Primary PL-Relation Calibrators in the Milky Way: Cepheids and RR Lyrae

Physical basis, Calibration, and Applications

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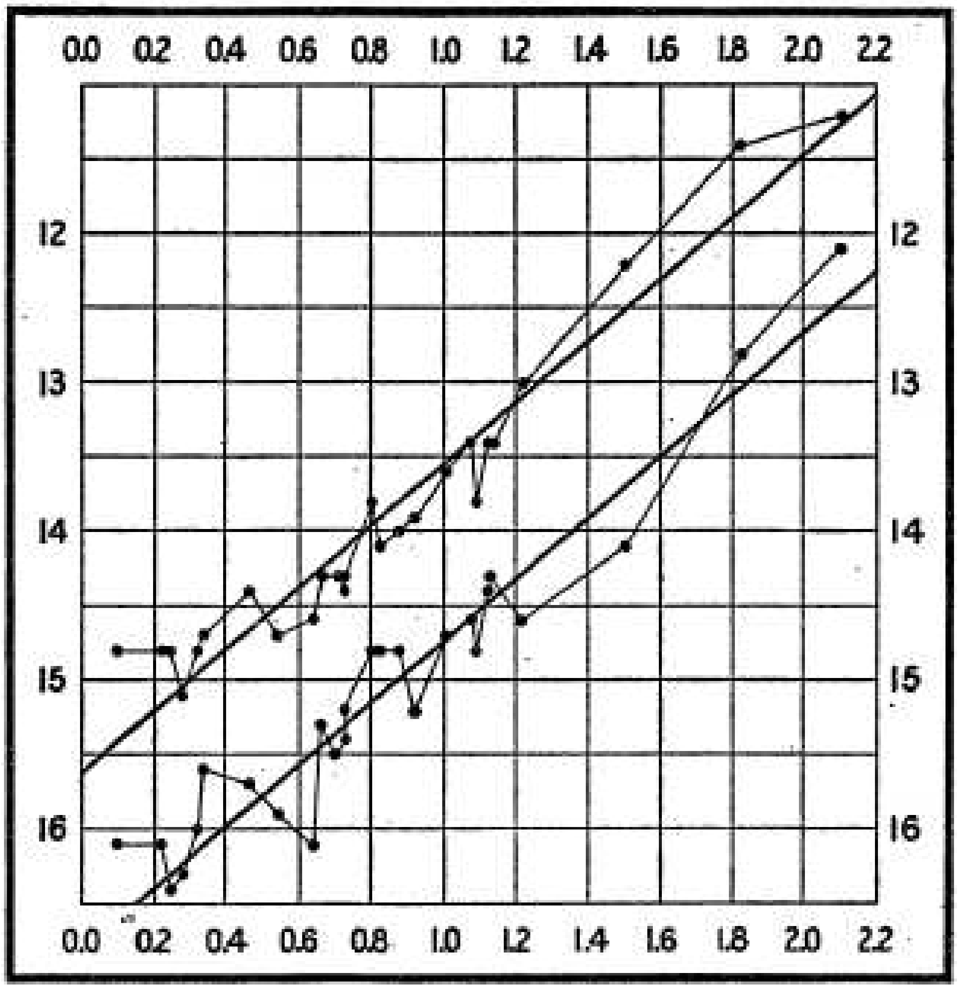
Overview Talk

- Introduction
  - Hipparcos and beyond
- PL-relation: Application
  - Galactic Structure
- PL-relation: Calibration
  - Distance scale
    - Cepheids in Clusters
    - Reddening
- Concluding remarks

When it all started



Leavitt & Pickering (1912)
(Leavitt 1908)

$\Delta \log P / M = 0.48$

$$M = (-2.02 \pm 0.10) \log P + (16.16 \pm 0.10)$$

Hipparcos

Feast & Catchpole (1997, MN 286)
220 classical Cepheids
$M_{\rm V} = -2.81 \log P + (-1.43 \pm 0.10) \Rightarrow$ DM= 18.70 ± 0.10
ONLY Polaris (FO), -1.41 ± 0.14

Madore & Freedman (1998, ApJ 492) BVIJKH 7-19 stars
$\Rightarrow$ DM= 18.44 ± 0.45 to 18.57 ± 0.11

van Leeuwen, Feast, Whitelock & Laney (2007, MN 379)
$M_{\rm K} = -3.258 \log P + (-2.40 \pm 0.05) \Rightarrow$ DM= 18.47 ± 0.03

Gratton (1998, MN 296)
3 RR Lyrae, 9 RHB, 10 BHB
$M_{\rm V} = (0.22 \pm 0.22) \cdot ([{\rm Fe/H}] + 1.5) + (0.66 \pm 0.11)$

post-Hipparcos, pre-Gaia

FGS/HST:
Benedict et al. (2002 AJ 123; 2007 AJ 133; 2011 AJ 142)
Benedict et al. (2017, PASP 129): 105 objects with FGS
WFC/HST:
Riess et al. (2014, ApJ 785; 2018, ApJ 855)

Fouqué et al. (2007, A&A 476) CEP PL-relations in 9 bands using 59 calibrators (FGS/HST, rev. Hipparcos, Baade-Wesselink method, Clusters [ZAMS fitting])

$$W_{\rm VI} = (-3.477 \pm 0.074) \log P + (-2.414 \pm 0.032)$$
$$W_{\rm K} = (-3.365 \pm 0.063) \log P + (-2.282 \pm 0.019)$$

Benedict et al. (2011) for RRL

$$M_{\rm V} = (0.214 \pm 0.047)([{\rm Fe/H}] + 1.5) + (0.45 \pm 0.05)$$
$$M_{\rm K} = (-2.11 \pm 0.17)(\log P + 0.28) + (0.05 \pm 0.07)([{\rm Fe/H}] + 1.58) + (-0.56 \pm 0.03)$$

Photometric surveys

Gaia DR3:
Clementini et al. (arXiv220606278) 270 900 RRL
(70 600 new; 234 700 not in directions MCs; 96 GCC)

Ripepi et al. (arXiv220606212) 15 000 of ALL types
(3300 DCEP, not in direction MCs/M31/M33)

OGLE:
78 000 RR Lyrae Stars Galactic Bulge and Disk Fields
(Soszyński et al. 2019, AcA 69)

1370 BLG+330 GD T2C (Soszyński et al. 2020, AcA 70)

Photometric surveys

VVV/VVVX:
RRL: Contreras Ramos et al. (2018, ApJ 863), Dékány et al. (2018, ApJ 857), Majaess et al. (2018, Ap&SS 363)

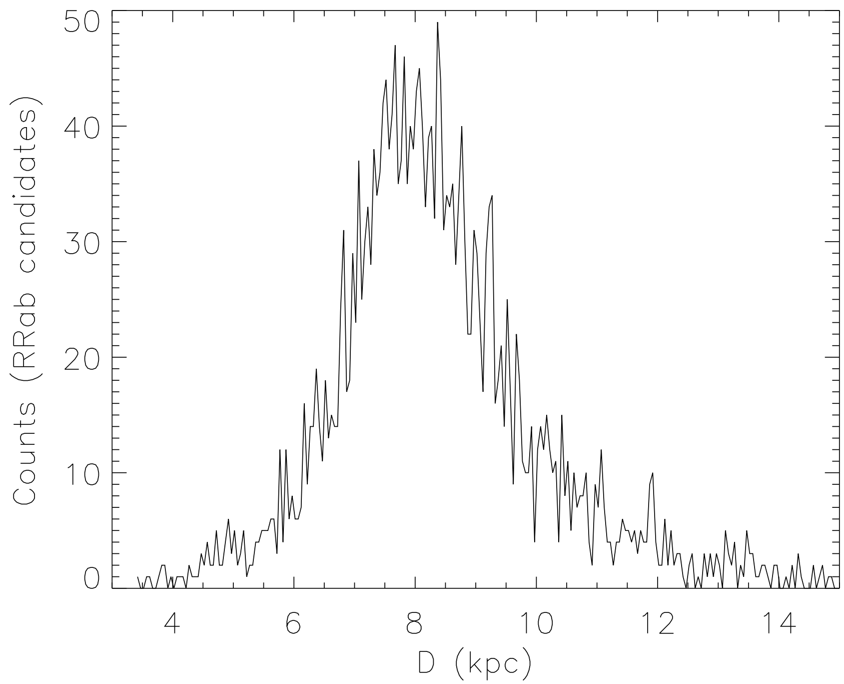
T2C: Braga et al. (2018, A&A 619; 2019, A&A 625)

Machine Learning: Molnar et al. (2022, MN 509) analysed 490 million VVV LCs $\Rightarrow$ 1.4 million likely variables; 39 000 are RRab stars, 8000 RRcd, 187 000 (s)dEBs, 18 000 contact EBs, 1400 DCEP, 2200 T2C

WISE - ASAS - ASASSN - ZTF - Catalina Sky Surveys

Pietrukowicz (2021, AcA 71)
List of Galactic Cepheids: 3666 (version Sept. 2022)

Galactic Structure



Majaess et al. (2018, Ap&SS 363)

4194 RRab from VVV

$M_{\mathrm{K}} = (-2.66 \pm 0.06) \log P - (1.03 \pm 0.06)$ [DM$_{\mathrm{LMC}}$=18.43]

$(J - K)_0 = (0.31 \pm 0.04) \log P + (0.35 \pm 0.02)$

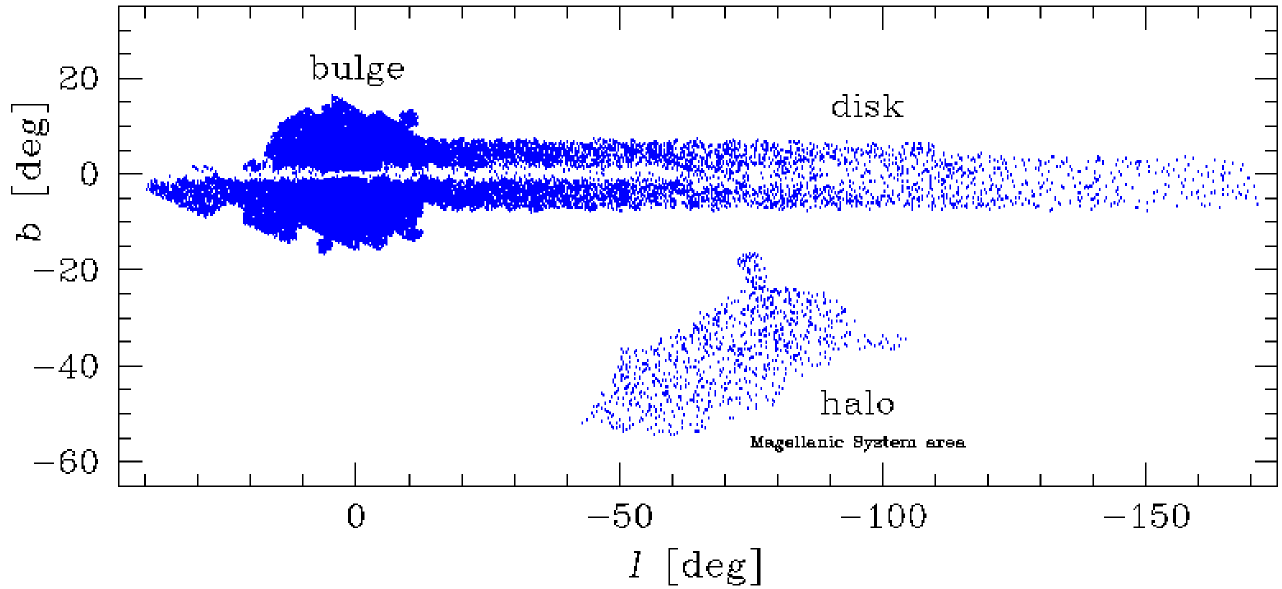
$d_{\mathrm{GC}} = 8.30 \pm 0.36$ ($| b | > 4°$)

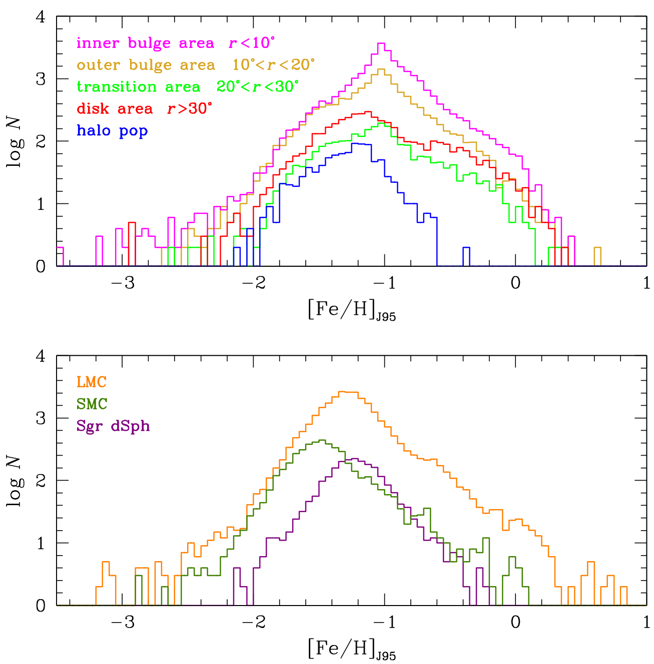
Using T2C from VVV:

Braga et al. (2018, A&A 619) $d_{\mathrm{GC}} = 8.46 \pm 0.11$ kpc

Griv et al. (2020, A&A 499) $d_{\mathrm{GC}} = 8.28 \pm 0.14$ kpc

Galactic Structure





Pietrukowicz et al. (2020, AcA 70)
OGLE 56 000 GB/GD + 34 000 MCs RRab
photometric metallicities
halo/bulge/disk [Fe/H]=-1.2,-1.0,-0.6
1/3 RRL within Bulge area belong to the Halo.

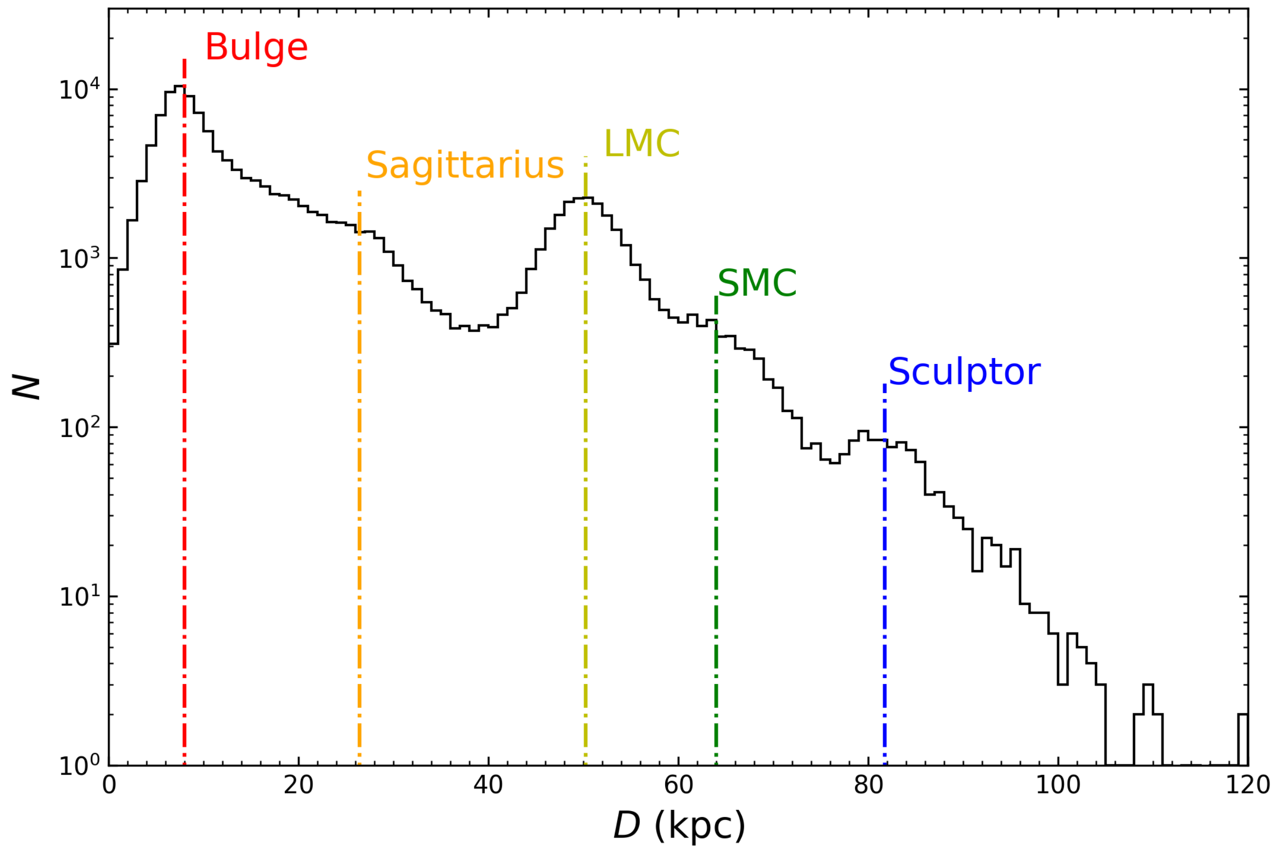
Galactic Structure

Li et al. (2023, ApJ 944)

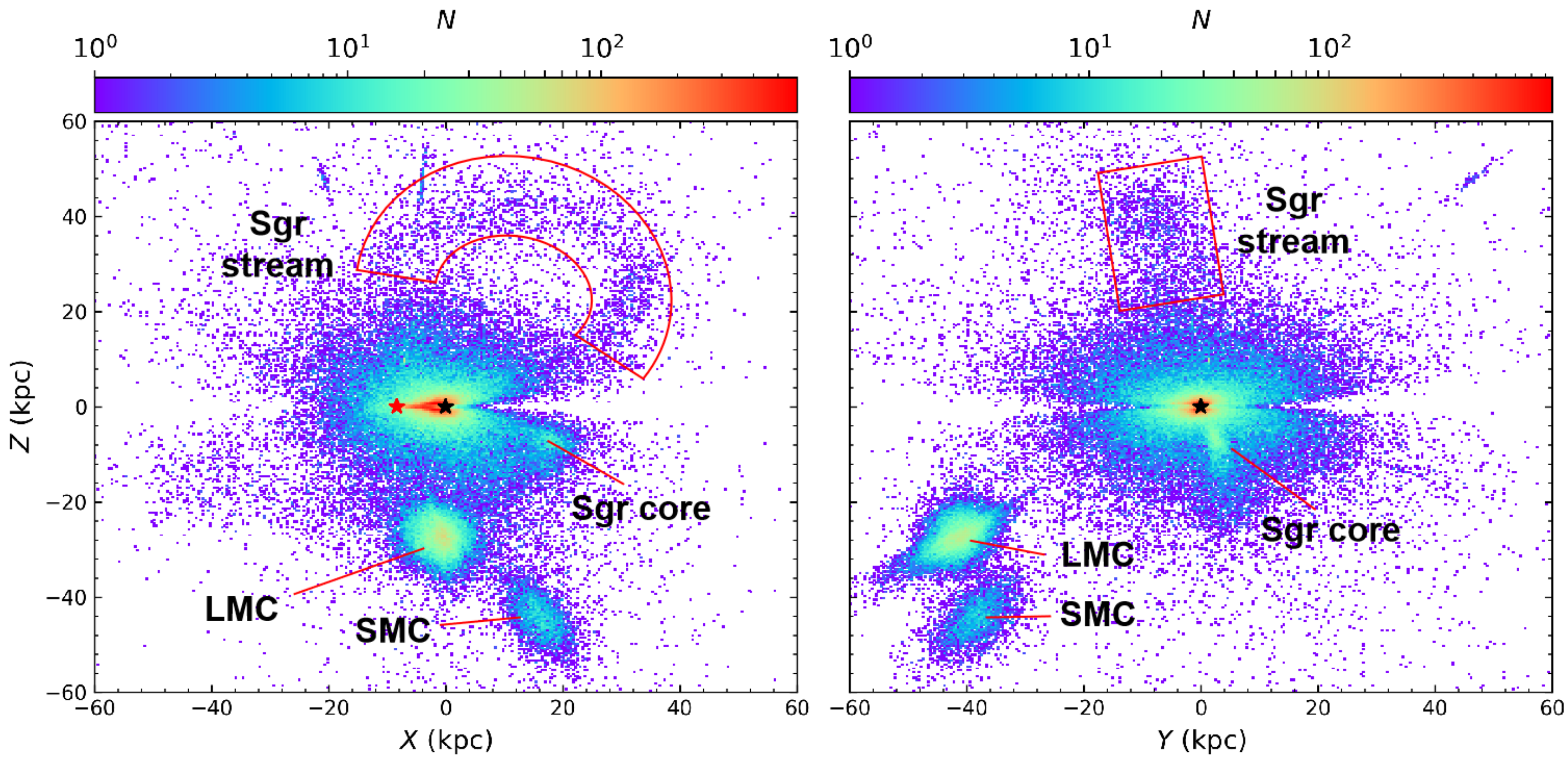
Calibrate: $P - f31 - R21 - [\mathrm{Fe/H}]$ (RRab, RRc, #2700)

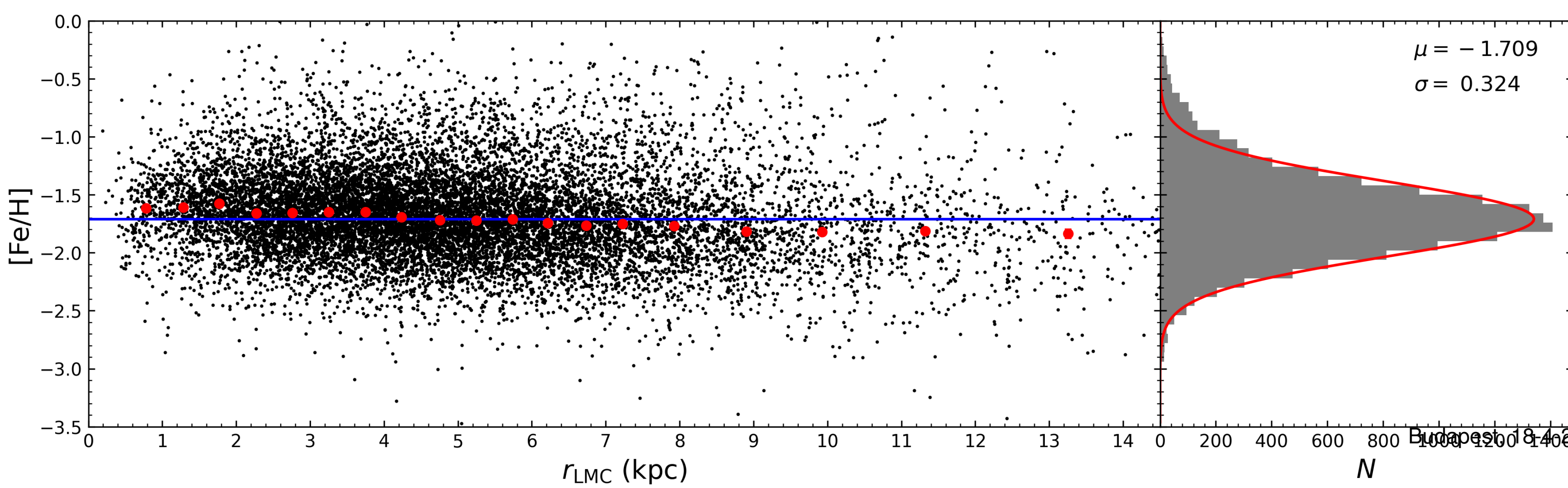
$M_{\mathrm{G}} - [Fe/H]$ (#200)

Apply to: 115 410 RRab and 20 463 type RRc stars

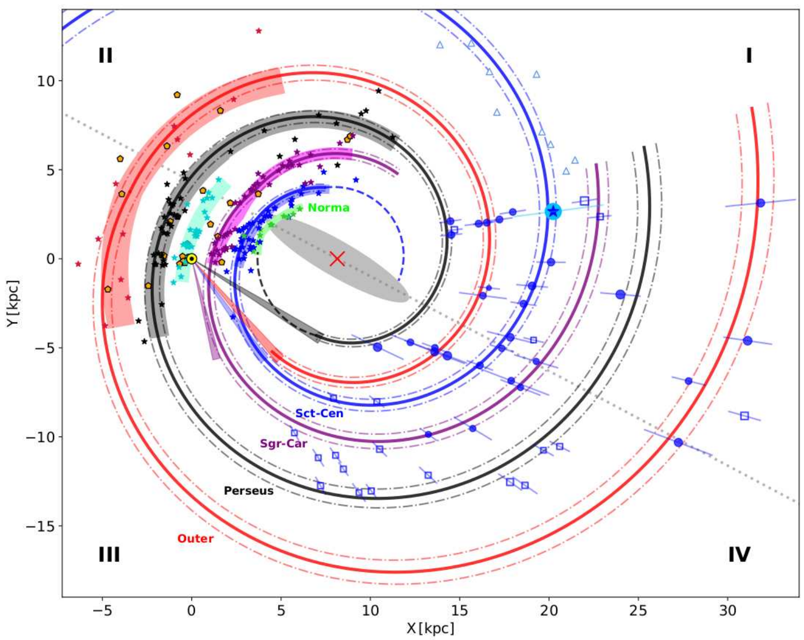


Galactic Structure

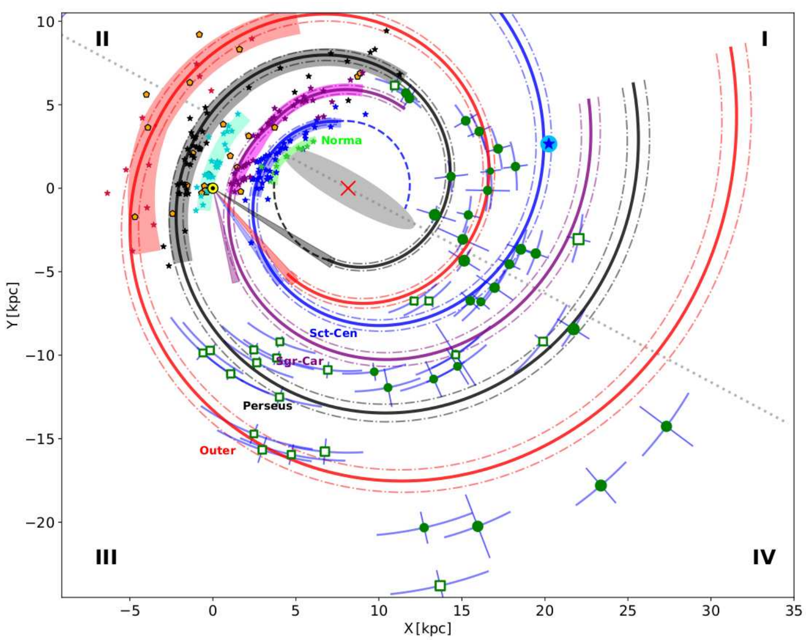




Galactic Structure



Minniti et al. (2021, A&A 654)
50 CCs from VVV
in quadrants I and IV

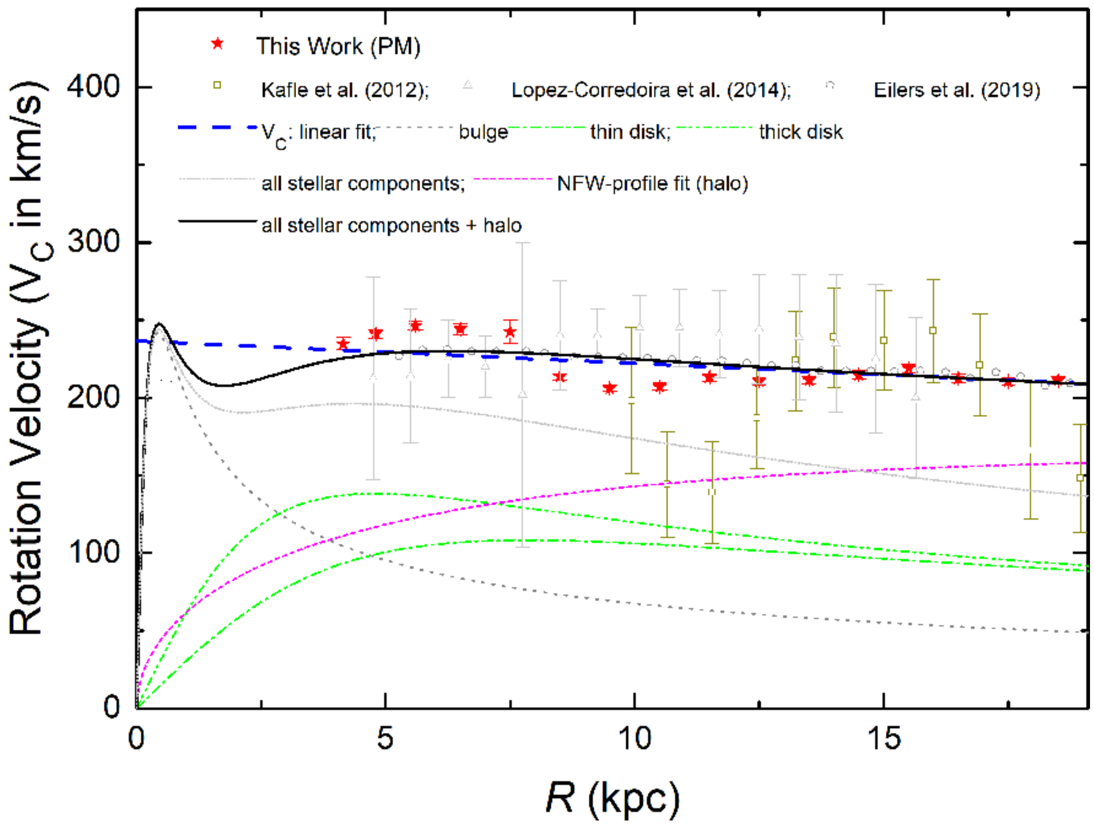


$$\ln\left(R/R_{\rm ref}\right) = -\left(\beta - \beta_{\rm ref}\right)\tan\psi$$

Talk Thurday

Galactic Structure

Ablimit et al. (2020, ApJL 895)
3480 CCs, distances based on *Wise* PL-relations
1040 PM from GDR2, RV from GDR2/LAMOST



$\Theta(R) = (232.5 \pm 0.8)+$
$(-1.3 \pm 0.1) \cdot (R - R_0)$
km/s

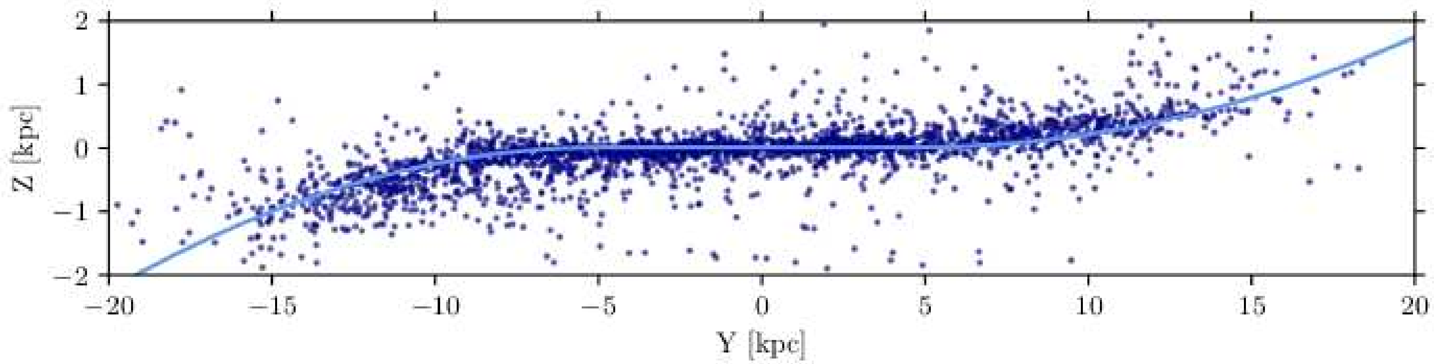
Also:
Bobylev, Bajkova, et al. (2021, MNRAS 502; 2023, RAA 23)

Galactic Structure

Lemasle et al. (2022, A&A 668)
unWISE photometry for 3260 MW CCs
W,W1W2= W2 -2.0 · (W1-W2)

$$M_{W,W1W2} = (-2.436 \pm 0.013) \log P + (-3.196 \pm 0.019)$$

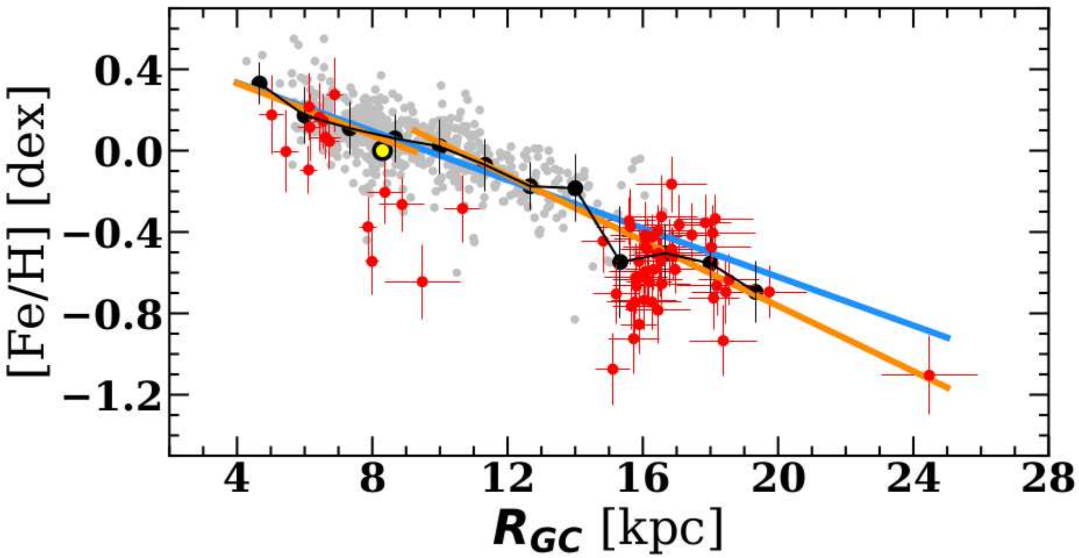
$$z(r,\Theta) = \begin{cases} z_0 & r < r_0 \\ z_0 + (r - r_0)^2 \times [z_1 \sin(\Theta - \Theta_1) + z_2 \sin(2\,(\Theta - \Theta_2))] & r \geq r_0 \end{cases}$$



Also:
Chen et al. (2019, Nature Ast 3)
Kovtyukh et al. (2022, MNRAS 510)

Galactic Structure

Trentin et al. (2023, MNRAS 519)
637 CCs, $M_{W,G}$ relation
$(-0.060 \pm 0.002) \cdot R_{\rm GC} + (0.573 \pm 0.017)$ dex ($R_{\rm GC} > 4$ kpc).
Possible break at 9.25 kpc (Talk: +3)



Also:
Lemasle et al. (2022, A&A 668)
Hocdé et al. (2023, A&A 671) (Talk: Thursday)

Calibration

$M - m_0 = 5\log(d/10$ [pc])

$M = F$(P, [Fe/H])

$\omega = 10^{0.2(m_0 - F - 5)}$

- $\omega_{\rm G}$ - PZPO
  DR2: -29 μas (QSOs),
  -46 ± 13 (Riess+ 2018), -49 ± 18 (Gr18) (CEP)
  -56 (Murareva+ 2018), -42 (Layden+ 2019) (RRL)

  DR3: -17 μas (QSOs)
  Lindegren et al. (2021; L21)
  Maíz Apellániz (2022, A&A 657)
  Groenewegen (2021, A&A 654)
- $\omega_{\rm G}$ - PZPO + $\Delta\omega$

Hipparcos ⇒ HST ⇒ GDR3

Benedict et al. (2007 AJ 133; 2022 AJ 163)
Riess et al. (2014, ApJ 785; 2018, ApJ 855)

Name	$\pi \pm \sigma_\pi$ (rev. Hipparcos)	$\pi \pm \sigma_\pi$ (HST)	$\pi \pm \sigma_\pi$ (GDR3)	GoF
η Aql	2.36 ± 1.04	3.71 ± 0.07	3.67 ± 0.19	29
β Dor	3.24 ± 0.36	3.14 ± 0.16	2.93 ± 0.14	47
δ Cep	3.77 ± 0.17	3.66 ± 0.15	3.56 ± 0.15	31
FF Aql	2.11 ± 0.33	2.81 ± 0.18	1.91 ± 0.07	1.5
l Car	2.09 ± 0.29	2.01 ± 0.20	1.98 ± 0.11	24
RT Aur	-1.10 ± 1.41	2.40 ± 0.19	1.81 ± 0.12	66
T Vul	2.71 ± 0.43	1.90 ± 0.23	1.69 ± 0.06	5.3
Y Sgr	2.64 ± 0.45	2.13 ± 0.29	1.97 ± 0.06	13
X Sgr	3.31 ± 0.26	3.00 ± 0.18	2.81 ± 0.14	5.1
ζ Gem	2.37 ± 0.30	2.78 ± 0.18	3.07 ± 0.22	22
W Sgr	3.75 ± 1.12	2.28 ± 0.20	2.37 ± 0.18	36
SY Aur	-1.84 ± 1.72	0.428 ± 0.054	0.427 ± 0.020	2.5
SS CMa	0.40 ± 1.78	0.389 ± 0.029	0.287 ± 0.013	4.0
XY Car	-1.02 ± 0.88	0.438 ± 0.048	0.378 ± 0.014	2.1
VX Per	0.87 ± 1.52	0.420 ± 0.076	0.364 ± 0.017	3.5
VY Car	0.36 ± 1.42	0.586 ± 0.045	0.554 ± 0.017	-2.4
WZ Sgr	3.50 ± 1.22	0.512 ± 0.039	0.574 ± 0.028	-1.1
S Vul		0.322 ± 0.040	0.205 ± 0.020	1.1
X Pup	1.97 ± 1.26	0.277 ± 0.048	0.376 ± 0.020	1.2

Hipparcos ⇒ HST ⇒ GDR3

Benedict et al. (2011 AJ 142)

Name	Type	$\pi \pm \sigma_\pi$ (rev. Hipparcos)	$\pi \pm \sigma_\pi$ (HST)	$\pi \pm \sigma_\pi$ (GDR3)	GoF
SU Dra	RRab	0.20 $\pm$ 1.13	1.42 $\pm$ 0.16	1.332 ± 0.014	0.4
RR Lyr	RRab	3.46 $\pm$ 0.64	3.77 $\pm$ 0.13	3.985 ± 0.027	0.9
UV Oct	RRab	2.44 $\pm$ 0.81	1.71 $\pm$ 0.10	1.838 ± 0.012	0.0
XZ Cyg	RRab	2.29 $\pm$ 0.84	1.67 $\pm$ 0.17	1.586 ± 0.015	4.1
RZ Cep	RRc	0.59 $\pm$ 1.48	2.54 $\pm$ 0.19	2.401 ± 0.012	-0.3
VY Pyx	BL Her	5.01 $\pm$ 0.44	6.44 $\pm$ 0.23	3.950 ± 0.019	-3.6
κ Pav	W Vir	6.52 $\pm$ 0.77	5.57 $\pm$ 0.28	5.245 ± 0.122	38

Proxys

- Cepheids with Companions
  Polaris A: Hipparcos revised parallax 7.54 ± 0.11 mas
  Polaris B: GDR3 7.287 ± 0.018

  Kervella et al. (2019) "proper motion anomaly"
- Cepheids in Clusters

Breuval et al. 2020, A&A 643
22 spatially resolved companions +
14 Cepheids that are candidate cluster members
DR2 + offset

α	β	σ	Band	
-2.481 ± 0.244	-3.731 ± 0.050	0.18	V	-46 mas
-3.257 ± 0.163	-5.323 ± 0.026	0.14	K	-46 mas
-3.332 ± 0.177	-5.965 ± 0.029	0.17	WH(T)	-46 mas
-3.340 ± 0.180	-6.010 ± 0.030	0.16	WH(T)	-31 mas
-3.322 ± 0.175	-5.904 ± 0.029	0.18	WH(T)	-61 mas

Cepheids in Open Clusters

- Zhou & Chen 2021, MNRAS 504
  33 Cepheids in OCs (DR2/3)
  Medina et al. 2021, MNRAS 505
  19 Cepheids in OCs (DR2)
- Riess et al. (2022, ApJ 938)
  17 Cepheids, HST photometry
  DR2 membership (Cantat-Gaudin et al. 2020)
- Hao et al. (2022, A&A 668)
  39 "probable" Cepheids in OCs, DR3
  Lin et al. (2022, ApJ 938), DR2 + DR3.
- Cruz Reyes & Anderson (arXiv:2208.09403)
  34 Cepheids in 28 OCs, DR3 (Talk: +2)
- Groenewegen (this work)

Cluster Cepheids

Cluster	$\pi \pm \sigma_\pi$ (Riess+)	$\pi \pm \sigma_\pi$ (Cruz-Reys+)	$\pi \pm \sigma_\pi$ (Hao+)	$\pi \pm \sigma_\pi$ (Gr23)	N	R (′)
Berkeley 58	336 ± 8	336 ± 7	290 ± 20	302 ± 11	85	4.0
NGC 129	559 ± 7	557 ± 7	530 ± 30	529 ± 10	290	6.5
FSR 0951	594 ± 7	610 ± 7	570 ± 30	566 ± 11	128	6.8
vdBergh 1	579 ± 10	585 ± 10	550 ± 40	543 ± 13	50	1.9
Ruprecht 79	274 ± 8	281 ± 7	240 ± 20	244 ± 11	99	2.8
NGC 5662	1322 ± 7	1336 ± 6	1300 ± 30	1292 ± 12	225	18.1
Lynga 6	408 ± 9	421 ± 8	380 ± 40	383 ± 11	157	5.2
NGC 6067	496 ± 7	513 ± 7	470 ± 30	473 ± 11	671	4.5
NGC 6087	1057 ± 7	1073 ± 7	1020 ± 30	1025 ± 11	154	7.7
IC 4725	1540 ± 7	1554 ± 6	1520 ± 50	1514 ± 12	325	11.6
NGC 6649	508 ± 8	514 ± 7	470 ± 50	474 ± 11	301	3.1
UBC 129	886 ± 7	880 ± 7	850 ± 20	852 ± 11	116	11.7
UBC 130	428 ± 8	425 ± 9	400 ± 20	396 ± 11	36	2.4
NGC 7790	331 ± 8	322 ± 7	290 ± 30	293 ± 11	114	3.0
{ UBC 231	356 ± 8	345 ± 8		312 ± 11	56	7.9
OC – 0717			370 ± 10	370 ± 10	64	24.4
{ NGC 3496	439 ± 8			408 ± 10	464	7.6
Ruprecht 93		482 ± 7		448 ± 11	169	4.7

Spatial covariance !

PL-relations: CEP

$$M = \alpha \cdot (\log P - c) + \beta + \gamma \cdot [\mathrm{Fe/H}]$$

α	β	γ	Band	GAL	N	σ	remark
Ripepi et al. (arXiv220606212)							
-3.317 ± 0.007	15.998 ± 0.005	0.0	WG	LMC	2477	0.075	
-3.382 ± 0.021	16.592 ± 0.026	0.0	WG	SMC	839	0.156	$P > 2.95d$
Ripepi et al. 2022 A&A 659; DR3, L21+Riess21							
-3.294 ± 0.040	-6.042 ± 0.013	0.0	WG	MW	372	0.017	
-3.178 ± 0.048	-5.971 ± 0.017	-0.661 ± 0.077	WG	MW	372	0.011	
Molinari et al. 2023 MNRAS 520; DR3, L21 + fitted offset							
-3.167 ± 0.053	-5.887 ± 0.035	-0.43 ± 0.12	K	MW	443	0.017	-24.8 $\pm$ 4.6 μa
-3.333 ± 0.057	-6.178 ± 0.038	-0.40 ± 0.12	WJK	MW	443	0.017	-21.9 $\pm$ 5.0 μa
-3.191 ± 0.042	-6.018 ± 0.028	-0.32 ± 0.10	WH(T)	MW	430	0.016	-23.6 $\pm$ 4.1 μa
Breuval et al. 2022, ApJ 939; BJ21+correction (L21+Riess21) [10 bands+ 5 Wesenheit]							
$-3.222F(\pm 0.013)$	-5.899 ± 0.033		K	MW	65	0.17	
$-3.222F(\pm 0.013)$	-5.827 ± 0.034	-0.321 ± 0.068	K	MCs/MW	2017	0.034	
$-3.338F(\pm 0.012)$	-6.006 ± 0.021		WG	MW	596	0.32	
$-3.338F(\pm 0.012)$	-5.959 ± 0.021	-0.384 ± 0.051	WG	MCs/MW	2473	0.025	
$-3.323F(\pm 0.009)$	-6.184 ± 0.038		WJK	MW	63	0.18	
$-3.323F(\pm 0.009)$	-6.133 ± 0.042	-0.322 ± 0.079	WJK	MCs/MW	2014	0.042	
$-3.305F(\pm 0.038)$	-5.955 ± 0.024		WH	MW	60	0.16	
$-3.305F(\pm 0.038)$	-5.931 ± 0.027	-0.280 ± 0.078	WH	LMC/MW	130	0.027	
Riess et al. 2022, ApJ 938; MW Cluster Cepheids							
$-3.299F(\pm 0.015)$	-5.890 ± 0.018	$-0.217F(\pm 0.046)$	WH	MW	17	0.06	$0F$ μas
Cruz Reyes & Anderson 2023, arXiv:2208.09403; MW Cluster+Field Cepheids							
$-3.299F(\pm 0.015)$	-5.914 ± 0.017	$-0.217F(\pm 0.046)$	WH	MW	82		-13 ± 5 μas

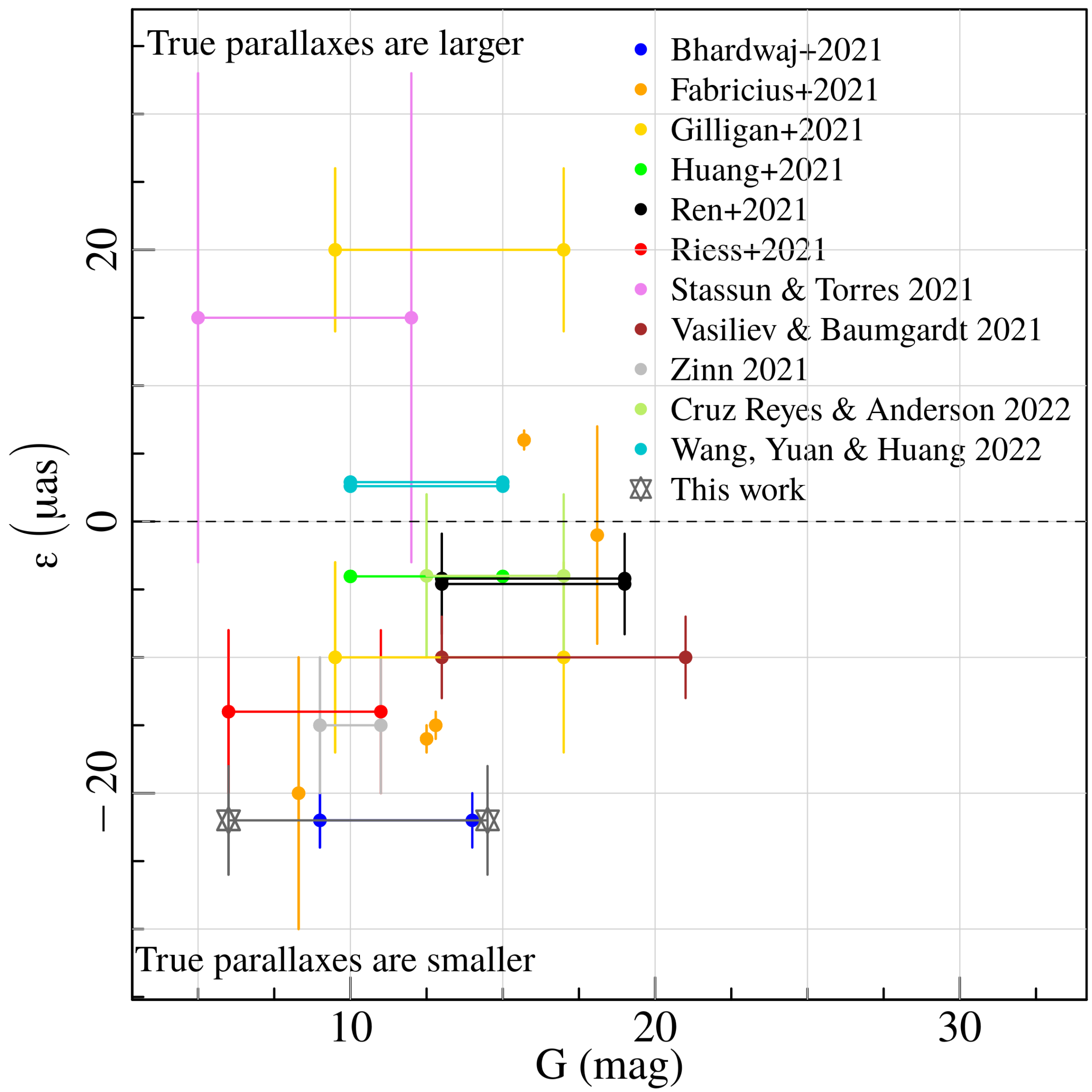
PL-relations: RRL

$$M = \alpha \cdot (\log P - c) + \beta + \gamma \cdot [\mathrm{Fe/H}]$$

α	β	γ	Band	GAL	N	σ	Remark
Bhardwaj et al. 2023, ApJL 944; DR3, L21 (Talk Thurday)							
-2.37 ± 0.02	-0.80 $\pm$0.03	0.18 ± 0.01	K	MW/GC	1077	0.05	RRabcd
-2.73 ± 0.02	-1.06 $\pm$0.03	0.16 ± 0.02	WJK	MW/GC	1096	0.06	
Garofalo et al. 2022, MNRAS 513; DR3, fit global offset							
	1.13 ± 0.03	0.33 ± 0.02	V	MW	400	0.02	-33 ± 2 mas
-2.49 ± 0.21	-0.88 $\pm$0.09	0.14 ± 0.03	WG	MW	400	0.09	-33 ± 3 mas
Looijmans, Lub, Brown 2023, arXiv: 2303.0332; DR3, fit global offset							
$+0.393 \pm 0.049$	-0.45 $\pm$0.10	0.273 ± 0.022	V	MW/GC	200		-14 ± 9 mas
$-2.48 \pm 0.07^{\star}$	-0.93 $\pm$0.02	0.121 ± 0.010	WG	MW/GC	200		-8 ± 3 mas
Mullen et al. 2023 ApJ945; DR3, L21+ error inflation							
-2.44 ± 0.10	-0.841 $\pm$0.008	0.144 ± 0.014	W1	MW/GC	1052	0.02	
-2.54 ± 0.10	-0.857 $\pm$0.009	0.151 ± 0.014	W2	MW/GC	397	0.02	
Li, Huang et al. 2023, ApJ 944; DR3, L21+BayesianEstimate							
	$+1.106 \pm 0.021$	0.350 ± 0.016	G	MW	205	0.12	RRab
-2.465 ± 0.084	-0.792 $\pm$0.043	0.161 ± 0.011	K	MW	159	0.14	
-2.452 ± 0.080	-0.834 $\pm$0.031	0.179 ± 0.011	W1	MW	164	0.09	
Neeley et al. 2019, MN 490; DR2, -30 mas							
-2.40 ± 0.27	-0.87 $\pm$0.02	0.18 ± 0.03	[3.6]	MW	55	0.21	
-2.45 ± 0.28	-0.89 $\pm$0.02	0.18 ± 0.03	[4.5]	MW	55	0.21	
-2.60 ± 0.25	-1.01 $\pm$0.02	0.13 ± 0.04	WVI	MW	55	0.18	

*used $WG = G - 1.85(Bp - Rp)$

Counter correction



Molinaro et al. (2023)

Reddening

Fitzpatrick (1999); Cardelli, Clayton, & Mathis (1989)
Wang & Chen (2019 ApJ 877; arXiv230109146)

		A_λ/A_V		
Filter	λ_0	F99 $R_V = 3.3$	CCM $R_V = 3.1$	WC $R_V = 3.4$
$'B'$	4354	1.303	1.341	1.295
$'V'$	5414	1.000	1.017	1.019
I(ogle-iv)	7930	0.571	0.607	0.581
J(2mass)	12350	0.262	0.335	0.304
H	16620	0.162	0.178	0.135
K_s	21590	0.112	0.117	0.079
F555W	5350	1.024	1.032	1.034
F814W	8090	0.548	0.584	0.562
F160W	15330	0.184	0.203	0.160
WVI		1.33	1.54	1.32
WJK		0.74	0.54	0.35
WH		0.386	0.454	0.338
$\frac{E(V-I)}{E(B-V)}$		1.415	1.270	1.491

Reddening

Filter	mag	m_0		
		F99, $R_{\rm V} = 3.3$ $E(B-V) = 1.0$	CCM, $R_{\rm V} = 3.1$ $E(B-V) = 1.0$	WC, $R_{\rm V} = 3.4$ $E(B-V) = 0.15$
V	11.511	8.211	8.411	11.001
I	10.007	8.123	8.125	9.697
J	8.846	7.981	7.808	8.675
H	8.188	7.653	7.636	8.097
$K_{\rm s}$	8.058	7.688	7.695	7.998
F555W	11.750	8.371	8.551	11.224
F814W	9.973	8.165	8.163	9.675
F160W	8.384	7.777	7.755	8.280
WVI	8.007	8.005	7.745	7.964
WJK	7.475	7.472	7.612	7.497
WH	7.698	7.698	7.604	7.682

$WVI = I - 1.55 \cdot (V - I)$,

$WJK = K - 0.69 \cdot (J - K)$,

WH = F160W $-0.386 \cdot$ (F555W − F814W).

Conclusions

- Consensus on metallicity dependence Cepheid PL-relation
- All PL-relations in practical use show no 'break'
- Wesenheit indices
- Spectroscopic surveys (Opt, NIR)
- Binarity
  Karczmarek (2204.00661, 2303.15664)
  -No effect on slope
  -Small effect on ZP (depends on filter and binary fraction)
- NIR excess
  (dust?; ionized gas? Hocdé et al. 2020 A&A 633)
- PZPO. Large 'counter-corrections' (DR4)

THE END