RR Lyrae in LMC Globular Clusters: Insights into the Oosterhoff Phenomenon and Milky Way Formation

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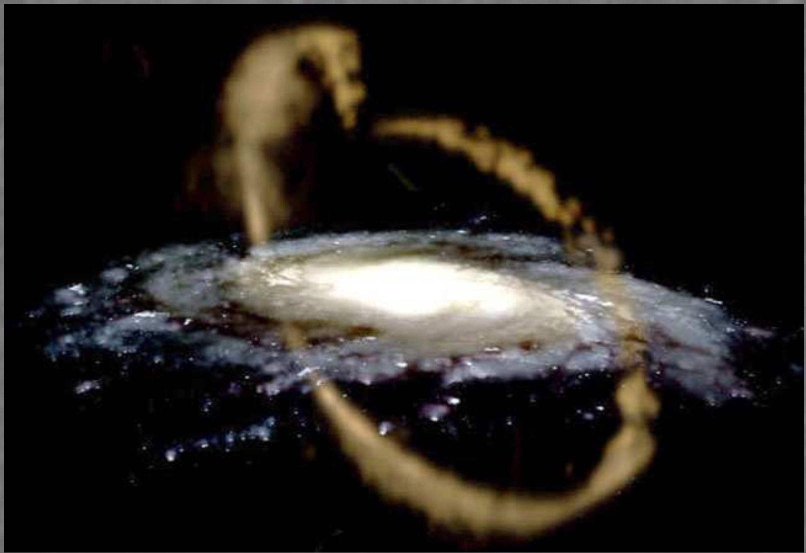
Galaxy formation mechanisms

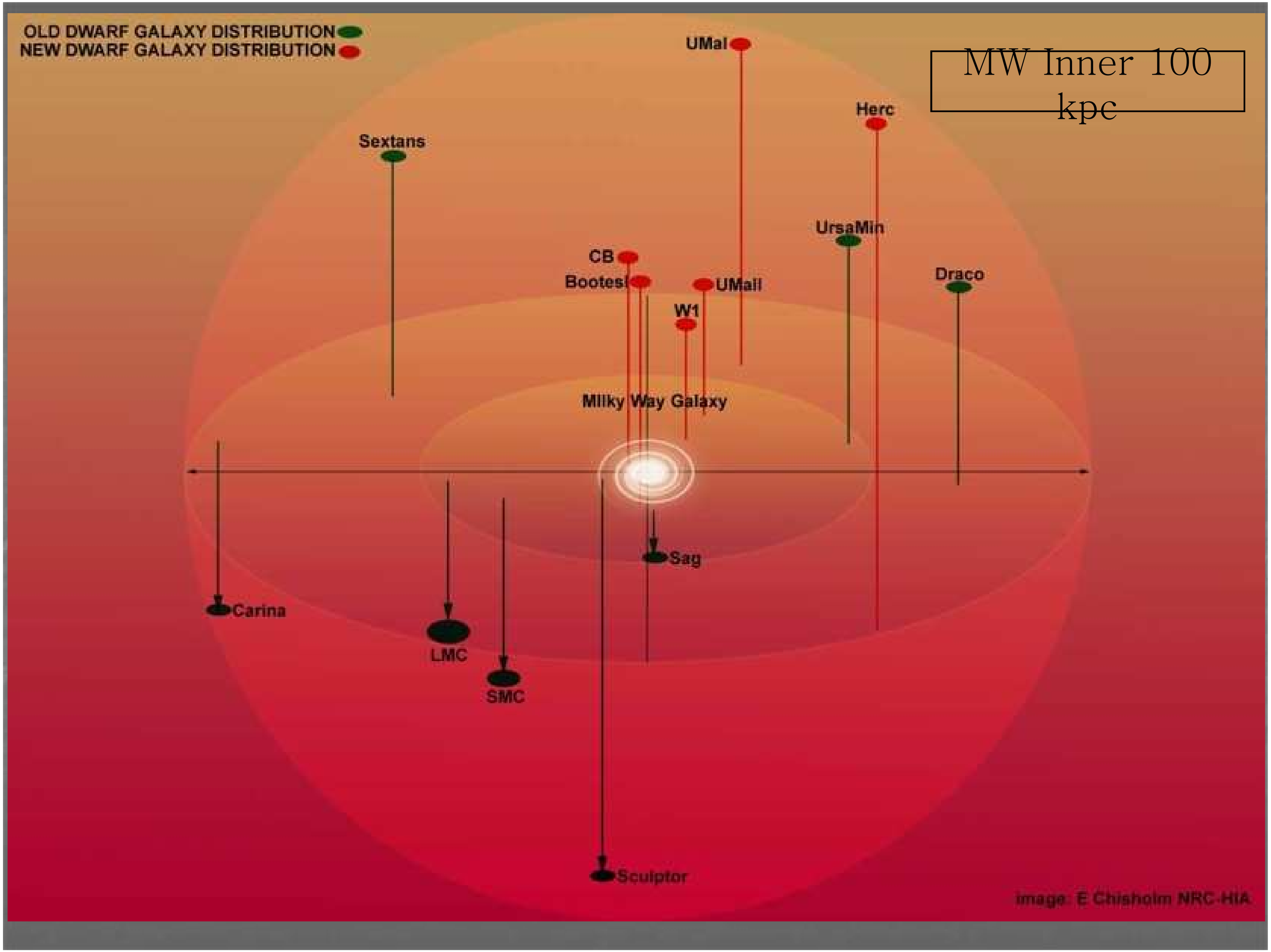
- Cloud collapse
- Merging



Many observational evidences of merging:

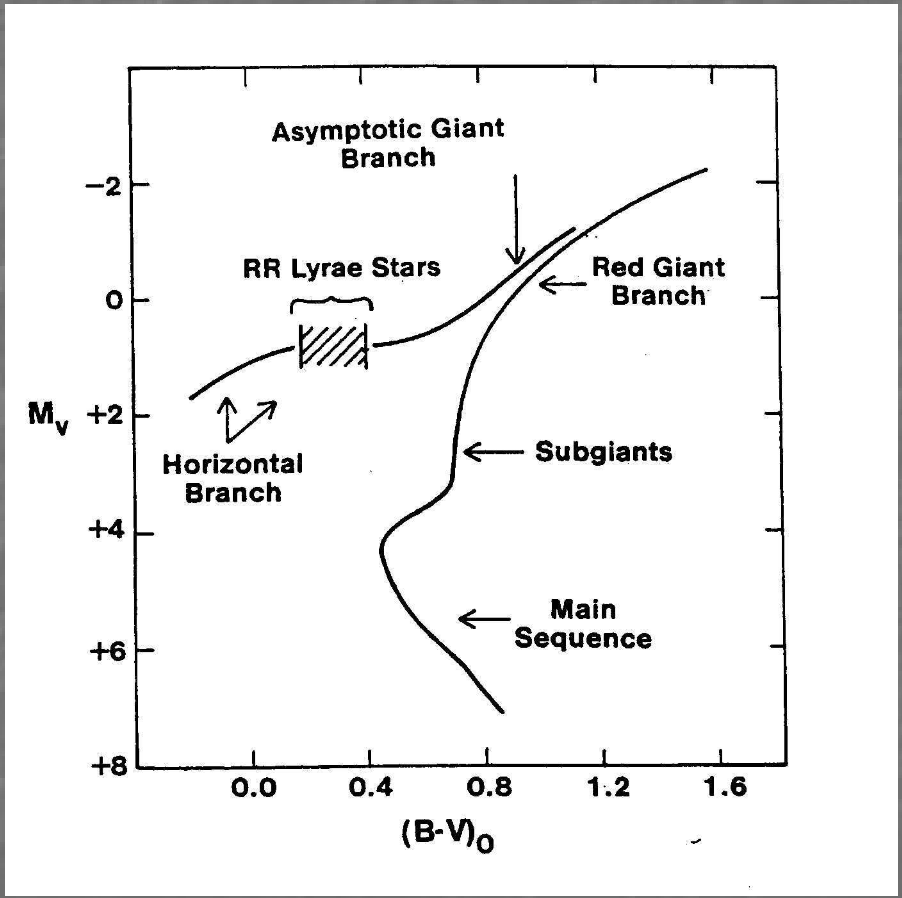
- Sag dSph
- CMa dSph

- Substructures in the M31 halo


OLD DWARF GALAXY DISTRIBUTION
NEW DWARF GALAXY DISTRIBUTION
MW Inner 100 kpc
UMaI
Herc
Sextans
UrsaMin
CB
BootesI
UMaII
Draco
W1
Milky Way Galaxy
Sag
Carina
LMC
SMC
Sculptor
image: E Chisholm NRC-HIA

RR Lyrae

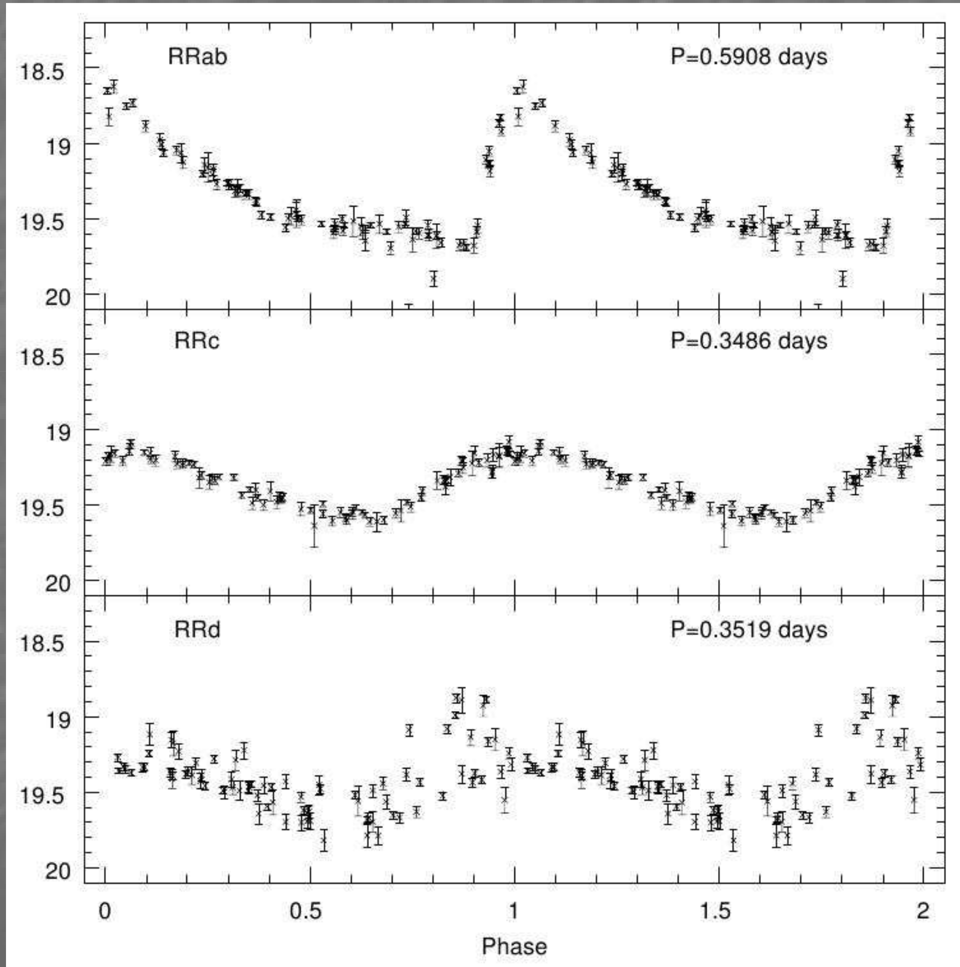
- Old Stars (> 10 Gyr)
- Horizontal branch stars that lie in the instability strip
- Burn He in core
- Intrinsically variable
- Radially pulsate
- Amplitude's between 0.1 and 1 magnitudes
- Periods less than a day



(Smith 1995)

Bailey Types

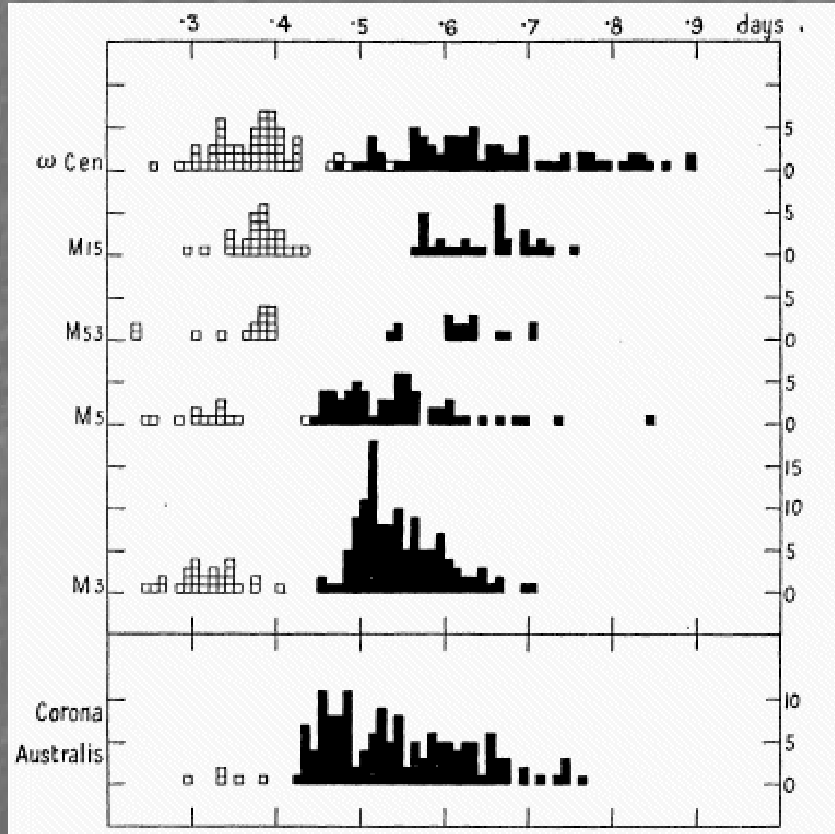
- Based on shape of light curve
- RRab pulsate in the fundamental mode
- RRc pulsate in the first overtone
- RRd stars pulsate in a combination of the fundamental mode & the first overtone



Oosterhoff Groups

- In 1939 Oosterhoff noticed a division in the properties of globular cluster RR Lyraes

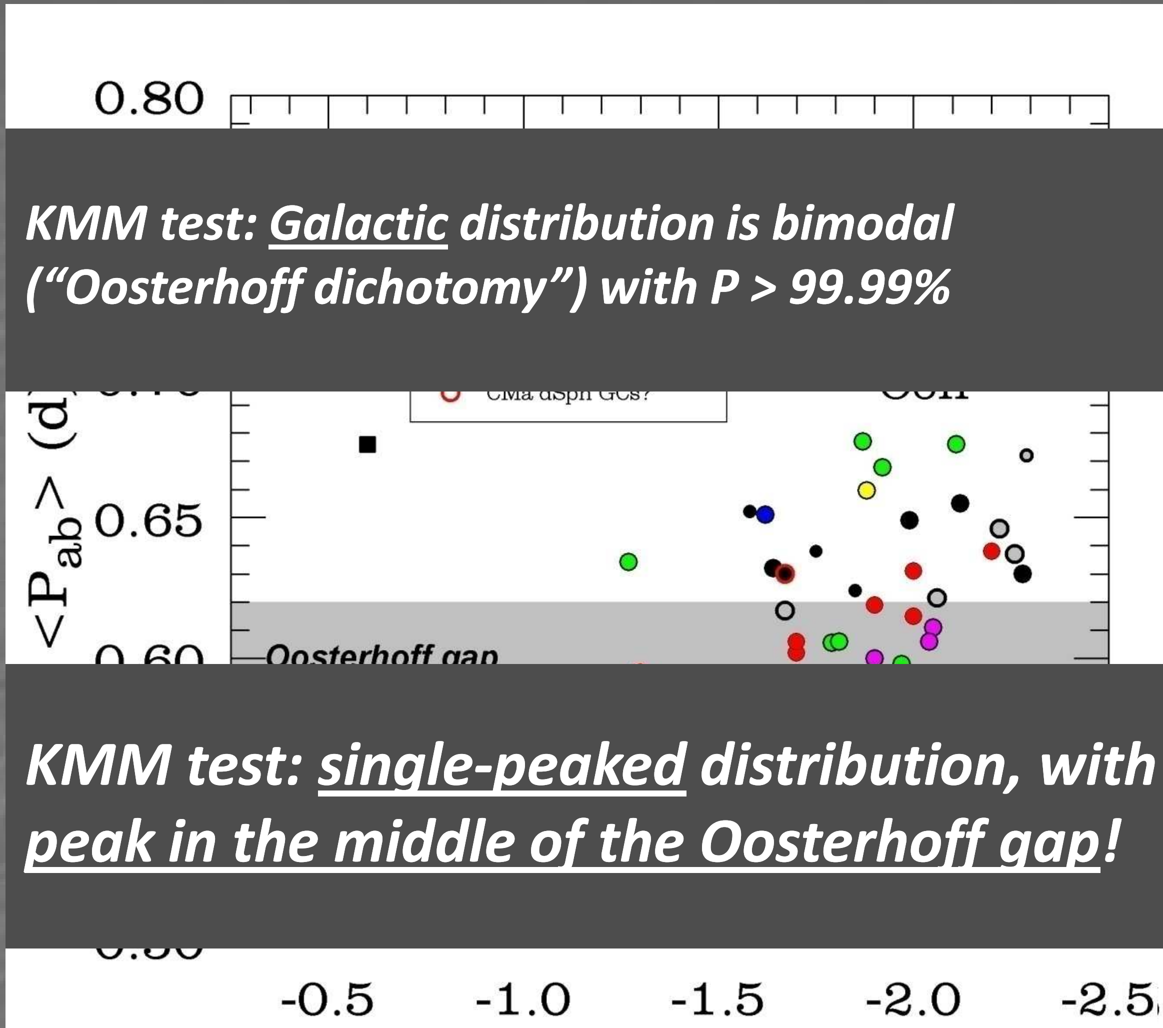
	OOI	OOII
$\langle P_{ab} \rangle$	.55d	.65d
$\langle P_c \rangle$	.32d	.37d
N_{RRc}/N_{total}	.17	.44
[Fe/H]	>-1.7	<-1.7



Frequency distribution of periods of cluster variables.

(Oosterhoff 1939)

The Oosterhoff dichotomy poses strong constraints on the Galaxy's early history:



KMM test: Galactic distribution is bimodal ("Oosterhoff dichotomy") with P > 99.99%

KMM test: single-peaked distribution, with peak in the middle of the Oosterhoff gap!

The Galaxy is unlikely to have formed early on by accretion of protogalactic fragments resembling the early counterparts of its present-day dwarf satellite galaxies.

Oo-Intermediate Milky Way

Old halo	**2/24**
Young halo	**2/17**
Bulge/disk	**0/02**
TOTAL	**4/43**

9.3%

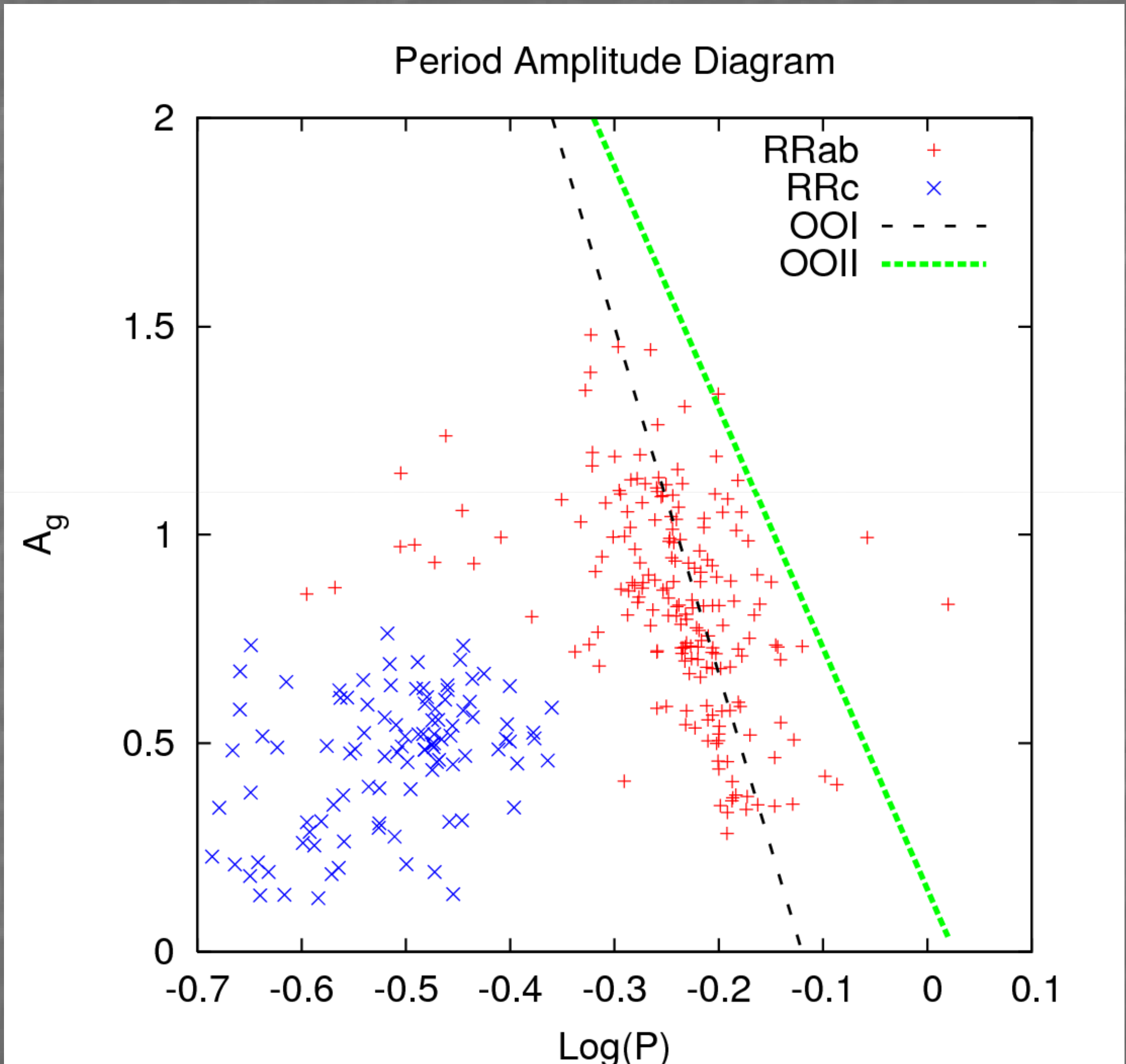
Oo-Intermediate "External"

ω Cen	**0/01**
LMC GCs	**4/12**
dSph, MCs	**8/11**
For GCs	**3/05**
Sag GCs	**2/04**
CMa GCs	**0/03**
TOTAL	**17/36**

47.2%

Catelan 2009, Ap&SS

Field Stars in the Milky Way Halo



- The majority of the RRab stars fall along the Oosterhoff I line.

(Courtesy of N. DeLee)

Understanding the Oosterhoff dichotomy

- Conduct a systematic study of the behavior of RR Lyrae stars in Oosterhoff intermediate globular clusters

- How do the physical properties of RR Lyrae stars change when going from Oosterhoff-I/II clusters to Oosterhoff intermediate ones?

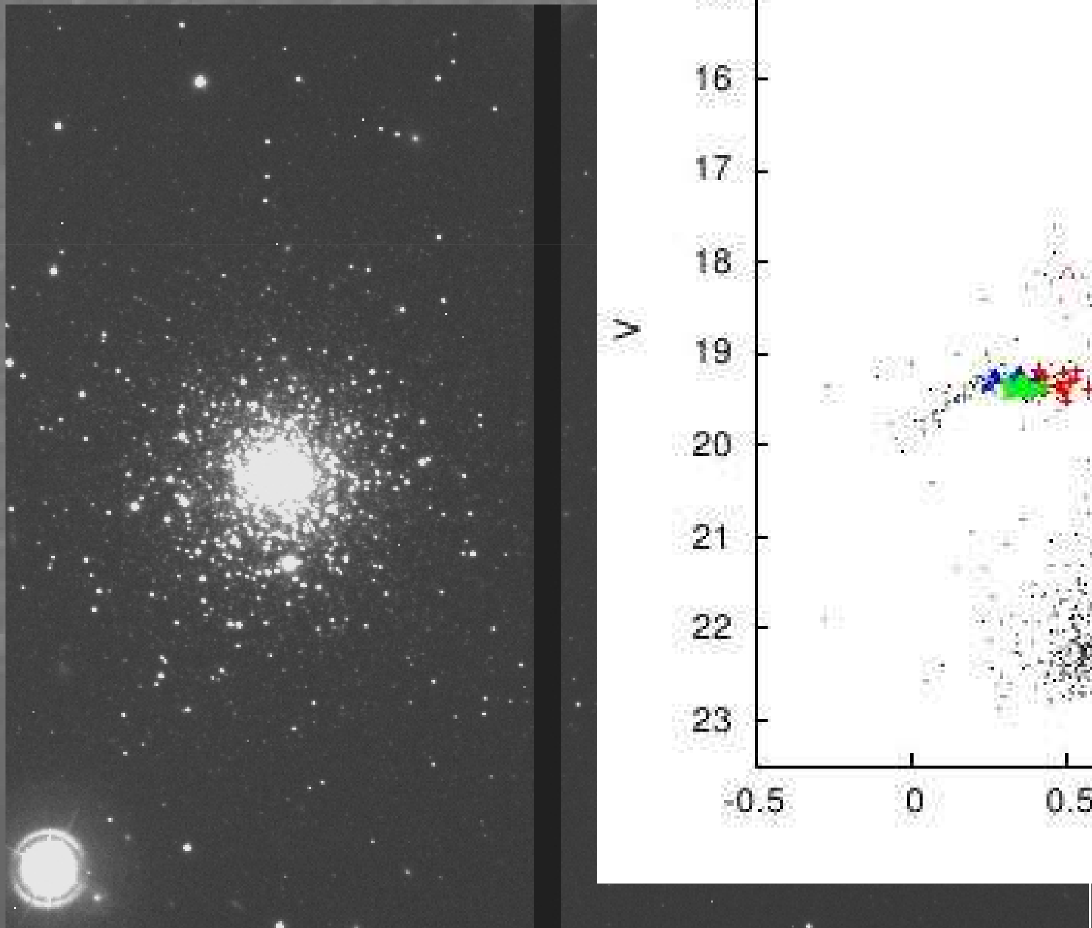
Target Objects

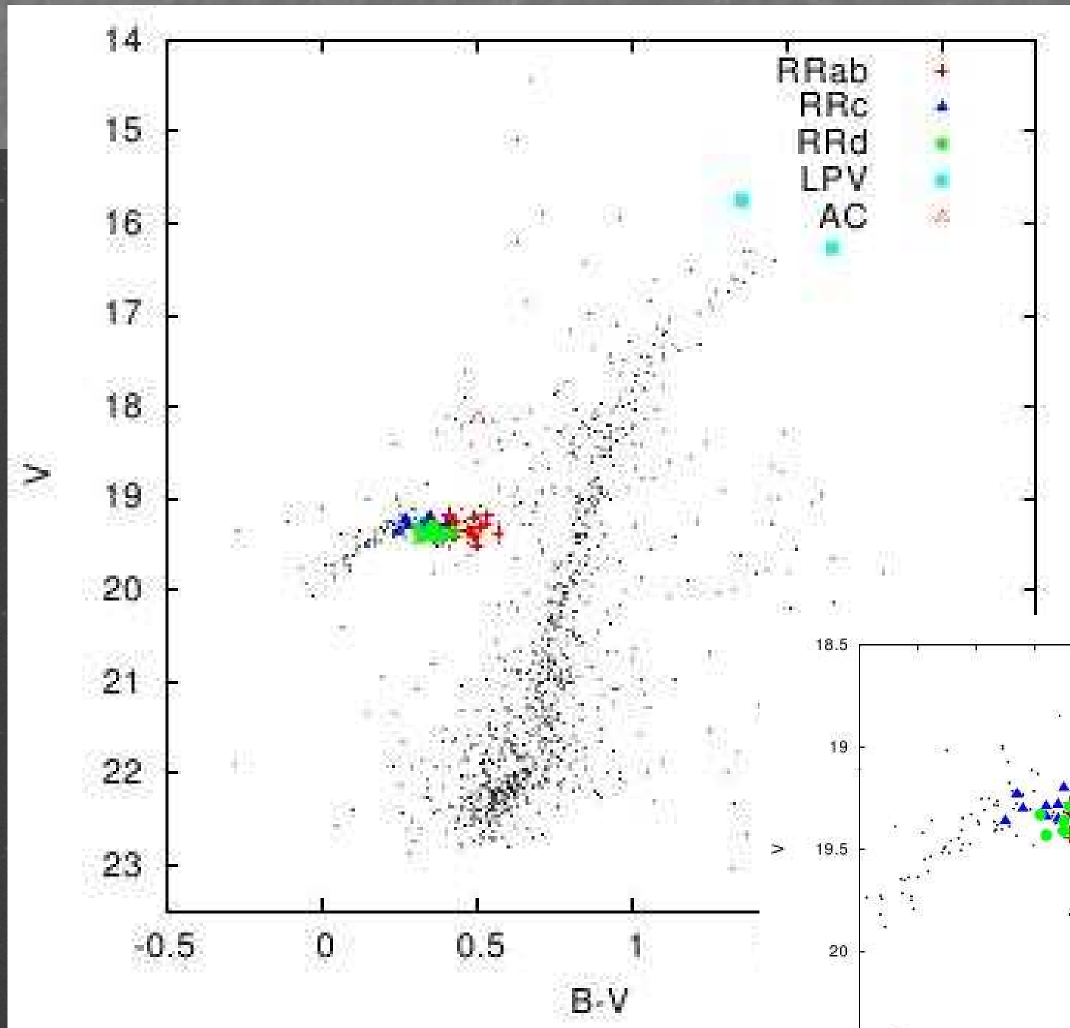
- 5 LMC globular clusters
- NGC 1466: Oo-Int
- NGC 1754: Oo-I object
- NGC 1786: Oo-Int/II object?
- NGC 2210: Oo-Int object
- Reticulum: Oo-I
- 3 of our clusters were also included in the Ogle III Catalog of Variable Stars (Soszyński et al. 2009)

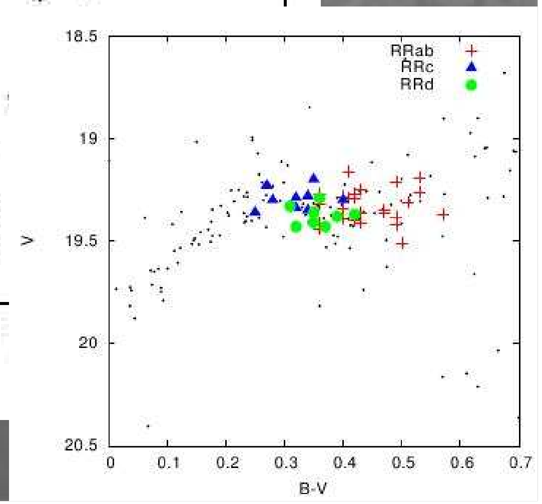
Observations

- Smarts - 1.3 m telescope
  - ANDICAM
  - Taken from 10/08/2005 to 12/24/2005 and 09/04/2006 to 12/31/2006
  - Average of 130 BVI images for each target
- SOAR - 4 m telescope
  - SOI
  - Taken December 2005, January 2006, and Febuary 2008
  - 61 BVI images for NGC 1754, average of 180 BVI images for other clusters
- OGLE – 1.3m telescope
  - From the OGLE III Catalog of Variable Stars (Soszyński et al. 2009)

NGC 1466







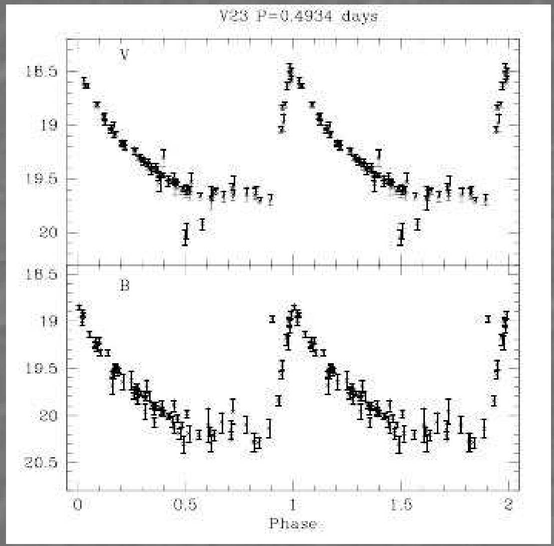
NGC 1466

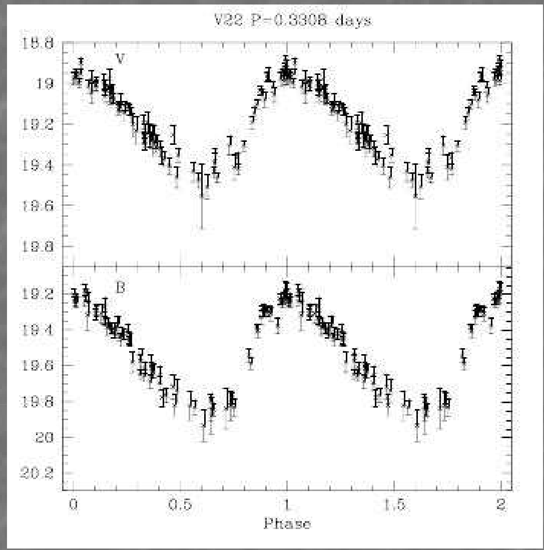
- Previously studied by Wesselink (1971) & Walker (1992)

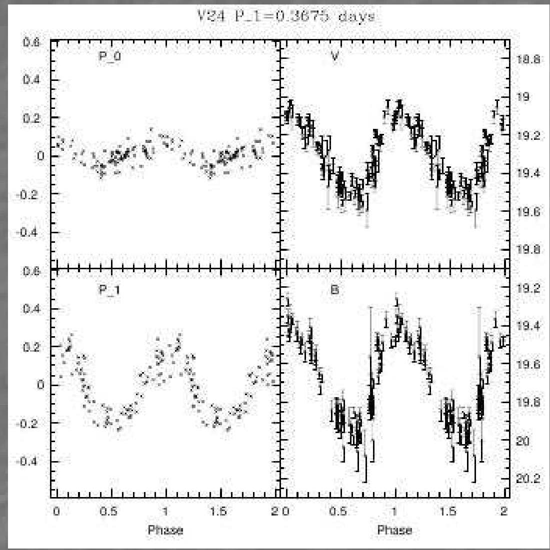
	Walker	Kuehn
RRab	25	30
RRc	17	12
RRd	0	7

  - We found 6 additional RRab stars, 1 found by Walker did not appear to vary in our data
  - Found 1 additional RRc star
  - 5 of Walker's RRc stars were found to be RRd stars
- Also found 1 candidate RR Lyrae, 1 anomalous Cepheid, 2 long period variables, and 9 variables of unknown classification

NGC 1466







- Periods accurate to between 0.00001-0.00003 days

- [Fe/H]ZW84 = -1.60 +/- 0.05 – from RR Lyraes
- Gives an absolute magnitude for the RR Lyrae stars of Mv=0.62+/-0.14 (Catelan & Cortés 2008)
- Apparent magnitude for RR Lyraes: V=19.324+/-0.013
- E(B-V)=0.09+/-0.02
- (m-M)0=18.43+/-0.15

NGC 1466

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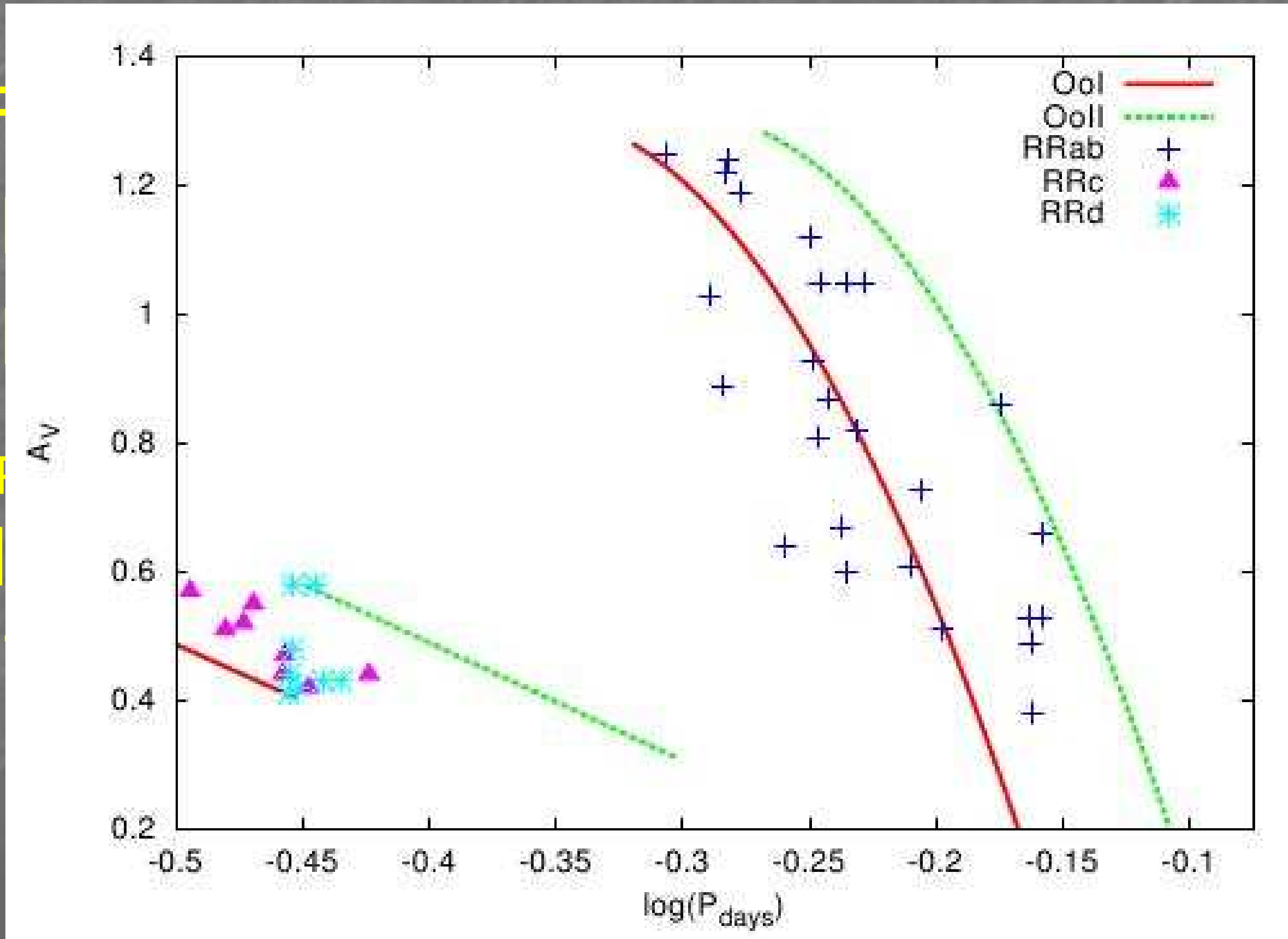
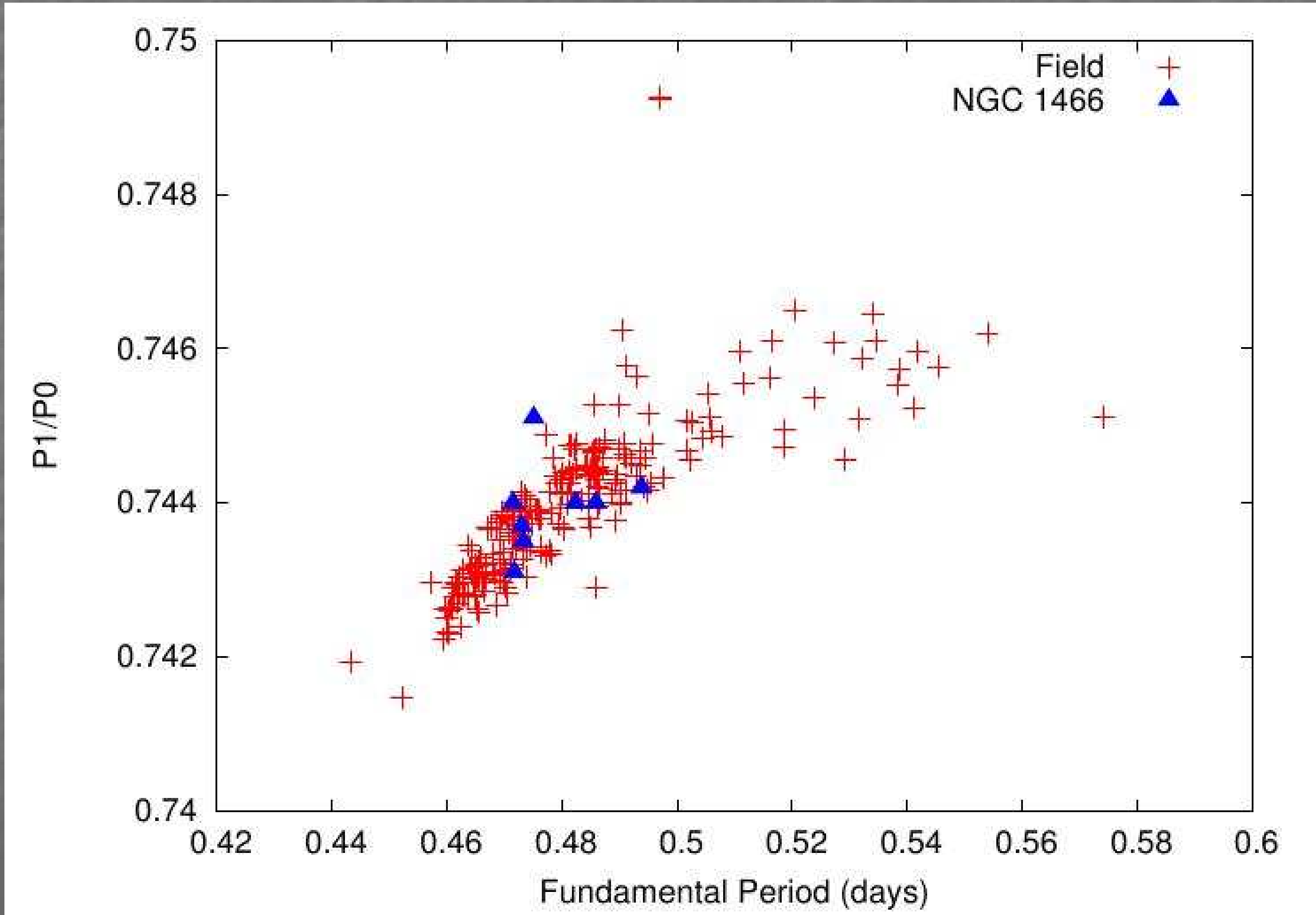
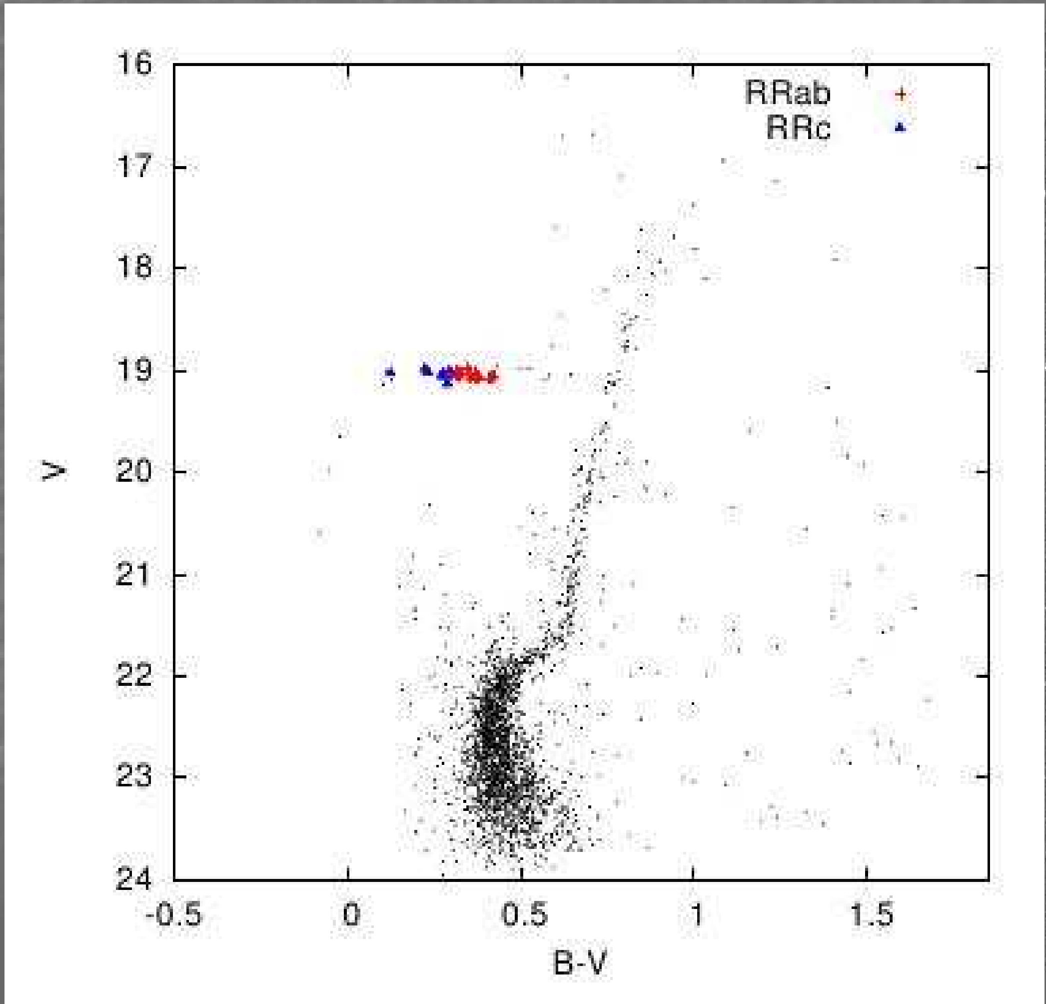
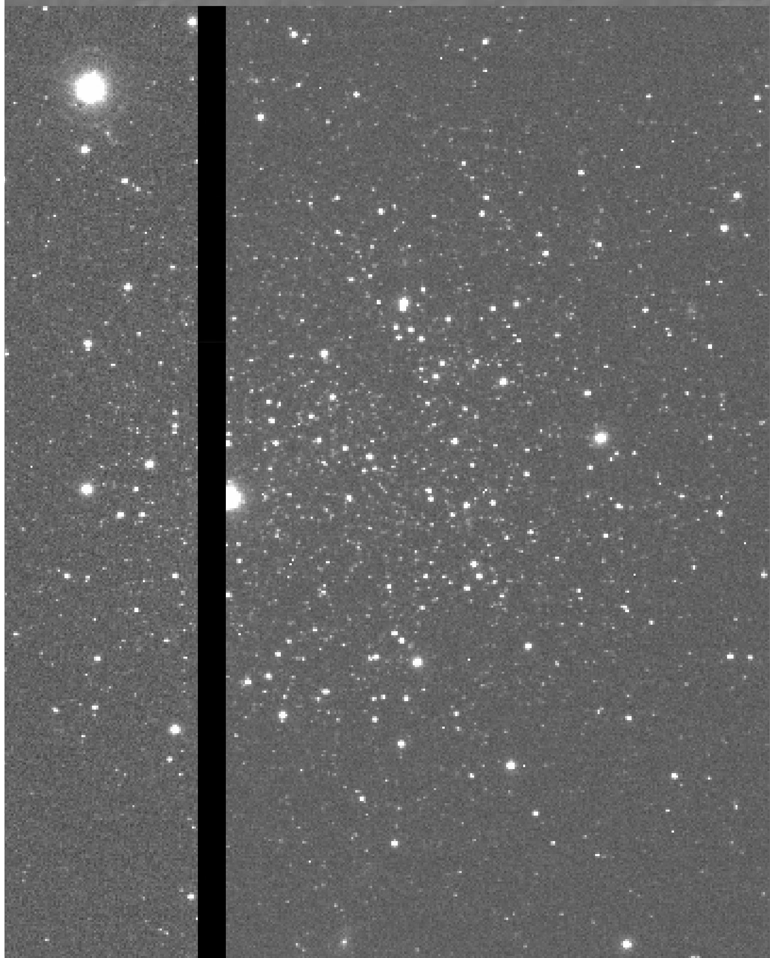


NGC 1466


Field
NGC 1466
P1/P0
0.75
0.748
0.746
0.744
0.742
0.74
0.42
0.44
0.46
0.48
0.5
0.52
0.54
0.56
0.58
0.6
Fundamental Period (days)

Reticulum





Reticulum

- Previously searched by Walker (1992)

	Walker	Kuehn
RR_{ab}	22	22
RR_c	10	9
RR cand		1

  - Includes all RR Lyrae found by Walker
  - Ripepi et al. (2004) found 4 possible RRd stars, have not checked ours yet for double-modes

Reticulum

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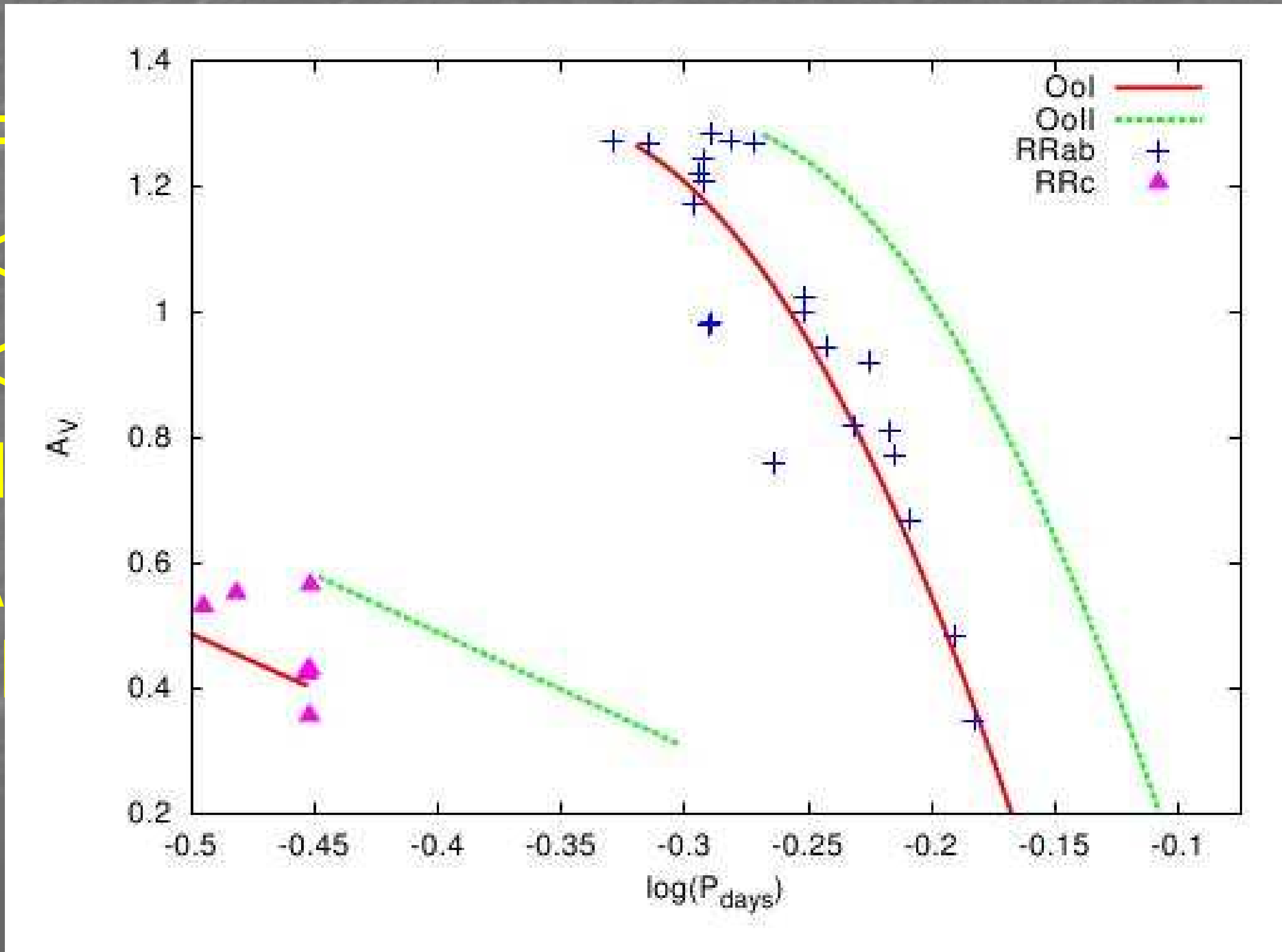


Other Clusters

- 3 clusters included in the OGLE III Catalog of Variable Stars

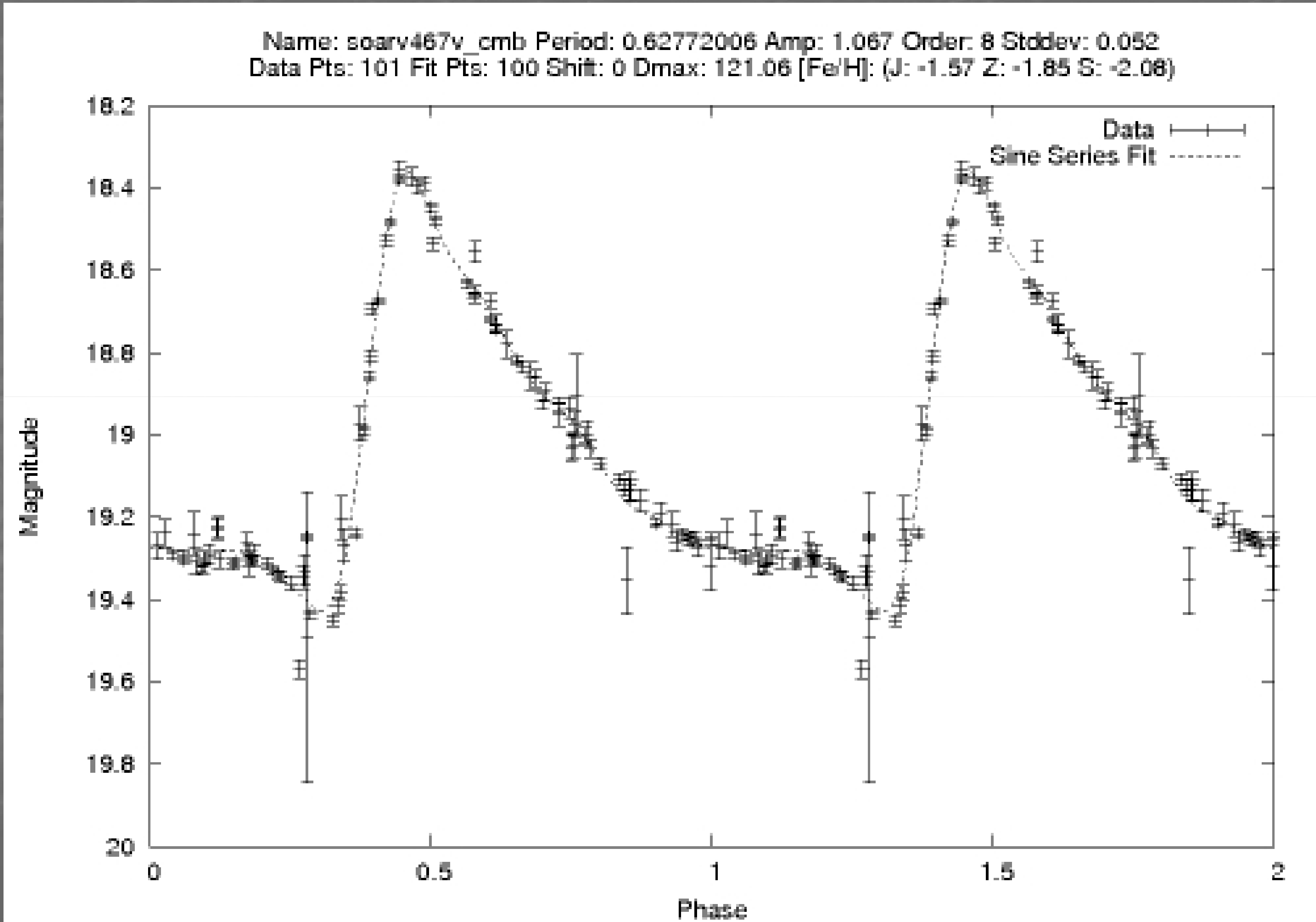
	Kuehn	OGLE
NCG 1754		
RRab	17	20
RRc	5	15
Many additional candidate RR Lyrae		
NGC 1786		
RRab	19	28
RRc	17	18
RRd	3	9
RRcand	10	0
NGC 2210*		
RRab	33	34
RRc	14	21
RRd	4	0

  - * Work done in conjunction with Young-Beom Jeon, James M. Nemec, & Alistair R. Walker. Preliminary results in (Jeon et al. 2009)

Fourier Decomposition

- Lightcurves fit with fourier series
  - $\text{Mag} = A_0 + \Sigma A_j \sin(j\omega t + \varphi_j + \Phi)$
  - RRab stars are traditionally fit with a sine series while RRc stars are fit with a cosine series
- Fourier coefficients give us properties of the stars
  - $\varphi_{ij} = j\varphi_i - i\varphi_j$ $R_{ij} = A_i/A_j$

Fourier Fits



Fourier Derived Parameters

- RRc stars
  - $\text{Log } M/M_{sun} = 0.52 \log P - 0.11\phi_{31} + 0.39$
  - $\text{Log } L/L_{sun} = 1.04\log P - 0.058\phi_{31} + 2.41$
  - $\text{Log } T_{eff} = 3.775 - 0.1452\log P + 0.0056\phi_{31}$
  - $[Fe/H] = 3.702(\log P)^2 + 0.124[\phi_{31}]^2 - 0.845\ \phi_{31} - 1.023\ \phi_{31}\log P - 2.620$
  - $M_v = 1.261 - 0.961P - 0.044\ \phi_{21} - 4.447A_4$

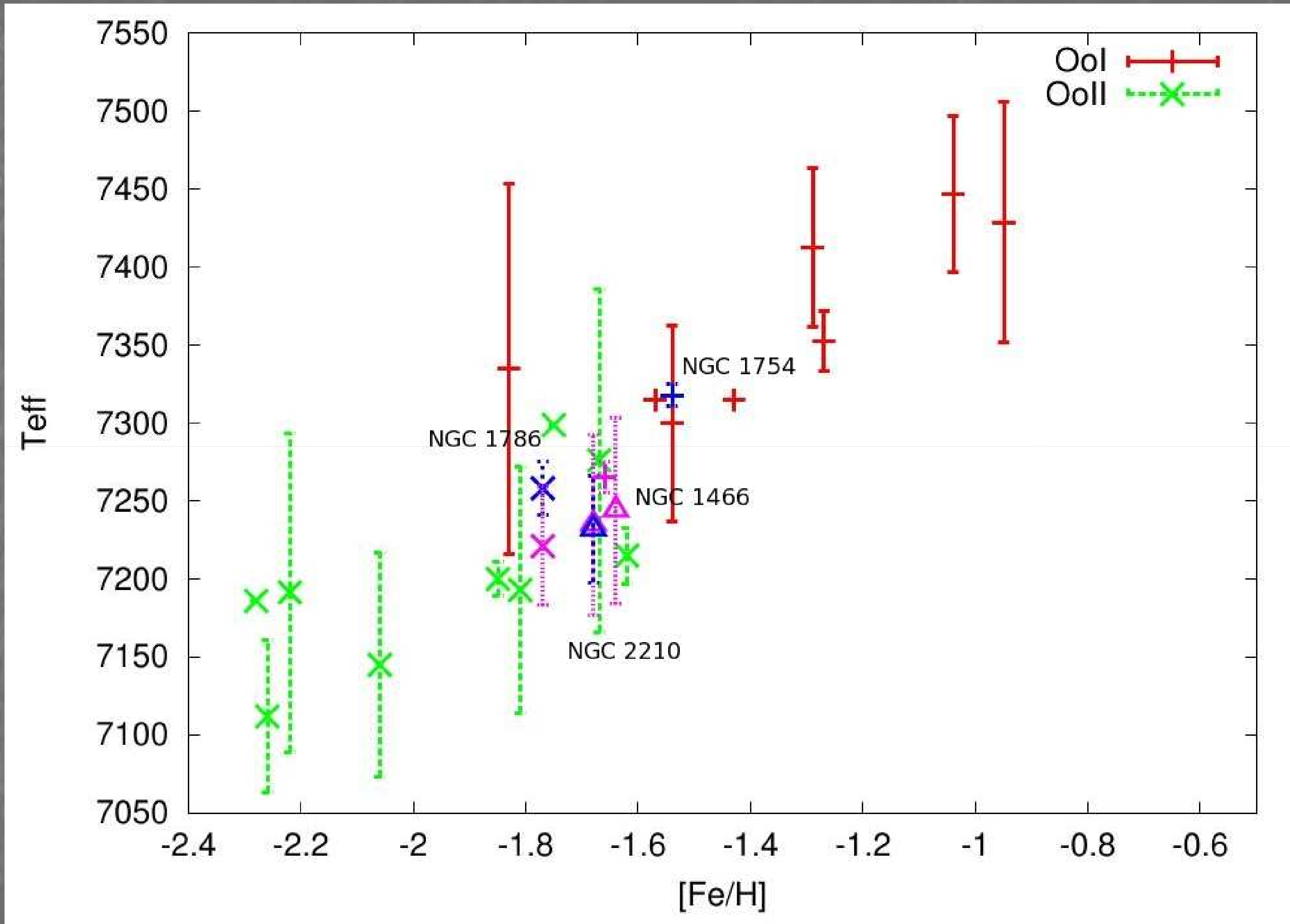
Equations from Simon & Clement (1993), Morgan, Wahl & Wieckhorst (2007), and Kovács (1998)

Fourier Derived Parameters

- RRab stars
  - $[Fe/H] = -5.038 - 5.394P + 1.345\phi_{31}$
  - $M_v = 1.221 - 1.396P - 0.477A_1 + 0.103\phi_{31}$
  - $(V-K)_0 = 1.585 + 1.257P - 0.273A_1 - 0.234\phi_{31} + 0.062\phi_{41}$
  - $\log T_{eff} = 3.9291 - 0.1112(V-K)_0 - 0.0032[Fe/H]$

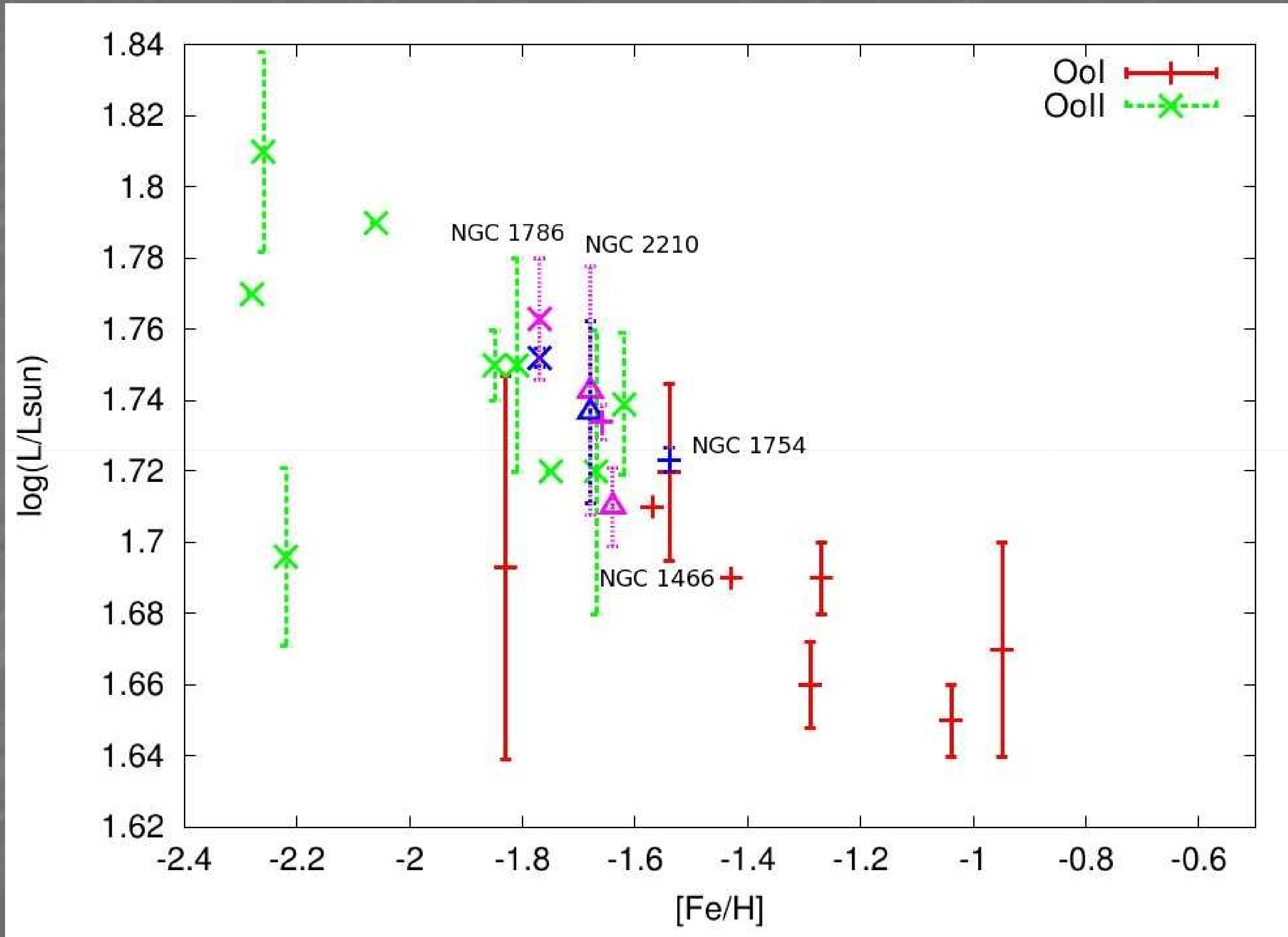
Equations from Jurcsik & Kovács (1996), Kovács & Jurcsik (1996), and Jurcsik (1998)

Trends in Fourier Parameters



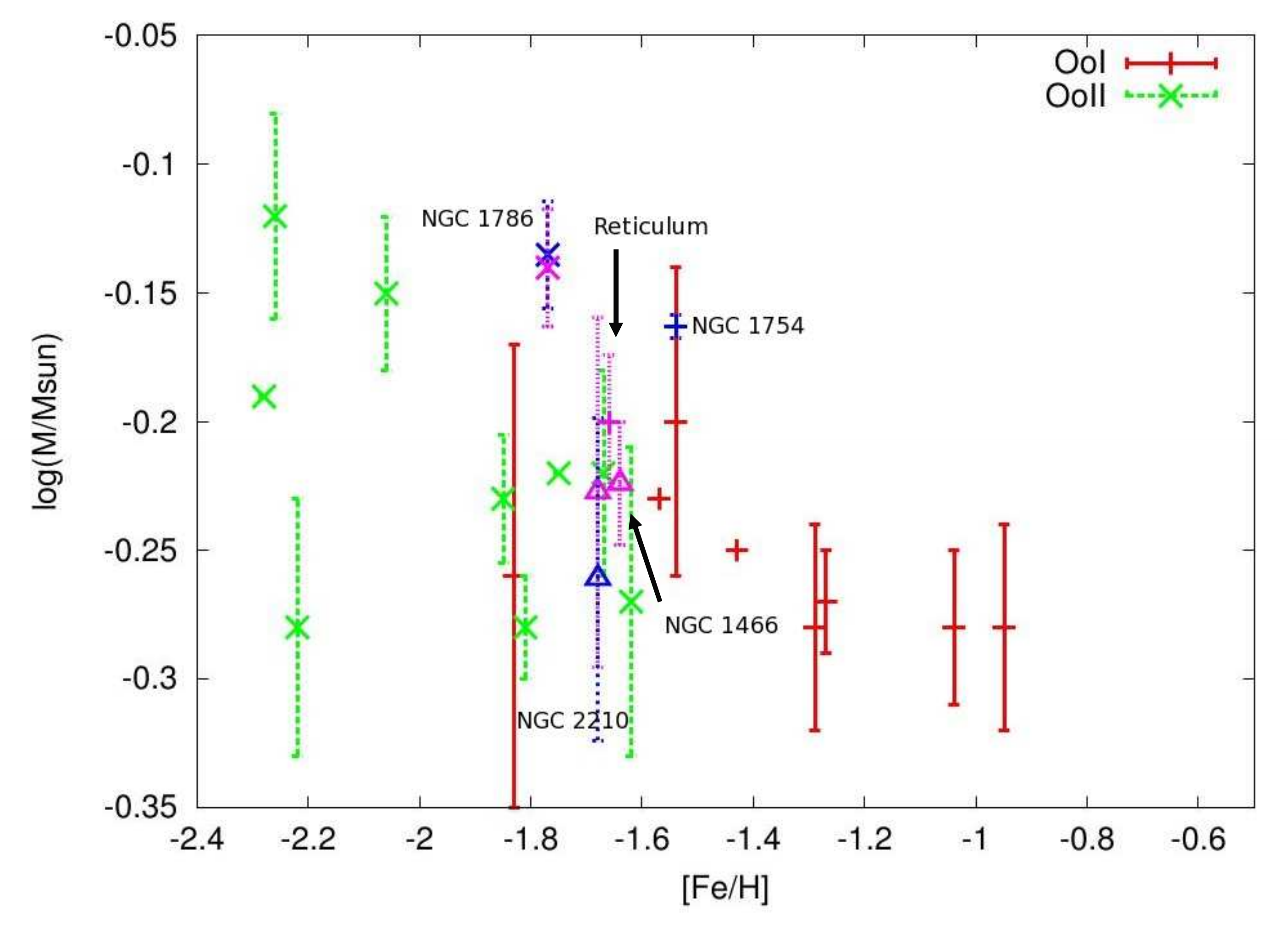
<Teff> vs Cluster Metallicity for RRc stars in Globular Clusters. Data from Lázaro et al. (2006), Arellano Ferro et al. (2008), Contreras et al. (2010), Zorotovic et al. (2009), Soszyński et al. (2009), Kuehn et al. (2010).

Trends in Fourier Parameters



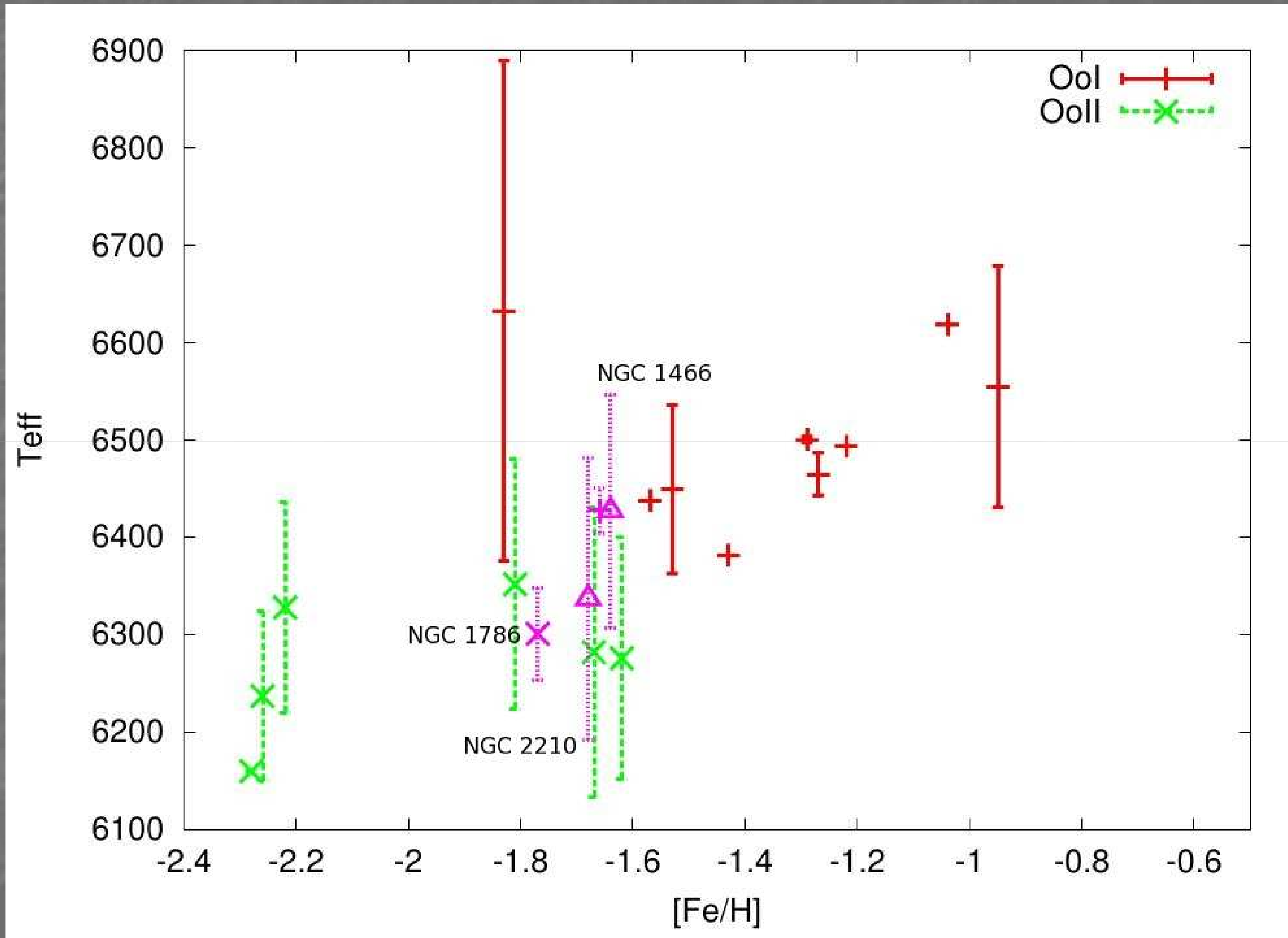
<Luminosity> vs Cluster Metallicity for RRc stars in Globular Clusters. Data from Lázaro et al. (2006), Arellano Ferro et al. (2008), Contreras et al. (2010), Zorotovic et al. (2009), Soszyński et al. (2009), Kuehn et al. (2010).

Trends in Fourier Parameters



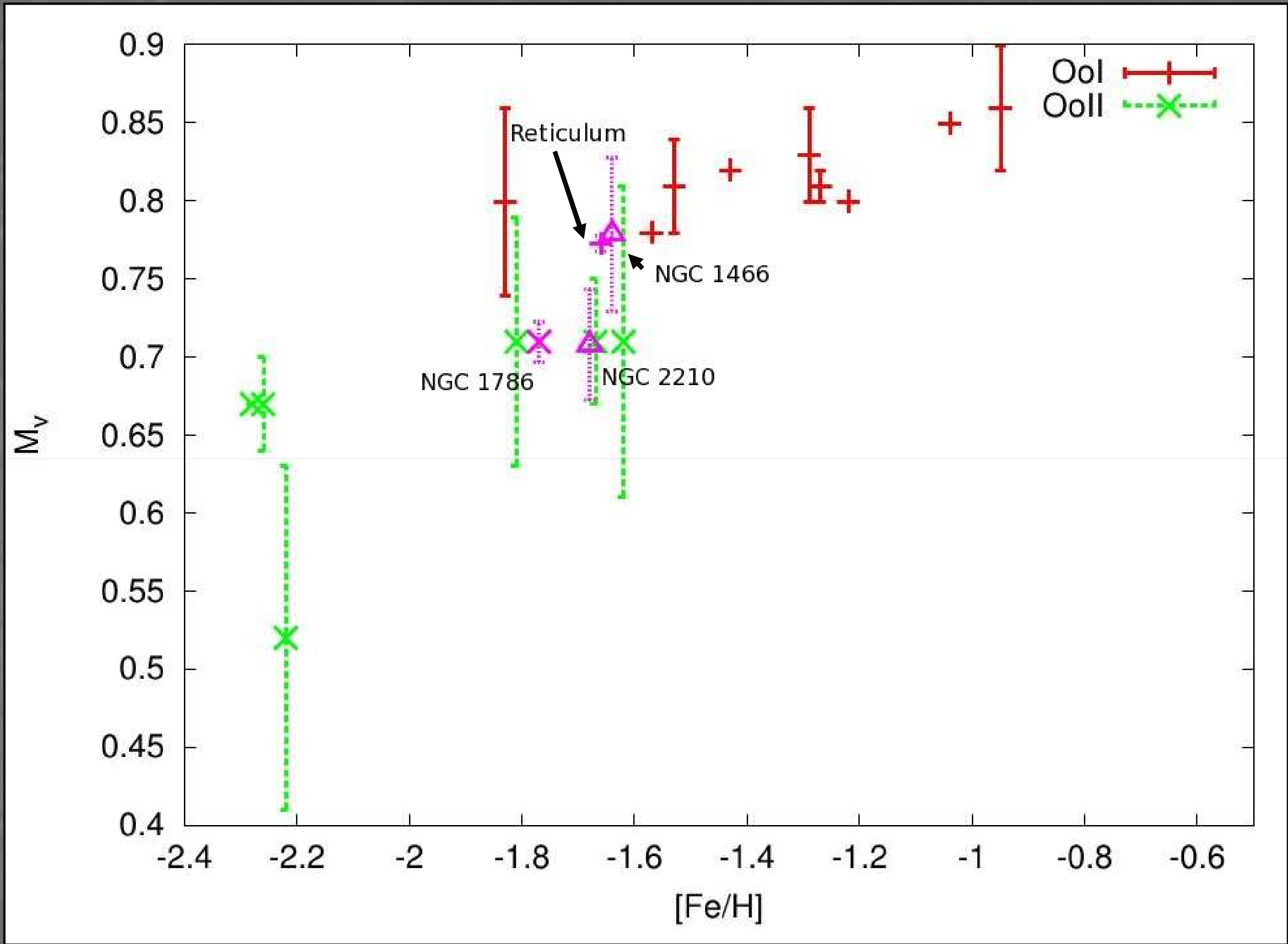
<Mass> vs Cluster Metallicity for RRc stars in Globular Clusters. Data from Lázaro et al. (2006), Arellano Ferro et al. (2008), Contreras et al. (2010), Zorotovic et al. (2009), Soszyński et al. (2009), Kuehn et al. (2010).

Trends in Fourier Parameters



<Teff> vs Cluster Metallicity for RRab stars in Globular Clusters. Data from Lázaro et al. (2006), Arellano Ferro et al. (2008), Contreras et al. (2010), Zorotovic et al. (2009), Soszyński et al. (2009), Kuehn et al. (2010).

Trends in Fourier Parameters



<V> magnitude vs Cluster Metallicity for RRab stars in Globular Clusters. Data from Lázaro et al. (2006), Arellano Ferro et al. (2008), Contreras et al. (2010), Zorotovic et al. (2009), Soszyński et al. (2009), Kuehn et al. (2010).

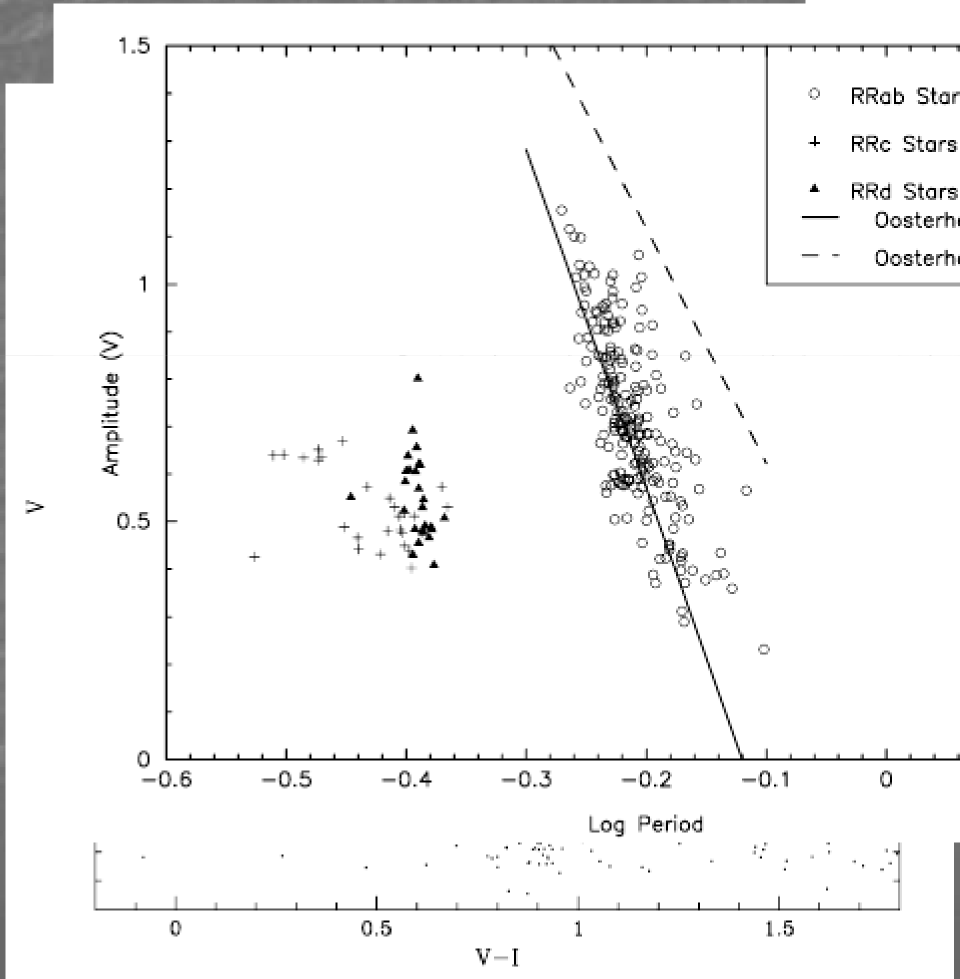
Summary

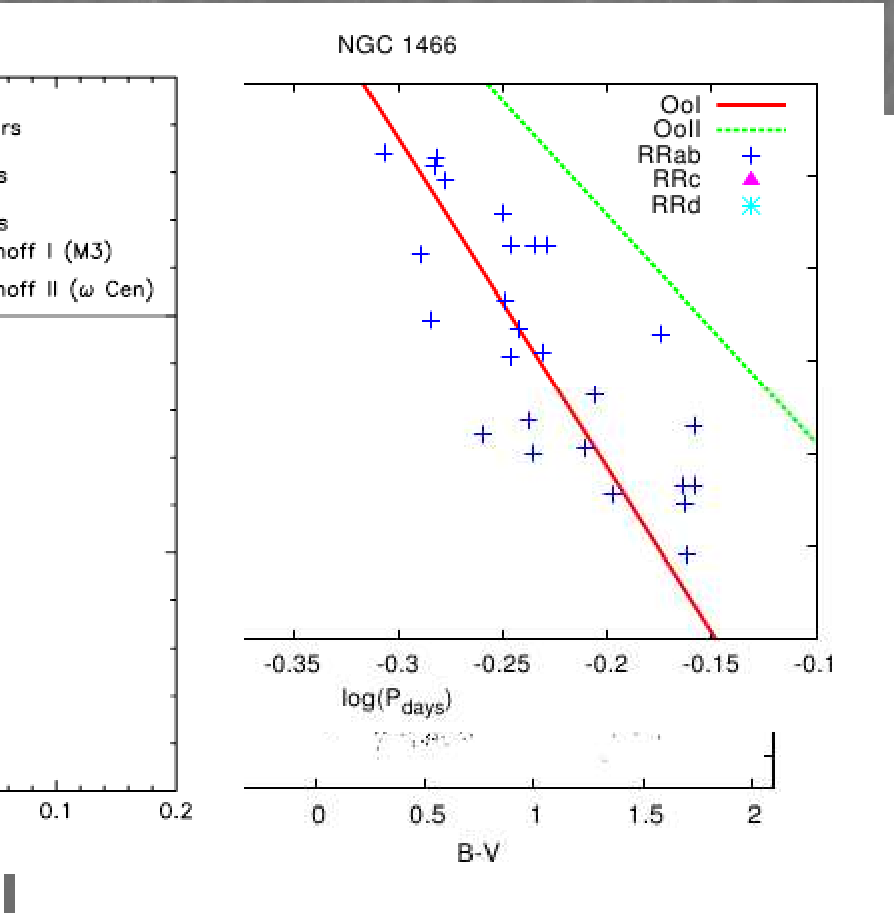
- The processes that created the RR Lyrae stars in the OO-Int clusters produce the same trends as seen in Oo-I/II system but appear to have been cut out in the Milky Way.

But

- Are all Oo-Int systems equal?

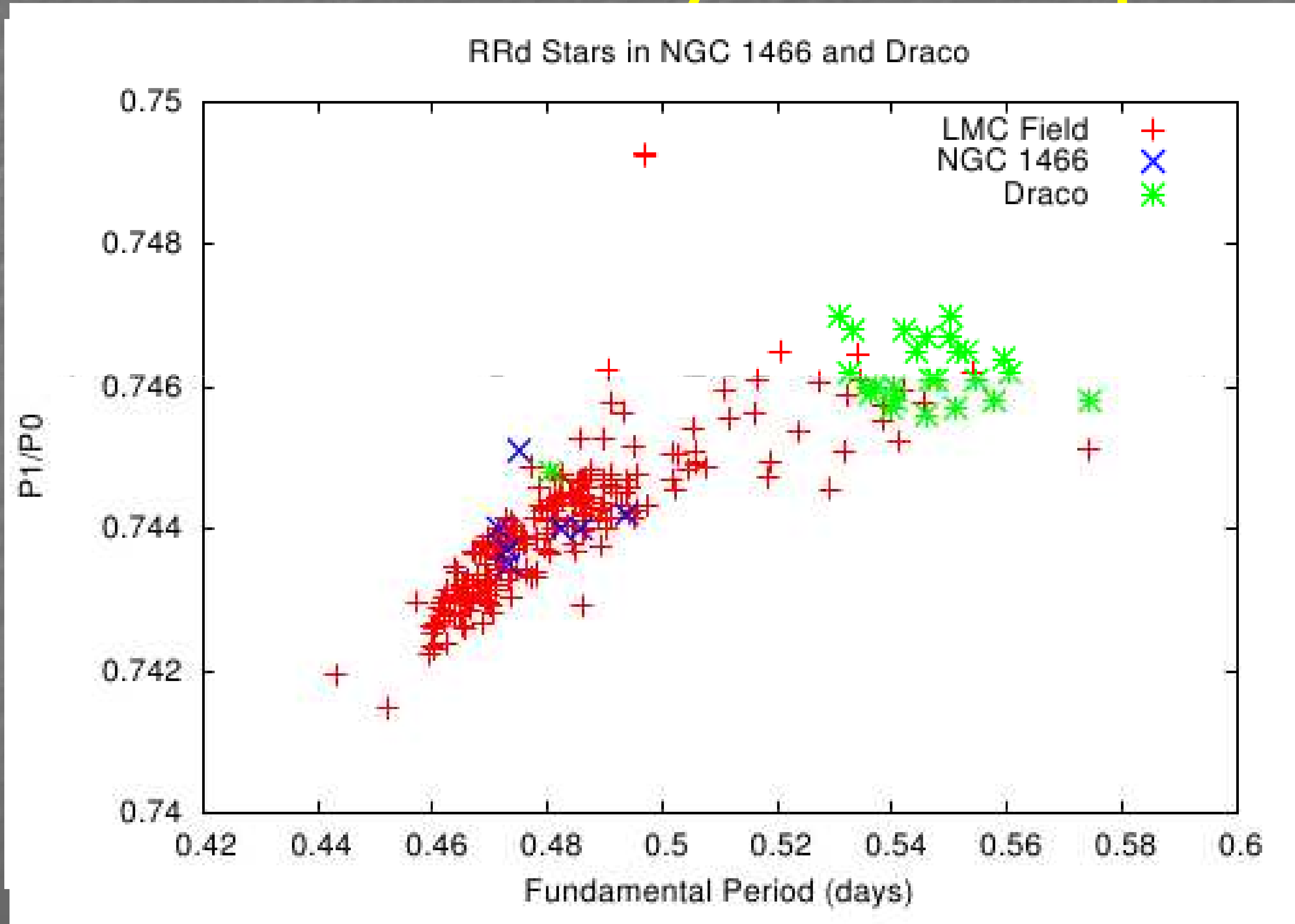
Are All Oo-Int Systems Equal?





Draco images and data from Kinemuchi et al. 2008, AJ, 136, 1921

Are All Oo-Int Systems Equal?



Draco images and data from Kinemuchi et al. 2008, AJ, 136, 1921

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