The distance scale of Type II Cepheids from near infrared observations in the Magellanic Clouds

Teresa Sicignano

INAF Osservatorio Astronomico di Capodimonte, Naples

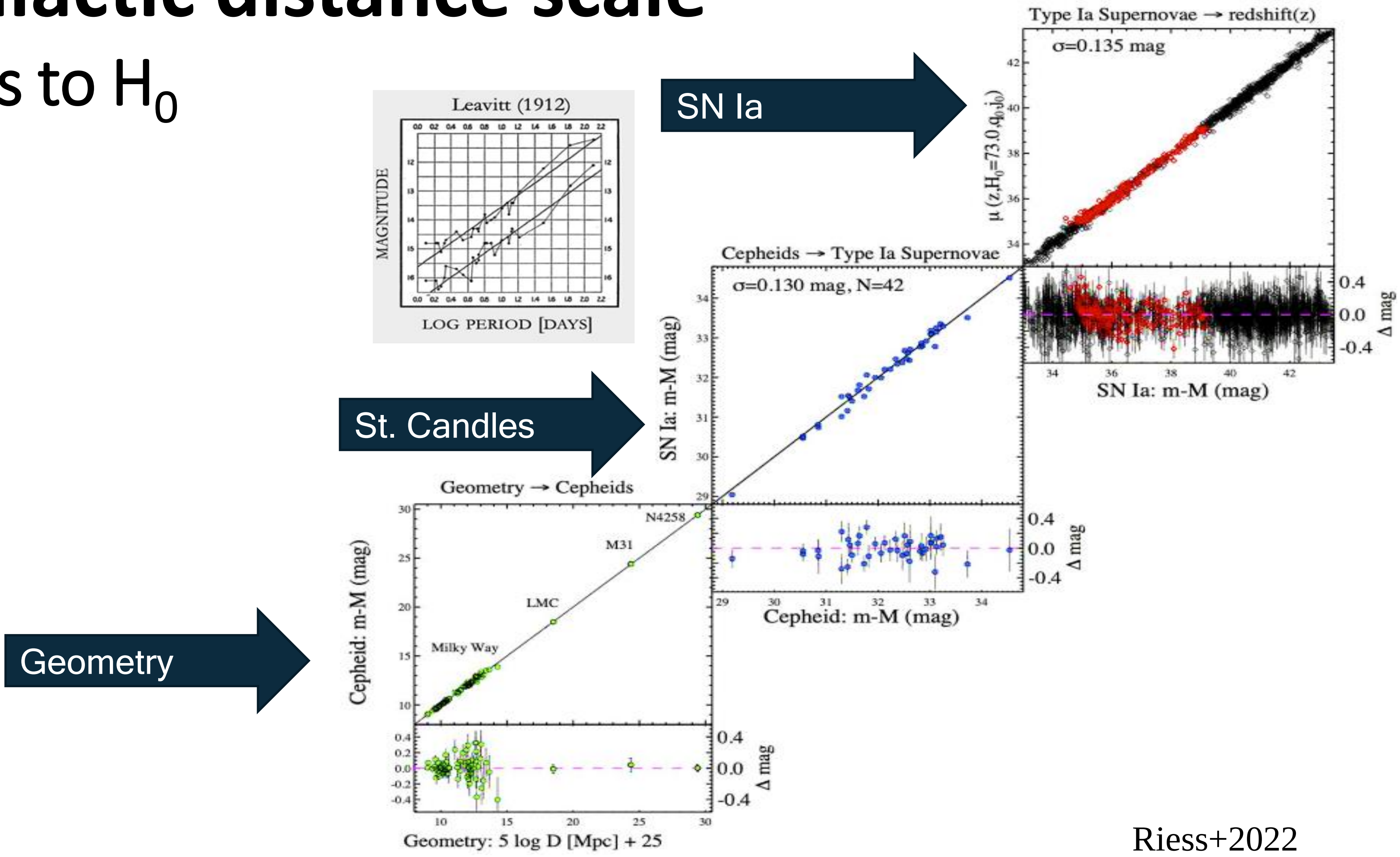
In collaboration with Ripepi V., Molinaro R., Bhardawj A., Marconi M., De Somma G., Cioni M.R. and VMC team

OUTLINE

- Extragalactic Distance Scale
- Pulsating stars in the Magellanic Clouds
- Data analysis
- Results
- Conclusions

The extragalactic distance scale

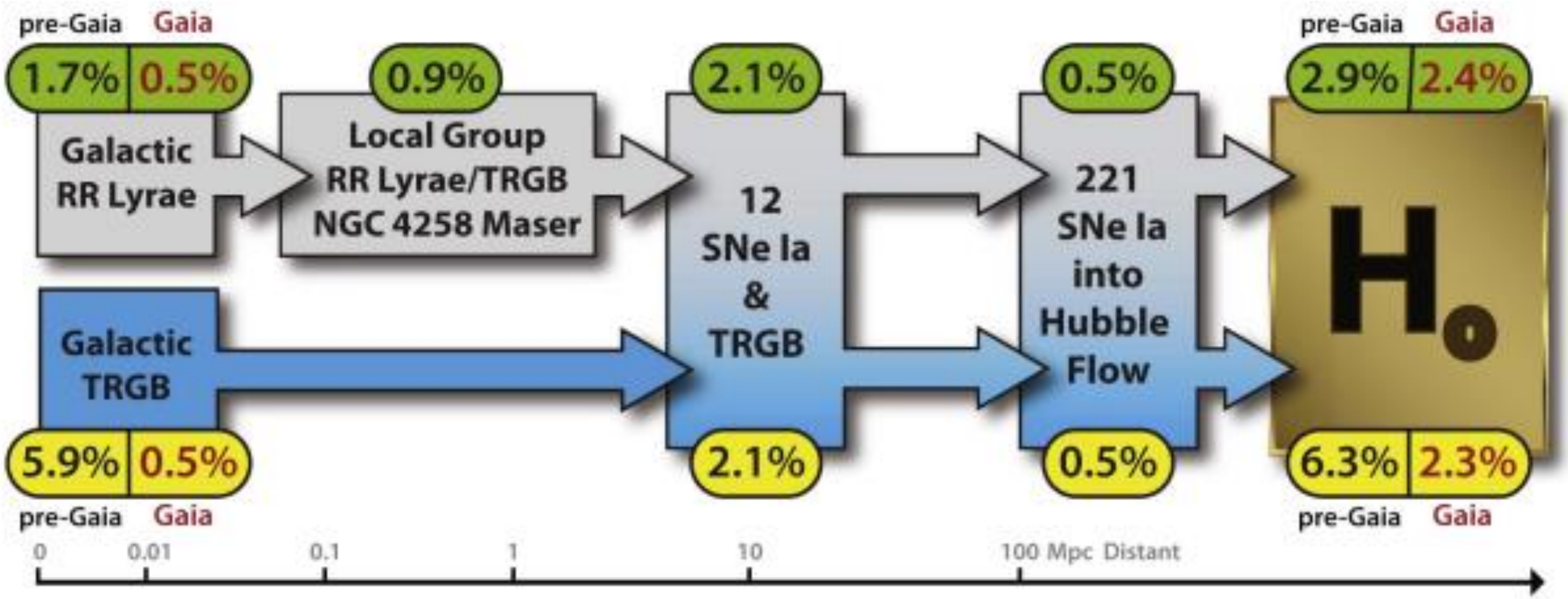
The three steps to H_0



Riess+2022

The extragalactic distance scale

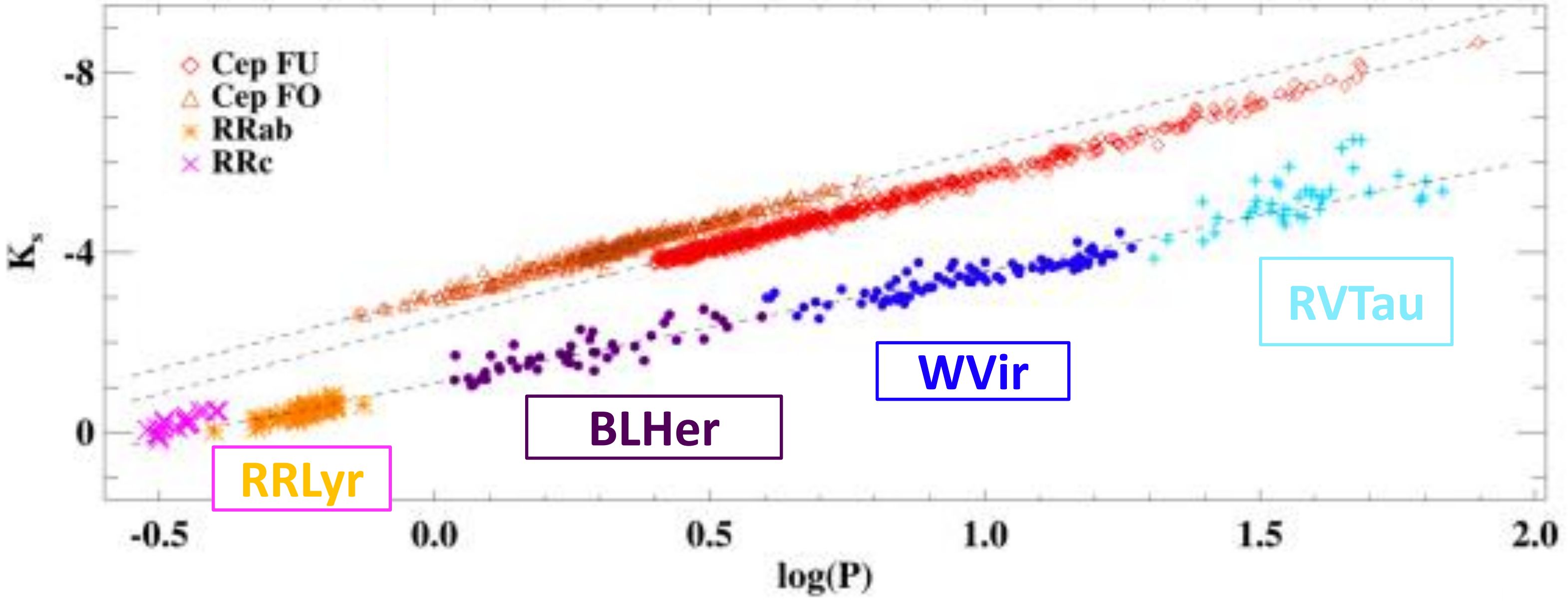
Alternative route:

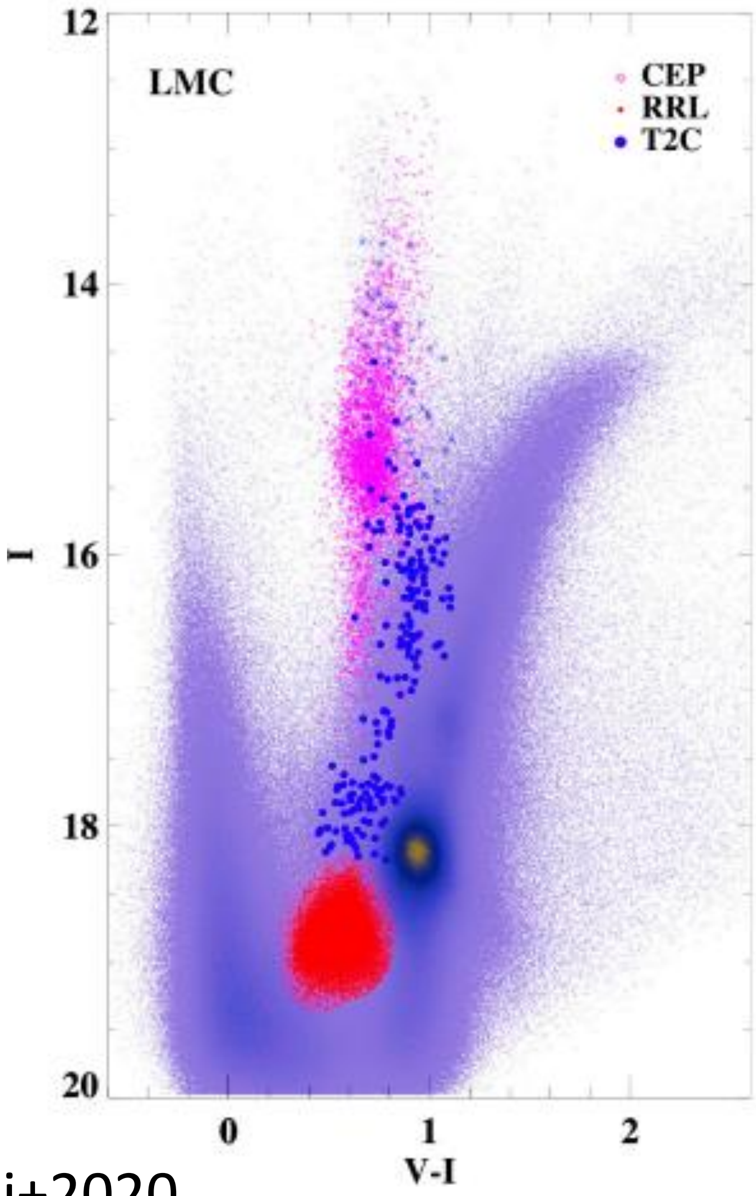


Beaton+2016

Why T2Ceps are distance indicators?

- Obey to a tight Period Luminosity relation with small dependence on metallicity (Ngeow+2022)
- Brighter than RRLyrae and 1-1.5 mag fainter than the TRGB





Bhardwaj+2020

The extragalactic distance scale

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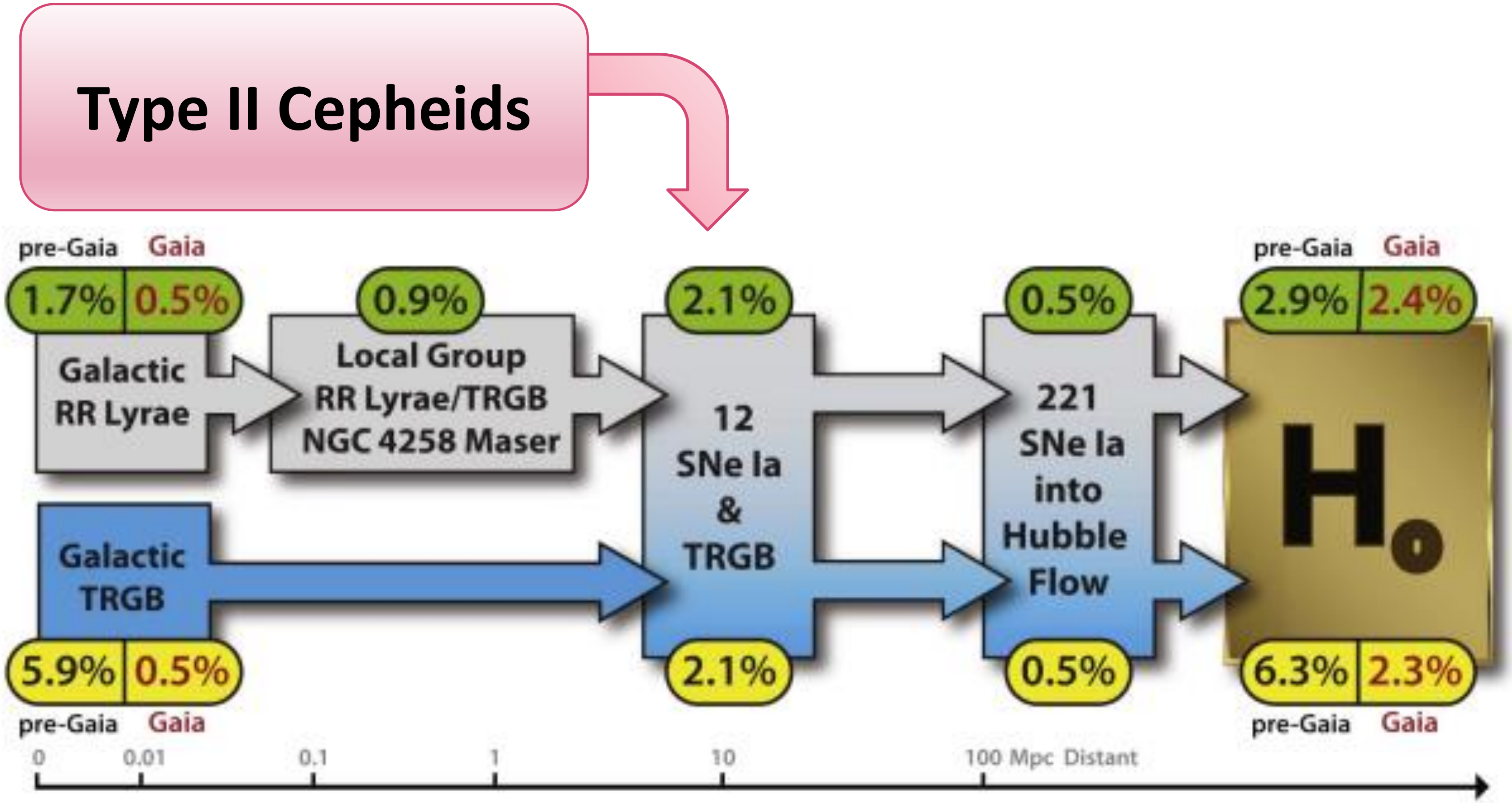
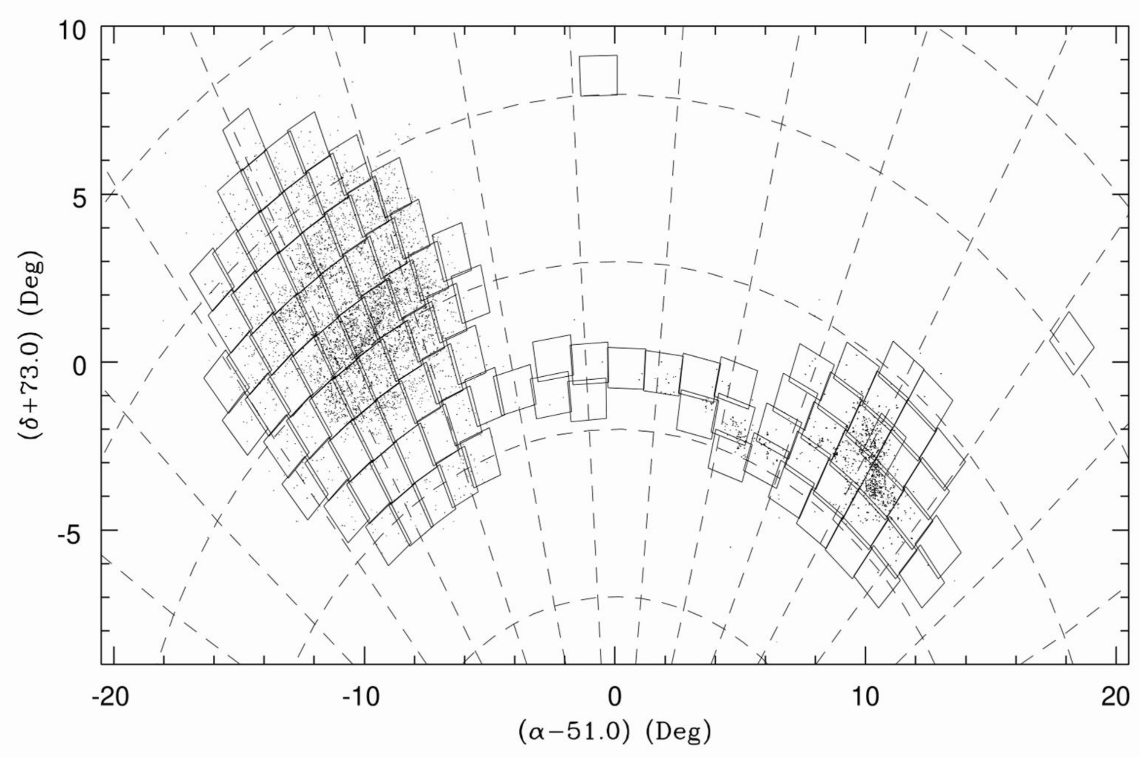


Beaton+2016

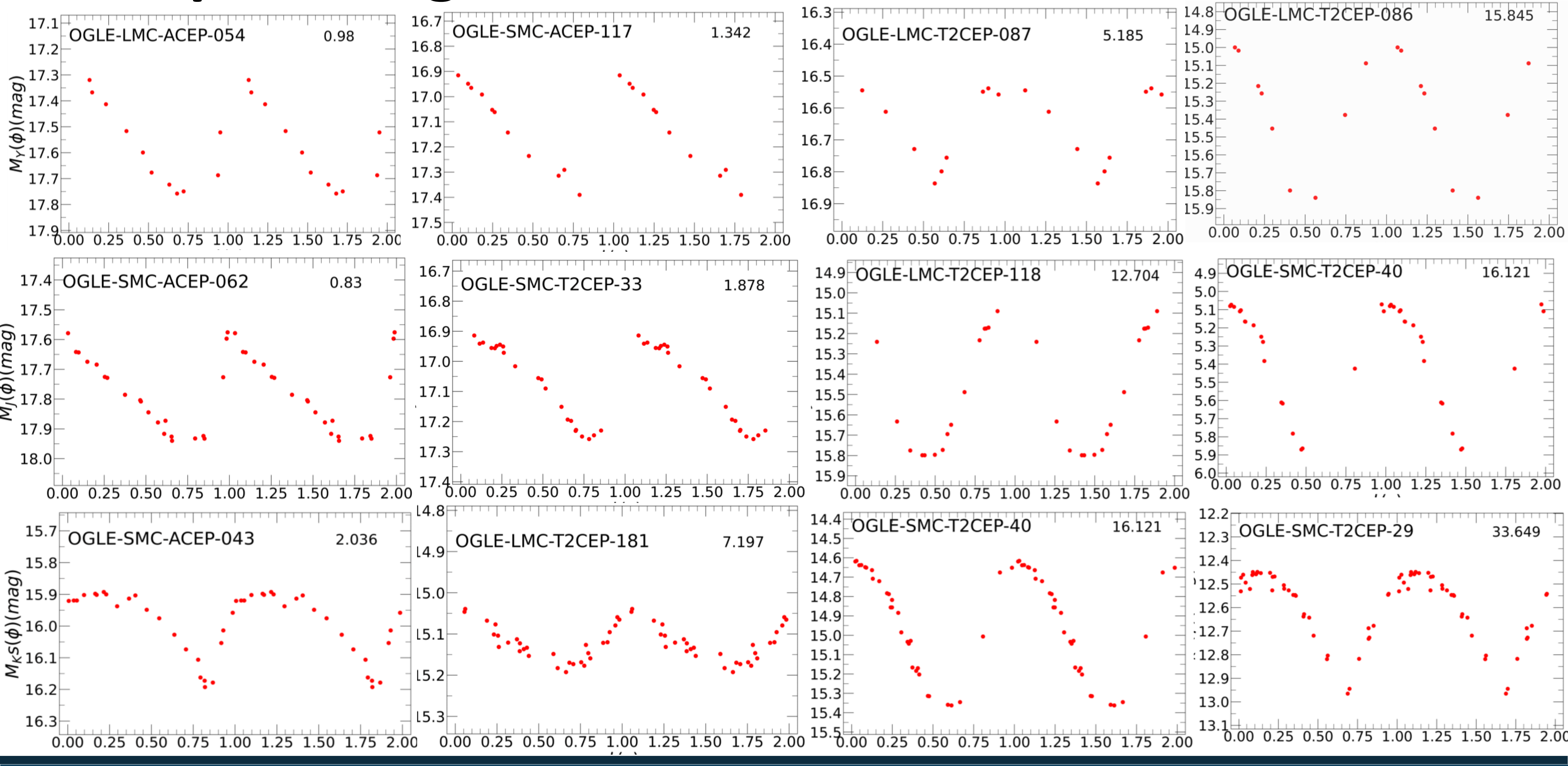
The VISTA Magellanic Clouds (VMC) survey

- VMC is an ESO public survey (P.I. M.R. Cioni, see Cioni+2011; http://star.herts.ac.uk/ ~mcioni/vmc)
- The sensitivity limit is Y = 21.1 mag, J = 21.3 mag and Ks = 20.7 mag with a signal-to-noise ratio S/N = 10.
- Total surveyed area ~ 180 deg² (LMC = 116 deg²; SMC = 45 deg² ; Bridge = 20 deg²)
- Specifically designed to have a good sampling of RR Lyrae and Cepheid light curves
- Observations in YJKs with VIRCAM@VISTA 4 m (Paranal, Chile)
- Data reduction with the VISTA Data Flow System (VDFS) pipeline at CASU (Cambridge Astronomical Survey Unit)
- Catalogues handling through the Vista Science Archive (VSA)



Cepheids: Ripepi+2012,2014,2015,2016,2017,2022
RRLyrae: Muraveva+2018,Cusano+2021

Examples of light curves

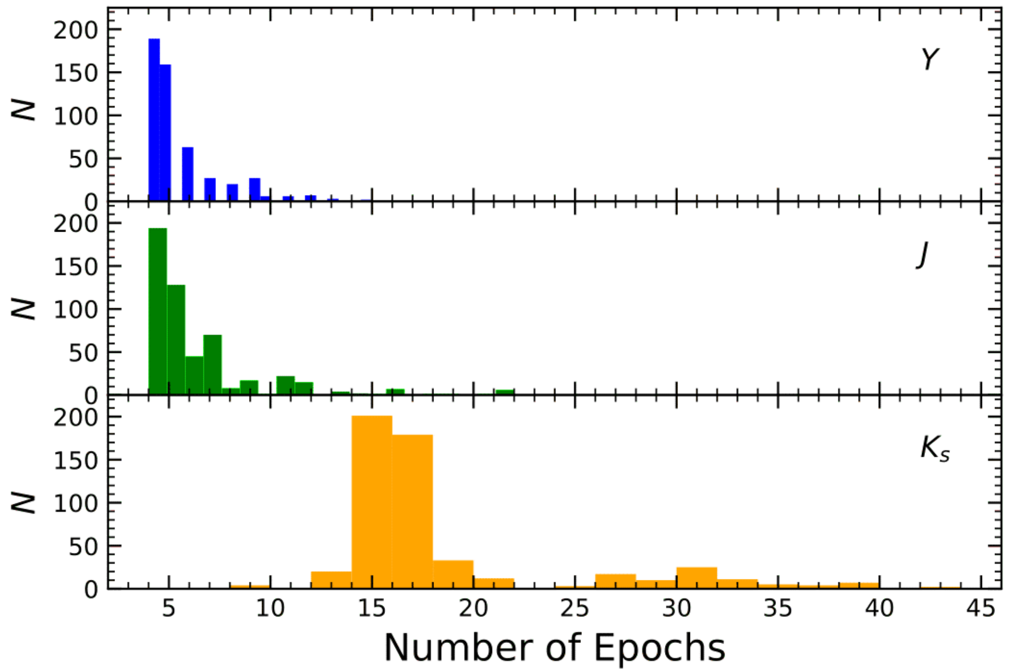


VMC data

Sample of T2Cep and ACep (identification and periods taken from OGLE IV+Gaia).

539 stars with VMC time series photometry: 200 ACs (135 F-mode and 65 1O-mode); 339 T2Cs (106 BLHer, 121 WVir, 33 pWVir and 79 RVTau).

Band	Number of epochs
Y	5 ± 2
J	6 ± 3
Ks	17 ± 6



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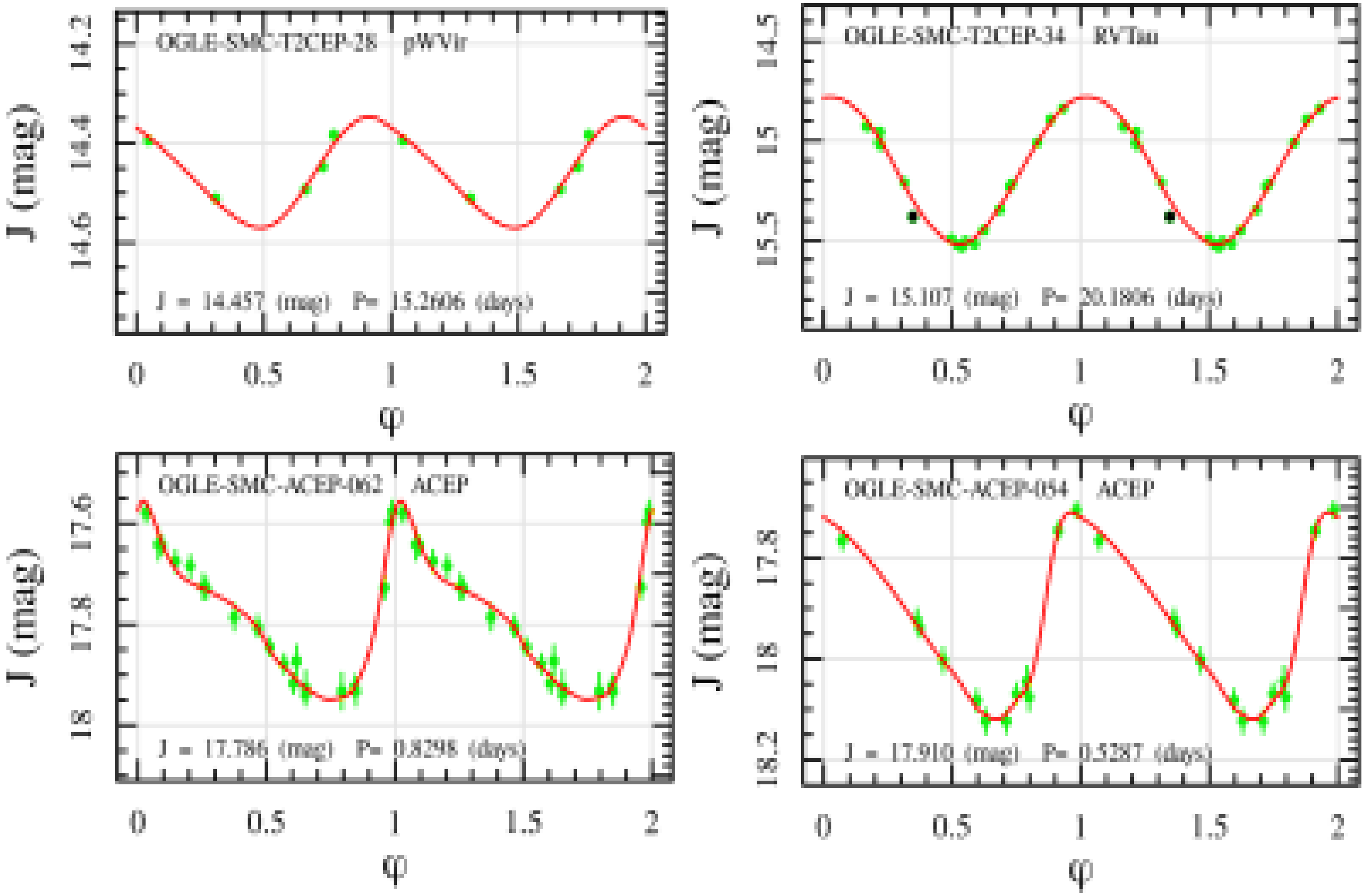

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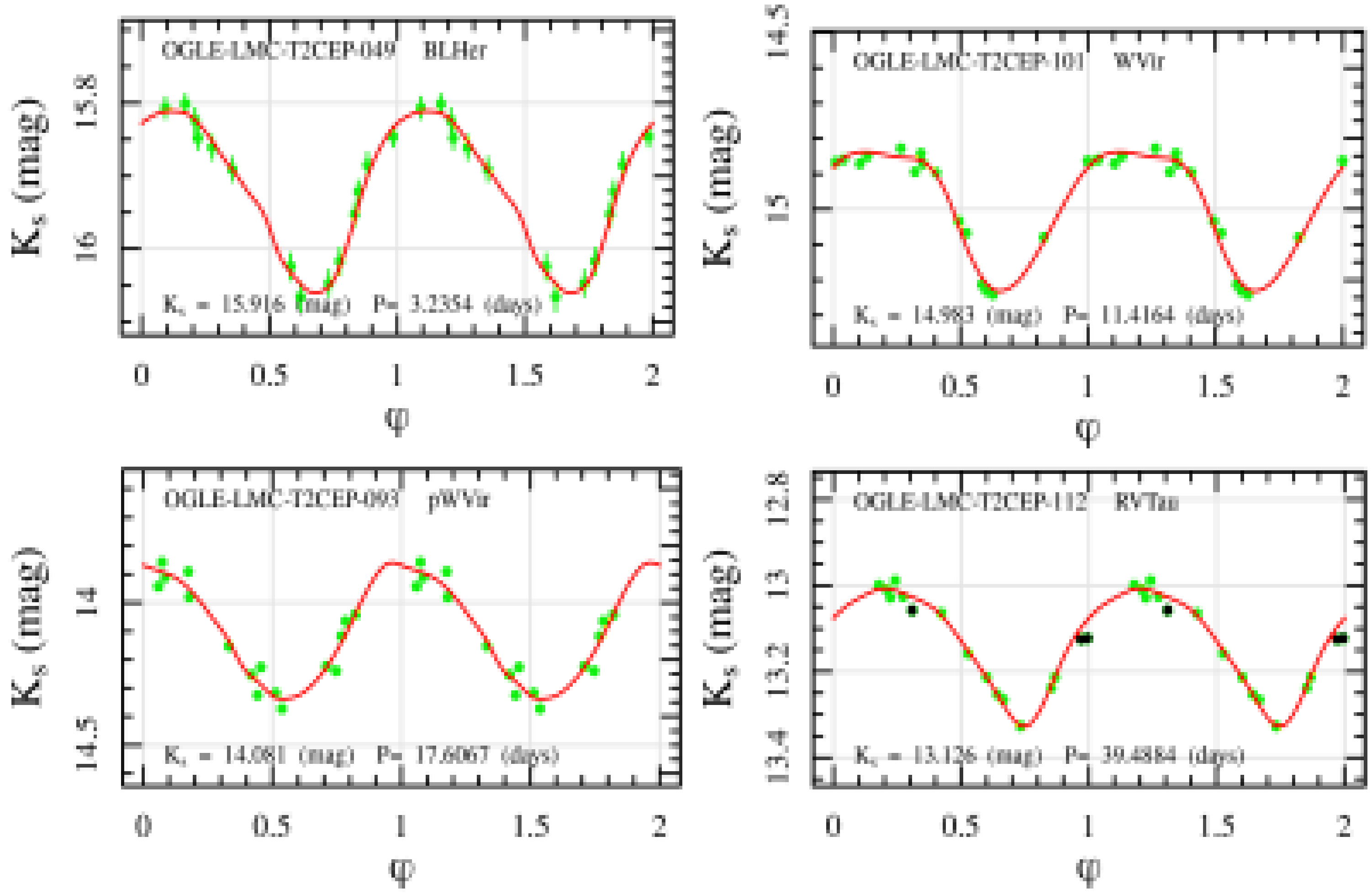
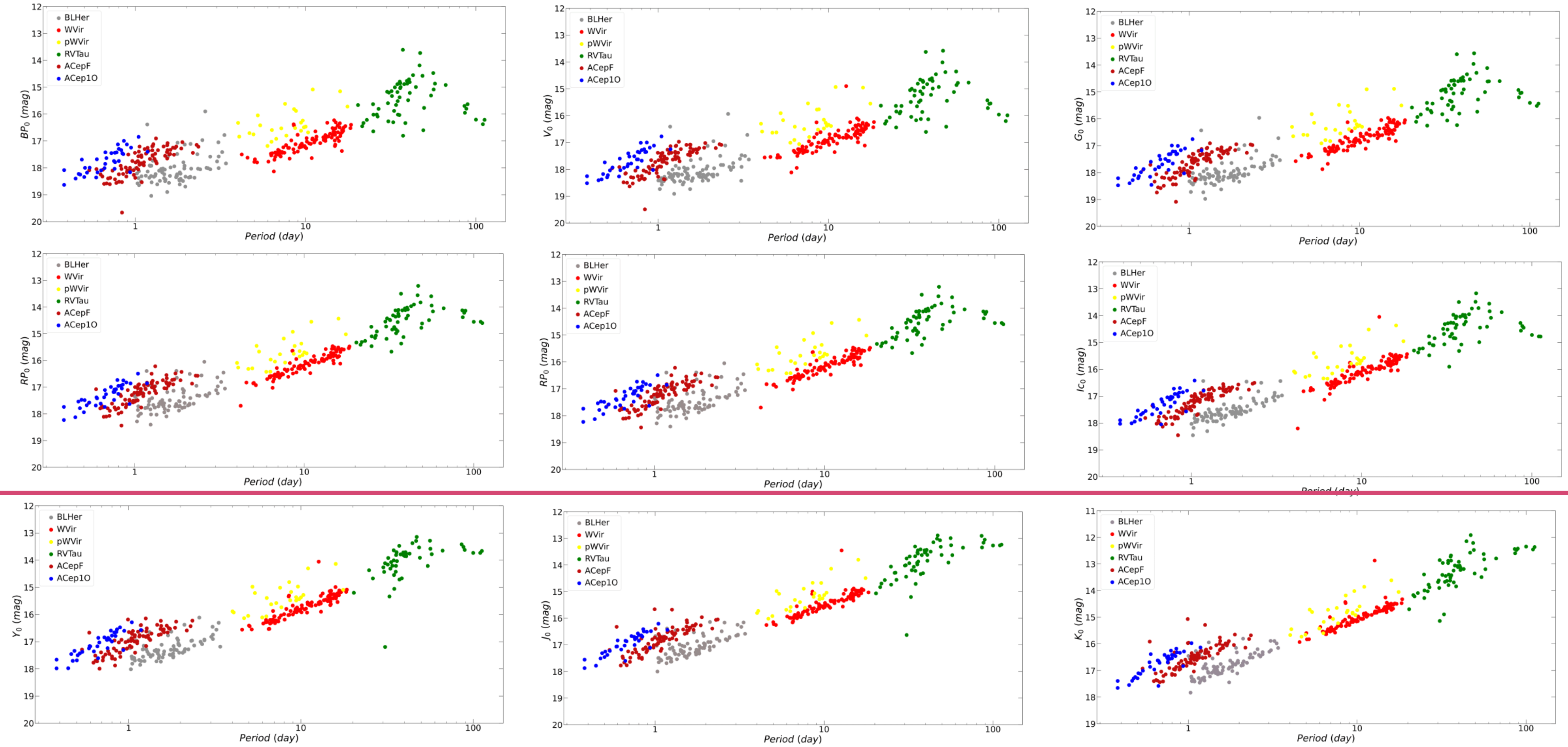


Complemetary optical photometry

- G_{BP} , G, G_{RP} bands from **Gaia**
- I, V bands from OGLE
- Reddenning maps by Skowron+2021, and Cardelli law (1989) with $R_V = 3.23$

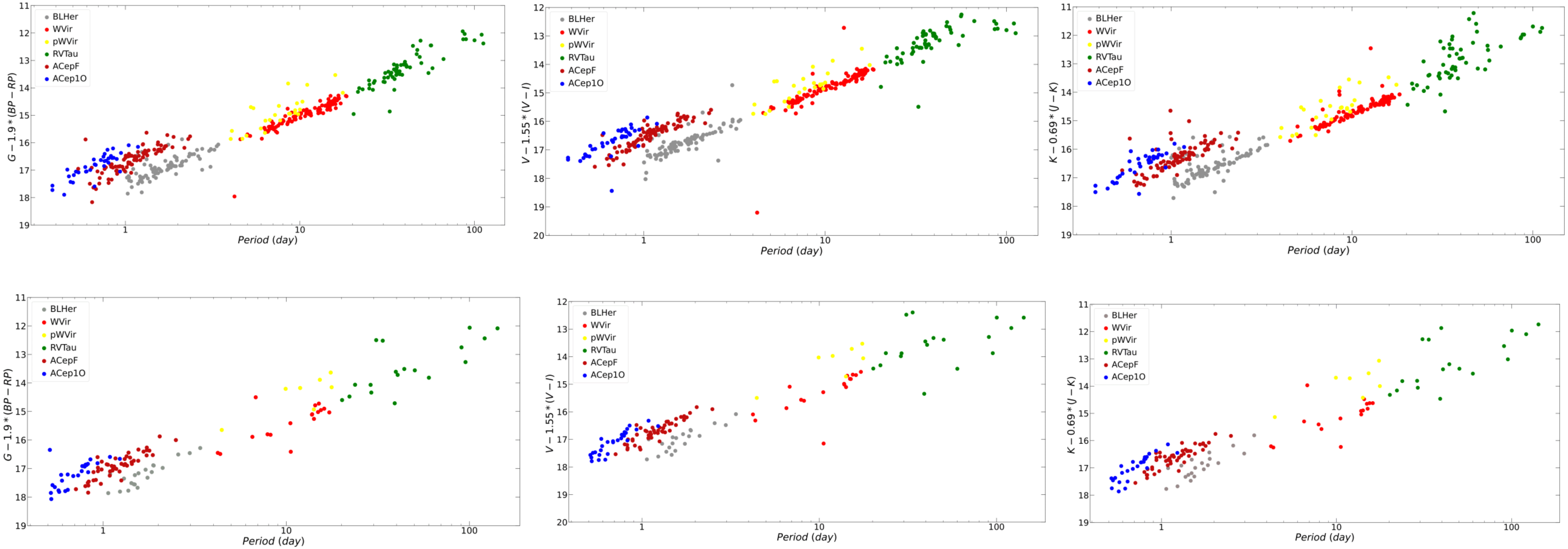
Observed *PL* relations in LMC



Observed *PW* relations

LMC

SMC



PL/*PW*/PLC derivation with the Least Trimmed Squares algorithm (Cappellari +2013)

$$m_{\lambda_0} = \alpha + \beta \cdot \log P \qquad PL$$

$$m_{\lambda_{1,0}} = \alpha + \beta \cdot \log P + \gamma \cdot \left(m_{\lambda_1} - m_{\lambda_2}\right)_0 \qquad PLC$$

$$w(\lambda_1, \lambda_2) = \alpha + \beta \cdot \log P \qquad PW$$

PL/PW/PLC

$$m_{\lambda_0} = \alpha + \beta \cdot \log P$$

Relation (1)	Group (2)	α mag (3)	σ_α mag (4)	β (5)	σ_β (6)	γ (7)	σ_γ (8)	RMS (9)	Used stars (10)	Total stars (11)
PLBP	BLHer	18.348	0.130	-0.840	0.250			0.29	74	83
PLBP	WVir	19.266	0.039	-2.190	0.110			0.18	98	103
PLBP	BLH&WVir	18.505	0.020	-1.439	0.047			0.27	175	186
PLG	BLHer	18.382	0.082	-1.450	0.160			0.20	78	85
PLG	WVir	19.019	0.029	-2.270	0.082			0.13	93	103
PLG	BLH&WVir	18.454	0.014	-1.722	0.034			0.19	178	188
PLRP	BLHer	17.945	0.097	-1.670	0.200			0.25	72	83
PLRP	WVir	18.538	0.033	-2.363	0.092			0.14	100	103
PLRP	BLH&WVir	18.092	0.012	-1.943	0.030			0.17	160	186
PLV	BLHer	18.432	0.079	-1.250	0.160			0.18	73	85
PLV	WVir	19.066	0.039	-2.150	0.110			0.17	99	104
PLV	BLH&WVir	18.520	0.016	-1.618	0.037			0.21	178	189
PLI	BLHer	17.973	0.067	-1.800	0.140			0.16	79	85
PLI	WVir	18.483	0.036	-2.370	0.100			0.16	102	104
PLI	BLH&WVir	18.028	0.012	-1.940	0.029			0.17	182	189
PLY	BLHer	17.711	0.082	-1.680	0.170			0.19	68	77
PLY	WVir	18.266	0.028	-2.473	0.080			0.13	97	100
PLY	BLH&WVir	17.823	0.012	-2.048	0.029			0.16	162	177
PLJ	BLHer	17.657	0.069	-2.250	0.140			0.17	73	83
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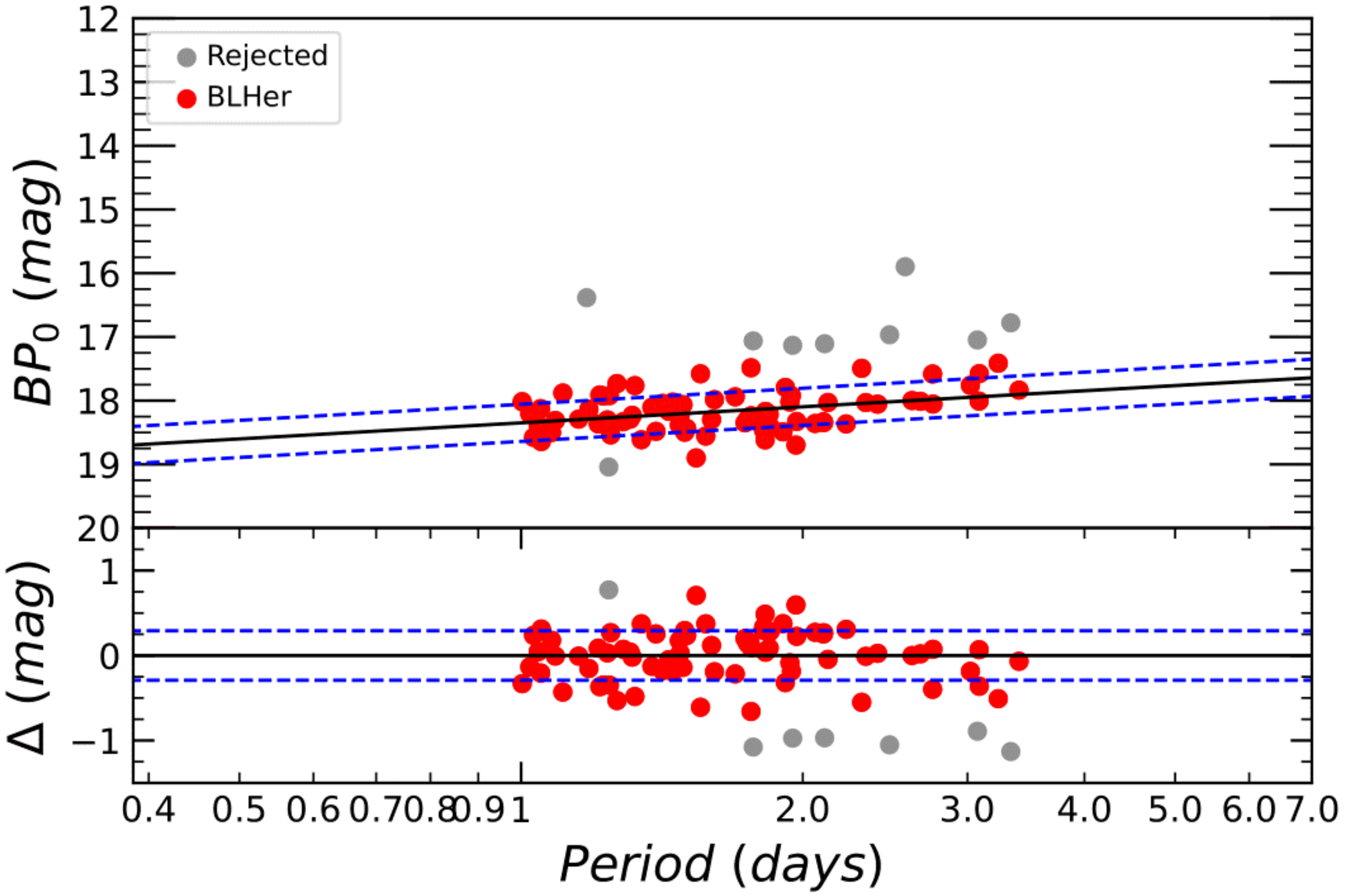
PLK	BLHer	17.444	0.066	-2.560	0.140			0.16	73	84
PLK	WVir	17.508	0.019	-2.439	0.053			0.08	98	103
PLK	BLH&WVir	17.410	0.009	-2.348	0.019			0.10	165	187



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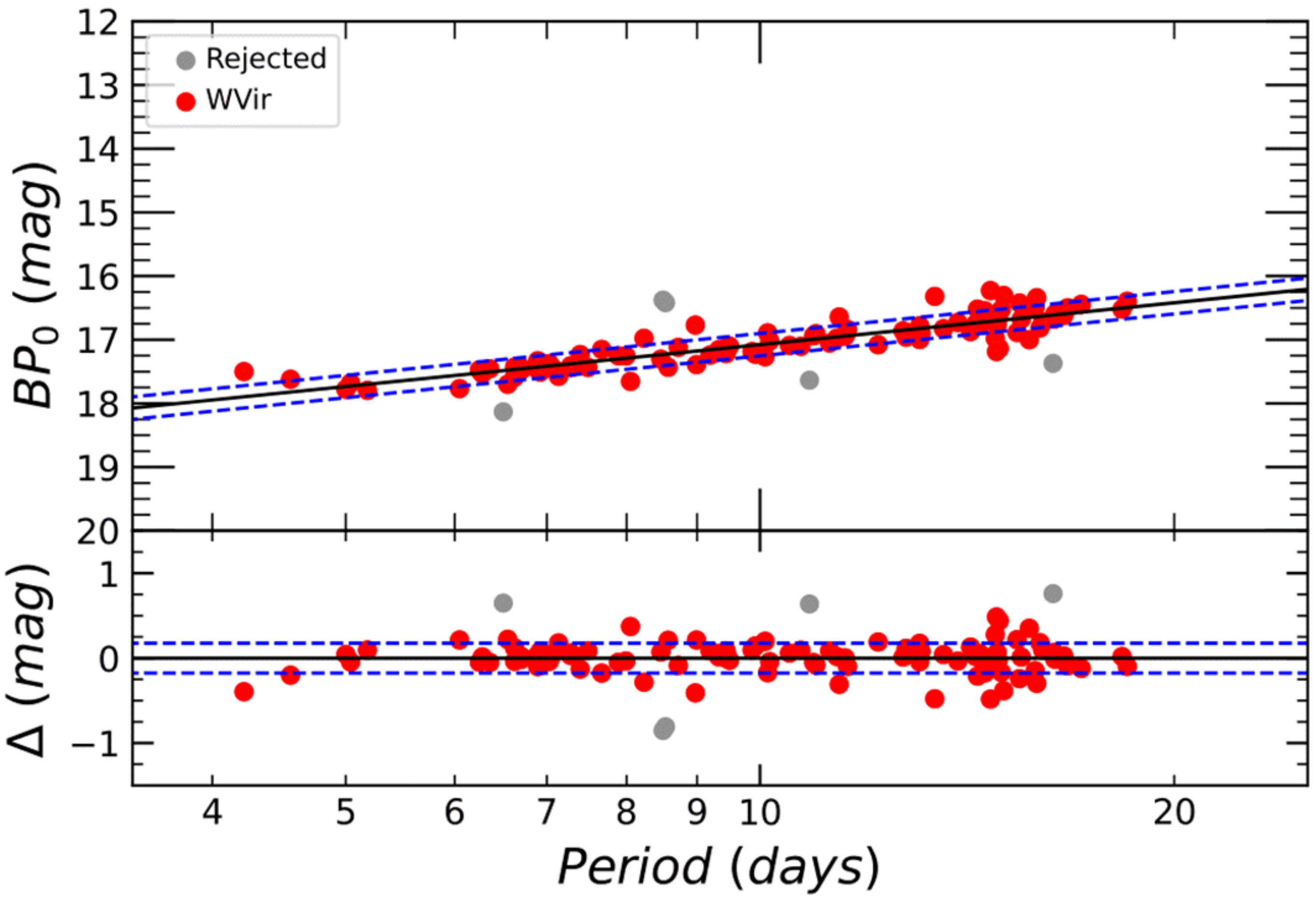

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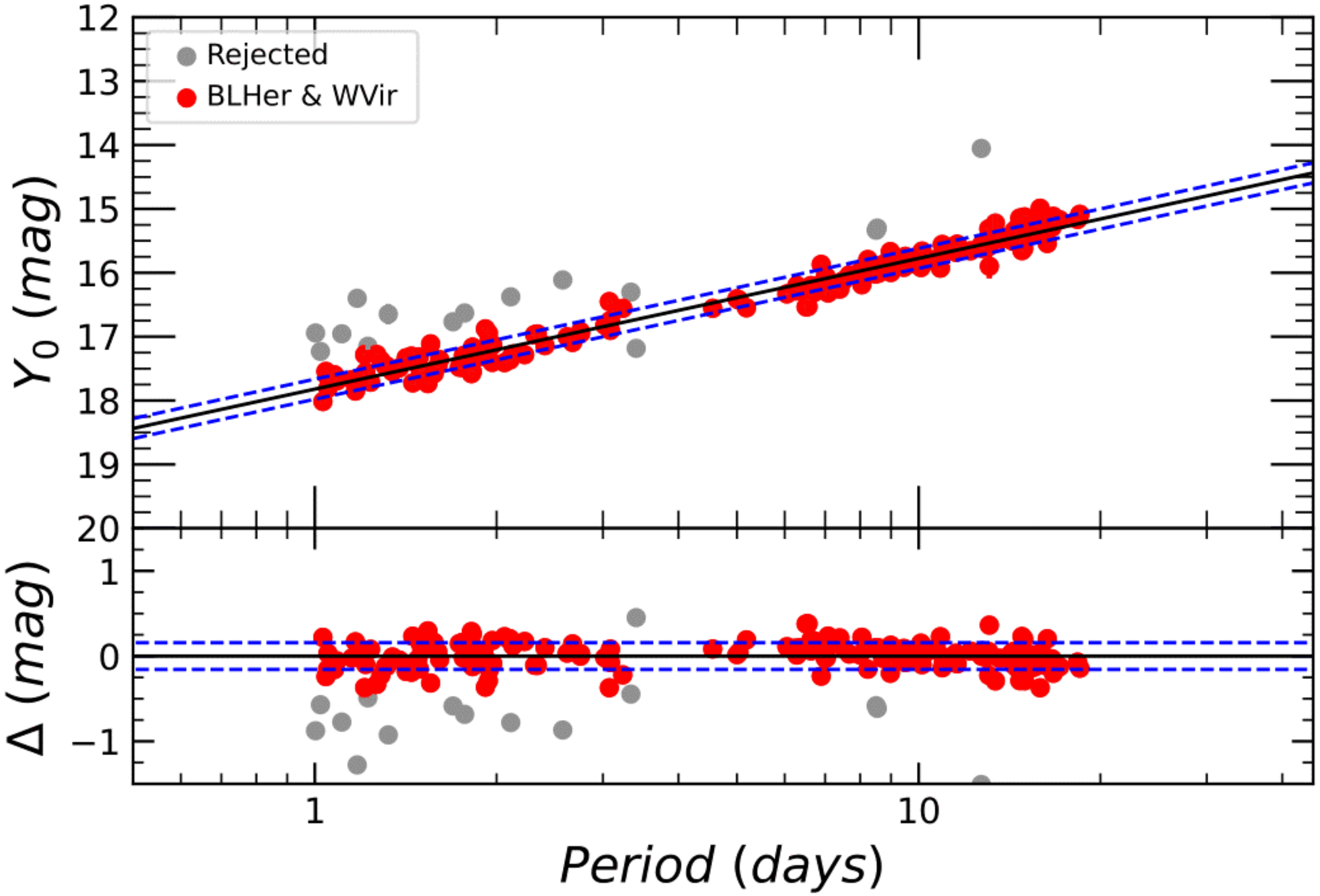

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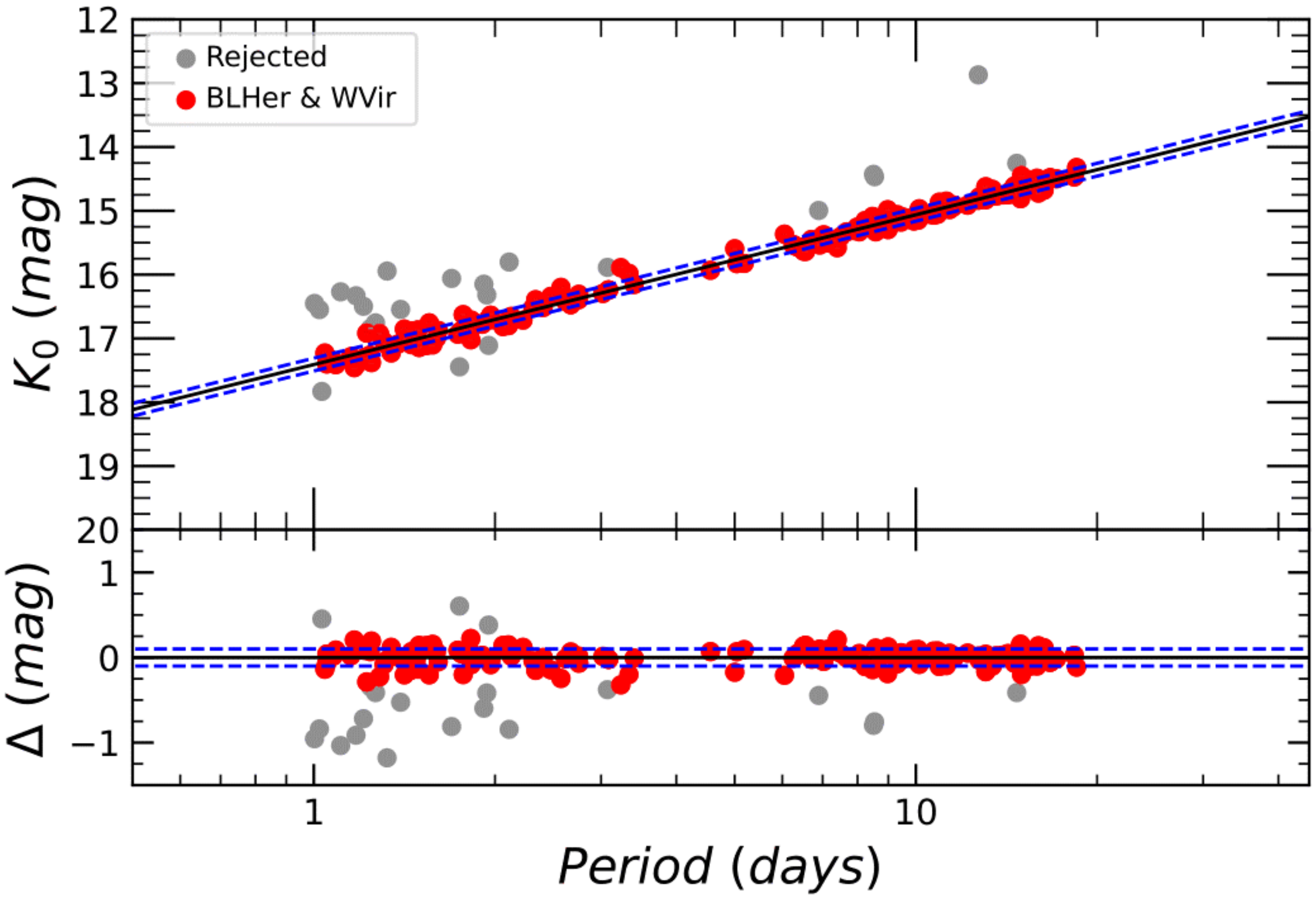

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PLK	BLHer	17.444	0.066	-2.560	0.140			0.16	73	84
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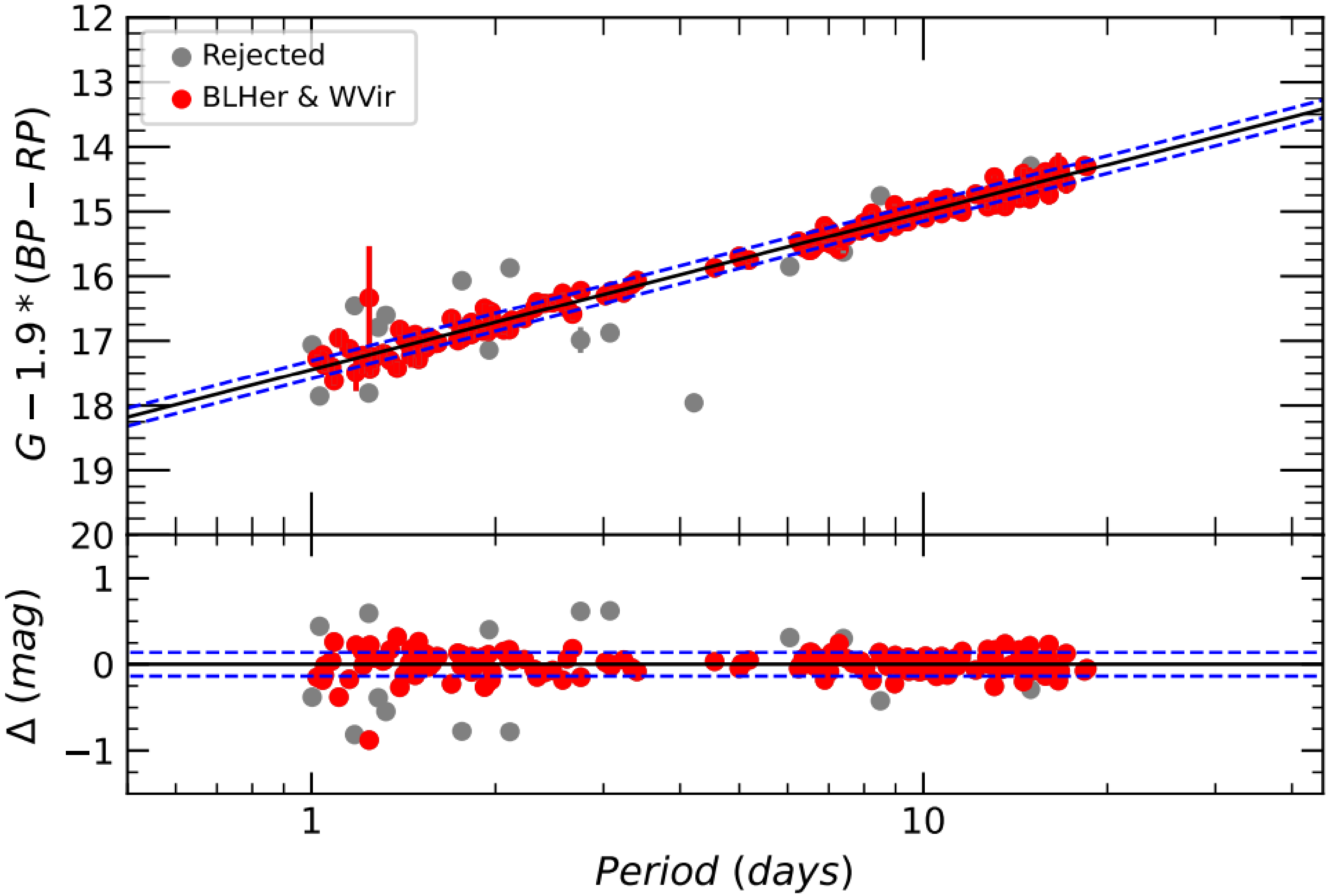
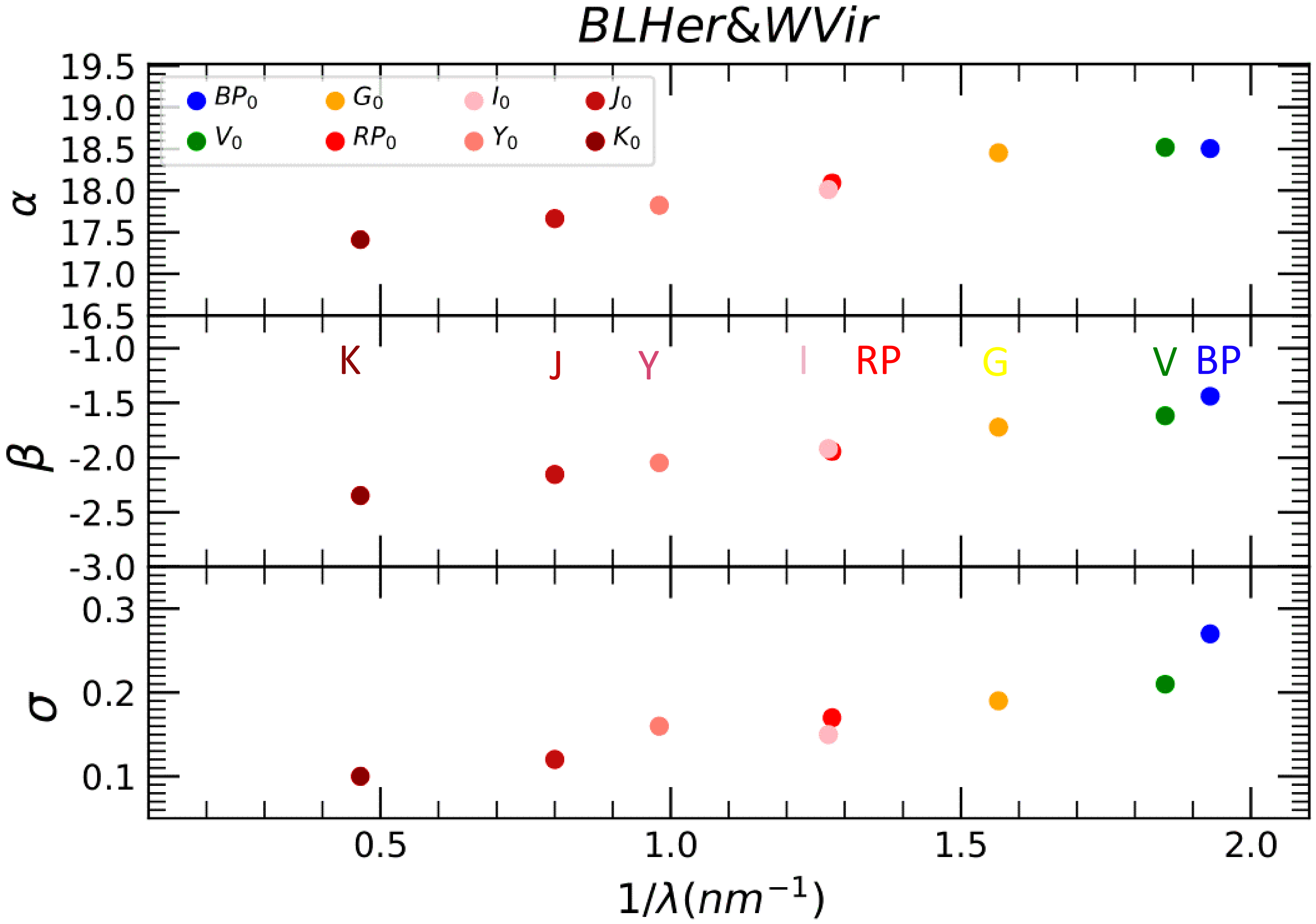
PWG	BLH&WVir	17.445	0.009	-2.436	0.022			0.14	170	186
PWVI	BLH&WVir	17.337	0.010	-2.491	0.022			0.12	177	189
PWVK	BLH&WVir	17.282	0.007	-2.475	0.017			0.09	160	187
PWYK	BLH&WVir	17.226	0.007	-2.516	0.017			0.09	151	177
PWJK	BLH&WVir	17.251	0.006	-2.501	0.016			0.08	146	181
PLCG	BLH&WVir	17.334	0.009	-2.501	0.033	2.070	0.062	0.15	170	186
PLCVI	BLH&WVir	17.143	0.013	-2.604	0.036	2.912	0.092	0.10	168	189
PLCVK	BLH&WVir	17.295	0.007	-2.447	0.029	0.118	0.030	0.09	162	187
PLCYK	BLH&WVir	17.325	0.008	-2.421	0.026	0.223	0.059	0.09	157	177
PLCJK	BLH&WVir	17.372	0.008	-2.379	0.031	0.150	0.110	0.11	161	181



Wavelength dependence of the *PL coefficients* in the LMC

$$m_{\lambda_0} = \alpha + \beta \cdot \log P$$

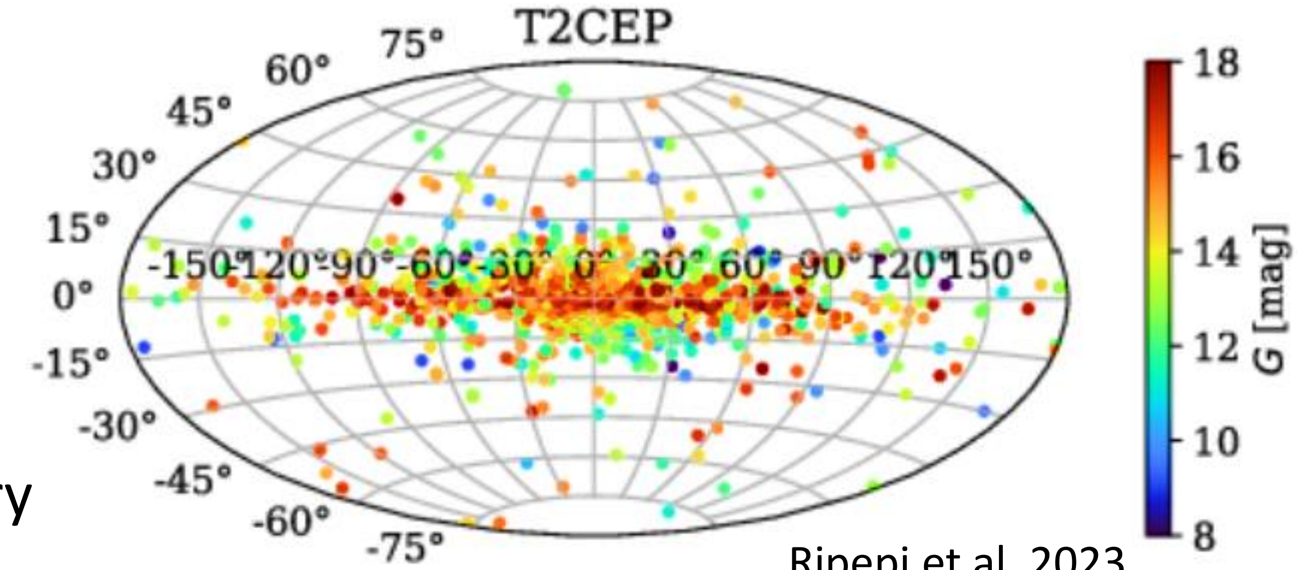


Absolute Calibration with Gaia parallaxes

➔ Dataset collected in Gaia DR3 (Ripepi et al.2023), complementary optical photometry from literature:

1635 Galactic T2C (579 BLHer, 795 WVir, 262 RVTau).

Small amount of this has NIR photometry (Wielgorski et al. 2022).

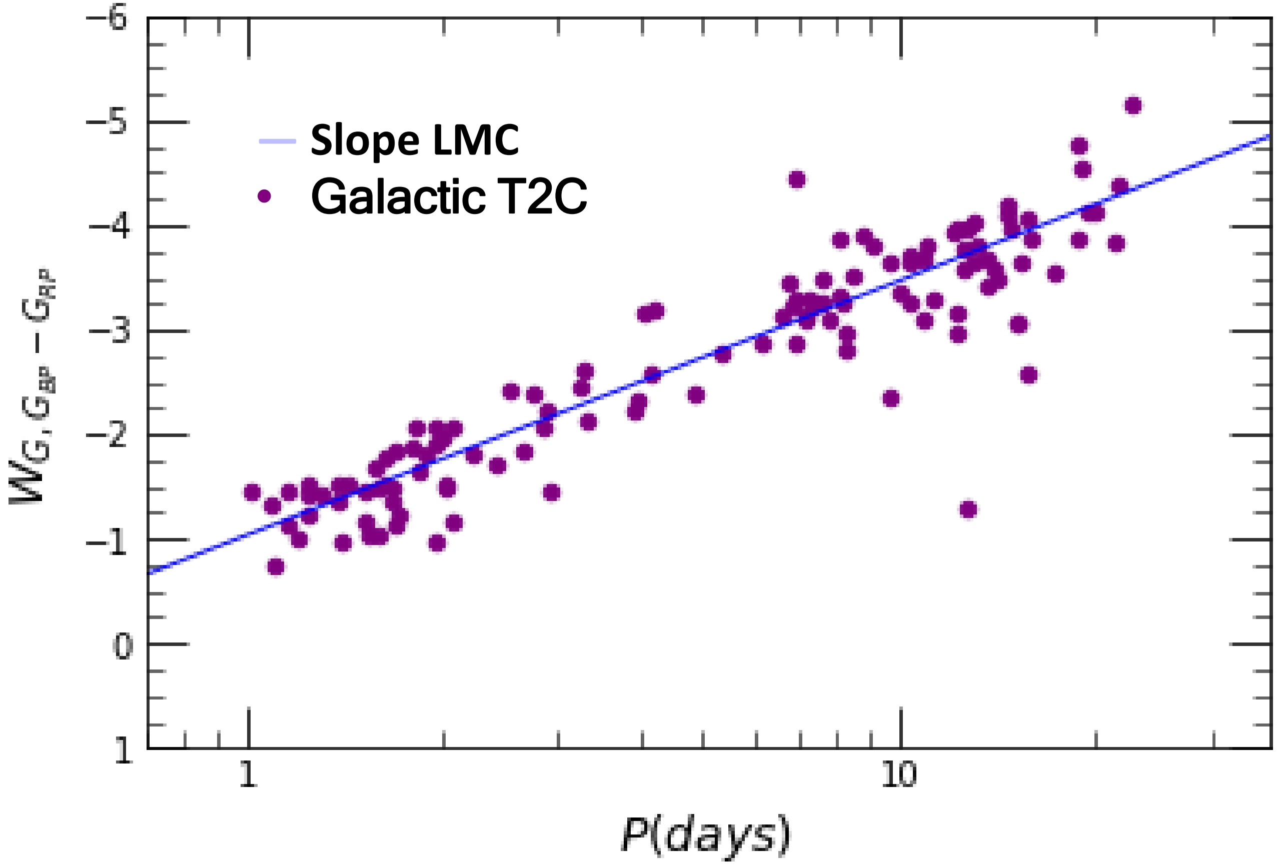


Ripepi et al. 2023

Absolute Calibration with Gaia Parallaxes

Is the slope of the PL/PW the same in LMC and in the Galactic field?

$$W_{G,G_{BP}-G_{RP}} = m_G - 1.90 \cdot \left(m_{G_{BP}} - m_{G_{RP}}\right) + 5\log\pi - 10$$



Calibration with different techniques:

$$w_G = m_G - 1.90 \cdot (m_{BP} - m_{RP})$$

ABL

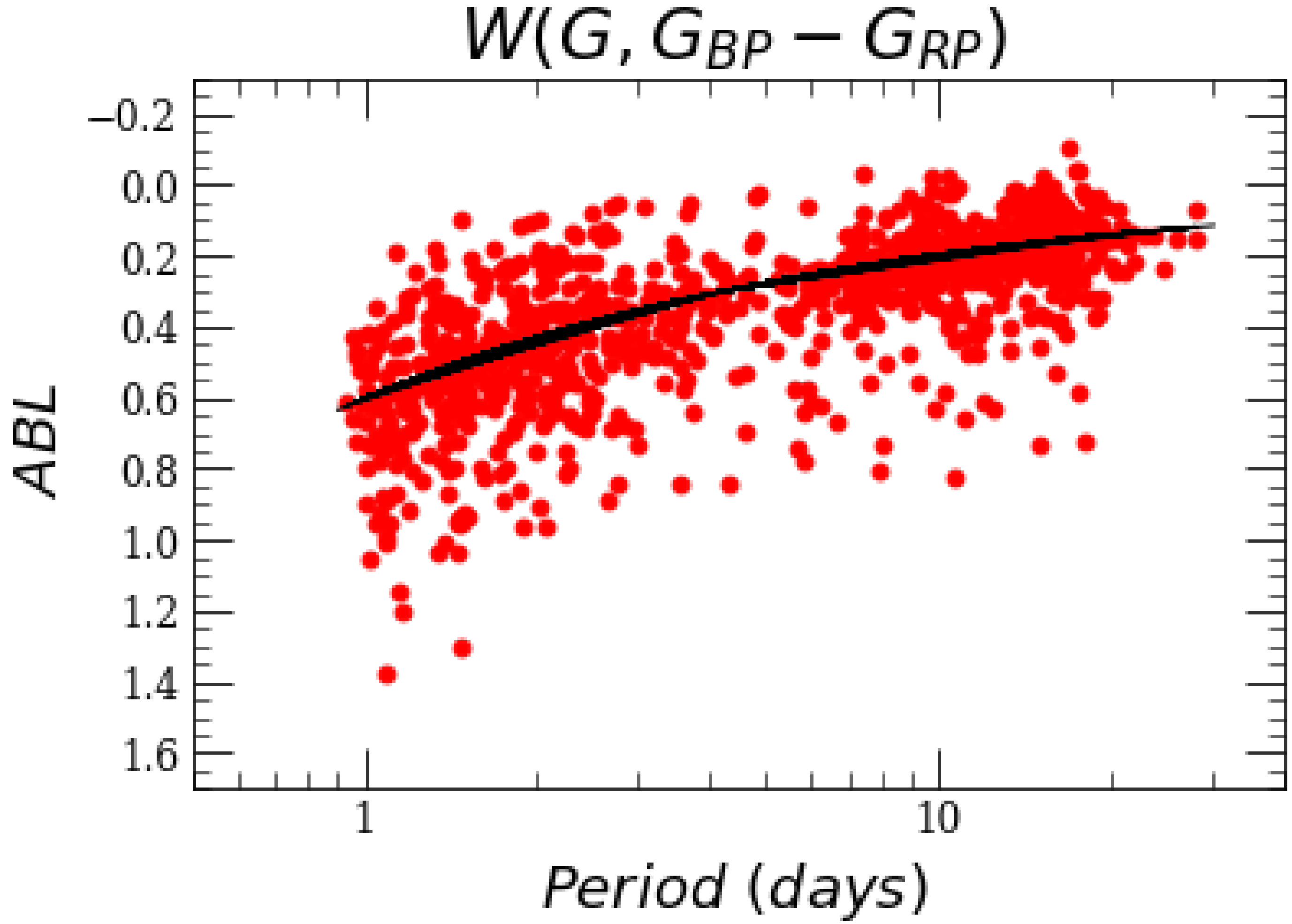
$$\varpi 10^{0.2\, w_G\, -2} = 10^{0.2\,(\alpha+\beta_{LMC} \cdot log\ P)}$$

ZP: $-1.09 \pm 0.02\, mag$

Photometric Parallax

$$\varpi = 10^{-0.2 \cdot (w_G - (\alpha+\beta_{LMC} \cdot log\ P) - 10)}$$

ZP: $-1.04 \pm 0.02\, mag$



Calibration with different techniques:

$$w_{JK} = m_{K_s} - 0.71 \cdot (m_J - m_{K_s})$$

ABL

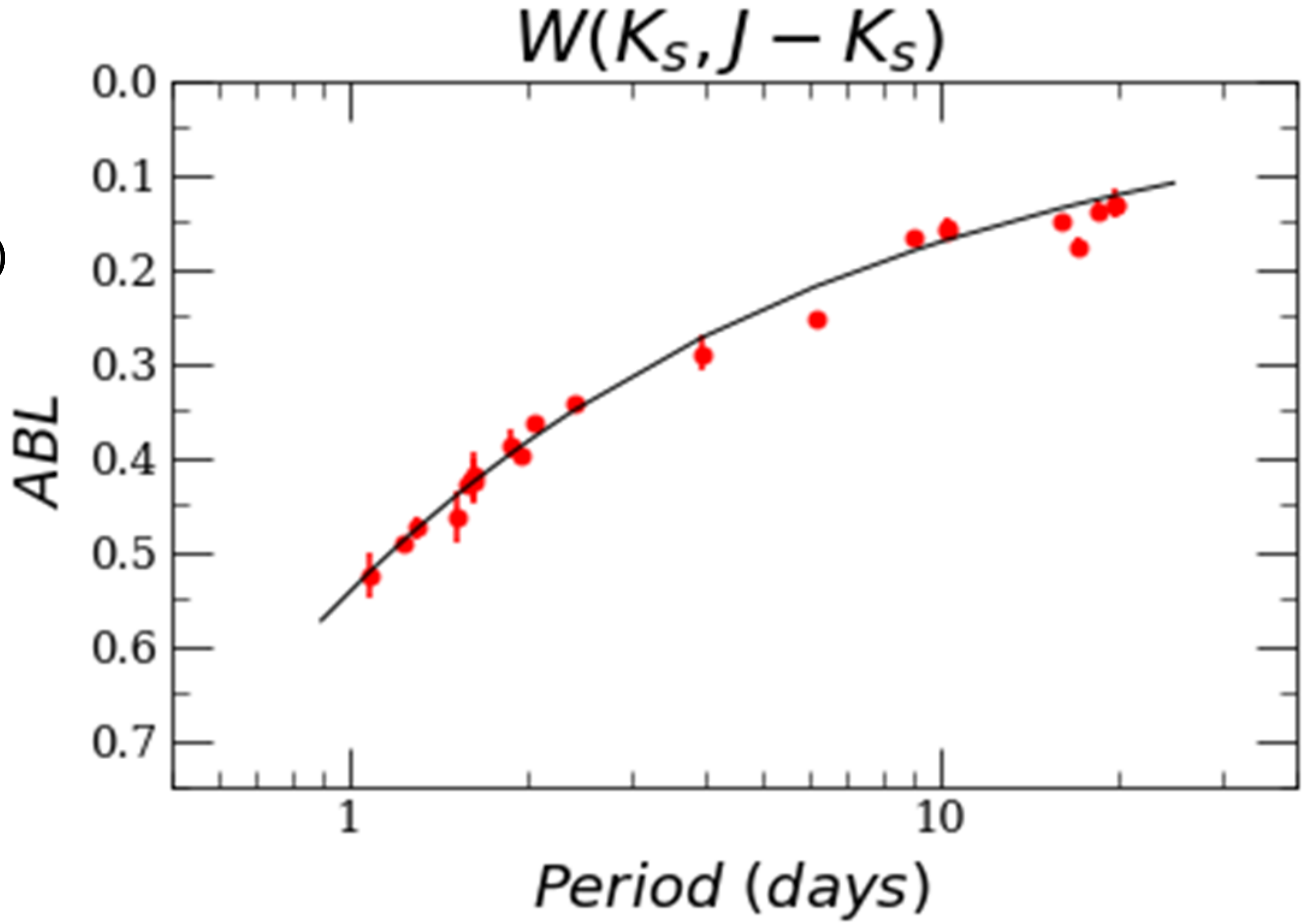
$$\varpi 10^{0.2\, w_{JK} - 2} = 10^{0.2\, (\alpha + \beta_{LMC} \cdot \log P)}$$

ZP: $-1.32 \pm 0.03\, mag$

Photometric Parallax

$$\varpi = 10^{-0.2 \cdot (w_{JK} - (\alpha + \beta_{LMC} \cdot \log P) - 10)}$$

ZP: $-1.29 \pm 0.03\, mag$



Calibration with different techniques:

$$w_{VK} = m_{K_s} - 0.13 \cdot (m_V - m_{K_s})$$

ABL

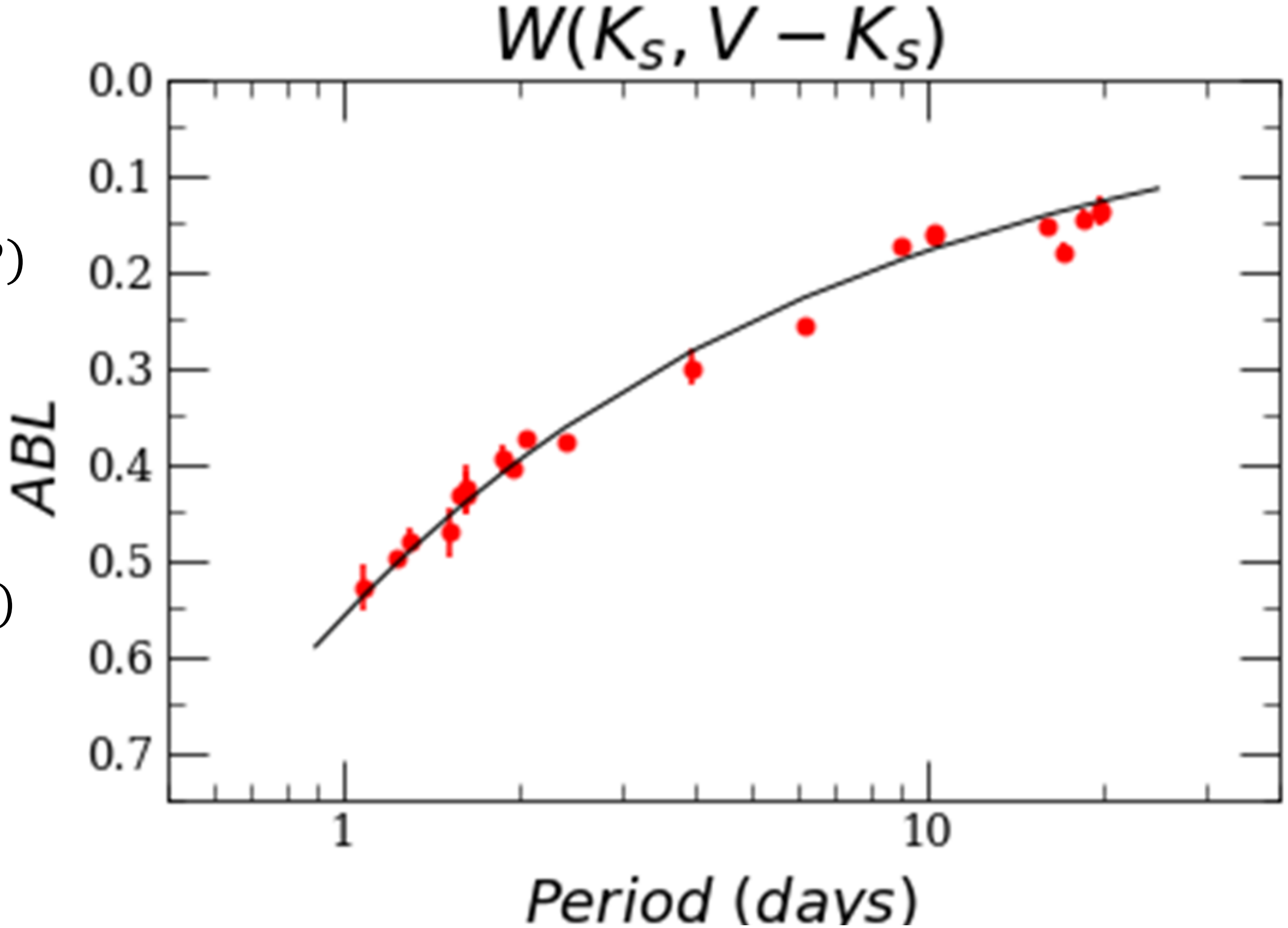
$$\varpi 10^{0.2\, w_{VK} - 2} = 10^{0.2\,(\alpha + \beta_{LMC} \cdot \log P)}$$

ZP: $-1.26 \pm 0.03\, mag$

Photometric Parallax

$$\varpi = 10^{-0.2 \cdot (w_{VK} - (\alpha + \beta_{LMC} \cdot \log P) - 10)}$$

ZP: $-1.24 \pm 0.03\, mag$



Application of PL/PW/PLC relations:

➔ Large Magellanic Cloud Distance

From LMC, apparent PW:

$$w_{G,G_{BP}-G_{RP}} = 17.445 - 2.436 \cdot logP$$

$$w_{K_s,J-K_s} = 17.251 - 2.501 \cdot logP$$

$$w_{K_s,V-K_s} = 17.282 - 2.475 \cdot logP$$

From galactic T2C, absolute PW:

$$W_{G,G_{BP}-G_{RP}} = -1.041 - 2.436 \cdot logP$$

$$W_{K_s,J-K_s} = -1.291 - 2.501 \cdot logP$$

$$W_{K_s,V-K_s} = -1.244 - 2.475 \cdot logP$$

$$D_{LMC}\left(W_{G,G_{BP}-G_{RP}}\right) = 18.49 \pm 0.03\, mag$$

$$D_{LMC}\left(W_{K_s,J-K_s}\right) = 18.54 \pm 0.03\, mag \; *$$

$$D_{LMC}\left(W_{K_s,V-K_s}\right) = 18.52 \pm 0.03\, mag$$

* Same as Wielgorski et al. 2022

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$$W_{K_s,V-K_s} = -1.244 - 2.475 \cdot logP$$

$D_{LMC}(W_{G,G_{BP}-G_{RP}}) = 18.49 \pm 0.03\ mag$	$0.01 \pm 0.04\ mag$
$D_{LMC}(W_{K_s,J-K_s}) = 18.54 \pm 0.03\ mag$ *	$0.06 \pm 0.04\ mag$
$D_{LMC}(W_{K_s,V-K_s}) = 18.52 \pm 0.03\ mag$	$0.04 \pm 0.04\ mag$

* Same as Wielgorski et al. 2022

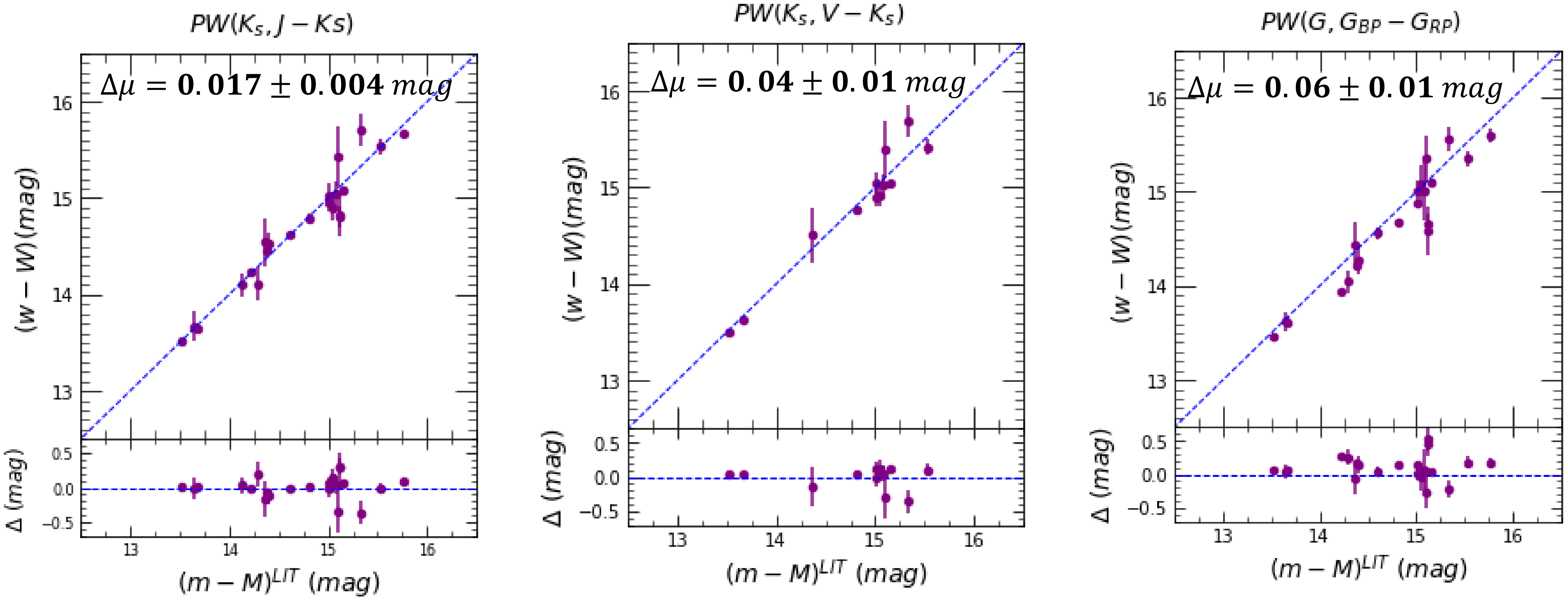
Application of PL/PW/PLC relations:

➔ Calculation of the distances for Galactic Globular Clusters hosting T2Cep.

Distances	Baumgardt &Vasiliev 2021
Intensity-averaged magnitudes	Bhardwaj 2017,2022 ; Braga 2020
Reddening	Harris 2010

Comparison between our distances (mag) and those by Baumgardt &Vasiliev 2021

$$\Delta\mu = \mu_{LETT} - \mu_{TW}$$



The distance moduli of GGCs are **overestimated**.

Summary

- ✓ Construction of PL/PW/PLC for T2Cs (in different combinations) in the optical and NIR bands based on accurate intensity-averaged magnitudes from a sample of 539 starmetry observed in the context of the **VISTA Magellanic Clouds survey** .
- ✓ Study of the wavelength dependence of the PL\PW\PLC coefficients.
- ✓ Distance of LMC from our PW relations in agreement with geometric distance by 1σ.
- ✓ Application to Galactical Globular Clusters hosting T2Cs suggests an overestimation of the literature distances by some 2-5%.

Future developments

- ➔ Exploitation of PL/PW/PLC for ACs (in different combinations) in the optical and NIR bands.
- ➔ Comparison of the distance scale for Classical , Type II and Anomalous Cepheids .

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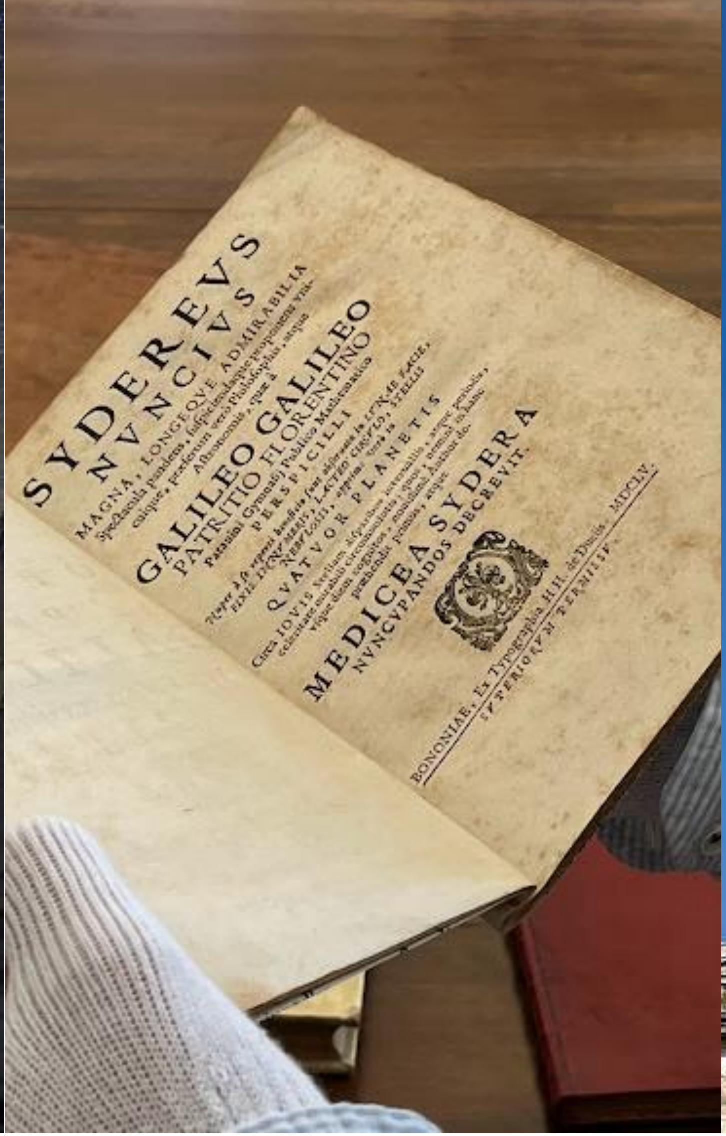

VMC

teresa.sicignano@inaf.it
INAF-Osservatorio Astronomico di Capodimonte, Naples