Institution: University of Southampton

Unit of Assessment: 09 Physics

1. Unit context and structure, research and impact strategy

1.1 Overview and context

The School of Physics and Astronomy (P&A) at Southampton thrives as a centre of world-leading research and discovery. We provide a collegial, supportive environment for our staff and students who come from a diverse set of backgrounds. In P&A, we want to understand the physics behind the fabric of the universe and how it affects the world we observe: 1) What are the most fundamental physical laws of the universe? 2) How do they influence the evolution of the universe from its beginning to the present day, and into the future? 3) How can we harvest our knowledge of these fundamental laws to improve our daily lives?

Our mission is to find answers to these questions, ranging from the smallest to the largest scales, and combining theory, computation, and experimentation. Our research is focused through three established research groups: *Astronomy*, *Theoretical High Energy Physics ('Theory')*, and the experimentally-focused *Quantum Light & Matter (QLM)*. As part of our evolving strategy, we are also building a flourishing *Space Environment Physics (SEP)* group under the umbrella of the Astronomy group (for details on strategy, see §1.2).

P&A, part of the Faculty of Engineering and Physical Sciences, has 98 academic staff at the REF census date (39 academic staff with teaching and research duties, 7 Independent Researchers, and 52 research fellows/postdocs). Of the 45 REF-submitted staff, 38 identify as men and 7 as women. 9% of staff have a BAME background. Improving upon this imbalance is one of our key goals and ties into our ED&I action plan (§2.1 & 2.3). We ensured that our output selection reflects this ratio and does not discriminate on the basis of gender or ethnicity (§2.3.6). Staff are supported by 10 technical research-support staff and 6 professional administrative staff. The following will detail the individual topics addressed by each group.

The **Astronomy** group's research programme (13 academic staff) is linked to the physics of compact objects: from supernova explosions that create and destroy them, to accretion that makes them luminous and outflows that appear to accompany accreting systems, to the effect they have on their host galaxies throughout cosmic evolution. Our goal is to understand the physics behind these phenomena and exploit them, especially for cosmological purposes. We have a particular interest in time-domain astrophysics and data-intensive science techniques as a tool for pursuing these goals. This topical focus and our associated hiring strategy has resulted in a group that is well balanced: our interests cover diverse topics, but with a necessary overlap that allows effective collaboration.

The emerging **Space Environment Physics (SEP)** group (4 academic staff) focuses on magnetospheric and ionospheric dynamics. This includes the large-scale dynamics of the magnetospheres of Earth, Saturn, Jupiter and Mercury down to auroral processes on scales of tens of metres and fractions of a second. The associated physical processes underly the concept of 'space weather,' an aspiring centrepiece of our research and public engagement activities. Over the last five years, we have invested in a new generation of staff with highly complementary areas of expertise in these areas.

The **Theory** group (13 academic staff) is one of the largest theoretical particle physics groups in the UK. We generate innovative theoretical progress responding to formal and experimental developments across the field of fundamental physics. The core question we are addressing is "what are the mathematical building blocks and laws that underlie nature at the shortest distance scales?". Our phenomenology work with experimentalists ensures that the Standard Model is well tested and that current and future data is searched thoroughly for signals from new theories. The

theoretical model building and mathematically-based research supports this phenomenology and explores the space of models at yet higher scales that might explain fermion mass patterns, dark matter, and matter anti-matter asymmetry. We are making state-of-the-art predictions for Quantum Chromo Dynamics and develop new directions in field theory (including quantum gravity) that underpin future advances in our descriptions of high energy phenomena.

The **Quantum Light and Matter (QLM)** group (15 academic staff) hosts the core of the School's experimental research in fundamental and applied physics, connecting the scales between the Astronomy and Theory groups, and serving as a platform to turn our fundamental knowledge of physics into technology. We work on a diverse set of topics that are aligned with national and international efforts (e.g., our participation in European and national Quantum Technology (QT) initiatives; §1.2). These include i) quantum science and technology with photonic, atomic, solid-state and optomechanical systems, covering topics like matter-wave interferometry and quantum simulators by exciton-polaritons; ii) nano-photonics, metamaterials and plasmonics experiments paralleled by Raman and THz spectroscopies as well as X-ray imaging; iii) the synthesis of nanomaterials and devices. Research in the QLM group is interdisciplinary, linking fundamental and applied physics, e.g., through collaborations with Electronics & Computer Science (ECS), Zepler Institute (ZI), Institute for Life Sciences (IfLS), and medicine. Our research is being enabled by strong ties to national facilities (Diamond Light Source), nanofabrication in local and national/international facilities, industries in the photonics, space and QT segments, and the European Space Agency (ESA).

1.2 Research Strategy

P&A is growing and ambitious. We have positioned ourselves as one of the top physics departments in the UK and Europe, with a research strategy guided by the three fundamental questions we want to answer (§1.1), influenced by the national and international research landscape. We attract the best scientists from all backgrounds (§1.1 & §2) who can help answer our fundamental research questions, providing opportunities to become leaders in their field (§4.6). This includes support to participate or lead national and international research initiatives (see below and §3&4), and support to remove barriers they may experience (§2). We aim to respond with agility to new opportunities, as with the formation of the SEP group.

While the research groups work mostly autonomously, the School has oversight to ensure alignment with our strategy. This is done via committees bringing together School and group leadership: general strategic discussion and decisions, such as hiring or major investment, are made at the fortnightly School's Senior Management Team (SMT) meeting while the Research Enterprise Committee discusses, enables, and supports research initiatives. In the following, we will outline how our research groups position themselves within the School's research strategy.

The **Astronomy** group's strategy following REF2014 consisted of three main goals: (1) expand our "compact object"-centred research into extragalactic/cosmological areas; (2) exploit links and synergies between our Galactic and extragalactic compact object research; and (3) develop into a true multi-frequency, rather than just high-energy, group. This was a major shift in focus and a direct response to developments in the field, specifically the emergence of extragalactic surveys in the optical (e.g., DES, PESSTO, LSST) and new facilities, already operational or soon to start (e.g., NICER, NuSTAR, ALMA, 4MOST, MOONS, JWST). This shift was enabled by strategically filling replacement positions and enabling targeted hires (§2.1.1). As a result, extragalactic research now covers supermassive black hole and galaxy formation through cosmic time, surveys of the evolution of active galactic nuclei, as well the physical characterisation and simulation of accretion onto supermassive black holes from the event horizon to galactic scales.

For the next 5 years, our main strategic aim is to establish the group as a world-leading centre of excellence in data-intensive and time-domain astronomy as part of our '*Physics of Compact Objects*' theme. This strategy is driven by our international scientific leadership in current and upcoming synoptic sky surveys and instrument consortia and growing expertise in data-intensive

science, including time-series analysis and machine learning. We were able to join major surveys and collaborations such as the Rubin Observatory LSST, 4MOST, MOONS, or GRAVITY+ in support of our goal

The **SEP** group is a prime example of our successful strategy implementation and identification of opportunities. Its expansion followed an external review to assess the needs and viability of our activities in this field. As such, it was approved by the University, and the group has since been extremely successful, winning fellowship and grant support from STFC, NERC, SPRINT and SPITFIRE at historically high levels for SEP. The group is now a major player in the field of magnetosphere and aurora research with support from the School, e.g., through involvement in EISCAT. Over the next 5 years, the group will also play an ever-growing role in our research with public outreach via the AuroraZoo project (§1.3; Astronomy Public Engagement ICS).

The **Theory** group's current work is addressed to four "Grand Challenges": 1) helping the experimental community pin down the Higgs sector that underlies the standard model; 2) exploring the key mystery of the flavour problem of fermion masses; 3) tackling the problem of our inability to calculate at strong coupling; and, 4) searching for a consistent quantum theory of gravity. The key to advancing these goals is building a state-of-the-art modelling framework (HEPMDB, CalcHEP) for experiments. Two group members joined CMS (**Belyaev**, **Moretti**) and our Directorship of the NExT Institute fosters the link to experiments. Our linked model building work has addressed the flavour puzzle and been responsive to the discovery of neutrino mass/mixing and experiments on CP violation and absolute neutrino mass scale. We have developed our work in cosmology and leptogenesis proposing related signals at gravitational antennas and using the 21 cm cosmological global signal. Our lattice work has been strengthened with resulting precise results for light-flavour phenomenology (e.g., the QCD+QED hadronic vacuum polarization computation for muon g-2). The lattice work has diversified through an innovative project linking holography, cosmological observations, and field theory to study the physics of the very early universe. There has been an expansion in work on amplitudes at high order including links to AdS/CFT and we made important understandings of the renormalisation group for perturbative quantum gravity. We have used holography to study strong coupling in QCD, composite Higgs models and defect theories linking to condensed matter, collider and gravitation wave phenomenology plus lattice studies.

Over the next 5 years, we will diversify our main research strands: the lattice work will solidify its strong presence in light-flavour phenomenology but develop it into cosmology work. We are keen to broaden this area to prepare for the exascale computing era, responding to the upcoming international landscape in the field. In phenomenology, we will be led by the new era of Precision Higgs Physics at the LHC as well as future electron-positron Higgs factories. Dark matter searches and other non-accelerator experiments will become a field of increased attention by our group. We will continue to develop models led by new data, e.g., in neutrino physics where we are preparing for data from T2HK and DUNE. Our model building will seek unified structures in flavour, neutrino masses, dark matter and matter-antimatter asymmetry. After the large growth of the formal area in collaboration with Maths, the two groups will exploit this growth to build an international agenda in perturbative quantum gravity, string theory, applied holography, conformal field theory and amplitude techniques. Goals include a geometric formulation of QFT amplitudes, understanding the nature of quantum gravity in AdS space, understanding entanglement across black hole horizons, and describing the QCD equation of state in conjunction with gravitational wave data.

For REF2014, the **QLM** group identified *'Quantum Technology'* as the unifying theme linking engineers, physicists, chemists, and mathematicians. The research strategy has since seen an expansion in this direction, and three main thematic areas are the focus of our 5-year strategy.

(1) Foundations of quantum physics and quantum metrology. We are working to establish the Penrose Institute (PeI) of Physics of the Universe at the University of Southampton. This will foster

dedicated experimental and theoretical research to understand physical effects at the interplay between General Relativity and Quantum Mechanics. We will develop new experiments that target new physics and test fundamental theories of nature, including quantum optomechanics and magnetomechanics of large-mass systems and cold-atom BEC experiments.

(2) Photonic and polaritonic quantum technologies. We are building on international partnerships with experimental and theoretical groups working on Quantum Polaritonics. A second area of growth is in silicon-based solid-state integrated photonic quantum simulators, photonic quantum memories, and single-photon sources. This area is pushed forward through a $2M Moore Foundation grant (**Sapienza**), and through new entrepreneurial activities, such as Duality Quantum Photonics.

(3) Advanced materials and Nanoscience. We are going to increase our lead multidisciplinary, cross-faculty and cross-university initiatives on priority areas in energy, healthcare and ICT. We will develop underpinning science, new instruments and tools, and advanced materials for a wide range of research activities. We will expand the strong links with the Diamond Light Source through a recently awarded UKRI Future Leaders Fellowship on coherent X-ray experiments (**Newton)**.

1.3 Developing Impact

The School actively encourages individual researchers, as well as the research groups, to develop impact from their applied and blue-skies research. The main vehicle for this is the annual STFC Impact Acceleration Award where seed funding is locally available for projects that drive our impact cases. Successful examples include **Sullivan** (MoleGazer), **Bird** (Symetrica), **Knigge** (DataKind), and **Shankar** (blood pressure monitoring).

Through our established coordination channels (e.g., Research & Enterprise Committee, Impact Champion), we identified four cross-group strategic pillars of impact from our research: *Data Science*, *Sensor & Display Development*, *Public Engagement*, and *Industrial Engagement*. Implementation of the strategy is supported by tailored administrative and financial services at University, Faculty, and School level, e.g., via central *Research & Innovation Services (RIS)*, the faculty's *Future Worlds* hub facilitating industrial engagement, and the School's *Business Engagement Manager*.

A cornerstone of implementing our Impact strategy is seed funding through our STFC Impact Acceleration Account, allocated via a competitive process to projects reaching beyond our core research. Projects in Data Science and Sensor & Display development have profited from such funding, going on to secure external grants (e.g., **Shankar** for blood pressure monitoring; **Bird** for coded aperture mask development, leading to a KTP grant). A further highlight is our placement scheme for postgraduate students: Through our Business Engagement Manger, local and regional companies, from SMEs to large enterprise and non-profits, offer multi-week to several month-long placements enabling bidirectional knowledge transfer and plant seeds for further research impact. In addition, we have been successful in attracting a Royal Society-funded Entrepreneur-in-Residence to help develop our impact strategy further (Hill).

We highlight major initiatives in our four impact pillars:

(1) Data Science: Data science is now a cornerstone in the UK's industrial strategy and a key component of Industry 4.0. As a result, the School has placed an increased focus on this pillar of our impact strategy. For example, our leading roles in large astronomical surveys (e.g., 4MOST, MOONS, Rubin Observatory, VEILS) has led to broad expertise in the analysis, modelling, and interpretation of multi-dimensional datasets. Topics of particular interest include time-series analysis, the analysis of "big data", machine learning and image processing. **Jackman** and **Shankar** are fellows of the Alan Turing Institute.

A basis for our work in data science beyond physics is our leadership of the STFC-funded CDT in data intensive science *DISCnet*. This CDT provides a vehicle for knowledge transfer to industry.

PGR students in this programme receive training in big data techniques, including Machine Learning and Artificial Intelligence. During their 4-year PhD, students participate in two 3-month industrial placements where they apply their acquired skills in industry or the third sector. These placements and training will be sustained beyond the lifetime of the *DISCnet* CDT with other studentships. An example of how *DISCnet* seeds future impact work is a recent School-funded PhD studentship in direct collaboration with the data science start-up company *HAL24K.*

We are actively working to generate impact in the Third Sector via the growing field of Data Science for Social Good (DSSG). We have been working closely with DataKind UK to make our expertise available to charities who need assistance with data-science related problems (led by **Knigge**). With the Office of National Statistics, we co-hosted an extreme DataDive event at Southampton in Sep 2018 and will host further events. We have volunteered to contribute to the organization of the Turing Institute's 12-week internship programme in DSSG.

A growing field of our impact work in Data Science concerns applications of our research to medicine. **Shankar** used his galaxy evolution model to improve blood pressure monitoring of the population. This work is carried out in collaboration with the British Heart Foundation Centre and the Department of Clinical Pharmacology at Kings College London. Another project applies techniques used to identify supernova in survey images to detection and monitoring of malign melanoma. This 'Molegazer' programme is supported by an ERC Proof of Concept grant (**Sullivan**/Smith). Based on our experience with time series analysis, we recently started a new STFC-supported project on cardiac arrest prediction (**Sullivan**/Frohmaier), and during the COVID-19 crisis, PhD students and postdocs were recruited by the Faculty of Medicine/University Hospital to assist in analysing data from COVID test trials.

Finally, the Theory's group work in lattice QCD has significant impact on the development of parallel supercomputers. With UKRI Strategic priorities funding under 'Excalibur', our *'Exalat'* project (**Flynn**, **Jüttner**) will develop a roadmap for training, algorithm development and application of lattice methods in industry (ATOS, Dragonfly Labs).

(2) Sensor & Display development: Our second impact pillar is the work of the Astronomy and QLM groups in detector and display technology development. The Astronomy group has a long-standing relationship with Symetrica, where the company's founder was a past member of the group and developed high-energy detectors, a line of research with a 20+-year track record in P&A. In 2016, a new lab for **Bird** was established to facilitate further R&D links to Symetrica as part of a KTP project (£101k), with further strengthening of links via a parallel instrumentation development activity funded by the Impact Acceleration Account. Recent work focused on medical and defence-related applications of coded mask apertures as used in high energy detectors in space.

In QLM, we are working actively on new sensor technology. Piezoelectric energy recuperation and harvesting – a process to convert mechanical energy to electrical power via the piezoelectric effect in crystalline materials – has been exploited in a new device by **Newton** (patent filing number EP19156606) and we are discussing with Merck licensing the technology for use in novel pressure sensors. **Kaczmarek** has developed an Optical Multi-Parameter Analyser for liquid crystals based on new optical methods developed in P&A. A first device has been sold to Facebook Reality Labs for display performance analysis, and further expressions of interest have been received.

(3) Public Engagement: The School runs a major public engagement programme based on research from all the groups. Our key goal is to reach audiences that are traditionally underrepresented in public engagement through our 'New Audiences' scheme. Since 2014, we have had more than 105,000 face-to-face interactions and more than 1M engagements on-line (including social media). We have a strategic partnership with the Winchester Science Centre, where our exhibition was visited by about 75,000 people. In addition, our appearances on BBC TV programmes reached almost 5M viewers. For astronomy, more details can be found in our Public Engagement Impact Case Study "Astronomy with US", but we also have a stategic public

engagement programme in QLM that significantly contributed to these numbers (corresponding impact case not submitted).

We own and operate the inflatable planetarium "Astrodome" as a vehicle for public engagement, and frequently work with regional schools as part of a programme to engage children from age 8-17 in STEM, which also includes lectures by PGRs and academics. We also run more focused events, such as a supernova exhibition at Southampton airport where passengers can learn and engage about our research. A recent focus is *'AuroraZoo'*, a citizen science project run by the SEP group on the Zooniverse platform. Our researchers (**Whiter**/SEP) reach out to the public to help classify aurora required to reveal physical process of aurora formation. These classifications are subsequently used in research papers.

(4) Industrial Engagement: QLM research is directed towards producing industrial impact. As our work spans the gap between physics and engineering, we actively collaborate with the ZI on research and impact falling into REF descriptors of physics and engineering (e.g., nanoscale physics, lasers, optoelectronics and photonics). This makes our research inherently interdisciplinary (§1.4), as evidenced by the selected Impact Case Studies ("5D memory", "Covesion"). Our photonic and polaritonic quantum technologies group is pursuing new routes to optical computing and quantum simulators of spin Hamiltonians through strong industrial-academic partnerships with IBM Zurich and MIT-Skoltech. We are expanding our diverse funding support on the national and international level, for example through the recently awarded FET-Open project "Polariton Logic (POLLOC)". Several group members have filed patents with the goal of commercialisation (**Muskens**, **Newton**, **Freegarde**). Another example is our work on metal-oxide metasurfaces for infrared active coatings (**Muskens**). This technology is being picked up by Italian commercial R&D centre CREO, with whom we started to develop flexible radiative cooling panels for satellites.

1.4 Interdisciplinary Research

Our goal to exploit advancements in the understanding of physics to improve daily lives naturally leads to collaborations outside physics, supported through our research and impact strategy. We actively engage with interdisciplinary Centres of Excellence at Faculty level, where researchers from across engineering, computer science, chemistry, and physics are brought together (e.g., IRIS, the Centre of Excellence for In-situ and Remote Sensing).

The **QLM** group has strong engagements within the wider university including ZI, Chemistry, Engineering, Life Sciences, Mathematics, and Electronics and Computer Science. QLM-led research increasingly makes use of local world-leading infrastructure such as the Southampton cleanroom facilities and Diamond Light Source. An example of such cross-disciplinary research is our Advanced Materials and Nanoscience research, where we are transitioning from the Physics rapid prototyping facility to the use of ZI cleanroom facilities. This strengthens ongoing collaborations with the ZI and ECS on emerging topics related to photonics for AI, Space, and Defence. Several staff (**Smith**, **Kanaras**, **Muskens**) have an established track record of interdisciplinary collaboration between QLM, Chemistry and Life Sciences (IfLS), e.g., for cancer treatment (£1M BBSRC grants).

In the **Astronomy** and **Theory** groups, we conduct interdisciplinary research around data science. To support this, we have 3 joint studentships between Astronomy/Theoretical Physics and Computer Science. The Astronomy and Theory groups also participate in interdisciplinary research through DISCnet and NGCM CDTs. The DISCnet CDT receives matched funding from P&A for all STFC-funded studentships. The DISCnet CDT students are engaged with mandatory placements in industry, which are also open to other PGR students.

The **SEP** group has strong ties to aeronautics and space engineering, in part facilitated by the UKRI-funded *SPRINT* innovation network. Space weather (the effect of solar wind/magnetosphere/ionosphere coupling on space- and ground-based technology) is inherently

interdisciplinary, and we collaborate with colleagues in Ocean & Earth Sciences, supported by a NERC Highlight Topic grant (Co-Is on SWIGS).

We are co-founders of the *Southampton Theory Astrophysics Gravity (STAG)* Research Centre, formed in 2012 to develop science at the interface between three research groups from two UoS faculties: Theory and Astronomy in P&A, and the Gravity Group in Mathematical Sciences in FSS. Both faculties support STAG financially, and STAG has developed its international profile through hosting scientific and public engagement events, including the annual STAG public lecture series promoting the research centre. Most of the past speakers are Physics Nobel Prize laureates, supporting engagement with our research in schools and the community.

1.5 Open Data

We are strongly committed to an open research policy and contributing to an environment that allows open access to data from publicly funded research. Our objectives for open access align with the University (REF5a§2.4). Most importantly, we are committed to address the "reproducibility crisis" by working towards general access to data produced by our research. Outputs are deposited in *PURE* which delivers them to the University repository ePrints (see REF 5a). We follow open data rules and procedures as required by national and international funding bodies (e.g., STFC, EPSRC, NERC, EU). In general, research papers produced by our staff, postdocs, and PGRs will be accessible through arXiv. All groups in the School follow the provisions for reproducibility and open data/open software as required by funders and the major academic journals. Where we are involved in large collaborations or use international research facilities, data are stored and publicly available through archives (e.g., ESO).

1.6 Research Culture

We provide an inclusive and diverse working environment with tailored support to set our researchers up for success. A key part of this is our Code of Conduct that all members of P&A are committed to. We follow mandatory training by the university on topics surrounding research culture. Our PGR students receive training on research integrity and research ethics as part of their skills training provided by the Doctoral College.

The University is a signatory to the *Concordat to Support Research Integrity* and we follow policies derived from the framework by the University (REF5a§2.8). Breaches of research integrity will be pursued through the faculty research ethics committee, which serves as outside counsel and decision-making body to reduce potential conflict-of-interests. Since 2014, no research ethics issues within the School have been brought to our attention.

Since 2008, P&A has been part of *SEPnet* (the South-East Physics Network) with nine partner universities. *SEPnet* provides a network to promote excellence in physics research, impact and teaching, works to improve diversity by sharing best practice amongst its partners, and raises the quality of postgraduate training through shared 'GRADnet' tuition.

2. People

2.1 Staff

2.1.1 Staffing strategy and staff recruitment policy

Our strategy is to recruit the best researchers who will help us address the three fundamental questions we want to answer (§1.1) and enrich our impact work. Careful planning allowed us to grow the number of academic staff from 42 in 2014 to 45 in 2020 despite a challenging funding environment. Most of our recruitment happens though internationally open competition (60% of submitted staff are international), but we also make target-of-opportunity hires of excellent candidates (e.g., **Banerji-Wright**, **Gingell**). Recruitment follows ED&I policies (§2.3). All staff involved in recruitment receive unconscious bias training. When recruiting, we specifically invite strong candidates from underrepresented groups to apply. School interview panels aim at

representing the diversity of the shortlisted candidates. The 7 staff recruitments since implementing the ED&I policies in 2016 resulted in the hire of 4 women and 3 men, demonstrating the effectiveness of our new approach.

Since 2014, P&A have made 14 new appointments at the Lecturer and Associate Professor levels. With only two anticipated retirements over the next 5 years, we now have the required continuity to implement our research strategy. Our major challenge will be staff development to lead more junior members into senior roles. Hence, we encourage and invite junior staff to participate in management training offered by the University's Leadership & Management Development programme (e.g., through Leadership Circles, Line Manager Development), and guide them towards higher responsibilities by assigning leadership roles in specific fields. The major vehicle for encouraging staff is our appraisal, support and management strategy (§2.1.2). This approach has led to the award of 9 Chairs and 12 Associate Professorships over the last 5 years. The fraction of men and women promoted reflects the current gender distribution in the School.

Currently six academic staff are on fixed-term contracts while holding a long-term (5+ years) personal fellowship. We have an excellent record in converting suchpositions into permanent posts. Newly appointed independent fellows (e.g., RS URF, STFC ERF, EPSRC fellows) are treated on the same basis as other staff, fully integrated into research groups, and are encouraged to supervise PhD, Masters and UG project students. Evidence of the effectiveness of our strategy is our attractiveness to external research fellows: since 2014, 6 long-term (5+-year duration) research fellows have arrived at P&A, including 3 transferring their fellowships from other universities. We also attracted shorter-term research fellowships including 6 Newton International Fellows and 3 Marie Curie Fellows.

Since the last REF, the Astronomy group has seen turnover from retirements (Charles, **Coe**) and departures (Breton, Croston, Ho, Scaife). This has been used as an opportunity to hire staff to support our expansion in the extragalactic field and with a multi-wavelength approach (**Banerji-Wright**, **Childress**, **Gandhi**, **Hoenig**, **Middleton**, **Raimundo**). Five of the six new staff came with fellowships, demonstrating the high quality of our recruitment. The SEP group was expanded over this REF period in line with our research strategy. Following the retirement of Lanchester, the proleptic appointment of **Fear** has been made permanent. In addition, we were able to recruit three new staff, all of them holding long-term fellowships (**Jackman**, ERF; **Gingell**, URF; **Whiter**, NERC) with permanent positions at the conclusion of the fellowships. The Theory group has been strengthened through the hiring of **O'Bannon** who came to us from Oxford on a Royal Society (RS) URF. In the QLM group, hiring since the last REF was used to support expansion in quantum technology, one of our key strategic fields (§1.2). This was achieved by making the appointments of **Sapienza** and **Himsworth** permanent and recruiting **Ledingham**. In addition, we were able to strengthen our X-ray imaging group by the new appointments of **Thibault** and **Zanette** and making **Newton** permanent.

2.1.2 Staff development

Our staff are the key to achieve the School's goals outlined in §1, which is why we have developed policies to support them developing their careers.

All new P&A staff are assigned a line manager, who coordinates their mandatory UoS **induction** and oversees the two-year (postdocs one year) probation period. Our induction includes signposting to policies on diversity, discrimination, our Dignity at Work and Study policy, our School Code of Conduct, our School Workload model, and online courses that all new staff must take (e.g., ED&I training; safeguarding training). New staff are made aware of university-wide mentoring schemes, the WISET+ network and the Springboard development programme available to women (P&A pays for women to take this course). Postdocs and junior staff can join the *Concordat to Support the Career Development of Researchers* that has recently been launched by the University (REF5a§3.5).

New staff are offered a **mentor**, who is named in the induction material. The mentor is available to discuss all aspects of academic life, to assist the new academic staff to settle into the School, and to discuss career development. Once staff have completed probation, they have mandatory annual **appraisal** meetings with their line managers (REF5a§3.1). All line-managers take mandatory appraisal training, monitored by the University, which includes further elements of unconscious bias and 'managing diversity' training. Promotion and long-term ambitions are discussed during appraisal and recorded.

Promotions for ERE staff are considered on an annual cycle, with two annual university-wide information events run for staff. Potential promotion applications are first informally discussed with line-managers, who are proactive in encouraging staff to apply. The application form includes space to describe individual circumstances (e.g., career breaks). Applications are then considered by a P&A School panel, then by a faculty panel. For promotion to Associate and Full Professor, the faculty panel will have representation from external to the Faculty. Interviews are conducted, and the university offers day-long interview training for short-listed candidates ('Excelling at Interviews'). The purpose of the P&A SMT review is (1) to provide feedback to applicants to strengthen applications, and (2) to decide whether P&A will support the application (applicants are free to proceed with their application regardless of P&A support). This P&A step is designed to strengthen applications prior to faculty review, and to identify any applications that may be considered premature. The fraction of women applying for promotions is consistent with our staff profile and have been successful 100% of the time. Unsuccessful candidates receive in-person feedback from the HoS and/or Dean.

Research Innovation Services (RIS) hold a library of successful grant proposals (contributed by staff). All major UKRI and EU **grants** undergo a formal internal peer review process in the School before submission. Mock interviews are offered for those who reach the interview stage of grants or fellowships (uptake is 100%). The PG lectures on '*Applying for Fellowships*' are also open to junior postdocs. Our self-assessment since 2015 has identified a need to better support staff with unsuccessful grant applications. Although our existing mentor/line-management system is the first point of contact, we have established the role of School '*Fellowship Champion*', who highlights opportunities and offers advice for potential applicants.

2.1.3 Support for early-career researchers

Students and postdocs are critical to the success of P&A. They are fully integrated with our research life, including organising the seminar series of their parent research groups. In 2018 we set-up a new postdoc network, with a focus on peer support, and with seminars on applying for fellowships, grants, including resilience aspects of such proposals. In addition, postdocs have the option to be paired with a permanent staff as a career mentor.

We also have a *Women's Physics Network* (WPN; open to all members of the School) that seeks to highlight the profile of junior researchers in physics. WPN is self-organised by PhD students and postdocs and receives an annual £1k budget from the School to support events. The group is represented on our ED&I committee (§2.3) and part of the university-wide *WiSET+* group (REF5a§3.8). Since 2014, WPN holds regular networking events, seminars on careers in science, and public outreach events.

2.1.4 Sabbatical/leave policy

Academic staff with a mix of teaching and research responsibilities are eligible to apply for a semester of research leave every 4 years. While business needs may require flexibility on the timing of the sabbatical, the School will usually make arrangements to allow for the leave as requested by the staff member. This policy also applies to part-time staff.

2.1.5 Rewarding impact

Most academics are on a 'balanced' pathway (see University Environment statement). All impact (including public engagement) is fully accounted for in the School's workload model, with the same status as teaching or university administrative duties: to encourage our staff to carry-out impact, we do not count it as time towards their 'blue skies' research. In addition, we offer our staff the opportunity of 30 days per year for work in industry or third sector bodies as part of their normal working contracts to stimulate knowledge exchange with academia.

2.2 Research students

2.2.1 Recruitment

Over the REF period, we have been home to 141 PGRs, retaining the annual average from the last REF. A fall in STFC DTP studentships due to a flat-cash funding landscape combined with more universities bidding for the same studentship pool was offset by individual grants (ERCs, Leverhulme, John F Templeton foundation) and new doctoral training centres (ITNs, STFC and EPSRC CDTs). We also offer studentships jointly with world-class research institutions (ESO, JAIST).

We regularly receive a factor of 10 more applications than PGR places available. The international profile of the School is reflected in our PGR recruitment: 79 entrants were UK nationals and 62 came from abroad. 26% of the recruited PGR students identify as women. Our PGR students are recruited by the individual research groups with central administrative support from the faculty. While the groups are responsible for selecting students, the process is governed by the School's recruitment guidelines along the principles of equality, diversity, & inclusion (ED&I) and set out in our Athena Swan Silver Action Plan. All staff involved in the recruitment will have undergone the university's mandatory ED&I training.

The undergraduate summer research placement scheme within the School and across SEPnet serves as an initial point of contact with the best undergraduate students from our own university as well as the partner universities in the South East. Moreover, we regularly recruit PGR students from our undergraduate flagship programmes, where the best students in Theory, Astronomy and QLM spend a year at CERN, the Centre for Astronomy at Harvard, and our research labs, respectively, to undertake a research project.

2.2.2 Support and monitoring

Each PGR student has a supervisory team comprising at least two academics. The University provides mandatory training for new supervisors. Main progression events for PGRs are: start of year 1 training evaluation, 9-month report and viva, 18-month report and upgrade viva, and 36-month report on progress to submission. These are evaluated by two academics independent of the supervisory team. Additionally, students produce regular, short 3-month reports on progress, including meetings with their supervisory team and training.

All students are monitored through '*PGRTracker*' – a bespoke UoS web-based interface that provides a personalised record of student training, monitors all progression events and automatically sends e-mail reminders to staff and students to prompt each stage of progression. It also allows the Graduate School staff to access all progression information on a student very simply.

Each student, regardless of funding source, receives a Research Training Support Grant (RTSG) of £1,230. We have a dedicated PGR student representative to communicate concerns of the wider PGR community to the School's Senior Management Team, if necessary. Moreover, each research group has a PGR Senior Tutor who provides confidential pastoral support to PGR students.

Over the current REF period, we have awarded 134 doctoral degrees (17 women, 83 men). Against the 141 entrants during the same time, this implies a more than 90% success rate

considering that overall entries remained about constant. Of those not graduating, about half moved to a different institution (e.g., because their supervisor moved).

2.2.3 Skill development

We run lectures for our PGR students on pursuing an academic career and applying for grants and fellowships, and diversity/unconscious bias. Uptake is 100% by first year PGR students. SEPnet/GRADnet runs and funds many other career development events and workshops, some of which are considered mandatory. This includes exercises in leadership, team-working skills, CV writing, and science communication. In addition, GRADnet runs a mentoring scheme connecting PGR with physicists ready to act as mentors. Since 2017, we have offered a PGR training programme in data science techniques (e.g., Machine Learning, Statistics, or Big Data handling and visualisation) as part of the *DISCnet* CDT. All lectures are open to and used by PGRs beyond the CDT. The CDT, including its training programme, has recently been reviewed and awarded an 'A' grade by STFC, one of only two such grades in the country.

Students are led towards independence with small exercises in grant bidding within SEPnet where they can competitively bid for grants to organise student-led conferences. Such conferences were funded and hosted in Southampton by our students in March 2017, April 2018, and April 2019, attracting students and postdocs from across the UK. Students also self-organise journal clubs and compete in the Three Minute Thesis competition. For experimental PGRs, we run 1-2 week-long workshop courses per year, covering both mechanical and electronic engineering.

2.2.4 Stimulation of knowledge exchange

We employ a SEPnet Employer Engagement Officer to run our undergraduate placement scheme (more than 35 students placed since 2014). Since 2018, we also employ a Business Engagement Manager funded by our STFC Impact Acceleration Account.

Our DISCnet CDT placements have placed 10 of our CDT PGR students in 3-month placements in local industries. We host a 0.2 FTE Royal Society Entrepreneur in Residence (Hill, a previous PhD student in the Astronomy group) from the *HAL24k* data science company.

2.3 Equality, Diversity & Inclusion (ED&I)

2.3.1 Overview

Since 2014, P&A has achieved Athena Swan (AS) Bronze (2015), AS Silver (2018), Project Juno (PJ) Practitioner (2017) and PJ Champion (2019). This is driven by our Equality, Diversity and Inclusion committee (EDIC), whose mandate is to develop, implement and monitor (local P&A) policies and best practices that promote ED&I in the School, including the AS/PJ action plans. The EDIC is fully embedded within the School, and the Chair regularly attends SMT meetings to discuss EDIC policies. These have always received approval from SMT.

The EDIC consults five established focus groups: UGs, PGs, postdocs, and one each for Support and Technical staff, led by the reps on the EDIC. The groups are informal, and the student groups are open to all in the cohort. We have gained detailed (and frank) perspectives on experiences in P&A using these groups that have driven much of our work and change in P&A.

2.3.2 Career pathways for part-time and fixed-term staff

Part-time and fixed-term staff are treated the same way as staff on open-ended contracts. All academic staff independent of their contractual circumstances belong to our ERE (Education, Research, Enterprise) job family over Levels 4-7 (L4-7; REF5a §3.1). Reward and leave process are open to fixed-term and part-time staff as they are for permanent staff and they are fully integrated within the School.

2.3.3 Support for staff and research students with special needs

The School established a dedicated ED&I fund that can support staff and research students with care responsibility or other special requirements. The fund is supported by an annual contribution of £2k from faculty. In addition, we have used a donation from the Hercock family of £50k to award scholarships to research students to attend conferences, with a particular focus on students with responsibilities outside of academia. Up to £5k is reserved for a hardship fund to support disadvantaged research students.

2.3.4 Support for extended leaves

Before taking leave, staff meet line managers to plan for changes in workload and cover, discuss career aspirations, and plans for their return. In case of maternity leave, P&A has a flexible approach and, where the job descriptions allow, we offer flexible working arrangements during pregnancy, e.g., working from home if that is more comfortable. Research groups facilitate remote working and participation in key meetings via remote conferencing. We enable partners to attend as many ante-natal appointments as required.

The University has a maternity/shared parental leave package for all staff beyond statutory requirements: for the first 26 weeks, this is full contractual maternity pay (CMP), for the next 13 weeks statutory maternity pay (SMP), and a final 13 weeks unpaid. To qualify for CMP, staff are required to return to work for at least 52 weeks after the leave period. While on leave, P&A uses the 10 Keeping in Touch (KIT) days (or 20 SPLIT days) to provide the opportunity for staff to undertake a limited amount of work and training, attend group meetings, seminars or social events, meet with their PG students or postdocs, or simply introduce their child to colleagues. This has helped ease the return to work and benefit both parties. PGR students are usually eligible for paid maternity (or adoption) leave following normal UKRI rules: 26 weeks of maternity leave on full stipend and a further 26 weeks of unpaid maternity leave. The 26 weeks of paid leave is in addition to the original length of stipend support.

We offer a 50% reduction in teaching load for the first year upon return, tracked via the School's workload model. Staff can transition from full-time to part-time and back again via amendments in their contract.

2.3.5 Wellbeing

P&A has a formal core hours policy: regular or major meetings should be scheduled during (i.e., neither starting nor ending outside of) the hours of 9.30am to 4pm on normal university working days. Our email etiquette policy also reflects these hours, and staff are not expected to respond to email outside of these hours. These policies are disseminated to staff each year and during induction. In addition, we have rolled out a "Code of Conduct" for the School, which highlights our commitment to good practice in all areas of ED&I.

The *Women's Physics Network* (*WPN*) (§2.1.3), founded as part of our first Athena Swan Bronze submission in 2014, holds events to support women in physics via careers seminars and networking events. These events typically have a mix of genders in attendance, are open to everyone in P&A, and are attended by members of other departments/Schools within our faculty.

2.3.6 Equality and diversity in REF submission

At every stage of preparing the REF submission, we have monitored the impact of decisions on diversity and equality aspects. This was specifically important where unconscious biases may become important, such as selection of outputs. The selection matches the gender distribution of the School (15% women) and includes 13% of outputs from staff with a BAME background (9% of staff). In line with University policy, all staff were given the opportunity to confidentially report any special considerations or concerns affecting their productivity during the REF period for an application to reduce their required numbers of outputs. No eligible staff opted for a reduced submission.

3. Income, infrastructure and facilities

3.1 Income and strategy

The School's total annual grant income averaged £5.28M per year over the REF period (£35.04M total). While a direct comparison to REF2014 is difficult due to a change of UOA accounting, we have seen an increase in annual income to the School from 2013 to 2016 of more than 40% from £3.7M to £5.4M, and which remained above £5M ever since. Our research is primarily funded via UKRI and the EU. The Astronomy/SEP and Theory groups hold STFC consolidated grants (£5.87M through REF period). In addition, between 2014 and 2019 we have hosted 5 ERC grantees as well as 6 RS URF fellows, 4 STFC ERF fellows, and 1 NERC fellow. The School led 3 STFC and EPSRC CDTs as well as a Marie Sklodowska-Curie ITN.

Aside from those traditional income streams, P&A diversified its funding basis through its interdisciplinary research. Via the SEP group, the School successfully bid for NERC grants (total income £1.4M). The QLM's involvement with chemistry and biology secured funding from BBSRC (total income £1M). Finally, several staff won competitive fellowship, prizes, or grants from private/charity funders, such as the Leverhulme Foundation (£1.49M), the Moore Foundation ($2M), and the Ogden Trust.

Our research output and impact cases were supported by several of these grants. For example, the Ogden Trust partly funded a public engagement officer. Other examples include support by the STFC IAA fund for the research collaboration with Symetrica and the blood pressure impact case study where galaxy evolution models have been transferred to medicine.

3.2 Research infrastructure

3.2.1 Areas of strategic expansion and investment

Since REF2014, significant areas of expansion include data science (Astronomy, Theory) and Quantum Technology (QLM), in line with our research and impact strategies. The School is the PI institution of the CDT *DISCnet*, the Data-Intensive Science Centre in the South-East Physics Network. The School provided 7 matched PGR studentships to secure 7 studentships from STFC (other *DISCnet* partners received similar or smaller shares). The CDT is now used as a vehicle to broaden the School's applied research Data Science and Artificial Intelligence, and to link to industry via *DISCnet* industry mixers, show cases, and student placements. QLM is a partner in the CDT in New and Sustainable Photovoltaics**.** This CDT supports the transformation of photovoltaics in the UK, achieving its renewable energy obligations.

The expansion of the Astronomy group's research into the extragalactic field was supported by investment into several projects. The faculty provided €100k to allow the Astronomy group to buy into the 4MOST collaboration to run a time-domain spectroscopic survey in the 2020s. The recent targeted hire of **Banerji-Wright** was support by £30k of funding to join the MOONS collaboration, a spectroscopic survey using ESO's VLT observatory. These buy-ins are seen as a strategic investment to support future grant income and impact in the field of time-domain astronomy and analysis of time-series data in general.

3.2.2 In-house infrastructure and related impact activities

P&A receives infrastructure support from the faculty and University. The University's central IT department iSolutions provides an embedded IT expert (shared between two iSolutions staff) to allow for day-to-day support with equipment and software. Our data and computing infrastructure is centrally hosted and maintained. To facilitate data science, with the focus on interdisciplinary and/or impact-creating projects, the faculty invested in a specialised 88-core high-performance server for P&A (£30k investment). In addition, staff, postdocs and PGR students in the School have access to and make extensive use of IRIDIS4 and IRIDIS5, two major computer clusters with

12,000+ and 18,000+ cores, respectively. In November 2017, IRIDIS5 was ranked as one of the top 500 supercomputers in the world.

The Astronomy group created a new lab with the purpose to support the KTP project by **Bird** on coded aperture masking. The data science activities use the School's computing facilities. Our QLM group and their laboratories are supported by the in-house research workshops. These employ 10 technicians with expertise in mechanical and electronic engineering. The research workshops provide invaluable capabilities in the design and fabrication of parts not commercially available, which underpin many of our experimental and impact activities, including a helium recovery system and liquefier. We also have access to the university's Cleanrooms (REF5a§4.2) for fabrication of nanomaterials, fibres, etc.

3.2.3 Specialist infrastructure and facilities

Data-heavy research within the Astronomy group is supported by several data storage and high-performance computing servers with a data capacity of >1Pb. In addition, the faculty-funded data science server provides a unique platform for advanced parallel processing beyond "embarrassingly parallel" problems.

The Theory group's modelling work is mostly carried out on local (IRIDIS) and national HPC facilities (DiRAC). In addition, the group operates several computer clusters, including a 512-core Knights Landing cluster.

The QLM group operates several research laboratories with optical tables, Lasers and spectroscopy equipment, cryogenic equipment (at 4K and 300mK), and ultra-high vacuum equipment. The facilities also support bio-sample handling as required for interdisciplinary projects. Further, the group uses the faculty clean rooms for nano fabrication.

The SEP group operate the arctic auroral instrument ASK (Auroral Structure and Kinetics). This instrument takes multi-wavelength observations of the aurora on the same spatial and temporal structure as the upcoming major radar facility EISCAT_3D and enhance its scientific quality.

3.2.4 Shared and collaborative infrastructure and facilities

The Astronomy group uses both shared computing and observing facilities. IRIDIS and STFC/DiRAC and IRDISis serve high-performance computing needs. For observations, major shared international ground-based and space-based facilities have been used (§3.2.6).

The Theory group makes use of local and national, RC-supported supercomputing facilities (§3.2.6). Through CMS experiments, our full and associate researchers access the major LHC programmes at CERN.

The QLM group makes extensive use of the RC-supported Diamond Light Source (**Thibault**, **Newton**) with about 120 days of beamtime awarded. In addition, the group has access to cleanrooms and laboratories at the National Institute of Standards and Technology, Gaithersburg (USA), at the Ecole Normale Superieure in Paris (France), and at The George Washington University, DC (USA).

Details on monetary equivalent where available are provided in §3.2.6.

3.2.5 Benefits-in-kind

For our impact case on code-aperture masking (**Bird**), Symetrica provided 1/3 of the postdoc plus material costs (£70k), essential contributions for the success of the case. **Bird**, **Shankar**, and **Knigge** received 3 Nvidia GPU Titan XP cards from Nvidia. The Royal Institute of Technology (KTH), Stockholm (Sweden) and the University of Tromso (Norway) provided the equivalent of £100k in staff time and EISCAT radar access (**Whiter**, **Fear**).

The QLM group received (non-competitive) access to various international research labs (see above) and fabrication samples for further analysis and investigation, e.g., from ENS, NIST, KIST,

Hong Kong University, IIT Genua, University of Lancaster, George Washington University. In 2016, an ultrafast laser system was awarded from the STFC laser loan pool retirement scheme (£350k in value).

3.2.6 Use of major national and international research facilities

Over the REF period, researchers in the School received non-UKRI-supported facility access with an equivalent value of £33.72M (see *REF4c Research Income in-kind*).

Astronomy/SEP (total £19.7M)

- XMM/Newton: £6.8M
- INTEGRAL: £6.1M
- ESO telescopes: £5.2M
- e-Merlin: £671k
- Liverpool Telescope: £369k
- EISCAT: £240k
- ALMA: £105k
- WHT/ING: £91k
- DiRAC: £57k

In addition, the astronomy group made use of international facilities where no monetary equivalent is available: Chandra X-ray space telescope (>200ks observing time), Swift-Gehrels space telescope (>1,730ks), NuStar space observatory (>250ks), AstroSat (>35ks), NICER on the ISS, (>372ks), Hubble space telescope (>22 orbits), Gran Telescopio de Canarias (10 hrs), VLA (133 hrs).

Theory group (total £9.9M):

- DiRAC HPC computing time: £9.9M

The theory group also received computing time on additional facilities without monetary equivalent available: Brookhaven National Lab Jpsi (27M core hours), IBM Blue Gene/Q (1.56B core hours), Edinburgh Extreme Scaling Service (100M core hours).

QLM (total £4.0M):

- Diamond light source: £2.9M
- ESRF: £77k
- E-XFEL: £1.0

The QLM group also made use of the Swiss Light Source (award of 2 beam times).

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

4.1 Overview

The School's research is inherently collaborative, and the individual groups have extensive national and international networks, including major and leading involvements in large projects. Since 2014, 87.6% of our research outputs had international co-authors, which is the highest fraction within the University (58% overall). On the regional level, the School provides all groups with the SEPnet platform (£35k annual buy-in; §1.6).

4.2 Support for collaborations, partnerships, and networks

The various collaborations and networks are supported by UKRI and EU grants as well as allocation of the School's DTP and university PGR studentships to projects relevant to those collaborations. The faculty supported the Astronomy group's participation in the 4MOST project with a 100k EUR buy-in to the collaboration.

With few exceptions, all the Astronomy group's research papers have been the result of national and international collaborations, where our staff take leading roles. These are supported by EU and STFC grants and studentships as well as successful bids to major observatories. **Banerji-Wright** (PI), **Hoenig** (Co-PI), **Sullivan**, and **Childress** are members of the VEILS, an international collaboration of ~80 astronomers running the ESO Public Survey VEILS. **Sullivan** (PI), **Hoenig**, and **Childress** are members of 4MOST/TiDES, a Southampton-led time-domain survey on the upcoming 4m Multi-Object Spectroscopic Telescope (4MOST). **Banerji-Wright** is Co-I of the MOONS extragalactic GTO survey team as part of the team currently building a new instrument for the ESO VLT. **Hoenig** is Co-I of GRAVITY+, an upgraded instrument approved by ESO after its 'ESO in the 2030s' review. **Knigge** is Co-I of the ThunderKAT MeerKAT Key Project on Astrophysical Transients. **Knigge** is Co-I and steering committee member of SCIP, a key project on stellar, circumstellar and interstellar astronomy within the WEAVE consortium. **Altamirano** is member of the NICER science team, a collaboration of ~70 astronomers using NICER data to understand the physics of accretion onto black holes and neutron stars. **Altamirano** (PI), **Gandhi**, **Whiter**, **Knigge** and **Middleton** lead the OPTICam collaboration to build a triple-beam fast imaging camera for time-domain astrophysics with UNAM (Mexico). **Gandhi** is member of the NuStar science team. **Banerji-Wright**, **Sullivan**, **Gandhi**, and **Hoenig** are Affiliate PIs of LSST:UK and members of various international LSST Science Collaborations. **Shankar** is PI of EU Horizon 2020 funded ITN *BiD4BESt* with partners in Italy, Spain, Germany, and the Netherlands.

The Theory group works closely with colleagues in Brookhaven and Columbia University in the USA and with the group in Edinburgh, under the RBC-UKQCD collaboration (**Flynn**, **Jüttner**, Sachrajda). Weekly collaboration meetings and sharing resources and simulation data in both collaborations gives increased leverage. We have the advantage of working very closely with LHC experimentalists through the NExT (New directions in Experiment and Theory) Institute, hosted in Southampton and directed by **Moretti**. NExT involves collaboration with Queen Mary, Bristol, Brunel, and the Rutherford Laboratory experimental particle physics group. As new data from the LHC and other facilities call for rapid interpretation, NExT provides the ideal environment for a new kind of interaction between theorists and experimentalists to meet this challenge. This is maintained by joint studentships, conferences and workshops.

Most of the QLM group's research papers are written with international partners based on a large network of international collaborations. Many of them are sustained by cross-national funding sources. As examples, **Muskens** is part of an EU Horizon 2020 Space project involving Italian and Danish partners, a Royal Society International Joint Project with Bordeaux, and a GCRF Seedcorn funding project that led to a Malaysian government grant. **Lagoudakis** is part of SkolTech and several EU-funded projects with international partners. **Ulbricht** is part of the EU Horizon 2020 FET Open project *TEQ*, the COST actions "Fundamental problems in Quantum Mechanics", the EU QTFlagship project, and has a long-standing collaboration with Tata Institute at Mumbai, India. **Politi** is part of the EU Horizon 2020 FET open project. **Kavokin** leads the Mediterranean Fundamental Physics Institute, is Head of the Spin Optics Laboratory at the University of St Petersburg, and Director of the International Center of Polaritonics at Westlake University.

4.3 Major international conferences organised

Several major international conferences and workshops have been organised in Southampton by members of P&A. These provided a very visible platform to engage with the relevant academic audiences, develop new relationships and widen the impact of our research.

- *TORUS 2015* (**Gandhi, Hoenig**): Triennial international conference on the environment of s supermassive black holes; 120 participants
- *XCalibur 2019* (**Gandhi**): International Workshop on "Next generation X-ray spectroscopy"; 100 participants

- *43rd Annual European Meeting on Atmospheric Studies by Optical Methods* (**Whiter**); 40 participants
- *Lattice 2016* (**Flynn**, **Jüttner**, Sachrajda): Major annual conference in Lattice Field Theory; 420 participants; supported by STFC, Intel, IPPP, SEPnet, SGI, DDN and Emmi
- *Quantum Science Distinguished Lectures* (**Sapienza**, **Ulbricht**): Series of lectures given by high-profile researchers from Harvard University (USA), National Institute of Standards and Technology (USA), Technical University Munich (Germany), University of Oxford and Southampton

To reach beyond the academic audience, we organise student placements and industry mixer events as part of our CDTs.

4.4 Wider contributions to the economy and society

The four submitted Impact Case Studies are only a small fraction of our wider contributions to the economy and society. We are running a far-reaching public engagement and outreach programme in all fields of research (§1.3). As highlighted in the Impact Case Study "Astronomy with US", we are specifically interested in targeting non-traditional audiences. This includes engaging visually impaired in astronomy by sonifying astronomical data and reaching out to schools with traditionally lower fraction of students from academic households. In 2018, we held our first DataKind event. Staff and PGRs from the School were paired for two days with two charities to work on a problem that can be solved with data science.

Beyond the presented ICS with companies, other active collaborations in the private sector include new detector design to be developed with Merck and screentesting devices with Facebook Labs. We integrate the knowledge transfer mentality that is a core trait of P&A into the training of our PGR students via industry mixers and placement scheme, as provided through SEPnet or our *DISCnet* and NGCM CDTs.

4.5 Sustainability of discipline and responsiveness to priorities

The Astronomy group developed several initiatives in the industrial strategy priority area of "data economy." Specifically, we have strong ties with more than two dozen SMEs and large companies on the south coast via the *DISCnet* industrial placement scheme. The group also runs the GCRF SITARE project (**Gandhi**) that focuses on advancing the physics knowledge base in India and Nepal.

For the academic community, we hosted the UK national community meeting in space science (Spring MIST) and the STFC Summer School in space science. We are part of the SPRINT innovation network, in support of government ambition for the UK to capture 10% of the global space market by 2030, and SWIGS, the NERC Highlight Topic into the effects of Space Weather, which is a threat identified in the UK national risk register.

4.6 Wider influence and recognition

P&A staff contribute to the research base in various ways. All staff regularly review journal articles and grant applications for private and governmental/inter-governmental funding bodies in the UK and abroad. They lead a wide range of national and international funded research programmes and serve on scientific organising committees of large international conferences or hold editorships at journals. The following lists positions by category:

- **Editorships and editorial board memberships**
  Optics Express (**Muskens**), Flavour Lattice Averaging Group (**Jüttner**), ROPP (**Moretti**), EPJC (**Moretti**), AHEP (**Moretti**), Space Research Today (**Altamirano**), IEEE TNS (**Bird**), Scientific Reports (**De Liberato**), Superlattices & Microstructures (**Kavokin**)
- **Advisory roles for national/international funding agencies**
  STFC Operations Review committee (**Altamirano**), STFC Astronomy Advisory Panel

(**Gandhi, Sullivan**), STFC Herschel Oversight Committee (**McHardy**), Italian Ministry of Education Scientific Advisory Board (**Shankar**), Czech Academy of Sciences (**Hoenig**), REF2021 panel (**Moretti**),

- **Award panels of national/international funding bodies**
  (i) Chairs: STFC PP Theory grants panel (**Evans**), STFC Astronomy Grants Panel (**Sullivan**), Horizon 2020 evaluation panels (vice-chairs: **Moretti**, **Kaczmarek**)
  (ii) Membership: STFC Astronomy grants panel (**Fear**), STFC equipment grants panel (**Evans**), EPSRC College Funding Panel (**Freegarde, Himsworth, Muskens**), Royal Society University Research Fellowship Panel (**Moretti**), Royal Society Research Grants panel (**Sullivan**), US Department of Energy award panel (**Moretti**), US NSF grant panel (**Gandhi**), Swiss NSF panel (**Moretti, Shankar**), Polish NSF panel (**Shankar**), Chilean CONICYT (**Shankar**), Swedish Wallenberg Foundation award panel (**Moretti**), RAS Astronomy Awards panel (**Jackman**), RAS Fellowship panel (**Jackman**)
- **Advisory roles for national/international research facilities:**
  (i) Chairs: CERN Computing Resource scrutiny group (**Flynn**), STFC gridPP oversight committee (**Flynn**)
  (ii) Memberships: DiRAC procurement board (**Jüttner**), VRO LSST Contributions Evaluation Committee (**Hoenig**)
- **Chairs and membership of facility access panels**
  (i) Chairs: STFC PP/NP DiRAC Resource Allocation Committee (**Jüttner**), Liverpool Telescope Time Allocation Group (**Sullivan**), Chandra Time Allocation Committee (**Middleton**)
  (ii) Membership: ESO Observing Program Committee (**Banerji-Wright**, **Hoenig, Sullivan**), XMM/Newton Time Allocation Committee (**McHardy**)
- **Memberships on accreditation bodies**
  IoP Degree Accreditation Committee (**Freegarde**)
- **Leadership roles in international organisations**
  European Interferometry Initiative (**Hoenig**), Optical Society of America Executive Committee of Nonlinear Optics Working Group (**Sapienza**),

The work of several staff was recognised by prizes and fellowships, including:

- Leverhulme Trust (Senior) Research fellowships (**Belyaev**, **Knigge**, **McHardy**, **Morris**, **Shankar)**
- ERC Grants (Starting/Consolidator) (**Drummond**, **Hoenig**, **Jüttner**, **Sullivan, Thibault**)
- STFC Ernest Rutherford Fellowships (**Jackman**, **Middleton**)
- Royal Society University Research Fellowships (**Banerji-Wright**, **Gingell, Zanette**)
- NERC Fellowship (**Whiter**)
- EPSRC Established Career Fellowship (**Kavokin**)
- Honorary Doctorates (**Kavokin**, **Moretti**)

In addition, **Gandhi** received a NASA Group Achievement Award as a leading member of the NuSTAR survey team. **Kanaras** was awarded the “SET for Britain” silver medal in biological and biomedical sciences.