A Bayesian Estimation of the Milky Way's Circular Velocity Curve using Gaia DR3

Code | Dataset

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Introduction

The circular velocity curve is an effective tracer for the total dynamical mass in the Milky Way (MW) and encodes valuable information about the dark matter (DM) mass distribution in the Galaxy. [1]

In the current era of precision astrometry, with surveys such as the Gaia Mission [2] delivering data with unprecedented precision, model systematics are the dominant source of uncertainty in DM density estimates. When not properly accounted for, assumptions about the distribution function of tracer stars in the disc and uncertainties in the Sun's Galactocentric distance can lead to significant systematic biases [3].

In our work, we present a Bayesian inference approach to estimate the circular velocity curve of our Galaxy that allows a straightforward incorporation of **systematic** and **statistical** sources of uncertainty. In particular, we use data from Gaia data release 3 (DR3) [4] to reconstruct the circular velocity curve of the Milky Way within 5 to 14 kpc from the Galactic centre and derive the local DM density with corresponding uncertainties.

RGB Sample

We used astrometric data and radial velocities from Gaia DR3 for 665 660 stars in the red giant branch. The sample was a result of various spatial and kinematic cuts imposed on the sample obtained in [4].

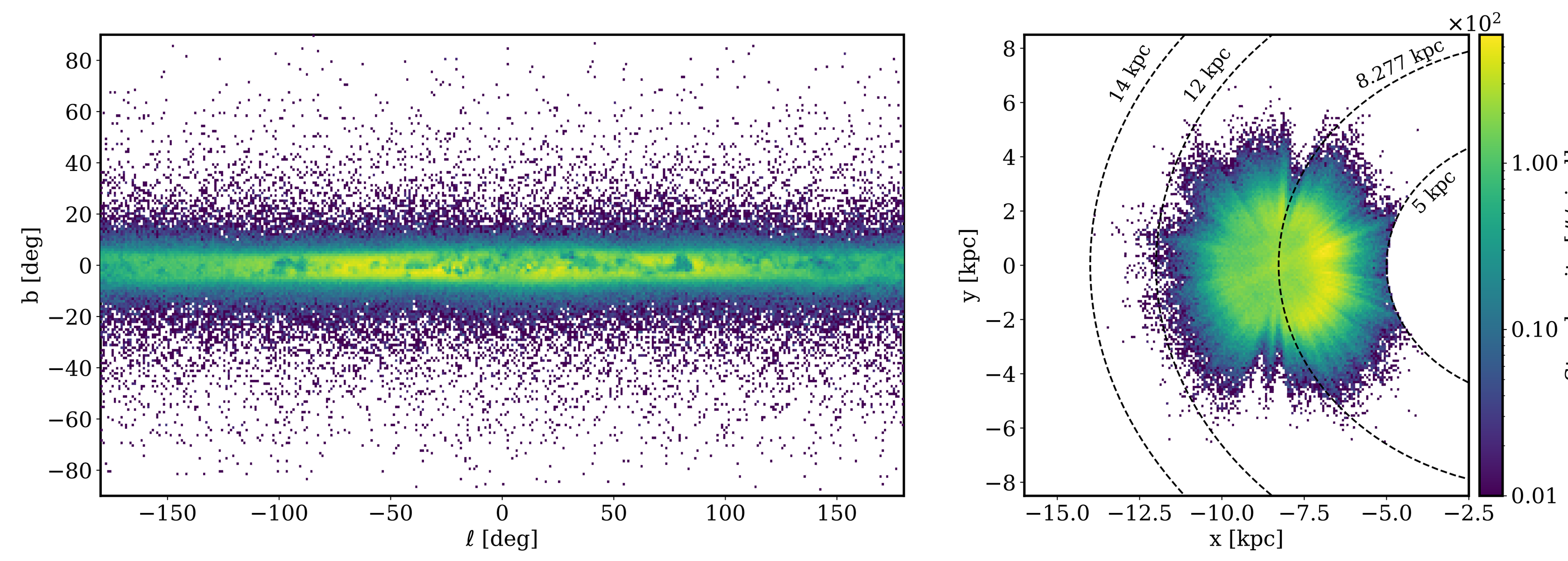

Figure 1. Spatial distribution of the final red giants sample. Left: distribution in the Galactic longitude (ℓ) and latitude (b) plane. The colour bar shows the number density of stars per pixel. Right: same but projected into the Galactic plane. In this figure, the Galactic centre is located at (0, 0), the Sun is located at $(-8.277\,\text{kpc}, 0)$ and the rotation of the Galaxy is clockwise. We added dashed, black circles at 5 kpc, $R_0 = 8.277$ kpc, 12 kpc and 14 kpc to ease visualisation.

Transformation and binning

Using the radial velocity measurements from Gaia, we constructed the full 3D space velocities of our sample and transformed them to the Galactocentric frame using the Sun's Galactocentric velocity.

In the coordinate and velocity transformation, we treated the Sun's Galactocentric distance R_0 as a nuissance parameter to account for uncertainties in its measurements.

After transformations, the sample is binned into radial bins as we marginalise over the azimuthal coordinate ϕ. In this way, we treat the rotational velocities in the Galactic disc as purely radially dependent.

Kinematic model and fitting

Our method involves a fitting procedure that combines the Jeans equation with a simple kinematic model, under the assumptions of steady-state and axial symmetry. Specifically, the rotational velocity of each radial bin is modelled as

$$v_{\phi,\text{model}} = v_c - v_a, \quad (1)$$

The asymmetric drift, which is the diffusion of stars in phase-space as they orbit the Galaxy, is derived from the radial Jeans equation [5]:

$$v_a = \frac{\sigma_R^{*2}}{v_c + \overline{v_\phi}} \left[\frac{\sigma_\phi^{*2}}{\sigma_R^{*2}} - 1 + R\left(\frac{1}{h_r} + \frac{2}{h_\sigma}\right)\right], \quad (2)$$

where $\overline{v_\phi}$ is the mean rotational velocity inside each bin and is calculated from the data. σ_ϕ^{*2} and σ_R^{*2} correspond to the variance of the azimuthal and radial velocity in the bin respectively and are also inferred from the data. In the last term in the bracket, h_r describes the disc scale radius and h_σ is the scale length of the radial velocity dispersion.

Fitting the circular velocities

Our Bayesian methodology relies on a Markov Chain Monte Carlo (MCMC) algorithm to effectively sample the posterior probability distribution of our model parameters. These parameters include:

1. $v_{c,j}$ - the circular velocity in each radial bin j
2. h_r, h_σ - parameters which describe the spatial-kinematic morphology of the tracer sample
3. R_0 - the Sun's Galactocentric distance

For R_0, h_r and h_σ, we defined flat prior ranges which encompass values found in contemporary literature. By allowing these nuissance parameters to vary, we propagate their uncertainties into the final circular velocity curve estimation.

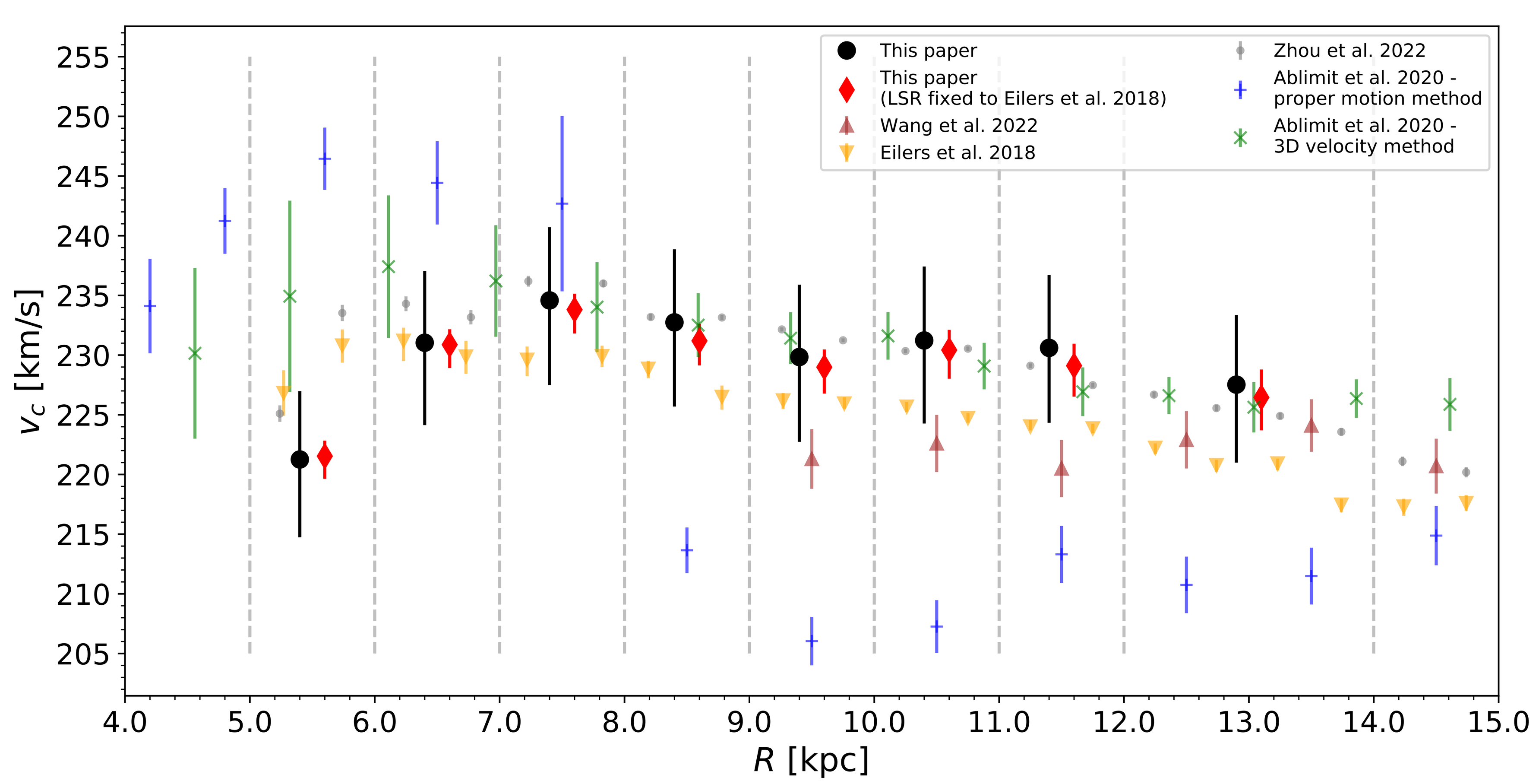

Figure 2. Circular velocity curve obtained from the MCMC. Grey dashed lines have been plotted to indicate the position of each radial bin. In black (with circles) we show the circular velocities as obtained in this paper where the error bars correspond to the 16th and 84th percentile of the circular velocity posterior distribution in a particular bin.

Smooth dark matter halo

The obtained circular velocity curve was used as a tracer for the dynamical mass. After accounting for the baryonic contribution (with corresponding uncertainties) in the observed region, we constructed the DM density profile which includes the propagated systematic and statistical uncertainties.

- We found that the local spherically averaged DM density is

$$\rho_{\text{DM}}(R_0) = \left(0.41^{+0.10}_{-0.09}\right)\ \text{GeV/cm}^3 = \left(0.011^{+0.003}_{-0.002}\right)\ \text{M}_\odot/\text{pc}^3. \quad (3)$$

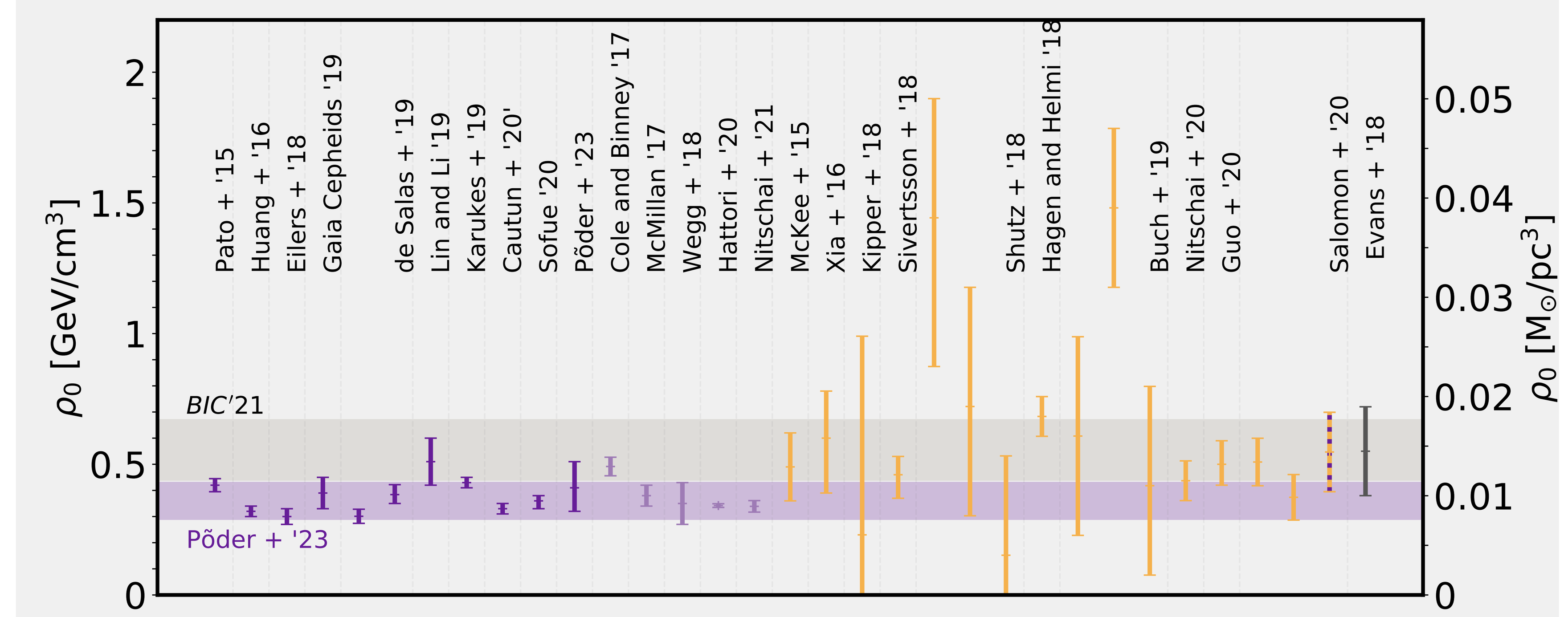

Figure 3. Global (purple error bars) and local (yellow error bars) estimates of ρ_0, and their comparison with our value.

- The total DM mass in $R < 14\,\text{kpc}$

$$\log_{10}\left[M_{\text{DM}}(R < 14\,\text{kpc})/\text{M}_\odot\right] = 11.2^{+2.0}_{-2.3}. \quad (4)$$

- Uncertainties self-consistently incorporate statistical and different sources of systematic uncertainty. The main sources of uncertainty arise from the measurement of R_0 and distance measurements of the sample stars.

References

[1] J I Read. The local dark matter density. *Journal of Physics G: Nuclear and Particle Physics*, 41(6):063101, may 2014.

[2] Gaia Collaboration, T. Prusti, J. H. J. de Bruijne, and et al. The Gaia mission. , 595:A1, November 2016.

[3] Maria Benito, Nicolás Bernal, Nassim Bozorgnia, Francesca Calore, and Fabio Iocco. Particle Dark Matter constraints: the effect of Galactic uncertainties. , 2017(2):007, February 2017.

[4] Gaia Collaboration, Drimmel, R., Romero-Gómez, M., and et al. Gaia data release 3 - mapping the asymmetric disc of the milky way. A&A, 674:A37, 2023.

[5] James Binney and Scott Tremaine. *Galactic Dynamics: Second Edition*. Princeton University Press, rev - revised, 2 edition, 2008.

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