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

Xinlun Cheng, Borja Anguiano, Steven R. Majewski, Christian Hayes, Phil Arras, Cristina Chiappini, Sten Hasselquist & APOGEE team

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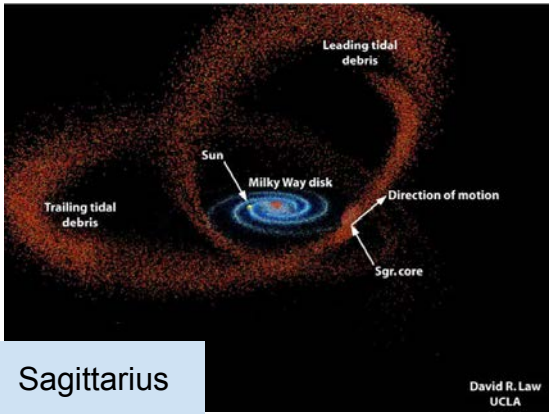
QR Code to paper

gaia

Background

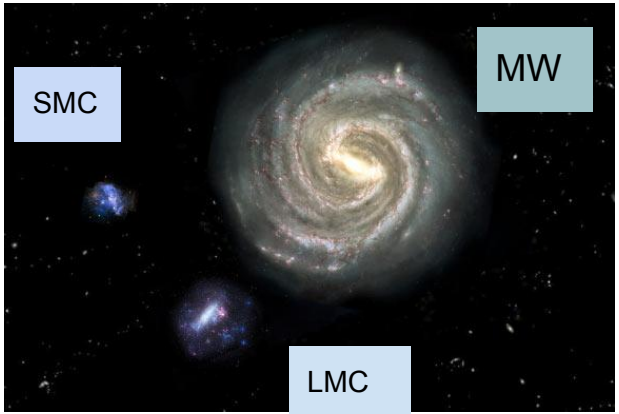
ΛCDM Universe - hierarchical galaxy formation.

The past few decades have seen a myriad of results affirming the role that mergers have had in the evolution of the Milky Way.



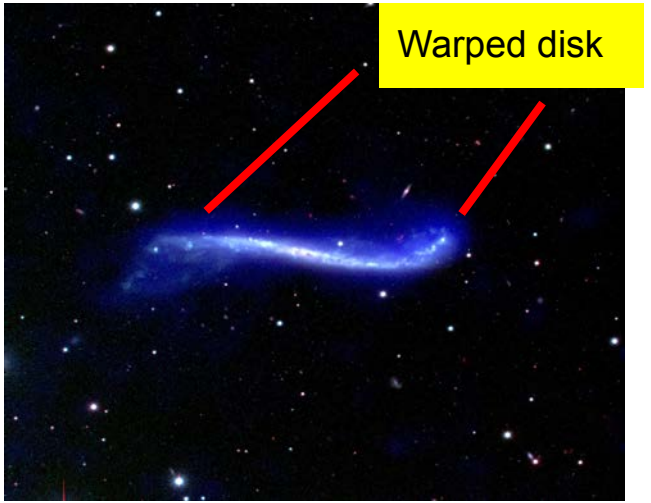
Sagittarius

Credit: Steven Majewski (UVA) & David Law (UCLA).



Credit: Nina McCurdy / Nick Risinger / NASA.

Image courtesy of R. Jay GaBany



Credit: NRAO/AUI/NSF

Introduction

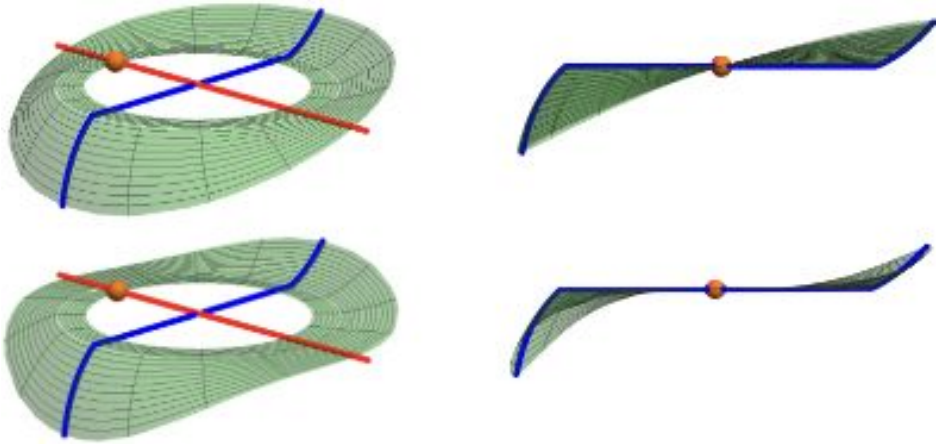
- Milky Way Warp
  - Bending of Galactic disk
  - Long known from studies of gas & stars
- Found in majority of spiral galaxies
  - Long-lived vs. repeatedly regenerated?
- Origin: under debate
  - Interaction with satellite galaxies
  - External torques of dark matter halos
  - Accretion of intergalactic matter
  - Misaligned dark matter halo
  - Intergalactic magnetic field

Artistic Rendering of the Galactic Warp

Credit: Cheng et al. 2020

Introduction

- Geometry: uncertain
  - Shape
  - Starting radius
    - Whether the Sun participates in the warp or not
- This work:
  - Kinematics from Gaia DR2
  - Chemistry from SDSS/APOGEE
  - Distance from StarHorse
  - Explore asymmetries in the outer Galactic disk



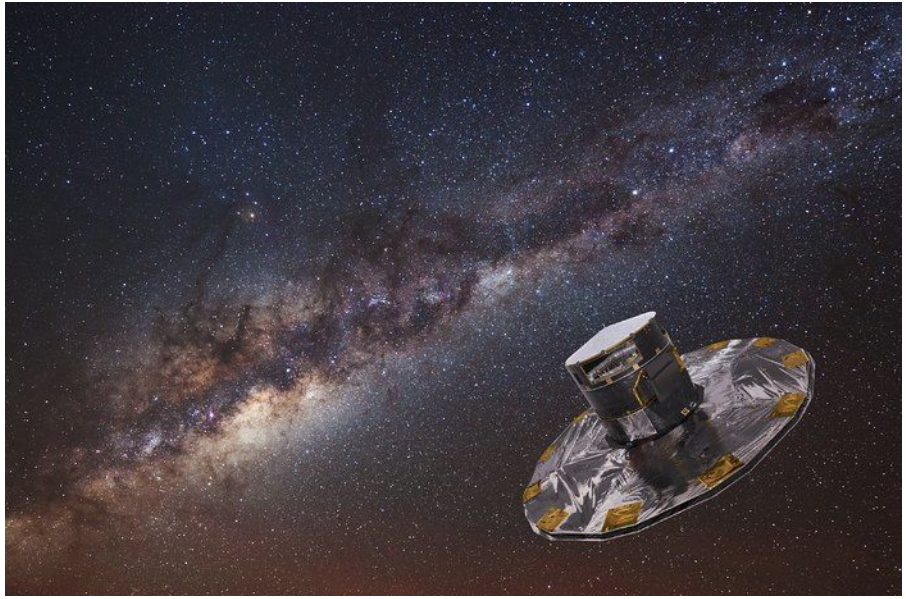
Possible Shapes of the Warp

Credit: Romero-Gomez et al. 2019

Getting the Warp Motion: Gaia Astrometry

- Measuring the motion of stars
  - Distance and transverse velocity
  - Size of effect: usually < 0.001 arcsec/yr

- Requires very accurate angular measurement of millions of stars
  - Astrometry satellite *Gaia*



Astrometry satellite *Gaia*

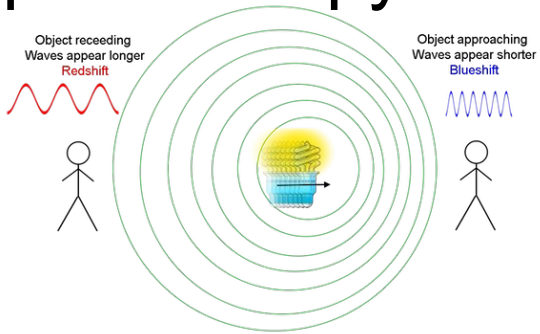
Credit: ESA/ATG medialab; background image: ESO/S. Brunier

Motions & Chemistry: APOGEE Spectroscopy

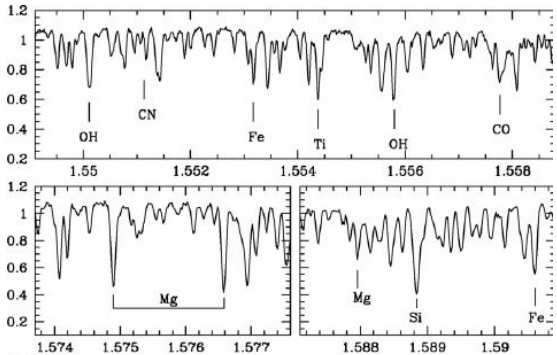
- Requires high-precision spectroscopic information
  - Apache Point Observatory Galactic Evolution Experiment (APOGEE)
- Radial velocity through Doppler shift
- Chemical composition of stars through absorption lines

Gaia + APOGEE

- Stars with full 3D position, motion and chemical composition



Doppler Shift
Credit: NASA's Imagine the Universe



APOGEE Spectrum & Chemical Composition
Credit: Schiavon et al. 2010

Stars Are Doing the Wave

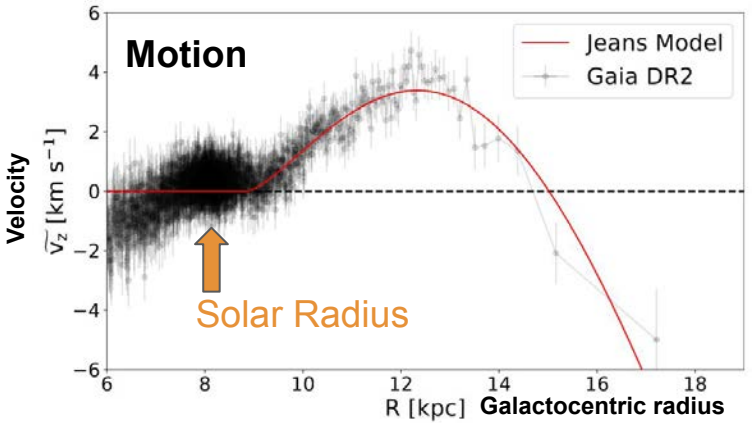
- Analogous to audience doing the stadium wave
  - Fans stand up and sit down one after another
  - To observer far away: a wave is rotating even though each individual is not rotating around the center of stadium

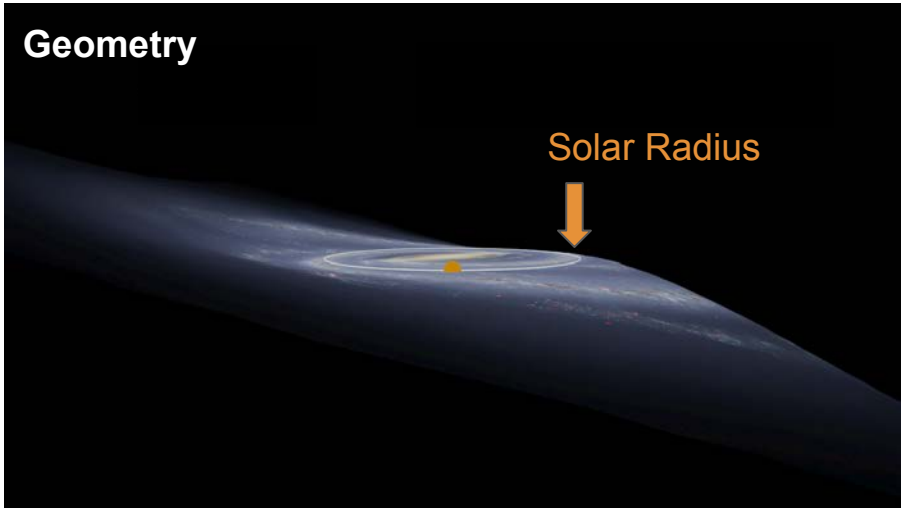
Waves in Stadium

Credit: YouTube

Our Discoveries

- Stars 1 kpc farther than the orbit of the Sun are doing the wave...





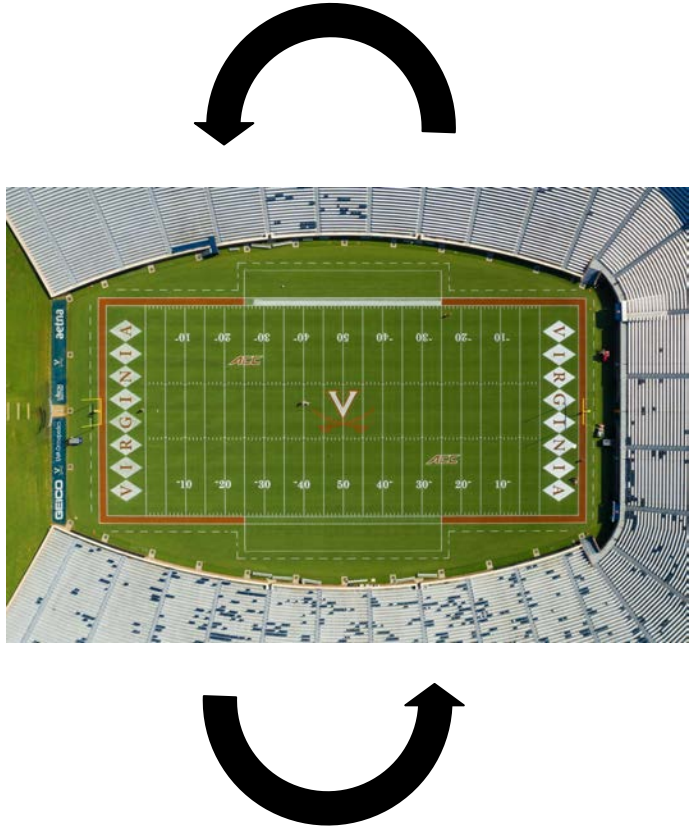
Galactic warp and orbit of the Sun

Credit: Cheng et al. 2020

Our Discoveries

- Stars 1 kpc farther than the orbit of the Sun are doing the wave...

  … but in a rotating stadium



Rotating UVA Scott Stadium

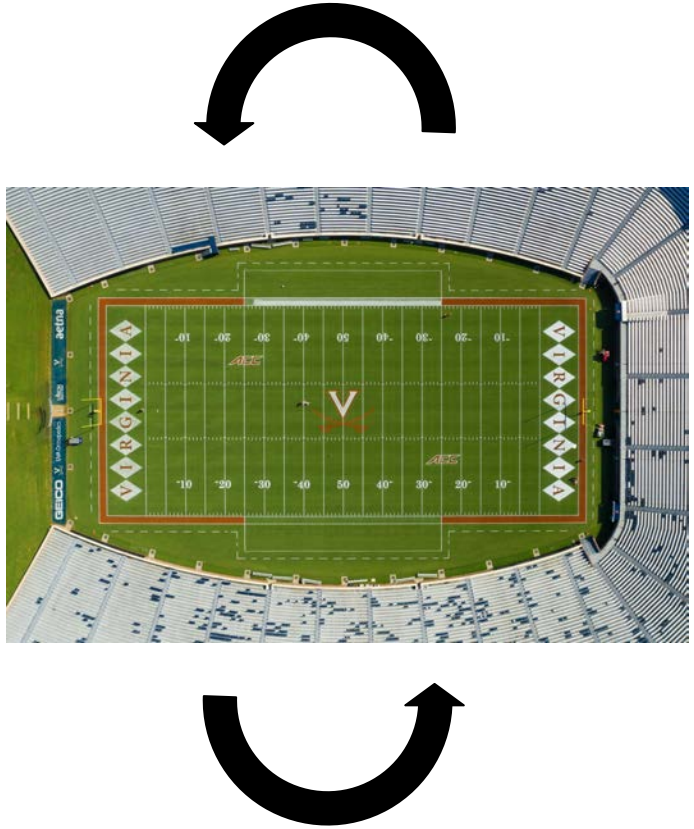
Credit: Sanjay Suchak, University Communications

Our Discoveries

- Stars 1 kpc farther than the orbit of the Sun are doing the wave...

  … but in a rotating stadium

- The warp is precessing (rotating) at half of the speed of the rotation speed of the Sun



Rotating UVA Scott Stadium

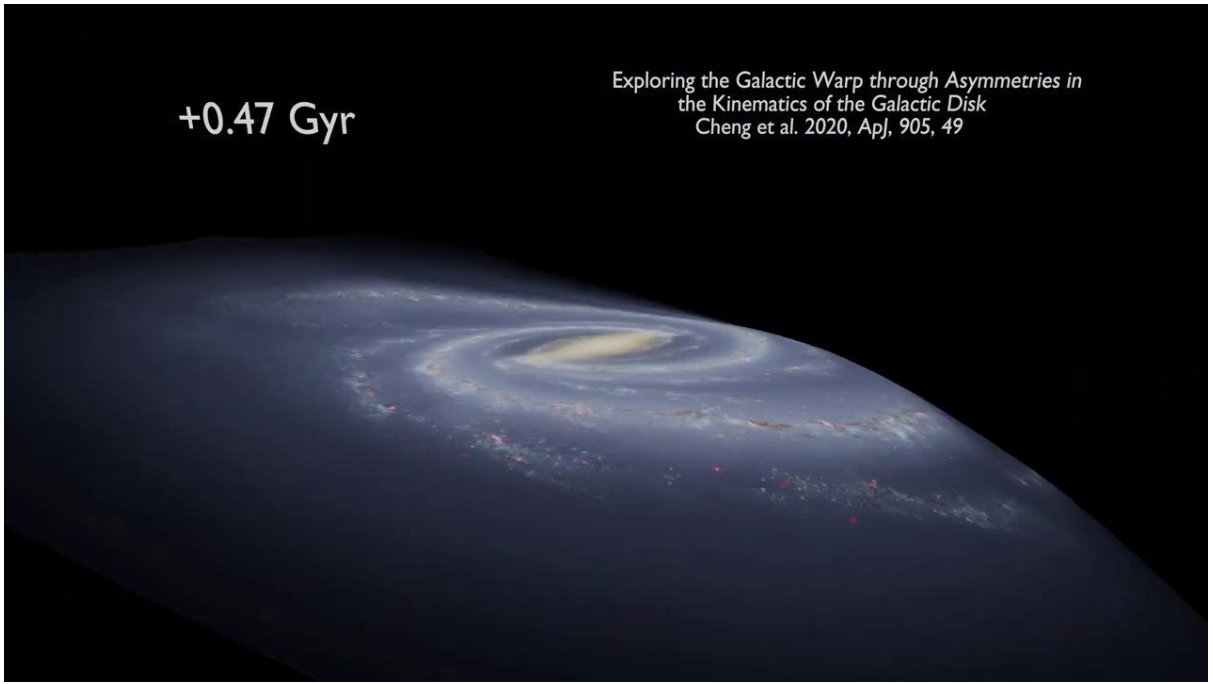
Credit: Sanjay Suchak, University Communications

Our Discoveries

- Younger stars are showing a stronger warp amplitude than the older stars.
- Points to possible origin of the warp: gravitational perturbation from satellite galaxy.
- Our results pinpoint this interaction to be less than 3 billion years ago.

Galactic Warp Induced by Satellite Galaxy
Credit: Stefan Payne-Wardenaar; Magellanic Clouds: Robert Gendler/ESO

Visualization of the Past & Future of the Warp



Animation of Galactic Warp

Credit: Cheng et al. 2020

Thank you!

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

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