Institution: The University of Manchester

Unit of Assessment: 9 (Physics)

1. Unit context and structure, research and impact strategy

OVERVIEW

All staff (87FTE, c.f. 79.3FTE eligible for *REF2014*) returned are from the Department of Physics and Astronomy at The University of Manchester (UoM), one of the largest UK physics departments covering most fields in the discipline, from fundamental physics to applied problems and interdisciplinary projects reaching well beyond the traditional subject.

P&A has three divisions, each encompassing research groups across several cognate areas and incorporating experiment and theory: Accelerator, Nuclear and Particle Physics (ANPP); Condensed Matter, Atomic and Biological Physics (CAB); and the Jodrell Bank Centre for Astrophysics (JBCA). Theoretical Physics is a cross-cutting theme allowing cooperative theoretical developments across P&A.

P&A operates Jodrell Bank Observatory (JBO), co-located with Jodrell Bank Discovery Centre, a UoM institution dedicated to public engagement, and the Square Kilometre Array Organisation Headquarters (SKAO-HQ).

Within UoM, P&A is part of the School of Natural Sciences, alongside Departments of Chemistry; Earth and Environmental Science; Material Science and Mathematics, in the Faculty of Science and Engineering (see *REF5a*).

Research institutes at UoM are pivotal to developing interdisciplinary research and impact activity and include: the UoM Photon Science (PSI), Dalton Nuclear (Dalton) and Data Science and Artificial Intelligence (IDSAI) Institutes and Graphene Engineering Innovation Centre (GEIC); the National Graphene (NGI) and Henry Royce (Royce) Institutes; and the Cockcroft Institute of Accelerator Science and Engineering (Cockcroft).

Highlights include:

- Transformational research in: 2D materials and their nano-capillary properties; neutrino oscillations; antihydrogen spectroscopy; breakthrough observations of Fast Radio Bursts; new constraints on cosmological parameters.
- Sustained performance in the Academic Ranking of World Universities in Physics, P&A was in the top 15 globally and top 5 in Europe.
- Two Nobel-prize winners, 22 prestigious early-career fellowships and 3 senior fellowships.
- Total research income of £197M, twice the average annual income in *REF2014* and growth in UKRI, European, charity and industrial funding.
- More than 100 PDRAs and an average of 45.5 PhD awards/year, 30% higher than *REF2014*.
- Foundation of Royce, NGI and GEIC representing investment of >£350M.
- Adoption of Jodrell Bank as permanent site of the SKAO-HQ.

RESEARCH STRATEGY

Our vision is to grow our position as a world-leading hub for research and innovation in physics and astronomy. Aligning with the UoM Strategic Plan, the overarching strategy is to focus on our people, supporting them in the optimal environment to foster creative ideas (including support for training our students) and undertake the best quality research. We aim to enable excellence in research and translate it into valuable economic, societal and cultural impact by harnessing areas of critical mass and employing our interdisciplinary capabilities.

Department of Physics and Astronomy

Divisional structure of P&A built around three UoM core areas with our people (staff and students) and values centremost; theoretical physics is a common theme; and some important institutes are indicated.

P&A divisional structure (summarised in the figure above) plays a strategic role in bringing together complementary interests, culture, ideas and expertise. Division leaders act as champions to help develop strategy, support staff to improve research quality, seek new opportunities and give a wider perspective to staff development, peer-review exercises, selection and recruitment.

P&A strategy is developed by research groups, assisted by division leaders. Two senior academics have roles as Heads of Research and Business Engagement, who coordinate approaches to research and impact, aligning them to institutional strategies with help of a research committee comprising representatives of divisions, ECRs and research support.

We have supported growth in strategically important areas, particularly those that foster interdisciplinarity through effective use of our research institutes, via key academic appointments, and by successfully supporting fellowships and converting to permanent appointments, where there is good performance and alignment with strategy. Areas that were strengthened or broadened by staffing initiatives are noted in sections below on divisional strategies and summarised in Section 2.

Accelerator, Nuclear and Particle Physics Division (ANPP) focuses on the fundamental nature and interactions of matter, alongside development of the experimental tools enabling this endeavour. ANPP tackles fundamental and applied problems and has strong involvement in Cockcroft and Dalton, along with international facilities. Our divisional strategy centres on development of scientific and technical expertise to enable leadership of international projects.

We have one of the largest UK ***Particle Physics*** groups, which exemplifies the divisional approach with a world-leading track record in contributions to international experiments. The long-term strategy, articulated in *REF2014*, was to maintain work on collider physics at ATLAS, and diversify and grow activities in other areas, notably LHCb, neutrino physics, muon flavour-physics and theory at the interface with cosmology.

We have grown ATLAS strength with new fellowships, securing senior leadership positions in operations (**Oh**: run coordinator) and physics analysis (new staff **Pilkington** and **Price**: Standard-Model and B-physics analysis-group conveners, respectively). LHCb was strengthened by three recruitments (**Gersabeck-M**, **Gersabeck-E** and **Fitzpatrick**). **Parkes** was elected as LHCb spokesperson (2020-23), after serving as deputy (2017-20). A similar strategy was pursued in neutrino physics with a new appointment (**Szelc**) building strength and supporting **Söldner-Rembold** as DUNE spokesperson. Theoretical work on QCD phenomenology, neutrino and beyond-the-standard-model physics was extended to the interface with cosmology by appointing **Bezrukov**.

We have added a new initiative in muon flavour-physics in *Mu2e* and *Muon g-2* experiments with a new professor (**Lancaster**) who was elected *g-2* spokesperson (2018-20). We joined a direct dark-matter search (DARKSIDE) in 2017 to complement our dark-matter searches at ATLAS and to build on our expertise with low-background and liquid-argon technologies.

Future priorities are exploitation of ATLAS and upgraded LHCb in CERN's next running period, exploitation of first *Mu2e* data and completion of *g-2*. Our leadership in DUNE will enable a strong position for future science exploitation. We will strengthen theoretical activities and grow our experimental engagement with low-background experiments.

Nuclear Physics interests lie experimentally in physics of exotic isotopes and applied work, and theoretically in QCD-inspired descriptions of nucleon structure and light nuclei. We planned to focus on new experimental opportunities, particularly ISOLDE-CERN, and expand applied areas.

We contributed leadership to new projects at ISOLDE, CRIS laser-spectroscopy programme (€1.8M) and the Solenoidal Spectrometer, which are both producing high-profile outputs after successful commissioning. Applied work on nuclear-fission data for industry and medical imaging with local hospitals grew, supported by STFC Network/Innovations funding (£2.02M) and Dalton. Theoretical approaches to dynamical responses of light nuclei based on Lorentz integral transforms were developed and used in calculating Compton scattering on ^{3}He.

Future priorities lie in exploiting CRIS and the Solenoid during the next ISOLDE/CERN running period and expanding into transfer-fission measurements, growing further applied activities and extending calculations to high-order to extract high-precision neutron polarizabilities.

Accelerator Physics aims to develop novel accelerators as tools for fundamental physics and solutions to practical problems. Cockcroft is critical to our strategy providing a wider range of expertise and infrastructure than is available to a single university. The £8.4M STFC core Cockcroft funding enabled significant leveraging of other income and in-kind contributions. Planning at *REF2014* envisaged expansion of work in novel acceleration, medical applications, neutral plasmas and lasers, building on end-of-period staff investment, alongside involvement in the LHC luminosity upgrade and fostering work with other divisions.

Successes in novel acceleration include demonstration of electron acceleration and beam manipulation by proton wakefields in AWAKE-CERN, and by THz sources, in collaboration with

CAB-Division colleagues (see below). Antihydrogen spectroscopy was performed in the ALPHA experiment, where **Bertsche** was technical coordinator (2011-17) and deputy spokesperson (2017-). We played a lead in high-luminosity LHC upgrade (**Appleby** UK-PI). We continued involvement in a local proton-therapy centre, the subject of an impact case.

Future priorities are delivery of UK contribution to the LHC luminosity upgrade, AWAKE Phase 2 with high-quality electron acceleration demonstration, and new physics searches with ALPHA. The group will also focus on cancer treatment with protons and electrons, strengthening work with the Christie Hospital and developing the use of high-energy electrons.

Jodrell Bank Centre for Astrophysics (JBCA) aims to understand the cosmic ecosystem from the largest structures in our Universe down to objects in our Solar System, particularly the Sun. We operated, supported and developed key astronomical facilities (Section 3). We created a new Lovell Chair (**Garrett**) in 2016, following an internally commissioned Jodrell Bank Observatory (JBO) review, to enhance strategic leadership in astronomy. We recently identified an opportunity to bridge cosmological studies to the evolution of galaxies in the early universe, with a future ambition to enhance our research in extra-galactic astronomy.

Our ***Cosmology*** strategy involved playing a major role in large-scale collaborations and in shaping the future of the field. *REF2014* planning included exploiting Cosmic Microwave Background (CMB) data, applying expertise in gravitational lensing for cosmological diagnostics, and developing future CMB observations, including SKA.

We exploited Planck data as lead contributor in CMB-foreground removal. Appointments at the end of *REF2014* (**Grainge** and **Bridle**) were used to develop cosmology areas of intensity mapping and strong/weak lensing and enhanced leadership positions in large optical and radio surveys (Dark Energy Survey, EUCLID: weak-lensing co-lead **Bridle**, SuperCLASS PI-**Battye**). A new fellowship (**Wolz**) consolidated plans to engage in SKA cosmological studies (e.g., HI-intensity mapping). We led UK contributions to next-generation experiments in the Simons Observatory (UK-PI **Brown**). We recognised our experimental work would benefit from deeper theoretical and numerical-modelling expertise and made a key appointment (**Chluba**) in CMB spectral distortions. This enhanced existing work on dark-energy phenomenology, structure formation and Sunyaev-Zel'dovich effect, and encompassed aspects of inflation, recombination, reionisation and particle physics.

Future plans are to capitalise on the Simons Observatory leadership via exploitation of early data; continue to play a major role in SKA Cosmology Projects and prepare for future CMB space missions.

In ***Pulsar and Time-Domain Astrophysics,*** *REF2014* plans included leading pulsar programmes in SKA precursors (LOFAR and MeerKAT) and defining pulsar requirements for SKA by leading non-imaging data processing.

We continued to lead studies searching for and monitoring pulsars. JBO contributes data and acts as a main processing centre for the Large European Array for Pulsars (€2.5M, 5 partners), which we exploited. We extended leadership to international facilities including LOFAR and MeerKAT (CoI-**Stappers** of pulsar working groups) and to developing non-imaging modes to the SKA Data Processor (**Stappers/Grainge**). A highlight of our work with precursors was the observation of the slowest pulsar ever discovered. Work in time-domain astrophysics was extended to search for exoplanets and characterise their atmospheres. Transient detection and modelling of gravitational-wave electromagnetic afterglows and nova outbursts were strengthened by appointing a multi-wavelength, time-domain astronomer (**Breton**).

Future plans are to exploit investment in SKA precursors, particularly the MeerTRAP project (PI-**Stappers** €3.49M) and securing leadership in SKA early commissioning. New instrumentation will be introduced to e-MERLIN to permit precision localisation of fast transients, a major growth area as more electromagnetic counterparts are associated with gravitational-wave events, and as fast-

survey telescopes come online. We will also follow-up observations of SETI candidates identified by the Breakthrough Listen Initiative and will develop a microlensing planet-search programme with EUCLID (co-lead **Kerins**).

Extragalactic and Galactic Astronomy activities use state-of-the-art ground- and space-based facilities, combined with theoretical and simulation studies to address themes from star-formation processes, to galactic evolution back to early cosmic times. Plans included furthering the use of large-scale multi-wavelength surveys to understand the role of key physics interactions in galactic ecosystems, an area which was strengthened by new appointments (**Scaife** and **Smith-R**). We enhanced our international leadership in facilities (including CoI-**Scaife** MeerKAT Polarization Surveys and LOFAR Magnetism Project), in collaborations (SKA working groups on extragalactic spectral lines, continuum, our Galaxy, VLBI and magnetism) and in programmes (RadioNet, JUMPING JIVE and Opticon-RadioNet Pilot).

Our strategy to maximally leverage our astronomy infrastructure (Section 3) and other telescopes delivered, for example, a follow-up of the first LIGO double-neutron-star afterglow, characterisation of polarised-dust emission, and identification of spinning nano-diamonds as sources of anomalous microwave emission. We developed astronomy applications of AI through the Turing Institute (**Scaife** £1.5M) and were a key partner in developing STFC's e-infrastructure through the IRIS project (£16M invested nationally).

We plan an e-MERLIN upgrade (bid ~£2M) to ensure it remains competitive until at least the end of this decade, with a flexible digital backend accessible via standard network facilities, new software correlator and enhancements to the large-area telescope connection network.

We identified an opportunity to create a focal point for radio instrumentation and techniques with a new ***Interferometry Centre of Excellence***. This unites e-MERLIN and ALMA support activities with other interferometry expertise, creating critical mass. We used this to drive forward technical contributions to SKA (**Scaife** is a work-package leader in the Horizon-2020 AENEAS project to design the European SKA Regional Centre) and grow our user-support network, critical in our provision of interferometry training which facilitated work in overseas development (Section 4). Combined technical expertise enabled leadership roles in SKA Signal and Data Processing, Non-Imaging and Imaging Pipelines, and multi-disciplinary computing, and will be key for a major future role in SKA Regional Centres.

Condensed-Matter, Atomic and Biological Physics (CAB) research encompasses both hard and soft condensed-matter physics including graphene and 2D materials (2DM), quantum fluids, liquid crystals, biological materials and complex systems. Strategic aims range from understanding quantum phenomena in materials through to light-matter interactions and statistical physics applied to composite physical and non-physical systems. CAB enables collaborative approaches between groups, which extends to other UoM departments (Chemistry, Computer Science, Mathematics, Materials, Chemical/Electrical Engineering) and faculties (Humanities and Biology, Medicine and Health). Institutes (PSI, NGI, Royce, Cockcroft) play a strategic role in enabling interdisciplinary work, particularly in societal grand challenges, mapping directly onto two of UoM's five research beacons: Advanced Materials and Energy.

Condensed Matter covers four themes: 2DM; plasmonics and quantum transport; spintronics; and superfluid helium. We successfully pursued plans from *REF2014* in plasmonics, liquid-helium topological states, and 2D crystals by creating heterostructures with 2DM Moiré superlattices. We realised opportunities to confirm UoM as an international centre of 2D materials by extending our activities with significant staff investment, new NGI infrastructure and 2DM-Theme leadership in Royce (Section 3).

Work on fundamentals of nanoelectronics expanded with the creation of new 2DM systems, reinforced by new appointments, **Gorbachev** and **Mishchenko**. Applications of permeability of 2D membranes and nanotube transport were facilitated by recruitment of **Lozada-Hidalgo** and **Boya**. Pioneering graphene research in *REF2014* revealed an opportunity for spintronics, leading

to a new hire (**Vera Marun**). We extended the interdisciplinary nature of nanoscale work by acquiring expertise in microscopic dielectric measurements (**Fumagalli**). We appointed **Walmsley** in quantum fluids to maintain strength.

In the future, we will expand these experimental activities using the infrastructure of NGI and Royce towards developing and studying nanocapillary systems; building quantum materials by 2DM twistronics using world-first UHV 2DM Press for orientation-controlled 2DM assembly and characterisation; creating programmable matter by exploiting solid-state chemistry of 2DM interfaces.

In parallel to strengthening the experimental base, we grew theoretical condensed-matter physics around 2DM, seeded by a senior appointment (**Fal'ko**) followed by a lectureship (**Principi**), who both collaborate with experimentalists, locally and internationally. We will grow these activities towards development of 2DM databases and artificial-intelligence software for predicting new functional 2DM heterostructures.

Photon Physics strategy is to engage in interdisciplinary activities where fundamental physics can advance real-world applications, with *REF2014* plans to focus on photonic materials for energy and other applications.

We continued work on quantum-dot characterisation for solar cells, GaN devices for solid-state lighting and biomedical laser physics. Fostering links with accelerator physics and Cockcroft, we developed THz electron-acceleration techniques for future accelerator-based light sources. An academic replacement (**Parkinson**) brought expertise in THz microscopy, helping to further align the group's work with Royce. The latter includes a recent successful initiative enabling Hard X-ray Photoelectron Spectroscopy. This group benefits from location in PSI with a collaborative environment spanning different disciplines and, more widely, with long-standing collaborations with the NHS and Cockcroft.

We will continue to integrate many of our activities with Royce, expanding collaborative work across disciplines, particularly materials, chemistry and biomedicine, and to expand work with the health sector by building on existing relationships with local NHS trusts.

In ***Biological Physics***, we exploit expertise in molecular self-assembly, cell-mobility tracking and modelling, with a common theme of computational biophysics and experimental validation. Plans at *REF2014* included developing functional bio-interfaces and biomaterials, and translating fundamental work on cardiac modelling to practical problems.

Interdisciplinary work with groups in the Faculty of Biology, Medicine and Health has focused on bio-interfaces (and their interactions with surfactants and biocides), bacterial capsules, biofilms and peptide hydrogels. Electrical modelling of the heart was combined with fluid-flow models and used to reveal cardiac abnormality and arrhythmogenesis.

Future work will focus on design of antimicrobial biocides with stronger potency, but less toxicity; understanding mechanistic processes underlying interfacial interactions crucial to their selective responses; and impact of interfacial adsorption on the stability of bioengineered-protein therapeutics.

Our study of ***Complex Systems***, applying classical statistical physics to composite systems in collaboration with other disciplines (e.g., life and social sciences and economics), was extended to stochastic modelling in developmental neuroscience and evolutionary ecology. This work was broadened to include open quantum many-body systems by an appointment (**Nazir**), also providing theoretical support to Photon Physics.

Future plans include collaboration with linguists on distribution and dynamics of typological features of language, and theoretical models of quantum devices, in collaboration with Electrical Engineering.

ENABLING IMPACT

Our approach to enabling impact focuses on fostering collaborative projects with industry through innovative research, translating serendipitous opportunities from research, and enabling research-linked public engagement. Staff development and infrastructure are used to support impact (Sections 2 and 3).

Since *REF2014*, we expanded impact support with a number of key positions. Most of our case studies were nurtured before the current period and this expansion adds support, ensuring sustainability of our impact activities. Academic roles were created in Business Engagement, Internationalisation and Social Responsibility to support our strategy. These coordinate effective interactions with partners, including universities, industries, charities and government departments. These roles are supported by new posts: P&A Technology-Transfer Fellow (£256k STFC part-funding) and Public-Engagement Manager (part-funded by the Ogden Trust). Three new Faculty Impact Officers work across disciplines and add to an existing business-engagement team (2FTE). This significantly expanded our ability to communicate effectively with business, leading to engagement with 90 companies and 300 industry-based individuals. An External Advisory Board comprising representative stakeholders across industry, education and public engagement helped develop our overall strategy.

Our strategy with non-academic partnerships starts with pilot activity, before growing relationships and building into more significant ventures. We apply a range of approaches from low-cost/low-risk activities, like student placements, to high-investment/long-term collaborations, providing options for organisations of any scale according to budget, timescale and IP requirements. This helps small companies to benefit from collaboration, with opportunity for relationships to deepen.

Key to relationship building was the introduction of industry-engagement days, initially as general events with growing attendance: 23 (2014), 43 (2016), 55 (2017). Outcomes include collaboration between Waters Corporation and accelerator physics (two CASE studentships, £51k and ~£70k in-kind contribution); Cake Solutions and The Start-up Factory funded a PhD and joint venture (Dataviewer Ltd); KTP with Lonza Biologics (£177k contribution for an interdisciplinary project including researchers from Biology, Medicine and Health). We continued with more targeted meetings and sandpits, information sessions, and visiting industrial speakers. Examples include a data-science event with Aeon Engineering, Digital-Applications International, and City Football Group; KTP information session with XCAM Ltd and Elekta; and *'Meet the Employer'* with AWE, Thorlabs, Edwards Vacuum, Appleyard Lees, Atkins Global and Leonardo. We developed a mailing list of ~90 subscribers who receive quarterly newsletters.

CASE studentships (26 across *REF2021*) and undergraduate projects are used as vehicles for developing relationships. Our data-science 4IR-CDT involves industrial placements, which we used to develop closer relationships with business, and NOWNANO-CDT has an active public-engagement programme. For example, the Graphene Hackathon (2019), involved >200 participants from industry, with similar events held in JBCA.

In developing projects with external partners, we make good use of knowledge-exchange funding; £1.1M from STFC Innovations Partnership Scheme; £126k in EPSRC-supported KTP/IAA projects, and £455k in projects supported by STFC-IAA. Also relevant to impact are ODA (>£3M) and public-engagement (>£100k) awards.

Our research institutes provide a rich interdisciplinary environment and infrastructure, where investments have been made (Section 3), both of which enable us to address practical problems. They also have active business-development groups, which we have used to initiate new relationships. Similarly, we employ our network of contacts with other UoM disciplines and external organisations to collaborate with complementary skills and expertise.

UoM's innovation company, *The Innovation Factory*, supports P&A in translating opportunities into commercial prospects including IP, licensing or spin-out. Their *Innovation Optimiser* programme

provides guidance to researchers with ideas for commercial enterprise. We filed 21 distinct patent families and 4 licences; compared to 10 and 1, respectively, across *REF2014*. Establishment of new companies from P&A (below and Section 4) was supported by seed funding through which follow-on funding was secured. Staff training is provided to develop business planning and pitching.

Many of these enablers are illustrated by the start-up company, *Artemis Analytical* (Director-**Flanagan**, incorporated 2016). It employs techniques from nuclear physics to provide single-atom sensitivity in mass spectrometry and trace-metal analysis for environmental testing. It uses institute infrastructure in PSI. Its early development benefited from advice from our Technology-Transfer Fellow and STFC-IAA funding. UoM innovation company supported it with seed funding (£10k) and business advice. It went on to win an STFC-CERN Business Incubation Centre Award (£40k 2018) and reached the Venturefest North-West finals (2019). A CDT student was used to initiate a project to expand its capabilities. *Artemis* received their first customers during *REF2021*.

Our approach to enabling public engagement (PE) is to harness our expertise and infrastructure (Section 3 describes specific investments for PE) to support staff and students in creation and delivery through local events and by contributing to larger activities (Section 4). Our PE Manager provides organisational support. We seek external PE funding (>£100k) supplemented by a Departmental budget (~£10k/year).

Academic leave and career progression (Section 2) support our impact strategy. For example, partial secondment allowed **Scaife** to co-direct *Policy@Manchester*, which aims to impact lives globally, nationally and locally by influencing and challenging policymakers with research-informed evidence and ideas.

Exemplars in Section 4 illustrate our interactions with research users and audiences; an increase in the former is summarised by the growing number of associated awards (industry, UKRI-KE schemes, CASE, and other KE income) from £4.0M (*REF2014)* to £14.3M.

The impact cases demonstrate some of these approaches. Those related to public engagement illustrate our commitment to outreach using our scientific expertise. Jodrell Bank impact harnesses local astronomy infrastructure and investments in the Discovery Centre over many years. Graphene impact was enabled by the *Manchester Centre for Mesoscience and Nanotechnology* (2003-15), which provided networks and infrastructure in a similar way to our current institutes. Partnership with external organisations plays a ubiquitous role, critical for impact in graphene standards (NPL), proton therapy (NHS/Cockcroft), radioastronomy infrastructure (SKA) and overseas training (several government agencies). Impact-related funding enabled some elements, for example, graphene products (KTP) and overseas training (ODA-Newton/GCRF). Additionally, funding for a Royal Society Professorship for Public Engagement facilitated the work of **Cox.**

SUPPORTING INTERDISCIPLINARY RESEARCH

The range of academic endeavours at UoM presents significant opportunities for interdisciplinary activities. *REF5a* describes high-level initiatives aimed at enabling institutional collaboration. Our institutes play an important role in providing environments and facilities across traditional discipline boundaries and act as a vehicle for interdisciplinary research. Over 40% of staff have involvement in an institute, an increase from ~30% at *REF2014*, demonstrating increasing engagement with “shared” problems. PSI and Dalton continue to be important for P&A, and Royce, NGI and IDSAI were launched during *REF2021*. We provide significant leadership across these institutes (see Section 3, along with their infrastructure). Cockcroft is critical to accelerator physics and enabling that expertise to have wider impact. Encouraging, supporting and facilitating relationships with external organisations is critical to cross-disciplinary research where SKA Organisation, local hospitals and NHS Trusts are key examples.

Interdisciplinary collaborations across departments and faculties also form outside of formal institutes, which we foster by facilitating contacts between researchers with interests in specific

topics. We encourage involvement in interdisciplinary networks, where funds facilitate connect researchers and support pilot projects, with four awards of networks (£2.76M) in food, nuclear data, radiotherapy and emergent phenomena.

Exemplars of interdisciplinary activities with institutes, organisations and networks are given in Section 4.

OPEN-RESEARCH ENVIRONMENT

REF5a describes UoM commitment to create an open-research environment including UoM open-research Statement, open-publication repository, two-click Open-Access (OA) service, Library open-research lead, and data repository. These have supported OA-compliance of all our submitted outputs and extend to OA student theses. All projects have data-management plans, where open data is a core principle.

P&A groups have traditionally been at the forefront of open and reproducible research via participation in public data archives and the *arXiv* preprint server. As examples of specific initiatives, the GridPP/IRIS Blackett computing facilities provide access to HPC and open data through the ATLAS Open-Data Project; data from UK Nuclear-Data Network projects are submitted to the open-access NEA database for researchers in participating countries; multiple Software-Sustainability-Institute fellowships were held by PDRAs, one received a Mozilla Open Leader award and gave reproducible-research seminars across the country. P&A manages open resources used by wider communities, such as pulsar databases and software for SKA data processing, modelling of pulsar timing, light curves and microlensing.

RESEARCH INTEGRITY

UoM has established a code of good research conduct, led by an Academic Director for Research Governance, Ethics and Integrity. Specific training in Research Integrity is mandatory for all PGR students and staff and is embedded in induction processes for new starters. Additionally, the New Academic Programme "*provides an understanding of the UK Higher Education system, including quality assurance and ethical practice, and how these are embodied at UoM*". New staff are assigned a senior mentor whose role includes sharing best practices in research ethics. UoM has an ethics decision tool to determine if projects require ethical approval and P&A has two Ethics Signatories who advise on approval and ethics.

2. People

STAFFING AND RECRUITMENT STRATEGY

Our approach to staffing is to: maintain successful areas with clearly defined opportunities, make strategic appointments to realise fruitful new avenues, and nurture continuing career development in staff at all levels. The need for effective leadership is a critical factor underpinning hiring and staff progression. We make effective use of prestigious fellowships to attract talent and convert them to permanent positions to retain talent, where there is excellent performance and strategic need. Individuals appointed are named in Section 1 where their connection to scientific programmes is highlighted, and a summary is given here.

During *REF2021*, 12.6FTE permanent staff departed (roughly equal numbers of retirements and moves to other HEIs), and 25FTE appointments were made (including decisions to convert fellowships to permanent contracts). Five were new senior appointments, others were relatively early in their career, demonstrating investment for the future. 60% were EU/international.

We have reacted to significant opportunities in condensed matter with seven appointments; two were subsequently promoted to chair and one to reader. We have revitalised condensed-matter theory to seize opportunities for collaboration with our world-leading experimentalists, with a new professor and lectureship, and plan to strengthen further. In particle physics, appointments were made replacing retirements and expanding in response to strategic initiatives: two appointments maintained strength in ATLAS, three expanded LHCb and a new appointment grew neutrino physics, where we plan to strengthen further. The latter two areas were new in *REF2014* and following a strategy to develop them. A senior appointment initiated a new area in muon flavour-physics. *REF2014* strategy resulted in a new reader at the interface of particle physics and cosmology, and we plan to rebalance career-stage profile in particle theory. In astronomy, we created a named chair to secure strategic leadership, and staff departures allowed us to make further new permanent appointments (reader, lecturer and three fellows) in burgeoning areas, with three subsequently promoted to chair. We have replaced retiring staff in photon physics and complex systems to maintain strength.

STAFF DEVELOPMENT STRATEGY

Induction and initial training: UoM provides induction and welcome guides for new staff covering the institutional context and policies, including the *Research Concordat* principles. Locally, P&A ensures a tailored induction for each specific role with introduction to key colleagues. A senior mentor is assigned, and an initial training plan agreed. All new academics/fellows participate in the *New Academics Programme* aimed at supporting staff to develop as world-class researchers and teachers, including preparing proposals, personal publication/impact strategy, leadership and management, social responsibility, ethics and EDI. Workloads are adjusted for the time involved and successful completion is necessary for passing probation.

Continuous training: P&A awaydays are used to bring academic and support staff together to generate contributions to help develop our strategies. A wide-ranging training programme is offered by Faculty with 38 different courses arranged around 5 key themes: Career Management, Communication, Leadership & Management, Research & Enterprise, and Teaching & Learning. These courses complement wider training from UoM Staff Training & Development Unit. For senior staff, UoM runs the *Inspiring Leader*s programme to develop their leadership skills.

Appraisal: Performance and Development Reviews (P&DRs) are an open and supportive discussion between reviewee and reviewer to enable every individual to perform to the best of their abilities and fulfil their professional ambitions. They provide an opportunity to update training plans and agree objectives. It is UoM policy for every employee to be offered an annual P&DR. (When declined, if concerns exist about performance, obligatory line-manager meetings are instigated). We actively encourage P&DRs and monitor both uptake and reasons for declining to understand barriers to participation. Uptake of P&DRs was 79% (2017-18) and 75% (2018-19) for academics. A somewhat lower uptake from PDRAs (55% and 60%) was found to be associated

with the relatively short contracts, where annual P&DR meetings are perforce superseded by more regular conversations about career development with line managers.

Promotions: All research staff can apply for promotion by an annual deadline, openly advertised along with corresponding guidelines and timescales. The Departmental Promotions Panel (DPC) considers cases, making a recommendation to a Faculty Promotions Panel (FPC). Both panels are gender diverse. DPC comprises members of the P&A Leadership Team, elected representatives to provide expertise across the breadth of research, and a member from another department to share best practice and ensure consistent approaches. Line managers provide initial promotion mentoring and candidates are encouraged to seek feedback on applications before submission. P&A runs a local training session on promotions and a similar session is organised by Faculty. Applicants who proceed to Faculty are assigned a DPC mentor to help them develop their case for the next stage. Over 2014-19, 40 cases went to FPC resulting in 9 promotions to chair, 13 to reader, 7 to senior lecturer and 6 to senior research fellow, an overall success rate of 88%.

The annual professorial pay review is a performance-related reward scheme with open applications for in-zone increments and rezoning against specified criteria. These are reviewed by a group of heads of departments before assessment by a Faculty panel.

Probation: We value probation as a means of monitoring the progress of new staff and as a development opportunity. In discussion between individual, line manager and Head of P&A, a set of measurable probation criteria are agreed to cover all relevant areas of their work, normally over the first three years of a four-year probation period. They are tailored to each individual, make expectations clear, identify training needs and thus initiate career development. Progress is reviewed annually. Probation success rate was 100%, reflecting talented recruits and support given.

Academic Leave: We value opportunities for staff to focus on research. Sabbatical leave can be requested in an open annual call, based on an associated research plan. A family-friendly approach is adopted as sabbaticals may be taken locally. We have also facilitated several staff in full or partial secondments for activities in external organisations, helping develop research programmes of individuals, external relationships and impact. Over the period, an average 5FTE were on sabbatical/secondment for a semester or longer. We also encourage flexible arrangements allowing staff to make shorter visits to external facilities and organisations as part of day-to-day operation.

Supporting and Rewarding Impact: *REF5a* describes UoM's mission, which has social responsibility at its core, with impact as an integral component. Public engagement and knowledge exchange form one of four key areas considered for promotion and pay review (alongside research, teaching and service & leadership). Probation requirements for new staff follow a similar structure, recognising impact-generating activities at all stages of our staff development. Training related to impact is available, as noted above. Academic leave can be requested for impact-related activities. Other initiatives celebrate successes, e.g., Faculty Better World Awards in which P&A staff won in environmental sustainability, EDI and public engagement.

SUPPORT FOR ECRS

REF5a outlines UoM's *Research-Concordat* Implementation Plan, which includes developing ECR fora, research-track promotions route, automatic transfer to open contracts after four-year service, research-excellence awards, collaboration/dissemination funding, and support for line managers. Many training courses mentioned above are designed to meet the needs of ECRs.

Within P&A, the Researcher Development Forum, chaired by an ECR Academic Champion, offers an independent discussion space for PDRA/research staff. The ECR Champion sits on the P&A Research Committee, providing a direct pathway of representation onto Departmental and Faculty committees. Efforts were made to gender diversify the Forum, and the proportion of women

attending rose from 17% to 33% between 2016 and 2019. The Forum allows ECRs to address collectively their career-development needs and have coordinated several workshops on fellowship applications, grant-writing sessions with successful applicants, research planning and peer support. (Similar initiatives across Faculty facilitated 51 workshops in 2018-2019 alone, with 163 sessions and overall attendance of 2996 ECRs.) The Forum collated information pertinent to ECRs on dedicated websites including new-starter packs, funding information, wellbeing initiatives, career development and EDI initiatives. PDRA coffee mornings are organised to tighten community links.

P&A has an active programme attracting and supporting applicants for prestigious personal fellowships, including mentoring from proposal development to mock interviews, generating a positive trajectory in fellowships: 8 in *RAE2008*, 14 in *REF2014*, to 22 in *REF2021*. This includes "advanced" fellowships from EPSRC and STFC, Royal Society University and Dorothy Hodgkin Fellowships, UKRI Future Leaders, Turing Fellowship and internal tenure-track fellowships (UoM Presidential and Faculty Ollerenshaw Fellowships).

RESEARCH STUDENTS

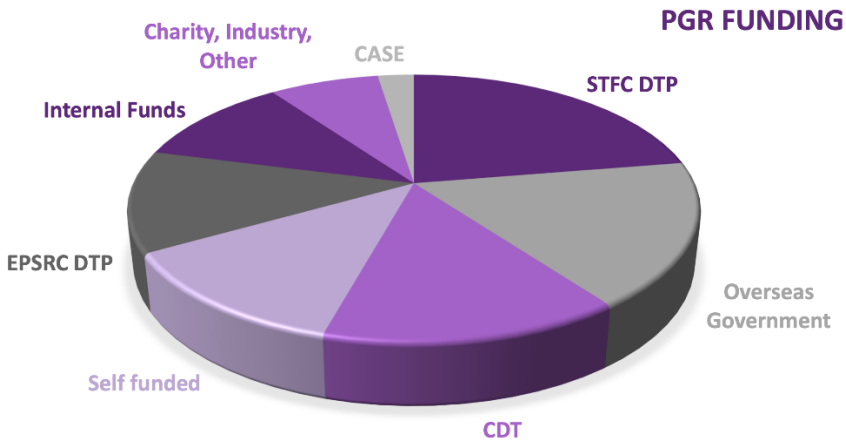
A senior academic acts as Departmental Head of PG Research (HoPGR) overseeing all aspects of PGR education, with academic PG coordinators in each research group.

PGR Recruitment and Funding: PGR cohorts have grown in *REF2021* (see table below), as have numbers of overseas students. Both were driven by diversification of funding streams and better marketing, particularly internationally. Although small in number, part-time PhD students take advantage of a flexible approach to research. Our commitment to EDI helped increase diversity.

	13/14	14/15	15/16	16/17	17/18	18/19	19/20
Total Cohort Registrations	169	190	201	215	245	252	249
Part-time	8	7	8	5	1	4	3
OS	51	51	38	66	75	82	82
%Women	20%	24%	21%	24%	26%	27%	29%
%BAME	30%	28%	29%	31%	32%	35%	39%

Recruitment is supported by administrative staff (1FTE) and assisted by the academic coordinators. PG Open Days give advice and showcase opportunities, while separate days are focused on external applicants and local undergraduates. We run a peer-to-peer event for UG students, led by current PG students. Some final-year UG courses focus on research topics, assisting internal recruitment. International recruitment is facilitated by research collaborations, but we benefit from UoM initiatives targeted at leading overseas universities in, for example, Brazil and Mexico. We interview all candidates to ensure excellence, with a policy of using small, gender-mixed panels with cross-group membership, after training in EDI and unconscious bias. We monitor admissions to ensure fairness and transparency, particularly in terms of diversity. In 2018, we created a role of deputy HoPGR with a recruitment focus who improved online marketing in the light of student feedback and supports applications to internal funding schemes.

Funding comes from a variety of sources, shown in the figure below for the 19/20 cohort. Funding is used flexibly to part-fund and leverage other sources. For example, STFC/EPSRC-DTP funds (algorithmically allocating ~11 and ~8 studentships/year) are also often combined with other funds to support higher head count. We also host CDT students and lead NOWNANO and STFC-4IR CDTs. Increased successes with ERC awards and Royal Society Fellowships have generated student funding.



We successfully accessed internal schemes to help fund outstanding overseas applicants early in the recruitment cycle, which includes 33 UoM Presidential Doctoral Scholarships and 6 Faculty Dean's Awards. P&A allocated an annual budget equivalent to 3-5 stipends for EU students but used flexibly. We also made strategic decisions to use internal funds to reduce OS fees to Home level to secure outstanding applicants in strategic areas.

PGR Progression and Development: P&A has a high overall completion rate, averaging 90% based on 5-year completion for 2010-14 entrants. Progression is overseen by HoPGR and supported by supervisory arrangements, training and monitoring, under the umbrella of the UoM Doctoral College. The HoPGR chairs the PG Committee, which includes coordinators and student representation from each research group. Administrative staff (3FTE) support PG activity.

Each research student has at least two supervisors: a primary supervisor directing research, and co-supervisor(s) from the research area. The primary supervisor must have significant supervisory experience. Every student also has an advisor, usually from outside the immediate group, who completes the supervisory team and provides pastoral support and oversight with a schedule of mandatory meetings. This arrangement ensures advice is available from multiple sources. Training in PG supervision is obligatory for new staff via the New Academics Programme. The *Postgraduate Research Experience Survey* results in 2019 reported that 85% of students enjoyed excellent supervision.

An online system (*eProg*) is used to monitor student support and progression. This structured framework gives a set of milestones, formal meetings, planning discussions and maps a student's training and project evolution. Attendance and engagement in research and training are recorded. Successful assessment, using an independent assessor at the end of each year, is required for progression.

Supervisors and advisors support individual student's wellbeing, assisted by the HoPGR, coordinators and administrative team. This is supplemented by a P&A Student Welfare Officer and wider UoM support and wellbeing services, including counselling service, occupational health and disability support (see *REF5a*).

We now have formal inductions for all students at the start of each year of study, critical for new starters, but important in reminding continuing students about key staff, important milestones, welfare and support services, training opportunities and career planning. UoM Careers Service supports students to explore career options and training is available in career and entrepreneurship skills (see *REF5a*). A majority of students volunteer as Graduate Teaching Assistants for UG teaching after suitable training, which helps develop transferable skills.

Bespoke training plans are agreed with the supervisory team, which draw on a portfolio of PG and extended-UG P&A courses, as well as courses and summer schools available in wider research communities. Students are required to attend Faculty introductory sessions and to maintain

personal development plans using *eProg*. Students are embedded in research groups and receive considerable formal and informal support and advice. Many groups provide student-led computer skills courses for new students. Across P&A, there are seminars and colloquia with internal and external speakers, including opportunities for students to present their own results to colleagues. We hold an annual Poster Session at which students present their work more widely. Students also have access to a faculty-led graduate development programme, with a mix of professional, research and transferable-skills training to optimise PhD completion and employability. There were 48 different training topics available in 2019/20, from introductory modules, academic writing, critical reading and project planning through to thesis writing, viva preparation, publishing, career planning and enterprise skills.

EQUALITY AND DIVERSITY

UoM's commitment to equality, diversity and inclusivity (EDI) (see *REF5a*) is firmly embedded in the P&A culture with supporting structures and policies, so that all staff and students are treated with respect and dignity to enable them to realise their own potential. We hold IoP-JUNO Champion and Athena SWAN silver awards.

The P&A EDI Committee coordinates and monitors our progress, with an academic chair who is a member of the P&A Leadership Team. EDI is a standing agenda item at Leadership Team meetings. The gender-diverse membership includes academic and support staff, PDRAs, PG and UG students. (An EDI Chair was subsequently appointed as Associate Dean for EDI.) Key P&A leaders report annually on EDI matters in their area; the Head of Research and HoPGR present, for example, gender monitoring of grant applications, fellowships and awards, PG recruitment and progression. We use a biennial survey of staff to monitor attitudes and awareness of EDI issues. We maintain an EDI action plan, which is regularly reviewed by the EDI Committee and P&A Leadership Team; a subset of the latter meets monthly to focus specifically on EDI progress. We've run two Gender-Diversity Days, preceded by a series of annual local Lovelace-Day events, to highlight the importance of women, trans/non-binary people and gender-diversity to STEM fields.

The Disability Advisory Support Service assists staff and students in applications for Disabled Student Allowance and Access to Work to fund specific equipment and/or reasonable adjustments required to conduct research. They provide a personal plan for each individual, which P&A implements.

There are staff networks across UoM, including the LGBT+, BAME and Disabled Staff Networks, which support staff with specific protected characteristics.

Promotion and progression are monitored in terms of gender. Promotion is available to both full-time and part-time staff. Any circumstances, such as parental leave or illness, can be disclosed by the applicant and considered by promotion panels. Training courses *Unconscious Bias*, *Diversity in The Workplace* and *Recruiting Staff at Manchester* are required for promotion and appointment panels, which are both gender diverse. The Head of P&A and Deputy, a gender-mixed team since 2017, review staff lists to identify potential candidates for promotion and pay review, to encourage those who might not otherwise apply, building on line-manager discussion in individual PD&Rs.

We have a strong commitment to flexible working. We advertise the opportunity to all staff annually, along with links to other UoM staff policies, including family-friendly initiatives, staff wellbeing and support services. Academics have traditionally utilised informal flexible-working agreements, but formal commitments are now recorded and harmonised with central timetabling. Support staff can utilise working policies such as "flexi-time". Flexible working opportunities are described in job advertisements.

Staff and students returning from leave, including illness and extended caring periods, meet with their line manager/supervisor who reviews workload and working conditions to ensure sufficient support in the transition back to work. We support *Keeping-In-Touch Days*, so staff do not feel isolated from work whilst on leave. We consider and support any flexible arrangements that are

necessary for returning staff, updating plans as necessary. Where staff are managing ill health, an ongoing review to manage workload and make necessary accommodations is undertaken with the line manager, informed by expert advice from the UoM Occupational Health Service.

We have monitored academic leave in terms of gender and, aggregated over several years, there is an indication that women appeared less likely to apply. Discussion with staff identified barriers to applying, which will inform future communications in order to emphasise the success of sabbaticals taken locally, encouraging staff with parental and caring responsibilities.

The staff submitted to *REF2021* are 16% women and 12% BAME. Appointees had higher proportions of women and BAME staff (20% and 33%, respectively) than those leaving (8% and 8%), increasing gender diversity compared to *REF2014* eligible staff (10% and 11%). The same statistics for academics promoted in 2014-19 (20% and 9%) are higher than, or statistically similar to the overall proportions. More widely, the annual diversity monitoring of all research staff also indicated rises in fractions of women and BAME from 16% and 12% in 2014 to 19% and 20% in 2019.

All staff involved with submission decisions and preparation have undertaken training in EDI issues. An equality-impact assessment revealed that the fraction of P&A outputs submitted by female, white, BAME and disabled staff match the proportions expected from the staff profile to within 1.4%; the deviations were small when compared to estimated statistical fluctuations. An institutional review of diversity in REF eligibility revealed some imbalances for BAME staff in another School. This prompted a new UoM positive-action policy to improve shortlist diversity; the first implementation was in the appointment of a new Head of P&A in December 2021.

We reacted to issues that arose during the pandemic, informed by a Faculty-wide survey undertaken to assess EDI concerns. We adapted working practices, to maintain social engagement and support. We introduced, for example, online coffee mornings and “wellbeing access” to campus after reopening. We encouraged more interaction between supervisors, students and PDRAs, monitoring with surveys, and ensured line managers kept regular contact with staff. “Zoom-free Fridays” were used to generate uninterrupted time to enable staff to concentrate on specific activities. A meeting-free period in early summer was used to encourage staff to take annual leave. Training courses were advertised to support managing stress, anxiety and remote working. P&A surveyed staff between campus closure and national lockdown to identify those with caring/childcare responsibilities to facilitate flexible approaches when schools closed. Probation periods were extended, and Covid Impact Statements are part of future promotion, pay-review exercises and thesis submissions. There is extensive signposting to UoM resources to support wellbeing and we continue to monitor for emerging issues.

3. Income, infrastructure and facilities

RESEARCH FUNDING STRATEGIES

Our funding strategy is based on building high competitiveness, diversification of sources giving resilience, agility to engage new funding schemes, and improved engagement with industrial funding.

We improved awareness by efficient dissemination of funding opportunities, cascading specific calls directly to relevant staff, and distributing monthly digests of opportunities. Headroom to prepare applications is created by incorporating grant-preparation activities into our workload model. Careful mentoring of ECRs (Section 2) helps secure funding early in a career.

Comprehensive pre-award support assists with proposals. Two onsite P&A research-support managers provide expert local knowledge and funding-scheme information. They coordinate a wider team working across departments that can react rapidly with generic requirements such as costing. Dedicated support is provided for European funding by UoM EU Office, complemented by 0.5FTE within P&A. Public-Engagement Manager and Technology Translation Fellow provide advice on Pathways-to-Impact statements and impact-related funding.

All applications are subject to internal peer review, assisted by a review college of experienced staff led by the Head of Research. This takes a streamlined approach to shortlisting, when relevant, making any selection criteria clear and providing feedback to all candidates to improve transparency and help their development. We spread best practice by sharing successful applications. We seek out and support both internal and external fellowship candidates. We support applicants with mock interviews for fellowships and grants that involve an interview stage.

A post-award research-support team simplifies the setup of a grant, including coordination with HR, contracts and compliance offices. They provide financial reports to funding bodies and help with grant management.

These strategies have successfully generated a significant research income, doubling the average to £28.1M/year from £14.2M/year in *REF2014*. This gives a total of £196.7M, which is ~8% market share in income across HESA Physics Cost Centres, compared with ~4% share of staff. This is driven by increases in UKRI and Royal Society funding, from £11.5M/year to £17.4M/year between *REF* periods, and diversification of sources, with increased EU funding (£1.8M/year rising to £4.3M/year) and charity funding (£63.5k/year increasing to £408.0k/year). Capital initiatives have increased income in certain years in some categories in *REF4b*. We increased UK industrial funding from low baselines (*RAE2008* £37.6k/year and *REF2014* £131.9k/year) to £232.3k/year, where our Translation Fellow was critical. Growth in UKRI income benefitted from increasing success in research fellowships (Section 2), and engagement with new funding schemes such as KE (Section 1) and ODA schemes, with 13 awards totalling >£3M (Section 4).

ORGANISATIONAL AND OPERATIONAL/SCHOLARLY INFRASTRUCTURE

Organisational support is provided by the team of staff providing pre/post award research expertise (noted above) co-located with many of our researchers.

Research is strongly supported by the UoM Library with one of the largest UK collections of both print and electronic resources. The Library administers OA funding, and the simple-to-use *OA Gateway* was instrumental in meeting open-access requirements. It gives data-management support, completing checks of researcher's plans and ensuring appropriate data sharing/curation. It also provides reports to enable benchmarking of research, informing research strategy and measuring effectiveness of communications and publications.

UoM's extensive IT Services support institution-wide needs, but also has a specialised research-support team (~40FTE) comprising software and infrastructure engineers providing support across software and data engineering, access to high-performance computing and data-storage

facilities, visualisation and analytics, and training. It organises licences for a wide range of professional software and applications. P&A researchers routinely access UoM high-performance computing, in particular, the Computational Shared Facility, a cluster of ~9500 nodes, and that provided by the N8 Research Partnership.

P&A is housed in adjacent Schuster and Turing Buildings. These buildings, and those of PSI, NGI and Royce and cognate departments (Chemistry, Mathematics and Earth Sciences) form a physical-sciences cluster on campus. Jodrell Bank is located ~32km south of UoM campus.

The Schuster Building was refurbished in 2007, with a new £11.5M annex opened in 2017, giving an additional floor of offices for staff and flexible space that is used to support public engagement and interaction with industry. The Turing Building (£59M investment in 2007) is home to on-campus astronomers, along with PSI and Mathematics. These estate investments over 15 years have resulted in a single site with generous state-of-the-art laboratories for all research groups, which include a number of local facilities (e.g., clean rooms and detector labs for nuclear/particle physics, rotating cryostats with He-liquefier/recycling plant, radiofrequency-engineering labs and local astronomy clusters with >4000 CPUs).

Technical services (total of 36 staff on campus, see below for JBO) underpin research both on and off site. Each research area has dedicated technical support (17FTE). A design office has state-of-the-art CAD and printing systems with two design engineers. A large mechanical workshop is hosted in Schuster equipped with CNC machines and 13 technicians, used by P&A, Chemistry and Earth Sciences. Since 2016, ~£115k was invested in new machines and welding equipment. P&A has a fabrication workshop with three staff and facilities for rapid design and manufacture, including 3D printing and local IT support; ~£70k was invested in new 3D printers and laser cutter. P&A contributes 1FTE to an electronics workshop, which provides services to design, build and repair equipment, fabricate PCBs and programme micro-control devices.

INFRASTRUCTURE FOR EDI AND IMPACT

In addition to buildings designed for disabled access and inclusive disabled toilets, the Schuster building has gender-universal toilets and a dedicated board for EDI-related activities, providing space for promotion of events and policies. In physics departments, historical photographic displays risk reinforcing associated gender and ethnic imbalances; we added diversity with photographs of successful alumni from a range of different backgrounds.

Newer buildings, such as NGI, Royce, PSI and the Schuster Annexe, are all equipped with modern meeting rooms and breakout areas with video-conferencing capability, providing space for relationship building associated with research and impact activities. Locally, the Schuster Annex has a large amount of flexible modern space, with a 120-person meeting room that can be used in tiered or flat-seating mode and a number of well-equipped breakout rooms. These are used to host conferences, industry days and public-engagement events. Our Technology-Transfer Fellow and Public-Engagement Manager enable our impact agenda, with support from the Innovation Factory (Section 1). Our fabrication facility, described above, was critical in a number of applied projects with industry, e.g., 3D printing enabled production of imaging “phantoms” for projects with the Christie Hospital.

The Jodrell Bank Discovery Centre is key to our PE impact with three exhibition halls with permanent exhibits, auditorium and space for educational programmes. A new exhibition centre, the First-Light Pavilion, is currently under construction, part-funded by the National Lottery Heritage Fund (£12.1M) and HM Treasury (£4M).

SPECIALIST AND SHARED RESEARCH INFRASTRUCTURE

P&A runs Jodrell Bank Observatory (JBO) with 47 technical and operations staff. It is the largest UoM research facility and a focus for significant impact through public engagement. It includes the 76-m Lovell Telescope, the world’s third largest fully-steerable radio telescope, and the e-MERLIN/VLBI National Facility, comprising seven radio telescopes located across England operated under contract with STFC (£2.5M/year). This interferometric array is used by a large

community of over 500 astronomers, with international groups accounting for 55% of use. JBO provides UK contributions to the European VLBI Network, linking telescopes across Europe, Asia, Africa and US. State–of–the-art laboratories are available for low-noise amplifier construction and testing. The site is shared with Jodrell Bank Discovery Centre (JBDC) and the Square Kilometre Array headquarters (see Section 4).

In 2014, UoM launched a £15.5M Jodrell Bank Master Plan investing in site-wide infrastructure (also required for extensions of JBDC and SKA-HQ), upgrades to the Lovell Telescope and building refurbishments. Master Plan expenditure to July 2020 totalled £10.3M, with the remainder to be used to strengthen foundations of the Lovell Telescope and areas of its metal structure, ensuring operation through the next decade. In recognition of historic and continuing scientific significance internationally, Jodrell Bank was awarded UNESCO World Heritage Site status in July 2019.

P&A hosts several important computing facilities used by national and international collaborations, including the GridPP/IRIS Blackett Facility (£2.5M recent awards) and ALMA Regional Centre, which support researchers from major international astrophysics and particle-physics experiments. In 2020, Blackett Facility computing resources were used to support research into Covid-19 using CPU-time for protein-folding simulations.

Created by a £50M investment in 2007, the Photon Science Institute (PSI) (Deputy Director **Dickinson-M**) provides state-of-the-art tuneable light sources across a comprehensive range of wavelengths, laser fluences, powers and temporal characteristics with an extensive set of detector, sensor, calibration and diagnostic resources. It is explicitly interdisciplinary in approach covering themes of *Photon Science and Applications* (lead-**Flanagan**), *Photonic Materials and Devices* (lead-**Binks**), and *Biophotonics and Bioanalytical Spectroscopy*. Its environment and facilities were key to facilitating many projects in photon physics and at interfaces of different disciplines, including applications of 2D materials as single-photon sources (**Parkinson**), optical properties of colloidal quantum dots (**Binks**), and use of ultrafast laser pulses to manipulate accelerated electron bunches (**Graham**). Typically, 8 staff, 5 PDRAs and more than 20 PhD students from P&A are based in PSI.

The National Graphene Institute (NGI) was a £62M investment by EPSRC and ERDF, now acting in a hub-and-spoke model for 2D material (2DM) groups at UK universities, cooperating with institutions overseas and engaging with businesses. It became operational from 2016, providing 7000 m^2 of laboratories, including 1500 m^2 grade 100/1000 clean rooms, equipped to the highest standard for various characterisations, scanning microscopy, and micro-/nano-device fabrication. Its infrastructure is used across multiple disciplines. It supports 12 academics and over 100 PDRAs and students from P&A, which also provides leadership (Director-**Fal'ko**). An example of infrastructure development (in association with Royce) is a world-first 'UHV 2DM Press', an integrated nanofabrication tool for 2DM dry transfer, characterisation and device fabrication in ultra-high vacuum (PI-**Gorbachev**). This is operated as a facility available to national and international researchers (including Sheffield, Cambridge, NPL, Herriot-Watt, NIST, Geneva and ETH-Zurich), and facilitated a step change in quality of 2DM heterostructures and devices.

The Graphene Engineering Innovation Centre (GEIC) addresses industry-led technology development in collaboration with academia. GEIC space and equipment were commissioned in 2018, funded by £60M+ investment from Masdar, ERDF, EPSRC and Greater Manchester Combined Authority. It focusses on TR levels 3-5, supporting scaling-up applications to the market, and began commercialising IP developed by the groups of **Geim** and **Novoselov** during *REF2021*.

The Henry Royce Institute, the UK national institute for advanced materials, was created in 2016 with £235M investment from EPSRC across nine partner universities, which UoM leads and underpinned with £59.8M in estate and capability. Royce provides world-leading facilities across core areas, to which P&A contributes substantially to "2D Materials" (lead-**Fal'ko**) and "Atoms to Devices" via condensed-matter and photon physics. P&A contributed to leadership of the £3.2M

EPSRC National Research Facility in X-ray photoelectron spectroscopy, HarwellXPS, which has a node in Royce (UoM-lead-**Flavell**) and led the development of a world-first £2.7M lab-based Hard X-ray Photoelectron Spectrometer (PI-**Flavell**), in collaboration with the National Physical Laboratory and Scienta-Omicron. This is available as a national facility via Royce and HarwellXPS.

The Cockcroft Institute is a partnership between Lancaster, Liverpool, Manchester, Strathclyde, and STFC for development and construction of accelerators and intense radiation sources. It is based at Daresbury, co-located with the STFC Accelerator Science and Technology Centre, facilitating work impossible under the limitations of a university campus. It allows access to space, infrastructure resources, and technical and engineering expertise unique to a national laboratory, enabling capabilities like CLARA, a normal-conducting 250-MeV electron machine used to test accelerator concepts.

The Institute for Data Science and Artificial Intelligence (IDSAI) is a focus for associated UoM expertise, facilitates interactions between researchers and problem holders, and delivers support for a community of more than 680 researchers across UoM. P&A staff in data-intensive areas such as astronomy and particle-physics engaged with IDSAI, which supported a successful application for a Turing AI Fellowship (**Scaife**).

BENEFITS-IN-KIND

P&A staff use national and international facilities including neutron and light sources, accelerator facilities, a range of different telescopes, and high-performance computing. UKRI-facility use totals £90.4M (see *REF4c*). P&A investigators also compete for time at a very large number of non-UKRI facilities, estimated at >£80M and summarised in the table below for different facility types. Additionally, the total cost Fermilab operations for experiments with P&A involvement (MINOS, MicroBooNE, g-2 and Mu2e) is estimated at ~£19M.

FACILITY TYPE		HOURS	ESTIMATED COST (£k)
Accelerator-Physics Facilities		64,614	950
Telescopes	Small/medium optical	1,634	653
	Large optical	181	542
	Small radio	7,377	1,475
	Medium radio	3,741	1,870
	Large radio	29,469	29,469
	Space-based	358	10,753
Nuclear-Physics Facilities		8520	18,744
Light sources		2,724	5,448
HPC		101,110,000	10,111
External Lab Facilities		100	10
TOTAL			**80,026**

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

RESEARCH COLLABORATIONS, NETWORKS AND PARTNERSHIPS

Staff lead many national and international collaborative projects (see examples below). Staff are supported in these roles by flexible approaches to allocation of teaching, administrative duties, sabbatical leave and secondments, facilitated by the size of P&A. Success in our collaborative efforts is evident with P&A achieving leadership positions in large collaborations. Collaborative effectiveness is also demonstrated by leading network grants awards [e.g., STFC Food Network+ (PI-**Bridle** P&A-£109k, Total-£585k) and Nuclear Data Network+ (PI-**Smith-AG** £984k); EPSRC Emergence Network+ (PI-**Galla** £232k); EU-MCnetITN (Lead-**Seymour** P&A-€522k, Total-€3.9M)] and participation in other UKRI- and EU-funded networks.

We have a strong relationship with the Square Kilometre Array Organisation (SKAO), which selected Jodrell Bank to host its permanent HQ (2015) and is home to >100 specialists in science, engineering, project management and business-enabling functions. Their building was extended (2017-19) with a £16.5M investment by BEIS (£9.8M), UoM (£5.7M) and Cheshire-East Council (£1M). SKA has 15 official member countries, but more than 20 participate. SKAO is an independent entity run by intergovernmental treaty, but their presence enhances onsite environments with significant interaction with P&A beyond our work on SKA (Section 1). This includes SKA staff holding honorary UoM appointments, visitors often interacting with both institutions, and joint activities (e.g., SKA-JBCA Machine-Learning Club).

Examples of Collaborative Project Leadership: **Söldner-Rembold**, DUNE co-Spokesperson (2018-22). **Parkes**, LHCb Spokesperson (2020-23) and Deputy Spokesperson (2017-20). **Bertsche**, ALPHA-CERN Deputy Spokesperson (2017-) and Technical Coordinator (2011-17). **Flanagan**, Chair ISOLDE-CERN Collaboration Committee (2020-23). **Lancaster**, co-Spokesperson Muon g-2 Experiment, Fermilab (2018-20). EU Graphene Flagship: **Fal'ko**, Head of Fundamental Research and Management Panel (2016-20) and Leader of Enabling Science (2013-); **Novoselov** Advisory Board. SKA: **Grainge**, Lead Signal and Data Transport Design Consortium (2013-19), **Scaife**: Lead Imaging Pipeline Development (2013-16), **Stappers**, Lead Non-Imaging Pipeline Development (2013-19). **Fal'ko**, PI Engineering Grand-Challenge Award Engineering Van-der-Waals Heterostructures (8 university and industrial partners; 2016-21). **Appleby**, UK-PI for HL-LHC-UK (2016-25). **Bridle**, UK-PI Large Synoptic Survey Telescope (2013-17). **Brown**, UK-PI Simons Observatory (2017-).

RELATIONSHIPS WITH KEY BENEFICIARIES, CONTRIBUTIONS TO ECONOMY AND SOCIETY, AND ENGAGEMENT WITH DIVERSE COMMUNITIES

These examples also illustrate some of the enablers of impact in Section 1.

Examples of relationships fostered by Research Institutes: Facilitated by NGI, UoM is one of the key partners in the €1B Graphene Flagship Project, research activities in FP7/H2020 spanning physics, chemistry, EEE, mechanical engineering, chemical engineering, with 150+ academic and industrial partners from 21 countries. (P&A leadership roles are listed above.) The Flagship facilitates multidisciplinary cooperation between partners, accelerating commercial application of graphene and 2DM.

Dalton, along with our Nuclear-Technology PGT programme, provides opportunities to interact with the nuclear industry; for example, facilitating an award on industrial nuclear data through the BEIS-Nuclear Innovation Programme (**Smith-AG**: £81k).

Example of relationships fostered by UKRI innovations funding: Facilitated by sabbatical leave, a series of STFC-IPS awards (**Cullen**: £1.04M) and CASE studentships strengthened our relationship with NHS Christie Hospital in projects using 3D-printed phantoms to improve dosimetry in imaging and radiotherapy, allowing the development of expertise to address challenges in X-ray imaging in other areas, such as cargo and vehicle inspection with Rapiscan Ltd.

Example of relationships fostered by student projects: City Football Group (CFG) presented their challenges with large and complex data, including player-performance statistics, match and training events, and player purchase and selling. We engaged by arranging a total of 20 final-year UG students, as part of their projects, to test approaches to these questions using different techniques from particle physics, astronomy, and statistical physics. The most successful joint P&A-CFG supervisory team is now in its fourth year, comprising two P&A and two CFG staff, and led to a CASE studentship and four paid summer internships for UG students at CFG.

Start-up Companies: *Artemis Analytical* has been discussed in Section 1. *Dataviewer Ltd* (2017) uses data-visualisation techniques from particle physics. *Third-Floor Systems* (2017), which uses data-science techniques to identify students with potential mental-health issues, reached the finals of Pitch@Palace (2018) and is trading. Expertise in 2D materials led to *Bespoke Crystals Ltd* (2019), producing high-quality crystals, and *Low Dee Ltd* (2017), using graphene membranes.

Public engagement (PE): Over many years, P&A has made a contribution to society via strong external engagement, stimulating interest in science and developing public understanding. Harnessing infrastructure at Jodrell Bank, the Discovery Centre has ~180,000 visitors/year, including 20,000 school children, and is an important focus for PE, including Bluedot festival and BBC's Stargazing Live TV programme. It is the subject of an impact case, as is the work of **Cox**.

Overall staff interaction with broadcast and social media is high. An exemplar is **O'Brien**, a significant astronomy presence in national media, who had a monthly phone-in on Radio 5 Live and was science expert on their Saturday Edition. He made numerous appearances on BBC-TV/Radio and at public events, usually over a dozen times per year. As Principal Scientific Advisor to the Discovery Centre, he co-won the IoP Kelvin Prize (2014). He also co-created the annual ScienceX event at the Trafford Shopping Centre to reach non-traditional audiences.

Our PE Manager (Section 1) developed and delivered outreach programmes, supported staff and students in their PE, interacted with networks on collaborative work, managed a £10k/year internal budget, and acted as contact for schools, teachers, families and the public. One highlight was leading our participation in *Diversity in Cultures of Physics*, an Erasmus-funded transnational partnership improving the physics gender balance and making outreach more inclusive.

Our PE programme continued, including contributions to National Science and Engineering week, Manchester Science Festival, Manchester Science and Industry Museum, Pint of Science, ScienceX and numerous other public events and talks to schools. PGRs from NOWNANO-CDT run a programme of PE and others won prizes in *I'm-a-Scientist-Get-Me-Out-of-Here!* online events.

We also engaged with large public-engagement events. For example, an exhibit at the Royal Society Exhibition 2019 (lead-**Bridle**) showcased food impact on climate change and received >6k visitors taking >2k items of supporting material, and led to 3 broadcast interviews, 25 articles (including the Sun, Telegraph and Daily Mail), an online game played 2.5k times and a YouTube video with 44k views (figures two months after). An antimatter exhibit at the 2016 Exhibition (co-lead-**Parkes**) was estimated to reach 10k visitors.

In addition to Science X, we reached new audiences with *Tactile Collider*, a project bringing science to blind and partially sighted people using an STFC award (£103k), addressing a lack of PE for the visually impaired, which reached over 12k people internationally. The project won many accolades including the European Physical Society Outreach and RNIB Innovator awards (2019). Best practice was shared via an associated journal paper, conference contributions and legacy of training in communication with the visibly impaired.

CONTRIBUTIONS TO SUSTAINABILITY OF DISCIPLINE

P&A staff contribute to the sustainability of the discipline by assisting strategic development in professional bodies and funding agencies, membership of advisory bodies and peer-review panels, and significant reviewing at an individual level.

Examples of strategic contributions: Institute of Physics Council Member [**Flavell** 2017-]; STFC Science Board Chair & Deputy Chair [**Freeman** 2014-18], Members [**Freeman** 2012-14, **Grainge** 2019-]; STFC Accelerator Strategy Board [**Owen** 2014-]; CERN Scientific Policy Committee [**Wyatt** 2007-16]; President of International Liquid-Crystal Society [**Dierking** 2020-].

Examples of advisory contributions: Scientific Advisory Committee for Research Complex at Harwell [**Flavell** 2013-17]; US-DoE/NSF High-Energy Physics Advisory Panel [**Söldner-Rembold** 2015]; EPSRC Fusion Advisory Board [**Browning** 2018-21]; External Advisory Committee TUNL, USA [**McGovern** 2014-19]; STFC Computing Advisory Panel [**Scaife** 2019]; STFC ETCC [**Bridle** 2014]; STFC Particle-Physics Advisory Panel [**Peters** 2019-]; STFC Nuclear-Physics Advisory Panel [**Flanagan** 2014-18, **McGovern** 2017-19]; STFC Astronomy Advisory Panel [**Battye** 2018-19, **Stappers,** 2019-, **Brown** 2012-15]; STFC Skills and Engagement Advisory Board [**Freeman** 2014-16]; Board Member European Centre for Theoretical Studies in Nuclear Physics, Trento [**McGovern** 2013-16].

Examples of peer-review contributions: Deputy chair *REF2014* Sub-Panel-9 [**Flavell**]; *REF2021* Sub-Panel-9 Members [**Flavell, Freeman**]; RS-FRS Selection Committee [**Wyatt** 14-17]; Chairs of STFC Reviews of Gravitational Waves [**Piccirillo** 2015], GRID-PP [**Evans** 2019-] and Accelerator Institutes [**Evans** 2020]; STFC Nuclear-Physics Grants Panel [**Flanagan** 2019-, **McGovern** 2019-, **Campbell** 2012-18]; Particle-Physics Grants Panel [**Price** 2019-, **Evans** 2015-,(chair 2019)]; Astronomy Grants Panel [subpanel-chair-**Browning** (2014-18)]; Projects Peer-Review Panel [**Appleby** 2020, **Garrett** 2020, **Dickinson-C** 2014-16].

Examples of programme advisory committees: Effelsberg Telescope [**Beswick** 2018-20]; NASA-Kepler-2 [**Kerins** 2015]; SOLEIL [**Flavell** 2006-17], MAXlab [**Flavell** 2012-]; ESRF [**Waigh** 2017-]; Jyväskylä Accelerator Laboratory [**Billowes** 2016-19]; INTC-CERN [**Billowes** 2010-14].

Chairs of IoP groups: Quantum Electronics [**Binks** 2013-17]; Non-Linear Physics [**Galla** 2011-14]; Nuclear Physics [**Sharp** 2020-]; Low Temperature [**Golov** 2015-19].

Examples of editorial boards: Phys.Rev.X [**Billowes** 2011-18]; Scientific Reports [**Grigorenko** 2015-]; Materials (2014-), Soft Materials (2012-) [**Dierking**]; PlosONE [**Waigh** 2013-]; JPhysB [**Murray** 2015-18]; JPhysG [**McGovern** 2017-]; 2Dmaterials (Editor-In-Chief) [**Fal'ko** 2014-]; Quantum [**Nazir** 2016-**]**.

Examples of large conference organisation: International Conference on Supersymmetry and Unification of Fundamental Forces SUSY-2014 [Chair-**Pilaftsis**; ~300 attendees]; International Symposium on Particle Physics, String Theory and Cosmology PASCOS19 [**Pilaftsis**; ~200]; IOP Particle, Astroparticle and Nuclear-Physics Conference 2015 [co-chairs-**McGovern/Söldner-Rembold**; ~400]; IEEE-NSS-MIC-RTSD-2019 [NSS-Chair-**DaVia**; ~1850]; CHARM-13 [chair-**Gersabeck-M**, ~175]; PHOTON-14 [**Binks,** ~350]; FewBody-15 [**McGovern,** ~250]; INPC-19 [**Flanagan,** ~450]; IAU Symposium 337 [chairs/co-chairs-**Breton/Keith/Stappers/Weltevrede**, ~200].

SUPPORT FOR AND EXEMPLARS OF INTERDISCIPLINARY RESEARCH
These also illustrate strategies supporting interdisciplinarity (Section 1).

Examples supported by research institutes: Interdisciplinary collaborations hosted by NGI cover several themes involving P&A staff, including fundamental science and technology of 2D materials, and twistronics; devices for application in optoelectronics, sensors and quantum technology; and biomedical and health applications. Twistronics, for example, arose from cross fertilisation of experimental and theoretical techniques between P&A (**Gorbachev/Fal'ko**) and Department of Material Science. We led an interdisciplinary EPSRC Engineering Grand Challenges Project *Engineering van-der-Waals heterostructures* (PI-**Fal'ko** £4.1M), to develop techniques making printable heterostructures from 2D inks. This involved collaboration with Chemistry, Materials and Electronic Engineering (the latter at UoM and Cambridge) and with

industrial partners BGT Materials, Cambridge Nanosystems, Merck, Tata Steel, FlexEnable, and Novalia. Studies of nano-capillary properties of graphene laminates and graphene-oxide membranes, applied to ion sieving in water solutions and separation of hydrogen isotopes, involved work at the interface with chemistry. This involved UoM Materials and Chemical Engineering, with international collaboration, for example, chemists at Zurich and Antwerp, and materials growers at NIST in Tsukuba, with associated collaboration agreements with UKAEA and Atkins.

Similarly, PSI enabled joint projects such as establishing a collaboration between P&A (**Flanagan**), Departments of Chemistry and Chemical Engineering to enhance ICP-MS technology by combining resonant-ionisation methods motivated by ^{90}Sr detection. Others were noted in Section 3.

Examples supported by interactions with other faculties: Our biophysics group has long-standing projects such as cardiac modelling, biofilms and anti-microbial resistance, which would not be possible without collaboration with the Faculty of Biology, Medicine and Heath. Our complex systems work involves strong collaborations outside of science and engineering, where methods and ideas from statistical mechanics are applied to solve problems in disparate areas. For example, collaboration with UoM life sciences led to fruitful research in stochastic modelling of data from experiments on cell differentiation, animal competition for limited resources as an evolutionary driver, and evolution of microbial resistance. Collaboration with social sciences covered social complexity of immigration and diversity. New connections were made with humanities and projects are underway looking at distribution and dynamics of typological features of language.

Examples supported by relationships with external organisations: Our relationship with the Christie Hospital in medical imaging is noted above. Additionally, aided by Cockcroft, P&A accelerator physicists grew strong connections with UoM Health Sciences and NHS. Contributions to a proton-therapy centre are the subject of an impact case, and the collaboration also worked on aspects of proton-treatment planning using data-science techniques (**Appleby/Scaife**), proton arc therapy (**Appleby**), and adaptations to cavity design for proton imaging (**Owen**). These activities are assisted by the Radiotherapy Network+ grant (noted above). Similarly, development of nailfold capillaroscopy (**Dickinson-M**) was undertaken with Salford NHS Trust.

Examples supported by use of networks: The STFC Food Network+ (PI-**Bridle**) is dynamic network of >800 researchers, bringing together 452 academic, 91 government, 88 industry and 61 STFC-Facilities participants. Using sandpit meetings, 40 interdisciplinary projects were kickstarted to tackle food challenges, enabling skills from data science, technology and facilities to address critical issues associated with sustainable food production, resilient food-supply chains, and improved nutrition and consumer behaviour. Similarly, the Nuclear Data Network (PI-**Smith-AG**) initiated 16 interdisciplinary projects with leads at 8 HEIs and 4 other organisations.

We ***responded to national and international initiatives*** in Official Development Assistance by submitting proposals to Newton and Global Challenges Research Fund with successful awards of >£3M in 13 applications. Partners include several African countries, Pakistan, Timor, Colombia and Thailand. We successfully applied expertise in astronomy to develop skills, technology and research capacity by training young researchers and developing interdisciplinary projects, such as mapping invasive weeds to inform famine policy and trends in greenhouse-gas emissions from food consumption in Brazil. These activities are undertaken with a range of partners, for example, N8AgriFood, International Institute of Tropical Agriculture (Zambia), Centre for Agriculture and Biosciences International (Kenya, Pakistan) and South African Tuberculosis Bioinformatics Initiative.

OTHER ESTEEM INDICATORS
Clarivate Highly-Cited Researchers: **Blake**, **Fal'ko**, **Geim**, **Gorbachev**, **Grigorenko**, **Grigorieva**, **Guinea**, **Mishchenko** and **Novoselov**.

Major Prizes: **Boya:** RSC Marlow Award 2020, UNESCO-L'Oréal International Rising Talent Award 2018, MIT Technology Review 2017 Innovators under 35; **Grigorieva:** IoP Tabor Medal 2019; **Novoselov:** Warburg Prize 2019; **Geim:** Prince Sultan Bin Abdul-Aziz International Prize for Water 2018; **Fumagalli**: RMS Medal for AFM & SPM 2020; **Evans** (2014) and **Gersabeck-M** (2017): IoP Particle-Physics Prize; **Browning:** RAS Chapman Medal 2016; **JBCA:** RAS Group Achievement Award e-MERLIN 2015 and Planck 2018; **O'Brien:** IoP Kelvin Medal 2014; **Söldner-Rembold:** IoP Chadwick Medal 2018; **Mishchenko:** European Magnetic-Field Laboratory Prize 2018; **Billowes:** IoP Nuclear Industry-Group Career Contribution Award 2019; **Scaife:** RAS Jackson-Gwilt Medal 2019, World-Economic-Forum Young Scientist 2014; **Appleby:** EPS Outreach Prize 2019, RNIB Seeing-Differently Award 2020; **Dawson:** IoP Optics-and-Photonics Prize 2016.

Prestigious Fellows: **Cox:** FRS 2016 (joining 10 others amongst current and emeritus staff); **Söldner-Rembold** (2015) and **Bertsche** (2017): APS Fellows; **Novoselov:** Academia Europaea 2015, US Academy of Science 2019; **Guinea**, US Academy of Science 2017.

PGR Prizes: Students won prizes for research, outreach and enterprise including: IoP Franks, RAS Tomkins and three Rutherglen prizes; Harari Enterprise award; 14 Springer awards and 2 UoM PGR Prizes.