The Carina dSph: towards a complete census of evolved helium burning variables

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& the Carina collaboration

Carina dSph

- 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
- Carina is particularly interesting:

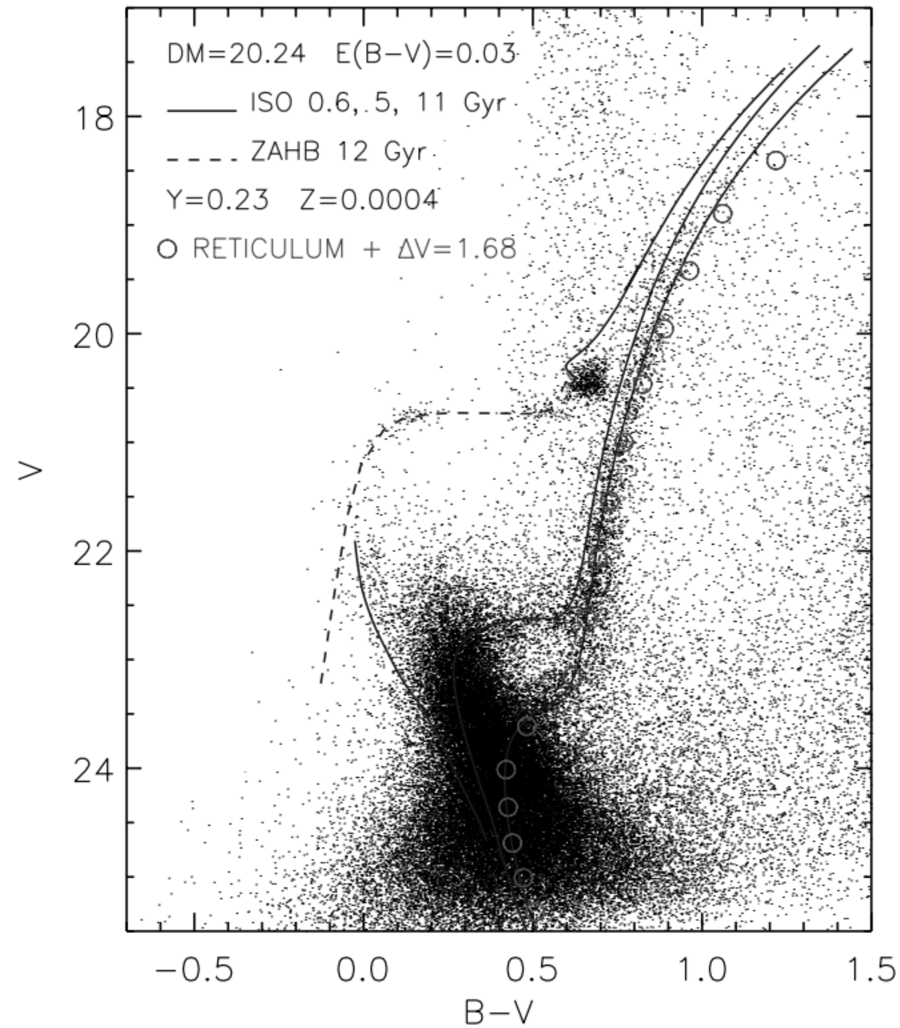
➢ Multiple separated star formation episodes ~ < 2, < 7, >10-11 Gyrs (Smecker-Hane, 1996, Monelli et al. 2003, Bono et al. 2010).

➢ Radial negative age gradient (Battaglia et al. 2012,).

➢ Extra-tidal members (Battaglia et al. 2012, Vivas & Mateo 2013, de Boer et al. 2014).

➢ Complex AMR (de Boer et al. 2014)

➢ Probable repeated interaction with the Milky Way.



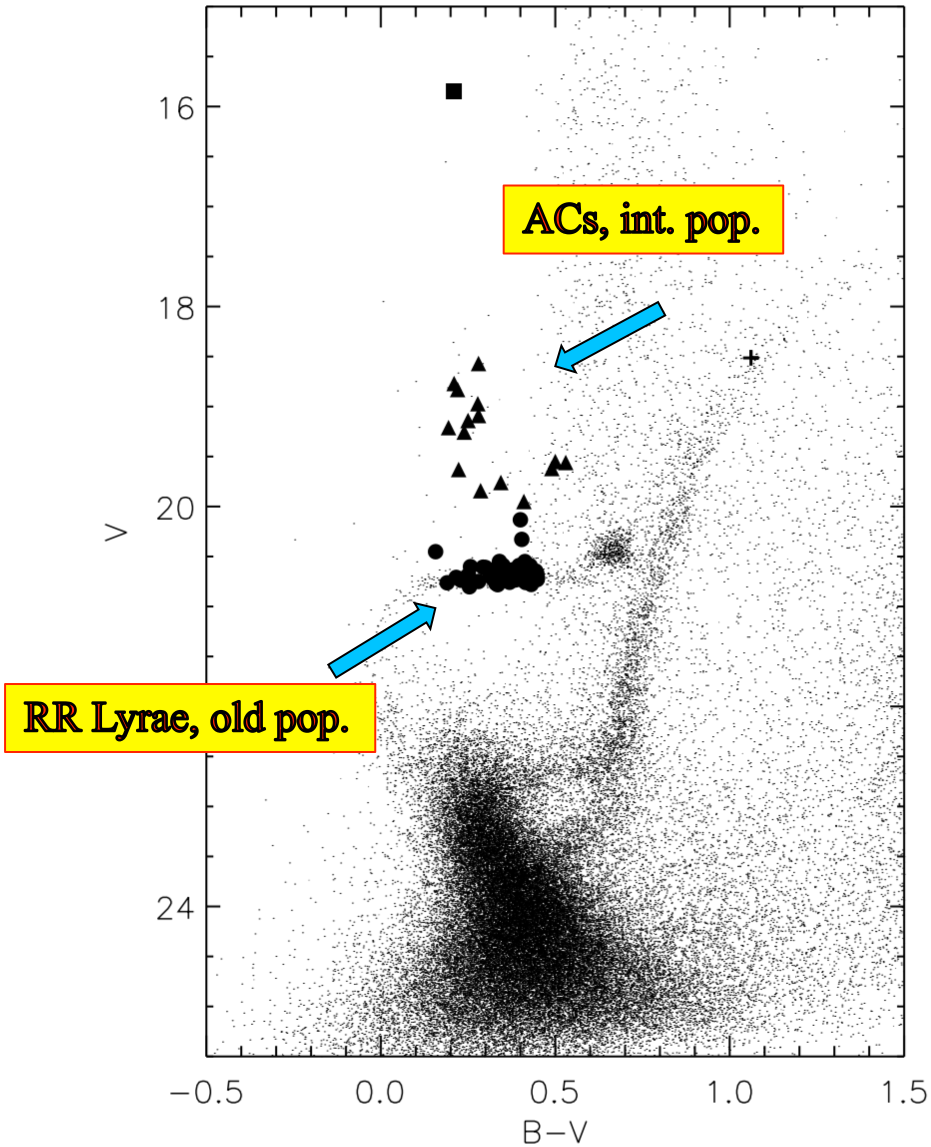
Monelli et al. (2003)

Pulsating variable stars

1. Usually bright and easy to detect, provide observables (Period, Amplitude,..) easy to measure, independent from distance and extinction ⇒correlated with the stellar parameters (Mass, Teff, Lum., Z)

2. Distance indicators ⇒ 3D structure (e.g. LMC, SMC, etc.)

3. Population tracers: e.g.
   RR Lyrae ⇒ old (t < 10 Gyr)
   Anomalous Cepheids (ACs) ⇒ interm. Age (1-6 Gyrs) and metal poor ([Fe/H] ≲ -1.6-1.7 dex)



Dall.Ora et al. (2003)

Observations

- Tektronix2K@CTIO 1.5 m ⇒ BI
- WFI@ESO/MPI 2.2 m ⇒ BV ~0.3° around the center of the dSph σ ~ 0.03 mag at minimum light
- MosaicII@CTIO 4 m ⇒ UBVI Complete coverage of central region (40'x55') + external pointing ~1.5° σ ~ 0.02 mag at minimum light
- Time baseline 26 years (1992-2008)

PHASE POINTS:

- **U ⇒ 4-15**
- **B ⇒ 43 to 167**
- **V ⇒ 41 to 222**
- **I ⇒ 10 to 75**

Data Reduction: DAOPHOT/ALLFRAME

Var. Star Search: Welch & Stetson (1993) method

Partial results already published Coppola et al. 2013, ApJ, 775, 6

Bright variable stars inventory

RR Lyrae ⇒ 85 (+ 7 from Vivas & Mateo (2013)) = 94

- 10 new with respect to Dall'Ora et al. (2003)
- 3 new with respect to Coppola et al. (2013)
- 7 from Vivas & Mateo (2013) well beyond the tidal radius

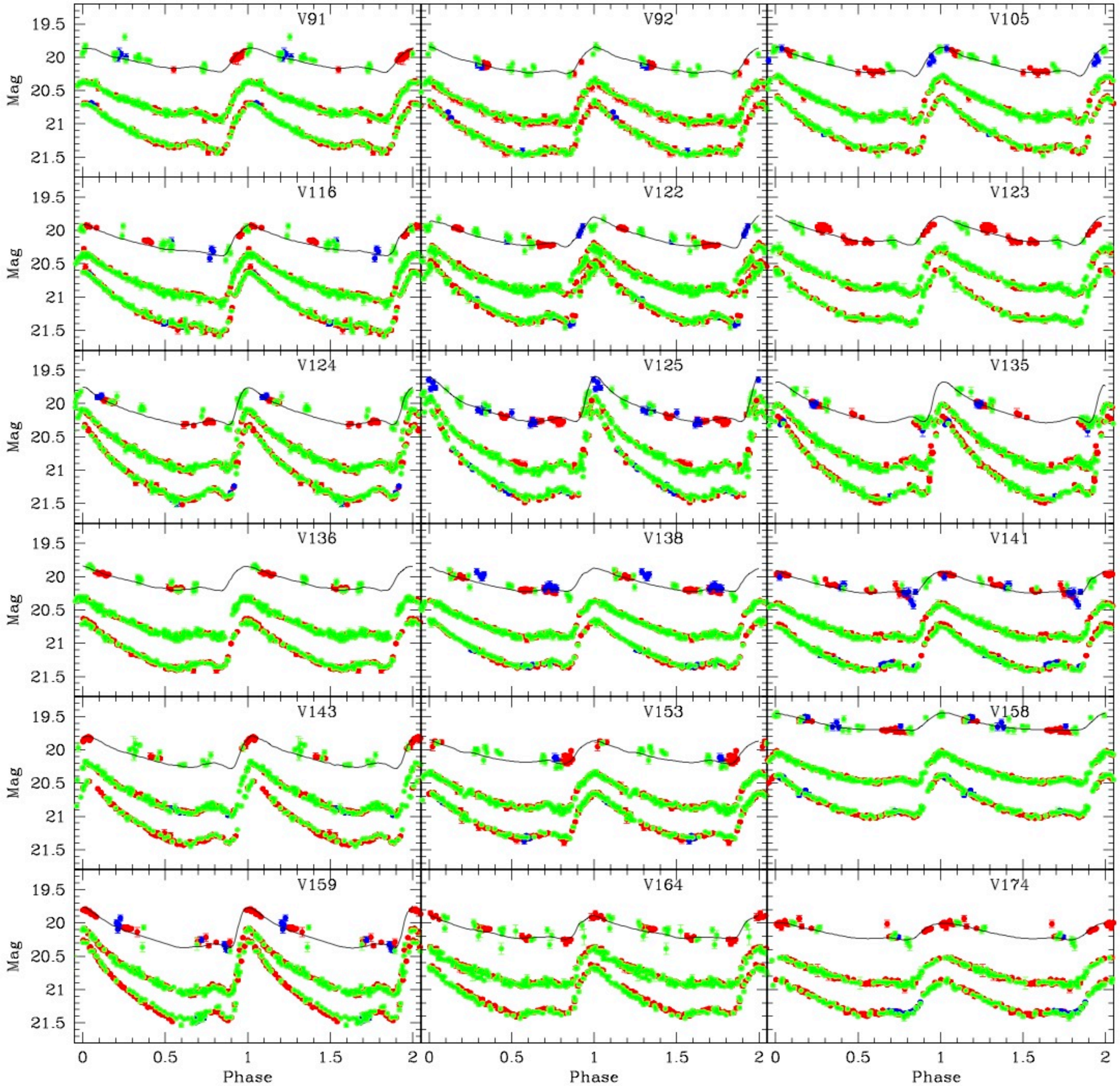
Our sample include: 67 RR ab (6 Blazhko) 12 RRc 6 RRd

Anomalous Cepheids ⇒ 19 (+ 4 from Vivas & Mateo (2013)) = 23

- 9 new with respect to Dall'Ora et al. (2003)
- 4 from Vivas & Mateo (2013) well beyond the tidal radius

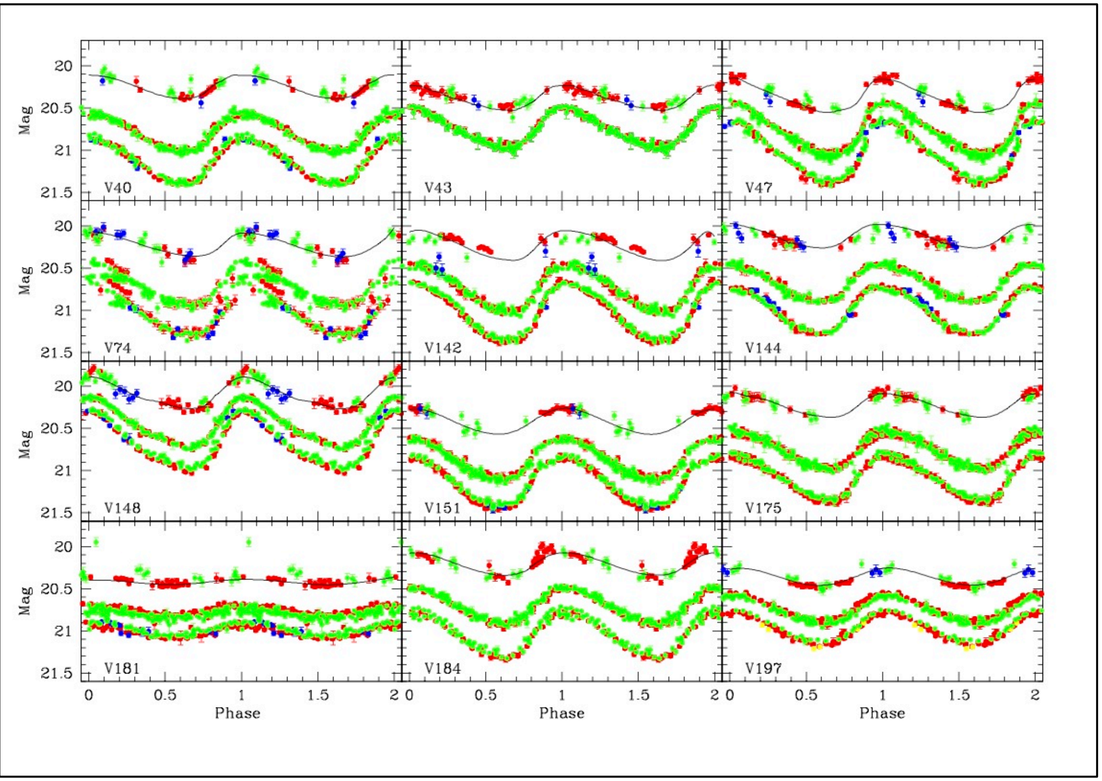
Miscellanoeus (W Uma, EB, LPVs) ⇒ 6

Sample of Fundamental mode RR Lyrae stars

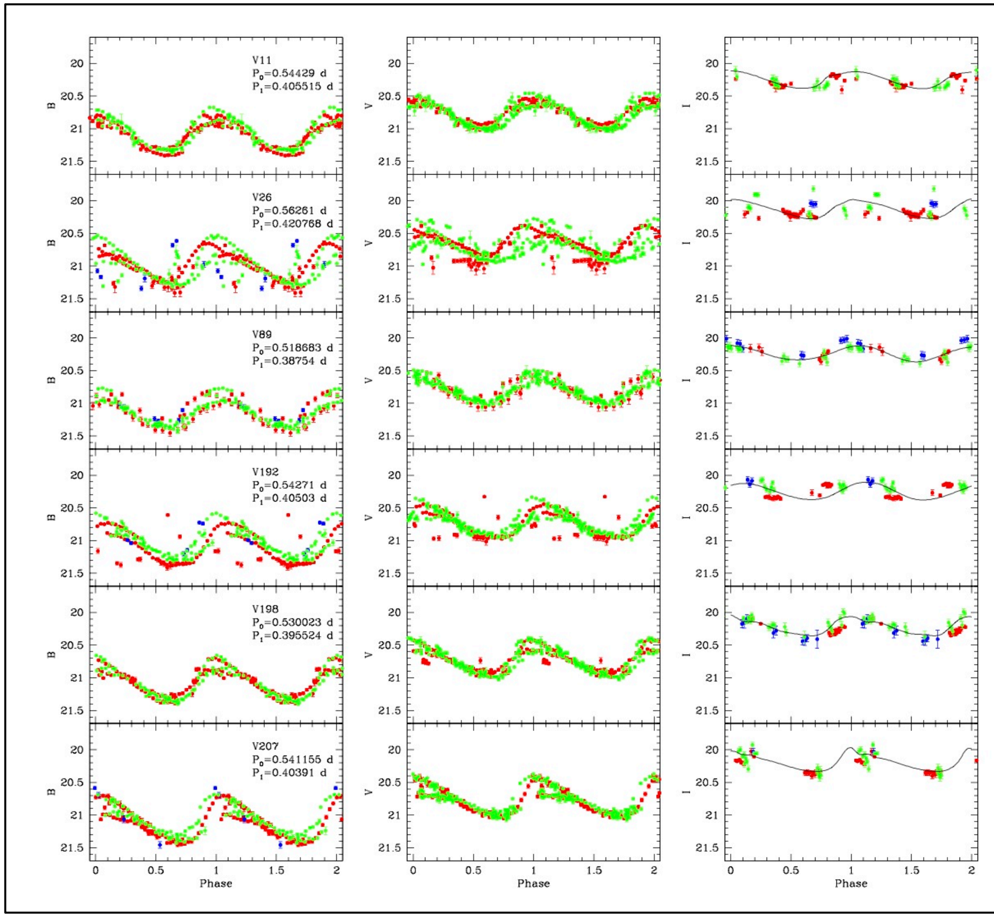


First overtone and Double mode RR Lyrae stars

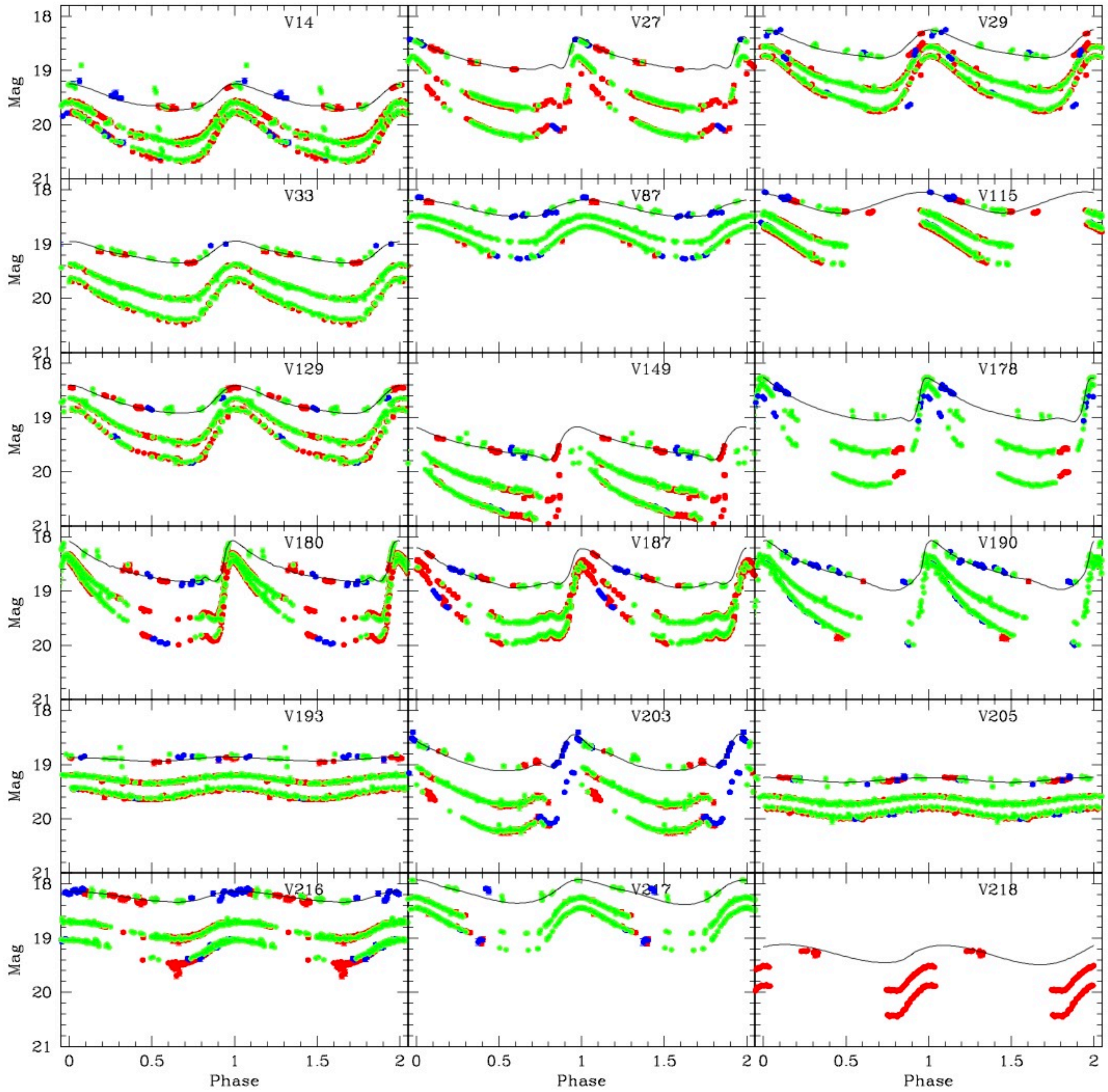
RRc



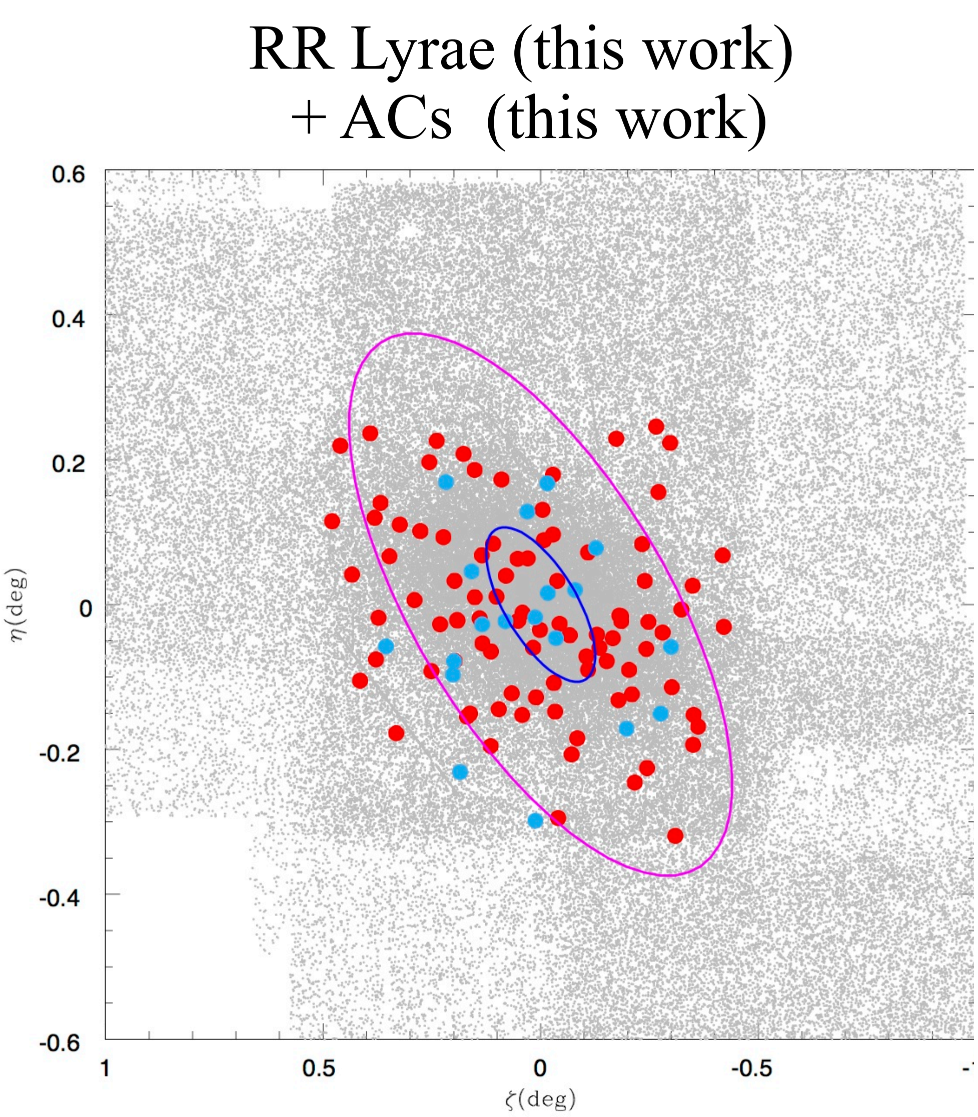
RRd

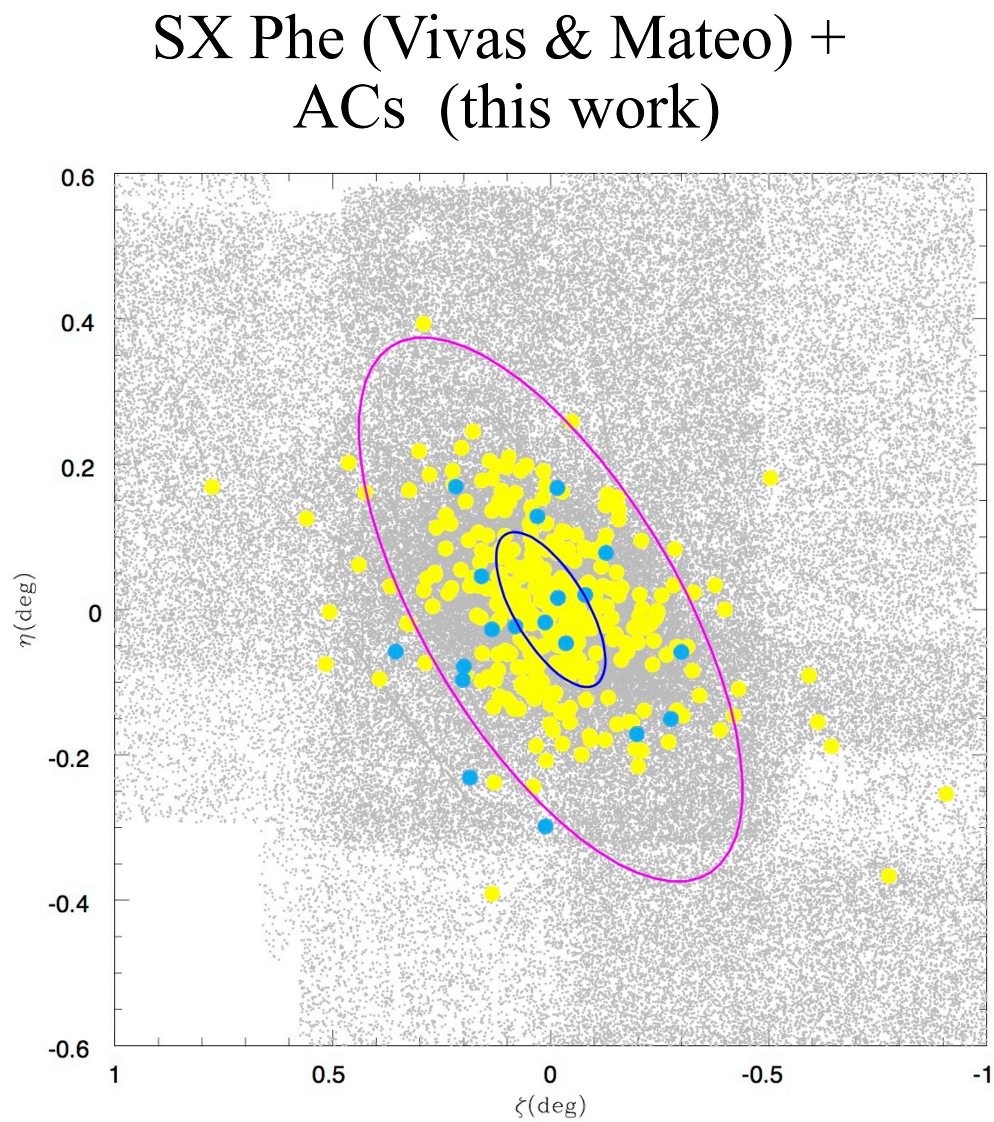


Anomalous Cepheids



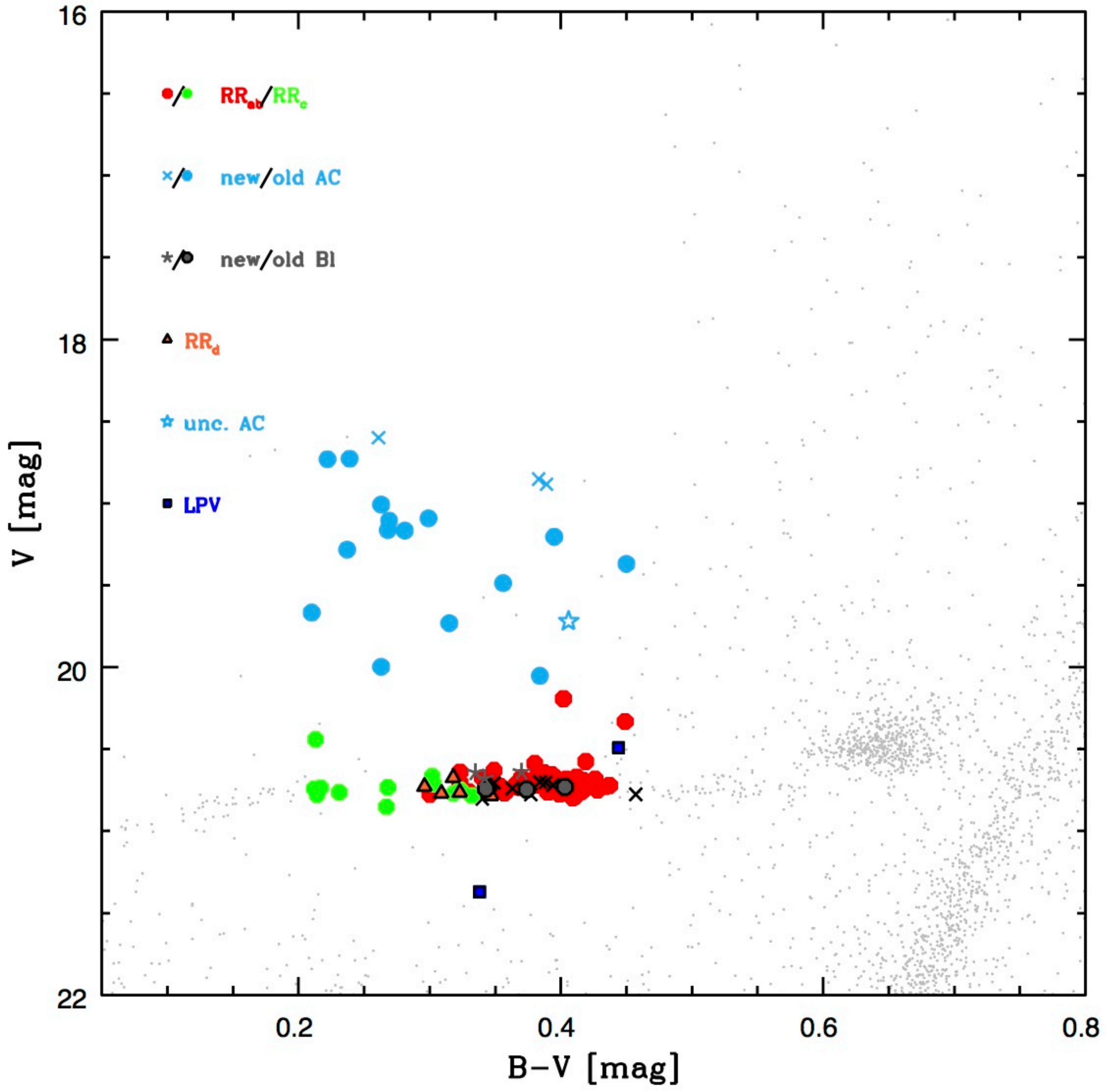
Radial distribution





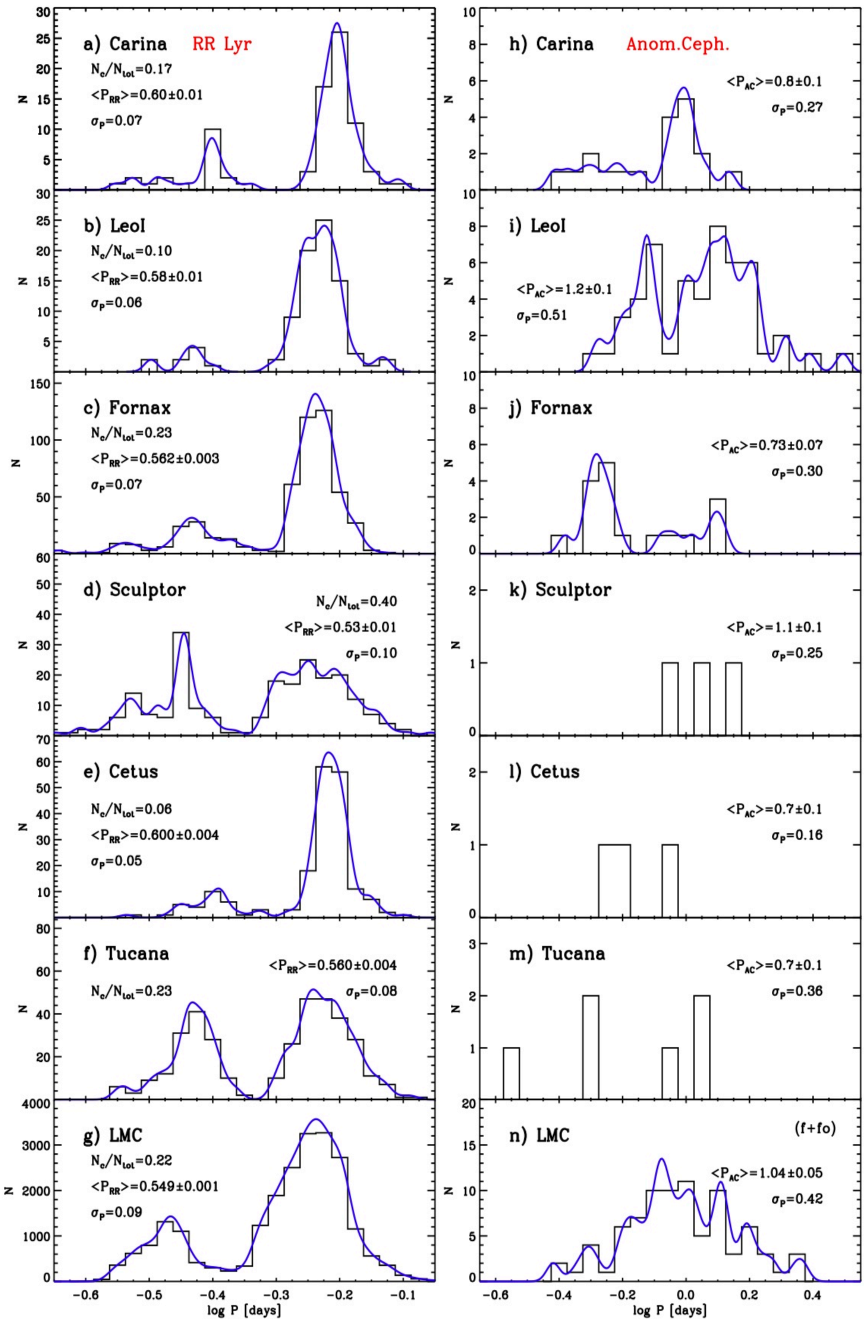
RR Lyraes appear more homogeneously distributed with respect to SX Phe and ACs

CMD pulsating stars



Discussed in detail in Coppola et al. (2013).

RR Lyrae Periods: Carina vs nearby dSph



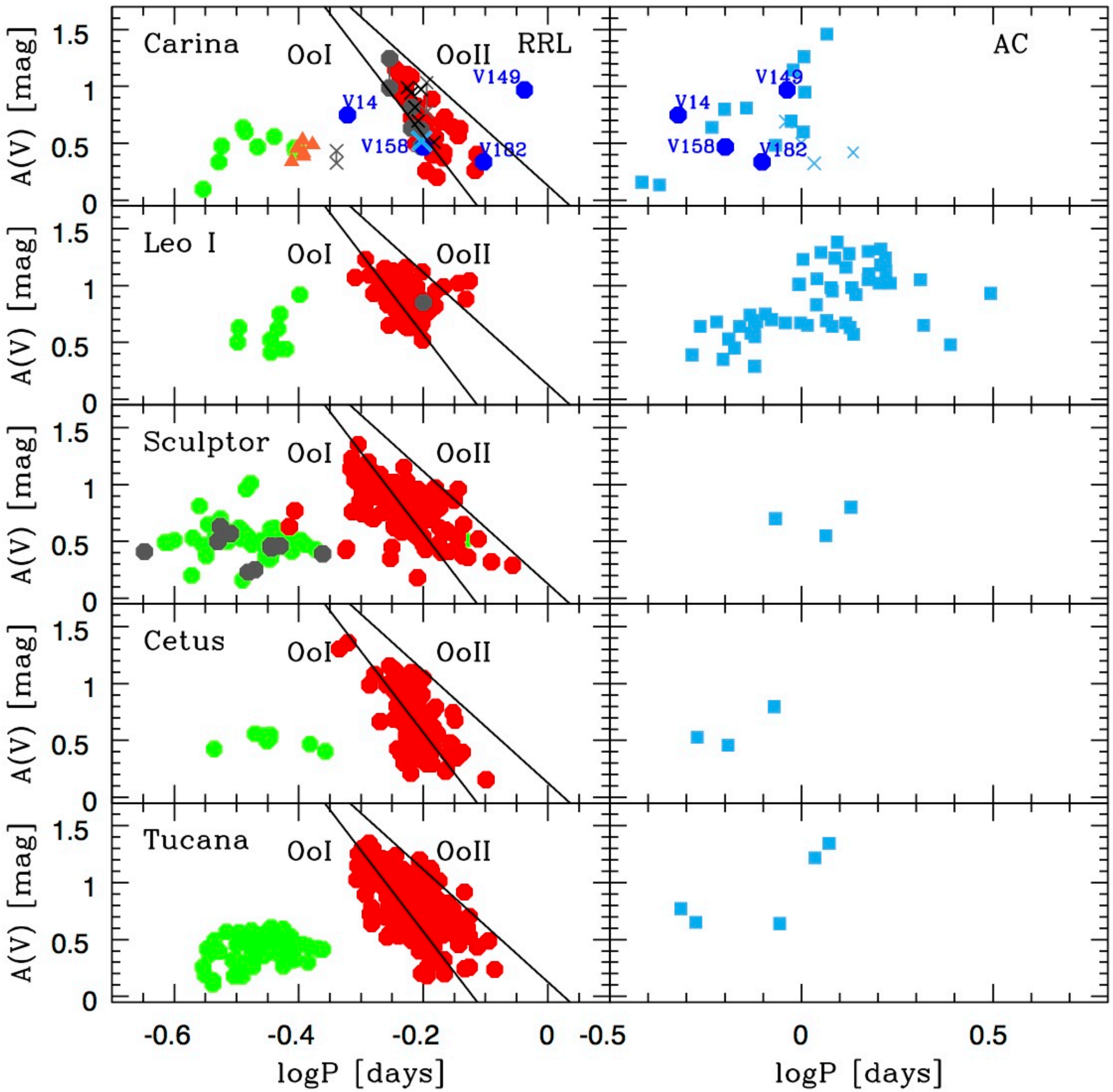
$\langle P_{RR}\rangle=0.60\pm0.01$ d ⇒Oo Int/Oo II

$N_c/N_{tot}\sim0.16$ ⇒ Oo I

- The Oo class depends on which parameter is used.
- Same mixture of Oo I and Oo II for other dSphs (except Tucana).
- In general similar period distributions.
- ⇒ old stellar populations share similar properties.

This is not the case for ACs period distributions ⇒ properties of intermediate-age stellar populations in the different systems are different (star formation and chemical enrichment history; Fiorentino & Monelli, 2012)

Bailey Diagram: Carina vs nearby dSph

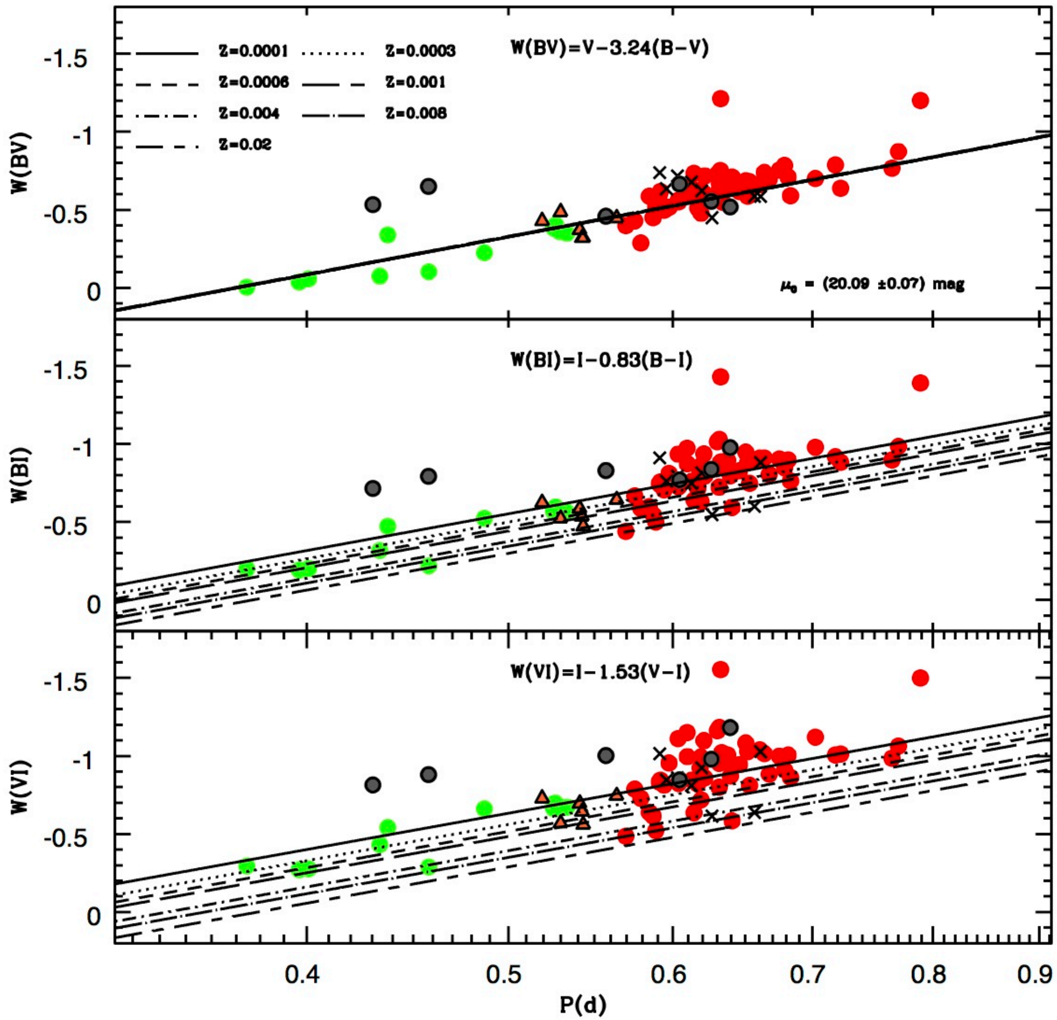


The Bailey Ddiagram confirms the Oo Int naure of Carina and other dSph.

Reduced spread in Carina (and Cetus) ⇒ small spread in metallicity of the old population

For the ACs, strong difference between Carina and Leo I distributions ⇒ confirms the results from the periods only.

Distance: the theoretical Period-Wesenheit relations



Reddening independent (Madore 1982)

Partially removes the dependence of the period on temperature (finite witdth of the Instability strip) at fixed luminosity.

New theoretical models from Marconi et al. (in prep) suggest that for the RR Lyrae variables, the PW relation is independent from metallicity ⇒ powerful distance indicator.

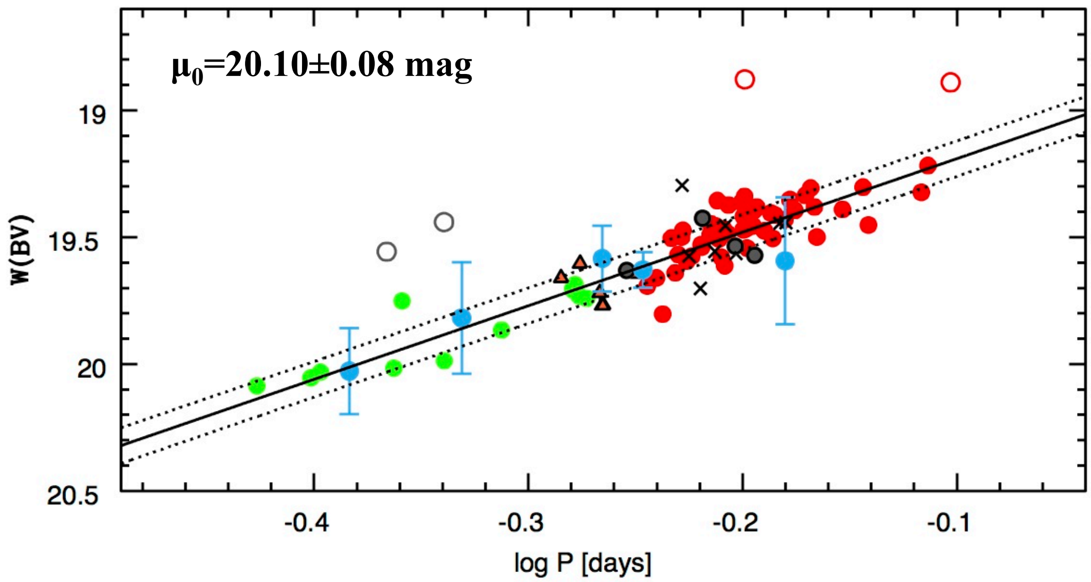
Using theoretical PW(BV) we obtain:

μ_0=20.09±0.07 mag

In very good agreement with literature:

μ_0	E(B-V)	Method	Reference
20.06 ± 0.12	0.025	PL (DC)	Mateo et al. (1998)
20.10 ± 0.12	0.03	PLC	MD03
20.00 ± 0.10	0.03	PLA	MD03
20.10 ± 0.04	0.03	FOBE	MD03
20.11 ± 0.13	0.06	TRGB	Pietrzyński et al. (2009)
20.17 ± 0.10	0.063	PL (DC)	Vivas & Mateo (2013)
20.09 ± 0.07	0.03	PLW	Paper I

Empirical Period-Wesenheit relations



Calibration of the empirical W(BV) relation

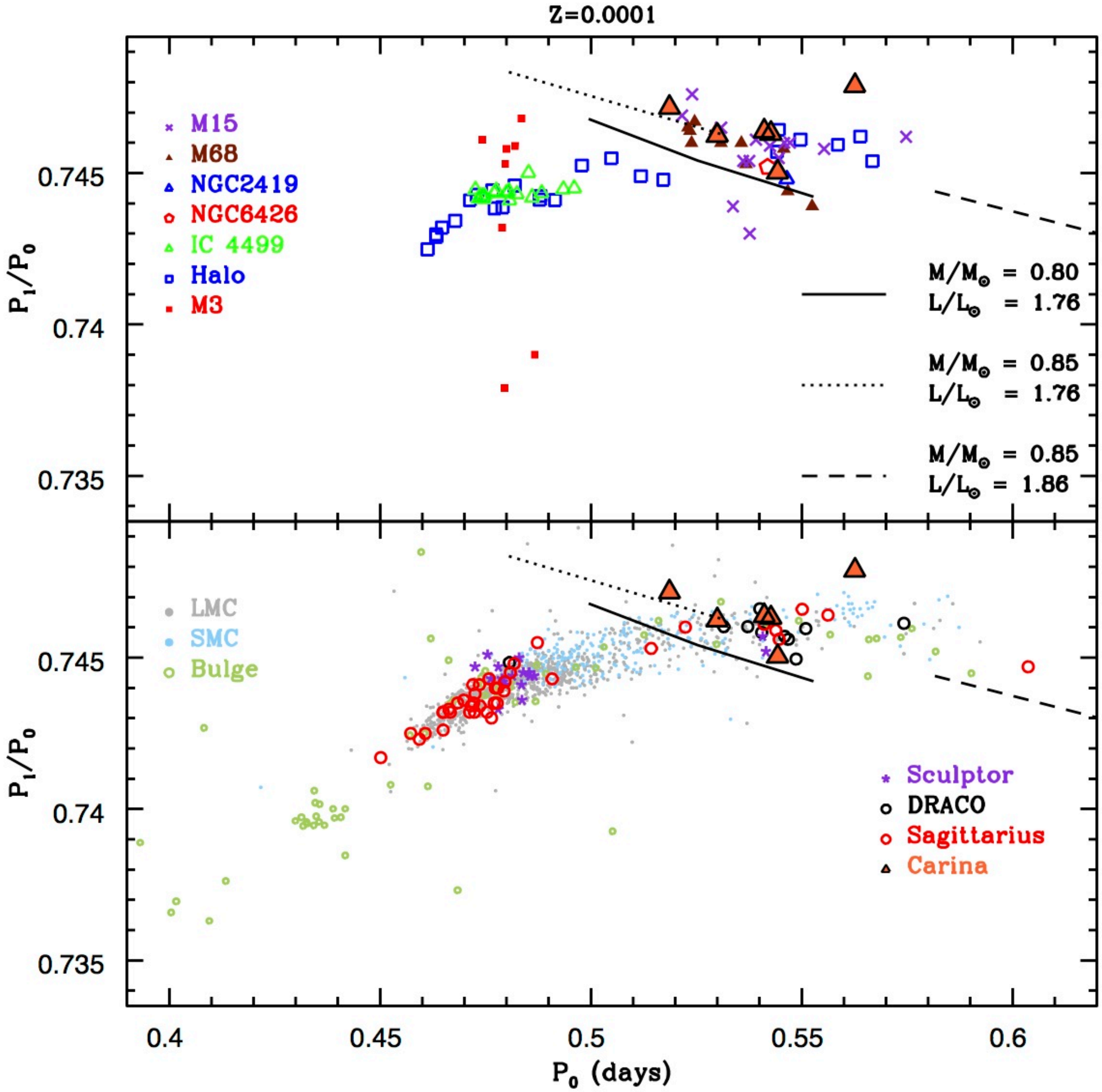
- Five RR Lyrae stars with HST parallaxes (Benedict et al. 2011)
- Different metallicity not an issue for W(BV)

μ_0=20.10±0.08 mag

⇓

Empirical and theoretical calibration of the PW(BV) relation show excellent agreement

Double mode RR Lyrae variables



- Six RRd in Carina
- Location in the Petersen diagram ⇒ metal poor as M15 or M68
- Pulsation predictions (Marconi et al. in prep) ⇒ Mass=0.85 $M_\odot$ for Z=0.0001 or 0.80 $M_\odot$ for lower Z
- The RR Lyrae in Carina are likely metal poor.

RR Lyrae Metallicity estimates from Fourier Param.

$$m(t) = A_0 + \sum_{i=1}^{F} A_i \sin[i\omega_0(t - t_0) + \phi_i],$$

Jurcsik & Kovacs (1996) for RRab

Morgan et al. (2007) for RRc

⇒ [Fe/H]=f(P,Φ_{31})

Relation inaccurate at [Fe/H] < -1.8-2.0 dex and

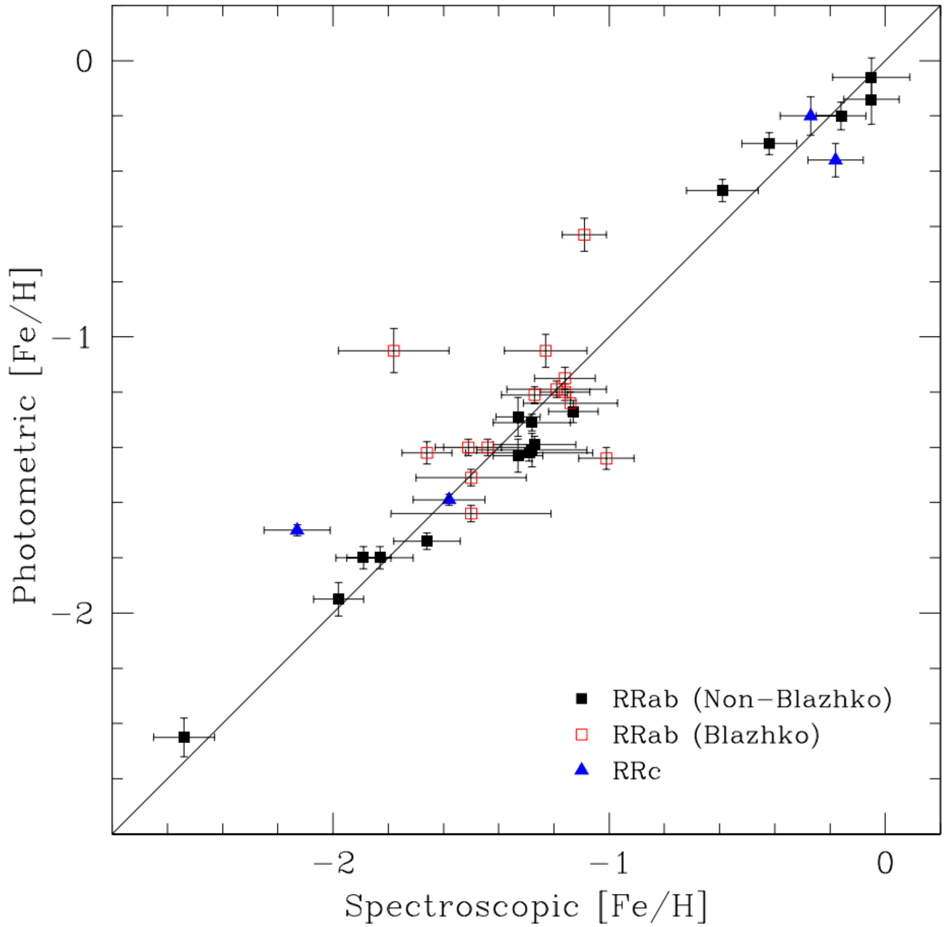
Both relations were recalibrated by Nemec, Cohen, Ripepi et al. (2013) using:

-Accurate Fourier params for a sample of 41 RR Lyrae observed by Kepler satellite

- HR spectroscopy (CFHT, Keck)

⇓

New [Fe/H]=f(P,Φ_{31}) relations (non-linear) whose validity extends to [Fe/H] as low as at least -2.4 dex



Nemec, Cohen, Ripepi et al. (2013)

σ[Fe/H]$_{RRab}$=0.084 dex

σ[Fe/H]σ_{RRc}=0.13 dex

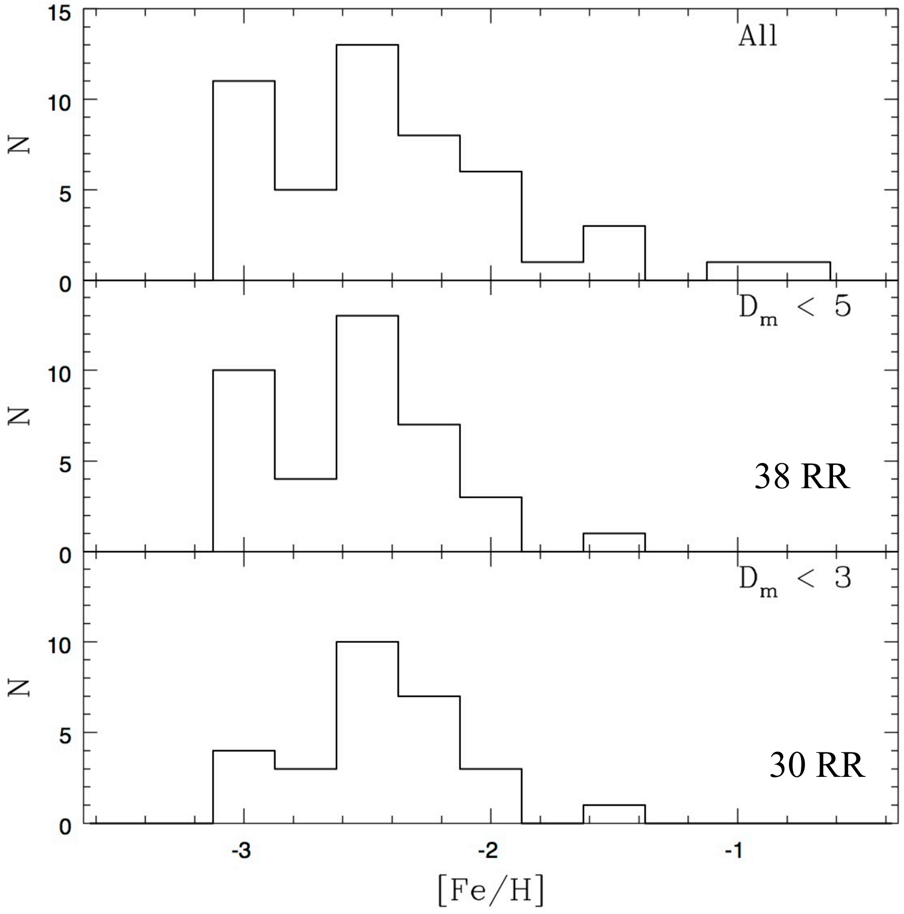
Metallicity of Carina RR Lyrae from Fourier Param.

Estimate of individual [Fe/H] for "normal" RRab and RRc stars in Carina by means of the new Nemec, Cohen , Ripepi et al. (2013) relations.

In Jurcsik & Kovacs (1996) accurate [Fe/H] estimates require the "compatibility parameter" $D_m < 3$ (or 5 for other Authors)

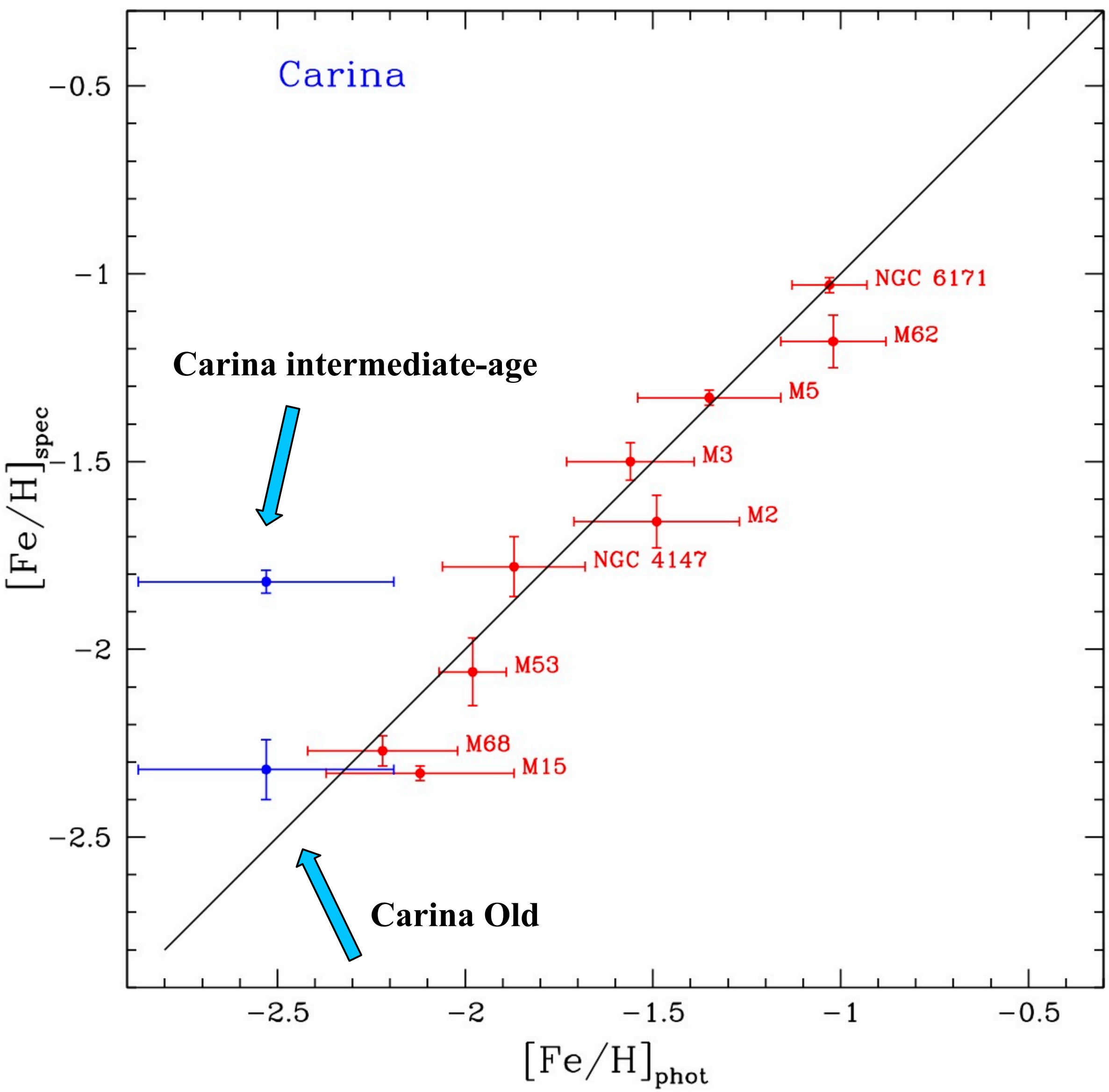
We verify that the result does not depend on the choice of the D_m theshold (3 or 5).

D_m<5 [Fe/H]~ -2.53 ± 0.34 dex
D_m<3 [Fe/H]~ -2.47 ± 0.31 dex



RR Lyrae in Carina are metal poor

RR Lyrae Metallicity estimates from Fourier Param.



Fourier params for GGCs RR Lyrae from literature ⇒ [Fe/H] estimated with Nemec et al. formulae.

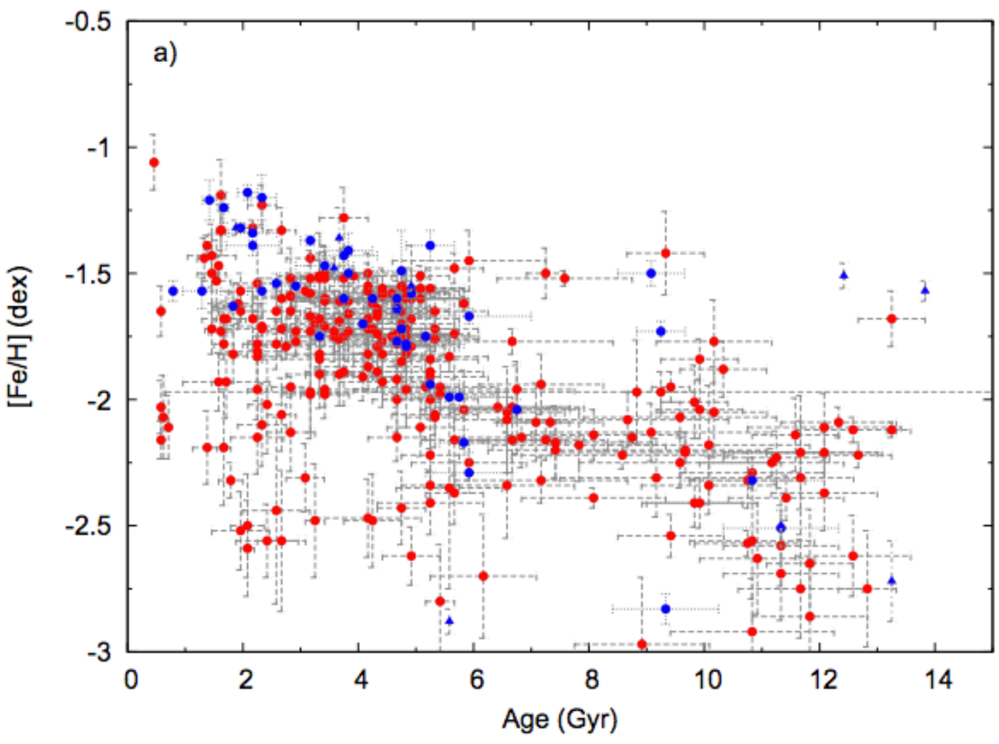
Comparison with spectroscopic [Fe/H] (Carretta et al. 2009)

Even if at the limit of validity of Nemec et al. relations ⇒ Carina RR Lyrae are most likely very metal poor ⇒ confirms results for RRd

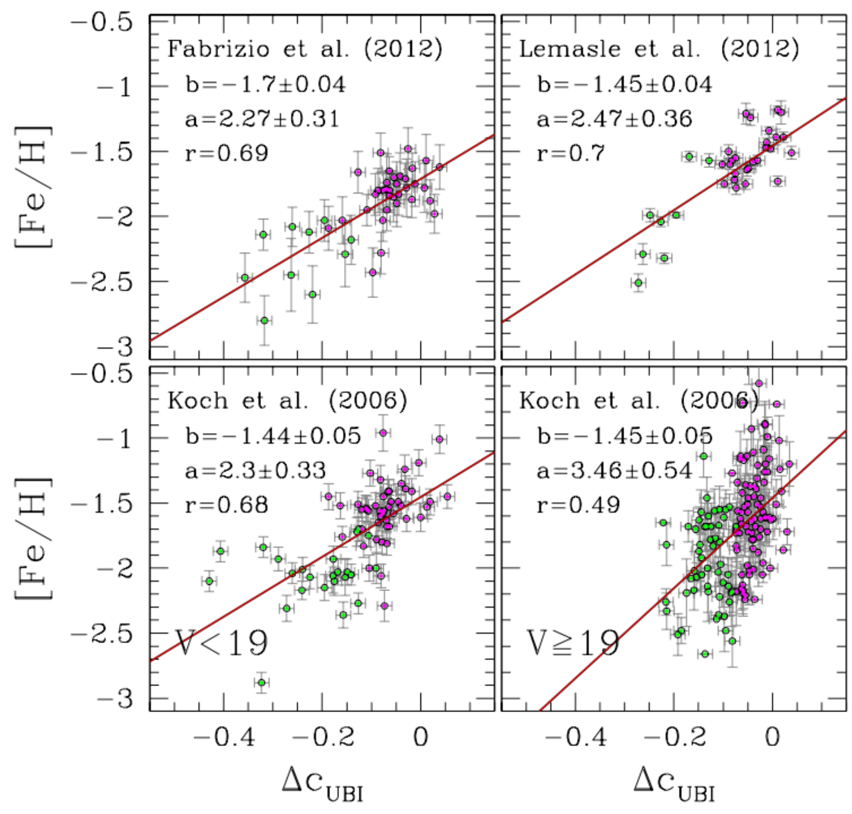
Metallicity of intermediate and old Carina populations by Monelli et al. (2014)

Metallicity of stellar populations in Carina

RR Lyrae results in agreement with recent independent literature findings based on different approaches.



de Boer et al. (2014)



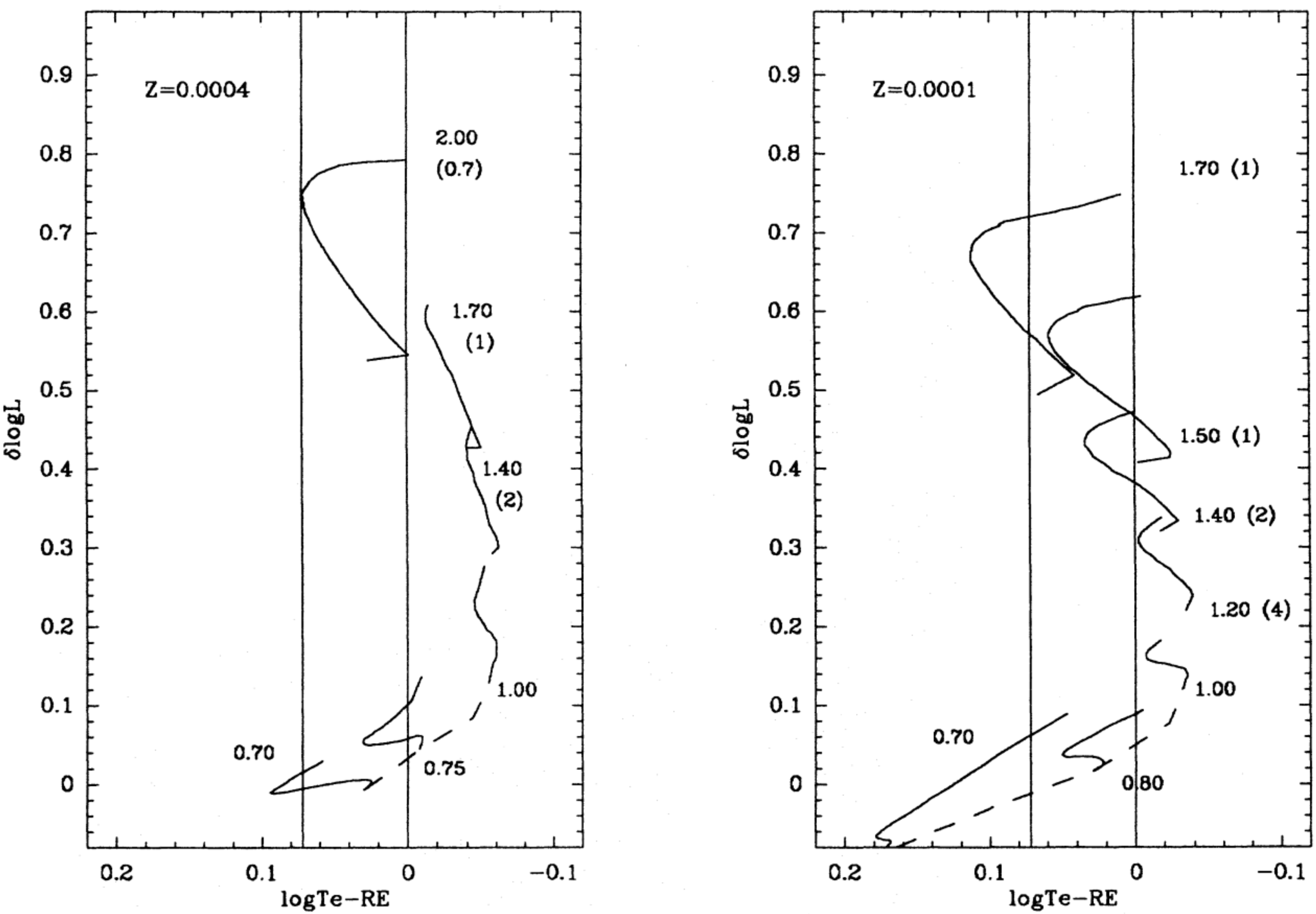
Monelli et al. (2014)

Conclusions

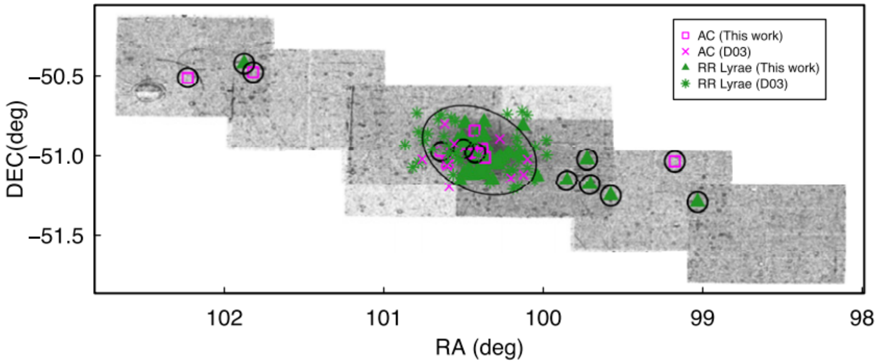
- We have presented a new census and analysis of the evolved variable star (RR Lyrae and ACs) in Carina.
- The pulsational properties of both RR Lyrae and ACs type of variables permit to add independent constraints on the star formation and chemical enrichment of host dSph.
- Updated pulsation models suggest that the PW(BV) do not depend from metallicity $\Rightarrow$ a powerful tool to estimate distances of systems hosting RR Lyrae.
- Theoretical and empirical (HST parallaxes) calibrations of the PW(BV) provide distances for Carina that are in close agreement one with each other.
- The analysis of the Carina RRd in the Petersen diagram $\Rightarrow$ metal poor at least as GGC M68 or M15
- Also the individual [Fe/H] estimates by means of Fourier params confirmas that the RR Lyrae in Carina (old polulation) should be definitely metal poor with [Fe/H] ~-2.4-2.5 dex in agreement with recent independent findings in the literature

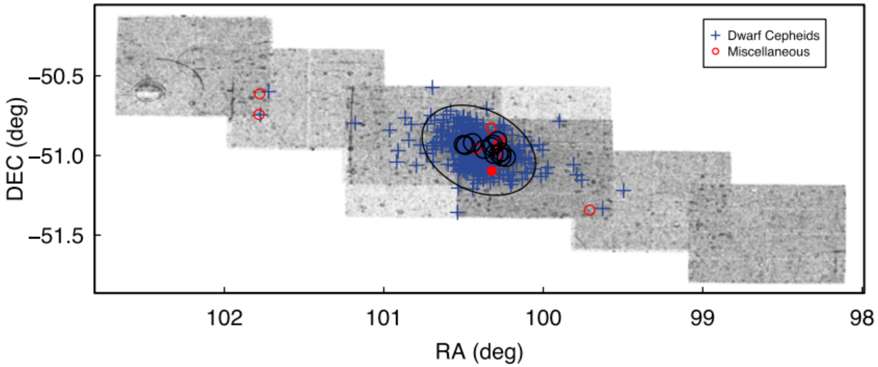
Coppola et al. in preparation

Anomalous Cepheids



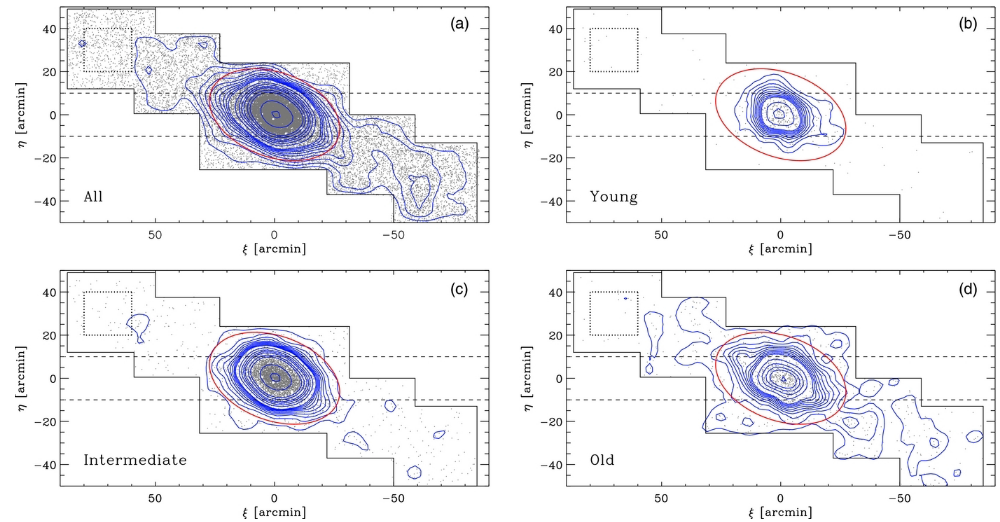
Position: Vivas & Mateo (2013)





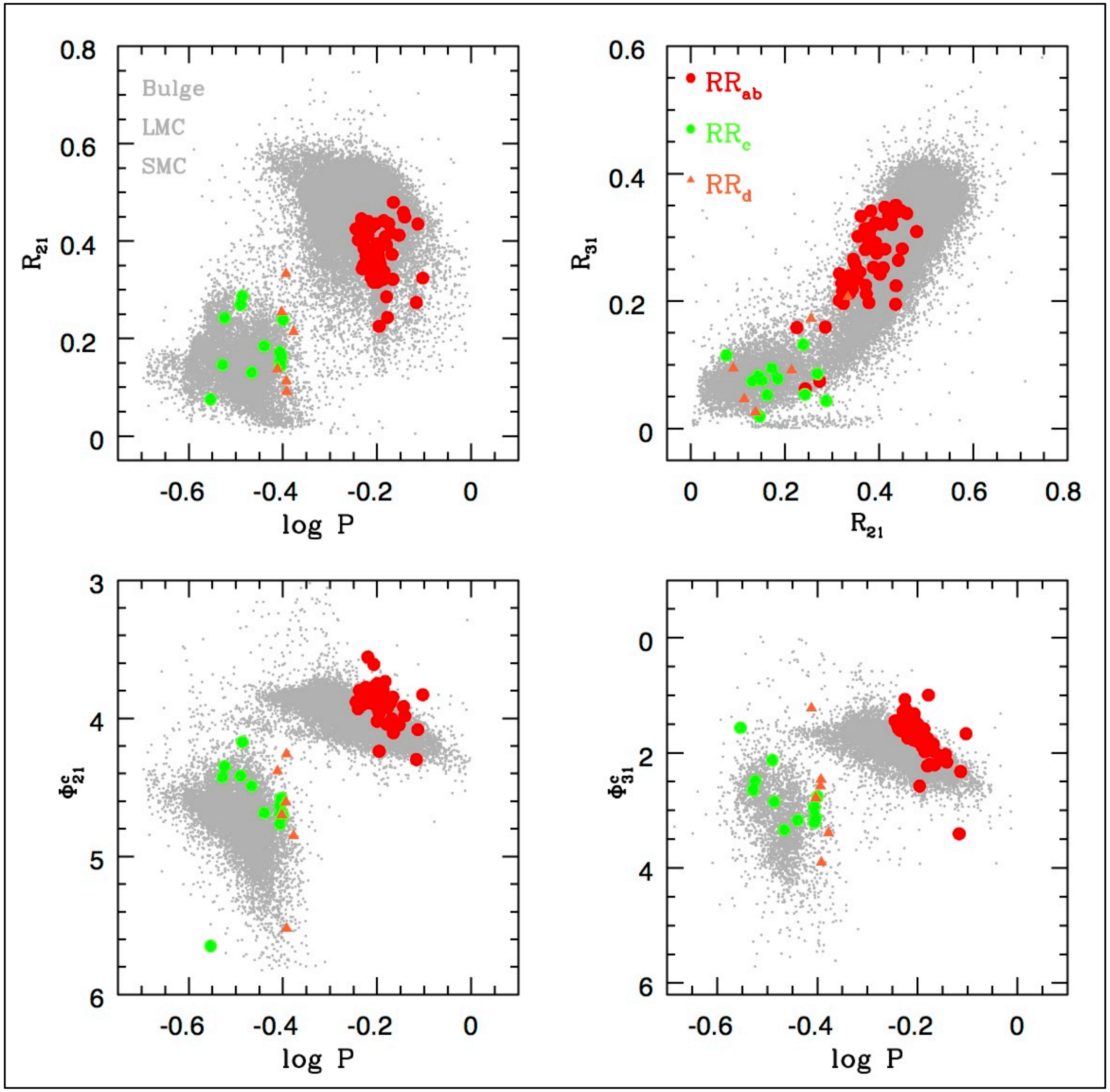
Extra-tidal RR Lyrae (old), ACs and SX Phe variables (intermediate)

In agreement with results by Battaglia et al. (2012)



Fourier parameters: RR lyrae

$$m(t) = A_0 + \sum_{i=1}^{F} A_i \sin[i\omega_0(t - t_0) + \phi_i],$$

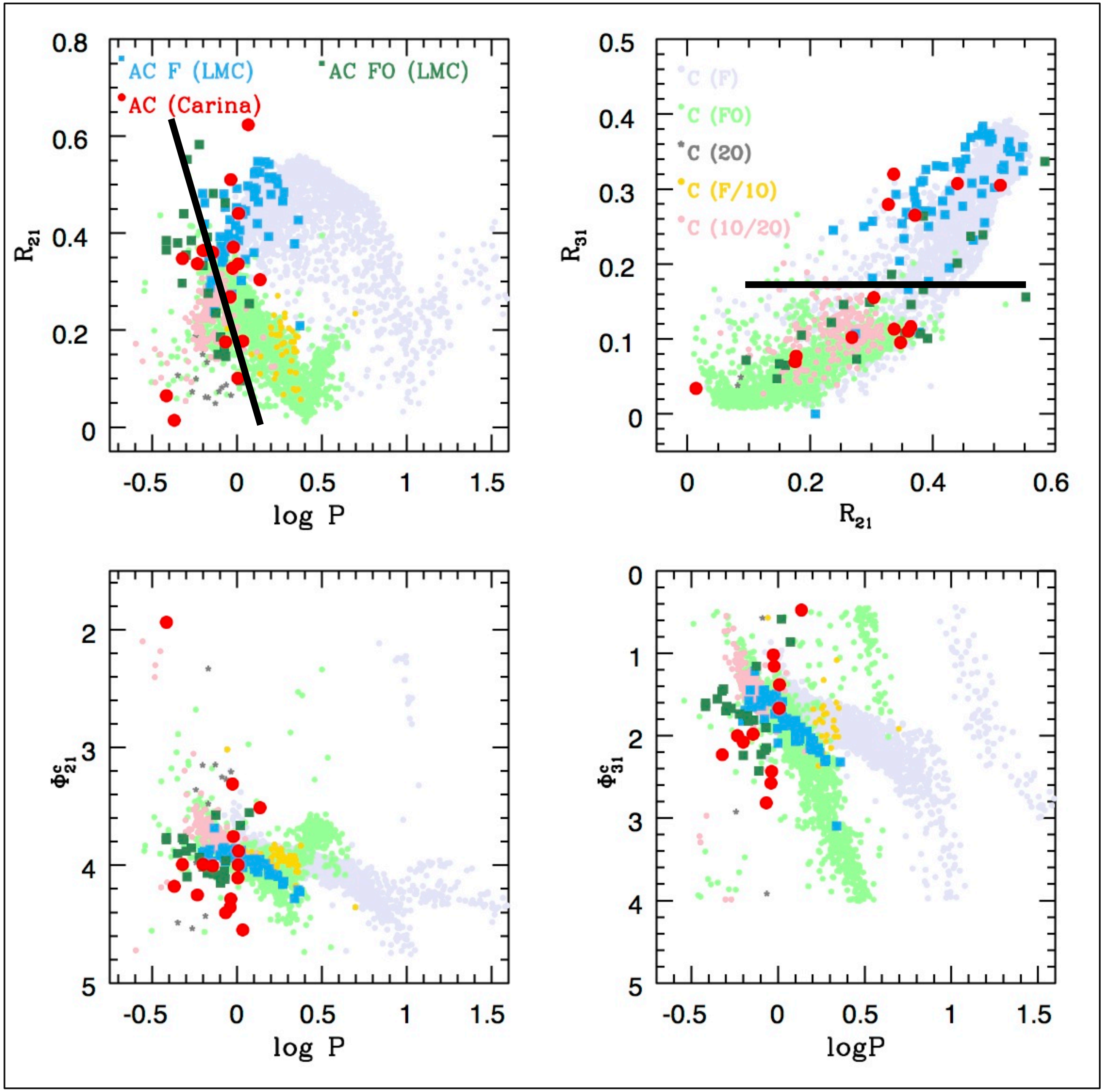


Useful to separate stars pulsating in different modes (e.g. Mantegazza & Poretti, 1992).

Almost straightforward for RR Lyrae

Bulge, LMC and SMC data from OGLE III

Fourier parameters: ACs



More tricky for ACs.

Try to use LMC as reference

The plane R_{21} vs R_{31} appears promising

Caveat: ACs in different environments have different properites

LMC and SMC data for Classical Cepheids and LMC ACs from OGLE III

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 <Pab> = 0.55 d

Oo II <Pab> = 0.64 d

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

Major Galaxy halo builders should show the same dichotomy.

The Carina project

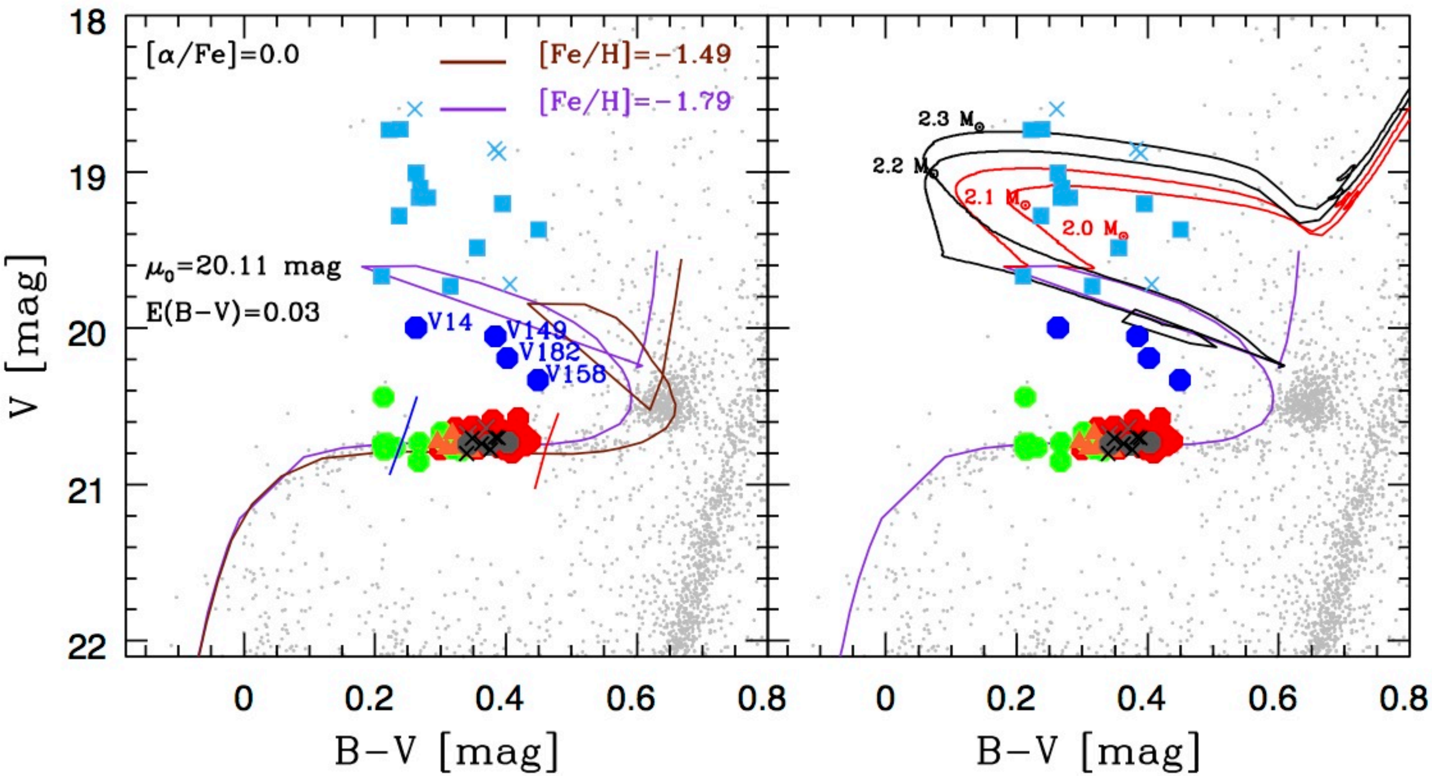
Previous papers of this serie:

- Photometry and Stellar polulation: Monelli et al. (2003), Bono et al. (2010), Monelli et al. (2014)
- Iron Content: Fabrizio et al. (2012)
- Radial velocities: Fabrizio et al. (2011); Fabrizio's talk
- Variable stars: Dall'Ora et al (2003), Coppola et al. (2013)

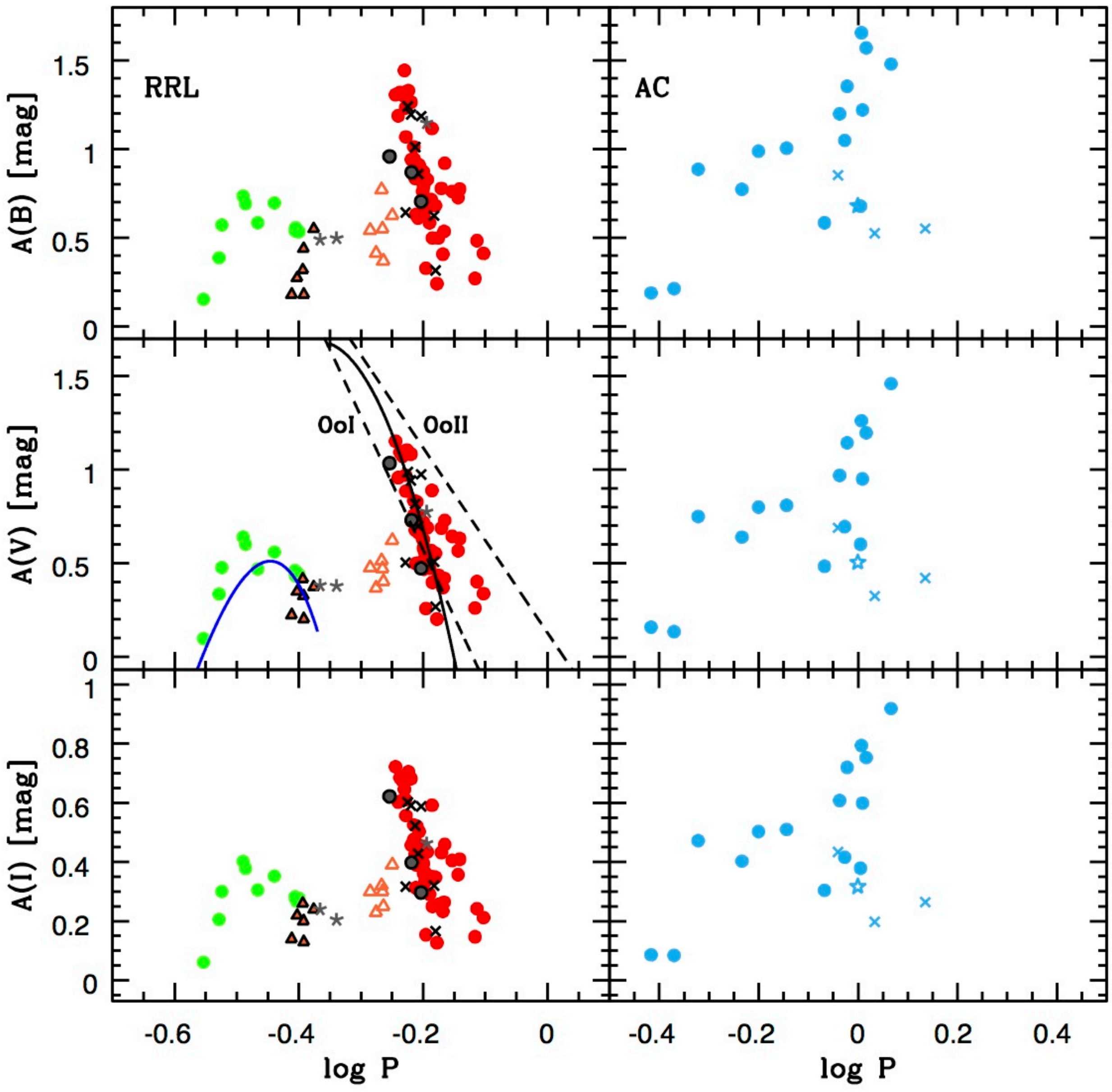
In this work we provide and discuss a complete inventory of the bright variable stars in Carina.

Partial results were already published in Coppola et al. (2013)

Bright variable stars



BVI Bailey diagram



Empirical Period-Wesenheit relations