Gravitational interactions between the Large Magellanic Cloud (LMC) and the stellar and dark matter halo of the Milky Way are expected to give rise to disequilibrium phenomena in the outer Milky Way. A local wake is predicted to trail the orbit of the LMC, and a large-scale overdensity is predicted to exist across a large area of the northern Galactic hemisphere. Here we report the detection of both the local wake and northern overdensity (hereafter the ‘collective response’) in a map of the Galaxy based on 1,301 stars at galactocentric distances between 60 and 100 kiloparsecs. The location of the wake is in good agreement with an N-body simulation that includes the dynamical effect of the LMC on the Milky Way halo. The density contrast of the wake and collective response are stronger in the data than in the simulation. The detection of a strong local wake is independent evidence that the Magellanic clouds are on their first orbit around the Milky Way. The wake traces the path of the LMC, which will provide insight into the orbit of the LMC, which in turn is a sensitive probe of the mass of the LMC and the Milky Way. These data demonstrate that the outer halo is not in dynamical equilibrium, as is often assumed. The morphology and strength of the wake could be used to test the nature of dark matter and gravity.

We combined optical photometry from the Gaia Early Data Release 3 and infrared photometry from the Wide-field Infrared Survey Explorer (WISE) to identify a pure sample of giant stars across the entire sky, excluding the Galactic plane (|b| < 10°, where b is the galactic latitude). Photometric distances were estimated with a 10-Gyr isochrone with metallicity of [Fe/H] = −1.5 (ref. 9). Distances were converted to galactic physical coordinates, and the final sample was selected to lie at galactocentric distances of 60 < R < 100 kpc, where simulations predict a strong signal due to the dynamical response of the Large Magellanic Cloud (LMC) and where contamination from previously known structures is minimized. Selections in sky coordinates and Gaia proper motions were used to remove stars associated with known objects, including the LMC and the Small Magellanic Cloud (SMC), Milky Way disk stars and the Sagittarius Stream (see Methods for details).

In Fig. 1a, we show an equal-area Mollweide projection map of the resulting sample of 1,301 stars in Galactic coordinates. The map has been smoothed by a Gaussian beam with a full-width at half-maximum (FWHM) of 30° and coloured by the density contrast. Grey regions indicate portions of the sky that have been masked. There are two notable overdensities spanning thousands of square degrees. The southern feature is strongest at Galactic longitude l > 0° but appears to connect directly to the LMC and the SMC (as can be seen more clearly in Extended Data Fig. 3). The overdensity in the north spans nearly one quarter of the entire sky. A portion of the southern feature was previously identified as the Pisces Plume, but the map here uncovers its full extent on the sky.

In Fig. 1b, we show predictions from an N-body simulation that includes the dynamical response of the Galactic halo to the LMC. The LMC orbit in this model matches existing constraints on the present-day position and motion of the LMC, and has the LMC on its first passage around the Galaxy. The model shown here assumed a total Milky Way mass of M_{tot} = 1.2 × 10^{11} M_{⊙} and an initial LMC mass of M_{LMC} = 0.18 M_{⊙} (where M_{⊙} is the mass of the Sun). The simulated halo has been processed to match the selections applied to the data, enabling a direct comparison between the two maps. The dynamical response of the Galactic halo to the LMC has two primary components. (1) In the south, a local wake is excited behind the orbit of the LMC. This is the classic Chandrasekhar dynamical friction wake. (2) A global, collective response is also created, and is mostly the result of the movement of the barycentre of the Galaxy in the presence of the LMC. This collective response manifests as a large-scale overdensity in the northern sky. An important consequence of the simulation is that the dynamical response should be manifest in both the stars and the dark matter, and so a detection of structure in the former suggests a similar level of structure in the latter.

There are several immediate implications of Fig. 1. First, the outer halo of our Galaxy is in a state of substantial disequilibrium, with order unity variations in the density spanning thousands of square degrees. Most previous work attempting to constrain the outer mass distribution in the Galaxy has by necessity assumed simple equilibrium models. Future studies must account for the disequilibrium now measured in the Galactic halo. Second, the very strong observed local wake is independent evidence that the Magellanic clouds are on their first passage around the Galaxy. Previous work analysing the positions and velocities of these clouds had also inferred a first-passage scenario for the orbits of the clouds, although those results are sensitive to the...
uncertain mass of the Galaxy. If the clouds had undergone more than one complete orbit, the local wake would be much weaker, and perhaps not even detectable, due to destructive interference after repeated orbits, as in the case of the Sagittarius dwarf galaxy. Third, the local wake is predicted to accurately trace the orbital path of the LMC, and so its observed location will provide stringent new constraints on the orbit of the LMC.

In Fig. 2, we provide a quantitative comparison between observations and simulations of the strength of the local wake and collective response. Regions encompassing the local wake (−60° < b < −20°, 45° < l < 90°) and the collective response (30° < b < 60°, 240° < l < 300°) are defined and the mean density contrast is measured within them (using unsmoothed versions of the maps in Fig. 1). Poisson statistics are used to estimate Poisson uncertainties. In Fig. 2, we show results for four simulations with a range of LMC masses at infall: (0.8, 1.0, 1.8, 2.5) × 10^11 M_⊙. The density contrast in the local wake increases with increasing LMC mass, but overall, the simulations predict a density contrast lower than observed. In the data, the collective response is largely confined to −180° < l < 0°. Although the collective response is expected to be broadly asymmetric, the observed footprint of the simulated collective response is approximately symmetric about l = 0° (see Methods for further discussion). We also show results for a smooth stellar halo as expected this model shows no notable excess or deficit of stars in the wake or collective response regions.

The simulation is a genuine prediction and was not calibrated in any way to reproduce the observed features. The overall agreement between the simulation and observations, especially in the southern hemisphere, is therefore quite striking. Unsurprisingly, given the large available parameter space, the agreement is not perfect. For example, the density of the local wake in the fiducial simulation is lower by a factor of 1.4 ± 0.2 (mean ± s.d.) and the location of the peak density occurs farther away from the LMC compared with the observations. In addition, the collective response in the northern hemisphere is not as asymmetric (west versus east) in the simulation as in the data. The precise location and density of the local wake is sensitive not only to the mass of the LMC but also, because the formation of the wake is a resonant process, to the orbit of the LMC and the distribution of orbits within and the shape of the Milky Way halo. Furthermore, the impact of the SMC on these predictions has not yet been studied. The initial simulated stellar halo was smooth; the amplitude of the wake in a realistic halo built from mergers might be different. Exploration of this parameter space will be necessary to determine whether such a large observed wake signal can be accommodated within conventional models for the Milky Way and the LMC. As the wake is sculpted by the total gravitational mass and not just the stars, its existence and detailed morphology may also provide stringent tests of non-standard dark matter (for example, fuzzy dark matter and self-interacting dark matter) and alternative gravity models.

The exact location of the collective response in the sky is also sensitive to the orbit of the LMC, which is in turn sensitive to the mass of the Milky Way. As with the local wake, the collective response is sensitive to the distribution of orbits within the Galactic halo. Simulations that explore these variables will be necessary to see whether the observed location of the collective response can be reproduced.
The Magellanic Stream is a vast structure of cold gas trailing and originating from the LMC and the SMC\textsuperscript{24,25}. Simulations predict a corresponding stellar stream in the vicinity of the gaseous stream\textsuperscript{27,28}, although its location and mass content is uncertain. The stellar stream is predicted to be narrower in the sky than in the local wake\textsuperscript{2} and to reside at $R_{\text{gal}} > 100$ kpc at the location of the local wake\textsuperscript{29}. There have recently been detections of cold stellar structure in this region of the sky, perhaps associated with the Magellanic system in some way\textsuperscript{30,31}. In the Methods, we provide an unsmoothed version of Fig. 1a that does not reveal a colder feature that could be associated with a stream. Kinematic information should be definitive—a stellar stream, if one exists, should have distinct kinematic behaviour compared with the local wake.

Simulations that include the effect of the LMC on the Galactic halo\textsuperscript{2,3} predict large radial and tangential velocity differences across the sky due to the dynamical response of the halo to the LMC, with amplitudes exceeding 45 km s$^{-1}$. The sample presented here will be ideal for measuring the velocity signal from spectroscopy and proper motions, as nearly all stars are brighter than $G = 17.5$ (where $G$ is the Gaia G-band magnitude). Independent work has recently detected the predicted velocity signatures\textsuperscript{32,33}. These detections provide strong corroboration that the density variations reported here are due to the dynamical response of the Galaxy to the presence of the Magellanic clouds. The joint mapping and modelling of the density and kinematic signatures is the next step in uncovering the complex phase space structure imprinted by the Magellanic clouds in the outer Galaxy.

Online content

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to the outer stellar halo across the entire sky, we need a means of identifying, with high purity, a sample of giant stars based solely on all-sky photometry. Previous work\textsuperscript{14,15} used 2 Micron All-Sky Survey (2MASS) JHK\textsuperscript{2} photometry to identify M giant stars by relying on the pressure sensitivity of continuous opacity sources (mostly H). However, the relatively shallow depth of 2MASS precluded a detailed view of the outer halo (our sample of stars is largely confined to \( K < 13 \)), whereas previous work was limited to \( K < 13 \). We recently presented a photometric selection technique\textsuperscript{16} based on Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and WISE colours that efficiently identified K giants to \( W1 - 15 \) (where \( W1 \) is the WISE WI magnitude). The downside to this approach is that Pan-STARRS is not an all-sky survey. We therefore decided to explore the possibility of using Gaia and WISE photometry to select giants across the entire sky. In order to correct for dust extinction, we adopt the following reddening coefficients \((A)\): \( A_{\text{B-V}} E(B-V) = 3.0, A_{\text{V-R}} E(B-V) = 1.92 \) and \( A_{\text{V-W1}} E(B-V) = 0.18 \) (where \( E(B-V) \) is the selective extinction, and \( V, B \) and \( R \) are photometric filters). The normalization of the standard \( E(B-V) \) dust map\textsuperscript{17} is reduced by 14\% following more recent work\textsuperscript{18}. We also make two selections on Gaia quality flags: renormalized unit weight error, \( r_w < 1.4 \) and 3\sigma clipping of the corrected BP and RP flux excess factor \( C \) (ref. \textsuperscript{19}). We also apply a parallax selection of \( \pi > 0.2 \) mass to remove obvious foreground stars, using the corrected parallaxes from Gaia\textsuperscript{20}. For the WISE data, we restrict to \( 12 < W1 < 15 \), a magnitude range that is nearly 100\% complete\textsuperscript{21} and has formal uncertainties of 0.01 mag at the faint end of this range.

Extended Data Fig. 1 shows the distribution in \( BP - RP \) and \( RP - W1 \) colours for stars with \( 12 < W1 < 15 \) at high Galactic latitudes. This specific subsample was chosen to minimize Galactic reddening. Two sequences are clearly visible, with the upper and lower branches containing giants and dwarfs, respectively. We fit a polynomial to the giant sequence:

\[
(RP - W1)_{\text{fid}} = -0.9134 + 2.5985 (BP - RP) - 0.4518 (BP - RP)^2
\]

and the red lines are defined by \((RP - W1)_{\text{fid}} + 0.06 \) and \((RP - W1)_{\text{fid}} - 0.05 \) (where ‘fid’ is fiducial). We also impose a limit of \( 1.8 < (RP - W1) < 2.5 \). This selection is applied to an all-sky catalogue of Gaia and WISE cross-matched sources. For a metallicity of \([Fe/H] = -1.5\), this colour range corresponds to red giants with an effective temperature \( T_{\text{eff}} < 4,400 \) K, that is, K giant stars. Distances are estimated for these giants by using MESA Isochrones and Stellar Tracks (MIST) stellar isochrones\textsuperscript{22}. Specifically, we select red giant branch stars from a 10 Gyr, \([Fe/H] = -1.5\) model and fit a quadratic function between the \( BP - RP \) colour and the W1 absolute magnitude:

\[
M_{\text{W1}} = 11.547 - 17.117 (BP - RP) + 3.9329 (BP - RP)^2
\]

This equation is used to estimate distances for all stars in the catalogue. Distances based on a single colour will not be very accurate as good photometric distances require some knowledge of the age and metallicity, both of which we have fixed here. The stellar halo is widely believed to be old, and even a factor of two change in the adopted age changes the inferred distance by only about 7\%. The metallicity has a larger impact on the inferred distances. For example, assuming a fixed colour of \( BP - RP = 1.4 \), increasing the metallicity to \([Fe/H] = -1.0\) would result in 25\% closer distances, while assuming \([Fe/H] = -2.0\) would place the distances 14\% farther away compared with our fiducial isochrone. We have adopted \([Fe/H] = -1.5\) based on the fact that the mean metallicity of the halo is \([Fe/H] = -1.2\) with some evidence for a slightly more metal-poor halo at \( R_{gal} > 50 \) kpc (ref. \textsuperscript{23}). We emphasize that precise distances are not required in this work—they are simply used to place stars in broad radial bins.

### Removal of structure and map-making

Starting with the catalogue of giant stars, we identify the parent sample as stars that satisfy a magnitude selection of \( 12 < W1 < 15 \) and a Gaia parallax selection of \( \pi < 0.2 \) mas (we use the corrected parallaxes available in Gaia Early Data Release 3\textsuperscript{24}). We also remove stars with \( E(B-V) > 0.3 \) (regions with such large reddening are masked in the all-sky maps). We then select stars with Galactocentric distances of \( 60 < R_{gal} < 100 \) kpc, and further require stars to lie off the Galactic plane (\( |b| > 10^\circ \)). We also remove stars clearly associated with the dwarf galaxies and globular clusters mentioned above. This sample comprises 146,926 stars (the vast majority of which are associated with the LMC and the SMC). Extended Data Fig. 3a shows the density distribution in Galactic coordinates of this sample in a Mollweide projection. Each pixel has an area of 13.4 square degrees and the colour is proportional to the number of stars in each pixel.

There is substantial structure throughout the sky. The brightest features in this map are associated with the LMC and the SMC (lower right), the Galactic disk and bulge (centre) and the Sagittarius Stream (centre-north, and at the edges of the map in the south). The overdensities associated with the local wake and collective response are clearly visible in this raw map. However, in an attempt to isolate the features of interest, we have selected various populations for removal on the basis of sky coordinates and proper motions.

The LMC and the SMC are removed via selections in Galactic \((l, b)\) space. In the case of the LMC, a circular region with radius of 8\° centred on the LMC was excised from the catalogue. For the SMC, an ellipse with semi-major and minor axes of 3.2\° and 2.5\° centred on the SMC was used to remove stars (additional LMC and SMC stars beyond the Galactic coordinate cut are removed via the proper motion selection below). These selections reduce the catalogue to 5,007 stars.

Proper motions offer an efficient means by which we can remove structure unassociated with the diffuse halo. We work with solar reflex motion-corrected proper motions. (We adopt the Galacticocentric frame implemented in Astropy v4.0\textsuperscript{25}, which has the following parameters: distance between the Sun and the Galactic Centre \( R_0 = 8.122 \) kpc (ref. \textsuperscript{26}), radial, azimuthal and vertical velocity of the Sun \([V_R, V_\phi, V_Z] = [12.9, 245.6, 7.78] \) km s\textsuperscript{-1} (ref. \textsuperscript{26}) and distance of the Sun from the Galactic midplane \( Z_0 = 20.8 \) pc (ref. \textsuperscript{26}). We use the gala\textsuperscript{4} package reflex_correct by setting radial velocities to zero to account for the imprint of the solar motion on our proper motions.) The effect of the reflex motion correction is shown in Extended Data Fig. 4. The upper left panel shows the raw proper motions while the upper right panel shows the reflex-corrected proper motions. The lower left panel shows the sample at \( b > 0^\circ \) and \( |b_{gal}| > 15^\circ \) where \( b_{gal} \) is the latitude in the frame of the Sagittarius orbital plane\textsuperscript{27}. The dense clump contains the Sagittarius Stream in the north at \( l = 0^\circ \). The red box is used to remove these stars and is defined by proper motion in right ascension \( \mu_\alpha > -1.3 \) mas yr\textsuperscript{-1}, proper motion in declination \(-0.4 < \mu_\delta < 0.3 \) mas yr\textsuperscript{-1} and \( \mu_\delta > 1.7 \mu_\alpha + 0.4 \) mas yr\textsuperscript{-1} for \( b > 0^\circ \) and \( |b_{gal}| < 15^\circ \). The remaining northern arm of the Sagittarius Stream is removed by simply masking the region \( b > 0^\circ \) and \( 180^\circ < l < 210^\circ \) (it has low proper motion and so cannot be easily isolated from the rest of the halo via proper motion selections).
The Sagittarius selections above reduce the sample to 2,744 stars. A final selection in proper motion space is indicated by the blue circles in the lower panels of Extended Data Fig. 4: $\mu^2 + (\mu + 0.1)^2 < 0.5^2$ (in units of mas yr$^{-1}$). This selection removes disk stars, LMC and SMC stars beyond the on-sky selection, the Sagittarius dwarf spheroidal (dSph) and other Sagittarius arms, and reduces the sample to $\mathcal{L}_{301}$ stars. Of the stars removed with this selection, 520 are associated with the LMC and the SMC and 78 with the Sagittarius dSph. The rest are associated with either a southern arm of Sagittarius or are confined to $|b| < 20^\circ$ (these are disk stars with incorrect photometric distances, probably due to their very different metallicities). We note that the median proper motion uncertainty of the sample of 2,744 stars is 0.07 and only 110 stars have an uncertainty in either right ascension or declination of $>0.15$ mas yr$^{-1}$.

The final catalogue of 1,301 stars is available for download at https://doi.org/10.7910/DVN/2DIH87. Extended Data Fig. 3b shows the distribution of the final clean catalogue. Comparison between the two panels reveals that the various selections have a small impact on the regions of the sky containing the local wake and the collective response. Importantly, both of these features are visible in the raw, unsmoothed map. Extended Data Fig. 5 shows an annotated map of the final sample, including the orbit of the LMC (white) and the regions used to define the number counts used in Fig. 2.

In an effort to provide a direct comparison between the data and models, we have applied the exact same selection criteria outlined above to the models. In particular, the sky-based selections (including the LMC, the SMC, the Galactic plane and locations where $E(B-V) > 0.3$ are applied as a spatial mask in the maps. Selections in (solar reflex-corrected) proper motions are applied within the catalogues. An exception to this is the selection of the northern Sagittarius arm in proper motion space; this selection is applied only in the data. We do this because, while the selection is very clean in data space, the model halo particles are somewhat kinematically ‘hotter’ than the data and so this selection would remove a larger number of model halo particles. We also re-sample the models to follow the same distribution in $R_{gal}$ as the data, and have applied a 20% uncertainty to heliocentric distances to mimic our photometric distance uncertainties.

The following steps were taken to compute smoothed maps (as in, for example, Fig. 1). First, we bin the stars into pixels. Second, we apply the spatial mask. Third, for the non-masked pixels, we compute the average density and divide the map by that average (and then subtract the spatial mask). Third, for the non-masked pixels, we compute the average density and divide the map by that average (and then subtract the spatial mask). Fourth, we smooth the map by average density and divide the map by that average (and then subtract the spatial mask). Fifth, we apply a 20% uncertainty to heliocentric distances to mimic our photometric distance uncertainties.

The concentration of stars towards the mid-plane is a reflection of the power-law stellar halo with ellipticity $\varepsilon = 0.76$ that is aligned with the plane of the sky. The resulting map is shown in Extended Data Fig. 7, which can be compared directly with Extended Data Fig. 3 (right panel). There are overall more RR Lyrae than K giants (as we have defined them here), so the range of the colour bar is larger in Extended Data Fig. 7. The Pan-STARRS survey is restricted to declinations greater than $–30^\circ$, so the map is missing data in the lower-right quadrant. We have also masked $|b| < 10^\circ$ regions with $E(B-V) > 0.3$, and $|b_{gal}| < 15^\circ$ (for $b > 0^\circ$). This last selection was imposed because the RR Lyrae are too faint to have high-quality Gaia proper motions ($G \approx 20$), and as a consequence we could not excise the Sagittarius Stream from the maps with the proper motion cuts used for the K giants. In this map, one sees clearly the local wake in the southern hemisphere (first reported as the Pisces Plume$^1$) at a location that is in good agreement with the K giant sample. Owing to the $–30^\circ$ declination limit and the Sagittarius mask, the RR Lyrae do not probe the overdensity at $b > 0^\circ$, $–180^\circ < l < 0^\circ$ as completely as in the K giant sample. Nonetheless, an overdensity is clearly visible in that region.

We provide a quantitative comparison between the RR Lyrae and K giant maps in the right panel of Extended Data Fig. 7 (cf. Fig. 2). Here we have computed the density contrast in the local wake and collective response regions, including only those pixels not masked. As the RR Lyrae map is much less complete than the K giant map, it is not possible to estimate a robust global mean density from the RR Lyrae map. We therefore normalize the RR Lyrae map to the K giant map using a large region that is well sampled by both maps ($30^\circ < b < 60^\circ$, $30^\circ < l < 120^\circ$). The density contrast of the collective response computed from the RR Lyrae is statistically indistinguishable from the measurement based on the K giant sample. However, the local wake is 50% stronger in the RR Lyrae sample. The reasons for this are unclear. The distance distribution of the RR Lyrae is weighted towards greater distances than the K giants, so the maps are not probing exactly the same radial distribution. We caution that the densities are sensitive to our renormalization procedure.

Further progress could be made employing an all-sky map of RR Lyrae. Gaia Data Release 2 provided such a sample$^{12,13}$. However, these maps are incomplete at the depths necessary to detect RR Lyrae at more than 60 kpc ($G = 20$), driven largely by the Gaia scanning pattern$^{14}$. For example, the local wake is not clearly visible in the Gaia RR Lyrae catalogue despite the fact that it is so prominent in the Pan-STARRS data at more than 60 kpc. Future data releases from Gaia will hopefully reach the depths necessary to deliver complete samples of RR Lyrae in the outer halo.

**Simulation details**

The simulations shown here were initialized with a spherical dark matter halo following a Hernquist profile$^{15}$, a stellar disk and a stellar bulge with masses of $1.54 \times 10^{10} M_\odot$, $5.78 \times 10^{9} M_\odot$, and $0.9 \times 10^{10} M_\odot$, respectively. Each particle has a mass of $m_p = 1.57 \times 10^4 M_\odot$. One model of the Milky Way has isotropic halo kinematics, whereas the other has a radially biased kinematic profile. The four LMC models were initialized with a spherical dark matter Hernquist profile with total halo masses of $0.8 \times 10^{10} M_\odot$, $1.0 \times 10^{10} M_\odot$, $1.8 \times 10^{10} M_\odot$, and $2.5 \times 10^{10} M_\odot$. The scale length of each of the LMC halos was chosen to match the observed rotation curve of the LMC within 9 kpc. Detailed parameters for these simulations can be found in Table 1 of the original simulation paper$^7$. All the initial conditions for the halos were built using GalIC$^8$. The N-body simulations were run with P-gadget3. The initial conditions for the orbit of the LMC were found iteratively until the present-day position
and velocity of the LMC was within 2σ of the present-day observed properties of the LMC.

In this work, we have used the raw dark matter particle data to apply a simple re-weighting scheme to match the observed density profile. The left panel of Extended Data Fig. 8 shows the N-body simulation presented in Fig. 1, now without any selections, aside from matching the density profile of the data and selecting stars with 60 < R < 100 kpc. The right panel shows the same simulation now viewed from an observer placed at the Galactic Centre. This perspective provides a sharper distinction between the local wake and collective response, but we opted not to make the observed maps in this way owing to the complex mapping of the Galactic reddening selection in this projection.

Another approach to constructing a mock stellar halo from these simulations is available for these simulations and was built in equilibrium with the dark matter halo, given a specified stellar density and velocity dispersion profile using a weighing scheme designed to reproduce the observed density profile of the stellar halo. We have compared our mock stellar halo to this alternative approach and find very similar results.

The detailed structure of the halo response to the passage of the LMC has been recently quantified using basis function expansions. The halo response to the LMC has a strong amplitude in odd l modes. In contrast, triaxial, oblate and prolate halos have no odd l terms, only even terms. As such, the deformations to the Milky Way halo caused by the LMC cannot be mimicked by a triaxial halo.

A tilted halo?
The observed all-sky map of halo stars shown in Fig. 1a shows a degree of symmetry in the sense that the overdensities are confined to the southwest and northeast. In this section, we explore the possibility that the observed density variation could be due to a smooth tilted stellar halo instead of our preferred interpretation of the impact of the LMC.

Extended Data Fig. 9 shows a smooth, tilted triaxial halo whose parameters were optimized (by hand) to mimic the observations in Fig. 1a. Specifically, the model has axial ratios of 0.2 (minor to major axes) and 0.6 (intermediate to major axes) and is rotated 60° anticlockwise along the y axis. Note that while this model reproduces some of the basic features of the data, in detail there are substantial differences in both the southern and northern hemispheres that leads us to disfavour this interpretation of the data. Moreover, independent results based on kinematics of the stellar halo also favour the LMC dynamical response interpretation of the observed outer stellar halo.

Data availability
The K giant catalogue used in this paper is available at https://doi.org/10.7910/DVN/2DIH8J.

Code availability
We have opted not to make the code used in this manuscript available because the data reduction and analysis is straightforward and can be easily reproduced following the methods described herein.

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Additional information
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Extended Data Fig. 1 | Photometric selection of giants. Colour–colour diagram for stars at high Galactic latitude ($b > 45^\circ$) with Gaia parallax $\pi < 0.1$ mas. Two sequences are clearly visible, with the upper branch being associated with giant stars, and the lower with dwarf stars. The red lines mark the selection boundary used in this work.
Extended Data Fig. 2 | Test of photometric distances. Comparison of our photometric distances against literature values for satellite galaxies around the Milky Way (red) and globular clusters (blue). Error bars represent the 1σ scatter in the photometric distances and dotted lines mark ±20% about the one-to-one line. The dwarf galaxies include Fornax, Draco, Sculptor, Carina, Ursa Minor, and the LMC and the SMC, and span average metallicities from [Fe/H] = −0.5 (LMC) to [Fe/H] = −2.2 (Ursa Minor)42.
Extended Data Fig. 3 | Maps of unsmoothed star counts. Mollweide projection maps of the observed sample of giants with pixels of size 13.4 square degrees. a, Map with no masking of known structure, either in sky coordinates or proper motions. The two main features identified here, the transient wake and the collective response, are still clearly visible even in this unfiltered map. b, Map showing the filtered catalogue used in Fig. 1a. The LMC and the SMC appear in the lower right as a merged region of high density. Other features include the stellar disk + bulge in the centre, and the Sagittarius Stream both in the north-centre and lower left and right.
Extended Data Fig. 4 | Proper motions of the halo sample. a, Proper motions of the K giants at 60 < $R_{\text{gal}}$ < 100 kpc with 12 < $W_1$ < 15 and the LMC and the SMC removed via on-sky selection. b, Solar reflex-corrected proper motions. Notice the much tighter distribution of stars near (0, 0). In this panel, the Sagittarius dSph is visible at (−2.5, −0.7) and LMC and SMC stars not removed by the on-sky selection are visible as a narrow vertical strip at $\mu_\alpha$ $\gtrsim$ 0.5 mas yr$^{-1}$. The northern Sagittarius arm is the large overdensity at (−0.7, 0.0) and a southern arm of Sagittarius is the diagonal cluster of points at $\mu_\delta$ $< -0.5$ mas yr$^{-1}$. c, Reflex-corrected proper motions focusing on the region of the sky containing the northern Sagittarius arm at $l$ = 0°. The red box indicates our selection for removing this feature. d, Stars not in the selection shown in c. Our selection for low proper motion stars is indicated by a blue circle in c and d.
Extended Data Fig. 5 | An annotated map of the outer halo. As in Extended Data Fig. 3 (right panel), now shown with the predicted orbit of the LMC (solid white line), a line at −25° declination (grey dashed line, marking the approximate limit of northern hemisphere surveys) and the locations of the two regions used to measure density ratios in Fig. 2 (solid yellow lines). The yellow region in the north measures the collective response while the yellow region in the south measures the local wake.
**Extended Data Fig. 6 | Predicted density distribution of a smooth model.**
The model has a smooth (oblate) stellar halo. **a**, The unfiltered smooth model. **b**, The smooth model with the same selection criteria as used in the data, including various coordinate and proper motion cuts. Both maps have been smoothed by a Gaussian with FWHM = 30°. Unlike the data, this map shows no obvious structure.
Extended Data Fig. 7 | RR Lyrae as a probe of the stellar halo. 

**a**, Binned all-sky map of RR Lyrae stars identified in Pan-STARRS data\(^1\). The data are restricted to declinations greater than −30°. The wake is clearly visible in the lower left quadrant (compare with Extended Data Fig. 4).

**b**, Measured densities in the wake and collective response regions for RR Lyrae (blue) compared with the K giants (black; compare with Fig. 2). Both the wake and collective response are clearly detected in the RR Lyrae.
Extended Data Fig. 8 | Predicted response of the Galactic halo to the LMC.

The N-body simulation presented in Fig. 1b is shown here without any selections, either in proper motions or on-sky (the density profile is still matched to the data, and only stars with $60 < R_{gal} < 100$ kpc are included).

a. Projection in the usual Galactic coordinates. b. Projection in Galactocentric coordinates (what an observer would see if placed at the Galactic Centre). In b, the model amplitude of the collective response is asymmetric and is largest near the Galactic plane.
Extended Data Fig. 9 | Predicted density distribution of a tilted stellar halo.
All-sky density distribution of a smooth triaxial model stellar halo that is tilted by 60° along the y axis. While this model captures some of the qualitative behaviour seen in the data (Fig. 1a), it fails to reproduce both the detailed shape of the local wake and predicts a precise symmetry in the north and south, which is not observed.