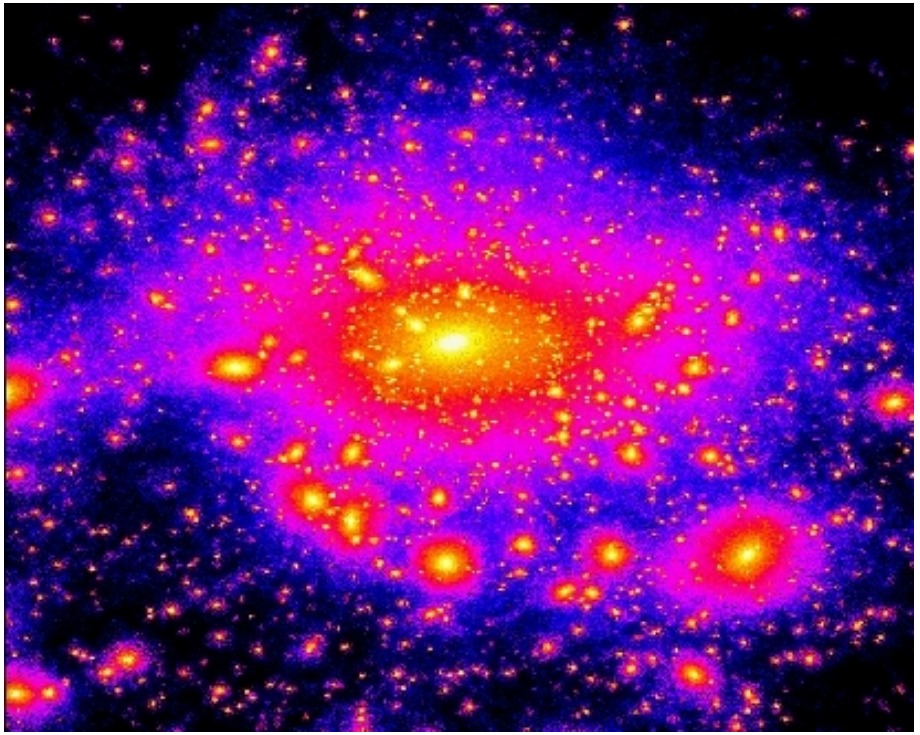
Dwarf spheroidal satellites of M31: Variable stars and stellar populations

Felice Cusano

INAF-Osservatorio Astronomico di Bologna
LBT Team Italy

collaborators:
Gisella Clementini, Alessia Garofalo, Michele Cignoni, Luciana Federici, Marcella Marconi, Ilaria Musella, Vincenzo Ripepi et al.

Context



http://home.slac.stanford.edu

- ΛCDM theory predicts formation of large galaxies by merging and accretion of small structures

- The satellite galaxies provide an important laboratory to study the galaxy formation on small scale and derive constraints for cosmological predictions

- Some issues:

  - Missing satellite problem (Klypin et al. 1999);

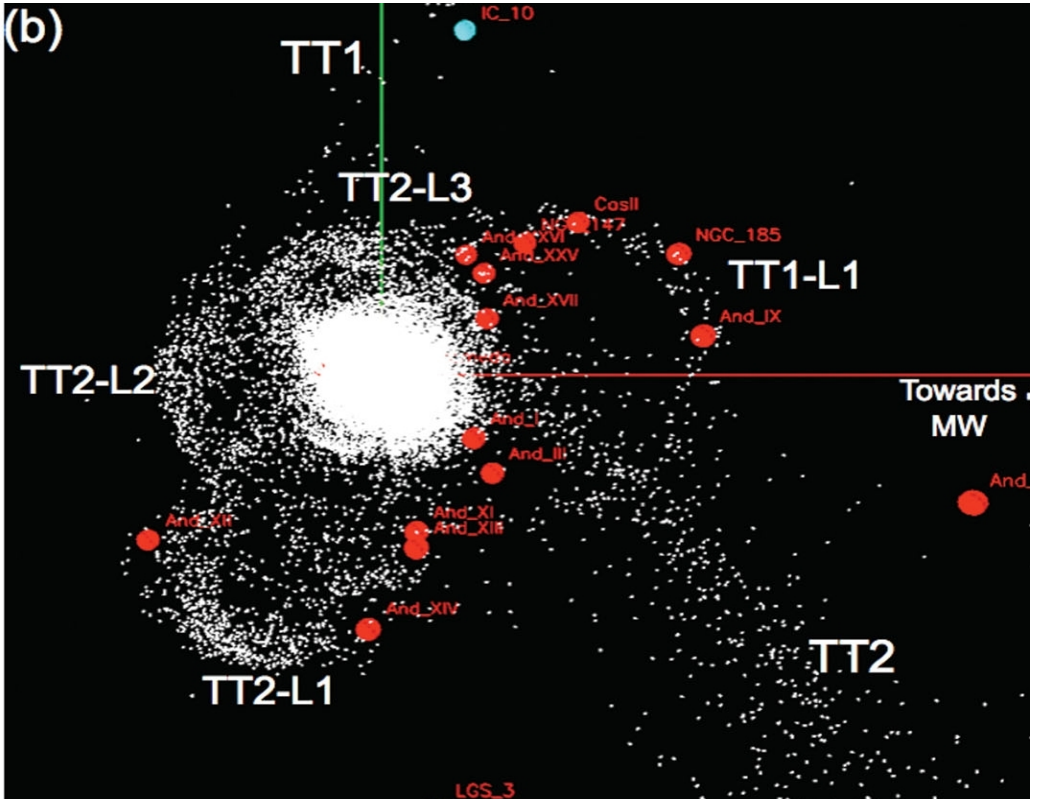
  - Metz et al. (2009) found that 11 satellites of MW are rotating their host in a thin plane called the Vast polar structure (VPOS)

  - Ibata et al. (2013) found a similar structure of 15 M31 satellites (Great Plane of Andromeda, GPoA)

  - there maybe tidal tails connecting the VPOS and GPoA (Pawlowsky et al. 2013)

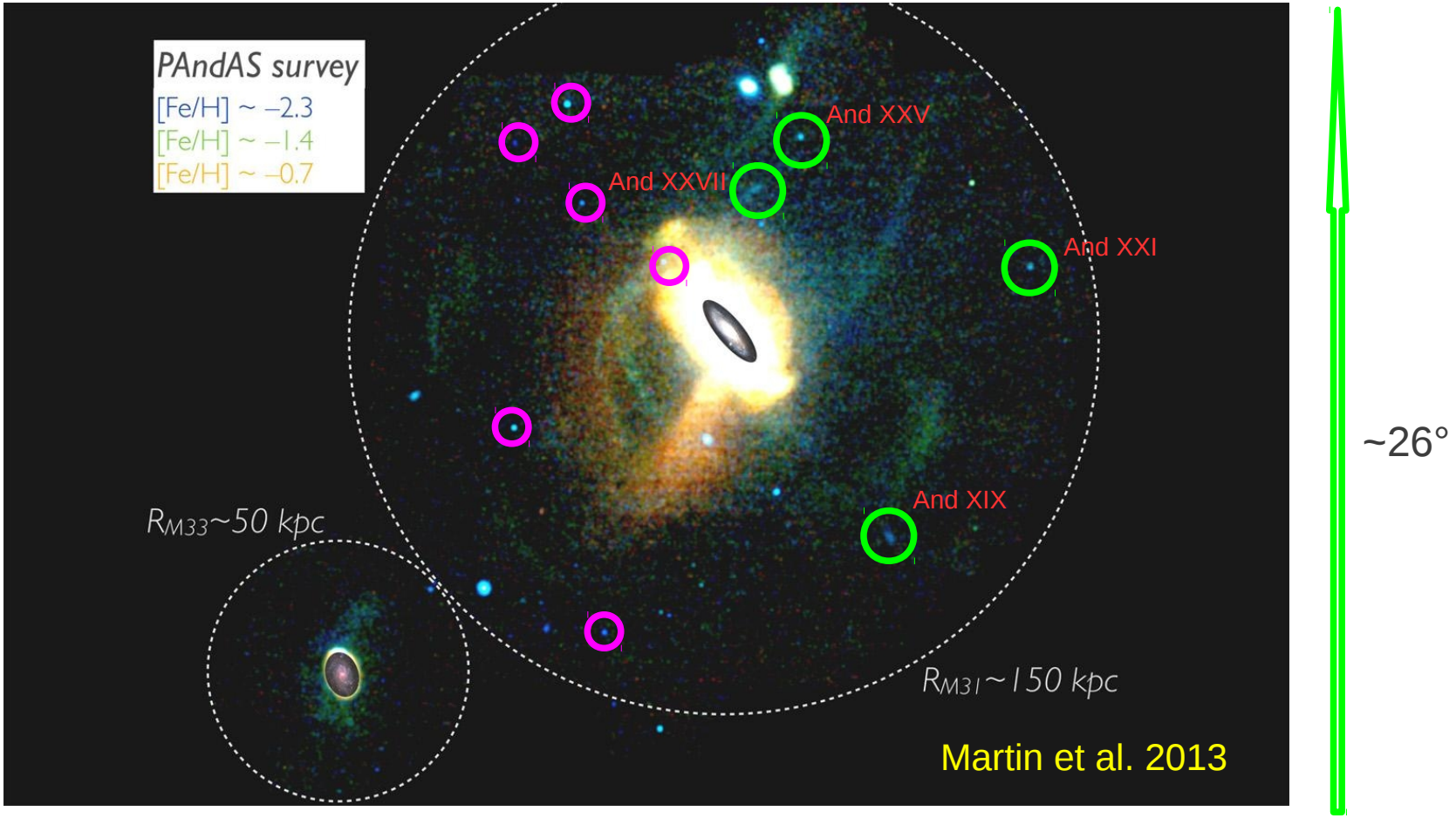
Context

- The satellites are tidal dwarf galaxies formed in a past major merge between M31 and a massive galaxy (Hammer et al. 2013; Pawlowski et al. 2013).
- Under the assumption of Milgromian dynamics, Zhao et al. (2013) found that M31 and the MW had a close encounter about 7-11 Gyr ago; the satellites probably formed in this fly-by
- Thus understanding the nature of these galaxies is fundamental to address theory of galaxy formation as well as cosmology



Hammer et al. (2013)

Our survey of M31 satellites



Aims:
- characterize the stellar populations of the satellites of M31
- derive their early star formation history
- provide hints on how the M31 halo has formed

Tools:
- variable stars
- color-magnitude diagrams

Variable stars as tracers of different stellar populations

example the Turn Off of a 10 Gyr stellar system is at M_V~ 3, at the distance of M31 is V ~ 28-28.5 mag

- Classical Cepheids ⟹ young (t < 100 Myr)

  P=1 – 100 d, M_V= -2 ÷ -7

- Anomalous Cepheids ⟹ intermediate age (t~ 0.75 -1.25 Gyr)

  P=0.3 – 2.5 d, M_V= -2 ÷ 0 but … binaries

- RR Lyrae stars ⟹ old (t >10 Gyr)

  P=0.2 - 1 d, M_V= 0 ÷ 1

The Oosterhoff dichotomy as a tool to investigate galaxy formation

RR Lyrae populations in the MW halo and GCs divide in two distinct groups, based on the average period of the fundamental mode RR Lyrae stars:

Oo I $\langle P_{ab} \rangle = 0.55$ d

Oo II $\langle P_{ab} \rangle = 0.64$ d

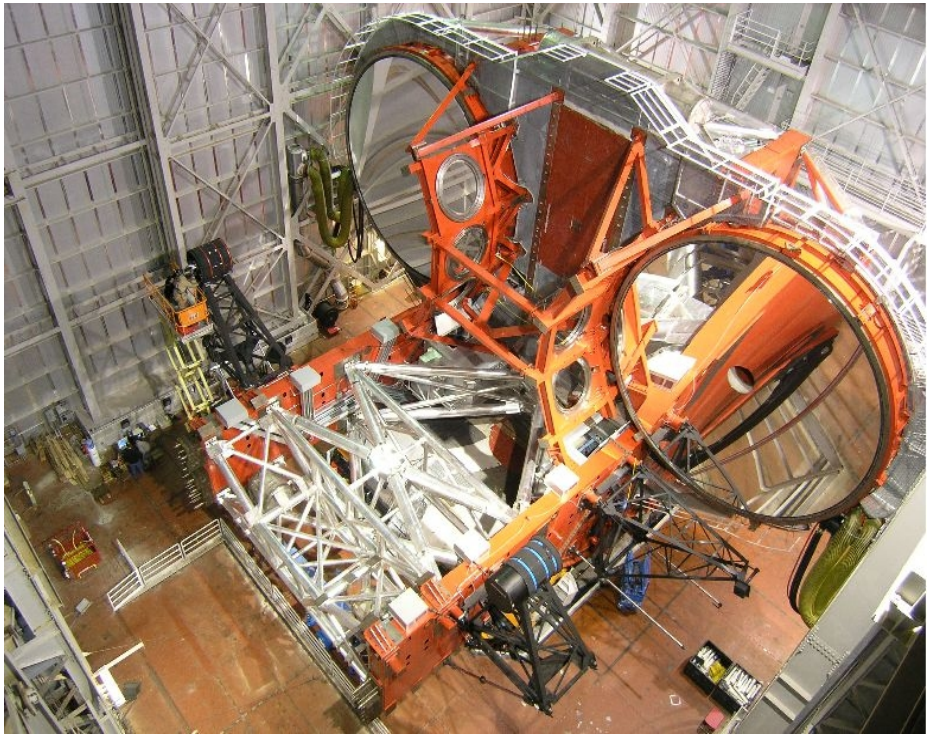
Type	$\langle P_{ab} \rangle$	$\langle P_{c} \rangle$	N_c/N_{total}	[Fe/H]
Oo I	0.55 d	0.32 d	0.17	-1.4
Oo II	0.64 d	0.37 d	0.44	-2.0

Confirmed by recent works on larger samples in the MW field and halo (e.g. see Catelan 2009; Sesar et al. 2013)

No Oosterhoff dichotomy is observed in the bright dSphs of the MW.

They can not be the building blocks of MW halo.

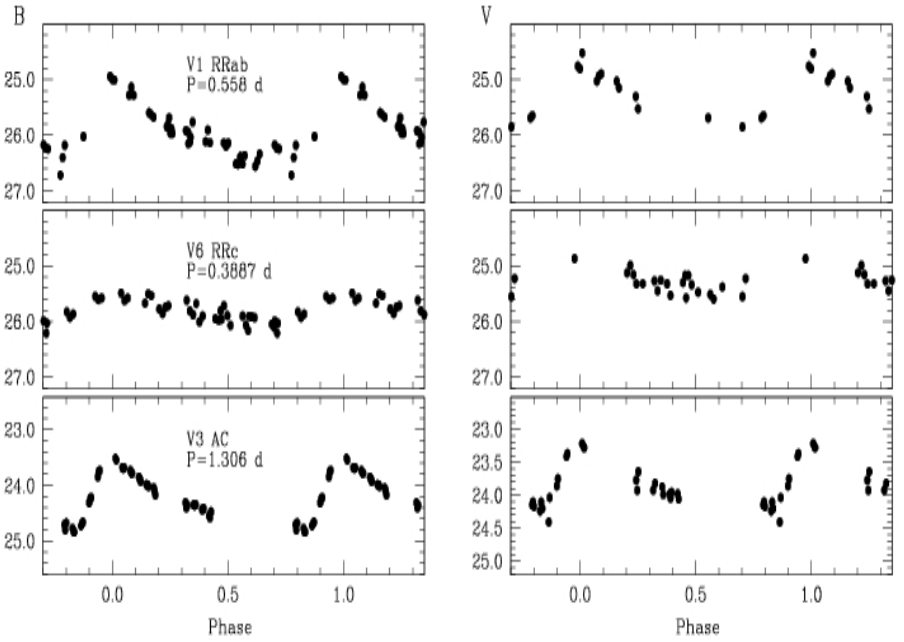
LBT observations of And XIX-XXI + data reduction



- Binocular mode LBC
- 44 exposures in B, 31 in V each of 420s for And XIX
- 46 exposures in B, 46 in V each of 420s for And XXI
- Pre-reduction LBT pipeline
- PSF-Photometry with DAOPHOT-ALLSTAR-ALLFRAME package (Stetson 1992)

Variable stars in And XIX

And XIX discovered by McConnachie et al. (2008), r_h =6.2' (1.5 Kpc), [Fe/H]=-1.8 dex and small velocity dispersion when compared to the large extension (Collins et al. 2013)



Cusano et al. 2013, ApJ, 779, 7

- *39 Variable stars*
- *8 Anomalus Cepheids*
- *31 RR Lyrae stars of which 26 RR_{ab} and 5 Rr_c*

From the RR Lyrae stars we derived:

- $\langle P_{ab} \rangle$=0.62 d σ=0.03 d

And XIX can be classified as Oo Int

- E(B-V)=0.11±0.06 mag using the method of Piersimoni et al. (2002)

- $(m-M)_0$= 24.52±0.23 mag

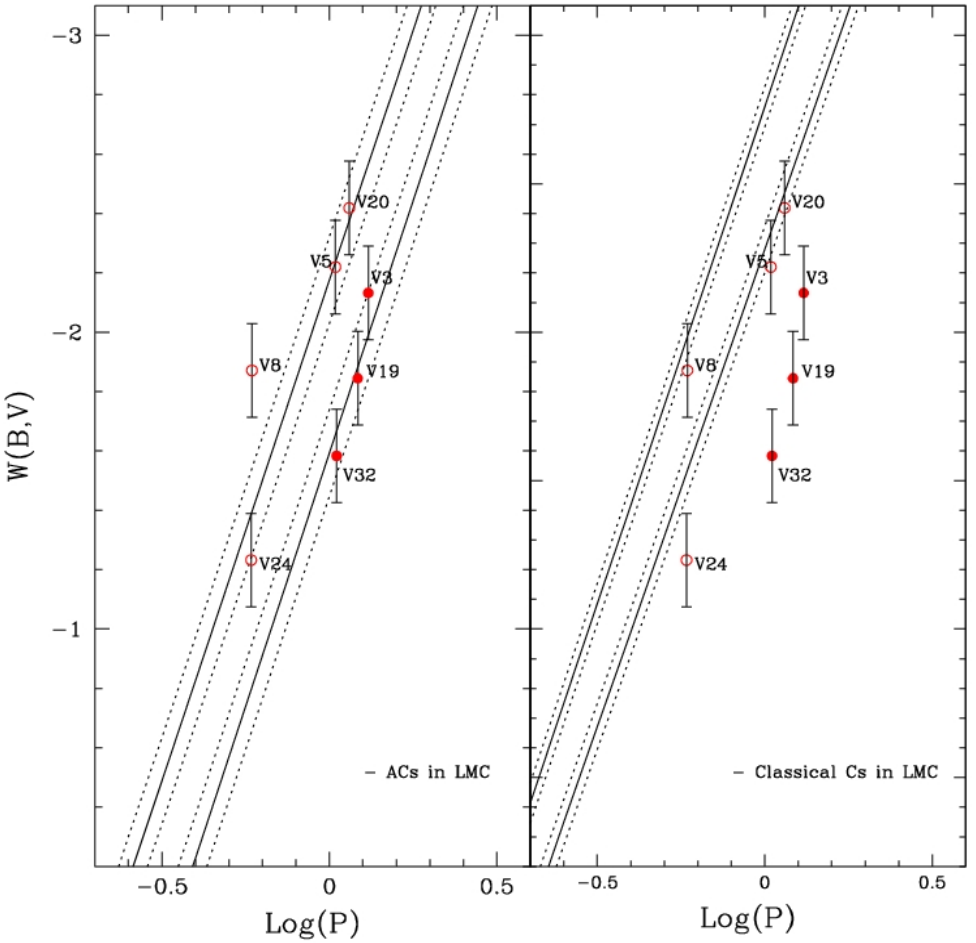
Anomalous Cepheids

- Period-Wesenheit relation (reddening independent)

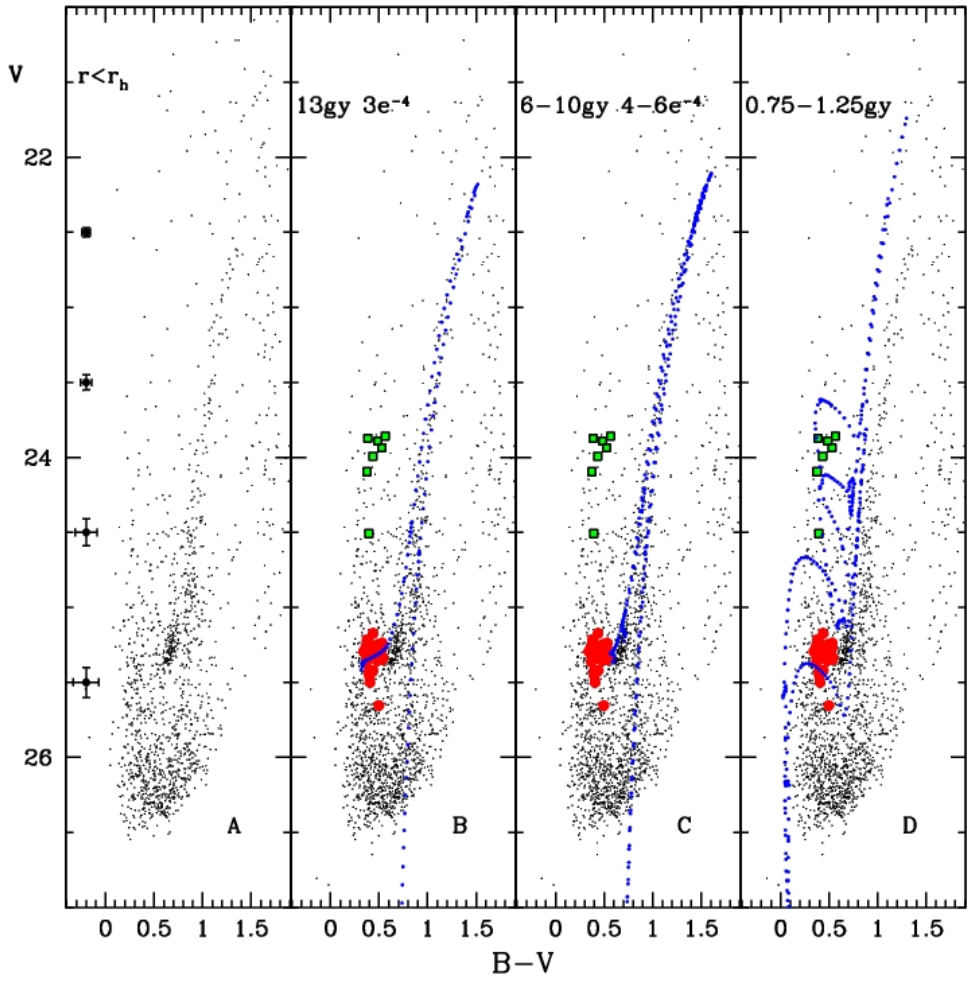
  $W(B,V)=M_V-3.1x(B-V)$

- PW for ACs in the LMC by Ripepi et al. (2013)
- PW for CCs in the LMC

  by Soszynki et al. (2008)



The Color-Magnitude diagram of And XIX

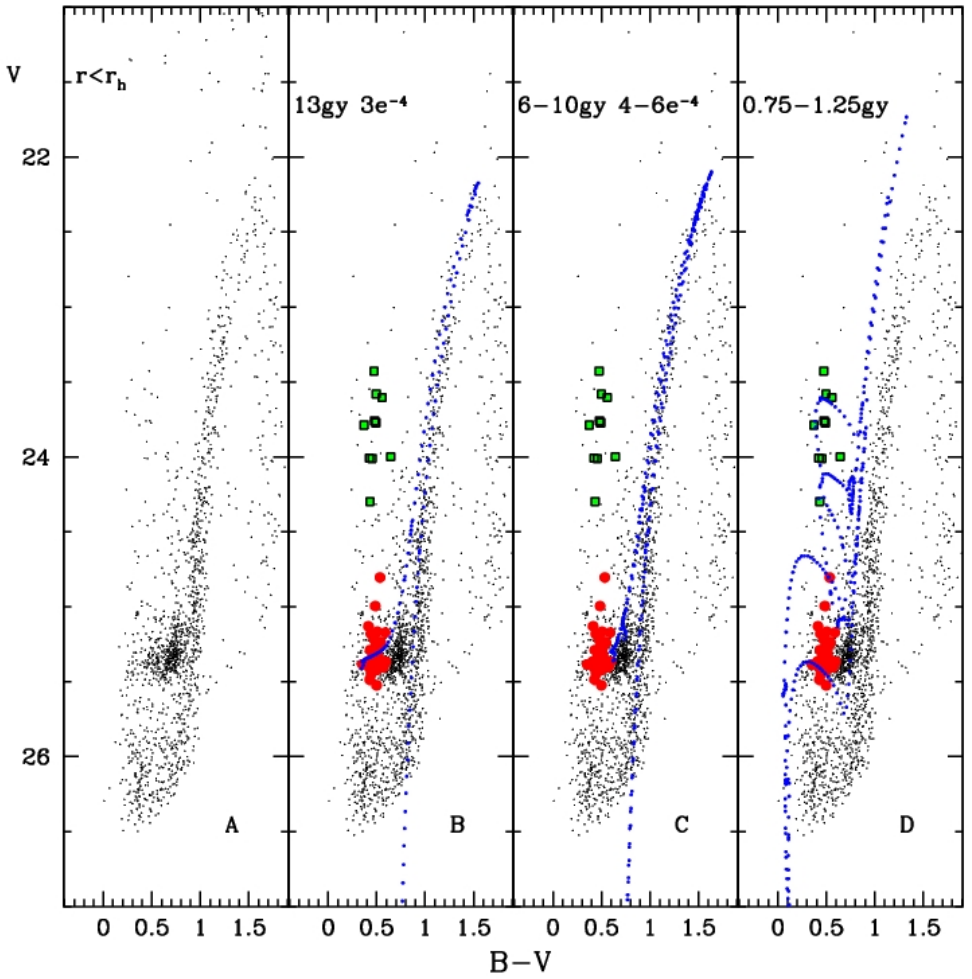


Stellar populations

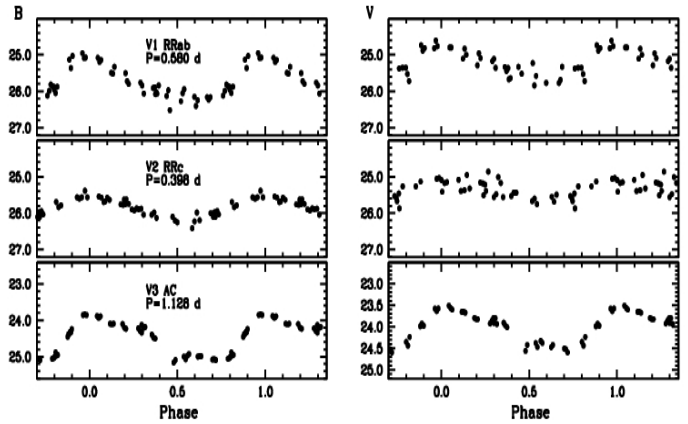
- B: ~13 Gyr [Fe/H]=-1.8 dex
- C: 10-6 Gyr, [Fe/H]~-1.5 dex
- D: 0.75-1.25 Gyr, [Fe/H]~-1.5 dex

isochrones by Bressan et al. (2012)

And XXI



- And XXI discovered by Martin et al. (2009) has [Fe/H]=-1.8 and r_h=3.6'

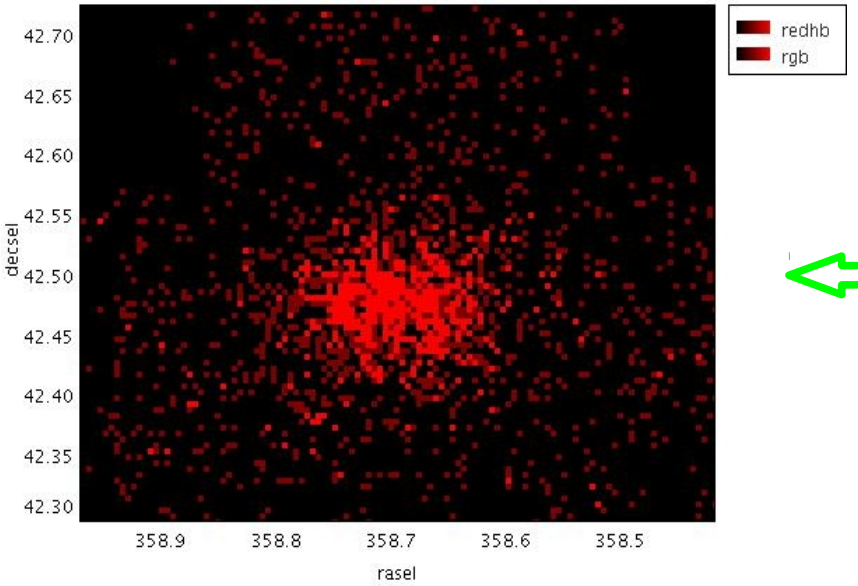


Our results:

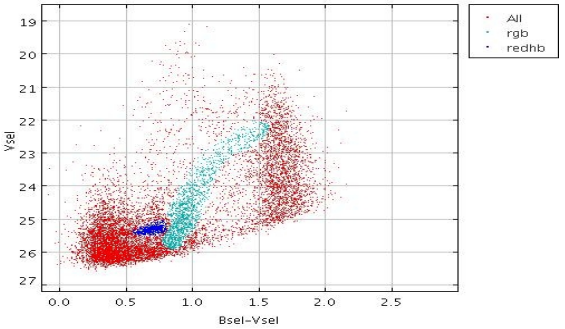
- 43 RR Lyrae stars

  (<P_{ab}>=0.63 d σ=0.03d; Oo Int)
- 10 ACs (intermediate population?)
- 2 (or 3?) stellar populations similar to And XIX

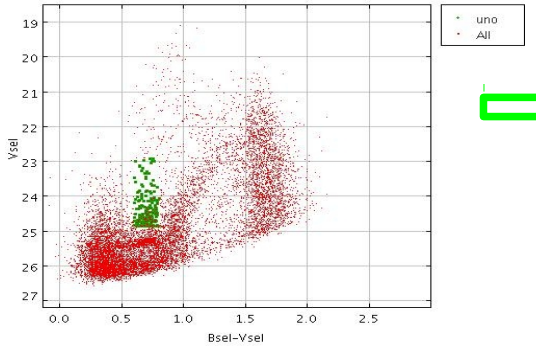
Spatial distribution in And XXI

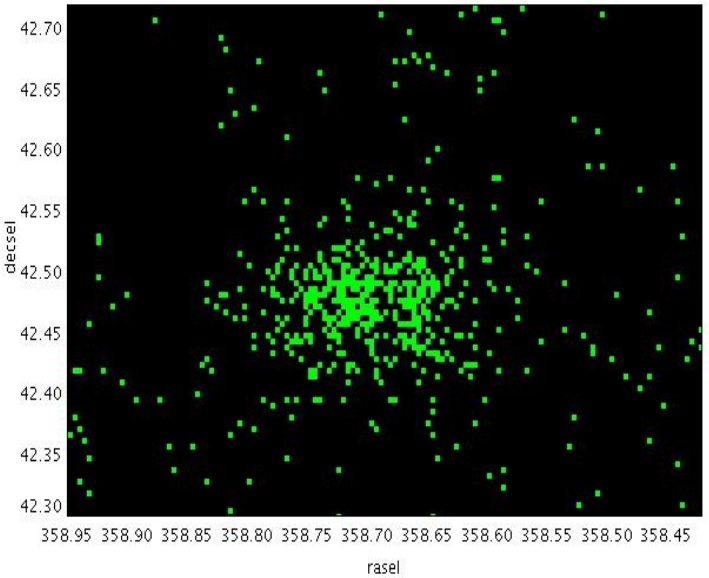


- Red clump + RGB



- Intermediate blue objects





Results

- We discovered 39 variable stars in And XIX of which 31 are RR Lyrae stars and 8 ACs and 53 variable stars in And XXI of which 43 are RR Lyrae stars and 10 Acs

- From the average period of the RRab stars and the Amplitude-Period diagram And XIX and And XXI can be classified as Oo Int objects

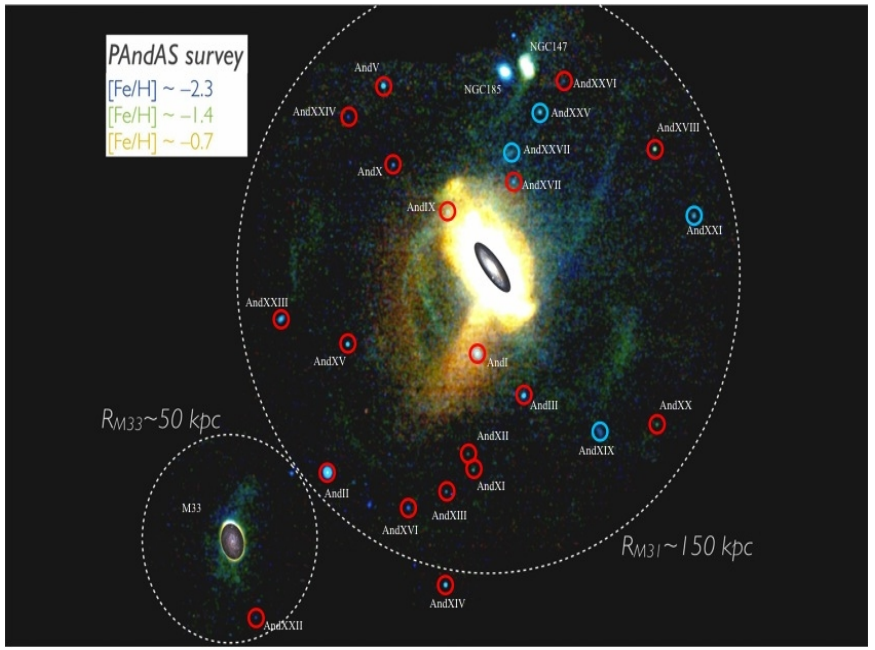
- We found evidence for two different stellar populations in And XIX and XXI, one of t~12 Gyr with [Fe/H]~-1.8 and the other of t~6-10Gyr with [Fe/H]~-1.5

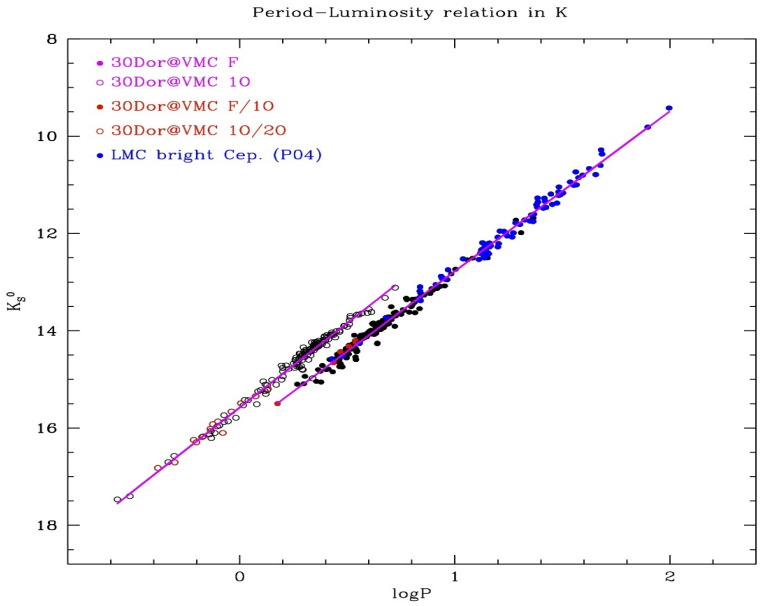
- ACs well follow a PW relation and give hints of a recent episode of star formation (0.75-1.25 Gyr)

….Thanks

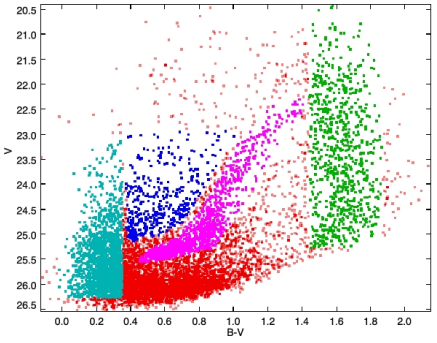
LBC upgrade

- Extension to NIR (600nm to 1.8μm) of Red eye, P-L of RR Lyrae and Cepheids in M31 and surroundings to derive accurate distance of different structures
- Increasing efficiency to 80% at 350nm of Blue eye, to map young blue stars and/or blur HB stars and planetary nebulae in M31 structures

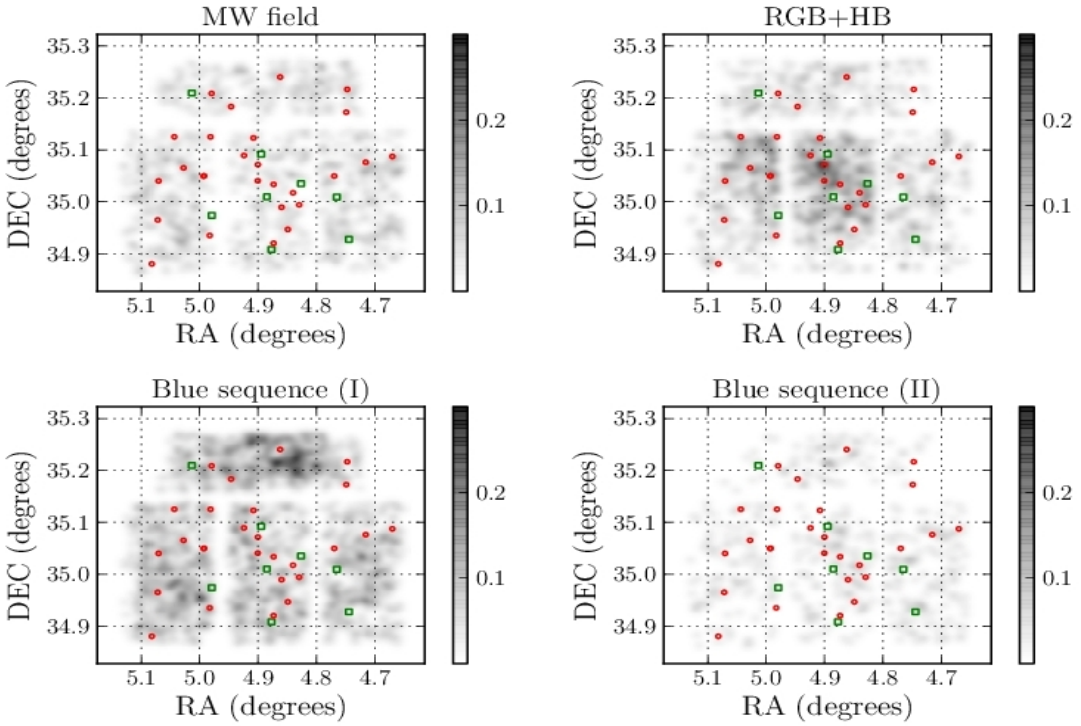




Spatial distribution of selected regions in the CMD

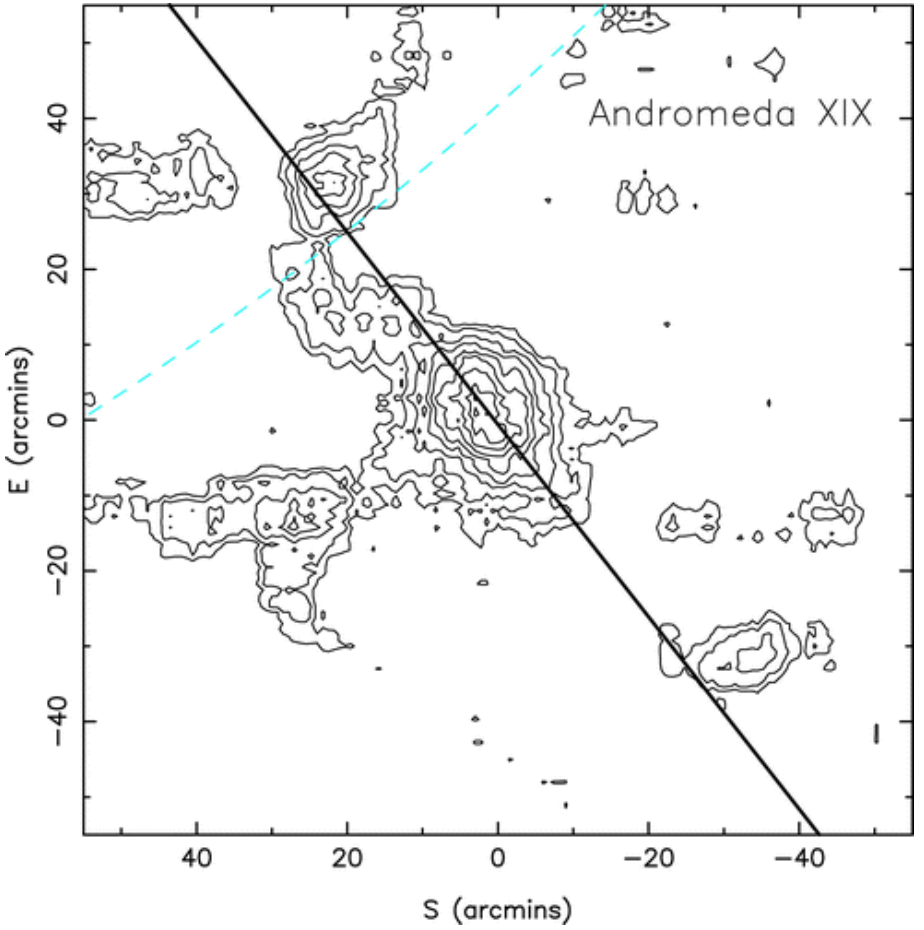


- MW stars homogeneously distributed
- RGB + HB stars along a diagonal bar pointing in the direction of M31 (most of the variables are along this bar)
- Blue sequence objects have an overdensity around R.A=4.84° Dec.=+35.22°, cluster of galaxies?
- Intermediate blue objects partially follow RGB + HB stars



Andromeda XIX

- Discovered in the CFHT/MegaPrime photometric survey around M31 (McConnachie et al. 2008)
- It is the largest dSph galaxy of the LG (r_h~1.5 Kpc)
- Collins et al. (2013) found a small velocity dispersion when compared to the large extention (tidal interaction?)
- Distance 830 Kpc (Conn et al. 2012), [Fe/H]=-1.8 dex (Collins et al. 2013), distance to M31 center ~ 120 Kpc



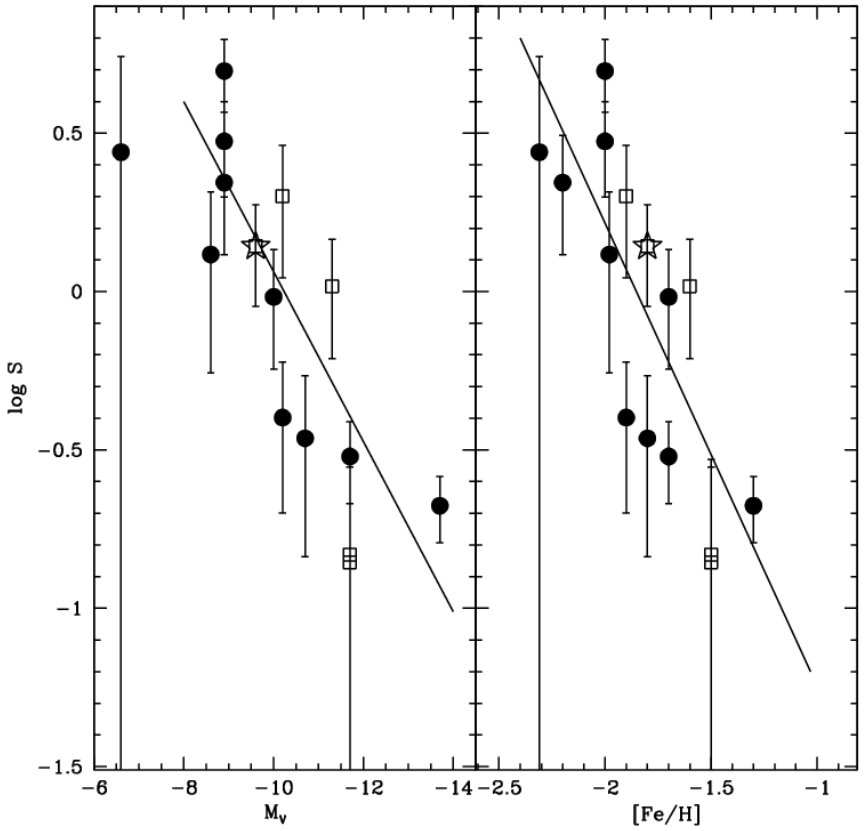
McConnachie et al. (2008)

RR Lyrae stars in And XIX

- Ellipse drawn using the parameters by McConnachie et al. (2008)
- $\langle P_{ab} \rangle = 0.61$ d $\sigma = 0.03$ d inside the r_h
- $\langle P_{ab} \rangle = 0.62$ d $\sigma = 0.03$ d all

Specific frequency of ACs in dSphs

- Number of Acs per 10^5 $L_{\odot}$ (Mateo et al. 1995)
- Squares are dSphs satellite of M31, circles of MW

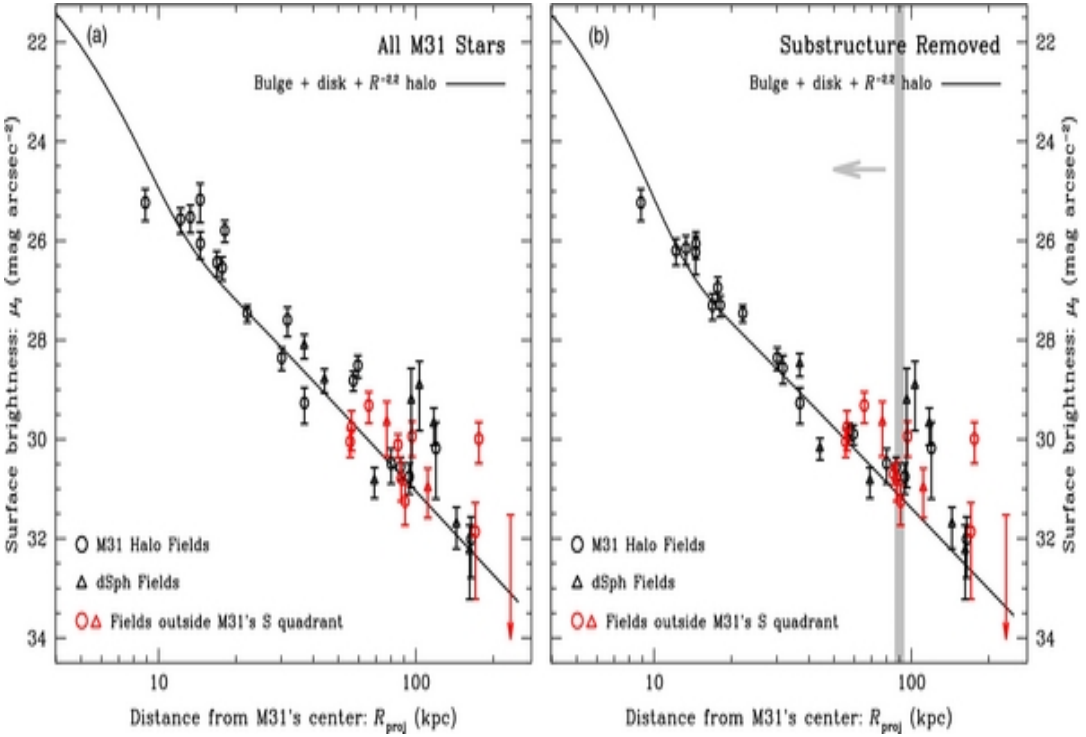


Distance from RR Lyrae luminosity

- Average V-mag of the RR Lyrae stars in And XIX <V>=25.34±0.10 mag
- E(B-V)=0.066±0.026 mag from Schlegel et al. (1998)
- E(B-V)=0.11±0.06 mag from the RRLyrae using the method of Piersimoni et al. (2002)
- We use as absolute mag of RR Lyrae M_V=0.54±0.09 mag at [Fe/H]=-1.5 dex and corrected for metallicity$\Delta M_v/\Delta$[Fe/H]=0.214±0.047 mag/dex (Clementini et al. 2003)
- ***$(m-M)_0$ = 24.52±0.23 mag using our reddening***
- $(m-M)_0$= 24.66±0.17 mag using Schlegel et al. (1998)

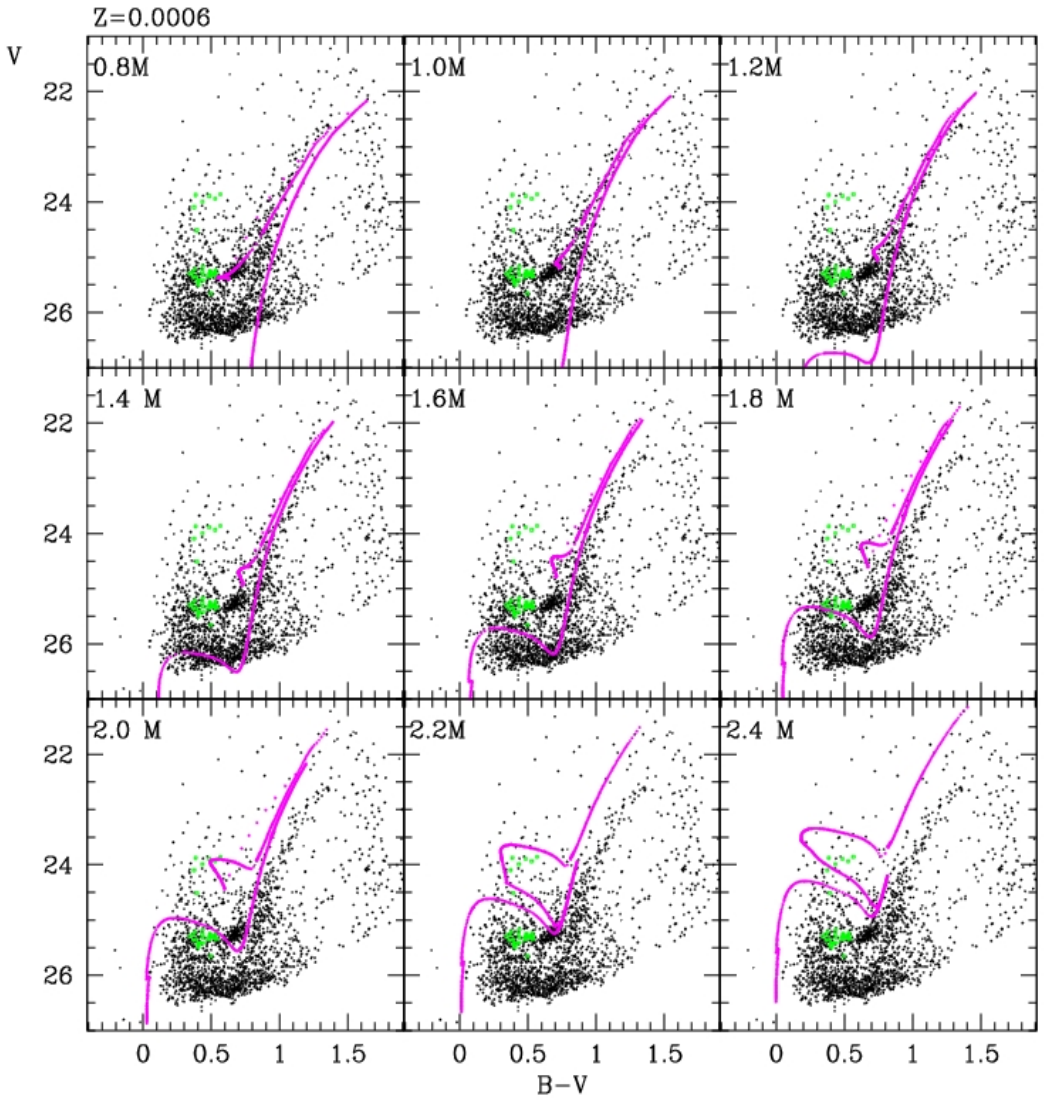
M31 halos contamination?

- And XIX distance from M31 center is ~120 kpc
- We use the result of Jeffery et al. (2011) to estimate the contamination from M31 halo variables
- We estimate 5 RR Lyrae stars and no ACs from M31 halo



Gilbert et al. (2012)

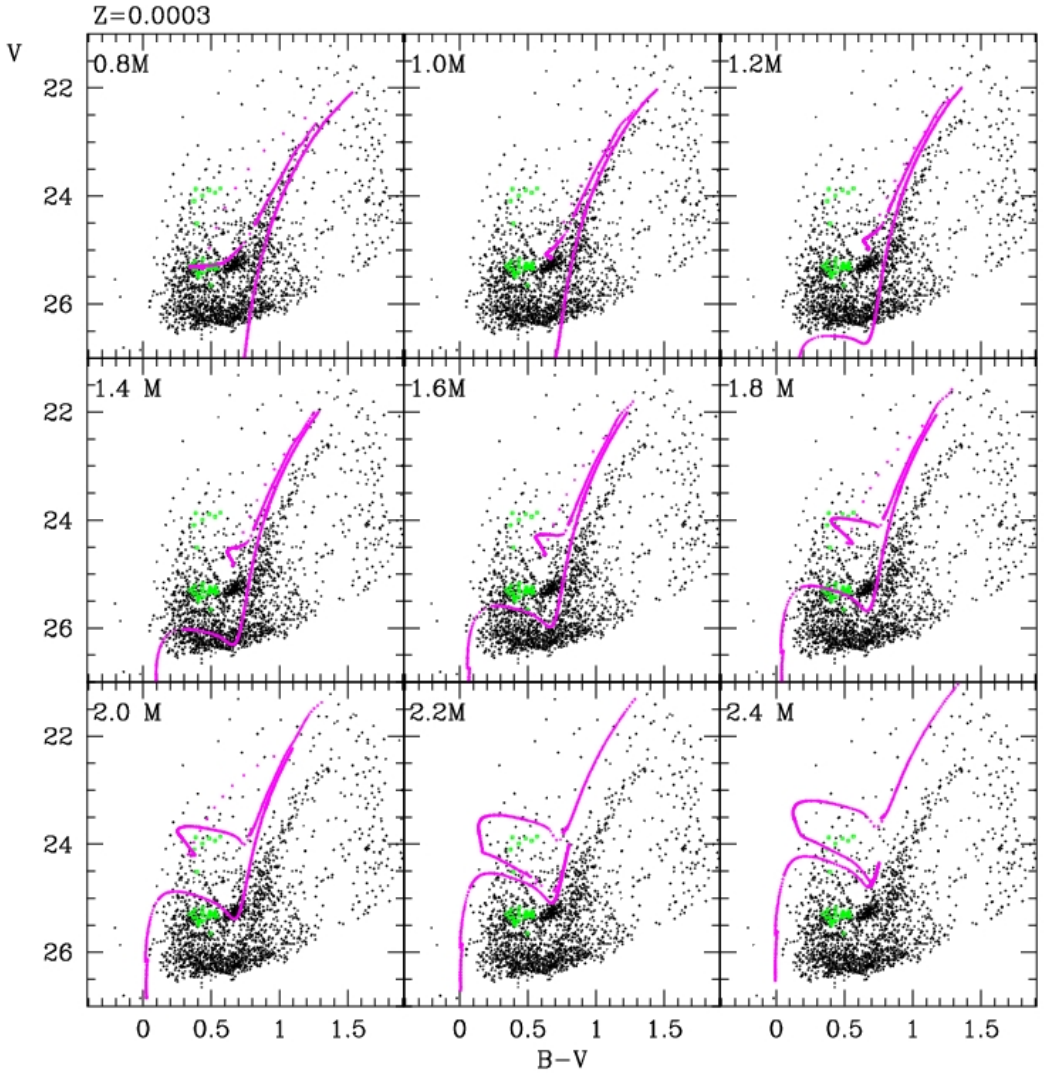
Interpretation of CMD: ACs



- … masses 2-2.2M☼ if [Fe/H]~-1.5

Interpretation of CMD: ACs

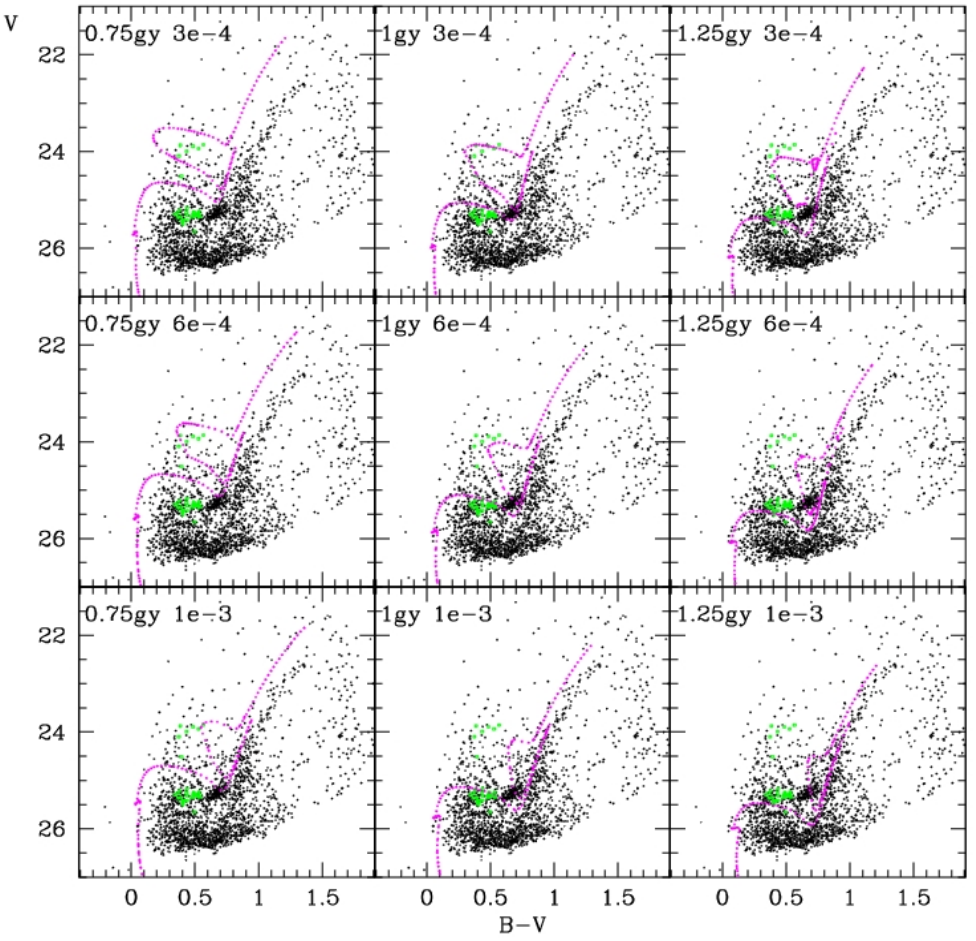
- Evolutionary tracks based on models by Pietrinferni et al. (2004)
- ACs stars have masses 1.8-2 $M_{\odot}$ if [Fe/H]~-1.8
- or ..



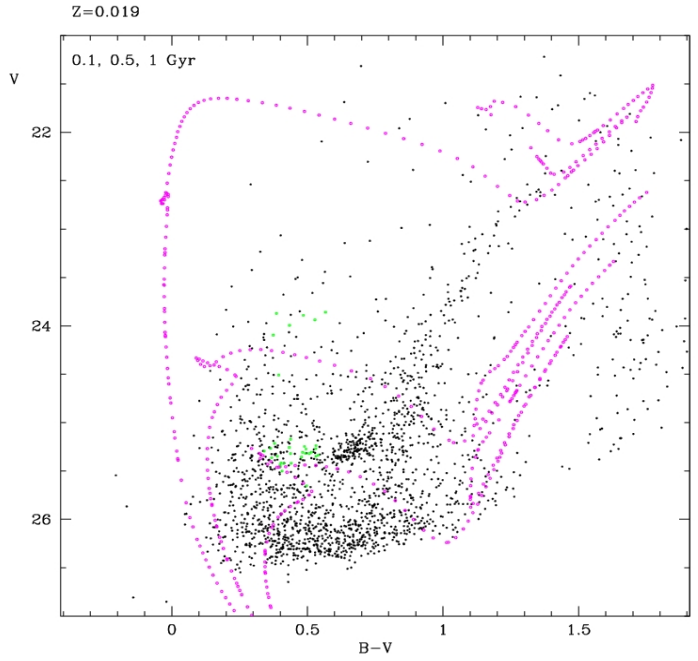
A recent episode of star formation?

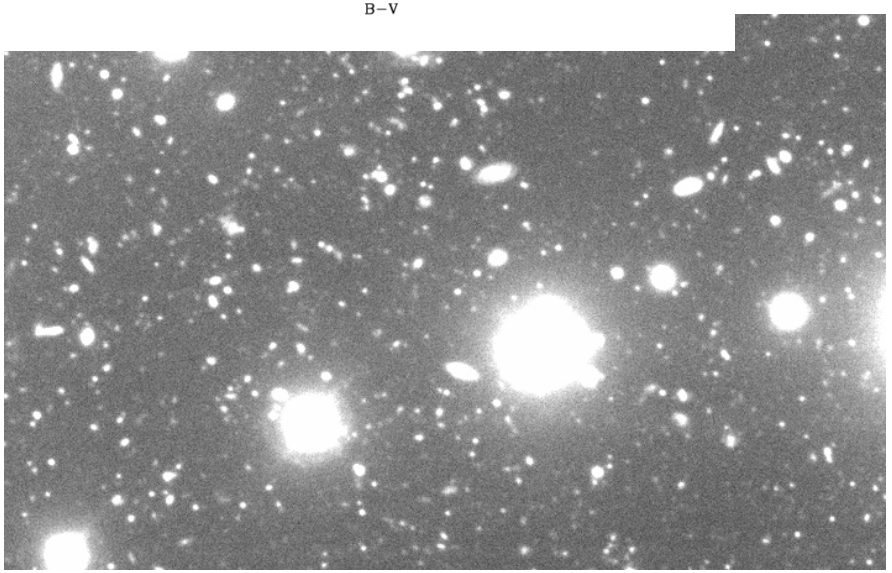
- ACs in And XIX have ages of 0.75-1 Gyr in the [Fe/H]~-1.8 case or 1-1.25 Gyr in the [Fe/H]~1.5

- Otherwise they are the evolved counterpart of MS blue stragglers (mass transfer in the last 1Gyr)



Background unresolved galaxies





- Blue objects are mainly unresolved galaxies
- Upper limit of unresolved galaxies in the LBC FoV by using the HST Ultra Deep Field catalog by Coe et al. (2005), we found comparable number of blue objects in the CMD

Does the Oosterhoff dicothomy exist in M31 ?

- Brown et al. (2004) identified 55 RR Lyrae stars in the M31 halo - Oo Int
- Sarajedini et al. (2009) found 681 RR Lyrae stars in two fields around M31 - Oo I
- Jeffery et al. (2011) found 108 RR Lyrae in six fields - Oo I and Oo Int
- Two GC: B514 (Clementini et al. 2009) Oo Int;

  G11 (Contreras Ramos et al. 2013) Oo II
- 6 dSphs satellites of M31 – Oo I, II, Int

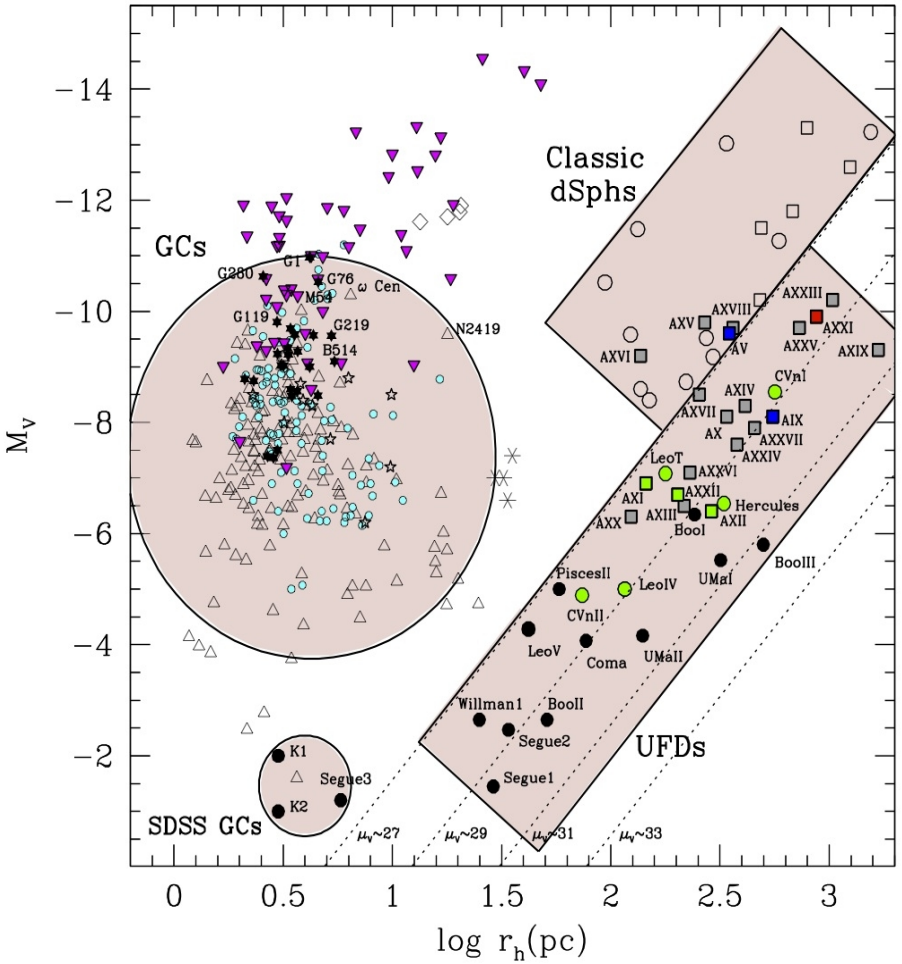
Context

- Missing satellite problem (Klypin et al. 1999); we observe an order of magnitude less satellites than predicted
- Ways to alleviate the missing satellite problem:

  -the discovery of Ultra Faint Dwarf (UFD) galaxies (μ_v>27 mag/arcsec^2)

  -not all the satellites can survive tidal interactions (Peñarubbia et al. 2008)

  -reionization suppressed star formation in most of the satellites (see e.g Brown et al. 2013)



Clementini et al. (2012)

Context

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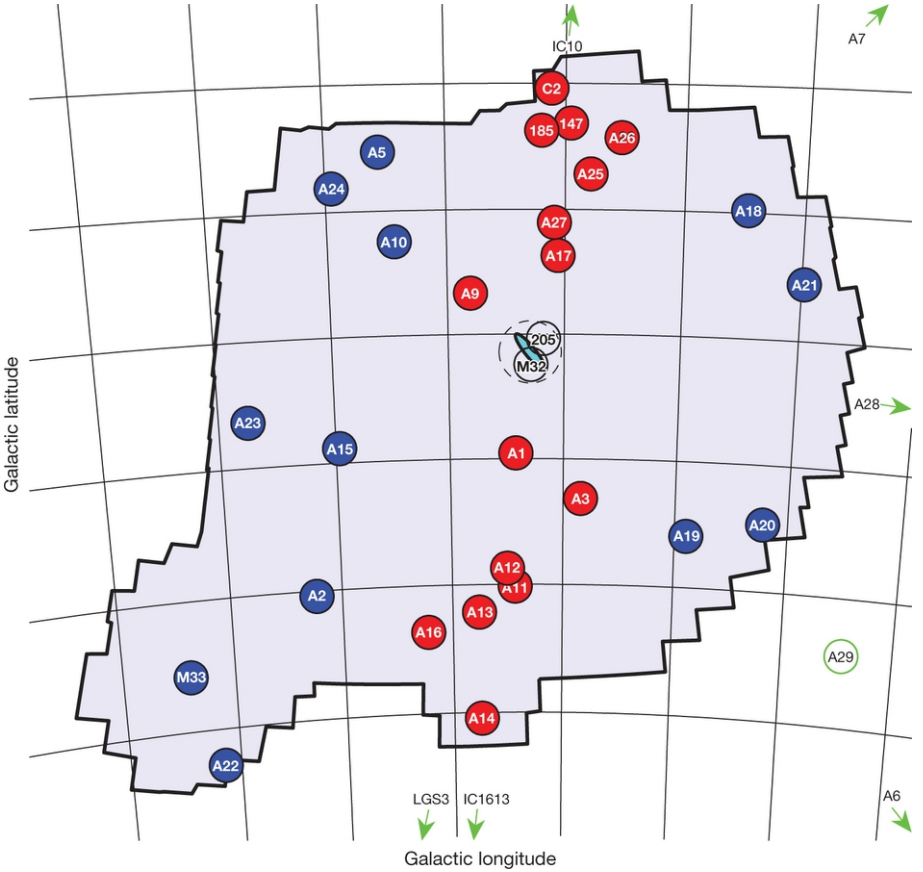
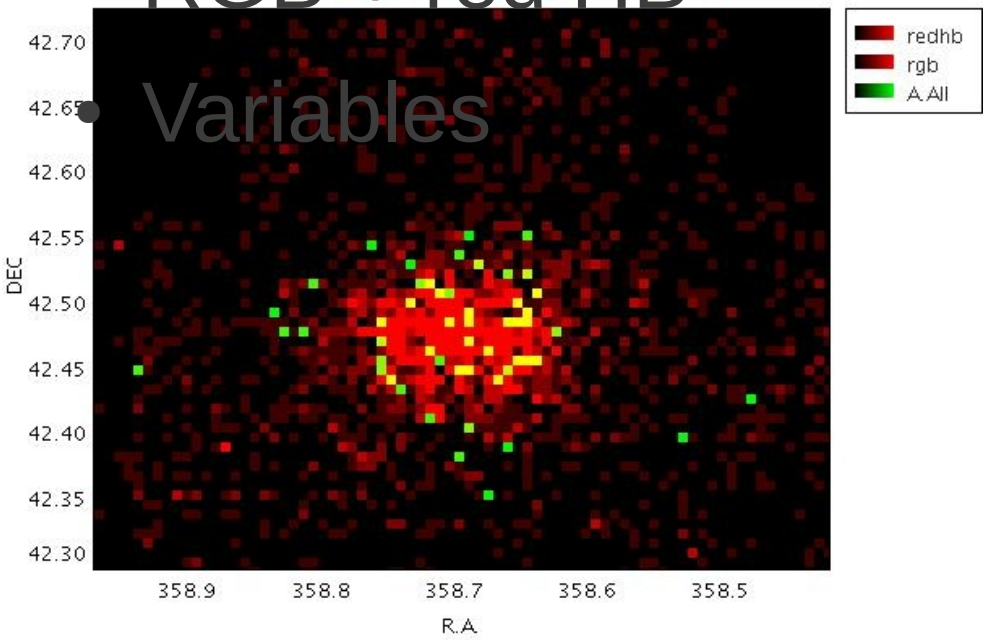


Ibata et al. (2013)

Spatial distribution

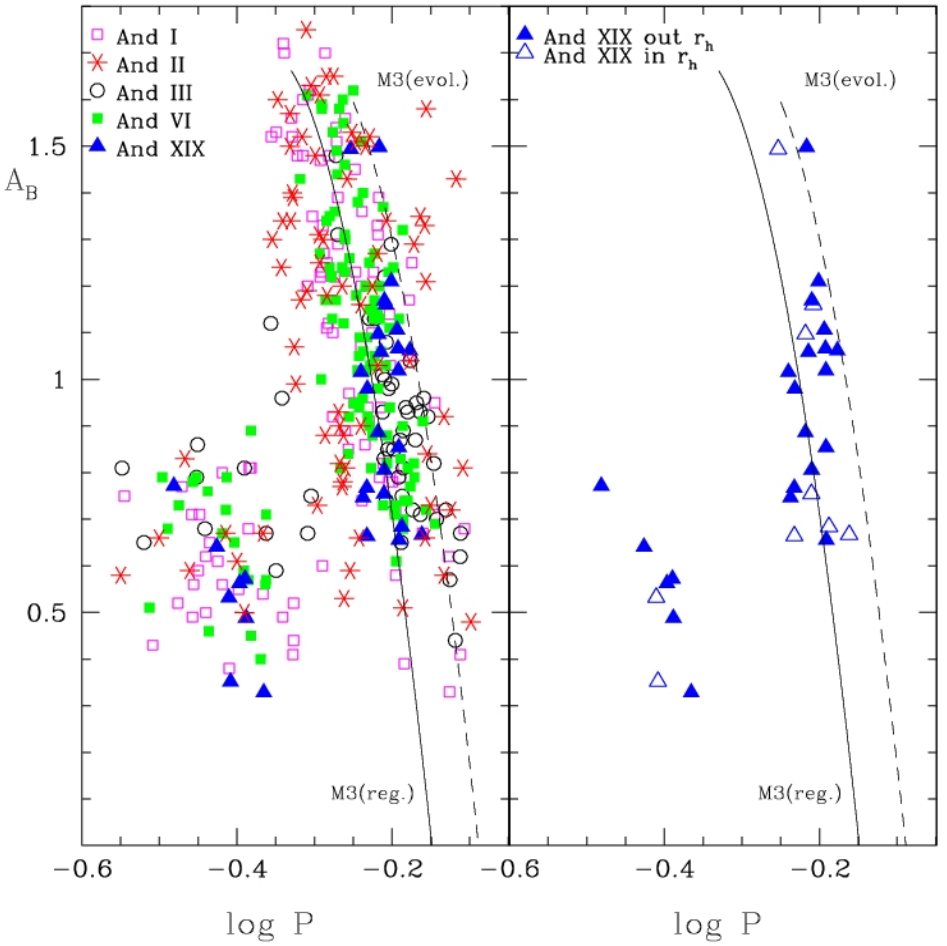
- RGB + red HB
- Variables

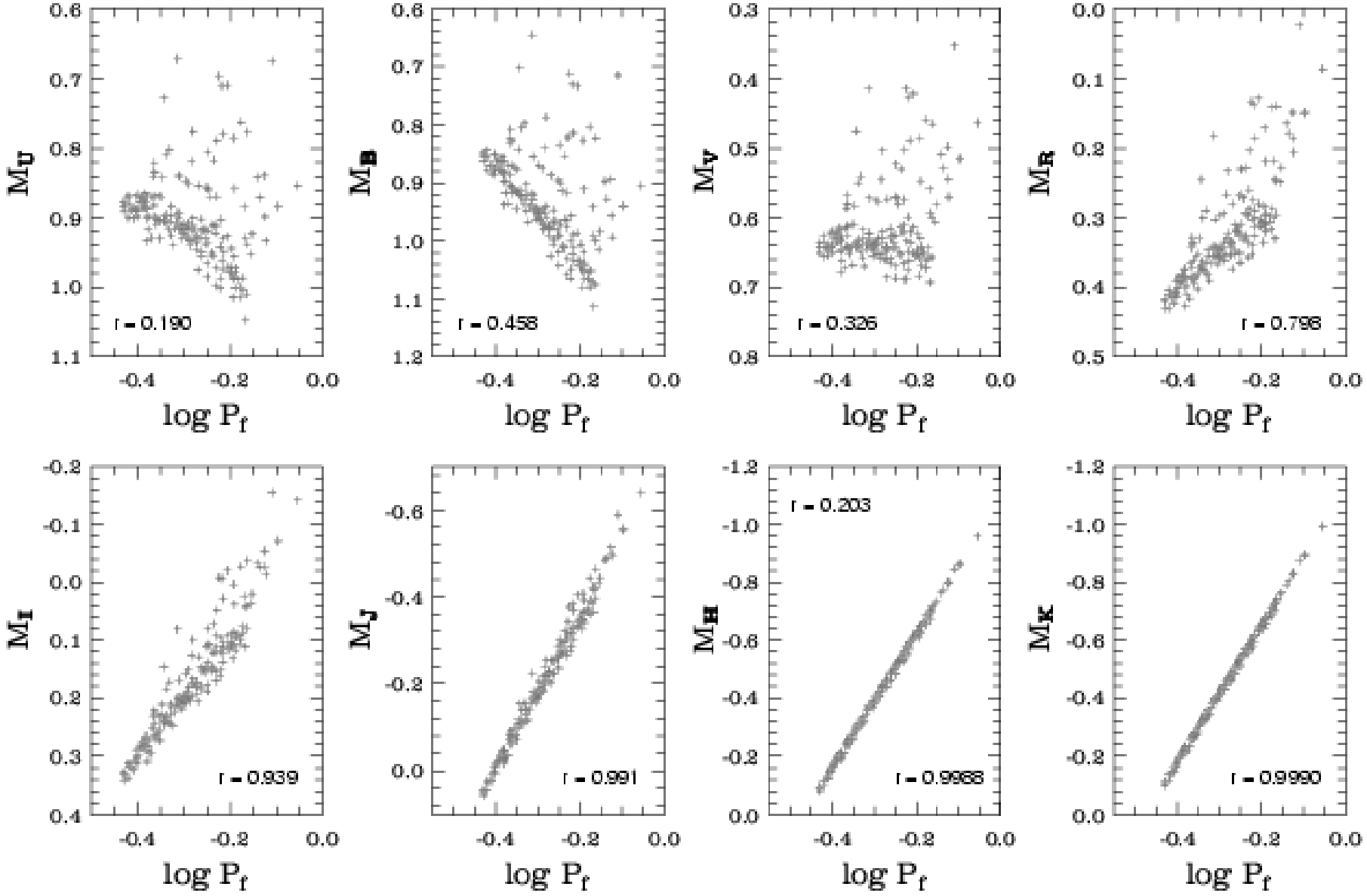


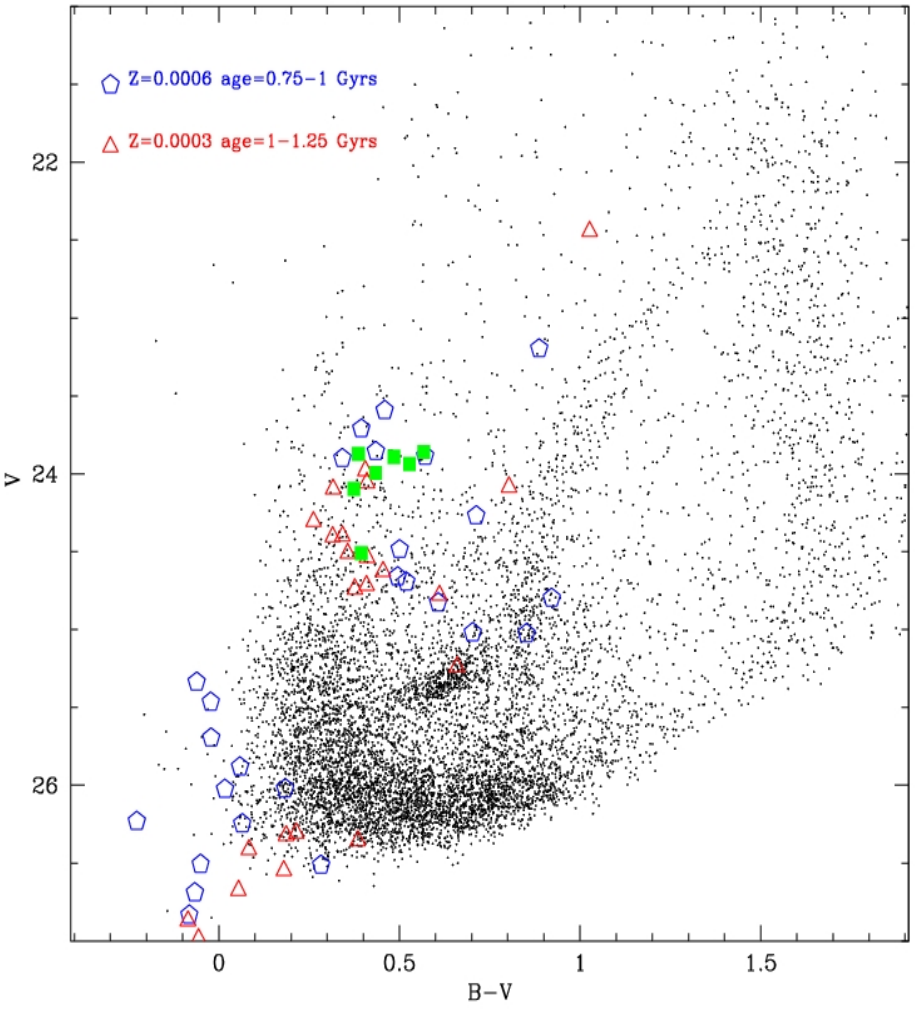
Amplitude-Period diagram of RR Lyrae in And XIX

- Continuous line is the locus for Oo I stars
- Dashed line for Oo II stars
- $<P_{ab}>=0.62$ d $\sigma=0.03$ d

Based on these evidences And XIX can be classified as Oo Int




M_U
M_B
M_V
M_R
M_I
M_J
M_H
M_K
log P_f
r = 0.190
r = 0.458
r = 0.326
r = 0.796
r = 0.939
r = 0.991
r = 0.203
r = 0.9988
r = 0.9990

A recent episode of star formation?

- Generate a synthetic population (using a Salpeter IMF) of young stars with the two possible scenarios
- Constant SF in the range 0.75-1 Gyr for [Fe/H]=-1.8
- Constant SF in the range 1-1.25 Gyr for [Fe/H]=-1.5
- We stop the procedure when the number of synthetic objects match the number of ACs