Structure, kinematics and time evolution of the Galactic Warp revealed by Classical Cepheids

The Milky Way Revealed by Gaia: The Next Frontier

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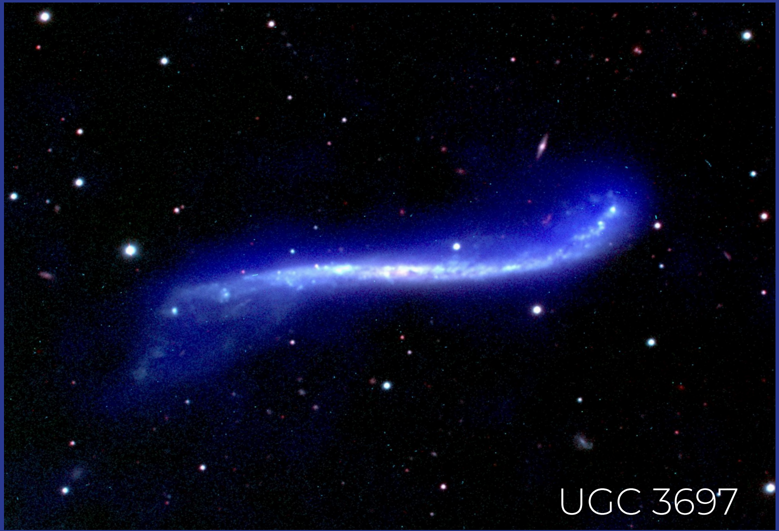
Warps:

Between 40-50% of observed spiral galaxies present a warped disc
(e.g. Sanchez-Saavedra et al. 1990, Reshetnikov & Combes 1998)



NRAO/AUI/NSF

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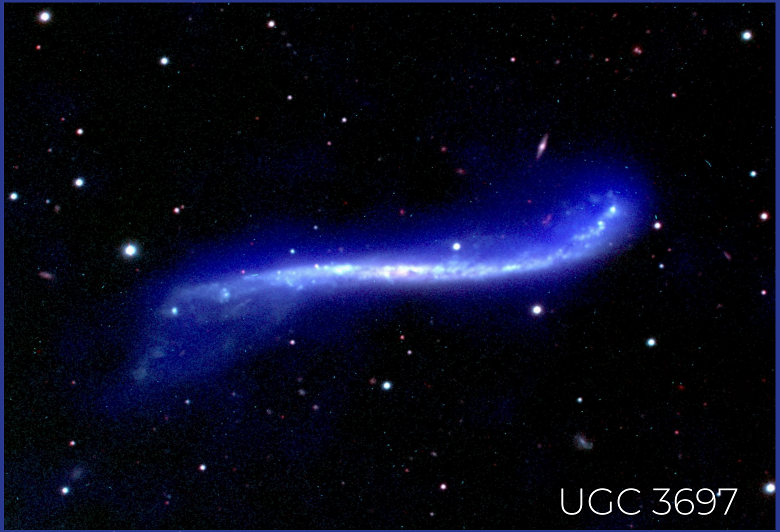
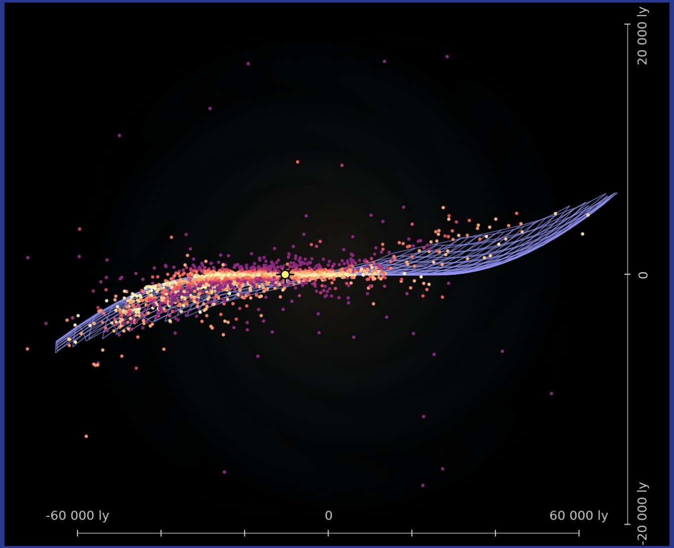


NRAO/AUI/NSF

In the MW: discovered in HI (Burke 1957) later found in the stellar component (Freudenreich et al. 1994). Recent studies with Cepheids have show a clear warped disc (e.g. D. Skowron et al. 2019a, Chen et al. 2019)



D. Skowron et al. (2019a) / OGLE / Astronomical Observatory, University of Warsaw

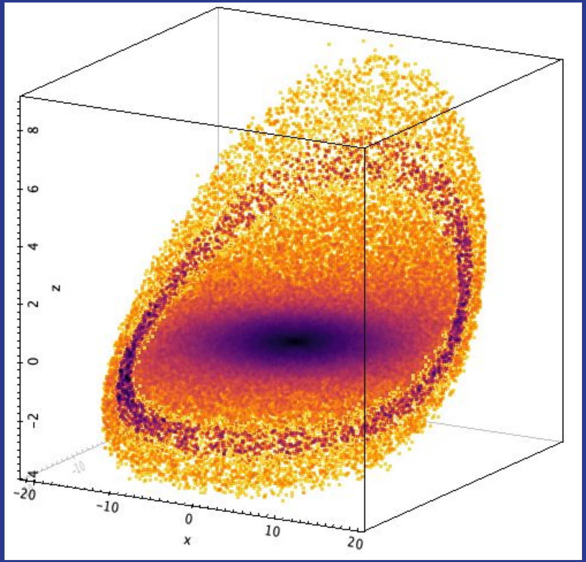
What's new in this work?

Fourier decomposition of the mean vertical high Z and mean vertical velocity Vz taking into account:

- **The warp lopsidedness**
- **No assumptions on the radial dependency of the parameters of the warp.**

We provide a new formalism to derive the time change of each mode amplitude and phase.

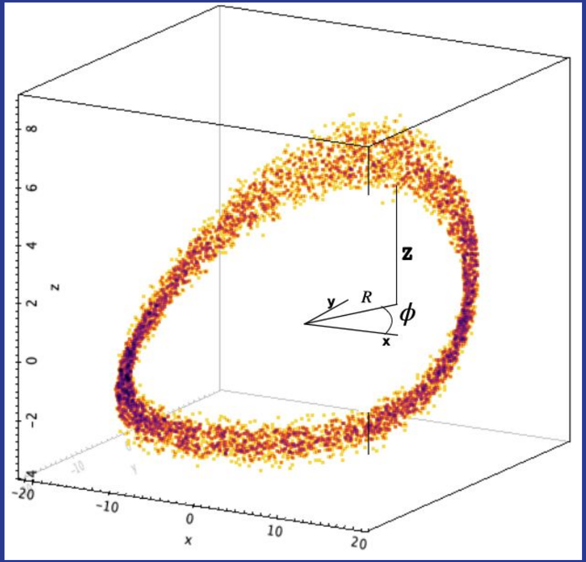
- **This method disentangles the evolution of the modes between them.**



Fourier in a ring

Fourier in a ring

We fit by least squares



$$Z(\phi) = \sum_{m=0}^{M} A_m \sin(m\phi - \varphi_m)$$

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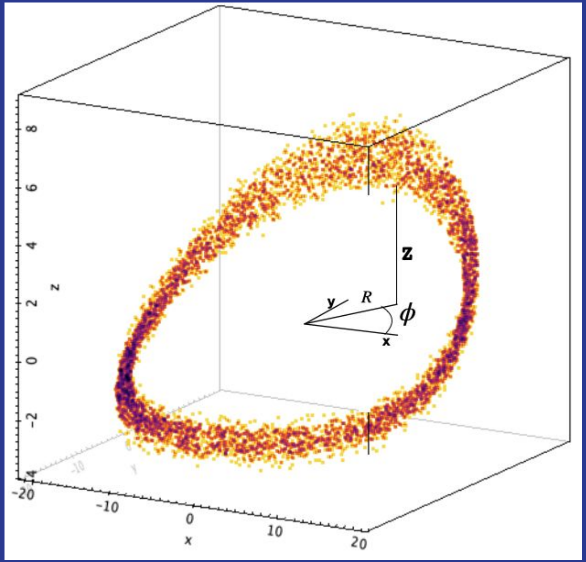

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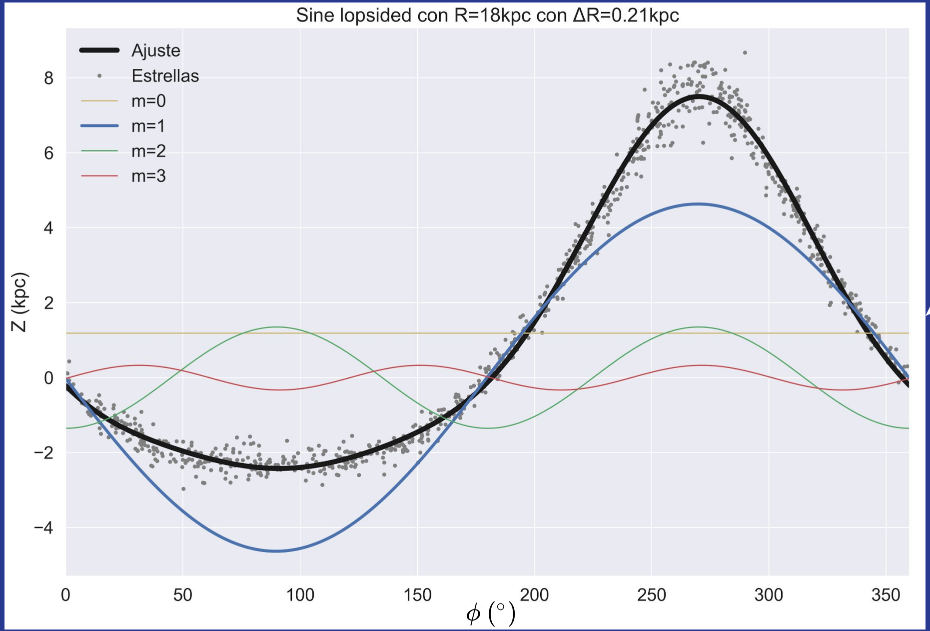

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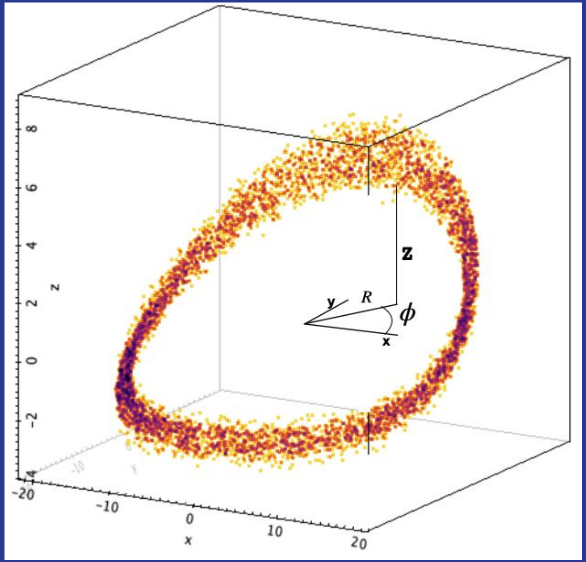

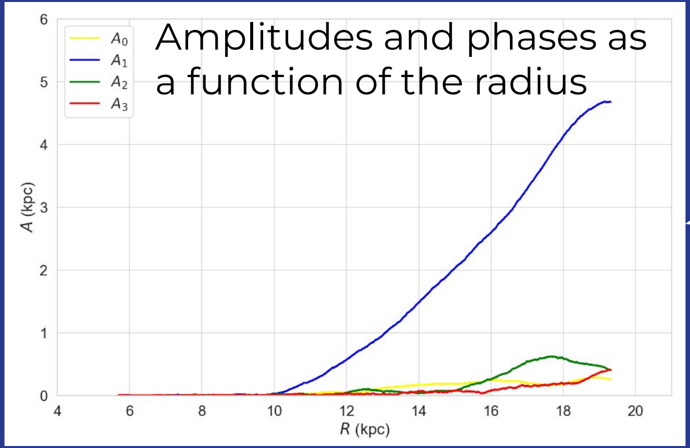

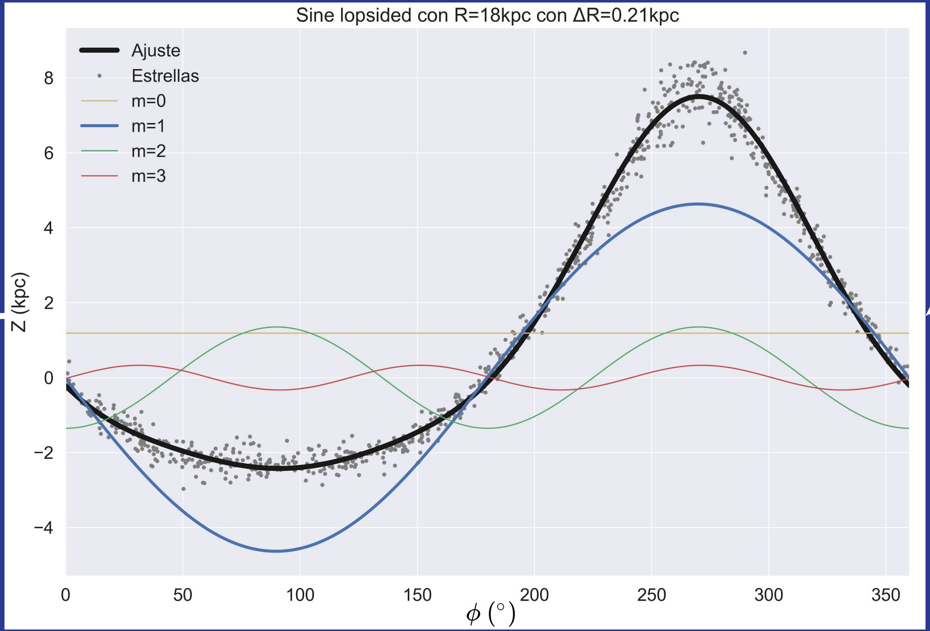

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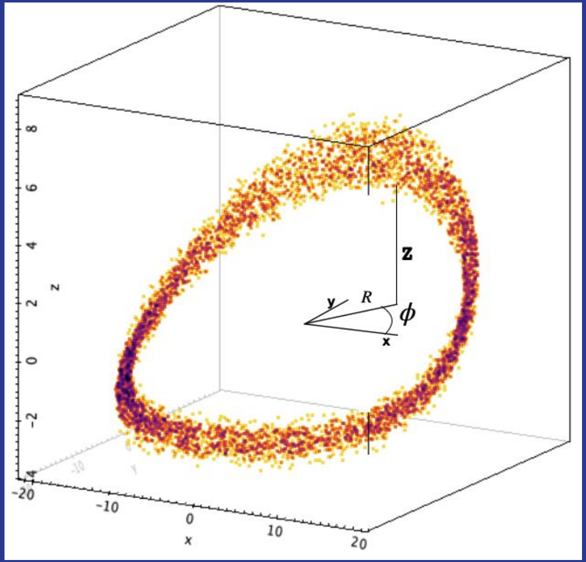
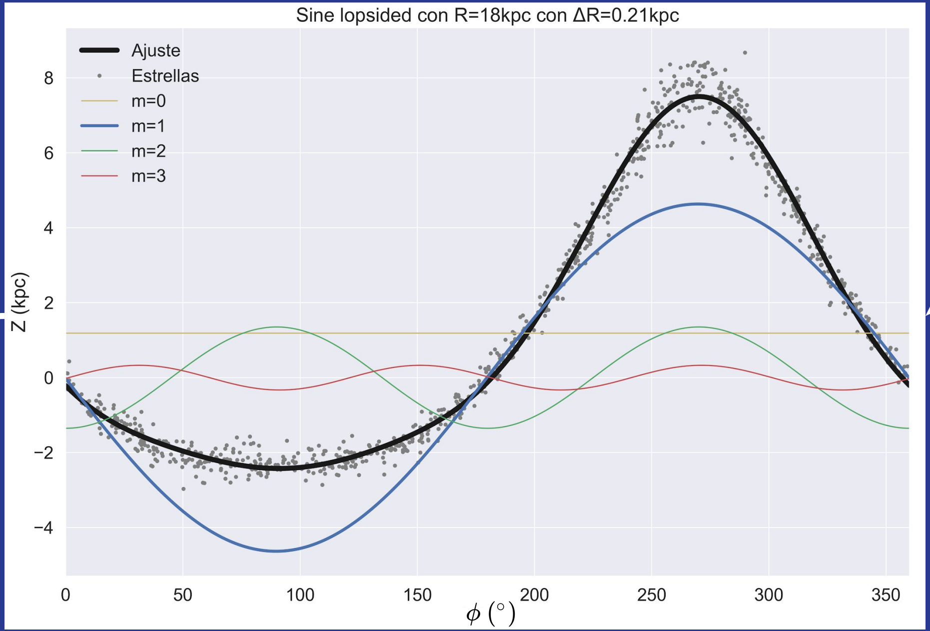


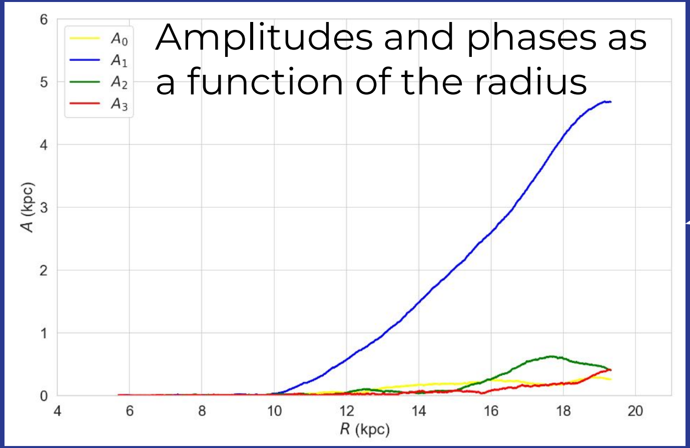
We fit by least squares

$$Z(\phi) = \sum_{m=0}^{M} A_m \sin(m\phi - \varphi_m)$$

The same applies for Vz

$$V_z(\phi) = \sum_{m=0}^{M} V_m \sin(m\phi - \varphi_m^V)$$





Data

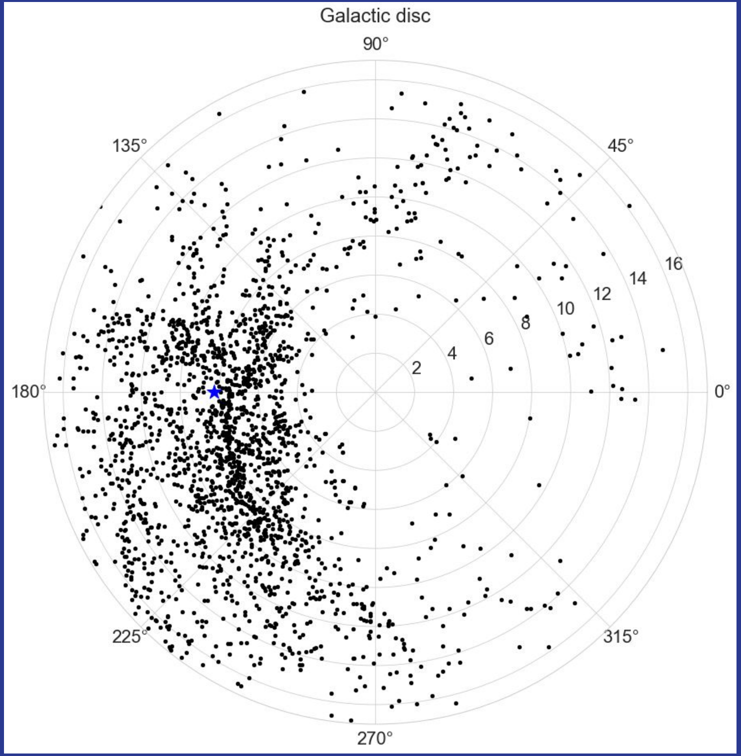
Cepheids:

- Young pulsating stars (<500 My).
- Photometric distance from a P-L relation.
- Uncertainty in distance is **less than ~4%.**

Skowron et al. (2019b) sample:

- 2385 Cepheids (OGLE+GCVS+Gaia DR2).
- Proper motions from Gaia DR3.
- Radial velocity from the rotation curve by Ablimit et al. 2020

Applying quality filters (in z, vz and astrometry) the final sample has **1997** Cepheids.

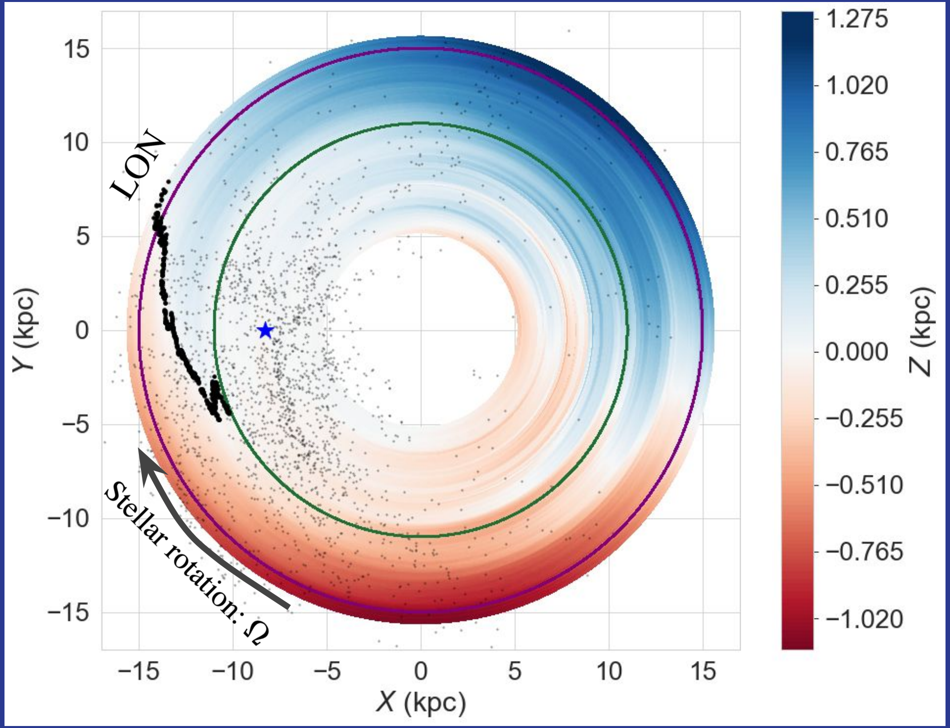


Structure and kinematics

Z

Vz

The Cepheid's warp: in Z



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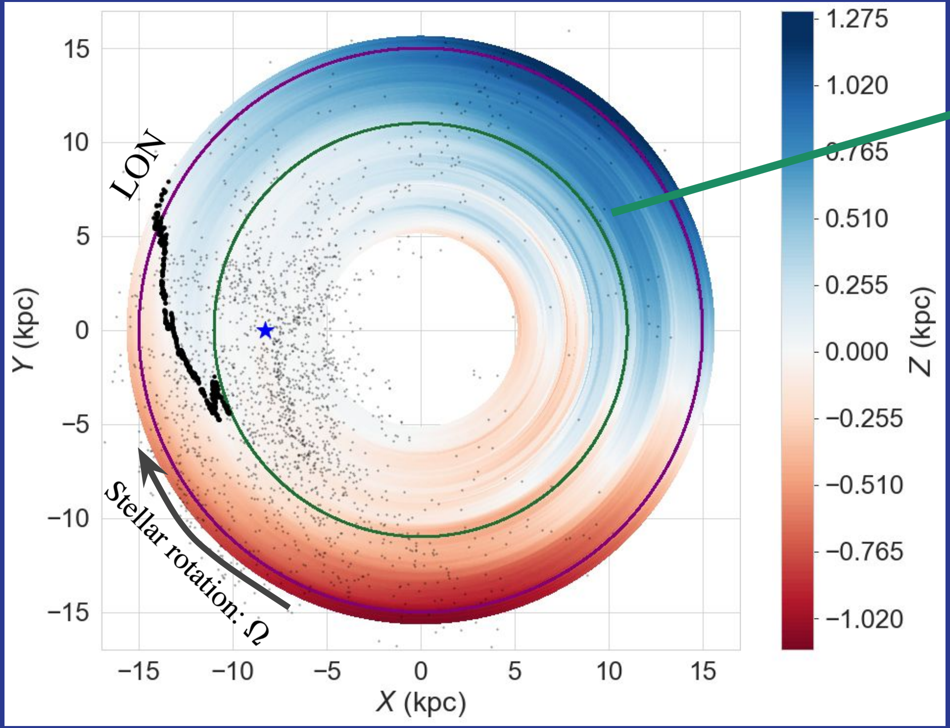
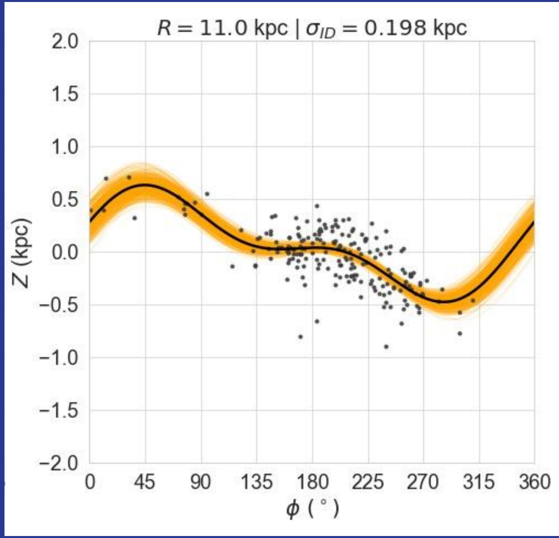
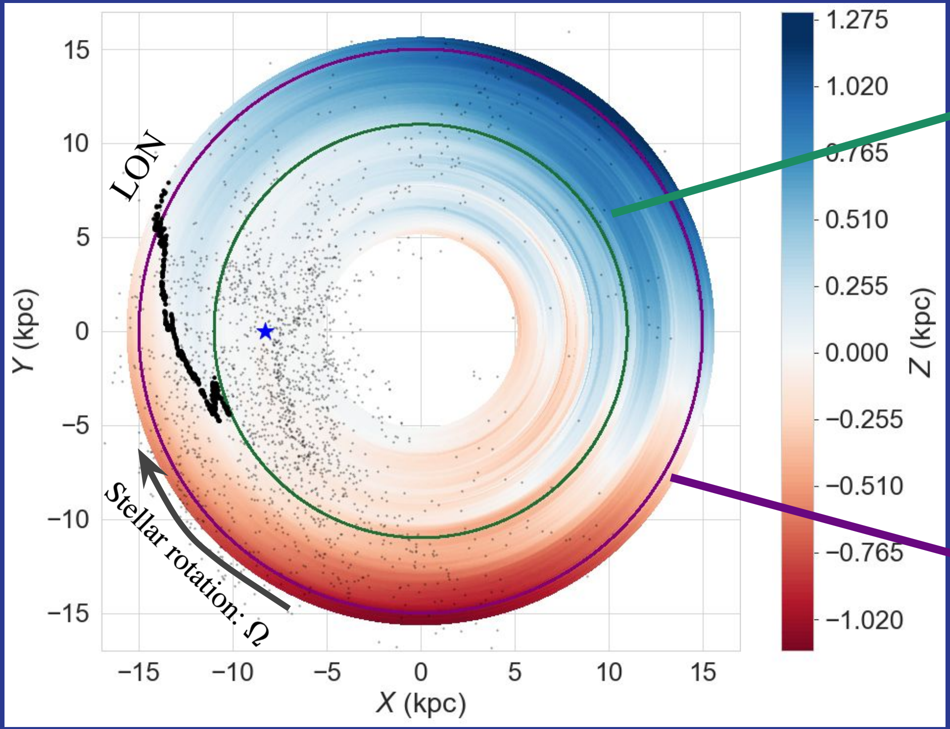
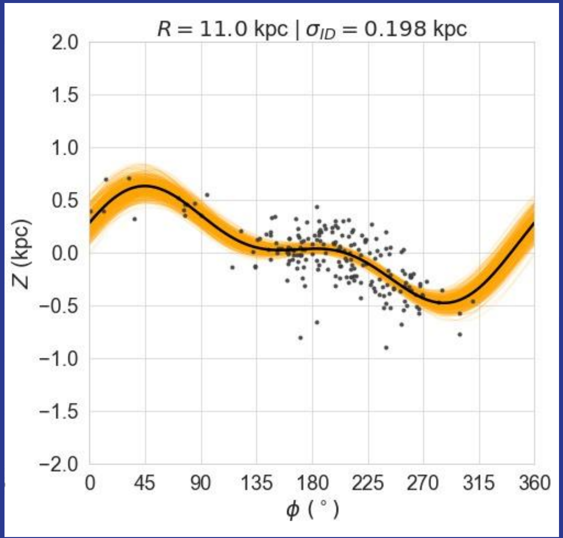


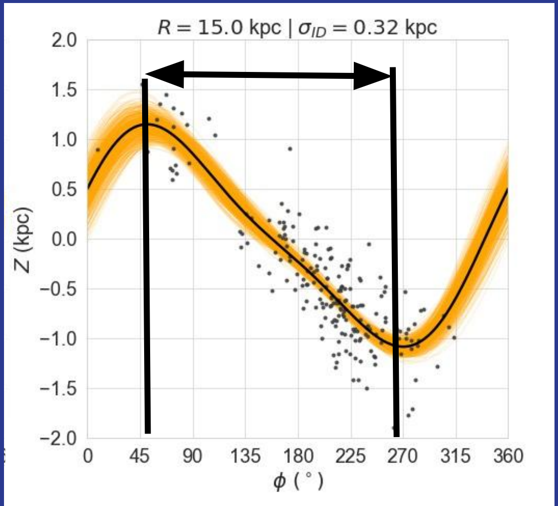


Plateau in R=11 kpc at the anticentere direction

The Cepheid's warp: in Z



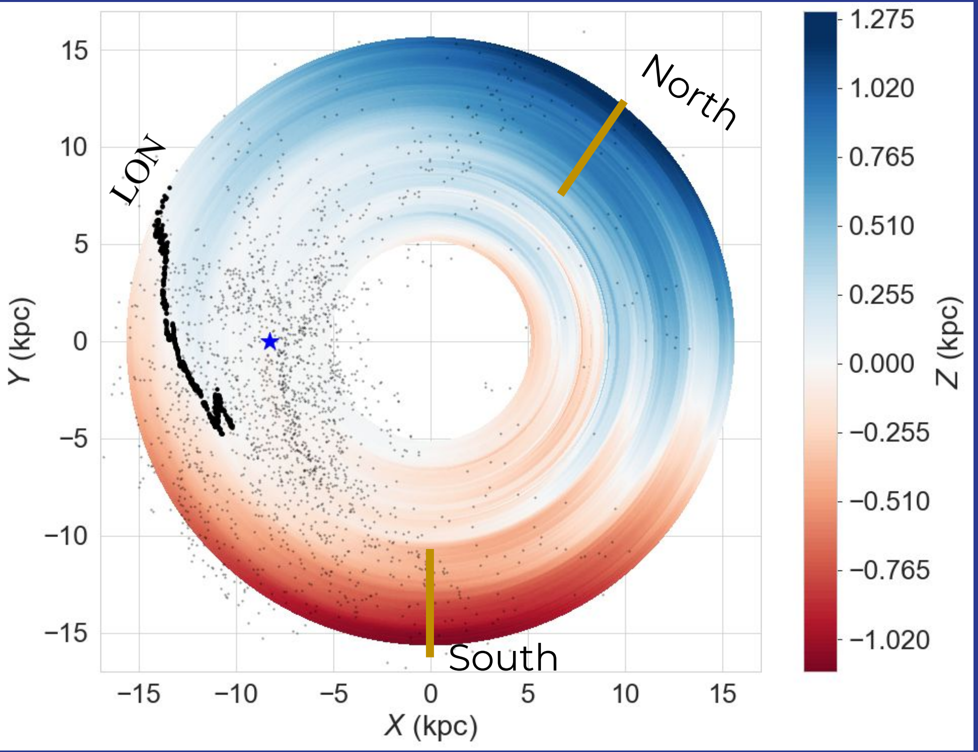


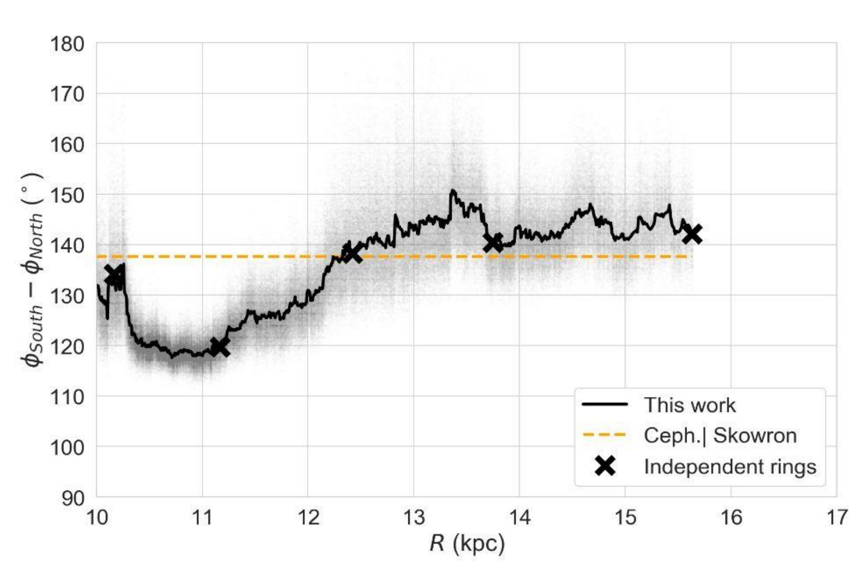


Plateau in R=11 kpc at the anticentere direction

North-South angular separation $\neq 180°$ (m=2 is needed)

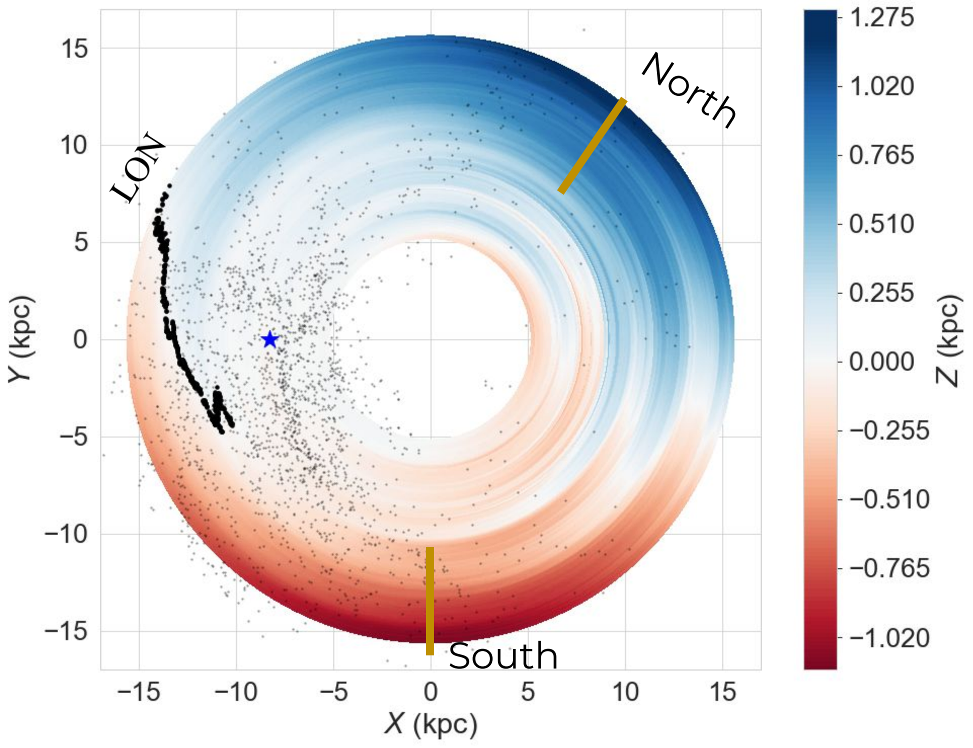
The asymmetry of the warp

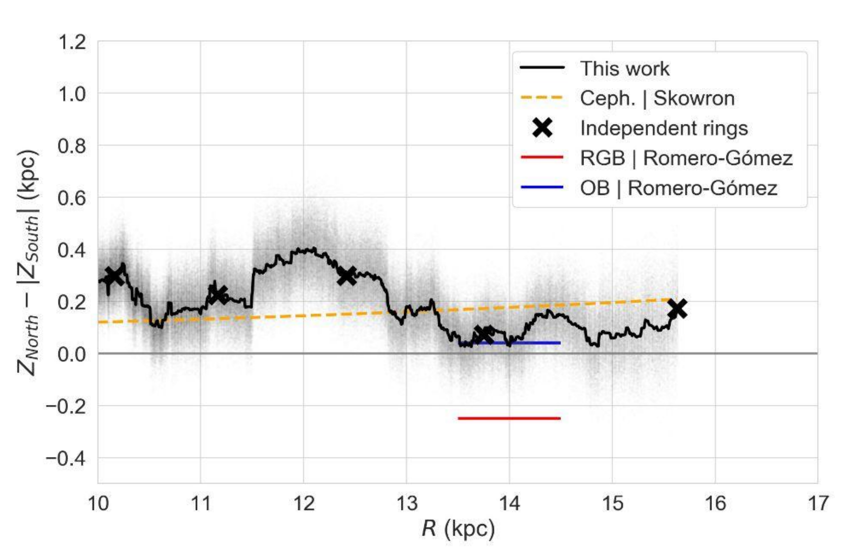




The extremes are never diametrically opposed.

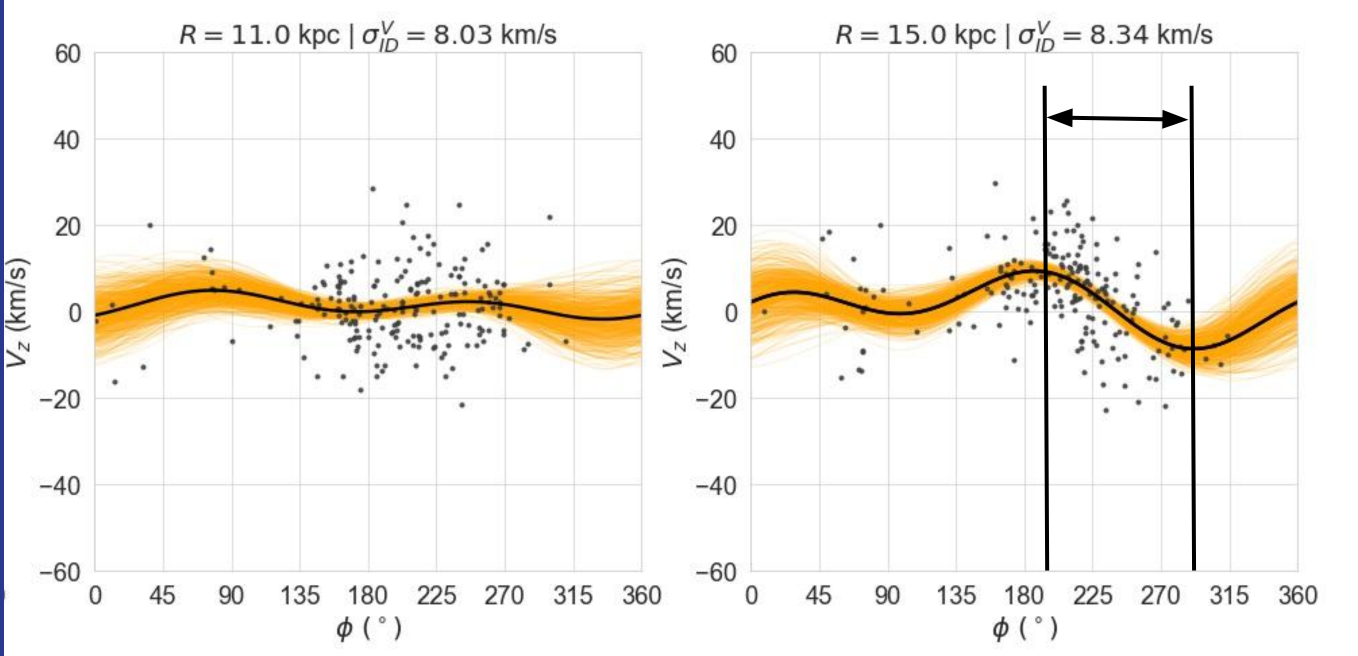
The asymmetry of the warp





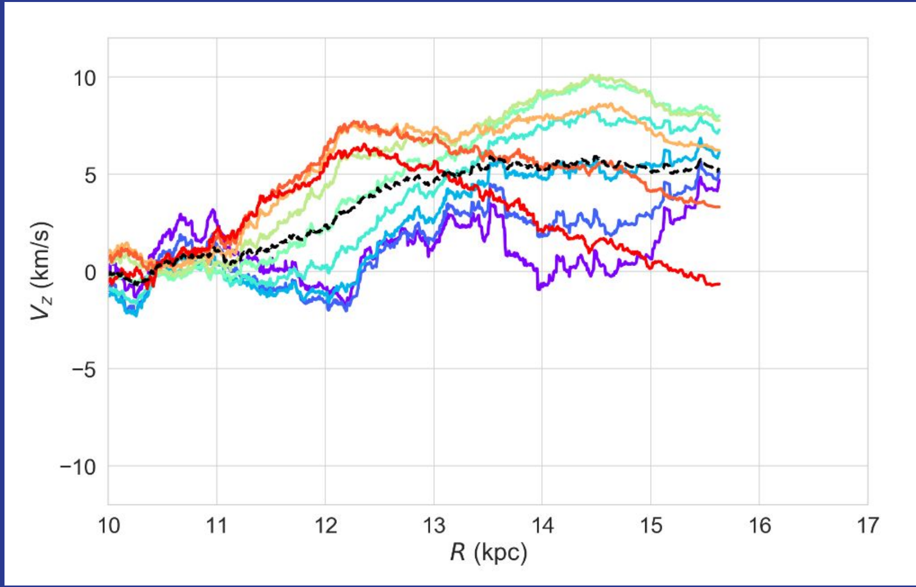
For R<13 kpc the warp is asymmetric (~250 pc). For R>13 kpc the warp is quite symmetric (~<100 pc)

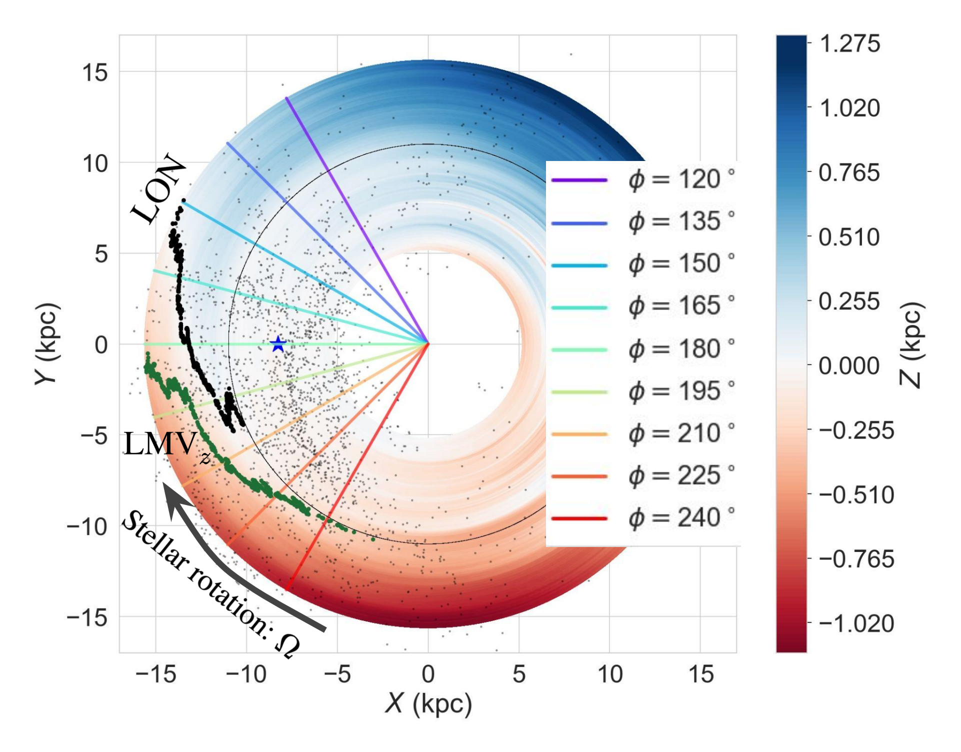
The Cepheid's warp: Vz



The extremes are closer than expected by a tilted ring model

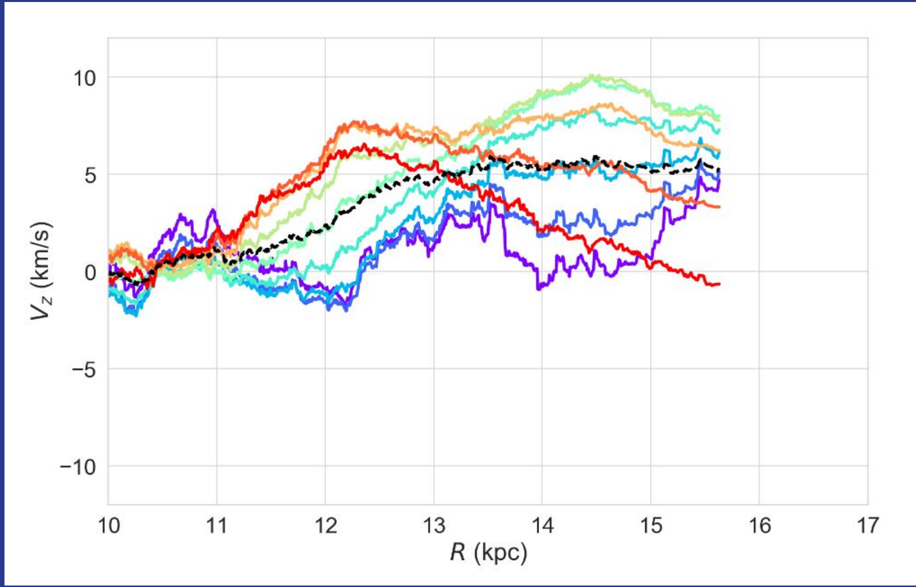
Vz arcs

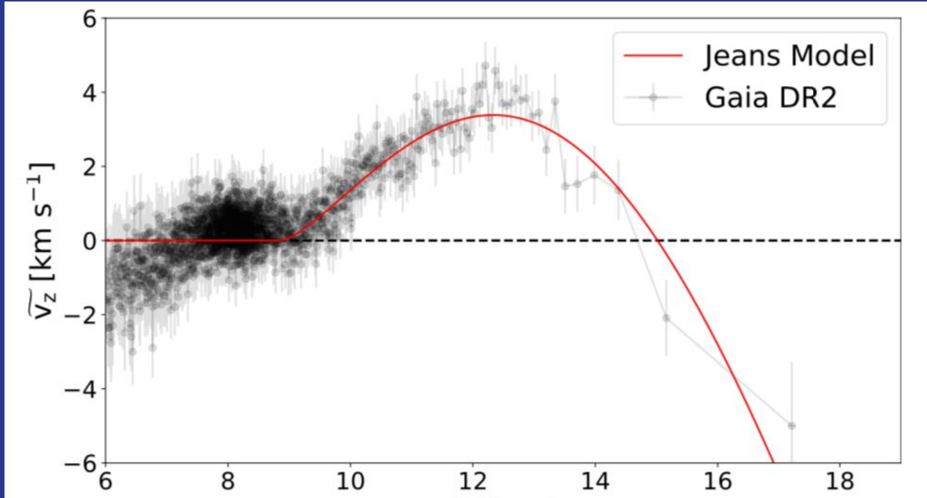




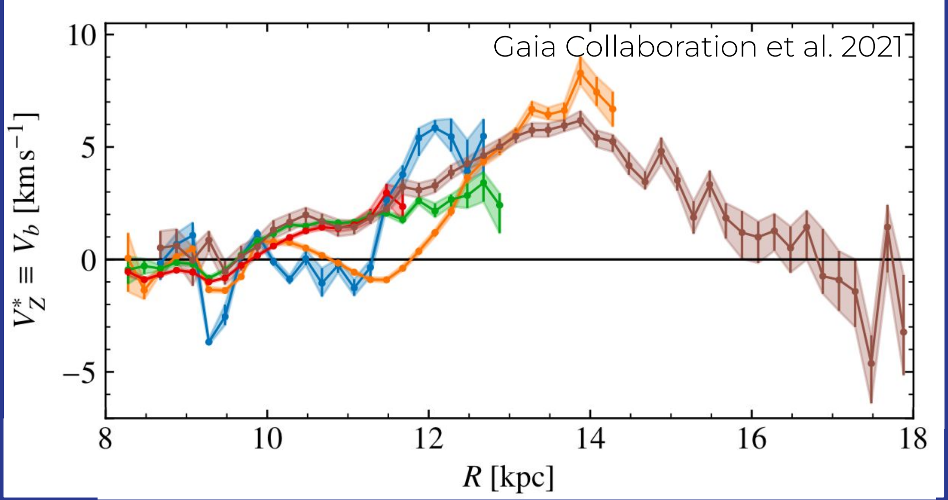
Vz arcs are a consequence of the twisted LMVz.

Vz arcs



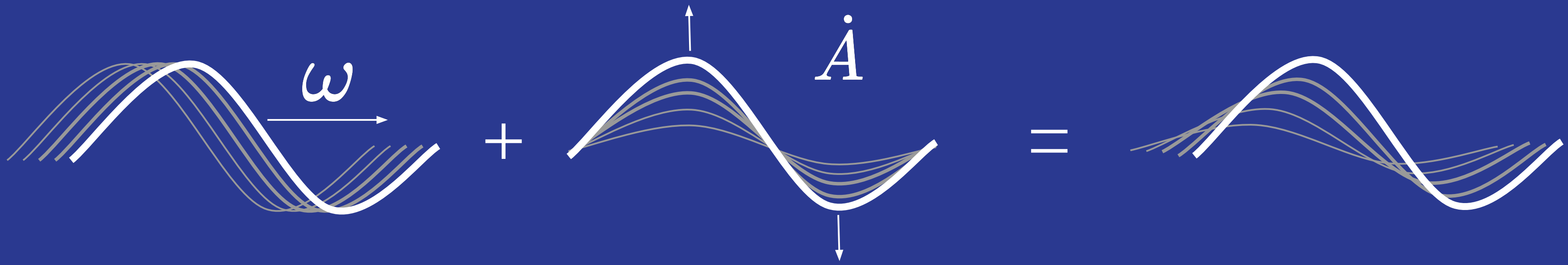


Cheng et al. 2020



Gaia Collaboration et al. 2021

Time evolution of the warp



The basic idea of the method

In a razor thin disc, the star height $z(t)$ is the warp expression $\mathcal{Z}(\phi)$ in the azimuth $\phi(t)$ of the star

$$z(t) = \mathcal{Z}(\phi(t)) = A\sin[\phi(t) - \omega t]$$

$$\phi(t) = \Omega t + \phi_0$$

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The vertical velocity is

$$\begin{aligned} v_z(t) = \dot{z}(t) &= A[\Omega - \omega]\cos(\phi(t) - \omega t) \\ &= \boxed{A[\Omega - \omega]}\sin(\phi(t) - \omega t + \boxed{\tfrac{\pi}{2}}) \\ &= V\sin(\phi(t) - \omega t - \varphi^V) \end{aligned}$$

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$$= A[\Omega - \omega]\sin(\phi(t) - \omega t + \frac{\pi}{2})$$
$$= V\sin(\phi(t) - \omega t - \varphi^v)$$

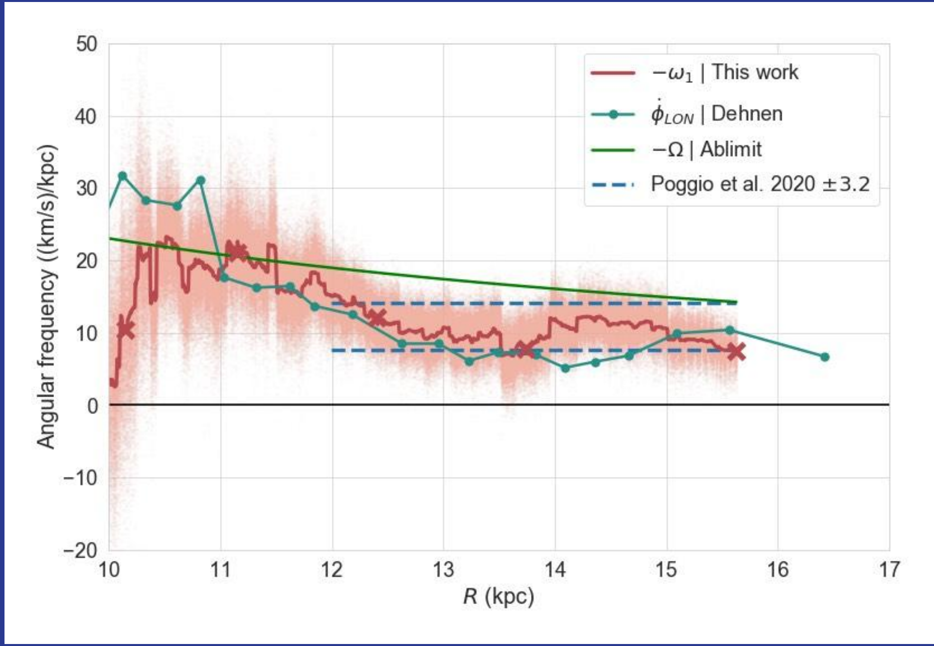
If the warp doesn't change in amplitude, then $\varphi - \varphi^V = -\frac{\pi}{2}$ and the ratio between the amplitudes give us the pattern speed $\frac{V}{A} = \Omega - \omega$

If $\dot{A} \neq 0$ then $\varphi - \varphi^V \neq -\frac{\pi}{2}$. A general equation can be derived to take into account $\dot{A}$

We get the pattern speed and change in amplitude for each mode as a function of the radius

$$\Omega - \omega_m = \frac{V_m}{mA_m}\sin(\varphi_m - \varphi_m^V)$$

$$\dot{A}_m = V_m \cos(\varphi_m - \varphi_m^V)$$



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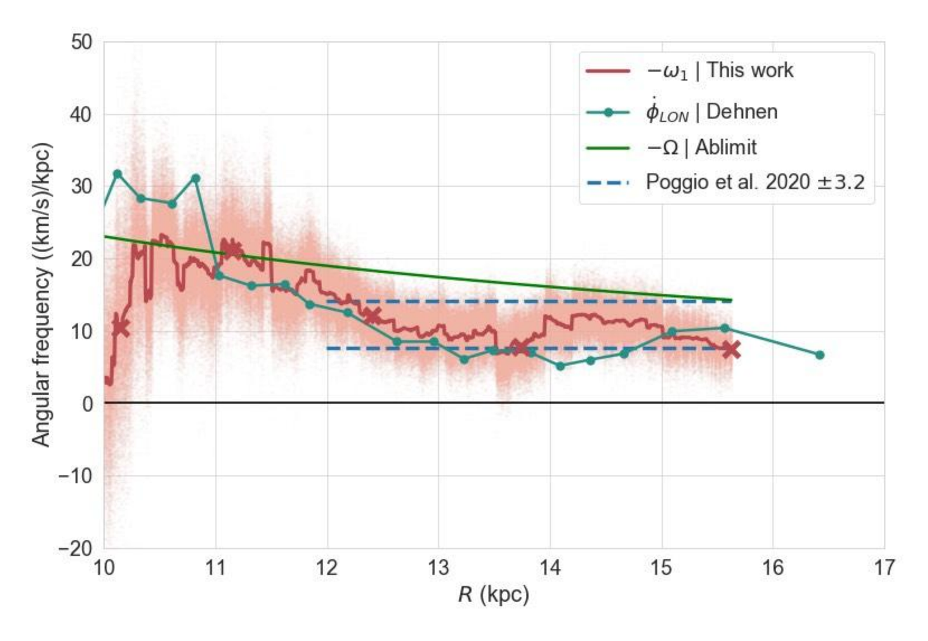
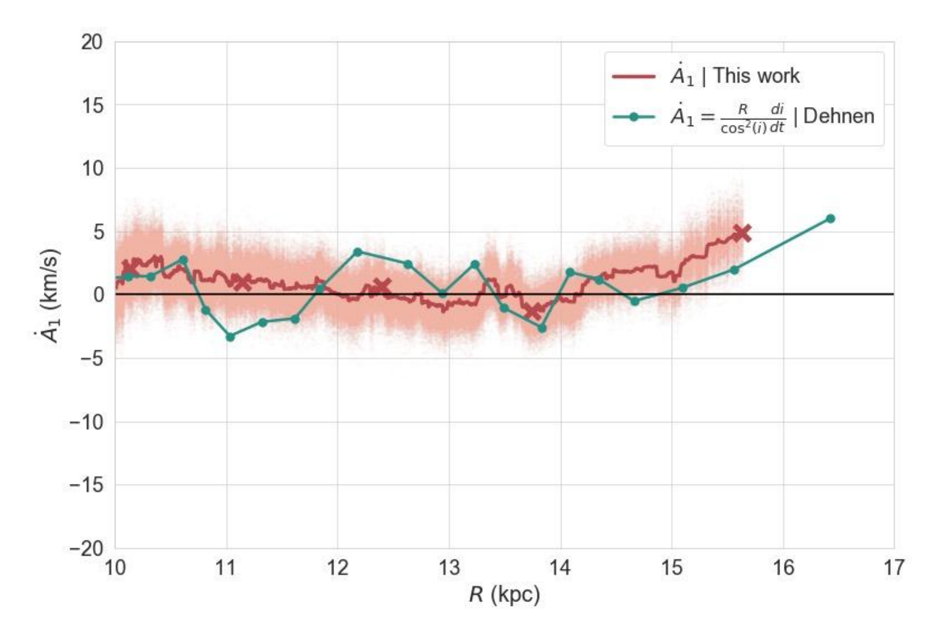




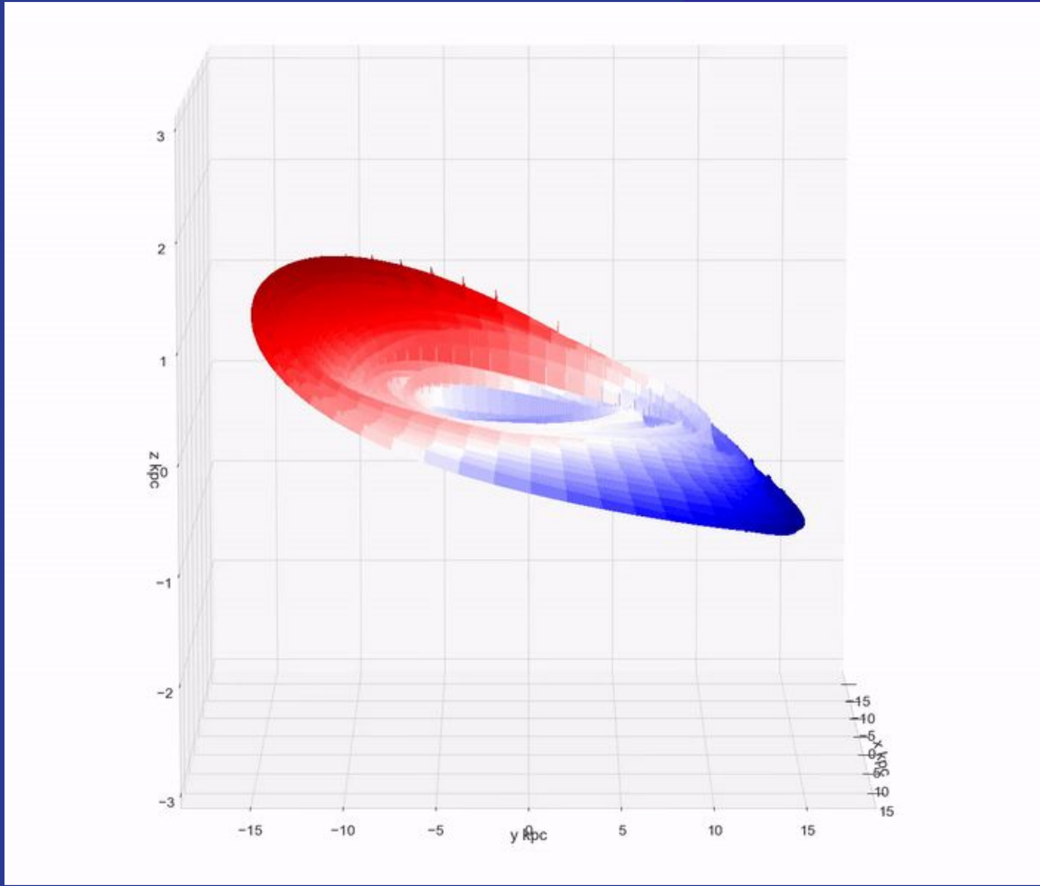
Conclusions:

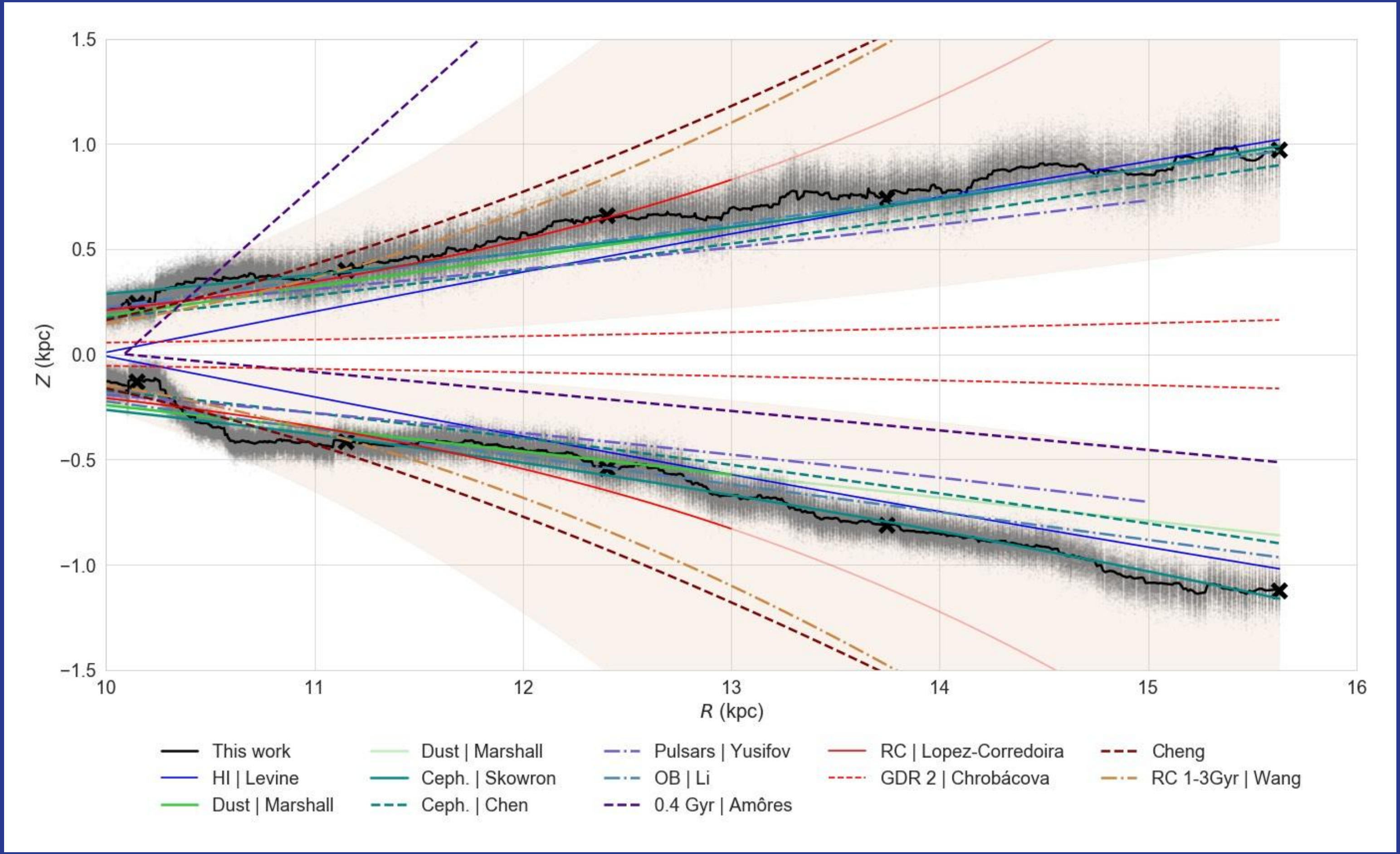
- The warp is lopsided. An m=2 mode is needed in Z and Vz.
- The extremes of the warp have different amplitudes and are never diametrically opposed

- The line of maximum Vz does not coincide with the LON. It trails behind it with a constant offset off 25.4 deg. Both are similarly twisted (leading).
- The arcs in Vz as a function of R observed in other stellar populations are also present in the Cepheids sample. We found it to be a consequence of the twisted LMVz.

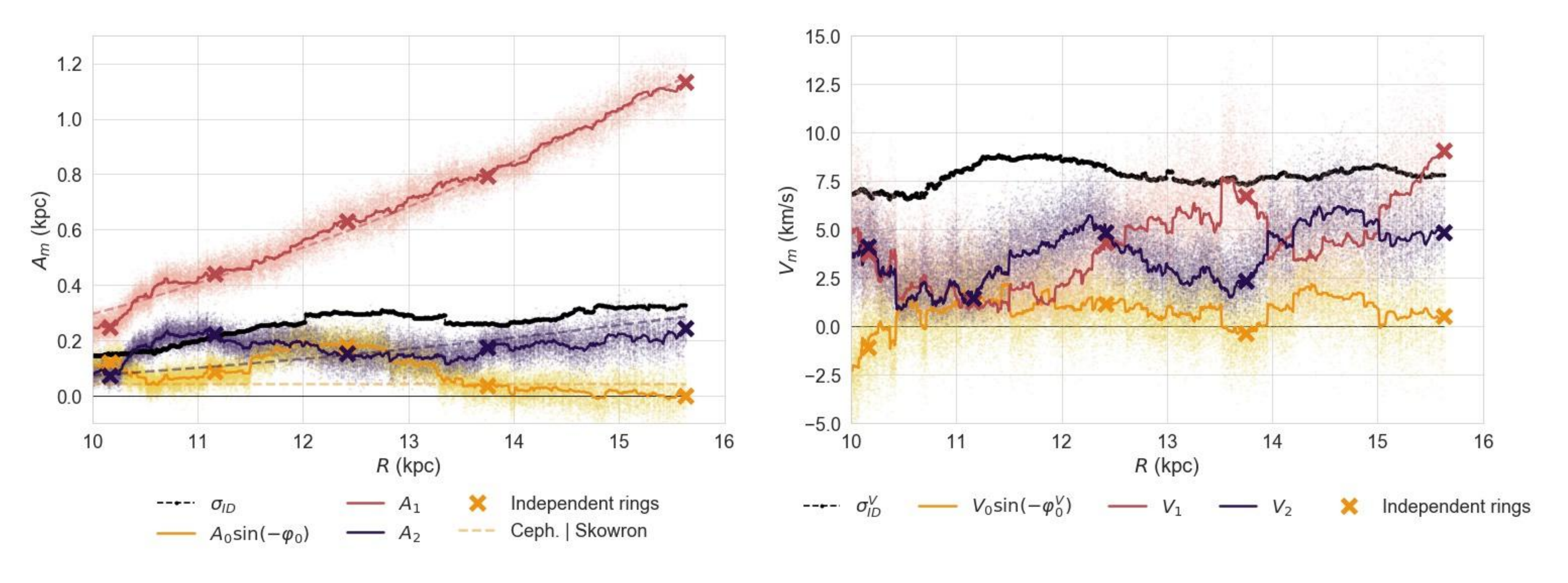
- Our new method takes into account the presence of any number of modes and disentagles them, Model independent, not equilibrium assumptions.
- We found a prograde rotation of the m=1 mode, with a slight differential rotation.
- The amplitude of the m=1 mode is constant in time for R<14 kpc but it has a grow tendency in the outskirts of the disc.

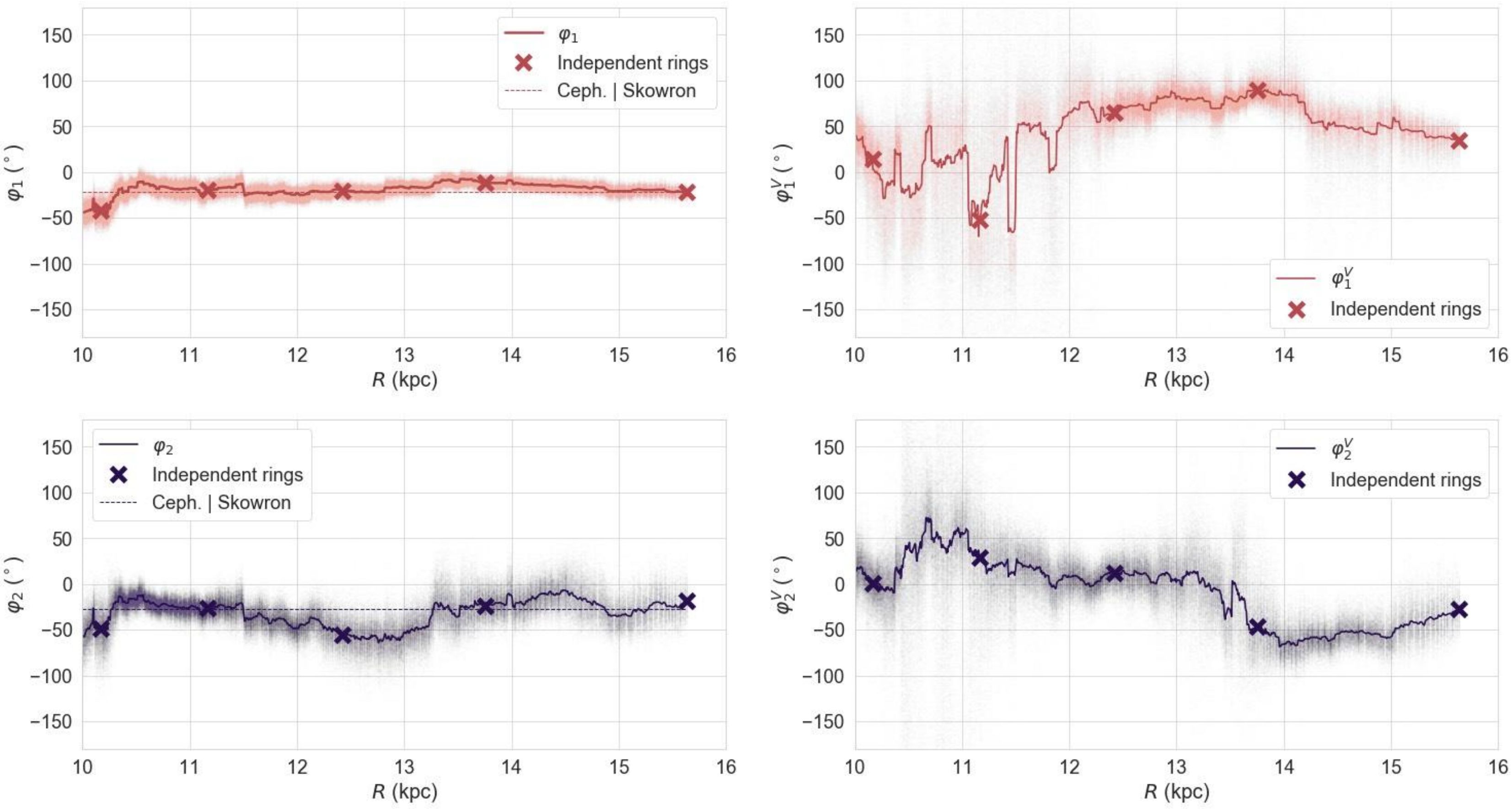
¡Thanks!



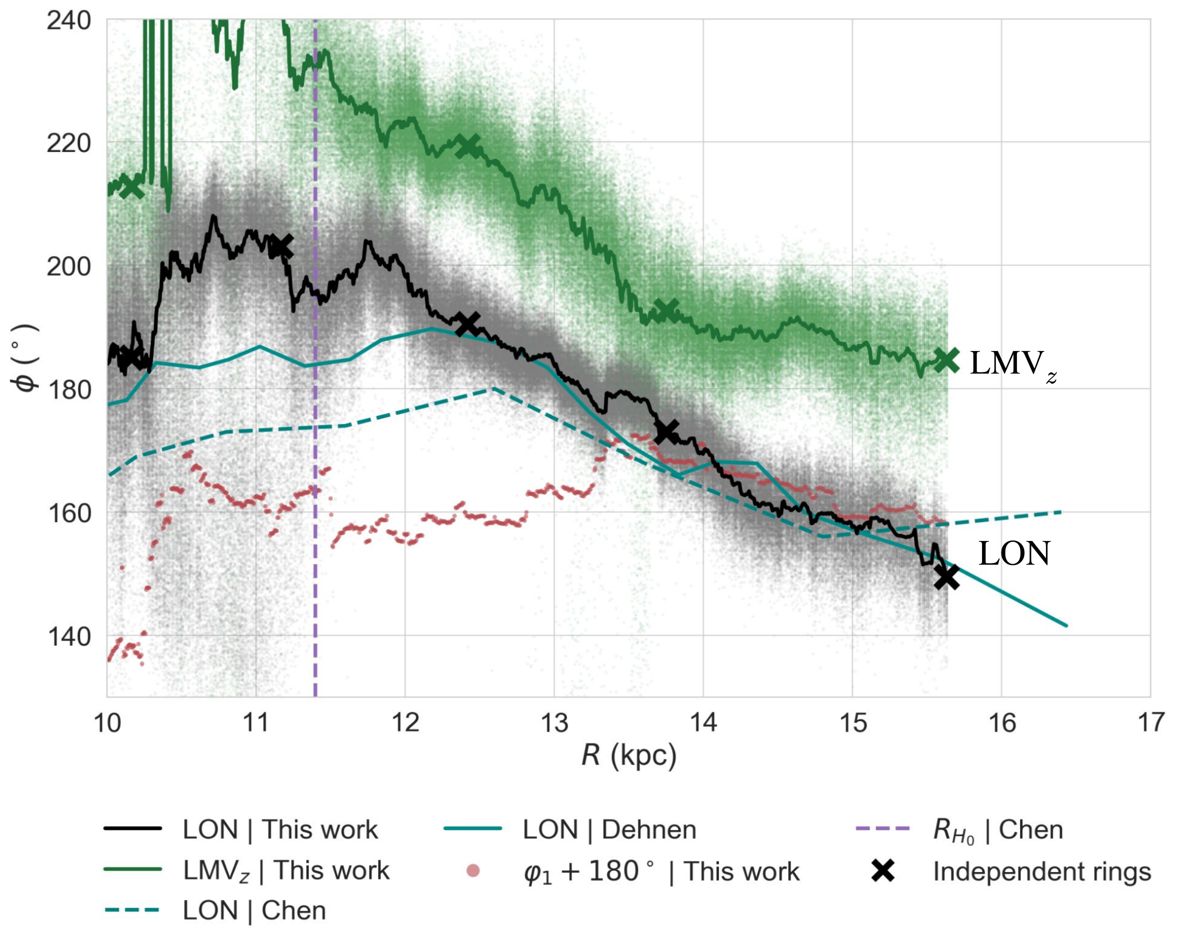


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Z (kpc)
10
11
12
13
14
15
16
R (kpc)
This work
HI | Levine
Dust | Marshall
Dust | Marshall
Ceph. | Skowron
Ceph. | Chen
Pulsars | Yusifov
OB | Li
0.4 Gyr | Amôres
RC | Lopez-Corredoira
GDR 2 | Chrobácova
Cheng
RC 1-3Gyr | Wang

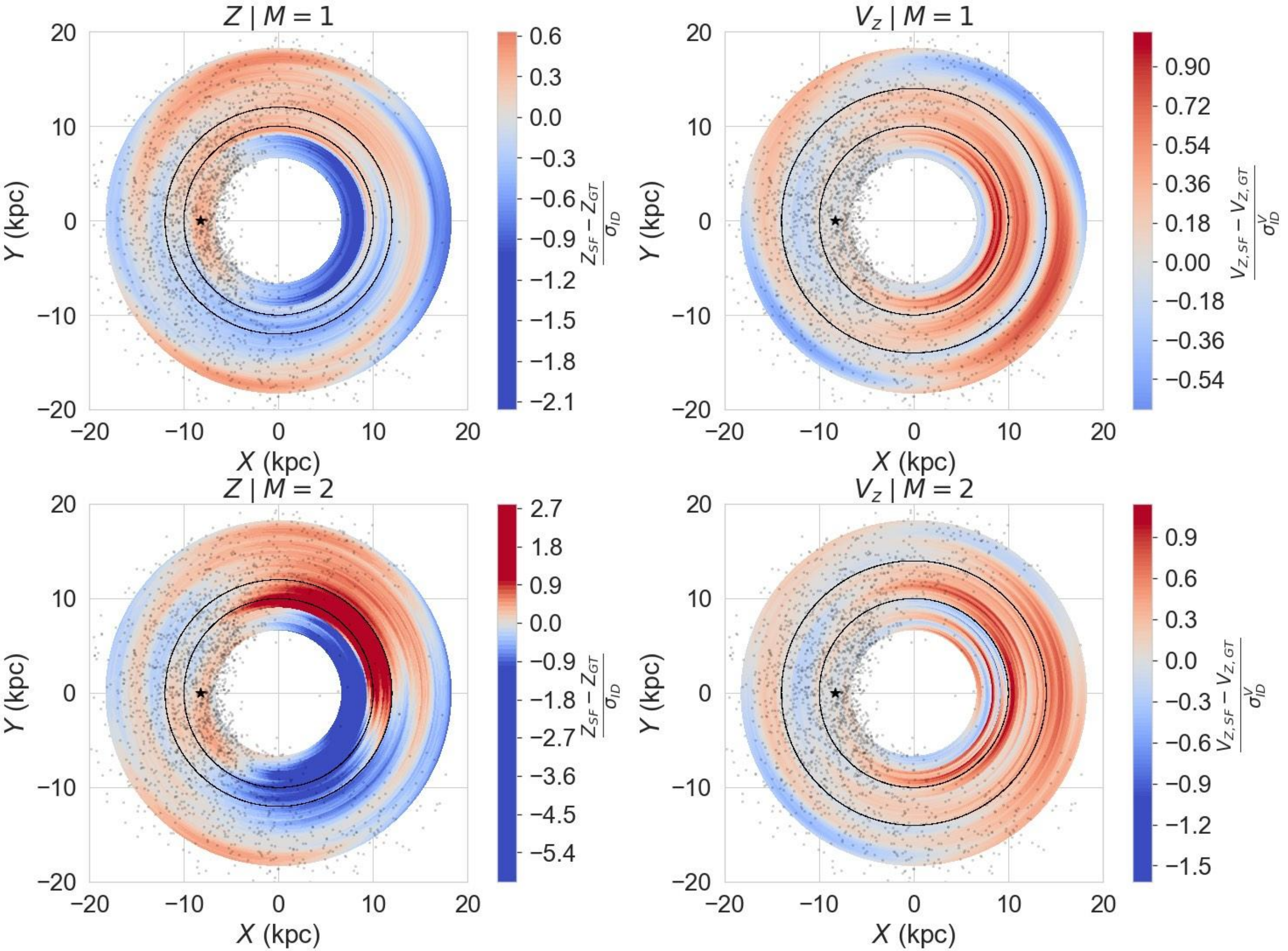

A_m (kpc)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10
11
12
13
14
15
16
R (kpc)
σ_{ID}
$A_0 \sin(-\varphi_0)$
A_1
A_2
Independent rings
Ceph. | Skowron
V_m (km/s)
15.0
12.5
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
σ_{ID}^V
$V_0 \sin(-\varphi_0^V)$
V_1
V_2
Independent rings



φ1
Independent rings
Ceph. | Skowron
φ1 (°)
R (kpc)
φ1V (°)
φ1V
Independent rings
R (kpc)
φ2
Independent rings
Ceph. | Skowron
φ2 (°)
R (kpc)
φ2V (°)
φ2V
Independent rings
R (kpc)



240
220
200
180
160
140
ϕ (°)
10
11
12
13
14
15
16
17
R (kpc)
LMV$_z$
LON
LON | This work
LMV$_z$ | This work
LON | Chen
LON | Dehnen
$\varphi_1 + 180°$ | This work
R_{H_0} | Chen
Independent rings



$Z \mid M = 1$
$V_z \mid M = 1$
$Z \mid M = 2$
$V_z \mid M = 2$
X (kpc)
Y (kpc)
$\frac{Z_{SF} - Z_{GT}}{\sigma_{ID}}$
$\frac{V_{Z,SF} - V_{Z,GT}}{\sigma^V_{ID}}$