Variable stars and stellar populations in the new satellites of the Milky Way and M31

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11° Potsdam Thinkshop: Satellite galaxies and dwarfs of the local group

Potsdam, 25-29 August 2014

- ✓ the Local Group
- ✓ galaxy formation mechanisms
- ✓ Local Group dSphs
  - the MW satellites
  - the Andromeda satellites
- ✓ tools:
  - **CMDs**
  - **pulsating variable stars**

The Team

Collaborators

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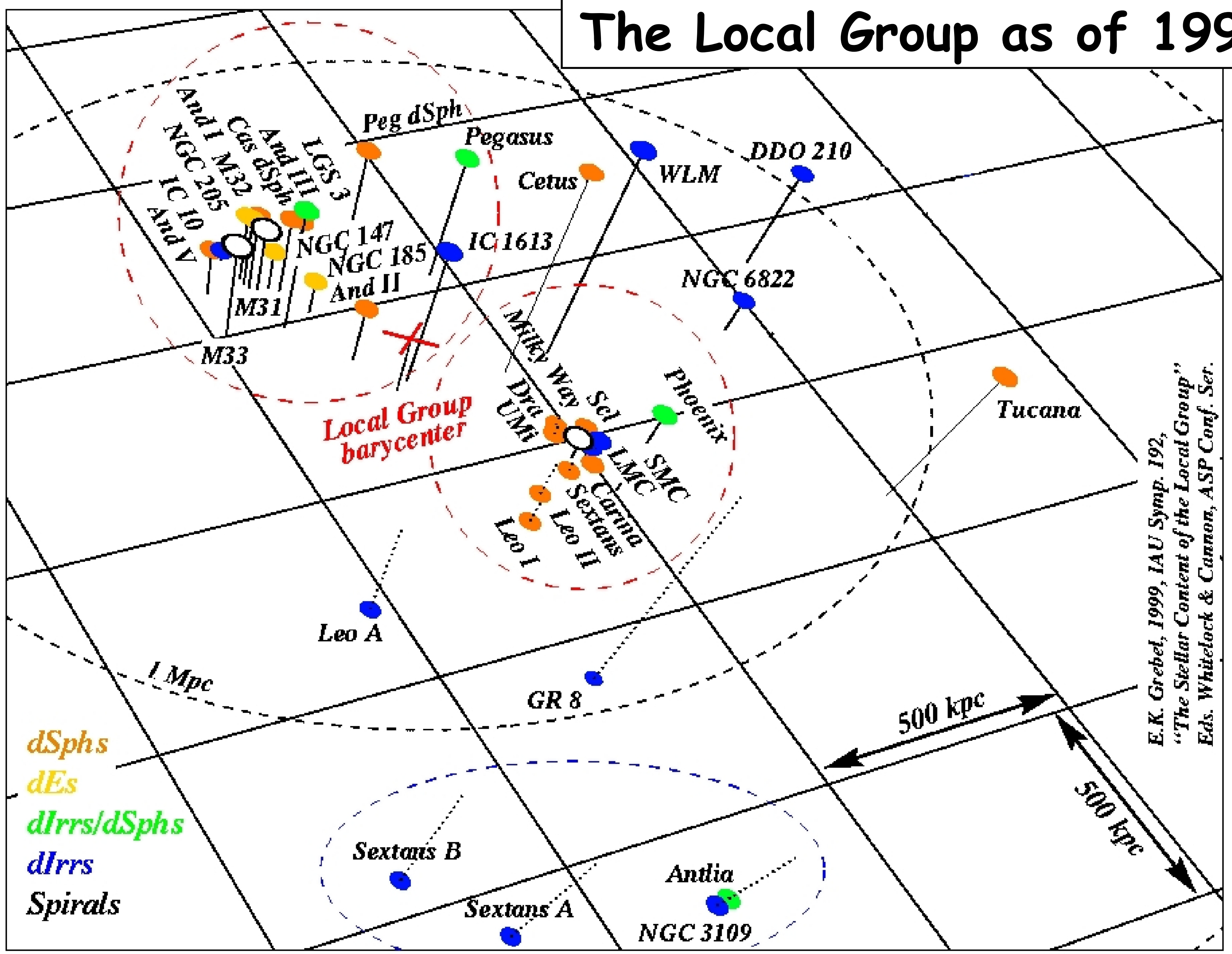
The Local Group as of 1999



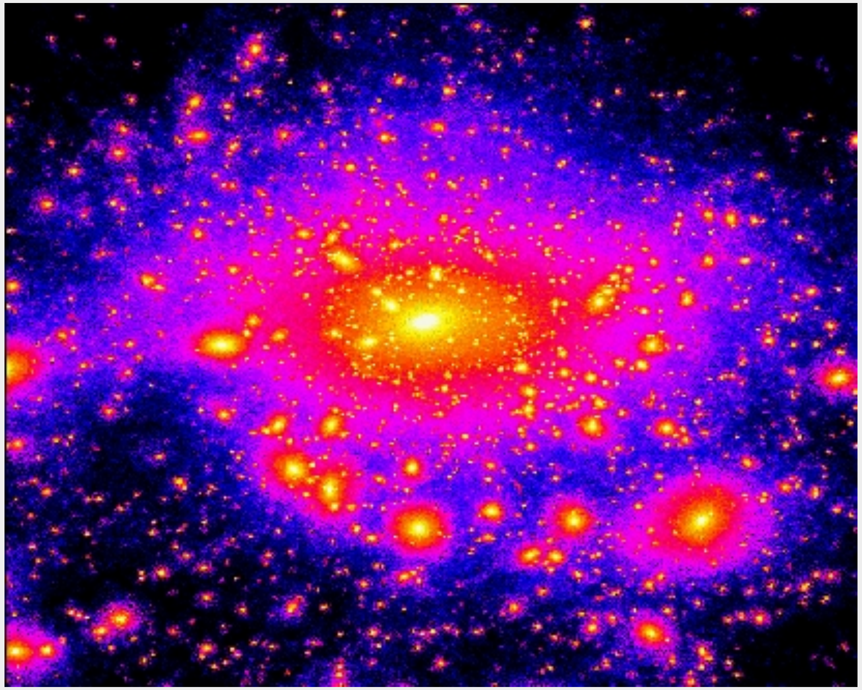
Galaxy formation mechanisms

- Monolithic collapse
- Hierarchical merging ---> dSphs as "building blocks" of larger galaxies (MW, M31) ?

Many observational evidences of merging:

- Sgr dSph
- M31 giant stream

- The 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
- dSphs as "building blocks" of large galaxies → we should see remnants of this process → the MW (and M31) halo properties should be homogeneous to those of the dSph satellites



http://home.slac.stanford.edu

Some facts and open issues about dSphs

- ✓ The most numerous in the LG
- ✓ The most dark matter dominated
- ✓ Complex and unique SFH

but....

- ✓ Missing Satellite Problem (MSP)
- ✓ Metallicity (chemistry) Problem
- ✓ Variable Stars Problem
- ✓ Dynamics Problem (?)

✓ Local Group dSphs - the MW satellites

9 (10) "Bright" dSphs

(known before 2005)

Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor

Sagittarius
(Canis Major)

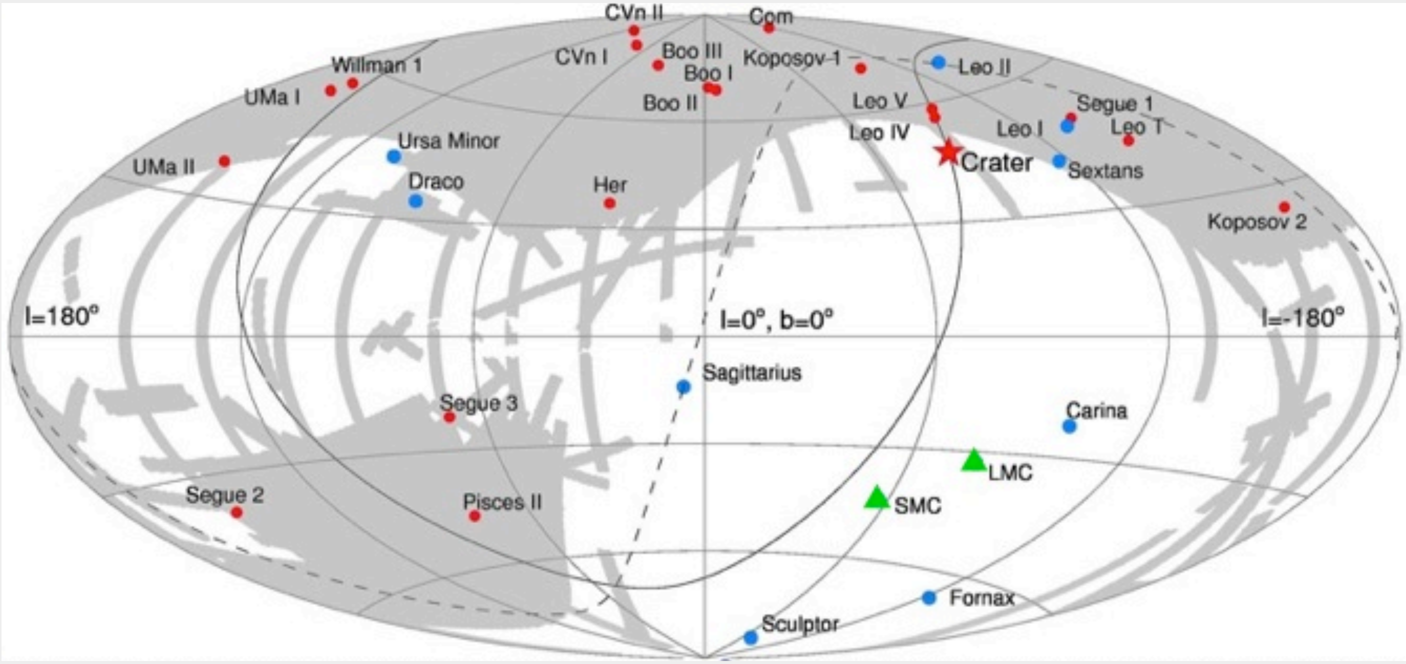
21 new "faint" systems

(discovered since 2005)

Leo IV
LeoV
Coma
Bootes I
Canes Venatici I
Canes Venatici II
Hercules
Leo T
Ursa Major I
Ursa Major II
Pisces I
Pisces II
Crater

Willman I
Bootes II
Bootes III
Segue I
Segue II
Segue III

Koposov I
Koposov II



Belokurov et al. (2014)

✓ Local Group dSphs - the MW satellites

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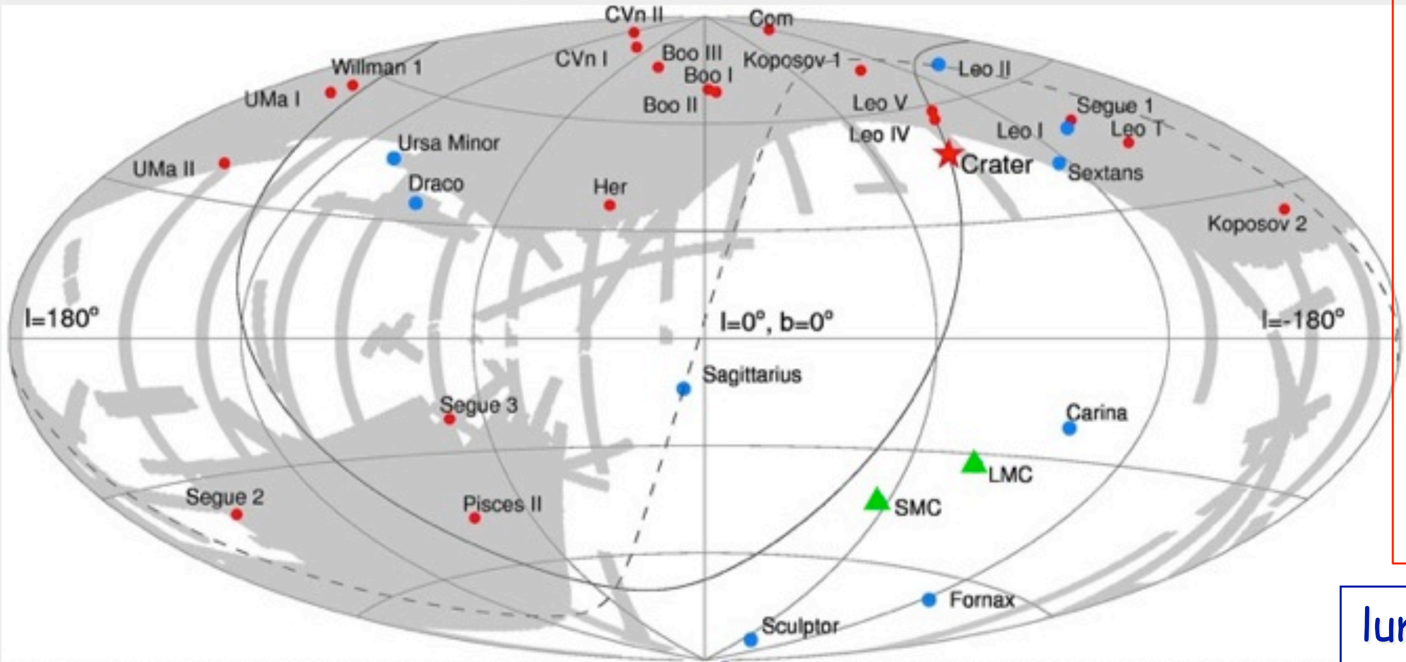
"ultra-faint" dwarfs

Leo T
Ursa Major I
Ursa Major II
Pisces I
Pisces II
Crater



Belokurov et al. (2014)

luminosity and mass limit of galaxy formation?
tidally disrupted remnants?

tiny GCs

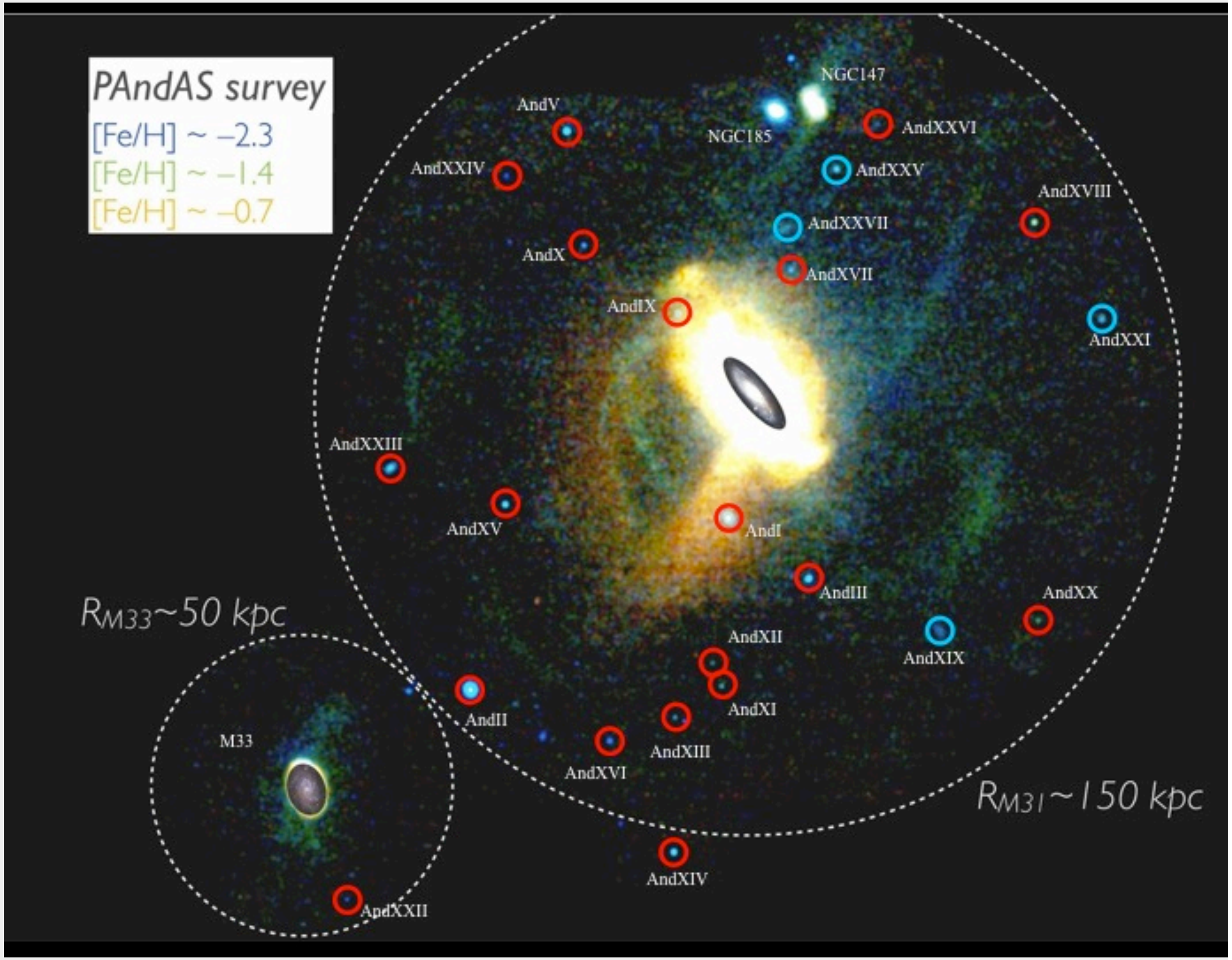
Properties of the MW "ultra-faint" dSphs

- fainter than previously known dSphs: μ_V>28 mag/arcsec^2
- properties intermediate between GCs and dSphs
- metal poor (…as metal poor as [Fe/H] ~ -3.0,-4.0 dex)
- irregular shape → distorted → tidally interacting with the MW
- high mass-to-light ratios → dark matter dominated
- host an ancient population, as old as ~ 10 Gyr
- GC-like CMDs, resembling metal poor GCs like M92 and M15
- all contain RR Lyrae stars

✓ Local Group dSphs - the Andromeda satellites

12 dwarf satellites known until 2004, of which only 6 are dSphs

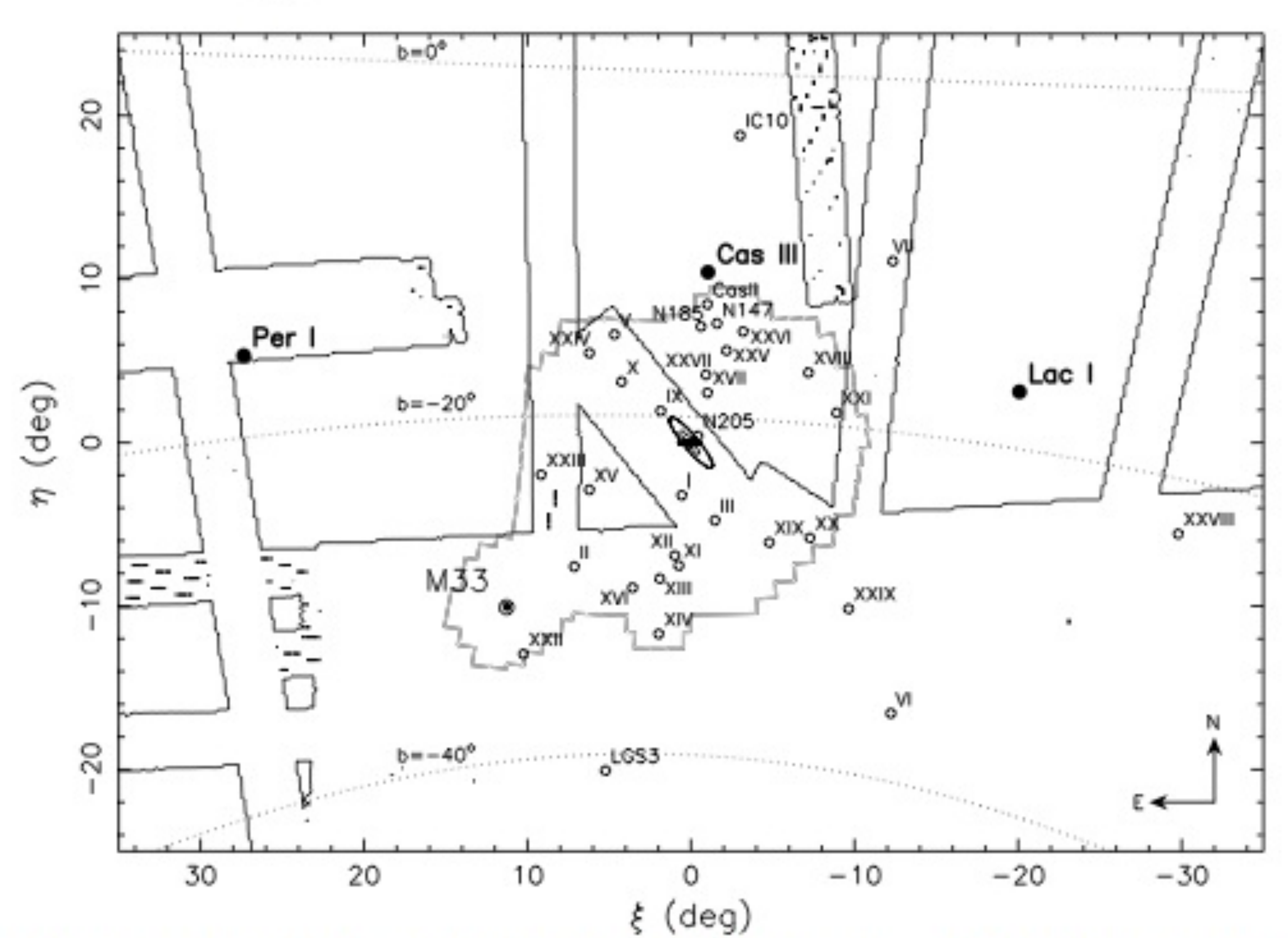
since 2004 26 new M31 dSphs satellites have been discovered by the CFHT, INT and PAN STARSS surveys of the Andromeda's halo



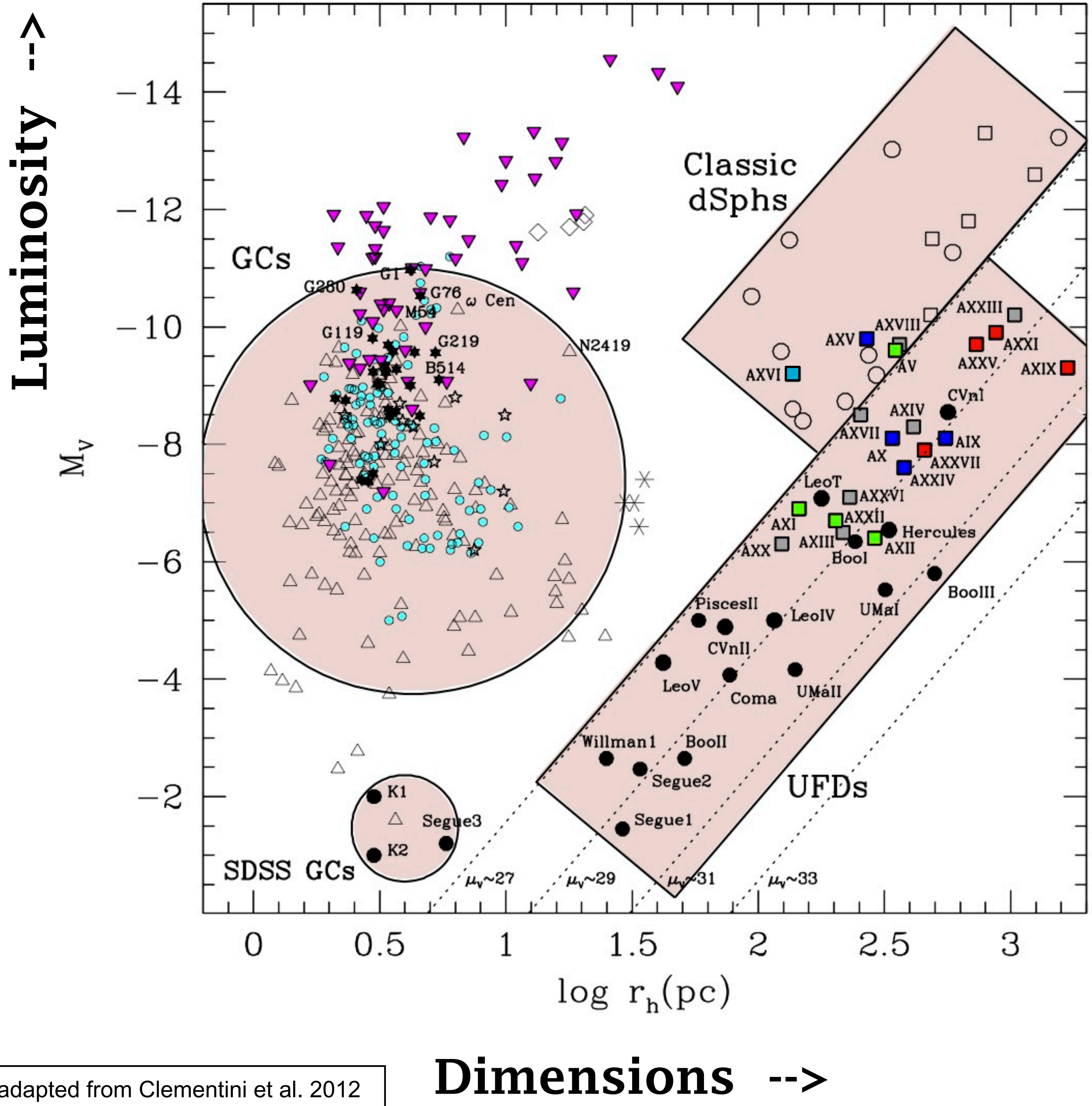
Martin et al. (2013, ApJ 776, 800)

✓ Local Group dSphs - the Andromeda satellites

The latest census of new M31 dSphs adds to a total of 32 dSphs (as of spring 2014)



Martin et al. (2013, ApJ 779, L10)



adapted from Clementini et al. 2012

○ MW dSphs and UFDs

□ M31 dSphs and UFDs

HST

LBT

GTC

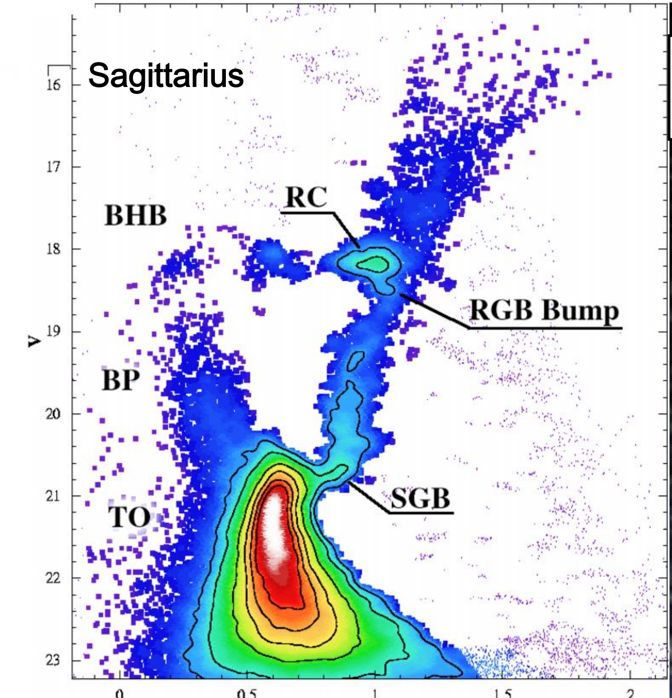
TNG

UFDs are fainter than previously known dSphs: μ_V>28 mag/arcsec^2

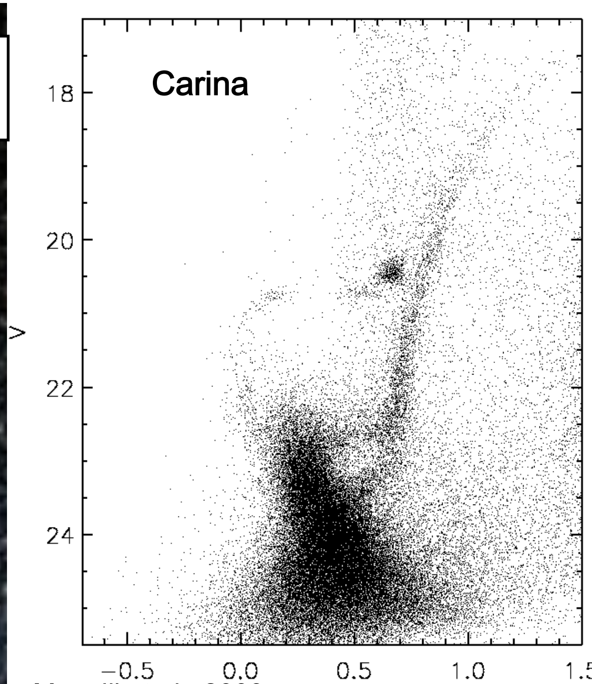
UFDs have luminosities (M_V) typical of GCs and dimensions (r_h) typical of dSphs

✓ tools: CMDs

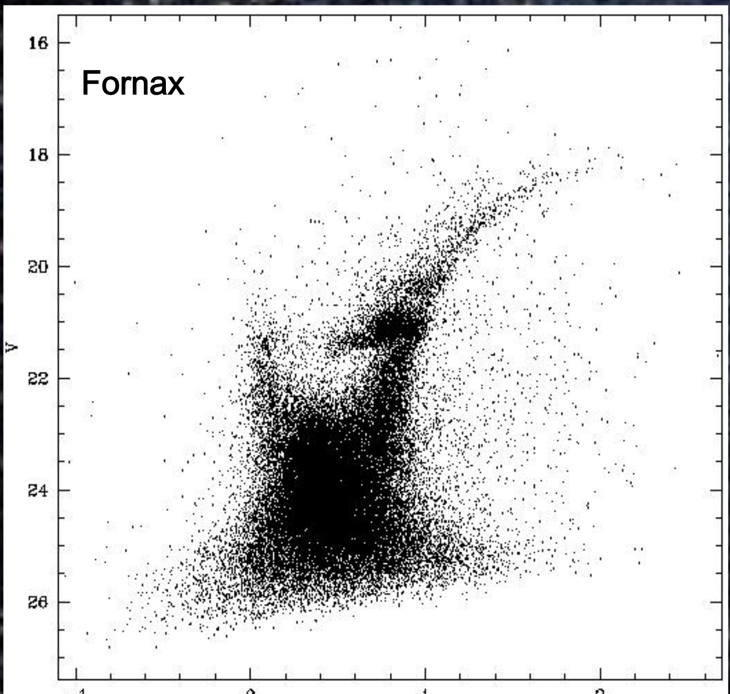
"Bright" MW dSphs



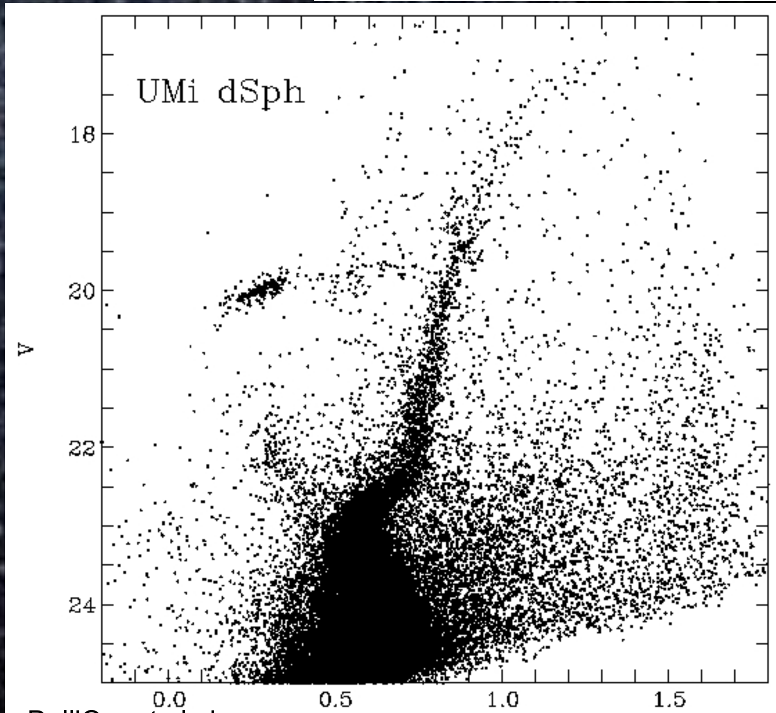
Bellazzini et al. 2006



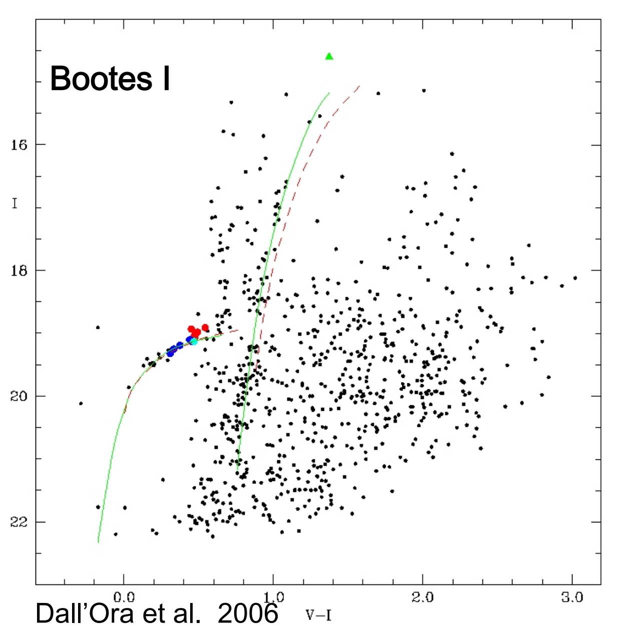
Monelli et al. 2003

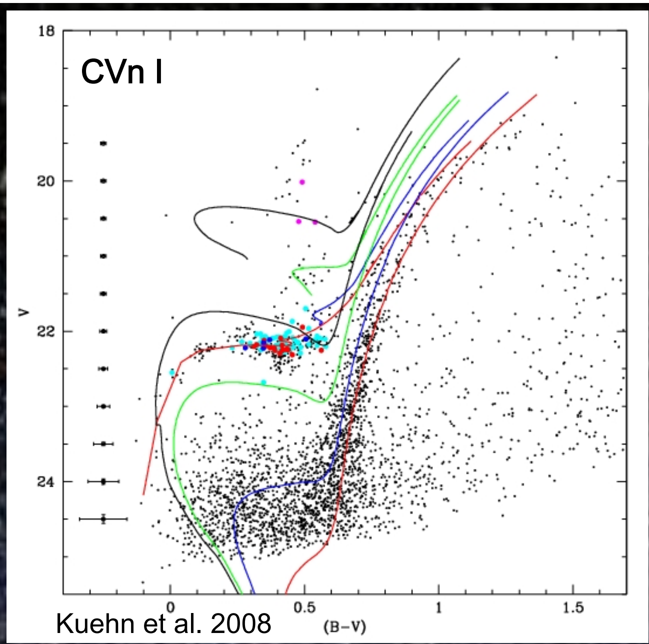


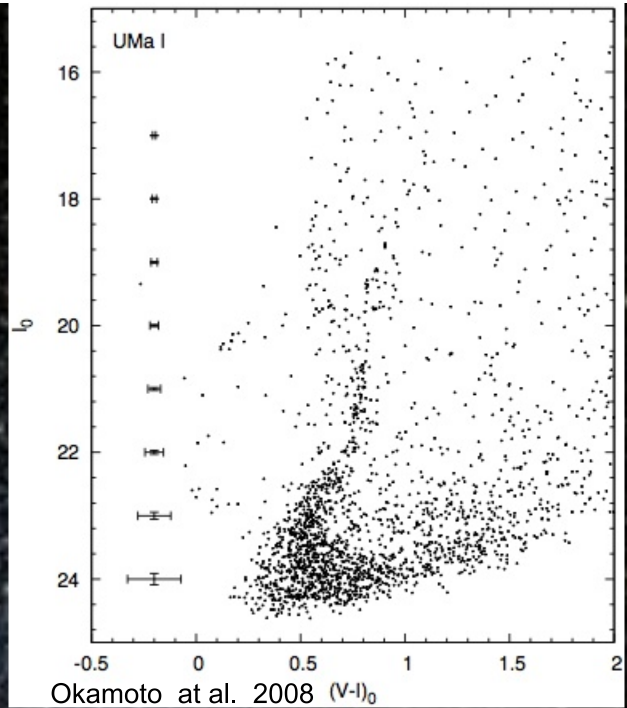
Greco et al. 2007



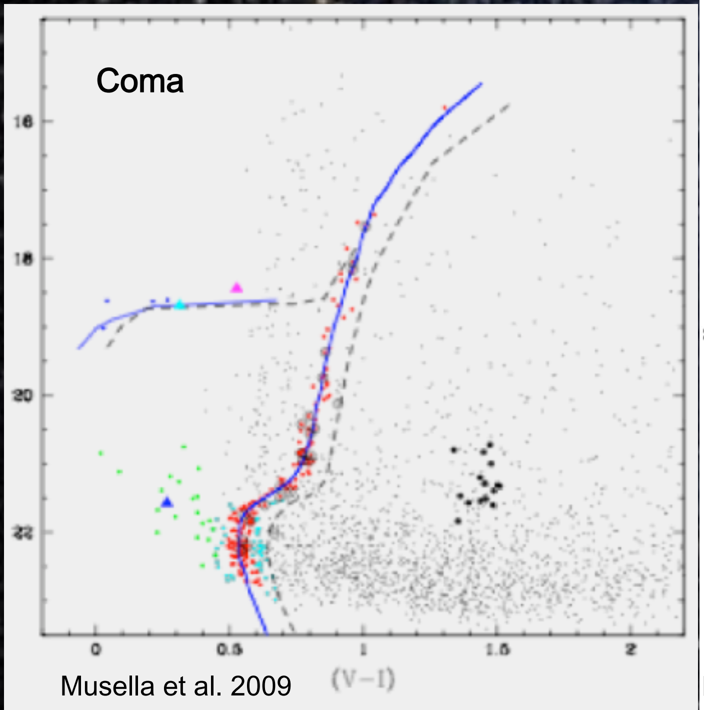
Dall'Ora et al., in prep

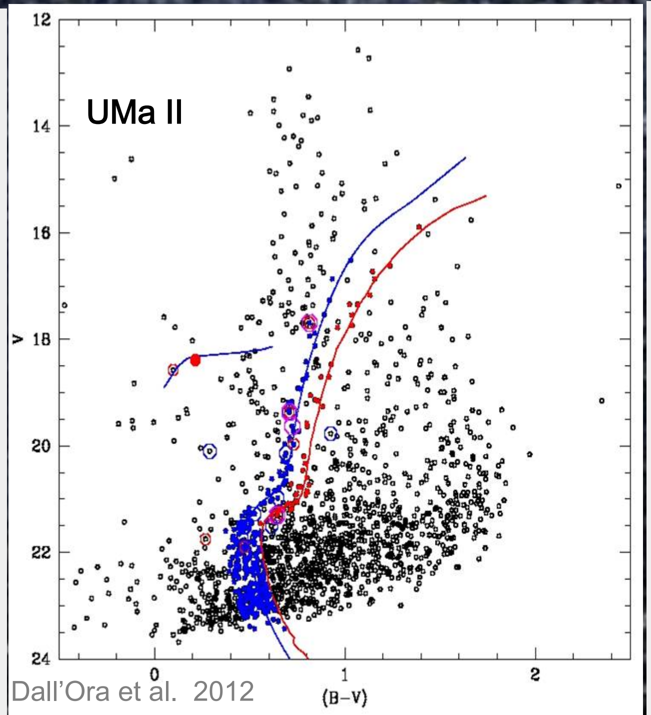


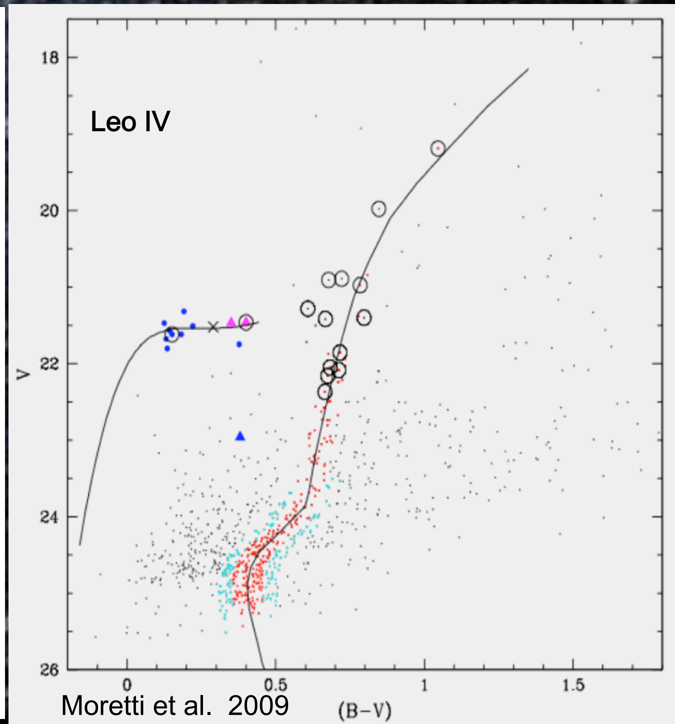


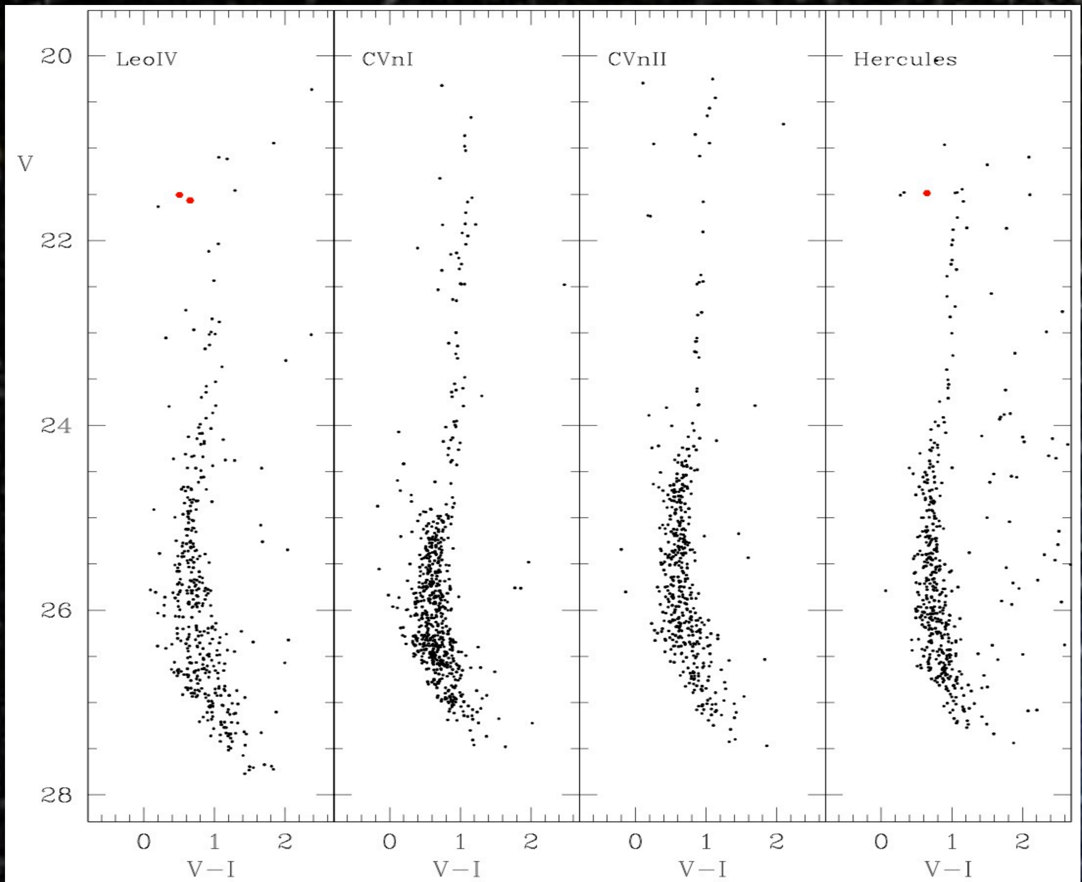


"ultra-faint" MW satellites

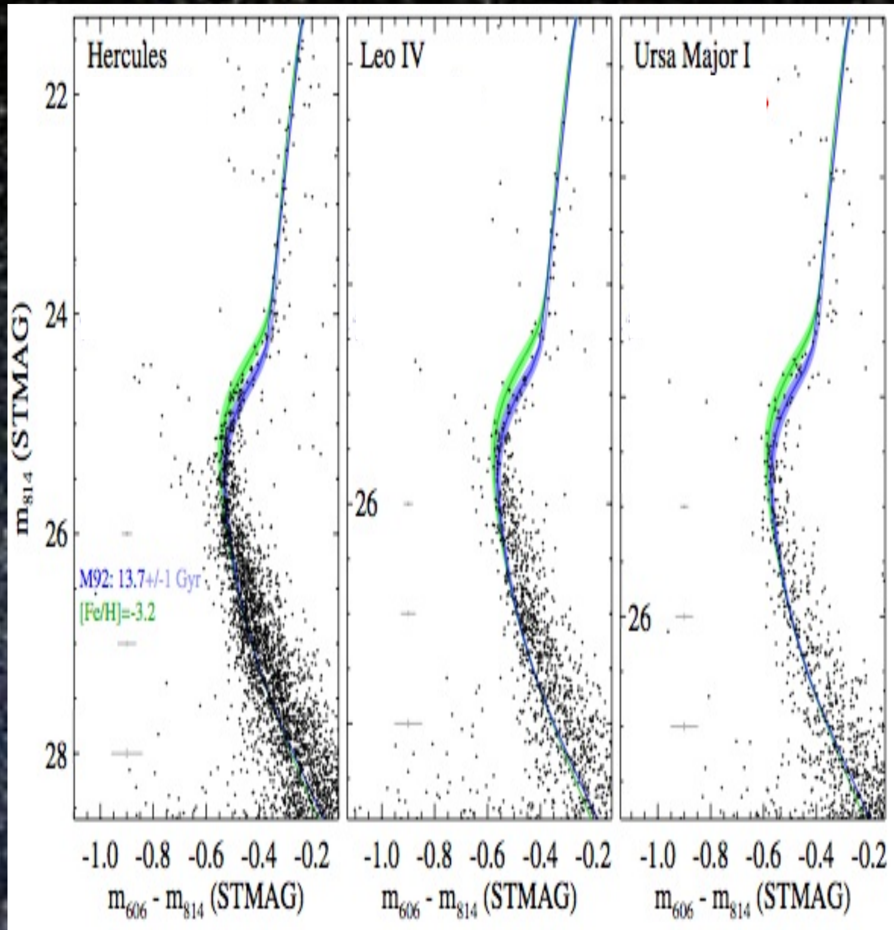








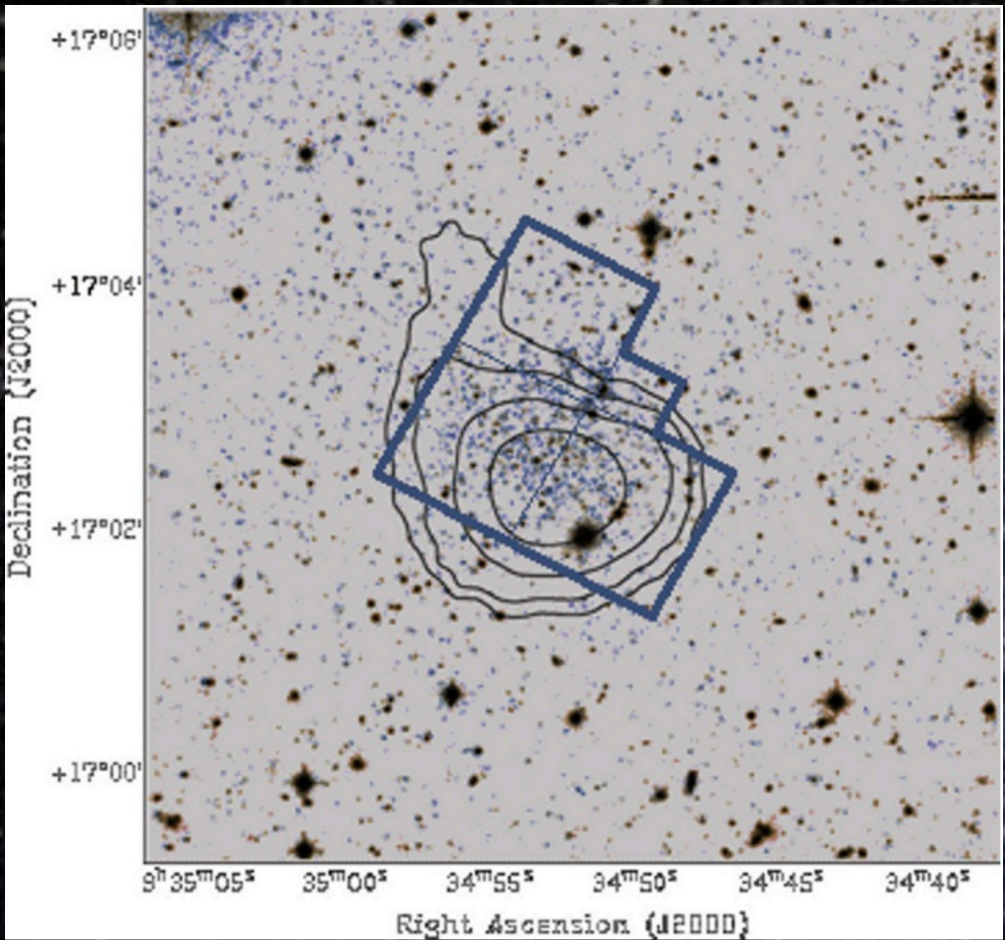
Garofalo et al., in prep,
WFPC2@HST data



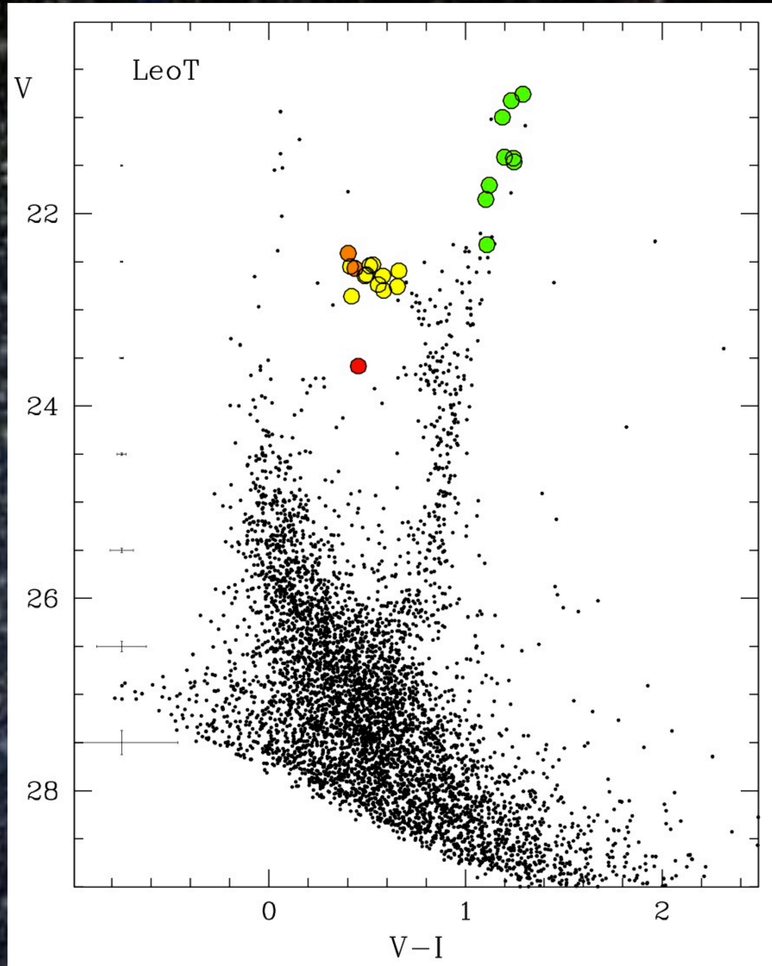
Brown et al. 2012,
ACS@HST data

"ultra-faint" MW satellites, HST data

“ultra-faint” MW satellites: Leo T



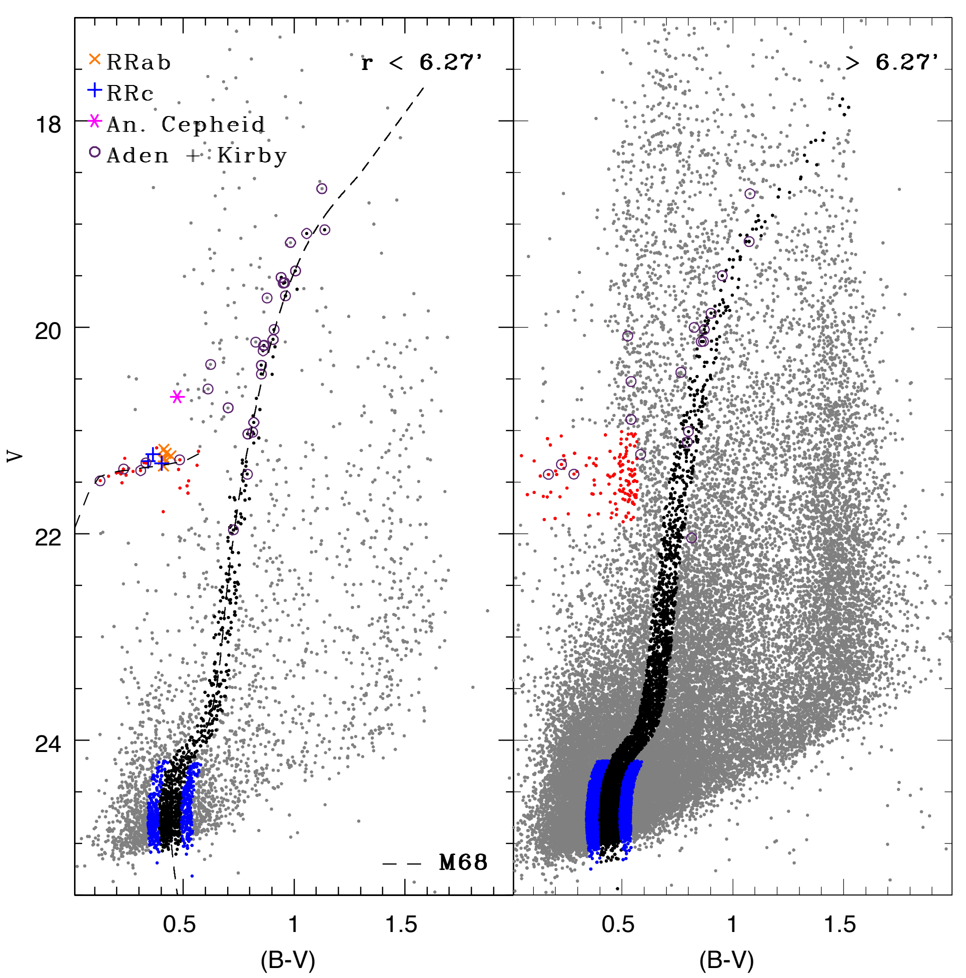
Clementini et al. 2012, adapted from Ryan-Weber et al. 2008



Clementini et al. 2012

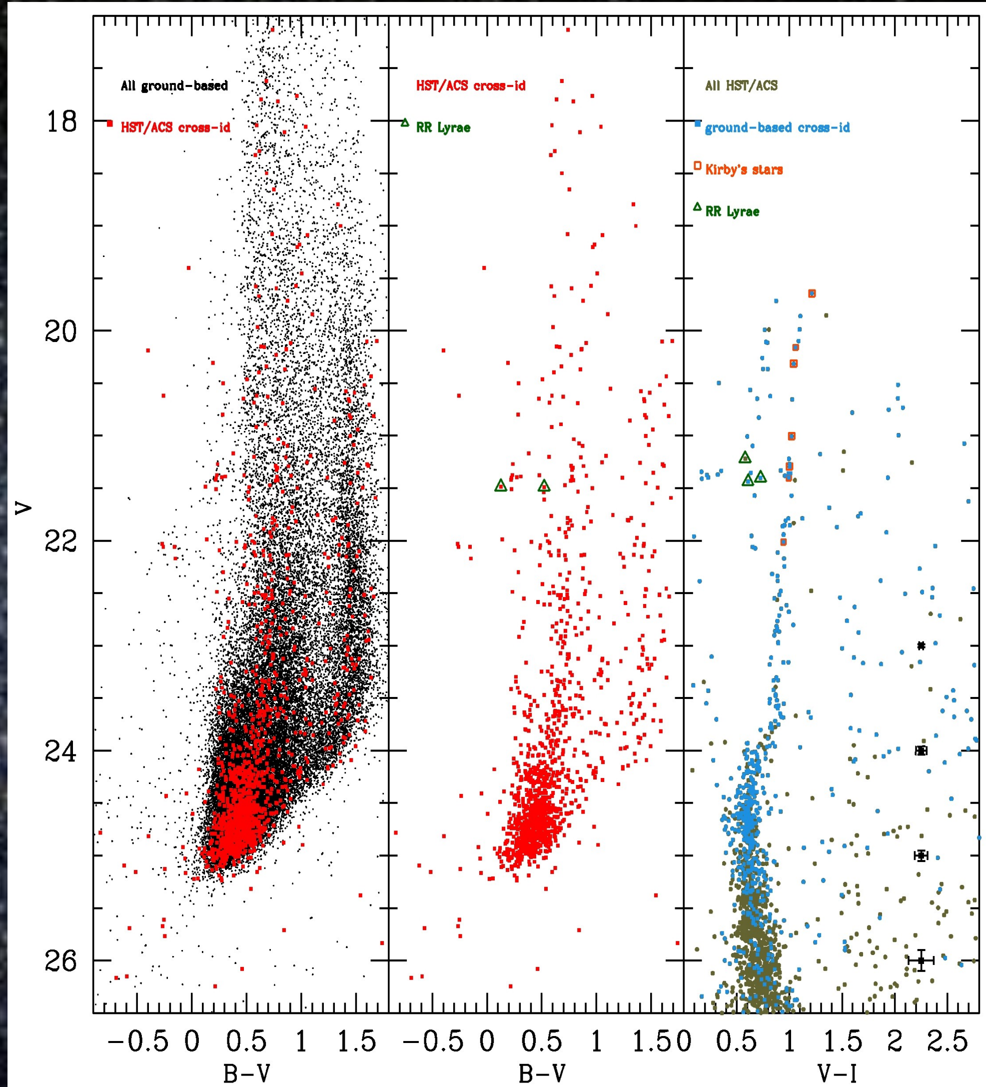
"ultra-faint" MW dSph satellites: Hercules

Coma



Musella et al. 2012

Hercules



Garofalo et al, in prep

see Fabrizio et al (2014), for proper-motion field decontamination of Hercules' CMD

And V - And XI - And XII - And XIII

from HST WFPC2 archive data

FOV = 1.3' x 1.3'

And V

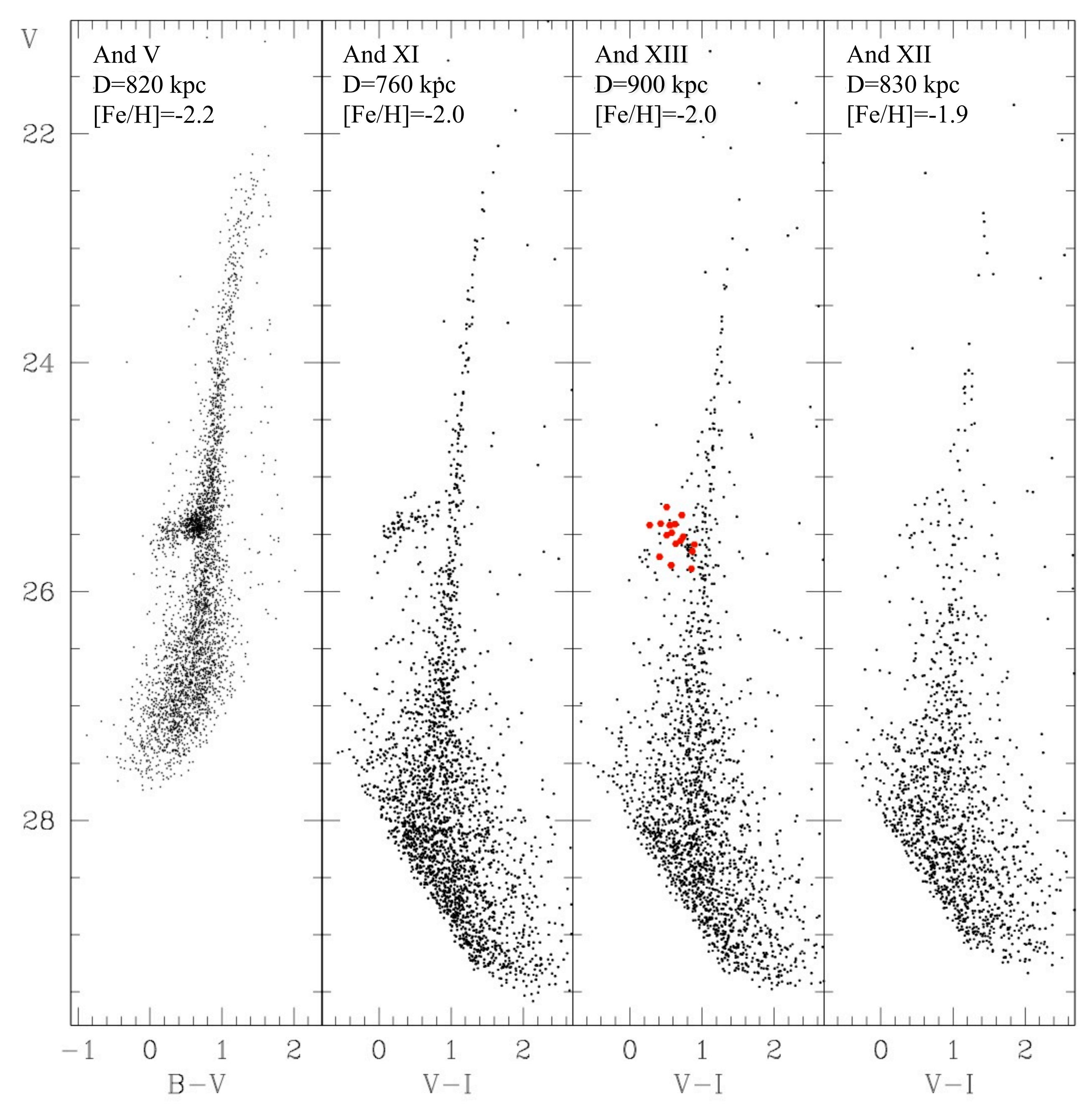
17 B+8 V of 1200 s
Total exps. 20400/9600 s

And XI- XII - XIII

16 V+ 26 I V of 1200 s
Total exps. 19200/31200 s

Typical errors

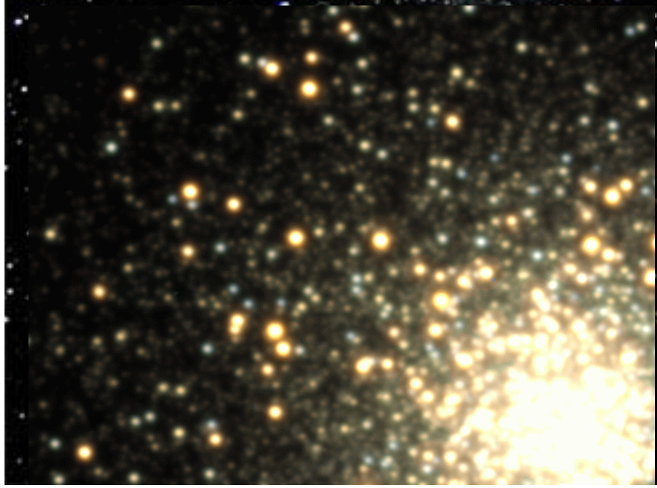
	σ_V	$\sigma_{(B-V)/(V-I)}$
V ~ 25.5	0.04	0.06
V ~ 27.5	0.18	0.20



✓ Tools: pulsating variable stars

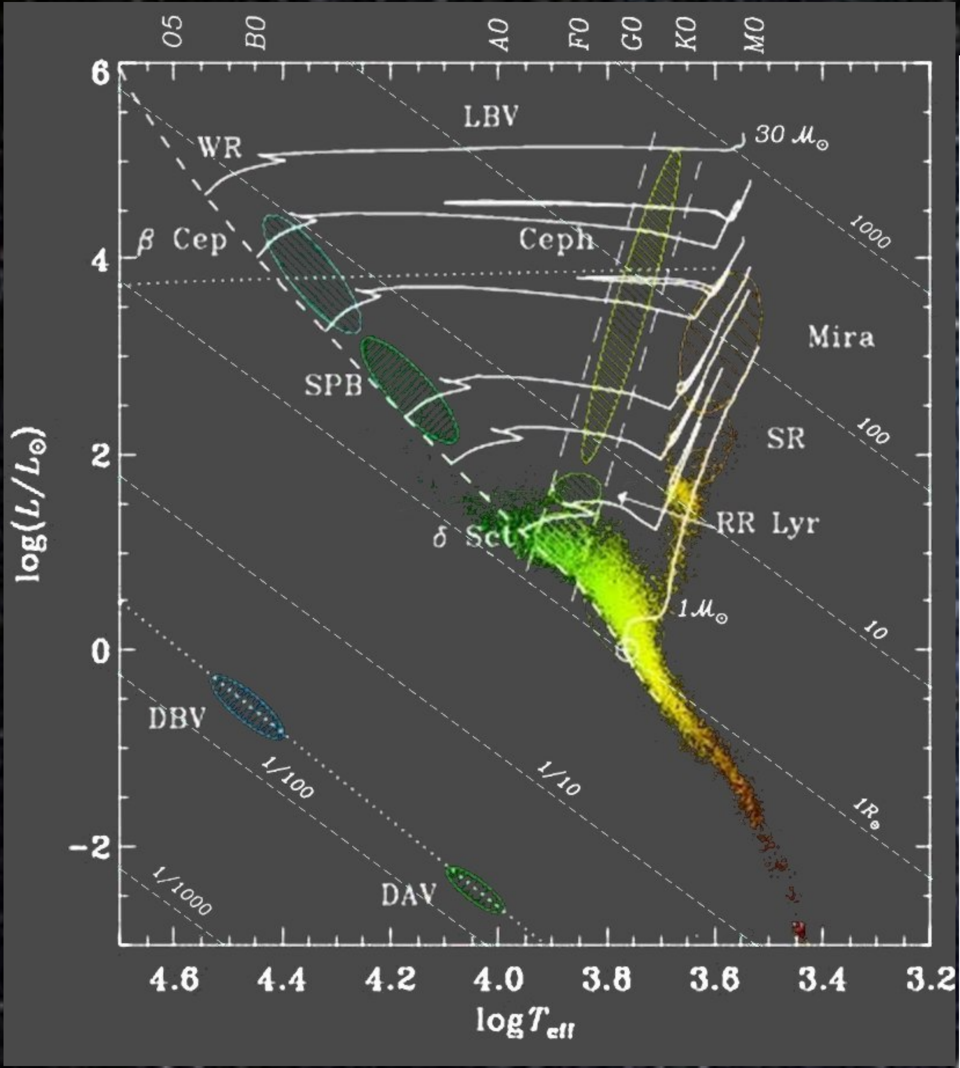
why?

- ➢ allow direct estimates of stellar parameters
- ➢ set the astronomical distance scale
- ➢ trace stellar populations of different age
- ➢ map 3D structures, radial trends, streams
- ➢ can provide hints on how galaxies have formed

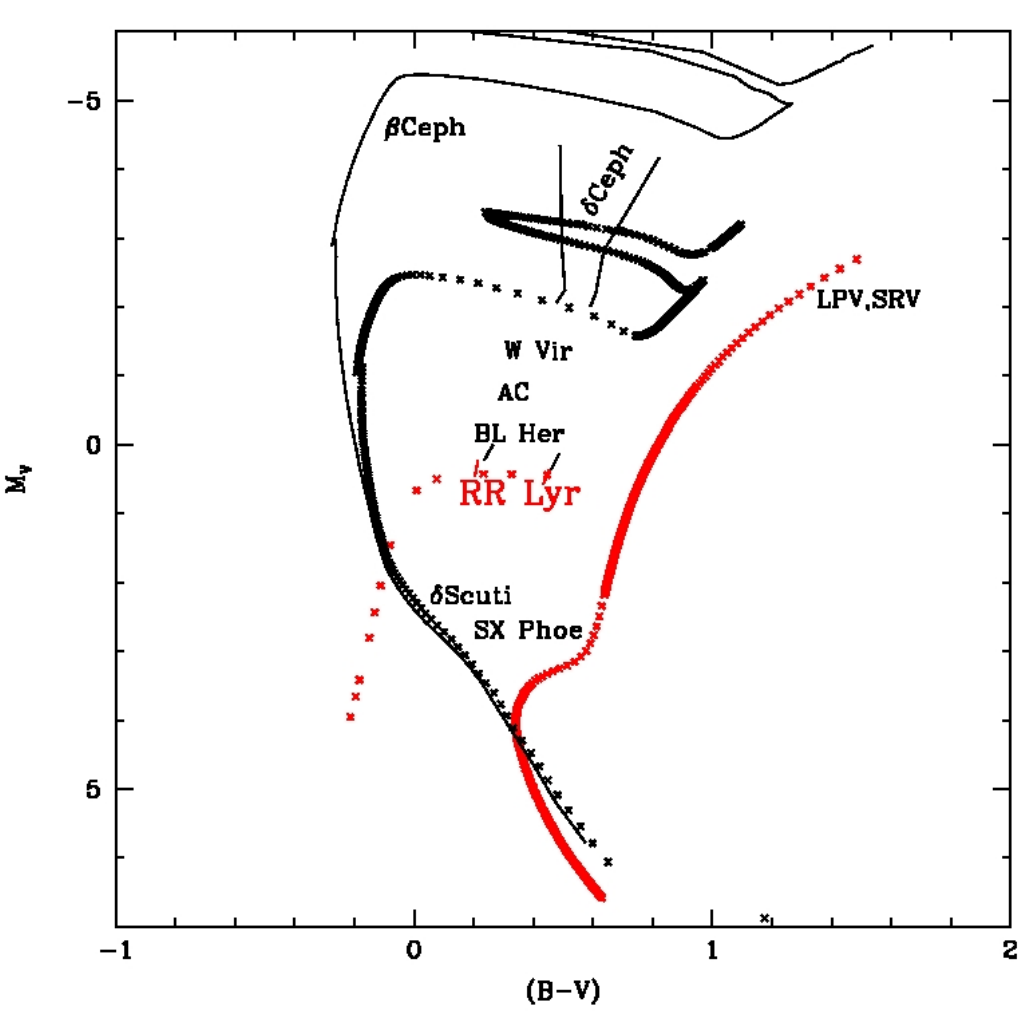


"easily" recognized thanks to the light variations periods and amplitudes are unaffected by distance and reddening

Pulsating variable stars



Clementini et al. 2009



Marconi 2001

Pulsating variable stars commonly found in dSphs

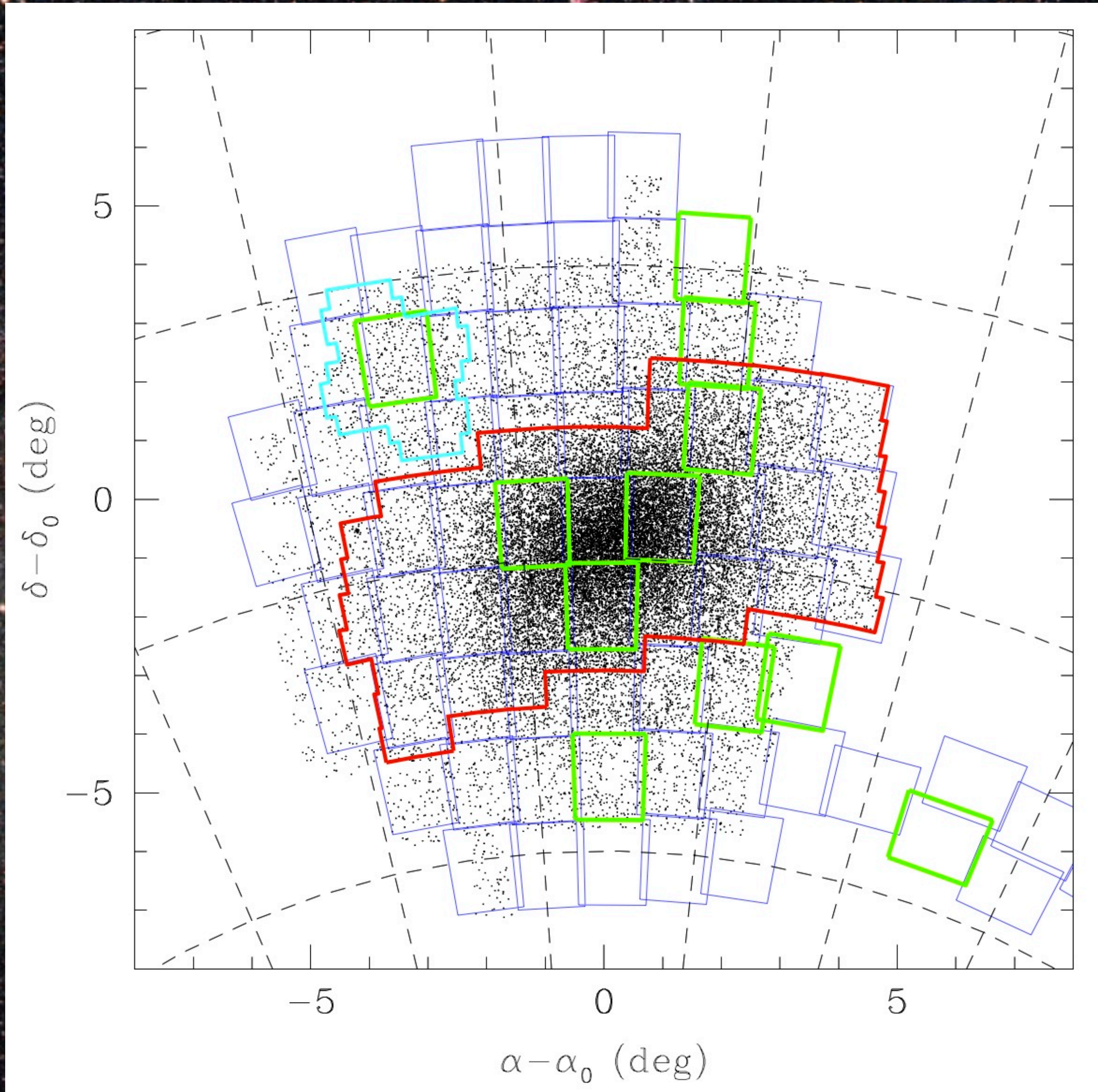
Class	Periods (days)	M_V	Pop	Evo. Phase
RR Lyrae	0.2 – 1	0.0 ÷ 1.0	II	HB
W Virginis	10 – 30	-3 ÷ -1	II	post-HB
BL Herculis	< 7-10	-1 ÷ 0	II	post-HB
SX Phoenicis	< 0.1	2 ÷ 3	II	MS
A.C.	0.3 - 2.5	-2 ÷ 0	?	HB

Pulsating variables map 3D structures, radial trends, halos & streams

A local overdensity of RR Lyrae stars in the Galactic halo is the northen tidal stream left over by the Sagittarius dwarf spheroidal galaxy.

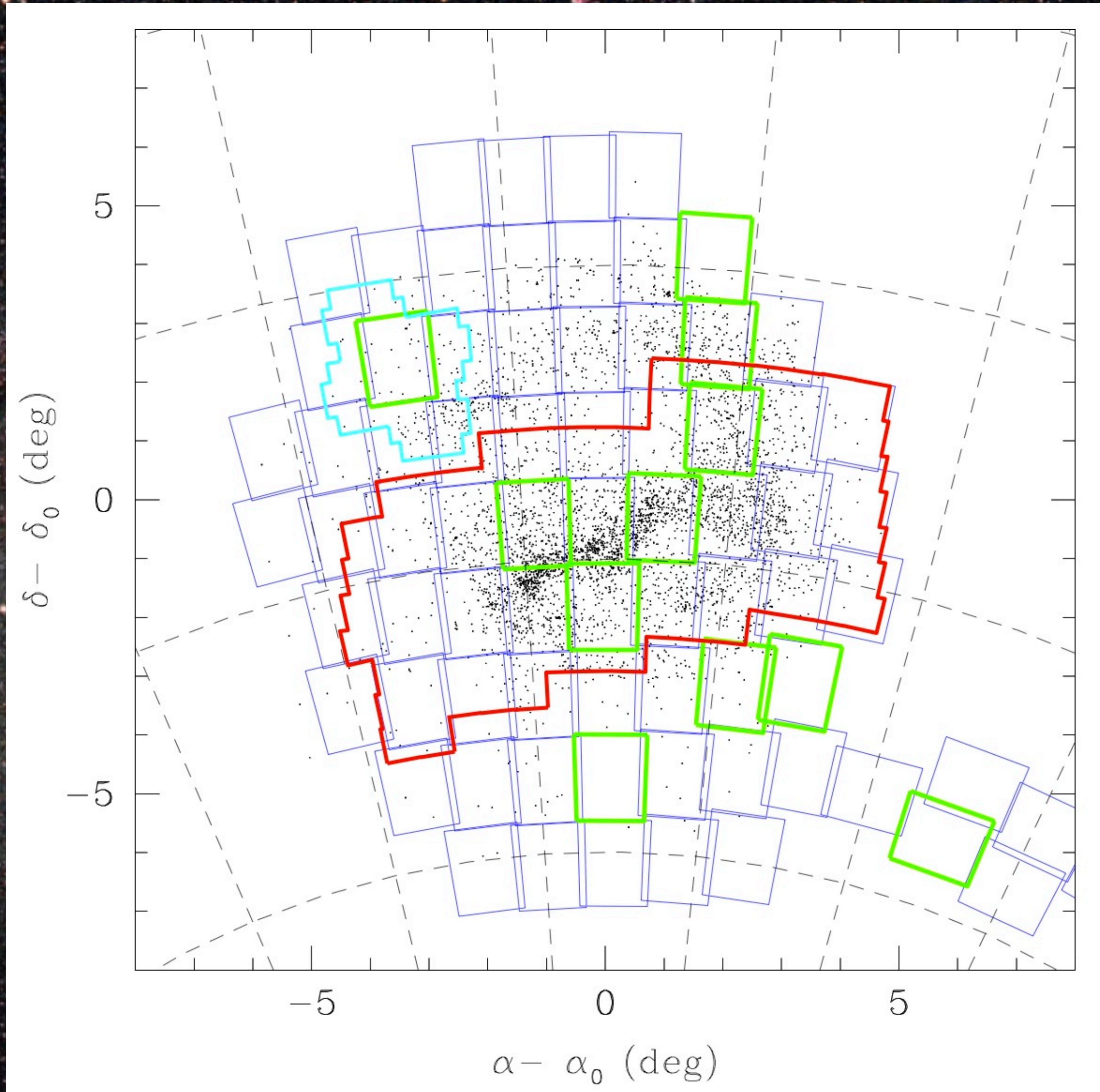
Classical Cepheids, RR Lyrae stars, (and “hot binaries”) trace different substructures in the LMC.

The LMC structure as traced by: RR Lyrae stars



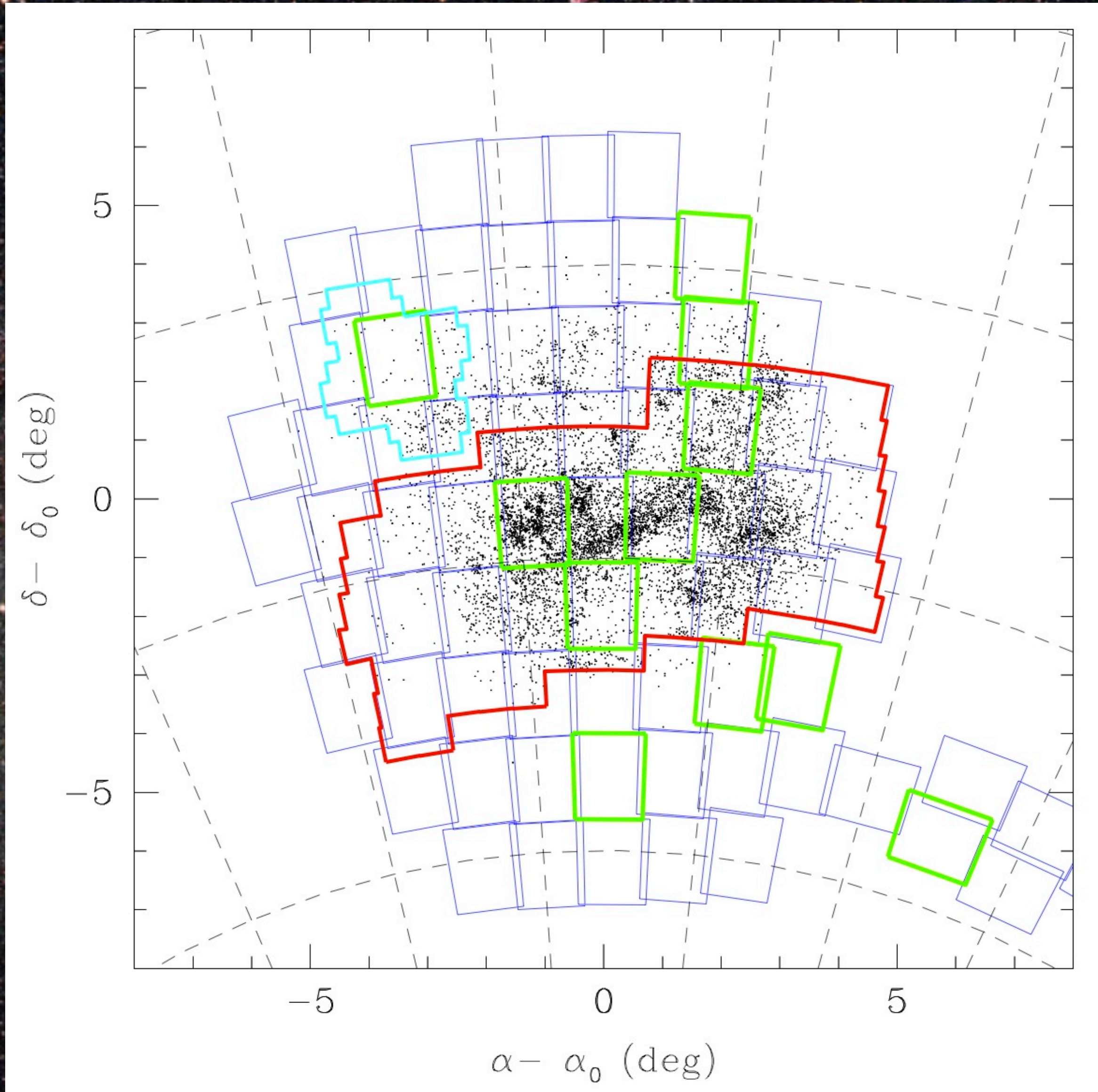
Moretti et al. 2014

The LMC structure as traced by: Classical Cepheids



Moretti et al. 2014

The LMC structure as traced by: "hot" binaries



Moretti et al. 2014

Pulsating variables trace the different stellar generations in galaxies

- young ($t < 100$ Myr) ➡ Classical Cepheids, δ Scuti stars – Pop I
- intermediate age ➡ Anomalous Cepheids
- old ($t > 10$ Gyr) ➡ RR Lyrae, Pop II Cepheids, SX Phoenicis

at the distance of M31 the Turn Off of a 10 Gyr stellar population is at V ~ 28-28.5 mag

RR Lyrae stars have been found in "all" Local Group galaxies where they have been searched for ⇒ "all Local Group galaxies contain a very old population component, i.e. all nearby galaxies started to form stars just after they were formed".
In other words there are **no truly young** galaxies in the Local Group.

RR Lyrae stars can provide hints on how galaxies have formed: "the Oosterhoff dichotomy"

In the MW, the GC RR Lyrae population divides into two distinct groups, based on the mean period of the fundamental mode RR Lyrae stars, <Pab>:

Oo I <Pab> = 0.55 d
Oo II <Pab> = 0.64 d

Oosterhoff 1939

Type	<Pab>	<Pc>	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

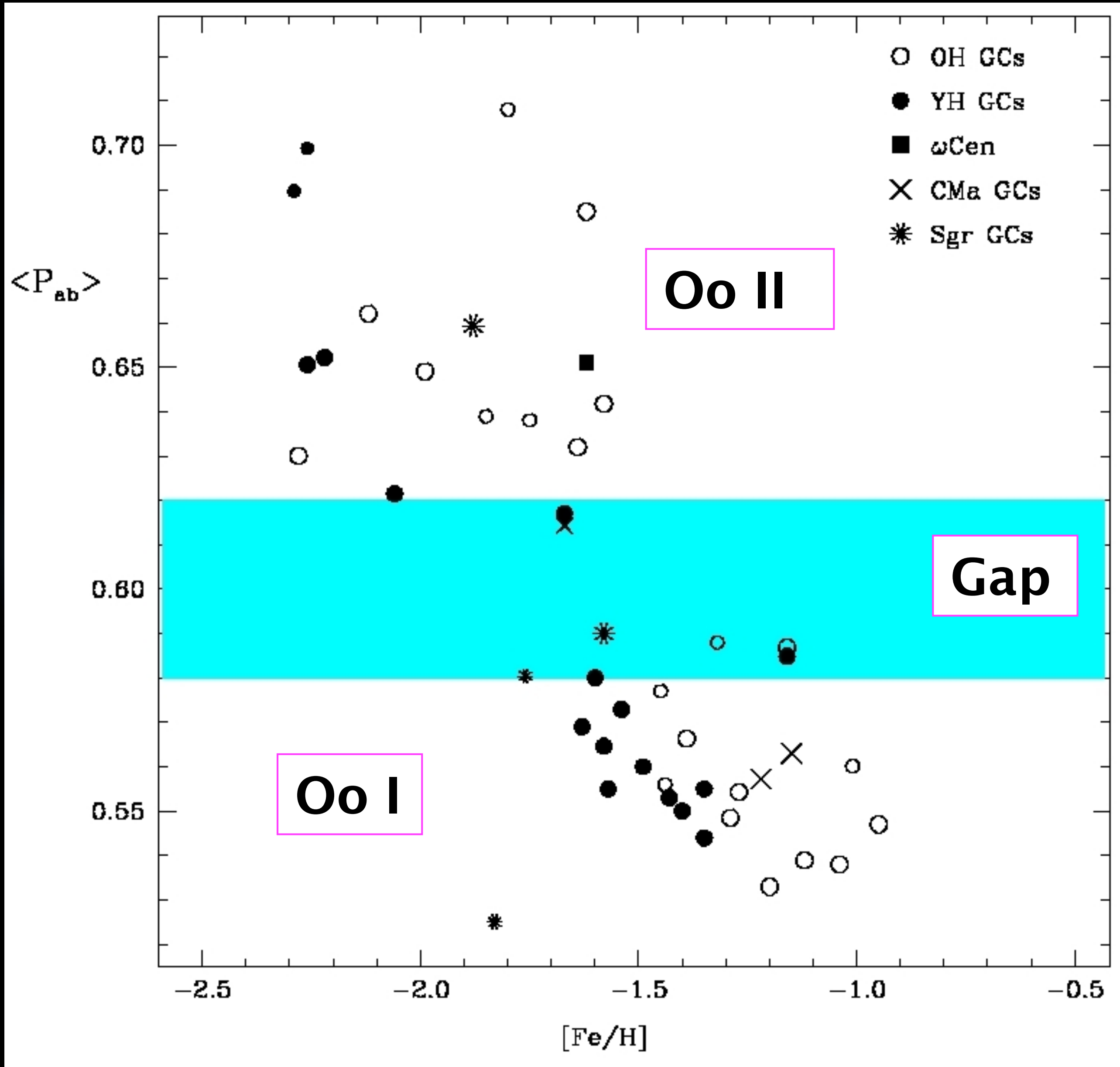
Oo Intermediate (Oo-Int) <Pab> ~ 0.60 d

The field RR Lyrae stars within the MW halo belong predominantly to the Oo I type, but with a significant Oo II component. The Oo II component appears to be more concentrated to the Galactic plane than the Oo I halo component.

The M31 field appears to be Oo I/ Oo Int.

Do the MW and M31 satellites conform to the Oosterhoff behaviors of their parent galaxies?

The Oosterhoff dichotomy: MW GCs



Oo I <Pab> = 0.55 d
OoII <Pab> = 0.64 d

Oo Int <Pab> ~ 0.60 d

The Galactic GC distribution is bimodal with p > 99.99%

Catelan 2009

Oosterhoff properties of the "bright" MW dSphs

dSph	<[Fe/H]>	N(RRab/c/d)	<Pab>	Oo Type
Ursa Minor	-2.2	47/35	0.638	Oo II
Draco	-2.0	214/30/26	0.615	Oo Int
Carina	-2.0	54/15/6	0.631	Oo Int
Fornax	-1.3	396/119(~2000)	0.595	Oo Int (field & GCs)
Sculptor	-1.8	132/74/18:	0.587	Oo Int
Leo I	-1.7	47/7(~250)	0.602	Oo Int
Leo II	-1.9	106/34/8:	0.619	Oo Int
Sextans	-1.7	26/7/3:	0.606	Oo Int
Sagittarius	-1.55	4200(>4200)	0.574	Oo I(field), I/II/Int(GCs)
C. Major(?)	-1.2/-1.7	>15	0.56/0.615	Oo I/Oo Int (GCs)
Cetus	-1.8	147/8/17	0.614	Oo Int
Tucana	-1.8	216/82/60	0.604	Oo Int

from Clementini 2010

The "bright" MW dSphs cannot have contributed to the Galactic halo

Oosterhoff properties of the MW UFDs

dSph	N(AC)	N(RRab/c/d)	<Pab>	Oo Type
Bootes I	-	7/7/1	0.69	Oo II
Canes Venatici I	> 3	18/5	0.60	Oo Int
Canes Venatici II	-	1/1	0.74	Oo II
Coma Berenices	-	1/1	0.67	Oo II
Leo IV	-	3	0.66	Oo II
Ursa Major II	-	1	0.66	Oo II
Ursa Major I	-	5/2	0.63/0.60	Oo Int
Hercules	1	6/3	0.68	Oo II
Leo T	11	1	0.60	Oo Int
Segue II	-	1	0.75	Oo II

updated from Clementini 2010, which is a summary of the following original studies:

Dall'Ora et al.2006, 2012, Siegel 2006, Kuehn et al. 2008, Greco et al. 2008, Musella et al. 2009, 2012, Moretti et al. 2009, Garofalo et al. 2013, Clementini et al. 2012, Boettcher et al. 2013.

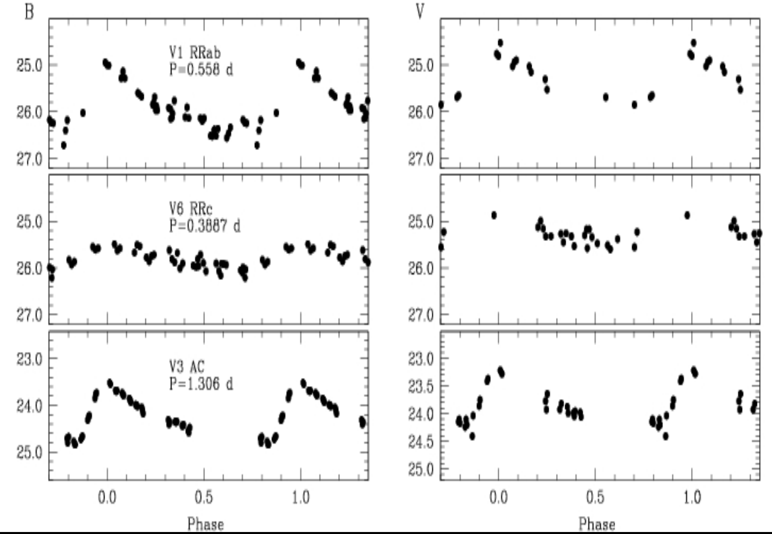
the MW UFDs may have contributed to the Galactic halo

Oosterhoff properties of the M31 "bright" dSphs

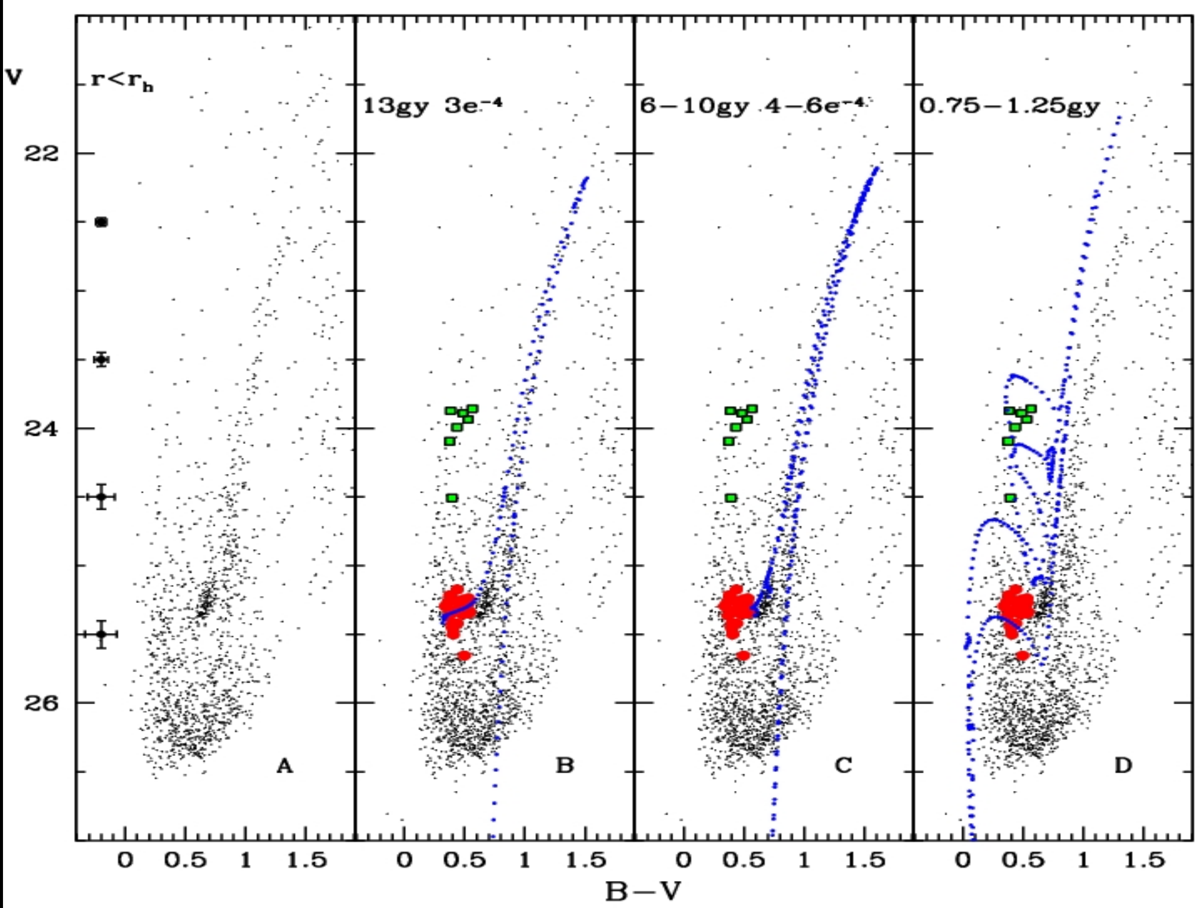
dSph	<[Fe/H]>	N(RRab/c/d)	<Pab>	Oo Type
And I	-1.5	72+26	0.575	Oo I/Int
And II	-1.5	64+8	0.571	Oo I
And III	-1.9	39+12	0.657	Oo II
And V	-2.2	7+3	0.685?	Oo II?
And VI	-1.6	91+20	0.588	Oo Int

from Clementini 2010

And XIX - LBT dataset



Cusano et al. 2013



39 variable stars:

- 8 Anomalus Cepheids
- 31 RR Lyrae stars

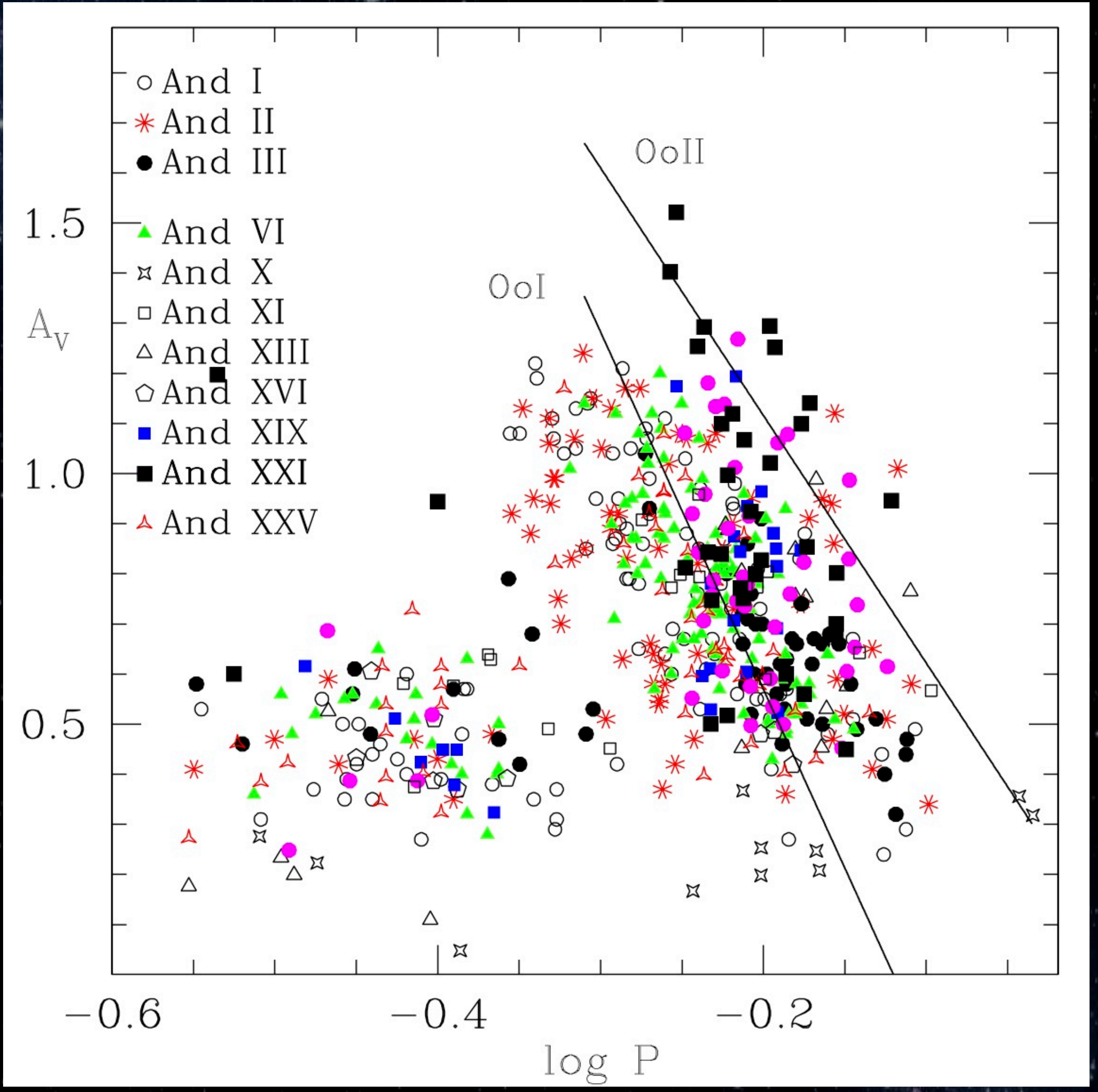
3 stellar generations:

- B: ~13 Gyr [Fe/H]=-1.8 dex (RR Lyrae stars)
- C: 10-6 Gyr, [Fe/H]~-1.5 dex
- D: 0.75-1.25 Gyr, [Fe/H]~-1.5 dex (ACs)

Oosterhoff properties of the M31 new satellites

dSph	N(AC)	N(RRab/c/d)	<Pab>	Oo Type
And IX	yes	>30	in progress	in progress
And X	yes?	9/6	0.71	Oo II
And XI	-	10(+2?)/5?	0.62?	Oo Int?
And XIII	-	12/5	0.66	Oo II
And XVI	-	3/6	0.64	Oo II
And XXI	8	37/5	0.63	Oo Int
And XIX	8	23/8	0.62	Oo Int
And XXV	-	35/20	0.59	Oo Int
And XII	in progress	yes?	in progress	in progress
And XV	in progress	yes	in progress	in progress
And XXIV	in progress	in progress	in progress	in progress
And XXVII	in progress	in progress	in progress	in progress

Period-Amplitude diagram of the M31 dSphs and UFDs



updated from Cusano et al. 2013

SUMMARY

- Most RRab stars in the MW and M31 halos belong to Oo I according to the period-amplitude diagram, but the inner MW halo at least has a significant Oo II component, by contrast Oo I is rare among the "bright" dwarf spheroidal galaxies.

- More massive dSphs tend to be Oo-Intermediate. ***The MW is unlikely to have formed early on by accretion of protogalactic fragments resembling the early counterparts of its present-day "bright" dwarf spheroidal satellites.***

- "Ultra-faint" dSphs tend to be Oo II (in so far as they can be classified). ***The MW may have formed early on by accretion of protogalactic fragments resembling the early counterparts of its present-day "ultra-faint" dwarf spheroidal satellites.***

- We detected pulsating variables in all the M31 satellites we have analyzed so far most of them are RR Lyrae, pulsation properties and Oosterhoff type are being defined. The sample analyzed so far contains both Oo II and Oo Int types, however, in the P/Av diagram these systems look preferentially OoI.
  First studies of the Oo-dichotomy in the M31 GCs, (Clementini et al. 2009, Contreras Ramos et al. 2013), show that both Oo Int and Oo II GCs seem to occur in M31.

Some issues about dSphs

- ✓ **Missing Satellite Problem (MSP)**
- ✓ **Variable Stars Problem**

Some issues about dSphs

✓ Missing Satellite Problem (MSP)

New satellites are being discovered in large numbers

✓Variable Stars Problem

MW UFDs are fine, "classical" dSphs aren't, less clear in M31


Thank you
Potsdam Dwarfs 2014

References

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Monelli et al. 2003, AJ 126, 218
Greco et al. 2007, PhD Thesis
Dall'Ora et al.2006, ApJ 653, L109
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