Milky Way's Gravitational Acceleration Field Measured from RR Lyrae in Gaia

Chris Wegg

Ortwin Gerhard and Marie Bieth

Observatoire de la CÔTE d'AZUR

LAGRANGE

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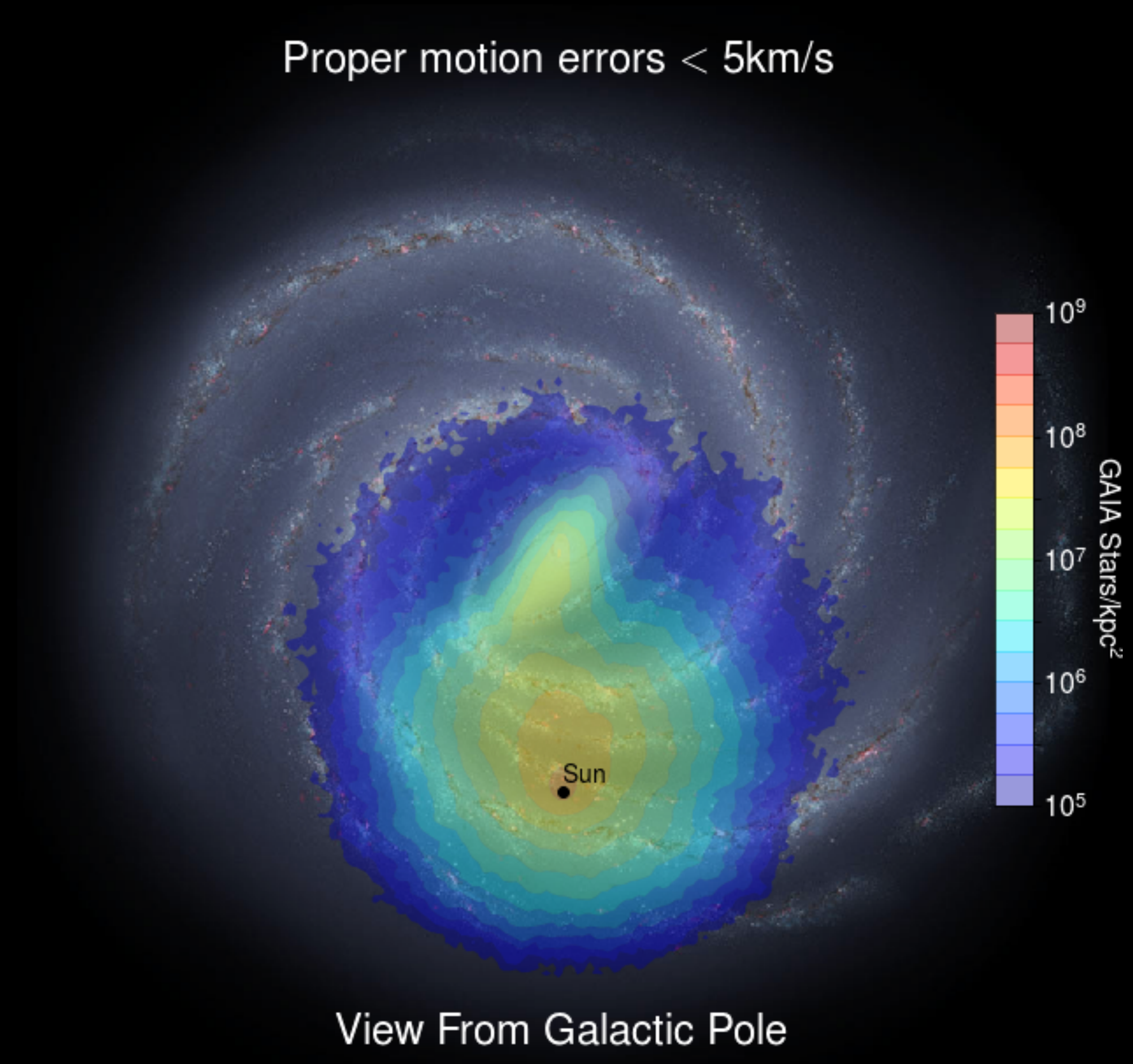
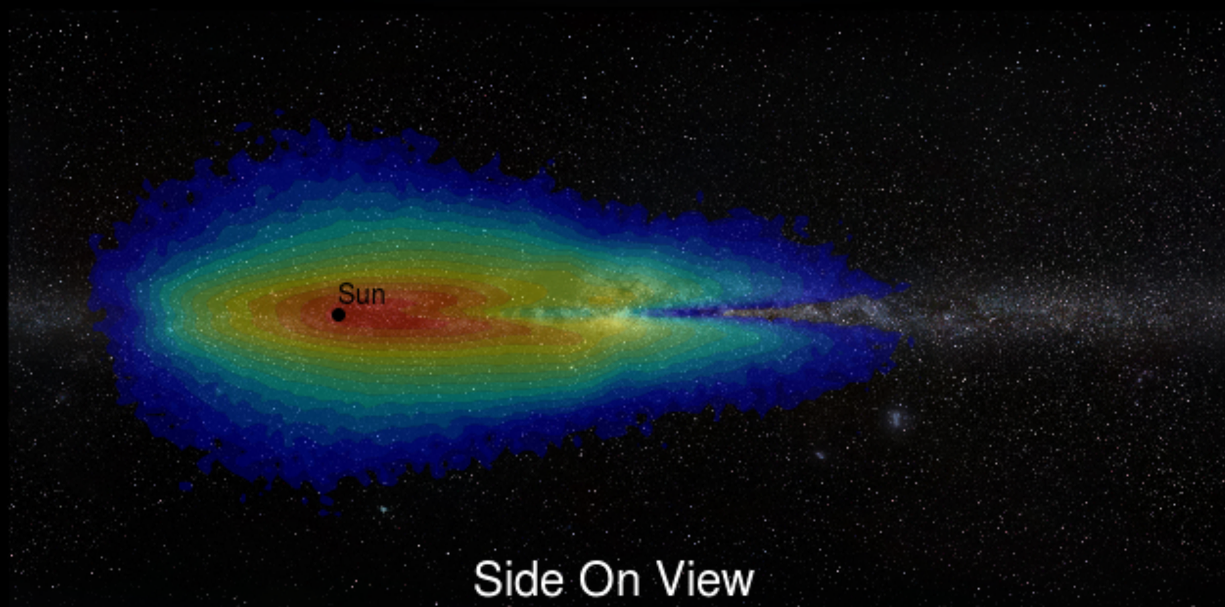
The Gaia Era





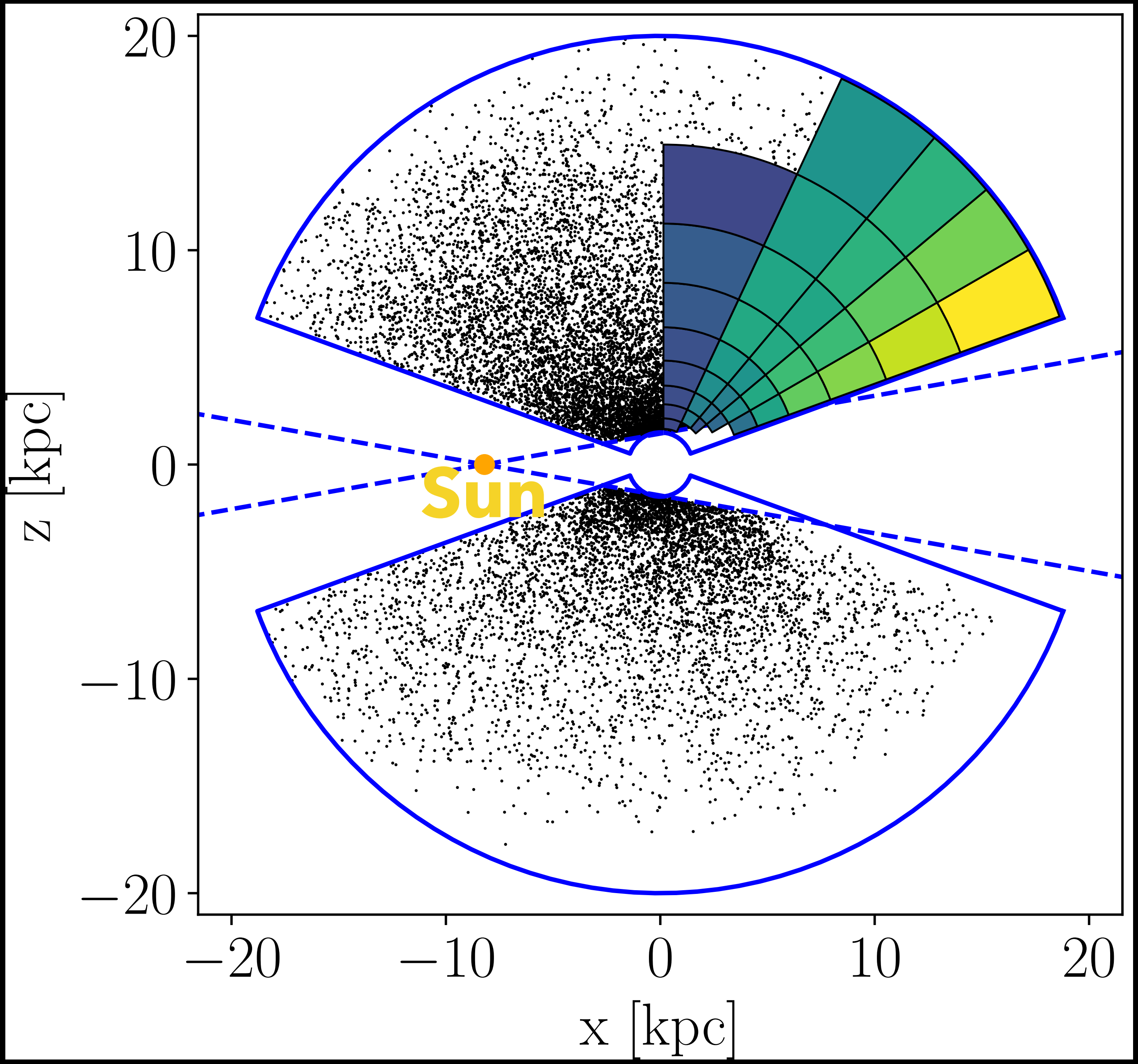
Galactic Archeology is about using the Milky Way as a prototype to understand how galaxies formed and evolved

This session – the distribution of DM in our halo

- Gaia has detected stars over a large fraction of the Galaxy
- Gaia's horizon for accurate parallaxes lies close to the sun
- But we still have very accurate proper motions – good to ~20kpc for horizontal branch stars.
- Can make exquisite dynamical models ***if we have accurate distances***

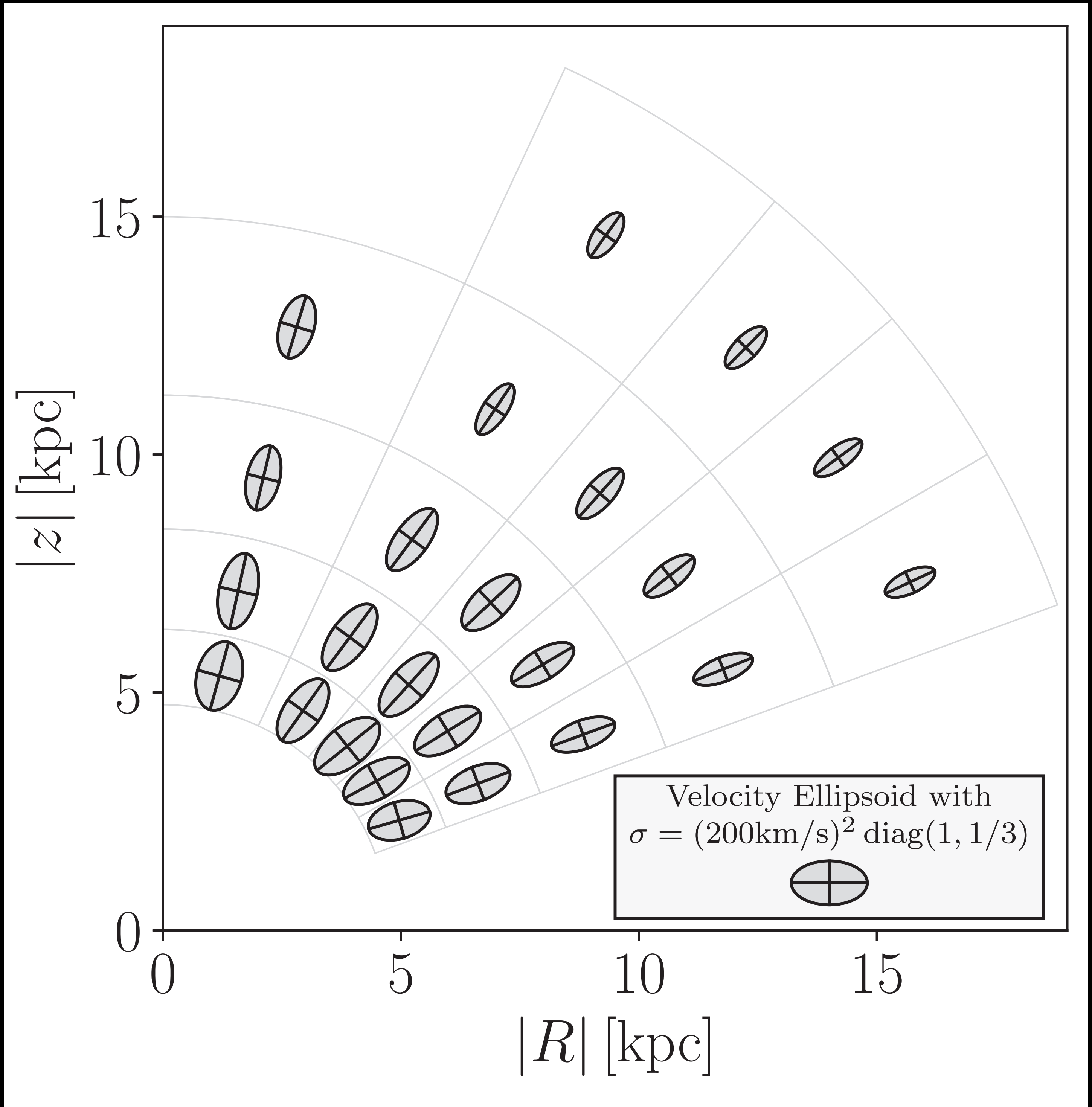
Halo RR Lyrae in Gaia DR2

- We use 16,000 RR Lyrae between 1.5kpc and 20kpc, avoiding the Galactic plane. From catalog by Sesar *et al.* (2017) using Pan-Starrs 3π survey
- Each has a accurate distance, and therefore transverse velocity from Gaia DR2
- But we have no radial velocities
- By assuming that are constant in rings around the galactic center we measure 3D kinematics



Kinematics of Halo RR Lyrae in Gaia DR2

- The halo is strongly radially anisotropic
- The velocity ellipsoid is nearly aligned in to spherical coordinates everywhere



The Gravitational Force Field of The Milky Way

- We have kinematics in 3D across a large fraction of the inner Galaxy. We can put these into the Jeans Equations to learn about the forces!
- If everything was isotropic things would be easy

$$\frac{1}{\rho}\frac{\partial \rho \sigma^2}{\partial r} = -F_r$$

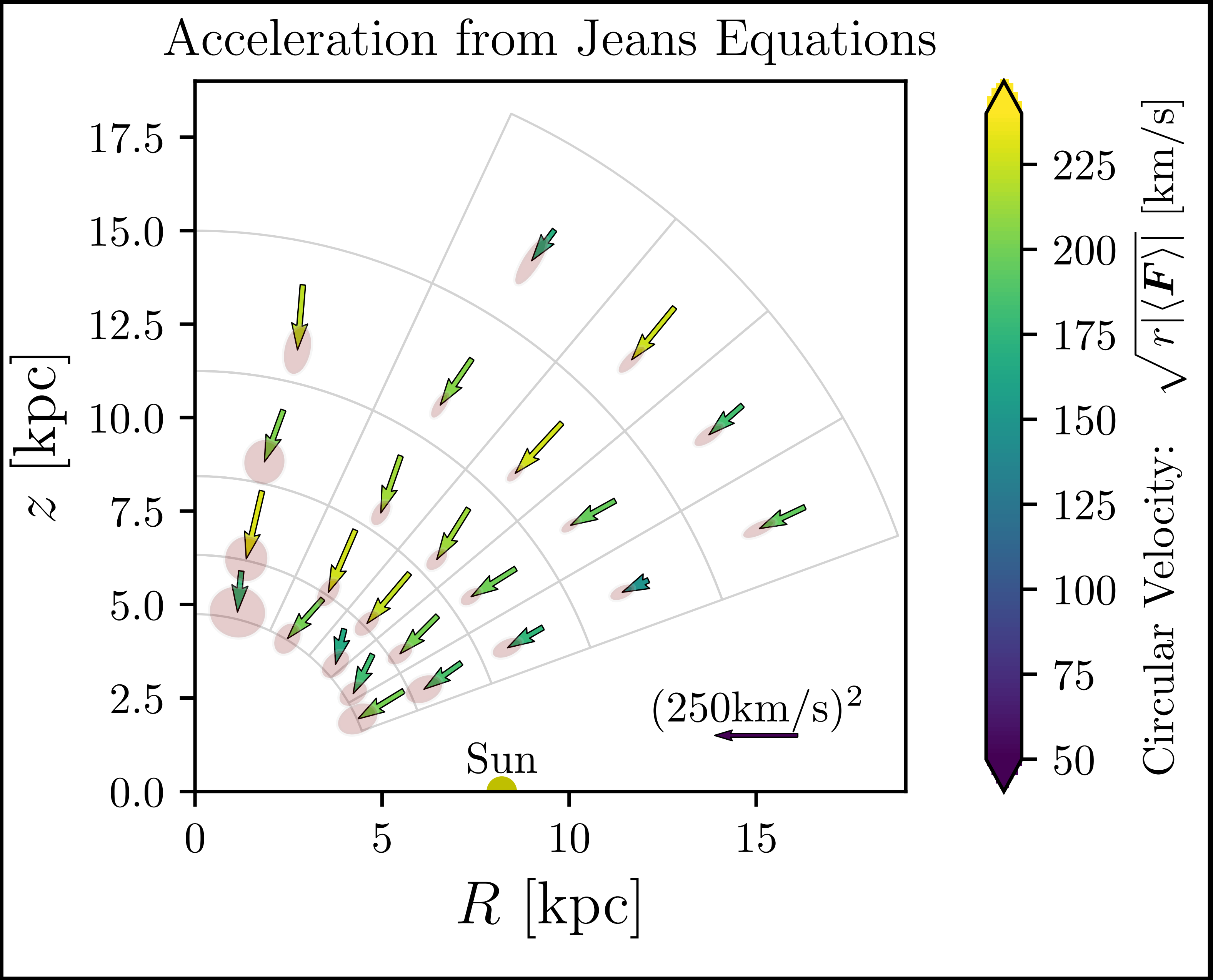
- But galaxies aren't isotropic, and so there's extra terms that we can't usually measure
- But the Milky Way is different
- Equations are long, but straightforward… and we have all the kinematic measurements we need from Gaia

$$\frac{\partial \rho \langle v_r^2 \rangle}{\partial r} + \frac{1}{r}\frac{\partial \rho \langle v_r v_\theta \rangle}{\partial \theta} + \frac{\rho}{r}\left[2\langle v_r^2\rangle - \langle v_\theta^2\rangle - \langle v_\phi^2\rangle + \langle v_r v_\theta\rangle \cot\theta\right] = -\rho\langle F_r\rangle$$

$$\frac{\partial \rho \langle v_r v_\theta \rangle}{\partial r} + \frac{1}{r}\frac{\partial \rho \langle v_\theta^2 \rangle}{\partial \theta} + \frac{\rho}{r}\left[3\langle v_r v_\theta\rangle + (\langle v_\theta^2\rangle - \langle v_\phi^2\rangle) \cot\theta\right] = -\rho\langle F_\theta\rangle$$

The Gravitational Force Field of The Milky Way

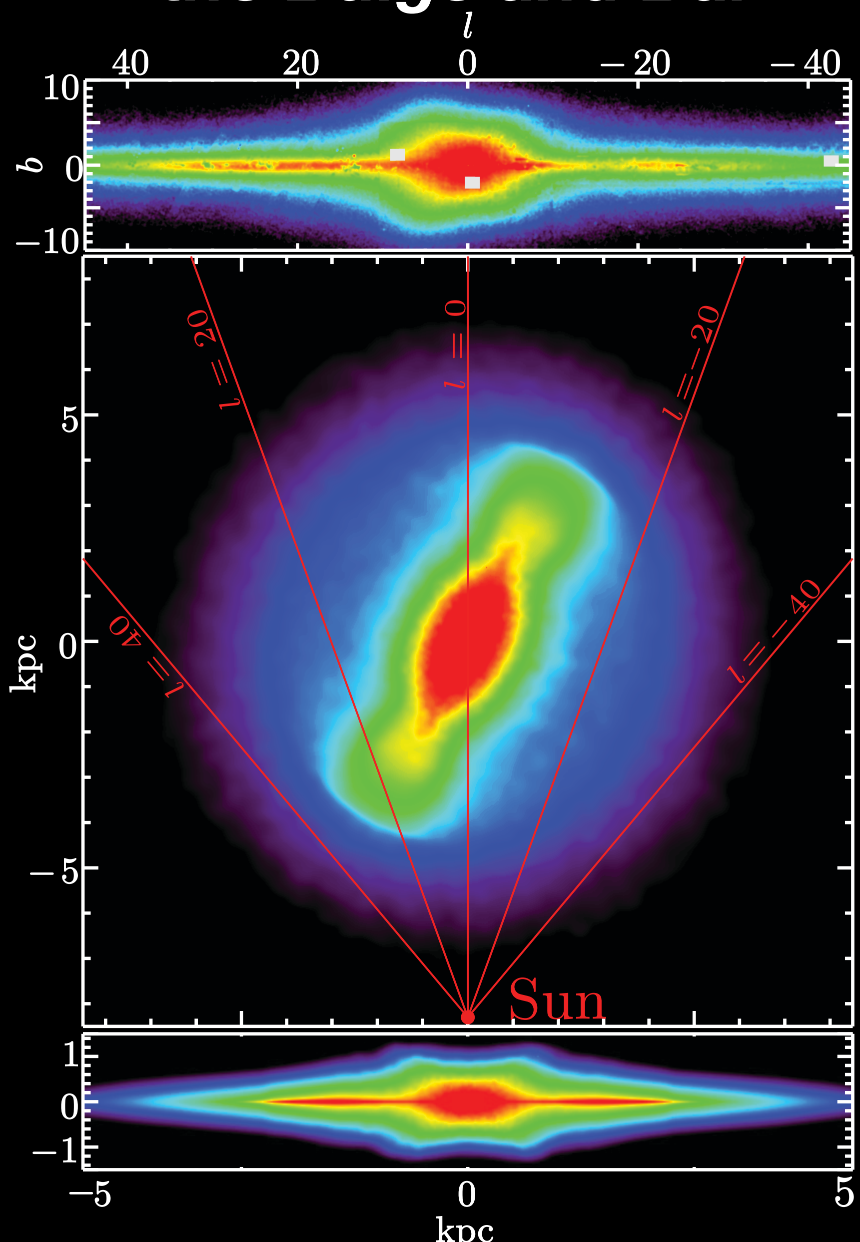
- Each arrow is a force measurement
- The pink ellipses have show the 1 sigma errors *ie* each arrow head can lie anywhere within the ellipse
- We can already see that the forces in the Milky Way are mostly radial



To get the dark matter contribution we need to subtract baryonic models

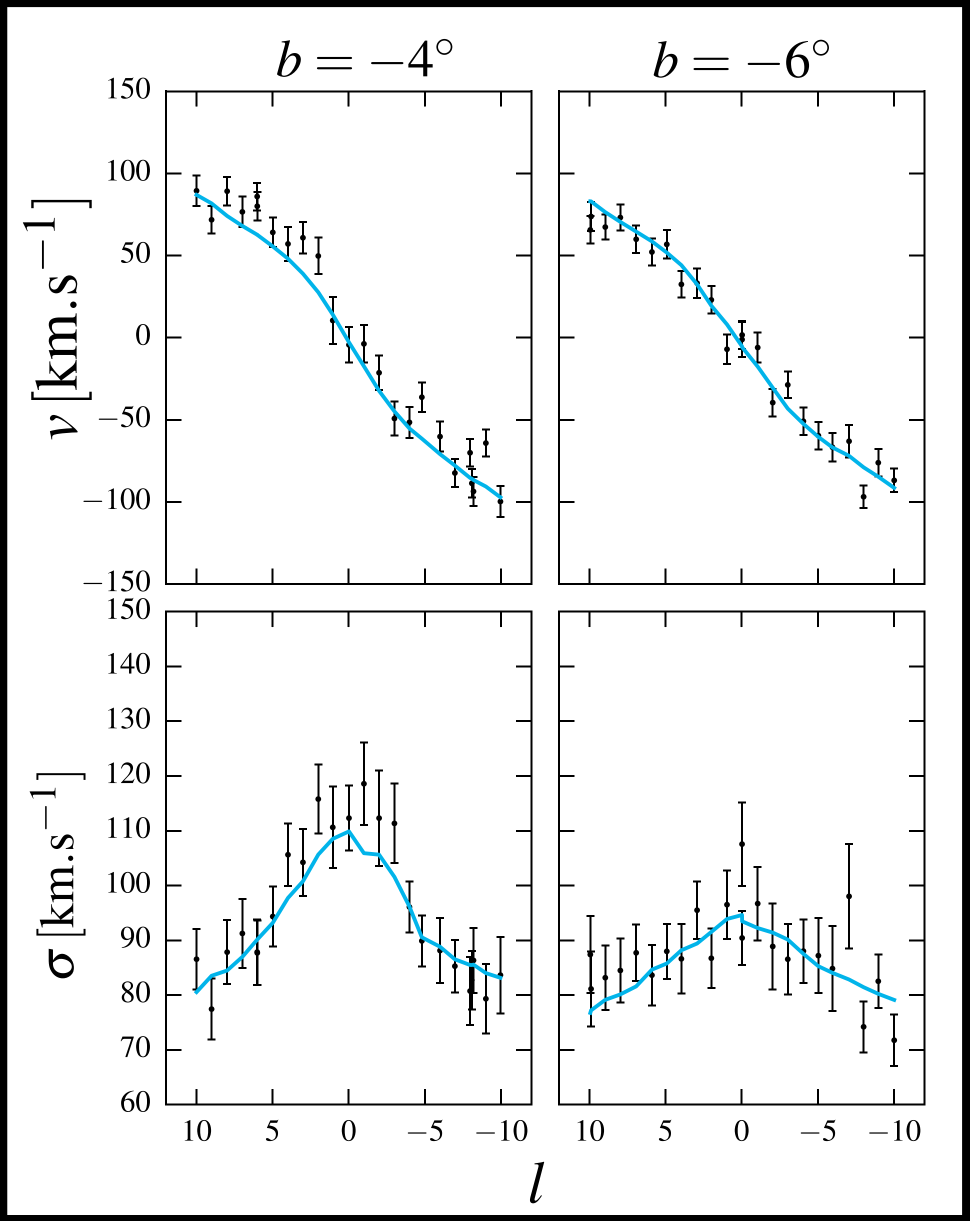
Constraints on Baryonic Models

Density maps & star counts in the Bulge and Bar



Shape of the stellar distribution:
CW & Gerhard (2013)
CW, Gerhard & Portail (2015)

Radial Velocities from spectroscopic surveys: BRAVA & ARGOS

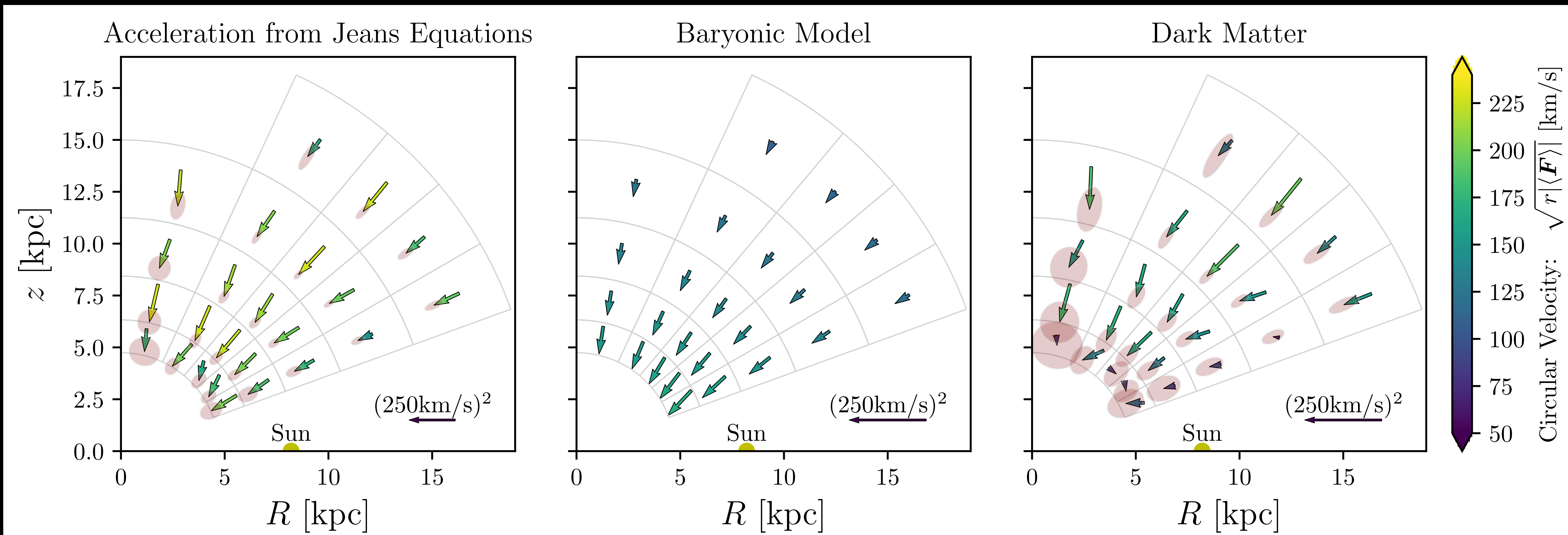


Stellar kinematics:
BRAVA: Kunder *et al* (2012)
ARGOS: Ness *et al* (2013)

Models fit to the central 5kpc. Outside use exponential disk surface density of stars and gas

The Gravitational Force Field of The Milky Way

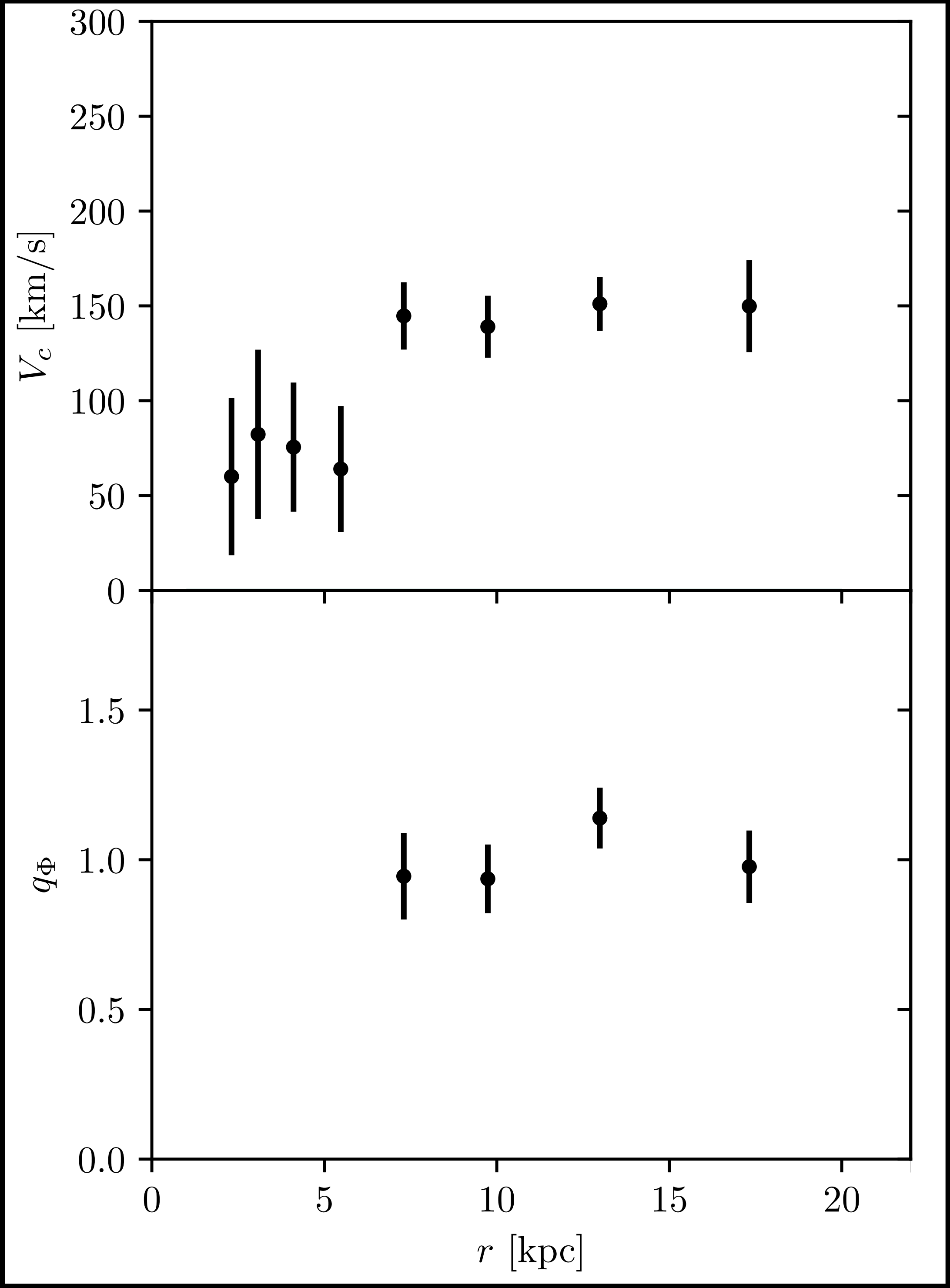
- Subtract the baryonic part to see the contribution from the dark matter



The Shape of the Milky Way's Dark Matter Halo

- We can use the forces to measure the DM flattening q_Φ and circular velocity V_c
- We can infer the profile of the flattening of the dark matter in the Milky Way
- Consistent with spherical:

$$q_\Phi = 1.01 \pm 0.06$$

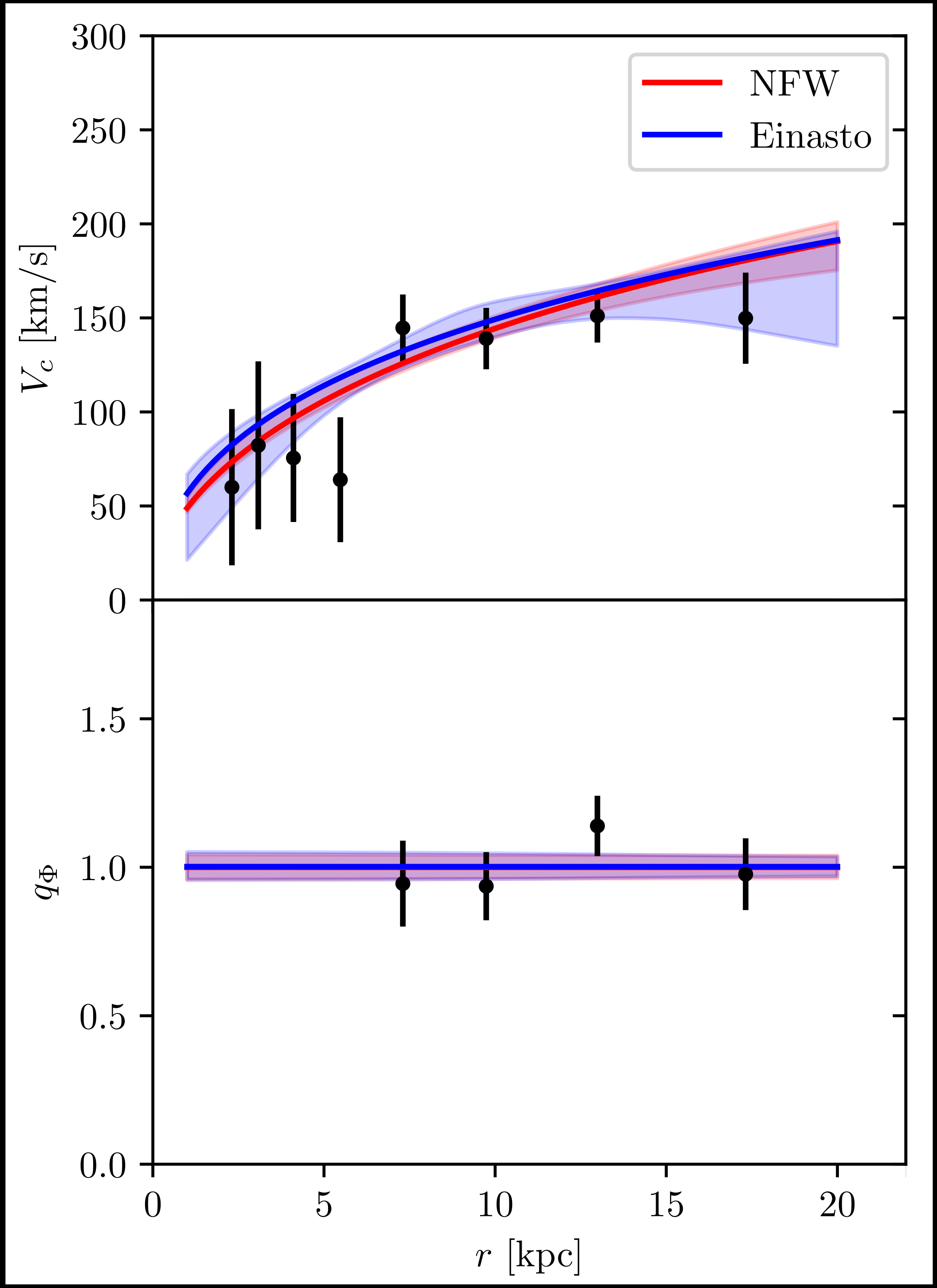


The Shape of the Milky Way's Dark Matter Halo

- We have also fit parametric dark matter models to the force field
- A range of dark matter profiles fit the data, but all agree on the flattening

$$q_\rho = 1.00 \pm 0.09$$

- $q_\rho < 0.8$ is ruled out at 99% significance



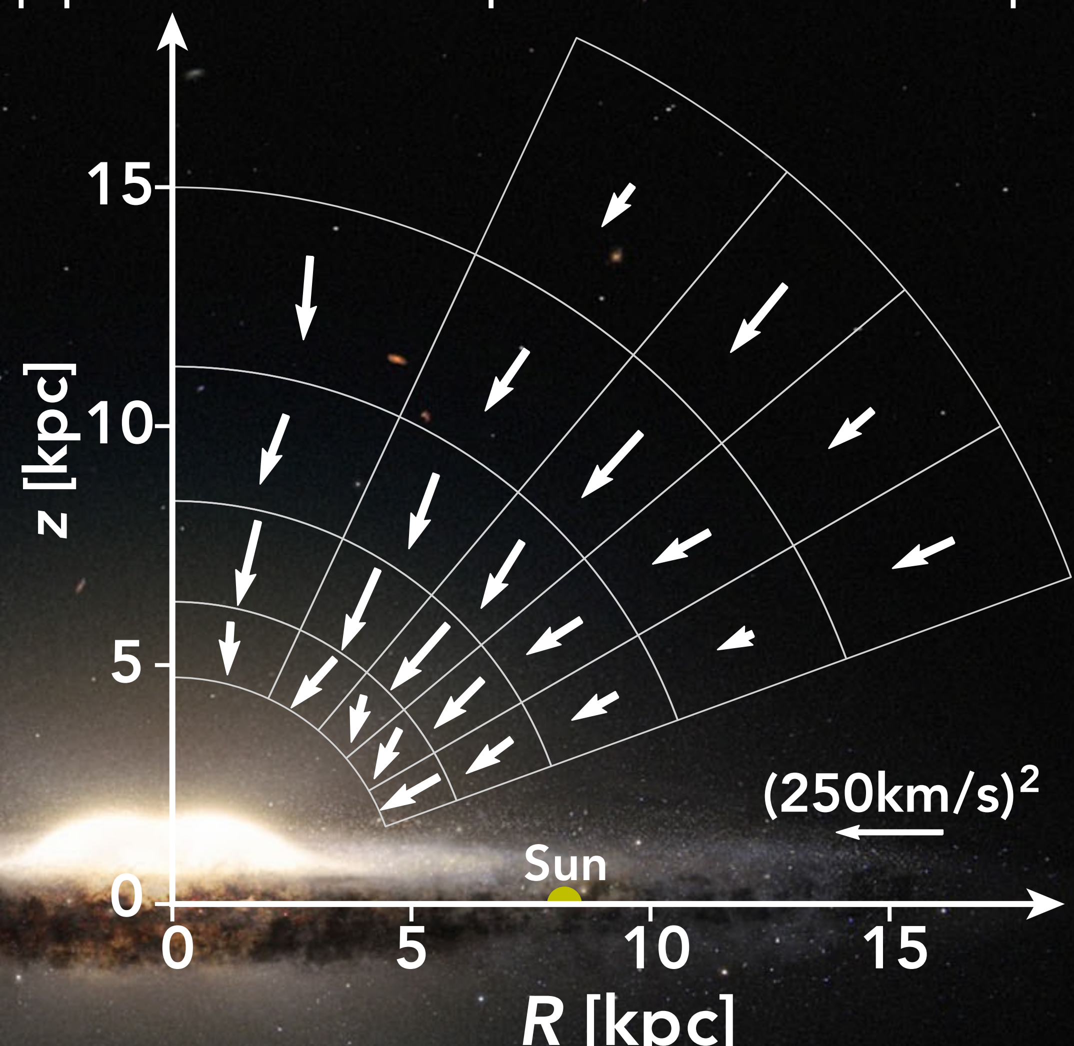
The Shape of the Milky Way's Dark Matter Halo

What does it mean?

- Our flattening value of $q_\rho = 1.00 \pm 0.09$ agrees with several other recent measurements of a near spherical halo
- Most common method for measuring halo shape are halo streams. Bovy (2016) finds $q_\rho = 1.05 \pm 0.14$. Similar to Koposov et al (2010), Bowden et al (2015), Kupper et al (2015)
- Such a spherical halo appears in tension with current LCDM simulations:
  - Dark Matter only simulations predict $\langle q_\rho \rangle \approx 0.5$
  - Baryons increase this, but in most simulations only by 0.1-0.3 e.g. Kazantzidis+04/10

Summary

- Inner halo strongly radially anisotropic everywhere over the volume 4-20kpc
- Using Jeans equations we can measure the gravitational forces. Subtracting baryonic models we find the DM contribution.
- Our DM flattening value of $q_{\rho} = 1.00 \pm 0.09$ is similar and complementary to recent measurements of a near spherical halo using streams. MWs DM halo appears more spherical than expected from simulations.
- WEAVE & 4MOST will measure millions of stars in halo can use method to measure the halo 3D



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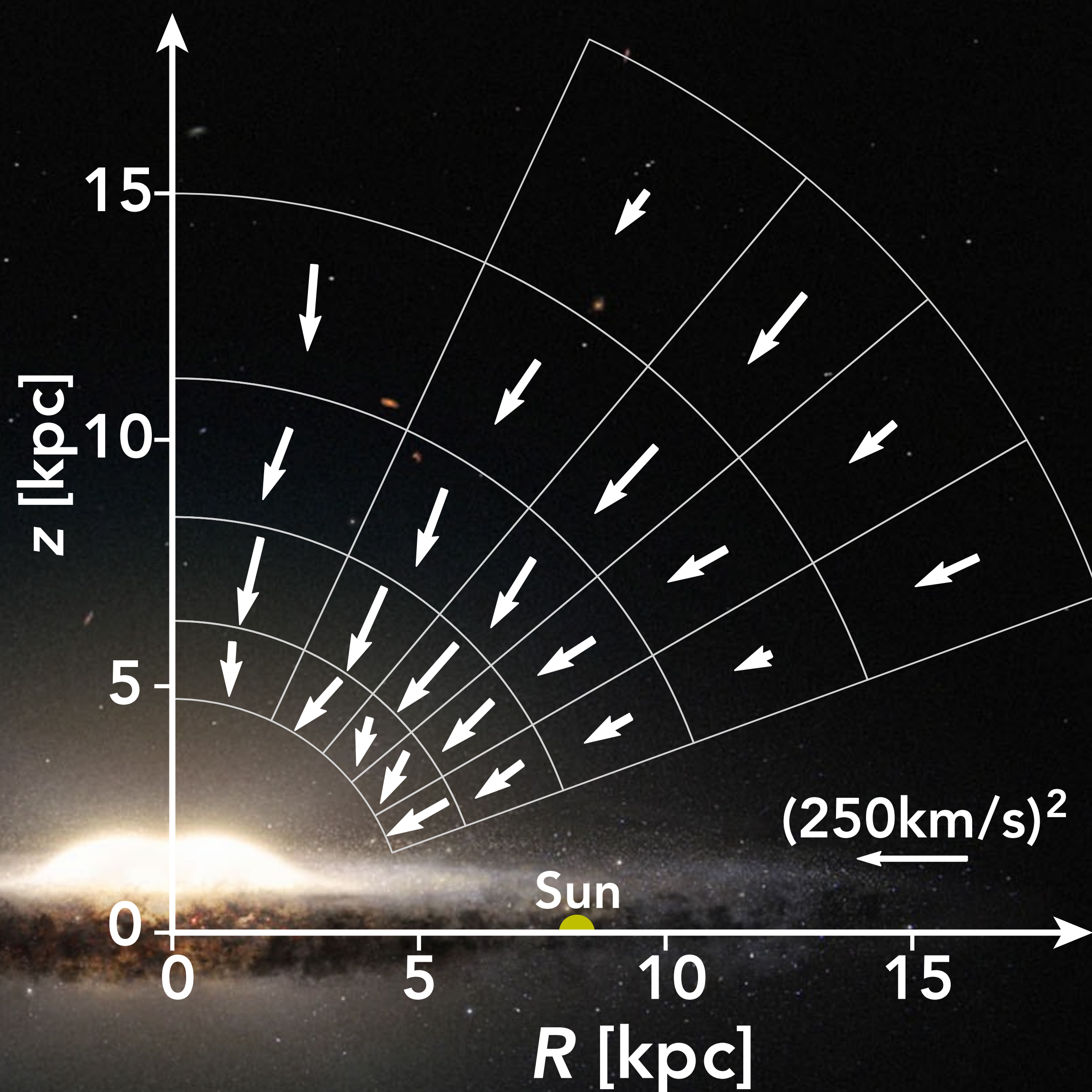
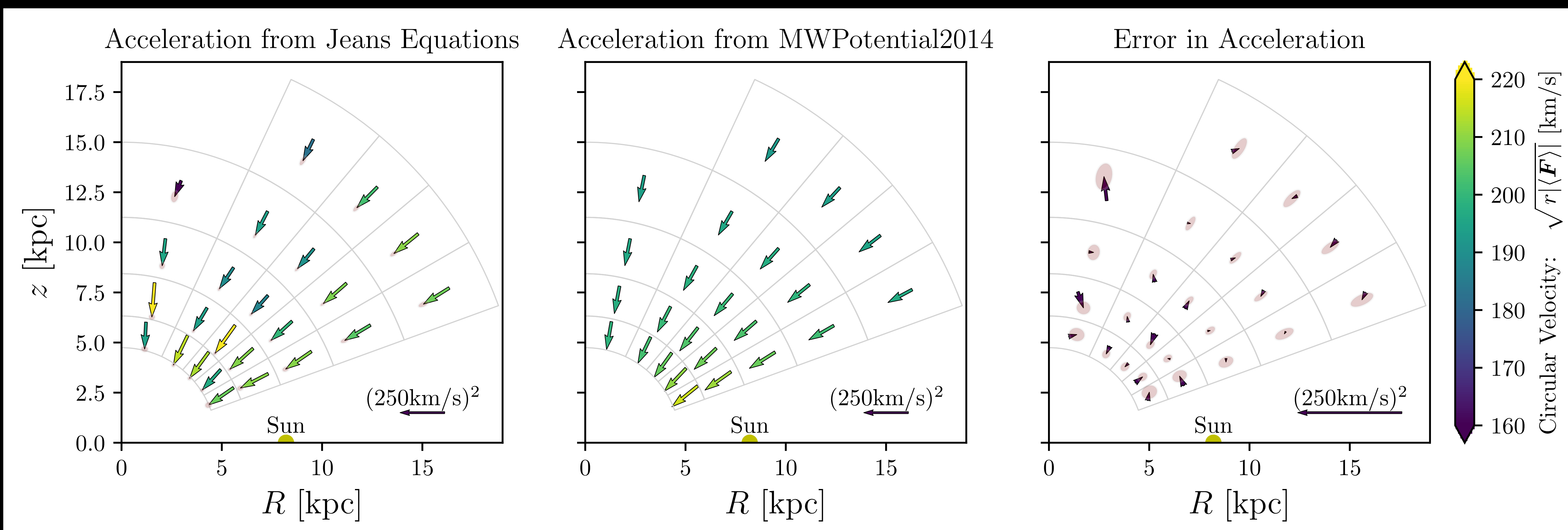


Non-axisymmetries and Non-Equilibria

- Generate toy halo by disrupting a satellite in fixed galpy potential. Looks similar to real halo in non-axisymmetries, profile, anisotropy
- Errors in acceleration are small, generally within errors
- Recover DM: $q_\rho = 1.01 \pm 0.03$ True was $q_\rho = 1$



Systematics

Variation	$V_c(R_0)$ [km s^{-1}]	$\rho_{dm}(R_0)$ [$M_\odot$/kpc^3]	q_ρ
Fiducial[a]	217	0.0092	1.00
$h_{R,\star}$ = 2.15 kpc[b]	217	0.0096	0.98
$h_{R,\star}$ = 2.68 kpc[c]	218	0.0091	1.03
$h_{R,\rm ism}$ = 3 × 2.4 kpc[d]	216	0.0090	1.04
$h_{R,\rm ism}$ = 1.5 × 2.4 kpc[e]	218	0.0094	0.98
P17 Boundary Model 1[f]	217	0.0094	0.99
P17 Boundary Model 2[g]	218	0.0093	1.01
RR Lyrae 0.03 mag brighter[h]	216	0.0095	0.99
RR Lyrae 0.03 mag fainter	219	0.0118	0.99
R_0 = 8.0 kpc	217	0.0090	1.04
R_0 = 8.4 kpc	216	0.0090	1.00
$v_\odot$ = (11.1, 255, 7.25) km/s	217	0.0089	1.02
$v_\odot$ = (11.1, 245, 7.25) km/s	218	0.0094	1.01
Fitting including Sgr Stream[i]	222	0.0083	1.06

- Systematics in flattening, q_ρ are at the level ± 0.04
- Smaller than the formal error of $q_\rho = 1.00 \pm 0.09$

[a] Uses stellar disk with scale length $h_{R,\star}$ = 2.4 kpc, gas disk with scale length $h_{R,\rm ism} = 2 \times 2.4$ kpc, and best fitting model of P17. This model has bar pattern speed $\Omega = 40$ km s^{-1} kpc^{-1}, mass-to-clump ratio $1000/M_\odot$ and nuclear stellar mass $2 \times 10^9 M_\odot$.

[b] Dynamical disk scale length measured by Bovy & Rix (2013). Has $\Sigma_\star(R_0) = 32 M_\odot/\mathrm{pc}^2$ to keep disk continuity at 5 kpc.

[c] Dynamical disk scale length measured by Piffl et al. (2014). Has $\Sigma_\star(R_0) = 44 M_\odot/\mathrm{pc}^2$ to keep disk continuity at 5 kpc.

[d] Has $\Sigma_{\rm ism}(R_0) = 16 M_\odot/\mathrm{pc}^2$ to keep disk continuity at 5 kpc.

[e] Has $\Sigma_{\rm ism}(R_0) = 10 M_\odot/\mathrm{pc}^2$ to keep disk continuity at 5 kpc.

[f] Uses bar pattern speed $\Omega = 37.5$ km s^{-1} kpc^{-1}, mass-to-clump ratio $900/M_\odot$ and nuclear stellar mass $2.5 \times 10^9 M_\odot$.

[g] Uses bar pattern speed $\Omega = 42.5$ km s^{-1} kpc^{-1}, mass-to-clump ratio $1100/M_\odot$ and nuclear stellar mass $1.5 \times 10^9 M_\odot$.

[h] Estimated systematic uncertainty by S17

[i] We remove the Sagittarius Dwarf, but leave the tail of the stream in the sample.