Evidence for dark matter in the inner Milky Way

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Materials and Methods

Compilation of kinematic data

The main features of the compilation of rotation curve data used in this work are summarised in Table S1. The different tracers adopted require rather different methodologies to determine their distances and velocities. While referring to the original references for thorough technical details, we summarise here the most salient points of all classes of tracers.

a) Gas kinematics

The motion (and quantity) of gas in our Galaxy has been extensively studied ever since the 1950s, mostly through the observation of the HI 21 cm line and the CO ($J = 0 \rightarrow 1$) 2.6 mm line. The Doppler shift of these lines has now been thoroughly surveyed across the Galactic plane, providing an ample coverage of line-of-sight velocities with excellent precision. The distance is more complicated to determine, but this has been achieved in a number of different ways as detailed below. In our compilation we include measurements from HI and CO terminal velocities, HI thickness, HII regions and giant molecular clouds.

For gas inside the solar circle, it is possible to use the so-called terminal velocities to constrain the rotation curve in the inner Galaxy. The gas along a given line of sight presents different radial velocities depending on its position. Assuming circular orbits, the maximal (terminal) velocity for any given line of sight is attained for the gas at the closest point to the Galactic centre, the tangential point. The distance to this point (or, equivalently, its Galactocentric radius) is thus univocally determined at the same time that the corresponding circular velocity is derived from the terminal velocity – for precise expressions, see next section. This method has been applied to
both HI\(^{1-3}\) and CO\(^{4-7}\) lines in both the first and fourth Galactic quadrants, yielding typical terminal velocity uncertainties of 1 – 10 km/s.

Outside the solar circle, the method of terminal velocities cannot be applied and we are forced to determine velocity and distance independently. One possibility is to use the HI thickness method\(^{8-10}\). In this technique the HI data cube is sliced at constant \(W(R) \equiv \frac{v_c(R)}{R/R_0} - v_0\), and then the longitude dependence of the angular thickness of the layer is used to derive the corresponding value of \(R/R_0\). It is thus possible to trace the outer rotation curve, with uncertainties typically lying at 6 km/s for \(W\) and 7% for \(R/R_0\).

Another possibility is to focus on gas regions with kinematics set by HI or CO data and distances determined independently. This is the case of HII regions\(^{1,11-14}\) (associated to known molecular clouds) and giant molecular clouds\(^{14}\), for which the line-of-sight velocities are determined with the CO line and the distances with photometry. In the case of HII regions common uncertainties are 1 – 3 km/s for line-of-sight velocities and 10 – 30% for distances, while for giant molecular clouds these figures lie at around 3 km/s and 20%, respectively.

b) Star kinematics

We include in our compilation four classes of stellar tracers, namely open clusters, planetary nebulae, classical cepheids and carbon stars. The details of each class are described in the following.

Open star clusters are prime dynamical tracers of the Galactic disc. Using medium-resolution spectroscopy to measure line-of-sight velocities of individual stars and all-sky surveys to set their proper motions, it has been possible to assign accurate cluster memberships and determine the bulk three-dimensional velocity of open clusters\(^{15}\). The distance to open clusters\(^{16}\) is estimated to within tens of percent in some cases (we conservatively assume 30%), whereas the typical uncertainty for proper motions is 1 mas/yr and for line-of-sight velocities about 0.8 km/s.

Also planetary nebulae can be used in kinematic studies of our Galaxy. Their line-of-sight velocities are usually determined to within 1 – 5 km/s through the Doppler shift of bright emission lines at optical wavelengths (e.g. H, He, [OIII])\(^{17}\), while distances can be estimated using the correlation between different properties of the nebulae with uncertainties of about 30%\(^{18}\). Given that planetary nebulae are a somewhat old population, we account for their asymmetric drift and (small) non-circular motion\(^{17}\).

Classical cepheids have been particularly important in tracing Galactic rotation owing to the excellent determination of their line-of-sight velocities and distances\(^{19,20}\). In fact, spectroscopy yields velocity uncertainties of order 1 – 5 km/s and BVI photometry is used to determine the distance to these objects through the period-luminosity-colour relation with an accuracy of 10%. We correct for the (small) non-circular motion of cepheids\(^{19}\).

Finally, our compilation of kinematic data includes carbon stars, which are good tracers of the outer Galaxy\(^{21,22}\). Using spectroscopic measurements at 6000 – 6900 Å to pinpoint the line-of-sight velocity and JHK photometry to determine the distance with a magnitude-colour relation, it is possible to reach accuracies of 5 km/s and 10%, respectively. We account for a 20 km/s random motion\(^{21}\) for each star.
c) Masers

The last few years have witnessed a very significant progress in the observation of high-mass star-forming regions through maser emission in the radio band, namely through the characteristic emission of methanol at 12 GHz and water at 22 GHz. Very long baseline interferometry efforts such as VERA, VBLA or BeSSeL are now able to provide precise parallaxes and proper motions which, together with the Doppler shift of the spectral lines, can be used to determine the full six-dimensional information of these objects (position and velocity). The non-circular motion of masers can thus be carefully studied – for more on this point, see the last section of this supplementary information. Typically, the uncertainties on parallax measurements lie at the 25 μas level, while proper motions are accurate to 0.3 mas/yr and line-of-sight velocities to 5 km/s. We have added in quadrature an uncertainty of 7 km/s (per coordinate) due to the virial motion of individual stars associated to masers and subtracted the known peculiar motions of these objects.

**Treatment of kinematic data**

Every adopted object or region described above has associated Galactic coordinates (ℓ, b), heliocentric distance d and heliocentric line-of-sight velocity v_H^los. The latter is usually reported in a given local standard of rest (LSR) frame rather than in the heliocentric frame, so that one has to subtract the peculiar solar motion used in the original reference to find v_H^los and then apply the desired peculiar solar motion (U, V, W)_⊙ to get the LSR line-of-sight velocity v_LSR^los. We follow closely each source reference to assign errors to d and v_LSR^los and to account for any peculiar motion associated with specific objects. Uncertainties on ℓ and b are largely sub-dominant in all cases and are therefore neglected. Finally, we exclude objects with insufficient or deficient data (e.g. on the distance determination), too close to the direction of the Galactic centre or anti Galactic centre and any other objects classified as suspect in the original references. After this selection, the compilation consists of 2780 individual measurements with the breakdown shown in Table S1.

We then constrain the rotation curve of our Galaxy v_c(R) for any given choice of the distance to the Galactic centre R_0 and local circular velocity v_0 ≡ v_c(R_0). Assuming circular orbits for the objects observed (a reasonable approximation outside the influence of the Galactic bulge, i.e. R ≳ R_{cut} = 2.5 kpc, see discussion in the last section of this supplementary information),

\[
v_LSR^{los} = \left( \frac{v_c(R)}{R/R_0} - v_0 \right) \cos b \sin \ell ,
\]

where R = (d^2 \cos^2 b + R_0^2 - 2R_0d \cos b \cos \ell)^{1/2}. For the particular case of terminal velocities, b = 0 and R = R_0 | \sin \ell |. When proper motions are available (e.g. for open clusters and masers), similar expressions apply for the object velocity along the longitude and latitude directions. For each object in the compilation, we have a measurement of R and we invert Eq. (1) to obtain the angular circular velocity w_c(R) ≡ v_c(R)/R and propagated error. Notice that we make use of the angular circular velocity w_c rather than the actual circular velocity v_c, because the error of the latter is strongly correlated with the error of R. Instead, the errors of w_c and R are uncorrelated. As noticed long ago^1, using v_c would introduce unnecessary complications in the statistical analysis and lead to a degradation of the precision.
Baryonic modelling

The exact distribution of baryons in our Galaxy is not precisely determined as of today, making it a major source of uncertainty in the present study. There are three main baryonic components: stellar bulge, stellar disc and gas. We have surveyed the literature exhaustively and collected a wide range of data-based, three-dimensional morphologies for each component. This allows for a quantitative assessment of the bracketing due to baryonic modelling, as shown in Fig. 2 in the main text. The details of bulge, disc and gas models are given below. All scale lengths and densities of the original models were appropriately adjusted to the adopted $R_0$.

The inner few kpc of the Milky Way are dominated by a triaxial, bar-shaped bulge of stars$^{29–31}$. Observations clearly place the near end of the bar at positive Galactic longitudes, but its precise orientation and morphology are less certain. For instance, the distribution of red clump giants in the bulge$^{31}$ is well fitted either by exponential or gaussian profiles (so-called E2 and G2 models, respectively). Apart from these two configurations, we also consider alternative truncated power-law bulges$^{32,33}$ and a bar-shaped model with a nuclear component$^{34}$. In view of recent developments, the possibility of an extra (long) bar$^{35}$ and a double-ellipsoid bulge$^{36}$ are implemented as well. The normalisations of all seven models (and corresponding uncertainties) are fixed by matching the predicted microlensing optical depth towards $(\ell, b) = (1.50^\circ, -2.68^\circ)$ to the 2005 MACHO measurement$^{37,38}$ $\langle \tau \rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$. The microlensing contribution due to disc stars is self-consistently accounted for in accordance to the disc models described below.

The stellar disc has been modelled by different authors with the help of comprehensive surveys of photometric data across the Galaxy. Typical parameterizations include thin and thick disc populations, usually featuring double-exponential profiles. We consider alternative thin plus thick configurations$^{39,40}$ as well as configurations with a stellar halo component$^{41,42}$. The single maximal disc suggested recently$^{43}$ is also implemented. All five models are normalised to the latest dynamical constraint on the local total stellar surface density$^{43}$ $\Sigma_* = 38 \pm 4 \, M_\odot/pc^2$, from which we propagate the uncertainty to the disc component. This constraint is in line with observation-based censuses of stars including stellar remnants$^{44}$.

Finally, a non-negligible part of the baryons in the Milky Way is in the form of gas, namely molecular, atomic and ionised hydrogen and heavier elements. The distribution of each component is relatively well-known but extremely irregular. This is for example the case of the gas within 10 pc of the Galactic centre$^{45}$, which for our purposes can be safely considered as a point-like mass. For the inner 2 kpc, we model molecular and atomic hydrogen in the central molecular zone and holed disc, and the distribution of ionised hydrogen is split into its warm, hot and very hot phases$^{46}$. In the range $R = 2 – 20$ kpc, instead, two alternative morphologies$^{47,48}$ are used for each gas component. We set up in this way our two gas models, whose uncertainties are assigned by taking a CO-to-H$_2$ conversion factor of$^{47,49}$ $(2.5 – 10) \times 10^{19} \, cm^{-2}(K \, km/s)^{-1}$ for $R < 2$ kpc and $(0.5 – 3.0) \times 10^{20} \, cm^{-2}(K \, km/s)^{-1}$ for $R > 2$ kpc.

Once a model for bulge, disc and gas is specified, the individual gravitational potentials (and thus the individual contributions to the rotation curve) can be easily computed through multipole expansion$^{50}$. Expanding up to $l_{\text{max}} = 2$ (see below for a convergence test) and averaging over the azimuthal direction, we can then derive the overall baryonic contribution to the rotation curve.
\[ \omega_b^2 = \omega_{\text{bulge}}^2 + \omega_{\text{disc}}^2 + \omega_{\text{gas}}^2 \]

and the corresponding propagated uncertainty.

### Statistical analysis

The central task in this work is to compare the observed rotation curve of the Galaxy \( \omega_c(R) \) to that expected from baryons \( \omega_b(R) \), and determine whether \( \omega_c^2 - \omega_b^2 \) is compatible with zero or not. This task is complicated by the sizeable error on \( R \) in the rotation curve data, especially at intermediate and large \( R \) as shown in Fig. 1 of the main text. Given the large amount of observations (see Table S1), a customary technique usually adopted in the literature is that of binning the data. Since binning entails loss of information, we opt not to do it and use instead the full power of the data taking proper account of Galactocentric radius errors. (We did however check explicitly that a binned analysis with a weighted mean of the measurements just reinforces the results presented in the main text.) Introducing the reduced variables \( x = R/R_0 \) and \( y = \omega/\omega_0 - 1 \) (with \( \omega_0 = v_0/R_0 \)), the two-dimensional \( \chi^2 \) reads

\[
\chi^2 = \sum_{i=1}^{N} d_i^2 \equiv \sum_{i=1}^{N} \left[ \frac{(y_i - y_{b,i})^2}{\sigma_{y,i}^2} + \frac{(x_i - x_{b,i})^2}{\sigma_{x,i}^2} \right],
\]

where \((x_{b,i}, y_{b,i})\) is the point in the baryonic curve \( y_b(x) = \omega_b(R = x R_0)/\omega_0 - 1 \) that minimises \( d_i \). Notice that the expression above can be applied because the errors on \( R \) and \( \omega \) (i.e. \( x \) and \( y \)) are uncorrelated and hence the error ellipse is not tilted in the \((R, \omega)\) plane. This would not be the case for the error-correlated pair \((R, v_c)\). We have performed Monte Carlo calculations for a fiducial baryonic model and typical uncertainties \( \sigma_{x,i}, \sigma_{y,i} \), and verified that the statistic in Eq. (2) follows approximately a \( \chi^2 \) distribution. The lower panel in Fig. 2 in the main text shows the reduced chi-square \( \chi^2/N \), where the sum in Eq. (2) is restricted to objects with Galactocentric radii below the given \( R \). Due to the breakdown of the assumption of circular orbits, all objects with \( R \leq R_{\text{cut}} = 2.5 \) kpc are ignored in the analysis.

### Robustness of the results

Our main findings are presented in Fig. 2 in the main text for a wide bracketing of baryonic models. This illustrates already the robustness of the results. However, that figure was obtained for fixed (albeit reasonable) choices of Galactic parameters and data selection. Here we show that different choices lead to the same conclusion as in the main text, i.e. that baryons cannot explain alone the observed rotation curve in the inner Galaxy.

We start by varying the fundamental Galactic parameters, namely \( R_0, v_0 \) and \((U, V, W)_{\odot}\). The existing determinations\(^{23,51-53}\) of \( R_0 \) do not all agree with each other, but are confined to a reasonably narrow range\(^{53} \), \( 8.0 \pm 0.25 \) kpc. We adopt a more conservative range \( 8.0 \pm 0.5 \) kpc in our tests. A similar situation holds for \( v_0 \) where the range \( 230 \pm 20 \) km/s encompasses most determinations\(^{23,28,54-56}\). As for the peculiar solar motion, we take\(^{57} \) \((U, V, W)_{\odot} = (11.10, 12.24, 7.25) \) km/s as our fiducial values, but consider as well other determinations in the literature\(^{23,56,58}\): \((U, V, W)_{\odot} = (10.00, 5.25, 7.17) \) km/s, \((U, V, W)_{\odot} = (10.00, 26.00, 7.25) \) km/s (with \( v_0 = 218 \) km/s) and \((U, V, W)_{\odot} =
(10.7, 15.6, 8.9) km/s (with $v_0 = 240$ km/s). The effect of taking different choices of Galactic parameters is shown in Fig. S1.

Fig. S2 presents instead checks regarding data selection and treatment. The first row shows the evidence obtained when using gas kinematics, star kinematics and masers separately. Notice that the gas can have non-negligible pressure support from cosmic rays and/or magnetic fields and thus the comparison between the rotation curves from gaseous and stellar tracers can be used to assess the importance of this phenomenon. However, given that pressure support is likely to be relevant only towards large Galactocentric radii, its effect does not change our conclusions because the evidence for dark matter is sizeable already inside the solar circle and strong even when excluding gas kinematics as shown in Fig. S2. In the same figure we checked as well the impact of streaming motions due to spiral arms by adding a 11.8 km/s systematic motion to each rotation curve measurement. Another important test consisted in raising the radius cut-off to $R_{\text{cut}} = 5$ kpc, below which the bar can arguably break the assumption of circular orbits for the tracers used.

We show in Fig. S3 additional tests related to the effect of baryonic uncertainties. First, we consider the potential morphological uncertainties in baryonic models. Taking our fiducial disc model, the error on the rotation curve contribution due to the disc scale length uncertainty is on average 13%, which is comparable to the 11% error due to the disc normalisation $\Sigma_\star = 38 \pm 4 M_\odot/pc^2$. Adding these two figures in quadrature leads to a 17% average uncertainty. To be conservative, we show in the left panel of Fig. S3 the case of a 20% overall error on the disc normalisation. Furthermore, we have tested the impact of a different model for the HI disc. Also, the convergence of the multipole expansion used to compute $\omega_0$ was tested up to $\ell_{\text{max}} = 8$.

In all cases shown in Figs. S1, S2 and S3 the discrepancy between observed and predicted rotation curves is high (> 5$\sigma$) and very robust against Galactic nuisances, baryonic uncertainties and data selection.

Finally, let us comment on the assumption of circular orbits. This can be explicitly checked for those objects in our compilation (in particular, masers) for which we have access to the full position and velocity through the measurements of direction, distance, line-of-sight velocity and proper motions. Fig. S4 shows the distribution of peculiar velocities for the 100 masers studied assuming our fiducial values $R_0 = 8$ kpc, $v_0 = 230$ km/s and $(U, V, W)_\odot = (11.10, 12.24, 7.25)$ km/s as well as a flat rotation curve. It is clear that on average masers present little deviations from circular orbits, in agreement with recent findings. Earlier analyses found masers to lag Galactic rotation by $\sim 15$ km/s due to a small value of $V_\odot$ (4 – 5 km/s), which has been revised upwards in the meantime. We stress that in our analysis we correct for the peculiar motion of masers, so, even if $V_\odot$ is small and masers follow indeed eccentric orbits, this does not change our results significantly as shown in the bottom left panel of Fig. S1. Therefore, our conclusions are robust against the assumption of circular orbits.
that the gas can have non-negligible pressure support from cosmic rays and/or magnetic fields when using gas kinematics, star kinematics and masers separately. Notice that the convergence of the multipole expansion used to compute the rotation curve contribution due to the disc scale length uncertainty is shown in Fig. S1.

parameters is shown in Fig. S1.

Therefore, our conclusions are robust even if we stress that in our analysis we correct for the peculiar motion of masers, so, the impact of streaming motions due to spiral arms by adding a constant term against the assumption of circular orbits, in agreement with recent findings. Earlier analyses found masers to lag Galactic rotation by ∼15 km/s due to a small value of $V_u$, which has been revised upwards to 23 km/s (with $V_u = 240$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s).

In all cases shown in Figs. S1, S2 and S3 the discrepancy between observed and predicted rotation curves is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s). The effect of taking different choices of Galactic parameters is high ($\sigma = 8$ km/s).

| Object type                      | $R$ [kpc] | quadrants | # objects |
|----------------------------------|-----------|-----------|-----------|
| HI terminal velocities           |           |           |           |
| Fich+ '891                      | 2.1 – 8.0 | 1,4       | 149       |
| Malhotra '952                    | 2.1 – 7.5 | 1,4       | 110       |
| McClure-Griffiths & Dickey '07   | 2.8 – 7.6 | 4         | 701       |
| HI thickness method              |           |           |           |
| Honma & Sofue '97               | 6.8 – 20.2| –         | 13        |
| CO terminal velocities           |           |           |           |
| Burton & Gordon '78             | 1.4 – 7.9 | 1         | 284       |
| Clemens '85                      | 1.9 – 8.0 | 1         | 143       |
| Knapp+ '85                      | 0.6 – 7.8 | 1         | 37        |
| Luna+ '06                       | 2.0 – 8.0 | 4         | 272       |
| HII regions                      |           |           |           |
| Blitz '79                       | 8.7 – 11.0| 2,3       | 3         |
| Fich+ '891                      | 9.4 – 12.5| 3         | 5         |
| Turbide & Moffat '93            | 11.8 – 14.7| 3       | 5         |
| Brand & Blitz '93               | 5.2 – 16.5| 1,2,3,4   | 148       |
| Hou+ '09                        | 3.5 – 15.5| 1,2,3,4   | 274       |
| giant molecular clouds           |           |           |           |
| Hou+ '09                        | 6.0 – 13.7| 1,2,3,4   | 30        |
| open clusters                    |           |           |           |
| Frinchaboy & Majewski '08       | 4.6 – 10.7| 1,2,3,4   | 60        |
| planetary nebulae               |           |           |           |
| Durand+ '98                      | 3.6 – 12.6| 1,2,3,4   | 79        |
| classical cepheids               |           |           |           |
| Pont+ '94                       | 5.1 – 14.4| 1,2,3,4   | 245       |
| Pont+ '97                       | 10.2 – 18.5| 2,3,4    | 32        |
| carbon stars                     |           |           |           |
| Demers & Battinelli '07         | 9.3 – 22.2| 1,2,3     | 55        |
| Battinelli+ '13                  | 12.1 – 24.8| 1,2      | 35        |
| masers                           |           |           |           |
| Reid+ '14                       | 4.0 – 15.6| 1,2,3,4   | 80        |
| Honna+ '12                      | 7.7 – 9.9 | 1,2,3,4   | 11        |
| Stepanishchev & Bobylev '11     | 8.3        | 3         | 1         |
| Xu+ '13                        | 7.9        | 4         | 1         |
| Bobylev & Bajkova '13           | 4.7 – 9.4 | 1,2,4     | 7         |

Table S1: Our compilation of rotation curve data for the Milky Way. For each object type and reference, we report the range of Galactocentric radius $R$ (assuming a distance to the Galactic centre $R_0 = 8$ kpc), the Galactic quadrant(s) as well as the number of objects analysed (after cuts).
Figure S1: The evidence for dark matter in the inner Galaxy and its dependence on Galactic parameters. The plots show the cumulative reduced $\chi^2$ for each baryonic model as a function of Galactocentric radius. The thick red line represents the reduced $\chi^2$ corresponding to $5\sigma$ significance, while the black line shows the case of the fiducial baryonic model.
Figure S2: The evidence for dark matter in the inner Galaxy and its dependence on data selection. The line coding is the same as in Fig. S1.

Figure S3: The evidence for dark matter in the inner Galaxy and its dependence on baryonic uncertainties. The line coding is the same as in Fig. S1.
Figure S4: The peculiar velocities of masers for \( R_0 = 8 \) kpc, \( v_0 = 230 \) km/s, \( (U, V, W)_\odot = (11.10, 12.24, 7.25) \) km/s and a flat rotation curve. The velocity components are defined at the source position and point towards the Galactic centre (\( U_s \)), in the direction of Galactic rotation (\( V_s \)) and towards the Galactic north pole (\( W_s \)). The average and standard deviation of each distribution read \( \bar{U}_s = 3.6 \pm 9.7 \) km/s, \( \bar{V}_s = -4.4 \pm 9.7 \) km/s and \( \bar{W}_s = -2.1 \pm 7.5 \) km/s.
1. Fich, M., Blitz, L. & Stark, A. A. The rotation curve of the Milky Way to 2 R(0). *Astrophys. J.* **342**, 272–284 (1989).

2. Malhotra, S. The Vertical Distribution and Kinematics of H i and Mass Models of the Galactic Disk. *Astrophys. J.* **448**, 138 (1995).

3. McClure-Griffiths, N. M. & Dickey, J. M. Milky Way Kinematics. I. Measurements at the Subcentral Point of the Fourth Quadrant. *Astrophys. J.* **671**, 427–438 (2007).

4. Burton, W. B. & Gordon, M. A. Carbon monoxide in the Galaxy. III - The overall nature of its distribution in the equatorial plane. *Astron. & Astrophys.* **63**, 7–27 (1978).

5. Clemens, D. P. Massachusetts-Stony Brook Galactic plane CO survey - The Galactic disk rotation curve. *Astrophys. J.* **295**, 422–428 (1985).

6. Knapp, G. R., Stark, A. A. & Wilson, R. W. The global properties of the Galaxy. III - Maps of the (C-12)(O) emission in the first quadrant of the Galaxy. *Astron. J.* **90**, 254–300 (1985).

7. Luna, A., Bronfman, L., Carrasco, L. & May, J. Molecular Gas, Kinematics, and OB Star Formation in the Spiral Arms of the Southern Milky Way. *Astrophys. J.* **641**, 938–948 (2006).

8. Petrovskaja, I. V. & Teerikorpi, P. Rotation curve of the outer parts of our Galaxy from neutral hydrogen 21 CM line profiles. *Astron. & Astrophys.* **163**, 39–42 (1986).

9. Merrifield, M. R. The rotation curve of the Milky Way to 2.5 R_0 from the thickness of the H I layer. *Astron. J.* **103**, 1552–1563 (1992).

10. Honma, M. & Sofue, Y. Rotation Curve of the Galaxy. *Pub. Astron. Soc. Jap.* **49**, 453–460 (1997).

11. Blitz, L. The rotation curve of the Galaxy to R = 16 kiloparsecs. *Astrophys. J. Lett.* **231**, L115–L119 (1979).

12. Turbide, L. & Moffat, A. F. J. Precision photometry of young stellar groups towards the outer Galactic disk and the Galactic rotation curve. *Astron. J.* **105**, 1831–1854 (1993).

13. Brand, J. & Blitz, L. The Velocity Field of the Outer Galaxy. *Astron. & Astrophys.* **275**, 67 (1993).

14. Hou, L. G., Han, J. L. & Shi, W. B. The spiral structure of our Milky Way Galaxy. *Astron. & Astrophys.* **499**, 473–482 (2009).

15. Frinchaboy, P. M. & Majewski, S. R. Open Clusters as Galactic Disk Tracers. I. Project Motivation, Cluster Membership, and Bulk Three-Dimensional Kinematics. *Astron. J.* **136**, 118–145 (2008).

16. Dias, W. S., Alessi, B. S., Moitinho, A. & Lépine, J. R. D. New catalogue of optically visible open clusters and candidates. *Astron. & Astrophys.* **389**, 871–873 (2002).
17. Durand, S., Acker, A. & Zijlstra, A. The kinematics of 867 galactic planetary nebulae. *Astron. & Astrophys. Supp.* **132**, 13–20 (1998).

18. Zhang, C. Y. A statistical distance scale for Galactic planetary nebulae. *Astrophys. J. Supp.* **98**, 659–678 (1995).

19. Pont, F., Mayor, M. & Burki, G. New radial velocities for classical cepheids. Local galactic rotation revisited. *Astron. & Astrophys.* **285**, 415–439 (1994).

20. Pont, F., Queloz, D., Bratschi, P. & Mayor, M. Rotation of the outer disc from classical cepheids. *Astron. & Astrophys.* **318**, 416–428 (1997).

21. Demers, S. & Battinelli, P. C stars as kinematic probes of the Milky Way disk from 9 to 15 kpc. *Astron. & Astrophys.* **473**, 143–148 (2007).

22. Battinelli, P., Demers, S., Rossi, C. & Gigoyan, K. S. Extension of the C Star Rotation Curve of the Milky Way to 24 kpc. *Astrophysics* **56**, 68–75 (2013).

23. Reid, M. J. et al. Trigonometric Parallaxes of High Mass Star Forming Regions: The Structure and Kinematics of the Milky Way. *Astrophys. J.* **783**, 130 (2014).

24. Honma, M. et al. Fundamental Parameters of the Milky Way Galaxy Based on VLBI astrometry. *Pub. Astron. Soc. Jap.* **64**, 136 (2012).

25. Stepanishchev, A. S. & Bobylev, V. V. Galactic rotation curve from the space velocities of selected masers. *Astron. Lett.* **37**, 254–266 (2011).

26. Xu, Y. et al. On the Nature of the Local Spiral Arm of the Milky Way. *Astrophys. J.* **769**, 15 (2013).

27. Bobylev, V. V. & Bajkova, A. T. Galactic rotation curve and spiral density wave parameters from 73 masers. *Astron. Lett.* **39**, 809–818 (2013).

28. Reid, M. J. et al. Trigonometric Parallaxes of Massive Star-Forming Regions. VI. Galactic Structure, Fundamental Parameters, and Noncircular Motions. *Astrophys. J.* **700**, 137–148 (2009).

29. Dwek, E. et al. Morphology, near-infrared luminosity, and mass of the Galactic bulge from COBE DIRBE observations. *Astrophys. J.* **445**, 716–730 (1995).

30. Stanek, K. Z. et al. Modelling the Galactic Bar using Red Clump Stars. In Buta, R., Crocker, D. A. & Elmegreen, B. G. (eds.) IAU Colloq. 157: Barred Galaxies, vol. 91 of Astronomical Society of the Pacific Conference Series, 545 (1996).

31. Stanek, K. Z. et al. Modeling the Galactic Bar Using Red Clump Giants. *Astrophys. J.* **477**, 163 (1997).
32. Bissantz, N. & Gerhard, O. Spiral arms, bar shape and bulge microlensing in the Milky Way. *Mon. Not. R. Astron. Soc.* **330**, 591–608 (2002).

33. Vanhollebeke, E., Groenewegen, M. A. T. & Girardi, L. Stellar populations in the Galactic bulge. Modelling the Galactic bulge with TRILEGAL. *Astron. & Astrophys.* **498**, 95–107 (2009).

34. Zhao, H. A steady-state dynamical model for the COBE-detected Galactic bar. *Mon. Not. R. Astron. Soc.* **283**, 149–166 (1996).

35. López-Coroerdia, M. et al. The Long Bar in the Milky Way: Corroboration of an Old Hypothesis. *Astron. J.* **133**, 154–161 (2007).

36. Robin, A. C., Marshall, D. J., Schultheis, M. & Reylé, C. Stellar populations in the Milky Way bulge region: towards solving the Galactic bulge and bar shapes using 2MASS data. *Astron. & Astrophys.* **538**, A106 (2012).

37. Popowski, P. et al. Microlensing Optical Depth toward the Galactic Bulge Using Clump Giants from the MACHO Survey. *Astrophys. J.* **631**, 879–905 (2005).

38. Iocco, F., Pato, M., Bertone, G. & Jetzer, P. Dark Matter distribution in the Milky Way: microlensing and dynamical constraints. *JCAP* **11**, 29 (2011).

39. Han, C. & Gould, A. Stellar Contribution to the Galactic Bulge Microlensing Optical Depth. *Astrophys. J.* **592**, 172–175 (2003).

40. Calchi Novati, S. & Mancini, L. Microlensing towards the Large Magellanic Cloud: self-lensing for OGLE-II and OGLE-III. *Mon. Not. R. Astron. Soc.* **416**, 1292–1301 (2011).

41. de Jong, J. T. A. et al. Mapping the Stellar Structure of the Milky Way Thick Disk and Halo Using SEGUE Photometry. *Astrophys. J.* **714**, 663–674 (2010).

42. Juric, M. et al. The Milky Way Tomography with SDSS. I. Stellar Number Density Distribution. *Astrophys. J.* **673**, 864–914 (2008).

43. Bovy, J. & Rix, H.-W. A Direct Dynamical Measurement of the Milky Way’s Disk Surface Density Profile, Disk Scale Length, and Dark Matter Profile at 4 kpc < R < 9 kpc. *Astrophys. J.* **779**, 115 (2013).

44. Flynn, C., Holmberg, J., Portinari, L., Fuchs, B. & Jahreiß, H. On the mass-to-light ratio of the local Galactic disc and the optical luminosity of the Galaxy. *Mon. Not. R. Astron. Soc.* **372**, 1149–1160 (2006).

45. Ferrière, K. Interstellar gas within ~10 pc of Sagittarius A. *Astron. & Astrophys.* **540**, A50 (2012).

46. Ferrière, K., Gillard, W. & Jean, P. Spatial distribution of interstellar gas in the innermost 3 kpc of our galaxy. *Astron. & Astrophys.* **467**, 611–627 (2007).
47. Ferriere, K. Global Model of the Interstellar Medium in Our Galaxy with New Constraints on the Hot Gas Component. *Astrophys. J.* **497**, 759 (1998).

48. Moskalenko, I. V., Strong, A. W., Ormes, J. F. & Potgieter, M. S. Secondary Antiprotons and Propagation of Cosmic Rays in the Galaxy and Heliosphere. *Astrophys. J.* **565**, 280–296 (2002).

49. Ackermann, M. et al. Fermi-LAT Observations of the Diffuse $\gamma$-Ray Emission: Implications for Cosmic Rays and the Interstellar Medium. *Astrophys. J.* **750**, 3 (2012).

50. Binney, J. & Tremaine, S. *Galactic Dynamics: Second Edition* (Princeton University Press, 2008).

51. Gillessen, S. et al. Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Center. *Astrophys. J.* **692**, 1075–1109 (2009).

52. Ando, K. et al. Astrometry of Galactic Star-Forming Region ON2N with VERA: Estimation of the Galactic Constants. *Pub. Astron. Soc. Jap.* **63**, 45– (2011).

53. Malkin, Z. The current best estimate of the Galactocentric distance of the Sun based on comparison of different statistical techniques. *ArXiv e-prints* (2012). 1202.6128.

54. Bovy, J., Hogg, D. W. & Rix, H.-W. Galactic Masers and the Milky Way Circular Velocity. *Astrophys. J.* **704**, 1704–1709 (2009).

55. McMillan, P. J. & Binney, J. J. The uncertainty in Galactic parameters. *Mon. Not. R. Astron. Soc.* **402**, 934–940 (2010).

56. Bovy, J. et al. The Milky Way’s Circular-velocity Curve between 4 and 14 kpc from APOGEE data. *Astrophys. J.* **759**, 131 (2012).

57. Schönrich, R., Binney, J. & Dehnen, W. Local kinematics and the local standard of rest. *Mon. Not. R. Astron. Soc.* **403**, 1829–1833 (2010).

58. Dehnen, W. & Binney, J. J. Local stellar kinematics from HIPPARCOS data. *Mon. Not. R. Astron. Soc.* **298**, 387–394 (1998).

59. Sánchez-Salcedo, F. J. & Santillán, A. Magnetic fields: impact on the rotation curve of the Galaxy. *Mon. Not. R. Astron. Soc.* **433**, 2172–2181 (2013).

60. Kalberla, P. M. W. & Dedes, L. Global properties of the H I distribution in the outer Milky Way. Planar and extra-planar gas. *Astron. & Astrophys.* **487**, 951–963 (2008).