ASTR 511

Galactic Astronomy

Lecture 11

Gravitational Potentials

Prof. James Davenport (UW)

Winter 2023

Notes about scheduling

- Reminder: March 2 class is now **Friday March 3 at 10 AM**
  - Prospective grads!
- HW 3 nominally due tomorrow
- Final Project, Part 1 due tomorrow
  - Talks: March 7 and 9 (7-10min, you pick the style)
  - Term Paper due March 14
- Planning to release HW 4 (final assignment) tomorrow!

Gravitational Potential

- $\Phi(r) = -\dfrac{GM}{r}$ (grav. potential energy radially from a point mass)
- MWY is *not* a point mass, so Φ depends on *enclosed* mass
    - Recall: Sag A* and nuclear cluster are not very massive, compared to disk(s), halo, etc
- Orbits in the galaxy constrained by the “shape” of the potential
- **Measure mass (enclosed) of each galactic component, “map” the potential**
- **Enclosed mass can be traced by velocities!**

Gravitational Potential

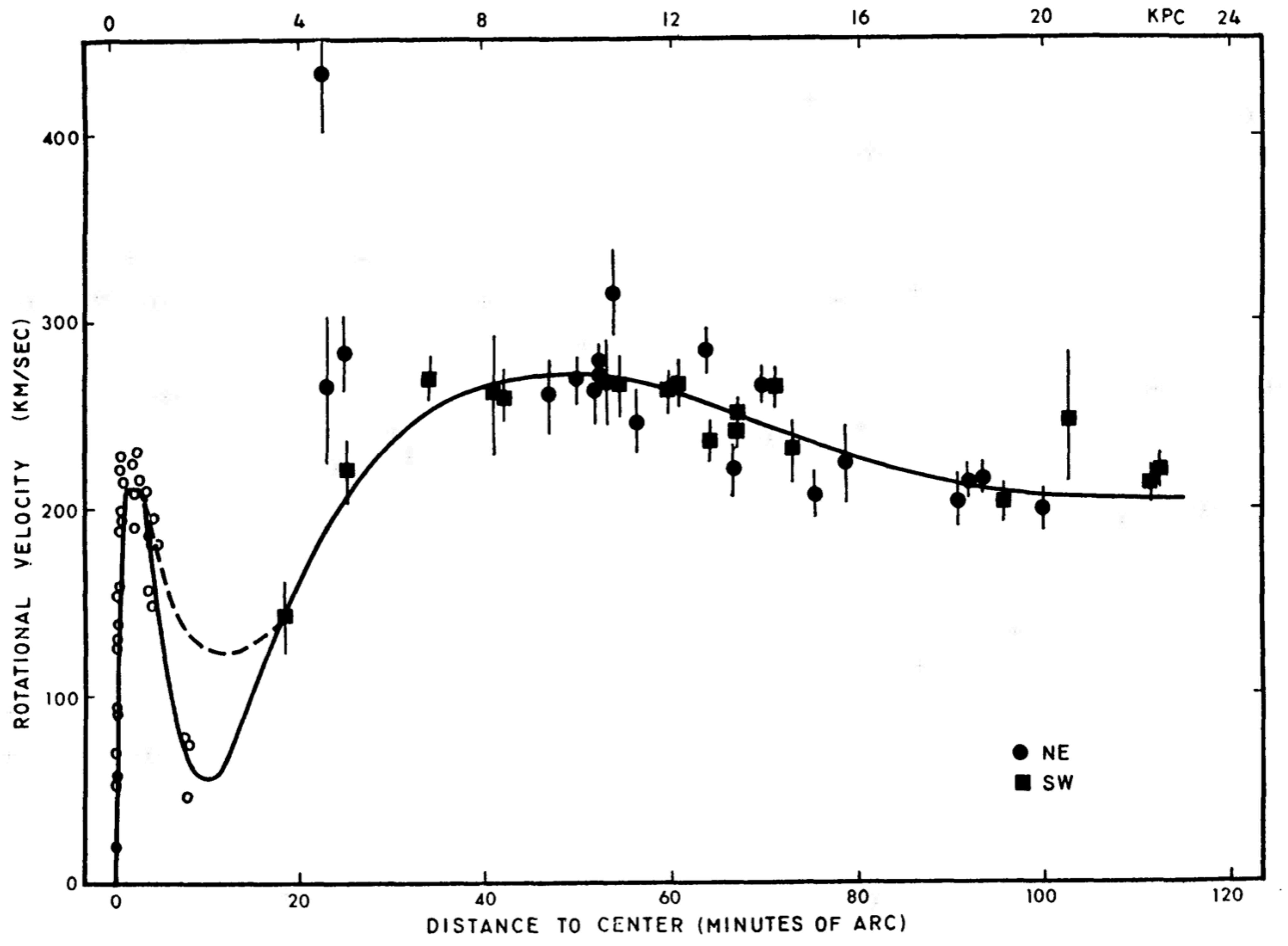
- So need to trace…
  - SMBH, bulge, bar
  - Thick disk
  - Thin disk
  - ISM (gas and dust)
  - Halo (stars)
  - Halo (Dark Matter)

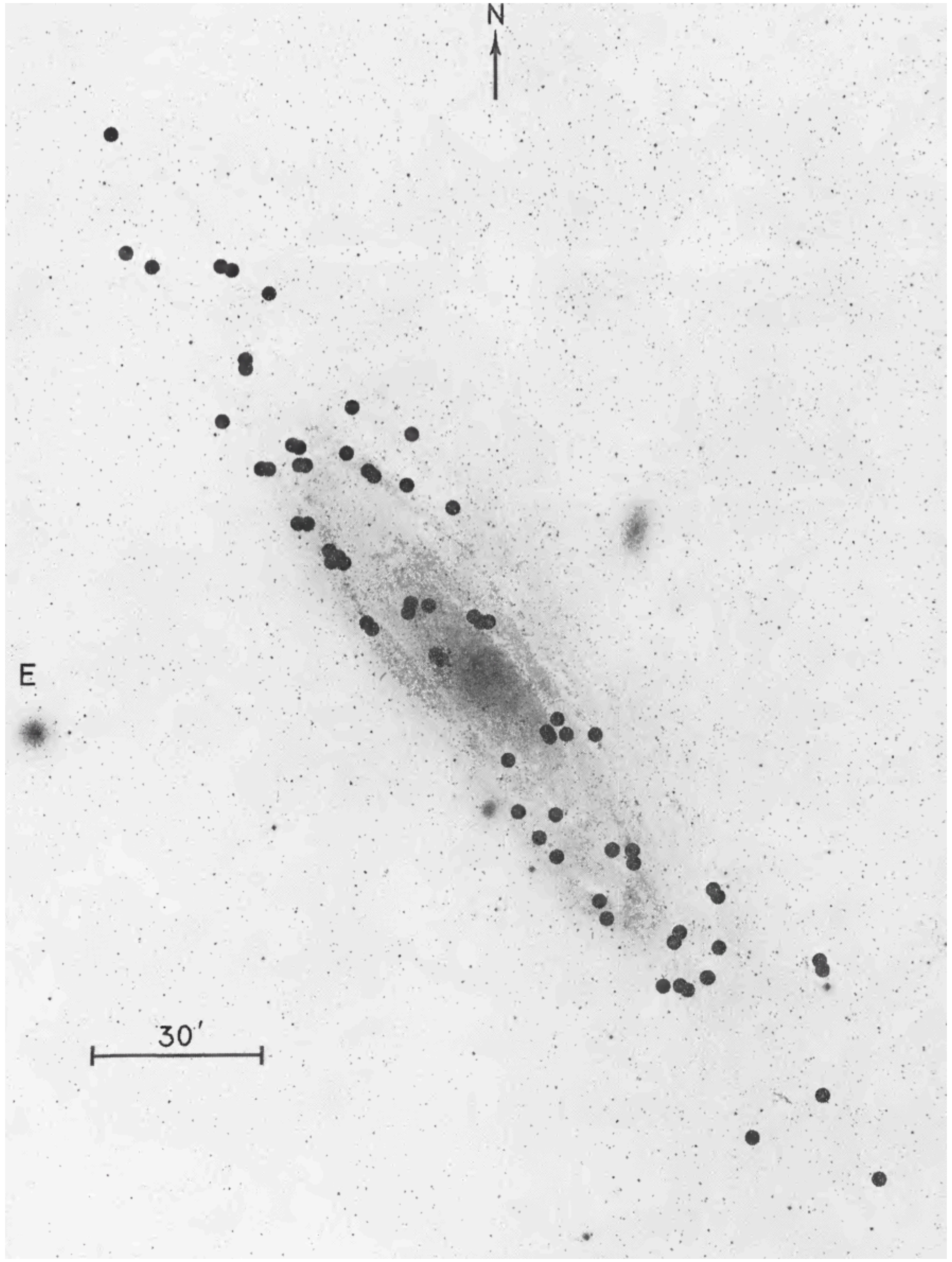
- and probably good to consider
  - Arms, density variations
  - Warps
  - Mergers/satellites

- AND worry about inconsistent tracers (i.e. what if gas impacted by heating, other physics, not just $\Phi(r)$?)

Dark Matter

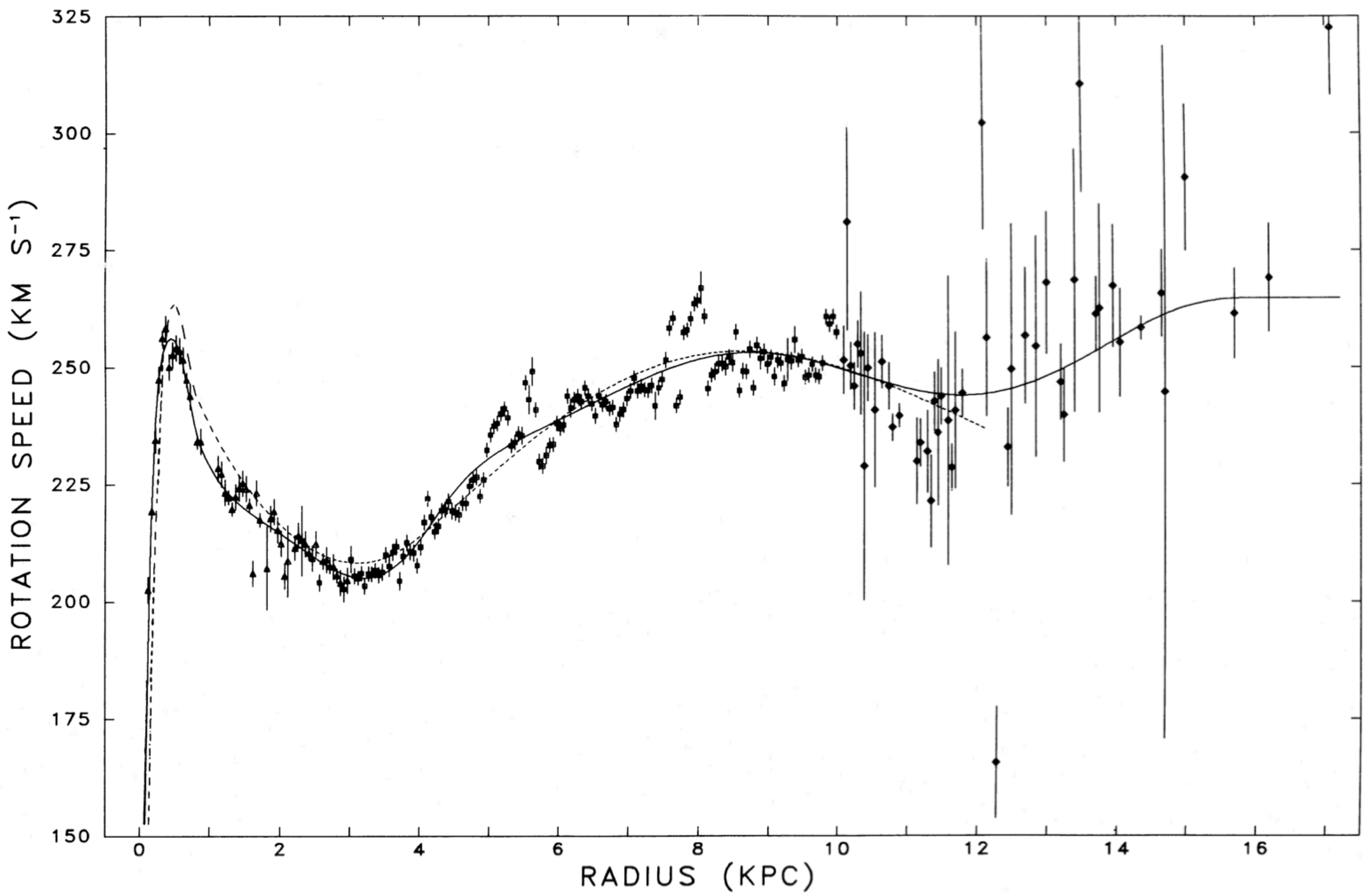
- Rubin & Ford (1970) a canonical paper on the Andromeda “Nebula” (M31)





Milky Way Rotation Curve

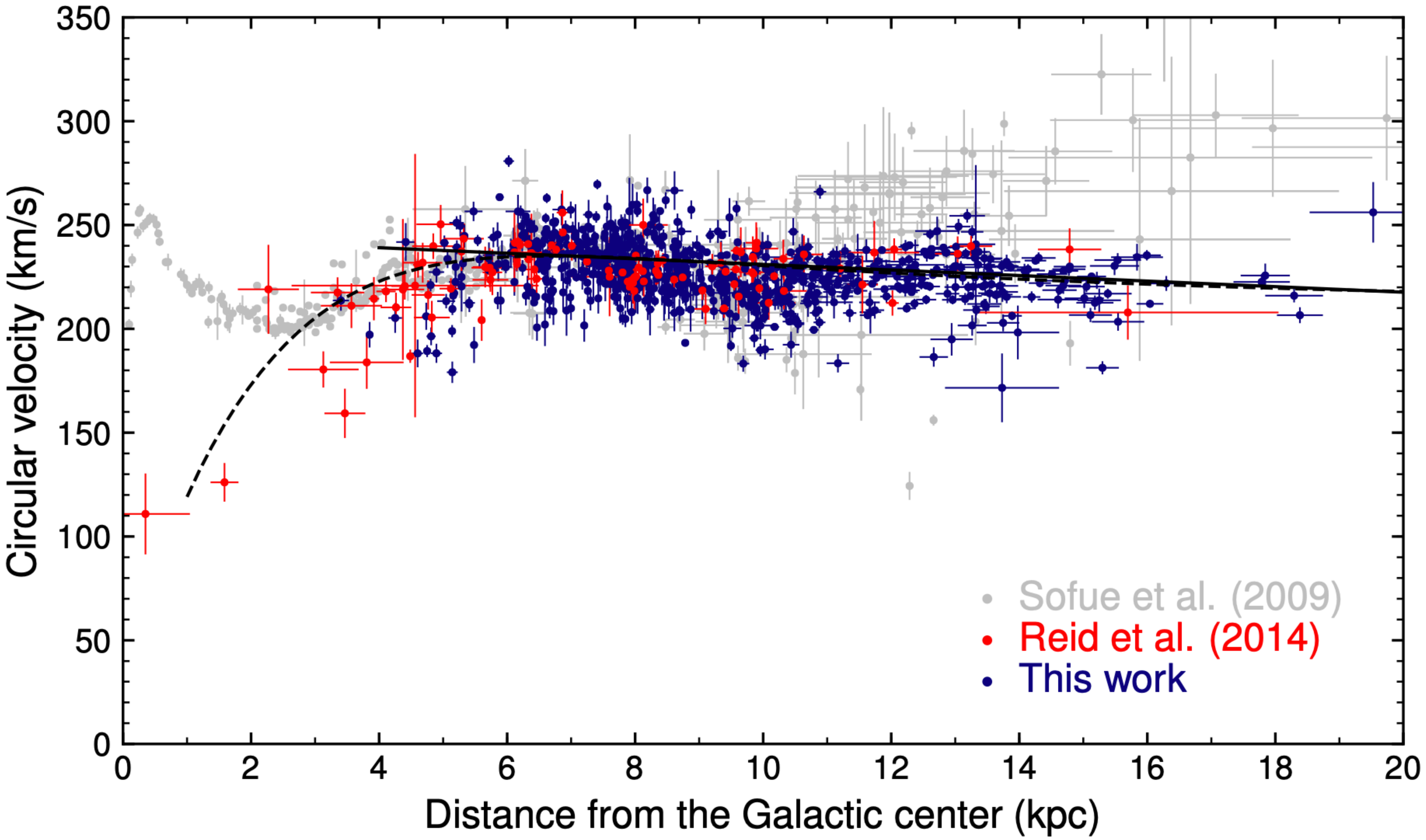
- Gas a useful/classic tracer
  - H I in the nuclear region
  - CO in the middle (near us)
  - H II in the outer regions



Clemens (1985)

Milky Way Rotation Curve

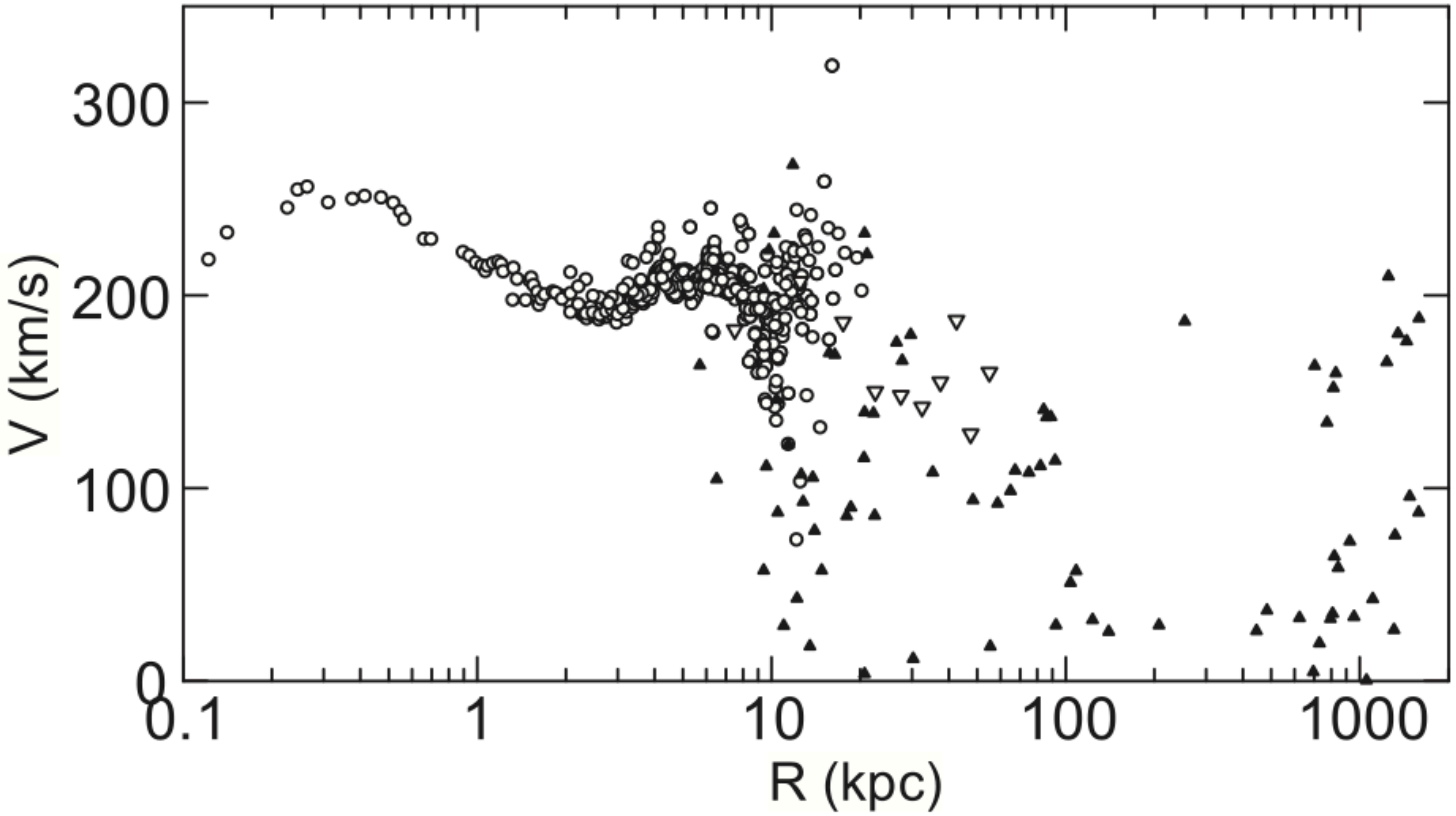
- Cepheids maybe better for outer disk?
- It's *really* flat… this means DM contribution must contribute a lot in outer disk
- It can't stay flat forever… right?!



Mroz+2018

The *Grand* Milky Way Rotation Curve

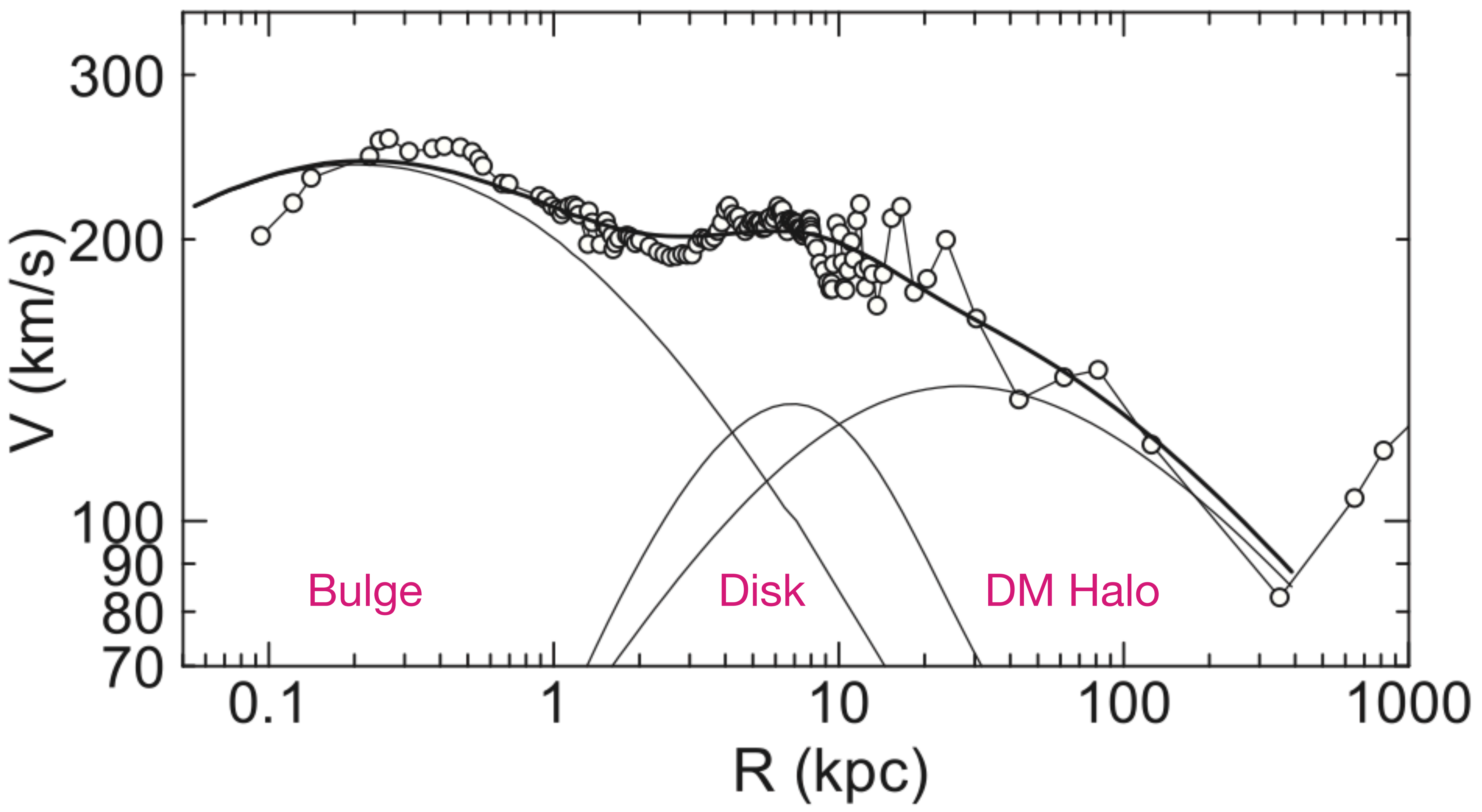
- Combining lots of tracers
- Need long lever arm to really measure the mass distribution contained in the Dark Matter Halo!
- Out to ~1 Mpc (!)
  - Note: M31 is < 1 Mpc…



Sofue (2012)

The *Grand* Milky Way Rotation Curve

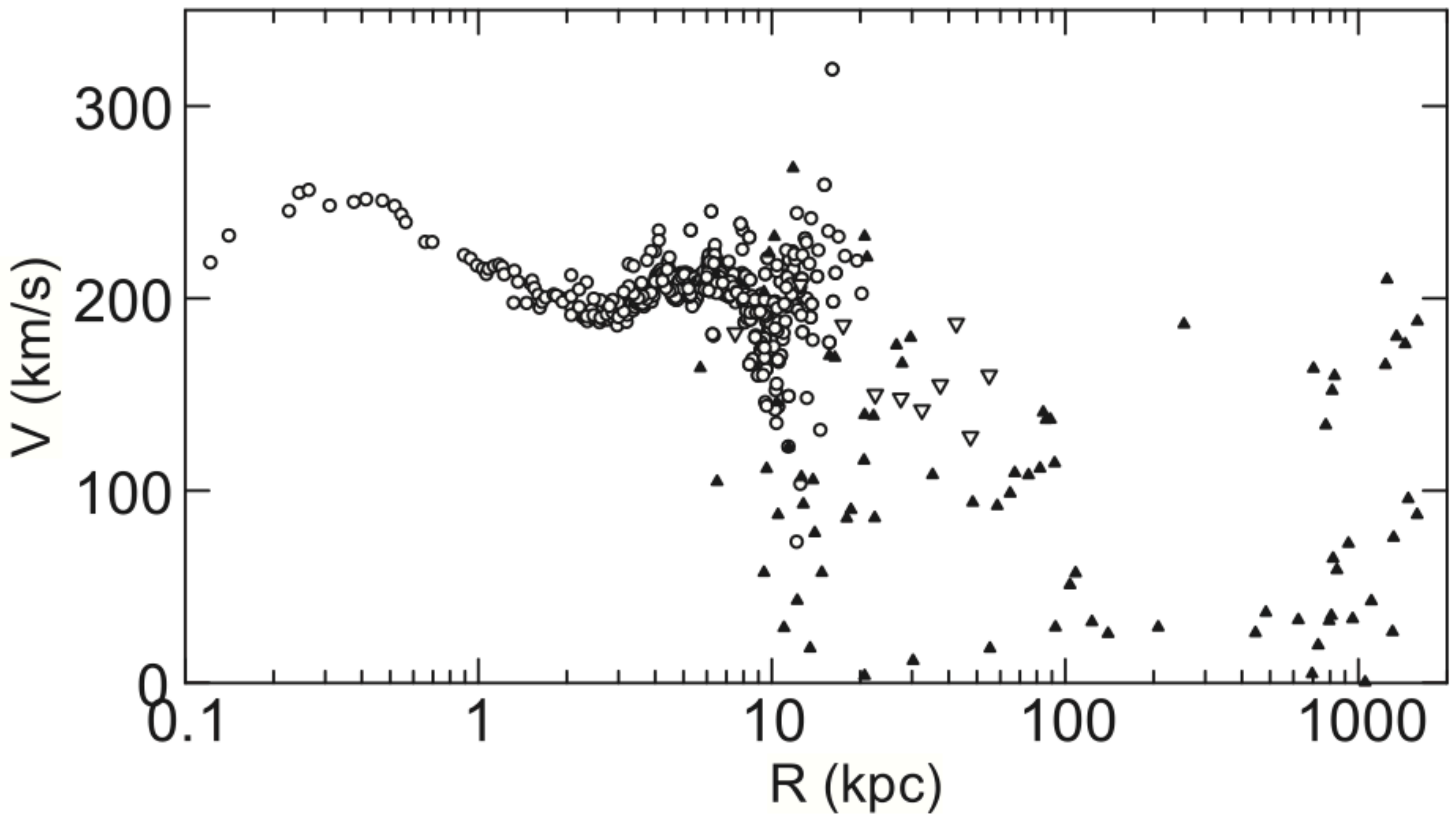
- Combining lots of tracers
- Need long lever arm to really measure the mass distribution contained in the Dark Matter Halo!
- Out to ~1 Mpc (!)
    - Note: M31 is < 1 Mpc…



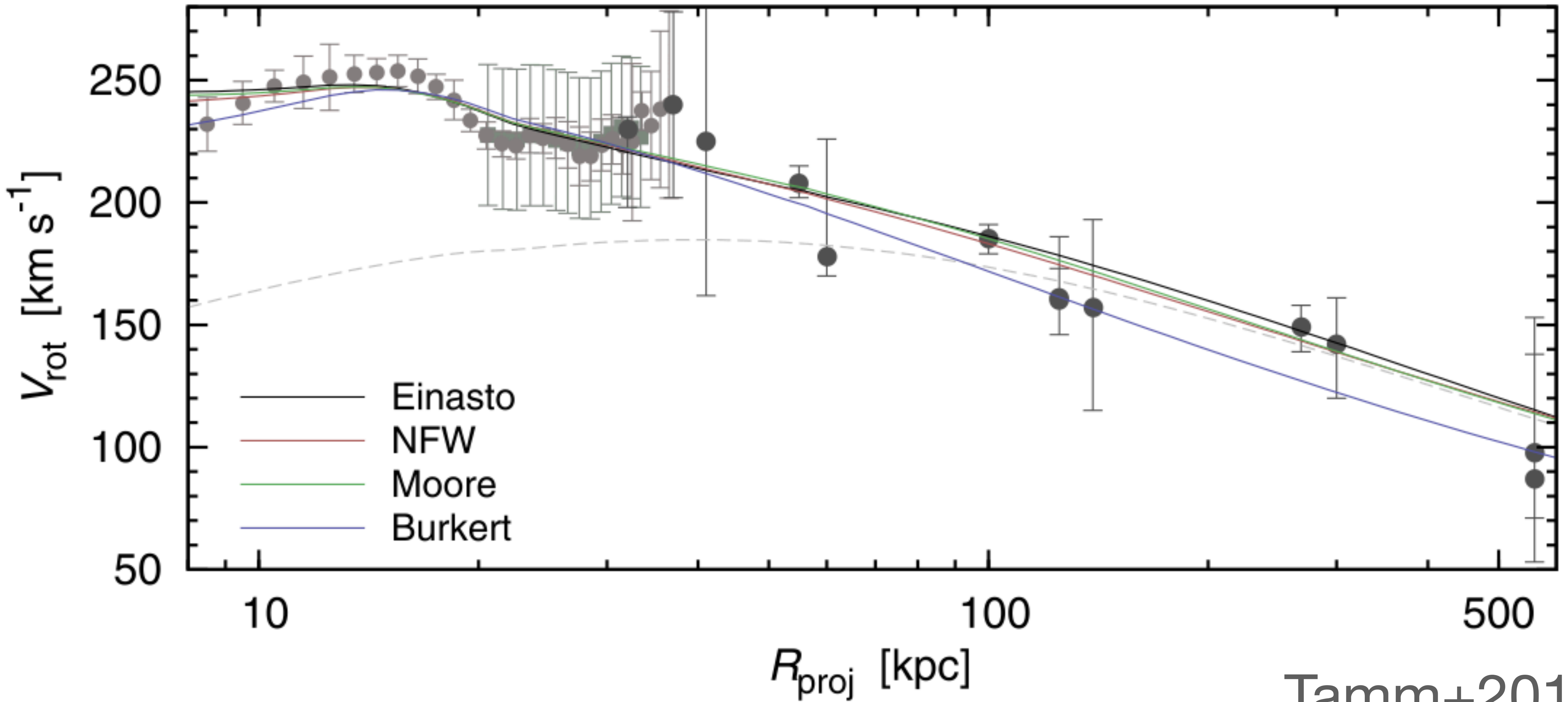
Sofue (2012)

An Aside: The view from 1000 kpc

- Distance is ~725kpc to center of Andromeda
- Milky Way & Andromeda are probably *already* touching!
  - Esp. their DM halos (see rotation curves below)
- Some indication their CGM is already interacting! Lehner+2020



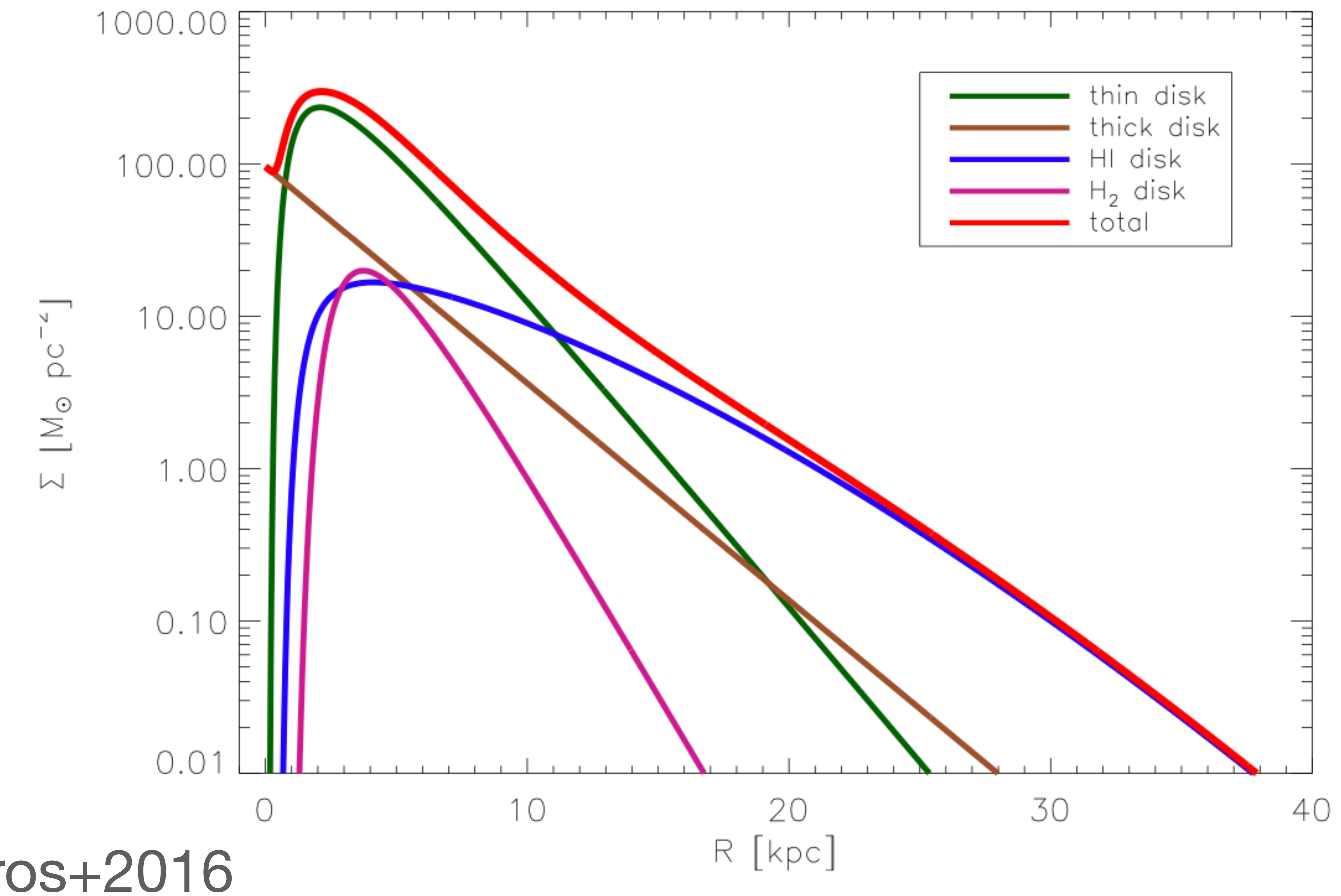
Sofue (2012)

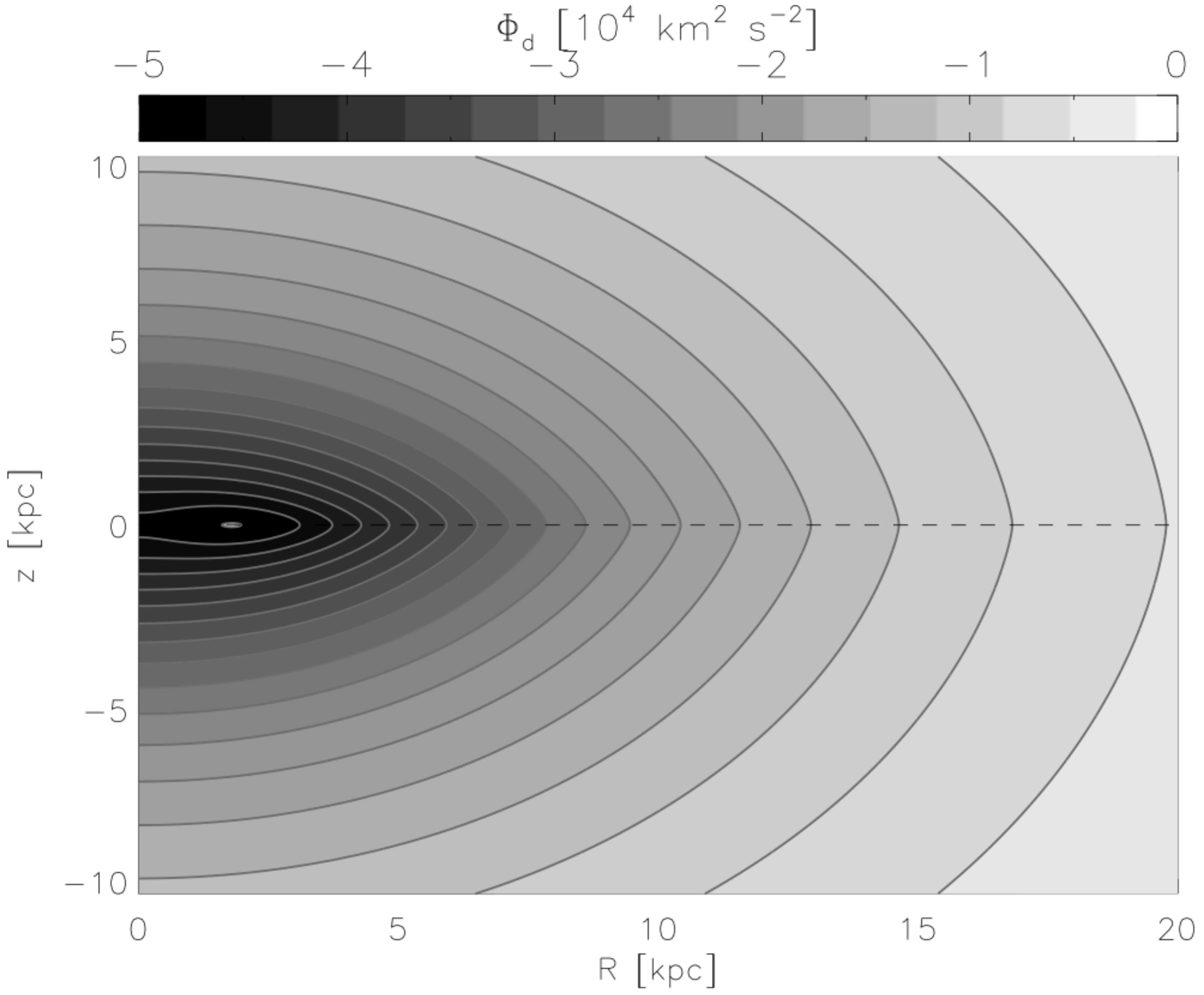


Tamm+2012

Gravitational Potential of the MWY Disk

- Good, classical models for axisymmetric disk potentials exist (e.g. the Miyamoto-Nagai potential)
- Fit the traced mass distribution of stars and gas pretty well!

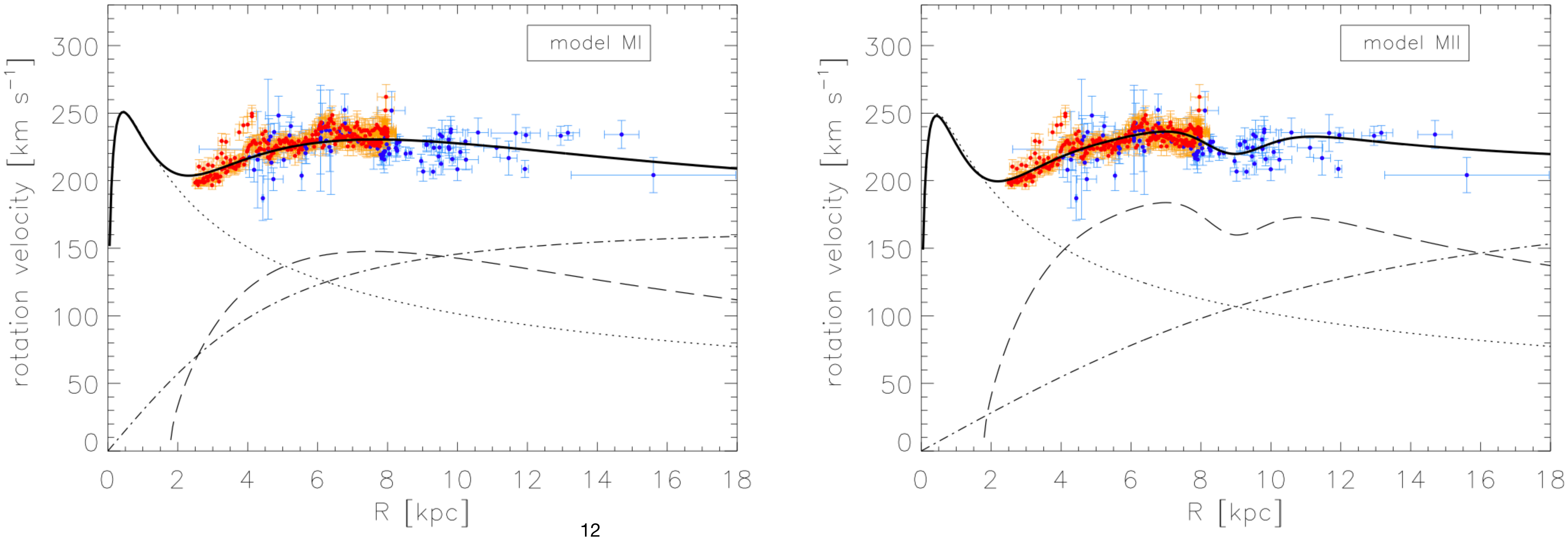




Barros+2016

Gravitational Potential of the MWY Disk

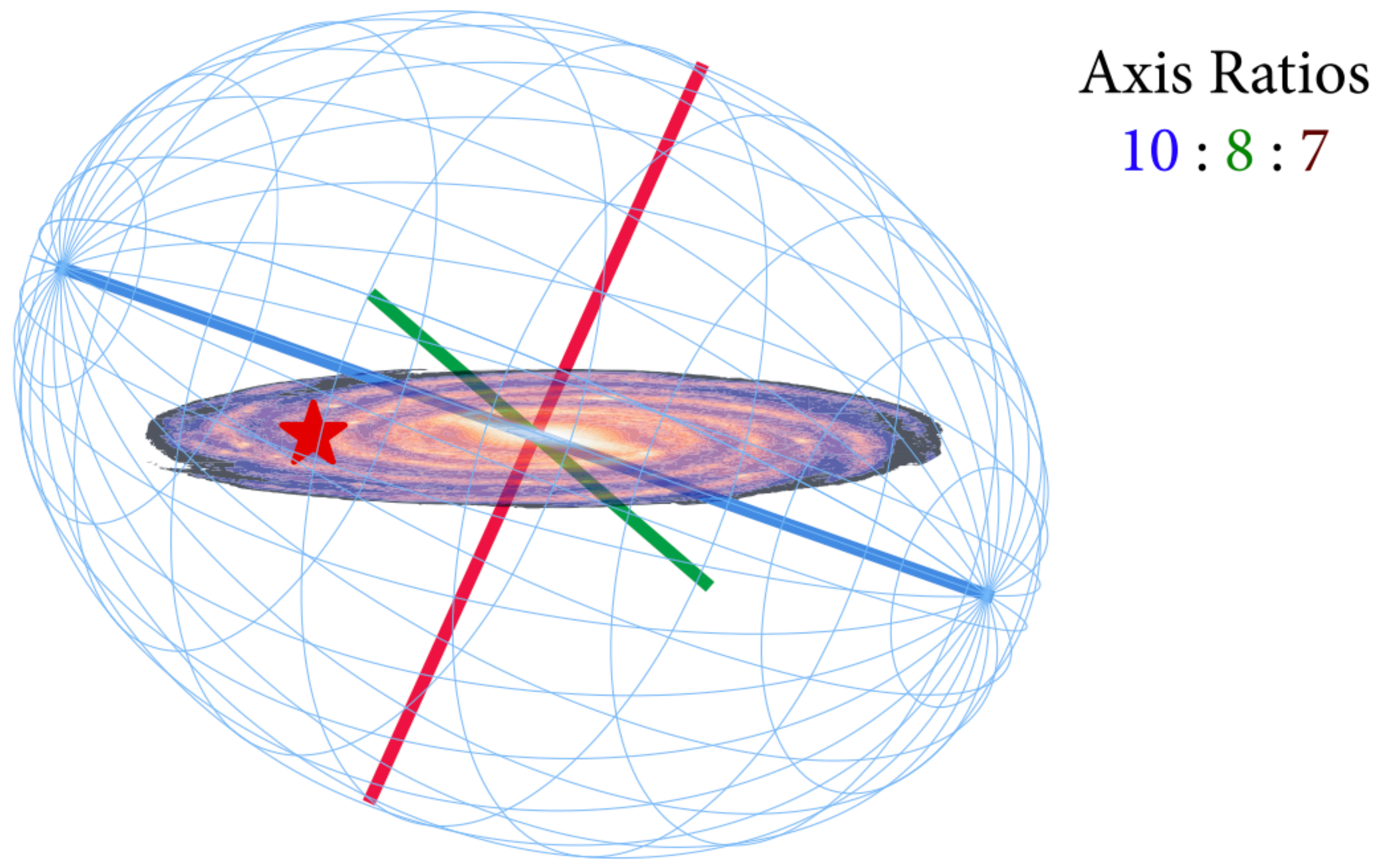
- Could the disk have a ring? (M31 has a star forming ring)
- *Could* explain “ripple” in rotation velocity at 8-10kpc
- But also… arms? Local substructure? Need sample outside solar cylinder!
- Haven’t yet seen Gaia DR3 evidence for this

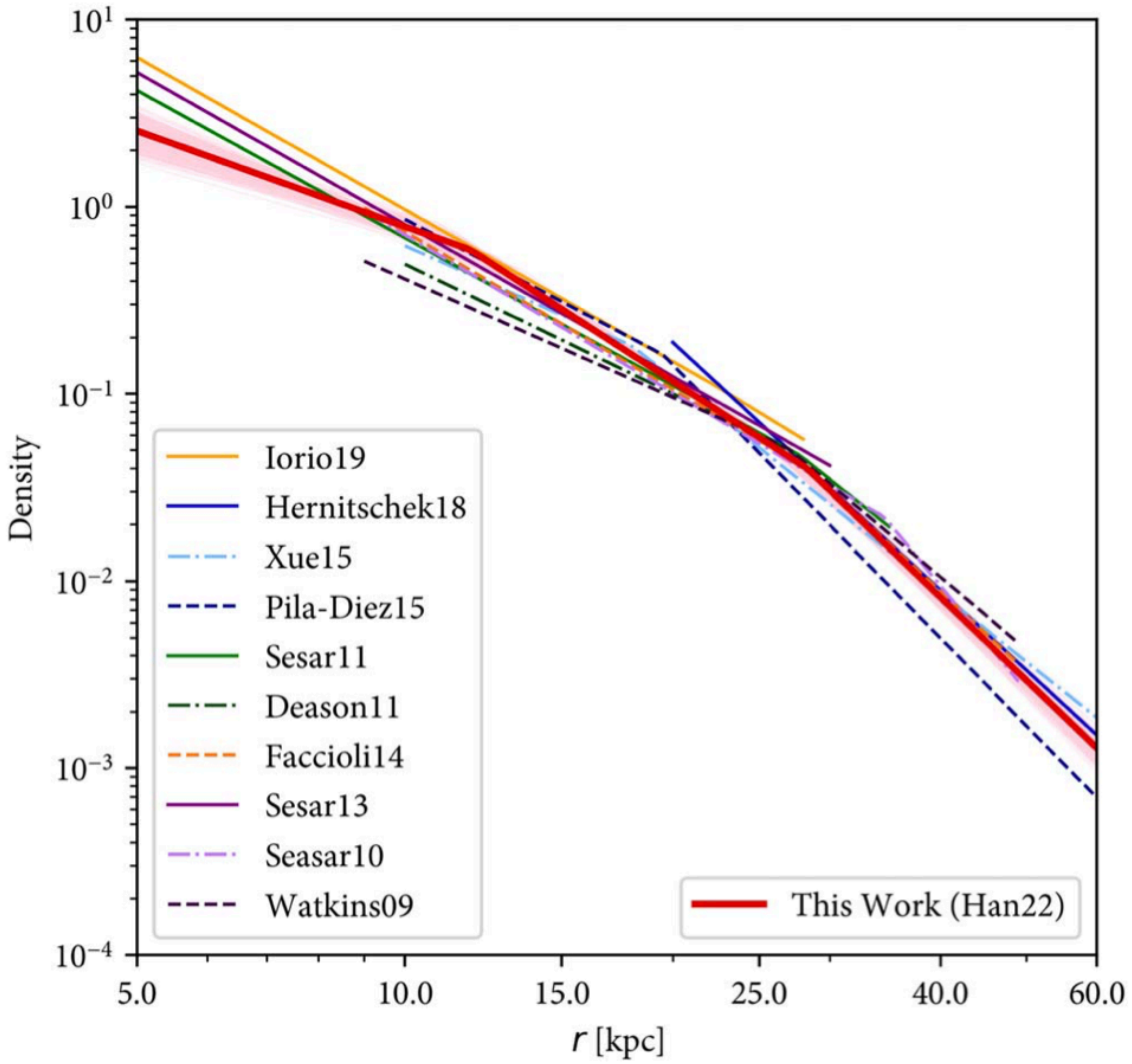


Barros+2016

Stellar Halo

- Stellar halo is likely tilted and “broken” probably largely due to Gaia-Enceladus Sausage
- Does the DM “feel” that?
- Did the Sausage merger bring Dark Matter (and if so, how has it relaxed into our DM Halo? Theorists, help!)





Han+2022

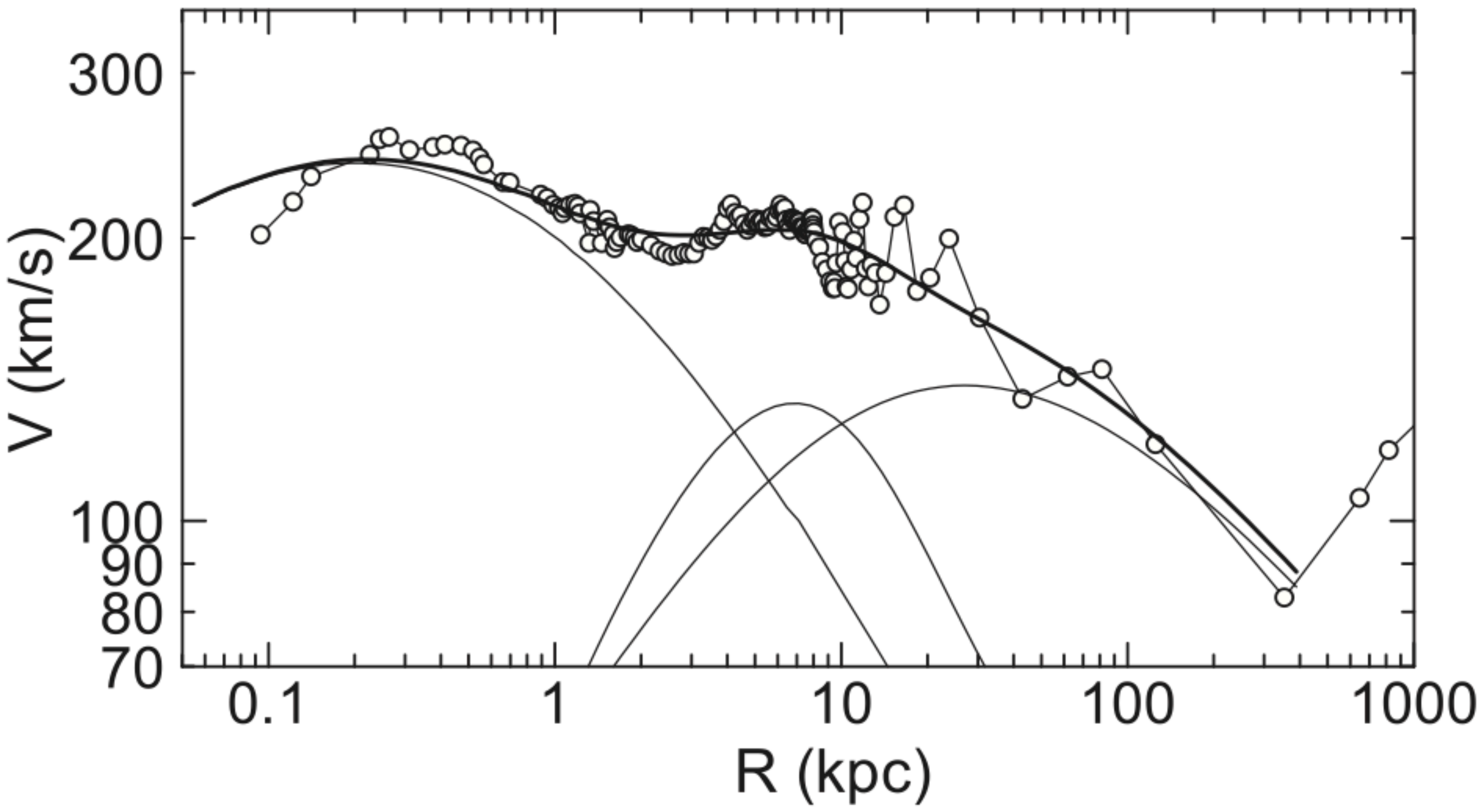
Dark Matter Halo

- The now classic cold dark matter potential model: Navarro, Frenk, and White (1997)
    - *but also laid out in NFW (1996)*
- **Known as an "NFW" profile**
- It's not the *only* good DM halo profile, but seems to trace mass distributions for galaxies in wide range of sizes, even galaxy clusters!
- $$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

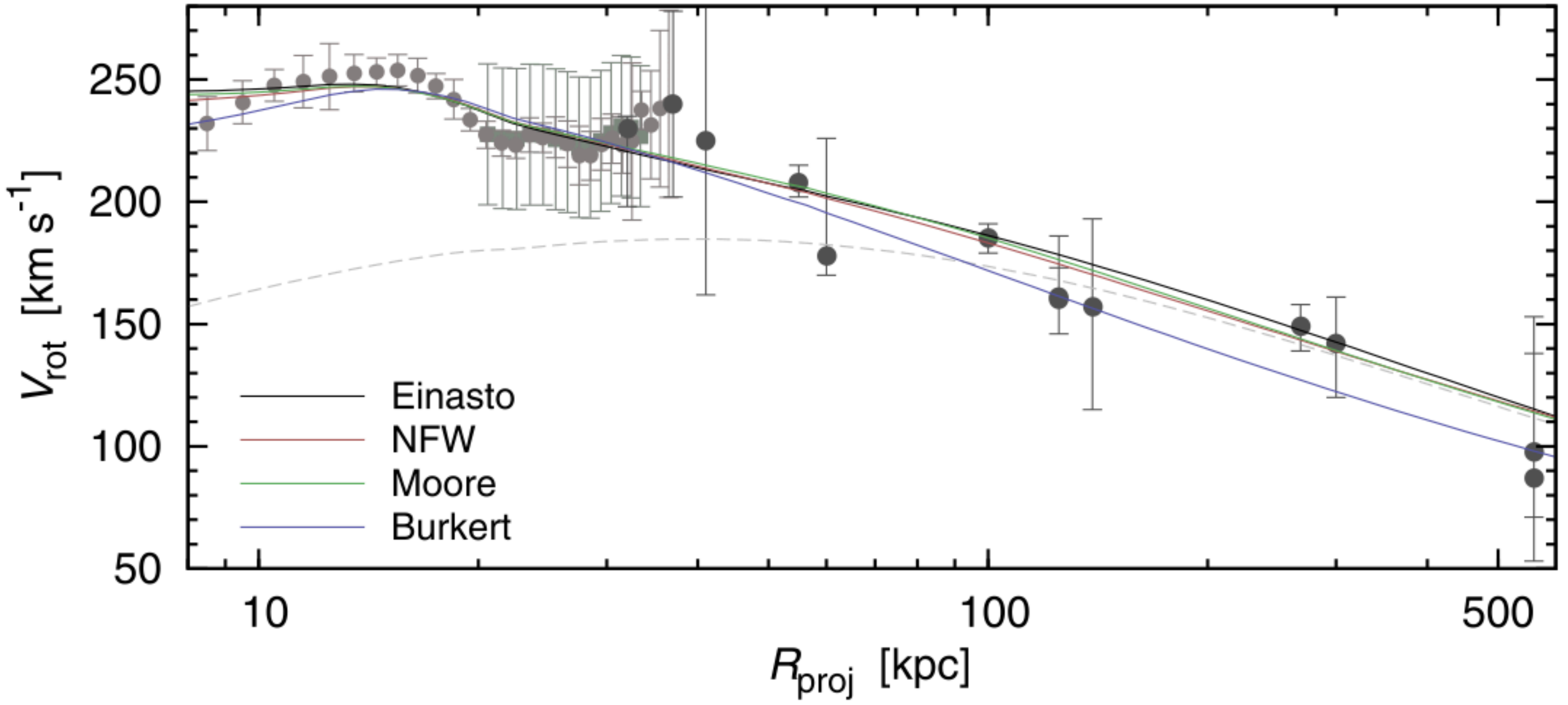
$$\Phi(r) = -\frac{4\pi G \rho_0 R_s^3}{r} \ln\left(1 + \frac{r}{R_s}\right)$$

Dark Matter Halo

- NFW profile works for both MWY and Andromeda out to extreme radii



Sofue (2012)



Tamm+2012

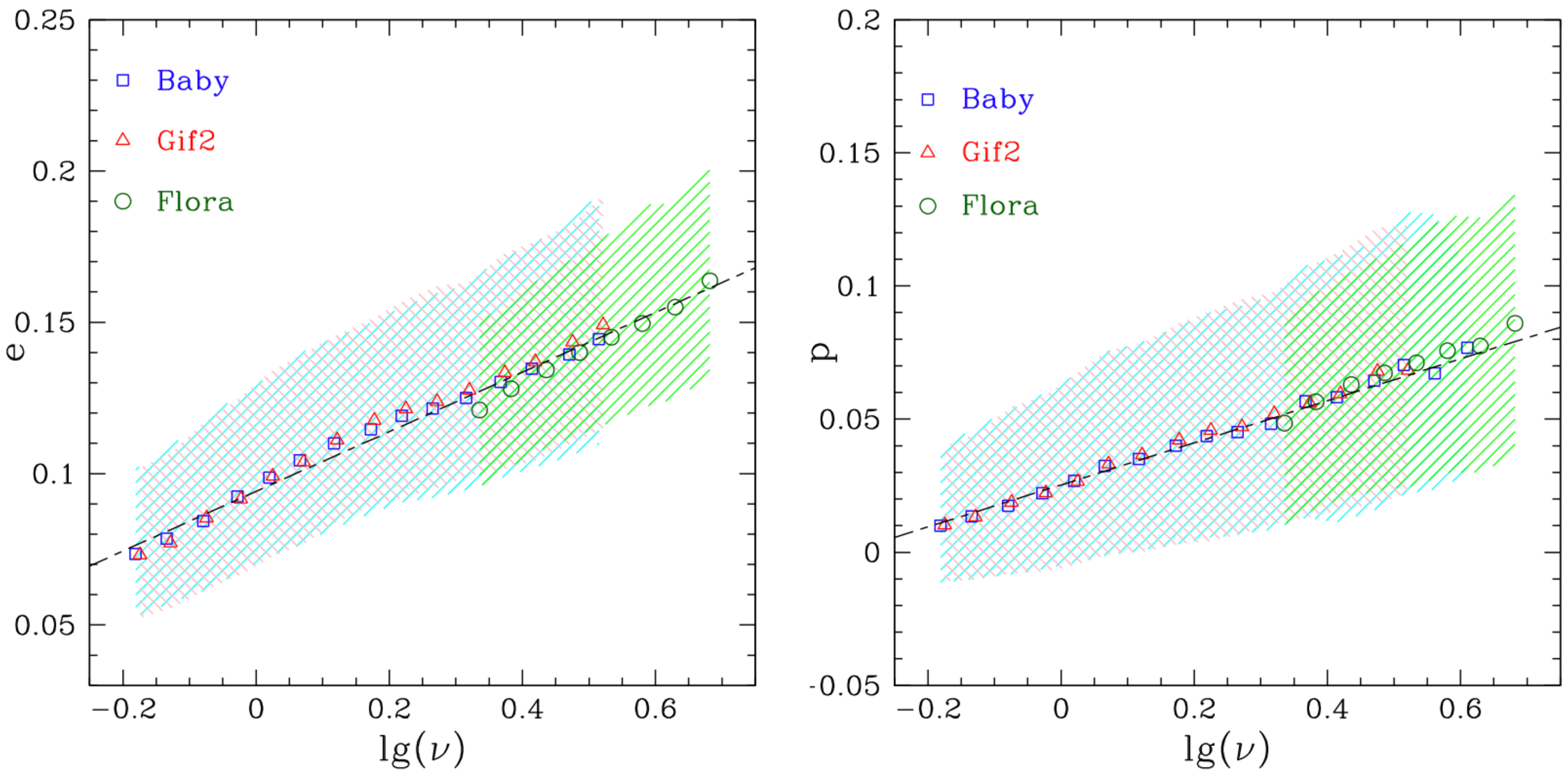
$$\Phi(r) = -\frac{4\pi G\rho_0 R_s^3}{r}\ln\left(1+\frac{r}{R_s}\right)$$

Dark Matter Halo

- NFW has a few challenges:
  - Predicts high density of DM in the center of galaxies (the “core-cusp” problem), not seen in low surface brightness galaxies
  - Maybe some tension at very large radii for galaxies (small samples)
  - Smooth versus lumpy DM distribution?
  - **Spherical DM halo, versus “triaxial”?**

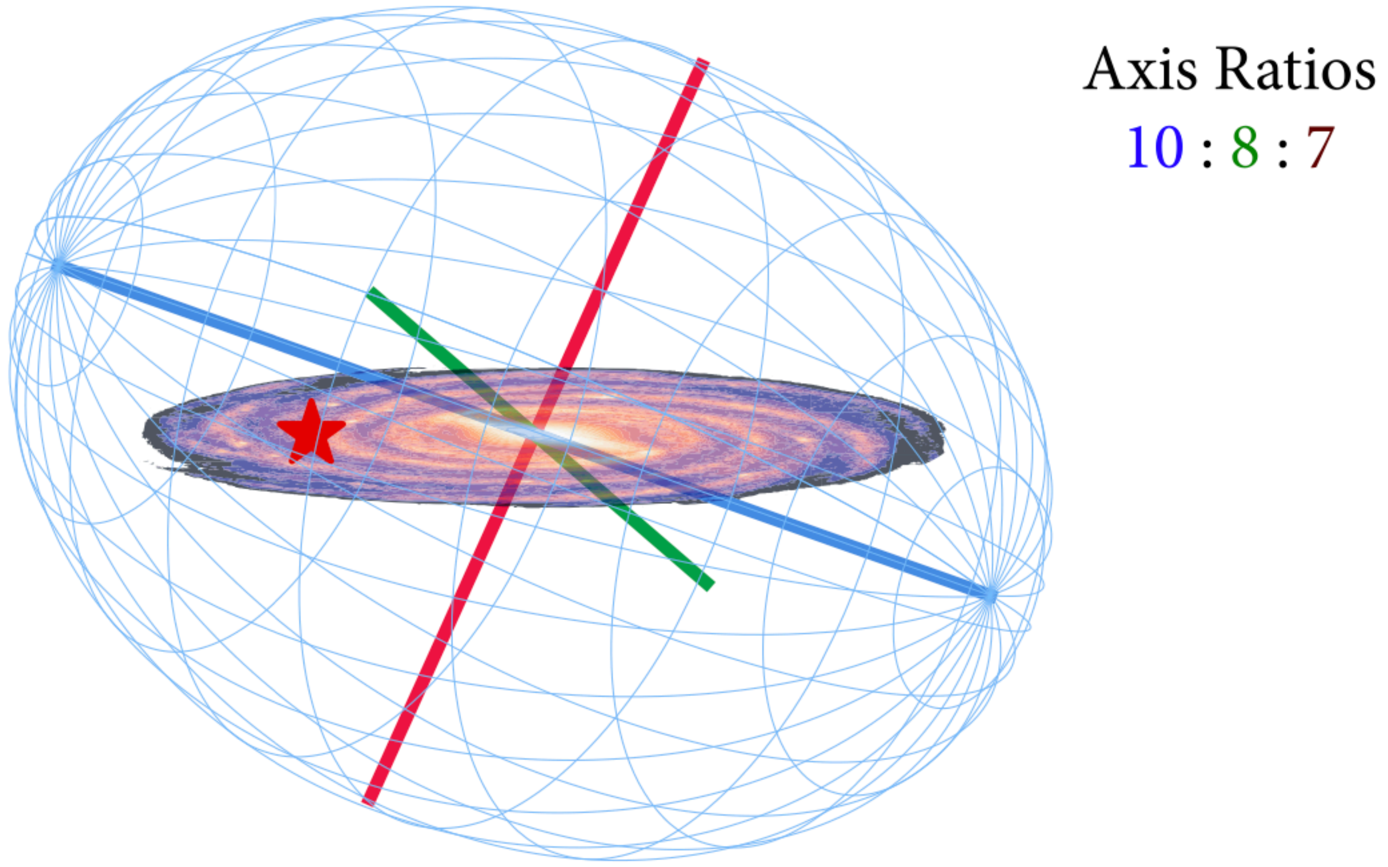
Triaxial DM Halo?

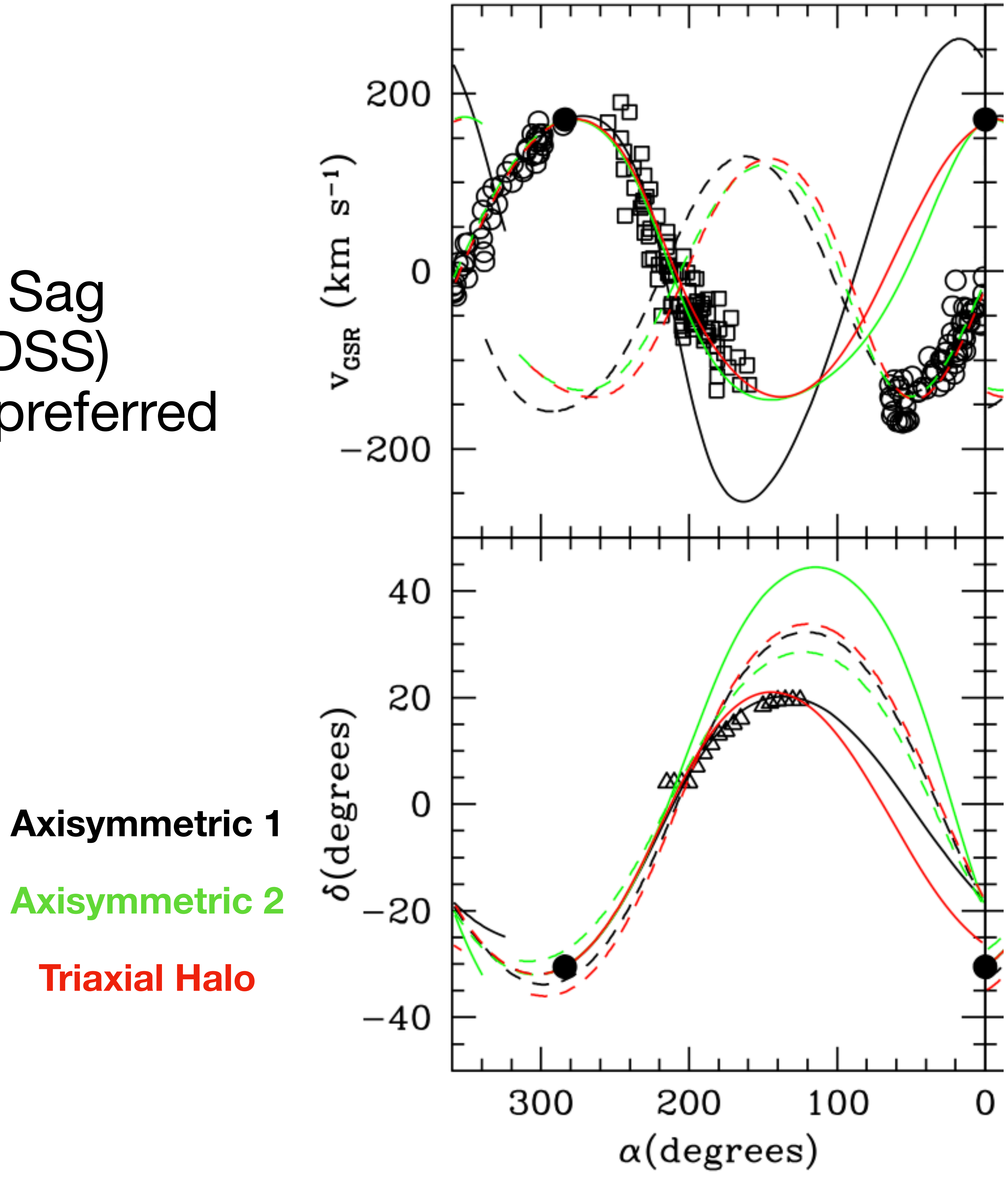
- Simulations can produce triaxial DM halos
- e.g. Giulia+2014, Heller+2007, & many simulation papers…
- DM-only simulations more likely to be triaxial, baryons make halos rounder and more oblate (Chua+2019)



Triaxial DM Halo?

- Some evidence from early models of Sag dwarf spheroidal stream (esp from SDSS) that a spherical DM potential wasn't preferred
- Triaxial DM *seemed* to work bettter
  - e.g. Law+2009



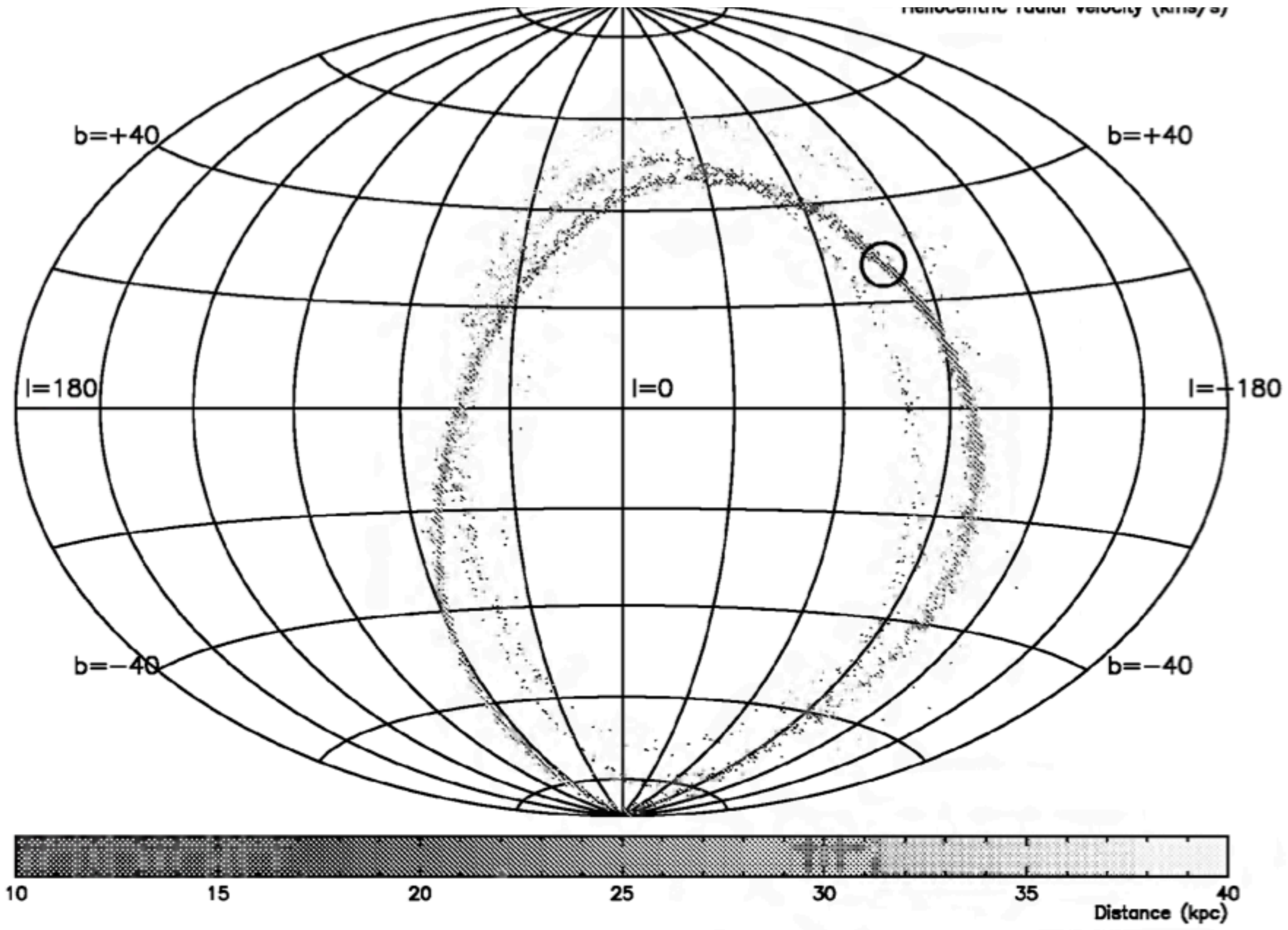


Also recall the stars!… Han+2022

Tracing the Potential with Streams

- Disrupted clusters or dwarf galaxies can not only trace the entire potential, but help rule out a lumpy DM halo

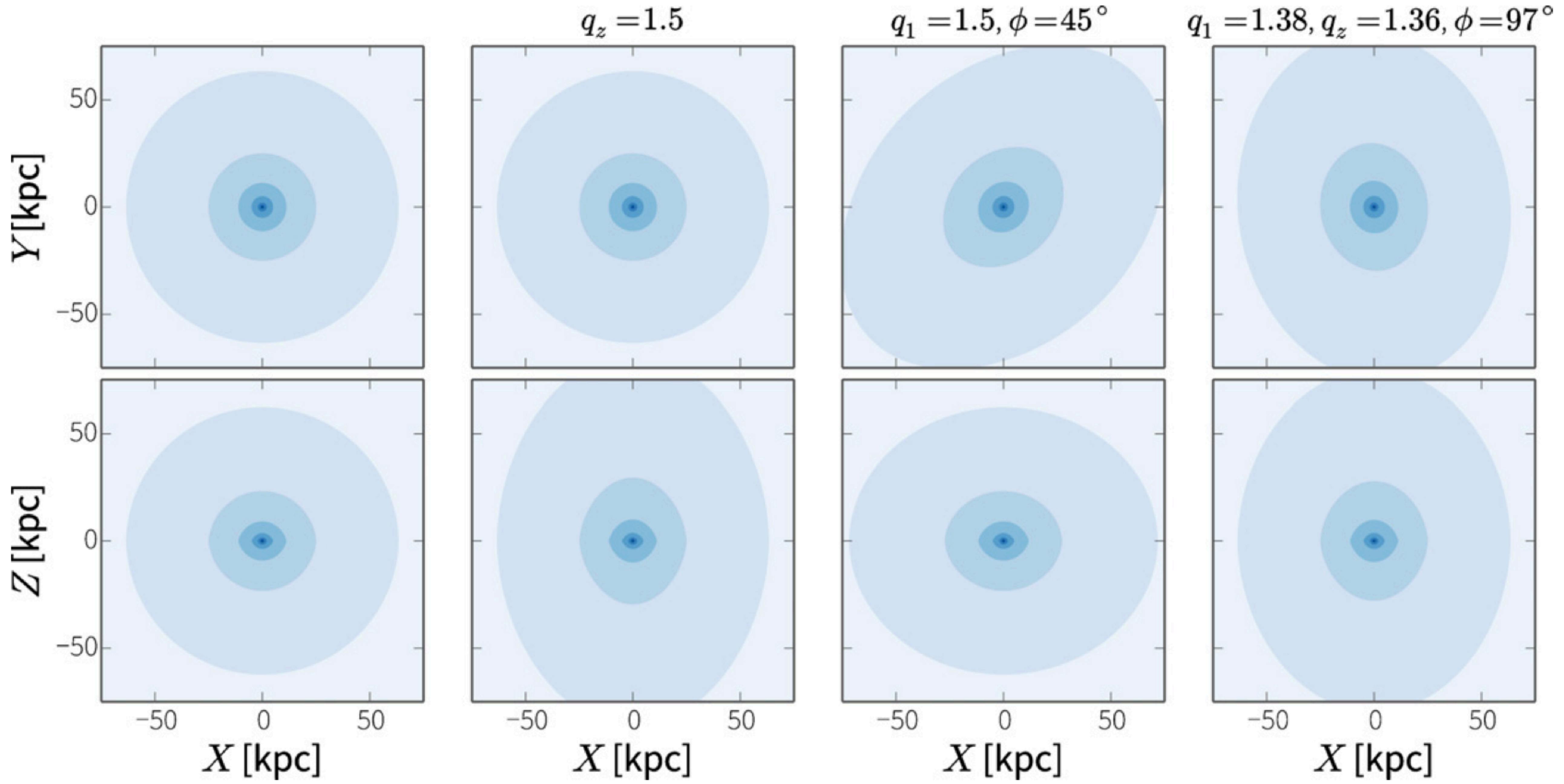
  e.g. see Ibata+2002

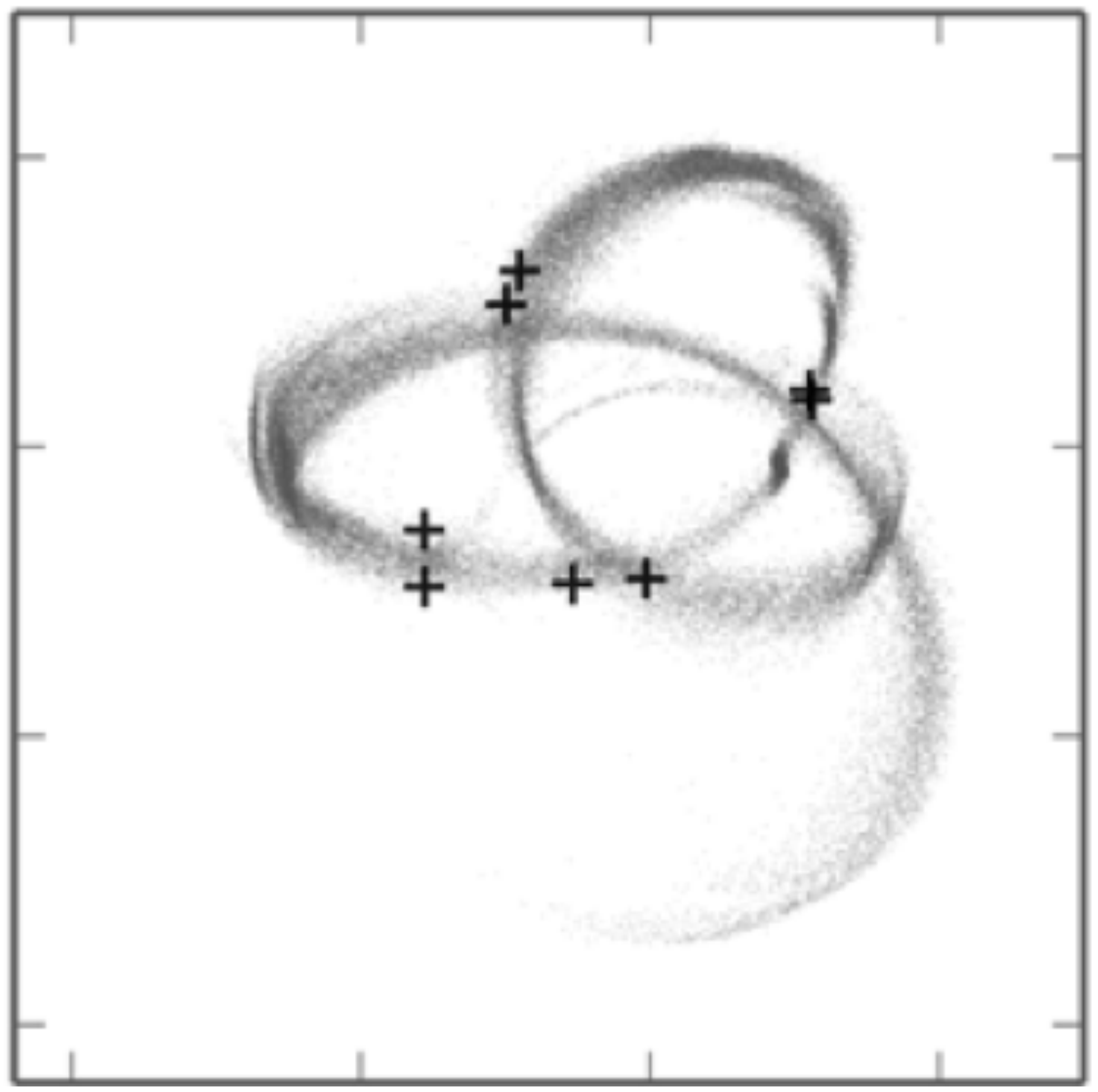


This work has shown that from an all-sky survey with high precision astrometry, such as will be obtained with the *GAIA* satellite, we will easily be able to detect globular cluster streams, and measure their kinematic properties, especially the dispersion in L_z.

Tracing the Potential with Streams

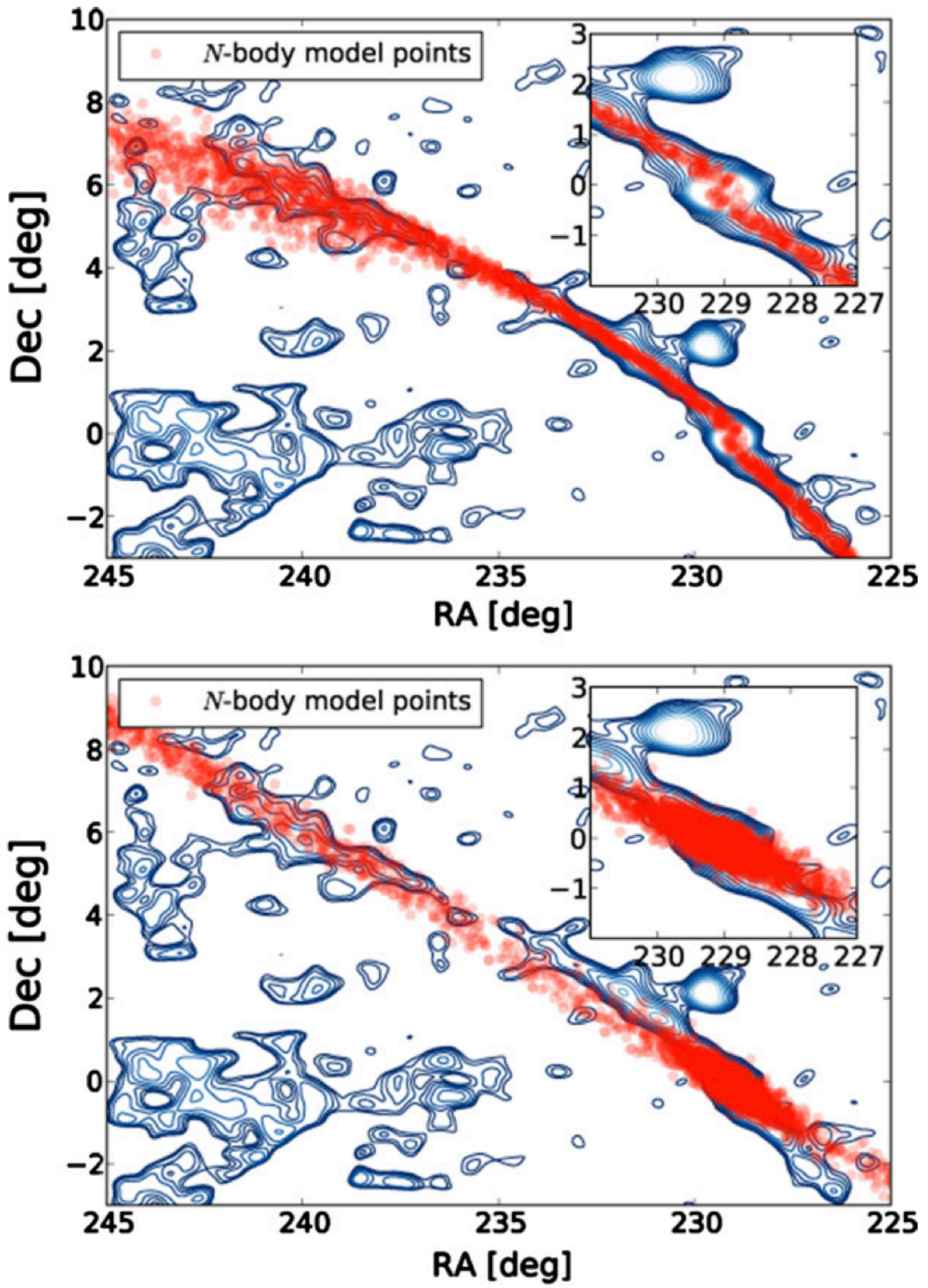
- Even a small # of stars w/ precise orbital elements can constrain the DM potential profile! Price-Whelan+2014





Tracing the Potential with Streams: Pal 5

- We've looked at this famous tidal stream before (see Lecture 4)
- Very useful for constraining Φ because so well sampled, system is "small" compared to galaxy mergers
- Spherical DM halo (+ realistic disk) model does a good job of reproducing both broad stream profile *and* nuclear "S" shape
- Triaxial shows *lots* of problems for stream
- Pearson+2015

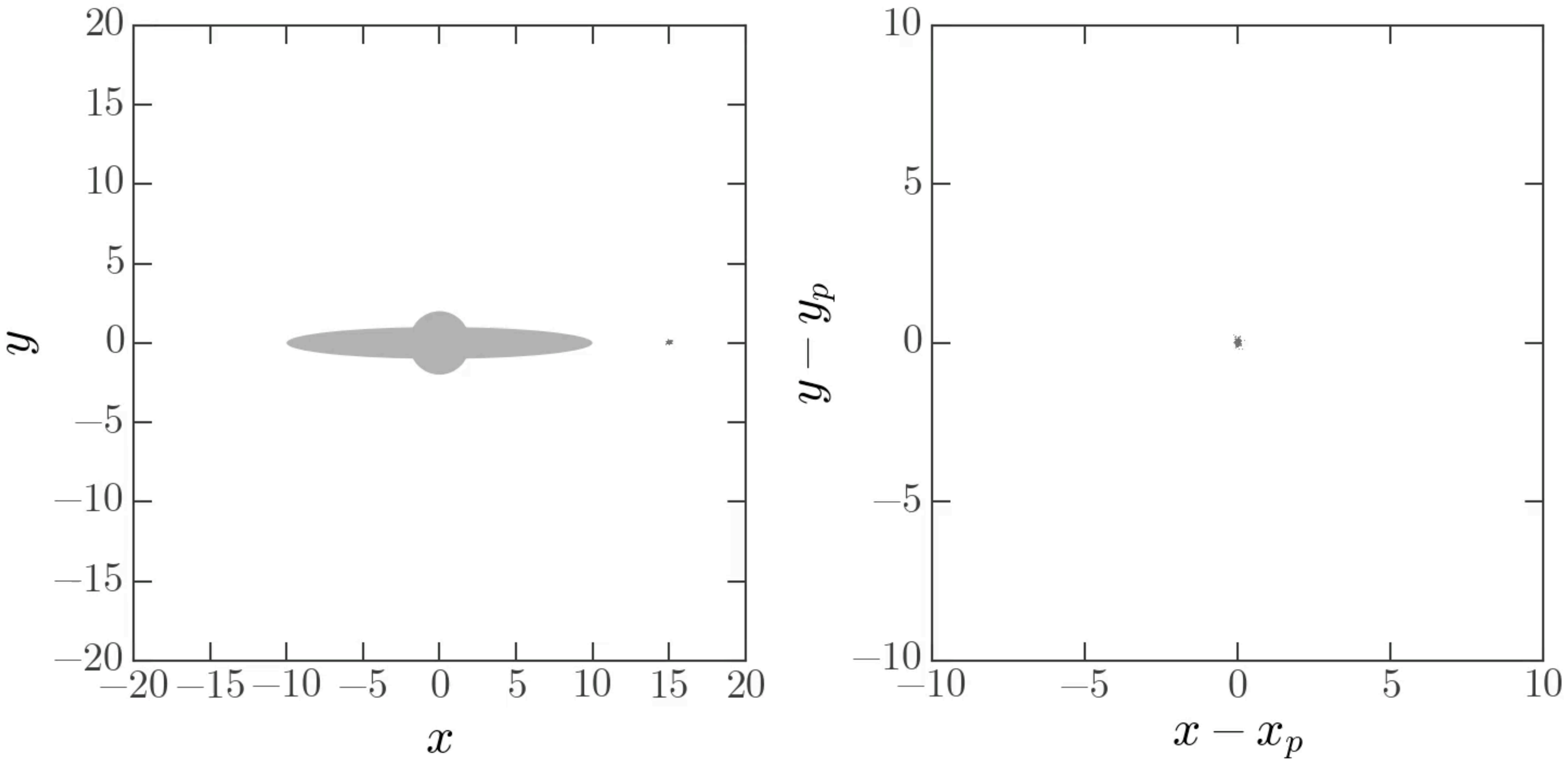


Spherical halo

Triaxial halo

Homework 4: *Destroy This Cluster*

- You lovingly characterized a cluster in Homework 2, explored a bit of the Galaxy it lives within in Homework 3…
- Now I want you to "destroy" it, i.e. try and turn it into a tidal stream!
- This is the final HW!
- Gala package suggested
  Could also do with e.g. Galpy



http://adrian.pw/aas237/

Homework 4: *Destroy This Cluster*

- Try MWY versus NFW potentials… can you destroy your cluster?!
- Two approaches you might explore here:
  - Do lots of orbits w/ small range of initial locations
  - Use a stream-generating prescription