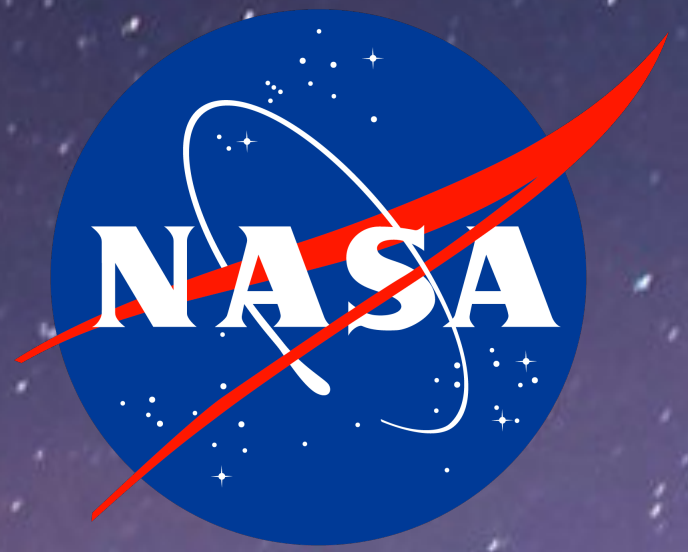
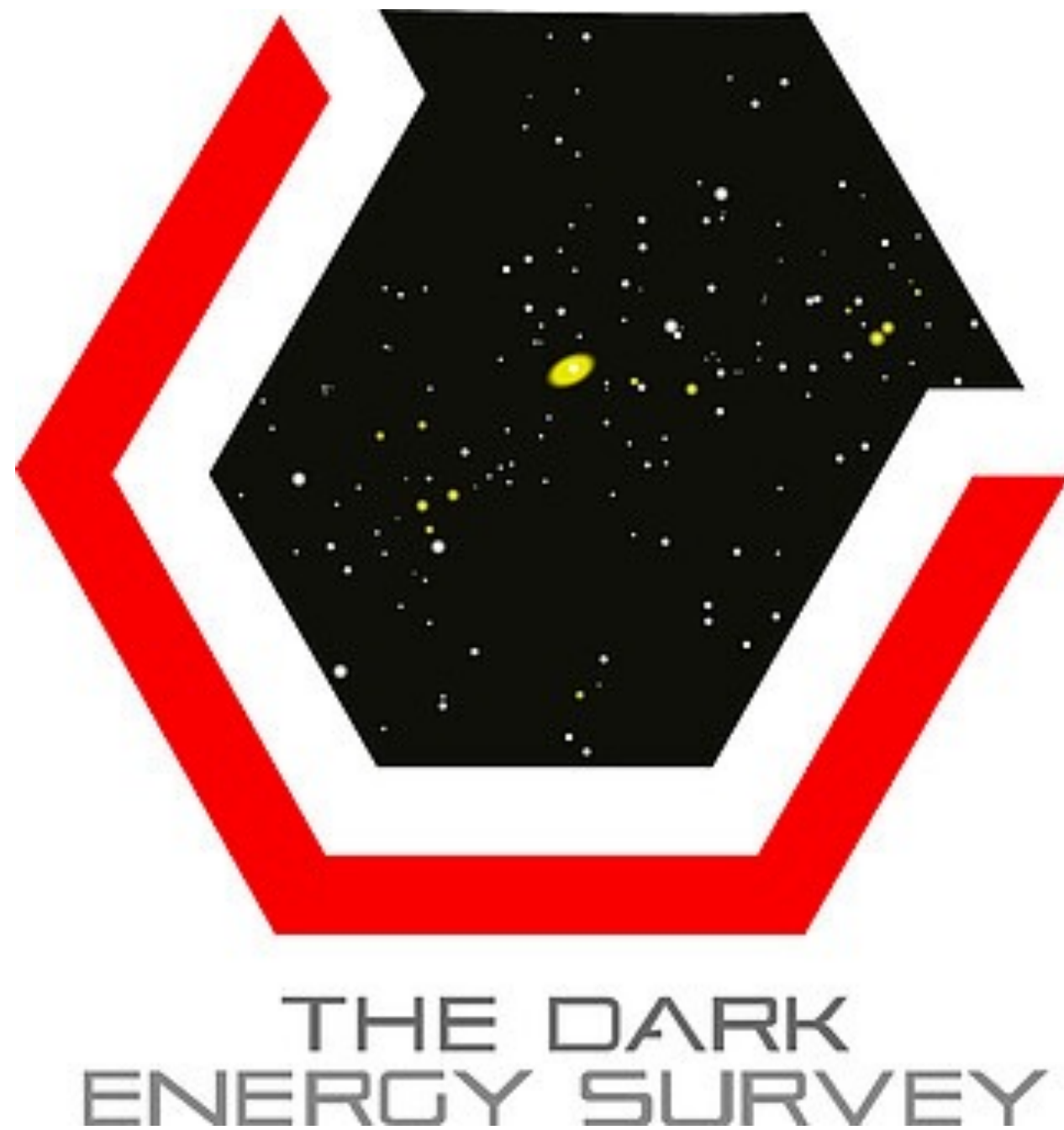


Milky Way Science Revolution: Yesterday, Today, and Tomorrow

Burçin Mutlu-Pakdil
Dartmouth College



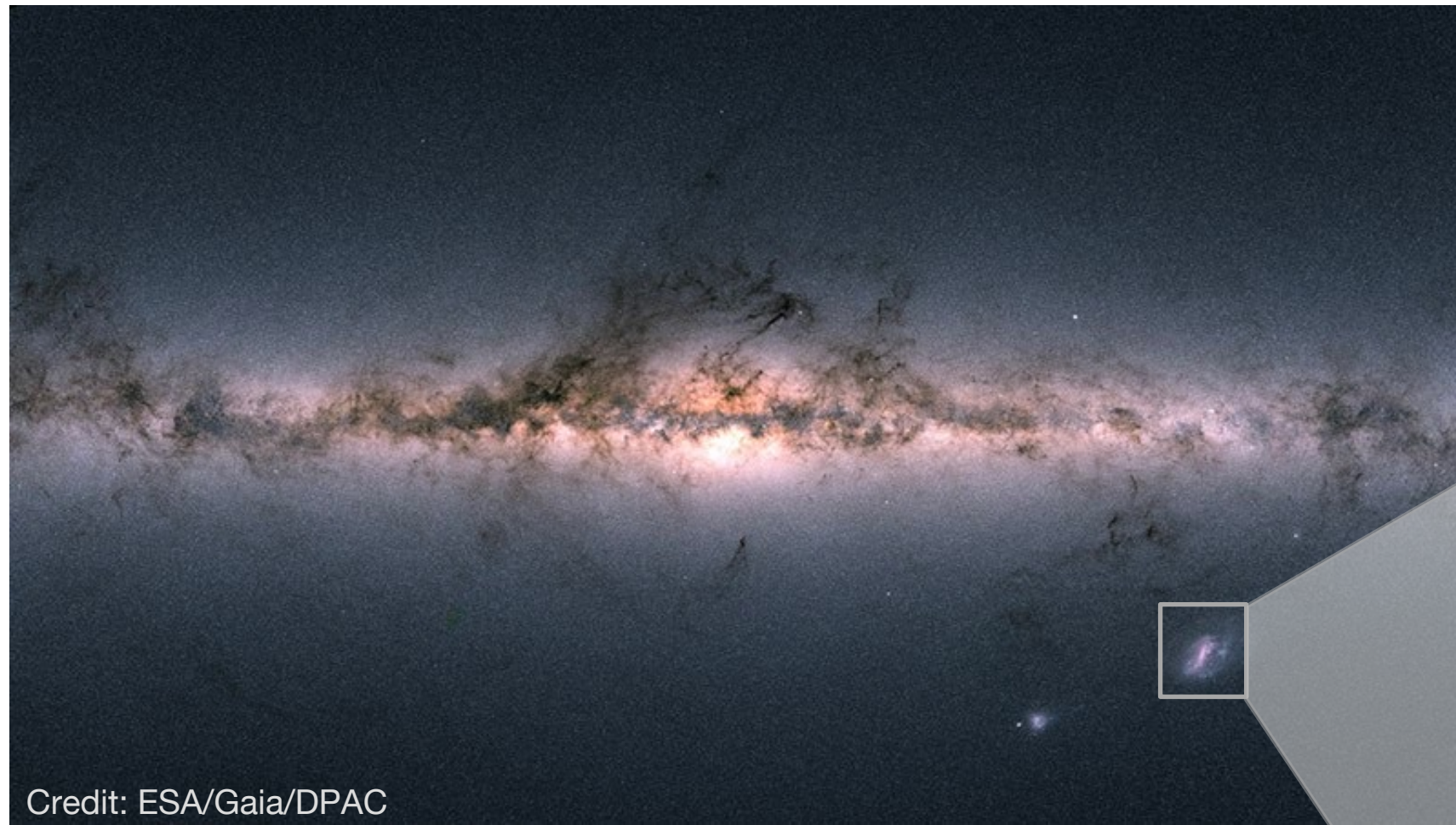
Milky Way Science Revolution with Dark Energy Survey



- New Ultra-Faint Milky Way Satellites
- New Stellar Streams
- Brown Dwarf Census
- RR Lyrae Variable Star Catalogue

Rossetto+11; Balbinot+15a,b; Bechtol+15; Drlica-Wagner+15a,15b,20; Simon+15,16,19; Luque+15,17a,17b; Li+15,17,18; Pieres+16,17,20; Albert+16; Hansen+17, 20; Nagasawa+17; Erkal+18; Shipp+18; Wang+18,19; Stringer+19,21; Marshall+19; Rosell+19; Martinez-Vazquez+19; Nadler+19,21; Dal Ponte+20; Cantu+21; Tanoglidis+21; Tavangar+22; Mau+22

How faint is “ultra-faint”?



Credit: ESA/Gaia/DPAC

Milky Way
 L_{MW}

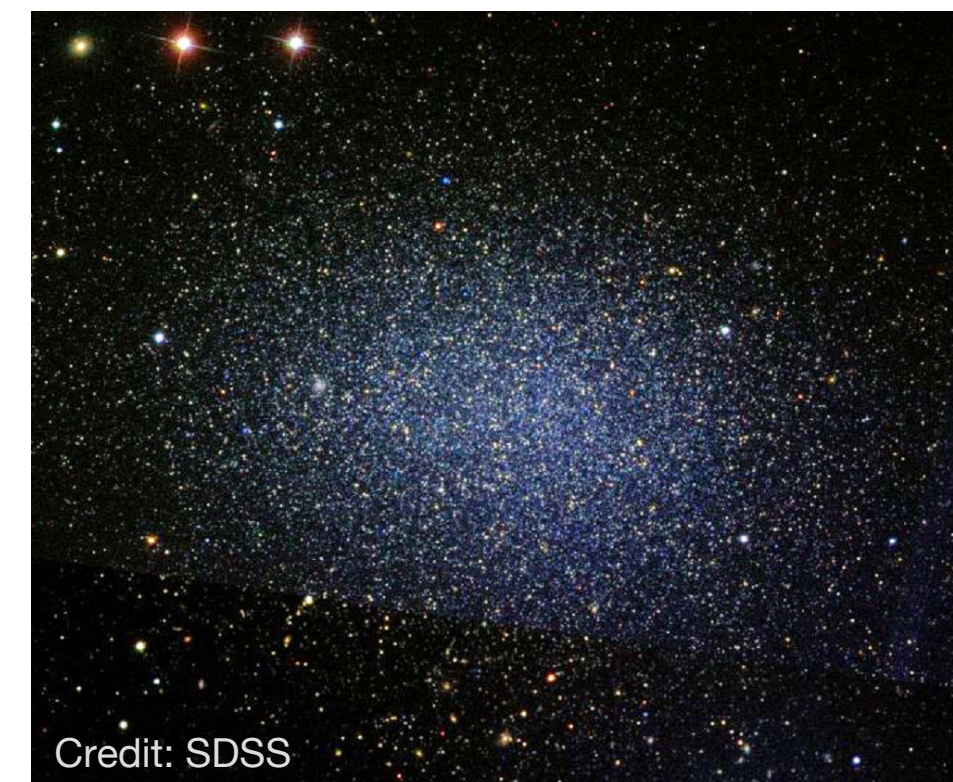
Large Magellanic Cloud
(LMC)



Credit: ESO/VISTA

$\sim 1/10 L_{MW}$
 $M_V = -18$

Leo I



Credit: SDSS

$\sim 1/10,000 L_{MW}$
 $M_V = -12$

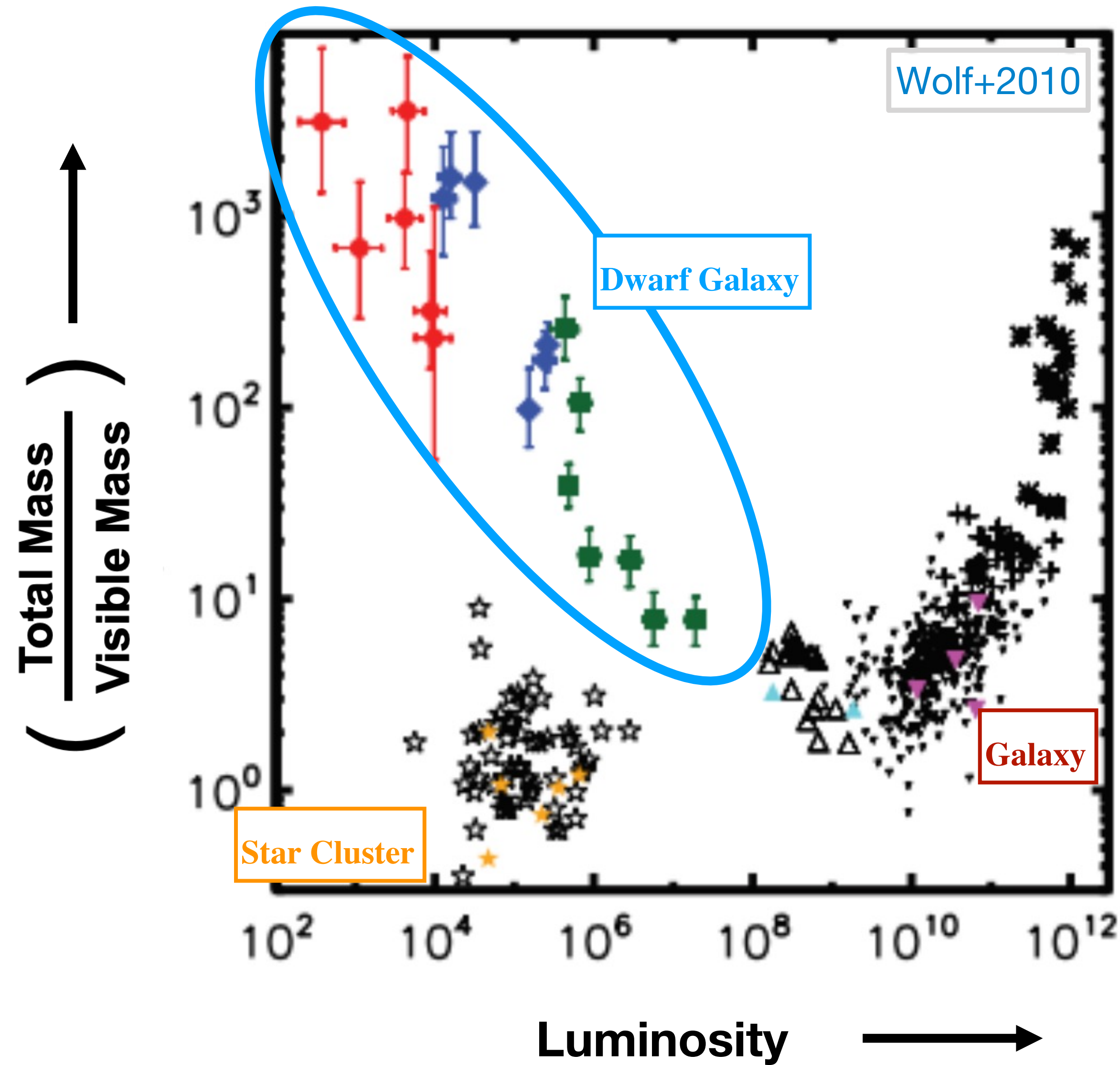
Eridanus II



Credit: Belokurov+Köposov

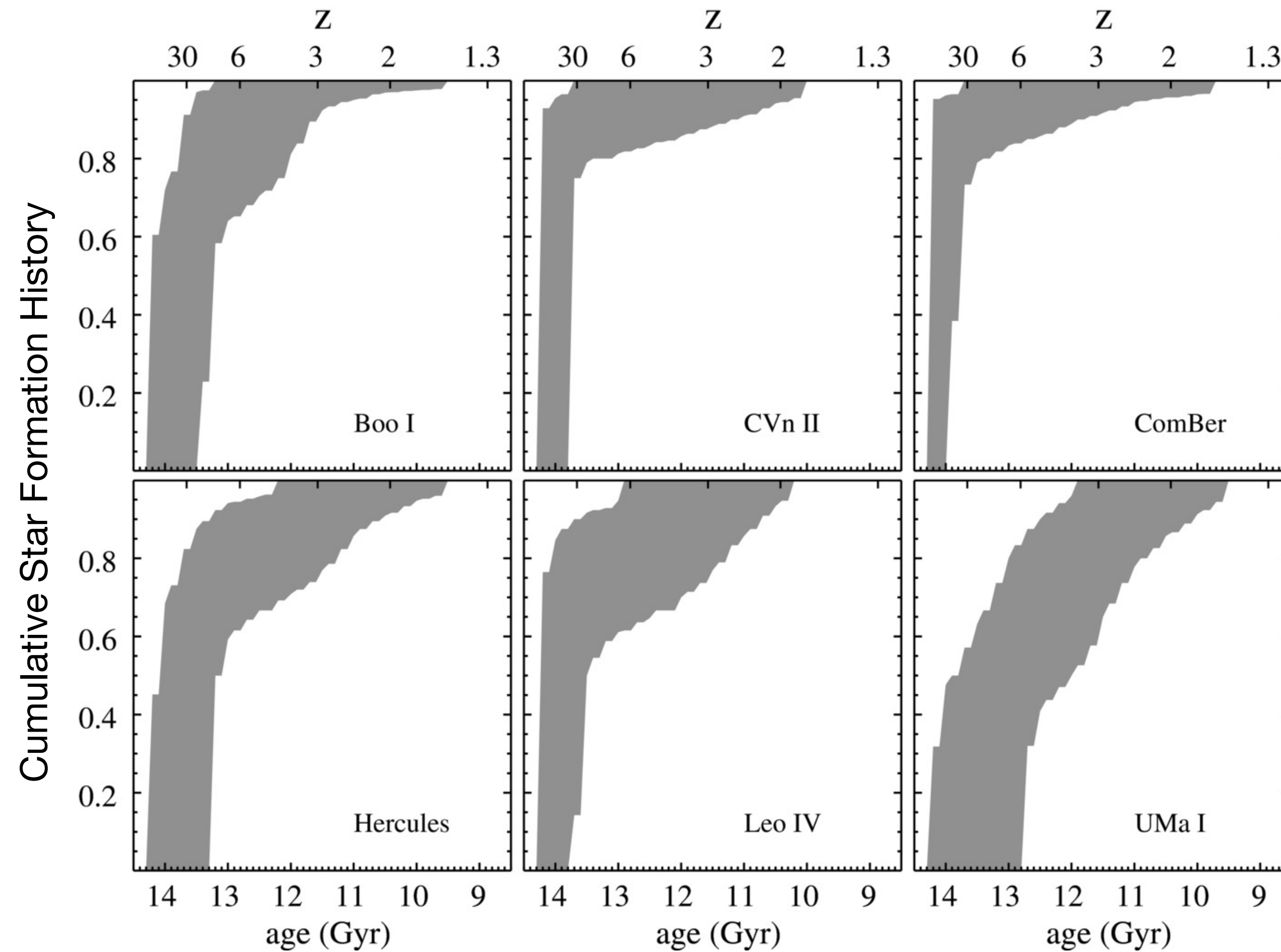
$\sim 1/1,000,000 L_{MW}$
 $M_V = -7$

The Most Dark Matter Dominated Systems



The Oldest Stellar Systems

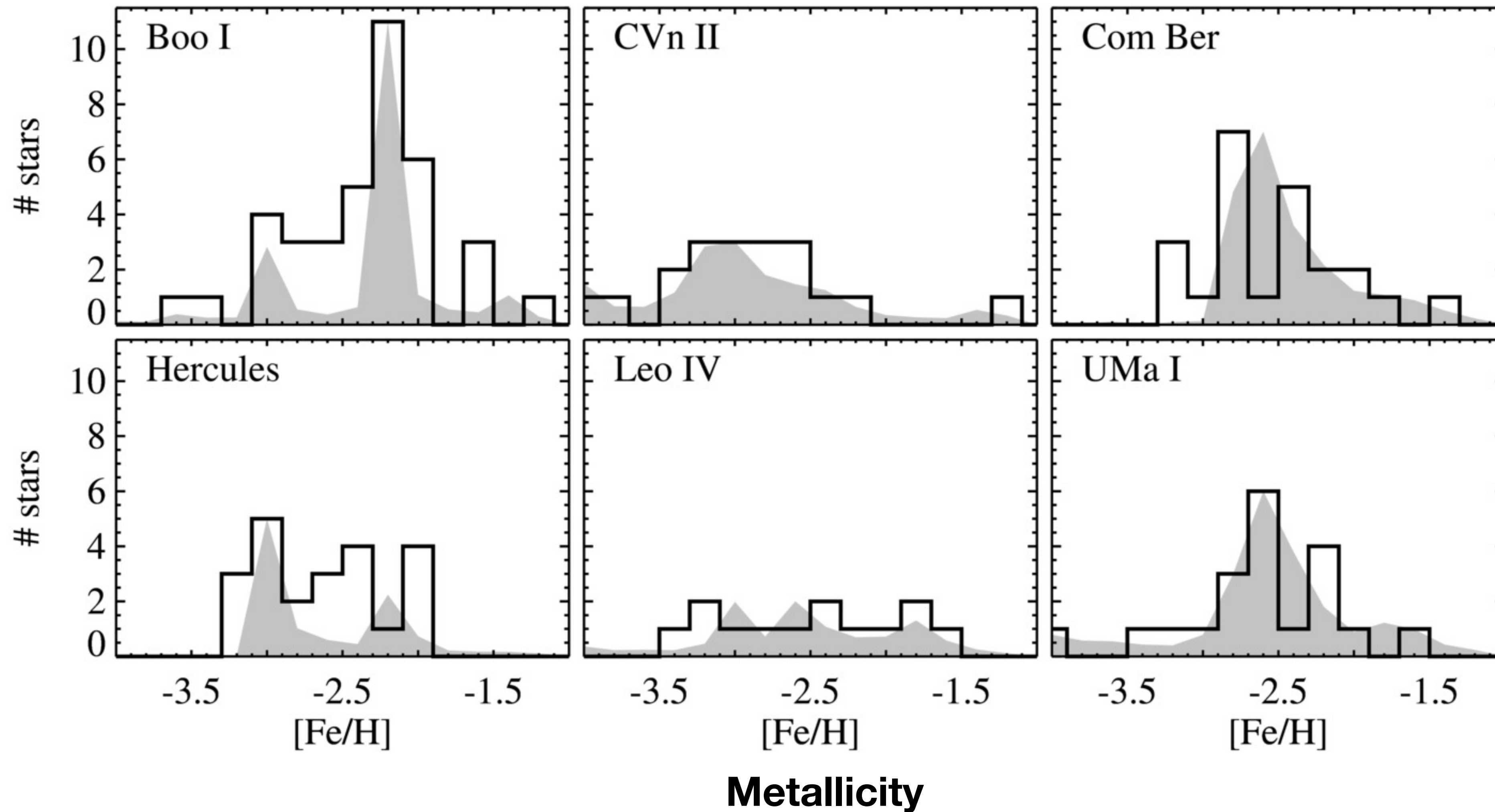
~80% of the stars formed by 12.8 Gyr ago



Are they quenched by reionization?

Brown et al 2014

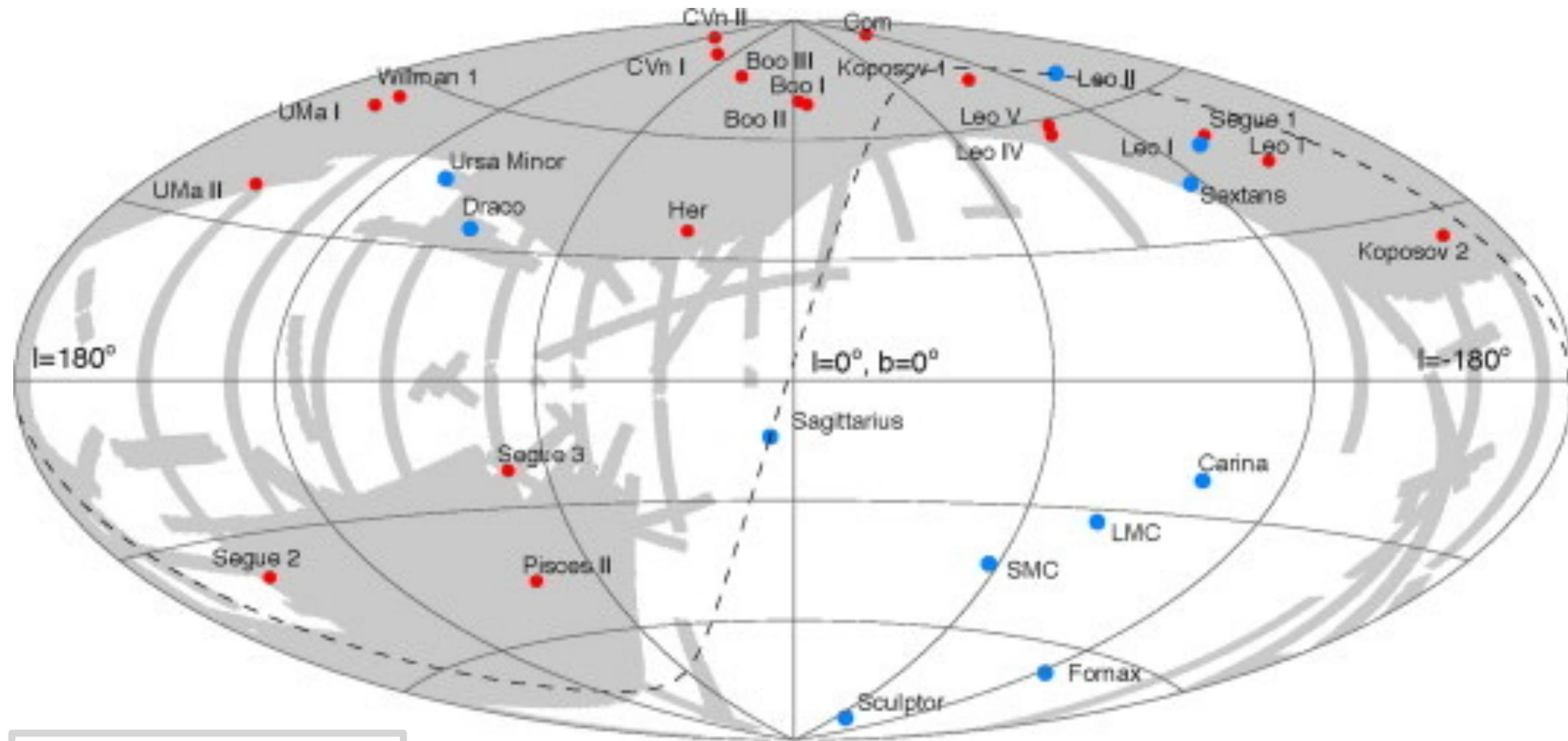
The Most Metal-Poor Stellar Systems



Brown et al 2014

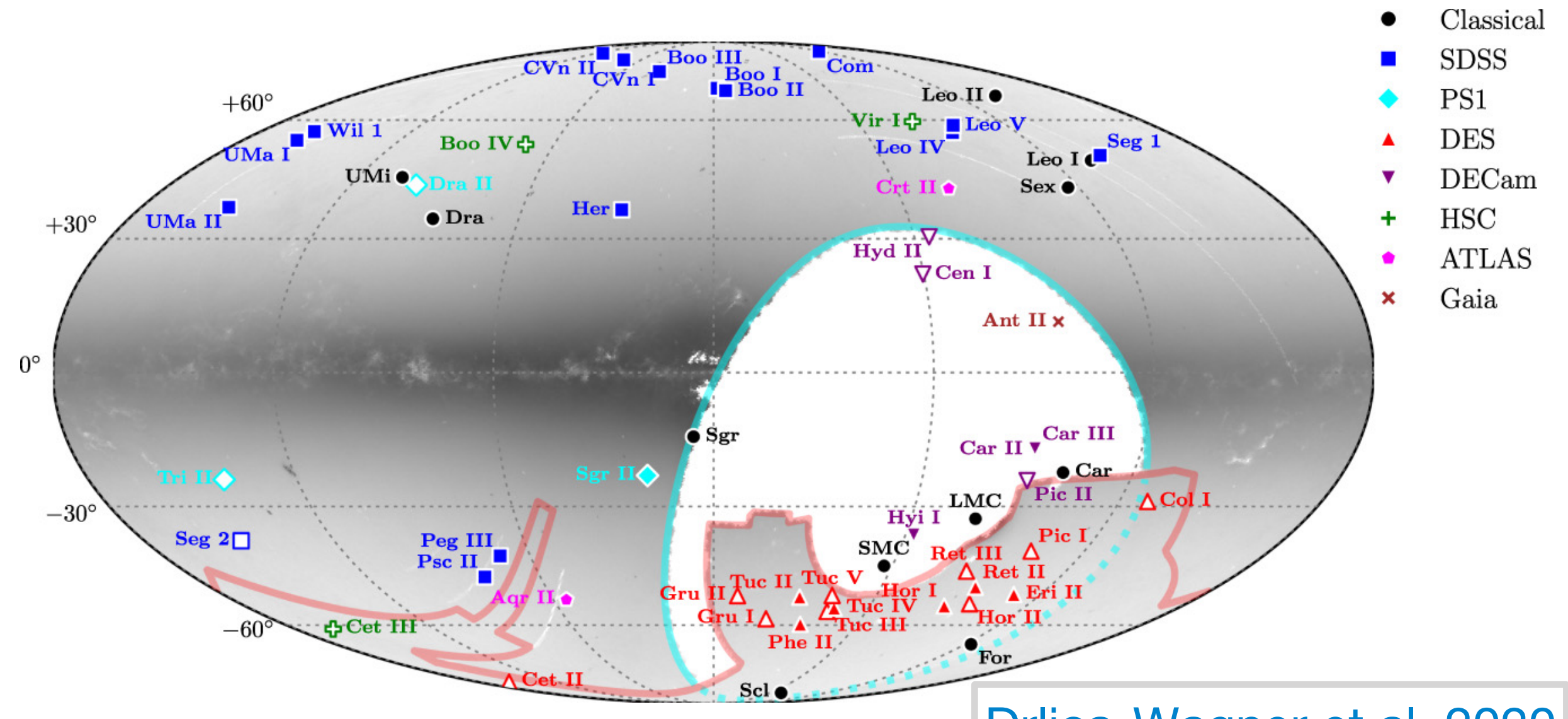
Era of Digital Surveys

Before DES



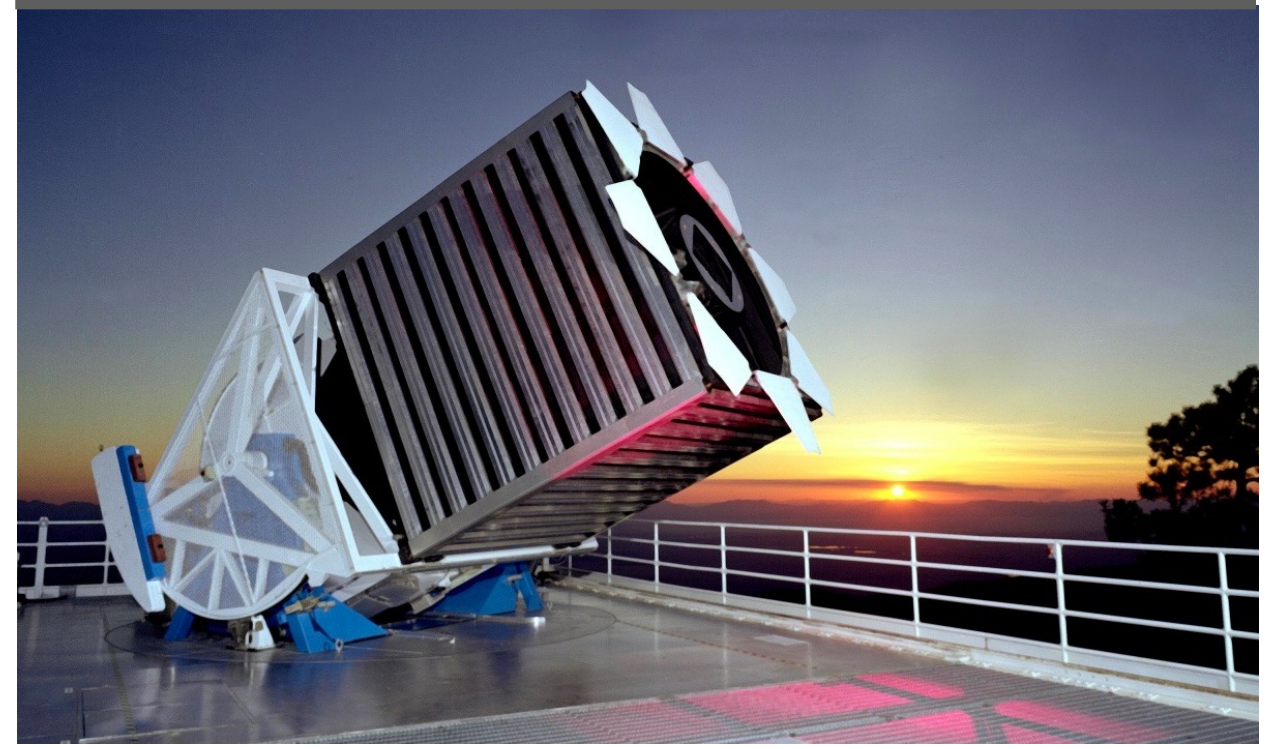
Belokurov 2013

After DES

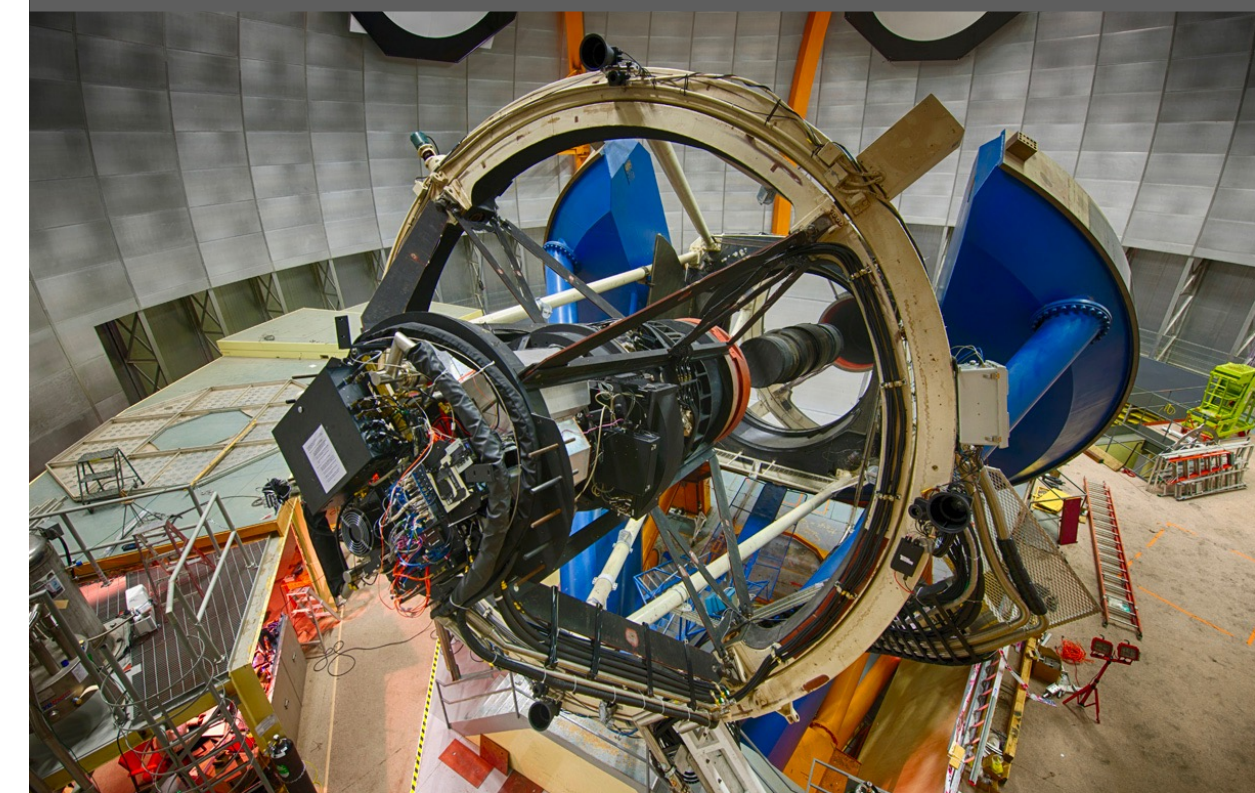


Drlica-Wagner et al. 2020
(DES Collaboration)

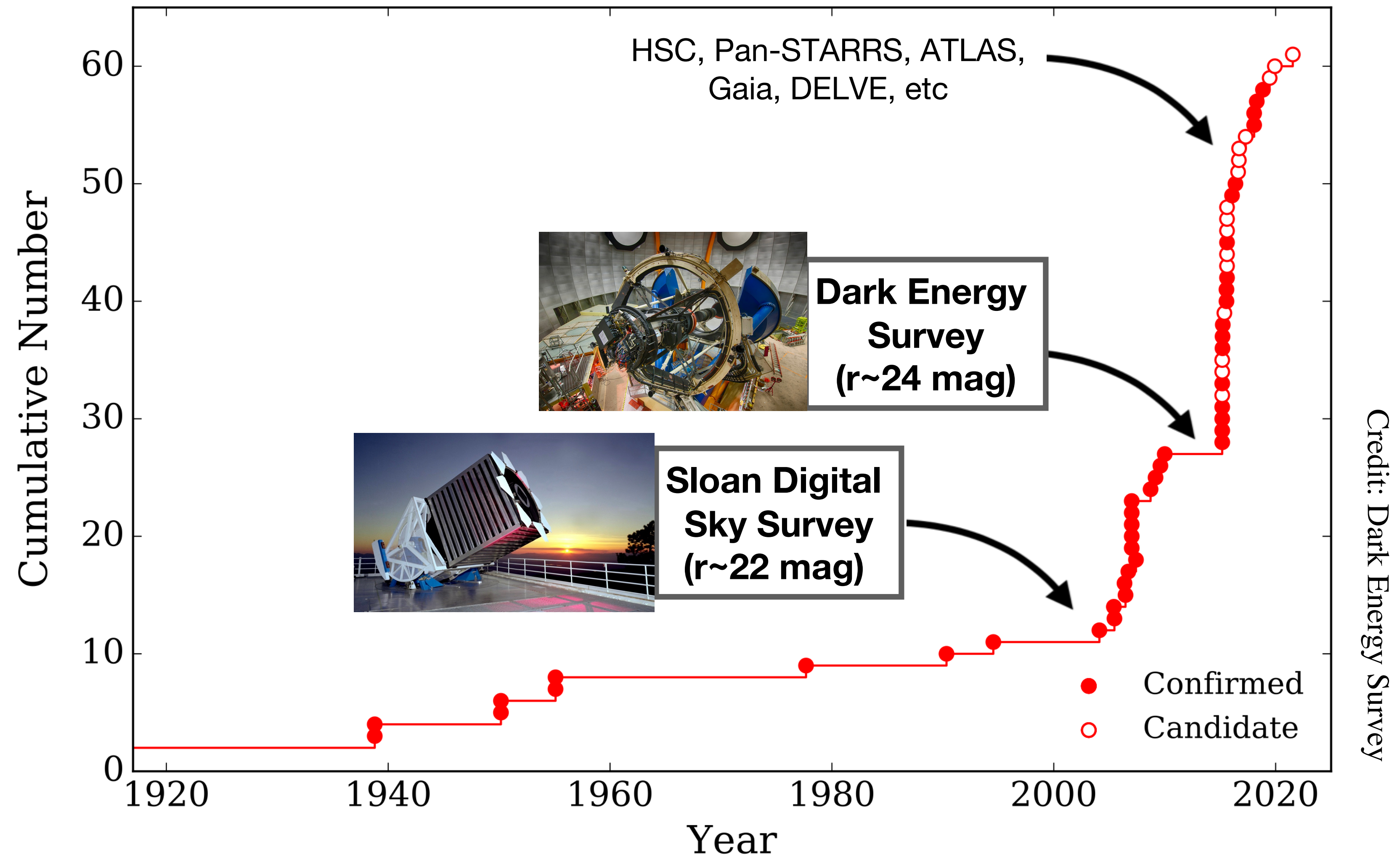
**Sloan Digital Sky Survey
($r \sim 22$ mag)**



**Dark Energy Survey
($r \sim 24$ mag)**



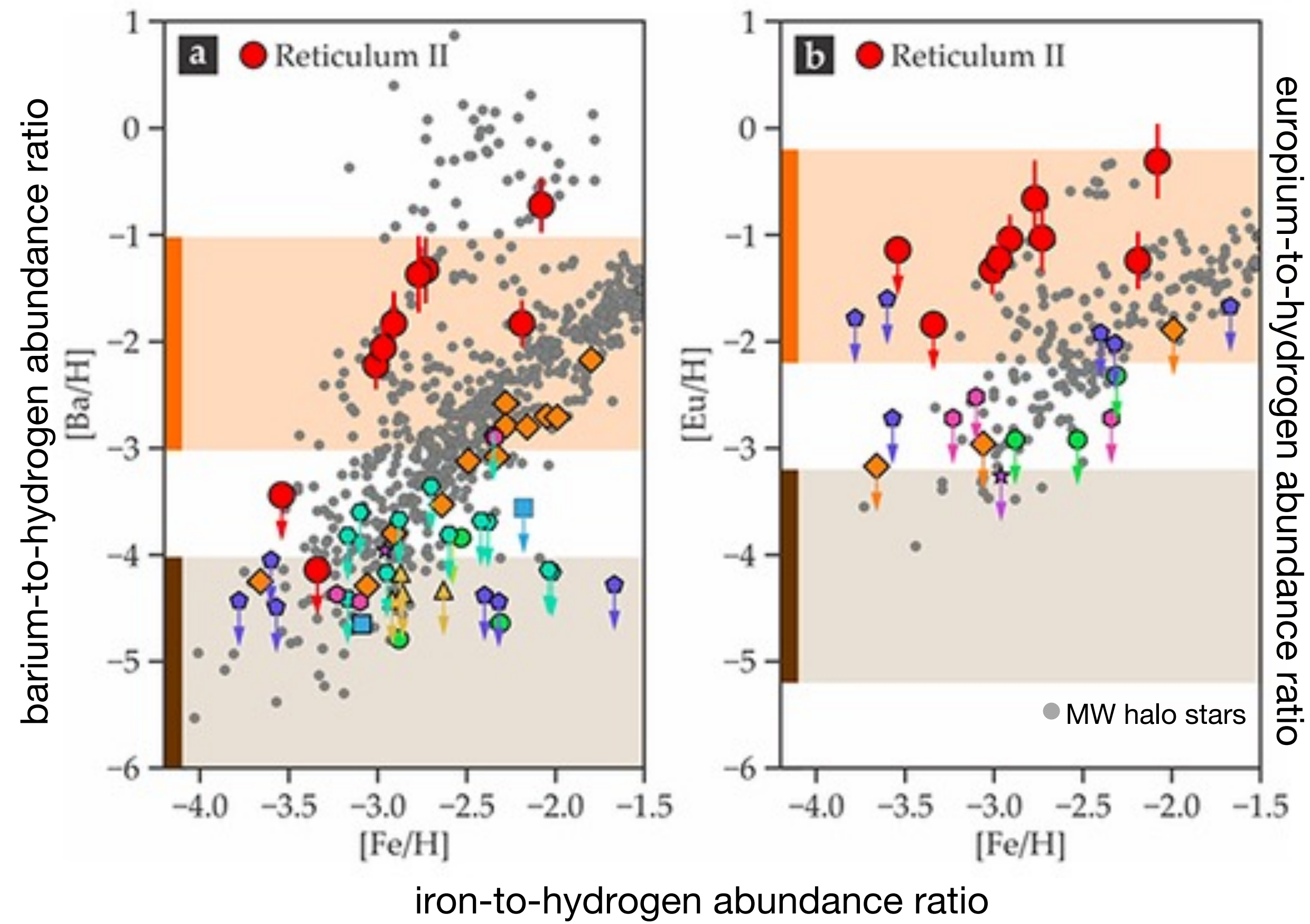
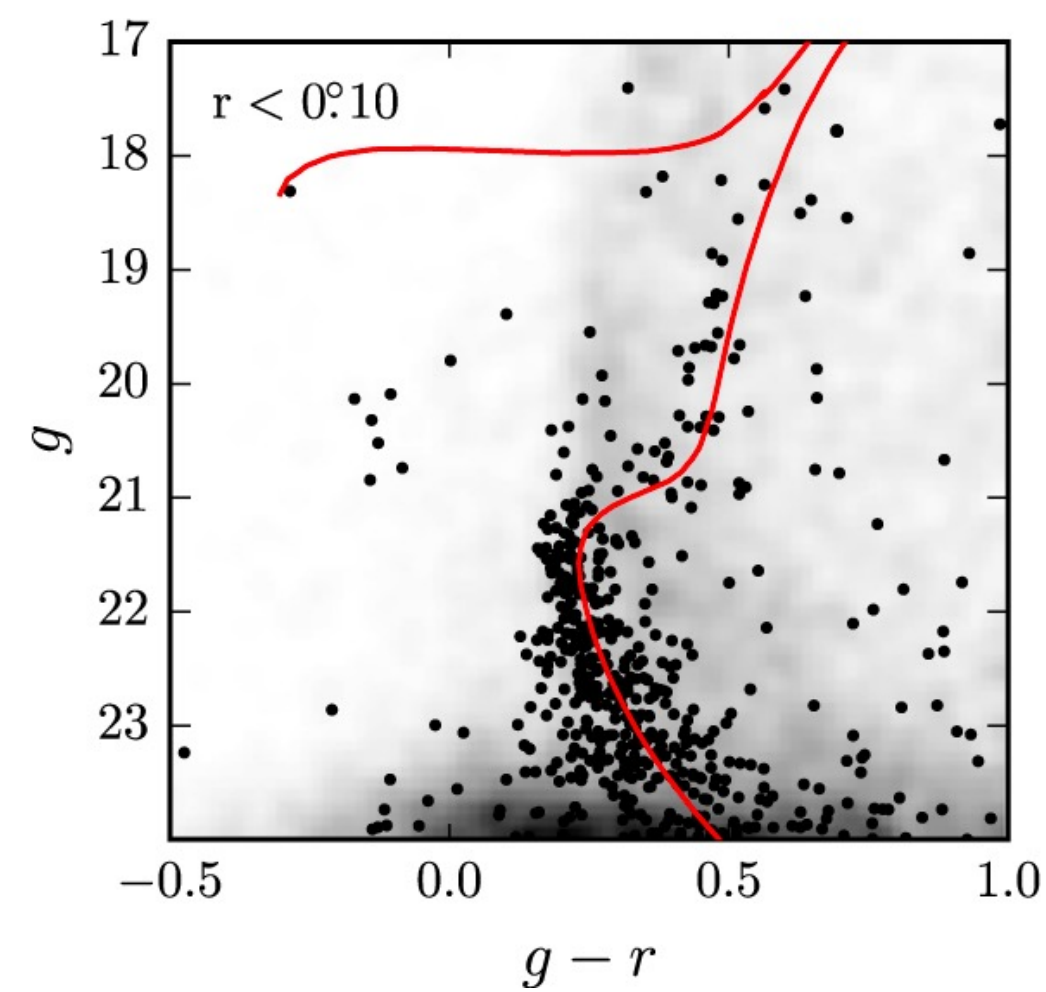
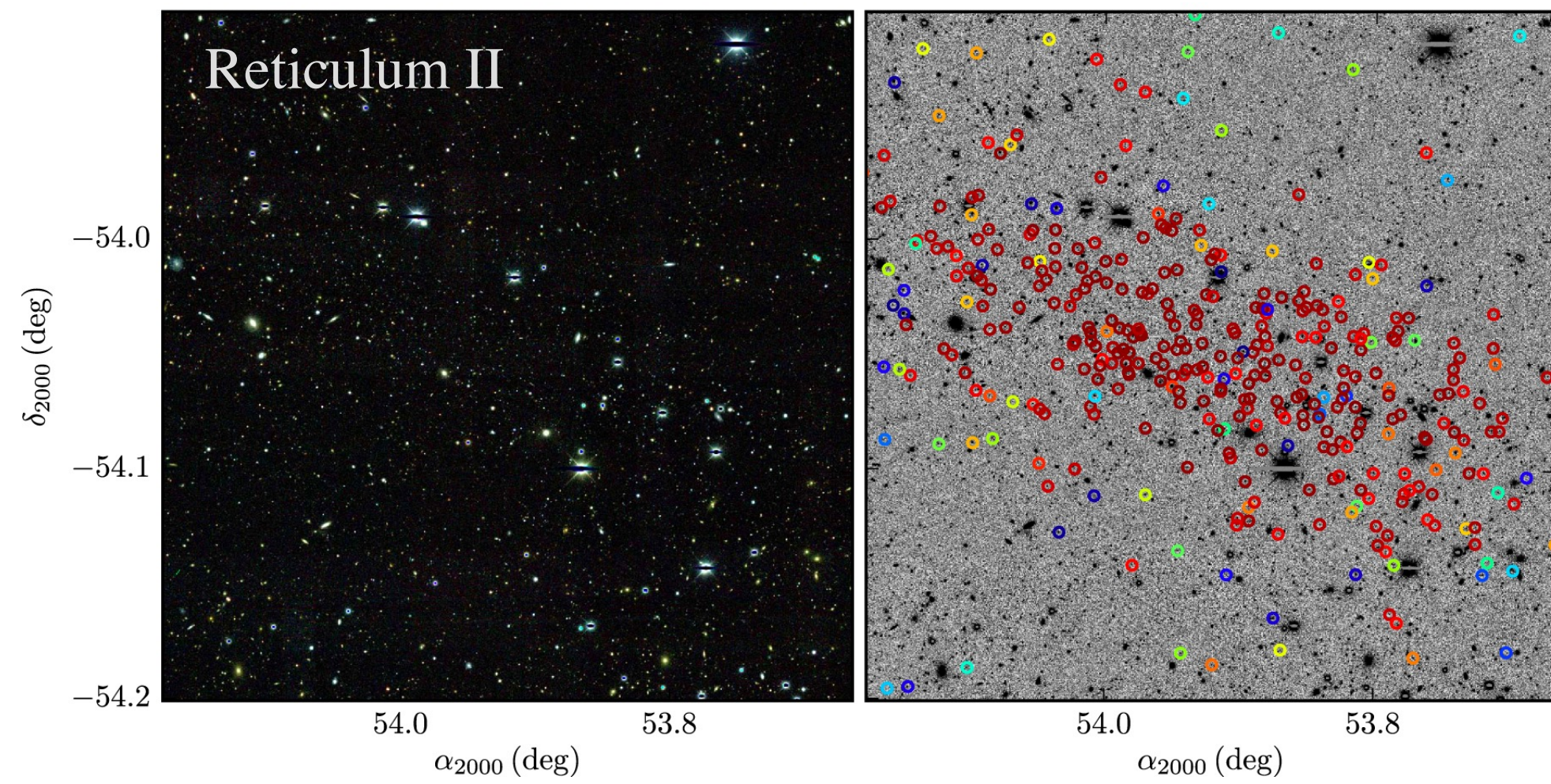
Growing Sample of Milky Way Satellites



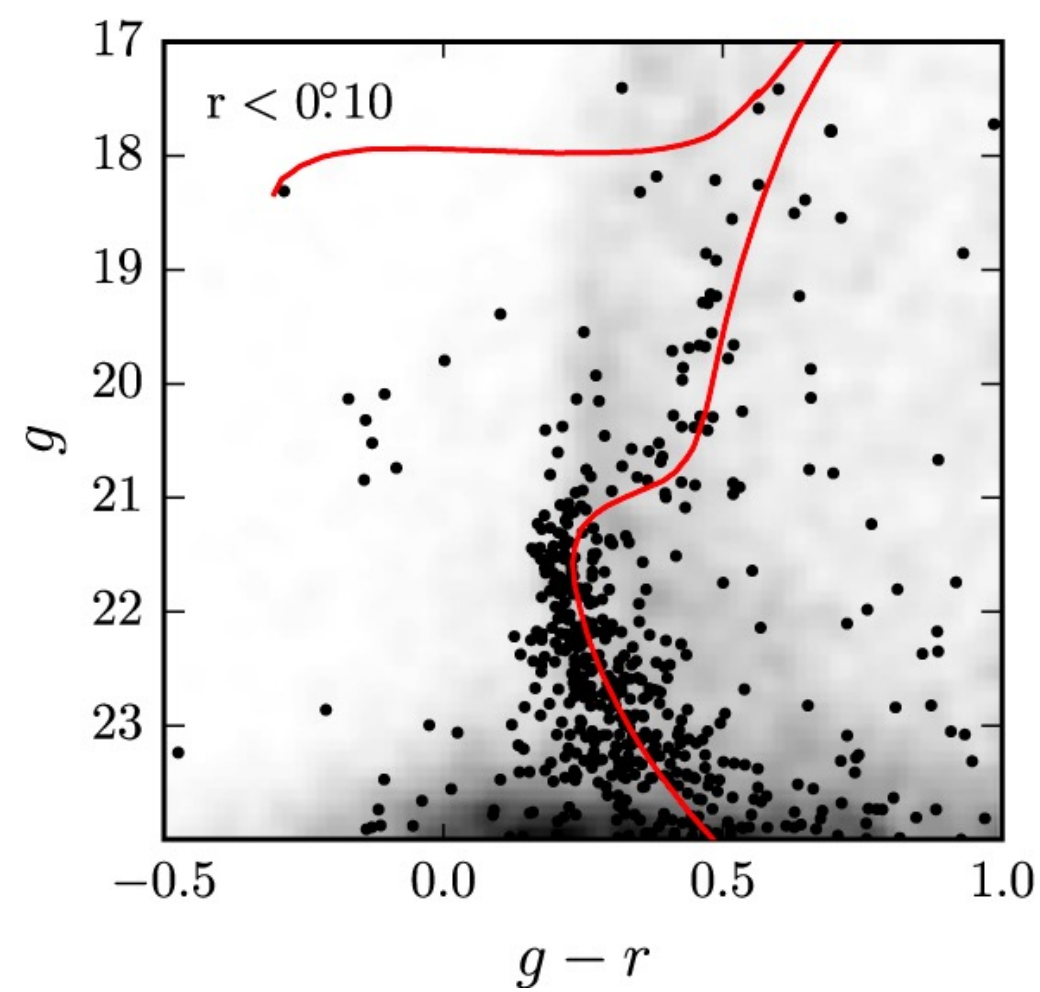
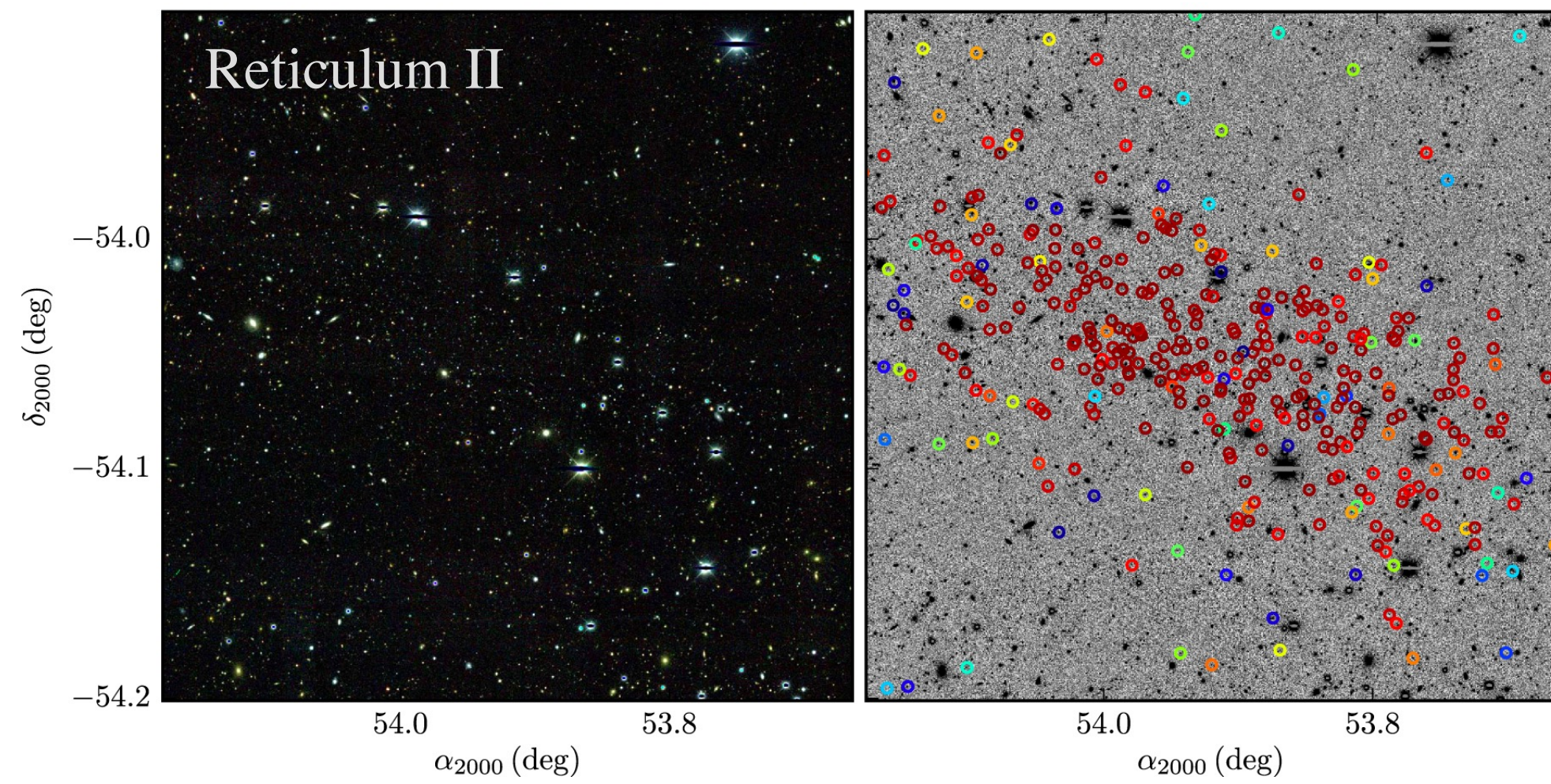
Credit: Dark Energy Survey

Discovery Timeline

Reticulum II: First R-process Enhanced Ultra-Faint Dwarf

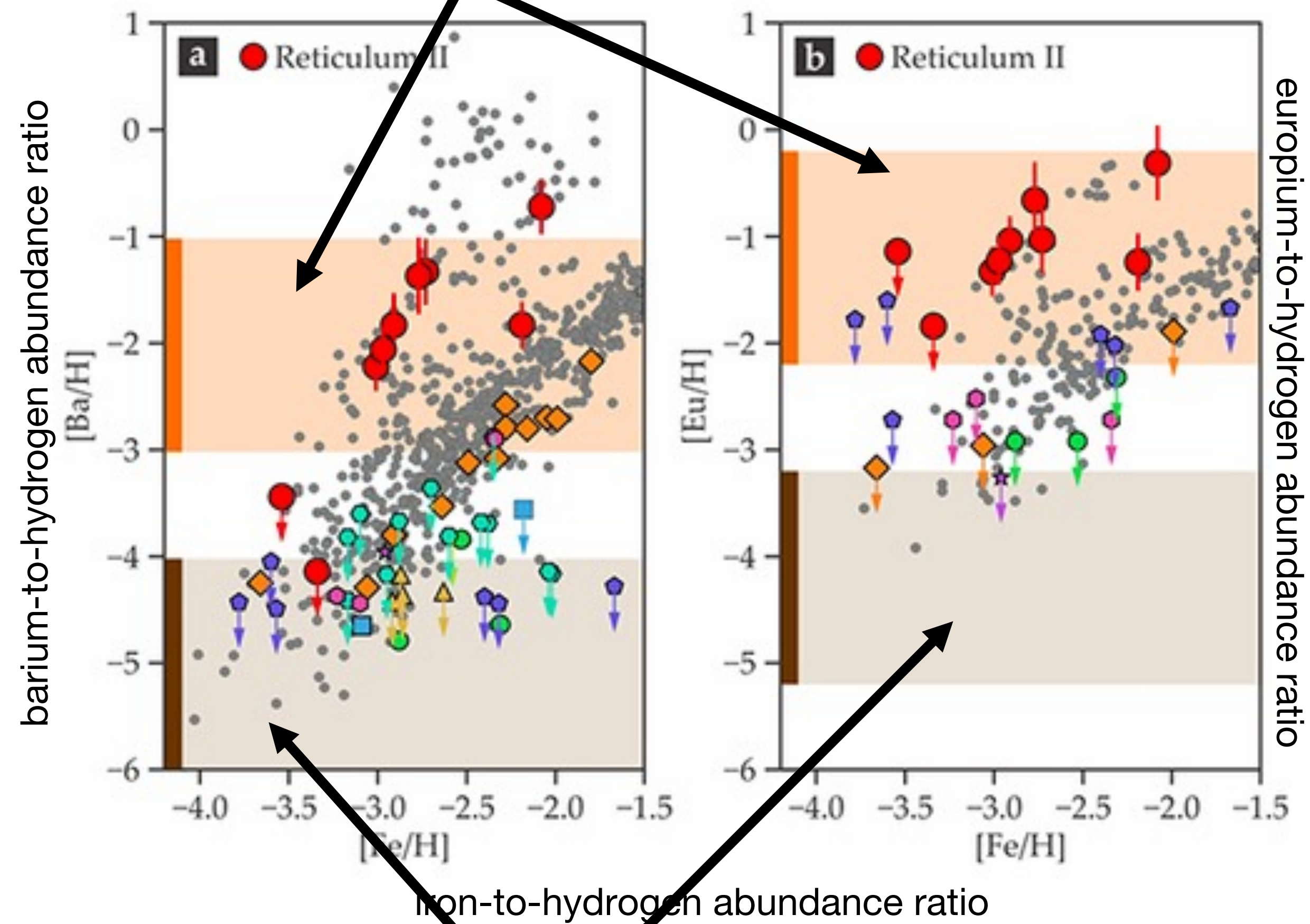


Reticulum II: First R-process Enhanced Ultra-Faint Dwarf



Bechtol et al. 2015 (DES Collaboration)

Neutron-Star Merger



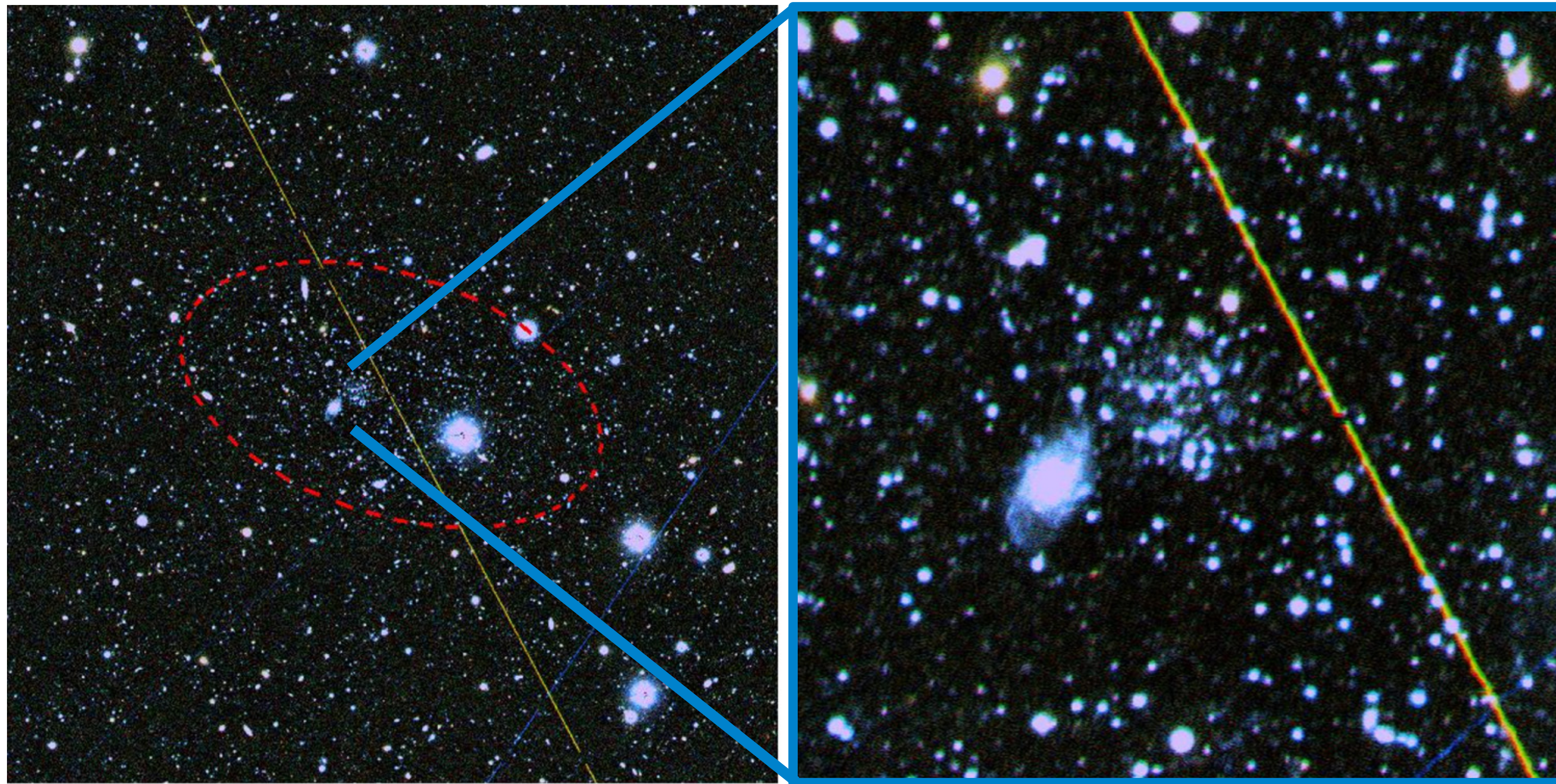
Supernova

Ji et al. 2016, 2022

Eridanus II: First Ultra-Faint Galaxy with a Star Cluster

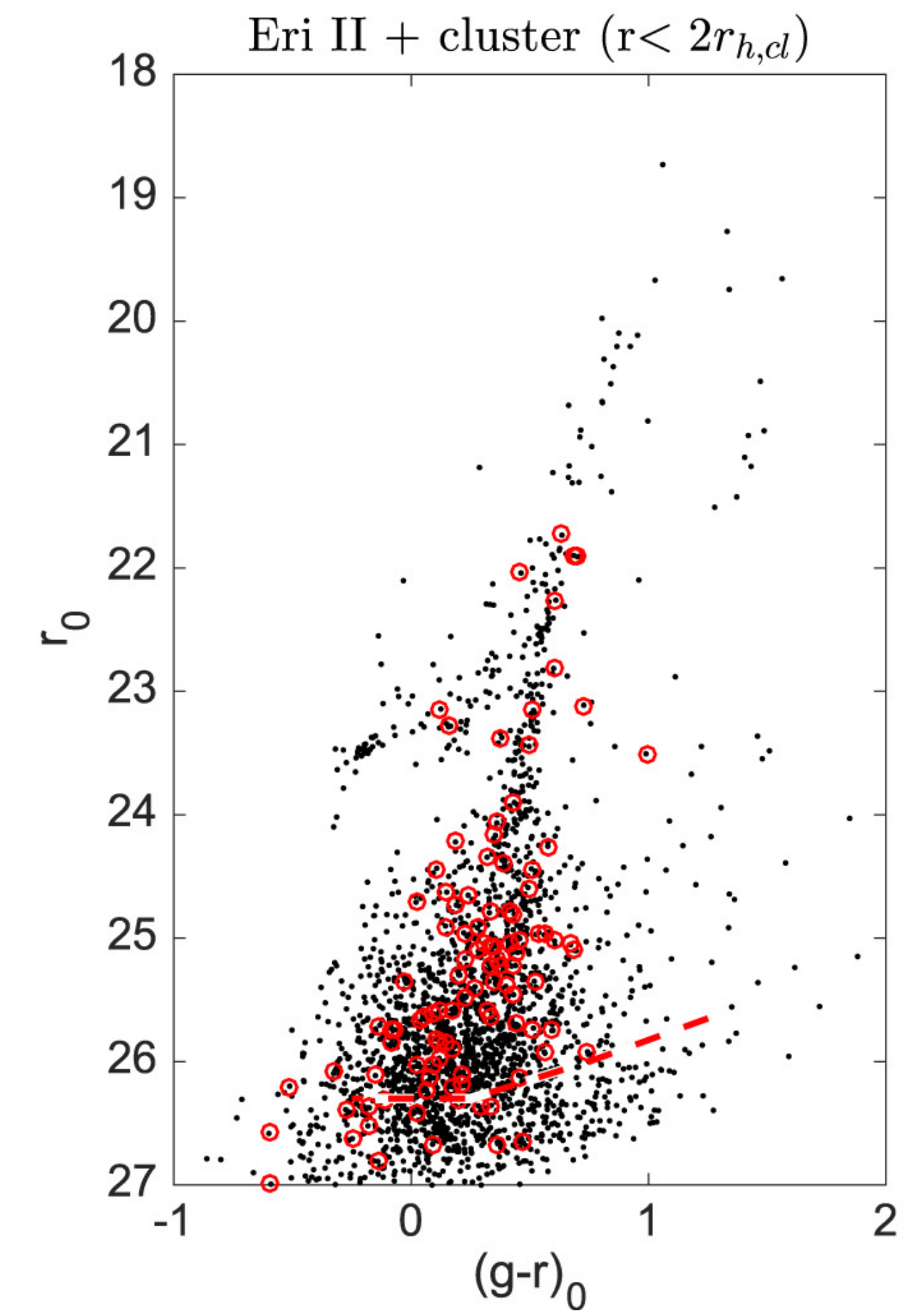
Eridanus II has a central star cluster!!!

Magellan+Megacam Deep Imaging



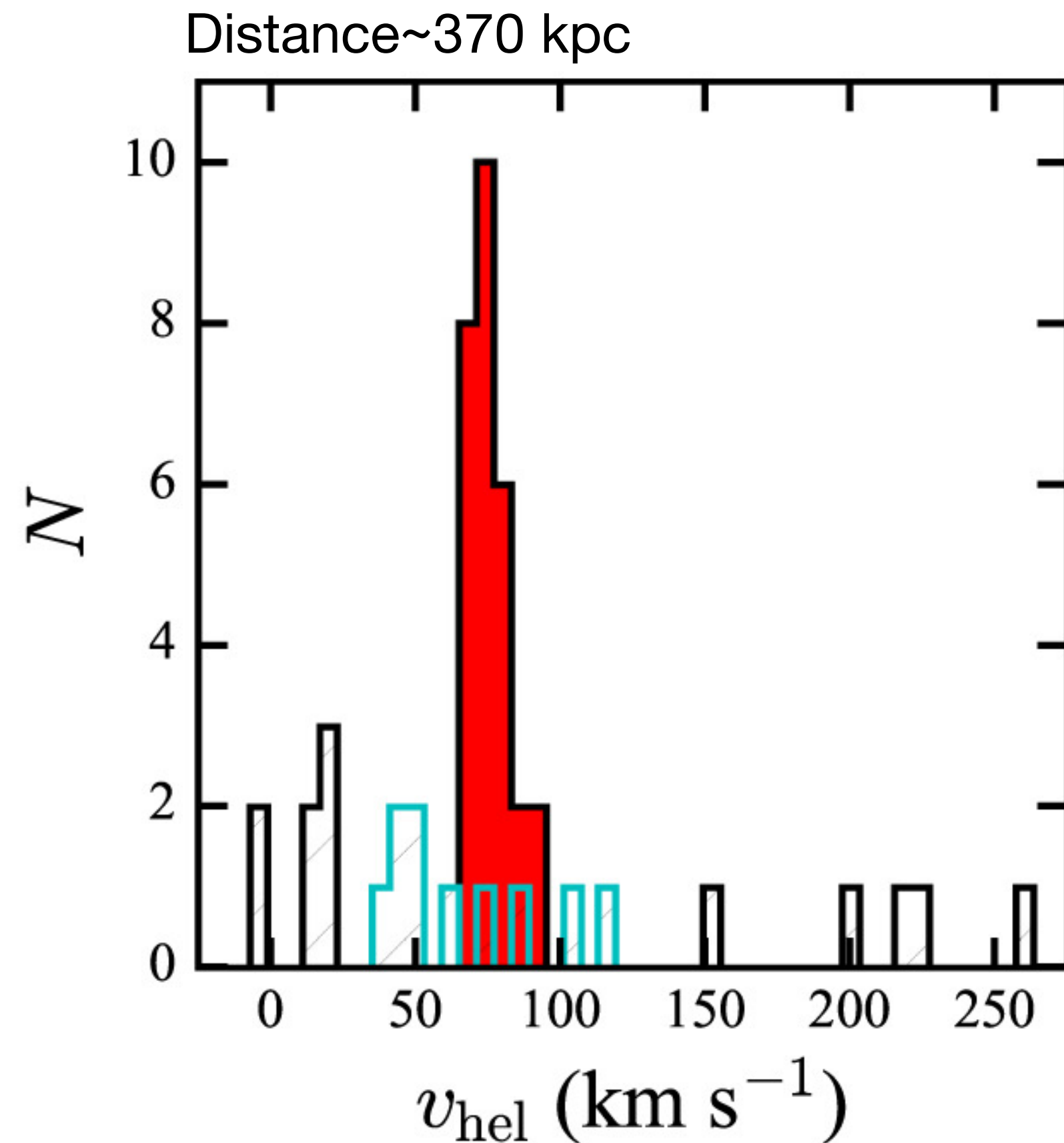
Eridanus II
($D \sim 370$ kpc)

its star cluster

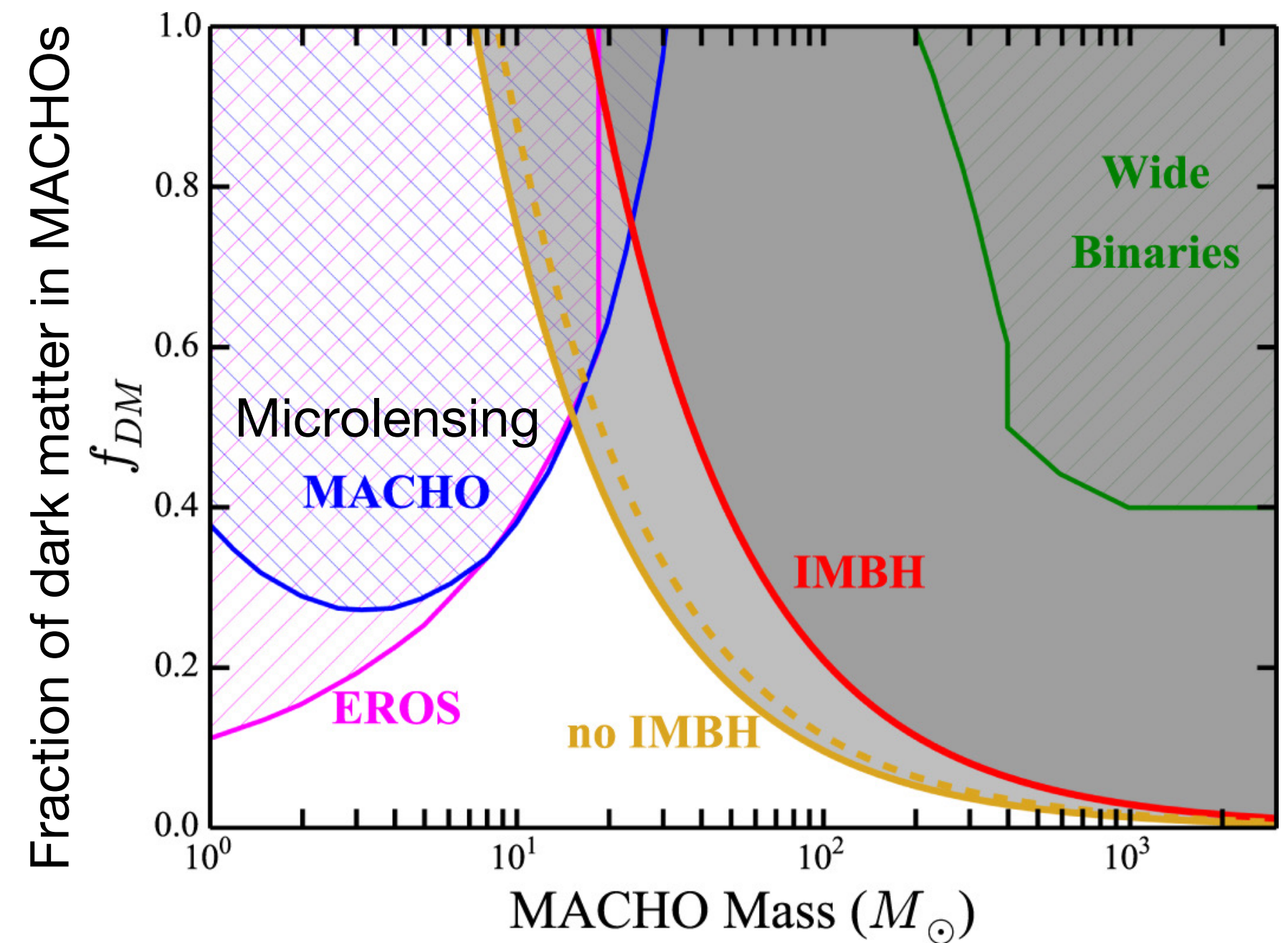


Eridanus II: First Ultra-Faint Galaxy with a Star Cluster

Eridanus II has a central star cluster!!!



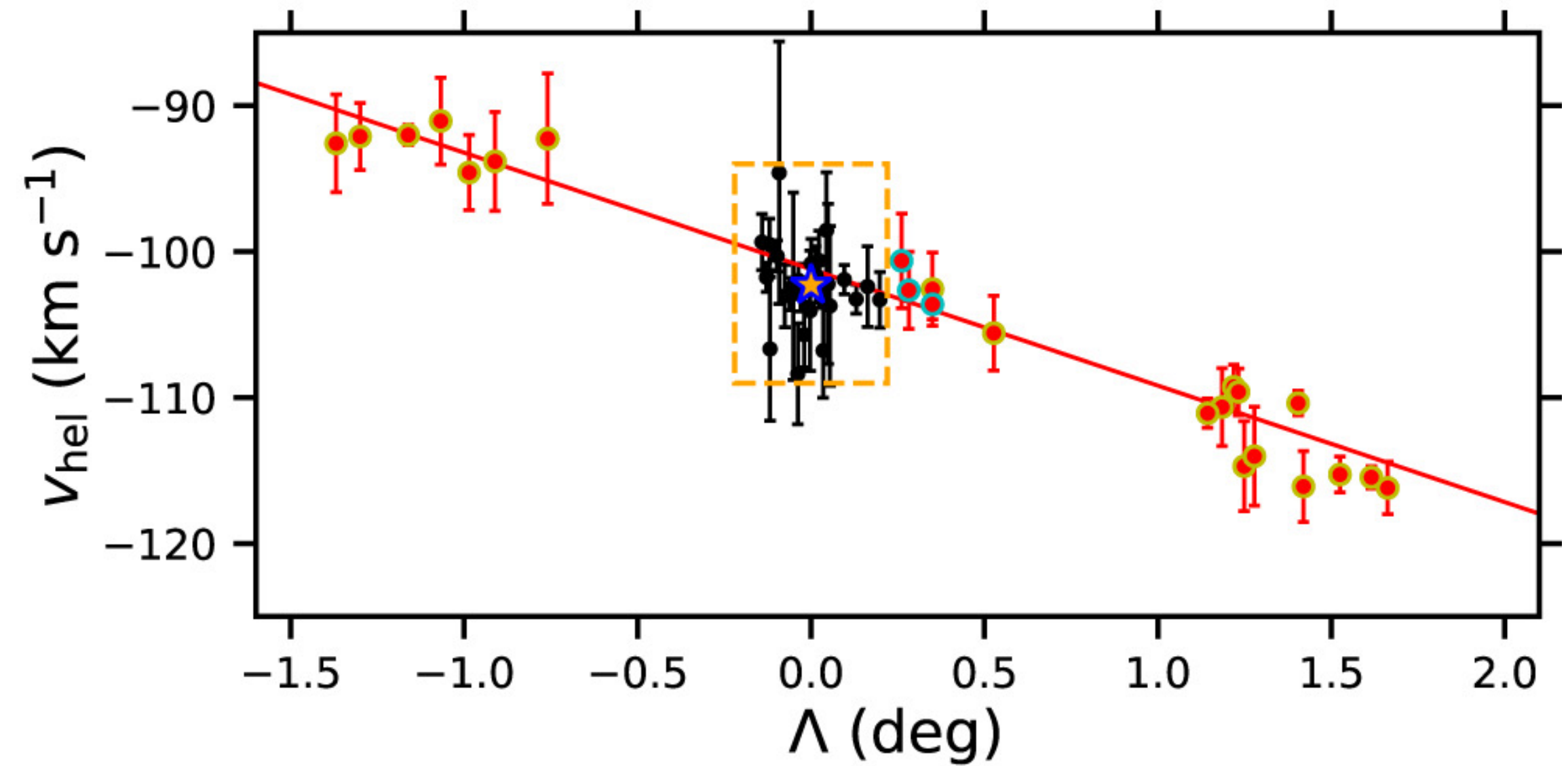
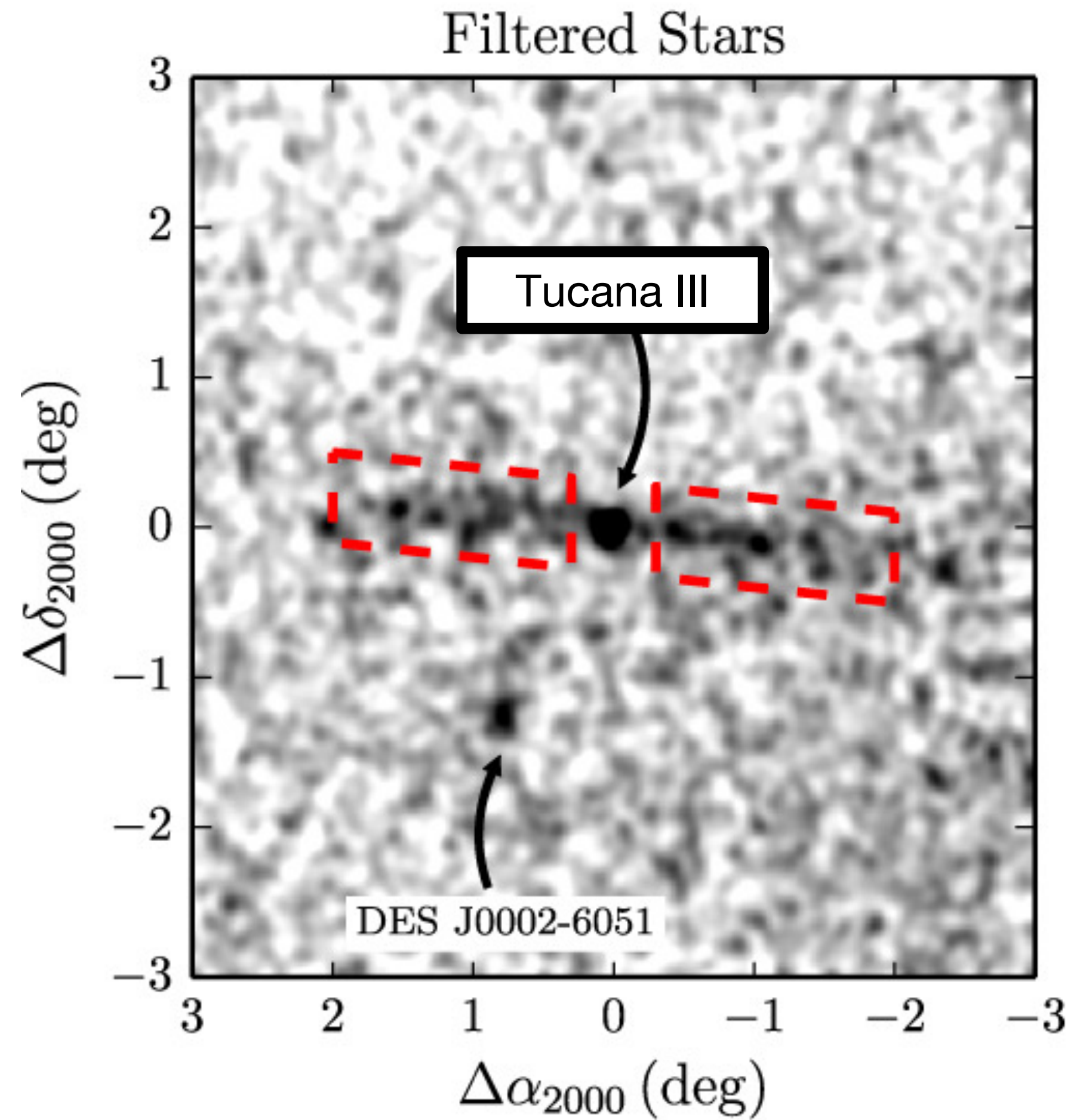
velocity dispersion~7 km/s
dark-matter dominated galaxy!



Rule out massive compact halo object (MACHO) as the dominated dark matter at 10-100 solar masses

Li et al. 2017 (DES Collaboration)
(also see Brandt et al. 2017)

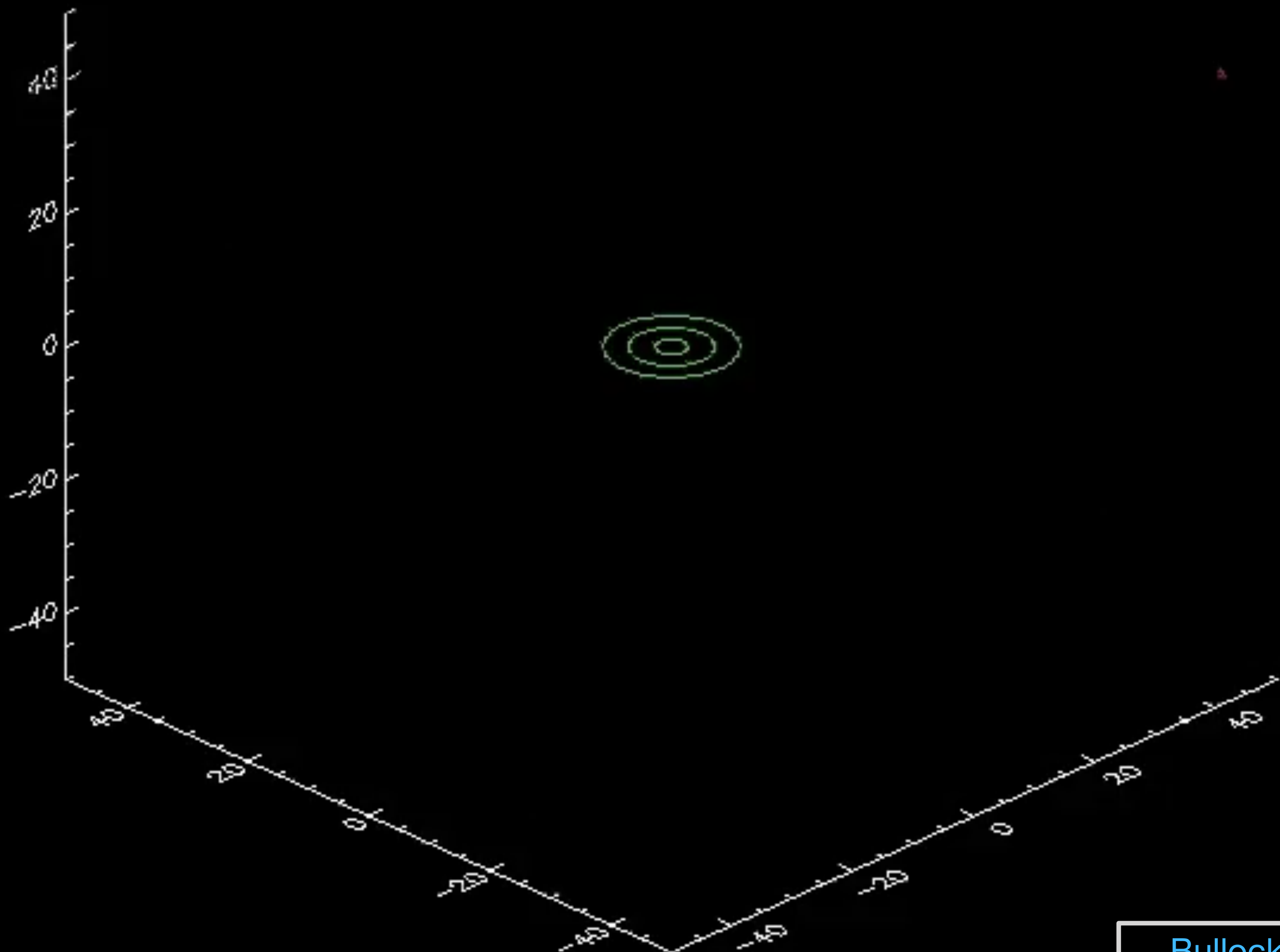
Tucana III: First Tidally Disrupted Ultra-Faint Galaxy?



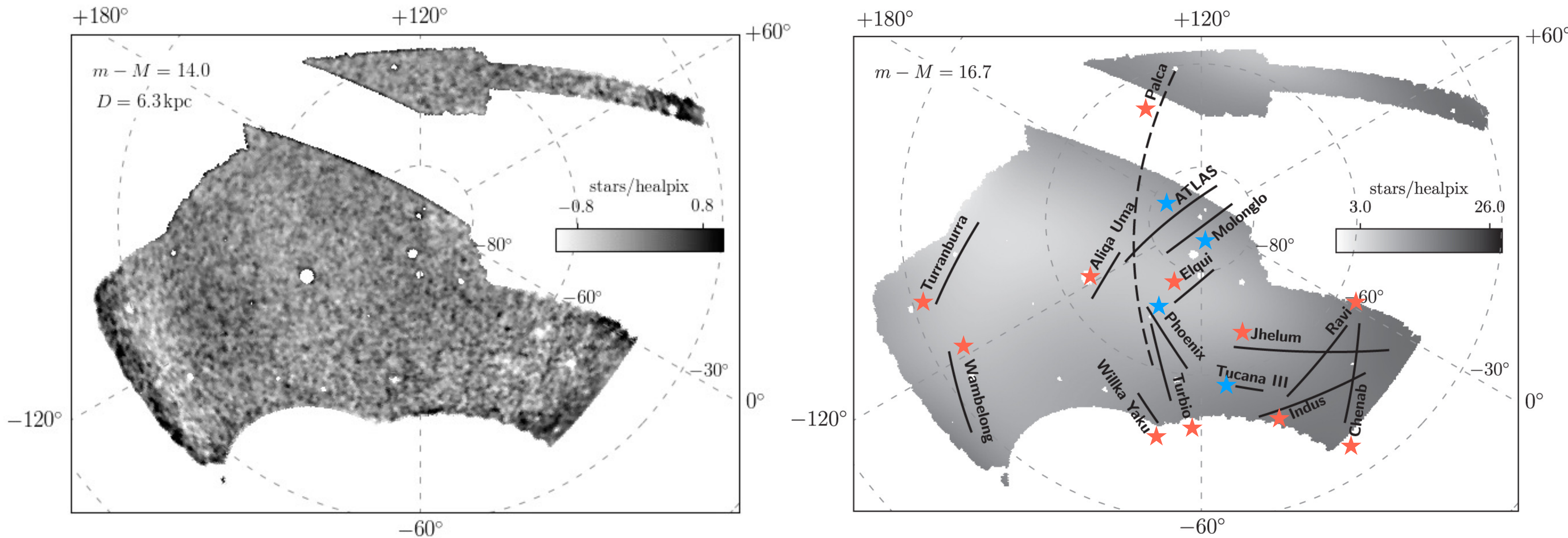
Velocity gradient across Tucana III

Drlica-Wagner et al. 2015 (DES Collaboration)

Simon et al. 2017; Li et al 2018
(DES Collaboration)



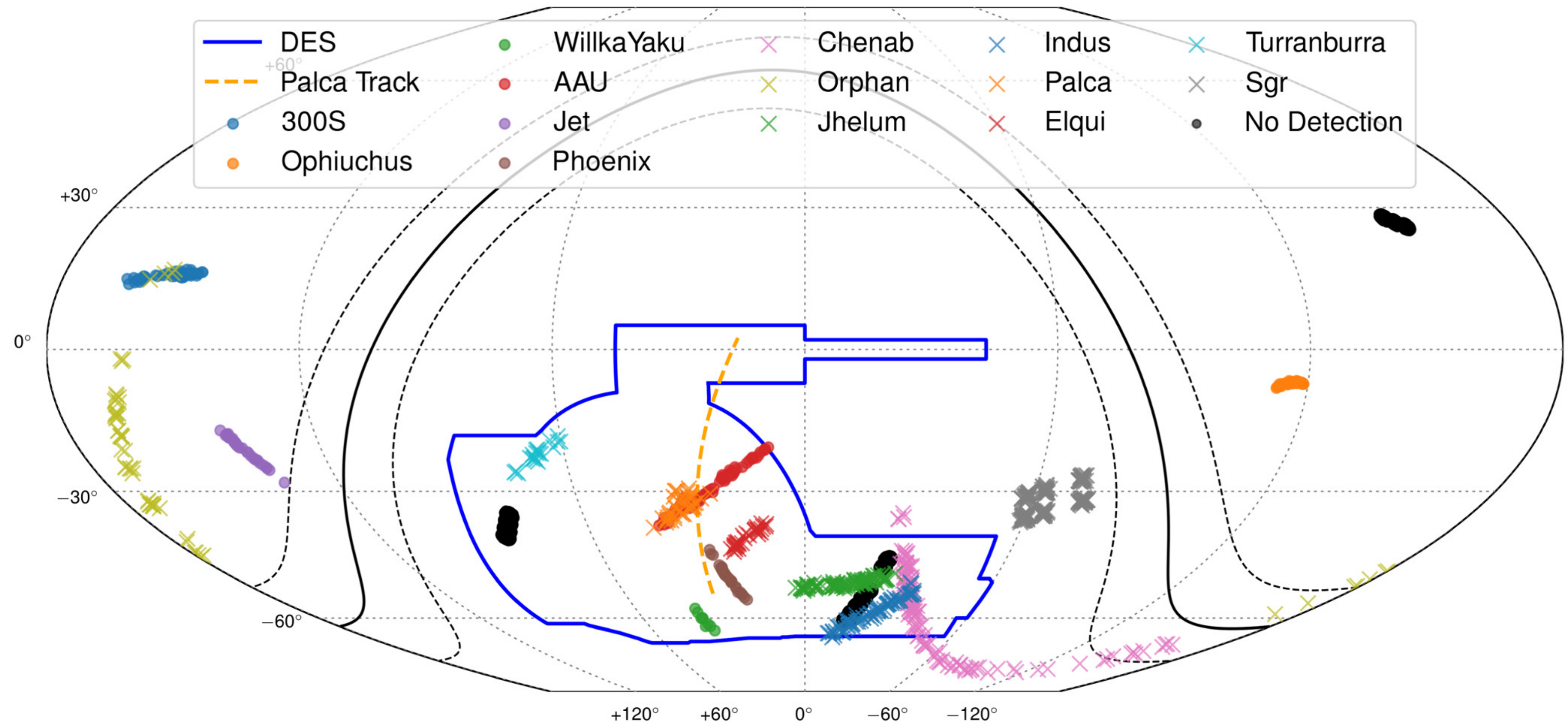
11 New Stellar Streams Discovered in DES



Shipp et al 2018
(DES Collaboration)

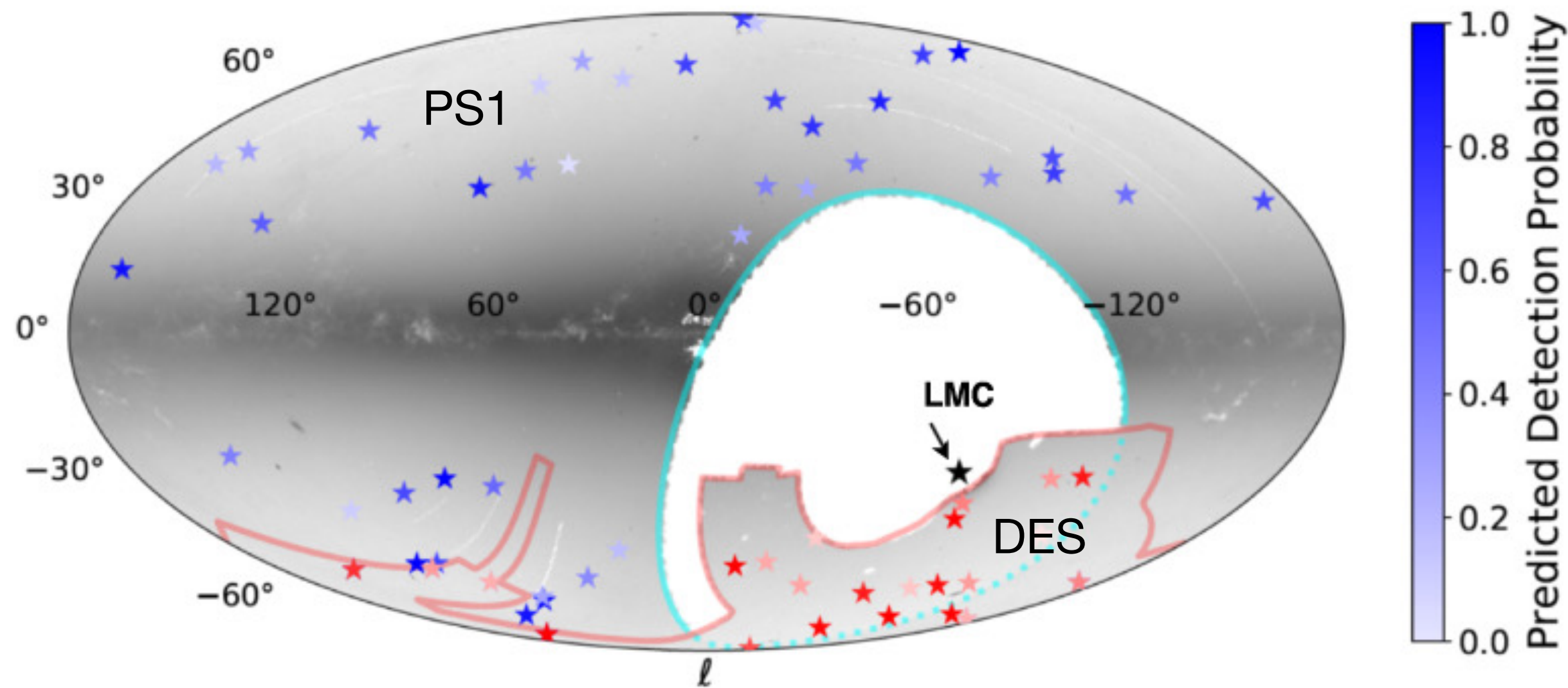
The Southern Stellar Stream Spectroscopic Survey (S⁵)

The largest homogeneously analyzed set of streams with full 6D kinematics and metallicities

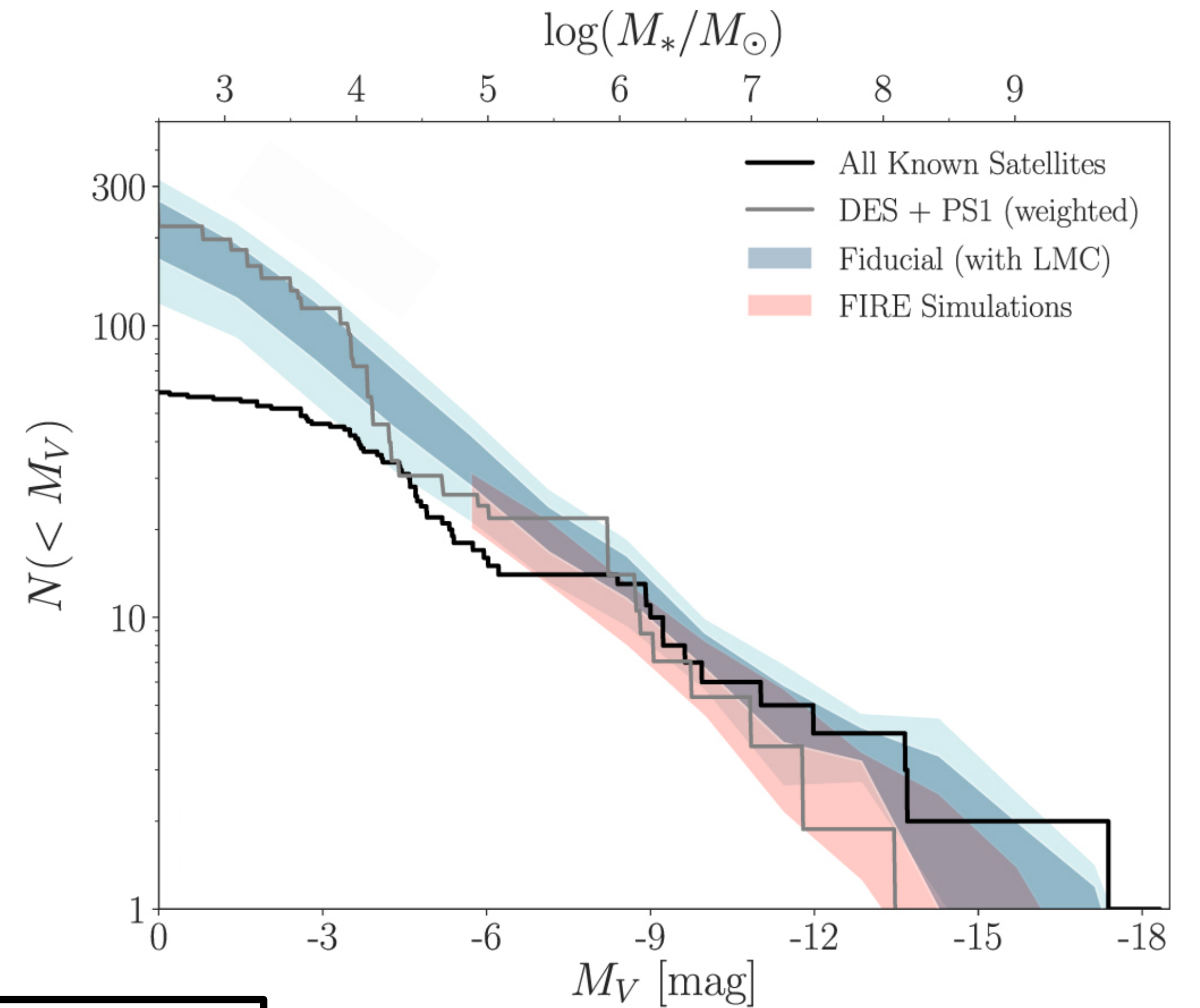


The Total Milky Way Satellite Population

The detectability of Milky Way satellites as a function of their distance, size, luminosity, and location on the sky.



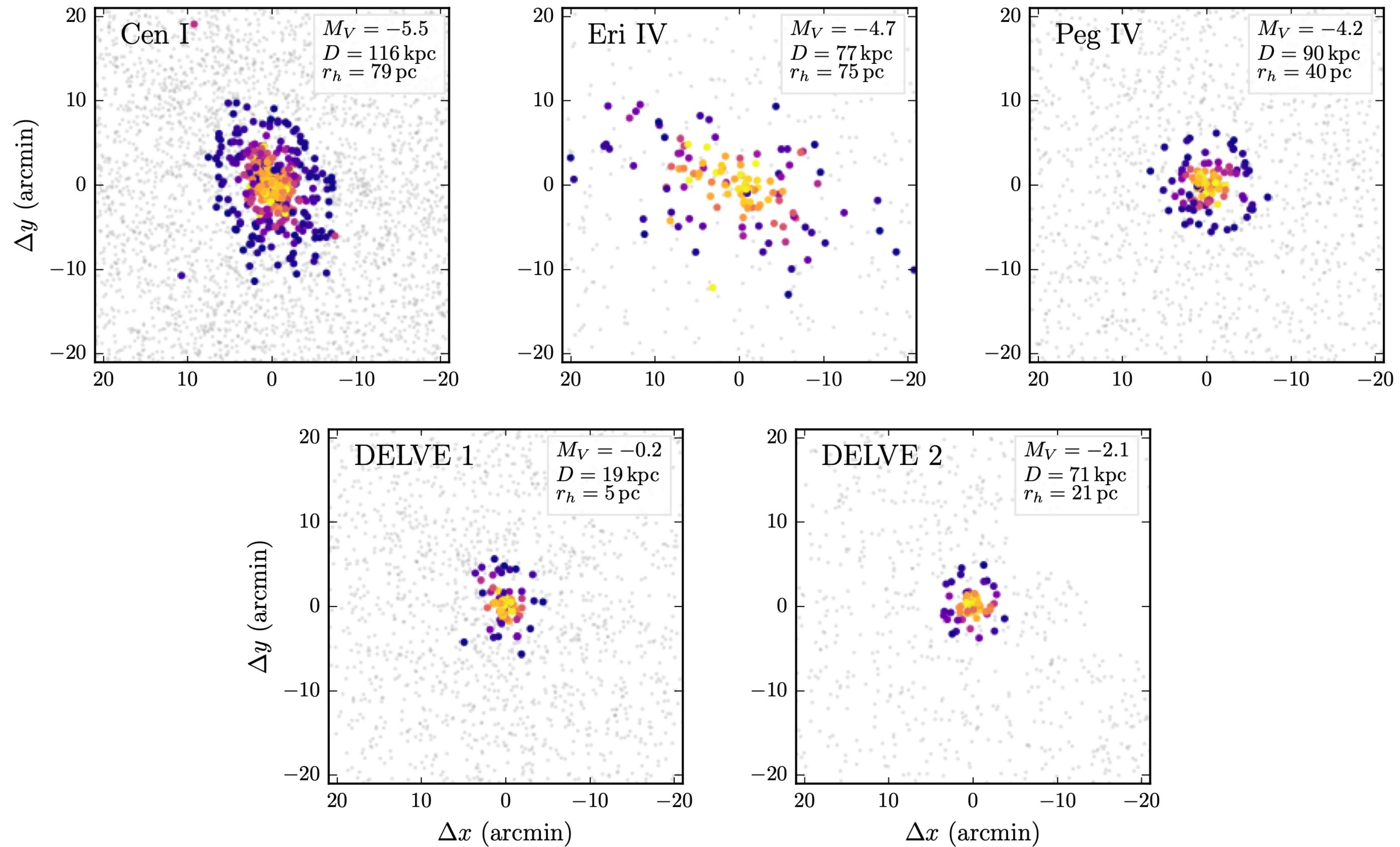
Drlica-Wagner et al. 2020
(DES Collaboration)



Nadler et al. 2020
(DES Collaboration)

Predict 220 ± 50 total satellites, consistent with other empirical models (Jethwa et al. 2018, Newton et al. 2018, Kim et al. 2018) and hydro simulations.

DELVE: The DECam Local Volume Exploration Survey



See Alex Drlica-Wagner's Talk

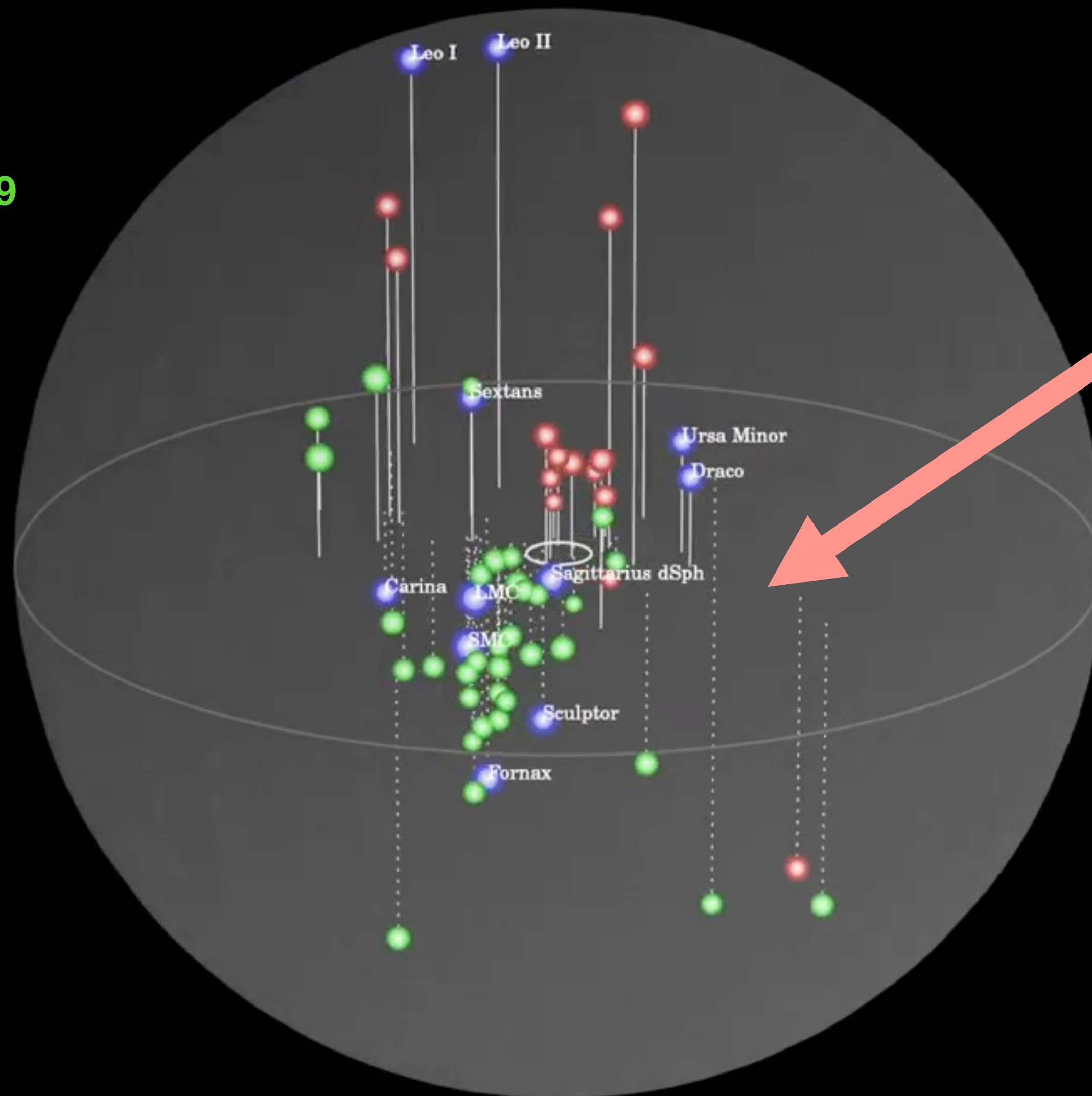
Mau et al 2020, Cerny et al. 2021a,b, 2022
(DELVE Collaboration)

Recently discovered satellites are not isotropically distributed

Previously known Dwarfs

Discovered in SDSS

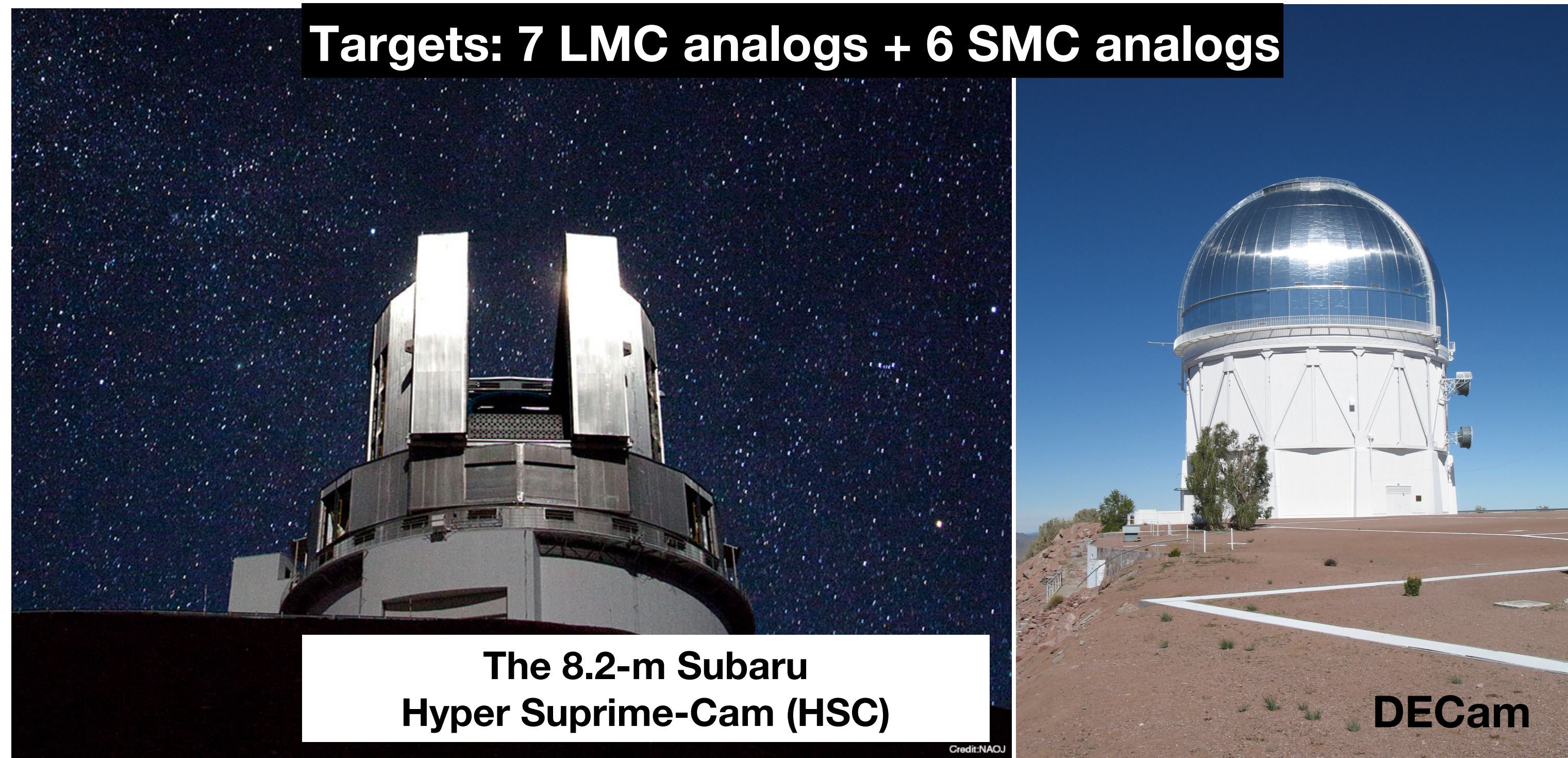
Discovered between 2015-2019



Are they associated with Magellanic Clouds?

- Jethwa et al. 2016
- Dooley et al. 2017
- Kallivayalil et al. 2018
- Jahn et al. 2019, 2022
- Erkal & Belokurov 2019
- Pardy et al. 2020
- Patel et al. 2020
- Santos-Santos et al. 2021
- Battaglia et al. 2022
- among others

MADCASH: Magellanic Analog Dwarf Companions And Stellar Halos Survey

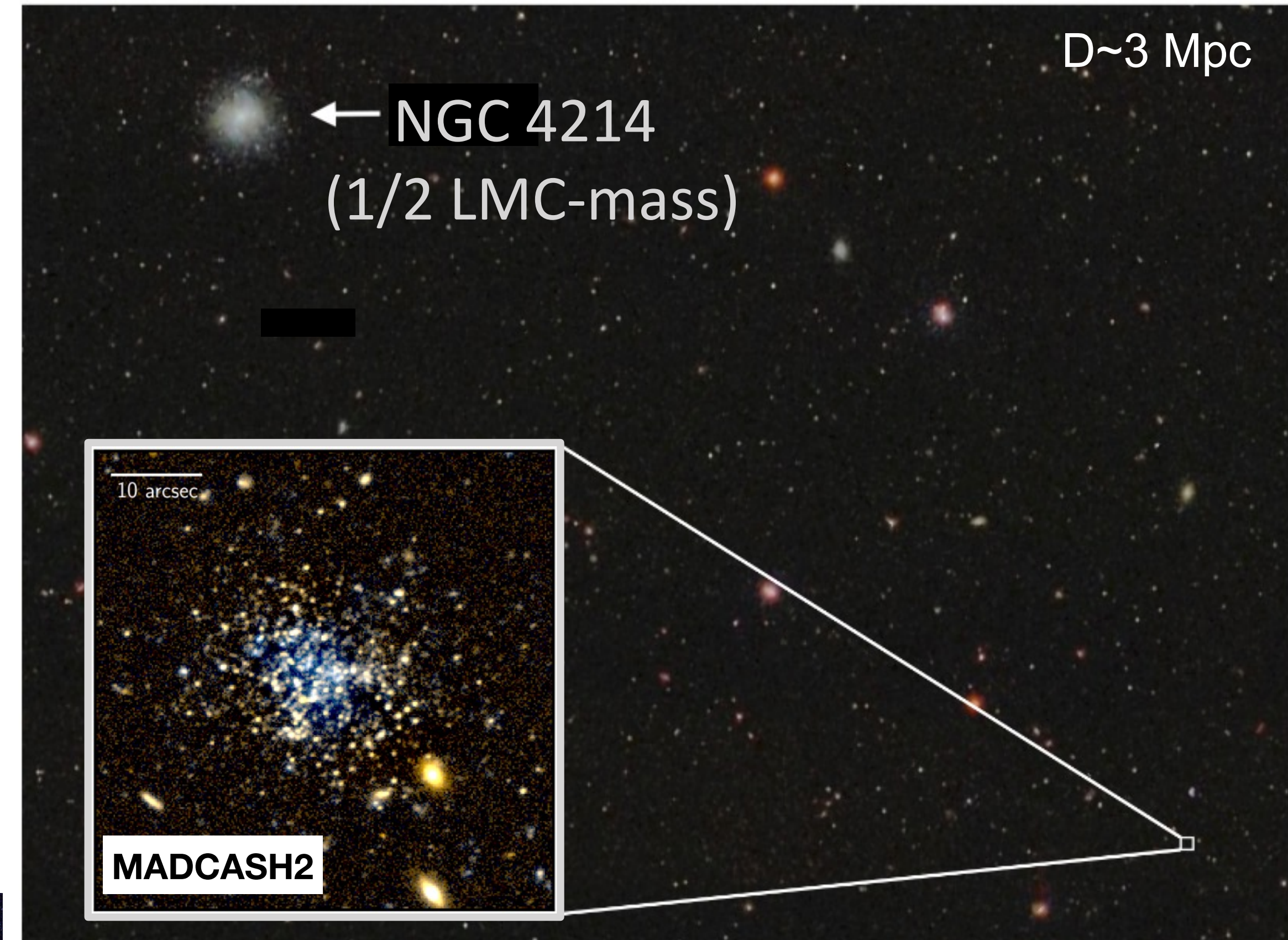
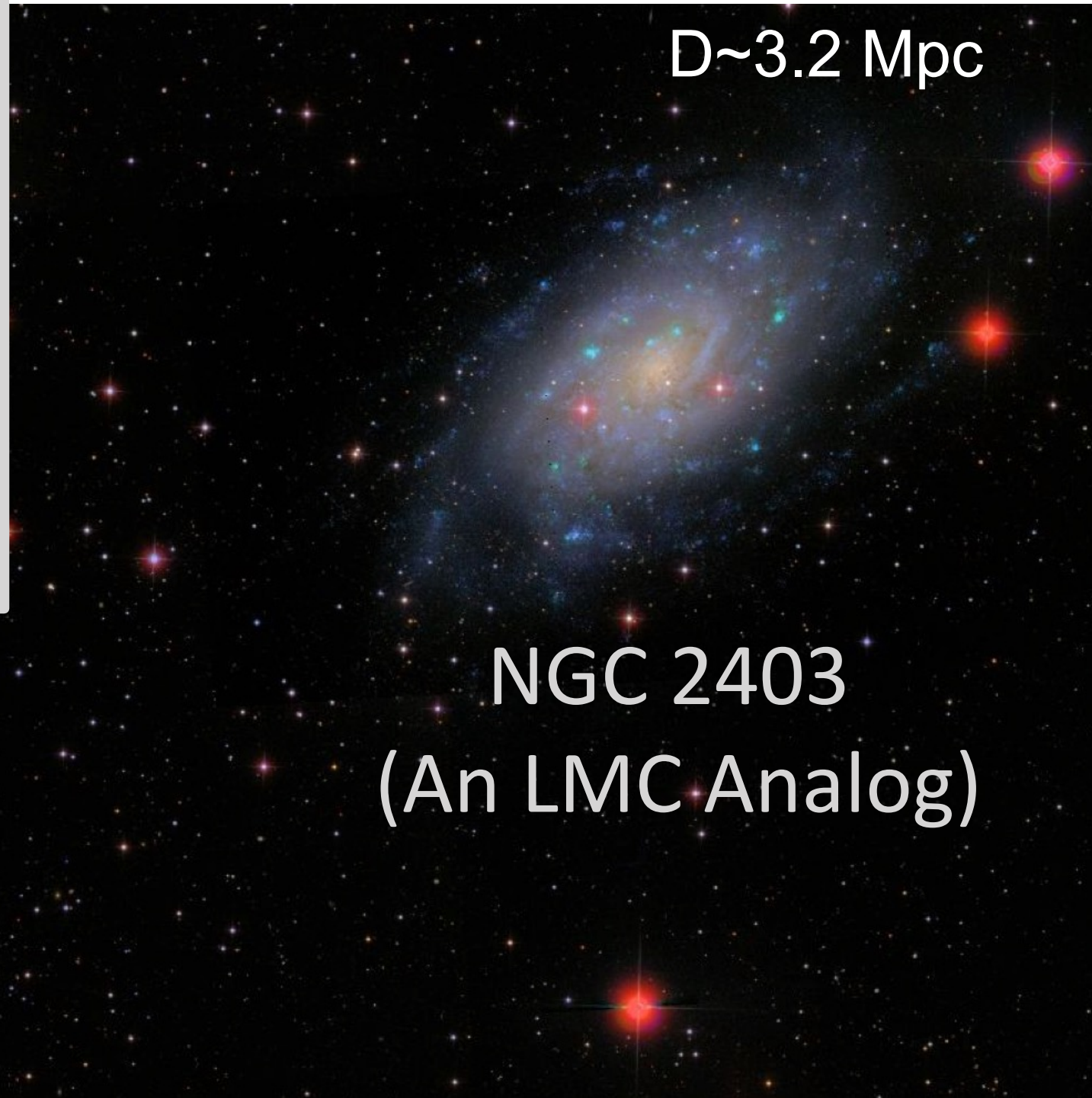
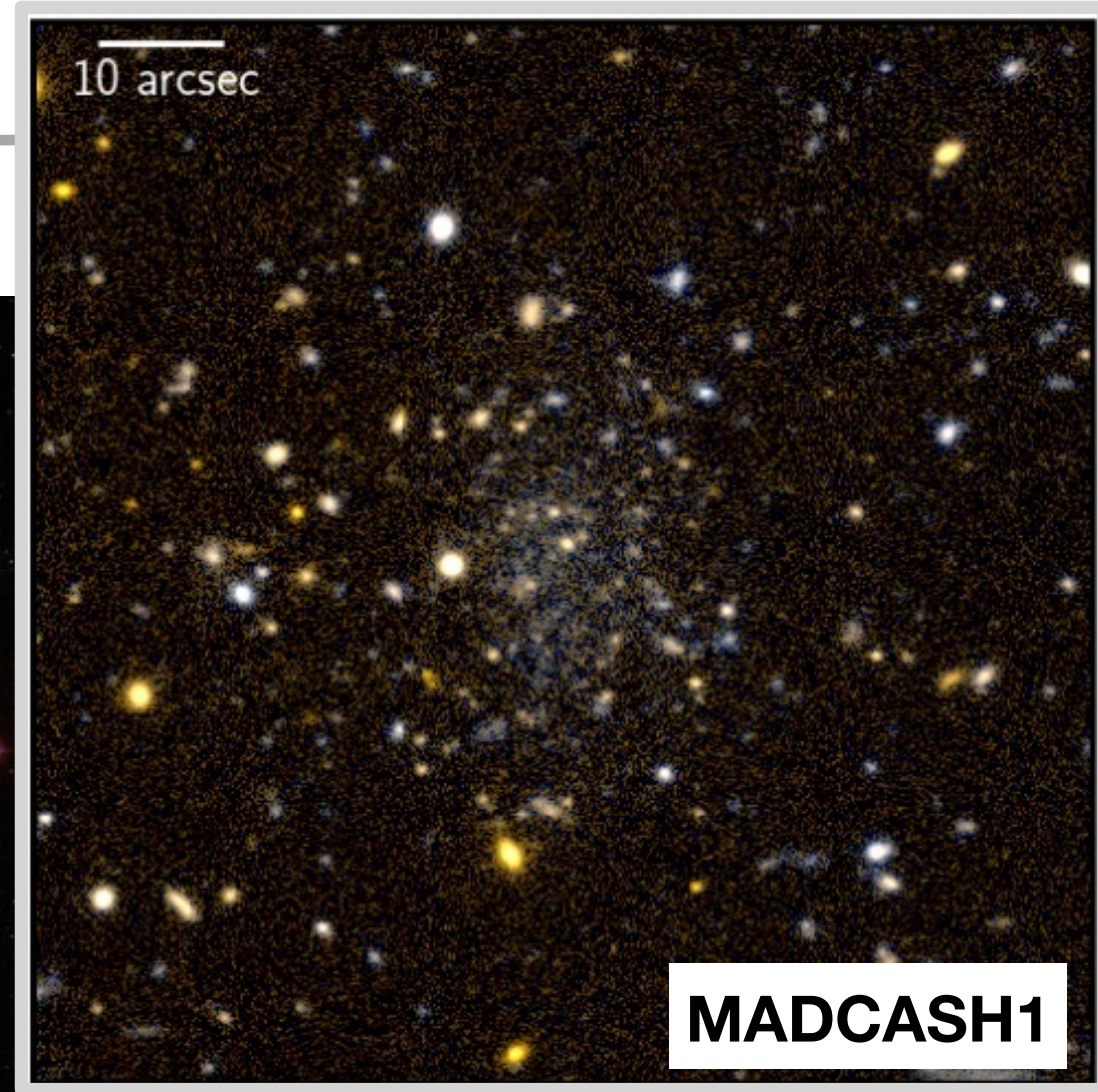


What is the goal?

To explore dwarf galaxy formation around low-mass galaxies

Carlin et al, 2016, 2021

First MADCASH Detections

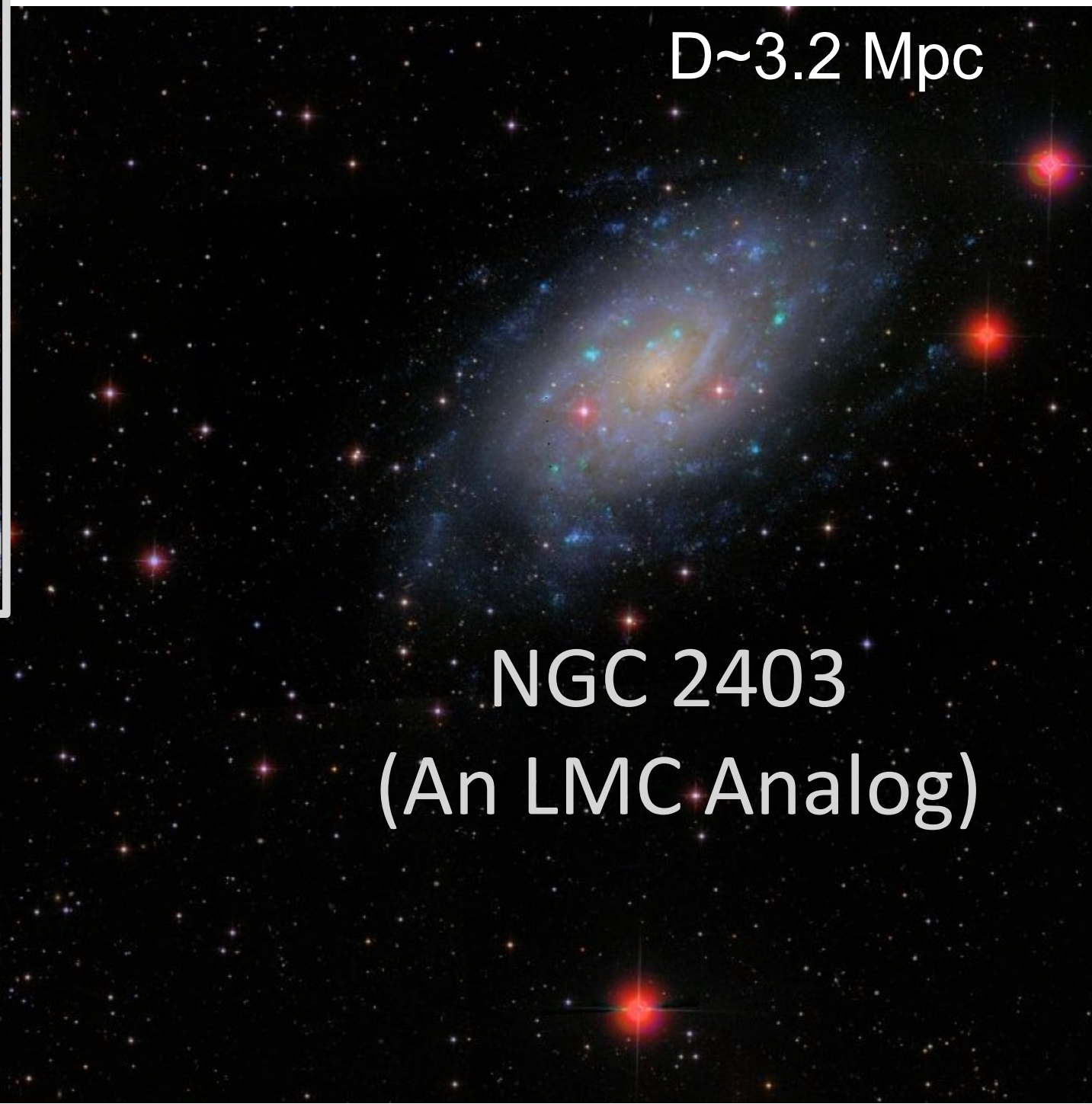
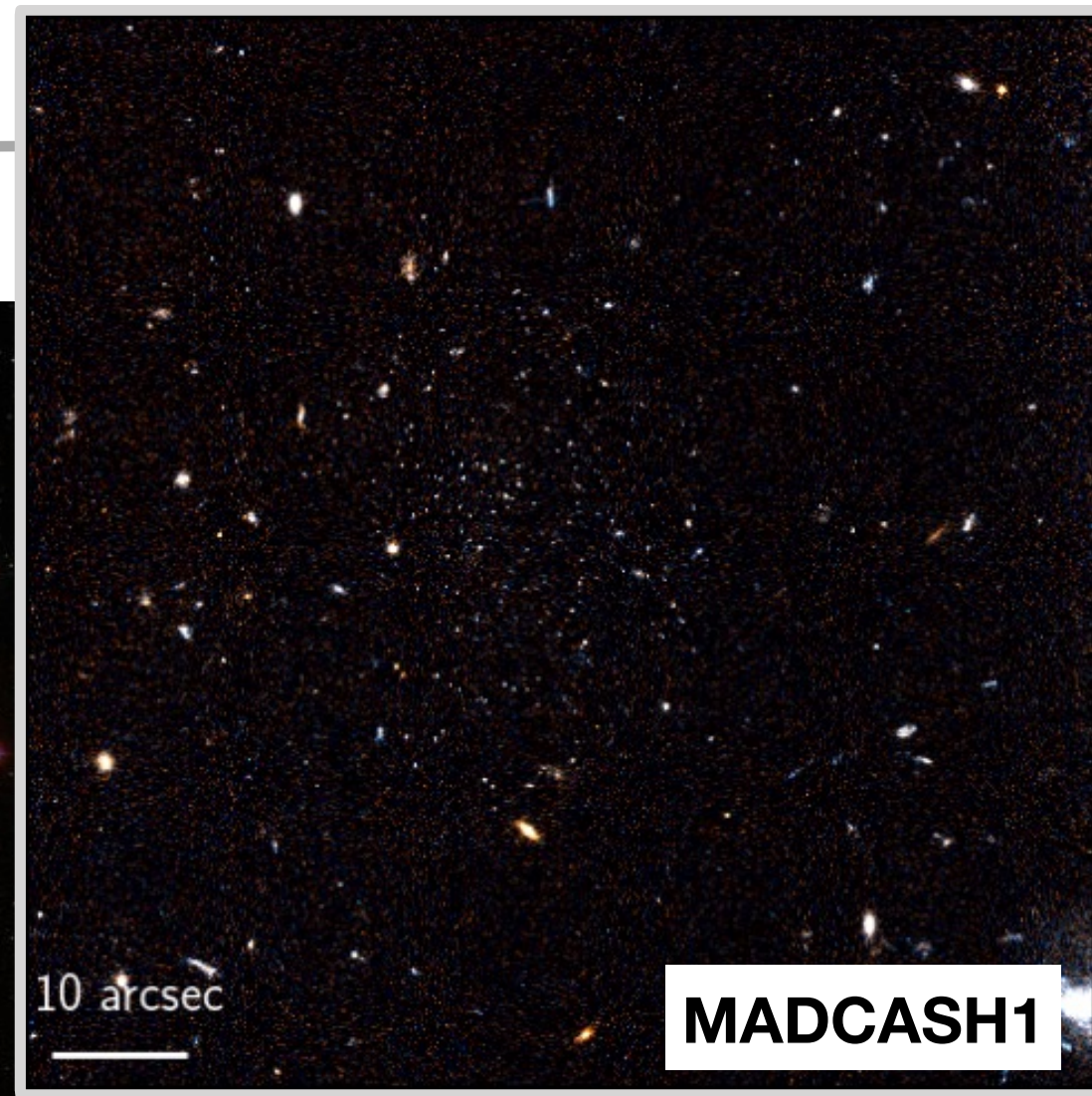


Carlin et al, 2016

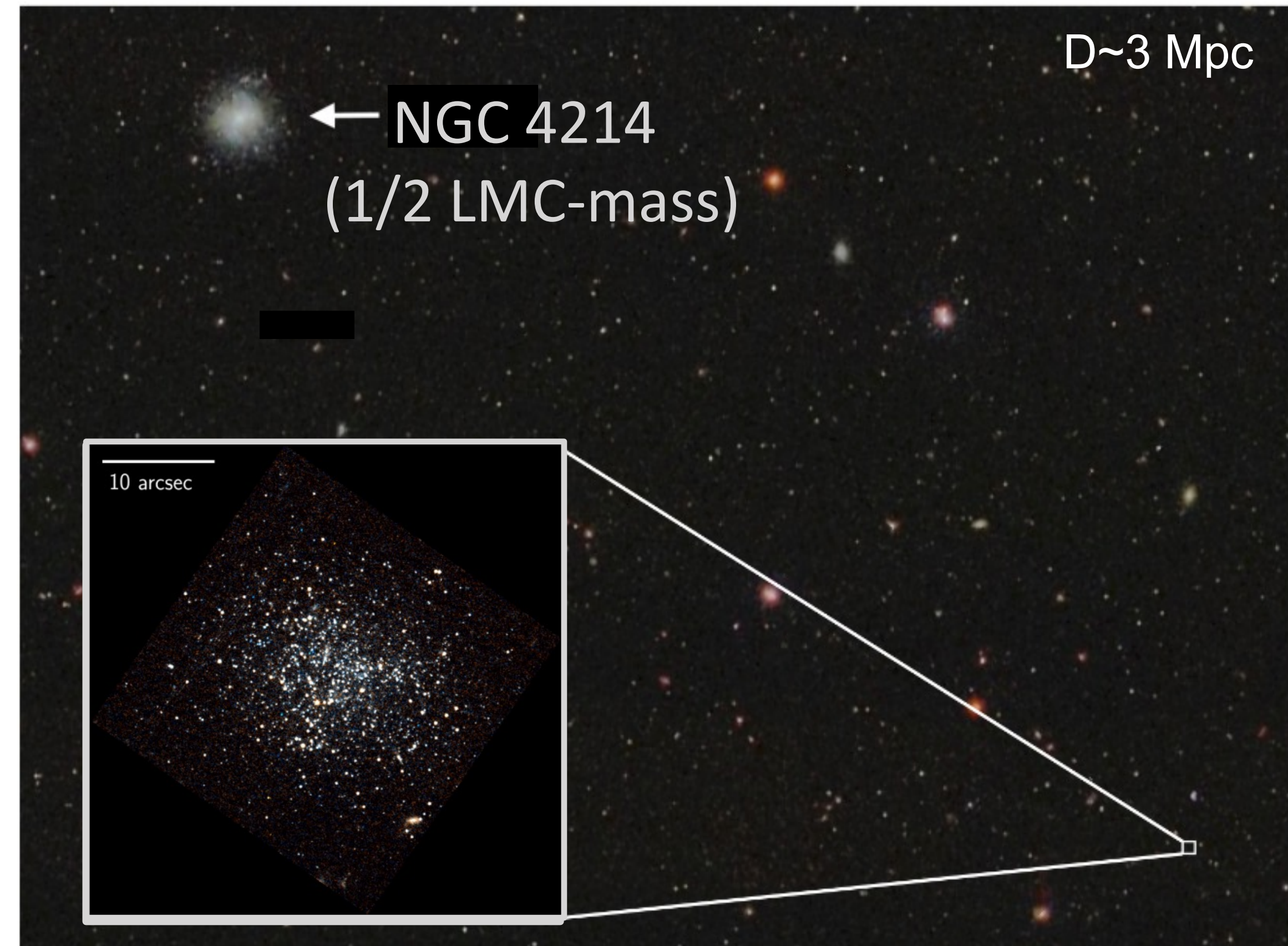
Carlin, Mutlu-Pakdil, et al. 2021



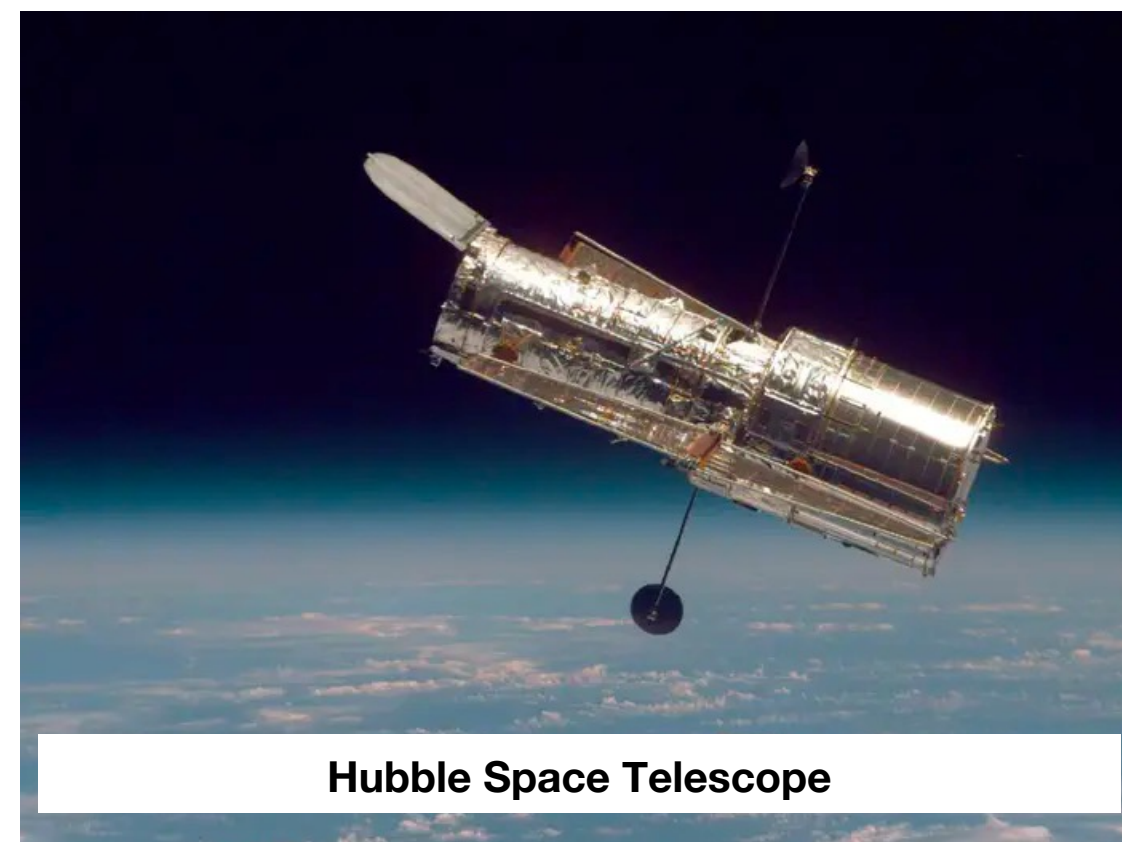
First MADCASH Detections



Carlin et al, 2016



Carlin, Mutlu-Pakdil, et al. 2021



These are the **faintest** dwarf satellites known around LMC-mass systems beyond the Local Group

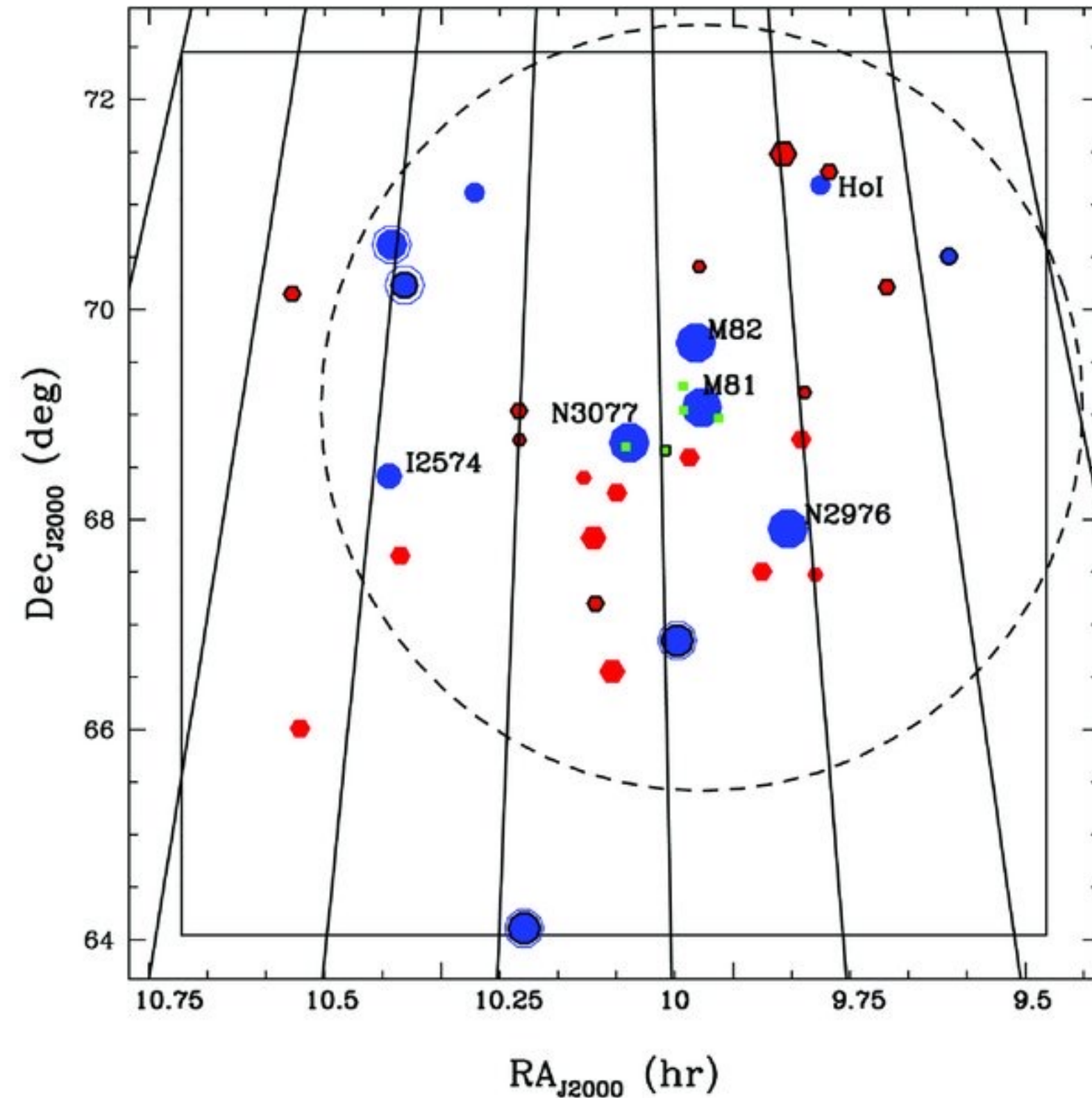
Search for Resolved Dwarfs and Stellar Streams Around Nearby Systems



The 3.6-m CFHT
MegaPrime/MegaCam Imager

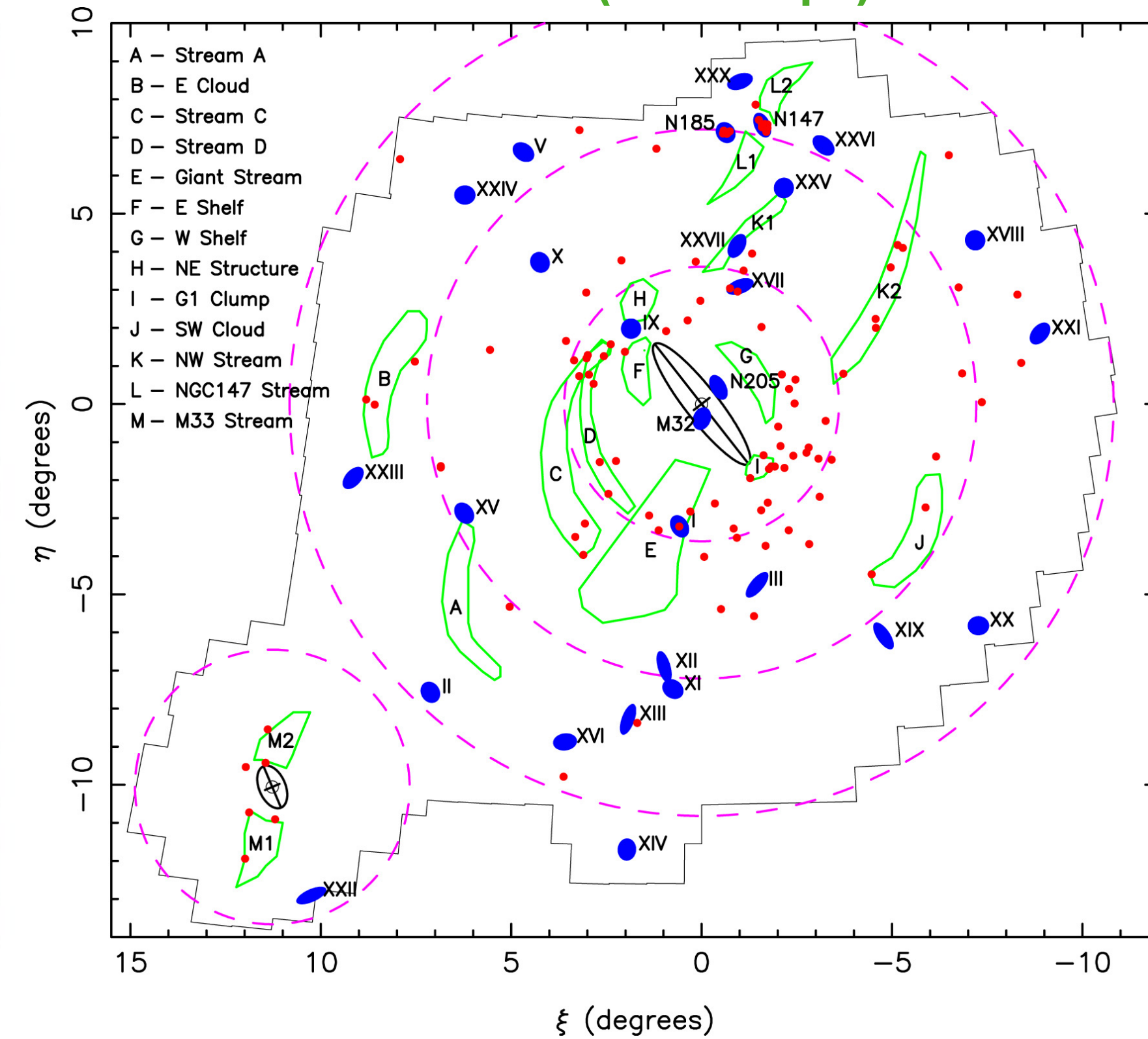


M81 (D=3.7 Mpc)



Chiboucas et al, 2009, 2013

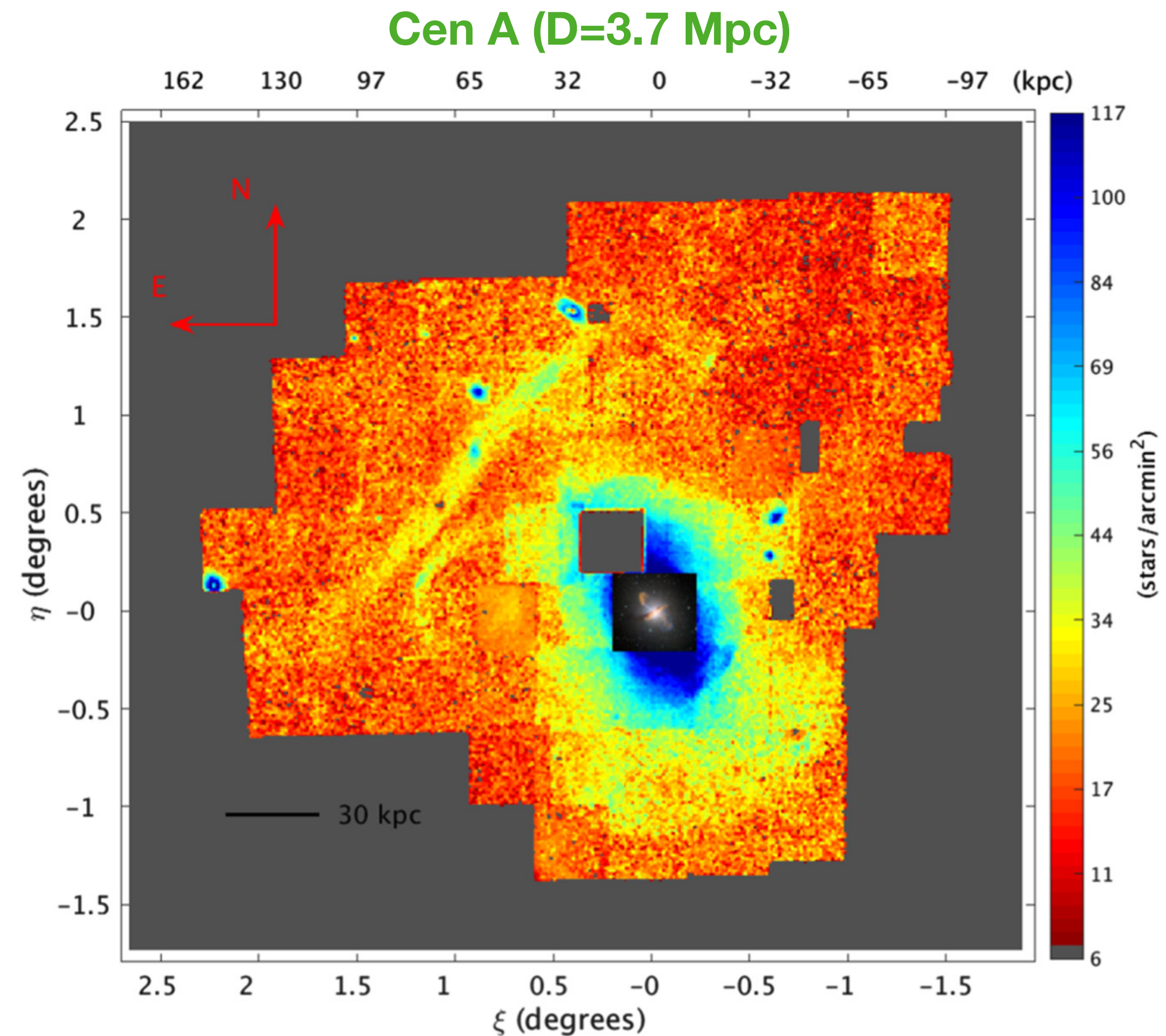
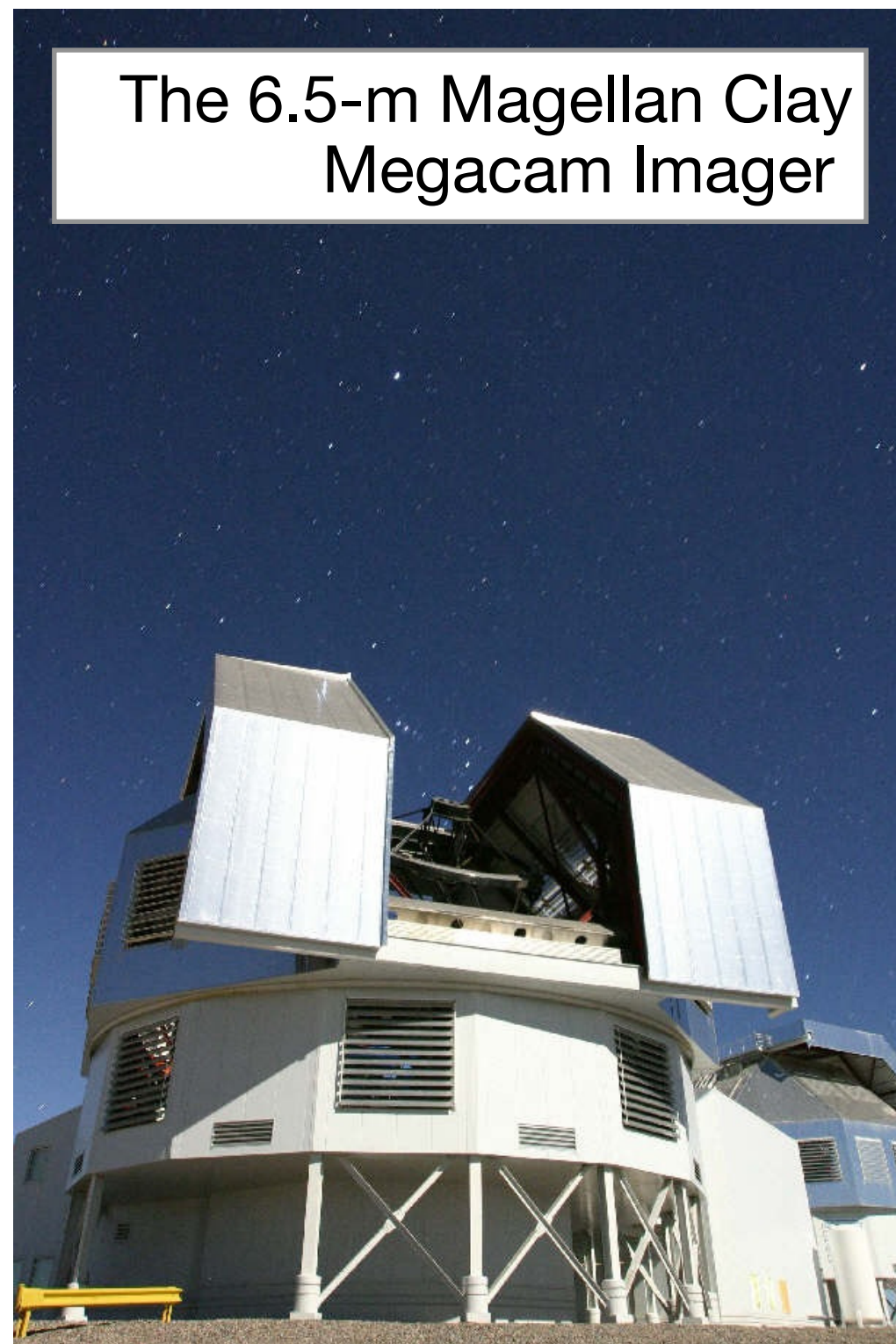
M31 (D=0.8 Mpc)



McConnachie et al, 2016

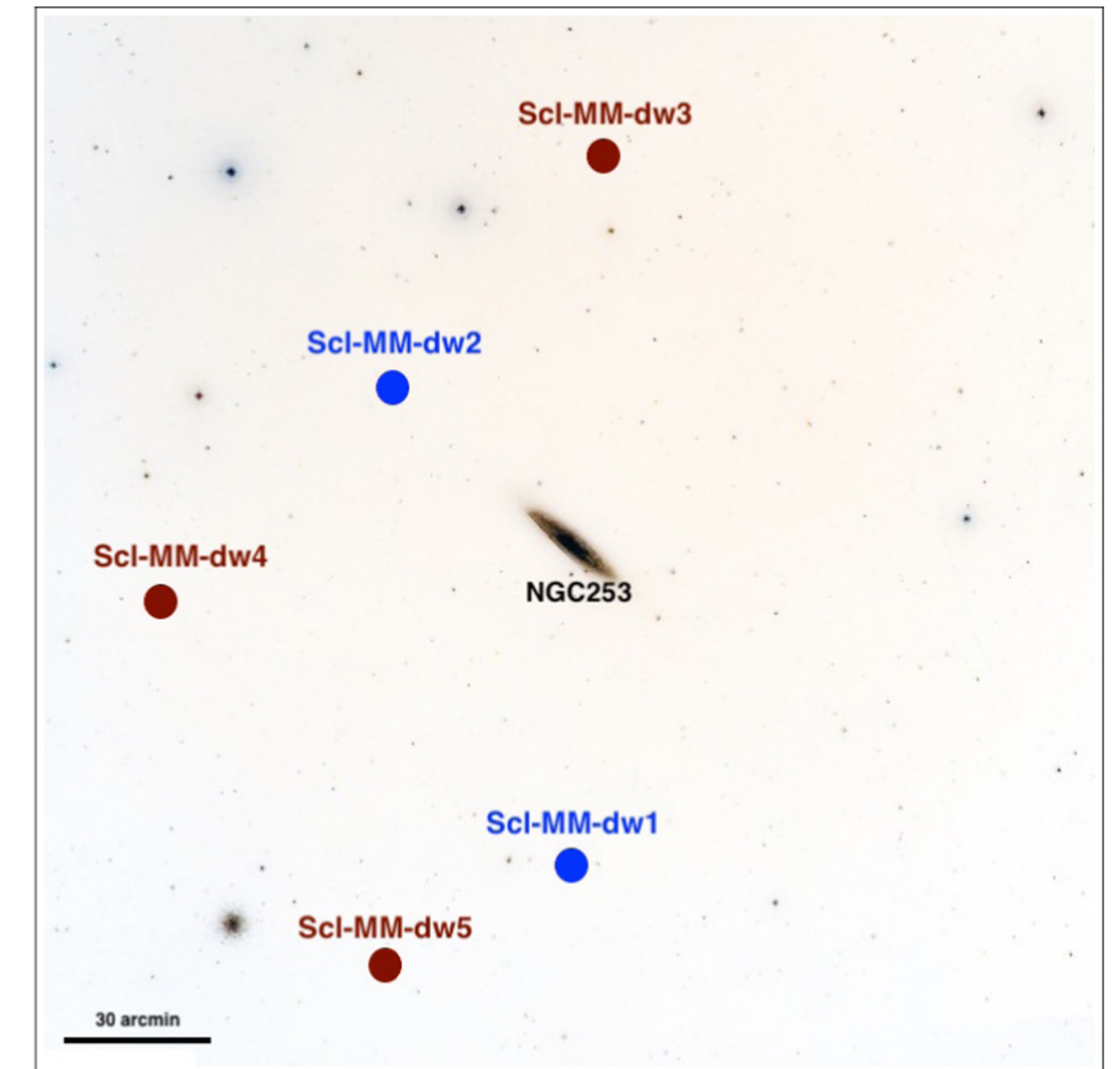
PAndAS:
The Pan-Andromeda
Archaeological Survey

Search for Resolved Dwarfs and Stellar Streams Around Nearby Systems



Crnojević et al, 2016, 2019

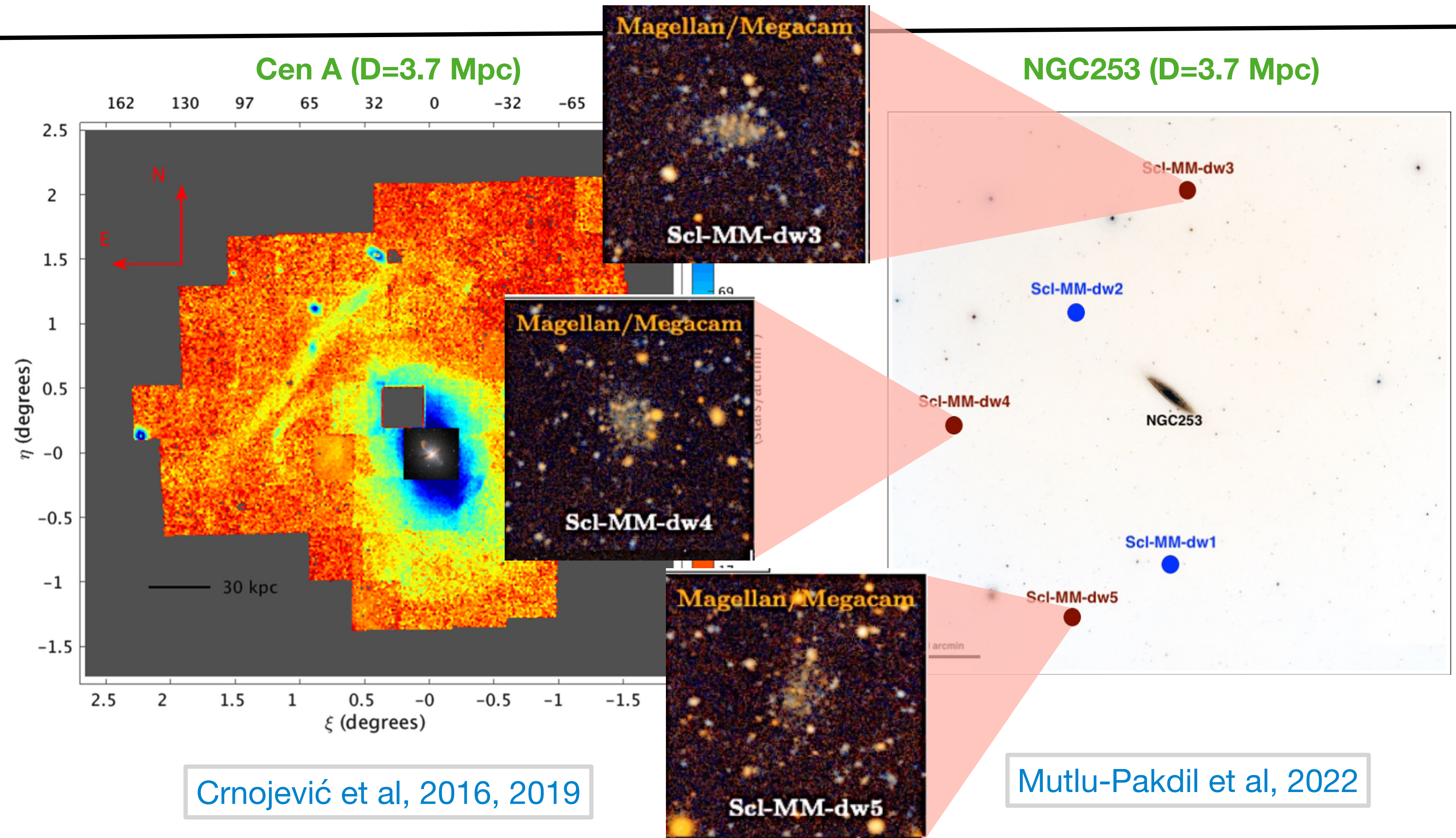
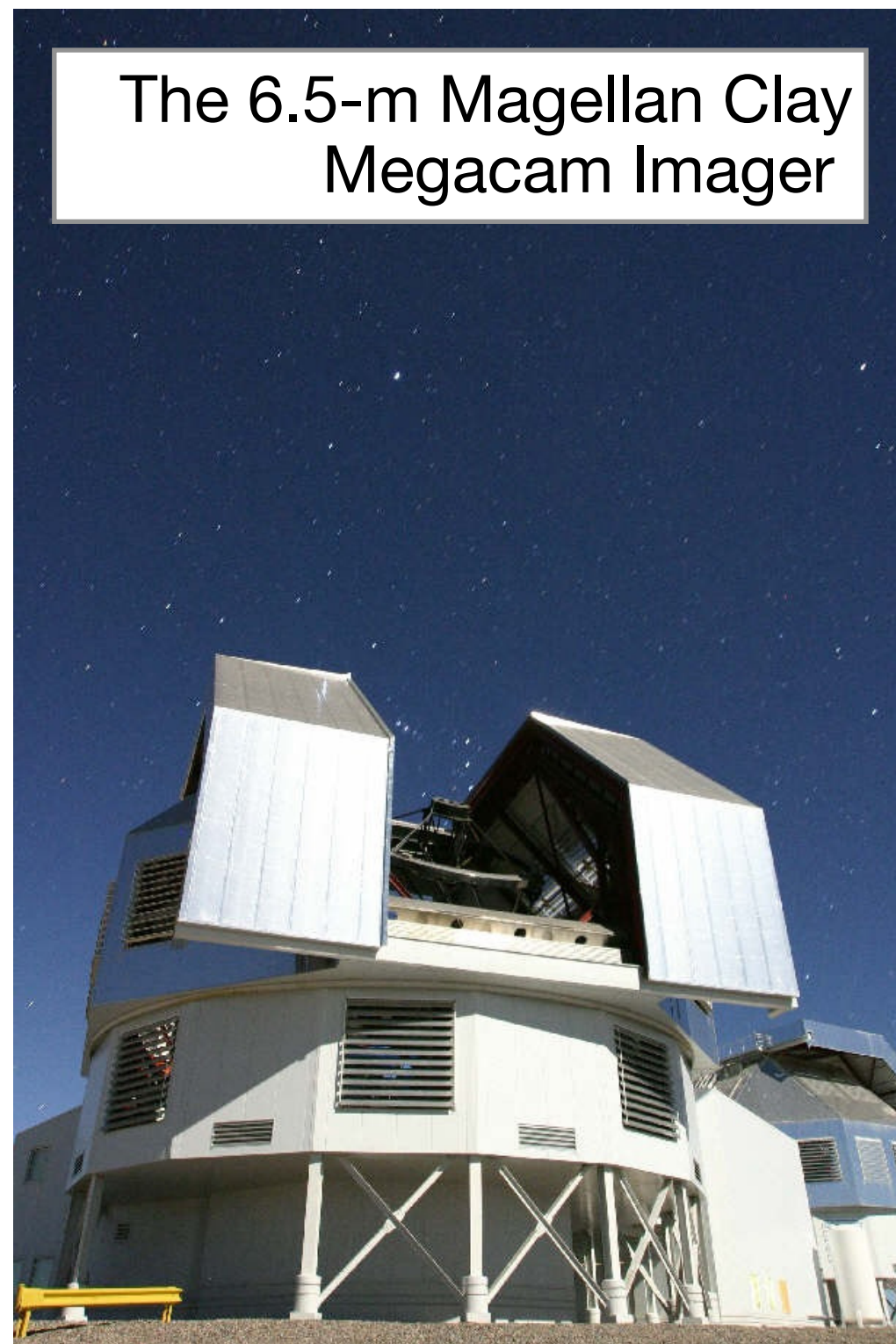
NGC253 (D=3.7 Mpc)



Mutlu-Pakdil et al, 2022

PISCES: The **P**anoramic **I**maging **S**urvey of **C**entaurus and **S**culptor

Search for Resolved Dwarfs and Stellar Streams Around Nearby Systems



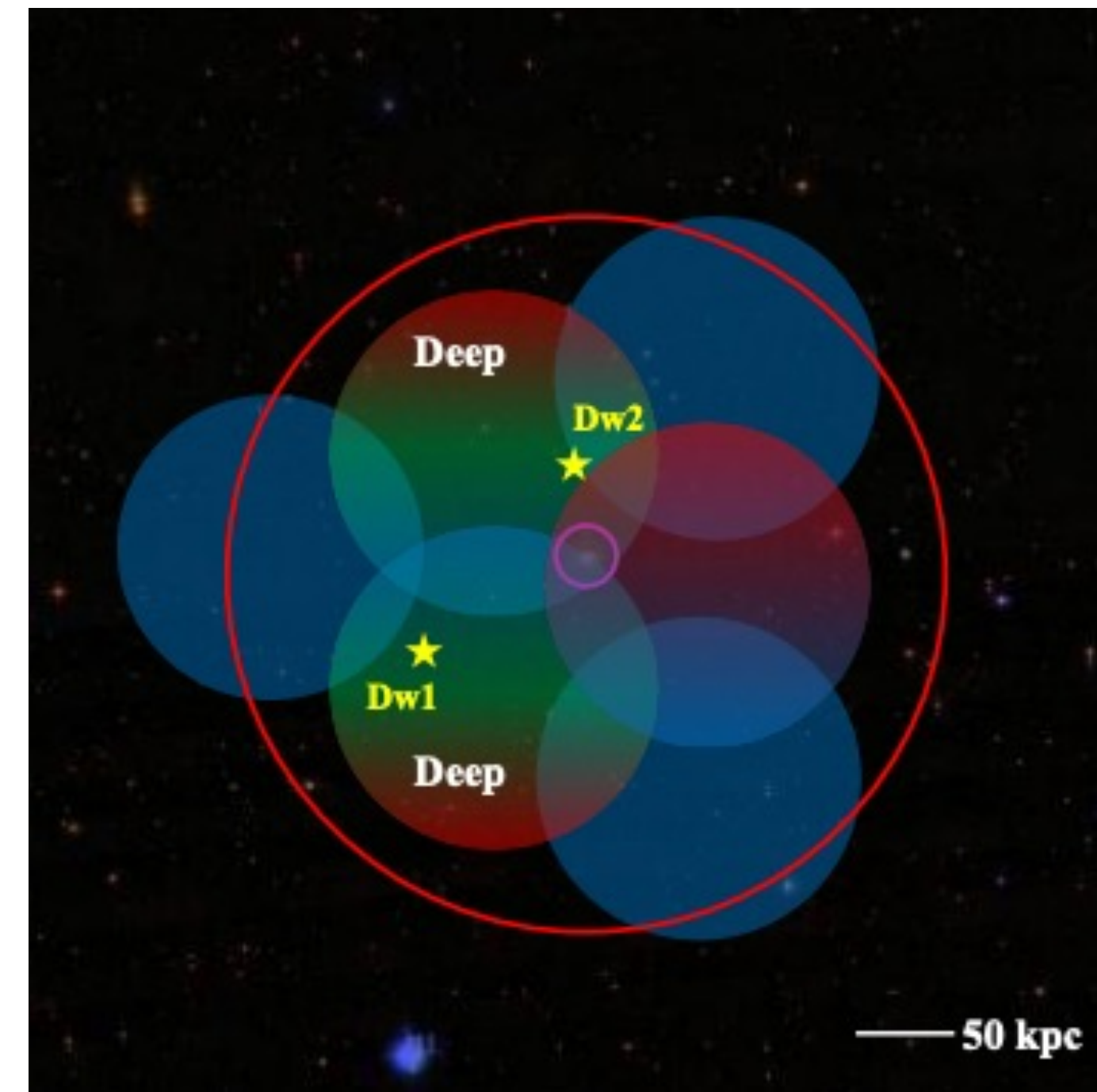
PISCES: The Panoramic Imaging Survey of Centaurus and Sculptor

Search for Resolved Dwarfs and Stellar Streams Around Nearby Systems



The 8.2-m Subaru
Hyper Suprime-Cam (HSC)

M94 (D=4.4 Mpc)



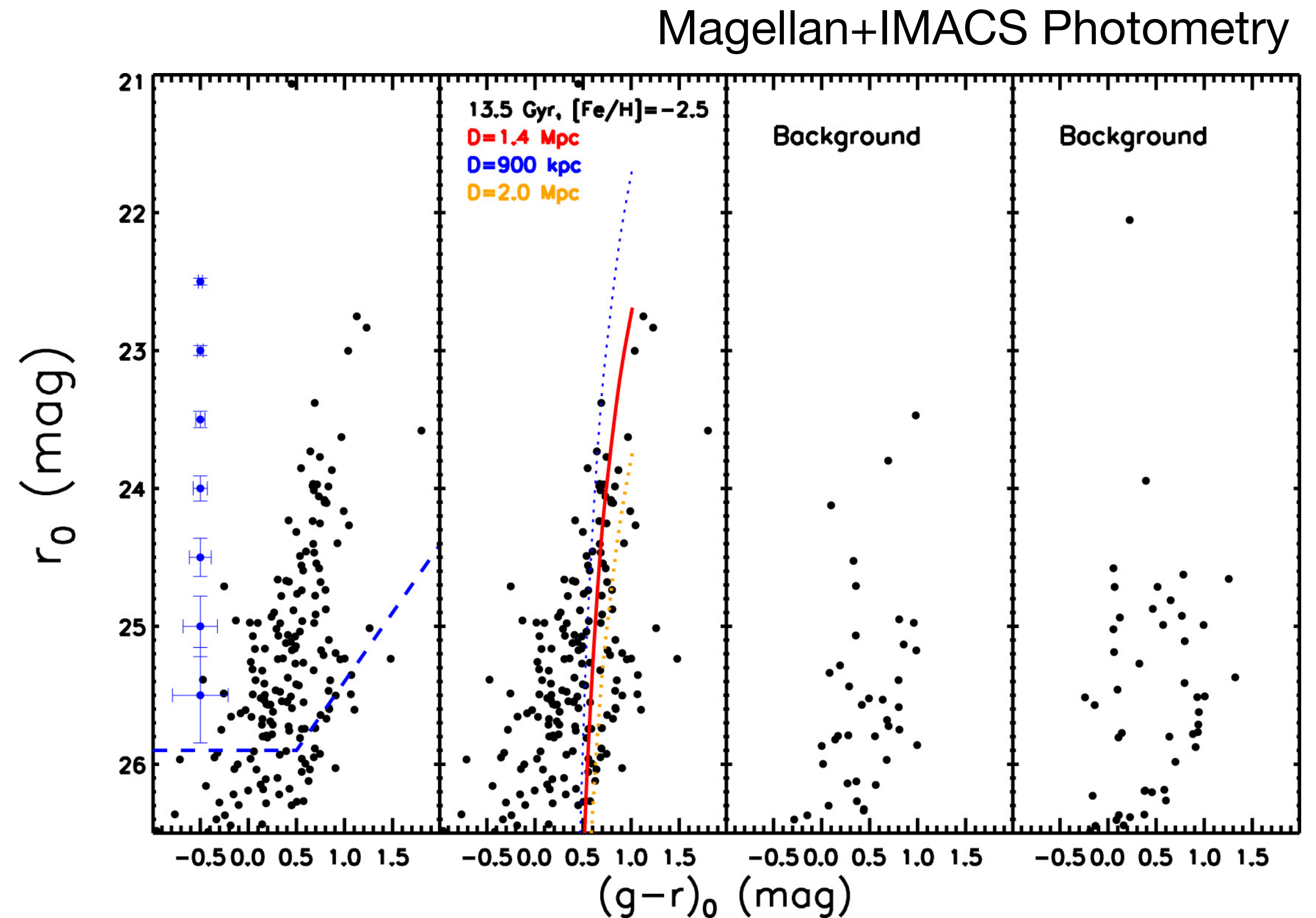
Smercina et al, 2018

The Discovery of An Isolated and Quenched Ultra-faint Dwarf Galaxy



DESI Legacy Imaging Surveys Data

Sand, Mutlu-Pakdil et al. 2022

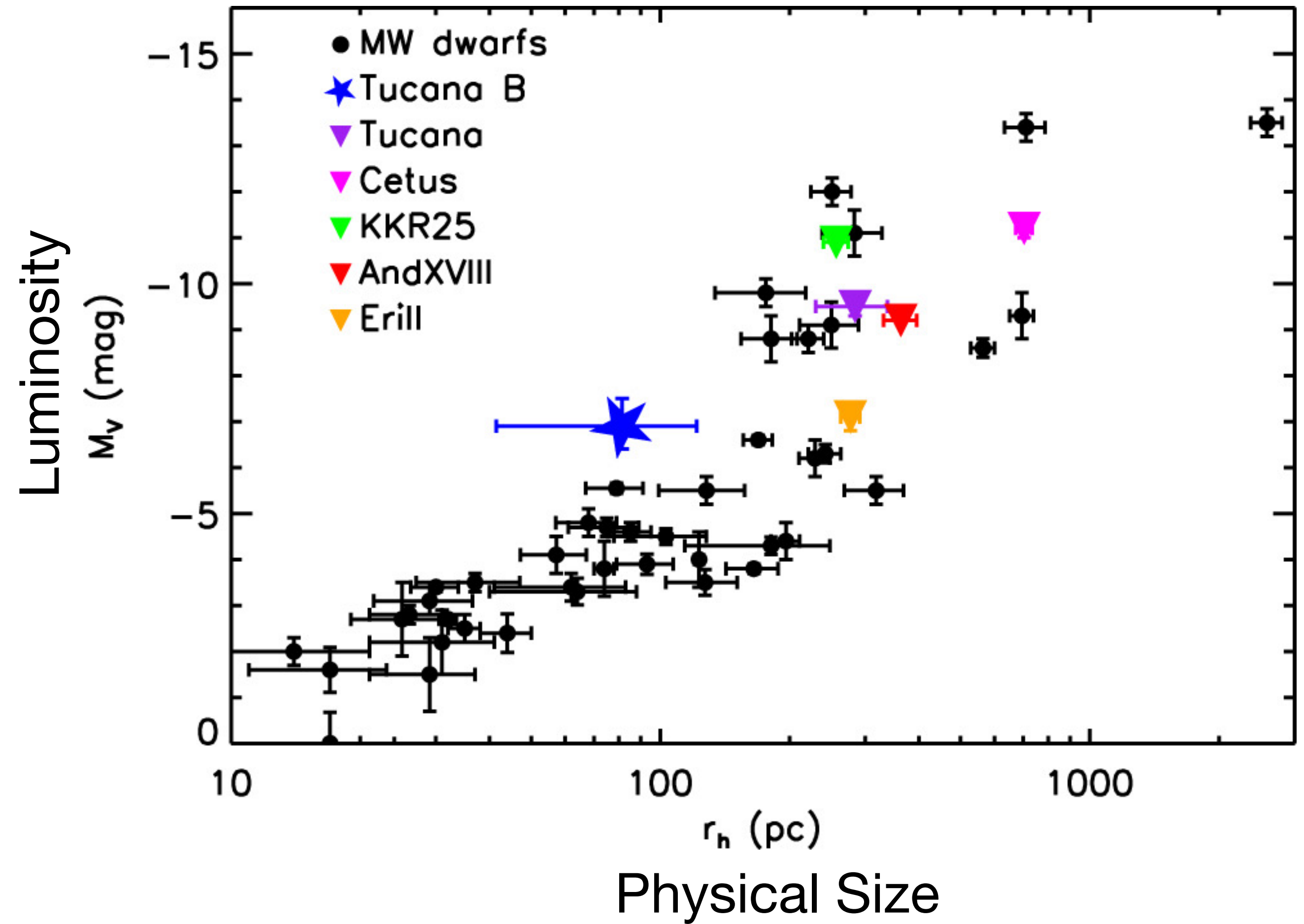


The Discovery of An Isolated and Quenched Ultra-faint Dwarf Galaxy



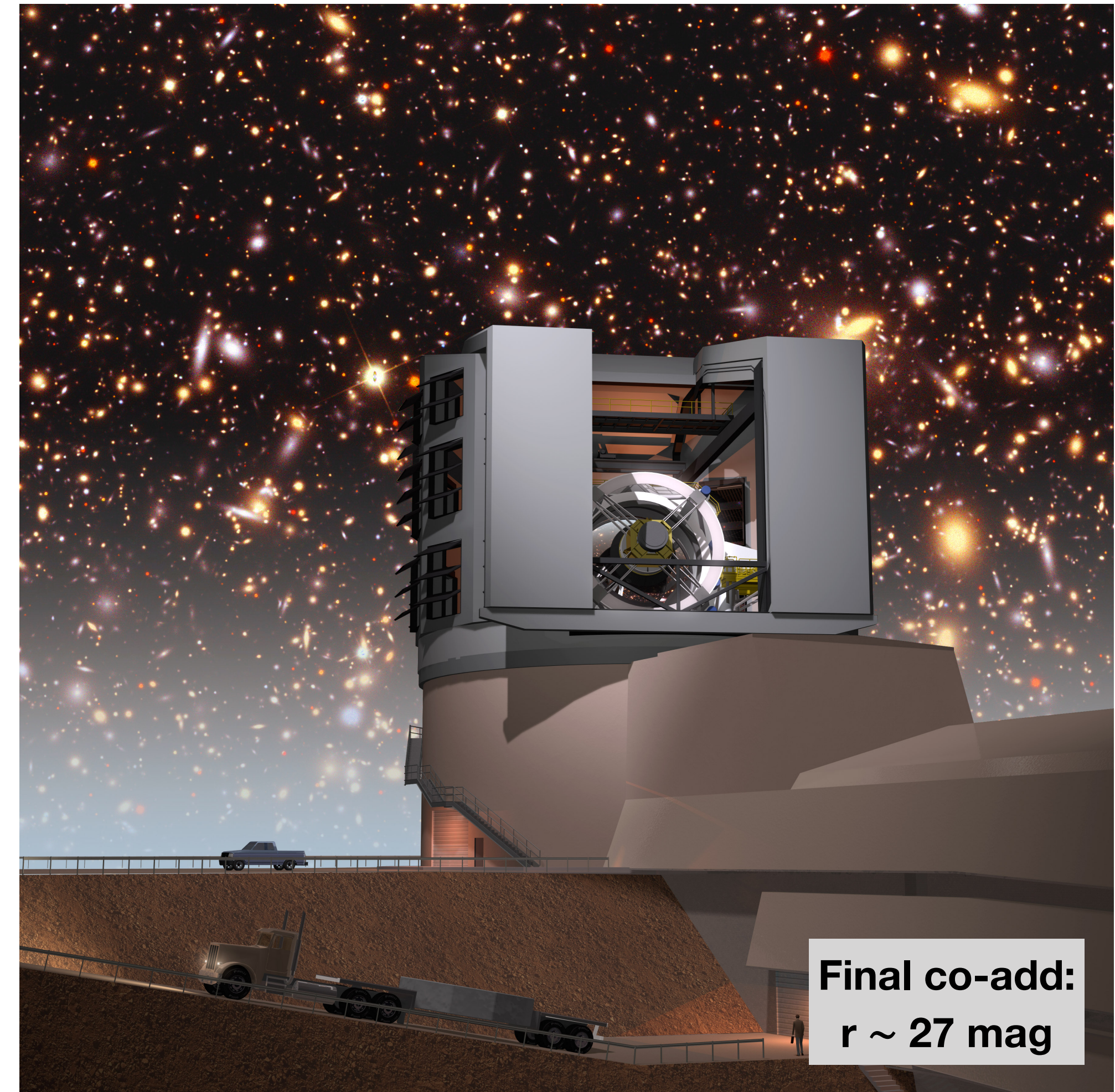
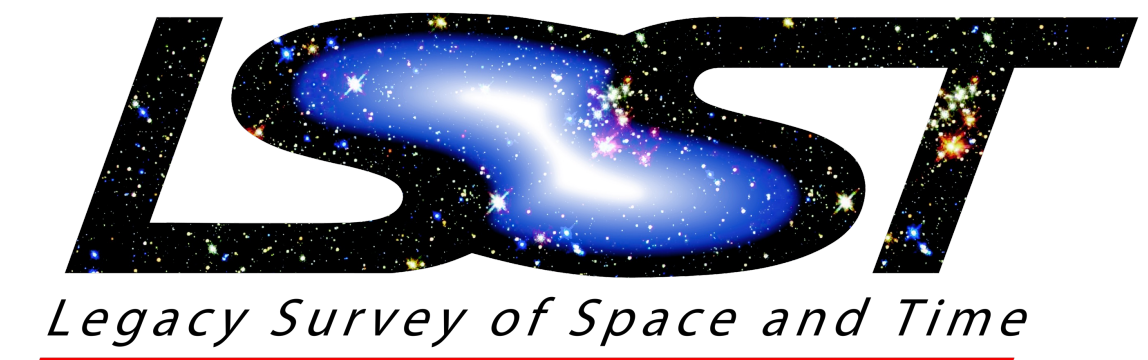
DESI Legacy Imaging Surveys Data

Sand, Mutlu-Pakdil et al. 2022



Is it quenched by reionization?

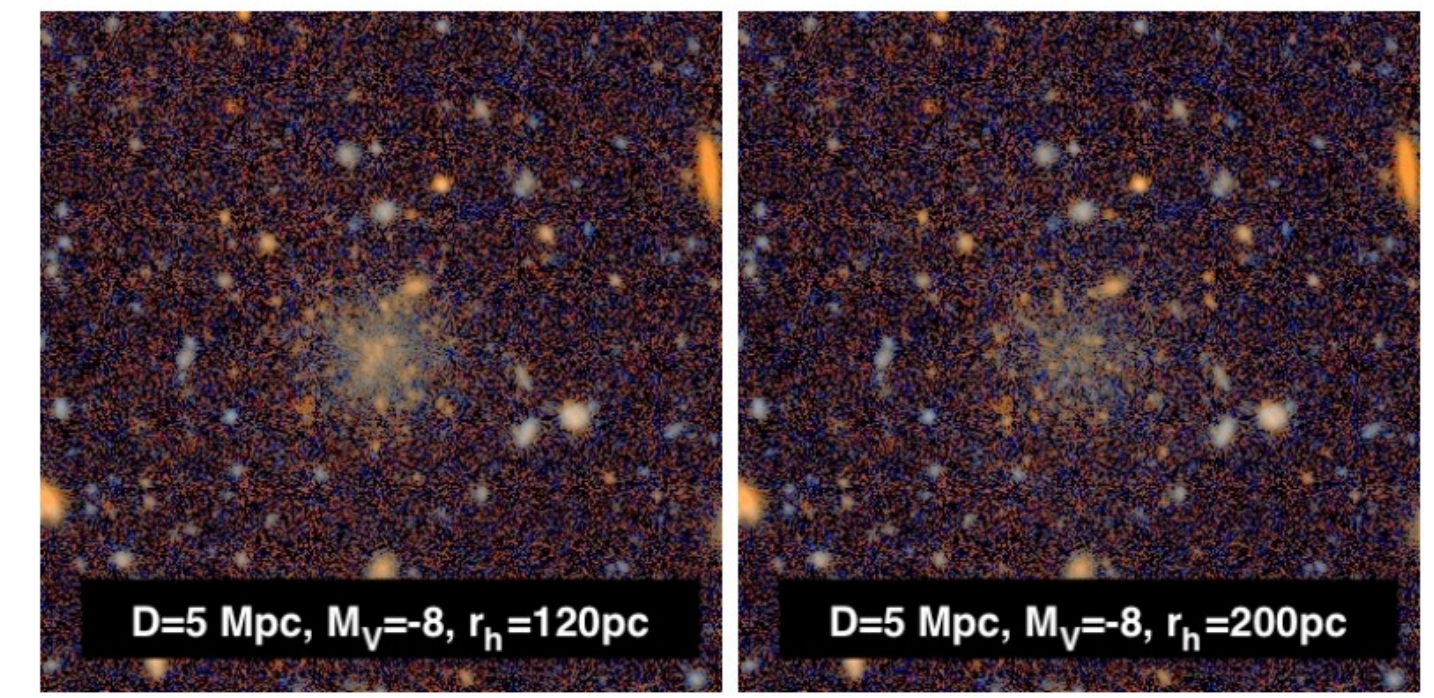
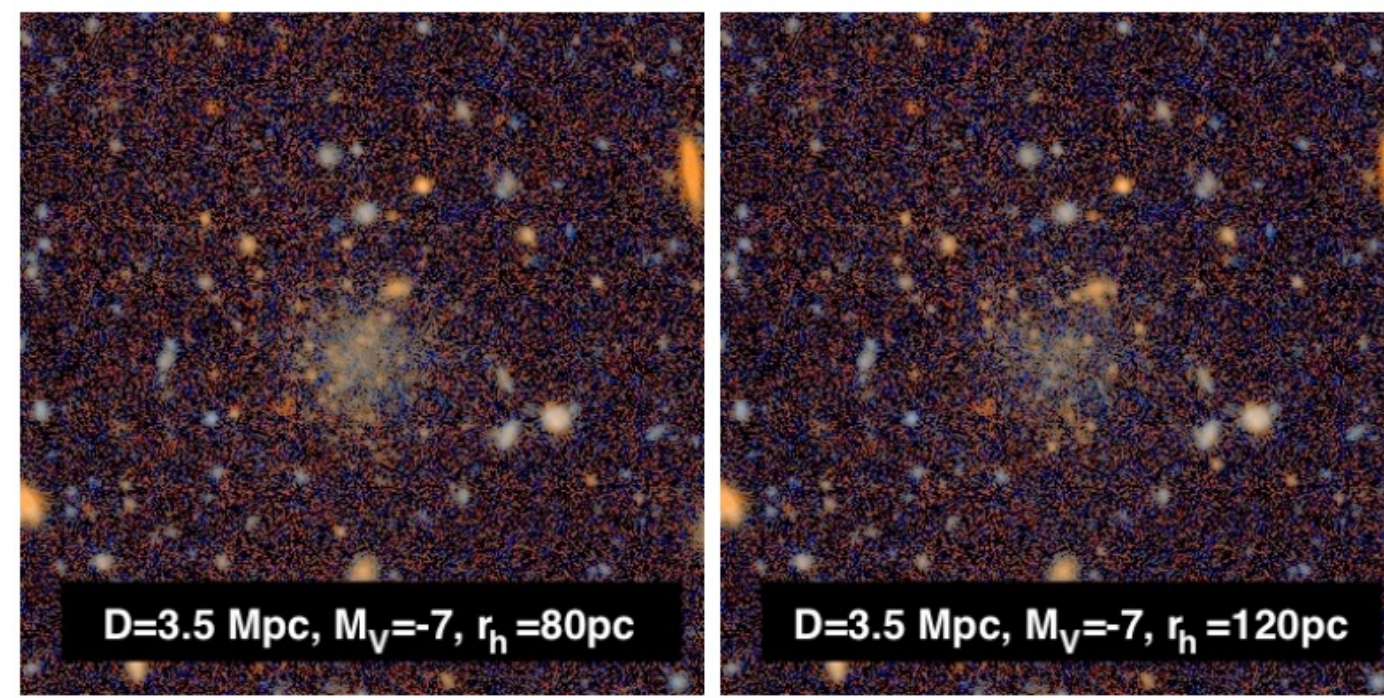
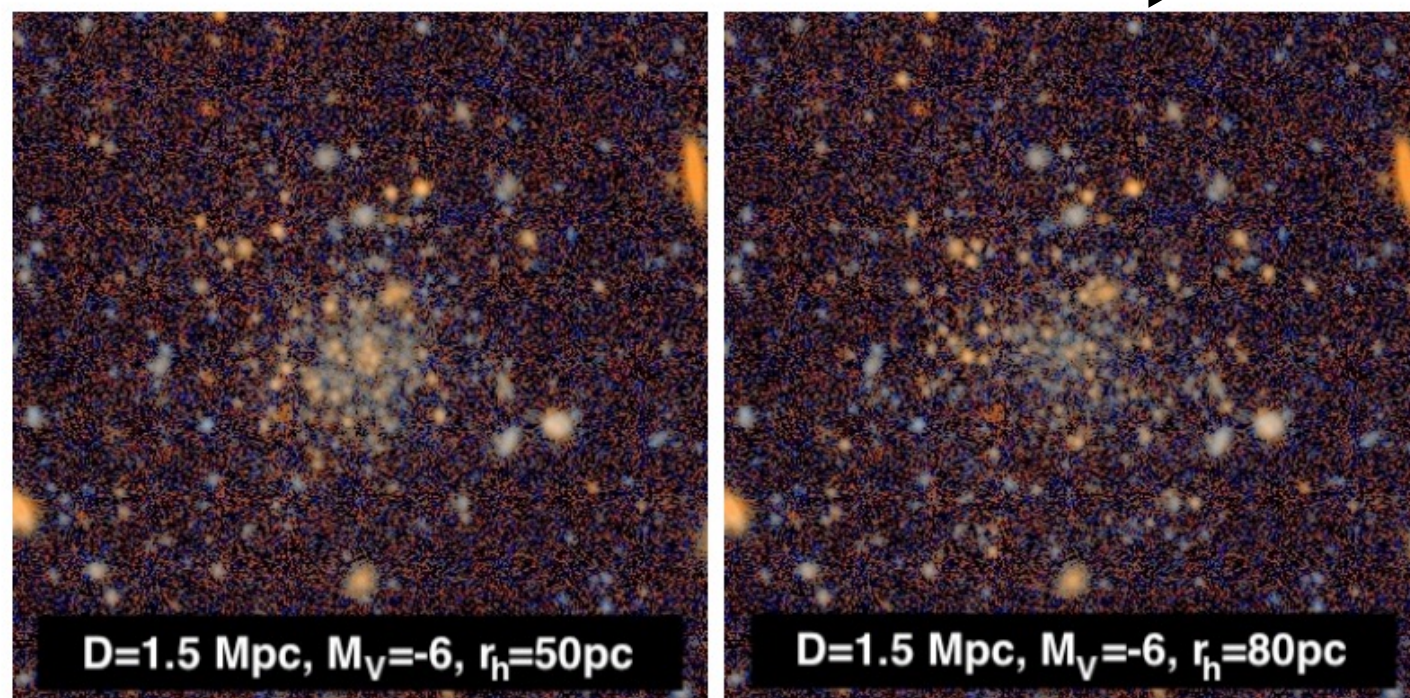
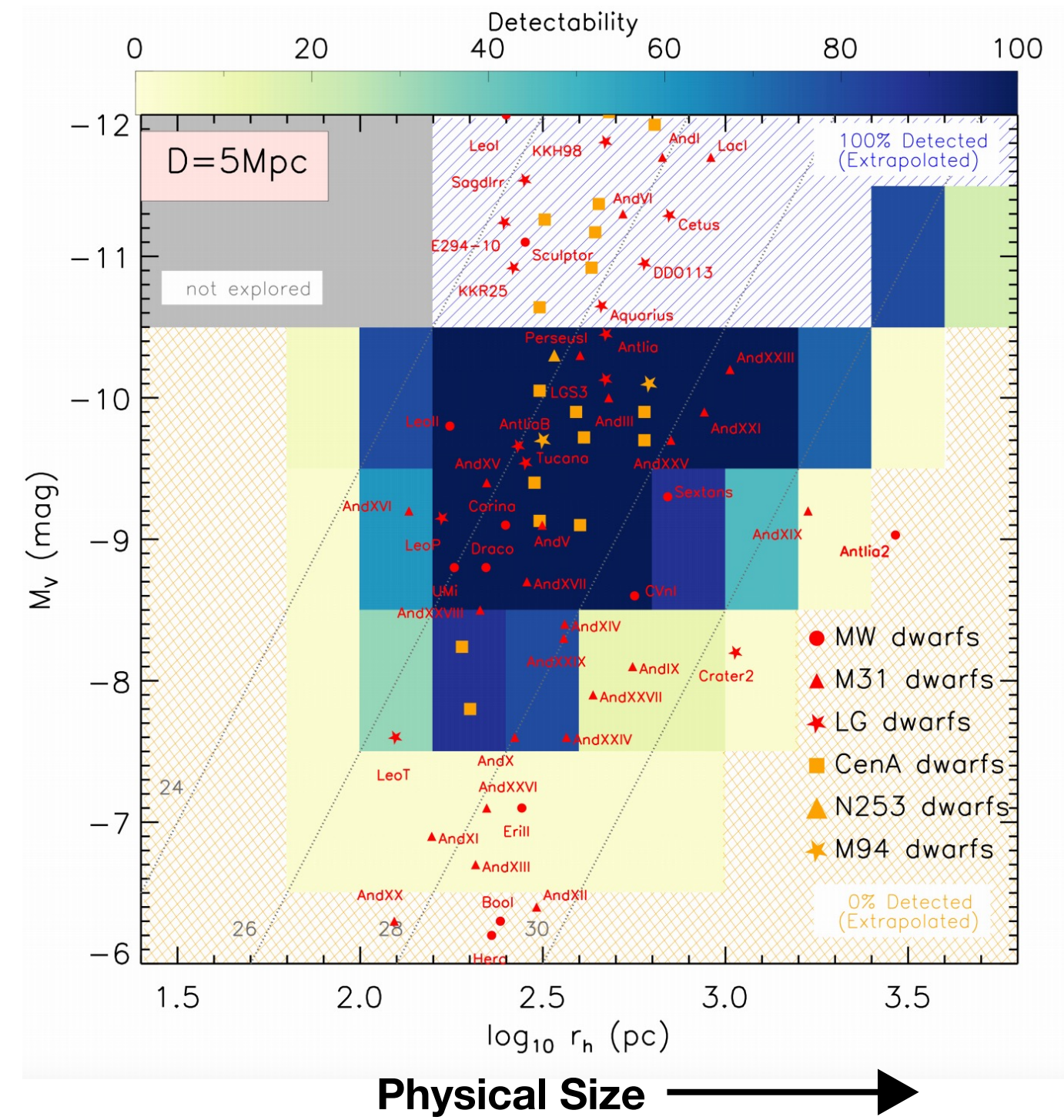
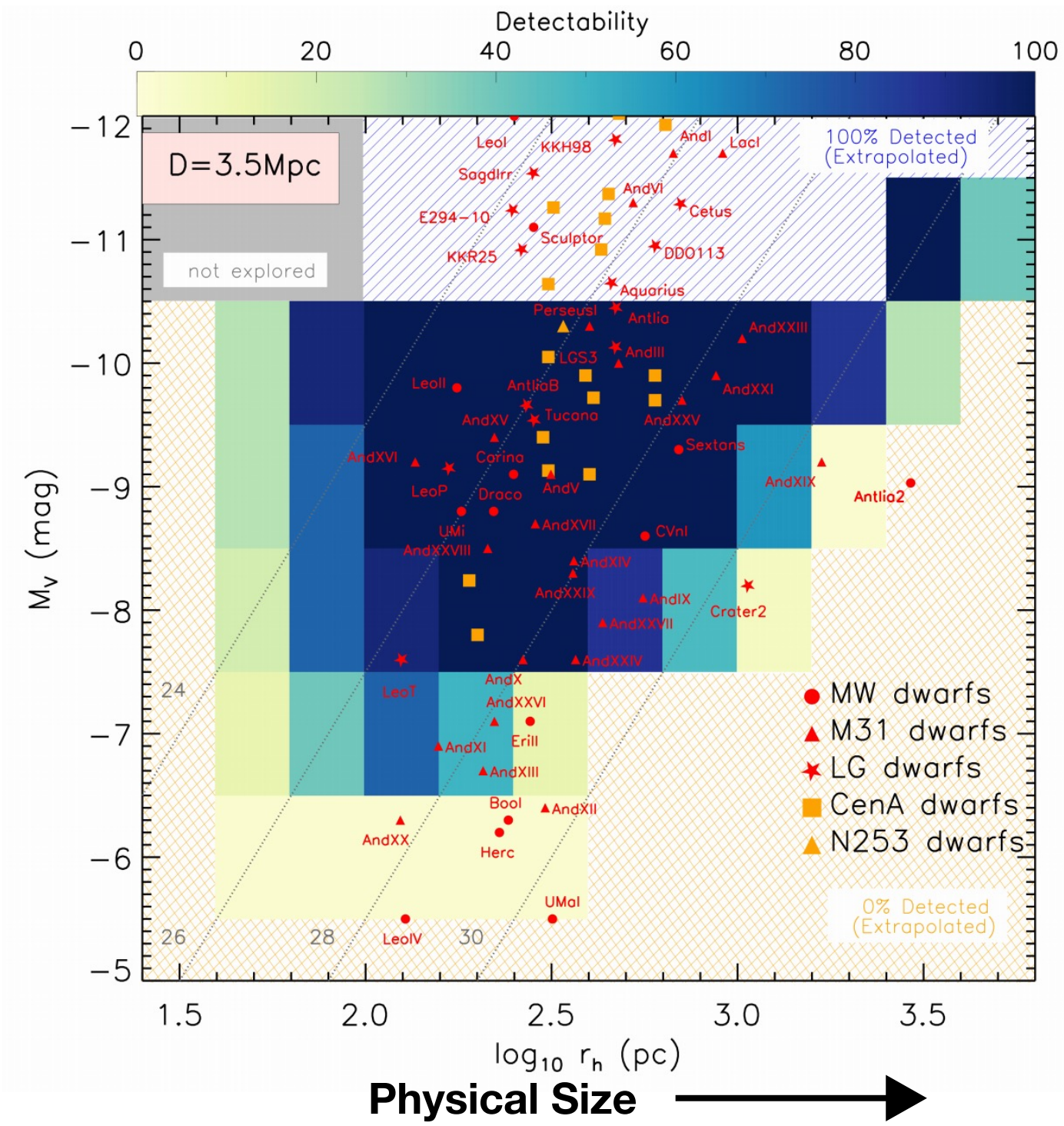
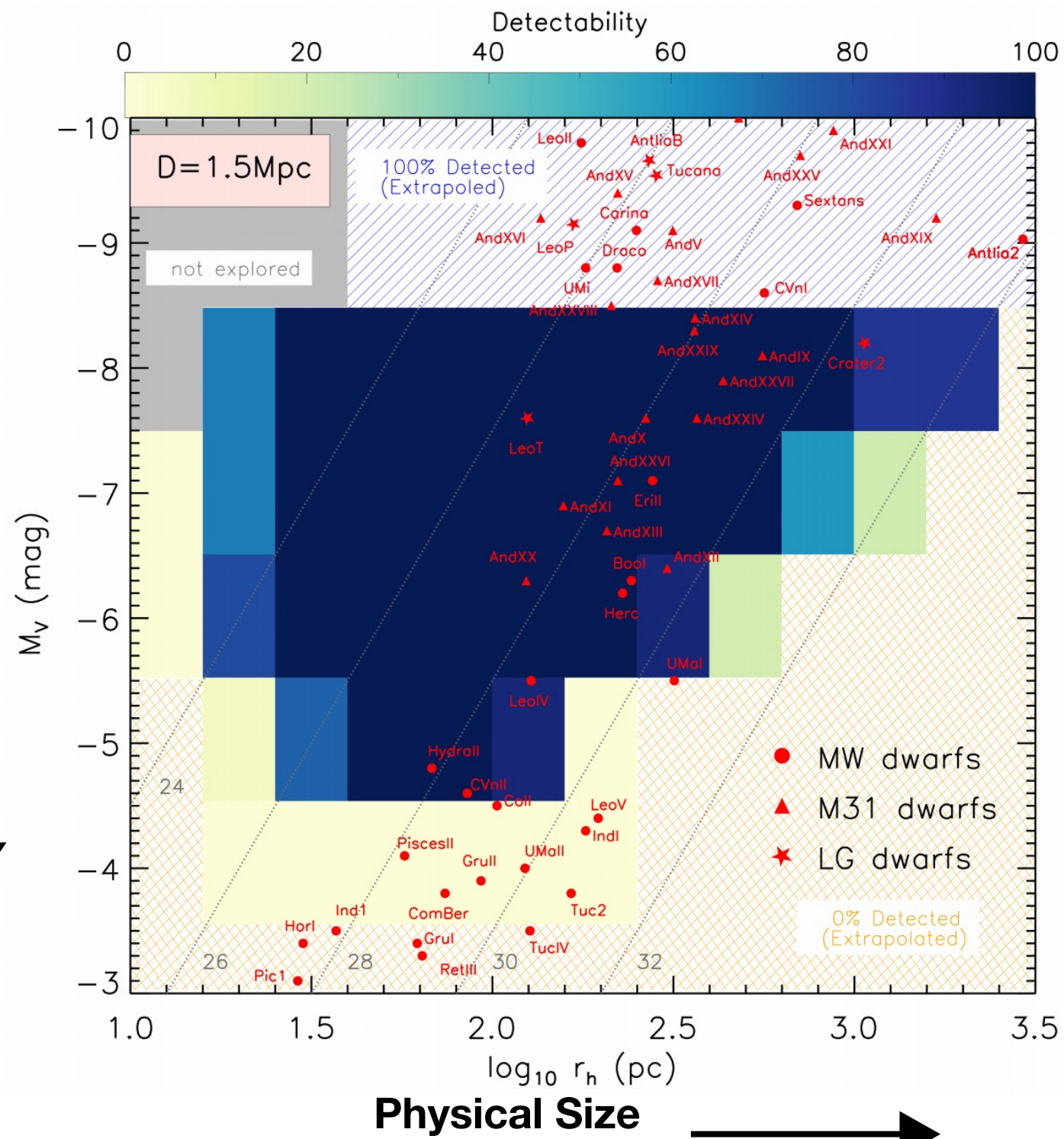
Rubin Observatory



A Preview of What is Possible in the Next Decade

Mutlu-Pakdil et al. 2021

Fainter
↓

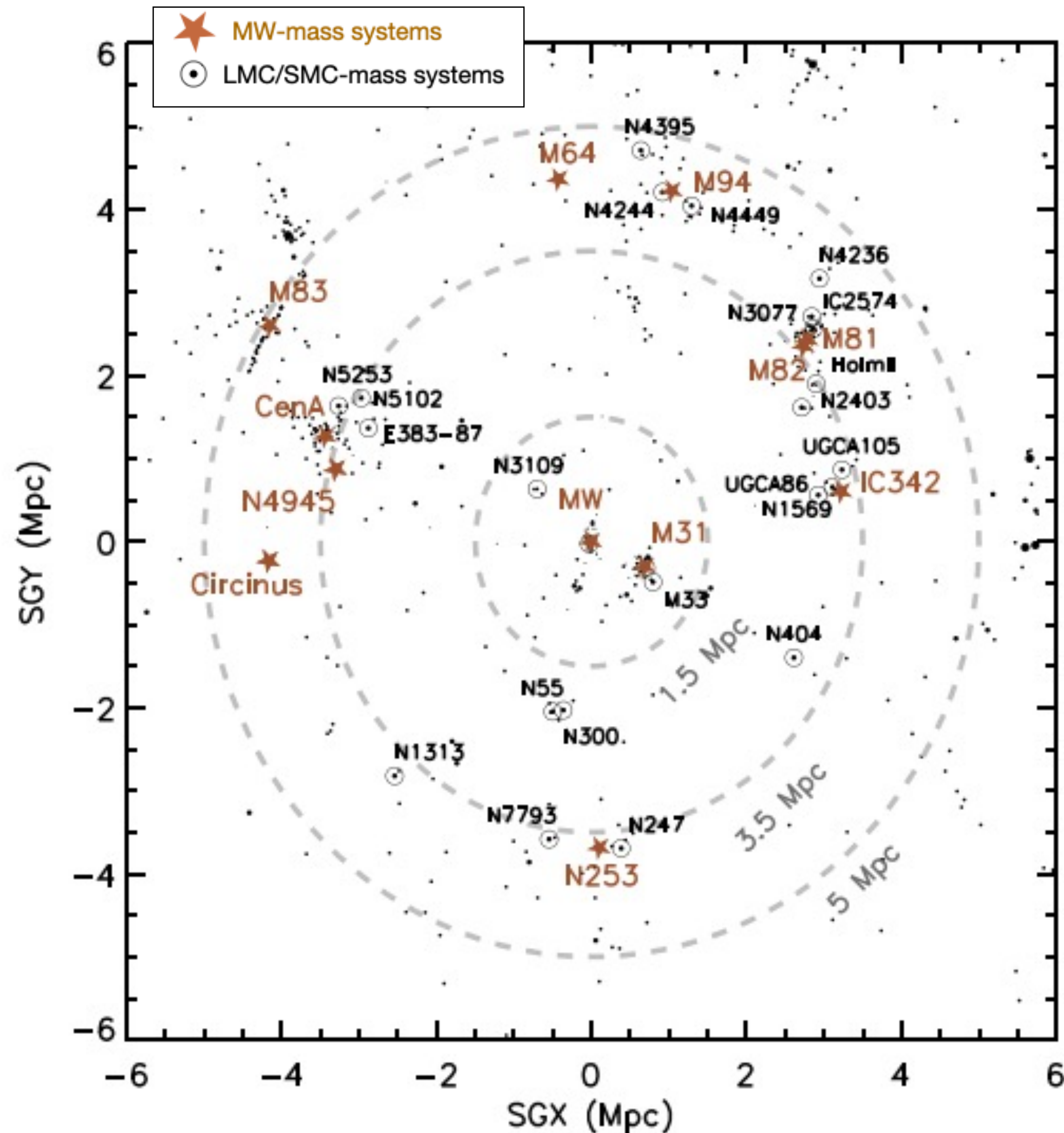


Fill out the census at 1.5 Mpc
down to $M_V \sim -5$

Fill out the census at 3.5 Mpc
down to $M_V \sim -7$

Fill out the census at 5 Mpc
down to $M_V \sim -8$

A Preview of What is Possible in the Next Decade



It will be possible to push the discovery frontier not just within our own Local Group, but well into the Local Volume in all environments

Mutlu-Pakdil et al. 2021

TAKE AWAY NOTES:

- 1) DES revolutionized the Milky Way Science with discoveries of dwarf galaxies, globular clusters, and stellar systems with extremely low luminosity.**
- 2) DES inspired many observational efforts to understand newly discovered systems and expand searches beyond the Local Group.**
- 3) Current frontiers are DELVE, S⁵, PISCES, and MADCASH Surveys.**
- 4) The coming decade is going to be rich in discoveries with Rubin/LSST.**