196. The rotation curve of our Galaxy

A GALAXY'S ROTATION CURVE describes the circular rotation speed as a function of radial distance. It provides important constraints on the galaxy's mass distribution. Since the work of Rubin et al. (1978), the flat rotation curves observed in spiral galaxies, in contrast to those expected from the *observed* mass distribution, is generally attributed to the presence of dark matter.

For our own Galaxy, the rotation curve similarly provides strong constraints on the mass distribution of its major structural components (bulge, thin and thick disk, and halo), including the effects of dark matter (e.g. Sofue et al., 2009; Salucci et al., 2010; Weber & de Boer, 2010; Sofue, 2012; Wang et al., 2015; Wang et al., 2020).

DEFINING OUR Galaxy's rotation curve is not straightforward. In the inner regions, it has been mainly determined from radio observations of the gas in the spectral lines of H I and CO (e.g. Burton & Gordon, 1978; Clemens, 1985; Fich et al., 1989; Levine et al., 2008).

Beyond the solar circle, it can be derived from the kinematic motions of suitable tracer populations, including H II regions (Fich et al., 1989; Brand & Blitz, 1993), planetary nebulae (Schneider & Terzian, 1983; Amaral et al., 1996; Maciel & Lago, 2005), classical Cepheids (Pont et al., 1997; Gnaciński, 2019; Mróz et al., 2019), blue horizontal branch stars (Xue et al., 2008; Deason et al., 2012; Kafle et al., 2012), red clump giants (Bovy et al., 2012; López-Corredoira, 2014; Huang et al., 2016), and masers (Honma et al., 2012; Reid et al., 2014; Gromov & Nikiforov, 2021).

This has been extended into the outermost regions of the Galaxy using the dynamics of globular clusters or dwarf galaxies (Spitler & Forbes, 2009; Watkins et al., 2010; Boylan-Kolchin et al., 2013; Li et al., 2017), most recently using data from Gaia DR2 (Li et al., 2020).

A compilation of 2780 measurements between 3–20 kpc, `galkin`, is given by Pato & Iocco (2017). And although often subject to large random and systematic errors, the general consensus is that the rotation curve is roughly constant at $R \sim R_0$, and fairly flat or with a slow decline at larger radii, at least out to $2R_0$, implying the presence of invisible or dark matter in the outer parts.

NEW DETERMINATIONS are being derived based on Gaia data, exploiting the much larger number of stars, much greater accuracies in distances and proper motions, and star classification.

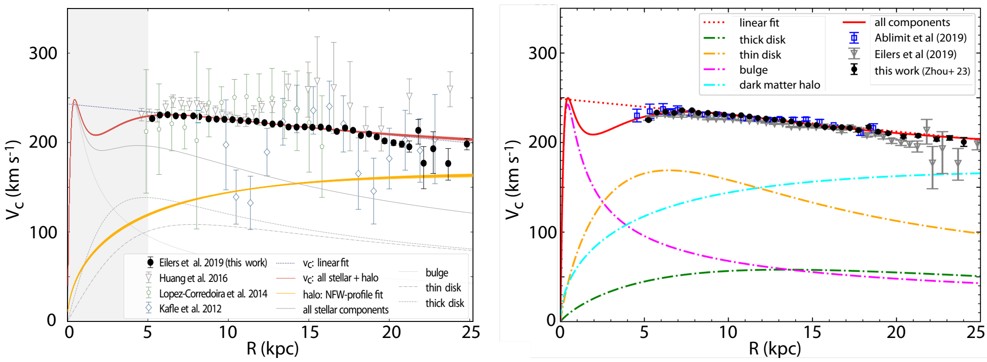
FROM AN APOGEE DR14 sample of red giants from Hogg et al. (2019), and Gaia DR2 data, Eilers et al. (2019) used 23 000 thin disk stars to determine the rotation curve between 5–25 kpc, based on a Jeans model, and assuming an axisymmetric gravitational potential.

The Gaia-based error bars of Eilers et al. (2019) are significantly smaller than previous determinations, but still result in large uncertainties beyond 20 kpc. This is clearly seen as the filled circles in their Fig. 3 (shown over, top left). This figure also shows the contributions due to the thin and thick disks (assuming the model profiles of Miyamoto & Nagai, 1975), the bulge (assume the spherical potential of Plummer, 1911), as well as their fit to a Navarro–Frenk–White (NFW) dark matter halo profile (Navarro et al., 1997).

THEIR *'most precise measurements of the circular velocity to date'* shows a gently declining slope beyond 5 kpc, -1.7 ± 0.1 km s^{-1} kpc^{-1}, in reasonable agreement with the classical Cepheid determination by Mróz et al. (2019), but less shallow than some earlier studies which have suggested a flat circular velocity curve (e.g. Bovy et al., 2012; Bovy & Rix, 2013; Reid et al., 2014).

The gradient is important because disk galaxies in the local Universe typically show a flat or even *increasing* rotation curve (e.g. Rubin et al., 1980; Sofue et al., 1999), while galaxies with declining curves have only been reported at higher redshift. This effect seen in the early Universe has been attributed to baryons efficiently condensing at the centres of dark matter halos at a time when gas fractions were higher and dark matter less concentrated (Genzel et al., 2017; Lang et al., 2017).

The rotation curve derived by Eilers et al. (2019) was used by de Salas et al. (2019) to evaluate the sensitivity of estimates of the local dark matter density to the assumed details of the dark matter halo, and the distribution of matter in the baryonic disk.

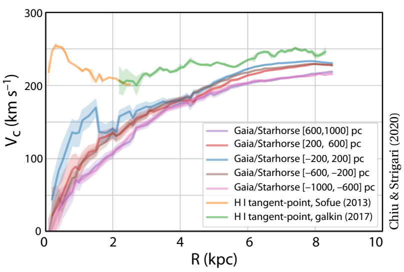


Gaia-based determination of the Galaxy's rotation curve from Eilers et al., 2019 (left) and Zhou et al., 2023 (right)

For the rotation curve within R_0, the assumption of circular orbits has underpinned use of the so-called 'tangent-point method' in interpreting the gas kinematics. This assumes that the observed radial velocity extremum along any line-of-sight is at the tangent point, allowing calculation of both Galactocentric radius and circular velocity (van de Hulst et al., 1954; Sofue, 2013).

Specifically, and pre-Gaia, Chemin et al. (2015) used numerical simulations to predict that, in part due to the effects of the bar, the tangent-point method overestimates the inner rotational velocity, and instead reflects local motions, concluding that *'the quest to determine the innermost rotation curve of the Galaxy remains open'.*

Indeed, a rather radical finding along precisely these lines was reported by Chiu & Strigari (2020). They used 6 million stars from Gaia DR2 to determine the rotation curve within the solar circle, which they compared with that derived from gas kinematics using the tangent-point method.



They found significant differences between the two methods: while the tangent-point curve is mostly in the range 200–250 km s^{-1}, that based on stellar kinematics increases to ~150 km s^{-1} at 2 kpc, rising to a plateau at 6–7 kpc. The peak using the tangent-point method at 1 kpc is absent in the curve based on stellar kinematics.

Using 54 000 thin disk red giants, selected from the APOGEE and LAMOST surveys and using astrometry from Gaia EDR3, Zhou et al. (2023) constructed the rotation curve from 5–25 kpc. With a 2–3 times larger sample than Eilers et al. (2019), their rotation curve also shows a weak decline beyond 5 kpc, with a similar gradient of $-1.83\pm0.02\pm0.07$ km s^{-1} kpc^{-1}, a circular velocity at R_0 of $234.04 \pm 0.08 \pm 1.36$ km s^{-1}, and a significantly better accuracy beyond 20 kpc (see figure, top right). They used this to construct a mass model for the Galaxy, yielding a mass of the dark matter halo $M_{200} = (8.05 \pm 1.15) \times 10^{11} M_\odot$, with $R_{200} = 192.37 \pm 9.24$ kpc, and a local dark matter density 0.39 ± 0.03 GeV cm^{-3}.

Further improvements came with Gaia DR3. Wang et al. (2023) extended the mapping to 30 kpc, and confirmed that the rotation curve indeed shows a significant decline of ~50 km s^{-1} between 15–30 kpc. The rotation curve (and azimuthal velocity) also presents a dependence on height above the disk for $R < 15$ kpc.

Ou et al. (2024) used APOGEE DR17 spectra combined with Gaia DR3, 2MASS, and WISE photometry, to construct the rotation curve out to 30 kpc. From more than 30 000 disk red giant branch stars they confirmed the previous findings. But they found an even faster decline beyond ~25 kpc, better matched to a 'cored Einasto profile' (Einasto, 1965) than the generalised Navarro–Frenk–White profile. It yields a significantly lower halo virial mass, in tension with mass measurements from globular clusters, dwarf satellites, and streams.

Jiao et al. (2023) compared the methods used in these Gaia-based determinations (Zhou et al., 2023; Wang et al., 2023; Ou et al., 2024). They also concluded that there is a sharp decrease in circular velocity of ~30 km s^{-1} between 19.5–26.5 kpc, matching a *Keplerian* decline, and so implying the absence of significant mass beyond 20 kpc (Zobnina & Zasov, 2020). This would imply a total Galaxy mass $2.0 \times 10^{11} M_\odot$, 4–5 times smaller than currently favoured estimates (essay 93).

It is too soon to conclude that the dark matter halo terminates at around 20 kpc, with all the implications that this would involve, and with the other inconsistencies that this might raise (e.g. Jiao et al., 2023, §6).

Meanwhile, work continues in probing other effects that might be complicating the determination and interpretation of the rotation curves, including the assumptions underlying use of the Jeans equation, the effects of coordinate transformations, and alternative models of (MOND-like) gravity (e.g. Chrobáková et al., 2020; Petersen & Frandsen, 2020; Natalia Cisneros et al., 2023).