Institution: The University of Leeds

Unit of Assessment: UoA 9 School of Physics and Astronomy

a. Overview

The School of Physics & Astronomy is part of the Faculty of Mathematics & Physical Sciences. It is divided into 5 groups: **Astrophysics** (**AP**) - star and planetary system formation; **Condensed Matter** (**CM**) - quantum nanoelectronics, magnetism, spintronics; **Molecular and Nanoscale Physics** (**MNP**) - experimental biophysics, bionanoscience; **Quantum Information** (**QI**) – Quantum information theory, applications; **Soft Matter Physics** (**SMP**) - dynamics of soft matter

b. Research strategy

Our aim is to develop our areas of international excellence in order to build critical mass to deliver our new research goals. Since RAE2008 the implementation plan has been to (i) *increase QI collaborations*, (ii) *increase activity in biophysics* and (iii) *strengthen existing groups* in key research areas. This resulted in: a sharper focus and better alignment with RCUK and EU grand challenges, optimised academic and industrial impact and the provision of high quality graduates.

Astrophysics – The group focuses on star formation, but applies techniques used in the main programme to other topics, including mass loss affecting the evolution of massive stars (Pittard1). Our work on processes led to the first measurement of the cosmic ray injection efficiency in a supernova remnant shock (Hartquist1) and established the Mach number and density contrast dependences of shocked clouds' lifetimes (Hartquist4). Our work on processes and implementation of a technique for treating turbulence in shocked clouds (Hartquist4) enable improved simulations of star formation feedback and modelling of the X-ray emission from young stellar cluster regions (Pittard2). We conduct surveys (e.g. we lead RMS and CORNISH (Hoare1,3)) to discover sources for targeted high resolution studies and reveal the distribution of young massive stars on cluster to galactic scales. Using RMS data, we showed that accretion rates during high-mass star formation rise with time, contradicting predictions of some well-known models (Hoare1). We employ optical/infrared (OIR) spectroscopy and interferometry (Lumsden1; Oudmaijer2), radio continuum interferometry and millimetre and submillimetre molecular line spectroscopy (Caselli1,3) to obtain high to extremely high resolution information to constrain models of star forming regions and discs. Our OIR spectroscopy and interferometry of W33A, a forming massive star, provided good evidence for a disc and allowed envelope characterisation (Lumsden1, Oudmaijer2). Our NH_3 observations show a sharp transition to coherent velocity structure in dense cores (Caselli3).

Condensed Matter – Since the last RAE CM have broadened activity to include most applications of spintronics. Cespedes was hired to bring expertise in molecular spintronics and Moore for domain wall effects. We continue to study fundamental phenomena related to magnetism such as artificial spin ices (Marrows1), exchange bias (Hickey1), magnetic anisotropy (Hickey3) and dissipation (Moore3). Electron transport features in much of the work where nonlinear GMR was discovered in dual spin valves (Hickey2) and spin polarization measure by Andreev reflection as well as transport (Hickey4). We have continued to combine our strengths of growth, characterization and transport as illustrated by Marrows3 for the L10-ordered ferromagnets FePd and FePt. Considerable progress has been made in work to underpin future information technology: world record domain wall speeds have revealed behaviour that has sparked new theoretical work (Moore2), electric field control of fast domain wall motion has been demonstrated (Moore1) and domain wall depinning profiles have been elucidated (Marrows4) as well as the role of spin transfer torque in the depinning mechanism (Marrows2). These papers have direct relevance to future storage paradigms such as the race-track memory. (Cespedes3) is a cross-disciplinary paper on radio frequency magnetic fields used to increase Fe uptake into cage proteins and (Cespedes2) shows how magnetic nanoparticles can be used in biological applications. Both are part of our strategy to apply the techniques used in spintronics to other fields.

Molecular and Nanoscale Physics – the MNP group undertakes research at the boundaries of Physics, Chemistry and Biology to develop our understanding of biophysical processes and to progress their translation into clinic. Based on his knowledge of lipid membrane systems (e.g. Evans1,2) Evans leads a healthcare technology programme that involves over 20 team members from medicine to engineering. Critchley is an expert in the development of novel inorganic quantum dots and nanowires (Critchley1) suitable for in vivo imaging/ cell tracking and biosensing for diagnosis (Critchley2). Shim is a recent appointee bringing microfluidic expertise from the Weitz laboratory (Harvard) and single molecule detection from the Klennerman group (Cambridge) to tackle problems of fundamental importance in protein folding and early diagnostic screening (Shim1). Connell is studying the role of membrane composition in microdomain formation (Connell1) and its subsequent role in protein organization. He has also developed low noise approaches for force spectroscopy and the built magnetic tweezers to measure forces in clinically relevant systems, for example with colleagues in biology and clinical medicine to investigate blood clot formation (Connell2). Dougan developed the first force clamp spectroscopy system in Europe (Dougan4) to study the mechanical stability and unfolding pathways of proteins. She is particularly interested in the role hydrogen bond formation plays in stabilizing proteins (Dougan1) and in collaboration with Soper (RAL) she is using neutron diffraction to understand the molecular mechanism of cryopreservation. Christenson is a world leader in surface forces techniques and interested in the effects of confinement particularly in relation to heterogeneous nucleation and crystal growth (Christenson1,2).

Quantum Information – QI currently conducts theoretical and experimental research into quantum information science, including its implications for fundamental physics; the utilisation of its concepts and techniques in other areas; and particularly its application to new quantum technologies. Key current research areas in quantum computing are scenarios that resist decoherence, and quantum simulation and algorithms. Delivery in the former is through our topological quantum computing research (Pachos1-4), currently expanding with a major EPSRC grant, collaboration with Leeds Mathematics and an international visitor programme. Delivery in the latter includes quantum walk research (Kendon3). Crucial for quantum technology delivery is study of quantum implementations and resource preparation; our research here covers both optics and matter systems (e.g. Beige1). Our technology application research features quantum metrology (Spiller1,4), tagging (Spiller2), with a new direction in secure communication developing through a spin-out company (see Ref3a).

Soft Matter Physics – The SMP group studies the dynamics of biological and non-biological soft matter, polymer physics, and statistical and non-equilibrium physics; often in close collaboration with industry. SMP study how dynamics and structure control mechanical and functional behaviour of biological soft matter, including DNA (Harris1-4) and lipid bilayer membranes (Olmsted4, with Connell [MNP] and Unilever). Harris (with Read and Harlen, Maths) devised a new coarse-graining method for biological macromolecular complexes. We have a strong focus on the relations among dynamics, structure, and mechanics, in glasses (Mattsson1,3,4), shear banding materials (Olmsted1), entangled polymers (EU ITN DYNACOP, with Mathematics), and polymer crystallization (Olmsted2,3). Cellulose, ionic liquids and hydrogen bonding are studied using advanced NMR (Ries1,4) and dielectric spectroscopy and scattering (Mattson1,4). A key theme is applying soft matter physics to industrial challenges, e.g. in polymer dynamics (DYNACOP), lightweight strong plastics (Ward12, Hine2) for commodities such as suitcases and ice hockey skates, and via consortia (EU FP7 HIVOCOMP and ESMI, DYNACOP, Unilever collaborations).

Objectives (labelled in brackets) for the next six years

Research in the School is overseen by the Research and Innovation (R&I) committee comprising the Head of School, Group Heads and chaired by the Director of Research and which is responsible for strategic planning, monitoring and promoting new research initiatives. The school is currently looking to strengthen activity in focused areas as indicated in the new objectives.

AP will perform dynamical simulations to understand the processes forming protoplanetary discs and feedback in star formation (AP1). Simulation results will be used in subsequent astrochemical and/or radiative transfer modelling to compare to observations (AP2). Molecular line interferometric observations of dense cores and of protoplanetary discs will be obtained to use in the comparisons (AP3). Much of the OIR work will be supported with radiative transfer modelling and involve the use of advanced high resolution techniques to study targets selected from surveys (AP4). AP's members will serve on scientific working and instrument planning groups to position AP for the exploitation of future multi-purpose major facilities (AP5).

CM's research overlaps strongly with three Grand Challenges: (i) *Assembly and control on the nanoscale*, (ii) *developing quantum physics for new quantum technologies*, and (iii) *understanding physical phenomena far from equilibrium*. It falls within the Advanced Materials remit of the eight great technologies defined by BIS. The goal, building on our traditional strengths of growth, characterisation and transport, is to create the spintronic equivalent of metamaterials i.e. new functionality where often *collective* behaviour emerges that comes from the combination of new materials. In particular the extension of conventional spintronics to single spin manipulation, pure spin effects, organics (CM1), quantum transport in topological systems (with QI) (CM2), systems with reduced dimensionality (with QI) (CM3), materials for lower power consumption and sustainability (CM4), materials for post CMOS electronics (CM5), and applying spintronics techniques to other fields such as biophysics (CM6). Pursuit of these goals involve increased levels of activity with Engineering to promote THz applications of spintronics and work on carbon materials.

MNP will seek to broaden its involvement in the translation of physics to biology and healthcare – e.g. magnetic tweezers for cardiovascular disease, single molecule sensing using microdroplets, diagnostic imaging and therapeutic delivery (MNP1). This will be achieved through developments of strategic partnerships with medicine eg through the recently awarded (NIHR) Healthcare Technologies Cooperative. Further, we will develop synthetic “components” biology (MNP2): in building complexity in minimal membrane systems and the role of protein structure in extremophile stability. Our goal to create such hierarchically assembled structures (MNP3) aligns with the EPSRC-funded *Directed Assembly Network, The EPSRC Grand Challenges for; The Physics of Life*, and *Understanding Physical Phenomena Far From Equilibrium*. We will explore new collaborations within the Astbury Centre for Structural Biology as well as with AP and chemistry on “life in extreme environments” (MNP4). Finally, we have recently established a new multidisciplinary centre in the area of crystallization within Leeds through which we will drive new collaborative research (MNP5). We will seek to grow our activity in these areas adding expertise in: membrane biophysics, single molecule optical spectroscopy or laser tweezers.

SMP will exploit a number of new areas and link to Grand Challenges (Physics of Life, Out of Equilibrium): a newly-developed biomolecular computational method will be used to study and visualize complex protein dynamics (e.g. motors, the ribosome, synthetic dynamical constructs) with Biology and Maths (SMP1). Fundamental links between gelation, flow, the glass transition, and complex structured materials will be exploited (e.g. battery/solar cell applications, microencapsulation, design of personal care products, pastes, and specialty thin films) (SMP2); we will study hydrogen bonding and supramolecular materials, including water, cryopreservation, and cellulose (SMP3), via the new EU ITN SUPOLEN and Ries’s Innovia Films/RS Industrial Fellowship; and continue the invention and exploitation of novel NMR methods for medical and biological applications (SMP4). New collaborative links will include Food Science, increasing EU consortia membership. Expertise to add includes experimental expertise among biological mechanics/rheology, scattering or optical techniques; and coarse-grained simulation.

The QI research strategy is to expand our studies of topological and other approaches to overcome decoherence in quantum computing and memory (with CM) (QI1), and our studies of the utilisation of unavoidable decoherence (QI2), such as in quantum resource preparation and processing. In addition, we are increasingly applying QI concepts and techniques to natural and biological systems (QI3). On the applied side, the QI strategy is to expand our research into next generation quantum technologies based on relatively modest and practical quantum resources, including new directions in quantum communications (QI4) and metrology (QI5). This thread has strong overlap with the EPSRC Physics Grand Challenge "Quantum Physics for New Quantum Technologies". We will strengthen our activity in experimental QI to deliver on the applied technology part of this strategy.

c. People, including:

i. **Staffing strategy and staff development –** the academic staff profile shows considerable vitality: 50% of staff are under the age of 45, 22% are female including one professor, 44% of academics are from outside the UK.

Recruitment

An important part of our research strategy has been focusing the research activity as outlined in (b) which in turn guided our recruitment strategy. A new head of QI, T Spiller (HP, Bristol) was appointed in 2009 (following the departure of Vedral to Oxford) closely followed by the appointment of Kendon to a permanent position, contributing to both strategic goals (i) and (iii). Olmsted replaced McLeish (who moved to be PVC Research at Durham) as head of Polymer and Complex

Fluids and, in keeping with goals (ii) and (iii), shifted the focus, supported by the appointment of Mattsson (dynamics), of the activity and renamed the group Soft Matter Physics. In MNP Staniland (bionanomaterials), Dougan (biophysics), Connell (biophysics), and Critchley (bionanomaterials) were appointed to expand the biophysics/bionantechnology activity, meeting goal (ii) (and to replace Smith who setup Avacta plc). Staniland left in Aug 2013 and was replaced by J Shim (microdroplet diagnostics). CM appointments implemented goal (iii): Cespedes (molecular spintronics) and Moore (domain wall motion, Rashba physics) making CM at Leeds one of the largest academic groups working on spintronics (named by EPSRC as leading in Magnetism and Spintronics). All these appointees are experimental and have been active in broadening our experimental capability (see infrastructure).

In the current census period there have been 14 externally funded fellowships: (EPSRC(5), Royal Society(5), EU(3), Welcome(1)), Among these Caselli (Senior, 2013) and Dougan (Starting Investigator, 2011) have won ERC fellowships.

Early Career Policy

New lecturers receive start-up funds ranging upwards from £30k. They and research fellows have preferential access to School and DTA studentships. New lecturers have less than half the average teaching load in the first year and gradually obtain an average load after 3 years. Our group structure facilitates rapid settling-in of new staff e.g. all the material growth and characterisation facilities are accessible to new staff and underwritten by the School. New staff are incorporated into existing work by including them as co-I's on applications, adding them as second supervisors of students and adding them to networks and collaborations.

Probation, Mentoring, Staff Development and Career Progression

A common probation procedure applies to PDRAs, research fellows, and new lecturers. The probationer and mentor, appointed by the Head of School, identify objectives and timescales. Midway through the probation period, progress is assessed and new objectives set and the likely benefits of any additional training are discussed. Progress against objectives and research outputs are assessed again at the end of probation. The University has numerous training hubs for Researcher Development, including the *Next Generation Researcher* developed in line with the Concordat. Leeds was awarded (2010) the HR Excellence in Research Award by the European Commission in recognition of our commitment to ensuring good working conditions and career development for researchers. Through this approach our 5 newly appointed lecturers have each been successful in first grant applications (EPSRC, BBSRC) within 18 months of taking up their positions. Five research fellows appointed in the past eight years have been promoted to Readerships. During the REF period, two other members of staff have been promoted to Associate Professor, one to a Lectureship and 3 to Personal Chairs.

All academic staff agree research targets that align their ambition to the goals of the school and that allow creativity to flourish. The School encourages participation of all staff in relevant national and EU research networks and promotes collaboration both internally and externally. At the heart of staff development is the **Staff Review and Development Scheme,** which helps staff achieve their full potential by providing a 2-way review of work to identify key objectives aligned with the School's strategic plan. All staff go through probation if they have not already done so for their current or similar role. The School's commitment to Equality and Diversity, and promotion of the role of women in physics, was recognised in 2012 by the Athena SWAN Silver Award to the MAPS Faculty. The award is based on achievements and on a plan for 2012-15 which commits us *inter alia*, to: presenting the Athena SWAN scheme at key meetings; ensuring selection policies for committee membership are transparent; reviewing workload allocations; supporting women returning from periods away from work; ensuring recruitment and induction processes are alert to equality issues; ensuring review meetings consistently focus on promotion and career development; aiming to improve gender parity among staff, PDRAs and PhD students.

ii. Research students

All postgraduates undergo transferable skills training throughout their studies. Following an induction day, which includes safety and demonstrating training, students receive regular training midway through each year. A training needs analysis tool allows students to tailor their own development. It focuses on progressively more specific skills, including those concerning safety, ethics, entrepreneurship, exploitation of research, impact, project management, cv design, and interviewing strategies. Progress against training needs is monitored at monthly formal supervisory meetings. In addition, students can draw from extensive "a la carte" training offered (from both University and School). Students regularly give talks within groups at a postgraduate forum. Final year students give talks and second year students present posters to the entire school at the annual Postgraduate Symposium. In every year from its inception students from Physics have been successful in winning PhD+ (4) and EPSRC Doctoral Prize fellowships (2). Former students have lectureships at Lingaya's University India, Durham, Edinburgh, Nottingham, York, Oman, and Malaysia.

Progress Monitoring

Each postgraduate has a supervision team comprising one or more supervisors, an assessment team comprising two members of staff and a support team (one member of which is on the assessment team). The assessment team reads the yearly reports and conducts the transfer vivas at the end of the first and second years. All students file monthly reports monitoring progress against research and training needs on the University's Postgraduate Development Record system and have a scheduled monthly meeting with their supervisory team.

International Travel

Each student receives £1.4k per year (independently funded students receive this from School funds) for minor consumables and travel to international meetings. Students are expected to present their work at international conferences We encourage students to work abroad, and ~10% have spent periods of time in industry such as IBM, Hitachi, SABIC, and Intel.

d. Income, infrastructure and facilities

Income: Research averaged £140k per annum per FTE the profile of which is 78% RCUK, 13% EU 4% UK-gov, 2% industrial and 3% charity. The latter is entirely biophysics or healthcare. Over the period we have been involved in £110M worth of research grants of which the School share was £37M. AP funding is assured for the next 3 years by the award of a new STFC Consolidated Grant. In addition, Caselli has won an ERC Advanced Grant (GA 320620 PALs, £2M). Significant other grants include a Platform Grant in Spintronics (CM, EP/G005176, £1.3M), Healthcare Partnership: Engineering Therapeutic Microbubbles (MNP, EP/I000623, £1.2M and **EP/K023845/1 £0.8M**), a Life Sciences Interface DTC on Complex Fluids and Soft Matter (SMP, EP/G500010, £1.2M), a Critical Mass Grant (4 other partners) on Ferromagnetic-Superconducting Hybrids (CM, EP/J010634, £2.3M), a Programme Grant on Lipid Membranes (EP/I0126060/1, £4.0M, MNP and led by Sheffield). Leeds (with Mathematics, Food Science, Computing, and Chemistry) is a partner in the newly-funded EPSRC Centre for Doctoral Training in Soft Matter and Functional Interfaces together with Edinburgh and Durham. Co-funding partners include 18 companies providing a cohort of 16+/year PhD studentships in soft matter and interdisciplinary science.
All our new appointees have obtained EPSRC First Grants: Critchley is a University Biomedical and Health Research Fellow, Dougan won an European Research Council (ERC) Starting Investigator Award and a major grant from BBSRC (£676k) (MNP3,4); Connell is part of an EPSRC Programme Grant (EP/J017566/1 £4.5M, with Olmsted and led by Imperial) on lipid membranes (MNP2, SMP1), and part of a (£1.2M) British Heart Foundation Grant using AFM and magnetic tweezers to study cardiovascular disease (MNP1); Cespedes led and won a large equipment grant (with 8 researchers) for a SQUID-VSM (EP/K00512X/1) which simultaneously has established a number of new collaborations(CM3, CM6). Moore has established a collaborative grant with Mainz and setup the UK's highest resolution Kerr microscope (CM3, 4, 5). Mattsson has won funds to establish a unique 3D Photon Correlation Spectrometer (EP/K005073/1) ideal for measuring the structure and dynamics of soft materials at high concentrations(SMP2,3).

Facilities: : As part of the UKMHD consortium, **AP** theoreticians have access to DiRAC II HPC, which will facilitate work on AP1 and AP2. **AP** and **SMP** are heavy users of the Leeds HPC (4k cores) (AP1, AP2, SMP1); **SMP** makes heavy use of HECToR (SMP1). **AP** will continue to exploit leading facilities, including ALMA, the VLT, and the VLTI, to achieve AP3 and AP4. The observers will achieve AP5 in part through Hoare's service on the SKA International Science Working Group and strong involvement in the MeerKAT Galactic Plane Survey and Oudmaijer's membership of the E-ELT METIS working group. Group PIs have been awarded 2000 hours, having an estimated in-kind value of roughly £3 million, on major non-STFC, non-ESO ground-based telescopes. This includes, but is not limited to, 700, 700, 140, 50, 48 and 48 hours, respectively, on ACTA, MOPRA, VLA, IRAM PdBI, CARMA and SMA. **CM** makes extensive use of neutron and x-ray scattering facilities: ISIS, Diamond, ESRF, as well as BNLS and ALS in the US (CFN 148 days, BNL 145 days, ALS 42 days). This work has led to many of CM's highest impact papers and will continue to feature in CMs objectives. **MNP** collaborate closely with researchers at ISIS and are strong users of neutron facilities at ISIS and ILL; while **SMP** use ISIS and ILL.

Specialist facilities: The School runs three EPSRC-SRFs: materials deposition (3 sputterers, 2 MBEs), cryogenics (helium liquifier and associated infrastructure) and scanning probe microscopy. It has an EPSRC-funded facility for the analysis of nano materials (Leeds EPSRC Nanoscience and nanotechnology research Equipment Facility, LENNF). The Squid-VSM was recently won in the new equipment-funding model and is now a national facility – the only one of its kind in the EPSRC database. Physics has played a leading role in the sharing of equipment scheme promoted by RCUK - Burnell has been instrumental in a project to classify, document and publicise the equipment database for Leeds. This inventory has been extended through the N8 universities to the entire region and has been supported by RCUK to develop the national technical standard for the sharing of research equipment.

Investments in infrastructure: In recent years the equipment infrastructure has benefited from several large-scale enhancements: the JEOL EBL system (EPSRC critical mass grant £2.2M) and associated clean room facilities. Bruker D8 x-ray diffractometer (£300k), MBE deposition system (£100k), Squid-VSM magnetometer (EPSRC £400k), Raman microscope (£100k), extensive mechanical testing and rheology equipment, new 3D Photon Correlation Spectroscopy (EPSRC) for multiple scattering media (unique in the UK), dielectric spectroscopy, 400MHz Solid State NMR with velocity profiling capability. Additionally an annual £100k equipment replacement scheme is run within the School and there is a wider University scheme for larger items from which we have secured an average of £200k per year.

Support Staff: 4 clerical and 2 administrative staff are involved in supporting research. The electronics workshop (3 staff) and the mechanical workshop (5 staff) provide the main technical support. Their staff design and build new equipment and maintain and repair existing equipment – we are well known for our skills in designing and building UHV chambers for deposition, cryostats and measurement systems. Career development for support staff is centred on acquiring specialist skills in areas that are vital for the research programme. In addition, two experimental officers oversee the maintenance of laboratories, health and safety, and specialised equipment; and are key to running our SRFs and EPSRC research facilities.

Industrial: Ward and Hine invented a higher performance plastic that is licensed and now used in a number of products (impact plan) and have worked with Victrex, Propex, Lucite International, QinetiQ, and Mitsubishi on topics in polymer processing. Olmsted has consulted with SABIC and GSK, and collaboration with Unilever (Olmsted4) on the physics of skin lipid bilayers has led to an entirely new research direction; Cespedes worked with Escubed and Nonwovens Research Institute, Ries collaborates with Innovia Films on cellulose processing. Varcoe has been engaged on faultfinding in pipelines (Speir-Hunter) and secure communication (Astrium).

e. Collaboration or contribution to the discipline or research base

Profile – 9 international conferences were held in Leeds, 49 instances of programme committee membership of which 26 were chairs, 261 invited talks. More than 700 refereed papers were published of which 88 were in journals such as Physical Review Letters, Nature et al, Astrophysical Journal. Outreach is promoted through our EU ITNs and through competitive scholarships. We promote our research widely through press releases, websites and newsletters.

QI hosted TCQ 2010, a major annual conference for the international QI community, with Kendon as Chair. CM hosted a two day meeting on Artificial Spin Ices (2012),; the MNP group hosted an Engineering Lipid Bilayers Symposium (2012), (http://www.lipidbilayers.leeds.ac.uk); the SMP group hosted an EU-ITN Network Final Conference (2012), which featured the world's foremost experts on entangled and branched polymer dynamics. These not only help start new collaborations, but also raise our profile, as in the more than 9 invited talks Marrows has given on spin ices in the last two years.

Astrophysics – collaborates with 150 universities and 50 research institutes. Hartquist, Falle

(Leeds Maths) and Raymond (Harvard Smithsonian CfA) made the first measurement of the cosmic-ray injection efficiency in a shock (*Hartquist1*), and Pittard is using 3D HD modelling of X-ray data (*Pittard3*) obtained with Townsley (Penn State) to estimate the fraction of energy escaping from young stellar clusters. Caselli leads the Herschel WISH prestellar core effort. Hoare, Lumsden and Oudmaijer initiated the RMS survey; Davies (Liverpool JMU), Hosakawa (JPL CalTech), Moore (Liverpool JMU), Robitaille (CfA), Urquhart (MPI Bonn) and others participate. The team obtained the luminosity distributions of High-Mass Young Stellar Objects and UCHIIRs and showed that the accretion rates increase with mass. Hoare leads the CORNISH surveys, and Oudmaijer heads an international collaboration exploiting X-Shooter data for Herbig Ae/Be stars. Collaborations with former members e. g. Davies, de Wit (ESO Chile), Mottram (Leiden), Purcell (Sydney), Urquhart and Van Loo (Harvard Smithsonian CfA), effectively provide additional resources for long-term programmes (*Hoare3, Lumsden3*). Results of such collaborations include Oudmaijer's, Hoare's, Lumsden's and Urquhart's inference, from CO 2.3 μm spectroastrometric data, of the existence of AU-scale discs around massive young stellar objects, consistent with formation via disc accretion.

Condensed Matter – works with 22 universities 6 international research institutes, 5 companies. The projects range from the large (3 EU –ITNs with > 10 partners each, *Spinicur* led by Hickey), to the medium scale (joint EPSRC with NSF, China and Japan), to the small scale (Basel, Mainz). Our collaborative team brings expertise in microscopy (IBM Zurich, Glasgow – *Marrows2,4, Moore2*), scattering (ISIS, Brookhaven, *Marrows1*), theory (Tokyo, Delft, Glasgow, NTNU, *Marrows2,4, Moore2*) devices and applications (Cambridge, Lisbon), low noise measurements in nanostructures (Helsinki), and new materials (Basel, Warsaw). As a result we have increased our activity in scattering at facilities, incorporated new measurement techniques in our labs, published higher impact papers (about ¾ of papers are collaborative) and enabled our students and postdocs to work in our collaborators' labs. Additionally, all students and postdocs have the opportunity to conduct scattering experiments. Exemplars of our collaborative research include new types of fabricated structures (Brookhaven: spin ice), new measurement techniques (ISIS-PSI-Diamond:PNR, muon spectroscopy, XMCD, Helsinki: low noise measurements) and new materials (Basel:CNT, Warsaw:Graphene). We have industrial partners in funded projects: IBM Zurich (Spinicur, WALL), Seagate NI (graphene), Hitachi Cambridge Lab (domain walls, Spinicur, spin Seebeck), Intel Ireland (graphene).

Molecular and Nanoscale Physics – works with 37 universities, 7 research institutes. Evans heads an Healthcare Partnership investigating microbubbles for therapeutic delivery with the Leeds Institute for Molecular Medicine (Markham), the School of Electronic Engineering (Freear) and Medical Physics (A.Evans) and industry (Epigem, Wiedlinger Assoc., Precision Acoustics, National Physical Laboratories, iThera), and an industrial advisory board including the NHS, Roche, and Astrazeneca (*Evans1,2*). Collaborators from UCL, Bradford and Imperial College bring expertise in pharmacology and modeling whilst NPL bring expertise in acoustic measurement. Critchley has developed semiconductor nanoparticles for medical applications with Michigan State and on nanowires for biosensing with Rice University (*Critchley1*). Dougan (*Dougan4*) collaborates with Chicago and ISIS to understand the effects of small molecules on water structure and with CUNY for force clamp experiments. Connell (*Connell1*) has developed force microscopy for studying membrane domains with Unilever, Stamou (Copenhagen) and Rugierro-Neto (San Paulo). Evans has developed patterned bilayers with Knoll (Vienna), Annexin V crystallization on bilayers Brisson (Bordeaux). We have established links with O Mater and C Pain (IC, London) to improve imaging at the single bubble/vesicle level and improve force spectroscopy under fluid and modeling. These developments are closely aligned to the findings of the 2011 EPSRC Review for Healthcare Technology. We will seek to combine with areas of existing Leeds clinical strength: oncology, musculoskeletal and cardiovascular disease (MNP2).

Soft Matter Physics – works with 20 universities, 7 research institutes. Harris collaborates with J Innes Centre Norwich (BBSRC BB/I019472/1 £280k) on DNA topology and dynamics; Ashcroft and Radford (Biology) on protein mass spectroscopy; Baylor University (USA) on DNA; Harlen and Read (Maths) and Burgess (Biology) on novel coarse-graining methods for proteins; Hardie (Chemistry) on nanoencapsulation (EPSRC EP/J001325/1 £473k). Mike Ries collaborates with Budtova (Ecole des Mines, France) on cellulose processing (*Ries1,3*). Olmsted, Fielding (Durham), and Adams (Surrey) explained shear banding and instabilities observed in entangled polymers (*Olmsted1*); Mattsson and Weitz (Harvard) showed how the elastic properties of a material determine the `strength' of the glass transition (*Mattson3*); Olmsted and Mattsson collaborate with Read (Maths), and Durham and Kyoto on entangled polymer dynamics. Olmsted and Connell collaborate with Imperial, Durham, Cambridge, Nottingham on lipid bilayer membranes. Industrial collaborations include: Unilever on skin lipid bilayers (*Olmsted4*); Dow and BASF as members of DYNACOP; next generation processing of carbon fibre/plastic composites in the EU Network HIVOCOMP (with Daimler, Volkswagen, Huntsman, Samsonite, Propex, and Benteler-SGL); Victrex and Propex on polymer composites; QinetiQ and Polystore on polymer gel electrolytes for lithium battery applications; Mitsubish (& ETH Zürich) on rubber properties for the automotive industry; Innovia Films on cellulose processing, for which Ries was awarded a RS Industrial Fellowship (2013-2018); Astra Zeneca (EPSRC CASE) on drug binding. Other EU projects include the Soft Matter Infrastructure network ESMI and the ITN SUPOLEN (supramolecular polymers).

Quantum Information: works with 31 universities, 4 research institutes and six companies. Two thirds of QI REF outputs feature strategic external collaboration. Pachos and Wang have made an important breakthrough in anyon theory and their transport (*Pachos4*), for topological quantum computing applications (with Microsoft Station Q). Other important industrial collaborations are with HP Labs (Palo Alto) on quantum optical materials (Spiller), with IP Group (Leeds) on the commercialization of quantum communications (Varcoe) and with Speir Hunter applying magnetic sensing techniques to pipeline imaging (Varcoe). In collaboration with Cirac, (director MP Garching) Pachos has invented a method for simulating interacting quantum field theories with cold atoms in optical lattices (*Pachos1*). Other strong international collaborations are with the National Institute of Informatics (NII), Tokyo (Spiller), NTT Labs Japan (*Spiller1,2*, *Kendon1,2*), University of Tokyo (Kendon), University of Keio (*Kendon1*), Seoul National University (Spiller) and the Center for Quantum Technologies at the National University of Singapore (Varcoe and Beige). These collaborations have produced novel developments in quantum metrology and new directions in both QI implementations and quantum walks and simulations. A number of our graduate students have taken up positions with our collaborators in Singapore and Japan. The group also has strong European collaborations across the spectrum of QI research, through EU projects and networks: EuroQUASAR, EMALi, CMMC, SCALA, HIP, Q-ESSENCE.

Interdisciplinary Research - All the research in the school involves some interdisciplinary aspect: mathematics, materials science, electronic and mechanical engineering, computer science, chemistry but increasingly dentistry, medicine and biology. Examples of leading roles include: International Society for Extremophiles, European Molecular Liquids group, CCPB, EU NOE SoftComp, EPSRC Directed Assembly Network, Synthetic Components (Synthetic Biology Network), EPSRC Physics of the Origins of Life Grand Challenge, NHS Healthcare Technology Co-operative for the treatment Colorectal Cancer, White Rose Doctoral Training Partnership, Centre for Doctoral Training in Molecular Engineering, Synthetic Biology Network "Synthetic Components". White Rose Consortium for Microbial Fuel Cells; UK Biochemical Society, IOP Liquids and Complex Fluids Group. Other examples are Astrobiology, and a collaboration with a chemist (Plane) to synthesize cosmic dust analogues and mesospheric nanoparticles.

Leadership - Participation in and leadership of research networks (17 networks of which 2 are led by Leeds). Staff sit on and chair panels of facilities such as Diamond Light Source, ILL, NSLS Brookhaven, Armagh Observatory, ESO TAC, and OPTICON TAC. In addition to peer review panels, staff have sat on and chaired panels such as Cross-Disciplinary Fellowship Panel (EPSRC), Large Facilities Soft Matter (EPSRC), JCMT TAC (STFC) and the Royal Society Fellowships Panel. Staff regularly engage with peer review and are editorial board members of Computational and Structural Biotechnology Journal, Superlattices and Microstructure, Physical Review E, Polymer, Journal of Modern Optics and have been Guest Editors of special editions of Phil. Trans. Roy Soc., J. Phys.: Cond. Matt., New J. Phys., Modern Optics, and the Journal of the Optical Society of America B. Staff hold visiting fellowships/chairs at Florida, Harvard, Indiana, ETH Zürich, Eindhoven, Chalmers, Federal University of Minas Gerais Brazil, Tokyo University, University of the Western Cape, University of Capetown, and Vrij University Amsterdam.