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Small Magellanic Cloud Cepheids Observed with the Hubble Space Telescope Provide a New Anchor for the SH0ES Distance Ladder

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ABSTRACT

We present photometric measurements of 88 Cepheid variables in the core of the Small Magellanic Cloud (SMC), the first sample obtained with the *Hubble* Space Telescope (*HST*) and Wide Field Camera 3, in the same homogeneous photometric system as past measurements of all Cepheids on the SH0ES distance ladder. We limit the sample to the inner core and model the geometry to reduce errors in prior studies due to the non-trivial depth of this Cloud. Without crowding present in ground-based studies, we obtain an unprecedentedly low dispersion of 0.102 mag for a Period-Luminosity relation in the SMC, approaching the width of the Cepheid instability strip. The new geometric distance to 15 late-type detached eclipsing binaries in the SMC offers a rare opportunity to improve the foundation of the distance ladder, increasing the number of calibrating galaxies from three to four. With the SMC as the only anchor, we find $H_0 = 74.1 \pm 2.1$ km s^{-1} Mpc^{-1}. Combining these four geometric distances with our *HST* photometry of SMC Cepheids, we obtain $H_0 = 73.17 \pm 0.86$ km s^{-1} Mpc^{-1}. By including the SMC in the distance ladder, we also double the range where the metallicity ([Fe/H]) dependence of the Cepheid Period-Luminosity relation can be calibrated, and we find $\gamma = -0.22 \pm 0.05$ mag dex^{-1}. Our local measurement of H_0 based on Cepheids and Type Ia supernovae shows a 5.8σ tension with the value inferred from the CMB assuming a ΛCDM cosmology, reinforcing the possibility of physics beyond ΛCDM.

Take-home messages

- SMC is added as 1 more anchor (now totally 4).

- The Cepheid-SN1a H_0 is updated to

$$H_0 = 74.1 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

SMC alone

$$H_0 = 73.17 \pm 0.86 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

4 anchors

Anchor: a galaxy that allows one-step distance measurement

MW – parallaxes
LMC – DEBs (late-time)
NGC 4258 – maser
SMC – DEBs (late-time)

Challenges for SMC to be an anchor

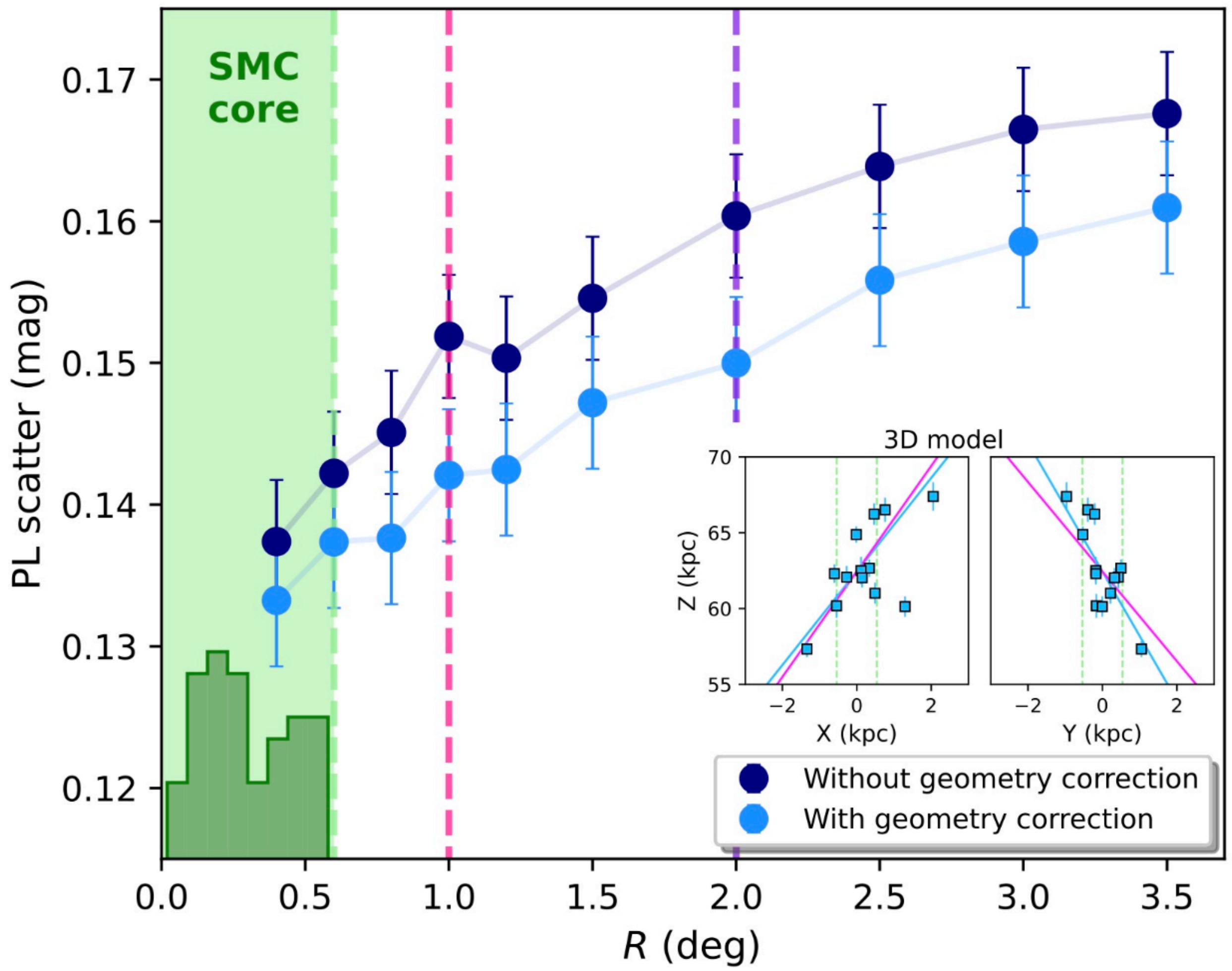
- Large angular size and elongated shape
  - Choose Cepheids close to the core
  - Model the shape of SMC

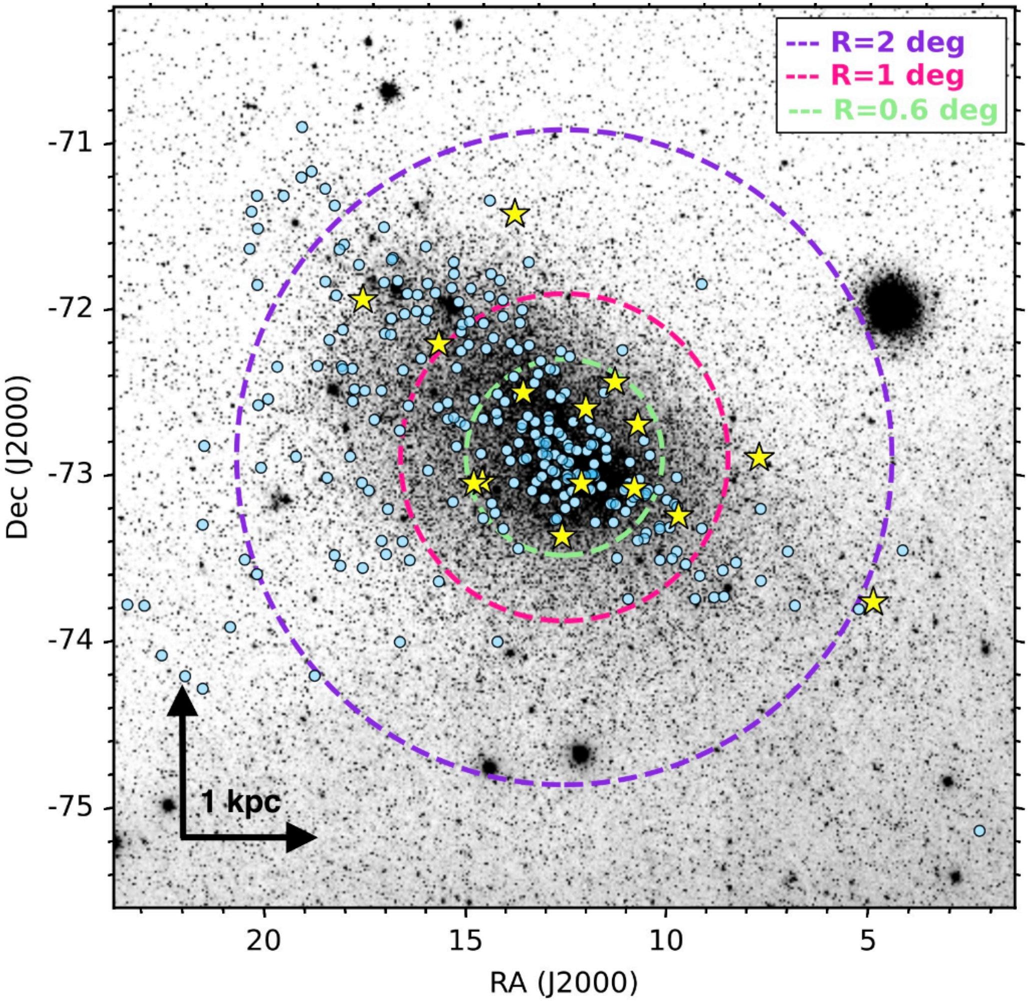
$$d(x, y) = +3.480\,x - 2.955\,y + d_{\mathrm{SMC}}$$

- Wide separation between Cepheids, so not HST friendly
  - Adopted a recently available rapid exposure observing mode.
  - HST photometry.

How to tell whether a P-L relation is good? – A parameter used is the scatter.

Geometric modeling decreases scatters in Cepheid P-L relation near the core to 0.13 mag.





The recent DASH mode allows multiple Cepheid observations in one orbit

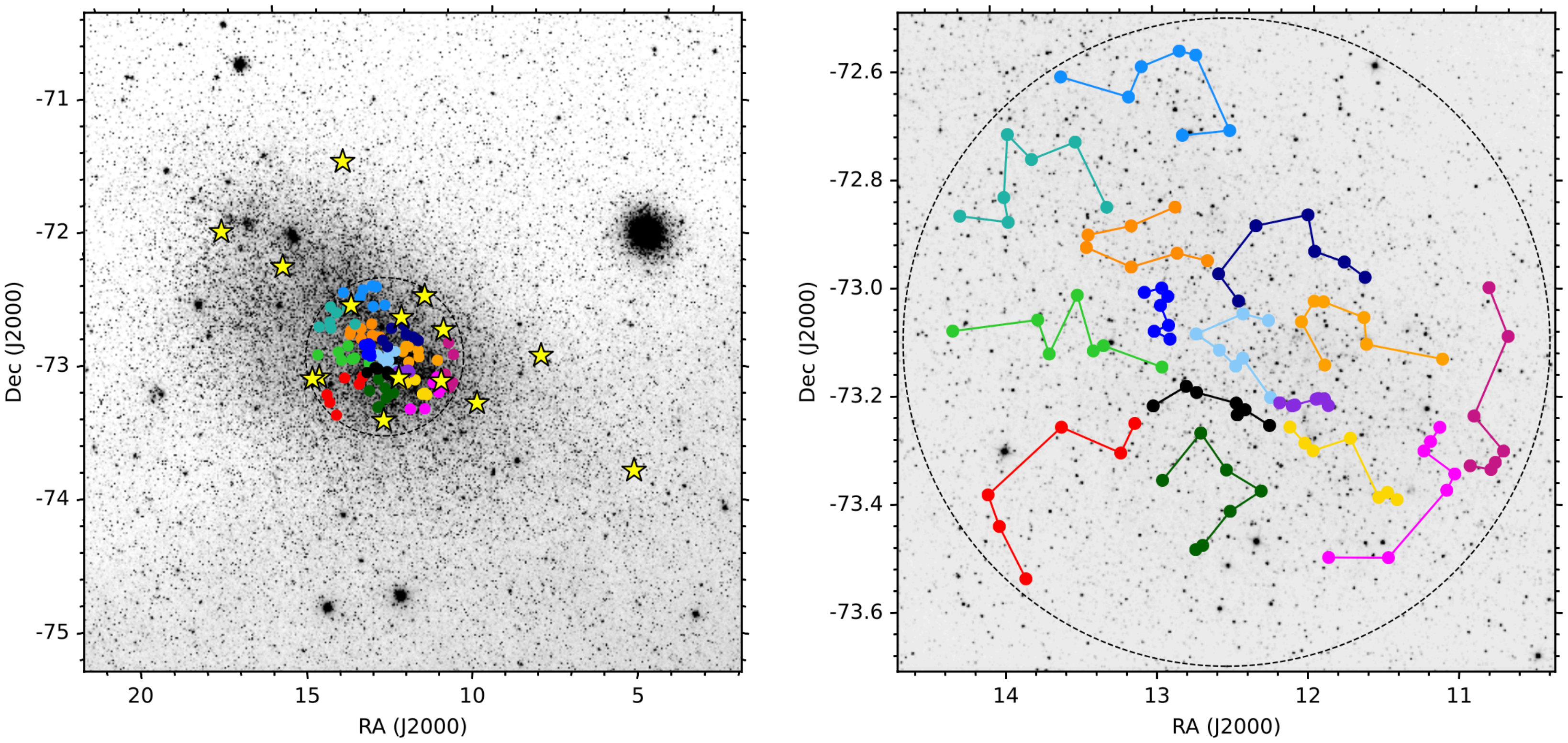


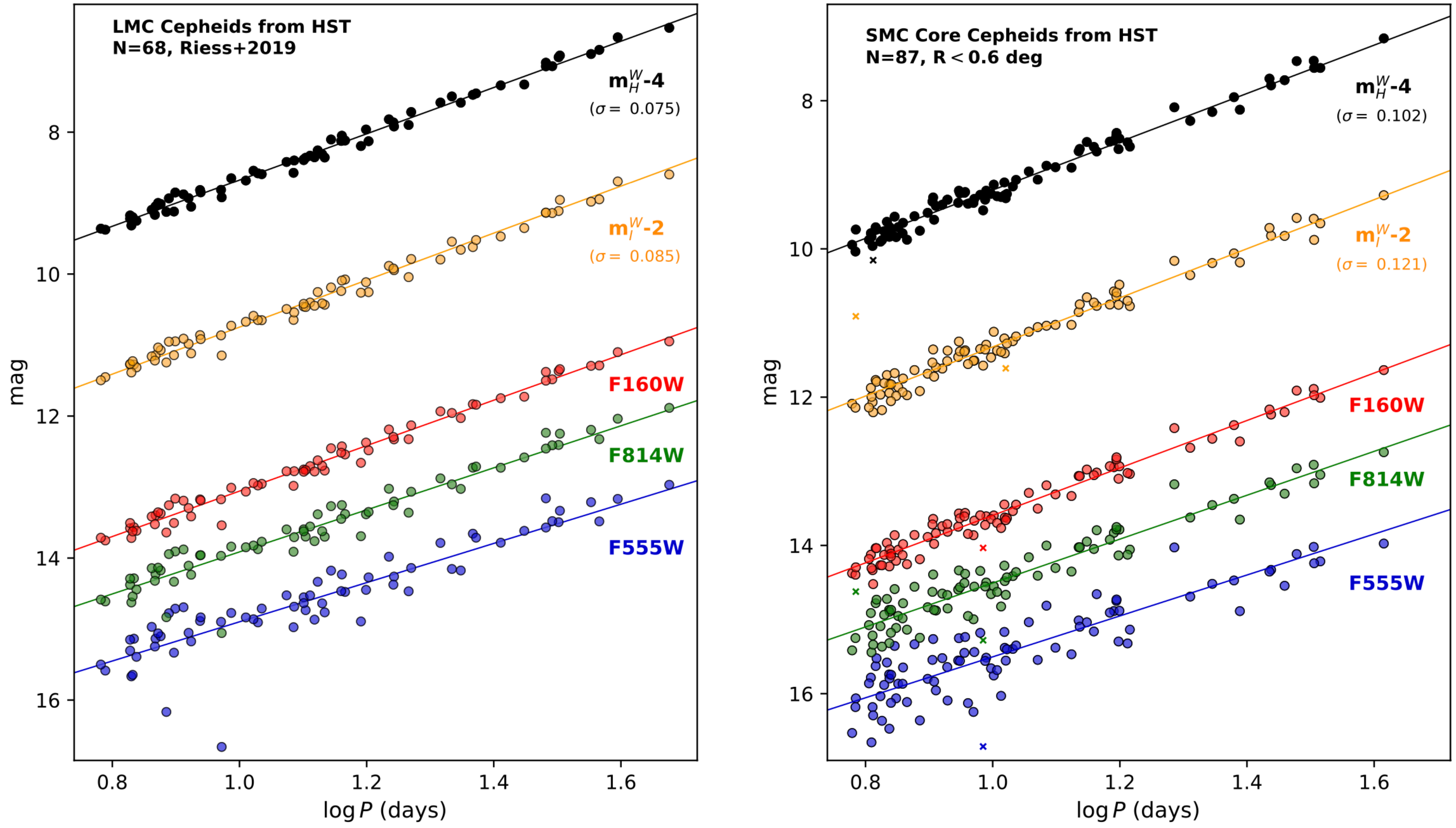
Figure 2. **(Left)**: The dashed circle shows the core region of the SMC ($R = 0.6$ deg). Detached eclisping binaries from Graczyk et al. (2020) are shown in yellow and the colored dots are the Cepheids from the present study. **(Right)**: Zoom-in of the SMC core region. The 15 Cepheid sequences (one per *HST* orbit) are shown in color.

1. Previously, ground-based photometry:
    - Crowding
    - Not the same 0 point as HST
2. Cepheid separation is 12', not suitable for HST before;
    - Now a rapid exposure observing mode is used.

P-L relations and comparison to LMC

$$m_H^W = F160W - 0.386\,(F555W - F814W)$$

$$m_I^W = F814W - 1.19\,(F555W - F814W)$$



- Scatter is higher for SMC cepheids;
- A scatter of ~0.1 is very close to state-of-the-art.
- No break is suggested in the P-L relation.

Figure 6. Period-Luminosity relations in the 3 *HST* filters and in the m_I^W and m_H^W Wesenheit indices. Outliers are shown by small "x" symbols and are excluded from the fit. Left and right panels show the Period-Luminosity relations in the LMC (Riess et al. 2019a) and SMC respectively.

P-L relations and comparison to LMC

Table 3. Cepheid P–L relations from *HST* photometry in the SMC: $m_H^W = \alpha \log P + \beta$.

Filter	α (this work)	α (R19)	β	σ
$F555W$	-2.65 ± 0.13	-2.76 ± 0.13	18.263 ± 0.031	0.287
$F814W$	-2.98 ± 0.09	-2.96 ± 0.09	17.467 ± 0.021	0.195
$F160W$	-3.22 ± 0.06	-3.20 ± 0.04	16.795 ± 0.013	0.122
m_I^W	-3.37 ± 0.06	-3.31 ± 0.04	16.632 ± 0.013	0.121
m_H^W	-3.31 ± 0.05	-3.26 ± 0.04	16.467 ± 0.011	0.102

- Scatter is higher for SMC cepheids;
- A scatter of ~0.1 is very close to state-of-the-art.
- No break is suggested in the P-L relation.

Error budges in the 1st rung

Table 4. Uncertainty in H_0 from leading term, geometric calibration of Cepheids (%).

Term	Description	Riess et al. (2022a,b)			This paper			
		LMC	MW	N4258	LMC	MW	N4258	SMC
$\sigma_{\mu,\,\mathrm{anchor}}$	Anchor distance	1.2	0.8 $^{(a)}$	1.5 $^{(b)}$	1.2	0.8 $^{(a)}$	1.5 $^{(b)}$	1.5
$\sigma_{\mathrm{PL,\,anchor}}$	Mean of P–L in anchor	0.4	...	1.0	0.4	...	1.0	0.5
$R\sigma_{\lambda,1,2}$	Zeropoints, anchor-to-host	0.1	0.1 $^{(a)}$	0.0	0.1	0.1 $^{(a)}$	0.0	0.1
σ_{Z}	Cepheid metallicity, anchor-hosts	0.4	0.15	0.15	0.4	0.1	0.1	0.5
	Subtotal per anchor	1.4	0.8	1.8	1.4	0.8	1.8	1.7
First Rung Total		0.65			0.60			

NOTE— (a) Includes both field Cepheids and cluster Cepheids; (b) Reid et al. (2019).

Metallicity dependence

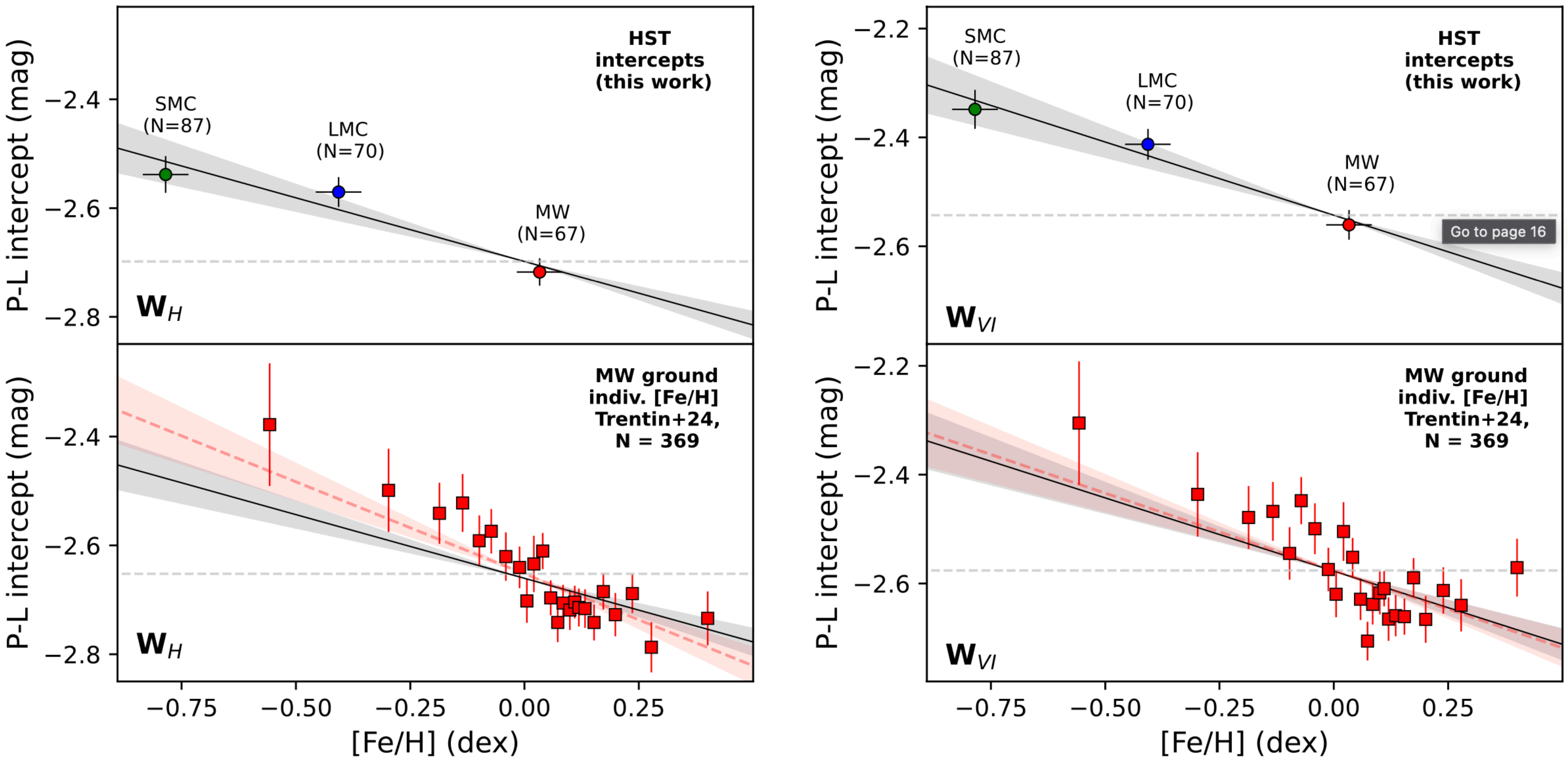


Figure 8. **(Top):** P–L intercept (at $\log P = 0$) in the Milky Way (red), LMC (blue) and SMC (green) based on HST photometry versus [Fe/H], where the slope is the metallicity dependence γ. **(Bottom):** Binned data (a square symbol is the average of 15 data points) from Trentin et al. (2024) based on ground-based photometry, *Gaia* DR3 parallaxes and high resolution spectroscopic measurements in the Milky Way. The solid black line is the slope obtained in the present paper, $\gamma\,(W_H) = -0.234$ mag/dex and $\gamma\,(W_{VI}) = -0.264$ mag/dex, and the dashed red line is the slope from Trentin et al. (2024). The left and right panels show the m_H^W and m_I^W Wesenheit indices respectively (their absolute magnitudes are called W_H and W_{VI}).

My big picture in the Hubble tension

If the problem is in the local measurement

- SN1a, 3rd rung? – Not likely
  - SN1a alone gives consistent result with Planck in Ω_m.
  - Replacing SN1a with other secondary distance indicators also give high H_0.

- 1st rung? – I don't think so
  - 4 anchors with 3 different methods all give high H_0.
    (This paper strengthen this conclusion)

- 2nd rung (10-30 Mpc)? -- Most likely
  - Crowding? – recently, JWST with 5 (out of 42) SN-Cepheid hosts justified the previous de-crowding method.
  - Local void? – possible, but difficult to produce a 10% difference in H_0.
  - Dust? Environmental difference? – needs to carefully revisit the Wesenheit magnitude.
  - Cosmic evolution in Cepheid P-L relation?
  - ….