Galactic Warp Through the Lenses of Gaia Data Release 2 and the APOGEE Survey

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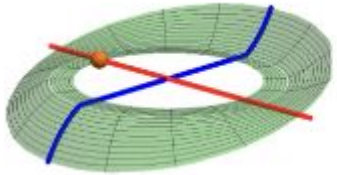
QR Code to ADS

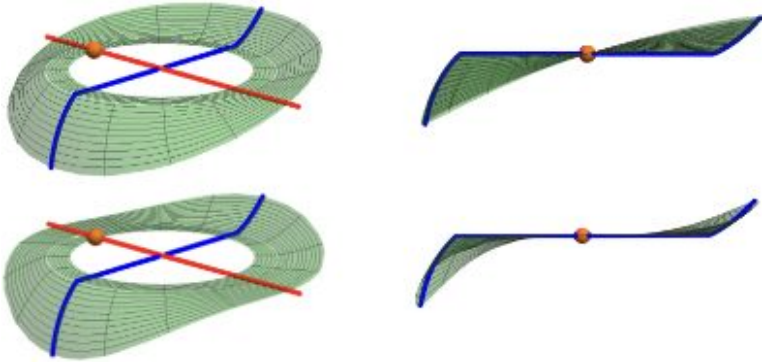
gaia

Introduction



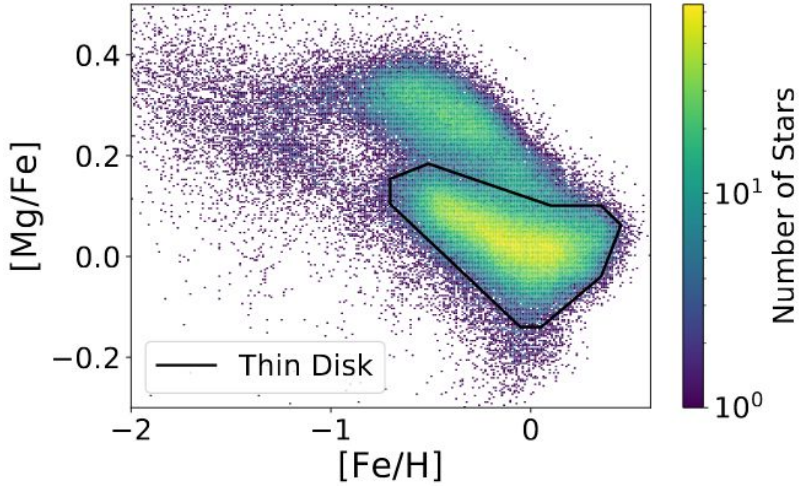
- Galactic Warp: the bending of Galactic disk
- Found in majority of spiral galaxies (Bosma 1978)
  - Long-live/repeatedly regenerated
- Origin: under debate
  - Interaction with satellite galaxies
    - Sgr dSph (Ibata & Razoumov 1998; Laporte et al. 2019)
    - LMC, SMC (Weinberg & Blitz 2006; Garavito-Camargo 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 analysis (Reyle et al. 2009; Derriere & Robin 2001)
      - Gaia DR2 kinematics (Romero-Gomez et al. 2019)
- This work
  - Kinematics from Gaia DR2
  - Chemistry from SDSS/APOGEE survey (Majewski et al. 2017)
  - Distance from StarHorse (Queiroz et al. 2018)
  - Explore asymmetries in the outer Galactic disk

Data



2 data-sets:

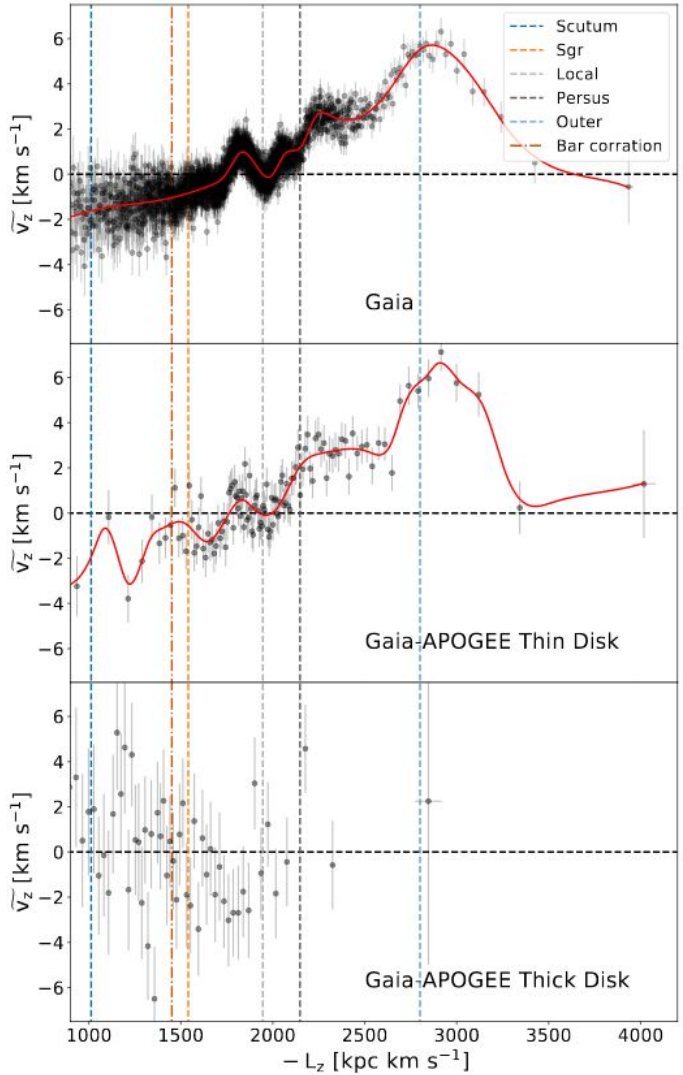
- Gaia
  - Proper motion + StarHorse distance + RV (Gaia)
  - G < 15 mag
  - Removal of stars with suspect photometry and RV based on < 4 visits
- Gaia-APOGEE
  - PM + StarHorse distance + RV (APOGEE) + chemistry information
  - Chemically selected thin disk

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

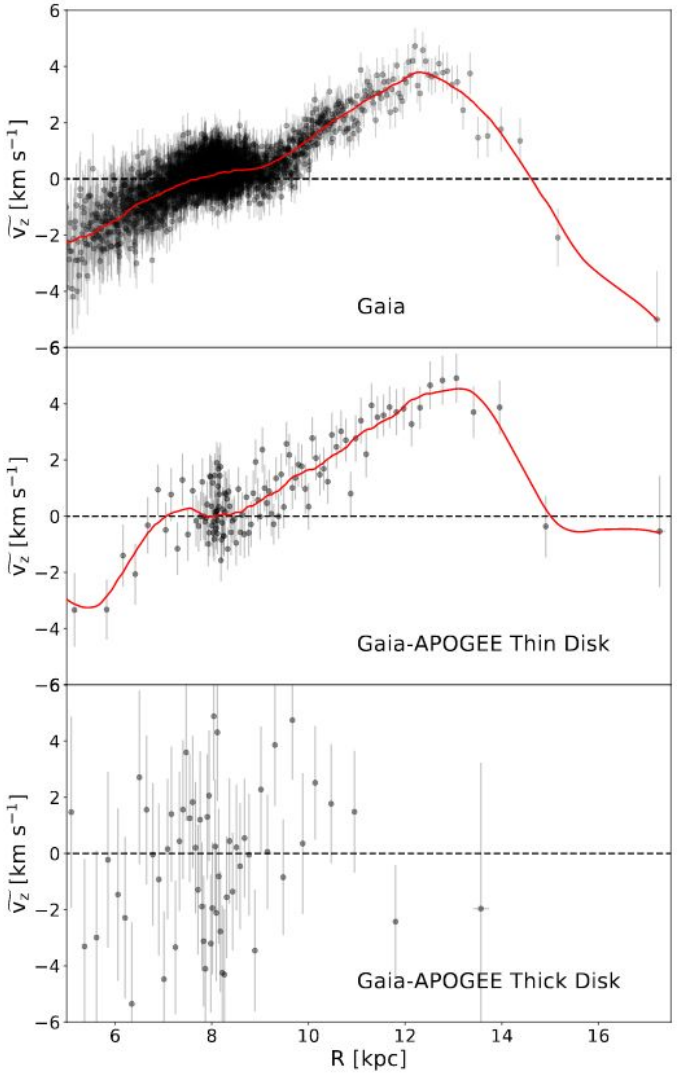
Structures in Vertical Velocity

- 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
- Decrease afterwards
- Discovery of a decline in vertical velocity for the first time
- Substructure (ripples)
  - Lz ~ 1700, 2000, 2200 kpc km/s
  - Some aligned with spiral arms



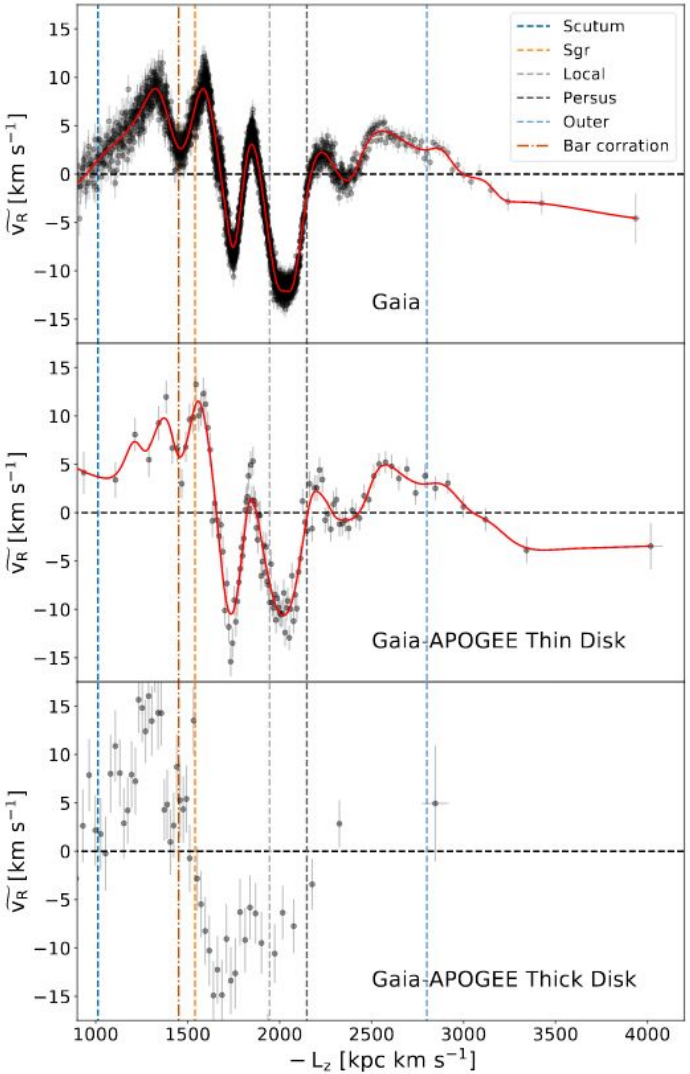
Structures in Vertical Velocity

- Global trend also exists when viewed against Galactocentric radius
- Substructures smeared out since R is not an integral of motion



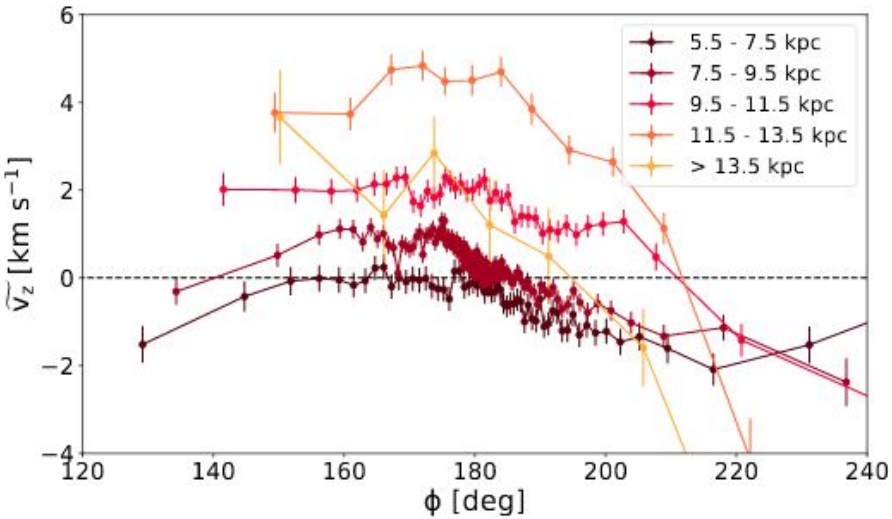
Structures in Radial Velocity

- 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 the peak
- Lopsided warp through stellar kinematics



Modeling the Observed Vertical Kinematics

- Non-zero radial velocity
- Warp precessing in galactic-rotation direction
- Axis-symmetry
- Plug into Jeans Equation:

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

- Double exponential law: $n(R,z) = n_0 \exp(-\frac{|z|}{z_h} - \frac{R}{R_h})$
- Plug in and crunch: $\frac{\partial \overline{v_R}}{\partial R} = \frac{\overline{v_R}}{R_h} + \frac{sign[z - z_0]}{z_h}\left[\overline{v_z} - \left(\frac{\overline{v_\phi}}{R} + \omega_p\right)h(R)\cos\theta - \overline{v_R}\frac{dh}{dR}\sin\theta\right]$
- 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

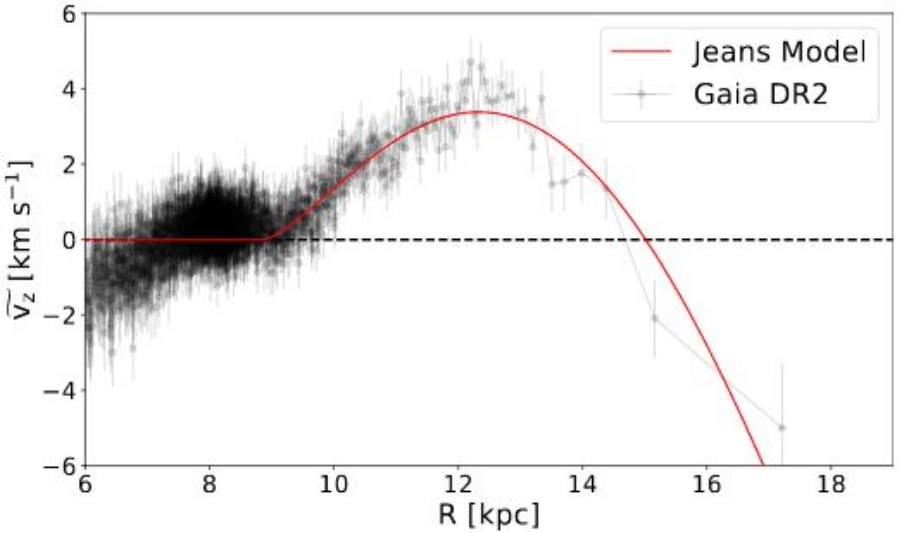
Analytical model:

- Based on Jeans Equation
- Including terms generally ignored

Warp stars at ~8.9 kpc

Precession period: ~450 Myr

- ~2.25x slower than Galactic rotation at Sun

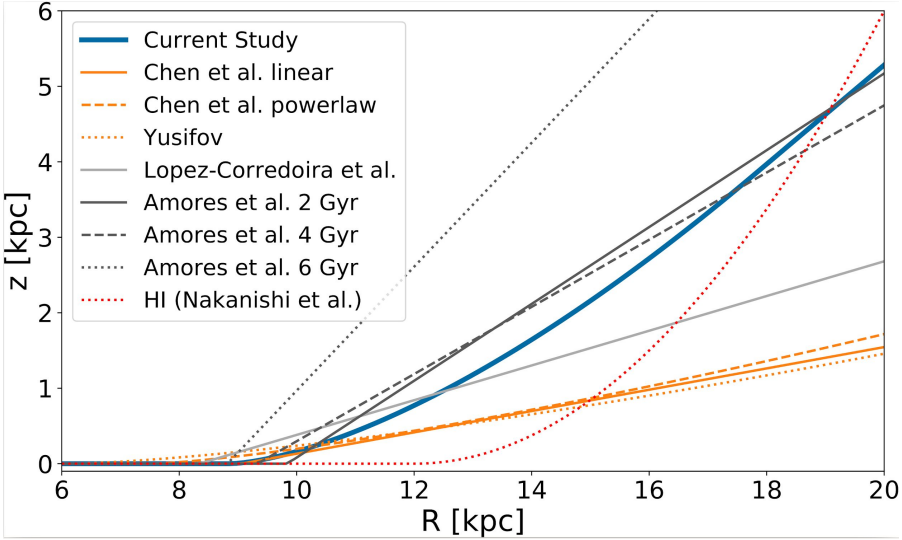


$$\overline{v_z} = \left(\frac{\overline{v_\phi}}{R} + \omega_p\right) h(R)\cos\theta + \overline{v_R}\frac{dh}{dR}\sin\theta$$

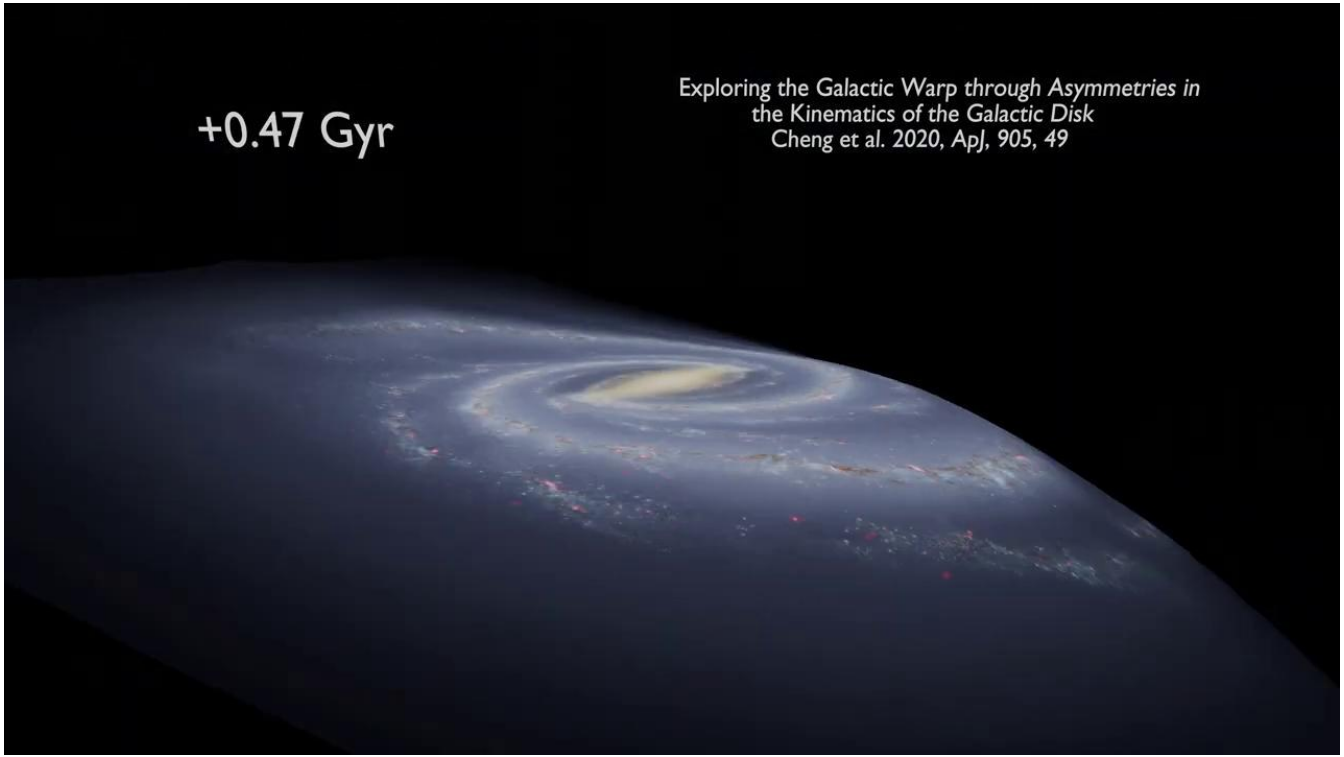
Full derivation in paper

Model Comparison

- Our model is stronger than most previous studies
- Similar to Amores et al. 2017
  - More physics
  - Flaring, disk truncation, star formation history, etc.
  - Reassuring check of our model

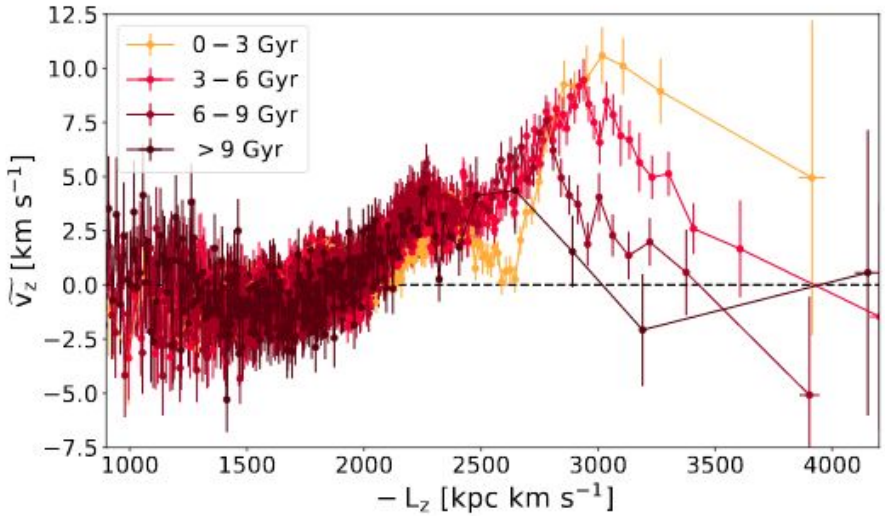


Model Visualization



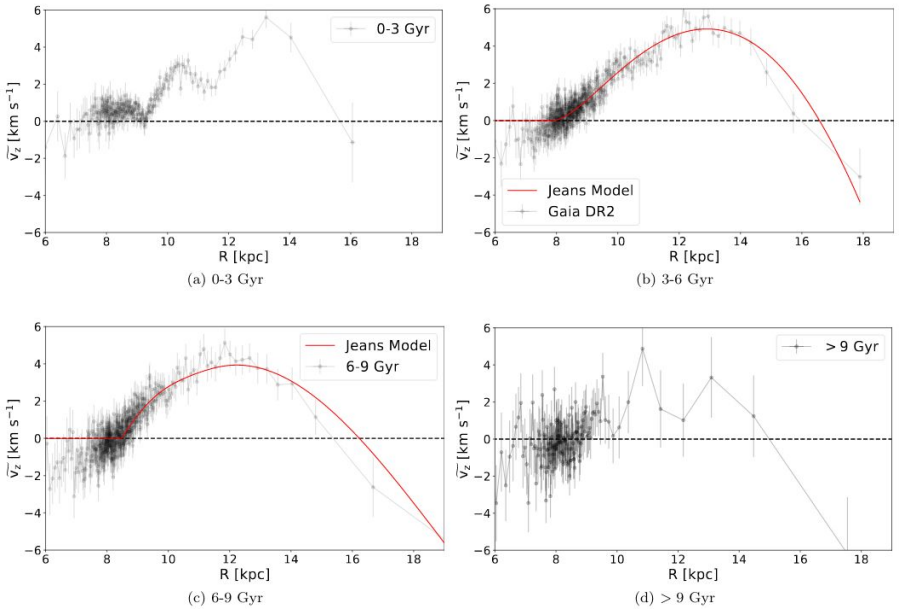
Dynamically Evolving Warp

- 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
  - Precession rate similar
  - Warp possibly caused by gravitational mechanism within the past 3 Gyr



Dynamically Evolving Warp

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



Conclusion

- First time discovery of a decrease in vertical velocity in the outer part of the galaxy
- Ripples in vertical and radial velocity
- Lopsided Galactic warp
- Able to interpret warp with simple Jean Eqn analytical model
- Evolution of warp with time
    - Younger population, stronger response
    - Possible gravitational instead of non-gravitational origin within the last 3 Gyr

Questions?