Parallax bias in Gaia EDR3

Why it matters, what it looks like, how it can be determined, and what to expect in the future

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NASA Stars Science Interest Group, 15 March 2022

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Cepheid distance scale

Current Challenges in Cepheid Distance Calibrations Using Gaia Early Data Release 3

Kayla A. Owens[1,2], Wendy L. Freedman[1,2], Barry F. Madore[1,3], and Abigail J. Lee[1,2]

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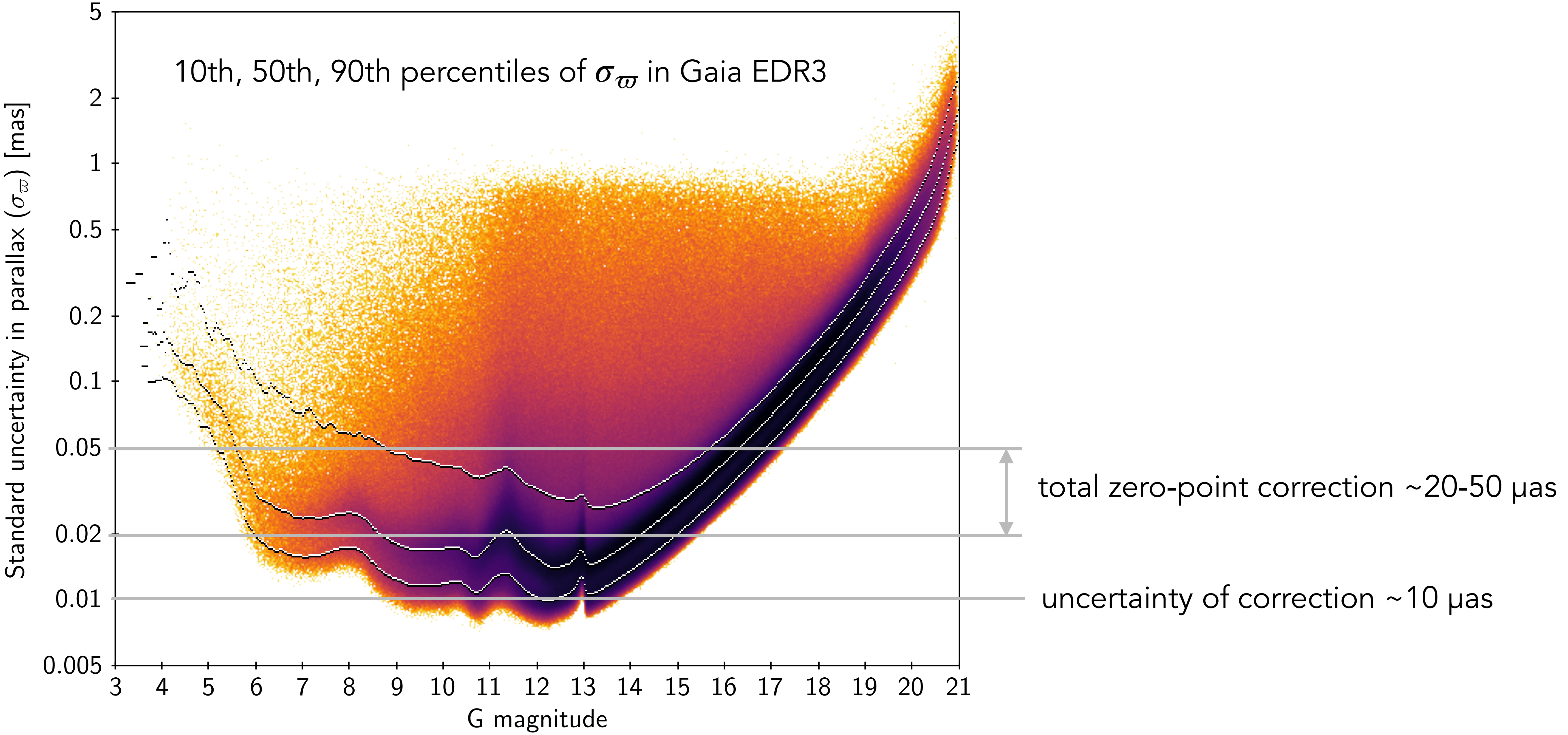
Table 10
Irreducible EDR3 Cepheid Error Budget

Source of Uncertainty	σ_{LMC}	σ_{SMC}
Metallicity Effects	0.028	0.053
Zero-point Prescription (L21b)	0.037 }	0.037
Additional ZP-offset	0.045 }	0.045
Reddening Coefficient Variation	0.002	0.002
Total [mag]	0.065	0.079
Percent Error	3.0%	3.6%

80% of the total error variance!

Cf. Riess et al. (2021) [RCY]:
Cepheid distance scale to 0.022 mag (1%)

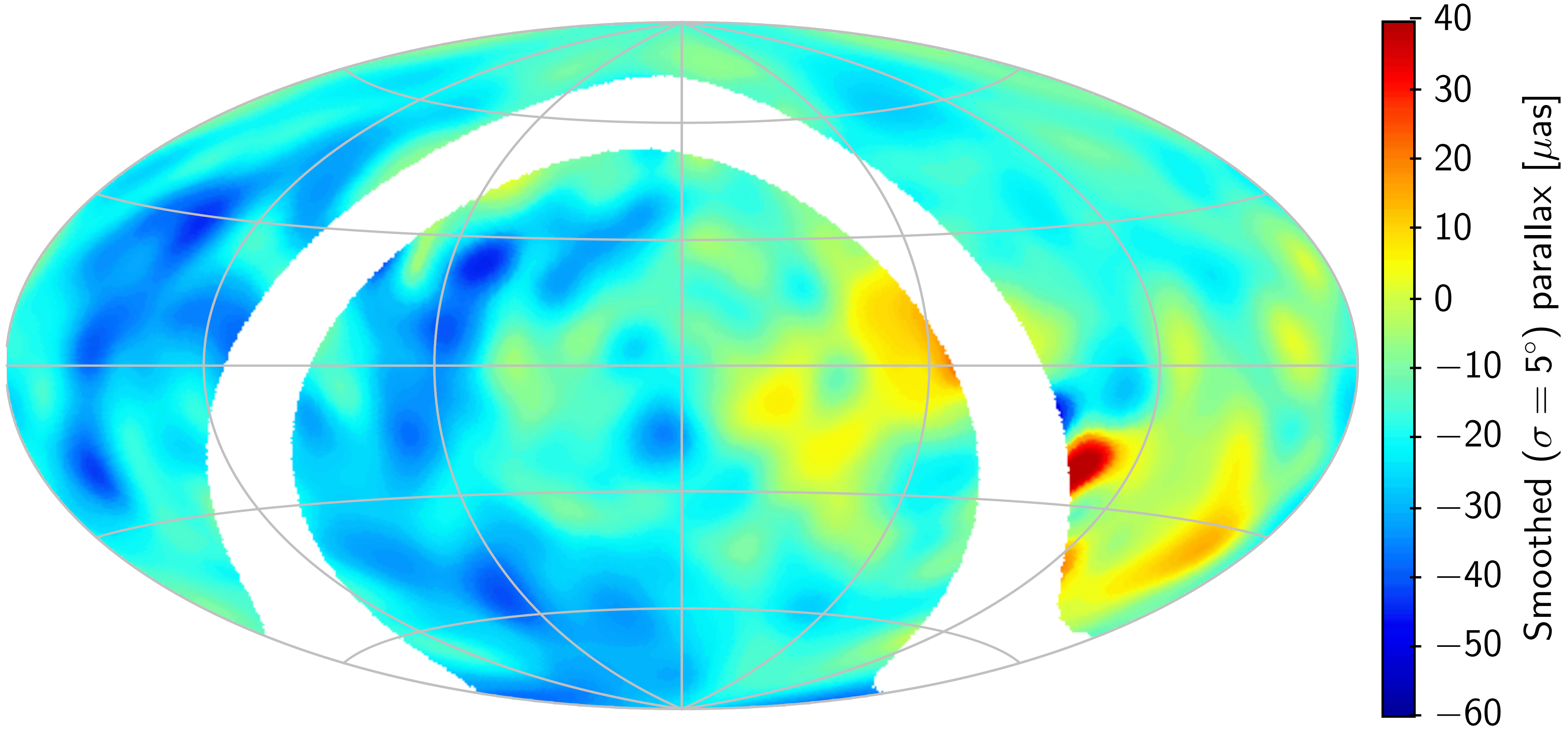
Zero-point errors are of a size similar to the random errors



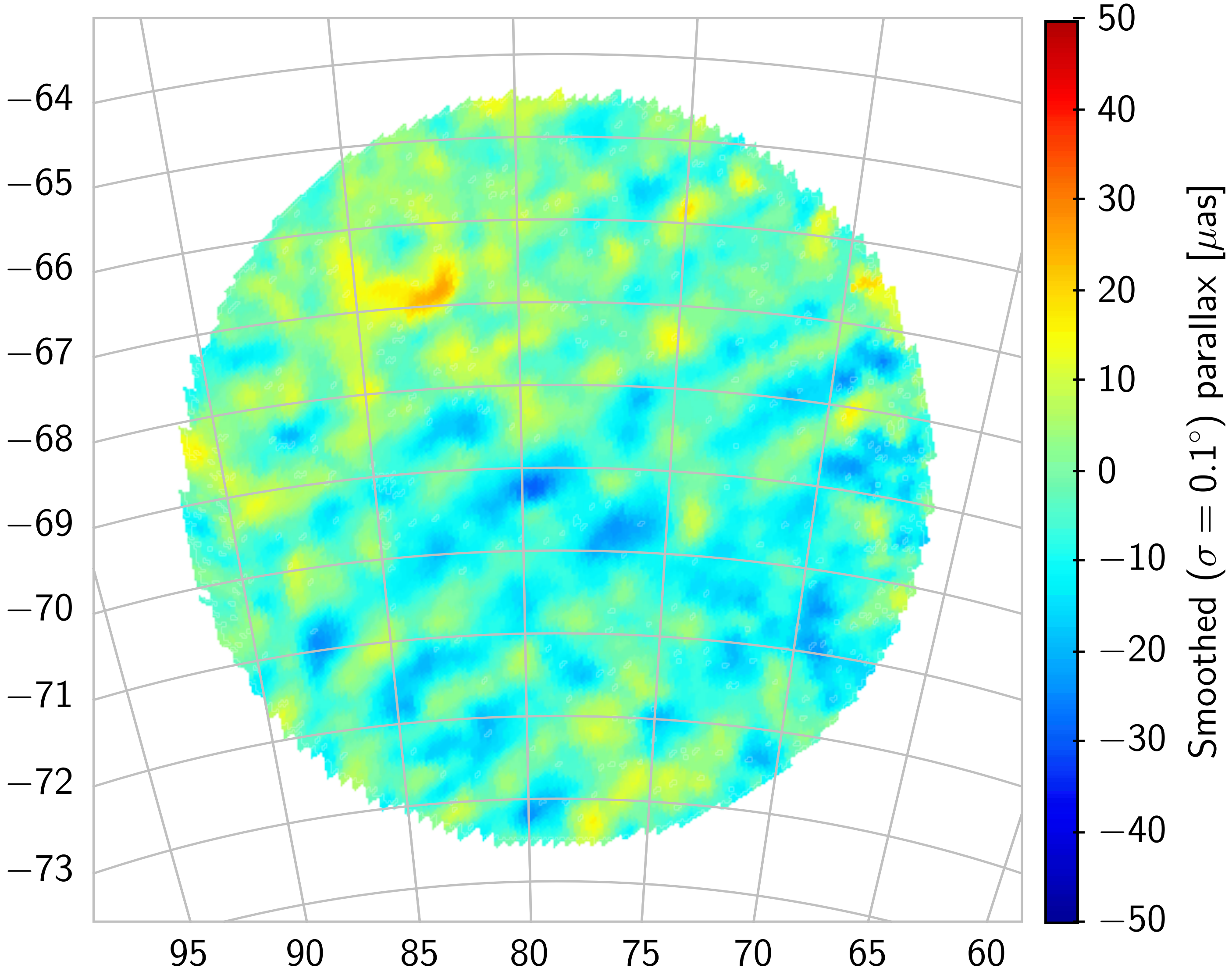
Lindegren et al. (2021), A&A 649, A2 [LKH]

Parallax bias - spatial variations on large and small scales

5° smoothed EDR3 parallaxes of QSOs
(RMS = 9.4 μas)

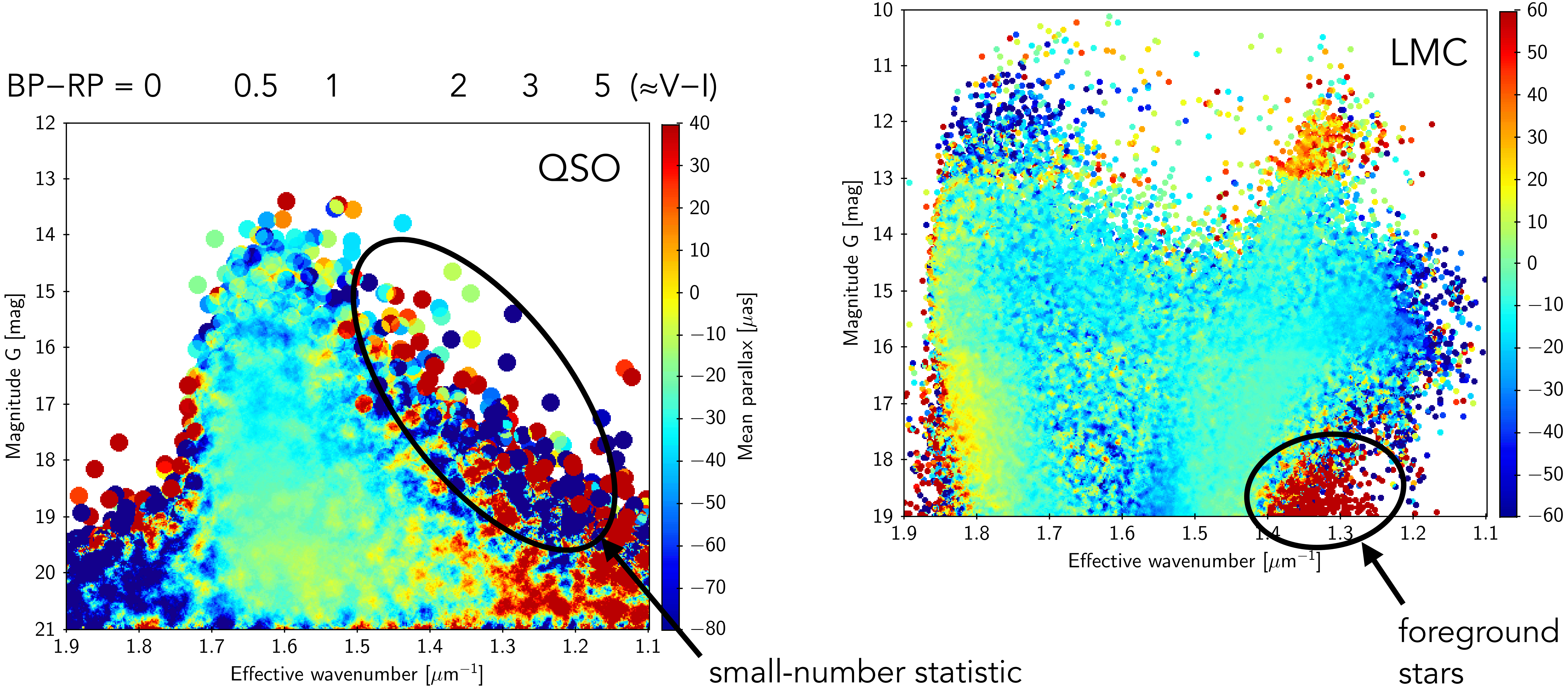


0.1° smoothed EDR3 parallaxes in LMC (G=16-18)
(RMS = 6.9 μas)



Lindegren et al. (2021), A&A 649, A2 [LKH]

Parallax bias - variations with magnitude and colour



The EDR3 parallax correction recipe in [LBB]

= Lindegren et al. (2021), A&A 649, A4

LBB estimated the parallax bias

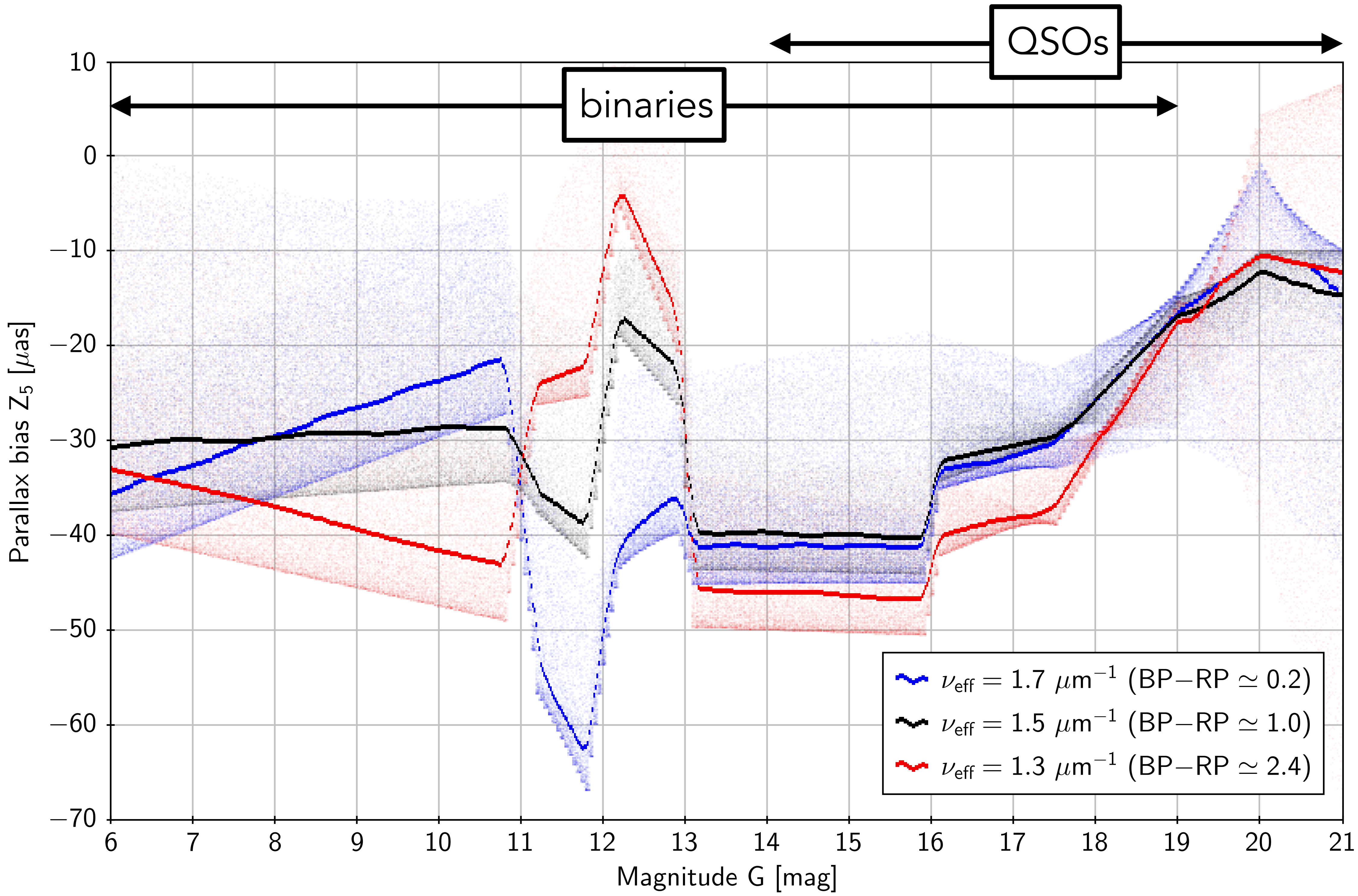
$$Z = \mathrm{E}\left[\varpi_{\mathrm{EDR3}} - \varpi_{\mathrm{true}}\right]$$

as a function of magnitude (G), colour (ν_{eff} = effective wavenumber) and ecliptic latitude (β) using a linear expansion in basis functions:

$$Z(G,\, \nu_{\mathrm{eff}},\, \beta) = \sum_i \sum_j \sum_k z_{ijk}\, g_i(G)\, c_j(\nu_{\mathrm{eff}})\, b_k(\beta)$$

Python code at https://gitlab.com/icc-ub/public/gaiadr3_zeropoint
(there are separate functions Z_5, Z_6 for sources with 5- and 6-parameter solutions)

Z_5 versus G at three different colours [LBB]



The LMC provided additional constraints on the dependence on colour

Some determinations of the bias (Z) and residual bias (ΔZ)

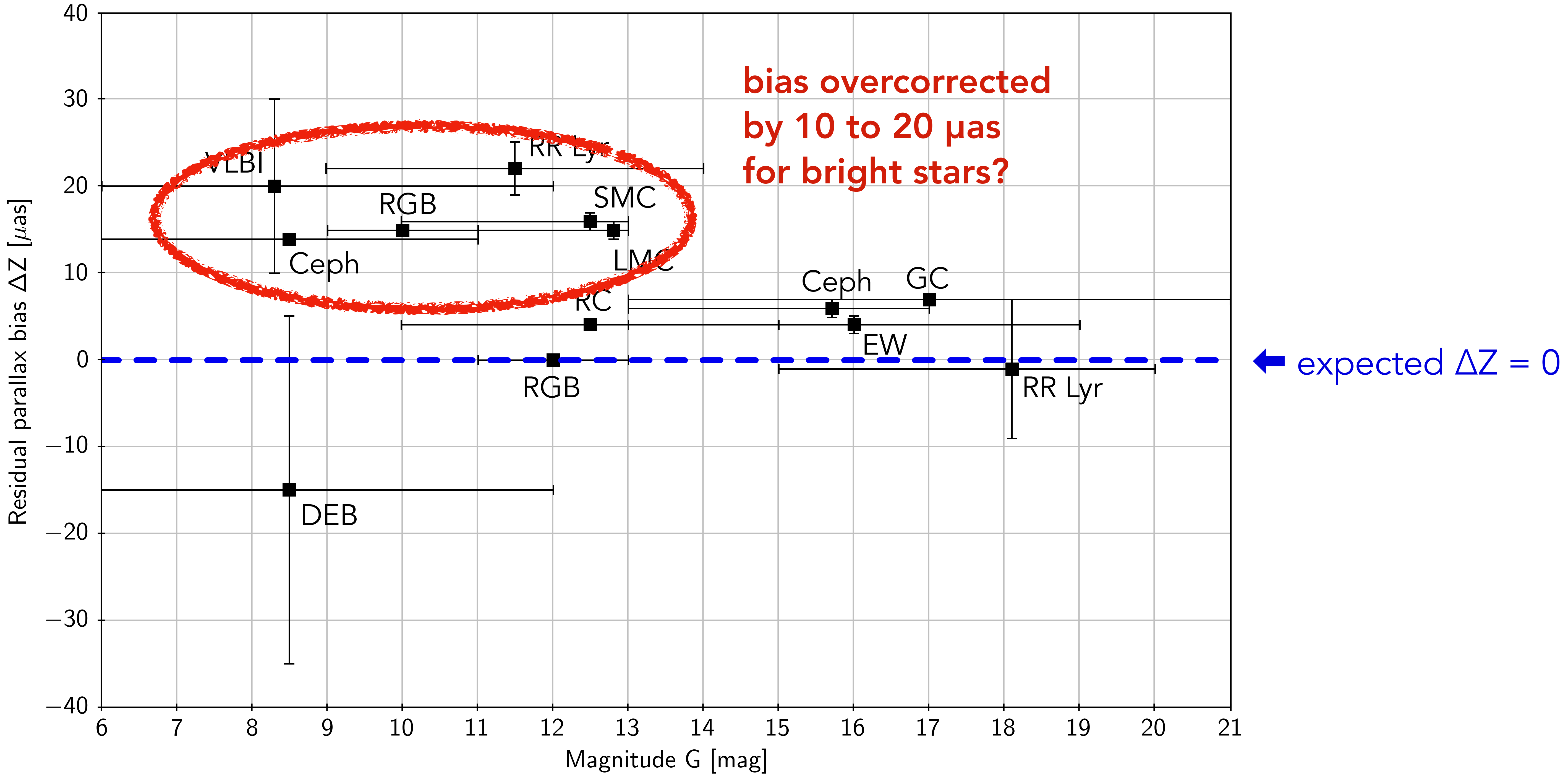
bias: $Z = \mathrm{E}\left[\varpi_{\mathrm{EDR3}} - \varpi_{\mathrm{true}}\right]$

residual bias: $\Delta Z = \mathrm{E}\left[\varpi_{\mathrm{EDR3}} - Z_{[\mathrm{LBB}]} - \varpi_{\mathrm{true}}\right]$ (NB: some authors define ΔZ with the opposite sign!)

Reference	Type of object	N	G	ν_{eff} [μm^{-1}]	Z [μas]	ΔZ [μas]
Bhardwaj et al. [BRG]	RR Lyr	350	9–14	1.59 ± 0.04	-7 ± 3	$+22 \pm 2$
Fabricius et al. [FLA]	VLBI	40	8.3		-10 ± 10	$+20 \pm 10$
”	Ceph	1372	15.7		-28 ± 1	$+6 \pm 1$
”	RR Lyr	318	18.1		-30 ± 8	-1 ± 8
”	LMC	318	12.8		-4 ± 1	$+15 \pm 1$
”	SMC	114	12.5		-6 ± 1	$+16 \pm 1$
Huang et al. [HYB]	RC	65 k	10–15	1.47 ± 0.05	-26	$+4$
Ren et al. [RCZ]	EW	110 k	13–19	1.50 ± 0.10	-29 ± 1 (5p)	$+4 \pm 1$ (5p)
”					-25 ± 4 (6p)	$+5 \pm 4$ (6p)
Riess et al. [RCY]	Ceph	75	6–11	1.42 ± 0.06		$+14 \pm 6$
Stassun & Torres [ST]	DEB	76	5–12	1.60 ± 0.10	-37 ± 20	-15 ± 18
Vasiliev & Baumgardt [VB]	GC	170	13–21			$+7 \pm 3$
Zinn [Z]	RGB	2000	9–13	1.45 ± 0.05	-22	$+15 \pm 3$ ($G < 10.8$)
”						$\simeq 0$ ($G > 10.8$)

(Lindegren, EDR3 Workshop, June 2021)

Residual parallax bias ΔZ after application of Z_5 from [LBB]



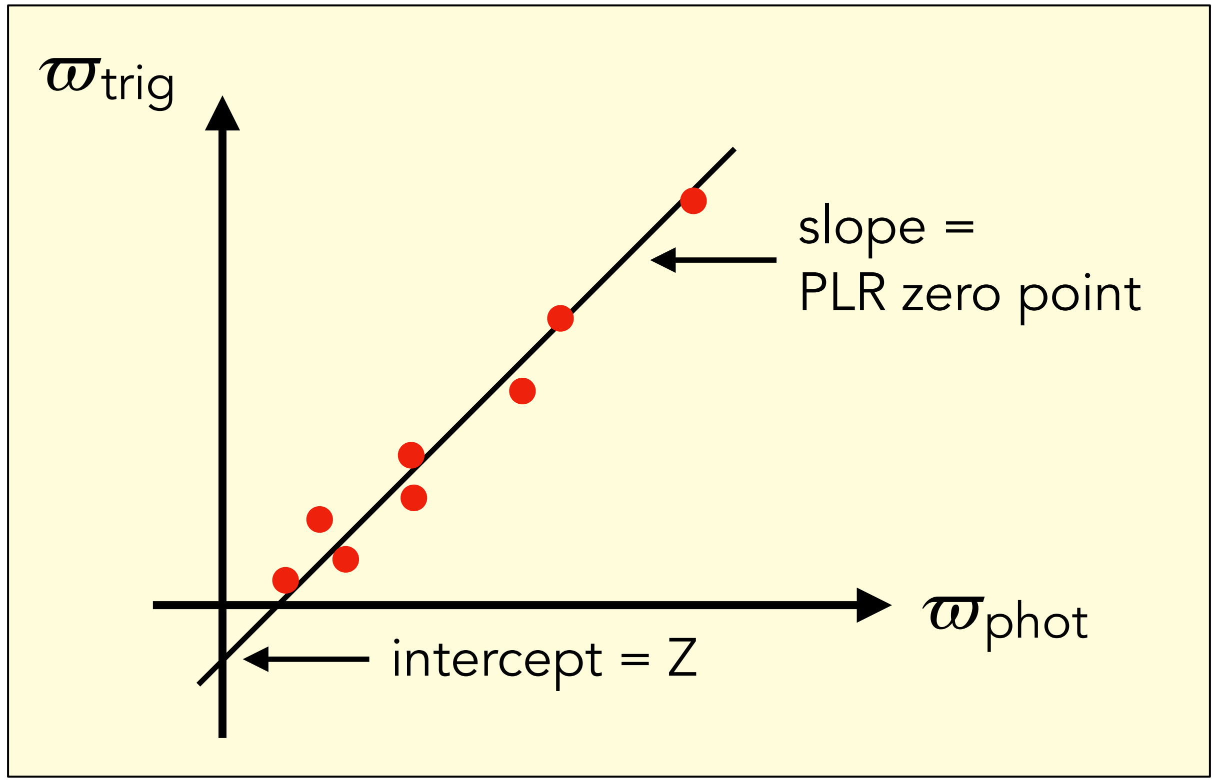
Methods for the determination of Z (and their problems)

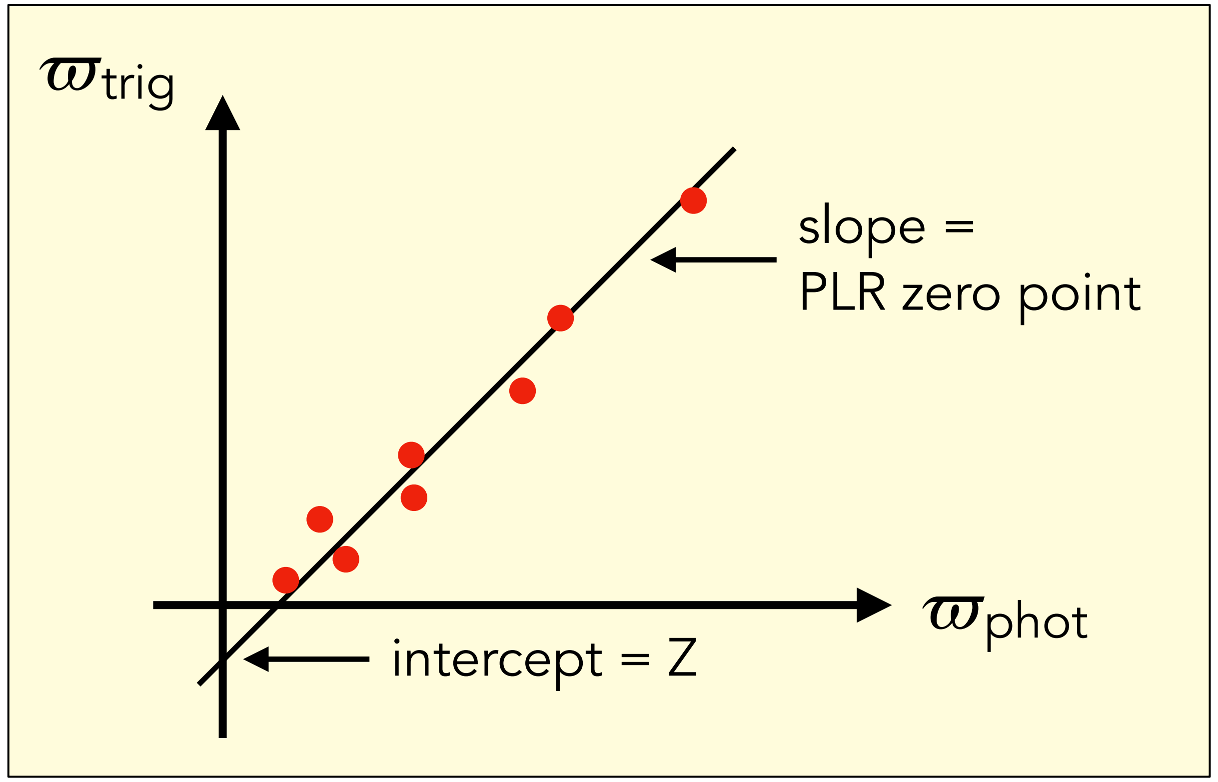
A. Direct comparison: sources with parallax known *a priori* or by independent methods

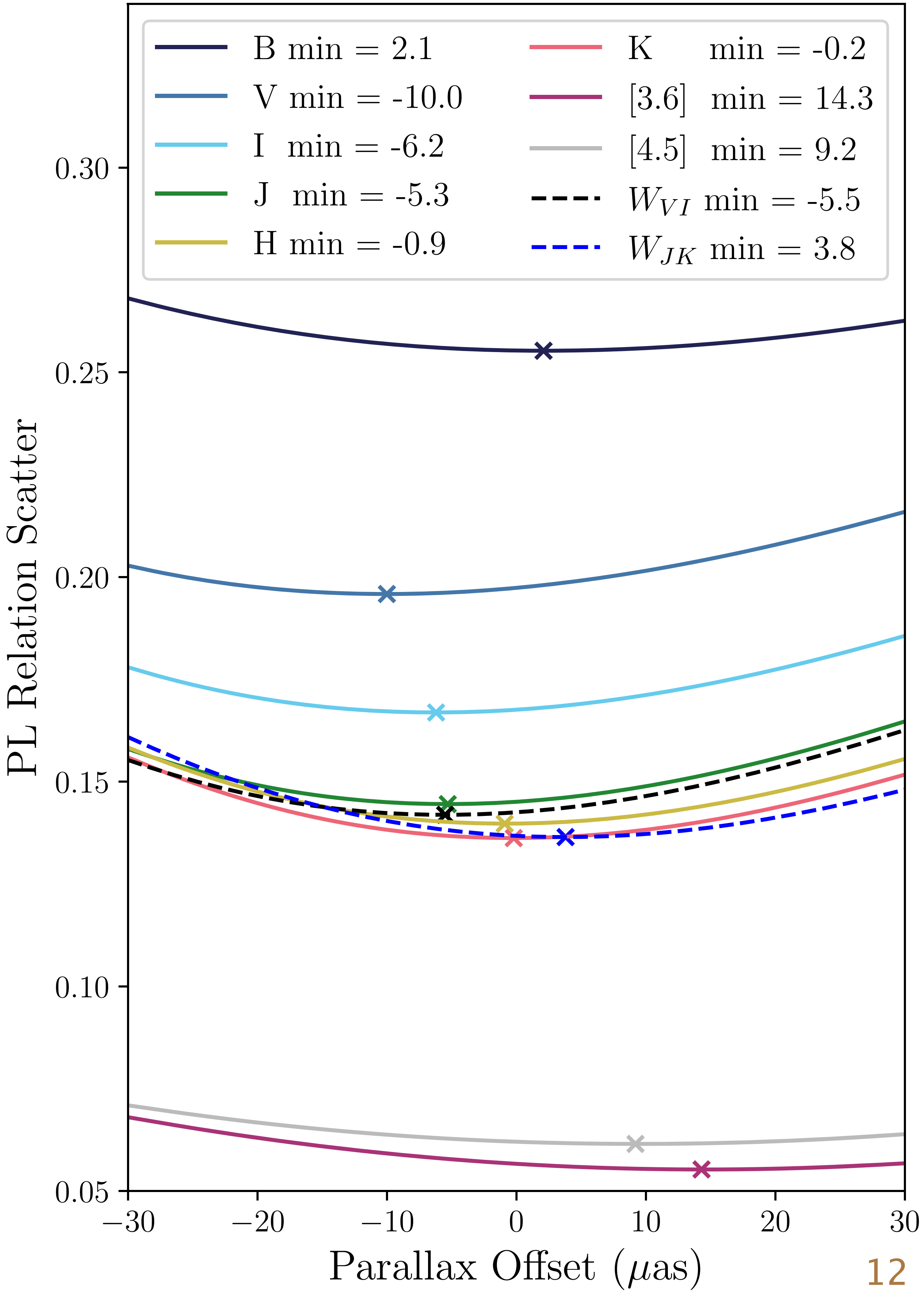
- AGN/quasars (faint, restricted range of colours, not in Galactic plane)
- other techniques: HST, VLBI (small number of objects)
- special objects: detached EB, asteroseismic RGB, … (extinction, surface brightness calibration, …)

B. Joint solution with calibration of standard candles

- various PL relations: Cepheids, RR Lyr, contact EB, … (extinction, metallicity, …)







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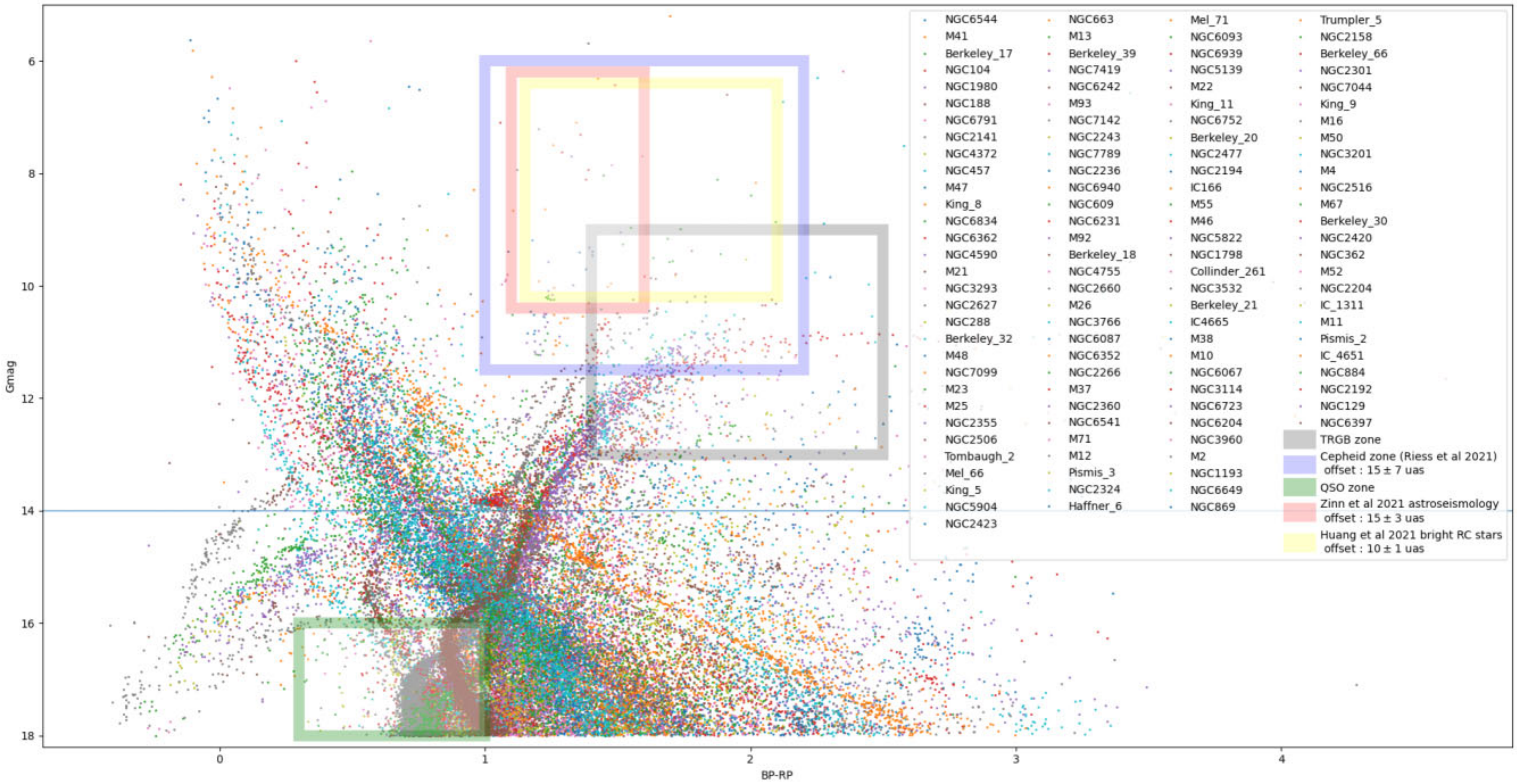
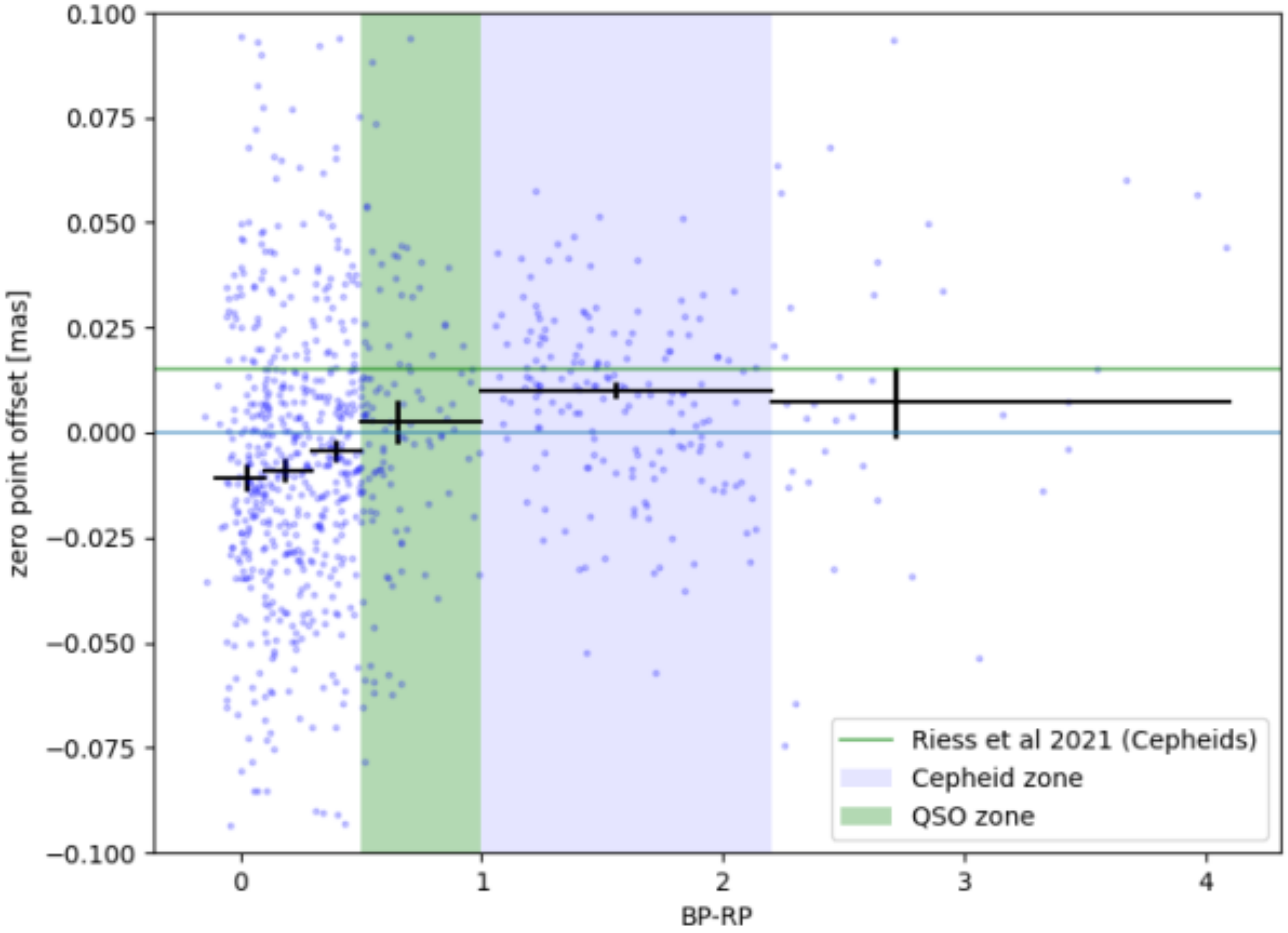
B. Joint solution with calibration of standard candles
   - various PL relations: Cepheids, RR Lyr, contact EB, … (extinction, metallicity, …)

C. Differential methods
   - binaries (optical pairs)
   - open clusters (membership, only in Galactic plane)
   - globular clusters (crowding)
   - dwarf galaxies incl. LMC, SMC (crowding, …)



Flynn et al. (2021) MNRAS 509, 4276 [FSV]

Residual parallax bias from cluster data (G = 9–11)



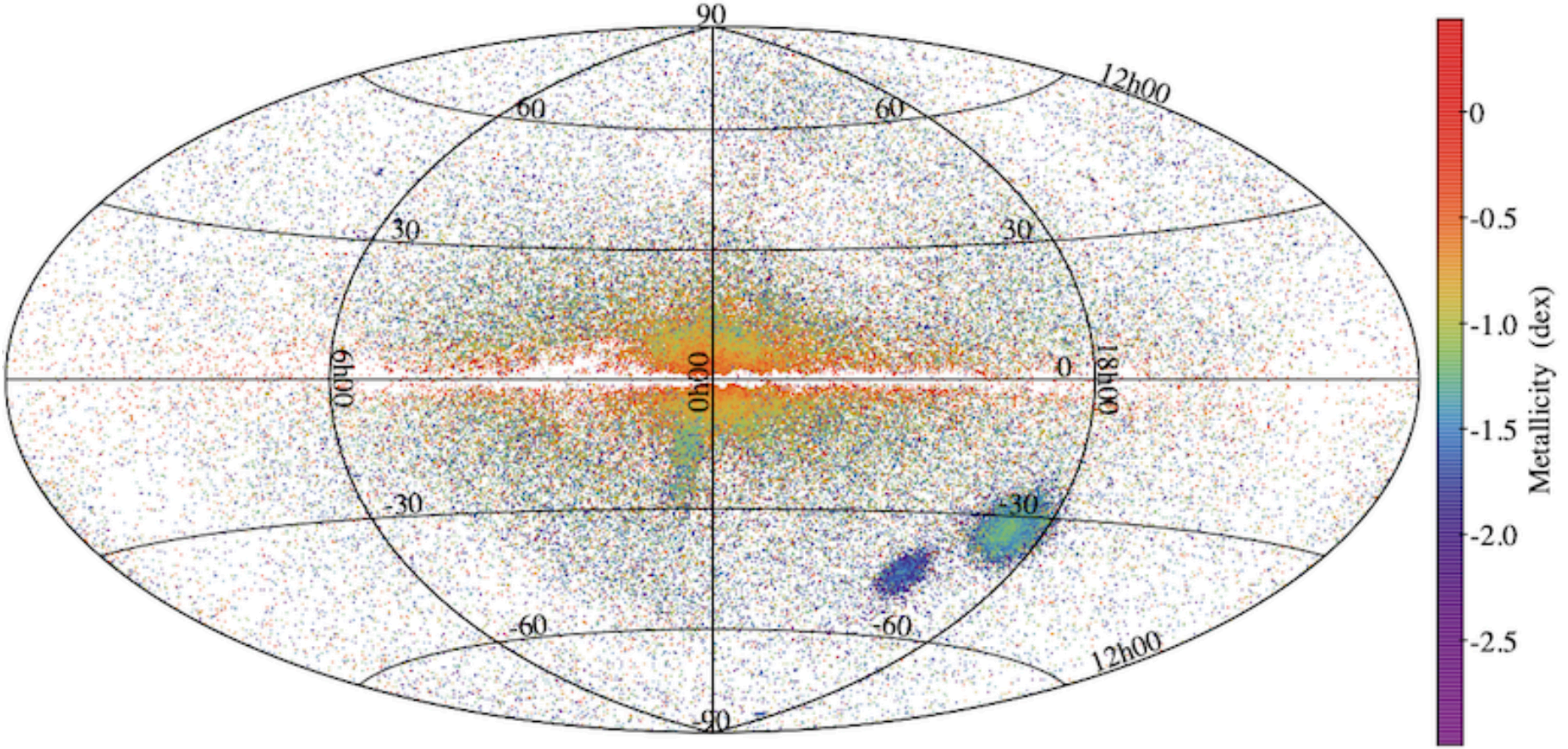
Flynn et al. (2021)
MNRAS 509, 4276 [FSV]

G = 9–11:
Blue stars: [LBB] undercorrects
Red stars: [LBB] overcorrects

Summary - What can be expected in the future?

- Gaia data releases
  - (E)DR3: 2.8 years of data
  - DR4: 5.5 years of data
  - DR5: ~10? years of data (7.5 years to date)
- Random parallax errors will be reduced by a factor 0.6 to 0.52 (best case)
- There is potential to reduce systematic uncertainties down to ±1 μas using a combination of methods (mainly QSOs + differential)
- Dependence on astrophysical models should be minimized (to avoid risk of circularity)
- Very bright stars ($G < 6$) and extreme colours ($BP-RP < 0$ or > 2.5) will remain very difficult
- A lot more can be done already with (E)DR3 data

Gaia DR3 (13 June 2022): >100,000 RR Lyr with metallicities



Gaia Image of the Week, 2022 Feb 25