The Ellipticity of the Milky Way Disk with APOGEE & Gaia:

A Window on the Shape of the Dark Matter Halo

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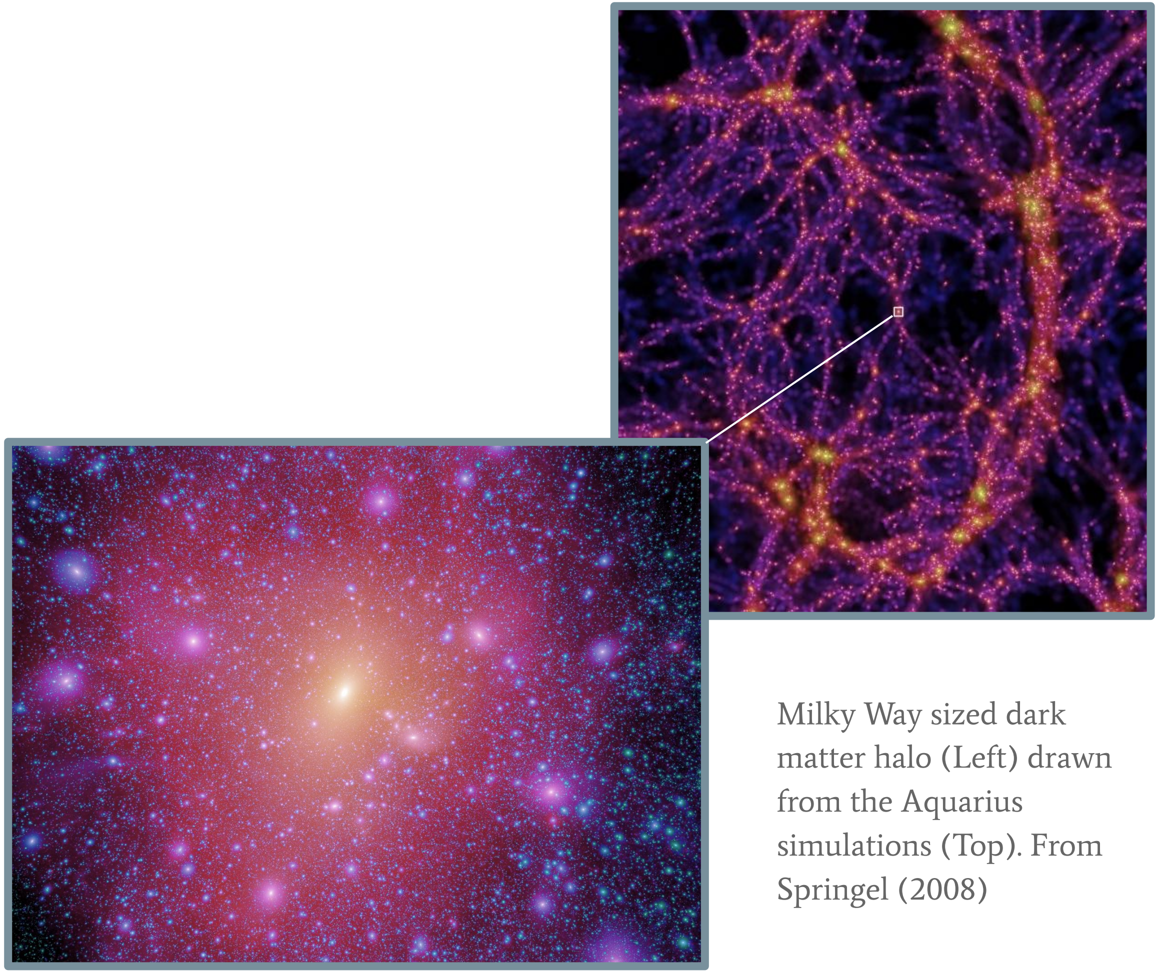
Road Map

- Introduction — Why does halo shape matter?
- Data — APOGEE & Gaia
- Models — Determining ellipticity from the data, and predictions from theory
- Results — Inferred halo shape
- Conclusions — What did we learn? What's next?

Dark Matter Halos

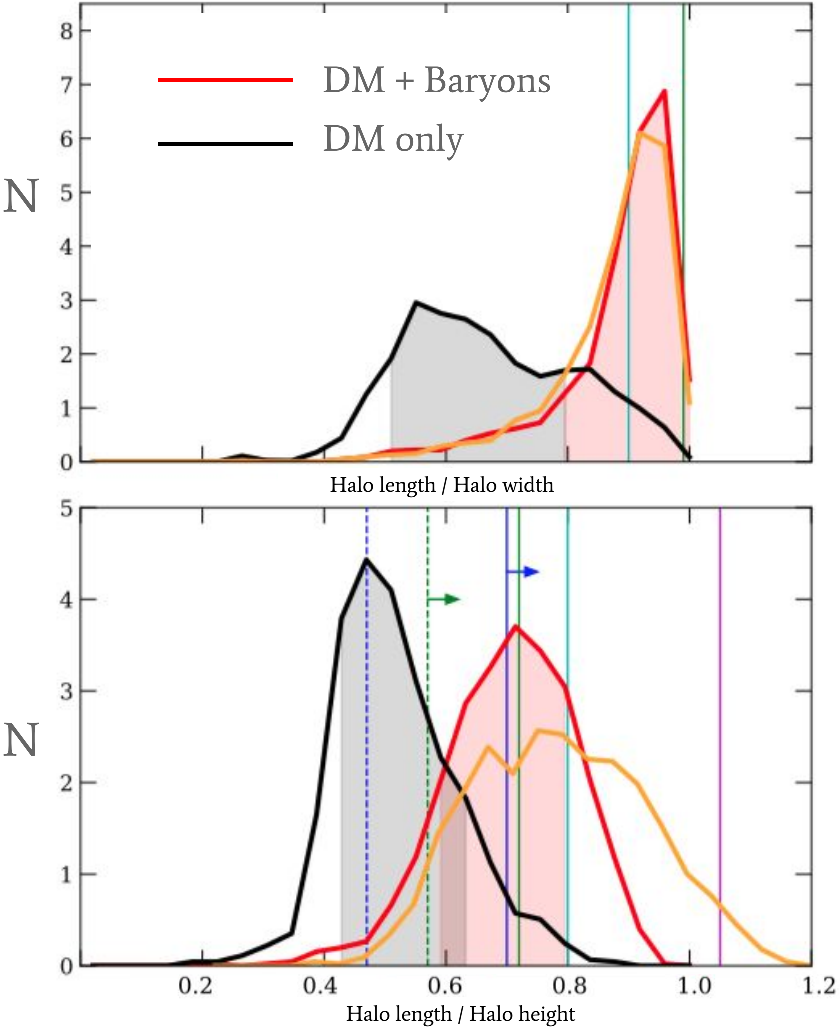
- Halos seed galaxy formation.
- Shapes often non-spherical.



Milky Way sized dark matter halo (Left) drawn from the Aquarius simulations (Top). From Springel (2008)

Why does halo shape matter?

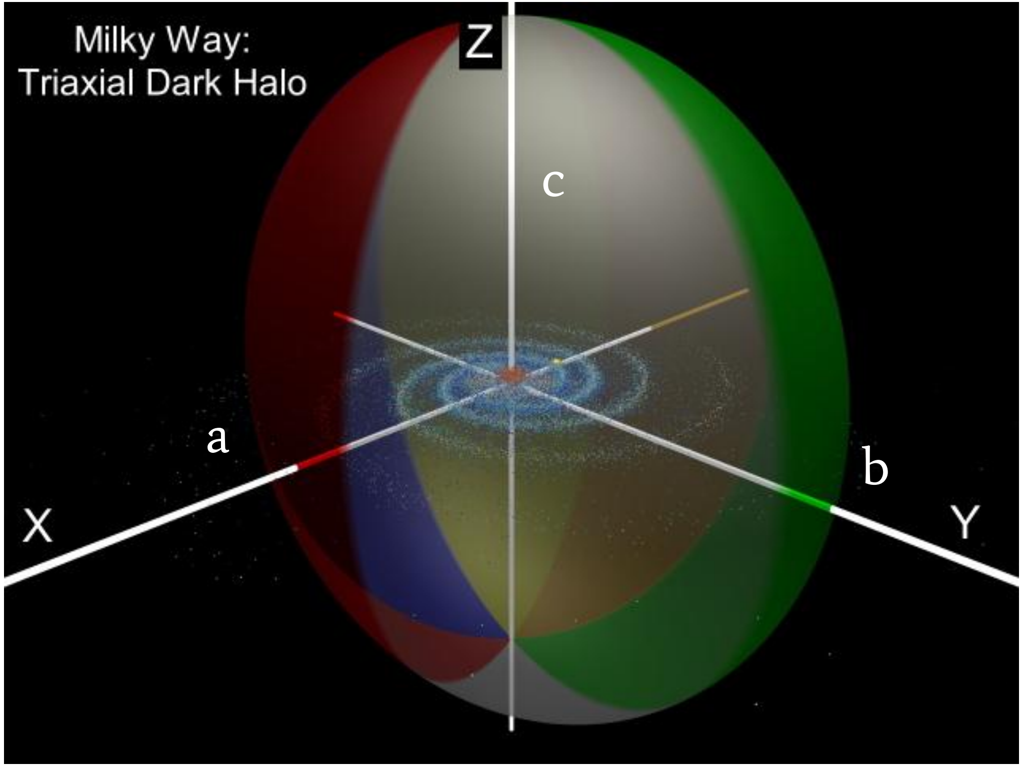
1. Calibrate simulations of galaxy formation.
2. Detailed modelling of Milky Way satellite orbits
3. Constrains nature of dark matter particle



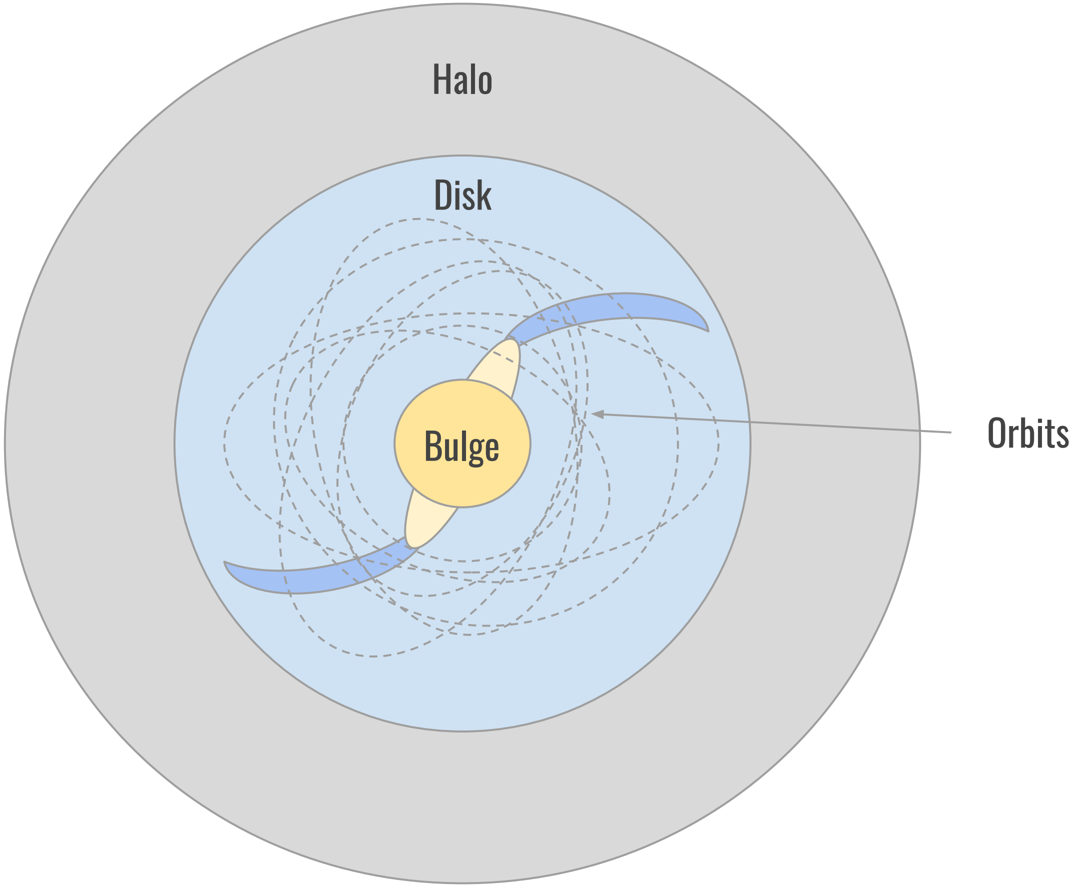
Right: Illustris halo flatness (top), and axis ratio in the plane of the galaxy (bottom). From Chua+ 2019

Terminology & halo geometry

- Refer to scale length of halo as ***a***
- Axis ratio in the plane of the disk: **b/a**
- Vertical axis ratio: **c/a**



What are we measuring? The *Gaia* connection



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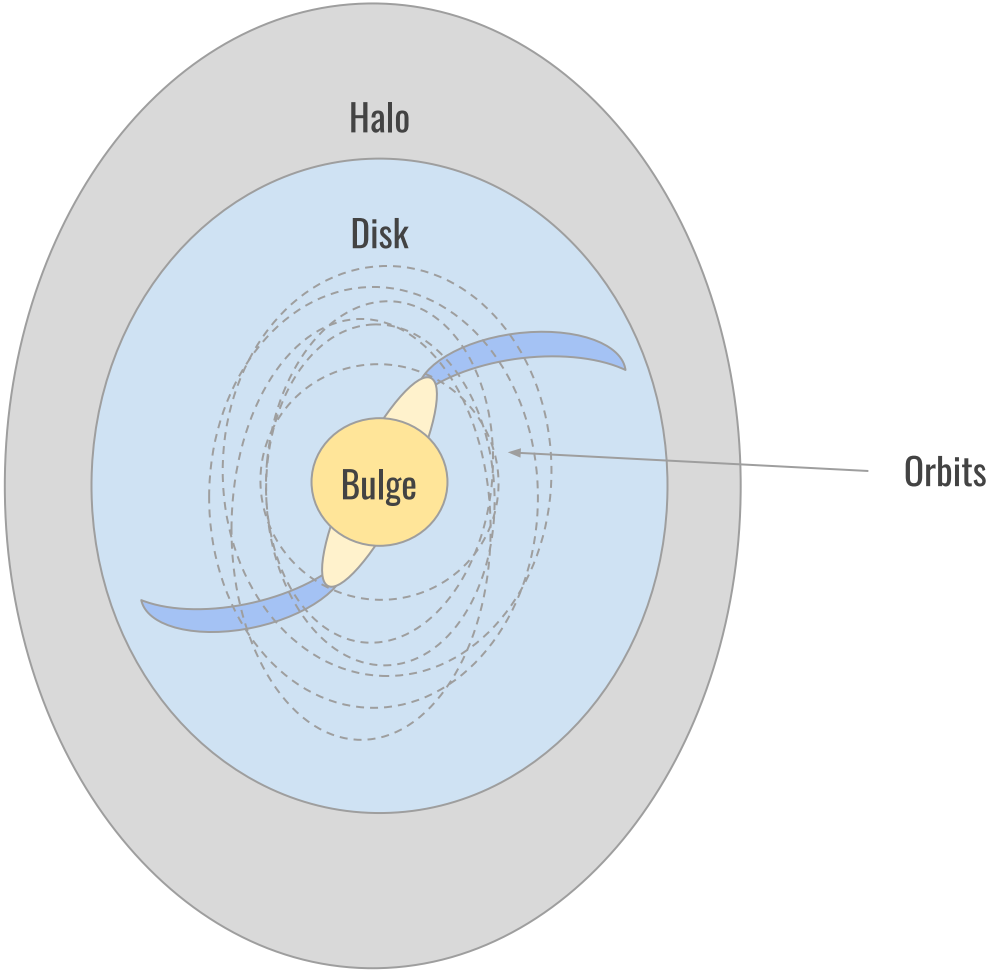
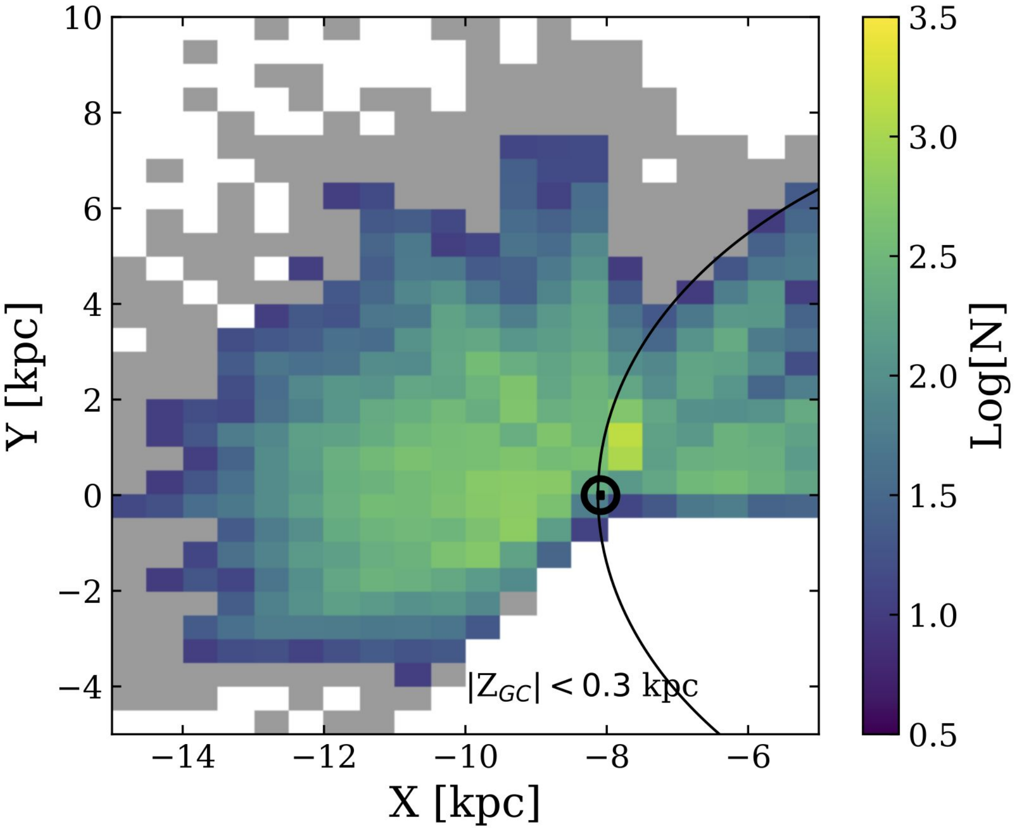


APOGEE + Gaia DR2 Synergies

- *Gaia* DR2: 5D phase space information
- APOGEE+AstroNN: radial velocity and improved distances. About 40,000 stars after selection



APOGEE + Synergies

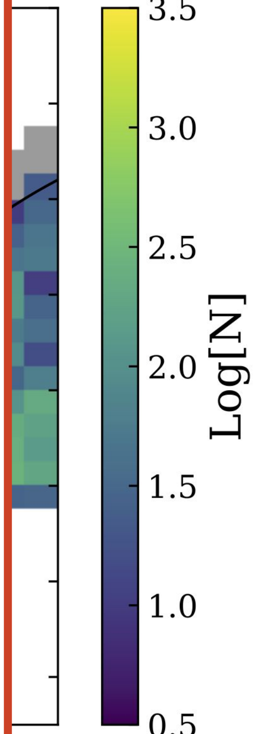
- *Gaia* DR space inf
- APOGEE radial ve improve About 4 selection

AstroNN:

Bayesian neural network abundances, stellar parameters, ages, distances (accurate to 10 kpc) for DR14 / DR16 (is an announced VAC)

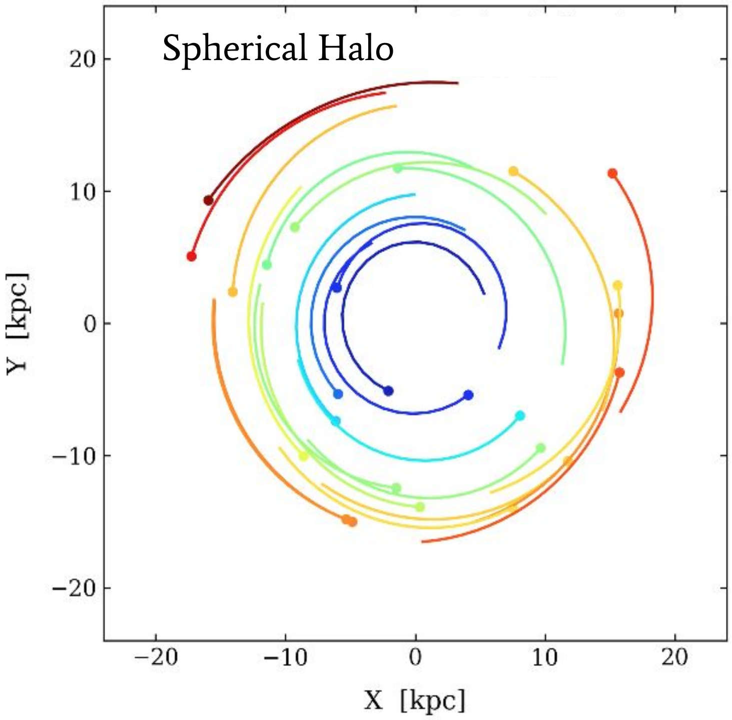
Leung & Bovy (2019a/b), Bovy+ (2019), Mackereth+ (2019)

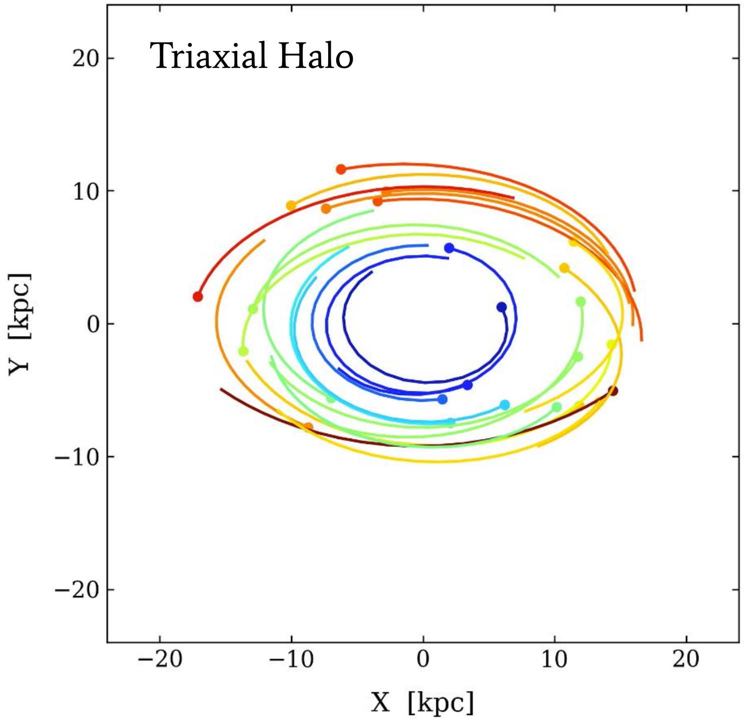
github: henrysky/astroNN



Building a Model

Disk orbits in a spherical and triaxial halo

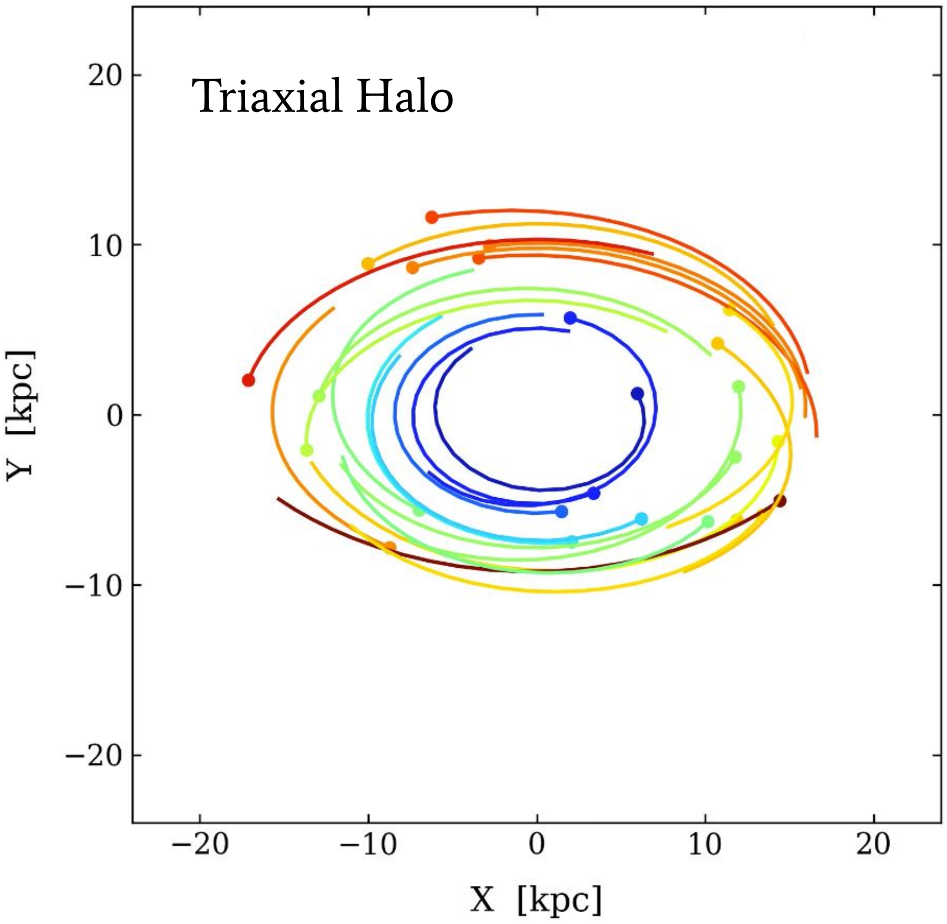




Building a Model

Simple assumptions about triaxial halo:

- Velocity field in disk is m=2 sinusoid
- Phase of velocity field constant with radius
- Amplitude constant at each radius, and changes smoothly with radius



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Tangential velocity

Circular velocity

m=2 sinusoid

$$v_T(R,\phi) = v_{T,0}(R) + A_T(R)\cos\left[2(\phi - \phi_b)\right]$$

$$v_R(R,\phi) = v_{R,0}(R) + A_R(R)\sin\left[2(\phi - \phi_b)\right]$$

Radial velocity

Fluctuation amplitude with radius

Phase of perturbation

Building a Model

Simple assum
triaxial halo:

- Velocity
  m=2 sinu
- Phase of
  constant with radius
- Amplitude constant at each radius, and changes smoothly with radius

Model is linear, can be solved analytically for maximum likelihood *A* and v_0 using Bayes theorem with simple Gaussian likelihood and prior.

Tangential velocity

Circular

m=2 sinusoid

$$\ldots s\left[2(\phi-\phi_b)\right]$$

$$\ldots n\left[2(\phi-\phi_b)\right]$$

Radial velocity

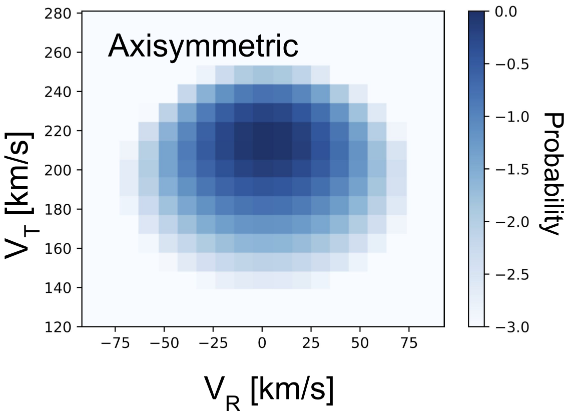
Fluctuation amplitude with radius

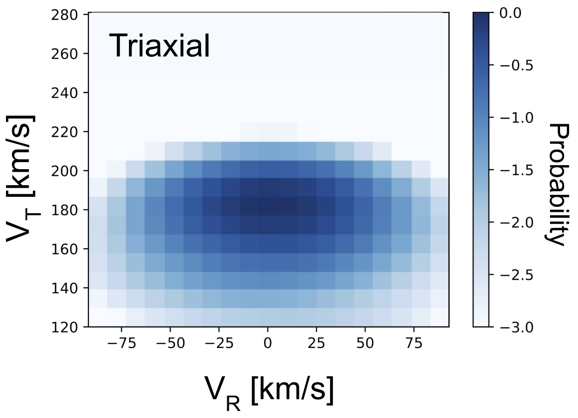
Phase of perturbation

Predicting Triaxial Halo Properties

- Want to know, given b/a and ϕ_b what amplitudes would we see (What are the *A*(R))?
- Allows us to infer halo shape from *Gaia* data

Predicting Triaxial Halo Properties



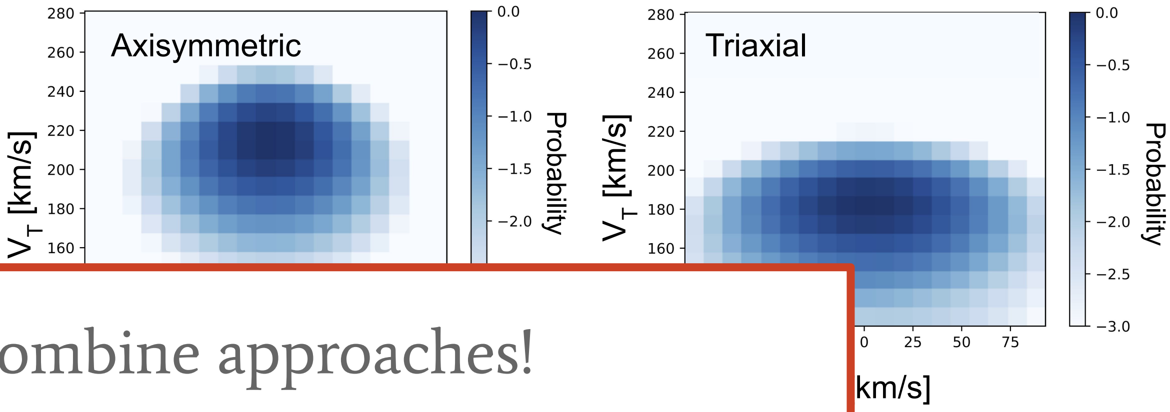


- Want to know, given b/a and ϕ_b what amplitudes would we see (What are the *A*(R))?
- Allows us to infer halo shape from *Gaia* data

Two methods:

- Distribution function mapping
  - Numerical, correct, (relatively) computationally expensive. (Dehnen 2000)
- The elliptical disk potential.
  - Analytic, approximate, computationally inexpensive. (Kuijken & Tremaine 1994)

Predicting Triaxial Halo Prop



Solution: Combine approaches!

Calibrate the <u>fast</u> potential model using the <u>accurate</u> distribution function method

- Want to k
  and ϕ_b wh
  would we see
  the A(R))?
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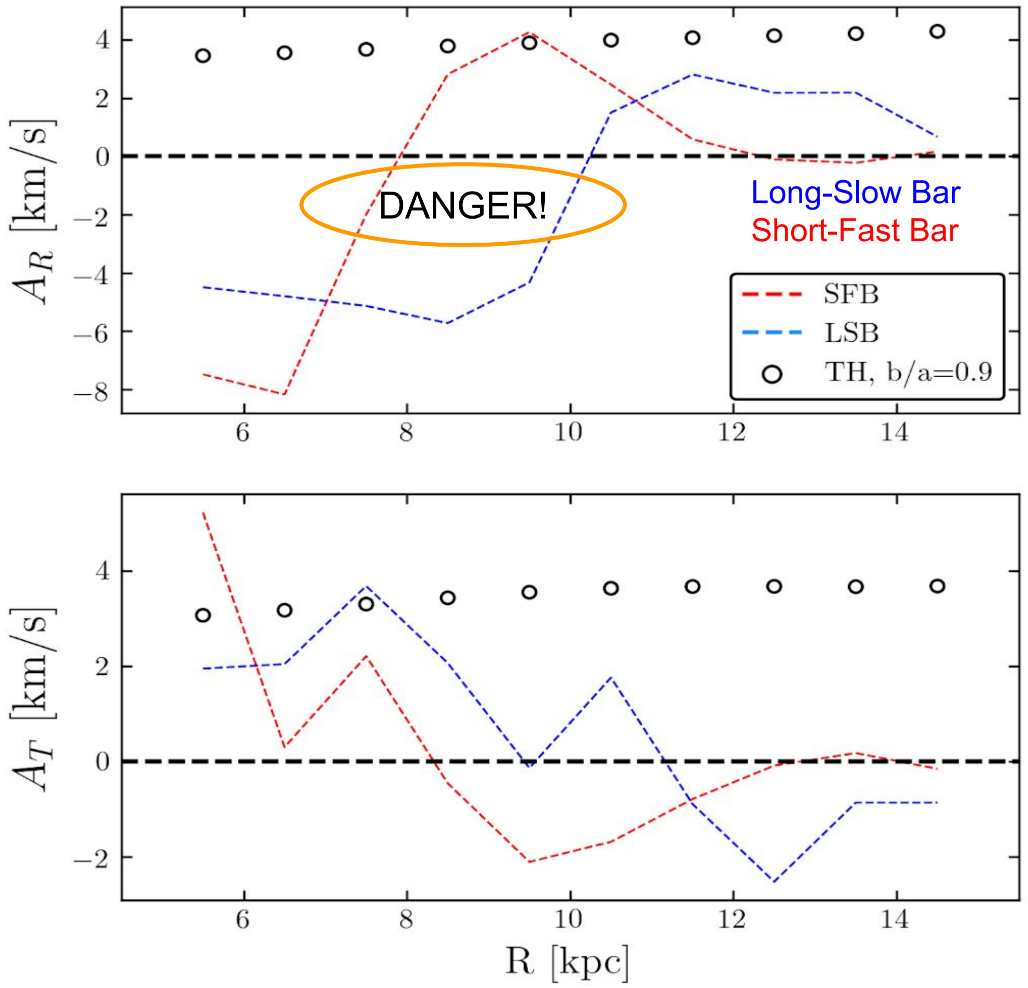
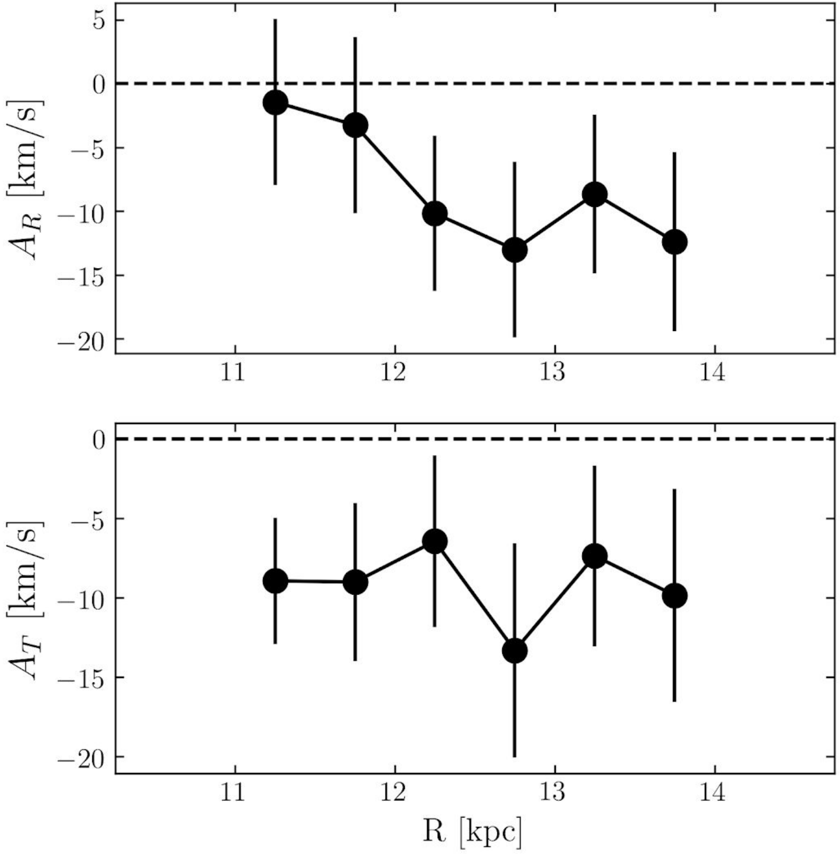
The Bar & Spiral Arms?

- Non-axisymmetric structures induce competing fluctuations
- Resonances make disentangling potentials difficult
- Safe to work outside of ~10 kpc



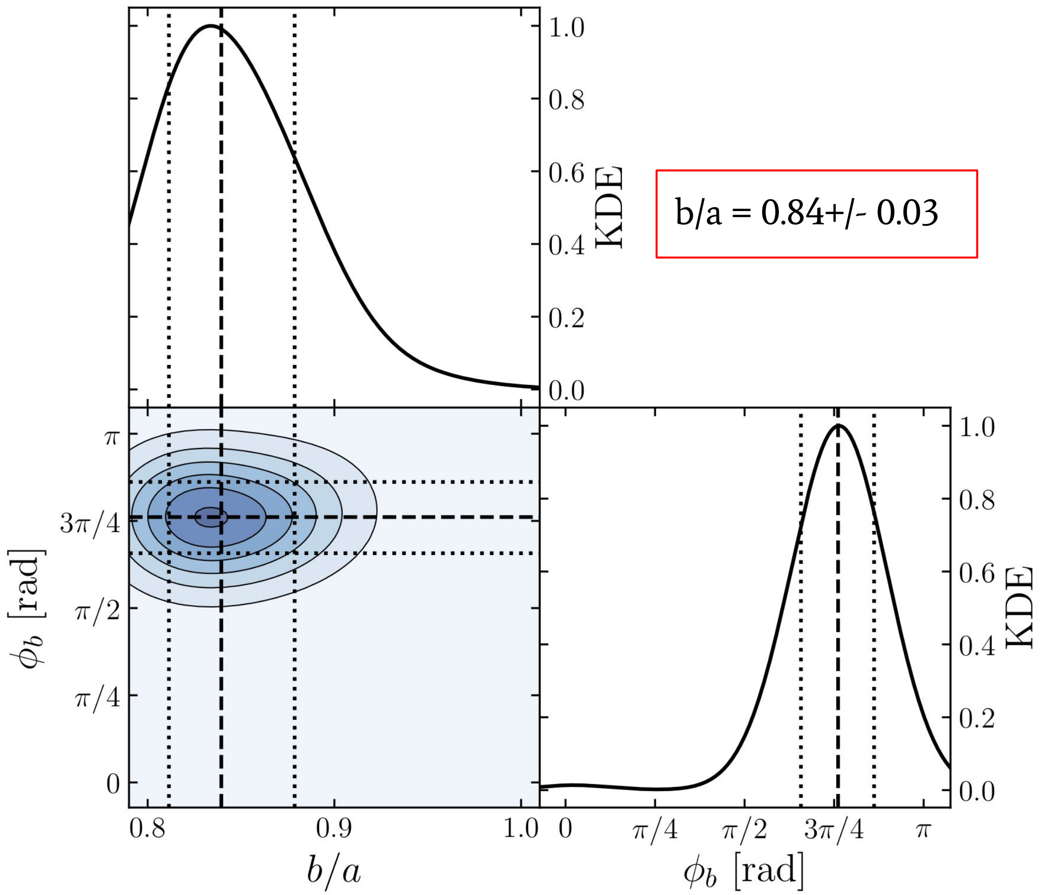
Linear Model m=2 Amplitudes In Outer Disk



Inferring halo parameters

We use an ABC method to infer PDF of *b*/*a* and ϕ_b

1. Randomly pick halo parameters & determine velocity field
2. Add bar model velocities
3. Mock up field to look like *Gaia* data
4. Calculate linear model amplitudes
5. Looks like APOGEE-*Gaia* data? Accept halo parameters in PDF



b/a = 0.84+/- 0.03

Summary

- We model observed velocity fields & theoretical fields from triaxial halos + bars
- We have demonstrated that the MW halo has b/a ~ 0.9 or less
- Still need to examine more non-axisymmetric potentials and Milky Way-like potentials to confirm results.

Thanks for listening!

Data in Outer Disk