Thin and Thick Disk as Seen by Gaia - The Circular Velocity Curve of the Milky Way

Eilers et al. (2019), Nitschai et al. (2021)

Zuzanna Ryduchowska and Erin Corcoran

The Circular Velocity Curve of the Milky Way from 5 to 25 kpc - Anna-Christina Eilers et all 2019

- Measure highest precision Vc(R) of MW across Galactocentric distances 5<=R<=25 kpc
- Sample of >=23,000 luminous red giant stars with precise parallaxes measured combining spectral data from APOGEE and photometric info from WISE, 2MASS, and Gaia.
- M e Sun

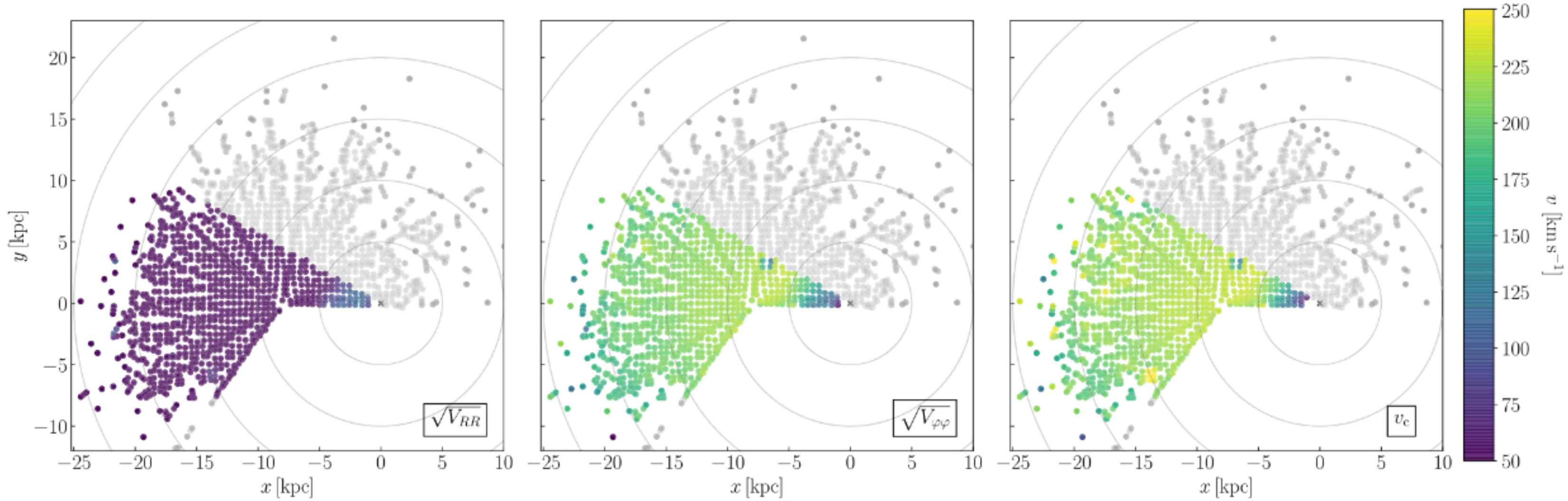


Figure 2. Maps of the Milky Way colored by the components of the velocity tensor $\sqrt{V_{RR}}$ (left panel), $\sqrt{V_{\varphi\varphi}}$ (middle panel), and v_c (right panel). Each dot represents an average of the ensemble of stars located within 1 kpc^2 in the x- and y-directions. Stars in the gray region are not taken into account for our analysis of the circular velocity curve.

Circular velocity

The circular velocity Vc(R) is the speed at which a test particle must orbit the Galactic center, at the height of galactic plane, to maintain a stable, circular orbit at a given Galactocentric radius can be defined as:

$$v_c^2(R) = R\frac{\partial \Phi}{\partial R}|_{z=0}$$

Total Enclosed Mass and Rotation Curve

Assuming a particle is on a circular orbit at radius r, there is a relationship between the circular velocity v_c and $\frac{d\Phi}{dr}$

$$\frac{d\Phi}{dr} = \frac{GM(<r)}{r^2} = \frac{v_c^2}{r}$$

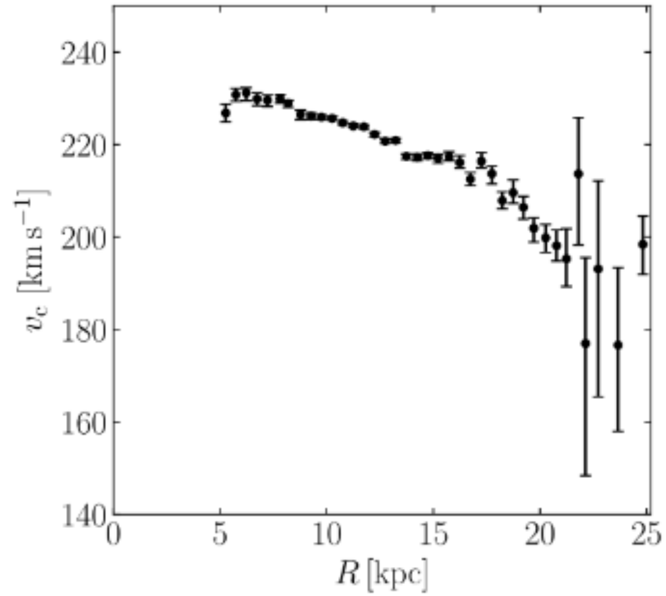
Using this relation, the Jeans Equation can be written as

$$v_c^2 = \frac{GM(<r)}{r} = -\overline{v_r^2}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\overline{v_r^2}}{d\ln r} + 2\beta\right)$$

From this expression, we see that if we can measure the density of stars ν, the velocity dispersion in the radial direction, and anisotropy function, we can determine the enclosed mass inside some radius

Why measuring circular velocity is important

- If we measure Vc(R) at many radii, we can reconstruct how much total mass is present at each distance
- As we have good constraints of Baryonic matter, with having circular velocity we can construct local dark matter density
- The observed gentle decline of circular velocity curve rather than a steep one is direct evidence that an extended dark matter halo provides extra gravitational support
- The slope of the declining curve constraints which dark matter density profile best fits the data, revealing how dark matter is spatially distributed in the halo



Methodology

Similar to us in class authors used Jeans equations to obtain circular velocity, however they assumed axisymmetric not spherical symmetric potential which leads to cylindrical form of Jeans equations:

$$\frac{\partial \nu \langle v_R^2 \rangle}{\partial R} + \frac{\partial \nu \langle v_R v_z \rangle}{\partial z} + \nu \left(\frac{\langle v_R^2 \rangle - \langle v_\varphi^2 \rangle}{R} + \frac{\partial \Phi}{\partial R} \right) = 0$$

The equation can be solve in form:

$$v_c^2(R) = \langle v_\varphi^2 \rangle - \langle v_R^2 \rangle \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \langle v_R^2 \rangle}{\partial \ln R} \right)$$

Assumption: radial density profile for the tracer population exponential with R_exp = 3kpc

$$\nu(R) \propto \exp\left(-\frac{R}{R_{\exp}}\right)$$

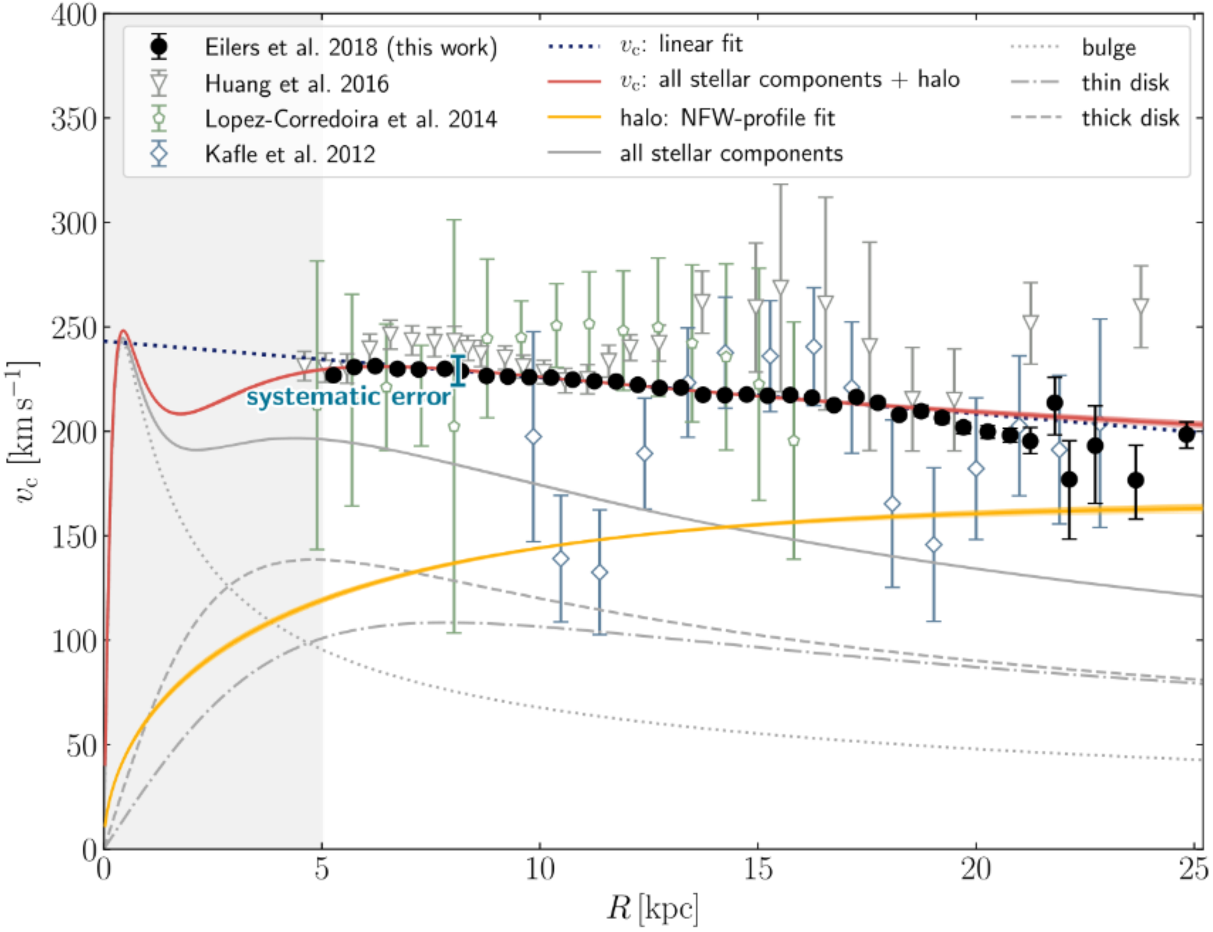
Results

$$v_c(R_\odot) = (229 \pm 0.2)\text{km s}^{-1}$$

$$\alpha_c = (-1.7 \pm 0.1)\text{km s}^{-1}\text{kpc}^{-1}$$

$$\rho_{\text{dm}}(R_\odot) = 0.30 \pm 0.03\,\text{GeV}\,\text{cm}^{-3}$$

A decline of circular velocity curve has not been observed in many other disk galaxies in local Universe, they have been only reported at higher redshift



Four parameters describe the Navarro-Frenk-White dark matter halo profile:

$$\rho_{\rm DM} = \rho_s \left(\frac{m}{r_s}\right)^{\alpha_{\rm DM}} \left(\frac{1}{2} + \frac{1}{2}\frac{m}{r_s}\right)^{-3-\alpha_{\rm DM}}$$

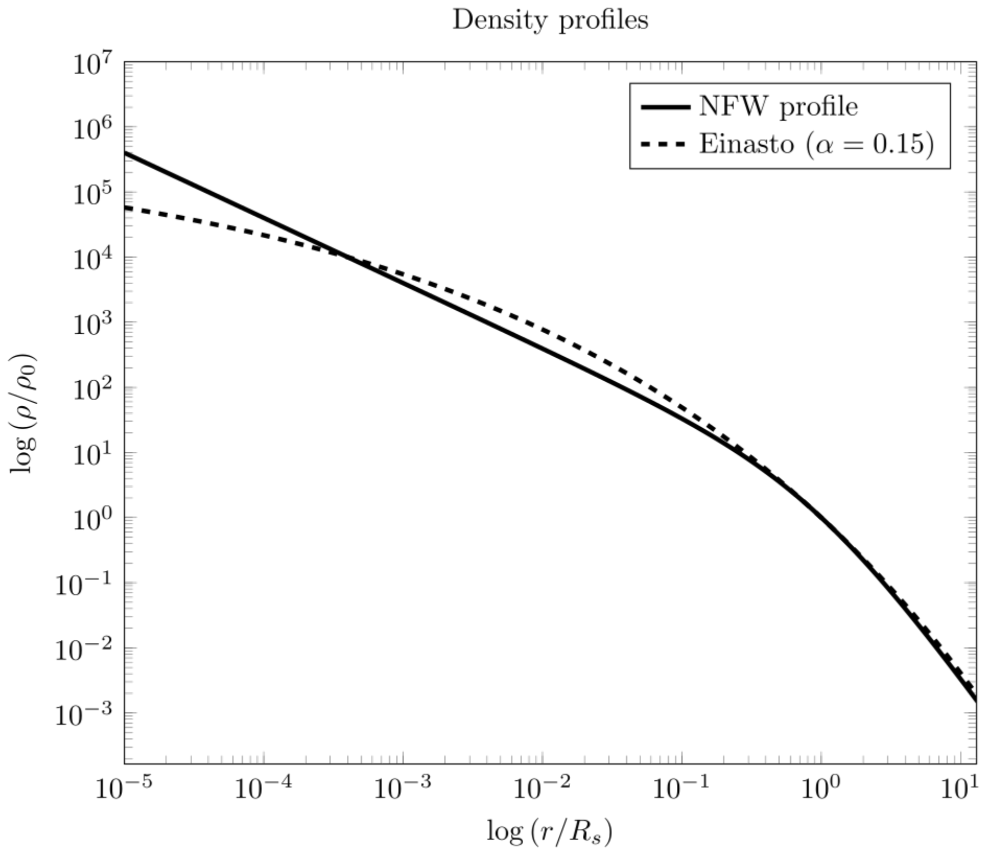
$$R_{\rm vir} = 189.3 \pm 2.2\,{\rm kpc}$$

$$M_{\rm vir} = (7.25 \pm 0.25) \times 10^{11}\, M_\odot$$

$$R_s = 14.8 \pm 0.4\,{\rm kpc}$$

$$\rho_0 = (1.06 \pm 0.09) \times 10^7\, M_\odot\,{\rm kpc}^{-3}$$

Milky Way dominated by dark matter for R> 14 kpc

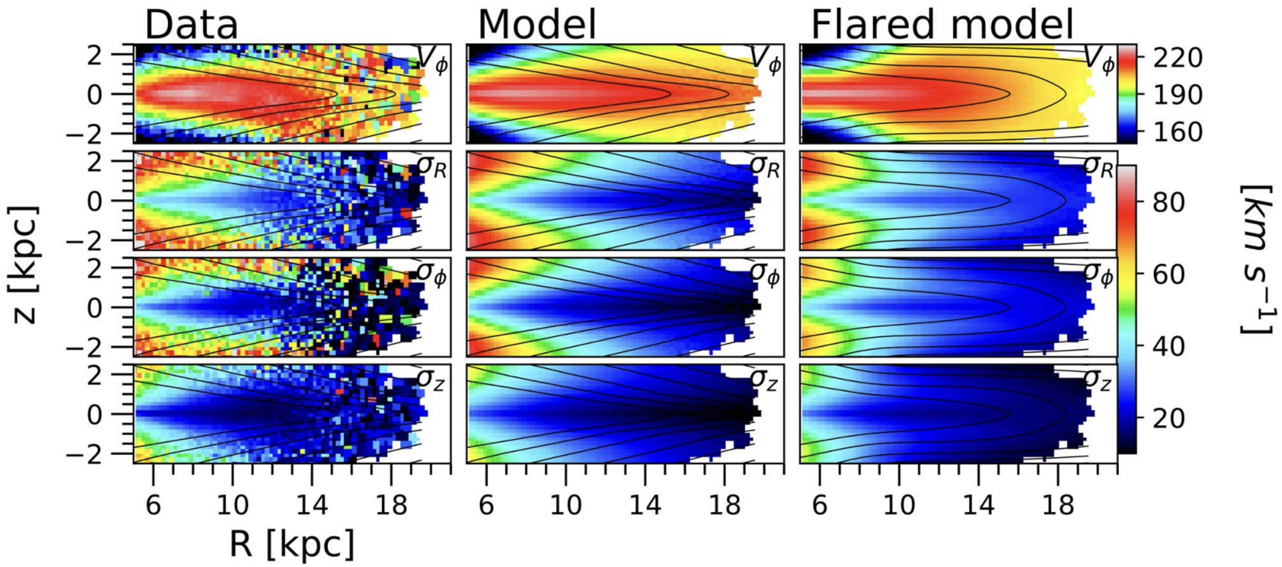


By W - Own work

Plot of NFW dark matter profile for α_{DM} =-1

Dynamical Model of the Milky Way Using APOGEE and Gaia Data - Nitschai et al 2021

- Combined Gaia EDR3 + APOGEE data to model stellar velocities and velocity dispersion
- Large sample of 2.86 million RGB stars
- Covers radius of $5 \leq R \leq 19.5$ kpc, $|z| \leq 2.5$ kpc
- Applied spherically aligned Jeans Anisotropic Modeling (JAM) to model 2D spatial distributions

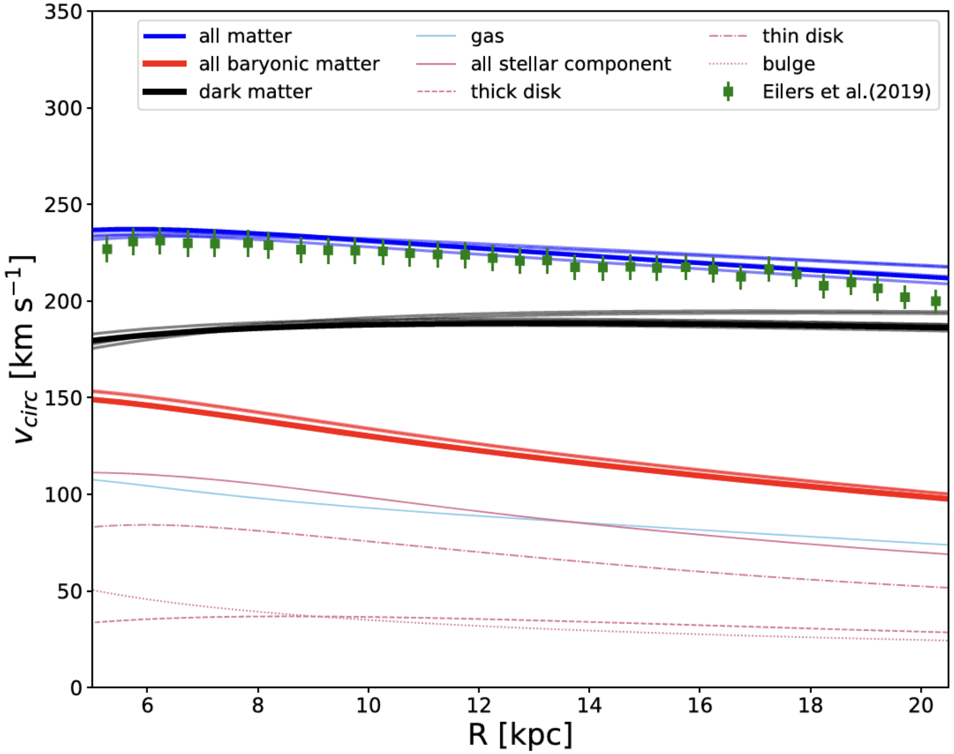


Dynamical Model of the Milky Way Using APOGEE and Gaia Data - Nitschai et al 2021

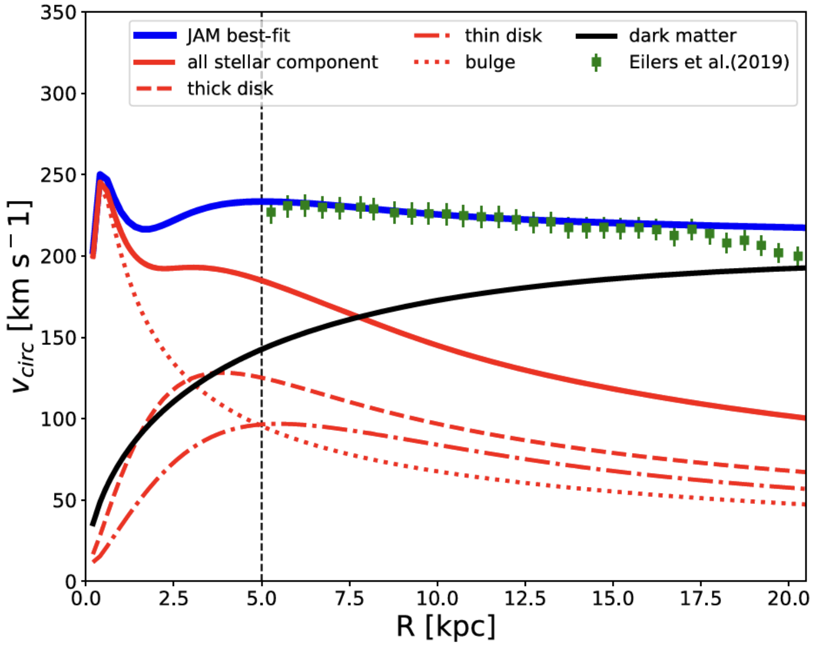
- Calculated circular velocity at the solar radius 234.7 km/s and a rotation curve with a declining slope of -1.78 km/s/kpc
  - Both consistent with Eilers et al. (2019)

- The dark matter has a logarithmic density slope of −1.602
  - Steeper than the standard NFW profile assumption of -1

- Implies the mass of the Milky Way is more concentrated toward the center than previously believed



Comparison of Results



	$v_c(R\odot)(kms^{-1})$	$\alpha_c(\mathrm{km/s/kpc})$	$\rho_{\mathrm{dm}}(R_\odot)(\mathrm{GeVcm}^3)$
Eilers (2019)	229.0	−1.7	0.30
Nitschai (2021)	234.7	−1.78	0.339