Dark matter halos:
Predictions and Observations

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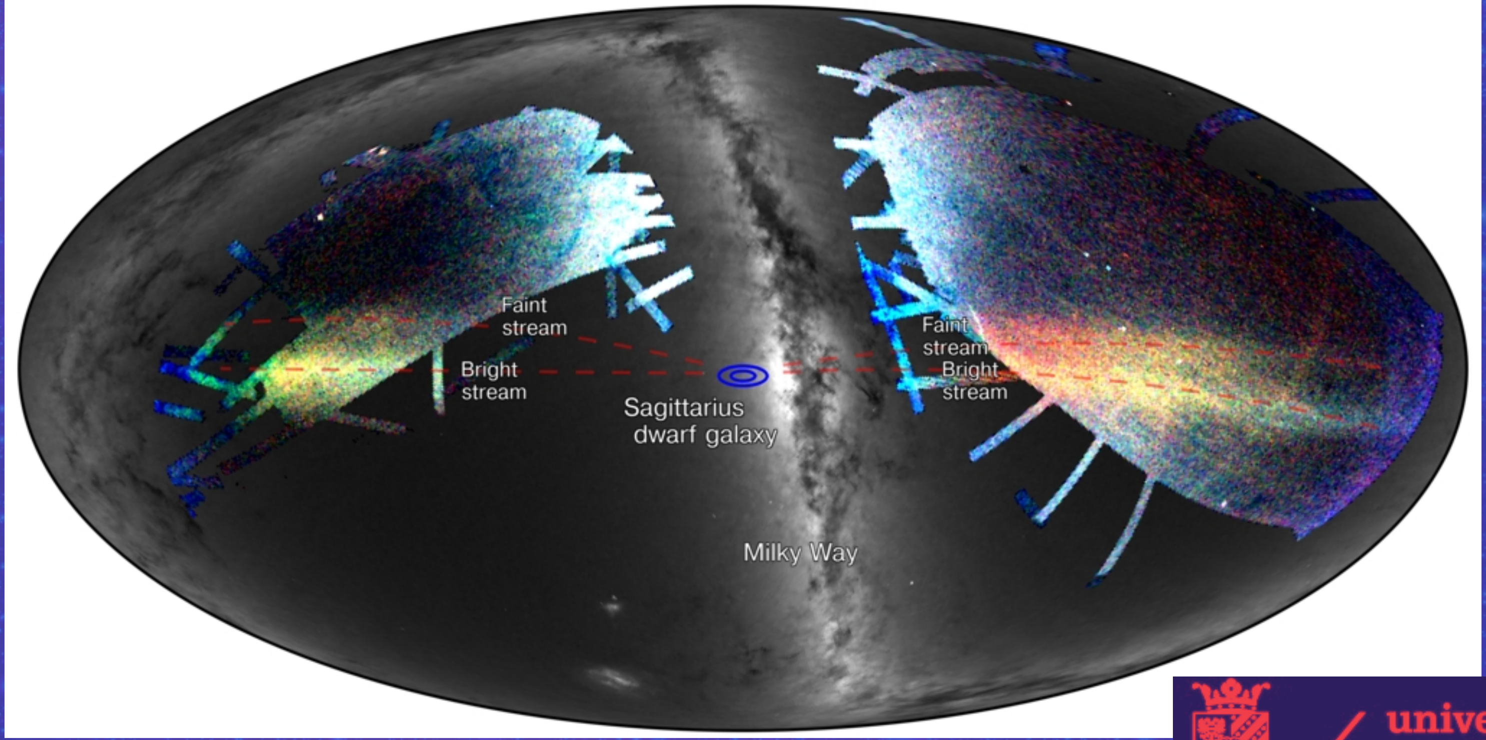

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Outline

- Introduction: cosmological predictions
  - Density profiles and shapes

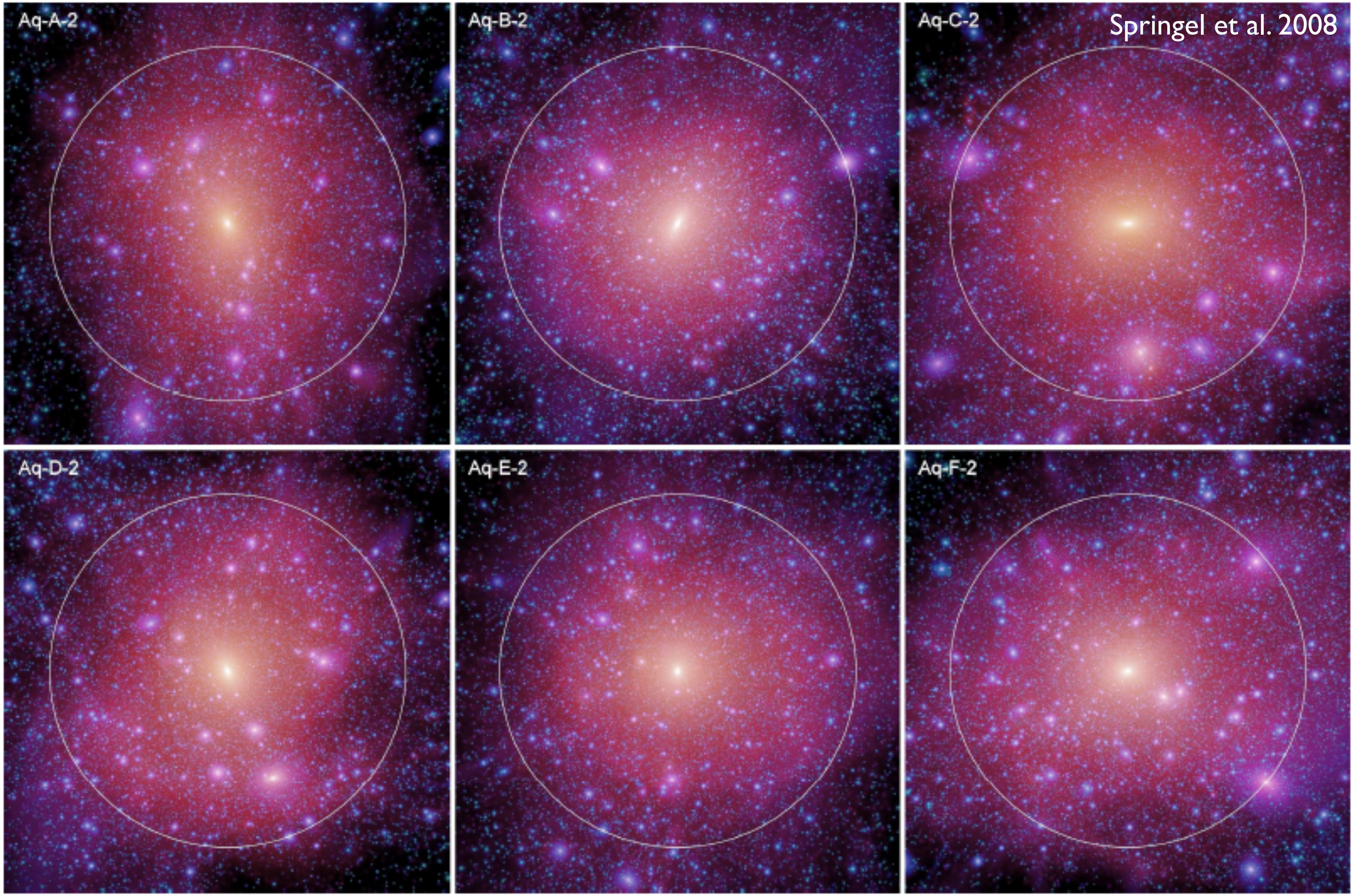
- Dwarf galaxies
  - Observations
  - Dynamical modeling with Schwarzschild's method

- The Milky Way
  - Sagittarius stream observations
  - Shape of the Galactic halo

- Conclusions

Special thanks to: Maarten Breddels & Carlos Vera-Ciro

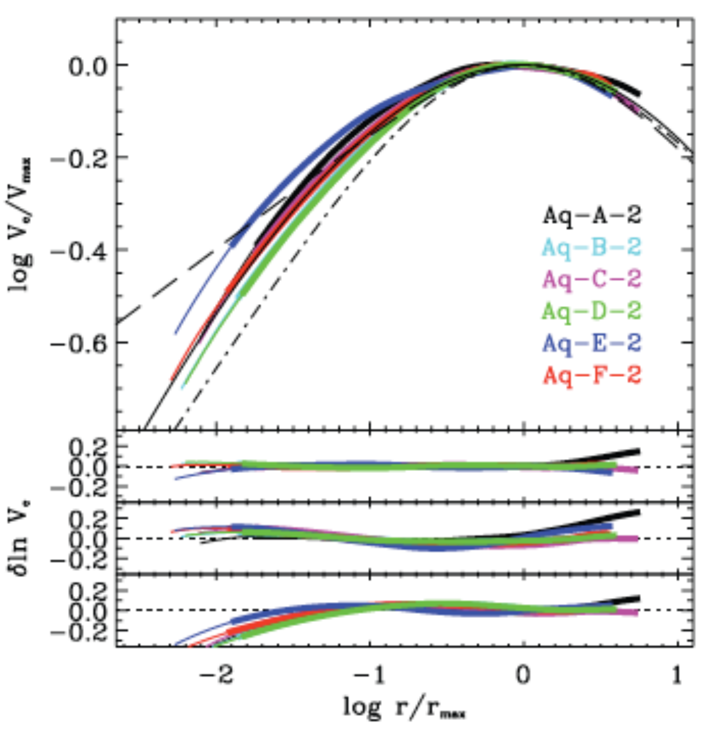
Dark matter halos in LCDM



Springel et al. 2008

Cosmological predictions: density

- Pure N-body CDM simulations make definitive predictions about structure of halos



Navarro et al. 2010

- Density profiles

  - NFW $\rho(r) = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2};$

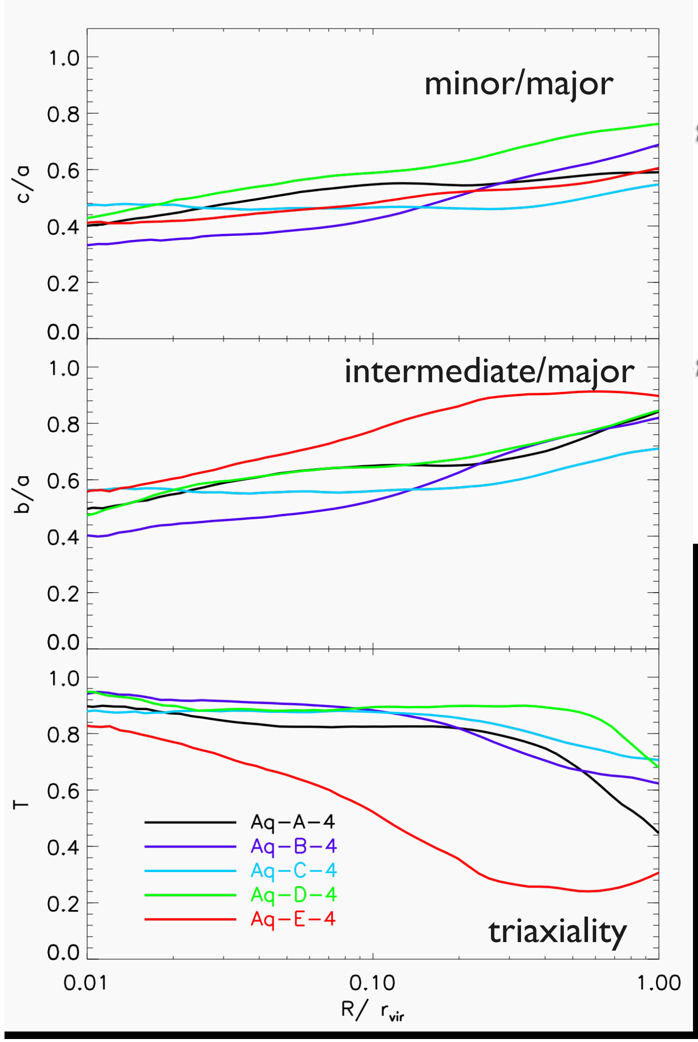
  - Einasto $\rho(r) = \rho_{-2} \exp\left\{-\dfrac{2}{\alpha}\left[\left(\dfrac{r}{r_{-2}}\right)^{\alpha} - 1\right]\right\}$

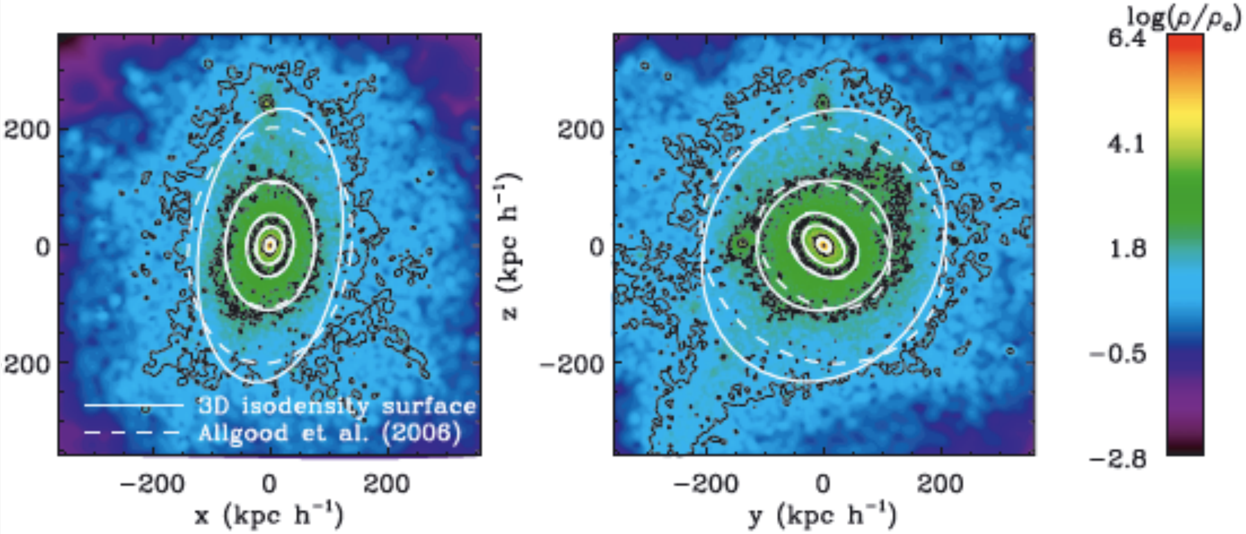
  - For satellites, Einasto profiles fit slightly better

!! Baryons and their effects can modify inner profiles (e.g SN feedback), can lead to a core (Governatoet al. 2010)

Cosmological predictions: shape

- Shapes
  - Triaxial: from prolate to triaxial/oblate in the outskirts





Vera-Ciro et al. (2011)

!! Baryons (especially a massive disk like MW) will modify shape at small radii (flattened oblate towards the disk; Tissera et al. 2011)

What’s so interesting?

- Structure and substructure of halos depend on nature of dark matter particle

  - Density profiles:
    - WDM have lower average densities
    - Depending on implementation/particle properties simulations show
      - NFW form (Busha et al. 2007; even for HDM Wang & White 2008)
      - A core (of varying size; Maccio et al. 2012,2013)

  - Shapes are generally rounder for HDM

- We can (attempt to) measure these!!

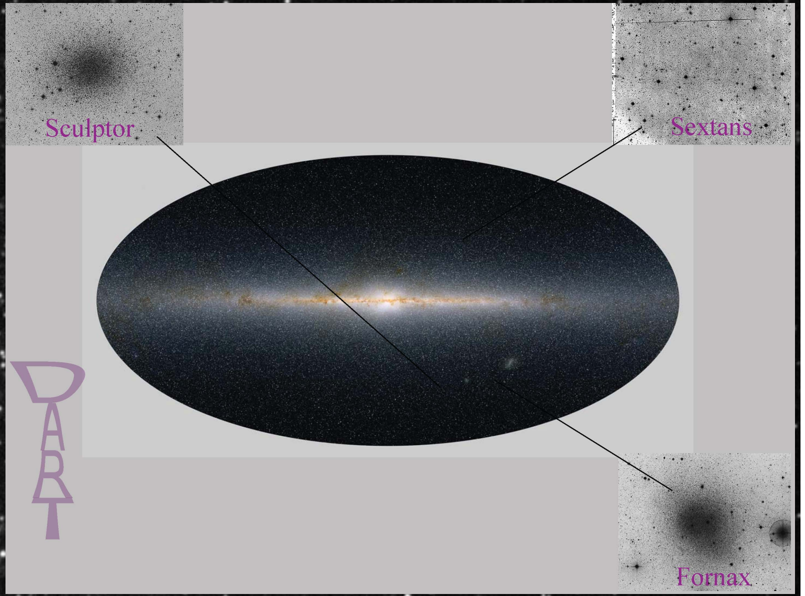
Dark matter density profiles from the dynamics of dwarf spheroidals

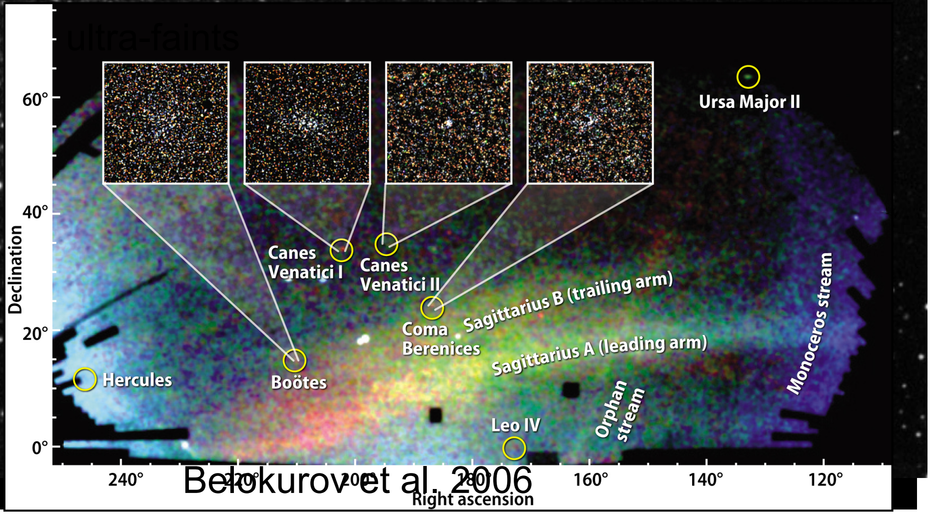
The satellites of the Milky Way: dwarf spheroidal galaxies

Very faint systems: 100 – 10^7 Lsun

Dynamical mass estimates: 10^7 – 10^9 Msun

- ➢Most DM dominated systems known
    - ➢Dynamical modeling can neglect the effect of baryons
    - ➢Probe the innermost regions (constraints on cusps vs cores)





ultra-faints

Belokurov et al. 2006

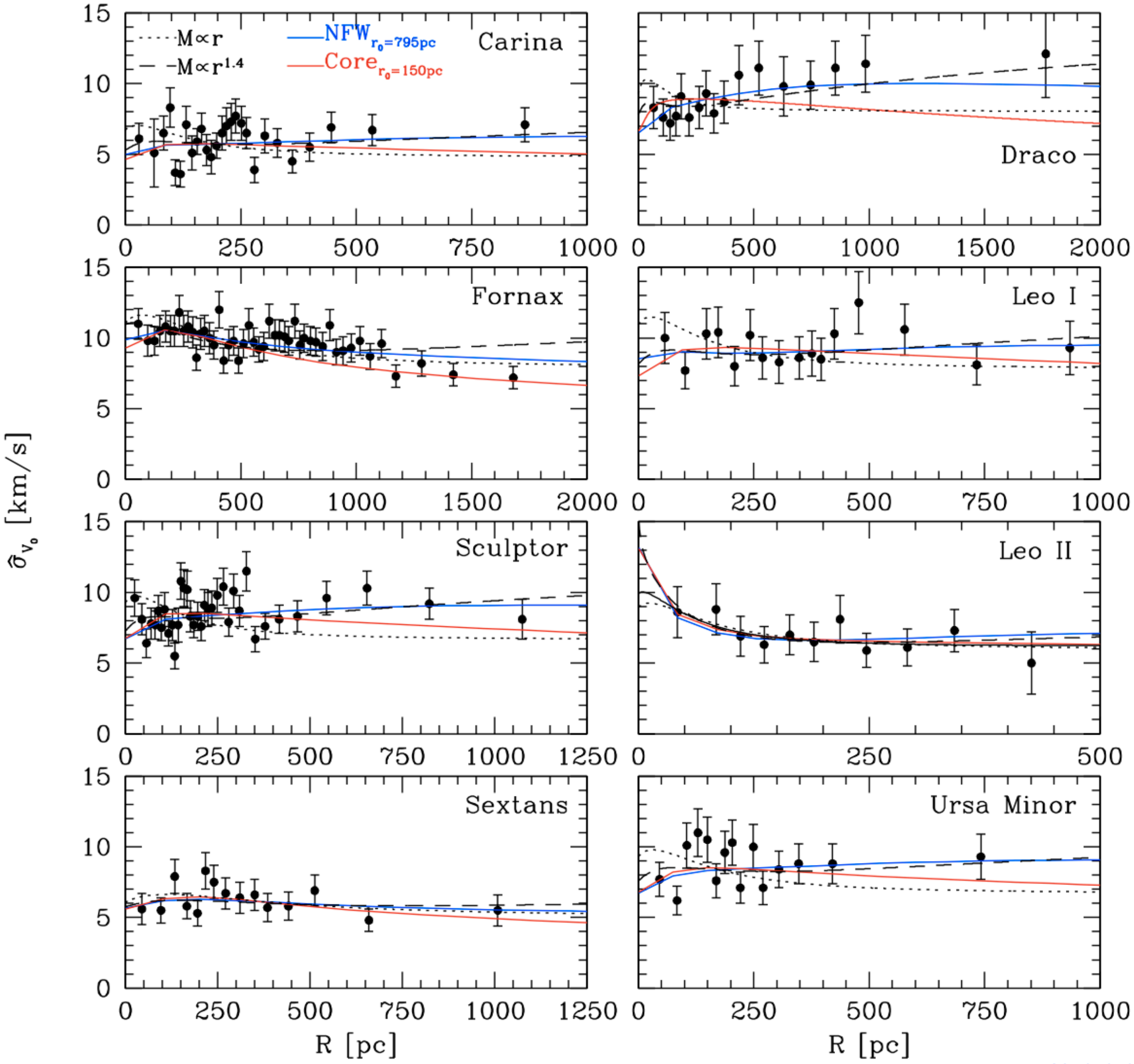
MW satellites

- Recent years huge data growth:
  - MOS on 4m & 8m-class telescopes
    - WHT: Kleyna et al (Draco, Umi); VLT: Battaglia et al (Scl, Fnx, Sex) - Koch et al. (Leo I, Leo II); Magellan & MMT: Walker et al (7 dSph); Munoz et al (Carina)

- Fairly flat velocity dispersion profiles

- What kind of dark halo profiles are consistent with these data?

- Modeling limited to Jeans: parametric & assumptions regarding orbital structure

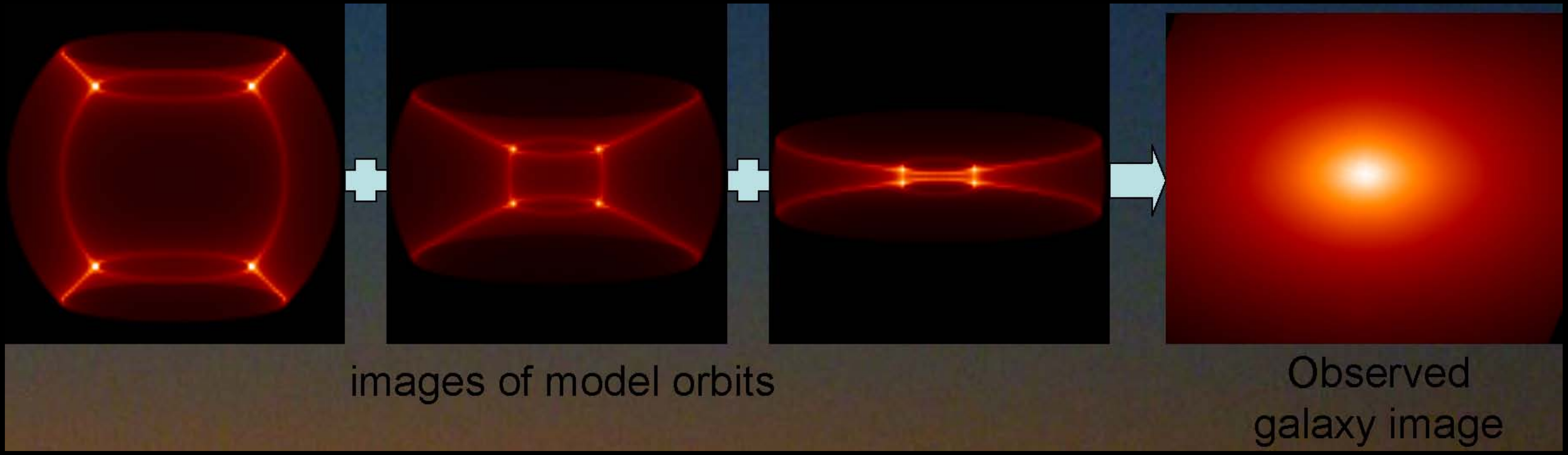


Walker et al (2009)

Schwarzschild models

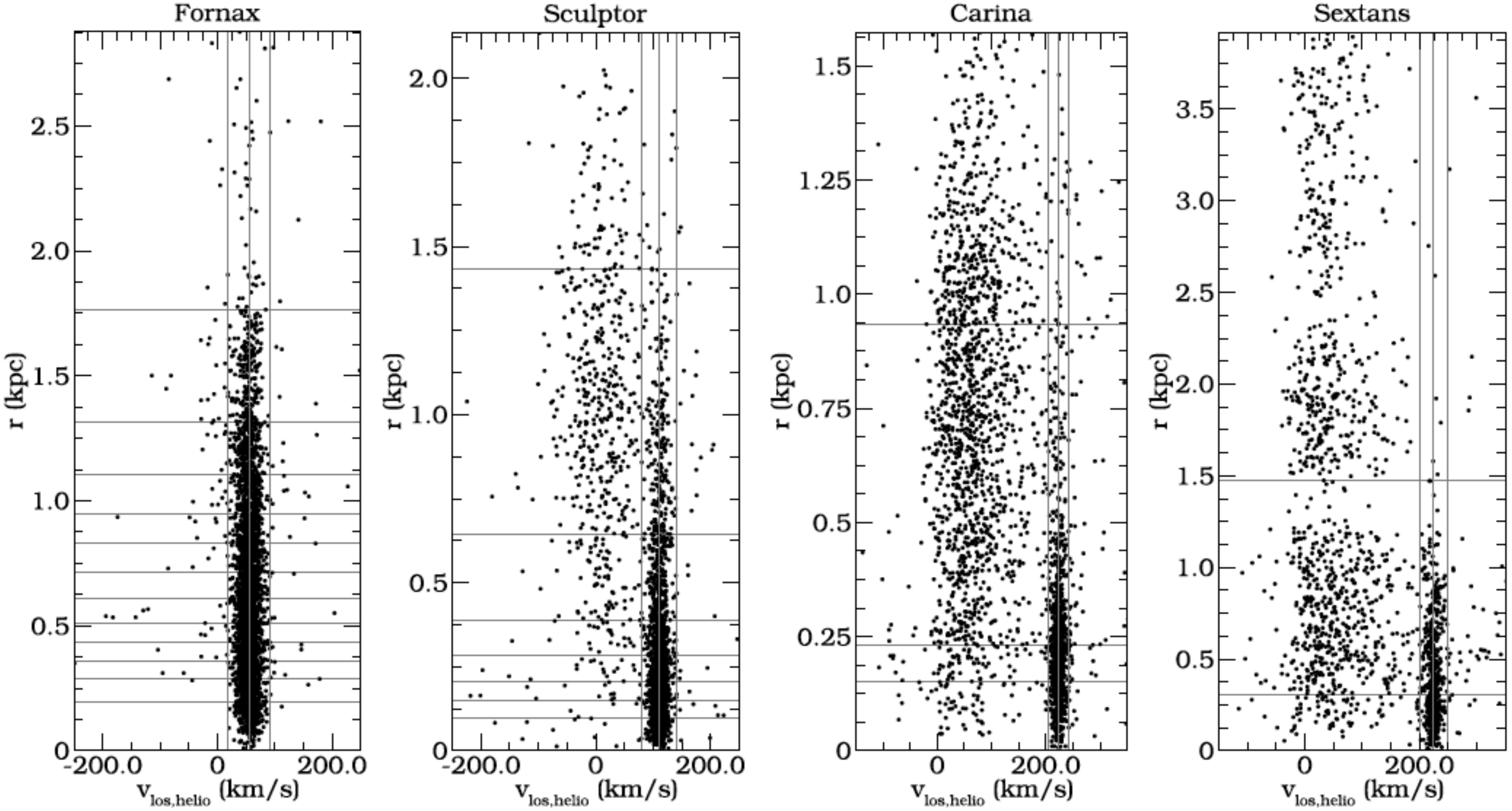
- Integrate orbits in a given potential, and find their weights such that the observables (surface brightness, velocity dispersion curve) are reproduced

- Best model obtained via max likelihood, and this gives best fit parameters of the gravitational potential, as well as distribution function (anisotropy) of the model



Observables

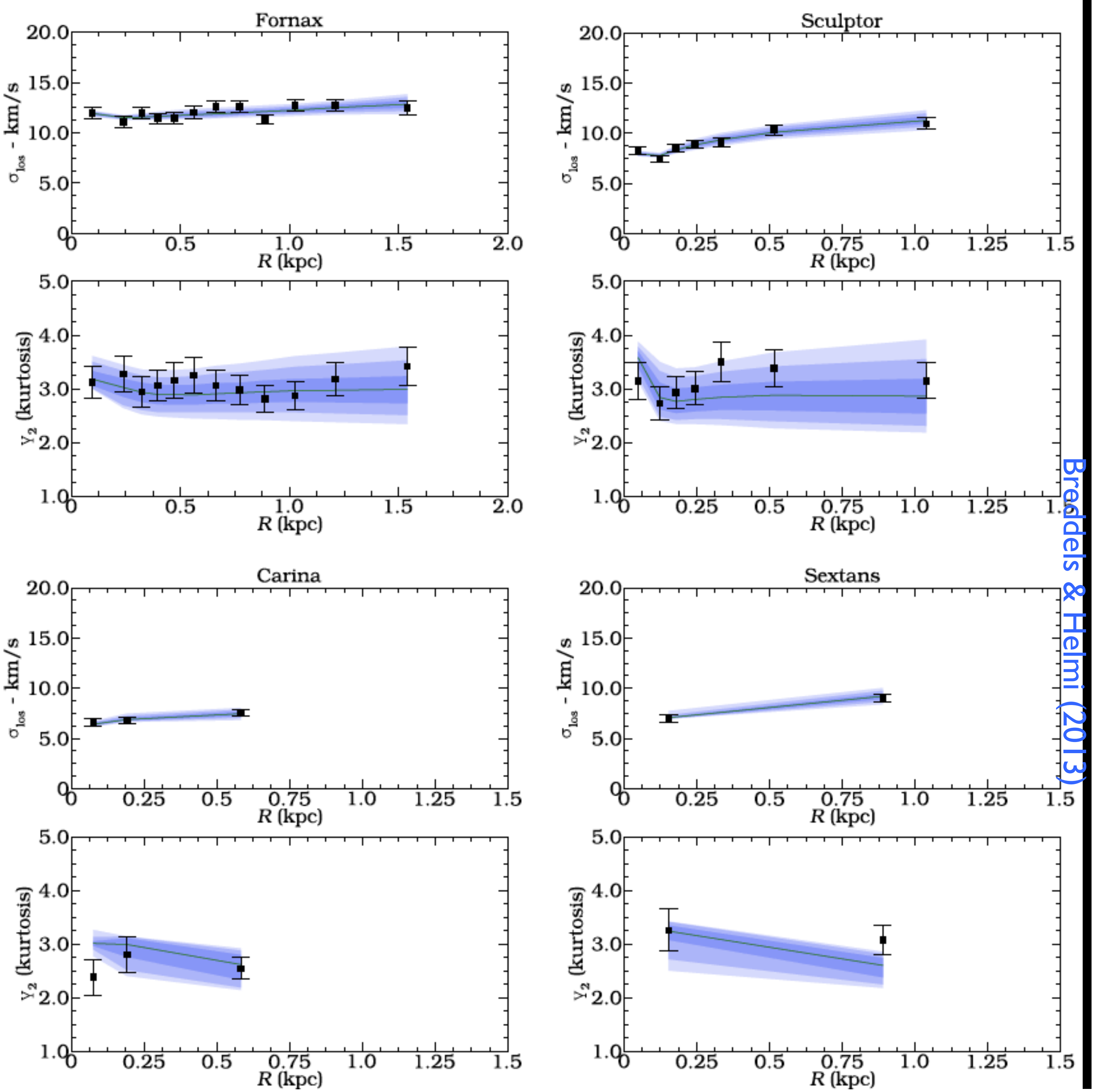
- •Measurements for individual stars: los-velocity and position from galaxy's centre
- •Determine membership (contamination by foreground Milky Way stars)



Breddels & Helmi (2013)

Observables

- Moments of the l.o.s. velocity distribution
- 2nd moment, Dispersion σ
- 4th moment (Kurtosis; needed to constrain anisotropy/types of orbits)



Breddels & Helmi (2013)

Models

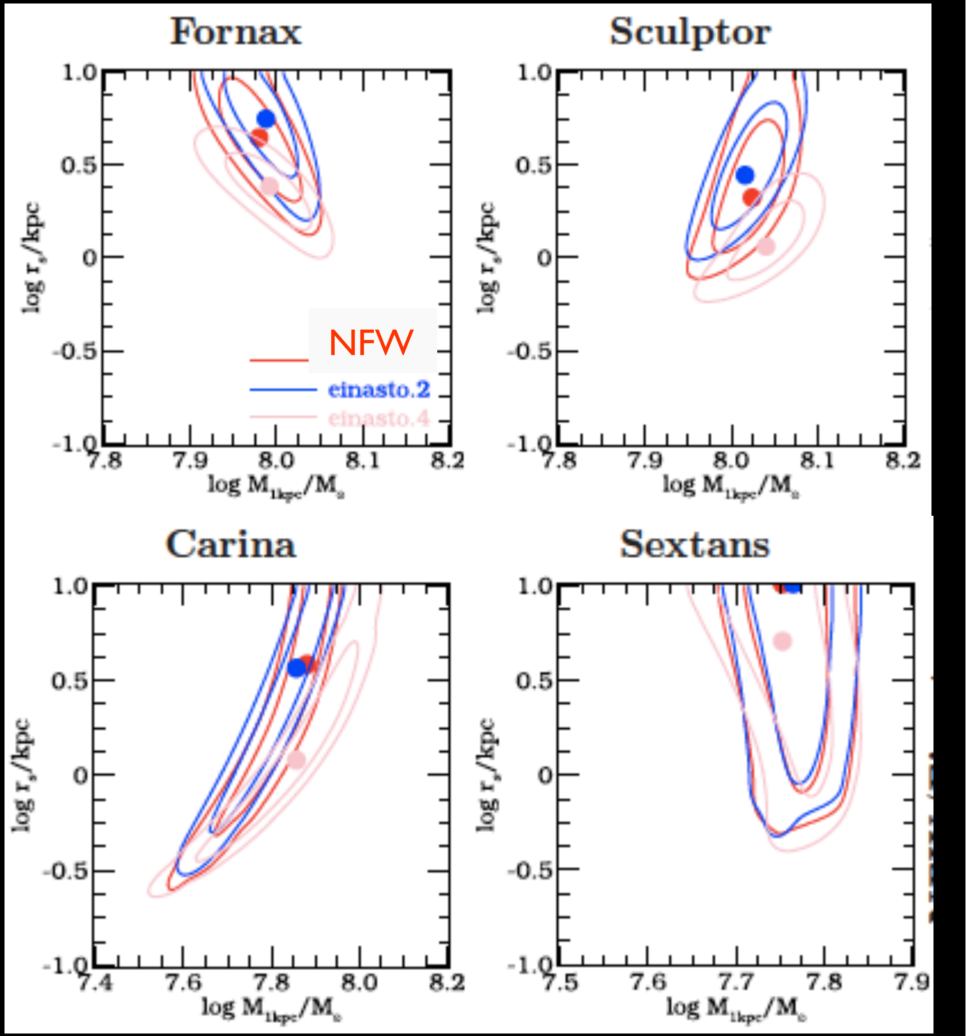
- Assume a dark halo potential, e.g. NFW
- Integrate orbits
- Vary parameters (Mass, scale radius) until χ^2 is minimized

- Vary halo potential/density

$$\rho(r) = \frac{\rho_0}{(1+x^\gamma)^{\beta/\gamma}}$$

β = 3, 4 and γ = 1, 2

- Fit again …

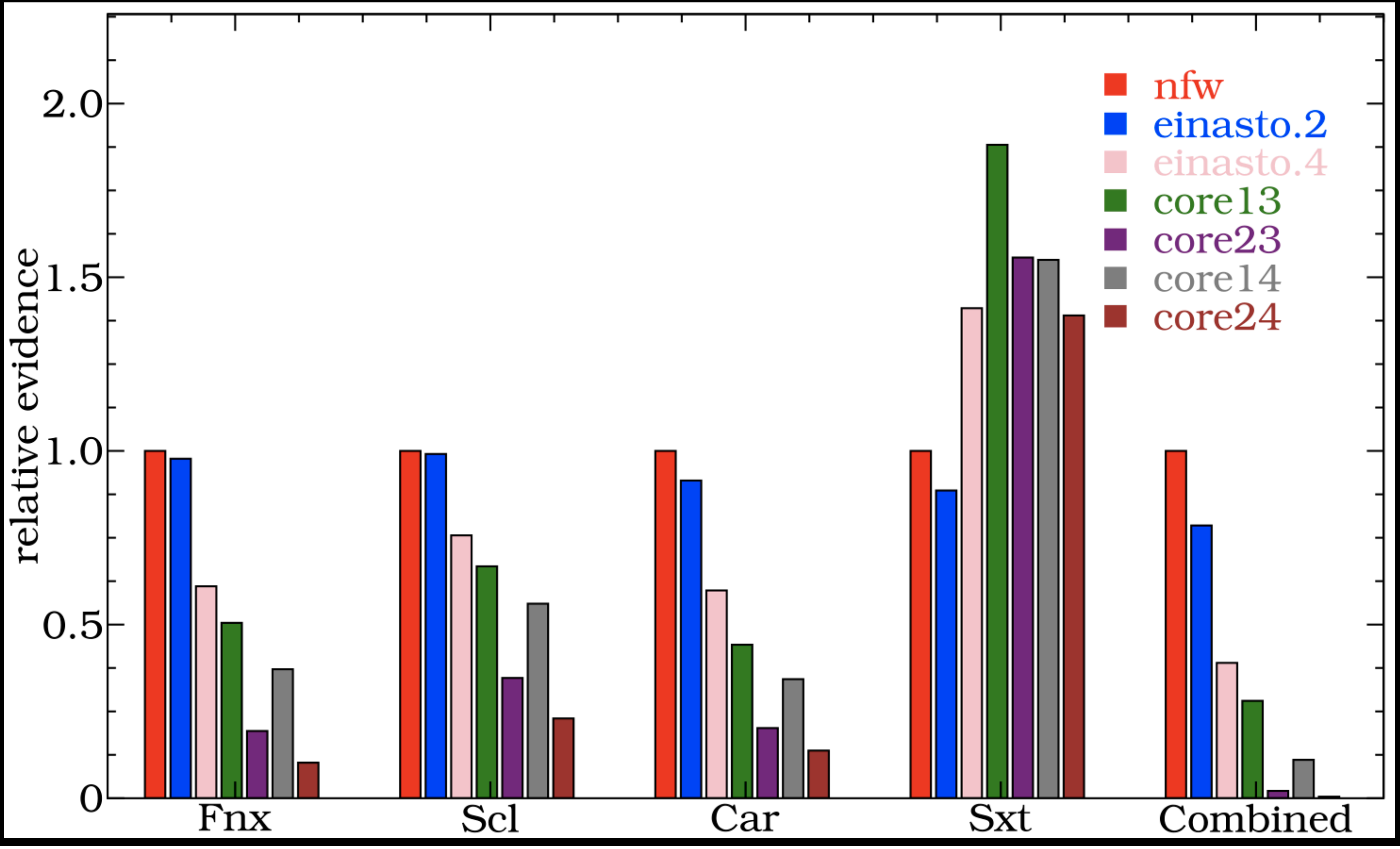


Breddels & Helmi (2013)

Bayesian evidence: Which give better fits?

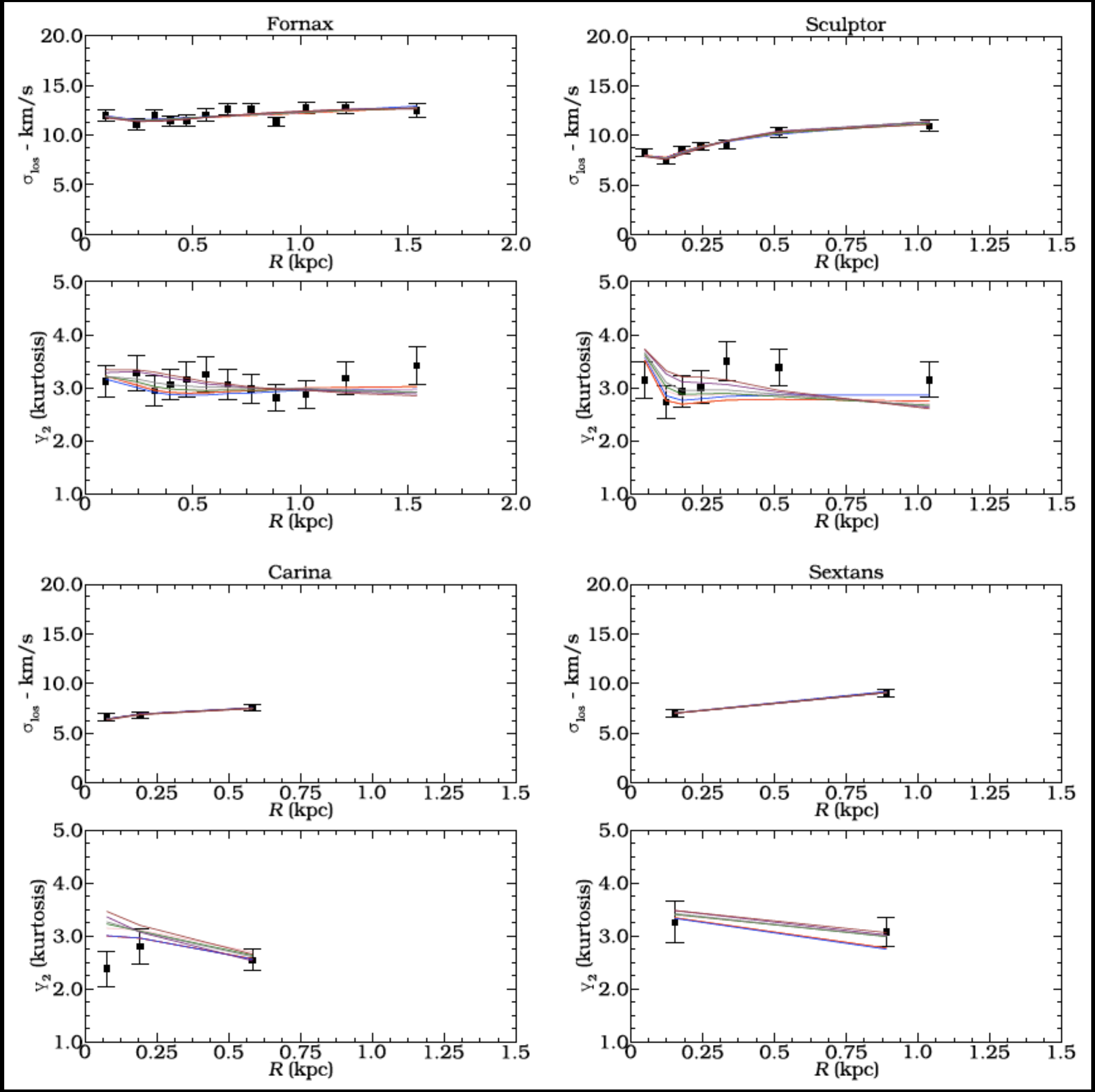
- In Bayesian framework: determine evidence: $p(M_1|\text{data})/p(M_2|\text{data})$

- Comparing different models for same galaxy: none is preferred
- Are all galaxies are embedded in same profile? cored $1/(1+r^2)^{3,4}$ are disfavored

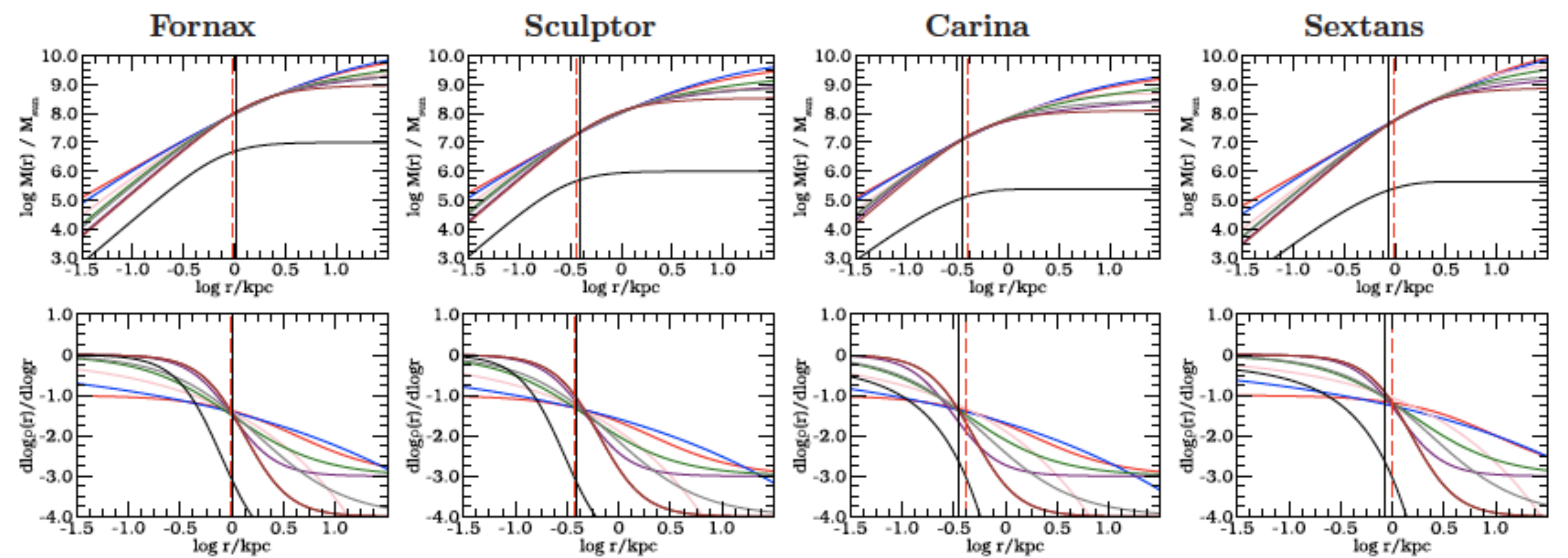


Breddels & Helmi (2013)

- The best fit models found give fits that are effectively indistinguishable



Resulting mass profiles



- For each galaxy, finite region where all profiles conspire to give same mass distribution
    - From r_{-3} to last measured data point

- Therefore, slope of dark halo density profile can be measured and is model-independent at ~r_{-3}

- We find $\gamma(r_{-3})$ ~ -1.1 (Sextans) to -1.5 (Fornax) at ~ 1 kpc

Summary on density profiles

•Bayesian evidence shows that no profile is preferred, but not all galaxies in the same cored halo

•Model fits are indistinguishable given our data

•Models conspire to give all the same mass distribution within region ~ 1 kpc in extent

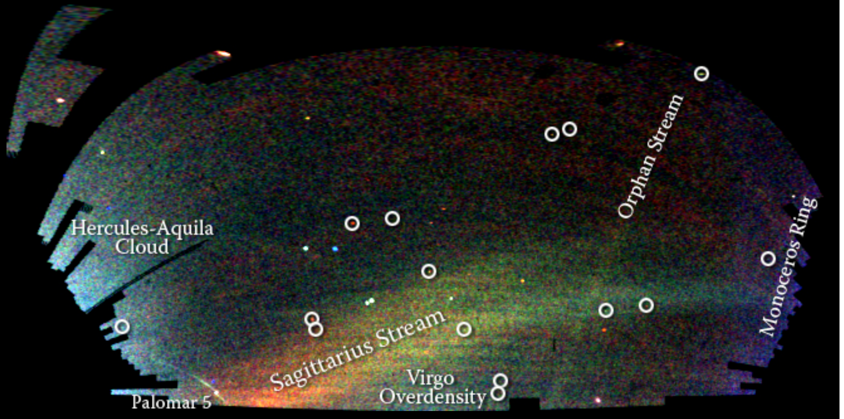
•Slopes can be measured in model independent way

•Remains to be seen if these new constraints are consistent with properties of subhalos in LCDM

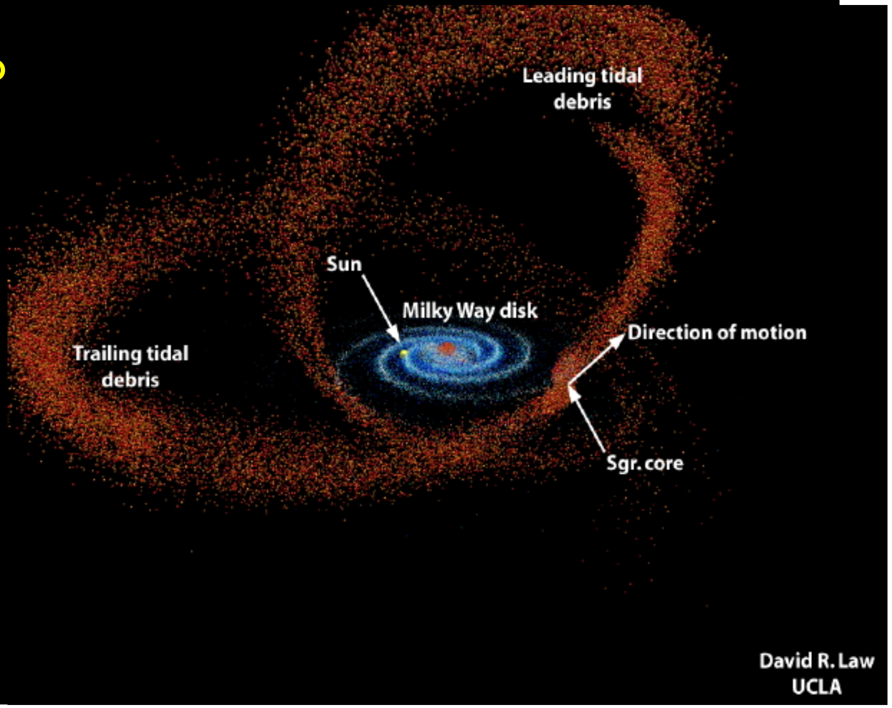
Constraints on the shape of the MW dark halo from the Sagittarius streams

The Milky Way's dark halo shape

- CDM simulations predict for 10^{12} Msun MW- hosts
  - prolate in center, more triaxial in outskirts
  - c/a ~ 0.9; b/a ~ 0.95 on average in the potential (Hayashi et al. 2007)



- Streams in halo excellent probes:
  - stars on parallel orbits moving under dark halo potential



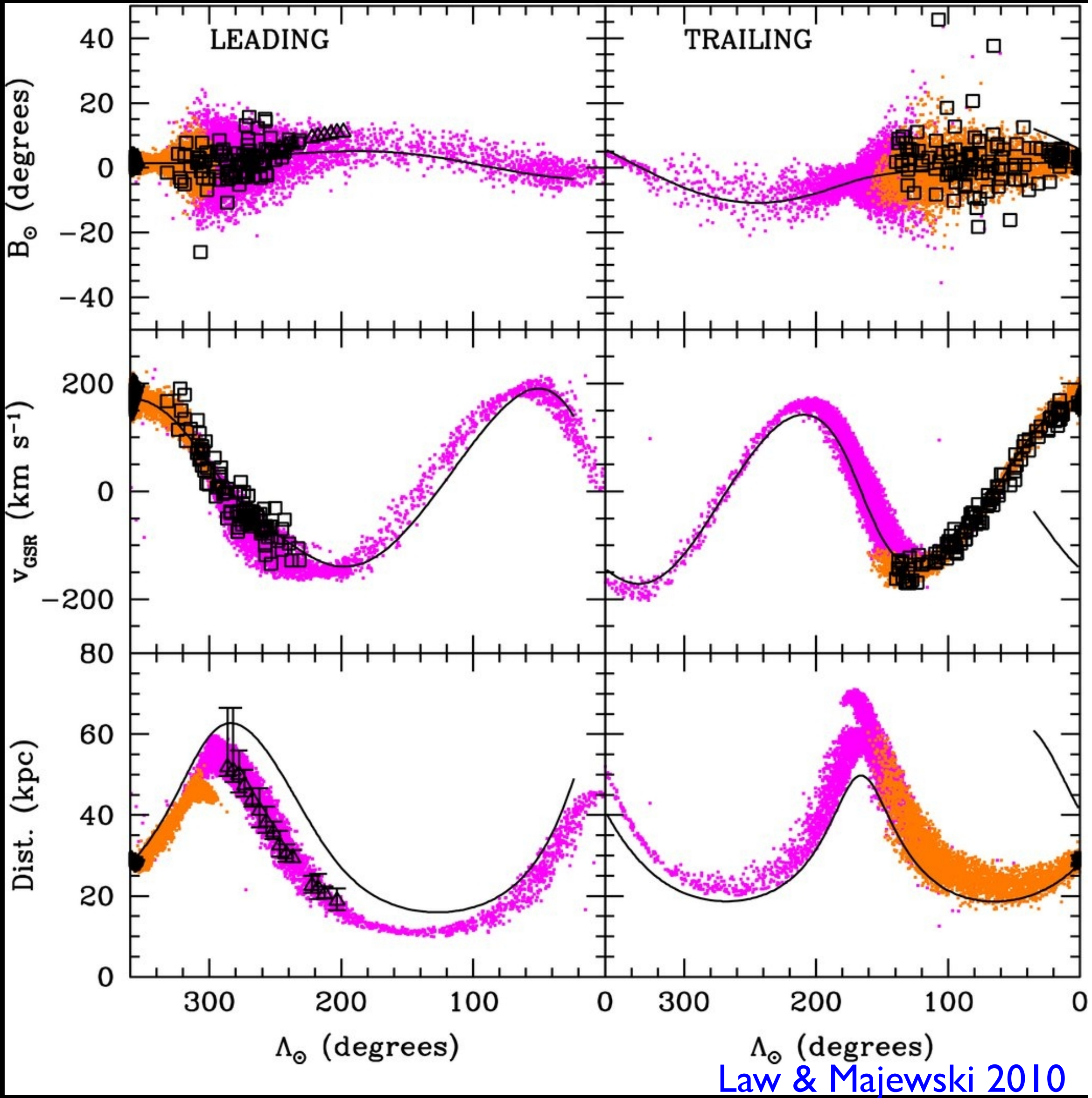
David R. Law
UCLA

- PUZZLES from models of Sgr stream in axisymmetric potentials
  - *Precession signal* (non-spherical halo): clearly favour OBLATE (Johnston et al. 2004)
  - *Radial velocities*: clearly favour PROLATE (Helmi 2004)

Solution: A triaxial halo?

- Model by Law & Majewski (2010)
  - ✓ Positions on the sky (hence precession)
  - ✓ Radial velocities

- However, it is odd…

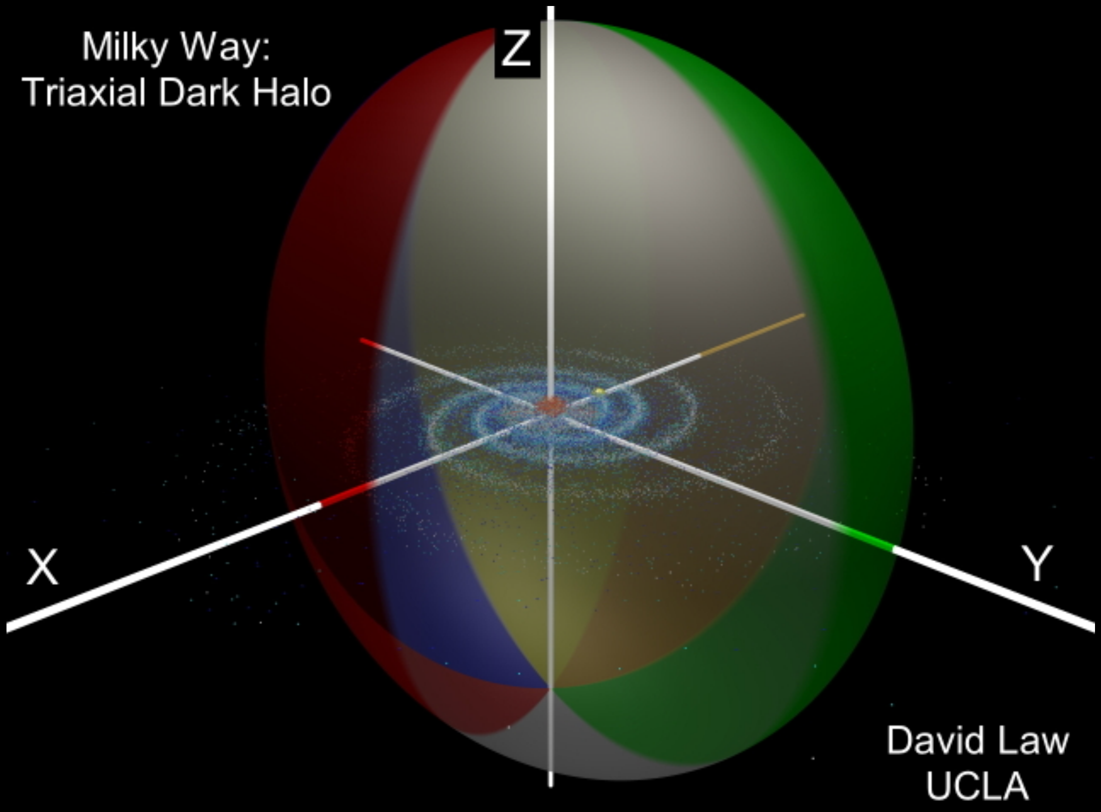


Law & Majewski 2010

Solution: A triaxial halo?

- Triaxial potential, but odd:
  - Nearly oblate shape:

    axis ratios c/a = 0.72 b/a = 0.99
  - Minor axis: in the plane!
  - Symmetry plane: yz, i.e. perpendicular to the disk



Problems:

- Not stable configuration for disk
- Unexpected: dark halo ought to respond to disk and become oblate in the center (towards disk)
- Not very likely in LCDM

Solution. I.

- Model should satisfy
  - Oblate in the inner regions
  - Triaxial in the outskirts (as in LM10)

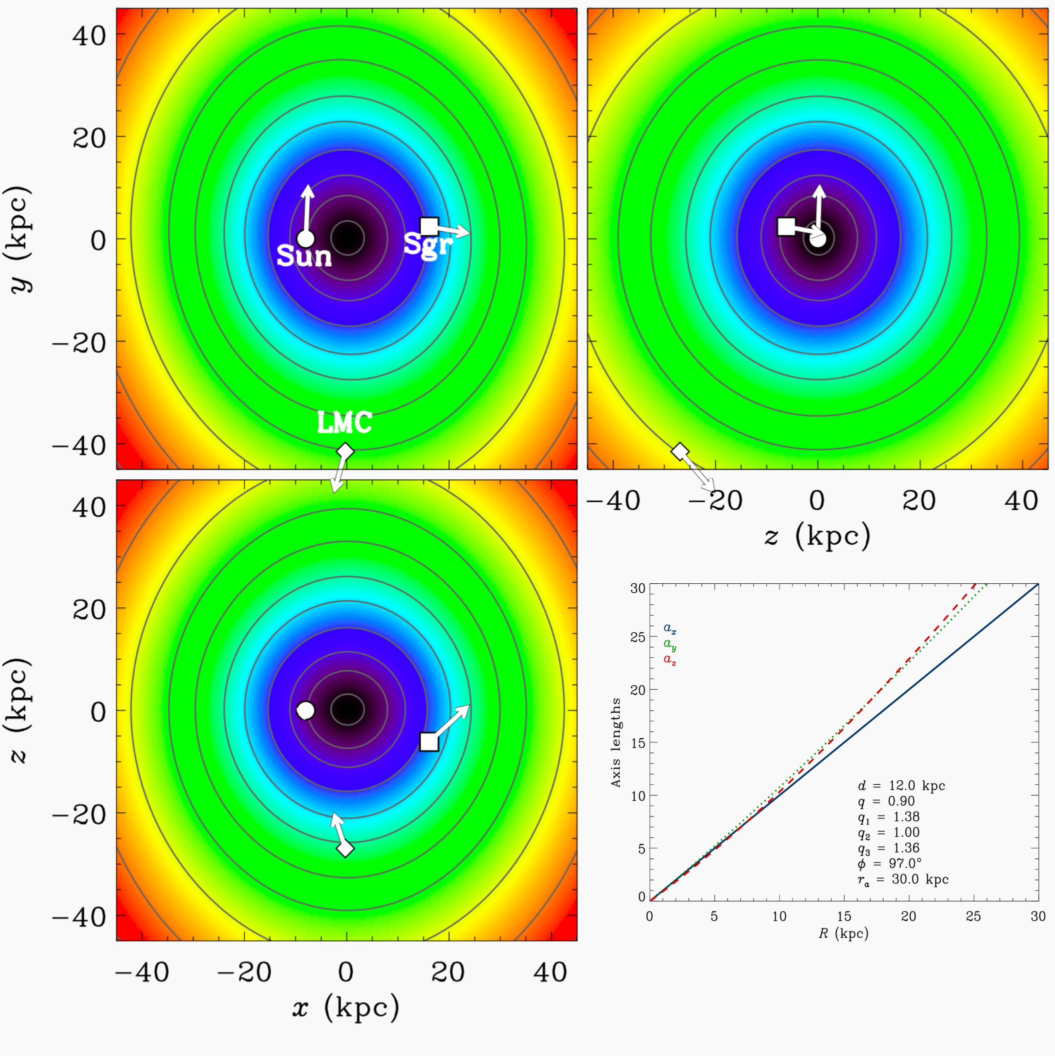
$$\Phi_{\rm halo}(x,y,z) = \Phi_s(\tilde{r}(x,y,z))$$

$$\tilde{r} \equiv \frac{r_a + r_T}{r_a + r_A} r_A$$

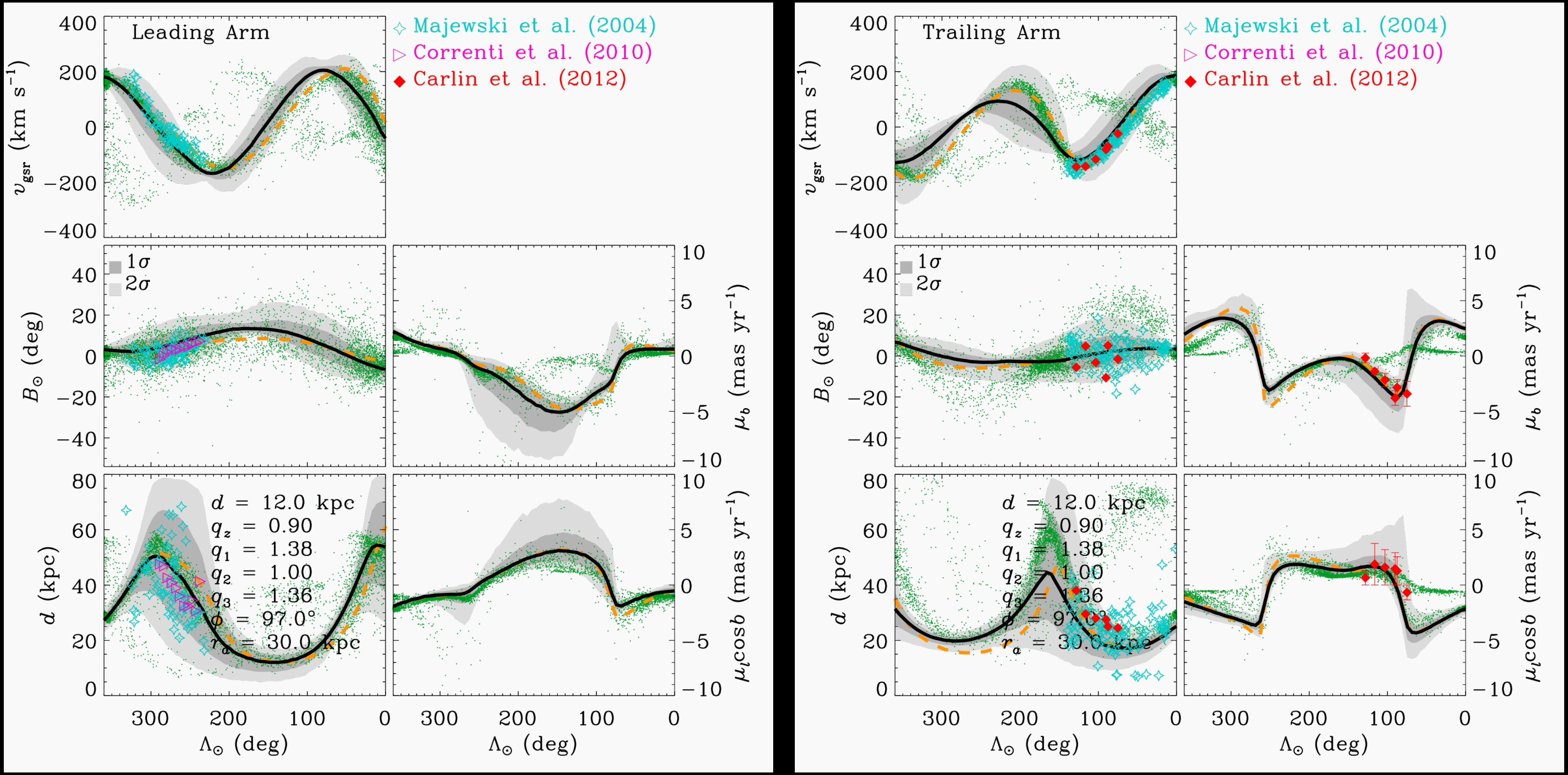
$$r_A^2 \equiv x^2 + y^2 + \frac{z^2}{q_z^2} = R^2 + \frac{z^2}{q_z^2},$$

$$r^2_T = x^2/q_2^2 + y^2/q_1^2 + z^2/q_3^2$$

- $r \ll r_a$ → $\check{r} \sim r_A$ axisym
- $r \gg r_a$ → $\check{r} \sim r_T$ triaxial



Solution. I: Inner oblate halo

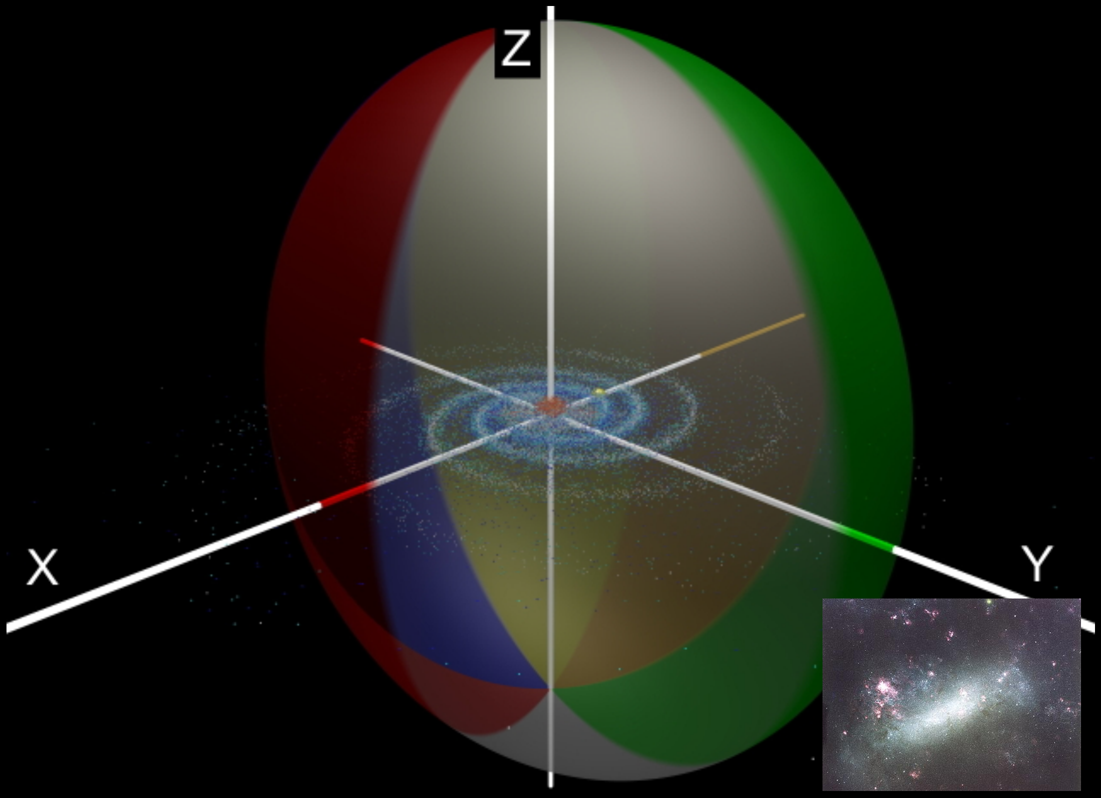


Vera-Ciro & Helmi, 2013

- Very good fit to the positions and velocities
- Where data is present, effectively indistinguishable from purely triaxial model
- Physically more plausible: oblate in disk dominated region (R < 10 kpc)

Solution: A triaxial halo?

- We have fixed the stability/ formation problem of the disk
- Potential is still a bit odd on large scales
  - unexpectedly axisymmetric
  - inconsistent with LCDM
- Long axis along z:
  - consistent with distribution of satellites around Milky Way
- Why long axis along y??!!



LMC

The effect of the LMC

- Compare torque by LM triaxial halo on Sgr to that by LMC: τ = r x F

  Sgr plane of motion has y ~ 0, and strongest pull by halo is in y-direction ➔ focus on τ_z

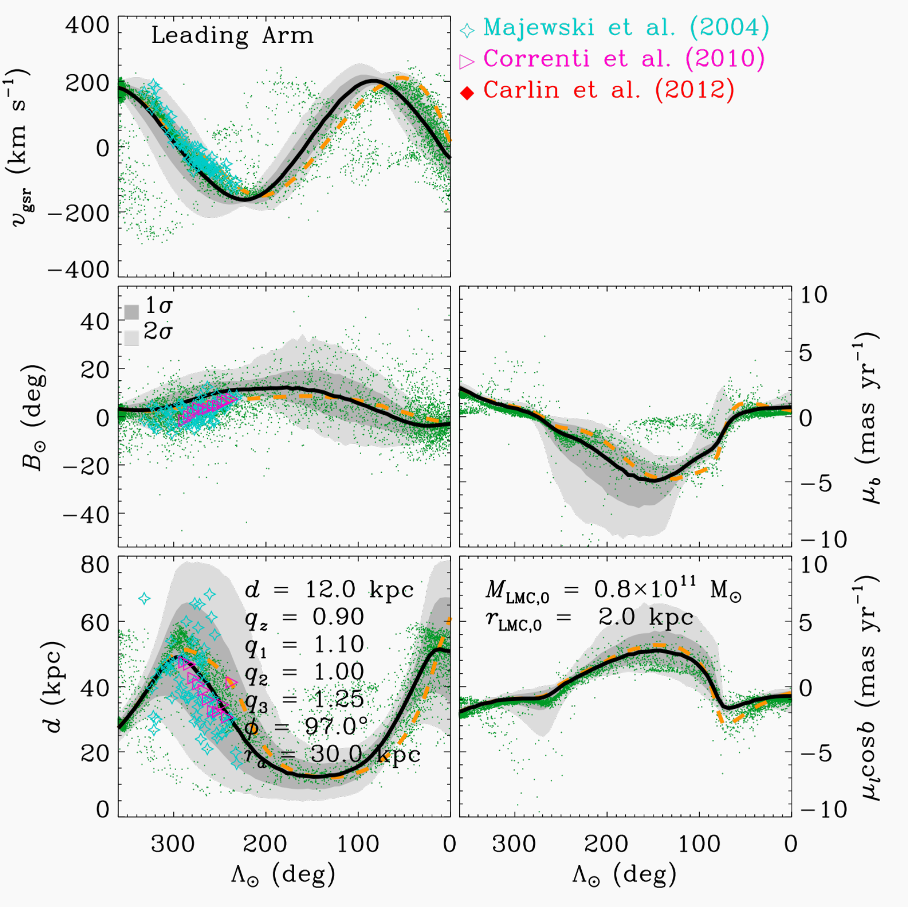
- The relative strength

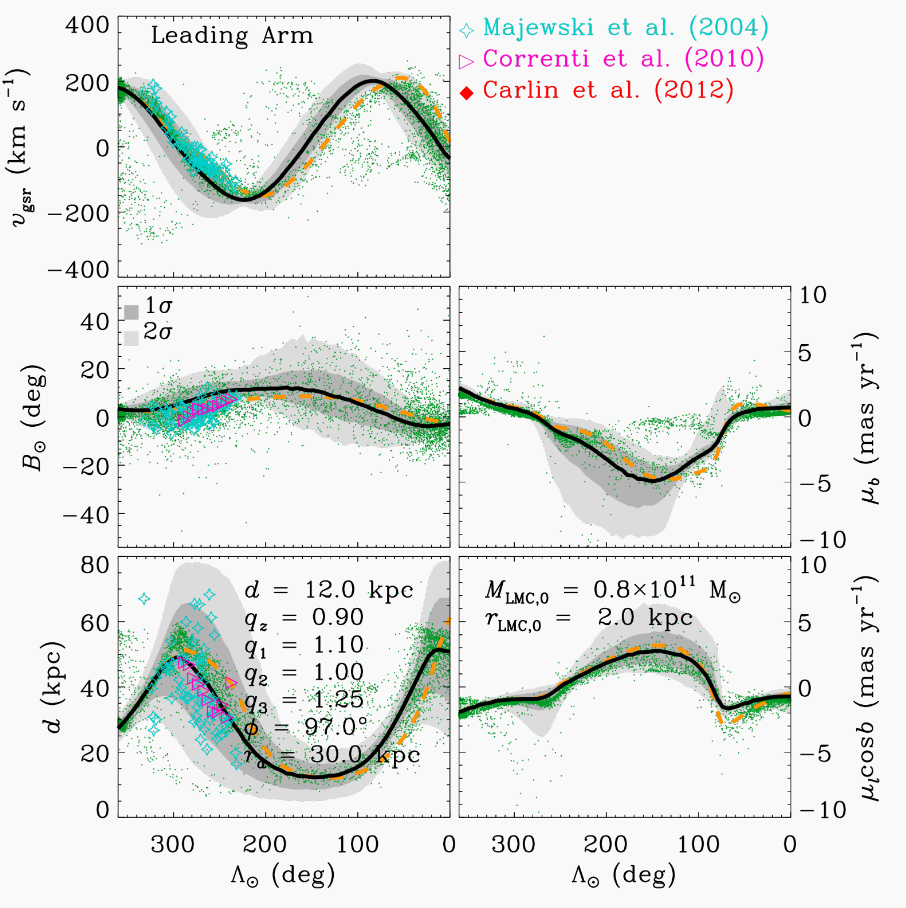
$$\frac{\tau_z^{\mathrm{LMC}}}{\tau_z^{\mathrm{halo}}} \sim \frac{M_{\mathrm{LMC}}}{M_{\mathrm{halo}}(\tilde{r})} \frac{\tilde{r}^3}{r^3_{\mathrm{sgr/LMC}}} \frac{y_{\mathrm{LMC}}}{y} \frac{1}{1/q_1^2 - 1}$$

  - M_{halo}(15 kpc = today's Sgr pos) ~ 10^{11} Msun ~ M_{LMC} (Besla et al. 2010)
  - ř ~ 15 kpc, while r_{SGR2LMC} ~ 30 kpc
  - All factors of similar order > torque ratio is of order unity!

- Orbital integrations now including
  - More triaxial Galactic dark halo, less elongated in y-direction (q_1 ~ 1.1)
  - Hernquist sphere to represent LMC, M_{LMC} ~ 8 x 10^{10} Msun, r_s ~ 2 kpc
    - On orbit consistent with current estimates of proper motions, position and los velocity

Solution. II.





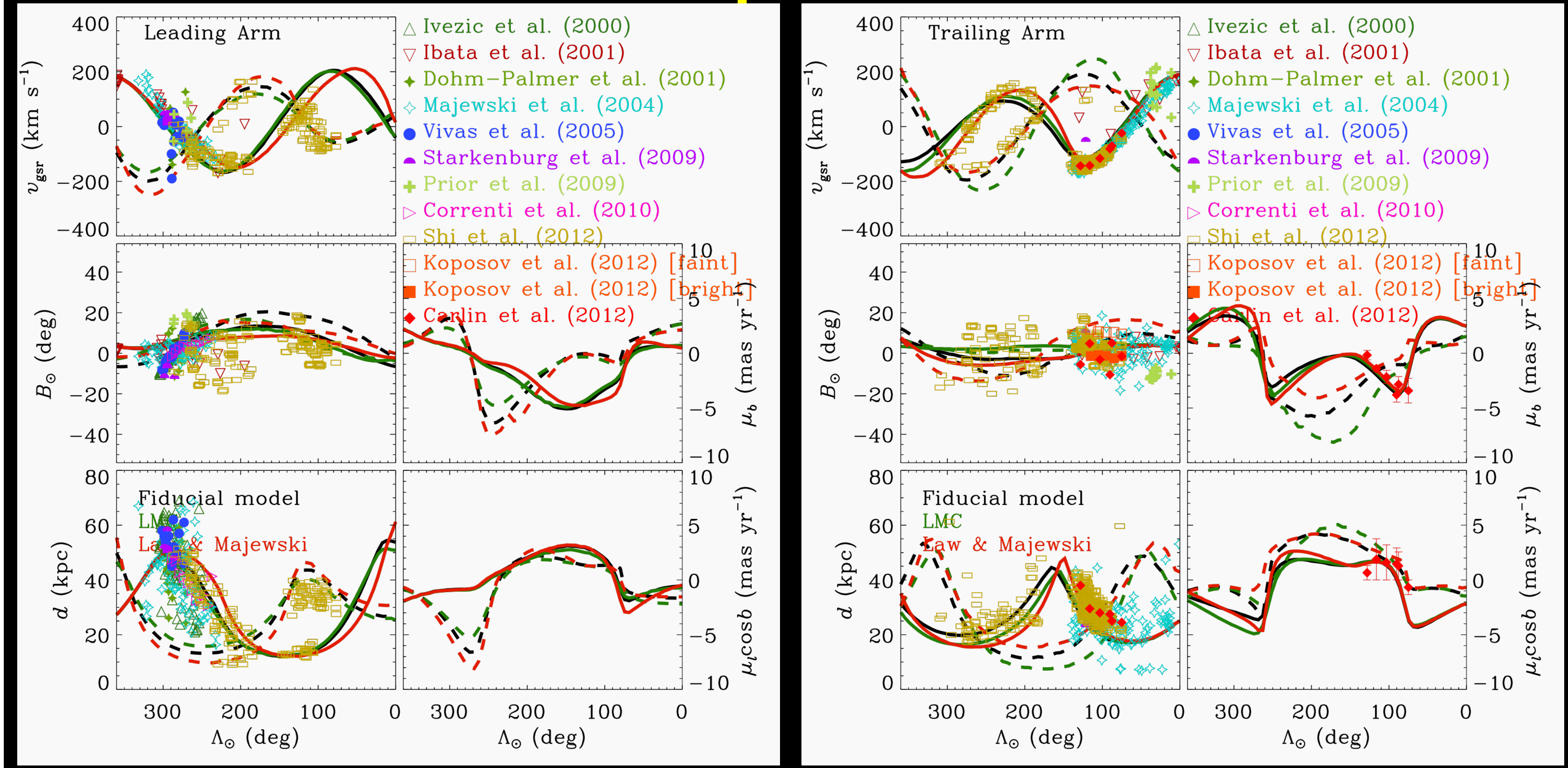
Vera-Ciro & Helmi, 2013

Fits including the LMC and more realistic triaxial halo are just as good!

At large distances $c/a_\Phi \sim 0.8$, $b/a_\Phi \sim 0.9$

(exploration of parameter space not exhaustive)

Comparisons



Vera-Ciro & Helmi, 2013

- Differences between models are small, are slightly more apparent for older wraps
  - Need more systematic searches of parameter space to establish robustness of predictions
  - N-body simulations as streams do not follow single orbit

Summary

Streams useful tracers of dark halo potential: Sgr dwarf tails to constrain shape

- Triaxial models by Law & Majewski (2010) fit all observables, but are odd
  - Oblate spheroid normal to disk plane (baryonic effects/instability)
  - Shape inconsistent with LCDM

Solution

- Halo changes shape with radius, i.e. oblate towards the disk (R < 10 kpc)
  - $q_z \sim 0.9$

- The effect of the LMC is not negligible, and torque on Sgr orbit is important
  - Triaxial halo now has c/a ~ 0.8 and b/a ~ 0.9, more consistent with LCDM