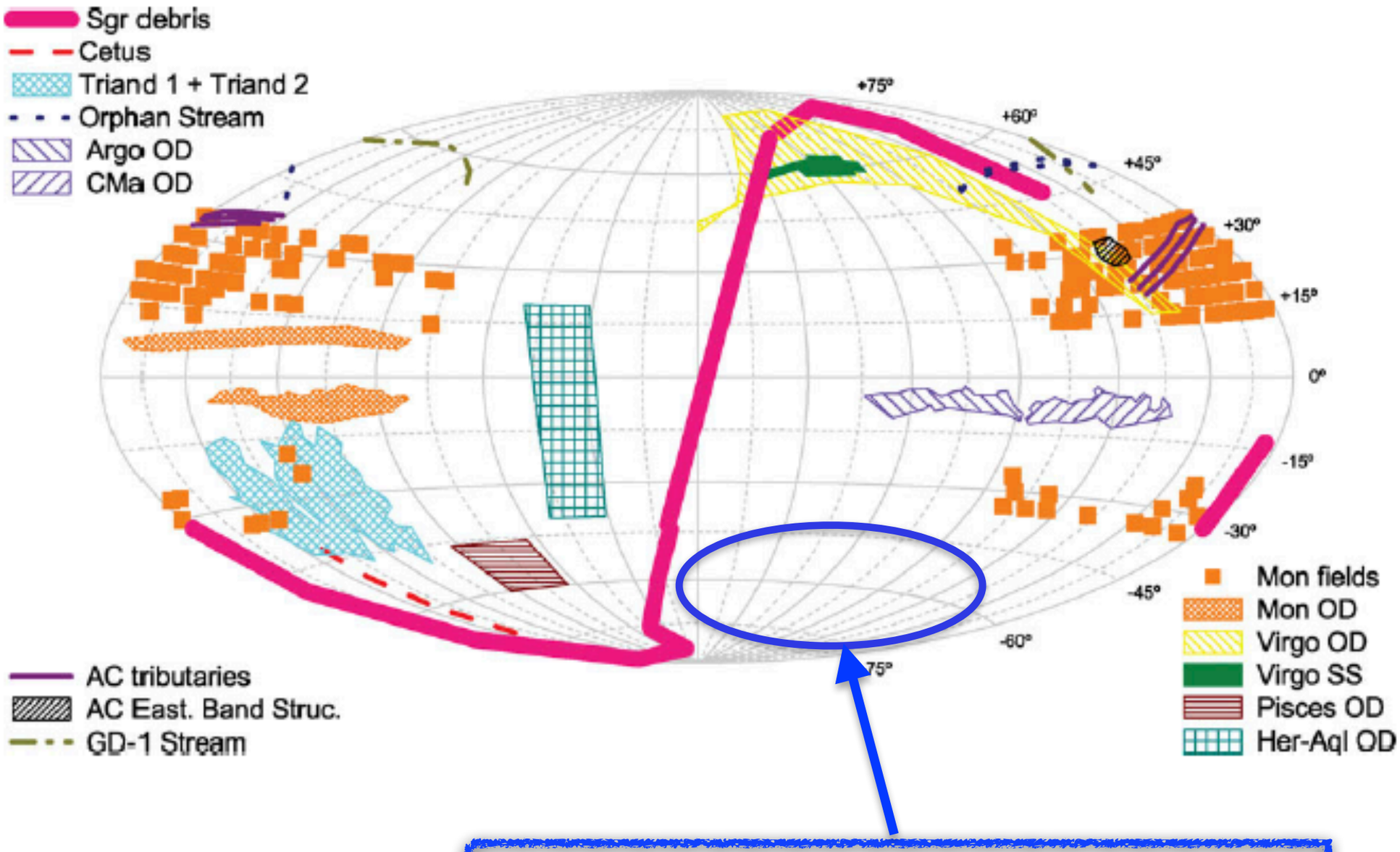
DECal Team: DePoy, Marshall, Rheanult, Li, Wester, James, Allen, Prochaska

Overview

- Milky Way Formation and Halo Substructures
- The Dark Energy Survey (DES)
- **Latest Milky Way Science Discoveries from DES**

Collaborators: Jennifer Marshall, Josh Simon, Marla Geha, Brian Yanny, Eduardo Balbinot, Alex Drlica-Wagner, Keith Bechtol, Basilio Santiago…. and DES Milky Way Science Working Group.

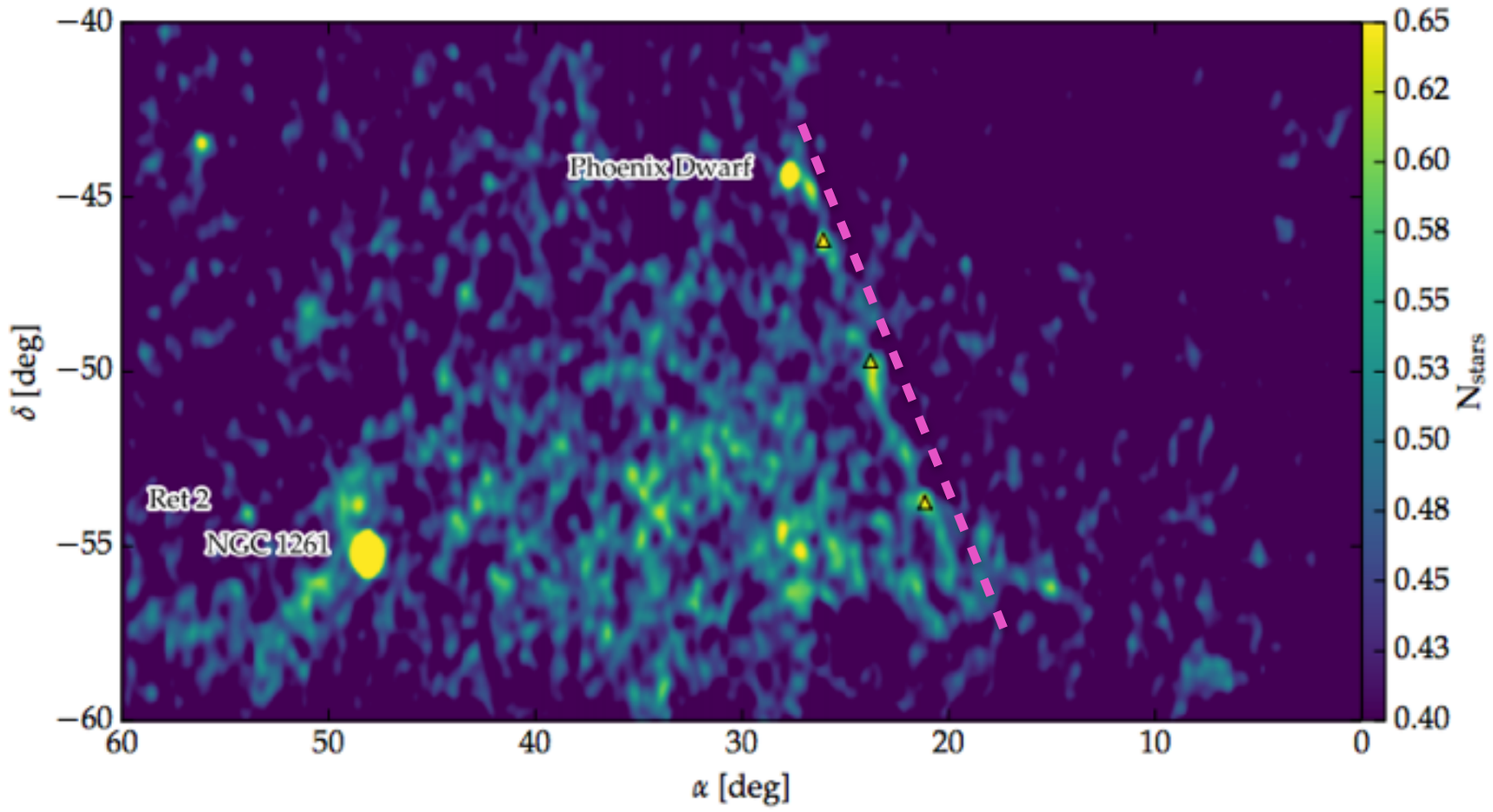
Known Diffuse Halo Substructures Before DES



- **What will DES discover?**

Phoenix Stream

- **Density map with MSTO stars from Year 1 DES data**
- **A narrow stream stands out from the density map**

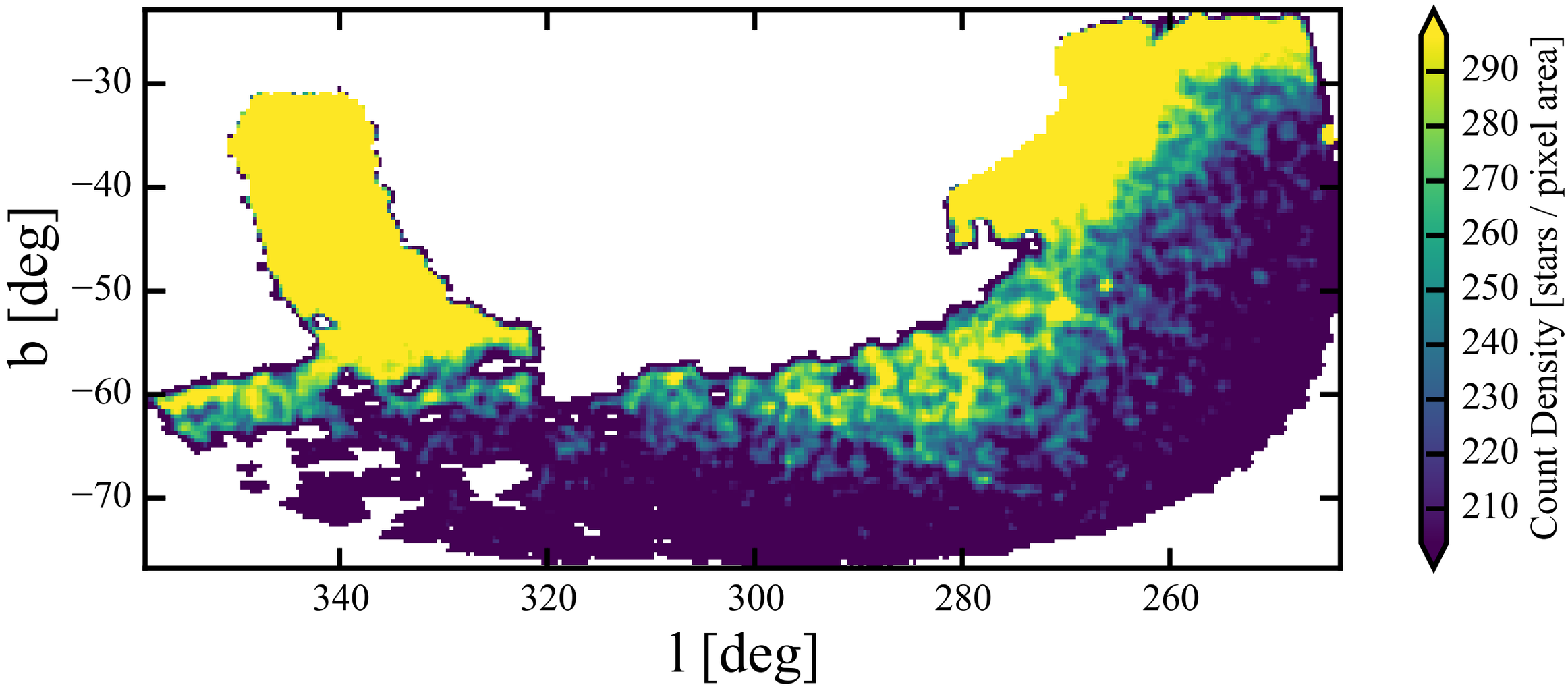


Balbinot, Li + 2015
(DES Collaboration)

- **stream width ~54 pc**
- **progenitor likely to be a globular cluster**
- **heliocentric distance ~ 17.5 kpc**

Eridanus-Phoenix Overdensity

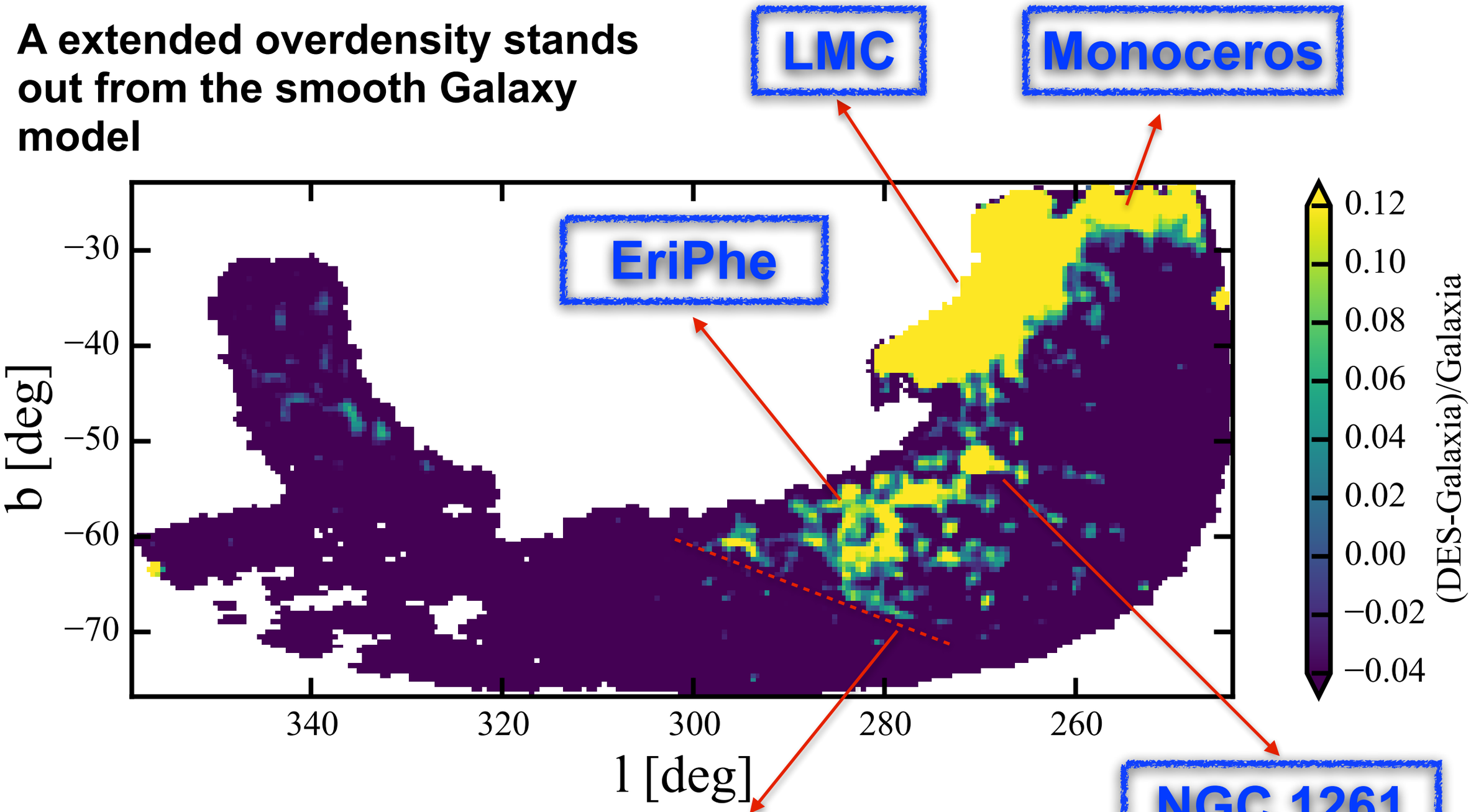
Galactic coordinates



Li et al. 2015
(DES Collaboration)

Eridanus-Phoenix Overdensity

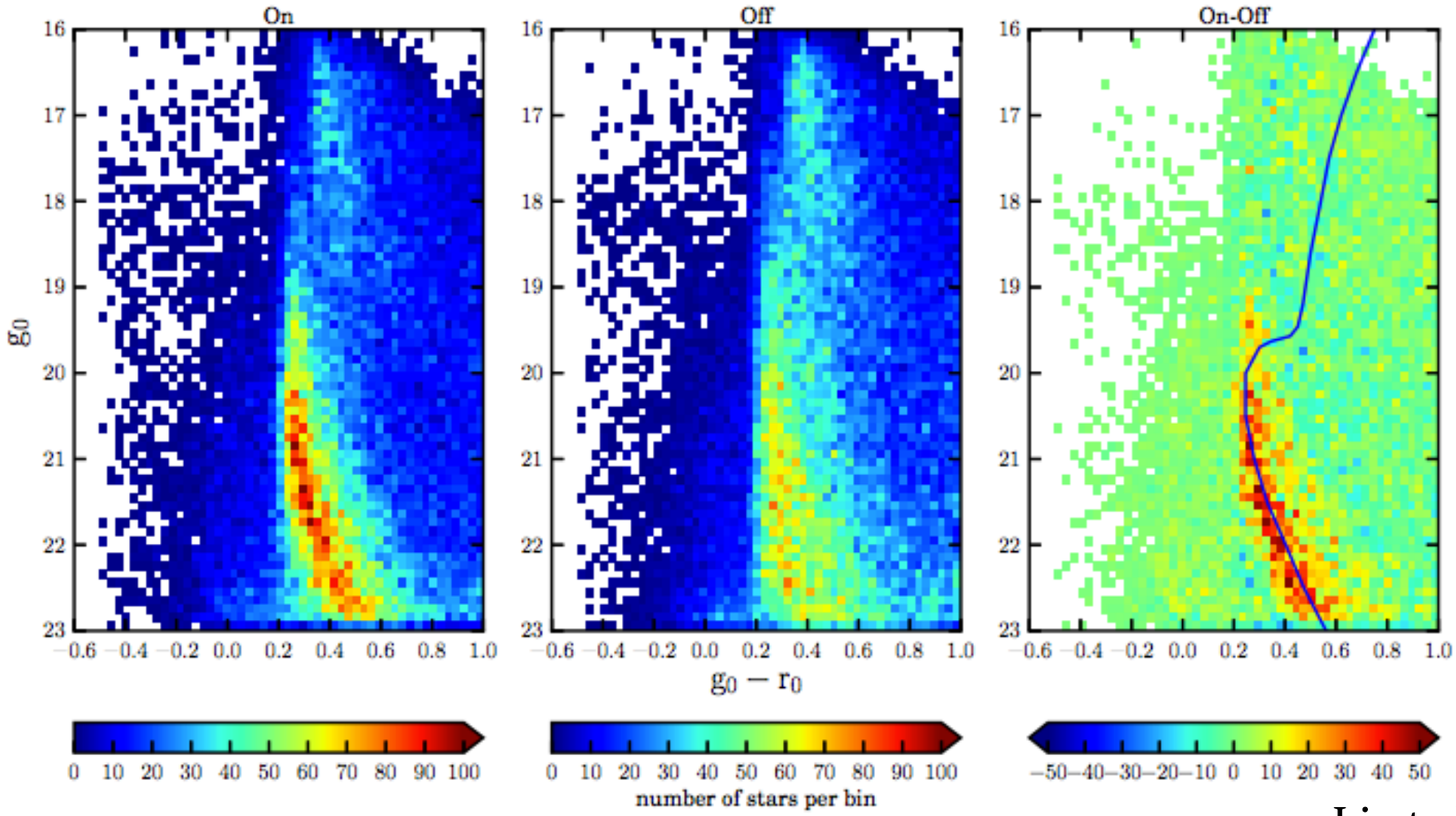
A extended overdensity stands out from the smooth Galaxy model



Li et al. 2015
(DES Collaboration)

Eridanus-Phoenix Overdensity

- **Overdensity also shows in color-magnitude space**

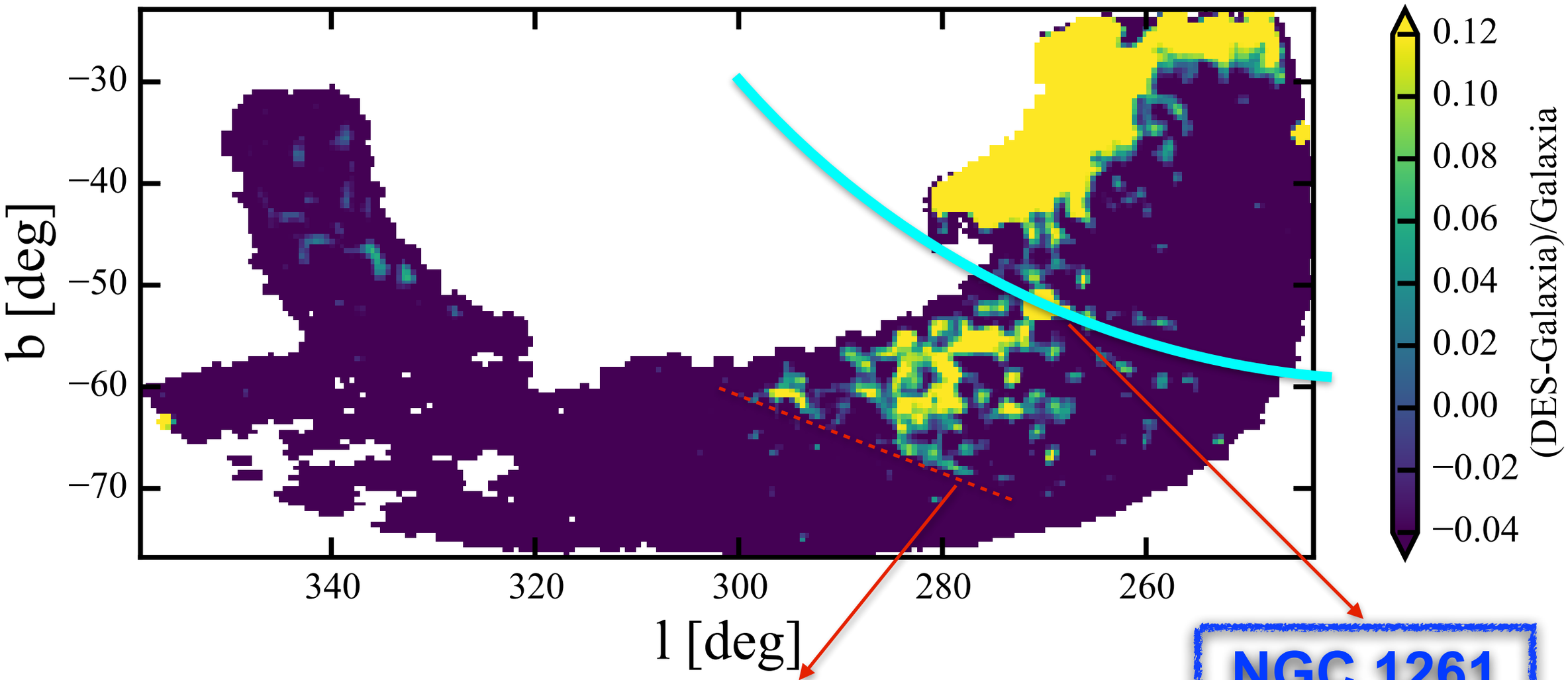


Li et al. 2015
(DES Collaboration)

Isochrone from NGC 1261
EriPhe is at a similar distance as NGC 1261 — 16kpc from the Sun

Eridanus-Phoenix Overdensity

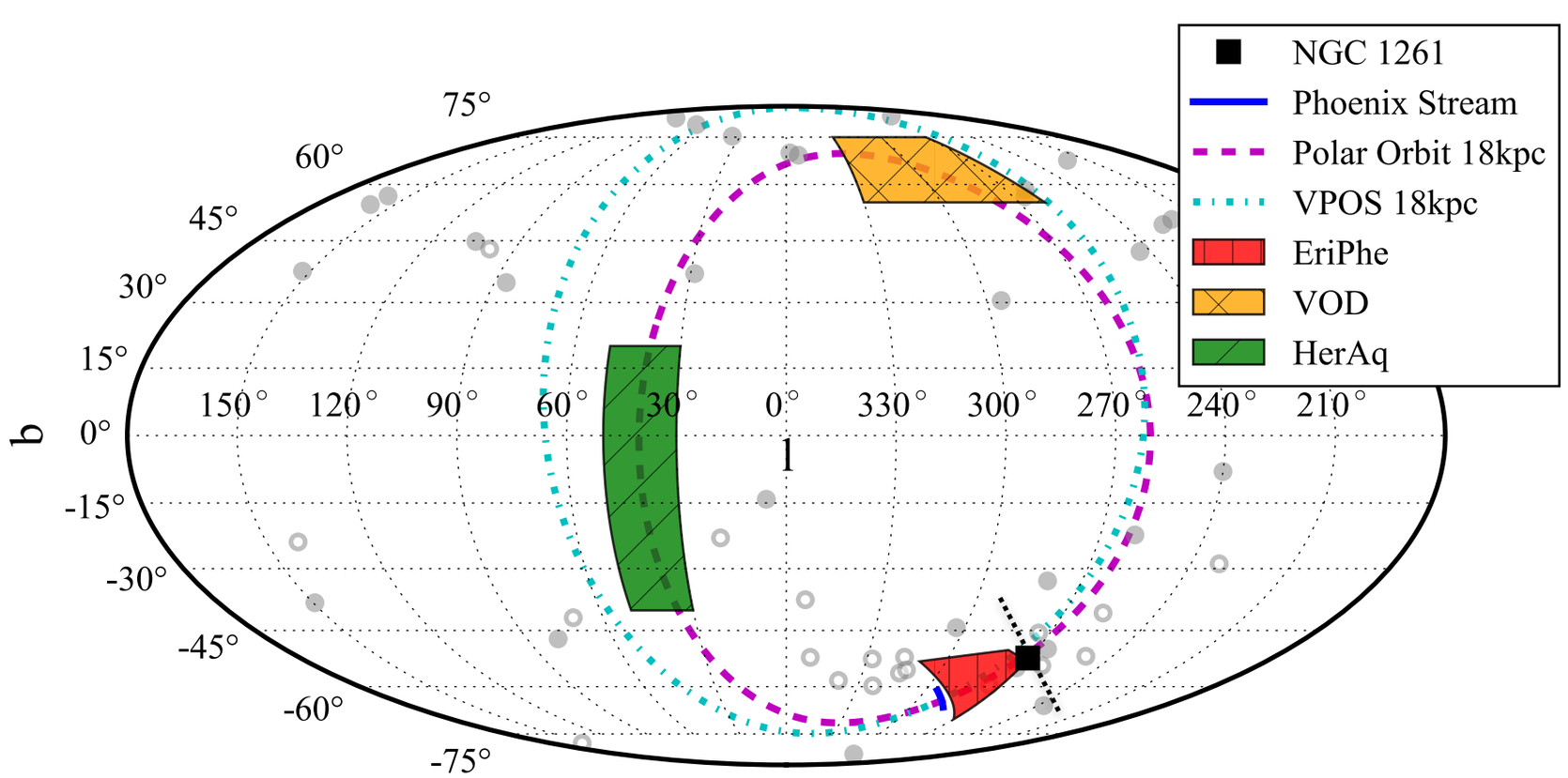
Distance: ~16kpc from sun
Size: ~4kpc x ~3kpc in projection
Luminosity: ~10^5 solar luminosity



Li et al. 2015
(DES Collaboration)

Polar Structure?

- **Polar orbit formed by EriPhe, Virgo overdensity and Hercules-Aquila cloud**
  - — close to VPOS plane



Li et al. 2015
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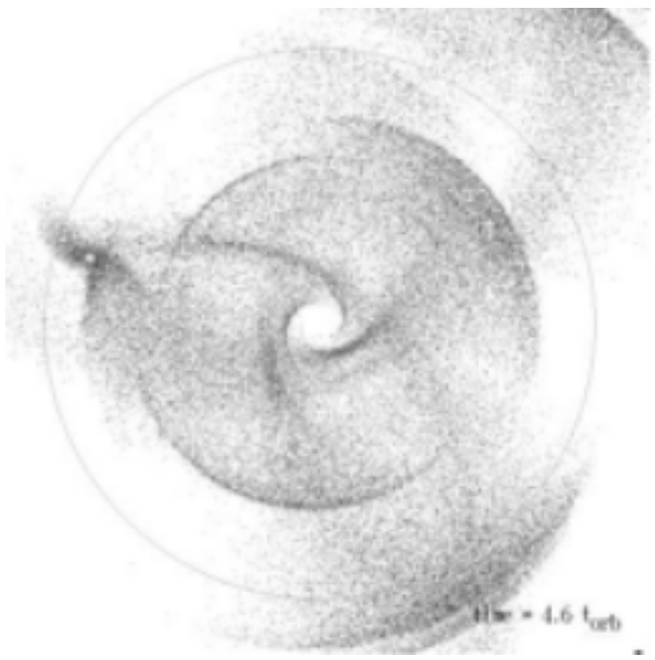
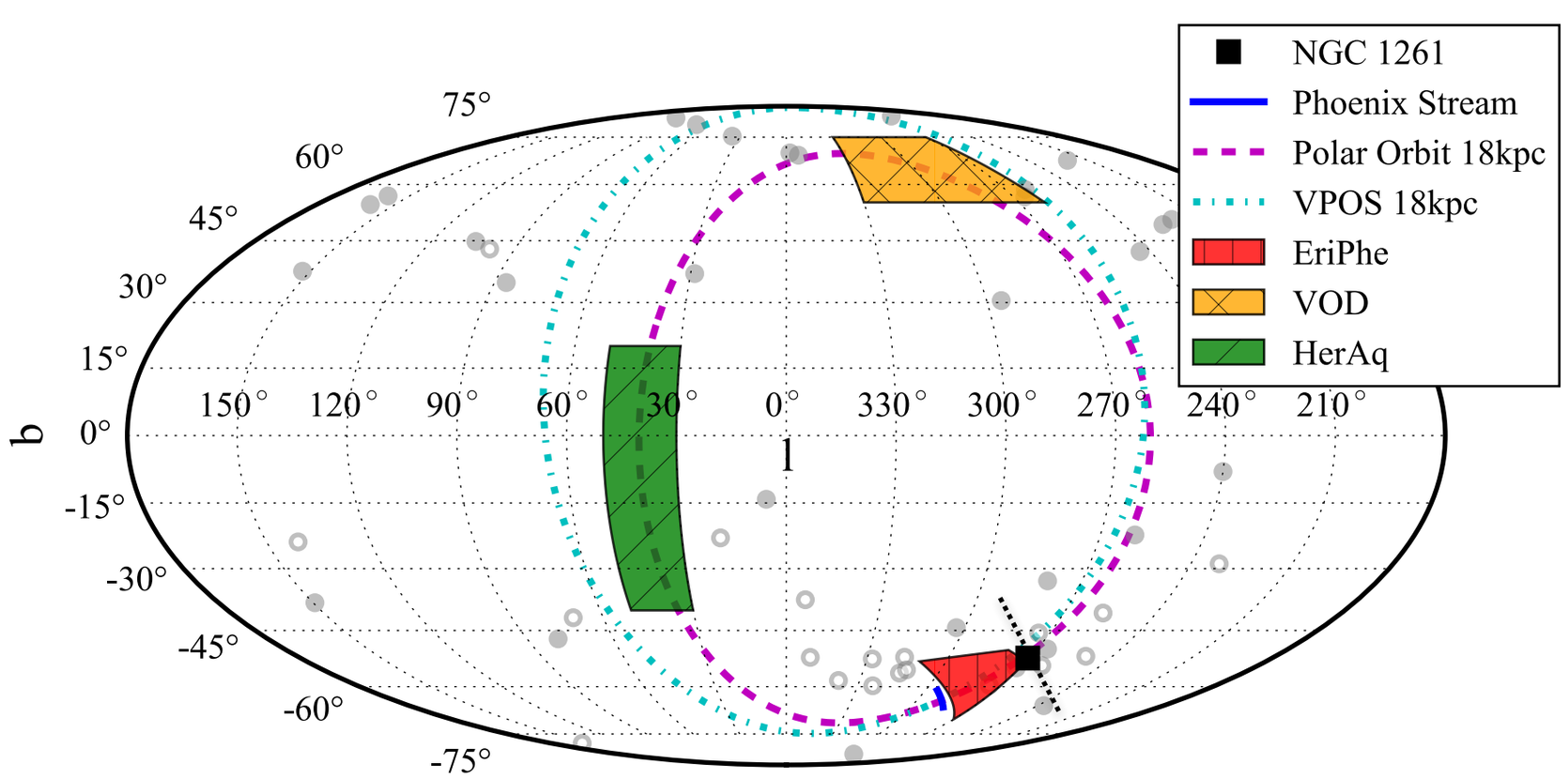


Hayashi et al. 2003



Polar Structure?

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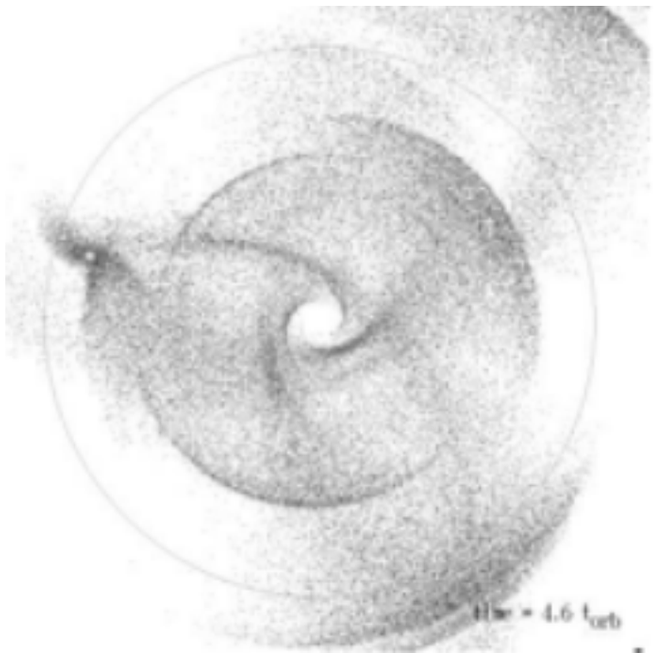
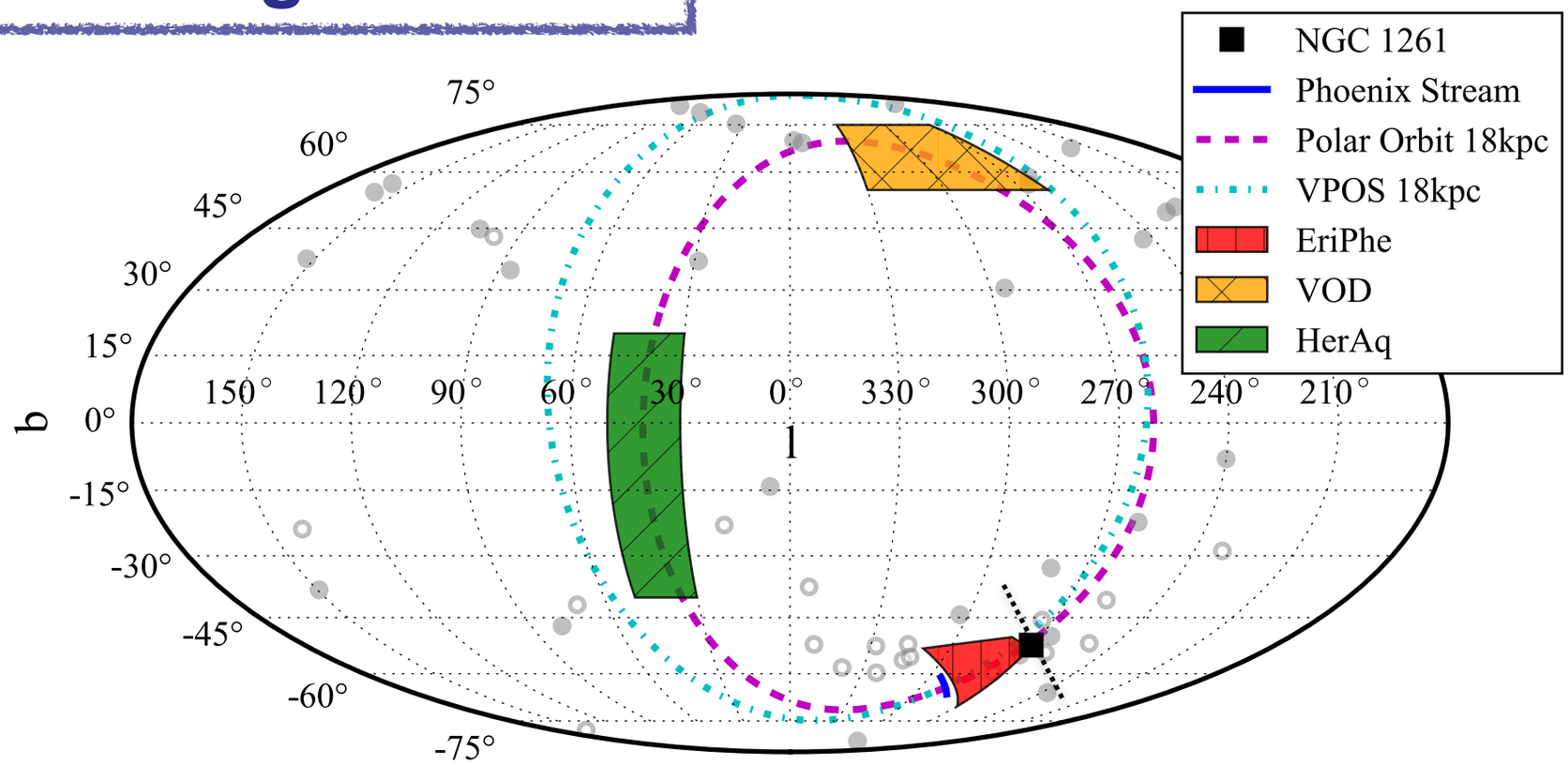
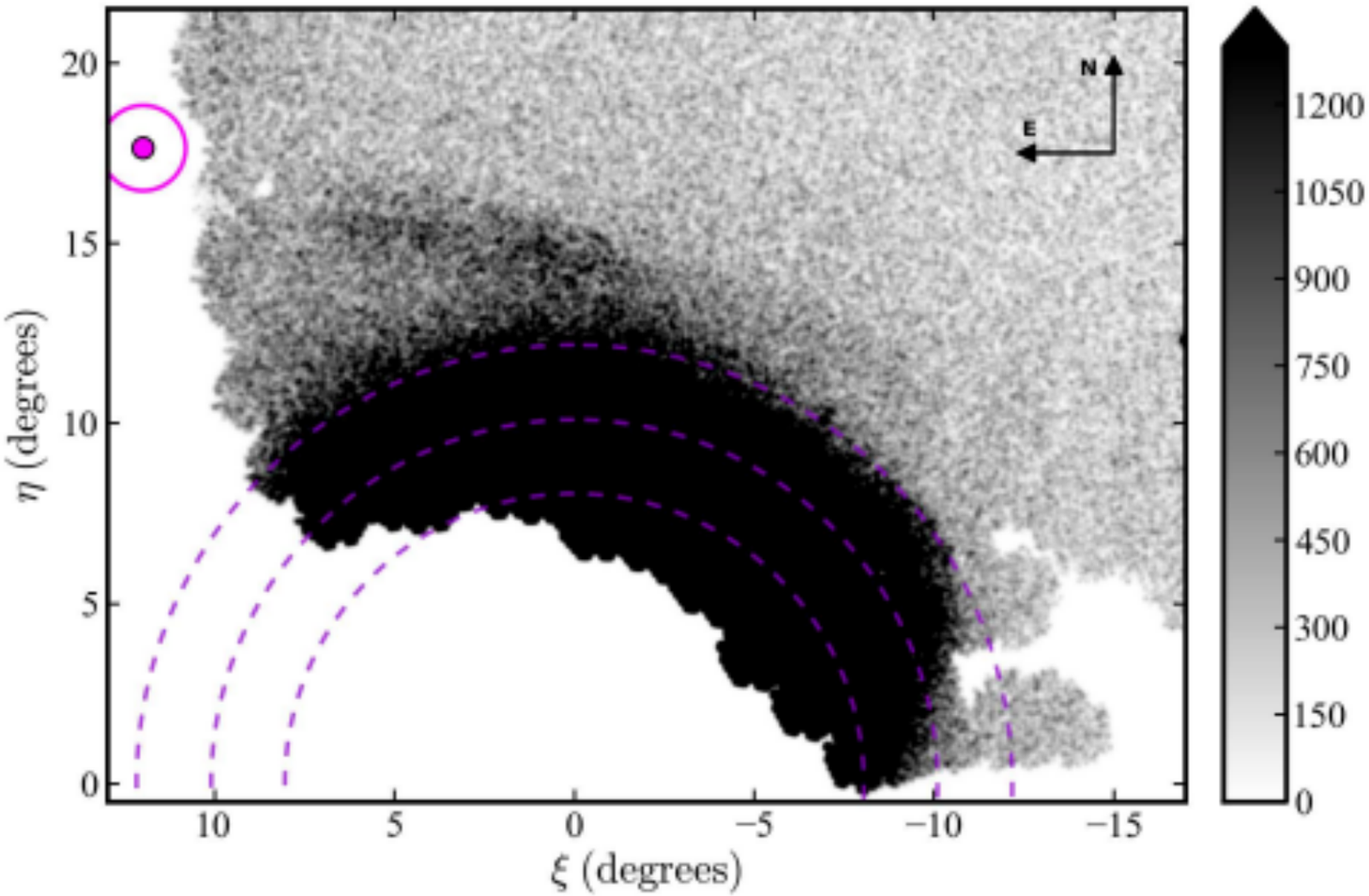
Spectroscopic Follow-up
Proper motion
Modeling

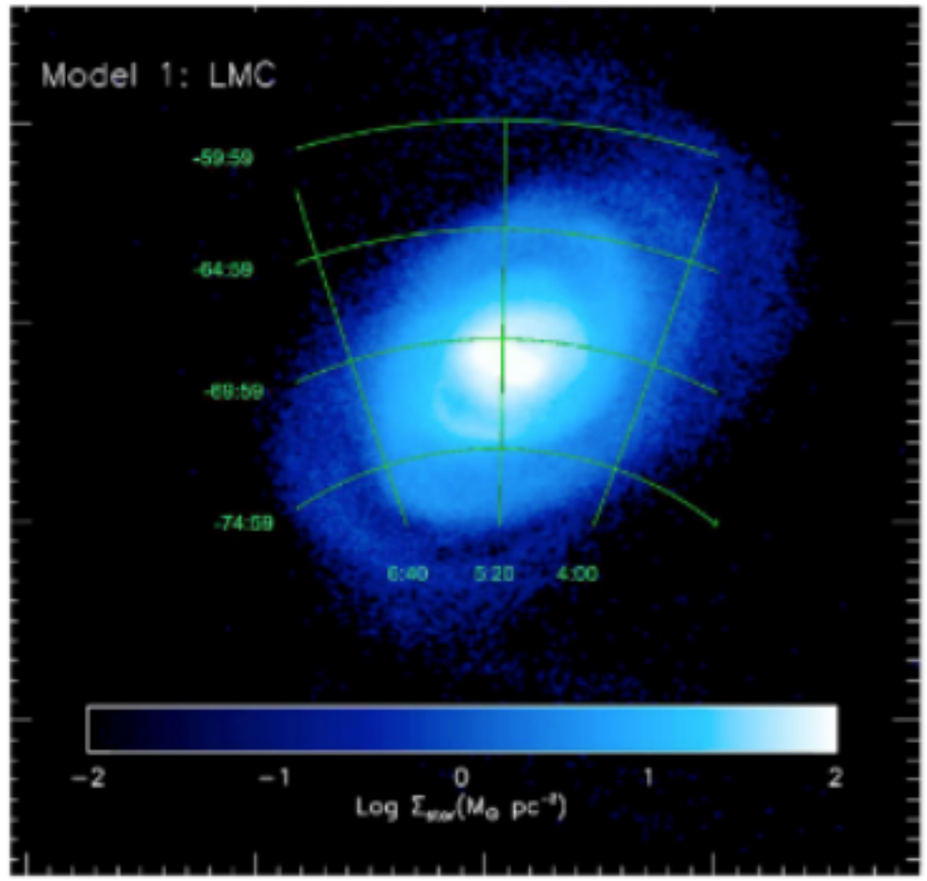


Hayashi et al. 2003



LMC stream discovery using DES data

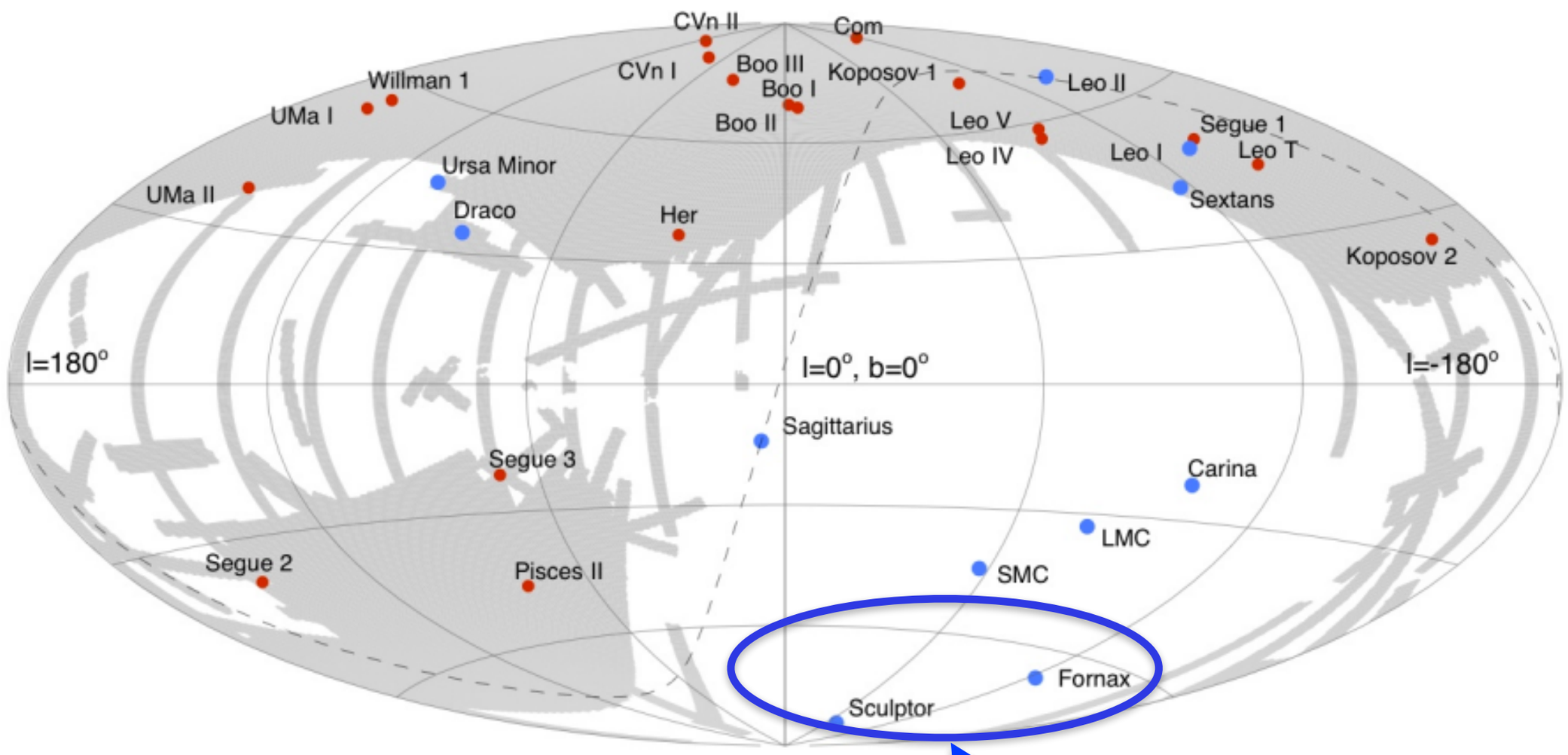




Mackey et al 2015
Using public Y1 DES image data

Modeling predicted by
Jin & Lynden-Bell 2008

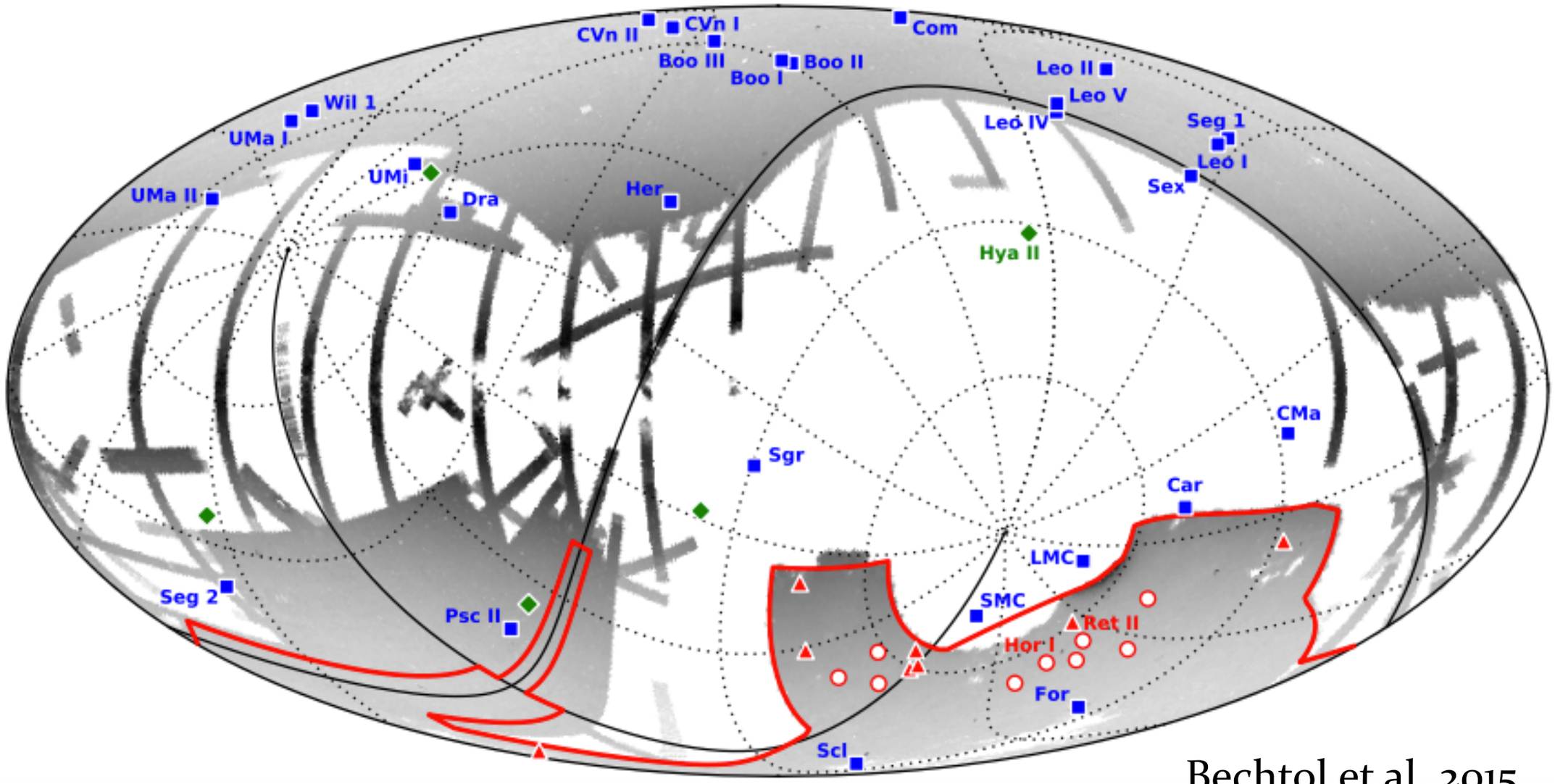
Known Dwarf Galaxies Before DES



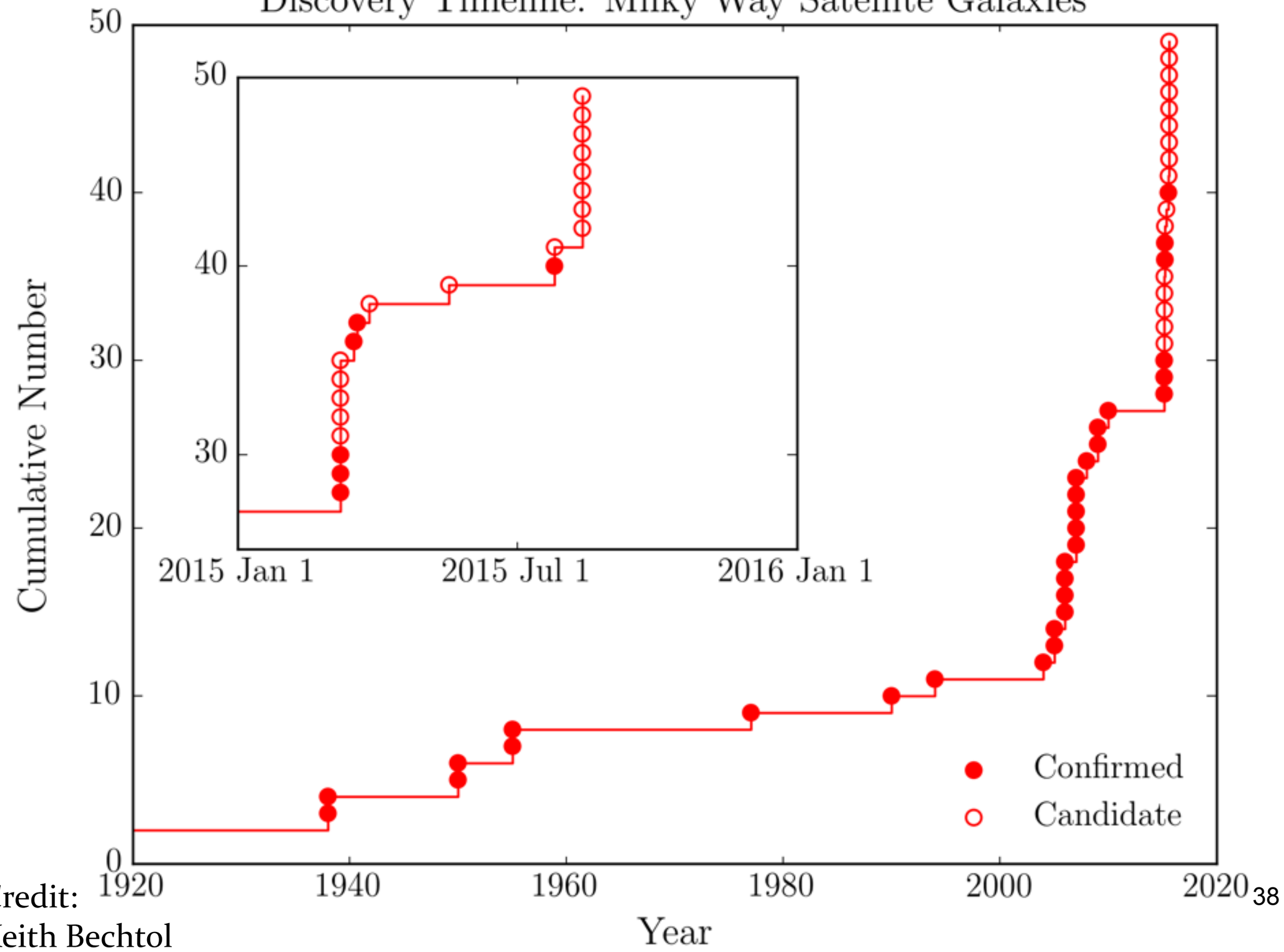
- **What will DES discover?**

Dwarf Galaxy Candidates

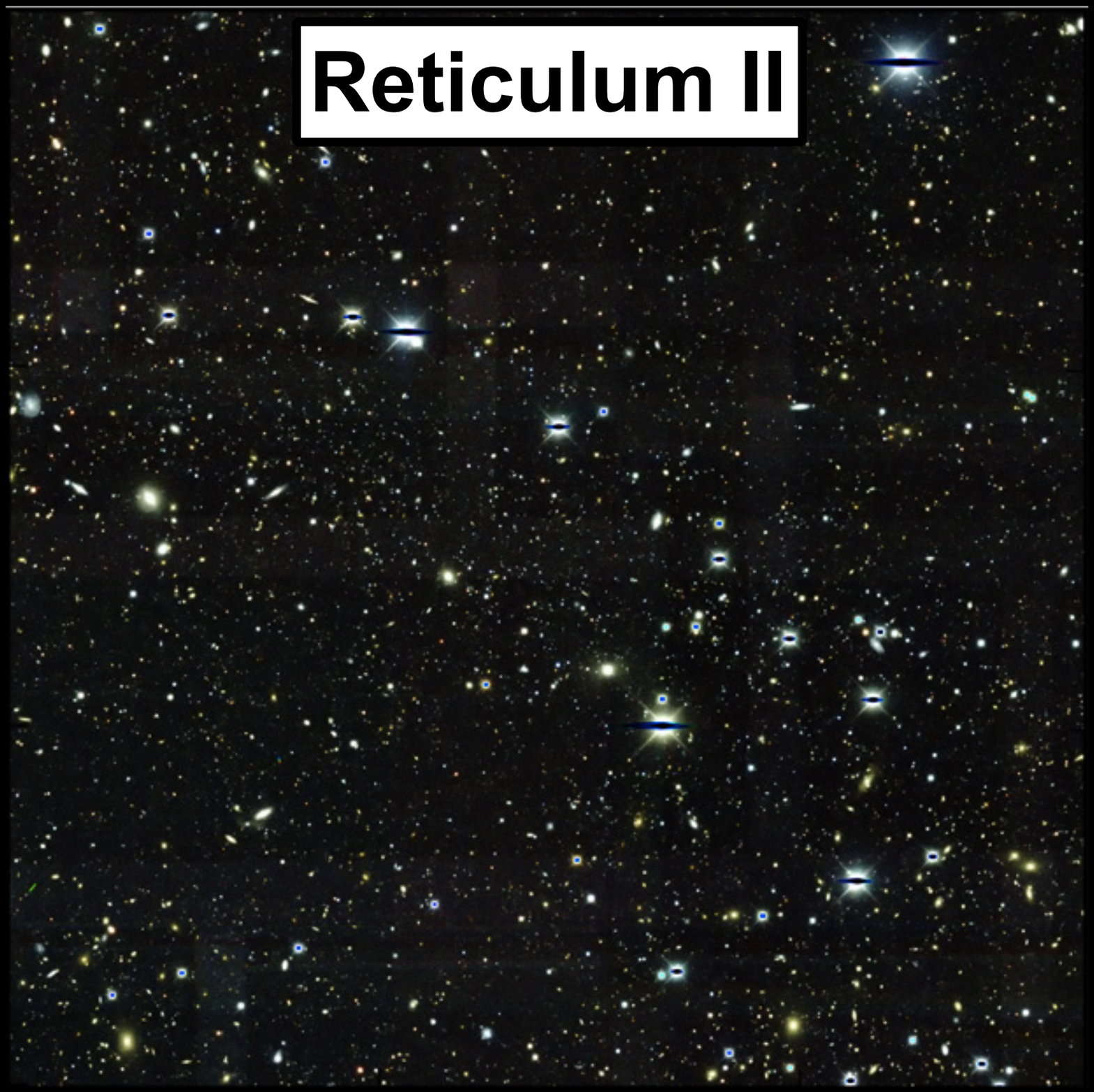
Y1+Y2 data release



Bechtol et al. 2015
Drlica-Wagner et al. 2015
(DES Collaboration)

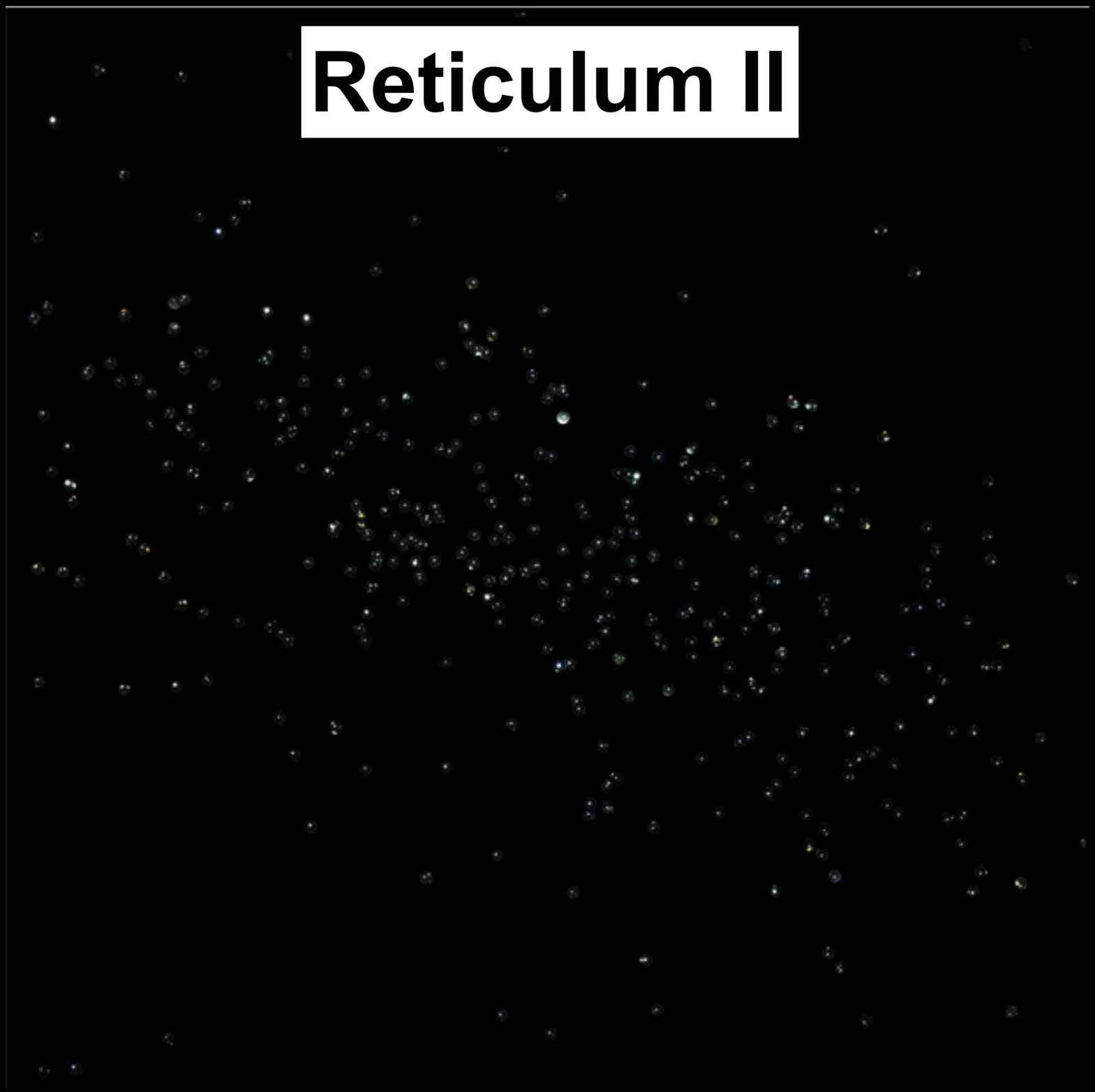


Credit:
Keith Bechtol



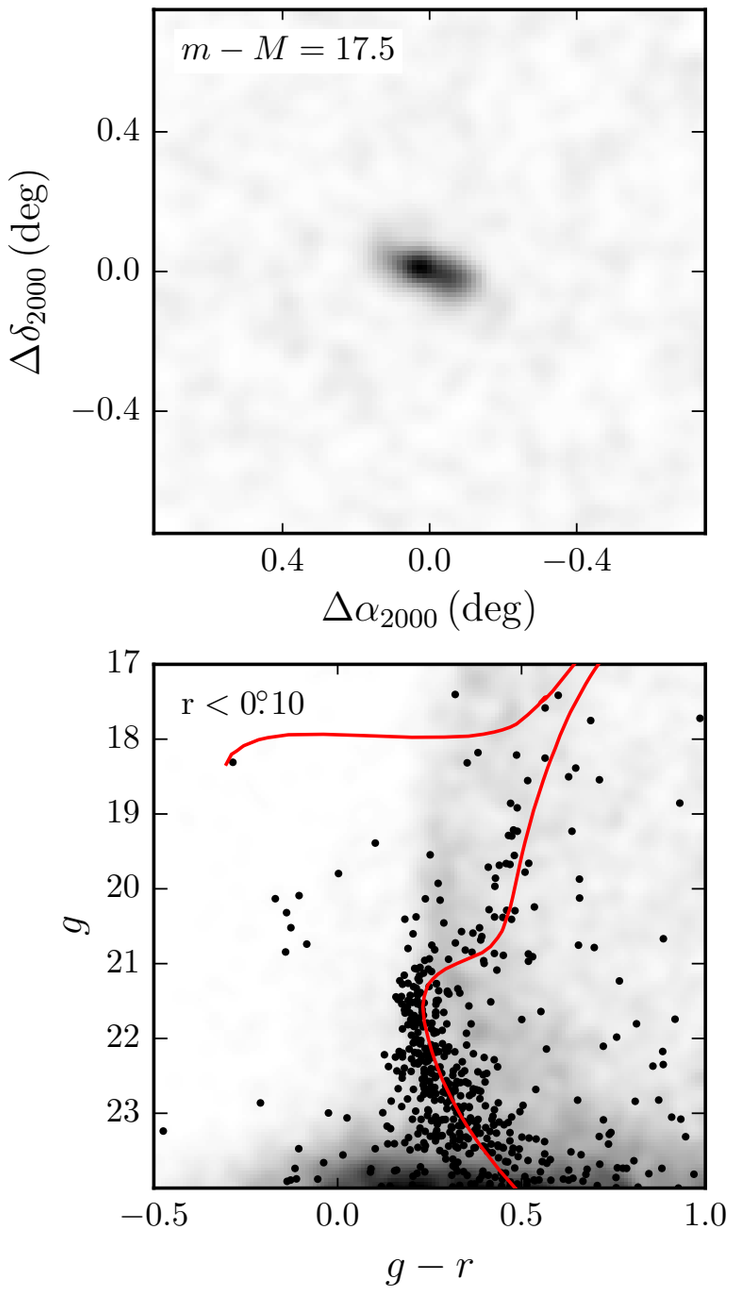
DES Collaboration

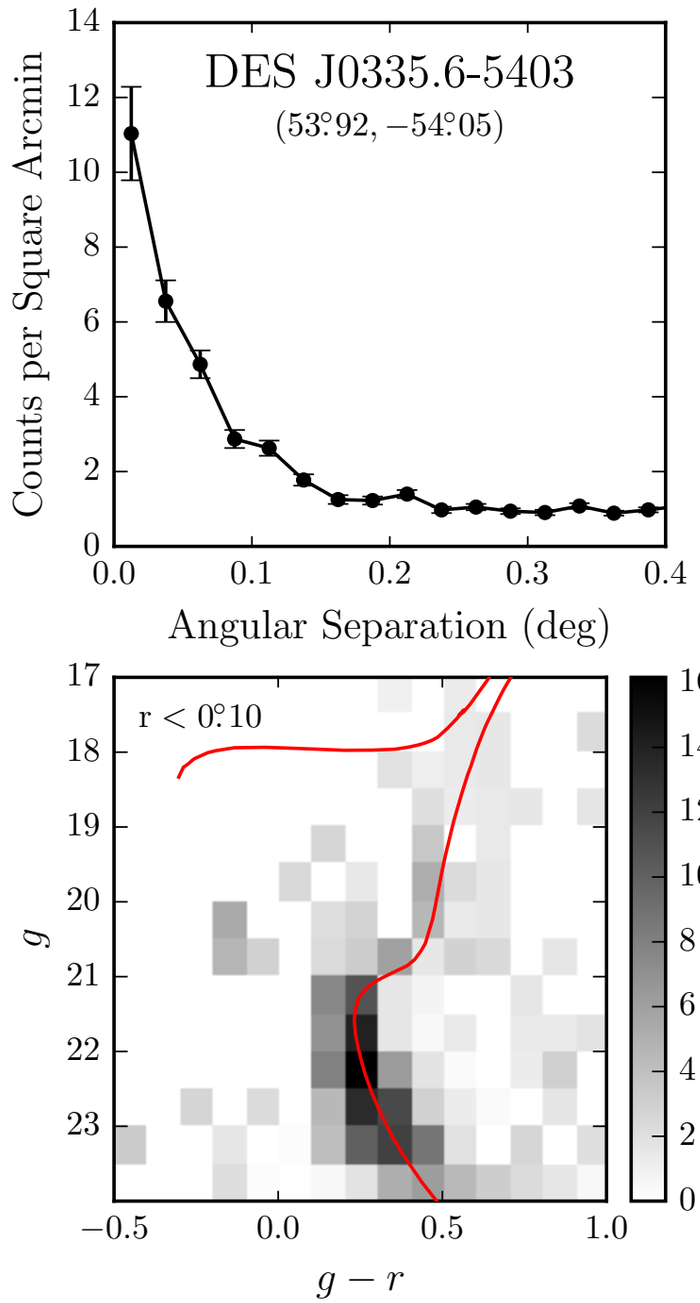
Reticulum II

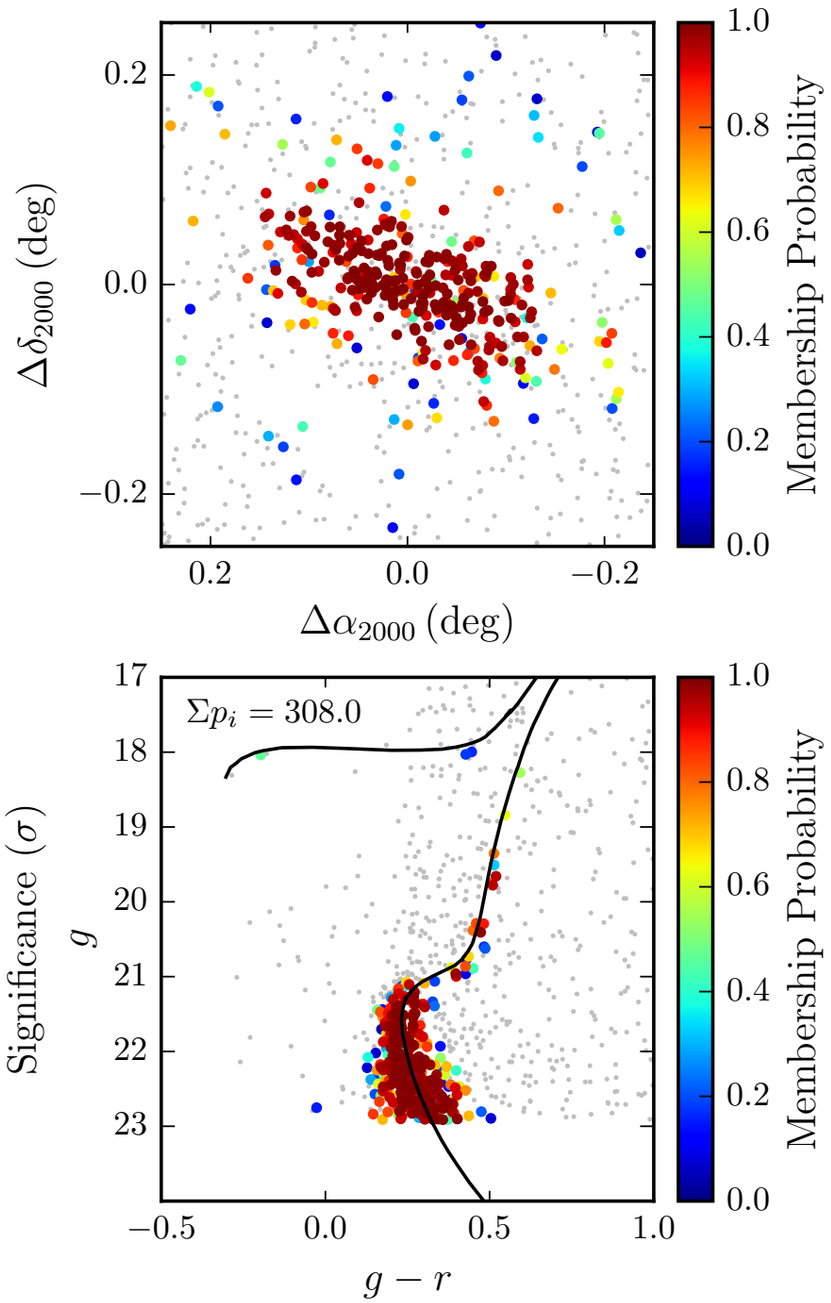


DES Collaboration

Reticulum II: Newest Dwarf Galaxy?



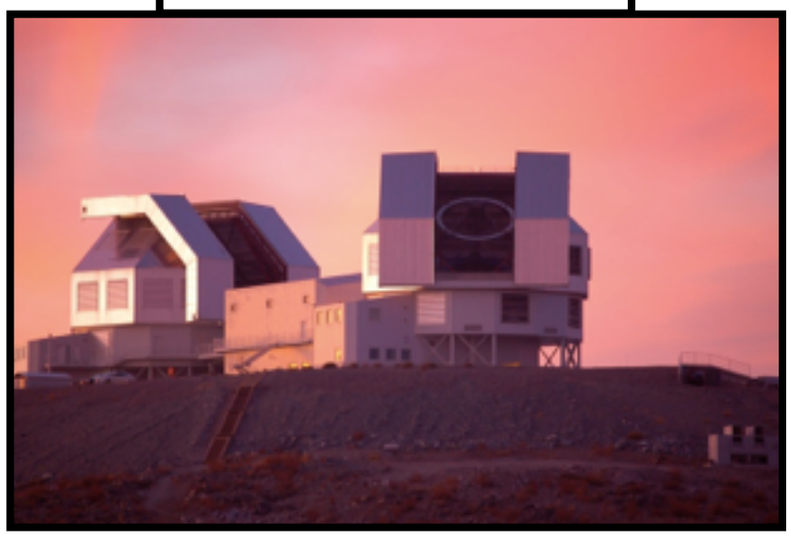




Bechtol et al. 2015
(DES Collaboration)

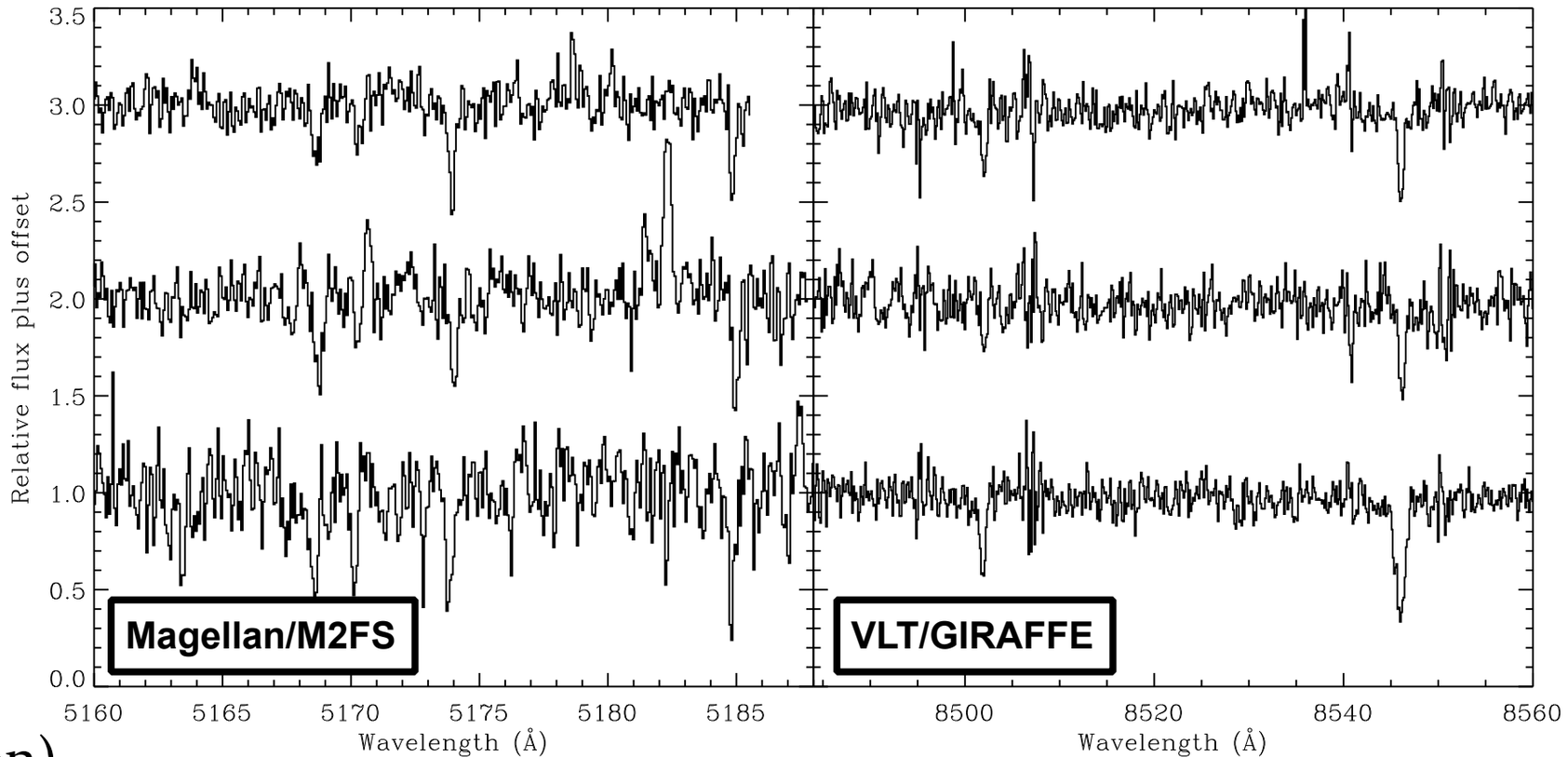
Reticulum II: Spectroscopy Campaign

Magellan/M2FS



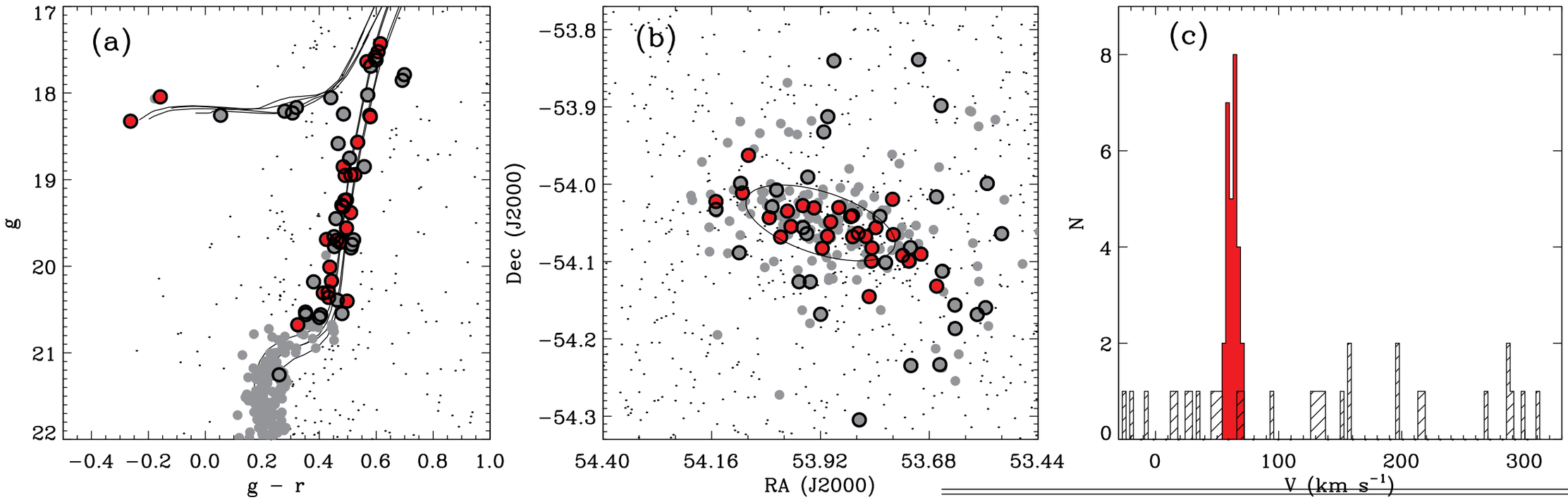
Gemini/GMOS

VLT/GIRAFFE



Simon, Li + 2015
(DES Collaboration)

Reticulum II: Newest Dwarf Galaxy



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

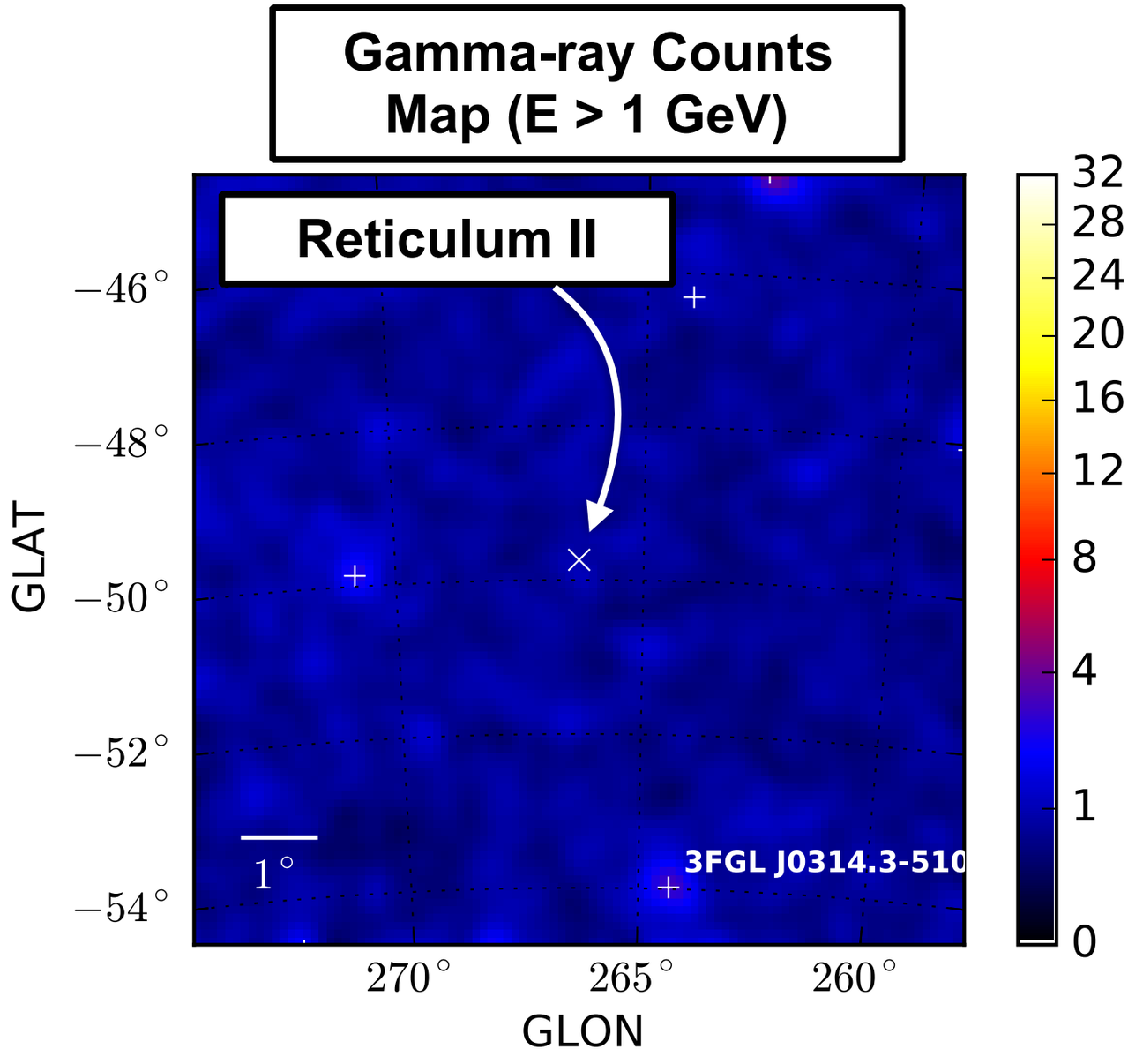
Quantity	Value
Systemic Velocity	$v = 62.8 \pm 0.5\,\mathrm{km\,s^{-1}}$
Velocity Dispersion	$\sigma_v = 3.3 \pm 0.7\,\mathrm{km\,s^{-1}}$
Metallicity	$[\mathrm{Fe/H}] = -2.65 \pm 0.07$
Metallicity Dispersion	$\sigma_{[\mathrm{Fe/H}]} = 0.28 \pm 0.09$
Dynamical Mass	$M_{1/2} = 5.6 \pm 2.4 \times 10^5\,\mathrm{M_\odot}$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

Simon, Li + 2015
(DES Collaboration)

Dark Matter Searches in Gamma Rays

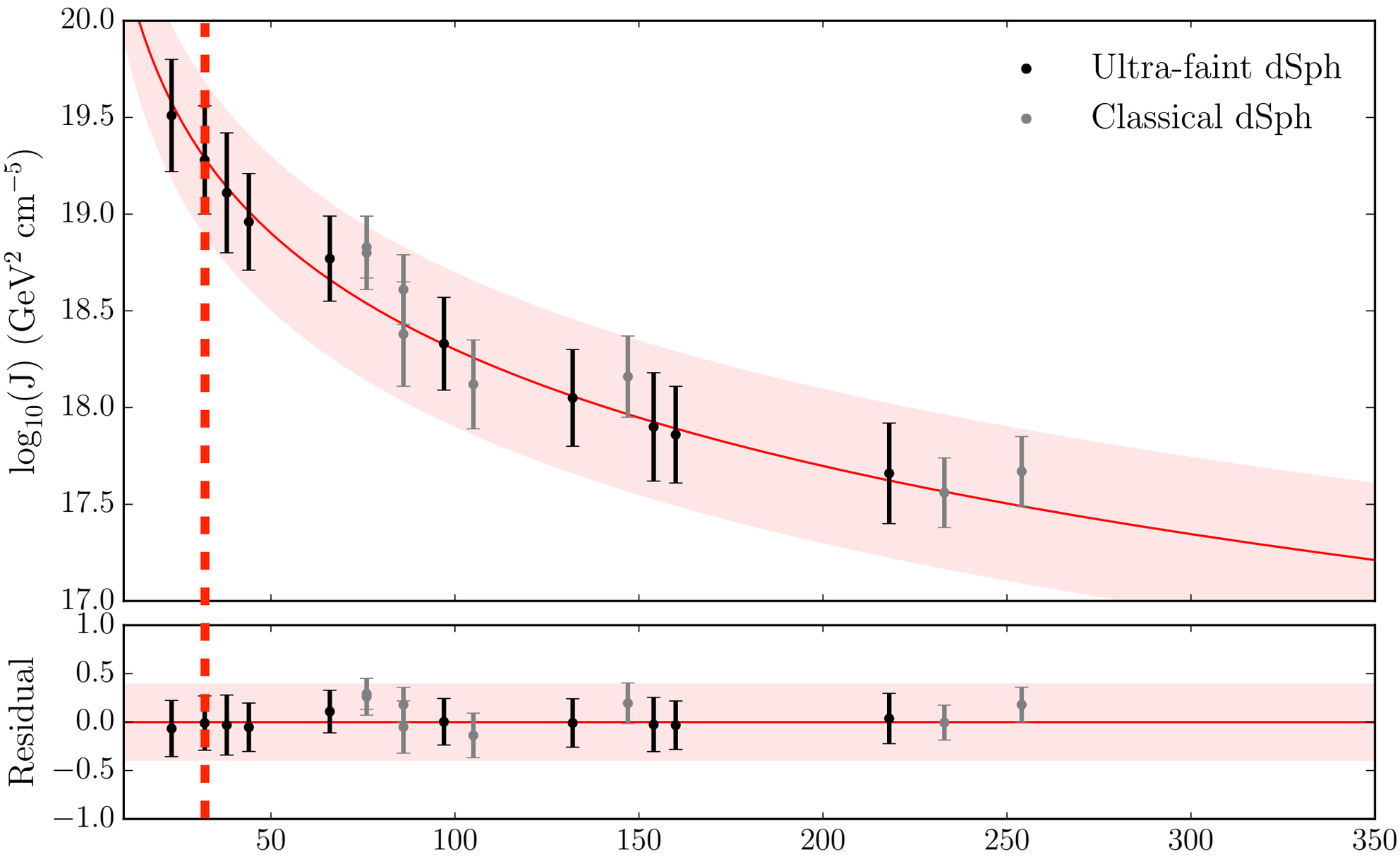
- Search for discrete gamma-ray sources coincident with the DES dwarf galaxy candidates
- No significant gamma-ray sources detected over background
- Most significant excess coincident with Reticulum II
  - LAT Collaboration, Pass 8: local pvalue = 0.06 (1.5σ)
  - Geringer-Sameth+, Pass 7: local pvalue = 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)

Dark Matter Searches in Gamma Rays

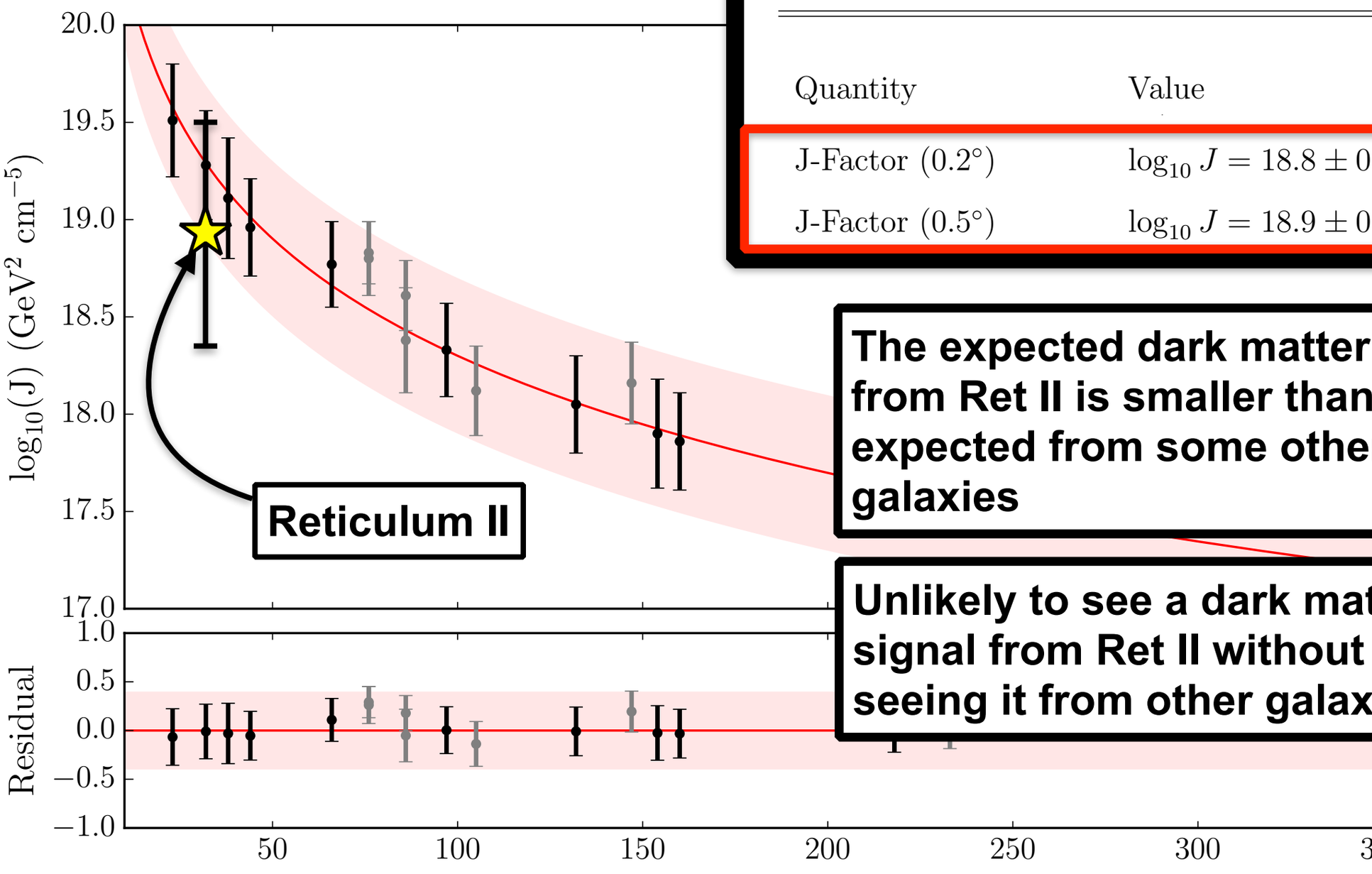


Drlica-Wagner et al. 2015
(LAT & DES Collaboration)

Dark Matter Searches in Gamma Rays

Table 1. Reticulum II

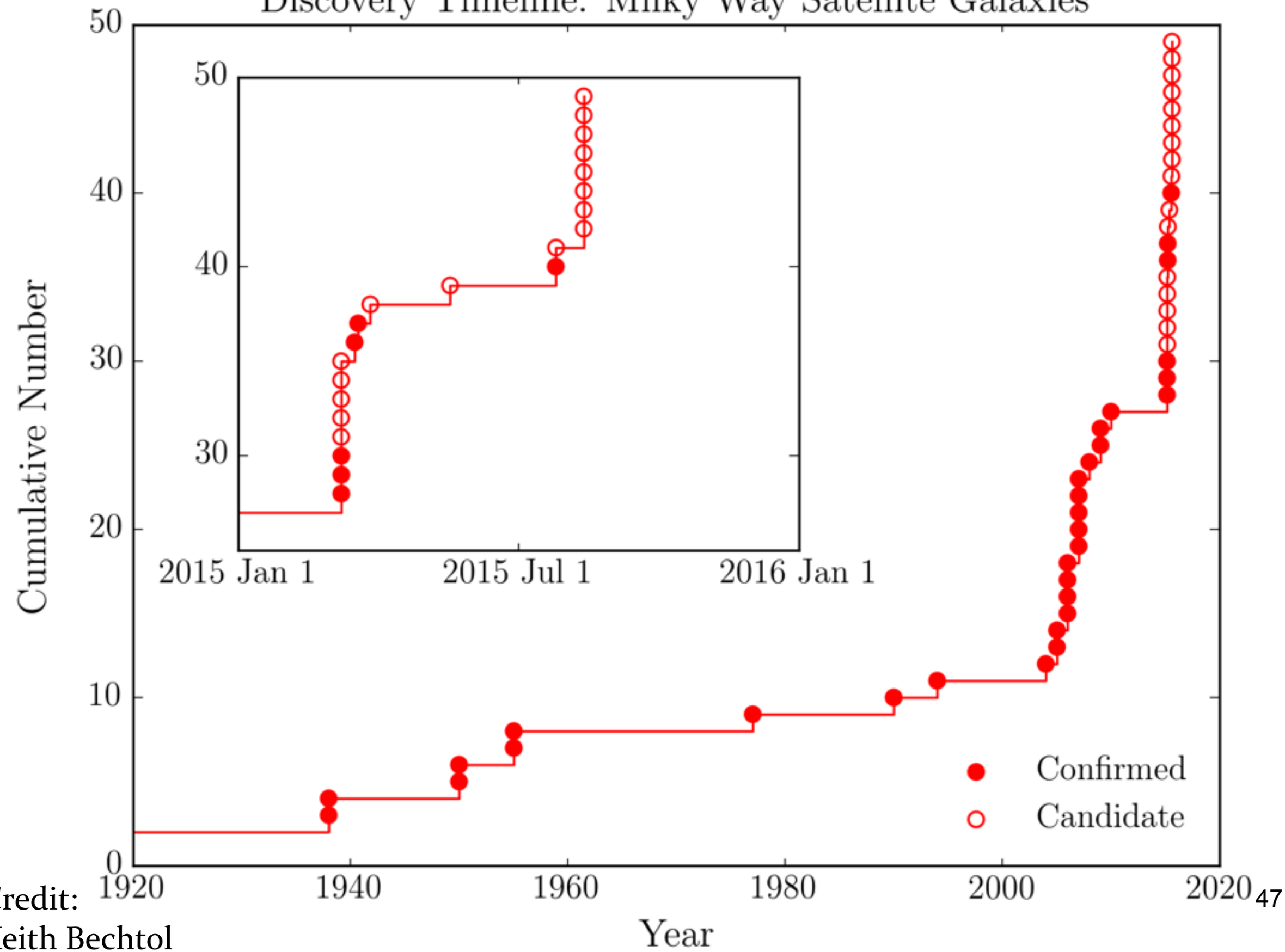
Quantity	Value
J-Factor (0.2°)	$\log_{10} J = 18.8 \pm 0.6\,\mathrm{GeV^2\,cm^{-5}}$
J-Factor (0.5°)	$\log_{10} J = 18.9 \pm 0.6\,\mathrm{GeV^2\,cm^{-5}}$



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.

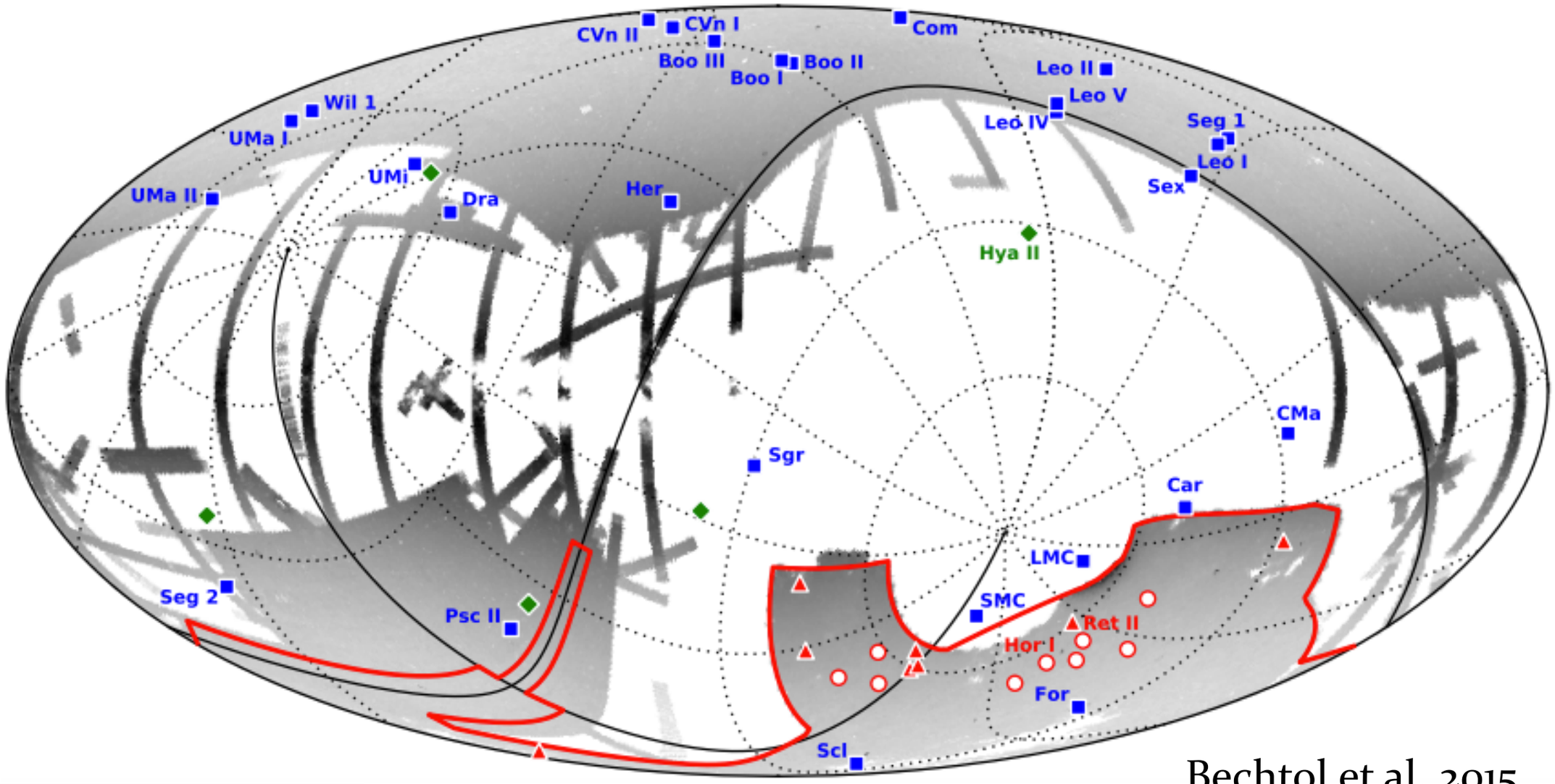
Simon, Li + 2015
(DES Collaboration)



Credit:
Keith Bechtol

Dwarf Galaxy Candidates

Y1+Y2 data release

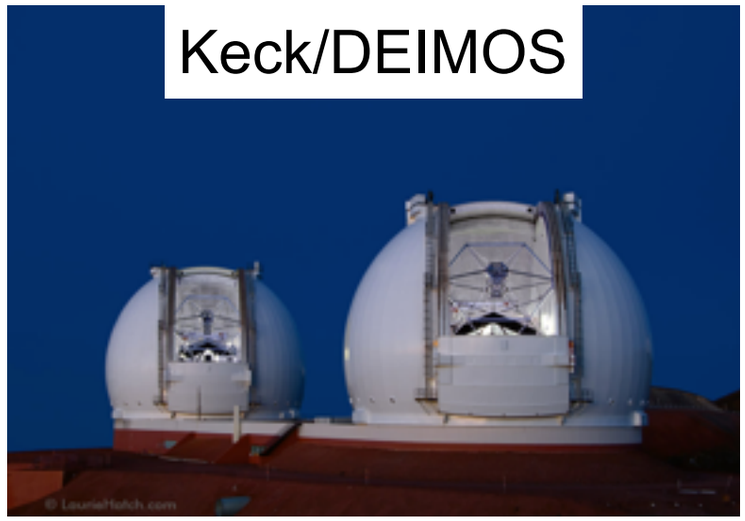


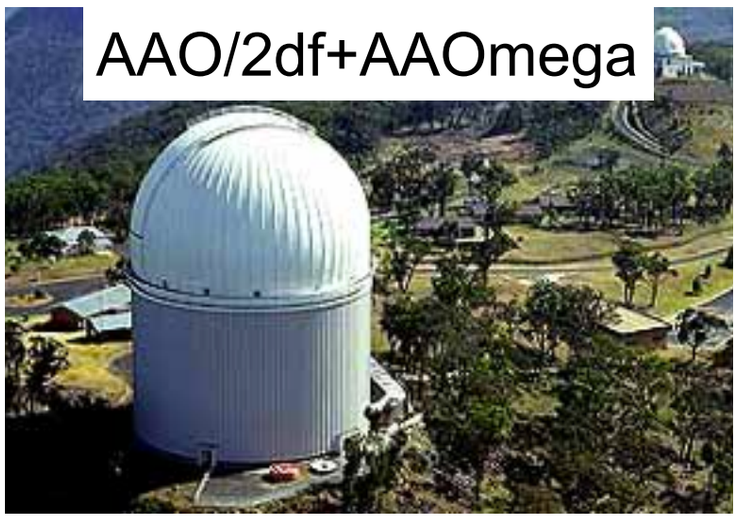
Satellites of the Magellanic System?

Bechtol et al. 2015
Drlica-Wagner et al. 2015
(DES Collaboration)

Looking Forward

- **More spectroscopic follow-ups**
  - **Magellan**
  - **VLT**
  - **Keck**
  - **AAT**





- **DES Year 2 catalog construction**
- **DES Year 3 operation**

Summary

- **Large-area imaging surveys provide extremely powerful datasets to study substructures in the Milky Way halo.**

- **A lot of dwarf galaxies and substructures have been discovered in the DES**

- **Spectroscopic follow-up is underway!**
  - **Constrain the orbits of EriPhe and Phoenix Stream**
  - **Confirm the dwarf galaxies**