Gaia Challenge: GREAT workshop | Scientific report

Justin I. Read[1], Mark Gieles[1] & Daisuke Kawata[2]

[1]Department of physics - University of Surrey - Guildford - Surrey - GU2 7XH - United Kingdom

[2]Mullard Space Science Laboratory - University College London - Holmbury St. Mary - Dorking - Surrey - RH5 6NT

Science Meeting Type:	Workshop
Title of Meeting:	Gaia Challenge
Location of Meeting:	University of Surrey, Guildford, GU2 7XH, UK
Date of Meeting:	August 19th - 22/23rd, 2013
Organisers:	Justin I. Read, Mark Gieles & Daisuke Kawata
Contact [E-mail]:	justin.inglis.read@gmail.com
Web:	http://astrowiki.ph.surrey.ac.uk/dokuwiki/
Application reference:	4732

1 Summary (up to one page)

With the Gaia launch next year, we proposed a workshop – Gaia Challenge – aimed at improving our mass modelling methods from Jeans modelling and distribution function modelling to Schwarzschild modelling, M2M and others. We were fortunate enough to receive ESF GREAT funding for this workshop of €5000 of which we have received €4000 so far. This was later was revised to €8000. We used a portion of this money ($\sim$ €2000) to fully fund the registration fee for five participants who would otherwise be unable to participate. The rest was used to generally subsidise the meeting. We had some 59 participants from all over the world spanning a wide range of astrophysics communities from observers working on dense stellar systems to cosmological simulators. All were brought together by a shared interest in exploiting the forthcoming Gaia data to understand our Galaxy and its constituents.

The workshop revolved around a series of test problems (mock data) posted online in advance[1]. We divided activities into four main working groups:

1. *Spherical & Triaxial (P.I. Read)*
2. *Discs (P.I. Kawata)*
3. *Streams & Halo Stars (P.I. A. Font)*
4. *Collisional/Star Clusters (P.I. Gieles)*

Attendees were invited to apply their favourite methods to these mock data to recover the underlying gravitational potential and/or phase space distribution function. Building dynamically realistic mocks meant bringing together N-body simulators, dynamicists and the stellar population synthesis and dust extinction community. A key goal of this workshop – in addition to improving mass modelling techniques – was to facilitate the exchange of expertise between these communities and to foster longer term collaborations.

Several exciting new results already came out of the meeting. Key highlights include: (i) standard mass modelling techniques that assume spherical symmetry can be reasonably applied to triaxial models provided that we are not ‘staring down the barrel’; (ii) for 1D disc models, it is sampling that is all important; (iii) a single globular cluster stream – given good enough data – can give tight constraints on the halo mass and shape (and several very different techniques look capable of doing exactly this); and (iv) simple distribution functions give an excellent fit to collisional star clusters, but which one depends very much on how tidally limited the cluster is. Each of these key results has potentially far-reaching implications: for measuring the dark matter distribution in dwarfs; for measuring the local dark matter density near the Sun; for probing alternative gravity models and cosmology; and for hunting for intermediate mass black holes (see §3 for further details).

The workshop was extremely well received by all involved and we hope to run Gaia Challenge-II in Heidelberg next year. The goal is to have a meeting $\sim$ every year up to final Gaia data release building mocks of ever

---

[1] See http://astrowiki.ph.surrey.ac.uk/dokuwiki/.

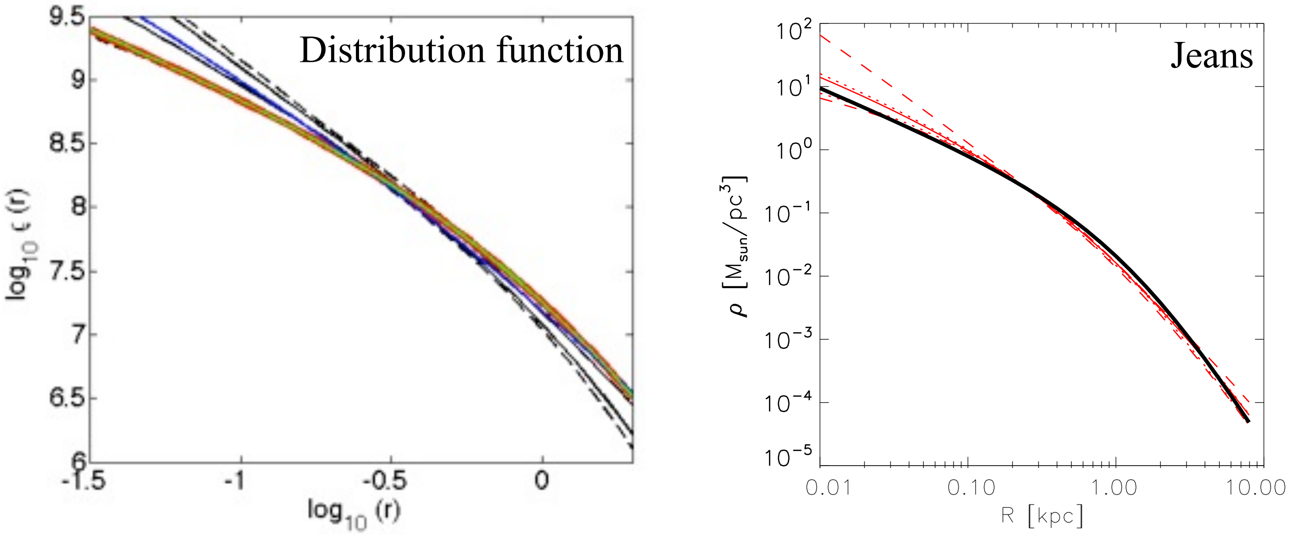

Figure 1: Preliminary results for modelling a triaxial mock dwarf galaxy. The panels shows the 68% (dotted) and 95% (dashed) confidence interval for the recovered mass density of a triaxial dwarf viewed along an intermediate axis. The red/green (left) and thick black (right) lines show the input model. The left panel shows results using a spherical distribution function method (Wilkinson et al. in prep.); the right using a spherical Jeans method (Walker et al. in prep.). In both cases a simple parameterised form is assumed for the underlying mass distribution. Notice that despite an incorrect assumption of spherical symmetry, the recovery is very good in both cases. The recovery is not good if the triaxial system is viewed 'down the barrel' (not shown), leading to the perhaps counter-intuitive result that *dwarfs that look spherical are most likely to be strongly biased when applying spherical models.*

increasing realism and sophistication. Only by honing our methods on these mock data, will we truly become ready for the 'Gaia Challenge'.

2 Scientific content and discussions (up to four pages)

As mentioned above, the workshop was split into four main working groups. We deliberately arranged the program to give participants significant time to work in separate breakout rooms on the test problems, coming together to share progress and ideas between groups at least twice per day. Many participants moved freely between groups and a key result of the workshop was the cross-pollination of ideas between normally disparate communities. For example, many tools and techniques routinely employed for mass modelling dwarf galaxies were new to the field of star clusters; work began at the workshop to try out dwarf modellers on the mock star cluster data. I now discuss the scientific content of each working group in more detail.

2.1 Spherical & Triaxial (P.I. Read)

These mock data were designed to mimic spherical/triaxial collisionless stellar systems (e.g. dwarf galaxies and giant elliptical galaxies). Key questions included: (i) What quality of data are required to determine the mass profile? (ii) How can we best break the degeneracy between velocity anisotropy and mass? (iii) How badly do we do if we assume spherical symmetry but the galaxy is actually triaxial?

For this working group, a significant amount of mock data were posted in advance. The first task was to pare this down to a manageable number of standardised mocks. This led to the development of a Default Mock Data Suite. This has 12 spherical mocks that test the ability of a method to recover the gravitational potential for cusped and cored light profiles, cusped and cored mass profiles and different velocity anisotropy (isotropic, radial and tangential); triaxial mocks; and (to be added) some tidally stripped mocks. The application of several mass modelling methods to these data will be published over the next year in the first Gaia Challenge paper. Some preliminary results are shown in Figure 1. Despite an incorrect assumption of spherical symmetry, the recovery is very good for both the distribution function method (left; Wilkinson et al. in prep.) and the Jeans method (right; Walker et al. in prep.). The recovery is not good if the triaxial system is viewed 'down the barrel' (not shown), leading to the perhaps counter-intuitive result that *dwarfs that look spherical are most likely to be strongly biased when applying spherical models!* John Magorrian also showed some very encouraging results for a brand new mass modelling technique that he has recently proposed[2]. This new method had some problems with the parameter initialisation at the start of the workshop, but was already producing exciting results for the Default Spherical Mock Data Suite by the end of the week.

2.2 Discs (P.I. Kawata)

These mock data were designed to mimic the Milky Way disc – both locally (i.e. near the Sun) and globally. Key questions included, for the local problem: (i) What quality of data are required to determine the local dark matter density? (ii) Do multiple populations (e.g. split by abundance/age) help? (iii) Is 1D modelling sufficient? And for the global problem: (i) Can global models simultaneously recover the disc phase space distribution function and the gravitational potential? (ii) What are the key degeneracies in the problem and how can these be broken?

2.2.1 Determining the local disc potential near the Sun

For the local problem, J. I. Read set up some 1D data using a distribution function assumed to be perfectly separable so that: $f \equiv f(E_z)$, where $E_z = \frac{1}{2}v_z^2 + \Phi(z)$ is the vertical energy. These 1D mocks were set up to be 'as good as it gets' in that they imagine perfect error-free 1D data with no coupling between the radial and vertical motions[3]. Results from applying a 1D Jeans method to the full mock suite are shown in Figure 2. These tests will be published as part of a review article on 'The Local Dark Matter Density' by J. I. Read (Journal of Physics G) later this year. The recovery in every case is good (compare the input model blue lines with the 68% (dotted) and 95% (dashed) confidence intervals. But what is striking is the role of data versus prior. Without any prior, $n_* = 1000$ tracers give a very large error on the surface density $\Sigma_z(z)$ at all heights. Adding a 'Rot' prior that constrains the dark matter contribution by wrapping in constraints from the rotation curve assuming spherical symmetry (b), the errors shrink a little. Adding a 'Scale' prior that constrains the visible disc gives much tighter errors at low z, but large errors at high z remain (c). Combining these two priors tightens the errors to $\sim 10\%$ (d). The same order of magnitude of error is achieved by increasing the sampling to $n_* = 10^4$ stars (similar to what is currently possible using SDSS data; e), in which case no prior is required. Panels f) - h) show that population splitting, or going to large height above the disc do not necessarily yield significantly improved constraints. It seems that in a world with perfect data, perhaps unsurprisingly, it is the sampling n_* that is all important.

2.2.2 Determining the global Milky Way potential

The rest of the focus for the week was on recovering the global potential of the Milky Way in some large volume around the Sun. Several mock data sets were provided from analytic distribution functions and N-body models using either analytic (McMillan, Figueras, Romero-Gomez) or fully self-consistent (Hunt, Read, Debattista) gravitational potentials, as detailed on the wiki site[4]. Painting 'red clump' stars on these mock data and including realistic Gaia errors was also initiated. Some groups were interested in recovering the potential from these data; others in recovering the pattern speed of the bar, demonstrating the versatility of such mock data. Highlights include Jo Bovy successfully recovering the vertical force K_z at 1.1 kpc from featureless disc data (a pre-cursor to the more difficult problem of perturbed discs with a bar/spiral arms and/or warp). Chemic also successfully recovered the rotation curve of an N-body disc assuming perfect data. On the bar pattern speed side there was also much activity. Monari recovered the pattern speed of test particle data by identifying an outer Lindblad resonance feature; Chemin recovered the bar and spiral arm feature using the Tremaine-Weinberg method (assuming perfect data); Pfenniger recovered the bar and spiral pattern speed with Fourier decomposition and moment of inertia (both with and without errors) from a simple test particle model; Hunt recovered the bar pattern speed using Made-to-Measure modelling; and Long presented their recovery of the bar pattern speed and position of the Milky Way from BRAVA data. The hope is to streamline these data, collate the results and write this up as either one or two publications over the next year.

---

[2] See http://astrowiki.ph.surrey.ac.uk/dokuwiki/lib/exe/fetch.php?media=workshop:magog.pdf and here.

[3] See http://astrowiki.ph.surrey.ac.uk/dokuwiki/doku.php?id=discs.

[4] See: http://astrowiki.ph.surrey.ac.uk/dokuwiki/doku.php?id=discs.

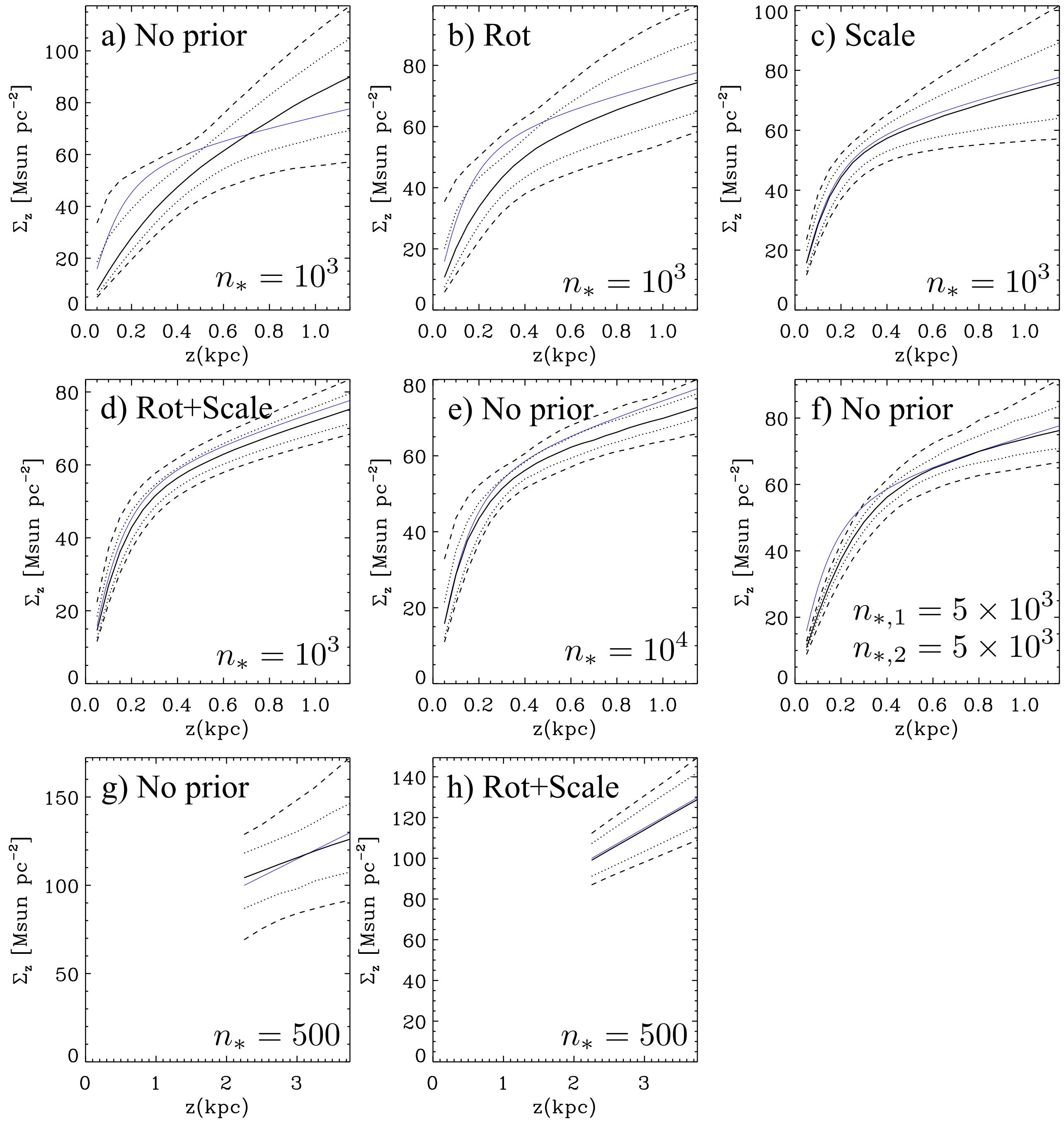

Figure 2: 1D mock data tests of the recovery of the disc surface mass density $\Sigma_z(z)$. The solid, dotted and dashed lines show the median, 68% and 95% confidence intervals for 250,000 models sampled with an MCMC. The blue line shows the input model. The mock data are 'as good as it gets' in that I assume no observational errors; zero tilt and rotation curve terms; and perfect self-consistent tracer stars. Panels a) - d) explore the effect of increasingly strong model priors (as marked) for $n_* = 10^3$ tracers from a Simple exponential tracer model. Panel e) shows results for 10^4 tracers; and f) the same split into two populations (Simple and Simple2 – both exponentials with different scale heights). Finally, panels g) and h) explore results for just 500 tracers high above the disc plane (the 'High' mock data set). These tests will be published as part of a review article on 'The Local Dark Matter Density' by J. I. Read (Journal of Physics G) later this year.

2.3 Streams & Halo Stars (P.I. A. Font)

These mock data were designed to mimic cold/hot streams in the Milky Way halo and the halo star population. Key questions included: (i) What can we learn about the gravitational potential from such cold streams or halo stars? (ii) Can we find clear evidence for triaxiality? (iii) Can we find any evidence for granularity or substructure in the potential?

Most activity in this group ranged around recovering the Galactic potential using stellar stream data. An impressive six mock data suites were posted. Seven different methodologies were applied to these data, focusing on a test suite designed to mimic the Palomar 5 (Pal 5) globular cluster stream around the Milky Way. Some preliminary results for four different methods are shown in Figure 3. This test is a starting point for more difficult/sophisticated tests and starts out also in the spirit of 'as good as it gets' with perfect error free data in a simple Logarithmic halo:

$$\Phi = \frac{V_c^2}{2}\log\left(R^2 + \frac{z^2}{q^2}\right) \tag{1}$$

Most participants fixed this simple potential also in the recovery, attempting to recover just V_c (or equivalently the halo mass) and q_z. As can be seen from Figure 3, all methods obtain the correct answer within their quoted uncertainties but some are more accurate than others. Some of this comes down to how much freedom was allowed in the fitted gravitational potential, but it is clear that some methods – for this particular problem – perform better than others. It remains to be seen how this will change as more realistic data with errors is employed with more complex gravitational potential functions, and potentially multiple streams being simultaneously fit together. It is encouraging though as it suggests that stream data really will tell us about the shape of the Galactic dark matter halo.

2.4 Collisional/Star Clusters (P.I. Gieles)

These mock data are designed to mimic collisional systems like star/globular clusters. Key questions included: (i) What is the role of mass segregation in the models? (ii) What is the role of tides? (iii) What is the role of rotation?

A number of mock data tests were posted on the wiki[5]. The first considered a single mass N-body cluster evolved until dissolution in a tidal field. The goal was to see what type of distribution function can reasonably represent a post-core collapse cluster, and to look at how tides introduce tangential anisotropy at the cluster edge. Some preliminary results are shown in Figure 4. The isotropic King model (often employed in the literature) gave a poor fit to the compact high mass cluster (left), but an excellent fit to the tidally limited cluster at late stages of evolution (right). The radially anisotropic f_ν models – designed to describe the outcome of incomplete violent relaxation in galaxy mergers – gave a surprisingly excellent description of the compact cluster (left). At the same time, it failed to reproduce the tidally limited case at late stages (right).

The working group went on to also consider models with stellar evolution and/or mass segregation. The hope is that a streamlined test suite with some core tests will be published over the next year. Note that – amazingly – this is really the first time that such distribution functions have been confronted with collisional N-body models. There is much yet to be learned, in particular in forming useful priors about which distribution functions are best employed in which situations. Ultimately, this will allow us to build more accurate and faithful models of star clusters in and around the Milky Way addressing such issues as the possible presence of intermediate mass black holes, and understanding an important phase of star formation (globular clusters) most likely responsible for a large fraction of the stellar feedback experienced by our Galaxy over its lifetime.

3 Assessment of the results and impact of the event on the future directions of the field (up to two pages)

Each of the four working groups has already uncovered new and interesting results, simply by confronting standard mass modelling techniques with 'perfect data'. The spherical/triaxial group have tested a brand new method for mass modelling stellar systems and found that it shows promise (Magorrian); they have also shown

---

[5] See http://astrowiki.ph.surrey.ac.uk/dokuwiki/doku.php?id=collision.

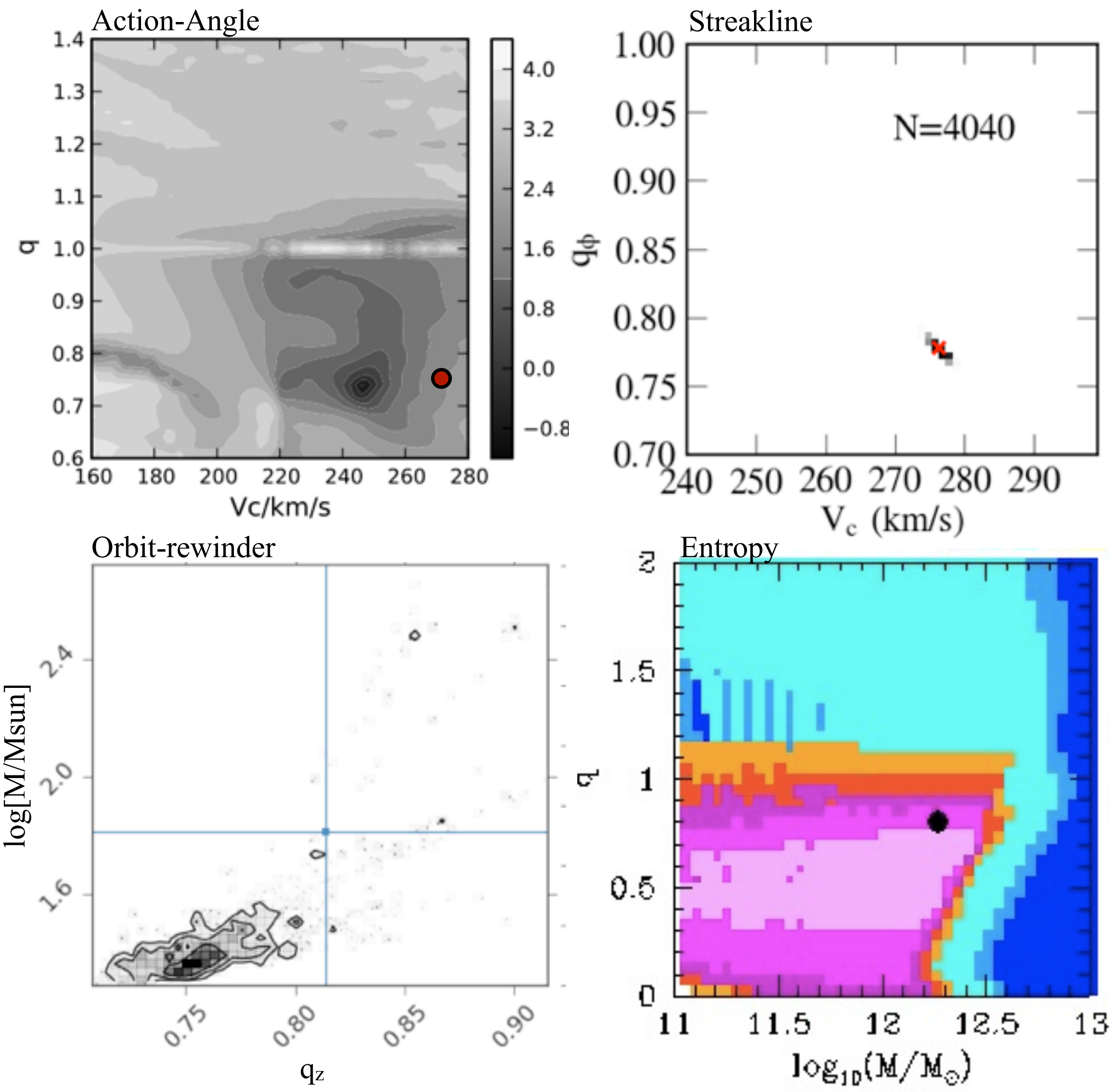

Figure 3: Results for the recovery of V_c (or equivalently the halo mass) and the flattening q_z for Pal-5 like globular cluster stream in a Logarithmic halo assuming perfect error-free data, using four different methods as marked (*Action-Angle*; Sanders, *Streakline*; Küpper/Bonaca; *Orbit-rewinder*; Price-Whelan, and *Entropy*; Penarrubia). The correct answer is marked by the solid black/red circles.

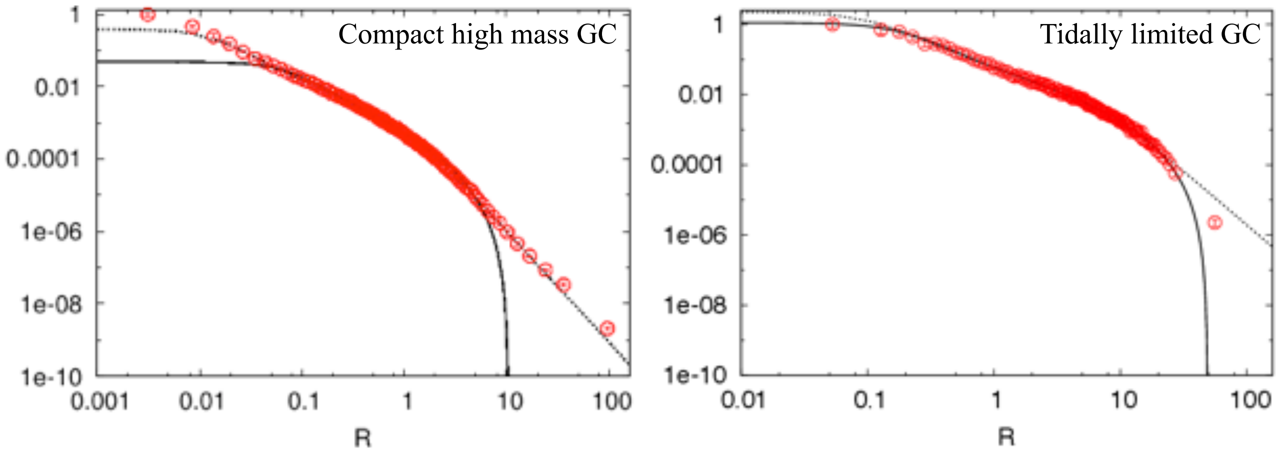

Figure 4: Results comparing a simple isotropic King distribution function (solid) and f_ν model (dotted) to an N-body single mass star cluster evolving in a tidal field (red circles). The left panel shows a compact high mass GC; the right a lower mass more extended GC at late times that has become tidally limited.

that standard techniques that assume spherical symmetry (assuming current sample sizes) can be reasonably applied to triaxial models provided that we are not 'staring down the barrel'. This is good news. The increased complexity of triaxial models may only be necessary, paradoxically, if a dwarf appears *spherical* on the sky. Any dwarf with such an orientation (there are none so far) could simply be discarded from a statistical study. The disc group have shown that for 1D models, it is sampling that is all important – something that will increase by orders of magnitude once the Gaia data becomes available, holding out the promise of precision measures of the matter density near the Sun. For global models, current methods perform well on undisturbed discs but work is on-going looking a more complex and realistic scenarios that include spiral arms, a bar, and a warp. The halo/streams group have shown that a single globular cluster stream – given good enough data – can give tight constraints on the halo mass and shape. Furthermore, there are now many new and exciting methods in the literature that appear to work. Which of these is most promising when applied to real data remains to be tested, but most likely they will continue to all have their strengths and weaknesses. It can only be a good thing if we have multiple methodologies with which to inter-compare our results – especially if we uncover evidence for something exciting like a triaxial Milky Way halo. Finally, the collisional group are performing detailed tests using N-body mock data for the first time. With the promise of proper motion and radial velocity data for nearby star clusters from Gaia, the time is ripe to re-asses model systematics. These tiny star clusters could hold the clue to several important problems in modern astrophysics, if we can get the mass modelling right: What is the link (if any) between stellar and supermassive black holes? And, what do old star clusters tell us about the tidal field of their host Galaxy – can this tell us about mass or even the mass evolution of our Galaxy?

The Gaia Challenge website is now open as a lasting community resource. We hope and indeed commit to develop and expand on the existing mock data tests there. At Gaia Challenge-II – already in planning – we hope to begin to add realistic observational errors, to test sample selection effects, and to wrap in dynamical nasties like tidal forces, dynamical instabilities, and stellar evolution/mass segregation. It is an exciting time as we ramp up to being fully prepared for the Gaia data. Such tests not only give us confidence in our methodologies, they also help us to know how and where improvements are vital, and – which is most exciting – exactly what kind of data we will need to answer key questions in astrophysics. This latter is perhaps the most exciting aspect. Perhaps just a slightly deeper observation, the 'right kind' of stellar velocity data, or the 'right sort' of survey selection function can make all the difference – if only we could know. Our mock data suite will enable us to ask and answer these kinds of question more easily than ever before, driving new and exciting Gaia-related science.

4 Annexes

4.1 Programme of the meeting

Please see pages appended to the end of this file.

4.2 Full list of speakers and participants

1. Matthew Walker
2. Gerry Gilmore
3. Andreas Kpper
4. Paul McMillan
5. Hans Buist
6. Anna Lisa Varri
7. Pascal Steger
8. Vincent Henault-Brunet
9. Laura Watkins
10. Adrian Price-Whelan
11. Shigeki Inoue
12. Justin Read
13. Mark Gieles
14. Daisuke Kawata
15. Jason Hunt
16. Alice Zocchi
17. Antonio Sollima
18. Thomas Richardson
19. Richard Parker
20. Michiel Cottaar
21. Giacomo Monari
22. Chervin Laporte
23. Malcolm Fairbairn
24. Andreea Font
25. Jorge Penarrubia
26. Mark Wilkinson
27. Stefano Pasetto
28. John Magorrian
29. Annie Robin
30. Alex Buedenbender
31. Raphael Errani
32. Ana Bonaca
33. Richard Long
34. Anthony Brown
35. Francesca Figueras
36. Santi Roca-Fbrega
37. Jason Sanders
38. Jo Bovy
39. Markus Weber
40. Rachel Kennedy
41. Ben Lowing
42. Daniele Fantin
43. Daniel Pfenniger
44. Richelle de Bocx
45. Sanjib Sharma
46. Glenn van de Ven
47. Amina Helmi
48. Brad Gibson
49. Victor Debattista
50. Walter Dehnen
51. Tjibaria Pijloo
52. Nathan Deg
53. Laurent Chemin
54. Maider Sancho Miranda
55. Adriano Agnello
56. Nicola Cristiano Amorisco
57. Hamish Silverwood
58. Klaudia Kowalczyk
59. Ben MacFarlane

Gaia Challenge Workshop Programme

Main talks will be in lecture Theatre F (please see the campus_map.pdf on the Gaia Challege Wiki).
Working group sessions will be in Theatre J (spherical/triaxial); Theatre H (discs); Theatre F (streams/halo stars); and Theatre B (collisional systems).

Monday	**Chair: Justin Read**	**Welcome; Gaia Review**
9 - 9.30am	LOC	Welcome | [1]
9.30 - 10am	Anthony Brown	Gaia: Counting down to launch | [2]
10.00 - 10.30am	Gerry Gilmore	Gaia Science
10.30 - 11am	Coffee	
11am - 12.30pm	Structured working groups	Working group discussions | [3]
12.30 - 1.30pm	Lunch	
1.30pm - 3pm	Structured working groups	
3 - 3.30pm	Coffee	
3.30pm - 4pm	Annie Robin	Gaia Challenge Mock Catalogue
4 - 4.30pm	Sanjib Sharma	Generating Mock Data From Models | [4]
4.30 - 4.50pm	Stefano Pasetto	Star count modelling | [5]
4.50 - 5.10pm	Andreea Font	Pathways to forming disc galaxies in a hierarchical cosmology [6]
5.10 - 5.30pm	Giacomo Monari	3D test particle simulations of the Galactic disks. The kinematical effects of the bar | [7]
5.30 - 5.50pm	Santi Roca-Fàbrega	On galaxy spiral arms' nature as revealed by rotation frequencies | [8]
5.50 - 6.10pm	Daniel Pfenniger	The bar corotation, a bridge between the bar and the thick disk | [9]
6.10 - 6.30pm	LOC	Report back from working groups
6.30pm	Dinner	

Tuesday	**Chair: TBD**	**Spherical/Triaxial systems**
9 - 9.30am	Matt Walker	My Struggles with Jeans Modelling
9.30 - 10am	Mark Wilkinson	Distribution function modelling
10am - 10.30am	John Magorrian	Bayes versus the virial theorem | [10]
10.30 - 11am	Coffee	
11am - 12.30pm	Structured working groups	Working group discussions | [11]
12.30 - 1.30pm	Lunch	
1.30pm - 3pm	Structured working groups	
3 - 3.30pm	Coffee	
3.30pm - 4pm	Walter Dehnen	Made to Measure
4 - 4.20pm	Thomas Richardson	Modelling dSphs with higher moments of the Jeans Equations | [12]
4.20 - 4.40pm	Pascal Steger	Non-parametric Jeans modelling | [13]
4.40 - 5pm	Chervin Laporte	Measuring the slope of mass profiles for dSphs in triaxial CDM potentials | [14]
5 - 5.20pm	Klaudia Kowalczyk	Can we measure the slopes of density profiles in dwarf spheroidal galaxies?
5.20 - 5.40pm	Adriano Agnello	Dynamics of the GC system of M87
5.40 - 6pm	LOC	Report back from working groups
6.30pm	Dinner	

Wednesday	**Chair: Daisuke Kawata**	**Discs**
9 - 9.30am	Glenn van de Ven	The Gravitational Potential Near the Sun
	Alex Buedenbender	
9.30 - 10am	Jo Bovy	A dynamical disk-halo decomposition in the inner Milky Way | [15]
10 - 10.30am	Paul McMillan	How to find the Milky Way potential from the disc - don't use an orbit library | [16]
10.30 - 11am	Coffee	

11am - 11.20am	Richard Long	Made-to-measure galaxy models: Modelling with Milky Way observations | [17]
11.20 - 11.40	Jason Hunt	A Particle by Particle M2M Algorithm: PRIMAL | [18]
11.40 - 12pm	Laurent Chemin	Milky Way Disc Kinematics and Dynamics | [19]
12 - 12.20pm	Shigeki Inoue	Can Gaia conclude the local dark matter density problem? | [20]
12.20 - 12.40pm	Marcus Weber	The local dark matter density in the light of recent Fermi and AMS-02 data | [21]
12.40 - 1.30pm	Lunch	
1.30pm - 6.30pm	Free for work/activities	
6.30pm	Workshop dinner	
Thursday	**Chair: Andreea Font**	**Halo/Streams**
9 - 9.30am	Amina Helmi	TBD
9.30 - 10am	Jorge Penarrubia	Statistical Mechanics of tidal streams | [22]
10am - 10.30am	Victor Debattista	The Milky Way in its Triaxial Halo | [23]
10.30 - 11am	Coffee	
11am - 12.30pm	Structured working groups	Working group discussions | [11]
12.30 - 1.30pm	Lunch	
1.30pm - 3pm	Structured working groups	
3 - 3.30pm	Coffee	
3.30 - 3.50pm	Jason Sanders	Constraining the Galactic potential with streams in angle-action space | [24]
3.50 - 4.10pm	Nathan Deg	Streams and the Single Particle Approximation | [25]
4.10 - 4.30pm	Daniele Fantin	Constraining the Galactic potential with streams | [26]
4.30 - 4.50pm	Ana Bonaca	Most Valuable Progenitor: How to constrain the Galactic potential using tidal streams? | [27]
4.50 - 5.10pm	Andreas Küpper	Orbital information encoded in stream substructure | [28]
5.10 - 5.30pm	Hans Buist	Tracing back the effect of a smoothly growing galaxy on streams | [29]
5.30pm - 5.50pm	Rachel Kennedy	Stellar Haloes: Models and Mocks | [30]
5.50 - 6.10pm	Adrian Price-Whelan	Probing the Galactic potential with 6D information
6.10 - 6.30pm	LOC	Report back from working groups
6.30pm	Dinner	
Friday	**Chair: Mark Gieles**	**Collisional systems**
9 - 9.30pm	Brad Gibson	(Non-)Cosmological Disks: Metal Distributions and Tracking Cluster Debris | [31]
9.30 - 10.00pm	Antonio Sollima	The comparison of luminous and dynamical masses in low mass stellar systems | [32]
10 - 10.30pm	Anna Lisa Varri	Self-consistent non-spherical models for quasi-relaxed stellar systems | [33]
10.30 - 11am	Coffee	
11 - 11.20pm	Vincent Henault-Brunet	Dynamics of young massive clusters | [34]
11.20 - 11.40	Michiel Cottaar	Measuring the radial velocity dispersion of a cluster corrected for binary orbital motions | [35]
11.40 - 12pm	Richard Parker	Modelling young star clusters in the GAIA era | [36]
12 - 12.20pm	Alice Zocchi	Observational tests of the dynamics of small stellar systems | [37]
12.20- 12.40pm	Laura Watkins	Discrete dynamical modelling of Omega Centauri | [38]
12.40pm - 1.30pm	lunch	
1.30 - 2.30pm	Structured working group	
2.30 - 3pm	LOC	Final report back from working groups | [39]
3 - 3.30pm	Coffee	

1. Welcome to Gaia Challenge

Authors: DK, JR, MG and AF.

Abstract:
- Welcome and practical information.

- Explain the purpose and scope of GC.

- Short intro from each working group leader.

2. Gaia: Counting down to launch

Abstract:
ESA's Gaia mission is the next European breakthrough in astrophysics aimed at producing the most accurate 3D map of the Milky Way to date. The resulting stereoscopic census of our Galaxy will represent a giant leap in astrometric accuracy complemented by the only full sky homogeneous photometric survey with an angular resolution comparable to that of the Hubble Space Telescope, as well as the largest spectroscopic survey ever undertaken. The scientific bounty will be immense, not only unravelling the formation history and evolution of our Galaxy but also revealing and classifying thousands of extra-solar planetary systems, minor bodies within our solar system and millions of extragalactic objects, including some 500000 quasars. Moreover, such a massive survey is bound to uncover many surprises that the universe still holds in store for us.

Gaia will be launched very soon (September 2013 being the current target date) and preparations by ESA and the Gaia Data Processing and Analysis Consortium (DPAC) are in full swing. I will provide an overview of the Gaia spacecraft status, the data processing, and the expected scientific performances of the mission. I will also look ahead to the exciting time just after launch when Gaia will be commissioned and we will get a first glimpse of its actual capabilities. Finally, I will discuss the plans for intermediate data releases as well as the plans for providing you with access to the Gaia catalogue and archive.

3. Working group discussions

- What are the (best) test problems?

- Who will generate mock data?

- Who will run models?

- What data format is best for the mocks?

- Preliminary results (please post on the wiki).

4. Generating Mock Data From Models

Abstract: We are in an era where systematic surveys of the Milky Way are giving information about the properties of a large number
of stars. Proper interpretation and analysis of the data requires comparing the data with models. This is best done by converting models to the observational space rather than other way around. To this end we discuss efficient techniques for converting models to synthetic data. First we discuss
techniques for sampling analytic models and then N-body models.
In order to sample N-body models, we present a scheme that disperses the stars spawned by an N-body particle, in such a way that the phase space density of the spawned stars is consistent with that of the N-body particles.

5. Star count-modelling technique for Gaia challenges

Abstract: I present the ongoing work to upgrade the Padua Galaxy model. My goal is to interpret in great detail the upcoming Gaia data. I will review the synthetic CMD generation technique updated by Pasetto et al. 2012a in order to easily handle high number of stars as required by Gaia. I will discuss the implemented Poisson solver that, combined with a Boltzmann collisionless equation cumulants (Pasetto et al. 2012b) synthetically generates the phase-space of the Milky Way model. The major differences from the already available on-line star count models (Besançon, Trilegal etc.) will be reviewed in detail. The model is undergoing major revision and will be advertised on-line after the Gaia launch. Further details are available in (Pasetto et al. 2012a, A&A, 545, 14, Pasetto et al. 2012b, A&A, 547, 70, Vallenari, Pasetto et al 2006, A&A, 451, 125).

6. Pathways to forming disc galaxies in a hierarchical cosmology

Abstract: The observed ubiquity of disc galaxies in the Universe may be reconciled with the high rate of disc-damaging mergers predicted in a LCDM model, if mitigating gas processes are taken into account. The GIMIC cosmological gas-dynamical simulations show explicitly that realistic disc galaxies can form in abundance by z=0 while experiencing merger histories representative of a LCDM model. Many of these mergers can destroy galaxy discs, particularly those more massive than the total stellar component of their hosts. We find that a significant fraction of present-day disc galaxies have had such active merger histories since z=2, e.g. about half of Milky Way-like galaxies had mergers more massive then the stellar mass of their host and a third had mergers three times as massive. This demonstrates that extended quiescent merger histories are not a prerequisite to form large disc galaxies like the Milky Way. Overall, the correlation between merger histories of galaxies and present-day disc morphologies is much weaker than predicted by collisionless studies. This suggests that the prospects of reconstructing the merger activity of the Milky Way from the present-day structure of its disc need to be re-evaluated.

7. 3D test particle simulations of the Galactic disks. The kinematical effects of the bar.

Authors: Giacomo Monari, Teresa Antoja, Amina Helmi

Abstract: I present one of the first 3D test particle simulations of the thin and thick disks in a Galactic potential including a rotating Ferrer’s bar. Our goal is to study the imprints of the bar on the kinematics of stars throughout the Galaxy. We aim to quantify how much of the evolution of the disks is driven by secular mechanisms in contrast to external processes, such as accretion. We find that the velocity distributions of both thin and thick disk change when the bar is included, and that strong transient effects are present for ~10 bar rotation periods after its adiabatic growth. On longer (more realistic) timescales, the effects of the bar are stronger on the kinematics of thin disk stars, and weaker on those in the thick disk, but in any case significant. Furthermore, we find that it is possible to trace the imprints of the bar at least up to z~1 kpc and 2 kpc for the thin and thick disk respectively.

8. On galaxy spiral arms' nature as revealed by rotation frequencies

Authors: S. Roca-Fàbrega, O. Valenzuela, F. Figueras et al.

Abstract: We will present how high-resolution N-body simulations using different codes and initial condition techniques reveal two different behaviours for the rotation frequency of transient spiral arms like structures. Our results show that whereas unbarred discs present spiral arms nearly corotating with disc particles, strong barred models (bulged or bulgeless) quickly develop a bar-spiral structure dominant in density, with a pattern speed almost constant in radius. As the bar strength decreases the arm departs from bar rigid rotation and behaves similar to the unbarred case. In strong barred models, we detect in the frequency space other subdominant and slower modes at large radii, in agreement with previous studies, however, we also detect them in the configuration space. We propose that the distinctive behaviour of the dominant spiral modes can be exploited in order to constraint the nature of Galactic spiral arms by the astrometric survey Gaia and by 2D spectroscopic surveys like Calar Alto Legacy Integral Field Area Survey (CALIFA) and Mapping Nearby Galaxies at APO (MANGA) in external galaxies. Furthermore we will show our first results using ART plus hydrodynamics code.

9. The bar corotation, a bridge between the bar and the thick disk

Abstract: Bars are ubiquitous in spirals, and one of the most powerful internal dynamical feature in term of capability to modify the disk radial and vertical profiles producing a thick disk like component. The basic dynamics of the bar corotation explaining why it is so will be reviewed.

10. Bayes versus the virial theorem

Abstract: For many purposes each stellar population with a galaxy is completely described by two unknown functions: the phase-space distribution function (DF) f(x,v) and the underlying gravitational potential Phi(x). An outstanding challenge in stellar dynamics is how best to constrain Phi given only some limited information about the population's DF f (e.g., from Gaia or other catalogues). I present a general scheme for calculating the likelihoods of different potentials by marginalising the unknown DF and demonstrate that the scheme works in practice. One way of thinking of this new method is as a development of Schwarzschild's method with the inclusion of two new ingredients.

11. Working group discussions

Either:

a) Show and compare latest results from running mocks;

And/or:

b) Chalk and talk about different methodologies:

- How to generate mock data?
- How does Jeans/M2M/Schwarzschild etc. really work?
- Strengths and weaknesses of different methodologies?
- A new "super" method?
- What is the ideal data?

12. Modelling dSphs with higher moments of the Jeans Equations

Abstract: Under the assumption of dynamic equilibrium the Jeans equations provide constraints on the gravitational potential of spherical systems via the moments of the line-of-sight velocity distribution rather than the more cumbersome six dimensional phase distribution of the tracers. The cost for this simplicity is that with a truncated series of moment equations one cannot guarantee that the solutions enable physical phase space distributions and additionally there exists a degeneracy between the unknown anisotropy of velocity moments and the mass profile which we hope to extract. One means to try and break the degeneracy, that is increasingly feasible with larger data sets, is to fit both the second (variance) and fourth (kurtosis) moments of LOS velocity data. While such methods have been used before we describe a new method that for the first time is as general in the description of anisotropy as the traditional Jeans analysis of LOS dispersions. Results of an application to MW dwarf spheroidals are discussed and compared to other methods in the literature.

13. Non-parametric Jeans modelling

Abstract: We propose a new non-parametric method to determine the mass distribution in spherical systems. A high dimensional parameter space encoding tracer density, line of sight velocity dispersion and total mass density is sampled with an Monte Carlo Markov Chain. Without assumptions on the functional form of any of these profiles, we can reproduce reliably the total mass density of mock dwarf galaxies, and disentangle the degeneracy between dark matter density and tracer velocity anisotropy. We show early applications to observed dwarf galaxies.

14. Measuring the slope of mass profiles for dSphs in triaxial CDM potentials

Abstract: We generate stellar distribution functions (DFs) in triaxial haloes in order to examine the reliability of slopes inferred by applying mass estimators assuming spherical symmetry to two stellar sub-populations independently tracing the same gravitational potential. The DFs take the form f(E), are dynamically stable, and are generated within triaxial potentials corresponding directly to subhaloes formed in cosmological dark-matter-only simulations of Milky Way and galaxy cluster haloes. Additionally, we consider the effect of different tracer number density profiles (cuspy and cored) on the inferred slopes of mass profiles. For the isotropic DFs considered here, we find that halo triaxiality tends to introduce an anti-correlation between effective radius R_e and dispersion when estimated for a variety of viewing angles. The net effect is a negligible contribution to the systematic error associated with the slope of the mass profile, which continues to be dominated by a bias toward greater overestimation of masses for more-concentrated tracer populations. We demonstrate that simple mass estimates for two distinct tracer populations can give reliable (and cosmologically

meaningful) lower limits for
the logarithmic cusp slope of the dark matter profile, irrespective of the degree of triaxiality or shape of the tracer number density profile.

15. A dynamical disk-halo decomposition in the inner Milky Way

Abstract: The Milky Way's (MW) density distribution in its inner parts and its decomposition into disk and halo components are fundamental to our understanding of the MW's formation and evolution and to determining the importance of dark matter within the inner parts of galaxies. However, currently only the circular velocity curve is well known while the density distribution away from the Galactic mid-plane is poorly constrained, especially away from the solar radius. I will present a new dynamical measurement of the MW's surface density between 4 and 10 kpc, obtained by rigorous 3-integral modeling of the vertical kinematics of abundance-selected stellar samples from the SDSS/SEGUE. Combined with the latest measurements of the MW's rotation curve, this allows us to separate the disk and halo contributions to the gravitational potential and to determine the radial profile of the dark matter halo. Our results show that action-based distribution-function modeling is now a feasible approach that will be fruitful for interpreting Gaia data.

16. How to find the Milky Way potential from the disc - don't use an orbit library.

Abstract: Methods using orbit libraries, such as Schwartzschild
modelling, are widely used to determine the potentials of external galaxies. I'll show, using the example of torus modelling of orbits, that this approach leads to an unacceptably high level of numerical noise when working data from the Milky Way. I'll show that an alternative approach, which relies upon the ability to find the phase-space density of a dynamical model at a given position and velocity, can reduce this noise to manageable levels.

17. Made-to-measure galaxy models: Modelling with Milky Way observations

Abstract: We demonstrate how the Syer & Tremaine made-to measure method of stellar dynamical modelling can be adapted to model a rotating galactic bar. We validate our made-to-measure changes using observations constructed from the existing Shen et al. (2010) N-body model of the Milky Way bar, together with kinematic observations of the Milky Way bulge and bar taken by the Bulge Radial Velocity Assay (BRAVA). Our results for a combined determination of the bar angle and bar pattern speed (~30 degrees and ~40 km/s/kpc) are consistent with those determined by the N-body model. Whilst the made-to-measure techniques we have developed are applied using a particular N-body model and observational data set, they are in fact general and could be applied to other Milky Way modelling scenarios utilising different N-body models and data sets. Additionally, we use the exercise as a vehicle for illustrating how N-body and made-to-measure methods might be combined into a more effective method.

18. A Particle by Particle M2M Algorithm: PRIMAL

Abstract: We have developed our particle-by-particle adaptation of the made-to-measure (M2M) method, with the aim of modelling the Galactic disc from upcoming Galactic stellar survey data. In our new particle-by-particle M2M algorithm, PRIMAL, the observables of the target system are compared with those of the model galaxy at the position of the target stars. The mass of the model particles are changed to reproduce the observables of the target system, and the gravitational potential is automatically adjusted by the changing mass of the particles. We applied PRIMAL to mock barred disc galaxy data created by an N-body simulation in a known dark matter potential, with the expected Gaia errors in the observables, using bright stars as tracers. We show that PRIMAL can recover the structure and kinematics of the target discs, along with the apparent bar structure and pattern speed of the bar despite the error in the target data.

19. Milky Way Disc Kinematics and Dynamics

Abstract: Results from the analysis of mock data from the Disc suite and from the Gaia Universe Model Snapshot will be presented. In particular, I will try to answer whether one can apply an "extragalactic" view of observables to determine kinematical quantities.
I will also present provisional results of the analysis of thin Disk spectroscopic
data from the Gaia-ESO survey. Finally I will introduce the

basis of a new VLBI astrometry project that could probe the kinematics of the most obscured inner regions of the Galaxy, and help constraining the inner rise of the rotation curve or the bar pattern speed at very low Galactic latitudes.

20. Can Gaia conclude the local dark matter density problem?

Abstract: To determine the local dark matter density (LDMD) of the solar system is a classical problem in astronomy but still under debate. Recently, Garbari et al. (2011, 2012) have devised a novel method of determining the LDMD from stellar distribution and vertical velocity dispersion profiles. This method has the advantage of abolishing conventional approximations and using only a few assumptions. This study is aimed at carefully scrutinizing this method and examining influences by uncertainties of astrometric observations. I created mock observation data for stellar dynamical tracers based on an analytical galaxy model and applied parametrized observational errors to the mock data. I find that the Garbari et al. method is capable of determining the LDMD with accuracy if the sample size and observational precisions are satisfactory. I estimate the required precisions of the parallax measurements to be approximately 0.1-0.3 milliarcseconds at 1 kpc away from the Sun. From this result, I expect that Gaia will provide data precise enough to determine the LDMD using the Garbari et al. method.

21. The local dark matter density in the light of recent Fermi and AMS-02 data

Abstract: The rotation curve, the total mass and the gravitational potential of the Galaxy are important tracers of the dark matter halo profile. In the present talk the total density distribution is constrained by astronomical observations: 1) the total mass of the Galaxy, 2) the total matter density at the position of the Sun, 3) the surface density of the visible matter, 4) the surface density of the total matter in the vicinity of the Sun, 5) the rotation speed of the Sun and 6) the shape of the velocity distribution within and above the Galactic disc. The mass model of the Galaxy is mainly constrained by the local matter density (Oort limit), the rotation speed of the Sun and the total mass of the Galaxy from tracer stars. The change of slope in the rotation curve may be a hint for substructure in the dark matter profile and is in agreement with structure in the gas flaring. Such substructure influences the dark matter annihilation flux which is proportional to the density squared. Therefore, hints for substructure are important for the interpretation of the recent Fermi and AMS-02 data, as will be discussed quantitatively.

22. Statistical Mechanics of tidal streams

Abstract: Tidal streams trace the trajectory of their progenitor systems through phase space, a property that has been extensively used to constrain the host's gravity via the construction of dynamical models that best match the location of stream stars in phase space. However, this approach suffers from two limitations: as the host evolves hierarchically so does its overall gravitational potential, hence none of the integrals of motion remains constant. Furthermore, dynamical methods require solutions to the equations of motion, which tends to be a thorny task in modified gravity theories. In this talk I will show that mechanical statistics provide a complementary approach which does not suffer from the above limitations. Combined with the construction of dynamical invariants, i.e. quantities that are conserved throughout the motion of stars, statistical mechanics furnish a powerful methodology for studying the evolution of tidal substructures in time-dependent potentials under generic gravity models.

23. The Milky Way in its Triaxial Halo

Abstract: I examine the claim that the Milky Way disc is perpendicular to the intermediate axis of its triaxial halo. I show that this is very unlikely and suggest instead that the disc may be tilted relative to the halo.

24. Constraining the Galactic potential with streams in angle-action space

Abstract: Angle-action coordinates offer a pleasingly simple way to view stream formation. Only in the correct potential will the angle-action structure of the stream look correct. We present a probabilistic model for parameters of the potential given stream observations by exploring the expected correlations in angle-action space. We show that this can be used to constrain the parameters of the potential successfully with realistic stream observations, and show what we can do without full 6D data.

We hope to present results obtained using the provided Gaia Challenge stream dataset.

25. Streams and the Single Particle Approximation

Abstract: The simplest approximation of a stellar stream is that of a single particle orbiting in a fixed potential. We examine the success of this approximation using a three component Milky Way model and Bayesian statistics. In particular, we focus on how well the shape of the halo can be inferred for streams of differing angular sizes and temperatures. We show some of the inherent difficulties of using the single particle approximation and how they may also apply to more complicated stellar stream modelling techniques. Finally, we examine the benefits of combining observations of multiple streams to constrain the Milky Way model.

26. Constraining the Galactic potential with streams

Abstract: During the past 20 years, numerous stellar streams have been discovered in both the Milky Way. These streams have been tidally torn from orbiting systems, which suggests that most should roughly trace the orbit of their progenitors around the Galaxy. As a consequence, they play a fundamental role in understanding the formation and evolution of our Galaxy. In the talk I will present the results obtained by testing the orbit-fitting technique developed by Binney in 2008 by using the substructures in the Milky Way stellar halo detected applying the “modified great circle cell method” (Mateu et al, 2011) to the mock Gaia catalogue of Brown et al. 2005. This catalogue includes a realistic Galactic background and observational errors, with the addition of detailed star formation histories for N-body simulated dwarf galaxies. The simultaneous application of the technique to multiple, nearby streams will hopefully allow to severely reduce the degeneracy and to strongly constrain the potential of the Galaxy.

27. Most Valuable Progenitor: How to constrain the Galactic potential using tidal streams?

Abstract: Tidal streams discovered in the Galactic halo have been used to constrain the underlying gravitational potential. Although there has been some success in measuring the inner halo potential, there remain many uncertainties regarding the halo shape on the global scale. The existing debates are expected to be resolved with more data on the streams. However, given the wide extent of the streams on the sky, such follow-up campaigns are very time consuming. In order to maximize their scientific return, it is prudential to identify which stream properties provide the most stringent constraints on the potential and focus the observational efforts accordingly.

We address this question by analyzing cold tidal streams with Palomar 5-like progenitors in the Via Lactea II (VL2) simulation. Our sample includes a total of ~10,000 streams formed during the last 6 Gyr on a range of orbits, spanning galactocentric distances out to 150 kpc. These streams are modeled using the streakline method, assuming a parametric representation of the VL2 potential. For each stream, the best-fit potential is obtained through Bayesian sampling of the parameter space. We identify the properties of streams that lead to a fast potential convergence. We also discuss how these optimal properties change after taking into account the accuracy of the current and upcoming observational data.

28. Orbital information encoded in stream substructure

Abstract: Exact orbital information of galactic satellites is crucial for modeling their dynamical evolution, their dissolution and hence the formation of their tidal streams. Tidal streams of dynamically cold satellites like globular clusters are expected to contain epicyclic substructure. This substructure contains detailed orbital information, encoded as over- and under-densities. On the example of Palomar 5, we show how this substructure can be identified and used in the modeling process to constrain the satellite's orbit and the underlying galactic potential.

29. Tracing back the effect of a smoothly growing galaxy on streams

Authors: Hans Buist, Amina Helmi

Abstract: We investigate the effect on streams of a smoothly growing galaxy using test-particle simulations and a phase-space evolution code. Streams consist of stars that orbit the galaxy on similar trajectories, therefore responding quite

directly to the galactic potential. As the galaxy accretes mass, the potential changes at the position of the stream. We find this to have an effect on the evolution and properties of the stream. Unlike most studies in the literature, we use a time-dependent potential that is cosmologically motivated and at the same time preserves the notion that galaxies (and their halos) grow inside out.

30. Stellar Haloes: Models and Mocks

Abstract: The accreted component of a galactic stellar halo offers a unique record of the galaxy's assembly history. However, only a small fraction of the total stars in the galaxy resides in the halo. Hydrodynamical simulations are unable as yet to resolve the detailed stellar streams and structure that LCDM predicts should be present. Instead, in this talk we use a particle tagging technique to study the structure of the accreted halo and show how it can be dominated by single objects. In order to allow comparisons to observations we have created a set of mock catalogues using a combination of a stellar population synthesis model together with a phase-space sampling technique. These catalogues will be publicly available and allow the testing and interpretation of current and future observational strategies.

31. TraCD: Tracking Cluster Debris

Authors: Brad Gibson, Chris Flynn, Jarrod Hurley, Guido Moyano Loyola, Chris Brook, Gareth Few, Jeremy Bailin

Abstract: We describe the new Tracking Cluster Debris (TraCD) programme, making use of ~1,000 simulated NBODY6 open clusters and associations, dissolved in a realistic Milky Way potential. By chemically-tagging each parent cluster/association, we track the orbital dynamics of millions of individual stars, each carrying their parent's chemical "fingerprint", convolved with empirical uncertainties drawn from both Gaia and GALAH expectations. The debris experience secular heating and churning, and via the use of higher-order group-finding algorithms (CLIQUE, Cluster3.0, and EnLink), attempts are made to associate the debris to their parent birth locations. In parallel, we describe our application of Synthetic CMD Generators to our suite of ~50 fully cosmological, chemo-dynamical disks, realised as part of the RaDES, MUGS, and MaGICC collaborations; by re-sampling our composite star particles as such, users will be able to explore these simulations in a manner similar to that as an observer, with realistic luminosity and colour cuts applied for an arbitrary observer placed within the data. We will provide the community with these potentially useful testbeds for Gaia analysis.

32. The comparison of luminous and dynamical masses in low mass stellar systems

Abstract: I review the advancements in the determinations of dynamical and luminous masses in low mass stellar systems like dwarf galaxies and star clusters. The mismatch between these two quantities has deep relevance in the context of the dark content of these stellar systems with important implication on their formation mechanism and their role in the process of hierarchical formation of large size galaxies. I show the result of the comparison of specifically developed dynamical models to a set of Galactic globular clusters. The generally observed overestimate of dynamical mass (up to 40%) is interpreted in terms of the abundance and efficency of retention of dark remnant, and on the possible presence of a modest amount of dark matter in these objects. The impact of GAIA on the future perspectives of this topic is also discussed.

33. Self-consistent nonspherical models for quasi-relaxed stellar systems

Authors: Anna Lisa Varri (Indiana University, USA / University of Edinburgh, UK)

Abstract: To fully understand the internal dynamics of globular star clusters, a number of important physical ingredients, in particular the three-dimensional effects of external tides, internal rotation, and anisotropy in velocity space, should be added to the traditional paradigm that primarily relies on spherical non-rotating models of quasi-relaxed stellar systems. New wide-field high-precision photometric and spectroscopic observations and HST proper motion studies of thousands of stars are beginning to reveal detailed information about the internal structure and kinematics of selected Galactic globular clusters. In this context, the future mission GAIA will reveal a view of the phase space of numerous star clusters with unprecedented accuracy.

Driven by these motivations, I will review some recent results on the development of more realistic self-consistent models for quasi-relaxed stellar systems, and their application to the interpretation of the internal dynamics of selected Galactic globular clusters. In particular, I will present a family of triaxial models that incorporate in a self-consistent way the tidal effects of the host galaxy. I will also discuss the effects of the presence of internal rotation and pressure anisotropy, studied by means of two new families of axisymmetric equilibria, flattened by either solid-body or differential rotation.

Within this new dynamical framework, several observational and theoretical issues can be addressed, including and role played by the degree of relaxation in shaping the observational properties of star clusters and the dynamical interplay between angular momentum transport and two-body relaxation processes.

34. Dynamics of young massive clusters

Abstract: The few nearby young massive clusters for which individual stars can be resolved provide important insights into the early dynamical evolution of dense stellar clusters and the initial conditions for their longer term evolution. I will review the current constraints on the dynamics of these systems (velocity dispersion and systemic rotation) coming from multi-epoch radial velocity surveys or precise proper motion measurements. I will also discuss the challenges introduced by the fact that most obvious tracers are luminous massive stars, a high fraction of which are found in binary systems.

35. Measuring the radial velocity dispersion of a cluster corrected for binary orbital motions

Abstract: Measuring the velocity dispersion of a stellar cluster is crucial to determine its virial state (for young clusters) or its dynamical mass (for older clusters). Spectroscopic binaries can significantly broaden the observed radial velocity distribution, inflating the measured velocity dispersion for intrinsic velocity dispersions below ~10 km/s. Correcting for these binary orbital motions is crucial to determine a cluster's dynamical state from radial velocities alone (i.e. when no proper motions are available) or to fully exploit the 3-dimensional velocity space, which Gaia will provide. Multi-epoch data can partially resolve this by detecting some spectroscopic binaries, however others will remain undetected (for any reasonable measurement uncertainty and baseline). We present a maximum-likelihood procedure to compute the velocity dispersion corrected for the effect on the observed radial velocity distribution from these undetected spectroscopic binaries given single- or multi-epoch radial velocity data. If the binary properties are well constrained (e.g. for solar-type stars) velocity dispersions below the 1 km/s can be accurately measured (Cottaar et al., 2012, A&A, 547, A35). If the binary properties are very uncertain (e.g. for OB stars) multi-epoch data is needed to accurately measure the velocity dispersion (Cottaar & Henault-Brunet, 2013, in prep). We discuss the required baseline and measurement uncertainty to accurately measure the velocity dispersion corrected for binary orbital motions and if the multi-epoch radial velocity observation from GAIA will match these requirements.

36. Modelling young star clusters in the GAIA era

Abstract: How ready is the young star cluster community for GAIA? Significant progress is being made on the observational side, but on the modelling and theory side, a coherent effort is distinctly lacking. Indeed, an oft quoted statement is that "GAIA will solve problem X" in relation to star clusters, but in reality very little modelling effort is being devoted to assessing the questions on young star clusters that GAIA will be able to address. In this contribution I will present recent results on modelling young clusters in the era of GAIA, and discuss potential avenues of further research.

37. Observational tests of the dynamics of small stellar systems

Abstract: As gas-free, self-gravitating systems, globular clusters (GCs) are excellent laboratories for studies of stellar dynamics and ideal targets for N-body simulations. Even though GCs are now recognized to be rather complex systems, their dynamical properties are still commonly studied by means of idealized spherically symmetric, isotropic, single-mass King models. New, more realistic dynamical models have recently become available, allowing us to measure more accurately the structural properties of these systems, to classify their complexity, and thus to shed light on the relevant formation scenarios. It is therefore particularly important to carry out thorough tests of the different dynamical models, by using all the information that can be obtained from dedicated photometric and spectroscopic observations. In this context, the advent of Gaia will make it possible to accurately measure proper motions for a large number of stars in GCs, opening the possibility of some decisive tests.

38. Discrete dynamical modelling of Omega Centauri

For objects in the Local Group, we are in the fortunate position of having discrete, resolved datasets - often of both high quality and high quantity - yet the dynamical modelling techniques employed typically degrade the data by spatially binning, are often overly simplified, and make assumptions that are not always (astro)physically justified. To address

these issues, we are developing discrete dynamical modelling tools that use maximum-likelihood analysis to fully exploit the resolved nature of the data. Such an approach avoids the loss of information due to spatial binning and allows contaminant populations to be included directly in the models for better membership identification. With these models, we hope to better constrain the dark matter content of dwarf galaxies and address the question of the presence of intermediate-mass black holes and dark matter in globular clusters. The work I will describe is some of the steps we have taken towards this goal. This includes the application to the globular cluster Omega Centauri, which is a calibration object for HST/WFC3 and, as such, has a wealth of high-quality data available. In particular, I will present new insights regarding a central IMBH.
39. Final report back from working gorups

We will use the wiki site to give:
- Status report of mocks and tests
- What remains to be done?
- Discussion on should we publish, if so what, and by when?
- Publication policy?
- Usage policy for GC mocks
- Next workshop?
- What next?