

# The Virgo Overdensity as seen by RR Lyrae Stars

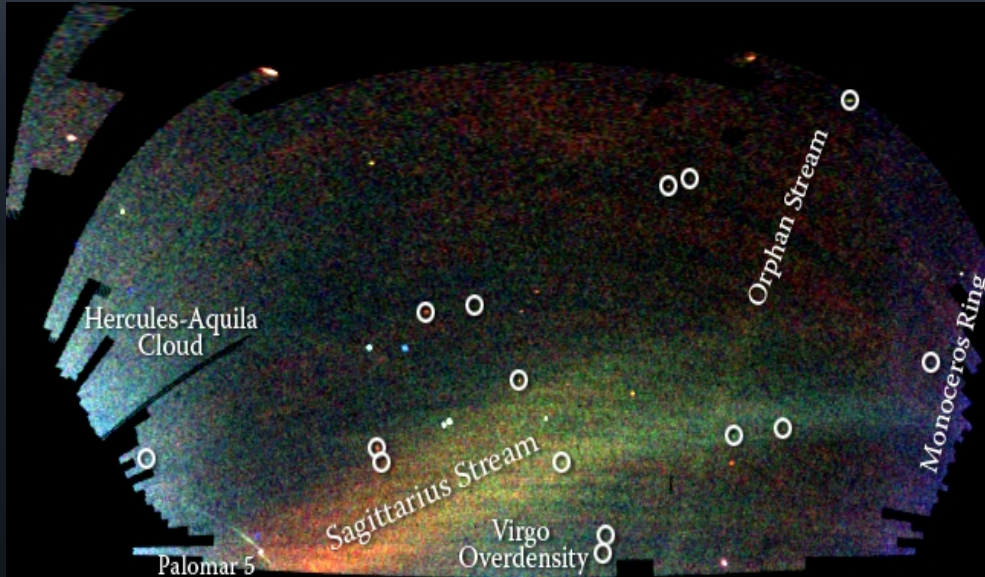
**Kathy Vivas**

*Cerro Tololo Interamerican Observatory  
La Serena, Chile*

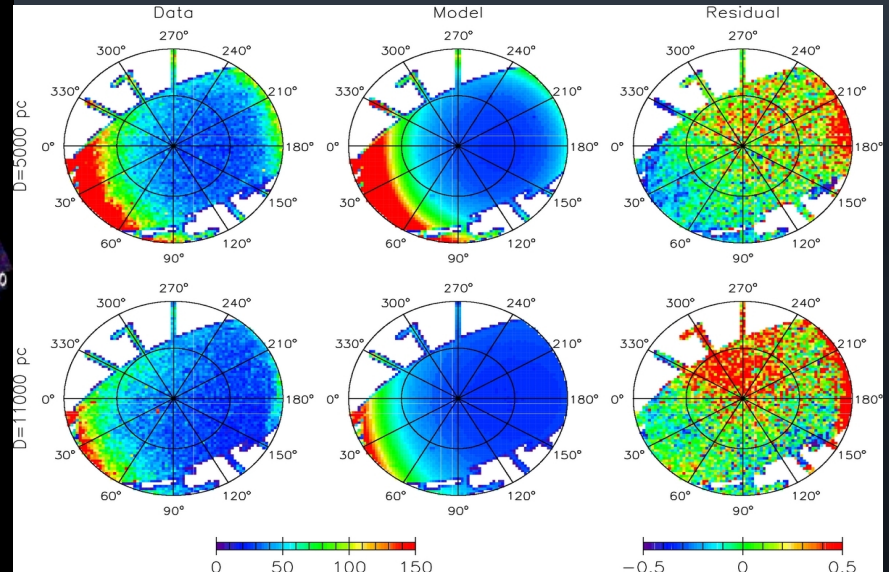
*Collaborators: Bob Zinn (Yale University), John Farmer (Clemson  
University & CTIO REU student), Sonia Duffau (PUC)*

# The Virgo Overdensity

Field of Streams, Belokurov et al (2006)



Bonaca et al (2012)



Large overdensity of stars seen in SDSS spanning at least 2000 sq deg of the sky (maybe more if it extends to the South) (Bonaca et al 2012)

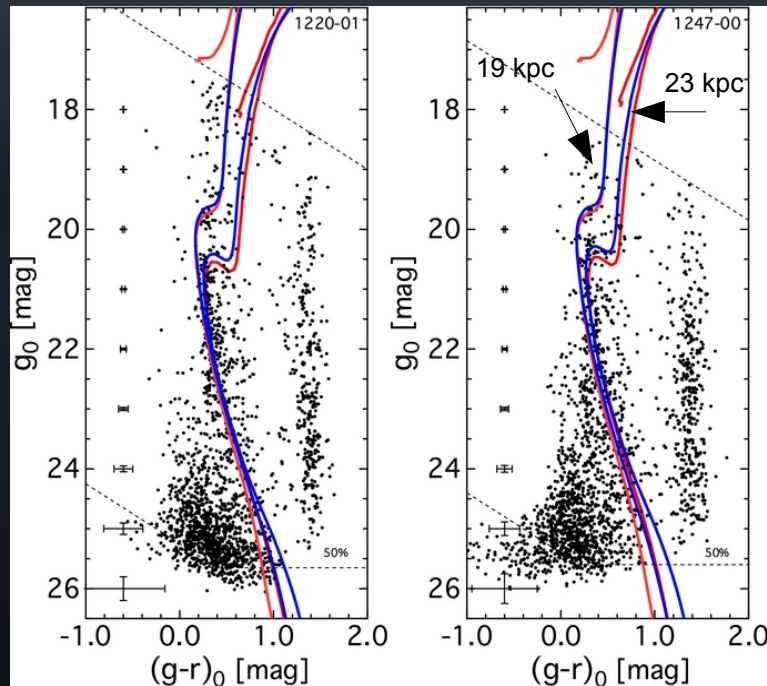
Distances (based on main sequence photometric parallaxes) go from ~6 to 20 kpc (Juric et al 2008)

Cloud-like (not the typical stellar stream)

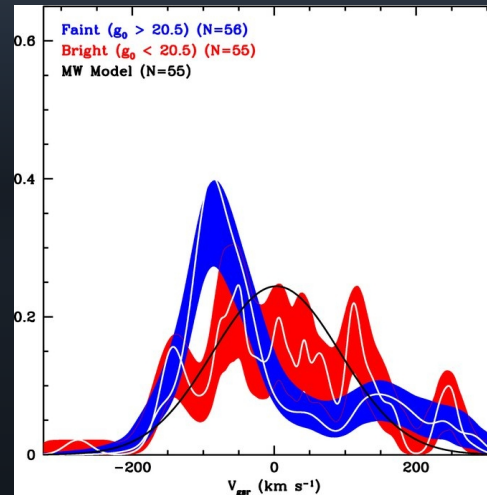
Rough estimate of the luminosity =  $10^6$  stars over the whole area (Bonaca et al 2012)

Not clear yet what the origin is. Destroyed galaxy? Destroyed galaxies? Halo ellipsoid tilt?

# The Virgo Overdensity



Jerjen et al (2013) identified a main sequence at 23 kpc with properties similar to the stellar population of Sgr. No features detected at closer distances.

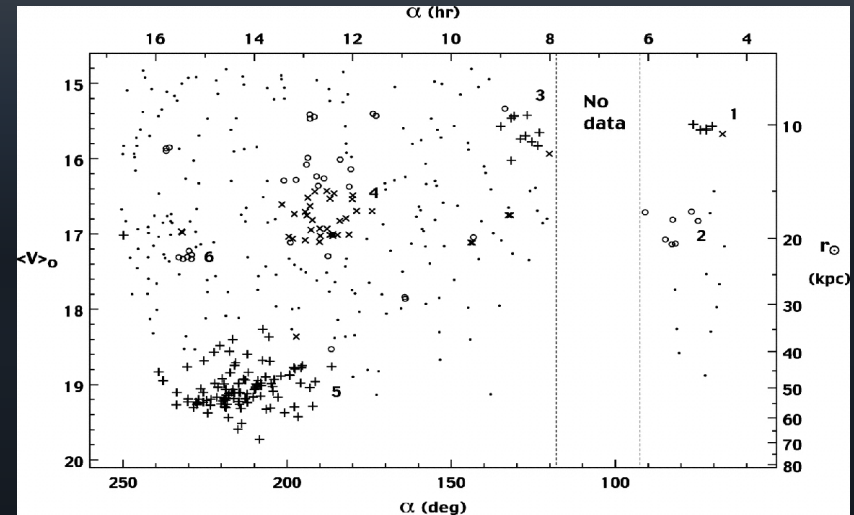


Spectroscopy of main sequence candidates by Brink et al 2010 (over small fields) show different kinematic features. Again some of them beyond  $\sim 20$  kpc.

**Detailed studies are difficult since they are confined to small areas of the sky and this is a very large feature (with very low surface brightness)**

# The Role of RR Lyrae Stars

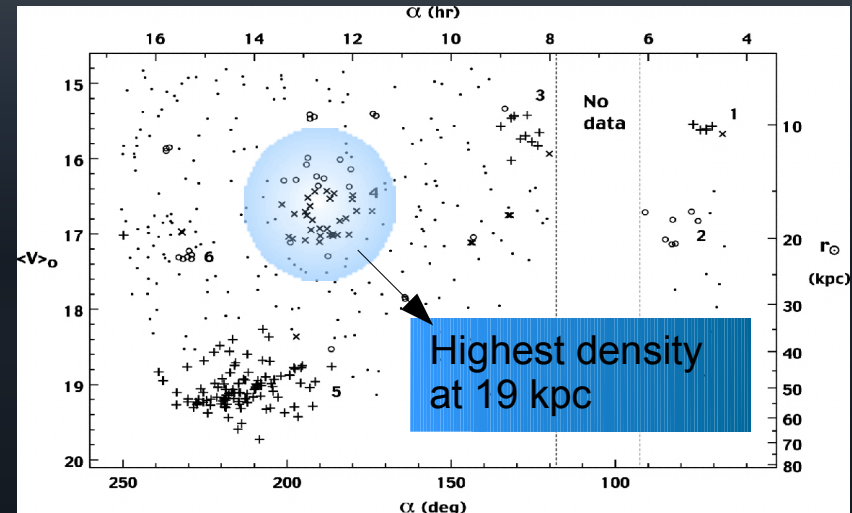
- ★ Old stars ( $>10\text{Gyr}$ )
- ★ Standard candles.  
Distances good to  $\sim 5\%$
- ★ Solid classification
- ★ Several wide field surveys covering most of the sky now available



*Overdensities of RR Lyrae stars in the QUEST survey (Vivas et al 2001, 2006)*

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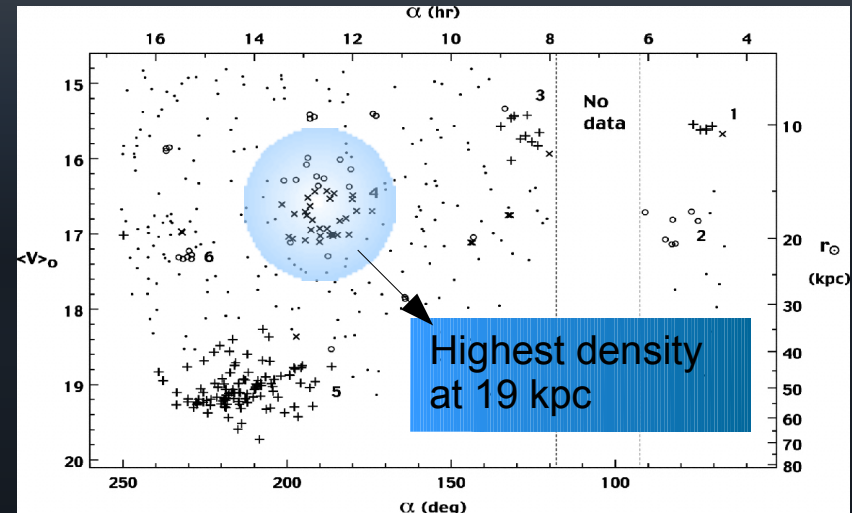
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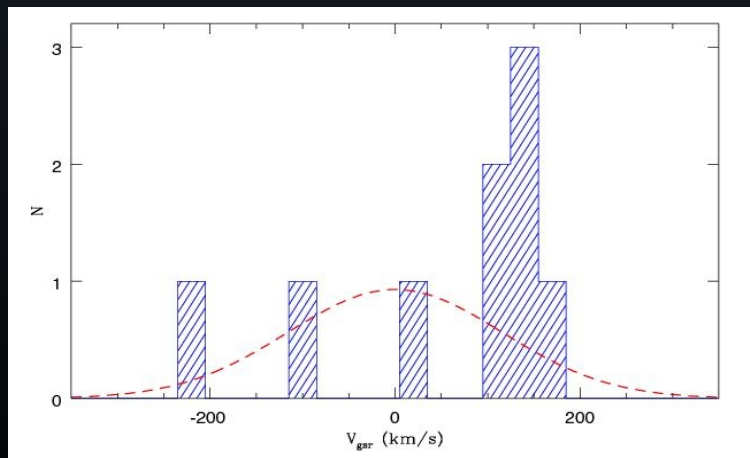
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# The Role of RR Lyrae Stars

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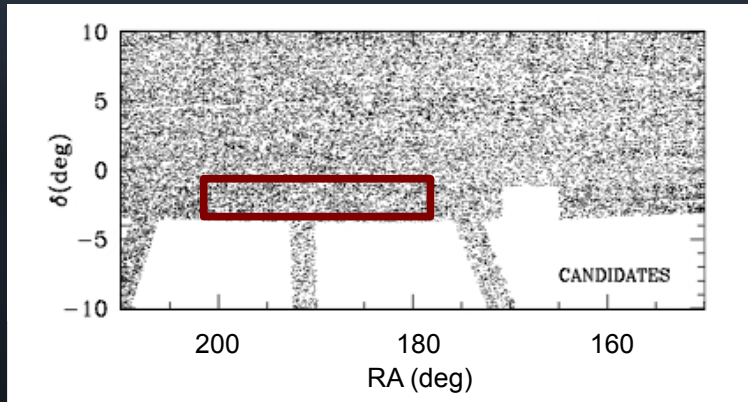


Overdensities of RR Lyrae stars in the QUEST survey (Vivas et al 2001, 2006)



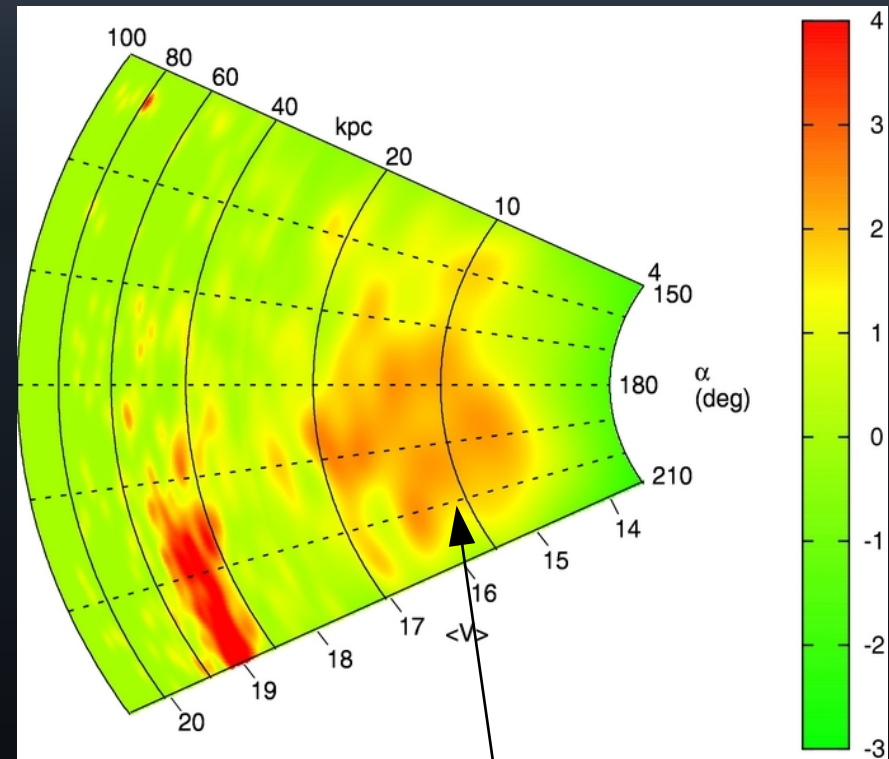
Velocities of RR Lyrae stars  $\sim 19$  kpc show a strong kinematical signature at  $V_{\text{gsr}} = 128$  km/s  $\rightarrow$  the **Virgo Stellar Stream** (Duffau et al 2014, revised value from Duffau et al 2006)

# New Surveys of RR Lyrae Stars



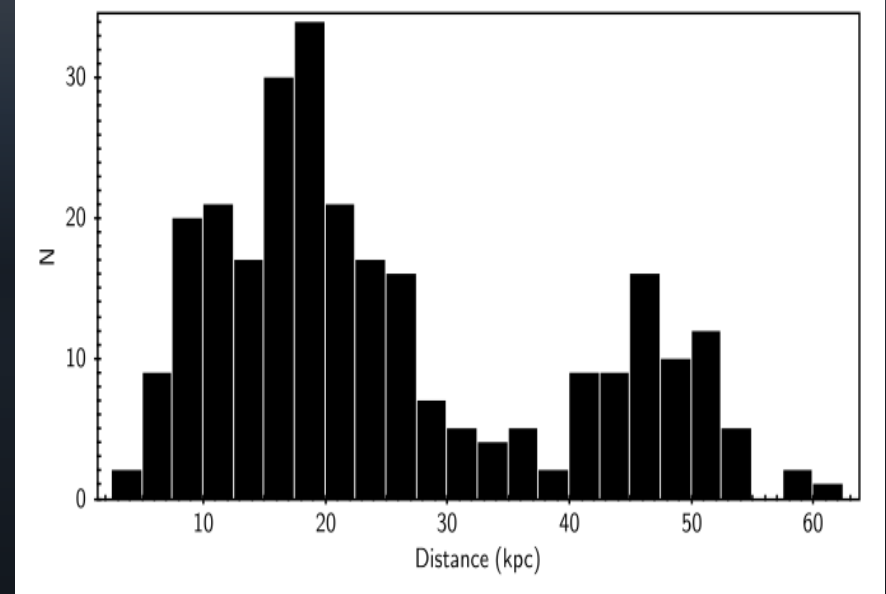
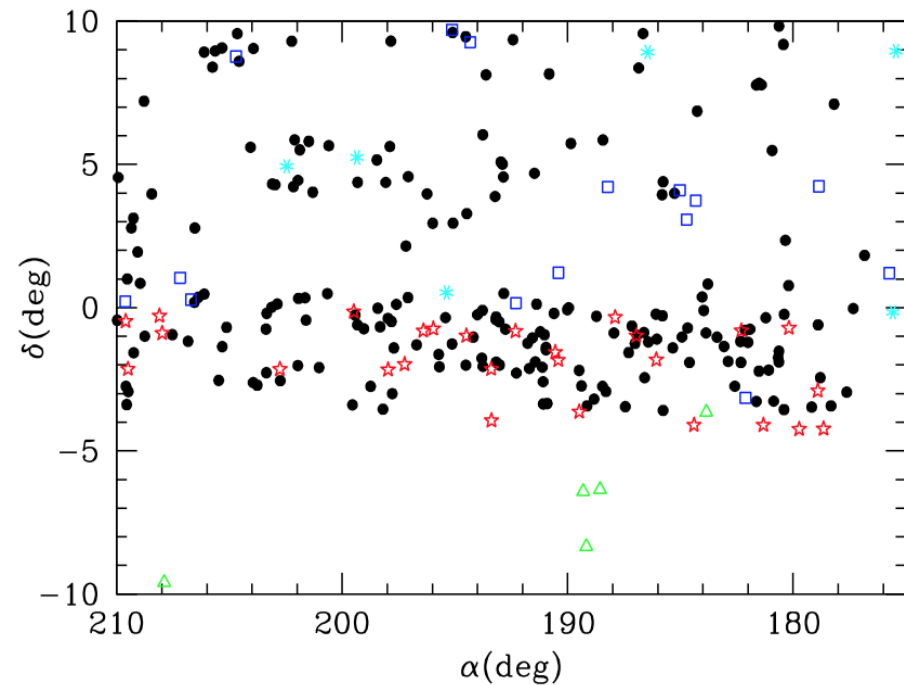
La Silla-QUEST survey (Zinn et al 2014)

- ★ 112 CCD camera at the 1m Schmidt telescope in La Silla Observatory
- ★ FOV = 10 deg<sup>2</sup>
- ★ Single broad-band filter
- ★ Coverage = 840 deg<sup>2</sup>
- ★ ~ 1300 RR Lyrae stars up to ~80 kpc ( $V \sim 20.5$ )



Density of RR Lyrae stars clearly shows an enhancement due to the Virgo overdensity (Zinn et al 2014)

Goal: Understand the origin of the Virgo overdensity by studying their kinematic properties



★ 274 RR Lyrae stars in the Virgo region (La Silla-QUEST: circles; QUEST: stars; Catalina Sky Survey: squares; LINEAR: asterisks; SEKBO: green)

Sample contains observations obtained with SOAR, WIYN, Magellan + stars in the SDSS database (only suitable spectra) + stars reported in Duffau et al 2014 and Prior et al 2009  
→ Sample >3x larger than previous works, covering 5x the area



# Finding sub-structures

Find pair of stars close in the sky and with similar velocities. Pairs interconnected formed a group.

In practice,  $4d_{ij} < \text{critical value}$

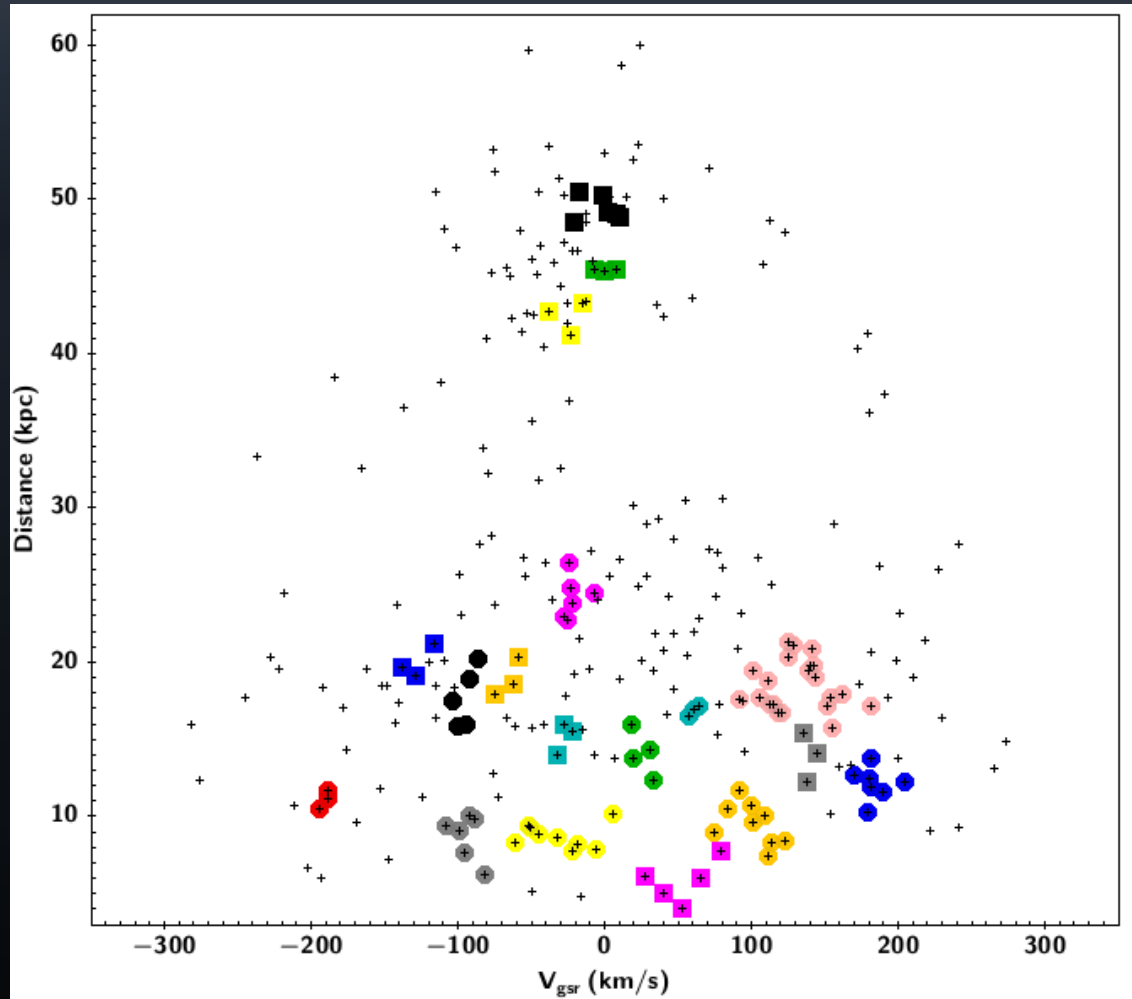
$$(4d_{ij})^2 = \omega_{3d_{ij}}^2 (3d_{ij})^2 + \omega_v (v_i - v_j)^2 \quad (3)$$

where  $3d_{ij}$  is the three-dimensional distance between two stars calculated from their galactocentric cartesian coordinates  $(x, y, z)$ :

$$3d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \quad (4)$$

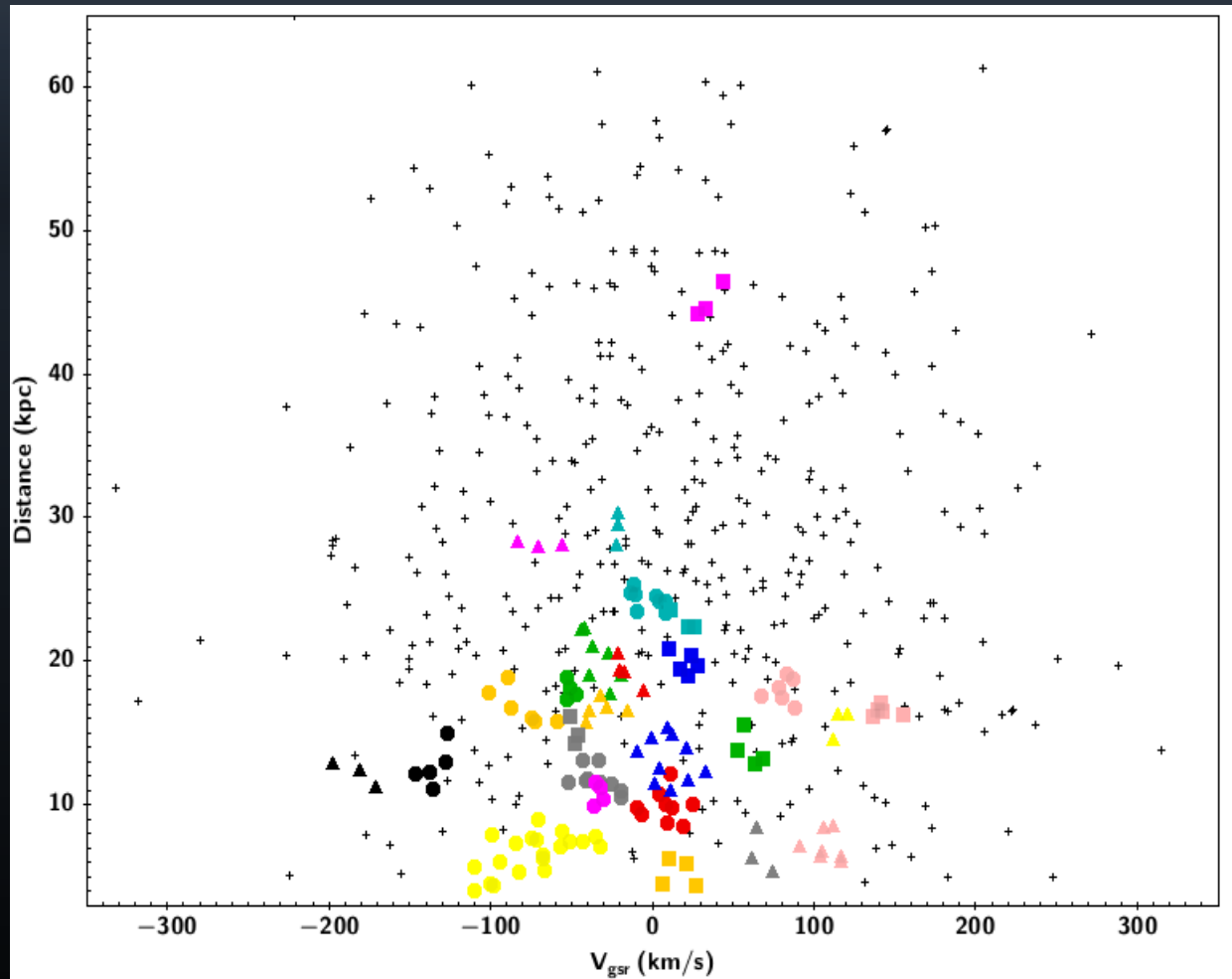
*Modification of the definition in Starkenburg et al 2009 (details in Duffau et al 2014)*

# Sub-structures



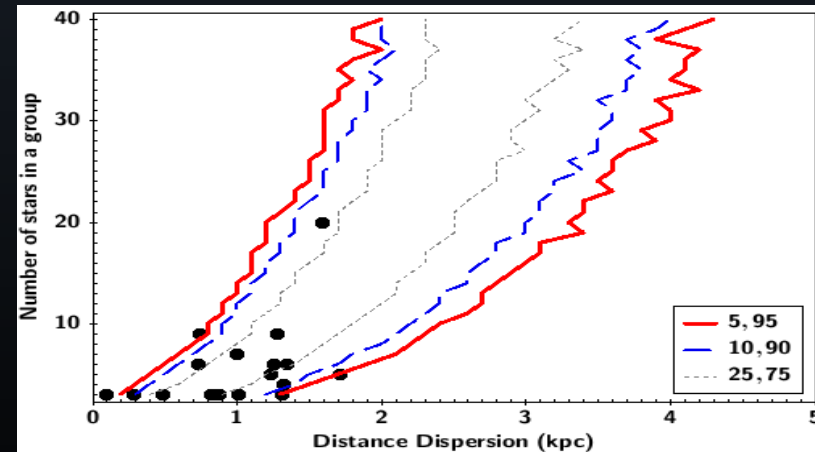
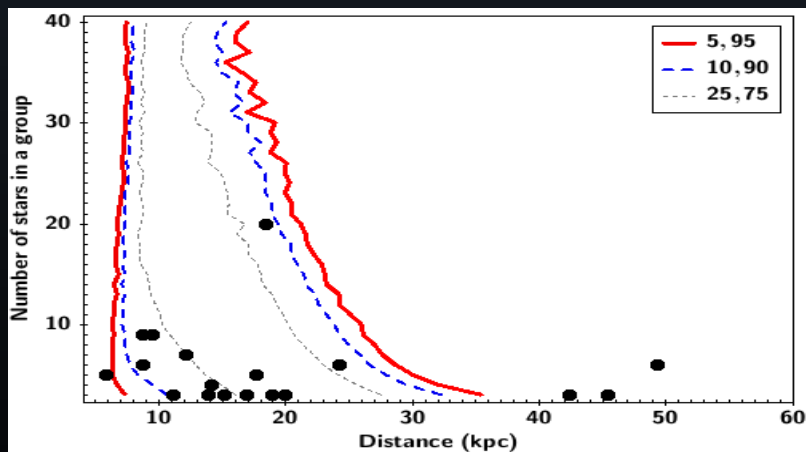
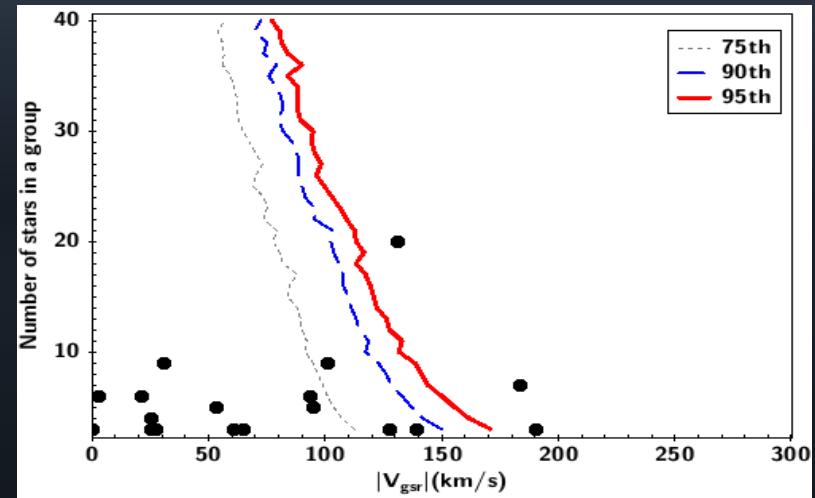
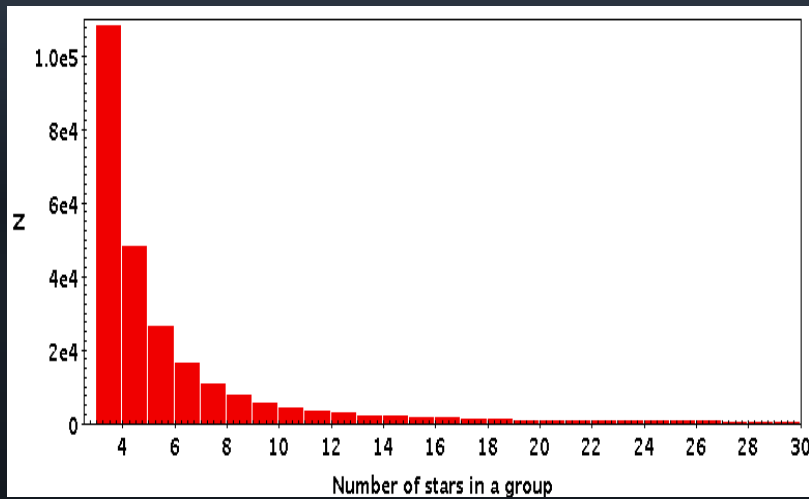
Are all of the real?  
Can a smooth halo  
produce groups like  
these ones?

# Simulations

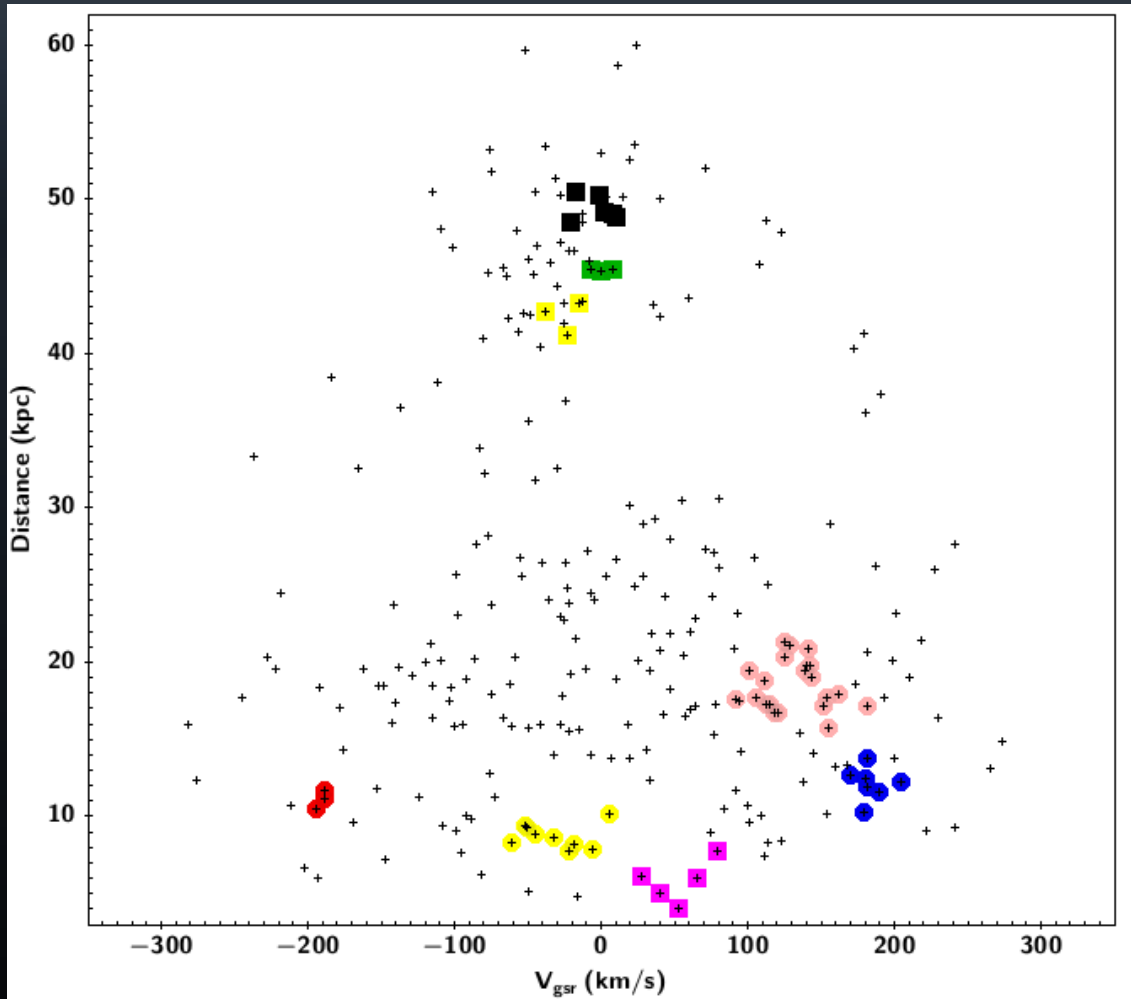


- ★ Number of stars from integrating the density power law of the halo of Zinn et al (2014)
- ★ Random position in the region of study
- ★ Distance drawn from a distribution following the Zinn et al (2014) halo profile
- ★ Velocity drawn from a Gaussian distribution.
- ★ Observational errors added
- ★ 10,000 simulations

# Properties of Fake Groups



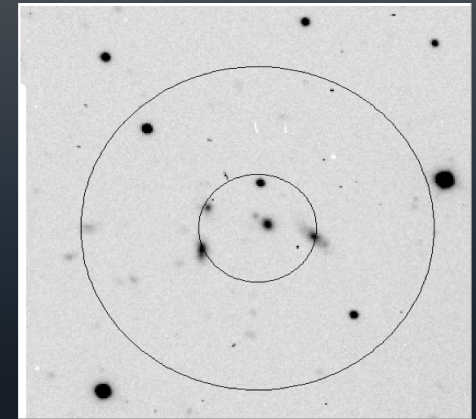
# Significant Groups



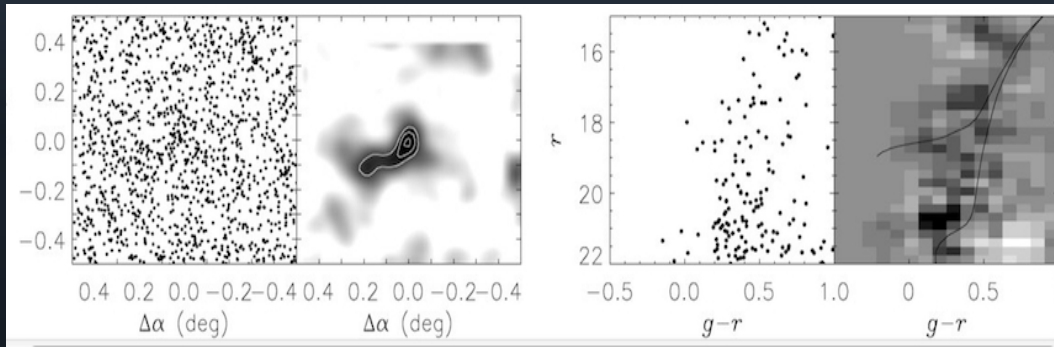
Sagittarius Stream

Multiple features in the range of distance of the VOD

# Virgo Z

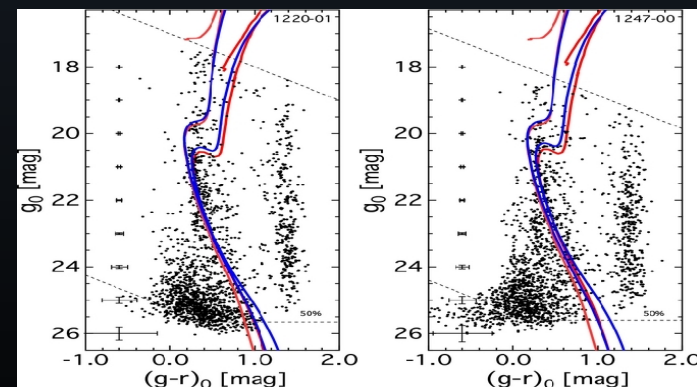


Barbuy et al (2013) suggested it is a cluster of galaxies, not a dwarf.



Dwarf galaxy candidate discovered by Walsh et al (2009) at 40 kpc

Jerjen et al (2013) found a strong main sequence in the location of Vir Z but at 23 kpc



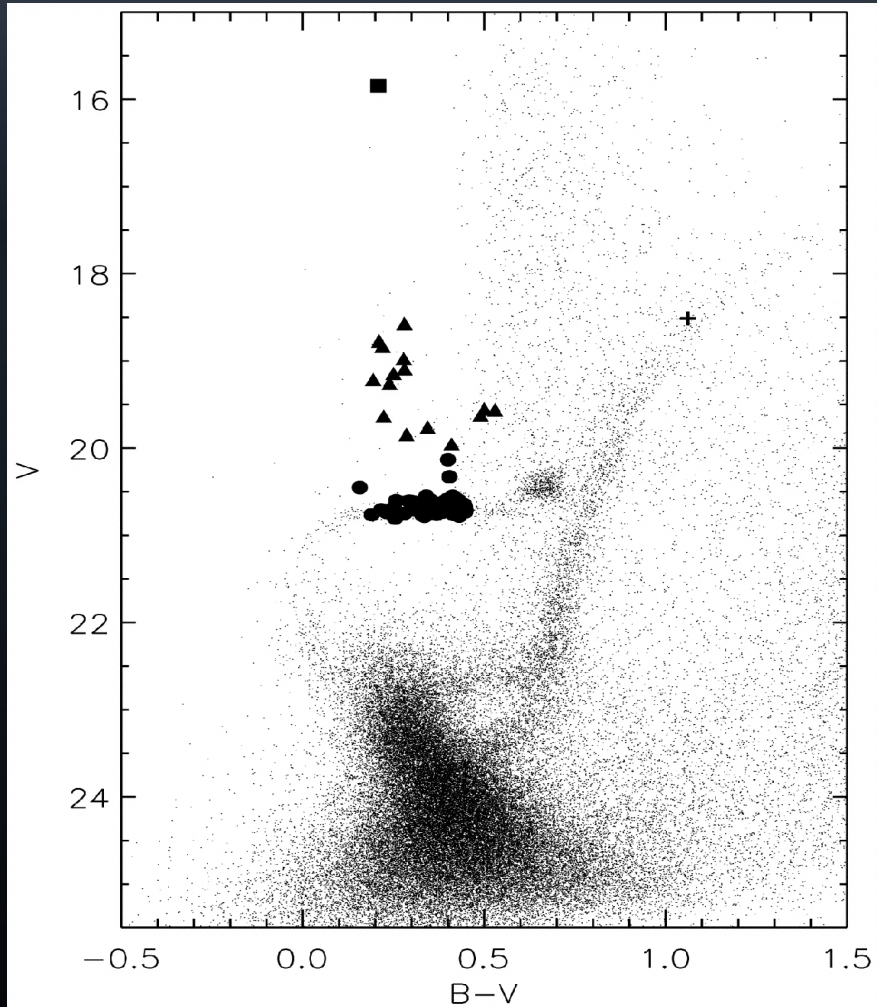
# RR Lyrae stars in Vir Z

RR Lyrae Variables Near 1220-1

LSQ	$\alpha_{2000}$ (deg)	$\delta_{2000}$ (deg)	Type	$\langle V \rangle$ (mag)	$\langle V \rangle_0$ (mag)	$d_{\odot}$ (kpc)	$\phi^a$ (deg)	$V_{\text{gsr}}$ (km/s)
515	184.67940	-0.71070	c	17.18	17.07	20.2	0.754	-85.7
525	184.92920	-1.02490	c	17.73	17.63	26.0	0.358	227.3
532	185.33610	-1.40380	ab	17.77	17.66	26.4	0.262	-23.7
550	186.04470	-1.09790	ab	17.77	17.69	26.8	0.997	-54.8

Tentatively, stars 532 and 550 are associated with Vir Z which then will be located at 26.5 kpc.

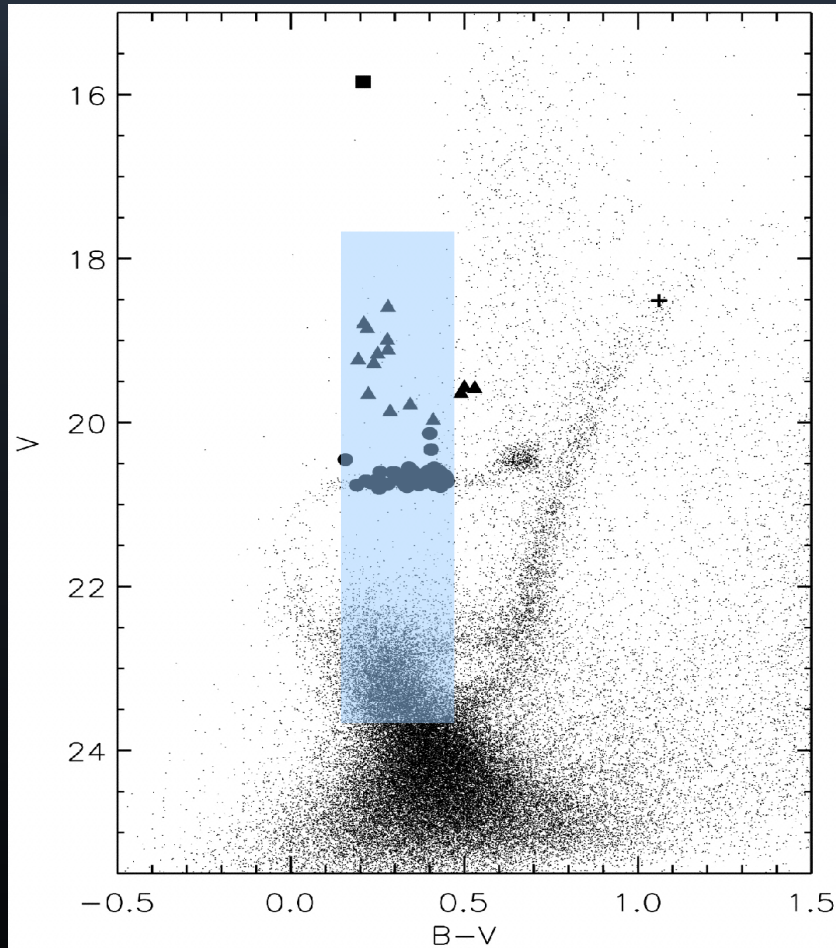
# Dwarf Cepheids: another suitable tracer?



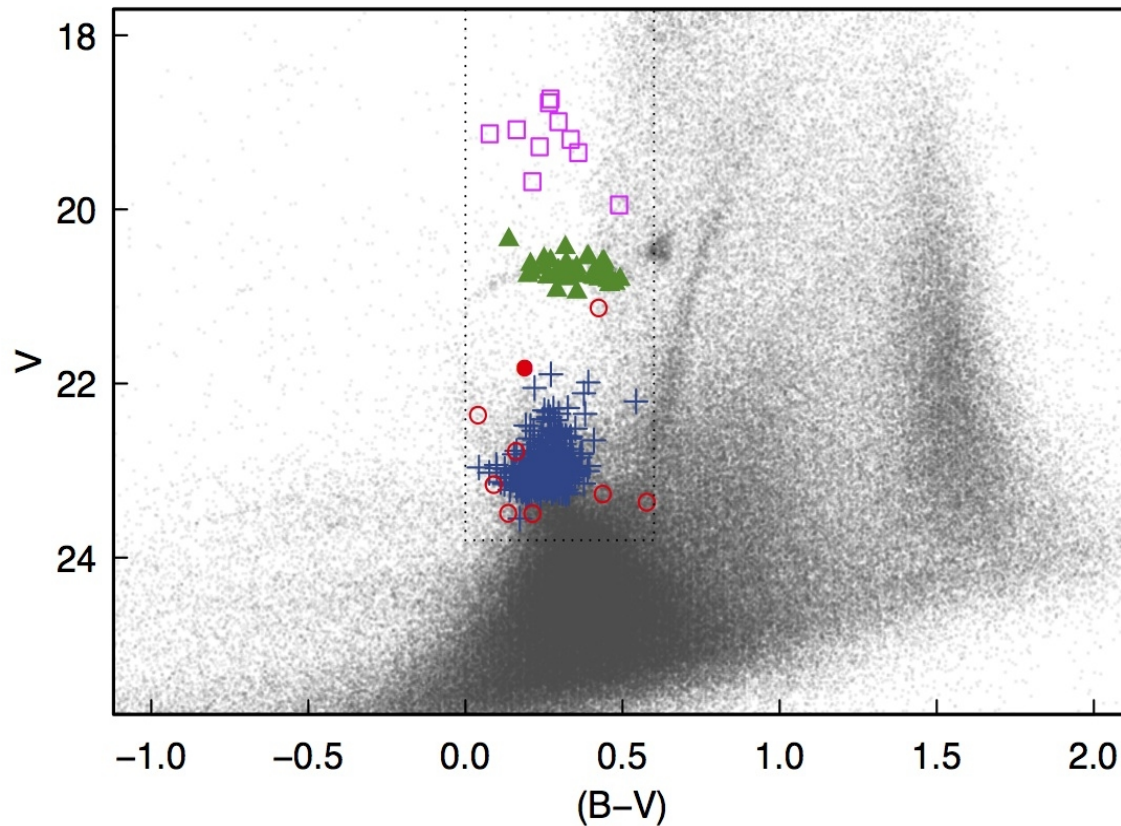
Carina dSph  
Dall'Ora et al (2003)



# Dwarf Cepheids: another suitable tracer?



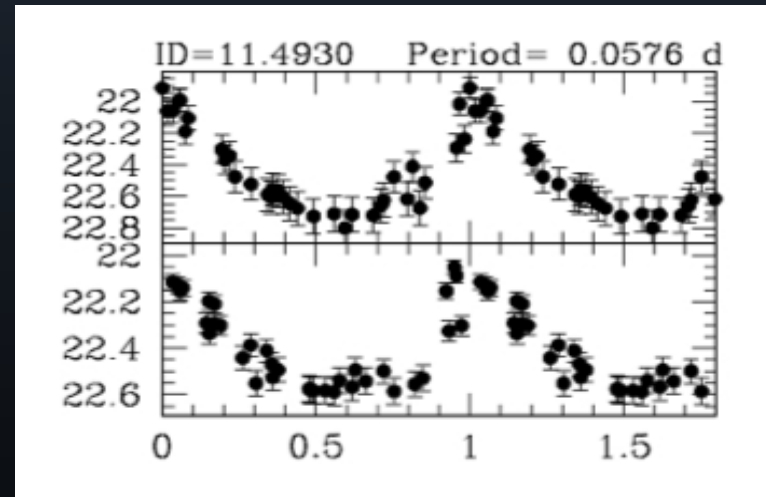
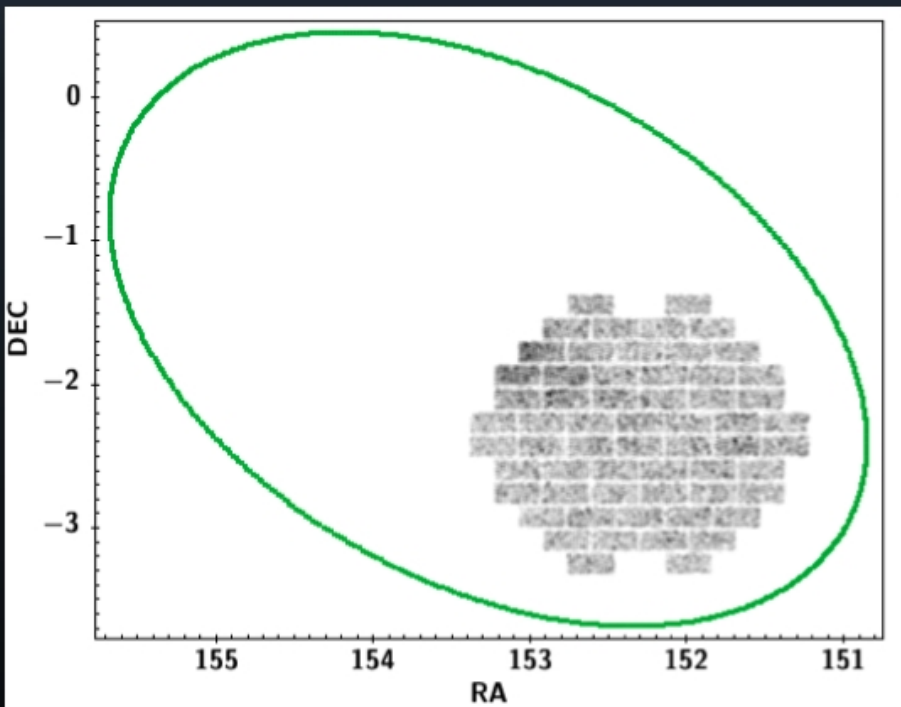
# Dwarf Cepheids: another suitable tracer?



- \* Standard candles
- \* Large amplitudes (in dSph galaxies): 0.2-1.2 mag
- \* Short periods (~1-2 hours)

Carina: Vivas & Mateo (2013)

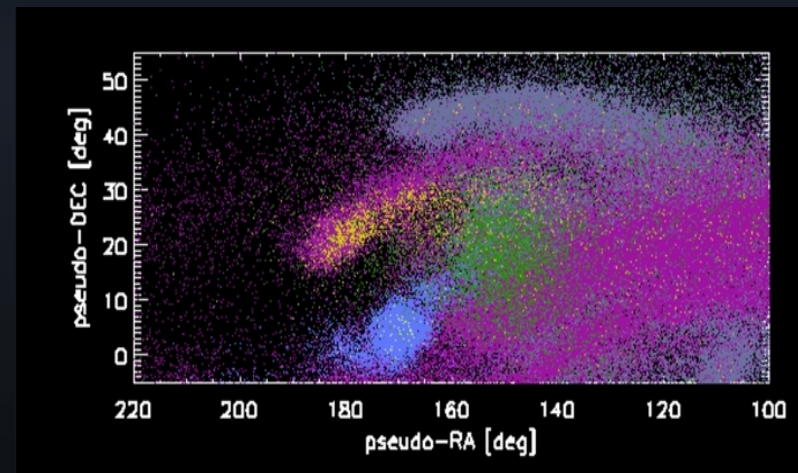
# Sextans galaxy



One of two DECam fields with time series in the Sextans dSph galaxy

# Summary

- ★ VOD composed of multiple kinematical groups
- ★ The most prominent group in RR Lyrae stars is the VSS at a velocity of  $\sim 130$  km/s.
- ★ It is probable that an additional sub-structure is located behind the VSS but it is not rich in RR Lyrae stars.



Stars from different disrupted galaxies along the same line of sight in the Aquarius simulation (Helmi et al 2011)

