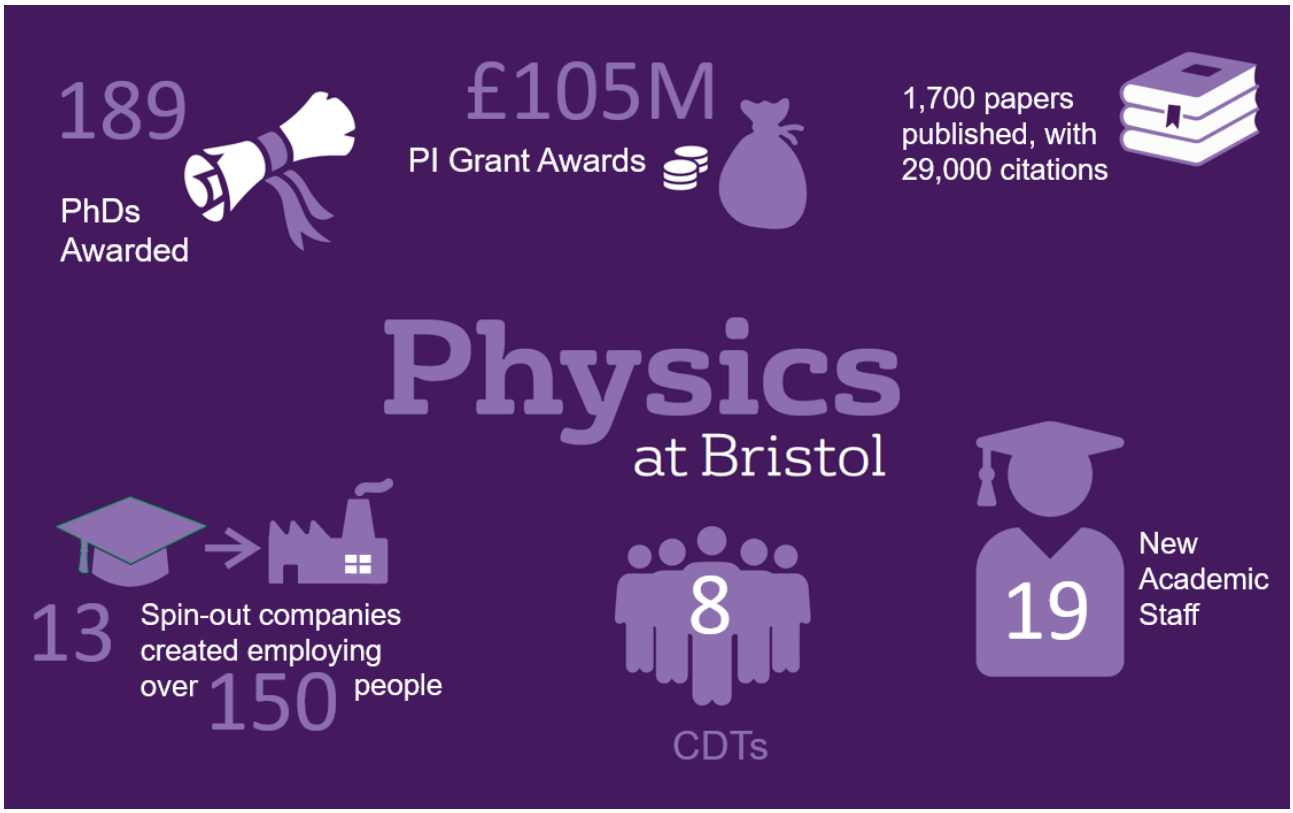
Institution: University of Bristol
Unit of Assessment: 9: Physics
1. Unit context and structure, research and impact strategy

Overview

The University of Bristol (UoB) School of Physics (SoP) has a vibrant and productive portfolio of research activities spanning quantum devices, condensed matter and materials physics, astrophysics, and particle physics. With a current complement of 48.8 FTE academic staff and 5.3 FTE independent research fellows, plus 57 postdoctoral researchers and 184 PhD students, we have the critical mass necessary for world leading research in all our activities, whilst providing a friendly and supportive research community. Collaboration within the SoP and internationally is our lifeblood, and our broad portfolio of research partnerships enables us to deliver top quality research. This, combined with a strong ethos for entrepreneurship, means that Bristol Physics punches well above its weight in world leading research and impact.



The REF2021 assessment period has been highly successful. Key highlights arising from our REF 2014 objectives are:

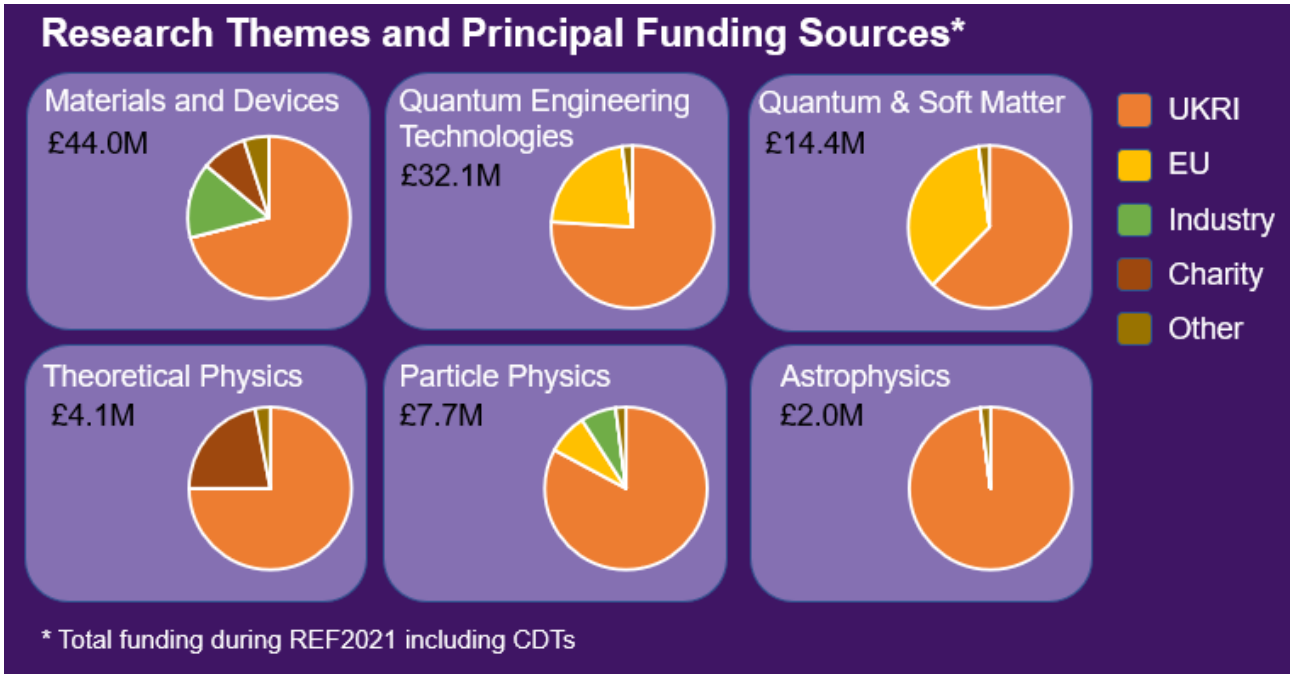
- *Leading Publications and Collaborations* - Outputs published in top journals: Nature/Science (18), Nature Physics/Photonics/Materials/Plants/Chemistry/Astronomy (34), Nature Communications (33), Physical Review Letters (140). Our outputs have attracted more than 29,000 citations during REF2021 and over half our papers have an international co-author.
- *Leading Graduate Training* - We have led 4 EPSRC Centres for Doctoral Training (CDT) and partnered in a further 4 CDTs. We have awarded 189 doctoral degrees in the

assessment period. A £6M bequest for PhD studentships is permitting new forms of industrially co-sponsored doctoral training and more flexible recruitment of international students.

- *Improved Diversity* - We have substantially increased diversity across our staff by attracting 19 new academic staff from top institutions worldwide. 19% of our REF2021 submitted staff are female (8% in REF2014).
- *Substantial Grant Funding* - £105M of new funding awarded as Principle Investigator (PI).
- *Entrepreneurial Culture* - our academics have spun-out or started 13 companies during REF2021, together generating £160M of new investment and over 150 new jobs. We have been awarded 9 patents (with 9 further patents pending).
- Cutting Edge Facilities and Instrumentation – we have in excess of £35M of research equipment with £14.3M of new investment in REF2021.

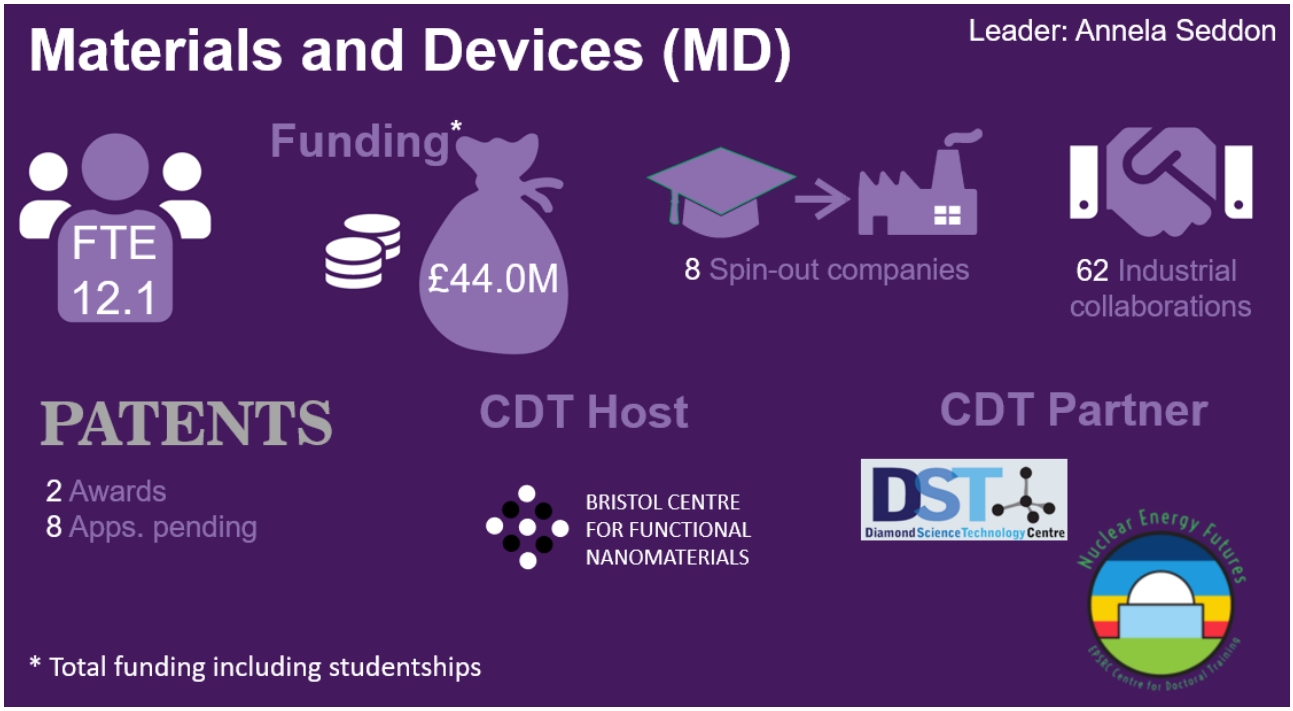
Research Structure

Our key strategic aims in REF2014 were to build on our core research strengths and to improve links across the School, the University and with industry. During REF2021 our research activities have been restructured around 6 Themes. The rationale for the restructure was to break down barriers between traditional sub-disciplines and to enhance meaningful interactions between researchers. For example, bringing the Nanophysics and Interface-Analysis groups under the umbrella of the Materials and Devices Theme has led to new projects with industry, applying high speed AFM to analyse nuclear and biophysical materials. Cross Theme collaboration is strongly encouraged and facilitated through the School's Research Committee, where a Theme Leader represents each Theme.



While all Themes interact with industry, this is particularly strong for the Materials and Devices Theme which has received £7.7M of industrial funding, and the Quantum Engineering Technologies (QET) Theme where there has been very substantial technology transfer to start-up companies.

Theme Leaders are selected by merit, rather than seniority. We promote leadership experience by rotating the role on a 3-year cycle. Leaders assume responsibility for maintaining a productive and highly supportive research environment and for coordinating and facilitating activities and interactions. A key aspect of the role is to ensure strong support for career development, particularly of early career researchers (ECR) though mentoring and providing guidance on grant applications and developing new collaborations.



This Theme conducts research across a wide range of applied topics and is strongly interdisciplinary, with a focus on the boundaries between Physics and Engineering/Life Sciences. To support and enhance the visibility and impact of its research, particularly to industry, the Theme has created two research centres and has a strong Nano/Biophysics strand.

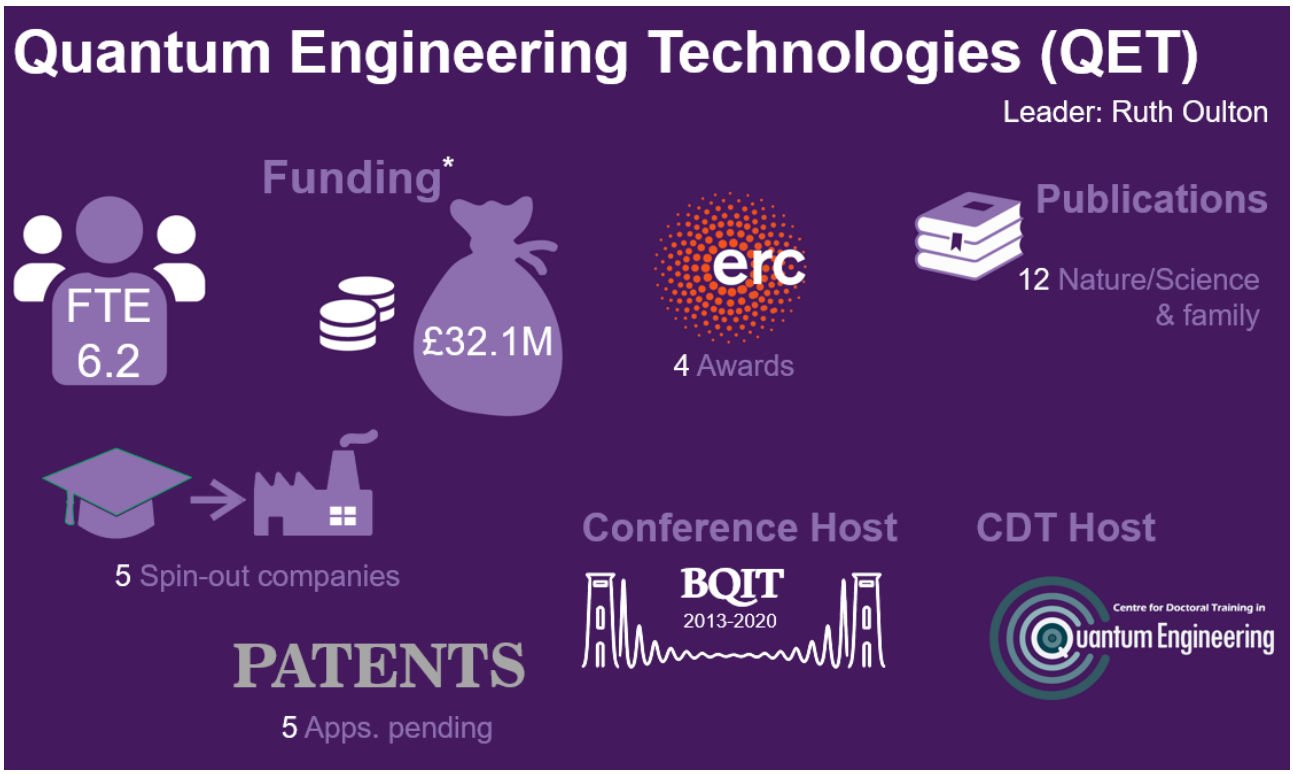
The **Interface Analysis Centre** (IAC) specialises in materials science and instrument development for industrial applications, particularly in the civil nuclear sector, and is supported by £17M of funding. A focus is in helping to resolve failure, contamination and performance issues in materials and providing expert analysis and consultancy services to industry and external collaborators. The IAC's research is based around a dedicated materials analytical facility (see Section 3). Their work is a major contributor to the knowledge base that underpins strategic decision making in the nuclear sector: including the safety of EDF Energy's nuclear reactors, the safe storage of uranium fuel and developing instrumentation to monitor environmental radioactivity with application to nuclear facilities in the UK, Fukushima and Chernobyl. These applications are detailed in three of our Impact Case studies. The strength of this activity led to the founding of the South West Nuclear Hub in 2016 which provides a regional focus for civil nuclear research (see Section 4).

The **Centre for Device Thermography and Reliability** (CDTR) has pioneered device reliability assessment based on a novel sub-micron spatial resolution thermal imaging system using Raman spectroscopy. This enables the study of technologically relevant physical phenomena that are critically dependent on micro and nanostructure in wide band-gap semiconductor materials and devices. Supported by £8M of grants (including leading the EPSRC programme grant GaN-DaME

and platform grant MANGI), the CDTR has developed power electronics based on GaN, Ga_2O_3, and diamond for the low carbon economy, and RF electronics for next generation communications. Major industrial collaborations exist with more than 20 companies including UMS (France/Germany), WIN Semiconductors (Taiwan), Northrup Grumman (USA) and Infineon (Germany/Austria).

Nano/Biophysics: Working with partners across Chemistry, Life Science and Engineering this strand develops new methods of nanoscale imaging for applications. They have pioneered the development of high-speed atomic force microscopy (AFM) which has applications across science, healthcare and manufacturing (see Impact Case study). New developments have enabled a huge increase in the signal to noise ratio, enabling AFM scanning at ultra-high rates over a large area - leading to breakthroughs in both applied and fundamental science (*e.g.*, phosphorene nanoribbons Nature 2019). The discovery of a technique to image nanoscale fluctuations in the bacterial cell envelope has led to the development of a rapid antibiotic susceptibility instrument (Longitude Prize discovery award).

The appointments within this Theme of Springell, Liu and Martin in Nuclear Materials (3 FTE), and Payton in AFM development (0.5 FTE) during REF2021, follow from our strategy to increase our impact and engagement with industry in these already successful areas.



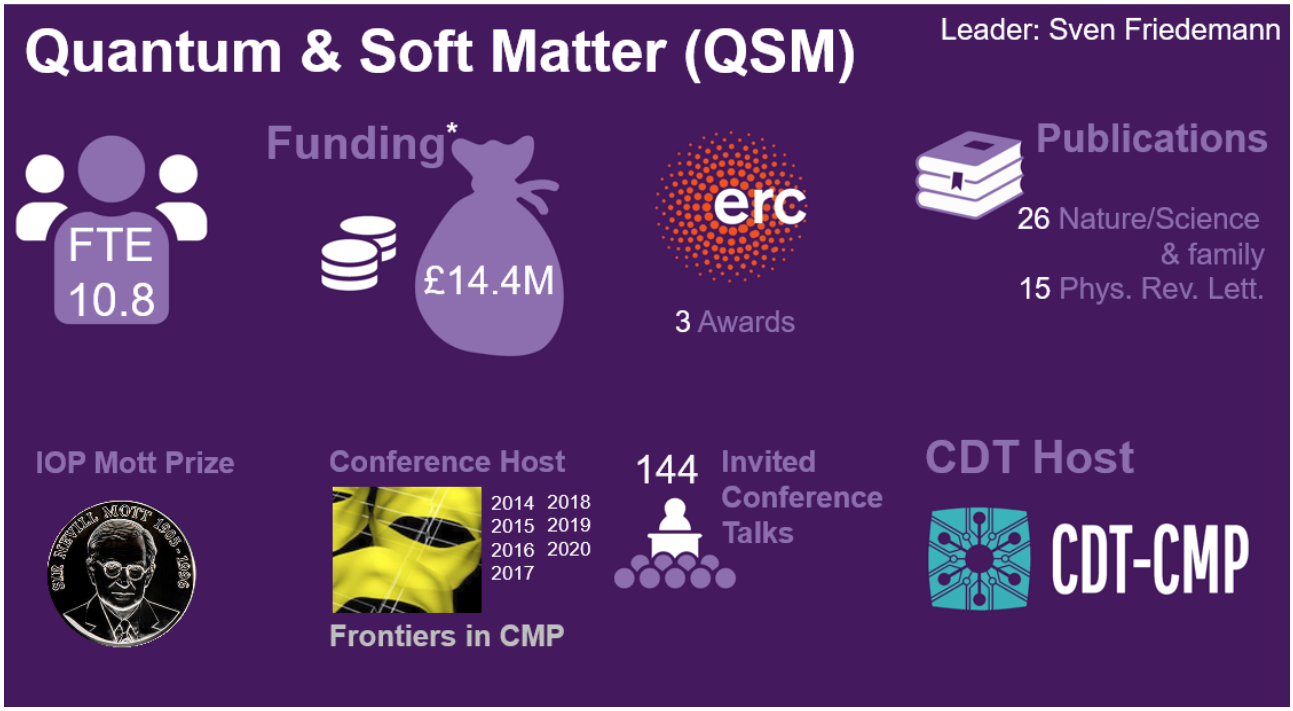
This Theme has pioneered the field of integrated quantum photonics, showing that photonic circuits can be implemented in waveguide architectures on-chip. Working closely with industry, the Theme has continued to lead the field throughout REF2021 by developing key components needed to advance the integrated approach, including development of quantum communication transmitter and receiver chips. They have developed a single reprogrammable optical circuit that can implement all possible linear optical protocols (Science 2015, with Nokia and NTT), a chip-based quantum key distribution system (Nature Comms. 2017, with NICT), a paired photon source

on a single chip (Nature Photon 2014, with Toshiba), a new architecture combining a reconfigurable photonic quantum processor with a conventional computer for quantum chemistry calculations (Nature Comms. 2014), and a device which can perform 15-dimensional entanglement (Science 2018).

The four areas of interest for commercial exploitation are quantum-enhanced sensors, secure communication systems and networks, quantum simulators, and quantum information processors. Theme members conduct theoretical and experimental research to develop convincing prototype technology demonstrators.

Quantum research at UoB is highly interdisciplinary and QET members also belong to QET Labs which spans Physics and Engineering, as well as the Bristol Quantum Information Research Institute (see Institutional-level Environment Statement: REF 5a) which includes academics from Mathematics and Electrical Engineering. The Theme is part of three of the four EPSRC Quantum Technologies Research Hubs (Communications, Imaging and Computing hubs led by York, Glasgow, and Oxford respectively) and leads most of the experimental work in the Communications Hub. The strength of Bristol's quantum research has been a prime factor in the establishment of the new Quantum Technologies Innovation Centre (QTIC) - the world's first dedicated open-access innovation facility for developing a broad spectrum of quantum technologies. QTIC has raised £91M of funding and will be housed in Bristol's planned £300M enterprise campus at Temple Quarter (see REF 5a).

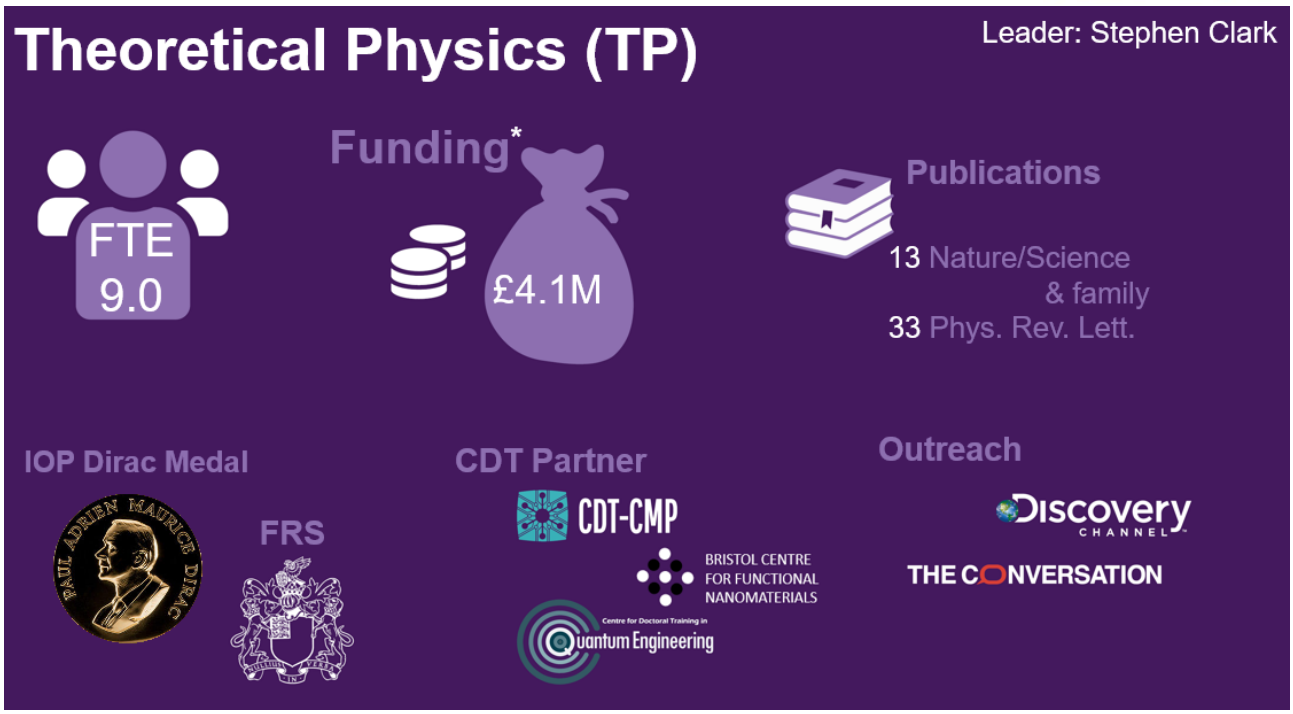
The lectureship appointment of Laing has developed our experimental applications of quantum computing to real-word problems, such as simulating the vibrational quantum dynamics of molecules (Nature 2018). The further joint lectureship appointments with Electrical Engineering of Barreto, McCutcheon, Sahin and Turner have supported the link to applied theory and expanded to incorporate a broader range of devices such as superconducting detectors and cryogenic electronics.



This Theme conducts fundamental research in Condensed Matter physics that spans hard and soft matter. A major strength is **Quantum Matter** with a focus on experimental studies of the fundamental physics of strongly correlated electrons in metals and insulators, and in particular high temperature superconductors. The Theme's comprehensive experimental approach includes development of novel instrumentation and analysis techniques both at Bristol and at international facilities, and the growth of state-of-the-art single crystal samples. REF2021 highlights include developing pressure cells for pulsed magnetic field measurements up to 70T (with EMFL-Toulouse) which provides new ways to study phase transitions in superconductors, and development of a new RIXS beamline at Diamond which offers new ways to study magnetic excitations. Discoveries include the nature of charge density waves in cuprate superconductors (PRB 2014 and Nature Comms. 2016) and quantum criticality in iron-based superconductors (Nature Phys. 2014). Success has been recognised by the award of the IOP Mott Prize (Hayden) and an €2.5M ERC advanced grant (Hussey -CATCH22) to study superconductors under extreme conditions. Building on the recent discovery of high temperature superconductivity in hydrogen containing compounds at very high pressure, the group has embarked on an ambitious and demanding programme to investigate the electronic properties of these materials which has been recognised by the award of an ERC starter grant (Friedemann - HPSUPER).

The joint professorial appointment of Hussey with High Field Magnet Lab at Radboud University (UoB 0.8 FTE) during REF2021 consolidates the group's world-leading status in this field and is enhancing collaboration with the European High Magnetic Fields Laboratory (EMFL).

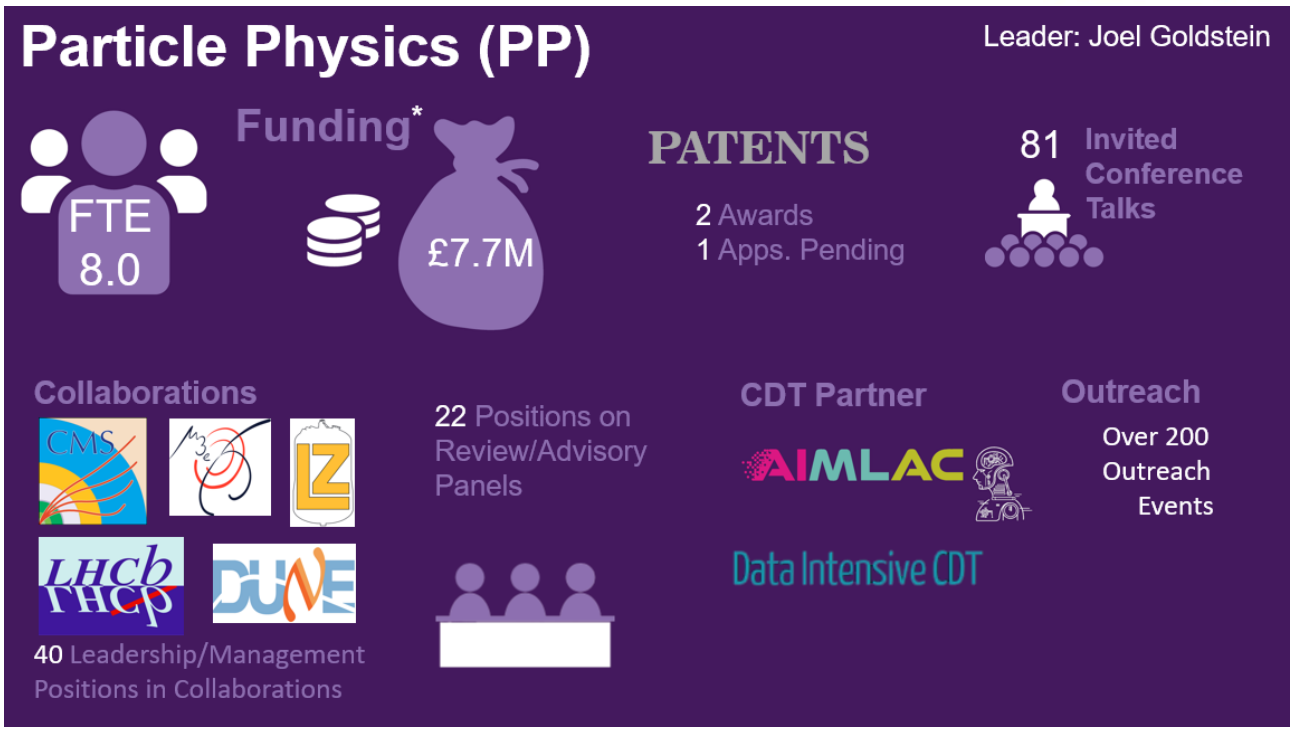
The **Soft Matter** strand focusses on biological, soft, and complex matter such as colloidal gels and proteins, elucidating key properties such as phase behaviour, nucleation properties and dynamical characteristics. A highlight was uncovering the structural relaxation mechanism in glass transitions (Nature Comms. 2015) and the award of an ERC consolidator grant (Royall-NanoPRS). Soft Matter is highly interdisciplinary with extensive links to the Schools of Chemistry and Mathematics supported by the Bristol Soft Matter Network which organises seminars and meetings. To exploit the potential for interactions with Biosciences, a new appointment (McManus) has been made, with a focus on understanding the self-assembly and phase behaviour of proteins.



The Theoretical Physics Theme's research can be grouped into three strands: **Quantum Information and Foundations** (QIF), **Hard-** and **Soft-Condensed Matter Theory** (CMT)**.**

The **QIF** strand explores the profound differences between the classical and quantum world revealed by quantum entanglement and non-locality. Its research has widespread applications to quantum optics, thermodynamics, and quantum biology. The activities of QIF are world leading as evidenced by the IOP Dirac Medal and FRS to Popescu for his research into nonlocality and his contribution to the foundations of quantum physics. Highlights include quantifying Einstein-Podolsky-Rosen Steering which has applications in quantum key distribution (PRL 2014) and developing a framework for extending thermodynamics to individual quantum systems (Nature Comms. 2014). Their work is also supported by rich interdisciplinary collaborations within Bristol's Quantum Information Research Institute, combining Physics with Mathematics and Engineering. The activity in this area has been strategically strengthened by the Lectureship appointments of Short and Skrzypczyk during REF2021.

Research in **CMT** spans the properties of novel quantum materials, both in and out of equilibrium, and the statistical physics of soft matter. Work in all of these areas involves a highly fruitful combination of foundational theory with significant efforts (31 papers co-authored with experimentalists) to drive their application in technologically important settings (2 joint industry supported PhDs). In hard-CMT, a major focus has been on understanding the microscopic interactions between carriers in topological and other exotic band structures and the fundamental physics of superconductivity and other quantum materials particularly in out-of-equilibrium conditions. This activity has been consolidated with two appointments during REF2021 (Gradhand and Clark) aligned with our strategy of building both industrial engagement with work on devices and collaboration with experimentalists. Highlights include theory of the spin Hall effect (PRB 2015), and light induced superconductivity in K_3C_{60} (Nature 2016). During REF2021, two new appointments (Machon and Wilding) have been made to exploit new developments in Topology and self-assembly, and their application to soft matter. This will forge new links to our experimental groups with potential industrial applications.



This Theme's activity is in the field of experimental Particle Physics, with a focus on development of detectors, data acquisition and data analysis using novel strategies. The theme is involved with multiple collaborations both within CERN and worldwide. In CMS (CERN), members are playing leading roles in searches for indications of non-standard model physics in Higgs boson decays. Highlights include setting limits on the invisible Higgs boson decays (EPJC 2014), and precision measurements in the top quark sector, as well as interpreting the results of CMS to tightly constrain new physics models (EPJC 2015). Members are making major contributions to operations, particularly on the Level-1 trigger, and to the Phase-2 tracker and trigger upgrades.

In LHCb (CERN), the theme leads measurements of the CP violating phase γ and CP-violation in charm and plays a central role in the investigation of lepton anomalies in the flavour sector including investigations of lepton flavour universality (PRL 2014) and angular analysis of B meson decays to leptons (JHEP 2016). They are also working on current and future LHCb upgrades.

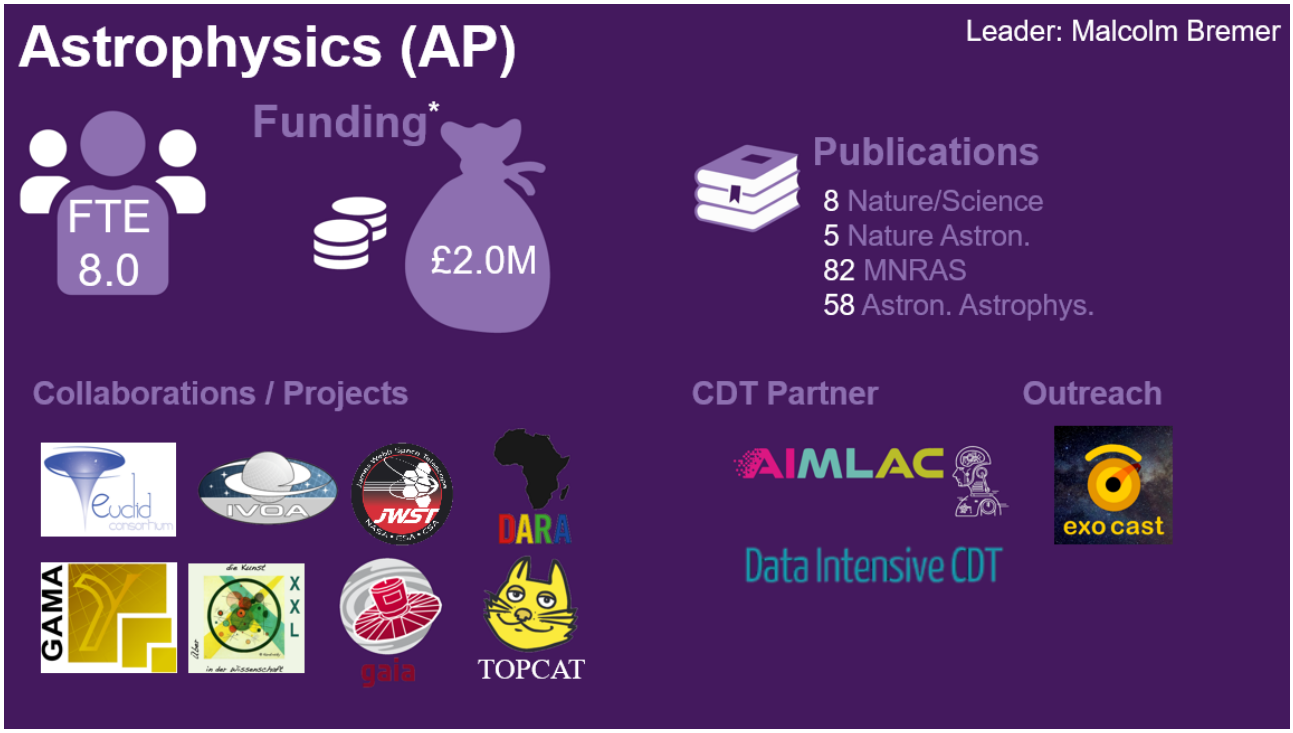
During REF2021, the Theme has joined the DUNE, LZ and Mu3e collaborations. Dune (Fermilab, USA) aims to investigate neutrino science and proton decay studies, Lux-Zeplin (LZ) (Sanford USA) is a search for dark-matter and Mu3e (PSI-Switzerland) is a search for a lepton-flavour violating decay. Involvement with these collaborations is building on the established expertise in detectors, data acquisition and computational analysis to provide contributions to the timing and control systems, simulations, and production test systems to prepare for physics analysis over the next decade.

Members of the Theme capitalise on their experience with very large data sets to collaborate with the UoB Jean Golding Institute providing expertise to lead cross-disciplinary data science projects.

Work in detector development has spun out into fruitful collaborations in the fields of nuclear waste management, radiation measurements, radiotherapy and homeland security. Working with industrial partners Vivamos and IBA, a radiotherapy verification device to enhance

safety/throughput in Intensity Modulated Radiotherapy has been developed and commercialised. Two patents have been awarded in this area during REF2021 (Patent1, Patent2).

Three Lectureship appointments during REF2021 have strengthened the work of this Theme. Brooke brings expertise in data acquisition and physics to the DUNE effort, Petridis is leading the lepton physics on LHCb, and Paramesvaran's experience of trigger design improves our operations within CMS.



The Astrophysics Theme addresses profound questions concerning the way structure forms in the Universe, the feedback of energy and fields into this structure, the “dark” constituents of the Universe, the properties of black holes, and the variety of planetary systems. Research is focused on the observational opportunities offered by the largest major observatories that exploit a wide range of wavebands including the JVLA and LOFAR in the radio, the Very Large Telescope and Hubble Space Telescope (HST) in the optical, and XMM and Chandra in the X-ray regime. Members play active roles in the preparation of science programmes on the forthcoming Euclid satellite, the James Webb Space Telescope (JWST) and the Rubin Telescope.

Theme members have made important advances in the understanding of the evolution of galaxy populations and massive clusters as part of the XXL survey (A&A 2016). The work on clusters is multi-faceted and extends to the highest redshift protoclusters, with pioneering multi-waveband studies of the earliest phases in the evolution of their galaxy populations (ApJ 2018). Beyond observational research, the Theme continues to develop their TOPCAT utility which is a catalogue-handling software used extensively by the worldwide astrophysics community.

The lectureship appointment of Wakeford has opened up the new area of exoplanet atmosphere research. This is a highly topical area which is increasingly becoming the focus of many high-profile observational missions (HST and JWST) and will result in high impact research for the

foreseeable future. It is also one which strongly captures the interest of the public, which we will further bolster with our very successful on-line public engagement activities (Exocast).

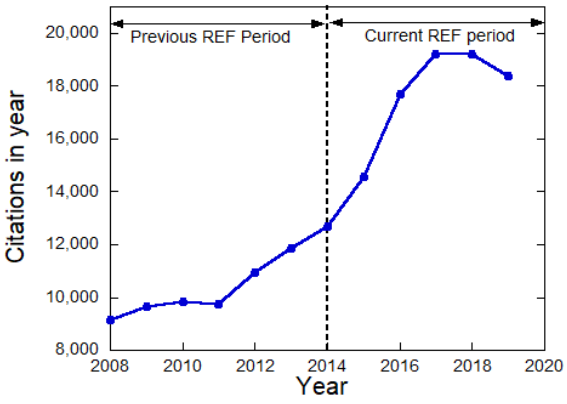
Physics research strategy and vision for the research environment

Our core Physics research strategy is to enhance our research in areas of existing strength, while fostering an environment in which we can respond nimbly to opportunities in exciting new fields particularly those which reach across traditional subject boundaries. A key route to this is through new appointments. These are made based on the candidates' suitability for all aspects of the academic role but with a focus on: (i) excellence in the research field with potential to become a research leader; (ii) fit with existing strengths with the potential to reach across discipline boundaries (where appropriate); (iii) potential to attract funding, either as an individual or part of a research team. In this manner, we build and maintain research teams which have the expertise and critical mass to facilitate effective collaboration and generate a constant flow of new ideas which inspire and motivate. Much of our work lies at the interface with other disciplines such as Electrical Engineering and Chemistry and capitalising on cross-disciplinary expertise within Bristol and beyond is a principal aim. To support this, we have seven joint academic appointments with other Schools (see Section 2).

We have successfully addressed our REF2014 objectives by enhancing our core research strengths with targeted appointments that build interdisciplinary links across the University and to industry. This is reflected in the growth in both quality and volume of our research outputs, which has been achieved whilst maintaining a research profile that contains a healthy mix of fundamental and applied topics. Such a broad portfolio allows us to thrive both in terms of basic science, where we expand fundamental knowledge and lay the foundations for the technologies of the future, and impact where we contribute to wealth creation and quality of life.

A strong international profile

Our general strategy has been to boost our international visibility and reputation. The success of this is evidenced by a substantial rise in our citations during REF2021 (see figure). Leadership and participation in collaborations between top researchers worldwide, are actively encouraged. UoB's international fund and the School's Research Initiator Fund provide seed corn funding to kick-start new international projects. For instance, we supported interactions with Heidelberg and Kyoto Universities, organising joint symposia and visits to build collaborations. Examples of these include collaborations in Quantum Matter where Kyoto expertise in sample growth of iron-based superconductors has been connected to Bristol expertise in measurements of physical properties (ARCMP 2014), and research into glass-relaxation dynamics (Nature Comms 2015) and radiation mapping (J. Env. Rad. 2016) linked to Kyoto researchers.



We host a steady stream of top international academics for seminars, colloquia, and research visits (~45 visits/annum of >2 days). High-profile academics are attracted to our Benjamin Meaker Distinguished Visiting Professorship Scheme, with 8 hosted during REF2021, resulting in collaborations and joint publications. Currently the School hosts 30 visiting industrial

fellows/professors, 7 honorary professors and 45 visiting/honorary research associates with whom we have extensive collaborations and links.

Each Research Theme runs a seminar programme and we run weekly School colloquia, attracting ~80 internationally prominent speakers each year. Colloquia attract a large audience and provide a focal point for our community of researchers to meet, interact and socialize. Academics lead and run international conferences and workshops in Bristol, and we support this by providing cost-free meeting/lecture rooms and administrative support. An example is the two-day Frontiers in Condensed Matter Physics Conference held annually in the School since 2014, which attracts a substantial proportion of the UK hard condensed matter community and international delegates (>100 attendees/year).

Research governance strategy

This is grounded in national policy frameworks including the QAA UK Quality code, and UoB's Policy on Research Governance and Integrity. The University strongly supports the Concordat on Research Integrity and is working to join the UK Reproducibility Network. Within the School, responsible research is monitored via Theme leads and the Science Faculty Ethics Committee. A course on research integrity forms part of the staff development for new academics. Postgraduate researchers (PGR) receive dedicated training on research governance and integrity as part of their induction programme.

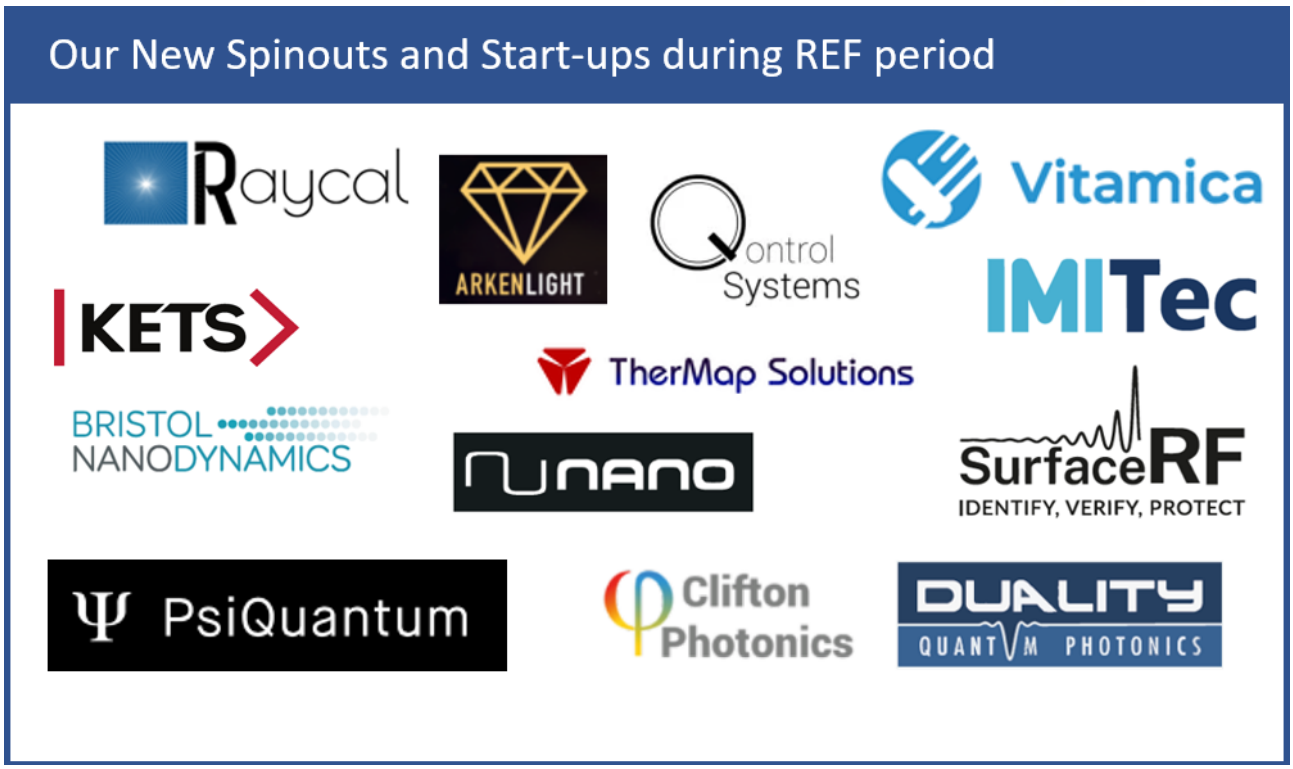
Open Science

We are committed to UoB's open access policies and ensure that papers are uploaded to the University's public repository (PURE), which underpins the public catalogue of UoB's research. Furthermore, many papers are deposited on preprint servers (arXiv) often before acceptance. Papers are publicised on ResearchGate and LinkedIn. For many journals (*e.g.*, Nature Comm. / Science Adv.), UoB funds open access publication where this is unavailable free of charge.

Individual researchers and collaborations are supported to plan, manage and share research data by the library's Research Data Service and archive significant primary research datasets in the University's publicly accessible Research Data Storage Facility. Where computational code is a key deliverable, our standard practice is to preserve and release the commented and documented code under an open license using a public repository (*e.g.,* SPOKnots on GitHub).

Strategy for Impact

A commitment to impact is deeply embedded across the School and we have an exceptionally strong culture of founding start-up/spin-out companies as well as building strong and enduring industrial partnerships. During REF2021, Physics staff have founded an impressive total of 13 companies (see graphic). These include PsiQuantum, the most highly funded quantum computing start-up in the world. Together these companies have generated investment of £160M and employ over 150 FTE (see impact case studies). Furthermore, we have worked with 72 different companies in the UK and worldwide including major players such as GlaxoSmithKline, Airbus, Syngenta, Northrop Grumman, Johnson & Johnson, and EDF. Our activity in quantum technologies has directly contributed to the establishment of the Quantum Technologies Innovation Centre (see above) which will help shape our plans for future impact in this area.



These successes arise from a strong commitment to identifying and capitalising on new and exciting research opportunities which have great potential for impact. To achieve this, we start by identifying areas of applied research -such as materials physics or quantum information technologies- with strong potential for ground-breaking applications and that interface well to industrial needs. Next, we grow strength in these areas by hiring top-flight academics with the requisite skills, experience and enthusiasm for collaboration, entrepreneurship and engaging with industry. Then we support and reward these individuals to engage with impact opportunities *e.g.,* through developing applications to the University's EPSRC/STFC Impact Acceleration Account (IAA) which provides start-up funding for promising projects. Since 2014, Physics academics have received £1.4M from the IAA for projects with 18 industrial partners, and SoP/UoB have contributed a similar sum in terms of estates/overheads costs. We also ensure that individuals have time to carry out impact-related activities, which are explicitly recognised in the University's promotion criteria.

Targeted impact initiatives

This broad strategy is underpinned by several bespoke impact-focussed measures. One is our "Impact Roadshow" in which we visit companies to explore opportunities for joint working. In the past 4 years we have visited 12 companies, resulting in several new collaborations, *e.g.*, our visit to Malvern Panalytical resulted in a representative joining our Industrial Advisory Board (see below), and was instrumental in them signing a strategic partnership with UoB (2019) to collaborate on student training in data science. We also run an annual 3-day quantum innovation event (QIL) which brings together industrialists and academic researchers in quantum technologies, with companies including Airbus, Deutsche Bank, and Hitachi. Internally, we have provided training about the commercialisation of research, for example a lawyer led session on intellectual property at a staff away-day, and a session on how to realise commercial impact from research through licensing or creation of spin out companies. UoB's Research Enterprise and Development (RED) unit supports staff with patent applications, negotiating contracts and license agreements with industry, and supports applications for different types of industry partnership

funding, such as the Industrial Strategy Challenge Fund, STFC-Innovations Partnership Scheme, InnovateUK, and Knowledge Transfer Partnerships/ Secondments.

Industrial Advisory Board (IAB)

We work hard to foster successful professional relationships between academics and key external users. To this end, we regularly seek the expert advice of members of our highly proactive IAB. The board meets biannually to help set the direction of our industrial, teaching and research activities. Members include representatives from Airbus, Oxford Instruments, NNL, NPL, AWE and Malvern-Panalytical and are chosen both for the collaborative opportunities which their sectors provide, and for their importance as potential career destinations for our graduates. Links established via the IAB have led to several joint ventures and Memorandums of Understanding *e.g.,* with Oxford Instruments and Malvern Panalytical, which facilitate skills and business training for PhD students, and co-sponsoring of PhD projects. Indeed, as a direct result, Malvern Panalytical established a new Data Science Hub at the Engine Shed incubator facility in Bristol in 2019. This employs 10 full-time staff and has become a favoured destination for undergraduate placements. As stated by Malvern-Panalytical's Vice President of R&D, Rowena Innocent: *"The decision to locate our expanding Data Science and Software development team in Bristol was a direct result of the collaborative environment, shared research and learning opportunities offered by the School of Physics and the wider university."*

Bespoke training for entrepreneurs

We train ECRs with promising ideas for spinout companies in the skills of entrepreneurship. To facilitate this strategy, members of our QET Theme founded the Quantum Technology Enterprise Centre (QTEC). This incubator supplies high-quality training for innovators in quantum-inspired technologies and is an EPSRC Skills and Training Hub and part of the National Quantum Technologies Programme. QTEC is housed in dedicated office/teaching space and offers a twelve-month fellowship programme to provide academics with the requisite skills to set up successful technology start-ups, which will underpin the UK's quantum technology industry. QTEC has supported the creation of 31 new companies based on technologies which underpin the quantum industry. A report in 2019 shows that a third of the UK's funded Quantum start-ups originated at QTEC. While many of these are still in their infancy, they have to date raised a total of £44.8M in funding and created 126 new highly skilled jobs.

2. People

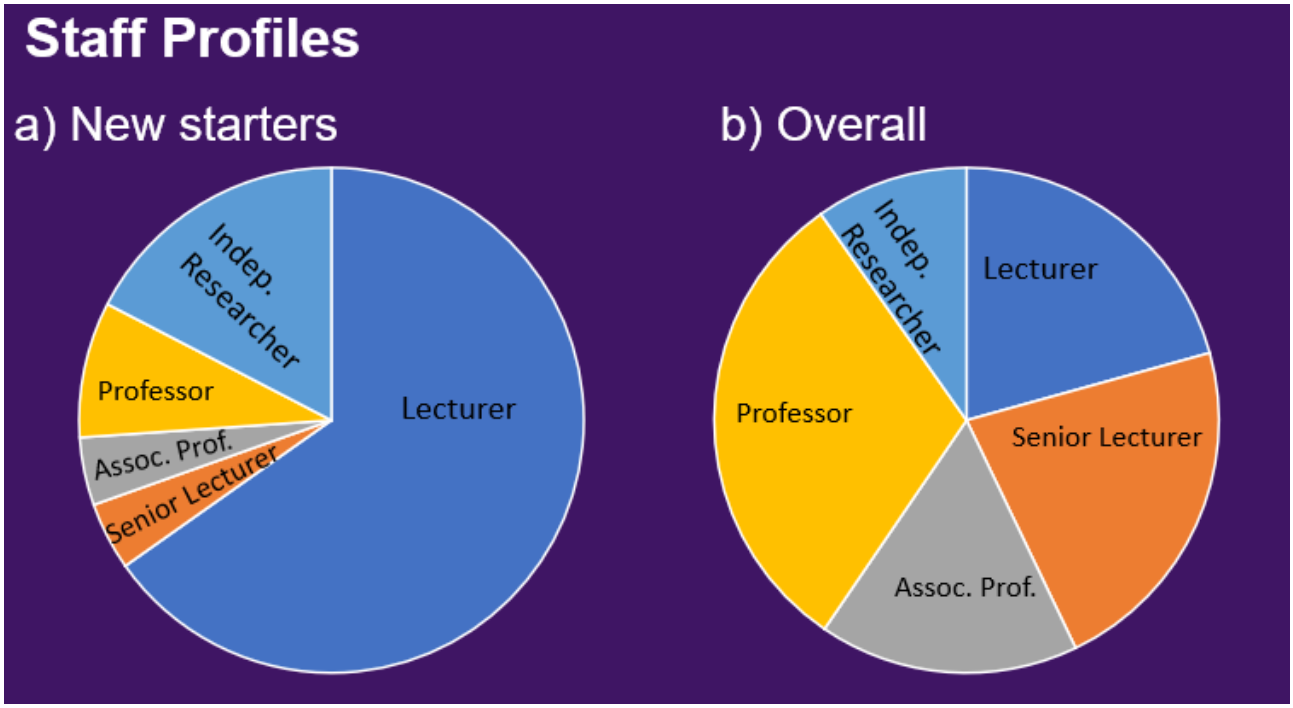
Staffing strategy and staff development

Our success in research and impact (and equally in teaching and outreach) depends critically upon building a working environment in which world class researchers can flourish professionally and personally. We support our researchers so that they feel enthusiastic about their work and valued for their contributions. Key to achieving this is a flexible and well-resourced research environment coupled with a workplace culture that promotes positive behaviours and provides robust processes that support career development, starting with recruitment and continuing through all levels of career progression. Our successes during REF2021 are evidenced by a large number of fellowship awards and promotions, as well as by marked improvements to the diversity of our academic cohort. Great strides have also been made in improving support for staff with regard to career progression, caring responsibilities, fair management of workload, and wellbeing.

Current profile and recruitment and diversity strategy

Implementing the criteria for hiring academics as set out in Section 1, has led to a large scale and highly successful renewal of our academic cohort. The starting profile of the 19 appointees during REF2021, fig a), demonstrates our emphasis on attracting excellent junior academics, coupled with strategic appointments of established academics to rapidly enact our research strategy. In addition to appointing topflight external candidates, we maintain a healthy pipeline of homegrown talent: Gradhand, Laing, Payton and Skrzypczyk were mentored to win prestigious fellowships and subsequently gained a permanent academic post. Several junior appointees feature strongly in our REF2021 outputs: Laing (5 papers), Wakeford (5), Skrzypczyk (5), Payton (3), Gradhand (3).

The current overall School profile demonstrates an excellent mix of senior and junior staff. With few retirements expected in the next 5 years, our priority will be to nurture new recruits to realize their full potential (see below). A strong group of research-active emeritus professors (including 4 FRS) contribute actively to School life and act as mentors for junior academics.



To support our drive for interdisciplinarity, we have invested in 7 joint appointments (4 since 2014) with both Electrical Engineering (EE) and Chemistry to synthesise knowledge and techniques from the individual disciplines when solving problems at the interface. Joint appointments with EE are in quantum technologies. Those with Chemistry are in colloids and active matter, and materials science. These appointments support our impact strategy (Section 1) by providing an excellent link between novel chemical growth and fabrication methods and materials characterisation using cutting edge instrumentation. As joint appointments with EE are inter-faculty, a special board chaired by the respective Deans helps coordinate research and supports staff needs.

Developing our academics

A range of support is available for the career development of staff, ensuring that they can become international research leaders.

The central RED team supports all forms of research, enterprise, and knowledge transfer and offers advice and support on funding opportunities, project management, research proposal preparation, stimulating collaborations with other universities and business, intellectual property management and commercialisation of research through consultancy, contracts, and spin outs.

Fellowships are a key enabler of research success and 31 fellowships (see Section 4) have been held in REF2021 including 9 ERCs, 6 EPSRC and 5 Marie Sklodowska-Curie. Preparation of applications is supported within the SoP by detailed internal peer review processes (also used for other grant applications) and centrally by RED. Fellowship bids requiring equipment are supported through faculty capital investment and cross-faculty practice interviews.

A prerequisite for research success is balancing the demands of teaching, administration, and research. A comprehensive **workload allocation model** for academic staff was introduced during REF2021 and has been widely welcomed by staff. It ensures that academic duties are distributed fairly and transparently, assuring that workload is manageable, and that no member of staff is disadvantaged for example because of their gender or contracted working hours. The model assigns reduced workload to staff returning from long-term caring or sickness leave. Allowance is made in the model for the disproportionate burden placed on female staff by serving on University committees. The model was developed by a diverse team of academics ensuring that the widest possible range of experiences could be incorporated, and their proposals were scrutinised by the Equality Diversity and Inclusion (EDI) committee.

The University funds **sabbaticals** enabling academics to focus on research for one academic year (see REF 5a). Additionally, staff members finishing major administrative roles are afforded a year without teaching and administrative duties to concentrate on research. During REF2021, 8 academics have benefited from sabbaticals. Honorary Senior Research Fellowships support the contribution of 7 emeritus staff to the research and academic life of the School.

Academic and research staff participate in an annual Staff Review and Development process where they reflect on their achievements and aspirations. The review is conducted by a more experienced colleague at the same academic level or one above, giving reviewees the chance to receive advice from someone who has recently been in their shoes. The review process provides an opportunity to flag up matters to the Head of School such as additional support requirements including those related to protected characteristics. Overall participation rates are high (80%), reflecting the success and popularity of the process.

A **mentoring scheme** introduced in 2018 has been well-received by junior academics. The scheme is being extended to all staff who wish to participate. Each mentee is paired with an experienced and enthusiastic mentor from a different research area. The relationship is supported by SoP guidelines to ensure development of a range of skills from building confidence to writing grant applications.

Advice on **career progression** is provided through Staff Review, mentorship, and the SoP Promotion Advisory Committee, which provides guidance on applications. The committee shares two members with the EDI committee and encourages strong (but reticent) candidates to apply, as well as ensuring that no-one with a protected characteristic is unfairly overlooked. Applicants are encouraged to submit an EDI statement to the panel. Since 2014, the University has promoted 6 of the School's academic staff to Professor (including one woman) and 7 to Senior Lecturer or

Reader/Associate Professor (including 3 women). The criteria for promotion have recently been transformed to explicitly recognise and reward impact-generating (industrial, community and policy-facing) activities. This change highlights and values the activities in which many staff in the SoP are involved.

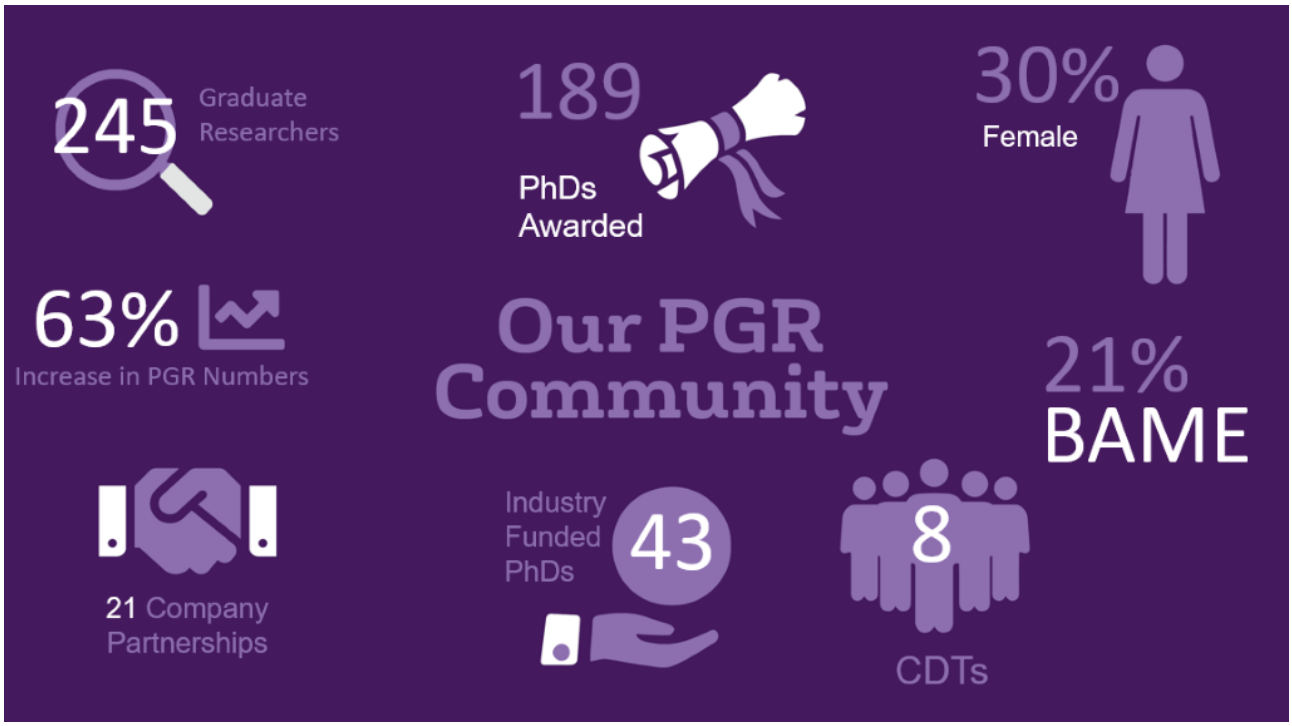
Nurturing Early Career Researchers

Our strategy of focussing recruitment on talented ECRs is backed up by continuing support for their careers. New academics typically receive funds to establish their research programme and access facilities such as the Cleanroom. They are prioritised in the distribution of PhD studentships and receive reduced teaching and administrative duties during their first three years. Our anti-casualisation policies have steadily reduced use of fixed term contracts so that 96% of our REF2021 Category A staff with teaching commitments have an open-ended contract with secure core-funding.

The probationary process for new academics is carefully managed with the primary aim being to accelerate research careers. In their first year, new academics meet regularly with the Head of School, their Theme leader, and their mentor to discuss progress. A central Staff Development team facilitates the CREATE course to enhance academic practice and gain a nationally recognised qualification (FHEA), see REF5a. Substantial advice is given in preparing EPSRC First Grant/New Investigator proposals, and 66% of these have been successful during REF2021. We also fund leadership training, including that aimed at female staff, and have supported several to apply for and take part in the Aurora and Bristol's FLi Leadership programmes, reporting that they have gained valuable new skills and increased confidence.

Our research strength is enhanced by our large cohort of 57 postdoctoral researchers. The University is a signatory of the Concordat to support research staff development. Staff Development and the Bristol Clear programme supplies a wide variety of developmental, leadership and generic skills training, including grant writing workshops and peer-to-peer mentoring (REF5a). The SoP is represented on the UoB Research Staff Representation and Working Party which ensures dissemination of best practice in supporting researchers and their career development. The Physics Early Careers Forum acts as a point of support, information and advocacy for research staff and liaises with the Head of School to ensure implementation of the Concordat. To supply opportunities for ECRs to showcase their research to colleagues, we reserve slots at the School colloquia. When funding expires, research staff are considered for redeployment and retraining within UoB.

Wellbeing is central to our strategic aims and data from the University's staff and Athena SWAN surveys informs our action plan. This has resulted in wellbeing becoming a focus of the staff review which starts with the question "How have you found this year?". The School's new **Code of Conduct** (2019) constructed around the core Theme of "Inspire, Respect, Include", is similarly designed to support positive behaviours and wellbeing. The University runs a staff mental health and wellbeing service, offering Staff Counselling and courses on topics such as Building Inner Resilience, Five Ways to Wellbeing, and Mindfulness in 8 Weeks. All staff and students are regularly sent updates on these activities via the weekly Physics News bulletin and are encouraged to attend the University Staff Health and Wellbeing Roadshow.



Our PGR strategy is founded on sustainable growth as measured by: (1) the number of students, particularly in partnership with external stakeholders; and (2) the quality of the training, support, and supervision environment.

Sources of studentships and growth

Principal sources of studentships are Centres for Doctoral Training (CDT), EPSRC Doctoral Training Partnership (DTP), STFC, industry, and legacy bequests. The School provides an excellent PGR training environment as recognised in successive awards for cohort-led thematic CDTs since 2008. Over the assessment period we have **led four EPSRC CDTs**:

- Quantum Engineering, I (2014-2022)
- Quantum Engineering, 2 (2019-2027)
- Condensed Matter Physics (2014-2022)
- The Bristol Centre for Functional Nanomaterials (BCFN) (2008-2023),

and are partners in further four UKRI CDTs:

- Data Intensive (2017-2024) (led by Cardiff)
- Artificial Intelligence, Machine Learning and Advanced Computing (2019-2027) (led by Swansea)
- Nuclear Energy Futures (2019-2027) (led by Imperial College)
- Diamond Science and technology (2014-2022) (led by Warwick)

The Condensed Matter CDT with Bath continues to offer an extensive programme of shared training courses, lectures and activities co-delivered as part of a wider GW4 collaboration. The BCFN continues to cater for a demand for PGR training in nanomaterials with strong industry involvement.

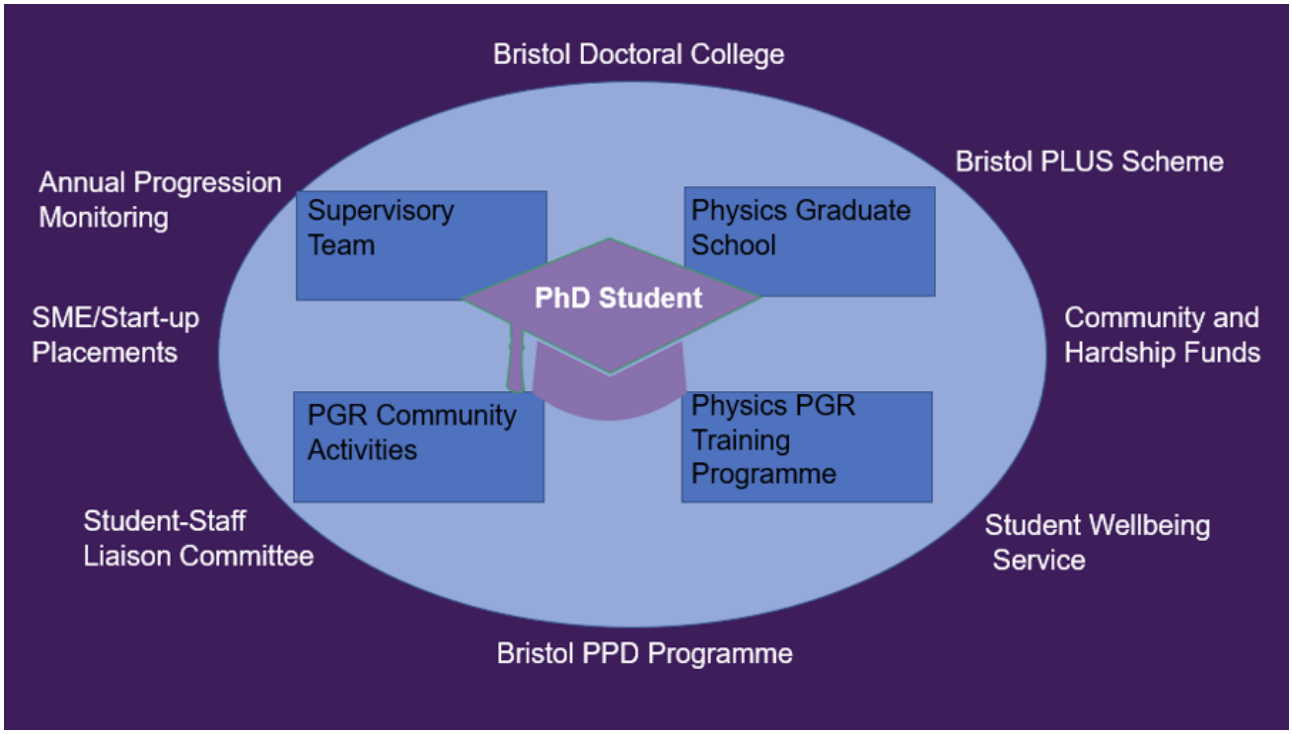
Thanks to a history of large donations, including a generous bequest from the family of a former academic of **£6M in 2018**, the SoP supports up to four new studentships per year. These funds allow us to admit a diverse cohort of international students and form collaborations with industry which would otherwise be more difficult, *e.g.*, by leveraging matched funding in a way which the DTP does not allow. The task of marketing our programme to international students is supported by the International Office and the School's team of international ambassadors.

The quality of the SoP PGR training environment is evidenced and endorsed by the continual attraction of highest quality students to the programmes: applications are oversubscribed tenfold. The School has attracted 13 China Scholarship Council (CSC) PhD students since 2017, and recruitment remains very strong from other countries. This, together with success in attracting industry co-funded studentships, has helped maintain large PGR intake numbers. The current cohort comprises 184 PhD students (85 in CDTs) and 13 MScR students. This represents an impressive **63% increase** over REF2014.

A total of 44 different companies have partnered with our PGR programmes during REF2021 with **43 PhD studentships having been 50% funded by industry** (see Section 3). Bristol boasts a vibrant SME and start-up sector, and we tap into this to give PGRs first rate entrepreneurial training, working with local incubator ecosystems Unit DX and Spin-Up Science (the latter founded by one of our PhD Alumni in 2015).

Physics Graduate School and Student Voice

All Physics PGR students belong to The Physics Graduate School and the Bristol Doctoral College (BDC). Alongside training and supervision support, the Graduate School organises social events and cohort-building activities. It is led by an Academic Director, a deputy and 2 FTE of administrative support. In addition to the nuts and bolts of delivering a successful and dynamic PGR ecosystem, the Graduate School carries out all Faculty PGR processes and provides an extensive student support system, with mechanisms for students to receive advice, pastoral support, mentorship and interfaces to other student and wellbeing services (see graphic).



Our proactive Student Staff Liaison Committee (SSLC) has two PGR representatives from each Research Theme, and two representatives from the SoP EDI Committee. There are 6 meetings per year to ensure coverage of the PGR brief, and all meetings are chaired by a PGR student. The national Postgraduate Researcher Experience Survey (PRES) is strongly promoted in the School and PGR representatives interrogate the survey data in partnership with the Graduate School to inform improvements in practice and policy. This relates to the Education Action Plan (EAP) process which is the School's working document which governs the PGR environment, and which feeds into the Faculty structure as part of a rigorous quality assurance system of PGR governance. The process of student-led interrogation of PRES data, and the use of this analysis to drive progressive policy change has been commended as "best practice" by the Bristol University Quality Team and will be disseminated to other Schools and Faculties.

Diversity

A key aim of the EAP is to increase the diversity of our PGR student population by fostering an ever-stronger culture of inclusivity. Advertising material has been made more appealing to prospective students with protected characteristics by demonstrating the welcoming, tolerant, and supportive environment. The School's recruitment of female PGRs is above the national average (30% average over REF2021 compared with 21.9% nationally). Women are equally likely as men to be made an offer of study or to accept an offer from us. We welcome applications from students who wish to study part-time or take leave due to caring responsibilities or ill health.

Training Opportunities

The emphasis on training enshrined in our successful CDT portfolio has deepened our commitment to PGR training for all students. We have completely overhauled our PGR induction programme with an extensive 3-week programme of events which are extremely well attended. This segues into the wider SoP training programme which alongside skills development opportunities in communication, writing and project planning, provides collaborative sessions led by companies on business-ready skillsets to support translation of research ideas to the commercial sphere, and to aid employability. The school-wide programme integrates with the tailored provision offered by Research Themes, CDTs, and wider University level programmes offered by the BDC. The latter includes the QAA-commended Personal and Professional Development Programme which features courses on project management, thesis writing, time management, presenting to diverse audiences, and outreach. The annual Research Without Borders PGR festival provides opportunities to work collaboratively with students from other disciplines. The SoP is developing new interfaces with the Careers Service to support the career prospects for PGR students, including promotion of the Bristol PLUS employability scheme.

Supervision

Each PGR student has two supervisors, chosen with the aim of maximising academic guidance and pastoral support. The central Academic Staff Development service provides staff training in high quality supervision, and this is complemented within the SoP by extensive mentorship activity and specific targeted training interventions. For interdisciplinary and some CDT projects, supervisor teams may span subject boundaries and Universities. For PGRs co-funded by industry (for example, Malvern Panalytical), we are promoting supervisory practices which retain all aspects of the academic environment and add to that reporting and professional development aspects of the commercial culture.

Progression and Assessment

Students have an Annual Progress Monitoring interview with two academics, neither of whom is part of the supervisory team. Following input from SSLC and PRES survey data, this process now places a stronger emphasis on personal and professional development. In year one, the interview assesses understanding of the project context and promotes discussion on the research environment; in later years there is a fuller research report to assess progress, and in the final year, a discussion of thesis plans. Interviews consider supervisory arrangements, wider training needs and opportunities to support the student to progress professionally as well as in their research.

Equality, Diversity, and Inclusion

Promoting diversity and Athena SWAN

The School supports all staff and students to realise their academic and personal potential irrespective of their gender, ethnicity, sexuality, disability, age, religion, and economic background. As part of our diversity agenda, in 2018 we agreed a set of 42 concrete actions which aim to make a real difference to those who work and study here. Examples of specific actions we implemented are: developing a code of conduct (see above), improvements to building accessibility, expanding provision of specialist equipment for office working, ensuring that deadlines for applications for internal research funds are announced well ahead of time, and an expectation that research seminars and committees are set to family-friendly hours.

Responsibility for fulfilling these actions falls to the EDI Committee, which is comprised of undergraduate and postgraduate students and staff of various categories and seniority (including the Head of School). The committee is gender-balanced and ethnically diverse. It is quick to respond to queries and suggestions from staff and students about how they can be better supported to conduct their research. A focus is ensuring that processes within the School promote inclusivity, thereby leading to a safe and welcoming environment for everyone. School Assemblies feature EDI items such as workshops on working together in a respectful manner, and unconscious bias. University networks support BAME and LGBTQ+ staff. We show support for our LGBTQ+ staff and students via a prominent flag in the main foyer, laptop stickers, encouraging the wearing of a LGBTQ+ themed lanyard, and encouraging use of gender pronoun labels on emails. The Women in the School of Physics group is open to all staff and students who identify as female and organises regular lunches and seminars. In decision-making around accessing internal funds, the School Executive ensure that they consider equality and diversity. Research-related leadership roles are advertised within the School and are open to all academic staff, with those from minority groups particularly encouraged to apply.

Our primary EDI focus has been the recruitment of a new and diverse group of staff. The fraction of female research staff in REF2014 was below the sector average. In response, recruitment procedures were overhauled to include more gender-neutral advertising material and soliciting applications from qualified members of under-represented groups. When shortlisting, the chair of the EDI committee checks that no excellent candidates have been overlooked unfairly, *e.g.*, because of a career break for caring responsibilities. These interventions have resulted in a greater number of high-quality female applicants applying to our roles and has carried through to appointments. In 2018/2019, 3 of our 6 new academic positions – Liu, Wakeford, McManus - were filled by women and 2 were filled by BAME candidates. Overall, in this submission **19% of staff are female (up from 8% in 2014)**. In 2019, we successfully renewed our Athena SWAN bronze

and Juno practitioner awards and aim to attain Athena SWAN silver and Juno champion status by 2022.

We have been successful in raising the attendance of female attendees at our conferences, for example female attendees at BQIT have risen from 13% to 31% during REF2021.

Support for carers

The University's Returning Carer's scheme provides funds to help re-establish research for staff returning from parental/caring leave. Support is also provided by the SoP Parents and Carers Group (established 2019) which provides coaching, advice on HR policies and procedures, social activities, and risk assessments. The group has helped establish a private space to express and store breast milk. Help in managing workload for staff with caring responsibilities is provided via the University's flexible working policy and timetabling policies. Typically, around 10 staff per year take advantage of these policies.

Building a sense of community

The School's executive team (led by Wilding as Head of School) sets a tone of transparency, clarity, inclusion, and collegiality. We celebrate colleagues' successes via the weekly Physics News bulletin. Our termly "Physics by the cake" event offers an opportunity for staff to showcase their research or outside interests to a general audience of academic and professional services staff in a relaxed social setting. Other popular social events are our Christmas and summer parties to which all staff and their families are invited.

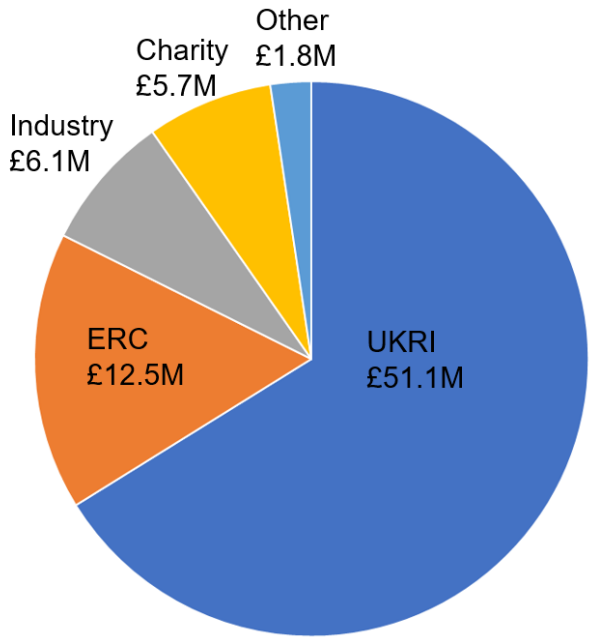
REF and EDI

This REF submission was compiled in accordance with the University's REF code of conduct, as described in REF 5a.

3. Income, infrastructure and facilities

Research income and strategy

New awards for research (including studentships) over the REF2021 period totalled **£105M.** This figure comprises £80M of research funding and industry supported studentships, and £25M for Doctoral training or studentships from UKRI. These awards represent a substantial increase compared with £38M of new funding reported in REF2014. The breakdown of funders is (see graphic): UK funding councils (66%), European Research Councils (16%), Industry (8%) and Charities (7%). UoB provided £2M for capital equipment and laboratory refurbishments. Our Research income during REF2021 as reported in REF4b (as opposed to the new awards above) was £57.6M (£8.2M/annum). This again shows a substantial increase over the £28.8M (£5.8M/annum) reported in REF2014.



Source of PI Research Awards for Bristol Physics during REF2021, excluding studentships except those funded by Industry.

In part, the increase in our research funding has resulted from our involvement in major consortia and large-scale collaborative programmes often including industry. We are members of 3 EPSRC Quantum Technology Hubs: Quantum Enhanced Imaging, Quantum Computing and Simulation, and Quantum Communications (£2.4M of awards in REF2021) and lead the QuPIC programme (£4.6M) to establish a UK quantum device prototyping service. Our QET Theme is also part of the EU QuChip programme (£300K). Our materials researchers participate in 6 programme consortia: NCNR, RAIN, CHIMP, ASPIRE, PACIFIC, DISTINCTIVE (~£5M awards in total). Our researchers working on semiconductor devices lead a EPSRC programme grant GaN-DaME (£4.3M), platform grant MANGI (£1.5M) and are also part of the EU H2020 HEATPACK consortium (£220K).

We have many direct research partnerships with companies which do not involve UKRI or EU participation. During REF2021 we have worked with 89 different companies worldwide, resulting in over £7.7M of industrial funding income (including £1.6M for consultancy). These include AWE £1.6M, Sellafield £1.0M, EDF £640K, Rolls-Royce £420K, and Northrop £400K. Capitalising on impact acceleration (IAA) funding is a key part of our impact strategy and SoP has received £1.4M of IAA funding spread over ~60 projects which include 18 industrial partners. These small-scale projects are drivers for larger future collaborations and technology transfer.

Project funding

Our success in winning major grants during REF2021 highlights both the research excellence of our staff and the quality of our research environment and the support it offers. Beyond the specific funding listed, there are dozens of other high profile intra-and inter-disciplinary projects from sources such as EPSRC, STFC, InnovateUK, ERC, USAirforce, GCRF, and Leverhulme. Our major success in Fellowship awards is detailed in Section 4.

Equality of opportunity

Internal funding, including studentships, equipment funds and facility access, is prioritised to kick-start research by ECRs or those returning from career/funding breaks. Fellowship applications are supported by mock panels and mentoring from experienced colleagues. The workload model allocates a minimum of 0.4 FTE of individual staff time for research.

Research Infrastructure and Facilities

Crucial for generating internationally leading outputs and impacts and maintaining our funding base, are access to world class facilities and infrastructure both in Bristol, the UK and world-wide. Below is a summary of the facilities we use.

Local Equipment and Facilities		External Facilities
Environment	Analysis / Spectroscopy	Diamond Light Source (DLS)
Superconducting Magnets	NanoESCA	ISIS
Low Temperature Cryostats	FIB/SEM/AFM/TEM	Institute Laue-Langevin (ILL)
High Pressure Cells	3D X-Ray Tomography	ESRF
Helium Liquefier	SAXS-WAXS	Paul Scherrer Institute (PSI)
NSQI building	Raman Microscopy Suite	APS / ALS
Device / Material Fabrication	SQUID Magnetometer	Spring-8
Clean Room/Fab Suite	Nanoscope	DESY
Materials Prep Lab	X-Ray Diffraction Suite*	EMFL
Thin-Film Deposition	NMR Suite *	National Epitaxy Service (NES)
Computing	EPMA*	Astronomy
Bluecrystal HPC	Bioimaging Facility§	ESO:VLT & ALMA
DICE data cluster	Workshops	ESA:Gaia, XMM-Newton, Euclid, HST, JWST
	Mechanical	NASA:Chandra, Suzaku, NuStar
	Electronics	LOFAR
	Glass	NRAO:JVLA
	* based in Chemistry	Particle Physics
	§ based in Life Sciences	CERN : CMS/LHCb
		SURF:DUNE/LZ
		PSI : Mu3e

Local equipment and facilities

The total value of our large-scale laboratory equipment exceeds £35M. Technical support is provided by 6 SoP technicians who support the running and maintenance of this infrastructure. The Science Faculty supports centralised workshops for the manufacture of bespoke equipment which is essential to much of our research. These include Mechanical, Electronic and Glass/Ceramics workshops and approximately 6 FTE is used annually by SoP. Centralised computing support handles both day-to-day office computing and specialist research requirements.

Clean Room: This high-spec facility housed in Physics, opened in 2015 with a build cost of £1.8M, supports experimental activity across the School. It hosts a wide spectrum of nanofabrication tools, including electron beam lithography, a laser mask writer, and a variety of wafer etching, deposition, and analysis instruments (total value £5.8M, with £3.8M of new equipment in REF2021). It is essential to the work of several research Themes including QET (fabrication of

photonic devices- see case study); Materials and Devices (ultra-high-power electronic materials and uranium based spintronics); Quantum and Soft Matter (active colloidal Janus particles).

The Interface Analysis Centre hosts an array of analytical equipment for conducting surface, materials and solution analysis. Equipment investment in the REF2021 period totals £4.9M. Key instruments include: 2 focused ion beam (FIB) instruments, 2 SEMs, a thin-film magnetron sputtering laboratory, a X-ray Tomography suite for high resolution 3D absorption imaging and 3 high-speed AFMs. Beside work on nuclear materials, the centre also collaborates with Rolls-Royce on aerospace engine turbine blades. Other work is developing high-speed AFM and Raman techniques for DNA mapping and medical devices (see case study).

The *Centre for Device Thermography and Reliability* host a wide range of instruments for analysing semiconductor devices, particularly high power and microwave devices. High resolution Raman thermal imaging and infra-red thermography equipment underpins the group's industrial collaborations with more than 20 companies. New investment in REF2021 includes a Nano-indenter (£1M), X-ray CT scanner (£500K) and an AFM, together with £200K of laboratory upgrades (UoB funded). This has considerably enhanced capabilities for device failure analysis and the quantification of the stability of interfaces in heterogeneously integrated semiconductor devices.

Low temperature and high magnetic field facilities: Our six superconducting magnet systems (14-19 Tesla) operate at temperatures down to 0.02K and are used to study high-T_c superconductors and other correlated-electron systems within the QSM and QET research Themes. This very extensive array of adaptable equipment gives us an edge in this highly competitive international field. More than £5M of funding was awarded in REF2021, including 2 ERC grants, to study high temperature superconductivity. A key use of the equipment is in preparing experiments for runs at international centres such as the European Magnetic Field Laboratory (EMFL). Such preparation is essential to be awarded access to these facilities (£2.5M usage of EMFL in REF2021).

A SQUID magnetometer (£350K, installed 2018) is used extensively by researchers in Physics and Chemistry working on novel materials, for example, measuring the effects of high pressure on the magnetic properties of superconductors. Our helium liquefier recycles helium (around 25,000 litres/year) for users including the cryomagnetic facility, QET and the NanoESCA (below). Recycling conserves this precious resource and lowers the cost to funders to around one third of the commercial rate.

Our high-pressure laboratory provides infrastructure, equipment, and skills for high-pressure measurements in excess of 200GPa. Customised pressure cells permit cryogenic use as well as in international high magnetic field facilities. These rare capabilities enable ground-breaking research in high-T_c superconductivity, particularly that involving novel hydrogen-based compounds which is funded by the ERC grant HPSuper (£1.6M). The facility supports collaborative projects across the University, including research on aqueous fluids in the Earth's crust (grant with Earth Sciences).

Bio/Soft matter suite: A SAXS-WAXS X-ray scattering instrument (£450K) allows structural determination of materials across length scales from 0.3nm to 150nm. It facilitates research of the QSM and Materials and Devices Themes into biomolecules, membranes and multifunctional gels. A stimulated emission depletion (STED) nanoscope (£700K), is used for 3D imaging of bulk polymers, proteins and amphiphiles. These instruments have driven cross-disciplinary

collaborations, particularly with Life-Sciences. For example, SAXS structural information was key to a recent pharmacological collaboration on a drug loaded supramolecular nucleoside gel.

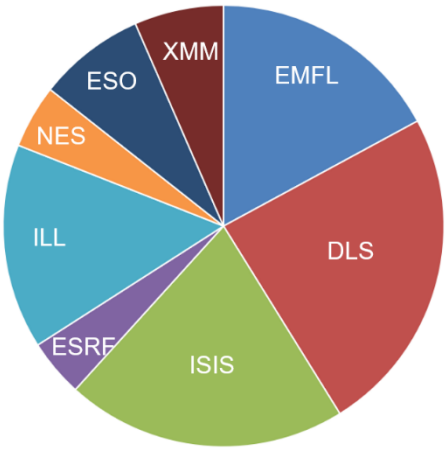
*NanoESCA II i*s a cutting-edge multi-platform instrument installed 2016 (EPSRC £1.8M, UoB £200K) which has capabilities that are unique in the UK. It permits extremely high-resolution analysis of surface structure using PEEM, XPS, LEED and μ-ARPES to evaluate band-structure on a micron-scale. The instrument supports research across the MD and QSM Themes, facilitating for example, research into the electronic structure of low dimensional materials such as dichalcogenides, multi-layer graphene and device structures based on diamond and gallium nitride.

High Performance Computing (HPC) is critical to maintaining a lead in our condensed matter and materials research. UoB has invested £16M in HPC and research data storage in the last 10 years. BlueCrystal (introduced 2017) has 15K CPU cores, 17 high memory nodes and 65 GPUs. In addition, UoB and STFC have invested £330K since 2015 in the Data Intensive Computing Environment (1.9K cores and 2.4PB disk), to provide cutting-edge high-throughput data analysis. This SoP cluster is essential for research in the Particle Physics and Astrophysics Themes and underpins our partnership in the Big Data and AI CDTs. UoB researchers also have access to GW4 supercomputer Isambard, a Cray XC50 system with over 21,000 cores.

External facilities

We are users of major national and international facilities. The total **income-in-kind from UKRI-supported facilities is £54M** including £38M for CERN (see graphic for others). For non-UKRI supported facilities, the income-in-kind is **£27M** (see table) for projects with a Bristol PI.

Usage of UKRI Supported Facilities (excluding CERN) by value



EMFL	European Magnetic Fields Laboratory
DLS	Diamond Light Source
ISIS	Neutron and Muon Source
ESRF	European Synchrotron Radiation Facility
ILL	Institut Laue–Langevin
NES	National Epitaxy Service
ESO	European Southern Observatory
XMM	X-ray space observatory

Usage of non-UKRI supported facilities.

Facility	Type	Location	Usage	Est. Cost
Advanced Photon Source	Synchrotron	Argonne, USA	23 days	£299K
SNQ @ PSI	Neutron Source	Switzerland	6 days	£96K
PETRA @ DESY	Synchrotron	Germany	6 days	£78K
Spring8	Synchrotron	Japan	51 days	£530K
Advanced Light Source	Synchrotron	Berkley, USA	8 days	£50K
Chandra	Satellite	NASA	3165 ks	£25M
LOFAR	Terrestrial Telescope	Netherlands	41 hours	£98K
VLA	Terrestrial Telescope	NRAO, USA	32.5 hours	£176K
NuStar	Satellite	NASA	58 hours	£300K
Suzaku	Satellite	JAXA / NASA (Japan/USA)	27.5 hours	£150K

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

Collaboration

Our research is characterised by a large volume of strong collaborations that span the globe. Over half of our outputs include an international co-author. Staff are strongly encouraged to form collaborations and join networks with leading researchers worldwide. Doing so is supported by the School's Research Initiator Fund, University International fund and by support for regular visits by leading scientists to Bristol. The table quantifies the volume of our success in this regard.

National collaborations	189
International collaborations	238
Interdisciplinary collaborations	188
Industrial collaborations	126
Consortia/networks	69

Sections 1 and 3 detail collaboration highlights.

Interdisciplinarity

We work hard to foster interactions with academics in other disciplines and 7 staff have joint appointments (see Section 2). The multi-disciplinary nature of our CDTs also provides major stimulus for interdisciplinary research. To leverage opportunities for cross-university interactions, staff work together with University Institutes such as the Jean Golding Institute and Bristol Quantum Information Institute (see Section 1). Staff are active in interdisciplinary consortia and networks on the national and international stage, for instance:

- EPSRC: NetworkPlus, CCPQ, CCP5, PoL
- H2020: HEATPACK, PowerBase, QuantERA;
- EU COST Actions: Nanoscale Quantum Optics, Quantum Thermodynamics, Topology
- JWST ERS exoplanet community consortium

Contributions to the discipline

Our academics have delivered over **450 invited talks** at international meetings during the REF2021 period. Highlights include:

- 7th Asian Colloid and Polymer Conference, Kuala Lumpur, 2017 (Keynote, **Seddon**)
- International Liquid Crystal Conference in Kyoto, 2018, associated with the award of the Glenn H. Brown prize (Prize talk, **Machon**)
- Thermodynamics, Edinburgh 2017 (Plenary, **Wilding**)
- XXXV Bienal de la RSEF, Gijón, Spain 2015 (Plenary, **Carrington**)
- SPIE Photonics West, San Francisco, USA, 2017 (Keynote, **Kuball**)
- International Nanotechnology Laboratory, Braga 2017 (Plenary, **Oulton**)
- Women in Quantum Technologies, Brussels (Plenary, **Oulton)**

We have organised or co-organised over 100 scientific meetings such as BQIT and Frontiers in Condensed Matter Physics. Further contributions arise from the following activities and grants:

- QTEC, an entrepreneurial training centre resulted from a £4.4M EPSRC grant in 2015 (see Section 1). It has created 31 new companies (24 of which are still active) and 126 jobs. Successful companies include four based directly on technology developed in the QET Theme (Raycal, QLM, KETS, FluoretiQ - see Impact Case).
- In 2016 the SoP established the South West Nuclear Hub supported by £2.4M from HEFCE's Catalyst Fund. This provides a focus for civil nuclear research, innovation, and skills in the region. The Hub partners with industry and academia to promote civil nuclear research and teaching activities. It involves 4 Physics academics and employs 2 FTE of industrial engagement support.
- The QE-CDT has pioneered the innovative Careers in Quantum event, showcasing the work of quantum technology start-ups and established industry. The event includes the world's first quantum job fair.

We are proactive in engaging with external agencies and stakeholders to help set funding and strategic priorities. Since 2014 we have been represented on 120 committees, highlights being:

- **Seddon**: EPSRC Physical Sciences Strategic Advisory Team (SAT); EPSRC High Level Group for National Research Facilities; Chair peer review panel for soft matter beamlines at Diamond
- **Bremer**: Vice Chair and Chair, STFC Project Peer Review Panel
- **Popescu**: Royal Society Selection Committee (choosing new Fellows)
- **Kuball:** EPSRC Information and Communication Technologies SAT
- **Scott:** Scientific Advisory Group for Emergencies (SAGE); EPSRC Fusion Advisory Board; Special Advisor to the House of Lords Science and Technology Committee
- **Birkinshaw:** Chair, Quantum Technologies for Fundamental Physics panel; Chair, Square Kilometer Array oversight committee; Chair, NASA review of the Chandra X-ray satellite programme
- **Hayden:** STFC Science Board, Chair of user Committee for i21 RIXS instrument (Diamond); Board, PACE data analysis project at ISIS
- **Hussey**: Executive Board, High Magnetic Fields Laboratory
- **Goldstein**: Chair STFC Particle Physics (experiment) grants panel; IPPP Steering Committee

Engagement with key research users

We actively encourage staff to undertake secondments or part time appointments to work with, or to start, a company. Our extremely proactive Industrial Advisory Board (see Section 1) helps to guide our portfolio of industrial links and our Impact Roadshow (Section 1) and Quantum Innovation Lab to bring together industrialists and researchers in quantum technologies, with companies including Airbus, Deutsche Bank, Hitachi, helping to establish contacts and collaborations. Our Impact Case Studies demonstrate the breadth and depth of engagement, as do our 13 spin out companies since 2014 and award of 9 patents (with a further 9 pending).

Editorships

The School engages extensively on an editorial level with scientific journals. 19 members of the School hold editorships in journals including New J. Phys., Molecular Physics. J. Optics, MNRAS, Quantum, Icarus, Nanotechnology, J. Mat. Sci., Scientific Reports.

Public engagement

This is an area about which we are particularly passionate and dedicate much resource. It is coordinated via our academic outreach director, CDT outreach officers and admin staff. A focus is widening participation in Physics from disadvantaged local schools. Events include:

- An annual week-long work experience programme introduces local children to laboratory work and provides accessible talks on topics related to our research.
- Workshops tailored to year groups designed to supplement pupils' practical skills. Activities begin with an introductory talk about the science, then the students complete experiments on topics such as "Waves" and "Fun with Liquid Nitrogen".
- A week-long summer school on quantum phenomena and light. Aimed at ages 16+, this free event includes lectures and demonstrations. The QET Theme's extensive outreach activities won the outreach team category of UoB's 2017 engagement awards for the breadth of activities and how this has facilitated a shift in culture in the research area.
- The Particle Physics Masterclass - an annual one-day workshop for sixth formers. Attendees meet our researchers, learn about their latest work at the LHC, and get a chance to analyse LHC data.

Several staff work with local teachers to support the curriculum, giving talks in schools on topics such as 'A beginners Guide to Space' and 'The Future of Physics'. We also co-organise subsidised events for Schools as part of the STEM outreach programme of the Unit DX incubator and IoP South West.

In terms of wider outreach

- The School funded and led the 2019 Soapbox Science event in Bristol to promote Women in Science, attracting 300 visitors.
- QET Theme were selected to exhibit at the Royal Society Summer Exhibition in 2017 (13000 attendees).
- Bristol leads the UK arm of HiSPARC, delivering cosmic ray detector kits and software to 23 secondary schools allowing students to participate in research.
- Our CDTs boast a strong outreach component and PhD students help deliver this, contributing displays and demonstrations related to our research. These are exhibited at cultural festivals including Blue Dot, Green Man, Cheltenham Science Festival, and Malvern Science in the Park.

- In 2016 the School purchased a branded “Bristol Physics on the Road” van to transport staff and equipment to events.
- The SoP was awarded £10K from the Royal Society of Chemistry for our outreach programme in 2019, allowing construction of a `laser piano’ and other outreach showpieces.

Media work is another focus. In 2015, Popescu appeared in Through the Wormhole with Morgan Freeman (Discovery Channel) to talk about “Can Time go Backwards?” which was viewed 350,000 times. Wakeford co-produces “Exocast" a regular 30-minute podcast on exoplanets with over 50 episodes to date. Each episode has ~1000 unique listens. She also runs an annual twitter-based competition ExoCup - which makes on average 350,000 impressions on Twitter throughout the month-long competition. She has given over 20 public talks, with a highlight being the Franklin Institute in Philadelphia for their women in Science Astronomy night. Currently Wakeford is working with a YouTuber producing videos asking if planets in sci-fi could really exist. One of these videos is based around Star Wars and has had 1.3 million views and another based on the Marvel Universe has 700,000 views.

Measures of Esteem

Prizes:

- **Popescu**: 2017 elected FRS
- **Popescu:** 2016 IoP Dirac medal and the Cozzarelli prize
- **Hayden**: 2019 IoP Mott Prize
- **Carrington**: 2015 IoP Brian Pippard prize.
- **Hanna** 2020: IoP Rosalind Franklin prize (Physics of Life UK Network)
- **Smith** 2020: IoP Phillips prize
- **Guillamon**: 2015 Oxford Instruments Kurti prize
- **Machon**: 2018 Glenn H. Brown prize (International Liquid Crystal Society)
- **Scott**: 2015 UKSAF Vickerman Prize
- **Royall**: 2019 Humboldt Foundation Bessel Award
- **Springell, Scott**: 2020 RSC Industry-Academic Collaboration Prize
- **Martin**: IOM3 2017 Cook/Ablett award
- **South West Nuclear Hub**: The Engineer: Academic Innovator prize
- **Paramesvaran**: CMS Young Researchers Prize 2017
- **Wakeford**: NASA Robert H. Goddard Honor Award for individual scientific achievement 2016; Geological Society of Washington’s Bradley Award 2017
- **Antognozzi, Oulton**: Longitude Discovery Award 2017
- **Kuball** 2019: Fellow IEEE
- 36 further minor prizes (such as poster prizes) have been awarded to PDRAs and PhD students.

Fellowships and Chairs:

- 2 RAEng Chairs in Emerging Technologies (10 years): Kuball and O’Brien
- RAEng Professorial Fellow: Scott (5 years)
- 9 ERCs (including 2 advanced) were held during the REF period: O’Brien(x3), Royall, Thompson, Friedemann, Rademacker, Matthews, Hussey
- 5 Marie Sklodowska-Curie: Badoux, Magalhaes, Marshall, McCutcheon, Sahin

- 6 EPSRC fellowships: Faulkner, Laing, Liu, Matthews, Oulton, Royall
- 1 Royal Commission 1851 Brunel Fellow: Liu
- 2 Royal Academy of Engineering: Payton, Martin
- 1 STFC Advanced: Leinhardt
- 1 STFC ERF: Whitehead
- 2 Leverhulme: Gradhand, Matthews
- 1 URF: Skrzypczyk.