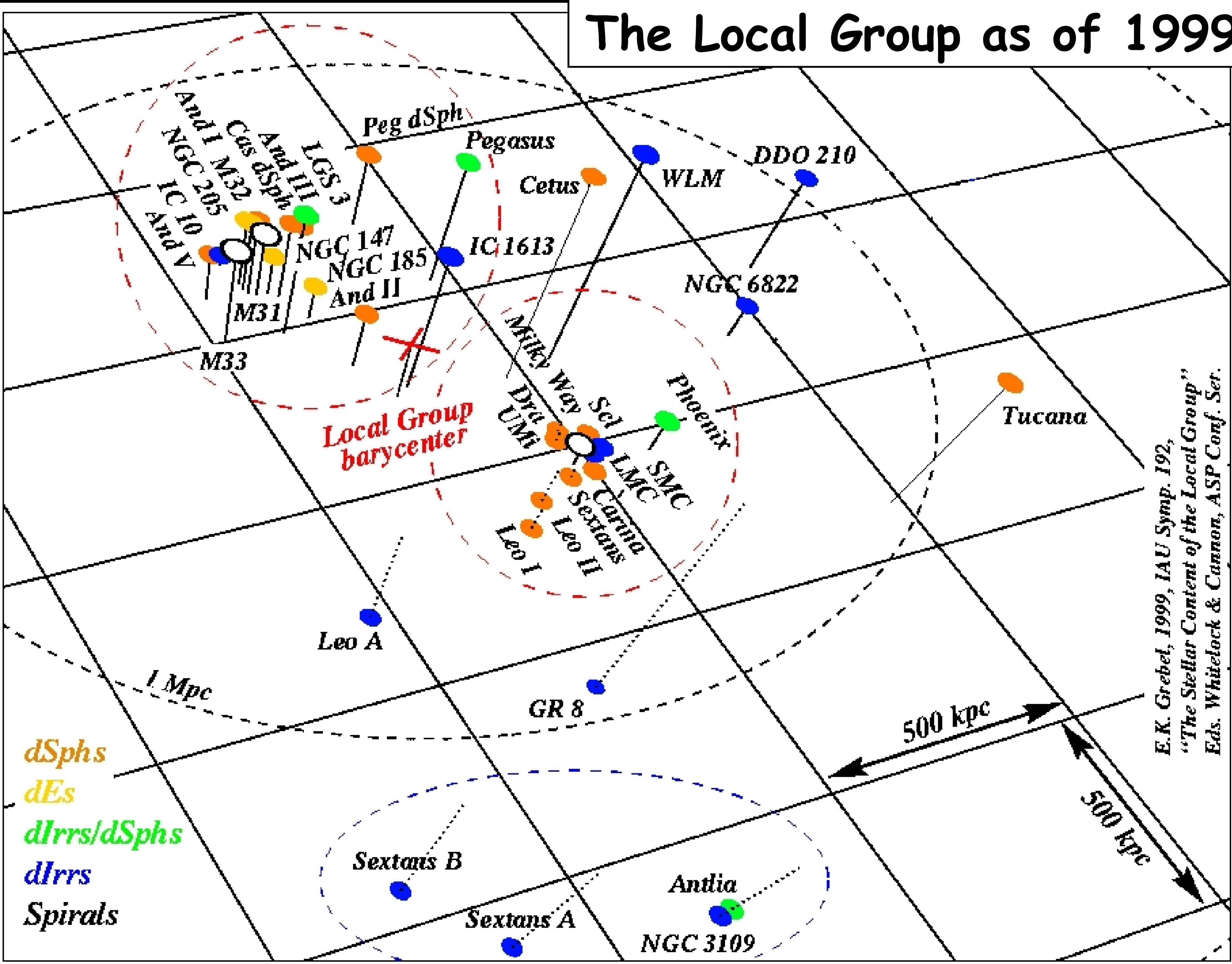
Galassie sferoidali nane “classiche” e satelliti “ultra-faint”della Via Lattea e di M31

Gisella Clementini
INAF - Osservatorio Astronomico Bologna

LVIII Congresso SAIT - Milano - 13-16 Maggio 2014

- ✓ the Local Group
- ✓ galaxy formation mechanisms
- ✓ the Local Group dSphs
  - the MW satellites
  - the Andromeda satellites
- ✓ tools:
  - CMDs
  - pulsating variable stars
  - abundances (iron and α-elements)
  - dynamical studies

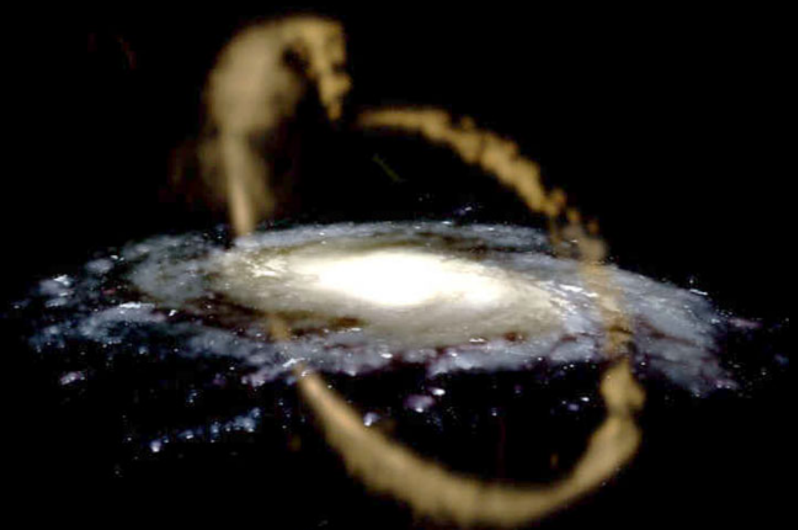
The Local Group as of 1999



Galaxy formation mechanisms

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

Many observational evidences of merging:

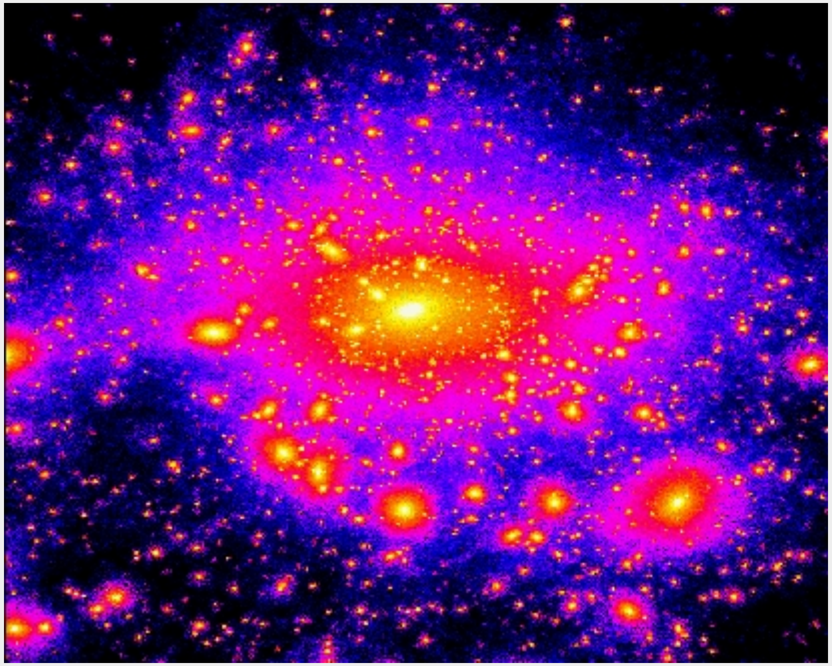


- Sgr dSph
- M31 giant stream

- 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


✓ the Local Group dSphs - the MW satellites
LVIII Congresso SAIT

Milky Way satellites census (as of 2005)

9 (10) “Bright” dSphs

Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor

Sagittarius
(Canis Major)

New Milky Way satellites discovered after 2005

21 new "faint" systems

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

"ultra-faint" dwarf galaxies

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

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

Koposov I
Koposov II

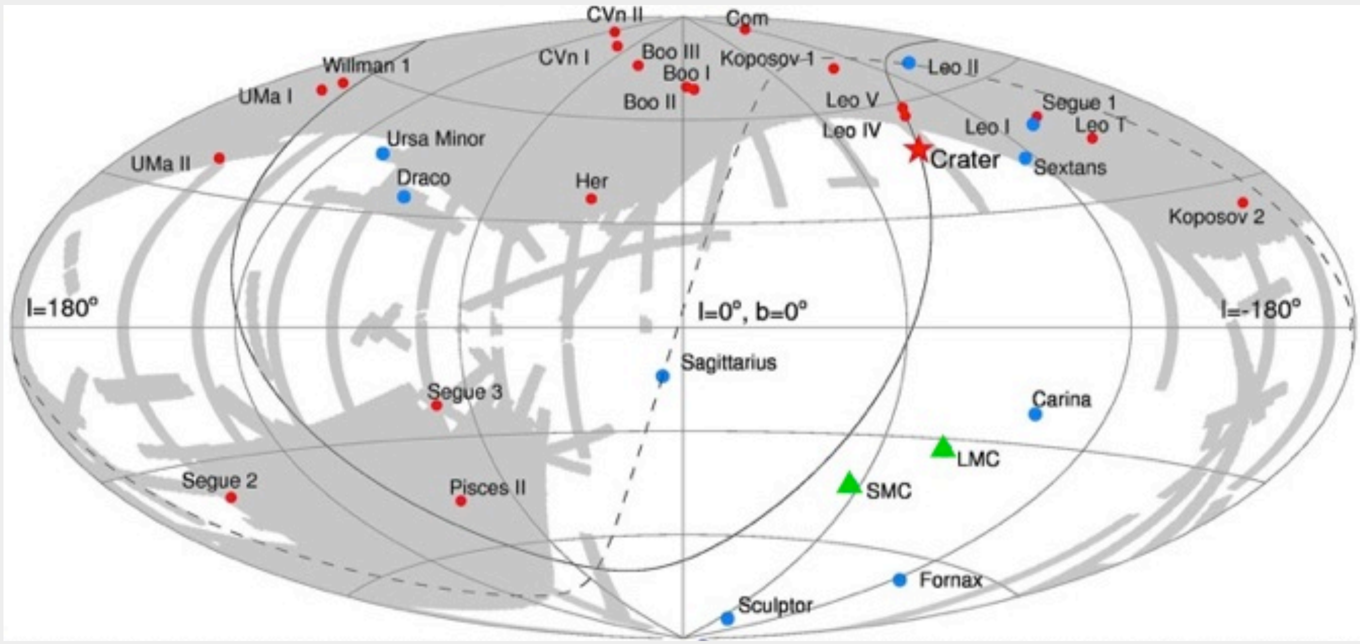
tiny globular clusters

Census of the Milky Way satellites as of 2014

"Bright" dSphs

Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor

Sagittarius
(Canis Major)



Belokurov et al. (2014)

"Ultra-faint" dSphs

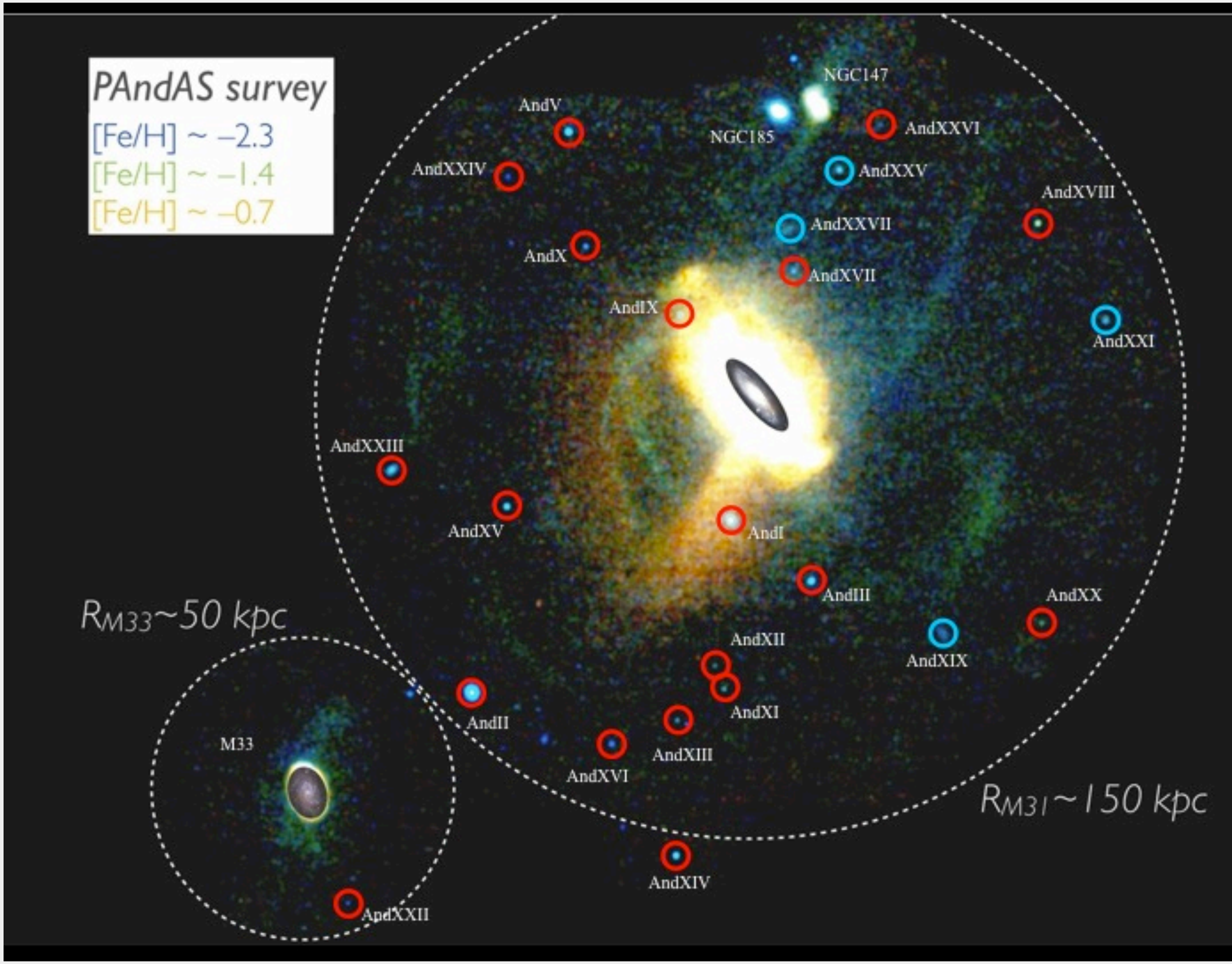
Leo IV
LeoV
Coma
Bootes I
Canes Venatici I
Canes Venatici II
Hercules
Leo T
Ursa Major I
Ursa Major II
Pisces I
Pisces II
Crater
Willman I
Bootes II
Bootes III
Segue I
Segue II
Segue III
Koposov I
Koposov II

✓ the Local Group dSphs - the Andromeda satellites

The satellites surrounding M31 (as of 2013)

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

since 2004 27 new M31 dSphs satellites were discovered by the CFHT, INT and PAN STARSS surveys of the Andromeda's halo

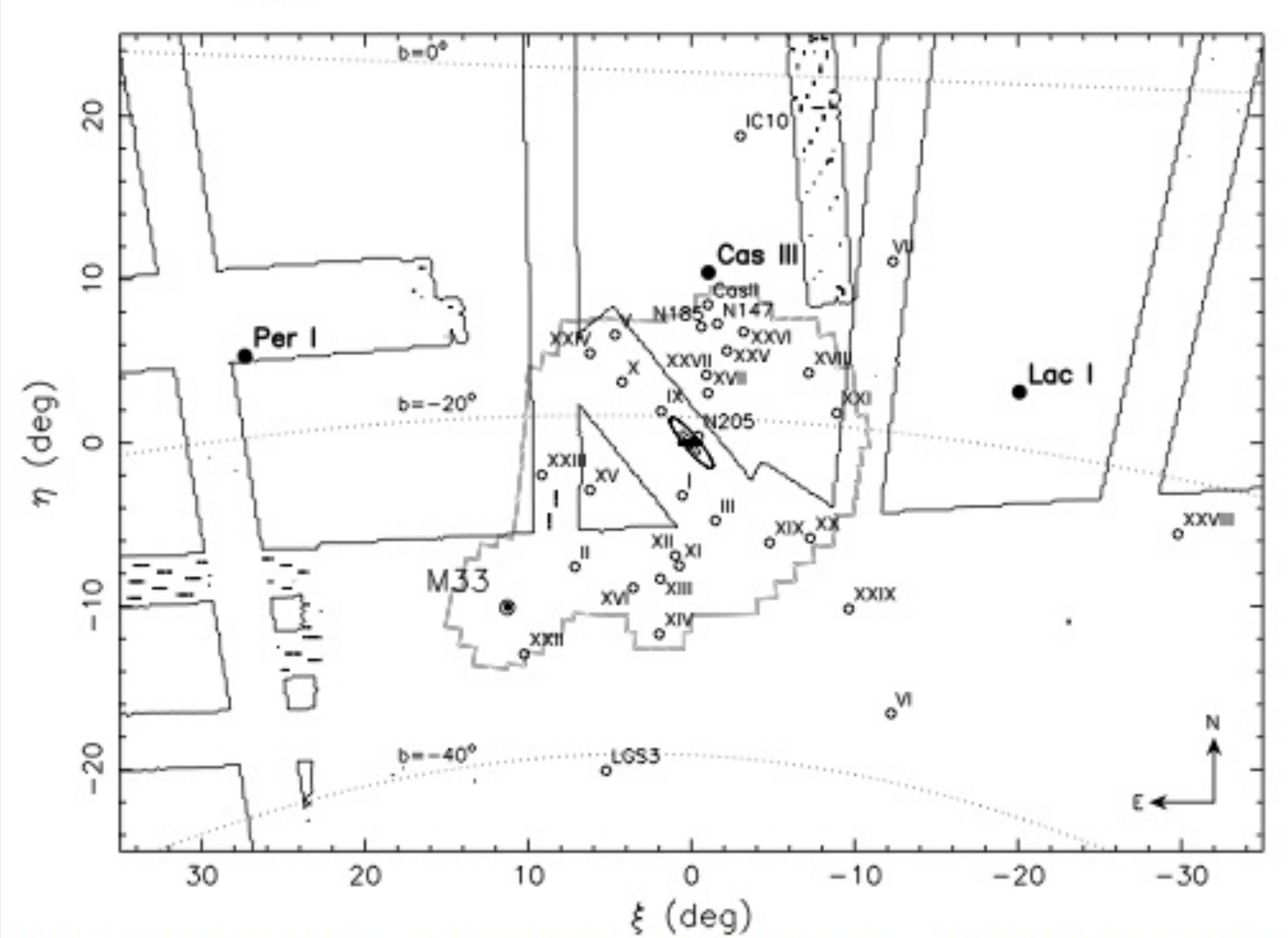


Martin et al. (2013, ApJ 776, 800)

The satellites surrounding M31 (as of 2014)

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

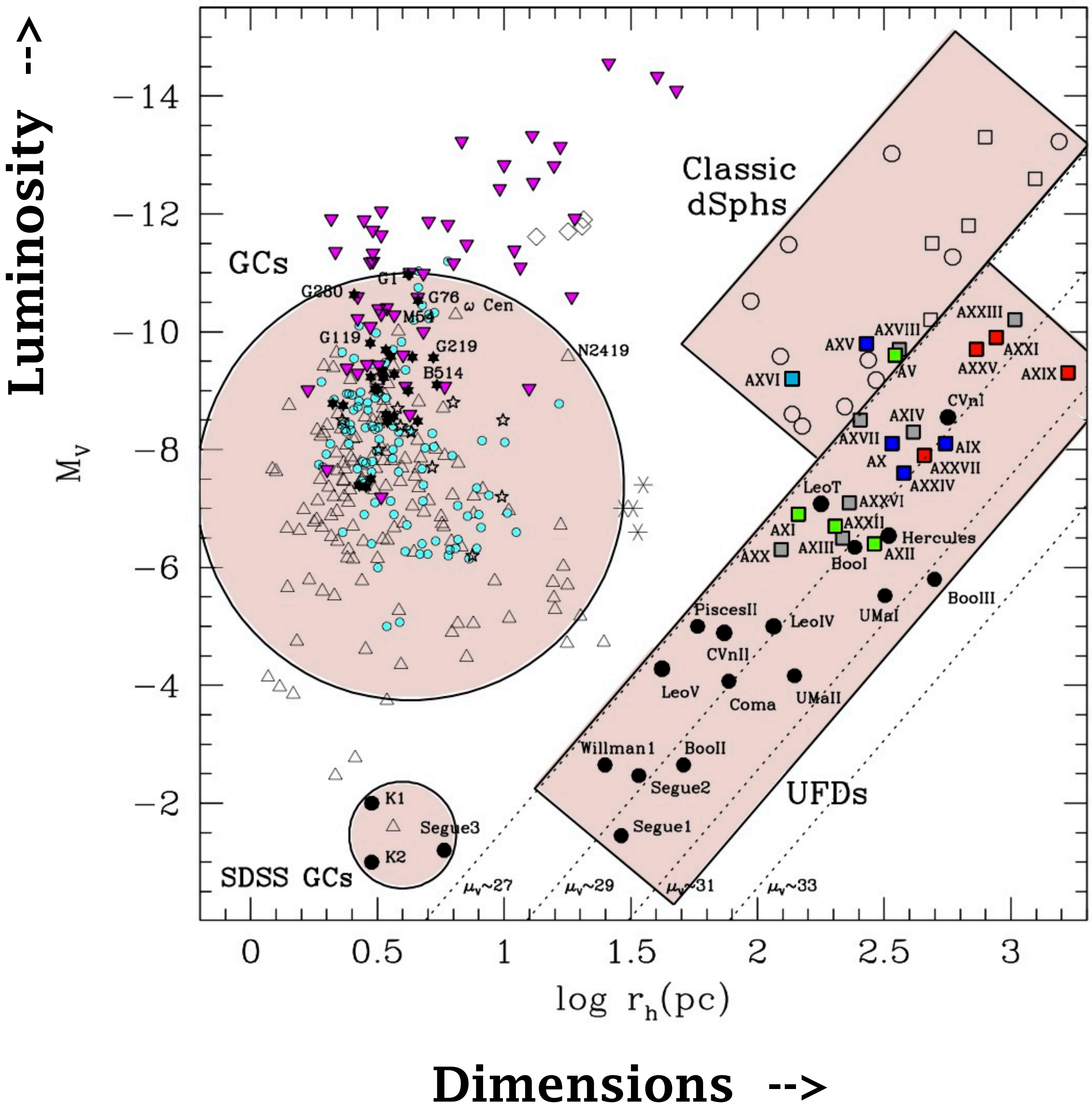
latest census of new M31 dSphs adds to a total of 32 dSphs



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

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



○ MW dSphs and UFDs

□ M31 dSphs and UFDs

HST (green)

LBT (red)

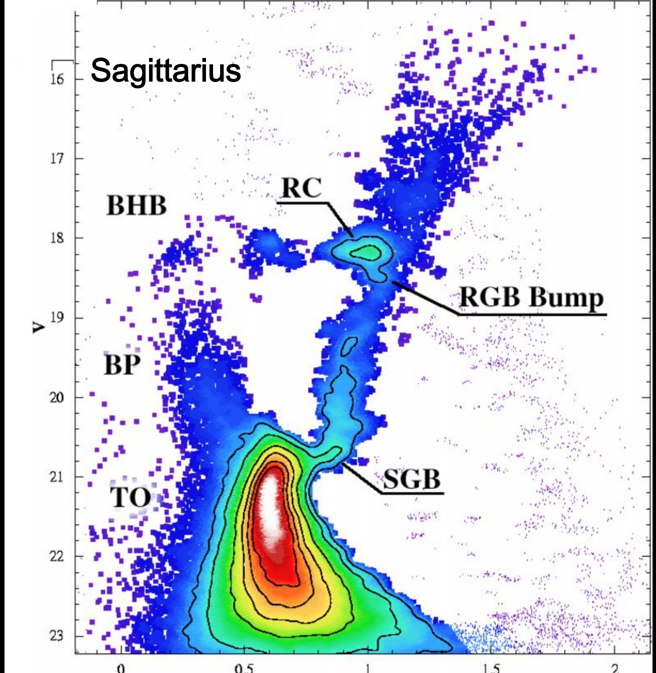
GTC (blue)

TNG (cyan)

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

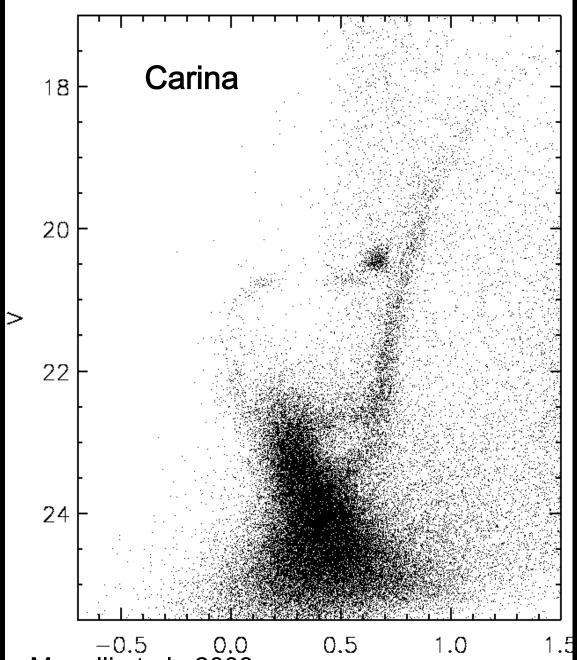
UFDs have luminosities (M_v) typical of GCs and dimensions (r_h) typical of dSphs

- ✓ tools:
  - CMDs
  - pulsating variable stars
  - abundance analysis
  - dynamical studies

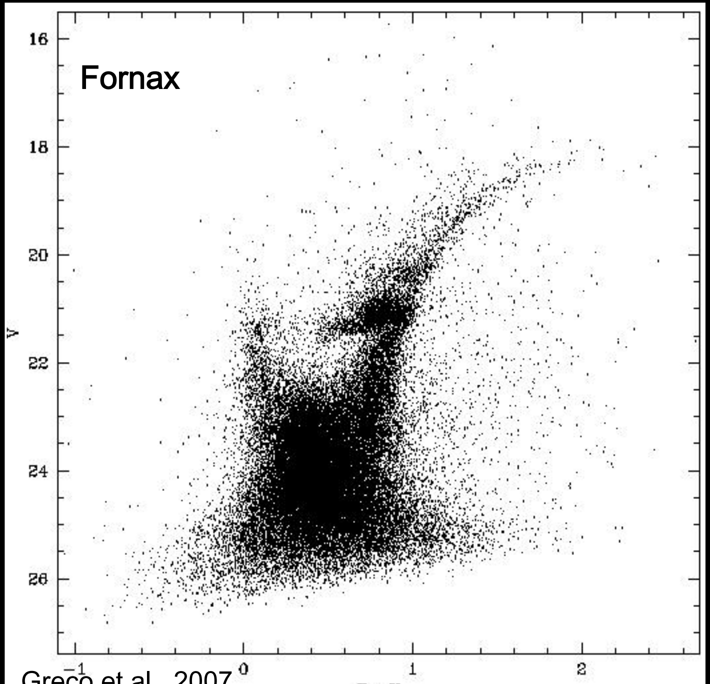


Bellazzini et al. 2006

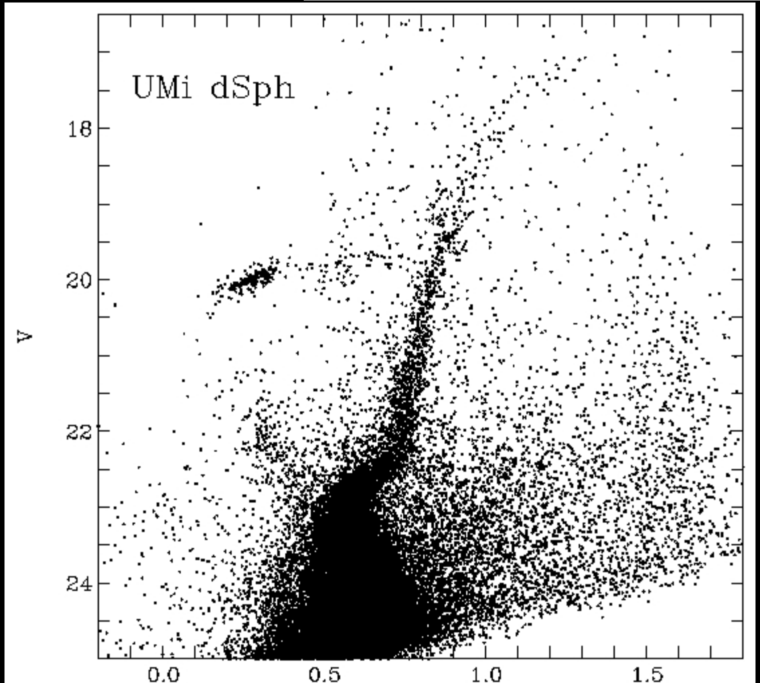
“Bright” MW dSph satellites



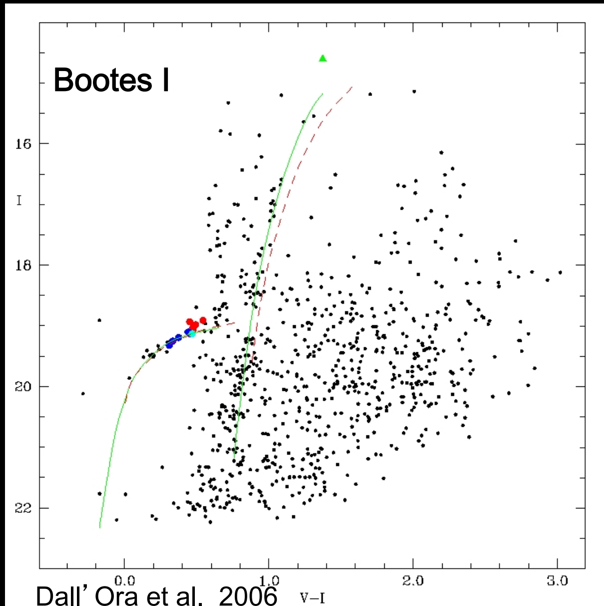
Monelli et al. 2003

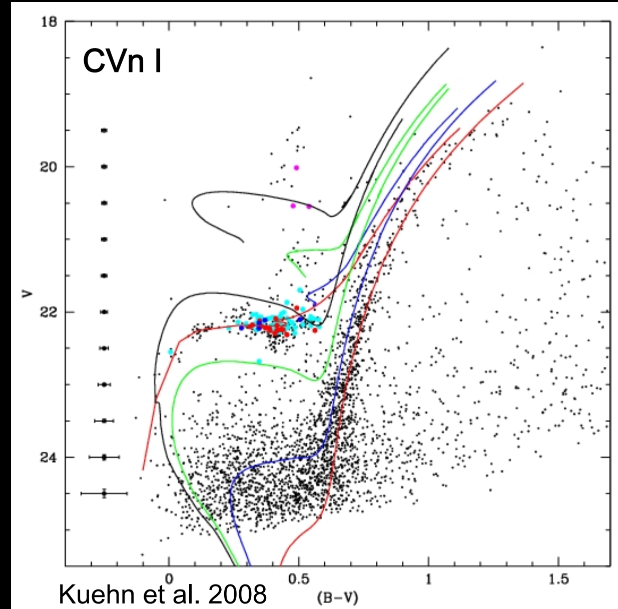


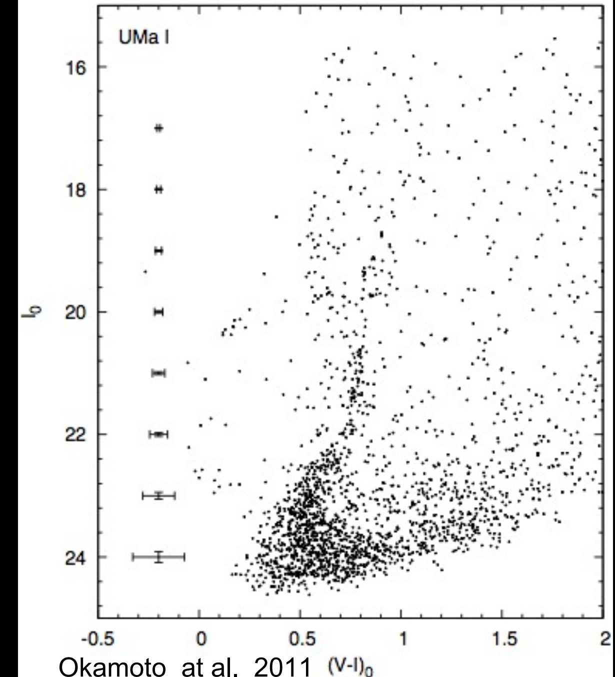
Greco et al. 2007



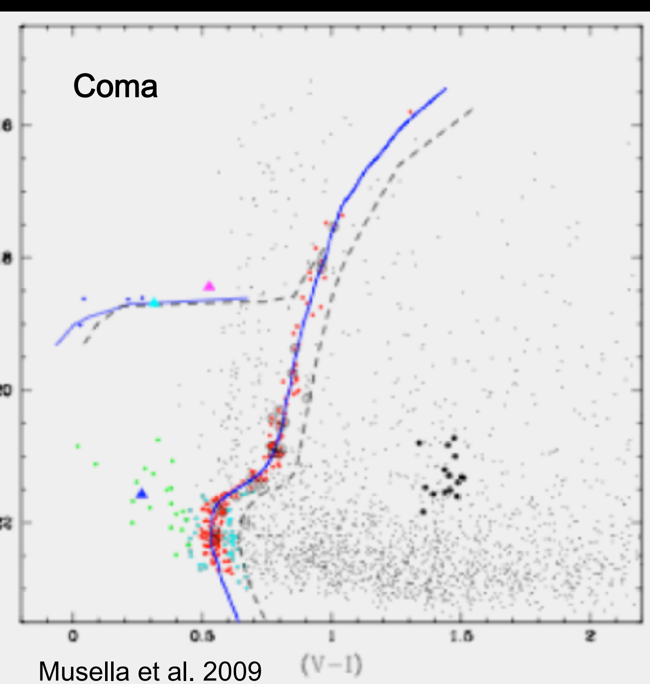
Dall’ Ora et al., in prep

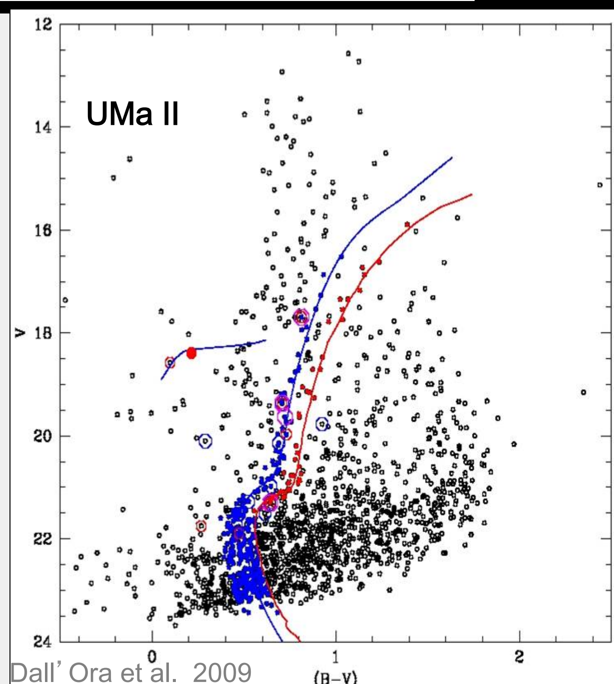


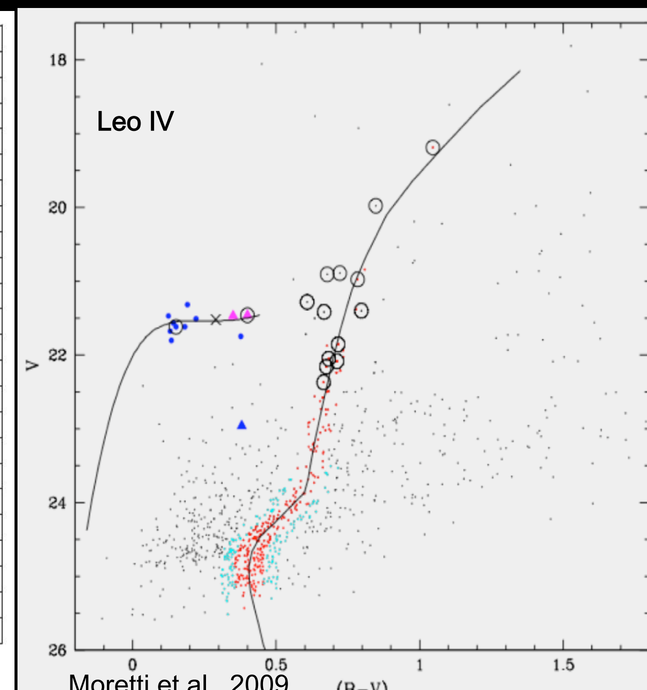


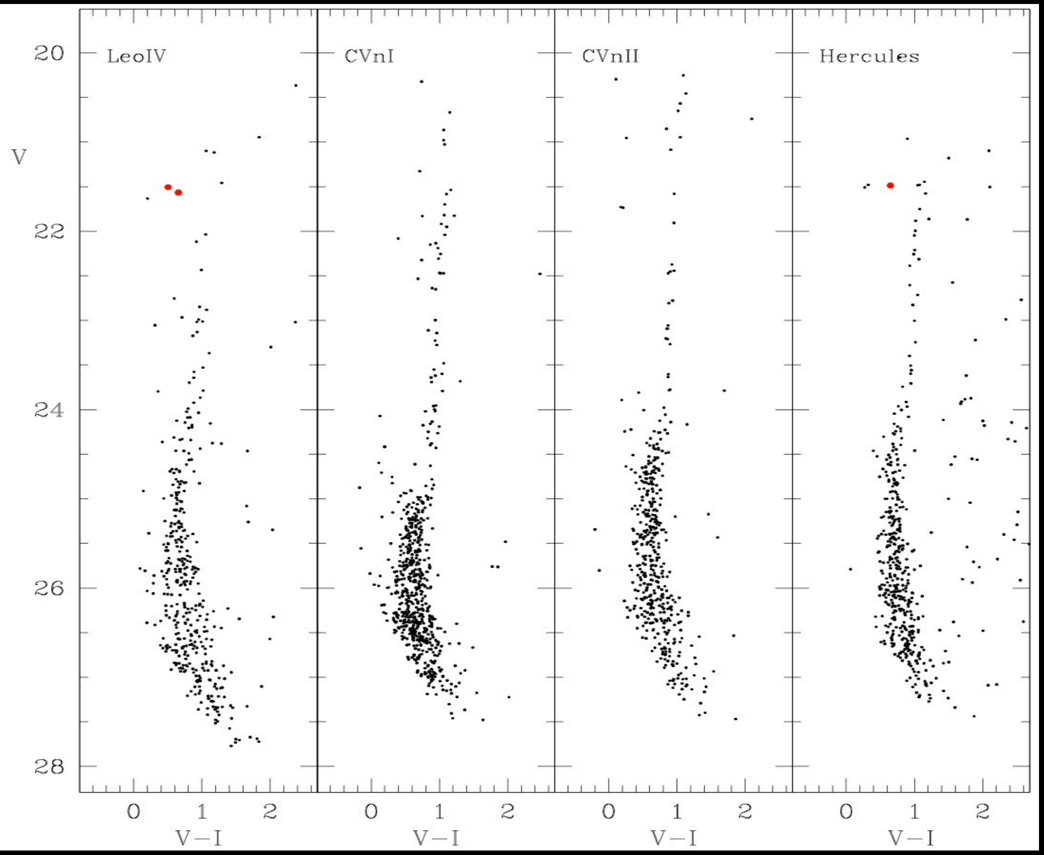


“ultra-faint” MW satellites

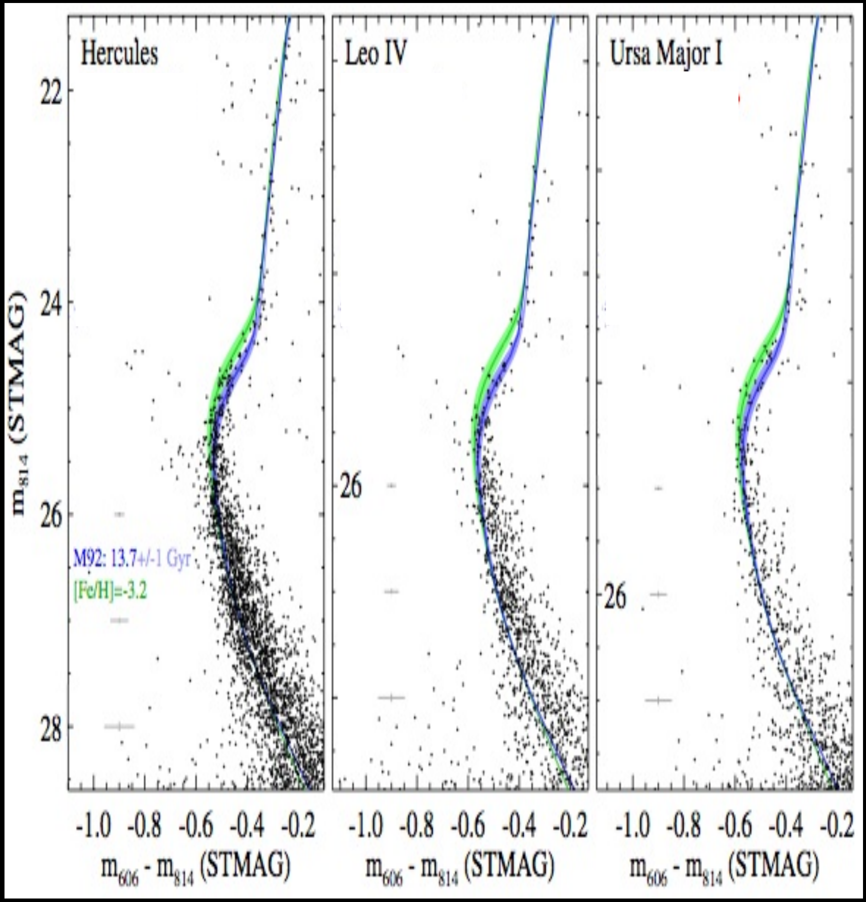








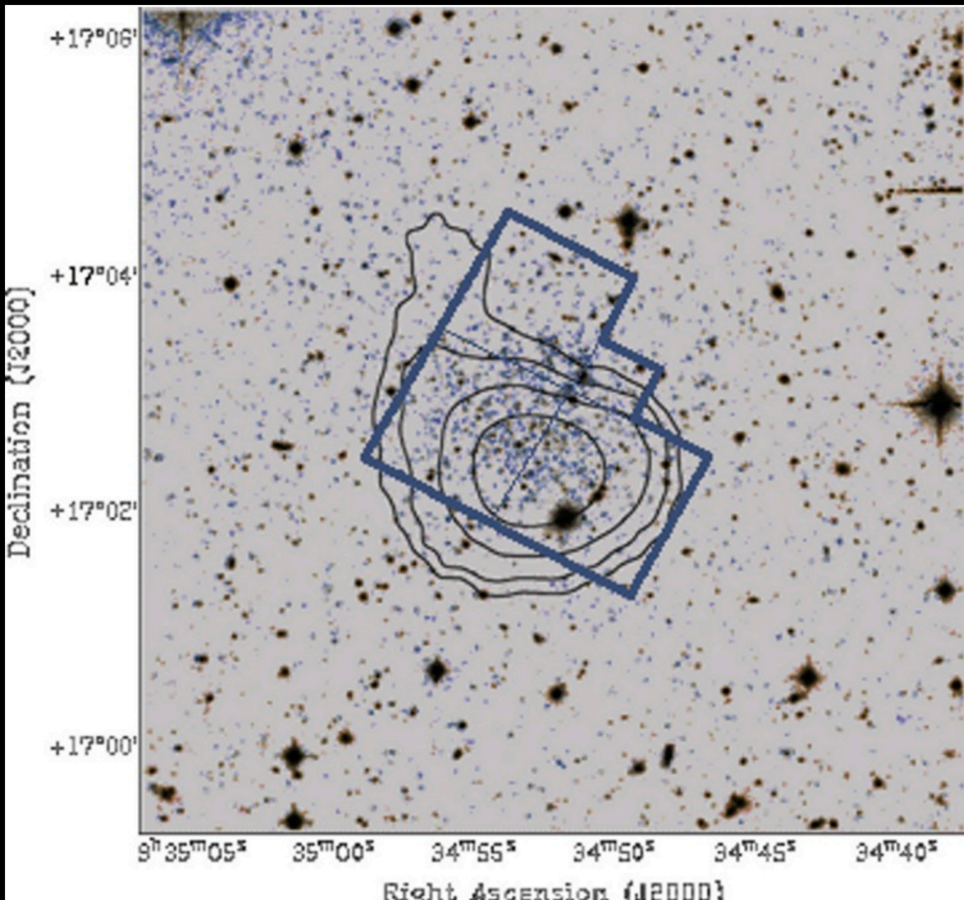
Garofalo et al., in prep



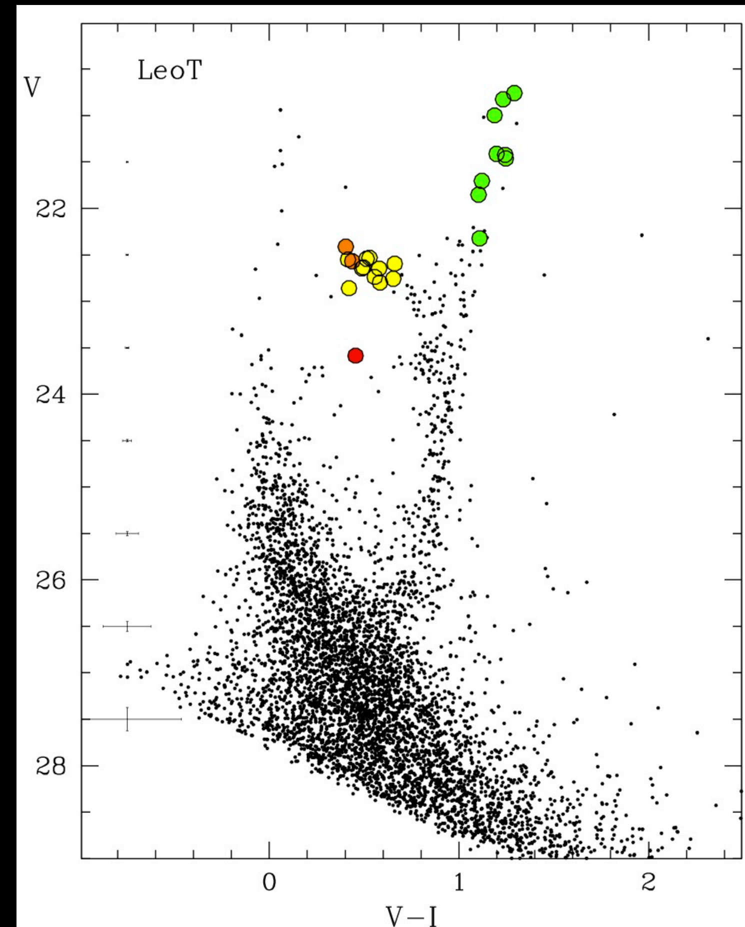
Brown et al. 2012

“ultra-faint” MW satellites, HST data

“ultra-faint” MW satellites: Leo T

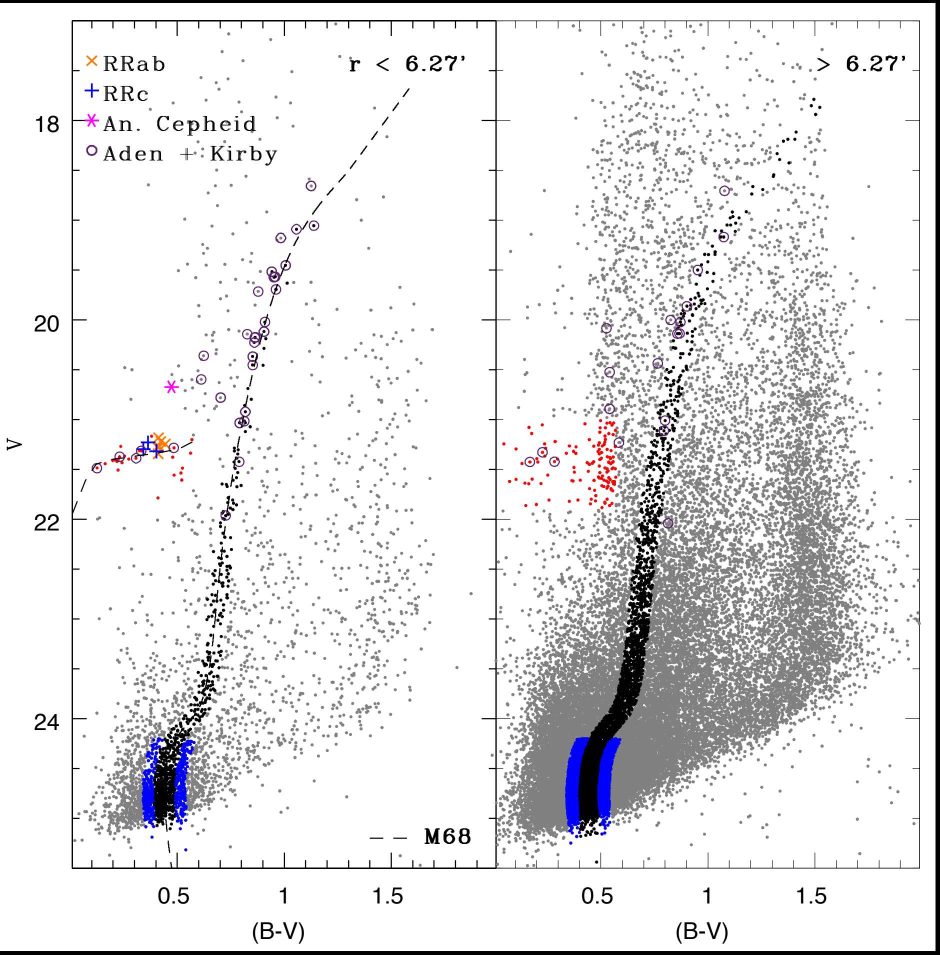


Ryan-Weber et al. 2008

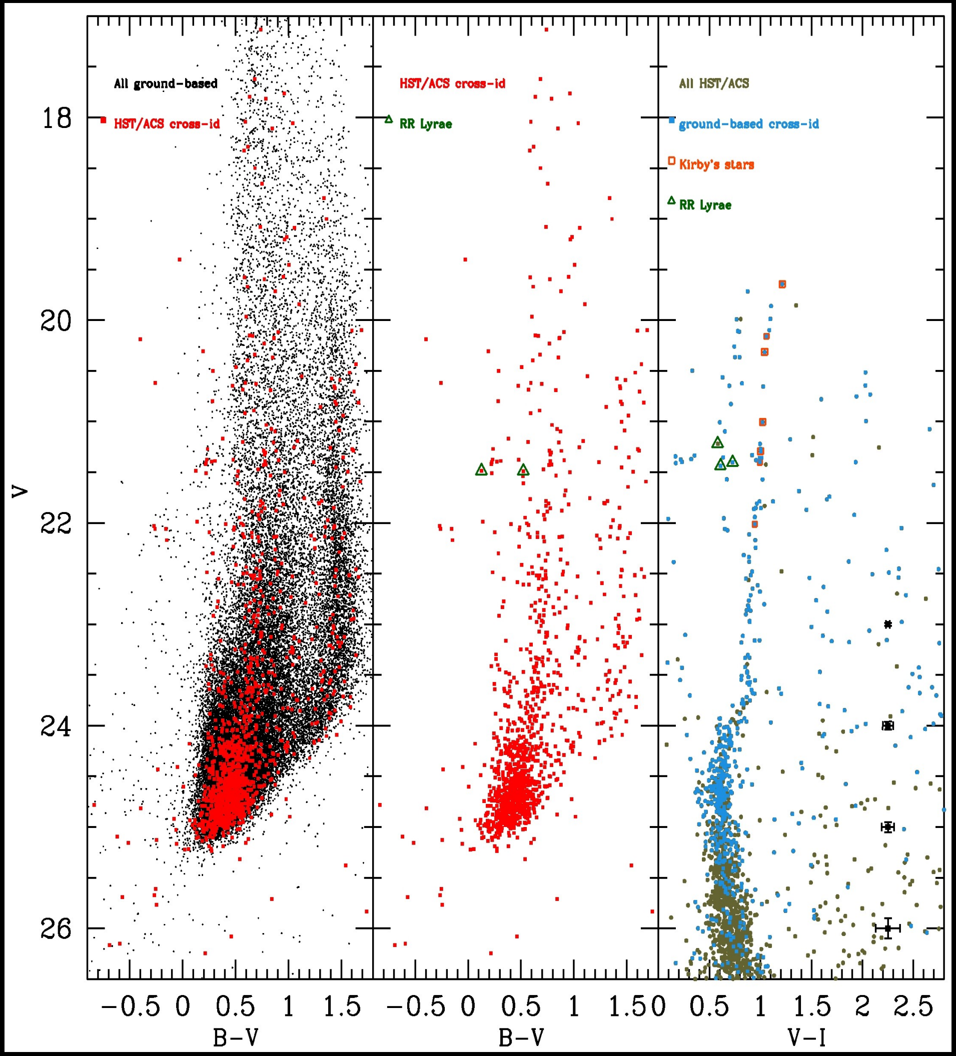


Clementini et al. 2012

"ultra-faint" MW dSph satellites: Hercules



Musella et al. 2012



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

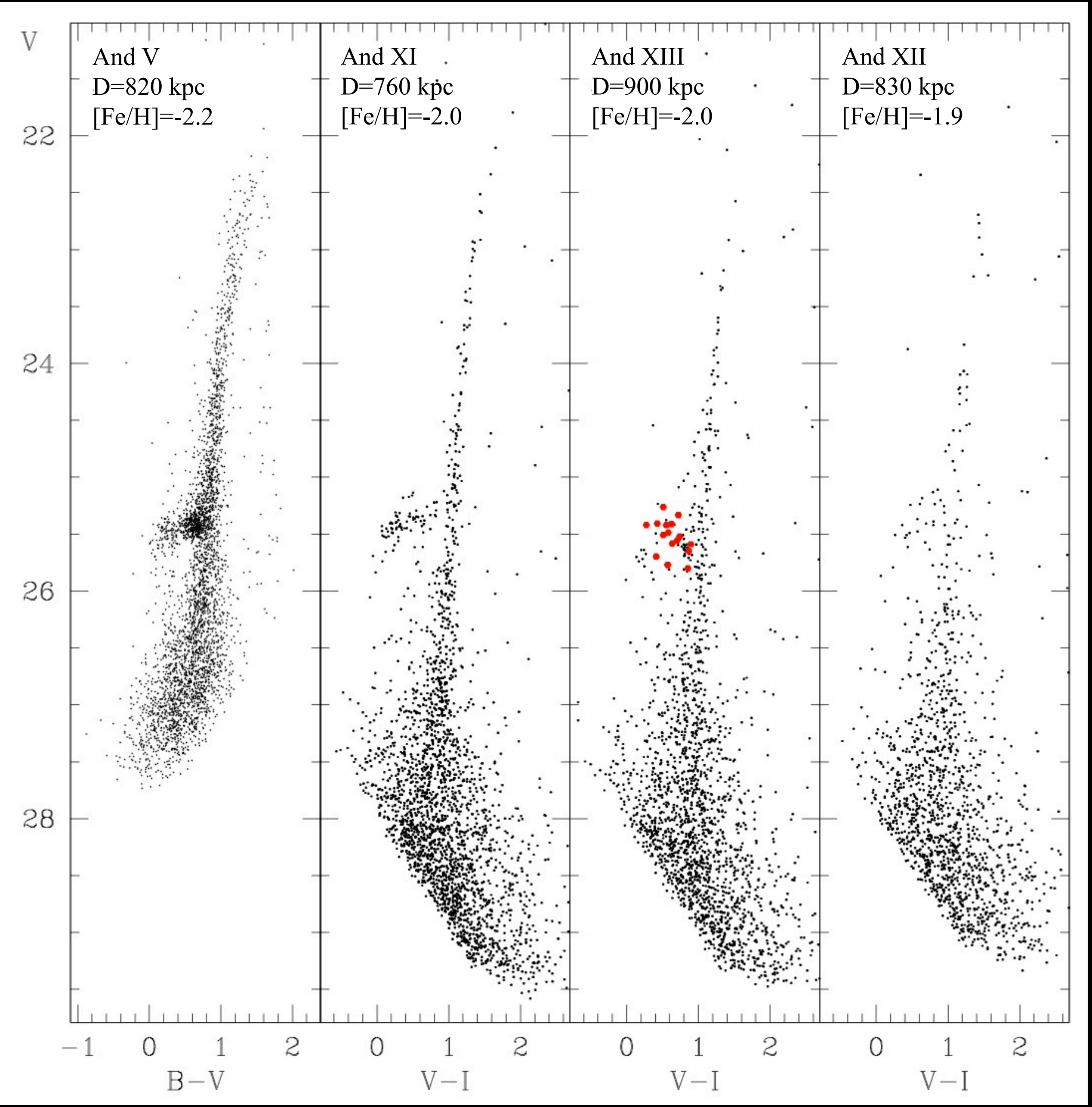
17 B+8 V of 1200 s
Total exps. 20400/9600 s

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:
  - CMDs
  - pulsating variable stars
  - abundance analysis
  - dynamical studies

Pulsating variables trace the different stellar generations in galaxies

- young (t < 100 Myr) → Classical Cepheids, (δ Scuti stars)
- 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 can provide hints on how galaxies have formed

"the Oosterhoff dichotomy"

Oosterhoff 1939

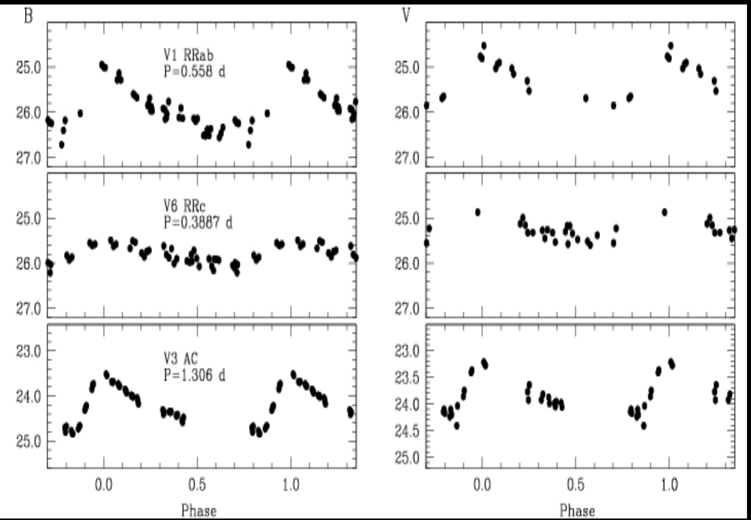
RR Lyrae Stars

RR Lyrae stars have been found in "all" Local Group galaxies where they have been searched for.

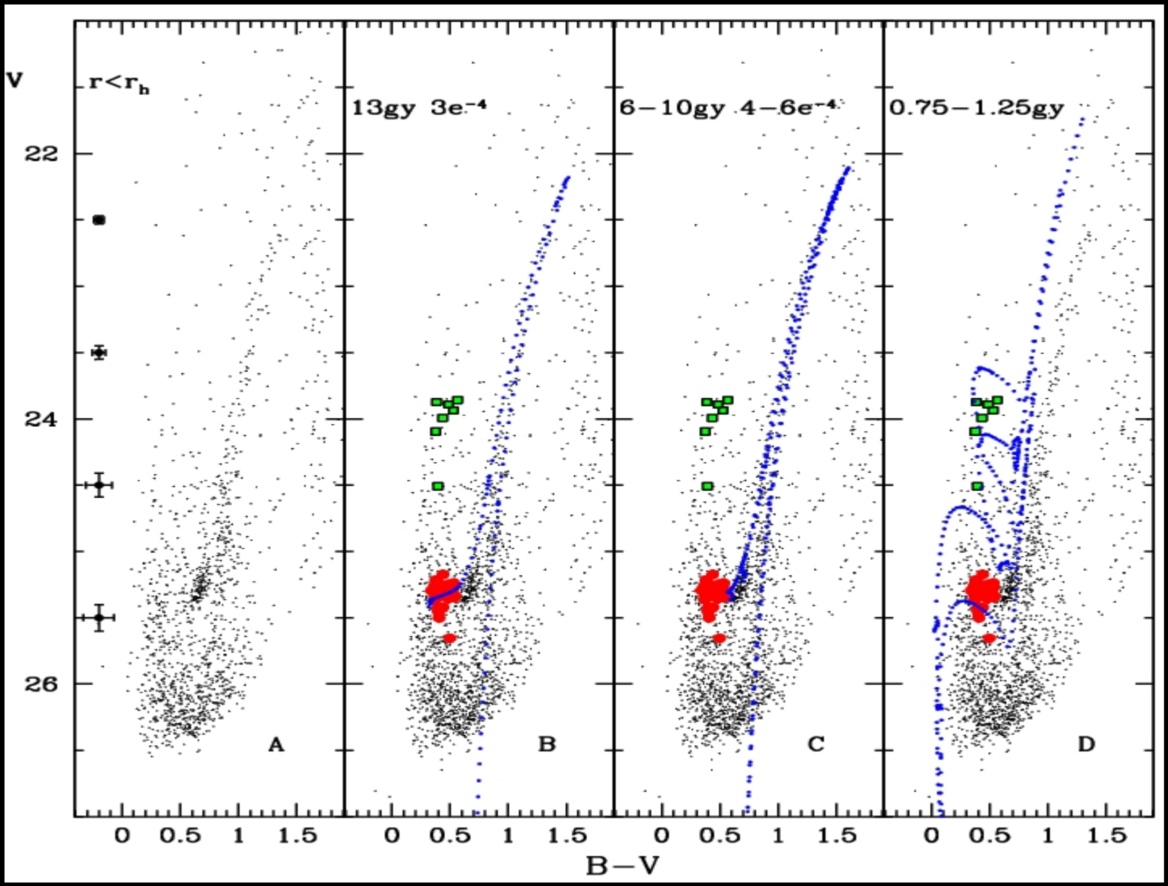
⇒ "All Local Group galaxies contain a very old population component, i.e. all nearby galaxies started to form stars just after they were formed".

In other words there are **no truly young** galaxies in the Local Group.

And XIX - LBT dataset



Cusano et al. 2013



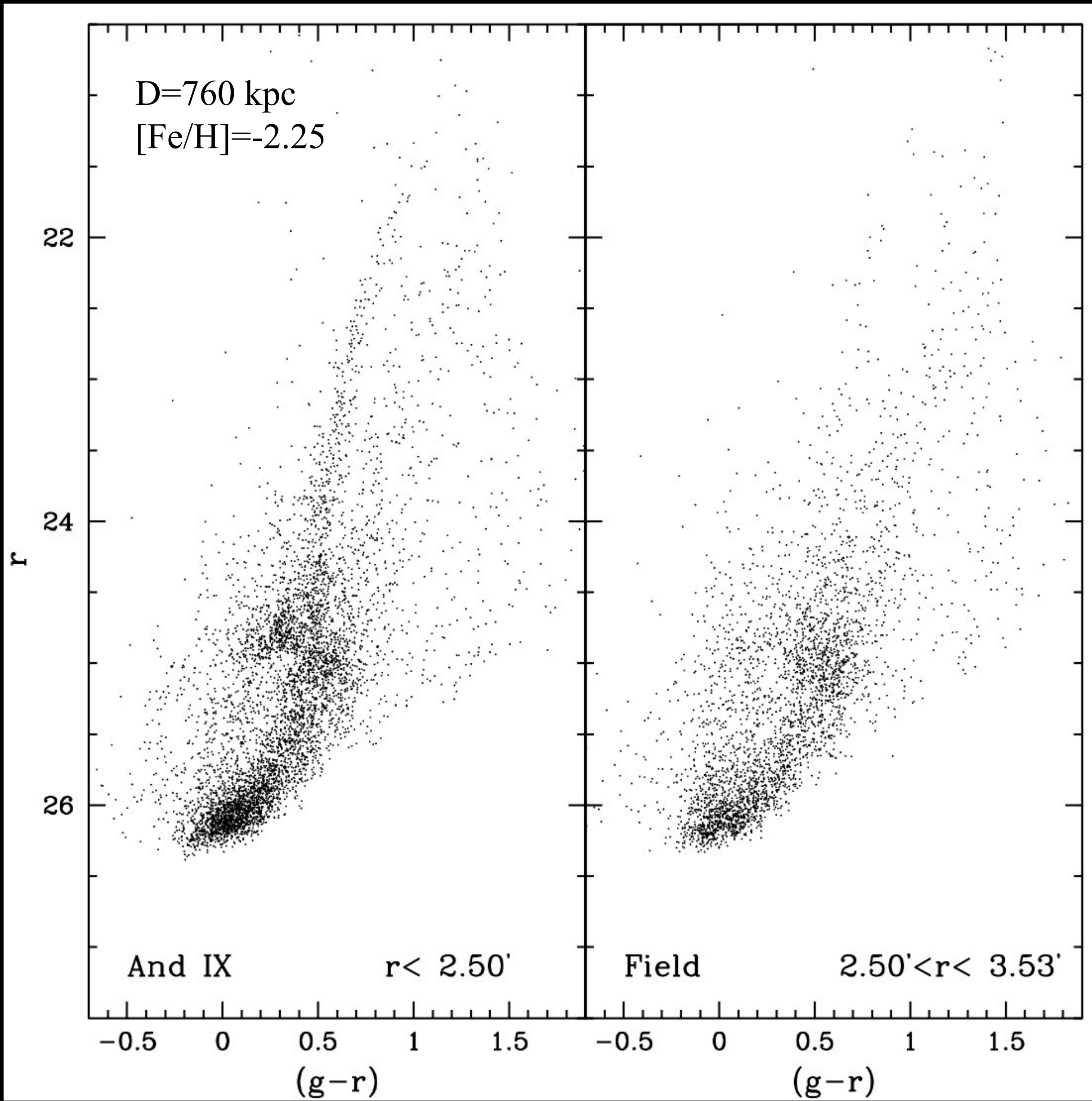
39 variable stars:

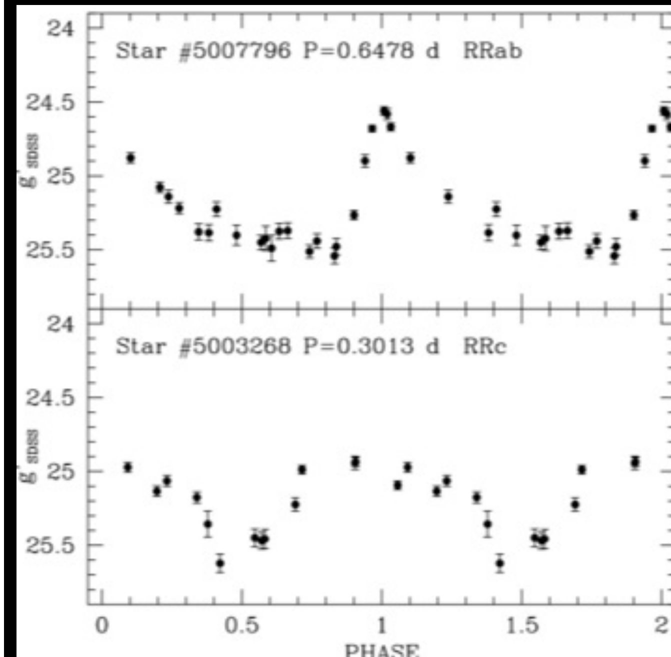
- 8 Anomalus Cepheids
- 31 RR Lyrae stars

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)

And IX - GTC dataset





Ripepi et al., in prep

> 30 RR Lyrae stars
a few candidate ACs

The Oosterhoff dichotomy

In the MW, field and GC RR Lyrae populations divide 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

The M31 field appears to be Oo I/ Oo Intermediate

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

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 MW "bright" dSphs cannot have contributed to the 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

our team:

Cignoni, Contreras, Coppola, Cusano, Garofalo, Greco, Moretti, Clementini, Ripepi, Dall'Ora, Musella, Marconi, Di Fabrizio, Mercurio, Testa, Tosi, Fusi Pecci, Ferguson

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

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 XII	in progress	yes?	in progress	in progress
And XV	in progress	yes	in progress	in progress
And XXIV		in progress		
And XXV		in progress		
And XXVII		in progress		

✓ tools: - CMDs
- pulsating variable stars
- abundances (iron and α-elements)
- dynamical studies

Iron

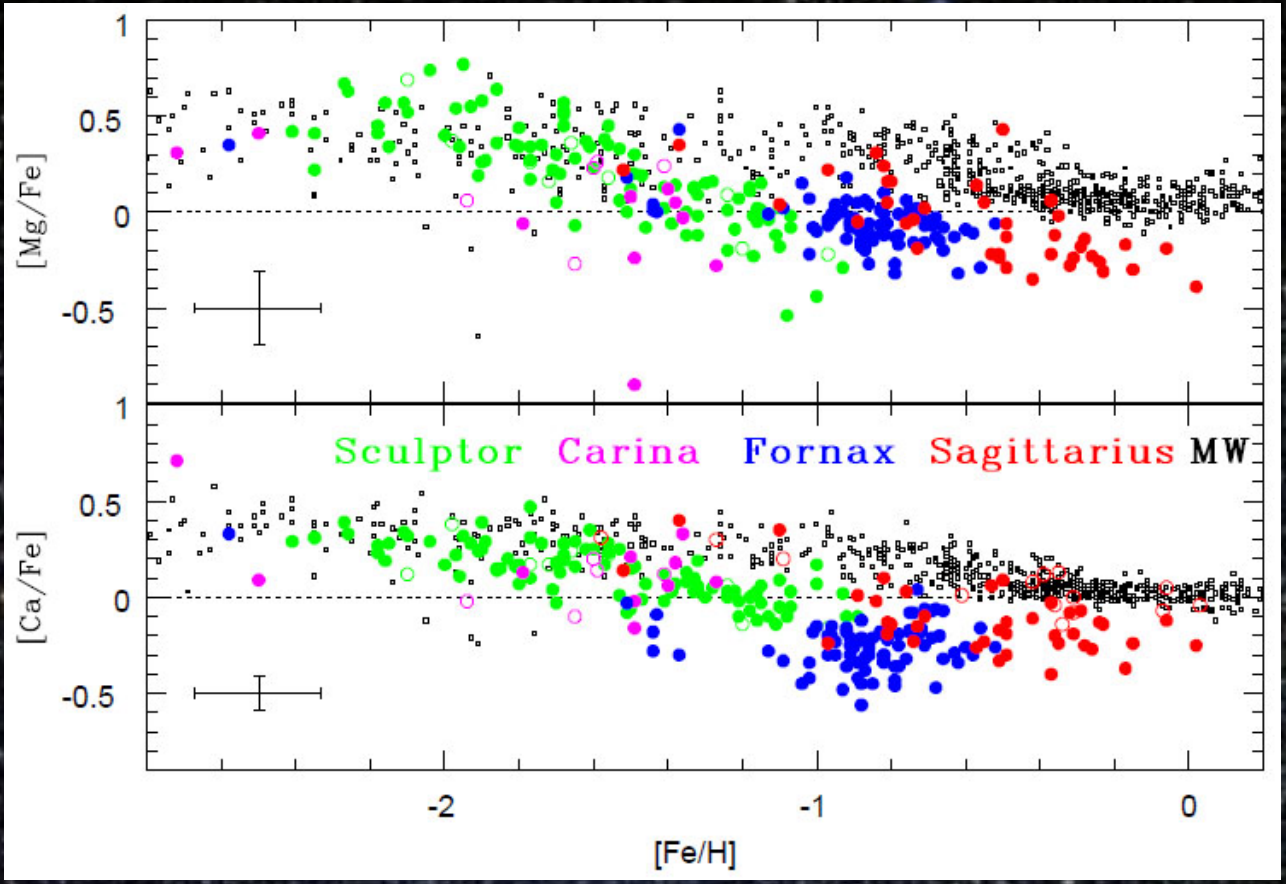
The MW halo contains very metal-poor stars ([Fe/H] ≤ −2 dex) and extremely metal-poor stars ([Fe/H] ≤ −3 dex) which show little dispersion, indicating a cosmic scatter as low as 0.05 dex (Cayrel et al. 2004) .

By contrast there seemed to be lack of extremely metal-poor stars in the "classical" dSps satellites around the MW (Helmi et al. 2006).

A new calibration of the CaT was derived using synthetic spectral modeling tied to observations valid to [Fe/H] = −4 dex. This analysis also brought the distribution of metal-poor stars in the classical dSphs in closer agreement with that of the Milky Way halo (Starkenburg et al. 2010).

Extremely metal-poor stars with metallicities as low as [Fe/H] ~ -3.4, -4 dex have discovered in the ultra-faint dwarfs (Kirby et al. 2008, 2009; Geha et al. 2009; Frebel et al 2010, etc.)

α - elements



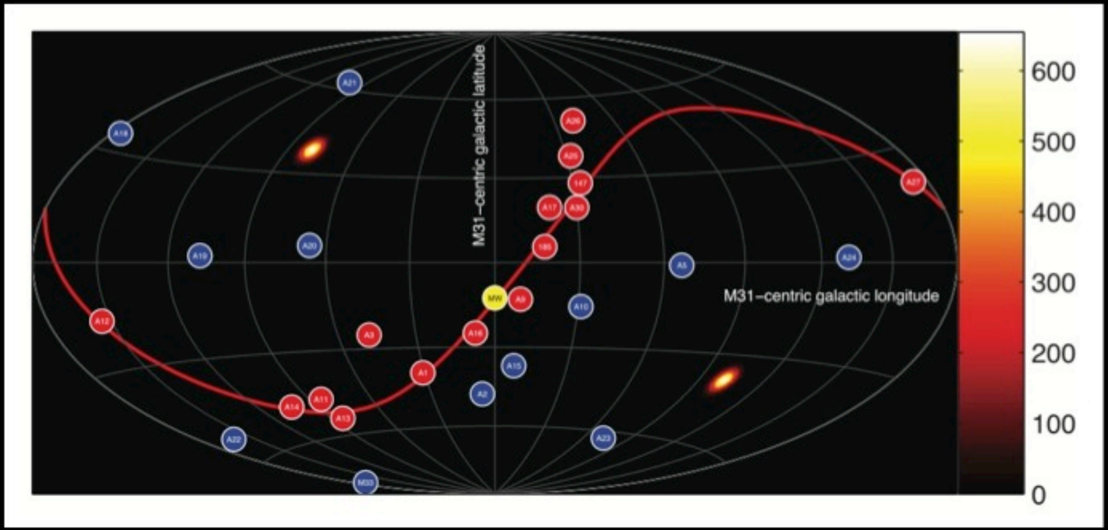
α-elements (Mg and Ca) in 4 "classical" MW dSphs. The small black symbols are a compilation of the MW disk and halo star abundances, from Venn et al. (2004).

The sample of UFDs analyzed so far has an [α/Fe] abundance pattern that seems to be inconsistent with a flat, Galactic halo-like α-abundance trend (Vargas et al. 2013).

✓ tools: - CMDs
- pulsating variable stars
- abundance analysis
- dynamical studies

- 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 may be tidal tails connecting the VPOS and GPoA (Pawlowsky et al. 2013)

The Great Plane of Andromeda

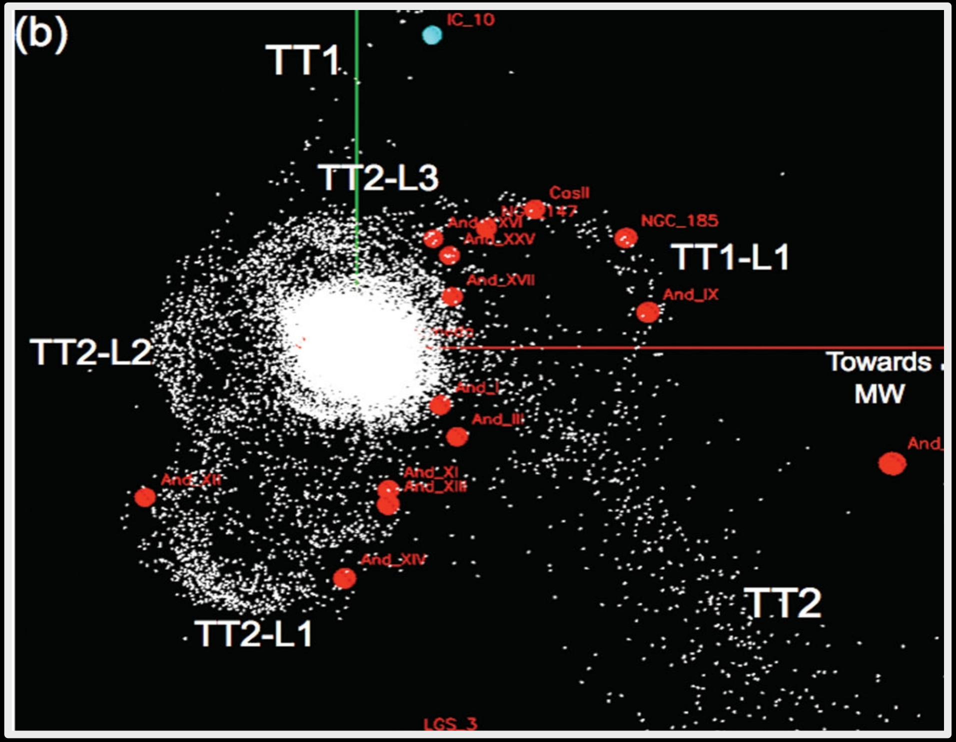


Ibata et al. 2013

- 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)

Some issues about dSphs

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

Some issues about dSphs

- ✓ Missing Satellite Problem (MSP)

  New satellites are being discovered in large numbers

- ✓ Metallicity (chemistry) Problem

  Iron is fine, α-elements still a problem (?)

- ✓ Variable Stars Problem

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

Thank you

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 XII	in progress	yes?	in progress	in progress
And XIII	-	12/5	0.66	Oo II
And XV	in progress	yes	in progress	in progress
And XVI	-	3/6	0.64	Oo II
And XIX	8	23/8	0.62	Oo Int
And XXI	8	37/5	0.63	Oo Int
And XXIV		in progress		
And XXV		in progress		
And XXVII		in progress		