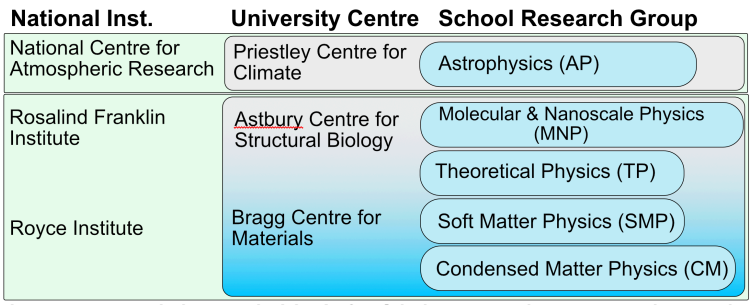
Institution: The University of Leeds

Unit of Assessment: UOA9 (Physics)

1. Unit context and structure, research and impact strategy



Overview. The School has **42** academic staff structured into five scientific research groups covering major fields in Physics and Astronomy. We are key partners in several multidisciplinary research centres across the University as well as a number of National Institutes (*Fig. right*); Capital letters used throughout *(AP, CM, SMP, TP and MNP)* refer to the research groups. **34** staff are being returned through UoA 9, **4** joint appointments through their partner schools/faculties (Medicine, Biology and Chemistry) and **4** have teaching roles.

Research strategy and plans. Our **aim** is to perform world-leading research in each of our research areas in both fundamental and applied research as well as addressing key questions and Global Challenges at multidisciplinary interfaces. The **primary objective for the school** as outlined in REF2014 was to grow our areas of strength, with particular emphasis on the development of interdisciplinary links at the biophysics/healthcare interface (MNP), in Astrophysics (AP) and in materials (CM). We also indicated the desire to strengthen the existing Soft Matter Physics (SMP) and Theoretical Physics (TP) groups. To this end the School has made **22** strategic new appointments, which equates to **16.4** FTE within the school. In pursuing the goal of strengthening multidisciplinary research **6** of these appointments have been made jointly across different schools / faculties within the University. Two major challenges/opportunities not foreseen in our strategy for REF2014 relate to: The departure of Olmsted, the previous head of SMP, to the USA. This allowed for a strategic appointment of Gleeson to lead the Soft Matter activity in the School and to establish a leading "Liquid Crystal" activity. The recruitment of Marsh, a former Deputy Director of the National Center for Atmospheric Research to the Priestley Chair in Comparative Planetary Atmospheres.

We now describe our Research strategy/plans at the group level, Objectives set in REF2014 are referred to by **Obj1**, etc. whereas objectives set in REF2021 are identified by group initials followed by a number e.g., **CM1**, etc.).

Astrophysics (AP). The AP group made 2 FTE University Academic Fellow (UAF)* appointments (Panić, Walsh) (*see Section 2), 1 FTE lecturer (Van Loo) and 0.2 FTE full professor (Marsh) taking the total number of academic staff to 7.2 FTE. These appointments bolstered our activity in the physical and chemical processes that are at work in planet-forming disks and planetary formation, in line with **Obj1, 2** and **3** set in 2014. These included expanding: efforts into MHD modelling of planet-forming disks (**Obj1**); use of astrochemical and radiative transfer modelling of star and planet formation (**Obj2**) to compare with high resolution techniques using leading telescopes at various wavebands (**Obj3, Obj4**), as well as maintain involvement in the planning of future facilities (**Obj5**). The new expertise strengthened links with Chemistry and Earth and Environment within Leeds. Panić won a RS Dorothy Hodgkin Fellowship and Walsh a UKRI Future Leaders Fellowship. Van Loo's interdisciplinary work on fluid dynamics has led to collaborations with Mathematics and Engineering at Leeds. The group is one of the few in the world that has all of the expertise required for attacking the key problems in this field; We apply basic hydrodynamic and magnetohydrodynamic (MHD) processes to gravitationally collapse and feedback in star formation. The group carries out high spatial and spectral resolution observational studies of accretion, outflows and binarity in massive protostars using cutting edge IR techniques and radio and (sub)-millimetre interferometry, supported by an STFC Consolidated Grant (**Obj 1-4**). AP also conducts observational and theoretical studies of the physical and chemical process in proto-planetary disks, the birthplaces of planets.

Astrophysics plans to extend their research into planet formation and exo-planetary atmospheres (**AP1**). These efforts concern both the use and further development of theoretical MHD models, dust Monte-Carlo radiative transfer, multi-dimensional chemical models, as well as bespoke atmospheric models to interpret observations from state-of-the art observatories and further into the REF period new facilities such as JWST, SKA and the ELT (**AP2**). We will incorporate new physics models and

radiative feedback processes in the 3D MHD models to understand massive star formation and its impact on the evolution of galaxies over cosmic time (**AP3**). The arrival of a new Head of School in Spring 2021 (Mark Thompson) will strengthen our efforts in survey astronomy and our involvement in the next generation radio telescope, SKA.

Condensed Matter (CM). Objectives from REF2014 were the extension of conventional spintronics to single spin manipulation, pure spin effects and organics (**Obj1**), quantum transport in topological systems (**Obj2**), systems with reduced dimensionality (**Obj3**), materials for lower power consumption, sustainability and post-CMOS electronics (**Obj4**). **CM** appointed two lecturers: Sasaki an expert in topological processing and superconducting materials (**Obj2,3**) and Barker (URF) who specialises in atomistic computational physics working on fundamental magnetism (**Obj1,3,4**), spin and heat transfer (**Obj1,3**) and sub-ps magnetisation dynamics (**Obj2**). This work is also supported by a RS top-up grant. All the objectives have been pursued by group-wide projects: two successive EPSRC Platform Grants, a Strategic Equipment grant for multifunctional scanning probe microscopy and Royce Institute support, which has provided a £2.2M UHV deposition system for growing complex oxides (PLD), organics (thermal evaporation), metals and other materials (sputtering) and topological materials (MBE) and has led to over 20 new international collaborators. Significant funding has been secured for (**Obj2,4**): **Skyrmions:** This work (supported by EU MagicSky, EMPIR TOPS and multiple EPSRC grants, including a Programme grant led by St. Andrews) is studying synthetic antiferromagnets in transport and Quantum Spin Hall effects. (**Obj1,2**): Pure spin currents and quantum transport in topological systems feature in a new EPSRC Programme Grant (£10M) led by Manchester that will develop advanced materials by ion implantation of samples grown in our 'Royce growth' system. (**Obj1,4**): **Molecular Hybrids.** A strong thread of the group's activity (EPSRC-SFI grant (£2M)) sustained by advanced characterisation using SQUID-VSM and Raman microscopy. **(Obj2, 3, 4): Magnetic nanostructures** including artificial spin ices, perpendicular magnetisation, hybrid piezo/magnetic structures (supported by 2 EPSRC grants and an EU ITN (MagnEFi).
CM plans to build on its strengths of growth, characterisation and transport, to create the spintronic equivalents of metamaterials. Our research objectives are (**CM1**) reducing the energy cost of spintronics, (**CM2**) creating and influencing quantum and classical states through topology, strain and hybrid structures, (**CM3**) neuromorphic computing applications (**CM4**) influencing the exploitable properties of magnets and heavy metals through the use of organic molecules (**CM5**).

Molecular and Nanoscale Physics (MNP). Objectives from REF 2014 for the group were to: Increase translation of physics to biology and healthcare **(Obj1)**; Develop further our work in synthetic biology **(Obj2)**; Develop hierarchically assembled (Bio)systems **(Obj3)**; Develop new collaborations on "Life in extreme environments" **(Obj4).** We appointed **6** (4.8 FTE) UAFs and **1** (0.4 FTE) associate professor in Biophysics/Bionanotechnology during the period. Our strength in ***membrane biophysics*** was recognised through ERC early career award (Richter), a BBSRC Early Leader Fellowship (Adams) as well as EPSRC programme grants CAPITALS (Connell) and Low-Dimensional Chemistry (Evans) and has focussed on the understanding of biomolecular interactions at membranes (**Obj2,3**), the in-vitro formation of minimal systems for light harvesting (**Obj2**). The EPSRC Fellowship (Dougan) focusses on development of protein-based gels for healthcare (**Obj1,2**). Our microfluidic based assembly of lipid membrane coated bubbles and LC droplets for diagnostics and therapeutic delivery (**Obj1-3**). Our excellence in ***Scanning Probe Microscopy /Spectroscopy*** of biological and soft matter systems has been strengthened through the appointment of Sweetman (UAF) a leader in low-temperature force-probe measurements, who holds two Fellowships (URF and ERC) and the recent appointments of Heath (UAF), to develop high-speed high-resolution AFM, and Ponjavic (UAF) to develop high-speed fluorescence microscopy. These appointments have led to a substantial award for a new Wolfson Imaging Facility aimed at imaging biological systems, from single molecules to whole cells and organoids (**Obj1**). We have strengthened links with Medicine through Ong (UAF) in nanomaterials for therapy and Peyman (UAF) in microfluidics for evaluation of cancer therapies and understanding cancer evolution (**Obj1**). Dougan's work on Life in Extreme Environments led to an ERC award and she has subsequently been instrumental in establishing an NSF funded Extreme Biophysics Research Coordination network (**Obj4**).
MNP plans to develop; improved, high-throughput, single cell approaches to understanding disease progression (**MNP1**); microfluidic platforms for the formation of complex cancer-on-chip and biofilm models (**MNP2**); improved understanding and control of hierarchical protein hydrogel structures (**MNP3**); novel high-speed, high-resolution, force probe microscopy/spectroscopy and fluorescence imaging platforms for imaging of membrane proteins involved in force transduction and immune

response (**MNP4**); hybrid biological model membranes for light harvesting (**MNP5**). These objectives align with EPSRC-funded Physics of Life Grand Challenges and Directed Assembly Networks.

Soft Matter Physics (SMP) and **Theoretical Physics (TP)** have transformed significantly since REF2014. SMP appointed Gleeson (Head of Group), Jones (Professorial EPSRC Advanced Manufacturing Fellow) and Nagaraj (UAF) to develop a new activity in LC research. TP lost Spiller, Kendon and Dunningham who were replaced by Papic and Jennings. Further, Harris transferred from SMP to TP to create a critical size of activity within Theoretical and Computational Physics. Thus, some of the objectives from REF2014 are no longer relevant/ or referred to in the following text.

Soft Matter Physics –SMP experimentalists continue to work closely with theoreticians **[Impact Case: McLeish]** and chemists. Our world-leading facilities include; LC characterisation and device fabrication as well as advanced tools for polymer systems (e.g. NMR, rheology, and mechanical analysis). ***In liquid crystals:*** investigations of novel materials led to: discovery of the first synthetic molecular auxetic system (a liquid crystal elastomer); advances in understanding molecular order; deducing the physics of anomalous elastic behaviour; finding novel field-behaviour in dark conglomerate phases; inventing new LC sensors and devices. ***In polymers, glasses, colloids and composites*** we have: improved knowledge of the dynamics, structure, and mechanics in glasses through model polymers; provided a deep understanding of hydrogen bonding in polymers, ionic liquids and cellulosic materials [**Impact case; Futamura] (Obj3);** invented new, sustainable, lightweight composites; found solutions for energy challenges, including Li^+ batteries through multidisciplinary research with collaborators **(Obj2)**. SMP works **closely with industry** applying fundamental understanding to applications, e.g. adaptive optics, sensors, lightweight strong cellulose-based composites, gel solutions for Li+ batteries; auxetic composites.
SMP plans appointments to grow theoretical research and stronger links with Chemistry, developing new soft materials. A Leverhulme EC Fellow joins in early 2021 to build critical mass in LC elastomers. Our key aims engage directly with Grand Challenges (Nanoscale design of materials; Physics of Life, Out of Equilibrium, Novel Manufacturing). Deducing fundamental links between gelation, flow, the glass transition, and complex structured materials (smart surfaces and speciality thin films) (**SMP1**); Controlling novel LC geometries and surfaces (design of devices/sensors (**SMP2**); Understanding auxeticity in LC elastomers, (**SMP3**); Understanding hydrogen bonding and supramolecular materials, eg water, cryopreservation, and cellulose (**SMP4**) and Exploiting novel LC devices (**SMP5**).

Theoretical Physics (TP). Papic (Leverhulme Trust's Research Leadership Award) and Jennings (Royal Society RF & UAF) extended the expertise of the group in quantum, statistical and condensed matter physics (**Obj1**). In addition to solving fundamental challenges of modern theoretical physics, all group members have close links to experimental research groups and have been Co-I's of the national EPSRC Quantum Technology Hubs. Current research covers key applications in quantum information science: from computation and simulation, metrology and sensing to communication. Our research has resulted in a spin-out company for medical applications (CREAVO by Varcoe) and a novel tool (UNISCAN) for the non-invasive detection of oil pipelines (***Impact Case: Speir Hunter***) (**Obj4**). In 2015, the group became a partner of the EU Coordination Action QUTE and hosted the leading European Quantum Information conference (QIPC2015).
TP plans to recruit in Soft Matter /Biological physics and to expand our activities in the applied quantum photonics area (**TP1**), to expand its research into exotic particles, topological effects and of open quantum systems to further reduce the resource requirements for quantum technology tasks (**TP2**). On the applied side, TP seeks to expand its research into near-term quantum technology devices, e.g., quantum sensors for medical applications (**TP3**). Our studies into quantum thermodynamics, into novel phenomena in quantum many-body physics and into computational biophysics aim at increasing our understanding of processes in designed, natural and biological systems (**TP4**). In addition, we will be applying concepts and techniques from quantum information science to condensed matter systems with applications in quantum transport (**TP5**).

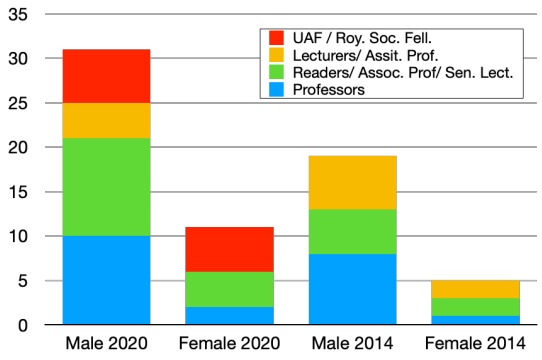
Impact Strategy. We support academics to develop commercial and public recognition/impact for their research. For ***"Outputs"*** the press office helps to generate publicity increasing both academic and wider public awareness; for example, recent press-release on 'Organic magnets' paper featured on the front cover of the journal Nature and achieved over 1M readership. All outputs and data are publicly available on local open access repositories and staff are moving towards publication in 'full open access journals' which carry the "DOAJ Seal", e.g., Phys. Rev. X.

The potential ***commercial impact*** of research is considered prior to publication through discussion with our Research and Innovation Services. Staff take advantage of Impact Acceleration Awards, MRC-Proof of Concept, Northern Triangle Initiative funding, etc, to develop further impact/IP or to partner with relevant companies. This led to 38 patents on ~9 research topics. We work closely with industry, both at the individual level via staff secondments or funded collaborations as well as through the development of larger strategic partnerships e.g., with Merck (on Liquid Crystals) and the Medicines Discovery Catapult (for Microbubble based Therapies). Our Physics Outreach Officer (1 FTE) leads ***engagement activities*** ensuring broad dissemination across age groups, genders and ethnicities. Highlights include the New Scientist 'The biggest questions in physics' Live lecture; a project with Royal Society and British Sign Language to develop 50 new signs for Exoplant research and the National Saturday Art Club. Outreach is supported by the Ogden Trust, IOP Public Engagement grants, Royal Society and Biochemical Society 'Diversity in Science' awards and have been recognised by a finalist award in the New Designers show at the London Business Design Centre and took silver at the Creative Conscience Awards. With artists at the Cultural Institute, we have led an initiative to pair scientists with creative artists providing innovation in materials design, including a partnership with Yorkshire Textiles, Caroline Horton Theatre and artist Dominic Smith.
The University requires all staff to operate in accordance with its 'Codes of Practice'. Details of the policies, procedures and codes of practice are available: www.leeds.ac.uk/secretariat/policies_ procedures_ codesofpractice.html

2. People

i. Staffing strategy and staff development

Recruitment. The School has grown, in accord with the strategy set-out in REF2014, from **28** staff (equating to a UoA9 return of **24** FTE + **4** FTE teaching related) to **42** staff (equating to a UoA9 return of **34** FTE + **4** FTE returned through other UoAs + **4** FTE teaching related). Our growth has been largely achieved through our success in winning both **External** (RS-URF and ERC) and internal **University Academic Fellowships** (UAFs), the latter being 5-year positions that lead to a permanent academic post on successful completion of probation (three of these have now done so and hold Associate Professor positions). These appointments have made a positive change to the gender balance within the School, with an ~50% F/M ratio for the new appointees, significantly above the sector norm, and is part of our continuing efforts to increase EDI in school (figure above shows changes since 2014).



Key strategic appointments. Gleeson was appointed as the Head of Soft Matter and Head of School to provide leadership to the Soft Matter Group and establish a leading Liquid Crystal activity with Jones (Prof.) and Nagaraj (UAF). The appointment of Marsh, Panic and Walsh was central to development of exo-planetary research. ***Personal Research Fellowships.*** During the census period our staff have been successful in achieving >12 of funded fellowships. Dougan, Sweetman and Richter have held/hold ERC early career fellowships. Sweetman, Barker and Jennings hold RS Fellowships (URFs), Panić is a Royal Society Dorothy Hodgkin Fellow. Walsh holds a UKRI FLF. Dougan holds an EPSRC Early Career Fellowship and Jones has an EPSRC Manufacturing Fellowship. Ries held a RS Industrial Fellowship, at Futamura (***Impact Case***). Critchley and Evans have both held discipline hop awards from the EPSRC and Wellcome Trust/MRC respectively. Adams held a BBSRC Future Leaders Fellowship. ***Future appointments.*** The School has identified Theory (Soft Matter/Biophysics) as a priority to support the experimental activities in these areas.

Staff Development. We provide a supportive environment to allow staff, at all levels, including support and technical staff, to reach their full potential. All academic staff are invited to agree challenging 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 provides all staff (including PDRA and support staff) with 2-way review process to identify key objectives aligned with the School's strategic plan, as well as opportunities for individual training and career progression. All new staff are allocated a mentor and undergo probation if they have not already done so for their current

or similar role. Progress is discussed annually, and formally assessed midway with new objectives set and potential training needs identified. The school introduced a Sabbatical policy in 2018 offering staff the possibility of taking one term after three years qualifying service or two terms after six years qualifying service. This has been used by Harris to build new links and become the lead for successful renewal of the UK CCP-BioSim Network and by Hickey to develop a 'Progamme Grant' application. Academics are supported during maternity, adoption, shared parental, additional paternity, extended carer's, or long-term sickness leave through the provision of temporary appointments that support their research and are entitled to one term of sabbatical leave on return without teaching commitments. This is designed to enable staff to maintain and re-integrate with their research activity. The school is supportive of staff undertaking exchanges with industry, discipline hopping and to other third sector bodies. For example, Ries spent 18 months working with Futamura plc and Evans' discipline hop led to his becoming the Research Director for the NIHR Surgical MedTech Cooperative, as well as being invited to sit on the Life Sciences & Healthcare Programme Expert Group for BEIS. ***Junior level appointees*** (University Academic Fellows /new lecturers) receive start-up funds ranging from £30k-£50k and a guarantee of at least one PhD within the first two years of their appointment to help build their research team. Their teaching duties are ramped-up to an average load over a 3-year period. The UAF scheme provides a bespoke training and support programme. All new appointees are expected to become a Fellow of the HEA, as part of their probation. **Reward & Recognition.** Staff, on grades 2-9, can apply for promotion at any time and are supported in the process by the Head of School. The University has a continuous process for recognition of exceptional contributions, made on the basis of recommendation by a line-manager these range from one-off payments to gift vouchers – since 2017 we have made 21 such rewards for researchers. There is also a reward scheme, based on a recommendation from the School, for discretionary payments/increments, recent examples, include Ye for the discovery of a method to create "atomically thin gold'' and Hanson for the development of a soft-matter outreach study. We also recognise research accomplishment or community service in our workload model.

ii. Research students

Recruitment. We recruit to MSc and PhD level programmes, engaging in CASE collaborations with industry and with CDTs including SOFI, Fluids (etc.). All prospective PGs are interviewed by their potential supervisor plus an additional member of academic staff and assessed against a standard set of criteria to ensure fairness and uniformity across the school. During the REF period the School has grown its PhD cohort from 1.7 to 2.4 students/FTE. The breakdown of our 229 PGRs was 141:19:69 Home: EU: Overseas and 157: 72 Male: Female.

Training & Support. All PGs undergo a training needs analysis to allow 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. Students give talks within their research groups and present their work at national and international conferences. Final year students give talks and second year students present posters to the entire school at the annual Postgraduate Symposium. Physics have been successful in winning EPSRC Doctoral Prize fellowships and our students have won numerous prizes, including the Glen Brown Award of the International Liquid Crystal Society 2020. The School has two post-graduate (PG) tutors for admissions and progression, plus a Women's tutor and an International tutor to support research students.

International Travel. Students receive £1.65k pa for minor consumables and attendance at conferences. Students are encouraged to present their work at international conferences and to apply for small travel grants (e.g. from the IoP, RSC, etc.) to support their attendance. Over 60% of students have been successful in this. Over 40% of our students take the opportunity to work at international facilities, in collaborators' laboratories or in industry during their PhD.

Progress Monitoring and Support. Each PG has a supervision team comprising of at least two academic supervisors, an assessment team comprising two members of staff and a support team. If the primary supervisor is on probation, an experienced staff member is appointed as the co-supervisor. The students have a transfer viva towards the end year 1 and a progress viva at the end of subsequent years. All students file monthly reports monitoring their progress. The PG researchers have group representatives who attend the School's PG committee and the School meetings to represent PG matters. Our PGs also undertake an anonymous survey each year to allow them to express their views regarding our PG processes including supervision, research culture, and issues affecting their PG experience as a whole. In addition, we have introduced an 'Expectations' document

for incoming PhD students and supervisors, a School Code of Conduct and a PhD+ scheme for International students (with an additional year support and training, prior to starting the research aspect of the PhD). Such innovative practises contributed to Gleeson being awarded the Times Higher Ed. 'Outstanding Research Supervisor' in 2018.

Studentships & Completion Rates. During the REF period 229 PhD students were registered within the school, of whom 182 have completed or are still studying and 5 students have withdrawn from their studies. The school has an expectation of completion within the funded period and the University has an expected completion within 4 years, supported through progression monitoring and an expectation of publication throughout the study period wherever possible. The students registered within the School are typically funded through RCUK (50%), the UoL and scholarships (25%), self-funded and other sources (25%). Members of the School supervise students from 3 Doctoral Training Centres (Soft Matter and Functional Interfaces (SOFI), Molecules-to-Manufacture, Fluid Dynamics).

Destinations. Approximately 56% of the PhDs during the REF period have remained in academia , either as PDRA's, research fellows or lectureships, 28% have moved into industry, 5% have gone into other/public sector and 11% are unknown/undecided.

iii. Equality, Diversity and Inclusion.

Our E&I committee works to ensures EDI is carefully addressed in all elements of school activity and has a developed action plan for promoting equality and diversity. We hold 'Juno Practitioner status' by the Institute of Physics, for our proactive approach to achieving equal opportunities and encouraging best practice among staff. This included a new School Code of Conduct for promoting inclusivity across the School. The committee continuously monitors both qualitative and quantitative data such as female to male ratios in staff recruitment, promotion, and student admissions through to graduation. The Faculties of Mathematics and Physical Sciences (Athena SWAN Bronze Award) and Engineering Faculty (Athena SWAN Silver Award) were merged in 2020. The School promotes the Athena SWAN scheme values, including;

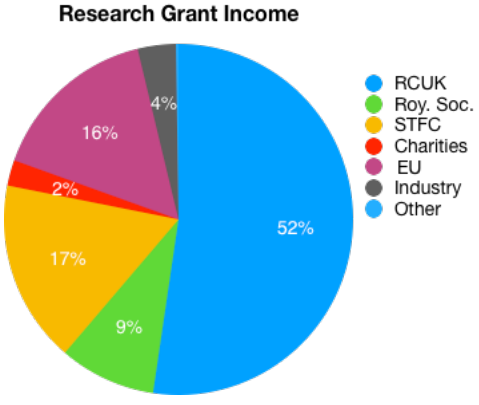
- transparency in policies for committee membership & selection
- ensuring recruitment and induction processes embrace equality issues and training
- ensuring review meetings consistently focus on promotion and career development
- aiming to improve gender parity among staff, PDRAs, and PhD students
- supporting researchers returning from periods away from work
- introduced a phased return to teaching for staff returning from parental leave
- supporting staff working part-time and working flexibly

The latter three have all been taken-up by staff during the REF period.

The School also runs an Annual Women in Physics lunch, for PhD level upwards, and encourages participation in a university-wide Women in Science, Engineering Technology group. We promote a culture of openness and inclusion via invitation of all staff to: Monthly School Meetings; Summer, Christmas and Eid events, to recognise their contribution to the school. An annual away day to discuss school operations and ambitions is attended by all permanent staff and representatives of PDRA/ PhDs. There is direct access to the Head of School via bi-weekly 'open-office' sessions.

All members of the school have access to counselling, mindfulness and a broad range of additional resources through the University's Staff Counselling and Psychological Support Service. All staff undertake an anonymous questionnaire on school operations/ management/ gender issues, etc. The results are fedback and discussed at a School meeting.

3. Income, infrastructure and facilities



Income. We have been investigators on grants worth £52M of which ~£27M has been attributed to the school, equating to ~£152k per annum per FTE. This figure should be taken in context that 11 of our staff are early career researchers in their first academic post. The School has ambitious plans to grow its research income, driven through a combination of factors including: the substantial investment in the new UAF cohort; a new state of the art building for the School (from 2021) and new collaborations arising from engagement within the Bragg Centre for Materials and the Royce Institute. These will be coupled with a strong internal peer review process and initiatives to incentivise grant submissions. The School has performed well through EU funding with

Advanced ERC Fellowship Awards to Caselli and ERC Awards to Dougan, Sweetman and Richter. The School has led numerous EU-ITNs (£0.5M, Oudmaijer), (Spinicur, £4M, Hickey) and EU-RIA (£2M, Lumsden). Other major grants within the current REF period include support for growth facilities in the Sir Henry Royce Institute of Advanced Materials (£2M), Wolfson Imaging Facility (£0.75k). EPSRC Fellowships to Dougan and Jones (£1M and £2M respectively), Royal Society Fellowships to Sweetman, Barker, Jennings and Panić ~£0.5M each). Healthcare Partnership: Engineering Therapeutic Microbubbles (£1.2M (0.6M EPSRC and 0.6M MDC), Support from Merck (£1M). The Astrophysics group has been funded through STFC Consolidated Grants (£3M over the 2014-2021 period) and a Newton Fund project funded via STFC (£3.8M) for human capital development in radio astronomy in Africa (DARA, led by Hoare, involving 15 African Universities and institutes). We have also been partners on several EPSRC Programme Grants with a total value in excess of £24M, including; Low Dimensional Chemistry (with Sheffield), Nanoscale Advanced Materials Engineering (with Manchester & Imperial), Sculpting Dynamic Amphiphilic Structures (with Imperial/ Durham) and Enabling next generation lithium batteries (with Oxford).

Infrastructure. The School is one of the major beneficiaries of the largest single investment that the University has made, namely £96M for the construction of a new building – the Bragg Building. The School will relocate in its entirety over the course of 2021. The Bragg Building will house the School of Physics and Astronomy, the Bragg Centre for Materials, and the School of Computing. It will provide an integrated suite of world-class research facilities covering all aspects of the research currently undertaken within the School. It is expected to underpin the development of new, stronger linkages to the schools of Chemistry, Chemical & Process Engineering, Electrical and Mechanical Engineering among others and thereby help facilitate the development of new multidisciplinary research. The building will provide state of the art clean rooms, laboratories for the deposition of metals and semiconductor thin films, low vibration laboratories for materials characterisation (electron and scanning probe microscopy) and biological and soft-matter physics research laboratories. The building will also house new undergraduate teaching laboratories and teaching space so that the UG student experience will be strongly embedded within our research environment. We have an annual investment of ~£150k for replacement/upgrade of equipment within the School.

Internal Facilities. The School operates three EPSRC recognised small research facilities (SRFs); i) materials deposition and cryogenics (3 sputterers, 2 MBEs, helium liquefier), ii) surface analysis & scanning probe microscopy (which will include new Wolfson Imaging Facility (£750k)) and iii) NMR of soft materials. The equipment facilities have been boosted by various grants from EPSRC, BBSRC, MRC as well as from the University. These facilities are widely available (School, Faculty, Bragg Centre, Royce Institute and Astbury Centre) via web booking portals, allowing both wider internal use and facilitating external academic and industrial access to our facilities. **Research Facility Support.** The School has 5 experimental officers who oversee the maintenance of laboratories, health and safety and operation/training of specialised facilities/equipment and are key to running our EPSRC recognised small research facilities (SRFs). **Technical Workshops.** The School has a dedicated electronics workshop (3 staff) mechanical workshop and cryogenics (5 staff) to provide expert technical support to researchers. 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 programmes. HFG chairs the University Technicians Commitment Committee and has ensured that staff are taking full advantage of available promotion opportunities. **Administrative Support.** 1 clerical and 2 administrative staff are involved in supporting the School's research activities.

External Facilities. Members of the School have access to world leading facilities. As part of the UKMHD consortium, **AP** theoreticians have access to DiRAC II high performance computing as well as the Leeds high performance computing facility ~1900 cores. **AP** use leading external facilities, including ALMA, ESO (including the very large telescope (VLT) and the VLTI), VLA, MERLIN and ATCA, as well as the MeerKAT. **Theory** makes heavy use of HECToR high performance computing and has recently taken over the lead of the EPSRC Supported CCP-BioSim network. **CM** makes extensive use of neutron and x-ray scattering facilities: ISIS, Diamond, ESRF, as well as BNLS and ALS in the US. **MNP** collaborate closely with researchers at ISIS and are heavy users of neutron facilities at ISIS while **SMP** use BESSY, Diamond, ISIS and ILL. Our use of International and RCUK facilities during the REF period amounts to an in-kind contribution to our research of **£6.36M**.

4. Collaboration and contribution to the research base, economy and society

Collaborations, Networks and Partnerships. All of the research groups are involved in national and international research projects. The latter are supported through the International lead for the School (Panić) and our International Office, which is responsible for drawing up Memoranda of Understanding (MoUs) and Collaboration Agreements.

The **AP** group collaborates with 150 universities and 50 research institutes. Members of the group have led several large international survey projects including the RMS survey (10 partners from Asia, Australia, Mexico and UK) and the CORNISH North and South surveys (18 partners from Europe, North- and South America, Africa and Australia). Exploitation of the large, well-selected samples derived from these surveys underpins some of their observational work. Other major international collaborations led by Leeds personnel include the e-MERLIN Legacy Programme on Feedback Processes in Massive Star Formation, EU ITN and Space projects led by Oudmaijer and Lumsden respectively, a large VLT X-Shooter collaboration on planet hosting stars (Panić) and an ALMA Large Programme on the Chemistry of Planet Formation (Walsh), all with partners from around the world. Hoare and Oudmaijer have important roles in the science teams for the SKA and ELT projects respectively. **CM** works with 30 universities 6 international research institutes, 5 companies. The projects range from the large (2 EU projects with ~ 10 partners each, joint EPSRC – SFI project), to the medium scale (EPSRC with 2-3 partners). Our collaborative team brings expertise in microscopy (IBM Zurich, Glasgow), scattering (ISIS, Brookhaven, PSI), theory (Tokyo, Tohoku, Delft, Bristol) as well as devices and applications (Cambridge, NPL). As a result, **CM** have increased its use of scattering facilities, incorporated new measurement techniques in our labs, published higher impact papers and enabled our students and postdocs to work in our collaborators' labs. The **CM** group have been partners in a JSPRC/EPSRC core to core programme with University Tukhuro, Japan. The **MNP** group have two ongoing JSPS / Royal Society awards. One to collaborate with Tokyo Institute of Technology (4 staff) for the peptide-controlled fabrication of nanomaterials – which has led to 7 joint papers to date and a second to work with Kobe University on the development of novel approaches to study light harvesting systems (4 staff). They are also collaborating with Tokyo University and are a member of the multinational network 'Serendipity Laboratory' led by Tokyo University (>50 staff). **MNP** hosts an annual International Microbubble Symposium (https://microbubbles.leeds.ac.uk) which brings world leaders to the UK (ran since 2011). MNP collaborates with Baumberg on nanomaterials; Schlau-Cohen (MIT), Montano (Northern Arizona Univ.) and Scheuring (Weill-Cornell Medical Institute, NY) in lipid membranes and have hosted and co-organised TETHMEM International Meeting on Lipid Membranes for ~20 yrs. We participated in the NSF/Deep Carbon Observatory workshop on Extreme Biophysics and co-wrote a 'white paper' to lobby for the funding of the Extreme Biophysics area, leading to the launch of the NSF funded Extreme Biophysics Research Coordination network **(MNP-Obj1)**. **SMP** –collaborate with Osipov and Mottram (Strathclyde) on theory, Goodby, Cowling and Mandle (York) on chemistry with Merck on novel LC devices, and with Warner and Terentjev (Cambridge), Evans (Exeter), Cleaver and Alderson (Sheffield Hallam), Mistry (Denver) on auxetic LCEs, and with Musevic (Ljubljana) on liquid crystal colloids. Nagaraj works with Tschierske (Halle) on materials. In polymer physics we collaborate with Budtova (Ecole des Mines, France) on cellulose processing and with Durham and Kyoto on entangled polymer dynamics. **TP** is internationally highly recognised, regularly welcomes international visitors (e.g. Jackiw, Lloyd, Haldane and many others) and has collaborators across the world (e.g. Spain, Italy, Belgium, Switzerland, France, US, India and China). External recognition is reflected in the fact that the TP group hosted the main European Quantum Technologies conference QIPC 2015 (funded by a European Cost Action) with Beige as Chair, and Photon 16, an annual IoP conference. In addition, TP hosted the QiICC Summer School 2019 with funding from the EPSRC.

Impacting Society. The School has a dedicated outreach officer to support the engagement of our research groups with local schools (including students and teachers) and the general public. All members of staff have been actively involved in local events such as Leeds Science Festival, Leeds Light Night, Pint of Science, Soapbox Science, the annual Be Curious Festival at UoL as well as the annual Astbury Conversation which includes a public engagement event. Our Bolton lecture in Astrophysics typically attract 400-500 attendees. Nationally, we have been involved in a number of Science festivals and other regional events (e.g., Sidmouth Science Festival), lead IOP CPD teacher training events and developed teaching frameworks for physics higher education. In 2018 alone we held 57 events as well as Pint of Science exposing over 5000 people to our research and to physics

more generally. This has included all age groups (240 early learners, 1200 primary, 1160 secondary, 380 A-level, >1900 general public and U3A). We have visited or had visits from over 120 schools from across England. In addition to these engagement events we make contact to a wider public through press releases, websites and newsletters and social media. Dougan won an EPSRC public engagement champion fellowship to establish the "Bragg Centre Creative Labs" which is establishing collaborations between scientists and artists. With over £3M support from the Newton Fund and the Global Challenges Research Fund we are leading the training of future generations of radio astronomers in Africa (& South America) to enable their participation in international projects (e.g. SKA) as well as to inspire younger scientists from a range of African countries to consider physics as a career. To date we have provided basic training to over 264 young graduates and postgraduate training to 31 students. A particular goal is to increase the economic development through the acquisition of transferable skills, especially in the space sector. We are also the lead partner in the refurbishment / re-use of three radio telescopes at Goonhilly, in Cornwall. This is expected to open radio astronomy to a large number of visitors as well as be beneficial for private investors (Deep Space Network) and thus be of significant benefit to the local community.

Impacting Industry. Our close collaboration with industry has led to indirect (>£1M) and direct investment to the School (>£1M) and has added benefit to those companies as well as leading to new spinout companies. During the REF period the staff in the School have filed over 9 key patents (with~40 separate filings) and created a number of spinouts including; Dynamic Vision Systems Ltd, Creavo Ltd. Our research has led to new technologies that are currently being evaluated in clinical trials in the US and UK for rapid, low cost diagnosis of acute myocardial ischaemia and could lead to significant savings in the healthcare sector as well as better patient treatment. The **TP** group has also developed new approaches for analysing the integrity of oil and gas pipelines which has led to significant collaboration with Speir Hunter (***Impact Case: Speir Hunter***). The **MNP** group has industrial collaborations on the application of force microscopy techniques to study soft materials with Pfizer, PepsiCo Int., Johnson Matthey, Syngenta/ Astra Zeneca, P&G. Further industrial collaborations have arisen with Medicines Discovery Catapult on therapeutic delivery, Astra Zeneca on cell-based sensing and Valeo (Spain) on quantum dot-based LEDs. The **SMP** group have extensive industrial collaborations: including the first Merck-university UK research partnership, DisplayData, Trelleborg and Ultravision on liquid crystals and their applications; Victrex and Propex on polymer composites; QinetiQ and Polystore on polymer gel electrolytes for lithium battery applications; Innovia Films on cellulose processing. Ries held a RS Industry Fellowship from 2013 to 2017 in which he worked with Futurama on the development of more efficient polymer processing and which has led to a significant cost saving for the company (***Impact Case: Futamura).***

Contributions to the Research Community. Since 2014 members of the school have hosted **20** international conferences in Leeds. We have >**50** instances of programme committee membership, of which **8** were session/conference chairs. We have given over **200** plenary, keynote and invited talks. More than **400** refereed papers were published of which **90%** were in sector leading journals such as Physical Review Letters, Nature, Astrophysical Journal etc. Members of the school have editorial roles in >**20** Journals (including: Phys Rev B, Nature Physics Journal Quantum Information, Biophysical Journal). The school has had representation at IoP Awards committee, Chair of the Bell-Burnell Graduate Scholarship Fund (Gleeson), REF2021 Panel (Gleeson) and EPSRC Physical Sciences Strategic Advisory Team Member (Marrows, Harris) and STFC (Hoare, Pittard). Members of the School sit regularly on EPSRC / STFC grant awarding panels, mid-term reviews and advisory boards as well as act as reviewers. Dougan sits on the STFC Life Sciences and Soft Materials Advisory Panel as well as the STFC Facilities Access Panel. Evans is a Healthcare & Lifesciences Programme Expert Group member for BEIS and a panel member for A4I (BEIS). Hoare is a member of SKA Science Working Group on Cradle of Life.

Prizes and Awards. Dougan was awarded the Water Woman award for Research Excellence (2020), the British Biophysical Society Young Investigator Medal (2018) and the Medical Research Council and Royal Society Suffrage Science Award (2015). Jones was awarded the Katherine Burr-Blodgett, Gold Medal and Award; IOP (2018) and the George Gray medal (2015). Gleeson was awarded the Rank Prize Lectureship (2016) and the Times Higher Ed. Outstanding Research Supervisor of the Year (2018). Nagaraj and Whale (PDRA in SMP) won the British LC Society Young Scientist Medal in 2015 and 2019 respectively.