# SEVENTH FRAMEWORK PROGRAMME

## “Ideas” specific Programme

## European Research Council

**Grant agreement for: Advanced Grant**

**Annex I - “Description of Work”**

Project acronym: *ESSOG*

Project full title: *Extracting Science from Surveys of our Galaxy*

Grant agreement no.: 321067

Duration: 60 months

Date of preparation of Annex I: March 11, 2013

Principal Investigator: *James Binney*

Host Institution: *University of Oxford*

## B1(a) Curriculum Vitae of James Binney FRS

### James Jeffrey Binney

born 12/4/1950, London

### Permanent address

Ruldolf Peierls Centre for Theoretical Physics, Keble Road, Oxford OX1 3NP, England: Tel. +44 1865 273979

### Degrees

BA University of Cambridge 1971, MA University of Oxford 1975, DPhil University of Oxford 1976.

### Appointments

Head of the Rudolf Peierls Centre for Theoretical Physics, University of Oxford 2010–
(The Peierls Centre has 20 Faculty members, 9 emeriti, 16 postdocs and 56 graduate students)
Professorial Fellow of Merton College Oxford 2007–
Professor of Physics, University of Oxford 1996–
Ad Hominem reader in Theoretical Physics, University of Oxford 1990-1996
University Lecturer in Theoretical Physics, University of Oxford 1981-90
Fellow and Tutor in Physics, Merton College, Oxford 1981–2007
Visiting Assistant Professor, Princeton University 1979-81
Fellow by Examination Magdalen College Oxford 1975-9
Lindemann Fellow Princeton University 1975-6
DAAD Studentship Albert Ludwigs Univ, Freiburg i Br., Germany 1971-2

### Honours and prizes

Eddington Medal of the Royal Astronomical Society 2013
Oort Professor, Leiden University, 2011
Vainu-Bappu Lecture (an annual event), Indian Institute of Astrophysics, Bangalore, 2010
Dirac Medal of the Institute of Physics 2010
Dirk Brouwer Award of the American Astronomical Society 2003
Fellow of the Royal Society of London 2000–
Maxwell Medal of the Institute of Physics 1986
Fairchild Distinguished Scholar, California Institute of Technology 1983-4

### Ph.D examiner

For the universities of Cambridge, Copenhagen, Durham, Edinburgh, Ghent, Göteborg, Leiden, Leicester, Manchester, Marseilles, Paris, Princeton, Rutgers, St Andrews and the Australian National University.

### Professional service

Chair Space Science and Astronomy Review Panel of the Academy of Finland February 2012
Member Steering Committee of ESO-Gaia survey on the VLT, 2011–
Principal Investigator for UK contribution to RAVE survey 2008–11
Member European Advisory Panel, Princeton University Press, 2011–
Member Panel to review departments of Physics and Mathematics Göteborg University, 2010
Member ESO Working Group on Galactic Populations, 2006–8
Chairman of SOC of IAU Joint Discussion 5, "Modelling the Milky Way in the Era of Gaia", Rio de Janeiro, August 2009
Member Advisory Board of Leverhulme Trust, 2006–
Member PPARC's Astronomy Grants Panel, 2005-8
Member of PPARC's Oversight Committee for the Advanced Ligo Project, 2003-11

Member Board of German Wissenschaftsrat charged with evaluation of Göttingen University, 2007 and Heidelberg University, 2006

Member Review Committee of Sonderforschungsbereich 651 for Deutsche Forschungsgemeinschaft, 2004

Member of panel to review Physics research at Nottingham University, 2003

Member Sectional Committee 5 of the Royal Society, 2001-4

Member Royal Society panels for award of research grants, 2002-4, and for exchanges with (a) third world countries, and (b) Australia and New Zealand, 2001-4

Member Organizing Committee of IAU Commission 28 (Galaxies), 2000-6

President of Division VII of International Astronomical Union, *The Galactic System*, 1994-7

President International Astronomical Union Commission 33, *Structure & dynamics of the galactic system*, 1994-7

Chairman of SOC of IAU Joint Discussion 10, "Low-Luminosity Stars", Kyoto, 1997

Member of UK PPARC panels (a) to review Physics Division of Rutherford-Appleton Lab. and (b) Fellowships, 2000

Member Joint Infrastructure Fund Board of PPARC, 1999-2000

Core Member Theoretical Research Assessment Panel of PPARC, 1997-9

Member Editorial Board of *European Journal of Physics*, 1995-9

Member Editorial Board of *Monthly Notices of Royal Astronomical Society*, 1992-5

Coopted Member Theoretical Research Assessment Panel of PPARC, 1995-6

Vice-President International Astronomical Union Commission 33, *Structure & dynamics of the galactic system*, 1991-4

Member Theory Panel of UK SERC, Astronomy, Space & Radio Board, 1986-8

For more than 38 yeas a regular reviewer for the principal astronomical journals: ApJ, AJ, MNRAS, and A&A

## Publications

Three research monographs, *Galactic Astronomy*, *Galactic Dynamics* and *The Theory of Critical Phenomena* have over 6 800 citations in the literature. *Galactic Dynamics* has been translated into Chinese, while and *The Theory of Critical Phenomena* has appeared in both Chinese and Polish. *Galactic Astronomy* and *Galactic Dynamics* were reissued in heavily revised editions 17 and 21 years after original publication.

In all my publications have over 17 000 citations; my h index is 58.

## Funding ID

STFC grant ST/K00106X/1 "Astrophysics and Planetary Science at Oxford 2013-16", PI Davies, provides for the period 1 April 2013 – 31 March 2016 22.5% of Binney's salary and 12% of Magorrian's salary. It also provides the salary P.J. McMillan from 1 April 2013 – 30 September 2014 and the salary of S. Sale from 1 April 2013 – 31 January 2015. As indicated in the original proposal, the plan is to ramp up the level of ERC funding as the level of STFC funding diminishes in such a way that we maintain a constant research effort throughout the grant. The level of this effort being 55% on Binney's time, 30% of Magorrian't time, and four postdocs.

## B1(b) 10-Year track Record

**1. Top 10 papers 2002–2012** *(Papers published in this period attracted 2602 citations. Paper 1 is fundamental to the proposed work and was made possible by several visits of Prof. Sellwood to Oxford from Rutgers. Papers 2–5 lie somewhat outside the area of this proposal: Omma was my student while Famaey and Fraternali were my postdocs when the papers were written. Papers 6–10 are all quite closely related to the project: Schönrich and Aumer were both visiting students from Munich, while Marinacci was a visiting student from Bologna. Besides supervising the work, I played a large part in writing these papers, which all appeared in Monthly Notices of the Royal Astronomical Society, which has an impact factor 4.89, versus 6.06 for the leading journal The Astrophysical Journal and 4.41 for the principal continental journal Astronomy & Astrophysics.)*

1. "Radial Mixing in Galactic Discs", Sellwood, J.A. & Binney J., 2002, MNRAS, 336, 837 (178 citations)
2. "Heating Cooling flows with Jets", Omma, H., Binney, J., Bryan, G. & Slyz, A., 2004, MNRAS, 348, 1105 (122 citations)
3. "Modified Newtonian Dynamics in the Milky Way", Famaey, B. & Binney, J., 2005, MNRAS, 363, 603 (141 citations)
4. "On the Origin of the Galaxy Luminosity Function", Binney, J., 2004, MNRAS, 347, 1093 (99 citations)
5. "Accretion of Gas on to Nearby spiral Galaxies", Fraternali, F. & Binney, J., 2008, MNRAS, 386, 935 (51 citations)
6. "Chemical Evolution with Radial Mixing", Schönrich, R. & Binney, J., 2009, MNRAS, 396, 203 (104 citations)
7. "Kinematics and History of the Solar Neighbourhood Revisited", Aumer, M. & Binney, J., 2009, MNRAS, 397, 1286 (51 citations)
8. "Distribution Functions for the Milky Way", Binney, J., 2010, MNRAS, 401, 934 (26 citations)
9. "Local Kinematics and the Local Standard of Rest", Schönrich, R., Binney, J. & Dehnen, W., 2010, MNRAS, 403, 1829 (89 citations)
10. "The Mode of Gas Accretion onto Star-Forming Galaxies", Marinacci, F., Binney, J., Fraternali, F., Nipoti, C., Ciotti, L., Londrillo, P., 2010, MNRAS, 404, 1464 (11 citations)

### 2. Research Monograph

"Galactic Dynamics" Binney, J. & Tremaine, S., 2008, Princeton University Press 885 pp
(The two editions of this book attract ∼ 240 citations p.a. in research papers.)

**3. Patents** none

### 4. Invited Presentations at conferences and schools

Lecturer at 2011 Winter School of the IAC, Tenerife
Plenary Lecture "Modelling the Milky Way", 10th Hellenic Astronomical Conference, Ioannina, Greece, September 2011
Invited review at 25th Anniversary Symposium of EPL, Munich, May 2011
Invited review "Accretion by the Galaxy" at "The puzzle of the Milky Way", Grand Bournand, France, April 2011
Oort Lecture "What Makes Spiral Galaxies Tick", Leiden, March 2011
Invited review "Extracting Science from Surveys of our Galaxy", at Chandra Centenary Meeting, Indian Institute of Astrophysics, Bangalore, December 2010
Lecturer at Lamost Summer School, Kavli Inst, Beijing University, July 2010
Invited review "Modeling the Galactic Disk", at "Dynamics from the Galactic Center to the Milky way Halo", Harvard University, May 2010
Invited review "Chemodynamical evolution of the Milky Way" at "Structure of our Galaxy", Princeton NJ, February 2009
Invited review "Modelling the Milky Way" at RAS/JENAM National Astronomy Meeting, University of Hertfordshire, April 2009
Invited review "The challenge of modelling the Milky Way" at Lorentz Centre workshop, Leiden July 2009

Invited review "The challenge of modelling the Milky Way" at JD5 of General Assembly of the International Astronomical Union, Rio de Janeiro, August 2009

Invited review "Torus dynamics" at workshop "Phase Space" International Center for Mathematical Meetings, Luminy, November 2009

Invited review "Bulge-disc connection in the Milky Way" at IAU Symposium 254 "The Galaxy Disk in Cosmological Context", Copenhagen, June 2008

Summary talk at IAU Symposium at IAU Symposium 245 "Formation and Evolution of Galaxy Bulges", Oxford July 2007

Invited talk "Galactic Structure from Microlensing" at the 12th International Conference and ANGLES Workshop, Manchester 2007

Invited talk "Modelling for Gaia" at "Dynamics of Galaxies", Pulkovo Observatory, August 2007

Invited talk "Dynamics of Disks" at "Island Universes", Terschelling, July 2007

Invited review "Modelling the Galaxy for Gaia", at "The Three-Dimensional Universe with Gaia", Paris-Meudon, October 2004

Invited talk "The Cosmological Context of Extraplanar Gas", at "Extra-Planar Gas" Dwingeloo, June 2004

## 5. Research expeditions

none

## 6. Organisation of international conferences, SOC membership

Member of SOC "Galactic Archaeology Surveys" Sydney, June 2012

Member of SOC , "Radial Migration", Slovenia, May 2012

Member of SOC "Dynamics Meets Kinematic Tracers" Ringberg Castle, April 2012

Chair of SOC of meeting "The ISM in 3d", Leiden, July 2011

Member of SOC of "The Puzzle of the Milky Way", Grand Bournand, France, April 2011

*A similar level of activity for earlier years, but I no longer have records of most of it.*

Chair of SOC of Joint Discussion Meeting 5 "Modelling the Milky Way in the Era of Gaia", at the XXVII General Assembly of the IAU, Rio de Janeiro, August 2009

Member SOC Commission 28 (Galaxies) of the International Astronomical Union 2000-2006

## 7. International prizes, Academy memberships

2010 Dirac Medal of the Institute of Physics (The gold medal for theoretical physics: "For his contribution to our understanding of how galaxies are constituted, how they work and how they were formed.")

2003 Dirk Brouwer Award of American Astronomical Society (for dynamical astronomy)

2000 elected a Fellow of the Royal Society of London

2000 elected Fellow of the Institute of Physics

## 8. Contribution to early careers of excellent researchers

My former students and research assistants now occupy long-term positions at the universities of Princeton (Spergel & Goodman), Leicester (Dehnen), Zurich (Saha), Oxford (Magorrian), Helsinki (Kaasalainen), Exeter (Tabor), Bologna (Fraternali, Nipoti), Durham (Jenkins), Tsing Hua (Jiang), Munich (Gerhard), Imperial College (Petrou), Nice (Petit), Washington (Quinn), Madrid (Knebe, Ascasibar), John Moore's Liverpool (Maciejewski), Strasbourg (Famaey)

M.E.J. Newman (http://www-personal.umich.edu/∼mejn/) was my undergraduate pupil and during his time as a graduate student we co-authored two books, so I like to think he served an apprenticeship in book writing with me.

## B2(a) State of the art and objectives

The ΛCDM cosmological model has enjoyed such success in accounting for observations of the Cosmic Microwave Background (CMB) and the large-scale clustering of galaxies that it is widely believed to be essentially true. Given this success, considerable resources have been devoted to simulating the formation and evolution of stellar systems from the initial conditions that the ΛCDM model provides. From such simulations it has become clear that a valid ab initio simulation of the formation of a galaxy would have an outer scale of $\gtrsim 10\,\mathrm{Mpc}$ and an inner scale of $\lesssim 1\,\mathrm{pc}$: scales as large as 10 Mpc are required because infall and late-type tidal disturbance play significant roles in shaping a galaxy, and scale as small as a pc are important because the ability of stars to heat the interstellar medium to the virial temperature hinges on whether a massive star can migrate in its short lifetime from a region of very high interstellar density to one of low interstellar density, where radiative cooling is not very rapid. It is not currently feasible to simulate cosmic structure formation with a linear dynamic range of $10^7$, so simulators resort to various models of "sub-grid physics". On account of the uncertainty of these models (which are usually chosen to maximise agreement with observations), we have limited knowledge of what predictions ΛCDM makes for the structures of galaxies.

In light of this situation, the astronomical community is now pursuing a three-pronged attack on the problem of galaxy formation. One prong is simulations of galaxy formation, a second prong is observations of the high-redshift universe, and the third prong is detailed study of nearby galaxies. The study of our Galaxy is crucial because it can be observed in enormously greater detail than any other stellar system and is typical of the galaxies that currently dominate the cosmic star-formation rate. It is also crucial for cosmology in that it provides the foreground through which we are obliged to observe the CMB.

It is widely expected that this three-pronged attack will enable us to understand how galaxies formed and evolved to their current states. In particular, surveys of our Galaxy are expected to reveal: (i) the structure of the Galaxy's gravitational field and thus, subtracting the contribution from stars and gas, the Galactic distribution of dark matter (DM); (ii) the histories of star formation and metal enrichment in the halo, bulge and disc; (iii) the nature of the Galaxy's bulge and the impact that its bar is having on the disc and DM halo; (iv) the relation of the thick disc to the thin disc and the bulge; (v) the form and dynamics of the Galaxy's spiral structure and warp; (vi) the extent to which the halo is composed of incompletely digested satellites, and whether field halo stars formed in disrupted satellites or in situ.

**Galaxy surveys** We are in the middle of the golden age of surveys of our Galaxy. Important near-infrared photometric surveys include the 2MASS survey[1] of the infrared sky, which was completed in the last ten years, the UKIDSS survey[2], which is essentially complete and a couple of deeper surveys that are now getting underway with ESO's VISTA telescope. The SDSS project[3], which was completed a few years ago, obtained visual multi-band photometry of tens of millions of stars. The SDSS project was extended by the SEGUE project[4], and together these surveys obtained low-resolution spectra of several hundred thousand stars. The RAVE survey[5], which is just finishing, will provide spectra at resolution $R = 7\,500$ for $\sim 500\,000$ stars. The LAMOST telescope, which is currently being commissioned in China, will take optical spectra of huge numbers of halo stars. The ESO-Gaia[6] and APOGEE[7] projects have both just started to gather $\sim 100\,000$ spectra at $R = 30\,000$; the ESO-Gaia spectra are taken from Chile with the VLT in the $R$ band, while the APOGEE spectra are taken from New Mexico in the near-infrared. From 2013 the HERMES project will obtain a similar number of optical spectra in the southern hemisphere.

Astrometric astronomy was revolutionised by the European Space Agency's (ESA) Hipparcos mission, which published a catalogue[8] of $\sim 100\,000$ parallaxes in 1997. Hipparcos established an all-sky reference frame that was tied to quasars. The US Naval Observatory used this reference frame to re-reduce a large body of terrestrial observations, leading to the UCAC3 catalogue[9], which gives proper motions for $10^8$ stars. The Pan-Starrs survey[10] is now imaging much of the sky to magnitude $V \sim 24$ on a regular basis. It will discover enormous numbers of variable stars and provide astrometry for all the objects it detects. In early 2013 ESA will launch Gaia[11], the follow-on to Hipparcos and the first satellite to conduct an astrometric survey of the sky – Hipparcos had an input catalogue while Gaia will itself identify objects. Gaia will obtain photometry and astrometry of unrivalled precision down to magnitude $V \sim 20$ and spectra for objects brighter than $V \sim 17$. In all the Gaia Catalogue will contain astrometry for $\sim 10^9$ stars and stellar parameters and line-of-sight velocities for $\sim 10^8$ stars. It is anticipated that a preliminary catalogue will be produced after three years of data have been taken, so during 2017, and the definitive Catalogue should be available $\sim 2020$. Crucially, these catalogues will be immediately released to everyone, so the kudos for extracting the key science from it will go to those who have used the years prior to its release to build and test the tools that will be required for this job. If the best-prepared groups are in the USA, it will count for nought that the $\sim 1.5 \times 10^9$ Eu cost of the project is borne by European taxpayers.

The goal of this proposal is to establish the infrastructure required to extract the promised science from the Gaia Catalogue. This involves developing algorithms and computer codes and also training the people who will do the final job. On the road to this long-term goal we will synthesise data from existing and on-going ground-based surveys into a coherent physical model of the present structure and likely history of our Galaxy.

**Importance of models** Surveys endeavour to be complete in the sense that the resulting catalogue contains every star that satisfies well defined criteria, summarised in the survey's "selection function". When a survey is complete, information is conveyed as much by the absence of objects from the catalogue as by their presence. Most of the stars in the Galaxy will fail to make it into a given catalogue because they will be too faint, either because they are distant or because they are obscured by foreground dust, or because they lie in a crowded field within which the images of stars become confused. Galaxy models are crucial for the interpretation of survey data because they enable us to assess the impact of these effects and therefore to infer how many stars of each type are out there given the contents of the catalogues. Moreover, different surveys are effective at probing different parts of the Galaxy, and models enable us to collate results from a variety of surveys into a single coherent picture of reality.

We like to conceive of the Galaxy as an object that lives either in three-dimensional "real" space, or better in six-dimensional phase space. Actually, below we shall argue that even the most basic Galaxy model inhabits a space of at least ten dimensions, but for the moment let's be conservative and imagine that it inhabits phase space, where we can readily write down the equations that govern the evolution in time of the probability density function (pdf) of a system of mutually gravitating particles.

Unfortunately, we do not directly measure the natural coordinates of this space. For example, Gaia will measure two angular coordinates $(\alpha, \delta)$ and a parallax $\varpi$ instead of a distance. For many stars it will measure the line of sight velocity $v_{\rm los}$ and for all objects it will measure two components of the proper motion $\boldsymbol{\mu}$. So for many stars Gaia will measure six coordinates that form rather an odd set from the perspective of physics. In particular, the star's physical location and two of its components of velocity depend on the measured parallax, which for a distant star may be negative. Clearly a negative parallax is unphysical, but it does carry information: it tells us that the star is more distant than the distance that corresponds to the uncertainty in the parallax. Our modelling strategy must be such that we can make good use of stars with negative measured parallaxes

Because the inverse of a negative parallax cannot be interpreted as a distance, a strategy that is *not* going to work is to infer the star's phase-space coordinates from the data; we cannot carry the star from the space of the data into the space of the model, namely phase space; we *must* project the model into the space of the observables. Then negative parallaxes are in no way problematic – indeed a catalogue in which negative parallaxes did not occur is what would be problematic.

Even for stars with safely positive parallaxes, there is a huge advantage in carrying the model into the space of observables because in this space the errors are likely to be largely uncorrelated and even, by the central-limit theorem, Gaussian. The pdf in phase space into which a Gaussian pdf in $(\alpha, \delta, \varpi, v_{\rm los}, \mu_\alpha, \mu_\delta)$ space would map would be strongly non-Gaussian and predict large correlations between errors in distance and the components of tangential velocity, for example. With such a complex pdf for the errors, it would be incredibly hard to determine the uncertainties in the parameters of our models.

Let us examine more carefully what coordinates the space of observables really has. In addition to $(\alpha, \delta, \varpi, v_{\rm los}, \mu_\alpha, \mu_\delta)$ we will invariably measure an apparent magnitude $m$ and a colour such as $V-I$. The spectrum from which $v_{\rm los}$ was extracted will also have yielded the star's effective temperature $T_{\rm eff}$, surface gravity $\log g$ and measures of metallicity, such as [Fe/H] and possibly [$\alpha$/Fe]. If a medium- or high-resolution spectrum is available, there will be measurements of the abundances of many individual chemical elements, such as C, O, Mg, Ti, Eu, etc. Hence, the dimensionality of the space of observables $(\alpha, \delta, \varpi, v_{\rm los}, \mu_\alpha, \mu_\delta, m, V-I, T_{\rm eff}, \log g, [{\rm Fe/H}], \ldots)$ will normally be as high as 10, and it may be significantly higher. Our modelling strategy must be designed to cope with such large dimensions.

The high dimensionality of the space of data makes any analysis that involves binning the data very unattractive. To see this, imagine establishing a Cartesian grid in data space with each axis having just $n$ graduations. Then $d$-dimensional data space is divided in to $n^d$ cells, so to determine the density of stars in the majority of these cells with any precision we need $> 10n^d$ particles. If the catalogue contains say $10^8$ stars, $n$ must satisfy $10n^d < 10^8$ or $n < 10^{7/d} \simeq 5$ for $d = 10$. With so few bins in each of Galactic longitude, latitude, line-of-sight velocity, etc., we would be degrading the data to the point that we noted only the sign of each star's velocity etc, and whether it was large, small, or negligible in magnitude. Any refinement in the number of graduations and most bins will be empty, a minority will contain one star, and a negligible minority will contain enough stars to yield a meaningful estimate of the local density.

If we accept that binning is not a fruitful procedure, how can we ask whether the observed distribution of stars is consistent with a model? In these circumstances people project both the model and the data into a subspace of sufficiently low dimension for binning to be useful. Unfortunately, the act of projection, or "marginalisation" as it is commonly called, obliterates correlations between the marginalised variables. Our hopes of unravelling the Galaxy's formation history turn on correlations that are know to exist between kinematic and chemical variables.

From this analysis we infer that *we require models that provide the pdf in data space rather than merely supplying a discrete realisation of it.*

We must use multiple lines of evidence. If a star is near enough, no measure of distance can trump a parallax. But usually the majority of the objects measured in a survey lie far away, and then a parallax measurement carries less information. For these objects spectrophotometric distances are likely to be important. In many cases a small parallax will imply that the star is distant, and from its apparent magnitude it will be evident that it is a giant. This information can inform the choice of template star used in the analysis of the star's spectrum and thus the determination of its values of $v_{\rm los}$, $\log g$ and [Fe/H], as well as its distance. Thus the pdf of the distance upon which we finally settle will depend on several sources of information and a great deal of modelling.

Several of the quantities we measure are connected by well-understood physics. For example, the theory of stellar evolution constrains stars to a small subset of $(T_{\rm eff}, \log g, [{\rm Fe/H}])$ space. The principles of Bayesian inference give us a framework for using such constraints to reduce the uncertainties in stellar parameters e.g. [12]. Ideally we would extract stellar parameters in parallel with fitting a Galaxy model to the data, since the stellar parameters depend on the distance, just as the parallax and tangential velocities do. This scheme appears to be hard to implement in practice, so in the near future stellar parameters extracted from spectrophotometric data in isolation will play a large role in Galaxy modelling. However, multiple passes over the data should prove useful. For example, on the first pass, kinematics may indicate that a given star is likely to be nearby, and then the star's spectrum could be re-analysed using a prior that favoured its being a dwarf rather than a giant.

### B2(b) Methodology

The Galaxy is not in a steady state, most obviously because it contains a bar near the Centre, and spiral structure within the disc, and more subtly because the SDSS survey revealed that the stellar halo is largely comprised of streams and still-enigmatic "clouds" like the Hercules-Aquila Cloud[13,14]. None the less, modellers of the Galaxy have no option but to start by constructing steady-state models.

The reason for this necessity is that DM makes a major contribution to the Galaxy's gravitational field – current data indicate that the Sun lies close to the radius at which baryon-domination at small radii gives way to DM-domination at large radii. At present, we can detect DM only through its contribution to the gravitational field, which we map through the influence it has on objects that we can see – on Galactic scales this amounts to studying the dynamics of gas and stars. In principle *any* phase-space distribution of stars is consistent with *any* gravitational field. It is only when we insist on some sort of statistical equilibrium that the distribution of stars imposes constraints on the gravitational field, and thus on the combined density of stars, gas and DM. For example, the assumption of statistical equilibrium enables us to rule out a weak gravitational field because in that field the observed distribution of stars would expand systematically. More subtle devices for determining the gravitational field, such as the use of hydrodynamical simulations of the flow of gas[15,16], or stellar streams[17,18], also rest on the assumption that the Galaxy is broadly in statistical equilibrium.

Actually, even if we could observe DM directly, and hence determine the Galaxy's gravitational field without recourse to dynamics, it would still make sense to seek an equilibrium model of the Galaxy first. For by comparing the predictions of this model with the data we would identify features that signalled departures from equilibrium, and we could seek to model these features by perturbing our equilibrium model. In this connection it is salutary to recall the extent to which the language of physics, and thus our understanding of phenomena, has been moulded by perturbation theory: dispersion relations, photons, phonons, Feynman diagrams, orbital elements, mean-motion resonances, etc., are all concepts, introduced by perturbation theory. These concepts loom large in our understanding of how the world works because they are simultaneously useful mathematical abstractions and essential tools for understanding. Historically, perturbation theory has been rather little used in galactic dynamics, and we are all the poorer in understanding for it. Our approach to Galaxy modelling promises to rectify this situation.

**Jeans' Theorem** Jeans pointed out that the distribution function (DF) of a steady-state Galaxy can depend on the phase-space coordinates only through integrals of motion. In the second half of the 20th century it emerged that typical Galactic potentials often admit three isolating integrals[19,20], so if the Galaxy were in a steady state, its DF would be a function of three integrals. Since any function of integrals is itself an integral there is in principle great freedom in what we take to be the arguments of the DF, but one particular choice stands head and shoulders above the rest: action integrals $J_i$ are uniquely favoured in that (i) they may be embedded as the momenta of a canonical coordinate system for phase space (the conjugate coordinates are the "angle" variables), and (ii) they are adiabatic invariants and therefore constant during slow deformation of the Galaxy's potential, for example as a result of flows of gas into and out of the Galaxy. Angle-action coordinates are indispensable tools for perturbation theory and will revolutionise galaxy dynamics just as they did celestial mechanics. In fact, we shall argue that through perturbation theory angle-action coordinates provide the key to Galaxy dynamics even in parts of phase space that do not admit three integrals of motion (where orbital motion is chaotic rather than quasiperiodic).

**Chemodynamical evolution** It was discovered in the 1950s that the chemical compositions of stars are closely related to their kinematics: stars on eccentric orbits tended to be metal-poor. Over the last 15 years high-resolution spectra of relatively faint stars have considerably deepened our knowledge of the entanglement of kinematics with chemistry. These new data have caused us to extend chemical space to two dimensions, with axes given by iron abundance [Fe/H] and abundance [$\alpha$/Fe] of $\alpha$-elements (Ne,Mg,Si,S,Ca). The second dimension is important because it is sensitive to the epoch of a star's formation: a significant fraction of the Fe produced by the Galaxy was synthetised by type Ia supernovae, which have a gestation period $\sim 1\,$Gyr that is much longer than the gestation period $\sim 10\,$Myr of the very massive stars that dominate production of $\alpha$ elements. Thus a high value of [$\alpha$/Fe] suggests that a star was formed in the first $\sim$Gyr of the Galaxy's life.

The central assumption of models of the chemical evolution of the Galaxy is that stars form in the equatorial plane from gas that has a chemical composition $\mathrm{Ch}(R,t)$ that is the same at all azimuths at a given time. This composition reflects the flow of gas into and out of that annulus, and the history of mass ejection by stars. For many years it was assumed that each annulus of the

Galactic disc evolved independently[21], but the discovery by Sellwood & Binney[22] that the dominant effect of spiral structure is to cause stars to change their angular momenta without significant change in eccentricity or inclination made a major revision of such models mandatory. Schönrich & Binney[23] made a first cut at this task and extension of this work comprises a major goal of this proposal.

Scattering by spiral arms, giant molecular clouds and satellite objects causes stars to diffuse from in-plane circular orbits to eccentric and highly inclined orbits. Since this diffusion increases the random velocities of stars, it is referred to as "stellar heating". Gas flows play a key role in chemical evolution: the flow of gas from the intergalactic medium (which contains more baryons than do galaxies) brings relatively metal-poor gas to the interstellar medium; the inward drift of gas under the influence of accretion and spiral structure moves heavy elements synthesised at $R$ to $R' < R$; the supernova-driven wind off the disc carries heavy elements either right out of the disc or moves them to another, possibly larger, radius. Hence gas flows must be included in models of chemodynamic evolution and will be constrained by the observed entanglement of chemistry and kinematics. Our task is to infer from the latter the history of chemical evolution $\mathrm{Ch}(R,t)$ and the rates of stellar migration and diffusion.

**N-body models** N-body models have been enormously important for the development of stellar dynamics, and are likely to remain important for modelling the MW because (i) simulations of cosmological clustering generate N-body models of galaxies with credible histories, and (ii) spiral structure has been crucial for the evolution of the MW and, while our understanding of it is incomplete, the most promising route to deeper understanding of how it works is meticulous analysis of high-quality N-body models.

We can learn from N-body models only to the extent that we can meaningfully characterise them. Conventionally an N-body model is a list of phase-space coordinates, which are non-unique in the sense that some integration steps later the phase-space coordinates will all be different but the model will be the same. A vastly improved characterisation is given by a list of the stars' action integrals. From this list one can determine the distribution of stars in three-dimensional action space, which uniquely characterises an equilibrium galaxy. We will analyse N-body models in this way.

The study of disc dynamics and spiral structure would be greatly facilitated by an ability to choose initial conditions that to high precision correspond to equilibria of stellar discs with predetermined properties. Traditional approaches to choosing initial conditions[24,25] generally involve the assumption of Gaussian velocity distributions because they rely on the Jeans equations, which return only moments of the velocity distribution, not the distribution itself. The velocity distribution near the Sun is highly non-Gaussian, so initial conditions of traditional models are significantly out of equilibrium, and the simulation starts with an uncontrolled relaxation to equilibrium[25]. This initial period of relaxation makes it impossible to control precisely the axisymmetric equilibrium from which the long-term evolution driven by spiral structure starts. By sampling models with analytic DFs $f(\mathbf{J})$ we can generate initial conditions for disc galaxies that deviate from equilibrium only by irreducible discreteness noise.

## Our recent work

Over the last couple of years we have sought to explain current data with models that have analytic DFs $f(\mathbf{J})$. Our DFs are constructed from simple building blocks, called "pseudo-isothermal" DFs: $f(\mathbf{J}) = f_{\sigma_r}(J_r, J_\phi) f_{\sigma_z}(J_z, J_\phi)$, where

$$f_{\sigma_z}(J_z, J_\phi) \equiv \frac{\nu_z}{2\pi\sigma_z^2}\mathrm{e}^{-\nu_z J_z/\sigma_z^2} \quad \text{and} \quad f_{\sigma_r}(J_r, J_\phi) \equiv \left.\frac{\Omega\Sigma}{\pi\sigma_r^2\kappa}\right|_{R_c}[1+\tanh(J_\phi/L_0)]\mathrm{e}^{-\kappa J_r/\sigma_r^2}.$$

Here $R_c(J_\phi)$ and $\Omega(J_\phi)$ are the radius and the azimuthal frequency of the circular orbit with angular momentum $J_\phi$, while $\kappa(J_\phi)$ and $\nu_z(J_\phi)$ are corresponding radial and vertical epicycle frequencies. $\Sigma(J_\phi) \simeq \mathrm{const} \times \mathrm{e}^{-R_c/R_d}$ is a function that ensures that the disc's surface density is approximately exponential with scale length $R_d$, and $\sigma_r(J_\phi)$ and $\sigma_z(J_\phi)$ are chosen to ensure that the scale height of the disk is approximately radius independent, as observations suggest, and the velocity ellipsoid does not become highly non-spherical, which would destabilise the disc[26].

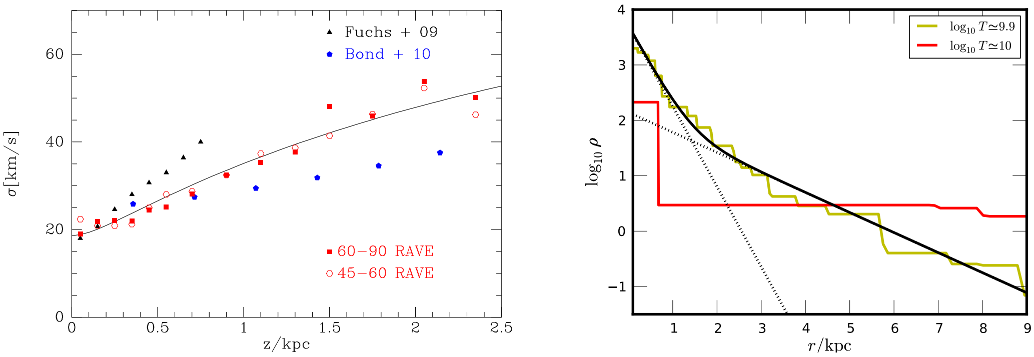

**Fig. 1** Left: velocity dispersion as a function of distance from the plane near the Sun. Full curve: prediction from [27]. Red squares: subsequent measurements in Burnett's thesis based on RAVE stars with latitudes $45° \leq |b| < 60°$ and $60° < |b| \leq 90°$. Two prior estimates from SDSS data are also shown by black triangles and blue dots. Right: the density of stars as a function of distance from the plane near the Sun: stars with ages $< 10^{0.9}$ Gyr buff, older ages red. Dotted black lines exponential profiles with scale heights 0.3 and 1.2 kpc; black curve the sum of these.

Binney[27] used superpositions of such DFs to argue that the Sun's velocity w.r.t. the LSR had been materially underestimated, a problem which Schönrich, Binney & Dehnen[28] traced to neglect of chemistry. [27] also concluded that neither of the (mutually inconsistent) profiles $\langle v_z^2 \rangle^{1/2}(z)$ for the variation of velocity dispersion with distance from the plane near the Sun were consistent with standard assumptions about the Galaxy's mass distribution. Subsequently, preliminary analysis of data from the RAVE survey yielded a profile $\langle v_z^2 \rangle^{1/2}(z)$ in perfect agreement with what our models required under standard assumptions (Fig. 1 left).

**Age of the solar neighbourhood** Aumer & Binney[29] re-analysed the velocities of stars with well-determined parallaxes as a function of stellar colour. They showed (i) that the solar neighbourhood is remarkably old $\gtrsim 10$ Gyr, (ii) that in this time the star-formation rate has declined only slowly and by a factor $\sim 3$, and (iii) that random velocity increases as $\sim \frac{1}{3}$ power of age.

**Radial migration** Sellwood & Binney[22] showed that the main impact of spiral structure is not to heat the disc but to induce radial migration of stars. This finding violates a basic assumption of traditional models of the Galaxy's chemical evolution: that each annulus evolves independently. Schönrich & Binney[23] presented a model of chemical evolution that was designed to be the simplest that included radial migration. In the new model stars form in the plane at a rate determined by the local surface density of gas, which changes in response to (i) accretion from a slightly metal-enriched intergalactic medium, (ii) inwards spiralling of gas through the disc, and (iii) ejection of metal-rich gas from the disc by supernovae and fast stellar winds. Gas is constantly being enriched with heavy elements by stars that die at the given radius. Stars are born on nearly circular orbits, but the velocity dispersion of their cohort increases with age. Stars also suffer changes in angular momentum. As a result stars often die and enrich the Interstellar medium (ISM) at locations far removed from their places of birth. The models yielded a remarkably accurate account of the observed chemistry of the solar neighbourhood. In particular it called into question the belief that the existence of the thick disc is proof of a discrete star-formation episode or early major merger in the life of the Galaxy[30]. The models also explained why the traditional derivation of the local standard of rest from the kinematics of nearby stars fails[28].

**Accretion of intergalactic gas** Fraternali & Binney[31,32] developed a model of the extraplanar gas seen in galaxies such as NGC 891 and NGC 2403. Although this gas is principally comprised of gas ejected from the disc by star formation, both data and theory required non-trivial interaction with the corona of virial temperature gas that is thought to surround all galaxies and to contain over half of the Universe's baryons. In a series of papers with students and collaborators[33,34,35] they went on to show that the interaction between clouds of gas ejected from the disc and coronal gas explains rather beautifully not only the observational data for both external galaxies and the Milky Way, but also explains why cooling from the corona feeds the disc rather than the black hole or bulge, which reside in regions where the coronal gas is denser and would be expected to have a shorter cooling time. The model predicts that once a galaxy has lost its disc of cold gas, most likely in the course of a major merger, it is unlikely to replace that disc, with the result that star formation in its disc dies out, and the galaxy becomes "red and dead".

**Actions for axisymmetric potentials** A prerequisite of exploiting models with DFs $f(\mathbf{J})$ is the ability to calculate actions from given phase-space coordinates $(\mathbf{x}, \mathbf{v})$. The underpinning of our work is a technique we developed in the 1990s to fit orbital tori with known actions to a given gravitational potential[36,37,38,39]. The central idea of torus fitting is to write down the generating function $S(\mathbf{J}, \boldsymbol{\theta}')$ of the canonical transformation between the angle-action variables $(\boldsymbol{\theta}', \mathbf{J}')$ of a "toy" Hamiltonian that has known analytical expressions $\boldsymbol{\theta}'(\mathbf{x}, \mathbf{v})$ and $\mathbf{J}'(\mathbf{x}, \mathbf{v})$ and the angle-action variables $(\boldsymbol{\theta}, \mathbf{J})$ of our Galaxy. The generating function contains parameters which are numerically adjusted to minimise the r.m.s. variation of the actual Hamiltonian $H$ over the image of the toy torus. Once this has been done for a range of different values of $\mathbf{J}$, the average value of $H$ on each image torus defines an integrable Hamiltonian $\overline{H}(\mathbf{J})$ that is typically extremely close to the actual Hamiltonian. In fact the perturbation $h \equiv H - \overline{H}$ can often be neglected. In this case, the fitting algorithm has delivered analytic expressions for $\mathbf{x}(\boldsymbol{\theta}, \mathbf{J})$ and $\mathbf{v}(\boldsymbol{\theta}, \mathbf{J})$. We demonstrated this process for the cases in which $H$ was associated with either an axisymmetric gravitational potential $\Phi(R, z)$ or a planar barred potential $\Phi(x, y)$, which may have a steadily rotating figure[40].

Classical galaxy and cluster modelling (e.g. §4.3 of [41]) assumes that the DF is a known function of $(\mathbf{x}, \mathbf{v})$. Since orbital tori yield $\mathbf{x}(\boldsymbol{\theta}, \mathbf{J})$ and $\mathbf{v}(\boldsymbol{\theta}, \mathbf{J})$ rather than the inverse functions, classical modelling is not immediately applicable to models based on torus fitting. Fortunately, the "adiabatic approximation" makes it possible to obtain a good approximation to $\mathbf{J}(\mathbf{x}, \mathbf{v})$ for stars that do not stray more than $\sim 1.5\,\mathrm{kpc}$ from the plane: Binney[27] introduced this approximation and Binney & McMillan[42] used orbital tori to verify and improve its accuracy. A further refinement was described by Schönrich & Binney[43] and we will shortly release code for obtaining $\mathbf{J}(\mathbf{x}, \mathbf{v})$ using this refinement so colleagues can also determine the actions of disc stars.

**Fitting models to data** Our models provide the pdf of stars in the space of observables. McMillan & Binney[44] sampled the pdf of the observables of a model whose DF contained certain parameters, and then added "observational errors" to the data points to form a pseudo-catalogue. From this catalogue they determined the pdf of the DF's parameters by exploring the parameter space by a Markov-Chain Monte-Carlo process in which the likelihood of the data given the model is used in the Metropolis algorithm to choose the next point in the chain. They found that the algorithm is outstandingly successful in the case of chemically indistinguishable stars in a given gravitational potential.

**Debris from merger events** It has long been recognised that stellar streams, which almost certainly consist of stars torn from a satellite by the Galaxy's tidal field, are potentially powerful diagnostics of the Galaxy's gravitational field. From the work of [17] it was assumed that streams delineated the orbits of the satellite. In three papers[45,46,47] we explored the consequences of this conjecture. We showed that if the gravitational field is considered known, all six phase-space coordinates of stars can be inferred from the stream's path across the sky and either measurements of the line-of-sight velocities or proper motions. Then one can test whether these coordinates are consistent with the equations of motion, and reject the proposed gravitational field if they are not. In a fourth paper[18] we showed that the streams actually deviate from orbits quite significantly, even in the case of negligible satellite mass. Although traditional diagnostic techniques are undermined by this finding, we were able to show that streams have a simple structure in terms of angle-action variables, and this finding suggests that it will be possible to develop diagnostics that use angle-action variables instead of assuming that streams delineate orbits.

Along these lines, McMillan & Binney[48] showed that by using angle-action variables, debris from tidal destruction of a globular cluster can be identified from full phase-space data even after the debris have become phase mixed. Moreover, the date of destruction can be determined.

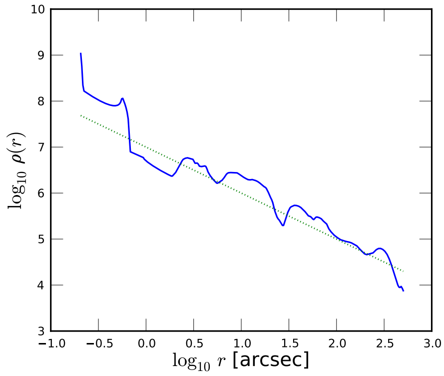

**Fig. 2.** The density of stars in the Galaxy's central parsec. The dashed line shows the best-fitting power-law mass-density profile, while the jagged curve is the best fitting number density of stars.

**Distances to stars** The scientific exploitation of stellar surveys hinges on the accuracy with which distances to catalogued stars can be determined. Until the Gaia Catalogue becomes available (in 2017?), we are overwhelmingly dependent on distances inferred by fitting stellar models to the observed colours and spectra (if available). Burnett & Binney[12] introduced a new Bayesian algorithm for doing this when spectral data are available and applied it to data from the Geneva-Copenhagen and RAVE surveys[12,49]. Unfortunately, these approaches are liable to systematic error (on account of defects in the stellar models of defects in the fitting process). Schönrich, Binney & Apslund[50] present techniques for using the kinematics of stars to detect and correct for such systematic errors.

**The Galaxy's central parsec** The Galaxy's central parsec is of interest because: (i) it consists of a black hole of mass $4 \times 10^6\,\mathrm{M}_\odot$ surrounded by a nuclear star cluster and is by far the nearest object of its ill-understood class; (ii) it involves the fascinating transition from degenerate (Keplerian) dynamics to the non–degenerate dynamics of a stellar system; (iii) its dynamics yield the distance to the Galactic centre and the local circular speed[51]. Moreover, the problem of fitting a dynamical model to observations of this region is good test problem because it is conceptually very similar to modelling the Galaxy's global dynamics but much more tractable computationally.

Magorrian[52] has fitted dynamical models to the proper motions of 6000 stars observed in the NIR within 1 pc of the centre supplemented by number counts out to projected radii $\sim 2\,$pc. These are the first orbit-superposition models of the Galactic centre to make no assumptions about the internal orbit distribution or deprojected number-count distribution, and the first to include the effects of incompleteness and dust extinction. The best-fitting models have an underlying mass-density profile that is broadly consistent with the observed number-count distribution (Fig. 2). This presents a challenge to models of the GC, which generally predict a steep Bahcall-Wolf-type density cusp.

## B2(c) Research plan and resources

**Local disc structure** Different stellar populations (young stars, old stars, high-$\alpha$ stars, etc.) have different vertical density and velocity-dispersion profiles. Determination of density profiles from star counts in a cone around $b = \pm 90°$ is a classic problem, which we need to understand thoroughly before we move on to more sophisticated problems. We have fitted "nonparametric" profiles to the 2MASS and SDSS colours of stars, making no prior assumption about how the densities of different populations behave, save that they decrease outwards. Sophisticated stellar isochrones are used to predict colours as functions of age and chemistry, but we do not attempt to assign individual stars physical parameters. The best-fit models show the traditional decomposition into a thin young disc, a thicker old disc and a very extended old metal-poor population (Fig. 1 right). Both disc populations are consistent with exponential profiles that have scaleheights similar to those traditionally ascribed to the thin and thick discs. It is very satisfying to see these component for the first time emerge naturally from the data.

Our work with the RAVE survey data has yielded the velocity dispersion as a function of distance from the plane for the sampled population (Fig. 1 left). Complementing this with our density profiles, we can find how the mass density varies with distance from the plane. We will go on to combine the analysis of the number counts with the spectroscopic data to refine our knowledge of both the confining potential and the DFs of individual populations. This work should be completed within the first year of the project.

**Disentangling the thin and thick discs** We will use modest developments of our current models to lay bare the connection between the Galaxy's thin and thick discs. These components were originally introduced by Gilmore & Reid[53] to explain the vertical density profile of the disc, which they fitted by the sum of two exponentials. Subsequent studies of the chemistry of stars near the Sun[54,55] showed that the stars with the highest values of [$\alpha$/Fe] at a given value of [Fe/H] tend to be on highly inclined and eccentric orbits. Recently it has become possible to examine the chemistry of stars at a significant distance from the Sun[56,57] and ask how the balance between $\alpha$-enhanced and normal stars varies with both distance from the plane and azimuthal velocity $v_\phi$. There is an urgent need to relate the separation of $\alpha$-enhanced and normal stars in local velocity space to the spatial separation and rotation lags of the two populations – currently there is much confusion because observers select stars that are presumed to sample one disc or another using a mixture of kinematic and spatial criteria. The relationship between these criteria is determined by dynamics, so dynamical models are required for the synthesis.

Our models with DFs based on pseudo-isothermals can do this once they have been extended to include the chemical dimension by making the parameters occurring in them, such as $\sigma_r$ and $\sigma_z$, vary with chemistry as well as with $J_\phi$. Then it will be possible to define the thin and thick discs as objects in action space, which then have predictable visibility in any given sample, be it selected kinematically or spatially. We believe there is much valuable work to be done with models of this type. The steps we have to complete are: (i) modify our DFs by making the parameters $\sigma_r$, etc functions of chemistry as well as $J_\phi$; (ii) add to our models a DF for the stellar halo, which has distinct chemistry and contributes significantly to the observations $\gtrsim 2\,\mathrm{kpc}$ from the plane; (iii) for the SDSS/SEGUE, RAVE, and ESO-Gaia survey establish what the selection function is: i.e., the probability that a star of given type at a given location is included in the survey; (iv) apply these selection functions to our models to predict for each observed volume the number of stars of each species expected in each region of velocity space; (v) adjust the parameters of the model to optimise the fit to all surveys. Steps (i) and (ii) are being investigated by a graduate student. The rest of this project should take 1–1.5 years in the first instance, although it will have to be revisited from time to time to take account of additional data.

**Determining actions** We have code based on the adiabatic approximation that returns $\mathbf{J}(\mathbf{x},\mathbf{v})$ for stars that do not move more than $\sim 1.5\,\mathrm{kpc}$ from the plane of an axisymmetric Galaxy. We need to complement this alternative to torus fitting [which yields $\mathbf{x}(\boldsymbol{\theta},\mathbf{J})$ and $\mathbf{v}(\boldsymbol{\theta},\mathbf{J})$ rather than $\mathbf{J}(\mathbf{x},\mathbf{v})$] with a procedure that works for halo stars. A student is currently testing a scheme that determines $\mathbf{J}(\mathbf{x},\mathbf{v})$ by fitting a Stäckel potential to the real potential in the neighbourhood of the orbit. Meanwhile an undergraduate is exploring a technique for determining actions potentials from time integrations. Binney & Spergel[58] showed how to do this by Fourier decomposing the numerically determined time series of the particle coordinates. This approach was not as robust as is desirable. Our new approach is based on the existence of a generating function and we expect it to be more robust. The two new schemes should be applicable to both axisymmetric potentials and triaxial potentials that have negligible pattern speeds (such as those generated by dark-matter halos). We expect work on determining actions to be complete within the first year of the project.

**Characterisation of cosmological simulations** Several groups make model Galaxies by simulating the clustering of DM and baryons, including star formation, chemical evolution, feedback and gas outflows. In collaboration with such a group we will analyse the endpoints of such simulations by calculating actions for all their particles and fitting, as a function of chemistry, a DF in action space (rather than the space of observables) – these fits will take advantage of all the stars in a simulation, whereas most of these stars will be too distant to satisfy the selection function of any survey. This exercise will not only inform our choice of fitting functions for DFs, but may resolve the problem posed by the impracticability of binning stars in the space of observables: having fitted an analytic DF to the simulation, we can then examine the fit of the data to the pdf provided by the DF in the space of observables. This is a project for a student who starts after work on action determination is complete.

**N-body models of stellar discs** We will use high-quality N-body simulations to investigate how rapidly stars diffuse through action space, and how anisotropic such diffusion is. Our torus machinery enables us to generate initial conditions for N-body simulations that have appropriately non-Gaussian velocity distributions and are thus in near perfect equilibrium from the outset. A paper describing such setups is in preparation. We will run simulations started with this technology and allow spiral structure to emerge within them (probably with some artificial seeding of structure to avoid total dependence on Poisson noise). Then at a number of times during the simulation we will calculate the actions of all or many stars in a temporarily axisymmetrised and frozen gravitational field. Hence we will determine the probability $P_t(\mathbf{J},\boldsymbol{\Delta})$ that in a given small time $t$ a star with actions $\mathbf{J}$ suffers a change in actions $\boldsymbol{\Delta}$. The diffusion coefficients $\overline{\boldsymbol{\Delta}}$ and $\overline{\Delta^2_{ij}}$ that govern the diffusion of stars through action space are the expectation values of $\boldsymbol{\Delta}$ and $\Delta_i\Delta_j$ under $P_t(\mathbf{J},\boldsymbol{\Delta})$. Hence $P_t(\mathbf{J},\boldsymbol{\Delta})$ determines both the speed of radial migration and the speed of disc heating[59]. We expect to complete a paper on this work about two years into the programme but work in this area is likely to continue throughout the project.

**Modelling chemodynamical evolution** Our first-cut DFs for stars of specified chemistry will use the "pseudo-isothermal" DFs described above in which the parameters $\sigma_r$ and $\sigma_z$ are judiciously chosen functions of $J_\phi$, metallicity (and possibly age). This exercise will characterise the distribution of each type of star in phase space without explaining the distribution. In the next phase we will explore the reason why by improving and extending the approach of [23] to chemodynamic modelling. A significant problem is the way [23] infers the velocity dispersion of stars that are observed at $R'$ but were born at a very different radius $R$ – stars are assumed to carry their velocity dispersion $\langle v_z^2\rangle^{1/2}$ with them when they should really carry $J_z$. Also the algorithm used to handle radial migration of both stars and gas was rather crude, and in the case of gas not well motivated physically.

We will determine the chemistry of the ISM as a function of time and radius substantially as now. Stars will form on near-circular orbits, i.e., along the $J_\phi$ axis of action space, and will then be diffused through action space according to the previously determined diffusion coefficients. When stars die, their synthesis products will be distributed in radius according to the radial density profiles of their final orbit. The part of the code described in [23] that deals with chemical evolution (initial mass functions, isochrones, yields, etc) require essentially no change. We merely have to update the probability distribution of final orbits and the routines that predict survey numbers.

The first set of models we produce in this way will be based on analytic approximations to the diffusion coefficients – see [60] for details. After the N-body modelling of discs has been completed, we will produce a new set of models using the diffusion coefficients extracted from the models. This work will take 2–3 years.

**Impact of spiral structure** When the Hipparcos Catalogue first became available, Dehnen[61], working in our group, showed that the density of solar-neighbourhood stars stars in velocity-space is significantly different from what you would expect from Jeans' theorem: the surfaces of constant stellar density are not surfaces on which some function of the actions is constant. Recently, it has become possible from the RAVE survey to determine the velocity-space distribution of stars at points $\gtrsim 1\,\mathrm{kpc}$ from the Sun, and the conclusion is broadly similar. The APOGEE survey[7], which takes infrared spectra, will be a particularly effective probe of the phase-space structure of the disc to significant distances from the Sun. Finally, the Gaia Catalogue will increase the quantity and range of the available data enormously by providing proper motions for tens of millions of stars with known parallaxes.

It is generally agreed that the violation of Jeans' theorem by nearby disc stars is caused by a combination of the bar and spiral structure, which perturb stars from the orbits they would follow in an axisymmetric Galaxy. Efforts to model the phenomenon have been largely numerical and have had mixed success[62,63]. If we could do better, we should be able to extract from the stellar distribution

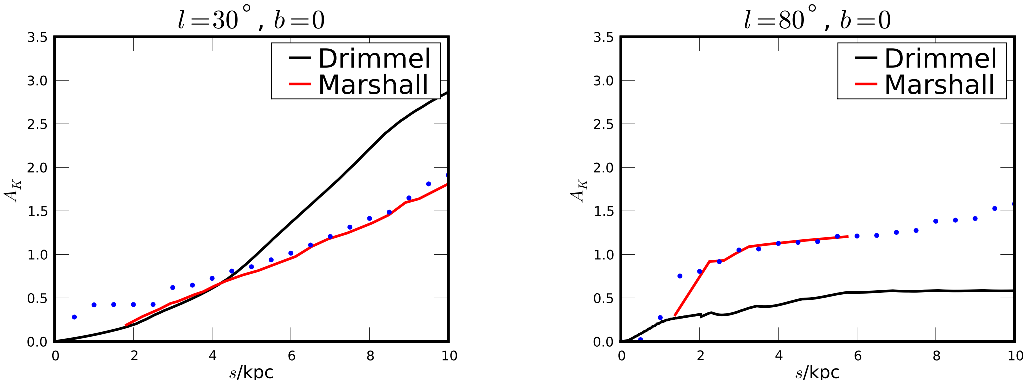

**Fig. 3** Extinction as a function of distance down two sight lines within the plane. Blue dots: values inferred from 2MASS star counts using a new algorithm; Red curves: results of [68]; Black curves: results of [69].

significant information about spiral structure: its spatial form, pattern speed and the mass associated with it. We believe that the keys to doing better are (i) to include the dynamics of the ISM in the analysis (see below) and (ii) to apply Hamiltonian perturbation theory to our axisymmetric models, which have well defined DFs $f(\mathbf{J})$. In essence, for any given spiral perturbation to the potential, the shift in actions $\delta\mathbf{J}(\boldsymbol{\theta},\mathbf{J},t)$ is readily derived from our expressions for $\mathbf{x}(\boldsymbol{\theta},\mathbf{J})$ and $\mathbf{v}(\boldsymbol{\theta},\mathbf{J})$ so we have the perturbed DF $f_1(\mathbf{J},\boldsymbol{\theta},t) = f_0(\mathbf{J}-\delta\mathbf{J})$. Since $|\delta\mathbf{J}| \ll |\mathbf{J}|$, linear theory can be used, so the stellar distribution will be linearly related to the spiral potential. On account of this linearity, we should be able to infer the potential from the observed distributions.

The Hipparcos data suggested that the vertical motions of disc stars are not significantly correlated with their planar motions[61], so progress may be possible with perfectly planar models, and we would start with such models. However, since obscuration in the disc will have the effect of confining quality data for stars far from the Sun to significant distances from the plane, and the response of a star to spiral structure decreases with increasing $J_z$, we suspect that understanding of the ESO-Gaia, APOGEE and Gaia data will require fully three-dimensional models. This is an ambitious project and will require more than two years of work towards the end of the project.

**The ISM** Since Gaia will observe the Galaxy at optical wavelengths, obscuration by dust will have a big impact on the Catalogue's contents. Hence exploitation of the Catalogue will require knowledge of the three-dimensional distribution of gas and dust within the Galaxy. The Catalogue also provides the opportunity to determine this distribution since it will furnish an unprecedented list of stars with geometrically determined distances. Consequently, once the Gaia Catalogue is available, two issues will arise: (i) how to determine the extinctions to catalogued stars, and (ii) how to synthesise a large body of extinctions into a coherent model of the ISM. These tasks were the focus of an ESF-sponsored workshop we organised in Leiden in July 2011[64]. Work on the determination of extinction from Gaia spectrophotometry is underway in Bailer-Jones' Heidelberg group, and several other groups around Europe are working on extracting extinctions from ground-based spectra, mostly of early-type stars (e.g., [65,66,67]).

An STFC-funded postdoc (S. Sale) is currently working on a project (i) to determine the distribution $a(\mathbf{x})$ of obscuring dust from the 2MASS (near-IR) star counts, and then (ii) to refine both $a(\mathbf{x})$ and our estimate of the potential $\Phi(R,\phi)$ that drives the gas by using hydrodynamical simulations of gas flow and the observed intensities of emission by hydrogen and CO at 21 cm and 2.6 mm. We have tested a new scheme for obtaining the K-band extinction $a_K(s)$ along individual lines of sight from star counts (Fig. 3). The next step is to solve for the extinction along all lines of sight simultaneously while constraining $a(\mathbf{x})$ to vary smoothly between points that are close to one another but lie on different lines of sight. We propose to do this by expanding the dust density in logarithmic spiral waves and varying the coefficients in this expansion rather than the dust density at individual spatial points. Finally we will use a cold-gas density distribution from a snapshot of a hydrodynamical simulation (we have considerable experience of such simulations[70,71,72,33]) as a prior during the recovery of $a(\mathbf{x})$ from the extinction data.

In the last two years of this grant we will extend this STFC-funded work on near-IR extinction (i) to optical bands, (ii) to include information from pulsar dispersion measures, and (iii) to exploit measured extinctions to large numbers of stars with measured parallaxes. The extension to optical bands is non-trivial because, whereas the extinction in the $J$ band is reliably 2.5 times that in the $K$ band, the ratio of $V$-band and $K$-band extinctions is known to vary with location as a consequence of spatial variations in the size-distribution of dust particles[73]. We will follow [73] in assuming two parameters suffice to parametrise the extinction law, and adapt out star-count analysis to fit these parameters as a function of location in parallel with the density of dust. Given a candidate $a(\mathbf{x})$ the likelihood of the measured extinctions of a star with known parallax is readily computed. The overall likelihood to be maximised is the product of this new likelihood factor and the likelihood factor that we now obtain from the star counts. Work on the three-dimensional model of the ISM will continue throughout the project and the model itself will be an important resource for the whole community.

**Barred models** Our Galaxy is barred and the chemodynamics of the bar are being intensively studied with souther-hemisphere spectrographs. The data from these studies need to be incorporated within a dynamical model. N-body models are reasonably well suited to this job[74], but our understanding of what is going on in such a model would be enhanced if we could study it is action space. As mentioned above, in the 1990s we demonstrated that orbital tori can be constructed for two-dimensional barred systems even though a band around the corotation radius phase space is generally dominated by chaotic orbits – Kaasalainen[40] was able to construct orbital tori in these regions, and these orbital tori define an integrable Hamiltonian $\overline{H}$ that is close to the true Hamiltonian $H$. Some orbits in $H$ are chaotic because the perturbation $h = H - \overline{H}$ causes obits to drift from torus to torus. We need to understand this drift and ideally reproduce it from Hamiltonian perturbation theory – insights may be gained here that are applicable far from Galactic dynamics. Crucially, we must obtain a Fokker-Planck-like equation that governs the diffusion of stars through chaotic regions of phase space. This work could bring us much closer to a secure understanding of the secular evolution of disc galaxies[75].

Our programme for including the bar is as follows. (i) We will extend our work on planar bars to fully three-dimensional bars so we can foliate the phase spaces of such bars with orbital tori. (ii) We will fit analytic DFs for $\overline{H}$ to suitable N-body models and thus understand better the bar's structure. (iii) For a selection of plausible bar potentials we will fit the analytic forms of the DF identified in step (ii) to survey data and thus form a clearer picture of the Galaxy's bar/bulge. (iv) Using our orbital tori we will study how stars on numerically integrated orbits in $H$ move through the action space that the orbital tori define. In particular, from orbit integrations we should calculate scattering probabilities $P_t(\mathbf{J}, \boldsymbol{\Delta})$ similar to those to which spiral structure gives rise. (iv) Ideally we would show that the diffusion coefficients $\overline{\Delta^2_{ij}} \equiv \langle \Delta_i \Delta_j \rangle_{P_t}$ to which these scattering probabilities give rise can be derived from the perturbation $h = H - \overline{H}$ through first-order perturbation theory[59,60]. Work on the bar constitutes a major research programme, which will require the dedicated efforts of an experienced postdoc and would continue throughout the project.

**Fitting models to data** We argued above that the promised science will be extracted from surveys including the Gaia Catalogue by fitting the data to model pdfs of stars in the high-dimensional space of observables. In [44] we made a promising start on this task but major extensions of this work are required. We have to extend the methodology to include information about physical properties of catalogued stars – their chemistry, surface gravity and effective temperature. The natural formalism for doing this uses stellar isochrones from the theory of stellar evolution in the course of model fitting. We want to implement this formalism as soon as possible. Next we must extend the search from just the DF to the DF and the gravitational potential $\Phi$ combined. The observables are linear in the DF but non-linear in $\Phi$, so it is much harder to compute the effect of changing $\Phi$ rather than the DF. Also our experiments indicate that discreteness noise causes more trouble when $\Phi$ is varied. In fact it may not be possible to determine $\Phi$ from the global likelihood alone: we should consider systematic variations in the distribution of stellar likelihoods at different points in the space of observables.

Given the importance of observational errors, computing likelihoods involves integrating the model pdfs over each star's error ellipsoid in the 10 or higher-dimensional space of observables. From

**Table 1: Work packages**

| Package | Tasks |
|---|---|
| Effects of non-axisymmetry | Use Hamiltonian perturbation theory to modify the phase-space distributions predicted in the axisymmetric case by our "quasi-isothermal" DFs. Fit perturbing potential to data from Hipparcos and RAVE survey, later from ESO-Gaia and APOGEE surveys. Simulate flow of gas in these potentials, predict distribution of HI and CO emission in $(l, v)$ plane and compare with observational planes. Develop code for generating 3d orbital tori for rotating barred potentials and use to fit analytic DFs to N-body bars. Fit same analytic DFs to survey data. Study the diffusion in action space of stars in a bar's chaotic region. Try to recover this diffusion from perturbation theory. Seek signatures of chaos-driven diffusion in observed chemo-kinematic correlations. |
| Chemodynamical modelling | Use our DFs to set up high-quality N-body simulations of discs and determine how self-consistent spiral structure causes stars to diffuse through action space. Try to reproduce diffusion from perturbation theory. Model the evolution of the abundances of the principal elements in the ISM as a function of radius and time. Use the diffusion coefficients to predict the radial distribution of the metals ejected by each cohort of stars. Hence also determine the present action-space distribution of stars by chemistry and age. Compare with both survey data and predictions of cosmological models. Identify observational signatures of heating and migration. |
| ISM Modelling | From 2MASS star counts determine a spatially coherent distribution of extincting dust $a(\mathbf{x})$ first with a smooth prior and then with a prior from a hydrodynamical model of gas flow, possibly refining the non-axisymmetric potential recovered from stellar kinematics. Extend the extinction distribution to optical bands. Refine the distribution by incorporating measured extinctions to stars with known parallaxes. |
| Model fitting | Assemble selection functions for principal catalogues (RAVE, SEGUE, APOGEE, etc. Vertical structure at $R_0$: use 2MASS, SDSS and RAVE data to determine the vertical distributions of different stellar populations and the overall density of matter. Global modelling: use models with analytic DFs to elucidate thin/thick disc/halo divisions; extend range of stellar data employed; include constraints from stellar evolution; determine how best to constrain potential; seek numerical optimisations to ensure it's feasible to apply to the Gaia Catalogue. Extend this work to DFs derived from modelling SFR, gas infall, etc. Modelling debris: model principal streams with angle-action variables and determine constraints they can place on $\Phi$. |

our experiments to date, it is clear that doing this for the tens to hundreds of millions of stars that will be in the Gaia Catalogue will be a huge challenge computationally, and we will have to think very carefully about algorithmic efficiency, the judicious use of approximations and the effective control of discreteness noise. Our experiments have raised many questions that we currently lack the time to pursue. Devising and executing optimum fits of the models to various catalogues will require a dedicated postdoc for the duration of the project.

## Resources

**Work plan & funding** The team will consist of Binney, his former student and current Faculty member J. Magorrian, four postdocs, and 3–5 research students. We estimate that Binney will devote 55% of his time and Magorrian will devote 30% of his time to the project throughout the 60 months from Month 1. For the first three years of the grant an element of the PI's time on the project will be paid for by existing arrangements with the STFC with the balance of time being claimed from the project. In the last two years of the grant all the PI's time spent on the project will be claimed from the grant. Two postdocs (McMillan and Sale), each devoting 100% of their time to the project, will be in place on Month 1, but they are funded by STFC until 30/9/2014 and 31/1/2015, respectively. We are in the process of recruiting two addition postdocs and one student to work full time on the project from as soon as possible after Month 1. Additional students working full time on the project

**Budget Table 1**

| | Months | | | | |
|---|---|---|---|---|---|
| Cost Category | 1-18 | 19-36 | 37-54 | 55-60 | Total |
| Direct Costs: | | | | | |
| Personnel: | | | | | |
| PI | 56,371 | 56,370 | 79,566 | 26,522 | 218,829 |
| Senior Staff | 21,336 | 21,335 | 39,633 | 13,212 | 95,516 |
| Post docs | 229,813 | 229,812 | 375,688 | 125,230 | 960,543 |
| Students | 58,648 | 58,648 | 46,433 | 15,478 | 179,207 |
| Other | 0 | 0 | 0 | 0 | 0 |
| **Total Personnel:** | 366,168 | 366,165 | 541,320 | 180,442 | 1,454,095 |
| Other Direct Costs: | | | | | |
| Equipment | 6,336 | 6,335 | 3,344 | 1,115 | 17,130 |
| Consumables | 0 | 0 | 0 | 0 | 0 |
| Travel | 31,701 | 31,700 | 41,166 | 13,722 | 118,289 |
| Conference fees | 1,500 | 1,500 | 1,500 | 1,000 | 5,500 |
| Visiting experts | 1,000 | 1,000 | 1,000 | 500 | 3,500 |
| Publication costs | 5,336 | 5,335 | 5,780 | 1,260 | 17,711 |
| **Total Other Direct Costs:** | 45,873 | 45,870 | 52,790 | 17,597 | 162,130 |
| Total Direct Costs | 412,041 | 412,035 | 594,110 | 198,039 | 1,616,225 |
| Indirect Costs (overheads $\leq$ 20% of Direct Costs): | 82,408 | 82,407 | 118,822 | 39,607 | 323,244 |
| Subcontracts including Audit (No overheads) | 5,545 | 5,544 | 3,902 | 0 | 14,991 |
| Total Costs of project (by year and total) | 499,994 | 499,986 | 716,834 | 237,646 | 1,954,460 |
| Requested Grant (by year and total) | 499,994 | 499,986 | 716,834 | 237,646 | 1,954,460 |

The PI will spend at least 55% of his working time on the project for all 60 months
Dr Magorrian will spend at least 30% of his working time on the project for all 60 months

should start on 1 October 2014 and 1 October 2015. Thus we anticipate having two postdocs on the project throughout the 60 months and two more working on it for from 60 to 54 months depending on how soon we can make appropriate appointments. STFC will be funding 40 postdoc-months of this total requirement for 222 to 234 postdoc-months.

Table 1 lists four work packages, one associated with each postdoc. Magorrian is an expert on the dynamics of galactic nuclei[76,77,78] and would contribute his expertise with a range of astronomical inverse problems, including fitting dynamical models. There will be weekly team meetings for relatively formal discussions and daily informal contacts between team members. A new student will start in each of the first three years and would be assigned a project that fell within one of these packages, which each cover an enormous amount of ground.

Two of the work packages are currently funded for limited periods by the UK STFC: model fitting is funded at the level of one postdoc (McMillan), two students until end September 2014, while work on the ISM is funded at the level of one postdoc (Sale) until end January 2015. It is obviously of the first importance that expertise can be retained in the team right up to the end of the grant period, which is when the preliminary version of the Gaia Catalogue will appear.

The job of taking charge of work on chemodynamical models has been offered to, and been informally accepted by Ralph Schönrich, who is currently a Hubble Fellow at Ohio State University. We expect Til Pifl to join us from Potsdam postdoc to undertake the work on non-axisymmetry.

The project involves a great deal of computation and document preparation, which will be largely carried out on laptops, but workstations and file servers will also be required. The University does not routinely provide researchers with computers – it is normal institutional practice for research projects to fund any such purchases from project funding. Therefore under "equipment" the budget contains a provision for equipping all team members with a suitable laptop and software etc.

This work is very much part of an international effort and attendance at meetings, workshops and steering committees of collaborative projects is essential for all participants. Although conference

**Budget Table 2**

| Key intermediate goal | % of total grant | Month of completion | Comment |
|---|---|---|---|
| Submit papers on determination of the potential from a survey | 5 | 12 | |
| Submit papers on equilibrium models from RAVE data | 4 | 12 | |
| Submit papers on construction of ISM model from IR extinction measurements | 5 | 18 | |
| Apply above models to extinctions to RAVE stars | 3 | 24 | |
| Submit papers on fitting DFs to cosmological simulations | 5 | 24 | |
| Submit papers on torus fitting to 3d rotating bars | 6 | 24 | |
| Complete work on analysis of RAVE survey | 3 | 36 | |
| Submit papers on using hydrodynamical models to constrain ISM model | 6 | 36 | |
| Submit papers on determining $\mathbf{J}(\mathbf{x},\mathbf{v})$ in non-rotating triaxial potentials | 5 | 36 | |
| Submit papers on action-space diffusion of stars from N-body simulations | 5 | 36 | |
| Refine RAVE-based models by adding SDSS/SEGUE data | 3 | 40 | |
| Build DF based model of Galactic bar | 6 | 40 | |
| Extend equilibrium models to embrace streams & use to constraint $\Phi$ | 3 | 40 | |
| Extend ISM models to include visual extinctions | 3 | 48 | |
| Submit papers combining action-space diffusion with chemical evolution | 6 | 48 | |
| Submit papers on using H perturbation theory to model spiral structure | 5 | 48 | |
| Submit papers fitting chemical evolution models to cosmological simulations | 5 | 54 | |
| Use torus models of bar to study orbit diffusion | 6 | 54 | |
| Derive survey observables from combined bulge/disc/halo model | 4 | 54 | |
| Apply results of H perturbation theory to Gaia-ESO & APOGEE or other IR survey | 5 | 60 | |
| Perfect algorithms that will be used to analyse Gaia data with sufficient rapidity | 7 | 60 | |

fees are generally waived for invited speakers, postdocs and students generally have to pay these so the budget includes an estimate of this cost. Colleagues from institutes around Europe will need to visit to coordinate their work with ours, and when they do, it is often expedient to pay for their accommodation in Oxford, so we have included a budget item for such costs. Visits will be on a one-off basis (and not recurrent) and will be from key figures in the field. The financing of expenses incurred by visiting experts will follow Oxfords usual accounting and management practices; and the host institution will ensure that costs are reasonable (not excessive) and comply with the principles of sound financial management. These expenses will be recorded in the accounts of the host institution and will be appropriately substantiated; and the visits by the visiting experts will have a demonstrable link to the project which will derive value from the experts' participation.

Two of the premier journals in the field impose page charges, and we fear more journals will go over to this funding model as part of the move to "open access". Therefore the budget includes an estimate of the cost of publishing results.

The only item covered by "subcontracting" is auditing.

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## B2(d) Ethical and security issues

### Research on Human Embryo/Foetus

Does the proposed research involve human Embryos?

Does the proposed research involve human Foetal Tissues/ Cells?

Does the proposed research involve human Embryonic Stem Cells (hESCs)?

Does the proposed research on human Embryonic Stem Cells involve cells in culture?

Does the proposed research on human Embryonic Stem Cells involve the derivation of cells from Embryos?

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do

### Research on Humans

Does the proposed research involve children?

Does the proposed research involve patients?

Does the proposed research involve persons not able to give consent?

Does the proposed research involve adult healthy volunteers?

Does the proposed research involve Human genetic material?

Does the proposed research involve Human biological samples?

Does the proposed research involve Human data collection?

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do

### Privacy

Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?

Does the proposed research involve tracking or observation of people?

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do

### Research on Animals

Does the proposed research involve research on animals?

Are those animals transgenic small laboratory animals?

Are those animals transgenic farm animals?

Are those animals non-human primates?

Are those animals cloned farm animals?

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do

### Research Involving non-EU Countries (ICPC Countries)

Is the proposed research (or parts of it) going to take place in one or more of the ICPC countries?

Is any material used in the research (e.g. personal data, animal and/or human tissue samples, genetic material, live animals, etc):

a) Collected in any of the ICPC countries?

b) exported to any other country (including ICPC and EU Member States)?

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do

### Dual Use

Research having a direct military use

Research having the potential for terrorist abuse

I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL I do