Inferring elemental abundances of variable stars

How to tackle very complex stars!

Valentina D’Orazi
University of Rome Tor Vergata / INAF Padua

BTL 2024 – December 2-4, 2024 -- ESO (Chile)

Credits

- Vasu Pipwala (UniToV, PhD student)
- Antonino Nunnari (UniTov/INAF, PhD student)
- Bruno Benkel (Deutsches Elektronen-Synchrotron DESY, PhD student)
- Alexey Bobrick (Technion Haifa / Monash)
- Giuliano Iorio (Universitat de Barcelona)

Classification*

Variable stars may be either intrinsic or extrinsic.

- **Intrinsic variable stars**: stars where the variability is being caused by changes in the physical properties of the stars themselves. This category can be divided into three subgroups.
  - Pulsating variables, stars whose radius alternately expands and contracts as part of their natural evolutionary ageing processes.
  - Eruptive variables, stars who experience eruptions on their surfaces like flares or mass ejections.
  - Cataclysmic or explosive variables, stars that undergo a cataclysmic change in their properties like novae and SN

*https://en.wikipedia.org/wiki/Variable_star

Classification

- **Extrinsic variable stars:** stars where the variability is caused by external properties like rotation or eclipses. There are two main subgroups.

  1. Eclipsing binaries, double stars or planetary systems where, as seen from Earth, the stars occasionally eclipse one another as they orbit, or the planet eclipses its star.

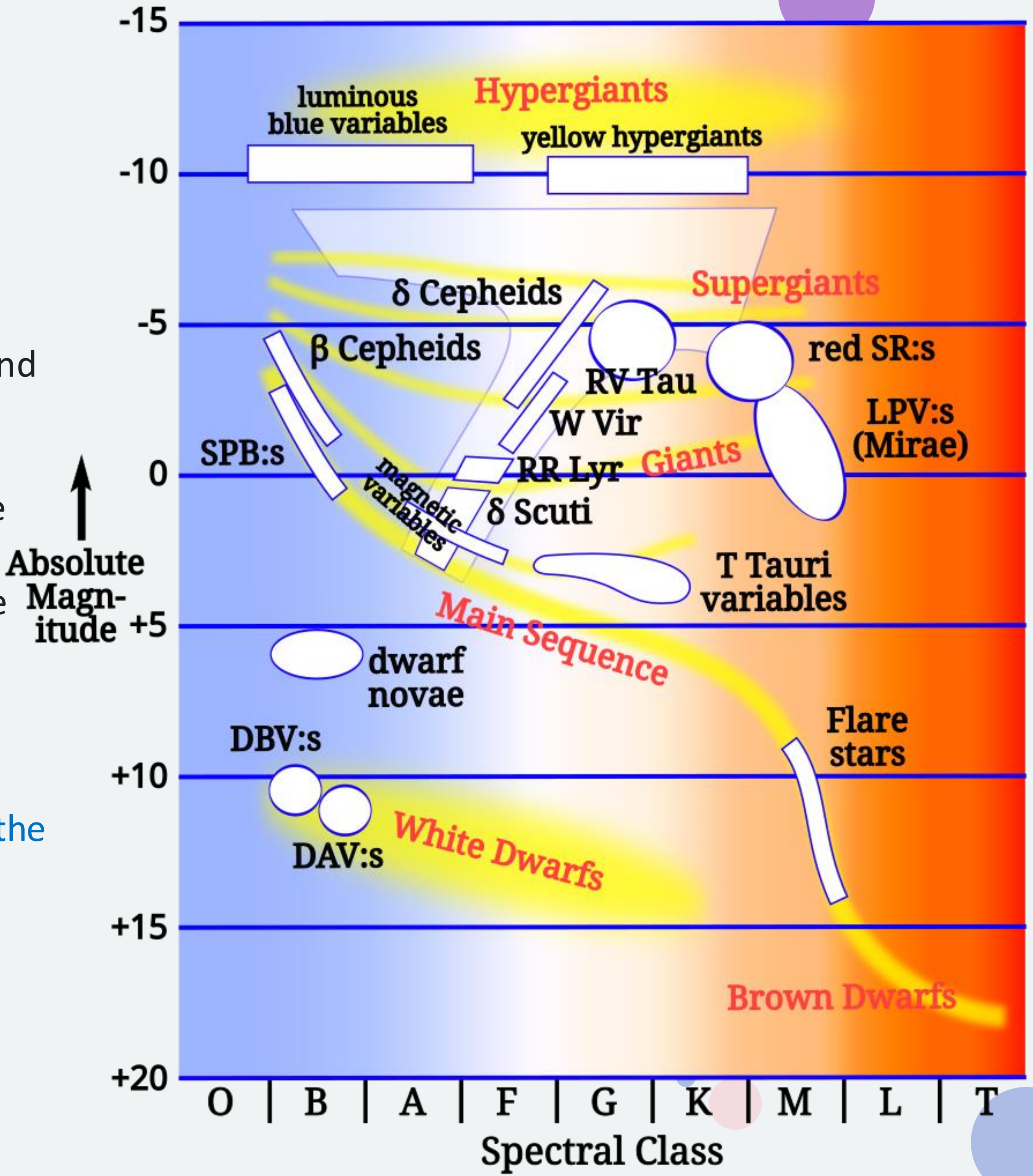
  2. Rotating variables, stars whose variability is caused by phenomena related to their rotation. Examples include stars with extreme "sunspots" which affect the apparent brightness.

Pulsating stars

Pulsating stars swell and shrink, affecting their brightness and spectrum.

Pulsations are generally split into: RADIAL, where the entire star expands and shrinks as a whole;
and NON-RADIAL, where one part of the star expands while another part shrinks.

Depending on the type of pulsation and its location within the star, there is a natural or fundamental frequency which determines the period of the star. Stars may also pulsate in a harmonic or overtone which is a higher frequency, corresponding to a shorter period.



Cepheid Variable Stars

- The term Cepheid originates from the star Delta Cephei in the constellation Cepheus, which was one of the early discoveries (by John Goodricke)
- In 1908, **Henrietta Swan Leavitt** discovered the relationship between the period and luminosity of classical Cepheids while studying thousands of variable stars in the Magellanic Clouds (published in 1912, then revised to PLC)
- Cepheid variables were initially observed to exhibit radial velocity variations that matched their luminosity changes → might be part of a binary system?
- In 1914, Harlow Shapley demonstrated that this interpretation should be abandoned.
- By 1916, Shapley and others discovered that Cepheid variables changed their spectral types during their pulsation cycles.

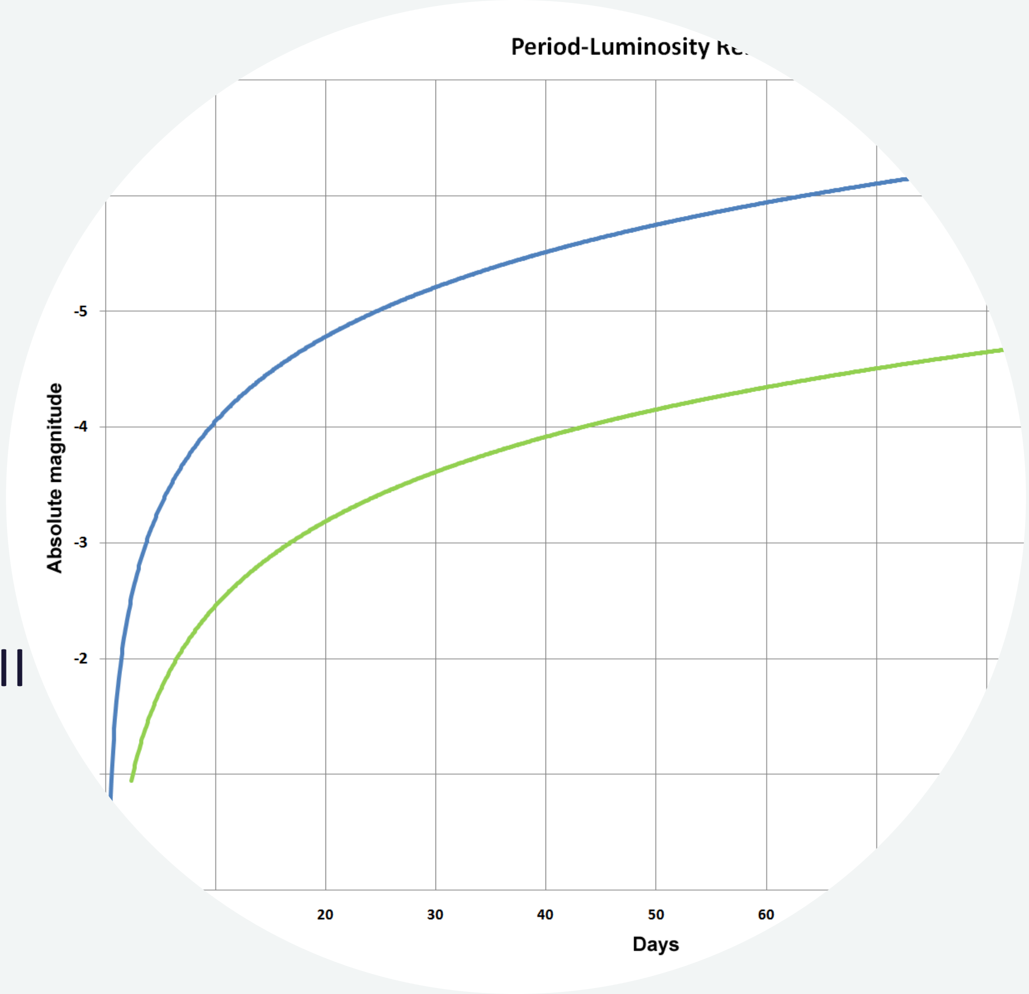
Cepheid Variable Stars

In the mid 20th century, significant problems with the astronomical distance scale were resolved by dividing the Cepheids into different classes with very different properties.

In the 1940s, Walter Baade recognized two separate populations of Cepheids (classical and type II).

Classical Cepheids are younger and more massive population stars, whereas **type II Cepheids** are older, fainter Population II stars (e.g., Wallerstein 2002)

Classical Cepheids and type II Cepheids follow different period-luminosity relationships



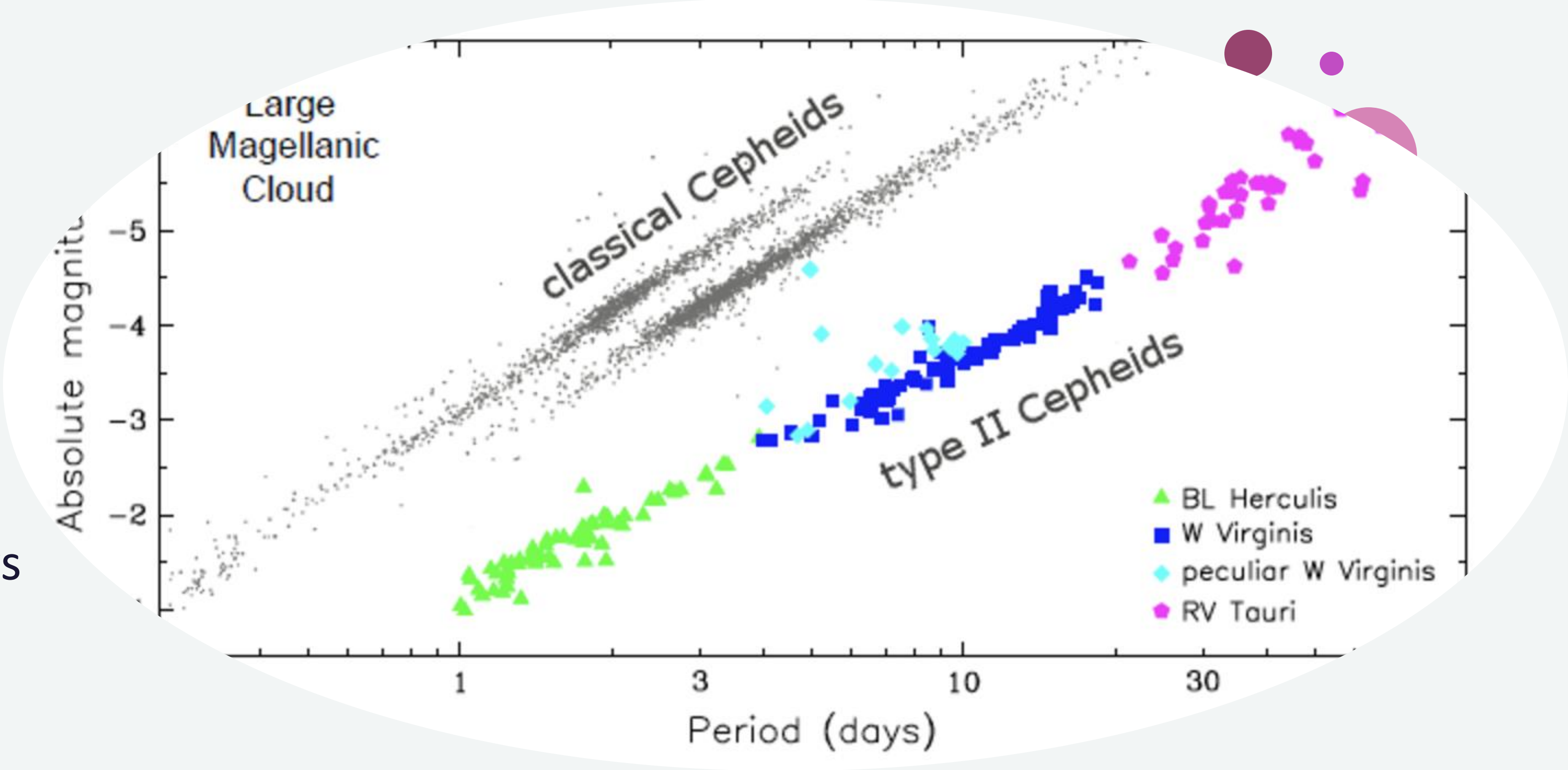
Classical Cepheids

1. Classical Cepheids [*aka* Population I Cepheids, type I Cepheids, or Delta Cepheid variables **(DCEP)]** exhibit pulsations with highly regular periods ranging from days to months.
2. Ages of less a few hundreds Myr and are 4 to 20 times more massive than the Sun, with luminosities up to 100,000 times greater.
3. Classical Cepheids are yellow bright giants and supergiants, classified within the spectral types F6 to K2.
4. During a pulsation cycle, their radii can vary by approximately 25%, undergoing changes that span millions of kilometers.

Type II Cepheids

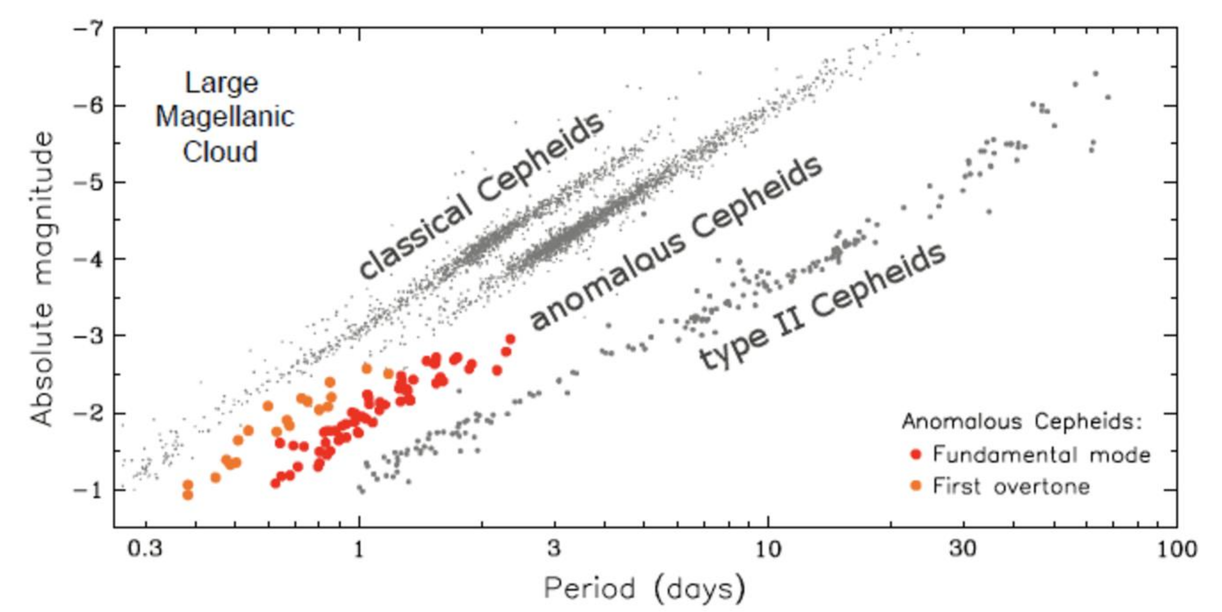
- Type II Cepheids are low-mas (0.5-0.6Msun) stars which pulsate with periods typically between 1 and 50 days (e.g., Soszyński+ 2008). They are population II stars: old, typically metal-poor, low mass objects.

- Type II Cepheids consist of three subclasses - BL Herculis, W Virginis and RV Tauri stars - each one in a different stage of stellar evolution.



The shortest-period BL Herculis stars cross the pulsation instability strip in the HR diagram evolving from the horizontal branch toward the asymptotic giant branch. W Virginis stars cross the instability strip as a result of the helium-shell-flash episodes which occur during the asymptotic giant branch stage. The brightest type II Cepheids are the RV Tauri stars, which cross the instability strip evolving away from the asymptotic giant branch toward the white dwarf domain

Anomalous Cepheids

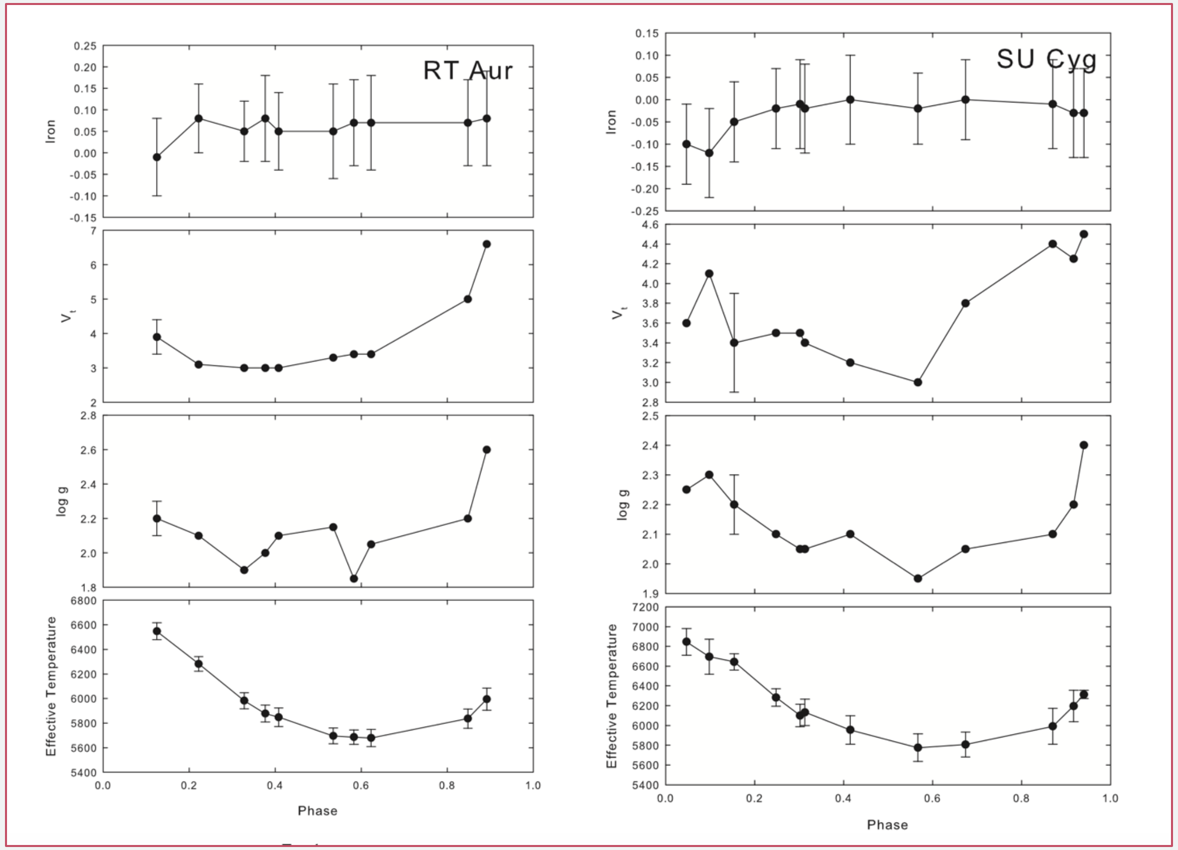


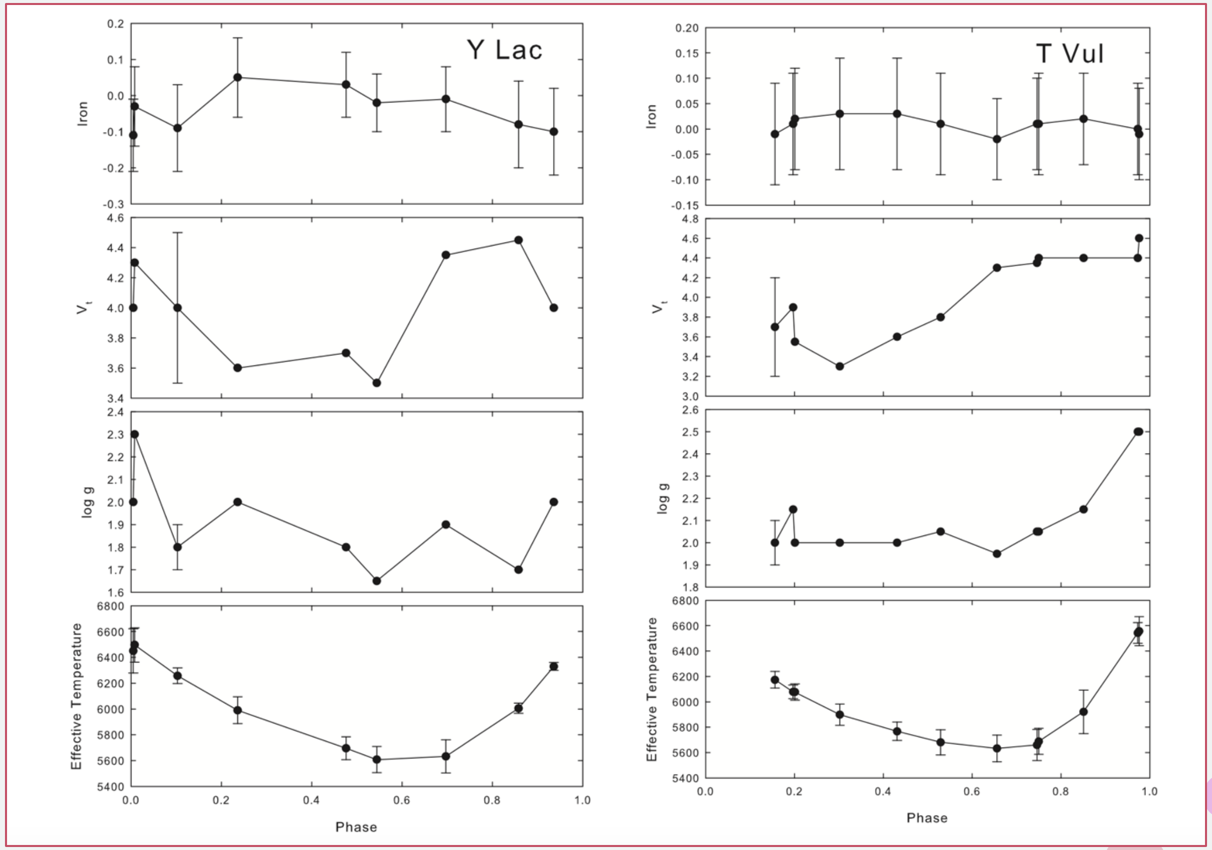
Sometimes called BL Bootis stars, these are relatively massive (1-2 Msun), metal-deficient pulsating stars, which spread between classical and type II Cepheids in the period-luminosity diagram.

There are two leading hypotheses for the origin of anomalous Cepheids: that they are intermediate-age stars with exceptionally low metallicity, or that they are coalesced old binary stars.

https://ogle.astrouw.edu.pl/atlas/a

Variation of parameters across the pulsational phase



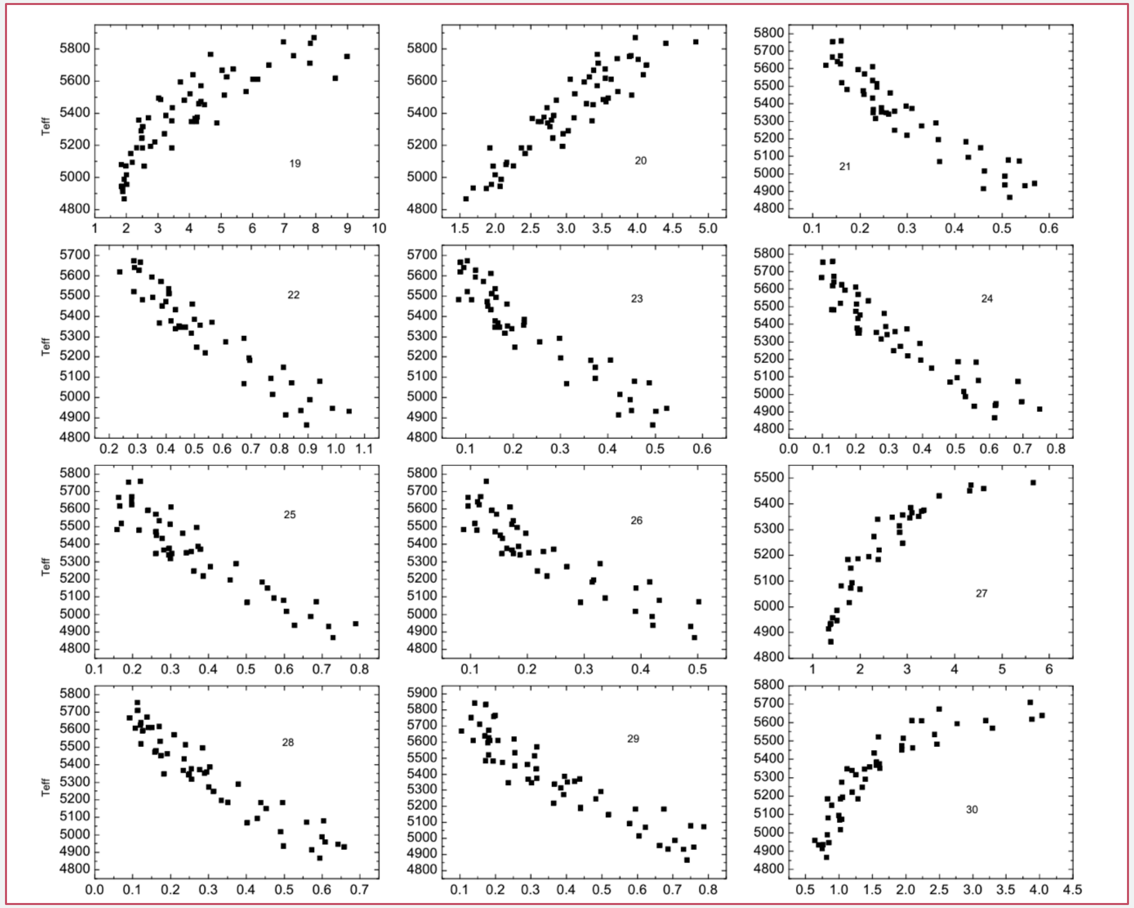


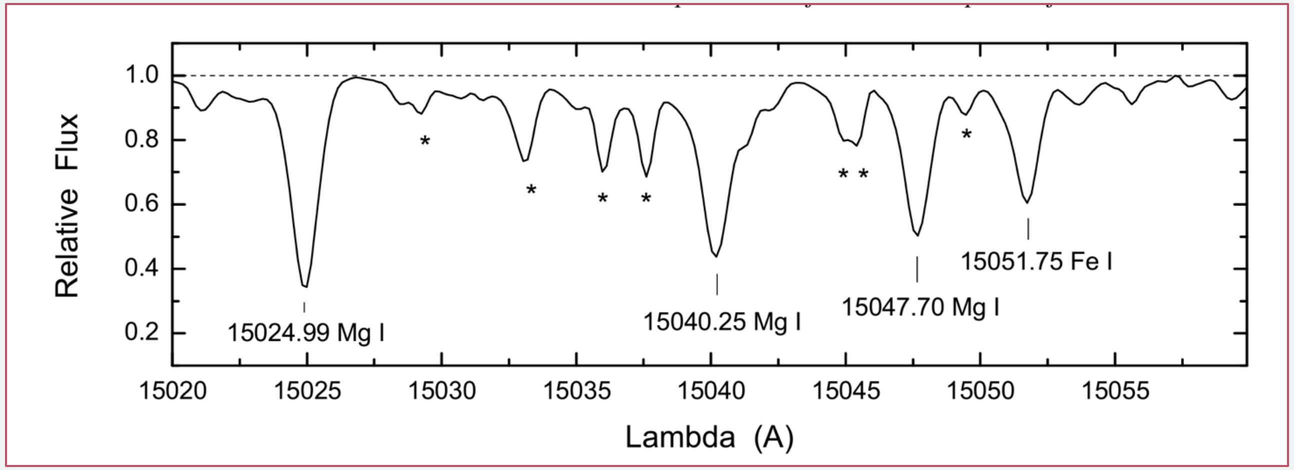
Andrievsky+ 2005

Estimating Teff values

The LDR ratio

Kovtyukh+ 2023





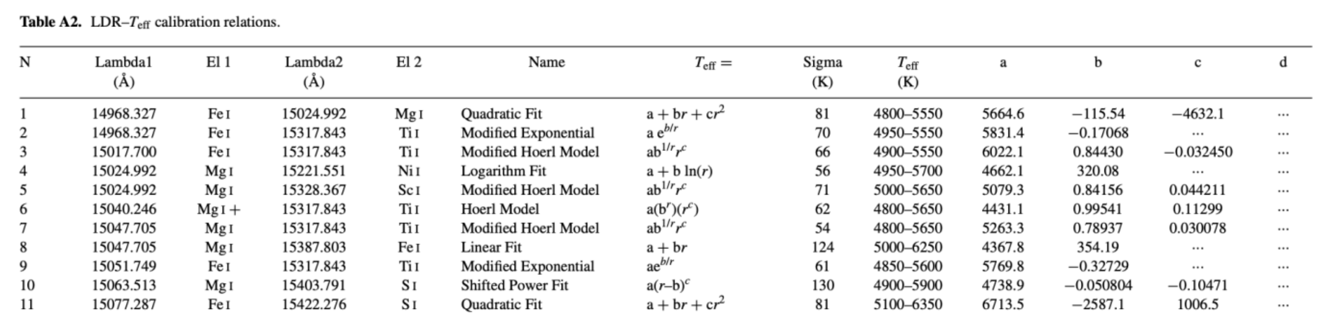
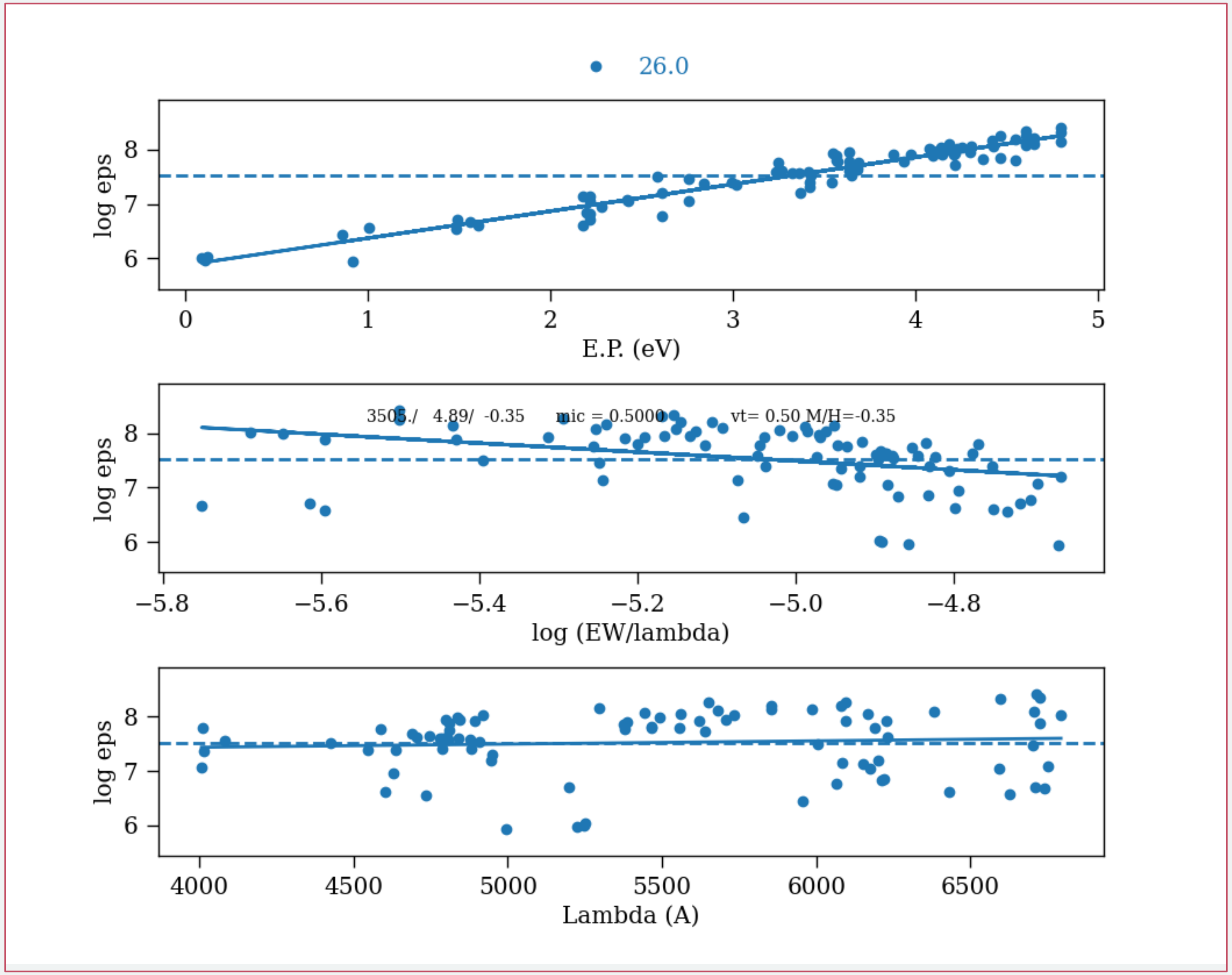


Table A2. LDR–$T_{\rm eff}$ calibration relations.

N	Lambda1 (Å)	El 1	Lambda2 (Å)	El 2	Name	$T_{\rm eff} =$	Sigma (K)	$T_{\rm eff}$ (K)	a	b	c	d
1	14968.327	Fe I	15024.992	Mg I	Quadratic Fit	$a + br + cr^2$	81	4800–5550	5664.6	−115.54	−4632.1	···
2	14968.327	Fe I	15317.843	Ti I	Modified Exponential	$a\ e^{b/r}$	70	4950–5550	5831.4	−0.17068	···	···
3	15017.700	Fe I	15317.843	Ti I	Modified Hoerl Model	$ab^{1/r}r^c$	66	4900–5550	6022.1	0.84430	−0.032450	···
4	15024.992	Mg I	15221.551	Ni I	Logarithm Fit	$a + b\ln(r)$	56	4950–5700	4662.1	320.08	···	···
5	15024.992	Mg I	15328.367	Sc I	Modified Hoerl Model	$ab^{1/r}r^c$	71	5000–5650	5079.3	0.84156	0.044211	···
6	15040.246	Mg I +	15317.843	Ti I	Hoerl Model	$a(b^r)(r^c)$	62	4800–5650	4431.1	0.99541	0.11299	···
7	15047.705	Mg I	15317.843	Ti I	Modified Hoerl Model	$ab^{1/r}r^c$	54	4800–5650	5263.3	0.78937	0.030078	···
8	15047.705	Mg I	15387.803	Fe I	Linear Fit	$a + br$	124	5000–6250	4367.8	354.19	···	···
9	15051.749	Fe I	15317.843	Ti I	Modified Exponential	$ae^{b/r}$	61	4850–5600	5769.8	−0.32729	···	···
10	15063.513	Mg I	15403.791	S I	Shifted Power Fit	$a(r–b)^c$	130	4900–5900	4738.9	−0.050804	−0.10471	···
11	15077.287	Fe I	15422.276	S I	Quadratic Fit	$a + br + cr^2$	81	5100–6350	6713.5	−2587.1	1006.5	···

Estimating Teff values



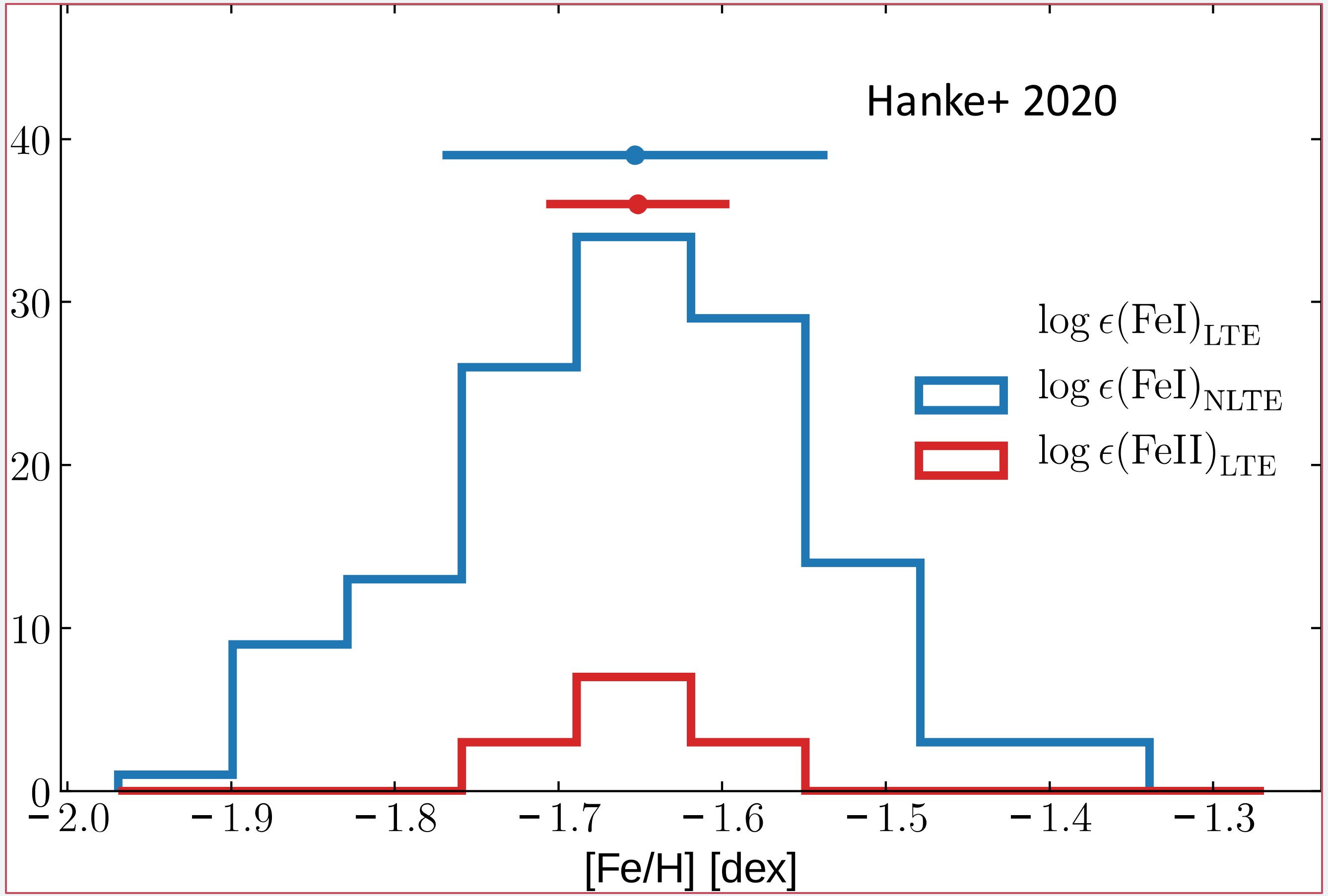
Excitation
Equilibrium
Temperature

pyMOOGI (Adamow+, Sneden+)

Logg from ionization balance

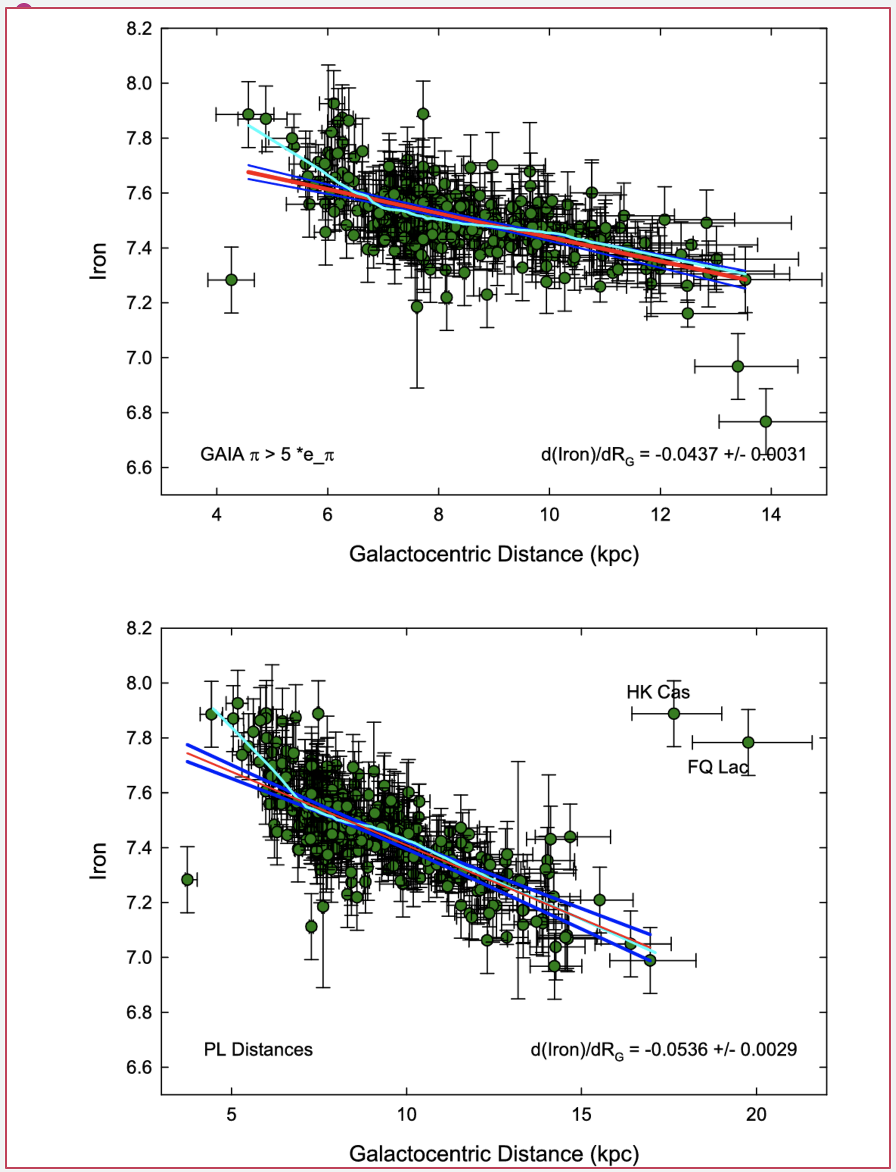
- (Abundances A(X) neutral lines – Abundances A(X) ionized lines)

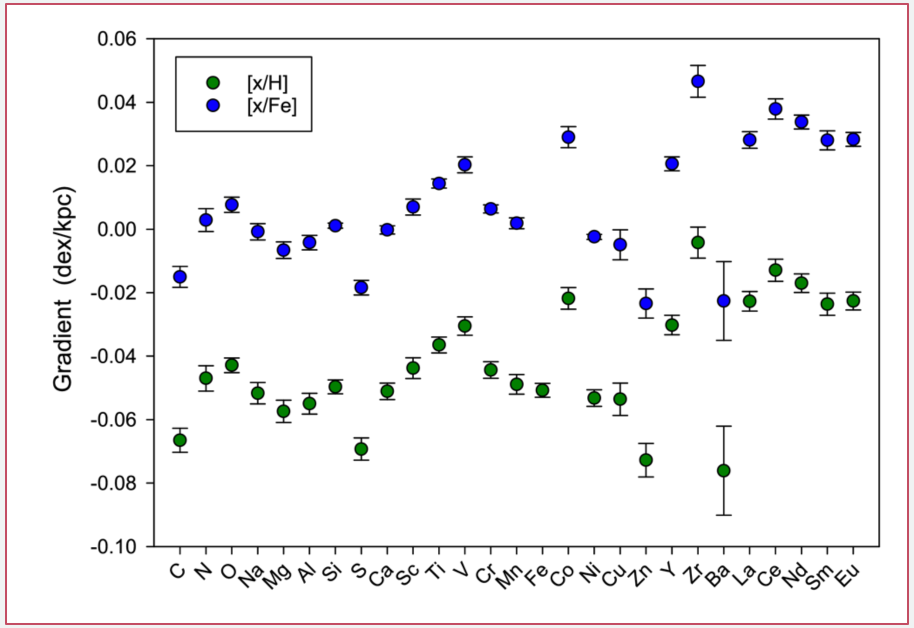
→ consistent with 0



Careful about LTE assumption!

(Present) Galactic metallicity gradients





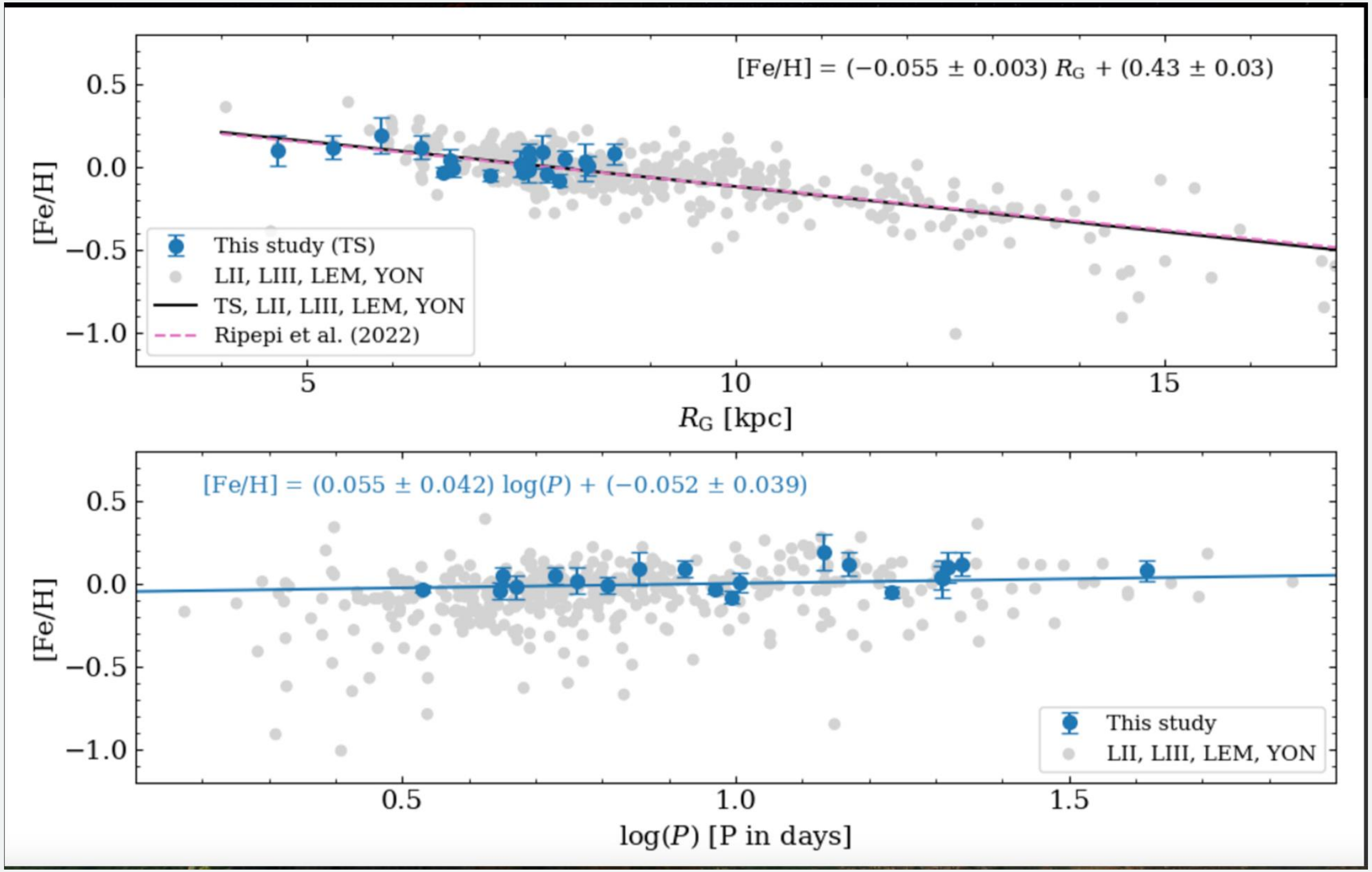
Luck et al. 2018

Iron Gradient:

$$d\frac{[Fe/H]}{dR_G} = -0.05\, dex\, kpc^{-1}.$$

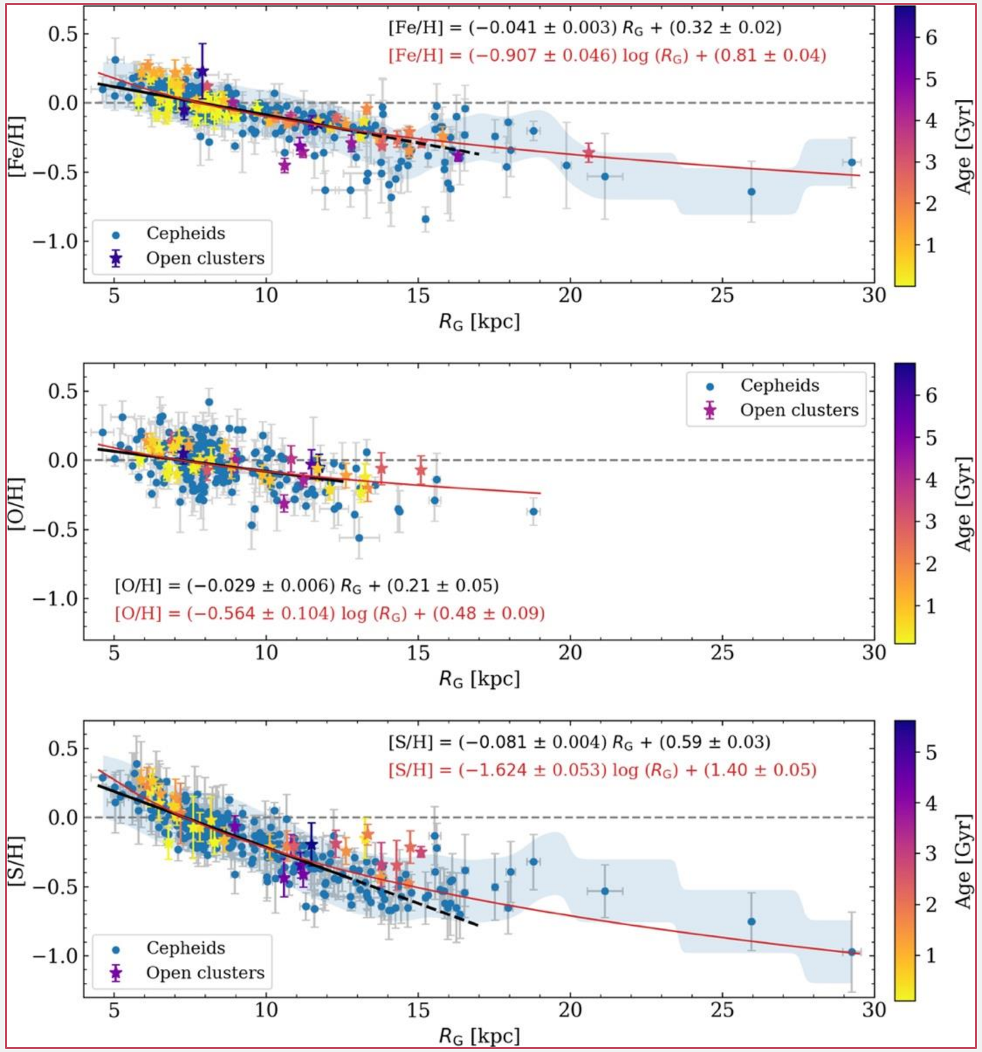
(Present) Galactic metallicity gradients

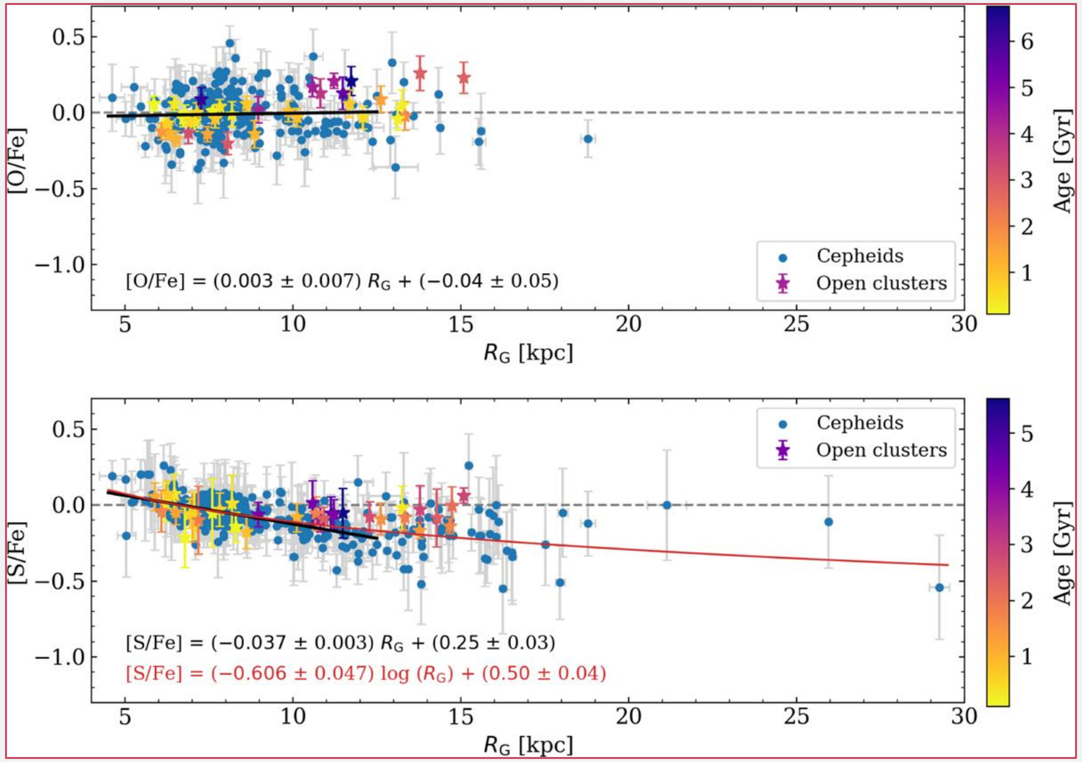
- da Silva et al 2022



(Present) Galactic metallicity gradients

- da Silva et al. 2023



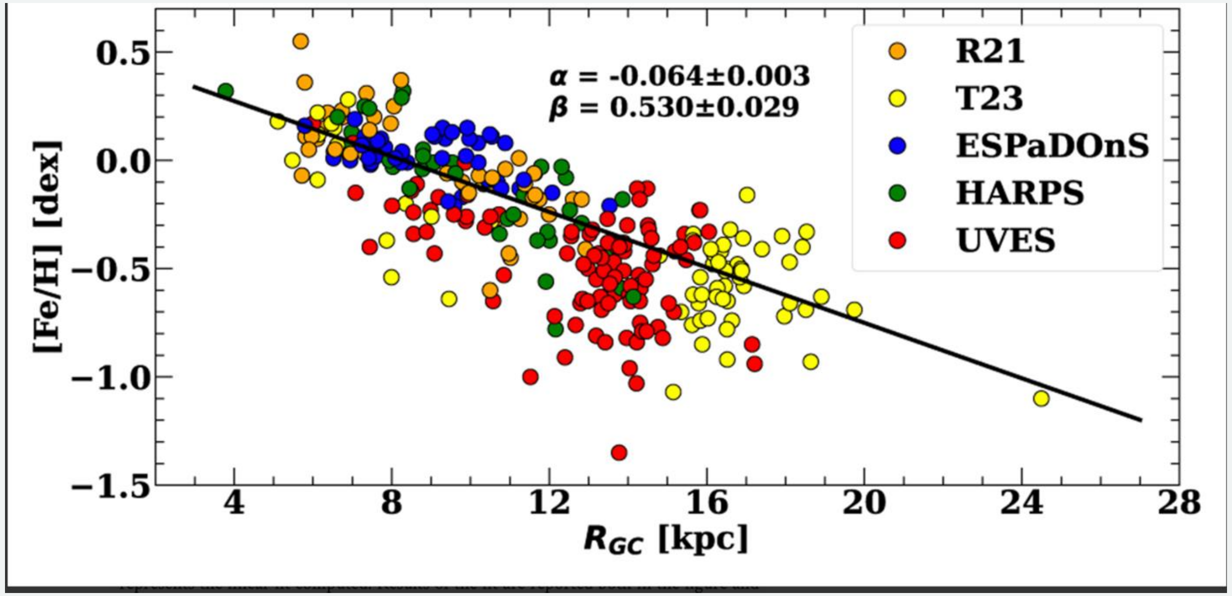


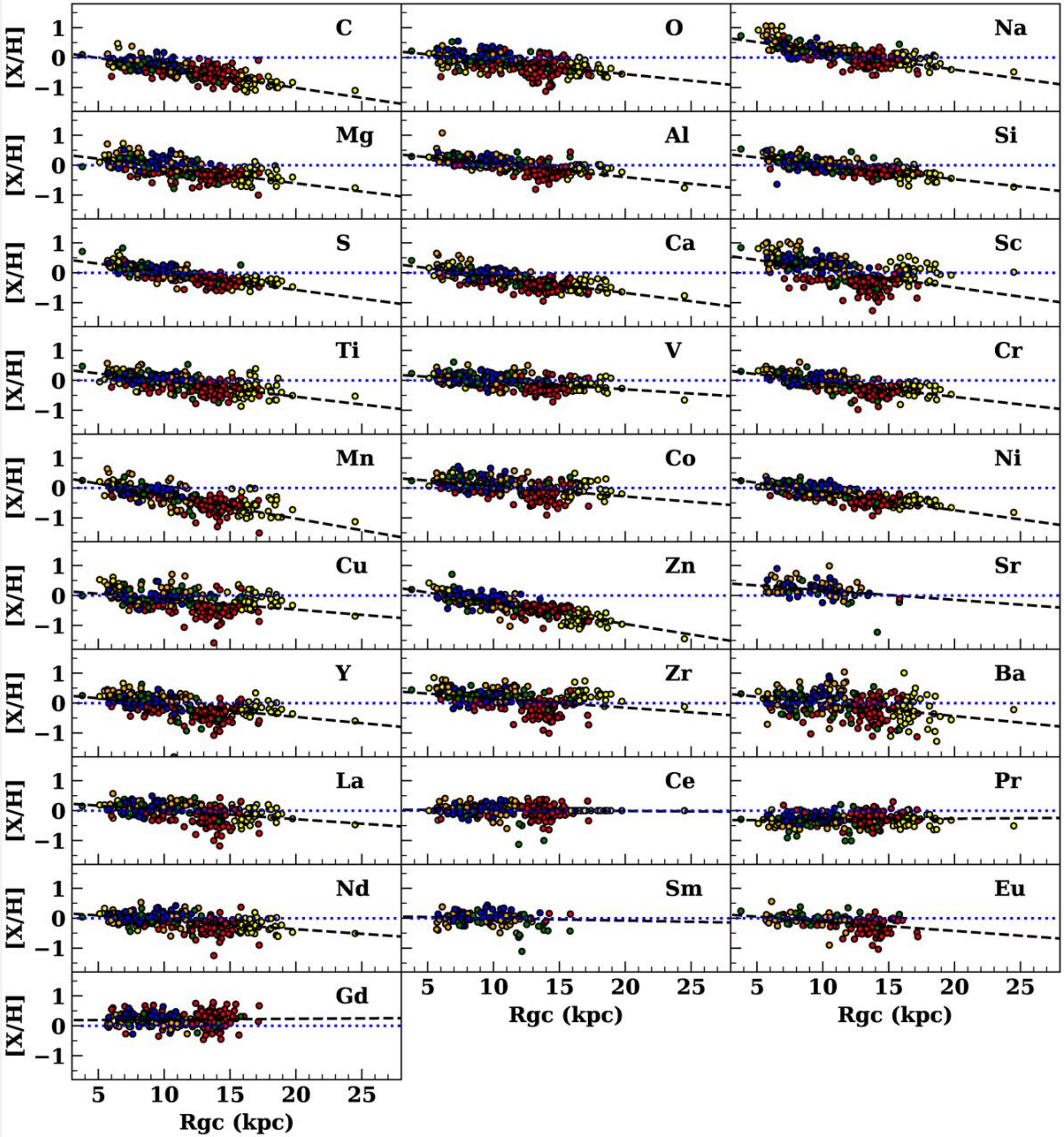
S steeper gradient than Fe

Different behaviour of S and O

(Present) Galactic metallicity gradients

- Trentin et al. 2024

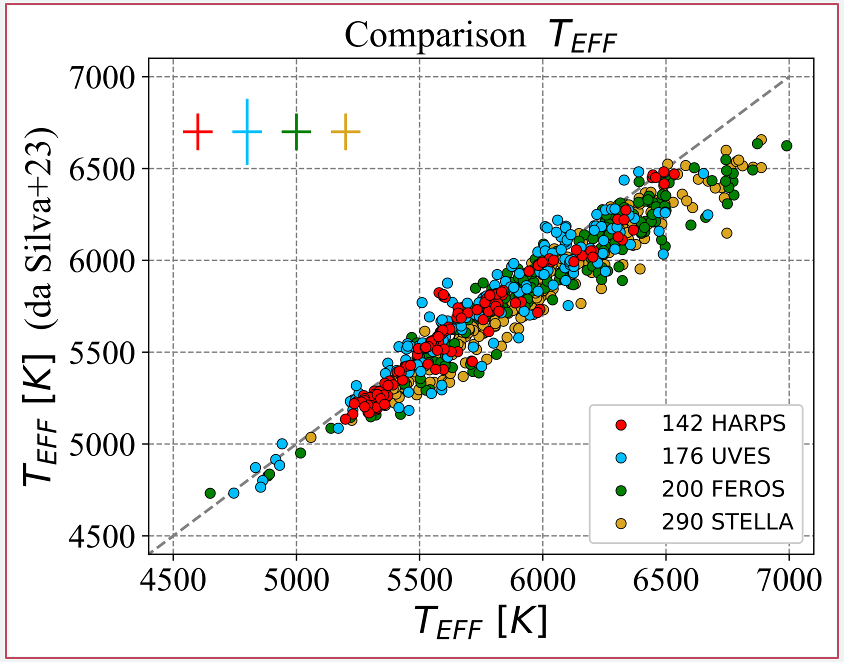


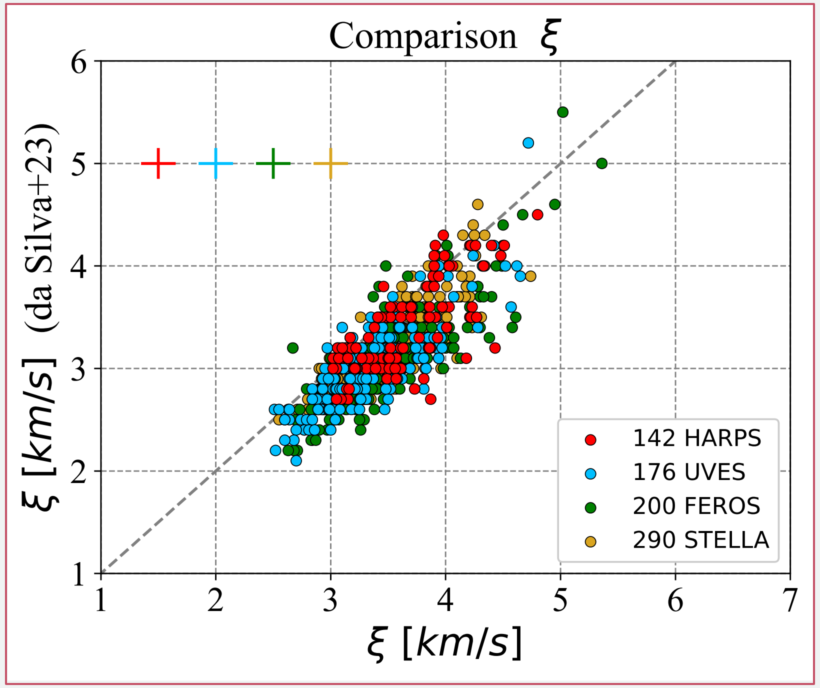


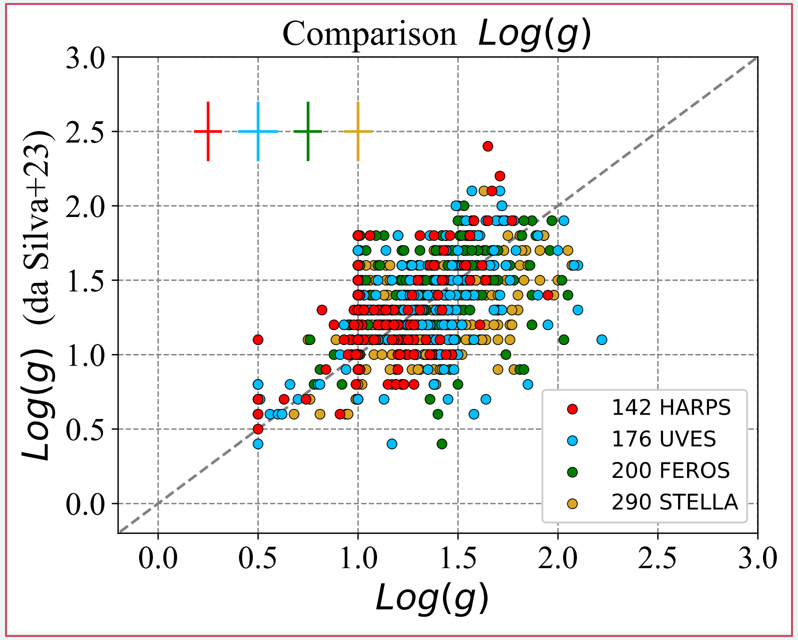
Different behaviour between S and O
But different gradient slopes for Fe, S, O

(Present) Galactic metallicity gradients

Nunnari et al., in prep. (`pySME` , NLTE on the fly)

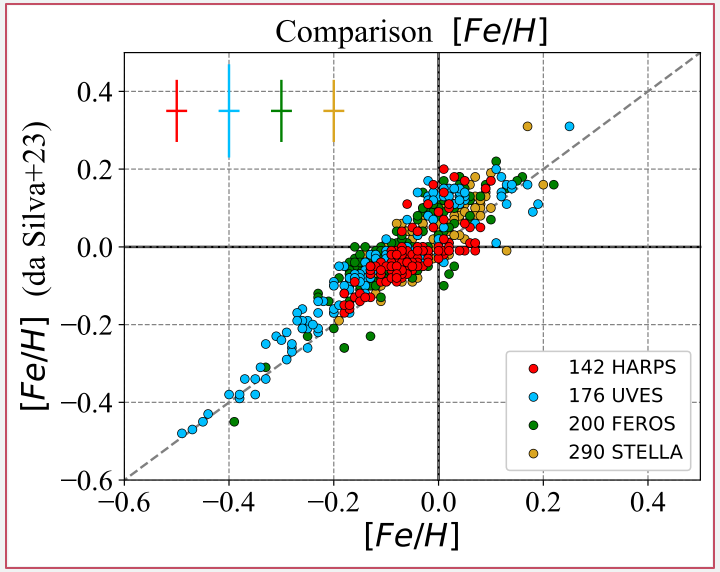


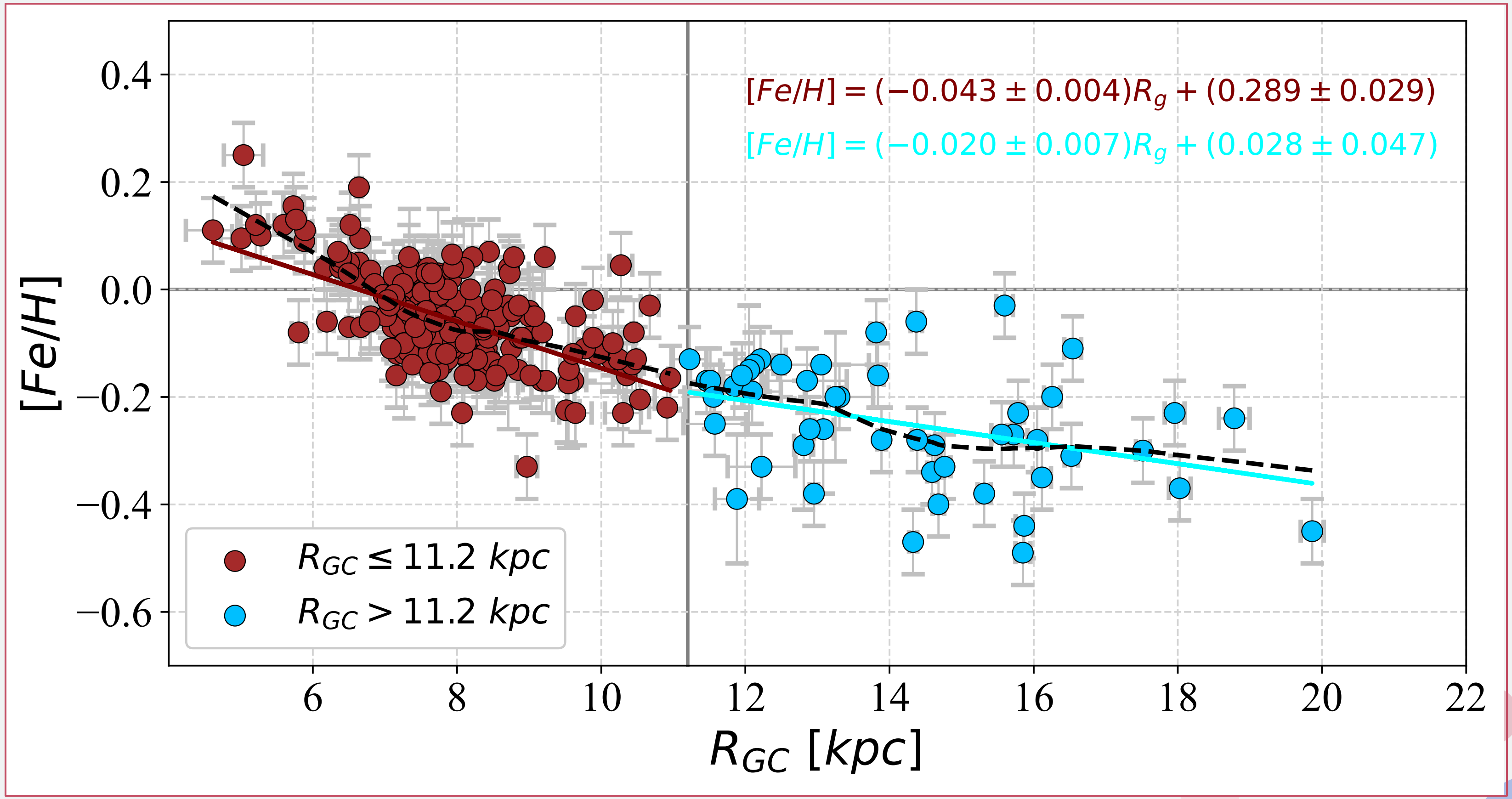




(Present) Galactic metallicity gradients

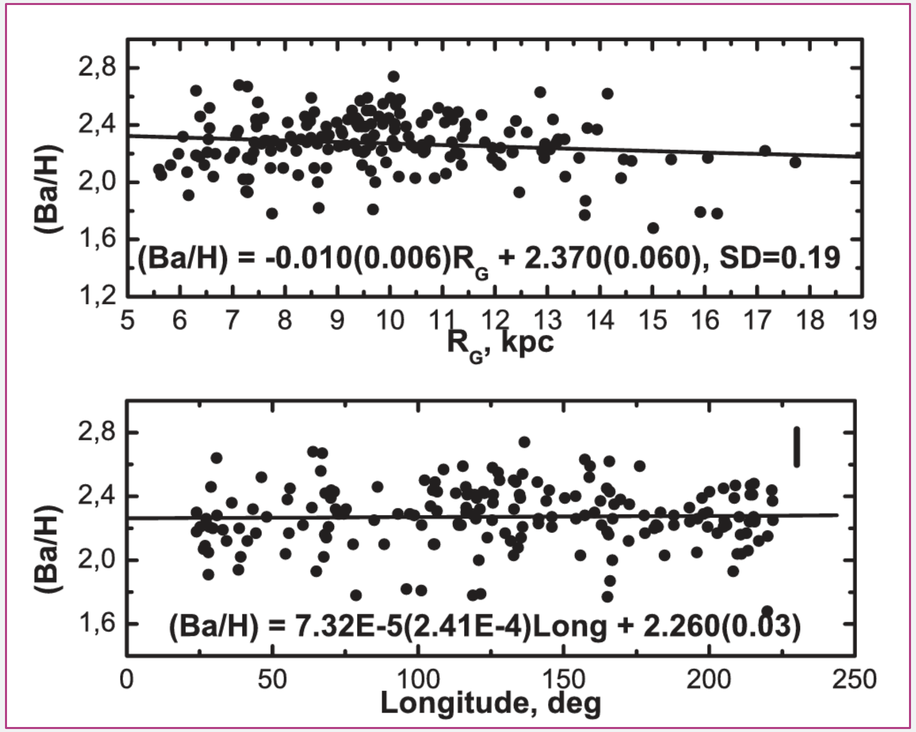
Nunnari et al., in prep. (`pySME` , NLTE on the fly)

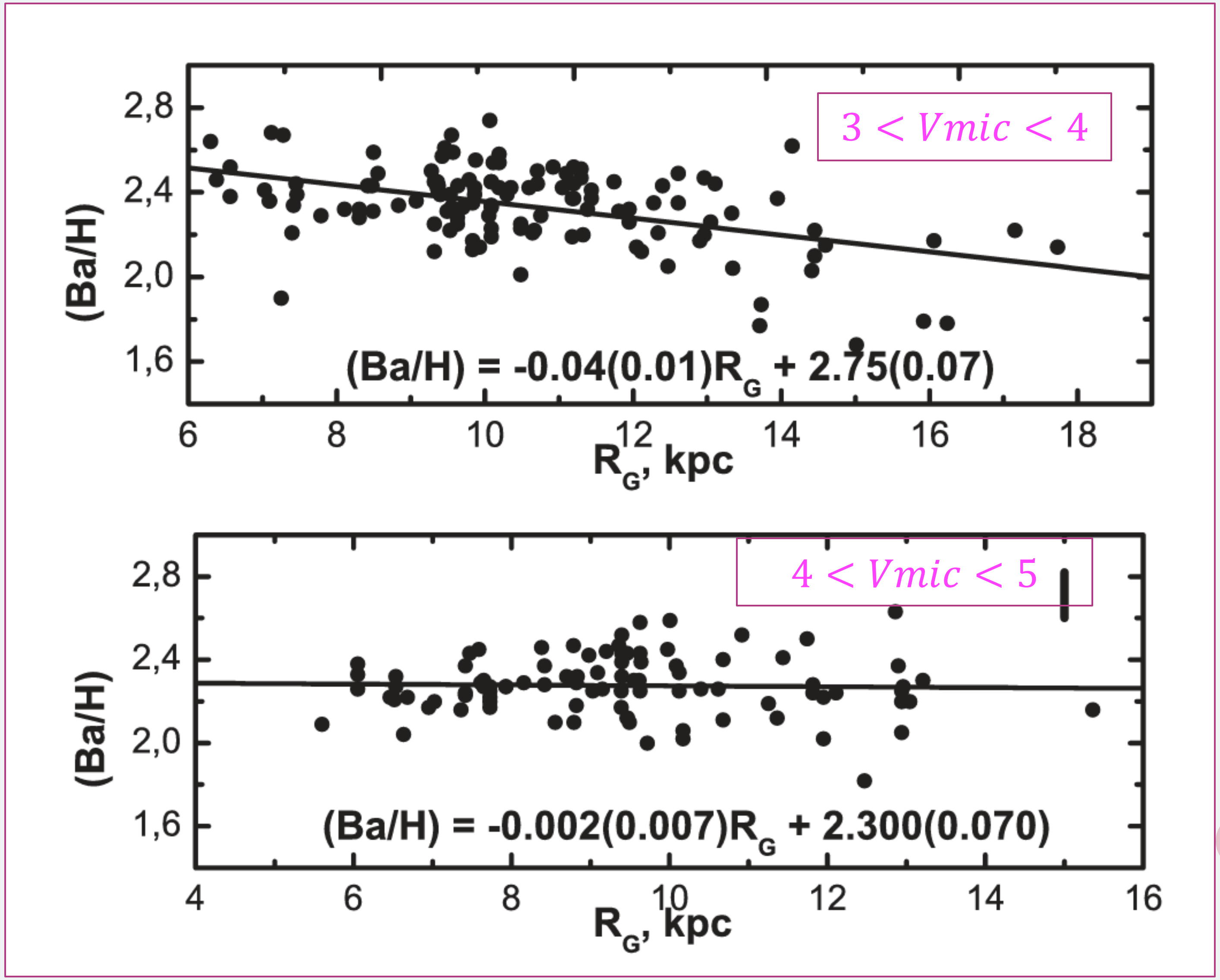




The Barium issue (oh no, here again!)

Andrievsky et al. 2014: **NO barium gradient** (in contrast to other s-process elements)

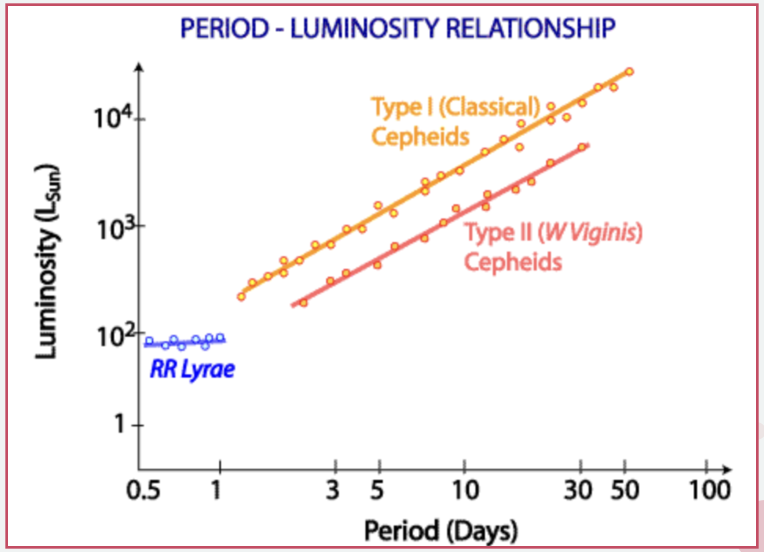




The RR Lyrae stars

- Named after the archetypical variable star in the Lyrae constellation, variability first identified by Williamina Fleming in 1901
- Pulsation period between 0.2 and 1 days, up to 100 solar luminosities, variation amplitude of 0.6 - 1 mag - approximately factor of 2 in luminosity!
- Distance indicators: tighter P-L-Z relation than in Cepheids, but RR Lyrae are fainter - limiting the range to few Mpc, used in the cosmology distance ladder
- RR Lyrae are divided into RRab, RRc and RRd pulsation classes based on their lightcurves, explained as different pulsations modes for same types of stars

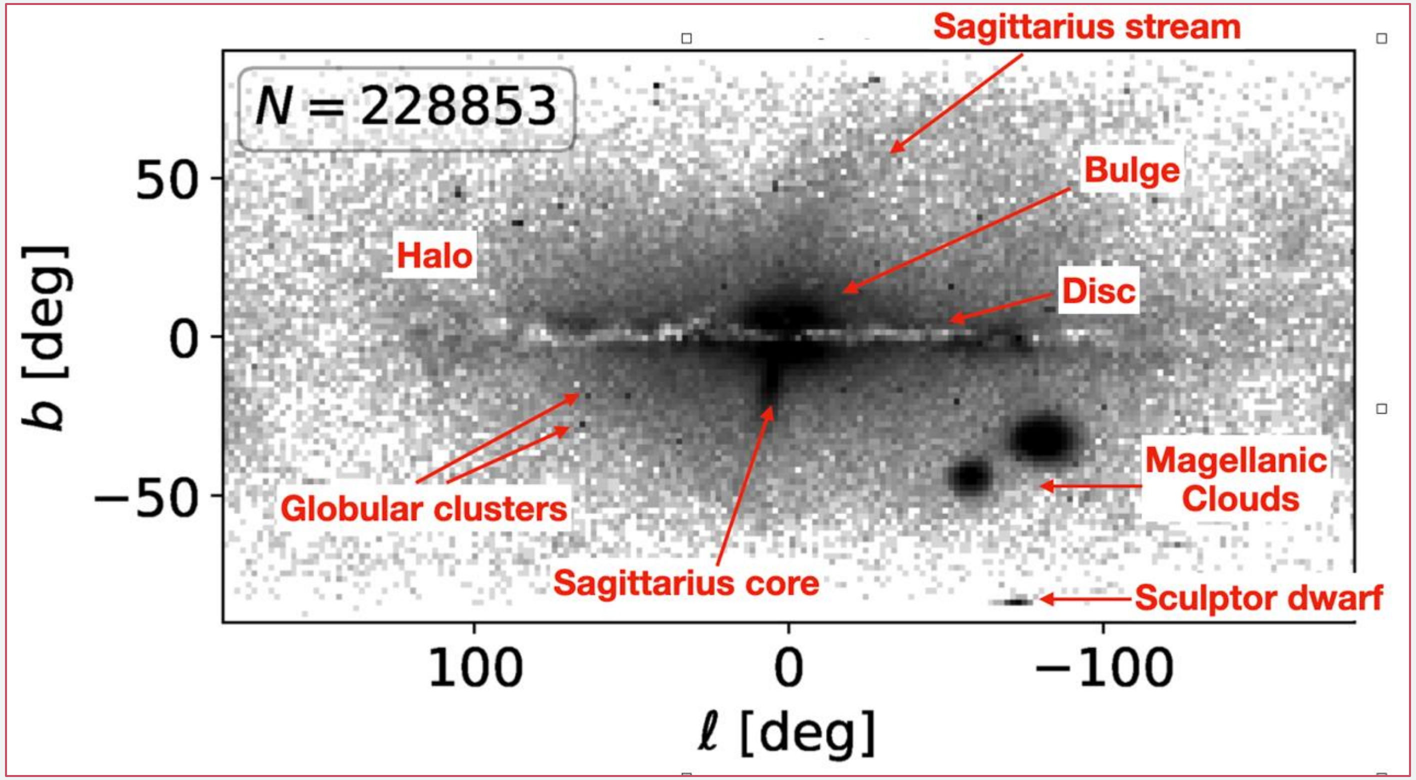
RR Lyrae, R. Vanderbei



P-L Relation, ATNF

The RR Lyrae stars

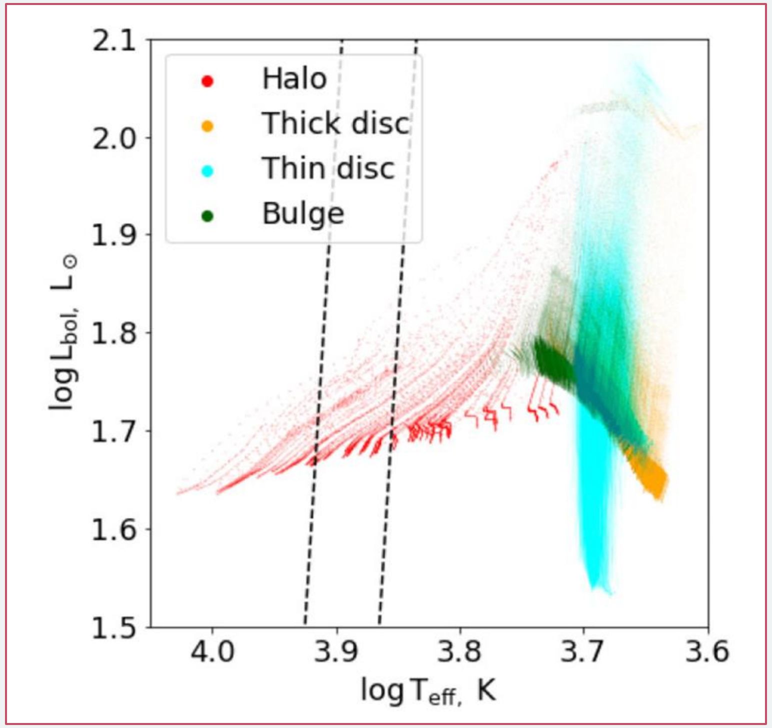
- Have been commonly found in old and metal-poor stellar populations: the halo, thick disc, bulge, globular clusters, old stellar streams, dwarf Galaxies
- Believed to be core He-burning stars of 0.5-0.85 M located in the portion of the instability strip crossing the HB. They have particularly (optically) thin envelopes compared to typical horizontal branch stars

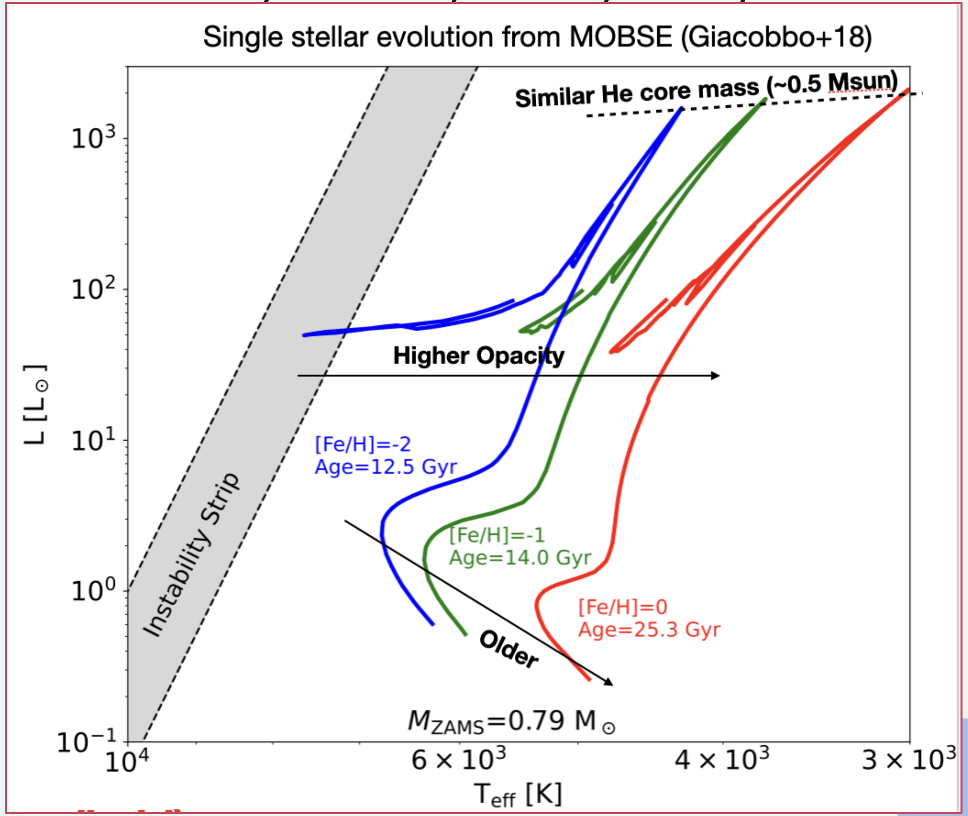


Iorio & Belokurov 2019

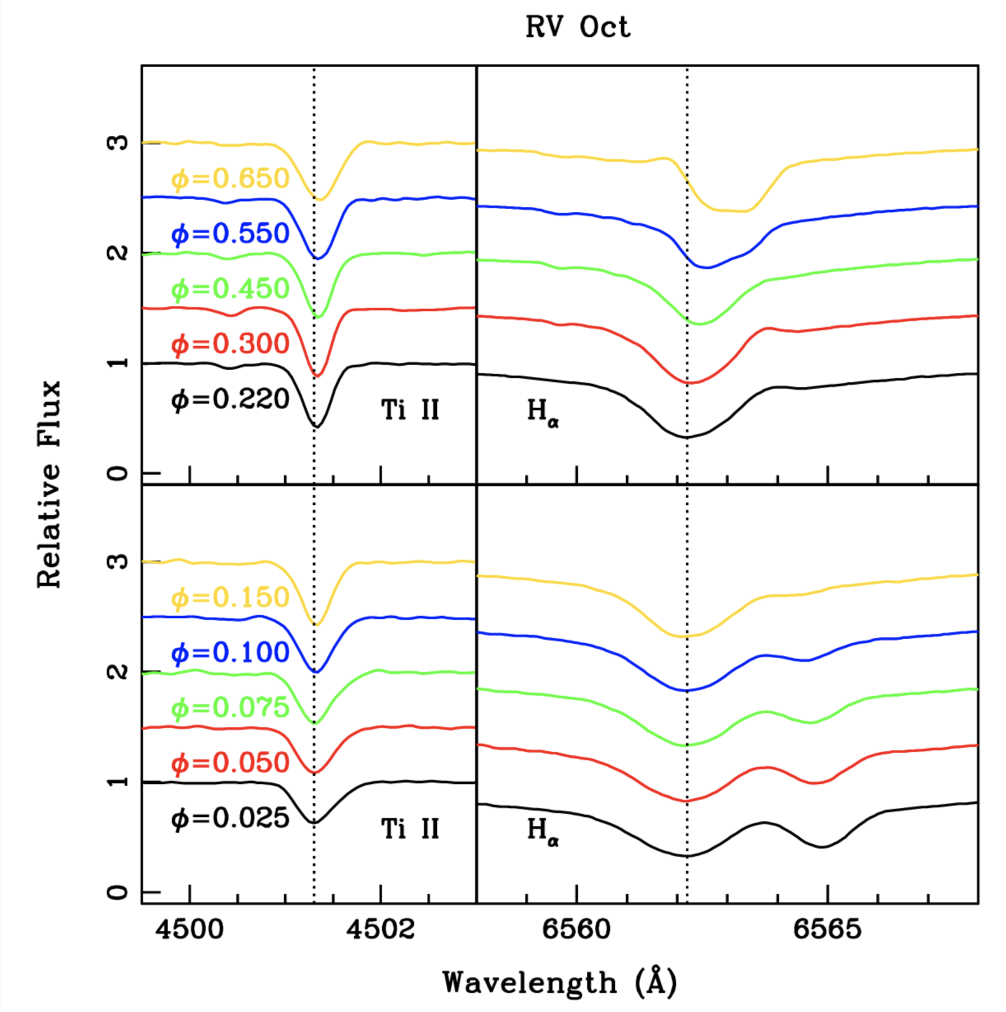
The RR Lyrae stars

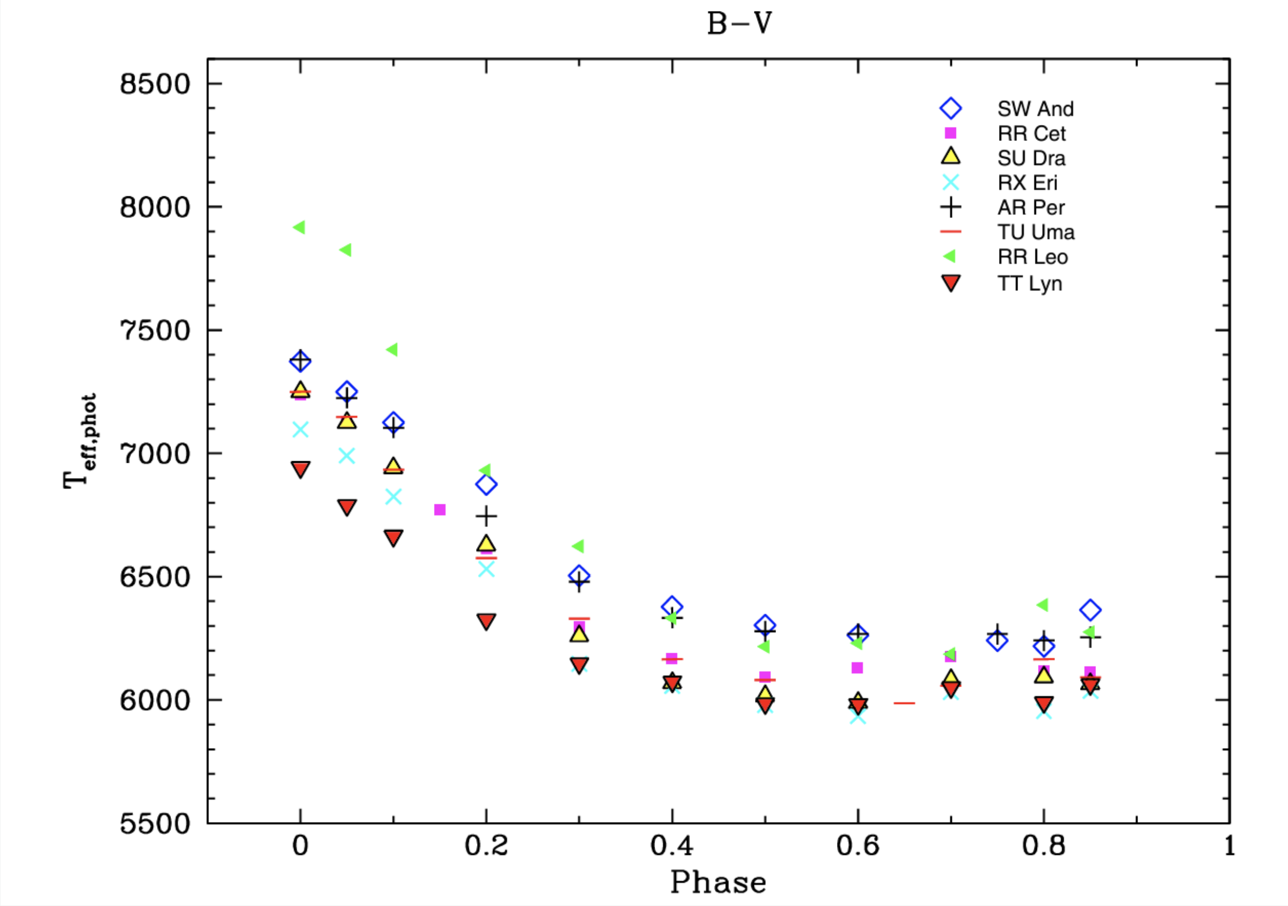
- Old (> 9 Gyr) and metal-poor ([Fe/H] < -1) stars are a natural explanation (e.g. Catelan, 2009): all horizontal branch stars have similar cores. Old stars have particularly thin envelopes, and low metallicity further reduces optical thickness.
- Stars stripped after mass transfer in binaries can also produce horizontal branch stars with thin envelopes. Such RR Lyrae can form at any age or metallicity (Karczmarek+17; Bobrick, Iorio+, 2024).



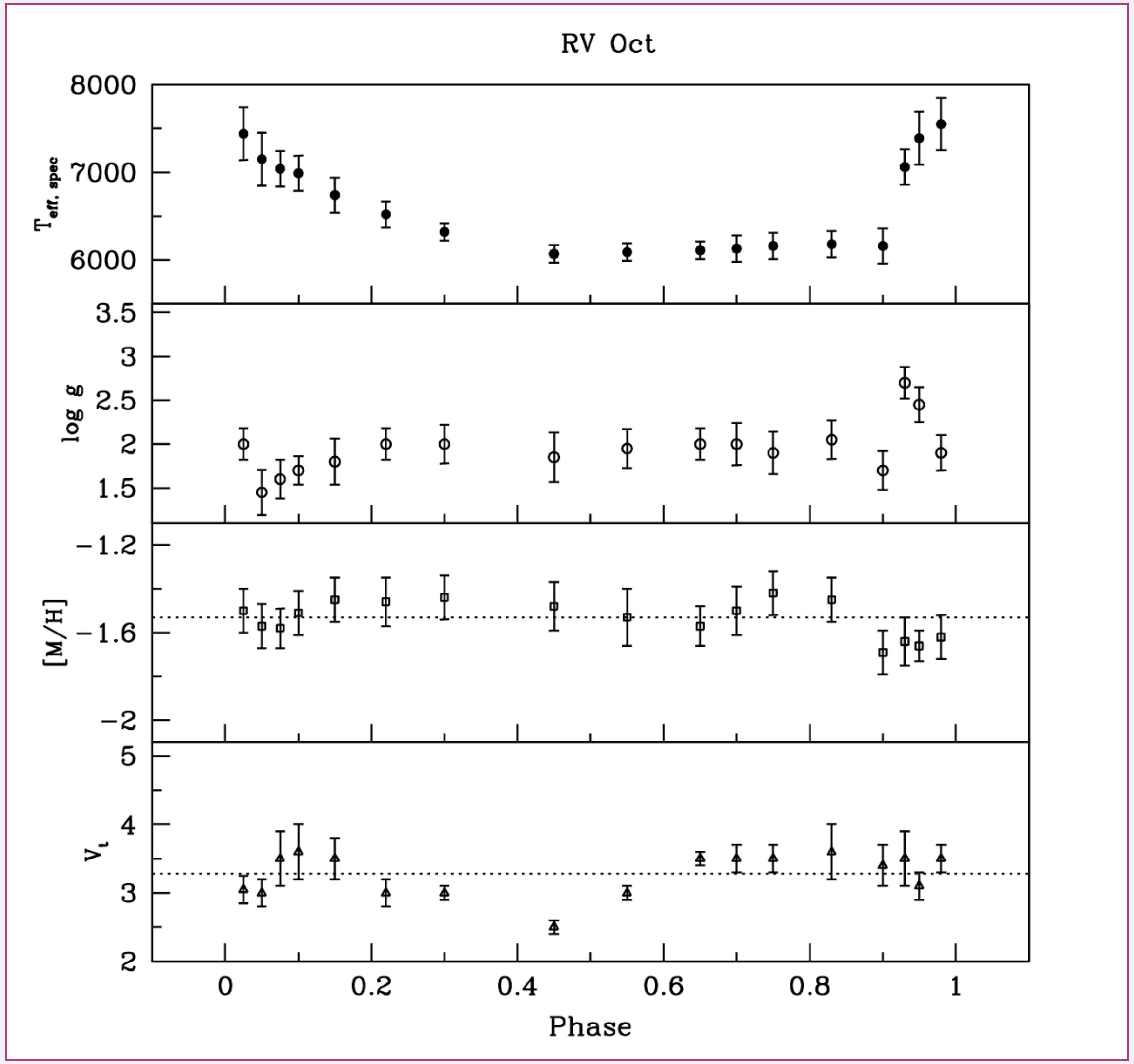

Single stellar evolution from MOBSE (Giacobbo+18)

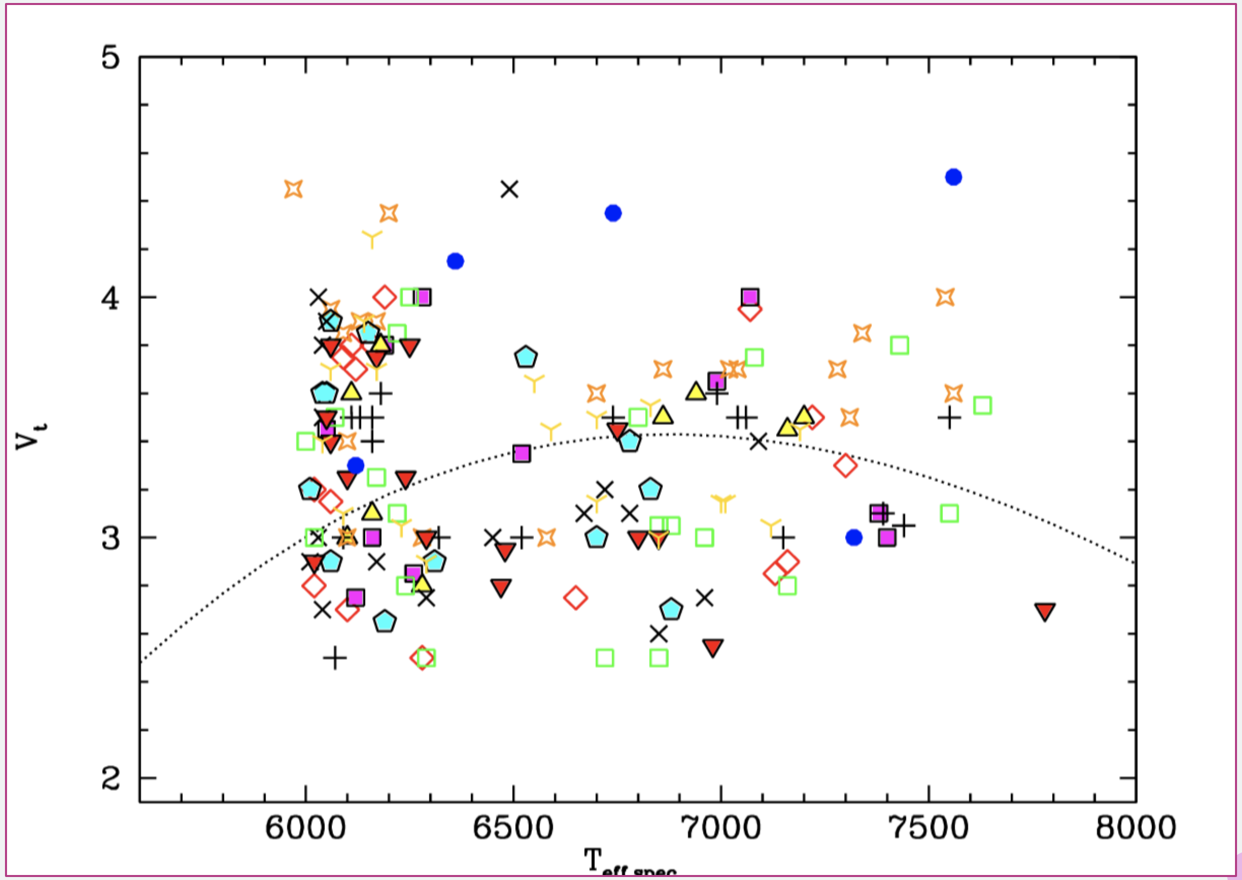
For, Sneden & Preston (2011)





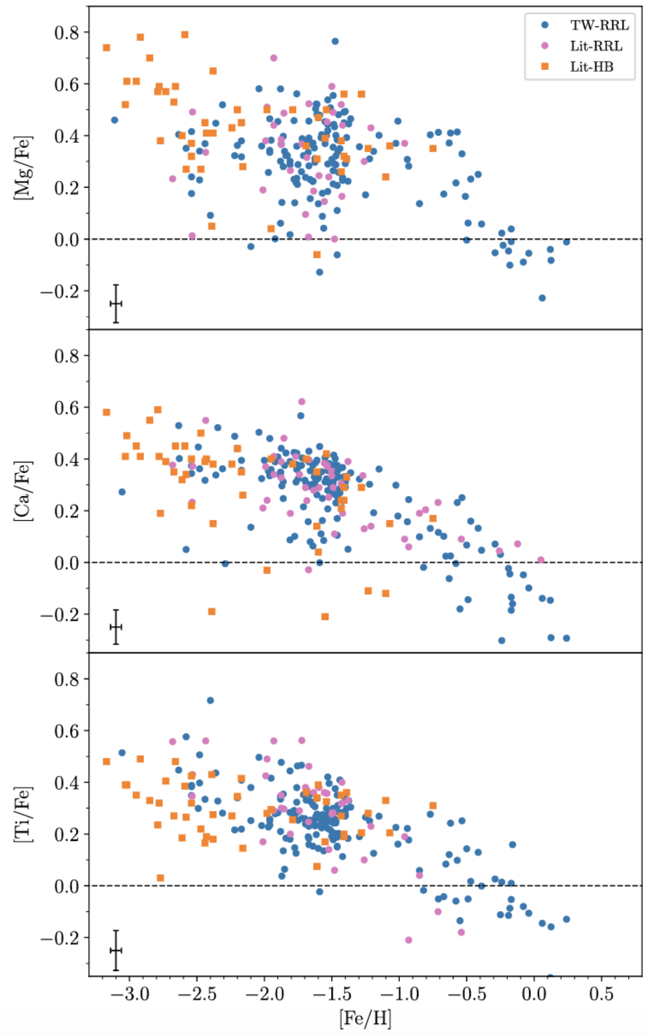
For, Sneden & Preston (2011)



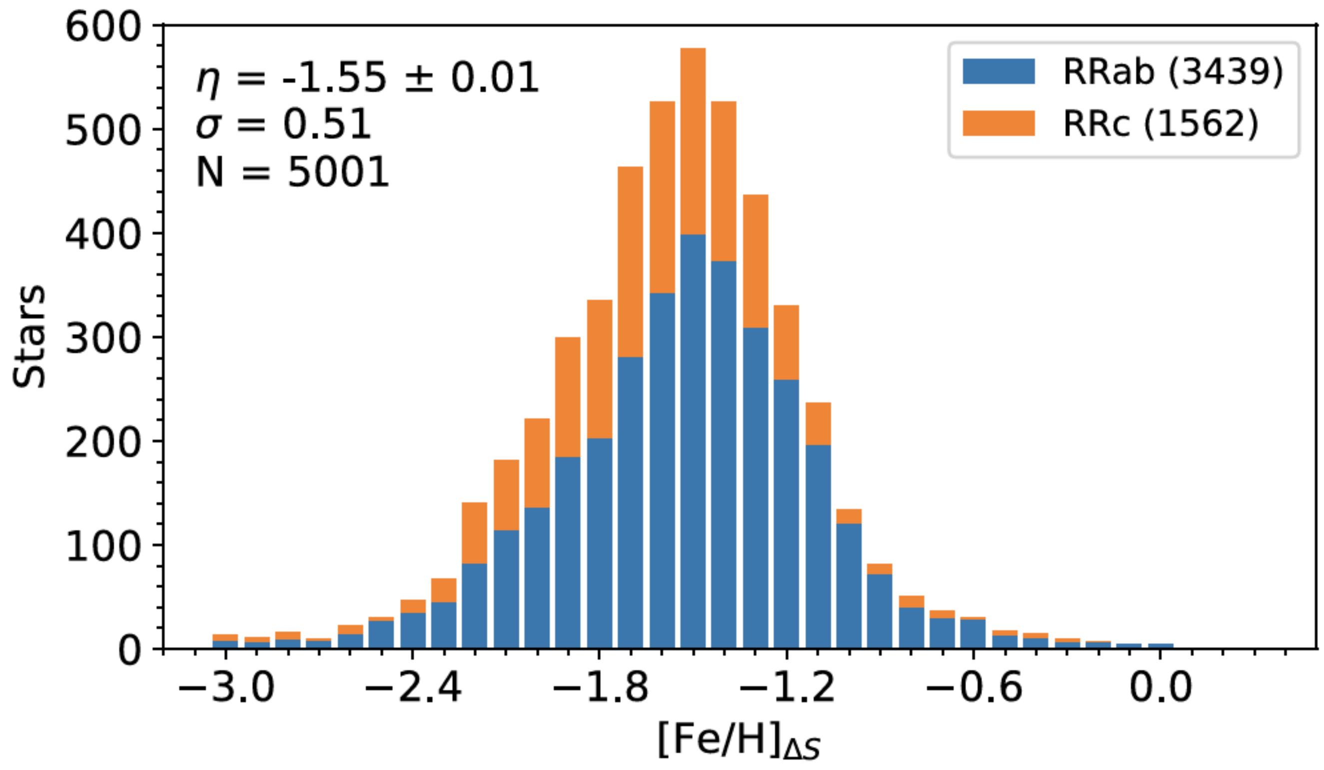


Nevertheless, chemistry in agreement with halo stars (non variable)

Crestani's study (2021a,b)

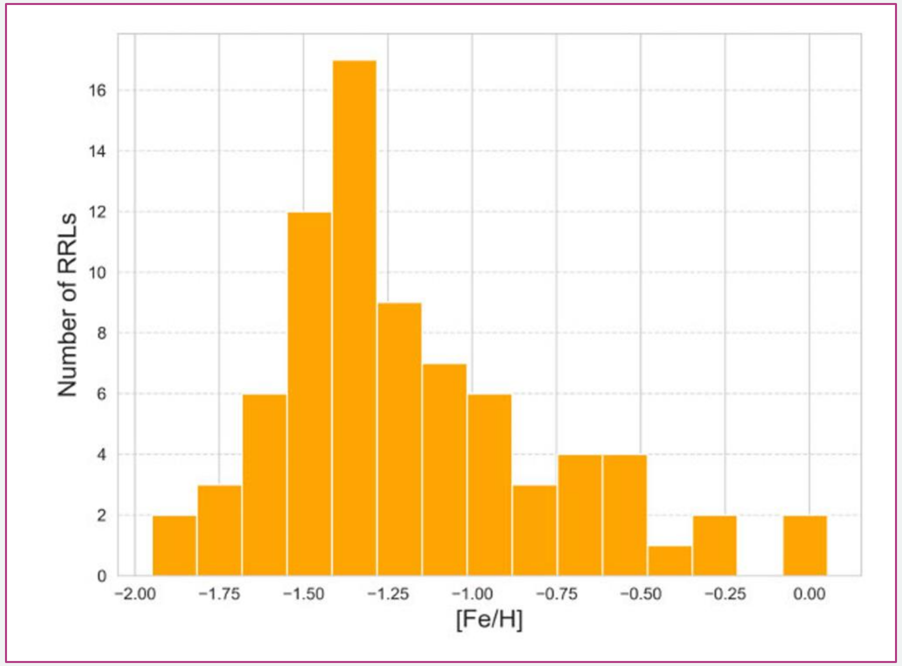


Metal-rich ([Fe/H] > -1) RRLs with sub-solar alpha-element abundances!



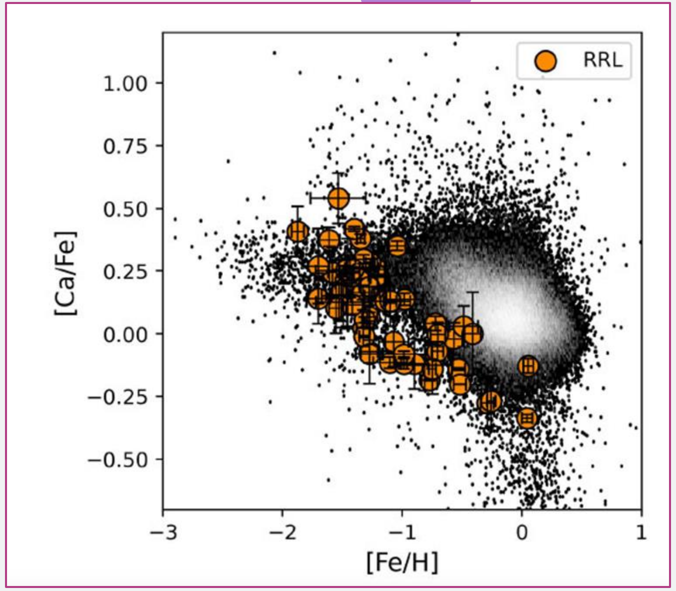
The GALAH survey’s RRLs

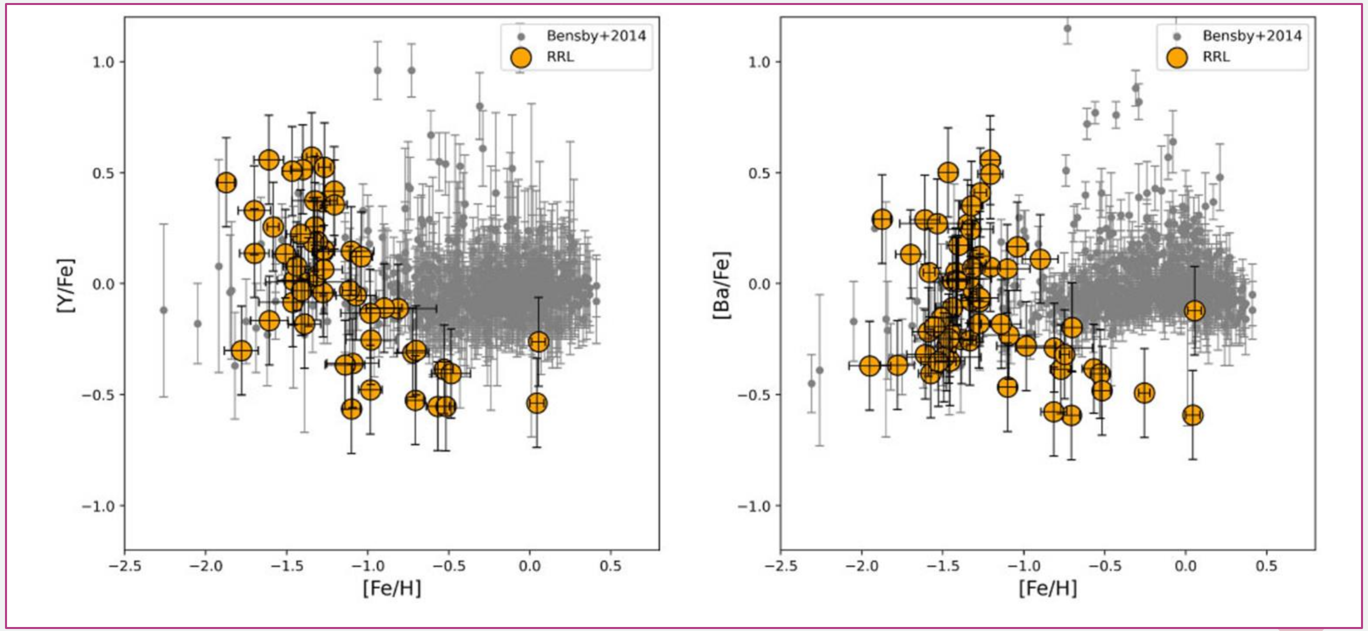
VD, N. Storm, A. Casey + 2024



Metallicity peaks at the halo MDF
(as expected)

Synthetic NLTE on the fly
TSFitPy (Gerber+ 2023)

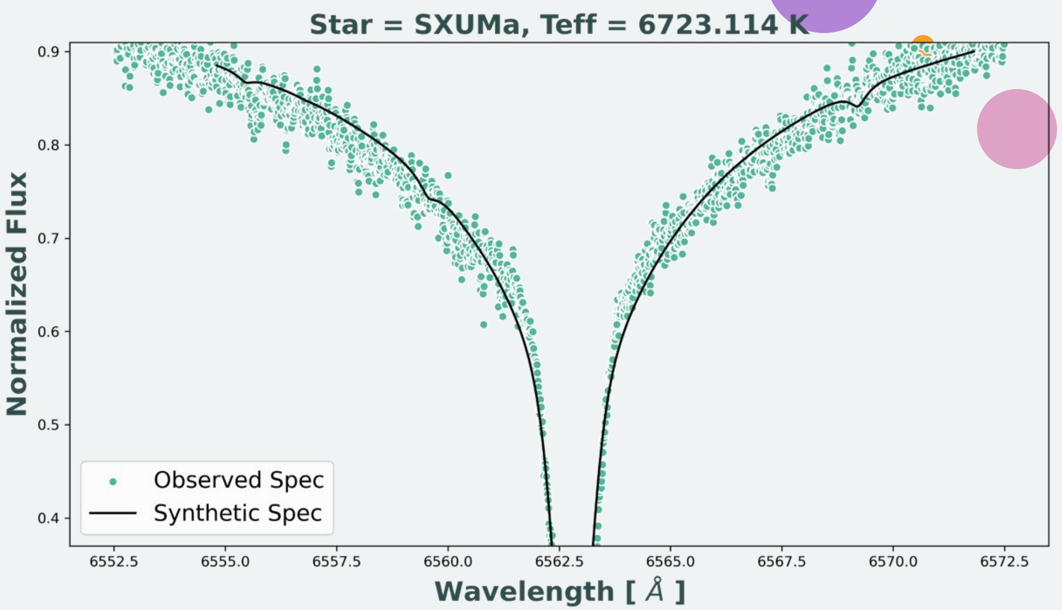


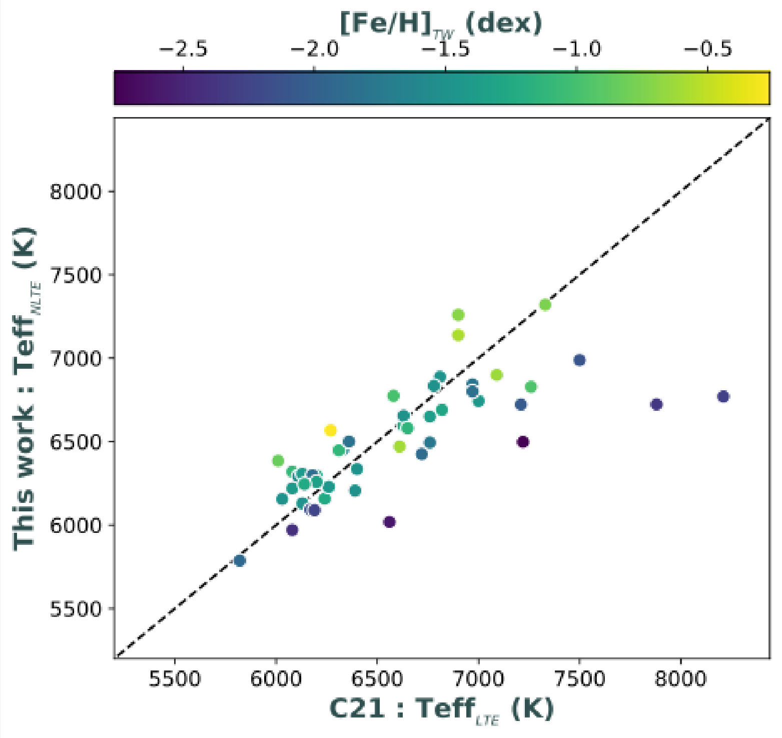


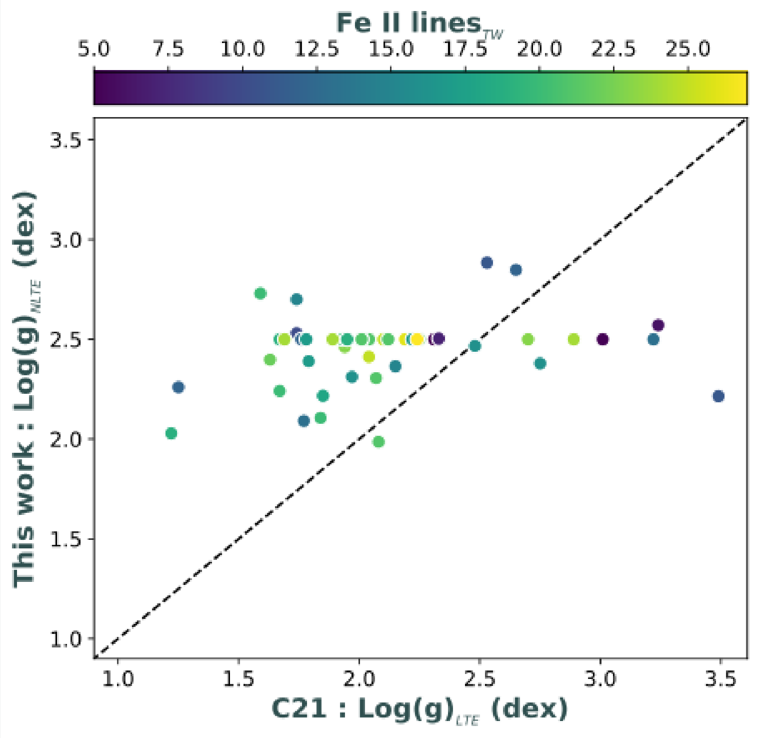
MR RR Lyrae subsolar in Ca and Y.
Product of binary evolution (Bobrick+ 2024) or very old disk component?

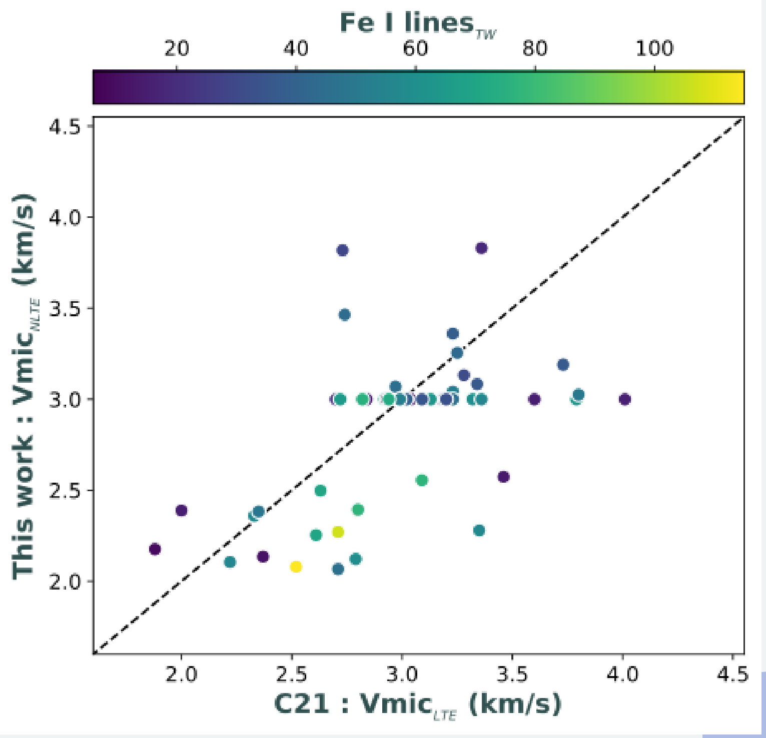
New study

- Pipwala+, in prep. : NLTE + Largest HR RRL sample
- Crestani+2021: LTE , EW measurement
- NLTE : Strong Correlation with Teff



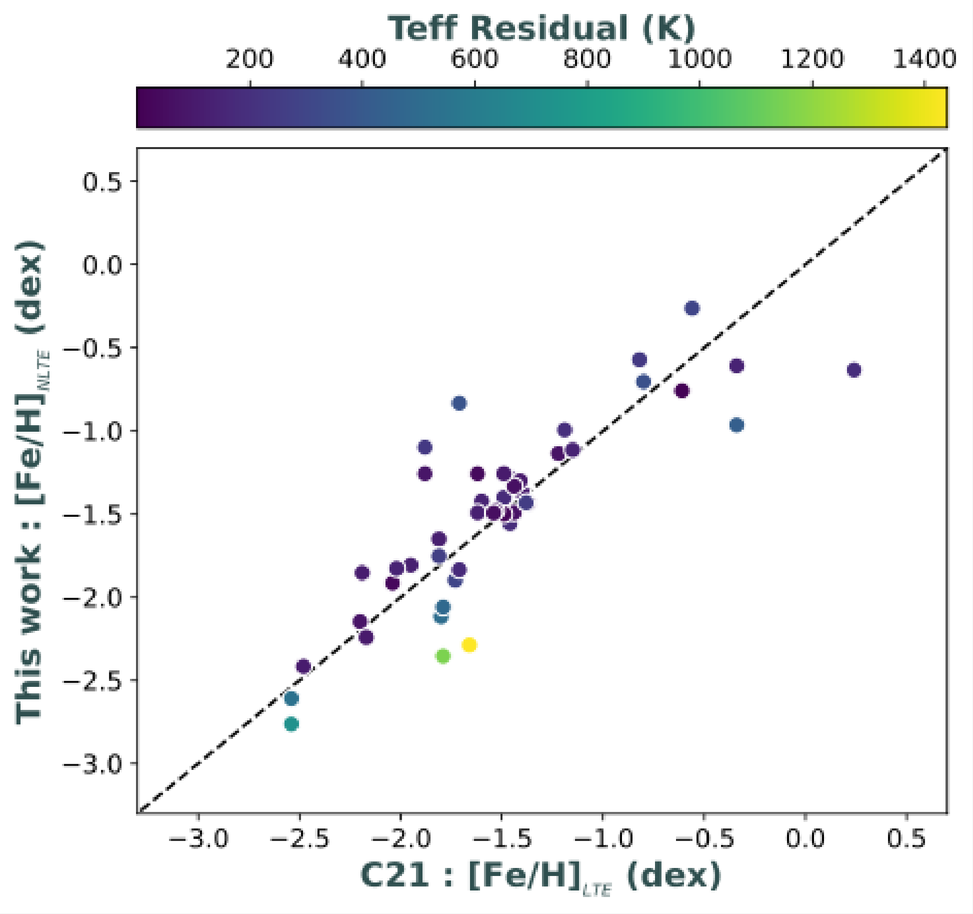


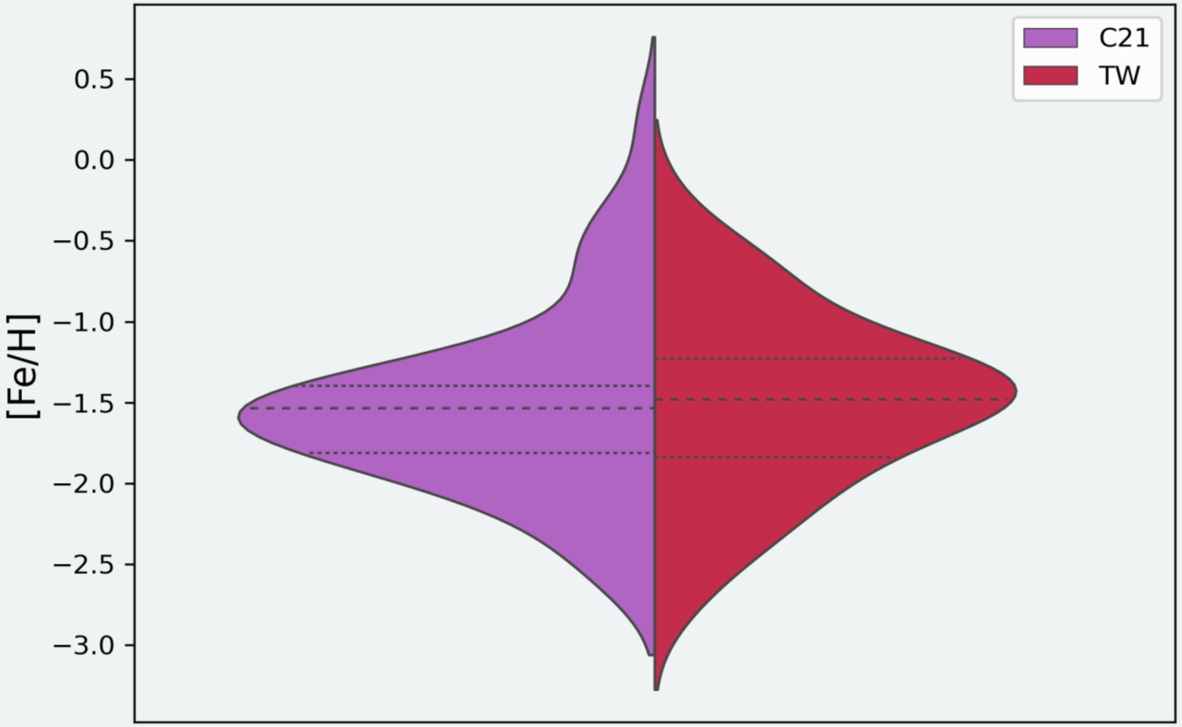




New study

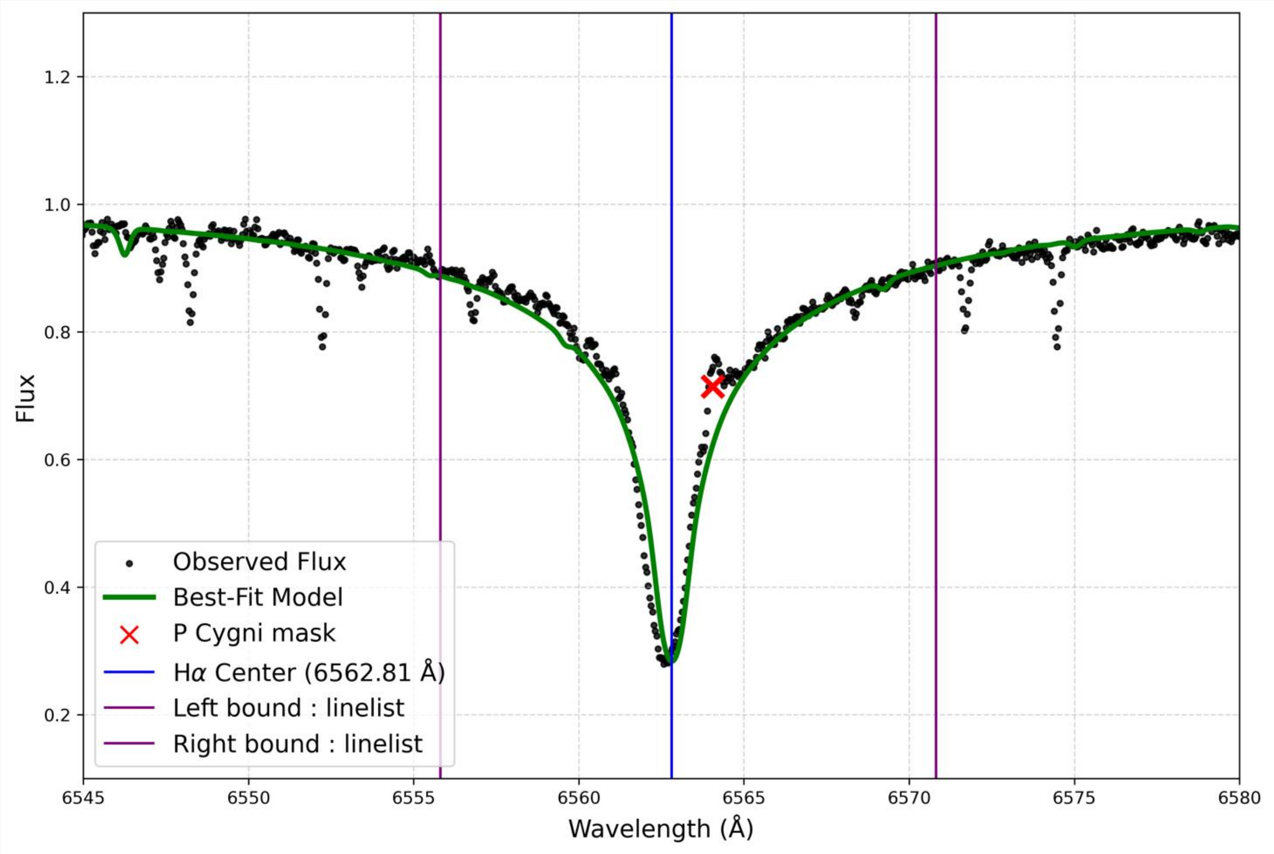
- Pipwala+, in prep.

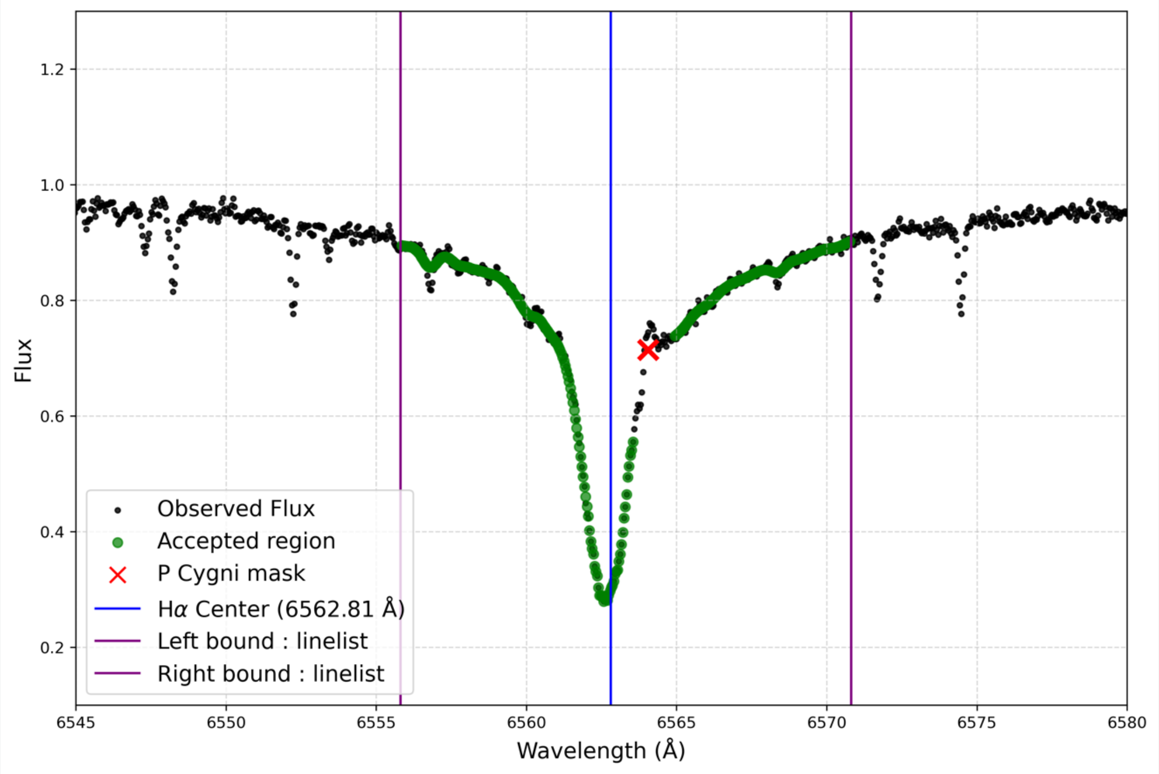




New study

- Pipwala+, in prep. : Remove P Cygni profile
- Statistically significant improvement in Teff
- Will provide robust abundances estimate





Thanks to Andrew Casey!

Advanced statistics and Variables

- Currently, estimating variable stars' labels requires a slow and involved simulation process. This can be improved by leveraging Machine Learning techniques.

- As a first approach, we developed a T_{eff} estimator with supervised learning (**Principal Component Analysis + Linear Regression**). Performance is promising, with an R^2 score of 0.92 on the worst shuffled training/testing sample.

- Input data comes from the GALAH survey #330, with a sample size of 200 stars.

Define wings

Extract features

Train Linear Regression Model

Advanced statistics and Variables

Next steps:

- training set on mock **4most** (de Jong+ 2019) spectra
- correct for the emission in the cores (WIP);
- improve wing selection (WIP);
- train more sophisticated models, like Bayesian LR or Dense Neural Networks;
- improve the robustness of models by studying Hβ, Hγ, and Hδ; and
- estimate log g from FeI/FeII lines, estimate Vmic, abundances

Soon, the **4MOST spectograph** on the VISTA telescope will be giving us > 20,000 of RRL spectra. Quick label estimation will be crucial to kickstart analysis.