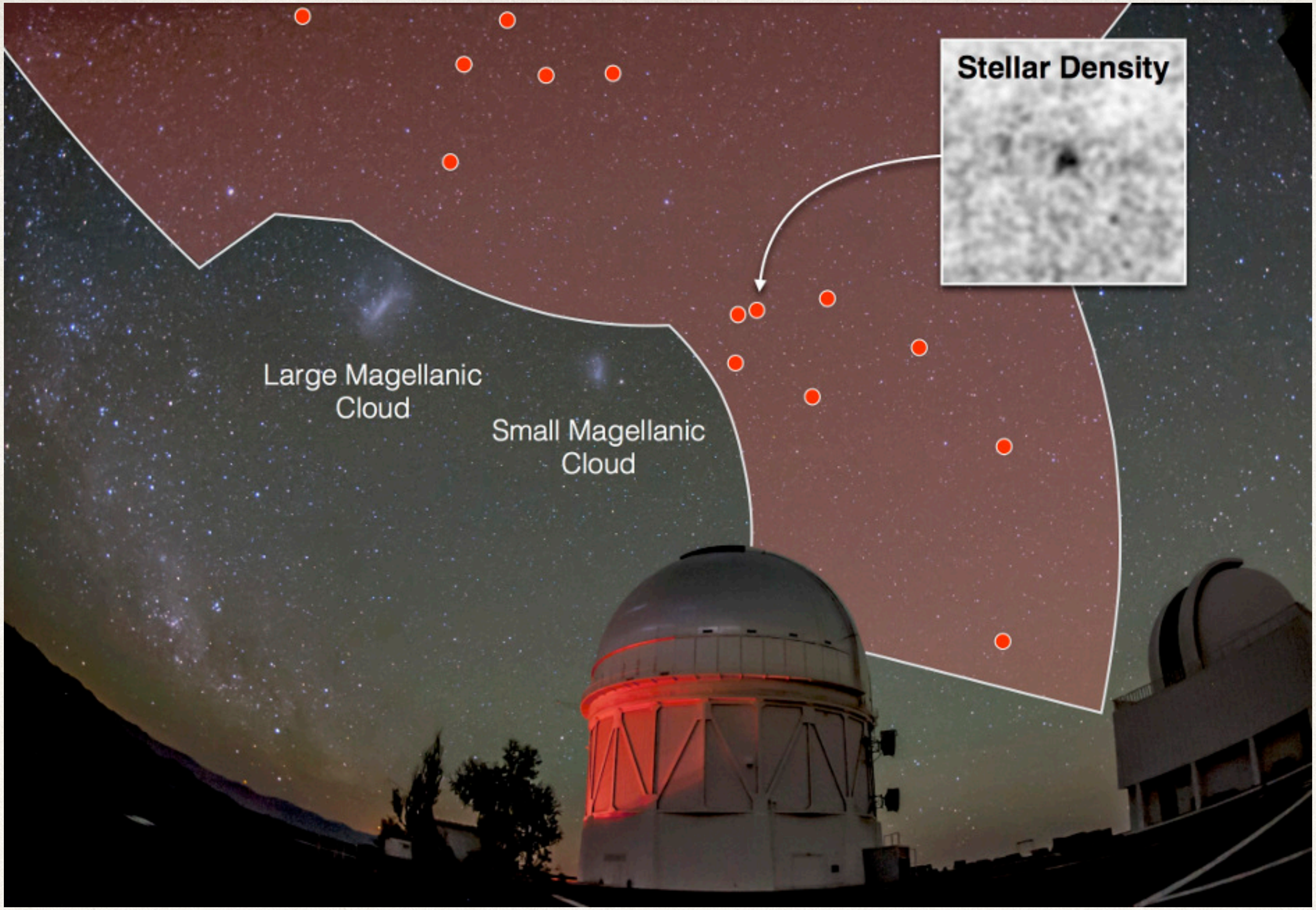


Ultra-Faint Dwarf Satellites of the Milky Way and their relationship with the Galactic Halo

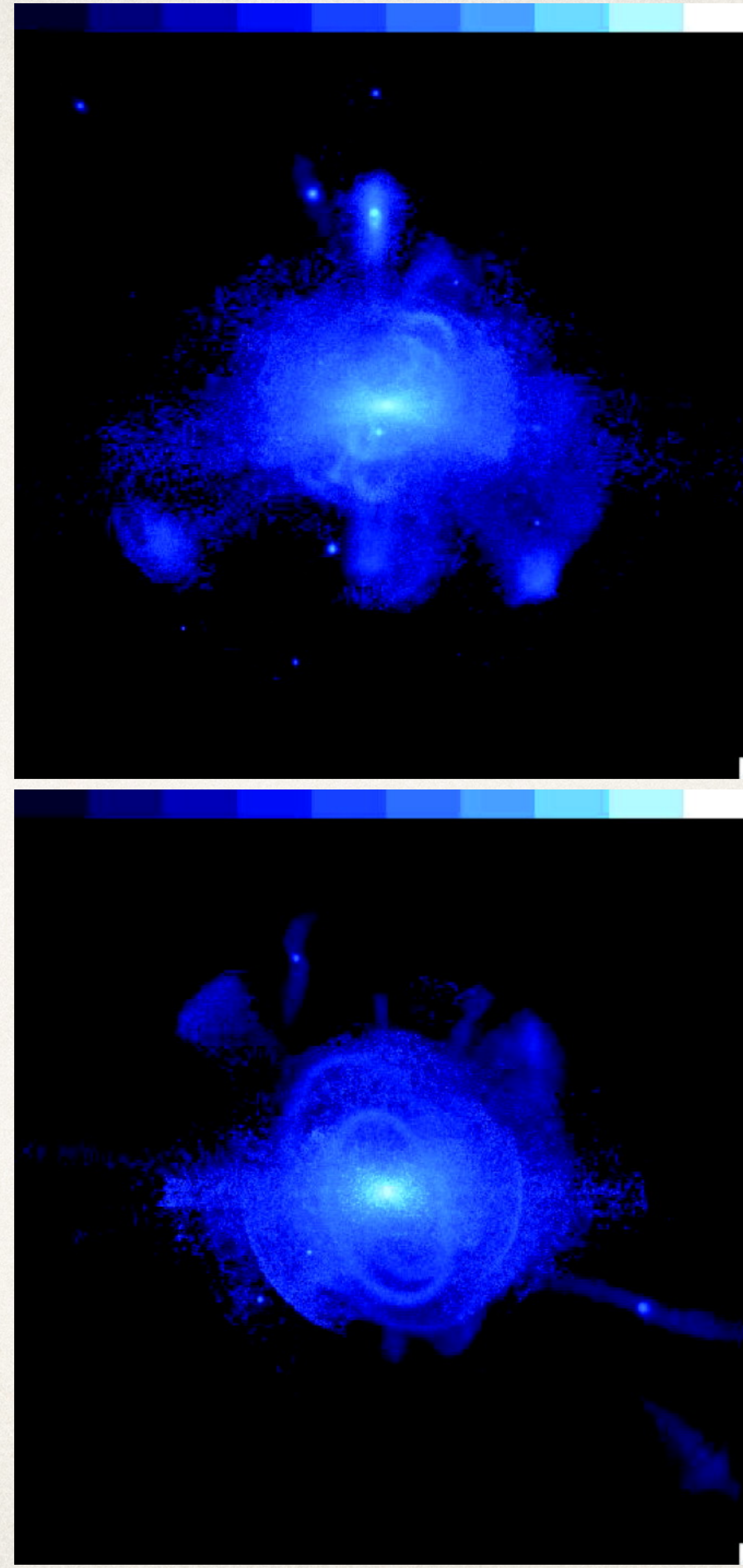
Kathy Vivas, Cerro Tololo Inter-American Observatory, NSF's NOIRLab, La Serena, Chile

Universidad de Chile, Octobre 2020

Hierarchical Formation of Galaxies

- In a hierarchical formation scenario, galaxies like the Milky Way should have accreted ~100-200 satellite galaxies
- Multiple substructure should be visible, specially in the outermost parts of the Halo

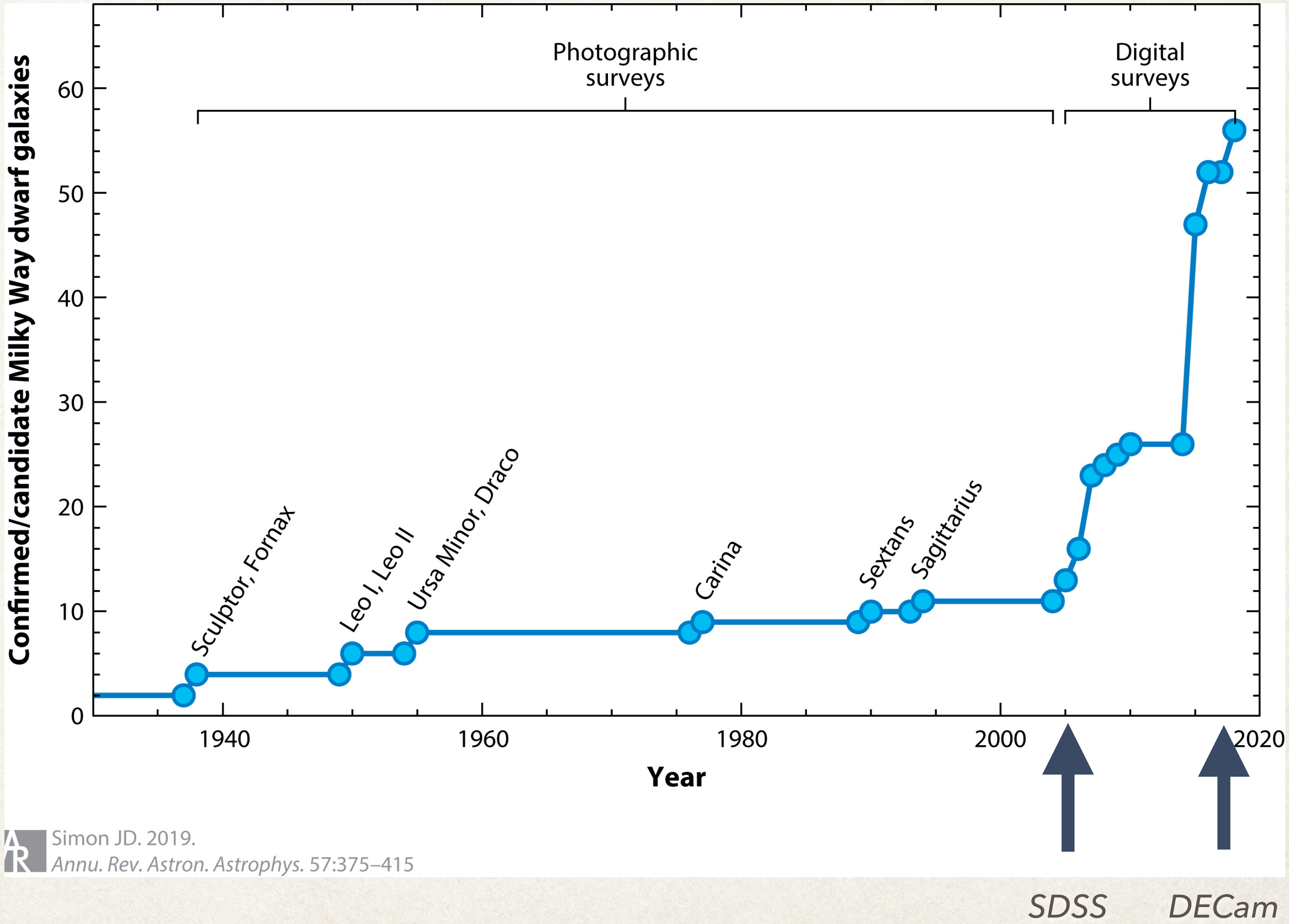
It is important to characterize the stellar populations of the satellites to understand the accretion history of the Milky Way



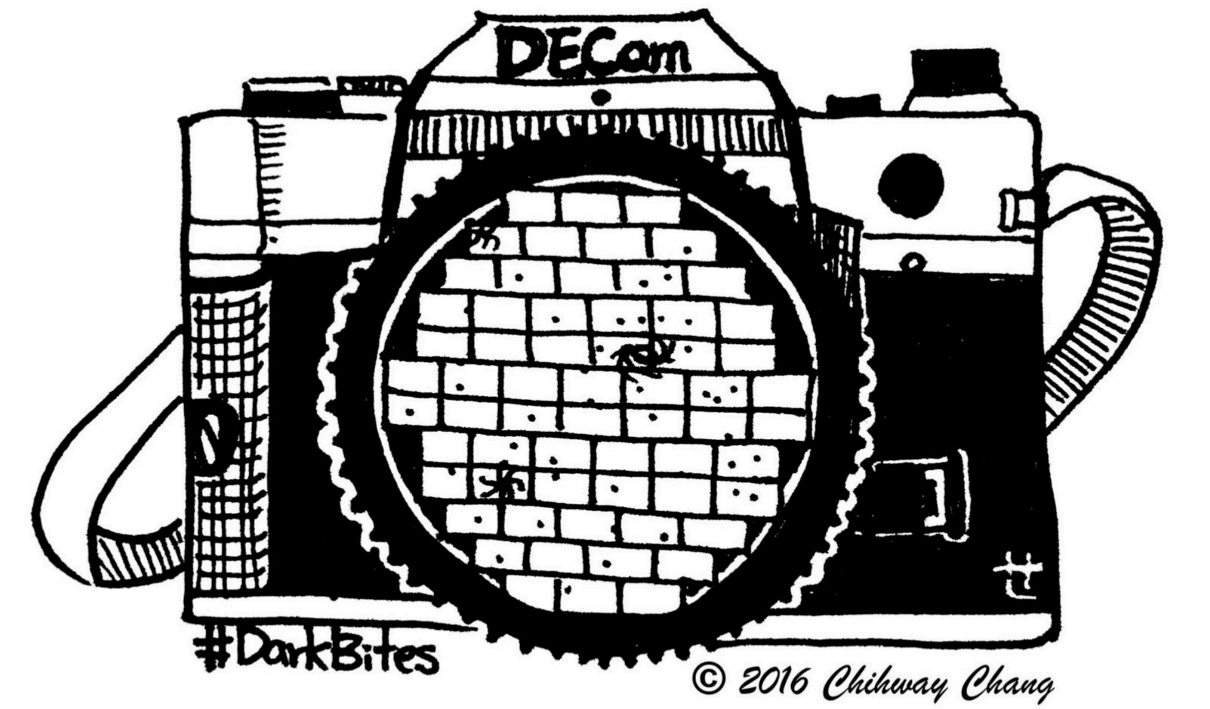
Bullock & Johnston (2005)

New satellite galaxies of the Milky Way

- ~60 satellite galaxies around the Milky Way
- Large surveys with wide-field cameras have allowed the discovery of many new satellites in recent years
- Many of the new discoveries may be associated with the Magellanic Clouds



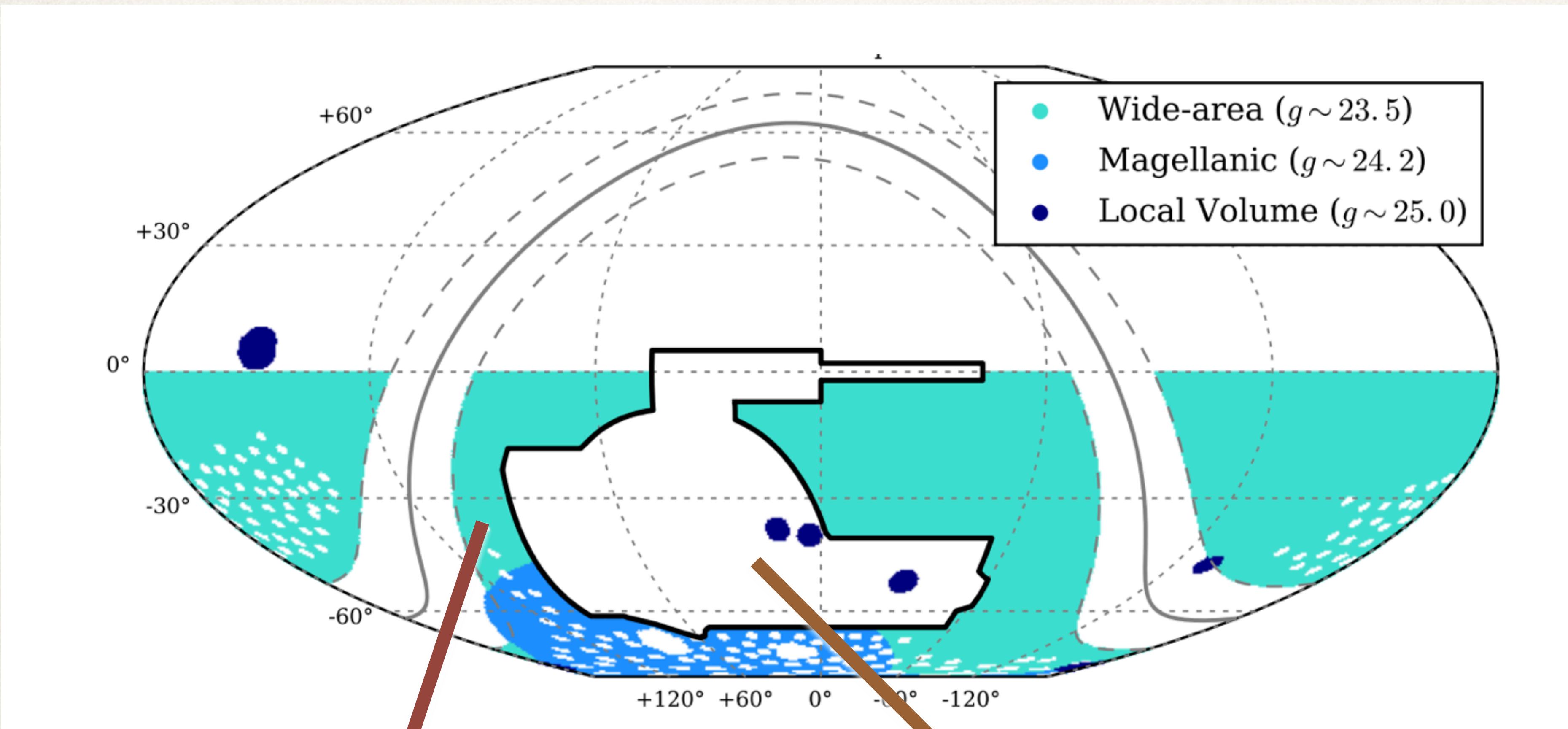
Dark Energy Camera (DECam) @ CTIO



The Dark Energy Camera: the world's largest digital camera (570 megapixels) and our instrument for the Dark Energy Survey. For comparison, the iPhone 6 has an 8 megapixel camera.

- 570 Megapixels
- 62 science CCDs
- Field of view of 3 sq degrees
- Very efficient
- Ideal for surveys
- Installed at the Blanco in 2012

Dark Energy Survey (DES) and other DECam surveys



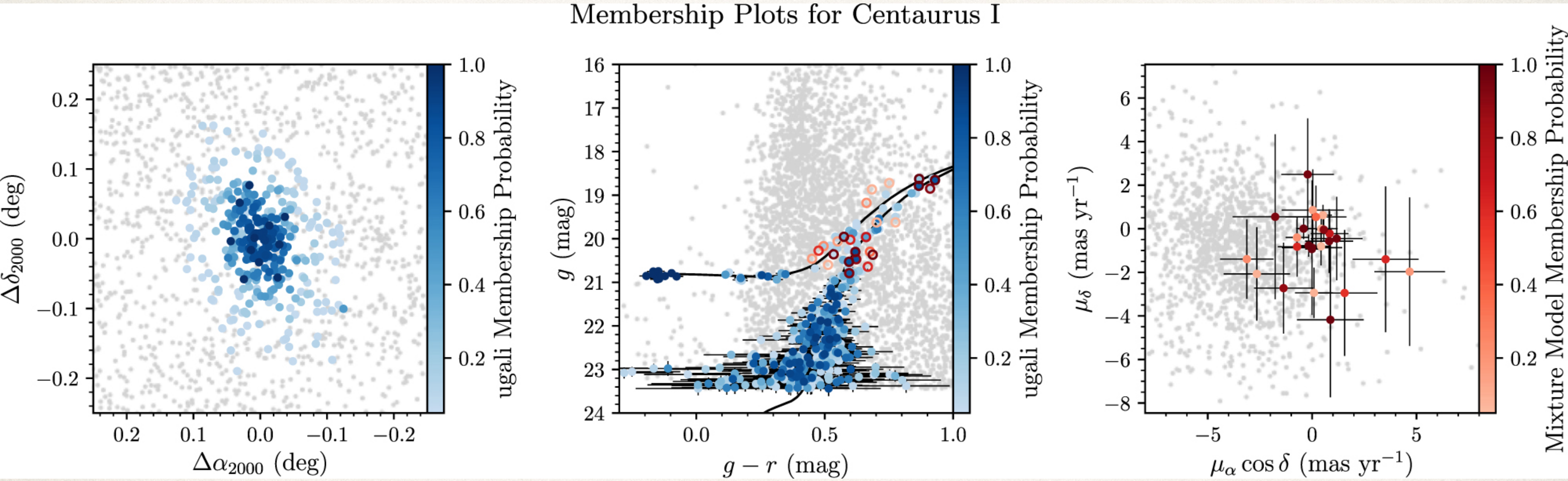
- **DES**
- SMASH
- MagLiTES
- **DELVE**

DELVE: 10500 sq degrees in 2 bands (g~23.5)

DES: 5000 sq degrees in 5 bands (g~24.5)

Other discoveries also with Pan-STARRS, ATLAS, and HSC

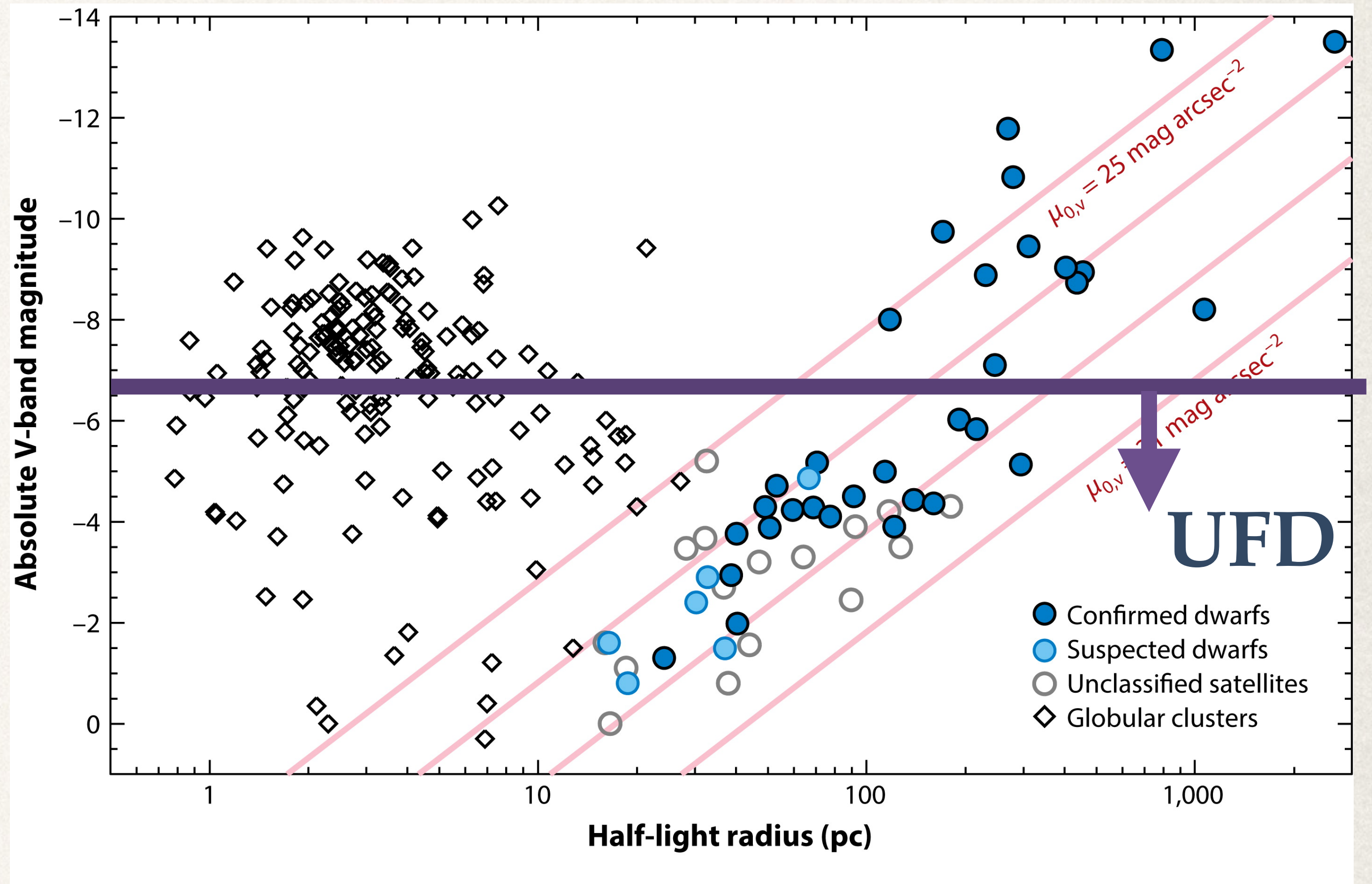
New galaxy in DELVE survey: Centaurus I



Mau et al 2020

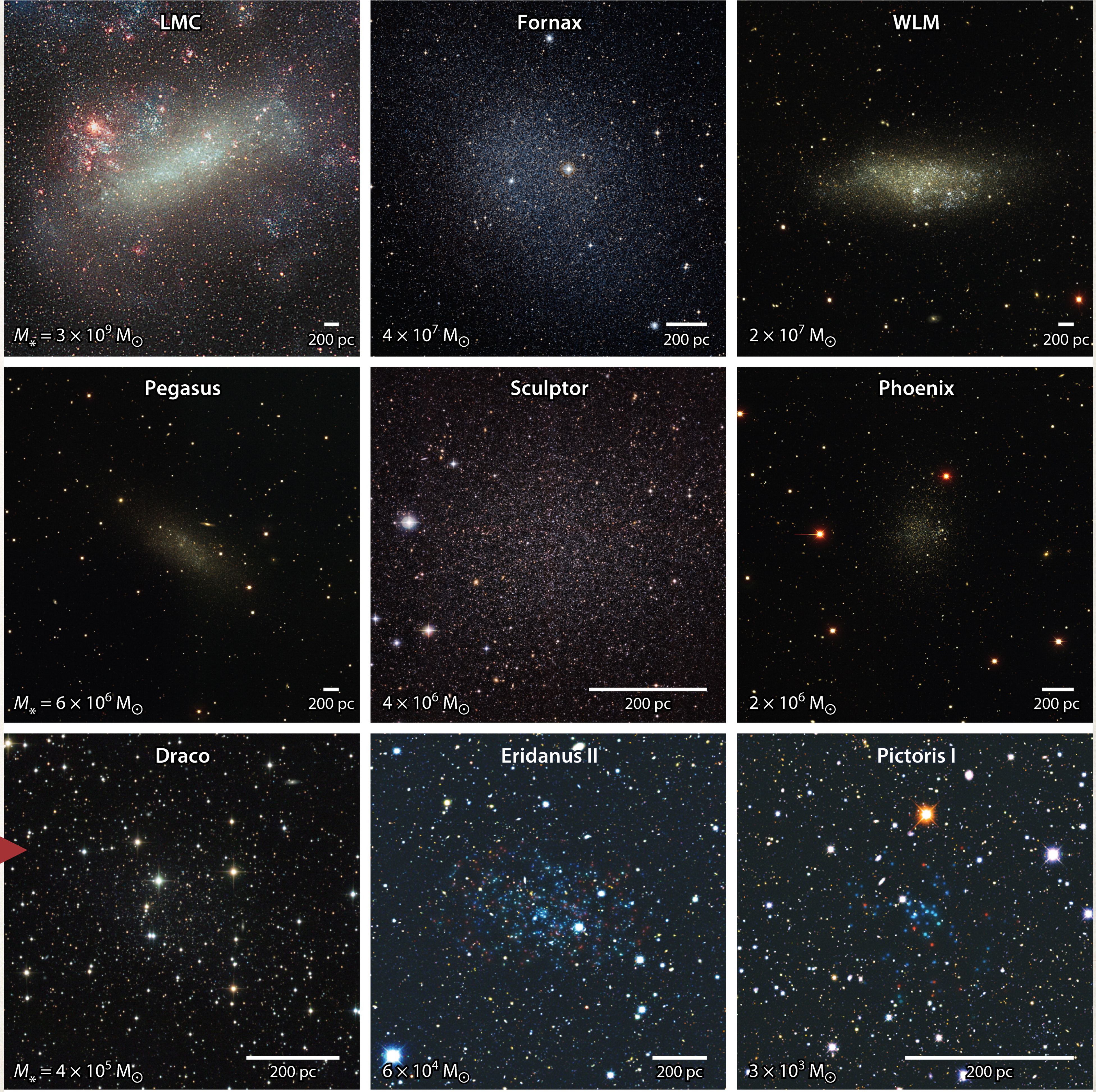
New galaxies: challenges ahead

- Many of the new discoveries in a regime diffuse region between globular clusters and ultra-faint dwarfs —> **Confirmation is needed**
- Distance is not necessarily easy to measure



Simon JD. 2019.
Annu. Rev. Astron. Astrophys. 57:375–415

- Faint
- Small
- Large contamination by for / background
- Old population, metal-poor

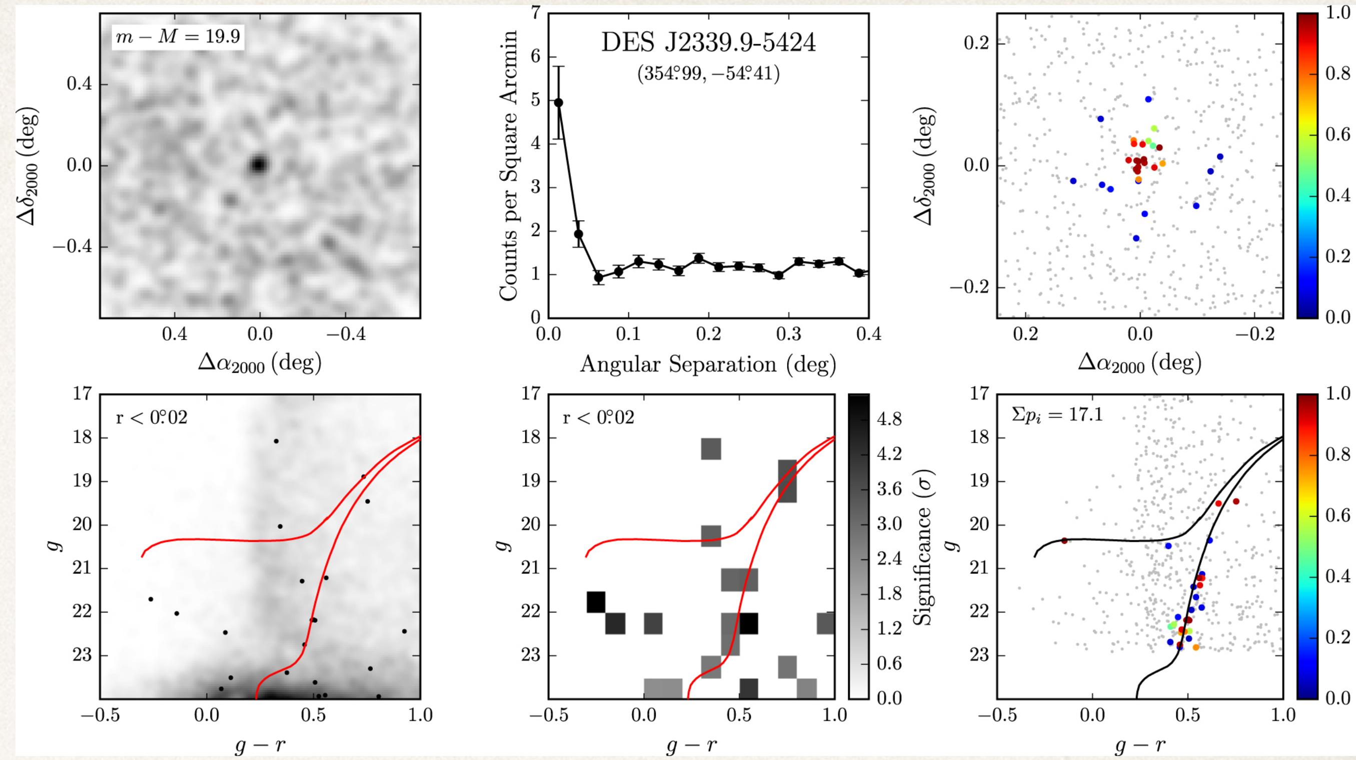


Bullock JS, Boylan-Kolchin M. 2017.
Annu. Rev. Astron. Astrophys. 55:343–87

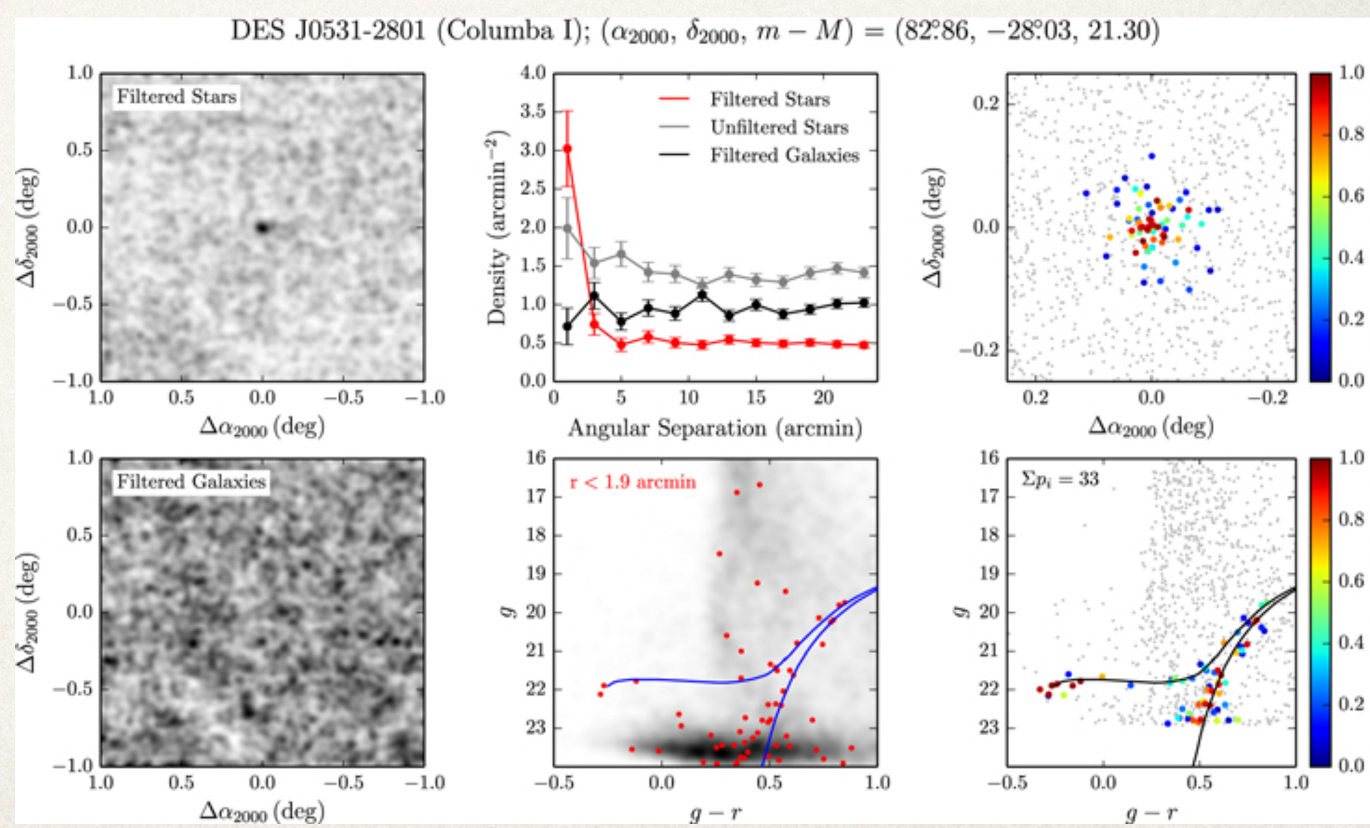
New galaxies: challenges ahead

- Scarcity of stars, particularly in the upper part of the CMD
- Turn-off not readily available for distant systems

Follow-up is needed



Phoenix II, *Bechtol et al (2015)*

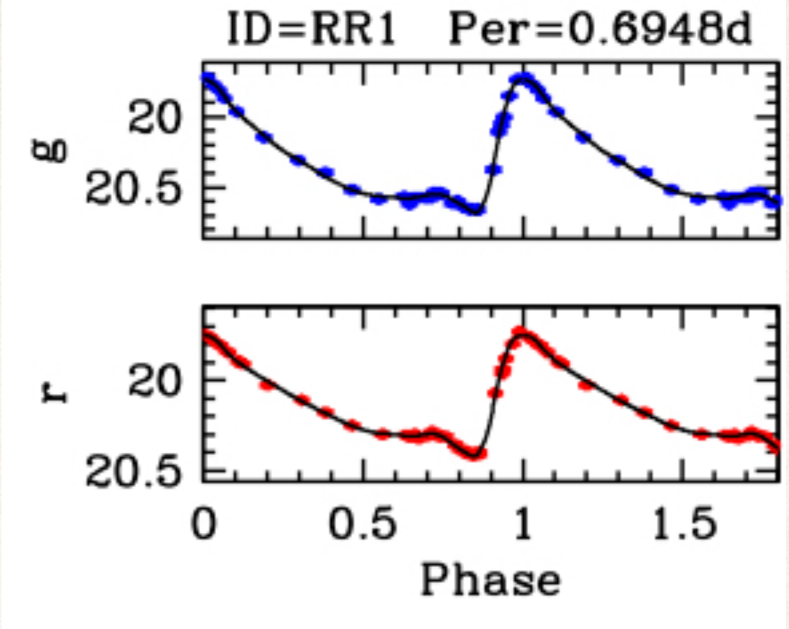


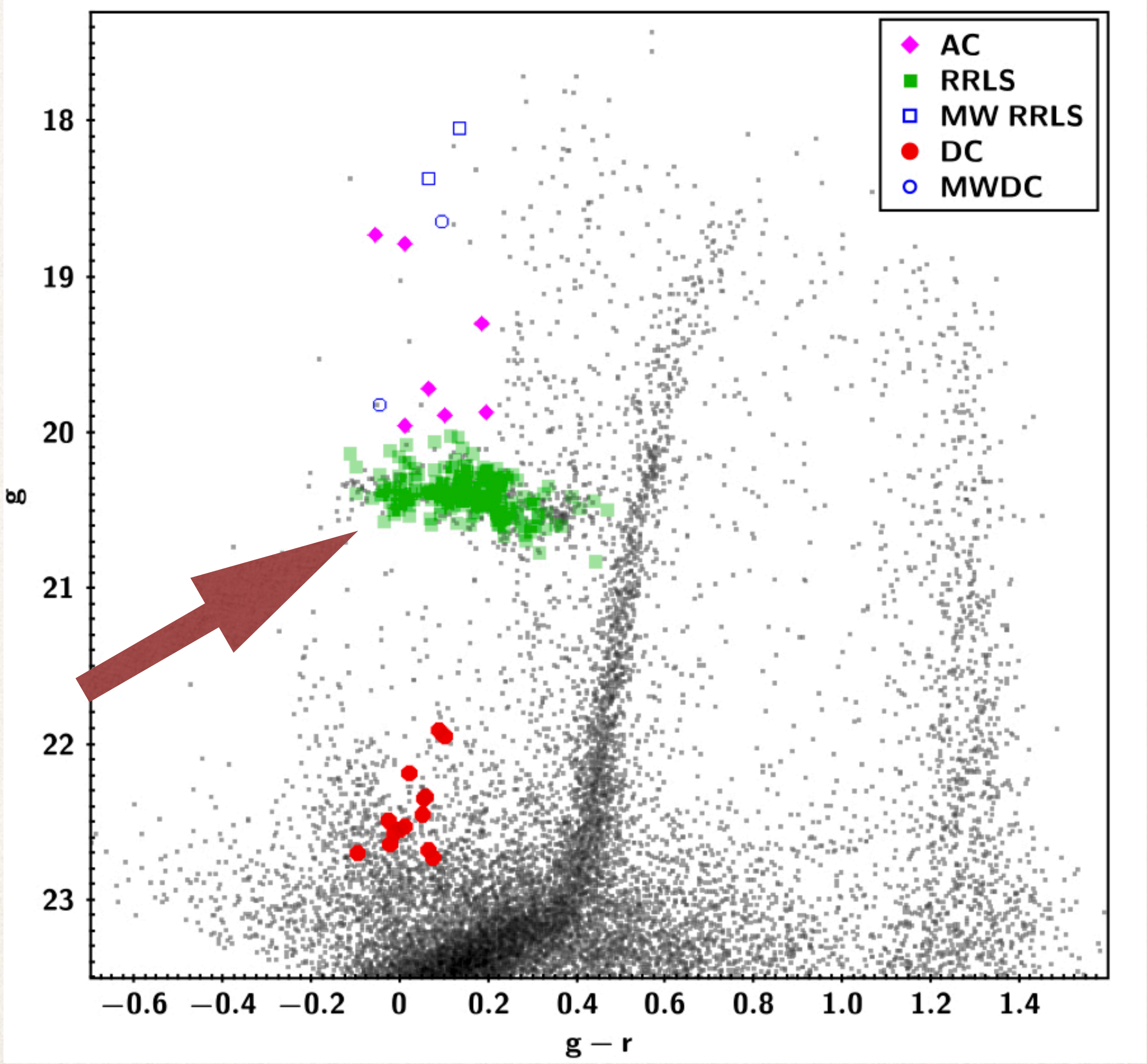
Columba I, *Drlica-Wagner et al (2015)*

RR Lyrae Stars

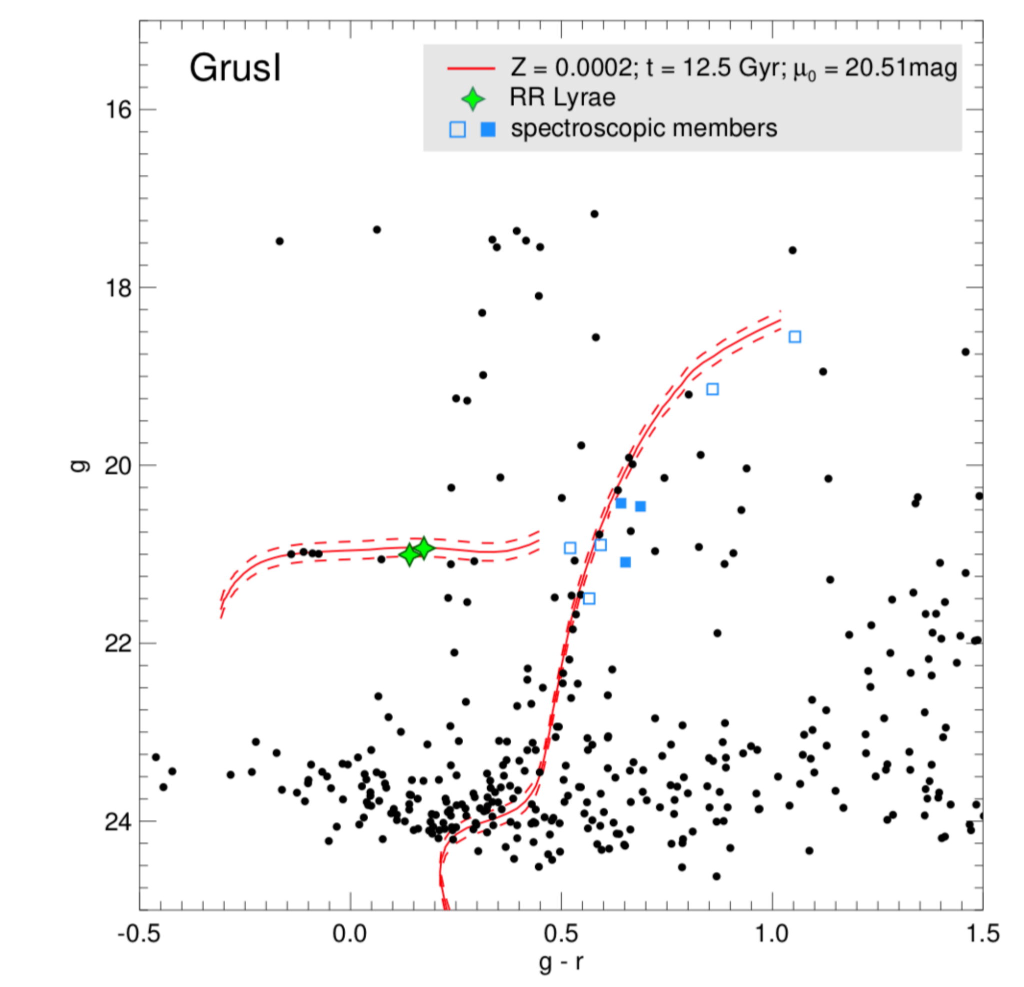
- Excellent standard candles
- Old stars (>10 Gyrs): and **UFDs are dominated by old population.** ~~ALL~~ MOST satellites have at least 1 RR Lyrae star.
- Horizontal branch stars (i.e. relatively bright)
- Easy to recognize using time-series
- Pulsational properties may give clues on origin of population

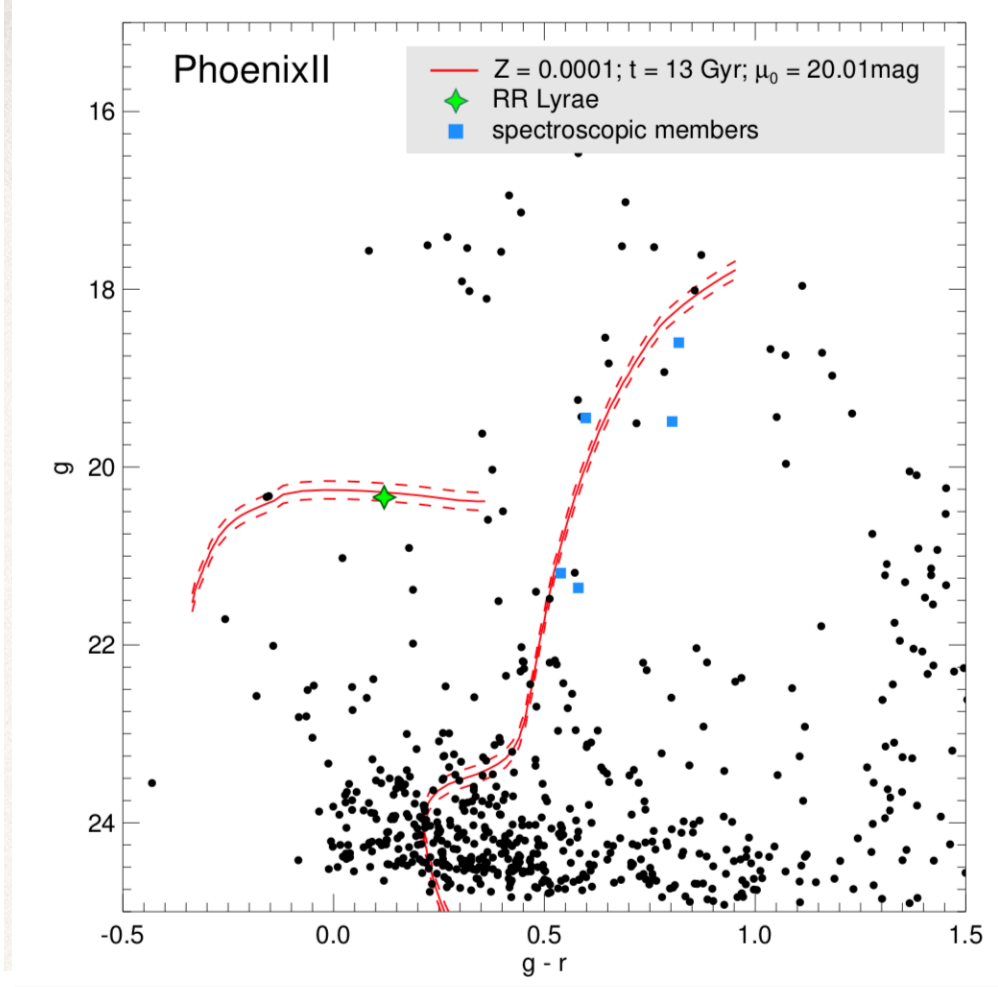
Ongoing observational program to search for RR Lyrae stars in new satellites

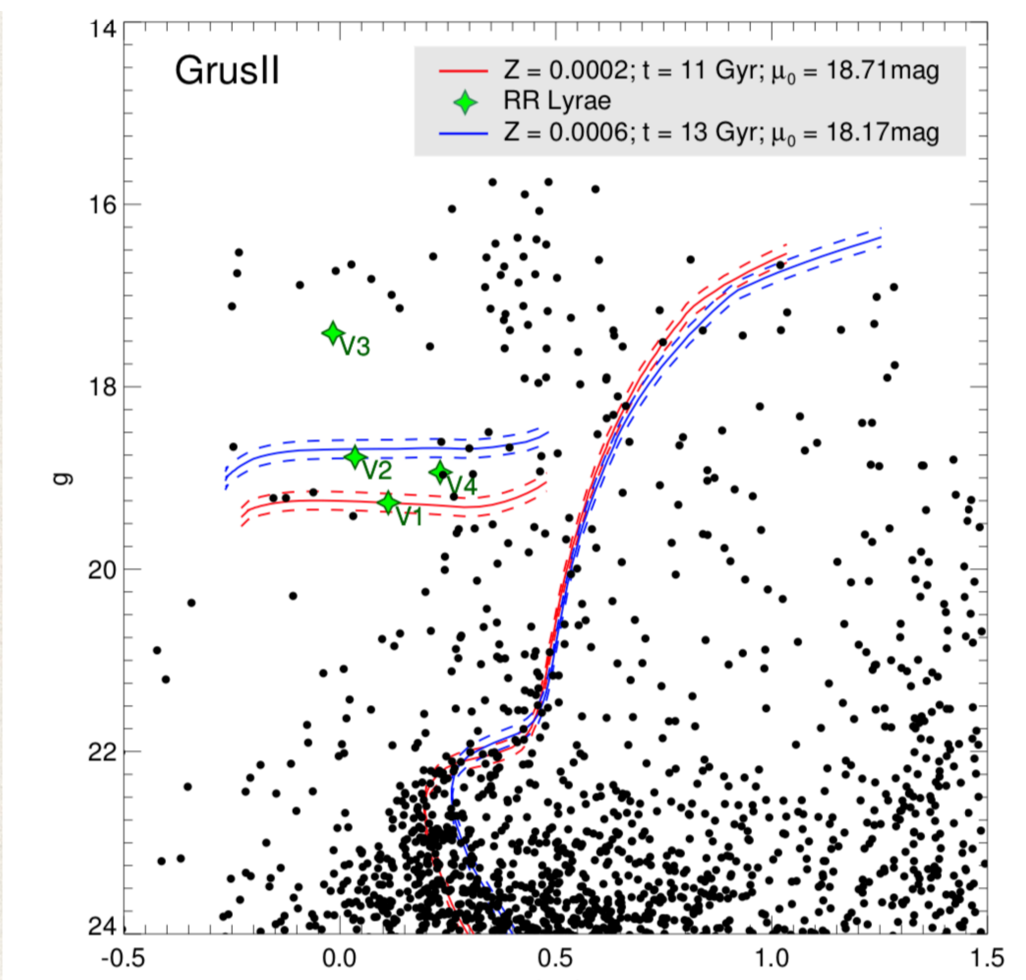




Sextans *(Vivas et al 2018)*







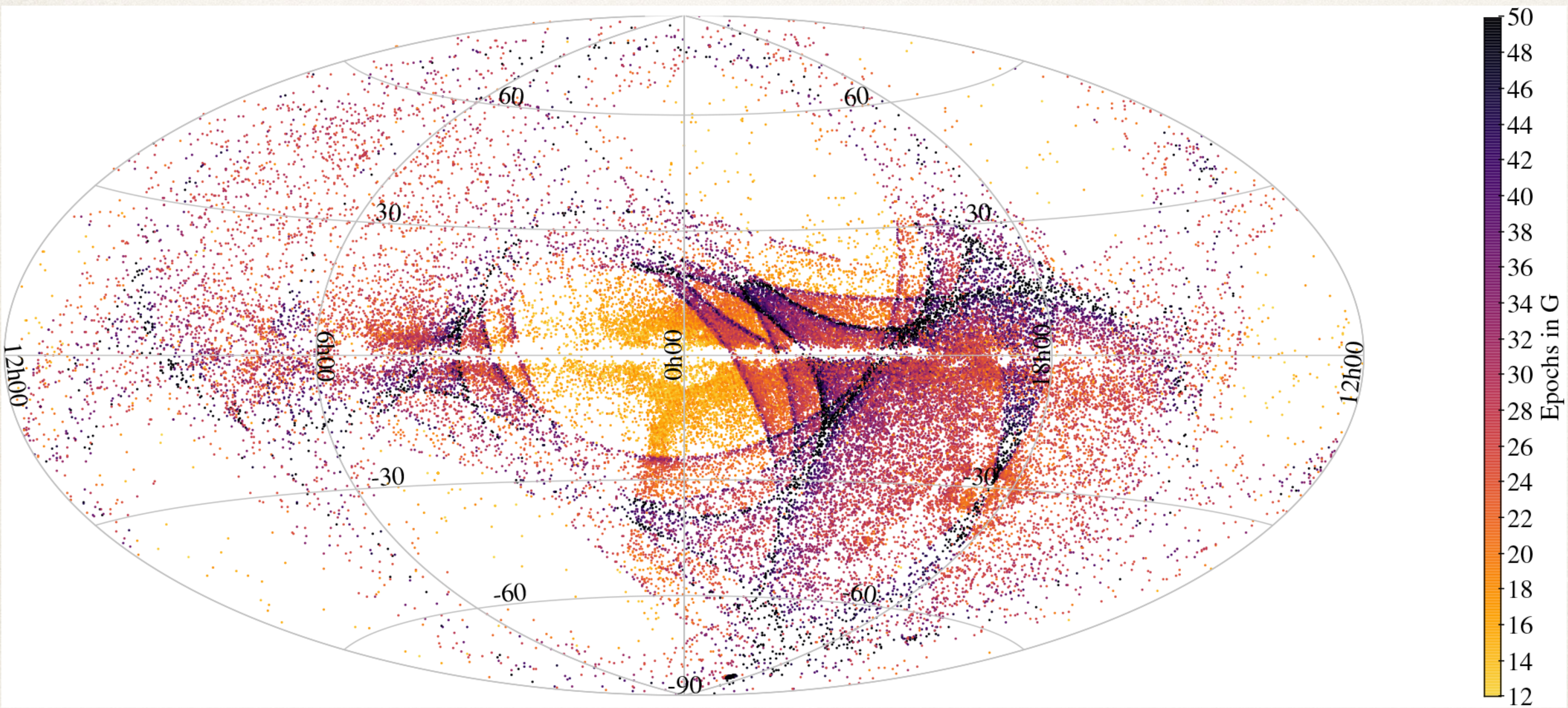
- Follow-up program with SOAR and DECam
- Recent results in **Martínez-Vázquez et al 2019**
- UFDs have very few RR Lyrae stars

Using Gaia DR2

(with C. Martínez and A. Walker)

- 140,784 RR Lyrae stars in Gaia DR2
- Magnitudes 9 < G < 21 → ~100 kpc
- All sky but **not complete** (~60%)
- **There are 27 UFDs within Gaia's limits**

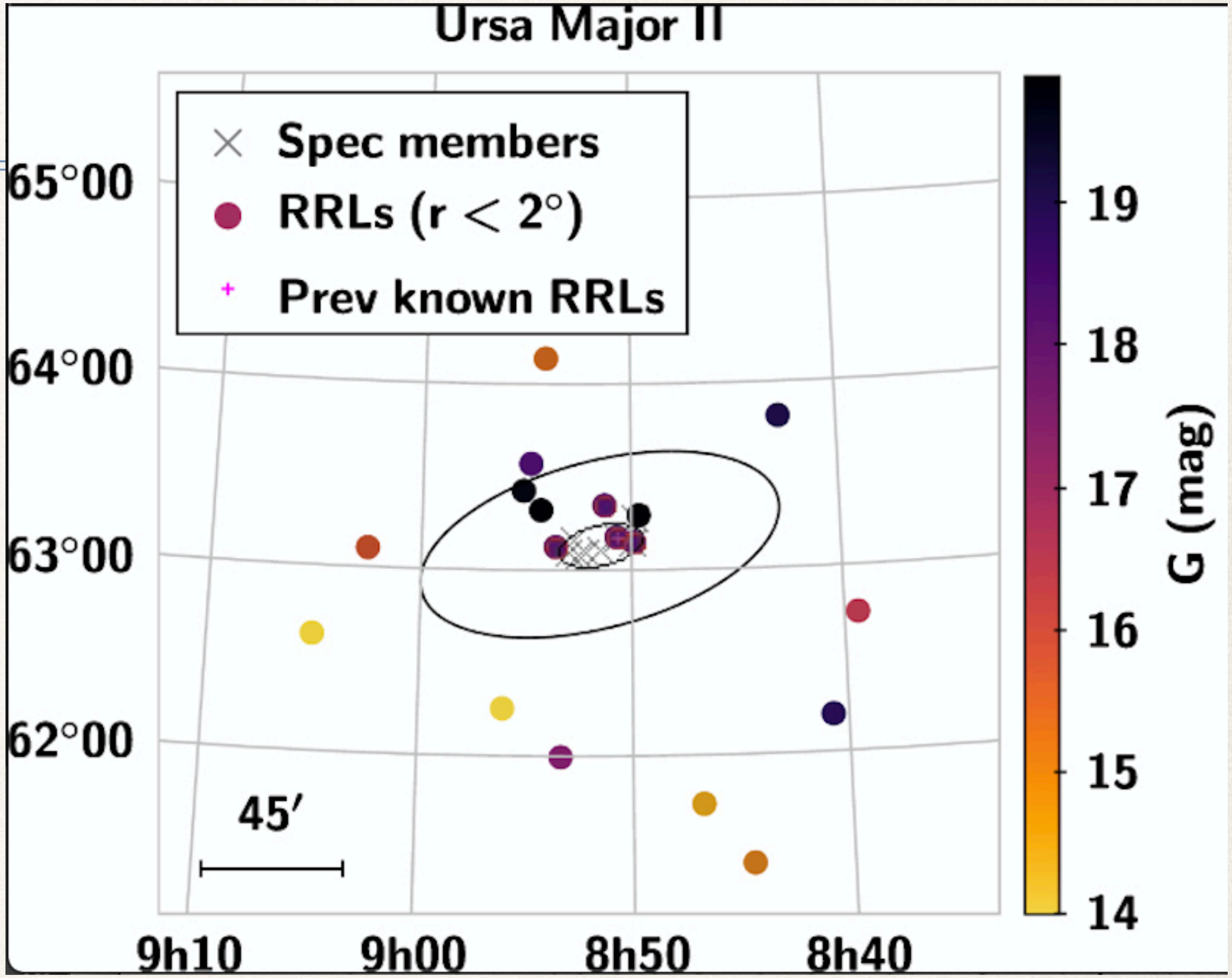
Clementini et al. 2019



Method

Vivas et al 2020

- Compile data (structural parameters, distance) for all 27 UFDs within 100 kpc (thanks Ricardo Muñoz for your wonderful papers!).
- Proper motion of known members in the UFD mostly from Simon 2018 and Pace & Li (2019)
- Find stars based in spatial distribution, proper motion and location in the CMD

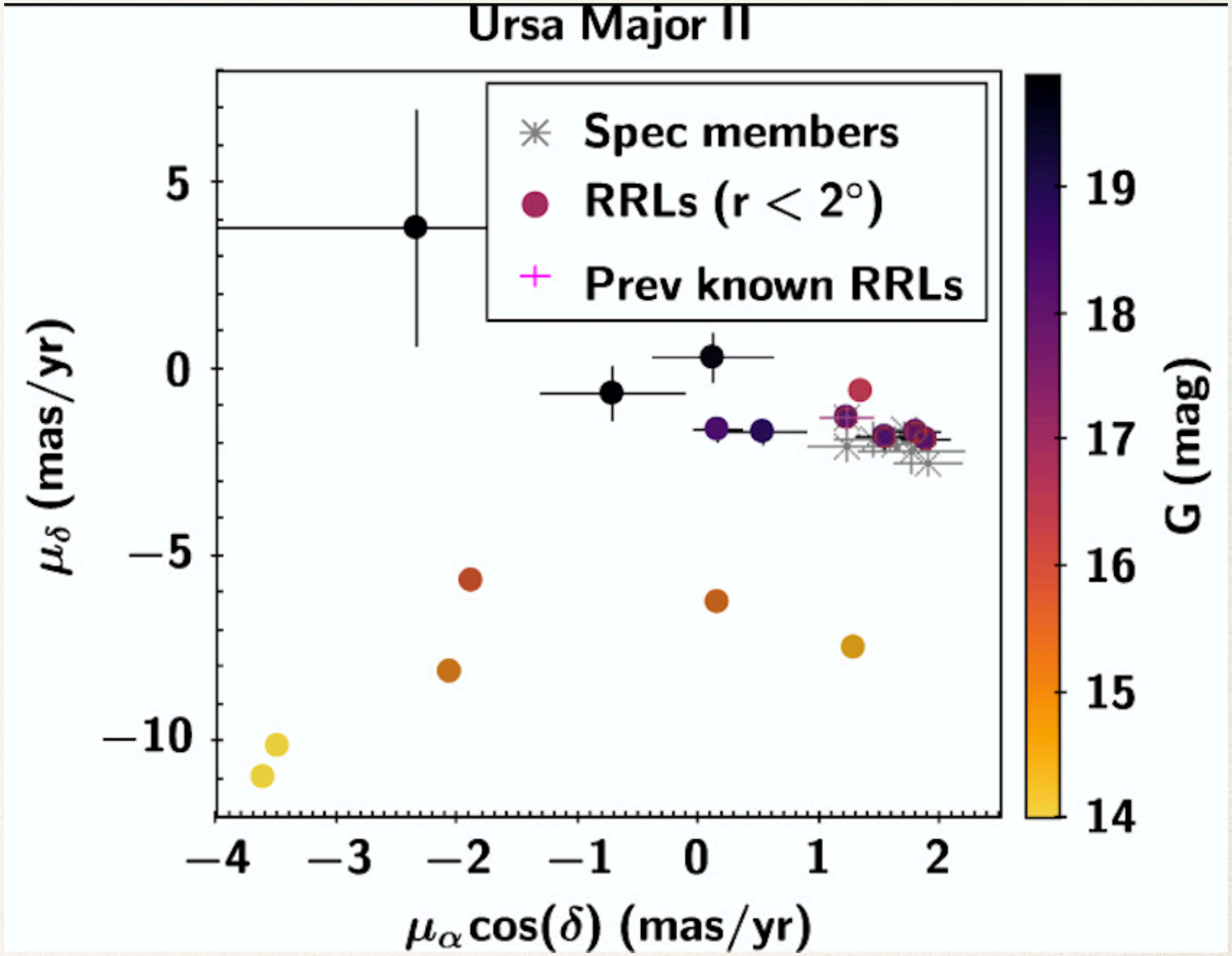


We look in an extended area to search for possible extra-tidal material

Method

Vivas et al 2020

- Compile data (structural parameters, distance) for all UFDs (thanks Ricardo Muñoz for your wonderful papers!).
- Proper motion of known members in the UFD mostly from Simon 2018 and Pace & Li (2019)
- Find stars based in spatial distribution, proper motion and location in the CMD

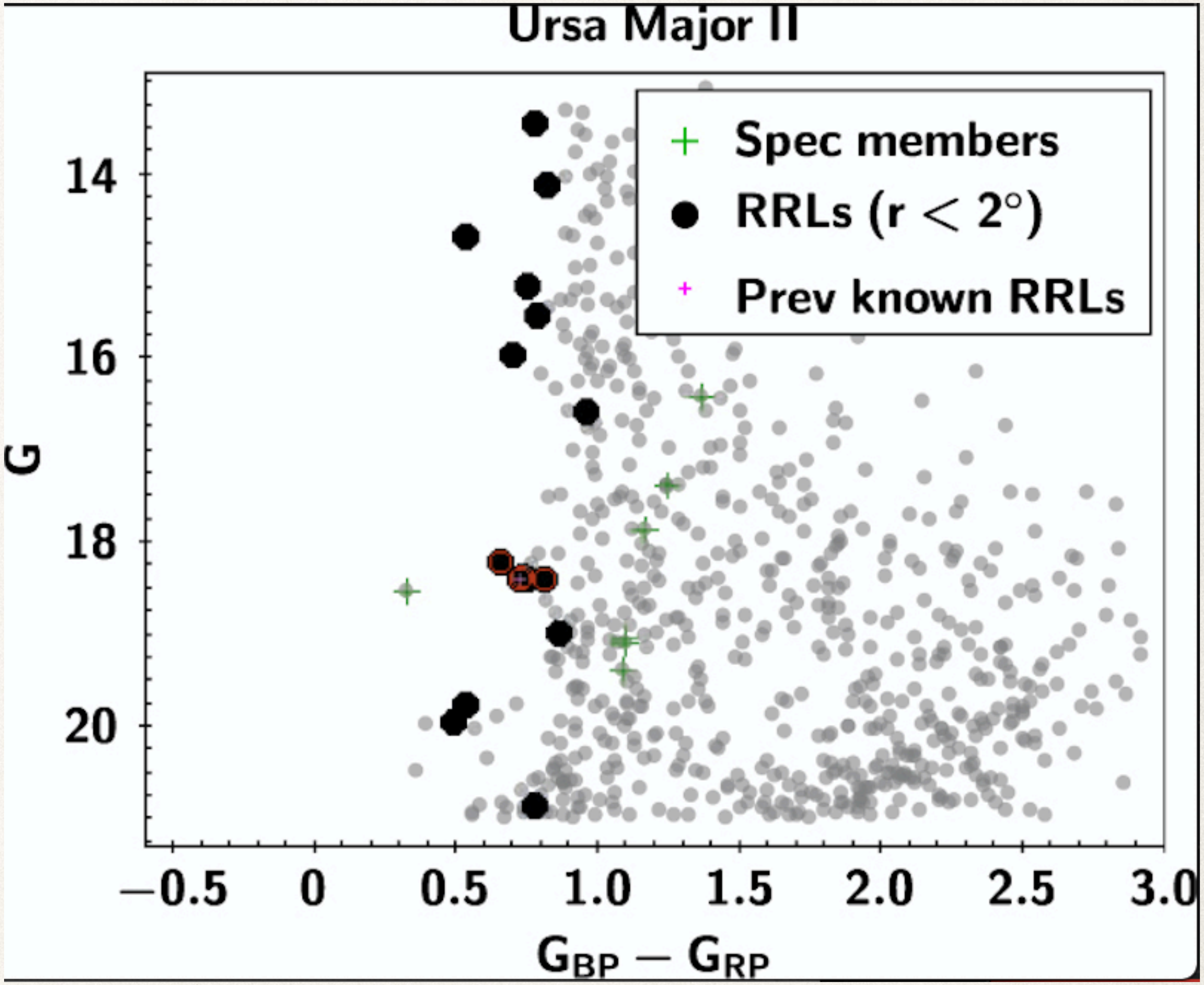


Most stars are rejected based on their proper motions

Method

Vivas et al 2020

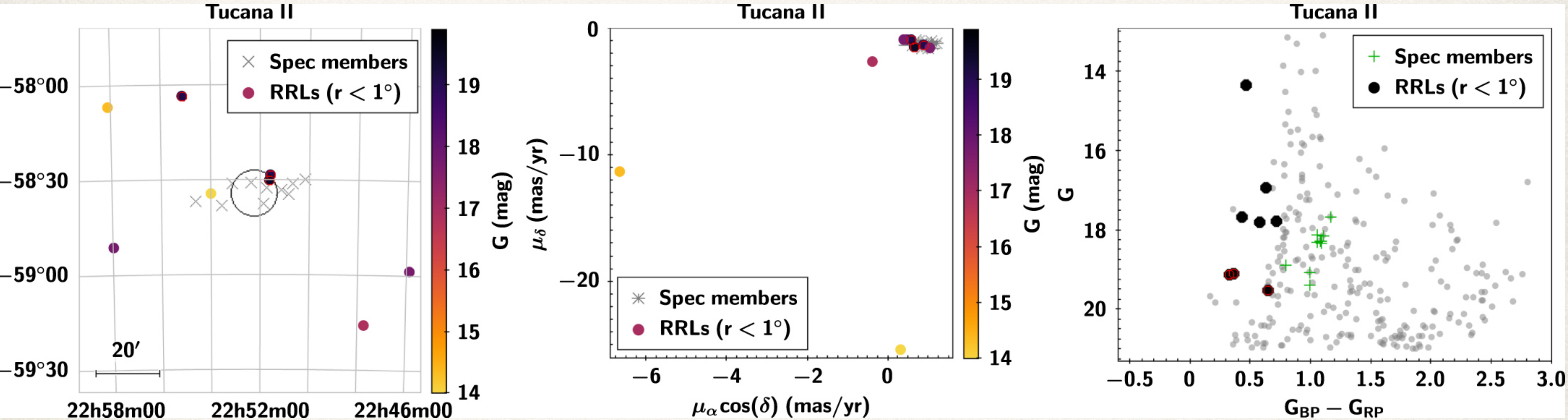
- Compile data (structural parameters, distance) for all UFDs (thanks Ricardo Muñoz for your wonderful papers!).
- Proper motion of known members in the UFD mostly from Simon 2018 and Pace & Li (2019)
- Find stars based in spatial distribution, proper motion and location in the CMD



Ursa Major II has 4 RR Lyrae stars (only one was previously known)

First RR Lyrae detections in some UFDs

Vivas et al 2020

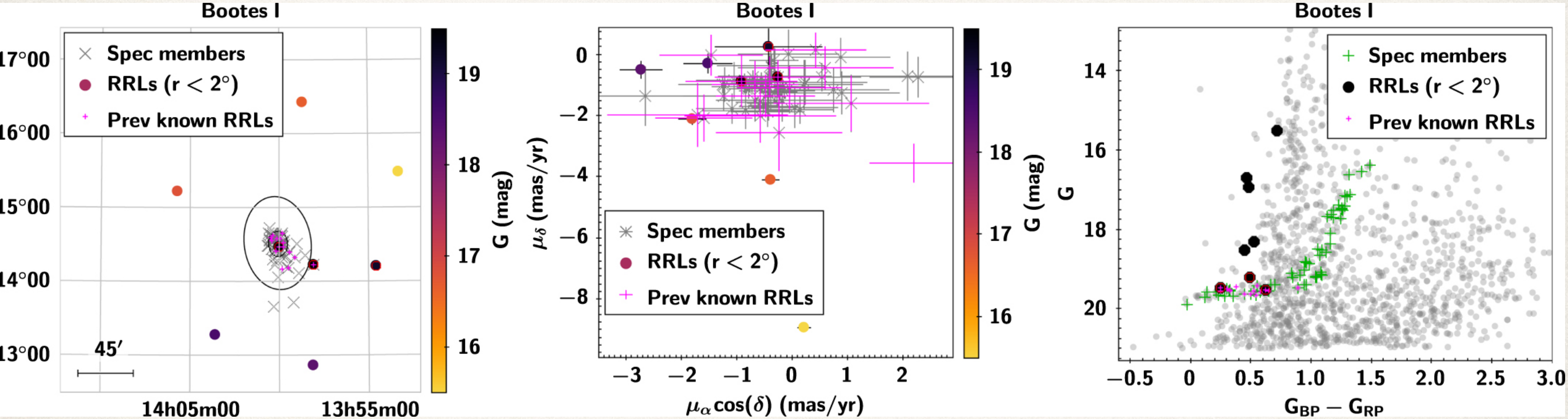


Tucana II has 3 RR Lyrae stars; one may be an extra-tidal star.

No RR Lyrae stars were previously known in this galaxy.

Completeness Issues

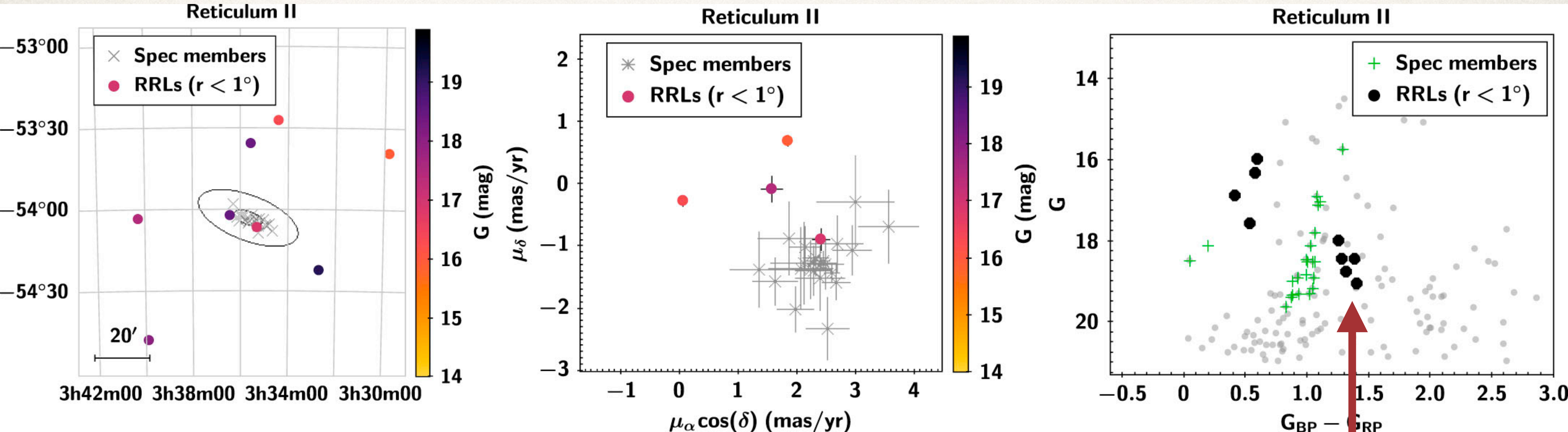
Vivas et al 2020



Bootes I had 15 RR Lyrae stars previously known.

Gaia DR2 recovered only 3 (one new, which is extra-tidal).

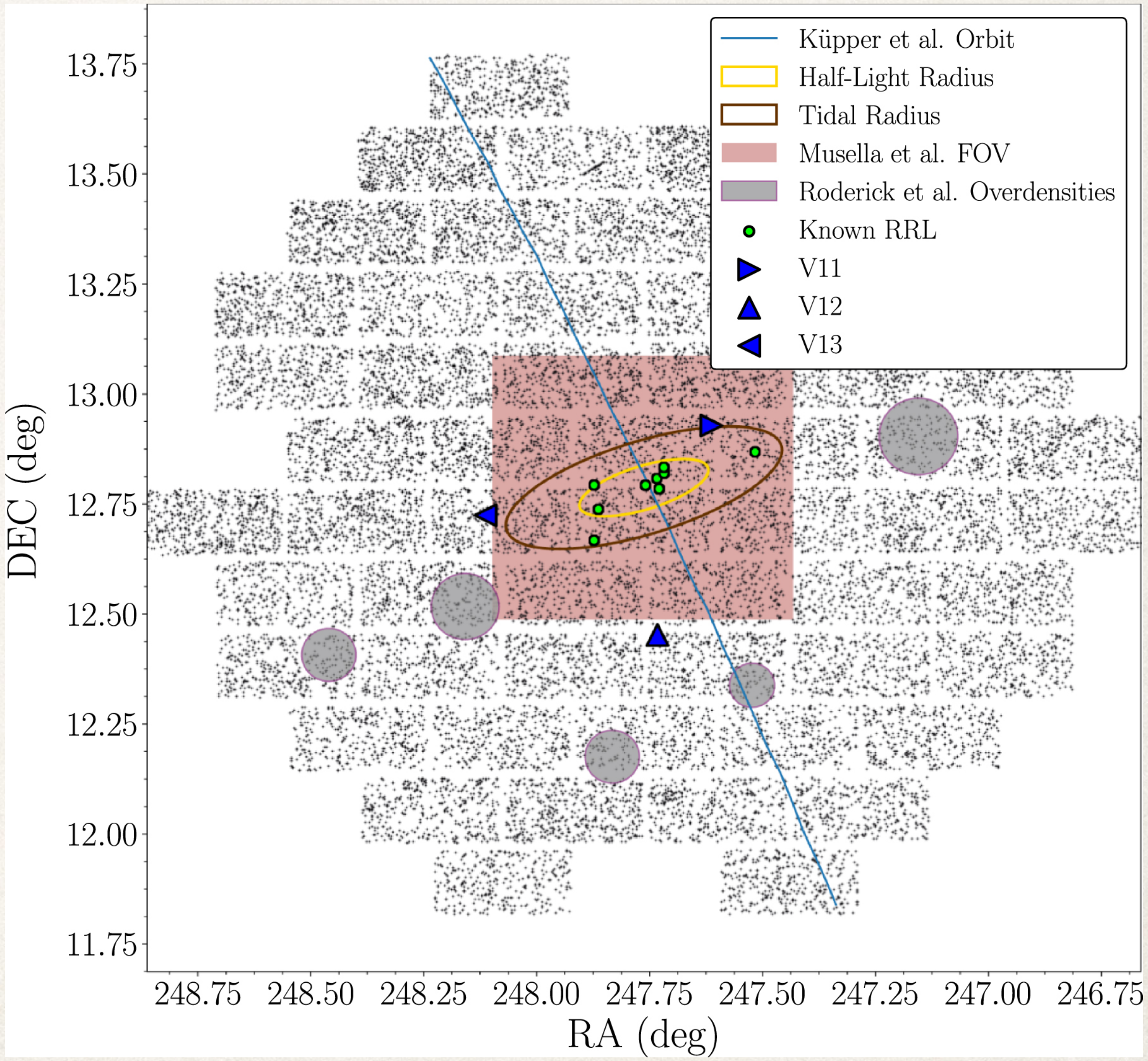
Bad identification problems



Wrong colors for RR Lyrae stars

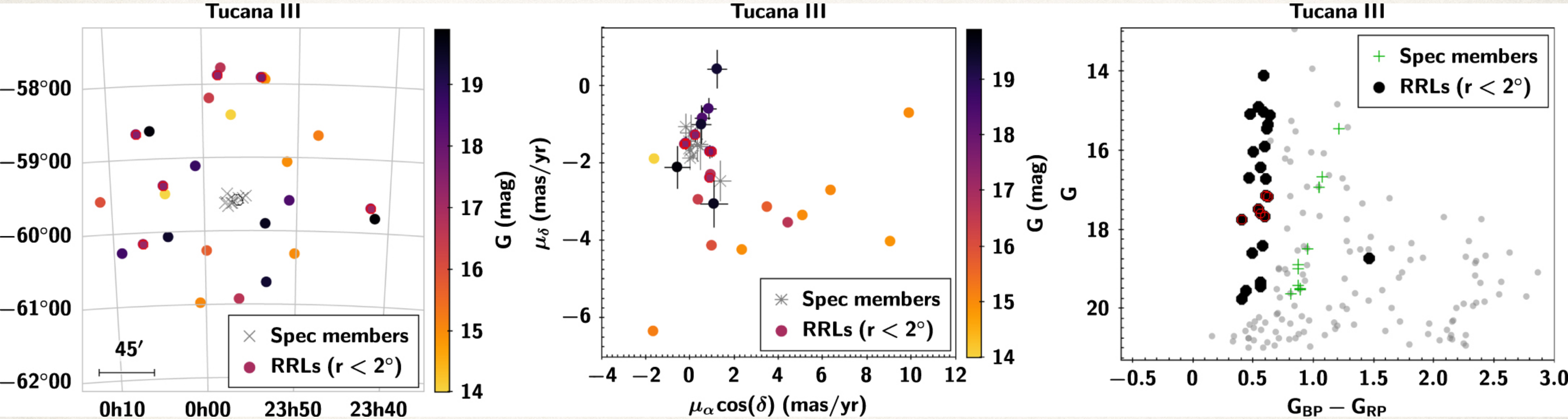
UFD Galaxies with extra-tidal RR Lyrae stars?

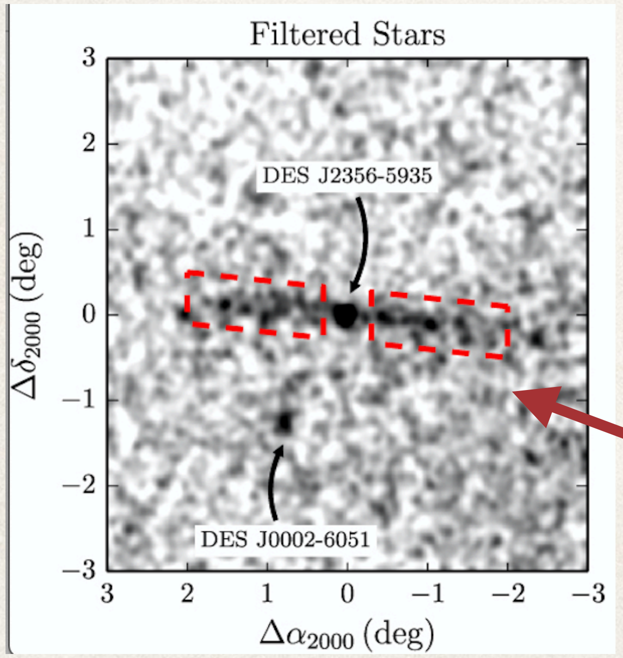
- This has already been seen already in the Hercules UFD by Garling et al (2019)
- RR Lyrae stars are a good tracer because the expected contamination by halo stars is negligible, particularly at large distances



Tucana III

Vivas et al 2020





6 extra-tidal RR Lyrae stars in Tuc III

Tucana III has extended tails (Drlica-Wagner et al 2015)

Gaia DR2 RRLs in UFDs: summary

Out of 27 galaxies with d<100 kpc

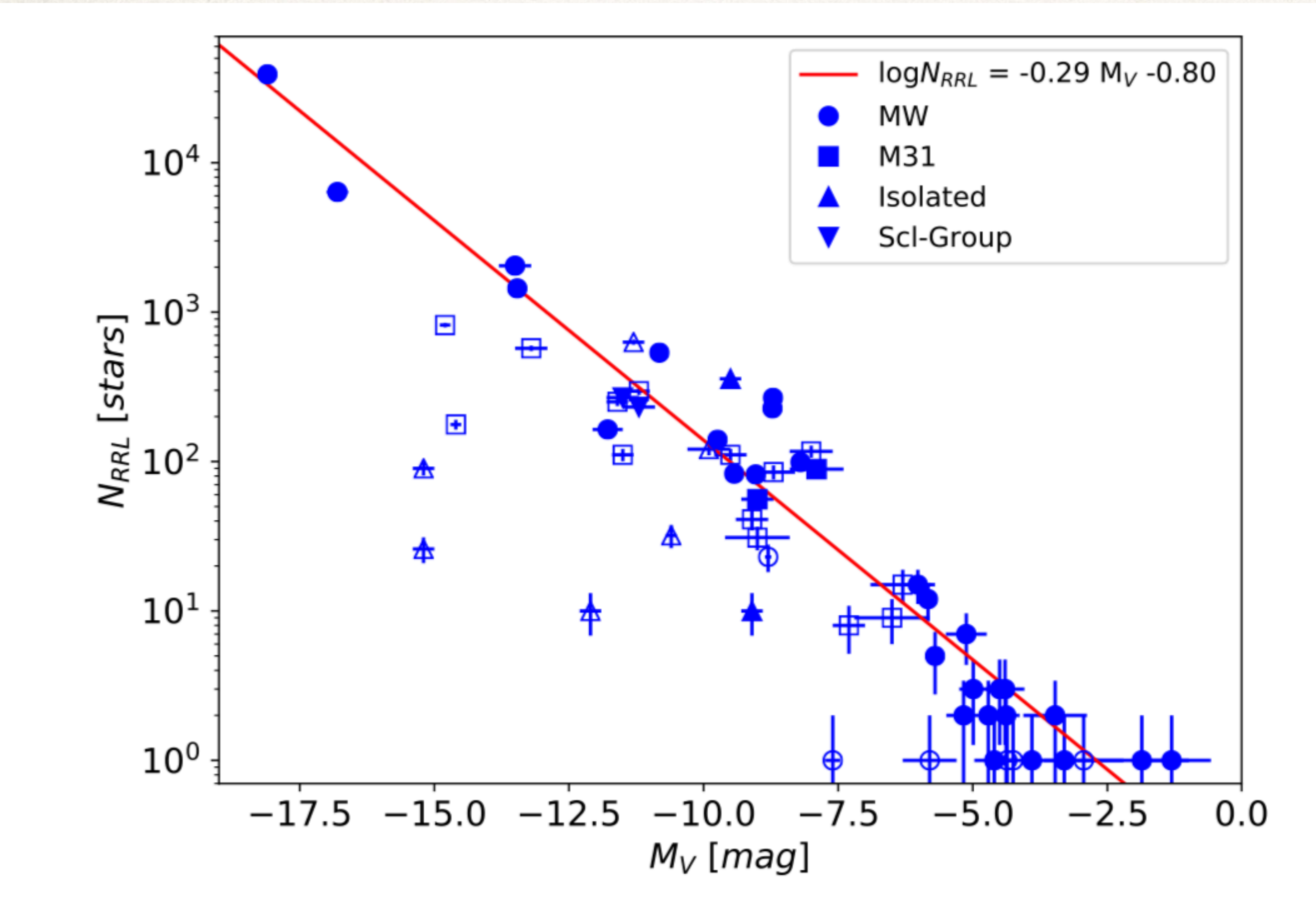
- 12 UFDs with no RR Lyrae
- 50 RRLs in 15 UFDs (26 new)
- New members for 5 galaxies
- First RR Lyrae stars detected in 2 galaxies
- 7 UFDs with extra-tidal candidates

Previous distance for Eri III ranged between 87 - 95 kpc

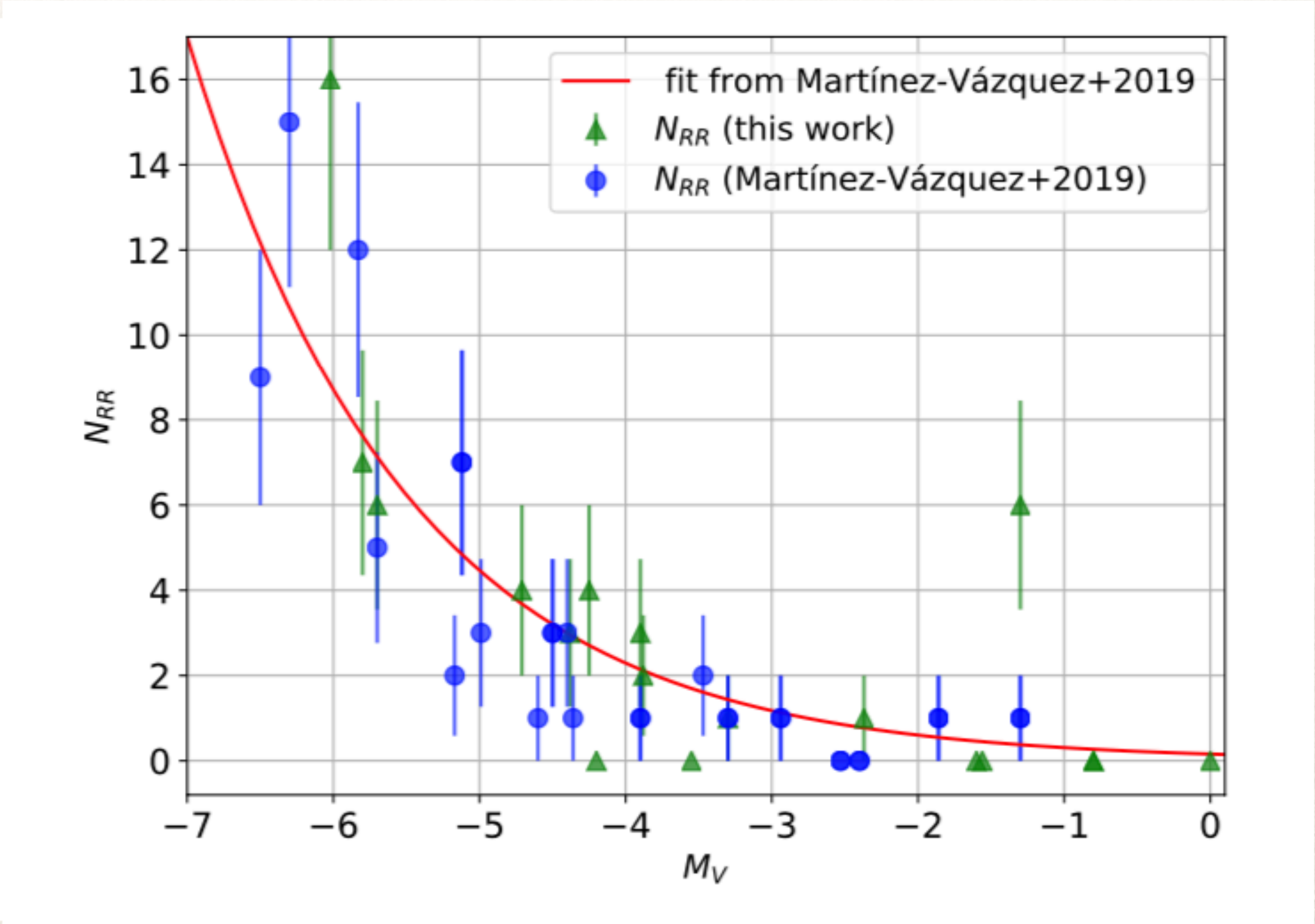
Table 3. Distance modulus and Heliocentric distances to the UFDs with Gaia RRLs

Galaxy	DM_0 (mag)	σ_{DM_0} (mag)	$D_\odot$ (kpc)	$\sigma_{D_\odot}$ (kpc)
Boo I	19.04	0.22	64	6
Boo II	18.00	0.22	40	4
Boo III	18.34	0.19	47	4
Car II	17.68	0.22	34	3
ComBer	18.00	0.20	40	4
Eri III	19.96	0.21	98	9
Hyd I	17.31	0.22	29	3
Phe II	19.99	0.22	99	10
Ret II	18.06	0.21	41	4
Ret III	19.70	0.21	87	8
Sag II	18.97	0.20	62	6
Tuc II	18.75	0.20	56	5
Tuc III	17.02	0.21	26	2
UMa I	19.93	0.19	97	9
UMa II	17.60	0.20	33	3

Number of RR Lyrae stars in UFDs



Martínez-Vázquez et al. 2019



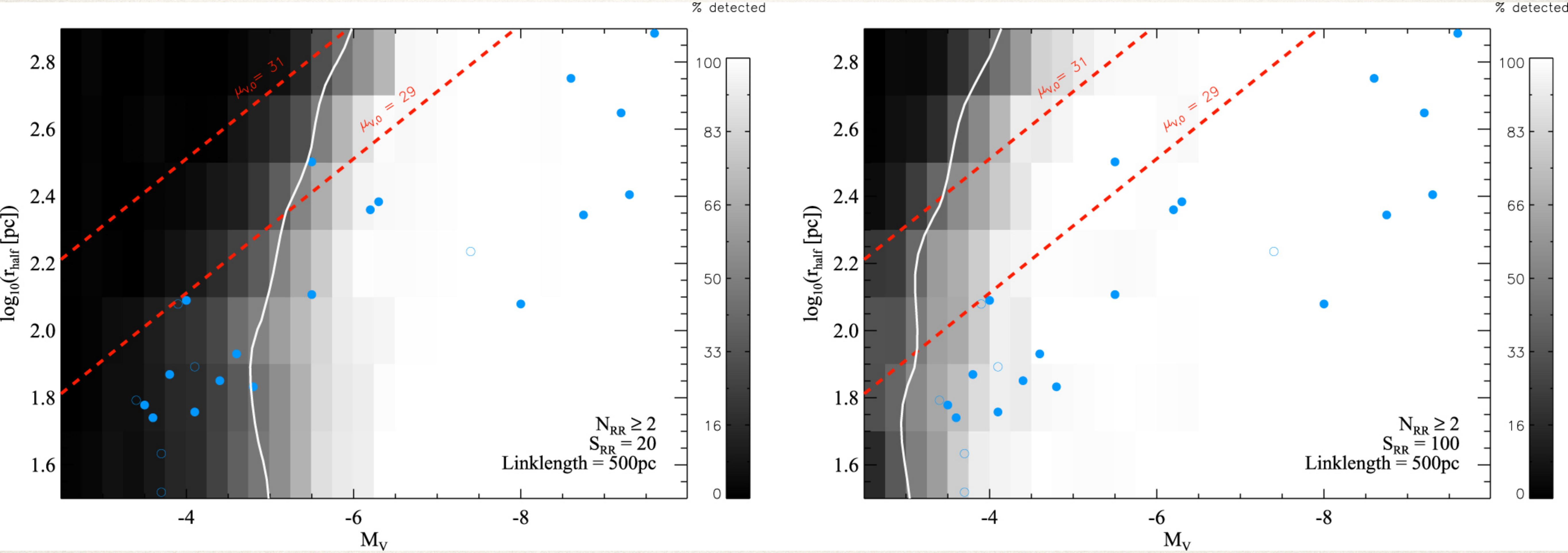
Vivas et al. 2020

Dwarf galaxies in the Local Group

UFDs

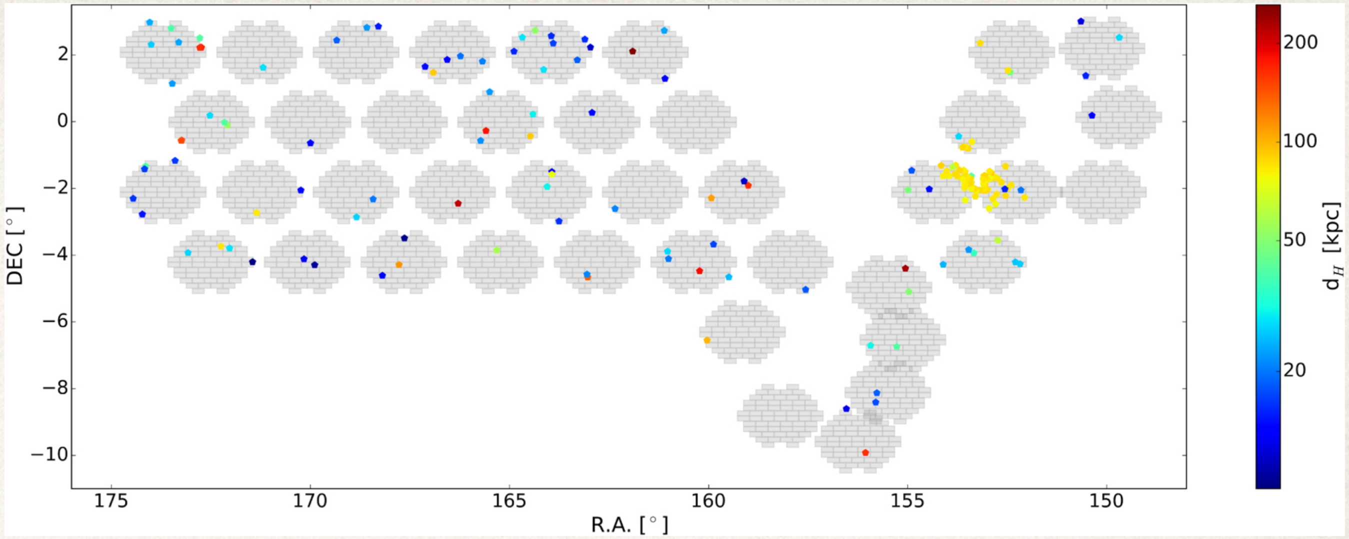
Finding new galaxies with RR Lyrae stars

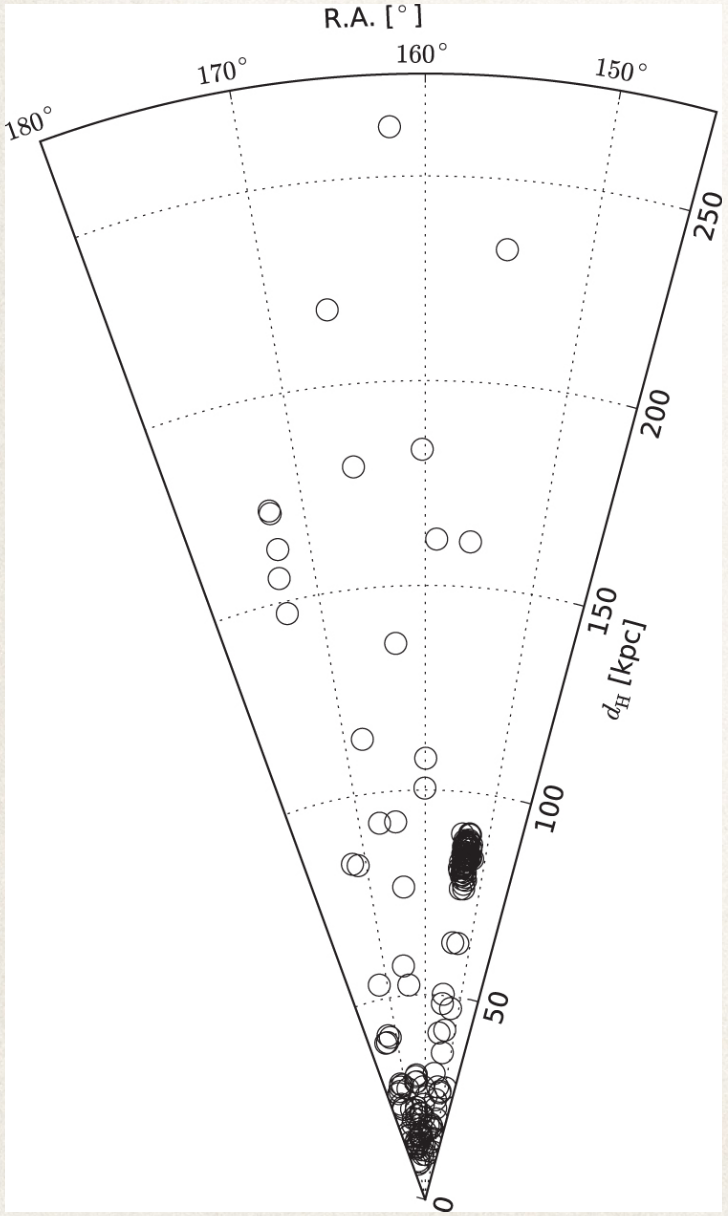
- Baker & Willman (2015) proposed that groups of 2 or distant RR Lyrae stars may be useful to uncover faint satellites



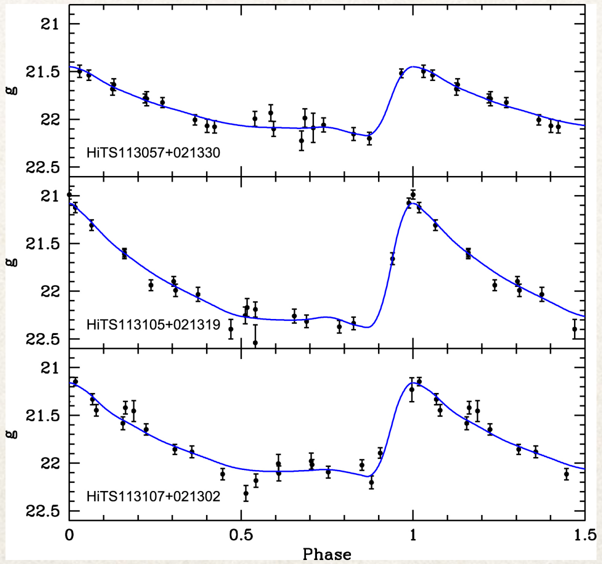
Leo V (Mv=-4.4)

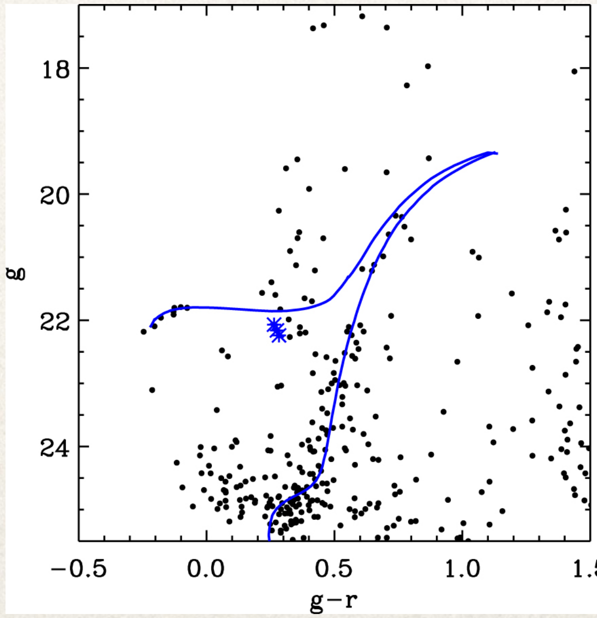
(with **G. Medina**, *R. Muñoz, J. Carlin)*

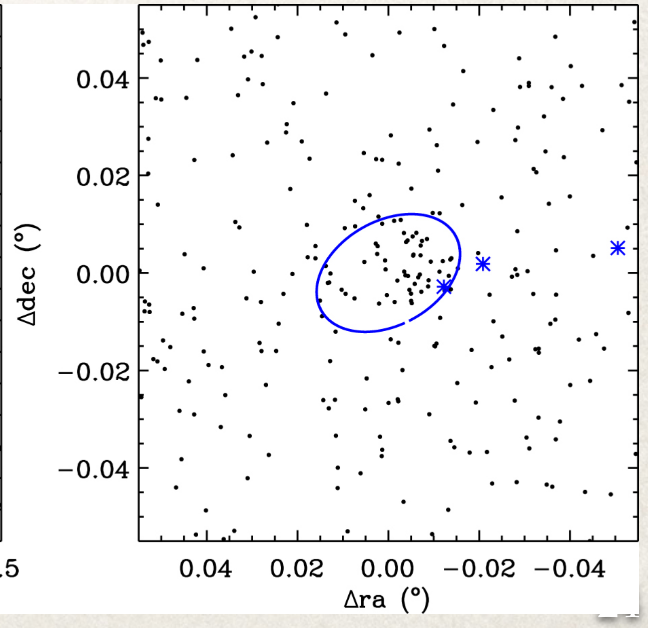




- We searched for groups of RR Lyrae stars in HiTS (Forster et al 2017, Medina et al 2017, 2018)
- Found two groups of 2 and 3 RR Lyrae stars —> Leo IV and V
- Leo V RR Lyrae stars were new discoveries

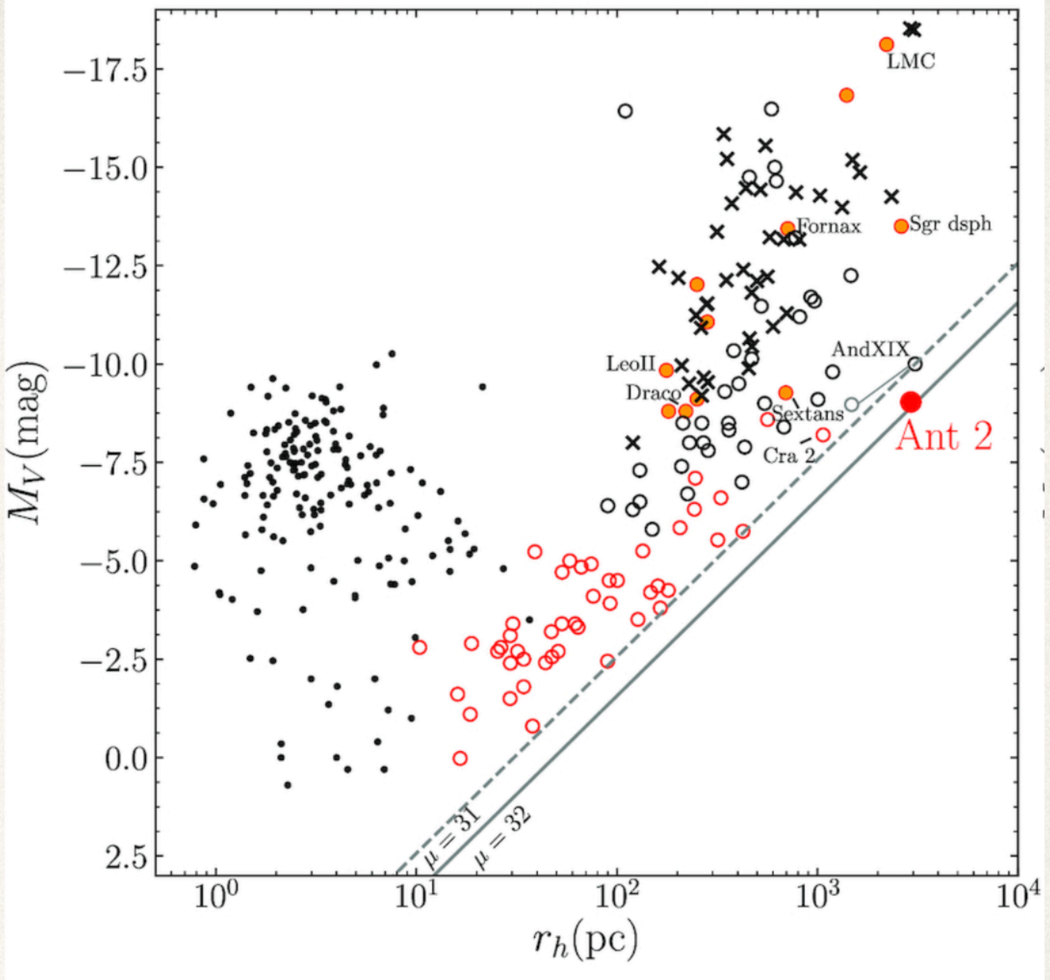


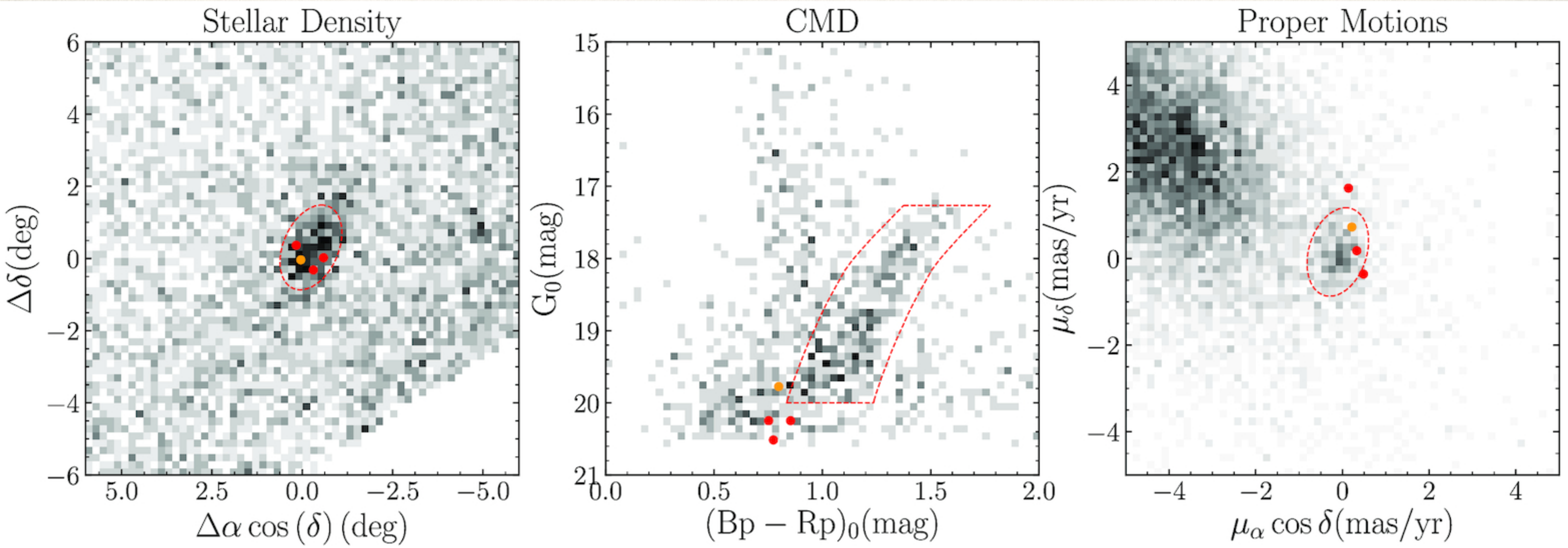




Antlia II

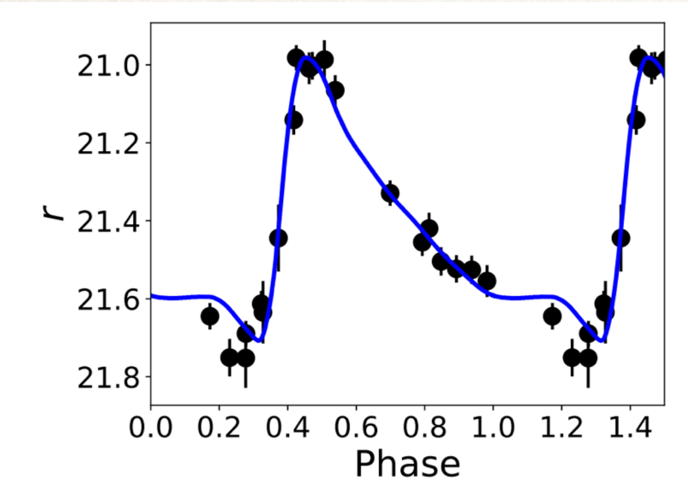
Torrealba et al 2019 found Antlia II using the Gaia catalog of RR Lyrae stars

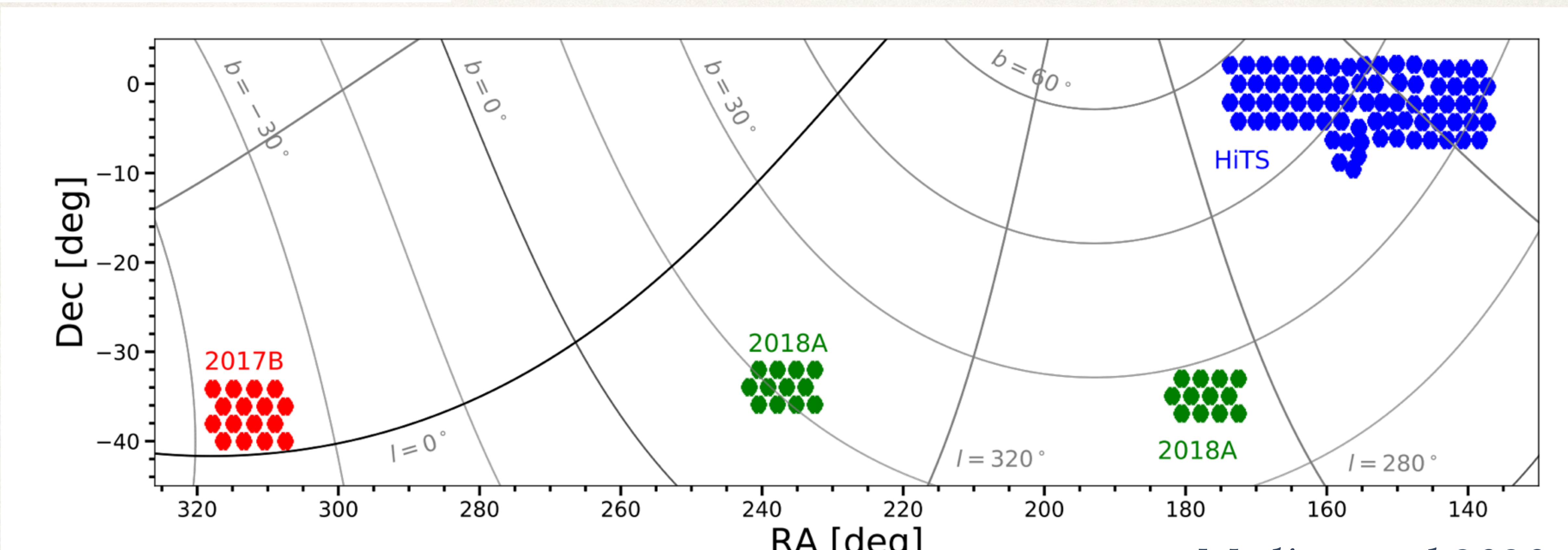




HOWVAST (Halo Outskirts With VAriable STars)

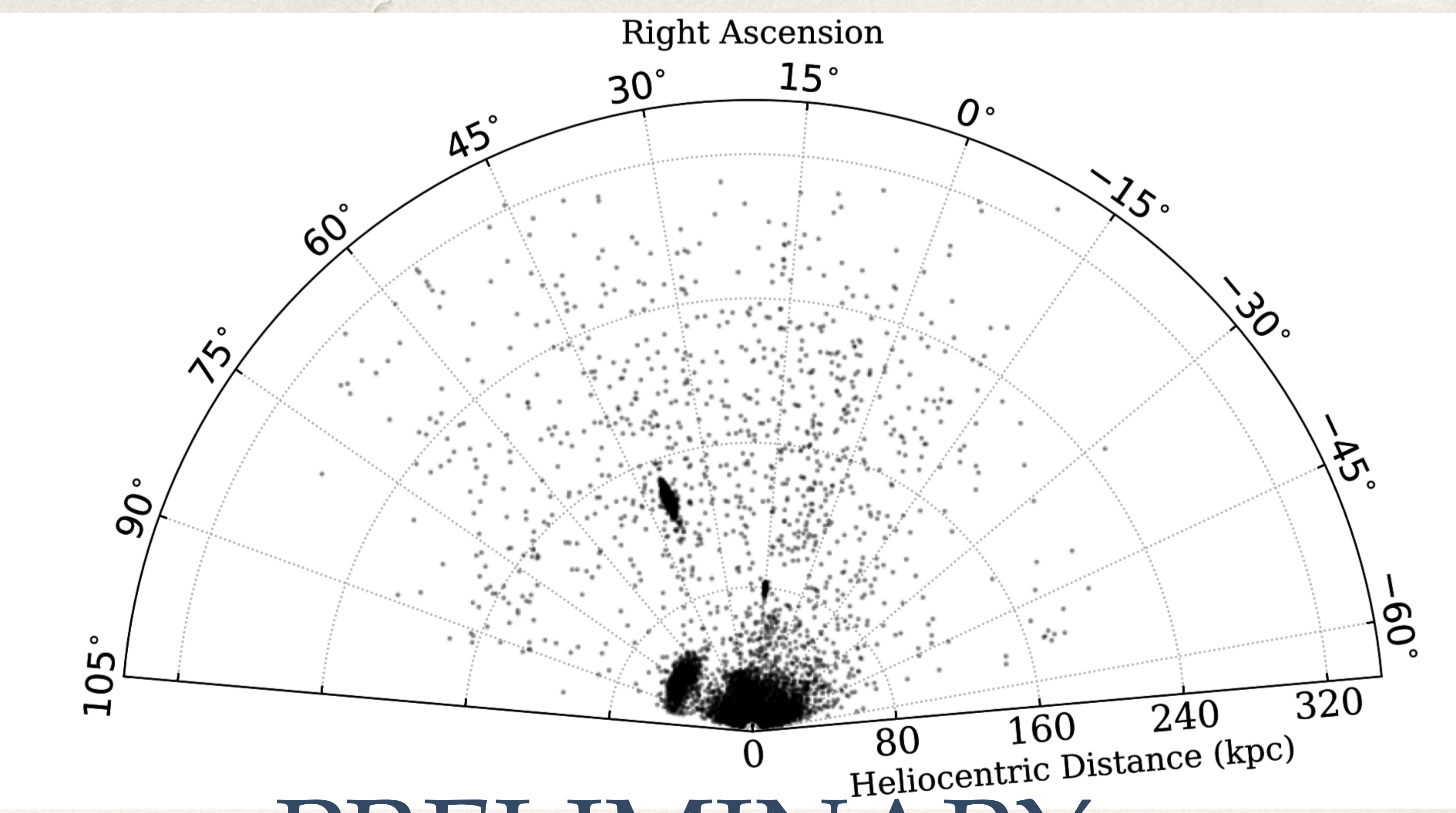
- DECam survey to find very distant RR Lyrae stars (**Ricardo Muñoz, Jeff Carlin**, Gustavo Medina, Kathy Vivas, Clara Martínez-Vázquez)
- 350 sq degrees; ~600 RR Lyrae stars up to 250 kpc
- Precursor survey for LSST



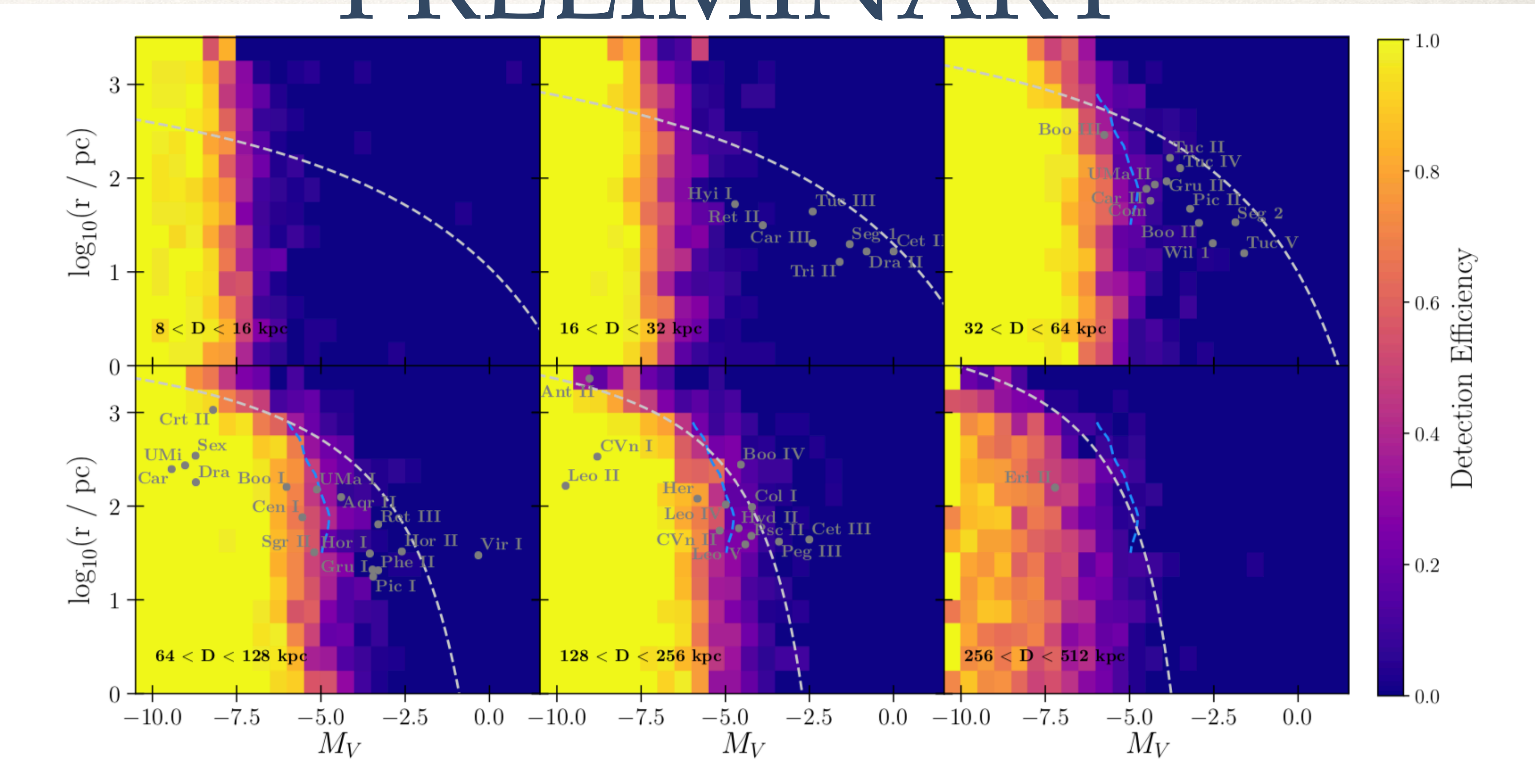


Medina et al 2020

RR Lyrae stars in the Dark Energy Survey (DES)



PRELIMINARY

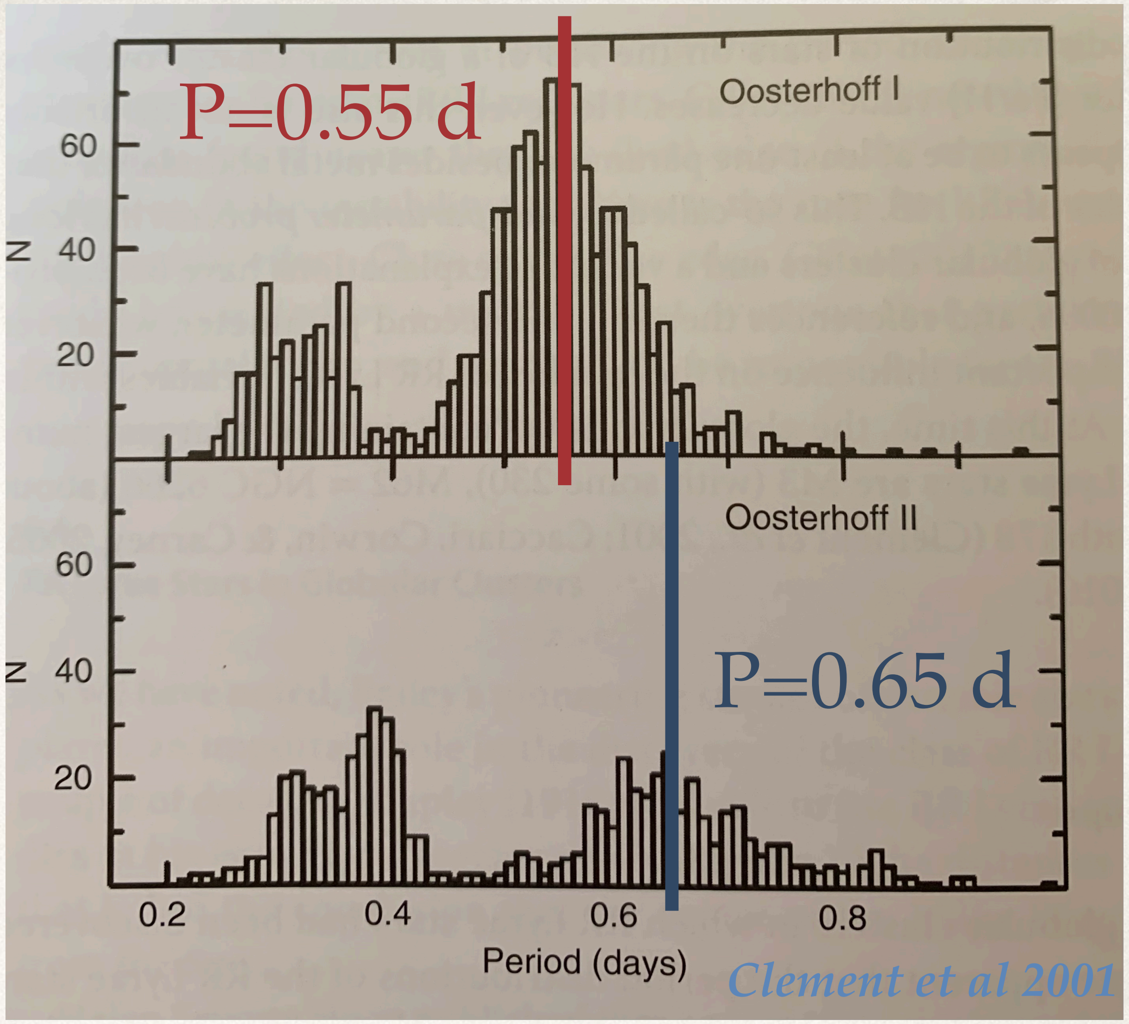


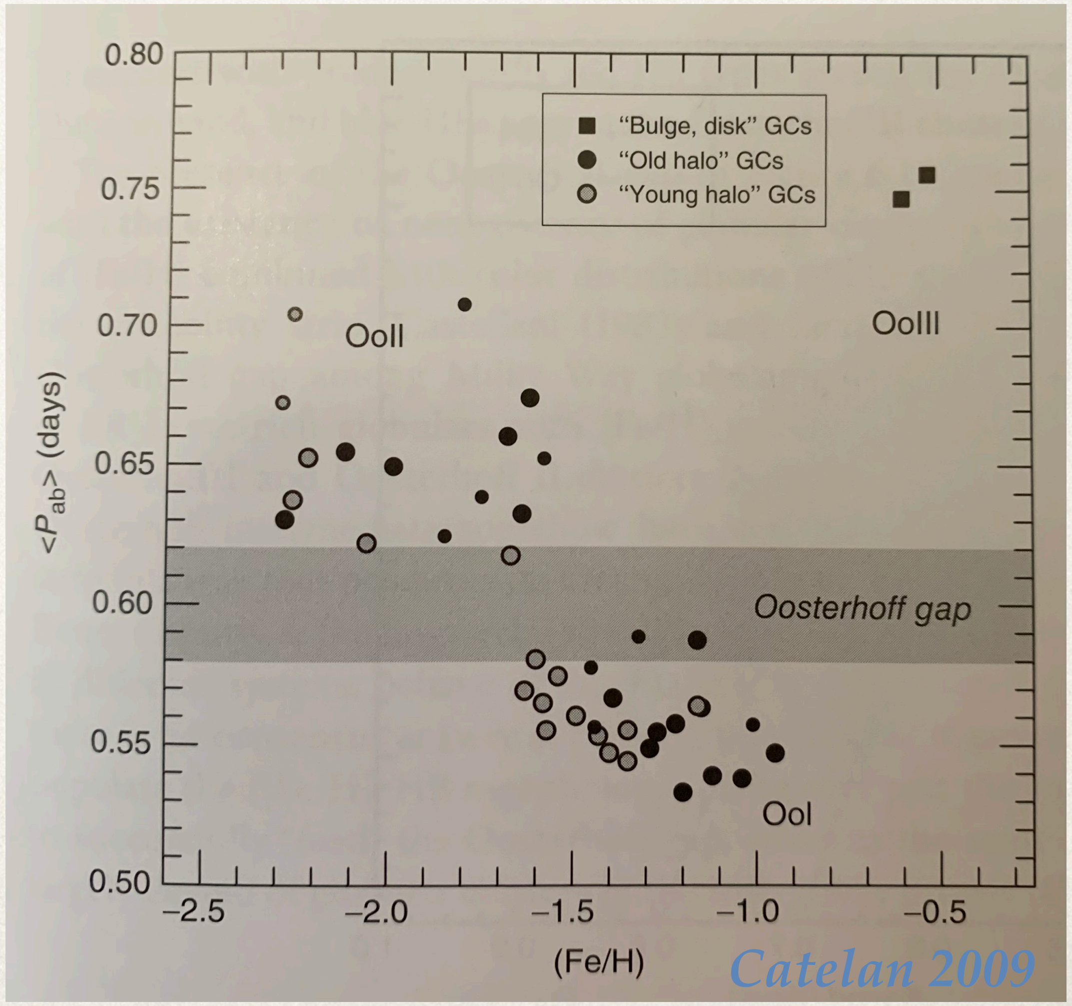
- Not a variability survey but few epochs in 5 filters
- RR Lyrae star candidates up to 350 kpc
- Completeness and purity issues
- 5,000 sq deg

Stringer et al, in preparation

Oosterhoff Groups

- First introduced by Oosterhoff in 1939
- Two groups of globular clusters based on the mean period of their RR Lyrae stars
- The Oosterhoff gap indicates there are no globular clusters with mean periods of RRab near 0.60d

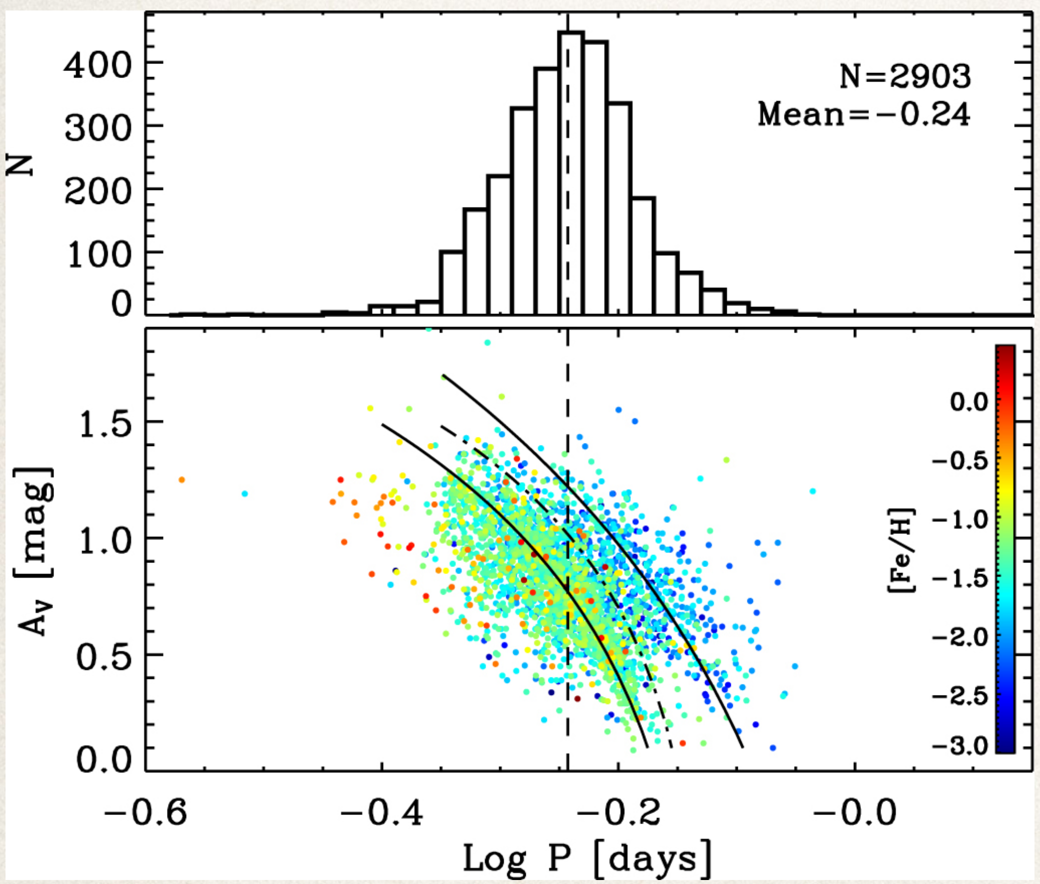




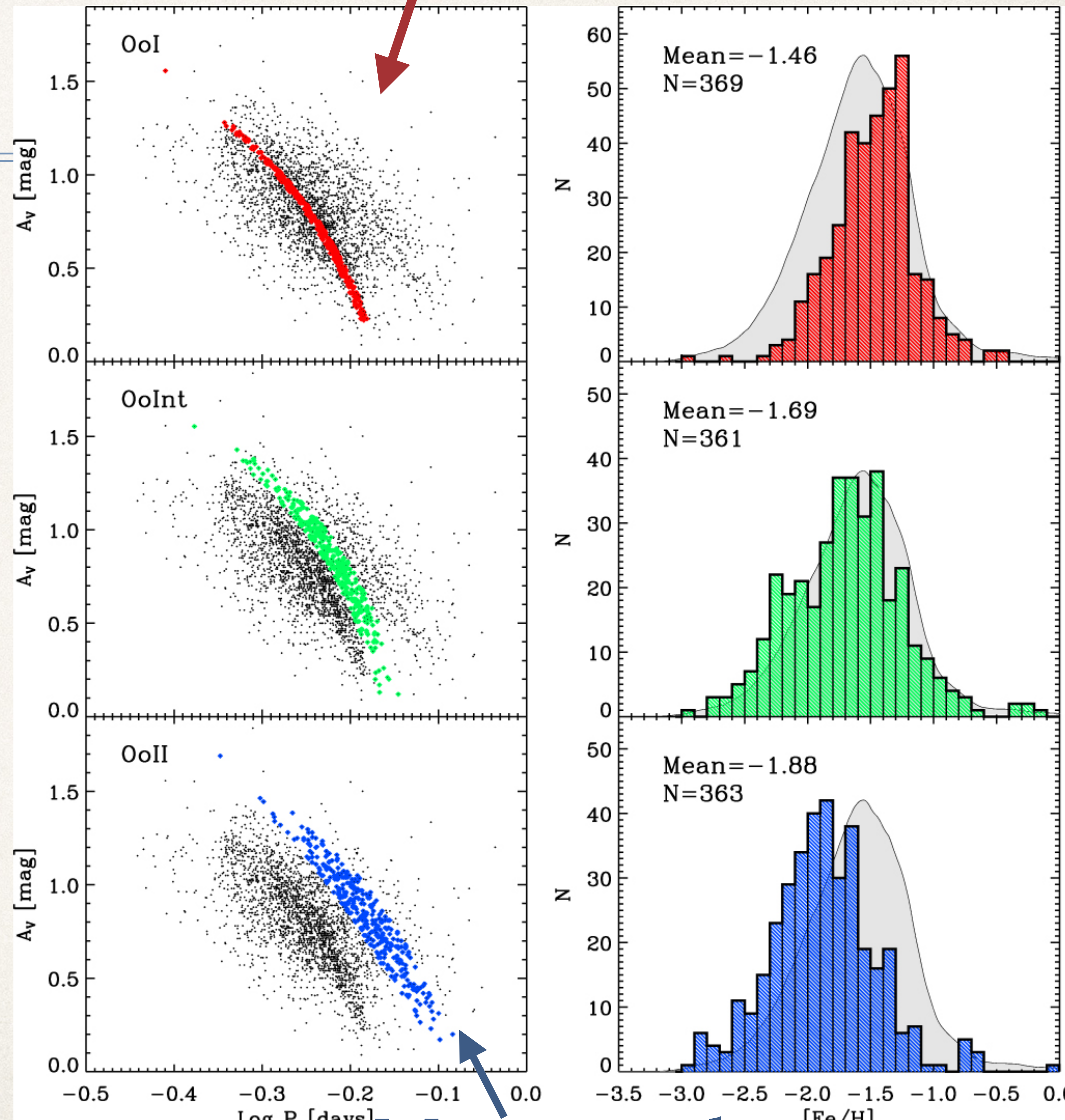
Oosterhoff groups in the halo?

More metal rich

Not a gap. Continuous gradient of metallicity

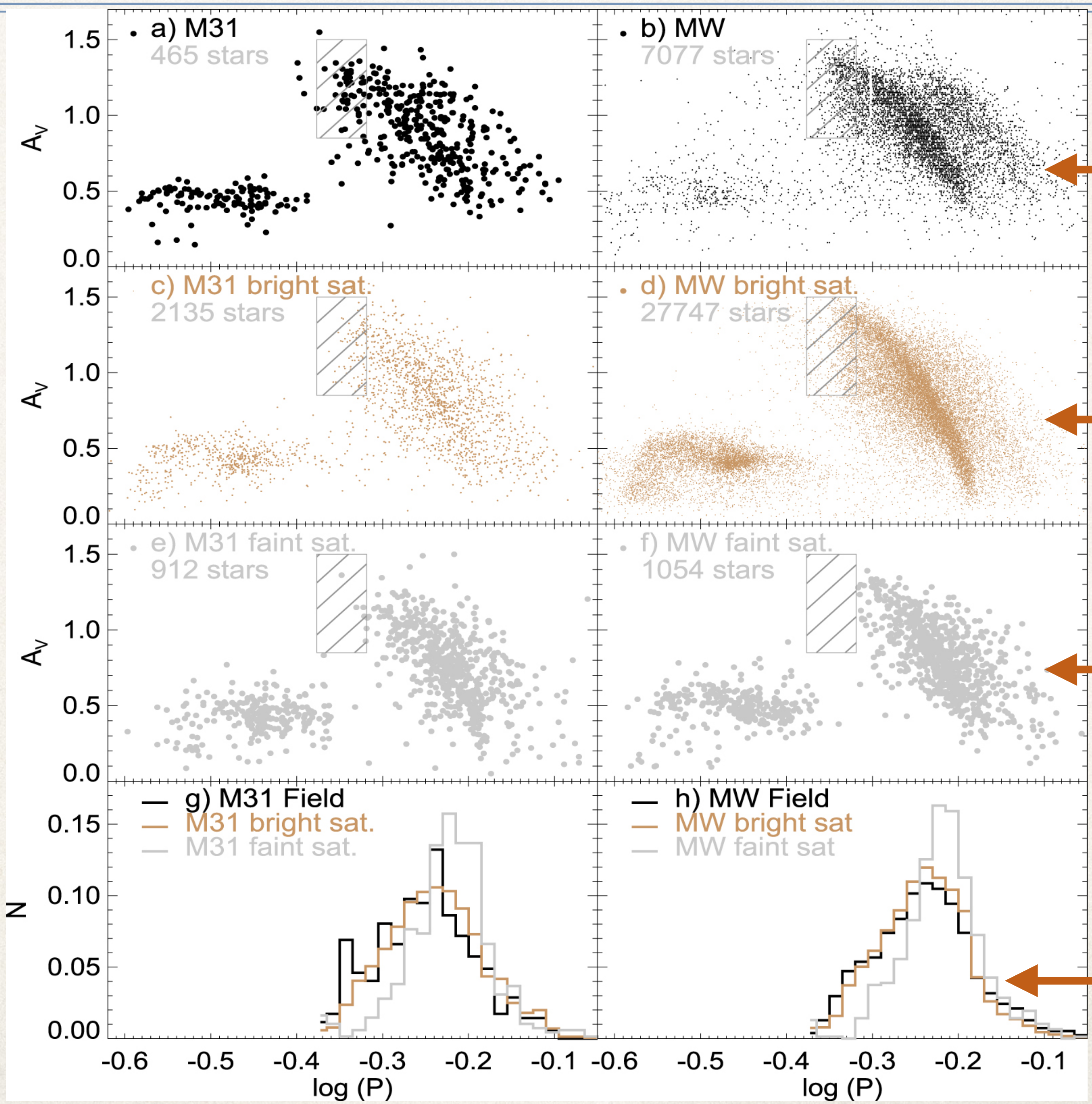


Fabrizio et al 2019



More metal poor

Oosterhoff groups in large satellite galaxies



Halo

LMC, SMC, Sgr

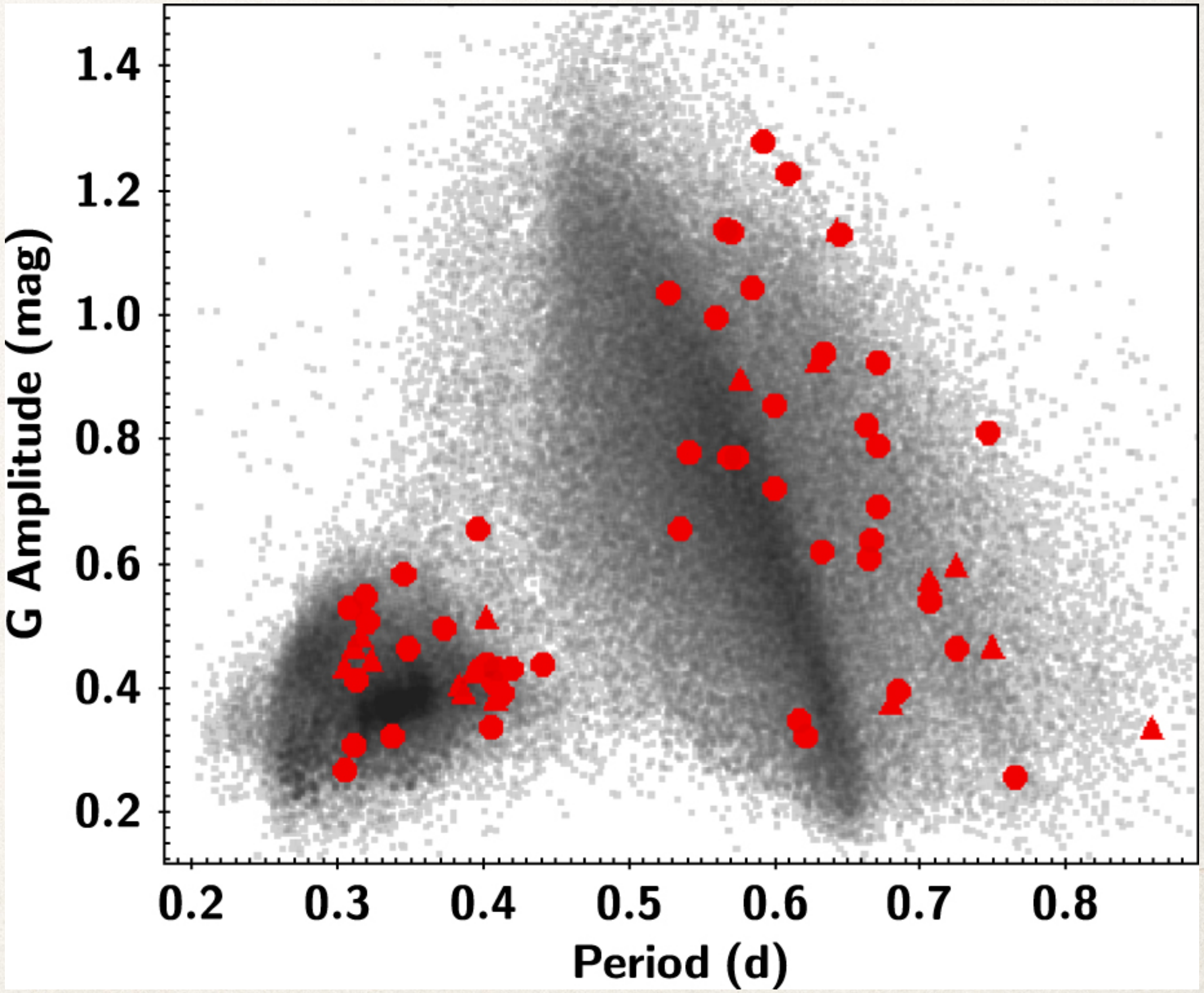
Faint galaxies (but not UFDs)

MW halo and bright satellites have identical population of RR Lyrae stars

Monelli et al 2017

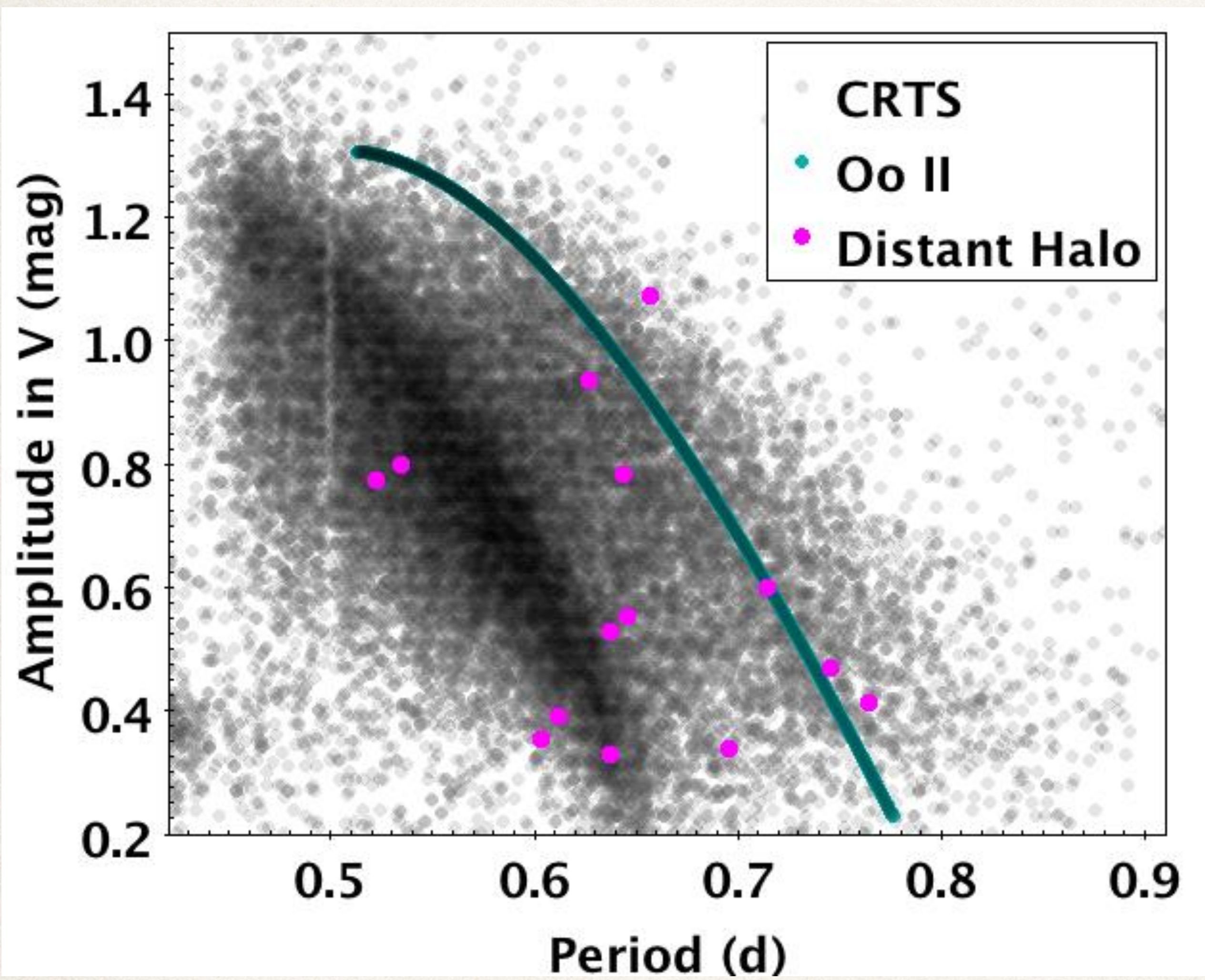
Period-Amplitude Diagram of UFDs

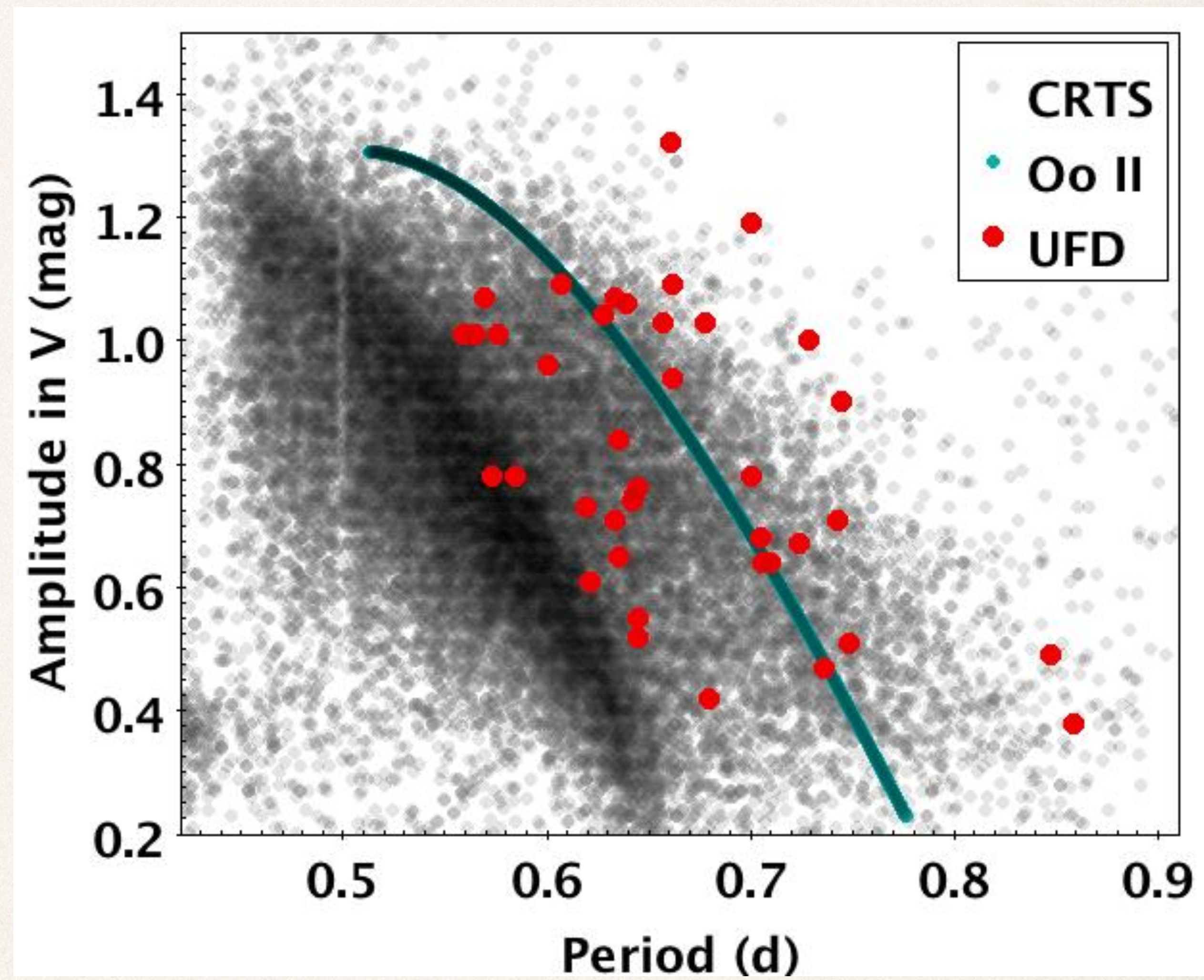
- RR Lyrae stars in UFDs do not follow any of the Oosterhoff sequences
- The halo population mostly follows the Oo I sequence
- UFDs do not seem to be the main contributor to the halo population, at least for d<~60 npc



The outer halo

Outer halo and UFDs look more similar





Distant halo are stars > 90 kpc in Medina et al 2018

Summary

- RR Lyrae stars are wonderful tracers of the population of dwarf satellites
- Gaia DR2 has been very valuable to uncover RR Lyrae stars in UFDs. Cannot wait for DR3!
- Pulsational properties of RR Lyrae stars allows to investigate the role of UFDs in the formation of the halo of the Milky Way.
- The outermost parts of the halo of the Milky Way is still uncharted territory. Surveys like HOWVAST and LSST in the future will help to improve the census of distant halo stars