Exploring the Galactic Warp Through Asymmetries in the Kinematics of the Galactic Disk

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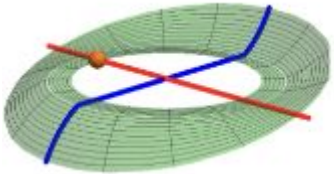
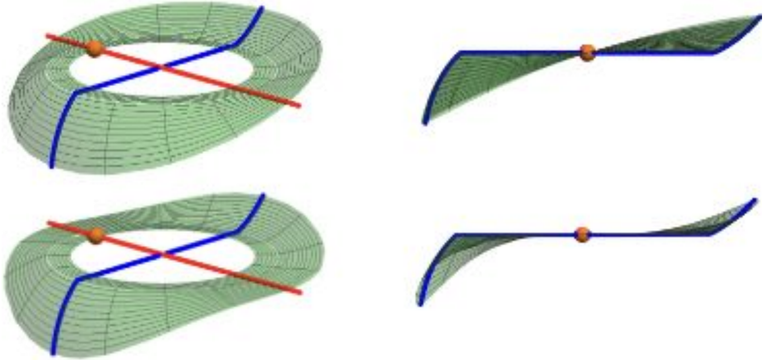
QR Code to Paper

Introduction



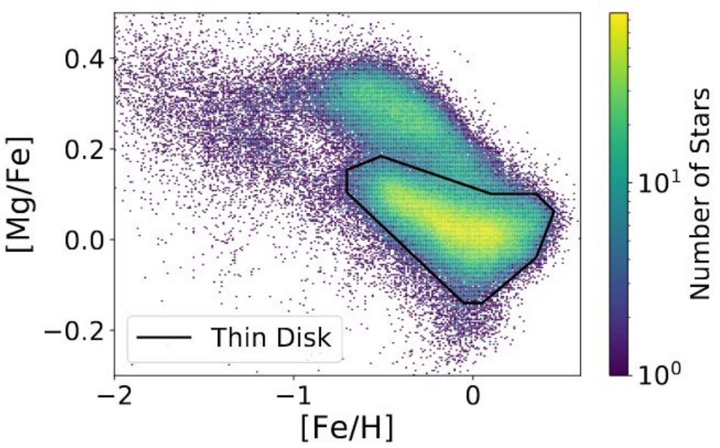
- Galactic Warp: the bending of Galactic disk
- Found in majority of spiral galaxies (Bosma 1978)
  - Long-live/repeatedly regenerated
- Limited to solar neighborhood before Gaia
- Cause: under debate
  - Interaction with satellite galaxies
    - Sgr dSph (Ibata & Razoumov 1998; Laporte et al. 2019)
    - LMC, SMC (Weinberg & Blitz 2006; Garavito-Camargo et al. 2019)
  - External torques of dark matter halos (Widrow et al. 2014)
  - Accretion of intergalactic matter (Ostriker & Binney 1989)
  - Misaligned dark matter halo (Sparke & Casertano 1988)
  - Intergalactic magnetic field (Battaner et al. 1990; Guijarro et al. 2010)

Introduction



- Geometry: uncertain
    - Shape
        - Sine-lopsided or S-lopsided (Romero-Gomez et al. 2019)
    - Starting radius
        - Inside solar circle
            - J/K-band surface brightness fitting (Drimmel & Spergel 2001)
            - Gaia-TGAS (Schonrich & Dehnen 2018), LAMOST-TGAS (Huang et al. 2018)
        - Outside solar circle
            - Star count (Reyle et al. 2009; Derriere & Robin 2001)
            - Gaia DR2 kinematics (Romero-Gomez et al. 2019)
- This work
    - Kinematics from Gaia DR2
    - Chemistry from APOGEE
    - Explore asymmetries in the outer Galactic disk

Data

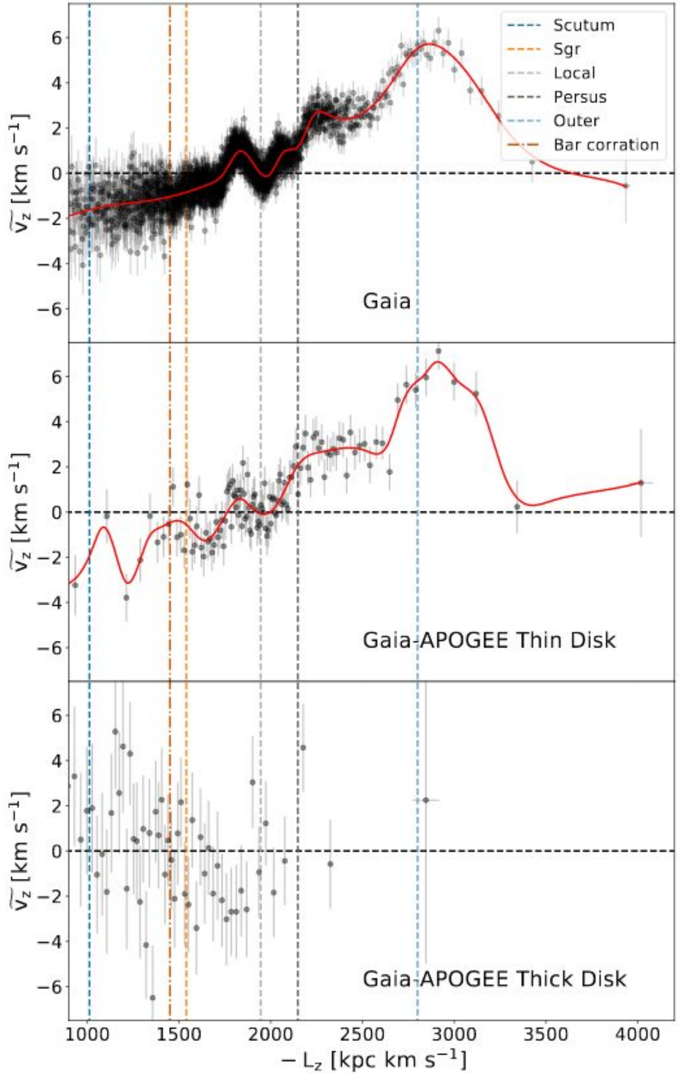


- 2 data-sets
- Gaia
  - Proper motion + StarHorse distance (Gaia) + RV (Gaia)
  - G < 15 mag
  - Removal of stars with suspect photometry and RV based on < 4 visits
- Gaia-APOGEE
  - PM (Gaia) + StarHorse distance (Gaia) + RV (APOGEE) + chemistry information (APOGEE)
  - Chemically selected thin disk

- StarHorse distance
  - Bayesian estimation of stellar parameters, distances and extinctions with the combination of photometric and parallax information from Gaia, Pan-STARRS1, 2MASS, and AllWISE

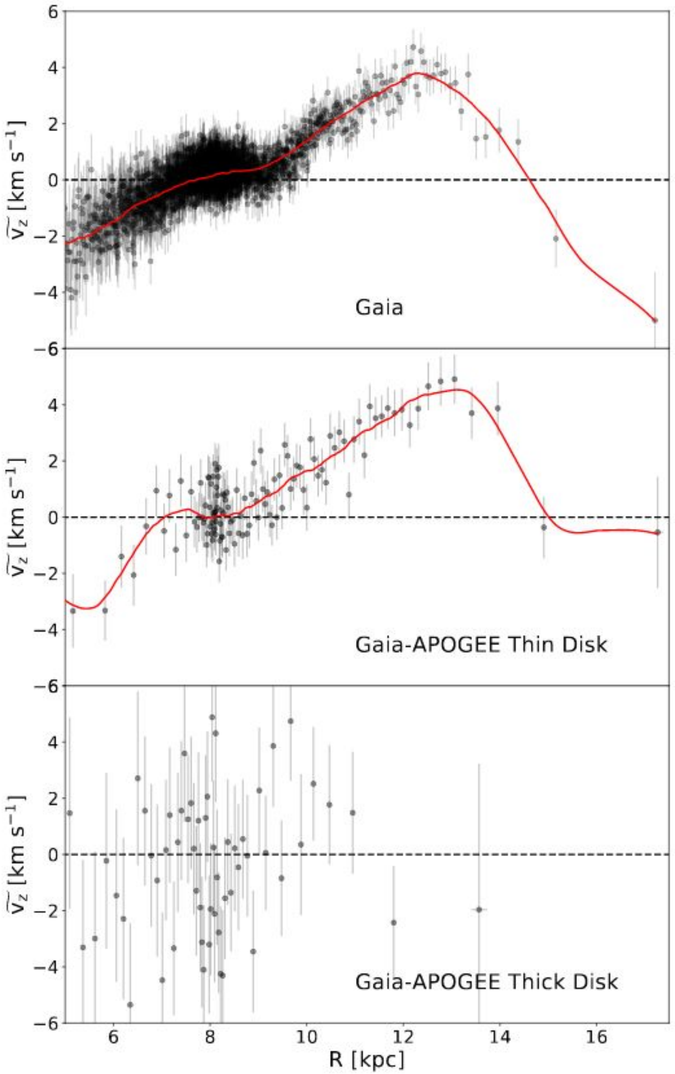
Structures in Vertical Velocity

- Vz increase with Lz
  - Lz < 2800 kpc km/s
  - Previously observed and attributed to Galactic warp
- Peak Vz = 6 km/s
  - Lz ~ 2800 kpc km/s
- Drops to 0
  - Lz ~ 3500 kpc km/s
- First time discovery of the drop-off
- Substructure (wiggles)
  - Lz ~ 1700, 2000, 2200 kpc km/s
  - Some aligned with spiral arms



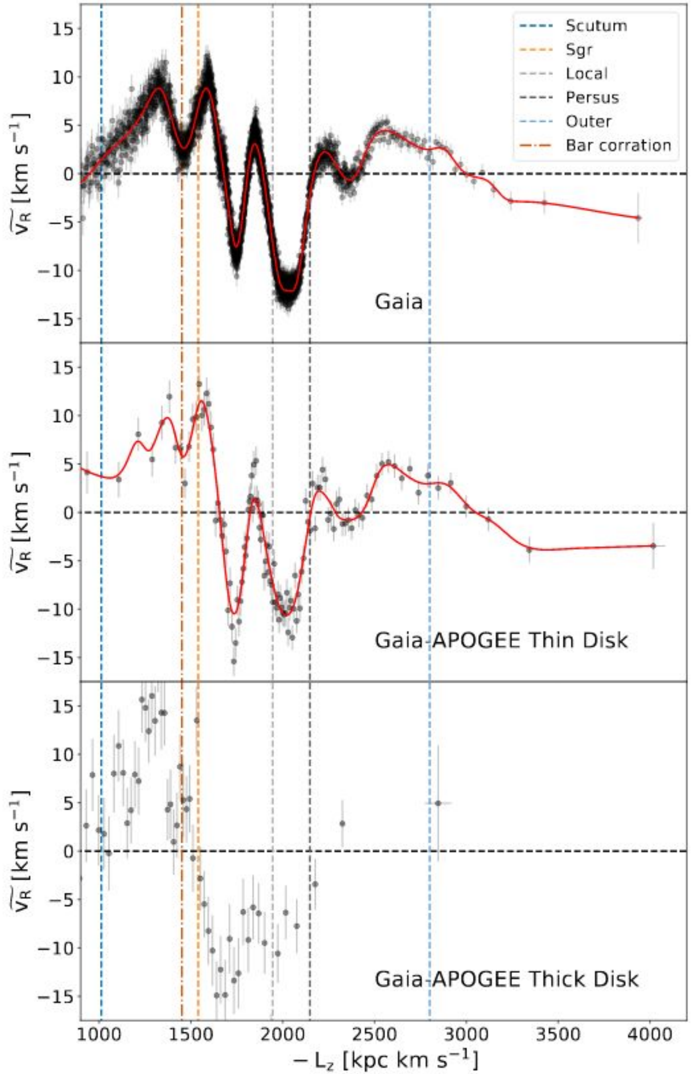
Structures in Vertical Velocity

- General trend also exist when viewed against Galactocentric radius
- Substructures smeared out since R is not an integral of motion
- Plateau of Vz~0 at solar neighborhood



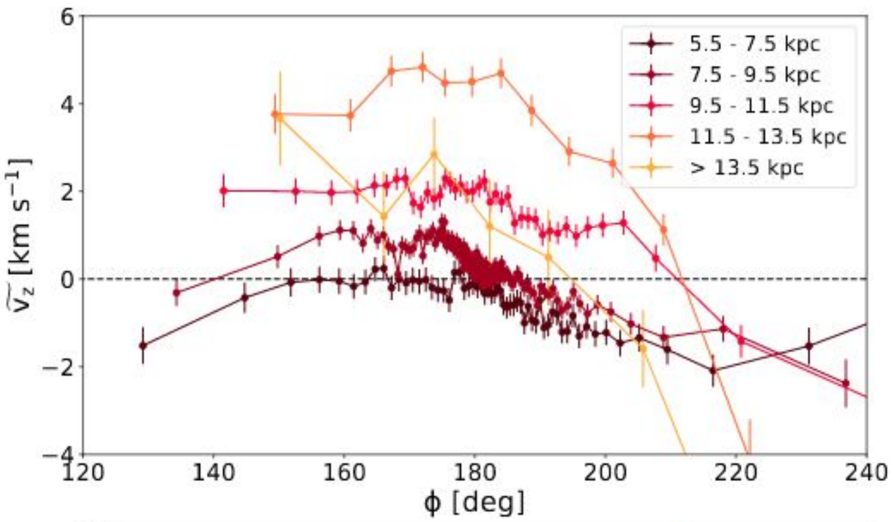
Structures of Radial Velocity

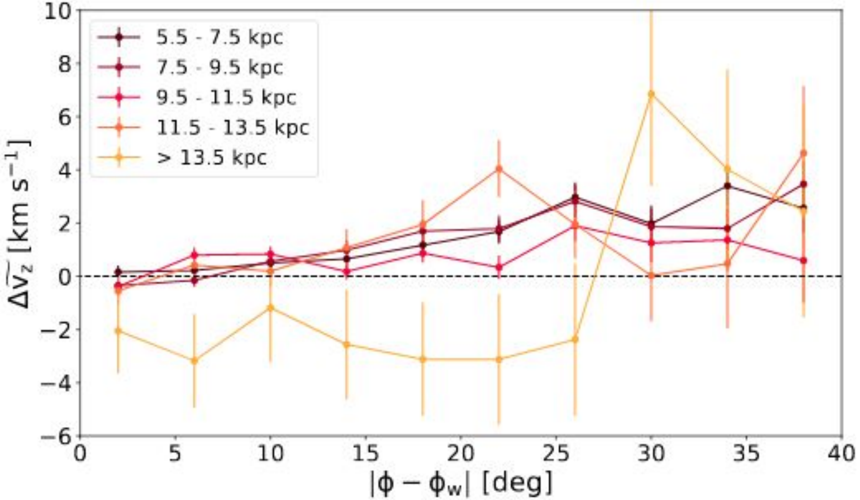
- Large-amplitude (~13 km/s) ripples detected
- Phase difference with vertical velocity
- Not all peak/valley aligned with spiral arms



Lopsided Warp

- Romero-Gomez et al. 2019: up and down sides are not symmetric -> lopsided
- Peak velocity at ~170 deg
- Rate of change in vertical velocity not symmetric with respect to maximum point





Modeling the Observed Vertical Kinematics

- Physical reason for the drop-off
- Stellar number density separable in R and z: $n(R,z) = f(R)g(z)$
- Warp precessing in galactic-rotation direction: $z_0 = h(R)\sin(\phi + \phi_w + \omega_p t)$

$$h(R) = \begin{cases} 0 & R \le R_1 \\ \frac{R_w}{R_2 - R_1}(R - R_w)^\alpha & R_1 < R \le R_2 \\ h(R_2) + \frac{dh}{dR}|_{R=R_2-R_1}(R - R_2) & R > R_2 \end{cases}$$

- The first Jeans Equation: $\frac{\partial n'}{\partial t} + \frac{\partial(n'\overline{v_R})}{\partial R} + \frac{1}{R}\frac{\partial(n'\overline{v_\phi})}{\partial \phi} + \frac{\partial(n'\overline{v_z})}{\partial z} = 0$
- Axis-symmetry $\frac{\partial \overline{v_\phi}}{\partial \phi} = 0$. and $\frac{\partial \overline{v_z}}{\partial z} = 0$ but a non-zero radial velocity

$$[\overline{v_z} - (\frac{\overline{v_\phi}}{R} + \omega_p)h(R)\cos(\phi + \phi_w + \omega_p t) -$$
$$\overline{v_R}\frac{dh}{dR}\sin(\phi + \phi_w + \omega_p t)]f(R)\frac{dg}{dz}$$
$$+ \overline{v_R}\frac{df}{dR}g(z - h(R)\sin(\phi + \phi_w + \omega_p t)) + \frac{\partial \overline{v_R}}{\partial R}n' = 0$$

Modeling the Observed Vertical Kinematics

- If the Galaxy has the same IMF everywhere, the average mass of stars would also be a constant, thus the number density if proportional to mass density

$$n(R,z) = n_0 \exp(-\frac{|z|}{z_h} - \frac{R}{R_h})$$

- Plug in and crunch: $\frac{\partial \overline{v_R}}{\partial R} = \frac{\overline{v_R}}{R_h} + \frac{sign[z - z_0]}{z_h} \left[\overline{v_z} - \left(\frac{\overline{v_\phi}}{R} + \omega_p \right) h(R) \cos\theta - \overline{v_R} \frac{dh}{dR} \sin\theta \right]$

  where zh is the scale height and Rh is the scale length

- Population is symmetric about z0, so average Z>Z0 and Z<Z0

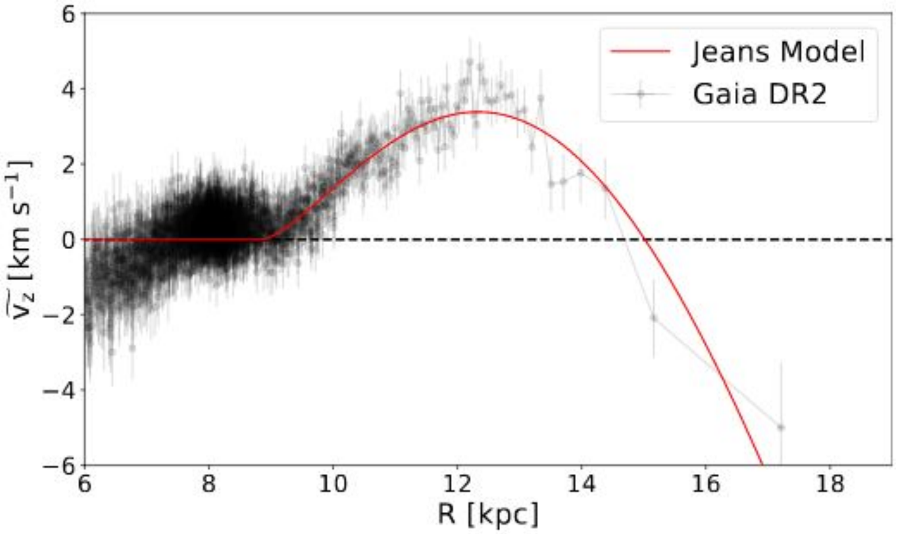
$$\overline{v_z} = \left(\frac{\overline{v_\phi}}{R} + \omega_p \right) h(R) \cos\theta + \overline{v_R} \frac{dh}{dR} \sin\theta$$

Modeling the Observed Vertical Kinematics

- MCMC fitting

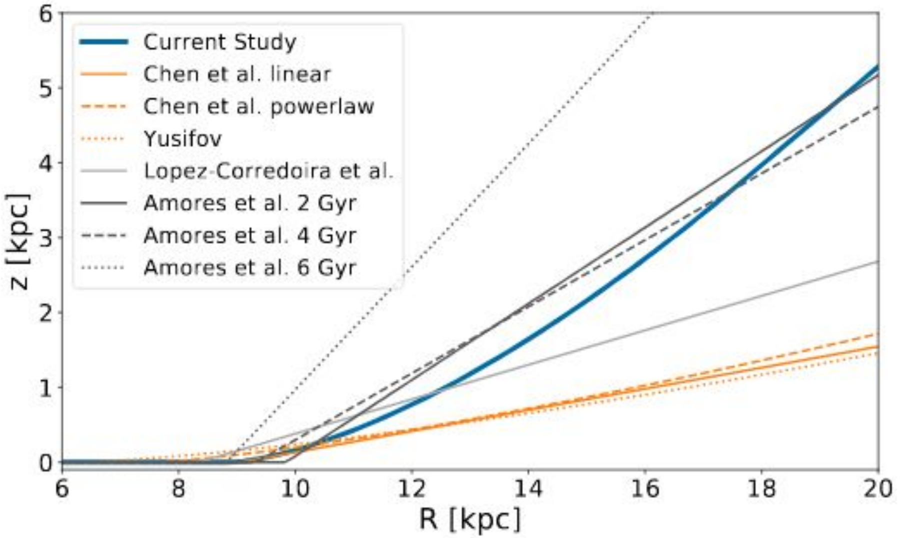
$$\begin{cases} \omega_p = -13.57^{+0.20}_{-0.18} \text{ km s}^{-1} \text{ kpc}^{-1} \\ R_1 = 8.87^{+0.08}_{-0.09} \text{ kpc} \\ R_2 = 17.78^{+1.56}_{-1.86} \text{ kpc} \\ R_w = 1.20^{+0.28}_{-0.26} \text{ kpc}^{2-\alpha} \\ \alpha = 1.53^{+0.10}_{-0.09} \end{cases}$$

- Consistent with Poggio et al. 2020
- Not sensitive to ending radius due to the lack of data points beyond R=16

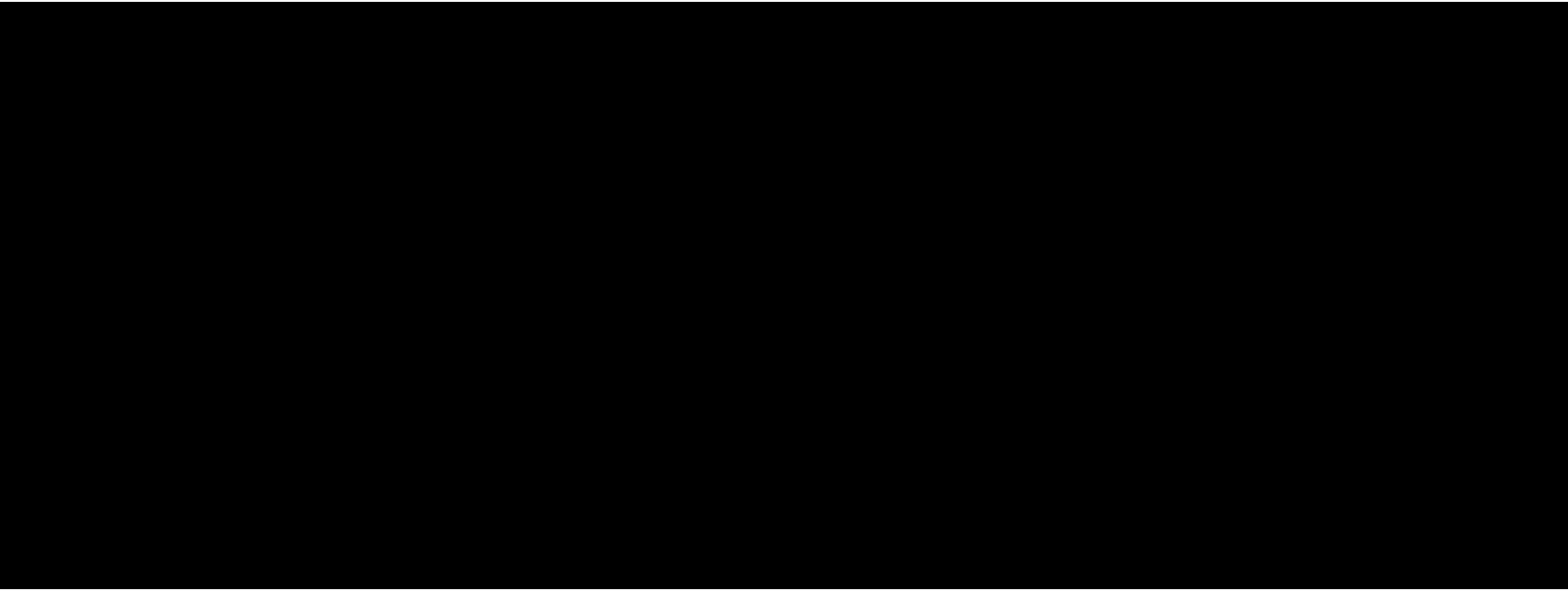


Model Comparison

- Our model is stronger than most previous studies
- Similar to Amores et al.
  - More physics
  - Flaring, disk truncation, star formation history, etc.
  - Reassuring check of our model



Model Visualization

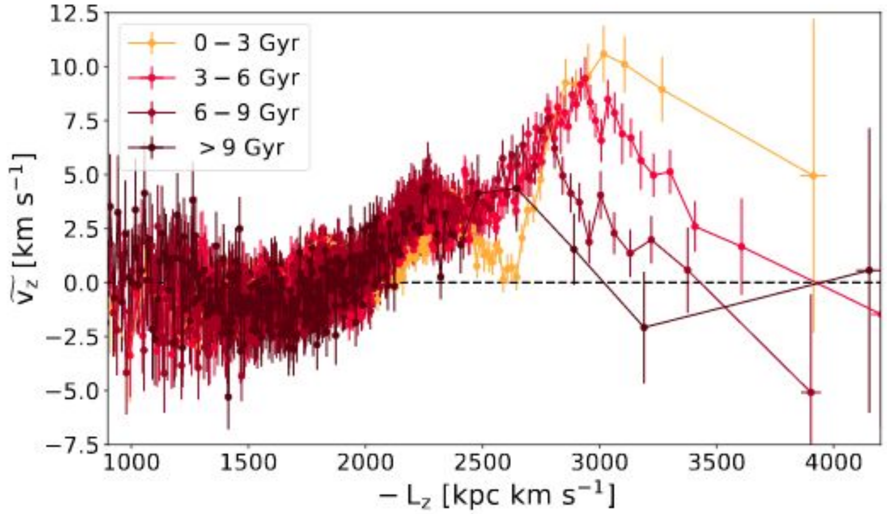


Fixed point above the Galaxy

Following the Sun above the Galaxy

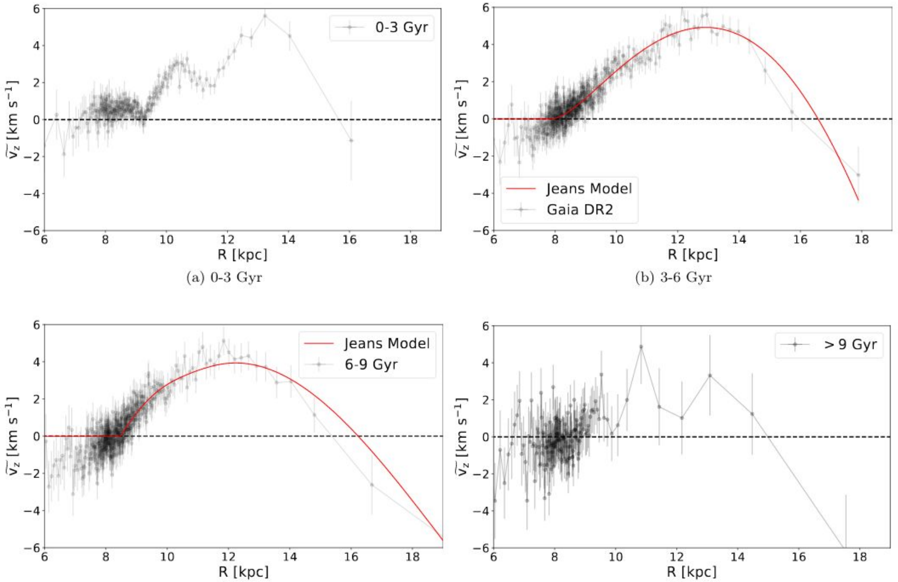
Dynamically Evolving Warp

- Age from Sanders & Das (2018)
    - Bayesian isochrone fitting
    - RV, stellar parameters from APOGEE, GALAH, LAMOST, RAVE, and SEGUE
- Warp parameters dependent on age
    - Warp amplitude decrease with age
- Consistent kinematic signature across different age population, except the > 9 Gyr
    - Warp possibly caused by gravitational mechanism



Dynamically Evolving Warp

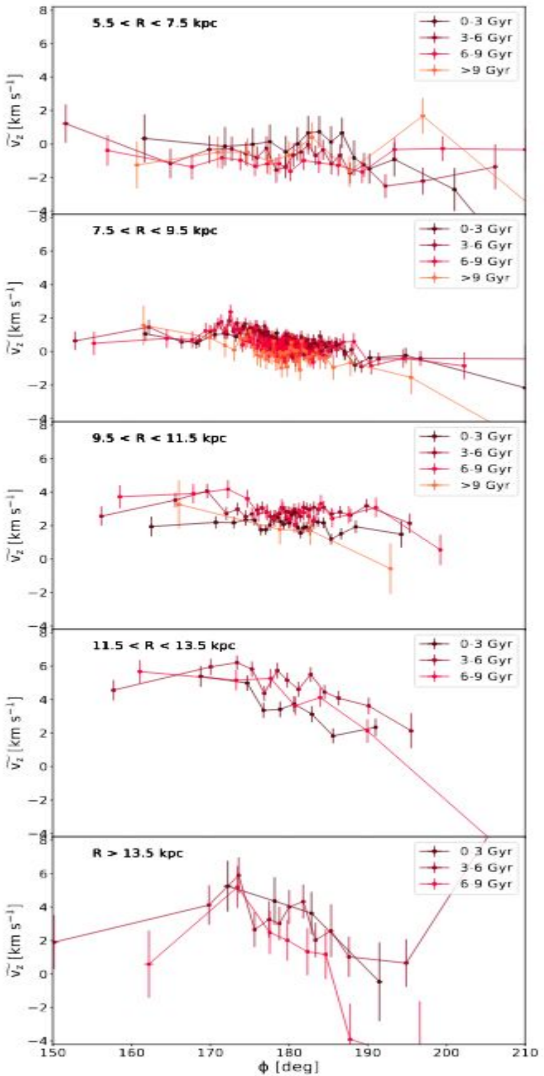
- Precession remains consistent across time
  - 0-3 Gyr: Unable to fit
  - 3-6 Gyr: $-11.59^{+0.30}_{-0.25}\ \mathrm{km\ s^{-1}\ kpc^{-1}}$
  - 6-9 Gyr: $-12.19^{+0.49}_{-0.39}\ \mathrm{km\ s^{-1}\ kpc^{-1}}$
  - >9 Gyr: dominated by halo stars



(a) 0-3 Gyr (b) 3-6 Gyr (c) 6-9 Gyr (d) > 9 Gyr

Dynamically Evolving Warp

- Galactic warp remain lopsided across different age population



Conclusion

- First time discovery of the drop-off in vertical velocity
- Ripples in vertical velocity
- Ripples in radial velocity
- Lopsided Galactic warp
- Consistent modeling of the Galactic warp
- Evolution of warp with time
    - Signature remains consistent for a long time
    - Dynamically evolving
    - Possible gravitational instead of non-gravitational mechanism

Questions?