

RR Lyrae as a probes of Galactic Archaeology with Morfeo

Emanuela Luongo

Phd student at University of Salerno, INAF – OA Capodimonte

Supervisors:

Marcella Marconi (INAF – OA Capodimonte)

Vincenzo Ripepi (INAF – OA Capodimonte)

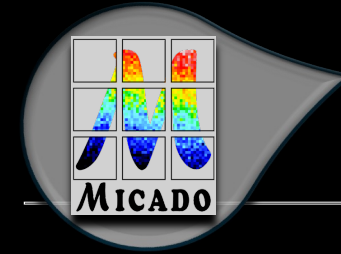
Amata Mercurio (University of Salerno)

In collaboration with:

Marina Rejkuba (ESO)

Zdenek Prudil (ESO)

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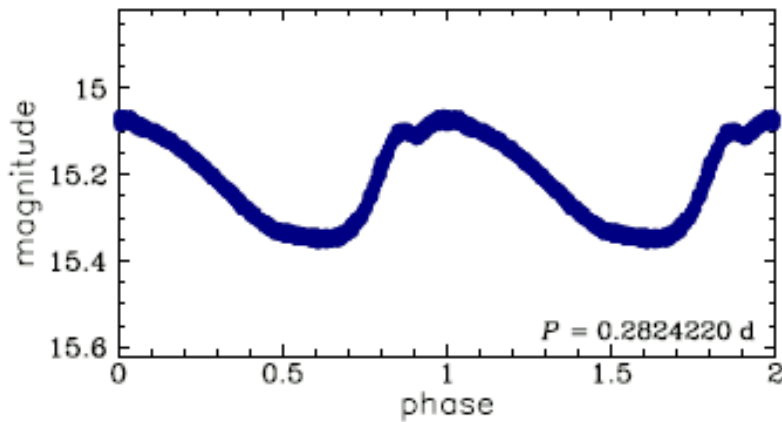
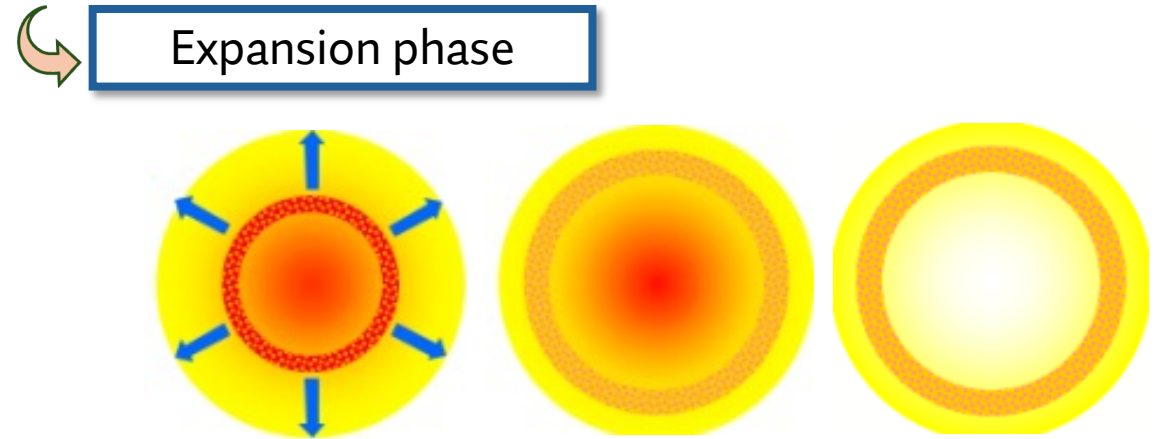
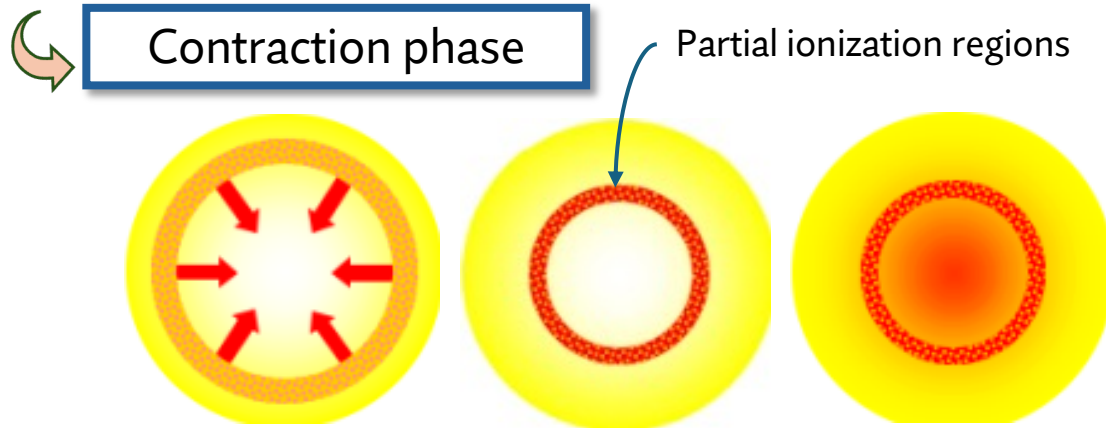
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Pulsation Theory – The Valve Mechanism



Fourier series:

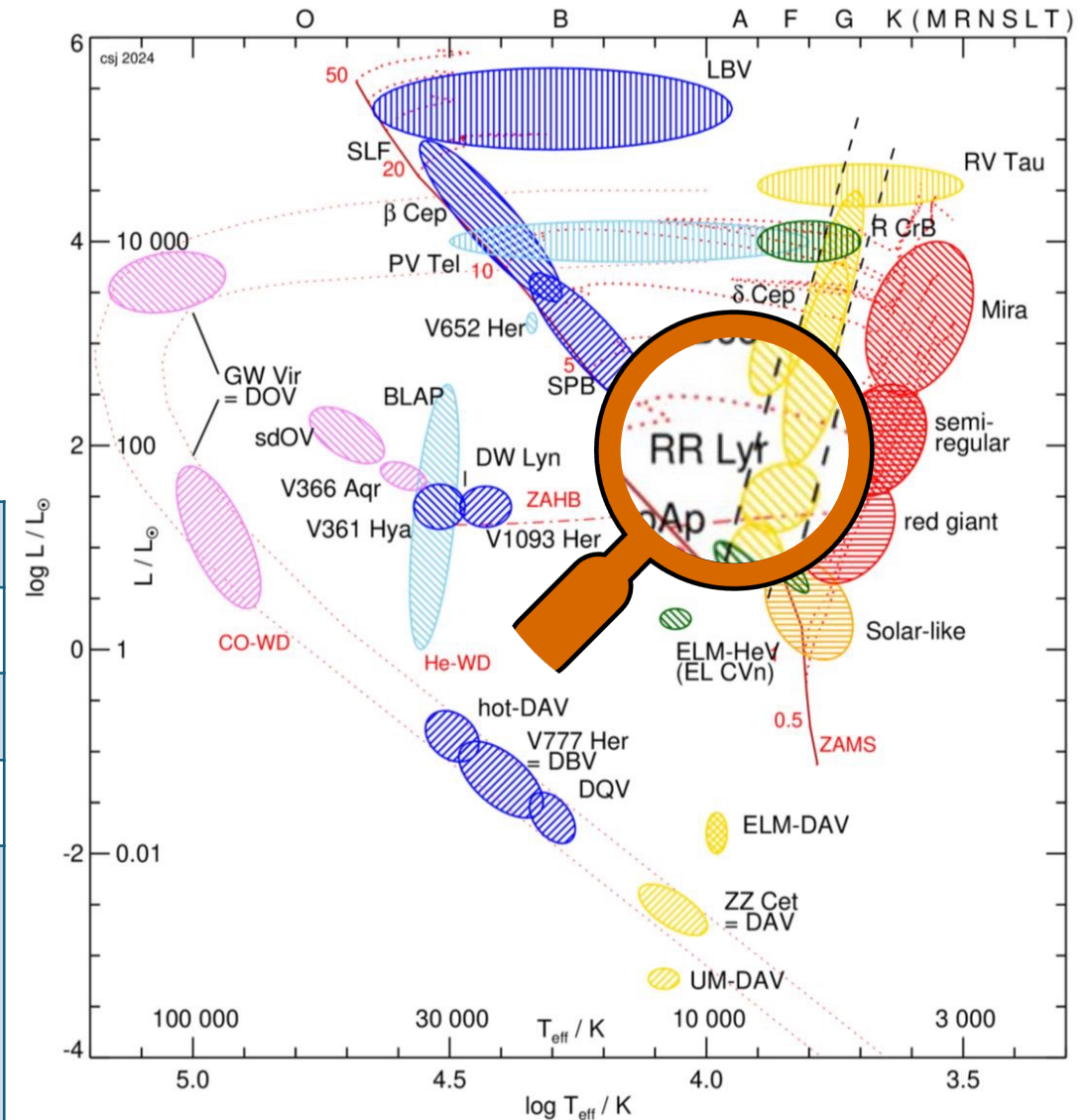
$$m = m_0 + \sum_{k=1}^N A_k \sin(2\pi kx + \phi_k)$$

- Period
- Amplitude
- Fourier parameters:
 $R_{k1} = \frac{A_k}{A_1}$
 $\phi_{k1} = \phi_k - k\phi_1$

RR Lyrae variable stars

- RR Lyrae are old variable stars that inhabit the Horizontal Branch of the HR diagram.
- We observe them in the halo, bulge and globular clusters of the Milky Way and neighbouring dwarf galaxies.

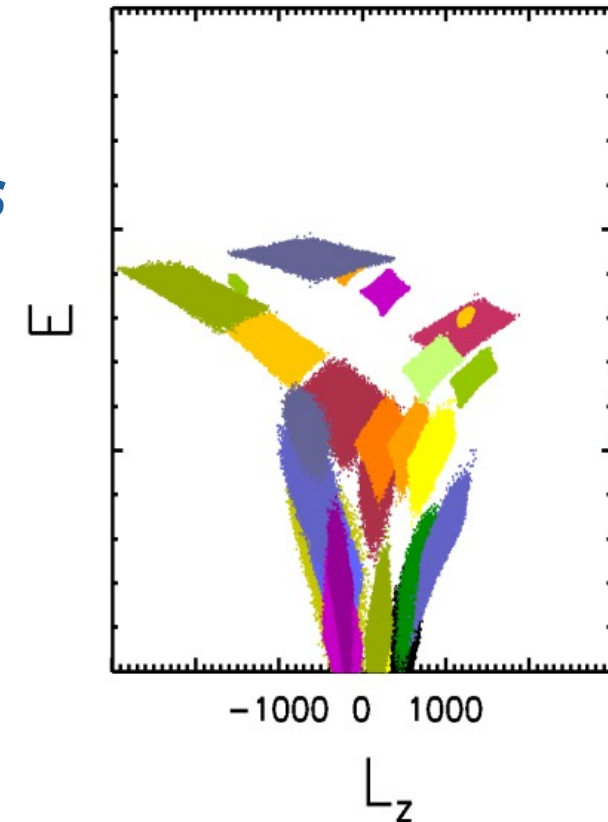
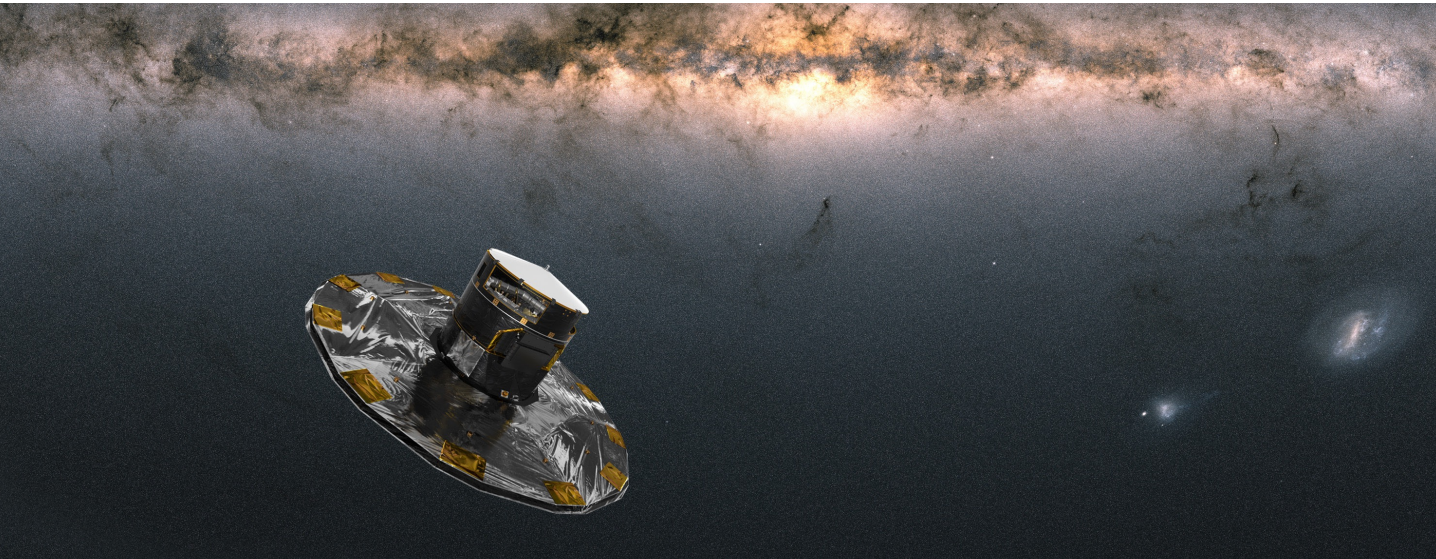
Population type	II
Age	> 10 Gyr
Mass	$0,5 < M/M_{\odot} < 0,8$
HR-diagram position	Horizontal Branch (HB)
Where	<ul style="list-style-type: none"> • Halo • Bulge • Galactic Globular Clusters (GGC) • Disk



Milky Way Progenitors :

RR Lyrae as tracers of ancient stellar populations

- From the Λ CDM model, massive galaxies like the MW evolve by devouring lower-mass galaxies.
- Our halo is made up of stars and GGCs that were once part of other galaxies.

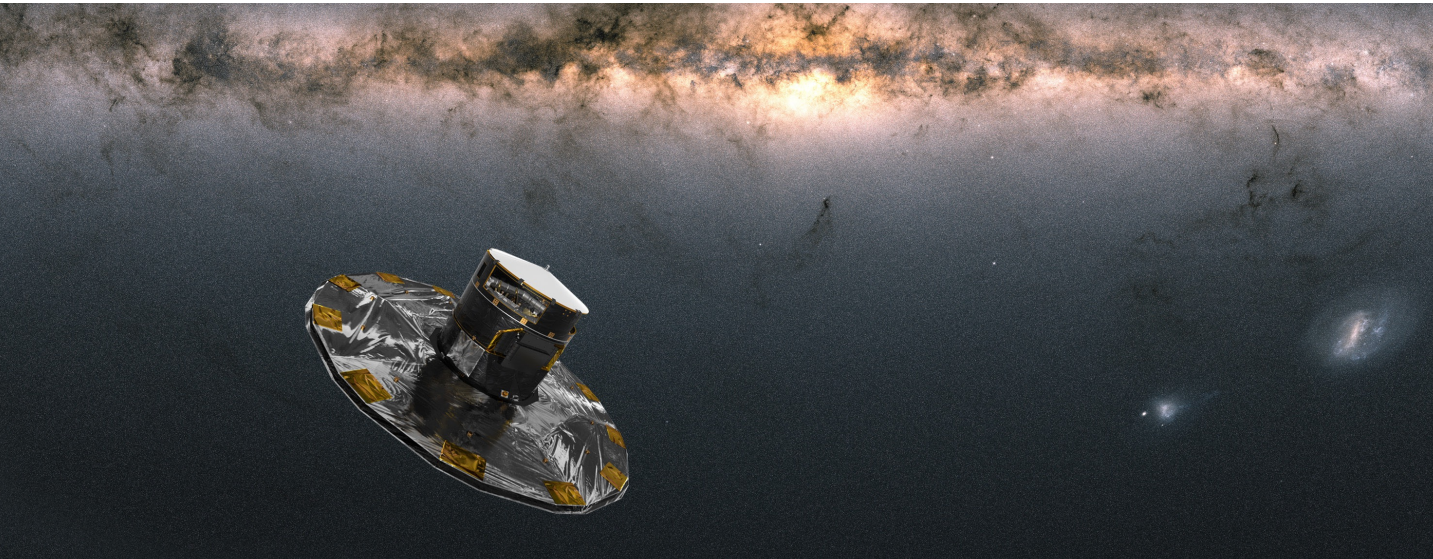
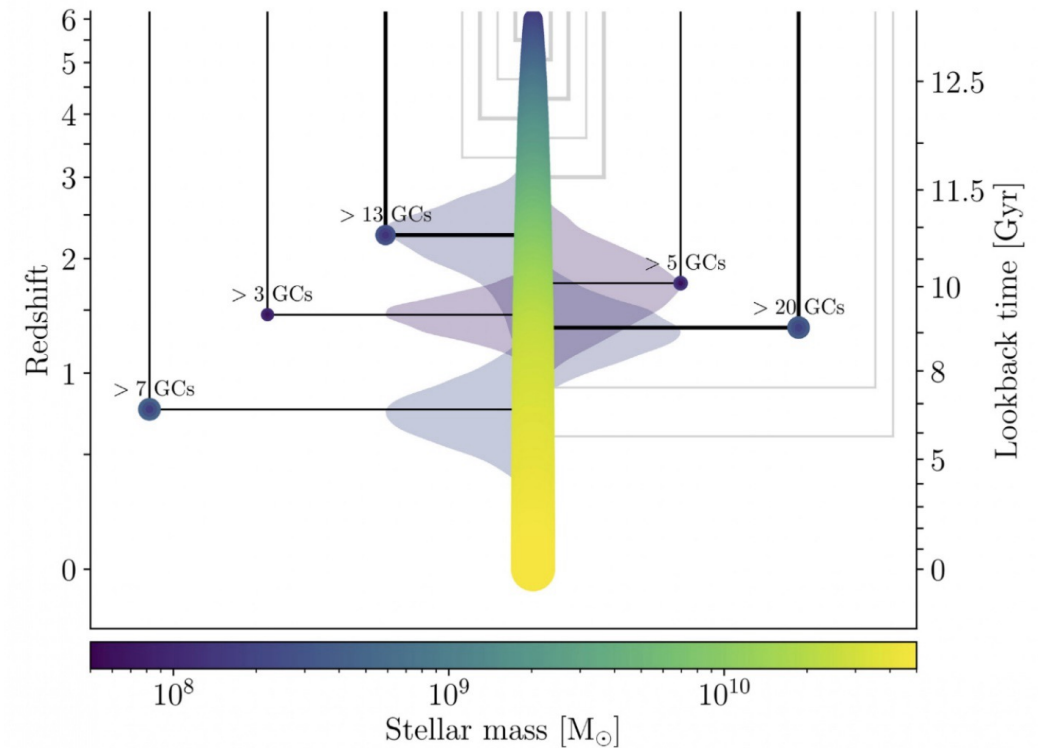
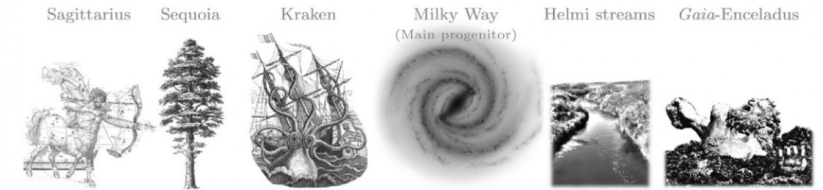


- The debris whose remnants mix and spread into the stellar halo, preserving structure in the space of motion integrals (Helmi, 2020).

Milky Way Progenitors :

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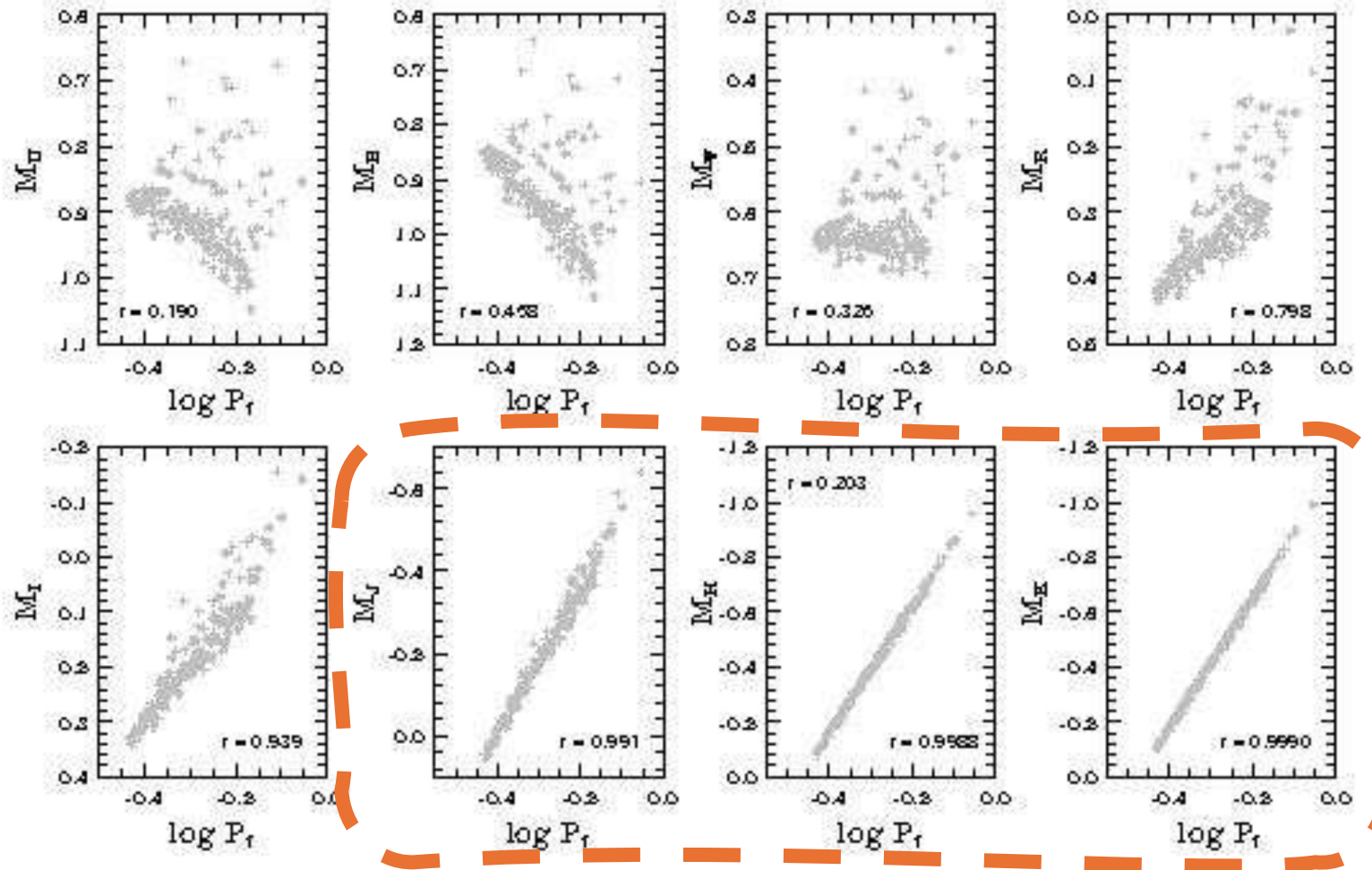


PL relations:

RR Lyrae as primary distance indicators

- From the pulsation properties, we are able to infer a Period-Luminosity relation (PL) in near-infrared bands (JHK).
- The PL slope increases from the optical to the JHK bands because bolometric corrections are much less sensitive to temperature in the infrared.

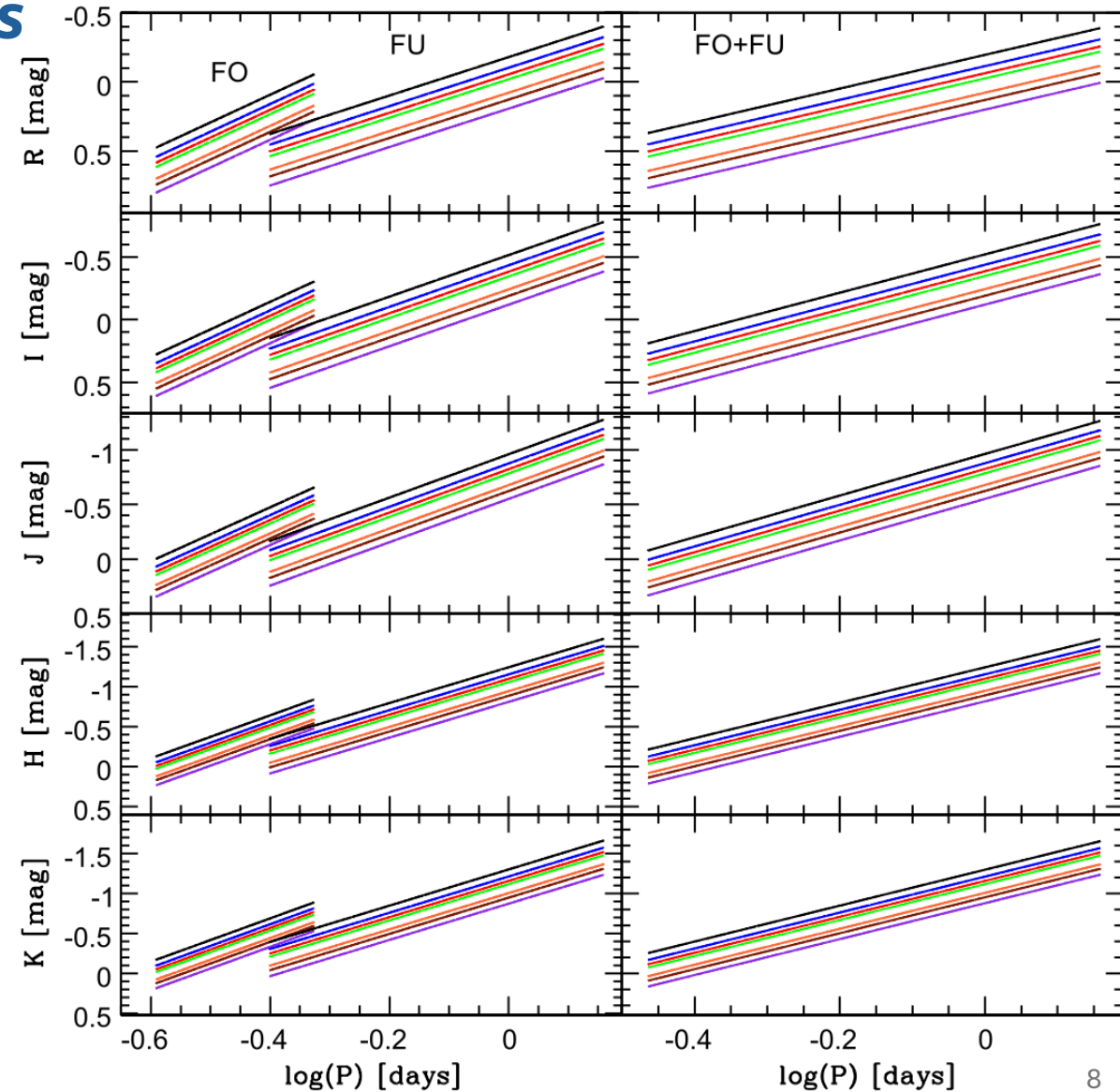
$$M_{JHK} = \alpha + \beta \cdot \log_{10}(P)$$



PLZ relations: RR Lyrae as primary distance indicators

- The RIJHK Period–Luminosity–Metallicity (PLZ) relations become progressively steeper and less dispersed from the optical to the NIR bands. In particular, the scatter decreases significantly in the K band, improving the precision of individual distance estimates.

$$M_{JHK} = \alpha + \beta \cdot \log_{10}(P) + \gamma[Fe/H]$$



PWZ relations:

RR Lyrae as primary distance indicators

- The Wesenheit magnitude is a reddening-free quantity obtained by combining magnitudes and colours through the extinction law. It reduces the effects of interstellar extinction.

$$W_{(X, Y-Z)} = m_X - R_X (m_Y - m_Z)$$

Diagram illustrating the components of the Wesenheit magnitude equation:

- $W_{(X, Y-Z)}$ is labeled as **Wesenheit**.
- m_X is labeled as **Magnitude Term**.
- R_X is labeled as **Total to selective absorption ratio**.
- $(m_Y - m_Z)$ is labeled as **Colour Term**.

$$R_X = \frac{A_X}{E(m_Y - m_Z)}$$

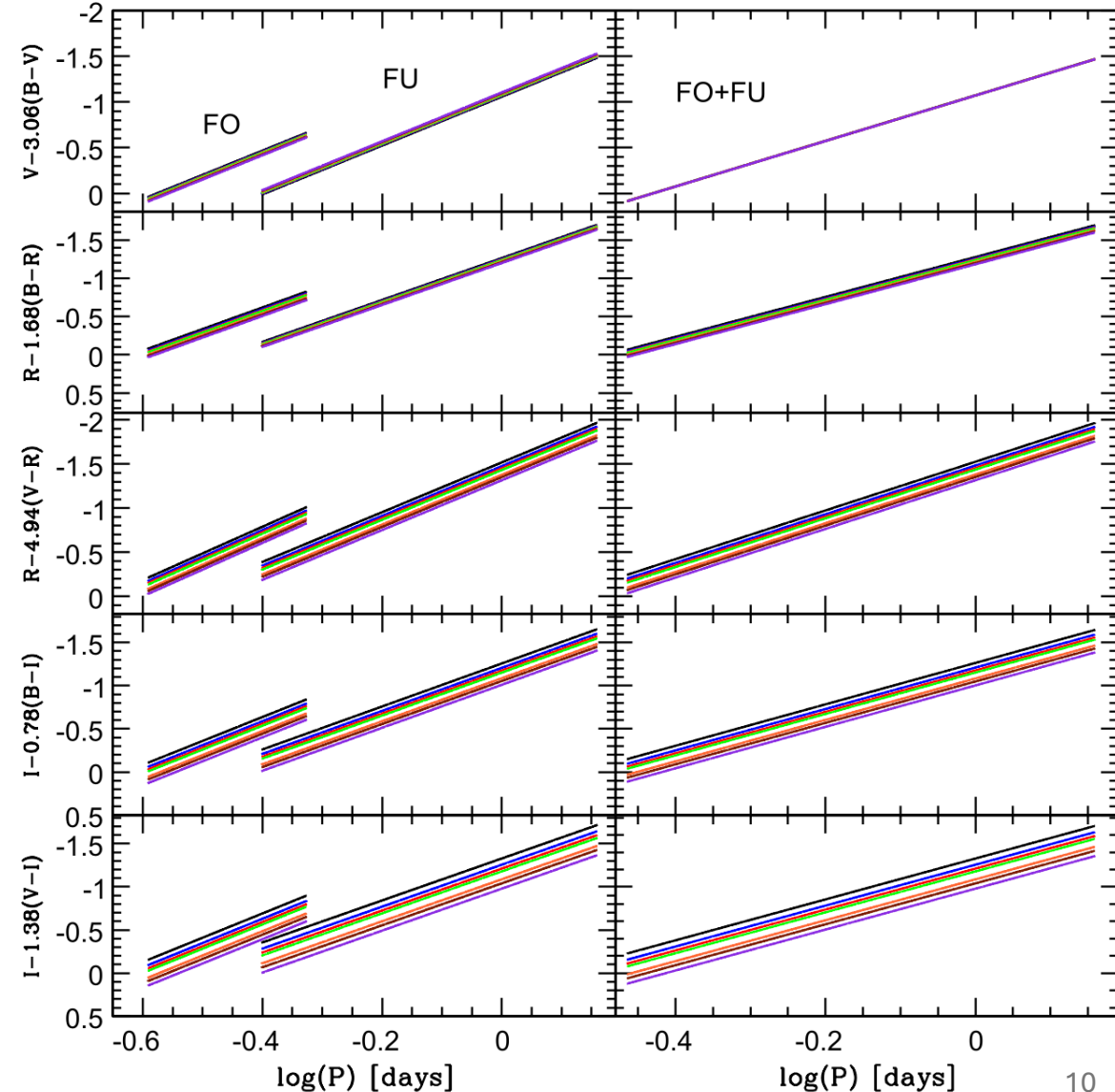
Total to selective absorption ratio

PWZ relations:

RR Lyrae as primary distance indicators

- Period–Wesenheit–Metallicity (PWZ) relations combine period, colour, and metallicity information, providing reddening-free distance indicators by construction.
- Theoretical models predict that PWZ relations are tighter and more accurate than standard PL relations, making them powerful tools for precision distance measurements.

$$W = \alpha + \beta \cdot \log_{10}(P) + \gamma \cdot [Fe/H]$$





Distance

Period-Wesenheit-Metallicity relation in G Gaia band

$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

W_G → Absolute Wesenheit

α → Zero-point

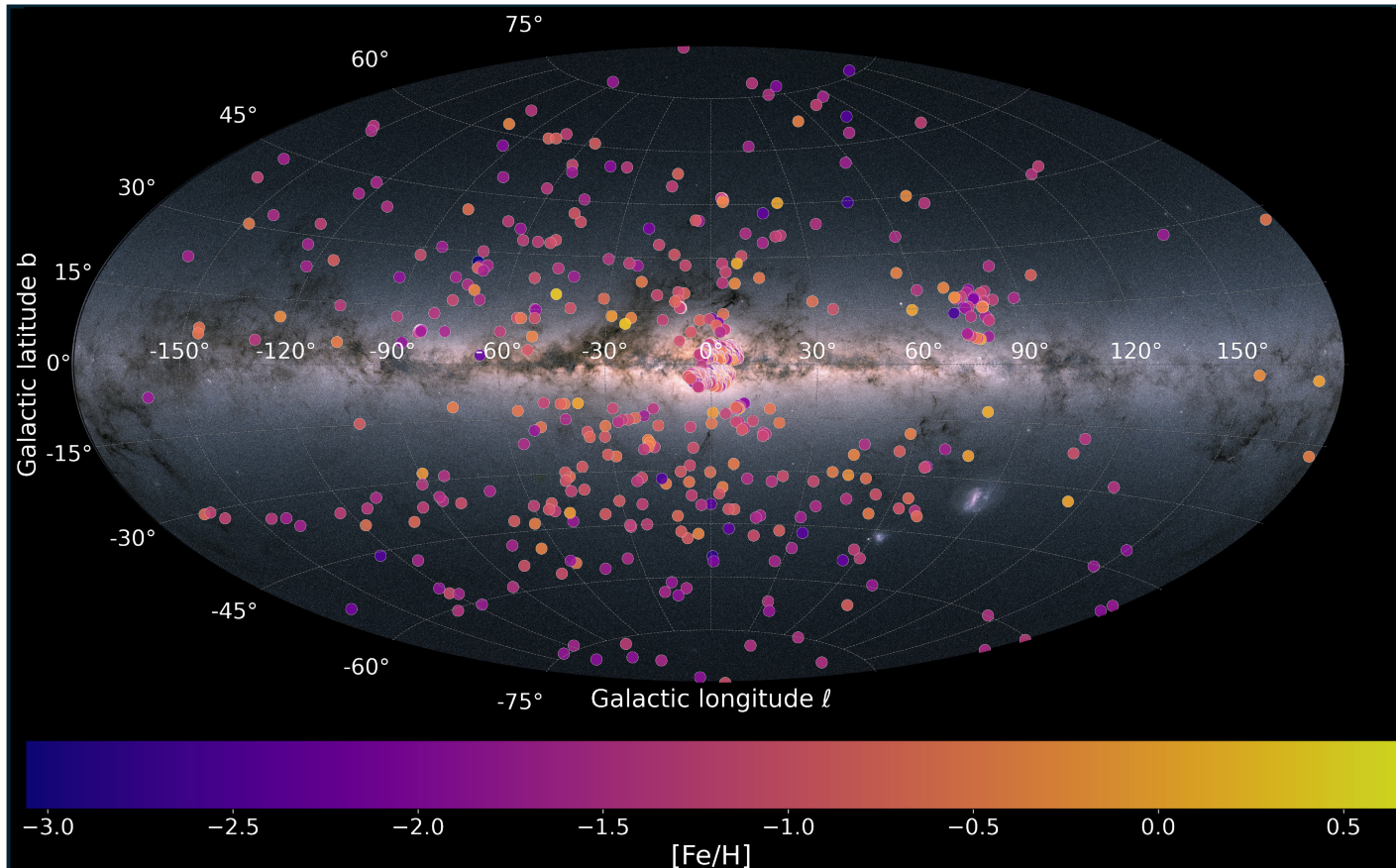
$[\log_{10}(P) + 0.3]$ → Period Term

$[Fe/H]$ → Metallicity Term

Distance : Period-Wesenheit-Metallicity relation in G Gaia band



- To infer a new Period–Wesenheit–Metallicity (PWZ) relation, we collect the $[Fe/H]$ measures from HR observations.



$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

$$w_G = G - \lambda(BP - RP)$$

$$d = 10^{\frac{w_G - W_G + 5}{5}}$$

Number of RRL with
[Fe/H] HR data /
Total

1476 / 435 645

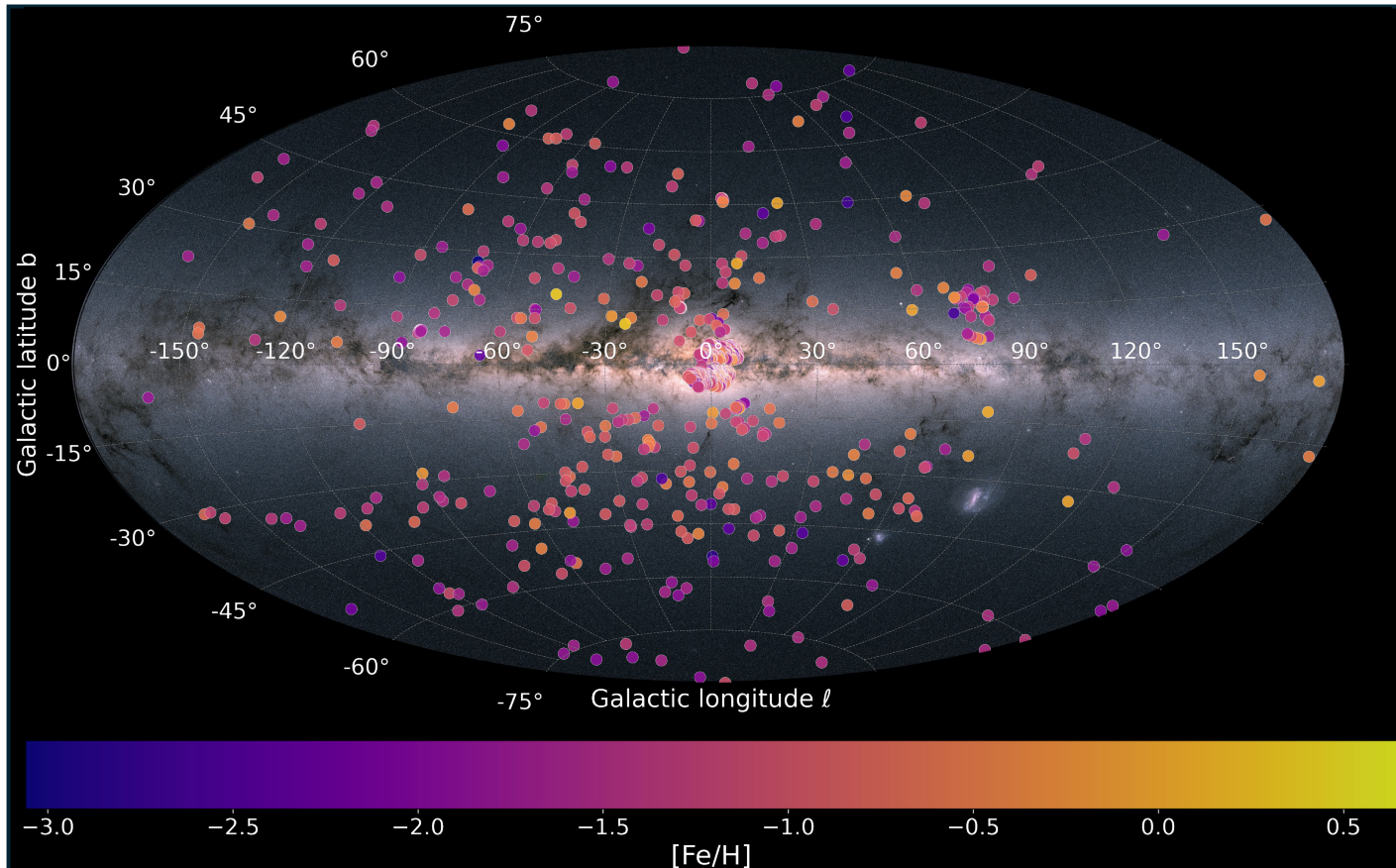
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- GALAH DR4 – Buder et al. 2021
- Marconi et al. 2021
- Crestani et al. 2021
- Gilligan et al. 2021
- Nemec et al. 2013

Luongo et al. in prep.

Distance : Period-Wesenheit-Metallicity relation in G Gaia band



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$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [\text{Fe}/H]$$

$$w_G = G - \lambda(BP - RP)$$

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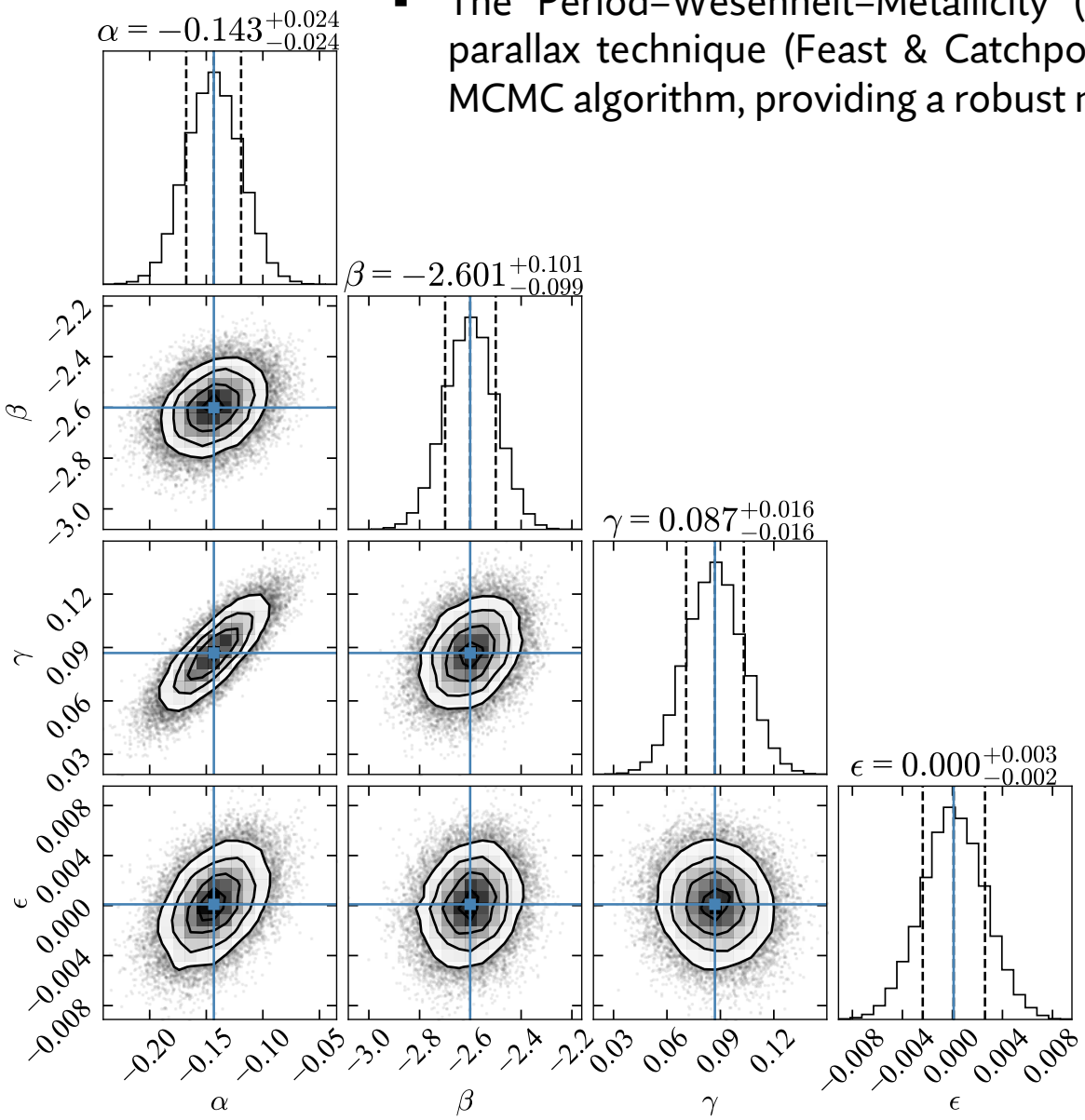


Luongo et al. in prep.



Distance : Period-Wesenheit-Metallicity relation in G Gaia band

- The Period-Wesenheit-Metallicity (PWZ) relation was derived using the photometric parallax technique (Feast & Catchpole 1997, Riess et al. 2021) combined with a Bayesian MCMC algorithm, providing a robust method for accurate distance estimates.



$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

- Lindegren correction, zero-point bias ($\Delta\varpi = ZP$):

$$\varpi_{lind} = \varpi_{obs} - \Delta\varpi(m_G, v_{eff}, \beta)$$

- Counter-correction, residual bias (ϵ):

$$\varpi_{corr} = \varpi_{lind} + \epsilon$$

- Photometric parallax:

$$\varpi_{phot} = 10 \frac{W_G - W_G + 10}{5}$$

- Cauchy loss function to assign different weight:

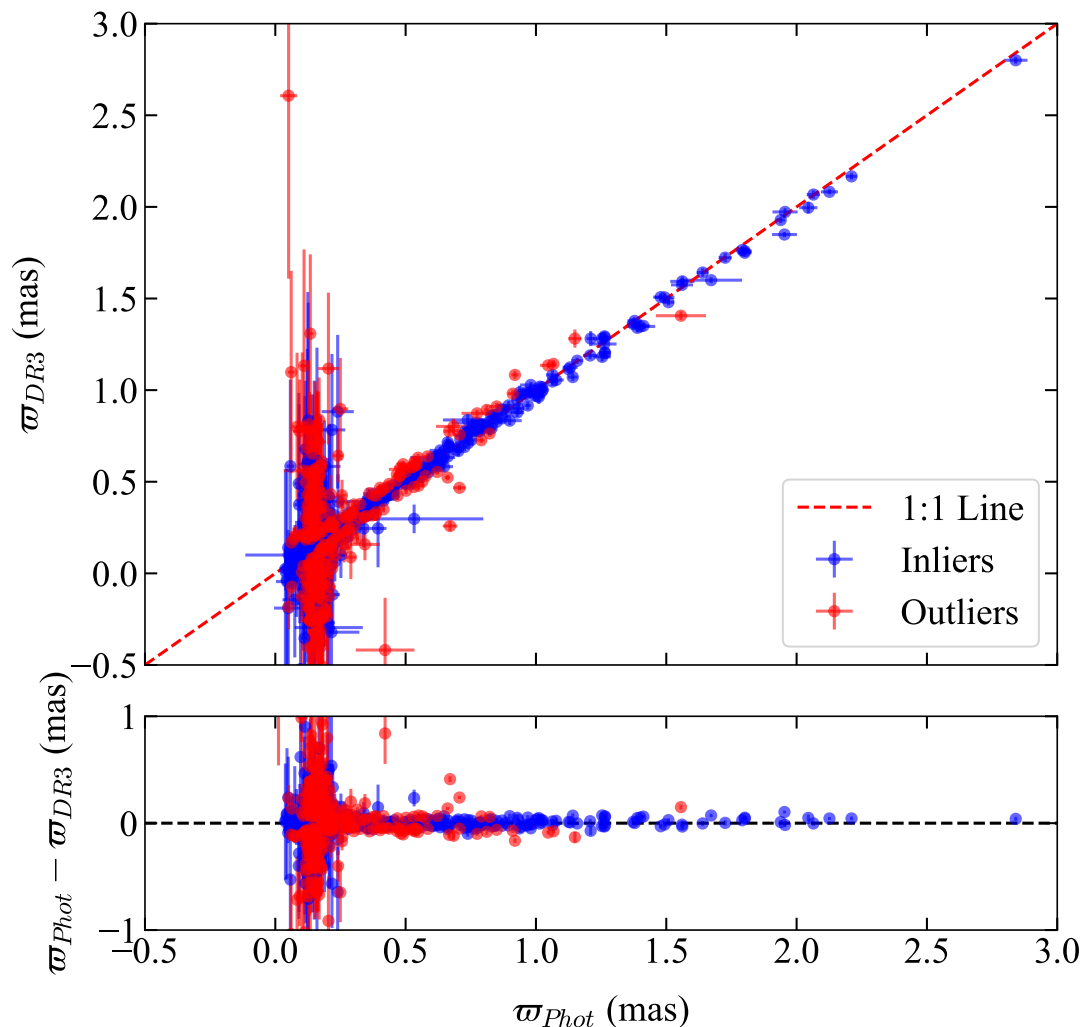
$$\mathcal{L}_{Cauchy} = \frac{c^2}{2} \sum_i \log\left(1 + \left(\frac{r_i}{c}\right)^2\right)$$

where $r_i = \frac{(\varpi_{lind} + \epsilon - \varpi_{phot})}{\sigma^2}$



Distance : Period-Wesenheit-Metallicity relation in G Gaia band

- The observed Lindegren-corrected parallaxes show excellent agreement with our photometric model along the 1:1 line. Outliers (red) are handled via a Cauchy loss function, which is also minimized in our MCMC fit to ensure robust parameter estimation.



$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

- Lindegren correction, zero-point bias ($\Delta\varpi = ZP$):

$$\varpi_{lind} = \varpi_{obs} - \Delta\varpi(m_G, v_{eff}, \beta)$$
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- Photometric parallax:

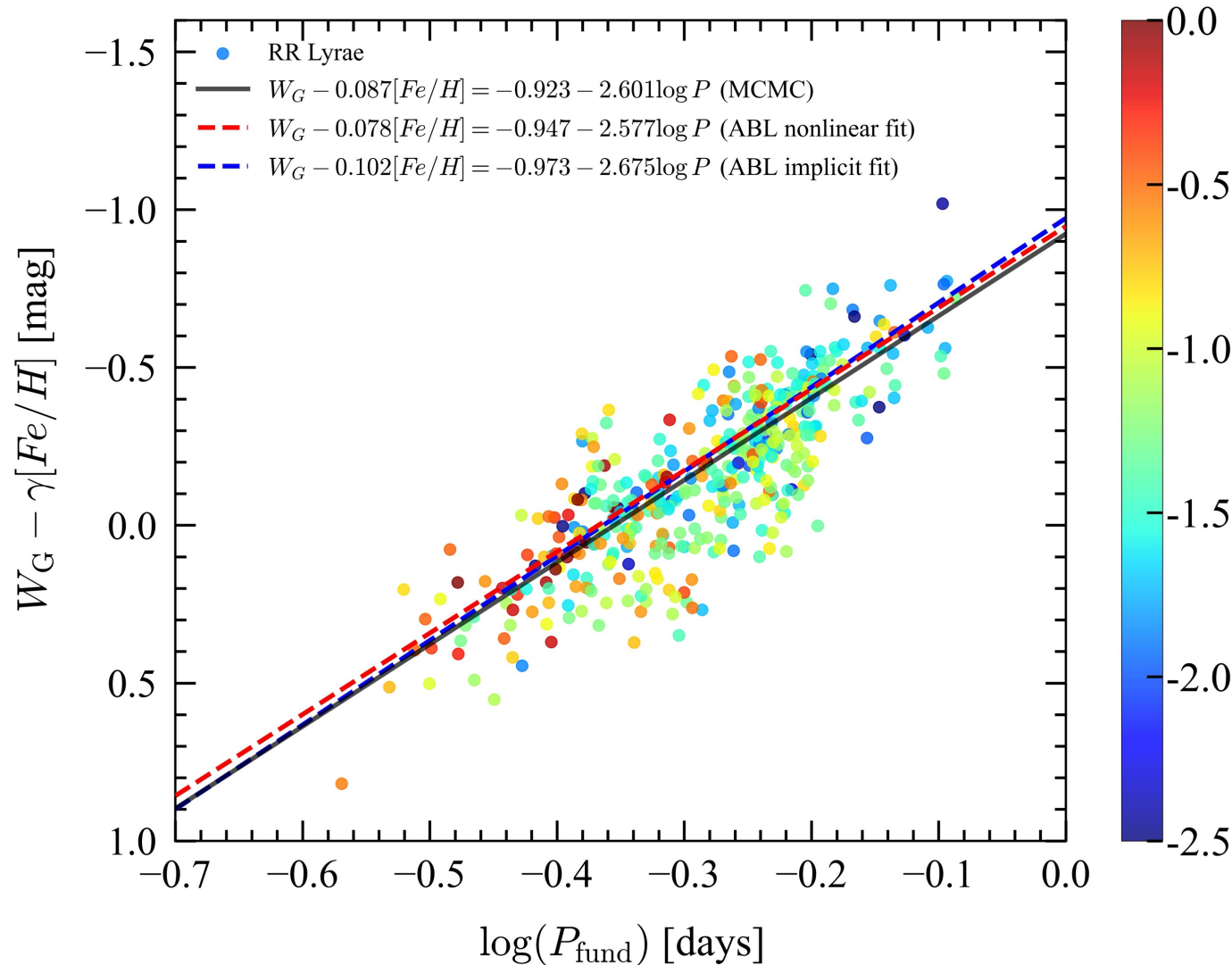
$$\varpi_{phot} = 10 \frac{W_G - W_{G+10}}{5}$$

- Cauchy loss function to assign different weight:

$$\mathcal{L}_{Cauchy} = \frac{c^2}{2} \sum_i \log\left(1 + \left(\frac{r_i}{c}\right)^2\right)$$

where
$$r_i = \frac{(\varpi_{lind} + \varepsilon - \varpi_{phot})}{\sigma^2}$$

Distance : Period-Wesenheit-Metallicity relation in G Gaia band



$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

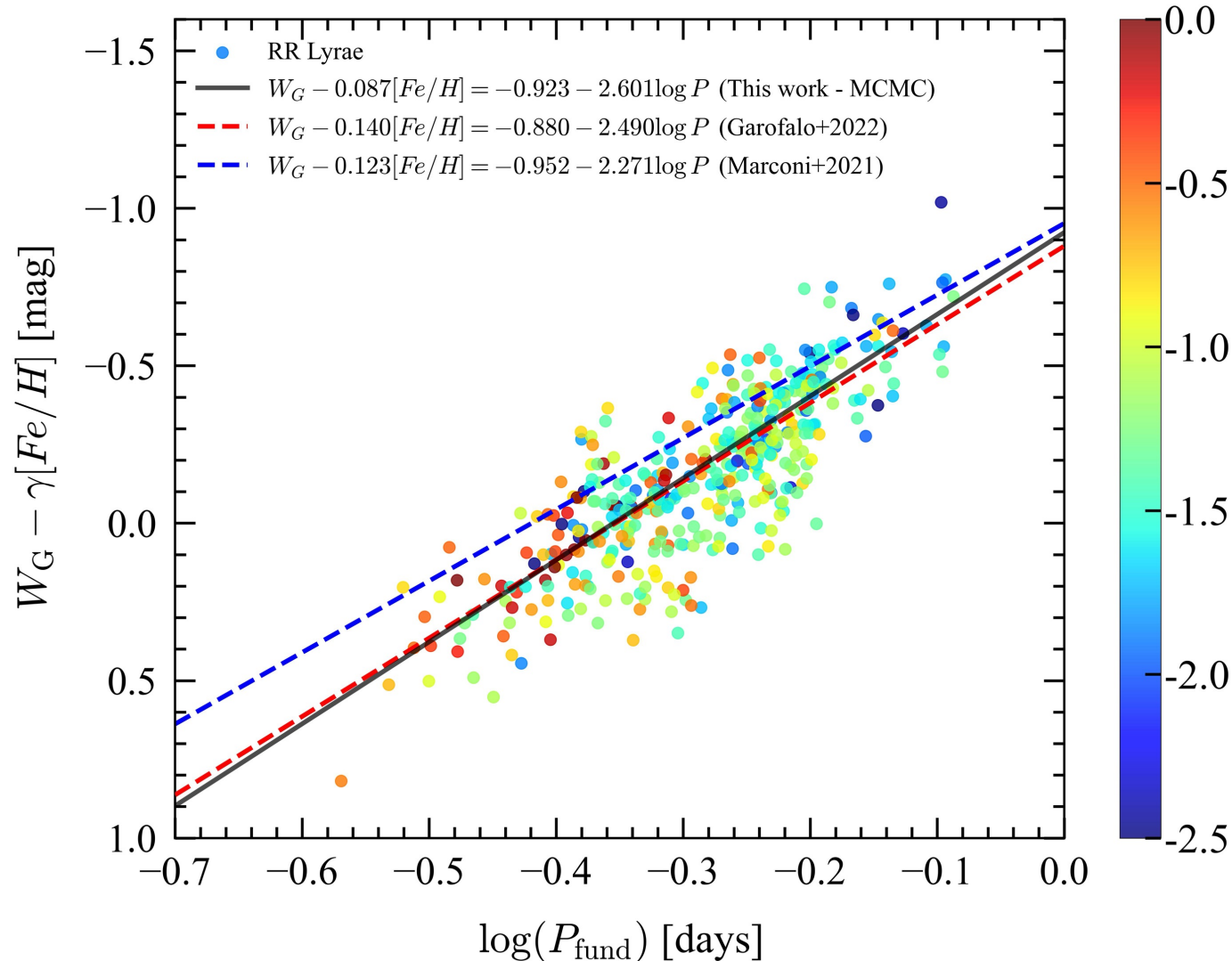
$$w_G = G - \lambda(BP - RP)$$

$$d = 10^{\frac{w_G - W_G + 5}{5}}$$

- We estimated the PWZ coefficients using three different methods: MCMC, ABL nonlinear fit and Implicit fit. The resulting coefficients are comparable.

Luongo et al. in prep.

Distance : Period-Wesenheit-Metallicity relation in G Gaia band



$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

$$w_G = G - \lambda(BP - RP)$$

$$d = 10^{\frac{w_G - W_G + 5}{5}}$$

- The estimated PWZ coefficients are consistent with literature results within the errors.

Luongo et al. in prep.

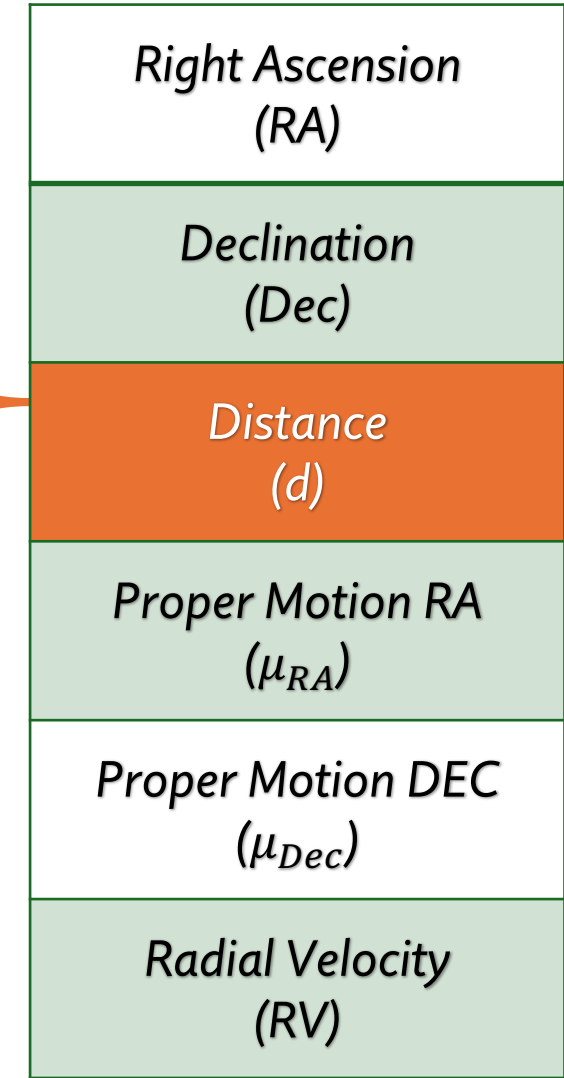
Distance : Period-Wesenheit-Metallicity relation in G Gaia band

Distances for LMC and three GGCs were derived independently by excluding them from the PWZ calibration sample. Reliability is ensured by using external [Fe/H] values from high-resolution compilations, the Gratton et al. (2004) catalogue (LMC), and the DESI survey (NGC 5904). The excellent agreement with literature values confirms the model's accuracy across diverse distance scales.

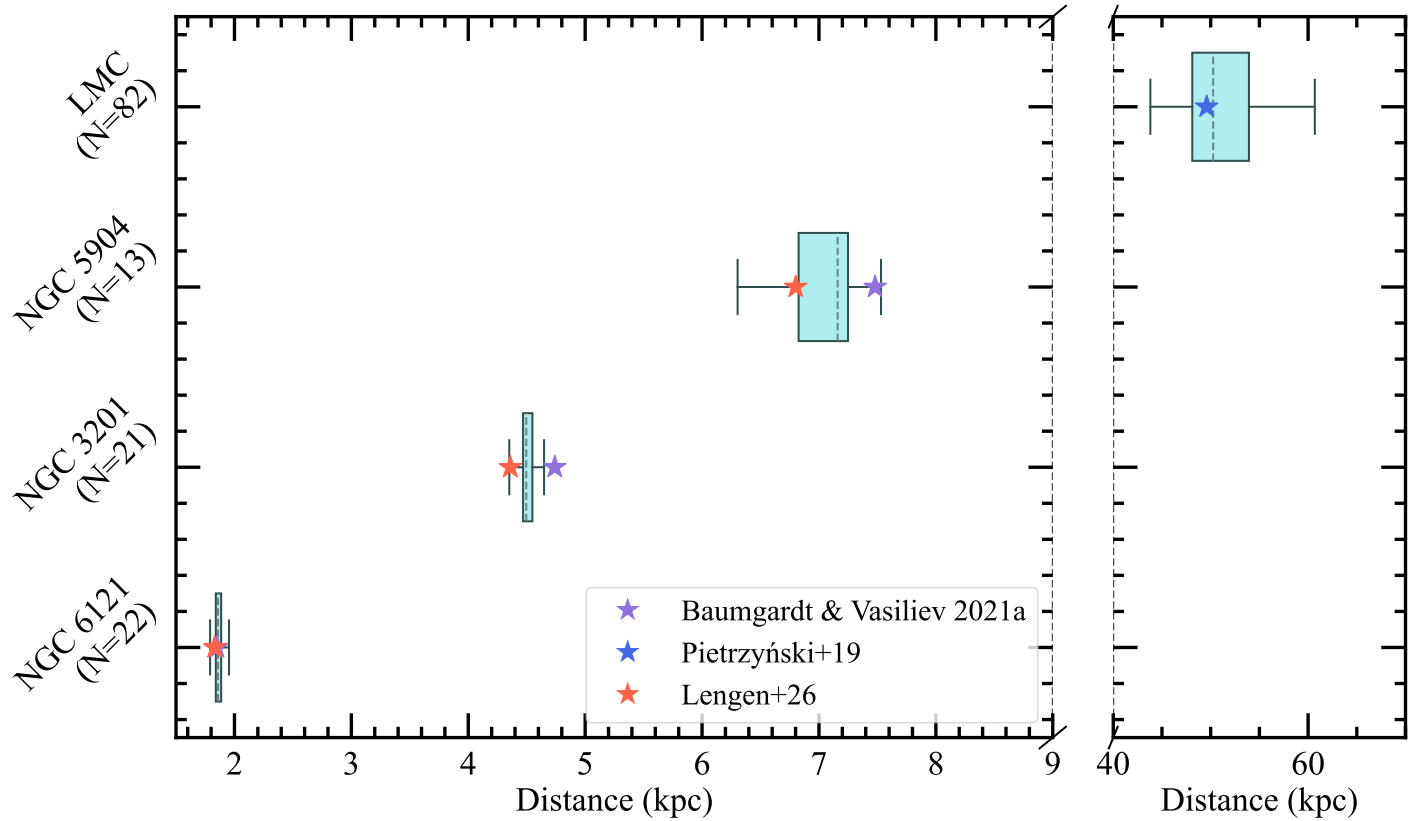
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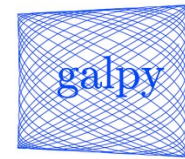


Luongo et al. in prep.

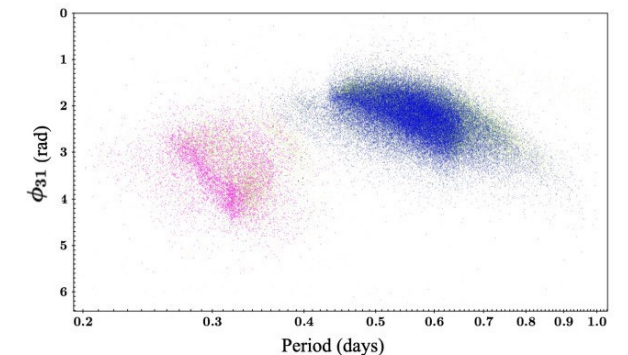
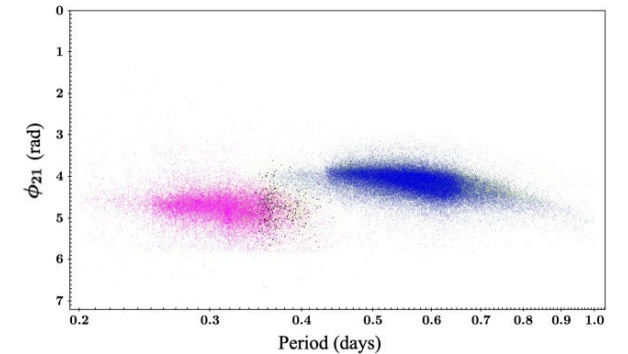
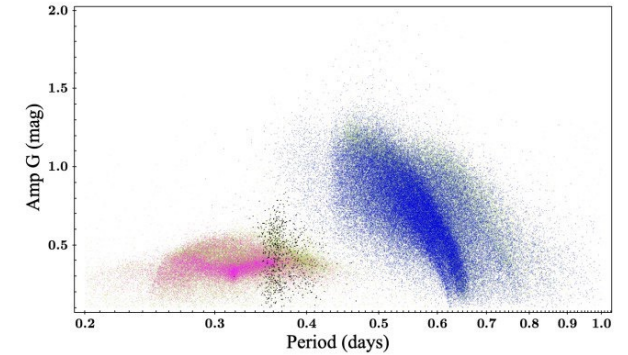
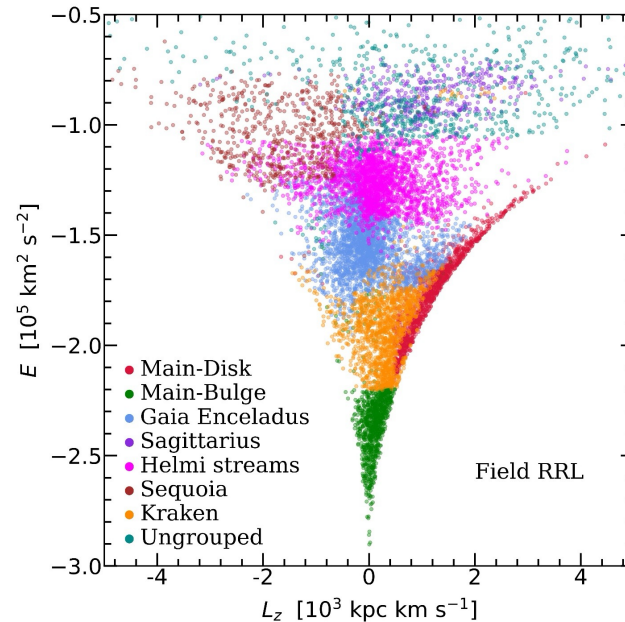


From Chemo-dynamical classification to Pulsational properties

Right Ascension (RA)
Declination (Dec)
Distance (d)
Proper Motion RA (μ_{RA})
Proper Motion DEC (μ_{Dec})
Radial Velocity (RV)
+
[Fe/H]

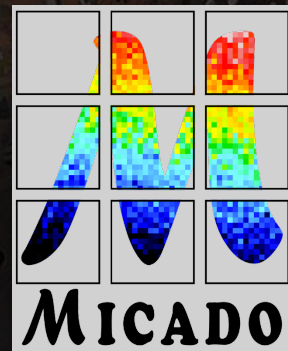


Integrals of motion

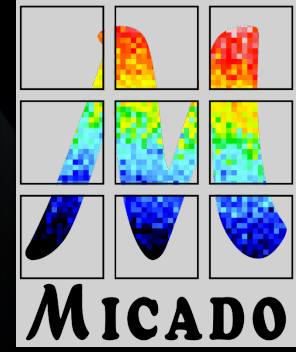


- For each distinct class, we investigate the pulsational properties of the RR Lyrae stars that belong to that class.

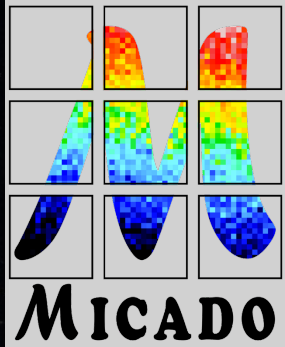
Applications of RR Lyrae properties with



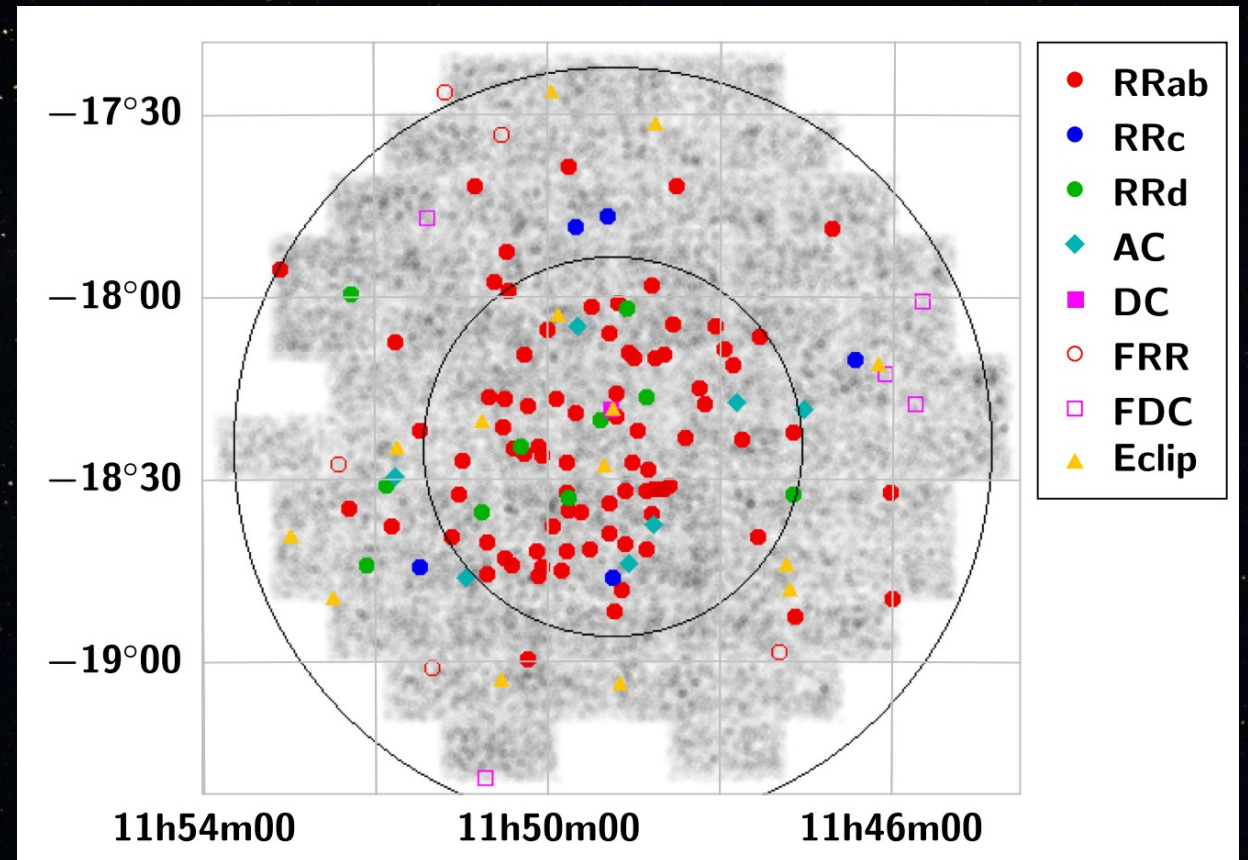
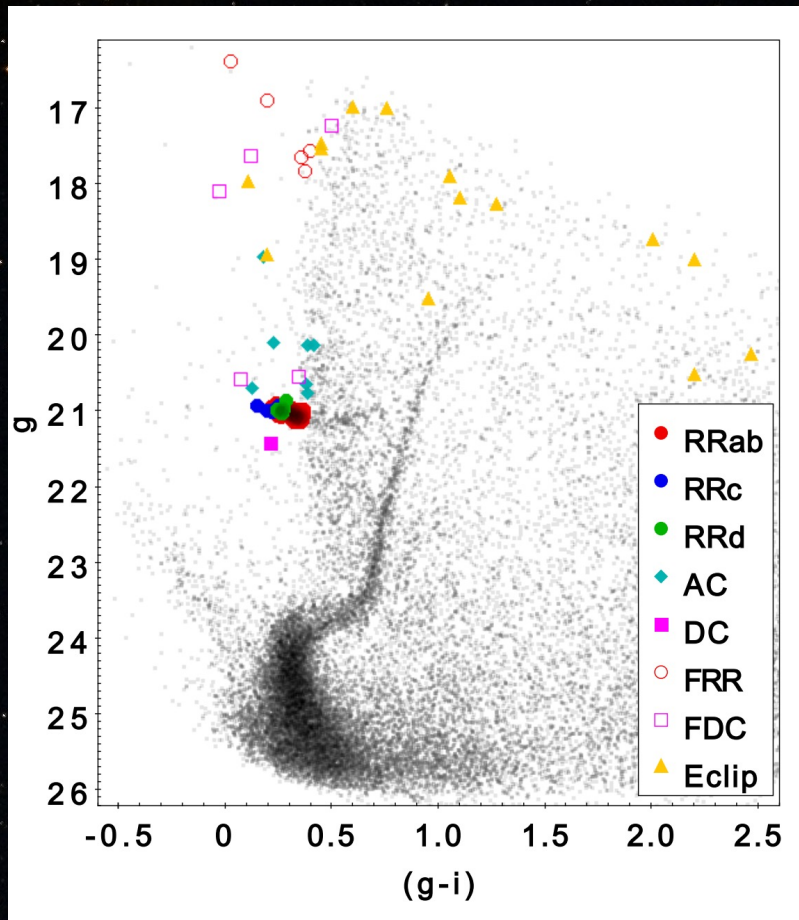
Galactic archaeology: Local volume observations



... and beyond ...



Crater II

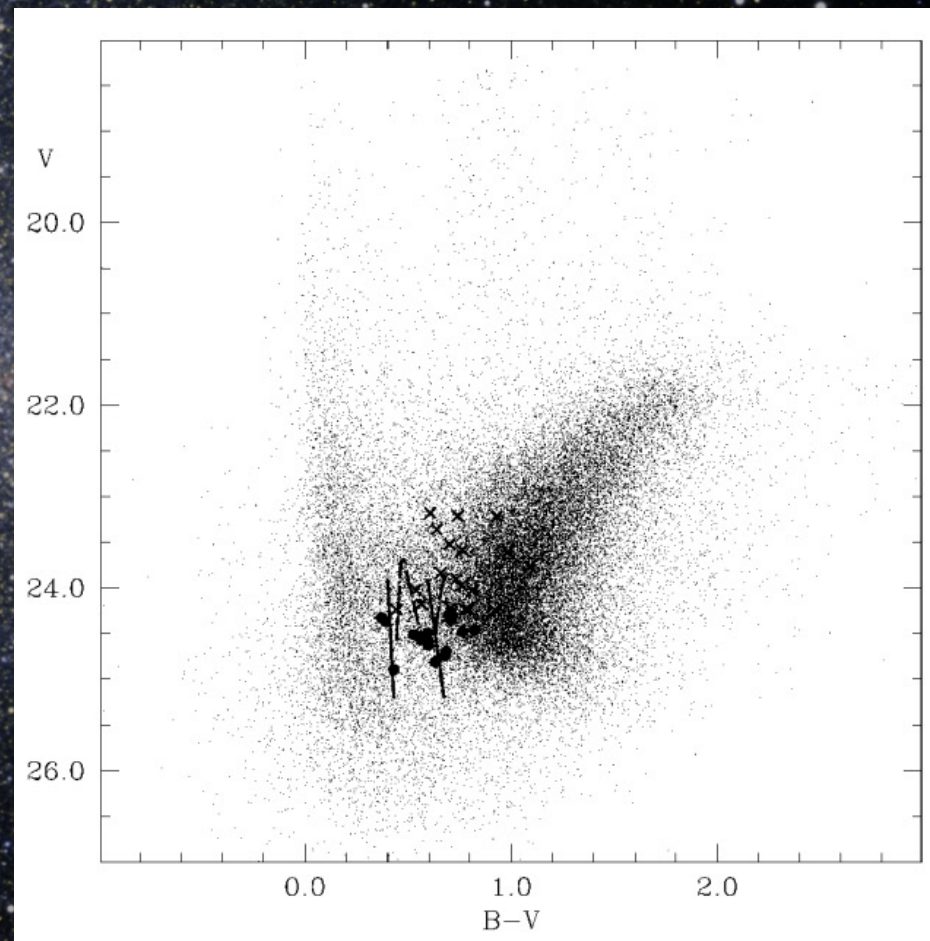
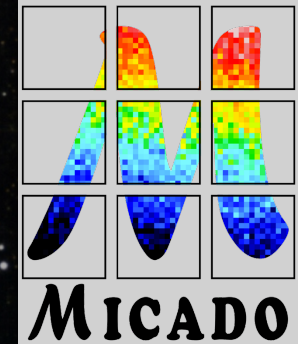


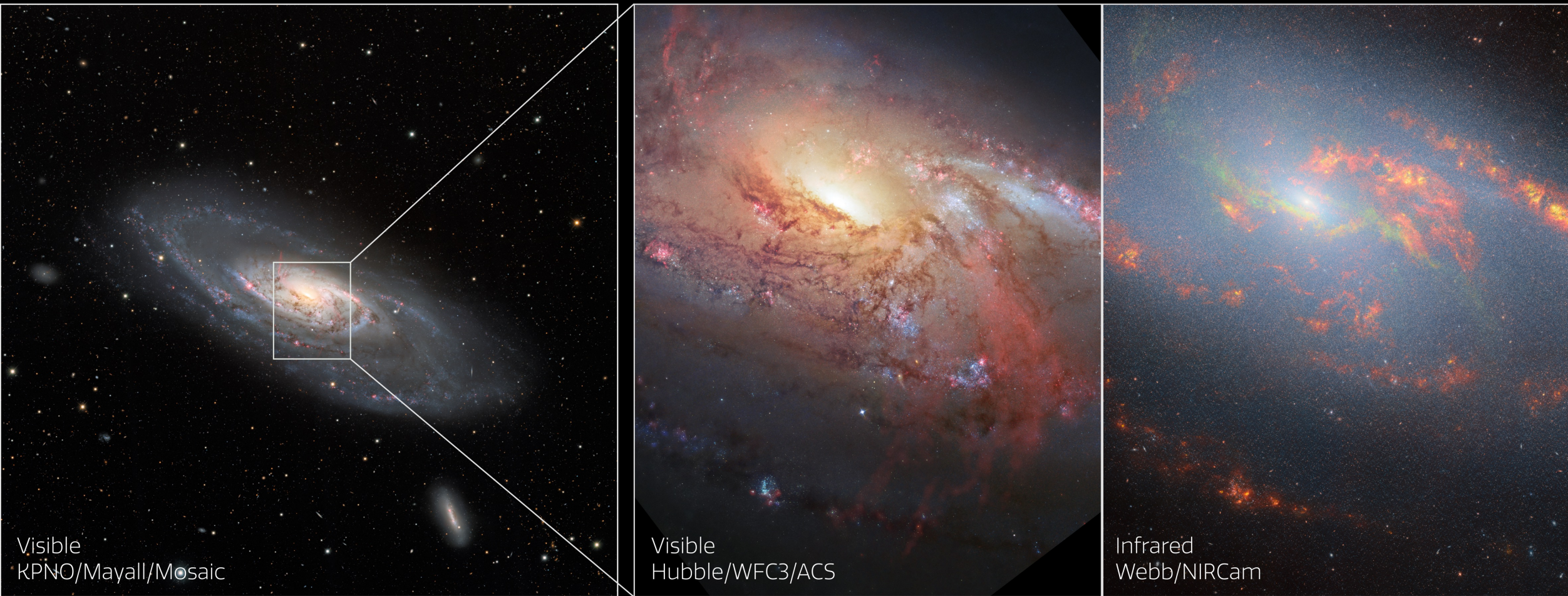
120 kpc

... and beyond ...

NGC6822

500 kpc





Visible
KPNO/Mayall/Mosaic

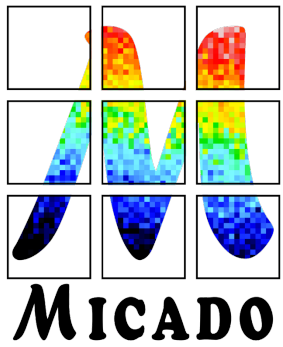
Visible
Hubble/WFC3/ACS

Infrared
Webb/NIRCam

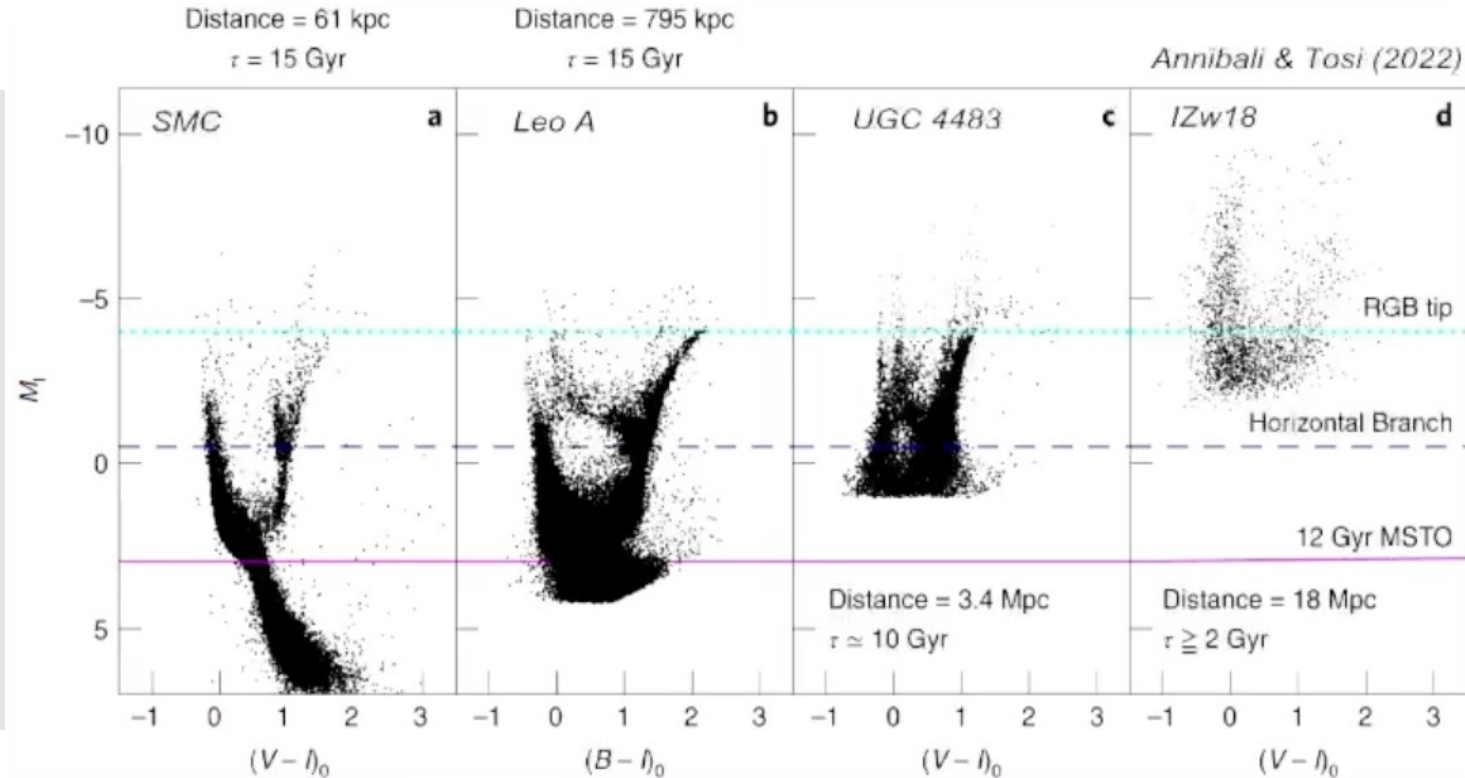
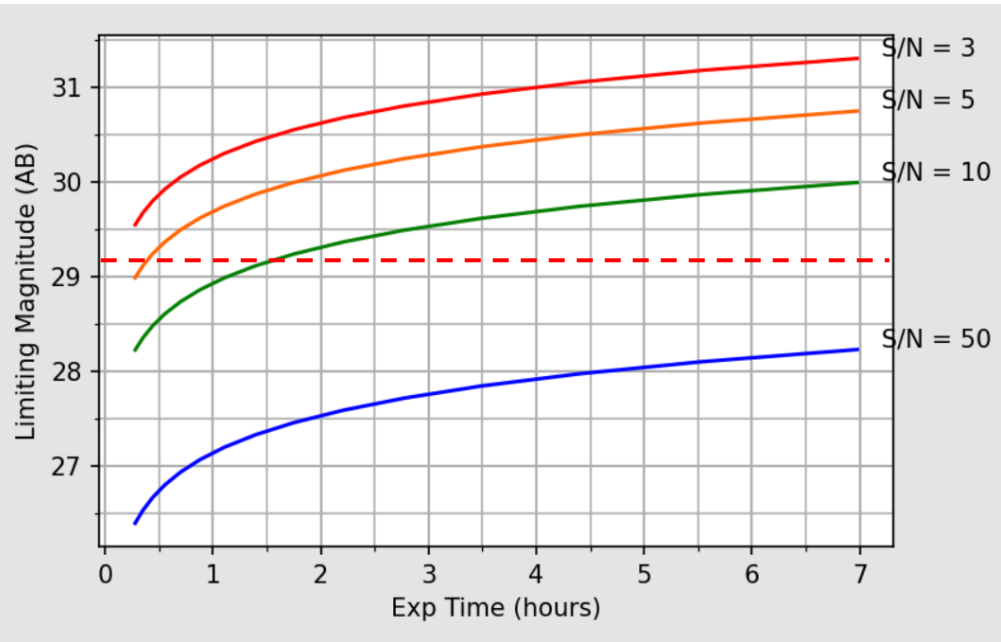
NGC 4258

- A cornerstone of the SHoES distance ladder and the only geometric anchor observed by JWST. These observations further refine the cosmic distance scale and our understanding of the H_0 tension.

Can we observe NGC4258 ?



- Red dashed lines indicate the predicted J and H magnitude levels for RR Lyrae stars based on the distance modulus of NGC 4258.



- HB Visibility vs. Distance: Comparison between 4 Mpc and 18 Mpc. Dedicated simulations for NGC 4258 (7.6 Mpc) are now required.

Summary

- RR Lyrae stars are powerful tracers of ancient stellar populations and key Population II distance indicators.
- New Gaia and NIR PWZ relations provide accurate and robust distance estimates with reduced reddening effects.
- Future facilities such as James Webb Space Telescope, Nancy Grace Roman Space Telescope and Extremely Large Telescope will enable RR Lyrae studies in external galaxy halos.
- Detecting RR Lyrae in NGC 4258 would provide an important independent anchor for the cosmic distance ladder and for investigations of the Hubble tension.



Early Formation and Evolution of the Bulge and Halo (EFEBHO)
The Greek artist Polykleitos, XXV centuries ago, wrote in a book "Canon" the rules for the ideal beauty (Pliny the Elder, Nat. Hist., XXXIV, 8). Polykleitos was mainly interested in the mathematical proportions of the human body and in the balance of the standing figures. To improve the stillness of the statues He introduced the "chiasmus" (from the greek letter χ) in which the young athlete has one lower limb flexed and the upper limb on the opposite side stretched, and vice versa. A perfect realisation of these rules is the Etehebos (Charistoteer) at the Whitaker Museum in Motya.



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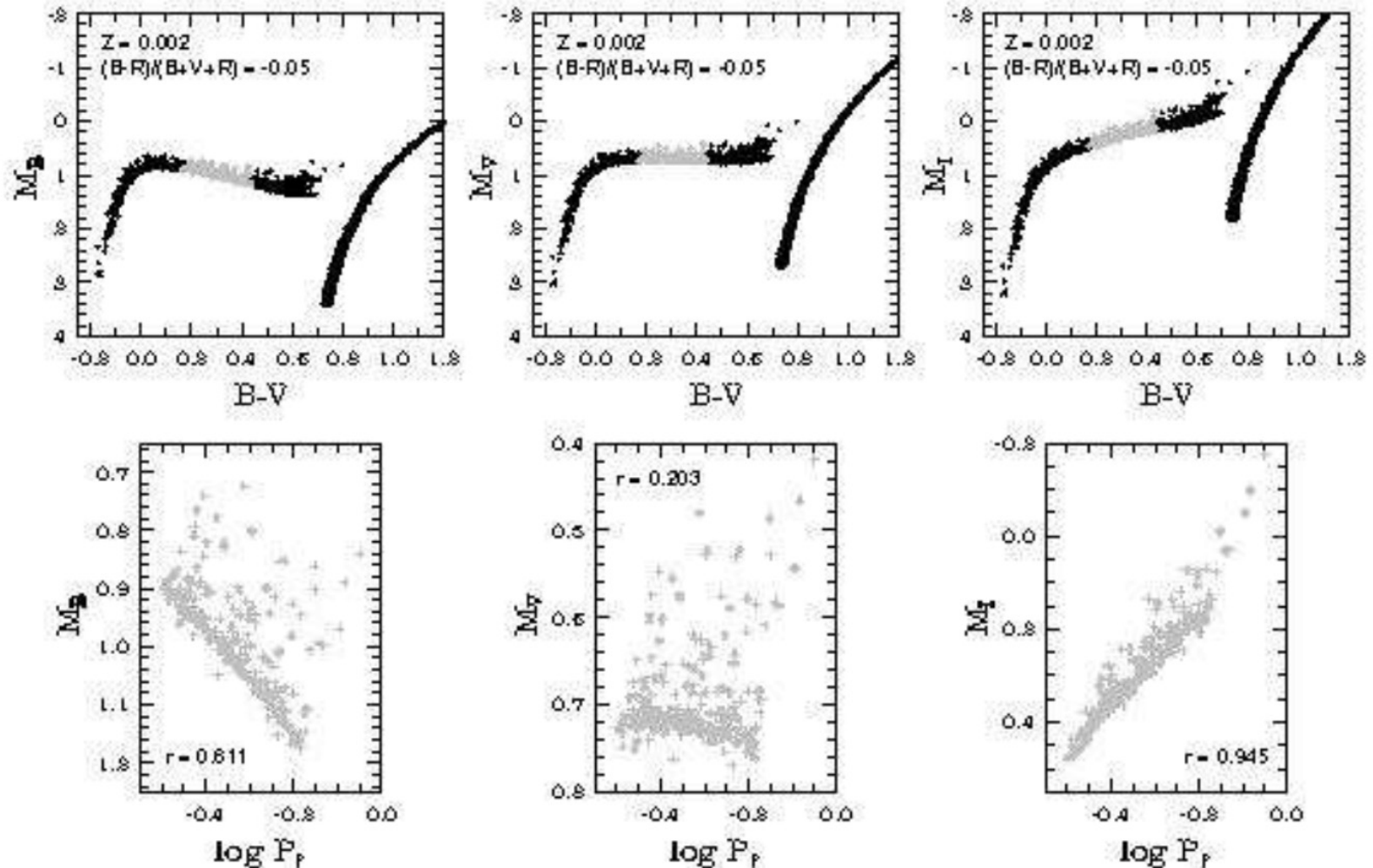


PL relations:

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- From the pulsation properties, we are able to infer a Period-Luminosity relation (PL) in near-infrared bands (JHK).
- The PL slope increases from the optical to the JHK bands because bolometric corrections are much less sensitive to temperature in the infrared.

$$M_{JHK} = \alpha + \beta \cdot \log_{10}(P)$$



Distance: Period-Wesenheit-Metallicity relation

A limitation is that some of these surveys do not collect multi-epoch spectra.

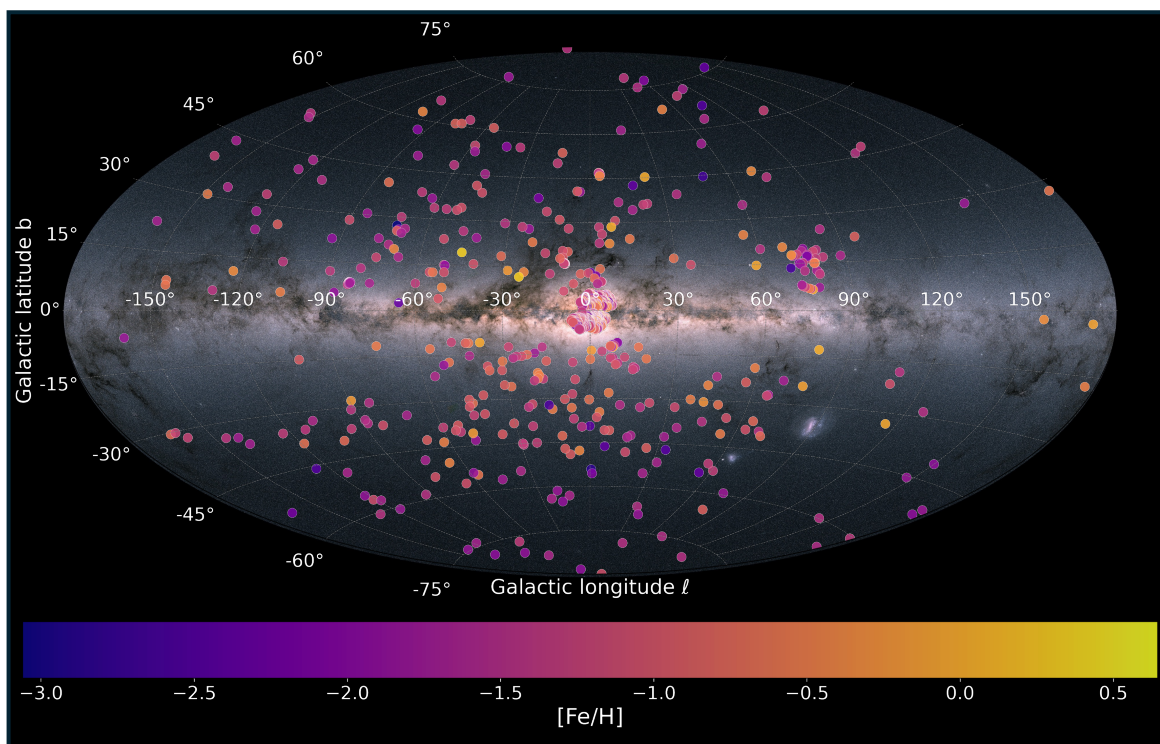
This happens because the RR Lyrae star is observed at an arbitrary phase of its pulsation, which could correspond to a shock event, so [Fe/H] could be not accurate.

$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

$$w_G = G - \lambda(BP - RP)$$

$$d = 10^{\frac{w_G - W_G + 5}{5}}$$

$$\lambda = \frac{A(G)}{E(BP-RP)} = 1.9$$



Ripepi et al. 2019

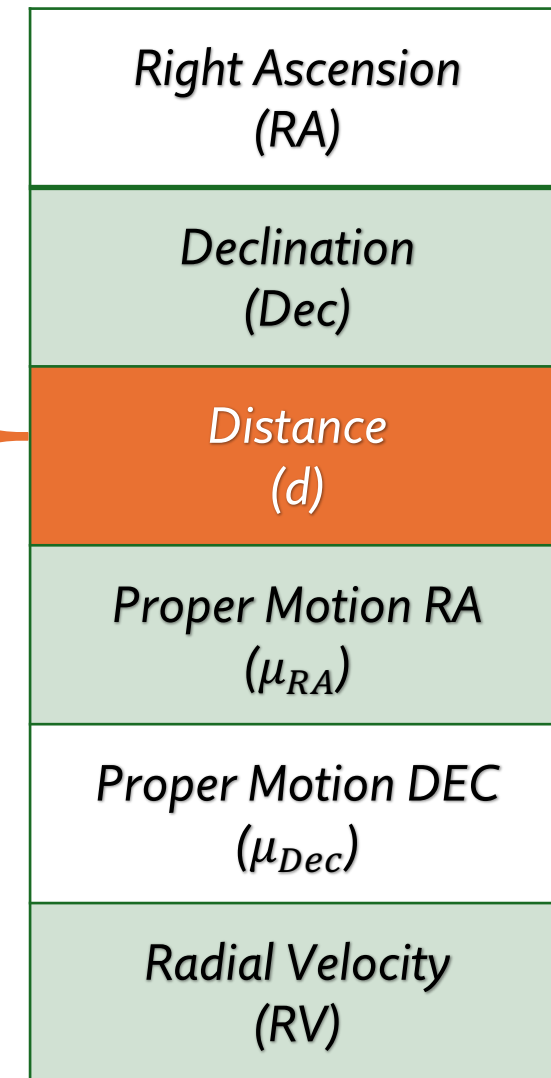
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- Nemeč et al. 2013



- log(g) < 1.5
- log(g) > 3.5
- T_{eff} < 5500
- T_{eff} > 7500



Luongo et al. in prep.

Distance: Period-Wesenheit-Metallicity relation: Astrometric Based Luminosity (ABL) method

$$W_G = \alpha + \beta \cdot [\log_{10}(P) + 0.3] + \gamma \cdot [Fe/H]$$

$$ABL = \varpi 10^{0.2m-2} = 10^{0.2(\alpha+(\beta+\delta[Fe/H])(\log P-\log P_0)+\gamma[Fe/H])}$$

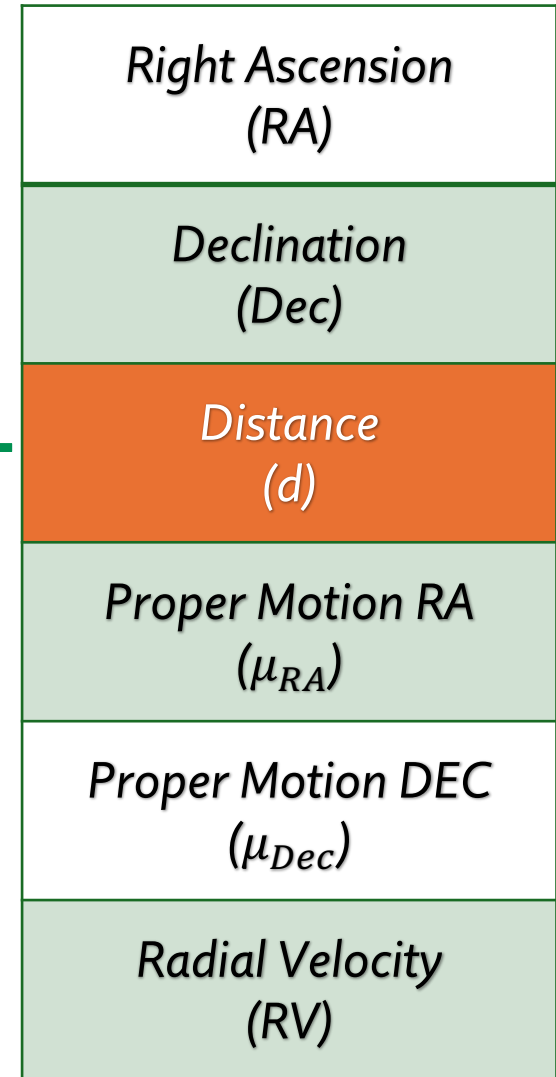
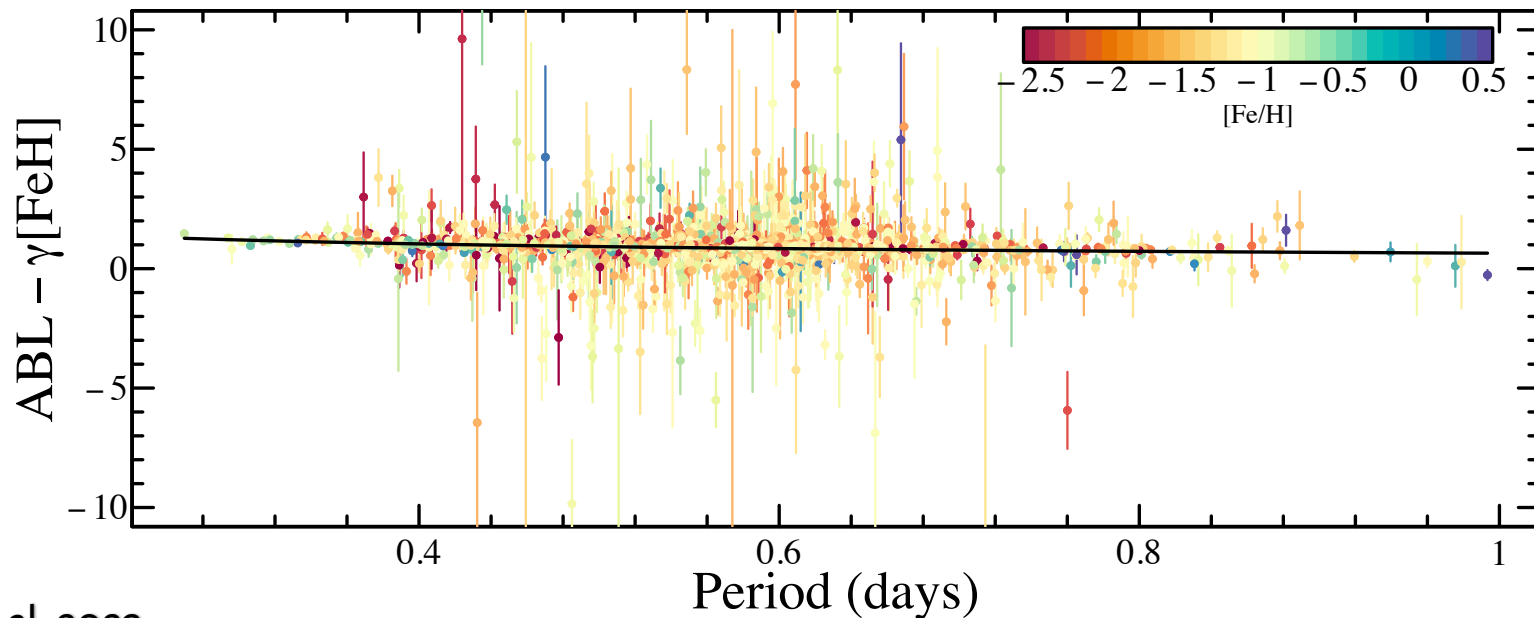
- Implicit fit:

$$f = 10^{0.2(\alpha+(\beta+\delta[Fe/H])(\log P-\log P_0)+\gamma[Fe/H])} - (\varpi + \epsilon)10^{0.2m-2} = 0,$$

- Nonlinear fit:

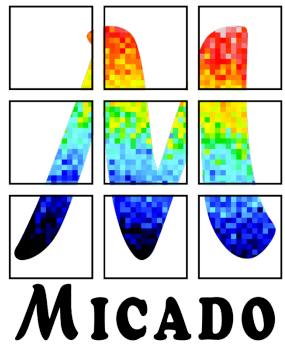
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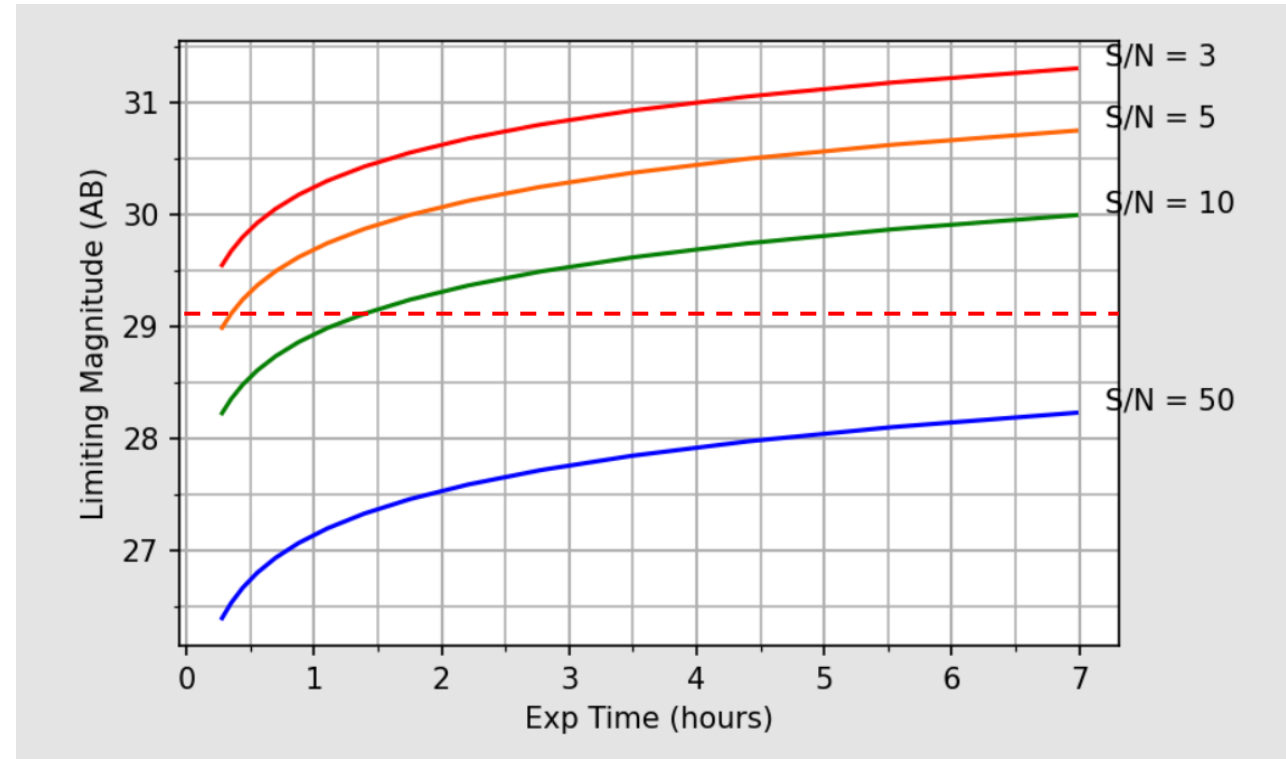
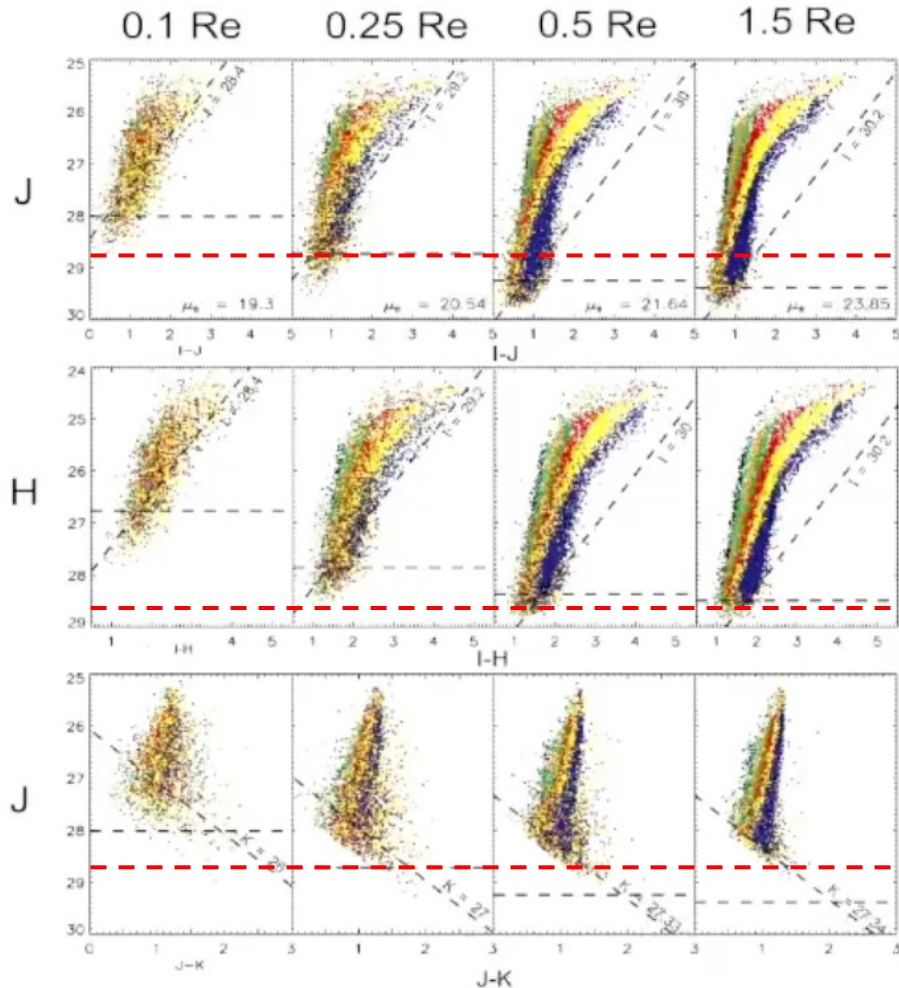


Luongo et al. in prep.

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