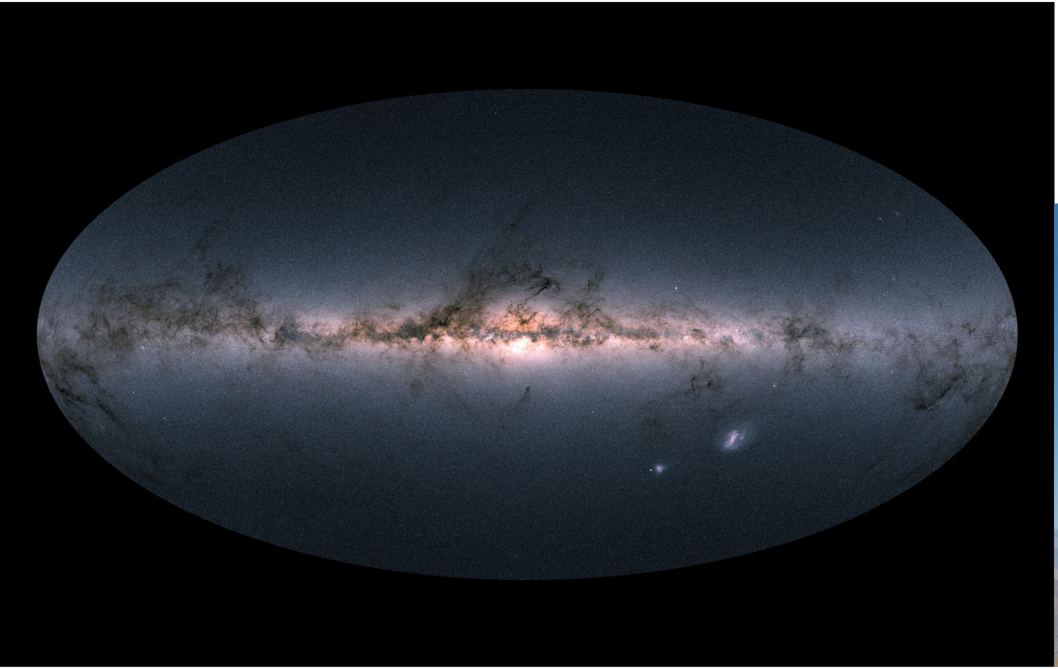
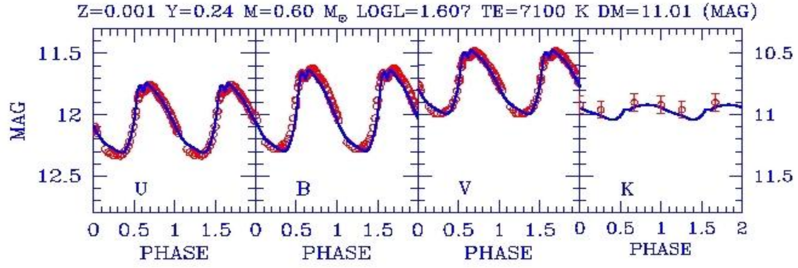
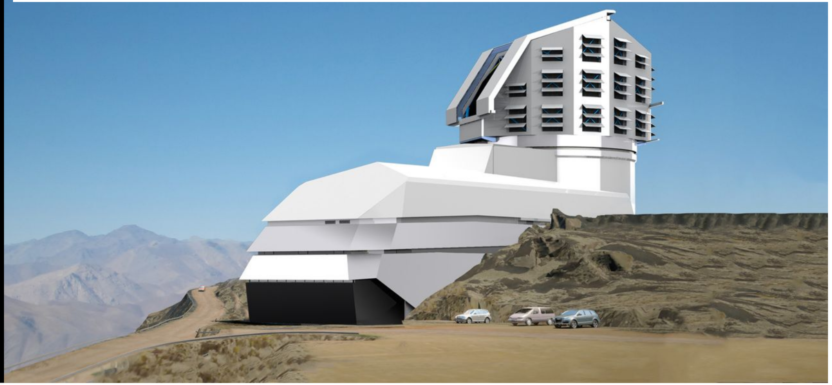
Modeling of RR Lyrae pulsating stars in the Gaia and Rubin-LSST era







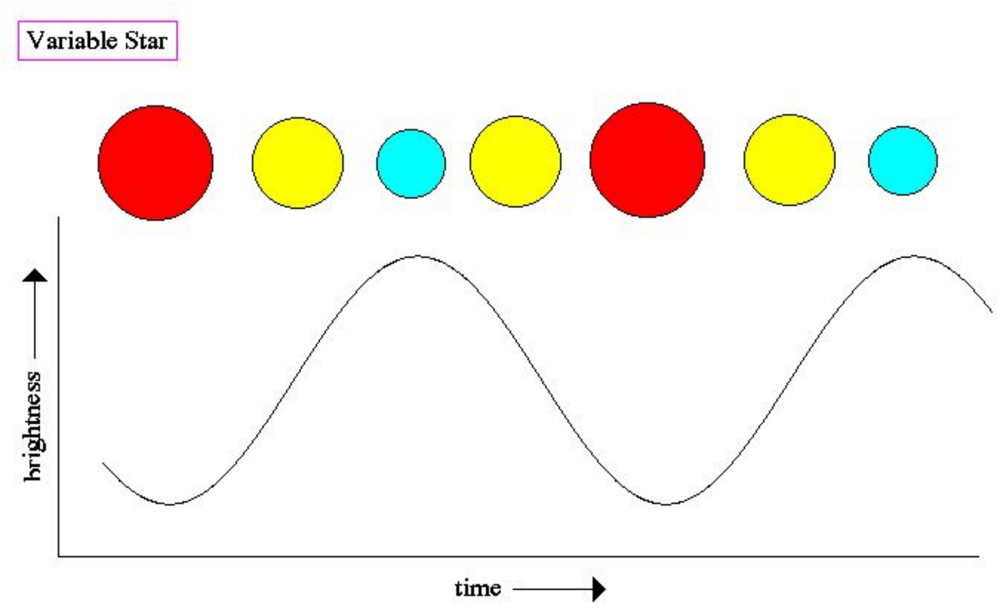
Marcella Marconi - INAF Osservatorio Astronomico di Capodimonte

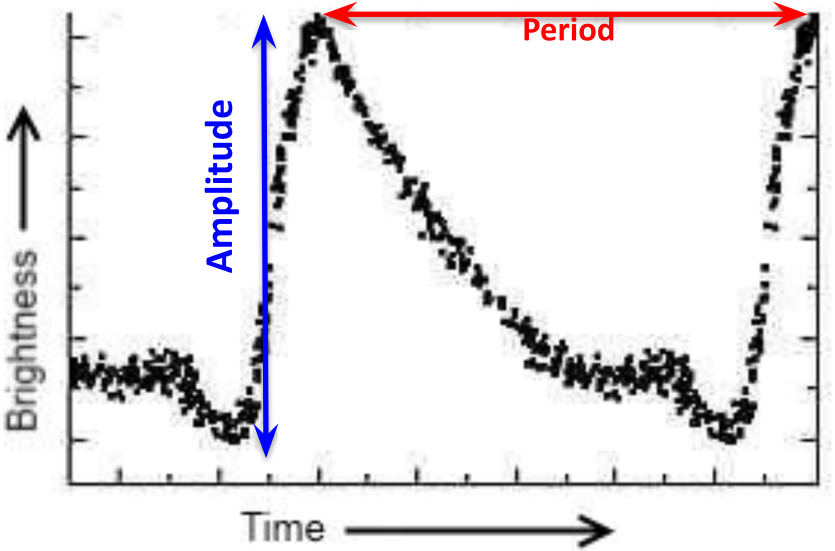
Outline

- Introduction on RR Lyrae stars
- RR Lyrae as standard candles
- Stellar pulsation model predictions
- The application to observations
- Next steps

RR Lyrae

RR Lyrae are pulsating variable stars





RR Lyrae

RR Lyrae are pulsating variable stars: the van Albada & Baker relation

$P\sqrt{\rho}$= costant + Stefan-Boltzmann → Period is a function of mass, luminosity, effective temperature (and chemical composition)

RR Lyrae

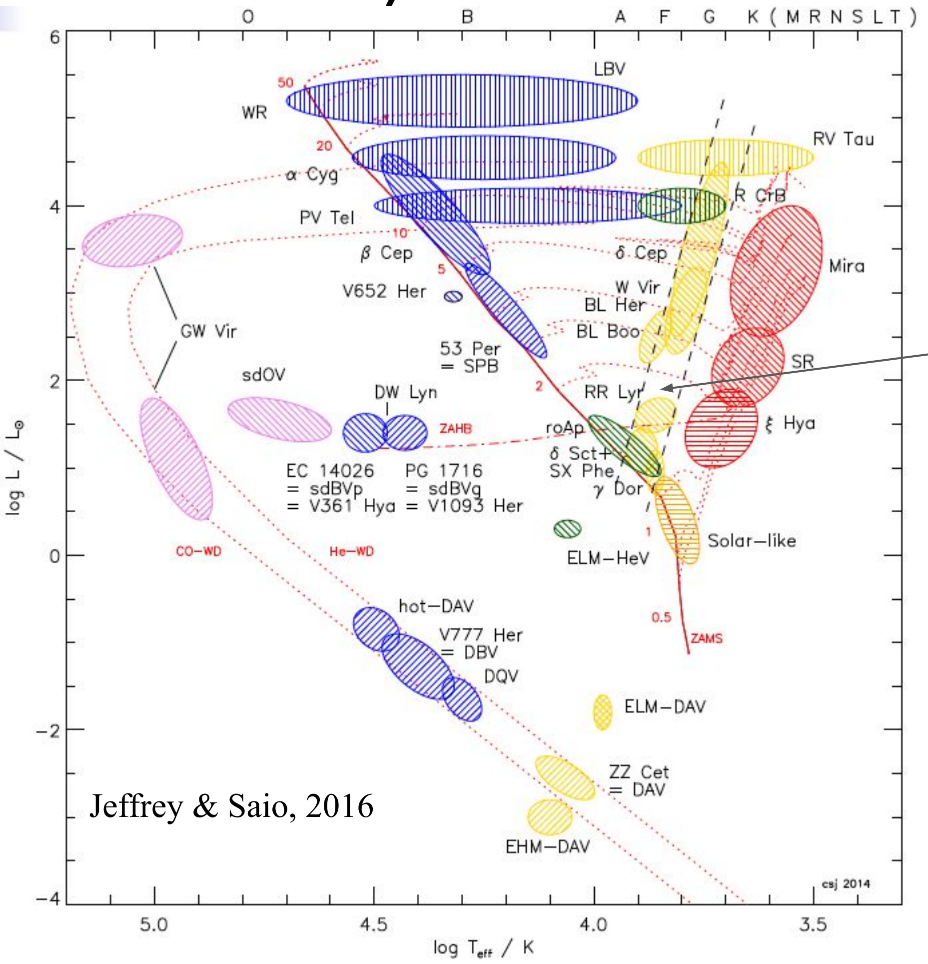
RR Lyrae are pulsating variable stars: the van Albada & Baker relation

$P\sqrt{\rho}$= costant + Stefan-Boltzmann → Period is a function of mass, luminosity, effective temperature (and chemical composition)

$$\log P = 11.497 - 3.48 \log T_e + 0.84 \log L - 0.68 \log M$$

(Van Albada & Baker 1971) for RR Lyrae (F mode)

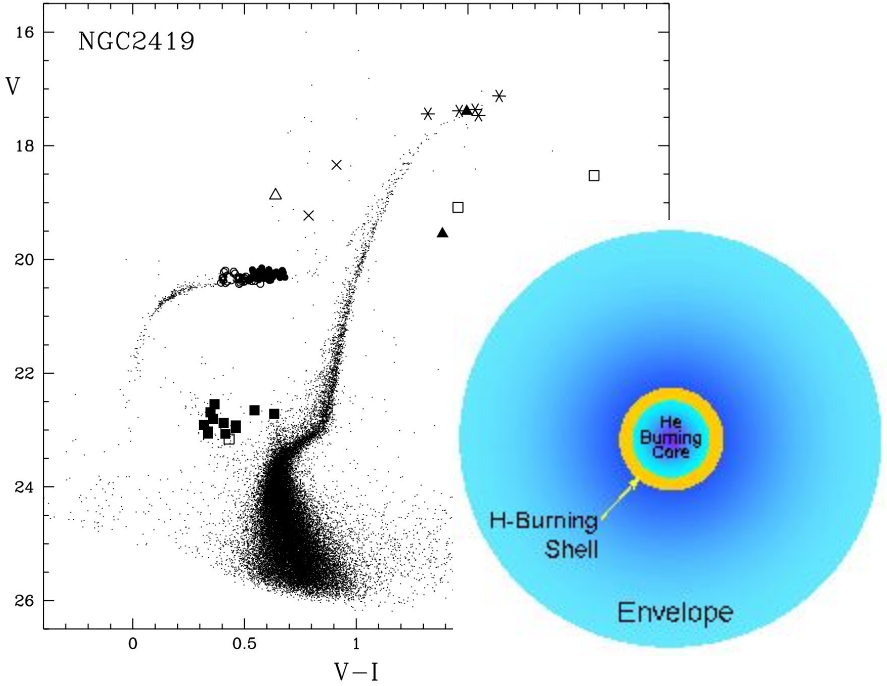
RR Lyrae within the instability strip



RR Lyrae lie within the classical instability strip → they share the same pulsation mechanisms with the other classes

RR Lyrae stars from the point of view of stellar evolution

- Low mass stars (typically from about 0.5 to about 0.8 $M_{\odot}$).
- Belong to old stellar populations (> 10 Gyr).
- Centrally helium burning (3 alpha) and shell CNO burning.
- They belong to the Horizontal Branch.

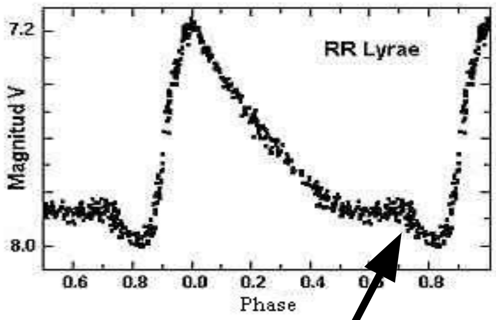


Credits: Di Criscienzo, Greco, Ripepi et al. 2011

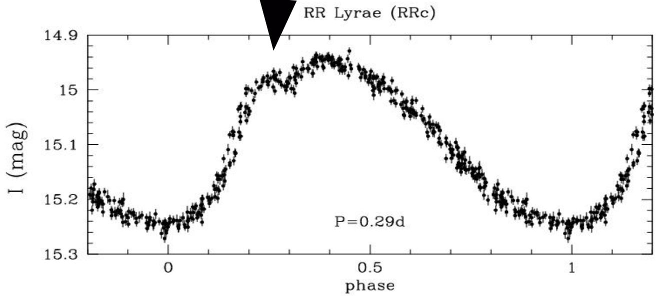
RR Lyrae as pulsating stars

- Periods typically between ~0.2 e ~1.0 d
- Well defined visual magnitude Mv~0.5-0.6 mag
- Three subgroups: RRab, RRc, RRd.

RR Lyrae types

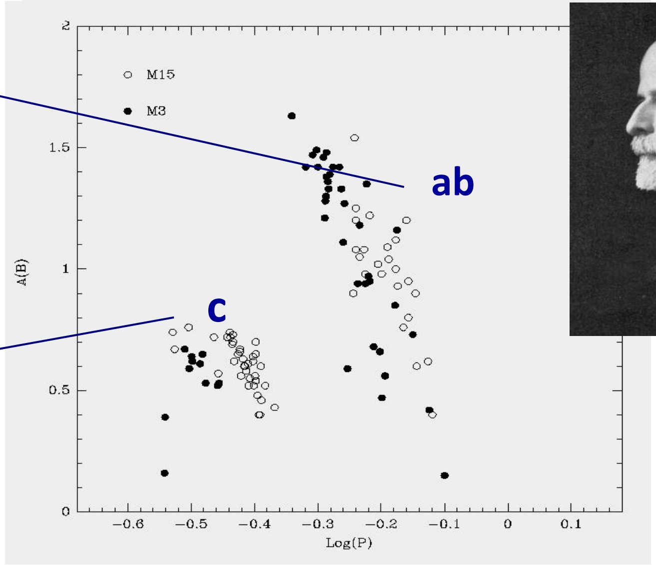


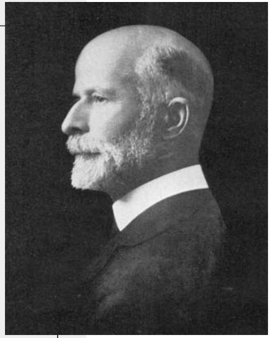
Light curve shape



Bailey diagram

S. I. Bailey (1854-1931)



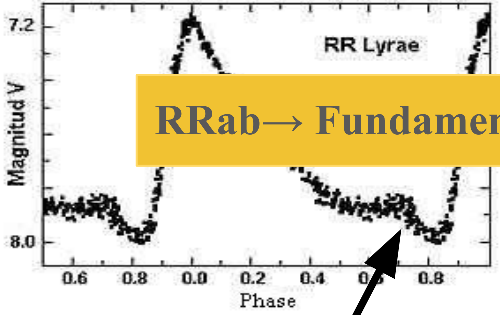


Amplitude

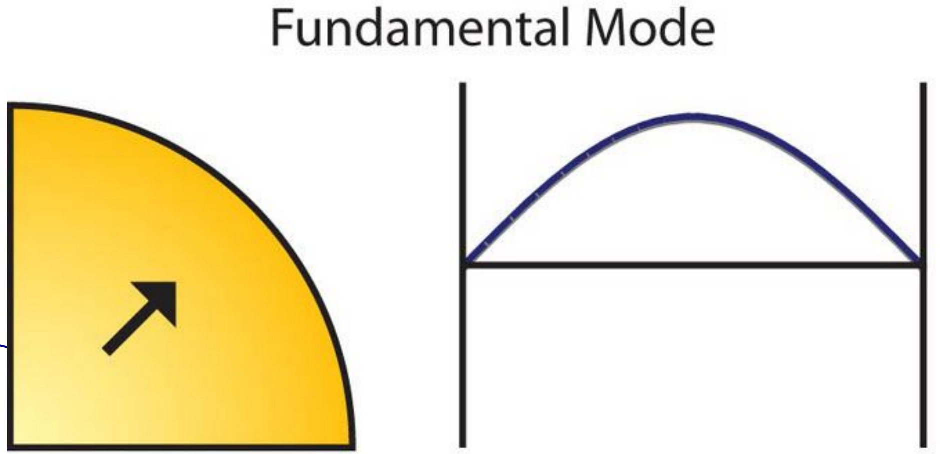
ab

c

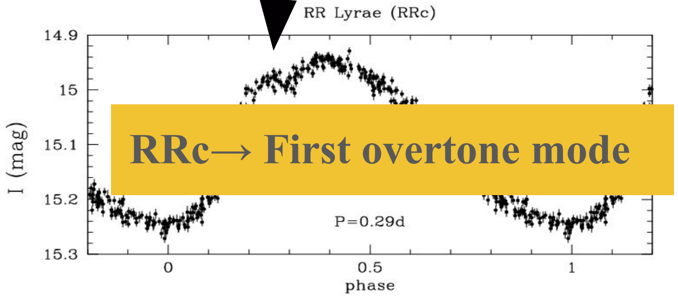
log Period



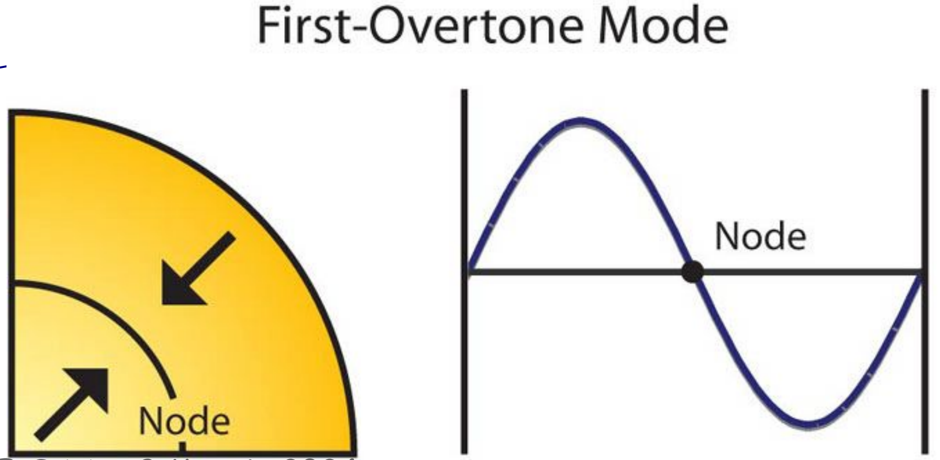
RRab→ Fundamental mode



Forma della curva di luce

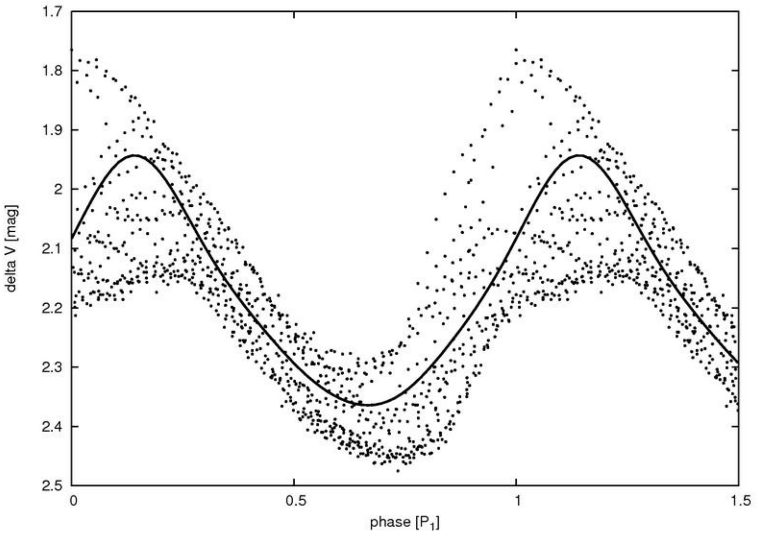


RRc→ First overtone mode



RR Lyrae types

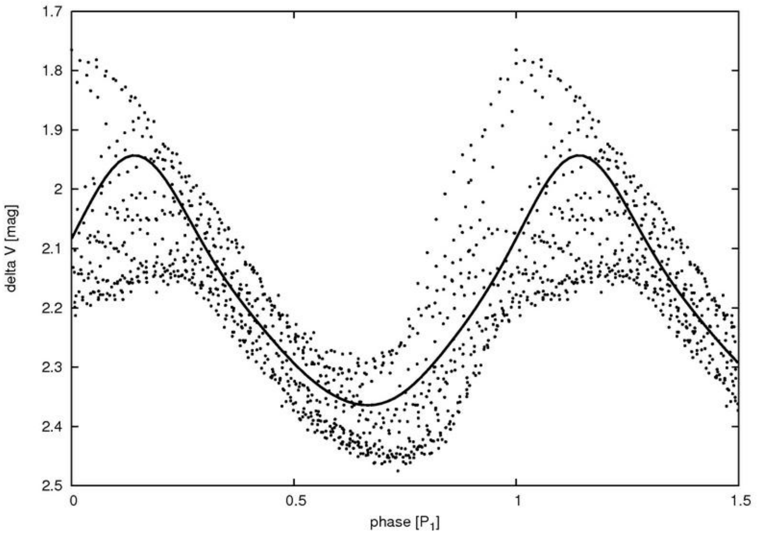
RRd pulsator



RRd are double mode RR Lyrae, oscillating both in the Fundamental and in the First Overtone mode.

RR Lyrae types

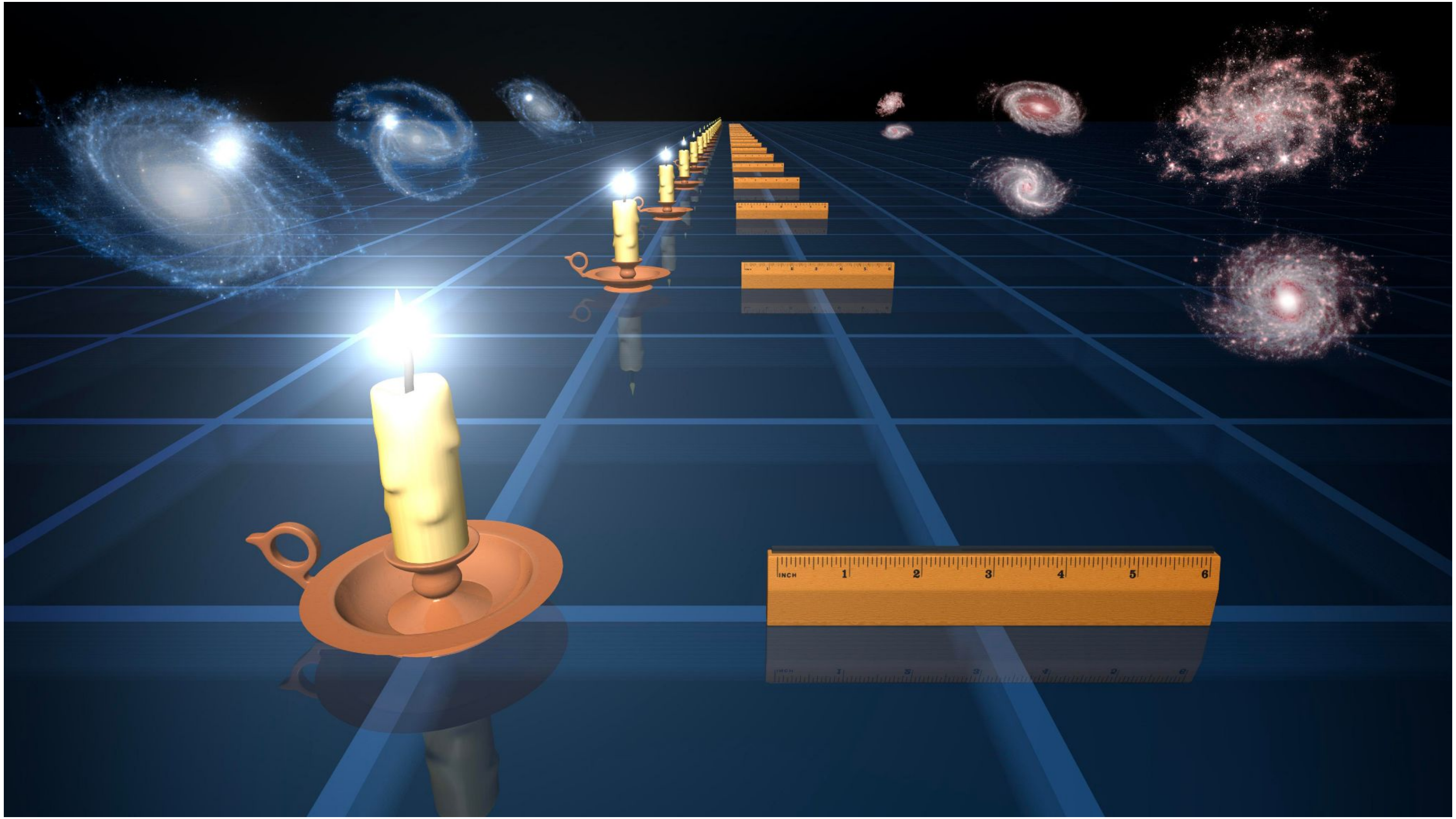
RRd pulsator



RRd are double mode RR Lyrae, oscillating both in the Fundamental and in the First Overtone mode.

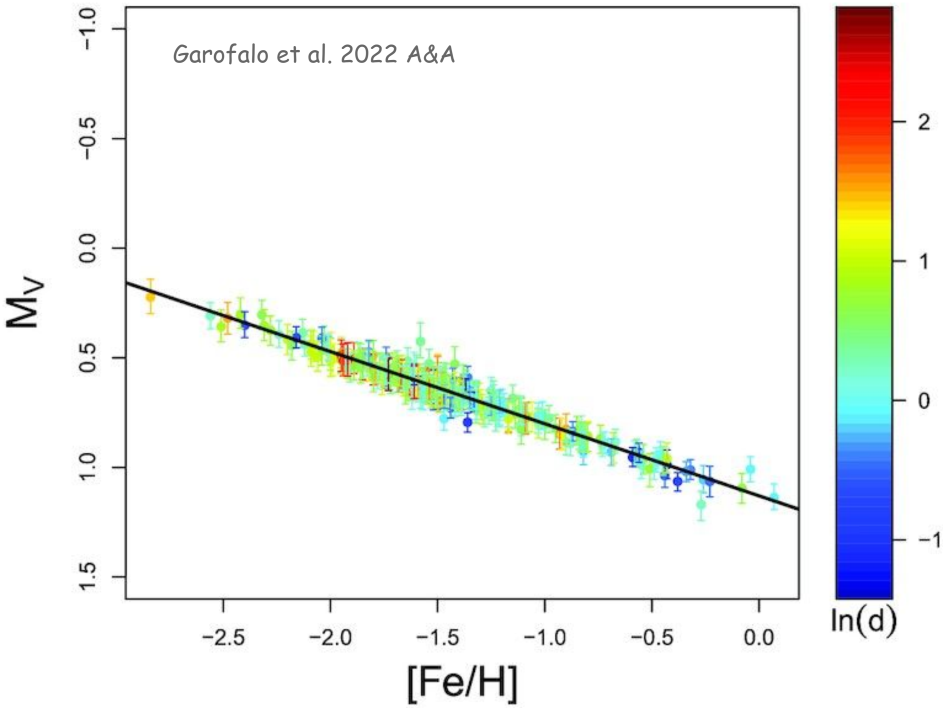
The period ratio depends on the stellar mass (Petersen diagram)

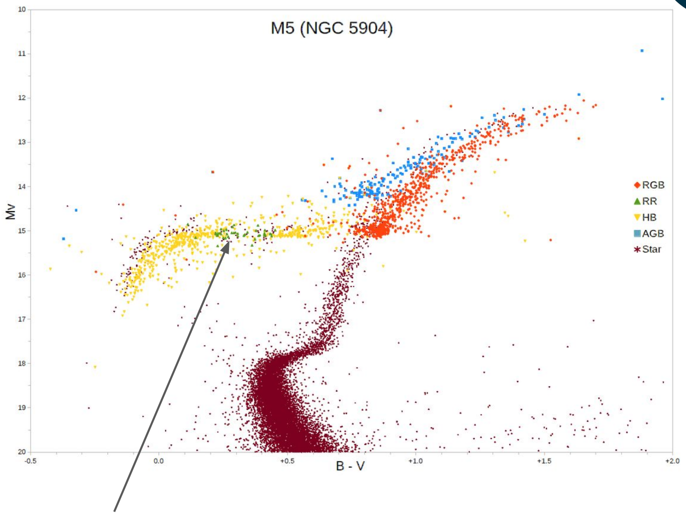
RR Lyrae are standard candles



RR Lyrae as standard candles: the MV-[Fe/H] relation

Visual luminosity versus metallicity





RR Lyrae belong to the Horizontal Branch phase so that their visual magnitude is ~constant at varying the effective temperature but depends on metallicity.

RR Lyrae as standard candles: the MV-[Fe/H] relation

Possible sources of uncertainties:

M_V(RR) depends on the RR Lyrae evolutionary status (ZAHB versus evolved RR Lyrae)

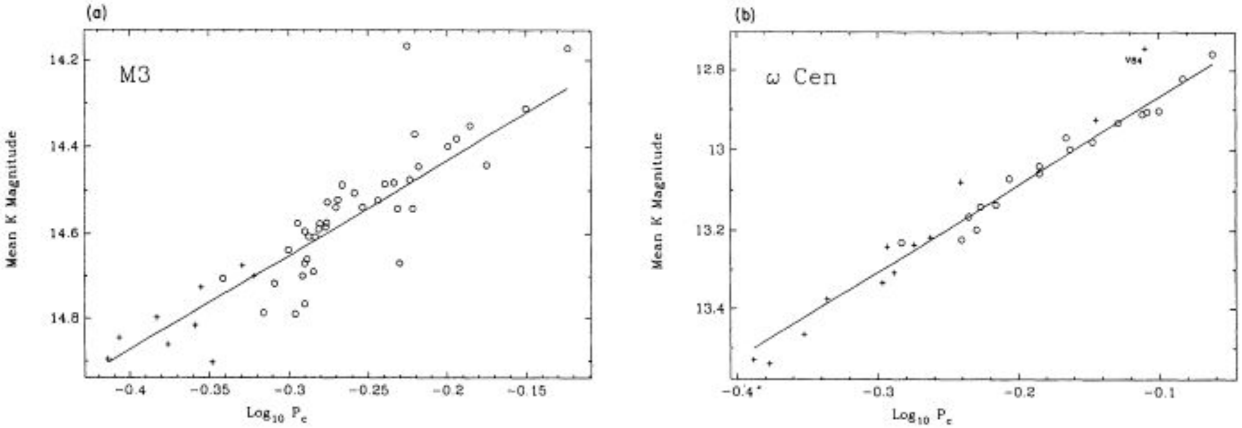
The individual M_V(RR) are mean magnitudes different from static ones (be careful when comparing with M_V(ZAHB) or M_V(HB))

As for the metallicity term the α element enhancement has to be taken into account and there is a non negligible dependence on the adopted metallicity scale.

Results of stellar evolution and pulsation models suggest a NON linear relation when the whole observed metallicity range is considered

Note also that M_V(RR) is affected by the He content.
If Y increases from 0.24 to 0.38 at Z=0.001 the predicted $\log L/L_{\odot}$ increases by about 0.2 dex

RR Lyrae as standard candles: the NIR PL relation



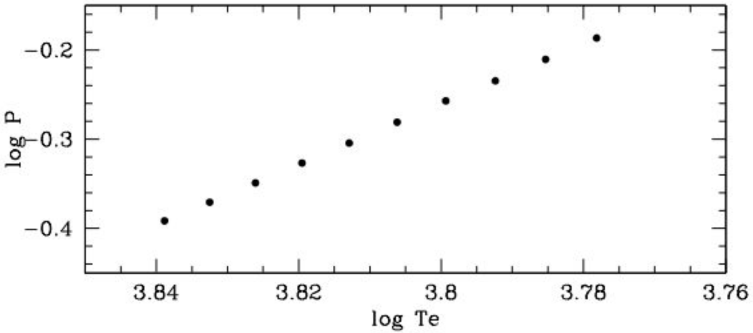
Adapted from Longmore et al. 1990 MNRAS

In the NIR bands and, in particular in K, RR Lyrae obey to a PL relation
(since the pioneering investigations by Longmore et al. 1986, 1990 MNRAS)

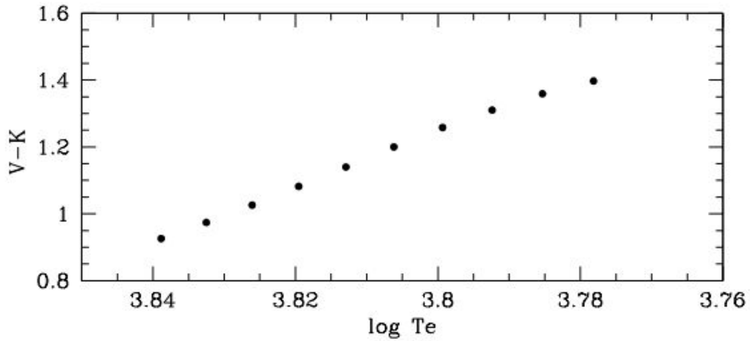
RR Lyrae as standard candles: the NIR PL relation

Why a PL relation?

Model predict that at roughly fixed mass and luminosity the pulsation period is anticorrelated with the effective temperature ← *Period-Mean density relation*

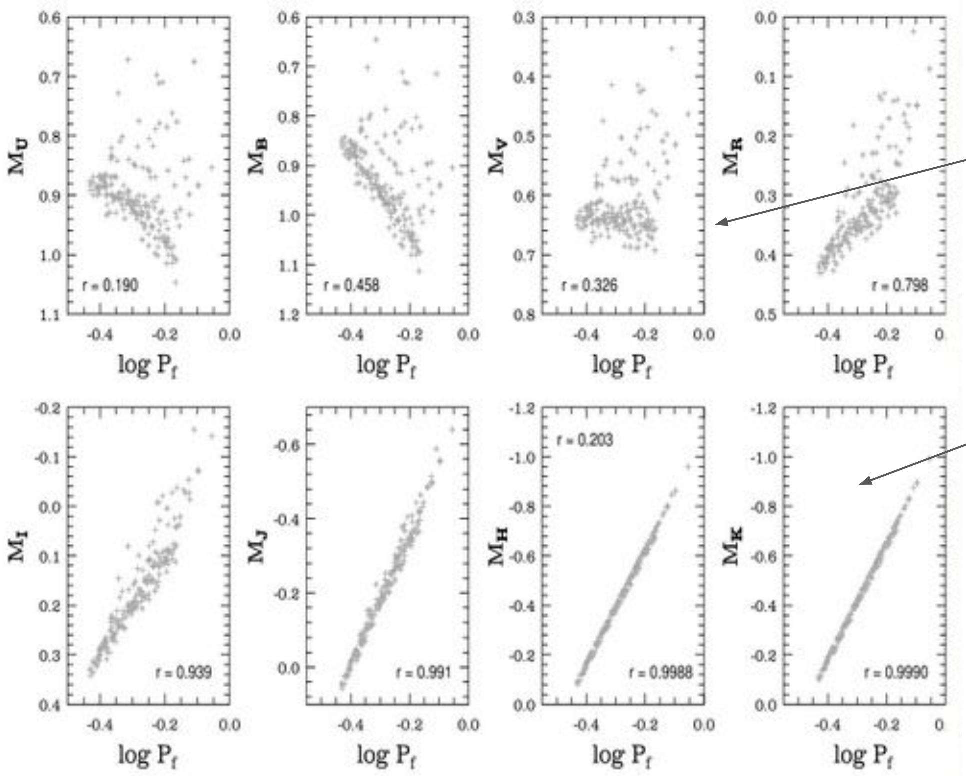


The V-K color is a well known linear function of $\log T_e$



RR Lyrae as standard candles: the NIR PL relation

The Period-Luminosity relation

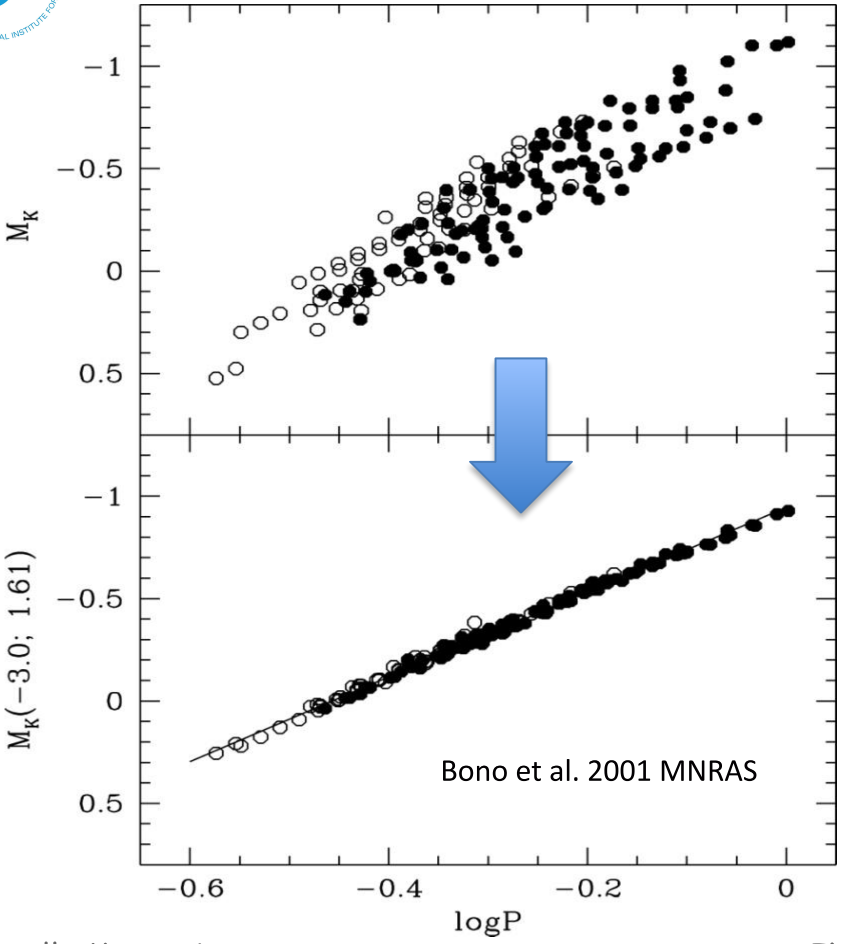


The optical magnitude does not correlate with the pulsation period.

In the NIR bands → PL relation

Catelan et al. 2004 ApJS

RR Lyrae as standard candles: the NIR PL relation



Correcting for metallicity differences and evolutionary effects the dispersion is significantly decreased !

The true relation is of the form

$M_K = a + b \log P + c\,[Fe/H]$

RR Lyrae as standard candles: the NIR PL relation

Difficult to quantify the [Fe/H] term

Stellar evolution and pulsation models of RR Lyrae stars ⟶ ~0.18 mag/dex in JHKs (Catelan et al. 2004; Marconi et al. 2015).

RR Lyrae as standard candles: the NIR PL relation

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Empirical studies ⟶ wide range (0.03–0.23 mag/dex in Ks; Sollima et al. 2006, 2008; Bono et al. 2011; Muraveva et al. 2015; Braga et al. 2018; Muraveva et al. 2018; Layden et al. 2019; Neeley et al. 2019; Cusano et al. 2021; Muhie et al. 2021, and references therein).

RR Lyrae as standard candles: the NIR PL relation

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Most of the empirical investigations were carried out only in the Ks band, and very few of them included all three JHKs filters.

Neeley et al. (2019) → metallicity coefficient consistent with theory but with 4 times larger scatter

Bhardwaj et al. (2023) → excellent agreement with theory (see following slides)

Stellar pulsation model predictions

Current approaches in the modeling of RR Lyrae stars

Stellar pulsation model predictions

Current approaches in the modeling of RR Lyrae stars

Linear non adiabatic pulsation models

Typically predict periods and (blue) edges of the instability strip

Stellar pulsation model predictions

Current approaches in the modeling of RR Lyrae stars

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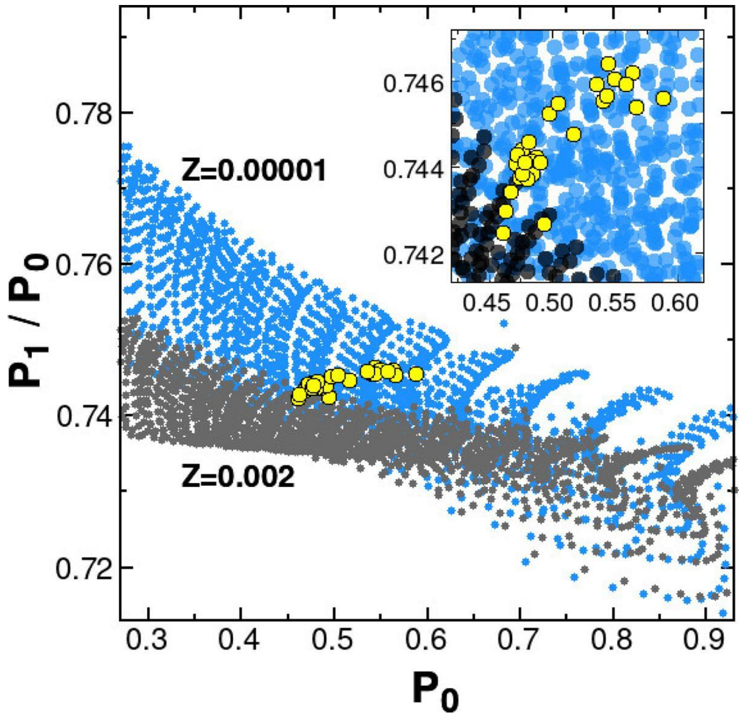
Kovacs & Karamiquchan 2021 A&A → Modelling double mode RR Lyrae



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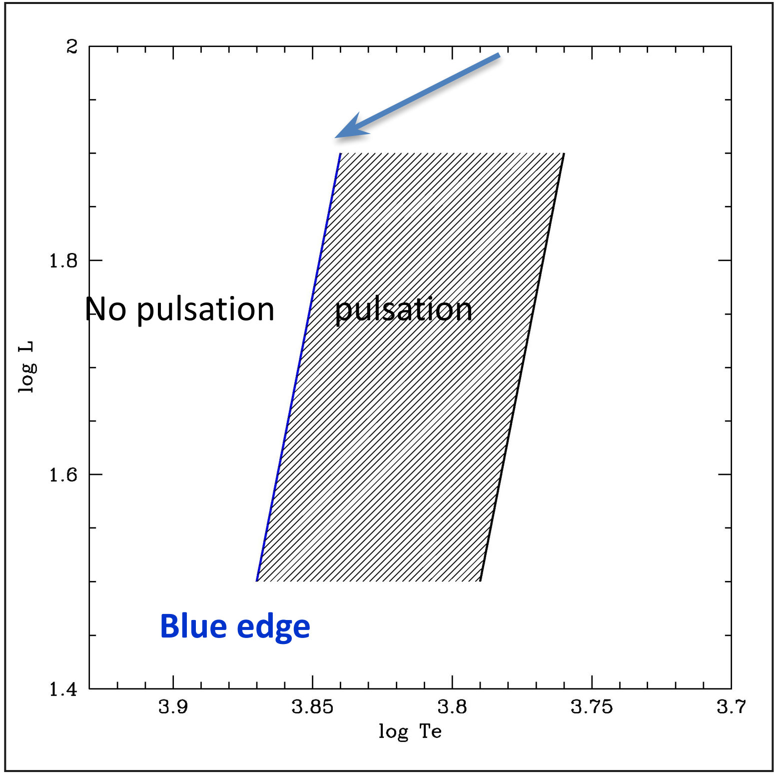


Stellar pulsation model predictions

Current approaches in the modeling of RR Lyrae stars

Linear non adiabatic pulsation models

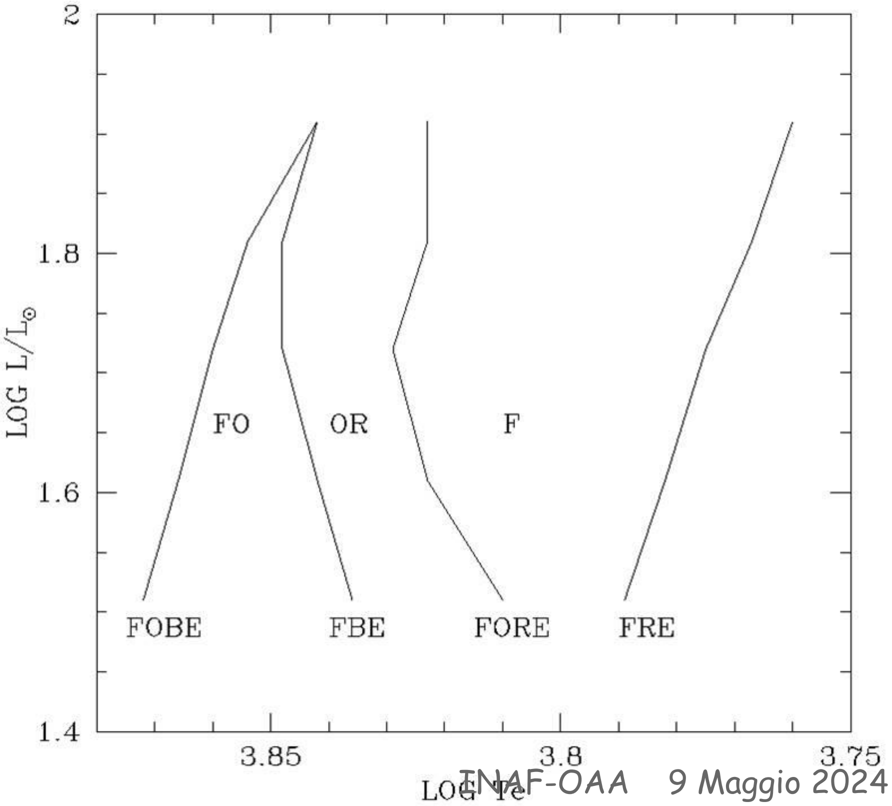
Typically predict periods and (blue) edges of the instability strip

Non linear convective pulsation models

All the pulsation observables: periods, amplitudes, light curve morphology, blue and red edges of the instability strip

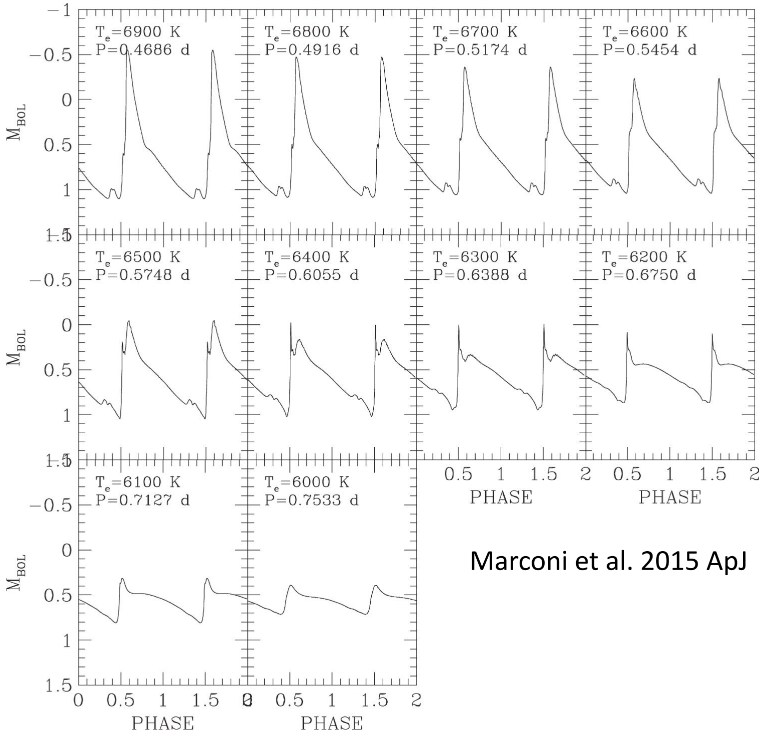
Stellar pulsation model predictions

Nonlinear convective pulsation models of RR Lyrae stars (e.g. Bono & Stellingwerf 1994, Bono et al. 1997, 2001, 2003, Di Criscienzo et al. 2004, Marconi et al. 2003, 205,2018,2021, Paxton et al. 2019)



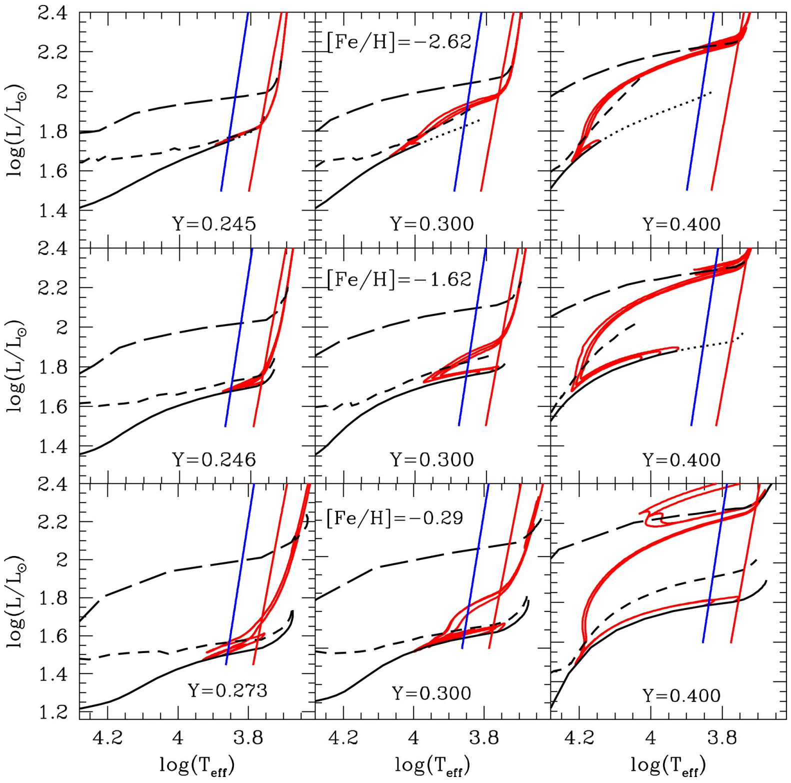
Nonlinear convective RR Lyrae pulsation models

Predicted light curves



Marconi et al. 2015 ApJ

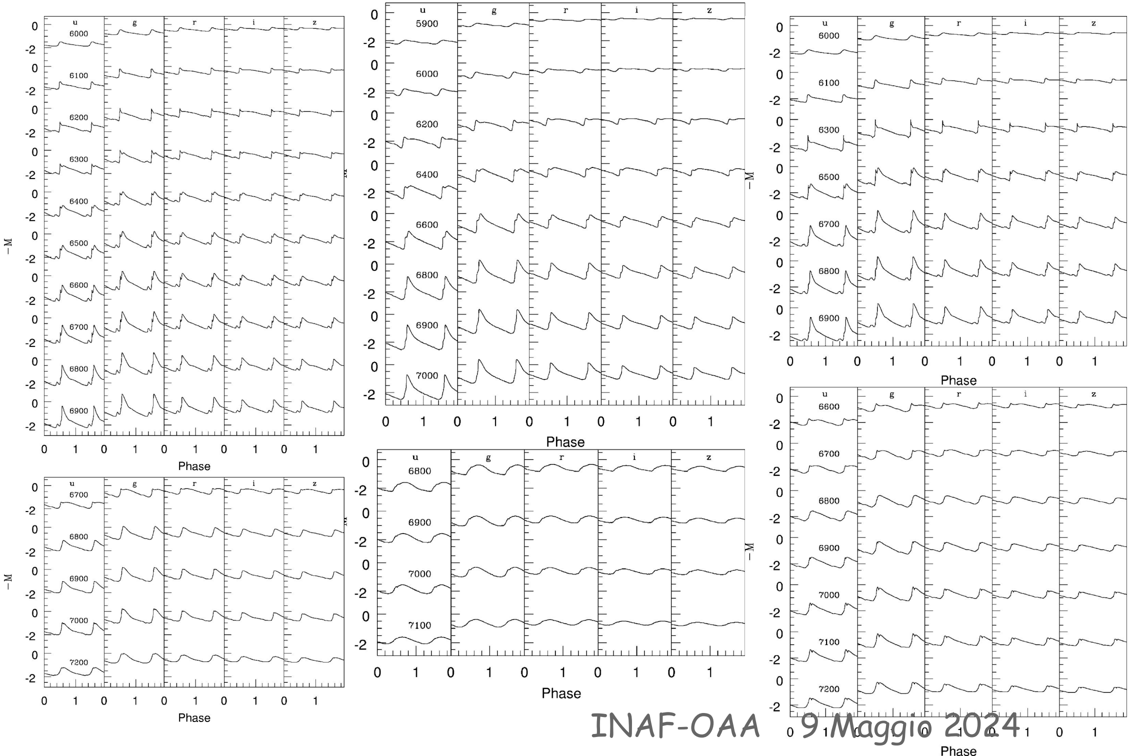
The predicted instability strip



Marconi, Bono, Pietrinferni et al. 2018 ApJL

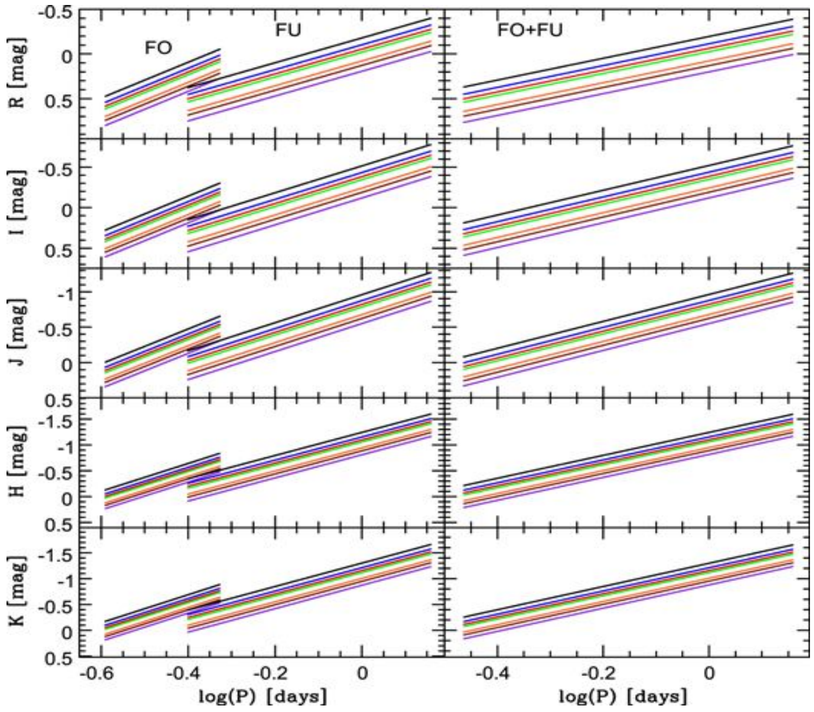
From bolometric to the various bands

Bolometric light curves + model atmospheres → predicted multi-filter light curves, mean magnitudes and colors

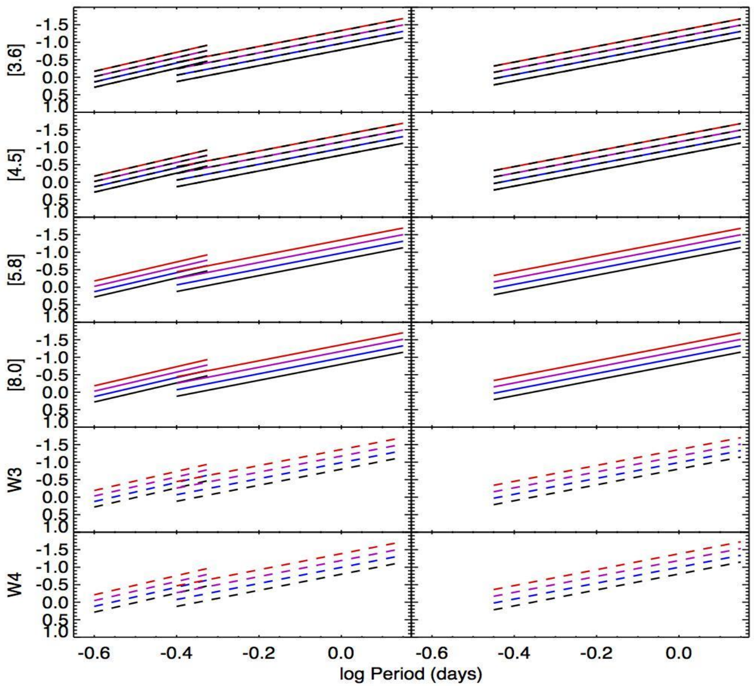


Marconi et al. 2006 MNRAS

Predicted RR Lyrae PL relations: the metallicity effect



Marconi+ 2015 ApJ



Neeley+ 2017 ApJ

Predicted RR Lyrae PLZ relations

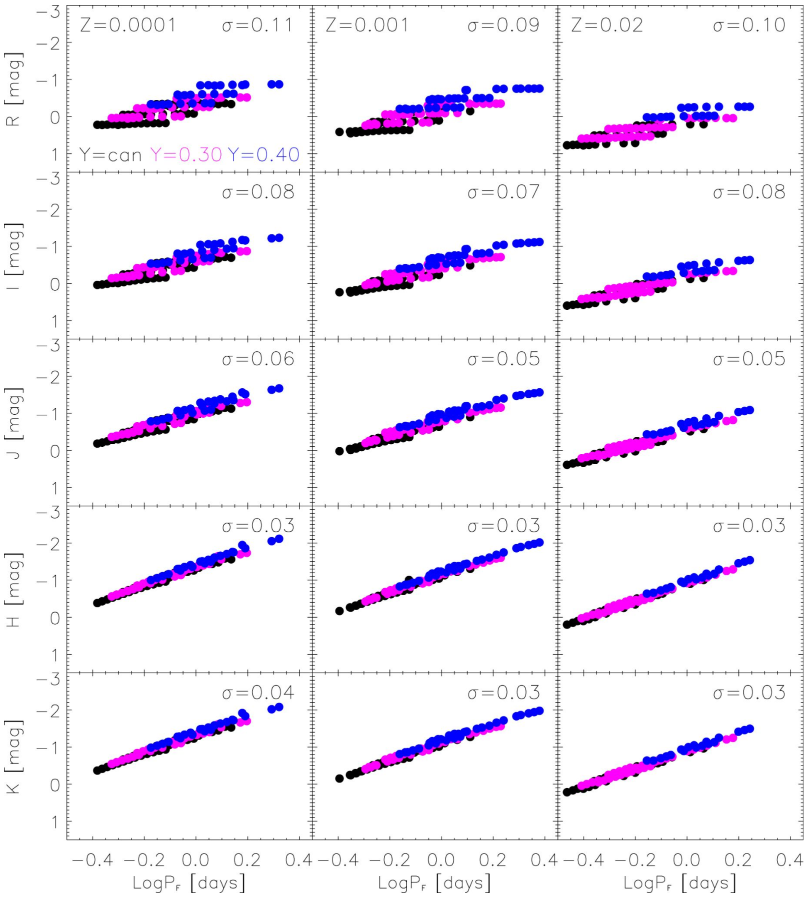
Mag = a + b logP + c [Fe/H]

Coefficients of the Predicted Metal-dependent Optical and NIR (*RIJHK*) PLZ Relations for FU, FO, and FU+FO Pulsators

Type[a]	Band[b]	a[c]	b[d]	c[e]	σ_a[f]	σ_b[f]	σ_c[f]	rms[g]
FU	*R*	0.24	−1.39	0.17	0.02	0.07	0.01	0.10
FO	*R*	−0.34	−2.00	0.14	0.07	0.10	0.01	0.07
Glob	*R*	0.25	−1.22	0.17	0.02	0.06	0.01	0.10
FU	*I*	−0.07	−1.66	0.17	0.02	0.06	0.01	0.09
FO	*I*	−0.65	−2.20	0.14	0.06	0.10	0.01	0.05
Glob	*I*	−0.07	−1.53	0.17	0.02	0.04	0.01	0.09
FU	*J*	−0.51	−1.98	0.17	0.01	0.04	0.01	0.06
FO	*J*	−1.07	−2.46	0.15	0.04	0.08	0.01	0.04
Glob	*J*	−0.50	−1.90	0.18	0.01	0.03	0.01	0.06
FU	*H*	−0.76	−2.24	0.19	0.01	0.02	0.01	0.04
FO	*H*	−1.31	−2.70	0.16	0.02	0.04	0.01	0.02
Glob	*H*	−0.76	−2.22	0.18	0.01	0.02	0.01	0.04
FU	*K*	−0.82	−2.27	0.18	0.01	0.02	0.01	0.03
FO	*K*	−1.37	−2.72	0.15	0.02	0.04	0.01	0.02
Glob	*K*	−0.82	−2.25	0.18	0.01	0.02	0.01	0.04

Marconi et al. 2015 ApJ

Predicted RR Lyrae PL relations: the effect of He abundance



Y=0.40

Y=0.30

Standard Y

Marconi et al. 2018 ApJL

Predicted RR Lyrae PLZY relations

Coefficients of the Predicted Global (Fundamental Plus First Overtone) Period–Luminosity–Metallicity–Helium (PLZY) Relations for RRLs in the Form $M_X = a + b \log P + c[\mathrm{Fe/H}] + d \log Y$, where X is the Selected Band

Band	a	b	c	d	σ
R	−0.63 ± 0.13	−1.30 ± 0.03	0.195 ± 0.007	−1.34 ± 0.07	0.13
I	−0.80 ± 0.11	−1.58 ± 0.03	0.190 ± 0.005	−1.10 ± 0.06	0.11
J	−1.00 ± 0.08	−1.92 ± 0.02	0.187 ± 0.004	−0.82 ± 0.04	0.08
H	−1.14 ± 0.06	−2.23 ± 0.02	0.188 ± 0.003	−0.55 ± 0.03	0.06
K	−1.16 ± 0.06	−2.26 ± 0.02	0.185 ± 0.003	−0.52 ± 0.03	0.06

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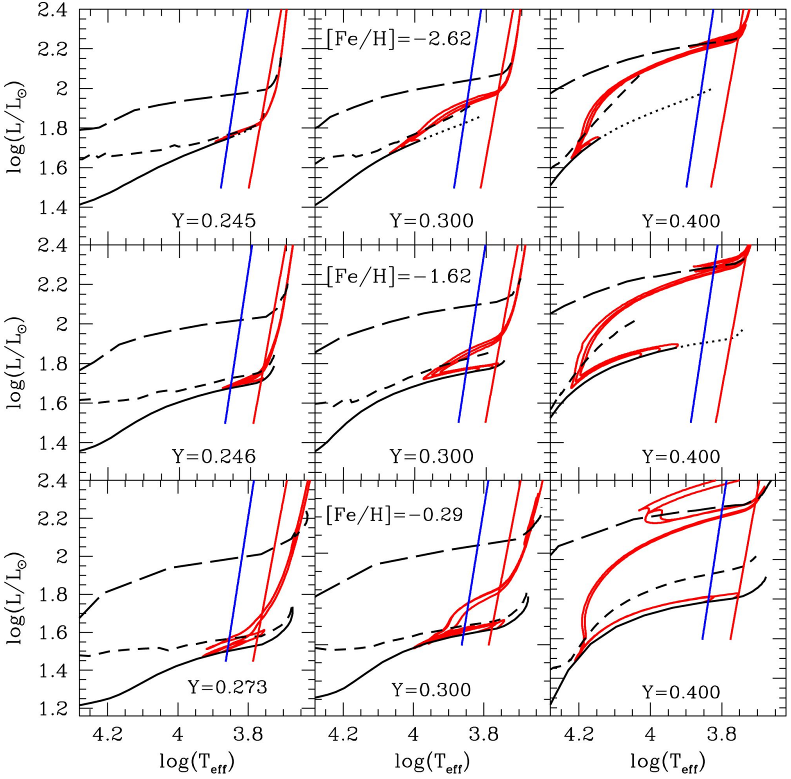
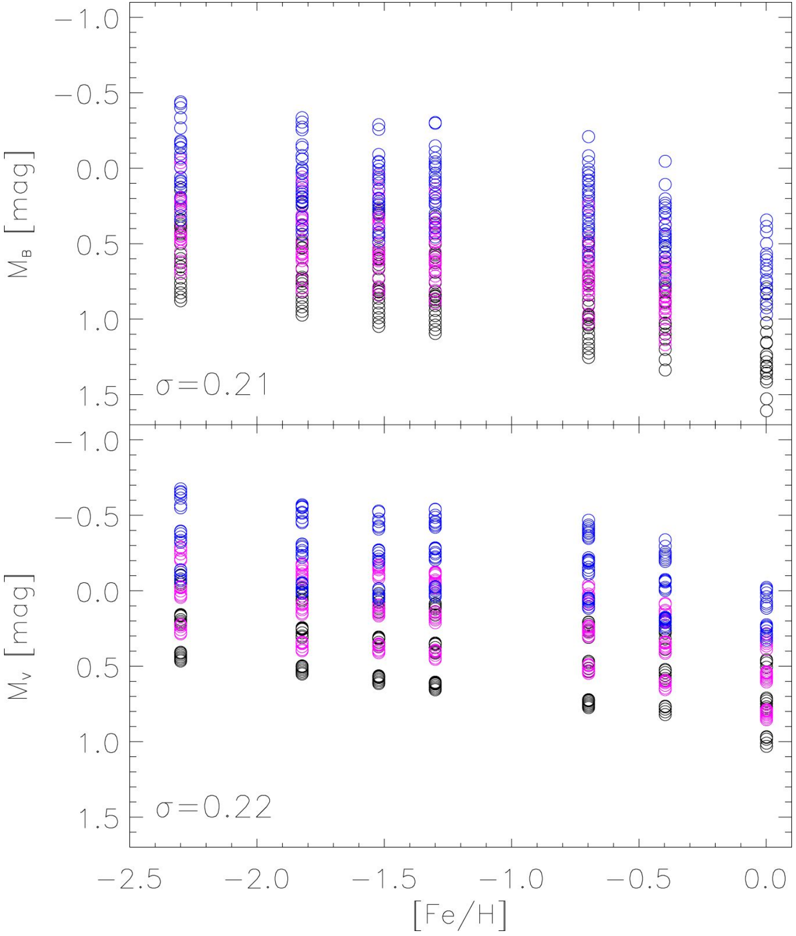
Helium abundance term

The Y effect on the visual magnitude versus [Fe/H] relation





Y=0.40

Y=0.30

Standard Y

Marconi et al. 2018 ApJL

A third method to infer RR Lyrae distances: the ***Period-Wesenheit*** relationship

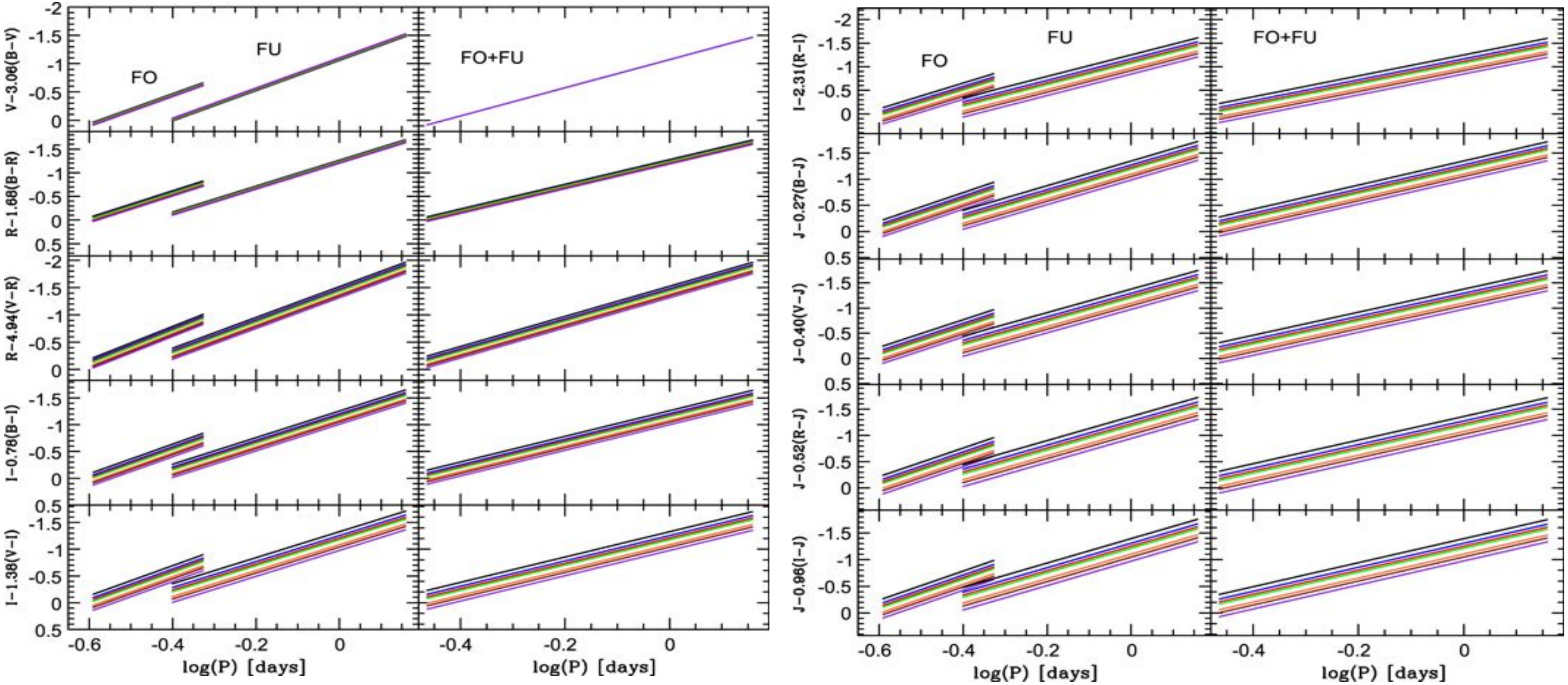
$$W(X,Y) = M_X - \xi\,(M_X - M_Y)$$

where $\xi = A_X/E(X-Y)$

Reddening free by definition

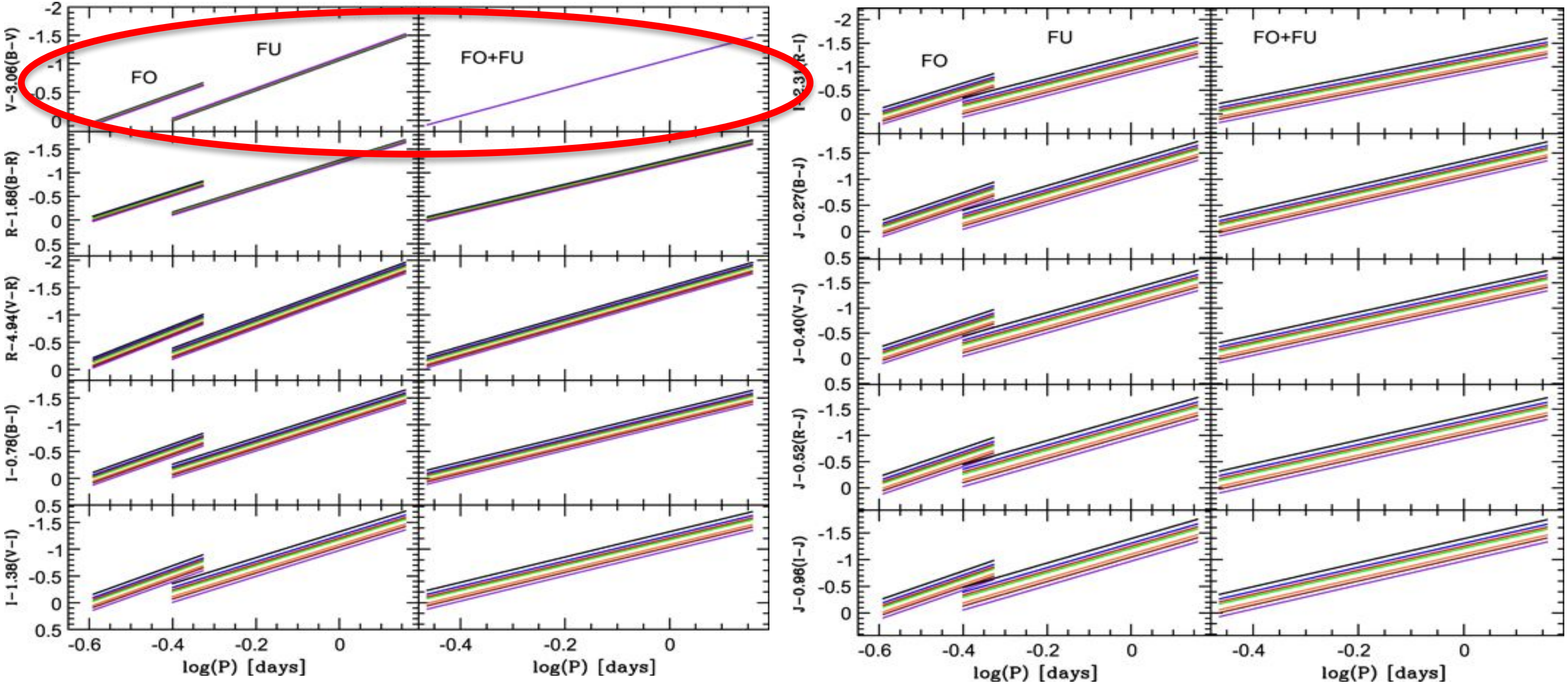
But it requires the assumption of an extinction law

The predicted Period-Wesenheit relationship



Marconi et al. 2015 ApJ

The predicted Period-Wesenheit relationship



Marconi et al. 2015 ApJ

Observational constraints to models

The RR Lyrae PLZ AND PWZ relations: theory versus observations

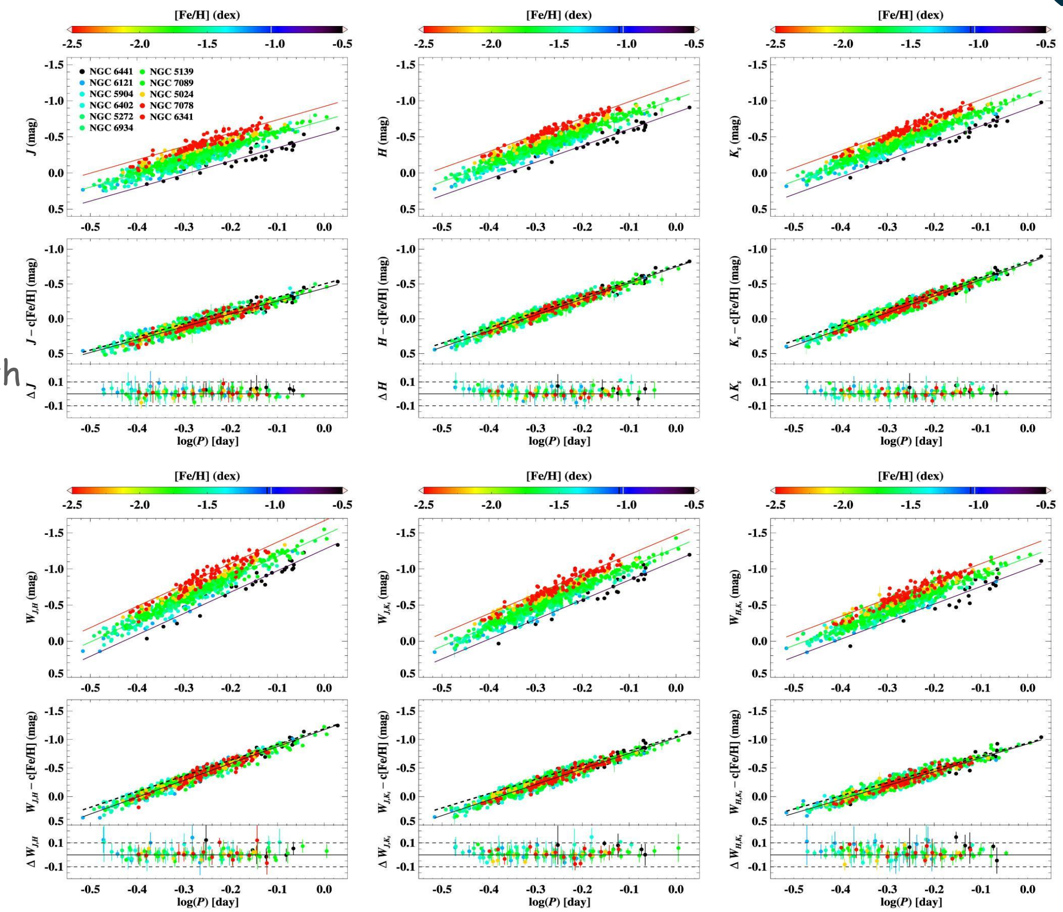
Homogeneous, accurate, and precise photometric data for 964 RR Lyrae variables in 11 globular clusters covering a large metallicity range

→ JHKs PLZ and PWZ relations anchored using 346 Milky Way field RR Lyrae stars with Gaia parallaxes

→ significant metallicity dependence of ~0.2 mag/dex in the JHK s -band PLZ and PWZ

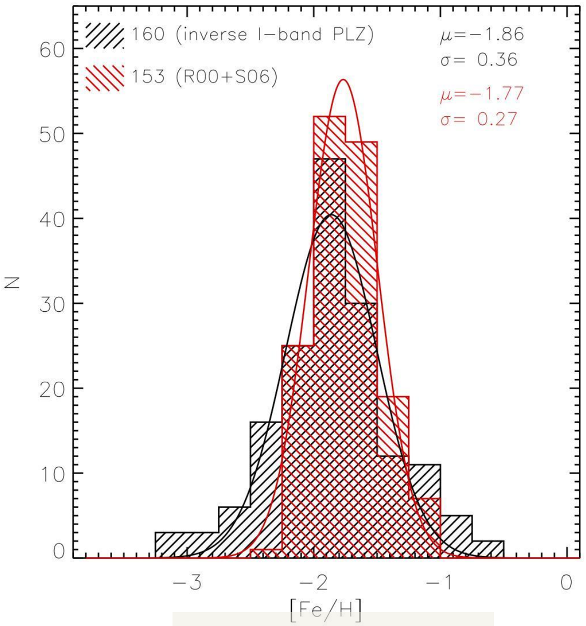
Excellent agreement with the predictions from the horizontal branch evolution and pulsation models.

Bhardwaj+ 2023 MNRAS



From inversion of PLZ relations to metallicity distributions

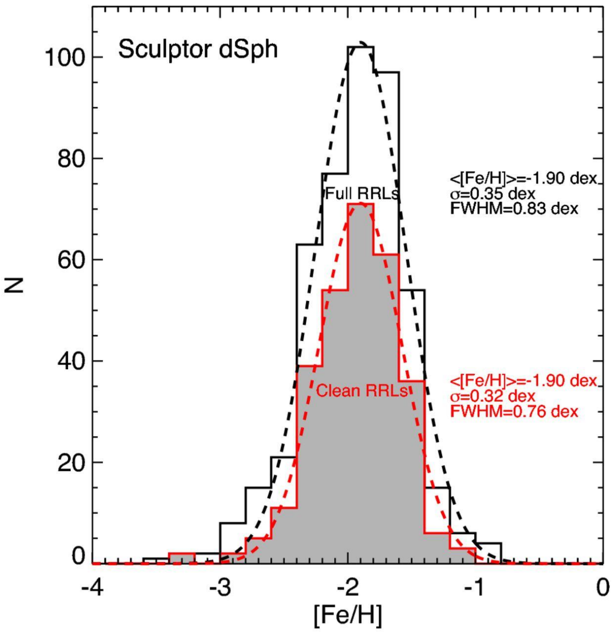
The case of ω Cen: application of the M_I-logP-Z relation



Braga+2016 ApJ

From inversion of PLZ relations to metallicity distributions

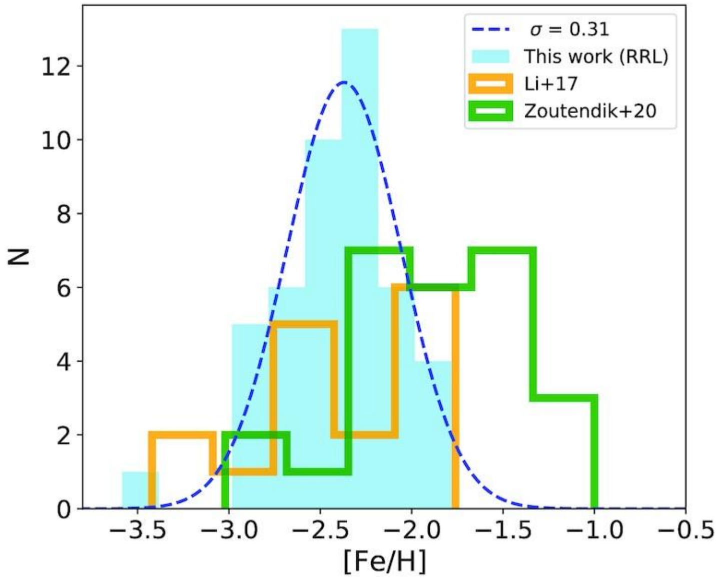
The case of Sculptor: inversion of the M_I-logP-Z relation



Martínez-Vázquez+ 2016 MNRAS

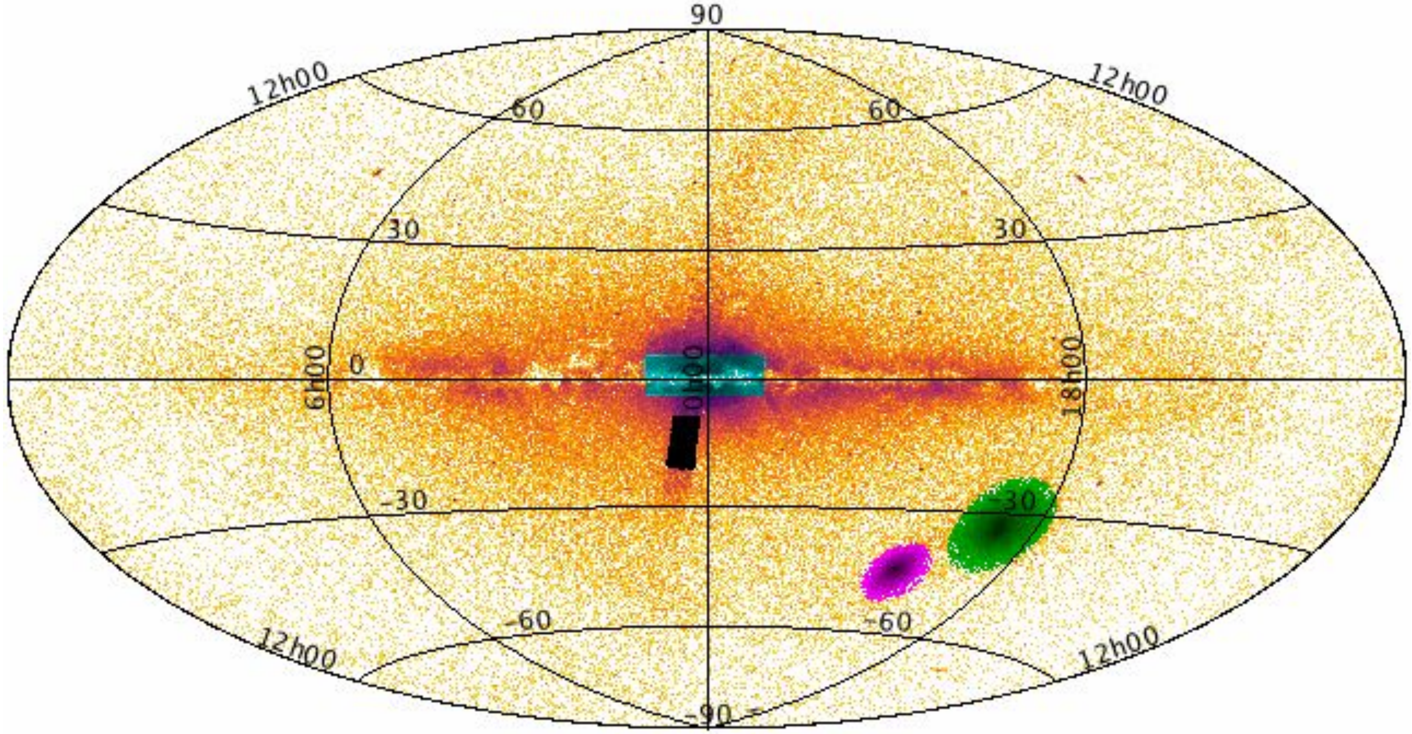
From inversion of PLZ relations to metallicity distributions

The case of Eridanus: application of the M_{i_sdss}-logP-Z relation



Martínez-Vázquez+ 2021 MNRAS

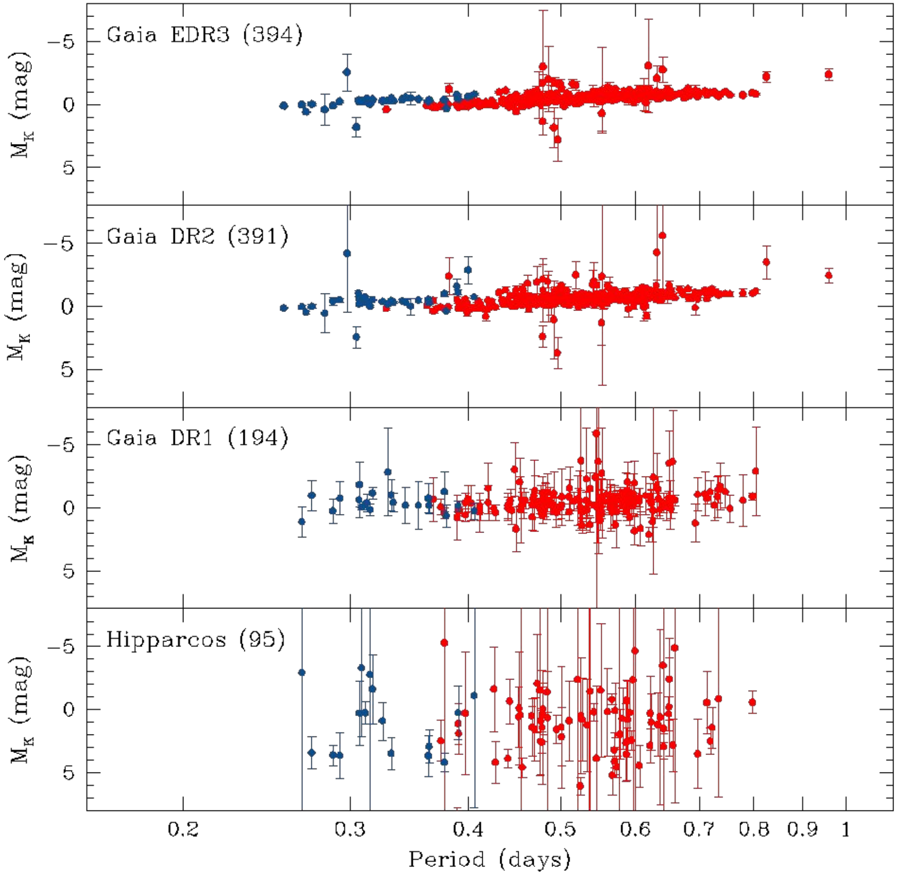
The ESA Gaia Data Release 3 RR Lyrae



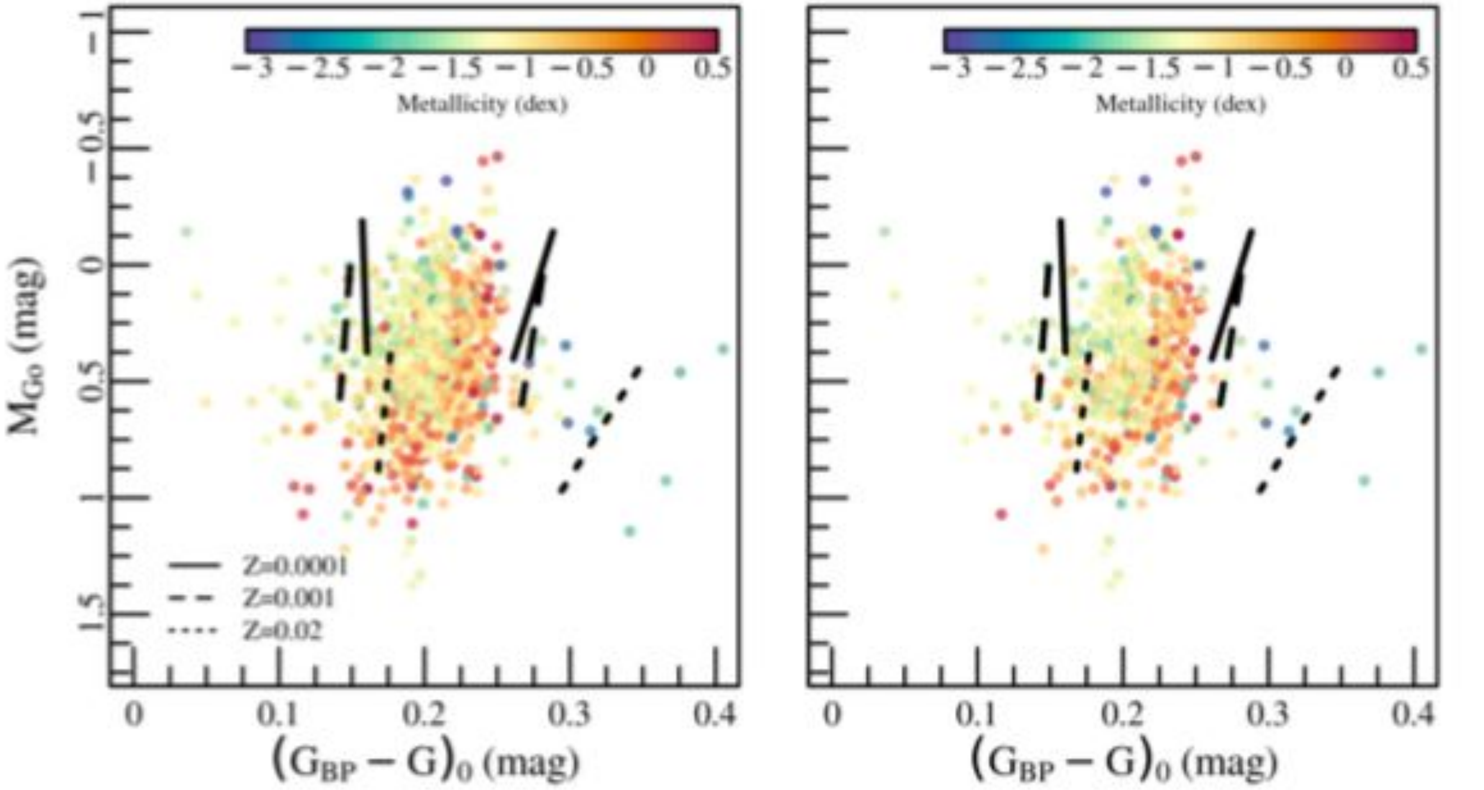
About 270000 RR Lyrae !

Clementini et al. 2023 A&A

The ESA Gaia RR Lyrae PL(K) relation

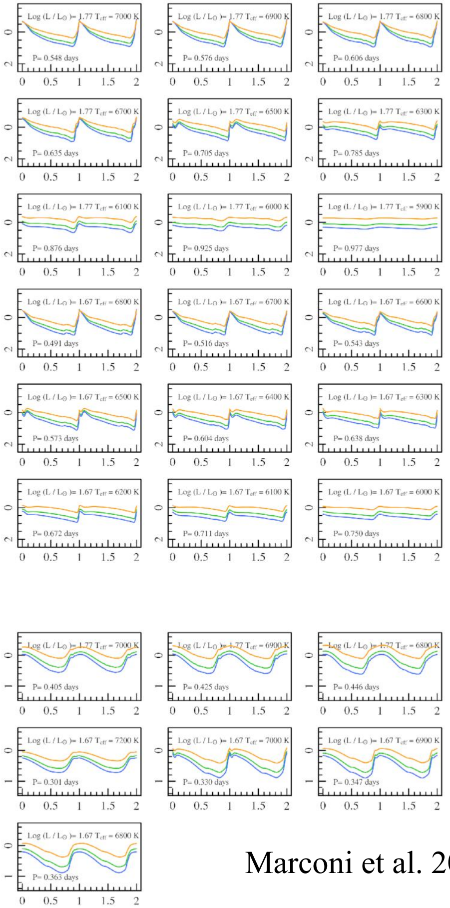


The RR Lyrae instability strip: Gaia versus model predictions



Clementini et al. 2023 A&A

The predicted RR Lyrae light curves in the Gaia filters

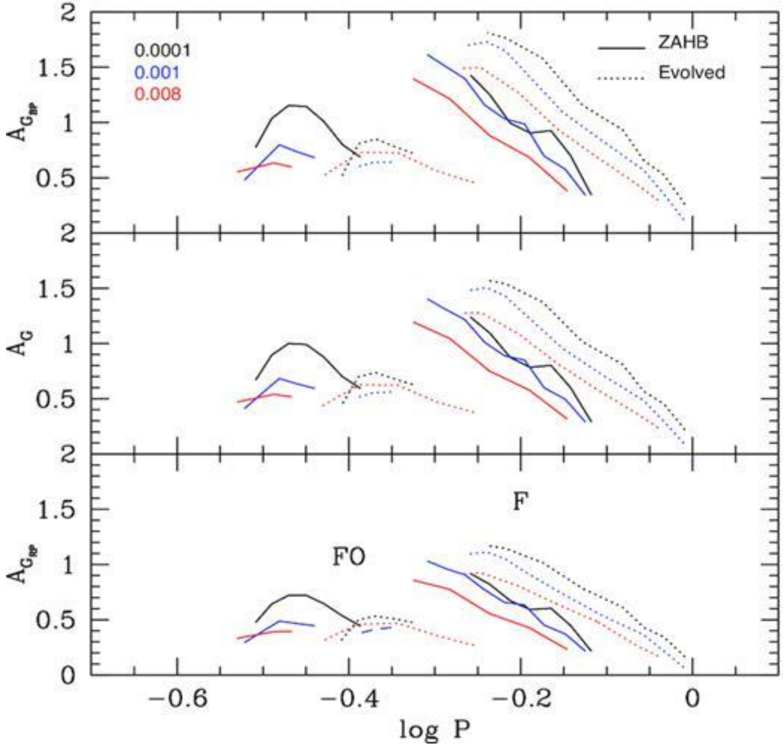


Marconi et al. 2021 MNRAS

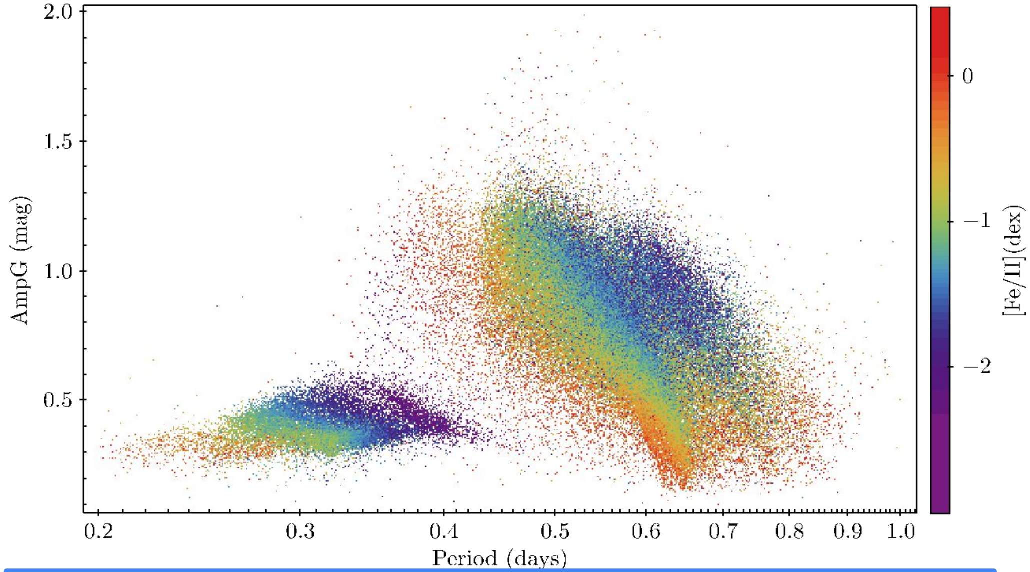
mean magnitudes and colors, pulsation amplitudes

The RR Lyrae Bailey diagram: Gaia versus model predictions

Marconi et al. 2021 MNRAS

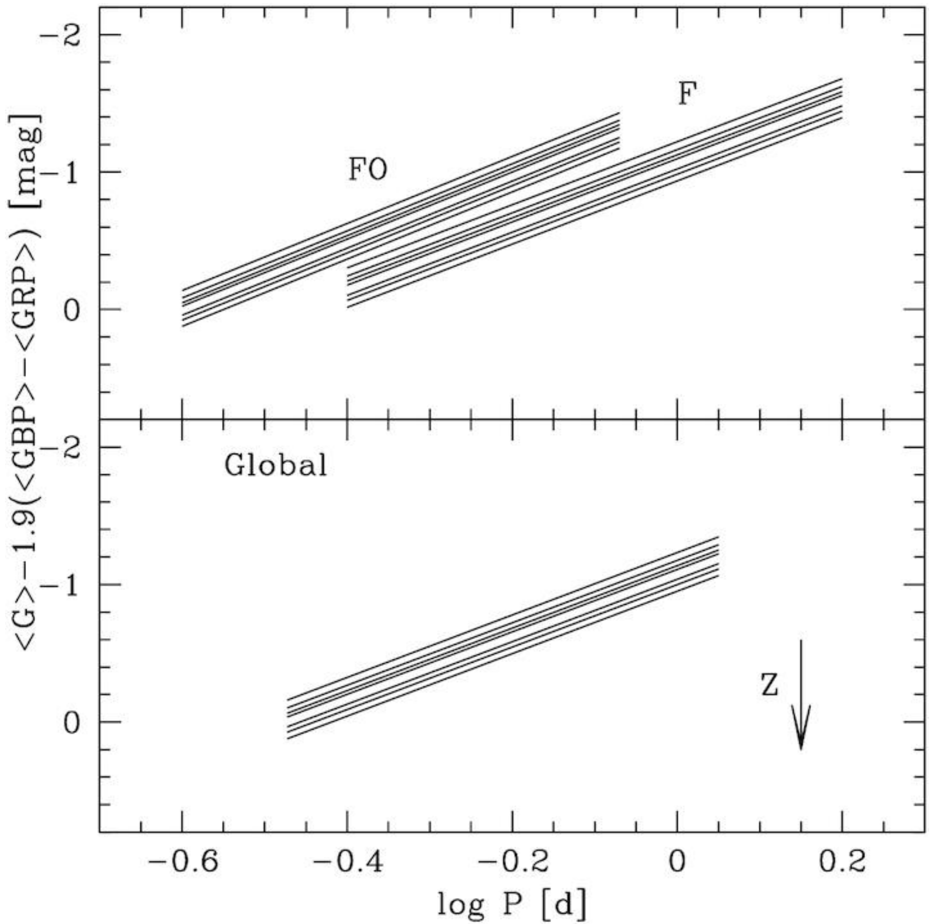


Clementini et al. 2023 A&A

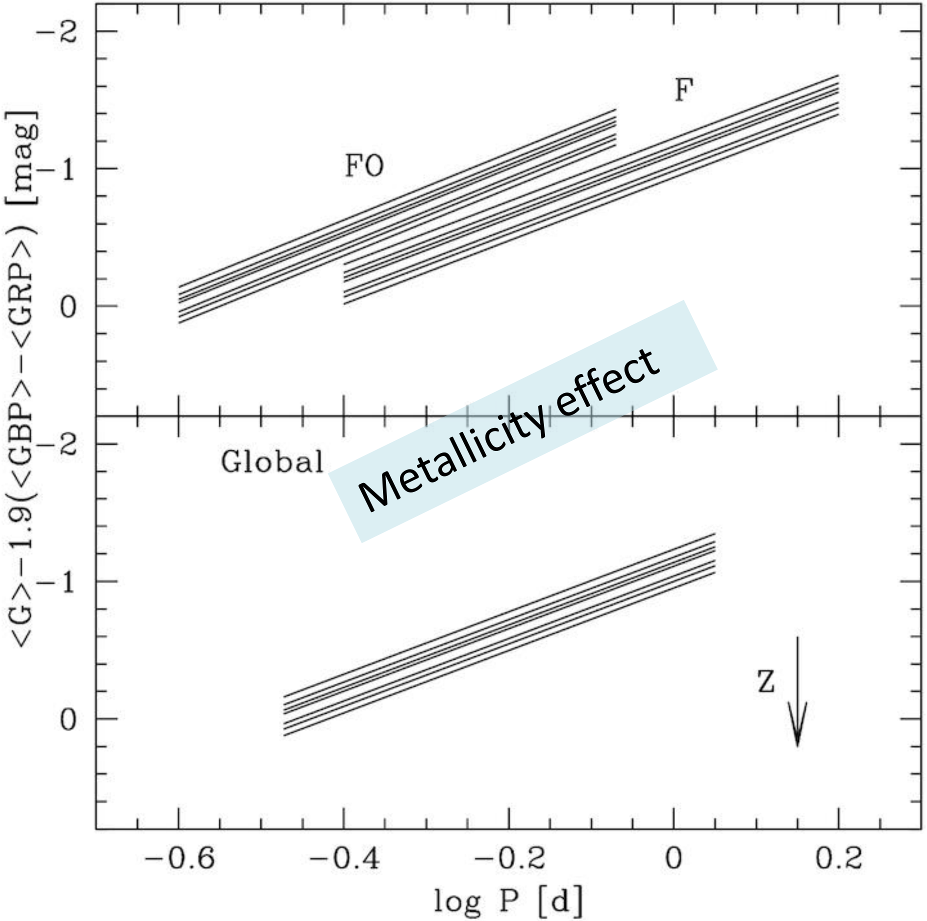


Both theory and observations predict shorter periods and lower amplitudes for more metallic RR Lyrae.

Predicted Period-Wesenheit relations in the Gaia bands

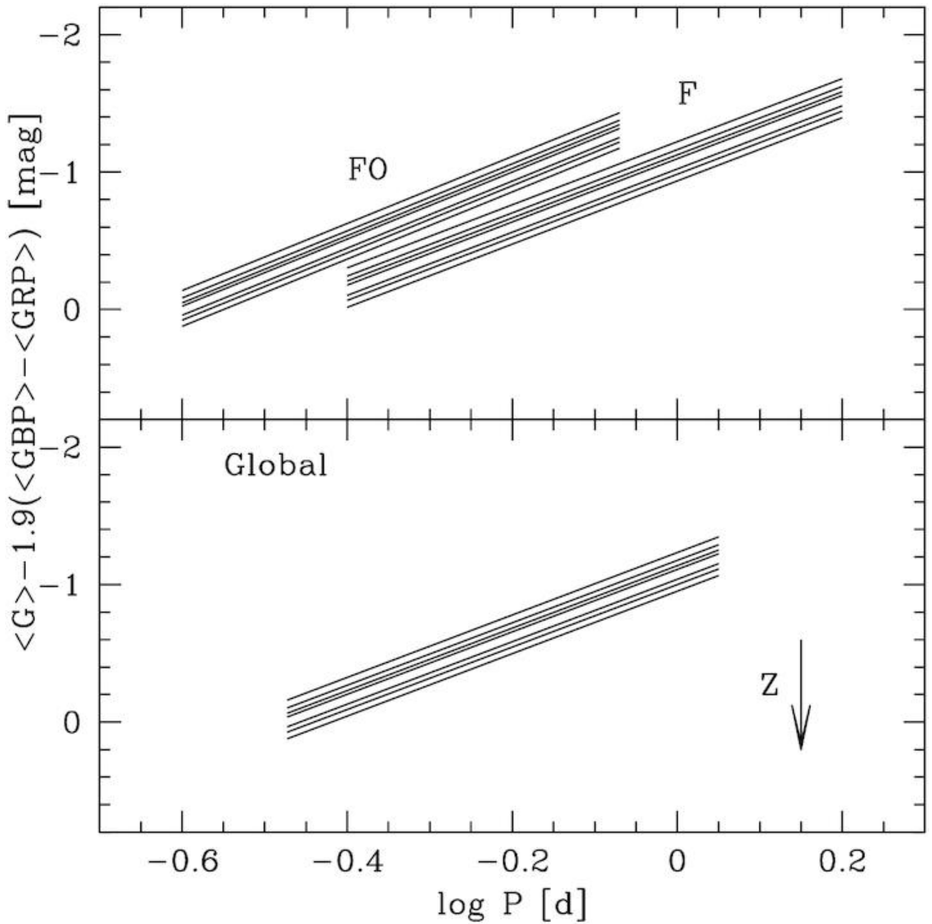


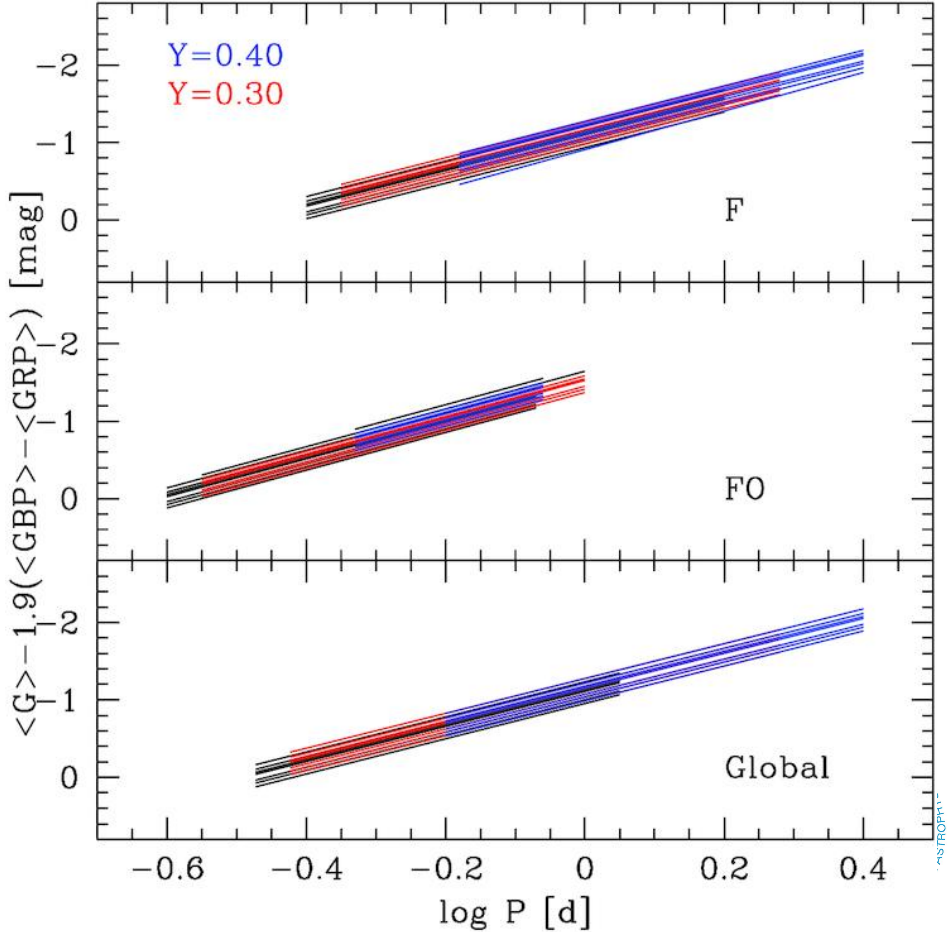
Predicted Period-Wesenheit relations in the Gaia bands



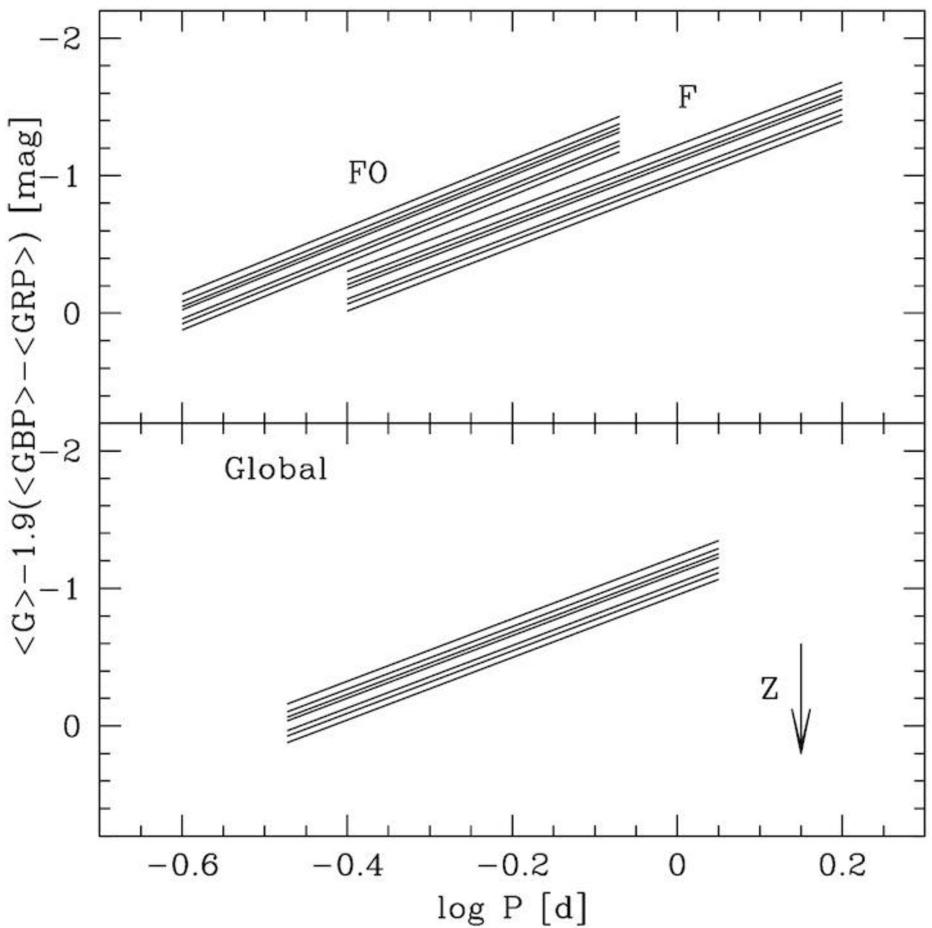
Marconi+ 2021 MNRAS

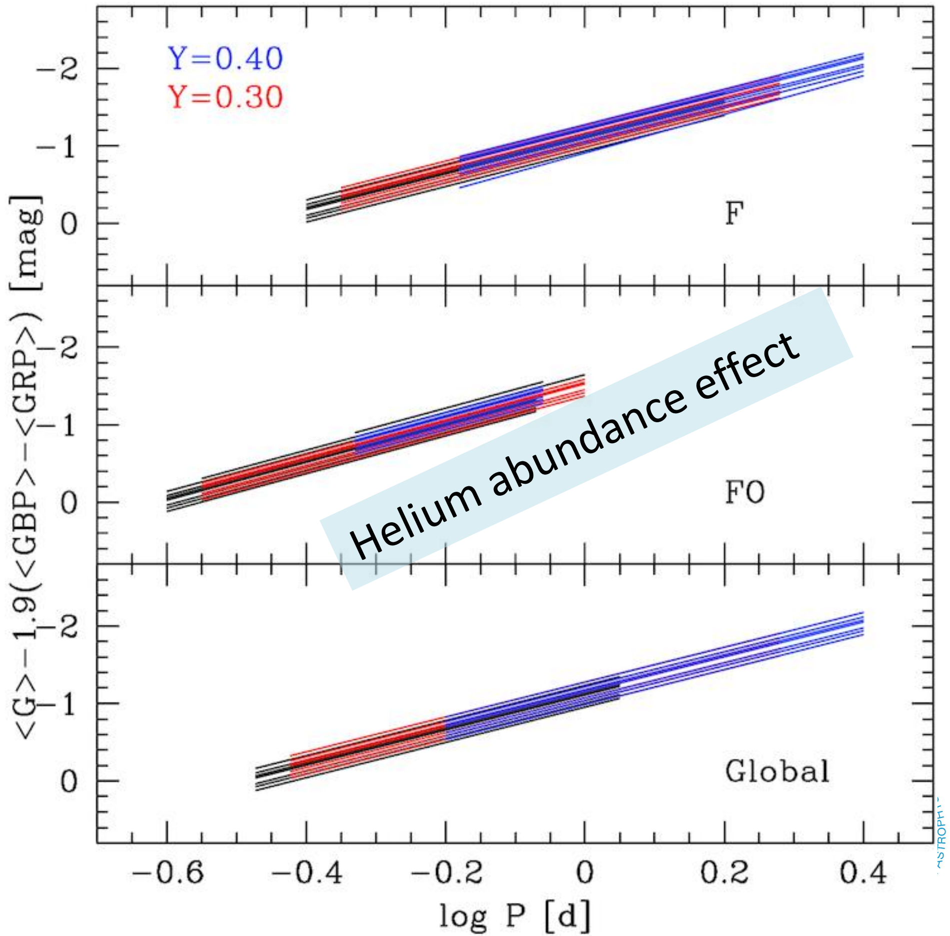
Predicted Period-Wesenheit relations in the Gaia bands





Predicted Period-Wesenheit relations in the Gaia bands





The theoretical PWZ and PWZY relations in the Gaia bands

Table 3. The coefficients of the metal-dependent PW relations $W = a + b \log P + c[Fe/H]$ for F and FO models. The last column represents the root-mean-square-deviation (σ) coefficient.

Mode	a	b	c	σ_a	σ_b	σ_c	σ
F	−0.936	−2.296	0.124	0.049	0.032	0.005	0.05
FO	−1.344	−2.440	0.112	0.033	0.028	0.005	0.03
GLOBAL	−0.952	−2.271	0.123	0.051	0.024	0.004	0.05

Table 4. The coefficients of the metal- and helium-dependent PW relations $W = a + b \log P + c[Fe/H] + d \log Y$ for F and FO models. The last column represents the root-mean-square-deviation (σ) coefficient.

Mode	a	b	c	d	σ_a	σ_b	σ_c	σ_d	σ
F	−1.277	−2.298	0.123	−0.573	0.044	0.014	0.003	0.028	0.04
FO	−1.600	−2.436	0.120	−0.442	0.031	0.020	0.003	0.031	0.03
GLOBAL	−1.278	−2.257	0.126	−0.558	0.047	0.012	0.002	0.025	0.05

Marconi+ 2021 MNRAS

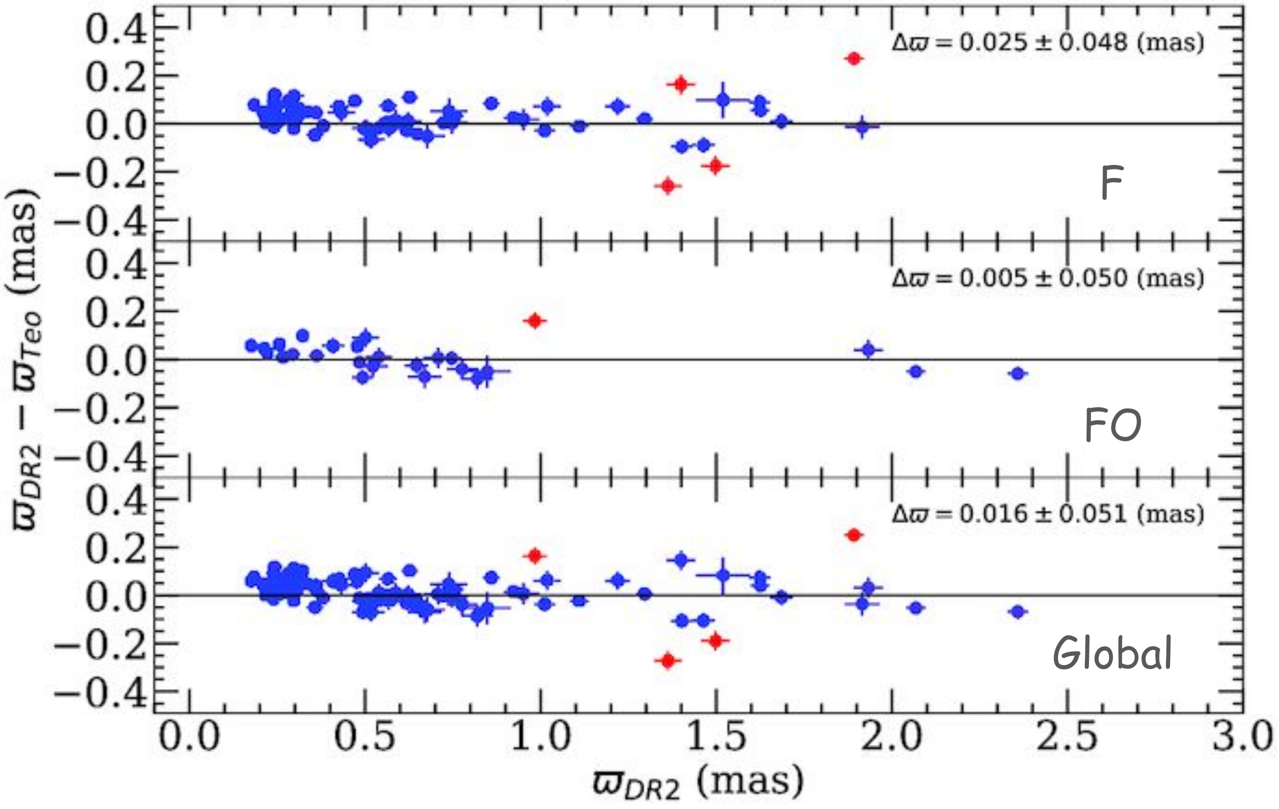
From theoretical PWZ relations to theoretical parallaxes

The derived **theoretical Period-Wesenheit-metallicity relations** for both the Fundamental and first overtone mode can be applied to **Galactic RR Lyrae in the Gaia database** and complementary information on **individual metal abundances**.

↓

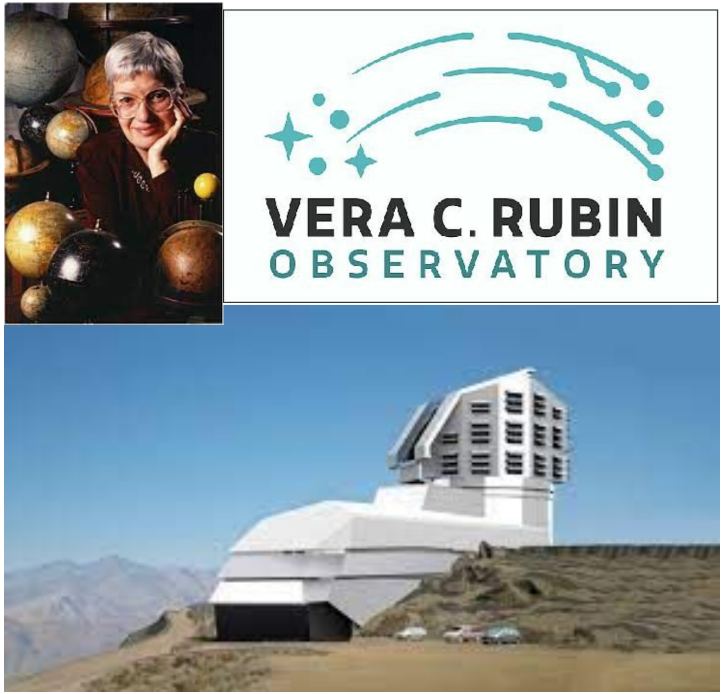
theoretical distances and parallaxes

Theoretical versus Gaia parallaxes of Galactic RR Lyrae

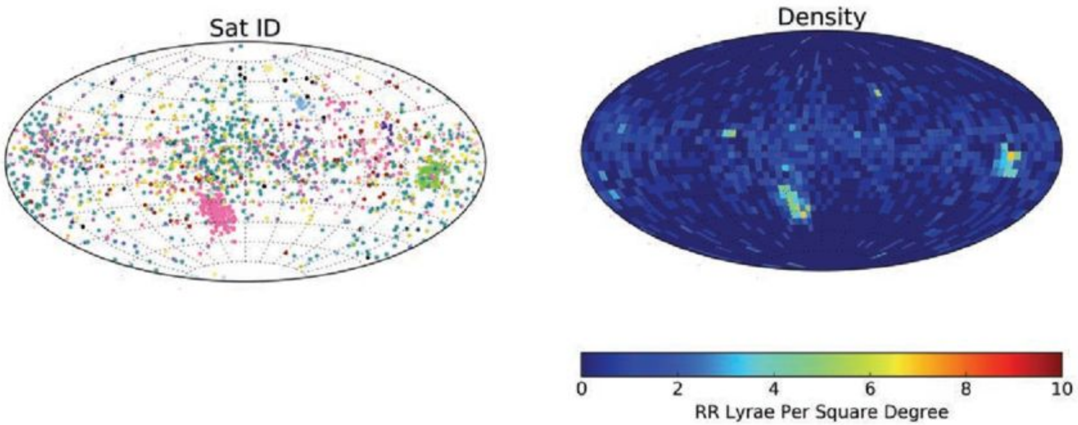


Marconi et al. 2021 MNRAS

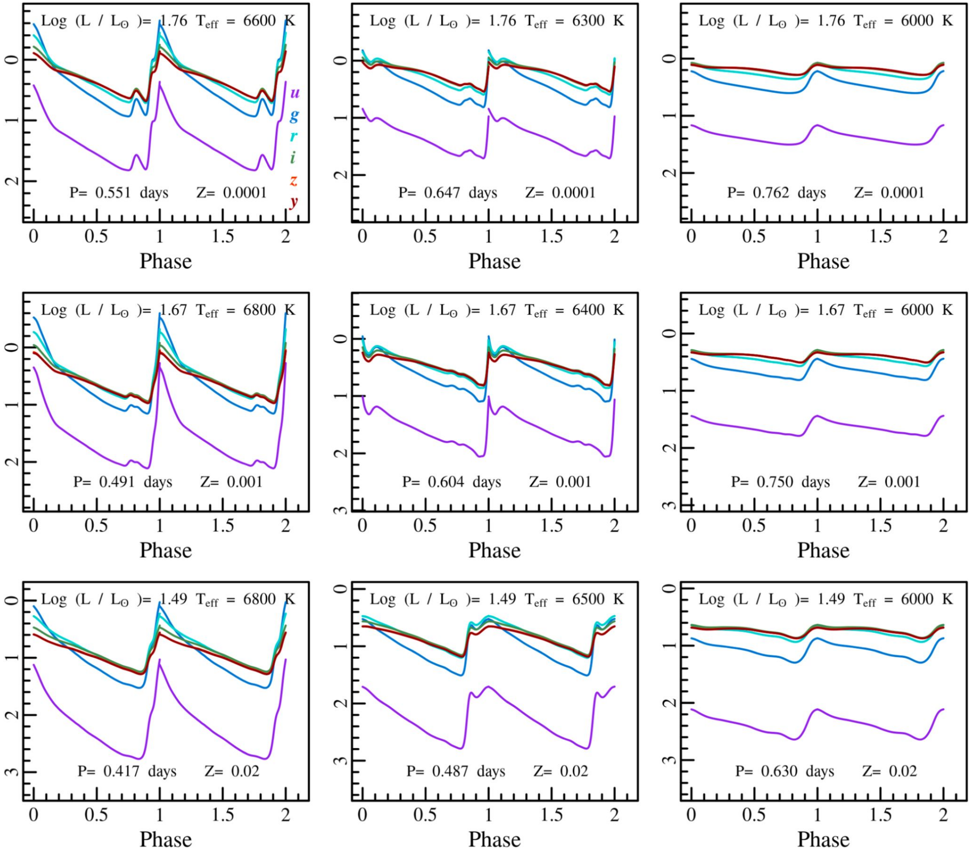
Waiting for Rubin-LSST



The Rubin-LSST survey will allow to observe a huge number of RR Lyrae to be investigated as standard candles and old stellar population tracers.



RR Lyrae models in the the Rubin-LSST filters



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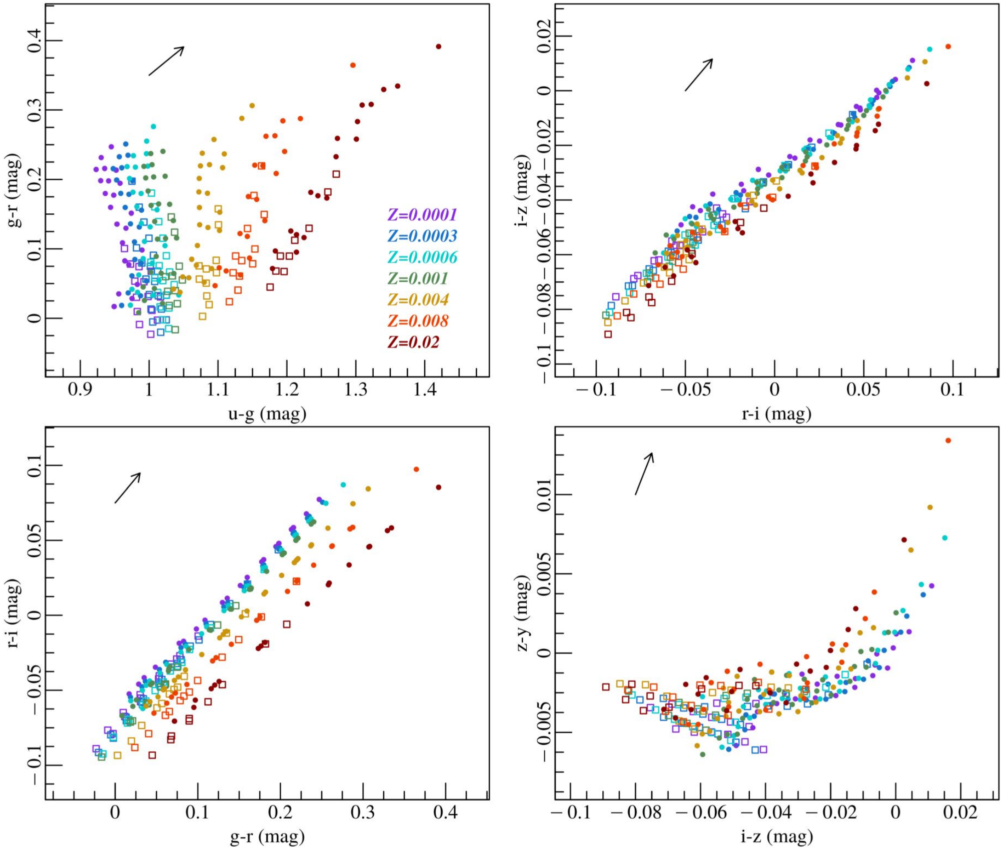
The predicted Rubin-LSST color-color plots



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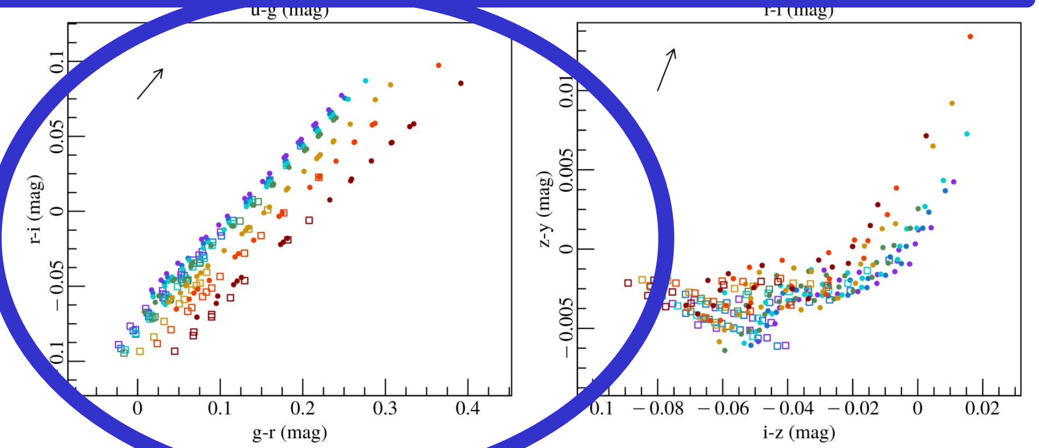
The predicted Rubin-LSST color-color plots

Table 5
Fitting Results for Color–Color–[FeH] Relations

Col1	Col2	α	β	γ	σ	R^2
		$Col_2 = \alpha \cdot Col_1 + \beta[Fe/H] + \gamma$				
$(g-r)_{LSST}$	$(r-i)_{LSST}$	0.562 ± 0.006	-0.0215 ± 0.0007	-0.1089 ± 0.0013	0.008	0.97
$(r-i)_{LSST}$	$(g-r)_{LSST}$	1.73 ± 0.02	0.0381 ± 0.0012	0.193 ± 0.002	0.013	0.98
		$[Fe/H] = \alpha \cdot Col_1 + \beta \cdot Col_2 + \gamma$				
$(g-r)_{LSST}$	$(r-i)_{LSST}$	21.4 ± 0.6	-37 ± 1	-4.36 ± 0.1	0.313	0.82

Note. Columns 1 and 2 contain the fitted colors, while the coefficients of the obtained relations are reported in columns 3–5. Finally, Columns 6 and 7 contain the rms of the residuals around the fit and the coefficient of determination, respectively.



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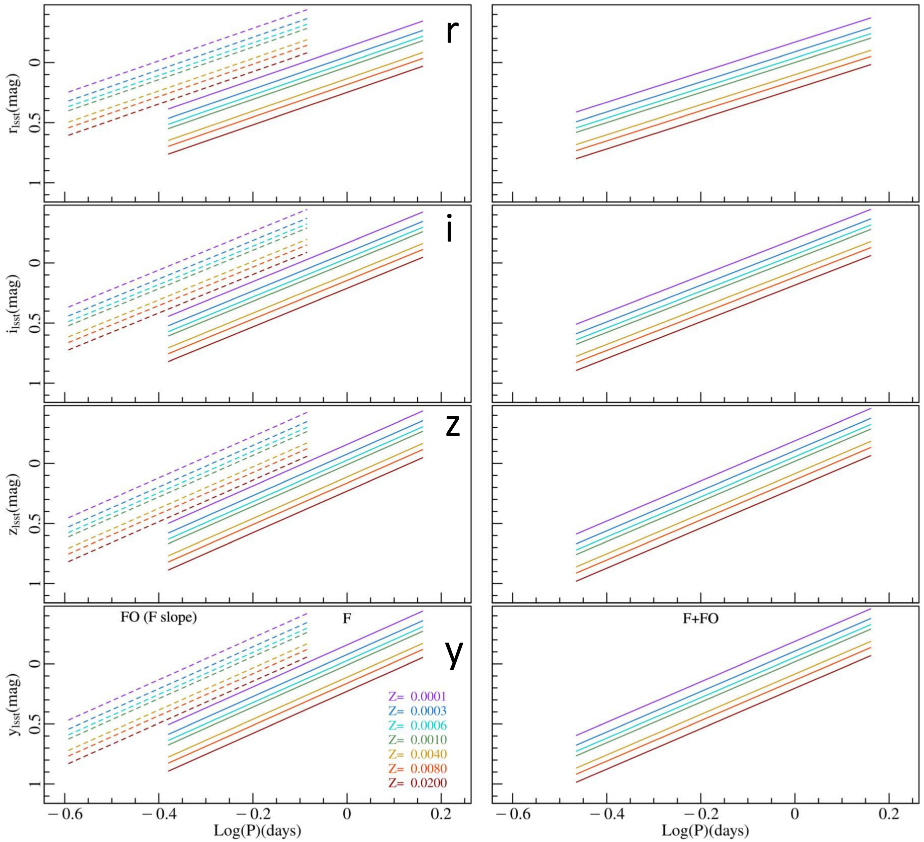
Metal dependent PL relations



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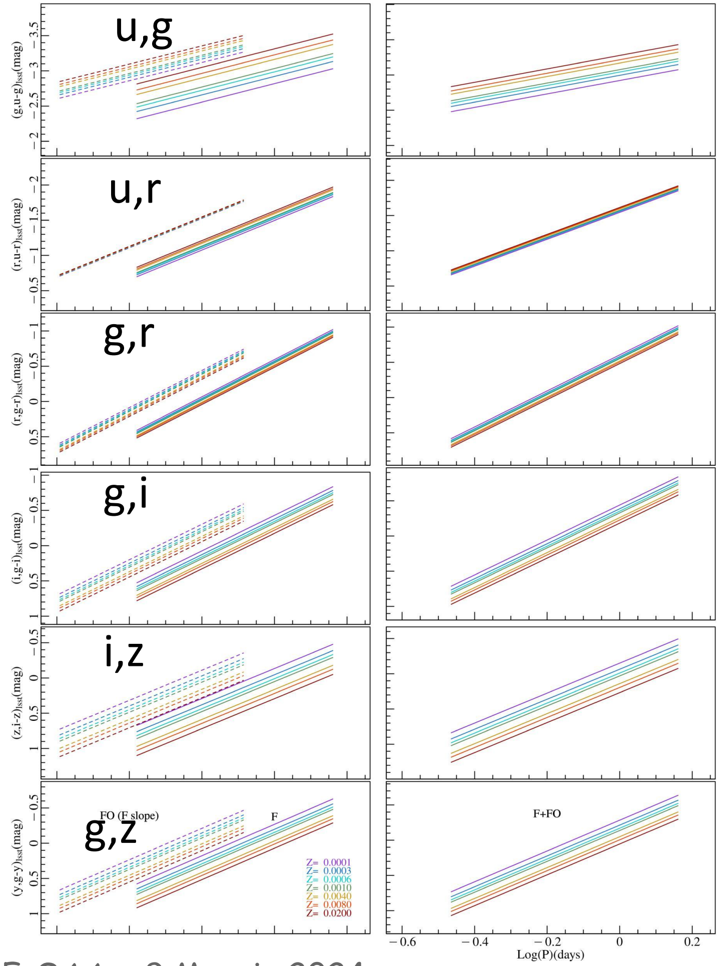
The Period-Wesenheit relations for RR Lyrae



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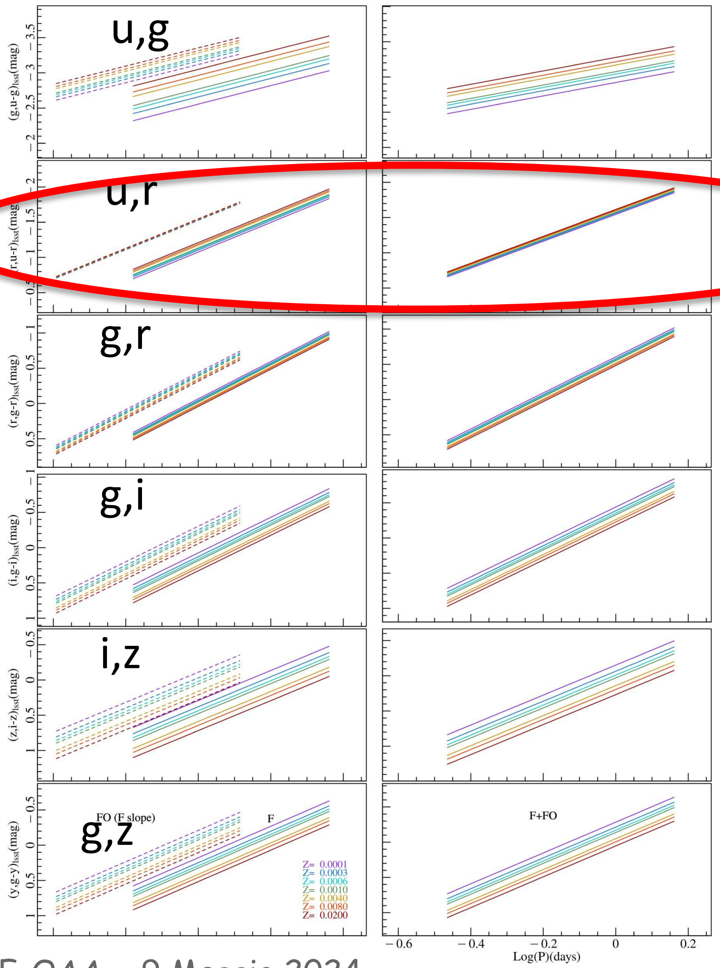
The Period-Wesenheit relations for RR Lyrae

Almost metal independent



Marconi+ 2022 ApJ

Conclusions

- RR Lyrae are excellent Population II standard candles.
- Current pulsation models are able to predict all the relevant properties.
- The predicted pulsation properties show a good agreement with the observations but a non negligible dependence on chemical composition.
- Gaia astrometry and spectroscopy + complementary high resolution spectroscopy for Galactic RR Lyrae allowed us to test the predictive capabilities of current theoretical scenario.
- Rubin-LSST will help exploiting the powerful role of RR Lyrae as distance indicators and old stellar pop tracers and new models have been computed to provide the theoretical framework in the corresponding filters.

Next steps: the EFEBHO project

Early Formation and Evolution of Bulge and HalO (EFEBHO)
*Responsabile nazionale: **Marcella Marconi***

CoIs: **Giuseppe Bono, Luca Ciotti, Maria Francesca Matteucci, Vittorio Francesco Braga, Massimo Dall'Ora, Silvio Leccia, Roberto Molinaro, Ilaria Musella, Silvia Pellegrini, Vincenzo Ripepi**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Finanziato dall'Unione europea
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Ministero dell'Università e della Ricerca

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PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE – Bando 2022
Prot. 2022ARWP9C

The EFEBHO project

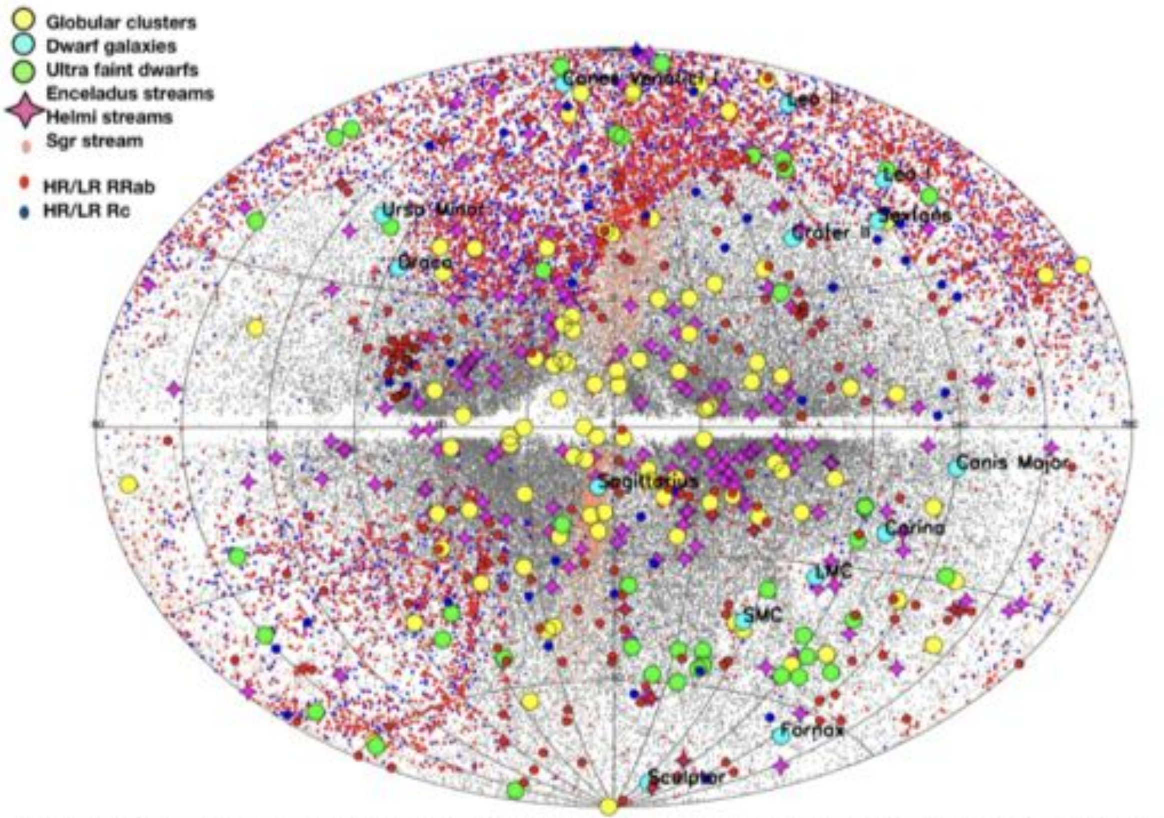


Fig. 1 Distribution in Galactic coordinates of both photometric (grey dots) and spectroscopic (coloured symbols) EFEBHO RRL catalogs. Blue and red circles display RRc and RRab variables with HR (247) and LR (9397) spectra. Nearby stellar systems are marked with different colours (see labels).

The EFEBHO project

*EFEBHO aims at **investigating and reconstructing the star formation history of the Milky Way spheroidal components** (Halo an Bulge)*

- *Characterization of Gaia RR Lyrae*
- *New NIR and MIR PL/PLZ relations*
- *New PW/PWZ relations in all the photometric filters*
- *Comparison between observed and predicted density profile*
- *Comparison with pulsation models and derivation of intrinsic stellar parameters*
- *3D structure and chemical characterization of the Galactic Halo and Bulge and of stellar populations in satellite galaxies using RR Lyrae*

SPECTRUM

Stellar Pulsation and Evolution: a Combined Theoretical physical Renewal and Updated Models

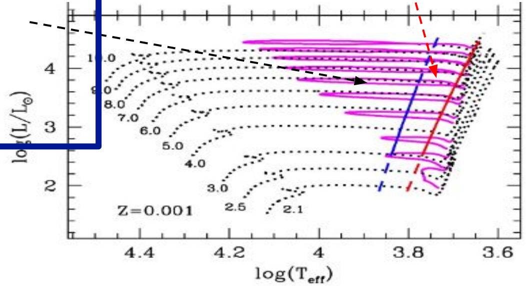
Project just funded by INAF and led by Giulia De Somma (INAF-OACN)
Supervisors: Santi Cassisi (INAF-OAAb) Marcella Marconi (INAF-OACN)

SPECTRUM

To link the pulsational and evolutionary model computations: the **RA**dial **P**ulsating star (**RAP**) tool.

BaSTI evolutionary code → check the model stability for radial pulsations → **YES** → **RAP** computing the radial pulsations → **Light curves, amplitudes Periods, mean magnitudes, colors, PL, PLC, PW relations…**

NO → No pulsation predictions → Change input parameters → **BaSTI evolutionary code**




Thanks!