Institution: Lancaster University

Unit of Assessment: 9 Physics

1. Unit context and structure, research and impact strategy

The Lancaster University Physics Department creates, fosters and maintains international research excellence in the areas of astrophysics, experimental condensed matter, particle and accelerator physics, and theoretical physics. The Department has successfully completed a period of significant strategic growth since REF2014, including supporting the establishment of a new Observational Astrophysics group, diversification into space and planetary science and significant growth in cross-disciplinary quantum technology and materials science research. Our academic staff has increased from 39 to 61, with a vibrant research portfolio supporting 49 postdoctoral research staff and 98 research students.

The Department was ranked 2nd for world-leading (4*) research outputs REF2014, attained the highest grade-point average for physics in RAE2008 and was awarded a 5*A rating in RAE2001. We have built on that success in the REF2021 period, with achievements such as the world's coldest electron temperature in a device, development of a revolutionary semiconductor memory, and the award of three Breakthrough Prizes for Fundamental Physics. Our research is highly cited, with 5.7% of our articles in the 99th percentile for citations since 2014 (compared with 3.1% for Russell Group) [SciVal]. During the REF2021 period, 20% of our academic staff have held prestigious personal fellowships such as ERC, Royal Society and Rutherford. Since 2013/14 our annual research grant award has more than doubled, reaching £11.1 million in 2019/20. University and grant capital investment of over £20 million has established world-class environmental isolation laboratories and new capabilities in condensed matter research at microkelvin temperatures, quantum technology, femtosecond science, advanced particle accelerators, and observational astrophysics. This investment complements our internationally leading ultra-low temperature capabilities, and comprehensive facilities for experimental condensed matter research.

The Department holds Athena SWAN silver status, and Institute of Physics Juno Champion equality and diversity accreditation (since 2013). Through a strategy of monitoring and action, our research student recruitment has reached near gender parity (PhD intake of 45% women in 2019), and we have nearly doubled the proportion of women in academic and research positions over the REF2021 period.

1.1 Structure

The Department is structured into four major research groups (MRGs), **Astrophysics** (16 academic staff); **Experimental Condensed Matter** (20 academics); **Particle and Accelerator Physics** (15 academics); and **Theory** (10 academics). Within the MRGs the research is organised into a total of 11 subgroups. This structure of coalesced research subgroups was implemented during the REF2021 period to rationalise management at Departmental level, and to reflect and further stimulate collaboration. It has facilitated a strategic expansion of our low temperature physics research towards low-temperature quantum device research, and the establishment of an internationally-competitive observational astronomy activity. Intra-Major Research Group research and collaboration is common place, encouraged, and supported by investments in our facilities and research centres (§3.2): examples include theoretical and experimental studies of molecular transport, and research on quantum devices for axion-like particle searches. MRGs align with our undergraduate degree programmes, facilitating our research-led teaching.

Responsibility for Departmental research strategy lies with the Director of Research (DoR) and a Research Committee with membership including: DoR (chair), Head of Department (HoD), the heads of MRGs, the Postgraduate Academic Advisor, the Director of the Lancaster Quantum Technology Centre (LQTC), plus academic champions for Outputs, Impact and Environment, and two Departmental-based research support staff. Most Research Committee members are also in the Physics Executive Committee. There are two Departmental committees whose remit includes impact: the Physics External Engagement Committee (PEEC), which is focused on industrial interaction, and the Public Engagement and Outreach Committee. PEEC is chaired by the Departmental Industry Coordinator (also presently DoR and Impact Champion), and attended by Heads of MRGs, LQTC Director, Postgraduate Academic Advisor and Careers Champion. It has

substantial representation beyond the Department; including the Faculty Associate Dean for Research, the Faculty Impact Manager, members of the Faculty Business Partnerships team and the University's Intellectual Property Manager. This unusual composition for a departmental committee is highly effective at bringing wider Faculty and University resources to Physics, and places Physics at the forefront of University industrial engagement. The DoR and Impact Champion contribute to the wider University research and impact agenda through membership of the Faculty Research and Impact Committees, respectively. The success of this approach is reflected in case studies with diverse impacts, driven by research from across the Department (§4.2).

1.2 Major research groups

The **Astrophysics** MRG has strong and growing prominence on the world stage, achieved by driving new developments in the field. It contains subgroups in **observational astrophysics** (OA), **theoretical particle cosmology** (TPC), and **space and planetary physics** (SPP).

The OA subgroup was established in 2015 following a strategic investment by the University in a chair (Hook) plus three further academic posts, a postdoctoral position and four PhD studentships. Since then, the academic staff in OA has grown to six, including a Rutherford Fellow (Wardlow). The group has recognized leaders in their fields, with recent research highlights such as the discovery of the most luminous galaxies in the early universe and their impact on reionisation (Sobral), demonstration of the importance of the merger-free route for galaxy evolution (Simmons), development of a new machine-learning technique to find clusters of galaxies (Stott), and prize-winning work on the discovery of gravitational wave sources (Pitkin). Our research is based on significant allocations of competitively-awarded observing time on state-of-the-art telescopes such as the Hubble Space Telescope (HST) and European Southern Observatory (ESO) facilities Atacama Large Millimeter/submillimeter Array (ALMA) and the Very Large Telescope (VLT) (§3.3). OA group members also hold leading roles in major international telescope and instrument projects, including the European Extremely Large Telescope and the European Space Agency's (ESA's) Euclid mission (§4.5). Since September 2018 (from when all group members were UK-based), 98% of the OA's publications have been with international co-authors. In 2016 Lancaster University invested £100,000 in the 4-metre Multi-Object Spectroscopic Telescope (4MOST) project, providing membership Hook, Simmons and their research students. This enabled Lancaster to become a founding member of the 4MOST Time-Domain Extragalactic Survey (TiDES), a unique spectroscopic survey for transients expected to begin in mid-2023. Sobral is a member of the MOONS instrument team and will have guaranteed time on this VLT instrument. Pitkin is a member of the LIGO Scientific Collaboration, giving complete unembargoed access to all data from the LIGO and Virgo gravitational-wave detectors, and access to the collaboration's computing resources.

TPC pursues a broad spectrum of research encompassing the major themes of cosmology, engaging with new developments in observation and theory, in a rapidly-evolving research area. Inflation is a major focus of the subgroup's research, complemented by activity in models of baryogenesis, dark matter, dark energy, supersymmetric cosmology, quantum gravity, the initial state of the Universe and mathematical aspects of cosmology. TPC has been a member of the STFC-funded Lancaster-Manchester-Sheffield Consortium for Fundamental Physics since 2011.

SPP has a long track-record in space- and ground-based ionospheric diagnostic experiments to study the geospace environment. In the REF2021 period this has strategically expanded to build leadership in observation and theoretical modelling of the plasma environments of the outer planets of the solar system. Ray and Arridge have exploited *in-situ* measurement of magnetic reconnection in Saturn's dayside magnetosphere made by NASA's Cassini mission to challenge prevailing theories on location and occurrence of reconnection and implications for mass outflow. Badman undertook the first comparison of HST images and *in-situ* data from NASA's Juno mission to analyse the response of Jupiter's aurorae to interplanetary conditions, showing the coupling to be more diverse than previously thought. Grocott, Honary, Kosch and Wild investigate the impact of space weather on the terrestrial atmosphere and climate, and on human technology, now recognised as a significant socioeconomic threat in the UK Government's National Risk Register of Civil Emergencies. Because of this work, the group is engaged with industry stakeholders and policy-makers to transfer knowledge and co-create research (*e.g.* UK Met. Office, EDF Energy, Atkins, BEIS). Our research into aurora (Kosch) underpins the smoke plume detection algorithms

in forest fire monitoring systems used internationally, generating multi-billion pound savings over the REF2021 period (§4.2).

The **Experimental Condensed Matter** (ECM) MRG is structured into three subgroups, **low temperature physics, quantum nanotechnology, and nonlinear and biomedical physics**. There is significant synergy between these subgroups, and group members are typically highly interdisciplinary. Our strategy centres on establishing outstanding in-house infrastructure, leveraging it to attract excellent researchers and collaborations and, in turn, producing high quality outputs and impact. During the REF2021 period, almost half of our full-time academics have held personal fellowships that allowed them to dedicate their time to research (Laird, Zmeev, Thompson, Jarvis, Robinson, Ponomarenko, Young, §4.6). Scientific achievements include a novel form of non-volatile memory that exploits resonant tunnelling (Hayne), the potential for 3D-printed insulation to reduce the size, weight and power profile of low temperature refrigerators (Zmeev), non-invasive diagnostic methods based on a theory of living systems as open systems (Stefanovska), pioneering a novel device for authentication, in which quantum effects are harnessed to read atomic imperfections for fingerprinting (Young), and discoveries in the exotic fluidic behaviour of electrons in 2D materials (Ponomarenko)

ECM academics represent the core of the Lancaster Quantum Technology Centre (LQTC), a cross-departmental research centre established in 2013 through strategic investment from the University. The LQTC houses nanofabrication, characterisation and measurement facilities that include epitaxial growth, three cleanrooms, an ultralow temperature laboratory (ULT) with a suite of dilution refrigerators for low-temperature physics, and IsoLab (§3.2). IsoLab is a world-unique facility, opened in 2017, that mechanically and electromagnetically isolates experiments from the influence of the outside world in three separate laboratories for low-temperature, quantum-optics, and atomic-scale research. A world record for the lowest electronic temperature recorded in a device has been set in the ULT laboratory. The subgroup is a member and facility host in the European Microkelvin Platform, a 17-partner EU consortium engaged in ultralow temperature research, supported by a €10 million H2020 grant. ECM staff also have lead roles in other cross-departmental centres and institutes, such as the Material Science Institute (Kolosov Acting (founding) Director), Security Lancaster and Energy Lancaster.

ECM staff and facilities provide a platform to produce outstanding innovations and impact in the nascent field of quantum technologies. Twenty patent applications submitted in the REF2021 period have been granted, with another 33 pending. We have spun out three trading companies, including Quantum Base Ltd (valued at >£10 million), and have co-development projects with more than 100 others, including Oxford Instruments, OpSec, IQE and Leonardo. The significance of our research and innovation activities has been recognised through global media interest, with multiple discoveries reported by hundreds of outlets with a combined reach of about half a billion people (§4.2).

We are engaged with national metrology institutions in Germany and Italy. The National Physical Laboratory (NPL) is a key stakeholder of our nanoscience research through the appointment of their Chief Scientist (Janssen) to a visiting professorship and the involvement of NPL staff in teaching and joint research activity in collaborative projects. Training the next generation of scientists is an important priority for the group. We have participated in or lead three European Innovative Training Networks, a Leverhulme Doctoral Scholarship training programme Award and the EPSRC-funded centre for doctoral training (CDT) 'Graphene-NOWNANO' (with the University of Manchester). Forty-eight PhD students in ECM have graduated since REF2014.

The **Particle and Accelerator Physics** MRG is engaged in **experimental particle physics** (EPP) and particle **accelerator physics** (AP) research. The EPP subgroup's interests are in probing the phenomena of matter/antimatter asymmetry, spontaneous symmetry breaking, CP violation and flavour changing. Since 2013, we have diversified, expanded and reinforced our research programme with strategic recruitment. On the T2K neutrino-oscillation experiment, Lancaster analyses fed directly into the recent constraints on CP violation in the lepton sector (published in 2020). These hint, for the first time, at a role for neutrinos in producing the unexplained matter/antimatter asymmetry in the universe. In T2K's successor Hyper-Kamiokande, we lead sensitivity studies for CP violation. In Fermilab experiments, our event reconstruction expertise underpins Main Injector Neutrino Oscillation Search plus's (MINOS+'s) sterile neutrino constraints; Deep Underground Neutrino Experiment (DUNE) neutrino oscillation sensitivity studies; the Short-Baseline Near Detector (SBND) Monte Carlo simulation processing and ν_μ oscillation analysis;

and our leadership in MicroBooNE's measurements of ν_μ cross sections and low-energy excess studies. We have led analysis programmes in DUNE UK physics and computing management (Blake), the physics programme design for the protoDUNE detector (Nowak), and the T2K near-detector physics programme (O'Keeffe). In ATLAS, Lancaster has the academic leadership in the B and light states (BLS) and in the CP violation measurements (Jones). We have also shown leadership in Higgs decays to taus (Fox), exploited synergies between the tools for BLS and hadronic tau decay studies, and extended our research into long-lived new particle searches and di-Higgs studies. Our Large Hadron Collider QCD programme, in particular single, double and associated production of quarkonia and high mass dijet resonances (Karvelishvili, Bertram), probes Beyond Standard Model physics, as do lepton flavour violation searches in top decays (Borissov). We joined the NA62 experiment, studying ultra-rare kaon decays and lead the flagship $\pi\nu\nu$ analysis (new appointment Ruggiero, physics coordinator 2016-19, deputy spokesperson since 2019).

During REF2021, the group has computing and software roles in ATLAS, DUNE, Hyper-Kamiokande, MicroBooNE, SBND and T2K, as well as review responsibilities including speakers committee chairs in DUNE, SBND (Nowak) and T2K (Kormos). Jones provides leadership of the computing infrastructure underpinning STFC research in the UK, chairs the Worldwide LHC Computing Grid Collaboration Board, leads ATLAS UK computing and software and is in the project management of GridPP and IRIS. We lead detector design and technology development in the liquid-argon DUNE Anode Plane Assemblies (Nowak); the Hyper-Kamiokande data acquisition systems (O'Keeffe), and also convene operations of a current T2K subdetector (Kormos). Our immediate strategic priorities are the ATLAS upgrade and construction of DUNE and Hyper-Kamiokande, in parallel with increasing our recent involvement in neutrinoless double beta decay via LEGEND; the CepC; the Electron Ion Collider, investigating Dark Matter via DarkSide; and developing novel photosensors.

The accelerator physics (AP) subgroup has expanded its position in the Cockcroft Institute, a collaboration spanning four universities, seven departments and STFC's national accelerator centre at Daresbury Laboratory. The Directorship of the Institute has been held by Lancaster Physics (Ratoff) since 2014. We have made a strategic shift to advanced laser acceleration as the major research strand, with appointment of a chair in experimental novel acceleration (Jamison) and two lecturers. We have established new ultrafast laser facilities at both Lancaster and Daresbury, with successes including the first demonstration of laser-driven acceleration of relativistic electron beams at terahertz frequencies. In plasma acceleration we are undertaking high-performance computing (HPC) investigations of laser-ion acceleration and electron external-injection for high-quality plasma acceleration (Boella). In conventional accelerators, we contribute crucial spin-tracking studies to the Fermilab-based "g-2" experiment for the precision measurement of the muon anomalous magnetic moment (Bailey). Our future strategy is to further build the international standing of our advanced laser and plasma acceleration programme, exploiting the large-scale facilities at Daresbury; and to achieve near-term impact in laser driven electron injectors and electron-diffraction.

The **Theory** MRG undertakes research within three subgroups, **theory of molecular-scale transport** (TMST), **condensed matter theory** (CMT), and **mathematical physics** (MP). Since 2014 the MRG has strategically diversified its research portfolio, establishing international leadership in modelling of molecular and low-dimensional materials, quantum optics and topological photonics.

The TMST subgroup is a centre for theory and modelling of molecular-scale materials, with research achievements including enhanced performance of single-molecule switches and molecular-film transistors, and the realisation of multiple original theoretical concepts in trendsetting collaborative molecular electronics experiments (Lambert). TMST collaborates with over 30 groups from the US, East Asia, Oceania, Europe and the UK. Collaborative programmes include four EU networks and a Programme Grant with Oxford. TMST is a lead developer of the GOLLUM code, used by more than 396 groups in 29 countries to predict quantum transport through molecular structures and their full thermoelectric properties. The abovementioned work has led to the design of new organic thermoelectric materials, novel water-splitting systems based on atomic quantum clusters for green energy harvesting, and new organic battery materials for energy storage.

CMT research ranges through material modelling, quantum transport, topological quantum optics and photonics. Research highlights include predictions and demonstrations of collective light-matter interactions leading to the demonstration of the cooperative light-scattering effects in atomic clouds (Ruostekoski); the spearheading of the major field of topological lasers with the original concept and its collaborative realisation in hybrid semiconductor lasers, while also giving the impetus for substantial mathematical physics activities in non-Hermitian topology (Schomerus). The group's modelling and description of two-dimensional materials includes foundational first-principle work on transition metal dichalcogenides (Drummond), multilayer graphene theory (McCann) and interacting and open quantum systems with seminal work on weak measurements (Romito). CMT has been a partner in the Quantum Technology Hub for Sensors and Metrology, the Graphene NOWNANO CDT with Manchester, and a Programme Grant with Sheffield. It has extensive international collaborations with over 40 groups, including experimental partners such as Institut d'Optique, University of Pennsylvania and CNRS Institut de Physique de Nice. These led to the abovementioned predictions of collective light-matter interactions and topological lasers (2018 "Highlight in Optics" in journal OPN). CMT drives modelling as a lead developer of the Quantum Monte Carlo code CASINO, and makes heavy use of overseas HPC facilities (§3.3).

The MP sub-group specialises in applying modern differential geometry to matter under extreme conditions, from axion-like particle searches to modelling radiation reaction and astrophysical acceleration. As long-standing members of the EPSRC ALPHA-X consortium for laser-plasma interactions as well as the STFC Cockcroft Institute for particle accelerator science, MP strategically expanded its activities to non-standard electromagnetic materials, contributing to the Roadmap on Transformation Optics (Gratus).

The Theory MRG has strategically strengthened its impact potential and diversified the income streams of its research via collaborations with experimental research institutions such as the National Graphene Institute (research on 2D materials, including photodetection methods) and major companies including BP Exploration, Castrol Plc, and IBM Zurich (molecular electronics applications to energy and sensing).

1.3. Future strategy

Having undergone a period of rapid growth in academic staff and broadened our research portfolio during the REF2021 period, our on-going strategy is to consolidate and strengthen our MRGs with steady growth in academic FTE (full-time equivalent), whilst also increasing research income per FTE as new staff become more established. Implementation includes periodic review of MRG strategic plans, identifying opportunities and threats, potentially leading to expansion, or retrenchment, in subfields. Reviews will occur at least annually, but also in response to institutional or external changes in landscape. MRG strategies will inform the Departmental Strategy Committee (Chaired by Head of Department), which also looks for other new areas of activity beyond the existing portfolio. In spite of the Covid-19 pandemic, our community has remained active and resilient, and we are confident that our future plans are realistic and achievable.

An important outcome of this process, includes strategically directing the continuation of our highly-successful approach to recruiting promising staff via personal fellowships, and maintaining an environment attractive to such staff. To ensure maximum mutual benefit for staff and the Department, we will strengthen our existing support and mentoring of early career researchers. Furthermore, we will continue to diversify the academic staff profile in order to build organisational insight, creativity and robustness. Implementation of this strategy has already identified short- to medium-term strategic goals of an academic appointment in Theory MRG and expansion of the LQTC cleanrooms to support new funding opportunities and research directions. We will increase cross- and multidisciplinary research in our institute partnerships (§4.1), building on existing collaborative links, via, for example, cross-Faculty institute studentships and strategic use of studentships allocated to Physics. In particular, we will foster increased interaction and seek further funding opportunities in collaboration with the Faculty of Health and Medicine and the Health Innovation Campus, for example in health monitoring (*e.g.* blood sugar) and biomaterials characterisation. This will prepare the foundations for a possible expansion of biophysics when a suitable opportunity is identified by our strategic process. Commensurate with the institutional strategy that places engagement alongside research and teaching as a core activity of the University, we will continue to refine, enhance and implement our Engagement Strategy, with the

objective of widening and strengthening links with industry and society for impact generation and improved performance in the Knowledge Exchange Framework (KEF).

2. People

2.1 Academic and research staff

Our people strategy seeks to recruit and retain world-class early-career and senior academics in research areas aligned to the MRG themes, and to support research achievement through active career development and the promotion of a culture of research ambition. We develop researchers' careers through training, guidance and investment in research support. We offer indefinite academic positions to personal fellowship holders where the research area is aligned to the Department's research themes and strategy, encouraging the development of longer-term and ambitious research programmes. Principles of equality, diversity and inclusion are embedded in Departmental culture, and are pillars in our recruitment of the best researchers and academics. We have held Athena SWAN silver and Juno Champion awards since 2013 and 2014, respectively.

We foster an environment of collegial support, encouraging cross-group collaborations and sharing of facilities and expertise. In supporting an environment of Departmental cohesion and research ambition, all academic staff are actively engaged in research, with no teaching-only contracts.

We have invested in the establishment of a new observational astrophysics group, through the initial establishment of a chair (Hook) and 3 lectureships. The group has since further expanded with appointment of two further lectureships. The accelerator physics subgroup has expanded and been redirected towards laser-driven acceleration research, with appointment of a chair (Jamison) and 2 lecturers. We have been successful in attracting and appointing early career candidates already holding personal fellowships [Wardlow, (Rutherford, Durham); Mikhaylovskiy (ERC, Radboud); Laird (RAEng, Oxford); Simmons (NASA Einstein fellowship, UC San Diego); Arridge (URF, UCL); Jarvis (Leverhulme, Nottingham)], and developing and retaining fellowship holders across the whole Department. More than twenty percent of our academic staff have held an externally-funded personal research fellowship since 2013 (§4.6). Our academic staff has increased from 39 to the current complement of 61, with a demographic rebalancing towards early career (Fig. 1). This growth has been accompanied by a more than doubling of research income (§3.1). Pro-active search committees are mandatory for all academic posts, ensuring that the application pool for the positions is both diverse and of the highest quality. Recruitment statistics for application, interview and appointment rates are monitored within a culture of continuous improvement in equality, diversity and inclusion. All vacancies are vetted for unconscious bias in the advertisement and job specification, and Departmental policy requires recruitment selection panel members to undertake unconscious bias training. These processes have contributed to women being appointed to 23% of academic vacancies over the REF2021 period, increasing the proportion of female academic staff from 8% to 16% between the REF2014 and REF2021 census dates.

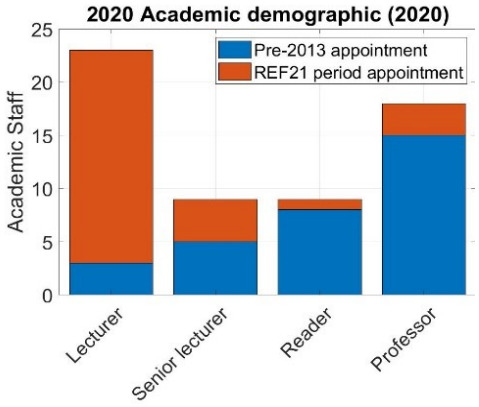

Figure 1. Academic staff

Career progression and support

A range of support is provided to our academics to aid their research development. All academic staff are eligible for sabbatical leave of one year after seven years service, or a pro-rata shorter period after four years. Newly appointed academics are given a reduced teaching and administration workload, with an initial 90% research allocation which tapers to a normal load in the third year in-post. The Department awards all academics an annual personal allowance to enable discretionary research activities such as conference travel. A Departmental-based research development officer provides assistance in the preparation of research grant proposals. All research proposals are supported with review by a minimum of two academic colleagues before

submission. The Department also benefits from a centrally-funded, post-award administrator dedicated to supporting Physics grants. Departmental and Faculty studentships are allocated to provide all new academics with a research student, with a strategic goal of ensuring that every academic has at least one PhD student. Where strategic needs require, the Department and the University offer start-up resources or equipment to enable effective and rapid establishment of research capability. A total workload allocation model is applied for the sharing of teaching and administrative responsibilities across the Department's academic staff. Staff on personal fellowships have higher research allocations of approximately 90%, consistent with the specific fellowships and the career development goals of individuals. The anonymised workload allocation distribution is shared with all academics, enabling transparency in relative workload and non-research duties, while respecting privacy and individual circumstances.

All staff, including academic staff and postdoctoral researchers, participate in annual Performance Development Reviews (PDRs), which review past performance measured against agreed objectives, set new objectives, and identify appropriate career development and training needs. Research staff are reviewed by their line manager, and academic staff members are reviewed by their group leader or other senior academic in the Department. For academics within the first three years after appointment the PDR is integrated into the three-year probation process overseen by the Head of Department. The Department's Career Development Committee annually reviews all academic and research staff to identify promotion-ready candidates and candidates with near-term potential, irrespective of self-nomination. Individual staff are assigned to support developing those cases that are considered to have a good chance of success. This process addresses known gender biases in advancement through self-nomination, as well as supporting rapid but appropriate advancement with targeted advice on development paths. The Career Development Committee has no mandate to refuse any candidates case for promotion: self-nomination is an option and all promotion cases are reviewed external to the Department.

The University is a signatory of the Vitae Concordat to Support the Career Development of Researchers, and the Department is committed to its full implementation. In recognition and support of equality of standing in opportunities for training, development and career progression, we offer all research staff indefinite appointments. Where postdoctoral research posts are dependent on future grant income, in consultation with staff, we seek career development pathways directed to future security, both internal and external to academia. Our postdoctoral researchers are represented on the Physics Staff Advisory, Safety, Equality Diversity & Inclusion (EDI) and other major Departmental committees, and all are entitled to attend termly Physics Committee meetings and biannual Departmental Away Days (both chaired by HoD).

We recognise the needs of all staff with caring responsibilities, and offer flexible working where possible, without detriment. We have a culture of acceptance, and in the REF2021 period a total of 39 months of parental leave was taken by academic and postdoctoral researcher staff. Flexible working, including condensed working hours, is an established process with uptake by a small number of academic and professional staff.

2.2 Impact and engagement

Physics fully embraces Lancaster's institutional strategy that places engagement alongside research and teaching as a core activity. Impact and engagement form an important strand of the University's academic promotion criteria, and are recognised in the Departmental academic workload allocation model. Training is offered at University, Faculty and Departmental level on a wide range of aspects of engagement to all staff and research students, often with a focus on targeting early career researchers. Academic and postdoctoral staff have benefitted substantially from Impact Acceleration Account (IAA) research funding from EPSRC, STFC, ESRC and HEIF. Awards are typically in the form of up to £10,000 of seed funding or up to £25,000 of co-funding, at least cash matched by an industrial partner. Whilst co-funding has mostly been used by EPSRC-facing academics with track-records of industrial collaboration, seed funding has been very effective in introducing researchers without previous experience into working with companies. The Faculty has also run an Impact Fund to complement the research-council-specific IAAs. Advice and support within Physics for individuals is provided by the Departmental Industry Coordinator and the Outreach and Engagement Champion. Over the REF2021 period a third of our academic staff have held externally-funded joint projects with industrial collaborators, whilst 93% have been involved in public engagement, with major activities including the establishment of the World of

Physics at the World of Music, Arts and Dance (WOMAD) festival and four successive installations at the Royal Society Summer Science Exhibition (§4.4).

The University's longstanding generous approach to income from intellectual property (IP), with 50% of net proceeds going to the inventors, has been recently improved further to between 70% and 100% of net income going to inventors. A coherent support structure for researchers covering legal and commercialisation aspects of IP is provided at Departmental, Faculty and University level. Over the REF2021 period eight academics, seven research staff, ten PhD students and five undergraduate students have been named as inventors on patent applications.

2.3 Postgraduate research students

Over the REF2021 period, Physics registered 161 PhD students. Our funding includes EPSRC DTP (27), STFC (35), EPSRC NowNano CDT (7), STFC CDT on Data intensive science (3), Horizon 2020 and other EU sources (9), foreign governments (36) and self-funded students (14), as well as charities and professional bodies (*e.g.* Leverhulme Trust and the Royal Society (5)). We regularly obtain external funding from industrial partners to convert our EPSRC studentships into CASE and attract ICASE studentships, with partners such as Castrol, IQE (3), Quantum Base and Selex.

According to the Postgraduate Research Experience Survey, the Department performs well in the quality and quantity of supervision provided to postgraduate research (PGR) students with an overall satisfaction of 82%, and 90% satisfaction with the supervisor skills and knowledge and with the PGR working space. We seek a strong sense of academic community for our postgraduates, which is recognised by the strong rating (70%) in the Research Culture subtheme. There has been a significant increase in overseas students entering the Department (currently 35 non-UK resident students, or approximately one third of our PhDs, of which 48% are female). Efforts to promote a sense of inclusion and belonging in the Department include; establishment of a dedicated postgraduate forum; representation on the Physics Staff Advisory Committee and Staff Student Consultative Committee; adding more social events to facilitate the integration of PGRs in the Department. We are committed to promoting equality, diversity and inclusion in our PGR recruitment and admission. All of our funded studentships are advertised openly and widely. All adverts encourage diversity in applications, highlight our Juno and Athena SWAN status and the

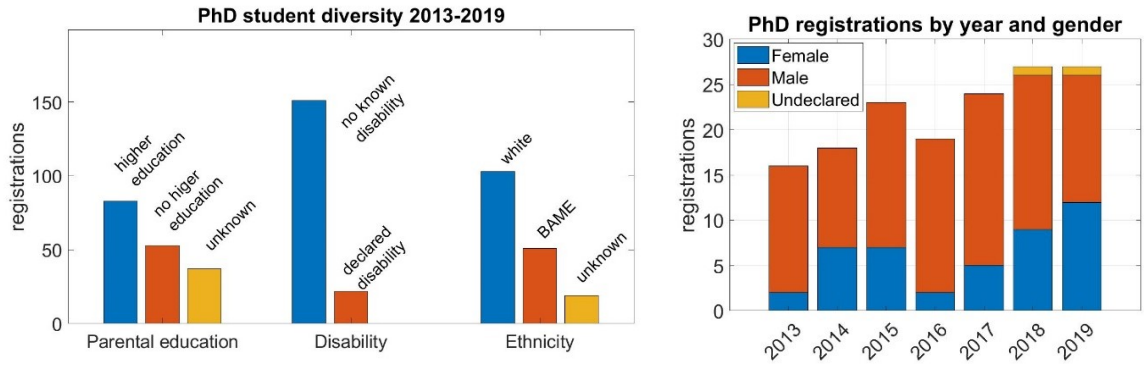

Figure 2. Indicators of equality, diversity and inclusion in postgraduate student recruitment.

positive culture of the Department. The policy of the Department is to support part-time study where requested, with a 4% PGR uptake. In line with other Departmental recruitment practices, all panel members are required to have completed inclusive recruitment training, and gender-inclusive representation is sought for interview panels. Recruitment and admission processes are regularly monitored by the Department's postgraduate committee, which reports to both the Departmental executive and Faculty management. Best practice is shared amongst other Lancaster departments as well as local equality, diversity and inclusion committees and Lancaster's "Inclusion in Physics" group. Our postgraduate recruitment strategy has delivered significant improvements in gender representation, with a 45% female PhD student recruitment rate in 2019. We monitor diversity in postgraduate student recruitment according to disability, ethnicity, parental background and gender. Over the REF2021 period 30% of our postgraduate students identified as BAME, while 12% have a declared disability (Fig. 2).

Supervision and training

All PGR students have a supervisor, a deputy supervisor and an independent advisor from a different MRG. This panel reviews student progress annually, and in months four and ten in the students' first year of studies. The month-ten review includes a formal report from the student covering progress and the future research plan, and serves as a PhD study confirmation panel. The University has implemented an online record of student-supervisor meetings, for monitoring compliance with expected regular supervision meetings. Each student is allocated an office with other students who work on a similar topic. The MRGs organise regular topical seminars and journal clubs open to all members of the Department. In many seminars a dedicated time is allocated when only students can pose questions to the speaker. There are also Departmental Colloquia that address topical research in a context that is aimed at a broad physics audience, including undergraduates. The Cockcroft Institute offers a two-year rolling programme of postgraduate lectures in accelerator science, while other groups offer regular informal teaching seminars and/or send new students to international summer schools (*e.g.* the European School on Nanosciences & Nanotechnologies, Grenoble). Many of our students benefit from working within multiple-university and (inter)national collaborations, such as secondment to CERN or the National Physical Laboratory. Six of our students from Graphene-Nownano CDT had second supervisors at the University of Manchester, working at and accessing resources available at the National Graphene Institute. Observational astronomy students within the Data Intensive Science CDT receive data science training and external placements. Four students in the Nonlinear and Biomedical Physics subgroup received double doctorates, being jointly supervised with Physics Departments in Barcelona, Florence, and Amsterdam, alongside Lancaster. Formal training is provided by both the Department and the wider University and is mapped to the Vitae Researcher Development Framework (RDF) for tracking student development. Training sessions cover a wide range of aspects from wellbeing to thesis writing, and careers to ethics. Example training sessions include; "The art of networking and social media", "Public speaking" and "Engagement impact and communicating with non-specialists". We also require all PGRs to undertake "Diversity in the workplace" training ahead of their first appraisal.

2.4 Equality, diversity and inclusion

The Department has held Athena SWAN silver status since 2013 and the Institute of Physics Juno Champion award since 2014. An Equality, Diversity and Inclusion committee, chaired by the Head of Department, oversees Departmental practice in EDI and sets strategy for continuing improvement. The committee includes representation from postgraduate students, postdoctoral researchers, professional and support staff. Equality and diversity is monitored through routine collection of disaggregated data in all areas of Departmental practice, including recruitment, workload, administrative responsibility and leadership and career progression. Transparent reporting on EDI status and achievements occurs in termly Physics Committee meetings and biannual Away Days, both of which are open to all staff.

In order to create a family-friendly environment for staff and postgraduate students, all meetings, seminars and colloquia are scheduled between 9:30 am and 4:30 pm to accommodate child and carer responsibilities. In line with University practice, scheduling of lectures seeks to take into account individual family and carer responsibilities of lecturers.

The Department is engaged in supporting improvements in gender equality in the wider scientific and academic community. We led joint academic and industry STEM (science, technology, engineering, maths) workshops on equality in the workplace in 2014 and 2020 ("A Woman's Place?" and "A Better Place"), and a women in STEM session at international conference LINAC 2020. As hosts of the National Astronomy Meeting in 2019, we introduced free childcare facilities for attendees, and a formal meeting Code of Conduct with diversity and inclusion at its core.

The Department aims to provide an environment free from bullying, harassment and sexual misconduct. We have dedicated harassment officers from the academic and professional support staff who accept and guide the handling of reported incidents; cases may be reported to harassment officers outside the Department through cross-departmental partnering. The Department's policies offer a route to rapid resolution of incidents, and supplements the formal University reporting and resolution processes.

Equality, diversity and inclusion considerations have been embedded into the REF2021 preparation process. The HoD and REF2021 Environment Champion are chair and deputy-chair of the Departmental EDI Committee, and the Director of Research (overall REF2021 lead) is in

attendance. The Department was involved in the preparation of the University's REF2021 Code of Practice, through consultation and briefing meetings, and gave individual feedback on the draft Code. The HoD and all members of the REF2021 team attended targeted Code of Practice training events, and REF2021-specific unconscious bias training. The Department fully adhered to all aspects of the REF2021 Code of Practice, including the voluntary and confidential declaration of personal circumstances (centrally reported to a highly restricted group) and selection of outputs. For the latter, potential outputs were primarily self-nominated by individual Category A staff, but this was supplemented by a metrics-based search. All outputs were reviewed by at least two experienced (internal/external) researchers that were not co-authors, and selection was based on the outcome of those reviews. Each colleague returned was attributed their best output, with the remaining outputs strictly ranked according to the review score. Analysis of the attribution reveals that, on average, women in the Department returned 2.6 outputs, while men returned 2.4 outputs.

3. Income, infrastructure and facilities

3.1 Income

The REF2021 period has seen a dramatic improvement in research income and research spend for the Department. Since 2013 our annual research income (award) has grown from £4.2 million to £11.1 million. Research spend has risen from £5.9 million to £7.7 million, despite a significant slowdown in spend during the 2020 pandemic. The majority (63% or £32.1 million) of our income comes from the research councils, of which £19.3 million is from STFC and £9.9 million is from EPSRC, with most of the remainder from NERC, BBSRC and Innovate UK. A further £11.4 million of H2020 and ERC EU funding has been awarded. We are successful in attracting fellowships and funding from organisations such as the Royal Society and Leverhulme Trust, and have capital funding from charitable foundations such as Wolfson. Our REF2021 performance of 30% growth in research spend contrasts with REF2014 where our spend was stable between 2008/9 and 2012/13, averaging £(4.6±0.2) million. This testifies to the successful strategic expansion of the Department and the vitality of our research portfolio. There has also been a commensurate rise in the number of undergraduate students: growth of the Department is entirely sustainable and balanced in terms of research and teaching income.

Year	Income (award)	Spend (HESA)
2013/14	£ 4,201,362	£ 5,852,984
2014/15	£ 6,265,645	£ 6,313,032
2015/16	£ 6,290,310	£ 6,390,909
2016/17	£ 7,270,738	£ 6,739,981
2017/18	£ 7,192,970	£ 6,778,238
2018/19	£ 8,426,156	£ 7,718,062
2019/20	£11,086,420	£ 7,660,331
Total	**£50,733,601**	**£47,453,537**
Average	**£ 7,247,657**	**£ 6,779,077**

In addition to increasing our research council income, we have also substantially diversified our research funding streams, such that one third of our REF2021 income comes from sources other than research councils and the Royal Society. £11.4 million has been awarded by the EU, for a range of projects including the European MicroKelvin Platform (Haley, Tsepelin), ERC Starter and Consolidator grants (Mikhaylovskiy, Laird), collaborative research awards and several MSCA training grants and networks, including PROMIS (Krier coordinator). In the REF2021 period we have attracted £2.4 million from commercial organisations, publicly-owned companies and government agencies (principally Innovate UK and DSTL), including £1.3 million from the US Air Force for quantum technology research: double the REF2014 spend in this category. Furthermore, £4.9 million of our income from research councils is from projects with industrial partners, bringing the total income derived from inter-sectoral collaborative projects in the REF2021 period to £13.4 million, up from £8.1 million in REF2014. With a significant increase in impact-related research during the REF2021 period, a commensurate flow-through to impact related funding opportunities is envisaged over the next 5 years. Following on from the post-Brexit UK-EU agreement we will strengthen our collaborative research activity via Horizon Europe, and continue to increase our income from industrial collaboration.

3.2. Infrastructure and facilities

Over the REF2021 period Departmental and institutional infrastructure investment has been directed to research facilities for mechanical and electromagnetic isolation (IsoLab), the establishment of ultrafast-physics laboratories, enhancement of the Lancaster Quantum

Technology Centre and ultralow-temperature physics research. In 2017 the University invested £15 million in a full refurbishment of the Physics Department's 1960s building. The refurbishment included rewiring for power and data, mechanical services, specialist lab gases, upgraded and new research labs, and the addition of personal services such as shower areas, gender-neutral toilets, baby-changing facilities and an allocated space for breastfeeding in private. The works involved extensive remodelling of office space for academic and research staff and postgraduate students, the addition of a variety of meeting, breakout and informal learning spaces, and an upgrade of fabric elements throughout to increase accessibility, usability and aesthetics.

Local facilities, technical and professional support

The Department invests in the central provision of electronics and mechanical workshop facilities, with twelve FTE technical staff in support of our research groups. A further five experimental or technical officers provide specialist support for cleanroom and semiconductor manufacturing facilities, for cryogenics activities, and local computing support. Four FTE of professional services staff assist in grant preparation, human resources, financial and grant administration in the Department, in addition to the University's Research Support Office.

We operate substantial cryogenic liquid services, typically providing 100,000 litres of liquid nitrogen and 14,000 litres of liquid helium per year. Lancaster researchers have access to liquid helium at below-market (<50%) cost, and benefit from technical expertise in maintaining vacuum and cryogenic equipment. Helium recovery pipework throughout the Physics building minimises wastage of this non-renewable resource and allows us to work during times of helium shortage. Our cryogenic facilities support research in the Ultralow Temperature (ULT) Laboratory, LQTC, EPP and, outside Physics, the Chemistry Department and the Lancaster Environment Centre. The diverse range of state-of-the-art tools in the Department underpin multidisciplinary research activities in the departments of Physics, Engineering, Chemistry, Environmental Sciences, Biology, Psychology and the Faculty of Health and Medicine. The LQTC has outstanding facilities for materials growth, nanofabrication and characterisation, allowing condensed matter research to be rapidly undertaken through the full process from design to fabrication and testing in-house. We operate two molecular beam epitaxy machines for the growth of compound semiconductors, one of which was bought during the REF2021 period with an investment of £900,000.

There are three cleanrooms (classes 100, 1,000 and 10,000) with photo- and electron-beam lithography; wet and dry (inductively-coupled plasma, reactive-ion) chemical etching; material deposition by thermal and e-beam evaporation, plasma-enhanced chemical vapour deposition, sputtering and atomic layer deposition (£150,000); plasma ashing; semi-automatic dicing and wire bonding. Through University investment of £700,000, an X-ray photoelectron spectroscopy suite is now available for materials analysis along with advanced facilities for X-ray diffraction and reflection, scanning probe microscopy and scanning electron microscopy (located in Chemistry). Extensive facilities are available for optical characterisation from visible through to the mid-infrared, across a broad range of temperatures (1 to 400 K), and in magnetic fields up to 17 T. Similarly, for transport measurements (1 to 300 K, 17 T), and at world-record-breaking temperatures in the ULT laboratory. The LQTC supports research activities from 23 PI's, seven having joined in this period, much of which involves industrial collaboration. The LQTC hosts two spin-out companies (Quantum Base and Lancaster Materials Analysis), and facilitates access to the cleanroom for external parties (Precision Polymer Engineering and Trelleborg Sealing Solutions).

Beyond our conventional cryogenic liquefaction facilities, we have extensive ULT capabilities, with a world-leading suite of cryostats for research down to the microkelvin regime. The ULT laboratory holds a number of low-temperature records including the coldest sustained measured temperature of 5 μK for a solid, and record-breaking cooling of electrons in nanoelectronic devices to <4 mK. The laboratory is supported by excellent technical backup, developed over many years, and builds its own dilution refrigerators, which currently hold the world record for lowest temperature operation at 1.6 mK. The extensive suite of cryostats includes a range of 1 K cryostats; two 8 mK dilution refrigerators with magnetic fields up to 8 T; a 100 μK quantum fluids refrigerator; a double-stage demagnetisation custom cryostat designed to reach the nanokelvin regime and helium-4 cryostats for device testing. We are currently expanding our low-temperature facilities with two new Triton dry dilution refrigerators equipped with electronic access across the frequency range from DC to 18 GHz, dedicated to quantum electronics research. These refrigerators are accompanied by specialised low-noise radio-frequency measurement

electronics. Our ULT Laboratory and supporting facilities such as LQTC cleanrooms and IsoLab are available to external users free-of-charge through the European Microkelvin Platform infrastructure award.

In 2017, the Department opened IsoLab, a dedicated laboratory building with world-leading environment isolation capabilities. IsoLab houses three 'pods' to support research in quantum optics, low temperature electronics, and nano-imaging and microscopy. The IsoLab facility was delivered through University investment and philanthropic funding of £1.95 million. An initial complement of experimental equipment (£917,000) was supported by a grant from EPSRC. IsoLab capabilities are enabling research within the European Microkelvin Platform, a range of Innovate UK projects in collaboration with industrial partners and by early career fellowships holders (Royal Academy of Engineering, Leverhulme), generating more than £5.5 million in additional funding for research to date. The facilities in IsoLab are available to both internal and external users: since 2017, 16 companies have collaborated on research based in IsoLab.

Lancaster University provides a High-End Computing (HEC) facility delivering high-performance and high-throughput computing for research within and across departments. The HEC is equipped through grant funding combined with direct investment from the University, and is housed in a purpose-built central facility with water-cooled racking; the facility is staffed jointly by University-funded and grant-funded effort. All researchers at the University can access the facility for trial work, and are encouraged to win funding for equipment. Centralisation leads to over 90% central processing unit usage and savings on support effort. The HEC currently has 9,820 job slots (without hyper threading): 800 supporting IRIS/STFC science, 5,000 supporting Grid computing (GridPP, largely particle physics) and 4,020 for Lancaster local tasks. 480 cores are in high memory nodes, and we currently have two graphics processing unit blades. For storage we have 1 PB of IRIS and 3.9 PB of Grid storage.

Since 2018, the University invested over £300,000 in the expansion of accelerator physics and Cockcroft Institute activities, establishing new ultrafast laser laboratories for laser-driven electron acceleration and particle-beam diagnostics. This laboratory, including an amplified Ti:Sapphire laser, has leveraged opportunities for cross-disciplinary research in ultrafast dynamics in magnetic materials and an ERC award (Mikhaylovskiy, £1.2 million) in ultrafast magnetism. The ERC award is equipping a second laboratory with ultrafast laser systems covering mid-infrared through to the optical, closed-cycle optical cryostats and magnet systems. A further high-power laser system with sub-100 fs synchronisation to particle accelerator beams has been added to our facilities through an STFC grant and support of Lancaster, Manchester and Liverpool universities (Jamison, £350,000); the laser is based at STFC Daresbury laboratory, enabling use in conjunction with STFC-operated particle accelerator test facilities (§ 3.3).

3.3 External facilities

In addition to locally-operated facilities, Department researchers have benefited from access to a range of external national and international facilities, through collaboration and direct investment, and through competitive facility-access awards.

The particle physics group has access through the GridPP and Worldwide LHC Computing Grid collaborations to 90,000 computer cores from over 170 sites in 42 countries. Lancaster is one of five major university sites in the UK providing expertise and resources to this worldwide effort, producing a massive distributed computing infrastructure that provides more than 12,000 physicists around the world with near real-time access to LHC data, and the power to process it. In addition, the astrophysics and non-Large Hadron Collider experiments have access to IRIS resources across the UK. Lancaster is one of the major sites hosting and running IRIS facilities, with direct benefits to our research. There are 7,968 cores and 3,345 TB of storage available. During the REF2021 period, Lancaster Physics had access to a 1/8th share of the N8 Research Partnership (§4.1) Polaris high performance computing facility in Leeds, which is capable of 100 trillion teraflops, but benefitted from a larger share by agile use of idle cycles.

The Astrophysics MRG are active participants in the space mission community for astronomy and solar system science, serving on advisory and award panels (§4.5, 4.6). The group is engaged in research with NASA and ESA space missions, where the data sharing model is one of free-access utilisation of data from THEMIS (Time History of Events and Macroscale Interactions during Substorms), GEOTAL, ACE (Advanced Composition Explorer), Cassini-Huygens space missions, and the X-ray observatories XMM-Newton, Chandra and NuStart.

Non-UKRI competitive facility access.

The Observational Astronomy, Space & Planetary Physics, Condensed Matter Theory and Accelerator Physics subgroups have received over £20 million worth of competitive access to international facilities, of which £6.3 million is as principal investigator [Table 1]. Our largest access allocations are for observation time at European Southern Observatory's VLT on a wide range of instruments, and on the Hubble Space Telescope. Our research has also benefited from access to facilities such as the Spitzer space telescope, the IRAM (Institut de Radioastronomie Millimétrique) 30-m telescope and the Gemini and SALT (Southern African Large Telescope) 8-m telescopes.

We have been awarded computing access on the US TITAN 10 petaFLOPS facility for condensed matter modelling, and Italy's tier-0 Marconi with >150,000 cores for plasma acceleration. Through competitive beam-time awards we received significant access to relativistic electron beam test facilities VELA (Versatile Electron Linear Accelerator) and CLARA (Compact Linear Accelerator for Research and Applications): in both 2018 and 2019 we had the highest beam-time allocation amongst over 40 UK and European supported projects.

Table 1. Non-UKRI Facility competitive access obtained by our staff over the REF2021 period. Each facility listing may represent multiple distinct access awards. * Value excluding income-in-kind returned within REF4c.

Facility awards as Principal investigator		
Facility	usage	Value £k
Telescopes and radar		
Hubble space telescope	222 orbits	* 2628
VLT/X-shooter, HAWK-I, KMOS	225 hours	* 94
GTC	12 hours	132
CFHT	11 nights	154
INT	57 nights	* 386
VST	86 hours	69
WHT	14 nights	196
UKIRT	14 nights	196
Keck	4.5 nights	450
ALMA	51 hours	* 665
EISCAT	179 hours	268
Particle accelerators		
CLARA / VELA†	40 shifts	340
Computing facilities (excl. GridPP)		
Marconi	16.5M CPU hours	445

†hosted in UK but not operated as a UKRI Facility

Major (selected) facility awards as co-investigator		
Facility	usage	Value £k
Telescopes		
Hubble space telescope	993 orbits	11,916
VLT/VIMOS (LEGA-C)	128 nights (1152 hours)	5,120
VLT/X-shooter, SINFONI	438 hours	1,028
ALMA	182 hours	2,320
Computing facilities		
Titan	225M core hours	1,900

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

4.1 Support for collaboration, networks, joint research

Lancaster Physics is highly integrated into the international research community, with 80% of our publications co-authored with international partners. Our particle physics, observational astronomy and space science research activities involve over 3,000 partners in ~50 countries,

while other research groups maintain collaborations with scientists in more than 250 groups spread over 32 countries.

We have a sabbatical policy that encourages both staff and research collaboration development (§2.1). We are a member of the N8 Research Partnership of research intensive universities in the north of England. Through the N8 we share access to equipment and facilities, such as the N8 computing capabilities. We are the Principal Investigator department in the Cockcroft Institute for Accelerator Science, with the Institute Director from our staff (Ratoff, Director since 2014). The Cockcroft Institute brings together seven departments in four universities, and STFC Daresbury National Laboratories department for accelerator development, ASTeC. Through the Cockcroft Institute, Lancaster is enhancing its research in advanced particle accelerators, contributing to fundamental physics such as the muon magnetic moment, with applications from CERN operations to x-ray sources. The Department leads the LQTC (§1.2-ECM, 3.2), facilitating cross-disciplinary research across the departments of Physics, Chemistry and Engineering in low-temperature physics, quantum and semiconductor devices. We are leading members of the Lancaster Materials Science Institute and participants in the cross-departmental Lancaster Data Science Institute, and research centres Energy Lancaster and Security Lancaster.

The Department is highly supportive of industrial collaboration, and of academic-led commercial enterprises. Three spin-outs have been started since 2013, Quantum Base, Lancaster Material Analysis, and Lancaster Helium (§4.3). To support entrepreneurial activities, the Department recognises filings for intellectual property protection alongside journal publications as metrics to support probation fulfilment and promotion applications. As spin-out companies grow, the Department adapts its support to address their needs, facilitating joint research proposals and providing access to facilities and office space. Quantum Base, a spin-out focusing on quantum security devices (Young, academic co-founder), was registered with Companies House in 2013 and began commercial activity in 2014. Recognising the importance of co-locating Quantum Base's product development team with the research group to accelerate the growth of the company, dedicated office space within the Department was made available for ten company personnel.

4.2 Evidence of how staff interacted to develop impact

The Department is highly active in the generation of impact from across the breadth of its research portfolio. More than 70 impact generating activities in health, creativity and culture, commerce and the economy, policy, environment and public understanding were enhanced by £760,000 of Impact Acceleration Account awards (EPSRC, STFC and ESRC) and Faculty Impact Fund awards, which was supplemented by £370,000 of external commercial funding.

The LQTC is a key strategic tool that provides the infrastructure, expertise and culture to allow staff to deliver impact, leading to the genesis and development of three of our five impact case studies. This is exemplified by Young, LQTC Director and co-founder of the spin-out Quantum Base that has rapidly established itself in the nascent field of quantum security, achieving a valuation of >£10 million in six years (Impact Case: Young).

Young, Jarvis and Robinson led a team of Lancaster researchers in delivering an exceptional level of public engagement centred on LQTC research through three successive stands (2017-19) at the prestigious Royal Society Summer Science Exhibition (SSE), at New Scientist Live and a dedicated exhibition at the London Barbican Centre (by invitation). These events have a combined media reach in excess of 118 million. Combined audiences of a further 78 million were achieved by global publicity surrounding the inception by Hayne of the compound semiconductor 'universal memory', ULTRA**RAM**™ (Impact case Hayne, Jarvis, Robinson, Young).

LQTC/ULT's flair for public engagement is further demonstrated by the 2019 award-winning 'homemade' documentary film "The World's Coolest LEGO® Set! (Literally)", viewed ~450,000 times and attracting global publicity with a combined reach of more than 275 million (Impact case Haley, Pickett, Prance, Zmeev).

Auroral detection techniques underpin forest fire reduction systems which, with Kosch's long-standing involvement with South-African company EVS and its ForestWatch® product, has contributed to in excess of £2 billion of commercial savings for forestry, and stopping the release of more than 50 million tonnes of CO_2 into the atmosphere (Impact case: Kosch).

Dimopoulos (theoretical particle cosmology), Stefanovska (nonlinear and biomedical physics) and Jones (experimental particle physics) worked directly with artists and cultural organisations to cross the arts and science cultural divide through the media of art, film, music, and dance and

major cultural festivals; Dimopoulos has participated in interdisciplinary AHRC funded research leading to a series of interdisciplinary workshops, public talks, two art exhibitions, and a highly successful short documentary film shortlisted for "Best Research Film of the Year" for 2017 by AHRC. Dynamical analysis of biological signals, using techniques developed by Stefanovska, formed the basis for original works of music by composer Prof. Nigel Osborne MBE. In 2016 Jones initiated the World of Physics at the WOMAD cultural festival, bringing physics to a diverse audience through workshops, a walk-by discovery zone, planetarium and an 'accelerator in the sky' installation. The World of Physics concept has been successfully exported by Jones to cultural festivals Roskilde in Denmark, Pohoda in Slovakia, Ostrava in the Czech Republic, and WaterFire in the USA (Impact case Dimopoulos, Stefanovska, Jones).

In addition to the activities in the impact case studies, our portfolio of impact includes instrument sales of spin-out Anasys Instruments (co-founding by emeritus Sloan was a REF2014 impact case) and its acquisition by Bruker for $32 million in 2018; for semiconductor memories, Hayne received technology advice from IBM, IMEC, Micron and TSMC, seed investment and bespoke semiconductor wafers from IQE, and a UK government Department for International Trade Export Licence as a prelude to early-stage funding and patent agreements from a >$100 billion per annum turnover company; Kolosov's co-founding spin-out Lancaster Material Analysis; Hayne's development of (patented) telecoms-wavelength vertical-cavity surface-emitting lasers using quantum rings in an extensive collaboration with IQE plc; Marshall's development of next-generation infrared photodetectors with Amethyst Research, Leonardo and Selex.

4.3 Wider contribution to economy and society

Our staff contribute substantially to wider society, through numerous collaborative interactions with commercial organisations, advice to government and business emanating from long-standing expertise, and expert support to charitable and volunteer organisations. Wild is a member of the UK Space Environment Impacts Expert Group, providing advice on space weather and its impacts on national infrastructure such as power grids and rail to the UK government and policy-makers. He is also on the Government Office for Science Expert List for Emergencies, the pool of experts available at short notice to support the Government's Scientific Advisory Group for Emergencies (SAGE). Through his spin-out company Lancaster Helium Ltd (incorporated 2016), McClintock has been supplying the isotopically-purest ^{4}He in the world; the isotope purification capability has been generated through over two decades of ultralow temperature research within the Department. The product is being used in Germany, USA and Canada, eliminating the potential for tritium production in fusion research programmes. Within the European Microkelvin Platform, our low temperature physics group leads the innovation management, promotion, and exploitation work package, which includes the world's three leading dilution refrigerator manufacturers (Oxford Instruments, Leiden Cryogenics, Bluefors). The aim of this work package is to move innovation up the value chain, with particular focus on thermometry, cold electronics, and measurement platforms.

Our theorists are generating impact through collaborations with leading research institutions, multinational companies and SMEs. These include researching quantum transport in multilayer graphene (McCann), providing material modelling expertise for other 2D topological materials (Drummond), with the National Graphene Institute, and leading an EPRSC project and collaborating with NPL on quantum-interference-enhanced thermoelectricity (Lambert). They are collaborating internationally in impact-potential research, for example in demonstrating topological photonic devices for mode selection, developing a topological receiver-protector via a CNRS fellowship, and developing transition-edge sensors with the Space Research Organisation Netherlands (Lambert). The theory group also directly engages with a range of global companies such as IBM Zurich (in an FET-Open project to enhance thermopower on a molecular scale) and Castrol Plc (through ICASE and IAA awards), as well as nanotechnology SMEs (developing sustainable biofuels with Nanogap in the H2020 project BAC-TO-FUEL).

As Deputy Project Scientist, Simmons is a leader in Galaxy Zoo and Zooniverse, a distributed public-participation science project with over 1 million volunteers engaged in scientific projects, from searching rare events in LHC data, to wildlife protection and searches for new antibiotics. On behalf of the Zooniverse project, Simmons has delivered keynotes on machine learning to combat the illegal wildlife trade, and demonstrated technology to ministers, foreign ambassadors and key decision makers at the Foreign and Commonwealth Office's invitation. Simmons has also been consulting for the data science company 1715 Labs, applying techniques from citizen science to

the commercial sector. Honary has promoted the advancement of gender equality in Physics in the UK as a member of Institute of Physics JUNO equality accreditation panels since 2016.

4.4 Further engagement with diverse communities and public through its research

In addition to the impact-case engagement activities detailed in §4.2, we have a wide-ranging school outreach and public engagement strategy. Since 2016, we have provided an annual planetarium festival for 1,000 primary and secondary children. We have invested in a mobile planetarium (LUniverse) which our staff and students use to deliver educational shows to schools and community groups. In the face of the ongoing pandemic, we developed a virtual planetarium show, which is being delivered remotely to schools. We run multiple Physics Masterclasses annually (2015-2020) for A-level students. Since 2018, with support from Ogden and Nuffield Trusts, we have delivered a series of research-themed Professional Development workshops for A-Level Physics Teachers, and we have hosted summer internships. The Space and Planetary Physics subgroup operate AuroraWatch UK, a free service offering members of the public alerts when the aurora borealis might be visible from the UK. Users receive alerts via social media and smartphone apps with the service currently engaging with 103,000 Twitter and 214,000 Facebook followers in addition to 193,000 users of the bespoke app.

4.5 Evidence of contribution to sustainability of the discipline; interdisciplinary research; national/international priorities and initiatives

We regularly contribute to international research agencies through review and advisory roles. Drummond served on the review panel of the US Computational Materials Science Centres. Hook is chair of a Large Scale Structure of the Universe observing time allocation panel for the first cycle of the James Webb Space Telescope, an upcoming flagship NASA/ESA mission. Honary was a member of SuperMAG steering committee (2011-2019). Ray is the Vice-chair of the Europlanet Ireland-UK hub, and Arridge has represented the UK community in the development of new missions to Uranus/Neptune for ESA's calls for medium-class missions and the L2/L3 selection process.

Seventeen of our staff have been members on EPSRC and STFC grant and advisory panels, and we have chaired STFC Particle Physics Grants, Particle Physics Advisory, Astronomy Grants, and Solar System Advisory panels (O'Keeffe, Jones, Wild, Arridge, Kormos) and EPSRC Physics and CDT panels (Lambert, McCann). Pitkin was a review panel member for the British Council Researcher Links and is a member of the UK SKA Science Committee; Honary has served on the NERC Radar Advisory Group and the UK Space Agency Science Programme Advisory Committee. Jamison is a member of the UK Plasma Wakefield Acceleration steering committee; Grocott served on RAS Fellowship panels and Academy of Finland Research Council review panels. Lambert was a member of an Academy of Finland, Natural Sciences and Engineering Panel.

Thirteen of our academic staff are coordinators or project leads within the particle physics community, having held 34 convenor or spokesperson roles in the REF2021 period, including: convenor of D0 QCD and B-physics (Bertram); convenor of proto-Dune analysis and SBN Monte Carlo groups (Nowak); co-convener of the T2K near detector selection development and neutral pion analysis groups, UK work package manager for Hyper-Kamiokande experiment Data Acquisition (DAQ) systems and co-leader of SNO+ (Sudbury Neutrino Observatory plus) experiment radioactive backgrounds group (O'Keeffe); ATLAS UK Software and Computing Co-ordinator and Software and Computing Upgrade Project Leader, member of the IRIS Deployment Board, and ATLAS UK B-physics convenor (Jones).

Drummond is developer of the widely-cited CASINO quantum Monte Carlo molecular electronic structure package, and the Gollum code (Lambert) is used by more than 396 groups in 29 countries to predict quantum transport through molecular structures.

Our staff have contributed to the organisation of 152 conferences and workshops in 26 countries. Our astrophysicists organised and hosted the Royal Astronomical Society's National Astronomy meeting in 2019 (conference chairs Wild and Hook, Scientific Programme committee chair Badman). Our 61 academic staff have given over 300 invited or plenary talks in more than 40 countries. We have organised 27 scientific schools, including international schools on science and technology with the Extremely Large Telescope, ELT (Hook), four summer schools in Italy and one in India on the CASINO Quantum-Monte-Carlo code (Drummond), and the CCP9 "Widening Participation Workshop on Graphene" (Drummond). In particle physics we have hosted

5 GridPP collaboration meetings in the period, and also hosted the RD50 collaboration meeting on next generation position sensitive detectors.

We are participants in European FP7 and H2020 projects such as BAC-To-FUEL for bacterial fuel production (Lambert), Quantiheat for development of scanning probe microscopy (Kolosov), and three projects for sensor technology development through the CERN-led ATTRACT programme (Hayne, Marshall, Zhuang). We are founder members of the European Microkelvin Platform (Haley, Tsepelin), led the €2.5 million, Marie Skłodowska Curie ITN Nanoelectronics (Lambert) and the €4 million PROMIS ITN (Krier), and participate(d) in ITNs COMRAD, MOLESCO, QUANTIMONY (Hayne chairs project Board) and COSMOS (Stefanovska).

4.6 Indicators of wider influence, contribution and standing.

Our staff hold numerous positions of leadership and influence in science institutions and major international projects. Wild served as Vice-President (Geophysics) of the Royal Astronomical Society (2014-2016) and Chair of the STFC Astronomy Grants Panel (2012-2019). Arridge is a member of both the Cassini magnetometer (MAG) and plasma spectrometer (CAPS) teams, a co-investigator on the JUICE J-MAG instrument and co-chair of ESA's Voyage 2050, charged with developing a roadmap for space science missions through to 2050, including setting the themes for ESA's three large-class missions beyond 2035. Stott is on the UK executive board of Large Synoptic Survey Telescope (LSST) based in Chile. Hook is a member of ESO Council, a member of the international Project Science Team for the Extremely Large Telescope (ELT) (invited by ESO), and member of the Tri-Agency (NASA/DoE/NSF) international task force on survey coordination between future projects Euclid, LSST and WFIRST. Sobral is a Board member on Portugal's Astronomical society. Kosch serves as executive committee member of the International Association of Geomagnetism and Aeronomy (IAGA), South African representative on the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP) and is Head of Space Research and Applications (chief scientist) at the South African National Space Agency (SANSA). Jones is chair of the collaboration boards of the UK GridPP and WLCG global distributed computational effort for LHC; he also Chairs the STFC Particle Physics Advisory Committee. O'Keeffe is a member of the UK Committee on CERN (UKCC), chair of the STFC Particle Physics Grant Panel (2019-22), a member of the Near Detector Steering Committee on T2K, and as convener of near detector physics analysis is responsible for the output and prioritisation from over 100 analysts. Kormos is T2K ECal detector convenor. Lambert serves on the CECAM (Centre Européen de Calcul Atomique et Moléculaire) Council.

Thirteen of our academics have held one or more prestigious early and advanced career fellowships during the REF2021 period, including Royal Society URF (Arridge, Ponomarenko, Young), Leverhulme (Jarvis), ERC Starter (Mikhaylovskiy), ERC Consolidator (Laird), RAEng Fellowship (Marshall, Laird, Thompson), Rutherford Fellowship (Ruggiero, Wardlow, Badman), EPSRC Established Career Fellowship (Ruostekoski), EPSRC Early Career Fellowship (Zmeev) and Royal Astronomical Society Fellowship (Badman). Lambert was elected a member of the Academia Europaea in 2016.

Since 2015, six of our postgraduate students have been awarded Springer Distinguished Thesis Prizes and had their thesis published, approximately 1 in 60 of all theses selected by Springer-Nature Worldwide.

The contributions of our research to the global community is indicated by an average of 32.5 citations per paper, across 2392 publications since 2014. Over a third (35%, Scival) of our publications are in the top 10% of field-weighted citations. Ponomarenko has been designated a Highly Cited Researcher by Clarivate Analytics throughout the period 2016 to 2020.

Our staff include winners of the Breakthrough Prizes for Fundamental Physics: in 2016 for the work on neutrino oscillations (Kormos, Nowak, O'Keeffe, Ratoff); in 2015 as a member of the Supernova cosmology project (Hook); and as a member of the LIGO Scientific Collaboration, Pitkin shared the 2016 Special Breakthrough Prize in fundamental physics for the first detection of gravitational waves, which also won the 2016 Gruber Prize in Cosmology and the Nobel Prize for Physics in 2017. As members of the SNO collaboration, Kormos and O'Keeffe contributed to the neutrino flavour-change research that was awarded the 2015 Physics Nobel prize. We shared in the 2019 European Physical Society prize for the D-Zero experiment (Bertram, Borissov, Fox, Ratoff).