The New SDSS dSph galaxies and their variable stars

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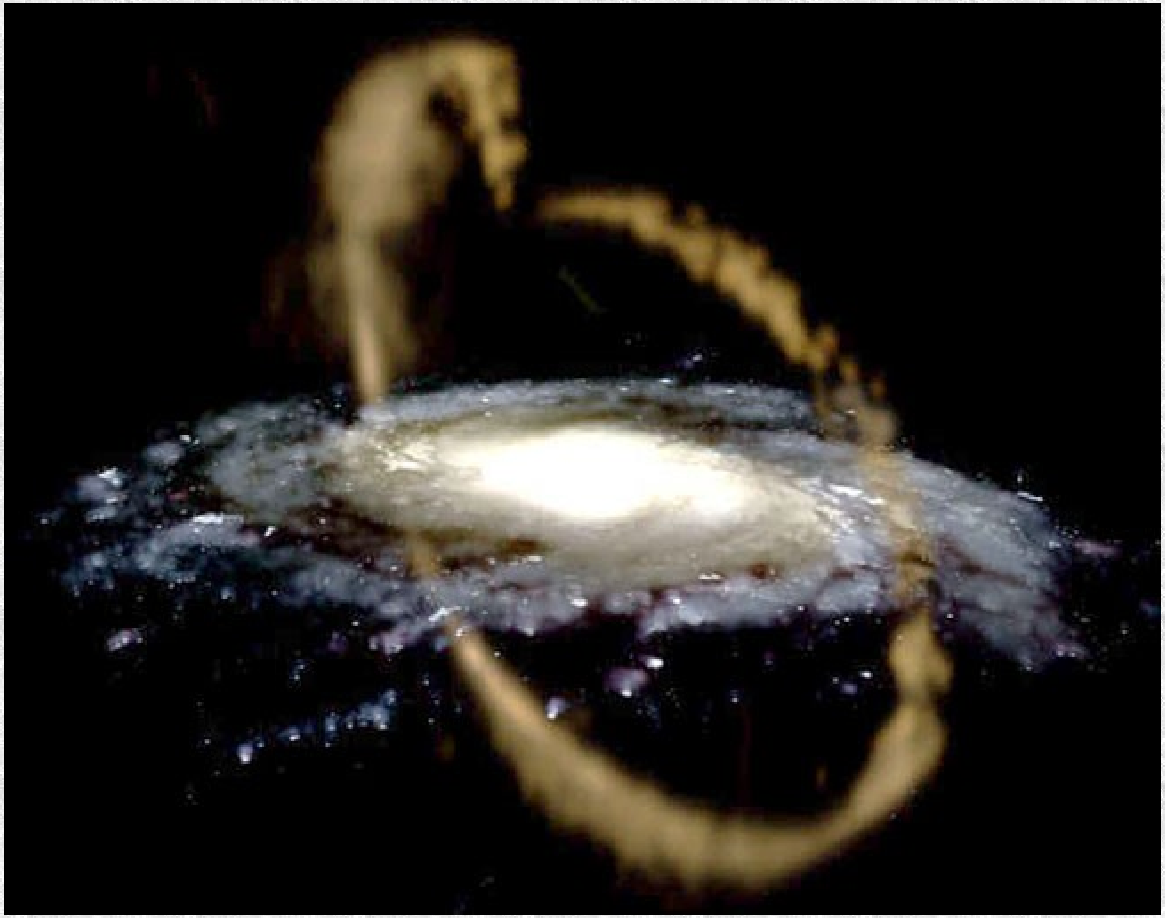
What's going on? Let's ask our neighbors....

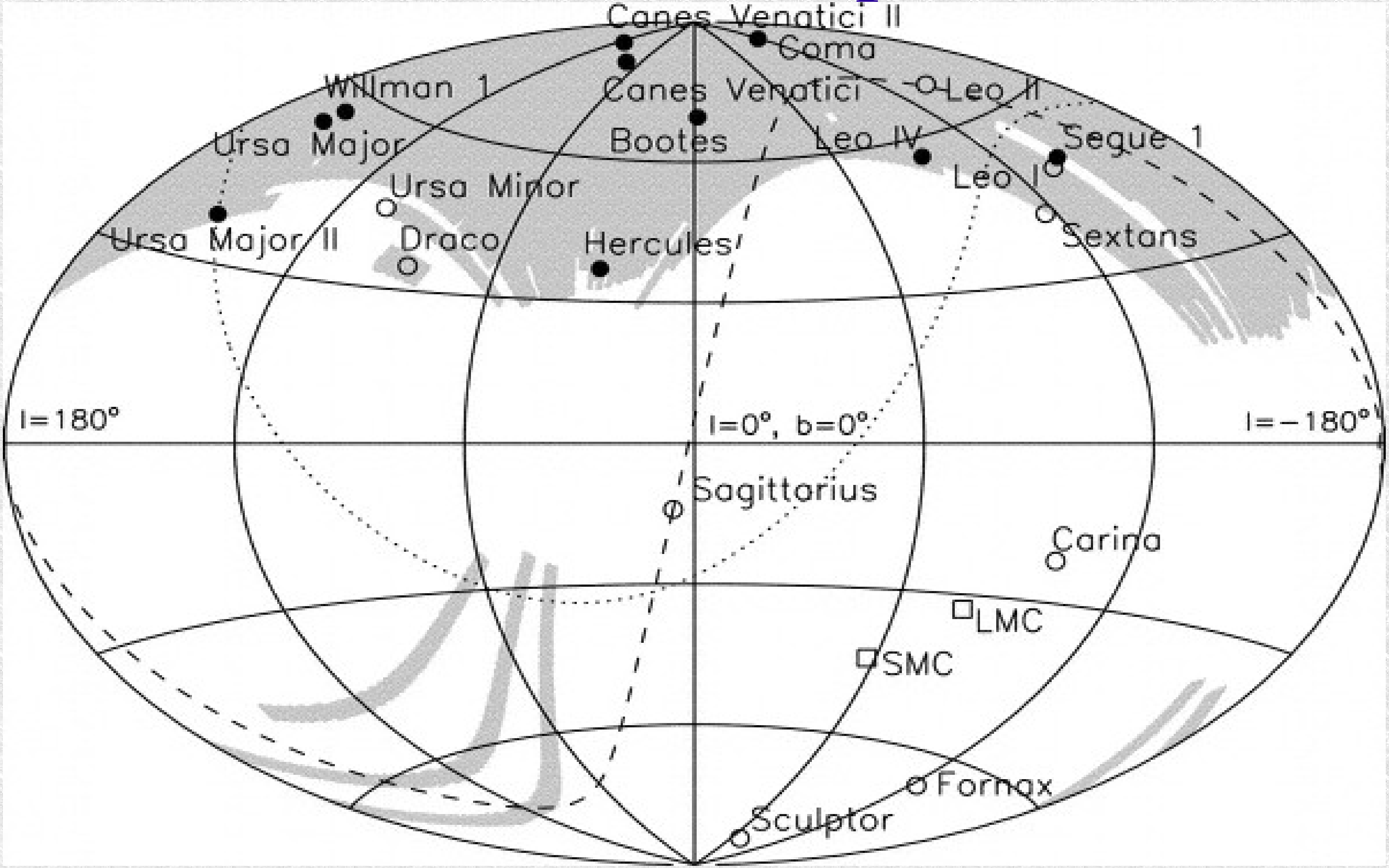
- Our Milky Way Galaxy – how was it formed?
- Evidence of accretion of smaller objects...
- Was this a dominant mechanism for the MW?
- How do we inquire?

Galaxy Formation Scenarios

- Monotonic Cloud Collapse (ELS Model)
- Merger/Accretion (SZ Model)
- Hierarchical Galaxy Formation (ΛCMD)

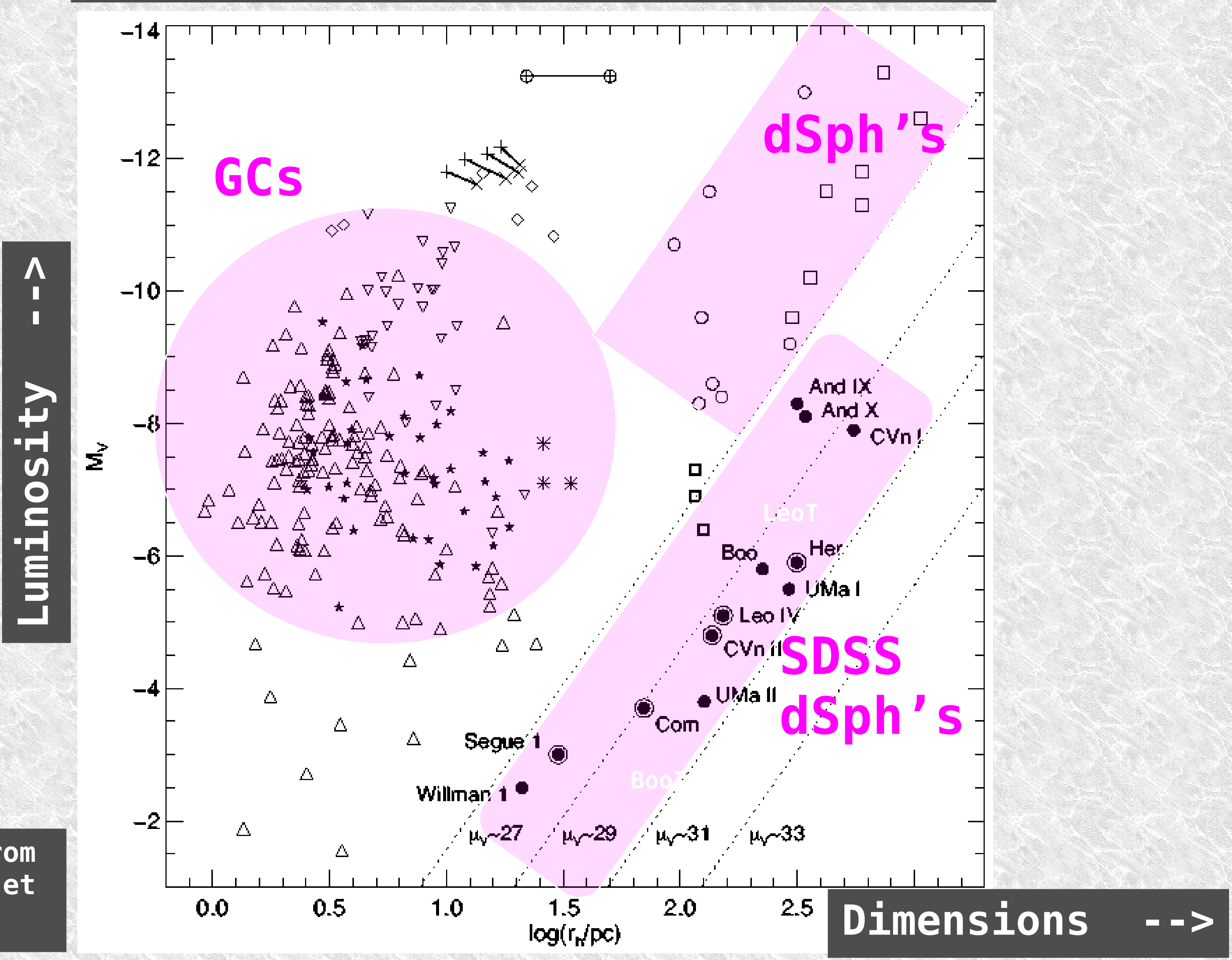


New SDSS Dwarf Spheroidal Galaxies (dSph)



Belokurov et al. 2007

Building blocks of the MW halo?



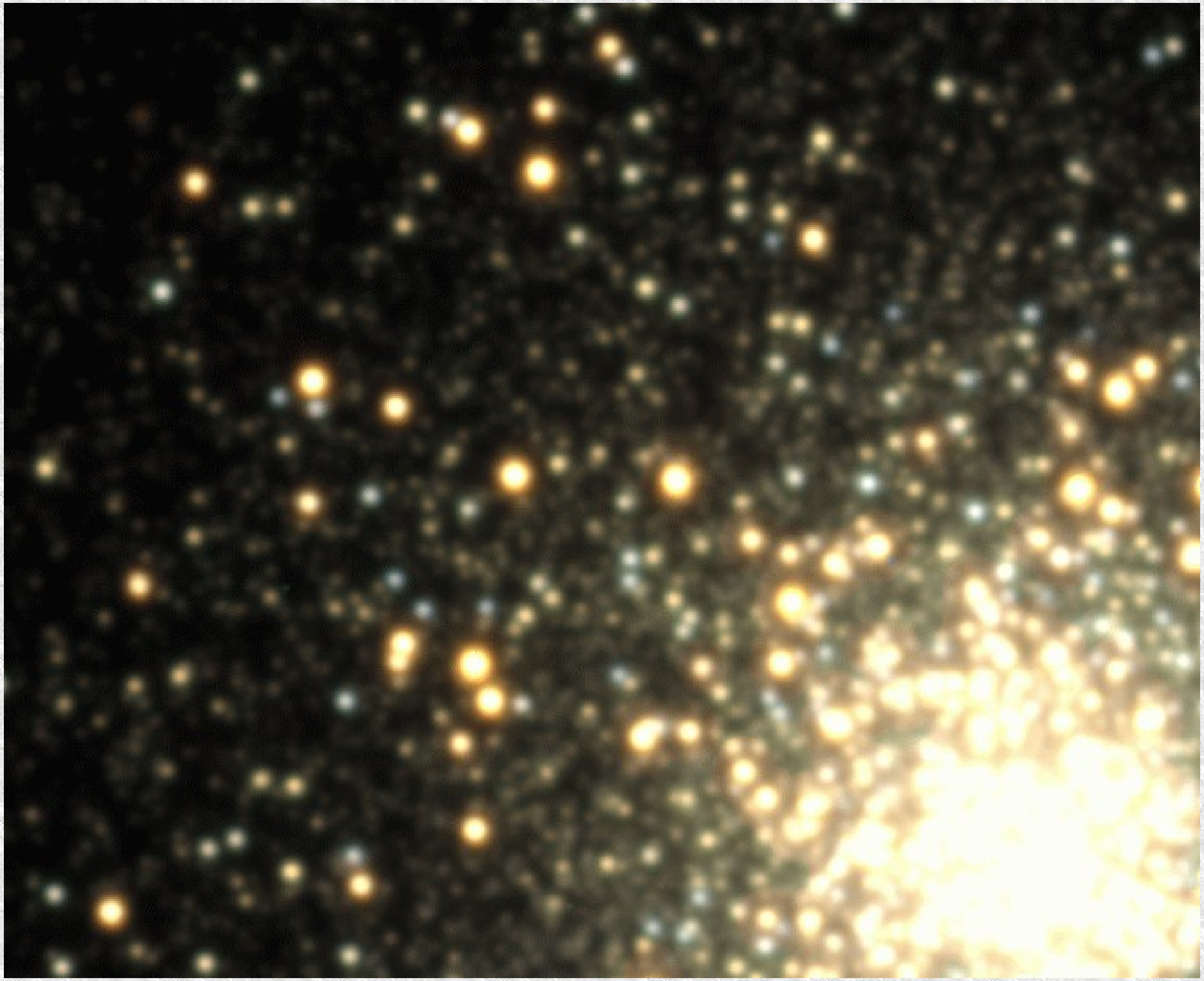
adapted from Belokurov et al. 2007

Eyewitnesses to Galaxy Formation?

The RR Lyrae variable stars, of course!

RR Lyrae Stars

- Old stellar population
- Intersection of the HB and IS
- Distance indicators
- Periodic variable stars
  - RRab
  - RRc
  - RRd

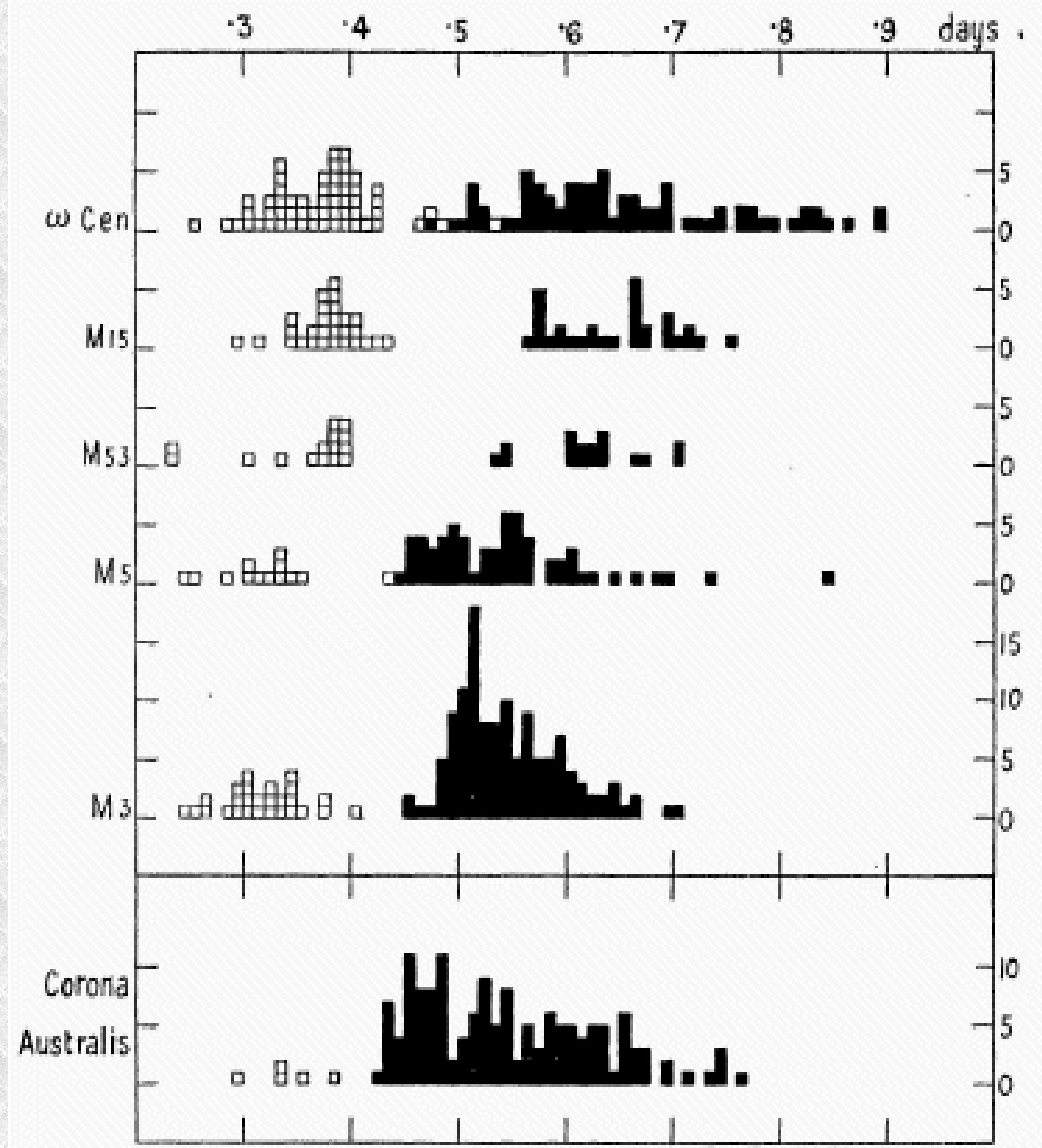


Oosterhoff Phenomenon/Dichotomy

- Empirical phenomenon based on RRL properties in MW GC
- period, number density, [Fe/H], kinematics

What Oosterhoff found in 1939...

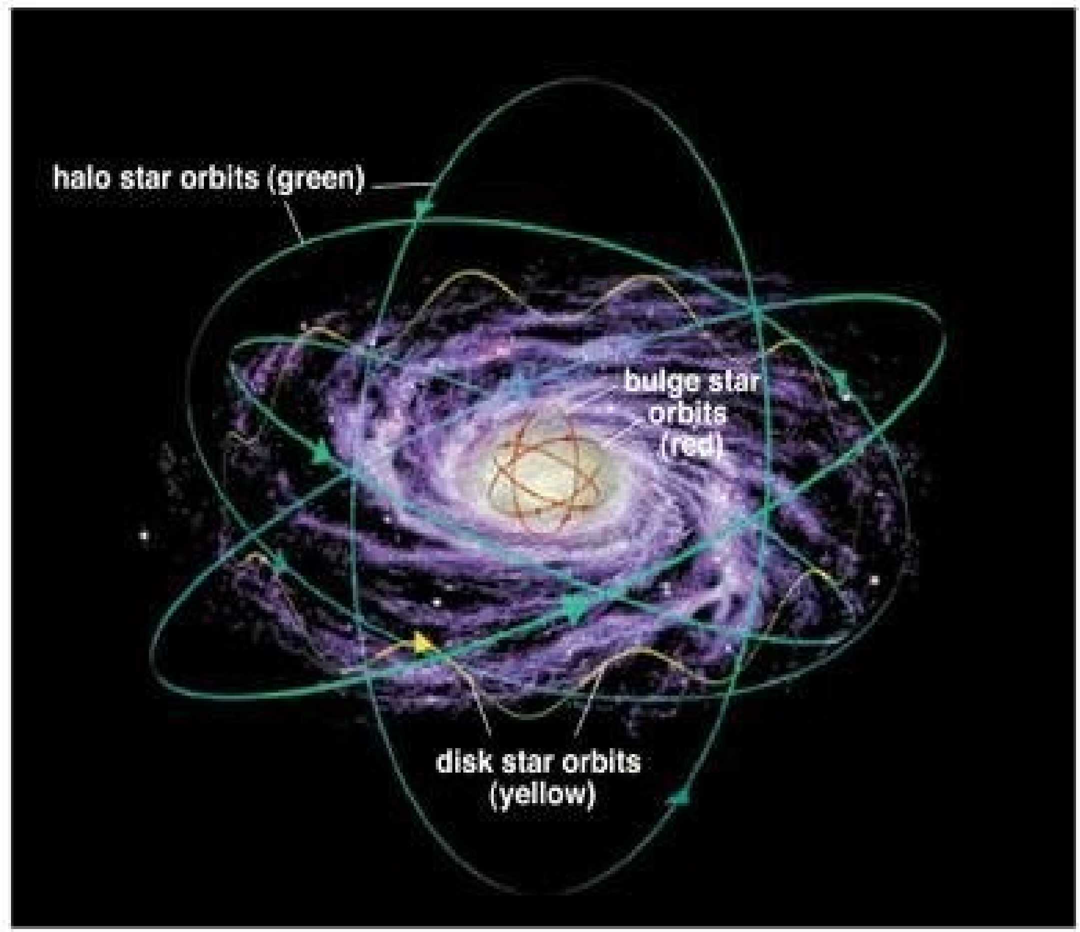
- Oosterhoff I Class:
  - $\langle P_{ab} \rangle = 0.55$d
  - $\langle P_c \rangle = 0.32$d
  - $N_c/N_{all} < 0.2$
  - [Fe/H] > -1.7
- Oosterhoff II Class
  - $\langle P_{ab} \rangle = 0.64$d
  - $\langle P_c \rangle = 0.37$d
  - $N_c/N_{all} > 0.3$
  - [Fe/H] < -1.7



Frequency distribution of periods of cluster variables.

What Carney & Lee found 60 years later...

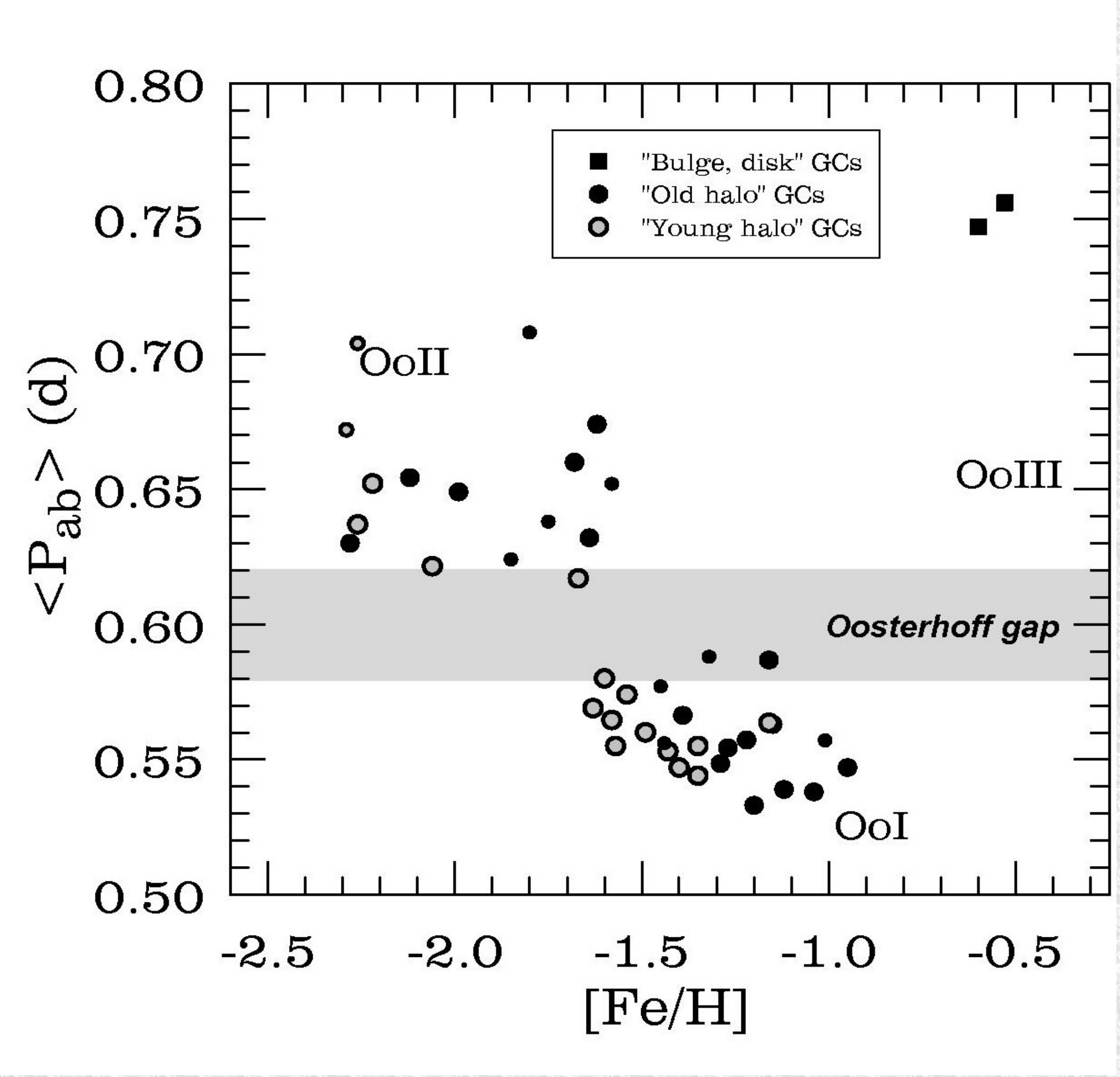
- Oosterhoff I = retrograde or net 0 motion (merger/accretion)
- Oosterhoff II = prograde motion (monatonic collapse)



Our picture of the MW globular clusters...

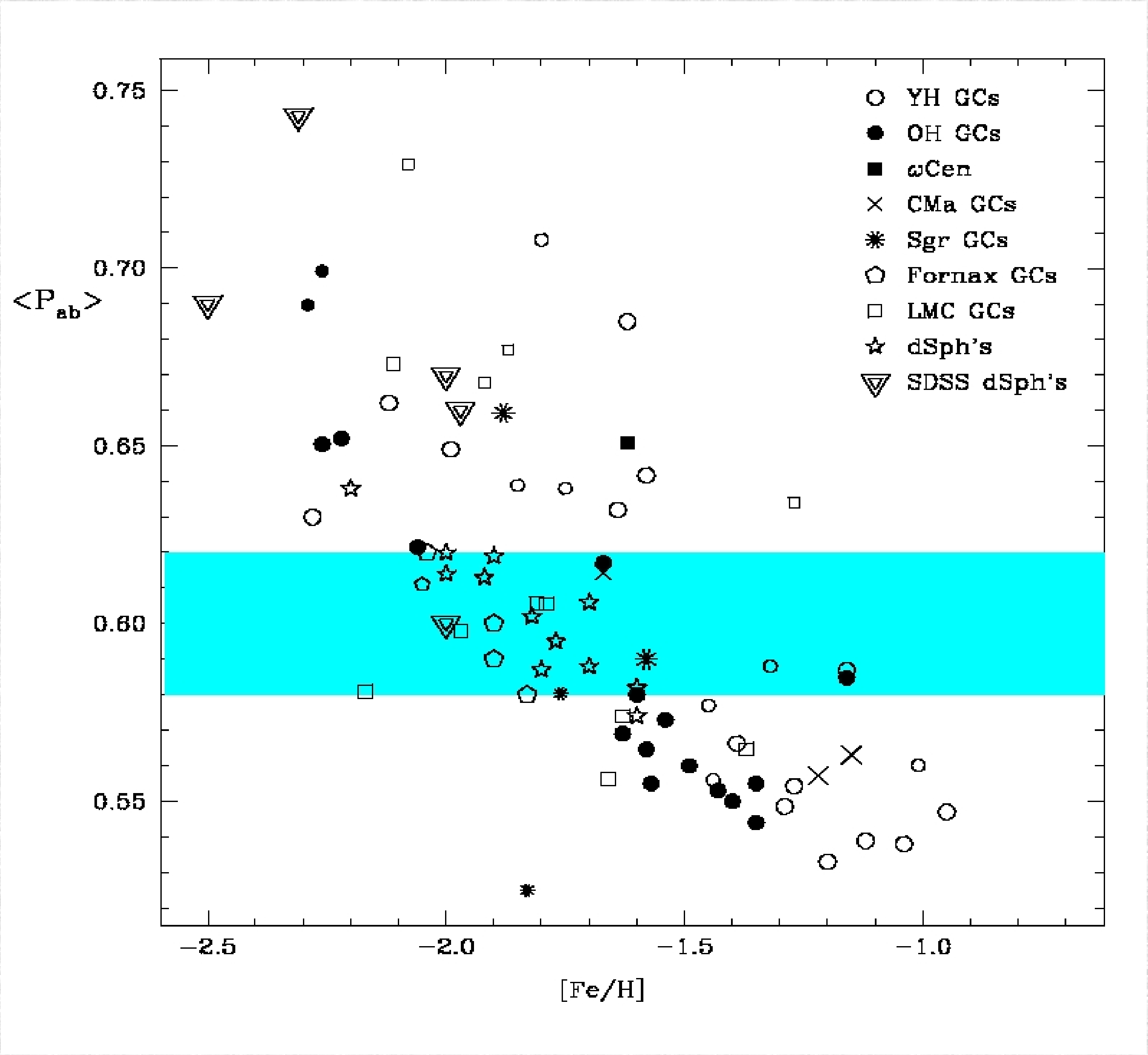
- Within the MW, GC separate into 2 groups
- "Oosterhoff Gap" is sparsely populated

Oosterhoff plane



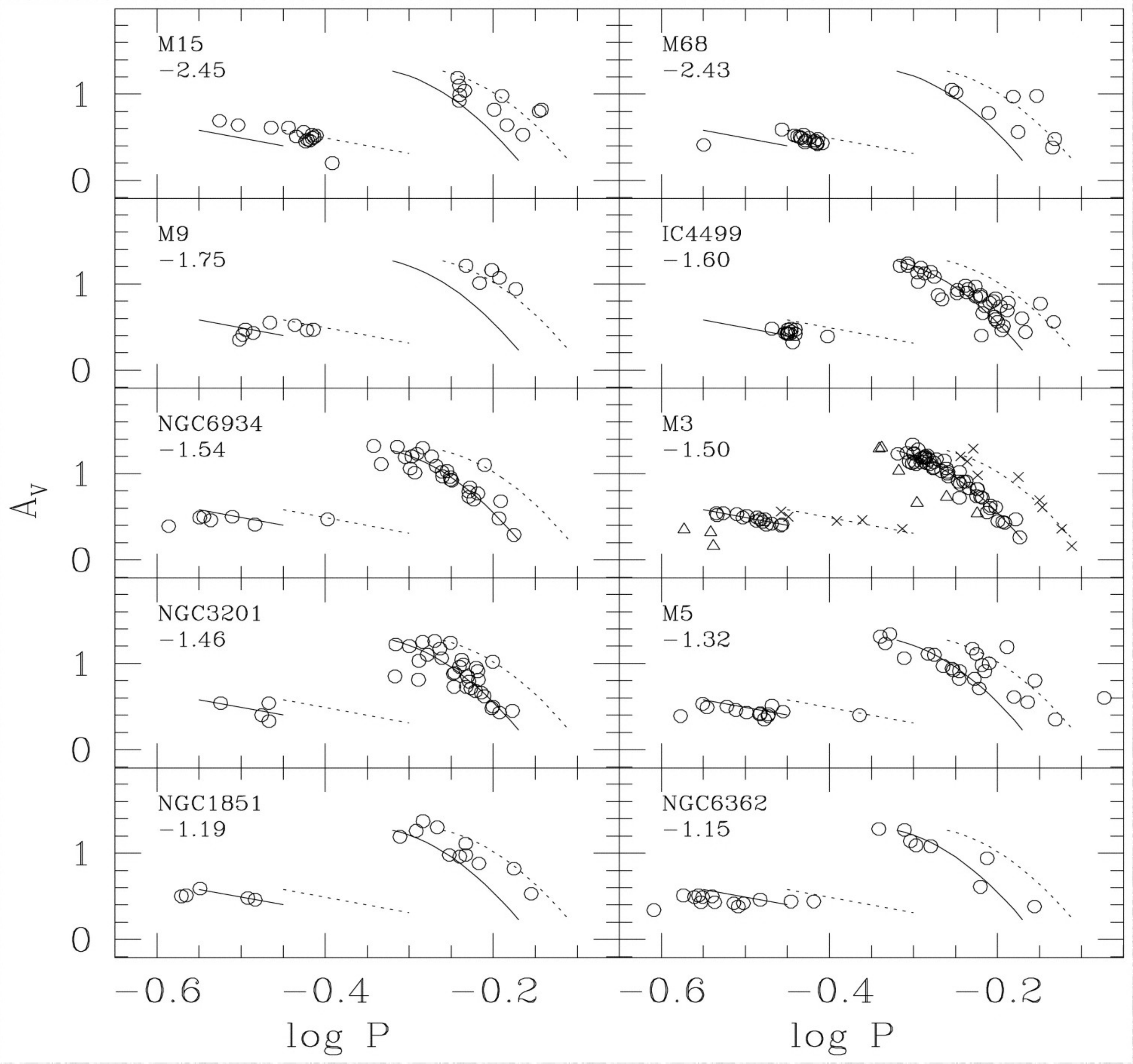
Catelan 2005

What our old neighbors tell us....



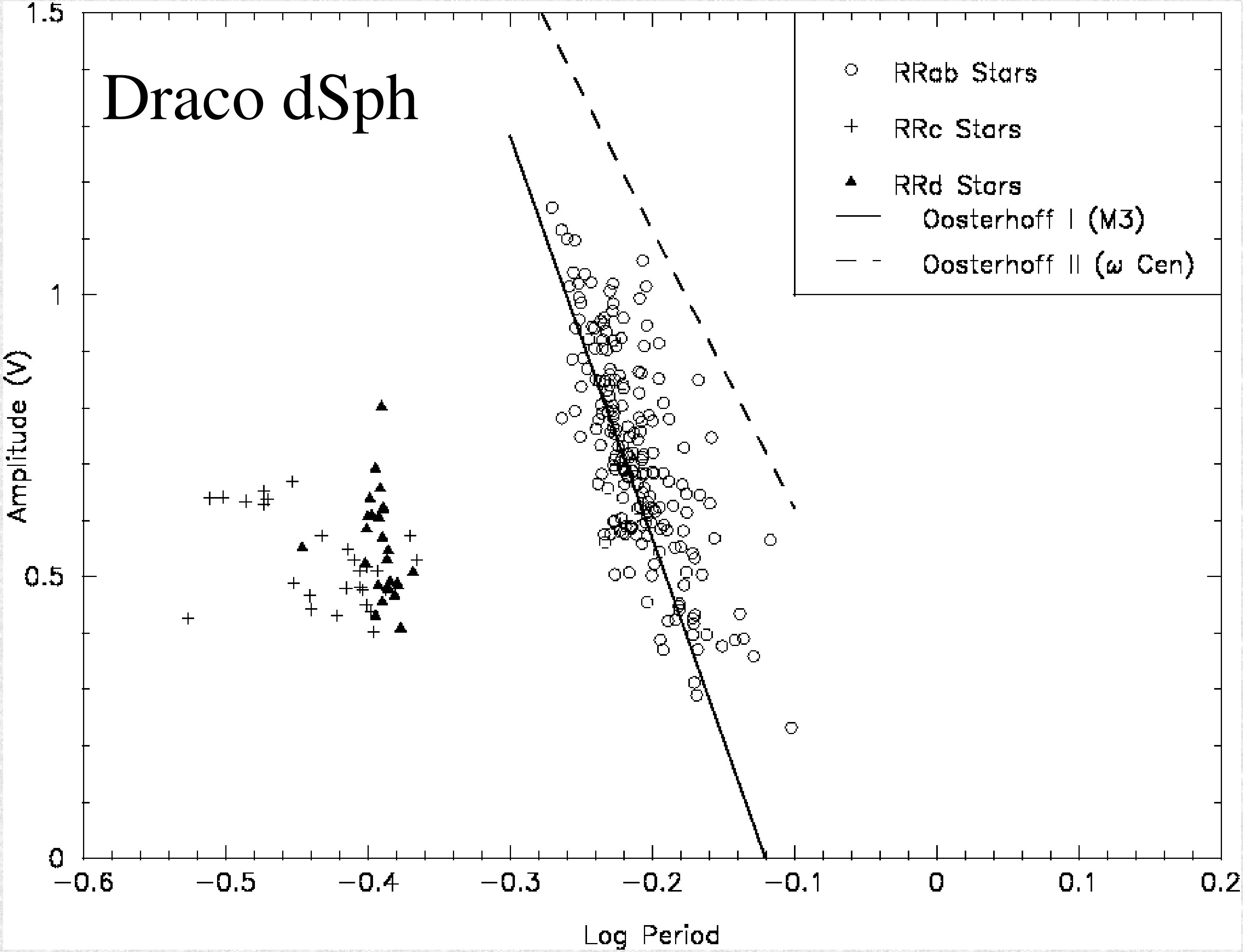
adapted from Catelan, Greco et al. 2007

Bailey Diagram



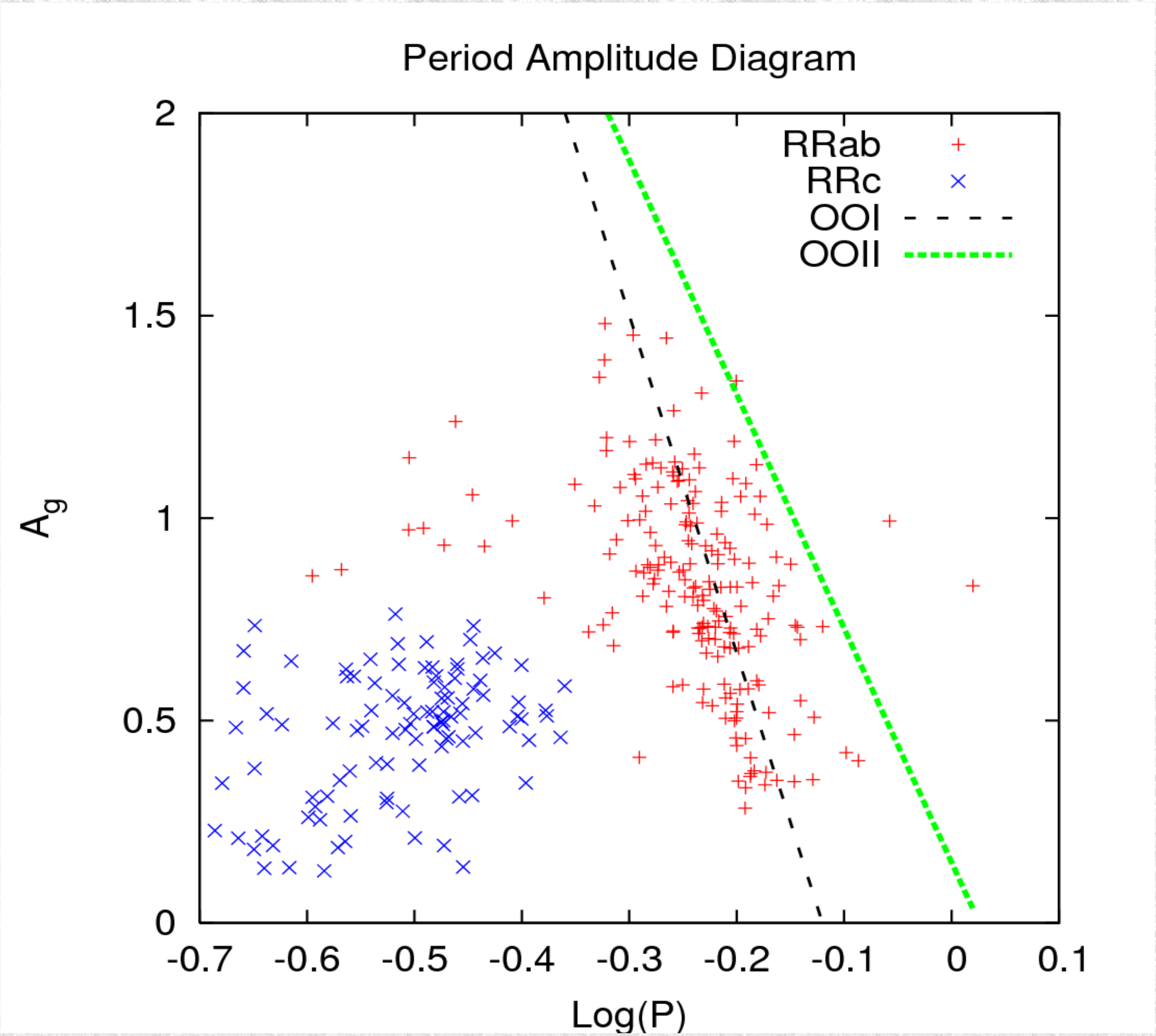
Cacciari, Corwin & Carney 2005

Caveat Emptor!



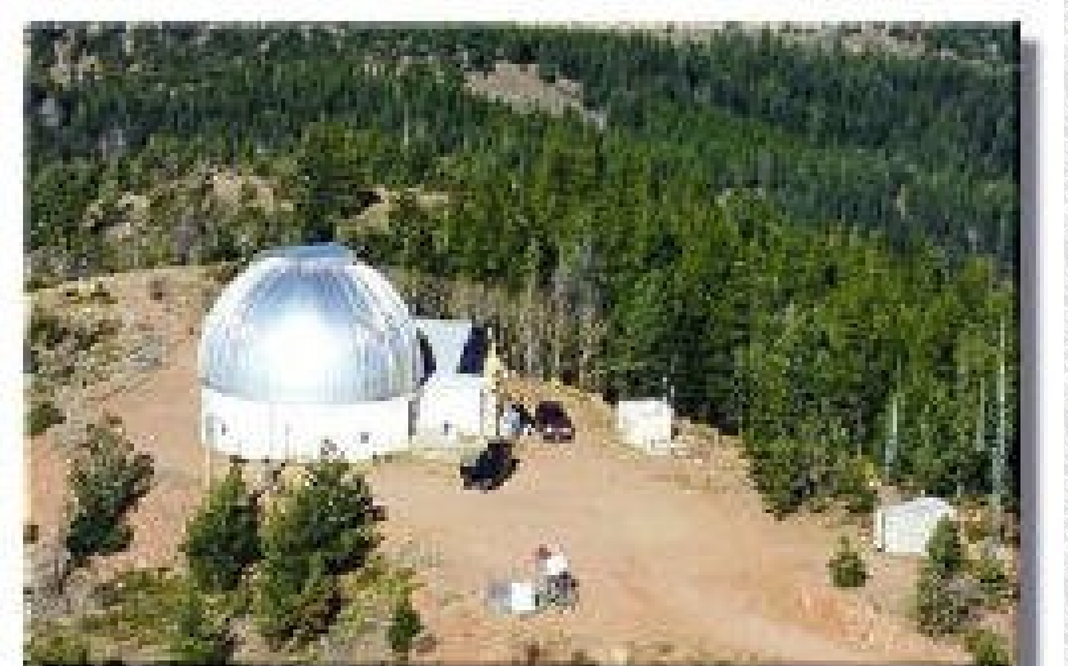
Kinemuchi et al. 2008

What about the Galactic Halo?



courtesy of N. Delee

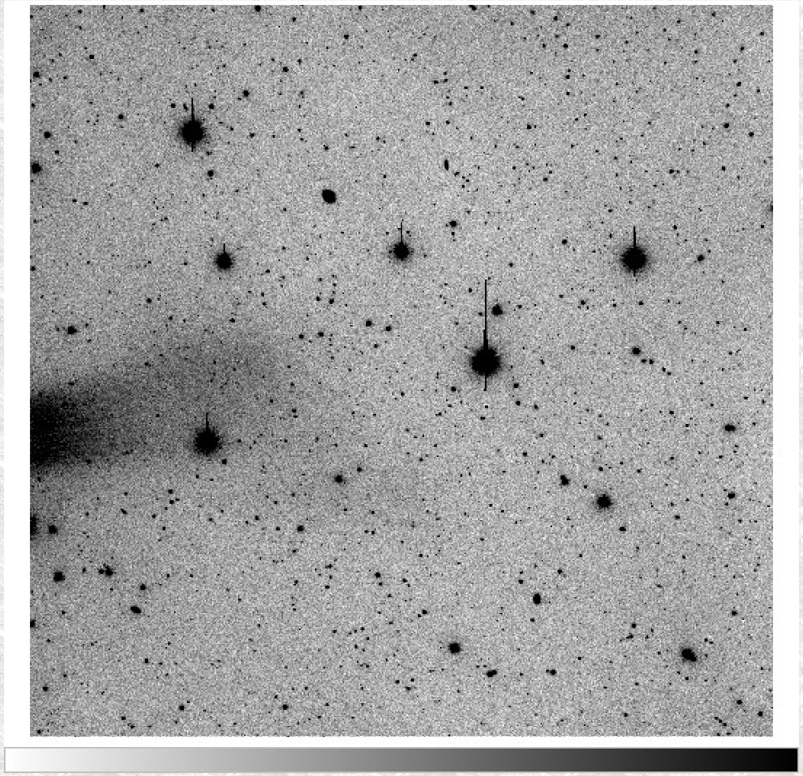
Our Observing Campaign



- Wyoming Infrared Observatory (WIRO 2.3m)
- WHT (4.2m)
- SOAR (4.2m)
- TNG (3.58m)
- INT (2.5m)
- ESO (2.2m)
- Lowell Observatory (1.8m)
- Loiano Observatory (1.5m)

Bootes dSph

Position: RA = 14:00:06 DEC= +14:30:00

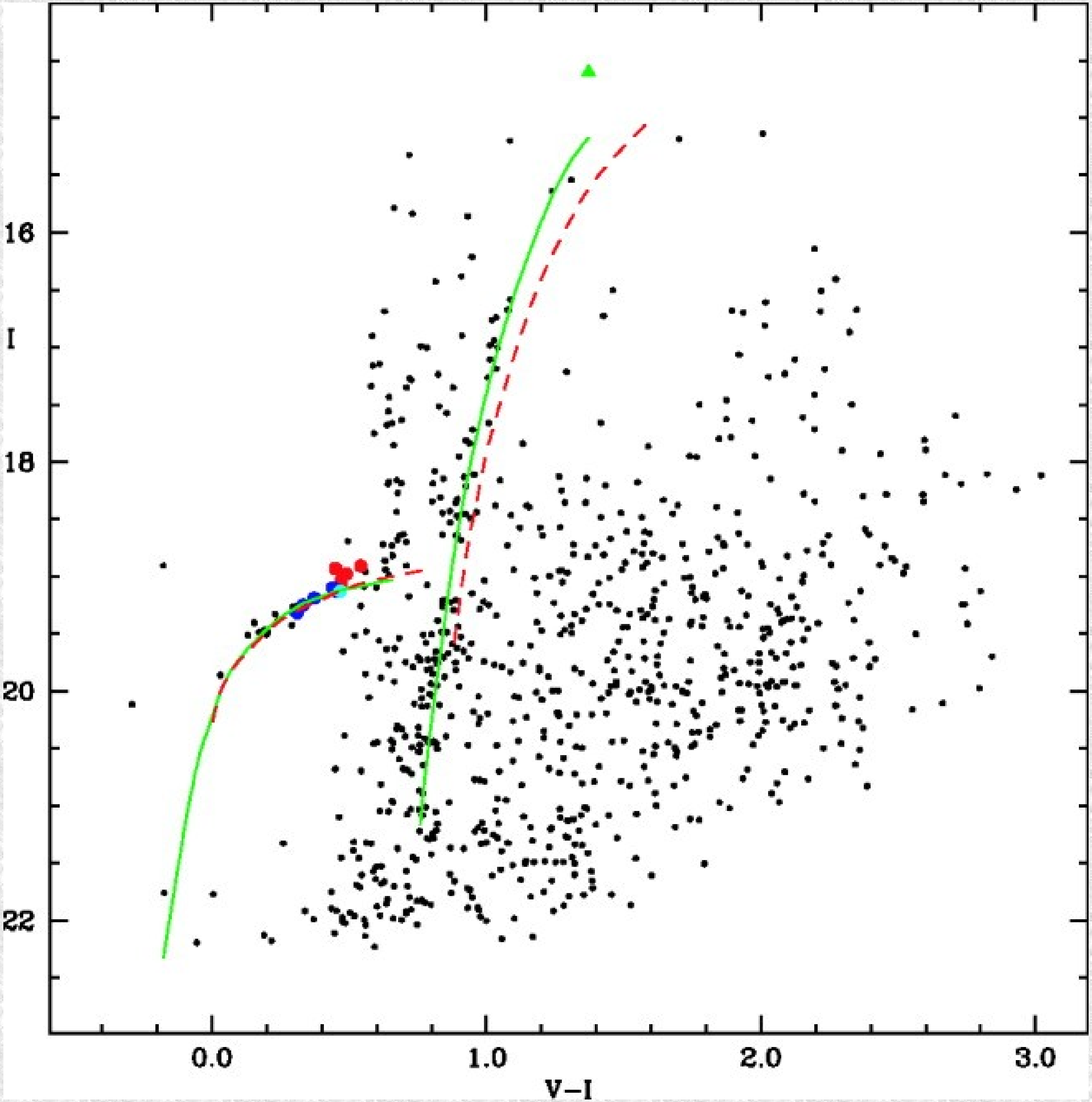


WIRO field

Ellipticity	0.33
R_h	13.0 ± 0.7
V_{tot}(mag)	13.6 ± 0.5 mag
[Fe/H]	-2.00 ± 0.07
$(m\text{-}M)_0$	18.9 ± 0.2 mag
Distance	60 ± 6 kpc
M_V	-5.8 ± 0.5 mag
μ_V	28.3 ± 0.5 mag/arcsec^2
M/L	130 – 680

Belokurov et al. 2006

Bootes CMD



Total 11 RRL

5 RRab

5 RRc

1 RRd

$<P_{ab}> = 0.64$ days

$<P_{c}> = 0.37$ days

1 long period var.

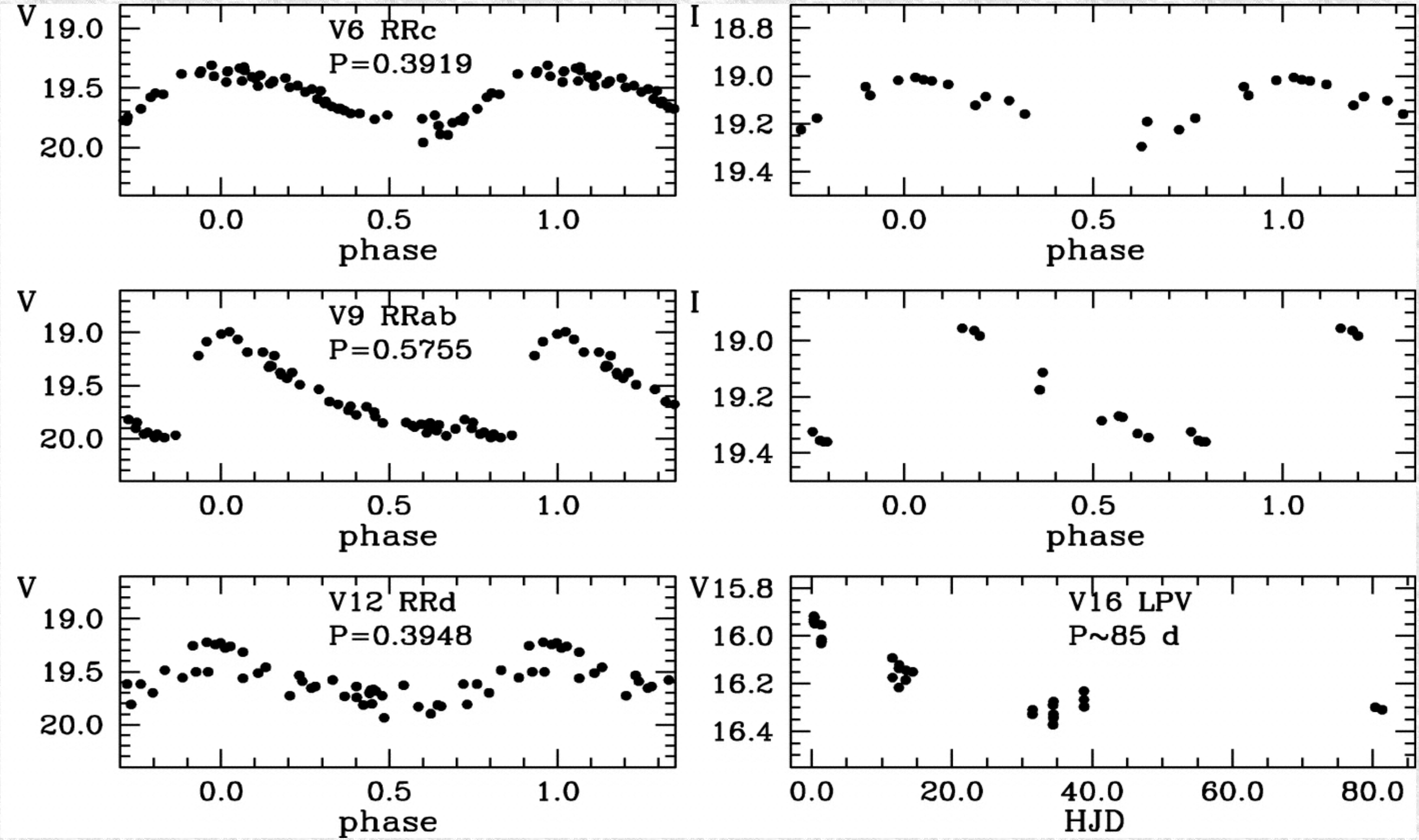
$\mu_0 = 19.11 \pm 0.08$ mag

$D = 66 \pm 6$ kpc

Dall'Ora et al. 2006

Siegel 2006

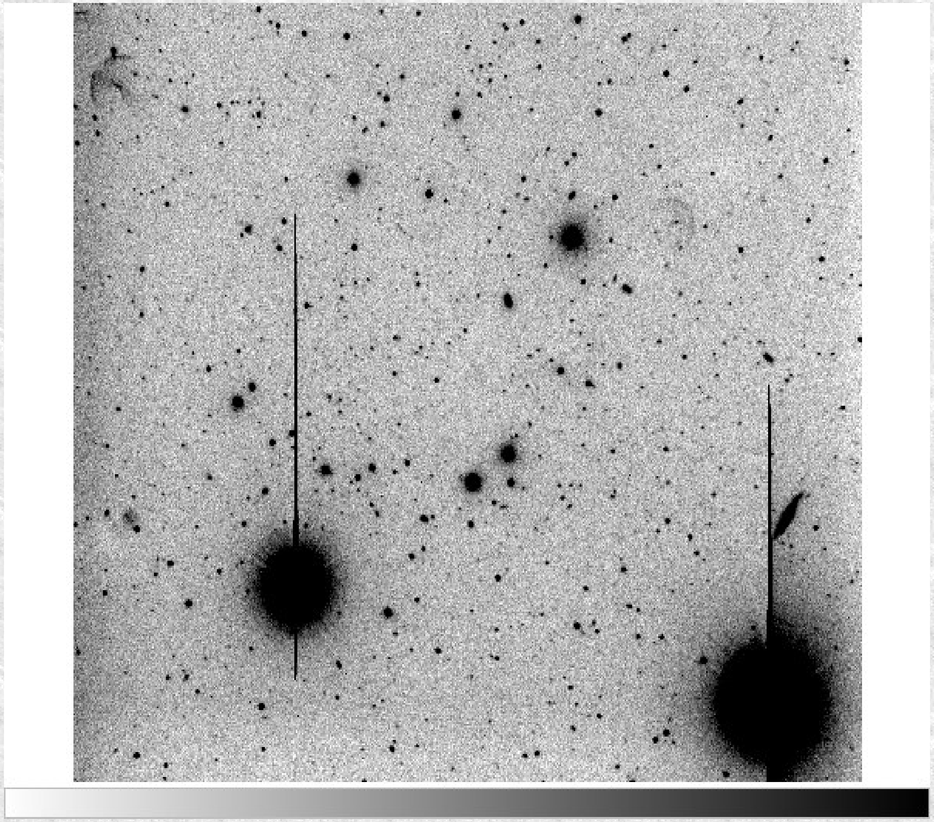
Bootes Variable Stars



Dall'Ora et al. 2006

Canes Venatici I dSph

Position: RA = 13:28:03 DEC= +33:33:21.0

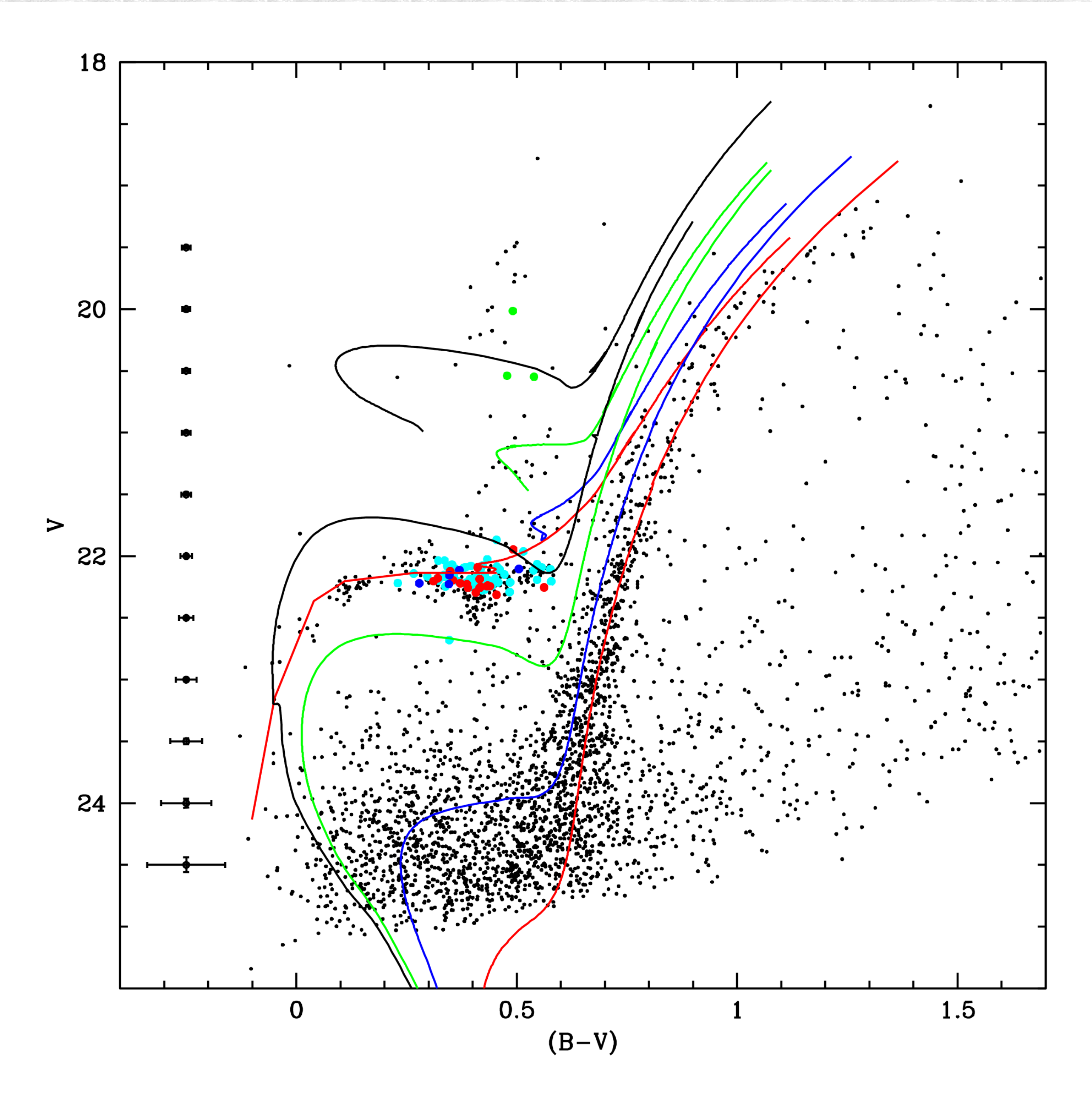


WIRO field

Ellipticity	0.38
R_h	8.5 ± 0.5
V_{tot}(mag)	13.9 ± 0.5 mag
[Fe/H]	-2.09 ± 0.02 dex
$(m-M)_0$	21.75 ± 0.2 mag
Distance	224 +22/-20 kpc
M_V	-7.9 ± 0.5 mag
μ_V	28.2 ± 0.5 mag/arcsec^2
M/L	221 ± 108

Zucker et al. 2006

CMD of CVn-I dSph



From Pisa isochrone dataset

13 Gyr

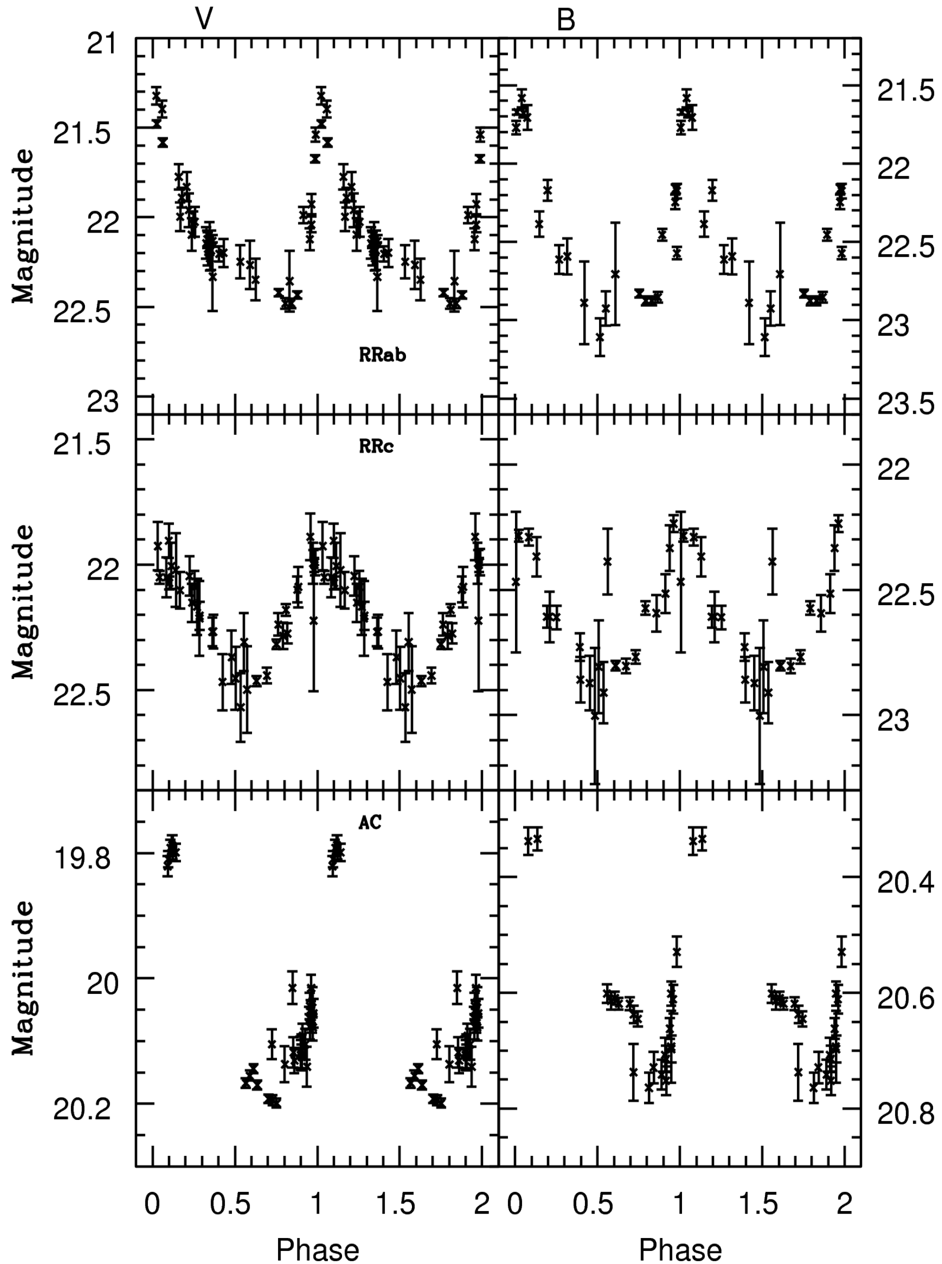
5 Gyr

1.5 Gyr

0.6 Gyr

Kuehn et al. 2008

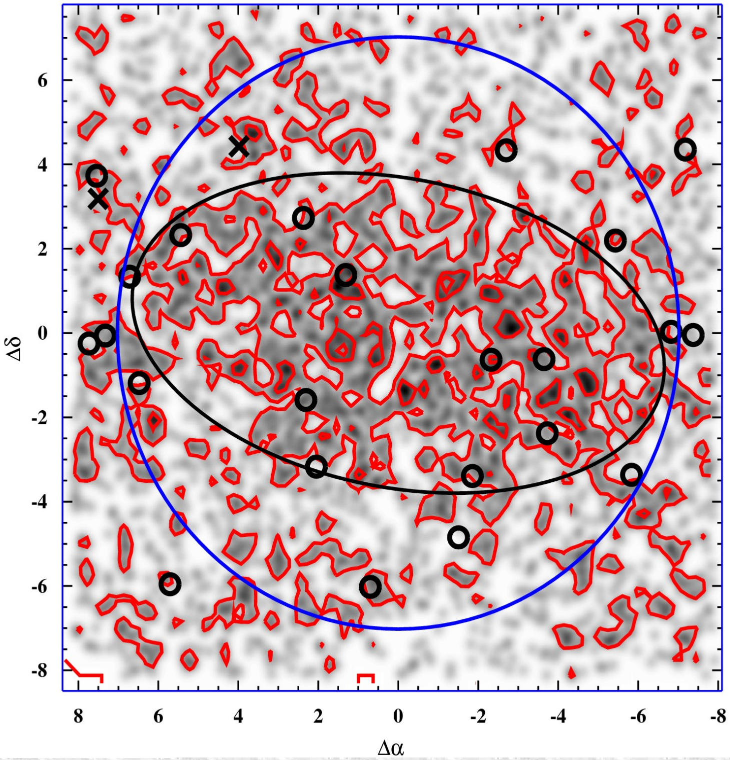
Variables in CVn-I



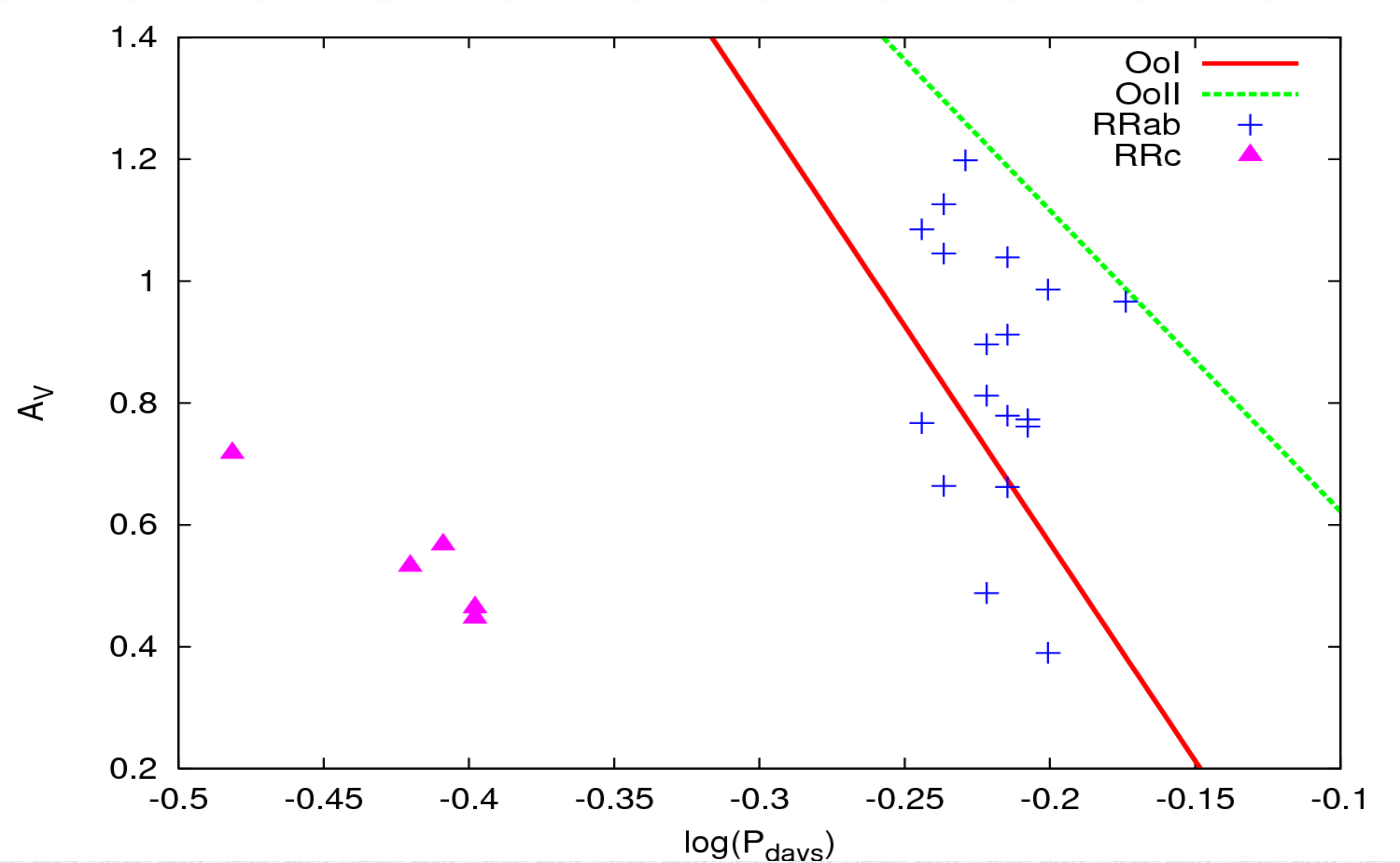
23 RRL (18 RRab)

3 anomalous Cepheids

84 candidate variables



Period-Amplitude Diagram

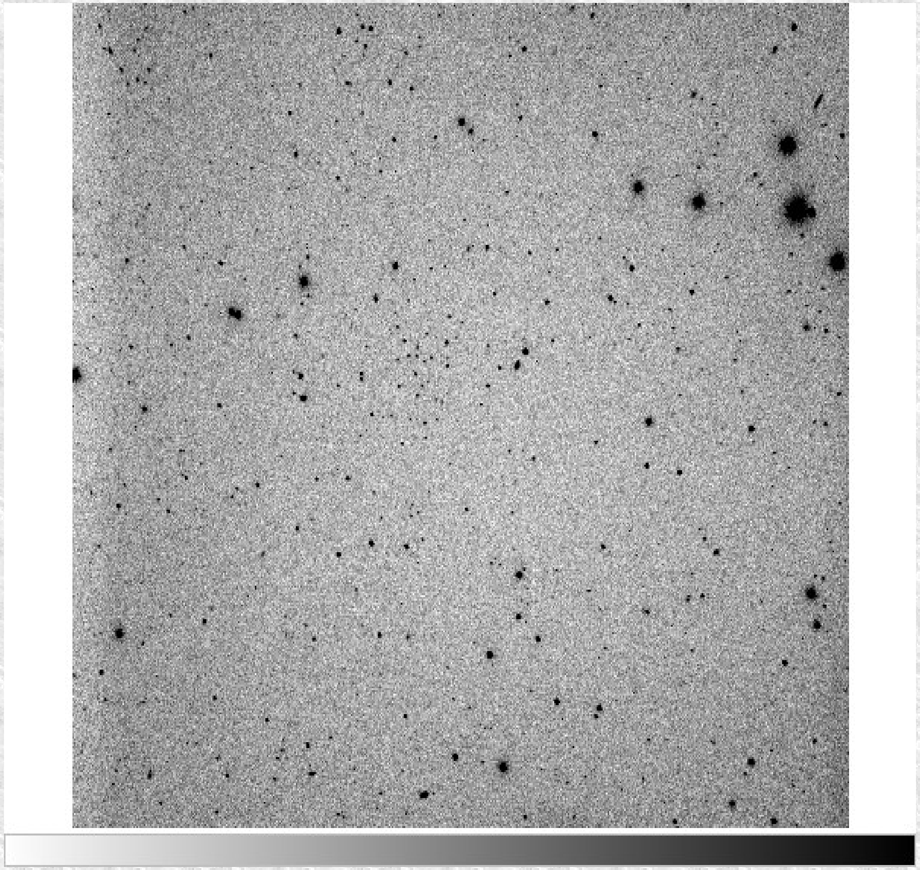


Kuehn et al. 2008

Canes Venatici II dSph

Position: RA = 12:57:10 DEC= +34:19:15

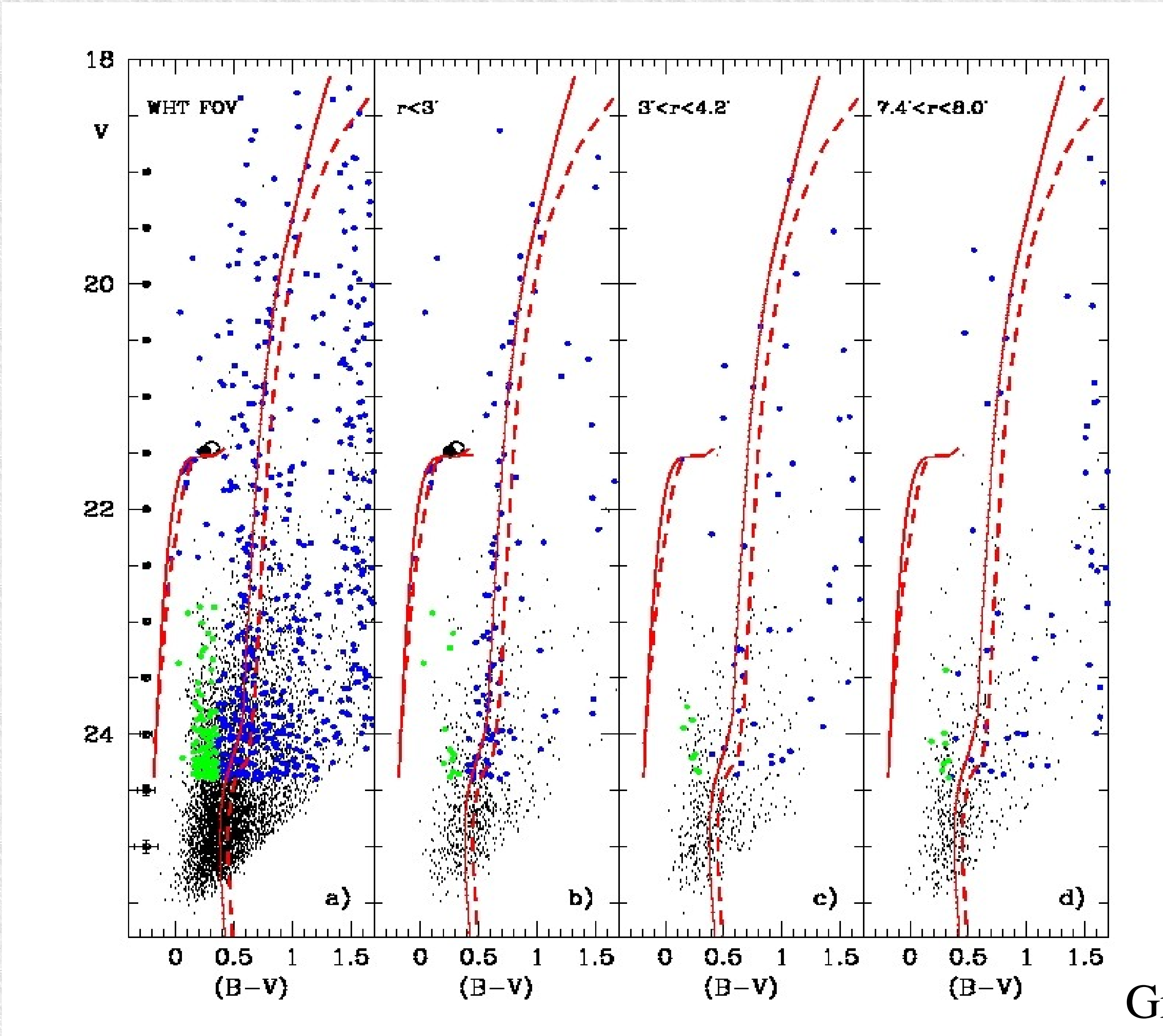
Ellipticity	0.3
R_h	3.0
V_{tot}(mag)	15.1 ± 0.5 mag
[Fe/H]	-2.31 ± 0.12 dex
$(m-M)_0$	20.9 ± 0.2 mag
Distance	151 +15/-13 kpc
M_V	-4.8 ± 0.6 mag
μ_V	29.5 mag/arcsec^2
M/L	336 ± 240



WIRO field

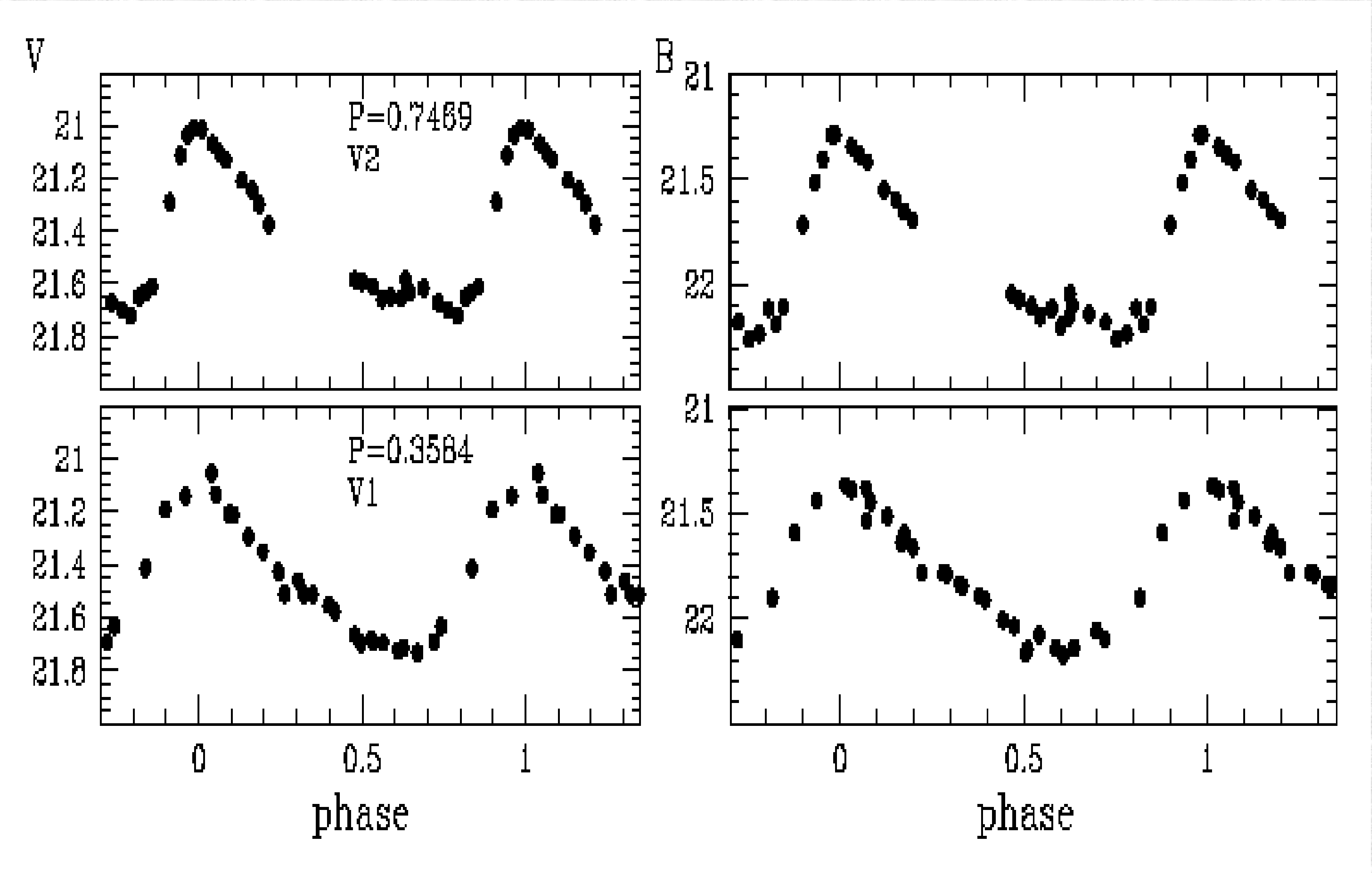
Belokurov et al. 2007

CMD of CVn-II



Greco et al. 2008

Variables of CVn-II



RRab

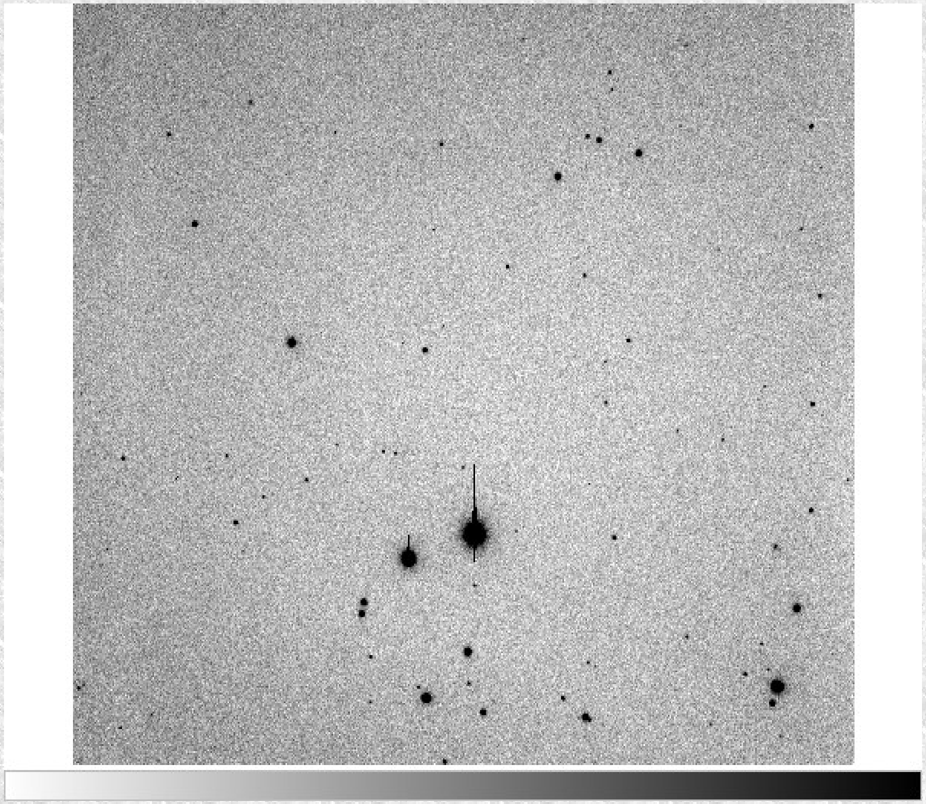
RRc

Greco et al. 2008

Coma dSph

Position: RA = 12:26:59 DEC= +23:54:15

Ellipticity	0.5
R_h	5.0
V_{tot}(mag)	15.1 ± 0.5 mag
[Fe/H]	-2.00 ± 0.07 dex
$(m-M)_0$	18.2 ± 0.2 mag
Distance	44 ± 4 kpc
M_V	-3.7 ± 0.6 mag
μ_V	29.0 mag/arcsec^2
M/L	448 ± 297



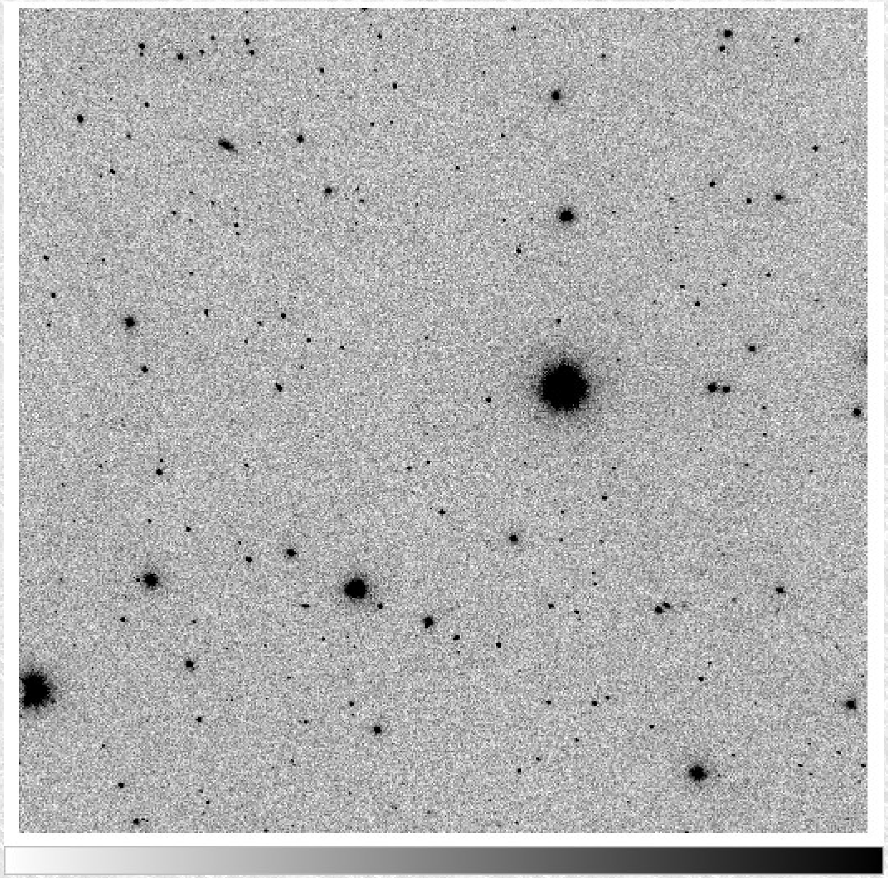
WIRO field

Belokurov et al. 2007

Ursa Majoris II dSph

Position: RA = 8:51:30 DEC= +63:07:48

Ellipticity	0.5
R_h	13.6
V_{tot}(mag)	14.3 ± 0.5 mag
[Fe/H]	-1.97 ± 0.15 dex
$(m\text{-}M)_0$	17.5 ± 0.3 mag
Distance	32 +5/-4 kpc
M_V	-3.8 ± 0.6 mag
μ_V	30.0 mag/arcsec^2
M/L	1722 ± 1226



WIRO field

Zucker et al. 2006

What the new dSph RRL tell us....

Oosterhoff Classes

Oo I ($P_{ab} = 0.55^d$, $P_c = 0.32^d$)

Oo II ($P_{ab} = 0.64^d$, $P_c = 0.37^d$)

Bootes: $<P_{ab}> = 0.64^d$, $<P_c> = 0.37^d$ 11 RRL Oo II

CVn-I : $<P_{ab}> = 0.60^d$, $<P_c> = 0.38^d$ 23 RRL Oo-Int

CVn-II: $P_{ab} = 0.743^d$, $P_c = 0.358^d$ 2 RRL

Coma: $P_{ab} = 0.67^d$, $P_c = 0.32^d$ 2 RRL

UMa-II: $P_{ab} = 0.66^d$ 1 RRL

Comparison with known dSphs....

- UMi : P~0.638, N=0.43 Oo II
- Draco :P~0.616, N= 0.17 Oo-Int/OoI
- Carina: P~0.631, N=0.22 OoII/Oo-Int
- Fornax: P~0.585, N = 0.23 Oo-Int
- Leo I: P~0.602, N=0.13 Oo-Int/OoI
- Leo II: P~0.619, N=0.24 Oo-Int
- Sagittarius: P~0.574, N=0.20 OoI
- Sculptor: P~0.585, N=0.40 Oo-Int/OoII
- Sextans:P~0.606, N=0.21 Oo-Int

Dall'Ora et al. 2003, Kinemuchi et al. 2008

What does this mean??

- Not conclusive with Oosterhoff classification for 3 of 5 SDSS dSph galaxies
- In terms of outer halo Galactic formation – most likely not objects like currently known dSph galaxies
- However, we have evidence that dSphs are crashing into our Galaxy, as well as in M31!

Future Work

- Gathering follow-up photometry on 4 of 5 dSph galaxies
  - classification and phase coverage of the variables
  - photometry in the U band for chemical evolution studies
  - deeper CMDs for in depth study of stellar populations