Geometry-driven Milky Way rotation curve with Gaia DR3: direct comparison with DM and MOND paradigms.

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ABSTRACT

Rotation curves constitute the distinctive signature of disc galaxies and their stellar kinematics traces the gravitational potential due to different matter components. Therefore, we select 719'143 young disc stars within $|z| < 1$ kpc and up to $R = 19$ kpc from the Gaia DR3, providing a much larger sample of high-quality astrometric and spectro-photometric data of unprecedented homogeneity. This sample comprises 241'918 OBA stars, 475'520 RGB giants, and 1'705 Cepheides that we use to compare three different dynamical models: a classical one with a dark matter halo, the MOND analogue, and a general relativistic one derived from a dust disc-scale metric. The three models are found to explain, with similar quality, the new observed rotational velocities of the different stellar populations of our Galaxy, providing parameter estimates consistent with previous works. Moreover, predictions on the total baryonic mass are in agreement between the models, at least within the radial range covered by our samples. Finally, the geometrical effect is expected to drive the velocity profile from 10-15 kpc outwards, while being responsible for 30-37% of this profile already at the Sun distance, similarly to the halo contribution in the classical model and the pure MONDian boost in the low acceleration regime. With the best ever Gaia data at our disposal, we are not yet able to exclude either scenario, as they are statistically equivalent.

INTRODUCTION

The *ESA Gaia mission* delivers highly accurate kinematics of individual stellar components of the Milky Way that has been processed through general relativistic astrometric models [1]. For consistency, the MW reconstruction should be treated according to the theory underlining the data analysis: *General Relativity* (GR). On galaxy scales, common practice is to consider the Newtonian limit of Einstein's equations, while general relativistic effects are intended as weak corrections only. Therefore, in the **classical framework**, a massive **dark matter** halo is required to explain the observed flat profile of galaxy rotation curves. However, the small curvature limit in GR may not generally coincide with the Newtonian regime, as a **general relativistic model** for the Milky Way has been recently found successful in reproducing the observed rotation curve without the need for extra matter [2]. On the other side, the **MOdified Newtonian Dynamics** (MOND) [3] represents one of the most robust alternatives to dark matter on galaxy scales, since it has provided a remarkable predictive power in explaining several observational evidences, such as the Baryonic Tully Fisher Relation and the Radial Acceleration Relation. These reasons should suffice in pushing the investigation of *to what extent Newton's approximation of Einstein's field equations represents galactic dynamics.*

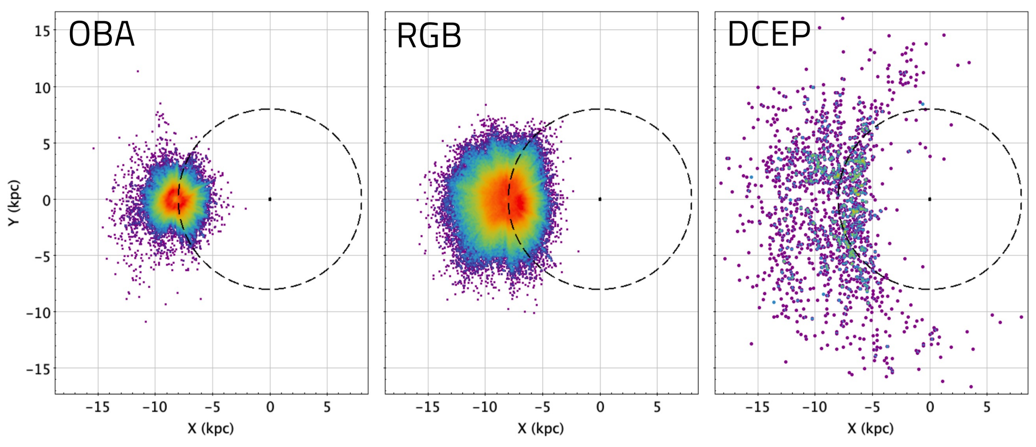
DISC TRACERS FROM GAIA DR3

From ~33 million stars with high precision astrometry and spectroscopic LOS velocities, we focus on three disc populations, namely:

- **O-,B-,A-type stars (OBA)** from the Golden Sample, kinematically selected based on the Toomre diagram to minimize possible halo contaminants. Trigonometric distances with parallaxes good up to 20%.
- **Red Giants (RGB)** with spectroscopic-derived metallicity $[M/H] > -0.5$ dex and disc-like kinematics. Only objects on nearly-circular orbits (eccentricity < 0.1) are retained. Distances from parallaxes good up to 20%.
- **Classical Cepheids (DCEP)** with distances estimated from photometry.

To avoid the influence of the MW bar a radial cut at 4.5 kpc is set, while halo stars are further discarded requiring $|z| < 1$ kpc. The final sample is made of 719'143 stars including 241'918 OBA, 475'520 RGB and 1'705 DCEP. Average rotation curves are finally derived for each disc population after binning data along the radial coordinate: as uncertainties, observed velocity dispersions are considered instead of bootstrapped ones.

Figure 1: Disc populations projected on the galactic plane. Most of OBA stars are within 2-3 kpc from the Sun, therefore local gravitational effects are expected. RGB giants are typically within 4-5 kpc of the Sun, while DCEP range up to 20 kpc: local effects are azimuthally averaged.



THREE DYNAMICAL MODELS

➤ **Classical model with dark matter (MWC)**:

- Plummer stellar bulge (2 DoF) + Miyamoto-Nagai thin and thick stellar discs (2 x 3 DoF):

$$\rho_b(r) = \frac{3b_b^2 M_b}{4\pi(r^2+b_b^2)^{5/2}} \qquad \rho_d(R,z) = \frac{M_d b_d^2}{4\pi}\frac{\left[a_d R^2 + \left(a_d + 3\sqrt{z^2+b_d^2}\right)\left(a_d+\sqrt{z^2+b_d^2}\right)^2\right]}{\left[R^2+\left(a_d+\sqrt{z^2+b_d^2}\right)^2\right]^{5/2}\left(z^2+b_d^2\right)^{3/2}}$$

- Navarro-Frenk-White halo (2 DoF): $\rho_h(r) = \frac{\rho_{0,h}}{(r/A_h)(1+r/A_h)^2}$
- The total velocity resulting from the Poisson equation is: $V_{MWC} = \sqrt{V_{bar}^2 + V_h^2} = \sqrt{V_b^2 + V_{td}^2 + V_{Td}^2 + V_h^2}$

➤ **MOND model**:

- The gravitational acceleration is $g_{MOND} = \nu\left(\frac{g_N}{g_0}\right) g_N$, with $\nu\left(\frac{g_N}{g_0}\right) = \left(1 - e^{-\sqrt{g_N/g_0}}\right)^{-1}$
- $g_0 = (1.20 \pm 0.02)\, 10^{-10}$ m s^{-2} is tightly constrained by the observed RAR of external galaxies (1 DoF) [4].
- Same modelling of baryonic distribution of the classical model (8 DoF).
- The expected circular velocity is function of the Newtonian one: $V_{MOND}(R, V_{bar}) = \frac{V_{bar}}{\sqrt{1-e^{-V_{bar}/\sqrt{Rg_0}}}}$.

➤ **General relativistic model (BG)**:

- Stationary and axis-symmetric spacetime: $ds^2 = -(dt - Nd\phi)^2 + \left[e^\nu(dr^2+dz^2) + r^2 d\phi^2\right]$
- Pressure-less perfect fluid: $T^{\alpha\beta} = \rho u^\alpha u^\beta$
- The corresponding Einstein equations are:

$$r\nu_z + N_r N_z = 0$$
$$2r\nu_r + N_r^2 - N_z^2 = 0$$
$$\nu_{rr} + \nu_{zz} + \frac{1}{2r^2}\left(N_r^2+N_z^2\right) = 0$$
$$N_{rr} + N_{zz} - \frac{N_r}{r} = 0$$
$$\frac{1}{r^2}\left(N_r^2+N_z^2\right) = k\rho e^\nu$$

Solution of **Balasin** and **Grumiller** (**BG**, 3 DoF) [5]:

$$N(r,z) = V_0(R_{out} - r_{in}) + \frac{V_0}{2}\sum_{\pm}\left(\sqrt{(z\pm r_{in})^2 + r^2} - \sqrt{(z\pm R_{out})^2 + r^2}\right)$$

$$e^{\nu(r,z)} = e^{\nu_0}$$ Assumed constant and constrained to the local baryonic density at the Sun (1 DoF)

- ZAMO: locally non-rotating observers that have no angular momentum relative to flat infinity and move on worldlines orthogonal to the hypersurfaces t = const. With respect to this class of observers, the velocity of a co-moving dust particle is:

$$\zeta^{\hat\phi} = \frac{\sqrt{g_{\phi\phi}}}{M}(\beta + M^\phi) \longrightarrow \zeta^{\hat\phi} = V_{BG} = \frac{N(r,z)}{r} \propto g_{0\phi}$$ for a static observer like Gaia.

- The expected rotation velocity is proportional to the off-diagonal term of the spacetime metric: pure GR effect that we call **gravitational dragging**.

RESULTS

The three velocity profiles, estimated with a Bayesian analysis and drawn as coloured solid lines in Figure 2, are all good representations of the observed (binned) data. The three models are found to be **statistically equivalent**, as their comparisons with the WAIC and LOO tests show almost identical values.

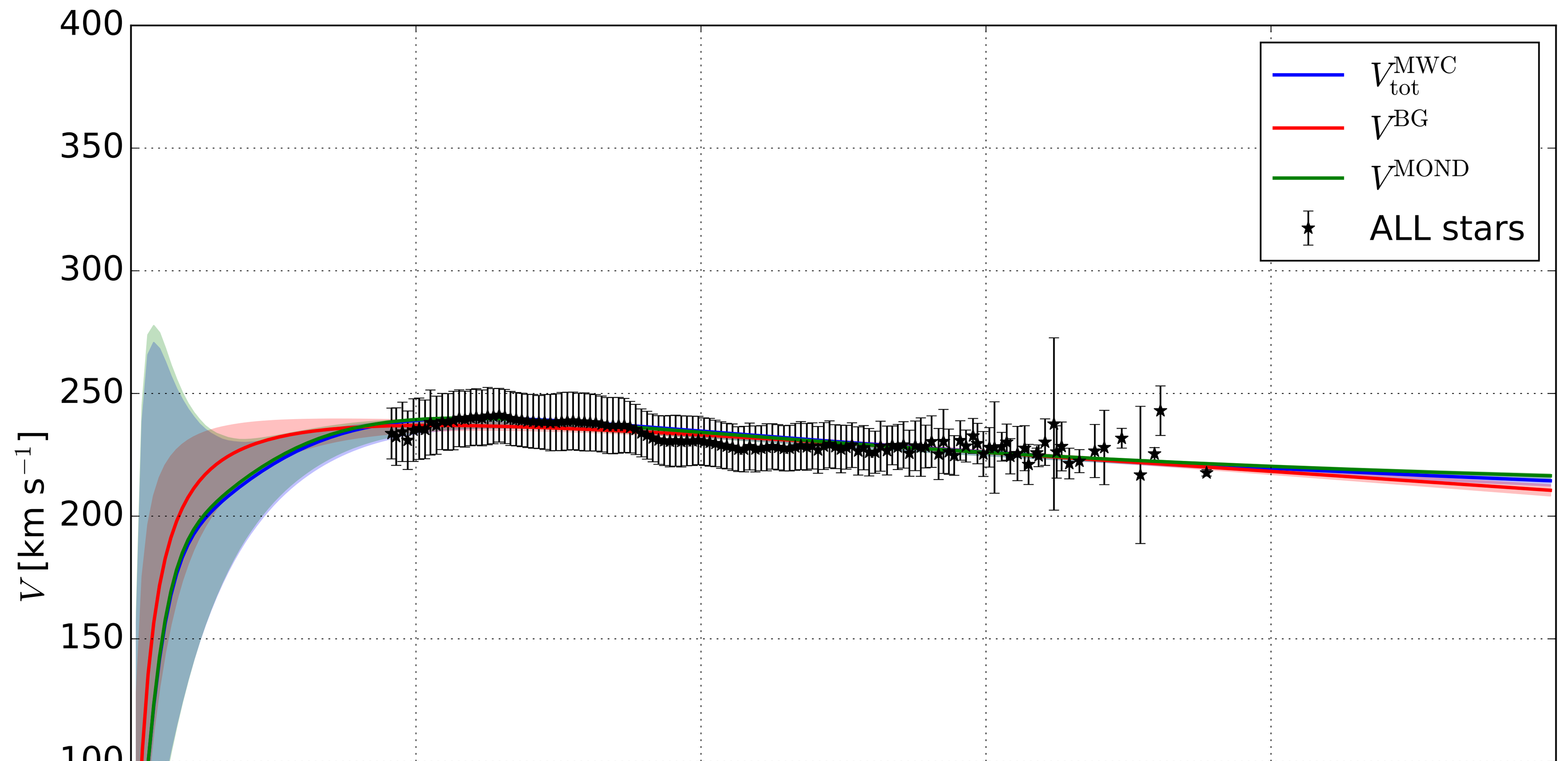
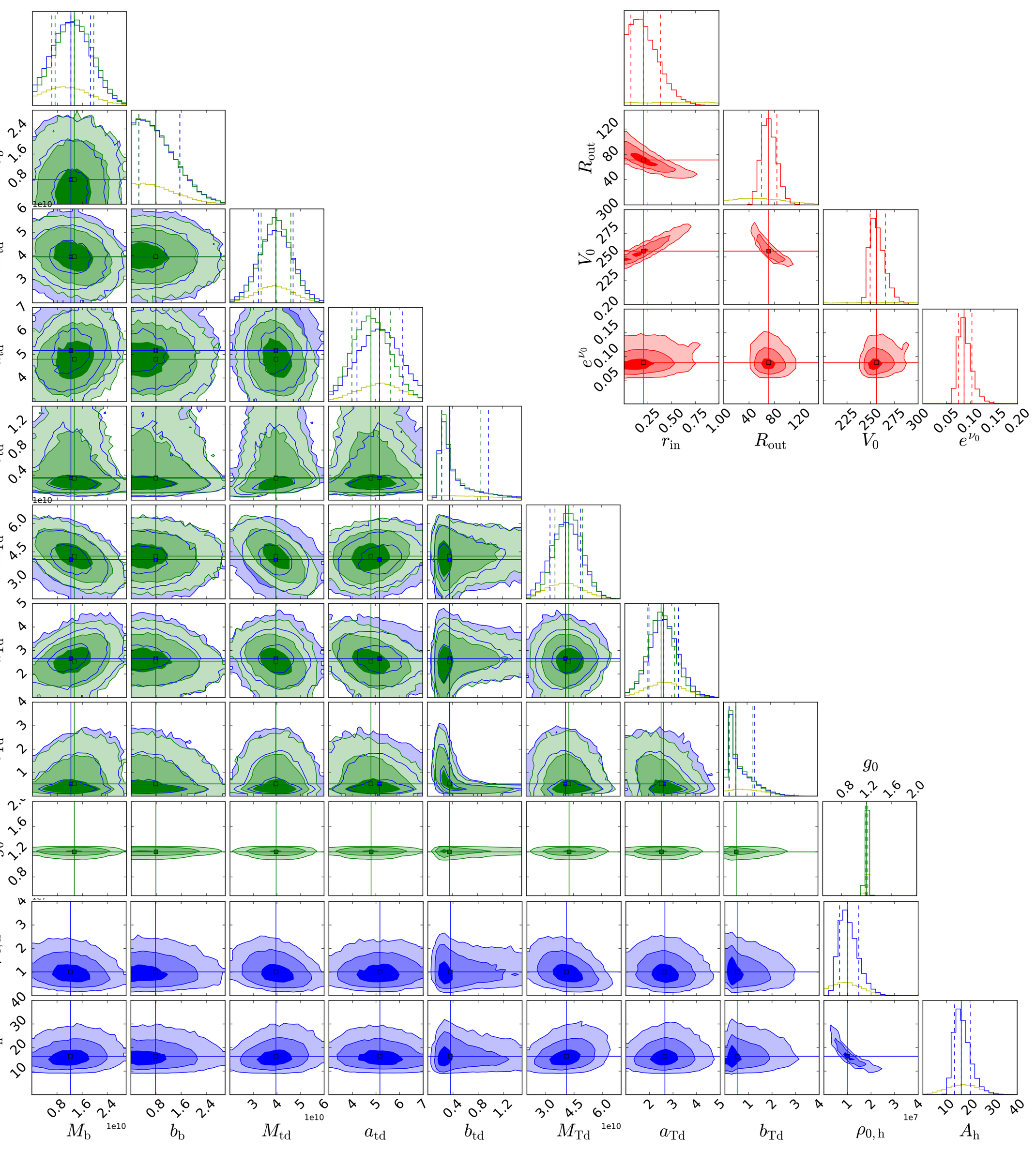


Figure 2: Fitted rotation curves of the three dynamical models. Binned data points for the full sample of selected disc tracers are represented with corresponding error bars. The filled areas represent the 68% reliability intervals of each rotation curve; note that for $R \lesssim 4.5$ kpc the curves are very uncertain because of the lack of data in that region. Our Bayesian estimations are in good agreement for all the disc populations utilised, and for the mixtures thereof, in the regions of physical validity of the models.

Figure 3: Corner plots representing the 2D posterior distributions of the parameters: the contours indicate the 1σ and 2σ credible levels. The marginal posterior distributions of each parameter against the corresponding prior distribution (in yellow) are shown on the diagonal: the dashed lines mark the 1σ intervals around the median values (solid lines).

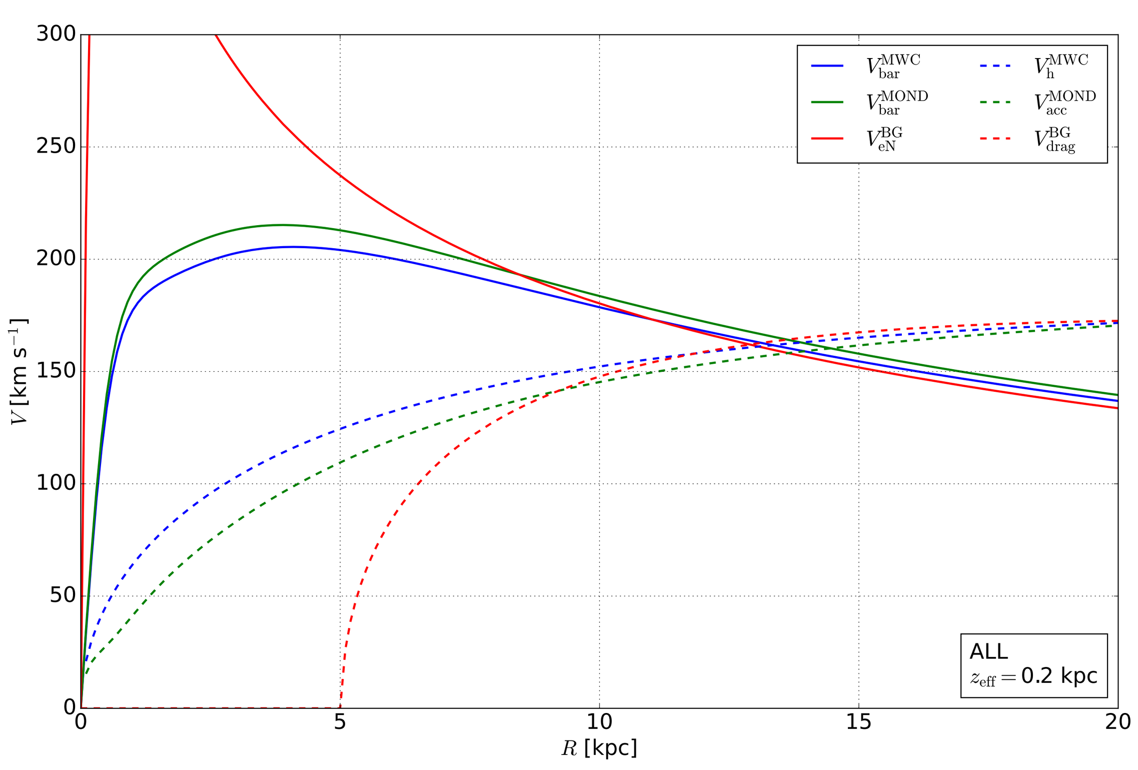


All parameters are consistent with previous works [1; 6-8], in particular:

- The baryonic matter components for MWC and MOND are in agreement; both models estimate a **total stellar mass of** $\sim 9 \cdot 10^{10}\, M_\odot$.
- MWC: more extended bulge than previous assumptions; total virial mass of $\sim 1 \cdot 10^{12}$ $M_\odot$.
- BG: larger value of R_{out} than [2] due to wider radial coverage of DR3 over DR2.
- **Baryonic mass in agreement** between all three models within the region of validity of BG (relativistic mass defined via the Komar integral).

Non-Newtonian contributions to the rotation curve **are consistent with that of the dark matter halo**: they become predominant over the classical baryonic counterpart from 10-15 kpc outwards and, at the Sun distance, they are responsible for the 30-37% of the velocity profile.

Figure 4: The **MONDian boost** (V^{MOND}_{acc}) in low acceleration regimes follows from the expression of V_{MOND}. The **gravitational dragging** contribution of the BG model (V^{BG}_{drag}) is computed as the difference between the total BG velocity profile and the effective Newtonian contribution (V^{BG}_{eN}), i.e., the predicted Newtonian velocity given by the BG relativistic mass distribution.



CONCLUSION

- From Gaia DR3, we built rotation curves of the MW from R = 4.5 kpc to 19 kpc by carefully selecting stellar populations that best trace the Galactic disc, including 241'918 OBA stars, 475'520 RGB giants and 1'705 Cepheides. RGB and DCEP stars are less affected than OBA objects by local non-axisymmetric perturbations.
- We showed that the general relativistic solution of [5] for an axisymmetric stationary metric coupled with a pressure-less perfect fluid is consistent with the new analysis based on the latest Gaia data release, consolidating the findings of [2].
- We also provided up-to-date results for both the classical model with dark matter and MOND: all the three dynamical models can equivalently explain the observed rotational velocities of different MW disc populations, predicting comparable estimates of the total baryonic mass and non-Newtonian contributions to the velocity profile that quite favorably compensate the dark matter halo counterpart.

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