**Institution: Imperial College London**

**Unit of Assessment: UoA 9 (Physics)**

## 1. Unit context and structure, research and impact strategy

### Overview

The aim of the **Department of Physics** at Imperial College London is to inspire world class science in fundamental theory, experimentation, leadership of large international projects, applications in advanced technology and development of specialist infrastructure and facilities. We are one of the largest Physics Departments in the UK and in Europe, which enables us to create groups of international standing, and with sufficient scale and critical mass, that they influence the research agenda and attract the world's top researchers. Our research portfolio covers the full range of theoretical and experimental physics, allowing us to respond rapidly to opportunities and initiatives, from research into 'Massive Gravity' to our recent expansion into Quantum Technology.

The Department has four overarching collaborative themes through which new research directions are driven: **Fundamental Physics; Space, Plasma & Climate; Condensed Matter Physics;** and **Photon Science**. We are structured into nine research groups: Astrophysics (**ASTR**), Condensed Matter Theory (**CMTH**), Experimental Solid State Physics (**EXSS**), High Energy Physics (**HEPH**), Plasma Physics (**PLAS**), Photonics (**PHOT**), Quantum Optics & Laser Science (**QOLS**), Space & Atmospheric Physics (**SPAT**), and Theoretical Physics (**THEO**). Research is not siloed in these formal groups and staff are encouraged to collaborate and interact via the themes. Staff associate with multiple themes, providing the flexibility needed to tackle multidisciplinary challenges.

This flexible and nimble thematic approach has created vibrant collaborations and new research directions, e.g. combined laboratory fusion plasma modelling with planetary magnetospheres, to enable space weather prediction (SPAT, PLAS); Quantum Technology and Quantum Information Science (QOLS, CMTH, EXSS with participation in the Strategic Advisory Board (*Knight*-Chair) and three UK Hubs with leadership from *Kim(M)*, *Hinds, Walmsley*); generated activities in Fundamental Physics such as cosmology (ASTR, THEO), dark matter (ASTR, HEPH), phenomenology (HEPH, THEO) and emerging activities in advanced statistics, AI and machine learning (all groups). Space Plasma & Climate provides a natural forum for our work on exoplanets (ASTR, SPAT) and in Condensed Matter Physics techniques are brought together from metamaterials and nanophotonics (EXSS, CMTH).

We attract substantial funding, with an annual research turnover of ~£25M. Over the REF2021 period, we received grant income totalling: UKRI & related (£122.5M), EU (£27.3M), UK Government and others (£18.6M including tax credits), Non-EU (£8.5M) and UK Charities (£6.3M).

We are returning 146 academic staff (including 23 independent fellows) to REF2021. Additionally, our community comprises 168 research staff; 5 teaching fellows; 93 technical and operational staff; 289 research students; 143 postgraduate masters students; and 874 undergraduate students. Since REF2014, we have recruited 18 academic staff members as part of our focus on supporting early career researchers into academic posts. We have invested over £4.5M in new laboratory facilities (e.g. Ultrafast Quantum Optics, Liquid Xenon Detectors and Atmospheric Trace Gas Measurement), over and above regular maintenance and upgrades to existing laboratories.

**Research Mission:** With our capacity spanning theoretical concepts through to impactful translation, our research diversity is a driver for innovation. We invest strategically to maintain our strengths while expanding our research pipeline with agility to meet new and emerging national and international challenges. This is underpinned by an inclusive research culture for staff and students where all can flourish. The following aims drive the fundamentals of our strategy:

- Appoint and retain world class scientists (e.g. by hiring *de Rham* and *Tolley*)

- Enable independent inquiry and collaborative research (e.g. Imperial SpaceLab network)
- Play leadership roles in large international consortia (e.g. instrument leadership roles in spacecraft missions, *Dougherty*)
- Focus in areas where we have the biggest impact, balancing strength in existing areas with expansion into new areas (e.g. Quantum Sensors for Fundamental Science)
- Foster a stimulating, positive, inclusive and supportive environment enabling our staff and students to thrive (e.g. open staff meetings enabling exchange of ideas; termly discussions between the Head of Department (HoD) and post doc/fellow and student representatives; research-led education via UG projects and summer placements)
- Expand and diversify our research funding streams (e.g. USA funders including national labs and foundations >£2M)
- Expand industrial collaboration and translation (e.g. Samsung award for new Quantum materials, £1.6M)
- Develop specialist infrastructure, enabling our research (e.g. Quantum Measurement Lab, £1.45M)
- Train and enable future researchers and leaders of tomorrow (e.g. appointment of 2 UKRI Future Leaders in this REF period)
- Inject new ideas into our portfolio with a focus on appointments of early career scientists (e.g. exoplanet (*Owen*), quantum computing activity (*Connolly)*)
- To capitalise on excellence throughout College and beyond by encouraging collaboration (e.g. new Physics Research Workshops)

The HoD (*Dougherty*) heads an Executive Committee that enables a transparent environment to drive through strategic initiatives. Members include: Associate HoD (*Weir*), co-Directors of Research (*Araujo* and *Chittenden*), Faculty Vice-Dean for Education (*Thompson*) and Departmental Operations Manager (DOM, *White*) and they work closely with the Department's Diversity (*Wascko*) and Industry Engagement (*Oulton*) champions. For REF2021, the Committee has included the Department REF lead (*Heavens*).

Our Departmental strategy aligns with Imperial's academic strategy (see REF5a - Institutional Environment Statement), with emphasis on working across disciplines, quantitative approaches to research, translating ideas into impact and collaborating with stakeholders locally, nationally and internationally (examples detailed below). Of our submitted outputs, 68% are collaborations with other UK institutions and 79% are collaborations with international institutions. These principles permeate our research culture and steer new research directions, along with regularly reviewing our internal research strategy whilst monitoring UKRI, industry and national and international strategic priorities.

**Some of our Major Highlights in REF2021**

- A key outcome of our strategy to lead the design and upgrade of particle physics experiments resulted in T2K's publication (Nature) of the first substantive indication of CP violation in neutrinos (*Dunne, Uchida, Scott(M)*, *Wascko*, HEPH). This result could be the first indication of a solution to the Universe's matter-antimatter asymmetry. This success will facilitate our continued leadership in the recently approved T2K-II upgrade and future experiments DUNE and Hyper-K (STFC funds ~£6.3M).
- Our long-term strategy of focusing our international magnetometer instrument program to answer major science questions, led to the unexpected confirmation of Saturn's extremely small dipole tilt. Published in Science (*Dougherty*, SPAT), this discovery, the culmination of analysis of 13 years of orbital data from Cassini, requires a rethink of the planetary dynamo process, which we are well-placed to address with international collaborators at Harvard, Caltech and Max Planck Institute.
- Our strong links between theoretical and experimental physics are evidenced by the theoretical explanation of the first single-molecule strong coupling in ambient conditions, paving the way for high-impact photonic quantum technologies at room temperature and quantum immunoassay sensing (*Hess*, CMTH). Immunoassay sensing will profit from this

technology (with 1500% increase in sensitivity) and collaboration with the University of Cambridge, Physics has begun (EPSRC funds £1M).

- The impact of our diverse research strategy can be evidenced by a new development in novel ultrafast lasers to realise universal all-fibre-integrated picosecond and femtosecond pulse sources in the visible spectrum for the first time (*Taylor*, PHOT) – developed in collaboration with a commercial company (Gooch and Housego). These compact, efficient, hands-free versatile sources of wavelength, repetition rate and pulse width are highly applicable to many imaging platforms.
- The strategic decision to pursue mid-IR laser development has enabled participation in the large US-led MURI project (QOLS with PLAS, £4.6M) resulting in a world-record coherent x-ray generation in the important "water-window" (*Marangos*, *Tisch*, QOLS). This new light source is ideal for time-resolved x-ray absorption and x-ray microscopy measurements. The findings inform the design of a roadmap for developing future attosecond x-ray sources. This led to a £1.3M EPSRC grant jointly held with Chemistry, to study with 100x the previous time resolution fundamental processes in physics, e.g. exciton formation and charge migration, and key processes in chemistry, e.g. electron transfer and bond-breaking/making.
- The impact of our leadership of large international collaborations is evidenced by the first reporting of the radiation reaction process, following the announcement of the highest energy ever reported from an all-optical inverse Compton scattering scheme, with laser-wakefield accelerators, in Physical Reviews (*Mangles*, PLAS). Understanding this result will be crucial to experiments using the next generation of multi-petawatt laser pulse under construction worldwide. The breakthrough was supported with grants from STFC and ESPRC (£1.3M) and ERC (£1.4M).
- Our excellence in string theory is highlighted by the ERC Advanced Grant funded work of *Gauntlett* (THEO); using string theory dualities to find remarkable relationships between the physics of black holes and transport properties in conventional strongly-coupled field theories, with important implications for understanding potentially novel classes of metals and insulators seen in the context of strongly correlated electrons. A pivotal new connection between geometry and string theory (*Waldram*, THEO), explains part of the underlying symmetries and provides new natural stringy generalisations of General Relativity.
- We place importance on impactful research that can directly benefit community systems. One example is the energy system design underpinning the successful application of solar power in minigrids in Rwandan refugee camps (*Nelson*, EXSS). In collaboration with MeshPower Ltd. (Rwanda) and Strathmore University (Kenya), energy system modelling was applied to reveal that solar generation and battery storage installed in a minigrid system can reduce diesel usage and emissions. MeshPower are utilising this as the blueprint for implementation in two further refugee camps (see B9-7, *Nelson*). The translation of this research has been recognised by initial grants from the Strategic Priorities Fund (UN, ~ £140k).
- Investment in new laboratory facilities is crucial to enable expansion in response to new opportunities. Creation of the state-of-the-art Quantum Measurement Laboratory (of 200m$^2$) has been built in response to the UK Quantum Technology programme, exploring fundamental quantum physics, and with technology applications involving several commercial partners (supported by a £1.6M FLF award (*Vanner*, QOLS) and £1.67M EPSRC strategic equipment grant). A second major capital investment project, funded through College (£2.1M), has increased our physical experimental footprint by 196m$^2$. The new laboratory houses state-of-the-art facilities such as superconducting transition-edge sensors that can resolve up to 15 photons each, unique in the UK (*Walmsley*, QOLS), to enable quantum technologies such as light-based quantum computers and simulators, communications, and sensors.

**Summary of Achievements**

Three of our research groups collaborate in the **Fundamental Physics** theme**:**

***High Energy Physics (22.8FTE, 74 grants, total £43.6M)***

Our strategy for leadership in designing, constructing, and exploiting scientifically the leading experiments in particle physics sustains our high international profile. We have been at the core of major advances in the Higgs sector and searches for new physics and CP violation at **CERN's Large Hadron Collider (LHC)**, in **neutrino physics** at the long-baseline experiments, and pursuing **dark matter detection** through a variety of techniques. In addition to major project-specific awards, exploitation activities were supported by STFC Consolidated Grants (£18.1M). We have leading roles in scientific discovery at the **LHC** and in detector and accelerator development, with former spokespersons of CMS and LHCb experiments (*Virdee, Golutvin*). We continue to lead the highest profile measurements in the search for new physics, including lepton flavour violation and characterising the Higgs boson (*Patel, Wardle*). In parallel, we drive the **LHC upgrades** (*Dauncey, Hall, Tapper, Virdee),* strengthened by a new appointment (*McCann*), with grants from UKRI, ERC (£6.5M); all underpinned by our **GridPP-computing** group (*Colling*), (£5.2M in grants).

The **neutrino sector** is another international priority and *Wascko* was international Co-Spokesperson of T2K in Japan (2015-19), when the experiment won the Fundamental Physics Breakthrough prize (2016). The group has leading roles in both next-generation experiments – DUNE (USA) and Hyper-K (Japan) – that will characterize the recent hints of CP violation observed in the neutrino sector (Nature front-cover). Recent awards showcasing this research include two UKRI FLFs (*Dunne, Scott(M),* >£3M). A new hire (*Vacheret*) is spokesperson of the complementary short-baseline neutrino experiment SoLiD (Belgium), with ERC and STFC funds of £1.4M. We have substantially expanded research into the **dark sector** and are a founding member of the flagship US LUX-ZEPLIN (LZ) experiment, with *Araujo* as UK spokesperson (£2.6M). We initiated and led (*Golutvin*) the SHiP collaboration, numbering 250+ physicists from nearly 20 countries pursuing a different solution to the dark matter problem. At the interface of EPSRC and STFC, we lead the Atom Interferometer Observatory and Network (AION) collaboration (*Buchmueller*), which was recently awarded £8.6M nationally to probe fundamental physics with quantum technologies, heralding a new research avenue in the search for ultra-light dark matter and gravitational waves in the mid-frequency band. In **accelerator physics**, we recently demonstrated muon ionisation cooling in the MICE experiment (Nature front-cover) and this R&D is paving the way to future colliders and medical applications (>£2.3M).

Our future strategy will: continue exploitation of LHC science leadership; elucidate evidence for leptonic CP violation, in parallel to our non-accelerator neutrino programme; focus work on SHiP; concentrate on Dark Matter searches; open a new window on fundamental physics with AION; and pursue future collider opportunities along with our impact agenda through the application of HEP technologies.

***Theoretical Physics (16.2FTE, 20 grants, total £9.1M)***

Our research focuses on areas at the forefront of theoretical physics with significant funding from STFC Consolidated Grants (£4.3M) and 6 personal fellowships (RS and Leverhulme Trust). We made significant strategic investment in **cosmology** through high-profile hires (*de Rham* and *Tolley,* 2016), with RS Wolfson Merit Awards (£200k) and *de Rham's* ERC Consolidator Grant, appointment as Blavatnik Laureate (£1.7M) and upcoming Simons Investigator award ($660K). Their ongoing work in massive gravity, Gallileons and UV completions is a major highlight of our output. Another highlight in cosmology is studying the effects of spacetime curvature on Higgs stability during inflation which shapes our understanding of the very early Universe (*Rajantie*).

In **string theory,** major new developments include the study of deformed superstring sigma models (*Tseytlin*) and the study of holographic lattices and their thermoelectric properties (*Gauntlett*, ERC funds £1.4M). Building on our strong links to mathematics, we uncovered an important new string-generalisation of Riemannian geometry (*Waldram*) and found new relations between brane physics and hyper-Kahler geometry (*Hanany*); initiating new avenues of research, with implications for the fundamental structure of the theory and its symmetries, for mathematics, and for generic properties of strongly coupled systems. Our significant investment in teaching

through the Quantum Fields and Fundamental Forces postgraduate master's degree trains highly qualified theoretical physics graduates (225 during the REF2021 period).

Our strategic research plan will: enhance our formal theory effort by focusing on new emerging areas at the intersection of string theory, QFT and mathematics; and developing expanded focus on gravitational wave physics; and enhancing ASTRO links by exploiting our expertise in gravitational physics and effective field theory.

***Astrophysics (12.6FTE, 34 grants total £9.4M)***
Following our strategic decision to expand into astrostatistics and exoplanets, we have formed world-leading expertise in these areas, supported by STFC Consolidated Grants (£4.3M). A key stake in **exoplanets** was consolidated when our RS URF was appointed as a lecturer (*Owen*) with RS and ERC funding (£1.9M). His seminal work explains physically the 'evaporation valley' and completes an expert group of critical mass (*Mohanty, Unruh*). Further growth is in the **epoch of Cosmic Dawn** (*Pritchard*, ERC Starting Grant £1.1M, and new RS Dorothy Hodgkin Fellow, *Chapman,* £1M).

Our strategic move into astrobiology yielded the first tentative presence of phosphine in the Venus atmosphere (*Clements*). The interdisciplinary **Imperial Centre for Inference and Cosmology** (ICIC; dir. *Heavens*), has 23 members spanning Physics and Mathematics, attracting RS URF (*Leistedt,* £0.7M). Its specialisation is in Bayesian cosmological and astrophysical data analysis, especially in cosmic shear analysis, with the ICIC hierarchical model adopted in a Euclid key project (*Heavens, Jaffe*). Our long-standing expertise in **CMB beams** (*Jaffe*) underpins the seminal cosmological results from Planck. The broader applicability of our Bayesian expertise is exemplified by our evidence for the continuous decline of stratospheric ozone in mid-latitude atmospheres (*Mortlock*). Role in international projects include: the Euclid spacecraft Legacy Science programme (*Warren*); and various groups preparing SKA and JWST.

Our strategic aims are: to capitalise on our expertise in Bayesian methods to analyse Euclid and LSST data; prepare for analysis of 21cm data from SKA; and develop further leading theories of exoplanet formation and properties, including habitability.

Together with **ASTR**, two other groups link via the **Space, Plasma & Climate** theme:

***Plasma Physics (11.4FTE, 66 grants, total £19.5M)***
Our experimental and theoretical work ranges from extreme materials science through **high energy density plasmas** (HEDP) to magnetic and **inertial confinement fusion** (ICF). Our strategy to develop a leading role in HEDP science has led to major roles in ICF (*Rose*, *Chittenden*), laser plasma acceleration (*Najmudin*, *Mangles*), mid-infrared high-power lasers (*Smith*), and laboratory astrophysics (*Lebedev*). On-site facilities include the world's largest university-based pulsed power generator (*Lebedev*) and the UK's largest university-based laser (*Smith*). Breakthrough achievements have been made in the study of magnetic reconnection (*Lebedev*), the two-photon Breit-Wheeler process (*Mangles*, *Rose*), magnetising igniting plasmas on the National Ignition Facility (*Chittenden*) and the Richtmyer-Meshkov instability in the warm-dense matter using the ESRF synchrotron (*Bland*).

The group hosts the **Centre for Inertial Fusion Studies** (*Rose*, *Chittenden*) providing leadership in engaging UK universities with AWE and US national laboratories in ICF and HEDP (£3.1M). We are part of the **STFC John Adams Institute** (with Oxford and RHUL, £2.1M), leading work (*Najmudin*, *Mangles*) on laser acceleration to advance fundamental science (ERC grant, £1.4M), medical hadron therapy and advanced light sources A new major project (*Smith,* with QOLS) on the development and exploitation of **new ultra-high brightness mid-IR light sources** with applications in particle acceleration, high-field physics and fundamental optical science. Strong collaborations (*Chittenden*, *Bland*, *Smith*) have been developed with a UK company, First Light Fusion, which developed a 10MA pulsed power facility, the biggest in Europe, providing PhD studentships (6). In a cross-disciplinary success story, the group's MHD simulation code has been

adapted to simulate solar-terrestrial interaction (*Chittenden, Eastwood* (SPAT)) ensuring the UK has strategic independence in real-time space weather prediction capability.

We will continue to lead on the development of ICF and HEDP studies; grow the pioneering role in pulsed power facilities for laboratory astrophysics; strengthen our work in fundamental studies at the crossover between plasma physics, material science, astrophysics and nuclear physics; and consolidate our position as world leaders in laser driven particle acceleration.

***Space & Atmospheric Physics (17.9FTE, 89 grants, total £33.9M)***
In Space Physics we continue successful exploitation (supported by STFC Consolidated Grants - £4M) of **magnetometry** space mission involvement. Recent successes include ESA's **Rosetta cometary mission** (2016) which discovered auroral emissions, in the far ultraviolet, demonstrating their relevance for space weather application (*Galand*) and the 2017 finale of NASA's **Cassini mission to Saturn**, confirming the surprising lack of dipole tilt at Saturn (*Dougherty,* £1.43M). Upcoming mission involvement includes ESA's **Solar Orbiter** (*Horbury,* £2M), **JUICE** (*Dougherty*, £4.96M) and Comet Interceptor (*Galand*). Two new appointments (*Masters*, *Matteini*) are associated with this success. **Novel miniature magnetometer development** has led to selection for an ESA space weather mission RADCUBE. Recent ventures include work in magnetospheric modelling and simulation with PLAS for space science and operational use by the Met Office for extreme space weather events. Space is now seen as a critical national infrastructure. Through Imperial's **SpaceLab** (dir. *Eastwood*), we have collaborated with the Institute for Space Policy and Law, on a report on UK Space Safety policy recently delivered to UK Government and other key stakeholders.

Evidence-based policy is also important in the Atmospheric Physics section where we have inter-disciplinary expertise in Climate science, Carbon Cycle, Atmospheric Composition and Earth Observation from space. We provided evidence for the report impacting the first National Strategy for the Adaptation to Climate Change introduced by the Government of Cyprus (B9-8, *Voulgarakis*). We founded (with Life Sciences) the Leverhulme **Centre for Wildfires, Environment and Society** (*Voulgarakis*, £0.6M) and lead (*Brindley*) ESA's **FORUM mission** (£0.5M). *Graven* continues to expand work in **greenhouse gas emission detection** and attribution and ocean heat uptake (ERC funds, £1.75M), as well as influence and inform the climate change policy (see B9-4, *Graven*). Building on **Grantham Institute** support, we steer the agenda worldwide via the US CLIVAR working group (*Czaja*) on "Frontal-Scale Ocean-Atmosphere Interactions and Influence on Large-Scale Climate", and have strengthened our fundamental climate research, appointing in Climate Sensitivity (*Ceppi*).

Our future strategic aims include: exploitation of our scientific leadership in Solar Orbiter and development of science for JUICE; deepen our work on societal impacts and prediction of space weather; and lead FORUM. With the GI: enhance greenhouse gas detection and attribution; pursue ocean-atmosphere connection; and strengthen fundamental climate research.

Two groups are closely linked via the **Condensed Matter Physics** theme**:**

***Condensed Matter Theory (6.85FTE, 31 grants, total £5.1M)***
**Plasmonics and metamaterials** (*Pendry* & *Hess*) remains a high-profile area following the invention of metamaterials and transformation optics (*Pendry*). With more than 70 patents, *Pendry's* innovative discoveries underpin many spin-off products commercialised in the optical, medical, aerospace, and communication industries, with revenues at the multibillion-dollar level (see B9-9, *Pendry*). Interdisciplinary ground-breaking work (*Hess*) created, for the first time, single-molecule strong coupling in ambient conditions, paving the way for photonic quantum technologies at room temperature and quantum immunoassay sensing. In strongly correlated materials, our research was much enhanced by the strategic hiring of *Knolle,* with leading theoretical work on quantum magnetism and collaborations with Manchester experimental groups, and initiation of a new area of simulating correlated materials with newly available quantum computers (grants of £2.5M, with QOLS, Materials and Computing).

**CMTH** was pivotal for the **Thomas Young Centre** (TYC) (*Sutton*, *Mostofi*), a prime example of interdisciplinary collaboration, and nationally leads the UK's Materials and Molecular Modelling Hub. We will develop and extend our expansion into condensed matter theory for quantum technologies in line with the strategic research direction of Quantum Simulation/Computation and Quantum Materials (EPSRC). A collaboration established with DeepMind Ltd (*Foulkes*), uses neural networks to learn the wavefunctions of systems of many interacting electrons. This interdisciplinary work, linking physics with computer science and machine learning, develops new techniques that will advance the fields of quantum chemistry and physics. It also led to the development of ONETEP software which is used in the simulation of the properties of materials and molecular systems, with commercial sales exceeding $6M and widely used in the semiconductor and biomedical industries (B9-5, *Mostofi*). We are well positioned with a globally competitive team in the expanding topics of time-dependent metamaterials and topological materials (*Hess*, *Knolle, Lee, Mostofi, Pendry, Vvedensky*). The **CDT in Theory & Simulations of Materials** (TSM) (dir. *Mostofi*, £4.4M) has created a new generation of scientists in materials physics spanning traditional disciplinary boundaries.

Our future strategic aims include: expanding theoretical condensed matter physics into quantum technologies simulation and materials; exploring machine and deep learning of wavefunctions; and enhancing investigations into time-dependent metamaterials and topological materials.

***Experimental Solid State Physics (13.2FTE, 110 grants, total £26.2M)***
The group has strengthened and broadened its research profile through strategic hiring (*Sapienza, Connolly*) and attracting high calibre research fellows (*Frost*). Our world-leading activities in structure-activity relationships in **solution processable solar cells** (*Nelson, Kim (J-S)*) has been amplified by new staff working on **perovskite photovoltaics** (*Barnes, Frost*) and **photocatalytic hydrogen evolution** from water (*Guilbert*) (£13M). The already internationally established group in **plasmonics** and **nonlinear nanophotonics**, driving light matter interactions with sub-picovolume sensitivity and at the single photon limit (*Maier, Oulton, Phillips*) has been enhanced by new staff (*Sapienza*) with grants of £7.7M.

A common theme in our future strategy is development of neuromorphic computing hardware building on strengths in **nanomagnetism** (*Branford, Cohen*), perovskites (*Barnes, Kim(J-S)*), and nano/random lasing (*Oulton, Sapienza*) (£0.7M). A second strand is work at the interface with life sciences building on unique IR **bio-imaging** (*Phillips*) and complemented by innovation in device materials and design in electrochemical biosensing (*Kim(J-S), Campbell*) (£0.7M). Work on **quantum optics** highlighted by single photon source sculpting with dielectrics (*Maier, Sapienza*) is strengthened by activities linking to the Quantum imaging hub on correlated photonics for bioimaging (*Phillips, Oulton*) (£3.7M). Our new staff member (*Connolly*) brings new strengths in ultralow temperature capability with £1.7M new capital investment, complementing established magnetism/superconductivity activities and a new direction in device design and characterization in topological and superconducting/ semiconducting **Qubits** (£0.6M). Research into greenhouse gas mitigation via low carbon energy solar-cell technologies has led to our development of models of community-scaled electrical power systems, impacting refugee communities in Africa where in collaboration with industry and refugee organisations this has led to the installation of solar powered minigrids (B9-7, *Nelson*).

Our future strategic aims include: furthering development, from fundamentals to application, of energy efficient solution processable photovoltaics; energy conversion and storage; hybrid optoelectronics; plasmonics; bioimaging; nanomagnetism; topological qubits; and the underpinning materials physics.

Two groups collaborate in the **Photon Science** theme:

***Photonics (13FTE, 56 grants, total £10.2M)***
Activities span laser and fibre laser technology, fundamental electromagnetic theory and imaging science and biophotonics. Our **biophotonics** work has extensive interaction at the life sciences and medical interface (*Dunsby*, joint with Medicine), with developments enabling translation to in-

vivo imaging and clinical diagnosis and leveraging our expertise in photonics technology to create new tools for molecular cell biology and drug discovery. Collaborating with industrial partners, clinicians and scientists across Imperial, UK Institutes (*French*, Crick Institute, ICR, CRUK Edinburgh) and internationally, has enabled us to secure key funding (£5.8M) from a wide range of sources (including CRUK, EPSRC, BBSRC, BHF). We lead (*French*) an exciting new, collaborative multi-discipline flagship project (CRUK, EU partners, £2.7M) to improve imaging technologies for cancer drug discovery as part of a new CRUK Convergence Science Centre.

Two new appointments were made (*Murray, Runcorn*) to maintain excellence in **fibre laser research** (*Taylor*). Developments in ultrafast laser technology have realised unique, all-fibre-integrated picosecond and femtosecond pulse sources in the visible spectrum. In collaboration with commercial company (Gooch and Housego), supported by EPSRC (£0.5M); the temporally and spectrally versatile compact systems have been applied to FLIM and STED microscopy, and are widely applicable in other imaging platforms. Research on developing **lasers for satellite-based remote sensing** has flourished (ESA, £0.8M), we are sole developers of a wavelength tuneable diode-pumped Alexandrite laser with world-record performance (including record pulse energy, efficiency, and wavelength tuning range). Operating in the “red-edge” band of vegetation (700-750nm) and enabling remote sensing of vegetation and the atmosphere with industrial partners (Cosine BV), opens the way to single-photon counting vegetation lidar.

Photonic devices underpin diverse industries. Our fully fibre integrated supercontinuum source has been exploited in combination with gated image intensifiers in fluorescence lifetime imaging configurations, commercially developed in collaboration with two UK companies (NKT, Kentech) generating >£12M income (B9-3, *French*).

Future strategy will build on: vibrant biophotonics activities to develop techniques with improved resolution and contrast; grow applied research activities and resources in lasers and optical technologies for satellite-based lidar and other industrial applications; and establish new opportunities and potential for growth in nanoscale photonics.

***Quantum Optics & Laser Science (16.3FTE, 73 grants, total £39.6M)***
Our portfolio has grown and diversified in response to a rapidly changing landscape, stimulated by UK National Quantum Technologies Programme (with major roles (*Knight, Walmsley, Kim(M)*, *Hinds*) and progress in x-ray free electron lasers (XFELS). There are four overarching activities, which we describe in turn.

In **Quantum Photonics and Measurement**, two strategic appointments (*Vanner and Kolthammer*) and targeted investment to provide state-of-the-art laboratories (£1.5M) has provided opportunities for rapid growth. Investment (£1.6M, EPSRC) in a dilution refrigerator facility was further strengthened by *Walmsley*’*s* move from Oxford. Our portfolio has grown and diversified in response to a rapidly changing landscape, stimulated by the UK National Quantum Technologies Programme (funding >£1B) with leadership from *Knight*, *Kim(M)*, *Hinds, Walmsley* (B9-6, *Knight*). Employing photonic architectures, we developed and using fusion gates based on silicon photonics, has led to venture capital investment (>$250M) in the company PsiQuantum, with 10% of employees Imperial alumni, to develop a quantum computer (B9-1, *Rudolph*).

Activity in **Quantum Theory** (*Kim(M), Mintert*) continues to pursue fundamental research and support experimental activities, as part of EPSRC’s Quantum Hub in computing and simulation (£1.5M, *Kim(M), Walmsley*). Successful international collaborations have been developed, securing industry funding (£1.6M Samsung, *Kim(M)*). The **Centre for Cold Matter** (*Sauer, Tarbutt*) remains at the vanguard of AMO physics at low temperatures, activities have broadened to include ultracold molecules (and atoms) achieving world-record cooling of molecules (5μK) (EPSRC awards £4.8M). New activities in quantum nanophotonics with organic molecules (*Clark*, RSURF) have links to EXSS. Table-top tests of fundamental physics (*Fitch*, RSURF) address questions in high energy physics and cosmology. Investment in laboratory refurbishment enabled a major new programme on atom interferometry for inertial navigation (*Tarbutt, Cotter*) with funding from DSTL UK (£3.9M), Innovate UK (£200k with M-Squared lasers) and the EPSRC Quantum Hub in

Sensing and Timing (£1.5M, *Hinds*). Together with M-Squared we have established an industrial development lab where we translate our research into high-TRL technologies for commercialisation.

The **Extreme Light Consortium** (*Marangos*, *Tisch*) has broadened to cover coherent light of extreme properties (attoseconds, X-rays, ultrahigh intensity) from traditional lasers, but also from the new generation of XFELS which have seen rapid global development. Staff (*Marangos*, *Frasinski*) have been involved/lead in 10 XFEL beamtimes (LCLS, Fermi, Sacla, Soleil). The strategic decision to pursue mid-IR laser development and their use in light-matter interactions has enabled participation in a large US-led MURI project (£4.6M, *Marangos* with PLAS) leading to world-record coherent x-ray generation in the important "water-window" (*Marangos, Tisch*). A new area is mass-spectrometry of proteins and other biomolecules (*Averbukh*) growing from co-variance methods initially developed to study light-matter interactions (*Frasinski*), to uncover correlations between different molecular fragments. A new appointment (*Matthews*) has strengthened the group's activities in solid-state laser-matter interactions (with EXSS). State-of-the-art laser technology for temporally compressing femtosecond laser pulses was developed (*Tisch*) and transferred to more than 20 international laser laboratories.

Our strategic aims include: expansion in quantum computation, simulation and metrology; apply ultrafast laser technology and attosecond techniques to new applications; use interferometry with cold atoms and molecules to develop commercial quantum devices and test fundamental physics (e.g. AION); and continue to champion new science from XFELs.

**Physics Leadership in Imperial's Multi-disciplinary Research**

Our many collaborations are the lifeblood of our research ethos. We hold grants jointly with all departments in the Faculty of Natural Sciences (FoNS) and all faculties at Imperial. We enable and promote interdisciplinary work through college-wide Global Challenge Institutes and Centres of Excellence (see REF5a) across FoNS (with *French* being Vice-Dean for Research) and the Faculties of Engineering and Medicine. We are at the heart of the College's Quantitative capability, with *Eastwood* being the Theme Champion of the FoNS strategic research theme Quantitative Technologies, which pulls together instrumentation research which underpins our scientific endeavours. Physics staff have more than 180 affiliations with 25 of the 56 Centres and Networks at Imperial.

The College set up 7 Global Institutes to address some of the most important challenges facing the world today from health inequalities and action on climate change, to molecular engineering and cyber security. These Institutes bring together researchers, policymakers, and businesses to provide independent scientific advice. Physics staff are active in 5 of these with a lead role in the **Grantham Institute** (GI), which was established in 2007 (*Knight*) to focus on climate, thanks to a Grantham Foundation donation (£12.8M). Expanded in 2014 to include broader environmental issues (support increased to £24.1M), Physics staff play central roles (co-Directors: *Haigh* 2014-2019, *Toumi* 2020-) in driving College's activities in this area. GI is a gateway into inter-disciplinary research and an important avenue to impact through policy and guidance to Government (see B9-2, *van Sebille* and B9-8, *Voulgarakis*). A recent policy success (*Haigh*) is the UK's commitment (June 2019) to net zero carbon emissions by 2050. We have influenced new UK and EU plastic pollution policy with a RS Summer Science Exhibition and gave evidence to parliament (*van Sebille*). This evidence and expert witness together with quantification of the scale, extent, and dynamics of marine plastic pollution (see B9-2, *van Sebille*) led to the UK government ban on micro-beads and single use plastics. Six staff are formally affiliated with the GI via joint appointments (*Haigh*, *Toumi, Nelson, Ceppi*, *van Sebille*, *Graven*). Our NERC funded DTP and the GI has funded 15 Physics PhDs. We will continue to engage with the GI, focusing on climate change adaptation.

In this REF period staff have developed and led three new college-wide Centres/Networks:

- CCAP (Centre for Clinical Applications of Particles, Dir: *Long*) with members spanning fundamental physics to clinicians, from Physics, Faculty of Medicine, Imperial Academic Health Centre, Imperial CRUK Cancer Centre, Institute for Cancer Research and Oxford Institute for Radiation Oncology.
- QuEST (Centre for Quantum Engineering, Science and Technology, Dir: *Kim(M),* (6 Departments) has provided a natural channel for collaboration with Samsung (£1.6M).
- SpaceLab (Network of Excellence, Dir: *Eastwood*,14 Departments) collaborates with London Institute of Space Policy and Law contributing to evidence-based policy for space safety.

Centres established earlier continue to achieve:

- Centre for Processable Electronics (CPE), (4 Departments, *Kim(J-S), Nelson*) provides the conduit for $1M grant from South Korea.
- Centre for Plasmonics and Metamaterials (CPM), (Dir: *Sapienza*, 3 Departments) recently contributed to £2.5M EPSRC Programme Grant (PI, *Craster,* Mathematics).
- ICIC (Dir: *Heavens*, 2 Departments) has led to pioneering work in Bayesian analysis of cosmic shear.
- TYC (co-Dir: *Mostofi*, 8 Departments and 3 London colleges) leads UK's national Materials and Molecular Modelling Hub (£4.5M).

**Effective Cross-Disciplinary Research**

The Department maintains cross-departmental research appointments both internally with Materials (*Finnis, Haynes, Mostofi, Tangney*), Mathematics (*Mortlock*), and Medicine (*Dunsby*), and externally with RAL (*Long, Paternak, Pozimski*), as well as hosting 28 Case studentships, including with RAL, AWE, and NPL. We retain connections with Physics alumni in the form of visiting academic status/joint positions in the UK or overseas (Berlin, Munich, Crete).

The Faculty Research Strategy team supports the development and coordination of research strategy, particularly for multidisciplinary science, through a range of activities, including discussions of national, grand, and societal challenges in science, aiming to generate 'Big Ideas', theme champions (e.g. *Eastwood* for Quantitative Technologies), workshops designed to bring researchers together from diverse groups. The team also engages with funders via the College Research Office, allocating devolved funding and providing seed funding for multidisciplinary research and interactions with SME and other external stakeholders. The focus on interdisciplinary research has been manifest in the success of Physics staff with innovative schemes such as the Leverhulme Centre for Wildfires, Environment and Society, DUNE, MURI, and AION.

In addition to direct industrial collaboration, we encourage engagement with other departments, including Medicine, Life Sciences, Environmental Science, Materials, and Bioengineering, to further enhance our understanding of the relationship between cross-disciplinary research and transformative scientific outcomes. We host workshops accessible to researchers from various disciplines, for example the Physics of Life Network which uses biological physics to gain insights into fundamental biological problems for future (bio)technology, biomedicine, climate protection, food security, and national defence. The Department is also a regular contributor to the AI Network and encourages staff to participate in the centrally organised "Fast Track Impact" workshop, an international training programme for researchers.

Successful inter-group collaboration within the Department has been developed by *Chittenden* promoting wider use of MHD simulation tools for modelling laboratory fusion plasmas. *Eastwood* adapted these for the study of planetary magnetospheres, building a new UK capability for real-time space weather prediction. This led to a successful bid to UKRI Strategic Priorities Fund that seeded successful collaboration with the Met Office, and further interdisciplinary impact through joint work with the British Antarctic Survey and British Geological Survey (£0.6M).

**Impact Strategy**

We believe in, and are committed to, delivering on the importance of the impact of our diverse research portfolio; from scientific discoveries and their impact on society and technological development leading to commercialisation and input into government policymaking. Our 9 impact case studies reflect this diversity and emphasise delivering positive outcomes in healthcare, the environment, and the economy.

- The discovery of theoretical photonic architectures (B9-1, *Rudolph*) has resulted in the formation and commercial investment in a quantum computing company.
- The quantification of the scale and dynamics of marine plastic pollution (B9-2, *van Sebille*) led to the UK ban on micro-beads and single use plastics (along with the EU).
- Commercial impact has resulted from fluorescence lifetime imaging technology (B9-3, *French*).
- Informing and influencing policy arose from validation of $CO_2$ emissions which have informed climate change mitigation (B9-4, *Graven*).
- Commercial impact has resulted from the ONETEP materials modelling software (B9-5, *Mostofi*).
- Fundamental quantum optics research has directly influenced UK Government policy and investment (B9-6, *Knight*).
- Solar minigrids for productive energy are being used in a Rwandan refugee camp (B9-7, *Nelson*).
- Climate change risk assessment (B9-8, *Voulgarakis*) directly informed the Cyprus Government.
- The original invention of metamaterials (B9-9, *Pendry*) has led to new industrial markets (optical, medical, aerospace, military and communications) as well as commercial exploitation in these areas (with over 70 patents).

Planning for impact is considered at all levels, from focused group interactions, to coordination and direction-setting by the Department's Research Committee, to intellectual property and entrepreneurship via Imperial's Industry Partnership and Commercialisation team (see REF5a). Our impact strategy adapts to requirements, spans multi-disciplinary projects, engages with specific partners (companies, government agencies and charities), and enables patenting and licensing of technologies across whole industrial sectors. During the REF2021 period, there were 75 IP Disclosures and 20 Patents filed, 3 are published and 6 are pending.

Our strategy's success is reflected in our partnerships with international agencies such as CERN and ESA, and government agencies such as AWE, DSTL, RAL and NPL, charitable foundations such as Leverhulme, Royce, Sloan, and the Wellcome Trust, as well as conventional industries such as Samsung, and NKT Photonics.

**Industry**: We have appointed an Industry Engagement (Enterprise) Champion (*Oulton*) to foster closer engagement with industry and develop strong strategic alliances as our research income from industry continues to grow. *Oulton* acts as the conduit for interaction across all-levels and manages the Departmental Impact Acceleration Programme. The Department won £2.4M from the BBSRC, EPSRC, NERC and STFC impact acceleration awards devolved to Imperial to support business engagement and knowledge exchange and to accelerate the commercialisation and impact of our research, including 16 EPSRC Knowledge Transfer Secondments. A collaboration with Samsung has led to an investment of £1.6M in our quantum computing, recognising the expertise available at QuEST.

**Consultancies & Directorships:** Over 30% of our staff are engaged in commercialisation and consultancy. The establishment and management of external consultancies are facilitated by Imperial Consultants (ICON) which, during the REF2021 period, supported 35 members of staff on 116 projects with 82 companies with an estimated value of £3.2M. A further 8 company directorships and 7 commercial deals were established independently of ICON. Until 2020, our research commercialisation was advanced through Imperial Innovations, a publicly listed venture

capital investor that focuses on technology, and Faculty Industry Partnership and Commercialisation. Since then, College has separated from Innovations and taken this function in-house.

**Research Integrity**

As a signatory of the Concordat to Support Research Integrity, College is committed to "maintaining the highest standards of rigour and integrity in all aspects of research" (see REF5a). Principles of Universal Ethical Code for Scientists are adopted, ensuring research is conducted according to appropriate ethical, legal, and professional standards, and robust processes to deal with allegations of research misconduct are in place. The Department actively promotes training opportunities to research staff and students in areas including research integrity and online plagiarism. College is committed to sharing its world-class research and scholarship as widely as possible, supporting the principles of open access to research. Spiral is the College's free open access research repository and holds over 68,000 items, with authors uploading journal articles, monographs, or research not intended for journal publication. There is an Open Access Fund to pay the open access publication costs for articles in fully open access journals.

**2. People**

**Staffing Strategy and Employee Development**

We attract and retain staff of the highest international calibre and provide them with support and training to develop their skillsets and careers. We are continually injecting new ideas and vigour into the Department through our strategy, with 18 new academic appointments during the REF period (14 Lecturers, 3 Readers, 1 Professor).

**Academic Recruitment:** Our recruitment strategy is driven by a combination of group/theme ambitions, staffing profile and interdisciplinary research opportunities. Our Strategy Committee considers these factors in recommending new appointments to the HoD.

Advertisements for posts are framed broadly to attract applicants from a wide talent pool. We form search committees to target the best candidates from across cultures and circumstances. We continually strive to increase diversity of our staff (gender, race, religion or belief, disability, and sexual orientation with support from the Juno Committee (JUNO-C, see EDI). Each proposed interview shortlist is submitted with a Search Committee Report for approval by the HoD.

In 2015, we initiated new hiring procedures to expand the pool of female candidates, with a revised policy reflecting JUNO-C activities and College's diversity policies. This resulted in interview pools with more gender-balanced representation (the number of women on shortlists increased from 12% to 27%).

**Development and Support for Early Career Researchers (ECRs)**

**New academic staff**: New lecturers benefit from 50% reduced teaching load in year 1 and 25% reduction in year 2. They benefit from start-up funds, relocation expenses and preferential access to PhD students. Newly appointed lecturers are guided though their three-year probation period by academic mentors (a senior staff member in their research area) to review progress in teaching, training, and research grant applications. For a broader perspective, probationary lecturers are also appointed teaching buddies to provide constructive feedback on teaching performance, as well as independent mentors from outside their research areas who offer mentoring on all career aspects. New lecturers are expected to complete a Learning and Teaching programme within the first two years of appointment.

**Development Support:** The Postdoc and Fellows Development Centre (PFDC) has provided support to research staff since 2009 and offers multiple opportunities, including bespoke courses, funder showcases, one-to-one support and mock interviews, developing their skills, and applying them in the workplace. ECRs have 10 days of skills training per year written into their contracts to

ensure access to these services. Most provisions provided by the PFDC are delivered face-to-face, however, since COVID-19, this support programme is online. Furthermore, staff with contracts ending between March-December 2020 had their access to PFDC services extended for 3 months (12 staff). During the REF2021 period, our ECRs received 132 one-to-one meetings, 72 mock interviews and 137 courses, including residential courses, were attended.

**Research Fellows** benefit from all the support mentioned above, including a tailored programme provided by the PFDC. During the REF2021 period, 11 existing researchers transitioned to Independent Fellowships in the Department: (*Clark, Fitch, Guilbert, Kelleher, Kerridge-Johns, Malik, Masters, Matthews, Murray, Rakovich, Suzuki Vidal*), with 3 progressing from their first to their second (*Chapman, Chen*, *Gryspeerdt)*. We welcomed back researchers with Independent Fellowships (*Frost, Hietala, Wardle*), and saw previous researchers/fellows appointed to the staff (*McCann, Matteini, Barnes, Giannini*, *Patel, Scott(P)*). Four Fellows (*Masters, Matthews, Murray, Owen)* were appointed to proleptic positions.

**Postdoctoral Research Associates:** We are dedicated to supporting our fixed-term research staff members through implementing the Concordat principles. We offer research staff career advice and support through direct mentoring, including the annual Personal Review and Development Plan (PRDP), the College PFDC, and the RA Committee founded in 2009 to enhance RAs professional experience and career development. The RA Committee offers a comprehensive discussion forum to distribute information and identify training needs for RAs, hosting regular social events, organising meetings on topics relevant to their career stage with reps engaging in Group meetings. The chair meets monthly with the HoD, and is a member of JUNO-C, providing a direct link from RAs to the Department's EDI and wellbeing efforts.

During the REF2021 period, more than 430 RAs completed their post in the Department and 91 competitively awarded Fellowships began: 15 RS URF, 3 STFC ERF, 1 RS DH, 1 NERC, 5 RS Newton, 1 RAEng, 1 RAS, 1 RSEdinburgh/STFC Enterprise, 1 EPSRC PDF, 22 CEC MSCA, 21 EPSRC Doctoral Prize Fellowships, and 19 Imperial Research Fellowships (£20M, with £3.2M additional PI funding). We will welcome 11 new Fellowship holders this year.

**General Professional Support**

The College is dedicated to the ongoing support and development of all its research staff (see REF5a).

**Training**: College offers a wide range of training and development opportunities for all staff, irrespective of working hours or contract type. The Learning and Development Centre (LDC) offers various training courses to enable staff to learn skills relevant to their current role or to advance their career. During the REF2021 period, academic staff attended 191 courses and researchers attended 134. The Leadership and Management courses are particularly beneficial for staff looking to further their academic careers.

**PRDPs:** The Department supports staff in meeting the needs and goals identified in their Personal Review and Development Plan (PRDP). All staff are expected to undertake an annual PRDP with an appraiser (usually their line manager). This exercise is designed to help staff realise their goals within a confidential environment. Following advice from JUNO-C, the PRDP form was redesigned in 2014 to emphasize defining future goals instead of focusing on past achievements. A further iteration (2019) added a new, separate section allowing direct feedback to the HoD (e.g. personal achievements, improving department processes etc.).

**Promotions:** Promotions and suitable development opportunities are typically discussed at PRDP meetings with the individual's line manager or Head of Group (HoG). All academic staff are also invited annually to submit a 2-page summary of their achievements to the HoD, including a request to be considered for promotion. HoGs proactively support academic colleagues to work towards promotion and to prepare their application when staff are ready. Recommendations for promotion to Professor level are discussed at a meeting with all professors where supported cases are then

considered by the Wisepeople panel (comprised of senior staff members). Recommendations for promotion to Senior Lecturer (SL) and Reader (R) are discussed at a closed HoGs meeting with supported cases considered by the SL/R panel. Both panels assess the promotion cases and provide constructive feedback. The HoG reports back to each staff member on whether their promotion is supported or how their case can be strengthened in the future. During the REF2021 period, 68 staff were nominated for promotion and 100% of these were successful: 22 L-SL, 27 SL-R, 1 L-R and 18 R-P. In 2019, a new salary structure was introduced for the Research job family with the addition of an Advanced Research Fellow grade to recognise research independence. Two researchers have since been promoted to ARF.

**Personal Support**

College provides a supportive and inclusive environment for all staff, so that they may do their best work. Policies are designed (e.g. flexible working, support for working parents) to support a positive work-life balance, promote welfare and good mental health. The Department is fully committed to ensuring a positive work experience, well balanced with personal life and wellbeing (see REF5a).

**Staff with Children:** The Elsie Widdowson Fellowship Award provides funding for 50% of salary costs for 12 months to relieve the returning academic of any teaching or administration duties. Two staff benefited from this during the REF2021 period.

**Sabbaticals:** Our scheme enables staff to continue their professional development and enhance their knowledge and connections. During the REF2021 period, 20 sabbaticals have been awarded, including: Taking leadership roles in major collaborations (*Buchmueller*, Convener of EXOTICA search Group, CERN); Strengthening international links as projects grow (*Araujo*, engaging a large UK team in the international LZ Project); and initiating collaborations in new areas, (e.g. with DeepMind Ltd on Machine learning, *Foulkes*).

**Academic Fellowships:** During REF 2021, 17 staff received support to hold fellowships: 2 RS Professorships (*Dougherty, Hinds*); 1 RS Industry Fellowship (*Ekins-Daukes*); 2 FLFs (*Scott(M), Vanner*); 5 Leverhulme Research Fellowships (*Schwartz, Magueijo, Jaffe, Rudolph, Warren*); 3 Leverhulme Emeritus Fellowships (*Duff, Leader, Sumner*); 1 Leverhulme Trust Senior Research Fellowship (*Hull*); 1 STFC Public Engagement Fellowship (*Trotta*); and 2 new appointments brought Fellowships with them 1 EPSRC CAF (*Connolly*) and 1 STFC ERF (*Vacheret*).

**Research Students**

**Postgraduate Research (PGR) Students:** Our strong research activities provide an excellent training ground for the next generation of researchers and innovators through our doctoral programme. We attract outstanding students from the UK and internationally. During the REF2021 period, 421 students enrolled, with almost three quarters of them holding a UG first or PG distinction, emphasising the quality of our applicant pool. Admission is very competitive, with 3339 applications, of which woman are 20% of applicants and 18% of enrolments.

**Training and Development:** We have a comprehensive monitoring and support system for PGR students. At three months, student and supervisor prepare an initial research plan setting out the PhD goals. The Early Stage Review (ESR) at nine months is followed by a Late Stage Assessment (LSA) at 18 months. These assessments, via written reports and oral viva, are key steps in which the student demonstrates knowledge of their field and ability to perform research. The ESR includes a literature review, helping the student reflect, placing their work into context, practicing scientific writing, and to experience a viva-like situation. A further review occurs at 24 months (and 36 and 42 if necessary) to ensure their thesis is on track. This system is highly effective, with over 90% of students completing within 48 months.

**Imperial College's Graduate School** provides professional training via online courses, seminars, and residential courses. All students are required to attend a minimum number of these courses

for e.g. Research Impact, Research Integrity and Ethics, Societal Engagement, and Computing Skills. During the REF2021 period, over 1500 places on 155 courses were taken up by our students and training must be completed by the LSA. This training also provides an excellent opportunity for students to network and collaborate with students from different departments and faculties. Over the same period, 41 Physics staff completed the Educational Development Unit (EDU) training course "Introduction to PhD Supervision".

**Support:** We have multiple layers of mentoring and wellbeing support, with PGR students either assigned a co-supervisor or an independent academic advisor. Each research group has a dedicated welfare mentor, which is overseen by our senior PG tutor and a disabilities officer. To maintain and enhance engagement, we hold Staff and Student Committee meetings to consult on student matters and share information collectively.

Our PGR students are supported from a variety of sources. The largest is via UKRI, which funds 77% of our studentships. Imperial College devotes significant internal resources towards PGR studentships, with 9% having fee waivers. This support aids diversity, since UKRI funding shows preference for home students. Physics students have won 44 President's Scholarships over the REF2021 period, and we host more than 10% of the President's Scholars.

**Awards:** Our postgraduate students have won numerous awards for contributions at conferences (e.g. Complexity Science, BritGrave). This demonstrates the high level of research achieved and the effectiveness of our training in presentation skills. Nineteen students have won EPSRC Doctoral Prize Fellowships and 5 students an STFC student enhancement programme award.

**Equality, Diversity and Inclusion (EDI)**

We are committed to improving EDI and taking active steps to ensure individuals are treated equally and have access to the same opportunities. The Department has two advocates (*Chapman*, *Richards*) on the College EDI Forum which serves as a listening platform to capture and discuss EDI (see REF5a). Our "**Have Your Say**" hotline provides a safe and confidential route for staff to speak anonymously about issues of concern.

**JUNO-C:** The Departmental Juno Transparency and Opportunity Committee was set up in 2007 to address the under representation of women and minorities, e.g. founding our Networking for Female Researchers and implementing new recruitment guidelines. JUNO-C supports the implementation of the Institute of Physics' Juno Code of Practice and is also guided by the Athena Swan Charter. We hold Juno Practitioner status (2020) and the Athena Silver Swan award (since 2009, renewed in 2012, 2015 and 2019). JUNO-C has 21 members (12 female, 9 male) with representation drawn from across the Department and College. The HoD and HoGs have endorsed an ongoing action plan to remain committed to the inclusion of underrepresented minorities.

**EDI within Recruitment**: Staff involved with the recruitment and selection process undertake a recruitment and selection training course, as well as attending unconscious bias training to ensure an unbiased and inclusive recruitment process. Upon the recommendation of JUNO-C, all job adverts now include the statement "*The Department of Physics is an IoP Juno Practitioner and an Athena Silver SWAN Award winner reflecting our commitment to building a supportive, inclusive and highly motivated community*".

It has become mandatory for all staff to attend an unconscious bias training workshop (provided by an external provider) that focuses on increasing self-awareness and identifying actions to foster equal opportunity and tackle all forms of discrimination. The success of this effort led to College launching its own unconscious bias training course, now offered to all new undergraduate and postgraduate students.

We offer an LGBT+ Awareness course to ensure staff understand intersectionality and what it means to be an effective ally to the LGBTQ+ community. Since 2018, we host the LGBT+ Allies Network consisting of trained members to provide support and offer advice for related issues.

**EDI and REF:** Each staff member was invited to submit up to six outputs, and output selection was based principally on quality assessments made by internal and in some cases external reviewers. Attributed authors were anonymised and papers treated on an equal basis. A panel of nine staff members with representatives from all research groups made the final selection. The average number of outputs selected per FTE was 2.56 for women and 2.49 for men. All HoGs identified potential impact cases, and 31 members of staff were interviewed, with 9 cases selected based on maturity, potential for development within 24 months, and supporting evidence (2 cases are led by women).

**3. Income, infrastructure and facilities**

Our research funding and investment strategy is underpinned by the Research Committee whose purpose is to discuss research strategies, identify new opportunities to extend and diversify our portfolio of funders and enhance our research dedicated infrastructure.

**Research Income**

The Co-Directors of Research present potential funding opportunities to the Committee and these are actively discussed and communicated to all staff. Recent examples have included opportunities arising through the Air Force Office of Scientific Research and mechanisms for engaging with US research foundations. This results in research income that is >£25M annually.

The Committee hosts workshops to discuss and plan new major research activities. A recent workshop in “Artificial Intelligence in Physics” led to the development of an AI forum to explore cross-physics project opportunities. The Committee also supports staff in all aspects of the application process for funding proposals by coordinating expert and non-expert review before submission. In terms of Industrial Engagement, the Co-Directors of Research and the Department’s Industry Engagement Champion liaise with the Industrial Partnership and Commercialisation team to help develop and maintain relationships with major companies such as AWE and Samsung.

**Annual Spend (see REF4):** During the REF2021 period, we maintained an average research spend of £25.5M per year (£24.6M over the last REF). The funding sources (excluding UK government tax credits) were: 68.6% UKRI Research Councils & related bodies; 15.3% EU; 7.9% UK government, Industry and other sources; 4.8% Non-EU; and 3.5% UK-based charities. Compared with the last REF our EU funding has increased (was 8.7%).

**Grants Announced & Awarded (during REF2021 period):** Research grants totalling £196.6M were awarded, made up of 553 new awards from 58 funders. Most of our funding from UKRI was STFC (£69M) and EPSRC (£49.5M) reflecting the fundamental physics base that is core to our activities, as well as funding from other UKRI bodies such as NERC (£3.9M), MRC (£3.5M) and BBSRC (£0.9M) as well as RS (£16.4M). These included 46 large grants (>£1M), with a total value of £101.8M, most notably from: EPSRC Programme Grant Quantum Science with Ultracold Molecules £3.1M (*Tarbutt* co-I, lead Durham); EPSRC Programme Grant Reactive Plasmonics £2.5M (*Maier* co-I, lead KCL); EPSRC mid-infrared laser MURI £4.6M (*Marangos*, *Smith*); STFC projects for CMS upgrade £3.6M (*Davies*); LZ £2.6M (*Araujo*); JUICE build phase £4.1M (*Dougherty*); CEC Marie Curie Innovative Doctoral Programme Frontiers in Quantum Technology (£2.7M) (*Kim(M)*); and DSTL £3.9M Navigation accelerometer (*Hinds*). STFC provides support for fundamental physics research through consolidated grants (renewed twice, total £31M): £4.5M (ASTR), £18.2M (HEPH), £4M (SPAT), £4.3M (THEO).

The ERC supports many crucial research projects and was an important part of increasing European funding. The Co-Directors of Research work in close partnership with College’s

Research Office to help staff identify funding opportunities through the ERC and plan their proposals. During the REF2021 period, staff gained 8 new awards: 3 Standard £3.2M, 2 Consolidator £2.8M, and 3 Advanced £5.4M. Additionally, 3 staff brought ERC awards with them on appointment (value £11.7M).

Other examples of major awards outside usual key funders included: Samsung £1.6M for New Quantum Materials (*Kim(M)*); CRUK Accelerator Award (£2.7M, *French*), Gordon and Betty Moore Foundation £740k (*Pendry*) and £555k (*Tarbutt*); Alfred P. Sloan Foundation £555k (*Tarbutt*); and Templeton Foundation £889k (*Hinds*), £270k (*Magueijo*). Significant funding across several awards came from Leverhulme £3M, US Department of Energy and US National Laboratories £2.7M, and AWE £1.6M.

During the REF period, our philanthropy funding was £2.9M, providing a new source of support for both research and teaching (e.g. studentships and equipment for Fourier Transform Spectroscopy research and teaching laboratory equipment).

Since the last REF, we have successfully diversified our funding profile with the Research Committee and the Department's Industry Engagement Champion support. We will continue to collaborate internationally and target EU, US funding opportunities as part of our diversification strategy. We are dedicated to creating and strengthening industrial connections to increase external funding opportunities.

**Research Infrastructure and Equipment**

The Department occupies 14,840m$^2$ on Imperial's South Kensington Campus, the majority in the Blackett Laboratory. We have 70 laboratories covering an area of 6028m$^2$. Each year, research groups review their infrastructure and facilities, outlining priority areas for future investment. This exercise, combined with internal consultations, provides a complete overview which informs our future capital development plans. Working in consultation with the College's Disability Advisory Service, we ensure that all new and refurbished laboratories and facilities comply with the Disability Discrimination Act. Through building adaptations, our DOM coordinates individual plans to help disabled staff access research facilities and all communal spaces safely.

Our next College approved projects include: upgrading our HEPH digital electronics labs and workshops (210m$^2$, £735k) to maintain leading contributions to the next generation LHC, long-baseline neutrino detectors and AI-on-Chip; the construction of the AION lab (92m$^2$), opening a new research avenue in the search for ultra-light dark matter and gravitational waves (STFC, ~£8.6M funding).

**Investment in Facilities:** During the REF2021 period, building and infrastructure spend totalled £10.3M (£5.9M on research operations, £4.4M on general maintenance). This included investment in new state-of-the-art laboratories identified as key priorities: a new suite of laboratories for quantum science and technologies research (490m$^2$, £3.6M); a quantum inertial navigation laboratory (£484k); a Xenon laboratory which is central to LUX-ZEPLIN and UK dark matter R&D effort (£431k); and an Atmospheric Trace Gas measurement (£71k). In addition to strategic investments, there is ongoing maintenance and upgrade to the laboratories, office accommodation and fabric of the building. This included a £3.4M project to rewire Blackett, £1.1M for the general fabric of the building and £1.1M on projects directly related to the research infrastructure (e.g. laser cooling upgrades, cleanroom fume extract upgrade).

In addition to investment in laboratory space and improving existing facilities, we support new appointments with start-up funds of £377k (£267k towards equipment and £110k for consumables) to ensure staff have access to necessary resources.

We support our experimental groups to secure state-of-the-art equipment, and during the REF2021 period, spent £2.2M on equipment (over that funded by grants), including contributions of £300k from EPSRC's Strategic Equipment Process.

To support our research students, part of the Campus Library Building underwent an extensive £5M reconfiguration (432m$^2$) to provide accommodation for the EPSRC Centres for Doctoral Training (CDTs) which began in 2014. The Centres span the Faculties of Engineering, Natural Sciences and Medicine, occupying a total area of 432m$^2$ of which 58m$^2$ was for Physics led CDTs - Controlled Quantum Dynamics, Plastic Electronics and TSM.

**Specialist Equipment and Facilities:** We currently host three specialist facilities that we charge out:

- The Raith e-line electron beam lithography facility (EXSS) provides sample nanofabrication and inspection by Scanning Electron Microscopy.
- The Glovebox (CPE) contains two thermal evaporators for top electrode evaporation and a spin coater unit for spin coating air and water sensitive small molecule and polymer materials.
- The EXSS Cleanroom performs semiconductor, nanotechnology, and polymer processing.

Examples of other facilities include: two other cleanrooms (ISO 6 and ISO 7) for radiation detector assembly and testing; the Mega Ampere Generator for Plasma Implosion Experiments (MAGPIE) which delivers an electrical current pulse of ~1.4M amperes in ~250 nanoseconds.

The Mechanical Instrumentation Workshop (678m$^2$) houses 15 FTE technicians and is crucial to facilitating our research through the design and manufacture of bespoke scientific apparatus. There are conventional machine tools and modern capabilities such as CNC machining Centres, mill/turn, laser cutting, EDM wire machining, welding, fabrication and 3D printing. We have additional specialist workshops (246m$^2$) in HEPH, PLAS and PHOT. We invested £290K in workshop equipment during the REF2021 period. We continue to play a lead role in the College Technician Apprentice Scheme (4-year programme), training the next generation of technicians with 10 graduates since inception in 2011 and 5 gaining employment within Imperial.

Our specialist electronics workshops (70m$^2$) undertake a range of modern electronic design and manufacture, including ASIC design and wafer-scale testing, specialised PCB manufacture and wire-bonding or bump-bonding of the circuits. We maintain a UK capability to make low-field, science-grade, space-borne fluxgates, and a unique capability for low magnetic field testing at very low cryogenic temperatures.

Since the last REF, we have benefited from three EPSRC Strategic Equipment awards which have enabled us to expand our portfolio of equipment:

- We collaborated with Materials (£2M, 2017) to develop a core SPIN lab to characterize isolated and coupled spins, contributing to our nanomagnetism and photovoltaic work.
- We lead (*Vanner and Connolly*) a collaboration with Chemistry, Materials and Electrical Engineering (£1.7M) to develop a Quantum Science and Device Facility (QSDF) which caters for users interested in performing scanning probe microscopy, transport, circuit quantum electrodynamics, and quantum optics experiments at very low temperatures. Currently being commissioned this will establish a UK-first facility.
- We are collaborating with Chemistry (£2M) to develop a Pulse Electron Paramagnetic Resonance Facility (currently being commissioned) which will be used in molecular electronics, magnetic materials and attosecond science.

**Research Computing Services (RCS):** College continues to invest >£4M annually in RCS, to support the community's diverse computing needs. Physics staff constitute the largest proportion of RCS users (combined usage of 55.8M CPU hours (FEC £372k pa) and 2.5 million jobs). Physics engage strongly with the new Research Software Engineering team on projects such as maintaining public access to the Cassini magnetometer data, porting space weather forecast capabilities to the Met Office Space Weather Operations Centre.

We are members of several national and international computing collaborations, providing one of five large Tier 2 centres for the GridPP Collaboration project, a community of particle physicists

and computer scientists. This supports a system of 11k computer cores and 11PB of disk storage used by scientists at Imperial and worldwide. Through GridPP, Imperial is a member of the Worldwide LHC Computing Grid and hosts one of the largest Tier 2 centres for CMS and LHCb experiments in the world. Part of this centre forms the UK Data Centre for the LZ collaboration and is linked with the US Data Centre providing the processing and analysis requirements for the LZ Dark Matter Experiment throughout Europe. Imperial is also a member of the IRIS collaboration which provides an extensive range of ICT infrastructure to a wide variety of STFC projects; and provides an OpenStack Cloud resource consisting of ~2000 compute cores for IRIS. STFC have provided £5.2M for Grid and Iris hardware and personnel.

**Use of Major Facilities:** Through extensive international collaborations, staff have access to facilities, labs and subscriptions across the world (in-kind value £101.8M). Most notably the Central Laser Facility, Diamond, ILL, NEF and CERN. Specific examples include:

- QOLS utilise X-Ray FEL labs in the USA (LCLS – 300 hours), Italy (FERMI – 140 hours), and Japan (SACLA – 60 hours); estimated total in-kind value of £4M.
- PLAS and QOLS utilise specialist facilities: Orion Laser (AWE UK, 6 weeks); OMEGA (Rochester, USA, 3 shot-days); NIF (LLNL, USA, 1 shot-day), SGII (Shanghai); FORTH (Greece); and SOLEIL Synchrotron (France).
- Staff access high performance computers through the IBM Quantum Experience (>10,000 hours, *Kim(M)*) and the Swiss National Computing Centre (*Foulkes*).
- Major collaborations in HEPH provide access to Modane Underground Laboratory (France), Fermilab (USA), Sanford Underground Research Facility (USA), J-PARC and Kamioka Observatory (Japan).
- Collaborations in ASTR provide access to facilities including Planck, Herschel, and NERSC at Lawrence Berkeley Lab, USA.
- Successful bids for access to ground-based telescopes include Keck (40 nights), JVLA (195 hours), IRAM (879 hours), HST (21 orbits), Spitzer (1380 hours). Operational cost of ground-based observations are typically estimated at £18,000 per observing night.

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

**Leadership in Research**

A key research area for the Department involves working with other groups across the College, particularly Medicine, Biological Physics and Life Sciences:

- *Long* is the Director of CCAP and PI of the Laser-hybrid Accelerator for Radiobiological Applications (LhARA).
- *French* is PI of a £4.5M Cancer Research UK Accelerator multidisciplinary collaboration, employing photonics expertise in Physics to work with cancer biologists at the Francis Crick Institute, Institute of Cancer Research, Cancer Research UK Edinburgh Centre and Institute for Research in Biomedicine Barcelona. *French* also serves on the management committees of the ICR/Imperial CRUK Convergence Science Centre and CRUK Imperial Centre, helping to co-ordinate multidisciplinary research to develop innovative ways to address cancer research challenges.

Leadership roles in multi-disciplinary, multi-institution collaborations, include:

- TYC (*Mostofi*, co-director) brings together over 100 research groups and 500 researchers at all career stages at the four London universities of Imperial, UCL, King's College London and QMUL.
- CPE (*Nelson and Kim(J-S)*) brings together more than 40 academics from different disciplines across Imperial, QMUL and Oxford, and industrial partners including Samsung Electronics, CSEM Brazil, KP-Tech, CDT Ltd. and NPL.
- Leverhulme Centre for Wildfires, Environment and Society, founded by *Voulgarakis* in 2019 with £10M from the Leverhulme Trust, a highly multi-disciplinary collaboration combining social, ecological, and physical sciences and involving departments from five institutions.

Furthermore, teams from across College (10 academics and 15 postdocs/fellows) are working together on the CMS and LHCb experiments at the LHC, leveraging £64M of in-kind support from CERN. These bring several leadership roles in project delivery, including CMS HGCAL Project Manager (*Virdee*) and CMS L1-Trigger Project Manager (*Tapper*).

**Leadership Roles & Specialisms**

We are a globally minded Department and value national and international partnerships as a core part of our research and learning communities. We believe this international collaboration is synonymous with enhancing global knowledge and research excellence. Within Europe, our research collaborations have been developed through FP7 and H2020 Networks which extends across 21 EU countries, 6 partners from outside the EU, and involves 164 research institutions and 38 industrial/other partners. We are engaged in over 50 international collaborations worldwide.

Our staff hold/have held important leadership roles, both national and international. *Knight* has played a pivotal role in conceiving, designing and delivering the UK National Quantum Technologies Programme from 2014-2019 (B9-6, *Knight*). *Marangos* is the Science Lead on a science case for a UK XFEL, carried out on behalf of STFC, engaging with a broad range of potential user communities via 6 workshops, with 120 experts from wide-ranging disciplines including Structural Biology, Catalysis, Additive Manufacturing, Engineering and Quantum Materials, High Energy Density Physics, Chemical Science and Physics.

Another recent example is leadership of the AION project, to harness cold atom technologies to address key issues in fundamental physics, astrophysics, and cosmology. This project is a uniquely interdisciplinary mission involving 7 UK institutions and has received £8.6M of initial funding from EPSRC and STFC via the Quantum Technology for Fundamental Science and is in partnership with UK National Quantum Technology Hub in Sensors and Timing, and the MAGIS Collaboration in the USA.

Further highlights over the REF period are given below:

**Plasma Physics:** We are the first UK university to receive a US-UK Multidisciplinary University Research Initiative (MURI) award from the US Department of Defense, exploiting new ultra-high brightness mid-infrared light sources. During REF2021:

- Contributed to the NNSA Review of Inertial Confinement Fusion and High Energy Physics (*Chittenden*).
- Served on the National Implosion Stagnation Physics (NISP) Working Group (*Chittenden*).
- Deputy leader for Plasma Targetry in the EUPRAXIA project which is now on the EU ESFRI roadmap (*Najmudin*).
- PI of the UK Inertial Fusion Energy Network (*Smith*).

**High Energy Physics:** During REF2021, we held major leadership positions in global experiments. Major highlights include elected international spokespersons:

- Co-spokesperson for T2K in Japan, comprising 70 institutes from 12 countries (*Wascko*).
- UK spokesperson for CERN-based CMS experiment (*Davies*).
- Spokesperson for the MICE experiment was hosted at RAL, comprising 33 institutes from 12 countries (*Long*).
- Spokesperson for the developing SHiP experiment at CERN, comprising 57 institutes from 18 countries (*Golutvin*).
- Spokesperson for the SoLiD experiment at the SCK/CEN reactor complex in Belgium, comprising 14 institutes from 5 countries (*Vacheret*).

**Space Research:** We hold international leadership positions, especially in magnetometry:

- Rosetta mission (in orbit around Comet 67P Churumov Gerasimenko in 2014-16). *Carr* (PI) led the Plasma Consortium (one of 11 experiments) which coordinated a suite of 5 instruments from 5 nations measuring the comet's plasma interaction with its environment.

- Solar Orbiter launched February 2020. *Horbury* (PI) leads the magnetometer (one of 10 instruments) with a science team from 12 countries. Orbiter is the flagship European Space Agency (ESA) mission to explore the Sun and solar wind.
- Cassini, in orbit from 2004, with its 'Grand Finale' of polar orbits ending by burning up in Saturn's atmosphere in 2016. *Dougherty* (PI) led the magnetometer which was the scientific focus of this phase of the mission, to determine the true nature of Saturn's magnetic field.
- Cluster, ESA's mission reached 20 years in orbit, exploring the Earth's magnetosphere. Imperial is PI institute and provided several PIs (most recently *Carr*) for the magnetometers on the four Cluster spacecraft which have worked flawlessly since launch. As of October 2020, 2,897 Cluster papers have been published, the vast majority using magnetic field data in their analyses.
- ESA's first large-class mission in the Cosmic Vision 2015-2025 programme - JUICE (*Dougherty*, PI).

**Cosmology:** We have established an international consortium, with Imperial academics holding leading roles in some of the largest ESA and NASA missions in this research area:

- Lead of "Geometry and Topology" programme in Planck (*Jaffe*).
- Legacy Science Coordinator and joint lead of "Local Universe" science working group in Euclid (*Warren*).
- Square Kilometre Array Chair of SKA-EoR Science Working Group and Vice-Chair of SKA-EoR Science Team (*Pritchard*).

Physics leadership contributions in major consortia, many involving the delivery of large experimental programmes, include:

- **ASTR**: Chair of the STFC UK-SKA science committee (*Pritchard*). Planck Consortium Editorial Board (*Jaffe*); Joint lead of Euclid "Local Universe" science working group (*Warren*); Lead of Euclid Magnification WP (*Heavens*); UK Project Scientist, SPICA (*Clements*); JWST Advisory Board, Trappist-1 (*Owen*); Co-chair foreground mitigation focus group (*Chapman*).
- **HEPH**: UK PI for the CERN-based CMS experiment and its upgrade (*Davies, Tapper*); UK PI for the US-based LUX-ZEPLIN experiment (*Araujo*); PI for the AION project (*Buchmueller*); and LZ Xenon Detector co-Manager (*Araujo*). Level-2 manager roles include: CMS Computing (*Colling*); HGCAL (*Dauncey, Seez*); LHCb (*McCann, Patel*); SuperNEMO (*Sedgbeer*); and DUNE, T2K/Hyper-K (*Tapper, Uchida, Scott(M)*).
- **SPAT**: Comet inceptor (*Galand*, PI, magnetometer); Radcube (*Eastwood*, PI, magnetometer); FORUM (*Brindley*, Science Lead, MAG); Space Lab (*Eastwood* – Director).
- **THEO:** The group is the UK lead partner in CNRS International Research Network on Quantum Fields and Strings (with other 80 international institutions, one of eight lead organisations).

**Recognition: Awards & Honours**

Our staff have received a wide range of prestigious awards and honours for their scholarship and outstanding contributions to the national and international science community. The following awards reflect the breadth of their work and efforts.

Our staff have been awarded over 50 prizes from learned and related societies during the REF2021 period, including:

- **Institute of Physics:** Isaac Newton Medal (*Kibble*); Honorary Fellow (*Knight, Pendry*); Paul Dirac (*Duff*); Michael Faraday Medal/Prize (*Taylor, Nelson*); Holweck IoP-SFP Medal/Prize (*Galand*); Glazebrook Medal/Prize (*Dougherty, Virdee*); Joule Medal/Prize (*French*); Paterson Medal (*Maier, Kelleher*); John William Strutt, Lord Rayleigh Medal/Prize (*Stelle*); Cecilia Payne-Gaposchkin Medal/Prize (*Schwartz*); James Chadwick Medal/Prize

(*Hall*); Nevil Mott Medal/Prize (*Finnis*); David Tabor Medal/Prize (*Sutton*); Bell Burnell and Daphne Jackson Medal/Prizes (*Wade* [RA]).

- **Royal Society:** Bakerian Medal and Lecture (*Hinds*); Rumford Medal (*Walmsley* [at Oxford], *Hess*); Athena Prize (*Chapman* DHRF); RS Wolfson Fellowship (Merit Awards) (*Kim(M), Graven, de Rham, Tolley*).
- **Royal Astronomical Society:** Gold Medal (*Dougherty*); Fowler Award (*Pritchard*, *Owen*); Annie Maunder Medal (*Trotta*); Winton Geophysics Award (*Stawarz* [RA]); Michael Penston thesis prize (*Alsing*).

The breadth and significance of our work is evidenced in the receipt of awards from a wider range of bodies: Blaise Pascal Medal (*Virdee*); EPS HEPP Award (*Davies*); EPS Quantum Electronics and Optics Prize for Fundamental Aspects (*Pendry*); IEEE Quantum Electronic Award (*Taylor*); Fellowship of IAA (*Heavens, Jaffe, Mortlock, Trotta*); Kavli Prize in nanoscience (*Pendry*); Institute of Measurement and Control Oxburgh Medal (*Taylor*); NASA Reid and Lawrence awards (*Brindley*); National Measurement Institute Prize, Australia (*Vanner*); Simons Foundation Award (*de Rham*); Blavatnik National Laureate (*de Rham*); Young Scientists (*de Rham*); U of Cambridge Adams Prize (*de Rham*); APS Panofsky Prize (*Virdee*); Outstanding Young Scientist Award of EGU Ocean Sciences Division (*van Sebille*); HO-Am prize in science, S Korea (*Kim(M)*); NNSA Defence Programs Award of Excellence (*Chittenden*); Philip Leverhulme Prize (*Graven*); Optical Society Herbert Walther Award (*Knight*).

**National Honours**: During REF2021, two staff received knighthoods: *Kibble* for services to physics, and *Virdee* for services to science. *Southwood* was awarded the CBE for services to space science and industry, *Dougherty* was awarded the CBE for services to UK Physical Science Research, *Wade* was awarded the BEM for services to gender diversity in science, and *Brown* (Mechanical Instrumentation Workshop Manager), was awarded an MBE for services to science.

**Group Prizes**: Our contributions to outstanding international collaborations are recognised with the following group achievement awards: Gruber Prize (Planck Team, *Clements, Heavens, Jaffe, Mortlock*); Giuseppe and Vanna Cocconi Medal (Planck: *Jaffe, Mortlock, Clements*); RAS Group Award (2018 Planck Team); Royal Astronomical Society Group Achievement Award (Herschel-SPIRE Consortium: *Mortlock, Clements, Gryspeerdt*); Group Achievement Award in Geophysics, awarded by the Royal Astronomical Society (Magnetometer Team on the Cassini Spacecraft: *Dougherty*); NASA Group Achievement Award (*Dougherty, Masters, Southwood*); International Breakthrough Prize in Fundamental Physics (Fundamental Physics Prize Foundation, *Members of HEPH*); NMI Award for Prestigious Research Collaboration of the Year, sponsored by STFC (Ultra Electronics, *Carr*).

**Named Lectures:** During REF 2021, staff have delivered many prestigious lectures. UK lectures include: The Royal Institution Discourse (*Dougherty*); Bakerian Lecture (*Hinds*); Isaac Newton Medal Lecture (*Stelle* – in honour of *Kibble*); Sir Neville Mott Lecture at Loughborough (*Pendry*); Rochester Lecture, Durham (*Knight*); annual Imperial Schroedinger Lecture (*Dougherty*). International lectures at institutions around the world include: Distinguished Lecture GIST (*Kim(M)*); Abdus Salam Lecture (*Duff*); O'Raifeartaigh Lecture (*Duff*); Distinguished Lecture NTU (*Hess*); Trotter Prize Lecture (*Duff*).

**Honorary Awards:** Several honorary awards have been made to Physics staff including: Honorary Causa (*Pendry* x3, *Knight* x5); Honorary Fellow (Melbourne University, *Hinds*); and Honorary Doctorate (*Virdee* x2).

**Serving the Community, Economy, and Society**

Our staff are internationally recognised for their expertise and are in demand to serve on national and international science, advisory and policy committees, and as international reviewers for national funding agencies, institutional and faculty reviews.

**UKRI and Research Council Committees**: Physics staff provide significant support to UK Research Council activities:

- 28 of our staff have served on 25 STFC Boards, panels, advisory groups, strategic reviews and committees, including: 6 members of the highest-level Science committee (Science Board); Chairs of the Central Laser Facility (CLF) Board, CLF Access Panel, SWIMMR SAB, UK SKA Science Committee and Baseline Neutrino Experiment Strategic review; Science lead for the UK XFEL Project (*Marangos*).
- For EPSRC, staff have served on: EPSRC Council (*Cohen, Walmsley*); Strategic Advisory Board (*Cohen, Gauntlett, Kim(J-S)*); College of Mathematics, Science Engineering and Technology Board (*French*).
- For the UK Space Agency; Advisory Committees for Programmes (*Dougherty as* Chair*; Heavens*), Earth Observations (1) and Space Science (2).
- Divisional director for NERC National Centre for Earth Observation (*Brindley*).
- For UKRI: UKRI National Quantum Technology SAB (*Kim(M), Knight, Walmsley*); UKRI National Quantum Computing Centre SAC (*Knight*); Interim Challenge Director for Innovate UK and UKRI for the Industrial Strategy Challenge Fund in Quantum Technology (*Knight*).

**Committees Influencing Policy:** Physics academics have served society more generally in policy committees including:

- UK Space Agency steering board (*Southwood*)
- Space Expert Advisory Group European Union (*Southwood*)
- Science Environment Impact Group (*Eastwood*)
- BEIS Quantum Expert Group Road-mapping Committee (*Knight, Walmsley*)
- HMG Cabinet Office Strategy Group on Position, Navigation and Timing (*Knight*)
- Triennial Review of NRAC and DNSC for MoD and Cabinet Office (*Knight*)
- Government Office of Science Review (*Knight*)
- All-party Parliamentary Group on Fusion Energy (*Smith*)
- Expert Advisory Group on Energetic Materials (*Proud*)

Besides formal committee work, our staff present at Parliamentary Select Committees (*Walmsley*, *Knight*) and influence climate policy through joint positions with the GI. Examples include Prime Minister Theresa May's decision to announce the UK's commitment of net zero emissions by 2050 at Imperial College. This followed a letter from leading UK climate scientists, written and coordinated by *Haigh* in May 2019. *Haigh* also gave the first expert talk on Climate Science at the Citizens' Climate Assembly which was requested by six committees of the House of Commons and has since been referenced widely by politicians.

**Fellowship of Learned Societies:** Our staff support their specialist areas through membership and fellowships of over 130 learned societies, including 12 FRS. During the REF period: 3 Fellows were elected to the Royal Society (*Nelson, Taylor, Cowley*); 8 to the Institute of Physics; 2 to the Royal Microscope Society; 1 to the RAEng; 1 to the RAS; and 1 Fellow of the Norwegian Academy of Science and Letters. Internationally, there were new Fellows of the: Optical Society (4); American Physical Society; American Geophysics Union; Royal Society of SA; and Institution of Engineering Technology.

**Supporting Societies**: During REF2021, staff have supported our learned societies by serving on IoP Council (*Cohen*) and Group committees (4). Our FRSs have supported 20 of the RS Committees and Panels, with other staff active on the RS URF Selection Panel (*Davies, Jaffe, Heavens*), and RS Grants Committee (*Rajantie, Stelle*). We have a member of the council of the Royal Microscopial Society (*French*), the Optical Society Meetings Council (*French*), and a Chair of the Optical Society (*Walmsley*).

**Reviewing:** In addition to reviewing UKRI and ERC proposals, staff reviewed proposals for national funding agencies in over 30 countries. Our staff have been active in at least 33 departmental, institution and facility reviews, with 27 of these being outside of the UK. Internationally, our staff have served on ESA Council, advisory councils/boards/groups (43), and ad hoc panels and steering committees (23). These include chairing SABs at Max Planck Institute

for Structural Dynamics, LCLS (Stanford), Quantum Matter Institute UBC (Canada), NanoGUNE, San Sabastian, NTT Basic Research Laboratory Atsugi (Japan).

**PhD Examining:** Over half the population of our staff (67) examined a total of 247 research degrees at 94 different institutions during the REF2021 period, 74 of these were outside the UK.

**Support Through Training:** We accept approximately 250 students per year on the MSci and BSc undergraduate physics courses and 125-170 students per year on Master level programmes, including the high-level MSc Quantum Fields and Fundamental Forces. Research groups take on typically 70-80 students for doctoral degrees in our research areas annually. We run training workshops and summer schools for PhD students, including: ICIC's biennial Bayesian Data Analysis Workshop, supported by STFC and Winton Capital (80-90 students); HEPH's Machine Learning & Deep Learning Course in association with Yandex; an annual Plastic Electronics CDT Winter School; and an annual Quantum Information Computing and Control Summer School (50-60 students).

**Editorships:** Nine staff have served as editors for international journals including: Journal of Physics A (*Tseytlin*); Applied Physics Letters (*Cohen*, Editor-in-Chief); High Energy Physics (*Gauntlett*); Modern Optics (*Marangos*); Philosophical Transactions of the Royal Society (*Marangos*); Optics Communications and Progress in Quantum Electronics (*Kim(M)*); Contemporary Physics (*Knight*); and High Energy Density Physics (*Rose*). We have 9 associate editors (3 at Physical Review Letters), and 22 members of editorial boards.

**Conferences, Invited Reviews, and Visitors:** During the REF2021 period, we organised over 120 national and international conferences, of which 35 of our staff have acted as chair, co-chair or served on the Advisory Board. We have hosted more than 91 academic visitors from over 25 countries and our staff have written over 19 review papers.

**Public Engagement**

We make it a priority to inform and inspire the public through our extensive outreach and public engagement activities, supported by a full-time departmental Outreach Officer and Outreach Coordinator. This dedicated staff resource is in recognition of the importance we place on inspiring the next generation of physicists but also contributing to the diversity and quality of the future Physics research community.

**Recognition:** *Richards* was recognised by the US State Department for his innovative outreach and engagement, and toured the USA studying initiatives that supported minority students. Both *Richards* and *Wade* (RA) were selected for the US International Visitor Leadership Programme, the latter for engaging women in science. In 2019, *Richards* was formally elected a Fellow of the City & Guilds Institute of London in recognition of "unwavering support to education and training of young people".

*Trotta,* through his STFC Public Engagement Fellowship developed "The Hands-On Universe: Making Sense of the Cosmos with All your Senses", a programme to reinterpret and understand big questions in cosmology and astrophysics in terms of everyday experiences. He expanded his work to reach non-traditional audiences, e, g with G-Astronomy: The Taste of the Cosmos for People with Visual Impairment and was awarded the RAS 2020 Annie Maunder Medal for his work.

**Schools Outreach**

The Department introduced the Insights Work Experience programme in 2012 which has supported 250 students from 2000 applications, with a 50:50 gender balance. Almost half of our Insights students apply to Imperial for further study. Insights has been replicated in other departments across the College and been adopted by the Universities of York and Nottingham.

**Department Women in Physics Open Day:** Over 2000 female students have attended since inception in 2013. We also run an annual Physics Easter School with 60-80 places available to Year 12 pupils from a diverse range of backgrounds in West London. We developed a six-week structured Tutored Maths Programme in 2015 for Year 12 and 13 students supported by the Amos Bursary, set up to support students of African and Caribbean heritage. This has now evolved into the AiMS (Accelerate into Maths and Science) programme, administered by the College Centrally with *Richards* and *Tymms* as academic leads.

**Blackett Academy:** The COVID-19 pandemic has affected educational systems worldwide. We recognised the impact this would have on young students and in response setup the 'Blackett Academy' – an online tutoring scheme designed to support Year 10-13 state school pupils in South Kensington and White City with their learning. We approached 50 schools in the local area that had indicators of high numbers of widening participation students which led to 100 students from 15 schools participating. Based on the positive feedback received from teachers and students, we aim to expand the scheme.

**Community Outreach & STEM Initiatives**

As part of our commitment to widening participation and improving access to our research and teaching activities, the Department delivers talks and workshops to a variety of community groups and a wide range of audiences including young people, their parents, carers and wider families to help build their science capital. Some of these groups include:

- **NOVA:** a charity based in North Kensington that provides skills and employment training for local disadvantaged families. We conducted events, such as 'Discovery Days', at the Invention Rooms in White City where a full day of events was organised around a research topic such as 'Climate Change' or 'Quantum Physics'. We have continued to engage online with events such as 'Solar' and 'Rocket' discovery days through the pandemic.
- **STEM the Violence**: an organisation that uses STEM engagement to inspire young people to develop their interests and set them on a path away from knife and gang crime and back into education and the workplace.
- **Royal Borough of Kensington and Chelsea and Hammersmith and Fulham Council** work with us on activities to engage with young people in the community, such as the Youth Takeover Challenge Day 2019, held at Stamford Bridge stadium, where 130 young people from the community shared views on crucial issues such as mental health, knife crime and employability. *Eastwood* and *Foster* represented the Department and College, discussing the latest Space Science research and education and employment opportunities.
- **Phoenix Space**: a non-profit organisation focused on providing STEM education based around the topic of Space Science to refugee and disadvantaged students in the Middle East to help improve their life outcomes.
- **Accelerate Mentoring**: a student-led initiative setup by Physics Masters student *Jasneet Kaur* which aims to support students from BAME backgrounds and other underrepresented groups who wish to pursue a STEM-based degree and career, by providing mentors, role models and resources to help the students achieve their potential and improve diversity in education and the workplace.

**Quantum City:** In partnership with the UK Quantum Technologies Programme, QOLS assisted in the development of the 'Welcome to the Quantum City' aimed at helping students and the public understand current and future quantum technologies. In 2018 and 2019, the Department toured the activity nationwide, e.g. Cheltenham Science Festival and New Scientist Live. This culminated in the 'Quantum in the City' event at the Royal Institution, co-organised by *Foster*.

**Exhibitions:** The Great Exhibition Road Festival has steadily grown since its inception in 2012 to an audience in 2018 of over 20,000. The Department has been heavily involved by delivering talks, workshops, pop-up stands, and planning and development. *Foster* gave the opening address at the 2014 Festival.

The Department frequently gives talks at local societies and is a regular contributor to the RS Summer Exhibition (participating between 2015-2019), the Science Museum Lates, and the White City W12 Festival in 2016 and 2017. The Department also appointed an artist-in-residence, *Geraldine Cox,* who won the American Institute of Physics (AIP) Gemant Award in 2020 for her depiction of complex scientific concepts through a variety of artistic media.