Population II pulsating stars as tracers of the Milky Way and Local Group evolution. I

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Outline

- **RR Lyrae Stars** (+ Anomalous cepheids)
    - star formation history tracers
    - metallicity tracers
    - distance tracers
    - population tracers

- **The Local Group**
    - a changing scenario
    - the impact of surveys

Take-home message

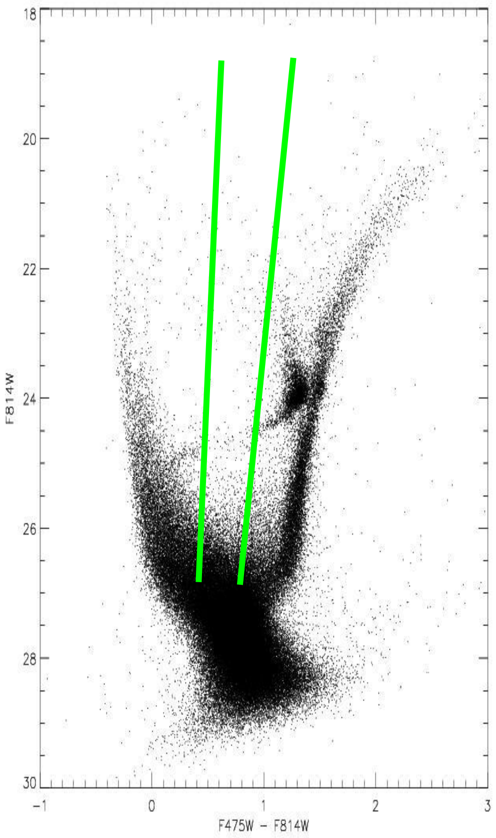
Take-home message

You will be drowning in data!

RR Lyrae stars

Pulsating stars: Context

Large Magellanic Cloud, OGLE IV

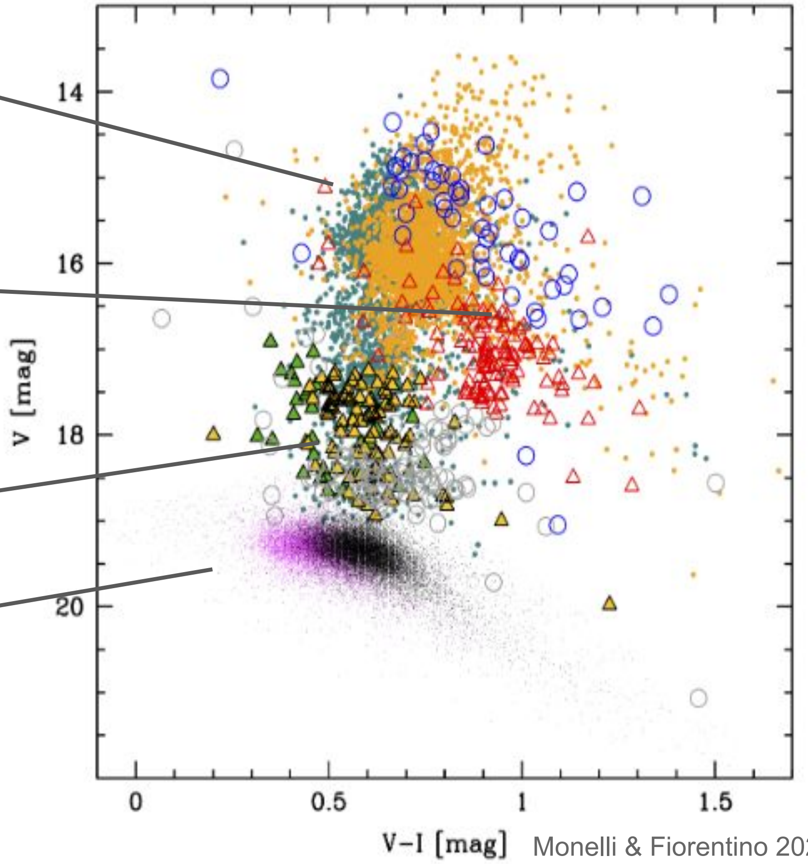


Classical Cepheids

Type II Cepheids:
RV Tau
W Vir
BL Her

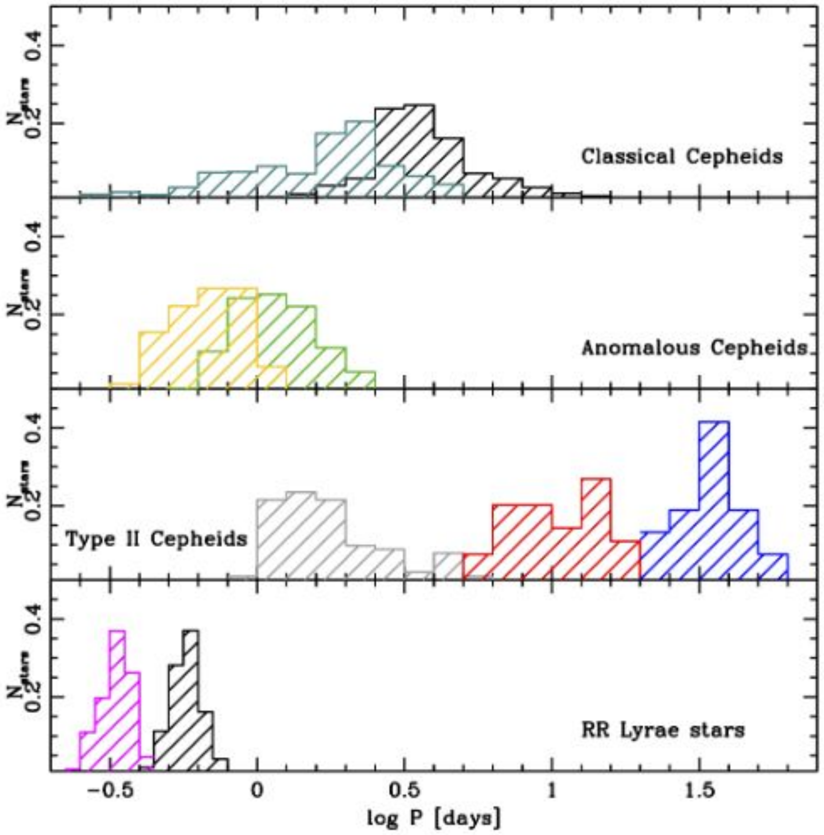
Anomalous Cepheids

RR Lyrae



Monelli & Fiorentino 2022

Pulsating stars: Context



Classical Cepheids
0.5 - > 150 d

Anomalous Cepheids
0.5 - 2.5 d

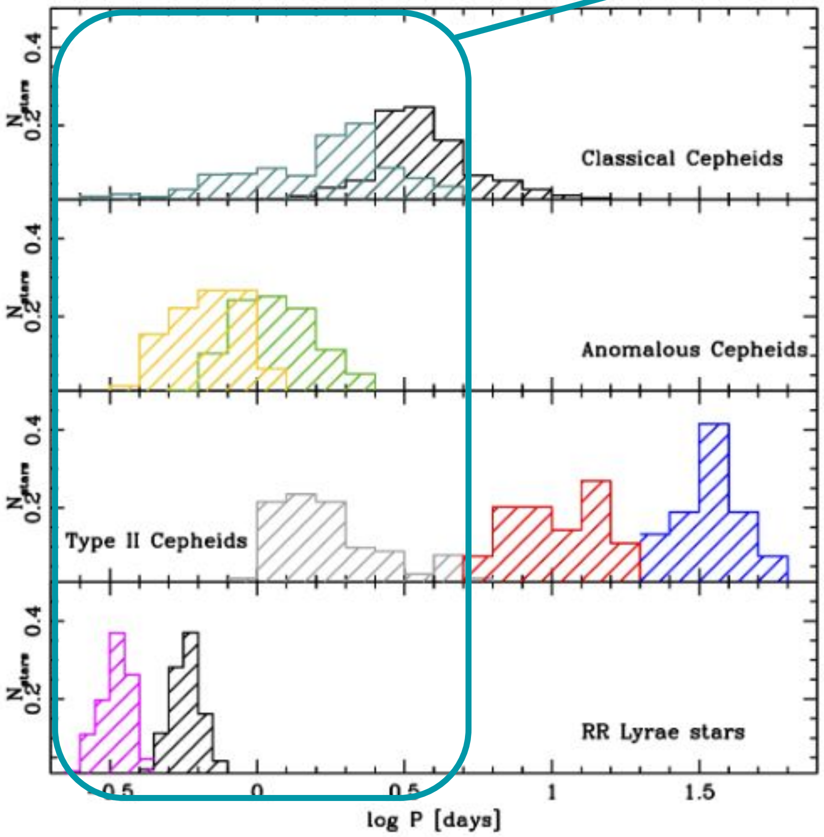
Type II Cepheids
BL Her: P < 4 d
W Vir : 4 < P < 20 d
RV Tau : P > 20 d

RR Lyrae
0.2 - 1.0 d

Monelli & Fiorentino 2022

Pulsating stars: Context

Central helium-burning phase



Classical Cepheids
0.5 - > 150 d

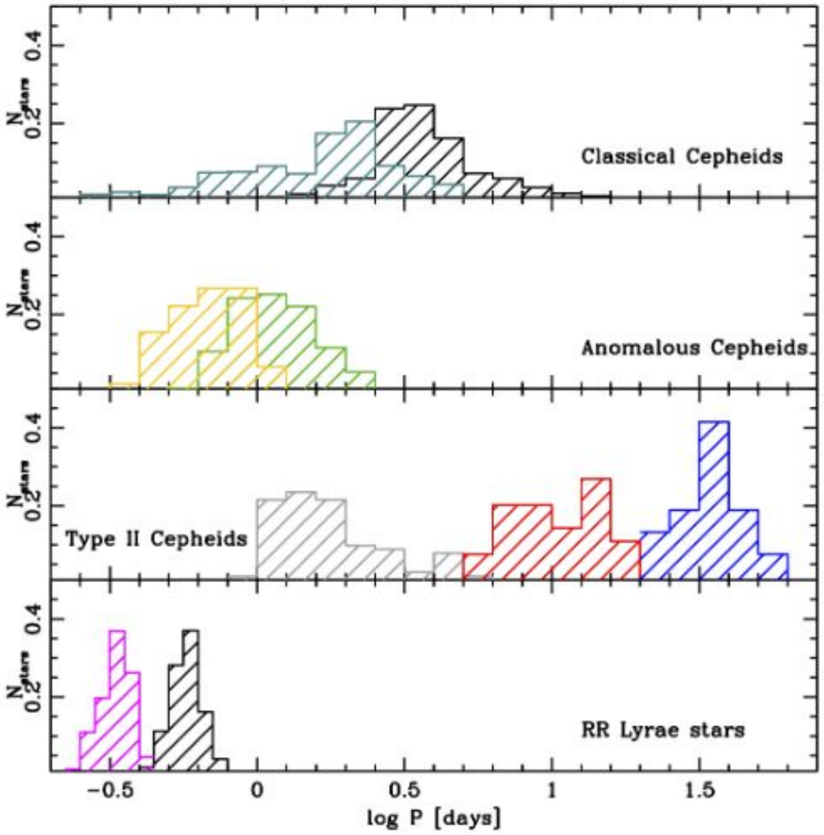
Anomalous Cepheids
0.5 - 2.5 d

Type II Cepheids
BL Her : P < 4 d post-(blue)HB
W Vir : 4 < P < 20 d AGB
RV Tau : P > 20 d post-AGB

RR Lyrae
0.2 - 1.0 d

Monelli & Fiorentino 2022

Pulsating stars: Context



Classical Cepheids
0.5 - > 150 d

Anomalous Cepheids
0.5 - 2.5 d

INTERMEDIATE-AGE 1-6 Gyr
OLD > 10 Gyr

Type II Cepheids
BL Her : P < 4 d
W Vir : 4 < P < 20 d
RV Tau : P > 20 d

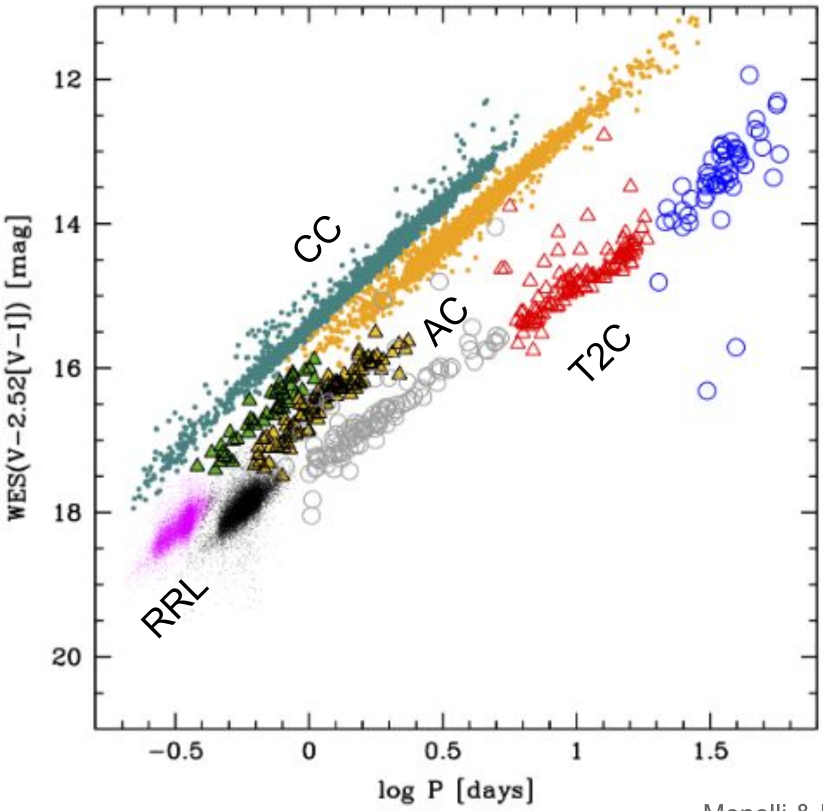
OLD > 10 Gyr
$M < 1 M_\odot$

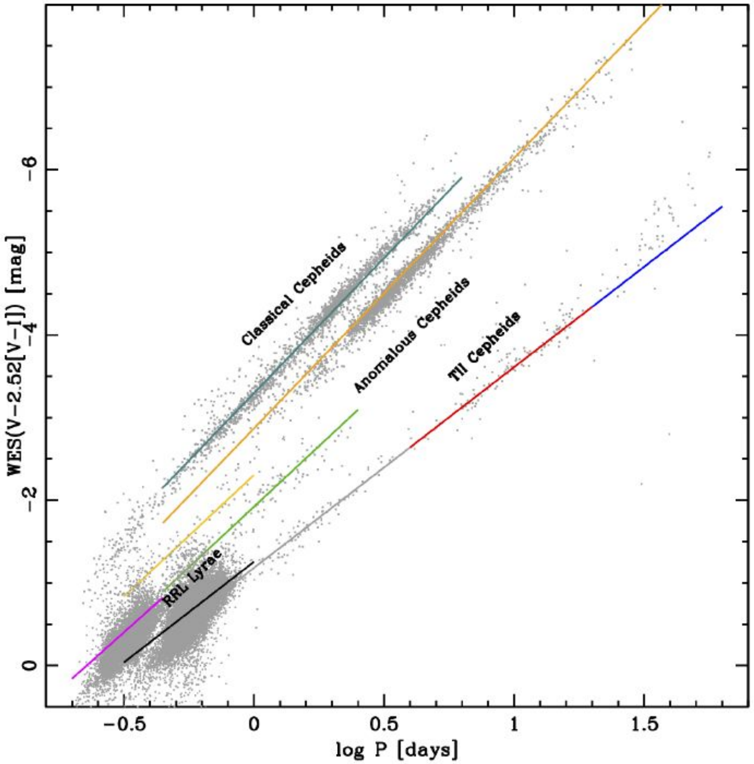
RR Lyrae
0.2 - 1.0 d

Monelli & Fiorentino 2022

Pulsating stars: Context

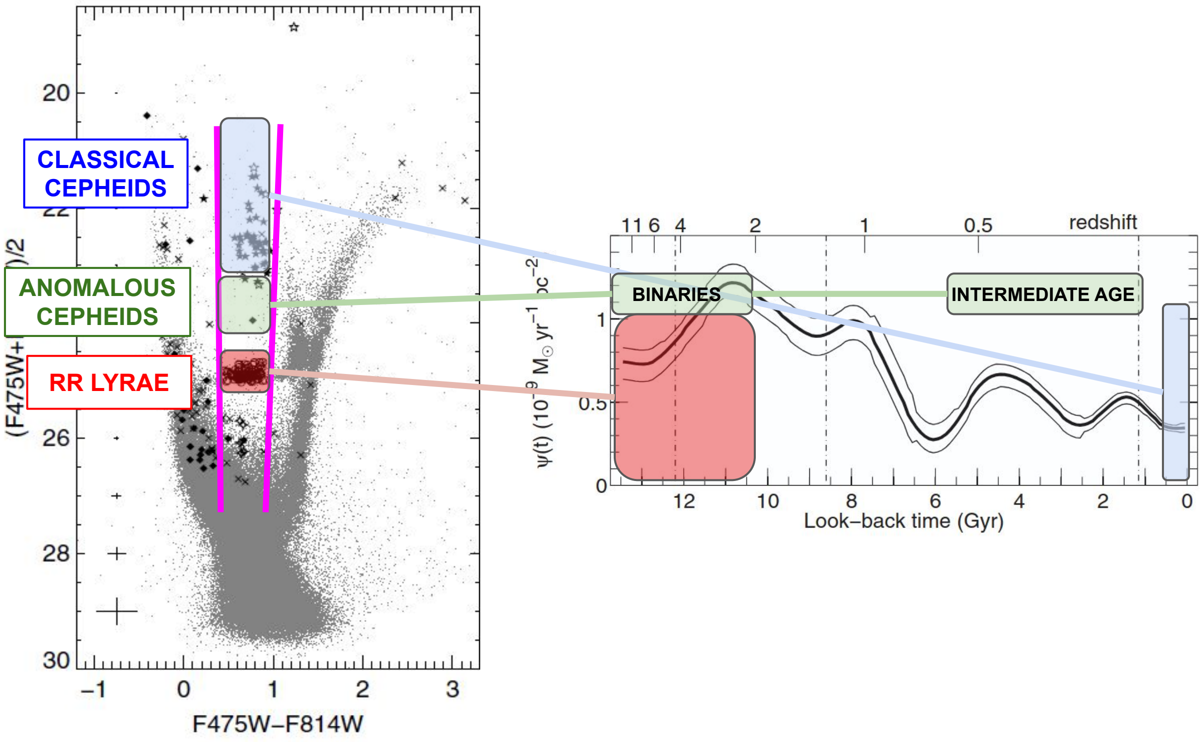
$M_X = a + b\cdot\log P + c\cdot[Fe/H]$





Monelli & Fiorentino 2022

Pulsating stars: Context



Pulsating stars: Context

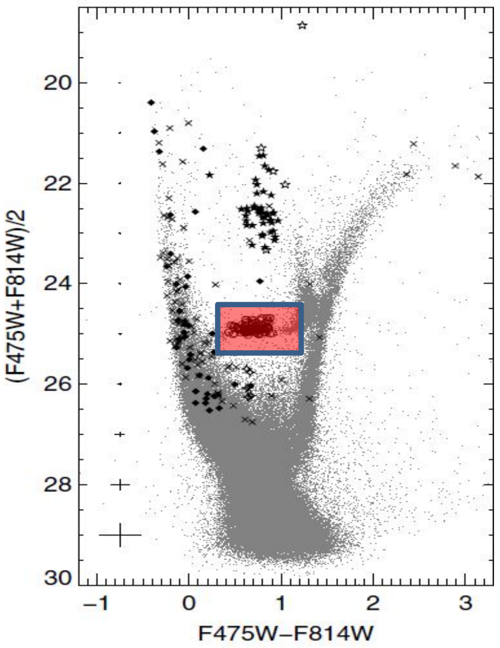
RR Lyrae as:

★ tracers of the old population
  ➔ Milky Way
  ➔ Local Group (dwarf) galaxies

★ tracers of metallicity and chemical evolution and chemical gradients

★ fundamental distance indicators

IC1613, Bernard+2010



RR Lyrae

Best **old pop. tracers** (> 10 Gyr)

➔ halo, thick disc, dwarfs, GCs

Low-mass (~0.6-0.8$M_\odot$) HB stars

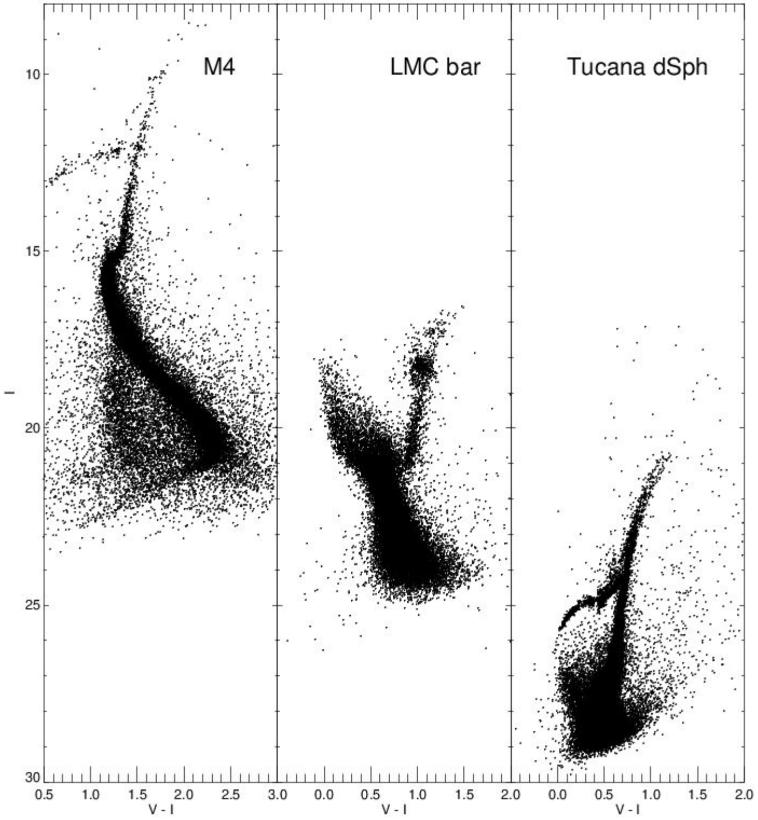
P ~ 0.25 to 1 d

Amplitude(V) ~ 0.3 to 1.5 mag

Intrinsically bright (M_V ~ 0.5)

Fundamental **distance indicators**

How far is the most distant known RRL star?



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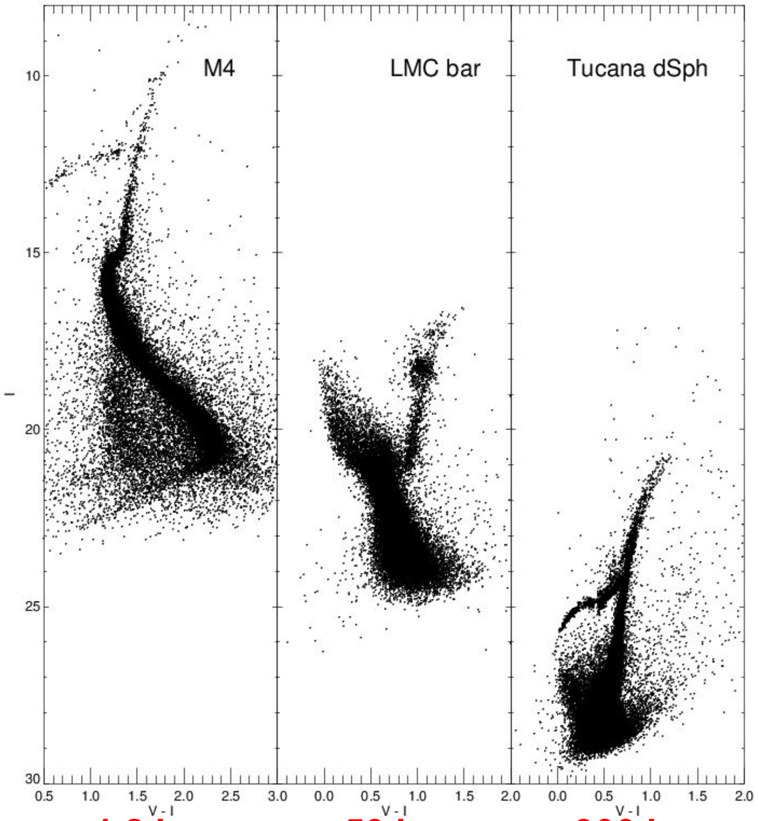
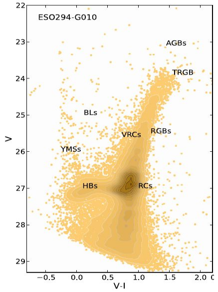
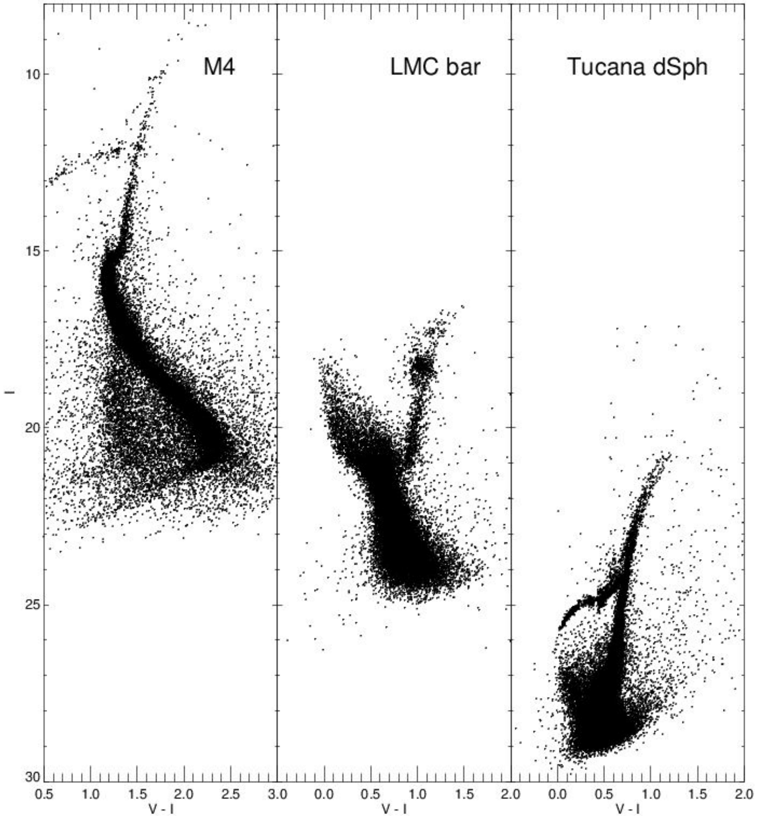




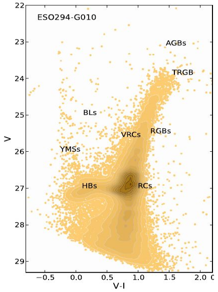
1.8 kpc **50 kpc** **900 kpc** **2 Mpc**

How far is the most distant known RRL star?



1.8 kpc 50 kpc 900 kpc

…and the closest?



2 Mpc

How many RRL stars do we know?

How many RRL stars do we know?

OGLE	2002-	129,000	VI
PAN-STARRS	DR2 (3 yr)	45,000	griz
ASAS-SN	2013-	36,000	VI - g
ZTF	DR3 (21 months)	70,000	gri
Gaia	DR3 (34 months)	270,000	$G\ G_{BP}\ G_{RP}$

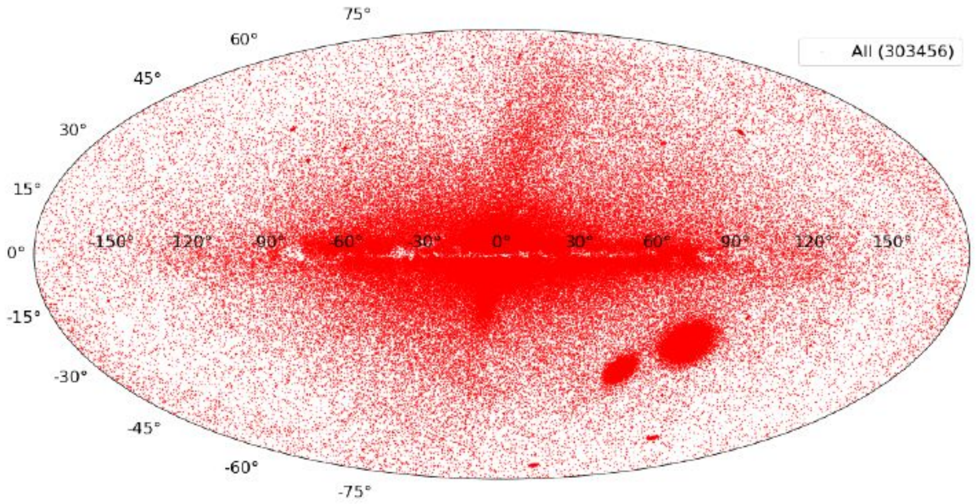
The most comprehensive catalogue of RR Lyrae stars

Full credit for the next slides to
Vittorio Braga and Giuseppe Bono

The most comprehensive catalogue of RR Lyrae stars

Photometric catalogue

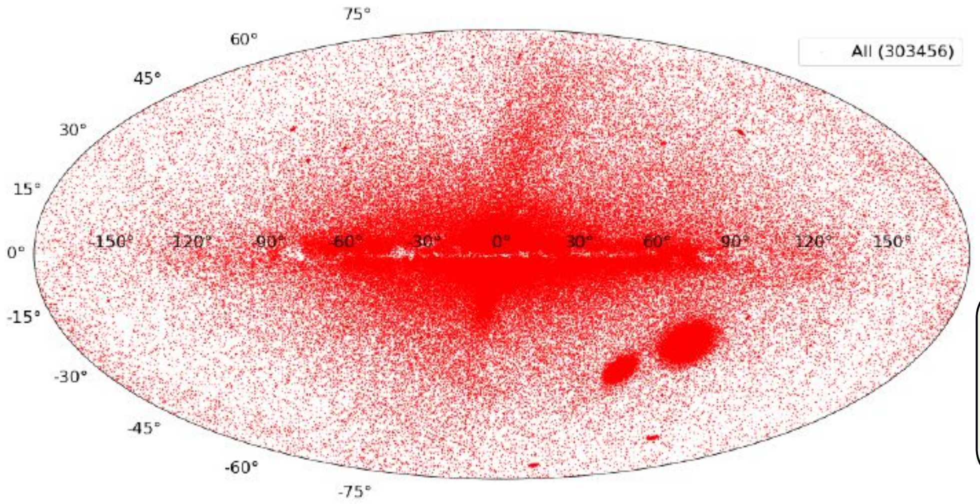
Bono, Braga+ subm.



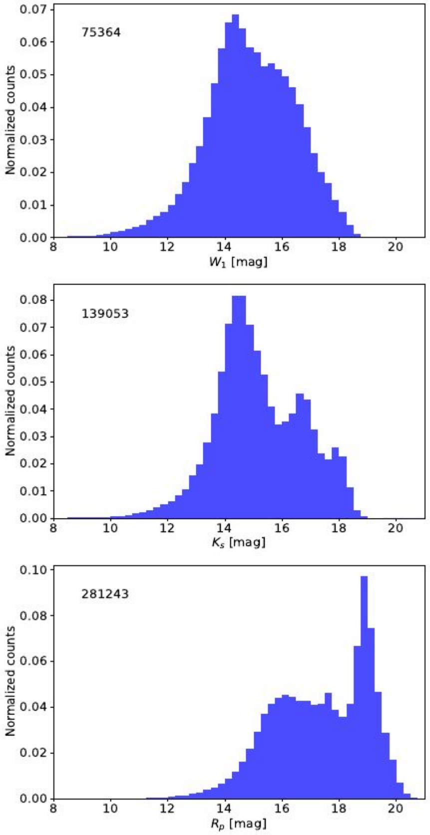
Gaia
optical - Catalina, ASAS, ASAS-SN, GCVS, SDSS, OGLE, Pan-STARRS1, LINEAR, ROTSE-I, LONEOS, ZTF, QUEST,
near infrared - 2MASS, UKIRT, VHS
mid infrared - WISE, NEO-WISE, AllWISE, SPITZER
ultraviolet - GALEX

The most comprehensive catalogue of RR Lyrae stars

Photometric catalogue



7.62 < G < 21.19 mag
4.35 < K < 19.31 mag
5.94 < W1 < 19 mag
12.5 < NUV < 23.2 mag



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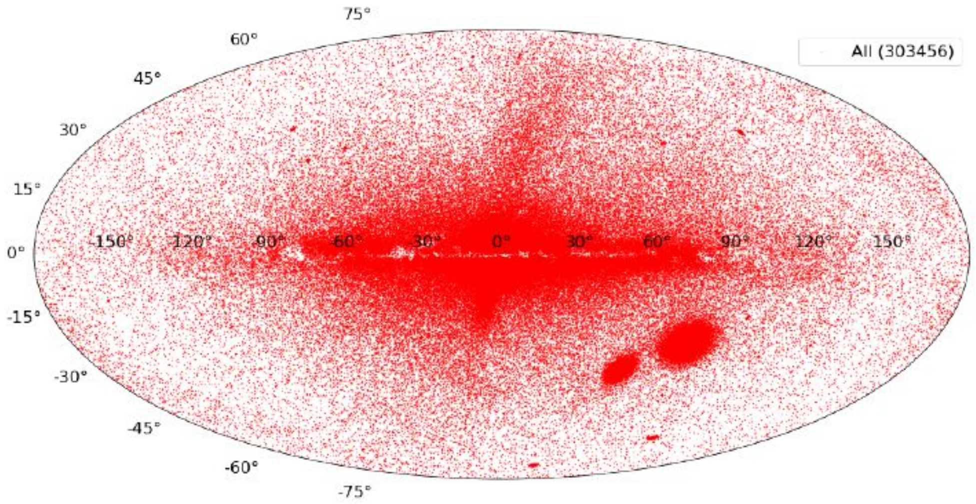

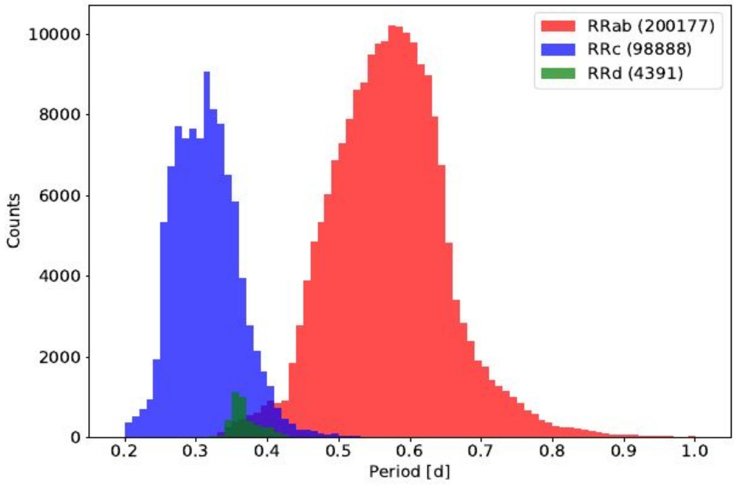

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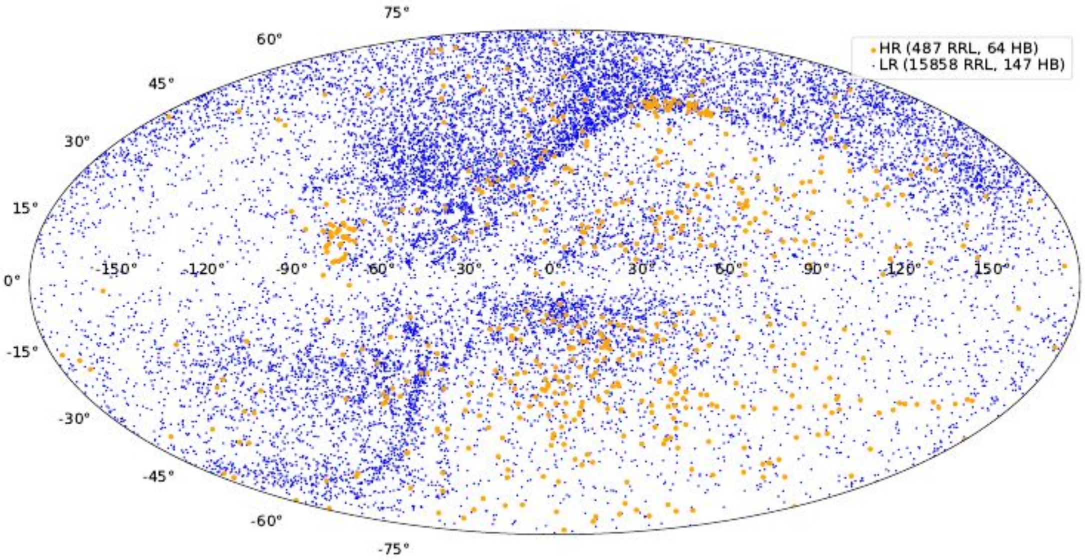
The most comprehensive catalogue of RR Lyrae stars

Spectroscopic catalogue

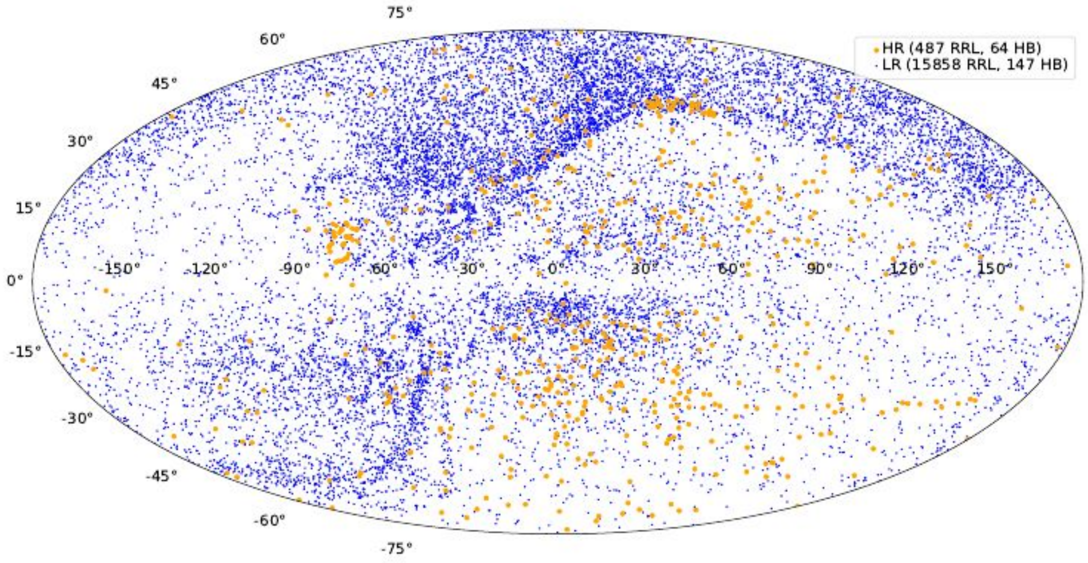


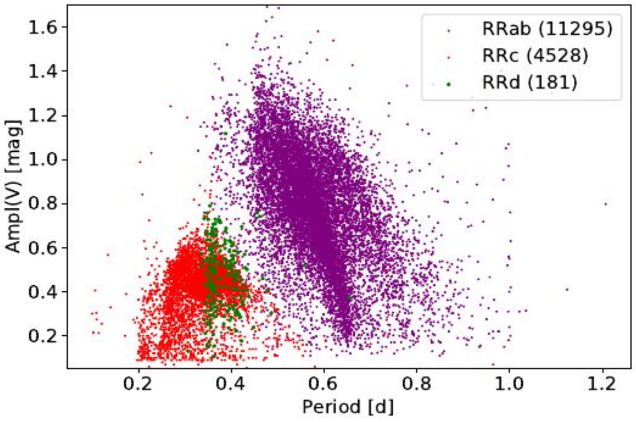
Dataset	RV LR	RV HR	[Fe/H] LR	[Fe/H] HR	[α/Fe] HR
—RRL—					
Crestani	...	576[a]	8117[b]	159+78[c]	201[d]
D24	...	...	...	78	60
D25	...	...	...	3	...
Sesar et al. (2013)	...	...	21	...	...
Liu et al. (2020)	...	...	303	...	...
LAMOST	5436	...	...	...	...
SDSS	1688	...	...	...	...
Gaia	5895	...	...	...	...
GALAH	...	2307	...	119	51
Zinn et al. (2020)	104	...	195	...	...
Kinman et al. (2012)	...	...	51	...	...
Dambis et al. (2013, 2014)	...	...	9	...	...
RAVE	...	...	3	...	...
Duffau et al. (2014)	...	39	...	36	...
Hansen et al. (2011)	...	2	...	...	...
Nemec et al. (2013)	...	11	...	...	...
DESI	1227	...	...	...	...
G21	...	...	...	14	...
Medina et al. (2021)	...	15	...	...	...
—HB—					
For & Sneden (2010)	...	45	...	46	39
Kinman[e]	123	18	...	9	7

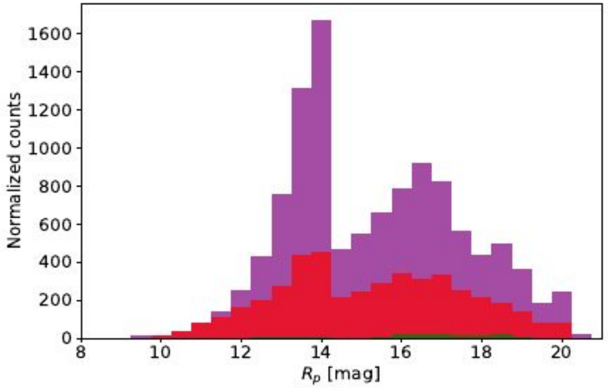
Total of ~16,000 stars

The most comprehensive catalogue of RR Lyrae stars

Spectroscopic catalogue







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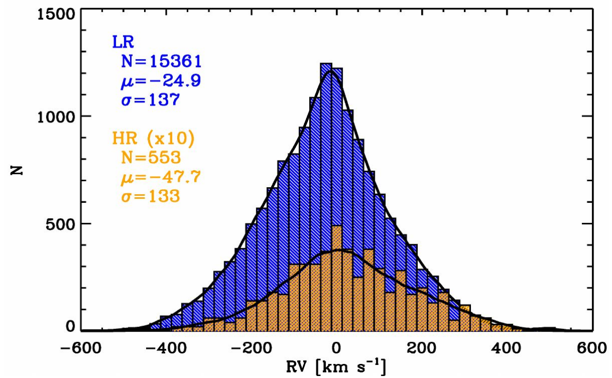
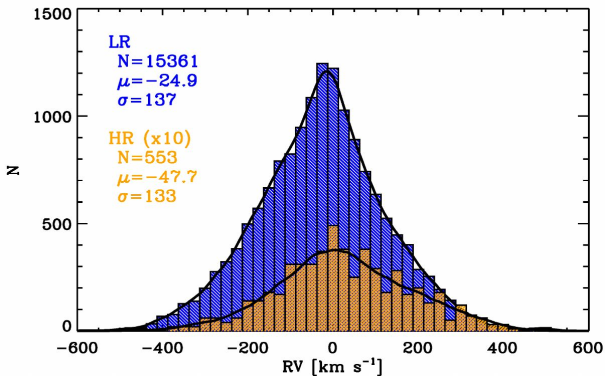
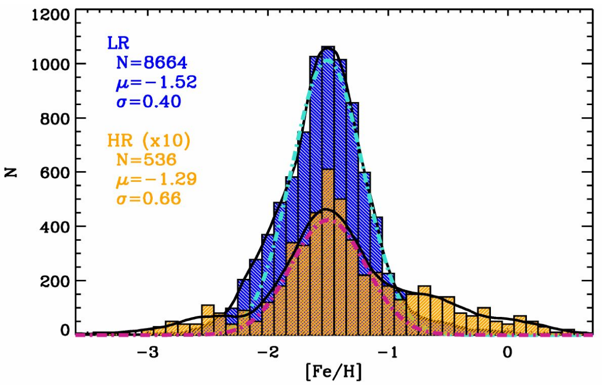
Spectroscopic catalogue



Radial velocity

- symmetric around 0
- HR and LR similar
- high velocity tails





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Metallicity

- similar distribution (peak)
- tails biassed by the samples

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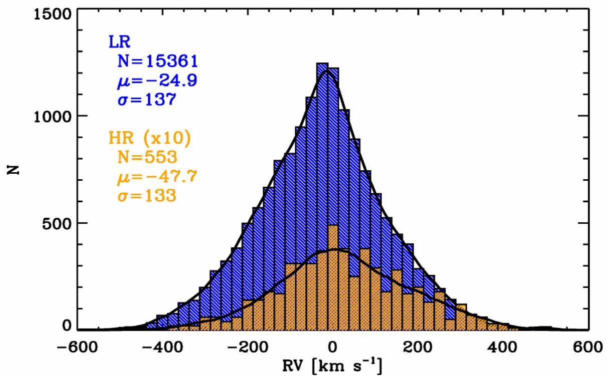
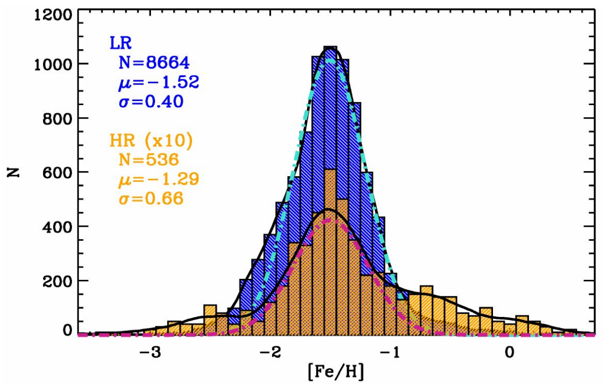
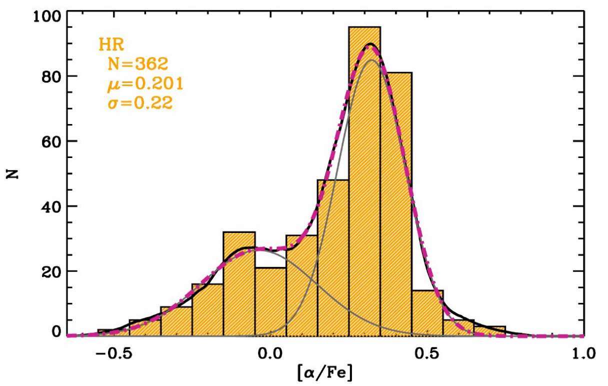
Spectroscopic catalogue







Radial velocity

- symmetric around 0
- HR and LR similar
- high velocity tails

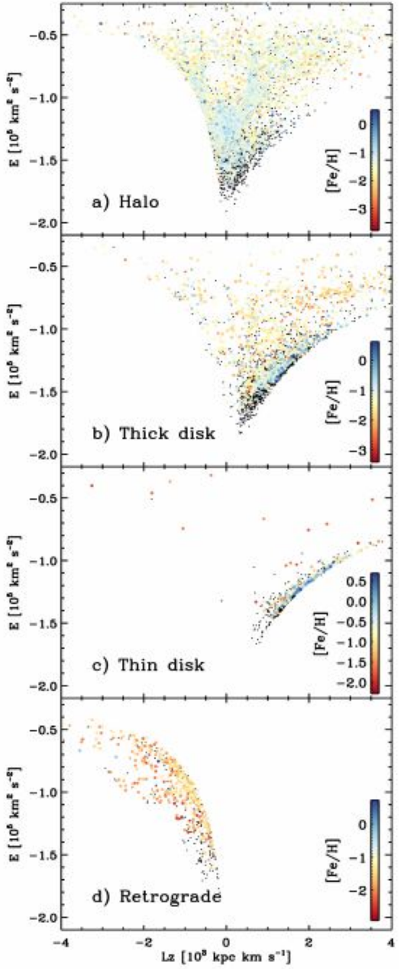
Metallicity

- similar distribution (peak)
- tails biassed by the samples

α-elements

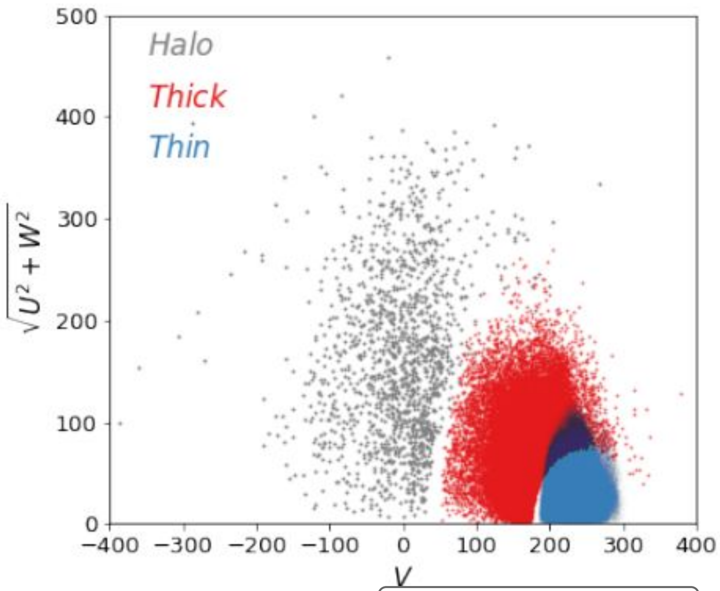
- Ca, Mg, Ti
- two peaks:
  - **α~-0.04**+/-0.01 dex σ=0.11+/-0.01 dex
  - **α~+0.32**+/-0.01 dex σ=0.19+/-0.01dex

Dissecting the MW with RR Ly



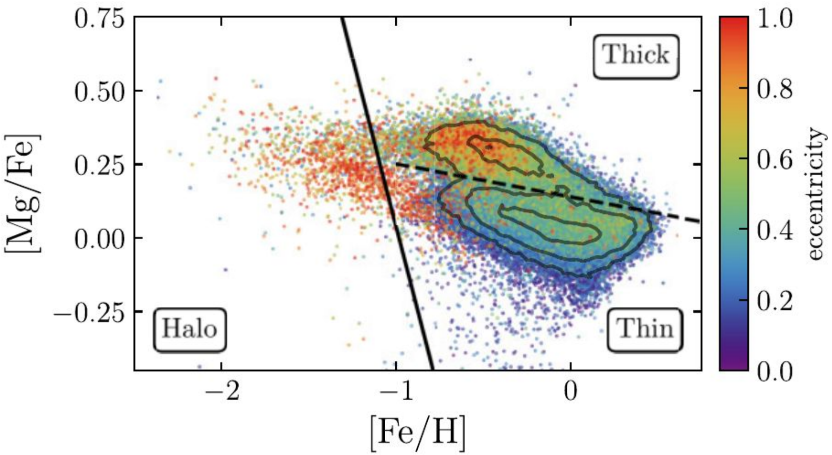
Dissecting the MW with RR Lyrae stars

Lane+2022



Fernandez-Álvar+2025

Kinematical definition



Chemical definition

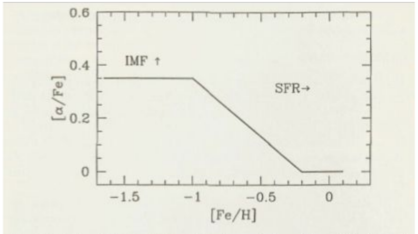


Figure 1 A schematic diagram of the trend of α-element abundance with metallicity. Increased initial mass function and star formation rate affect the trend in the directions indicated. The knee in the diagram is thought to be due to the onset of type Ia supernovae (SN Ia).

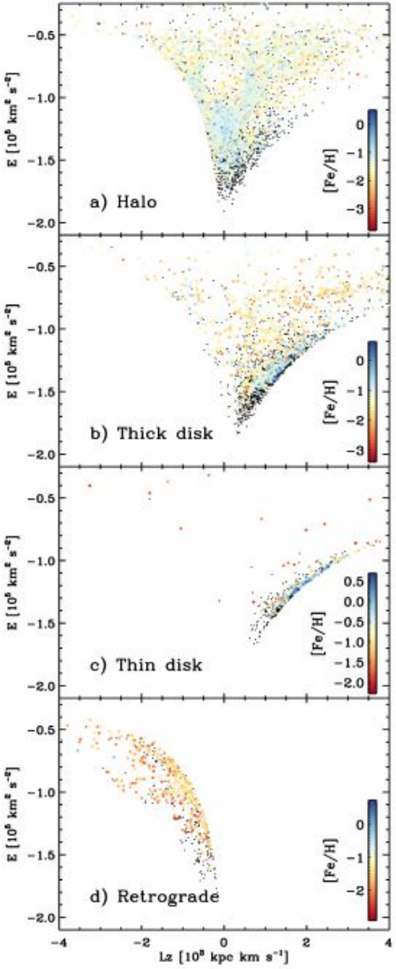
McWilliam 1997

Dissecting the MW with RR Ly

Assumptions:

- Galactic potential
- Sun position
- Sun motion
- a code to reconstruct orbits (galpy, agama)

- distance to stars



position	**2D**
distance	**3D**
proper motion	**5D**
radial velocity	**6D**

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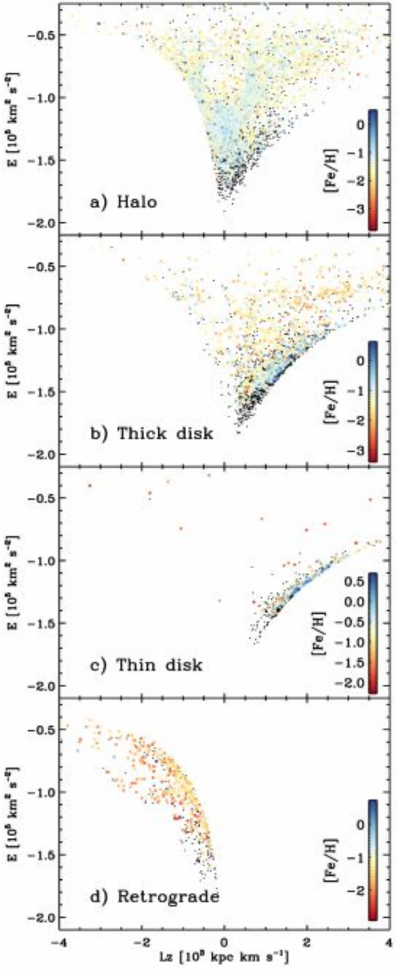


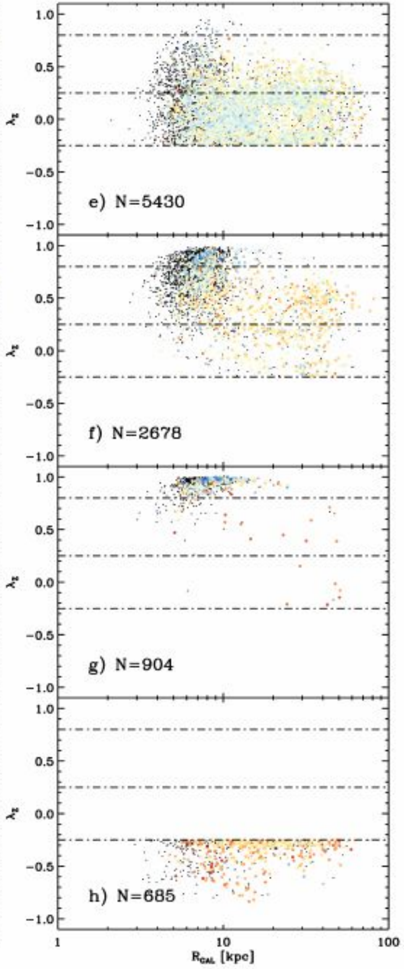
circularity
(0 = radial, cold)

Halo: mostly cold, extend to large distances

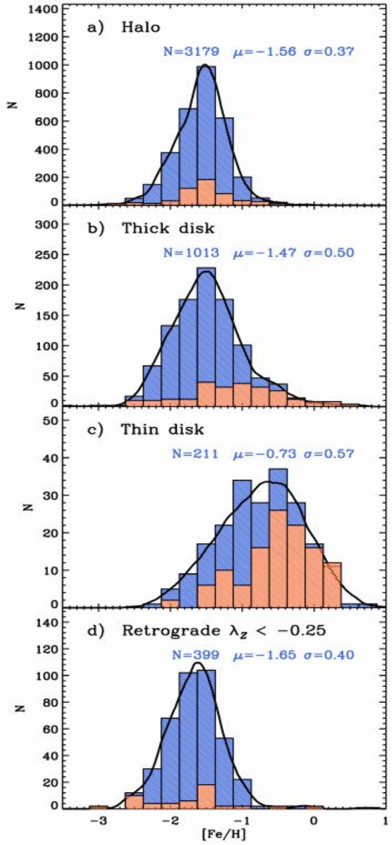
Thick: warmer, more confined

Thin: mostly hot

Retrograde: confined in both parameters



Dissecting the MW with RR Lyrae stars



Chemical Characterization

Metallicity distribution:

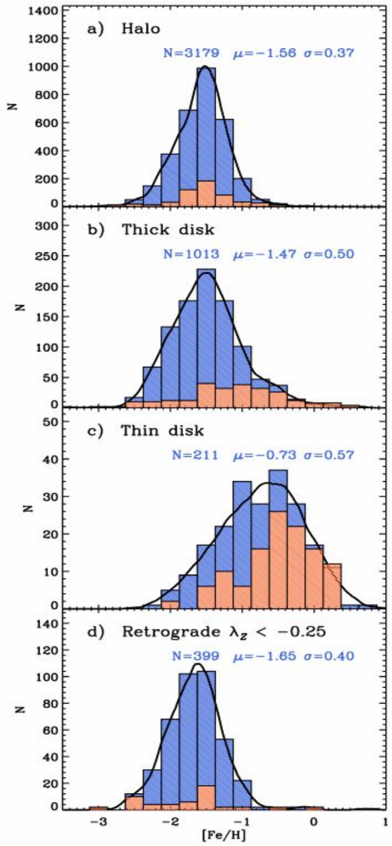
★ **Peak** shifts to higher metallicity
halo → thick → thin

★ **Dispersion** increases

★ Metal-rich tail in the thick disk

★ Retrograde ~ halo

Dissecting the MW with RR Lyrae stars



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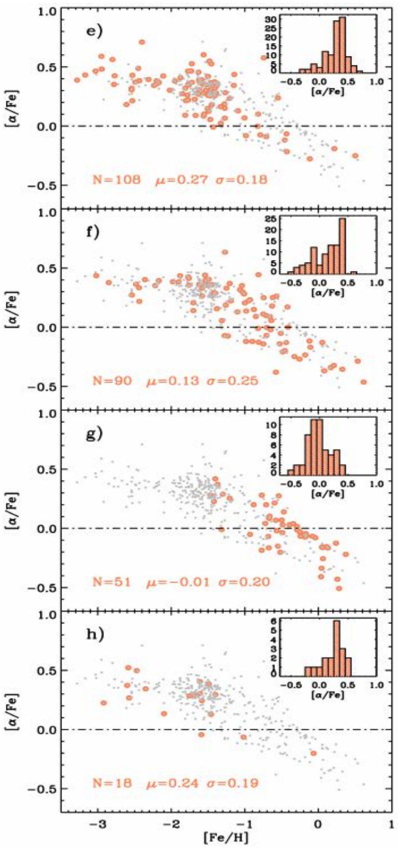


α-elements:

★ **halo**: α-enhanced [α/Fe]~0.27 and metal poor

★ **thick**: α-enhanced and metal poor or α-poor and metal-rich

★ **thin**: mainly α-poor/depleted

★ Retrograde ~ halo

Dissecting the MW with RR Lyrae stars

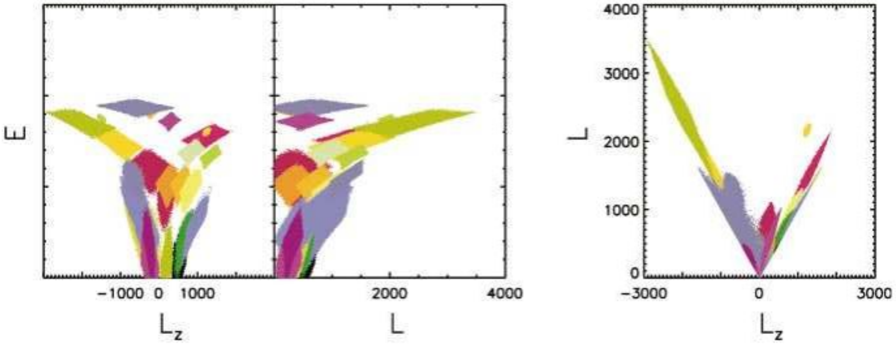
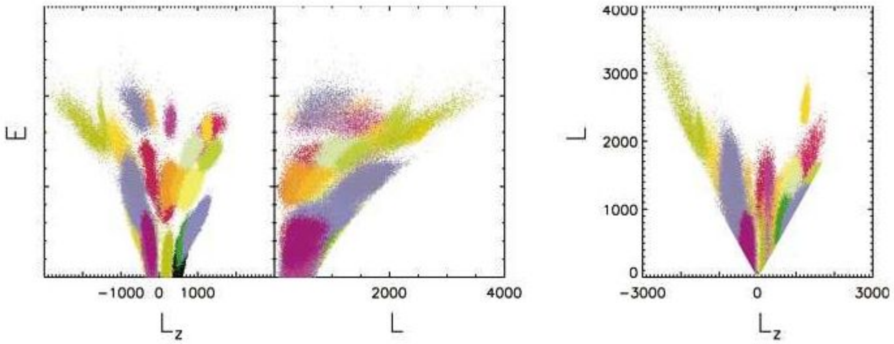


Figure 3. Initial distribution of particles in the integrals of motion space. The different colours represent different satellites.



Helmi+1999,2000

Dissecting the MW with RR Lyrae stars

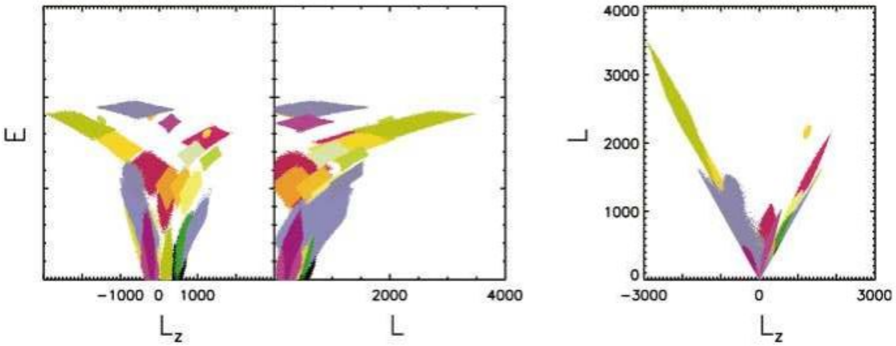
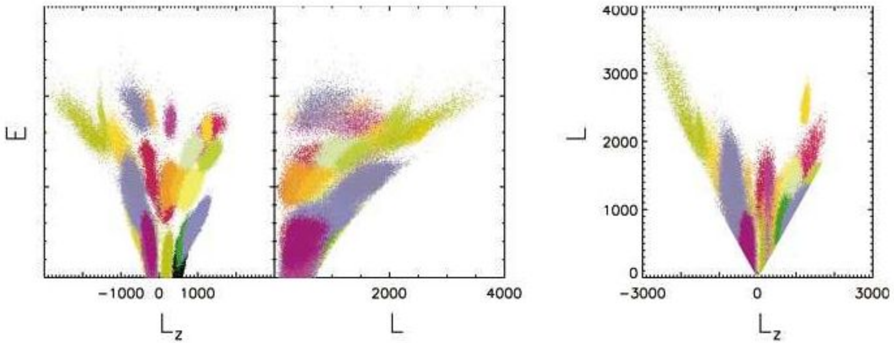


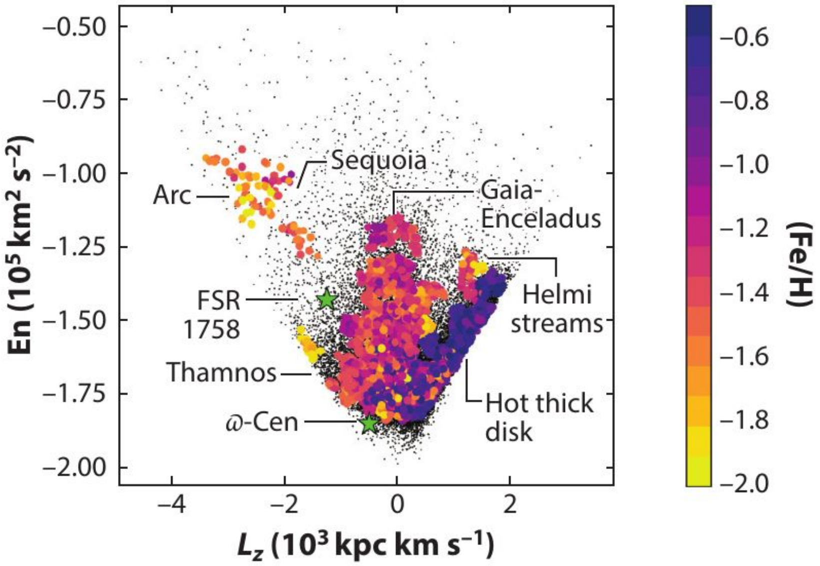
Figure 3. Initial distribution of particles in the integrals of motion space. The different colours represent different satellites.



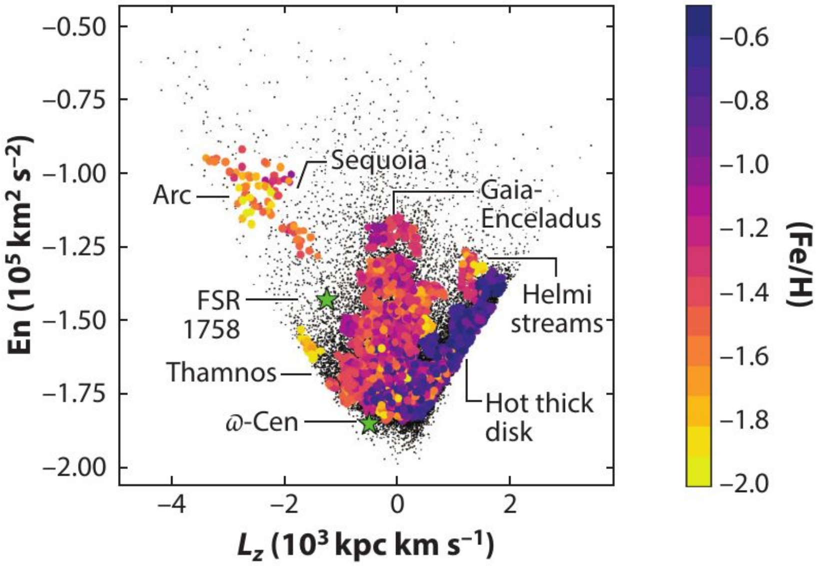
Helmi+1999,2000

Dissecting the MW with RR Lyrae stars

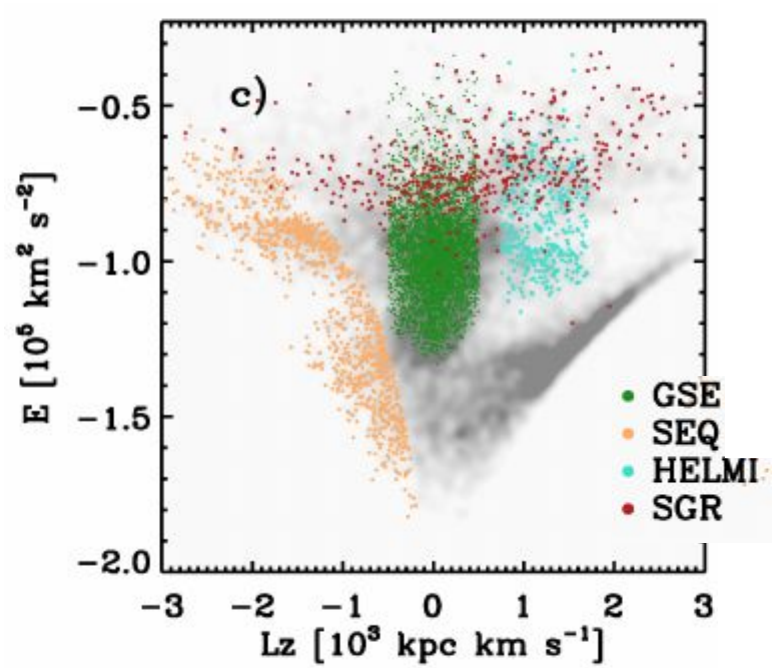
Helmi 2019



Dissecting the MW with RR Lyrae stars



Helmi 2019



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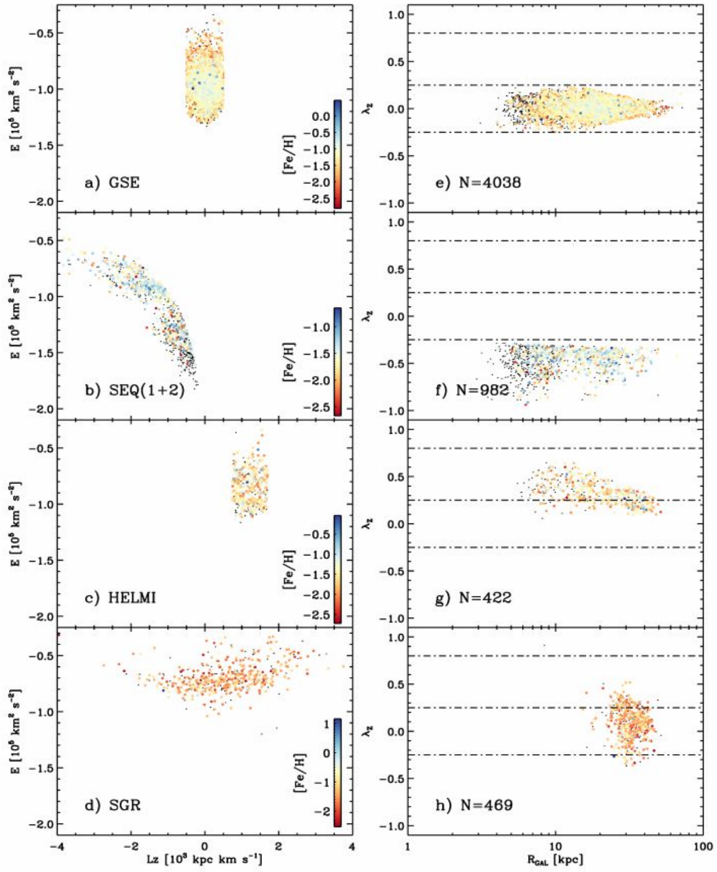


- ★ GES: homogeneous both in metallicity and and orbital energy over a wide range of distances
- ★ Sequoia: more confined and metal-rich, retrograde
- ★ Helmi: hints of metallicity gradient
- ★ Sagittarius: more metal poor, radial orbits

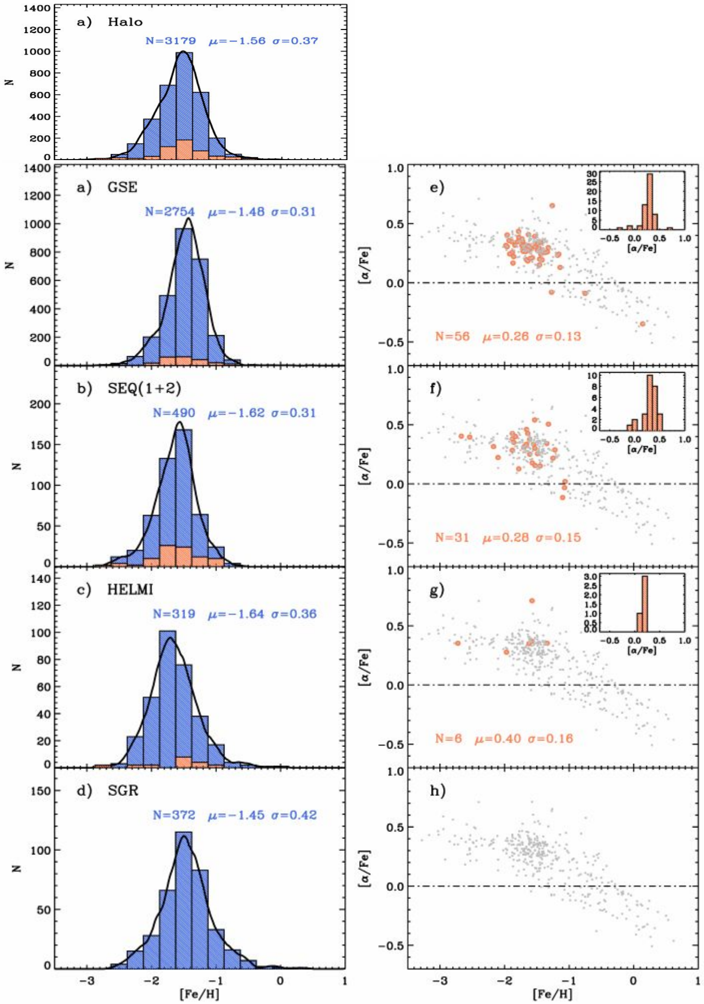
Dissecting the MW with RR Lyrae stars

★ overall large similarities with the halo sample

★ mild dispersion variations

★ small samples with α-abundances

➔ a lot to be done! Gaia DR4 + spectroscopic surveys



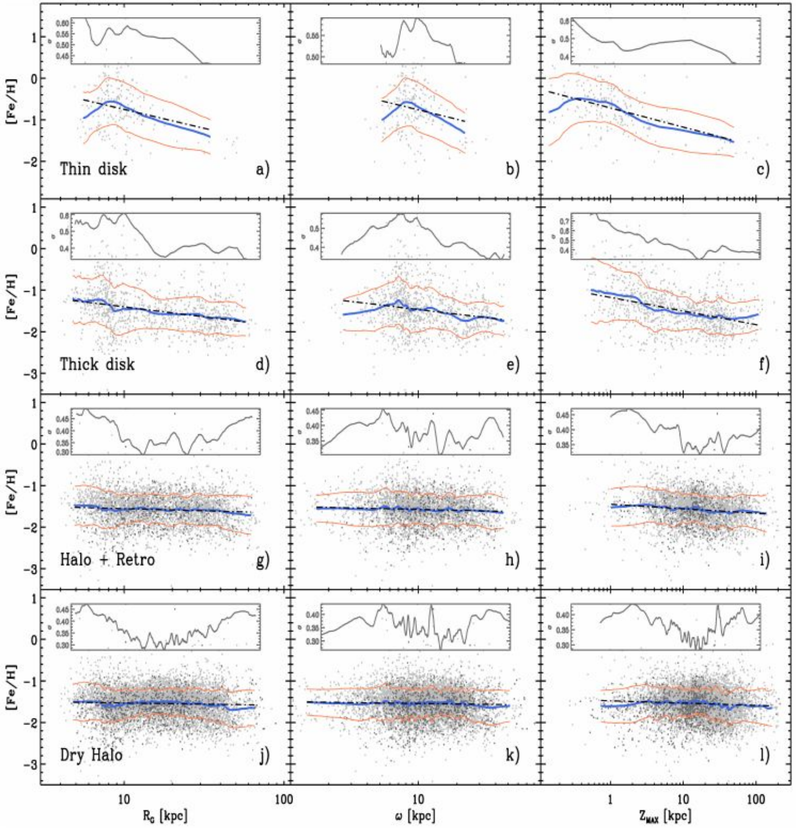
Metallicity gradients

★ **Thin**: limited distance but steeper gradient

★ **Thick**: well defined radial gradient; increase of dispersion at the solar circle

★ **Halo+retro**: mild gradient and large dispersion over a large distance range

★ **Dry halo**: no stars from streams.

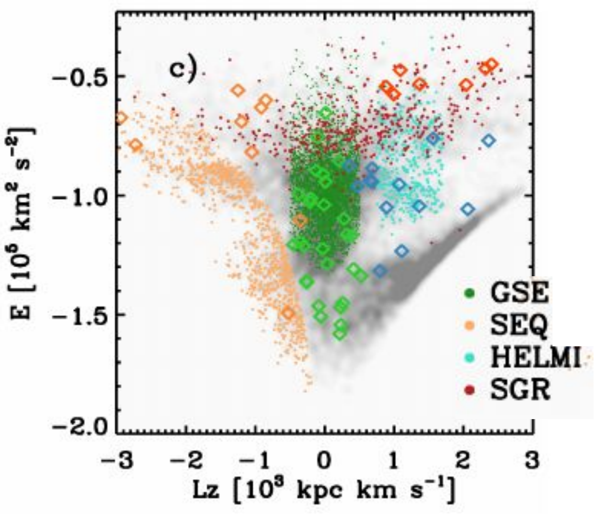


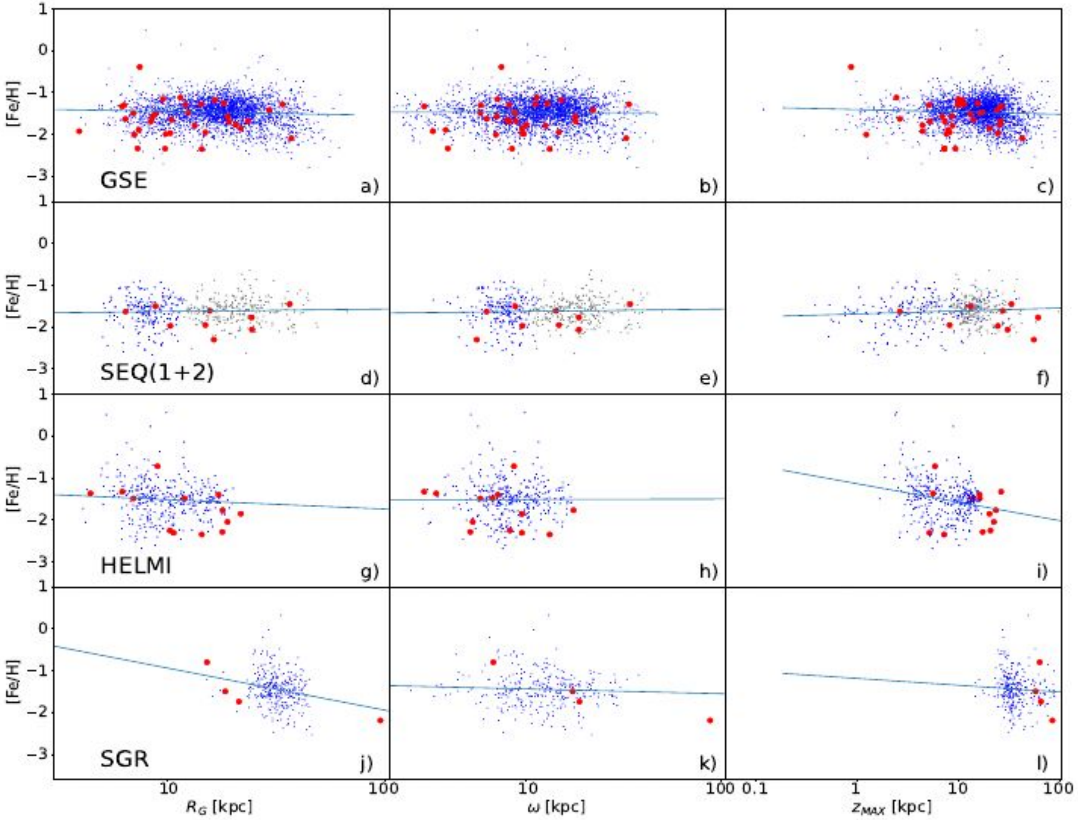
Galactocentric radius

Projected on the plane

Maximum height above the plane

Metallicity gradients





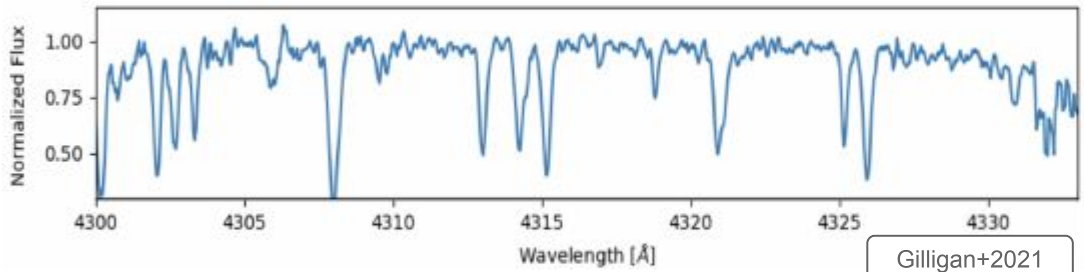
★ Overall good agreement between field and GCs stars

★ **GES**: flat + constant dispersion. Good agrement with GCs.

★ **Sequoia**: differentiation between Seq. 1 and 2

Metallicity of RR Lyrae stars: Spectroscopy

High Resolution



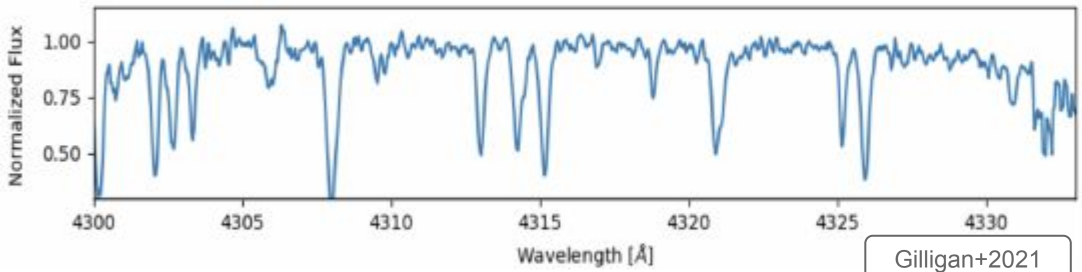
Gilligan+2021

★ R > 20,000
★ fundamental parameter determination
★ line/spectral synthesis
★ errors in [Fe/H] ~ 0.2 dex

❖ tricky business!
❖ doppler shift, line deformation, P Cygni profile, shocks
❖ high S/N in a short time
❖ slow process

Metallicity of RR Lyrae stars: Spectroscopy

High Resolution



Gilligan+2021

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❖ tricky business!
❖ doppler shift, line deformation, P Cygni profile, shocks
❖ high S/N in a short time
❖ slow process

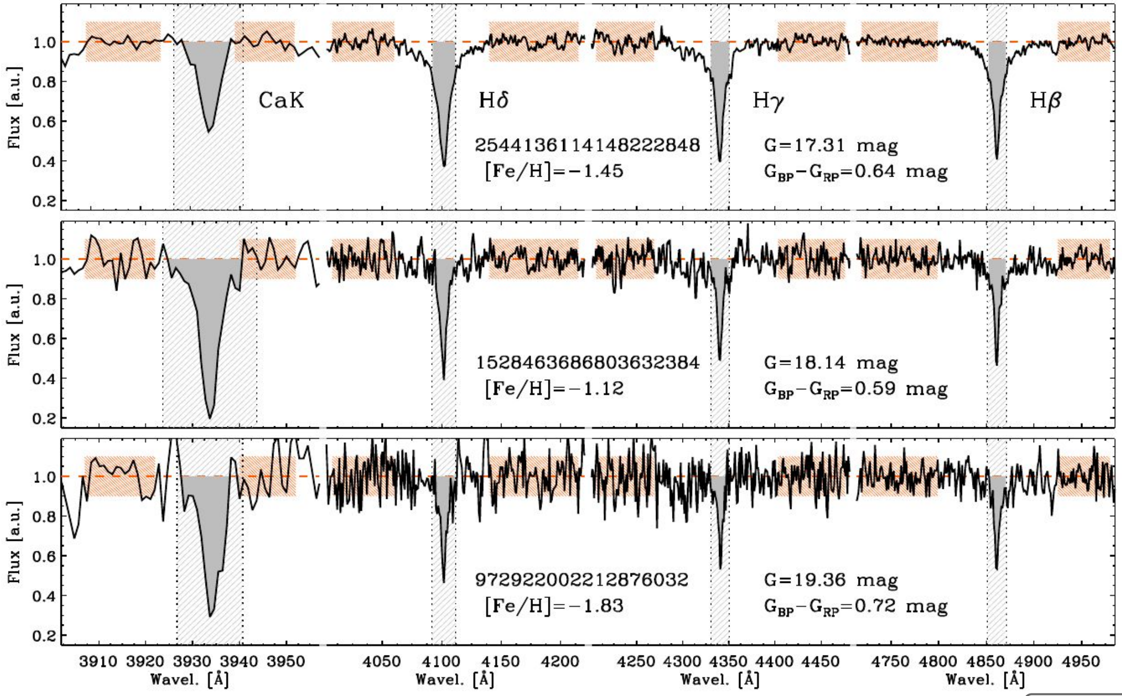
Radial velocity:
< 3000 *

Metallicity:
< 400 *

➔ 4MOST
➔ WEAVE
thousands of RRL stars

Metallicity of RR Lyrae stars: Spectroscopy

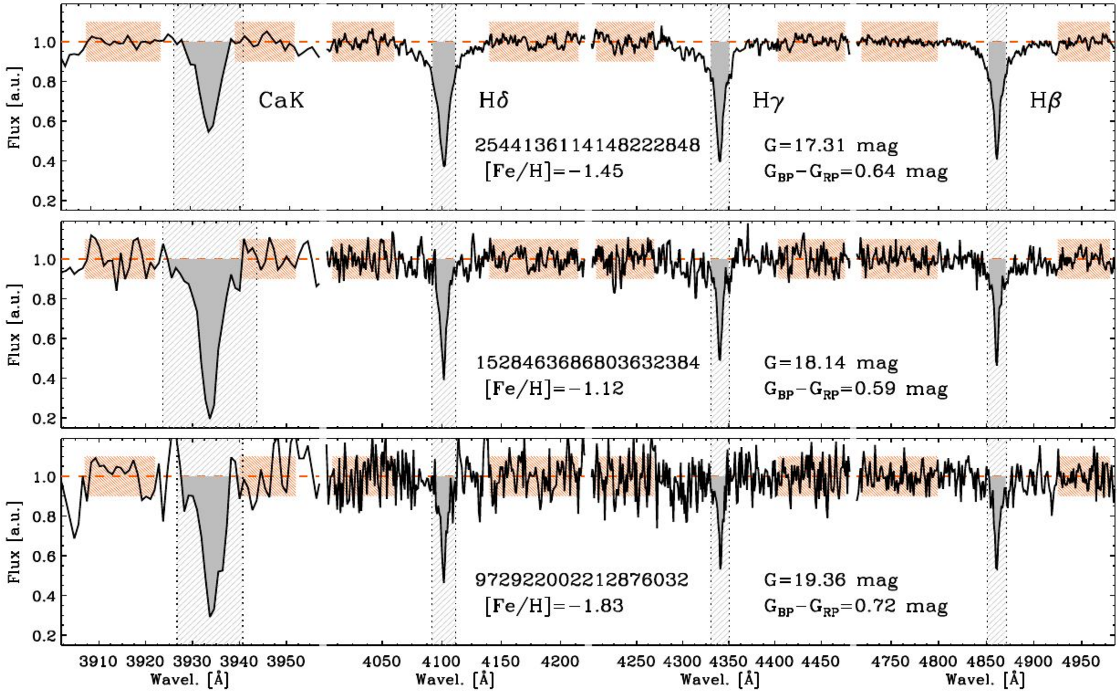
Low Resolution



Fabrizio+2019

Metallicity of RR Lyrae stars: Spectroscopy

Low Resolution

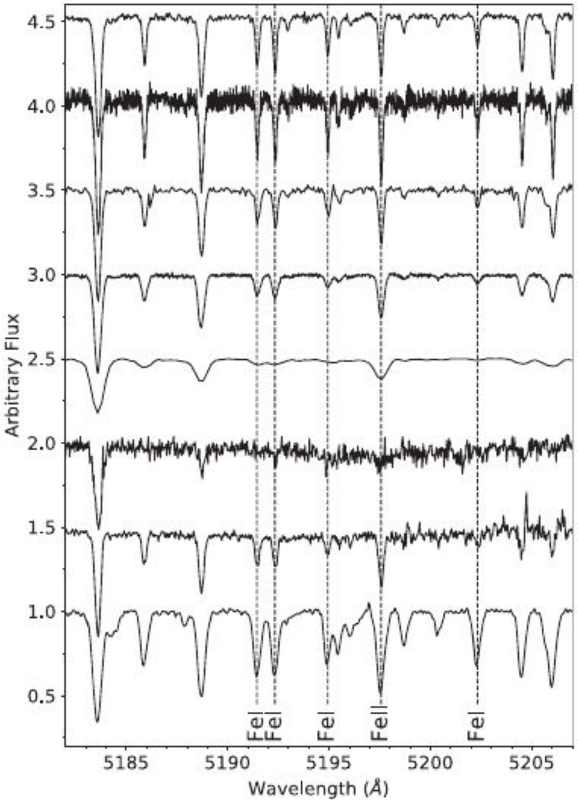


- ★ R > 2,000
- ★ Preston (1959) difference in equivalent width of Ca II Kline and Balmer lines
- ★ more efficient
- ★ less precise ~0.3-0.4 dex
- ★ Crestani+2021 calibration on 143 stars with HR

Radial velocity:
~13000 *

Metallicity:
< 8000 *

Metallicity of RR Lyrae stars: Spectroscopy



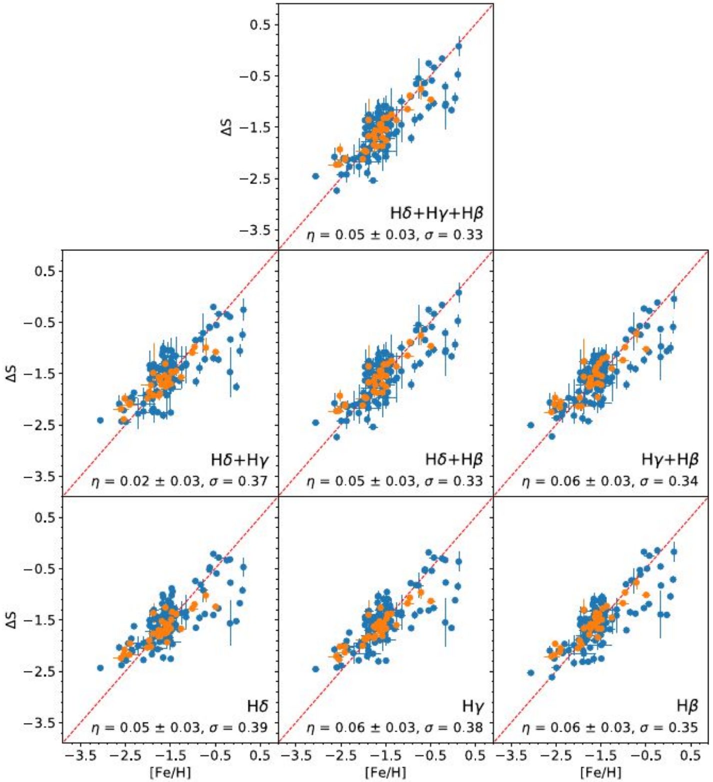
[Fe/H]=-1.67

[Fe/H]=-2.59

[Fe/H]=-1.37

[Fe/H]=+013

Crestani+2021



Metallicity of RR Lyrae stars: Photometry

The pulsational properties are connected to the chemistry of the star

Different relations have been proposed to infer the metallicity of the RRL star from its light curve properties, correlating [Fe/H] with

- the **Fourier** parameters (Jurcsik & Kovacs 1996, Nemec 2013)
- the period (Sarajedini 2006)
- the period and the amplitude (Alcock+2000)
- the period and the amplitude (theoretical, Bono+2007)
- the period and the **luminosity** (Braga+2016)

Fourier coefficients

- ★ Jurcsik & Kovacs (1996) first find a linear relation between [Fe/H], the period and the Fourier coefficients

$$m(\phi) = A_0 + \sum_{i=1}^{n} A_i \sin[2\pi i(\phi + \phi_0) + \phi_i]$$

- ★ Certain coefficients correlate with metallicity

$$\Phi_{31} = \Phi_3 - 3\Phi_1$$

- ★ different relations in different filter passbands: V, G (Gaia), Kp (Kepler), I (OGLE), mid IR

Radial velocity:
~13000 *

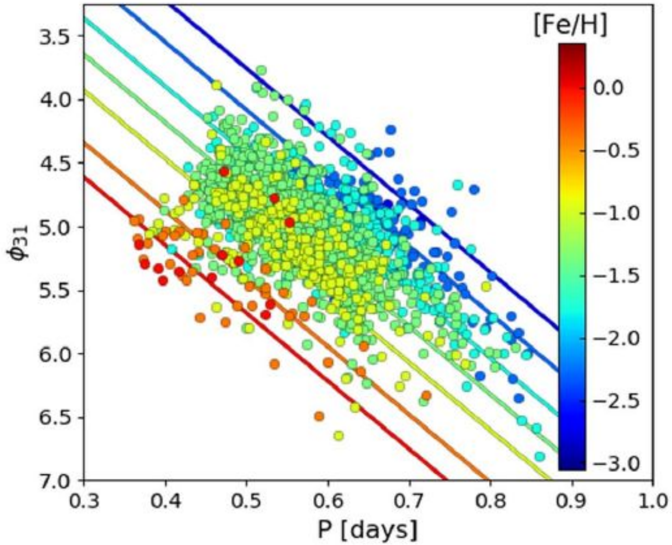
Metallicity:
< 8000 *

Metallicity of RR Lyrae stars: Photometry

Mullen+2021,2022

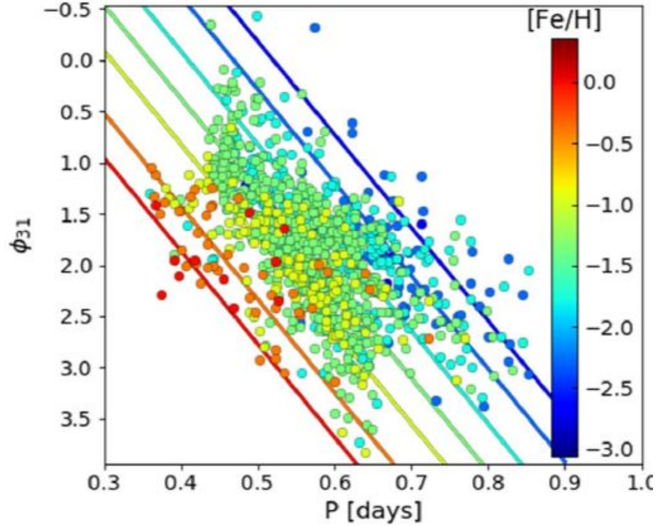
Fourier coefficients

ASAS-SN V



$$[\mathrm{Fe/H}] = (-1.22 \pm 0.01) + (-7.60 \pm 0.24) \cdot (P - 0.58) + (1.42 \pm 0.05) \cdot (\phi_{31} - 5.25) \; ; \; \mathrm{rms} = 0.41,$$

WISE MidIR



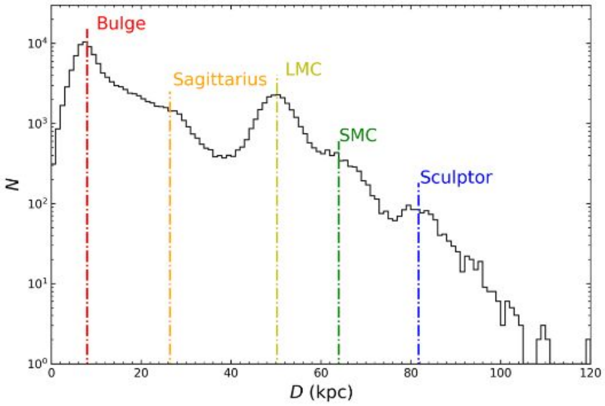
$$[\mathrm{Fe/H}] = (-1.47 \pm 0.02) + (-8.33 \pm 0.34) \cdot (P - 0.58) + (0.92 \pm 0.05) \cdot (\phi_{31} - 1.90) \; ; \; \mathrm{rms} = 0.50.$$

Metallicity of RR Lyrae stars: Photometry

- Hajdu+2018, Dekany+2018,2021, 2022: application to OGLE and VVV

- Li+2023: recalibration of the Fourier-metallicity relation, based on ~5,000 LAMOST star (low-res); metallicity and distances of 136,000 RRL

$$[\mathrm{Fe/H}] = a_0 + a_1(P - 0.6) + a_2(\phi_{31} - 2) + a_3(R_{21} - 0.45),$$



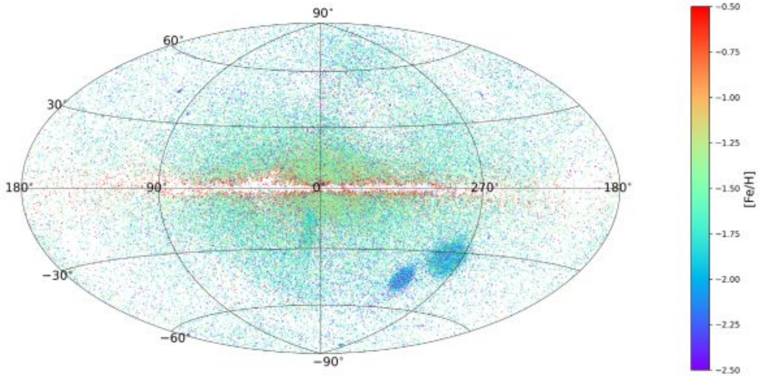


Figure 5. The sky distribution of our final RRL sample of 135,873 RRLs (115,410 type RRab and 20,463 type RRc stars) in Galactic coordinates, color-coded by metallicity, as shown in the color bar.

Metallicity of RR Lyrae stars: Photometry

- Hajdu+2018, Dekany+2018,2021, 2022: application to OGLE and VVV

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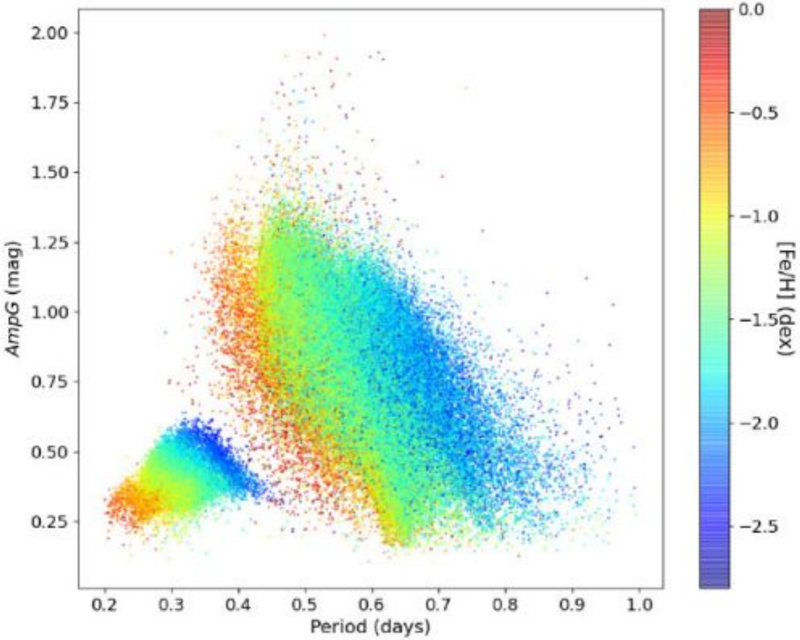
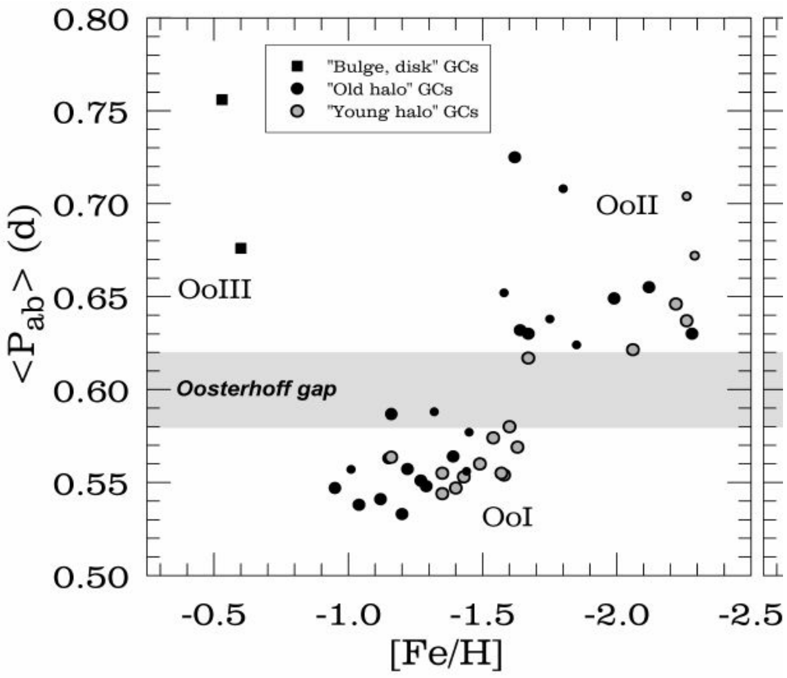
- Muraveva+2025; 134,000

$$[\mathrm{Fe/H}] = (-8.54 \pm 0.42)P + (0.23 \pm 0.04)\phi_{31} - (9.34 \pm 1.41)A_2 + (0.80 \pm 0.19).$$



On the Oosterhoff dichotomy

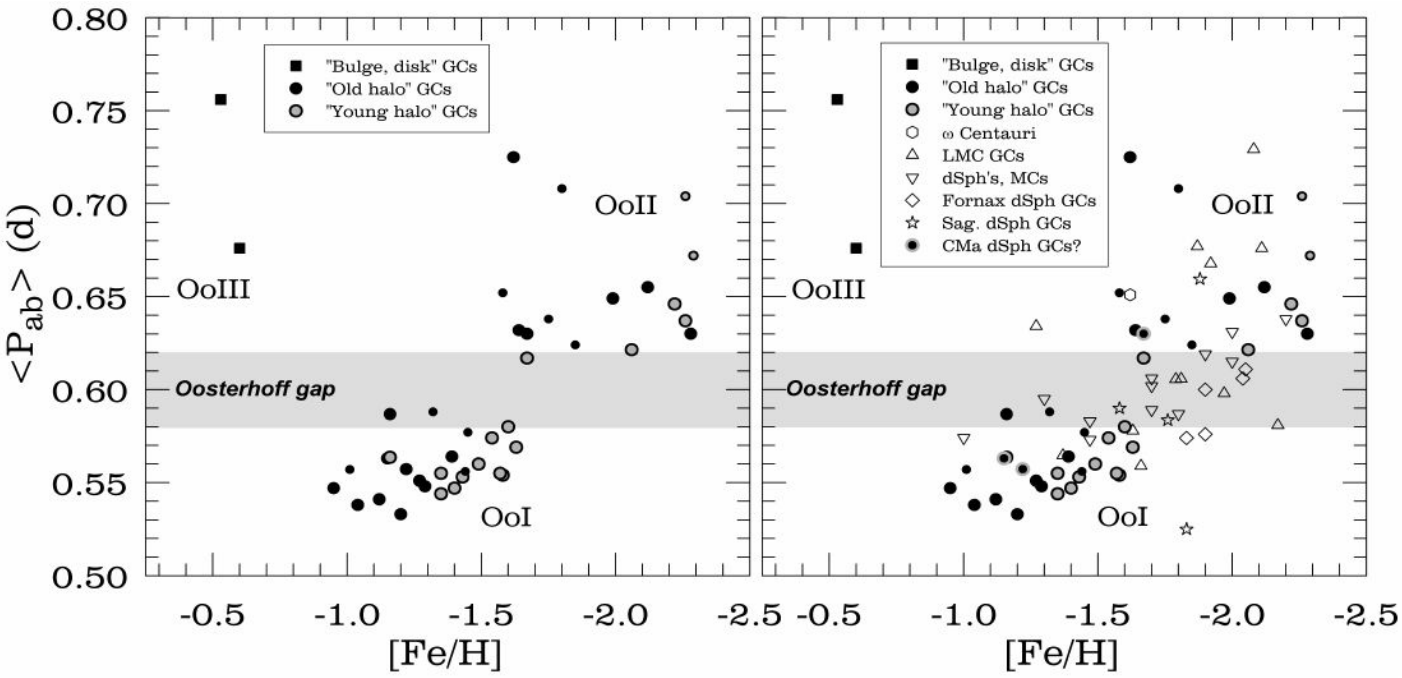


Catelan 2009

	c-type.			a- and b-type.		
	Number.	Median period.	Mean period.	Number.	Median period.	Mean period.
		d	d		d	d
ω Cen . . .	57	·38'	·37	77	·63	·65
M 15	28	·38	·38	31	·66	·65
M 53	15	·38	·36	17	·62	·62
M 5	13	·32	·32	63	·54	·54
M 3	27	·32	·32	124	·54	·55

Oosterhoff 1939

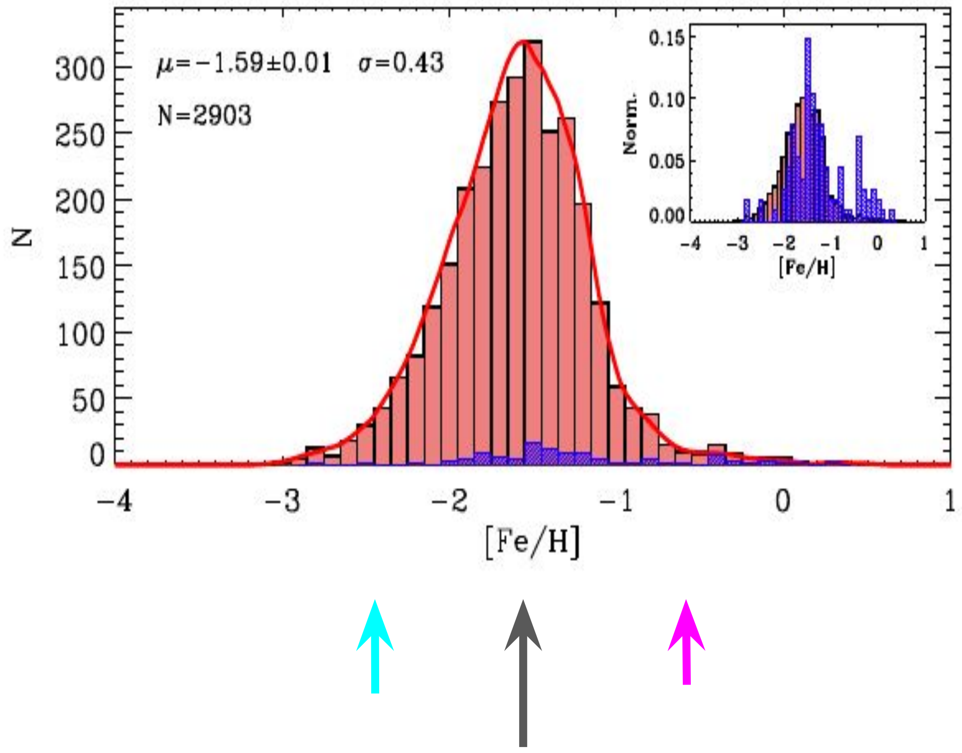
On the Oosterhoff dichotomy

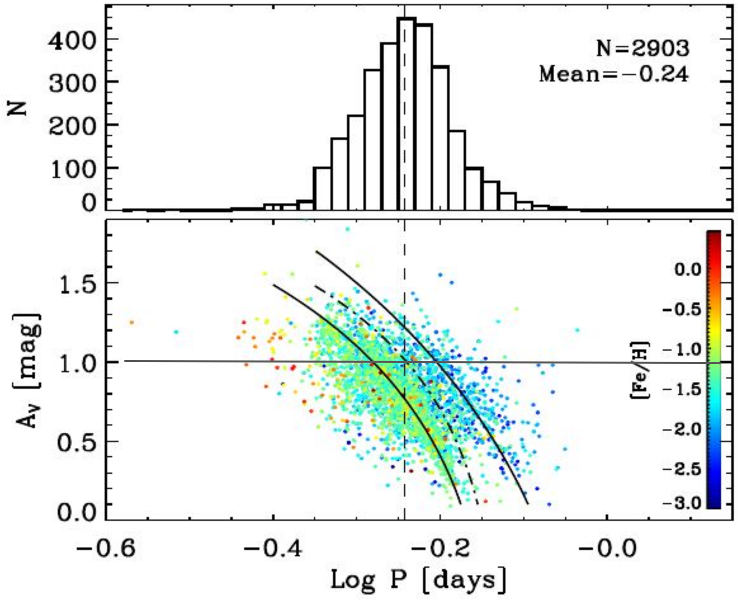


Catelan 2009

On the Oosterhoff dichotomy

Fabrizio+2019



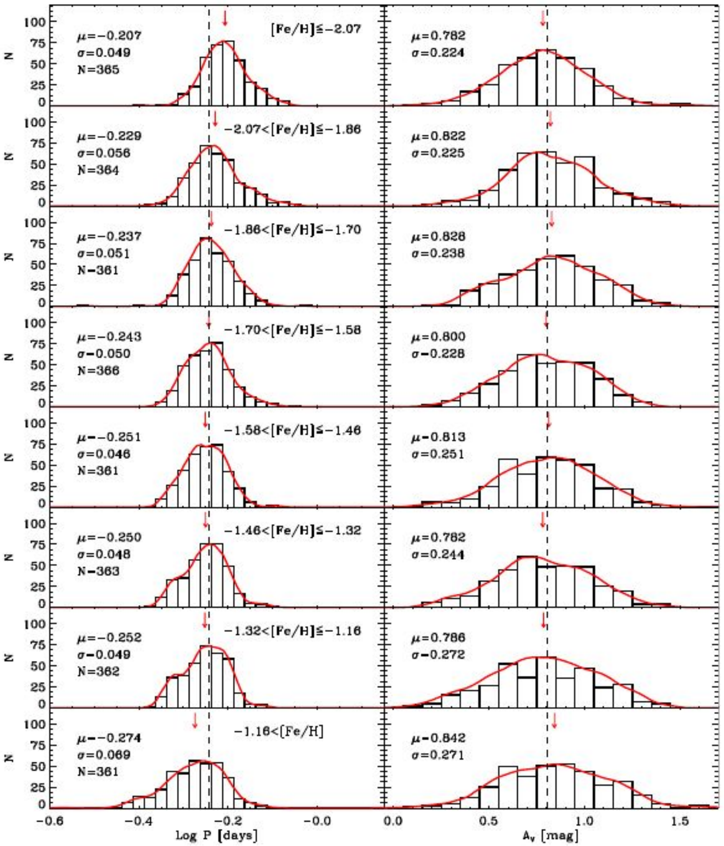


On the Oosterhoff dichotomy

Fabrizio+2019

- ★ the mean period decreases for increasing metallicity
- ★ asymmetric distribution
- ★ skewness moves from the metal-rich to the metal-poor tail for increasing metallicity

metallicity



On the Oosterhoff dichotomy

Fabrizio+2019

- ★ the mean period decreases for increasing metallicity
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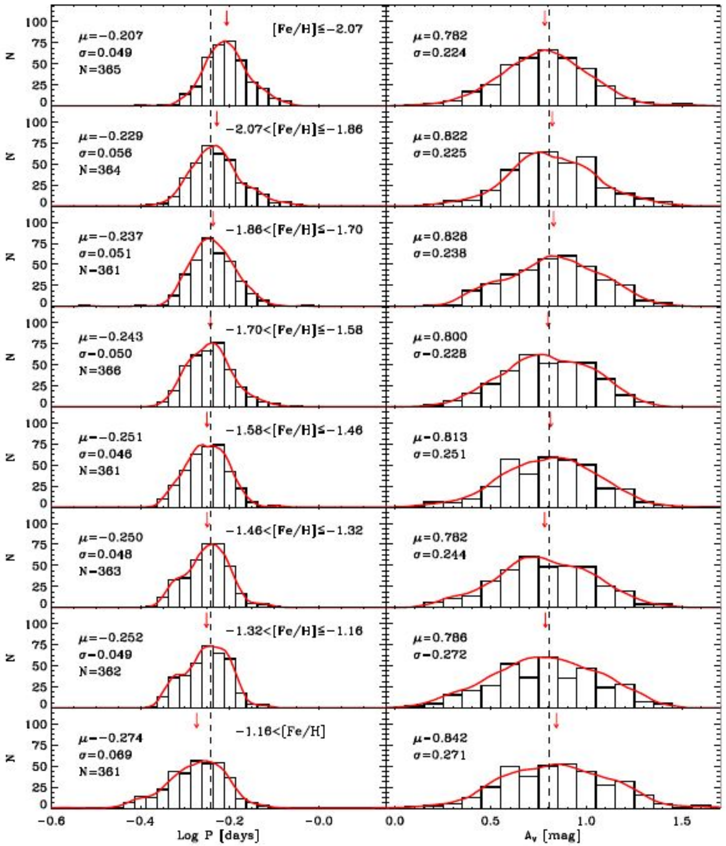
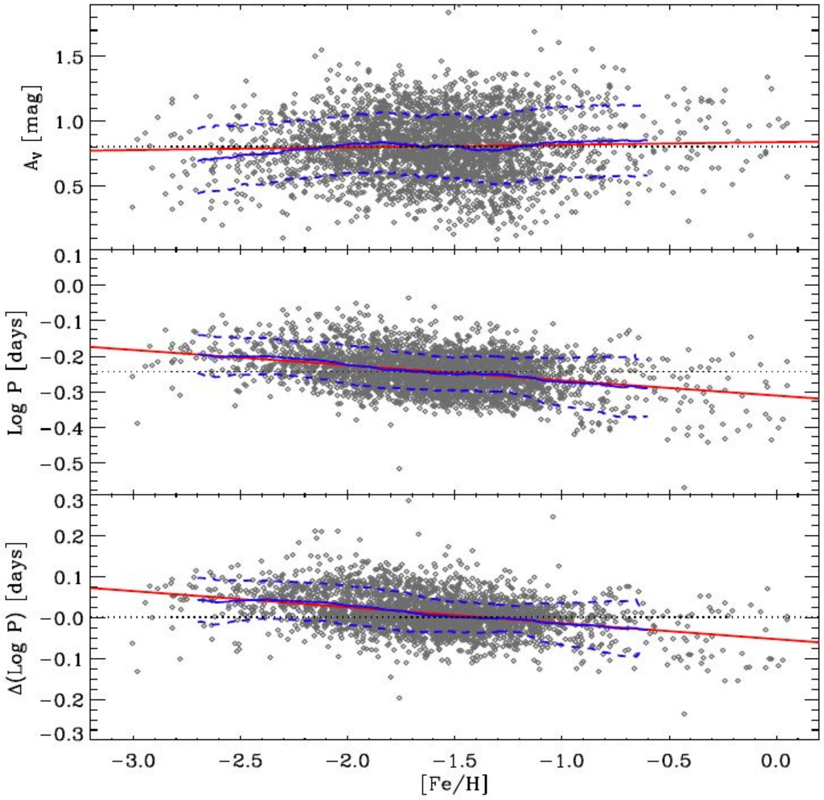
metallicity



- ★ not so clear trend for the amplitude

On the Oosterhoff dichotomy

Fabrizio+2019



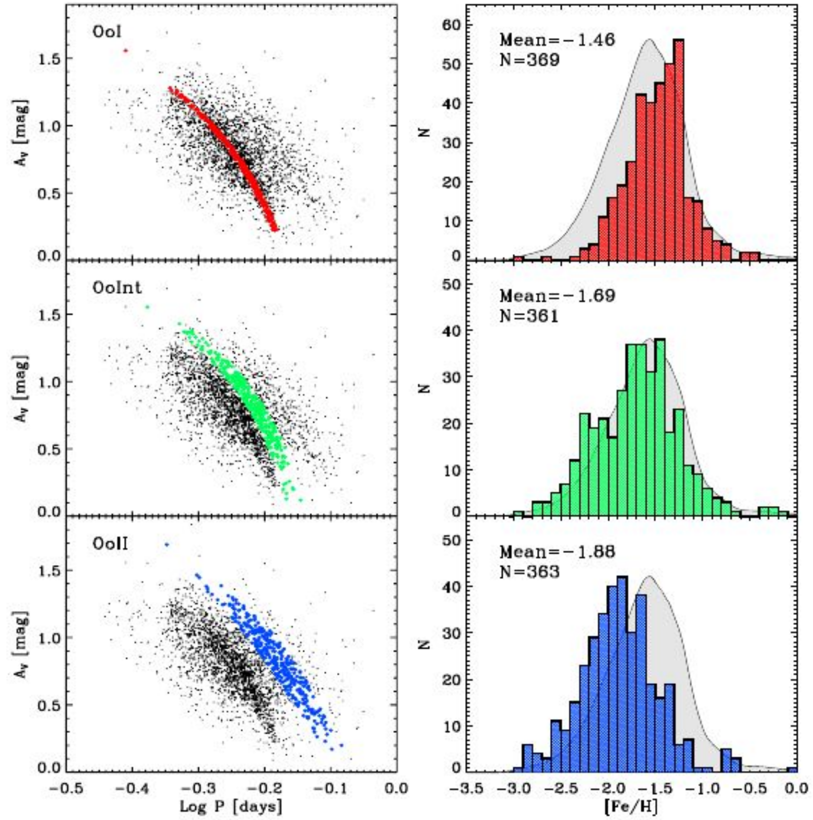
$$A_V = 0.84(\pm 0.02) + 0.02(\pm 0.01) \cdot [Fe/H].$$

$$\log P = -0.311(\pm 0.004) - 0.044(\pm 0.002) \cdot [Fe/H].$$

$$\Delta \log P = -0.054(\pm 0.003) - 0.040(\pm 0.002) \cdot [Fe/H].$$

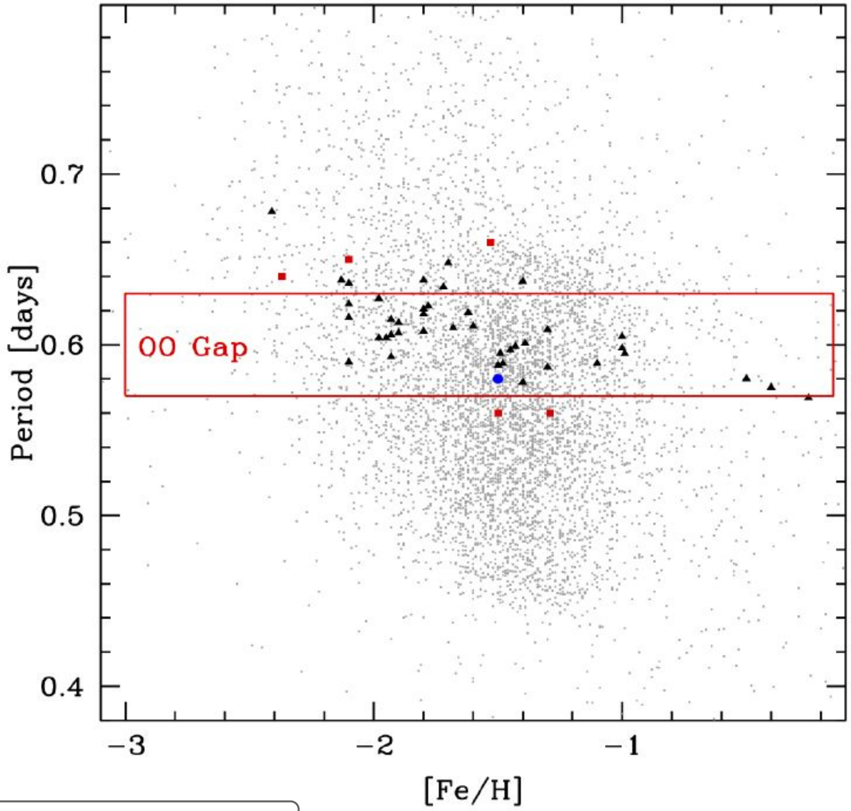
On the Oosterhoff dichotomy

Fabrizio+2019

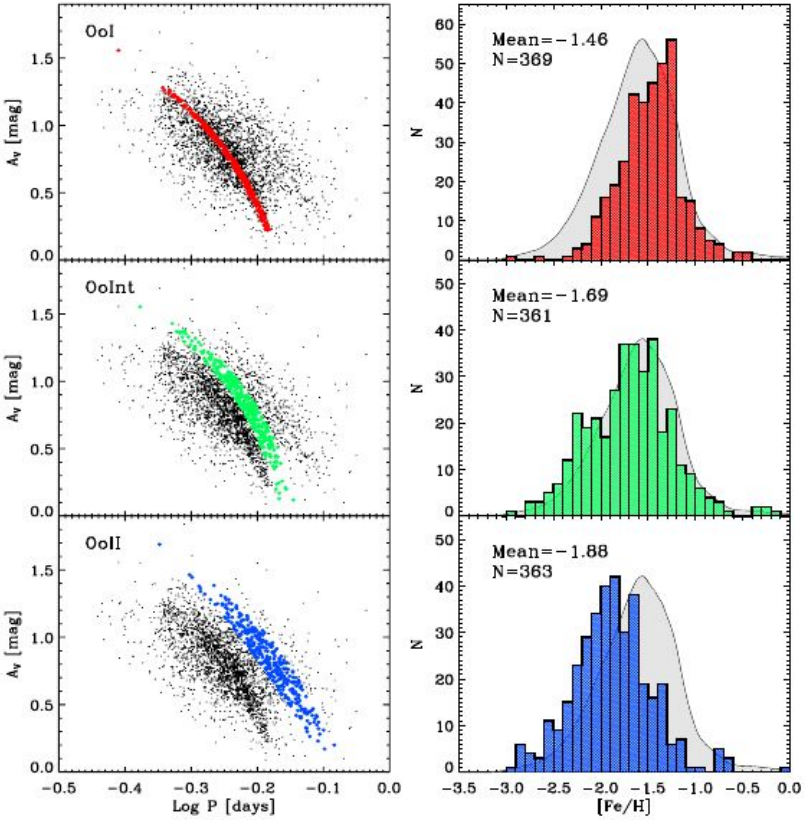


On the Oosterhoff dichotomy

Fabrizio+2019



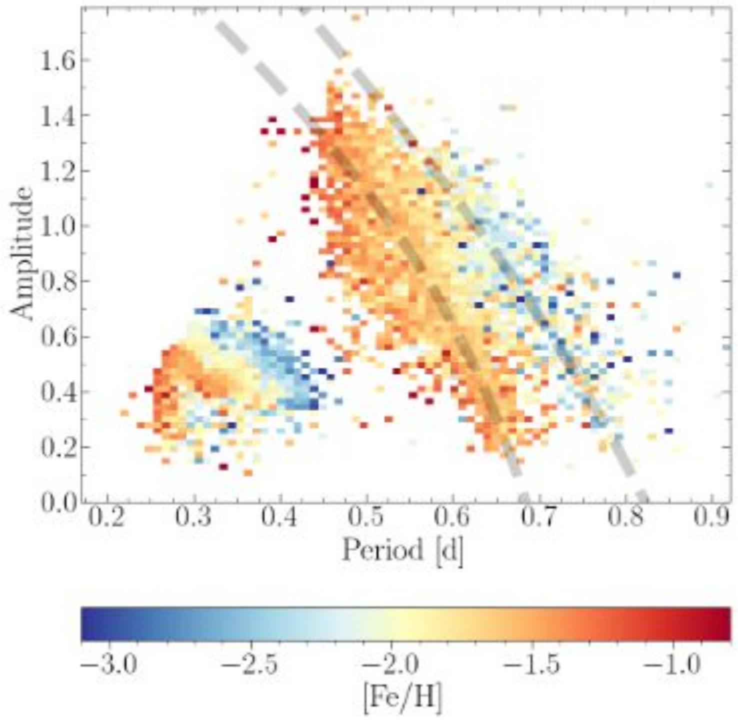
Monelli & Fiorentino 2022



On the Oosterhoff dichotomy

Medina+2025abc

- ★ DESI DR1
- ★ 6420 RRL
- ★ R~2,500



On the Oosterhoff dichotomy

Medina+2025abc