Institution: The University of Edinburgh

Unit of Assessment: 9 (Physics)

1. Unit context and structure, research and impact strategy

1.1 Overview – Context and Structure

The current REF period commenced with the award of the Nobel Prize in Physics to Emeritus Professor Peter Higgs (announced in October 2013). Over the ensuing 7 years, Physics & Astronomy at the University of Edinburgh (**UoE)** has built on this legacy, founded on the potent combination of theory, experiment, simulation, and the innovative analysis of big data. We have expanded significantly in both size (from 66.2 to 118.04 FTE Cat-A staff) and scope, have created the Higgs Centre for Innovation (**HCI**) to complement the thriving Higgs Centre for Theoretical Physics (**HCTP**), and have now recruited Professor *Neil Turok*, ex-Director of the Perimeter Institute, as the inaugural Higgs Chair of Theoretical Physics.

Our research is motivated by the desire to be at the forefront of understanding fundamental physics within our three key Research Themes:

- **1.2.1** Astronomy (**AST**), with 42.0 FTE Cat-A staff
- **1.2.2** Condensed Matter Physics (**CMP**), with 39.04 FTE Cat-A staff
- **1.2.3** Particle and Nuclear Physics (**PNP**), with 35.0 FTE Cat-A staff

During the REF period we have spent over £100M of competitively-awarded research funding, secured/exploited time on international facilities to a value of ~£150M, and invested over £75M in infrastructure. This activity has taken place in the context of major capital investments within UoE, which have allowed us to pursue new directions, especially in interdisciplinary research and industrial connections. Chief among these developments are the £13M UoE+STFC+BEIS investment in the HCI, and the University's new £40M Bayes Centre, integral to Big-Data collaborations. This also connects to the £1.3B Edinburgh City Deal, which provides the UoE with £660M for Data-Driven Innovation (DDI: £237M from the UK and Scottish Governments, 2018).

The vibrant and productive research environment within Physics & Astronomy at Edinburgh is both demonstrated and fuelled by our ability to attract numerous high-profile grants/awards and talented researchers, including 17 European Research Council (ERC) grants and 23 prestigious early career fellowships over the REF period: Royal Society University Research Fellows (RSURF); STFC Ernest Rutherford Fellows (ERF); EPSRC Fellows and, exceptionally, 5 UKRI Future Leader Fellows (FLF) from the first 4 rounds. Since 2014, we have published over 5000 papers, of which ~250 have over 100 citations.

Our excellence is reflected in our 2019 placing as 10th in the world and top in the UK (for the last 3 years) in the research-oriented Academic (Shanghai) World University rankings for Physics.

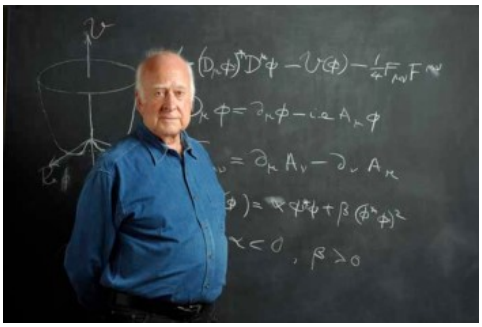

Figure 1. *Edinburgh is now home to the Higgs Centre for Theoretical Physics (in the James Clerk Maxwell Building) and the Higgs Centre for Innovation (at the Royal Observatory Edinburgh). The HCI, opened in 2018, is a multidisciplinary hub, mixing data-driven research in astronomy and particle physics with the incubation of start-up companies, sponsored by STFC.*

For REF2014 we made a joint submission in Physics with St Andrews, as PHYESTA. This collaboration continues to be very productive, with a strong track-record of joint publications and funding: exoplanet research is a highlight (30 joint publications since 2014) supported by the FP7 ETAEARTH grant; collaborative work in cosmology and galaxy evolution has also been productive (45 joint publications); research in Condensed Matter has led to a 2018 £1.2M UoE+StA EPSRC grant and a CDT.

Nonetheless, in recent years we have substantially broadened our research connections within the Scottish Universities Physics Alliance (**SUPA**) and beyond, in part driven by the HCI, which acts as a hub for SUPA activity in Astronomy, Data Science, Particle Physics, and Industry Engagement. We host an STFC CDT in data science (ScotDIST) with Glasgow and St Andrews, and existing Edinburgh-Glasgow connections in Particle Physics have been strengthened/broadened through developments in Gravitational Wave physics. Our annual Scottish Exoplanet & Brown Dwarf meeting now involves partners from Dundee, while the annual DEX (Cosmology & Extragalactic Astronomy) and Higgs-Maxwell (Particle Physics) meetings foster collaborations between Edinburgh, Glasgow, Durham and Lancaster.

The dramatic growth of Physics & Astronomy at Edinburgh and the expanded breadth of our collaborations underpin our submission to REF2021 as a single institution. Our renewed research strategy develops new and exciting links across the Scottish, UK, and international research landscapes.

1.2 Research Strategy

We aim to advance knowledge by addressing the key fundamental questions in Physics & Astronomy. We place strategic emphasis on linking experiment, simulation and theory, and on addressing the biggest outstanding problems (often found at disciplinary boundaries). Subject to these principles, research quality is the overriding factor in determining our investment choices.

We drive cross-theme research and links to other disciplines by hosting and leading a number of research centres that provide advanced infrastructure. The largest of these is the Edinburgh Parallel Computing Centre (**EPCC**), which has powerful HPC facilities (e.g. ARCHER2, ~£46.5m, EPSRC/NERC 2014-2020; DiRAC, ~£23M, STFC 2014-2020). The Centre for Science in Extreme Conditions (**CSEC**) is a collaborative centre spanning Physics, Chemistry, Engineering and Geosciences. We enjoy close research links to the STFC-funded UK Astronomy Technology Centre (**UKATC**), located at the Royal Observatory Edinburgh (**ROE**), links now further strengthened by the **HCI** (2018). Through recent appointments we have also sought to exploit and deliver on the data-science ambitions that are a key driver of the Edinburgh City Deal. Via these and other channels, we maintain/develop strong collaborative links with industrial partners and other non-academic stakeholders.

More broadly, a key strategic goal is to promote collaborative work across Scotland (acting as a focal point of SUPA), the UK, and the wider international community, either via major international facilities in which we play a prominent role (CERN, ESO, ESA) or through direct bi-lateral agreements with internationally-leading universities (e.g. Leiden University, University of Tsukuba).

Delivery against these goals is the responsibility of our School Executive Committee (**SEC**), comprising the Head of School (*Dunlop*) and the heads of the three Institutes (Institute for Astronomy (**IfA**) - *Best*; Institute for Condensed Matter & Complex Systems (**ICMCS**) – *McMahon (M)*; Institute for Particle & Nuclear Physics (**IPNP**) – *Murphy*) that map onto our three key Research Themes. This committee is advised by the School Research Committee, led by the Director of Research (*Evans*), and by the Higgs Centre International Advisory Board (*Turok*). SEC oversees/approves the plans of individual Themes and Research Groups and advises the Head of School when prioritizing hiring decisions for new academic posts. Such posts are allocated strategically rather than on a replacement/pro-rata basis.

We now describe our Research Strategy in more detail at Theme/Group level; within each Theme we explain how our strategic approach has enabled key research breakthroughs in the REF period, and outline how recent appointments and future plans can advance our strategy.

1.2.1 Astronomy

The **AST** Theme is organized as a single large research group, which has grown significantly over the REF period to 43 (42.0 FTE) Cat-A staff: *Aird, Alam, Asgari, Best, Beutler, Biller, Bonavita, Cai, Carnall, Cataneo, Cockell (0.5), Cross, Cullen, Dave, Davidson, Duncan, Dunlop, Dupuy, Ferguson, Hall, Hambly, Heymans, Khochfar, Koposov, Lawrence, Mann, McLure, McMahon(S) (0.5), Meiksin, Peacock, Penarrubia, Rice, Ross, Rowell, Sabater, Smith, Snodgrass, Taylor, Tittley, Trew, Troester, Varri, Zuntz.*

Figure 2. *A small sub-region of the infrared image of the COSMOS field from the UltraVISTA survey, the deepest degree-scale near-infrared survey undertaken to date. This international programme is led by Dunlop, exploiting the VISTA telescope designed in Edinburgh at the UKATC.*

AST's strategy is to combine observational astronomy, theory, and numerical simulation in order to address four key scientific questions: What is the nature of dark matter and dark energy? How do galaxies and black holes form and evolve? What processes drive the formation of stars and planets? Are we alone in the universe? Our programme is supported by two STFC Consolidated Grants (£3.23M), a wide-field astronomy grant (£1.0M), major project grants for Euclid (£4.9M), LSST (£2.7M) and Gaia (£1.9M), and numerous smaller project grants, ERC grants and fellowships.

Our strategy has, to a large extent, been to build successfully on our long-standing expertise in survey astronomy. Through the REF period we have invested heavily in delivering and exploiting major new surveys across the electromagnetic spectrum. This work has often featured telescopes and instruments designed or built in Edinburgh by the UKATC, where the synergistic co-siting at ROE has allowed IfA astronomers deep insight into scientific opportunities with these facilities (e.g. the near-IR VIRCAM and WFCAM imagers on VISTA and UKIRT; the sub-mm SCUBA-2 camera on JCMT; the high-precision radial-velocity spectrograph HARPS-N). We have complemented these opportunities with collaborative programmes where we jointly bid for UK funding (e.g. joining the US-led Dark Energy Survey, and leading LOFAR-UK), as well as using our internal funding to buy into consortia offering complementary data that fit our scientific priorities (e.g. the US-led SDSS-eBOSS spectroscopic survey). The expertise developed in these diverse projects allows us to take a lead in other projects purely on scientific ability/experience (e.g. the KiDS optical survey, the leading international project studying the dark universe via gravitational lensing). Our multi-wavelength survey strategy has allowed us to provide key insight into many scientific problems. For example, we have established a comprehensive picture of cosmological star-formation history using the UltraVISTA survey (Fig 2) in combination with SCUBA-2 surveys and deep ALMA imaging. Our recent appointment of *Aird* is designed to expand our survey expertise to the X-ray regime.

A further major element of our survey strategy is built around the grant-funded Wide-Field Astronomy Unit (**WFAU**), our world-leading astronomical database centre. WFAU expertise allows us to host and lead the UK's main STFC/UKSA data-centre for wide-field survey astronomy, releasing new data (and science) from the VISTA and WFCAM science archives, as well as contributing to the Gaia Data Flow system, ensuring the satellite meets its astrometric goals. Our strategic approach has ensured that this prominent role will continue, as we host the UK Science Ground Segment and UK Science Data Centre of ESA's Euclid mission, and spearhead UK effort for LSST.

To maintain/enhance our position at the scientific forefront of these forthcoming world-leading Dark Universe surveys, we have further strengthened our world-leading expertise in statistical analysis, large-scale structure and cosmology, by recent appointments *Cai*, *Zuntz*, and *Beutler*. To aid the interpretation of these complex datasets, numerical simulations of cosmological structure formation are essential. We have therefore made a substantial expansion of our capability in this area, with recent recruits *Dave* and *Smith* strengthening our capability to develop powerful new simulations of galaxy formation and evolution (e.g. FiBY, SIMBA; see Fig 3). These simulations support our leading roles in the powerful next-generation facilities that promise to revolutionize our understanding of cosmology and galaxy evolution, such as JWST, Euclid, LSST, DESI, MOONS, WEAVE, and SKA.

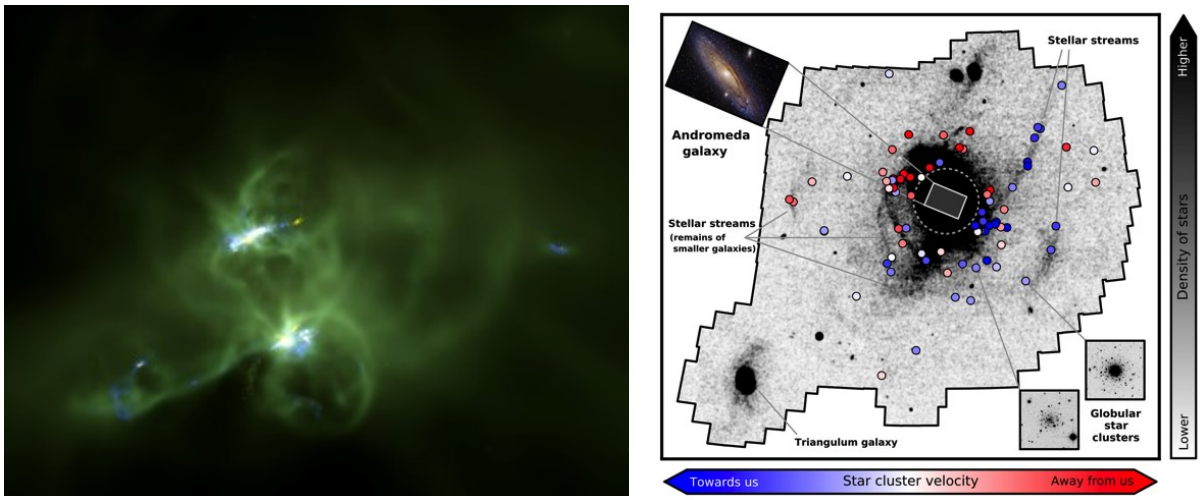

Figure 3. Left: *First Billion Years (FiBY) high-resolution hydrodynamical simulations of early galaxies, showing gas outflows driven by supernovae explosions.* ***Right:*** *A deep Subaru map showing the distribution of stellar streams and globular clusters in the Andromeda galaxy halo; the insert shows the 'normal' image of the galaxy, emphasizing the depth of the new data and the large-scale structures revealed.*

A novel element of many new surveys is a focus on the time domain: the study of astronomical transients. We have a long-standing interest in AGN variability, but a new dimension is supplied by the advent of gravitational-wave astronomy. We contributed to the historic first detection of an electromagnetic counterpart to merging neutron stars in 2017, and will use our expertise in large-scale structure to seek out statistical correlations between LIGO events and the galaxy distribution. We will combine such work with our expertise in modified-gravity theories, where we were the first to show that the speed of gravitational waves rules out many such models.

We complement large-scale cosmology with galactic archaeology and near-Universe cosmology; highlights include the revelation of the cannibalistic past of the Andromeda galaxy (see Fig 3). Our ongoing strategy is to combine new data from Gaia (and follow-up spectroscopic surveys) with detailed simulations and surveys of the Milky Way and local galaxies. Our data-analysis expertise in this area has been further strengthened by the recent appointment of *Koposov*, while new FLF *Varri* enhances our expertise in simulations of the dynamics/evolution of stellar systems and strengthens our links with mathematicians working on gravitational dynamics.

More locally, we aim to detect, study and understand exo-Earths, and the requirements for life. Highlights have included the study of evolving cloud structures, first on the nearest Brown Dwarf star and then on a free-floating exoplanet, and the detailed study of the comet 67P with Rosetta (Fig 4). We have significantly enhanced and broadened this area of research in Edinburgh, through the appointments of *Snodgrass* (planetary science), *McMahon(S)* (astrobiology) and *Dupuy* (exoplanets). This expanded expertise will enable us to take a holistic approach, combining direct exoplanet observations (with JWST, ERIS, and E-ELT) with detailed planet-formation simulations, new Solar-System observations and missions (e.g. our lead role in ESA's Comet Interceptor), and studies of habitability/life in extreme conditions, including astrobiology experiments both in the lab and on the ISS.

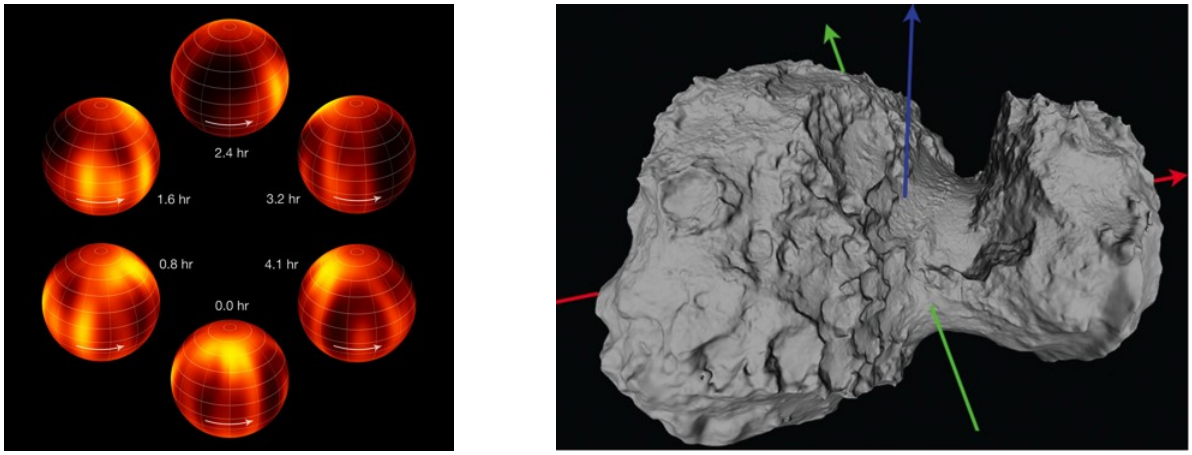

***Figure 4**. **Left:** The first map of clouds on a brown-dwarf star, produced using ESO's VLT. **Right:** The nuclear structure of comet 67P revealed by Rosetta imaging.*

1.2.2 Condensed Matter Physics

The **CMP** Theme is organized into two research groups:

- Hard Condensed Matter (**HCM**) physics studies correlated many-electron systems and the effects of extreme conditions on structure, dynamics and properties of condensed phases.
- Soft Matter, Statistical and Biological (**SMSB**) physics studies complex fluids, interfaces, active matter, statistical mechanics and PALS (physics at the life science interface), and applies the knowledge to industrial problems.

Hard Condensed Matter
HCM has 14 (13 FTE) Cat-A staff: *Ackland, Cockell (0.5), Gregoryanz, Hermann, Huxley, Loa, Loveday, Martinez-Canales, McMahon(M), McMahon(S) (0.5), McWilliams, Pena-Alvarez, Santos, Stock*

HCM's strategy is to use state-of-the art facilities, both in-house and at external international laboratories, to explore the physics of condensed matter under extreme temperatures (high and low), magnetic fields, and pressure, and to develop a deep understanding of the phenomena under study via theory and simulation. Our research aims to answer fundamental questions: What is the nature of matter at densities where ion cores overlap and valence electrons are highly confined? How can we use pressure and temperature to tune Fermi surface topology and magnetic interactions? What is the nature of hydrogen at ultra-high pressures? Our research ranges from exotic magnetic and superconducting phenomena at low temperatures, to high-density high-temperature material states at extreme pressures. Our programme is supported by £4M of EPSRC grants awarded in the REF period, an ERC grant, and two EPSRC Fellows.

We have uncovered new states of hydrogen at extreme density (Fig 5), in lithium at low temperature, and in metals under shock compression. We have found novel topological states in

magnetic and mixed molecular systems. Our studies have wide-ranging implications for materials science and planetary science. New hire *McMahon(S)* has further strengthened our astrobiology activities, and created exciting strategic links to astronomy.

Our future strategy centres on forging strong links with laboratories hosting world-class facilities such as high-energy lasers, synchrotrons, neutron sources and XFELs. Recent hire *McWilliams* strengthens our leadership of high-pressure studies at EuXFEL, while the appointment of FLF *Pena-Alvarez* means we are ideally placed to exploit the capabilities of the ESRF-EBS synchrotron. Our experimental work is both underpinned and directed by theory and simulation. As part of a strategy to increase the breadth of such studies we have appointed *Santos* to spearhead research in energy materials.

Figure 5. *Recent breakthroughs in our understanding of hydrogen through experimental studies at extreme pressures/densities.* ***Left:*** *our research featured on the cover of Nature in 2016;* ***Right:*** *our work on metallic hydrogen in Jupiter's interior featured in a 2018 BBC Horizon documentary.*

Soft Matter, Statistical and Biological Physics

SMSB has 27 (26.04 FTE) Cat-A staff: *Allen, Arlt, Bouzid, Brackley, Blythe, Brown, Clegg, Direito, Evans, Lips (0.34), MacPhee, Marenduzzo, Martinez (0.8), Melaugh, Michieletto, Morozov, Nash, Poon, Royer, Schofield, Shendruk, Stratford, Szavits Nossan, Thijssen, Titmuss, Waclaw, Wood (0.9)*

SMSB's strategy is to combine experiment, theory and HPC simulation to address the physics of colloids, polymers, liquid crystals, multiphase soft solids, biomolecules, and biological many-body systems such as bacterial colonies. Since REF2014, we have significantly increased our activities in bacterial and active-matter physics, and in applications-inspired science.

We are now one of the largest groups in the world focusing on the physics of bacteria and other microbes in the context of soft/active matter and statistical physics. Much of SMSB experimental research relies on imaging, and we have developed and exploit a range of imaging facilities (see Section 3). Our biophysical researchers work in recently-upgraded state-of-the-art microbiological laboratories while our computational researchers have exploited access to ARCHER Director's time. Our programme is supported by major EPSRC awards (£4M Programme Grant funding plus £7M of new co-I awards during the REF period), £15M from BBSRC (as co-I), an EPSRC fellow, and three ERC grants.

In the rapidly-evolving field of active matter, we have made breakthroughs in understanding paradigmatic model systems and phenomena such as low-Reynolds-number turbulence in dense bacterial suspensions (Fig 6), and self-propulsion in active colloids. Application of physical

principles to complex biological phenomena has also yielded novel insights (e.g. resistance to chemotherapy in cancer tumours; Fig 6).

We have built on our expertise in fundamental non-equilibrium physics to extend this knowledge towards applications. This is not only in response to external drivers towards industrial/societal impact, but also reflects growing confidence in our ability to extract new fundamental science from industrial problems. The Edinburgh Complex Fluids Partnership (**ECFP**) now turns over ~£0.5M annually, impacting companies over ten sectors, and generating a pipeline of fruitful fundamental research questions arising from industrial practice. One striking example of such bi-directional knowledge exchange comes from our industrially-sponsored work on the flow of ceramic pastes and of molten chocolate, which helped precipitate a paradigm shift in suspension rheology. The invention of new materials based on bijels (an Edinburgh invention) for a new generation of advanced batteries with potentially 10x current energy densities (Fig 6) offers another example of how we have reoriented our research towards applications.

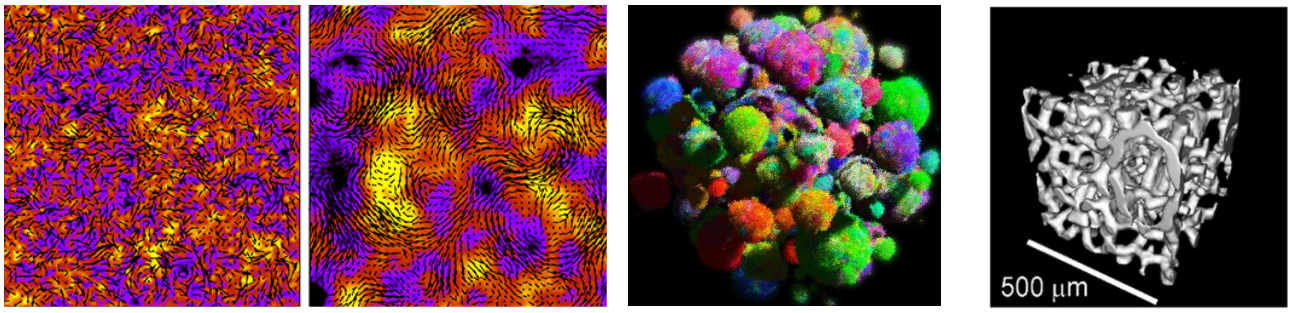

***Figure 6**. **Left:** Two simulation snapshots of the fluid flow created by swimming bacteria, showing the transition to a large-scale coherent flow called bacterial turbulence. **Centre**: A simulated cancerous tumour, with cells colour-coded depending on mutations; different genetic mutations respond differently to therapy. **Right:** a 3D-printed bijel-derived microarchitecture used as a template to create structured hybrid electrolytes with bi-continuous ceramic and polymer microchannels.*

Eight new strategic appointments in this REF period underpin the continued/future development of these growth areas. Thus, in biological physics and active matter, we will pursue research into novel collective behaviour (*Morozov*, theory/simulation), spontaneous flows and their applications (*Shendruk*, theory/simulation), the soft-matter physics of genomes (*Brackley*, theory/simulation), and the biophysics of viruses (including SARS-CoV-2) and infections more generally (*Brown*, experiments/theory). Industrially-inspired suspension physics will explore realistic flows such as spin-coating and granulation, and complexities such as polydispersity (*Royer*, experiments). We will grow energy-inspired soft-matter work (*Thijssen*, experiments) via interdisciplinary collaborations with other institutions, and plan a new research direction into synthetic topological soft matter based on work in genome packing and epigenetics (*Michieletto*, simulations/experiments). Finally, a new chair in Formulation Science (*Lips*, experiments) extends our ability to impact industrial practice and, in parallel, extract new fundamental science.

1.2.3 Particle and Nuclear Physics

The **PNP** Theme is organized into three research groups:

- Particle Physics Experiment (**PPE**) is a leader within the ATLAS and LHCb experiments at the Large Hadron Collider (LHC) at CERN, and has expanded in new directions.
- Particle Physics Theory (**PPT**) studies theories within and beyond the Standard Model, and pursues novel research on scattering amplitudes and gravitational waves.
- Nuclear Physics (**NP**) explores nuclear reactions of astrophysical significance, exotic nuclei and shell-structure, via pioneering measurements at world-leading international facilities.

Particle Physics Experiment

PPE has 13 (12.6 FTE) Cat-A staff: *Clark, Clarke, Eisenhardt, Farrington, Faucci Giannelli, Gao, Leonidopolous, Martin, Mijovic, Muheim, Murphy (0.6), Needham, Williams*.

In PPE, we have made a strategic decision to broaden our research by joining collaborations in new areas, while strengthening our leading roles in ATLAS and LHCb. We seek to further investigate the energy frontier, increase the precision of flavour physics, and look for physics beyond the Standard Model in neutrino physics and dark-matter searches. Our programme is supported by a £3.1M STFC Consolidated Grant, STFC grants for ATLAS and LHCb upgrades, LUX-ZEPLIN construction, GridPP, an EU ITN, an ERC grant and an RSURF.

At the LHC, we have strengthened our position in ATLAS through the recruitment of *Gao* and *Farrington* (ATLAS-UK PI, coordinating 350 physicists), and in LHCb through the addition of *Williams*. Our expertise in photomultipliers, silicon detectors and trigger technology allows us to play a major role in the upgrade of both experiments; our leadership within ATLAS and LHCb is evidenced by multiple collaboration convenorships. Key resulting science highlights in the REF period include precise measurement of the Higgs boson (ATLAS) and the most precise measurement of CP violation (LHCb). Our exploitation of the vast amount of data from the High-Luminosity Run of the LHC has led to new research in Machine Learning and the use of novel computing architectures (e.g. GPUs), with links to industry.

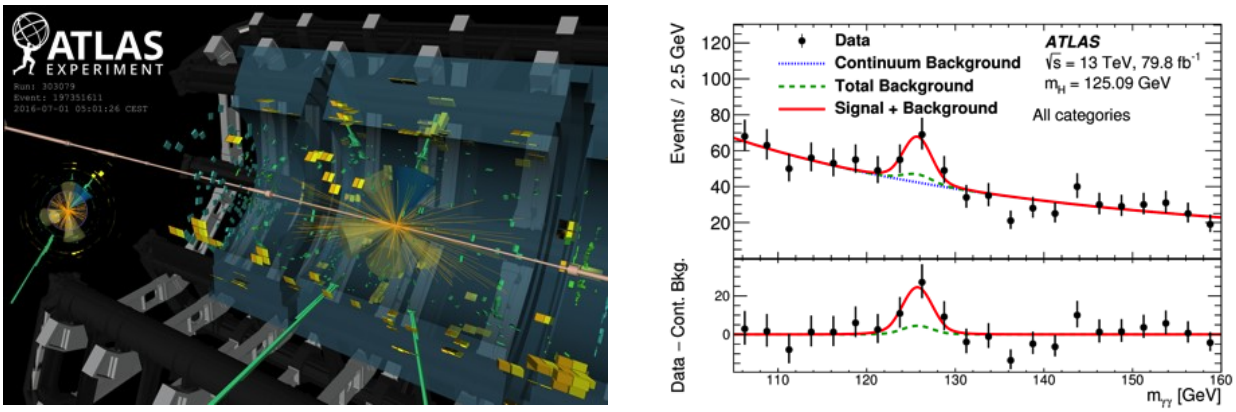

Figure 7. Left: *visualisation of a candidate event in which a top quark and anti-quark pair was produced in conjunction with the Higgs boson in the ATLAS detector.* ***Right:*** *we used the excess of signal events over the background to establish that the top quark obtains its mass through interactions with the Higgs boson.*

PPE plays a prominent role in the LUX experiment and the construction of LUX ZEPLIN. LUX has published multiple best limits on dark matter searches, including Edinburgh-led searches for axions and mirror-dark matter. We lead the LUX ZEPLIN collaboration's searches for axions, hidden photons and a number of other New Physics candidates.

Over the REF period we have made a strategic decision to significantly expand our profile in the neutrino sector, joining ANNIE, Watchman, DUNE and HyperK, building up new skills and exploiting existing expertise in photo-detectors and data processing. We led the ANNIE publication measuring the neutron background, critical to future performance. In Watchman, an experiment that aims to demonstrate the use of reactor neutrino monitoring for non-proliferation, we hold several key roles, while for DUNE, we chair the International Computing Contributions Board, tasked with securing compute resources from partner countries.

Looking ahead, we aim to further develop our leading role in the PP community, working on construction and development for LHC upgrades, neutrino physics (DUNE), physics for future colliders (e.g. ILC, CLIC, FCC, CEPC), and direct detection of dark matter with third-generation instruments.

Particle Physics Theory

PPT has 16 (16.0 FTE) Cat-A staff: *Ball, Berera, Boyle, Del Debbio, Gardi, Guelpers, Herzog, Horsley, Kennedy, Kenway, Khamseh, O'Connell, Portelli, Smillie, Turok, Zwicky*.

PPT's strategy is to advance understanding of the fundamental laws/symmetries of physics by developing theoretical tools and maximising the phenomenological impact of data from a range of experiments (ATLAS, CMS, LHCb, plus LIGO, and cosmological surveys). In doing so, we aim to explore the nature of space-time, and fundamental particles beyond the current Standard Model of Particle Physics. Our programme is supported by a £1.7M STFC Consolidated Grant, an EU ITN, two ERC grants, one FLF, and one RSURF.

One key strand of our strategy is focused on developing world-leading tools that drive the computation of observables measured at the LHC. Here we have released a new generation of parton distribution functions (PDFs), have developed High Energy Jets (a framework for describing the leading-logarithmic corrections essential for reliable predictions of multi-jet processes), and have grown activity in the computation of scattering amplitudes. The theoretical tools developed for scattering amplitudes have also fuelled activity in our second strategic area, cosmology, where we have pioneered a novel application for gravitational waves predictions, and derived the warm-inflation paradigm from a simple quantum-field-theory model. The third major strand of our strategy deals with the flavour sector of the Standard Model, where we have studied flavour anomalies, extended our lattice studies to rare kaon decays and QED effects, and successfully applied lattice techniques to the study of strongly-interacting theories for physics beyond the Standard Model. Lattice QCD has played a key role in the development of HPC, and we have developed a new collaboration with Intel, leading to new hardware.

Over the REF period we have strengthened our lattice activities by hiring *Herzog, Guelpers* and *Portelli*. In 2020, *Turok* was appointed as the inaugural Higgs Chair for Theoretical Physics, a key strategic appointment further strengthening theoretical activity in PP and connections with Cosmology. Edinburgh hosts the STFC DiRAC HPC machine Tesseract, soon to be augmented by the DiRAC3 Extreme Scaling facility (£22.8M awarded in REF period, including £7.9M in 2020 for DiRAC3). PPT also leads the STFC-funded EXALAT initiative, which aims to prepare the UK lattice-QCD community to fully exploit the power of future Exascale supercomputers, keeping the UK at the forefront of high-performance simulation science.

Our future strategy is directed at maximising our contribution to precision studies at LHC Run-3 and other current/future experiments, while also investigating any signals of new physics at colliders, in cosmology, and from gravitational waves. In PDF calculations we will release a new generation of fits, reinforcing our world leadership. Lattice simulations of QCD will reach sub-percent precision, providing crucial theoretical input for the analysis of experimental results, while lattice field theory beyond QCD will include models of Composite Higgs and holographic cosmology. We will exploit High Energy Jets for the analyses of Higgs-boson-plus-jets and vector-boson scattering (key studies of electroweak symmetry-breaking), and will further explore the potential of QCD amplitude calculations to provide novel insights into gravitational waves.

Nuclear Physics

NP has 7 (6.4 FTE) Cat-A staff: *Aliotta, Bruno, Davinson, Lederer-Woods, Murphy (0.4), Reiter, Woods.*

We explore the nuclear astrophysical origins of the elements in quiescent and explosive burning phases of stars, and the big bang. Our strategy is to identify key scientific issues in the field, and then develop innovative techniques and advanced new instrument systems to address these challenges, particularly utilising our world-leading expertise in silicon-strip detector technology. Our systems are employed at the world's leading nuclear accelerator facilities: e.g. two versions of the Advanced Implantation Detector Array (AIDA), led and developed by Edinburgh, are being used simultaneously at RIKEN (Japan) and GSI/FAIR (Germany) to study neutron-rich heavy nuclei produced in neutron-star merger and supernovae events. During the REF period we initiated and led the largest STFC Nuclear Physics Project Grant of this period (ISOL-SRS) to construct

advanced detector systems for nuclear/astrophysical reaction studies using radioactive ion beams injected into a storage ring. Our programme is supported by a £2M STFC Consolidated Grant, one STFC project grant (~£4.5M in total, ~£1M to Edinburgh), an ERF and an ERC grant.

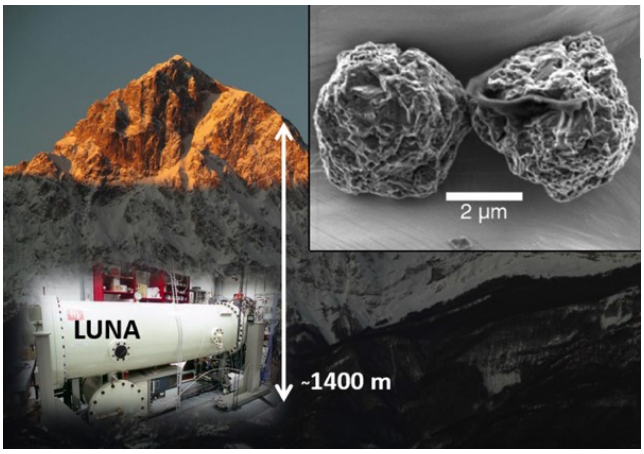

Figure 8. *The LUNA accelerator, 1400m below the Gran Sasso massif in Italy. The cosmic background reduction afforded by the underground environment, and our development of a charged-particle detection capability for the facility, were crucial for establishing the origin of cosmic dust pre-dating the solar system.*

Our strategic investment in advanced particle detection has enabled a number of science breakthroughs in the REF period, including: new results on the destruction of deuterium in the Big Bang; the nature of dust prior to formation of the Solar System (Fig 8); the origins of cosmic gamma-ray emitters; X-ray bursts; the production of heavy elements in the astrophysical r-, s- and p-processes; and on doubly-magic nuclei.

The recent appointment of *Reiter* significantly extends our research programme: he is an expert in innovative MR-TOF systems, a key technology for high-precision mass measurements of highly-unstable nuclei, critical for modelling heavy-element production in the astrophysical r-process and revealing nuclear shell structures.

1.2.4 Inter-theme and Interdisciplinary Research

As well as performing world-leading work within each of our Research Themes, a key strategic goal is to tackle the profound problems that often arise at the boundaries between traditional sub-disciplines, and to seize the opportunities presented by applying methods developed in one field to another. To further promote interdisciplinary work, we are actively developing a number of strategic links between Research Themes: Astronomy, Condensed Matter and PPT in theoretical physics through the HCTP; Astronomy and Condensed Matter through the UK Centre for Astrobiology and the Centre for Exoplanet Science; and between all research areas and EPCC in computational physics. We are also working to promote interdisciplinary research through links with other academic units including Chemistry, Biology, Medicine, Geosciences, Maths and Informatics (through CSEC, the Bayes Centre, and the Alan Turing Institute). Alongside these we will continue to develop our multidisciplinary links to industry, in particular through the HCI and ECFP, links discussed further below in the context of 'Impact'.

The **Higgs Centre for Theoretical Physics** (**HCTP**) was created in 2012 as an international centre for research and graduate education. It brings together all areas of theoretical physics, including particle physics, astrophysics, cosmology, condensed-matter physics and mathematical physics, and acts as a key focal point for interdisciplinary work between Physics and Maths. HCTP had a successful quinquennial review in 2017, which highlighted the international standing of the Centre. The HCTP has a vibrant visitor programme and has gained a high international standing in organising conferences, workshops and schools. It runs an innovative series of conferences "New Directions in Theoretical Physics", and has organised several international conferences, including

the prestigious Amplitudes meeting in 2017. The HCTP also regularly runs a summer school, "The Higgs Centre School of Theoretical Physics", attracting over 50 PhD students from across the UK, and revived the "Physics by the Lake" summer schools in condensed-matter physics. The HCTP MSc programmes attract ~250 applicants yearly (from >50 countries), yielding an annual cohort of ~30 students (over half of whom continue for a PhD). Finally, the HCTP contributes significantly to outreach, e.g. through interaction with schools across Scotland and public talks by renowned physicists (e.g. Frank Close (Oxford), Nima Arkani-Hamed (Princeton) and Gian Giudice (CERN)).

Figure 9. *The Centre for Science at Extreme Conditions (CSEC).*

The **Centre for Science at Extreme Conditions** (**CSEC**), established in 2000, is a world-class collaborative centre for extreme-conditions science. CSEC brings together 60 researchers and 79 PhD students from the Schools of Biological Sciences, Chemistry, Engineering, GeoSciences and Physics & Astronomy, with interests in experiments at high pressures, under magnetic fields, over a wide range of temperatures, in extreme-conditions technologies, and in computational materials science. CSEC's mission is to carry out adventurous, far-reaching research through enhanced facilities for sample preparation and characterisation, exploitation of multi-disciplinary expertise in extreme-conditions science, and effective use of central facilities for neutron and X-ray scattering. CSEC is internationally recognised as a world-leading centre, and its research graduates now occupy staff and postdoc positions at government labs and universities in the UK, US, Europe, Asia and Australia.

The **UK Centre for Astrobiology**, established in 2013, is the UK research affiliate-node with the NASA Astrobiology Institute (NAI). The centre has carried out laboratory, field and space-mission work at the interface between astronomical/planetary and biological sciences, focusing on life in extreme environments and the preserved record of microbial life. The Centre's staff sit on the science teams for missions such as ESA's ExoMars mission, and the Centre planned and implemented the first bio-mining experiments with ESA on-board the International Space Station (ISS). The Centre has hosted many international visitors and operates a deep subsurface astrobiology lab at the UK's Boulby mine, carrying out science and planetary technology testing with collaborators from NASA, ESA, and India. The Centre has developed educational programmes including an Astrobiology Academy, bringing secondary-school teachers together to work with the Scottish government's RAISE programme (Raising Aspirations in Science Education) to develop material now part of the National Education Portal. The Centre launched/operates a programme across Scottish prisons involving prisoners in planning for a human future beyond Earth by designing stations for the Moon and Mars.

The **Centre for Exoplanet Science**, established in 2016, brings together researchers from Physics & Astronomy and Geosciences with an interest in exoplanet science. This includes atmospheric modelling, exoplanet detection and characterisation, planet formation and evolution, and the study of planetary interiors. The hire of *Snodgrass* has expanded work to include study of

small bodies in our own solar system, complementing existing research on planet formation and planetary interiors. This puts the Centre in a strong position as exoplanetary science moves from detection to the study of planetary-system processes. *Snodgrass* also works with spacecraft exploration, through involvement in the highly-successful ESA Rosetta mission and leadership (joint with UCL) of the newly-approved ESA Comet Interceptor mission, adding in situ measurements to our existing observational and computational work.

Physics Education Research. The strategy of the physics-education research group (2.0 FTE Cat-A staff: *Hardy, Galloway*) is to capitalise on our position as active physics educators to undertake evidence-based research into the learning and teaching of physics while embedded in physics teaching at university level. We address the fundamental question: how can we improve the effectiveness of physics education? A major focus of our research is on the use and impact of active learning strategies, including peer instruction, flipped-classroom approaches, student-generated content, and the use of digital resources in active-learning classes. While our research is firmly rooted in physics, and benefits from direct access to a diverse cohort of students, a number of our projects include cross-disciplinary elements, providing additional insights into teaching and learning in both our own and cognate disciplines.

1.3 Ethics, integrity and open research

1.3.1 Research ethics & integrity

UoE has a commitment to promote and facilitate the conduct of ethical research, and has adopted the UK Research Integrity Office's Code of Practice for Research and the Concordat to Support Research Integrity. Within this framework, Physics & Astronomy has Ethics Review procedures, Research Misconduct policies, and training in Ethics and Integrity. In line with this, our ethics procedures are designed to identify issues that may arise during the course of research. These procedures apply to all research performed within the School, whether by staff, students, or visitors. As well as complying with legal and ethical requirements, their aim is to promote best practice through the University's Worktribe research management and administration system. The procedures take a tiered approach, with the level of scrutiny dictated by each set of circumstances.

In terms of training, incoming PhD students are required to take the on-line course *Research Ethics and Integrity – an introduction*, run by the 40-FTE Institute for Academic Development (IAD), with access to the *Global Research Ethics and Integrity* course. We also run *compulsory supervisor briefings* with the IAD.

Our public Research Ethics & Integrity webpage (https://www.ph.ed.ac.uk/research/ethics-and-integrity) provides details of the key ethics and integrity point of contact (the School Director of Professional Services), and links to the School Ethics procedures for staff and students on the School Intranet. Here, clear procedures are provided for **i)** *Reporting Staff Misconduct in Research;* **ii**) *Reporting Student or Teaching Misconduct;* **iii**) *Reporting Personal Misconduct;* **iv**) *Ethics screening of Grant Applications*, along with a link to the UKRIO Code of Practice for Research (adopted by the School/University).

Through the DDI programme, founding membership of the Alan Turing Institute, its provision of UK HPC services and its historical strength as the largest centre for AI research in the UK, UoE is building a world-leading position in data-driven research and innovation. Central to this is public trust in our use of data. UoE established an AI and Data Ethics Advisory Board (first chair *Kenway*) to steer AI-X, its new multidisciplinary centre for shaping our AI future, and to find responsible and sustainable solutions for the new ethical problems that are expected to arise. This work is technically-driven and the School is contributing by developing algorithms for analysis of huge physics and astronomy data sets (where privacy issues are not a constraint), and a better theoretical understanding of machine learning to enable explicability, safe operation and, eventually, inclusion of physics in autonomous decision-making systems.

1.3.2 Creating an open research environment

UoE is committed to promoting an open research environment, both in terms of data access (where possible) and accelerating the transition to full and immediate Open Access to scientific publications. Within Physics and Astronomy >90% of our outputs are Green Open Access (~60% Gold). The vast majority of our reported outputs, as well as being released through the Edinburgh Research Explorer (https://www.research.ed.ac.uk), are immediately world-public on the arXiv, and are based on datasets that are either immediately or rapidly made world-public through, for example, releases by ESO, ESA, or our own WFAU. CERN has addressed open data access seriously for some time, and the access policy can be found at: http://opendata.cern.ch/.

1.4 Impact Strategy

Approach

Our approach to impact is governed by three principles. First, we aspire to excellence in both basic research and impact generation, and these attract equal recognition and reward. Second, we take full advantage of the University's Business Development (BD) and Knowledge Transfer (KT) services augmented by our RS Entrepreneur-in-Residence (Bruce-Gardyne). Third, we actively invest in KT-related projects, and many of our new academic appointments since REF2014 (*Royer, Smith, Zuntz, Snodgrass, Gao, Portelli, Brown*) have been made with explicit expectations of working with industry. These have: led to the establishment of new businesses; improved the competitiveness of existing industries; enabled quality-of-life improvements; stimulated the public imagination and improved science education through outreach, engagement and teacher training; influenced national policy.

Our Impact Strategy is to grow existing collaborative research activities with companies where these can improve their processes (e.g. through **ECFP**), and to add to these through a number of interdisciplinary activities that aim to promote new businesses directly: the **HCI** and our **DDI** theme within the Edinburgh City Deal. In these latter areas we benefit from the recognition that the data collection, storage and analysis techniques developed in particle physics and astronomy have a very broad impact, and that our data resources can be used to test new methodologies without data protection issues as, for example, in medicine.

The **HCI** is a Business Incubation Centre (BIC) for CERN, UKSA, ESA and STFC, located at the STFC's UKATC. It is focused on business incubation and start-up business support, leveraging cutting-edge UKATC remote-sensing and Space-instrumentation expertise, UoE facilities and Big-Data capabilities for up to 12 start-up companies. We have adopted a phased approach to introducing new businesses to create a spread of company maturity, and in the two years since opening, HCI has attracted 8 start-up firms, principally in the Space sector. A key differentiator from other business incubators is the HCI's co-location with the IfA; this enables companies to interact closely with academics and PhD students, fertilising new ideas and breaking down barriers to PhD students and ECRs moving into business ventures.

This model of "breathing the same air" is also central to the University's investments in DDI, directly interacting with the incubated companies. Today, our key links are with the £40M **Bayes Centre** (opened in 2018; Deputy Director *Trew*), the University's innovation hub for Data Science and Artificial Intelligence with particular application in Space and Satellites, and Big Data. Bayes has a community of ~600 scientists, PhD students, industry experts and innovation support professionals (including EPCC), working together across disciplines to advance data technology and apply it to real-world problems. More generally, we make targeted use of Impact Acceleration Accounts and other KT funds generated by the School to leverage non-academic co-funding for work on new projects. Our focus is on encouraging new projects that can subsequently apply for support through the Innovations Partnership, Proof of Concept, and ultimately to Innovate UK or GCRF. Two projects that we have so funded, and expect to mature into future Impact Case studies, are collaborations with Lockheed Martin on monitoring near-space objects, and the

development of more sensitive radiation monitors.

We protect our IP wherever we judge there to be strong prospects for its exploitation and seek to build coherent IP positions in targeted technology areas, ensuring that full value can be obtained through licensing across a whole technology sector rather than by a piecemeal approach.

Results

Since 2014, we have formed 5 start-up companies, granted 7 licences for the exploitation of existing IP, and been awarded 11 patents. Our total industrial income over the REF period was £14M: £2.04M of consultancy income (113 contracts); £2.14M of cash and royalties (30 projects); £9.8M for projects at EPCC. We also received undisclosed but substantial hardware discounts from Intel, in lieu of royalties, on computers worth many millions of pounds.

Our nine **Impact Case Studies** are chosen both to reflect the breadth of our impact, and to demonstrate how our supporting infrastructure promotes impact delivery. Some case studies show how a sustained research effort spanning several decades can continue to underpin an entire technology sector (*ECFP, Suspensions, Emulsions, Gluten-free foods*). A second key message of our case studies is that the technologies we invent to do basic research can yield far-reaching impact when partnered with the industrial muscle and vision needed to exploit them across broad client sectors (*Intel, Blackford Analysis*). We also show how our research in curiosity-driven basic science can spark the imagination of adults and children through high-quality engagement activity, enhance and broaden educational opportunities (especially for disadvantaged members of society), and even inform wider ethical debates about mankind's place in the Universe (*Astronomy, Soft Matter, and Prisoner Outreach, Engagement & Education*). Given its impact on the Economy and Society, the results of our work with **industry**, in **public engagement/education**, and tackling **COVID-19** are described further in Section 4.3.

Our **policy impact** flows naturally from the research and interests of several staff. We support staff involvement in the provision of policy advice at every level: e.g. *Kenway* was a founder member of the UK e-Infrastructure Leadership Council, is a Trustee of the Alan Turing Institute and a member of STFC Council; *Trew* is the UoE representative on Turing's University Partners' Board. Crain, until his move to NPL in 2016, was seconded part-time as Head of Physical Sciences at NPL, responsible for its interaction with government departments (BEIS, InnovateUK); Ivison was seconded (2014-2019) to ESO as Director of Science, while supported by an ERC Advanced Grant at Edinburgh. Finally, our public-engagement work in astronomy has influenced public-engagement policy in the UK and internationally, through the development of a clear *evaluation framework* for public-engagement activity, and the expanded implementation of Continuing Professional Development (CPD).

The Future

Looking ahead, we plan an increasing programme of Impact-generating activities. New opportunities include: development of the collaboration with **Lockheed Martin** (*Mann*); a new start-up, **Dyneval**, aiming to commercialise a portable, reliable semen analyser for the farming community (*Wood*); new industrial collaborations with **Premier Foods**, **Quorn** and **Afton** (*Poon*); expanded work on disease and pandemic management/control triggered by our recent innovative efforts to help combat **COVID-19** (*MacPhee, Allen*: see Section 4.3).

Our ambitions are supported by investments in targeted academic posts, our Entrepreneur-in-Residence, centres that facilitate enhanced engagement (ECFP, HCI, Bayes), and closer collaboration with Edinburgh Innovations. Moreover, the management skills used to build EPCC up into a technology-transfer centre with 110 staff and a turnover of £13M will enable us to grow these new activities and spin-off companies in a way that is market-relevant.

2. People

2.1 Staffing Strategy and Staff Development

Staff Recruitment & Turnover: Edinburgh recruits outstanding physicists globally, by competitive advertisement, informed by the research strategy outlined above. Since 2014 we have appointed 31 highly-qualified staff to academic posts: *McMahon(S), Royer, Dave, Smith, Snodgrass, Varri, Zuntz, Farrington, Gao, Portelli, Reiter, Davinson, Thijssen, Brown, Lederer, Smillie, Guelpers, Bouzid, Shendruk, Brackley, Michieletto, Koposov, Dupuy, Beutler, Aird, Herzog, Cai, Turok, Williams, Santos, Lips*.

New chairs are *Dave, Ferguson, Heymans, Khochfar, Penarrubia, Mann, McLure, Rice*, *Biller* (**AST**), *Allen, Blythe, Clegg, Marenduzzo, Morozov* (**CMP**), *Aliotta, Davinson, Murphy*, *Farrington, Leonidopoulos, Martin*, *Boyle, Gardi* (**PNP**), *Poon* (Natural Philosophy), *Hardy* (Physics Education), and *Turok* (Higgs Chair). The School now has 9 women Professors (compared to 1 in 2013).

Only a very small number of academic staff have left Edinburgh Physics & Astronomy during the last 7 years, and these departures have generally been to rare high-profile positions (e.g. Cates to the Lucasian Professor of Mathematics at Cambridge in 2015; Ivison to ESO Director of Science in 2019), which we believe reflects well on the research environment and career development provided at Edinburgh. In general, therefore, the picture has been one of sustained, vigorous growth over the REF period. Among recently-hired staff, *Brown, Gao, McMahon (S.), Portelli, Royer, Smith, Snodgrass, Thijssen* and *Zuntz* were appointed on 5-year Chancellor's Fellowships; these University-funded tenure-track posts allow early-career staff to focus on developing their independent research, prior to conversion into permanent lectureships/readerships.

Staff Development & Training: We are committed to maintaining a supportive environment in which staff are given every opportunity for their research to flourish. New appointees are assigned a mentor to assist and advise them in all aspects of their work. We offer flexible start-up packages that include funding for new facilities, PDRAs and travel. New academics get preferential access to PhD studentships, and a gradual ramp-up of their teaching load over the first 5 years. Each Fellow or PDRA is also supported by a mentor from within their research group. While focusing on research, they are encouraged to gain experience in teaching through tutorial workshops, graduate lectures or undergraduate projects.

Annual *Performance and Development Review* (PDR) is central to our staff-development process – for academics, researchers, and for support/technical staff. Training sessions are provided (for appraisees and appraisers) on how to obtain the most from the PDR process. Our average annual PDR completion rate over the REF period is 98% (for all academic, research, and support staff). We also provide (funded) access to a wide range of professional-development courses provided by UoE or SUPA. These include induction courses for new staff, training in PhD supervision, workshops in grant applications and research management, courses on best practice in KT, outreach, and teaching/learning, and annual Senior Leadership programmes.

Research Fellows & Associates: We aim to attract the very best fellowship applicants through an open call advertised well in advance of funding-body deadlines, and to support all strong candidates (external or internal) who wish to apply for research projects that fit, or enhance/extend our research strategy. Where a funding body imposes a quota we operate a rigorous and prompt internal selection process, and ensure unsuccessful candidates are given both feedback and adequate time to apply elsewhere. We then assign an academic mentor to each candidate to help develop the final proposal. If candidates are successful in being selected for interview, we provide a series of rehearsal interviews to assist every candidate to optimize their presentation (our mock interview panels contain both senior staff and recently-successful fellows).

The success of our approach, and the strength of the applicants we attract, are reflected by the fact that 25 of our 119 Category A staff currently hold full-time personal fellowships awarded competitively by UKRI, STFC, EPSRC, Royal Society, Royal Astronomical Society, Royal Society of Edinburgh, Leverhulme Trust and the EU, including 5 UKRI FLFs awarded from the first 4

rounds. During the REF period, 17 ERC grants have been held by Cat-A staff, with 12 ERCs still currently active at the census date: 2 Advanced (*Ackland, Peacock*); 4 Consolidator (*Allen, Farrington, Heymans, Marenduzzo*); 6 Starting (*Beutler*, *Lederer-Woods, Michieletto, Portelli, Shendruk, Smillie*). About 17% of our other Research Associates are funded via strategic funds, and the other 83% through research grants. The total number of Research Associates has increased by 15% from 116 in 2013 to 133 in 2020. Finally, we operate a Fellowship Conversion Policy that guarantees an interview for tenure to any individual who secures two major fellowships.

Developing Impact: We encourage all academic and research staff to apply for fellowship schemes that support the commercial exploitation of basic research, such as the STFC-funded Innovation Partnership Scheme, RS Industry Fellowships (*Wood*), InnovateUK Innovation Fellowships (*Brown*), and RSE/BP Fellowships (*Thijssen*). We offer advice and mentoring to all staff wishing to pursue impact-generating activities, aiming to build their skills and contacts (e.g. Ben Panter, astronomy PDRA turned CEO of Blackford Analysis). We place no limit on the duration of such secondments and encourage these activities by returning all surpluses generated to the group/individual to build intellectual capital for future work. Our workload model includes impact-generating work on a par with other academic duties. Our annual staff PDRs also encourage reporting of impact roles and discussion of the support required.

Equality, Diversity & Inclusion (EDI): Physics & Astronomy has an EDI strategy with action plans overseen by an EDI coordination team led by the Director of EDI (Martin). These range from family-friendly scheduling of staff meetings to proactive reintegration strategies following career breaks, for example the University's "Returning Parents Coaching Programme". Online EDI training, Equality and Diversity Essentials and Challenging Unconscious Bias, is mandatory for all staff, and we have also offered in-person workshops addressing bullying and harassment. Flexible-working arrangements can be applied for and include Job Share, Compressed Hours, Part-Time Working, and Flexible Retirement. The School's EDI Director sits on the sabbatical selection panel and we participate in the new additional sabbatical scheme for women at grades 8 and 9 operated by the College of Science & Engineering.

We have improved the proportion of women at all levels, currently: 28% of PhD students, 26% of PDRAs, and 20% of academic staff (IoP UK benchmark figures are respectively 22%, 19% and 18%), including 9 Chairs (up from 1 in 2013). We aim to further improve these figures and those for other under-represented groups. Our progress during the REF period has been recognized by **IoP Juno Champion** status (awarded 2014, renewed 2019) and by **Athena SWAN Silver award** (renewed 2019; we plan to apply for Athena SWAN Gold in 2022). The School is also heavily involved in an EPSRC Inclusion Matters project: *eBase: Evidence-Base; Growing the Big Grant Club - EP/S012087/1* (£0.5M). Our leadership in improving EDI has also been recognised by the award of a CBE to *MacPhee* (2016) for "Services to Women in Physics".

We have recently developed a School Equality, Diversity and Inclusion (EDI) website, dedicated to providing information and resources for staff and students: https://www.ph.ed.ac.uk/equality-diversity-and-inclusion. In 2020 we have collated statistics on BAME staff and students to add to this website. We have also used social media and 'imagebites' on plasma screens to highlight the website and other EDI initiatives/support for students and staff, including the University's 'Don't Cross the Line' campaign.

EDI in the REF2021 submission. All staff involved in the submission process have undertaken specific training on EDI for REF. We have followed the policies and processes in our institutional Code of Practice in preparing the UoA-9 submission. Inclusion in the output portfolio is based solely on merit, as assessed by a panel of senior academics. We have checked the resulting average number of outputs per Cat-A staff member for sub-groups of interest, and find that these differ little from the global average of 2.5. Specifically, the averages are 2.5 for BAME staff, and 2.3 for women; this latter number partly reflects an average of 2.3 for our 32 early-career researcher (ECR) Cat-A staff, with 1/3 of submitted women designated as ECR.

Concordat: We recognise the importance of contract research staff (CRS) and fully endorse the

UK Concordat for their career development. We have also implemented the principles of the European Charter for Researchers, leading to the EC "HR Excellence in Research Award". We have a Code of Practice in place for the management of research staff, with an action plan that supports their career development. Examples include a mentoring scheme in which CRS are mentored by an academic who is not their line manager, a CRS forum for identification and resolution of issues affecting CRS, and supportive PDRs in which career goals are discussed and associated training identified and fulfilled, often by courses designed specifically for CRS.

Sabbaticals & External Visits: These are encouraged as they help create/develop links with other top institutions, and enhance/retain research momentum. Each year ~5% of academic staff take a half-year or full-year sabbatical to develop new contacts, improve facility access, and initiate new (or complete existing) areas of research. Such visits are frequently supported by prestigious visiting funding awards. Examples in the REF period include Ball, Del Debbio, Gardi, Martin, Muheim (CERN Scientific Associateships), Ferguson (AAO Shaw Visitor, and IAC Severo Ochoa Distinguished Visitor), Farrington, Muheim (Senior IPPP fellows), Peacock (University of Cape Town), Playfer (KEK), Evans (Visiting Professor, Weizmann Institute), Poon (ESPCI, Paris).

Visitors and Visitor Programmes: We host visitors from a wide range of countries; these include senior researchers on sabbatical leave as well as visits by long-term collaborators, frequently funded by competitive applications to the SUPA Distinguished Visitor programme, or to the Carnegie and Leverhulme Trusts. A thriving new visitor programme has been established via our strategic investment in the HCTP, while several major grants in CMP and AST also include visitor funding. Examples of distinguished scientists who made extended/multiple visits during the REF period include: Arkani-Hamed (Princeton), Brandenberger (McGill/Perimeter), Canet (Grenoble), Ellis (Caltech/ESO/UCL), Gianotti (CERN), Heuer (CERN), Iijima (Nagoya), Kaiser (Hawaii/Paris), Krug (Cologne), Sauls (Northwestern), White (UC Berkeley), Wyse (Johns Hopkins).

2.2 Research Students

Edinburgh Physics & Astronomy delivers a highly-developed and closely-integrated programme of graduate education within the framework of the **SUPA Graduate School** (established 2006). This offers ~50 advanced courses (>800-hr of lectures) for physics PhD students across Scotland, as well as professional-development training. Courses, accessing the knowledge and skills of world-leading researchers from the eight partner universities are delivered by live video links using SUPA's e-learning portal with dedicated video classrooms. There are also tutorials, lab classes, workshops and the international Scottish Universities Summer Schools in Physics (SUSSP). Courses are aligned to pan-SUPA research themes (Astronomy & Space Science, Condensed Matter & Material Science, Energy, Nuclear & Plasma Physics, Particle Physics, Photonics) and two impact themes, (Energy, Physics & Life Sciences). Each PhD student must take at least 40hr of academic courses and 20hr of professional-development courses in their first two years.

As the largest Physics graduate school in the UK, the SUPA Graduate School continues to have a major impact on Physics research and graduate education. Indeed, the SUPA Graduate School has grown substantially: over the REF period an average of 111 PhDs have been awarded per year within SUPA, as compared with 78 per year in REF2014. Over the same period the SUPA Graduate School has delivered ~100,000 hours of training, comprising ~80,000 hours of Advanced Physics technical training and ~20,000 hours of Professional Development training. In addition to the PhD students, ~500 Masters-level students have enrolled on SUPA courses, benefitting from the large range of graduate-level training on offer. In 2019/20 Edinburgh hosted 185/849 (22%) of all SUPA graduate students, and taught 14/49 (26%) of its courses.

Student Numbers: We have seen a steady increase in our postgraduate student admissions, although PhD places at Edinburgh remain highly competitive, with currently 11 applicants per studentship awarded in Physics & Astronomy. Current student numbers within our three Research Themes are: AST 38, CMP 84, PNP 50, giving a total current head-count of 172. Of these, 60% are from the UK, 30% from the EU and 10% from further afield.

Training Centres: Since 2009 we have co-hosted (with St Andrews and Heriot-Watt) a £6M EPSRC Doctoral Training Centre in Condensed Matter (CM-CDT); we currently supervise 21/62 of its students. CM-CDT provides comprehensive training across the breadth of condensed matter, plus industrial partnership, outreach, and exchange programmes; much of this training is available to our non-CDT students. We are leading partners in two further CDTs, one in Data Intensive Science (ScotDIST, with Glasgow and St Andrews), and one in Soft Matter (SOFI2, with Durham and Leeds), and participate in the EU Marie Curie training network EuroPLEX (lattice QCD).

Funding & Sponsorship: UK students who began PhDs during the census period mainly hold EPSRC (64) and STFC (71) studentships. We make full use of UoE-funded studentships (primarily for EU and international students) and have also awarded 21 Higgs Studentships in the broad area of mathematical/theoretical physics. Our international students have come from 28 countries, many with their own funding. We host studentships co-funded by AkzoNobel, AWE, Cleveland Potash, ESO, GSK, ILL, Johnson Matthey, Mars Chocolate, Mondelez, Schlumberger, Thales and Toyota. UKRI-funded students are assigned DTG funds for minor equipment and for travel to national and international conferences (strongly encouraged). Over the REF period, Edinburgh Physics & Astronomy received Doctoral Training Grant (DTG) funding of £3M from EPSRC and £5M from STFC. In STFC-funded areas there is additional resource for long-term secondments to overseas facilities. For non-UKRI students, equivalent costs are met from UoE, SFC and School funds.

Training & Support: All research groups have regular seminars aimed at graduate students, and the School of Physics & Astronomy runs colloquia of general interest to all such students. The HCTP has a regular series of colloquia and lectures in theoretical physics. There are student-run interdisciplinary seminars where those from different groups exchange ideas, and postgraduate staff-student liaison committees to discuss training and support issues. UoE also organizes training workshops, courses, and online resources specifically for PhD students, including introductions to research, thesis writing, viva preparation, presentation skills, professional development and time/career management. We subsidise our students to spend a week together at the Firbush Outdoor Pursuits centre on the shore of Loch Tay with instructors on hand. There is an annual barbeque, ceilidh and games/pizza nights. Six months after arrival, all students have a pastoral interview with a faculty member unrelated to their research; this is an opportunity to check that students have settled in and also to flag up problems to an impartial third party. Pastoral support teams are selected with careful consideration for gender and age balance, and remain available to students throughout their studies. Our PhD students are trained for undergraduate teaching duties, and take part through tutorials, workshops, computing and experimental laboratories. The students are also enthusiastic contributors to our public-engagement events (see REF3a).

Progress Monitoring: Each PhD student has a first and second supervisor from within their research group. Our students also have two assessors (independent of the supervisory team) who interview them annually. For the first year, students submit a literature review and progress report, in preparation for their academic progression interview. In subsequent years, they submit an outline of their progress; the assessors monitor supervision, timelines and critical dependencies. In addition, early in second year each student meets with the Head of School and the Director of the Graduate School; this broader meeting explores issues such as training and support needs, and provides an 'early warning system' for potential problems. Early in their third year, students present their research at a School-wide poster session, with prizes awarded for the best posters.

Summer Schools: SUSSP has run 1-2 schools per year since 1960. During the REF period these included: Frontiers in Quantum Dynamics & Quantum Optics (2015-SUSSP71); Photonic Systems for Sensing & Metrology (2016-SUSSP72); Gravitational-Wave Astronomy (2017-SUSSP73); Innovation & Entrepreneurship in Photonics (2018-SUSSP74); and Nuclear Physics and its Applications (2019-SUSSP75). Each School was attended by ~100 students from across the world. CM-CDT runs biennial summer schools; our CMP students attend these and other EPSRC and IoP schools, while AST and PNP students attend STFC schools. All students are encouraged to participate in overseas graduate schools; most attend at least one during their PhD.

3. Income, infrastructure and facilities

3.1 Research Income

Edinburgh Physics & Astronomy has a very strong record of winning competitively-awarded research funding. Over the REF period we **spent £110M** of research income (REF4b). From all sources we have been **awarded** grants totaling **£130M**, including grants for managing national facilities and/or industry links. In addition, EPCC non-Cat-A staff attracted **£1M** of research funding.

We provide extensive training and mentoring for staff preparing proposals, have rigorous internal-review procedures for quality assurance, and support candidates selected for fellowship/grant interviews with extensive rehearsals. We believe this rigorous and collegiate approach contributes to the high success rate of our funding applications (~41% for the past two years).

We have grown our income by attracting funding from a wide range of sources: the breakdown for 2019/20 is 79.1% UKRI (STFC, EPSRC, BBSRC, MRC), 16.4% EU/ERC, 4.5% Other (Industry, Royal Society, Leverhulme Trust). We currently hold 40 large grants (over £0.75M each), whose values for each Research Theme amount to: **AST £13.1M**; **CMP £9.3M**; **PNP £25.9M**.

3.2 Local Infrastructure & Facilities

Edinburgh Physics & Astronomy has extensive in-house facilities open to all research staff and students. Within SUPA we also pool resources and equipment across Scotland. Since 2013 we have made strategic investments in facilities for all research areas. Technical support is provided by 13 research technicians, 10 computing staff, and by mechanical and electrical workshops.

We have comprehensive subscriptions to **electronic journals** and, over the REF period, have spent ~£350k to maintain the **ROE Library** as one of the world's premier astronomical libraries.

Computing and Data Facilities: EPCC (Chair *Trew*) is ranked among Europe's 3 leading centres for scientific HPC and its applications. Formed and developed within Physics & Astronomy, we floated EPCC as a stand-alone University centre in 2016. EPCC's 100+ staff undertake research with industry and academia, have led many European projects on advanced computing technologies, and support national facilities. EPCC hosts and manages the ARCHER/ARCHER2, Cirrus and DiRAC facilities and has coordinated EU-funded collaborative projects into exascale supercomputing, including CRESTA and NEXTGenIO. It has: £46.5M EPSRC contracts to run ARCHER/ARCHER2 (the UK HPC Tier-1 service); £3.5M for Cirrus (a UKRI HPC Tier-2 facility); and a £13.1M BEIS contract to expand the UK Research Data Facility. Agreement has been reached for EPCC to host all national HPC services for the next 20 years. Under its contracts, 5% of ARCHER is reserved for use by Edinburgh researchers, mostly in Physics & Astronomy. This 'Director's Time' is excluded from the UKRI figures (REF4b) and was worth £5.3M over the period. We also make use Cirrus (another £2.7M in Director's Time) and the Edinburgh Compute and Data Facility (ECDF), an IBM cluster with ~3k core processors, ~7TB of RAM, and 1PB of data storage (valued at £125k/yr). Recognizing the importance of scientific computing and HPC to all areas of our research, we employ 10 people (excluding EPCC staff), in computing-support roles (software developers, database managers, systems administrators and computing officers).

AST: To support simulation and observation analysis work, the IfA has made investments totalling over £0.6M in its local dedicated compute clusters, which offer ~1700 cores, ~3PB of storage, 4 dedicated GPUs, and peak performance of ~150 Tflops. **WFAU** hosts extensive data-archiving facilities, serving 2.8PB of data to the international astronomical community, and during the REF period we have invested £0.5M in hardware to enhance WFAU's capabilities. WFAU's WFCAM and VISTA Science Archives receive over a million SQL queries annually, returning tens-of-billions of rows of tabular data, and many hundreds-of-thousands of file downloads.

CMP: We have invested significantly in updating **CSEC**'s capabilities, including: a £0.6M Core Equipment award to update X-ray diffraction capabilities; £0.3M for a planetary simulator to

investigate life in exoplanetary conditions; £0.23M in detector, microscopy and sample-preparation upgrades. Outwith CSEC we have state-of-the-art cryostats, a materials-growth laboratory, and a £1.3M EPSRC multi-user focused ion-beam cryo-scanning electron microscope facility (**cryo-FIB/SEM)**. We also make extensive use of **COSMIC** (Collaborative Optical Spectroscopy, Micromanipulation and Imaging Centre), an interdisciplinary facility for spatially-resolved spectroscopy, coherent anti-Stokes Raman spectroscopy (CARS), and fast confocal microscopy coupled to rheometric flow cells for particle-tracking in flowing colloids. We run a suite of optical microscopes, host a femto-second pulsed laser allowing fluorescence lifetime imaging microscopy (FLIM), and a Leica high-speed laser scanning confocal microscope optionally coupled to a rheometer for real-time 3D imaging under shear. We have invested £0.67M to re-develop lab space for Food Science and Biological prep, and to establish a suite of microbiological wet-labs. To support its simulation/computational work, ICMCS has invested £0.25M since 2014 in a dedicated compute cluster with ~1300 cores, and a peak performance of ~35 Tflops.

PNP: The state-of-the-art facilities built in the previous REF period have allowed our PPE group to lead the development of the Inner Tracker Upgrade for ATLAS, and to coordinate the LHCb RICH photon-detector project. Our expertise with photo-detectors is key to advancing WATCHMAN. NP continue to build detectors that have been deployed at experiments worldwide (e.g. AIDA).

3.3 External Facilities

Our UKRI facility-usage income in kind of £121M (REF4c) is supplemented by ~£30M of estimated equivalent income from competitively-awarded time on other international facilities:

Facility usage (+est. equiv. value) over the REF period not reported in REF4c

CMP

Facility	Time Awarded	Value £k
PSI Neutrons	50 days	425
NIST	125 days	1063
FRM2 (Munich)	10 days	85
HZB (Berlin)	32 days	272
LLB (Sacley)	10 days	56
SNS (Oak Ridge)	50 days	280
APS	6 days	72
PETRA-III	41 days	492
Spring-8	12 days	120
LCLS	13 shifts	52
NIF	6 shots	4615
JANUS	8 weeks	208
	TOTAL	**7740**

AST

Facility	Time Awarded	Value £k
Chandra	60 ksec	830
Keck	8 nights	400
Gemini	14 nights	700
Subaru	3 nights	150
AAT	6 nights	120
CFHT	2 nights	40
SOAR	10 nights	200
IRTF	15 nights	300
Spitzer	295 hours	5900
IRAM	200 hours	300
VLA	300 hours	450
LOFAR	680 hours	1020
	TOTAL	**10410**

PNP

Facility	Time Awarded	Value £k
ANL	2 weeks	280
GSI	4 weeks	1120
JLAB	28 weeks	1960
LUNA	36 weeks	1260
NSCL	2 weeks	280
RIKEN	1 week	350
Texas A&M	4 weeks	140
TRIUMF	19 weeks	1995
	TOTAL	**7385**

Computing*

Facility	Time Awarded	Value £k
NERSCC	30M CPU hours	1500
DECI	17M CPU hours	850
NCSA Blue Wat.	46M CPU hours	2300
XSEDE	1M CPU hours	50
	TOTAL	**4700**
	OVERALL TOTAL	**30235**

* Computing time costed at ~£0.05/core-hour.

Our dark-matter research has been conducted at the Boulby mine, and at the Sanford Underground Laboratory (equivalent costs unknown). Other international facilities used include DESY (Hamburg), FNAL (Chicago) and J-PARC (Tokai).

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

4.1 Collaborations

AST: Due to the international nature of astronomy facilities, most of our observational research takes place in international collaborations. We play a leading role in many of these consortia. Examples include UltraVISTA (*Dunlop*, PI), VANDELS (*McLure*, co-PI), Euclid (*Taylor*, UK-PI), JWST (*Biller*, Exoplanet imaging ERS co-PI), LSST (*Mann*, UK-PI), LOFAR (*Best*, UK-PI), HARPS-N (*Rice*), KiDS (*Heymans,* co-PI), UKIDSS (*Lawrence*), PanSTARRS (*Peacock*), CFHT lensing (*Heymans*), Comet Interceptor (*Snodgrass*, deputy-PI).

CMP: We are partners in EPSRC networks addressing Fluids, the Physics of Life, Emergence and Physics Far From Equilibrium, and Advanced Materials for Energy Applications. We are a leading member of the BBSRC/Innovate UK National Biofilms Innovation Centre (NBIC). Interdisciplinary collaborations include nuclear-reactor materials (*Ackland*/Engineering); Li-ion battery electrodes and Fuel Cells (*Clegg*/Chemistry); molecular biophysics (*MacPhee*/Biology); physics of life (*Allen*/Biology), and collaborations with geoscientists and chemical engineers. Industrial collaborations inform our basic research: work on flowing chocolate has led to new theories of suspension flow, while work on reducing the calorie content of confectionary has produced new insights into colloids. Collaboration with AWE has influenced our strategic decision to work with free-electron lasers.

PNP: Our PPE group are leading members of the ATLAS and LHCb collaborations (*Clark, Farrington, Muheim, Martin*), the LUX and LZ dark-matter collaborations (*Murphy*), neutrino-physics collaborations WATCHMAN (*Muheim*, *Needham*) and DUNE (*Clarke, Muheim*), and GridPP (*Clark*, *Clarke*). *Leonidopoulos, Gao* and *Martin* are members of future-collider R&D collaborations (FCC, ILC, CLIC, CEPC). In PPT we participate in large collaborations in Lattice QCD (UKQCD, QCDSF), where *Boyle* leads in the development/procurement of new hardware in partnership with Intel, and NNPDF. Nuclear physics research takes place in small/medium-sized collaborations with PI roles taken by *Aliotta, Lederer-Woods, Murphy, Reiter* and *Woods*.

4.2 Contributions to the Research Base

It is impossible to give a comprehensive listing under this heading. For Review Panels, Policy advice and Prizes, we list selected exemplars. In addition, our staff have served on the Scientific Organising Committee (SOC) for more than 230 major international conferences, being SOC Chair/co-Chair for ~30% of these. Our staff have delivered invited presentations at over 450 major conferences, of which ~150 are designated Keynote, Plenary, or Invited Review.

Review Panels

AST: Our astronomers have served on numerous facility time-allocation committees (DiRAC - *Rice*; HST - *Ferguson*, *Biller, Dupuy*; Opticon - *Biller*; ESO OPC - *Heymans*; PATT - *Snodgrass*; Spitzer – *Dupuy*), grant-allocation committees (STFC Astronomy Grants Panel - *Lawrence* (Chair), *Best* (AO sub-panel Chair); PPRP - *Heymans*; US NSF Astronomy Grants - *Dave*), selection committees (RS Election - *Peacock* & *Dunlop*; Shaw Prize - *Peacock*; RSE Fellowships - *Heymans*; ERFs - *Biller*; Hawking Fellowships - *Biller*) and review panels (e.g. STFC Dark Matter Strategic Review Panel - *Heymans* (chair); SKA Science Review Panel - *Best*; NASA Astrophysics Theory - *Smith*; STFC Radio Astronomy Review Panel - *Heymans*; Max Planck Institutes Rapporteur - *Peacock*).

CMP: *Blythe, Evans, Huxley*, *MacPhee, Morozov, Santos* and *Stock* have served on EPSRC/STFC/NSF/DOE/SNF/DFG/GACR grants and fellowship panels. *MacPhee* chaired an ERC Advanced Grants panel, and *Marenduzzo* is an ERC Starting Grant panel member. *Poon* and *MacPhee* chaired an EPSRC prioritisation panel. *Ackland* served on a Finland Natural Science

funding panel. *MacPhee* served on a Swiss National Science Foundation panel. Facilities panel members have included *Huxley* (ISIS), *McMahon* (ALS, Soleil, Spring-8, PETRA), *Stock* (ISIS, Oak Ridge, NIST, CHESS, PSI, FRM2) and *Titmuss* (ISIS, ILL and Diamond). *Ackland* is a leading member of Rapid Assistance in Modelling the Pandemic (RAMP), which has reviewed over 300 COVID-19 papers.

PNP: *Ball* is a member of STFC PPGP. *Del Debbio* is chair of PRACE-AC (EU). *Farrington* is a member of STFC PPRP. *Martin* was Chair of STFC PPRP, member of STFC ERF panel, and member of STFC review panels on ASTeC, Accelerator Institutes, GridPP6, Accelerator Strategy, and Long-Baseline Neutrinos. *Leonidopoulos* was a member of PPGP. *Murphy* is a member of REF2021 sub-panel 9 (Physics). *Aliotta* sits on the UKRI FLF grants panel and the STFC Nuclear Physics grants panel.

Policy advice

AST: *Best* is Chair of the International LOFAR Telescope Board, and UK Science Director on the SKA Organisation Board. *McLure* is UK representative on the ESO Scientific and Technical Committee. *Taylor* was a member of the ESA Planck Satellite Mission Oversight Committee, and the Euclid & LSST Consortia Joint Analysis advisory group. *Mann* is UK rep on the LSST Corporate Operations Committee. *Ferguson* sat on the ING Board, and chaired the HST Users Committee. *Dave* was on the South African NRF Astronomy Advisory Panel and the DST Long-Term Strategic Plan committee. *Snodgrass* chairs the Europlanet telescope network scientific advisory panel.

CMP: *McMahon* served on STFC Science Board and on a STFC Strategic Review Panel. *Evans* was an EPSRC Networkplus advisory board member. *Galloway* chairs the IoP Degree Accreditation Committee. *Cockell* is on NASA, ESA, and UKSA panels. *Thijssen* served on RSE advisory groups on renewable energy and open data. *MacPhee* served on advisory committees for Okinawa, Monash, Singapore and Melbourne Universities. *Loa* and *Loveday* serve on the EHPRG executive committee. *McMahon* serves on the AIRAPT executive committee. *Ackland* is a member of the RAMP Steering Committee.

PNP: *Kenway* was first chair of the PRACE Scientific Steering Committee, member of the UK e-Infrastructure Leadership Council, sub-panel chair of Supercomputing and Big Data for the Helmholtz Association review of Forschungszentrum Jülich, and is trustee of the Alan Turing Institute, senior independent member of STFC Council and chair of the STFC Innovation Board. *Clarke* and *Murphy* have served on STFC Science Board. *Clarke* was chair of the External Expert Review Panel of STFC Network provision for science programmes, a member of STFC Balance of Programmes Review, a member of STFC Skills & Education Advisory Panel, and is Director of IRIS. *Martin* was chair of the CLICdp Collaboration Board, and a member of STFC Particle Physics Advisory Panel (PPAP). *Muheim* sits on the STFC ATLAS upgrade oversight committee. *Del Debbio* is a member of the Scientific Committee of OCEVU (Excellence Laboratory, France). *Murphy* was a member of the Nuclear Physics European Coordination Committee of the ESF. *Aliotta* was a member of the STFC Nuclear Physics Advisory Panel, and of the STFC Education, Training and Careers Committee. *Needham* is Chair of PPAP.

Journal editorships

AST: MNRAS (*Taylor*); Astronomy & Computing (*Mann*); Royal Society Open Science Journal (*Heymans*); Space Science Reviews (*Snodgrass*).

CMP: Phys.Rev.Lett., PLOS One, Entropy (*Blythe*); Astrobiology (*Cockell*); J.Stat.Phys., J.Stat.Mech., J.Phys. A (*Evans*); Int. J. Astrobiology, Science Advances (*Poon*); J.Cond.Mat.Phys. (*Stock*).

PNP: J.Phys.G, European Phys.J. A (*Woods*); Nuclear Physics (*Aliotta*); Universe (*Turok*).

Prizes

The excellence of our staff, and the international impact of our research, have been recognized by the award of numerous personal prizes and elected fellowships over the REF period. Prominent examples include: Nobel Prize in Physics (Higgs, 2013), Shaw Prize in Astronomy (*Peacock* 2014), CBE (*MacPhee* 2016), Fellow of the Royal Society (FRS: *Dunlop* 2016, joining *Peacock*), Royal Society Gabor medal (*MacPhee* 2019), Royal Society Wolfson Merit Award (*Ackland* 2014, *Del Debbio* 2015, *Taylor* 2015, *Boyle* 2016, *Dave* 2017), ISI Highly-Cited Researcher (*Dave* 2019, *Dunlop 2018-2020,* Ivison *2014, 2016, Peacock 2014*), Fellow of the Royal Society of Edinburgh (FRSE: Ivison 2014, *McMahon* 2014, *Cockell* 2015, *Ferguson* 2016, *MacPhee* 2016, *Best* 2018, *Heymans* 2018, *Allen* 2019), Fellow of the Learned Society of Wales (*Kenway* 2015), IoP Sam Edwards Medal & Prize (*Poon* 2019), ECIS Solvay Prize (*Poon* 2020), RAS Herschel Medal (*Dunlop* 2016), RAS George Darwin Lectureship (*Dunlop* 2014, *Heymans* 2017), Alexander von Humbolt Foundation Award (*Ferguson* 2017), Max Planck-Humboldt Research Award (*Heymans* 2018), RAS Caroline Herschel Prize Lectureship (*Varri* 2019), World Cultural Council Special Recognition Award (*Heymans* 2015), Royal Society of Chemistry and Society of Chemical Industry Thomas Graham Lectureship (*Poon* 2019), Einstein Dahlem Lectureship (*Heymans* 2019), BIS Sir Arthur C. Clarke Centenary Award (UK Gaia Science Team, inc. *Hambly, Davidson, Rowell* 2017), IoP Rosalind Franklin medal (*MacPhee* 2020), Charles Hatchett Award (*Santos* 2020), IoP Tom Duke Lectureship (*Allen* 2020), EPS PhD thesis prize (*Bruno* 2018), Lindau Nobel Prize meeting (*Shendruk* 2016, *Bruno* 2019*, Carnall* 2020).

4.3 Contributions to the Economy & Society

Engagement with Industry

Our direct engagement with industry ranges from cutting-edge applied science – targeting disruptive technologies with exploitation plans spanning decades – to short-term troubleshooting and development projects. The latter can generate new research ideas that in turn attract industry support for longer-term strategic work, such as a ~£1M consultancy with **Mars** Chocolate (*Poon*). With this new knowledge, Mars has undertaken a multi-year renovation of their conching process, expected to halve processing times, energy usage and costs (Fig 10). *Clegg* has worked for a decade on emulsion research with industry, including long-running collaborations with **Syngenta Crop Sciences, Marlow Foods** and **Unilever**, and now with **Mondelez** on fundamental challenges in the fabrication of low-calorie confectionary. *MacPhee* is a director of **NBIC** and has worked with **P&G**, **Croda**, **Corteva** and **DuPont** to develop and deliver specialty microbially-derived ingredients.

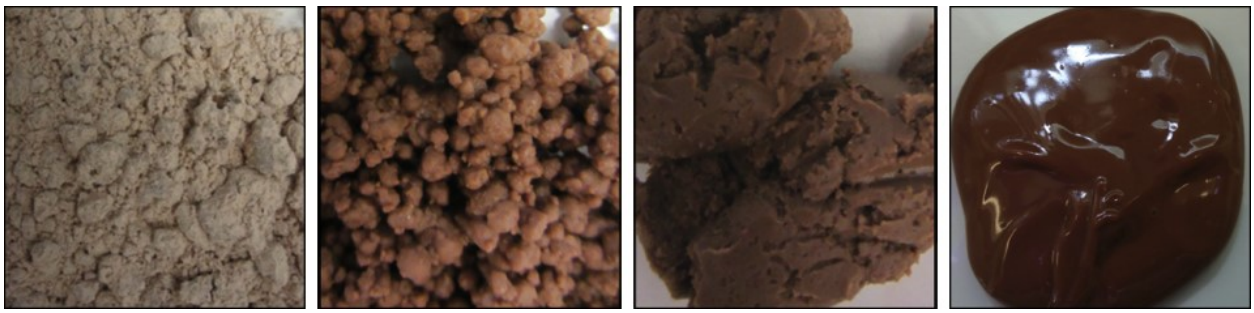

Figure 10. *Stages of conching chocolate: an initially inhomogeneous, non-flowing mixture of sugar, cocoa solids and fat is transformed to smooth liquid chocolate by mechanical agitation and the addition of lecithin, thus increasing the maximum jamming volume fraction (from a 2019 New York Times article on our work).*

Other partnerships with multi-nationals include collaborative research for their leading-edge products with an impact today, and on their roadmap. Our major partnership with **Intel**, building on earlier work with **IBM**, centres on product co-development and led Intel to open its first **European Research Centre in Edinburgh**. In our most recent ~£1M project with Intel (*Boyle*) we identified

software scalability limits/solutions for their flagship Omnipath cluster interconnect that enabled Intel to release improved software in 2019, and developed an improved floating-point format adopted by Intel for improved cost-effectiveness.

We have enjoyed strategic relationships with both the National Physical Laboratory (**NPL**) and the Atomic Weapons Establishment (**AWE**). These focus on joint translational research, via long-term senior staff secondments (Crain, *McMahon*) and placements for industry-oriented researchers (NPL £0.7M; AWE £0.5M). We also have extensive engagement (through consultancy and contract research) with companies from blue-chip multi-nationals to SMEs across many different market sectors targeting government and economic priorities, primarily through **ECFP** and **EPCC**.

ECFP provides consultancy and advanced measurement facilities to target industrial soft-matter systems. It has specialist facilities and expertise stemming directly from our basic research in soft matter. Since 2014, ECFP has developed relationships with 49 different companies (~50% SMEs), helping to generate at least £10M of value through improving process efficiency, supporting R&D, new product development, cost savings, and providing data to prove efficacy that has led to further investments. For example, ECFP worked with **Genius Foods Ltd** (*Poon*) to improve reliability, efficiency and quality in the production of gluten-free products, enabling increased capacity, and more consistent customer supply in the sale of products accounting for £25,000,000/year. Other companies engaged include: **MacPhie of Glenbervie** (food & drink), **Mentholatum** and **Lamellar Biomedical** (healthcare), **AkzoNobel** and **GlaxoSmithKline** (advanced materials), **Croda International** and **Syngenta Crop Sciences** (agri-chemicals).

EPCC offers consultancy and software development services to industry, and access to hardware that includes ARCHER/ARCHER2 (the National HPC Services). Today, it works with companies from blue-chip multi-nationals to SMEs, has a turnover of £13M and is a recognised world-leader. During the REF period EPCC has undertaken collaborative projects with over 70 companies of which ~80% are SMEs. Until 2016 EPCC ran 'Supercomputing Scotland', promoting industrial uptake of HPC solutions in key target sectors using **Scottish Enterprise** funds. This has been superseded by schemes funded by the EU (the **Fortissimo Marketplace**), UKRI (**Alan Turing Institute**) and the **Edinburgh City Deal**, enabling projects with greater depth/breadth.

Another valuable method of boosting economic impact is by creating and fostering new companies. Our approach to creating spin-out/start-up companies focuses on quality and long-term impact objectives rather than short-term statistical targets. An example is **Blackford Analysis Ltd** that started by developing a novel data-compression algorithm (MOPED) to enable rapid image alignment, and has grown into a company providing a range of innovative tools for the international medical-imaging market. MOPED was invented in Edinburgh by Heavens (now at Imperial) to tackle large datasets in astronomy, and developed by postdoc Panter (now Chief Executive). Blackford has won the Thales Scottish Technology Prize and the RCUK Business Plan Prize, and has received over £6M in investment. More than 2M medical scans per year are analysed using the Blackford Platform at 750 imaging centres, clinics, and hospitals. Faster image registration and data processing has accelerated diagnosis by up to 50%, saving clinician time equivalent to treating an additional ~200k patients per year. Through the HCI we aim to foster more small companies, and to create an atmosphere conducive to enabling/encouraging our students and post-docs to become the next generation of entrepreneurs.

Public Outreach, Engagement & Education

Outreach naturally has a societal and economic impact through a better-educated population, and we have spoken to and worked directly with over 300,000 people to explain our science and train educators. We promote outreach and public engagement through school visits, road-shows, science festivals, radio, television and newspapers, with active outreach programmes in all research areas (co-ordinated by our Director of Public Engagement, *Lawrence*). Over the REF period our Particle-Physics outreach programmes (including Particle Physics for Scottish Schools; **PP4SS**) have reached nearly 200,000 school pupils and adults at over 90 events. In Astronomy we

work closely with STFC's **ROE Visitor Centre**, interacting with ~100,000 school children and members of the wider UK public over the REF period, and engaging with millions more worldwide through events, TV programmes, movies, webinars, and press releases/news stories (Fig 11). Our Condensed-Matter outreach programme is performed as part of the UK-wide **Ogden Trust Outreach programme**, working with research staff, graduate students and undergraduates to engage with over 10,000 people.

We have established three **MOOCs**: "*Astrobiology and the Search for Extraterrestrial Life", "AstroTech: The Science and Technology behind Astronomical Discovery"* and *"The Discovery of the Higgs Boson"*. Collectively, these have attracted over 200,000 learners and offer a bridge between outreach and traditional education that complements our role as research-led educators.

Figure 11. *Our outreach and educational work ranges from:* ***Left:*** *major TV documentaries such as BBC Horizon, to* ***Right:*** *an award-winning design for a base station on Mars created by Scottish prisoners.*

Education has also been at the core of our work with **prisoners** (*Life beyond;* Fig 11); this has been transformative for them, and very influential in understanding the social-science aspects of life in colonies on other planets. This type of interaction is unique in its depth and impact on disadvantaged members of society, and points towards new methods for prisoner re-integration.

The shortage of **physics teachers** is a well-recognised national problem; we address this directly through events designed to educate those teaching the subject, but without a physics background, in current high-profile topics. To date, we have trained several hundred teachers through these courses with more watching the Education Scotland YouTube channel. Feedback has been extremely positive.

COVID-19

In the final months of the REF period, Edinburgh Physics & Astronomy contributed to the effort against COVID-19 through:
i) Computer modelling, including rigorous testing/re-writing of the Imperial College pandemic modelling code within **RAMP** (*Ackland, Rice,* PPE), and advice to **SAGE** on virus transmission (*Poon*);
ii) Working with **INEOS Hygenics** and **Aqualutions** to mass-produce quality hand sanitiser (over 1000 tons produced, and bottled in four new bottling plants) and whole-room/workplace disinfectants (*MacPhee*, *Thijssen, Brown, Direito, Allen*, ECFP);
iii) Collaborating with UoE's School of Medicine to develop methods for detection of COVID-19 through direct binding of the RNA genome (*Allen, Brackley*);
iv) Development of a new low-cost algorithm for COVID-19 screening by *Turok* and collaborators at the African Institute for Mathematical Sciences (**AIMS**). With UoE experts in medicine, robotics, statistics and public health, this is now being implemented at scale. This innovative project, **TestEd**, aims to screen over 500k samples collected from UoE students and staff, to help contain infection rates in the University and the wider community as we emerge from the pandemic.