An intuitive 3D map of the Galactic warp's precession traced by classical Cepheids

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Supplementary information

**Supplementary Table 1:** LONs and their statistical and systematic uncertainties as a function of radius.

R (kpc)	LON (°)
8.5	$28.5 \pm 11.9 \pm 7.4$
9.5	$15.5 \pm 4.5 \pm 2.2$
10.5	$9.9 \pm 4.0 \pm 2.4$
11.5	$6.1 \pm 4.0 \pm 2.7$
12.5	$1.7 \pm 3.3 \pm 2.7$
13.5	$7.9 \pm 2.7 \pm 3.5$
14.5	$21.7 \pm 2.9 \pm 0.8$
15.5	$23.0 \pm 3.2 \pm 0.8$
16.5	$21.1 \pm 6.0 \pm 1.1$
17.5	$27.5 \pm 11.5 \pm 7.4$

**Supplementary Table 2:** Adopted infrared extinction laws and possible biases affecting the distance modulus.

	α	A_J/A_{K_s}	A_H/A_{K_s}	A_{W1}/A_{K_s}	A_{W2}/A_{K_s}	$A_{[3.6]}/A_{K_\mathrm{s}}$	$A_{[4.5]}/A_{K_\mathrm{s}}$	$A_{[5.8]}/A_{K_\mathrm{s}}$	$A_{[8.0]}/A_{K_\mathrm{s}}$	Bias (mag)
ref. 9	2.05	3.005	1.717	0.506	0.340	0.478	0.341	0.234	0.321	0
	1.61	2.438	1.501	0.657	0.551	0.626	0.549	0.489	0.519	0.092
ref. 46	1.79	2.720	1.599	0.591	0.463	0.553	0.461	0.389	0.426	0.044
ref. 45	1.66	2.660	1.545			0.553	0.451	0.334	0.372	0.042
ref. 47	1.66	2.50	1.54			0.560	0.430	0.430	0.430	0.045

**Supplementary Video 1:** GIF animation of the Cepheid disc in 3D.

Supplementary Data 1: Full data set of our 2330 Cepheids. The columns contain the position, photometry, distance, extinction and velocity information. Descriptions of all columns are included in the data set's header information.
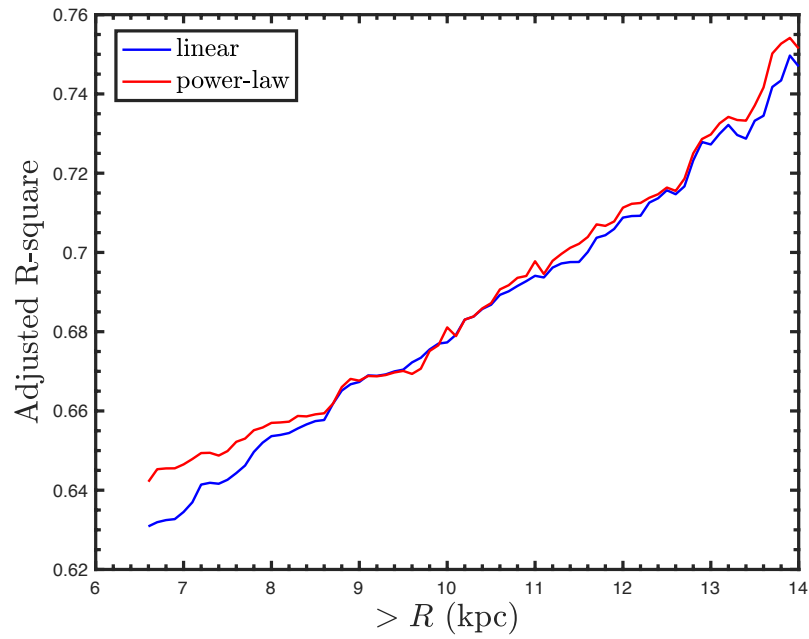
Supplementary Figure 1: Comparison of the power-law and linear warp models. Adjusted R^2 of the model fits for Cepheids at different Galactocentric radial ranges. Red and blue lines denote the adjusted R^2 of the power-law and linear models.
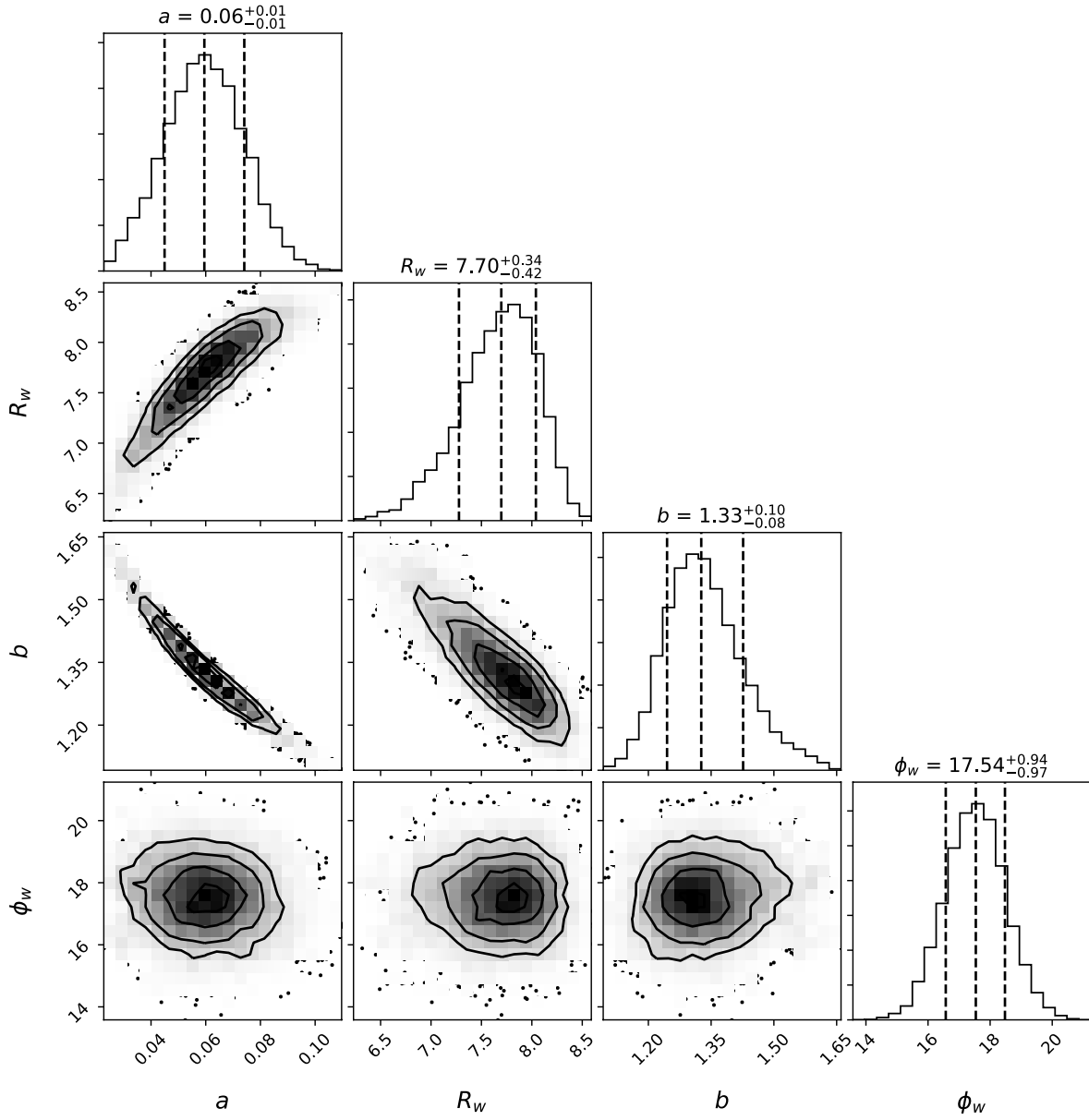
Supplementary Figure 2: Probability distribution of the parameters in the $z_{\mathrm{w}} = a(R - R_{\mathrm{w}})^b \sin(\phi - \phi_{\mathrm{w}})$ warp models determined based on our MCMC simulation. The median value and the 16 and 84 percentile probabilities are indicated.
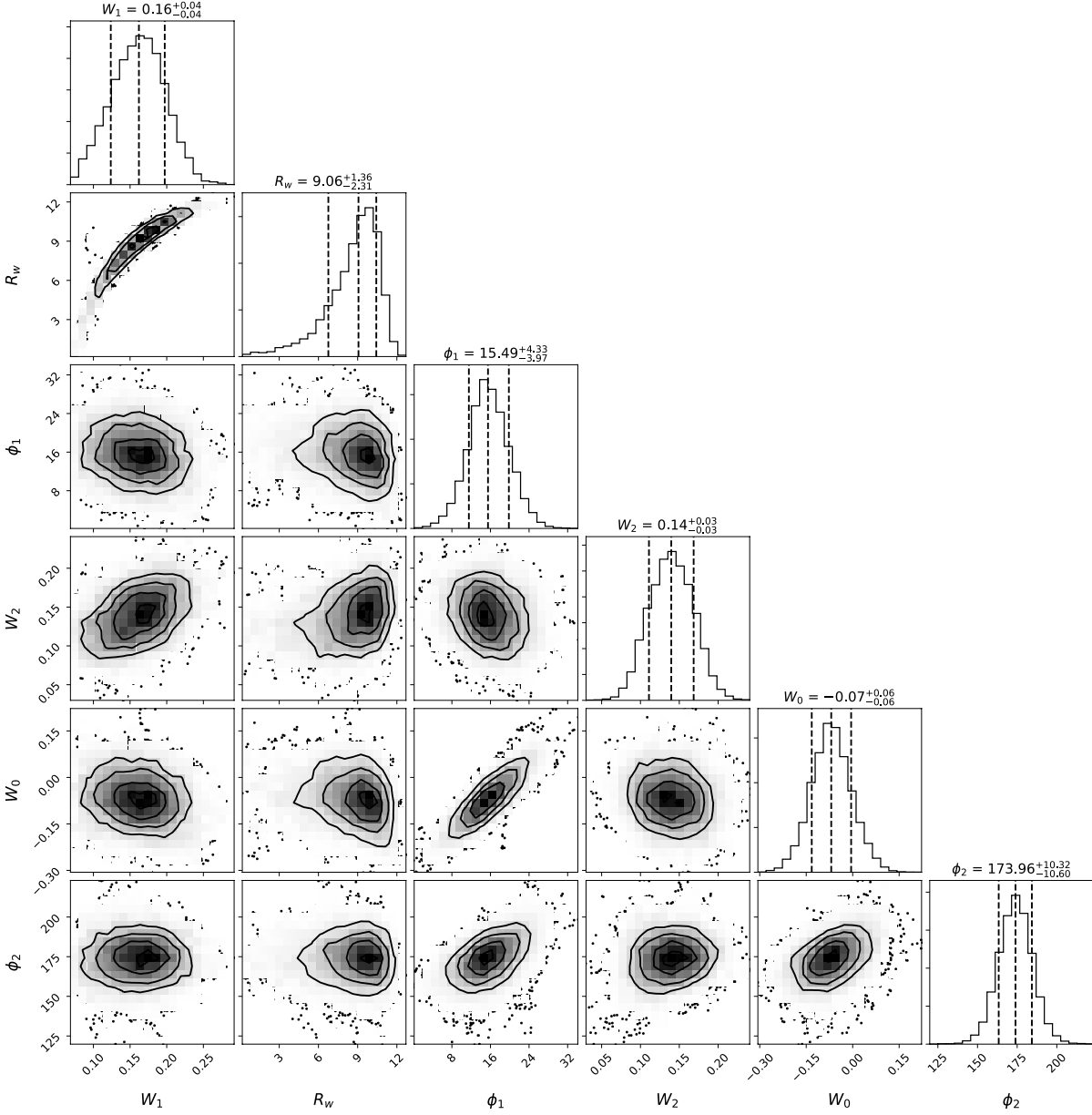
Supplementary Figure 3: Probability distribution of the parameters in the $z_{\mathrm{w}} = W_0 + W_1(R - R_{\mathrm{w}})\sin(\phi - \phi_{\mathrm{w}}) + W_2(R - 15)\sin(2\phi - \phi_{\mathrm{w}2})$ warp models for the $m = 0, 1, 2$ modes based on 146 Cepheids at $R > 15$ kpc. The median value and the 16 and 84 percentile probabilities are indicated.
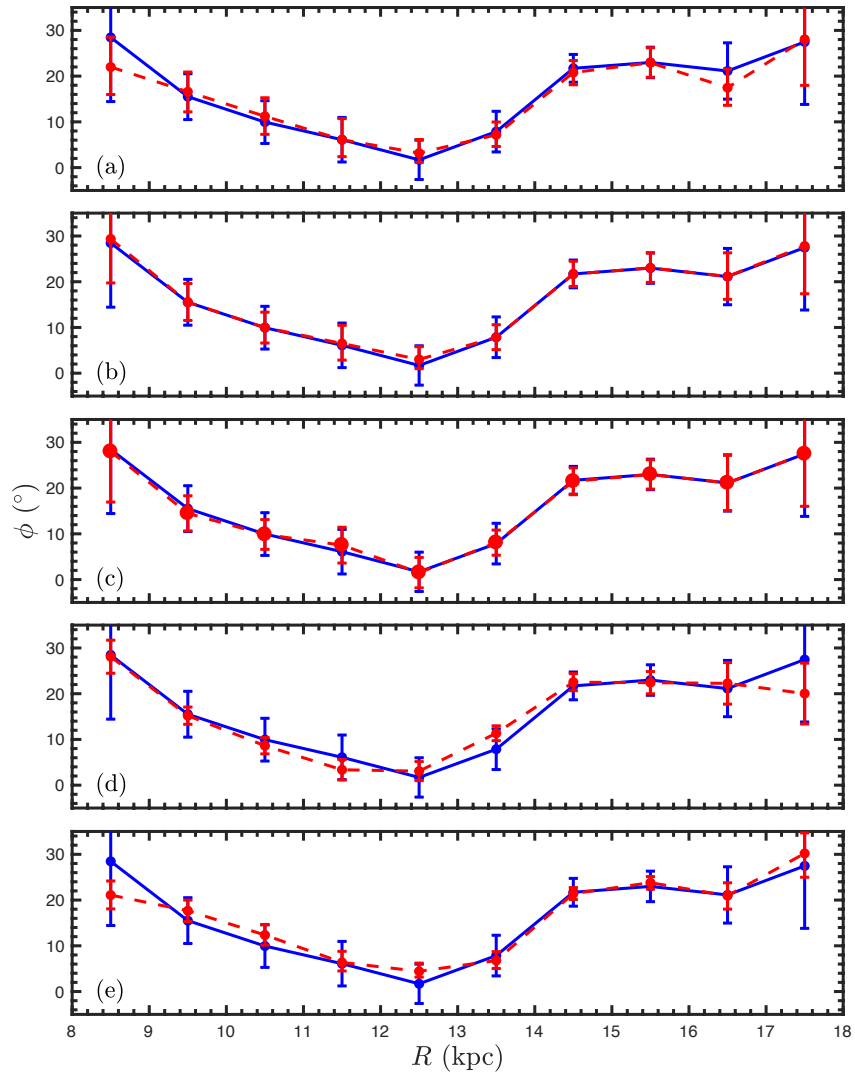
Supplementary Figure 4: Validation of the warp's LON for different conditions. Blue dots denote the LONs determined based on application of the nonlinear least-squares method to the warp model (identical to the blue dots in Figure 3). The blue error bars include systematic uncertainties and 1σ statistical uncertainties. Red dots in each panel denote LONs determined under different conditions. The corresponding error bars are the 1σ statistical uncertainties. a: MCMC simulation with free parameters; b: MCMC simulation with fixed parameters; c: Cepheids selected based on a 10% accuracy cut in distances; d: error propagation considered in the Monte Carlo simulations; e: resampling test to consider equal numbers of Cepheids in the northern and southern warps.
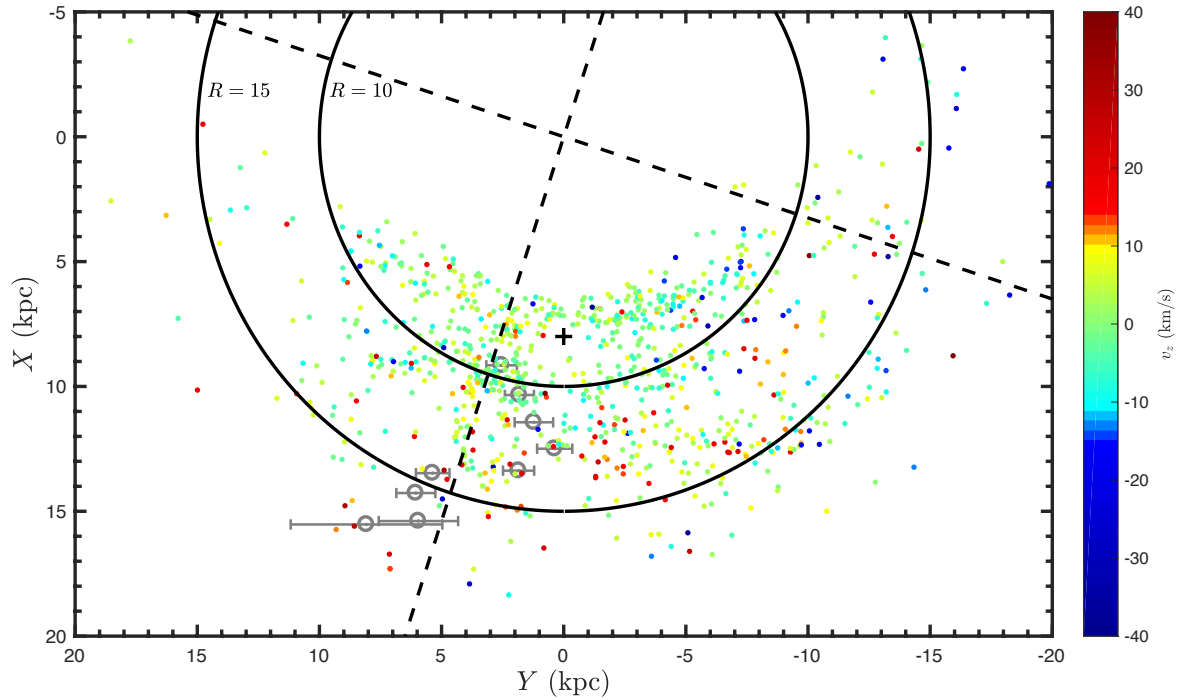
Supplementary Figure 5: v_z versus XY map traced by Cepheids. Cepheids with large positive v_z are shown in red, whereas their negative counterparts are shown in blue. The large black circles denote $R = 10, 15$ kpc and black dashed lines denote the LON line (close to the Sun) and the warp's maxima line. The Sun is shown as the black plus sign and the spatial LONs are represented by grey circles. The grey error bars represent the LONs' 1σ statistical uncertainties.

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