

Institution: University of Glasgow
Unit of Assessment: 9, Physics
1. Unit context and structure, research and impact strategy

School Structure and Context

This Unit of Assessment 9 submission is from the School of Physics and Astronomy at the University of Glasgow (UofG) and will be referred to hereafter as the “School”. It is one of seven schools within the University’s College of Science and Engineering, hereafter the “College”, and comprises 60 REF-eligible staff by headcount, 86 Research Assistants, Associates and Fellows, 143 postgraduate research students (July 2020). Since amalgamation of the departments of Natural Philosophy and Astronomy in 1986, we have maintained a strong tradition of world-leading research into the fundamentals of nature, resulting in major contributions to two recent **Nobel Prize winning discoveries** in particle physics and gravitational waves, and have developed new programmes to capitalise on expertise in emerging areas, such as **quantum technology**. We have exploited opportunities created by curiosity-driven research, **spinning out companies** based on the control of plasmas and the application of radiation detector technology. We have created a thriving and supportive research culture and working environment, as recognised by **Athena Swan Silver** and Institute of Physics (IoP) **Juno Champion** awards.

Research Group Structure and Research Themes: We engage in world-class research programmes, as evidenced by the many leadership positions held by staff in international collaborative projects, including the LIGO Scientific Collaboration, the LISA Consortium and the ATLAS and LHCb Collaborations at CERN (see also section 4). These programmes span pure and applied physics and astronomy, and are driven by a strong research group structure focused in six areas:

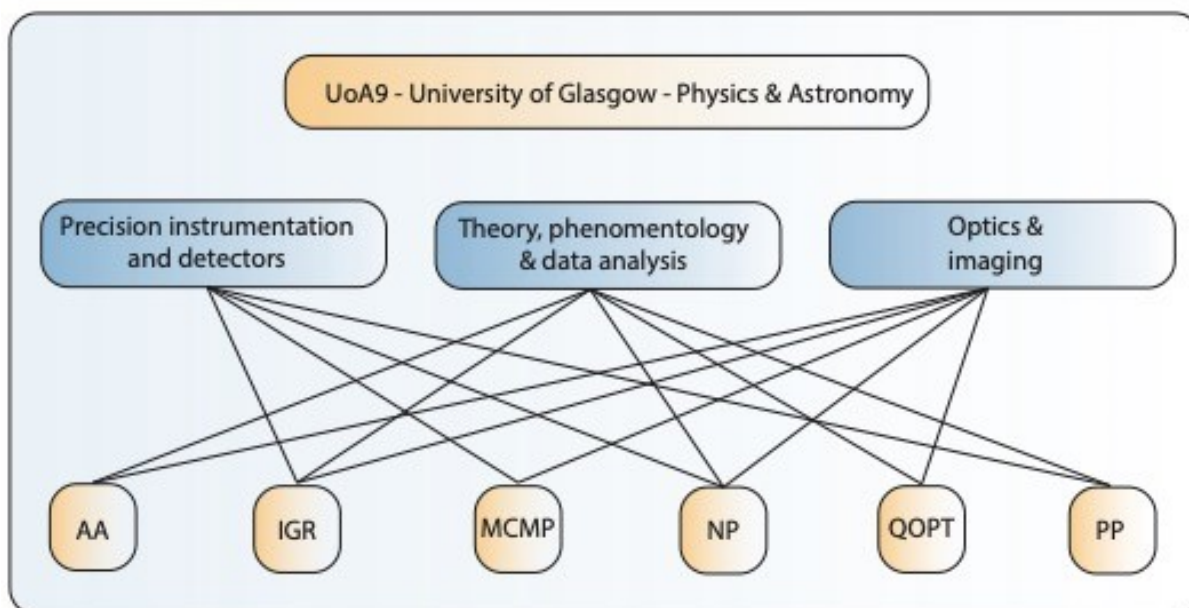
- astronomy and astrophysics (AA)
- the Institute for Gravitational Research (IGR)
- materials and condensed matter physics (MCMP)
- nuclear physics (NP)
- particle physics (PP)
- quantum optics and imaging (QOPT)

In addition, the School has identified and developed three cross-cutting themes which reflect enabling skills and expertise shared across our research groups:

- Precision instrumentation and detectors
- Theory, phenomenology, and data analysis
- Optics and Imaging

This approach has encouraged further collaboration across research groups. Recent examples include advanced materials characterisation for next generation gravitational-wave detectors (IGR and MCMP); optical simulations of curved spaces (QOPT and PP); application of novel machine learning methods for image characterisation and enhancement (AA, IGR, QOPT). This global structure into research themes and areas is summarised in the schematic on the following page.

Management Structure: School operations are overseen by a School Management Team (SMT), membership of which includes the Research Director and Learning and Teaching Convenor, and strategic planning is driven by our Research and Strategy Committee (RSC), comprising the School’s Professoriate; both are chaired by the Head of School. Several key colleagues report regularly to SMT, including: Impact Champion, Equality and Diversity Champion, Graduate School Convenor, Post-Doctoral Research Assistant (PDRA) and Postgraduate Research Student (PGR) representatives.



Research Objectives

The School identifies the following strategic objectives

- To maintain a global reputation for world-leading research in a range of fundamental and applied fields
- To enhance and diversify our activities and funding base in inter-disciplinary research
- To strengthen our international reputation as a leading centre for innovative, high-quality Physics and Astronomy research-led education

Since REF2014 we have pursued these objectives within the context of our strong engagement with and leadership, within the College, of the Athena SWAN process – fully embedding principles and working practices that support Equality and Diversity.

Research Highlights since REF2014

- Our long-term commitment to, and conviction of the importance of, the **discovery of gravitational waves** (GW) was rewarded in 2015 with their first detection – leading to the Nobel Prize in 2017 awarded to close collaborators, two of whom specifically identified UofG's ground-breaking contribution in their Nobel lecture. The UofG IGR group is the biggest gravitational-wave group in the UK, and one of the biggest in the world, as part of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration. As such it has played a key part in the multiple GW discoveries reported in recent years – with leading roles both throughout the construction of the Advanced LIGO detectors and in the analysis and interpretation of the detections. The group also has significant global leadership responsibility for developing the next generation of ground- and space-based GW detectors. UofG leads the UKRI-funded part of the Advanced LIGO Plus (ALIGO+) project, awarded £10.7 million from the Fund for International Collaboration through STFC (PI Strain). The recent successful LISA Pathfinder mission has further cemented UofG leadership of the development of space-based GW observation. Both ground-based and space-based GW detector development were highlighted as REF2014 objectives.
- The initial **discovery of the Higgs Boson** (awarded the 2013 Nobel Prize) has been followed by subsequent Higgs physics discoveries and advances at the LHC. The PP group was one of the main UK groups involved in the ATLAS detector at CERN – with significant global leadership responsibilities for construction and operation of the experiment, together with analysis and interpretation of its discoveries. The group also has major leadership responsibilities for design and implementation of the LHC upgrades, and future generations of experiments. The main data-crunching facility in the UK, GridPP, has a UofG PI (Britton). This is a key enabling technology for particle physics research with computing elements distributed worldwide and a bespoke new data centre to house both GridPP machines and

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other university research computing facilities will open imminently as part of the University's campus-wide development programme.

- **Quantum Technology.** The School plays a major part in the academic leadership, management and operation of the EPSRC-funded Quantum Technology Hub QuantIC (PI Physics, Padgett) – one of the UK's four Quantum Technology Hubs that unites researchers in Physics, Computing Science and Engineering. Establishment of a new Quantum Theory Group in 2013, led by one of the University's Lord Kelvin Adam Smith (LKAS) Professor appointments Barnett, has also been a key development – with Barnett awarded an RS Research Professorship in 2016. A second LKAS Professorial appointment (Faccio, Dec 2017) has strengthened the Unit and College in this area, further supported by his award of a Royal Academy of Engineering Chair in Emerging Technologies and cross disciplinary research involving healthcare technology and biosciences.

Progress on Objectives from REF2014

In addition to the above highlights, we have made significant progress on other REF2014 objectives:

- **Increase in interdisciplinary research, particularly with Engineering:** A key indicator here is the 2019 award of one of six "Physics of Life" EPSRC grants to investigate new science at the boundary between life sciences, physics and engineering (Physics PI - Faccio). The project has initiated a new collaborative study of cell dynamics and cell-engineering using tunable plasmonics and novel imaging approaches. Other key initiatives include a cross-disciplinary doctoral training school with 4-6 students/year and co-supervision from Physics and Engineering. Much of this success can be attributed to the decision to locate some of the Physics research laboratories within the Engineering building, fostering additional collaborations between the Schools.
- **Leadership of International Max Planck Partnership (IMPP):** Through significant investment in quantum measurement and technology, since 2014 the IMPP has developed as a collaborative partnership in quantum science between five Max Planck Institutes in Germany and the Universities of Glasgow, St Andrews, Strathclyde, Edinburgh and Heriot Watt. Led by UofG, the IMPP has leveraged: two School ERC grants in related areas; the first round of quantum technology hubs (with UofG leading one of 4 hubs and IMPP partners involved in all four) and their subsequent renewal; the UK contribution to the Advanced LIGO detector upgrades and participation in several EU Quantum Flagship grants. Further it has enabled joint UK-Max Planck graduate training via specialised summer schools and lecture weeks on relevant topics, including combined lecture weeks on gravitational-wave detection (Hannover and UofG). We have set a special focus on cohort building with international Max Planck Research Schools, IMPRS, at several of the partnering institutes, i.e. Erlangen, Dresden, Stuttgart, Hannover.
- **Materials:** The MCMP group is internationally pre-eminent in electron microscopy, specifically analytical and Lorentz techniques for investigation of magnetic materials. Its bespoke instrumentation and software developments have been adopted by manufacturers worldwide. The group enhanced its capabilities through installation of a unique plasma Focussed Ion Beam (FIB) system, which has supported 24 external users over the first 2 years of operation. Further notable funding includes EPSRC/JSPS Core-to-Core on Chirality and EC FET-OPEN funding for project MAGicSky project on skyrmions for nanospintronic devices. It is a founding member and partner in the EPSRC UK National Facility for Advanced Electron Microscopy (SuperSTEM) and is leading a current revolution in the field, to develop direct electron detectors for electron microscopy – with an Institute of Physics conference on the subject in July 2020 and the Medipix detector licensed and now being sold by Quantum Detectors Ltd.
- **Solar Physics:** The AA group continued building towards the exploitation of data from ESA's Solar Orbiter (launch 2020) and the \$300M Daniel K. Inouye Solar Telescope (first light 2020) with consistent funding over the REF period through sustained support on STFC consolidated grants and a multi-institute EC-funded grant to Fletcher (2014-2016). With emphasis on solar flares and particle acceleration, we have developed the theory and data analysis techniques for interpreting *in situ* observations combined with ground-based observations from the LOFAR radio array, and AI-based methods for rapid analysis of optical spectroscopy.

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- **Nuclear Physics:** The NP group completed an STFC-funded project as part of the \$340m Jefferson Laboratory (JLab) 12 GeV upgrade programme in Virginia, USA. Exploitation of this investment to study the structure and spectroscopy of strongly interacting matter is a key objective going forward.

Objectives for next 5 years:

GW astronomy: UofG's leading roles in the exploitation of data from Advanced LIGO will be strengthened in the next period, during which the field will be in 'discovery' mode. In parallel UofG leads the £10.7 million UKRI-award (2019, PI Strain) contributing to the Advanced LIGO Plus (ALIGO+) upgrade project, to deliver further dramatic improvements in event rate when completed in ~2023. Further, UofG (Rowan) sits for the UK on the steering committee of the 'Einstein Telescope' consortium working towards the next generation of European gravitational wave detectors.

Neutrino Physics: In 2018 we became members of the T2K collaboration in Japan. By appointing a leading neutrino physicist (Litchfield), together with Eklund and Soler, this provides a critical mass of neutrino researchers in UofG. We are now making rapid progress in neutrino physics and exploring its role in the early universe, which goes beyond the standard model of particle physics.

Quantic Phase 2: The EPSRC Quantum Hub in Imaging (PI Padgett) has been renewed until 2024 with funding of £25m. The renewal phase will differ from the previous Hub in both the partners and the overall goals and consequent spend profile. A key objective will be to build upon the engagement with industry and demonstrate fundamental research feeding through to commercial impact. SPIE have also contributed a £1m research endowment to our quantum research theme, the only such endowment outside the US at the time of award (2020). Research topics include next generation healthcare imaging technology, LIDAR and single photon counting technology across the full spectrum from UV to mid-infrared wavelengths. This will form a core deliverable and achievement over the forthcoming REF period.

Upgrades at the Large Hadron Collider in CERN: A key objective will be to complete detector upgrades for Run 3 (2020-2023) and future runs. Our leadership of the ATLAS pixels upgrade project (Buttar) and key involvements in the LHCb upgrade programme will enable this. In tandem, an extensive data analysis programme supported by the GridPP project (led by Britton) will be undertaken, to continue progress in understanding the new domains opened beyond the Higgs boson discovery. Additionally, our theorists will exploit the new £20 million upgrade to STFC's DiRAC HPC facility for precision QCD calculations for flavour physics. The current group of detector technologists, data analysts, phenomenologists and theorists led by Davies and Doyle provide strong teams in tackling these challenges.

Strongly Interacting Matter: The NP group will exploit the UK investment in the Jefferson Lab upgrade, by continual development of detector systems and data analysis methodologies, to investigate the structure of strongly interacting matter and the existence of so-called exotic particles. The next big development in this area will be construction of an Electron-Ion Collider (EIC) in the US. UofG NP will be a main proponent in the proposal to STFC-UKRI for UK leadership in a key part of the EIC programme.

Materials: Recent appointments of Fernandez-Pacheco (3D magnetism and magneto-optics) and Moorsom (molecular magnetism and plasmonics) have broadened MCMP group activities in areas complementary to our existing expertise. In the next REF period, we plan to strengthen our position as a pioneering TEM group by seeking funding for a bespoke instrument that capitalises on our leadership and developments in analytical and Lorentz microscopy, including the now-commercialised Medipix electron detector. The facility will be internationally unique, providing atomic-scale analysis of both the structure and function (chemical, magnetic and electrical) of advanced materials. These capabilities will be accessible to an enlarged external user-base and are essential to addressing grand challenges in energy (e.g. thermoelectric generators), engineering (e.g. materials for ICT) and healthcare (e.g. plasmonic sensors).

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Solar and Heliospheric Physics: The AA group will build on our investments in the Daniel K. Inouye Solar Telescope, the SKA pathfinder LOFAR, and our status as Co-Investigators on several instruments on ESA's Solar Orbiter, to drive forward our observational and theoretical research on solar flares and their heliospheric impact. We will exploit the revolutionary, joined-up, views of the Sun's atmosphere offered by these facilities, from the photosphere to the tenuous solar wind. Our existing leadership in solar X-ray observations, including with the NuSTAR mission, will allow us to capitalise quickly on Solar Orbiter observations of solar flares and coronal heating.

Facilitating Impact

The School has enhanced impact and knowledge exchange (KE) since REF2014 through diversifying use of our research infrastructure, and through institutional and external mechanisms, to build long-term partnerships with companies and other partners. Our appraisal and promotion processes are structured to recognise significant impact achievements, weighting these equally with outputs and research income. This coherent approach includes the following components:

Research infrastructure: Investment in research facilities has enhanced the School's ability to work with industry. Further details are in Section 3, but we note here that services are available to non-academic users through a centralised University facility (<http://tinyurl.com/GUlabs>) and include the *Kelvin Nanocharacterisation Centre* that is strongly linked to the *Glasgow Laboratory for Advanced Detector Development* and the *James Watt Nanofabrication Centre* in the School of Engineering.

Industry partnerships: The infrastructure mentioned above has been used by more than 20 companies, ranging from SMEs to internationals such as *Freescale*, *Coherent* and *Texas Instruments*, and organisations such as DSTL. Our strategy during the REF period has been to maintain existing partnerships, in addition to building new collaborations with *Optos*, *Leonardo*, *Qioptiq*, *STMicroelectronics* and *Findlay Irvine*. Our involvement as lead partners in the EPSRC Centre for Doctoral Training in Intelligent Sensing and Measurement (Director, Harvey), has put us in a unique position to continue to develop industry partnership through PhD student placements and industry involvement in the cohort training programme.

Institutional and external mechanisms: Using various mechanisms, in the last REF period the School has collaborated in applied research valued at £7.59M involving 49 companies. The collaborations and contributions of School staff involved are discussed further in section 4. However, key highlights are two companies spun out in recent years from School research: Anacail – using plasma technology to help extend the shelf life of perishable foods, and Lynkeos – using cosmic ray imaging to inspect radioactive waste barrels. Both companies form the basis of impact case studies and have benefitted from a supportive School environment, e.g. highlighting success in internal newsletters, and providing refurbished space in the Kelvin Building for development of technologies. The recent promotion of Diver to Professor, in part due to efforts related to Anacail, exemplifies the importance of impact, which is included in promotion criteria, to the overall success of the School. Ongoing support for staff also includes flexible timetabling of teaching and administrative duties.

Schools, public engagement and policy: For decades the School has invested significant infrastructure and personnel in support of schools – as demonstrated by our accommodation of the regional STEMNET office 'Science Connects' and the enrolment of 38 research students and early-career researchers (ECRs) in the STEMNET Science Ambassador scheme since 2008.

School staff deliver large numbers of outreach talks and other activities (over 1000 unique events since 2014). A particular focus has been supporting teachers across Scotland in delivering modern physics elements of the high school curriculum, and on schools masterclass series in particle physics, astronomy, and quantum technologies - attended by over 1400 pupils since 2014. Senior members of staff (e.g. Hendry, awarded MBE in 2015 for services to public understanding of science) have highly visible international roles in outreach, thereby encouraging a broad culture of participation. Contributions to national policy on science and education have been strong throughout the REF period. Key examples include Rowan's appointment as Chief Scientific Adviser (CSA) for Scotland in June 2016, and election as Institute of Physics (IOP) President elect in 2019; Hendry

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and Hammond's election as recent Chairs of IOP Scotland; Hough and Hendry's appointment as successive Chairs of the IOP Scotland Education Committee.

Supporting Interdisciplinary Research

Acknowledging that School interdisciplinary research had been hitherto ad hoc, we have introduced several initiatives to promote and foster interdisciplinary research and impact, resulting in numerous success stories within the assessment period.

Examples of relevant **strategic actions** include:

- Introduction of dedicated workshops bringing together University academics working in diverse fields, including STEM, biosciences and the arts, to tackle the barriers between disciplines. Several initiatives within the University have led to common grant proposals crossing e.g. Physics and the Arts and are forming the backbone of the future Advanced Research Centre, ARC (see below) that will host researchers from all of these areas. One key example is a 2020 AHRC award to Physics (Faccio) and Creative Arts (Ehmadi) to apply quantum-inspired haptics sensing technology to assist deaf/blind situational awareness.
- Establishment of the Glasgow Imaging Network, GIN (Twitter, @GlasgowImaging), led by School ECRs, bringing together life scientists, engineers and physicists. We currently host a yearly conference with over 200 attendees from across UofG and the Cancer Research UK Beatson Institute in Glasgow, and supported also by industry (e.g. Cairn, CoolLED, Horiba, MSquared, Nikon and Zeiss).
- Establishment of a world-leading experimental imaging facility (led by Faccio) based in the Engineering building. This has led to increased engagement and cross-disciplinary research with Engineering. One key example is a joint 2020 UKRI Healthcare Technologies programme grant award (£5.5m, PI Cooper; co-I Faccio).
- Active recruitment of academics and ECRs with a track record of interdisciplinary research, e.g. Bennett, Goette, Faccio, Fernandez-Pacheco, Harvey, Taylor – along with proleptic lecturer appointments of Research Fellows Muellenbroich and Moorsom – and establishment of an EPSRC-funded Advanced Optics Laboratory (led by Harvey).
- Supporting the successful applications of interdisciplinary LKAS Fellows, Almeida (material characterisation and paleontology), Turpin (machine learning applied to optics) and Nelson (machine learning applied to microscopy data from living material). The University's LKAS Fellowship scheme was introduced in 2012 in order to attract and retain outstanding researchers as they establish independent research careers.

University Advanced Research Centre (ARC): As part of the UofG estate redevelopment, the ARC research hub is a university-wide concept, with investment of £113m. It is a key component of the vision for a research-led university, with focus on creating a space for radically new research collaborations to flourish. The School's strategy will be to build on the imaging lab currently housed in the Engineering building, which has prompted a decision to devote a full floor of the ARC to the "Quantum and Nanotechnology" theme, to be led by Faccio. It will co-locate in common lab space School researchers active in this theme (Padgett, Franke-Arnold), and in the "Technology Touching Life" theme (Muellenbroich, Harvey, Taylor), together with researchers from Engineering.

Open Research Environment

We enable staff to comply straightforwardly with open access (OA) expectations: our Library is resourced to manage all OA requirements based on a single email from authors. The School maintains a commitment to open access publication, as evidenced by our 98.8% OA compliance across all publications. We are assisted by the SCOAP agreement, which is an international collaboration in the PP community to convert traditional closed access physics journals to open access. The participating journals cover much of NP and IGR as well.

Our research data management provision comprises an institutional repository and registry that can be used for long-term storage and sharing of data underpinning research publications. We are one of two UK HEIs that are signatories to the Concordat on Open Research Data. To promote

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awareness and compliance with open data policies, PGR students are required to complete a data management plan.

Research Integrity

The School's leadership structure and policies for supporting research integrity have been recognised externally, most recently by the Royal Society, Universities UK, and DORA. Our model is currently being written up as a case study for the UK Research Integrity Office (UKRIO).

2. People

Staffing strategy and staff development

We seek to attract, develop and retain researchers of the highest quality while ensuring that our staff profile strengthens our three research themes. In executing this, we aim to maintain critical mass and continuity in each research group to give a strong, diverse portfolio at the international forefront, with a resilient income stream. We have in place robust and transparent processes for recruitment, career development and progression, and actively promote and monitor equality, diversity and inclusion (ED&I) as a guiding principle embedded in all our practices. This has been recognised by the 2018 renewals of IOP Juno Champion and Athena SWAN Silver under the new charter, which includes technical and professional staff. Since REF2014 we have embedded new ED&I and staff support initiatives, with satisfaction scores in the 2018 University Staff Survey on indicators related to dignity and diversity in the School are 77 - 87%, consistently higher than University and College averages.

Equality, Diversity and Inclusion: ED&I is led by the Head of School and SMT, supported and advised by the Athena SWAN Committee which helps identify and oversee implementation of ED&I initiatives. The Athena SWAN Chair (Equality and Diversity champion) attends SMT meetings 3-4 times annually. Examples of ED&I in the School's culture appear in the narrative below, but a few general aspects are highlighted here. Our visible commitment starts with our annual 'Welcome to the School' event for all new staff and postgraduate researchers, featuring presentations emphasising our ED&I ethos and highlighting flexible working and leave policies. ED&I is a standing item on our twice-yearly research and teaching staff meetings, where Athena SWAN updates, initiatives and staff and student gender statistics are presented and discussed. Our two widely-advertised Equality and Diversity Officers (one a senior Professional and Support staff member) may be approached by staff and students for advice on any issues relating to ED&I. We are preparing for an IOP Juno "Excellence" application and in 2021 we will host the annual Conference for Undergraduate Women in Physics, focused on intersectionality and issues affecting Black and Minority Ethnic women. We lead the 'Cygnet' initiative, launching in 2021 to provide online mentoring for female and non-binary school pupils with a STEM interest, by postgraduate students and staff in the School. Our twitter feed @uofgphysastro and the internal newsletter, highlights events such as LGBTStem week, Black History Month, and staff/student profiles.

Current staffing snapshot: Table 1 shows all REF-eligible staff in the UoA, an increase of 30% since REF2014, from 44.9 FTE to 58.15 FTE, or 46 to 60 by headcount. Of these 60, 51 are Research and Teaching Academics, all on permanent contracts. The high percentage (47% by headcount) of Professors reflects both our current staff demographic, and their recognised research and academic leadership. A further 22% are Senior Lecturers or Readers. 12% are female with four professors (14% of professorial staff), three of whom (Davies, Franke-Arnold, Rowan) are research group leaders, and three are STFC consolidated grant PIs (Davies, Fletcher, Rowan). Among the 9 REF-eligible staff not on R&T contracts, staff, 4 (3M, 1F) hold a prestigious Royal Society University Research Fellowship or an STFC Ernest Rutherford Fellowship, demonstrating our ability to attract researchers of the highest calibre. The REF-eligible staff FTE is 34% international. Another 5 academic staff are on the learning, teaching and scholarship track (20% F).

Role	Number	FTE	F (No.)	F (FTE)	% F	%F (FTE)
Professor	27	26.6	4	4	14.8	15.0
Senior Lecturer/Reader	13	13	2	2	15.4	15.4
Lecturer	11	10.25	0	0	0	0
Total R&T	51	49.85	6	6	11.7	12.0
Research Professor	1	0.3	0	0	0	0
Research Fellow	7	7	1	1	14.0	14.0
Research Associate	1	1	0	0	0	0
Total Research-only	9	8.3	1	1	11.1	12.0

Table 1 REF-eligible staff at the census date by role, headcount and number/percentage of staff identifying as female. R&T indicates academic (Research and Teaching) staff.

The School is home to a further 86 research-only staff by headcount (17% female at the census date), and 143 postgraduate research students (27.3% female at the census date, varying from 23% - 33% over the REF period).

New Academic Staff Appointments: Opportunities and proposals for new academic appointments are developed by the Research and Strategy Committee who consider, among other aspects, how the proposed post develops our research themes, ensures research group viability continuity and future succession, and anticipates or capitalises on new developments and opportunities. Since REF2014 we have made 11 Lecturer appointments, one Senior Lecturer appointment, and recruited one senior Professor (as an LKAS direct appointment; all other positions were open and competitive). This includes active recruitment of academics with a track record of interdisciplinary research (Faccio, Fernandez-Pacheco, Harvey, Taylor). Recognising that our current female academic staff fraction of 12% is low (HESA reports 19% from 2014/15 - 2017/18), since 2018 we have worked with the University's Equality and Diversity Unit to pioneer more inclusive language and an emphasis on measurable, evidenced achievement in all job adverts, recognising that both can encourage a more diverse pool of applicants. We advertise carers' expenses for interviews and emphasise our Athena SWAN Silver and IOP Juno Champion awards.

Progression at all levels: In the REF period, 15 REF-eligible academic staff were promoted internally to Senior Lecturer/Reader and 14 to Professor. Our success rate for academic (R&T) staff promotions, (Table 2) is 83%. The success rate for female applicants, who apply at the same rate as males, is 100%. The corresponding numbers for research-only staff are 94% and 100%. We offer concrete support to staff in their promotion cases. Central to this and instituted in 2015 as part of our Juno Champion action plan is the annual academic promotions workshop. Aimed at academic and research staff, this workshop features case studies presented by male and female staff at different grades, and advice on the procedures and support available in the School. Research group leaders and the Head of School give individual advice on cases.

Role	Promotion applied for	F	M	Success rate F	Success rate M	Success rate total
Research & Teaching	Professor	2	17	100%	71%	74%
Research & Teaching	Sen. Lecturer/Reader	3	13	100%	92%	94%
	All R&T	5	30	100%	80%	83%
Research only	Research Fellow	4	23	100%	91%	93%
Research only	Research Associate	5	12	100%	100%	100%
	All R only	9	35	100%	94%	96%
R&T, R	All applications	14	65	100%	88%	90%

Table 2 Promotion applications and success rates for academic (Research and Teaching) and Research-only staff

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Academic Career Development: The School assists academics in advancing their careers in numerous ways such as: promoting visibility and recognition inside and outside the School and University; developing managerial and other transferrable skills and experience; (competitive) financial support from the Kelvin Endowment Fund for strategic investments in equipment or prestigious projects requiring a 'buy-in'. To assist those with constrained grant income, all staff can apply to the School annually for financial support to present at conferences or attend external CPD events. Help on grant applications, e.g. critical reading, comes from colleagues with panel experience or success on the relevant programme (the School maintains a list) and from a dedicated research support team. The percentage of REF-eligible UoA staff holding grants has been consistently above 90% for the past decade, and in our 2017 internal staff survey 75% of academic staff felt well-supported in their applications.

Within the School, the distribution of jobs such as class head or committee chair or member, is performed with attention both to staff skills and workload, and to the opportunities for career development and promotion that it brings at their career stage.

At the annual Performance and Development Review (P&DR) career development, including formal and informal training and support needs, is discussed with line managers together with setting and revisiting of career objectives. These may be designed with promotion in mind. Key members of the School have participated in bespoke career development programmes organised by the College and University for mid-career staff and "emergent leaders", both as participants and programme leaders.

Early Career Development: New early-career academic staff, and independent research Fellows, participate in the University's Early Career Development Programme. This provides intensive training aimed at promotion to Senior Lecturer/Reader/Senior Research Fellow, within eight years of appointment – achieved by all our enrolled staff. Early-career academics have a mentor from another Research Group, a start-up budget from the School, and have been successful in bids to the dedicated College fund for early-career research support. They have priority access to PhD students, and their teaching and administrative loads are built up gradually over approximately three years, providing experience in different areas of the School's activities. Many of our early-career staff attend a multi-day College Crucible event designed to encourage interdisciplinary collaboration, which includes externally-facilitated sessions on research creativity, pitching a proposal and preparation of high-impact journal articles. All new academics undertake the University's New Lecturer Programme which leads to a Postgraduate Certificate of Academic Practice.

Support of postdoctoral researchers (PDRAs): Support and recognition of PDRAs is central to the School's culture. PDRAs take an active part in career planning, professional development and objective-setting (which can be aligned with promotion criteria) through a formal annual PDRA-specific P&DR with their line manager. They attend the School's annual promotions workshop and are supported in promotion applications by a research-group mentor. 96% of applications have been successful (100% for female applicants, who apply at the same rate as males - Table 2). PDRAs undertake up to 6 hours per week teaching-related duties, with training provided by the School and University to develop relevant skills. They attend University-run courses – e.g. 17 PDRAs (2F/15M) attended a workshop on Fellowship applications in the REF period, with 7 subsequent successes (1F/6M). Many PDRAs attend the University's annual Research Staff Conference, which features talks on research careers, fellowships, funding opportunities, and outreach. The School's PDRA Forum, initiated as an ED&I activity, reports to the biennial Research and Teaching Staff meeting, and has a member on Teaching Committee. The Forum Chair attends SMT every quarter. The principles of the "Concordat to Support the Career Development of Researchers" are strongly embedded in School and University policies and structures, e.g. through the University's Code of Practice for the Management of Research Staff and our appointment of a School PDRA Champion.

Impact and Knowledge Exchange: The University places impact and KE activity, including outreach, on an equal basis to academic publications and grant income at all grades of academic appointment, promotion and Professorial re-zoning. Contributions and achievement in impact are developed and recognised through the P&DR and the Early Career Development Programme. Specific recent examples of impact and KE include: Rowan's role as Chief Scientific Advisor to the

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Scottish Government; Robson's engagement with schools and education policy; Hendry's public engagement leadership and curriculum development activities; Diver's role as Director of Anacail, and Kaiser's as Director of Lynkeos; McGrouther's work with Quantum Detectors and the Medipix detector. The School supports impact-oriented research projects e.g. through strategic allocation of discretionary resources, such as PhD studentships, and targeted support for leveraged external fellowships.

Staff participate in cross-College activities such as SpaceGlasgow, and the Scottish and College Crucibles, designed to develop their creative ideas. The College Business Development team delivers an ongoing program of industrial sandpits where specific companies are invited to be the focus of joint workshops. More generally, to develop a better interface to these mechanisms the School has formed an Industry Liaison Committee to identify and foster new partnerships.

Research students

There are currently 143 postgraduate research (PGR) students enrolled (135 PhD, 8 MSc by research), a 43% increase from 2014/15. These include students on interdisciplinary PhDs mainly supervised by other Schools or institutes. Our network of worldwide collaborations (for example LIGO-India) helps ensure international diversity; by student-year 27.2% of our students come from the EU and 14.1% from the rest of the world (including 1.6% US). Again by student-year, averaged over the REF period 28.5% of PhD students with *primary* supervisors (supervisory load > 0.5) within the School were female.

The SUPA Graduate School: The School was a founder of the Scottish Universities Physics Alliance (SUPA), among the first UK physics research pooling initiatives (starting in 2004) and emulated across the country and across different subject areas. One of SUPA's strengths, as highlighted by the Scottish Funding Council, is its graduate school with videoconferencing to support remote graduate teaching. There are now over 600 participating students across SUPA institutions. The SUPA graduate school provides our PGR students with a strong, supportive and wide-ranging training environment that develops discipline-specific and transferable skills, and complements the training and mentoring provided by the College Graduate school. The SUPA and College Graduate Schools also encourage participation in team-building and social activities, which lead to a greater sense of community and a vibrant, inclusive learning environment.

CDT programmes: UofG leads the EPSRC-funded CDT in Intelligent Sensing and Measurement and is a partner in the STFC-funded ScotDIST CDT in data-intensive science, and the EPSRC-funded CDTs in Applied Photonics (EngD) and in Photonic Integration and Advanced Data Storage. CDTs span our three main research themes, involving students from all research groups. CDT Students experience an extensive programme of cohort-building and transferrable-skills activities with colleagues in partner institutes, in addition to their activities within their research groups. To broaden their horizons, they undertake up to six months of industrial placements, working on projects unrelated to their PhD topic.

International PGR experience: Around 50% of our PGR students spend significant periods on long-term placements at world-leading laboratories and institutes including CERN, NASA GSFC, Jefferson Lab and the LIGO Observatories. This broadens and deepens their work with international collaborators and enhances their first-hand experience of the culture and environment of research at the very highest level. This has strengthened the students' roles within a range of high-impact analyses, including the first direct observations of gravitational waves detected by Advanced LIGO.

Equality and diversity in the PGR population: All PGR students undertake compulsory ED&I training. PGRs sit on the Athena SWAN committee, lead the Women in Physics Group (GUWiP) and are active in promoting LGBTQ+ events and activities, for example attending LGBTSeminar and providing profiles on the @uofgphysastro twitter feed during LGBT History Month. The School's PGR forum, which reports quarterly to SMT helps support and develop ED&I, and the School provides financial support where appropriate, e.g. for GUWiP, and LGBTSeminar attendance.

Unit-level environment template (REF5b)

Supervision and support: The School operates standard good practice in allocating first and second supervisors to research students, with the first supervising the project closely and the second providing more general support. The postgraduate tutor and the Equality and Diversity Officers are also available for advice and pastoral support. In addition to UKRI funds for PhD travel and research support, the School provides a budget to each research group for support of research students and operates a competitive research travel scholarship.

School strategy for PGR growth is to attract the highest quality PhD applicants, including international students with external scholarships, by promoting our strong reputation for world-leading research across a range of fields. Practical mechanisms for this (beyond UKRI doctoral training grants) include: consolidation of existing CDT partnerships (e.g. with Optos, Leonardo, Qioptiq); applications for new, collaborative CDTs aligned with our core research; promotion to staff of prestigious international scholarship programmes such as the China Scholarship Council; engagement with international pump-priming programmes supported via the GCRF and Newton Fund; engagement with industry via e.g. QuantIC and CENSIS, to deliver matched funding of studentships (e.g. Amazon, Clydespace, M-Squared Lasers, Schlumberger), CASE awards; capitalising on the international 'shop window' offered by the SUPA Graduate School for Scottish Physics via the annual SUPA Scholarship competition.

Creating a Supportive Research Environment

Awards and recognition: The Unit holds IoP Juno Champion and Athena SWAN Silver status, first awarded in 2011 and 2013 respectively, and twice renewed. The most recent renewal of Athena SWAN Silver in 2018 was under the new charter, which includes Professional and Support staff. We were the first Physics department in Scotland to receive these awards, and we promote them widely to staff, students, visitors and prospective students, on web pages, at open days, School welcome events and staff meetings. The Athena SWAN committee chair (Fletcher, to 2019) received the Herald newspaper's 'Scotland's Diversity Champion 2017' award and a 'Suffrage Science' Award for Engineering and Physical Science (2017).

Study Leave: Formal study leave for full- and part-time academic staff at all grades is awarded on the basis of specific goals and a plan of work, and a member of academic staff may reasonably expect to have paid study leave one semester in four years or one academic year in eight. Additionally, and less formally, the annual teaching and administration allocation allows staff members where possible to structure their commitments to accommodate research priorities and responsibilities.

Part-time and Flexible working: Information on applying for part-time and flexible working is advertised via the annual School Welcome event and the Staff Handbook, and we have had 100% success with these applications in the review period (2 academic staff, 4 professional and support staff). The School adjusts working patterns according to a staff member's needs wherever possible. Informal flexible working is embedded in the School's culture and is particularly useful in many of our 'Big Science' areas, where global research collaborations may require teleconferences scheduled well outside normal UK working hours. We operate a 'core hours' policy for School meetings, and staff and research students can arrange their duties to accommodate caring responsibilities.

Return to work: The School promotes the College Academic Returners' Scheme to all eligible Staff returning from maternity, shared parental or adoption leave. Up to £10K can be applied for to support the resumption of research (including teaching buy-out). Since the scheme's inception two eligible members of staff (1 Research-only, 1 R&T) have applied, and were approved. Workplace assessments are undertaken by building superintendents and occupation therapy personnel to establish whether any adjustments are required on the return of staff.

Support for carers: The School has a designated Parent and Child room furnished and equipped for feeding, changing, and quiet play. We are supportive of the internal conference support funds, to which academic staff are entitled annually, being allocated to meet additional caring costs (e.g. by contributing towards childcare).

Promoting and celebrating diversity: Activities include displays for the International Day of Women and Girls in Science, twitter campaigns for Black History Month, and to celebrate our LGBTQ+ staff and students, and physics education projects investigating male/female differences in undergraduate learning and experiences. We highlight ED&I at open days, in our advertising material, and in the Head of School message in all undergraduate course handbooks. Information about our two Equality and Diversity officers appears online and on posters throughout the School. Following a pro-active campaign by the organisers, over the REF period our fraction of female colloquium speakers has increased from 13% to 25%.

Health and wellbeing: The School has undertaken several initiatives to help staff and student wellbeing. The Common Room has recently been refurbished, creating a more welcoming space. The Reading Room has been designated as a quiet space in the afternoons, for the benefit of staff and students in shared offices. Several activities to promote (mental) health have been initiated, such as discussions during Mental Health Awareness week, “Mental Health First Aid” courses, professional neck and back massage sessions, and a “Strava” exercise group.

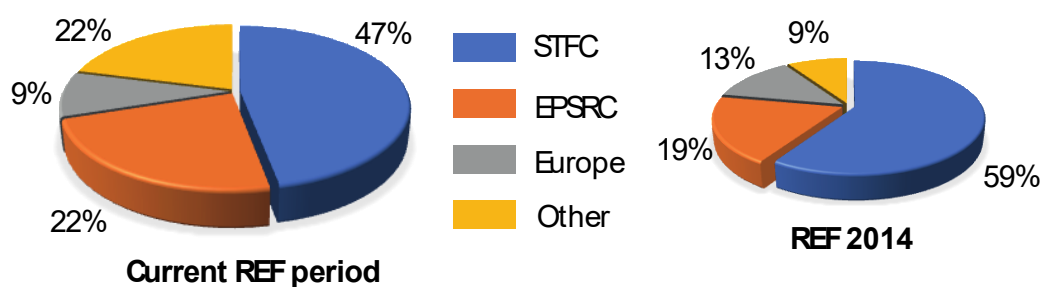
Social Activities: In the last REF period, we established a Social Committee to develop our range of social, networking and well-being activities, including “bring-and-share” lunches, barbecues, excursions and sporting activities. Doughnuts and coffee following colloquia, and MacMillan coffee mornings are a fixture, along with the Christmas Party for children of staff and students and a “Bring your child to work” day. There are frequent informal social gatherings with Research Groups across the School (now active online during the COVID pandemic), enabling conversations outside the hierarchical space of staff and student offices.

3. Income, infrastructure and facilities

Research Funding

In our REF2014 submission the School’s research portfolio was heavily weighted towards STFC-supported funding. Consequently, the School undertook a significant rebalancing of its funding streams, reducing over-reliance on any single funding scheme and encouraging growth across all research themes. Our strategy focussed on achieving sustained income growth across all EPSRC-supported groups – aligning strongly with the Government’s industrial strategy, particularly in quantum technology and advanced materials – while maintaining our STFC strengths. More generally we have diversified our research income beyond STFC and EPSRC to other research councils as well as industry, charities and other non-RCUK/UKRI sources. Our recruitment of Faccio as an LKAS Professor (Dec 17) and Moorsom (RAEng Fellow and proleptic lecturer, Aug 20) were key elements of the strategy developed at the beginning of the REF period.

The success of our strategy can be quantified in several ways. The pie charts below illustrate the volume and distribution of our research income during the current REF period (left chart) contrasted with the equivalent data for FY2012-13, reproduced from our REF2014 Environment Template. The area of each pie chart is proportional to the relevant total amount.



The total volume of the School’s research income has grown to **£79.5M** (left hand chart) during the current REF period, compared with **£49.8M** (right hand chart) reported in REF2014.

Unit-level environment template (REF5b)

Major highlights include funding for QuantIC (phase I and II); UK leadership of ALIGO+, GridPP and ATLAS upgrades at CERN; EPSRC “Physics of Life” programme grant; a New Horizons grant (with two recent hires as PIs: Bennett, Goette); Muon tomography project with the National Nuclear Laboratory (NNL).

The distribution of funding sources has diversified significantly, with the STFC share reducing from 59% in 2012-13 to 47% in this review period. However, our *volume* of STFC income has still grown, and the School is the top 8th STFC-supported department by volume. Meanwhile, the EPSRC share has grown from 19% to 22%. The “other” category, which includes funding from industry, other UK research councils, the Royal Society and charities, has increased from 9% to 22% – with other RCUK/UKRI funding alone now 6.5% of the total.

Our European funding growth has been excellent, mainly through success with Horizon 2020, with £6.99M reported in the current review period, almost 2.5 times the equivalent total for REF2014. Finally, our income from industry has also strengthened – led by our Muon Tomography project with the NNL that has resulted in ~£1m of research income in the present REF period, and the recent establishment of spinout company Lynkeos.

Between 2013-14 and 2016-17 the School retained its position in the Russell Group (RG) upper quartile for income/FTE. The substantial growth in our number of REF-eligible staff (increasing from 48 for REF2014 to 60) has moved the School towards the RG average income/FTE, as our newly-appointed staff fully establish their research portfolios. Fluctuations also arise due to the cyclical nature of our large STFC-supported consolidated grants – although our manifest success in funding diversification will mitigate this going forward. However, the School’s recent awards and applications are at record levels and we anticipate rapid improvement in our RG income/FTE position.

Local Infrastructure and Facilities

Specialist Materials Research Infrastructure: The School houses multiple instruments managed by MCMP, the **Kelvin Nanocharacterisation Centre (KNC)** providing powerful techniques for investigating materials on scales from sub-millimetre to the atomic. These include electron microscopes (SEM and TEM), focussed ion beam (FIB) microscopes and thin-film deposition equipment at a capital cost of £5M, which are available to industry at commercial rates, providing an important user community interface. Funded projects include materials used for: thermoelectrics, magnetic memristors, chiral materials, skyrmions, multiferroics and 3D-nanostructures.

Since REF2014 we have undertaken significant equipment investment and acquisition. In 2016, EPSRC funding of £1.1m was obtained for a Thermo Fisher Xe Plasma dual beam FIB-SEM with EDS (Energy Dispersive X-rays) and EBSD (Electron Backscatter Diffraction Detector). This funding was partly conditional on establishing an external user access scheme which has been successfully implemented locally and nationally. Our TEM imaging has been complemented with an EPSRC ECR capital project to install an electron biprism (£50k) within our JEOL atomic resolution microscope. This allows extremely sensitive phase imaging, ideal for studying nanoparticles.

In 2018 we appointed Senior Lecturer Fernandez-Pacheco who brought equipment from Cambridge University for studying 3D magnetic nanostructures: a magneto-optic Kerr effect (MOKE) system (£75k) plus gas injection systems for making 3D structures in FIB (£25k).

Advanced Detector Development: The PP Experimental group developed and utilised a new clean room as part of the **Glasgow Laboratory for Advanced Detector Development (GLADD)**. This £2m facility provides a unique, backend test facility for silicon detectors, including a state-of-the-art flip-chip bonder and X-ray characterisation units.

Funding from Sellafield Ltd via the NNL enabled the NP group to refurbish a Kelvin Building laboratory to develop and house a 3x3x3m³ muon imaging system. The associated spin-out company, Lynkeos, is the subject of one of our impact case studies, and has resulted not only in demonstration of the technology, but also capacity for scanning test containers for the nuclear industry.

The IGR hosts a variety of precision manufacture, test and measurement facilities housed in a suite of laboratories and clean rooms, offering surface measurement capabilities and environmental testing for space-qualification, including vibration and thermal vacuum equipment, as well as world-class expertise in silicate bonding of composite structures and precision metrology.

Services for non-academic partners: Investment in research facilities has enhanced the School's ability to work with industry. Key services are available to non-academic users through a centralised University interface (<http://tinyurl.com/GUlabs>) and include KNC, GLADD and IGR facilities. These facilities have been used by over 20 companies, ranging from SMEs to internationals such as *Freescale*, *Coherent* and *Texas Instruments*, and organisations such as DSTL. Additional £0.7m investment in imaging laboratories has enabled us to build new collaborations with *Optos*, *Leonardo*, *Qioptiq*, *STMicroelectronics* and *Findlay Irvine*.

Collaboration among research groups: Our vision to operate across research groups in thematic areas such as precision instrumentation and detectors has borne fruit during the REF period. For example, colleagues in the MCMP and PP groups constructed a lab prototype for assessment and exploitation of hybrid pixel detector technology (Medipix3) in electron microscopy. These tests showed significant performance advantages and potential for transformative imaging capabilities. Outcomes were twofold: the successful award of an EPSRC research grant ("Fast Pixel Detectors: a paradigm shift in STEM imaging", Univ. of Oxford) and leadership of a funded (~£200k) programme of technological commercialisation. The former allowed us to gain new insight into materials through developing novel imaging capabilities, producing 3 publications and open source software made available to the community. The latter, with Quantum Detectors Ltd (QD), resulted in a fully-developed commercial detector, installed at UofG and to date purchased by 15 labs worldwide (£1.5m sales revenue). Our relationship with QD continues through an STFC CASE PhD studentship exploring future detector technologies, and through McGrouther serving on QD's strategic advisory board.

Quantum Technology: Our Extreme Light research facility (led by Faccio) is a £1m refurbishment of 120 m² research space, with a 0.5-degree temperature stability environmental control and collaborative space for interdisciplinary research. Its development has spawned activities with two research groups in the School of Engineering and has co-funded laser systems with a group in Engineering and with QuantIC. We have also invested in superconducting nanowire detectors that are underpinning new collaborations with life sciences (deep body infrared imaging) and Engineering (far infrared entangled photon sources for satellite communication). These investments exceed £1m.

National Facilities

High Performance Computing: UofG has been a key player in setting up and running STFC's High Performance Computing Facility, DiRAC, for computations in theoretical particle, nuclear and astrophysics. Davies chaired the Project Board for the first five years (2012-17), as DiRAC was transformed with £15m of Capital funding into a world-class facility (five computers, two in the world's top 100, covering a range of architectures), with competitive open access and hundreds of users, through to its £20m upgrade in 2018.

ScotGRID: As part of the particle physics computing grid, GridPP (project leader Britton), ScotGRID is one of the four regional Tier-2 centres and includes hardware based at the universities of Durham and Edinburgh, as well as UofG. The UofG-based hardware, previously housed in the Kelvin Building, is now being transferred to a bespoke new data centre, part of the UofG campus redevelopment programme. Whilst part of the worldwide LHC computing grid, ScotGRID is also pioneering the widening use of national computing facilities through IRIS, a common infrastructure for STFC science, with our NP group developing Grid computing infrastructure for Jefferson Lab in the US.

RHESSI observations: The AA group maintains a UK X-ray solar observations archive that includes all RHESSI observations since 2002, thereby ensuring UK access to this important legacy dataset.

Unit-level environment template (REF5b)**International Facilities**

The use of international facilities by different research groups ensures our access to state-of-the-art scientific measurement data that enables world-leading scientific outputs.

Use of facilities not supported by Research Councils

The table below shows the UofG 'share' of running costs of overseas facilities used by our staff and provided by non-UK funding sources, either following an explicit competitive bidding process or implicitly through our expertise being sought within international collaborations.

Group	Facility	Total cost	UofG Share	UofG cost
AA	RHESSI (2014-2018)	\$2m p.a.	10% by authors	\$200k p.a.
IGR	Advanced LIGO	\$47.3m p.a.	5% by members	\$2.4m p.a.
IGR	GEO	350k€ p.a.	20% by members	70k€ p.a.
NP	Jefferson Lab, US	\$6m p.a.	5% by authors	\$300k p.a.
NP	Mainz, Germany	£1m p.a.	15% by authors	£150k p.a.
MCMP	ALBA Synchrotron, Spain	n/a	15 days	200k€
MCMP	Swiss Light Source, PSI	n/a	10 days	134k€
MCMP	SOLEIL, France	n/a	10 days	134k€
PP	Summit Oak Ridge, US	\$1.64m (CallAT)	7% by members	£115k

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

The UoA is playing a central role at the local (UofG), national and international level through its contributions to the research base and society in a number of areas. Rather than provide a simple list, we identify three of these areas (also showcased as “research highlights”, page 2) that are representative of our contribution to the research base and highlight some of the broader context and collaborative nature of our work.

1) Gravitational waves – LIGO and LISA

Overview: LIGO and LISA are two complementary, global projects central to the current and next generation of gravitational-wave astronomy, with ground-based and space-based detectors respectively. These projects represent two of the highest precision scientific experiments ever conceived.

Local contributions: UofG leads the £10.7 million UKRI-award (2019, PI Strain) contributing to the Advanced LIGO Plus upgrades. For LISA, projected costs of the UK Optical Bench development, through to launch in 2034, are ~£33M, with about one third expected to come through UofG.

National contributions: UK PI-ship for LISA has been with UofG (Ward) and was transferred (2020) to Fitzsimons (former UofG PhD student) at UK-ATC (Edinburgh) where the final LISA Optical Bench construction will take place. UofG and ATC now act as a single team with some components to be developed and assembled in UofG. Rowan is part of the UK Scientific Advisory Group for Government Emergencies (SAGE), representing the Scottish Government, and is Adviser to the UK quantum technologies Program Board.

International contributions: UoA members hold many international leadership roles that demonstrate wider economic and research community influence. The following are key examples. Rowan: Chair, Advanced Virgo+ International Review Committee; Adviser to the LIGO Director on the LIGO Observatories Programme; (re-)elected Gravitational-Wave International Committee Chair and spokesperson for the global field, particularly in advocacy with international agencies and Ministries; appointed by the Presidents of Leibniz Universität Hannover, TU Braunschweig, and the Physikalisch-Technische Bundesanstalt as Adviser for the QuantumFrontiers consortium. Heng and Hammond are UK PIs for the GCRF-supported GrEAT Network and Newton Bhabha Partnership, to enhance training and build capacity in research, outreach and innovation between the gravitational-wave community in the UK and in China and India respectively. Three former IGR researchers hold

Unit-level environment template (REF5b)

leadership positions with the 1000+ person LISA Consortium (Hewitson, Consortium Coordinator; McNamara, LISA Pathfinder Project Scientist; Jennrich, LISA Project Scientist) and Ward is a member of the LISA Consortium Executive Board. Examples of industrial and economic impact include deployment of IGR-developed MEMS-based gravitational sensors to field-trial geological measurements on Mount Etna (Hammond); collaboration with Optos, who have used IGR-developed data analysis techniques to improve medical imaging capabilities, now a School impact case study (Heng); adoption of the UofG platform for the LISA Optical Bench, resulting in the UK being supplier of this crucial LISA system.

Academic recognition: The UofG team has received numerous collective awards including: Princess Asturias Award, Bruno Rossi Prize, RAS Group Achievement Award, Physics World Breakthrough of the year (2017); Science Magazine Breakthrough of the year, Physics World Breakthrough of the year, Special Breakthrough Prize in Fundamental, Gruber Cosmology Prize (2016). All IGR Academic Staff were awarded the Royal Society of Edinburgh President's Medal (2016). Personal awards include: Hammond - Wolfson merit award (2019), Fellow Royal Soc. Edinburgh (2018); Hough – Royal Society Bakerian Medal and Lectureship (2019), Honorary Fellowship of the Royal Scottish Society of Arts (2019), Knight Bachelor (2018), Gold Medal of the Royal Astronomical Society (2018), Edison Volta Medal and Prize of the European Physical Society (2018), Honorary D.Sc. University of Edinburgh (2017), Royal Society of Edinburgh Royal Medal (2016), Honorary Fellowship of the Institute of Physics (2016), Phillips Award of the Institute of Physics (2015); Rowan – Sackler Lecture, Univ. of Cambridge, Honorary Fellowship Institute of Physics, Honorary DSc University of Strathclyde, Honorary DSc Robert Gordon's University, The Baird of Bute Innovation Award, Suffrage Science Award for Engineering and Physical Science LIMS/Medical Research Council (2017); Kelvin Medal Royal Phil. Society of Glasgow, Hoyle Medal of the Institute of Physics, Innovation Award: Scientific Breakthrough Wired Magazine/Audi (2016); Berry – IoP Astroparticle Physics early career prize (2018).

Public Engagement: Hendry is the Chair (since 2017) of the Communications and Education Division of the 1400-strong LIGO Scientific Collaboration. His work on international outreach is the basis of one of our Impact Case Studies. We are engaged in significant international outreach, again resulting from our high profile in GW research. For example, Rowan was the 2015 The Cockcroft and Walton Lecturer, India, resulting in a multi-state lecture tour, and was also the 2014 Australian Institute of Physics Women in Physics Lecturer. Hendry was awarded the Royal Society Senior Public Engagement medal (2015), the MBE (2015) and CBE (2021) for services to science.

2) The Quantum Imaging Centre - QuantIC

Overview: QuantIC is one of the UK four research Hubs in Quantum Technologies and is devoted to the development and exploitation of quantum technologies for imaging. The QuantIC PI (Padgett) and one other co-I (Faccio) are from the School.

Local contributions: Within UofG, QuantIC has intensified the School's engagement beyond physics, with increased investment in Engineering and in Computing Science. Long-term and stable research collaborations now exist with these disciplines, e.g. several co-supervised PhD students and a School LKAS fellow currently based in Computing Science, thus strengthening the link between Schools.

National contributions: QuantIC involves multiple UK partners (Bristol, Strathclyde, Heriot-Watt, Edinburgh, Imperial, Exeter) and is currently investing resources into attracting additional new UK partners. Phase 2 of QuantIC has been funded (start date 1st Dec 2019), and includes more emphasis on attraction of new academic groups, with a first round of funding assigned from the "QuantIC Innovation fund" (at the time of writing) to two new research teams. Others will follow as the programme moves forward.

QuantIC Business Development Managers have worked in close collaboration with UoA researchers, bringing industrial funding and engagement, e.g. Franke-Arnold with *Gooch & Housego* on light shaping elements for microscopy; Faccio holds a patent and ongoing activity with

Unit-level environment template (REF5b)

IDQuantique, Thales, DSTL, Caledonian Photonics and Photon Force; Padgett with M-Squared, on single-pixel cameras, e.g. for gas sensing.

The UoA (Faccio, Harvey, Taylor) is also leading the deployment of quantum imaging technology to: fluorescence lifetime imaging and optogenetic control of cancer cell collectives, together with Engineering and the Cancer Research UK Beatson Institute, with six academics, six PDRAs and four PhDs; a recent Healthcare Technologies 2050 Program grant (quantum sensing for next-generation homes) brings together the UoA, Engineering, Computing Science and UofG Medicine researchers, together with practising GPs.

International contributions: The four UK Quantum Hubs have served as a model for the rest of the world. Indeed, The UK Quantum Hubs were the first to be implemented worldwide. Three years later the EU introduced their Quantum Flagship programme and 5 years later the USA initiated their own quantum programme with the creation of excellence centres, replicating the UK strategy. QuantIC has also extended influence internationally e.g. through research in MEMS devices for ultra-sensitive gravity sensors currently deployed on Mount Etna (Hammond).

Academic recognition: Key indicators of success are: Faccio - Fellow of the Royal Soc. of Edinburgh (2018), Fellow Optical society of America (2019), Philip Leverhulme Prize in Physics (2017), Royal Society Senior Public Engagement medal (2017); Padgett - Kelvin Medal, Royal Society of Edinburgh (2014), Prize for Research into the Science of Light, European Physical Society (2015), Max Born Award, OSA (2017), Rumford Medal, Royal Society (2019), Optics and Photonics Prize IoP (2020); named by Web of Science as a globally highly-cited researcher (2019 and in 2020, one of only seven in the physics category in the UK). Barnett - Royal Society Professorship (2015), Faculty of Nuclear Sciences and Physical Engineering Medal, Czech Technical University, Prague (2015); Goette – Visiting Professor at Nanjing University; Editorial Board member IOP Journal of Optics, Journal of Optics Communications; Croke – Associate Editor NPJ Quantum Information, Emmy Noether Visiting Fellow, Perimeter Institute (2020/21); Courtial – Feature Editor, Journal of the Optical Society of America.

3) Particle Physics, Higgs and CERN

Overview: Our Particle Physics Group has a long record of construction and exploitation of experiments at CERN and other accelerator labs around the world, in related detector R&D and computing, and in lattice QCD and collider phenomenology. Our programme of detector development not only underpins our participation in collider experiments and the discovery and measurement of the Higgs boson, but also feeds our flagship knowledge exchange programme (O'Shea).

Local contributions: UofG has continued to invest in the Glasgow Laboratory for Advanced Detector Development (GLADD), for example adding flip-chip bonding and X-ray characterisation facilities (£650k). Collaboration with the UoA's unique electron microscopy facilities has led to spinout applications of Timepix- and Medipix3-based detectors, resulting in a Transmission Electron Microscopy system being licensed to and sold by Quantum Detectors Ltd. Medipix is one of CERN's most successful examples of knowledge transfer and has triggered a significant number of commercial activities in a range of application areas, including medical imaging, space dosimetry, education, and material analysis.

National contributions: The group works closely with the other UK institutes on the energy-frontier experiments ATLAS and LHCb at CERN's Large Hadron Collider (LHC), and the UoA provided the UK PI for the ATLAS Experiment up until 2019 (Buttar). Generic computing for the LHC and elsewhere is an essential activity in the LHC exploitation era, and our experimental work is further strengthened by leadership in e-Science. The GridPP project, a consortium of 19 institutes UK-wide that provides computing resource for particle physics, is led by a UofG PI (Britton) who also represents the UK on the Worldwide LHC Computing Grid Management Board and is a member of the UK e-infrastructure Project Directors Group. Davies chaired (2011-17) the STFC DiRAC facility providing resources for 700 physicists from 27 institutions. O'Shea sits on the Scientific Advisory

Unit-level environment template (REF5b)

Boards for *Scintacorp* and *Photonic Sciences* (UK) and *Precision X-ray Irradiation Corp* (USA). As a further example of KE, the group developed a Timepix1-based detector combined with CZT material for high-efficiency reconstruction of gamma fields for nuclear decommissioning applications, and the technology has been licensed to *Kromek Group plc* for commercial exploitation.

International contributions: In the last two years the UofG group has seen milestones in two of our long-standing efforts to discover particular new production and decay mechanisms of the Higgs boson at ATLAS (production with a top-quark pair; production with a W or Z boson; and decay to b-quarks), while also discovering new states at LHCb including the first doubly-charmed particle (Ξ_{cc}). Englert (theorist) was co-chair of the LHC Higgs cross-section working group (2014-17). In the last six years, four of our PhD students have been fully-funded by CERN. The group is collaborating with institutes worldwide, and industrial partners such as *Micron Semiconductor (UK)* and *Advacam*, in the construction of silicon tracking system upgrades for ATLAS and LHCb at CERN. Buttar is the global Project Leader for the ATLAS Pixel detector upgrade, due to be installed in 2026. Looking to the longer term, one of CERN's two main options for the next generation of particle accelerator is the Compact Linear Collider (CLIC), and Robson is the scientific leader of the Detector & Physics collaboration (CLICdp).

Academic recognition: As evidence of its success, the group currently includes three Royal Society URFs and an STFC ERF. Other examples are: Robson - CERN Scientific Associateship (2018-19); Doyle - Royal Society of Edinburgh Kelvin Prize (2016); Robson - elected Fellow of Royal Society of Edinburgh (FRSE) (2020); Davies - elected Fellow of the American Physical Society (2016) and Honorary Fellow of the Institute of Physics (2017); MacGregor - European Physical Society Achievement Award (2016); Mahon - Royal Society of Edinburgh Enterprise Fellow (2017), STFC Innovation Fellow (2018).

Engagement with the Physics Research Community and Other Indicators of Wider Influence

Science Policy: Rowan was appointed as the Chief Scientific Adviser (CSA) for Scotland in June 2016. The CSA is responsible for informing policy development to benefit the economy, people and environment of Scotland. She works closely with the Scottish Science Advisory Council, of which she is an *ex officio* member, to advise the Scottish Government across all areas of its work. She chaired the stakeholder external advisory group, providing advice on the development of the Scottish Government's STEM Education strategy, and currently chairs the external advisory board on implementation of the strategy. Rowan is also UK CSA Champion for Quantum Technology, chairing the program board of the UK National Quantum Computing Centre and represents the Scottish government in the UK Scientific Advisory Group for Emergencies (SAGE).

Participation on research council decision-making: Ireland is a member of STFC's Science Board and Davies was also a member (2015-2018). Rowan is a member of STFC Council. Members of the school have served on grant assessment panels in STFC, EPSRC, UKRI and beyond: MacGregor (STFC Nuclear Physics Grants Panel chair, 2015-2018); Diver (UKRI FLF Sift Panel Deputy Chair); Fletcher (Vice Chair STFC Astronomy Grants Panel 2017-19); Hendry (UKRI Hawking Fellowships Co-Chair, 2020); Barnett (Royal Society, Chair of Wolfson committee); Padgett (REF 2021 sub panel Chair, Leverhulme Research Awards Advisory Committee, Paul Instrument Fund, Blavatnik awards committee, Chair of Hong Kong REF panel, IoP Medals committee); Buckley (UKRI FLF, STFC Particle Physics Consolidated Grants, STFC CERN Fellowships Panel Chair); Seitz (STFC Nuclear Physics Advisory Panel, Cancer Detection Network); Owen (Royal Society Newton International Fellowship Panel); Hammond (STFC Ernest Rutherford Fellowships, Global Challenges Research Fund); Englert (STFC Particle Physics Consolidated Grants); Bouchard (STFC DiRAC Resource Allocation Committee).

International Advisory Roles: Since most of the UoA's research programmes are international in scope, we benefit from knowledge and experience gained by staff involved in international advisory roles. For example, Rowan is the elected Chair (2015-19) of International Union of Pure and Applied Physics (IUPAP) working group 11 – the Gravitational Waves International Committee (GWIC) – and a member of IUPAP working group 10 – the Astroparticle Physics International Committee (APPIC). Ireland is a member of the Nuclear Physics European Coordinating Committee (NuPECC) and the

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Mainz Mikrotron (MAMI, Germany) Programme Advisory Committee, resulting in key roles for determining European strategy for nuclear physics research. Kaiser's secondment to the International Atomic Energy Agency (IAEA) resulted in the development of applied nuclear physics projects and links to placements for students. Fletcher is a member of ESA's Solar System Exploration Working Group and was President of the International Astronomical Union's (IAU) Commission E1 on Solar Activity and, with Kontar, member of the steering committee of IAU Division E (Sun and Heliosphere).

Fellowships: During the REF period we have been awarded 2 Royal Society Research Professorships (Barnett, Padgett), 4 Royal Society University Research Fellows (Buckley, Hannah, Howarth, Owen), a Royal Academy of Engineering Chair in Emerging technologies (Faccio), 2 STFC Rutherford Fellowships (Montgomery, Milligan), 1 EPSRC Early Career Fellowship (Fernandez-Pacheco), 5 Leverhulme Fellowships (Boldrin, Butera, Croke, Moreau, Santacana), 1851 Fellowship (Westerberg), 4 EU Marie Curie Fellows (Defienne, Moreau, Muellenbroich, Keitel). In addition to the FRSE elections named above, Fletcher and Kaiser were elected FRSE, bringing the School's total to 12 FRSE, together with 4 Fellows of the Royal Society.

Institute of Physics (IoP) and Royal Astronomical Society (RAS): Most staff in the school are either Fellows or Members of the IoP and RAS. Rowan is the IoP President-elect, and Hendry (IoP Council Member) and Hammond are previous and current IoP Scotland Chair. Fletcher is Senior Secretary of the RAS. By maintaining these high-profile positions, we contribute strongly to the work of the national learned societies, which is especially important when requests for scientific input to political consultations are required.

Beyond the three areas detailed above, other key examples of industry partnerships include: working with the *National Nuclear Laboratory* in a £1.8m, 4-year programme to adapt our muon-detector technology for monitoring intermediate-level radioactive waste; an ultra-high bandwidth computer network developed in partnership with *Extreme Networks*, which was commercialised and nominated for an industry prize; transfer to the photonics industry of optical-interferometer technologies developed by the Institute for Gravitational Research - e.g. optical-bonding technology to *Gooch & Housego*; on-going collaborations (dating from 2005 and transferred to UofG by Harvey) with *Qioptiq*, *Leonardo*, *STMicroelectronics* and *Optos* for exploitation of computational imaging – e.g. miniaturisation of consumer imaging and aberration-free military imaging. Hammond now has ongoing projects with *Clydespace*, *Bridgeporth*, and *DSTL* amongst others.