Institution: University of Cambridge

Unit of Assessment: 09 (Physics and Astronomy)

1: Context and structure, research and impact strategy

CONTEXT AND OVERVIEW

The Cavendish Laboratory (the Department of Physics) and the Institute of Astronomy (IoA) together constitute one of the world's foremost centres of research in physics and astronomy. We host 81 permanent academic staff, 233 postdoctoral researchers and 390 doctoral students. Distinguished competitive research fellowships have been awarded to 131 of our scientists since August 2013. Together these create a vibrant and stimulating research environment.

Examples of outstanding research contributions since the REF2014 include:

- precise determination of cosmological parameters from the ESA PLANCK Mission;
- GAIA measurements of the positions and motions of stars in the Milky Way with unprecedented precision uncovering hitherto unknown structures within our Galaxy;
- direct searches for new particles and measurements of rare B-meson decays placing limits on physics Beyond the Standard Model;
- discovery of new states of matter at ultrahigh pressures, low temperatures and strong magnetic fields;
- development of computer codes to provide full quantum mechanical models of very large molecules and their interactions;
- new perovskite light emitters and absorbers unlocking charge transport physics and devices;
- development of spintronic devices for ultrafast magnetic switching;
- confinement of visible light on scales smaller than the size of an atom exploring molecule-metal interfaces;
- folded 2D materials trapping electrons to create qubits for quantum sensing;
- folding DNA into 3D shapes creating filters and sensors for biomolecules;
- experimental and theoretical discoveries of new organising principles in far-from-equilibrium quantum many-body systems.

Our research culture embraces challenging new areas, very often involving strong collaborations with other academic disciplines and institutions, while maintaining a powerful core of traditional areas of physics and astronomy. 32% of our research output is classified as multidisciplinary, meaning collaboration with other disciplines such as chemistry, materials and biology. Collaborations with industry and national and international bodies are essential features of our contributions to the many global challenges facing society.

Highlights of other developments since the REF 2014 include:

- twenty-five appointments to the tenured academic staff with 17 men and eight women appointees;
- three elections to Fellowship of the Royal Society (Hills, Queloz and Teichmann) and one to Fellowship of the Academy of Medical Sciences (Teichmann);
- two Royal Society Research Professorships (**Simons, Sirringhaus**) and a Research Professorship of the Royal Academy of Engineering (**Cole**);
- EU/ERC Awards include eight Advanced Grants, one Synergy Grant, three Proof of Concept Grants, six Consolidators Grants and five Starter Grants and five Future and Emerging Technologies Grants;
- Centres for Doctoral Training in Nanoscience (**Baumberg**) (now i4nano), Computational Methods for Materials Science (**Nikiforakis**) and Data Intensive Sciences (**Gilmore**);
- the opening of the Battcock Centre for Experimental Astrophysics (2013), consolidating collaboration between the Cavendish and the IoA;

- the opening of the interdisciplinary Maxwell Centre for collaboration between Industry and fundamental physics (2016).

Perhaps most exciting, and critical for the future strength of the Laboratory, is the construction of the *Ray Dolby Centre* which began in late 2018 on a neighbouring green-field site at a cost of £303M. Due to be opened in 2022-23, the Centre will complete the rebuilding of the *new Cavendish Laboratory*. It will be a national facility for physics, resulting in even closer collaboration with the national and international physics communities.

Research Structure

The Cavendish and the IoA are separate departments within the University's *School of Physical Sciences*. In 2018 the Cavendish *International Advisory Board (IAB)* was established, comprising senior members of the UK and international physics community. It meets annually and provides advice on the future programme, including proposals for appointments and strategic investments.

Table 1. **Research Theme** / **Research Group**	Astronomy, Astrophysics & Cosmology (AP)	High Energy Physics(HEP)	Biological & Biomedical Physics (BBP)	Energy Materials (EM)	Emergent Quantum Phenomena (EQP)	Assembly & Function of Complex Systems(AFCS)	Quantum Devices & Measurement (QDM)
Astrophysics (AP)							
Atomic, Mesoscopic & Optical Physics (AMOP)							
Biological and Soft Systems (BSS)							
High Energy Physics (HEP)							
Nanophotonics (NP)							
Optoelectronics (OE)							
Microelectronics (ME)							
Molecular Engineering (Meng)							
Quantum Matter (QM)							
Quantum Sensors (QS)							
Laboratory for Scientific Computing (LSC)							
Semiconductor Physics (SP)							
Surface, Microstructure and Fracture (SMF)							
Theory of Condensed Matter (TCM)							
Thin Film Magnetism (TFM)							
Collaborative/interdisciplinary research and training centres							
Centre for Scientific Computing (CSC)							
Kavli Institute for Cosmology (KICC)							
Cambridge Exo-planets Research Centre (CERC)							
Centre for the Physics of Medicine (CPOM)							
Maxwell Centre (MC)							
Nanoscience DTC (Nano CDT now i4nano)							
Data Intensive Science CDT (CDT Big Data)							

Since 2018, Cavendish research strategy has been realigned under seven *Strategic Research Themes* with the intention of enhancing collaboration across the numerous *Research Groups*

and *Research Centres*, which provide the focus for specific research projects. The relations between the themes, groups and centres are shown in Table 1. The themes are well matched to the UKRI's Industrial Strategy Challenges - quantum technologies, decarbonisation, the electric revolution, smart manufacturing and disease detection – as well as the four EPSRC Grand Challenges – Emergence and Physics Far From Equilibrium; Quantum Physics for New Quantum Technologies; Nanoscale Design of Functional Materials; Understanding the Physics of Life.

REVIEW OF REF2014 PLANS

Priority areas for investment described in the REF2014 have flourished, often exceeding our expectations.

Atomic, Molecular and Optical Physics (AMOP) The Group has capitalised upon the huge potential for impact in many areas of quantum technology. **Atature** won an ERC Consolidator award for work in solid state quantum experiments. New appointments include **Schneider** (topological optical lattices) and **Knowles** (quantum sensors based on nano-diamonds). A spin-out company, *NuQuantum*, offering single photon devices for quantum communications, attracted £650k seed-funding in 2019.

The **Winton Programme in the Physics of Sustainability** has been highly successful in addressing many physics aspects of the sustainability agenda in innovative ways. Project director **Friend** has led research in solar technology, directs Cambridge Photon Technology Ltd. and leads efforts on materials for low energy electronics through the Royce Institute. **Dutton** leads a *Faraday Institution* project on battery degradation and is a Deputy Director of the EPSRC SuperGEN Network Plus on energy storage. **Sebastian** works on high temperature superconductors for energy applications. Since 2014, ten Winton Advanced Research Fellows and 43 Winton Scholars (25 men and 18 women) have been supported. **Rao** (ultra-fast spectroscopy for energy materials) and **Ciccarelli** (spintronics) have been appointed to Lectureships. Seven Winton Fellows gained permanent employment in Cambridge and five at other universities. The *Winton Pump Prime scheme***,** encouraging 'high risk/high reward' projects, awarded 29 grants of up to £50k, the majority being collaborative across groups and departments. Fourteen are led by Early Career Researchers.

Collaborative astrophysical research has been greatly enhanced by the co-location of the Cavendish's *Battcock Centre for Experimental Astrophysics***,** the *Kavli Institute for Cosmology Cambridge (KICC)* and the *IoA*. The *KICC* facilitates joint activities with the Department of Applied Mathematics and Theoretical Physics (DAMTP) in the fields of cosmology and exoplanets, in advanced astronomical technologies and access to telescopes and space missions. Of the cohort of 23 Kavli Fellows during the REF2021 period, 11 have moved on to tenure-track positions. The appointments at Professorial level of **Maiolino** and **Queloz** have resulted in much stronger collaborations between the Cavendish and the IoA than ever before. **Maiolino** was appointed Director of the KICC in 2016, succeeding **Efstathiou**.

The Maxwell Centre, to enhance the long-term involvement and collaboration of industrial partners in research, was opened in 2016, providing offices for 260 staff, students and collaborators and state-of-the-art research laboratories. **Welland** took over as Centre Director from **Friend** in 2019. There are now six full-time resident companies (ARM, NPL, NuQuantum, Ovako, Sorex Sensors and Talga Technologies), and over 40 individuals from 15 companies such as Alphasense, Artemis Technologies, BT, IBM, IP Group, LGC, Magna International and Silicon Microgravity have benefited from part time access and hot-desking.

The **Centre for Scientific Computing** led by **Nikiforakis** has grown industrial partnerships with, among others, Boeing, Orica, AWE, Qinetiq and Jaguar Land Rover. In 2019 a major gift resulted in the *Gianna Angelopoulos Programme for Science, Technology and Innovation (GAPSTI)*, supporting four academic positions, two support staff and 15 PhD studentships in the fields of energy materials and devices, computational multiphysics and bioengineering. Of the

two academic posts, **Jasak** was appointed to a Lectureship in Scientific Computing and **Bale** to a joint lectureship in bio-compatible materials and biomechanics with Engineering.

Physical Biology is a strategic focus across the University. Cavendish research interests include the design of novel molecular imaging strategies for clinical application (**Bohndiek**), microfluidics (**Cicuta**), optical manipulation techniques (**Euser**), single-molecule microscopy, DNA origami and the fabrication of artificial ion channels (**Keyser**) and biofilms (**Fusco**). Theoretical activities include the development of novel image processing strategies for biological and clinical applications, bioinformatics, biological (and social) network analysis, evolutionary dynamics, and biophysical modelling (**Cicuta**, **Croze**, **Fusco**, **Terentjev**). **Simons** holds his Royal Society Research Professorship in DAMTP during a five-year period of leave, applying statistical methods from physics to biological problems. In 2016, **Teichmann** co-founded the Human Cell Atlas consortium to map the trillions of cells in the body. The impact is expected to be at least as significant as the human genome project.

The **Centre for the Physics of Medicine** participates in collaborative activities with partners across and beyond the University, including the Wellcome Trust-MRC Cambridge Stem Cell Institute, the Cancer Research UK Cambridge Institute, the Wellcome Trust-CRUK Gurdon Institute, the Departments of Chemistry, Genetics, Physiology, Development and Neuroscience and Zoology, the Clinical School, the Vet School, the Sainsbury Laboratory, the Wolfson Brain Imaging Centre, the EMBL European Bioinformatics Institute and the Wellcome Trust Sanger Institute.

The reconstruction of the Cavendish Laboratory will be completed in 2022/23, thanks to philanthropic, government and University funding. (see Section 3).

FUTURE RESEARCH PROGRAMME

The future research programmes are surveyed by theme involving all the Groups and Centres shown in Table 1.

Astronomy, Astrophysics and Cosmology (AP and IoA)
The STFC strongly supports UK leadership in the future development of the world's largest telescopes, the *European Extremely Large Telescope* **(***E-ELT***)**, the *Large Synoptic Survey Telescope* (*LSST*) and the *Square Kilometre Array* (*SKA*). These are key elements of the departments' future strategy.

Extragalactic astronomy is a major strength with active observational programmes in high-redshift quasars and their host galaxies (**Hewett, McMahon**), quasar absorption lines (**Pettini**) and star formation across cosmic time (**Maiolino**). The study of newly-discovered active galactic nuclei from all sky surveys (*UKIDSS, SDSS* and *VISTA*) will be transformed by observations with the forthcoming optical facilities as well as the *JWST, 4MOST* and *Euclid* projects. Data processing for the petascale optical datasets will be carried out by the *Cambridge Astronomical Survey Unit* (*CASU*). Theoretical support will be provided by **Sijacki** (structure formation) and **Haehnelt** (reionization).

Complementary observational studies of the epoch of reionisation will be undertaken by the *REACH* project (**Lera Acedo**) in South Africa, a precursor for the mapping of the reionisation epoch by the *SKA*. **Fialkov's** appointment enhances expertise in 21cm cosmology. **Alexander** led the *Cambridge Big Data Strategic Research Initiative***,** now the *Cambridge Centre for Data-Driven Discovery***.** The Astrophysics Group is leading the design of the *Square Kilometre Array (SKA)* computer and software system, one of the most advanced data analytics systems ever deployed in a large-scale science experiment.

Within the **Battcock Centre**, new capabilities in optical and infrared astronomy are strongly supported (**Buscher, Haniff**). *MOONS,* an NIR multi-fibre spectrometer for the VLT, will provide a powerful tool for studying galaxy evolution, the high-redshift universe and the structure of the

Milky Way. **Maiolino** is Project Scientist with about 40 scientists from six countries involved. Other projects include *HARPS3* for planet finding and *HIRES* for the *E-ELT*.

The **Cambridge Exoplanet Research Centre (CERC)**, led by **Queloz,** involves researchers from AP, the IoA and DAMTP. The IoA hosts theorists working on exoplanet atmospheres (**Madhusudhan**), protoplanetary disks (**Clarke**) and debris disks (**Wyatt**), as well joint-appointee **Shorttle** between the IoA and Earth Sciences and instrumentalists developing next-generation direct imaging techniques (**Parry**). There are strong connections with the *stellar astrophysics* group (**Tout**). The *Universal Life initiative* aims to understand pre-biotic chemistry in exoplanetary systems though collaboration with the *Laboratory of Molecular Biology*. **Queloz** and his colleagues are involved in future national and international instrumentation and satellite projects such as *NGTS, SPECULOOS, CHEOPS* and the *Terra Hunting Experiment*.

Near-field cosmology is focused on the **Gaia** mission with **Gilmore,** the UK PI of the Gaia data processing and analysis consortium, leading highly successful programmes probing the structure, dynamics and history of the Milky Way and its halo and the structure and dynamics of local group dwarf galaxies (**Gilmore, Belokurov, Evans**). These efforts exploit the infrastructure provided by *CASU* **(N.Walton, Worley)**, positioning the IoA to play key roles in the future *LSST*, *WEAVE* and *4MOST* projects.

The IoA maintains a strong programme in *high-energy astrophysics*, exploiting X-ray data from NASA, ESA, and JAXA facilities (**Fabian, Reynolds, D.Walton**). Significant advances are being made in the understanding of stellar and supermassive black holes, neutron stars and feedback processes in clusters of galaxies. These activities are supported by theoretical studies of relativistic accretion disks (**Reynolds**) and black hole feedback in galaxies and galaxy clusters (**Reynolds, Sijacki**). Time-domain astronomy will include studies of type-1a supernovae (**Mandel**) and fast radio bursts (**Fialkov**).

Cosmology and studies of large scale structure formation are fostered at the KICC particularly through the exploitation of cosmic microwave background (CMB) temperature and polarization data (**Efstathiou, Challinor, Gratton**). Both departments are closely involved in the next generation of CMB experiments.

High Energy Physics (HEP)

Research is focused on experiments at the *Large Hadron Collider* (*LHC*) at CERN, the neutrino facilities at Fermilab and R&D activities for future collider projects, supported by a team of theorists. Cavendish facilities are used to develop HEP detectors, their readout electronics and data acquisition and monitoring systems. The future research programme is well-aligned with 2020 European Strategy for Particle Physics.

ATLAS is the largest experiment at the LHC. The Group makes major contributions to the Semiconductor Tracker and Inner Detector (ID), having lead roles in the Inner Tracker (ITK) (**Hommels**) and Level-1 Calorimeter Trigger upgrades. **Robinson,** ID project leader and deputy ITK project leader, sits on the Executive Board. **Batley** oversees the ATLAS Standard Model Physics group and coordinates the Z to 4 leptons group. **Potter, Brandt, Lester** and **Williams** play leading roles in the continuing search for Beyond the Standard Model (BSM) physics. Future priorities are to understand the Higgs sector more deeply, to search for dark matter and to continue the search for evidence for supersymmetry. **Potter** is coordinator of the four lepton SUSY analysis and High-luminosity LHC SUSY groups. This activity is strengthened by the appointment of **Brandt** as convenor of the Dark Matter Group and the BSM Higgs group.

The LHCb experiment at the LHC involves studies of matter-antimatter asymmetries and searches for BSM Physics in heavy quark (B and D hadron) decays led by **Gibson**, who currently chairs the LHCb Collaboration Board. The HEP group leads the global particle identification for LHCb (**Jones**) and the development of the electronics readout for the two RICH detectors (**Wotton**). Science priorities include precise measurements of the CP-violating phase γ, and resolving the significance of the current lepton flavour non-universality anomalies in B-meson decays by measuring key rare decay channels (**Alvarez-Cartelle**). The breakthrough

discovery of B_S decays into muon pairs strongly limits BSM physics (**Bettler**). The group also led studies of electroweak physics and QCD, accessing a new kinematic regime (**Ward**).

The Group hosts the *Phenomenology Working Group*, bringing together experimentalists and theorists from the Cavendish and DAMTP, as well as international visitors and collaborators working on particle and astroparticle physics problems. **Mitov** is a world expert on top quark physics theory while **Gripaios** works at the cutting-edge of BSM Physics.

The HEP group plays major roles in the *MicroBoonE* and the *Deep Underground Neutrino Experiments* (*DUNE*) at Fermilab. *DUNE* is the flagship of the US neutrino programme, seeking to resolve the mass spectrum of neutrinos and CP violation in the neutrino sector. **Thomson** pioneered the technique of particle flow algorithms, now central to the DUNE pattern recognition techniques (**Whitehead**). While co-spokesperson of DUNE, **Thomson** secured UK investment of £65M in the project. While Thomson serves as STFC Executive Chair, **Uchida** has been appointed to lead the neutrino group and develop the electronics readout for the DUNE Liquid-Ar TPC anode planes.

Gibson, together with **Schneider**, are leading the *Atom Interferometry Observatory and Network* (*AION*) project which recently secured funding from the UKRI Quantum Technologies for Fundamental Physics programme to search for ultra-light dark matter and for the detection of gravitational waves. **Gibson** also joined the MAGIS experiment at Fermilab with Kavli support. The Cavendish team will develop the cold atom transport and final cooling stages for AION, the data readout and network capabilities for AION and MAGIS, and undertake data analysis and theoretical interpretation.

Brandt is the initiator of the ANUBIS proposal, searching for long-lived neutral particles predicted in many extensions of the Standard Model. **Gibson, Batley, Brandt, Lester** and **Potter** will continue their leadership roles while **Parker** will continue to serve on the International Advisory Board for a CERN Future Circular Collider.

Biological and Biomedical Physics (BBP)

The application of physics to the life sciences and clinical practice spans a very wide range of topics, particularly in the development of new instruments and the theoretical underpinning of these disciplines. These areas, falling outside conventional disciplinary boundaries, require a collaborative, multidisciplinary approach. Using techniques from classical polymer physics, fluid dynamics, soft matter physics and the physics of condensed matter, impressive progress is being made in understanding biological systems from molecular to cell levels (**Donald**, **Keyser, T.Knowles**, **Terentjev**), at tumour and organ levels (**Bohndiek**) and from host-pathogen (**Cicuta**) to more complex communities (**Croze**, **Fusco**). Optics, automation and microfluidics are the foundational technologies for much of this work. Future technological developments include single strand sequencing and custom imaging approaches, as well as emergent phenomena in biology as they occur from the genome, epigenome and transcriptome of single cells, through biomimetic synthetic biology systems up to laboratory-scale ecology.

New approaches in video and image processing (**Cicuta**) and biosensor technologies (**Bohndiek)** are being deployed from airway physiology, of relevance for understanding the impact of COVID-19, to tumour detection. In the area of imaging devices, the BBS theme has been expanded with **Bale's** joint appointment with Engineering**.**

Simons has opened up new areas of quantitative, multidisciplinary research in developmental and cancer biology. Using concepts from scaling theory and population dynamics, new avenues for therapeutic intervention in cancer based on cell differentiation have been discovered. **Ahnert** and **Teichmann** use network theory to investigate the enumeration and classification of all possible protein complex topologies. A theoretical model of genotype-phenotype (GP) maps reproduces a number of global structural properties observed across a number of biological GP maps. **Teichmann** is co-founder of the Human Cell Atlas (HCA) international consortium, as noted above.

Energy Materials (EM)

The efficient and sustainable generation, storage, transmission and use of energy are arguably the key challenge facing society. This highly interdisciplinary field involves chemistry, materials science, engineering and biology. The Cambridge spoke of the *Sir Henry Royce Institute* (*SHRI*) focuses on materials for energy efficient information and communication technology. New solar cell materials, such as organic and hybrid organic/inorganic (perovskite) semiconductors, are being developed with the aim of approaching, and potentially exceeding, the Shockley-Queisser efficiency limit. New thermoelectric materials based on conjugated polymers or topological insulators may reach the efficiency of conventional heat-engines. More efficient light-emitting diodes based on high bandgap inorganic semiconductors and hybrid organic-inorganic semiconductors could reduce significantly the amount of energy used for lighting.

Sirringhaus' work on the charge transport physics of conjugated polymers resulted in a new generation of donor-acceptor copolymers which were commercialised by BASF and Merck KGA. These processes find application in flexible electronics and spintronics, particularly in thermo-electric waste heat conversion. The operational stability of organic field-effect transistors is now at levels comparable to those of conventional inorganic semiconductors. This technology is exploited by our industrial partner *FlexEnable*.

Ciccarelli investigates spintronics systems in ferromagnets and antiferromagnets using magnetic resonance and ultrafast THz spectroscopy techniques in collaboration with the *Hitachi Cambridge Laboratory*. **Sebastian** investigates the new physics that will eventually allow superconductors to operate at room temperature, enabling essentially lossless transmission of electrical energy. **Rao** and **Dutton** are developing high-resolution optical microscopies to evaluate structural transformations and dynamics in battery electrodes.

The *Centre of Advanced Materials for Integrated Energy Systems* (*CAMIES*) is an energy materials network investigating the materials requirements for the transition to a zero-carbon economy by 2050 (**Friend, Greenham, Rao, Sirringhaus, Dutton**). **Friend** leads the University-wide Energy Transitions@Cambridge, which is part of the Cambridge Zero programme, and which spans topics from hard science to policy. A new strategy for the Maxwell Centre, launched in October 2019, will focus on proactive support for the Cambridge Zero initiative.

Emergent Quantum Phenomena (EQP)
This theme spans many areas of experimental and theoretical research in atomic, electron and light-matter systems including new coherent quantum phenomena, ultra-cold atomic physics, quantum many-body systems and characterisation of complex functional materials.

Hadzibabic specialises in novel collective quantum phenomena which can be studied using ultracold atomic gases as highly controllable, strongly correlated many-body systems. He has been awarded a Quantum Sensors for Fundamental Physics grant from the EPSRC entitled *Quantum Simulators for Fundamental Physics*. Current research in **Atature's** group includes optical control of single and multiple quantum-dot spins, high-resolution spectroscopy of diamond-based emitters (**H. Knowles**), solid-state cavity-QED and nanoplasmonics. **Schneider**'s research focuses on topological optical lattices which are loaded with ultracold atoms. The resulting periodic optical potentials play the role of the electrostatic potential felt by electrons in a conventional solid, resulting in a quantum simulator for condensed matter physics. **Baumberg** and **Euser** study quantum systems embedded in a variety of nanophotonic resonators.

Dutton, Grosche, Lonzarich, Rowley, Sebastian, Saxena and Sutherland address coherence phenomena in correlated electron systems, such as unconventional superconductivity and magnetism, and investigate quantum phase transitions, low-dimensional materials, structural instabilities and quantum functional materials, for example for cryogenic refrigeration. The group's laboratories access extremes of magnetic field (20.4 Tesla), low temperature (1 mK) and pressure (300 kbar). The *Advanced Materials Characterisation Suite* in the Maxwell Centre houses state-of-the-art facilities for the structural, electrical and magnetic characterisation of complex functional materials.

Theoretical work on novel quantum phases of matter addresses topological systems and out-of-equilibrium phenomena. **Castelnovo** is an expert on frustrated magnetism and glassy dynamics, **Cooper** on cold atomic gases and open quantum systems, **Béri** on interacting topological phases and **Slager** on topological crystalline materials.

Underpinned by this wide-ranging expertise, the research direction adjusts itself to emerging collaborative opportunities. Current priorities include quantum many-body systems far from equilibrium, involving pioneering studies in atomic physics (**Hadzibabic, Schneider**), in magnetic materials (**Grosche, Sebastian**) and in theory (**Castelnovo, Cooper**). Topologically ordered systems and their consequences for quantum information and quantum computing are studied theoretically (**Béri, Castelnovo),** and experimentally in semiconductor nanostructures (**Ritchie**). **Ritchie** runs an MBE topological Insulator growth system as part of the Royce initiative, with **Barnes, Ford** and **Smith** also studying topological insulators with theoretical expertise provided by **Slager** and **Monserrat**.

Assembly and Function of Complex Systems (AFCS)
This theme concerns how novel function arises in condensed matter through the assembly of molecular and nano-scale components into complex systems. In contrast to the 'emergent quantum phenomena' theme, the primary focus is on the emergence and control of structural, dynamical and optical behaviour from the nanoscale through the mesoscale to macroscopically observable phenomena. The theme encompasses many aspects of soft matter physics and the physics of biological systems. The activity is underpinned by the CDT in Nanoscience which will support more than 100 PhD students until 2028 through £6M third tranche funding.

Baumberg leads a wide range of activities in nanophotonics, specialising in constructing nano-materials with unusual interactions with light on a huge range of physical scales. These range from those that can be fabricated on a large scale, leading to practical use in kilometre-scale polymer opals, to exploring light confined to 1nm volumes or less, probing single molecules and reactions. **Euser** studies nanoscale light-matter interactions, including optical, thermal and fluidic forces using novel optical techniques based on optofluidic waveguides and spatial light modulators to study such interactions in a highly-controlled way. Joint sensing work on batteries is funded by the *Faraday Institution*, in collaboration with many industrial partners.

Construction of nanoscale systems with different components programmatically nano-assembled with DNA is a major strength together with nano-assembly (**Keyser, Eiser, Baumberg**). Other important areas include sensing and nano-microfluidic techniques (**T.Knowles, Cicuta**) for identifying trace proteins, pathogens, and hormones. Strength continues in functional polymer science, advanced materials and composite and granular materials (**Warner, Terentjev, Donald**). **Warner** started a revolution in shape-programmable materials drivable by light and heat, using differential geometry to engineer evolution to states of changed Gaussian curvature. **Terentjev's** work on new liquid crystal elastomer materials for use as mechanical actuators led to the start-up company, *Cambridge Smart Plastics*.

The theme involves strong collaboration with other Departments in the Schools of Physical Sciences, Technology and the Biological Sciences. The bottom-up assembly of functional systems has great potential for further coordination and synergy. Collaborations with both Chemistry and DAMTP, for example, are thriving in both experimental and theoretical soft matter. A major future direction is the construction of nanomachines.

Quantum Devices and Measurements (QDM)
This theme concerns the development of materials, devices and systems in which quantum and spin phenomena can be controlled for technological applications.

Ritchie uses MBE facilities to study two-dimensional electron and hole gases, quantum transport in low-dimensional structures and the use of terahertz radiation in quantum devices. The programme includes self-assembled InAs quantum dots and single and entangled photon sources for quantum information. **Smith** studies quantum phenomena using novel low-temperature probes, as well as investigating the physics of nano-MEMS devices and spin injection in semiconductors. He has created a 'laboratory on a chip' for micro-fluidic pumping. **Ford** uses surface acoustic waves passing through narrow channels to move and process

quantum bits ('qubits') of information. He is pioneering the generation and detection of single photons with Surface Acoustic Waves (SAWs) and using them to move single-electron quantum dots.

Theoretical collaboration includes **Béri's** work on interacting Majorana fermion systems, with new results on the topological Kondo effect, a paradigm for demonstrating Majorana-based topological qubits, now on the experimental roadmap for Microsoft/Delft. In collaboration with Hitachi, **Nunnenkamp** has introduced an innovative hybrid system called 'cavity optomagnonics', establishing Cambridge as a leader in the field.

Jardine, **Ellis** and **Avidor** are developing a new form of microscope using neutral helium atoms. Scanning helium microscopy (SHeM) has great promise for imaging samples which are damaged by conventional optical or electron microscopes. The dynamics of atoms and molecules on surfaces are observed on picosecond timescales and nanometre length-scales. **Jardine** investigates the fundamental processes which control the constitutive properties and failure of materials, a particular focus being atomic defects in diamond, and the development of damage in polycrystalline diamond, probed solid particle erosion and micromechanical testing.

Cowburn's team investigates nanoscale magnetism and spintronics, the aim being to create low energy computer chips, ultrahigh density three-dimensional data storage and healthcare devices. **Barnes'** bespoke MBE systems enable his group to study a wide variety of materials systems from magnetic oxides to topological insulators. His *Environmental Physics Group* is collaborating with three Peruvian universities to develop practical methods of carrying out environmental impact studies in extreme environments.

Sirringhaus and **Ciccarelli** study the charge and spin transport and photophysics of organic semiconductors as well as low-temperature processible hybrid organic-inorganic semiconductors. **Rossi** and **Ferguson** investigate spin states in silicon nanowires in collaboration with the *Hitachi Cambridge Laboratory*, leading to silicon-based quantum bits. Spin-based qubits are among the most robust implementations of quantum information. Hitachi aims to realise a silicon-based quantum computer by this means.

Withington's Quantum Sensors Group develops advanced instrumentation and ultra-low noise quantum electronics and sensors for fundamental physics, mostly at mm, submm and infrared wavelengths. The Group is developing superconducting imaging arrays for the ESA/JAXA far-infrared space telescope SPICA, and millimetre-wave chip spectrometers for space-based Earth observation. The Group collaborates with the NPL in various aspects of precision measurement, enhanced by the award of an EPSRC Quantum Sensors for Fundamental Physics grant entitled *Quantum Engineering of Solid State Technology (QUES2T)*.

Theory and Computation

Theoretical and computational expertise in astrophysics, cosmology and high energy physics are provided within the associated research groups (AP: **Lasenby, Hobson**, HEP: **Gripaios, Mitov** and **Webber**). The *Theory of Condensed Matter (TCM)* group brings together 15 principal investigators working on diverse problems in collective quantum phenomena, electronic structure, soft matter and biological systems, underpinning five of the research themes. The group has close links to experiment within the Department/University and internationally. It has an excellent track record of commercialising its research.

Contributions of the TCM group to the research themes are included above. TCM's work on *Electronic Structure* cuts across many research themes, through the development of new methods allowing calculations of ever wider classes of materials and regimes. The CASTEP code developed by **Payne** recently reached $40M total sales. **Artacho** introduced the use of Floquet theory to understand how ion projectiles are stopped by electrons in condensed matter systems through first-principles simulations of these highly non-equilibrium processes. **Needs** is pioneering studies of superconducting hydrides at high pressure, by incorporating anharmonic effects. **Monserrat** is developing novel computational techniques to enable the inclusion of finite temperature in first principles quantum mechanical calculations, permitting a 100-fold reduction in computational cost.

The interdisciplinary environment of TCM allows rapid transfer of ideas, and highly innovative research. For example, the group is currently developing novel applications of machine learning (ML) to address diverse problems. In electronic structure, the innovations of **Payne** and his colleagues on ML potentials are having enormous impact and provide the reference state-of-the-art in this field. **Conduit's** novel ML technique, originally for materials design, is being commercialised by the start-up company *Intellegens*. Eight new patented metal alloys have been designed for *Rolls Royce*, *Samsung Electronics* and *Welding Alloys* with superior properties to others commercially available. **Lamacraft** develops applications of ML to physics and ideas from physics to ML. This involves collaborations with *Spotify* and with *GTN* to bring physics and ML models into drug discovery. **Lee** develops ML algorithms that, for the first time, have outperformed skilled human chemists in predicting the outcomes of chemical reactions and ways to create complex organic molecules, paving the way towards solving a major stumbling block in materials and drug design.

The TCM group has particular expertise in the theoretical description of novel quantum phases of matter. **Castelnovo** has set up a theory-experiment collaboration with Oxford and Royal Holloway on tuning and characterising disorder in magnetic pyrochlore oxides. **Cooper** has led theoretical contributions to the realisation and characterisation of topological phases of cold atomic gases, opening up new avenues for the topological classification of non-equilibrium quantum phases of matter.

IMPACT AND IMPACT CASE STUDIES

Impact

Impact is an integral part of our research strategy. All researchers are encouraged to maximise the impact of their work, making use of the University's training programmes in entrepreneurship and commercialisation. The *Maxwell Centre* promotes closer interaction between Cambridge researchers, other collaborating UK universities, and industrial partners, led by the Centre's Director of Partnership Development and an Engagement Coordinator. Similar functions are provided by *ideaSpace*, particularly in helping start-up companies become successful businesses. The CDT in Nanoscience runs translational prize funding that leads to demonstrators and spinouts.

Cambridge Enterprise support includes advice on writing grant applications and identifying and connecting academics with potential beneficiaries of research. Particularly important are its role in patent filing, Intellectual Property (IP) issues and assistance in licensing and exploiting IP. They also advise on seed-corn funding for start-up companies and access to funding from industry and investors in the Cambridge Network. Measures of our impact in promoting innovative technology are the 184 active or submitted patent applications over the REF2021 period.

The Vice Chancellor's Awards for Impact and Public Engagement reward those whose research has led to outstanding impact beyond academia. **Patto** received the Vice-Chancellor's Impact Award in 2017 for his development with **Baumberg** of a cheap device built by 3-D printing for testing water quality in underdeveloped regions in Africa. Cambridge Enterprise and the Entrepreneurial Postdocs of Cambridge host an annual Postdoc Business Plan Competition.

During the REF2021 period, we have received 28 EPSRC and STFC Impact Acceleration Account (IAA) awards with total value £1.67M in the form of Follow-on Funding, Partnership Development Awards and Knowledge Transfer Fellowships involving secondments, both inwards and outwards. We are regularly a partner in Innovate UK awards: for example in obtaining pre-seed investment funding for the start-up company *NuQuantum*.

Impact Case Studies

Nine Impact Case Studies are described in document REF3. Most of these result from the commercialisation of ideas developed by members of the Cavendish. The 'Collider' case study, involving collaboration with the London Science Museum, is an example of research being used to educate the wider public and decision makers about value of basic scientific research. The late **David MacKay's** work on explaining how our choices on energy use and generation impact

climate change has had a large impact on government policy on climate change both in the UK and other countries. Another programme which is having enormous impact is the *Isaac Physics* project, which has raised the standard of physics teaching in schools in the UK and internationally (see also Section on *Outreach*).

In all the technological case studies, extensive use has been made of the advanced research facilities available within the Department, for example, **Smith**'s start-up company *Cavendish Kinetics,* based on his research into nano-mechanics. Other inventions and innovations are just beginning to be commercialised, for example, the endeavours of **Conduit** and **Lee** described above and *Cambridge Photon Technology* and *Helio Display Materials*.

Open research and research integrity

We support the University's policies on promoting open research and data sharing. Open access to research outputs and data sharing are mandated by EPSRC. Restrictions may apply, for example, when dealing with commercial interests and publisher requirements, third party rights holders, GDPR, patient confidentiality and confidential social data. The University's Research Data Management Policy Framework addresses how these issues are managed. At all times, researchers are required to act in accordance with the requirements of the funding bodies, following the guidelines set by regulatory bodies. **Baumberg** helped develop University policy on Electronic Laboratory Notebooks, which was recently approved.

Incoming doctoral students are given training in *ethical research* and *research integrity* as part of their induction. We follow rigorously the University's policies on these matters and take the recommended action when issues arise. We comply with all ethical requirements from our regular funding bodies and rely on the Committee on Benefactions and External and Legal Affairs and the University ethics officer for new funders and difficult cases.

2: People

There are 81 permanent academic staff and 233 postdoctoral researchers in the Cavendish and the IoA, including six inter-department lectureships. The Cavendish also hosts three affiliated Academic staff from other departments. The environment is significantly enhanced by 29 active emeritus Readers and Professors and by a constant flux of visitors, many of them international, typically at a level of about 240 researchers each year.

The research programme and the departments' infrastructure, buildings and estate are supported by the following:

- administration, human resources, finance, grant management (45)
- departmental management and project coordination (14)
- student services and outreach (23)
- health and safety, facilities and built estates maintenance support (63)
- instrumentation and technical equipment specialists (29)
- IT and scientific software developers (23)

STAFFING STRATEGY AND STAFF DEVELOPMENT

The staffing strategy for academic staff aims to appoint world-leading scientists at all academic levels. In the Cavendish, appointments to the permanent academic staff occur at a rate of typically two per annum. Priorities for future research are established by the research themes and discussed at the Annual Away-Day. These discussions inform the recommendations of the Laboratory's *Strategy Working Group,* which formulates a roadmap for future appointments. At the IoA four retirements are anticipated in the next seven years. The strategy is to identify a small number of key areas and to extend searches over more than a year if necessary. The intention is to coordinate appointments in the IoA and the AP Group, as successfully achieved in building up exoplanet research.

Evidence for the success of these processes is reflected in the prizes and leadership roles of our appointees (Section 4). Our ability to attract early career researchers of the highest calibre is demonstrated by the 131 prestigious, competitive Fellowships hosted since August 2013. These include:

- Marie Curie Fellows (28),
- Royal Society University Research Fellows (21),
- Kavli Fellows (17),
- Winton Fellows (7),
- Leverhulme Trust Fellows (11),
- EPSRC Fellows (4),
- Ernest Rutherford Fellows (7),
- Herchel Smith Postdoctoral Fellows (5),
- Oppenheimer Fellows (3)
- 1851 Exhibition Fellows (2).

Future Appointments

Three senior professorial appointments are planned, the overriding considerations being the distinction, future promise and leadership qualities of the candidates.

- The *Ray Dolby Professor* is funded by a £10M gift from the Dolby family. The appointee will establish a new research group in quantum materials and quantum technology, areas in which there is already considerable strength in personnel and equipment. The gift includes provision for fellowships, studentships and infrastructure support.
- The *Cavendish Professor* is the senior physics Chair in the Cavendish with a preference for a theorist in statistical physics.
- The *Professor of Astrophysics (1909)* is one of two senior Chairs in the IoA, the post becoming vacant with the retirement of **Efstathiou** in 2022.

Within the Cavendish Astrophysics theme, two lectureships in *exoplanets* and *galaxy formation* and a third appointment are planned in the next five years. At the IoA, opportunities will be sought to expand into *gravitational wave* and *time-domain astrophysics*. The exploitation of the next generation of major ground-based and space-based observatories is a key priority. These appointments will enhance synergies between DAMTP, the IoA and the Cavendish.

As part of the Cavendish's commitment to support the wider physics community, *three research fellowships per annum* of three years' duration will be awarded to young research workers from outside Cambridge from philanthropic and other resources. These can be held at any UK university, roughly 50% of the fellow's time being spent in the Cavendish exploiting our national facilities.

Academic and Support Staff Career Development

A formal *Training and Development Policy* was launched in July 2018. All staff are encouraged to attend University-provided *Personal and Professional Development (PPD)* and *IT* courses advertised in the monthly HR newsletters. Line managers must allow staff time off to attend these courses. *Non-University external course fees* are reimbursed and paid time-off for study and examination leave are allowed. Line managers discuss training requests with the HR Manager to ensure that staff receive appropriate support for their training needs.

Health and Safety training is mandatory for all staff. Staff members working with hazardous equipment, such as chemicals, lasers or biological materials, have to attend a mandatory Health & Safety briefing relevant to their work. The 2020 Covid-19 pandemic resulted in the closure of the Laboratory in March 2020, supervised by the outstanding efforts of the Strategic and Operational Emergency Response Teams. Remote working has been remarkably successful in maintaining the momentum of research, although experimental work has been significantly impacted. The Silver Team is managing a phased return to work, applying strictly the rules for the safe conduct of research, according to Government and University instructions.

Academic staff

A new *Staff Review and Development (SRD)* process was implemented for academic research staff in 2017. Comprehensive training for both reviewers and reviewees is mandatory. New appointees to University Lectureships and those still in their five-year probationary period are reviewed annually by a professorial staff member. For University Lecturers out of probation and those promoted to Senior Lecturer or Reader, an SRD by a senior academic staff member, not from the same research area, takes place every two years. New academics are given a senior mentor. Interdepartmental Lecturers are supported through mentoring to enable them to integrate with their academic colleagues and participate in the Cavendish's Annual Strategy Forum. New employees are offered an *Induction Buddy* from within their research area to help them settle into their new roles.

Career progression discussions are part of the *Senior Academic-Researcher Promotions* round, which requires Department Heads to meet with those seeking promotion. The guidance and evaluation criteria provide a structured framework within which to judge progress and future directions. During the REF2021 period, 17 promotions to Reader/Senior Lecturer were made and 16 from Reader to Professor. Five staff were promoted twice from Lecturer to Professor. In the 2020 round, **Bohndiek**, **Castelnovo**, **Mitov** and **Nikiforakis** were promoted to

Professorships and **Béri**, **Bronstein**, **Jardine** and **Potter** to Readerships, effective from October 2020.

There are well established academic sabbatical and secondment leave procedures for research staff. They are encouraged to take sponsored external secondments or academic leave of up to five years, provided funding can be obtained to cover their teaching**. Chapman** was posted to CERN for a period while **Cowburn** and **Hobson** had secondments to develop their companies. Doctoral students, postdoctoral researchers and faculty involved in the Winton Programme have the opportunity to take part in a five-year exchange programme with the University of Berkeley's Kavli Energy NanoScience Institute in California.

Support Staff
Most features of the staff review and promotion procedures for academic staff apply equally to support staff but the promotion criteria are more closely related to their career progression. There is a strong emphasis upon career development through specialised courses for all classes of administrative and support staff. To enhance the skills of the technical staff, training schools in the use of workshop equipment, manufacturing and 3D design modelling are offered. The workforce of apprentices is expanding to produce the top-quality technicians for the future. We strongly support the University's initiative for technician development and recognition. A Senior Technical Officer sits on the Technician Commitment Working Group and attends meetings and events, such as National Apprentice Week.

POSTDOCTORAL AND EARLY CAREER RESEARCHERS

University Provision
Postdoctoral researchers are the powerhouse of our successful research programmes. There are numerous mechanisms to ensure that they realise their potential and get the most out of their time in Cambridge. The University has made considerable efforts over the last few years to improve significantly support and facilities for them. Many have benefited from subsidised housing on the nearby Eddington site, where high-quality, sustainable accommodation for lower-paid staff is provided. Currently about 65% of the flats are occupied by postdocs, many of whom work in the Cavendish and the IoA.

Cambridge's *Postdoc Academy* supports postdocs across the University through programmes such as the Mentoring Scheme, which offers matching with mentors from academia, business or industry as appropriate with a focus on developmental mentoring. Many use the *University Postdoc Careers Service*, which helps with their next career choices. Specialised careers advisers arrange one-to-one meetings, review fellowship or lectureship applications, and help prepare for academic or industry interviews.

The University retained its *HR Excellence in Research Award* in 2015, recognising its commitment to improving the working conditions and career development of research staff. It has adopted and implemented the *Concordat to Support the Career Development of Researchers*. Researchers from both Departments have taken part in University courses on transferable skills, leadership development, time management, career planning and professional development.

Departmental Provision
There is strong support for *early career researchers* (ECRs). They are hosted within a research group and theme while they build their own groups. They can apply to local funding schemes, such as the Isaac Newton Trust, as well as seek doctoral students funded by University and Departmental endowments and the CDTs. They are provided with laboratory and office space and grant and general administrative support. ECRs are strongly encouraged and allowed time to develop and commercialise their research – the examples of **Conduit** and **Lee** were described above.

In 2016 the Cavendish adopted new provisions for ECRs with three years research experience to gain promotion to *Senior Research Associate* to accommodate both those likely to develop academic research careers, and those providing very high level professional scientific expertise to support the research programme. Those in research-only positions can now be promoted to *Principal Research Associate*, and *Director of Research*. We take part in the contribution increment scheme for researchers, which allows Heads of Institutions to reward research staff for outstanding work.

ECRs are encouraged to participate in academic staff recruitment processes at the search committee stage, helping identify strong candidates, encouraging them to apply and ensuring a reasonable gender balance. The result has been a more diverse and stronger shortlist of candidates and appointees.

The Cavendish *Research Staff Committee* (RSC), with a representative from each research group, meets once a term. Feedback is provided on all aspects of the provision at University and Departmental levels. We have adopted the good working practices codified by the IoP Juno and Athena SWAN principles. The RSC provides networking opportunities through a monthly social event and a termly film discussion evening to which all staff are invited. It also organises research showcasing days, highlighting their research to outside commercial interests.

The *Impulse Programme*, established in 2016 at the Maxwell Centre, is targeted at PhDs, postdocs and ERC entrepreneurs, as well as researchers, engineers and managers from the corporate sector. There are two intensive residential modules and individual assignments between the modules over a period of three months, including training by industry professionals and two alumni companies. For the four years 2017 to 2020, 13 doctoral students and postdocs have taken part. **Patto** (*Waterscope*) and **Palacios-Berraquero** (*NuQuantum*) have gone on to be involved in start-up companies. A *Research Development Coordinator* (**Sirringhaus**) was appointed in 2018 who works closely with the Maxwell Centre programme manager and coordinates weekly funding opportunity notifications through the Laboratory's Research Grant Office and the University's Research Operations Office.

DOCTORAL STUDENTS

Details of the doctoral students who have passed through the Departments during the REF2021 review period are given in document REF4a. On 31 July 2020 a total of 390 PhD students were registered, 340 from Physics and 50 from the IoA. About 55% of our PhD graduates continue to academic research on graduation, others finding employment in industry, commerce, the financial sector and the civil service, as well as teaching. The output of high-quality doctoral students is one of our most important contributions to the economy.

Many doctoral students go on to win competitive fellowships in Cambridge and elsewhere. Recent students who have become Cavendish ERCs include **Chikkaraddy, Engel, H. Knowles, Mathiesen, Monserrat Sanchez, Nikolka, Stern** and **Waldie.**

In the Cavendish, typically 70 Doctoral students are taken on each year and 13 at the IoA. 551.5 Cavendish and IoA doctoral students completed their PhDs during the REF2021 period. The number of registered doctoral students has been relatively stable for the past seven years, about 15% greater than the comparable figure in 2010, partly associated with the Cavendish's participation in Centres for Doctoral Training. The application rate for both Departments is about four to five applicants per place.

The University wishes to increase doctoral student numbers which could undoubtedly grow if the financial support and space were available. Every opportunity is taken to identify new sources of funding for PhD students (Section 3).

Centres for Doctoral Training (CDTs)
Our *EPSRC CDTs* are interdisciplinary initiatives involving staff based in Physics, Chemistry, Materials Sciences, Engineering and Chemical Engineering. The three CDTs in Nanoscience,

Computational Material Science and Big Data included shared courses between departments as part of the assessed first-year training programmes. The students' first-year mini-project work can be hosted in any of the participating departments, providing opportunities that might not be available in any single department.

The EPSRC recently announced a new award for a *Centre for Doctoral Training in Integrated Functional Nano (i4nano).* Now in its third phase and based in the Maxwell Centre, the Centre encourages interdisciplinary research and training in nanoscience, building on the world-leading work of the *Nano DTC Programme*. An overarching theme is understanding and control of the nano-interfaces connecting complex architectures, which is key to major advances in emerging scientific grand challenges. These span vital areas of Energy, Health, Manufacturing, Sustainability, ICT/Internet of things and Quantum Physics. The training grant of 40 EPSRC studentships is enhanced by pledges of more than 20 studentships from industry and other partners.

The STFC CDT in *Data Intensive Science* managed by DAMTP and the IoA has further strengthened doctoral training links between the Cavendish, IoA, DAMTP and the Department of Pure Mathematics and Mathematical Statistics (DPMMS). The CDT focuses on areas crucial for the exploitation of the vast datasets created by many of the world's largest scientific facilities supported by the STFC. Several companies fund PhD studentships, 30 sponsoring work placements. The research carried out at the IoA will have wide impact across many areas, including the medical sector through application of image-analysis techniques and in the space industry.

Doctoral student training, mentoring and assessment
Oversight of the Cavendish's doctoral training provision is the responsibility of the *Director of Graduate Education* supported by the *Graduate Education Committee* (GEC).The IoA supports a *Graduate Education Office*, with a senior academic serving as *Director for Postgraduate Students* assisted by a Graduate Student Administrator.

Our procedures and policies set the framework for a supportive and positive environment for all doctoral students. Both Departments have written policies on the appointment and functions of supervisors and advisers for doctoral students. We have adopted the best practices for research student training, as required by the Research Councils, in the areas of training, supervision, mentoring and assessment of progress, including transferable skills and career development.

The doctoral students and postdoctoral staff are strongly encouraged to participate in undergraduate teaching. In the academic year 2019-20, 172 graduate students and postdocs, about 50% each, participated in demonstrating in undergraduate practical classes, examples classes and computer courses. Many also participated in providing College supervisions, organised through the Colleges. These experiences are important contributions to their career development.

The *Cavendish Doctoral Student Conference*, largely organised by the students themselves, has been running annually for a number of years. It provides an opportunity for doctoral students to share their research and to learn about what their peers are studying, as well as building a friendly student cohort.

Both Departments have excellent Library resources, both in hard copy and electronically, and these are fully accessible by doctoral students.

Management and administration of the Doctoral student programme
Administrative support is provided by the Departments' *Graduate (Education) Offices***.** Their functions are to manage and deliver student recruitment, to provide effective face-to-face support for students, organise a wide range of transferable skills training and to collect and deliver enhanced tracking and feedback data required by sponsors and other stakeholders. Additional administrative support is provided by the CDTs.

The *Graduate Students' Consultative Committees* provide fora for the discussion of issues affecting doctoral students. They are proactive in supporting the students' training needs and takes initiatives to support them. Both departments provide strong support for students with

protected characteristics. We currently have a package of support measures in place for a student with very severe disabilities, for whom considerable funds were raised to support a personal science writer.

EQUALITY, DIVERSITY AND WELLBEING

Equality and Diversity

The departments aim to provide an environment in which all staff are valued and can flourish, actively promoting an inclusive culture as described in the principles enunciated by the *Institute of Physics Project Juno* and the *Athena SWAN* charter. Both departments have been actively engaged with the University-provided *Respect at Work* programme. Cavendish academics lead the Equalities, Diversity and Inclusion (EDI) agenda within the University, nationally and internationally. **Gibson** chaired the *IoP Juno Panel* and is the University's *Gender Equality Champion* for STEMM subjects, in succession to **Donald,** the first Equality Champion. She works with the VC and Pro-VCs on the University's EDI agenda.

The Cavendish was the first Department in the University and the first Physics department in the UK to attain *Athena SWAN Gold status* in 2014 and this has been renewed twice since 2014. The Cavendish has also held IoP Junior Champion status since 2013. There has been a 64% increase in the number of women academic staff. Of 25 academic appointments during the REF2021 period, eight are women. From 2014, all women academics eligible for promotion have been promoted at least once. Current lectureships are now more gender balanced with seven women and ten men, while among current Readers there are four women and eight men. Professorial promotion opportunities for women are therefore increasing as the more junior population advances. Sustaining this progress, and attracting more minority candidates, will enable the Cavendish to progress towards a gender and diversity balanced faculty.

The IoA has been awarded an *Athena SWAN Bronze Award* and *Juno Practitioner status*. An analysis of four years of recent data (62 students) showed that the percentage of women amongst its graduating PhDs who continued in academia was 29%, the same as the percentage in the IoA's PhD student population. The IoA has had notable success in attracting women *Senior Research Fellows*, the average percentage of women in the past ten years being 28%, similar to that of the research student cohort. The percentage of women among IoA tenured academic staff, three out of 18 or 17%, is similar to national benchmarks, a fall by a factor of two compared with the untenured postdoctoral researchers. IoA's Athena SWAN activities aim to encourage more highly qualified women to apply for forthcoming tenured academic posts.

The principles underlying the *Athena SWAN* and *Supporting Women in Physics* projects have driven much of the *Career Management and Development for contract research staff* activity. All contract research staff, college research fellows and those on personal fellowships are encouraged to take advantage of the wide range of activities and programmes available to help them develop their careers. From January 2019, all new Cavendish staff and line managers must attend *Equality and Diversity (E&D) training* before they can become involved in any recruitment process. All staff involved in hiring attend the *Unconscious Bias* training module.

Staff returning from parental or carer's leave are entitled to work flexibly either as part of a phased return to work, or more permanently. University Teaching Officers are relieved of their teaching duties, allowing them to revitalise their research programmes. Funds are provided for conference attendance and other means of getting their careers fully back on track. To support postdocs with young families, the IoA has introduced a policy whereby any extra costs involved in a postdoc completing their research programme following parental leave are borne by the IoA.

The Cavendish's Athena Swan Action Team is now part of a *Community Forum* under the Personnel Committee, where E&D issues are debated and pursued proactively. The Head of Department is present to take action as needed. The Forum identified *LGBTQ* and *BAME groups* as priorities for support and the Cavendish LGBTQ+ network was founded in 2019. The Cavendish supports University efforts in race equality, recently recognised by a Bronze award,

with the aim of balanced minority representation among its staff. The *IoA's E&D Committee* represents all groups and includes men and women at all career stages from undergraduates to academics and administrators.

Cavendish Inspiring Women (CiW) is a postdoc and student-led group supported by the Cavendish to promote and support women and non-binary people pursuing studies and careers in physics. CiW is open to undergraduate students, doctoral students and postdocs in Cambridge. It encourages school-aged girls to study physics through our outreach events. Talks by successful women physicists about their work are organised and there are numerous social events throughout the year. For *International Women's Day 2017*, CiW organised a day of festivities, including the launch of *Cavendish Values* by the Head of the Department and the Chair of the Athena-SWAN Self-Assessment Team.

As part of a new *Visitor and Access Policy* launched in 2019, the Cavendish clarified the provision and processes for supporting disabled visitors to the Cavendish.

Wellbeing

Both departments take the wellbeing and mental health of staff and students very seriously. Over the last three years active wellbeing programmes have been developed with four main aims:

- to promote and encourage good physical and mental wellbeing of all staff and students within an inclusive and positive working environment,
- to highlight the availability of effective interventions to managers, staff and students through increased provision and availability of information,
- to provide appropriate training and support for managers and supervisors to allow them to discuss concerns with and provide support to employees and students,
- to support our strategy for health and wellbeing as part of our commitment to maintain Athena SWAN Gold Award standards.

Since 2017, this is communicated through a regular *Wellbeing Newsletter* and through extensive information on internal webpages.

In the Cavendish, a formal *Wellbeing Committee*, reporting to the Personnel Committee, meets every two months. In the IoA, wellbeing lies within the remit of the *E&D* committee. There are currently seven trained *Wellbeing Advocates* in the Cavendish and four in the IoA who provide confidential guidance to all members of staff in matters relating to wellbeing, including mental and physical health and dignity at work. Two Cavendish staff have attended the MIND mental health first aid course. An annual *Wellbeing Week* takes place at the start of every year with a focus on postdoctoral concerns about resilience, mental health and work/life balance in the context of an academic career. Funds are available to pay for counselling sessions at very short notice.

The Cavendish supports an active *Social Committee* which is allocated an annual budget and includes representatives from administrative, technical and research staff groups. With the Research Student Committee, it organises a monthly social event, as well as arranging the annual Christmas lunch and a large summer BBQ event for staff and their families. At the IoA, regular social events are organised by staff and students, with participation extended to all members of the Cavendish Astrophysics and DAMTP staff working on the site.

3:Income, infrastructure and facilities

RESEARCH FUNDING AND STRATEGIES FOR GENERATING RESEARCH INCOME

As described in REF4b, the total research income for the period of the REF2021 is £340.86M. The year-on-year income increased from £23.3M in 2013/14 to £90M in 2019/20.

Funding is sought from a wide variety of sources: Government, UK and European Research Councils, industry, charities, philanthropy, grant awarding bodies and the University of Cambridge endowment. The strategic research themes, aligned with the UKRI priorities, have increased our focus on larger grants, crossing boundaries between research groups and involving cognate Cambridge Departments such as Chemistry, Material Science, DAMTP, Clinical Medicine and in partner Universities (see Section on Collaborative Use of Research Infrastructure).

Some examples of major grants received during the REF 2021 period include the following.

- **Government:** A grant of £75M from HM Treasury for the completion of the reconstruction of the Cavendish Laboratory in the 2016 Government spending review, administered by the EPSRC; Cambridge Physics Education Project ISAAC (£3.55m)(**Warner**)

- **EU/ERC Awards**: eight Advanced grants (**Clark, Fabian, Friend, Gilmore, Haehnelt, Maiolino, Reynolds, Terentjev**); one Synergy grant (**Sirringhaus**), three Proof of Concept grants (**Baumberg, Cicuta, Cowburn**); six Consolidators Grants (**Atature, Cicuta, Hadzibabic, Keyser, Mitov, Sebastian**), eight Starter grants (**Belokurov, Beri, Collepardo Guevera, Rao, Schneider, Sebastian, Sijacki, Wyatt**) and five Future and Emerging Technologies grants (**Atature, Baumberg, Dutton, Nunnenkamp, Thomson**). The total grant award to the Departments from these 31 programmes was £41.2M.

- **UK Research Councils**: Large grants awarded included:

    - EPSRC Centre for Doctoral Training in Integrated Functional Nano (i4Nano) (£6M) (**Baumberg**);
    - Control of spin and coherence in electronic excitations in organic and hybrid organic/inorganic semiconductor structures (£5.1M) (**Friend**);
    - Peta-5: A National Facility for Petascale Data Intensive Computation and Analytics (£5M) (**Alexander**);
    - EPSRC Centre for Doctoral Training in Computational Methods for Materials Science (£4.5M) (**Payne**);
    - STFC Dirac 2.5Y Facility (£3.1M) (**McMahon**).

    The HEP and AP themes and the IoA are leading large international projects including the LHC at CERN and the SKA with major investment in both projects by the STFC. The HEP and IoA research programmes are supported by large STFC consolidated grants, as is the HEP Theory Group jointly with DAMTP.

- **Research Council Initiatives:** The Energy Materials theme leads activities centred on the *Royce Institute* with £10M equipment funding. As part of the *Faraday Institution* project, the Cavendish leads on £3.2M of funding and collaborates on this and other awards with the Departments of Chemistry, Materials Science and Engineering and collaborators across the UK.

- **Industry and Defence:** Both *Hitachi* and *Toshiba* have supported research in semi-conductor physics for over 25 years. The Hitachi Cambridge Laboratory (HCL) will move into the Ray Dolby Centre for its long-term programme. The Maxwell Centre has produced a flow of new industrial income from embedded companies, including sponsorship of studentships for CDTs. **Parker** leads our relationships with companies involving defence, denuclearisation and counterterrorism, which have been fostered by the Cavendish since the 1940s. These projects and which are funded by the MoD and its industrial contractors.

- **Charities:** We have benefitted greatly from grants from the *Wolfson* and *Kavli Foundations*. The Wolfson Foundation has made significant grants towards the construction of the Physics of Medicine Building, the Battcock Centre for Experimental Astrophysics and laboratories to support the construction astronomical and high energy physics instruments in the Ray Dolby Centre. The *Kalvi* and *Simons Foundations* provide ongoing fellowships for research in Cosmology and Exoplanets.

- **Philanthropy:** For major philanthropic gifts, both Departments work closely with the Cambridge University Development and Alumni Relations team (CUDAR). Examples of major gifts include:

- A £75M donation from the *Dolby family* towards the construction of the *Ray Dolby Centre*, as well as a £10M donation to establish a new research group led by an endowed Ray Dolby Professorship.
- The *Winton programme for the Physics of Sustainability* was funded by a £21M donation by David Harding.
- The £5M *GAPSTI programme* has led to three permanent appointments, as well as support for a Reader, postdocs and students.
- A donation of £3M from the *Huo family foundation* has established three permanently endowed research studentships.
- A £3M gift by Humphrey Battcock, supporting areas of the Ray Dolby Centre devoted to the EQP, AFCS and QDM themes, will be named the *Battcock Laboratories for Quantum Nanoscience.*
- A gift of £2.7M has come to fruition to endow a Professorship in the name of the late Harold Aspden.

Other donations totalling £1.16M provide support for research and infrastructure projects, for student support and for outreach to the public and young people. This work is led by the Cavendish HoD, supported by a Development Director who together work closely with CUDAR. Since 2009, the Development Director has published the Laboratory's Alumnus magazine *CavMag* twice a year. It is sent out to over 8000 undergraduate and postgraduate Cavendish alumni and contains a wide variety of science and news about the Laboratory. It has been successful in generating philanthropic gifts.

In the Cavendish, support for doctoral students is obtained from the research councils as well as very significant contributions from the above sources. The IoA continues to be successful in winning STFC consolidated grants and UK Space Agency funding which enable the maintenance of a sizable cohort of funded PhD studentships.

PHYSICAL, OPERATIONAL AND SCHOLARLY INFRASTRUCTURE FOR RESEARCH

Personnel support for staff of both Departments was described in Section 2. In this section, the physical, operational and scholarly infrastructure supporting the programmes are described.

Operations and Infrastructure Support
The Departments have independent teams providing infrastructure support, administration, finance, technical infrastructure support for the buildings, general services, workshops and IT services. There are over 115 technicians whose primary role is research support, including specialists in electrical and electronic equipment, mechanical instrument making, IT support, laboratory technical support and other specialist skills and trades. The central mechanical and electronics workshops in the Cavendish provide excellent facilities for all aspects of the design and construction of medium to large scientific instruments, such as the large astronomical cameras for the MOONs project and the delay lines for the optical interferometer at the Magdalena Ridge Observatory in New Mexico. Support staff are offered professional development opportunities to remain up to date with technological advances

There is considerable interdepartmental collaboration in the use of our technical infrastructure facilities. For example, the SP Group provides semiconductor chips and devices for other Departments and Universities. Underpinning support is provided for cryogenics, micro- and nano-fabrication, cell cultures and electron microscopy. Likewise, we make use of specialist expertise in other Departments such as glass-blowing In Chemistry and microscope facilities in Materials Science. The Maxwell Centre provides facilities and services to the numerous companies which participate in joint projects.

Buildings
The Cavendish Laboratory comprises five main buildings in addition to the Maxwell Centre and the Physics of Medicine laboratories. Cavendish Astrophysics is housed in the Laboratory's Battcock Centre for Experimental Astrophysics on the Madingley Road Site, co-located with the IoA and the KICC. The IoA's premises include the historic Observatories complex and the more recent Hoyle Building and its extensions to house the expanding astronomy programme.

The proposal to rebuild the Cavendish Laboratory began in 2002, the first fruits of that programme being reported in the REF2014 submission. By 2015, £80M had been raised to provide the *Physics of Medicine (PoM)* building, the *KICC*, the *Battcock Centre for Experimental Astrophysics* and the *Maxwell Centre*, largely funded by philanthropic and other external sources.

The major current project is the *Ray Dolby Centre* which will house a large fraction of the Cavendish's research and teaching. The new Centre will be a state-of-the-art facility, designed to the highest environmental and technical standards. This £303M project will be completed by 2022/23. Capital funding has been raised from the Dolby family (£75M), the Government (£75M, matched by £75M from the University), other donors and resources (£6M) with the University capital fund underwriting the balance. The Ray Dolby Centre will include an *Advanced Instrumentation Facility (AIF)* sponsored by the Wolfson Foundation. The HEP and AP groups will use the AIF with dedicated areas for mechanical, electronic and detector activities. The Centre will also house the *Battcock Laboratories for Quantum Nanoscience,* described above.

The basement of the Ray Dolby Centre has been designed for very high vibrational and temperature stability. This will meet the stringent requirements of the EQP Theme, which will also benefit from more general-purpose laser optics laboratories and an extensive hall for 20 cryostats for low-temperature experiments, as well as a helium liquefier. The basement will support elements of the AFCS and EM themes where vibrational stability is vital, and an imaging suite including electron microscopy.

The EM theme has a particular focus on organic materials which will be served by a dedicated clean room. The Maxwell Centre houses an ambient temperature cluster deposition tool for such materials. The QDM theme will also use the cryostat hall for low temperature experiments, and will have access to a large shared inorganic clean room for the construction of devices, an electron beam lithography suite and extensive MBE facilities. Crystal growth facilities and

materials characterisation apparatus needed by the EQP theme are already available in the Maxwell/PoM complex. Specialist laboratories are included for particular industrial projects.

Staff and doctoral students will be rehoused in new office space in the Ray Dolby Centre in addition to those members of both Departments already housed in the Maxwell/PoM, KICC and Battcock buildings. The Dolby Centre has been designed to facilitate collaborative interactions and to be welcoming to staff and visitors. It will include shared mechanical and electronic workshops, teaching laboratories, lecture theatres, meeting rooms, social spaces, a family room, library, common room and exhibition space for public events. It has been built to the BREAM Excellent environment standard and will have a zero carbon footprint when fully commissioned.

Cavendish role as a National Facility

The Cavendish has made a commitment to Government to operate as a National Facility allowing scientists from outside Cambridge access to state-of-the-art equipment. This will in turn create new opportunities for collaborative research projects and optimise the investment in equipment. The Laboratory has undertaken to make available *up to 25% of the time* on the national facilities for non-collaborative programmes by members of other universities, subject to any conditions set by the sponsors for use of particular pieces of equipment. Use of the facilities will include full support by specialist technical staff. The facilities available to the community will be operated as *Small Research Facilities* with transparent booking and charging procedures. Access and consumables will be charged at the same rates as for the Cavendish researchers.

The *Facilities Steering Committee* is responsible for providing strategic direction and oversight of the national facility aspects of the project to ensure access by the whole UK physics community. It is monitored by external accountability mechanisms such as the BEIS Gateway Reviews. The Steering Group reports through the EPSRC to Government and includes wide representation of the Laboratory, senior representatives of the University community, the EPSRC and the NPL.

In preparation for this new role, a review of *professional services and support staff* is being undertaken. This will involve organisational restructuring of the roles of laboratory technicians and related scientific support staff. It will build on our experience of running shared facilities, such as the Physics of Medicine building, the Royce equipment and our existing Small Research Facilities.

Cross-HEI Shared or Collaborative Use of Research Infrastructure

Many of the research programmes involve collaborations with other HEIs, both in the UK and abroad. Our long-standing practice has been to engage with other universities in collaborative research programmes which generally involve shared or collaborative use of research infra-structure. As an example, in the academic year 2015-16, in addition to our own Research Council funded programmes, the Laboratory was involved in 16 EPSRC and 2 STFC jointly funded projects and leading on four. These involved collaborations with one or more Universities; the numbers were: Bath (2), Bristol (1), Durham (1), Edinburgh (2), Heriot-Watt (1), Imperial (9), Lancaster (1), London Centre for Nanotechnology (1), Leeds (3), Liverpool (2), Loughborough (2), Manchester (1), Nottingham (1), Oxford (4), Royal Holloway (1), Sheffield (2), Southampton (3), Strathclyde (1), Sussex (1), UCL (2).

Benefits in kind

We have won major allocations of time and access to many national and international facilities, including CERN, ESA and NASA satellites, ESO observatories, the observing facilities in Hawaii, the ISIS neutron source, the US National High Magnetic Field Laboratory, the UK National Epitaxy Facility, and the UK quantum technology hubs. A measure of our success in exploiting these facilities is given in document REF4c which shows the values of the Benefits in Kind in which the UK is a paying partner - the total in-kind value amounts to £63.1M. Participation in major facilities such as the LHC at CERN and the Hubble Space Telescope contribute to the high esteem in which our colleagues are held. Other benefits in kind have been provided by the companies with which we have long-standing collaborations.

ARCHIVES AND COLLECTIONS

The Cavendish Rayleigh Library has a very extensive collection of physics and physics-related books as well as access to all online literature, data handling, repositories and IT infrastructure. The IoA Library holds a large collection of about 35,000 books and 250 current periodical titles, including electronic publications, in astronomy, astrophysics, cosmology and cognate disciplines. Apart from a few special collections, all material is available on open shelves in both Libraries.

The Cavendish curates and maintains the *Cavendish Collection of Historic Scientific Instruments* which contains artefacts linked to many major physics discoveries. The collection will be refreshed and enhanced when relocated in the Ray Dolby Centre. Many of the important instruments, pieces of apparatus, events and the personalities have been preserved photographically, providing a vivid picture of the Laboratory from the Maxwell era onwards. The most important 400 or more images constitute the *Cavendish Digital Photo Archive* which can be accessed in the University Library's *Cambridge Digital Library*. Scholarly and research use of these images is allowed free of charge.

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

COLLABORATIVE RESEARCH PROJECTS

Research collaborations are essential in many of the most challenging projects being pursued by members of the Cavendish and the IoA, particularly in the use of major international facilities for 'big-science'. The paragraphs below give an impression of the very many different types of collaboration taking place.

Institute of Astronomy (IoA) Three key elements of the IoA's success are: (1) programmatic agility focusing on competitive access to national and international facilities such as ESO, HST and Chandra, (2) leadership of major surveys involving ground-based and space facilities, for example, *Gaia, VISTA, Spitzer, Planck, Herschel*, and (3) strategic investments in intermediate-scale non-nationally funded projects and theoretical investigations, where a relatively small funding commitment can leverage a proportionally larger and high-impact scientific return. A recent example was participation in the Second and Third Sloan Digital Sky Sky Surveys (SDDS). The IoA aims to extend this approach through involvements in the *Euclid, PLATO* and *IXO* missions and in the *UKIDSS* survey. Two leading candidates for future private and private-public partnerships include the *Large Synoptic Survey Telescope (LSST)* and the *Cerro Chajnantor Atacama Telescope (CCAT).*

Hitachi Cambridge Laboratory (HCL) employs an international team of researchers within an open research environment with collaborations over a wide range of research projects. Initially associated with the Microelectronics Group, collaboration now extends to the OE and SP groups with the aim of creating new concepts for advanced electronic and optoelectronic devices. Hitachi has begun a major programme in quantum computing with the Cavendish and other Departments as well as SMEs. **Smith** is Director of the HLC on a half-time basis.

The **Toshiba Cambridge Research Laboratory (CRL)** is a vital part of Toshiba's worldwide research and development network. It is responsible for a number of significant world-first developments in quantum technologies which find their way into new Toshiba products. Close collaborations take place with the SP Group.

The **Large Hadron Collider** is our largest international project, with the ATLAS experiment involving 3000 scientists and the LHCb almost 1000. We have made major contributions to the detector systems in both cases, and are leading efforts on the current upgrade programmes, which will take data for at least a decade.

DUNE, the Deep Underground Neutrino Experiment, involving almost 800 scientists and engineers from 145 institutions across 26 nations is a billion-dollar scale next-generation neutrino oscillation experiment, currently under review by the U.S. Department of Energy (DOE). Global interest in the project is made possible with the combination of the DUNE near and far detectors and the proposed Long Baseline Neutrino Facility (LBNF) at the Fermilab. First operations of the neutrino beam are expected in 2025.

HIRES is an optical/NIR high resolution spectrometer for the European Extremely Large Telescope (E-ELT). With ELT first light planned for 2024, the HIRES instrument is planned for delivery in 2028. Members of the IoA and Cavendish Astrophysics are carrying out a design study for mosaicing large gratings to make a single echelle grating over one metre long that operates at cryogenic temperatures for the near infrared arm of the spectrograph. The scientific motivations include exoplanets and cosmology.

OPTICON is an EC-funded 'Integrated Infrastructure Initiative' consortium of about 35 partners including all major European astronomy funding agencies and ESO. **Gilmore** is scientific coordinator. The project supports technology R&D across Europe, especially in high-order adaptive optics and related technologies. It supports Europe-wide projects and operates an

open-access telescope time allocation system. The project supports the IoA's European Projects Manager.

The Cavendish Laboratory for Scientific Computing is a federated initiative that encompasses high-level computing resources. The research is concerned with complex, multi-scale, multi-physics problems arising in science or technology that cannot be solved by current computational approaches or which involve mathematical formulations based on incomplete physical models. The research is predominately funded by industrial projects which include companies and organisations such as the AWE, BAE Systems, Boeing Research and Technology, BP Exploration Operating Company, Jaguar Land Rover, Orica Mining Services, QinetiQ and Schlumberger Cambridge Research.

ECONOMY AND SOCIETY

Our research programmes have a crucial role to play in contributing to the overall system of knowledge production and innovation nationally and internationally and in sharing these across academic communities and with industrial partners. The Cavendish and the IoA continue to deliver to the national labour force a supply of highly-trained and qualified workers who enter industry, commerce, the financial sector and banking, teaching and all the other major professions which value problem-solving skills. An analysis of the long-term career destinations of Cavendish physics alumni has shown that about 25% continue in academic university and research institution posts while over 50% end up in highly skilled employment in industry, commerce and finance. The most conspicuous example of the latter is Ray Dolby and his invention of the Dolby noise reduction audio system.

The roles graduates play in contributing to society and the economy are emphasised from the beginning of their PhD courses. Training courses are designed to prepare them for such future employment opportunities.

Public and Schools Outreach and Diverse Communities
We have made major commitments to communicating the excitement of physics and astronomy research to all sections of the community, particularly to young people and disadvantaged sections of society.

During the 2021 REF period, Cavendish staff members, **Jardine-Wright** and **Butler** have been employed full-time on outreach activities for schools and the general public. They lead educational programmes in physics for young people and their teachers. The very extensive schools programme also involves staff members who contribute popular lectures in Cambridge and throughout the country.

The *Physics at Work* programme is an annual event which runs for three days. The 24 displays are a roughly equal mix of science activities from the Laboratory, cognate departments and industrial companies. Each year this event attracts about 2,200 students and is always highly oversubscribed.

An annual *Gatsby Physics Lecture Series* is targeted at young people from disadvantaged backgrounds. For a week, a cohort of 20 students experience the full range of Cambridge college and University life, encouraging them to apply for entrance to the University. They pass on the message at their home locations urging their colleagues to aspire to excellence in higher education.

The week-long *Teacher Residential Courses* and *the Senior Physics Challenge* involve typically 30 teachers and about 70 of the brightest students from all over the country selected from over 300 applicants. The students are exposed to a wide range of challenging problems in physics, illustrating the power of mathematics to articulate their physical content and to their solution. Ten Cambridge colleges support the programme by offering accommodation. Many doctoral students are involved as demonstrators and course tutors. The *High Energy Physics Master Class* for school pupils performs a similar role and is held over two days each year.

Each year there is an influx of many young people and their families for our *Open Days*. The IoA hosts visitors as part of the Cambridge Science Festival. They browse displays and exhibits about astronomical research, typically attracting about 1500 people. In the Cavendish, the day

involves hands-on physics experiments and model-building exercises as part of Cambridge Science and Technology Week with demonstrations and experiments carried out by doctoral students. Typically 2000 visitors take part each year.

The IoA's vibrant outreach programme consists of a tiered set of programmes previously coordinated by the Institute's 'Public Astronomer' **Crawford** and now run by Outreach Astronomer **Bothwell**. The weekly public open evenings run for six months of the year, typically attracting 150–200 people. A 30-minute talk, often delivered by postdocs and doctoral students, is followed by observing through the16-inch, 12-inch and 8-inch telescopes. Approximately 80 visits per year are hosted for community groups, schools groups, and amateur astronomical societies. These activities are supplemented by 'one-offs' including popular arts-science events and public viewing of special astronomical events.

The IoA has also developed a Kavli-funded initiative, *Project AstroEAST*, specifically targeting underserved and under-privileged populations in the region to the north and east of Cambridge. It aims to attract more students to study A-level science, targeting young people before they take their GCSEs.

The Cavendish and the IoA have supported five Royal Society Summer Exhibition stands during the REF2021 period, each visited by roughly 14,000 of the public over six days.

Isaac Physics Project

Warner and **Jardine-Wright** lead the *Isaac Physics Project*, a radical, mass-scale programme harnessing computer technology to help all students, especially those affected by the national shortage of physics teachers, enter STEM subjects at university. The team works collaboratively with teachers, schools and partner universities to deliver extension materials, on-line learning, workshops for students and support for physics teachers. The reach of the programme includes a world-wide audience of young people. Department of Education funding of £7M was recently renewed with substantial help from the Ogden Trust. With the assistance of the Institute of Physics, Isaac now operates across the UK.

Students develop analysis skills and deeper understanding of physics through problem solving. Over 7,100 teachers and 185,000 14-19 year-old students have freely accessed the Isaac Open Platform for Active Learning (OPAL). More than 3,600 schools participate, many with over 50 registered students. Monthly, 28,000 students and 1300 teachers use OPAL with daily peaks of 145,000 problems answered. The 36% participation rate for women in Isaac compares with 21% in A-level physics

Progress of registered students is monitored, guided and encouraged on a highly interactive and individual basis, including live video tuition to students and teachers participating in continuing professional development programmes each week. Isaac sets, marks and reports homework, saving thousands of teacher hours monthly.

Other Inclusive Initiatives

A number of innovations specifically targeted at the disabled and minorities have featured in the activities of both Departments.

- **Laporte** has used the IoA 3D printer to create tactile experiences for blind people.
- **Padman**, Chair of the Cavendish Personnel Committee, was awarded the *Barbara Burford Excellence Award,* the inaugural Gay Times honour given to individuals who live openly as LGBT+ and whose work has had a profound impact on the lives of LGBT+ people.
- **Patto** developed *WaterScope*, a not-for-profit company spun out of research conducted within the NanoPhotonics Centre. Using an open source flexure microscope, *WaterScope* is developing rapid, automated water testing kits and affordable bacterial diagnostics to empower developing communities in Africa.
- **Cavendish and COVID-19** In response to the coronavirus pandemic, members of the BSS Group have realigned their specialised technologies to study basic aspects of the

virus infection. **Cicuta** collaborates with Bryant (Department of Veterinary Medicine) and Floto (Department of Medicine) making use of our facilities for cell handling, microfluidics, optical imaging and our experience of motile cilia in the lungs. With Mascolo in the Computer Laboratory, **Cicuta** has also launched a global project to record the sounds of breathing, cough and voice, and analysed these with the aim of providing a COVID-19 diagnostic. **Keyser** is using his specialised nanopore sensing expertise to develop of a test for the RNA viral genome, avoiding the bottlenecks of existing technologies. These long-term projects provide insight into the detection, biology and medical treatment of the coronavirus infection.

Wider Influence

The wider influence of the Cavendish and IoA staff members comes in a variety of forms. Most important is their full participation in national and international science. Such activities include Research Council service, committee membership of learned societies and national bodies, such as such the Royal Society, Institute of Physics and the Royal Astronomical Society. On the international scene, many staff are members of international committees, for example, for projects and programmes of the European Space Agency, NASA, CERN, European Southern Observatory, as well as review panellists for university departments worldwide. It is significant that staff members are members of more international committees than they are of UK funding bodies and learned societies, testifying to their high international profiles. Many staff have been honoured by delivering plenary lectures at major international meetings.

Other evidence of impact includes distinctions such as membership of prestigious academic institutions and prizes. Among the researchers submitted for REF2021, there are 12 FRSs and in addition 13 active Emeritus FRSs. Over the REF2021 period, the following were elected to prestigious fellowships:

Hills, Queloz and Teichmann (*Fellowship of the Royal Society*)
Teichmann (*Fellowship of the Academy of Medical Sciences*)
Fabian (*Foreign Associate of the US National Academy of Sciences*)
Simons, Sirringhaus (*Royal Society Research Professor*)
Cole (*Royal Academy of Engineering Research Professorship*)

Other marks of influence and distinction include:

Maiolino*: Knighthood of the Order of the Star of Italy, 2018*
Thomson*: Executive Chair of the STFC, 2018*
Donald: *Master of Churchill College, Cambridge*
Cooper*: EPSRC Established Career Fellow, 2013*

Members of the departments have won many prestigious prizes:

Royal Swedish Academy of Sciences:
Queloz *(Nobel Prize in Physics, shared with Mayor and Peebles, 2019)*
Norwegian Academy of Science and Letters:
Fabian (*Kavli Prize in Astrophysics 2020*).
Royal Society:
Barnes (*Brian Mercer, 2014*); Baumberg (*Rumford, 2014*); Sirringhaus (*Hughes, 2014*); Efstathiou (*Hughes 2015*); Simons (*Gabor Medal 2015*); Cowburn (*Clifford Patterson, 2015*); Gibson (*Athena, 2016*); Cole (*Clifford Patterson, 2020)*
Institute of Physics (IoP*)*:
Bohndiek (*Clifford Patterson, 2014*); Payne *(Swan, 2014*); Sebastian (*Brian Pippard, 2014*); Simons *(Rosalind Franklin, 2014*); Cliff *(Science in Society, 2015)*; Sebastian (*Philip Leverhulme Prize 2015*); Sirringhaus (*Michael Faraday, 2015*); Hadzibabic (*Holweck Medal and Prize 2016*); Baumberg (*Michael Faraday, 2017*); Rao (*Henry Moseley, 2017*); Warner (*Founders Prize, 2017*); Di Michele (*Liquids and Complex Fluids Group Early Career Award 2017*); Palacios-Berraquero (*Jocelyn Bell Burnell, 2018*);

Cooper (*Lord Rayleigh/Strutt, 2019*); Jardine-Wright and Warner (*Bragg, 2019*); Atature (*Thomas Young Medal and Prize 2020*)

Royal Astronomical Society:

Clarke *(Eddington, 2017);* Parry (*Jackson-Gwilt, 2017*); Challinor and Efstathiou (*Group Award Planck Collaboration, 2018*); Kennicutt (*Gold Medal, 2019)*

Other Notable Prizes:

Bohndiek (*EC MSCA prize 2014, WISE research award 2014, CRUK Future Leaders Prize, 2018* and *SPIE Early Career Achievement Award 2019)*; Cooper (*Simons Foundation Award and Prize 2017*); Gibson (*WISE Award 2013*); Lonzarich (*Kamerlingh Onnes Prize 2015*); Donald (DBE) *eight honorary degrees*; Keyser and Bell (*Helmholtz Prize for Applied Metrology, 2016)*; Longair (*two honorary degrees*); Padman (*Gay Times Barbara Burford Award*, 2017); Queloz (*Wolf Prize 2017*); Sijacki (*Ada Lovelace Prize 2019*); Teichmann (*Biophysical Society Bárány Award 2014*: *EMBO Gold Medal 2015*), Stranks and Paddison (*EPS Early Career Prizes, 2017*); Scott (*Thomson Reuters Citation Laureate 2014*); Schneider (*Rudolf-Kaiser Prize 2016*); McMahon, Irwin, N.Walton (*2015 Breakthrough Prize in Fundamental Physics*).

Our national and international impact is reflected in the high standing of the Departments in the various national and international reviews of Physics and Astronomy, Cambridge being consistently in the top five universities world-wide for Physics and Astronomy in QS rankings.