Institution: University of St Andrews

Unit of assessment: UoA 9: Physics

Section 1. Unit context, research and impact strategy

Unit context

The School of Physics and Astronomy at the University of St Andrews aims to undertake world-leading curiosity-driven research which both pushes the boundaries of fundamental science and achieves high impact. The School has 40.8 FTE Category A staff, whose research is focussed in three areas of excellence:

- Astrophysics
- Condensed Matter Physics/Physics of Quantum Materials
- Photonics

We have invested £15M building research facilities of international distinction to support these core areas, and accelerate impact through collaborations nucleated in seven interdisciplinary Centres and Institutes. The School is an active partner of the Scottish Universities Physics Alliance (SUPA), gaining critical mass, shared facilities and graduate school training. Our formal research partnerships now extend across the world, providing excellent training for early career researchers and leading international projects. Our research culture is anchored in an inclusive and supportive environment that values equality and diversity, reflected in the School's achievement of Juno Champion and Athena Swan Silver awards.

Research priorities

Staff listed with a star (*) are attributed to two of our priority areas, with two stars (**) are on joint appointment with other institutions and with a hash ($^{\#}$) submitted through other Schools. Appointments since last REF in ***bold****.*

Astrophysics

Staff: 12.8 FTE (Bonnell, Cameron, Cyganowski, Dominik, Helling, Horne, Jardine, Scholz, Tojeiro, Weijmans, Wild, Woitke, Wood, Zhao)

Evidence of vitality: Weijmans (Leverhulme Early Career fellowship) and Tojeiro (STFC Ernest Rutherford fellowship) have been promoted from advanced fellowships to Reader positions.

Major grants: ERC grants (3), an EU/FP7 grant (1), an H2020 Marie-Curie ITN (1), STFC consolidated grant

Distinctive facilities: James Gregory telescope (largest operating optical telescope in the UK), three 1m robotic telescopes in Chile, Australia and South Africa (SUPAscopes)

Selected research highlights: discovery of the two closest Earth-analogue rocky planets (Cameron, Nature Astronomy 2017), the first detection of a ring system around an asteroid (Dominik, Nature 2014), the first detection of relativistic deflection of light by a star other than the sun (Dominik, Science 2017), role of AGN in star formation (Weijmans, Nature 2016; Wild, Nature Astronomy 2019), discovery of brown dwarfs in massive star forming regions (Scholz, MNRAS 2017 (Figure 1)), use of baryonic acoustic oscillations to test General Relativity (Tojeiro, MNRAS 2017).

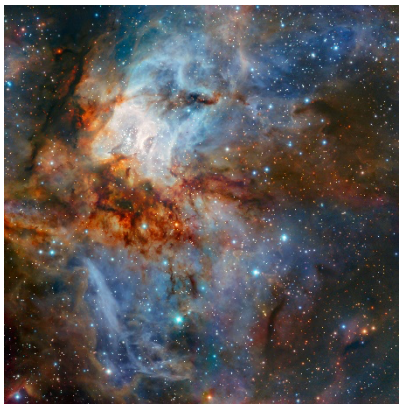

Figure 1: The star cluster RCW 38 imaged by ESO's Very Large Telescope as part of the brown dwarf survey (Credit: ESO/K. Muzic).

The research strategy of our Astrophysics group is to address some of the key questions about our Universe and the origin of life, for example what is the nature of dark matter? Are there exoplanets which host or are suitable for life? To achieve this, we combine observational research with advanced modelling

from the largest scales in the universe, galaxy evolution and cosmology, to the intermediate scales in molecular clouds and star formation, to the small scales in protoplanetary disks, stellar activity, and exoplanets. In our interdisciplinary **Centre for Exoplanet Science**, astrophysicists work with philosophers, biologists, geologists and linguists to identify and characterise new planets around distant stars, their environmental conditions and the possibility of extra-terrestrial life. Several of our Astronomers (Cameron, Wild, Scholz) are members of the **Institute for Data-Intensive Research** to explore new methodologies in scientific research in the era of Big Data.

Members of the group have leadership positions in several international collaborations (e.g. HARPS-N, CHEOPS (Cameron); SDSS-IV, MaNGA, WEAVE-Apertif (Weijmans); DESI, eBOSS (Tojeiro), MiNDSTEp (Dominik), JWST-NIRISS (Scholz), VLT (Wild)).

Condensed Matter Physics

Staff: 12.5 FTE (Braunecker, Cassettari, di Falco[*], Grigera[**], Höfling[*,**], Hooley, **Jagadamma**[*], Keeling[*], King, Lee, J. Lovett[*], Mackenzie[**], **Ohadi**[*], **Rhodes**, **Rost**, Samuel[*], **Schulz**[*], Smith[*], Wahl)

Evidence of vitality: Rost joined with an EPSRC early career fellowship. Lovett and King hold Royal Society URFs and King a Leverhulme Leadership award. Rhodes holds an 1851 fellowship.

Major grants: EPSRC programme grant (1), ERC starting grant (1), EPSRC fellowship (1), Royal Society URF (2), Leverhulme Leadership award (1), 1851 Fellowship (1), EPSRC standard grants (3), EPSRC strategic equipment grants (3)

Distinctive facilities: Ultra-low vibration laboratory with a suite of scanning tunnelling microscopes, Spin- and Angular-resolved Photoemission, Reactive oxide and chalcogenide molecular beam epitaxy, materials characterization suite (MPMS, PPMS, thin film x-ray, Nanoprobe)

Selected research highlights: new tools for imaging of correlated and emergent states in quantum materials at the atomic scale (Wahl, Science 2014 (Figure 2); Davis & Mackenzie, Nature 2016), uniaxial strain tuning as a new method, developed in St Andrews, to control the ground state of materials (Mackenzie, Science 2014, Science 2017), giant Rashba spin-splitting at the surface of a correlated oxide (King & Mackenzie, Nature 2019) and stabilization of magnetism at molecular interfaces of non-magnetic materials (Lee, Nature 2015).

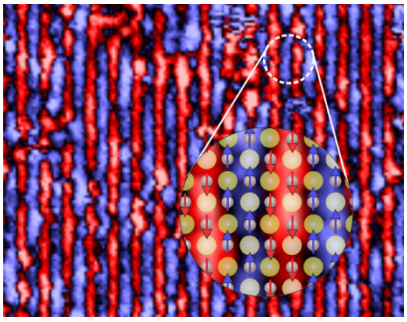

Figure 2: Atomic scale image of magnetism in a quantum material [Science 2014].

Our research strategy in condensed matter physics uses fundamental research into quantum materials using advanced spectroscopic probes and bespoke instruments to identify new ways to control the properties of quantum materials and opportunities for new technologies. These activities are concentrated in the **Centre for Designer Quantum Materials** (CDQM) which hosts world-leading facilities, unique in the UK, benefitting from an overall investment of more than £10M, all interconnected enabling transformative research into quantum materials in bulk and thin-film form. The overarching vision of the CDQM is to translate the exciting properties of quantum materials from research to applications by bringing together researchers from Physics, Chemistry and Engineering. While the research is fundamental in nature, it has resulted in successful commercialization of advanced instrumentation, for example through the spin-out company Razorbill Instruments.

Photonics

Staff: 15.5 FTE (Brown, Dholakia, di Falco[*], Gather, Harwell, Höfling[*,**], **Jagadamma**[*], Keeling[*], König, Korolkova, B. Lovett, J. Lovett[*], Mazilu, O'Faolain[**], **Ohadi**[*], Penedo[#], Robertson, Samuel[*], **Schubert**, **Schulz**[*], Smith[*], Turnbull)

Evidence of vitality: new hires Ohadi and Schulz, Jagadamma has secured a UKRI FLF. J Lovett holds a Royal Society URF, Schubert a Dorothy Hodgkins fellowship and Harwell an EPSRC fellowship.

Major grants: EPSRC programme grants (2), ERC grants (3), H2020 FET and Industrial Leadership grants (2), Royal Society URFs (3), UKRI FLF (1), JSPS core-to-core grant (1), EPSRC standard grants (3), Capital for eight great technologies (1).

Distinctive facilities: 2 clean rooms for nanofabrication and optoelectronic devices, femtosecond spectroscopy facility, 1000 m^2 of photonics laboratories.

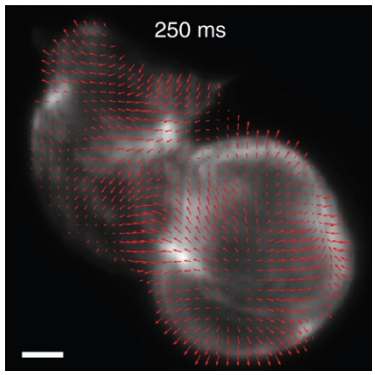

Figure 3: Zebrafish heart imaged with Lightsheet Microscopy [Nat. Meth. 2014] and held using acoustic confinement [Nat. Commun. 2019].

Selected research highlights: Light Sheet Microscopy using airy beams (Dholakia, Nature Methods 2014, Figure 3), electric pumping of exciton-polaritons in carbon nanotubes (Gather, Nature Materials 2017) and observation of non-hermitian behaviour in exciton-polariton resonators (Höfling, Nature 2015), development of elastic resonator interference stress microscopy to study cellular forces (Gather&Schubert, Nature Cell Biology 2017), demonstration of photon-mediated interactions in multimode cavity QED (Keeling, Phys. Rev. X 2018) and of an electric switch based on an optically trapped polariton condensate (Ohadi, Nature Materials 2016), realization of an organic vortex laser (Dholakia, Samuel&Turnbull, ACS Nano 2018)

Our photonics research has developed from a core of laser physics to a portfolio spanning biophotonics, organic semiconductors, nanophotonics, metamaterials, quantum optics, advanced imaging and metrology, and communications.

We have strategically developed activity in photonic materials and light-matter interactions, further strengthening this direction following appointments of Höfling, B. and J. Lovett in 2013, by recruiting Schulz and Ohadi. In the **Organic Semiconductor Centre** (OSC), with close links to Chemistry and Biology, we explore organic optoelectronic materials and their applications in sensing, communications and biophotonics.

Within the **Centre for Biophotonics** and through the **Mackenzie Institute for Early Diagnosis**, we actively pursue interdisciplinary avenues to apply our expertise in photonics to problems in biology and medicine. We have built strong international links through a partnership with Harvard Medical School (Gather) and a Global Challenges Research Fund project on using light sources to kill parasites and fungal infections (Samuel). Our research benefits from a suite of electron paramagnetic resonance (EPR) spectrometers, including world-leading mm-wave instrumentation (Smith, Robertson) and EPR techniques (J Lovett) for structure determination of proteins, providing a major facility for the **Centre for Magnetic Resonance**.

Research and Impact Strategy

The foundation of our research and impact strategy is to capitalize on the agility afforded by being a small School to undertake excellent world-leading research and promote interdisciplinary collaborations for accelerated impact. To realize these ambitions, we have organized our research in multidisciplinary centres to build critical mass and accelerate impact.

Creating Centres of Excellence

Our research activities nucleate around seven interdisciplinary centres and institutes (see Figure 4):

- The Centre for Magnetic Resonance (CMR, founded in 2009)
- The Organic Semiconductor Centre (OSC, 2010)
- Institute for Data-Intensive Research (IDIR, 2014)
- The Centre for Exoplanet Science (CES, 2016)
- The Centre for Designer Quantum Materials (CDQM, 2019)
- The Centre of Biophotonics (CB, 2019)
- The Mackenzie Institute for Early Diagnosis (MIED, 2019)

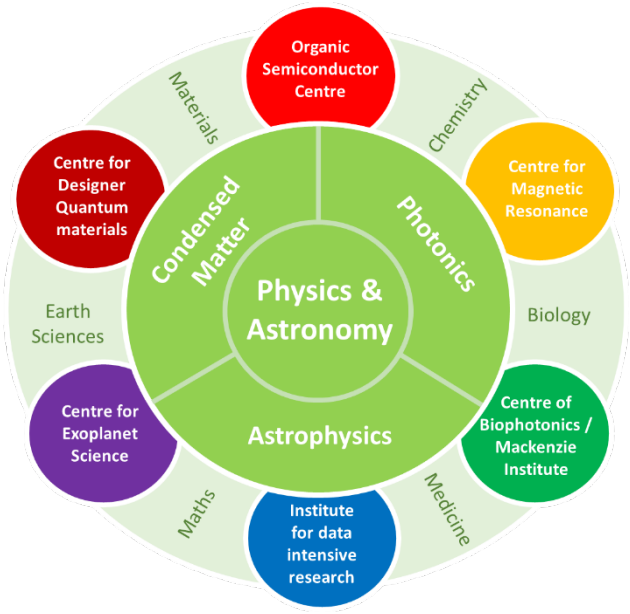

Figure 4: Interdisciplinary links of the Centres and Institutes in the School of Physics and Astronomy.

These centres and institutes provide a stimulating research environment and create international visibility and hubs for international and interdisciplinary collaboration. They are core to our research and impact strategy and tie into the University's interdisciplinary research priority areas (see Institution-Level environment statement, ILES, 2.5).

The centres build on substantial strategic investment in the research infrastructure (more than £18M investment since August 2013), strategic recruitments (since 2012 Braunecker, Gather, Höfling, King, J Lovett, B Lovett, Ohadi, Schulz, Wahl) and have attracted multiple fellows (Harwell, Jagadamma, Rhodes, Rost, Schubert). The investments include new Ultra-Low Vibration laboratories, Cleanroom and nanophotonics facilities, a molecular beam epitaxy lab for the growth of designer oxide heterostructures, and new facilities for spin- and angular-resolved photoemission and thin-film characterization.

From national leadership to international champion

At the beginning of the REF period, a focal point of our activities was our research partnership with the School of Physics and Astronomy in Edinburgh (PHYESTA), founded in 2010, with strong collaborative activities:

- the foundation of twin Centres for Exoplanet Science to study the abundance, formation and structure of exoplanetary systems.
- a Doctoral Training Centre (led by St Andrews, with Edinburgh, Heriot Watt) in condensed matter physics.
- major EPSRC-funded research activities through an EPSRC programme grant, hosted in St Andrews with Edinburgh as a key partner, and a standard grant (Wahl, Stock, EPSRC)

The research links built through PHYESTA remain an important element of our environment, but we have grown a wider portfolio of strategic partnerships in line with our strategic vision. Through our centres, we have built formal collaborations with international peers, including:

- an international research programme on new organic light emitting materials funded through a JSPS core-to-core programme with Kyushu University (OSC, Samuel)
- an International Max Planck Research School in the Physics of Quantum Materials, with TU Dresden, the Max Planck Institute (MPI) for the Chemical Physics of Solids and the MPI for the Physics of Complex Systems (CDQM).
- pan-European training and research programmes funded through a Marie-Curie ITN on exoplanets (CES, Helling) and a Quantera consortium (Korolkova), both led by St Andrews

- participation in major European grants PROSCOPE and DynAMic to use advanced optical techniques for diagnosis with partners in Germany, France, Greece, Austria and Ireland (CB&MIED, Dholakia)
- close collaboration with four Max Planck Institutes (MPIs of Solid State Physics, of Light, for the Chemical Physics of Solids, and for Physics of Complex Systems) in an International Max Planck Partnership (CDQM)
- a collaboration funded by the Human Frontiers Program with Harvard Medical School and University of Cambridge (CB&MIED, Gather).
- Leadership in the recently launched CHEOPS exoplanet space mission (CES, Cameron)

Evidence of the increased internationalization is the number of joint publications with overseas partners (Figure 5).

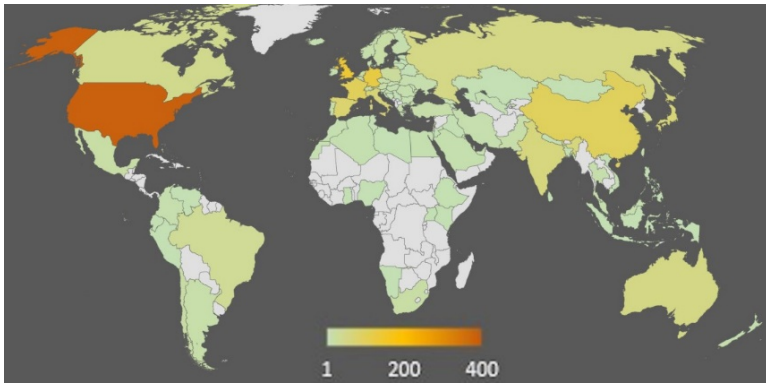

Figure 5: National and international partners in joint publications of the School of Physics and Astronomy.

Strategic growth

We aim to strategically grow our interdisciplinary centres through targeted recruitments and attracting independent fellows with a view to enable the transformative technologies promised by our fundamental research, building critical mass, capitalizing on synergies and strengthening links between our Centres and to other disciplines. Focus areas for strategic expansion include:

- From advanced quantum materials to technology: Creating prototype devices from the materials developed in the Centre for Designer Quantum Materials enables entirely new science, and is the first step on a route to electronic devices based on these.
- Use our expertise in biophotonics for applications in early diagnosis and treatment of diseases through a joint appointment with the Schools of Medicine and Biology.
- Link our activities in photonics and energy materials with the University's new Eden Campus (ILES, 2.1), and explore the Physics of Sustainable Energy with direct links to the Organic Semiconductor Centre.

Part of this ambitious strategy will be a major refurbishment and extension of the School's J F Allen building to create the space and modern research infrastructure for our growth. Through our strategy, we aim to facilitate excellent research, maximize opportunities to bid for strategic investments and accelerate impact, while being mindful to sustain and enhance our inclusive and supportive environment, promoting equality and diversity.

Accelerating Impact

Our interdisciplinary centres encourage translation of results from fundamental research to more applied disciplines and provide a point of contact for industry. Testament of the success of this strategy are three of our four impact case studies (ICSs Samuel, Smith and Dholakia) that have emerged from activities in our Centres. Several of our Centres have dedicated strands that pursue commercialization and activities with relevance for industry (Figure 6):

- The Organic Semiconductor Centre develops new application fields of organic semiconductors, and has been highly successful in realizing economic and societal impact (e.g. ICS Samuel).

- The Centre for Designer Quantum Materials works closely with industry partners (e.g. Razorbill Instruments, Pyreos) to identify routes towards commercialization of advanced instrumentation and applications of quantum materials.
- High-frequency antennas, developed in our Centre for Magnetic Resonance, have been commercialized (ICS Smith).
- The Centre of Biophotonics has been actively pursuing commercialization through collaboration and spin-outs (Bespoke Photonics, ICS Dholakia).

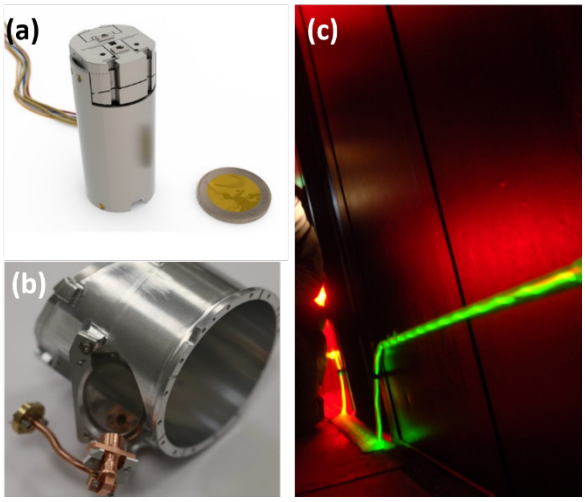

Figure 6: Highlights illustrating the impact of our research: (a) strain cell from St Andrews spin-out Razorbill Instruments, (b) high-performance reflector antenna for the TROPICS CubeSat constellation with dual-band feed (ICS Smith), (c) side-emitting fibres for safety applications (PhotoSynergy, ICS Dunn). Image Credits: Razorbill Instruments, Thomas Keating Ltd., PhotoSynergy.

Our strategy has provided a supportive and fertile environment for translating our research to applications and in realizing technological and economic impact (see highlights in Figure 6), including the following examples that are in addition to the impact case studies:

- two spin-out companies, Razorbill Instruments Ltd and Bespoke Photonics, making specialized scientific instrumentation
- long-standing close collaborations with a number of companies (M-Squared Life, PhotoSynergy (ICS Dunn), Ambicare Health, Thomas Keating Ltd., KP Technology)
- 355 patent applications filed by or granted to members of the School of which 78% are licensed. Our royalty income of more than £2M includes license deals with
    - Elliott Scientific (Dholakia)
    - Sumimoto/Oxford University via Cambridge Display Technology (Samuel)
    - M-Squared Lasers (Dunn, Dholakia and others)
    - Max-Planck-Institute for the Chemical Physics of Solids

Members of the School have been very successful in raising funds from schemes to support research impact and knowledge exchange with a total value of £833k.

Public Engagement

The School encourages academics, research staff and PhD students to engage with the public and attract students towards STEM subjects. Highlights include:

- an STFC Leadership Fellowship in public engagement held by Weijmans (2018-21)
- award-winning Cell Block Science reaching over 630 prisoners and family members annually
- Science Discovery Day, taking place in the School in the British Science Week with more than 1300 attendees each year (equivalent to ~10% of the population of St Andrews)
- Exhibit “A message from afar” at the Royal Society Summer Exhibition 2019 (Dominik)
- the national programme for the International Year of Light in 2015 of the Royal Society of Edinburgh (Lee)

Advocacy and informing policy

Through events highlighting our research and unique facilities we not only advertise St Andrews to outstanding talent, but also create opportunities to connect to policy makers. In the evaluation period, we have hosted events in the School with participation of Members of Parliament (Westminster and Holyrood), the First Minister of Scotland, the Cabinet Secretary for Education and Life-long learning and the Chinese Ambassador to the UK. Members of the School have participated in the Royal Society Pairing Scheme (Dominik, J Lovett).

We have taken an active approach to connect with research councils to inform policy. Samuel sits on EPSRC's Strategic Advisory Network and has presented his work at the Scottish Parliament. Members of the School have met with David Sweeney, Executive Chair of Research England, Sir Mark Walport, the Chief Executive of UKRI (2017-20), and Rebecca Endean, Director of Strategy at UKRI.

Open Research and Open Data

The School has a strong track record of ensuring open accessibility of outputs and publication of research data along with them. The percentage of outputs that meet open access requirements is 97%. School policy is that for any publication, underpinning data is to be made publicly available. All academic staff have ORCID IDs.

Research Integrity

All academic staff have participated in research integrity training, developed by the University. It is a mandatory part of the induction for new staff and training of PhD students. The University has held research integrity training modules at residential workshops of our Condensed Matter CDT. The University has established procedures to report and investigate allegations of scientific misconduct (ILES, 2.6).

Section 2: People

Staffing Strategy and Staff Development

Staffing Strategy

The School operates a multi-pronged hiring strategy, aiming to attract emerging leaders to apply for prestigious independent fellowships, providing a transparent path to a faculty position, and through targeted recruitment in strategic priority areas. Examples for the success of this strategy include:

- Advanced fellowships secured or held by King, Tojeiro, Weijmans, B. and J. Lovett, Rost, Jagadamma, Schubert, Keeling
- a number of fellows have been promoted to permanent positions (Tojeiro, Weijmans, J. Lovett, Rost). Jagadamma secured a UKRI Future Leaders Fellowship. Of these five, 80% are female.
- Recruitment in strategic areas: following appointment of Höfling and B. Lovett in 2013 to strengthen links between Condensed Matter Physics and Photonics, we have newly recruited Ohadi and Schulz in this area. Ohadi studies non-equilibrium condensates and exciton-polariton states while Schulz uses non-linear light-matter interactions to tailor and control light.

We envision further strategic recruitments in the areas highlighted in the Research and Impact strategy.

This recruitment strategy has led to an increasingly diverse faculty with well-aligned research interests and complementary expertise, evidenced through collaborative grant proposals and publications. The high quality of our personnel is evidenced by the offers our staff receive, which are at the highest level. Several have turned down opportunities to move to other leading Universities. Mackenzie has taken on a Directorship at the Max Planck Institute of the Chemical Physics of Solids, retaining close ties with St Andrews through a joint appointment, an international Max Planck Research School and an International Max Planck Partnership. Gather has been awarded a prestigious Humboldt professorship and maintains strong links with St Andrews through joint research programmes. Davis has secured an ERC Advanced Grant and taken on a joint appointment at Oxford University and University College Cork.

Since 2014, the number of category A staff has increased from 36.9 to 40.8 FTE. A breakdown of the distribution by career stage and gender is shown in Figure 7.

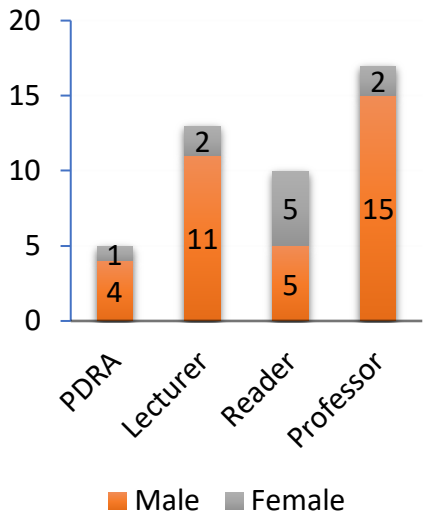

Figure 7: Distribution of category A staff by gender and career stage.

Technician Commitment

The University of St Andrews is a signatory of the Technician Commitment and we support the development of our technical staff and their skills through a variety of mechanisms, including:

- day-release HND (Higher National Diploma) and HNC (Higher National Certificate) courses
- internal continuing professional development training
- part-time secondments, e.g. to the Fraunhofer Centre for Applied Photonics.
- organisation of the technicians in teams to encourage development of skills and provide a pathway for career development to supervisory roles.

The success of our staff development strategy is evidenced by the cleanroom and cryogenics team having been awarded the 2020 IOP Technician Award.

Staff Development

Faculty

All faculty undergo annual academic reviews with the Head of School to discuss their career development, targets for the next year, workload, grant applications, as well as impact or research leave. For academics at Lecturer and Reader-level, the discussion also covers promotion. We have seen a high number of successful promotions since 2014 (4 to Reader, 6 to chair level). Figure 8 shows the distribution of category A staff by age and career-stage.

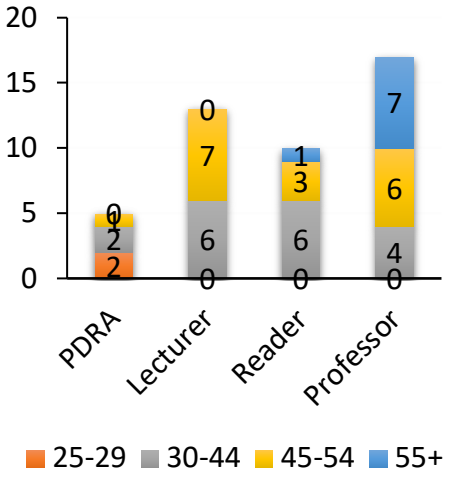

Figure 8: Distribution of category A staff by age group and career stage.

The School operates a transparent workload allocation model that accounts for teaching, admin, research and impact activities and is overseen by the Director of Teaching in coordination with the Director of Equality, Diversity and Inclusion and the Head of School. Newly appointed academics are assigned a senior member of staff as mentor, and are put on a tapered teaching workload. The mentors provide advice and guidance on funding opportunities, career progression and promotion.

All members of staff involved in recruitment processes are required to undertake Recruitment, Unconscious Bias and Equality and Diversity trainings. It is University policy that single gender shortlists are not allowed for academic recruitment (ILES, 3.1).

Fellows, Research Staff and Concordat to Support the Career Development of Researchers

We are committed to providing a supportive environment for our Fellows and Research Staff (RS) in line with the principles of the Concordat. Incoming Fellows and RS are assigned an academic mentor who is independent of their supervisor and who can also serve as role model, ensuring gender balance and diversity of the mentors. They provide career advice and guidance. Skills training is provided through our University's Organisational and Staff Development Services (OSDS) and Centre for Educational Enhancement and Development (CEED; ILES, 3.2-ii). Fellows and RS have annual review meetings with the Head of School or their line manager to discuss progress and define targets for the coming year as well as career progression. RS, like academics, have a formalized route to apply for promotion as their roles develop. In recognition of the

University's work in meeting the principles of the Concordat, the University obtained the European Commission HR Excellence in Research Award in 2012 and retained it successfully at the 6-year review in 2018.

Nurturing creativity for impact and research
Our philosophy is to treat impact-related activities on an equal footing with research and teaching and this is reflected in our workload model. For example, sabbaticals can be taken not only for research but also for impact-related activities (impact leave, ILES, 2.3).

Income generated from licensing fees is distributed to the inventors, recognizing their contribution and giving them flexibility to further pursue research and maximize impact. Due to the high percentage of patents licensed, this provides a considerable additional income stream.

We encourage staff to undertake training of their impact-related skills through relevant courses delivered by OSDS. Staff are made aware of these at the academic review meetings.

Research Students
In the evaluation period, 123 PhD students have graduated from the School, a number that has increased by about 50% compared to the previous REF period ending in 2013 (20% when accounting for the length of the evaluation period), commensurate with our vision of strategic growth in our priority areas.

Funding
UK students are predominantly supported through the EPSRC Doctoral Training Grant (DTG), the Doctoral Training Centre in Condensed Matter Physics, one of only two DTCs in Condensed Matter Physics in the UK, the Applied Photonics CDT as well as the STFC DTG. International students receive fellowships through a variety of schemes, including ERC and Leverhulme grants, the Chinese Scholarship Council, and the International Max Planck Research School with the Max Planck Institute for the Chemical Physics of Solids in Dresden. In 2018, the University has launched a new Physics of Quantum Materials Centre for Doctoral Training that provides specialised training of and funding for postgraduate students.

Award-winning Research Students
The quality of our PhD students and the education they receive is evidenced by the number of awards they have received for their thesis. About 10% have been awarded prestigious prizes, including the Springer thesis award (7), the Otto Hahn Medal of the Max Planck Society (2), the Richard L. Greene award by the American Physical Society in 2020 (1), the 'PhD Student of the Year' award in 2020 (1) and the IoP Superconductivity Thesis Prize in 2020 (1).

Training & Support – SUPA Graduate School
All our PhD students are part of the SUPA Graduate School, the largest graduate school for PhD education in the UK, providing a unique training network with an exceptionally broad course programme. The SUPA graduate School provides training

- For more than 600 graduate students across SUPA
- through more than 70 courses offered across the partner Universities. These include a variety of formats from courses transmitted via video conference to residential meetings and an annual gathering.

Our PhD students benefit from intense training, including

- 40 hours of courses during the first two years of their PhD. All the courses involve assessment, and students are required to gain a passing mark to count towards the required 40 hours.
- 72.5 hours of skills training per year, the majority of which must be transferable skills. The University's CEED offers 370 hours of distinct skills courses, including GRADskills, a suite of workshops and activities designed specifically for research postgraduate students. In addition, there are 102 hours of distinct skills courses through SUPA, and skills courses specifically relevant to Physics and Astronomy students which are run in the school (e.g. a School-specific induction, training for public engagement).

- All PhD students are required to complete online courses on research integrity before their first-year review can be completed.
- Specific training for students who teach, and for those involved in public engagement.

Progress Monitoring

Monitoring of student progress and training is through annual review. Our review process consists of

- Annual review meetings with two members of staff who are independent of their supervisors and discuss the progress of the thesis work, and provide advice and support.
- A presentation after six months to a group of staff, PDRAs and research students about the topic of their research
- A first year report summarising the background of the intended research, and progress so far.
- 2nd and 3rd year students need to present a talk or a poster, respectively, at an annual postgraduate conference, organized by the School (all PhD students and all staff are required to attend, and postdocs are welcome to do so)

In addition to annual assessment, there is continual mentoring support by assigning all PhD students a mentor, visibly independent of their research supervision. PhD students have full access to the University's Advice and Support Centre (ASC), providing help with financial issues, housing, counselling and other student issues. The ASC has dedicated advisors for research students. Academic staff have been trained on recognising and acting on mental health problems in the student population and will contact the ASC if further support is believed to be necessary.

Impact-related Training and Activities

Postgraduate students are offered the possibility to undertake internships during their PhD studies, for example with one of the more than 30 industrial associates of our Centre for Doctoral Training. Annual career fairs organised by SUPA, the CDT and the School provide opportunities to explore different career paths. All graduate students have to undertake at least one public engagement activity per year. For postgraduate students who are enrolled in the applied photonics and data intensive science (SCOTDIST) doctoral training programmes, industry placements are an integral part of their course.

Supervision

Supervisors are required to complete training on PhD supervision. No member of staff is permitted to supervise more than six students and the University requires at least 10 formal supervisory meetings take place per academic year. In practice, much more frequent meetings occur in the School of Physics and Astronomy. We monitor quality of supervision in a number of ways:

- through the annual progress reviews, where students are asked to comment on whether the form of supervision they receive is sufficient and suitable for their needs.
- opportunities for give anonymous feedback on their supervision
- monitoring of the outcomes of the student annual progress process to identify any systematic trends

Equality, Diversity and Inclusion (ED&I)

The School has a very active ED&I committee with representation from all staff and student categories, headed by the Director of ED&I, J. Lovett. The chair of the ED&I committee is member of the School management group, is involved in academic staff hiring, and consulted on promotions applications. The successes of our ED&I activities have led to us securing Juno Championship status and an Athena SWAN Silver award, and have made the School a model for other Schools in the University as well as for other Physics Departments in the UK, who have sought advice on best practices developed and implemented by us.

Our percentage of female academic staff in Astrophysics already achieves parity at Lecturer and Reader level. We have welcomed a further increase in the number of female faculty members, with female colleagues now well represented across all levels in the School, including in the School's management group. The number of staff applying for promotions has increased substantially, with success rates remaining high at ~80%.

Management
The main governing committees (Management Group; Teaching, Research & Impact, Safety, and ED&I Committees) of the School directly involve a large fraction of academic and support staff in our decision making. Female staff hold leadership positions in these and other University committees. The Head of School discusses and encourages such contributions in annual academic review meetings, including their role and value for career progression and promotion. The Head of School considers diversity of leadership whenever a position on the Management Group is due to be filled. We promote participation in mentoring and networking schemes for female staff, for example the Elizabeth Garrett scheme, which is run by the University and provides networking opportunities, mentoring and support for women in, or aspiring to, leading academic roles, and the Aurora scheme, an inter-institutional mentoring scheme to support female research staff and junior academics in becoming future leaders (ILES, 3.2-ii).

Promoting equality
The ED&I committee has a strong track record in ensuring that the School plays an active role in the development of best practice, evidenced by a number of notable changes that have been realised within the evaluation period, including

- the University has created a child care facility that meets the specific demands of faculty and university staff on initiative of our ED&I committee.
- Successful lobbying for changes to the semester breaks to align with local school holidays.
- addressing concerns about bias in student evaluation of teaching. The School Director of ED&I chaired a University working group to provide guidance on the use of such scores for staff assessment, as well as to revise the module evaluation questionnaires.
- Development of a Code of Conduct for academic staff and conferences held on campus.
- mandatory training for all academics in Equality & Diversity and Unconscious Bias, a prerequisite to be on appointment panels and supervise PhD students
- listening and ACAS bullying & harassment training for a number of staff, who are now available to discuss, e.g., sexuality and gender issues
- weekly colloquia with a 50:50 gender balance of speakers.
- Development of guidelines for seminar and conference organisers to promote gender-balance and diversity in conferences organized on-site. At several conferences organized by members of our School, such as EQM2016 and CMQM2019, we have achieved a gender-ratio of invited speakers close to parity.

Equality, Diversity and Inclusion in REF preparations
In the preparations for REF, we have ensured that those evaluating outputs have a diverse background and have undergone unconscious bias training. The School's Research and Impact Committee, which led the preparation of the submission for UoA9, has a balanced representation of academics from across the School. Staff have been encouraged to declare any circumstances to the University's ED&I review group, who have evaluated these independent of the School.

Supporting flexible working arrangements
The School aims to facilitate and encourage staff to implement flexible working arrangements which are suited to their circumstances. Five academic staff have benefited from formal flexible working arrangements since 2014. The School and University (see also ILES, 3.4) facilitate these through:

- a core meeting hours policy (ILES, 4.3)
- a caring fund operated by the University to support those with caring responsibilities, when, e.g., traveling to conferences or attending training (ILES, 4.3)
- An initially reduced teaching load for staff returning from maternity leave.

Postgraduate Students
The proportion of female post-graduates has risen steadily in recent years, and currently sits at 37%, more than 10% higher than the national average. All postgraduates receive an introduction by the Director of ED&I during their induction, including raising awareness of unconscious bias and imposter syndrome in academia.

Section 3: Income, infrastructure and facilities

Income

Strategy for generating income

Concentration of our research on our priority areas as well as through organization of our research in interdisciplinary Centres creates frameworks for larger interdisciplinary consortia combining areas of excellence from the School and from across the University (ILES, 2.5). Complementary expertise of the academics encourages collaboration across the School, evidenced by collaborative grant proposals with multiple investigators from the School. The Centres are designed to act as a springboard for applications for larger strategic grants and to provide critical mass, a stimulating environment and the infrastructure to maximize our chances for success. The Centres further support accelerating the impact, and provide a basis for funding applications to support realization of these. With the additional recruitment of staff, we expect to grow critical mass and grant income in our priority areas. We support and encourage researchers in the development of grant applications at School-level through strategic grant planning meetings with groups of academics to identify new directions and internal reviewing of grants. Our workload allocation model accounts for percentage time covered by grants.

Income from Industry

The School has been very successful in securing licensing deals and royalty income from industry partners who are using the IP generated in the School with a total value of more than £2M, linked to activities in our research Centres (for example the Centre of Biophotonics and the Centre for Organic Semiconductors).

Funding obtained

The School has been highly successful in raising funds to support the research. Our research has during the period since 2014 been supported through

- 8 ERC grants (5 Starting Grants, 1 Consolidator Grant and 2 Advanced Grants, Bonnell, di Falco, Gather, Helling, King, O'Faolain, Samuel, Wild)
- more than seven advanced fellowships (e.g. Rost (EPSRC Early Career Fellowship), Jagadamma (UKRI FLF), Schubert (Dorothy Hodgkins), King (URF), J and B Lovett (URF), Tojeiro (STFC), Keeling (EPSRC), Di Falco (EPSRC))
- a Leverhulme Leadership award (King)
- 4 EPSRC programme grants (3 held in St Andrews: Dholakia (2), Wahl (1), total budget >£15M; programme grant on hybrid polaritonics with Höfling, Keeling, Samuel, Turnbull)
- 2 EU FET grants (Korolkova, Dholakia), an Industrial Leadership grant (Dholakia)
- 2 Marie Curie ITNs (Helling, Dholakia)
- postdoctoral fellowships (Marie Curie, 1851, Leverhulme, EPSRC)
- a portfolio of EPSRC standard grants, as well as grants from the Leverhulme trust, DARPA and the NSF
- successive STFC consolidated grants.

The average funds raised per FTE is greater than £1M over the evaluation period. Nine members of staff, more than 20% of our current FTE count, have either held or been awarded an ERC grant during the REF period, with a total of 16 staff (~40% of FTE) on fellowships (ERC, Royal Society, UKRI, EPSRC, STFC, Leverhulme, 1851).

We have secured major strategic equipment grants with a combined value of more than £10M, funding unique infrastructure for characterization of advanced functional and quantum materials:

- a suite of electron microscopes and characterization suite for advanced materials (EP/L017008/1)
- a reactive oxide Molecular-Beam Epitaxy system (EP/M023958/1)
- a spin-resolved Angular-Resolved Photoemission setup (EP/R025169/1)
- bespoke instrumentation for thin film characterization (EP/T031441/1).

Members of the School have received a total amount of £833k for impact-related activities through our impact acceleration accounts, GCRF funding and knowledge exchange and impact funds.

Local infrastructure and facilities

An important factor shaping our research environment in the last decade has been the Scottish Universities Physics Alliance (SUPA), which has provided crucial underpinning research infrastructure through significant investment, and led to a number of strategic appointments (Braunecker, Gather, Höfling, B. and J. Lovett, King, Wahl).

Our research across the priority areas benefits from access to a high-performance computing cluster, Kennedy, operated jointly with the Schools of Mathematics and Statistics and Chemistry. It is used for materials prediction, calculation of entangled properties of quantum states, and simulations of galaxies and star formation.

Astrophysics

For time-domain astrophysics experiments, St Andrews owns three 1m robotic telescopes, the ***SUPAscopes***, located in South Africa, Chile, and Australia (Figure 9). These are fully integrated with the Las Cumbres Observatory (LCO) global robotic telescope network, on which we receive proportional time allocations, including 2m, 1m and 0.4m robotic telescopes. This unique UK facility enables our research programmes on discovery and characterisation of extrasolar planets, black hole accretion flows in active galactic nuclei, identification of rapid transient events, and variability studies in young stellar objects. The SUPAscopes secure our role in international collaborations through which we receive major awards of time on space telescopes for parallel X-ray and UV monitoring. The telescopes also provide observing time for astronomers across Europe, including researchers in Cambridge, Queens (Belfast), Warwick, Southampton and Heidelberg, as an OPTICON facility and through other funding streams.

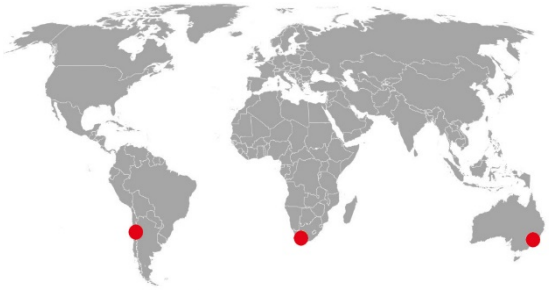

Figure 9: Locations of the three 1m robotic telescopes (SUPAscopes) owned by the University.

St Andrews, with Edinburgh and Belfast, paid for and fabricated key parts of the ***HARPS-North spectrograph***, a high-precision radial-velocity instrument located in the Northern hemisphere (La Palma) to allow for synergy with the NASA Kepler mission for the characterization and discovery of terrestrial planets. It is operated in collaboration with Harvard and led by Geneva. In exchange for the instrument, St Andrews has guaranteed observing time on the 3.5m telescope. To date it has produced 60% of the mass determinations for transiting super-Earth and mini-Neptune planets discovered with the NASA Kepler/K2 mission. Further guaranteed time has been awarded by the Italian Institute for Astrophysics (INAF) which operates the facility to characterise planets transiting brighter stars from the NASA TESS mission and the Swiss-led ESA CHEOPS satellite following their respective launches in 2018.

The School has the largest operational optical telescope in Scotland and one of the largest in the UK which is used to study exoplanets.

Condensed Matter Physics and Photonics

Since August 2013, the School has seen major investments linked to the University's priority area "Materials for the Modern World". The newly founded Centre for Designer Quantum Materials encompasses

- ***ultra-low vibration laboratories*** in a dedicated building that is unique in the UK (Figure 10), hosting a suite of four low temperature scanning tunnelling microscopes with unique capabilities (magnetic fields up to 16T, vector magnetic fields up to 5T, and temperatures down to 10mK)
- a ***dual chamber Molecular Beam Epitaxy system*** for the growth of chalcogenide- and oxide-based quantum materials
- two ***angular resolved photoemission systems*** (one commissioned before August 2013), including a setup for spin-resolved measurements that is unique in the UK.
- A bespoke ***nanoprobe system*** currently under development for in-situ transport and physical property measurements of thin films down to single monolayers and at the nanometre scale

Figure 10: The ultra-low vibration laboratory in St Andrews, a facility dedicated to scanning probe microscopy characterisation of advanced quantum materials.

These facilities enable growth and advanced characterization of thin films of quantum materials, a crucial step to bring their exciting properties from bulk crystals to technological applications.

Our activities in the Organic Semiconductor Centre and the Mackenzie Institute benefit from access to two class 10,000 cleanrooms, one of which has been commissioned in this REF period, extending our total clean room floor area to 175m^2. The cleanrooms enable a wide range of research in photonics, condensed matter, materials and nanoscience. They provide crucial space for equipment purchased via EPSRC programme and ERC grants, as well as accommodating the growing number of researchers funded by these grants.

Our research benefits from a £7M investment in infrastructure through the ***Capital for Eight Great Technologies*** programme, which has provided nanostructuring and characterisation tools, including a new electron beam lithography system, focussed ion beam, nanostructural characterisation tools (transmission and scanning electron microscopes, atomic force microscopy) as well as tools for nanofunctional characterisation (femtosecond spectroscopy).

As part of the infrastructure developed since before August 2013, the Centre for Magnetic Resonance has developed and now operates a world-wide unique mm-wave electron paramagnetic resonance instrument.

The School runs Scotland's only helium liquefier with recovery system, crucial to a large part of our research and teaching labs and with a sustainable recovery rate of more than 95%.

This infrastructure underpins a compelling vision for materials research at St Andrews, and supports a large portfolio of active research grants.

Technical Infrastructure

The School of Physics and Astronomy has a well-equipped and staffed mechanical workshop which through close collaboration with our industry partner Sodick Europe Ltd. features advanced manufacturing equipment, including an ultra-fast 5-axis milling machine, wire eroder and an electric discharge machining die sinking machine. These and a variety of precision computer numerically controlled tools, integrated with advanced computer aided manufacturing, enable in-house manufacturing of prototypes of advanced research instrumentation, including measurement heads for low temperature scanning tunnelling microscopes, evaporation sources and antennas for advanced radar applications.

Infrastructure to support Research

Our academic staff are supported in their research activities by a range of facilities at School level:

- The School's Research and Impact Committee (RIC), chaired by the Director of Research, with members including the Director of Impact and representatives from all priority areas, ensuring diverse representation. The RIC provides advice on
    - the School's research strategy
    - recruitment of new staff
    - opportunities to attract major awards
    - internal demand management
    - identification of academics for awards

  It supports staff in applying for grants, undertakes internal reviewing of grants, mock interviews and provides advice on how to write successful grant and fellowship applications.
- A dedicated research secretary, working as part of the School's admin team to support research and the RIC.
- A workload model that accounts for grant income and supervision of research students
- Discussion of grant applications as part of the annual review process
- A dedicated Business Development manager, who regularly visits the School and meets with staff to assist in the writing of grant applications, and alerts staff to funding opportunities.
- Organization of meetings in the School to promote networking and highlight our research to a national and international audience.
- Our unique research infrastructure.
- Access to research facilities across the University and across Scotland through SUPA
- An early career researcher forum, creating opportunities for networking and information exchange
- Organization of our research in Centres, creating critical mass, vitality, interdisciplinarity and attracting talent as well as creating opportunities for strategic funding bids.

Further support comes from the University through dedicated courses by Organisational and Staff Development Services on writing grant applications and publications, as well as networking events.

Infrastructure to Support Impact, Knowledge Transfer and Business Development

The strategic plan of the University of St Andrews highlights "Entrepreneurial St Andrews" (ILES, 1) as a key theme to promote entrepreneurship and create opportunities and space for spin-out and knowledge transfer.

Infrastructure to support Impact

Impact-related activities take a central role in the School and University strategy (Figure 11). The School supports impact-related activities through:

- Recognition of research, teaching and impact in academic reviews and promotion processes (ILES, 3.2-iii)
- the School's Director of Impact, who actively supports staff in realizing impact
- the Research and Impact Committee, which provides advice on the School's impact strategy

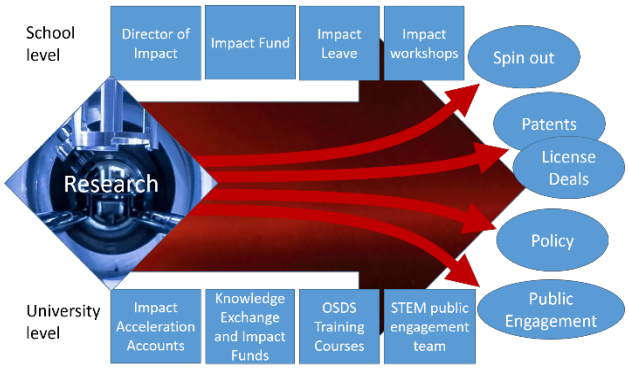

Figure 11: Infrastructures to support impact at School and University level.

- A discretionary impact fund (£10k annually) overseen by the Head of School and Director of Impact to support impact.
- Sabbaticals that can be taken as impact leave (ILES, 2.3).
- Workshops and joint meetings with industry to showcase our research and for networking

- Our photonics research and teaching programme (Applied Photonics CDT; an EPSRC Prosperity Partnership project with M-Squared Lasers; InnovateUK, EU and IBioIC projects; spin-outs and IP licensing).
- a dedicated Ogden Trust officer in the School supporting public engagement activities.

Impact activities are further supported through a number of University Units (ILES, 2.3):

- The Technology Transfer Centre
- our dedicated Business Development Manager
- provision of funds to support impact-related activities (EPSRC and STFC Impact Acceleration Accounts, the University's Knowledge Exchange and Impact Fund)
- a new Sustainable Power and Research Campus with £30M investment by the University and the Scottish and UK Governments.
- the public engagement team for the STEM subjects.

Facilities for an inclusive environment

Our ED&I committee has worked with the management group of the School to ensure that our facilities support an inclusive environment. New relevant facilities include gender neutral toilets, a wellbeing room for breastfeeding and expressing milk, and baby change facilities. Breastfeeding staff members are provided with fridges to store expressed milk in their offices. A multi-faith prayer room is available to staff and students within 500m from the School.

Facility sharing

Our major research facilities are listed in equipment sharing databases. The Centre for Designer Quantum Materials, the SUPAScopes and the Centre for Magnetic Resonance have entries in the UKRI infrastructure roadmap, ensuring awareness of these facilities and providing access for external researchers. Through SUPA, our facilities are easily accessible to researchers across Scotland, while at the same time SUPA enables access to facilities at other Scottish Universities. The SUPAscopes are listed as a resource in the OPTICON portfolio of telescopes, providing paid access to telescope time for external users and generating an income of more than £400k.

External facilities

Members of the School have used a range of high-performance computing facilities (tier-0: Fermi (Italy), ca. 6M CPUh; tier-1: Archer (ca. 1M CPUh); tier-2: Dirac (ca. 2.4M CPUh). Further HPC usage has been on Cirrus.

Astrophysics

For our wide-ranging observational programs, the rights to observe and to use data from a multitude of world-leading telescopes is crucial. Access to telescopes is granted either through competitive peer-reviewed applications (usually 3-10 times oversubscribed) or through buy-in or in-kind contributions which results in guaranteed time or access to large-scale databases. We make use of different paths to access telescopes covering the entire electromagnetic spectrum. Over the past five years, our astronomers have been extraordinarily successful in acquiring telescope time, which greatly enhances our ability to carry out an impactful and leading research program and a testimony to the quality of our work. Here, we only list the most prominent examples of this success story.

Members of our group have guaranteed access to

- the latest versions of the Sloan Digital Sky Survey (Weijmans)
- the dark energy survey DESI (Tojeiro)
- the planet search program at HARPS-N at the Telescopio Nazionale Galileo (Cameron)
- the Las Cumbres network of telescopes (Horne, Dominik et al.).
- the James Clerk Maxwell Telescope and the Vera Rubin Observatory through two consortia of UK universities of which we are members.
- guaranteed time at the James Webb Space Telescope through a collaboration (Scholz).

Through peer-reviewed applications, we have been granted observing time

- at the space telescopes Hubble, XMM, Swift (Horne), Kepler, Spitzer (Scholz); access to these is highly coveted by astronomers around the world.

- at some of the largest ground-based telescopes, including ESO/VLT and Gemini. We are involved in two large-scale public surveys with the ESO/VLT (Wild).
- with successful bids for telescope time, leveraging our guaranteed access to Las Cumbres (Horne, Dominik).
- access to ALMA data through observing time granted to Cyganowski, Scholz, and Woitke.

Access to all these observing programs is aided by the involvement in large international collaborations.

The value of the observing time is difficult to estimate and highly dependent on the business model of the observatory. As an approximation, the observing time acquired by our group through peer-reviewed applications or as guaranteed time for 2014-2019 corresponds to a monetary value of ~£20M.

Condensed Matter Physics

Our condensed matter group has been highly successful in obtaining competitively awarded measurement times at synchrotrons (King: Diamond (£2M equiv.), Astrid (Denmark, £253k equiv), Soleil (France, £781k equiv), Suisse Light Source (Switzerland, £110k equiv.), ELLETRA (Italy, £1.2M equiv.), HiSOR (£156k equiv.), MAX-Lab (Sweden, £1.1M equiv.; equiv. estimate from £6.5k per 8h shift) as well as muon sources (Lee: Paul Scherrer Institute (Switzerland), ISIS (£77k)). The external facility access totals to an in-kind value of more than £5.7M.

Section 4: Collaboration and Contribution to the Research Base, Economy and Society

Collaborations

The School of Physics and Astronomy is part of the Scottish Universities Physics Alliance (SUPA), which through major investment by the Scottish government and the partner Universities has created a unique brand for research in physics in Scotland with recognition beyond the UK. SUPA provides integrated training across the Scottish Universities through video-conferenced lecture courses, funding for exchange and a global distinguished visitor programme. SUPA has been featured in APS TV, the conference television programme of the March meeting of the American Physical Society, one of the largest international physics conferences. We have further a close research partnership with the School of Physics and Astronomy in Edinburgh (PHYESTA), evidenced through joint grants, residential meetings and collaborative publications.

The organization of our research in Centres encourages and facilitates interdisciplinary collaborations within the University and with national and international partners (ILES, 2.5). Our Centres create the critical mass and platforms for exchange of ideas to build strategic partnerships and foster collaborations.

Astrophysics

Research in Astrophysics strongly benefits from the involvement of our staff in a number of major international collaborations, which also often provide access to data crucial to our research. These include:

- Sloan Digital Sky Survey - Reverberation Mapping (SDSS-RM)
- Space Telescope and Optical Reverberation Mapping (STORM)
- SDSS-IV (Tojeiro and Weijmans are members of the SDSS-IV management team, Wild)
- SDSS-V Black Hole Mapper (Weijmans is data products manager and member of the management team, Horne co-chair of a working group)
- Las Cumbres Observatory (LCO)
- ROME/REA - a window to planets beyond the snow line
- Transiting Exoplanet Characterisation (TECH)
- Active Galactic Nuclei (AGN) Echo Mapping.

Helling leads a Marie-Curie integrated training network based at the Centre for Exoplanet Science on virtual laboratories to study exoplanets, with partners in the Netherlands, Denmark, Belgium and the UK, funding a total of 15 PhD students.

Condensed Matter Physics

Several investigators (King, König, Korolkova, Rost, Wahl) of the School of Physics and Astronomy are members of the International Max Planck Partnership, which has formalized collaborations with several Max Planck Institutes. There are now a number of direct collaborations, evidenced through joint publications, with the Max Planck Institutes for Solid State Research (Stuttgart; King, Wahl, Rost), for the Chemical Physics of Solids (Dresden; King, Wahl), for the Physics of Complex Systems (Dresden; Hooley) and for the Physics of Light (Erlangen; König, Korolkova). The School of Physics and Astronomy is a member of an International Max Planck Research School (IMPRS) with the Max Planck Institute for the Chemical Physics of Solids and TU Dresden, the first one of its kind in the natural sciences in the UK. The IMPRS covers research into quantum materials, building directly onto one of our priority areas and linking to the Centre for Designer Quantum Materials and the St Andrews Centre for Doctoral Training in Quantum Materials. It provides a route to recruit excellent international students to undertake their PhD studies on co-supervised projects between researchers at Max Planck Institutes and the University of St Andrews.

The condensed matter research group has attracted strategic collaborative funding, including an EPSRC-funded programme grant (TOPNES) with Oxford, UCL and University of Edinburgh and a CDT in Condensed Matter Physics with University of Edinburgh and Heriot-Watt. The Centre for Designer Quantum Materials has built collaborations and attracted international researchers via the Global Fellowship programme of the University (awardees include Prof Alexander Balatsky (Nordita) and Prof Peter Hirschfeld (University of Florida)).

Photonics

Our photonics group benefits from a range of strategic grants which support international collaborations. Linking to activities in the Centre of Biophotonics, Gather is part of an international biophotonics consortium working on “Lighting up the brain” with investigators at Columbia, Yale and U Texas Austin using optogenetics to control and read-out neuronal activity with light. This collaboration develops implantable photonic devices for use in animal models and ultimately in patients. Gather is part of a Human Frontiers Program to use techniques from biophotonics to image neurons with Harvard Medical School and University of Cambridge. Dholakia leads an EPSRC programme grant in biophotonics with collaborators at University of York and a network of international partners, including at Max Planck Institutes and the Massachusetts General Hospital to use light to image, manipulate and control matter on multiple scales. He further participates in FET-OPEN and Industrial leadership grants with a Europe-wide network of collaborators funded through Horizon 2020.

The Centre for Organic Semiconductors has a number of formalized collaborations, including through a JSPS core-to-core programme (Samuel) supporting a cooperation of physicists and chemists from Japan, St Andrews and Germany, where knowledge of optical and device properties will feed back into molecular design, and through rapid cycles of this process, new organic-semiconductor devices will be created while also developing the human resources to drive the next generation of organic optoelectronics.

Turnbull works as part of a NATO-funded program on developing techniques for demining with partners in Croatia and Bosnia and Herzegovina.

Korolkova leads an EU project as part of the Quantum Flagship programme to create light sources with sub-Poissonian noise characteristics for entanglement-enhanced imaging and atomic clocks, with partners in Germany, Belarus, the UK and Switzerland.

Contributions to the Research base, Economy and Society

Members of the School have made significant contributions to the research base in all areas. A selection of these is provided below.

Contributions to the Research base

Prizes, honours and personal fellowships

Prizes and honours: Cameron (2018, Docteur Honoris Causa, Université Toulouse II – Paul Sabatier), Davis (2016 Medal of Science of the Science Foundation of Ireland), Dholakia (2016 R.A. Wood Prize by the Optical Society of America, 2017 Thomas Young Medal and Prize, 2018

SPIE Dennis Gabor Award), Gather (2016 Patterson Medal and Prize by the Institute of Physics, 2019 Humboldt professorship), King (2015 Philip Leverhulme Prize), Samuel (2015 Clinical PDT research prize, 2016 RSC Chemical Dynamics prize), Jardine (2019 Suffrage Science Award for the Engineering and Physical Sciences), Korolkova (2015 Eugen Lommel Award), Zhao (2018, Kavli long-term visiting professorship at Cambridge; 2019 Gutenberg Chair in Strasbourg)

ERC grants: Bonnell (Advanced), di Falco (Consolidator), Gather (Starting), Helling (Starting), King (Starting), O'Faolain (Starting), Samuel (Advanced), Wild (Starting)

Fellowships: Dholakia (Leverhulme Trust Senior Fellowship), Jagadamma (UKRI Future Leaders award), Keeling (EPSRC), King (URF, Leverhulme Leadership award), B Lovett (URF), J Lovett (URF), Rhodes (Royal Commission of 1851), Rost (EPSRC), Schubert (Dorothy Hodgkins Fellowship), Tojeiro (STFC Early Career Fellowship), Weijmans (STFC Leadership Fellow in Public Engagement)

Leadership positions: Jardine (Scientific Advisory Board for the Leibnitz Institute for Astrophysics (Germany), Institute of Astrophysics and Space Science (Portugal)), King (Champion for a new NanoARPES flagship beamline at Diamond), Smith (President of European Federation of EPR groups, vice-president Europe of the International EPR Society)

Learned Societies: Höfling (Fellow of the Optical Society of America, 2019), Mackenzie (Fellow of the Royal Society, 2015)

Key invited talks: Davis (Perimeter Institute Distinguished Lecture, 2014; Simons Foundation Lecture, 2015), Dholakia (International Year of Light Lecture, 2015; OSA International Day of Light Festival, 2019), King (Lange lecture, 2017), Samuel (RSC prize talk, 2015), Tojeiro (Invited Keynote talk, XIII Meeting of the Spanish Astronomical Society, 2018)

Service to the Community

Dominik initiated and led a Working Group of the Global Young Academy (GYA) on Scientific Excellence and participated in the GYA Working Group on Open Science. He contributed to policy recommendations by GYA on consultations on research metrics and open science by the European Commission and on Plan S.

Policy advice: Samuel (EPSRC Strategic Advisory Network), Dominik (Global Young Academy)

Review panels: EPSRC Physical Sciences prioritization panel (di Falco, Lee, Hooley, Keeling, König, Samuel, Wahl), Bonnell (UKRI FLF prioritization panel, RSE fellowship panel), Dholakia (chair of EPSRC panels), Gather (ERC starting grant panel), Jardine (co-chair of ERC advanced grant panel, chair of RSE Fellows panel), Lee (RSE grants committee), B Lovett (Royal Society Grants panel), Rost (EPSRC mid-term review panel programme grant), Wahl (EPSRC Statement of need panel, chair of mid-term review panel programme grant, chair of interview panel for platform grants), Wild (STFC Astronomy Grant Panel)

Conference organization: MQT2014 (King, Mackenzie, Wahl), EQM2016 (King, Wahl), ICSCE8 2016 (Höfling, Keeling), JEMS2016 (Lee), Cloud Academy I (2018) and II (2020, postponed to 2022, Helling), CMQM2019 (Braunecker, Hooley, King, Lee, Ohadi, Rost, Wahl), Frontiers 2019 (King), SPIE PAMMWI 2017-2020 (Robertson), ICSM 2020 (postponed to 2021, Jagadamma, Samuel)

Journal editorships: Cameron (Scientific editor (exoplanets and stellar magnetic activity) for MNRAS), Brown (Scientific Reports), Cassettari (Scientific Reports), di Falco (Photonics and Nanostructures: Fundamentals and Applications), Dholakia (J Phys (IOP); Advanced Photonics (SPIE)), Jardine (Living Reviews in Solar Physics), Mazilu (Frontiers in Physics; Optics and Photonics), O'Faolain (Nanomaterials and Nanotechnology; Photonics and Nanostructures), Samuel (editor in chief "Synthetic Metals")

Contributions to the Economy

Through the organization of our research in interdisciplinary Centres, we have been very successful in realizing economic impact through a number of channels, including:

- successful participation in the Converge Challenge that supports commercialization of research (Ward and Barraclough (Razorbill Instruments), Gillanders)

- St Andrews spin-out company Razorbill Instruments has commercialized bespoke research instrumentation developed as part of an EPSRC-funded programme grant based in St Andrews to apply uniaxial strain to quantum materials
- High growth spin-out company Bespoke Photonics has secured funding from Scottish Enterprise (to launch 2021) to commercialize 3D volumetric imaging through scattering tissue (TRAFIX, Science Advances 2018).
- Commercialization of Airy Beam Light Sheet Microscopy with M Squared Lasers (ICS Dholakia)
- Innovative treatment for skin cancer using light (commercialized by St Andrews spin-out Ambicare, founded in 2004; ICS Samuel)
- Development of high-performance feedhorn antennas (ICS Smith)
- Spin-out company PhotoSynergy, founded in 2001 (ICS Dunn)
- Handover of a volcano monitoring radar developed in the School to Montserrat Volcano Observatory as an operational monitoring tool (2019) and basis for an early warning system.
- Development of compact, low cost drone detection radar prototypes for commercialisation.
- 355 patents and patent applications of which 78% are licensed out.
- Joint meetings with industry, e.g. EMSIG UK Radar Society annual meeting 2017-2019, IET Colloquium on Millimetre-wave and Terahertz Engineering&Technology 2016&2019, KTN Intelligent Imaging 2018&2015, IET Colloquium on Antennas, Wireless and Electromagnetics 2016, CENSIS/MarCE Subsea Sensing for Defence and Security 2014; University's EPSRC IAA Showcase 2015&2017

Contributions to Society

One of the primary impacts of our research is the education for highly-trained individuals, including training of PhD students and PDRAs.

A range of projects pursued by our academics have direct implications for public health and safety, for example:

- The use of Optoelectronics to purify water (Samuel) and detect water quality (Turnbull), potentially solving water quality issues in developed countries
- Radiation calculations for optimized cancer treatments (Wood)
- Phototherapy to treat skin cancer using light from wearable light sources (ICS Samuel)
- Award-winning and patented Lightpath technology, commercialized by spin-out PhotoSynergy, to facilitate and secure work in subsea marine environments (ICS Dunn)
- explosive detection using optical spectroscopy as well as bees for demining, funded by NATO (Turnbull)
- use of radar to monitor volcano activity and implement early warning systems (Robertson)
- Drone detection using mm-wave radar, e.g. for airport safety (Robertson)
- Development of secure quantum communications (Korolkova, with MPI Erlangen)

Response to Covid-19

In reaction to the Covid-19 pandemic, a number of projects have been either reprioritized or started afresh. These include the use of UVC light to deactivate the SARS-CoV2 virus (Wood), a project which featured in questions in parliament to Secretary of State for Health and Social Care, Matt Hancock, on 19.10.2020, as well as the development of surfaces which deactivate the virus as part of the Centre for Designer Quantum Materials (Wahl, King, di Falco) and funded by UKRI-NIHR.

Public engagement

The School has actively sought to engage with the public through a range of high-profile activities:

Figure 12: Neon spectrum at the University Observatory added as part of the Shine project. During Open Nights art exhibits are on display inside this otherwise empty dome. Image credit: A. Scholz; artwork by Tim Fitzpatrick.

- Lee led the national programme of the Royal Society of Edinburgh (RSE) to celebrate the UNESCO International Year of Light (IYOL) in 2015, including the IYOL National Launch Event and a number of public meetings with renowned speakers including Prof Peter Higgs and television and radio presenter Prof Jim Al-Khalili.
- Stand at the Royal Society Summer Exhibition 2019 “A message from afar” (Dominik)
- European Researchers Night (Explorathon) which around Scotland interacted with 17,600 people and is particularly successful in reaching new and hard to reach audiences.
- Science Discovery Day (as part of the National Science Week)
- The James Gregory Telescope is regularly open to the public and attracts about 1000 visitors every year.
- a regular programme at local secondary schools to increase the uptake of physics and other STEM subjects
- an STFC leadership fellowship (Weijmanns) to pursue public engagement activities, exploring the properties of light and its use in modern astronomical research (see, e.g., Figure 12) through science, art and music. This project, Shine, demonstrably reaches new audiences for science events.
- The Centre for Designer Quantum Materials that has been covered in several television features, shown on BBC television and radio channels and on STV (King, Wahl).
- An Ogden Trust Outreach Officer who works with staff and secondary schools in Fife to widen participation and increase interest in (astro)physics.