# The Gaia-ESO Public Spectroscopic Survey

Gerry Gilmore[1,*]
Sofia Randich[2,*]
Martin Asplund[3,+]
James Binney[4,+]
Piercarlo Bonifacio[5,+]
Janet Drew[6,+]
Sophia Feltzing[7,+]
Annette Ferguson[8,+]
Rob Jeffries[9,+]
Giusi Micela[10,+]
Ignacio Negueruela[11,+]
Timo Prusti[12,+]
Hans-Walter Rix[13,+]
Antonella Vallenari[14,+]
Emilio Alfaro[15,‡]
Carlos Allende-Prieto[16,‡]
Carine Babusiaux[5,‡]
Thomas Bensby[7,‡]
Ronny Blomme[17,‡]
Angela Bragaglia[18,‡]
Ettore Flaccomio[10,‡]
Patrick François[5,‡]
Mike Irwin[1,‡]
Sergey Koposov[1,‡]
Andreas Korn[19,‡]
Alessandro Lanzafame[20,‡]
Elena Pancino[17,‡]
Ernst Paunzen[21,‡]
Alejandra Recio-Blanco[22,‡]
Giuseppe Sacco[2,‡]
Rodolfo Smiljanic[23,‡]
Sophie Van Eck[24,‡]
Nicholas Walton[1,‡]

1 Institute of Astronomy, University of Cambridge, United Kingdom
2 INAF–Osservatorio Astrofisico di Arcetri, Italy
3 Mount Stromlo Observatory, Australian National University, Canberra, Australia
4 Dept. of Theoretical Physics, University of Oxford, United Kingdom
5 GEPI, Observatoire de Paris, France
6 Centre for Astronomy Research, University of Hertfordshire, United Kingdom
7 Lund Observatory, Sweden
8 Institute for Astronomy, University of Edinburgh, United Kingdom
9 Astrophysics Group, University of Keele, United Kingdom
10 INAF–Osservatorio Astronomico di Palermo, Italy
11 Departamento de Fisica, Universidad de Alicante, Spain
12 ESTEC, ESA, the Netherlands
13 Max-Planck Institut für Astronomy, Heidelberg, Germany
14 INAF–Osservatorio di Padova, Italy
15 Instituto de Astrofisica de Andalucia-CSIC, Granada, Spain
16 Istituto Astrofisica de Canarias, Tenerife, Spain
17 Royal Observatory of Belgium, Brussels, Belgium
18 INAF–Osservatorio di Bologna, Italy
19 Dept. of Physics and Astronomy, University of Uppsala, Sweden
20 Dipartimento di Fisica e Astronomia, Università di Catania, Italy
21 Institut für Astronomie, Universität Wien, Austria
22 Observatoire de la Côte d'Azur, Nice, France
23 ESO
24 Institut d'Astronomie et d'Astrophysique, Université Libre de Brussels, Belgium
* Co-PI
+ Steering Committee member
‡ Working Group coordinator

The Gaia-ESO Survey Team
Co-PIs: G. Gilmore[1], S. Randich[2]
CoIs: M. Asplund[3], J. Binney[4], P. Bonifacio[5], J. Drew[6], S. Feltzing[7], A. Ferguson[8], R. Jeffries[9], G. Micela[10], I. Negueruela[11], T. Prusti[12], H.-W. Rix[13], A. Vallenari[14], D. Aden[7], C. Aerts[15], L. Affer[10], J.-M. Alcala[16], E. Alfaro[17], C. Allende Prieto[18], G. Altavilla[19], J. Alves[20], T. Antoja[21], F. Arenou[5], C. Argiroffi[22], A. Asensio Ramos[18], C. Babusiaux[5], C. Bailer-Jones[13], L. Balaguer-Nunez[23], A.Bayo[24], B. Barbuy[25], G. Barisevicius[26], D. Barrado y Navascues[27], C. Battistini[7], I. Bellas Velidis[28], M. Bellazzini[29], V. Belokurov[1], T. Bensby[7], M. Bergemann[3], G. Bertelli[14], K. Biazzo[16], O. Bienayme[30], J. Bland-Hawthorn[31], R. Blomme[32], C. Boeche[33], S. Bonito[10], S. Boudreault[18], J. Bouvier[34], A. Bragaglia[35], I. Brandao[36], A. Brown[37], J. de Bruijne[12], M. Burleigh[38], J. Caballero[39], E. Caffau[33], F. Calura[40], R. Capuzzo-Dolcetta[41], M. Caramazza[10] . G. Carraro[24], L. Casagrande[3], S. Casewell[38], S. Chapman[1], C. Chiappini[42], Y. Chorniy[26], N. Christlieb[43], M. Cignoni[19], G. Cocozza[19], M. Colless[44], R. Collet[3], M. Collins[13], M. Correnti[29], E. Covino[16], D. Crnojevic[8], M. Cropper[45], M. Cunha[36], F. Damiani[10], M. David[46], A. Delgado[17], S. Duffau[33], S. Van Eck[47], B. Edvardsson[48], J. Eldridge[1], H. Enke[42], K. Eriksson[48], N.W. Evans[1], L. Eyer[49], B. Famaey[30], M. Fellhauer[50], I. Ferreras[45], F. Figueras[23], G. Fiorentino[21], E. Flaccomio[10], C. Flynn[31], D. Folha[36], E. Franciosini[2], P. Francois[5], A. Frasca[51], K. Freeman[52], Y. Fremat[32], E. Friel[53], B. Gaensicke[54], J. Gameiro[36], F. Garzon[18], S. Geier[55], D. Geisler[50], O. Gerhard[56], B. Gibson[40], A. Gomboc[57], A. Gomez[5], C. Gonzalez-Fernandez[11], J. Gonzalez Hernandez[18], E. Gosset[58], E. Grebel[33], R. Greimel[59], M. Groenewegen[32], F. Grundahl[60], M. Guarcello[61], B. Gustafsson[48], P. Hadrava[62], D. Hatzidimitriou[63], N. Hambly[8], P. Hammersley[64], C. Hansen[33], M. Haywood[5], U. Heber[55], U. Heiter[48], E. Held[14], A. Helmi[21], G. Hensler[20], A. Herrero[18], V. Hill[65], S. Hodgkin[1], N. Huelamo[39], A. Huxor[33], R. Ibata[30], M. Irwin[1], R. Jackson[9], R. de Jong[42], P. Jonker[66], S. Jordan[33], C. Jordi[23], A. Jorissen[47], D. Katz[5], D. Kawata[45], S. Keller[52], N. Kharchenko[42], R. Klement[13], A. Klutsch[67], J. Knude[68], A. Koch[38], O. Kochukhov[48], M. Kontizas[69], S. Koposov[1], A. Korn[48], P. Koubsky[62], A. Lanzafame[70], R. Lallement[5], P. de Laverny[65], F. van Leeuwen[1], B. Lemasle[21], G. Lewis[31], K. Lind[3], H. P. E. Lindstrom[68], A. Lobel[58], J. Lopez Santiago[67], P. Lucas[6], H. Ludwig[33], T. Lueftinger[20], L. Magrini[2], J. Maiz Apellaniz[17], J. Maldonado[67], G. Marconi[24], A. Marino[3], C. Martayan[24], I. Martinez-Valpuesta[56], G. Matijevic[57], R. McMahon[1], S. Messina[51], M. Meyer[49], A. Miglio[58], S. Mikolaitis[26], I. Minchev[42], D. Minniti[71], A. Moitinho[72], Y. Momany[24], L. Monaco[24], M. Montalto[36], M.J. Monteiro[36], R. Monier[73], D. Montes[67], A. Mora[74], E. Moraux[34], T. Morel[58], N. Mowlavi[75], A. Mucciarelli[19], U. Munari[14], R. Napiwotzki[6], N. Nardetto[65], T. Naylor[76], Y. Naze[58], G. Nelemans[77], S. Okamoto[78], S. Ortolani[79], G. Pace[36], F. Palla[2], J. Palous[62], E. Pancino[35], R. Parker[49], E. Paunzen[20], J. Penarrubia[25], I. Pillitteri[61], G. Piotto[14], H. Posbic[5], L. Prisinzano[10], E. Puzeras[26], A. Quirrenbach[33], S. Ragaini[19], J. Read[49], M. Read[8], A. Recio-Blanco[65], C. Reyle[80], J. De Ridder[15], N. Robichon[5], A. Robin[80], S. Roeser[33], D. Romano[35], F. Royer[5], G. Ruchti[3], A. Ruzicka[62], S. Ryan[6], N. Ryde[7], G. Sacco[81], N. Santos[36], J. Sanz Forcada[39], L. M. Sarro Baro[82], L. Sbordone[43], E. Schilbach[33], S. Schmeja[33], O. Schnurr[42], R. Schoenrich[3], R.-D. Scholz[42], G. Seabroke[45], S. Sharma[31], G. De Silva[44], R. Smiljanic[64], M. Smith[78], E. Solano[39], R. Sordo[14], C. Soubiran[83], S. Sousa[36], A. Spagna[84], M. Steffen[42], M. Steinmetz[42], B. Stelzer[10], E. Stempels[48], H. Tabernero[67], G. Tautvaisiene[26], F. Thevenin[65], J. Torra[23], M. Tosi[35], E. Tolstoy[21], C. Turon[5], M. Walker[61], N. Walton[1], J. Wambsganss[33], C. Worley[65], K. Venn[85], J. Vink[86], R. Wyse[87], S. Zaggia[14], W. Zeilinger[20], M. Zoccali[71], J. Zorec[88], D. Zucker[89], T. Zwitter[57]

Institutes: [1]IoA; [2] INAF–Obs. Arcetri; [3] MPA; [4] Univ. Oxford; [5] Obs. Paris; [6] Univ. Hertforshire; [7] Lund Univ; [8] Univ. Edinburgh; [9] Univ. Keele; [10] Obs. Palermo; [11] Univ. de Alicante; [12] ESTEC; [13] MPIA; [14] INAF–Obs. Padova; [15] Kath. Univ. Leuven; [16] INAF–Obs. Capodimonte; [17] IAA-CSIC; [18] IAC; [19] Univ. Bologna; [20] Univ. Vienna; [21] Kapteyn Inst.; [22] Univ. Palermo; [23] Univ. Barcelona; [24] ESO Santiago; [25] Univ. Granada; [26] Inst. Theo Phys & Astro., Lithuania; [27] Calar Alto Obs.; [28] National Optical Obs., Greece; [29] INAF–Obs. Bologna; [30] Obs. Strasbourg; [31] Univ. Sydney; [32] Royal Obs. Belgium; [33] Univ. Heidelberg; [34] Univ. J. Fourier; [35] INAF–Obs. Bologna; [36] CAUP Porto; [37] Univ. Leiden; [38] Univ. Leicester; [39] Centro de Astrobiología, Madrid; [40] Univ. Central Lancashire; [41] Univ. Rome; [42] AIP Potsdam; [43] Univ. Heidelberg; [44] AAO; [45] MSSL, UCL; [46] Univ. Antwerp; [47] ULB, Brussels; [48] Uppsala Univ.; [49] ETH Zurich; [50] Univ. Concepcion; [51] INAF–Obs. Catania; [52] ANU; [53] Univ. Boston; [54] Univ. Warwick; [55] Bamberg Obs.; [56] MPE; [57] Univ. Ljubliana; [58] Univ. Liege; [59] Karl-Franzens-Univ.; [60] Univ. Aarhus; [61] CfA; [62] Astr. Inst. Acad. Sci., Prague; [63] Univ. Athens; [64] ESO Garching; [65] OCA Nice; [66] SRON, Utrecht; [67] Univ. Madrid; [68] Copenhagen Univ. Obs.; [69] Univ. Athens; [70] Univ. Catania; [71] Univ. Catolica; [72] Univ. Lisbon; [73] Univ. Nice Sofia Ant.; [74] ESAC; [75] Obs. de Geneve; [76] Univ. Exeter; [77] Univ. Nijmegen; [78] KIAA, Beijing; [79] Univ. Padova; [80] Obs. Besancon; [81] Rochester Inst. Technology; [82] UNED, Madrid; [83] Univ. Bordeaux; [84] INAF–Obs. Torrino; [85] Univ. Victoria; [86] Armagh Obs.; [87] Johns Hopkins Univ.; [88] IAP; [89] MacQuarie Univ.

**The Gaia-ESO Public Spectroscopic Survey has begun and will obtain high quality spectroscopy of some 100 000 Milky Way stars, in the field and in open clusters, down to magnitude 19, systematically covering all the major components of the Milky Way. This survey will provide the first homogeneous overview of the distributions of kinematics and chemical element abundances in the Galaxy. The motivation, organisation and implementation of the Gaia-ESO Survey are described, emphasising the complementarity with the ESA Gaia mission. Spectra from the very first observing run of the survey are presented.**

"*Europe has led the way in Galactic research as regards astrometry and spectroscopy, and is on the brink of taking the lead in photometry: ESA's Hipparcos mission pioneered space astrometry and paved the way for the ambitious Gaia mission, which will perform the first parallax survey down to magnitude* V *= 20 in parallel with a complete characterisation of each observed object; ESO's innovative telescopes (NTT and VLT) coupled to leading capabilities in the construction of multi-object spectrographs have yielded detailed stellar abundances of faint stars; ESO is about to start massive programmes of optical/near-IR photometry with two dedicated survey telescopes (VISTA and VST).*" That impressive long sentence introduced the *Messenger* article (Turon et al., 2008b) describing the work of the ESA–ESO Working Group on Galactic Populations, Chemistry and Dynamics (Turon et al., 2008a). The same *Messenger* issue reported on the ASTRONET Infrastructure Roadmap: A Twenty Year Strategy for European Astronomy (Bode & Monnet, 2008), which concluded "*among medium-scale investments, science analysis and exploitation for the approved Horizon 2000 Plus astrometric mission Gaia was judged most important*". The ESO community and ESO's Scientific Technical Committee (STC) have continued the theme, leading to an ESO Workshop on Wide-field Spectroscopic Surveys, held in March 2009 (Melnick et al., 2009). This meeting concluded that a large public spectroscopic survey, using current ESO VLT instrumentation, "*could place the European community in a favourable situation ... and would go a long way towards generating the data required to complement Gaia if the surveys begin soon*".

That recommendation led, via a process involving Letters of Intent, review, and preliminary selection, to a 300-author proposal for the Gaia-ESO Public Spectroscopic Survey, a 300-night survey of all Galactic Stellar Populations, using FLAMES (both GIRAFFE and UVES) on the VLT's Unit Telescope 2 (UT2). Following the review and approval of the proposal, and the development of a detailed Survey Management Plan agreed between ESO and the two Co-PIs, the Gaia-ESO Survey began taking data on the night of 31 December 2011.

This ambitious survey, of similar scale to the Public Surveys on VISTA and VST, is very clearly the culmination of many years of hard work, initiative, planning and dedication by very many people, from the writing of the science strategy to the spectrum analysis software. With the European Space Agency Gaia mission due for launch in 2013, Europe is indeed well on the way to scientific leadership in quantitative studies of the formation and evolution of the Milky Way and its components. The Gaia-ESO Survey offers the opportunity to meet that challenge.

## What is the Gaia-ESO Survey?

The Gaia-ESO Public Spectroscopic Survey employs the VLT FLAMES instrument for high quality spectroscopy of some 100 000 stars in the Milky Way. With well-defined samples, based primarily on current VISTA photometry for the field stars, and on the Two Micron All Sky Survey (2MASS) and a variety of photometric surveys of open clusters, the survey will quantify the kinematic multi-chemical element abundance distribution functions of the Milky Way Bulge, the thick Disc, the thin Disc, and the Halo stellar components, as well as a very significant sample of 100 open clusters, covering all accessible cluster ages and stellar masses. This alone will revolutionise knowledge of Galactic and stellar evolution. When combined with precision astrometry, delivering accurate distances, 3D spatial distributions, 3D space motions, and improved astrophysical parameters for each star, the survey will quantify the formation history and evolution of young, mature and ancient Galactic populations. The precision astrometry will be provided by the Gaia "Galactic census", with the first astrometric data release likely to occur in 2016, in time for the full analysis of the complete Gaia-ESO Survey data.

The Gaia-ESO Survey is among the largest and most ambitious ground-based surveys ever attempted by European astronomy. The Survey consortium involves some 300 scientists in over 90 institutions (see the list of team members). This large allocation of telescope time, which followed a very detailed scientific and managerial peer review, is a robust measure of the strength and originality of the scientific case, the high legacy value of the Survey dataset, the appropriateness of the methodology being utilised, and the project implementation and management structure. There are two survey Co-PIs, Gerry Gilmore and Sofia Randich, leading the Milky Way and calibration aspects, and star cluster aspects, respectively. The important synergy from covering all Galactic components is a joint responsibility and opportunity.

## Gaia-ESO Survey scientific background

Understanding how galaxies actually form and evolve within our $\Lambda$CDM (Lambda Cold Dark Matter) Universe, and how their component stars and stellar populations form and evolve, continues to be an enormous challenge. Extant simulations of the aggregation of cold dark matter (CDM) suggest that galaxies grow through a sequence of merger and accretion events. Most events involve accretion of an object that is so small that it barely perturbs the system, some events involve an object large enough to produce a mild perturbation, and a handful of events involve an object that causes a major convulsion. Exactly how these events impact on a galaxy cannot be predicted at this time because the extremely complex physics of baryons cannot be reliably simulated: at a minimum it involves interstellar chemistry, magnetic reconnection, radiative transfer in the presence of spectral lines and significant velocity gradients, thermonuclear fusion, neutron absorption, neutrino scattering, radioactive decay, cosmic ray acceleration and diffusion. Theoretical models of galaxy formation rely more heavily on phenomenological models than on physical theory. Thus, these models require calibration with well-studied (nearby) test cases. For example, star formation involves turbulence, magnetic reconnection, collisionless shocks, and radiative transfer through a turbulent medium. Similarly, the treatment of convection, mixing, equations of state at high density, opacities, rotation and magnetic fields can all significantly affect stellar luminosities, radii, and lifetimes at different evolutionary phases. We are far from being able to simulate the coupled evolution of CDM and baryons from *ab initio* physics.

Observations are crucial to learning how galaxies and stars were formed and evolved to their present structure. Observations of objects at high redshifts and long lookback times are important for this endeavour, as is the detailed examination of our Galaxy, because such “near-field cosmology” gives insights into key processes that cannot be obtained by studying faint, poorly resolved objects with uncertain features. Just as the history of life was deduced by examining rocks, we expect to deduce the history of the Galaxy by examining stars. Stars record the past in their ages, compositions and kinematics. For example, individual accretion and cluster dissolution events can be inferred by detecting stellar streams from accurate phase-space positions. Correlations between the chemical compositions and kinematics of field stars will enable us to deduce the history of star formation and even the past dynamics of the Disc. The kinematic structure of the Bulge will reveal the relative importance in its formation of disc instability and an early major merger. The study of open clusters is crucial to understanding fundamental issues in stellar evolution, the star formation process, and the assembly and evolution of the Milky Way thin Disc.

Most stars form in associations and clusters, rather than singly, so understanding star formation also implies studying cluster formation. Advances in infrared astronomy have opened up the study of the formation of stellar cores in dark clouds, and the period in which a core grows by accretion. We know that outflows of various types disperse most of the gas of a cloud, and that the great majority of groups of young stars then quickly disperse. More populous groups survive the dispersal as open clusters, and subsequently disperse through a combination of internal mass loss, two-body scattering off other members of the group, and tidal disturbance by the gravitational fields of external objects such as giant molecular clouds and spiral arms. It is possible that open clusters are the dominant source of field stars. They trace different thin Disc components covering broad age and metallicity intervals, from a few Myr up to several Gyr, from 0.3 to two times solar abundance. Each cluster provides a snapshot of stellar evolution. Thus, observations of many clusters at different ages and chemical compositions, quantify stellar evolution, allowing increasingly detailed theoretical models to be tested. Much stellar and Galactic astrophysics hinges on these crucial comparisons between cluster observations and the predictions of the models.

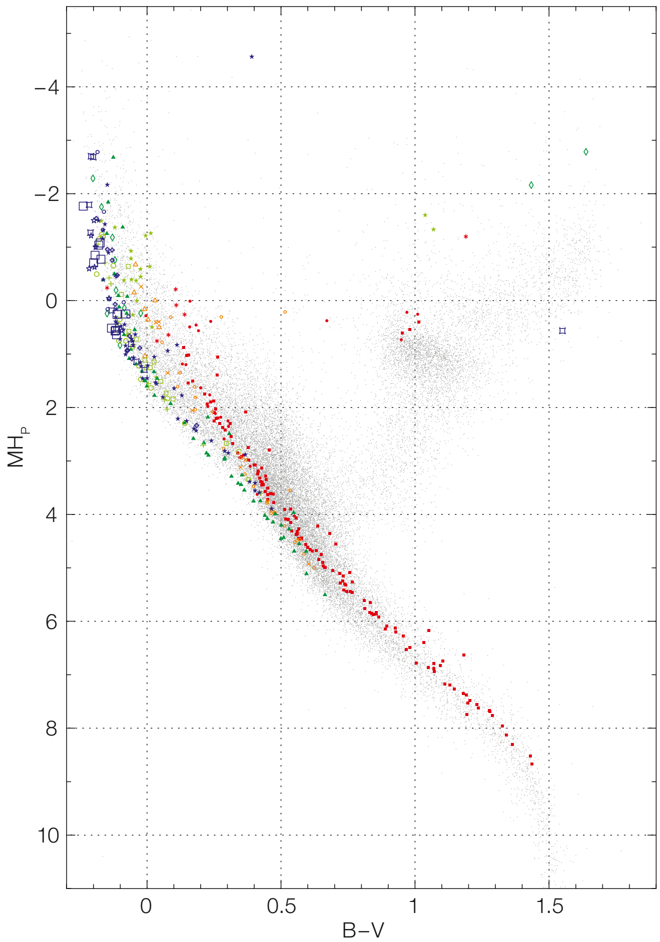


Figure 1. A colour–magnitude diagram based on the Hipparcos re-analysis by Floor van Leeuwen, of nearby precise luminosity and colour data. The open cluster data are colour-coded by age, blue being younger, red older. Local field stars are in grey.

Figure 1 illustrates the state-of-the-art colour–magnitude diagram based on a re-analysis of Hipparcos data (van Leeuwen, 2007) for nearby stars. The rich information content of precise stellar astrometric, kinematic, and chemical abundance data for both clusters and field quantifies not only stellar evolution models, and their limitations, but also Galactic evolution models, and their limitations. Adding 100 well-observed clusters, covering and characterising stars down to low masses, to this figure will be a revolution in our knowledge.

## Scale of the challenge and specific scientific objectives

The key to addressing these topics, and decoding the history of the formation and

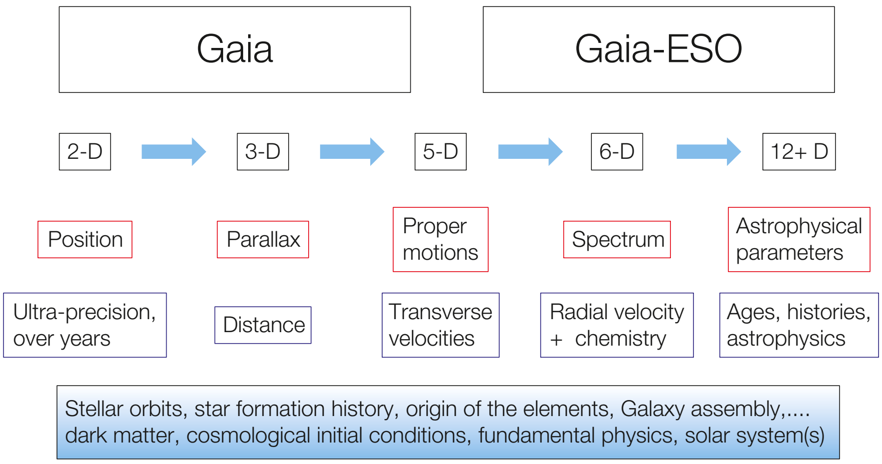



Figure 2. Diagrammatic representation of the outputs of the Gaia and Gaia-ESO surveys, showing how they are complementary.

evolution of the Galaxy and its components, involves three aspects: chemical element mapping, which quantifies timescales, mixing and accretion length scales, star formation histories, nucleosynthesis and internal processes in stars; spatial distributions, which relate to structures and gradients; and kinematics, which relates to both the felt, but unseen, dark matter, and dynamical histories of clusters and merger events. With Gaia, and stellar models calibrated on clusters, one will also add ages for (slightly evolved) field stars, for the first time. Manifestly, a spectroscopic survey returning data for very large samples is required to define with high statistical significance all these distribution functions and their spatial and temporal gradients.

The Gaia-ESO Survey is that survey. Moreover, it will also be the first survey yielding a homogeneous dataset for large samples of both field and cluster stars, providing unique added value. The specific top-level scientific goals it will allow to be addressed include:
– Open cluster formation, evolution, and disruption;
– Calibration of the complex physics that affects stellar evolution;
– Quantitative studies of Halo substructure, dark matter, and rare stars;
– Nature of the Bulge;
– Origin of the thick Disc;
– Formation, evolution, structure of the thin Disc;
– Kinematic multi-element distribution function in the Solar Neighbourhood.

## Gaia-ESO Survey legacy overview

This VLT survey delivers the data to support a wide variety of studies of stellar populations, the evolution of dynamical systems, and stellar evolution. The Survey will complement Gaia by using the GIRAFFE+ UVES spectrographs to measure detailed abundances for at least 12 elements (Na, Mg, Si, Ca, Ti, V, Cr, Mn, Fe, Co, Sr, Zr, Ba) in up to 10 000 field stars with $V < 15$ mag and for several additional elements (including Li) for more metal-rich cluster stars. Depending on target signal-to-noise (S/N) and astrophysical parameters, the data will typically probe the fundamental nucleosynthetic channels: nuclear statistical equilibrium (through V, Cr, Mn, Fe, Co), and alpha-chain (through Si, Ca, Ti). The radial velocity precision for this sample will be 0.1 to 5 $kms^{-1}$, depending on target, with, in each case, the measurement precision being that required for the relevant astrophysical analysis. The data will resolve the full phase-space distributions for large stellar samples in clusters, making it possible to identify, on both chemical and kinematic grounds, substructures that bear witness to particular merger or starburst events, and to follow the dissolution of clusters and the Galactic migration of field stars.

The survey will also supply homogeneously determined chemical abundances, rotation rates and diagnostics of magnetic activity and accretion, for large samples of stars in clusters with precise distances, which can be used to challenge stellar evolution models. Considerable effort will be invested in abundance calibration and ESO archive re-analysis to ensure maximum future utility.

## Why not just wait for Gaia?

The Gaia mission will provide photometry and astrometry of unprecedented precision for most stars brighter than $G = 20$ mag, and obtain low resolution spectra for most stars brighter than 17th magnitude. The first astrometry data release is likely to be in 2016, with spectrophotometry and stellar parameters to follow later, and 2021 for the final catalogue. Crucially, Gaia has limited spectroscopic capabilities and, like all spacecraft, does not try to compete with large ground-based telescopes at what they do best.

A convenient way of picturing the Gaia–ground complementarity is to look at the dimensionality of data which can be obtained on an astrophysical object. Larger amounts of information of higher quality are the goal, to increase understanding. Figure 2 gives a cartoon view of this information set. There are four basic thresholds which we must pass. The first is to know a source exists, its position, and basic photometric data. Photometric surveys, such as those underway at VISTA and VST will deliver this information. The second is to add the time domain — motions, including parallax, providing distances and speeds. Here Gaia will be revolutionary. The third threshold is radial velocity, turning motions into orbits. While Gaia will provide radial velocities, the magnitude limit is three magnitudes brighter than that of the astrometry and the precision is much below that of proper motions. Here the Gaia-ESO will be crucial to supplement Gaia spectroscopy. The fourth threshold is chemistry, and astrophysical parameters. These latter two both require spectroscopy, which is the key information from the Gaia-ESO Survey.

## Gaia-ESO Survey samples and observational strategy

The Gaia-ESO Survey observing strategy has been designed to deliver the top-level survey goals. The Galactic inner and outer Bulge will be surveyed, as will be the inner and outer thick and thin

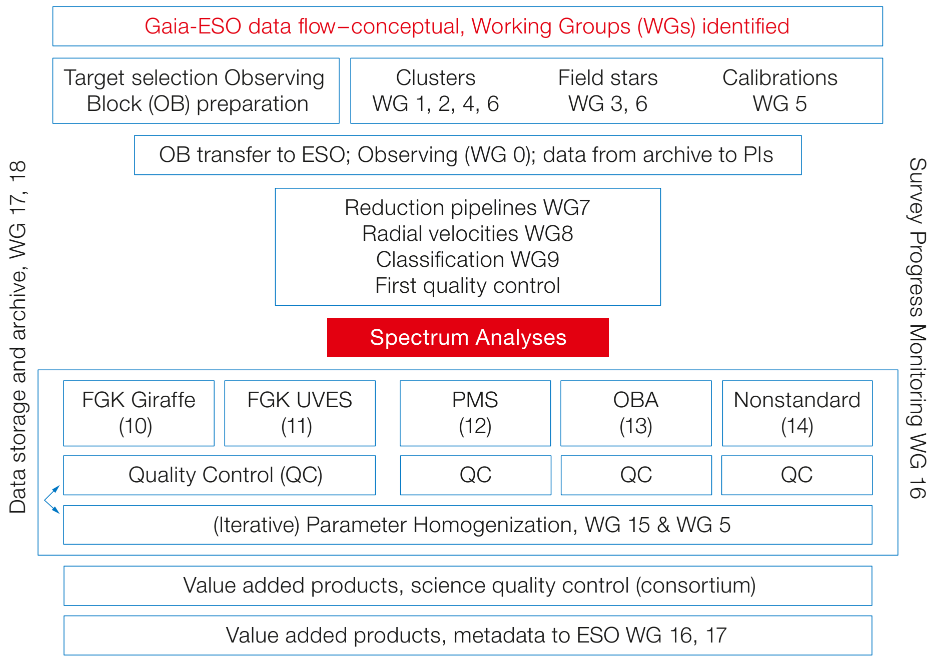



Figure 3. Data flow schematic, from the Survey Management Plan, to illustrate the challenges involved in the Gaia-ESO Survey. The logical path flows from pre-observation target selection through observing at the top, through data processing, data spectrum analysis, astrophysical parameter determination, calibration, homogenisation, to delivery of science data for verification analysis at the bottom. Infrastructure provision is down the sides, being relevant at all stages, as is the survey progress monitoring, and quality control by the Co-PI teams, preparatory for public data release.

Discs, the Halo and known Halo streams. Particular focus will be put on the local thin Disc, as this study both complements Gaia astrometry and will benefit most from the high precision Gaia data. More specifically, prime GIRAFFE targets in the Bulge are K giants, which dominate the relevant colour–magnitude diagram selection. Primary targets in the Halo and thick Disc are $r$ = 17–18 mag. F stars, with the bluer, fainter F stars probing the Halo and brighter, redder F stars probing the thick Disc. Sloan Digital Sky Survey (SDSS) photometry shows a clear thick Disc/Halo transition at $17 < r < 18$ and $0.2 < g - r < 0.4$ — and we use the equivalent selection from VISTA near-infrared photometry. In fields crossing known Halo streams (e.g., Sagittarius), K giant candidates will be included in the sample.

Outer thick Disc fields will have distant F stars as prime targets, like the Halo. This well-defined low latitude sample probes 2–4 kpc, more than a radial scale length. In addition, we will allocate 25 % of the fibres to brighter candidate K giants, which probe the far outer thick Disc, warp, flare and Monocerus stream, and will deliver excellent S/N. To quantify thin Disc dynamics, we will target 4–6 fields to $I$ = 19 mag. in the Plane to test spiral arm/bar dynamics obtaining several thousand radial velocities per line of sight. We will dedicate UVES parallels for the field surveys to an unbiased sample of 5000 FG stars within 2 kpc of the Sun.

Cluster selection is optimised to fine-sample the age–[Fe/H]–Galactocentric distance–mass parameter space. Clusters in all phases of evolution (except embedded), with ages from about 1 Myr up to 10 Gyr will be included, sampling different environments and star formation conditions. This will provide sufficient statistics to explore the dynamical evolution of clusters; the same sample will map stellar evolution as a function of metallicity for $0.1 < M/M_{\odot} < 100$, even for short-lived evolutionary phases, and provide a population large enough to throughly investigate metallicity as a function of Galactocentric radius and age. In all clusters GIRAFFE will be used to target faint cluster members (down to $V$ = 19), while parallel UVES fibres will be fed with brighter or key objects (down to $V$ = 16.5), to be used for accurate multi-element abundances.

For the field survey, two GIRAFFE high resolution setups are used, HR10 and HR21, which include a large enough number of Fe I and Fe II lines for astrophysical parameter determination, along with lines of other key elements. The parallel UVES observations will use the 580 nm setup. For the clusters, and depending on the specific targets, six GIRAFFE setups are employed (HR03/05A/06/14A/15N/21). HR03/05A/06/14A contain a large number of spectral features, to be used to derive radial velocities and astrophysical parameters of early-type stars. HR15N/21 are instead the most appropriate gratings for late-type stars; they access a large enough number of lines to derive radial velocities, as well as to retrieve key information on the star's characteristics (e.g., temperature, [Li/H], accretion rates, chromospheric activity, rotation). For UVES, the 520 nm and 580 nm setups will be used for hot and cool stars, respectively.

## Gaia-ESO Survey methodology and implementation activities

The Gaia-ESO Survey is a very large project, with substantial resource commitments in terms of telescope access. The greatest cost, and opportunity, is of course the time of the 300 scientists dedicated to this project over the next five years. To guarantee that this resource is utilised with maximal efficiency and effectiveness, we have developed a very detailed plan, clarifying every stage of information flow, decision dependency, data processing, information storage, and provision of documented data for team scientific analysis. This involved a 42-page science case, supplemented by a 25-page management plan, describing every stage of the project implementation, from science goal through detailed target selection, data processing, and readiness for scientific analysis. The science plan was reviewed and approved by a special ESO-organised science strategy panel, and by the ESO Time Allocation system. The management plan was reviewed by ESO and agreed after minor iteration. These documents form a memorandum of understanding between ESO

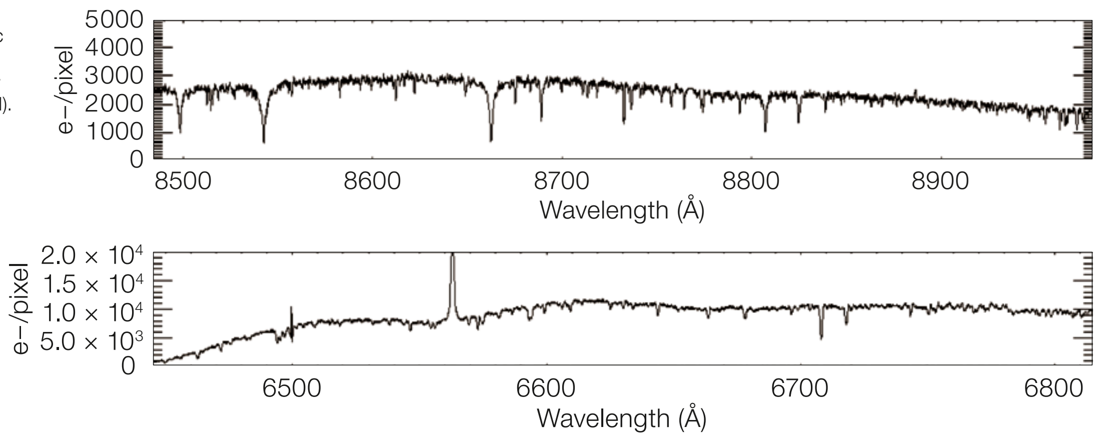
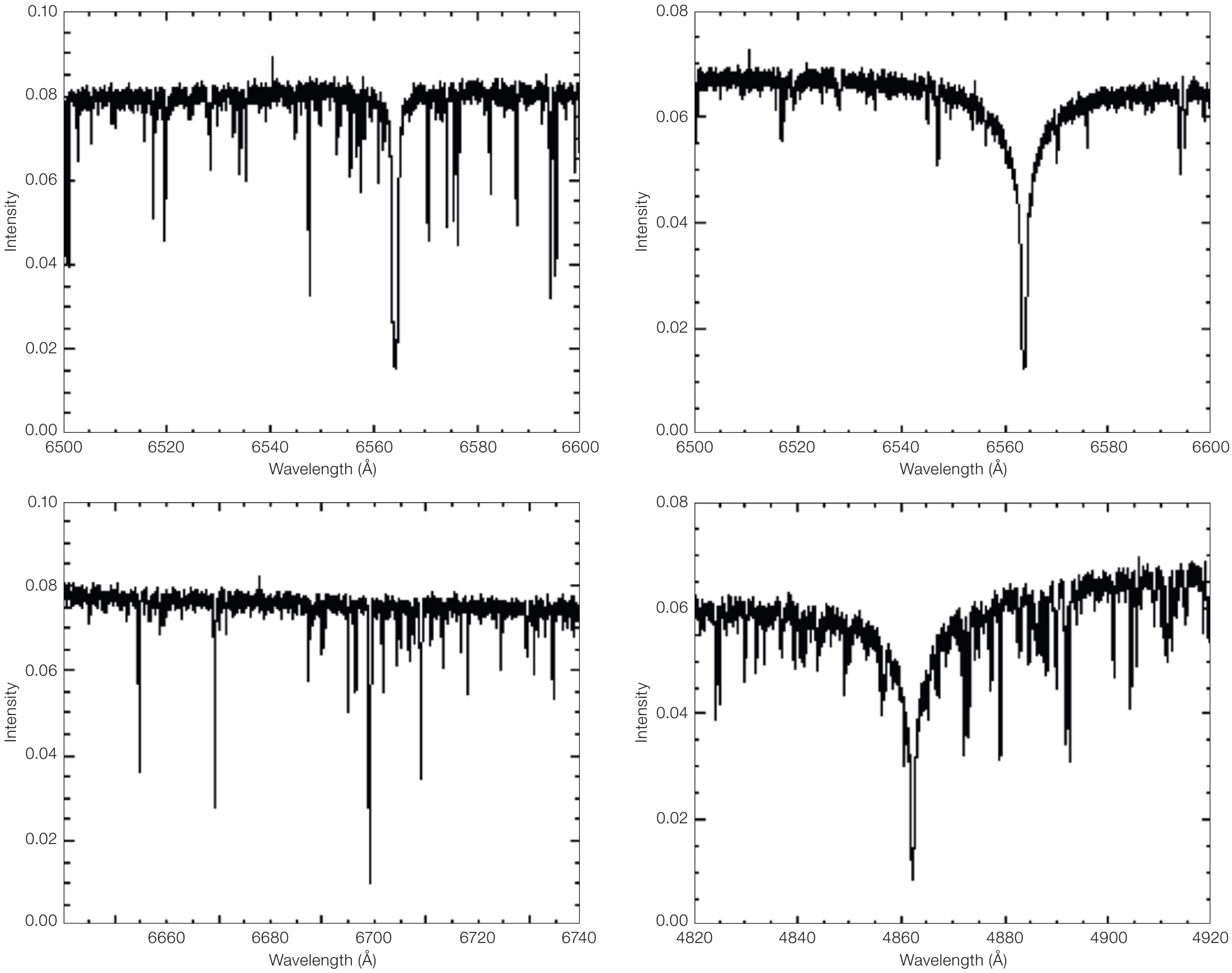



Figure 4. GIRAFFE spectra of a Milky Way star in the outer thick Disc (grating setting HR21, upper panel) and a member of the young cluster γ Velorum (setting HR15N, lower panel). Note the strong Hα emission and lithium 6708 Å line in the latter, both indicators of youth.

Figure 5. Left panel: UVES spectra are shown of a member of γ Velorum around Hα (upper) and the lithium line (bottom). Right panel: UVES spectra of a Milky Way field star in the Hα (upper) and Hβ (lower) spectral regions.



and the Co-PIs on Survey delivery. They are available on the survey wiki[1] and (forthcoming) web page[2].

A Survey Consortium Working Group structure has been created to match the information and requirements flow, from the scientific context which defines source selection, through selection, observation, data reduction, classification, spectrum analysis, astrophysical parameter determination, and collation of all the information necessary for science verification analysis (see Figure 3). The survey activities are structured into 18 Working Groups, one for each level of critical specialist activity, each with an identified coordinator, remit, requirements, and deliverables.

A 19th Working Group dedicated to communications is also included. The Working Group coordinators report to the Co-PIs, who are advised by a Steering Group, which acts as the project management board. The Steering Group members act to assist the Co-PIs in supporting the consortium activities. The Steering Committee and Working Group leads are identified as co-authors of this article. There are many more workers than there are managers — which is why the survey works!

At the heart of the survey data processing are the spectrum analyses. All extracted spectra are processed through general purpose pipelines, to refine astrophysical parameters, and deliver elemental abundances to a level appropriate for the relevant stellar type and available S/N. Separate pipelines manage, respectively, hot, warm and cool stars, as well as pre-main sequence stars, and GIRAFFE and UVES spectra. It is a strength of this Gaia-ESO Survey team that it includes a majority of Europe's spectrum analysis groups, which between them have available a wealth of expertise. All groups have agreed to adopt a fixed set of atomic data and model atmospheres for the analysis of FGK stars. Very considerable coordination between the teams has been underway for some months. This range of analysis excellence will be applied to the various stellar and data types as appropriate. Sanity checking will then deliver, for each star target, a "best" set of parameters and abundances, with corresponding random and systematic errors, and an explicit analysis of the effect of alternative analysis assumptions. All these results will be archived for later analysis, both in the operational database, and the Survey archive for later public analysis. All survey products will be delivered to the ESO archive.

## Complementary activities

Given the outstanding range of science opportunities in near-field cosmology, it is not surprising that Galactic surveys are a major research activity globally. One of these, AEGIS, using the Australian AAO 2dF facility, is coordinated with the Milky Way field part of Gaia-ESO, with shared photometric targets, and closely coordinated follow-up science planning. AEGIS, which targets candidate Halo stars identified from the SkyMapper photometric survey, aims to observe the rare relatively bright metal-poor stars, to add statistical weight in the wings of the Gaia-ESO distribution function. The AEGIS PI is Stefan Keller at the Australian National University (ANU). A second complementary survey is the RAdial Velocity Experiment (RAVE)[3]: a very-large-number survey, albeit restricted to low resolution calcium triplet spectra, and limited to stars brighter $I$ = 13 mag, brighter than the Gaia-ESO bright limit. RAVE kinematics are good, and so complementary analyses of the joint RAVE and Gaia-ESO kinematic samples will be enormously powerful. The RAVE PI is Matthias Steinmetz at AIP Potsdam. In order to maximise synergy between archive spectroscopy, the various bright star surveys underway, such as RAVE, or planned, Gaia-ESO, and Gaia itself, are investing considerable effort establishing common abundance calibrations between available and planned datasets. This work, coordinated by Elena Pancino and Sofia Feltzing, should ensure a real long-term legacy from the Gaia-ESO Survey.

## First light!

The first observations were obtained on 31 December 2011, by Thomas Bensby and Christophe Martayan. While the first spectrum was, unsurprisingly, a twilight standard star, real survey data soon followed. During the first run 12 different fields in the 10 Myr cluster $\gamma$ Velorum were observed, along with three fields in the outer thick Disc. Examples of GIRAFFE and UVES spectra are shown in Figures 4 and 5.

## Prospects

The big themes in European astronomy require both space and ground-based observations.

In the field of Milky Way studies, the key recommendations of the joint ESA–ESO working group (chaired by Catherine Turon) can be summarised in two words covering both space and ground: "Gaia" and "spectroscopy". The planned spectroscopic data products from the Gaia-ESO Survey will all be available to the community roughly at the same time as the first intermediate Gaia catalogue, expected around 2016. Future dedicated survey spectroscopy facilities are under study to allow Europe to carry the torch forward in years to come, learning from this first effort. The European scientific community has an enormous opportunity to address a multitude of Galactic astronomy topics with combined spectroscopic and Gaia data.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### Links

[1] Gaia-ESO Survey wiki page: http://great.ast.cam.ac.uk/GESwiki/GESHome
[2] Gaia-ESO Survey web page: http://www.gaia-eso.eu
[3] RAVE web page: http://www.rave-survey.org
[4] Homepage of ESF GREAT: http://www.great-esf.eu