Identification of Sagittarius stream members in Angular Momentum space with Gaussian mixture techniques

Jorge Peñarrubia\textsuperscript{1,2*}, Michael S. Petersen\textsuperscript{1}
\textsuperscript{1}Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
\textsuperscript{2}Centre for Statistics, University of Edinburgh, School of Mathematics, Edinburgh EH9 3FD, UK

24 June 2021

ABSTRACT
This paper uses Gaussian mixture techniques to dissect the Milky Way (MW) stellar halo in angular momentum space. Application to a catalogue of 5389 stars near the plane of the Sagittarius (Sgr) stream with full 6D phase-space coordinates supplied by Gaia EDR3 and SEGUE returns four independent dynamical components. The broadest and most populated corresponds to the ‘smooth’ MW halo. The narrowest and faintest contains 40 stars of the Orphan stream. We find a component with little or no angular momentum likely associated with the GSE substructure. We also identify 925 stars and 7 Globular Clusters with probabilities $>90\%$ to be members of the Sgr stream. Comparison against $N$-body models shows that some of these members trace the continuation of the leading/trailing tails in the Southern/Northern hemispheres. The new detections span $\sim 800^\circ$ on the sky, thus wrapping the Galaxy twice.

Key words: Galaxy: halo–galaxies: kinematics and dynamics–galaxies: evolution

1 INTRODUCTION
Since its serendipitous discovery by Ibata et al. (1994), the Sagittarius (Sgr) dwarf galaxy has become a poster child for the tidal disruption of satellite galaxies and the hierarchical build up of galactic stellar haloes. With early observations largely restricted to pencil-beam fields of view (Ivezić et al. 2000; Vivas et al. 2001; Newberg et al. 2002; Martínez-Delgado et al. 2002), the striking extent of the tidal tails was not revealed until all-sky 2MASS survey became available (Majewski et al. 2003). It was soon realized that dynamical modelling of the tidal tails provides powerful constraints on the gravitational field of the Milky Way (MW). Yet, after more than two decades of continuous research the Sgr stream still presents a number of theoretical challenges. For example, dynamical models of the Sgr stream that adopt a static MW potential have returned dark matter halo with prolate (Helmi 2004), oblate (Johnston et al. 2005) and triaxial (Law & Majewski 2010) shapes. This mismatch may be due to the gravitational attraction induced by a massive Large Magellanic Cloud (LMC) on first infall, which has two important effects: it perturbs the orbits of stream stars (Law & Majewski 2010; Vera-Ciro & Helmi 2013), and displaces the MW disc from the Galactic barycentre (Gómez et al. 2015; Petersen & Peñarrubia 2020), causing a reflex motion in the kinematics of distant halo stars (Erkal et al. 2020; Petersen & Peñarrubia 2021, hereafter PP21) and Local Group galaxies (Peñarrubia et al. 2016). Recently, Vasiliev et al. (2021, hereafter VBE21) show that the disparate constraints on the dark matter halo shapes may be due to the adoption of a static MW potential in earlier models. However, other issues, like the origin of the bifurcated tails (Belokurov et al. 2006; Koposov et al. 2012), remain poorly understood. E.g. it was suggested that the bifurcations could be caused by rotation in the progenitor dwarf (Peñarrubia et al. 2010). Yet, these models predict a significant amount of rotation in the remnant core, which has been ruled out by different kinematic surveys (Peñarrubia et al. 2011; Frinchaboy et al. 2012; Vasiliev & Belokurov 2020; del Pino et al. 2021). Furthermore, all published models predict the existence of old stream wraps populated by stars lost during early pericentric passages whose detection remains elusive, probably because they are more phase-mixed than those stripped recently. Finding this material may constrain the amount of dynamical friction experienced by the Sgr dwarf (Fardal et al. 2019b), and its infall trajectory (Dierickx & Loeb 2017).

This paper explores a statistical method to detect kinematic substructures in the halo that are partially, or even fully phase mixed. In particular, we use Gaussian mixture techniques to quantify clustering in angular momentum space. Previous attempts to detect the Sgr stream using catalogues of halo stars with full phase-space coordinates either apply cuts in energy and/or angular momentum (Li et al. 2019; Johnson et al. 2020), or search for stars on similar orbits with Friends-of-Friends algorithms (Yang et al. 2019). In contrast, our method draws statistical associations between objects in the halo without relying on assumptions on the form, shape or time-evolution of the MW potential, or introducing subjective cuts in integrals of motion. Its applicability is chiefly limited by the reduced number of halo stars with measured 6D phase-space coordinates. For example, Ramos et al. (2020) provides a catalogue of 182495 RR Lyrae in Gaia DR2 (Gaia Collaboration et al. 2018) with 5D information, that is approximately 17 times larger than the 6D data set introduced below.
2 DATA

We use a parent catalogue of 6030 K Giants and 3952 Blue Horizontal Branch (BHB) stars in the Milky Way stellar halo with available phase-space information compiled by PP21 from public data sets (Xue et al. 2008; Yanny et al. 2009; Xue et al. 2011) and updated with *Gaia* EDR3 astrometry (Gaia Collaboration et al. 2021).

One of the main goals of this paper is to identify Sgr stream members. For a better characterization of the angular momentum distribution of the Sgr stream, it is convenient to minimize the fraction of MW interlopers in the Bayesian fits of §3. To this aim, the reference frame is rotated such that the average polar angle measured from the Galactic centre is at $B_{gal} = 0$ (Majewski et al. 2003). Subsequently, stars within $|B_{gal}| < 20^\circ$ at Galactocentric distances $r > 20 kpc$ are chosen, which yields 3419 K Giants and 1970 BHBs, with mean distance errors $\epsilon_d / D \simeq 0.05$ and 0.17, respectively.

In addition, we also use published positions, distances, radial velocities, and proper motions of MW satellites (McConnachie & Venn 2020) and globular clusters (Vasiliev & Baumgardt 2021; Baumgardt & Vasiliev 2021) in order to explore possible associations with the Sagittarius dwarf. To convert heliocentric into Galactocentric quantities we place the sun at $\vec{v}_0 = (-12.9, 245.6, 7.78)$ km s$^{-1}$ (Drimmel & Poggio 2018).

3 BAYESIAN ANALYSIS

An efficient way to model the distribution of stars in angular momentum $\vec{L} = \vec{r} \times \vec{v}$, with $\vec{r}$ and $\vec{v}$ measured in a Galactocentric frame, is to adopt a Gaussian mixture likelihood (Kuhn & Feigelson 2017)

$$L(\vec{\theta}|\vec{S}) = \sum_{i=1}^{N} \alpha_i N(\vec{\theta}|\vec{S}_i),$$

with individual weights normalized such that $\sum_{i=1}^{N} \alpha_i = 1$. Here, $\vec{\theta} = \{D_i, \ell_i, b_i, v_{hel}, \mu_{hel}, \mu_D, i, \mu_{bD} i, \epsilon_L, \epsilon_b \}$ is a sample stars with full phase-space information, and $\vec{S}$ is the array of model parameters that define the multivariate Gaussian probability functions

$$N(\vec{\theta}|\vec{S}) = \frac{1}{\sqrt{(2\pi)^N |\text{det}(C)|}} \exp \left[ -\vec{(L - \vec{L})}' C^{-1} (\vec{L} - \vec{L}) \right],$$

where $C$ is the covariance matrix

$$C = \begin{bmatrix} \epsilon_\ell^2 + \sigma_\ell^2 & \epsilon_\ell \epsilon_b \sigma_b & \epsilon_\ell \epsilon_b \rho_{b}\ \epsilon_\ell \epsilon_b \rho_{b} \\ \epsilon_\ell \epsilon_b \rho_{b} & \sigma_\ell^2 + \sigma_b^2 & \epsilon_\ell \epsilon_b \rho_{b} \\ \epsilon_\ell \epsilon_b \rho_{b} & \epsilon_\ell \epsilon_b \rho_{b} & \sigma_b^2 \end{bmatrix}$$

and $\rho_{i,j}$ are correlation coefficients, while $(\epsilon_\ell, \epsilon_b)$ are uncertainties associated with individual angular momentum values estimated by Monte-Carlo sampling observational errors on heliocentric distance ($\epsilon_d$), line-of-sight velocities ($\epsilon_v$), and proper motions ($\epsilon_\ell, \epsilon_b$). The hyperparameters $\sigma_i^2$, with $i = x, y, z$, account for the spread in angular momentum of stars in each Gaussian mixture component beyond those introduced by statistical errors (e.g. see Hobson et al. 2002). For a better exploration of the prior volume, it is convenient to express the mean angular momentum in spherical coordinates $\langle \vec{L} \rangle = (L_\ell, L_y, L_z) = (L \cos \theta \cos \phi, L \cos \theta \sin \phi, L \sin \theta)$, and $\beta_i = \{\log L, \theta, \phi, \sigma_\ell, \sigma_b, \rho_{b}\}$, with $i = 1, \ldots, N$, hence the total number of parameters in our fits is $7N - 1$.

Our analysis uses $N = 4$ components with 27 parameters. We adopt flat priors on $\{\alpha, \log L, \cos \theta, \phi\}$, and Jeffreys priors for the hyperparameters $\{\sigma_\ell, \sigma_b, \rho_{b}\}$, with ranges that include reasonable values. Mixture models are fitted with the code MULTINEST (Feroz & Hobson 2008; Feroz et al. 2009), which uses a nested-sampling technique (Skilling 2004) to calculate posterior distributions and the evidence of the model.

From the posterior distributions, we estimate the probability that an object (star, GC or dwarf galaxy) with observed quantities $\vec{S}$ belongs to the Sgr stream as

$$p_{mem}(\vec{S}) = \frac{\alpha_{Sgr} N_{Sgr}(\vec{\theta}|\vec{S}_p)}{\sum_{i=1}^{N} \alpha_i N(\vec{\theta}|\vec{S}_i)}$$

where $\vec{S}_p$ is an array that contains the median of the posterior distributions.

Figure 1. Angular momentum components of stellar halo stars with available 6D phase-space coordinates and located within $|B_{gal}| < 20^\circ$ of the Sgr dSph orbital plane (see text). Stars are colour-coded according to their probability to belonging to the Sgr stream. Back stars mark the angular momentum components of the Sgr dwarf galaxy. Black/white circles show the exclusion limits applied by PP21 to remove Sgr stream stars from their analysis. Stars on the left of the dotted line were labelled Sgr stream members by Johnson et al. (2020). Orphan stream members ($p_{mem} > 0.9$) are shown in green. Magenta crosses in the bottom-left of each panel show the average uncertainty of angular momentum measurements, $\sim 600$ km s$^{-1}$. Right panel shows the angular momentum distribution of the stellar sample (black line). Coloured histograms weigh stars by membership probabilities (see text).
4 RESULTS

4.1 Halo stars in angular momentum space

Table 1 provides the median and 1-sigma uncertainties of the parameters of a Gaussian mixture model with $N = 4$ components. The posterior distributions on individual parameters are well behaved, with little covariance between them. Comparison against the angular momentum of the Sagittarius dwarf, $L_{\text{sgr}} = 72.6 \pm 6.6 \text{kpc km s}^{-1}$, is roughly perpendicular to the orbital plane of the Sgr dwarf. This is consistent with the hyperparameter $\sigma_z$, being approximately twice as large as $\sigma_x$ and $\sigma_y$ (see Table 1). Second, the distribution of non-members ($p_{\text{mem}} < 0.5$) is clearly non-Gaussian. As a result, our mixture models need at least $N = 4$ components in order to find a good match. The angular momentum $L = \langle \vec{L} \rangle$ distribution of the sample is shown in the right panel with a black line. To illustrate the location of the Gaussian mixture components we weigh each star by their membership probability and re-compute the histograms. As expected, we find that stars with high probability of belonging to the GSE substructure have little angular momentum. Stars labelled as members of the ‘smooth’ halo have a broad angular momentum distribution, whereas Sgr and Orphan stars clump in a relatively narrow region.

The angular momentum of the Sgr stream has been recently studied by Johnson et al. (2020), who propose a simple criterion for membership. Namely, stars with angular momentum coordinates $L_t \leq -2.5 \pm L_z / 0.3$, with $L_z$ measured in units of $10^3 \text{ kpc km s}^{-1}$ (dotted line in Fig. 1), are labelled members. Application of this cut to our dataset yields 1500 stars. All the 925 stream members detected in our analysis at $p_{\text{mem}} > 0.9$ satisfy this condition. We also find 317 likely interlopers ($p_{\text{mem}} < 0.5$). Hence, these results suggest that Johnson et al. (2020) sample is complete but has a low purity. Given the results from our sample, where 317/1500 $\approx 21\%$ of the stars selected by the Johnson et al. (2020) criterion are low-likelihood members, a similar fraction of the Johnson et al. (2020) stream sample may be MW interlopers. However, we caution that the Johnson et al. (2020) catalogue has different sky coverage and phase-space densities, which complicates a direct comparison.

PP21 studied the angular momentum distribution of stars in the outskirts of the MW with the opposite goal in mind, namely to remove Sgr stream members from a catalogue of ‘smooth’ halo stars. To this aim, they exclude 1062 stars with angular momenta similar to that of the Sgr dwarf, $L_t \leq -2.5 \pm L_z / 0.3$ (dotted-line black/white circles in Fig. 1). One can see by eye that this cut is imperfect, as some Sgr members are located outside the circled regions. Indeed, we find that 793 Sgr stream members ($p_{\text{mem}} > 0.9$) and 72 MW interlopers ($p_{\text{mem}} < 0.5$) are located within this volume. This implies that PP21 cut successfully removes a large fraction ($793 / 925 \approx 86\%$) of stream members from their halo sample, while the misidentification of smooth halo stars as stream members is relatively low, $72 / 1062 \approx 7\%$.

4.2 The Sagittarius & Orphan streams

In Fig. 2 we plot the observational coordinates of Sgr stream stars with membership probabilities $p_{\text{mem}} > 0.9$. Blue and red stars denote BHB and K Giant stars, respectively. This plot reveals that while the Sgr stream can be described by a simple multivariate normal function in angular momentum (see Fig. 1), the distribution in phase space is extraordinarily more complex. To guide the interpretation of the detections, we over-plot with dark/light grey particles the leading/trailing tails of the Sgr stream model recently published by VBE21, which accounts for both the gravitational attraction of the LMC as well as the displacement of the MW disc from the Galactic barycentre in response to the LMC infall (see detailed discussion in PP21).

Upper panel of Fig. 2 shows the sky projections of the stream members. The sky coverage is incomplete, with large gaps at $R.A. \gtrsim 200^\circ$ and $60^\circ \lesssim R.A. \lesssim 100^\circ$ owing to the limited SEGUE footprint.

Table 1. Posterior derived from a Gaussian mixture model with $N = 4$ components. Only halo stars within $|B_{\text{sgr}}| < 20^\circ$ of the Sgr orbital plane and at Galactocentric distances $r > 20 \text{kpc}$ are included in the fit. Angular momentum $L$ and the hyperparameters $\sigma_i$ are given in units of $\text{kpc km s}^{-1}$.

| Param. | #1 (Sgr) | #2 (GSE) | #3 (smooth) | #4 (Orphan) |
|--------|----------|----------|-------------|-------------|
| $\alpha$ | 0.322$^{+0.002}_{-0.002}$ | 0.239$^{+0.001}_{-0.002}$ | 0.438$^{+0.005}_{-0.005}$ | 0.0077$^{+0.0005}_{-0.0005}$ |
| $(L_x)$ | +426$^{+126}_{-126}$ | -90$^{+126}_{-126}$ | 144$^{+126}_{-126}$ | -3905$^{+126}_{-126}$ |
| $(L_y)$ | -495$^{+115}_{-115}$ | +11$^{+115}_{-115}$ | -279$^{+115}_{-115}$ | -232$^{+115}_{-115}$ |
| $(L_z)$ | -1436$^{+115}_{-115}$ | +11$^{+115}_{-115}$ | +126$^{+115}_{-115}$ | -4664$^{+115}_{-115}$ |
| $\sigma_x$ | 655$^{+5}_{-5}$ | 10.3$^{+0.3}_{-0.3}$ | 1755$^{+3}_{-3}$ | 13$^{+3}_{-3}$ |
| $\sigma_y$ | 1255$^{+3}_{-3}$ | 11.3$^{+0.3}_{-0.3}$ | 1926$^{+3}_{-3}$ | 12$^{+3}_{-3}$ |
| $\sigma_z$ | 659$^{+5}_{-5}$ | 10.7$^{+0.3}_{-0.3}$ | 1733$^{+3}_{-3}$ | 13$^{+3}_{-3}$ |
The authors found metal-poor stars associated with the Sgr stream that are both off-set and with a diffuse distribution of line-of-sight velocities compared to the metal-rich component, which led them to speculate the possible existence of a striped stellar halo of the Sagittarius dwarf. However, §3 shows that the proposed cut in \( L_s \) returns a non-negligible number of MW contaminants (\( \approx 21\% \) in our sample), suggesting that the broad velocity distribution may be partially explained the presence of MW interlopers. In contrast, selecting members from the Gaussian mixture of Fig. 2 shows that the older wraps of the trailing/leading tails are kinematically cold, in agreement with VBE21 models.

The mixture decomposition presented in §3 can be used to draw statistical associations between each of the Gaussian components and any object in our Galaxy with available phase-space information. For example, of the 170 known Globular Clusters in the Milky Way, we find 7 with high probability (\( p_{mem} > 0.9 \)) of being members of the Sgr system: M54, Arp 2, Pal 12, Whiting 1, NGC 2419, Terzan 7 and 8 (cyan boxes in Fig. 2). The rest have membership probabilities \( p_{mem} \lesssim 0.01 \), suggesting that there are no additional known GCs associated with the Sgr dwarf, in agreement with recent analyses (e.g. Arakelyan et al. 2021; Johnson et al. 2020). Our results do not support recent claims that NGC 5634 and 4147 trace ancient wraps of the stream (Bellazzini et al. 2020). No known satellite galaxy appears to be associated with the Sgr dwarf.

In addition, we also detect several members of the Orphan stream (component #4 in Table 1), shown in Fig. 2 with green dots. Comparison against the positions, velocities and proper motions found by Fardal et al. (2019b) shows excellent agreement, indicating that the Gaussian mixture decomposition of §3 can also uncover faint substructures in the stellar halo even when these contribute to \( \lesssim 1\% \) of the fitted sample.

5 DISCUSSION & SUMMARY

We show that modelling the distribution of stars in angular momentum space with Gaussian mixture techniques provides a powerful method to detect accreted substructures that are partially, or fully mixed in phase-space, without making assumptions on the form, shape or time-evolution of the MW potential. Application to a catalogue of 5389 stars in the plane of the Sgr stream with available 6D phase-space coordinates reveals the presence of at least four independent dynamical components. We associate the broadest and most numerous with the ‘smooth’ stellar halo, and the faintest (with only 0.8% of the sample) with the Orphan stream. Interestingly, we also identify a third component with little or no angular momentum that likely corresponds to the GSE substructure.

Our statistical technique detects two older wraps of the Sagittarius stream that correspond to the continuation of the leading/trailing tails in the Southern/Northern hemispheres, showing that the Sgr stream circles the Galaxy at least twice. The full extent of the tidal tails is shown in Fig. 3 in a reference frame aligned with the orbital plane of the stream. Dots show the orbital poles of individual stream members relative to that of the Sagittarius dwarf galaxy as a function of the angular separation from the remnant core (with notation \( \Lambda > 0 \) for the leading, and \( \Lambda < 0 \) trailing tails). The discovery of older wraps double the known extent of the Sgr stream. While published 6D data cover parts of the stream within \(-150^\circ \lesssim \Lambda \lesssim 200^\circ\) from the Sgr dwarf, 6D detections increase this range out to \(-300^\circ \lesssim \Lambda \lesssim 500^\circ\).

For comparison, the orbital poles of the N-body model are shown with grey dots. To estimate the time at which different parts of the stream became tidally unbound from the Sgr dwarf, we find the N-body particle closest to each individual star and colour-code stream...
members according to their stripping time. We distinguish between material lost at $t_{\text{strip}} < 1.5\,\text{Gyr}$ (cyan) and $t_{\text{strip}} > 1.5\,\text{Gyr}$ (orange), which approximately correspond to particles unbound during the last and penultimate pericentric passages of the progenitor dwarf, respectively (for details, see VBE21). As expected, the continua-
tion of the leading & trailing tails correspond to material stripped early. Interestingly, the orbital poles of the old wraps remain roughly aligned with the angle along the stream, $t$. Stars are colour-coded according to the time when they were tidally stripped from the progenitor (see text). The location of the Sgr dwarf is marked with a white star.

The Sgr stream in angular momentum

Figure 3. Galactocentric coordinates of the orbital poles of individual stream members ($p_{\text{mem}} > 0.9$) relative to that of the Sgr dwarf as a function of the angle along the stream, $\Lambda$. Stars are colour-coded according to the time when they were tidally stripped from the progenitor (see text). The location of the Sgr dwarf is marked with a white star.

ACKNOWLEDGMENTS

We thank Teresa Antoja, Pau Ramos, Eugene Vasiliev, Vasily Belokurov, Denis Erkal, Benjamin Johnson and Charlie Conroy for helpful comments. MSP acknowledges funding from a UK Science and Technology Facilities Council (STFC) Consolidated Grant.

DATA AVAILABILITY

The Sgr stream sample may be found on github: https://github.com/michael-petersen/SgrL.

REFERENCES

Arakelyan N. R., Pilipenko S. V., Sharina M. E., 2021, Astrophysical Bulletin, 75, 394
Baumgardt H., Vasiliev E., 2021, arXiv e-prints, p. arXiv:2105.09526
Bellazzini M., Ibata R., Malhan K., Martin N., Famaey B., Thomas G., 2020, A&A, 636, A107
Belokurov V., et al., 2006, ApJ, 642, L137
Belokurov V., Erkal D., Evans N. W., Koposov S. E., Deason A. J., 2018, MNRAS, 478, 611
Bennett M., Boyt J., 2019, MNRAS, 482, 1417
Dierickx M. I. P., Loeb A., 2017, ApJ, 836, 92
Drimmel R., Poggio E., 2018, Research Notes of the American Astronomical Society, 2, 210
Erkal D., et al., 2020, arXiv e-prints, p. arXiv:2010.13789
Fardal M. A., van der Marel R. P., Law D. R., Sohn S. T., Sesar B., Hernitschek N., Rix H.-W., 2019a, MNRAS, 483, 4724
Fardal M. A., van der Marel R. P., Sohn S. T., del Pino Molina A., 2019b, MNRAS, 486, 936
Ferco F., Hobson M. P., 2008, MNRAS, 384, 449
Ferco F., Hobson M. P., Bridges M., 2009, MNRAS, 398, 1601
Frinchaboy P. M., Majewski S. R., Muñoz R. R., Law D. R., Lokas E. L., Kunkel W. E., Patterson R. J., Johnston K. V., 2012, ApJ, 756, 74
Gaia Collaboration et al., 2018, A&A, 616, A1
Gaia Collaboration et al., 2021, A&A, 649, A1
Gómez F. A., Belsa G., Carpentero D. D., Villalobos Á., O’Shea B. W., Bell E. F., 2015, ApJ, 802, 128
Gravity Collaboration et al., 2019, A&A, 625, L10
Helmi A., 2004, ApJ, 610, L97
Helmi A., Babusiaux C., Koppelman H. H., Massari D., Veljanoski J., Brown A. G. A., 2018, Nature, 563, 85
Hobson M. P., Bridle S. L., Lahav O., 2002, MNRAS, 335, 377
Ibata R. A., Gilmore G., Irwin M. J., 1994, Nature, 370, 194
Ivezić Ž., et al., 2000, AJ, 120, 963
Johnson K. V., Law D. R., Majewski S. R., 2005, ApJ, 619, 800
Koposov S. E., et al., 2012, ApJ, 750, 80
Kuhn M. A., Feigelson E. D., 2017, arXiv e-prints, p. arXiv:1711.11101
Law D. R., Majewski S. R., 2010, ApJ, 714, 229
Li J., et al., 2019, ApJ, 874, 138
Majewski S. R., Skrutskie M. F., Weinberg M. D., Ostheimer J. C., 2003, ApJ, 599, 1082
Martínez-Delgado D., Zinn R., Carrera R., Gallart C., 2002, ApJ, 573, L19
McConnachie A. W., Venn K. A., 2020, Research Notes of the American Astronomical Society, 4, 229
Newberg H. J., et al., 2002, ApJ, 569, 245
Peñarrubia J., Benson A. J., Martínez-Delgado D., 2006, ApJ, 645, 240
Peñarrubia J., Belokurov V., Evans N. W., Martínez-Delgado D., Gilmore G., Irwin M., Niederste-Ostholt M., Zucker D. B., 2010, MNRAS, 408, L26
Peñarrubia J., et al., 2011, ApJ, 727, L37
Peñarrubia J., Gómez F. A., Besla G., Erkal D., Ma Y.-Z., 2016, MNRAS, 456, L54
6 Peñarrubia & Petersen

Petersen M. S., Peñarrubia J., 2020, MNRAS, 494, L11
Petersen M. S., Peñarrubia J., 2021, Nature Astronomy, 5, 251
Ramos P., Mateu C., Antoja T., Helmi A., Castro-Ginard A., Balbinot E., Carrasco J. M., 2020, A&A, 638, A104
Skilling J., 2004, in Fischer R., Preuss R., Toussaint U. V., eds, American Institute of Physics Conference Series Vol. 735, American Institute of Physics Conference Series. pp 395–405, doi:10.1063/1.1835238
Vasiliev E., Baumgardt H., 2021, arXiv e-prints. p. arXiv:2102.09568
Vasiliev E., Belokurov V., 2020, MNRAS, 497, 4162
Vasiliev E., Belokurov V., Erkal D., 2021, MNRAS, 501, 2279
Vera-Ciro C., Helmi A., 2013, ApJ, 773, L4
Vivas A. K., et al., 2001, ApJ, 554, L33
Xue X. X., et al., 2008, ApJ, 684, 1143
Xue X.-X., et al., 2011, ApJ, 738, 79
Yang C., et al., 2019, ApJ, 886, 154
Yanny B., et al., 2009, AJ, 137, 4377
del Pino A., Fardal M. A., van der Marel R. P., Łokas E. L., Mateu C., Sohn S. T., 2021, ApJ, 908, 244