Metallicity dependence of Classical Cepheids Period-Luminosity relations and the extragalactic distance scale

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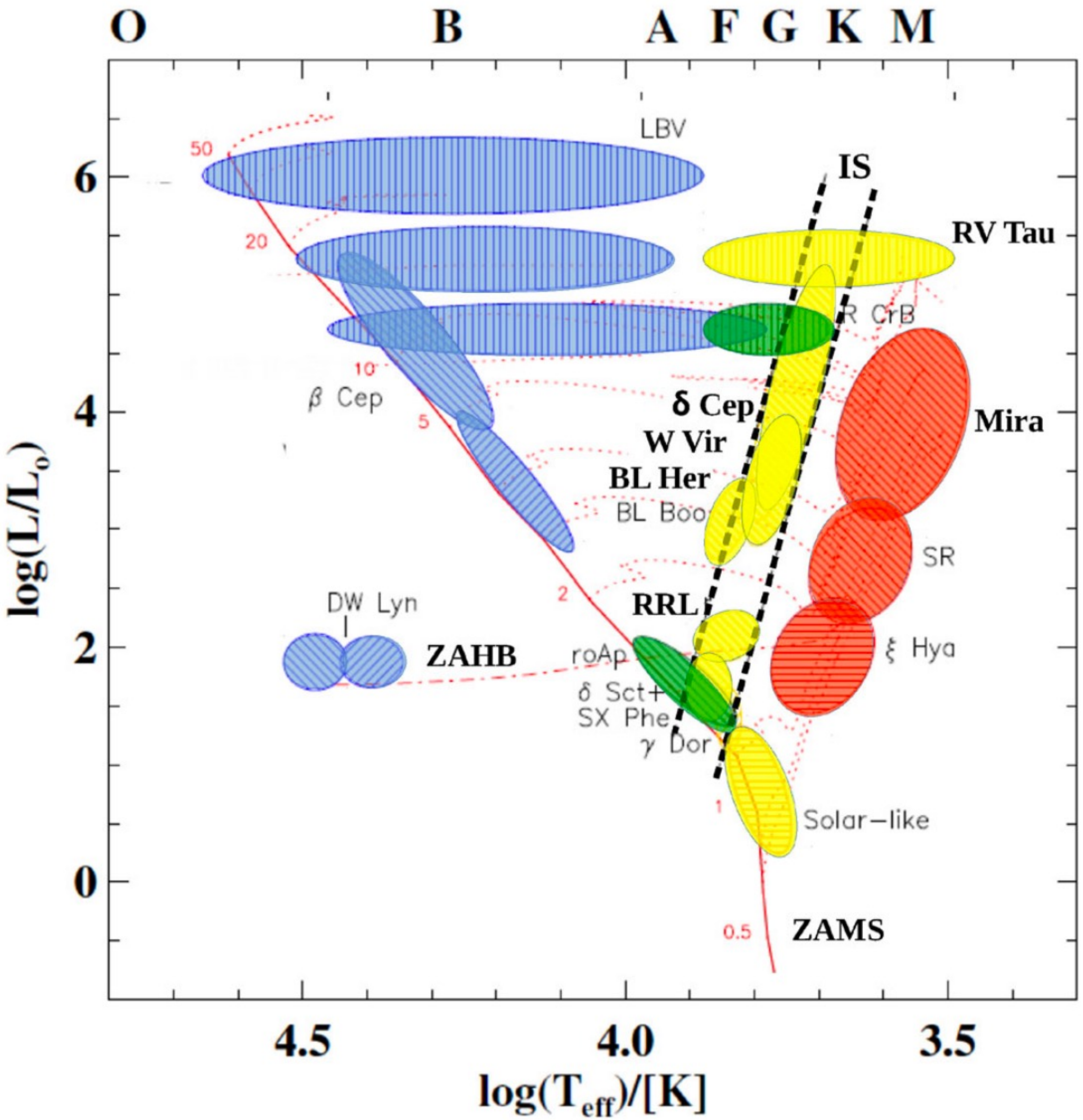
Outline

- Cepheid properties and their use
- Motivation for studying the metallicity dependence of the PLR
- C-MetaLL project
- Present baseline results
- Future improvement

Classical Cepheid



Classical Cepheids:

Central helium burning stars

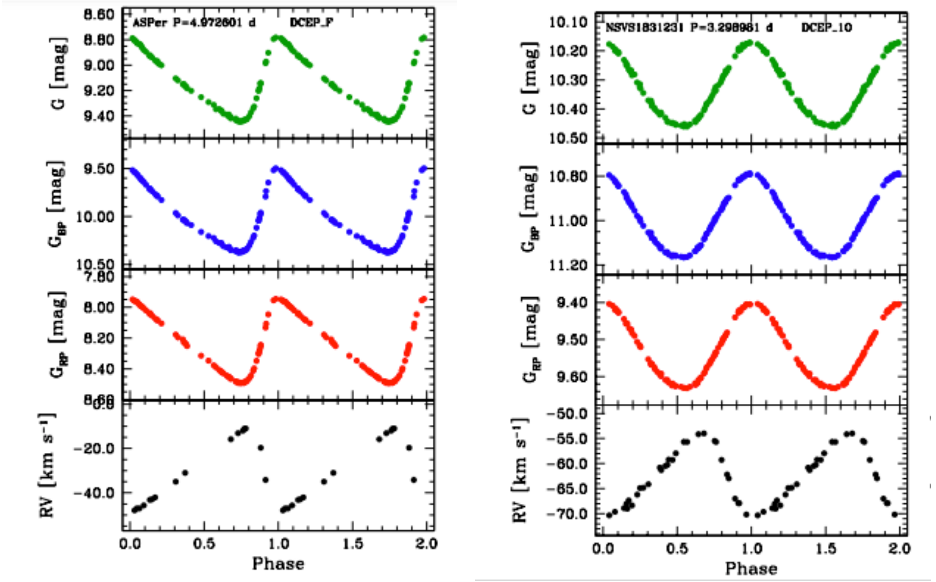
M=3÷13M$_\odot$

M$_V$= -2÷- 7 mag

P=0.2÷100 d

Ages: 50÷500 Myrs

Pulsate in F, 1O, 2O, Multiple modes.



Fundamental 1rst overtone

Ripepi et al. 2023

Why Cepheids are important? The discovery of the period-luminosity relation

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 173.

PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt.

Leavitt & Pickering (1912)

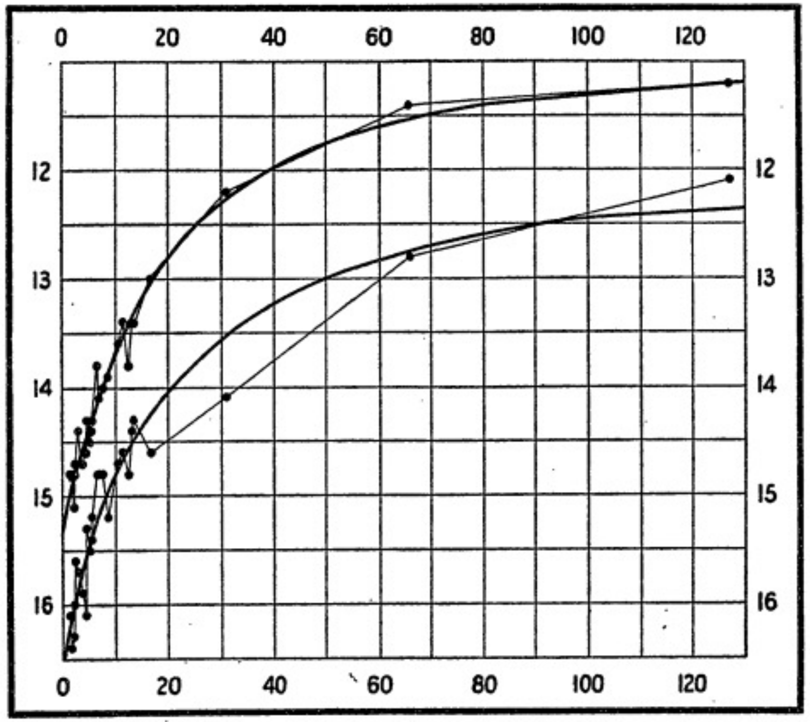


FIG. 1.

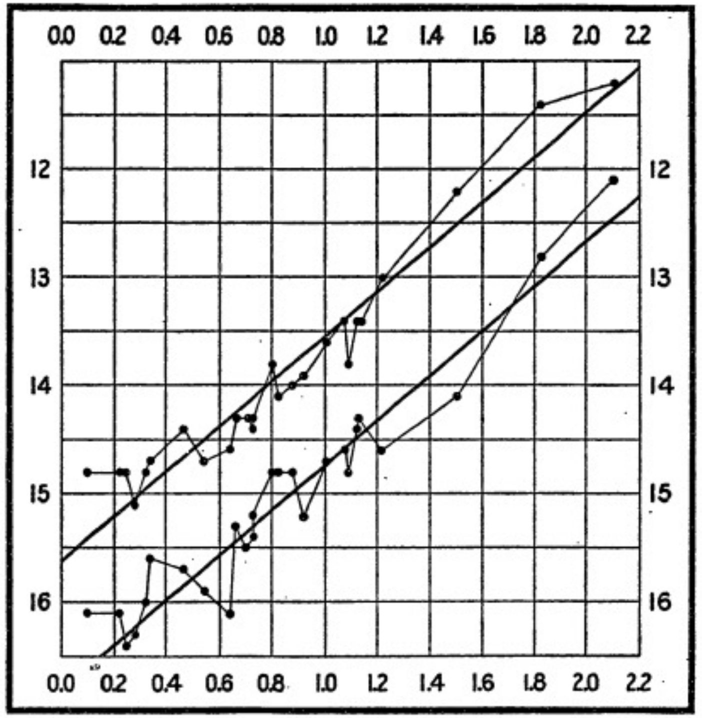


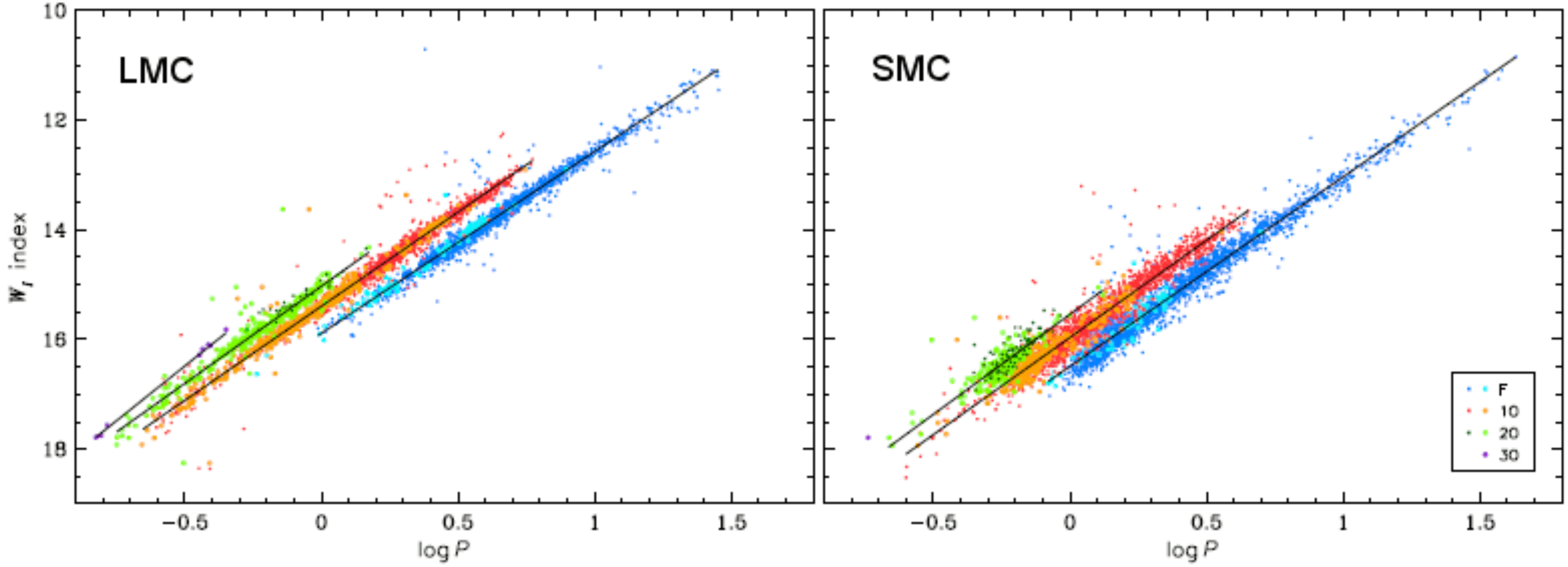
FIG. 2.

1. A straight line can readily be drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the variables and their periods.

H. Leavitt

Modern version of the Leavitt law

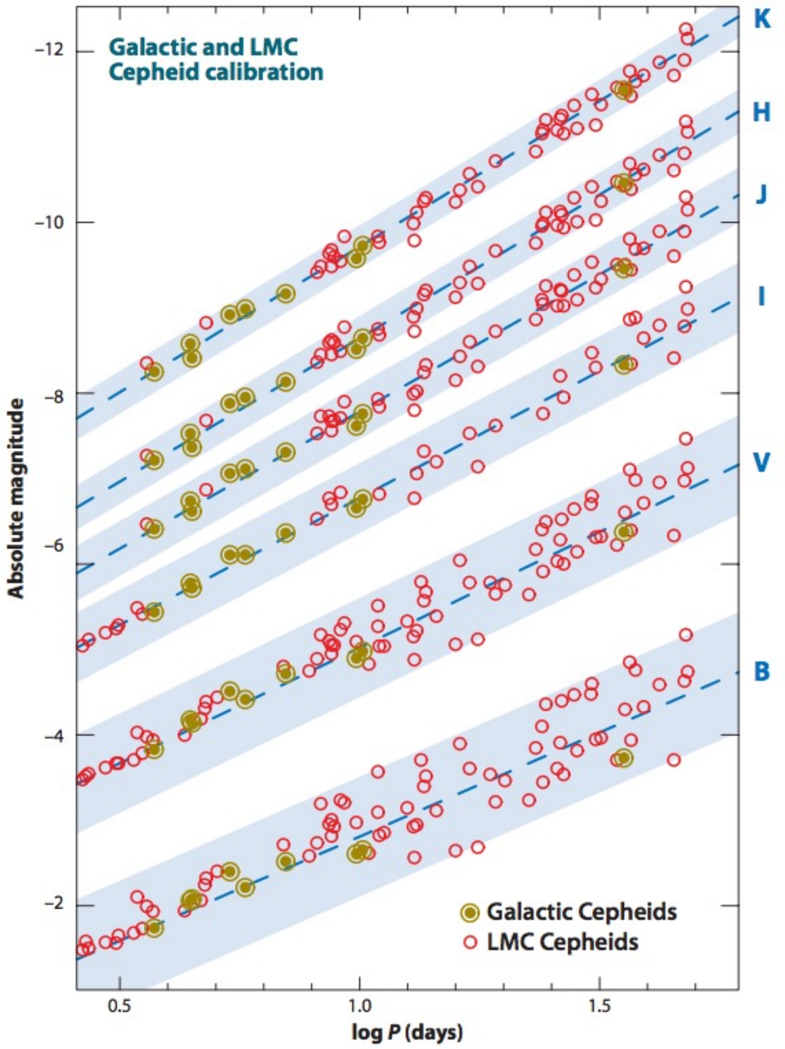
Tight PL relations in different modes



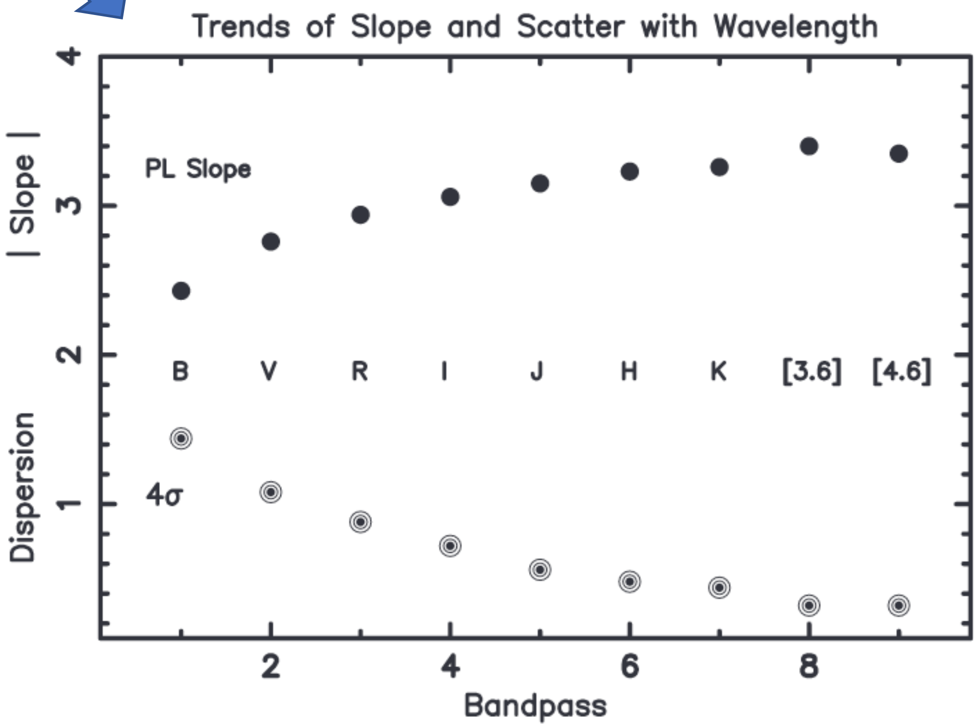
OGLE IV survey; Soszyński+2016

Properties of the PL relations

The slope of the Leavitt Law increases with increasing wavelength, with a corresponding decrease in dispersion.



Freedman & Madore (2010)



Madore & Freedman (2012)

The Wesenheit magnitudes

To bypass the reddening problem, in 1982 B. Madore introduced the so-called Wesenheit magnitudes *W* (Wesenheit is a German word meaning "essence", "real nature".
We adopt the V,I band as an example (any combination of magnitudes/colors can be used).
In this case, the ratio of total-to-selective absorption is $R_{VI} = A_V / E(V - I)$,

$$\boxed{W = V - R_{VI} \times (V - I),} \tag{10}$$

as well as an intrinsic Wesenheit magnitude, W_o:

$$W_o = V_o - R_{VI} \times (V - I)_o . \tag{11}$$

By construction,

$$W = V_o + A_V - R_{VI} \times (V - I)_o - R_{VI} \times E(V - I) \tag{12}$$

$$= V_o - R_{VI}(V - I)_o + A_V - R_{VI} \times E(V - I), \tag{13}$$

where $V = V_o + A_V$ and $(V - I) = (V - I)_o + E(V - I)$, and $A_V = R_{VI} \times E(V - I)$, thereby reducing the last two terms to zero, leaving $W = V_o - R_{VI} \times (V - I)_o$, which is equivalent to the definition of W_o.

Wesenheit magnitudes are reddening free ! → huge reduction of the uncertainty on the measure of H_0

Particularly important the Wesenheit magnitude in the HST filters used by the SH0ES team to estimate H_0: W_{HST} =F160W (H) - 0.386 (F555W (V) -F814W (I))

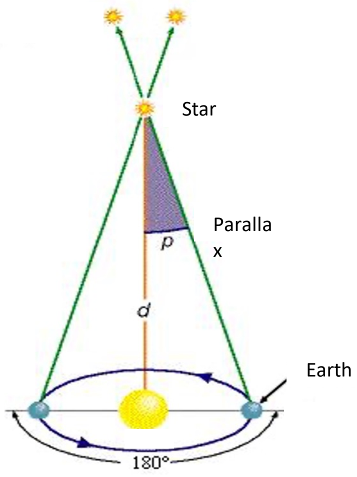
Classical Cepheids are Standard Candles (term introduced by H. Leavitt)

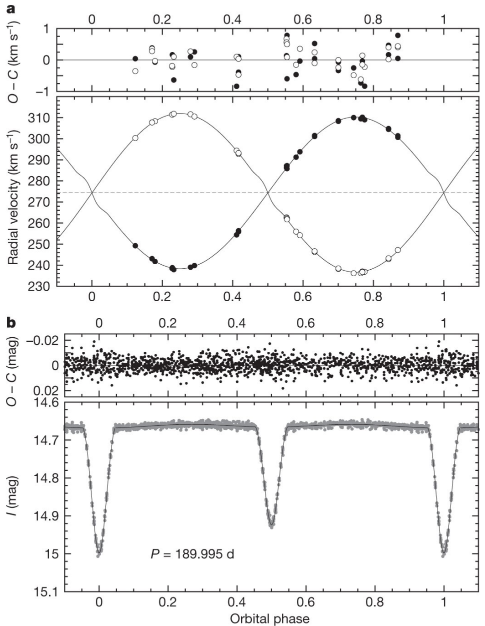
- Astronomical objects whose intrinsic brightness (absolute magnitude) is known → distance !

$$m - M = -5 + 5log_{10}\,\mathrm{D} \qquad \text{(D in parsec)}$$

Cepheids → PL relations: $M = a + b\ logP$

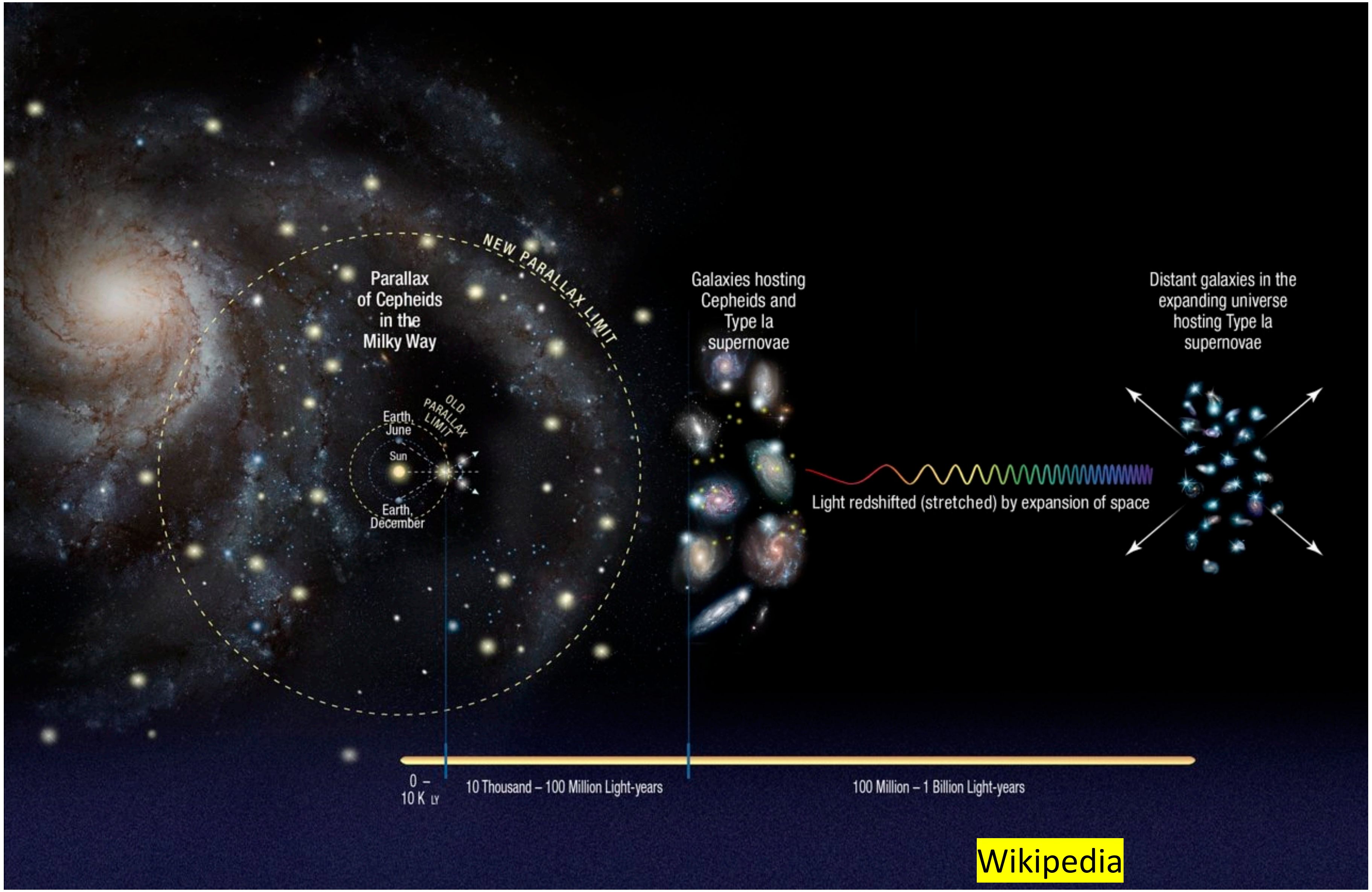
"a" must be calibrated with geometric methods (e.g. parallaxes, detached eclipsing binaries)





Pietrzyński+2013

The «distance ladder» to measure H_0: a three step process



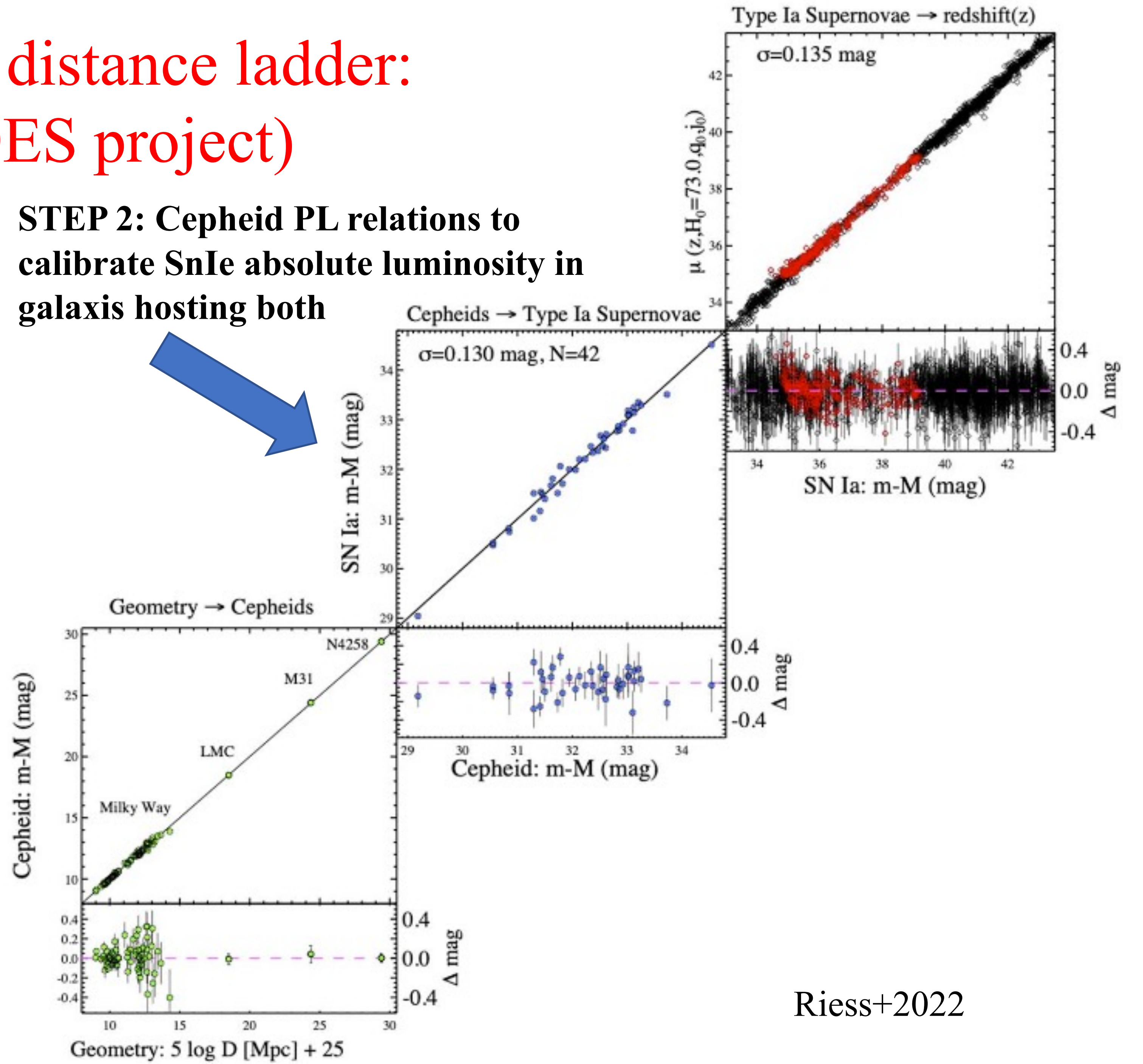
Wikipedia

Cepheids and the cosmic distance ladder: a three step process (SH0ES project)

STEP 1: Geometric distances to calibrate the PL relation of Cepheids:

- Parallaxes in the MW (HST, Gaia)
- Distance of LMC from DEBs
- Distance of NGC4258 from masers orbiting central supermassive black hole

STEP 2: Cepheid PL relations to calibrate SnIe absolute luminosity in galaxis hosting both

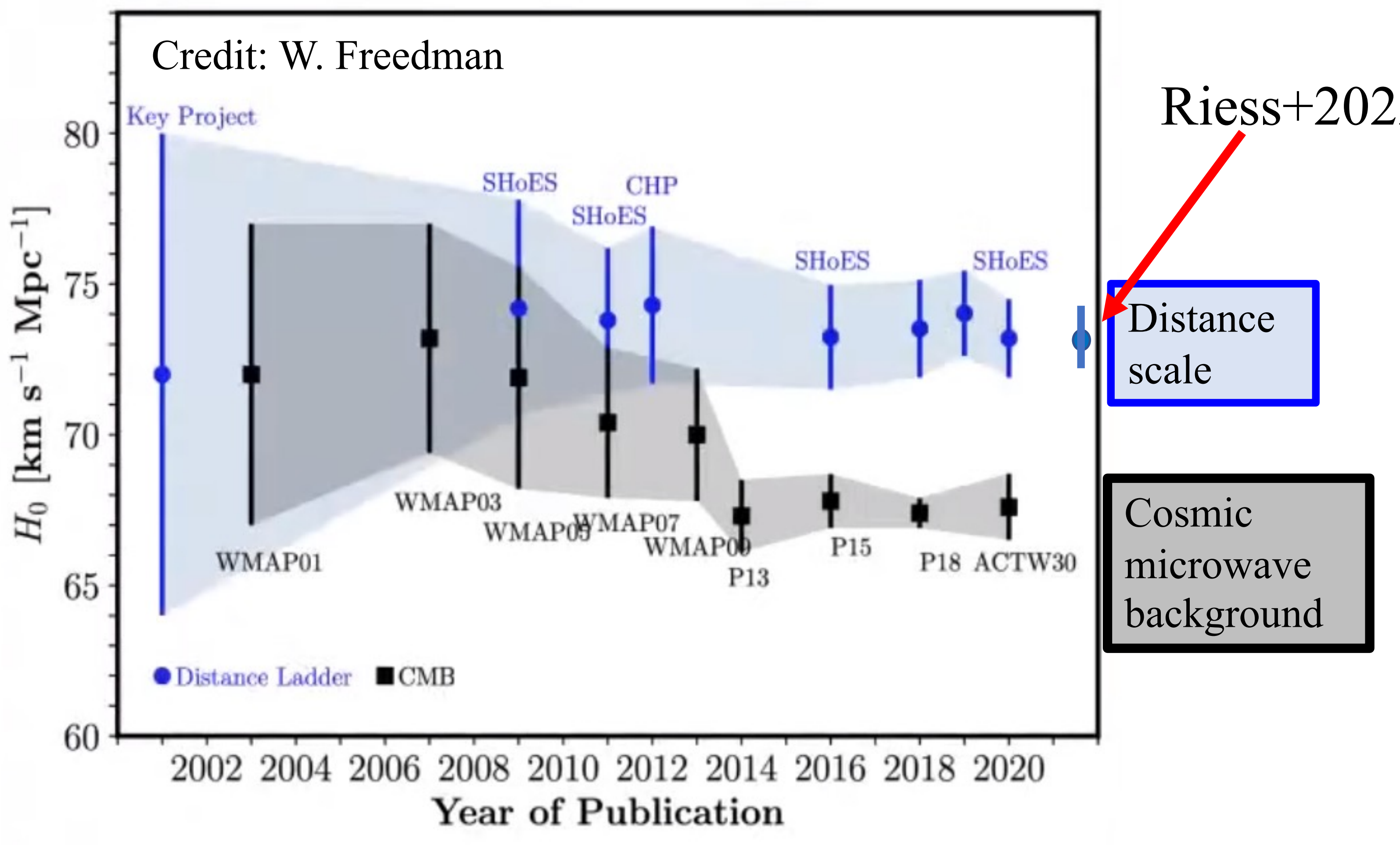


Strong assumption:
Universal PL relations

W_{HST} =F160W-0.386 (F555W-F814W)

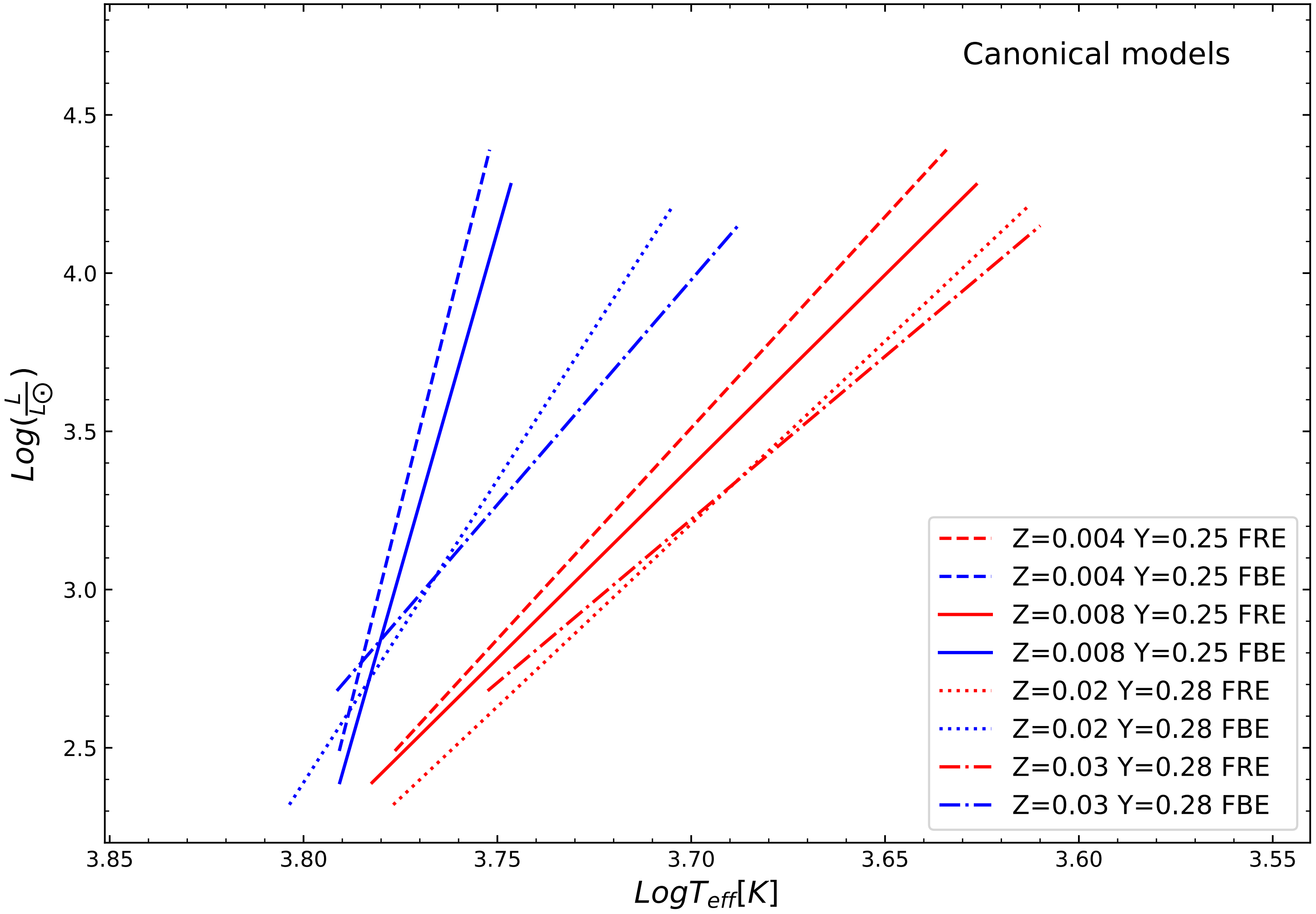
Riess+2022

Hubble tension



<u>**All the sources of systematic errors in the cosmic distance scale must be analysed. One of these is the metallicity dependence of PL**</u>

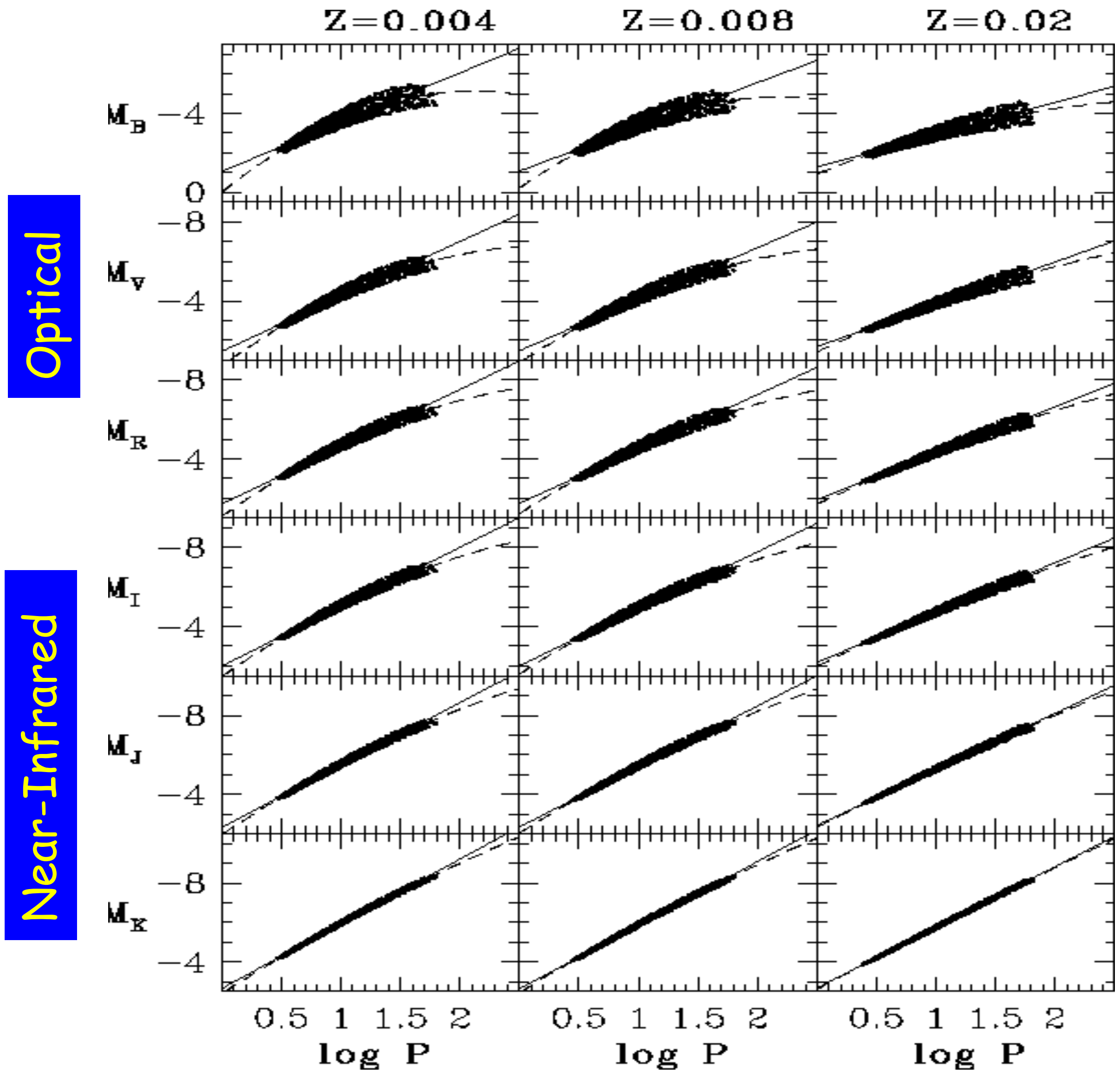
Period-Luminosity dependence on metallicity: Pulsation Theory



The Cepheids instability strip shifts towards cooler temperatures as the metallicity increases → impact on the PLRs

De Somma, Marconi et al. 2022 ApJS

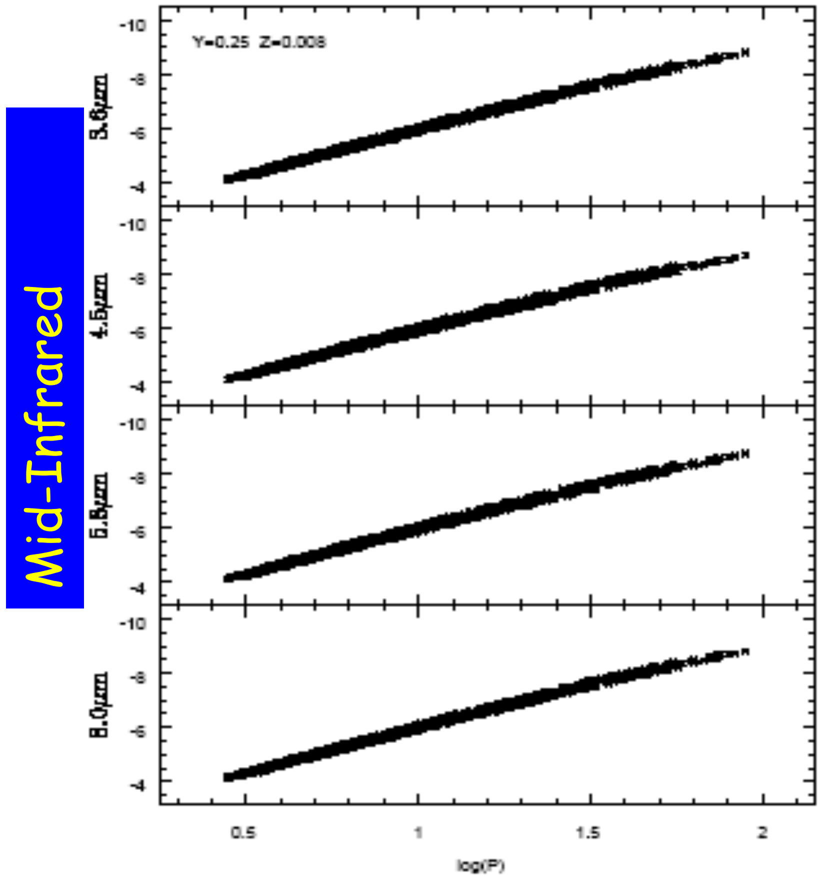
Synthetic multiband PL relations



Caputo et al. 2000 A&A

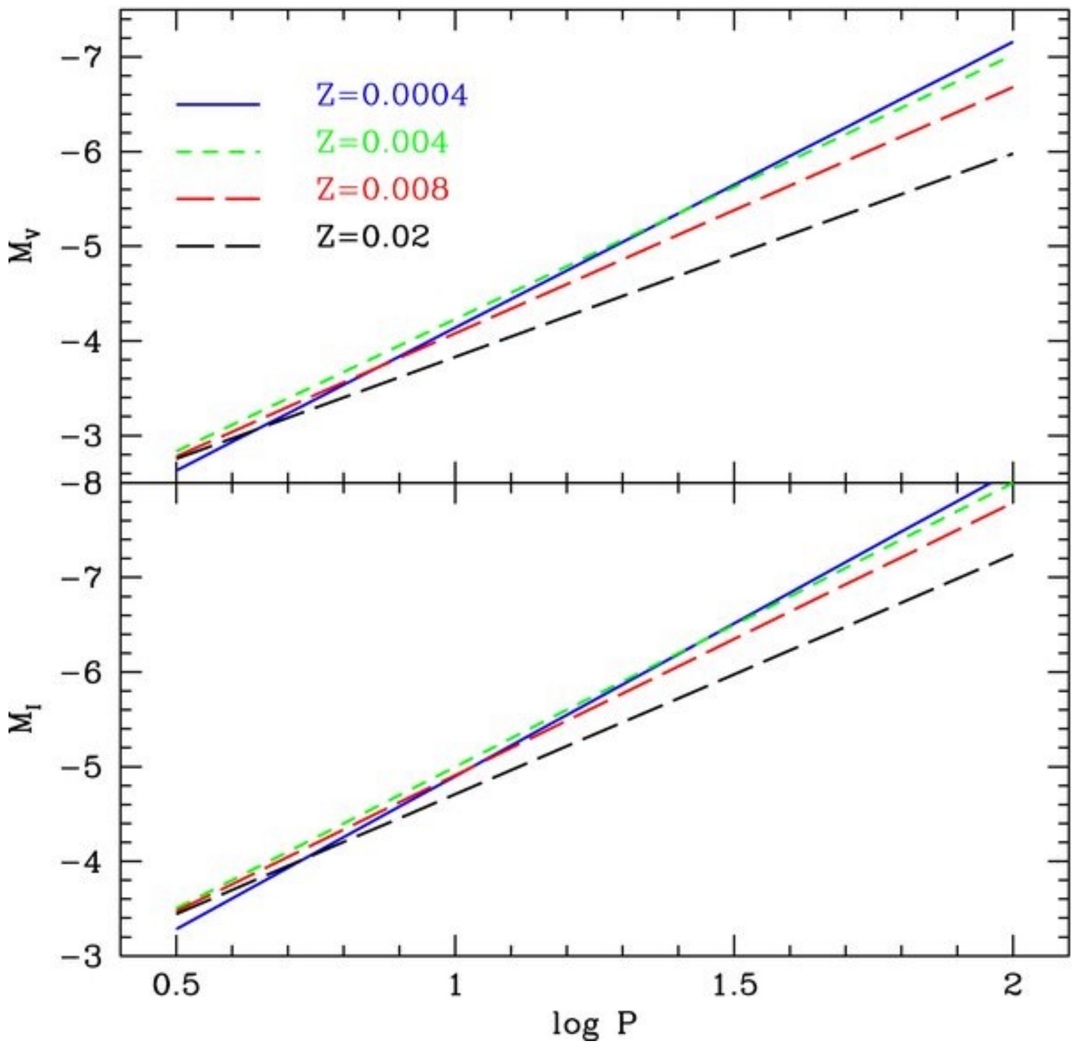
Synthetic multifilter PL relations

The effect reduces when moving towards longer wavelenghths



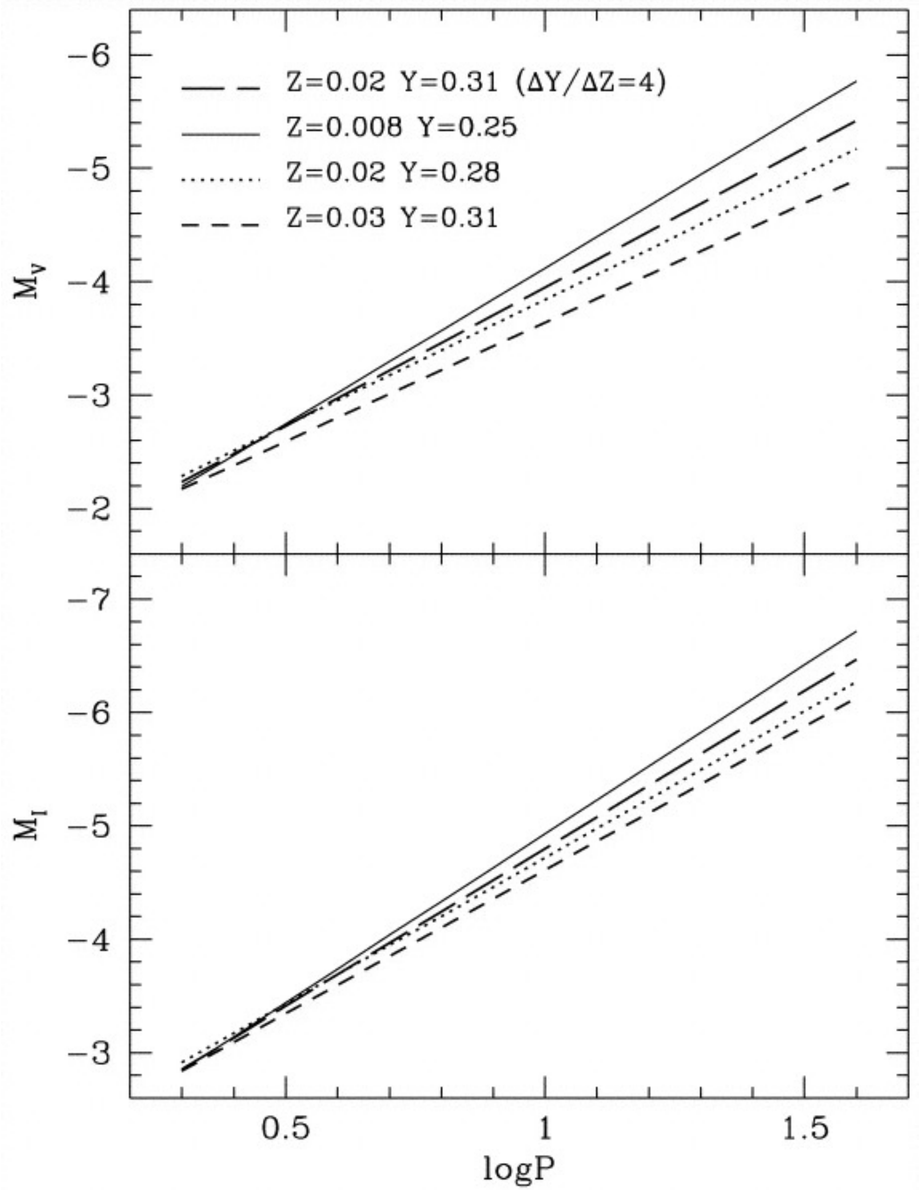
Universal slope?

- The Cepheids‘ PL relation is often considered “Universal“, for example the same slope is used for all the galaxies
- However, models predict different slopes at different metallicities.
- Smaller effect at low metallicities
- Smaller effect at longer wavelenghts



Marconi et al. 2010 ApJ (in agreement with results from the Araucaria project)

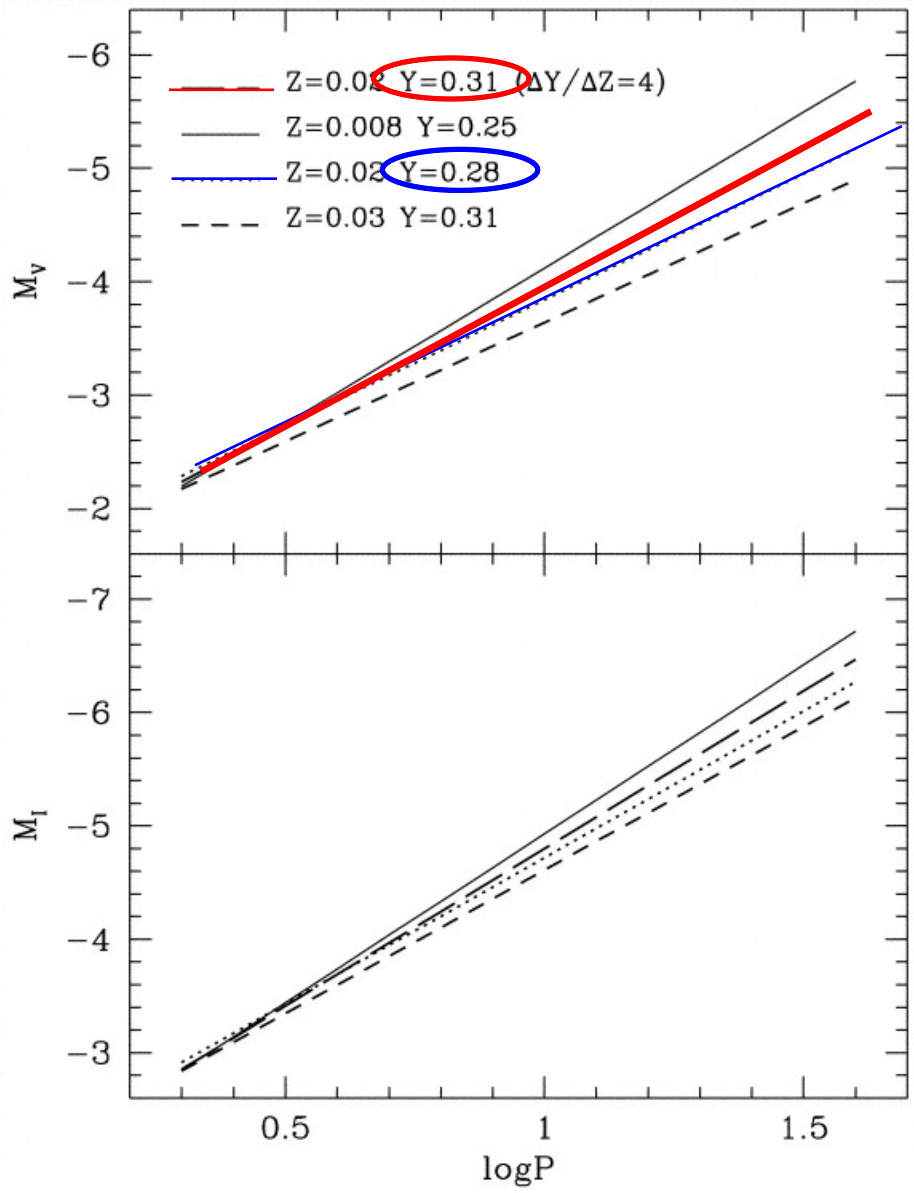
Dependence of Cepheid properties on Helium abundance → ΔY/ΔZ



The slope decreases as Z increases at fixed ΔY/ΔZ

Fiorentino et al. 2002 ApJ, Marconi et al. 2005 ApJ

Dependence of Cepheid properties on Helium abundance → ΔY/ΔZ



The slope decreases as Z increases at fixed ΔY/ΔZ

The slope increases as Y increases at fixed Z

As Z increases the PL gets flatter !!

As Y increases the PL gets steeper !!

Fiorentino et al. 2002 ApJ, Marconi et al. 2005 ApJ

Parametrization of the metallicity dependence of PLRs

The most general formulation uses four parameters, to take into account the possible metallicity effect on the slope of PLRs, which is predict by the models

$$M_\lambda = \alpha_\lambda + (\beta_\lambda + \delta_\lambda[Fe/H])\log P + \gamma_\lambda[Fe/H]$$

As this effect is mitigated at longer wavelength, usually δ_λ is ignored.

$$M_\lambda = \alpha_\lambda + \beta_\lambda \log P + \gamma_\lambda[Fe/H]$$

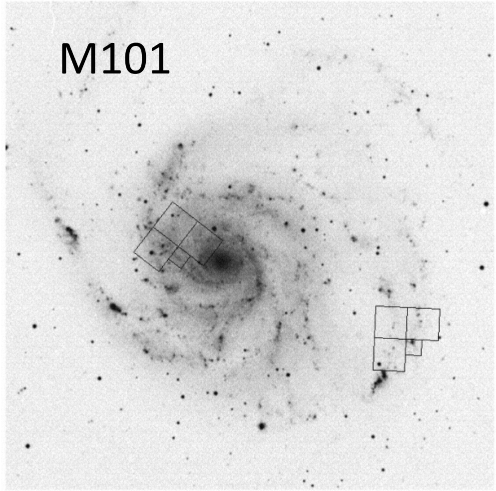
Intercept

Slope

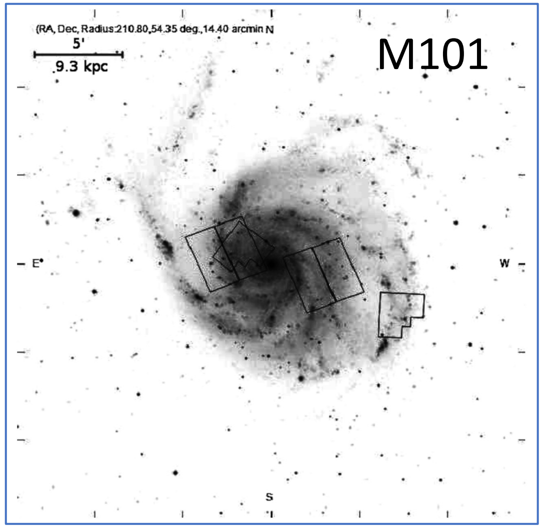
Metallicity term

Empirical tests for metallicity effect

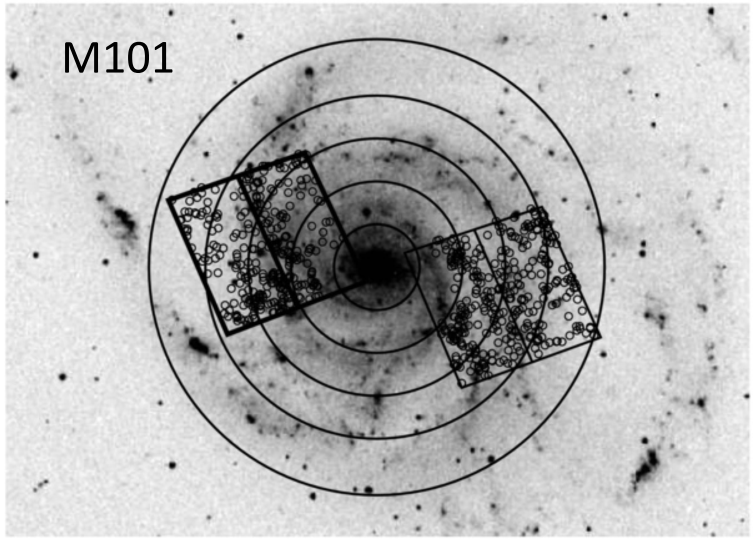
Several tests of the metallicity effect based on e.g.
the comparison between Cepheids belonging to 2 fields with different metallicity in the same galaxy.
The metallicity is estimated from the radial gradient of [O/H] measured in HII regions.



Kennicut et al. 1998
$\Delta\mu/\Delta[O/H]$ =
-0.24 ± 0.16 mag dex^{-1}



Shappee & Stanek 2011:
$\Delta\mu/\Delta[O/H] = -0.76\pm0.3\pm0.2$ mag dex^{-1}



Mager et al. 2013:
$\Delta\mu/\Delta[O/H] = -0.33$ mag dex^{-1}

$[O/H] \simeq [Fe/H] + 0.09$ dex (Romaniello+2022)

Metallicity dependence in the SH0ES project

γ

$$\mu_{0,i} = m^W_{i,H} - (M^W_{H,1} + b_W (\log P_i - 1) + Z_W \Delta[\mathrm{O/H}]_i),$$

W_{HST} =F160W-0.386 (F555W-F814W)

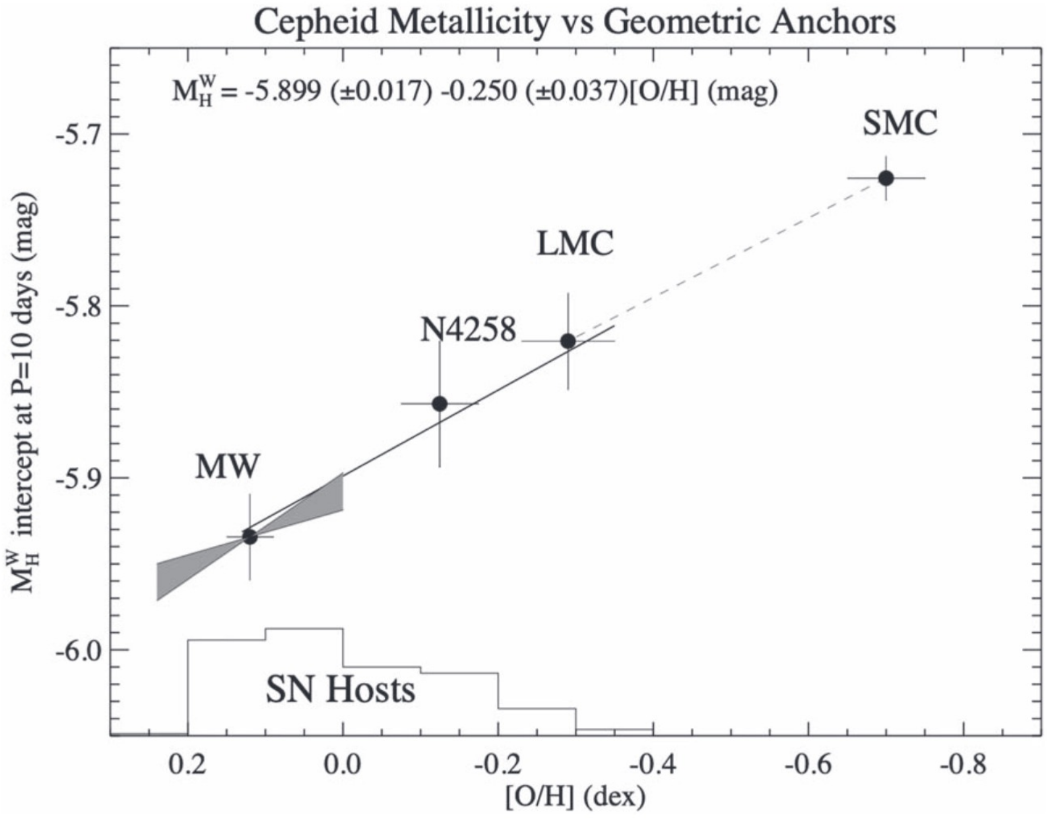
In the SH0ES project the metallicity dependence is a result of the multi-parameter fit; δ is neglected, the slope is the same for all the galaxies.

Their baseline value is

$$\gamma = -0.217 \pm 0.046 \text{ mag/dex}$$

Riess+2022

Metallicity dependence in the SH0ES project

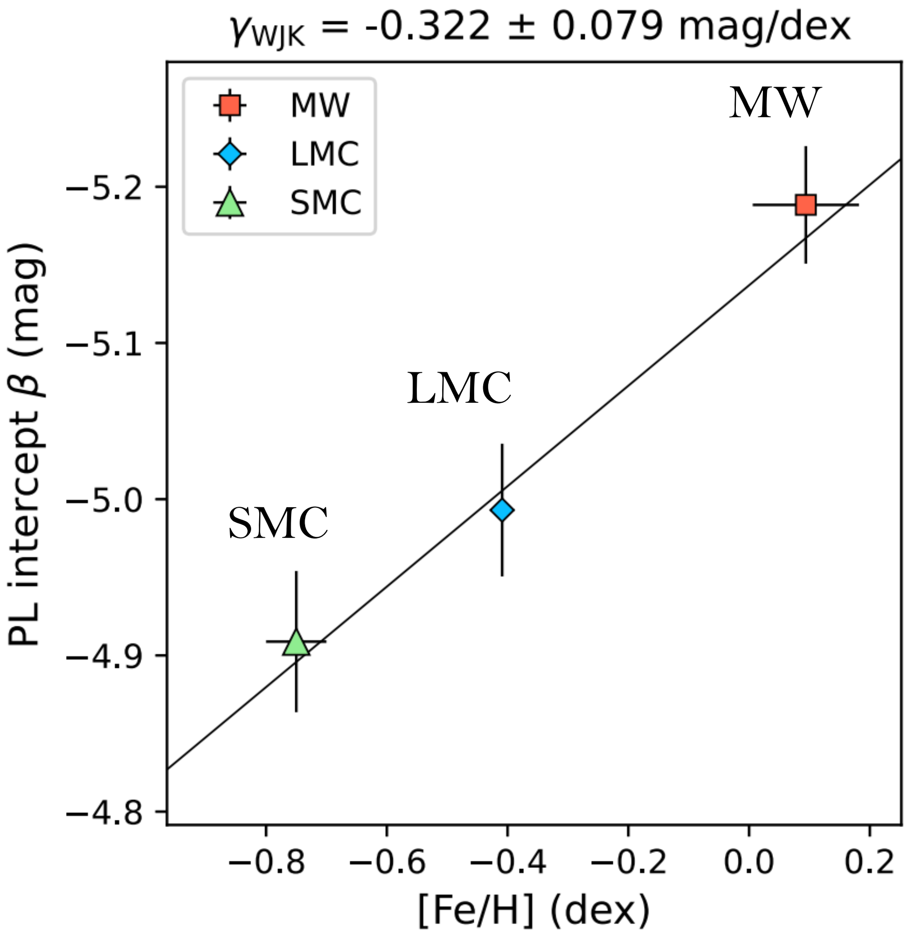


According to the SH0ES group, the metallicity problem should be mitigated by the fact that SNIa host galaxies have metallicities similar to those of the anchors.

Yet, to reach the 1% precision on H0, requires that we understand accurately the PLRs dependence on metallicity.

Riess+2022

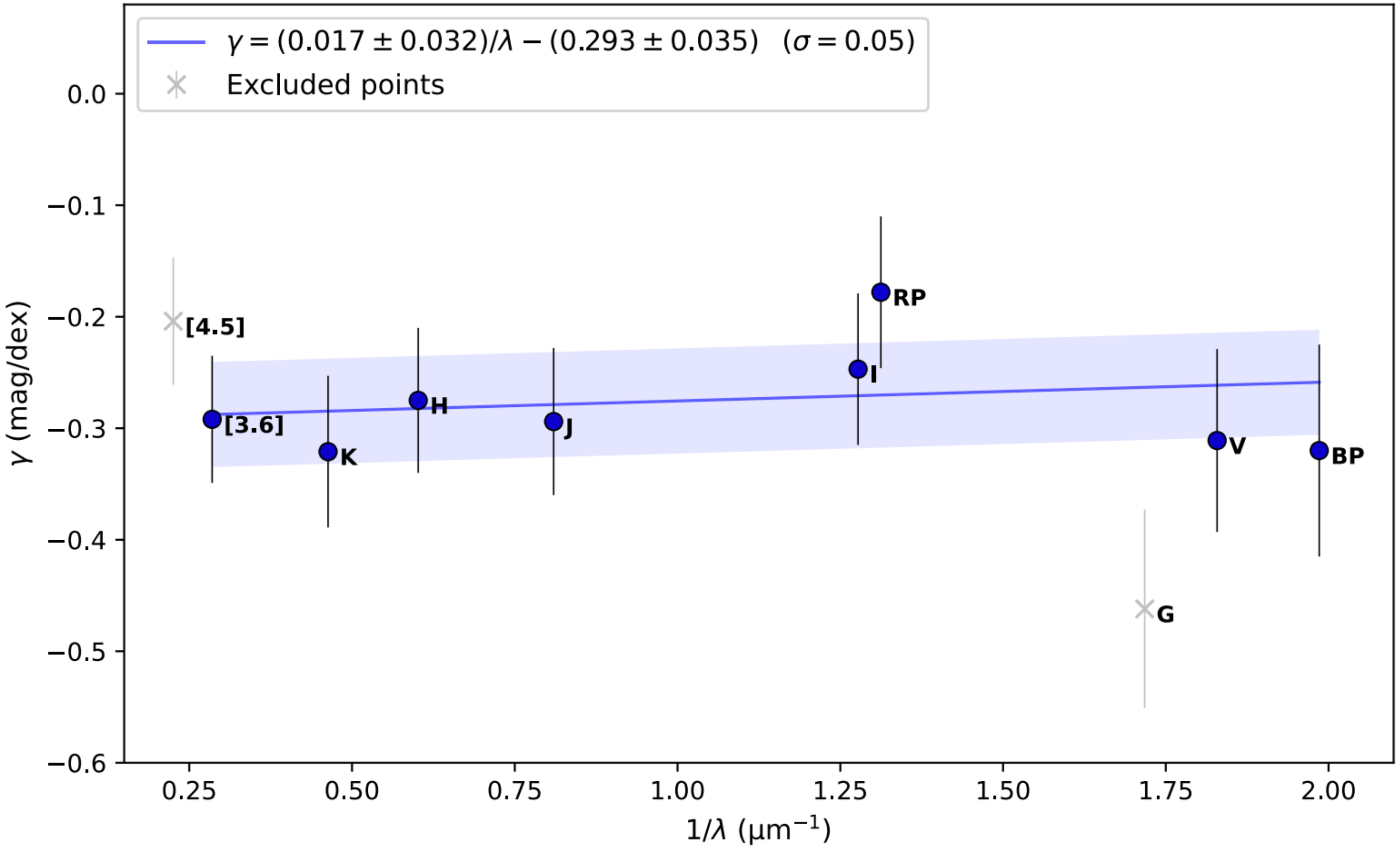
Metallicity dependence using, MW, LMC, SMC



- Multiband PL relation with the same slope in the MW, LMC and SMC: $\alpha * + \beta \times \log P$
- The value of "$\alpha *$" is fixed:
  - with the Gaia parallaxes in the MW for a sample of ~180 DCEPs close to the sun.
  - Geometric distances of LMC and SMC based on Detached Eclipsing Binaries (DEBs Pietrzyński+2019; Graczyk+2020)
- The MW is considered as "monometallic" ([Fe/H]=+0.08 dex). LMC and SMC metallicities from High-Res spectroscopy.
- $\alpha * = \alpha + \gamma\,[\frac{Fe}{H}]$

Breuval+2022

Metallicity dependence using, MW, LMC, SMC



γ in the interval -0.2:-0.35 mag/dex

Breuval+2022

Recent pulsation theory metallicity dependence estimates: Gaia Wesenheit G-1.90(GBP-GRP) and W_{HST}

γ

PWZ Coefficients in the Gaia EDR3 Filters ($W(G, G_{BP}\text{-}G_{RP}) = a + b(\log P - 1) + c\,[\mathrm{Fe/H}]$) for F and FO CCs Derived by Adopting the A, B, and C ML Relations and $\alpha_{ml} = 1.5$, 1.7, and 1.9

α_{ml}	ML	a	b	c	σ_a	σ_b	σ_c	σ	R^2
F									
1.5	A	−6.018	−3.314	−0.189	0.009	0.016	0.021	0.118	0.993
1.7	A	−6.072	−3.379	−0.129	0.010	0.016	0.021	0.090	0.996
1.9	A	−6.170	−3.472	−0.245	0.023	0.018	0.040	0.072	0.998
1.5	B	−5.853	−3.234	−0.190	0.011	0.016	0.022	0.139	0.991
1.7	B	−5.871	−3.262	−0.260	0.012	0.015	0.023	0.118	0.995
1.9	B	−5.968	−3.370	−0.189	0.026	0.017	0.047	0.092	0.997
1.5	C	−5.694	−3.270	−0.105	0.012	0.017	0.023	0.141	0.991
1.7	C	−5.722	−3.274	−0.140	0.012	0.015	0.022	0.116	0.994
1.9	C	−5.800	−3.327	−0.167	0.023	0.016	0.043	0.094	0.997

Table 20

PWZ Coefficients in the HST-WFC3 Filters ($W(\mathrm{F160W}, \mathrm{F555W{-}F814W}) = a + b(\log P - 1) + c\,[\mathrm{Fe/H}]$) for F and FO CCs Derived by Adopting the A, B, and C ML Relations and $\alpha_{ml} = 1.5$, 1.7, and 1.9

α_{ml}	ML	a	b	c	σ_a	σ_b	σ_c	σ	R^2
F									
1.5	A	−6.023	−3.340	−0.161	0.008	0.015	0.019	0.109	0.994
1.7	A	−6.060	−3.393	−0.135	0.010	0.015	0.020	0.085	0.997
1.9	A	−6.155	−3.484	−0.195	0.022	0.017	0.038	0.067	0.998
1.5	B	−5.858	−3.254	−0.125	0.010	0.015	0.021	0.129	0.993
1.7	B	−5.865	−3.280	−0.121	0.011	0.014	0.021	0.110	0.995
1.9	B	−5.952	−3.376	−0.136	0.025	0.016	0.045	0.088	0.997
1.5	C	−5.702	−3.274	−0.145	0.011	0.016	0.021	0.127	0.993
1.7	C	−5.717	−3.281	−0.130	0.011	0.014	0.020	0.104	0.995
1.9	C	−5.782	−3.329	−0.110	0.022	0.015	0.040	0.088	0.997

The predicted value of γ_λ varies in the range -0.11 : -0.26 mag/dex

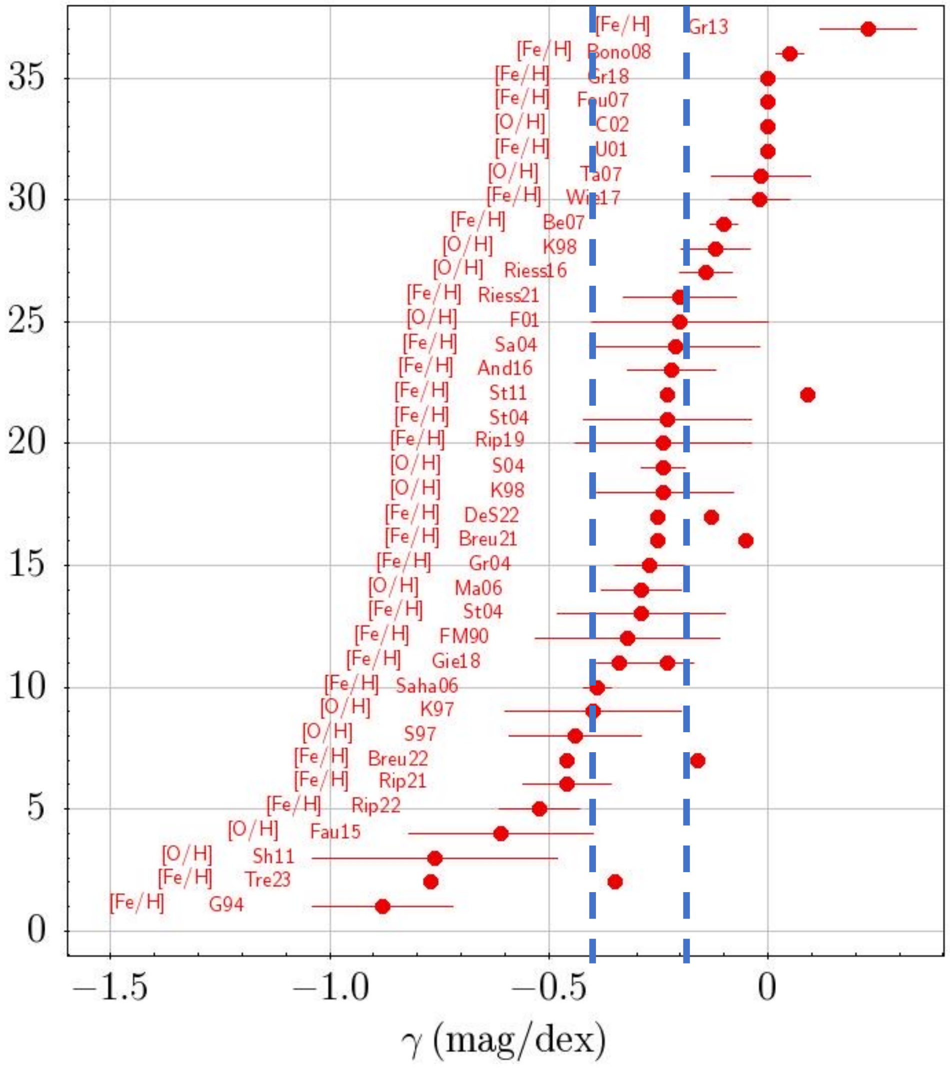
De Somma et al. 2022 ApJS

Metallicity dependence of PL

- Intercept of PL dependence on metallicity not well constrained empirically yet: most recent results: $\gamma \sim$-0.20: ~-0.40 mag/dex (e.g. Gieren+2018; Groenewegen+2018; Riess+2019,2021,2022; Ripepi+2019,2020,2021,2022; Breuval+2021,2022).

- The metallicity effect on both slope and zero point of the PLRs might not be critical for the estimate of H_0, but still relevant for measuring distances of individual galaxies: $\Delta\gamma \sim 0.2$ (mag/dex) if $\Delta[Fe/H] \sim \pm 0.2$ dex $\rightarrow \Delta\mu \pm 0.04$ mag $\rightarrow \Delta D \pm 2\%$

- Important to better constraint Cepheids models



C-MetaLL

Cepheids-Metallicity in the Leavitt Law

https://sites.google.com/inaf.it/c-metall/home

The C-MetaLL project

- Use Galactic Cepheids in conjunction with **Gaia parallaxes** to constrain the PLZ/PWZ relations but: i) **too narrow range in [Fe/H] in literature**; ii) **not enough stars with accurate NIR photometry, reddening estimates.**

1. Significantly enlarge (+~300 objects) the sample of Cepheids with metallicity measured from high-resolution spectroscopy *HARPS-N@TNG; UVES@VLT; PEPSI@LBT; ESPADONS@CFHT (~340 stars observed already; 90% complete)*.

2. Enlarge the range of [Fe/H] adopted in the determination of the PLZ/PWZ relations up to values typical of the SMC or more metal poor.

3. Obtain multiband g,r,i,z,J,H,Ks photometry for a large sample of Cepheids to obtain precise average magnitudes and individual reddening measurements (*30% complete*).

→ MEASURE ACCURATE PLZ/PWZ RELATIONS BASED ON **HOMOGENEOUS** SPECTROSCOPY AND PHOTOMETRY

The Team

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C. Catanzaro (co-PI)	INAF-Catania Observatory (IT)	Spectroscopy
A. Bhardwaj	INAF-Capodimonte Observatory (Naples, IT)	Photometry, Spectroscopy
G. Clementini	INAF-Bologna Observatory (IT)	Photometry
F. Cusano	INAF-Bologna Observatory (IT)	Photometry
G. De Somma	INAF-Capodimonte Observatory (Naples, IT)	Pulsational models
S. Leccia	INAF-Capodimonte Observatory (Naples, IT)	Spectroscopy
M. Marconi	INAF-Capodimonte Observatory (Naples, IT)	Pulsational models
R. Molinaro	INAF-Capodimonte Observatory (Naples, IT)	Photometry
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J. Storm	Leibniz-Institute for Astrophysics Potsdam (DE)	Spectroscopy
V. Testa	INAF-Monte Porzio Observatory (Rome, IT)	Photometry
E. Trentin	Leibniz-Institute for Astrophysics Potsdam (DE)	Spectroscopy

G. Catanzaro & E. Trentin (PhD)
Abundance determination

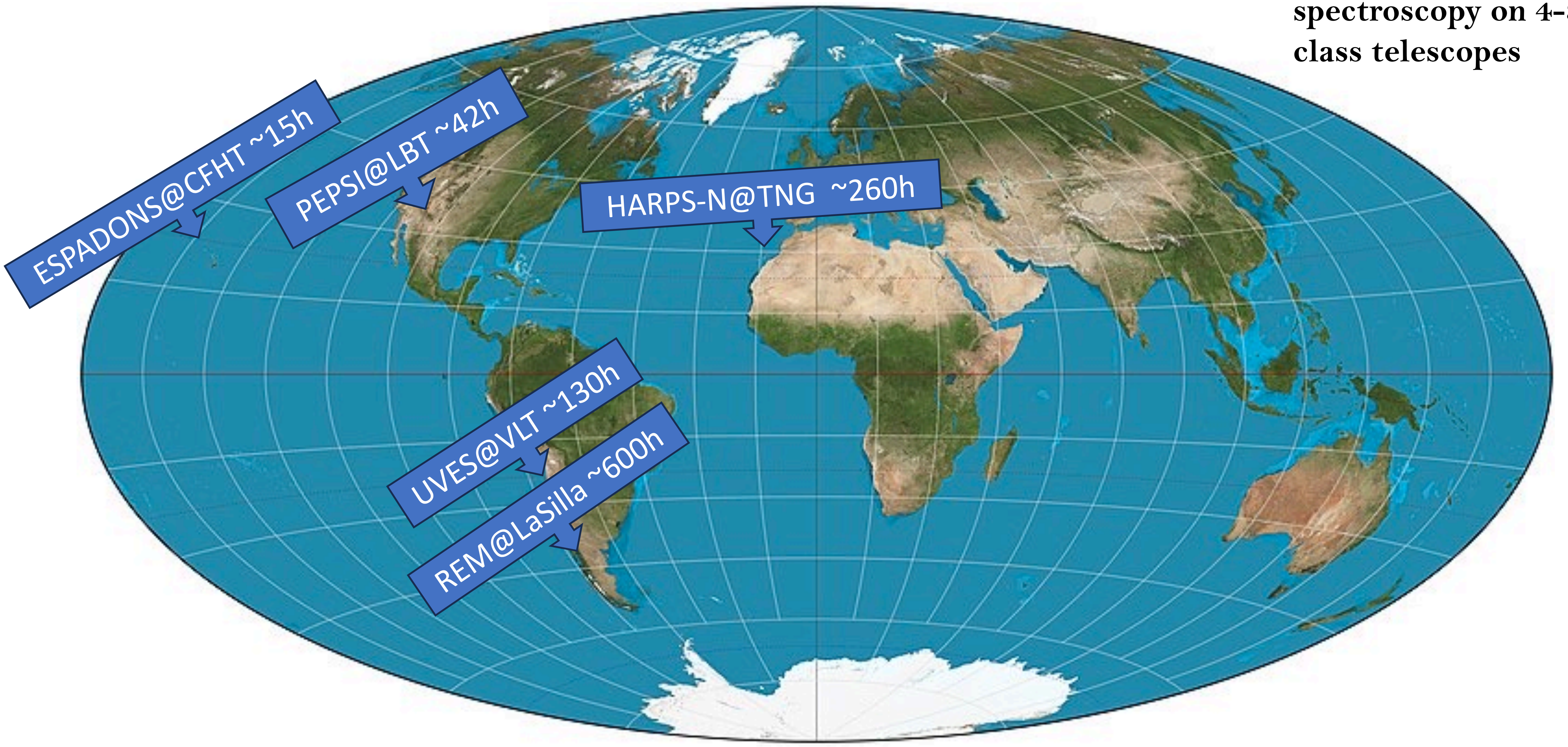
A. Bhardwaj
Photometry

R. Molinaro
Data analysis

M. Marconi & G. De Somma
Pulsation theory

Observations

~450 h high-resolution spectroscopy on 4-8m class telescopes



C-MetaLL Observations

Instrument@ Telescope	n. DCEPs Observed	n. DCEPs Published	n. DCEPs Next release
HARPS-N@TNG	104	49	40
UVES@VLT	166	65	101
PEPSI@LBT	22	0	(22)
ESPADONS@CFHT	42	0	42
Total	340	114	180

Spectroscopic observations started in 2019 and are still going on (TNG, VLT).
Next data release in preparation (Trentin et al. 2024, C-Metall VI).

	Bands	n. DCEPs Observed	n. DCEPs Published
REM@LaSilla	grizJHKs	88	78
REM@LaSilla	grizH	92	0

REM restarted full operations in January 2021 (after pandemic)

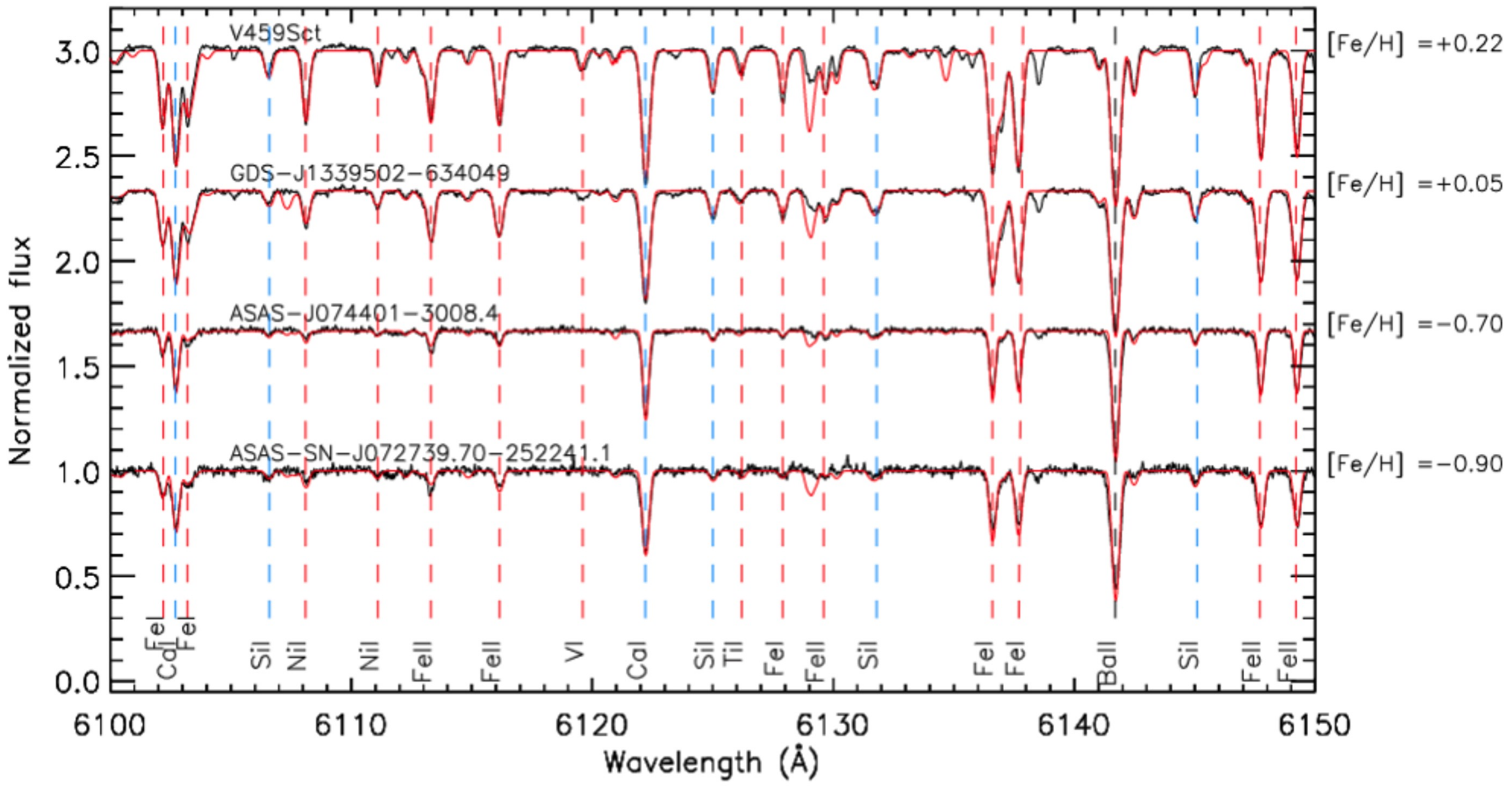
Since January 2023 the REMIR filter-wheel is fixed on the H-band

C-MetaLL Early Results – Ripepi+2021(C-MetaLL-I), Ripepi+2022

- HARPS-N@TNG based abundances for 49 Galactic Cepheids
- Complementary literature spectroscopic and photometric data → sample ~490 Cepheids
- Using Gaia EDR3 parallaxes → PLZ/PWZ calibration in Ks, W(J,Ks), W(V,Ks), W(H,V,I) (Ripepi+2021) and in W(G, G_{BP}, G_{RP}) (Ripepi+2022)
- In Ripepi+2021 → i) larger metallicity dependence compared with Breuval+2021 and Riess+2021; ii) Counter-correction and metallicity term are anticorrelated.
- In Ripepi+2022 → PWZ in the Gaia bands: The metallicity dependence in the Gaia bands is even larger than in the other bands (Confirmed by Breuval+2022, Reyes&Anderson 2023)

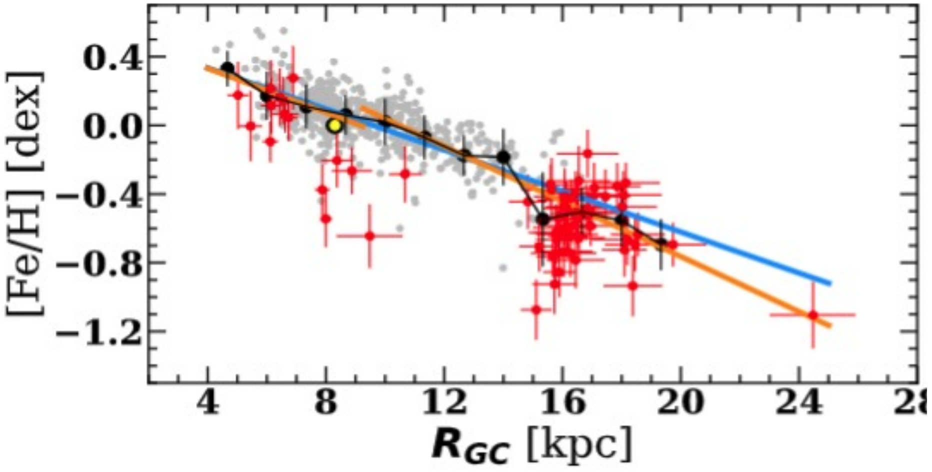
C-MetaLL Results – Trentin et al. 2023 (C-MetaLL-II)

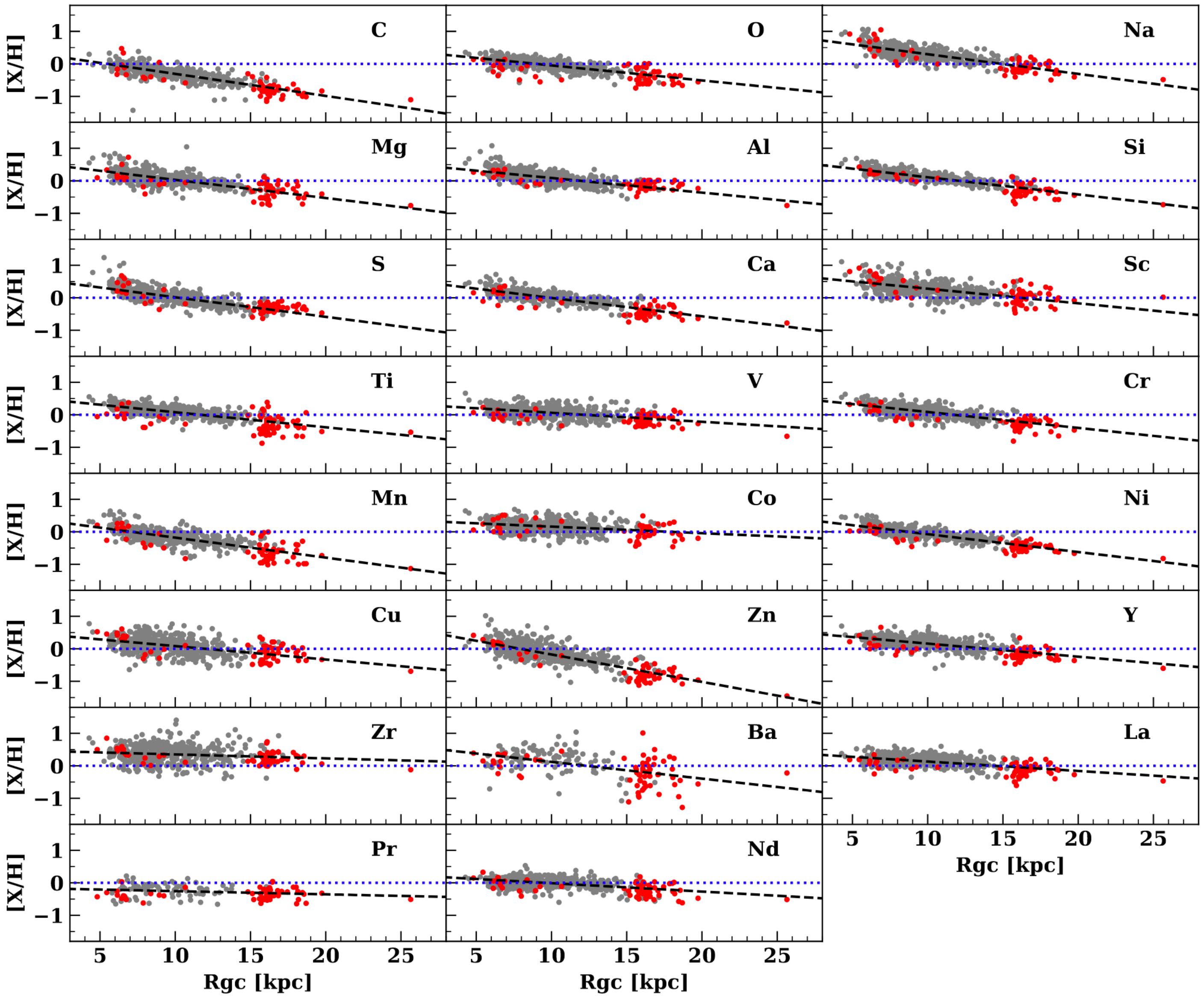
- UVES@VLT HiRes spectroscopy for additional 65 Cepheids
- ~50 faint objects chosen in the anticenter direction to have low metallicity.



C-Metall Results – Trentin et al. 2023 (C-MetaLL II)

- Study of the metallicity gradient of the MW disc for 23 elements
- Possible break at 9.25 kpc





Current baseline results of the C-MetaLL project

C-MetaLL results: New calibration of multi-band PLZ/PWZ relations Trentin et al. 2024 (C-MetaLL IV)

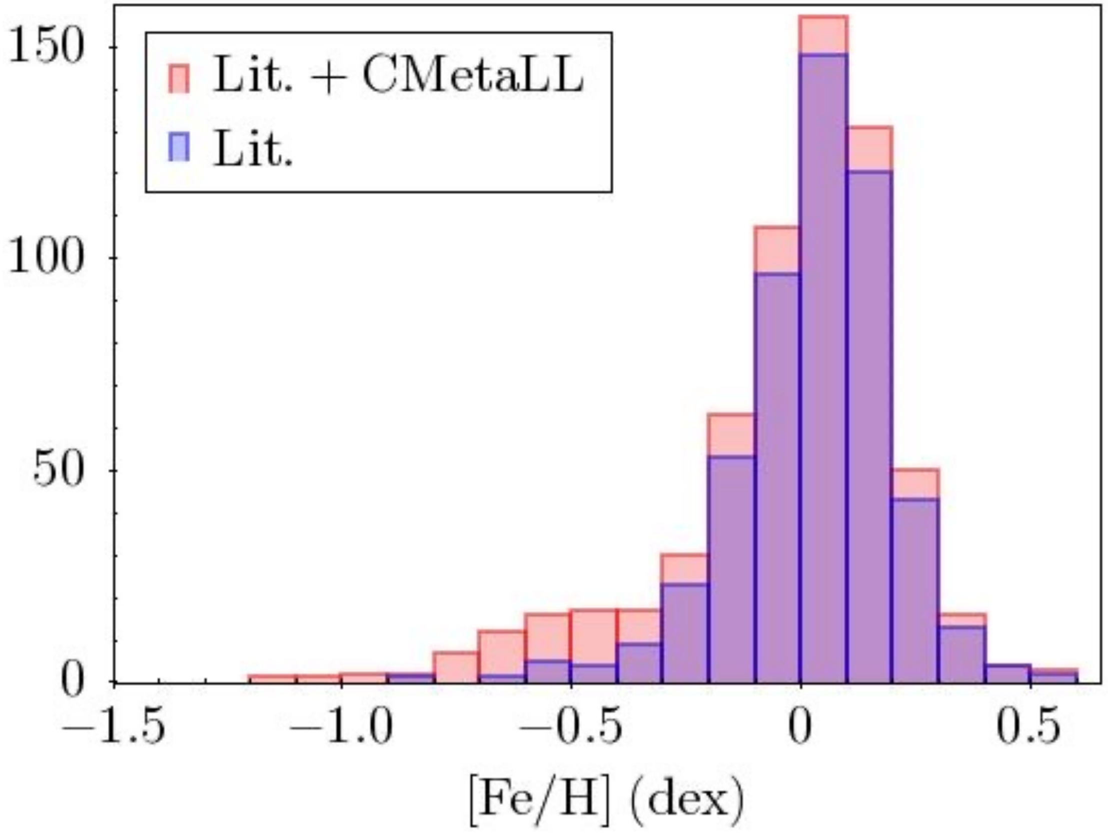
- Improved Cepheid sample thanks to C-MetaLL data (114 stars in total) and additional HiRes abundances for 68 Cepheids by Kovtyukh+2022

- Sample HiRes = 635 objects

- Plus 275 Cepheids with Gaia RVS [M/H] estimates (with good flags) → total 910 Classical Cepheids (all data published in the paper).

- Optical G, G_{BP} , G_{RP} , V, I and NIR photometry from the literature (more than 50% JHKs photometry from 1-epoch 2MASS data).

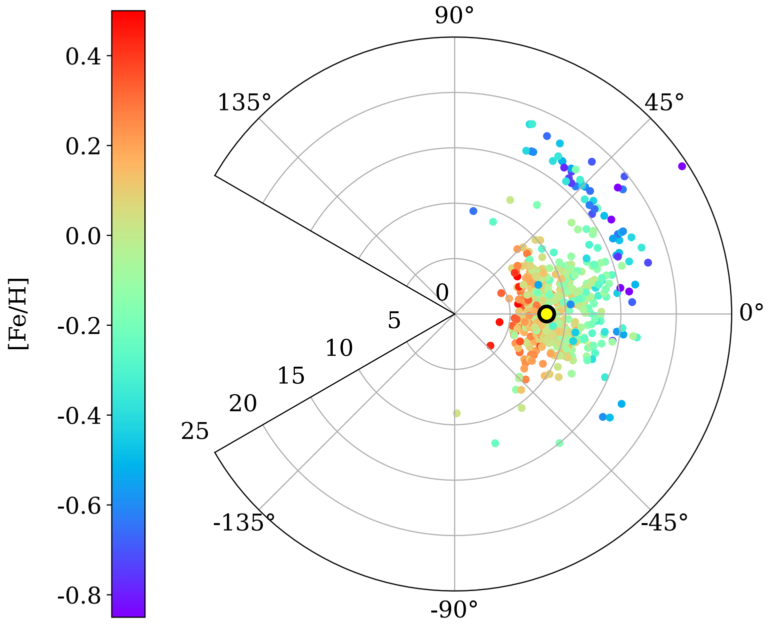
- Reddening from the literature or calculated (PC relations)



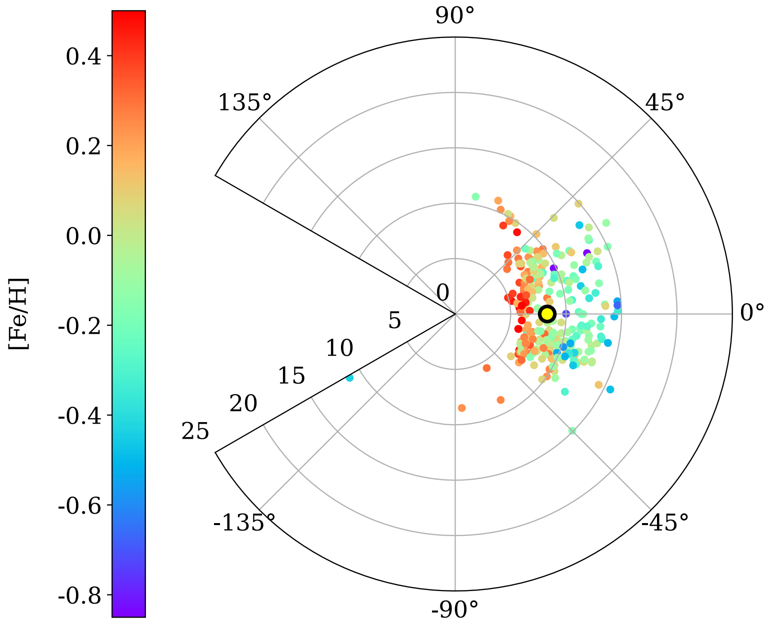
Trentin et al. 2024 (C-MetaLL –IV): The sample

- HighRes data including Groenewegen2018, Ripepi+2021, Kovtyukh+2022, Trentin+2023
- Gaia RVS abundances (Recio-Blanco+2023)

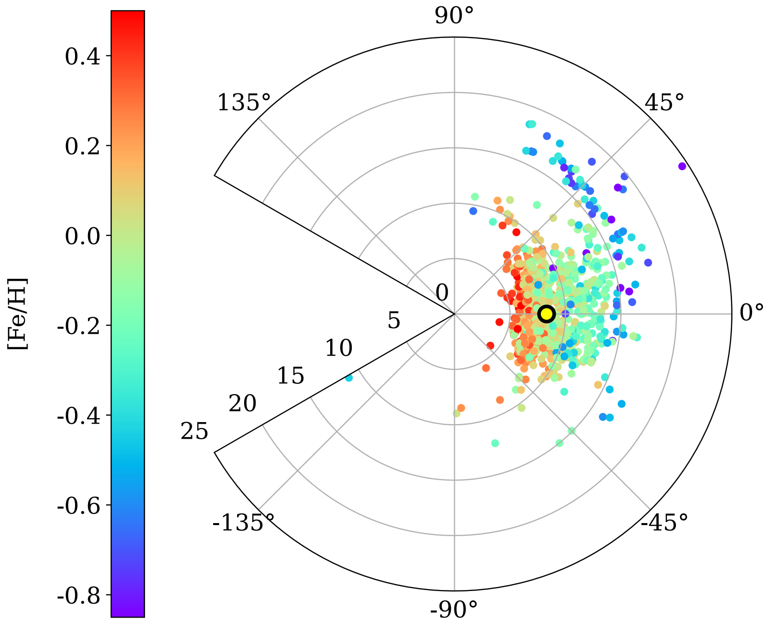
635 HiRes



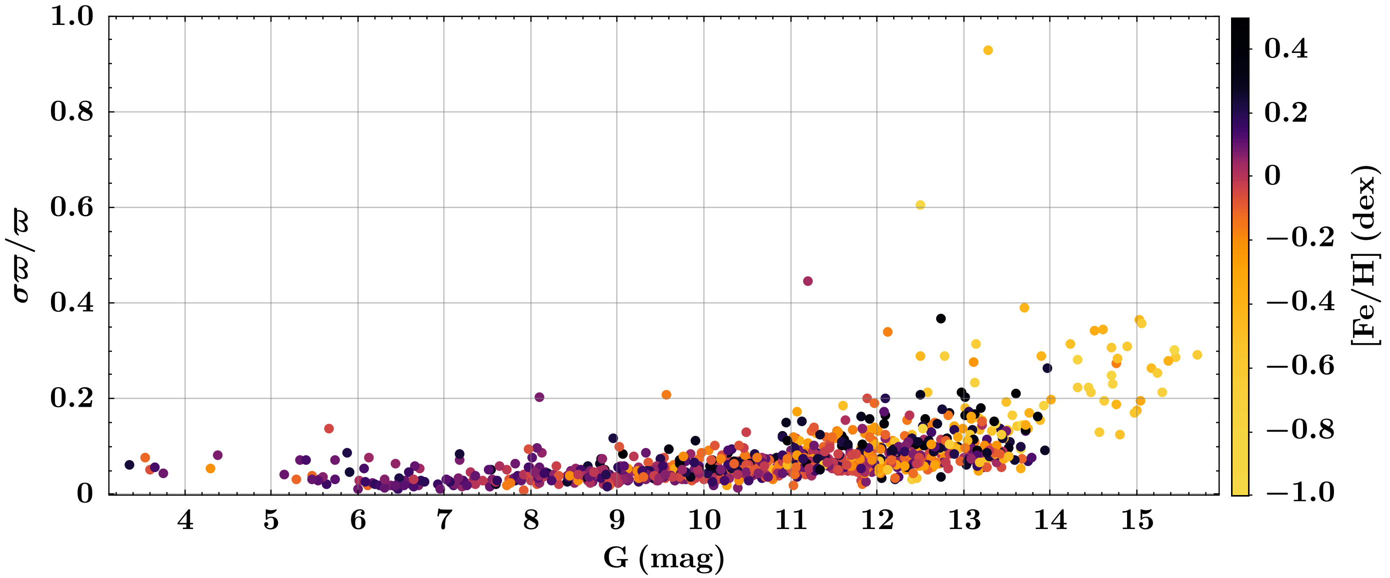
275 Gaia RVS

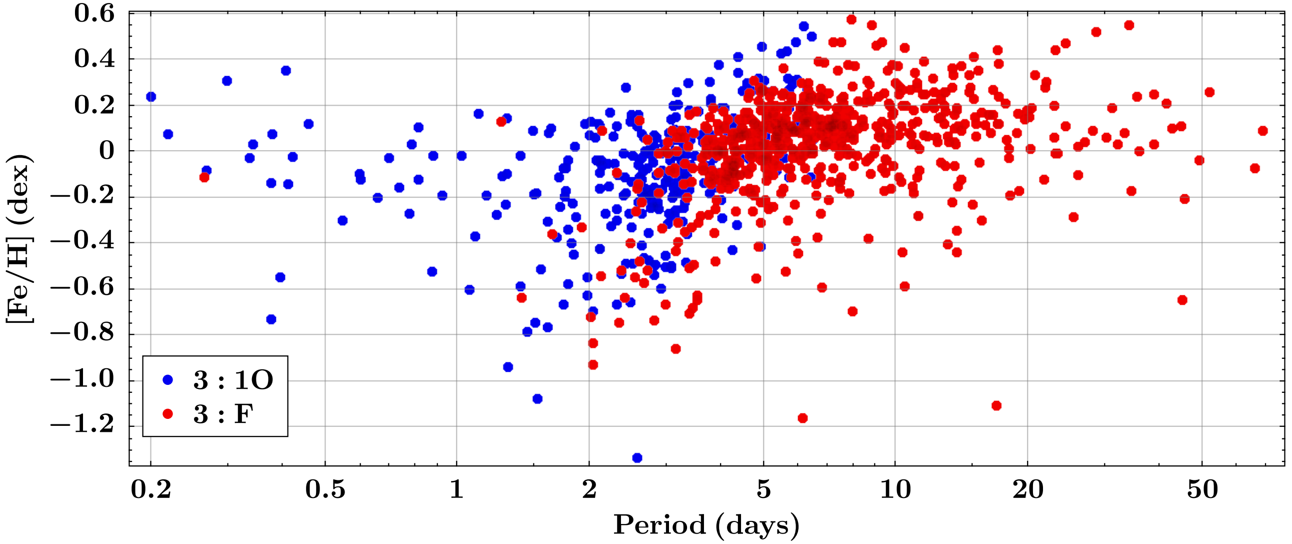


910 Total



Properties of the sample



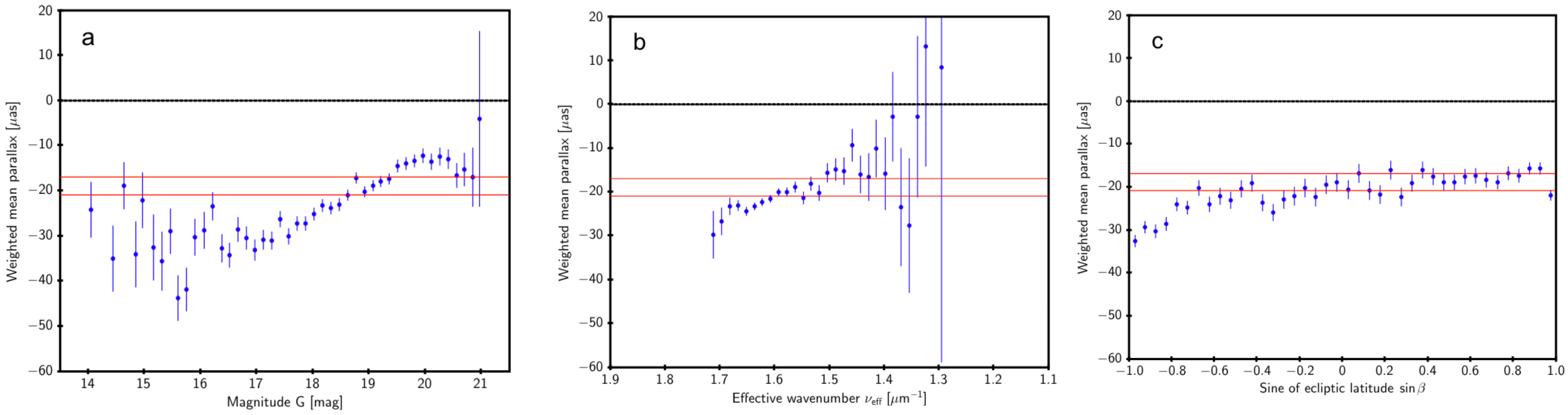


- Metal-poor objects are more distant in the anticentre direction → generally less precise parallaxes → observe more metal-poor Cepheids to compensate lower precision with increased statistics.

- There are few metal-poor objects with periods > 15 days → observe specifically those objects to fill the parameter space

Gaia Parallax zero point offset (PZPO)

- Distribution of measured QSO parallaxes: average should be around zero: It is not
- Certain perturbations of the basic angle are observationally indistinguishable from a global shift of the parallaxes (Butkevich+2017)
- Average effect for QSO on average ~29 μas in DR2 and 19 μas in DR3 (Arenou+2018, Lindegren+2021)

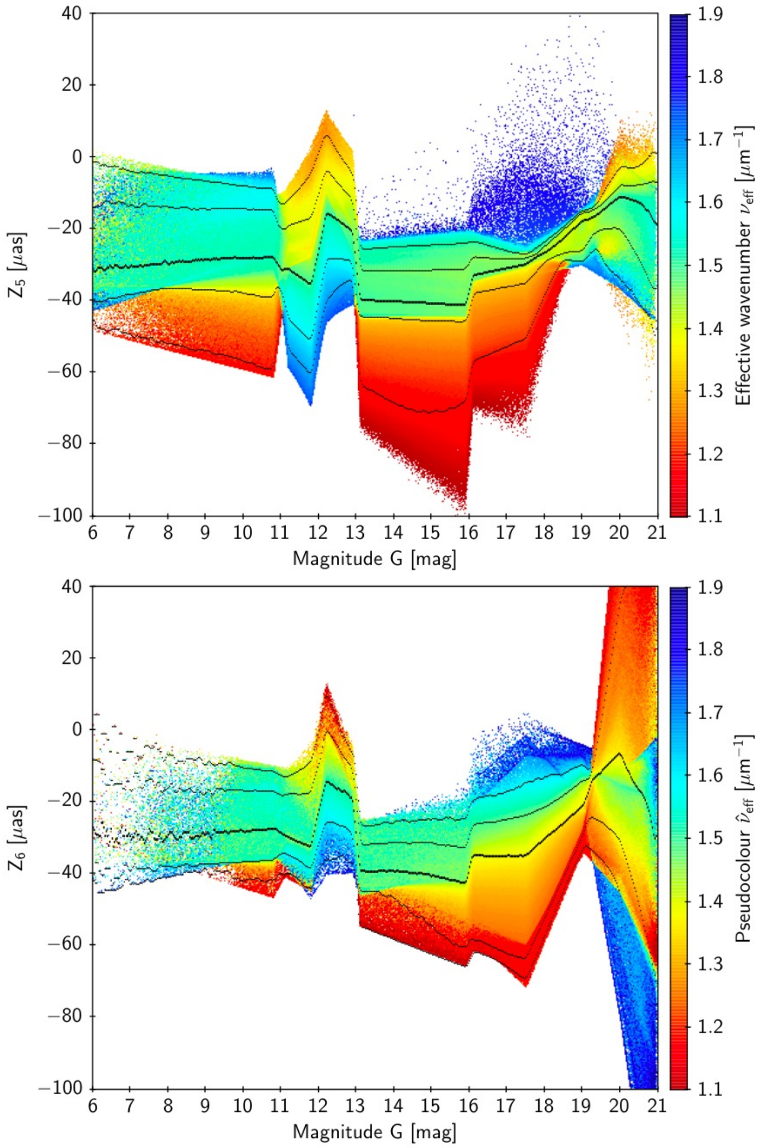


Lindegren+2021

Gaia Parallax zero point offset (PZPO)

$\varpi_{\text{True}} = \varpi_{\text{Gaia}}$-PZPO

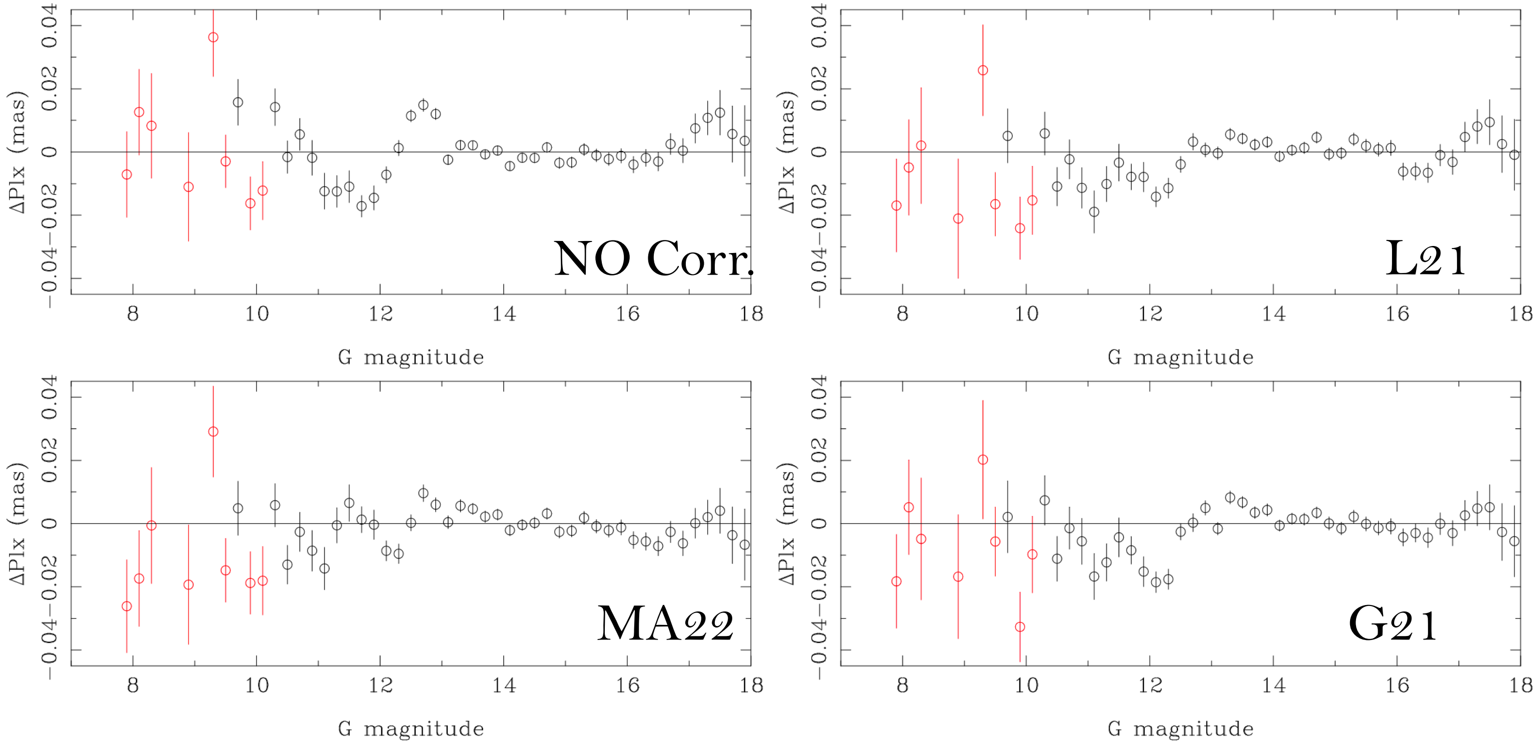
- The PZPO depends on Magnitude, colour, ecliptic latitude
- Lindegren+2021 (L21) provided individual offsets based on parallax comparison with QSO, Binaries and LMC
- Other corrections in the literature: Maíz Apellániz 2022 (MA22), Groenewegen 2021 (G21)



Lindegren+2021

Gaia Parallax zero point offset (PZPO)

$\varpi_{\mathrm{True}} = \varpi_{\mathrm{Gaia}} - \mathrm{PZPO}$



Test of the correction using open clusters.
Residuals between individual and cluster parallaxes summed over all clusters and plotted against G magnitude. → no correction is perfect

G (mag)	no PZPO (μas)	L21 (μas)	MA22 (μas)	G21 (μas)
All	9.78	9.37	9.45	9.41
$G \leq 13$ mag	13.37	12.83	13.10	13.06
$13 < G < 17$ mag	2.35	3.48	3.60	3.39
$17 \leq G \leq 18$ mag	8.62	6.06	3.97	4.33

Reyes&Anderson2023, Groenewegen 2023

Groenewegen 2023

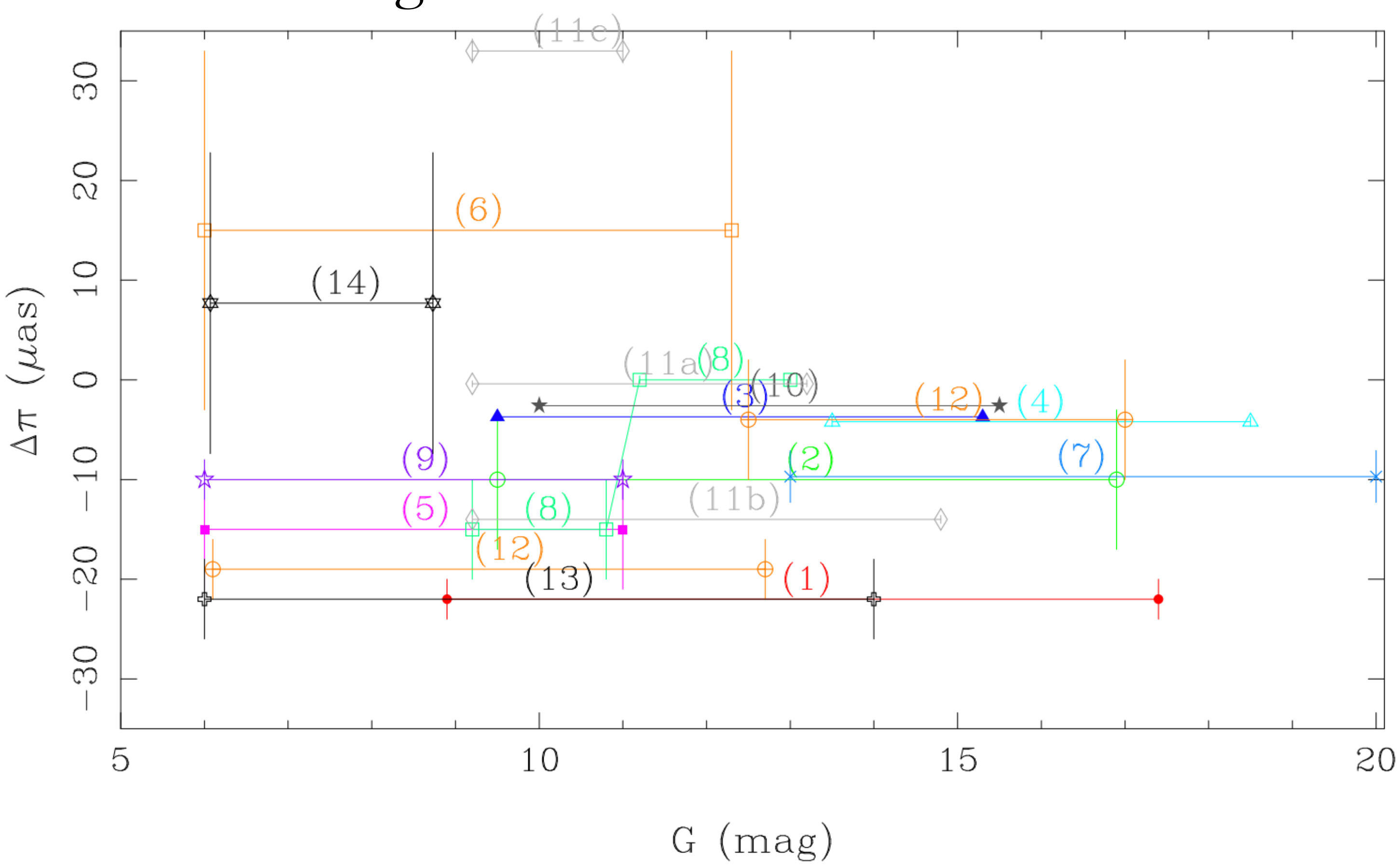


Figure 3. Countercorrection $\Delta\pi$ plotted against magnitude for (1) Bhardwaj et al. (2021), RRL; (2) Gilligan et al. (2021), RRL; (3) Huang et al. (2021b), red clump (5p solution); (4) Ren et al. (2021), WUMa EBs (5p solution); (5) Riess et al. (2021a), DCEP LMC; (6) Stassun and Torres (2021), EBs; (7) Vasiliev and Baumgardt (2021), globular clusters; (8) Zinn (2021), asteroseismology; (9) Flynn et al. (2022), open/globular clusters; $Bp - Rp > 1$ (10) Wang et al. (2022), giants; (11) Khan et al. (2023) red giants: asteroseismology, for the (a) *Kepler*, (b) *K2*, and (c) *TESS*-SCVZ fields ('E20', APOGEE DR17 values); (12) Cruz Reyes and Anderson (2023) Clusters ($G = 12.5 - 17$ mag, $0.8 < Bp - Rp < 2.75$ mag) and MW DCEPs; (13) Molinaro et al. (2023) MW DCEPS; (14) Groenewegen (2023) dynamical parallax of binary systems with spectroscopic and astrometric orbits.

PZPO counter-correction

$\varpi_{True} = \varpi_{Gaia}$-PZPO+$\Delta\varpi$

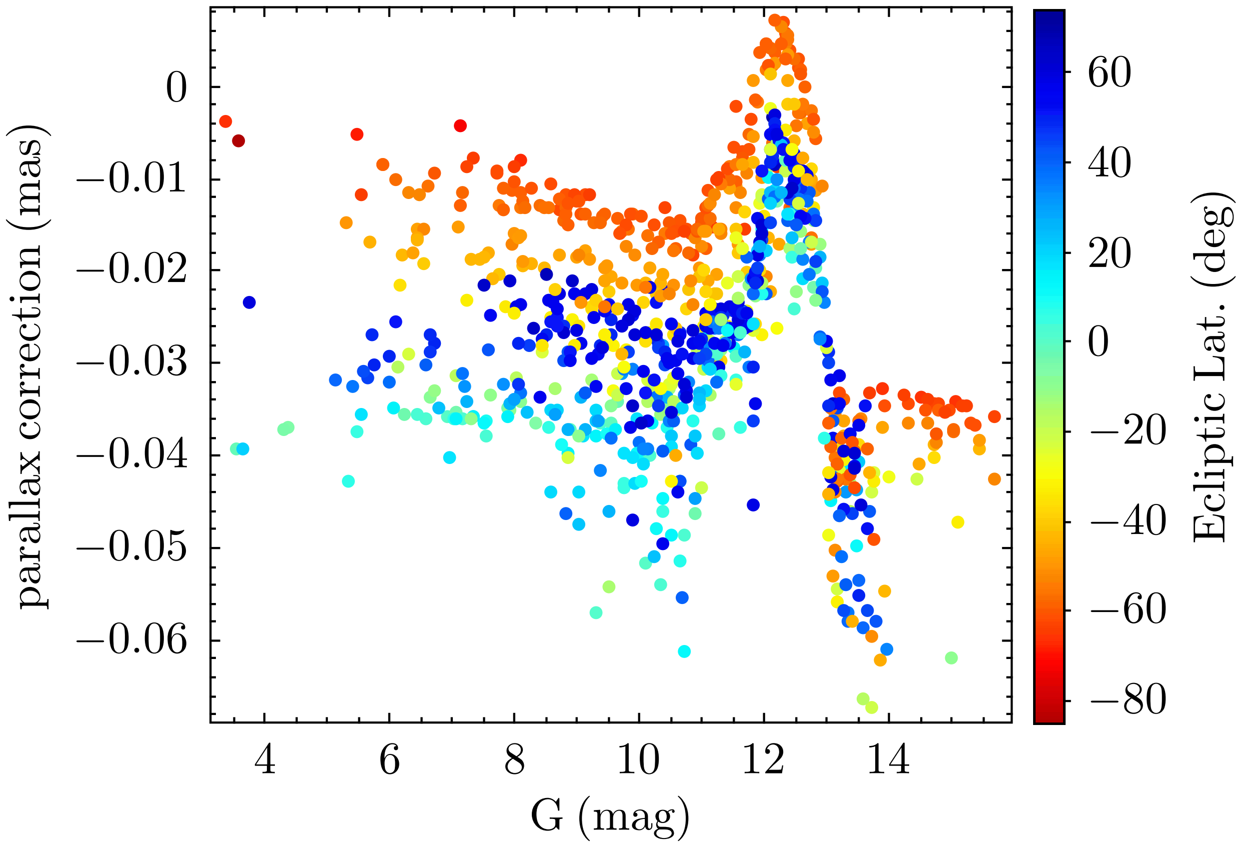
$\Delta\varpi$ is usually negative

No consensus on its value/error

The size of this counter-correction and the precision of its estimate may have a significant impact on the extra-galactic distance scale.

$\Delta\varpi = \pm 4$ μas → ± 0.02 mag at the distance of the LMC → 1% in distance → 1% on H0

Preparation of the sample



- Gaia EDR3 parallaxes PZPO corrected with Lindegren+2021 recipe.
- Complex dependence on Magnitude, colour and ecliptic latitude.
- Used RUWE (Lindegren+2018) and fidelity_v2 (Rybizki+2022) to cut-off objects with bad astrometry.

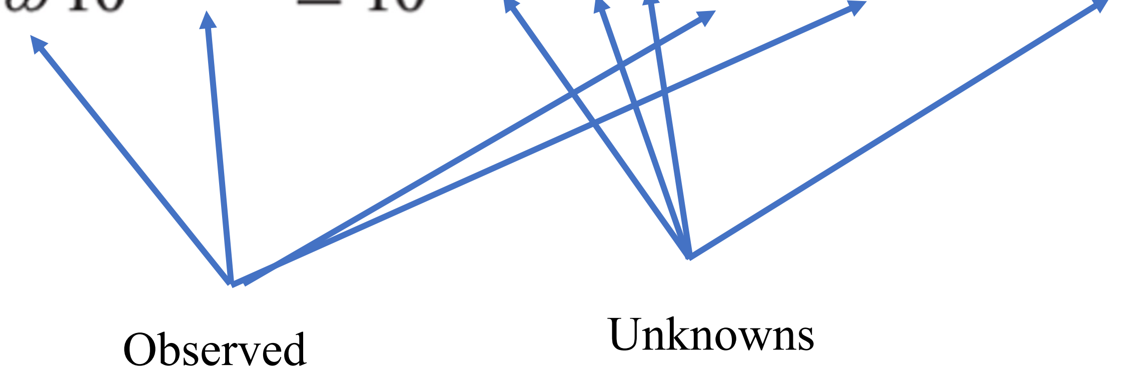
ABL fitting

To avoid bias problems, the **Astrometry-Based Luminosity (ABL)** method (Arenou & Luri 1999; Gaia Collaboration+2017): **linear in parallax; no selection on parallax (negative parallaxes are included) nor on σπ/π is needed.**

$$ABL = 10^{0.2M_\lambda} = \pi 10^{(0.2m_{\lambda 0}-0.2)}$$

$$M_\lambda = \alpha_\lambda + (\beta_\lambda+\delta_\lambda[Fe/H])\log P+\gamma_\lambda[Fe/H]$$

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



Non-linear fitting, robust errors with bootstrap procedure

ABL fitting

- We consider PL relations in G, G_{BP}, G_{RP}, V, I, J, H, Ks
- Cardelli+1989 reddening law to deal with extinction

Wesenheit magnitudes considered in this work

Bands	λ
$W_{G,G_{BP}-G_{RP}}$	1.9
$W_{H,V-I}$	0.461
$W_{F160W,F555W-F814W}$	0.386
$W_{K_S,V-K_S}$	0.130
$W_{K_S,J-K_S}$	0.690

Data analysis

Several possibilities were explored:

1. With and without Gaia RVS abundances

2. With and without fundamentalised 1O pulsators

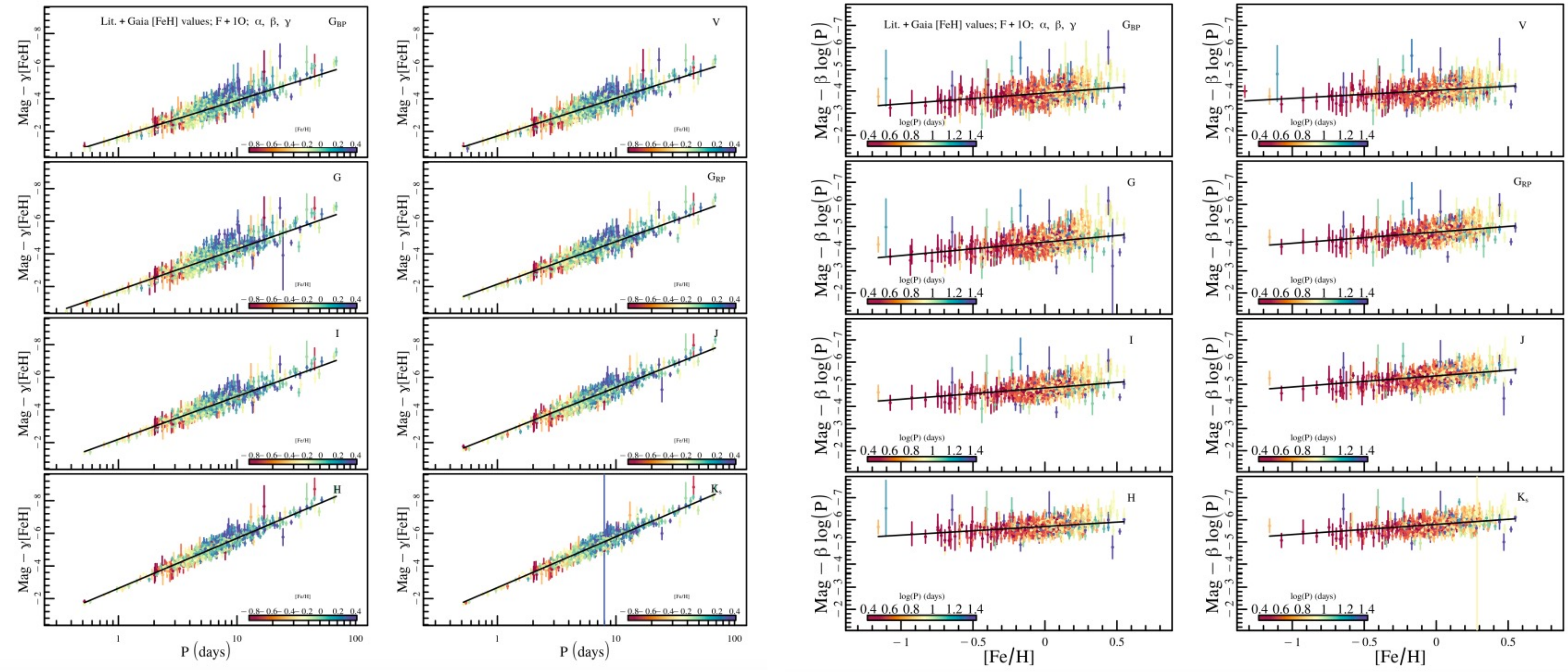
3. With different fixed counter-correction from the literature

4. With binning the data in metallicity

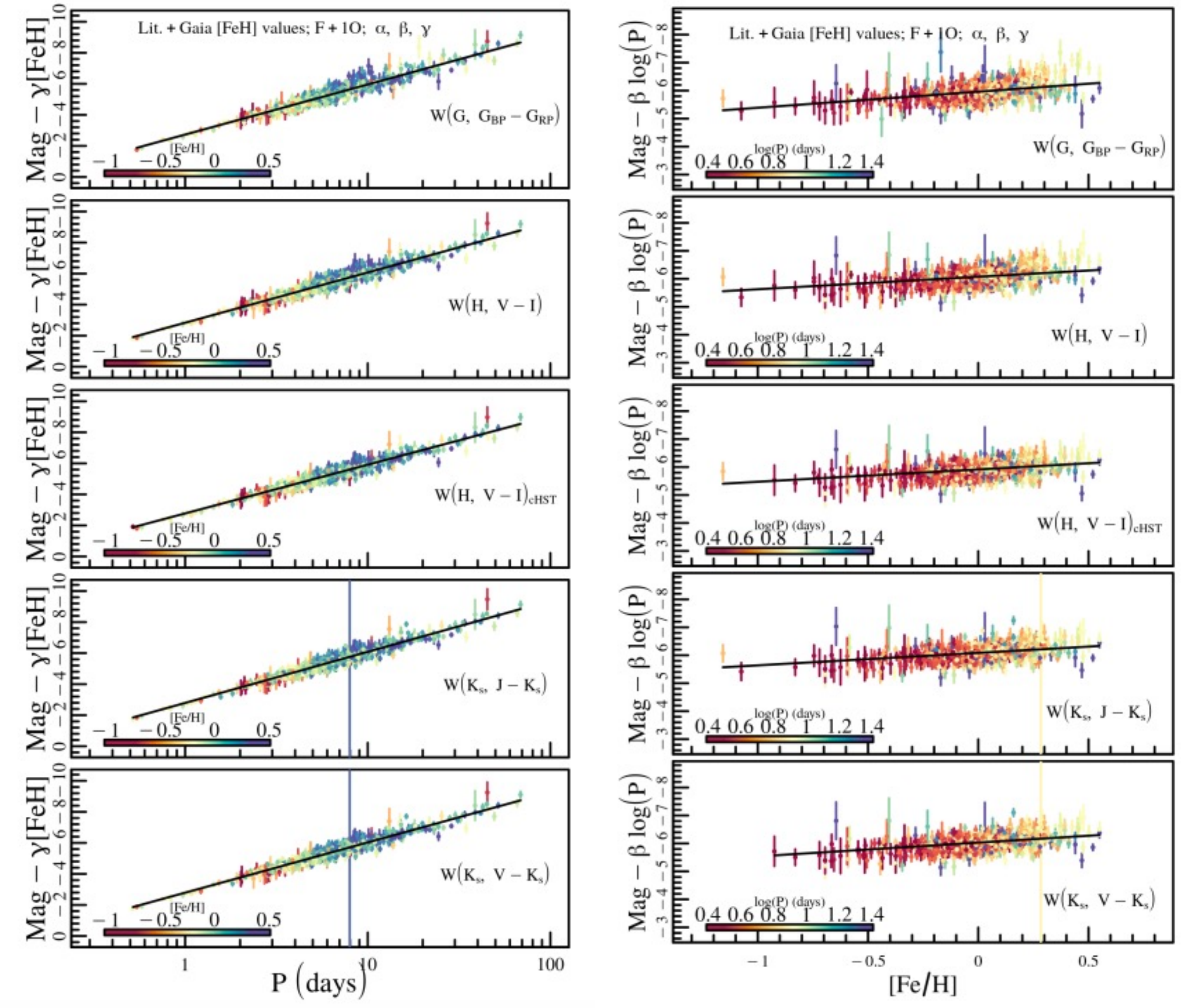
Baseline results: full sample (including Gaia RVS abundances) and F+1O

Results (Trentin et al. 2024, C-MetaLL IV)

Clear strong trend with [Fe/H] after removing the period dependence.
Possible flattening at low metallicity

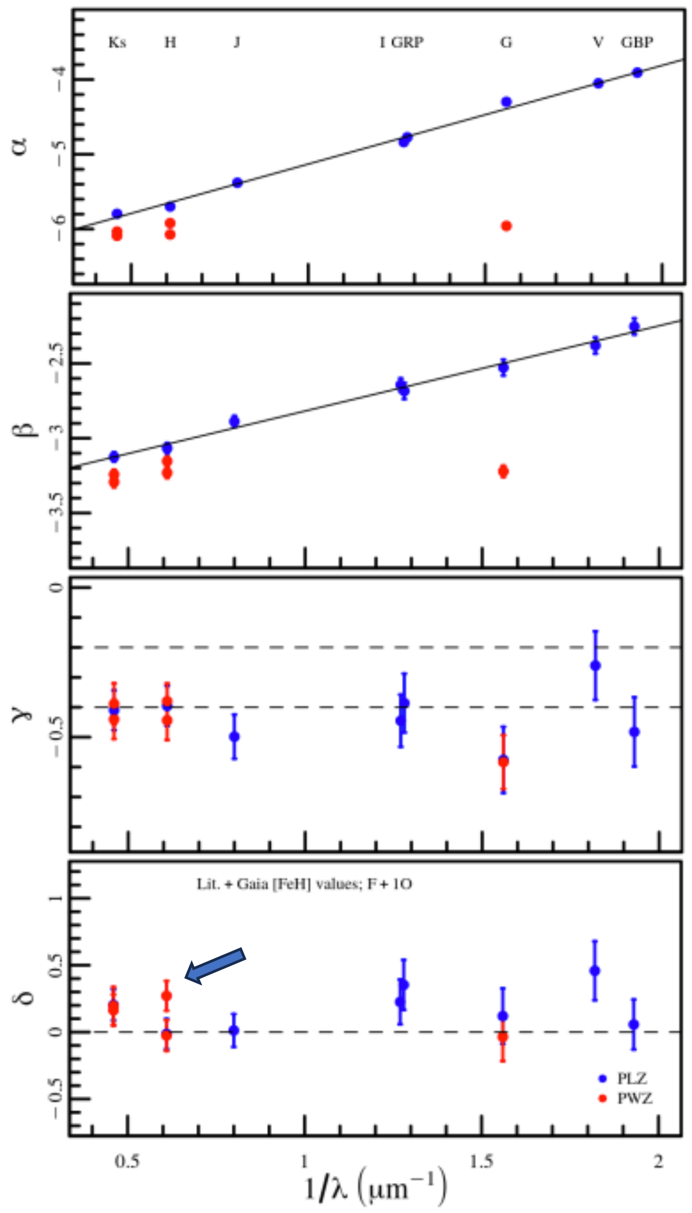


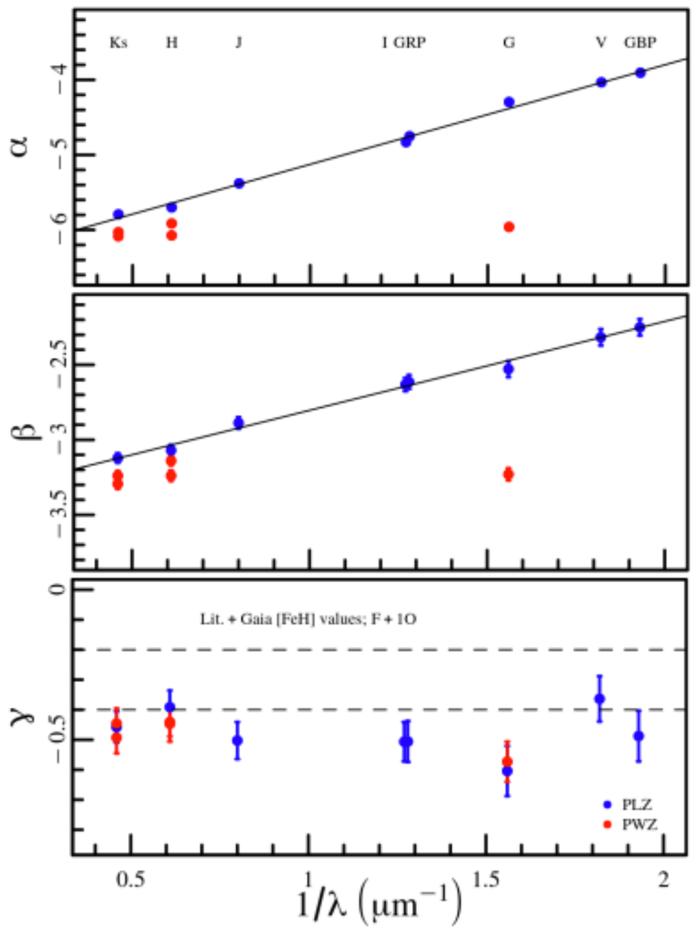
Results (Trentin et al. 2024, C-MetaLL IV)



Same but for PWZ relations

Results (Trentin et al. 2024, C-MetaLL IV)

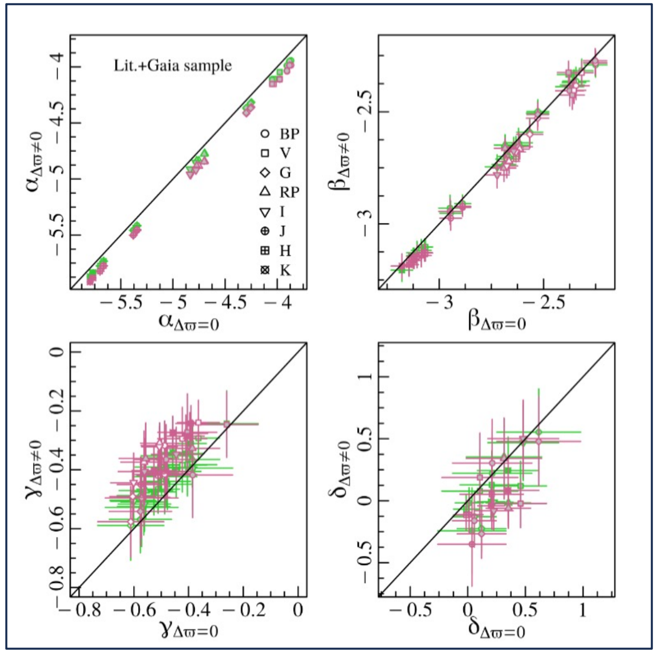




Blue → PLR
Red → PWR

- Baseline solution: HiRes+Gaia, F+1O sample, L21 PZPO, no counter-correction
- $\gamma \sim -0.4\!:\!-0.5$ mag/dex larger than recent results (Gieren+2018, Riess+2021, Breuval+2021,2022)
- No clear metallicity dependence on wavelength for γ term (as in Breuval+2021,2022)
- δ term significant only in V, I, G_{RP} and $\mathbf{W_{HST}}$ at > 1 σ → more data in the metal-poor regime needed to constrain this parameter.

Test of PLZ relations: different parallax counter-corrections

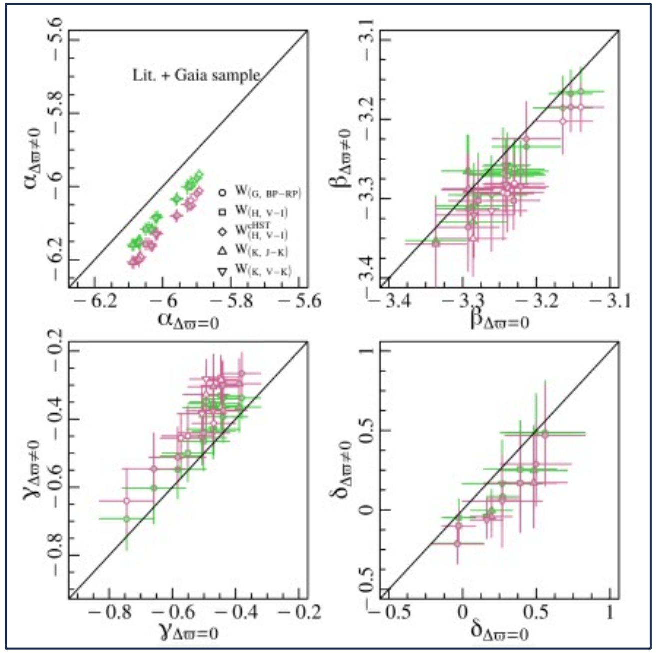


PL

Counter-correction is anticorrelated with the metallicity effect.

Global ZP = 22 μas (*Molinaro et al.* 2023)

Global ZP = 14 μas (*Riess et al.* 2021)



PW

If conter-correction increases → δ unaffected, γ **decreases (in absolute value).**

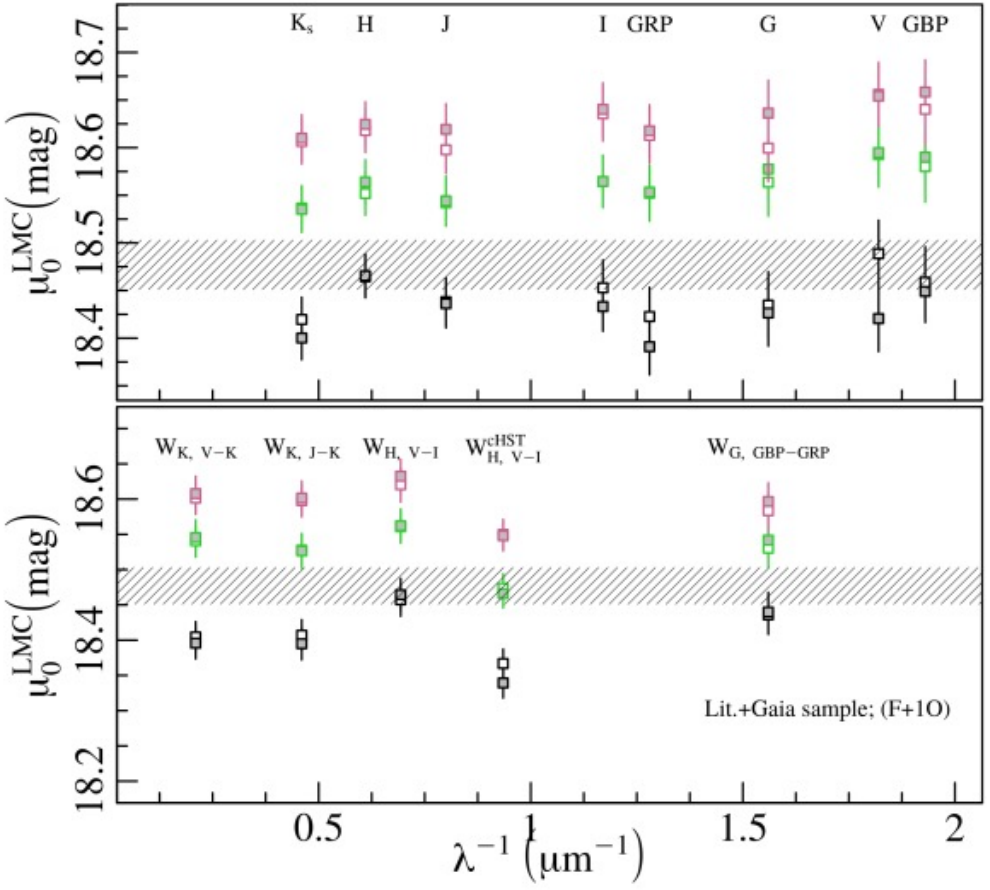
Right direction to reconcile our results with recent literature values.

But……

(Trentin et al. 2024, C-MetaLL IV)

Test of PLZ relations: different parallax counter-corrections

If we apply our PLZ/PWZ relations to LMC Cepheids (photometry from Gaia/OGLE/VMC, metallicity from Romaniello+2022) and compare the results with the Geometric distances by Pietrzynski+2019 as reference →



Counter-correction $= 22\ \mu as$ (*Molinaro et al.* 2023)

Counter-correction $= 14\ \mu as$ (*Riess et al.* 2021)

Counter-correction $= 0\ \mu as$

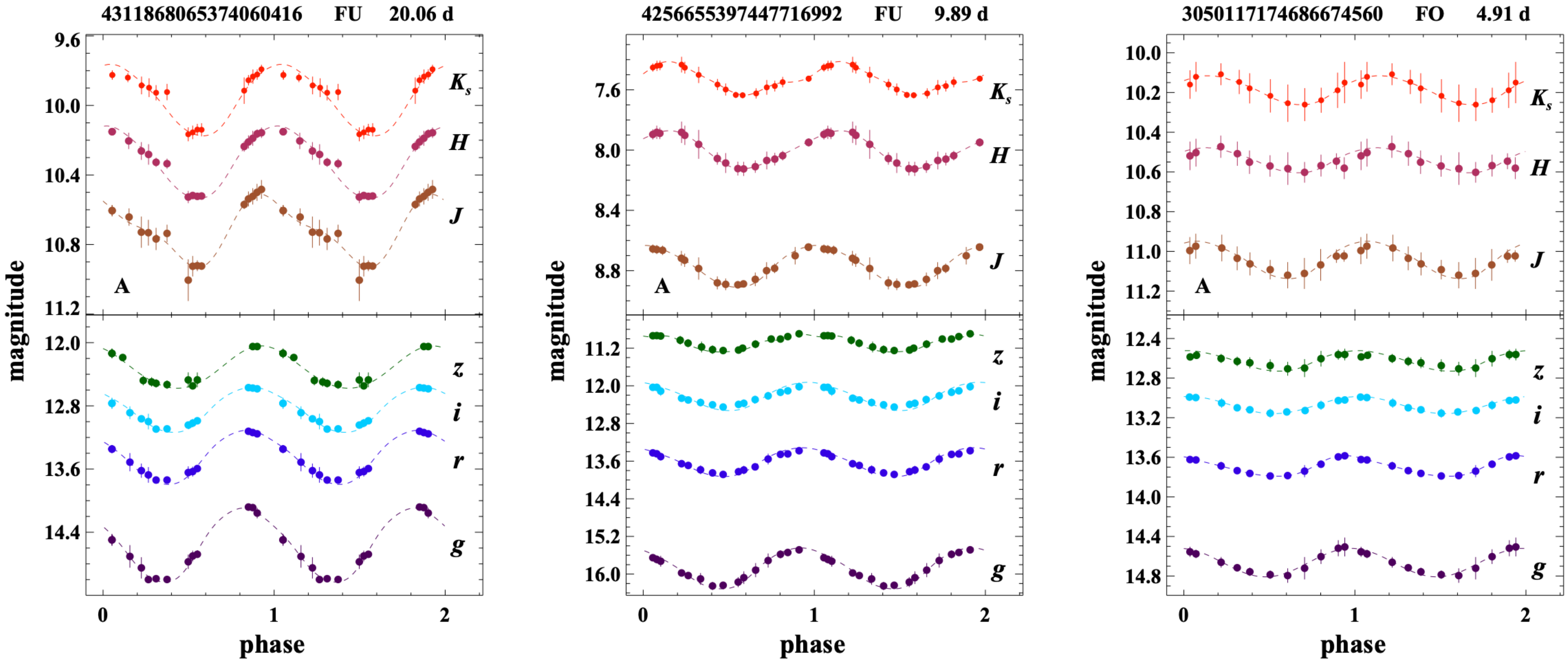
Estimated counter-correction $\sim 7\ \mu as$

We can recover the "right" distance of LMC only for $\gamma \sim -0.4 : -0.5$ mag/dex

(Trentin et al. 2024, C-MetaLL IV)

grizJHKs photometry (Bhardwaj et al. 2024, C-MetaLL-V)

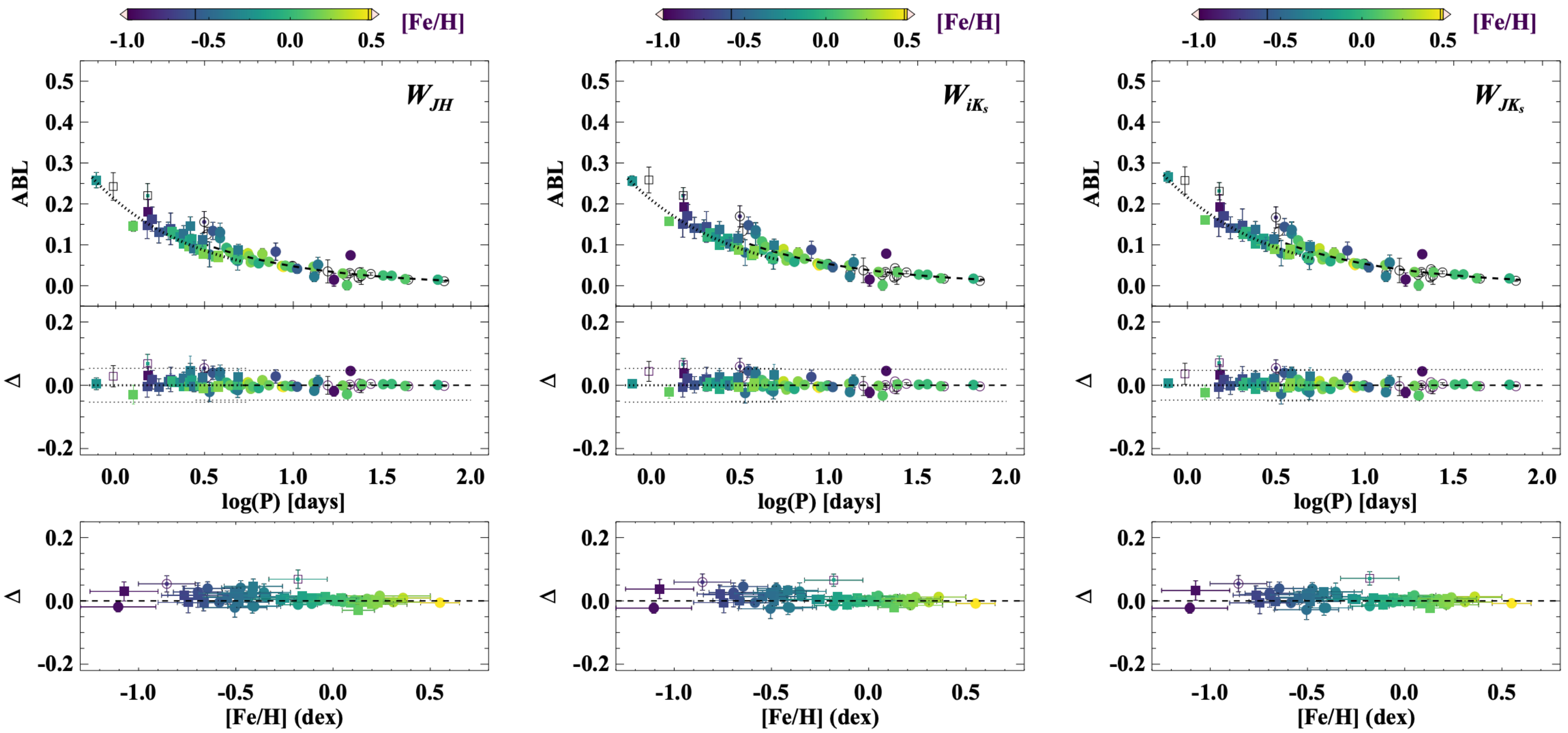
Homogeneous optical (griz) and NIR (JHK) photometry of 78 Cepheids (49 F and 29 1O) REM telescope (La Silla, Chile)



Bhardwaj et al. 2024

grizJHKs photometry (Bhardwaj et al. 2024, C-MetaLL-V)

PL/PW relations derived through ABL fitting → largest residuals with metallicity at low [Fe/H] due to the larger errors in parallax. Need to increase the sample.



Bhardwaj et al. 2024

Summary

- Gaia is great but the systematics on the PZPO still impact on the results. Expected a significant reduction of the systematics for DR4, but > 2 years!

- C-MetaLL project:
  1. New calibration of multi-band PLZ/PWZ relations using 910 stars spanning a range of metallicity of 1.5 dex.

  2. For the baseline sample, HiRes+Gaia, F+1O: $\gamma \sim -0.4 : -0.5$ mag/dex → disagreement with the results of the SH0ES group.

  3. Hints on a dependence of the slope on the metallicity in the optical bands and in the (in agreement with theory and other empirical evidences) and in the W_{HST} mag

  4. Low-metallicity DCEPs have the least precise parallaxes → need to increase the sample to compensate the lower precision.