Unit-level environment template (REF5b)

Institution: Durham University

Unit of assessment: Physics

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

1.1 Context

The Physics department is the largest of the eight departments and schools within the Faculty of Science at Durham and is a thriving centre for research and education. It is the fifth largest Physics department in the UK, with 85 Cat A staff, 95 PDRAs and 178 PhD students. We teach around 575 undergraduates per year through a combination of single honours four-year MPhys and three-year BSc Physics degrees, as well as 286 interdisciplinary students taking some Physics modules under our Natural Sciences programme. The department closely aligns the teaching and learning experience for its students with the research-intensive values and practices of the university. Research-led teaching is embedded at all levels from first year laboratory reports to the final year MSci flagship individual research project, worth half of the marks for that year. Our department is ranked 4th in the 2020 Complete University Guide subject league tables.

Highlights of the REF period include:

- Research grant funding of GBP87M, and GBP37M of in-kind funding;
- **Carlos Frenk** appointed as Commander of the Order of the British Empire (CBE) in the 2017 Queen's Birthday Honours for services to cosmology and public understanding of science;
- Outreach events directly involving over ~15,000 school children and ~500 teachers in local region which has high social deprivation;
- Teaching materials 'From Higgs to Hubble' used by over 100,000 secondary school pupils;
- Opening a new GBP12M building designed by world-renowned architect Daniel Libeskind;
- Economic impact from successful spin-out companies and partnerships with major global companies such as Procter and Gamble;
- Societal impact from leveraging computer simulation expertise to model the pandemic. This code is used by NHS England Emergency Preparedness Resilience and Response Group.

1.2 Research structures (see Figure 1)

There are six intermeshed research groups spanning a wide range of areas: from blue skies research in astronomy and cosmology (Centre for Extragalactic Astronomy: CEA and Institute for Computational Cosmology, ICC), elementary particle physics (Institute for Particle Physics Phenomenology: IPPP) and ultracold atoms/molecules (Quantum properties of Light and Matter: QLM), to the more applied groups which focus on understanding and fabricating new materials (Centre for Materials Physics: CMP) and precision optical devices (Centre for Advanced Instrumentation: CfAI). Economic impact is currently concentrated in the more applied groups, as these have most potential for industrial collaboration and spin out companies, while the more fundamental groups have societal impact through public understanding of science.

The university also has institute structures. These can be sharply focused to promote areas of excellence, such as the Institute for Particle Physics Phenomenology (IPPP, which includes all of the particle physicists), and the Institute for Computational Cosmology (ICC, incorporating the astronomers working on large scale computer simulations of the universe). Both of these Institutes are hosted entirely within physics and together make up the Ogden Centre for Fundamental Physics.

The other eight university Research Institutes span departmental boundaries, enhancing multidisciplinary collaboration. Physics is strongly represented in many of these, with significant leadership positions, for example:

- The Biophysical Sciences Institute (BSI: Director **Girkin** to 2019, which links to Biological Sciences, Chemistry, Engineering and Mathematical Sciences)
- The Durham Energy Institute (DEI: co-director **Halliday**, linking especially to Engineering and Chemistry)
- The Institute for Data Science (IDAS: Director **Krauss**, reaching across Mathematical Sciences and Computer Science).

These broader Institutes form the supporting context for the four multidisciplinary Centres for Doctoral Training (CDTs) with Physics leadership (Soft Matter and Functional Interfaces - BSI, Energy - DEI, Data Intensive Science – IDAS and a new Global Challenges Centre - DEI). Two additional CDTs with substantial Physics involvement are hosted by the DEI, on Fusion energy (with York, with CfAI and CMP) and on Renewable Energy North East (Newcastle and Northumbria with CMP).

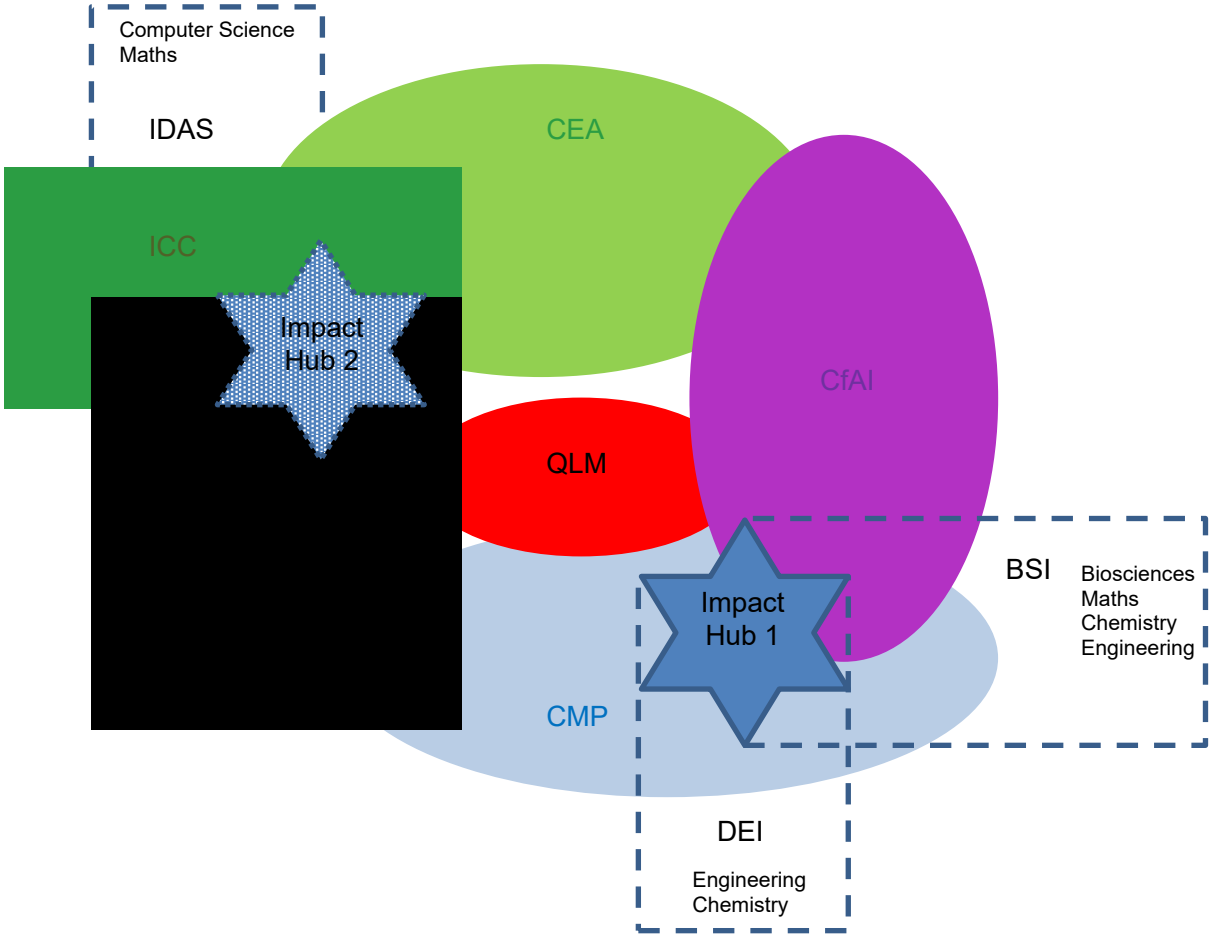

Figure 1: How groups in Physics relate to each other, to the Institute structures, and main linkages to other departments within Durham. Current impact is mainly concentrated in Hub 1. Additional planned, future impact growth areas in Data Sciences are shown as Hub 2.

CfAI Centre for Advanced Instrumentation Bourgenot (F), Brown (L), Chadwick, **Girkin,** S. Morris, T. Morris, O'Brien, Osborn (P), Saunter, Sharples, Wilson	Design, development and fabrication of precision optical instrumentation e.g. adaptive optics on large telescopes (Harmoni on the Extremely Large Telescope) and massively multiplexed fibre fed spectrographs, either robotically placed to enable efficient spectral surveys of galaxies and quasars (as used in the Dark Energy Spectroscopic Survey: DESI), or close packed into arrays to give true imaging-spectroscopy (integral field units) such as NIRSpec (James Webb Space Telescope) and KMOS (European Southern Observatory Very Large Telescope VLT). The same technology is applied to imaging spectroscopy of tokamak fusion plasmas.
CEA Centre for Extragalactic Astronomy **Alexander,** Cooke (P), Done (DoR), Edge, Fumagalli, Jauzac (P), Massey, Morabito, Norberg, Roberts (DoE), Smail, Smith, Swinbank	Predominantly observational studies using large scale surveys (including 4MOST and DESI) to trace the cosmic web of galaxies across the Universe. Multiwavelength observations of individual objects and populations using the largest available facilities (including KMOS on the VLT) to understand the astrophysics of galaxies and their central black holes. X-ray studies of accretion show the growth of quasars, while radio (LOFAR and SKA) and very high energy gamma rays (CTA) probe jets. Tracing the buildup of the elements using gas in the intergalactic medium.
ICC Institute for Computational Cosmology Amorisco (F), Baugh, Bower, **Cole**, Deason (P), Eke, Frenk, Jenkins, Lacey, Li, Theuns	Uses supercomputer simulations to understand the origin of galaxies and larger scale structures and their evolution across cosmic time in a Universe dominated by dark matter and dark energy. These models are tested by large scale surveys, including CEA. Calculating the imprint on large scale structure of new physics in the dark sector of the Universe.
IPPP Institute for Particle Physics Phenomenology Abel, Alonso, Andersen, Badger (P), Bauer, Cerdeno, **Ellis,** Glover (HoD), Huss, Khoze, Krauss, Maitre, Pascoli, Pecjak, Schoenherr (P), Spannowsky	Addresses the fundamental nature of matter from two major standpoints. Firstly, providing high precision calculations within the standard model to interpret results from the LHC at CERN and other experiments, and secondly investigating and modelling beyond the standard model effects at the LHC, in neutrino oscillation experiments, in quark flavour physics and the dark sector.
QLM: Quantum Light and Matter **Adams,** S Bromley (F), Carty, Cornish, Chancellor (F), Gardiner (0.5FTE as Deputy Executive Dean), Hughes, Jones, Kendon, Potvliege, Weatherill	Advance fundamental understanding of the quantum properties of atoms, molecules and solids and their interactions with light, using ultracold Rydberg atoms and molecules, Fermi degenerate gases, with quantum optics, technology, and computation.
CMP: Centre for Materials Physics Adeyeye, (College Head), Atkinson (DoF), **Clark**, E. Bromley, (DoEDI), Degiacomi (P), Dias, Fielding, Gidopoulos, Halliday, Hampshire, Hatton, He, Hindmarch, Hunt, Kusumaatmaja, Lancaster, Mendis, Monkman, Staykova, Szablewski, Terry, Tjhung (L), Voitchovsky	Topics range from understanding the electronic structure of complex materials, with applications in organic light emitting diodes, photovoltaic solar cells and semiconductors, to magnetism and magnetic devices at both the nano-scale and for superconductivity. The group now extends into soft matter, with experimental and theoretical research into materials such as polymers, gels, and colloids as well as bio-molecules, their dynamics and self-assembly.

Table 1: Staff and research topics for groups in Physics as shown in Fig 1. Staff in bold font are section heads. Other abbreviations are F – Early Career Fellow (fixed term), P – proleptic appointment, L – Lecturer (fixed term), HoD - Head of Department, DoR - Director of Research, DoE - Director of Education, DoF - Director of Facilities, DoEDI - Director of EDI

1.3 Research Strategy

Our stated goals from REF2014 were to:

- Increase grant funding;
- Increase postgraduate research (PGR) numbers and training provision at doctoral level;
- Complete the building program for Ogden Centre West, including the refurbishment and reconfiguration of the vacated space to rationalise and consolidate all the groups after a period of sustained growth.

All of these objectives have been successfully met despite the harsh economic climate (see below).

Our overarching research strategy during the period covered by REF2021 was to build critical mass in areas of excellence, both by consolidating existing core activity and responding to new opportunities. The centre and institute structures provide a coherent, focused and supportive environment, which is also flexible enough to adapt to the evolving research landscape. Our sustainability and vitality are demonstrated by the evolution of the groups during the REF period described in **Section 2,** and are underpinned by a commitment from the university to fully replace all vacated posts including retirements. We use open positions both to refresh existing research strengths, and to flexibly realign our research to exploit new opportunities, especially those which link between groups in a cross-cutting manner.

Going forward, we plan to build on this approach, and have identified several new areas in which to re-align existing group structures. Many of the research strengths in the department depend on high performance computing. This is required to produce, analyse and interpret the enormous datasets from simulations of the Universe (ICC), as well as those produced by current and upcoming new telescope surveys (CEA and CfAI). Similar computational challenges result from interpreting data from particle collisions at CERN, e.g. identifying the one Higgs interaction from the 10^{11} background events (IPPP), while in CMP the computational challenges are instead in determining the multi-electron orbital structures underpinning the behaviour of complex materials.

These strands have already been drawn together in the new Institute for Data Sciences, building on the success of the CDT in Data Intensive Science developed by Profs **Krauss** (IPPP) and **Baugh** (ICC) to train excellent researchers in cutting edge science and techniques in artificial intelligence and machine learning. This demonstrated the power in sharing research experience and techniques between the research groups in physics as well as strengthening links to industry via its placement scheme. Our aim is to use IDAS to strengthen our research, leveraging its multidisciplinary links to Mathematical Sciences and Computer Science to position ourselves in readiness to maximally exploit the science from the enormous datasets expected in the next REF period. Facilities such as the Large Synoptic Survey Telescope (LSST), an optical telescope which will map the sky every day to look for transients, and the Square Kilometre Array (SKA), the world's largest radio telescope, will produce PetaBytes of data every day for their operational lifetimes.

Another area of regrouping identified in our strategy links together the IPPP research expertise on exploration of physics beyond the standard model with QLM using laser cooled Rydberg atoms as exquisitely sensitive probes of new physics. Light dark matter (where ‘light’ refers to mass, ‘dark’ to its lack of any electromagnetic interaction) can potentially give distortions to the Coulomb potential or particle masses, leading to minute, time-dependent variations in spectral line energies. IPPP have the field theory expertise to predict masses and couplings from the various models of new physics (e.g. axions, hidden photons). QLM have the techniques and equipment to manipulate and cool atoms, producing systems with a single electron placed in a very high

principle quantum number shell. This gives a vastly inflated atomic size of order a micron, so the electron is extremely loosely bound and, hence, very sensitive to external fields or interactions, such as those expected from light dark matter. The precision of these experiments can be increased further when combined with CfAI expertise in designing and fabricating quantum sensors, and CMP theoretical understanding of electronic interactions in these sensors. The high risk/high reward outcome of this program would be nothing less than the discovery of a dark matter particle and the identification of the new physics behind the dark sector. However, the guaranteed return is in the development of laser cooling and sensors, controlling light photon by photon, and matter atom by atom, with the further aim of producing the world's first Rydberg Hydrogen and Helium atoms.

1.4 Impact Strategy

Our strategy to enhance the impact of our research is threefold.

i) Research driven impact, where a discovery gives clear potential for exploitation. This arises most often in CMP, as their work on understanding the structure of new materials has more immediate application in industry. Research & Innovation Services (RIS) supports academic staff through all the stages of commercialisation, as illustrated by the case studies below.

The classic spin-out company model allows the impact to be directly controlled and exploited. Two of our case studies illustrate this route at different stages of development. **Kromek** is a well-established spin-out, based on the discovery of a novel way to grow large, defect free, semiconductor crystals. The potential of these for detector technology was quickly recognised and the decision taken to form the company. This soon outgrew university premises in Physics, and moved to NETPark, the NE Technology park (see **Section 4**), becoming one of their anchor tenants. It employs over 100 people in the UK and USA and had a turnover of GBP14.5M in 2018-19. Kromek has impact in security, with its detectors in use in liquid screening in over 50 airports in 11 countries as well as in health via medical imaging, where contracts presently stand at over USD58M.

By contrast, **Durham Magneto-optics** is a much smaller scale spin out company. This grew out of research on magnetic switches, where the information is carried in the polarity of magnetic domain walls (spintronic devices) but nanoscale fluctuations in the size of the magnetic domains make these difficult to control. Researchers in CMP developed a unique instrument to sensitively resolve changes in magnetic structures in real time, and set up the company to make this commercially available as a scientific instrument.

Peratech instead grew from a new pressure-sensitive material discovered by industry, giving a potential new dimension of response for touch screens. CMP research revealed the physical origin of the special properties of this material, and this understanding was key to its successful commercialisation.

Licencing of IP (via RIS) gives another route to commercialisation, using an appropriate industrial collaborator as demonstrated by **Castep.** This is a computer code developed from research in CMP to predict the electronic, physical and chemical properties of materials from first principles in quantum mechanics by calculating the many body interactions between multiple electrons, now also including strongly correlated systems, not just density functional theory approaches. This has been cited by more than 982 patents since 2016.

ii) Planned engagement with industry. There has been a shift in the funding landscape toward larger, more complex grants, which involve multiple university and industrial partners. RIS supports academics through the process of applying for these grants, with expertise on the financial and legal aspects of contracting, as well as advice on building and managing the consortium.
The **Brucker** case study illustrates this, where Durham led a Euro2.65M European Commission Framework 7 ICT project with multiple partners in academia and industry to investigate Silicon

wafer failures in semiconductor manufacturing. Research in CMP showed that X-ray imaging was able to distinguish cracks which would fail during high temperature processing, and those which were benign. Jordan Valley Semiconductors UK, an SME in the consortium, made the strategic decision to develop this IP into a fully automated tool for in-line inspection and removal of suspect wafers, and current sales are in excess of GBP1M.

Case study **Fusion** instead highlights how a single research activity can play a key role in a much larger collaboration. The Euro20 Billion ITER project is building the first commercially viable tokamak. This uses low temperature, superconducting materials to carry the large currents required to confine the plasma, but these currents induce a magnetic field in the superconductor. Above some critical current, this turns the superconductor back into a normally resistive wire. Prof **Hampshire** (Durham Physics CMP and DEI) designed the first instrument to make high accuracy measurements of this critical current, which led to Euro2M of contracts to characterise the wires for the ITER magnet system. Those which do not meet the Durham tests are not used in the tokamak, avoiding potentially catastrophic failure of the superconducting ring.

iii) Long term, formal partnerships with industry. This third approach builds and extends on the planned engagements with industry described above. It was initiated from the success of a project with Procter & Gamble (P&G, a US USD 80Billion turnover company), where they were trying to develop low temperature, more efficient detergents to minimise energy costs and environmental damage. P&G were using optical microscopy to image the effect of detergent on fatty stains. However, fat itself acts as an optical element, so the images were distorted. Prof **Girkin** (BSI and a member of CfAI in Physics) used techniques from Adaptive Optics, developed to remove atmospheric distortion from large astronomical telescopes, into the process. This gave much higher resolution images, revealing new aspects of how molecular bonds are broken and reformed in the washing cycle which generated multiple spin off projects in Chemistry. In response, RIS set up a Master Collaboration Agreement to make a single structure for Intellectual Property (IP) and consultancy agreements covering all projects with P&G. This circumvents the hidden barriers in starting up a single collaboration, where these issues have to be negotiated from scratch with each individual academic and/or department. There is now a portfolio of over 100 funded projects leveraging GBP24.5M (including GBP11.5M in Government and Research Council support) across the university. P&G ranks Durham as a 'best in class' academic partner in recognition of its innovative approach to university - business partnering where research needs and research capabilities of both partners have been carefully mapped and core areas of mutual interest identified (see case study: **P&G-Durham Physics Partnership**).

Going forward, we will build on each of these three approaches to impact. We now have additional Master Collaboration Agreements building long term, formal partnerships with IBM, Akzo Nobel (who bought ICI), the BG Group (formerly British Gas PLC) and others, and these form part of our future strategy for developing new impact in Hub 1, focussed on the properties of materials.

We are also developing an additional impact direction (Hub 2 in Fig 1) based around the new Institute for Data Sciences. This will build on the industry links developed for the Data Science CDT (see **Section 2**), which required that the students did at least two placements in industry. Our partners for this include SME companies in NETpark, as well as the global industries in Hub 1, and international banks such as Barclays and Atom. Example projects included working with a local X-ray imaging company, IBEX at Netpark, on using machine learning to discriminate between bone and soft tissue in the presence of noise. The resulting software is now incorporated into the IBEX imaging system and the results presented at the influential SPIE Medical Imaging conference, as well as showcased to MPs at Westminster. Another project for the United Nations used artificial intelligence/neural networks to produce imaging software which could automatically classify and count temporary structures from satellite images of refugee camps, giving a real time estimate of occupancy to inform humanitarian relief work.

Larger scale impact is already starting to develop from this out of our mainstream research. For example, ICC simulations of the Universe are computationally very expensive and there are too many free parameters to fully explore the effect of each one. Instead, they have developed

Gaussian emulator methods in collaboration with statisticians in Mathematical Sciences, using sparse data to reliably predict how the results depended on the multiple input control parameters. The same methods are now being applied in a collaboration with P&G to control the operation of their drying towers to make washing powders more efficiently. This already gives results comparable to those that had developed over five years of experimental trial and error. P&G are rolling this out as a tool in all their drying plants (see case study: **P&G-Durham Physics Partnership**). The same approach is now being trialled with the Department of Work and Pensions for assessing the outcome of proposed public policy changes.

1.5 Interdisciplinary Research

There are multiple interdisciplinary aspects to our research. These are facilitated by the Institute structures (see Fig 1), which explicitly link thematically across to other departments. For example, the Durham Energy Institute (DEI) brings together staff in CMP working on understanding and characterising the behaviour of photo-active materials, both for lighting and solar cells, with the staff in Chemistry who make these highly specialised molecules, and staff in Engineering who design the systems. Similarly, the Biophysical Sciences Institute (BSI) links work in soft matter CMP on bio-inspired molecular design, such as a nano-scale motor that can 'walk' along DNA, with the biologists who work on synthesis of these proteins.

The more specialist institutes still have strong interdisciplinarity e.g. the IPPP has close links with the Theoretical Particle Physics group in Mathematical Sciences. Together they form the Centre for Particle Theory with a joint seminar program and PGT MSc student training course (see **Section 2.2**). **Gregory** (returned in UoA 10) is a joint appointment, while **Abel** (returned in this UoA) is in Mathematical Sciences.

Another strong driver of interdisciplinarity within the Science Faculty comes from the UKRI Centre for Doctoral Training (CDT) programs, described in more detail in **Section 2.2**. Broader cross-faculty projects are facilitated through the Institute for Advanced Studies and the wider Durham collegiate system, both of which foster contact between staff members across the university. For example, Prof **McLeish** (FRS, CMP in Durham until 2017) was Co-I on both an AHRC major project (led by History) on The Ordered Universe: Interdisciplinary Readings of Medieval Science, GBP0.8M from 2016 to 2020, and on a Templeton foundation grant (led by Theology) on Equipping Christian Leaders in an Age of Science of GBP0.7M (2015 to 2019). **Staykova** (CMP) is PI on a Royal Society Apex GBP0.1M award 'Material Imagination' in collaboration with Sociology, to establish the principles of a self-propagating bacterial factory as a new living material and to shape the future of this material using participatory design methods.

Our strategy for future growth in interdisciplinarity is to use the new IDAS to add to these existing links, strengthening collaboration with Mathematical Sciences and Computer Science in research techniques for big data, machine learning and artificial intelligence.

1.6 Open Access and Ethical Research

Open access to data, software and publications is routine in Astronomy and Particle Physics. Large scale sky surveys are made public in a series of data releases to maximise the science return. For example, the Panoramic Survey Telescope and Rapid Response System (PanSTARRS), designed to alert for collisions from Near Earth Objects, observed the entire available sky several times per month. The immense task of uniformly calibrating and releasing this dataset was led by **Metcalfe** (CEA, not returned in REF as his position is to support research and teaching in the department) as chair of the Science Consortium Data Verification Group. Similarly, the ICC have pioneered the release of data from their large scale computer simulations of the growth of structure in the universe in a similar manner to real observations.

Open access to publications was pioneered by the Particle Physics and Astronomy communities, with their preprint servers making research papers freely available worldwide, but it is now also

becoming standard to publicly release software. This includes both individual codes and the larger software tools such as Herwig and SHERPA, developed by IPPP for analysis of LHC data.

The new developments over the REF period have been the rolling out of open access/open data across the wider Physics and university community. The university is fully committed to sharing results of its research not only with academics but also industry, health services, government and the general public. Durham research online contains full text versions of publications by Durham staff, while the research data repository is used to store, curate and make available any research data/software as part of the research data management plan which is now required by most grant funders.

There is a departmental ethics committee, which assesses all relevant grant applications. These include scrutiny of collaborations outside of the EEA, especially those with developing countries, where inequalities in power and status of participating scientists could lead to bias in claiming intellectual property e.g. the Global Challenges CDT based around the UN sustainable development goals with Development Assistance Committee nations. The university also has a specialist Research Policy team, responsible for the review, development and implementation of all the processes which underpin Research and Innovation activities. This includes oversight of all funded work with outside bodies, including consultancy, commercialisation and engagement activities.

Section 2. People

2.1 Context

In REF2014 we submitted 74 Cat A staff out of a possible 82 whereas there are now 85 Cat A staff, showing the sustainability and vitality of the department. There is a university commitment to replace all vacant positions from either retirements or staff mobility. This has enabled the groups to consolidate after the period of more rapid expansion in 2008 to 2014, resulting in an approximately flat age profile from 35 upwards and a growing diversity at senior levels. We have similar numbers of postdoctoral fellows as in REF2014 and a 10% uplift in PDRA support. We have markedly increased our number of PhD students, from 154 in 2014 to 192 in 2019. This was a key forward goal from REF2014 which has been achieved despite a hostile economic climate. Much of this growth came from the externally funded CDTs, which leveraged substantial university and industrial investment in terms of funding additional studentships. Both postdoc and PhD cohorts are ~25% female.

2.2 Staff Development: Probation, Progression and Promotion

There are formal probation structures for all new academic staff, including a requirement to complete the PostGraduate Certificate in Academic Practice (PGCAP) which gives training and support on teaching methods and course design in accordance with the UK Professional Standards Framework supporting learning in Higher Education. Alongside this, we also assign a specific teaching mentor as well as a general mentor who can advise on all aspects of the role. The teaching load for a new lecturer is tapered at 1/3 and 2/3 for their first and second year, demonstrating our commitment to helping staff establish their research group, and complete the PGCAP whilst developing their new courses.

We have robust processes for promotion, with all academic and research track staff in post for more than two years submitting their CV each year for consideration against written criteria for each grade. Impact is explicitly included alongside research, teaching and citizenship roles. All other research staff have an Annual Development Review to give an opportunity for input on their career direction and goals as well as feedback and recognition for their achievements.

Staff are supported in terms of progressing their research though advice on applying for grants via departmental mentoring, and the university RIS structure. This advertises all grant

opportunities from external funding calls, as well as running drop-in sessions for each research section to give more tailored advice. They also circulate information on internal funding, such as the university seedcorn grants, which can be used for pilot studies to demonstrate feasibility before writing a grant application, or for impact activities. EPSRC and STFC Impact Accelerator Account funds are an additional source of support for developing impact from research. Recipients of these funds include for example **Girkin** (CfAI), for development of a near IR dental imaging instrument, **Massey** (CEA), modelling the growth of cancerous tumours using modern statistical techniques and **Kendon** (QLM), working with D-wave, the first commercially available quantum computer.

2.3 Staff recruitment

All groups have recruited new staff during this REF period, in line with departmental strategy of consolidating areas of existing excellence and repositioning groups to exploit future opportunities. We have a general policy of recruiting earlier career staff, appointing those with emerging leadership potential rather than hiring more established figures. We advertise internationally, including targeted searches, to ensure the largest and most diverse pool of talent. This, combined with our track record of appointing holders of long-term research fellowships to academic posts as proleptic appointments, has ensured the sustainable age profile and growing diversity discussed above.

New research areas identified as strategic future directions are specifically targeted for recruitment e.g. CfAI recruited **O'Brien** from Oxford for his work on Microwave Kinetic Inductance Devices (MKIDS). These quantum sensors are an emerging, disruptive detector technology that promises to revolutionize many areas of UV, Optical and Infrared instruments by giving energy sensitive imaging arrays, removing the need for the complex optics of a separate fibre fed spectrograph. These highly sensitive devices align with our planned activity in 'Quantum Sensors for Fundamental Physics', spanning across IPPP and QLM as well as CfAI and CMP, with **Bauer** hired in this area in IPPP. Similarly, CEA identified radio astronomy with the SKA as a future research priority, hiring **Morabito** for her experience in this field. The success and sustainability of this approach going forward into the future is highlighted by the recent announcement of both Bauer and Morabito as UKRI FLF (round 4).

University policy is currently focussed on hiring Cat A eligible, fixed-term lecturers to cover grant and/or fellowship teaching buyouts rather than fixed term staff on teaching-only contracts. These lecturers are independent researchers and contribute to the research environment as well as to the teaching programme. This also makes the posts more attractive as they encompass the full set of skills required for an academic post, giving a better defined pathway for future career development.

This approach is exemplified by recent staff developments within the relatively new soft matter group in CMP. This saw major expansion in the previous REF period, with five staff hires in response to the high level university joint appointment of **Mcleish** FRS as Pro-Vice chancellor for research and a Professor in Physics. Prof **McLeish** won the 2017 IoP Sam Edwards medal for his sustained and outstanding contributions to the fields of molecular rheology, macromolecular biophysics and self-assembly, before moving to York to take up a Chair in Natural Philosophy. The university commitment to replacements meant that we advertised a lectureship in this area, and the successful candidate, **Diagiacomi**, was appointed in 2019. He was part way through a GBP0.8M EPSRC early career fellowship and his teaching buyout funded a three-year fixed-term lectureship, with **Tjhung** appointed in 2020.

There is also the flexibility to respond to unplanned opportunities, as exemplified by the high level university appointment of **Adeyeye**, from the National University of Singapore, whose research field is nanomagnets in non-volatile memory technologies (an area of current CMP strengths, see also Impact Case Study: **DMO**). He was recruited to a joint position as both a Professor in Physics and as the Head of Trevelyan college, connecting us to the wider student experience as well as strengthening a strategic, impact generating, research strand. His research activity is supported via a Royal Society Wolfson Fellowship.

Succession planning highlighted a few key positions where appointments at a very senior level are required such as the Directorship of the IPPP and ICC. The university is fully supportive of this, and we recruited **Ellis** (FRS) in 2015 for IPPP from his position as Head of the Theory Department at Fermilab, USA. A similar search for a replacement for **Frenk** (FRS, OBE) led to **Cole** (Shaw prize winner, 2014) being appointed as director of the ICC.

2.4 ECR support (Cat A and B/Z)

All new staff appointments come with a negotiated start up package. This is especially important for early career experimentalists, where equipping a laboratory is required before their research can flourish. We offer consultation to all incoming academic staff to make sure that they are making an appropriate bid for support of their research, to overcome any biases which can arise from background.

All research staff are also encouraged to take part in teaching in the department to build experience and enhance their CV with transferable skills. This is limited to six hours per week in term time, so that their research is not unduly impacted, and they are recompensed by travel funds to attend conferences in their field. They are also encouraged to attend relevant skills training courses run by the university. These include ones specifically focused on ECR such as 'Networking and making the most of conferences', 'Hacking the academic job market' and 'Preparing for a non-academic career' as well as more general courses on entrepreneurial learning, innovation and enterprise. There are annual 'Physics Awards for Excellence' for fixed-term staff in the Physics department, allowing them to highlight the quality of their research on their CV.

Postdoctoral researchers hired on grants are also supported to develop their own independent research career. This is a key recommendation in the Concordat to Support the Career Development of Researchers. The department has implemented our Research Staff Consultative Committee proposal to allow 20% of time for development of independent projects and skills, and also provides a small funding stream of GBP 20k annually to support this e.g. for travel to build new collaborations or to cover minor equipment requests.

2.5 Sabbatical leave and secondments

All staff are actively encouraged to apply for sabbatical leave. This can be taken in Durham, to ensure it is equally accessible for staff with caring responsibilities, as well as the more traditional sabbatical leave hosted elsewhere. There is flexibility in scheduling this, so that it can be either taken as a single term e.g. **Lancaster** (CMP), who was invited to take up a visiting Professor position for three months at Universita di Parma, to collaborate on a project to develop theoretical and computational tools to model the interaction of muons with solids. Alternatively, it can be accumulated over a longer time in order to request several consecutive terms (up to one academic year) for longer projects e.g. **Done** (CEA) spent a year in Japan, working with the Japanese Space Agency, where she was part of their science exploitation team for a new X-ray astronomy satellite.

Sabbatical leave can also be spent on impact activities, for example **Saunter** in CfAI, developed a camera tracking system for pre-screening drugs on *C. elegans* nematode worms. Many of their genes have human orthologs, so they can replace mice in the early stages of testing. However, their use was limited as assessment was often invasive, disrupting the test conditions, with results limited to alive/dead rather than continuous monitoring. Instead, a standard CCD camera attached to a cheap Raspberry Pi computer enables real-time, continuous, non-invasive tracking of worm activity. He set this up as a spin-out company, Magnitude Biosciences, which has subsequently raised GBP375k in a stage 2 funding round.

The IPPP has a long history of strong links with CERN, hosting staff either on sabbatical leave or secondment. For example, **Richardson** (IPPP) had a five-year secondment (so is not eligible for inclusion in REF) as staff member in the theory division of CERN. He is a key developer of the

Herwig Monte Carlo event generator software, which encapsulates the current theoretical understanding of hadronic collisions and produces simulated events which can be compared with data. This is a standard tool for analysis of high-energy collisions, both for testing the Standard Model and in the search for physics Beyond the Standard Model.

2.6 Research students:

We have graduated 210 PhD students in the REF period. These form a vital part of our strategy to increase the reach and significance of our research activity. Our objective is that the facilities, financial support, training and mentorship for all our postgraduate students are amongst the best in the UK.

PhD students are directly recruited into one of the research sections, supported primarily by studentships from either UKRI or external funders. All potential supervisors have undergone unconscious bias training, and we record and monitor gender balance between applications, offers and acceptances.

2.6.1 Support from major funding bodies

The majority of PhD positions are funded from RCUK, with the EPSRC Doctoral Training Account currently totalling GBP1.3M and STFC quota studentships currently totalling GBP 6.0M. There is also additional support from various EU Training Networks. For example, there are four EU Framework 7 Initial Training Networks which have run from IPPP in the REF period: HiggsTools, (**Glover**, GBP0.6M) which investigated electro-weak symmetry breaking, MCnet (**Richardson**, GBP0.4M) which focuses on MonteCarlo techniques to understand collider experiment data from the LHC, Invisibles (**Pascoli**, GBP0.3M) on neutrino and dark matter phenomenology, and LHCphenonet (**Maitre**, GBP0.2M) on advanced particle phenomenology.

The department also receives students from multiple Doctoral Training programs. The largest of these are detailed below.

Soft Matter and Functional Interfaces (SoFI 2014 to 2022, GBP4.8M and now SoFI^2 2019 to 2028, GBP5.6M): The core aim is to deliver a comprehensive, team-based approach to solving complex industrial challenges with topics as varied as smart surfaces, recyclable plastics and new medicines as well as learning about all aspects of soft matter (CMP soft, joint with Chemistry). This is structured so that the first six months is cohort training, and the PhD includes the opportunity for a six month external placement with either another university group (Leeds and Edinburgh) or industrial partner (25 ranging in size from GSK and Nestle to local SME). The training also includes a mini-MBA coordinated by Durham Business School, with modules in project management, leadership and best practice in collaborative innovation. This has hosted 79 students since 2014, with 13 in Physics (predominantly in the CMP soft matter group)

Energy: PI **Halliday** (CMP and co-Director of DEI). It provides a wide ranging, stimulating and effective training program in all aspects of energy with particular emphasis on developing multidisciplinary perspectives and approaches to energy problems, from engineering to social aspects. A series of internal and external invited lectures from leading energy researchers allow the students to gain an insight into real energy challenges. An annual group project allows students, working in small groups, to carry out a project addressing current energy issues. Regular field trips and site visits allow students to see energy technologies in operation and how new approaches might be developed and implemented. This has hosted 31 students in Physics since 2014.

Data Intensive Science*:* This is a collaboration between the Astronomers and IPPP to combine their skills and expertise in handling the computational challenges of large datasets, with GBP 1M funding from STFC. **Krauss** (IPPP) and **Baugh** (ICC) are co-PIs. There is initial intensive training for nine months on generic technical skills and methods (statistics, numerical algorithms, high-performance computing, machine learning) and in their chosen subject specialisation (astronomy

or particle physics). There is also training in transferable skills, together with a mini-MBA and workshops on communicating science. Impact is embedded in the program, as it requires that students do two eight-week team-based projects, either in-house in our research groups or with external partners. This industrial placement element of the CDT has been so successful that we have rolled out this opportunity to all PhD students in Astronomy. All 22 students on this CDT since its start in 2017 are in Physics.

Global Challenges: This is the newest CDT, supported by GBP3M from a successful bid to the Global Challenges Research Fund by **Halliday** (CMP and co-Director of the Energy Institute) in 2019. Research focuses on multidisciplinary projects aligned with one (or more) of the UN Sustainable Development Goals. It will host 26 international students from 17 DAC nations, working across 15 departments across all Faculties in Durham (Sciences, Social Sciences, and Arts and Humanities). Students receive cohort-based training in a range of areas including development-related research methodologies, and spend four to six months in the country that is the focus of their research, working with a partner overseas university and/or other groups such as non-governmental organisations. Once they have completed their PhD, their knowledge and research can be communicated and implemented back to the student's country of origin where they will be continuing their work.

We also have students in Physics funded by the Fusion CDT (led by York, GBP3.7M, 2014 to 2022) and the ReNU CDT (led by Northumbria, GBP5.5M, 2019 to 2027).

2.6.2 Research student monitoring, support and training

Progress is tracked by both student and primary supervisor via quarterly reviews. This short questionnaire on the database gives a fixed timescale on which to assess achievements against goals for the period. Typically, this is only a brief record of ongoing discussions between student and supervisor, but it does also provide an opportunity for either party to voice concerns. Responses are monitored by the Director of Postgraduate Studies, so they can intervene on any issues raised.

There is an additional larger scale Annual Progress Review for all PhD students, again monitored by the Director of Postgraduate Studies. First year students write a 5000 word report, structured in a similar fashion to a thesis introduction, but with content appropriate to this more preliminary stage. The supervisory team nominates two Review Team members/examiners who interview the student, and make a recommendation on progression based on their assessment of the student's ability to complete a PhD in a timely fashion. Subsequent reviews take place annually, with a completion review in the final year where the students submit a plan indicating how they propose to finish their thesis by the end of the period of supervised study

The department of Physics recognises and celebrates excellence through the award of postgraduate prizes for outstanding achievement, both for first year and final year students.

Pastoral meetings are available to all students as an opportunity to informally discuss any problems that they are encountering that impact their research. Students can arrange these with any member of staff from the Postgraduate Studies Committee not connected to the students' academic research, in order to have an independent source of advice and support.

All students attend dedicated advanced lecture courses on the specific background science and techniques relevant to their field. For IPPP this comprises two terms of Masters level taught courses in order to fully cover the theoretical foundations of particle theory, string theory and cosmology. Other sections do a shorter combination of lectures and skills sessions. These can be tailored for each individual area, or shared where the groups require common skills such as in Optical Design (using Zemax) in both QLM and CfAI, or in the integration and computer control of experiments (using Raspberry Pi's) in both CfAI and CMP. Several of these courses are supported by textbooks written by Durham staff during the REF period:

- **Adams** and **Hughes**: Optics from Fourier to Fresnel (2018);

- **Kusumaatmaja**: The lattice Boltzmann method, principles and practice (2017);
- **Girkin**: A practical guide to optical microscopy (2019);
- **Spannowsky**: Looking inside jets (2019),
- **Krauss**: The black book of Quantum Chromodynamics (2018);
- **Mendis**: Electron beam-specimen Interactions and simulations methods in microscopy (2018).

There is training available on more generic skills development, based on the Research Councils' Joint Skills Statement. All students complete a training needs analysis every year to identify broader university courses which are relevant to their interests. All postgraduate students are also offered opportunities to develop their teaching portfolio at an appropriate level, such as demonstrating in undergraduate laboratories, example classes and workshops. Students are supported by compulsory training sessions and paid at an hourly rate for their work. Their contribution is limited to six hours per week in term time to ensure this does not negatively impact on their research time, whilst allowing them to accumulate evidence of teaching experience for their CV.

2.7 Equality and Diversity

The department is committed to upholding the principles of EDI. This is managed through the EDI committee, chaired by DoEDI (**Bromley**, CMP) comprising HoD, staff from across all demographics, PGR and UG students. The DoEDI is a core member of all senior committees, including Operations Group, the top level management team of the department, along with HoD, DoR, DoE, DoF, and the departmental manager responsible for professional services. This means EDI principles are embedded across the department, with the DoEDI monitoring outcomes (e.g. of applications for university sabbatical and equipment funding requests, and ranking of fellowship applicants) in terms of gender balance and other protected characteristics. This has resulted in Durham being one of only 18 Physics departments in the UK to hold Juno Champion status, and the department also holds a Silver Athena Swan award. A key strategic goal is to gain Athena Swan Gold status in the near future. **Bromley** has recently been appointed as Faculty of Science Athena Swan lead by the university in recognition of the quality and impact of her leadership of EDI in Physics.

All staff involved in selecting and hiring graduate students and postdocs are required to have undergone the 'Unconscious bias' university training course. This enables staff to recognise their own assumptions, and to actively deal with them. Staff on appointment panels for academic positions are further required to attend university training on recruitment and selection where there is emphasis on written criteria and standardised questions for each applicant.

Succession planning for the highest level departmental academic roles (HoD, DoR, DoE, DoF, DoEDI) is explicitly advertised across all staff. The system encourages the widest participation by circulating written descriptions of the roles, along with a questionnaire asking which position(s) staff might want to consider applying for in the short, medium and longer term. This has enabled a more transparent process, where all staff can identify what training and experience they might require to achieve their career goals.

EDI issues in recognising and rewarding staff are similarly monitored. The process is that all academic, teaching track staff and research track staff in post for more than two years are required to submit a CV annually to the departmental Progression and Promotion Committee. These are considered against published criteria for promotion and/or merit awards. The Director of EDI and a representative from the university HR department sit on this committee and monitor its processes and discussions to ensure that fixed-term staff are considered alongside permanent staff and that part time staff are not disadvantaged.

The department supports flexible working applications, allowing staff to temporarily or permanently change their contracted hours in response to circumstances, such as change in caring responsibilities. There is support for a reduced teaching load for people returning from parental

leave, or a period of ill health, where the department works closely with the university Occupational Health service to support staff on phased return where we make reasonable adjustments for disability. We advertise this by case studies on the 'Diversity' section of our website, to illustrate the range of adjustments which can be made to maximise staff engagement and productivity.

There is a full workload model for all teaching and administration roles within the department, costed in hours with rates which are openly advertised. The resulting spreadsheet of tasks is seen by all staff, with load pro-rata'd to FTE. This transparent process means that part time staff can ensure that their load is appropriately reduced, and that all staff, including BAME and other protected characteristics, can directly track and compare their contribution. Each member of academic staff has a rolling personal account, topped up with GBP1000 per year as part of research incentivisation. This can be used more flexibly than many research grant funds to cover a wider variety of additional costs involved with conference attendance, such as child care.

All departmental meetings and research seminars are held during core hours to ensure maximum accessibility for staff. University-wide processes around timetabling invite all staff to submit known schedule constraints in advance so that lectures do not clash with school pickup/drop off or other fixed time caring responsibilities. Additionally, there is a dedicated room in Physics which is private and lockable to support EDI activities such as breastfeeding.

The department is proactive in supporting wellbeing. There are also multiple posters advertising the 'Departmental Listeners' network, signposting confidential support for issues around health and wellbeing, including mental health and stress as well as bullying and harassment. The named Listeners can directly refer to university Occupational Health Service, bypassing the line manager in cases where staff feel uncomfortable in discussing sensitive issues with them. Copies of the IoP 'Resilience toolkit: A Physicists guide to building and maintaining wellbeing' are available on a dedicated noticeboard in the common coffee area, and posters outlining our code of conduct 'Respect at Work' are prominently displayed throughout the department.

The department followed the recommended university code of practice for selecting staff for submission. Of our 85 Cat A staff, 2 staff are on part time (0.6FTE) contracts so this gives 84.2 FTE, requiring 211 outputs. Of these, 29 are from female and 18 from BAME staff, in line with (and slightly above) their representation (12 female, and 6 BAME). We also included 12 outputs from early career Cat B staff to illustrate the quality of independent researchers who have held fellowships here during the REF period.

Section 3. Income, infrastructure and facilities

3.1 Research funding

Our strategy for generating research funding is to use RIS resources to advertise all grant opportunities to all staff. These include both UKRI/EU funding sources together with wider Grand Research Challenges Fund/industry/regional development opportunities. RIS holds drop-in sessions for each group to facilitate informal discussions on relevant grant opportunities. All staff are mentored through the application process, with the requirement that the case is read by a senior internal assessor before submission to ensure that they are well structured and focused on the grant criteria. This has resulted in the award of over GBP87M to the department in research grant income since the last REF, with large grants from major funders detailed below.

STFC Consolidated grants: The department holds two of these, one in Astronomy (ICC/CEA/CfAI) and one in particle physics (IPPP). These are a major source of funding for the research in these groups, with support totalling GBP6.1M (Astronomy) and GBP7.4M (IPPP) over the REF period. Each consolidated grant sets out multiple individual research cases contributed by all staff in these sections, forming a broad programme of related work across the group. This sets much of the research agenda for the three-year period of the grant application cycle.

STFC PPRP grants: CfAI have a substantial track record in Astronomical instrumentation. Over the past three decades, they have participated in the design and/or construction of common-user instrumentation for many of the world's major astronomical facilities (e.g. VLT, SALT, DESI, ELT, CTA). Currently the group holds contracts to develop instrumentation for the European Extremely Large Telescope (E-ELT), with 15 times more collecting area than any current telescope. First light instruments include Harmoni, an Integral Field Unit providing high resolution spectra for every image pixel simultaneously, while subsequent instrumentation will include a high spectral resolution and multi-object spectrographs. Durham was awarded a total of GBP3.3M to design and build optical components for all these instruments, and an additional GBP3.8M grant has just been announced (PI: S. **Morris**). These contracts include a guarantee of time for first light science data, with consequent high impact publications. The quality of these novel instruments also directly influences research in CEA and ICC: e.g. CfAI built part of the 5000 fibre multi-object spectrograph for DESI, a US-Europe-China collaboration led by the US Department of Energy (grants totalling GBP1M in the REF period). This will study the cosmological expansion rate and the growth of structure via a wide-angle spectroscopic galaxy and quasar redshift survey, with additional science, including studying galaxy formation and evolution, galaxy cluster surveys, the structure of the Milky-Way galaxy and Galactic archaeology. These data directly support multiple research strands in CEA.

Major Industry Grants: CfAI made a strategic decision to expand into satellite instrumentation when they were chosen to provide the precision optics for a spectrograph which will fly on the NASA James Webb Space Telescope, the successor to the iconic Hubble Space Telescope. There are limited opportunities in astronomy space-based missions, but there have been small contracts to design novel instruments for ESAs EXOMars mission and the ESA-Roskosmos Luna-2 moon lander (**Bourgenot**). There are many more Earth observation and remote sensing satellites, with a total of GBP4.2M from Airbus for METimage, a polar orbiting weather satellite and GBP2.2M for the ESA Sentinel system (PI: **Sharples**).

EPSRC program grants

Skyrmions: from magnetic excitations to functioning magnetic devices: **Hatton** (PI) and **Lancaster** (both CMP). Skyrmions are vortex-like excitations in magnetic fields which hold promise for advancing our basic understanding of matter, and also for technological deployment as highly efficient memory elements. The research combines expertise across universities, national facilities and industry to answer basic questions about the status of magnetic Skyrmions and to develop technological applications. GBP5.1M (GBP1.7M to Durham)

QSUM: Quantum science with ultracold molecules: **Cornish** (QLM). Entanglement is at the heart of quantum mechanics. Once two particles have interacted they cannot be treated as independent entities no matter how far apart their separation. These interactions are enhanced for particles which have a dipole field, making it easier to build a quantum computer from molecules rather than atoms. However, while the techniques to manipulate cold atoms are well developed, techniques to manipulate molecules are still in their infancy. This project will build up expertise, from control of isolated molecules and their coupling to single photons; to small arrays of interacting molecules, controlling interactions and entanglement in simple geometries; and then to two- and three-dimensional lattices to understand the complex behaviour of strongly interacting many-particle systems. GBP6.7M (GBP2.8M to Durham).

EPSRC platform grants

Atom based Quantum Photonics: **Hughes** (QLM), with **Jones**, **Gardiner** and **Weatherill** (QLM) as co-Is. This brings together a range of activities in the QLM group to make and manipulate photons rather than atoms. GBP1.2M.

EPSRC responsive mode: There are multiple grants held across QLM, CMP and CMP (soft) funding our research. Most of these are smaller scale than the programme/platform schemes,

though they can reach ~GBP1M such as the *Optical clock arrays for Quantum Metrology:* **Jones** and **Adams** (QLM).

3.2 Research fellowships

The department uses the same mentoring process for personal fellowship applications as used for grants, giving input from a senior staff member. Additionally, for those schemes which also involve a presentation and/or interview for the final round, the department sets up a panel of senior staff (generally including HoD and DoR) to hold a practice session and give feedback.

ERC grants held during the REF period:

Advanced	**Smail**, CEA GBP1.73M (2013 to 2018), **Frenk** ICC GBP2.5M (2018 to 2023) **Glover** IPPP GBP1.5M (2014 to 2018), **Frenk** ICC GBP1.7M (2011 to 2017)
Consolidator	**Pascoli** IPPP GBP1.2M (2014 to 2019), **Badger** IPPP GBP1.4 (2018 to 2023) **Fielding** CMP GBP1.5M (2012 to 2017)
Starter	**Li** ICC GBP1.0M (2017 to 2022), **Fumagalli** CEA GBP1.1M (2017 to 2022)

Staff in each of the groups have also won multiple, personal long-term fellowships, both from UKRI, and the Royal Society

For example, **Deason** was appointed as a proleptic lecturer to ICC in 2016 on a Royal Society URF with an enhancement award, bringing a new focus on large-scale simulations of the formation history of our Milky Way galaxy. These models can now be tested with data from large surveys, including ESA's Euro750M GAIA satellite which enables the most precise measurements of the dynamics and structure of the 100 billion stars in our Galaxy. Their kinematics retain traces of past events such as a major accretion event of a satellite galaxy of the Milky Way around the epoch of the formation of the galactic disc around 10Gyr ago, as well as pointing to a future collision with the Large Magellanic cloud in ~2Gy time. She was awarded the Philip Leverhulme Prize in 2018 for her research in this area.

Badger in IPPP was appointed as a proleptic lecturer in 2016 with a GBP0.6M STFC ERF for research in standard model physics at the precision frontier. His calculations of the multi-loop scattering amplitudes are needed to compare with current and future experiments at the Large Hadron Collider, and attracted further support both from STFC ERF with an enhancement grant for GBP0.4M and a Euro1.8M ERC consolidator grant. Most recently, **Schoenherr** was appointed in 2019 with research which is similarly aligned with this core IPPP activity on a Royal Society URF and an enhancement award.

CEA appointed **Cooke** from a Royal Society URF in 2016 to study elemental abundances in the most pristine material in the Universe to constrain Big Bang Nucleosynthesis and to directly observe the composition of gas out of which the first stars and galaxies form. One of his enhancement awards was for a deep learning workstation to train a convolution neural network to automatically fit the properties of intervening gas systems in the intergalactic medium along sightlines to distant quasars, connecting him to the IDAS. CEA also appointed **Jauzac** as a proleptic lecturer in 2019, after she won one of the first tranche of UKRI FLF. She is PI of one of the largest allocations of time on the Hubble Space Telescope for a program to study clusters of galaxies, mapping their dark matter distribution to unprecedented detail by using gravitational lensing distortions of background galaxy images. **Osborn** (CfAI) won one of the second tranche of UKRI FLF positions, with a research plan modelling the atmospheric distortion of large

telescopes and applying this to increase transmission rates in satellite communications, connecting to an impact area.

In the soft matter group, both **Voitchovsky** and **Diagiacomi** hold EPSRC Early Career Fellowships (GBP1.1M to track single ions which transport and store energy in both living organisms and in batteries and GBP0.8M to develop computational methods for modelling biomolecular systems at atom scale resolution).

Fellowships are also used to open up new areas of research in the department. **Kendon** was appointed in 2014, with her GBP1.3M EPSRC Established Career Fellowship, one of the first to be awarded from the Quantum Technology funding stream. Her work in quantum computing offered a new activity for the QLM group into a field with undoubted future potential, both for pure research and for impact. She is developing quantum algorithms as an interdisciplinary area, with reach into mathematical physics, computer science, and quantum many body physics. This has already attracted an EPSRC innovation fellow (**Chancellor**) to the group, and is an area identified for future growth, especially under the new IDAS multidisciplinary structure.

Impact is also recognised, with **Atkinson** holding a Royal Society Industry Fellowship. **Baugh** is an STFC Innovation Fellow, with a project to translate expertise on data sciences in Astronomy into industry, while ECR **Bourgenot** holds an EPSRC Innovation Fellowship to develop spectral-imaging technology for remote sensing on drones to monitor agricultural yields.

3.3 Organisational support for research and impact

The ICC, together with all of the astronomers in CEA and CfAI, moved into the Ogden Centre for Fundamental Physics West in 2017. This GBP12M dedicated building was designed by world-renowned architect Daniel Libeskind and funded by Durham university, together with a GBP3.35M donation from the Ogden Trust and GBP1.5M from the Wolfson Foundation. The new building is adjacent to the main Rochester building and the original Ogden Centre, so maintains Physics as a cohesive unit. The additional space has benefited the entire department by allowing all sections to reconfigure and regroup, rationalising their structure and use of space. This was supported by a major programme of refurbishment including new dedicated research laboratory space for CMP and QLM.

CfAI has a GBP6M dedicated instrumentation laboratory at NETPark with large-scale clean room and diamond machining capability to fabricate high precision optics. The university contributes GBP300k per year towards the cost of this, and it forms the home for the recently funded University Enterprise Zone (see **Section 4.2**).

3.4 Infrastructure supporting research and impact

The ICC hosts parts of STFCs Distributed Research utilizing Advanced Computing (DiRAC). This is an integrated supercomputing facility for theoretical modelling and High Performance Computing (HPC) based research in astronomy and cosmology. It is housed in the Lydia Heck data centre (named after the long term ICC computer manager), supported with university investment of GBP3.5M. The upgrade to DiRAC-2.5x was funded by STFC for GBP2.7M (**Frenk**, ICC). Time on this is allocated via proposal rounds in open, nationwide competition, but 80% is won by Durham.

The ICC also owns an additional large supercomputer, COSMA-VIRGO, which is not part of DiRAC, to directly support its own research program. This has 4800 cores with 38TB of RAM, 3.2PB of storage and a 6PB tape archiving system. It provides 42M core-hours per year. In 2016 it was upgraded with GBP200k of local funds for storage and tape archive. For most applications, its performance per core is within 20% of the newest DiRAC machine. COSMA-VIRGO running costs (GBP80k per annum) are covered by Durham. Together, the COSMA-VIRGO and DiRAC machines are key to the highest impact publications of the ICC, such as the EAGLE hydrodynamic simulation of galaxy formation. This was the most highly cited paper in Astronomy in 2015.

IPPP runs a High Throughput Computing centre. The 5000 physical core cluster has been funded by an equal mix of university and STFC funding, totalling GBP0.7M. This is part of the GridPP collaboration, bringing together particle physicists and computer scientists in the UK and at CERN, and the IPPP service runs jobs from ATLAS, CMS, LHCb when not fully utilized by IPPP for precision calculations. In return, IPPP users can access GridPP resources elsewhere in the UK.

The university also operates its own HPC service, a Linux distributed memory cluster, Hamilton. Use of this is free of charge for Durham users with grants funded under UKRI. This is a major resource for the theoretical CMP group for their work on understanding the structure of complex materials from fundamental quantum mechanics of the electronic configuration (see Case study: **Castep**). Durham have recently won a GBP3.1M EPSRC grant as part of the Northern Intensive Computing Environment to establish a new national Tier-2 HPC service ("NICE19") to provide a route to Exascale computing that serves experimental users who generate large data sets requiring analysis, and for modellers who use machine learning.

The Science Faculty operates an electron microscopy suite with five state-of-the-art scanning electron microscopes, transmission electron microscopes and focused ion-beam microscopes that are accessible to both staff and students to use for materials characterisation, as well as providing a commercial service to industry users. The CfAI diamond machining equipment is similarly commercially available to provide specialist expertise and equipment for manufacture of ultra-precision optical components for industry.

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

4.1 Research collaborations, locally, nationally and internationally

Locally, we have strong links to Newcastle in Quantum processes. The Joint Quantum Centre links research in QLM with theoretical Chemistry in Durham and staff in the School of Mathematics, Statistics and Physics at Newcastle university sharing a common interest in the study of the quantum properties of atoms, molecules and solids, and their interactions with light. The strength of these collaborations is indicated by the grant income to this group detailed in **Section 3.3.** The DEI also acts as a regional link to Newcastle, Northumbria and York universities, together addressing common topics in energy generation, storage and technology, with the joint CDT programs ReNU and Fusion.

On a national scale, the IPPP is the UK centre for particle phenomenology, and supports much of the theoretical and experimental activities in this field by running workshops, conferences and networks. An international expert panel report from the 2017 STFC review of particle physics theory states that *"The creation of the IPPP in Durham was very successful in focusing the UK activity on particle physics phenomenology in a single institution, catalysing remarkable progress in the field."*

4.2 Collaborations for impact and wider contributions to the economy

A key university-wide facility for capturing and exploiting impact is NETPark (North East Technology science park), located in Sedgefield, County Durham. This was started as an initiative between Durham university, Durham County Council and the Teeside-based Centre for Process Innovation (CPI), which specialises in printable electronics. Its focus is on developing technology in the physical sciences, supporting this by access to early stage venture capital and taking it to market readiness. Physics plays a major leadership role in NETPark, with CfAI and Kromek (a spin-out company from Physics, see case study: **Kromek**) as anchor tenants, along with CPI. There is a three-way MoU between Business Durham (who manage NETPark on behalf of Durham County Council), CPI, and Durham university, signed in 2015, committing the partners to working together to promote research, business and career opportunities in the North East. CPI have set up a National Centre for Healthcare Photonics and are collaborating with Durham

university on a European Regional Development-funded project (**Girkin**, CfAI is academic lead) to support SME companies developing technologies for medical applications. This has attracted investment of GBP20M for a new building, and GBP1.3M in funding for projects.

NETPark is unique in the UK in hosting two Catapult centres. These are designed to transform the UK's capability for innovation in specific areas and help drive future economic growth by bridging the gap between business and academia. The presence of CfAI expertise in Space Instrumentation was key to the North East Satellite Applications Catapult Centre of Excellence selecting the site. This is likely to be an area prioritised by post-BREXIT government investment in the NE as part of its levelling up agenda, as announced by then science minister Chris Skidmore at the opening of the Durham University Teaching and Learning Centre in January 2020[1].

In October the university, in collaboration with CfAI (**Girkin**), was awarded GBP1.5M to develop the CfAI facility at NETPark into a new University Enterprise Zone. This will house up to 17 SMEs and Micro-SMEs in a collaborative facility where they can utilise the expertise within the Physics department and beyond to help develop their technology and products.

4.3 Public engagement

The Physics department has a long history of engaging with the public, with Dr P. **Edwards** as our full time Outreach Officer (the first in the UK to be funded by a Research Council). The outreach program has directly engaged with ~15,000 school children across the age range, and over 500 of their current and future teachers during the assessment period. Teaching materials for this 'From Higgs to Hubble' program are used by around 100,000 secondary pupils per year. This work in strengthening science teaching and engaging children with education lies mainly outside of the REF definition of Impact but the significance of the program is enhanced by being in the North East, an area of high social deprivation. Dr **Edwards** was nominated as a TED Educator, and his YouTube teaching resource developed in 2014 on 'What light can teach us about the Universe' has been viewed by over 216,000 people, generating over 11,000 questions.

Durham Lumiere offers even wider engagement opportunities. This is the UK's largest light festival, where the entire city is transformed into an art installation, running for four consecutive nights every two years. In 2015 the ICC collaborated with lighting artists to provide the centrepiece of this festival, 'The World Machine', a celebration of cosmology projected onto Durham Cathedral, seen by an estimated 200,000 people. A new version of this, 'Cosmic Architecture', projected instead onto the Libeskind-designed Physics building in 2017 and 2019 (Fig 2).

Fig 2: The World machine (2015) & Cosmic Architecture (2017, 2019)

Other general outreach activities include 'Celebrate science', a three-day Science Festival that takes place during the local schools' October half-term holiday. It includes a wide range of science-

[1] https://www.gov.uk/government/speeches/levelling-up-research-and-innovation-right-across-the-united-kingdom

themed events and activities focused around a marquee on Palace Green, attracting around 7,000 visitors each year.

The annual Royal Society Summer Exhibition instead gives a more direct connection between the public and our research, with exhibits from the ICC 'Galaxy Makers' (2016) and IPPP 'Modelling the Invisible' (2017), and 'Ghosts in the Universe' (2018), each seen by around 15,000 visitors

4.4 Wider Indicators of esteem

Our staff are recognized nationally and internationally. We had four FRS in the department over the REF2021 period (**Ellis**, **Frenk**, **Glover**, with **McLeish** who left for York in 2017), as well as two Emeritus FRS (**Martin**, **Wolfendale**). Multiple staff have won awards for their research in this period: **Adams** (IoP: Thomson medal), **Chadwick** (IoP: Bragg medal), **Cornish** (IoP: Thomson medal), **Deason** (Philip Leverhulme Prize), **Done** (RAS: Darwin Lectureship), **Ellis** (Humboldt Foundation: Humboldt Award, IoP; Dirac medal), **Frenk** (RAS: Gold medal, IoP/German Physical Society: Max Born prize), **Glover** (IoP: Lord Rayleigh medal), **Li** (RAS: Fowler Award), **McLeish** (IoP: Sam Edwards medal), **Spannowsky** (Humboldt Foundation: Bessel Award), Tanner (IoP: Gabor medal, retired 2016). Royal Society Wolfson merit awards are held by **Adeyeye**, **Gregory** (joint appointment with Mathematical Sciences, returned with UoA10), **Khoze**, **Krauss, Pascoli**, and **Smail**.

A highlight from the REF2021 period includes **Cole** (ICC) winning the USD1M Shaw prize (2014) for his work on the 2dF Galaxy Redshift Survey, which conducted a study of 250,000 galaxies. This gave the first detection of baryon acoustic oscillations, the sound waves originating a few seconds after the Big Bang, which can be used to measure distances in the universe and the rate at which it is expanding.

Our students have also been recognised with major awards. Dr Dan **Whiting** (QLM): IOP Doctoral prize in Quantum Electronics and Photonics for 'Nonlinear Optics in a Thermal Rb Vapour at High Magnetic Fields'. Dr Matthew **Kirk** (IPPP): Springer thesis prize for 'Charming new physics in beautiful processes'. Dr Sownak **Bose** (ICC): RAS Michael Penston Prize for the best thesis in Astronomy and Astrophysics 'Beyond ΛCDM'.

4.5 Responsiveness to national and international priorities and initiatives

The global pandemic requires a global response, and its challenges go far beyond a medical understanding of the virus. It was clear from an early stage that governments needed new tools which could more accurately model how infection spreads. Individual based models give the best resolution, but there are computational challenges in handling large populations, and the huge input datasets on how people live, work, travel and socialise. **Krauss** (IPPP and director of IDAS) set up a network of volunteer coders from the Data Intensive Science CDT PhD students as part of the Rapid Assistance in Modelling the Pandemic (RAMP) initiative, coordinated by the Royal Society (initially 04-07/2020). Additional expertise was locally available, from advanced statistics in machine learning (**Bower**, ICC, and staff from Mathematical Sciences) to accessing the input data from the Office of National Statistics census data for England which is curated by Geography. This covers the whole country down to units of around 250 people with information on the distribution of age, sex, ethnicity, household type (single, couple, children and age distributions), employment, commute (private or public transport and distribution of distance), and statistics on their free-time activity. They continued to work on the code after July 2020, producing the most accurate, fine grained model of social and mixing networks in England, capable of calculating how COVID-19 infection rates respond to changes in government policy at a regional and even local level[2]. Dr Kevin Fong, National Clinical Advisor in Emergency Preparedness Resilience and Response for the Covid-19 Incident, wrote '*There is currently no other model in hand that is able to usefully explore inter-regional dependencies of the pandemic or the asymmetries produced by socioeconomic differences in the general population. Your work so far has provided unique and*

[2] https://www.medrxiv.org/content/10.1101/2020.12.15.20248246v2.full.pdf submitted 16/12/2020

valuable insight and has helped us to close the gap between the modelling needs of the strategic planners and those of our frontline operational teams.'

The modular structure of the code means it can be easily ported to model other populations, even those with very different demographics. It is completely open source (GPL3 license) so it can be freely downloaded and adapted. The team have already applied it to Cox's Bazar[3], a United Nations refugee camp in Bangladesh which is the most densely populated place on Earth. This code gives a dramatic illustration of our strategy for the future, where excellence in pure research has transformative impact in the real world.

[3] https://www.unglobalpulse.org/2020/10/modelling-the-spread-of-covid-19-and-the-impact-of-public-health-interventions-in-coxs-bazar-and-other-refugee-camps/