Precession of the Galactic warp with Gaia DR3

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Presentation outline

- Flare
- Warp
  - Warp in the Milky Way
  - Models of the Galactic warp
  - Precession of the Galactic warp
- Data
- Results
  - Flare
  - Warp
  - Precession of the Galactic warp

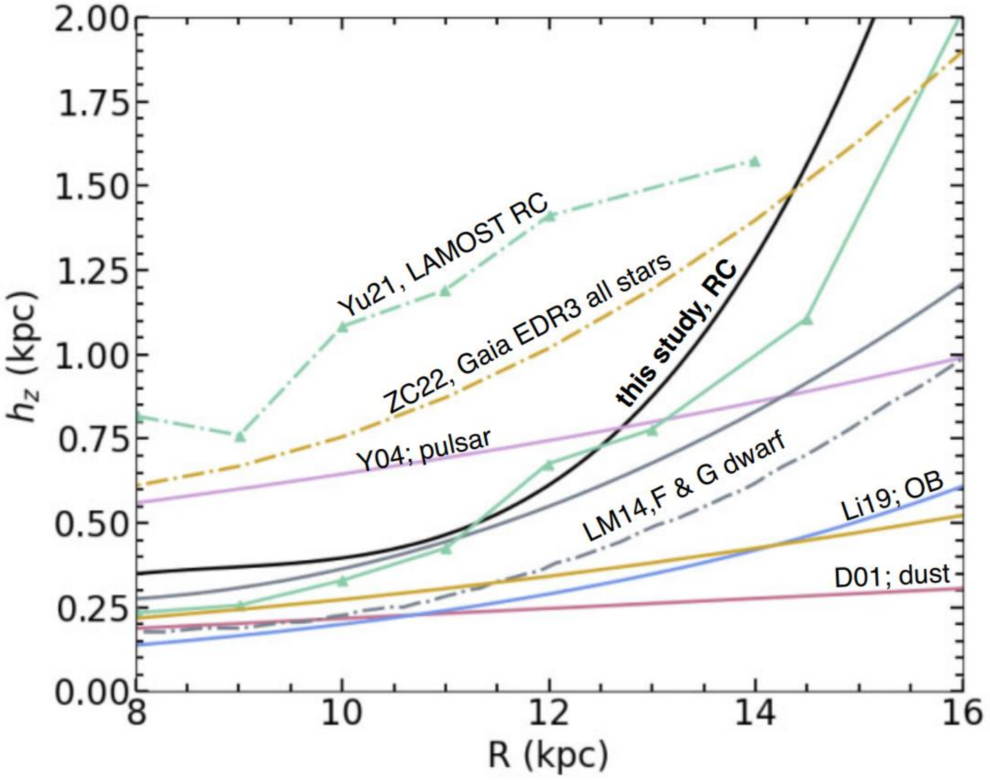
Flare

- Increase of the scale height h_z with radial distance

- Present in all components, with different profiles

- Double exponential density model:

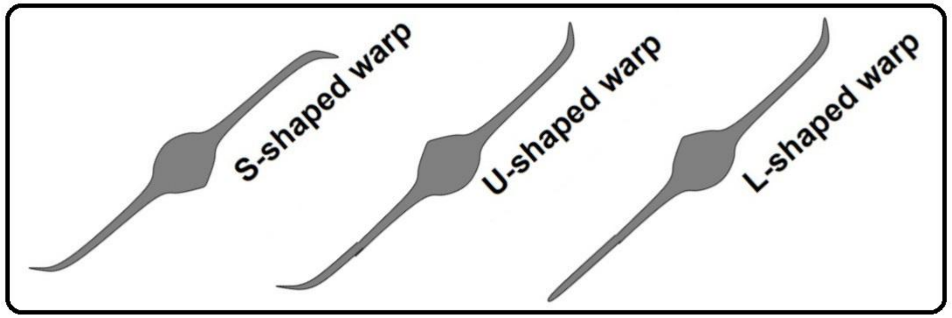
$$\rho(R,z) = \rho_s \exp\left(\frac{R_s - R}{h_r}\right) \exp\left(\frac{-|z|}{h_z(R)}\right)$$



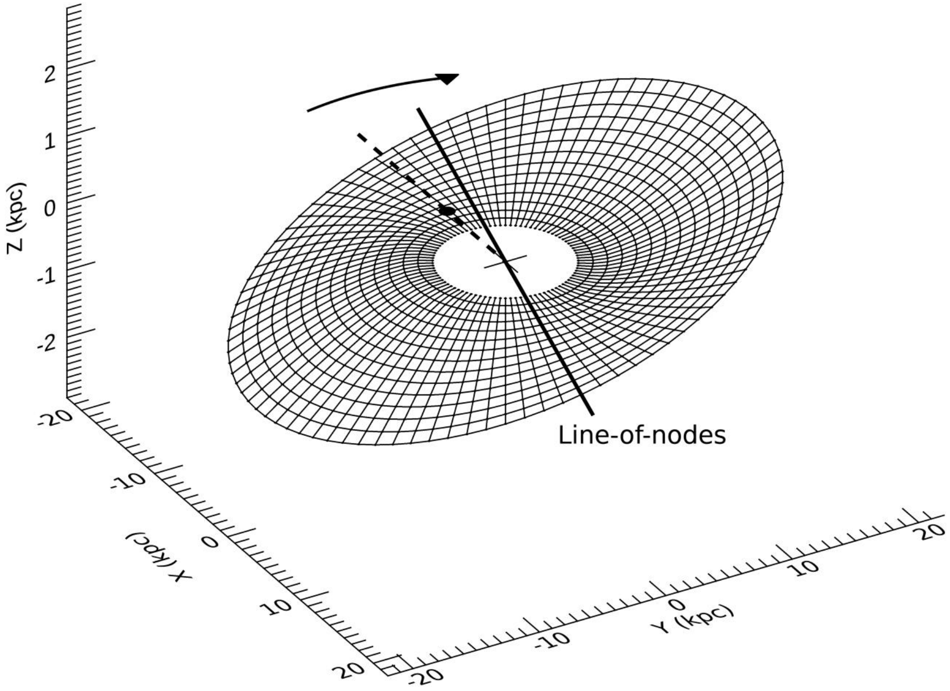
Uppal et al. (2024)

Warp

- Bending of the galactic disc; distortion from the flat shape
- Majority of spiral edge-on galaxies have warped discs
- 'S', 'U', 'L' types



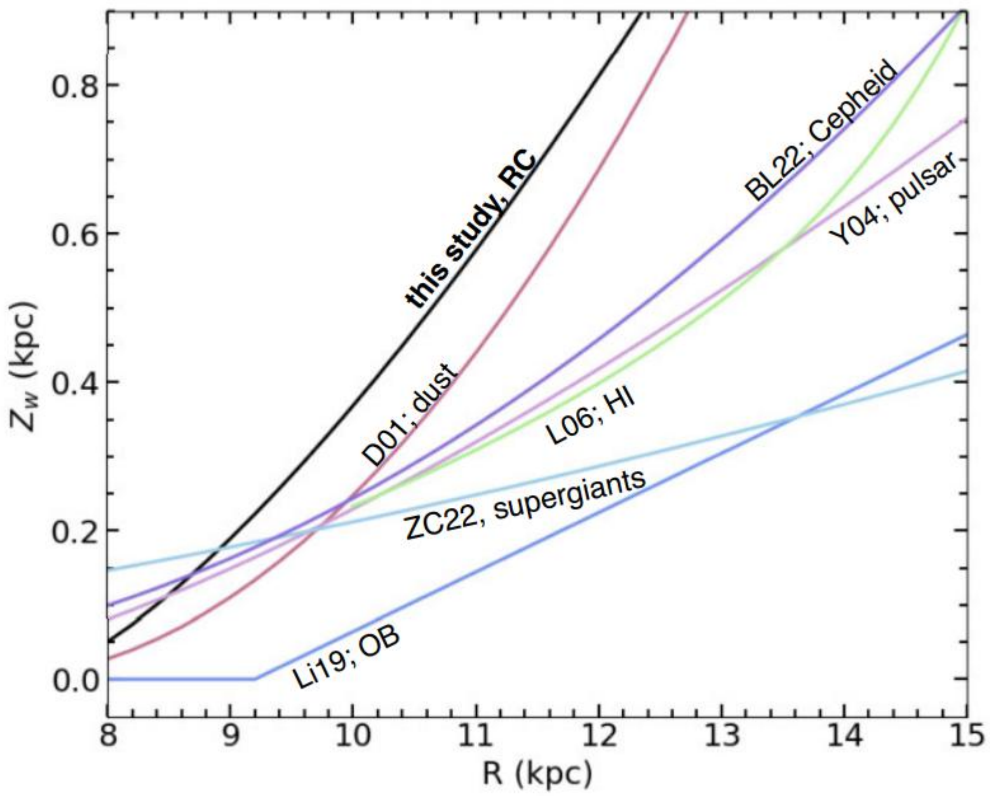
Sánchez-Saavedra et al. (2003)



Poggio et al. (2020)

Warp in the Milky Way

- 'S' shaped warp
- Observed in all disc’s components
  - Neutral hydrogen
  - Interstellar dust
  - Molecular clouds
  - All stellar populations
- Warp profile varies significantly in different tracers



Uppal et al. (2024)

Stellar warp

- Moderate northern-southern asymmetry (no consensus)
- Line of nodes (LON) between (-20°, 28°)
- Prominent age dependency:
  - warp amplitude increases with age
    - Romero-Gómez et al. (2019)
  - warp amplitude decreases with age
    - Wang et al. (2020), Chrobáková et al. (2022)
    - Young classical Cepheids – large warp amplitudes

Models of the Galactic warp

- Mean deviation from the Galactic plane:

$$z_w(R,\varphi) = \frac{\int_{-\infty}^{\infty} \rho(R,\varphi,z) z \, \mathrm{d}z}{\int_{-\infty}^{\infty} \rho(R,\varphi,z) \mathrm{d}z}$$

Simple sinus model

- The warp is described as: $$z_w(R,\varphi) = h_w(R)\,\sin(\varphi - \varphi_w)$$

where $h_w(R)$ is a shape function $$h_w(R) = h_{0,w}\,(R - R_w)^{\alpha_w}$$

Multi-mode model

- Levine et al. (2006) - two sinusoids

$$z_w = z_0 + z_1 \cdot \sin(\phi - \phi_1) + z_2 \cdot \sin(2\phi - \phi_2)$$

$$z_i = k_{0,i} + k_{1,i} \cdot (R - R_k) + k_{2,i} \cdot (R - R_k)^2 \;\; ; \;\; i = 0, 1, 2$$

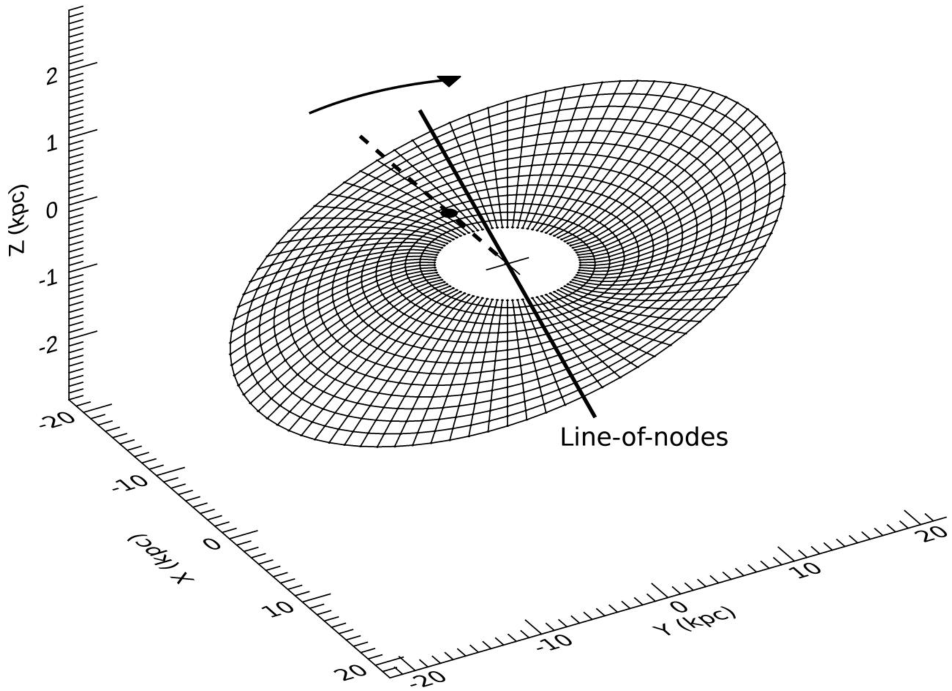
- Generalization - Fourier sine series

Precession of the Galactic warp

$$z_w(R, \varphi) = h_w(R)\,\sin(\varphi - \varphi_w)$$

- Precession = warp structure is not steady

$$\dot{\varphi}_w \equiv \omega \neq 0$$



Poggio et al. (2020)

Precession - model (Jeans equation)

$$z_w(R,\varphi) = h_w(R)\ \sin(\varphi - \varphi_w)$$

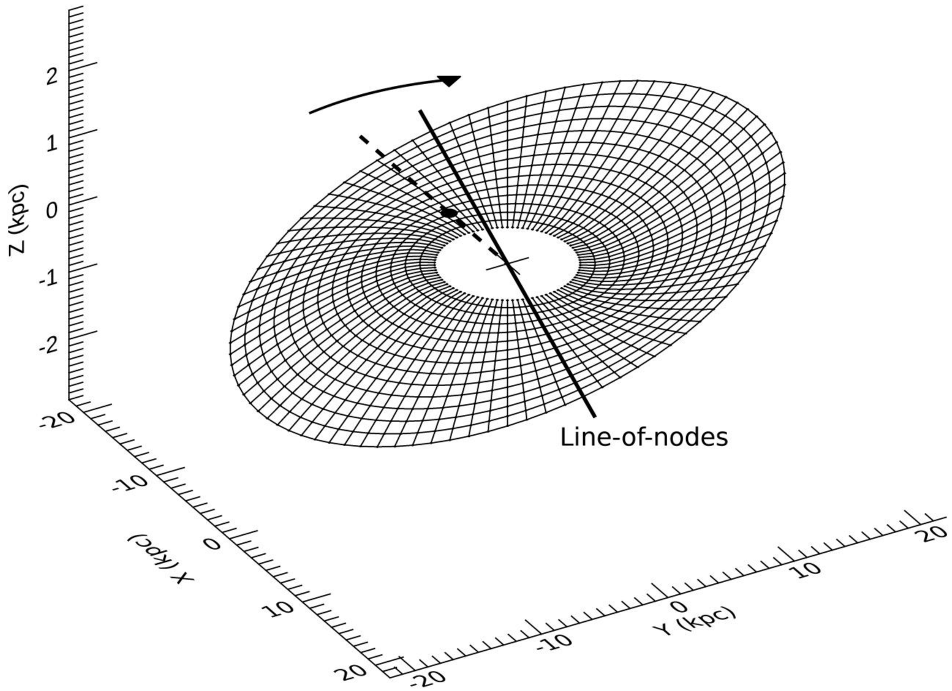
- Precession = warp structure is not steady $\dot{\varphi}_w \equiv \omega \neq 0$ $\varphi_w(t) = \varphi_{w0} + \omega t$
- Jeans equation $\frac{\partial \rho}{\partial t} + \frac{\overline{V}_\phi}{R}\frac{\partial \rho}{\partial \phi} + \overline{V}_z \frac{\partial \rho}{\partial z} = 0$

$$\bar{V}_z(R,\varphi,t=0) = \left(\frac{\bar{V}_\varphi}{R} - \omega(R)\right) h_w(R)\cos(\varphi - \varphi_{w0}) + \frac{\partial h_w}{\partial t}\sin(\varphi - \varphi_{w0})$$

$$\bar{V}_z(R,\varphi,t=0) = \left(\frac{\bar{V}_\varphi}{R} - \omega\right) h_w(R)\cos(\varphi - \varphi_{w0})$$ (geometric model)

Precession - observations

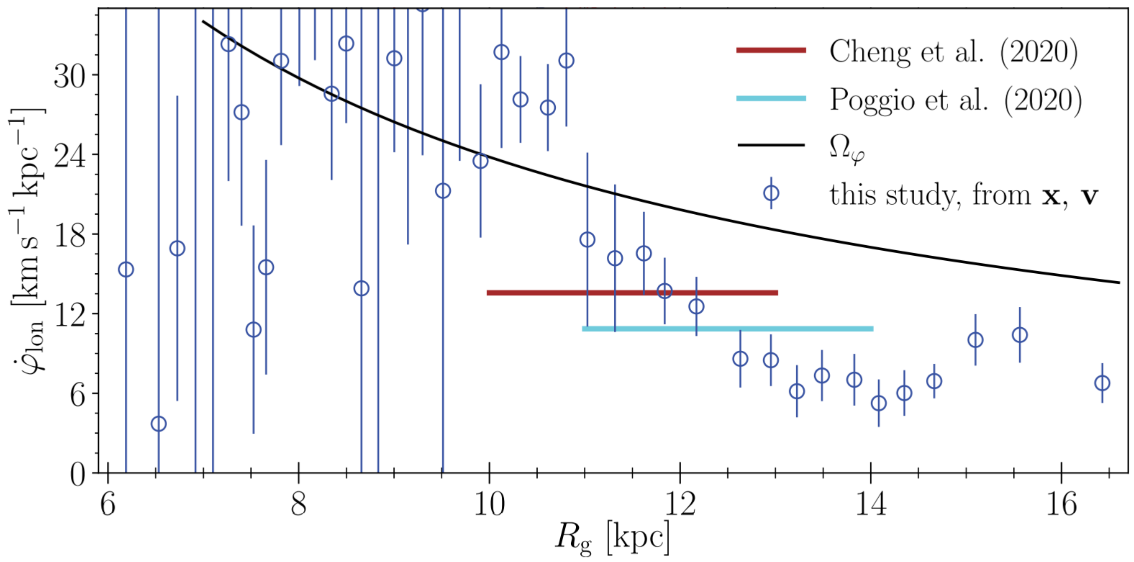
- First observation: Poggio et al. (2020)
  - Giant stars from Gaia DR2
  - $\dot{\varphi}_w = 10.86 \pm 3.23 \; km/s/kpc$
- Chrobáková et al. (2021)
  - $\dot{\varphi}_w = 4^{+6}_{-4} \; km/s/kpc$
- Cheng et al. (2020)
  - $\dot{\varphi}_w = 13.57^{+0.20}_{-0.18} \; km/s/kpc$



Poggio et al. (2020)

Precession - observations

- Cepheids: (Dehnen et al. 2023; Zhou et al. 2024; Huang et al. 2024)
- Gaia DR3 (Jónsson et al. 2024)
  - 13 km/s/kpc



Dehnen et al. (2023)

Data

- Gaia DR3

- **Position**: Gaia astrometry + geometric distances from Bailer-Jones et al. (2021)
  - ~1.4 billion stars

- **Velocity:** Gaia proper motions and radial velocities
  - ~33 million stars

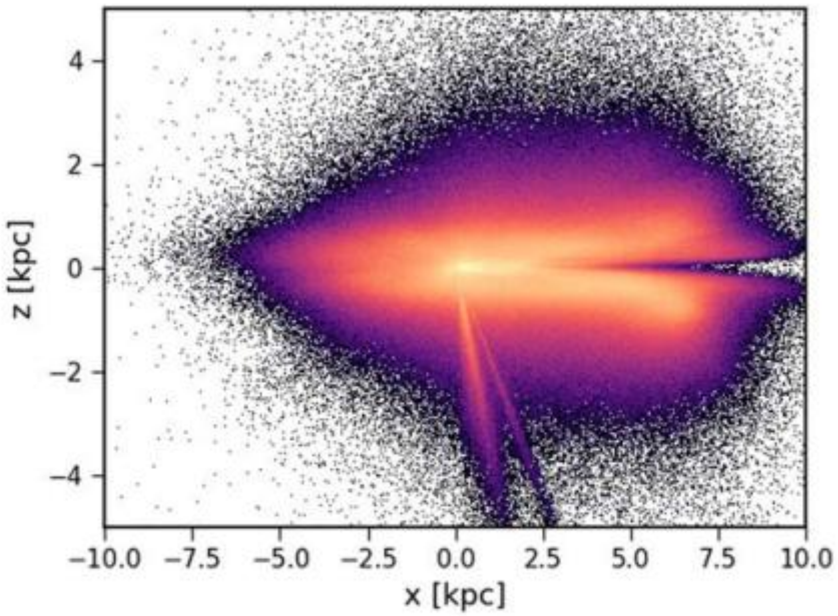
Results

Flare

- Ignoring thin disc due to lack of data
  - Thick disc
- Fitting the vertical profile for each bin:

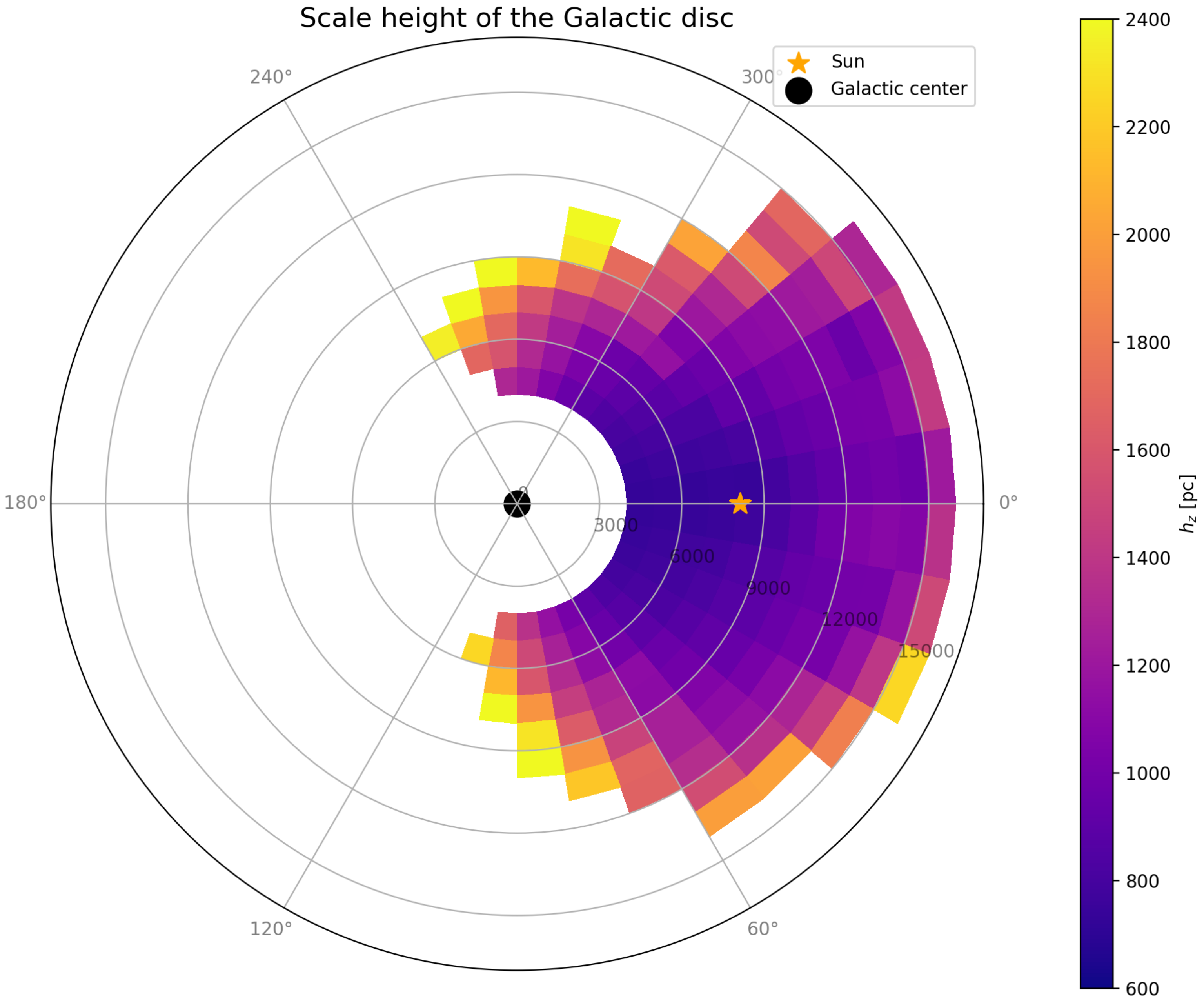
$$\rho(z) = \rho_0 e^{-|z-z_w|/h_z}$$

- Quality limit: $R^2 > 0.8$

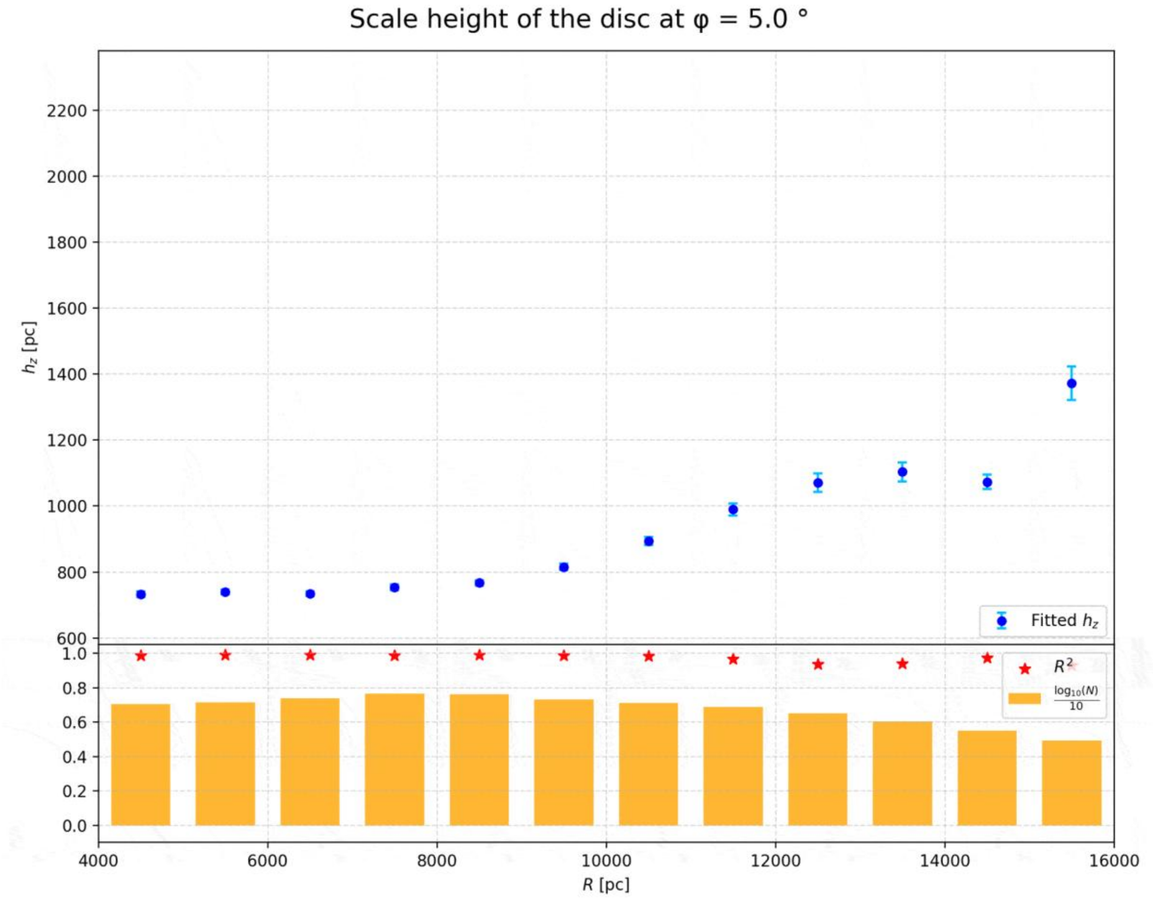


Bailer-Jones et al. (2021)

Flare - results



Flare - results vs literature



Our work

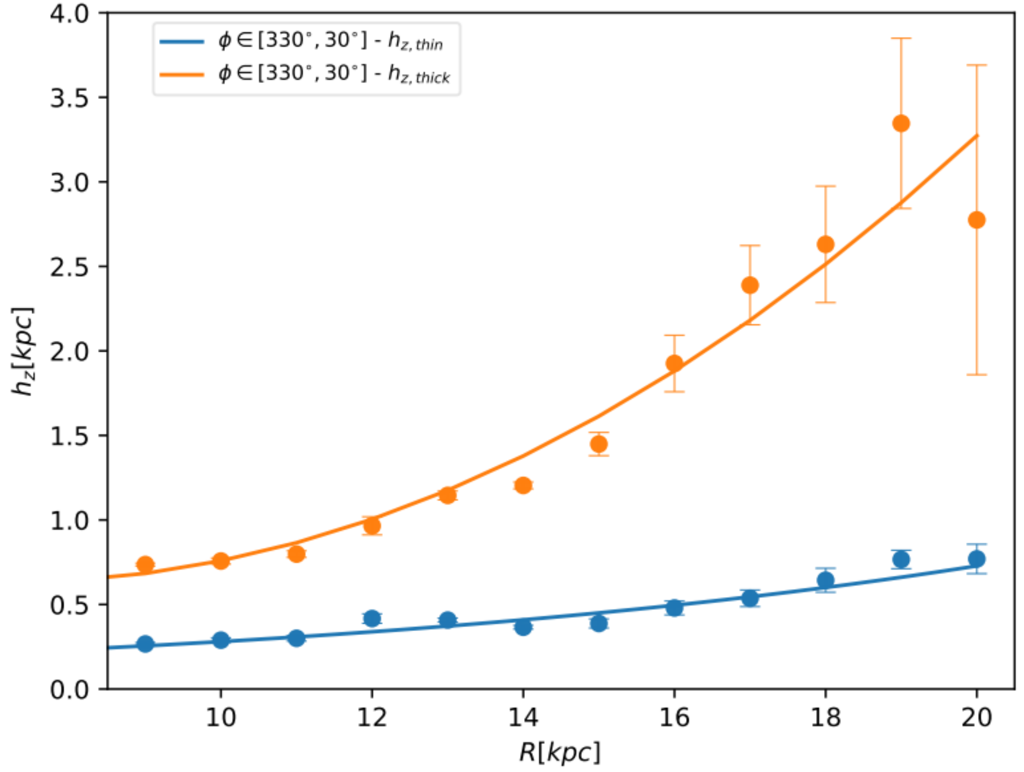
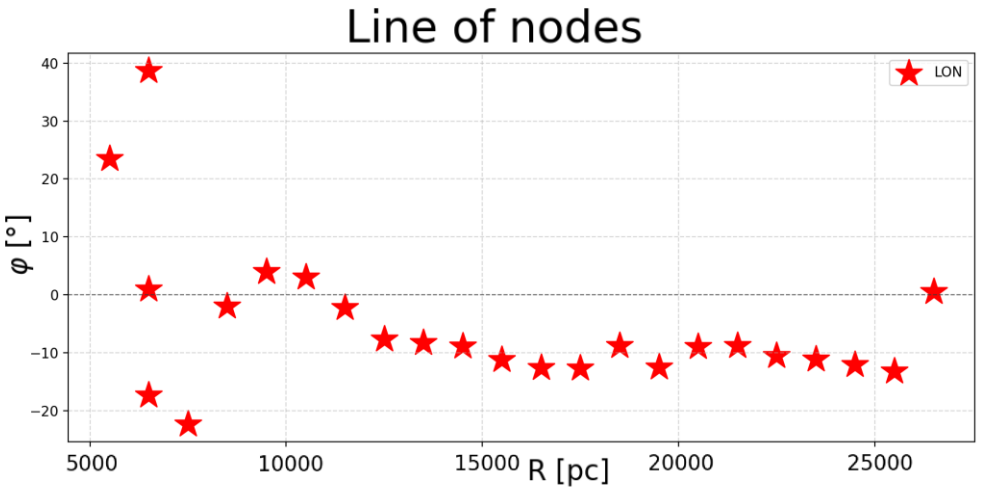


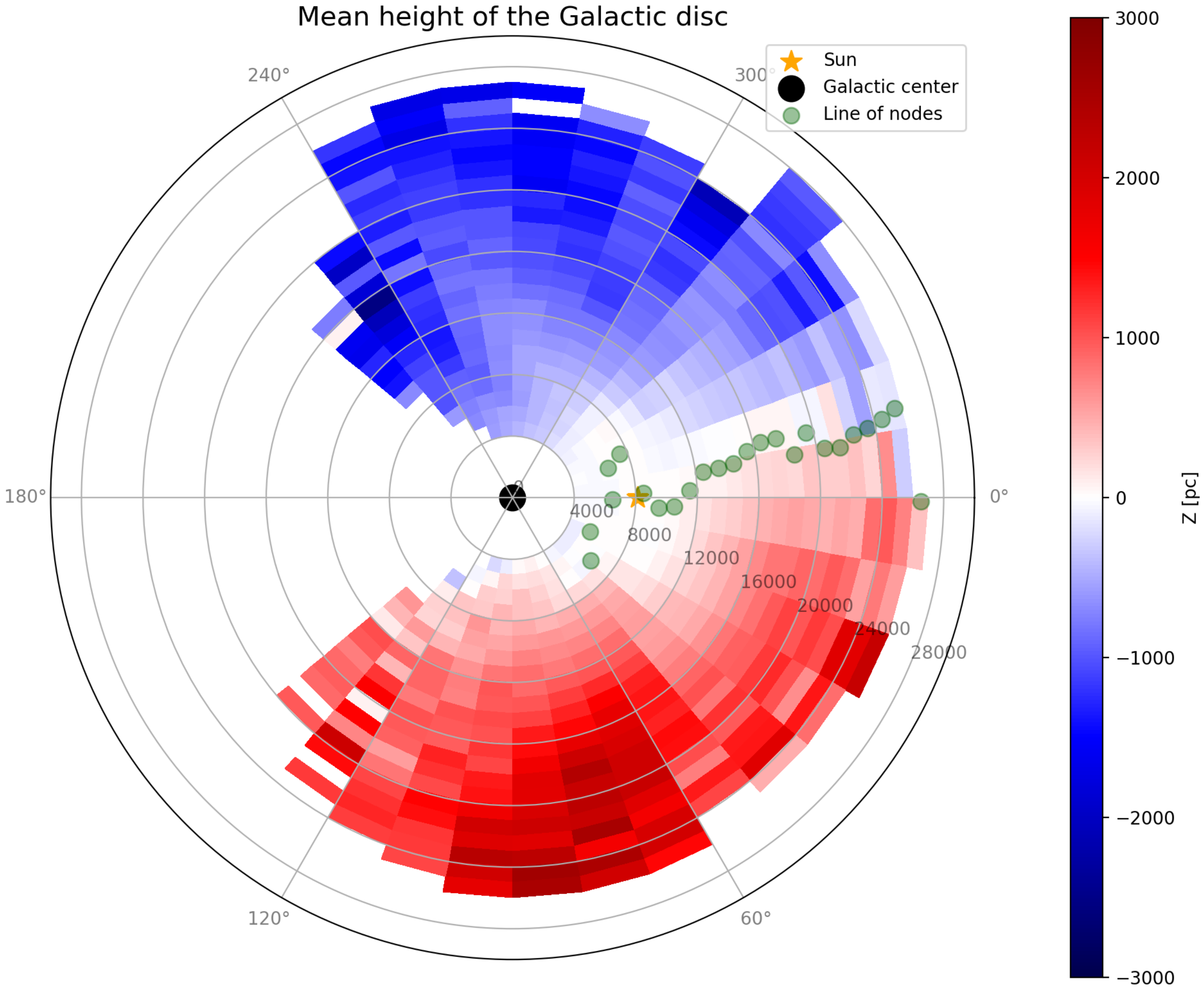
Fig. 8. Dependence of the scale height of the thick and the thin discs on the Galactocentric distance. The Galactic azimuth is $\phi \in [330°, 30°]$. The dashed line is the second-order polynomial fit to the data points.

Chrobáková et al. (2023)

Warp - results

- Mean of the vertical distribution
- LON:
  - z_w fitted with Fourier sine series of the second degree
  - For each R, LON = intersection of the fit with $z = 0$

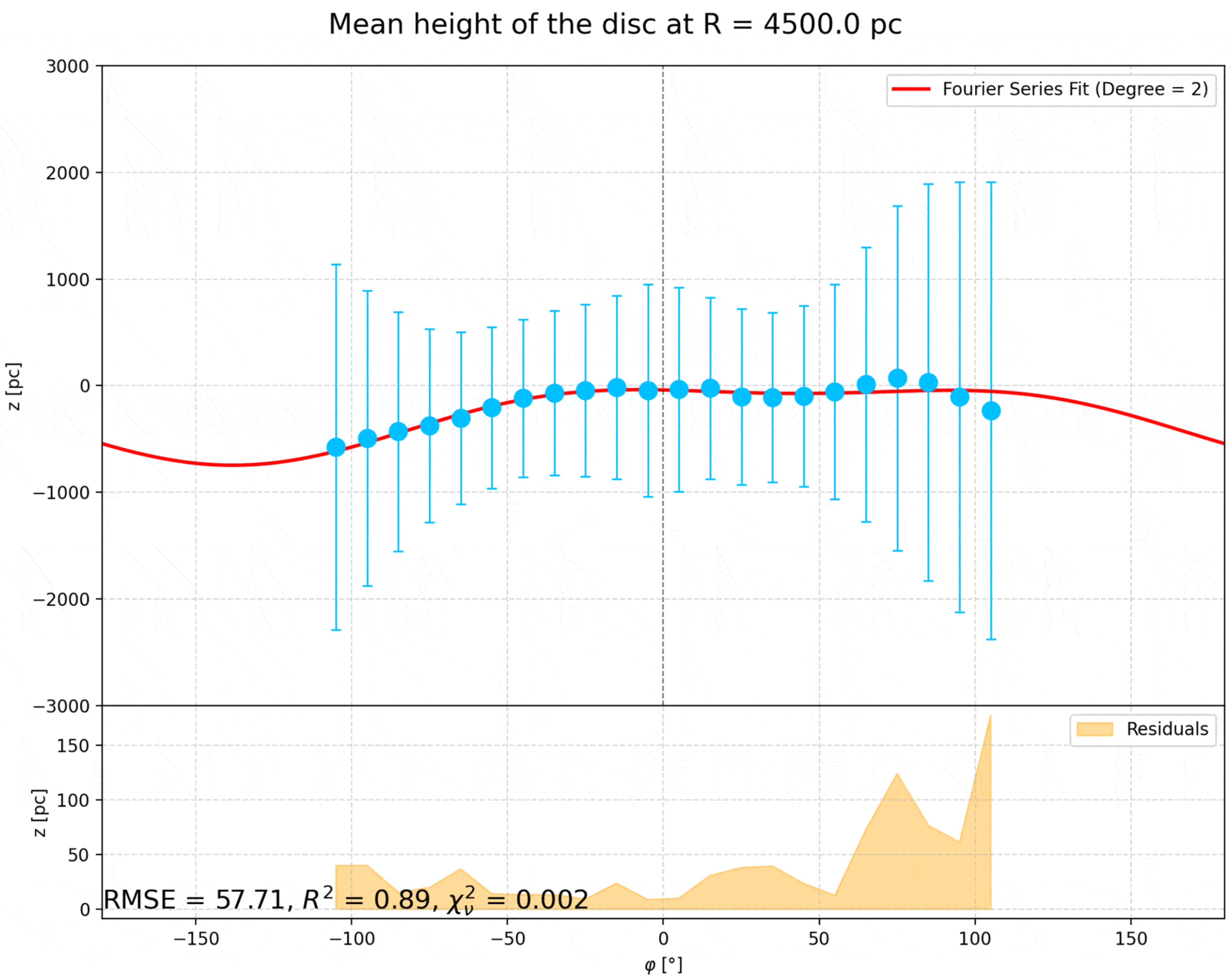




Our work

Warp - results

- Mean and standard deviation of vertical distributions
- Weighted Fourier sine series fit of the second degree



Warp - results vs literature

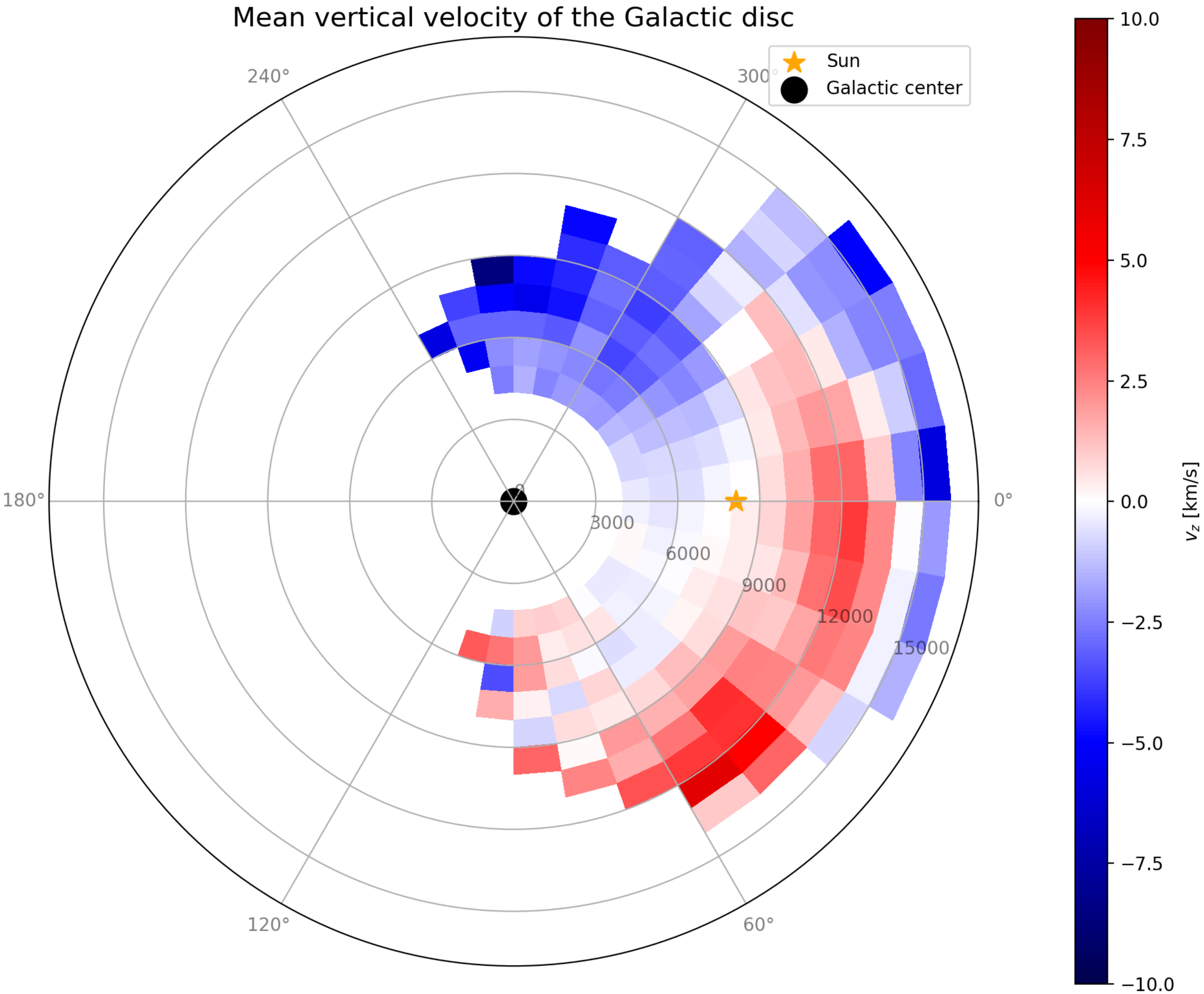
- Different warp model
- Different data processing
  - Lucy
  - Geometric distances
- No quality limits

Source	Tracer	Age [Gyr]	z_{up} [kpc]	z_{down} [kpc]
Levine et al. (2006)	LAB (gas)	–	0.74	−0.75
Drimmel and Spergel (2001)	COBE/DIRBE (dust)	–	1.34	−1.34
Uppal et al. (2024)	2MASS (RC)	≤ 10	1.3	−1.52
Amôres et al. (2017)	2MASS	0.075	3.86	−0.26
Amôres et al. (2017)	2MASS	0.575	3.35	−0.43
Amôres et al. (2017)	2MASS	1.5	2.59	−0.78
Amôres et al. (2017)	2MASS	2.5	2.1	−1.19
Amôres et al. (2017)	2MASS	4	2.19	−1.88
Amôres et al. (2017)	2MASS	6	4.27	−2.96
Amôres et al. (2017)	2MASS	8.5	10.9	−4.54
Romero-Gómez et al. (2019)	Gaia DR2 (OB)	≤ 1	0.23	−0.19
Romero-Gómez et al. (2019)	Gaia DR2 (RGB)	$3-7$	0.97	−1.22
Chrobáková et al. (2022)	Gaia EDR3 (whole population)	–	0.14	−0.15
Chrobáková et al. (2022)	Gaia EDR3 (young stars, $M_g < -5$)	–	0.36	−0.37
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	1	1.6	−1.6
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	3	1.6	−1.6
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	5	1.28	−1.28
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	7	1.28	−1.28
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	9	0.96	−0.96
Wang et al. (2020)	Gaia DR2 + LAMOST DR4 (RC)	12	0.64	−0.64
Yusifov (2004)	ATNF (pulsars)	–	0.62	−0.58
Chen et al. (2019)	WISE+optical (classical Cepheids)	≤ 0.4	0.69	−0.69
This work	**Gaia DR3 (whole population)**	–	1.16	−1.3

Precession

- Geometric model:

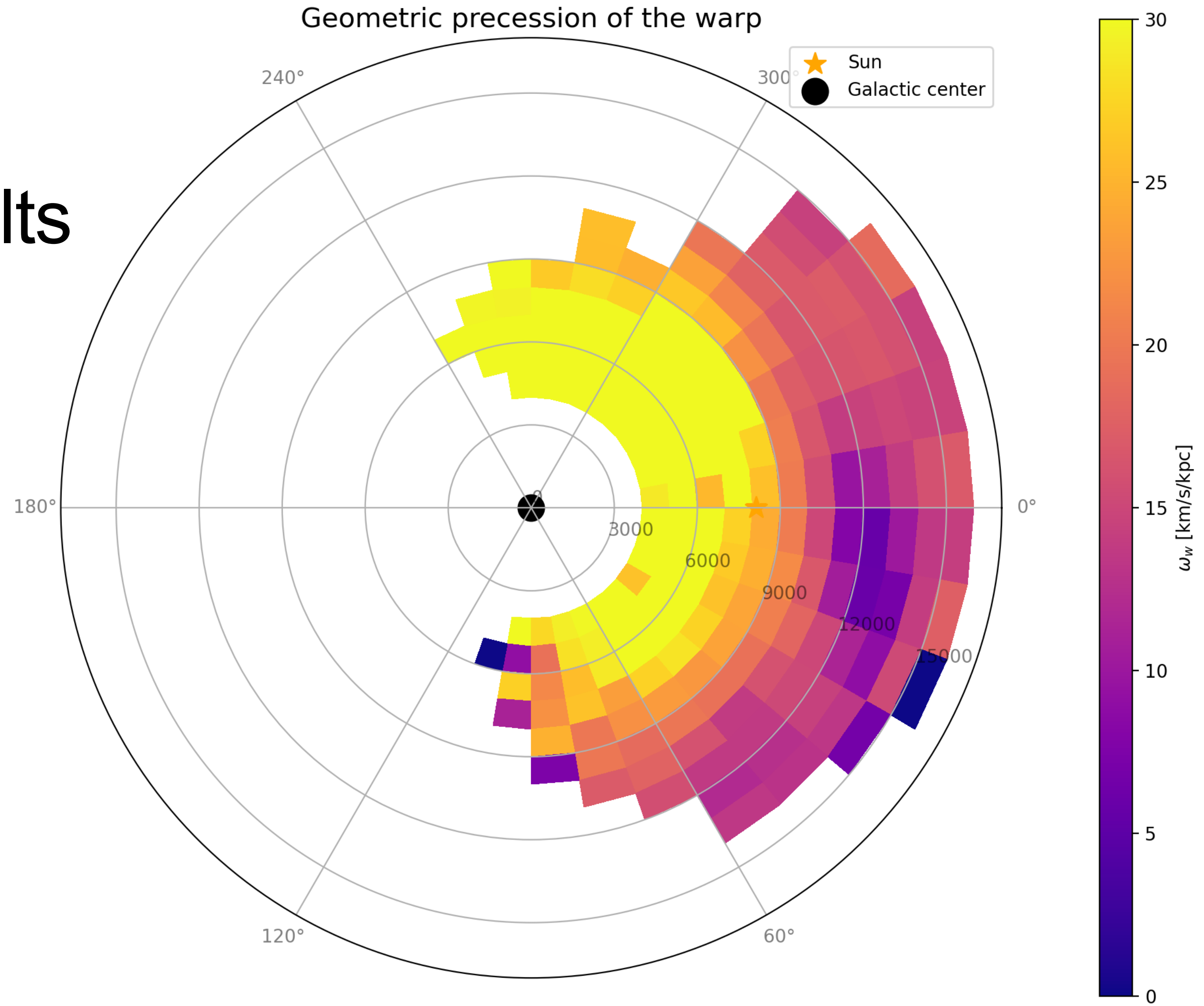
$$v_z = \frac{\partial z_w}{\partial \varphi}\left(\frac{v_\varphi}{R} - \omega\right)$$



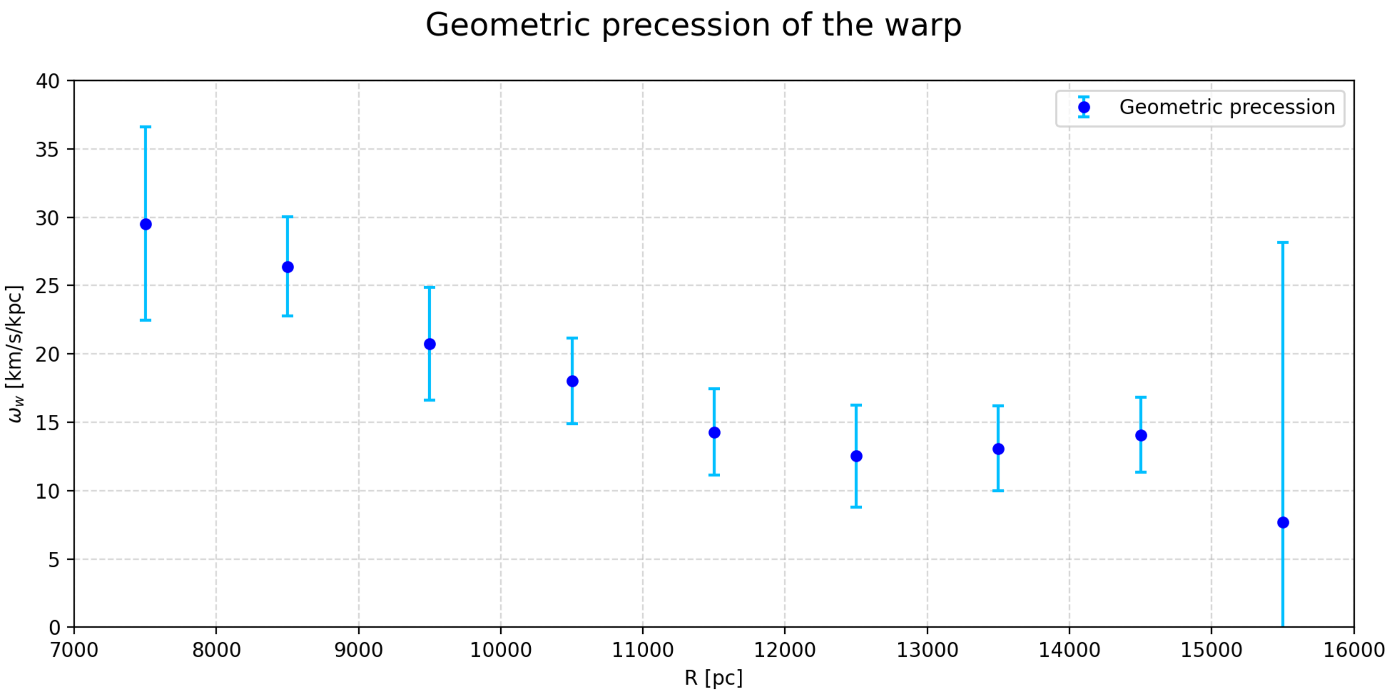
Precession - results

- Geometric model:

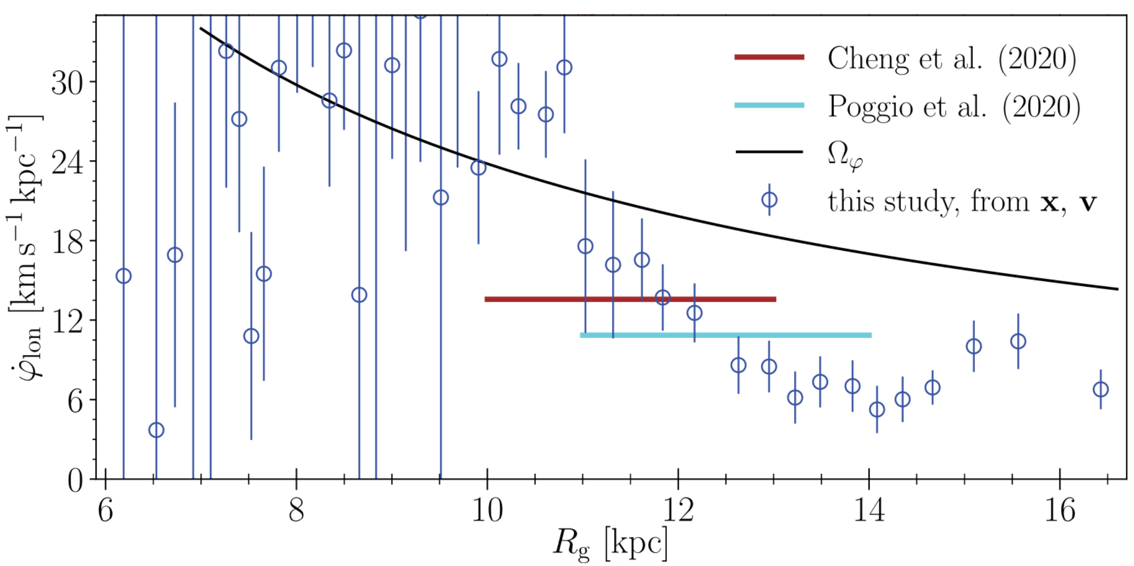
$$v_z = \frac{\partial z_w}{\partial \varphi}\left(\frac{v_\varphi}{R} - \omega\right)$$



Precession - results vs literature



Our work



Dehnen et al. (2023)

Future work

- Photogeometric distances
- Quality limits (only reliable sources)
- Improve filtering of LMC, SMC and other contaminations
- Velocities for the whole dataset (v_z estimated from proper motions)

Thank you for your attention

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