Institution: University of Birmingham (UoB)

Unit of Assessment: UoA9, Physics

1. Unit context and structure, research and impact strategy

1.1 How Research is Structured across UoA9

1.1.1 Who we are

Physics West building

UoA9 (School of Physics & Astronomy) sits in the College of Engineering and Physical Sciences and performs world-leading research covering: fundamental physics at large international facilities; pure laboratory-based physics and theoretical breakthroughs; and translation to impact, in collaboration with academic engineering and medical colleagues, and industry. The portfolio divides into three thematic areas:

- ***Astronomy and Experimental Gravity*** (18 staff, 18 postdocs/RFs, 30 PhDs)
- ***Particle and Nuclear Physics*** (18 staff, 24 postdocs/RFs, 30 PhDs); and
- ***Quantum Matter*** (22 staff, 23 postdocs/RFs, 58 PhDs)

Each theme covers a range of topics and types of activity, requiring diverse leadership expertise; hence, there is a **further natural sub-division into Research Groups**, whose leaders interact closely.

A proactive and responsive approach has seen UoA9 transformed over the past two REF cycles. Highlights in the current cycle included:

- External and institutional funding driving the creation of two major new initiatives (***Quantum Matter***), the establishment of a new research institute (***Astronomy and Experimental Gravity***), and new state-of-the-art facilities (***Particle and Nuclear Physics***).
- CAT-A staff growing by 40% thanks to strategic investment in priority areas; and 36% of hires in the last three years being women;
- A strong diversification and growth (68%) of research income, totalling £73M;
- Research awards totalling £100M;
- PhDs awarded growing by 42%;
- UoA9 staff winning 22 major individual research prizes/medals, including eight IoP prizes; holding seven ERC grants (with two more awarded) and five Royal Society URFs; and two staff elected FRS (*Charlton*, *Elsworth*)

1.1.2 How our Research Strategy is Set

Our strategy is to sustain a vibrant environment that supports and empowers staff to deliver research of world-leading quality, and has the agility to capitalize fully on developments and new

opportunities. It is set by tensioning a bottom-up approach, which propels our researchers to pursue excellence; top-down strategic steering by the Research Steering Group (RSG), informed by gap analysis and ongoing horizon scanning for opportunities in new areas, especially those not yet exploited in the UK, shaped pragmatically by our knowledge of UKRI and other funding possibilities; and Equality and Diversity (E&D) considerations.

The RSG comprises the Head of School (*Gunn*), Director of Research (*Newman*) and Heads of Groups. **We embed E&D within the process of setting research and impact strategy.** It informs how we support UoA9 members to realize their potential, respecting individual circumstances, ensuring we optimize opportunities around access to research facilities, development of leadership and skills, and promotion. E&D is a standing item on meetings of the RSG, and on the School Committee, which comprises all members of UoA9. The UoA E&D Committee (**Section 2.1.1**) makes recommendations and provides advice to all parts of UoA9.

1.2 Research and Impact Objectives during the Assessment Period and Next Five Years

The UoA9 strategy at REF2014 was distilled into three main goals:

- **To develop and grow world-leading research across our portfolio**, building on areas of strength. We invested in people: numbers of research active (CAT-A) staff grew by over 40% (41 to 58) and research income per CAT-A FTE by 19%. Total research income grew by 68%.

  We targeted hires across the portfolio (**Section 2.1**) to take advantage of new discoveries, in particular the discovery of gravitational waves, upcoming opportunities relating to major experiment upgrades, space missions and facilities (***Astronomy and Experimental Gravity*** and ***Particle and Nuclear Physics***) and new initiatives (***Quantum Matter***).

- **To construct routes to develop impact via applied science and engineering**, growing activities to translate pure science, through engineering applications, to impact in collaboration with business and industry. We won leadership of one of four UK Quantum Technology Hubs, for Sensors and Metrology (*Bongs*). With investment now worth £160M, this is a focus for impact. Building and expanding on the Centre for Nuclear Education and Research (BCNER) established in the last REF cycle, we led the creation and development of the Birmingham Energy Institute (BEI; *Freer*). The BCNER and BEI have provided a coherent focus for activities involving the UoA9 MC40 Cyclotron accelerator and Positron Imaging facilities, and new initiatives, e.g. the award of £8.8M through the National Nuclear User Facility Phase 2 Call to develop a new national Accelerator Driven Neutron Irradiation Facility.

  We began to re-shape strategically parts of the portfolio in ***Quantum Matter*** to provide a stronger bridge from pure science to the Quantum Hub. We proactively sought opportunities, establishing a cross-disciplinary Centre for Topological Science and Engineering (*Dennis*), with new hires and the award of an associated EPSRC Centre for Doctoral Training (£5.4M), to refocus theoretical research in ***Quantum Matter***.

- **To Renew and develop our physical infrastructure and secure significant institutional investment to enable the above goals**: In recognition of its aim to strengthen areas of excellence, set out in the Strategic Framework 2015 – 2020, the University (hereafter UoB) invested £10M in UoA9 over the census period. This included establishing an Institute for Gravitational Wave Astronomy (*Vecchio*) [£6M investment]; and the Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA; *Allport*) [£1M investment]. UoB also contributed £1.9M to establish our new neutron facility (see above).

Our overarching objectives for the next five years are:

- **To sustain excellence in fundamental science**, with exciting upcoming opportunities from upgrades to LIGO (gravitational waves) and at CERN, and new initiatives in the quantum and topological sciences. Targeted recruitment, notably to add outstanding mid-career expertise (see **Section 2.1**), will help underpin advances to our world-class fundamental physics profile.

- **To utilize as a multiplier the expertise of researchers across UoA9** to open exciting new cross-theme opportunities to expand our portfolio. An obvious focus with huge potential is the development of quantum sensors and detectors: We will use as a springboard our December 2019 application to the STFC/EPSRC Quantum Technologies for Fundamental Physics (QTFP) [UoA9 award of £4.5M now announced, and involvement in projects worth £14.9M], involving expertise from all themes.
- **To prioritise investment in the experimental condensed matter and metamaterials domains** and **build interdisciplinary collaborations** with Chemistry (UoA8), Engineering (UoA12) and Life Sciences (UoA5) in the area of optics, to provide a second *knowledge escalator* incorporating experience from the Quantum Hub.
- **To embed *impact* in the wider research culture of UoA9**, aligning with institutional-level objectives in the New Strategic Framework (**Section 2.4**, **REF5a**), opening new parts of our portfolio to translation to impact. Through in particular the Quantum Hub, and *Bongs'* appointment as College Head of Innovation, we aim to harness new industrial collaborations exceeding another £100M. Our strategy is to translate the latest understanding and achievements at the fundamental level into better technology; and hence to make better instruments for fundamental science.
- **We will continue to promote equality and diversity in all aspects of UoA9 research life** (reflected in working parties for our Athena Swan Action Plan).

1.3 Thematic Objectives in the REF2014 Period and Next Five Years

1.3.1 *Astronomy and Experimental Gravity* [awards £18M, income £11M] comprises two Groups, reflecting expertise in studies of high- and low-mass stellar evolution, respectively. There is cross-fertilization of experience in stellar evolution, population studies and advanced data analysis.

Gravitational Wave Astronomy (*14 staff, 11 postdocs/RFs, 20 PhDs*)

There are strands on instrumentation, analysis and theoretical astrophysics and general relativity; and in parallel, with growing synergies, an observational programme on galaxies and clusters.

REF2014 objectives: were to grow activity in anticipation of the first detection of gravitational waves, and were met with £6M investment in new staff, laboratory and office space, £11M in research awards, and the founding of the Institute for Gravitational Wave Astronomy. We developed and built sensors and electronics for LIGO, and took part in commissioning. Led by *Vecchio*, we developed core techniques to characterise astrophysical sources and population parameters and played a leading role analysing the first binary black hole mergers, including first estimates of merger rates and tests of general relativity (papers in PRL 2016), and the characterisation of the first binary neutron star merger and its electromagnetic counterpart (papers in ApJ Lett. 2017).

Objectives for the next five years: are to consolidate our world-leading position in instrumentation, analysis and theory. We will complete work on the LIGO A+ upgrade and explore participation in other experiments (e.g. LIGO India).

We will conduct R&D for next-generation instruments [(Einstein Telescope (Europe), Cosmic Explorer (US)] and detector applications involving quantum measurements with ***Quantum Matter*** and ***Particle and Nuclear Physics***, including a dark matter search for axions (*Martynov*, QTFP funds). We will contribute to the ground segment and science preparation of the Laser Interferometer Space Antenna (LISA) Mission. We will lead exploitation of gravitational wave data, conduct a theoretical astrophysics and general relativity programme on compact objects and pursue a new, optical transient astronomy programme using the Vera Rubin observatory. Finally, we will continue studies of galaxies and clusters, including quenching of star formation, the mass/baryon distribution, and searches for gravitationally lensed gravitational wave events.

Stellar Astrophysics (Asteroseismology and Helioseismology) and Exoplanets (*4 staff, 7 postdocs/RFs, 10 PhDs*)

Our programme on low-mass stars is founded on world-leading expertise in asteroseismology and helioseismology, the study of stars, and the Sun, by observation of their oscillations.

REF2014 objectives: were to capitalize on international leadership in the NASA *Kepler* and TESS Missions (*Chaplin*). The Group won three ERC awards. Research highlights included major catalogues (e.g., ApJ Supp. 2014), a new paradigm for rotation evolution in stars (Nature 2016), and new constraints on the ancient history of the Milky Way (Nature Astronomy 2020). We expanded our exoplanet activities with a new hire (*Triaud*), and were part of the discovery of the TRAPPIST-1 system (Nature 2017).

Objectives for the next five years: begin with becoming the internationally leading centre for asteroseismic studies of stellar populations using machine learning, exploiting data from *Kepler* and TESS. We will use the SPECULOOS telescopes to discover potentially habitable Earth-sized exoplanets around ultra-cool stars. We will complete upgrades to our robotic Birmingham Solar-Oscillations Network (BiSON), and track the seismic rise of the new solar cycle. Finally, we will lead on design, layout and working software for the asteroseismology pipeline of the ESA PLATO Mission.

Top: BiSON telescope, Western Australia; Bottom: Birmingham SPECULOOS telescope (second left), Chile

1.3.2 Particle and Nuclear Physics [awards £36M, income £18.5M] is organised across two Groups, with synergies from working at CERN and combined activities on future accelerator and detector technologies.

Particle Physics (*12 staff, 17 postdocs/RFs, 20 PhDs*)

Led by *Newman*, our programme builds on a long-standing record of excellence in detector and trigger construction, and data analysis.

REF2014 objectives: were to develop and exploit work in instrumentation and analysis, and to grow into strategically carefully chosen new areas. In 2016, UoB invested £1M in major new clean room facilities, establishing the Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA), expanding capabilities in semiconductor detector systems for large-scale construction, R&D and spin out activities (including a further £0.5M STFC funding in equipment).

UoA9 staff were Spokespersons for ATLAS (*Charlton*) and NA62 (*Lazzeroni*) at CERN. We tested the Standard Model at the energy [ATLAS] (e.g., Nature Physics 2017) and precision [LHCb and NA62] frontiers (e.g., JHEP2017), including evidence for lepton-flavour symmetry violation, a significant (potential) anomaly (PRL 2014). With £8M of core STFC funding, we characterised the Higgs boson at ATLAS (e.g., PRL 2015) through a central role in the first observation of the dominant decay mode to beauty quarks (Phys. Lett. B 2018). We also entered the DUNE long-baseline neutrino collaboration.

Objectives for the next five years: are to continue to grow strategically, and play leading roles in the development of future electron-proton, proton-proton and electron-positron facilities, and detectors (with ***Quantum Matter*** and ***Astronomy and Experimental Gravity***). We will deliver upgrades to the ATLAS tracking detectors and calorimeter trigger (two phases) and contributions to the DUNE readout. We will exploit leadership to be at the forefront of "stress testing" the Standard Model, using data from ATLAS, LHCb and NA62. Our new activity in DUNE aligns with UK and international priorities but needs nurturing to succeed, through construction and towards exploitation. We will seek to invest in more staff in this area. We will also play a leading role in direct searches for dark matter (*Nikolopoulos*), building from our initial UK-leading activity in the NEWS-G collaboration and exploiting synergies with UoA9's expertise in detectors and sensors.

Nuclear Physics (*6 staff, 7 Postdocs/RFs, 10 PhDs*)

We have world-leading expertise in studies of clustering and exotic structures in light nuclei, and nuclear matter under extreme conditions; and major initiatives in the energy sector (*Freer*).

MC40 Cyclotron

REF2014 objectives in the clustering theme were to exploit opportunities opened by new facilities in Europe and the US, as well as to develop our own MC40 cyclotron (*Wheldon*) incorporating both particle and gamma ray detection capabilities. We also successfully bid to develop a new national neutron irradiation facility to replace our old Dynamitron accelerator (**Section 1.2**). Research highlights included the measurement of a new excited state of Carbon, which affects nucleosynthesis in stars (PRL, 2014).

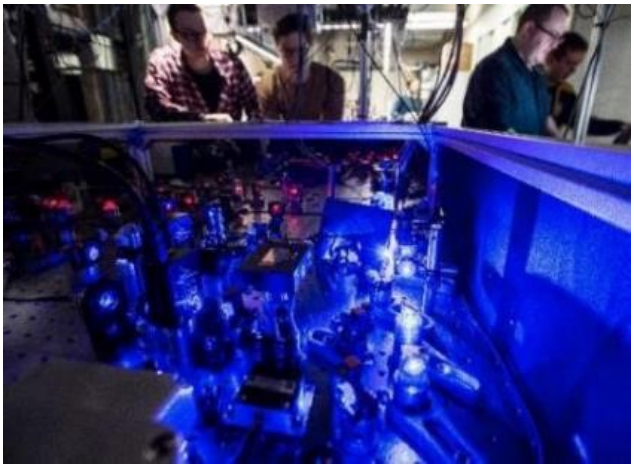
The objective in nuclear matter was to exploit our leading position in ALICE at CERN (*Evans*, *Jones*). We led design, construction and commissioning of the electronic trigger, with leadership in exploitation as members of the management, technical and editorial Boards. Highlights included the discovery of strangeness enhancement in proton-proton and proton-lead collisions (Nature Physics 2017).

Objectives for the next five years: are in structure studies to exploit the MC40 Cyclotron and new neutron facility (**Section 3.3**) to test nuclear ab initio models. These facilities link to the BCNER/BEI initiatives in energy (see **Sections 3.2.1**, **3.3**, **4.2**), We will exploit advances in gamma-ray beam facilities to make precise measurements of the cluster structure of states in light nuclei; and develop a state-of-the-art detection system based on Time Project Chamber technology with Texas A&M. In nuclear matter, we will exploit ALICE upgrades to explore the behaviour of hot QCD and the quark-gluon plasma, and measure rare probes such as jets and hadrons composed of heavy quark flavours. We will complete design, construction and commissioning of a new trigger for ALICE, and perform targeted R&D with BILPA toward a silicon vertex tracker for a future US electron-ion collider.

1.3.3 Quantum Matter [awards £46M, income £33M] comprises five co-located Groups, reflecting the dissolution of boundaries between cold atomic physics, condensed matter physics and optics, driven by emerging challenges. Looking forward, there will be vibrant new work on detectors with ***Astronomy and Experimental Gravity*** & ***Particle and Nuclear Physics***, supported by recently announced QTFP funds.

Cold Atoms (*8 staff, 16 postdocs/RFs, 20 PhDs*)

The focus of underpinning research is on control and manipulation of light and atoms through investigation of light-matter interactions with lasers and atoms, from ultracold to thermal temperatures. Activities cover the spectrum of Technology Readiness Levels, from pure science to working quantum sensor prototypes.



Cold Atoms Lab

REF2014 objectives: were to focus on translation of Quantum science into technology. This has been a success, with the award of the national Quantum Technology Hub in Quantum Sensors and Metrology (*Bongs*). Highlights included using quantum Zeno dynamics to generate multi-particle entangled states (Science 2015); the first direct measurement of the frequency ratio of two ytterbium clock transitions (PRL, 2014) and the production of a transportable optical clock with record sensitivity; and development of a gravity imager.

Objectives for the next five years: are to capitalize on the £23M already secured for the second phase of the Quantum Hub to create market pull (e.g. with BAE, BT and BP) by demonstrating the advantages of quantum sensors for real-world challenges, specifically a network of next-generation clocks (QTFP funding; *Barontoni*) with applications in geophysics, environmental monitoring, transportation and civil engineering; secure navigation for underwater and autonomous vehicles; assessing brain function for dementia; and advanced radar for future airspace control with millions of drones and flying taxis (see also **Section 1.2**).

We will also develop novel directions in quantum simulation, such as quantum thermodynamics and simulations of quantum biological systems.

Metamaterials (*3 staff, 3 postdocs/RFs, 8 PhDs*)

Our Centre for Metamaterials focusses on realising exotic topological photonic states; pushing the boundaries of nanophotonics from the classical to the quantum regime; and advancing metamaterials-based technology towards practical applications.

REF2014 objectives: were to capitalize on the investment that established the Centre in the preceding REF cycle (*Zhang*). Driven by two new appointments [*Demetriadou* (Royal Society URF), *Navarro-Cia*] there has been considerable success, with high-profile work on metamaterials, nonlinear optics, topological photonics, and invisibility cloaks operating at optical frequencies. Highlights included optical meta-surface holography with record-high efficiencies (Nature Nanotechnology 2015), and novel developments in metasurface holography (Nature Communications 2016/17); demonstration of ideal Weyl points, a platform for studying new physics related to photon transport, scattering, surface state arcs, and the chiral zero mode (Science 2018); and realization of single molecule strong coupling at room temperature using plasmonic nanocavities (Nature 2016).

Objectives for the next five years: are to strengthen the international leading position in the research areas of topological metamaterials and quantum plasmonics, the former taking advantage of recent appointments in ***Condensed Matter and Optics Theory*** (see below). We will expand into promising new interdisciplinary research areas such as metamaterials for medical sensing, and photonic machine learning.

Nanoscale Physics (*3 staff, 1 postdoc/RF, 10 PhDs*)

REF2014 objectives: were to leverage expertise in size-selected metal clusters, scanning probe and electron microscopy, to develop new multinational collaborations. Highlights included atomic scale tomography opening a window at the single-atom level (Nature Materials 2015); and constructing nanoclusters for electro-catalysis, with applications in hydrogen fuel cells for next-generation cars (Phys. Chem. Chem. Phys 2015).

Objectives for the next five years: will focus on a new thread, on metal/porous Silicon hybrid nanomaterials with potential for slow drug release, using new investment in instrumentation to develop medical applications.

Experimental Condensed Matter (*2 staff, 3 PhDs*)

REF2014 objectives: focussed on studies of materials with unconventional low-temperature (quantum) phases, using Nuclear Magnetic Resonance (NMR), neutrons, and muons as probes. Highlights included the demonstration of competition between charge density wave order and superconductivity in cuprates, and disentangling the domain structure (Nature Communications 2015/16); and use of NMR to probe superconductivity in strontium ruthenate (Nature 2019).

Objectives for the next five years: revolve around the UoA9 priority to develop this area, with one new mid-career appointment made (*Hicks*) and another planned, to focus on strain tuning of materials through quantum transitions, and studies of strongly correlated materials. We will also expand collaboration with inorganic chemists (UoA8) on using quantum magnets to study quantum criticality (*Jeong*).

Condensed Matter and Optics Theory (*6 staff, 3 postdocs/RFs, 15 PhDs*)

This Group helps bind the experimental groups in the ***Quantum Matter*** theme.

REF2014 objectives: focussed on many-body physics, disorder, optics and topology. The balance in the Group evolved with the recent appointments of *Dennis* (to lead the Group), *H. Price* (Royal Society URF) and *Von Keyserlingk*. *Dennis* led the successful application for an EPSRC CDT in Topological Design, and the attendant creation of the Centre for Topological Science and Engineering by UoB, fostering links to areas of experimental physics and mathematics, chemistry, computer science, medicine and engineering. The creation of the Centre was partly a celebration of the award of the 2016 Nobel Prize to Kosterlitz and Thouless for work performed in Birmingham.

Highlights included observing discrete time-crystalline order in a disordered dipolar many-body system (Nature 2017); exploring 4D quantum Hall physics with a 2D topological charge pump (Nature, 2018); and understanding polarisation knots in optics (Nature Physics 2018).

Objectives for the next five years: are to capitalize on leadership of the Centre and CDT to establish UoA9 as a world leader in the rapidly growing field of Topology, at the centre of a thriving interdisciplinary activity at UoB. We will support new experimental appointments across ***Quantum Matter*** and widen work in theoretical wave physics, optics and photonics.

1.4 How UoA9 Enables and Facilitates Impact from its Research

We identify areas with Impact potential, to develop and grow vibrant and sustainable programmes that have significance and reach, through gap analysis and horizon scanning. For

Impact involving industrial partners we work to identify the market pull and help co-create new opportunities.

We have well developed programmes that support and enable researchers to deliver impact working with industry, arranged around:

- The Quantum Hub (**Section 1.2**, **1.3.3**), which includes the ERDF-funded Centre for Innovation in Advanced Measurement in Manufacturing that already provides support for 40 regional businesses. Collaborative projects with industrial partners have created a commercial supply chain with over 25 products (including a Quantum Gravimeter with M Squared Lasers, and QT vacuum systems with Teledyne).
- The BCNER and BEI (**Section 1.2**) with accelerator and imaging facilities – including the MC40 Cyclotron, Positron Imaging Centre, and new national neutron irradiation facility (**Sections 1.3.2, 3.2.1**, **3.3**) – and the ERDF-funded ATETA programme that promotes research and innovation in adoption of zero carbon energy technologies by local SMEs.
- We utilize UoB infrastructure including College business development teams and UoB Enterprise (**Section 4.1**, **REF5a**), which manages technology transfer and academic consultancy: 36 UoA9 researchers used its services, with 13 active projects developed for income, 10 having patents filed. We also used EPSRC and STFC impact accelerator funds.

This expertise and experience will help guide opening further opportunities across the portfolio (**Section 1.2**), informed by E&D considerations for relevant individuals (**Section 1.1.2**). To strengthen bottom-up input to the process, we appointed a **Director of Innovation** (*Holynski*) to work across UoA9 to identify and develop opportunities.

UoA9's **Impact Lead** (*Mayhew*) oversees progress of projects at various levels of maturity that have developed as **UoA9's selected Case Studies.** They reflect the aim to develop, grow and sustain programmes with the potential for impact. e.g., cases based on Positron Emission Particle Tracking, ionisation mass spectrometry and Boron Neutron Capture Therapy. Another case, connected to the Quantum Hub, has realized impact very quickly.

Our final case builds on extensive UoA9 programmes **promoting novel forms of public engagement with research** focussed on long-term relationships with Schools, raising awareness of and interest in physics in disadvantaged and/or underrepresented groups; and vibrant collaborations with artists (spanning diverse practices).

Finally, we enable **Impact from influencing and shaping strategy and policy at national level** (see examples in **Section 4.3.3**), including help from the UoB Stakeholder Engagement Team to establish and build relationships with external stakeholders (e.g., policy professionals, local and national politicians).

UoA9 and UoB scholarly infrastructure (**Section 3.4**) has supported preparation of individual Pathways to Impact statements. Going forward we will provide workshops on embedding Impact within applications.

1.5 UoA9 Approach to Supporting Interdisciplinary Research

A vibrant environment provides opportunities and support for staff to interact with researchers from other disciplines, helped by UoB structures (**Section 2.3**, **REF5a**), e.g. the cross-discipline exchanges embedded in the nascent Centre for Topological Science and Engineering.

Horizon scanning flags potential opportunities that can be nurtured and supported by UoA9, e.g., forming new consortia and new applications, the UKRI cross-council Quantum Technologies for Fundamental Physics call being a recent example, and to help secure funding to develop ideas, e.g., two EPSRC New Horizons proposals submitted in June 2020 on astronomy instrumentation (*Martynov*, *Speake*) have just been awarded. Our new CDT in Topological Design is catalysing opportunities, bringing together UoB researchers from Mathematics, Chemistry, Computer

Science, Medicine and Engineering, led by UoA9, to research and train PGRs in problems requiring a multidisciplinary approach and pipeline of expertise from blue-skies research to industry.

Goals in the interdisciplinary domain have strongly influenced strategic thinking on new staff investment in ***Quantum Matter***, to build existing and developing strengths relating to opportunities with Engineering, Medical and Life Sciences, e.g. new joint BBSRC funding with UoA4 (Psychology); and EPSRC, Innovate UK and industry grants with UoA12 (Chemical Engineering, Civil and Electrical Engineering).

1.6 Progress towards an Open Research Environment

Our commitment to Open Research facilitates collaboration, removes barriers to knowledge and enables impact. We are guided by UoB's Open Research Board (**Section 2.2**, **REF5a**), whose commitment to DORA and Plan-S we implement, applying fair and responsible metrics in research and staff assessment (e.g. probation and promotion) and active promotion of open publication. This has supported the following UoA9 actions:

- **Maximizing open access to our research outputs** through Green archiving (e.g. arXiv), often the conventionally favoured route for our fields; utilizing institutional funds for Gold open access, where appropriate; and using the University of Birmingham Institutional Research Archive (UBIRA), an open access repository for full text research materials produced by UoB researchers. Large international collaborations usually have open data management facilitated at collaboration level (e.g., all CERN/LHC collaborations).
- **Providing wider community service on open access** by encouraging staff to act as editors for high-quality open access research journals (**Section 4.3.4**).
- **Encouraging researchers to make analysis codes available on repositories,** such as GitHub, and to "publish" codes (e.g. astronomical codes for asteroseismology). We provide training on open-access repositories, through workshops and research "hack sessions".

1.7 How UoA9 Supports a Culture of Research Integrity

We are strongly committed to the UK National Concordat to Support Research Integrity, as enshrined in UoB's Code of Ethics and Statement on Research Integrity (**Section 2.2**, **REF5a**). All staff and PGRs receive online Research Integrity training. PGRs also receive bespoke training on ethics and plagiarism.

We also champion Responsible Research and Innovation (RRI). Examples include a full RRI programme within the Quantum Hub, and Board representation for an EPSRC-sponsored public RRI dialogue; working with Birmingham City Council to ensure risks associated with our new national neutron facility are properly managed and communicated; and RRI training in the Topology CDT.

2. People

2.1 Staffing Strategy and Staff Development

2.1.1 Staff Development Strategy

Our strategy is to **sustain a vibrant, supportive environment, enabling all staff to play to their strengths, build confidence in new areas, and develop leadership and management skills**, guided by the key principles in the Concordat to Support the Career Development of Researchers and best practice in support of the Vitae Researcher Development Framework.

We embed Equality & Diversity (E&D) in all processes that shape and develop UoA9 strategy. Our E&D Committee – with representation from all levels of UoA9 – is an essential component in shaping our culture, and seen as a point of excellence at UoB. We successfully renewed our Athena SWAN Silver and IoP Juno Champion status in 2018 (*Wilkin* is national Juno Chair).

We aim to ensure a broad range of members across UoA9 own E&D strategy and the creation of an Athena Swan and Juno Champion culture, covering staff, postdocs, PGRs and research support staff (**Section 2.3**); and that we are on the path to convert Athena Swan Silver to Gold.

Factoring into strategy on training and recruitment is the need for UoA9 as a whole, and individual Themes/Groups, to have access to the range of skills in leadership, people/resource management, and project planning required to meet our objectives (guided by Belbin Team Roles theory).

Regarding processes:

- UoB (**Sections 3.4.2**, **3.4.4**, **REF5a**) and UoA9 offer induction, training and development courses, including compulsory and refresher E&D training. We successfully nominated 19 staff to take accelerated UoB programmes in leadership. Staff have gone on to major research leadership roles (e.g. *Freer* as College Director of Research, and head of the BEI; *Bongs* as College Director of Innovation; *Schofield* as Head of College, and now Vice Chancellor of Lancaster University).
- The annual Performance and Development Review (PDR) (**Section 3.4.3, REF5a**) supports career development for all staff. The Head of School performs professorial PDRs, and new staff PDRs as part of probation. Heads of Groups conduct PDRs for academic, research and technical staff within their groups.
- Early and mid-career staff are encouraged, with mentoring and coaching by senior UoA9 colleagues, to occupy positions of responsibility, developing the rounded experience to take on major leadership roles, e.g., leading research teams at CERN and in LIGO, or UoA9 positions such as Director of Innovation.
- We supported female staff to take external leadership roles, e.g., *Lazzeroni* as spokesperson for the NA62 collaboration at CERN. Bespoke support for women includes the Aurora Leadership Programme (**Section 3.4.4, REF5a**) [taken by *Tzanka-Wheldon* and *Wilkin*].

2.1.2 Recruitment Policy

Our goal is to **develop a diverse staff that delivers intellectual diversity across all themes** and to **nurture and sustain an environment that will attract applicants of the highest international calibre**. This underpins our objective to grow scientific leadership and excellence in research and impact, through investment in people.

Our goals over the current REF period were:

- **To focus on attracting high-calibre early-career staff** on a trajectory to be future leaders in their fields.

- **To follow an ambitious programme growing staff in areas aligned to strategic research priorities**, to build on existing research strengths and leadership, to capitalize on the potential to expand into adjacent research areas, and to grow grant capture.

They have been successful:

- Since REF2014, CAT-A submitted staff grew from 41 to 58 (FTEs from 39 to 55.2). All but three were early-career hires, with net CAT-A increases of six (***Astronomy and Experimental Gravity***), four (***Particle and Nuclear Physics***) and seven (***Quantum Matter***).
- In ***Astronomy and Experimental Gravity***, we focussed on new hires in instrumentation (notably *Martynov* from Caltech), and relativity (*Gerosa*, *Schmidt*); and opened new areas: transient phenomena (*Nicholl*) and exoplanets (*Triaud*).
- Expansion in ***Particle and Nuclear Physics*** focussed on the BILPA initiative, including professorial (*Allport* from Liverpool as lead) and early-career (*Gonella*) hires.
- In ***Quantum Matter*** we made a professorial hire (*Dennis* from Bristol) to lead the Topology initiative and refocus theoretical work in the theme; and eight early-career hires across the theme, including two institutional Innovation Fellows supporting expansion of the Quantum Hub (**Section 2.1.4**).
- Since 2016, six new hires were women (36%) (*Schmidt*, *Toonen* in ***Gravitational Wave Astronomy***; *Gonella* in ***Particle Physics***; and *Demetriadou*, *Guarrera* and *H. Price* in ***Quantum Matter***). The number of CAT-A women rose from five (12%) to nine (16%).
- Early-career staff won eleven national and international prizes (**Section 4.3.1**).
- Ten early-career hires (five women) held prestigious external fellowships (see **Section 4.3**): five Royal Society URFs, EPSRC Innovation Fellowship, two STFC Ernest Rutherford Fellowships and two *VENI* Fellowships from the Netherlands under the Money Follows Researcher scheme; four held ERC Starting grants.
- Ten early-career hires held competitive institutional Birmingham Fellow awards across all themes (four, two and five respectively), offering five years of protected high-quality research time (**Section 3.4.1**, **REF5a**).

Our objective over the next five years is to target staff growth in areas that bridge the pure and translational areas of our portfolio, notably in ***Quantum Matter***, to capitalize on the potential of the Quantum Hub and the new Centre for Topological Science and Engineering. We aim to recruit **outstanding mid-career researchers ready to step-up as leaders**. (Recent hires have refreshed the early-career profile.) This will underpin our goal to address gender imbalance in the Senior Management Group, with the aim of adding one to two more female members.

We will initiate changes, guided by UoB bodies (**Section 3.4.5**, **REF5a**), and recommendations such as those in American Institute of Physics Team-Up report *The Time is Now*, to attract and hire more BAME staff at all levels (currently five in CAT-A), and maintain 30% of new staff hires being women. Our E&D Committee is reviewing advertisement and recruitment processes to ensure they attract the full range of potential applicants.

2.1.3 Support for Early Career Researchers and Postdoctoral (Fixed-Term) Researchers

New faculty get a relocation package, start-up funds and (if relevant) are helped and financially supported through the visa process. We invested £3M to support hires over the current REF cycle. Senior professorial staff act as formal Mentor to support new appointees through a structured three-year probation, with targets, agreed with the Head of School in consultation with the Mentor, focussing on development of research activities. Teaching responsibilities are ramped-up slowly, with relief from teaching for those with prestigious fellowships or large grants. New hires are prioritised for PGR recruitment, and allocation of travel funds.

Postdoctoral researchers set objectives in the annual PDR with the relevant project/grant PI or Head of Group. Personal fellowship applications are encouraged and actively supported

(**Section 3.1.1**), with successes including Royal Society URFs, EU Marie Curie, and STFC Ernest Rutherford Fellowships.

Our early career researchers engage more widely across UoB, including College-run Grant Writing workshops, and the Postdoctoral/Early Researcher Career Development And Training (PERCAT) network (**Section 3.3**, **REF5a**), which provides support, events and networking for STEM researchers. Three committee members are UoA9 postdoctoral researchers. UoA9 also has its own postdoctoral Researchers' Network to promote networking and help shape UoA9 policies on early career issues.

UoA9 also initiated a Cultural Awareness course, tailored for overseas postdoctoral researchers, on interactions with undergraduate students in teaching.

2.1.4. Recognition and Reward for Carrying out Research and Achieving Impact

We sustain a supportive environment that proactively encourages (at Group and UoA9 level) promotion applications, and nominations for awards and prizes (**Section 4.3.1**).

Direct support from Group leaders helps develop and review promotion cases, with practice interviews for Readership and Professorial applications: Excluding teaching-focussed cases, there were 12 promotions to Senior Lecturer (17% women, 8% BAME), nine to Reader (22% women, 11% BAME) and seven to Professor (29% women, no BAME). [16% of CAT-A staff are women, 10% are BAME.] Promotions were well balanced across the portfolio.

To provide career progression focussed on impact, **we championed within UoB the successful introduction of an Innovation Fellows path** recognising criteria by which outstanding achievements for impact are judged differ from those commonly used. Two pioneering Fellows (*Holynski*, *Singh*) are leading members of the Quantum Hub.

We make appropriate reductions to teaching and administration following successes (significant grant awards and fellowships), or when taking on research leadership roles (e.g., *Bongs*, College Director of Innovation).

2.2 Research Students

2.2.1 Recruitment Strategy

Our strategy is to have a diverse cohort that makes a significant contribution to delivering our research goals, and contributes to **sustaining a vibrant research environment**.

Our objective at the previous REF was to maintain studentship levels (at least) from STFC/EPSRC Doctoral Training Award (DTA) funding, and to build numbers through diversification of funding.

We successfully awarded 188 PhDs. This represents 42% growth, from a yearly average of 19 over the previous REF to 27 in the current period. In the face of a challenging funding environment, this reflects successful new initiatives, including uplift to the EPSRC DTA from Quantum Hub funding, and the new EPSRC CDT in Topological Design. It took its first cohort in 2019 and will provide 50 studentships over 5 years, working on multidisciplinary projects across UoB, e.g., topological quantum optics for super-resolved protein imaging (with Biochemistry and Medical Sciences) and topological quantum plasmonics (with Metamaterials and Electrical Engineering).

We secured support from iCASE studentships with the National Physical Laboratory (NPL), the Atomic Weapons Establishment (AWE), and BAE systems; direct funding from Dstl; direct co-funding with NPL and AWE; and the Royal Society. We also secured co-funding from international partners, including Université Paris-Saclay, Southern University of Science and

Technology (SUSTech), China, and Mexico's Conacyt; and local partners, e.g. UoB Centre for Human Brain Health.

UoA9's Graduate Studies Committee and an Athena Swan action group, comprising members of the UoA9 E&D Committee, monitor recruitment data. The fraction of applications and acceptances from women is around 21%. Expansion of an initiative with the charity Generating Genius (who work with the CDT) will support our strategy to promote diversity in recruitment, and grow this fraction.

Our objective over the next five years is to work more closely with industry to secure co-funding for studentships – in particular extending to large companies such as BP and BT – and to build on partnership opportunities such as SUSTech, linking to UoB initiatives (**Sections 2.1.2**, **2.1.8**, **REF5a**).

2.2.2 Support for Skills and Career Development

Our aim is to develop highly skilled and rounded individuals, ready for careers in research, industry or beyond. Examples include faculty positions in the US, China and Hong Kong; a staff position at the UK Astronomy Technology Centre; postdocs at CERN, ESA, Max Planck (several institutes), Melbourne, and Monash; going to industry at UKAEA and QinetiQ, to Facebook, and founding an educational software company.

Activities to support development are ongoing at several levels, from those to deliver the main research goals, through regular support from supervisors to activities/programmes within UoA9, and at UoB level and beyond (including activities conceived, organised, and run by our students). **There is an underpinning process of ongoing skills gap analysis**, involving an annual Development Needs Analysis, which also identifies relevant courses and opportunities.

- Group/Theme and UoA9 activities include "hack" and PGR-led "code review" sessions to **develop good scientific programming practice**; and **sessions to develop critical analysis and breadth** (e.g. Journal Clubs), and transferrable skills (e.g. presenting, writing papers etc.). The UoA9 colloquium and Group/Theme-level seminars help **develop breadth and awareness of wider research culture**, with opportunities to interact with visiting speakers via "PGR only" sessions.
- PGRs have sessions on E&D, including Unconscious Bias training, in the weeklong UoA9 induction.
- PGRs are encouraged to participate in UoA9's vibrant and diverse public engagement programme (**Section 4.2**), **developing skills in communication and engagement**.
- We are active members of the Midlands Physics Alliance Graduate School, providing coordinated research training across six Universities, with modules and workshops delivered remotely and face-to-face by us, and colleagues at the partner institutes, e.g., in astronomical data analysis, particle physics techniques, and advanced condensed matter theory.
- Our PGRs tap into UoB's Graduate School courses on transferrable (e.g. project management, team-working etc.) and research-specific skills (e.g. "software carpentry") (**Section 3.2**, **REF5a**).
- Presentations at conferences and collaborations with researchers at other institutes develop communications and team working skills. **UoA9 helps fund these activities**, particularly relevant to PGRs without access to STFC and EPSRC DTA or ERC/EU funds. Top-up funds are available to all via the UoA9 Moreton Travel Award bequest.

UoA9 has a Careers Officer and a UoB-level Careers Network Advisor, who organise and run events/fairs for PGRs. UoB's Graduate School runs related seminars and workshops. Supervisors are encouraged to discuss, act as a sounding board for, and provide appropriate advice on careers, particularly towards the later stages of the PhD.

Public engagement, Birmingham New Street station

2.2.3 Monitoring and Support Mechanisms

There is a comprehensive multi-layered approach, involving supervisors, Groups and UoA9 processes, laid out in the UoA9 PGR Handbook and overseen by UoA9's Graduate Studies Committee (GSC) under the Director of Graduate Studies (*Lerner*), underpinned by formal training for supervisors (including induction meetings, workshops and refresher courses).

Research Groups act as natural "homes" for PGRs, providing a stimulating intellectual environment with informal mentoring and support from all staff, postdocs and senior PGRs.

Formal support begins with close oversight by the supervisor. There are monthly and half-yearly progress reviews, allowing short- and longer-term reflection on progress, skills (**Section 2.2.2**) and planning; a key progression milestone at the end of the first year, a mini-thesis examined with a viva by a member of staff from another Group; and in the final year a review on plans for completion of work and thesis. The GSC reviews and monitors progress of all PGRs.

Where difficulties arise, support mechanisms first seek a solution at Group level. PGRs receive clear guidance on who to turn to in case of problems and remedial action can involve the Director of Graduate Studies, the Postgraduate Welfare Tutor (**Section 2.3.5**) and the Head of School.

2.3 Equality and Diversity

2.3.1 Study Leave and Staff Exchange

UoA9 encourages staff (particularly early career) to plan and take leave, e.g., to develop collaborations, or for visits tied to new or critically timed obligations as part of international collaborations/projects.

- Staff may apply for one semester of leave in every seven. Examples of destinations included: the Kavli Institute for Theoretical Physics (Santa Barbara, US); the Laurence Berkeley National Laboratory (US); Padua (Italy), the National Institute for Standards and Technology, Washington (US); Shannxi Normal University, Soochow, Shanghai Jiaotong University, and Tsinghua (all China). There were three long-term secondments to CERN: two as experiment Spokespersons, and one on a CERN scientific associateship.
- UoA9 maintains a vibrant programme of visiting researchers, and is very successful at leveraging financial support from UoB's Institute of Advanced Studies (**Section 2.3**, **REF5a**)

Distinguished Visiting Fellowship (DVF) programme to bring world-leading academics to Birmingham. High-profile visitors have included Nobel laureate David Gross, former CERN Council President Michel Spiro, and former Nobel Committee member and string theory pioneer Lars Brink.

2.3.2 Flexible Working and Support for Those Returning from Periods of Leave

We have a holistic approach to accommodating flexible working. The Head of School considers requests, in consultation with relevant UoA9 stakeholders (grant PIs, Heads of Group, Director of Education, Director of Graduate Studies etc.). Planning around leave may vary, though always with full consultation across UoA9 and at UoB level as appropriate (e.g., with Occupational Health for returners from long-term illness).

Examples of support for flexible working and returners included staff:

- near retirement, reducing time to between 0.05 and 0.6 FTE to focus on either research or teaching;
- returning from parental leave, rebalancing time at work and home;
- suffering severe illness, who needed extended leave and flexible, part-time arrangements after returning;
- suffering a close bereavement or illness within the family, who needed to flex their time; and
- preparing for adoption.

UoA9 provides financial support for returners from breaks to help kick-start new initiatives (over £400K in the current cycle). We also used the EPSRC Developing Leaders (EDL) scheme, which supports returners to re-establish their research profile. Finally, there is relief from teaching on return from maternity or adoption leave.

Prior to COVID-19, 17% of academic staff had taken advantage of flexible arrangements, and four CAT-A staff are part-time (0.2 to 0.8 FTE). Enforced home working during the pandemic stressed the need for flexibility – particularly for those with caring responsibilities, underlying health concerns or with vulnerable/shielding family – and for UoA9 managers and supervisors to be as accommodating and understanding as possible. Staff have had to develop skills in managing teams remotely, which can positively influence incorporating flexible working going forward.

Part-time staff have equivalent career pathways to full-time staff: promotions panels consider the quantity of outputs and numbers of responsibilities in relation to working hours (e.g., a recent promotion to Senior Lecturer).

We achieve flexibility through a collegiate culture developed over time. The UoA9 "family" support works with UoB support, arranged around its Flexibility and Family-Friendly Working scheme.

2.3.3 Facilitating Travel to Support Research for those Caring Responsibilities, Returners etc.

We work with staff and PGRs on modifying research goals and restructuring schedules, as appropriate. Help might involve relief from teaching over a period when personal circumstances allow flexibility to travel. UoA9 provides targeted financial support to sustain or pump-prime collaborations and activities.

2.3.4 Support for Those with Protected Characteristics

Appropriate arrangements and reasonable adjustments to working patterns ensure those with one or more protected characteristics can work effectively (guided during the pandemic by the Equality and Human Rights Commission guidance on COVID-19-related reasonable adjustments for employees).

UoB's Disability Service (**Section 3.4.5**, **REF5a**) helps managers and supervisors understand needs of disabled employees; and provides employees with practical support and guidance, particularly in relation to workplace adjustments. UoA9 members receive training to understand the requirements of the Equality Act, reinforced by communication and messaging by the E&D Committee, which reviews and makes recommendations on the need to update UoA9 procedures.

UoA9 was first at UoB to address a lack of gender-neutral toilets and baby changing rooms. UoA9 members are active in "out in STEM" (oSTEM) and Black Ethnic and Minority Scientists (BEaMS) groups for staff and students. In January 2020, oSTEM hosted the 5th LGBT+ STEMinar, an annual research conference celebrating the work of STEM researchers who identify as LGBTQ+. A UoA9 postgraduate was chair of oSTEM, and one of our faculty was its academic mentor. We have also had committee members on BEaMS.

2.3.5 Supporting the Wellbeing of Staff and Research Students

Staff can seek guidance and help on wellbeing in various ways, ranging from confidential discussions with the Head of Group or Head of School, to using comprehensive UoB support mechanisms (**Section 3.4.5**, **REF5a**).

UoA9 has well-developed support structures for postgraduate students, embedded at all levels from individual supervisors, to Group postgraduate mentors, UoA9-level postgraduate mentors (three early-career staff), and a dedicated UoA9 Postgraduate Welfare Tutor. This support links closely with UoB Student Support and Counselling.

As noted in **Section 2.3.2**, modes of delivering support have evolved during the COVID-19 pandemic, helped by developing UoB-level guidance and structures. Input from staff and students – including a UoA9 online survey that explored challenges around home working and the returning to campus – helped guide re-opening UoA9 in Autumn 2020. Individual meetings with managers and supervisors assessed risks and agreed, where appropriate, bespoke workplace adjustments/arrangements.

2.3.6 How E&D has Informed Construction of UoA9's REF Submission

The UoA9 REF Outputs Panel comprised four senior staff (including one woman and the previous and current chairs of UoA9's E&D Committee). In accordance with UoB's REF Code of Practice, and to ensure the equity, equality and transparency of the process, members took compulsory EDI training. Eligibility for special circumstances was advertised to staff, and considered carefully by the Panel. The Panel confirmed that the pool of selected outputs was a consistent and fair representation of those available for submission, by staff gender, ethnicity, career stage, and contract status.

3. Income, infrastructure and facilities

3.1 Research Funding and Strategies for Generating Research Income

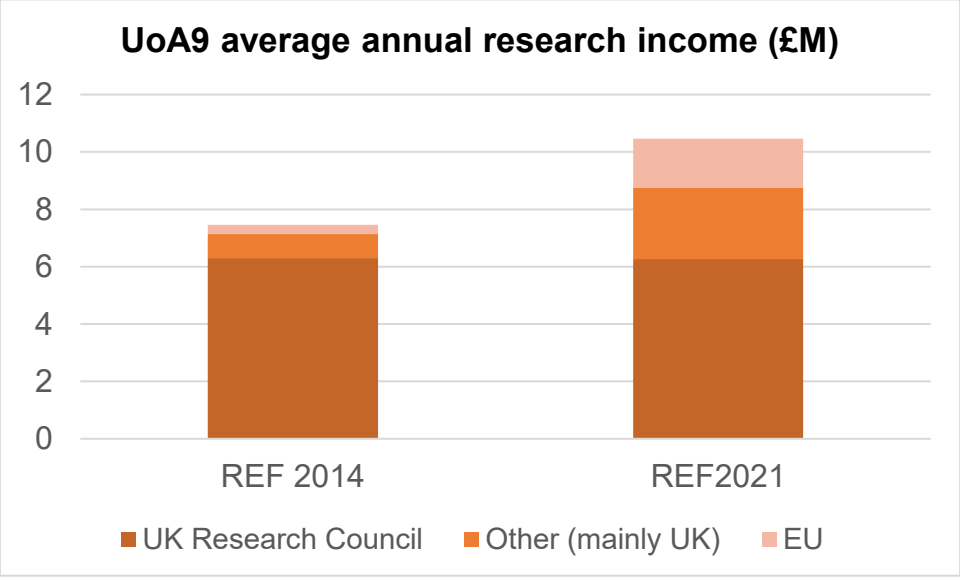
3.1.1 Strategy for Generating Research Income

Our strategy has been to diversify our income base to drive growth and to **build new partnerships** that open new funding from previously untapped schemes and routes. There is constant horizon scanning of funding opportunities, with consolidation of scanning at the strategic (Research Strategy Group, Group and Theme leaders) and bottom-up (individual staff) level.

We focus on people, giving the support and contiguous time to prepare strong grant applications. We tailor workload allocations to help achieve success, **ensuring appropriate support across the diversity** of our staff e.g., relief from teaching for new staff, or those returning from parental leave (see **Section 2.3.2**). We work hard supporting early-career researchers to apply successfully for high-profile fellowships (both internal and external candidates; **Section 4.3**).

3.1.2 Outcomes of the Strategy and Forward Planning

- **There has been a significant increase in research income (REF4b), at the level of 68%** compared to REF2014 to an average of £10.5M per year, with a **19% increase in income per CAT-A FTE**. In-kind income (REF4c) totalled £45.5M.
- **Sources of income diversified**: In REF2014, 85% came from UKRI funding, with just 4% from the EU. In this cycle, 60% came from UKRI, 16.5% from the EU, and 23.5% from other sources (mainly UK government bodies, charities and industry). Successes beyond core STFC and EPSRC funding (where we were also successful) included bespoke calls (e.g., the EPSRC National Nuclear User Facility Phase 2 Call); central UKRI (e.g., Fund for International Collaboration), government (e.g. Local Growth Fund) and EU calls (e.g., European Regional Development Funds, European Structural and Investment Funds).
- **We won high-profile individual fellowships and grants** (**Section 4.3**), including five Royal Society URFs and seven ERC grants.



We will target increasing income by diversifying income streams, e.g., crosscutting UKRI and central government schemes in areas aligned to our priorities, and **build on significant new partnerships with industry**, prominent examples being e2V, MSquared Lasers, Dstl and NPL and the High Value Manufacturing and Energy Systems Catapults.

The level of ambition follows UoB's goal of annual 10% growth in research income (**Sections 2.1.4, 4.1**, **REF5a**):

- We will build on the success of the Quantum Hub and BCNER/BEI as funding multipliers, to tap further into funding lines such as the Local Growth Fund and the Strength in Places calls. We will open new applications to industry of our MC40 cyclotron and Positron Emission Centre, and open a new income stream from the national neutron facility (**Sections 3.2.1**, **3.3**).
- We will expand applications of our STFC-supported work on detectors in ***Astronomy and Experimental Gravity*** and ***Particle and Nuclear Physics***, building on newly announced awards from the STFC/EPSRC Quantum Technologies for Fundamental Physics call. Interdisciplinary projects include medical applications, e.g., using BILPA to develop medical imaging and dosimetry systems for proton therapy with the PRaVDA project and the follow-on OPTIma, both linked to NPL; and opening new funding lines through, e.g., BBSRC and the Wellcome Trust.
- The Centre for Topological Science and Engineering will open new lines of collaboration across UoB, and cross-council opportunities in topology, optics and medicine. We are developing closer links with the School of Biosciences (UoA5) in optics and quantum sensors. We will also explore commercial medical applications of nanoporous silicon.
- We will continue to support staff to sustain success in winning high-profile individual fellowships and grants.

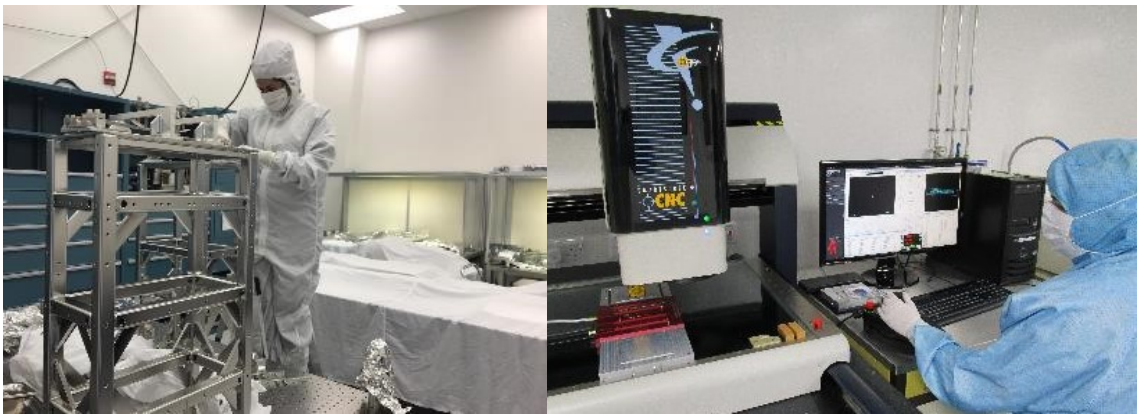
3.2 Organisational Infrastructure Supporting Research and Impact

3.2.1 Local Infrastructure and Facilities

The current REF period has seen over £10M invested by UoB in UoA9 infrastructure and facilities.

Astronomy and Experimental Gravity

Two optical labs and an electronic workshop support the Gravitational Wave Institute's programme of interferometry and technology development. **£6M of UoB investment in the Institute** funded new lab space for R&D of technologies for future experiments, and for spin-off applications (in collaboration with the Quantum Hub).



Gravitational Wave lab (left) and BILPA (right)

Particle and Nuclear Physics

In 2016, **UoB investment of £1M** established the **Birmingham Instrumentation Laboratory for Particle physics and Applications (BILPA)** to expand semiconductor detector systems R&D and production. The new laboratory has 200m^2 of clean rooms, accommodating work such as the High-Luminosity upgrade of the LHC at CERN, medical applications, and R&D into radiation hard Monolithic Active silicon Pixel Sensors.

Our MC40 cyclotron particle-accelerator facility has a wide-ranging portfolio of commercial and research applications. The research programme includes radiation hardness testing for the LHC upgrade, as part of the EU Horizon 2020 AIDA detector innovation programme; and materials irradiation for nuclear materials research. We discuss the industrial applications in **Section 3.3**.

The Positron Imaging Centre, operated jointly with UoB's School of Chemical Engineering (UoA12), uses Positron Emission Particle Tracking to study industrial mixing and processing with industry (**Section 3.3**). The cyclotron manufactures its own positron emitters.

Our new national Accelerator Driven Neutron Irradiation facility (**Sections 1.2**, **1.3.2**, £1.9M of UoB investment) will provide the highest intensity accelerator based neutron flux in the UK for fundamental nuclear physics, nuclear medicine, and materials for fission and future-generation fusion reactors. Partners include Rolls-Royce, China General Nuclear and NPL.

Quantum Matter

Major facilities in this theme are associated with the Quantum Hub. **We created a £5M state-of-the art Technology Transfer Centre** (£2M refurbishment, £3M equipment) with 800m^2 of laboratories and 400 m^2 of offices. **We won an additional £3M worth of equipment** from the Local Growth fund.

Quantum Hub

We will enhance the second phase of the project **with a further £2M of equipment,** and link into UoB facilities such as the £25M Centre for Human Brain Health and the £28M National Buried Infrastructure Facility (**Section 4.2.3**, **REF5a**).

UoA9 facilities also include a low-temperature scanning tunnelling microscope size-selected cluster beam source and deep plasma etching system; and a 200 KeV spherical-aberration corrected scanning transmission electron microscope, with high-angle annular dark-field imaging, electron energy-loss spectroscopy and high-energy X-ray dispersive detectors.

We also invested £0.25M in new facilities to support research on, and generate impact from, medical applications of nanoporous silicon.

3.2.2 External Infrastructure and Facilities

Astronomy and Experimental Gravity [REF4c in-kind income £0.9M]

UoA9 operates its own remote international telescope facilities. The robotic Birmingham Solar-Oscillations Network (BiSON) comprises six telescopes, five at large international observatories. We bought into the SPECULOOS Project, which is searching for exoplanets,

using £0.35M of UoB funding to purchase one of its four telescopes (Paranal Observatory, Chile).

We make extensive use of competitively awarded and open-access data from external ground-based telescopes and space-based facilities. Competitive ground-based awards contributing to REF4c income included the ESO 3.6-m and VLT, Liverpool telescope, the William Herschel and Isaac Newton telescopes, and eMerlin. We also won time on the CFHT, GEMINI, Magellan, GMRT, eVLA and ATCA, worth £3.2M. Competitive space-based awards included time on HST, Spitzer and XMM-Newton, worth £2.7M. We have access to proprietary ground-based data as members of LIGO, Virgo and SPECULOOS. Open-access usage of ground-based telescopes included large surveys, e.g., APOGEE/SDSS IV, Gaia-ESO and RAVE. Open-access usage of space-based facilities includes NASA's Kepler/K2 and TESS, and ESA's Gaia.

Over the next five years, we will also use data from the Rubin Observatory (*Smith* is UK lead for commissioning); ePPESTO+ (and the future ESO NTT SOX) and ENGRAVE; WEAVE on WHT (several science teams); MOONS on the VLT (membership of science team); SKA; and JWST.

Particle and Nuclear Physics [REF4c in-kind income £41.9M]

Most of our facilities usage continues to be at CERN. As members of ATLAS, LHCb and ALICE, we exploit the LHC and associated infrastructure; our NA62 activity relies on beams from the SPS accelerator. We routinely use beam facilities at DESY, Hamburg and have also used Fermilab (USA), TRIUMF (Canada), GANIL (France) and iThemba (South Africa). Our Dark Matter activity is focussed on the NEWS-G experiment at SNOLAB (Canada). Most of our analysis uses the Worldwide LHC Computing Grid. Our involvement in DUNE will ramp-up, through engagement in detector and readout deployment. Our detector activity is also leading towards exploitation of a new facility at Brookhaven, USA.

Quantum Matter [REF4c in-kind income £2.7M]

Local facilities are predominant in this theme, reflecting the nature of the work. However, we also won time at the ILL international neutron scattering facility; the STFC Diamond Light Source, and ISIS Neutron and Muon Source; the XMaS Materials Science Facility at the ESRF; the National Centre for Electron Microscopy at Berkeley, and the Swiss Muon Source at PSI.

3.3 How Infrastructure, Facilities and Expertise are Utilized for Impact

Local infrastructure and expertise **underpin vibrant impact activities that have created an extensive and growing network of collaborations with industry.**

- The Quantum Hub has worked with 70 companies and organisations (including BAE, BT and BP) with more than 50 projects funded jointly with industry and national laboratories, including Innovate UK (**Section 1.4**)
- The MC40 cyclotron produces medical isotopes for NHS hospitals, performs irradiation studies for the nuclear industry and automotive sectors (via the Alta Cyclotron Services Ltd spin out company), including "wear" testing for Formula 1 engines, and provides training for UK PhD students through the UK Nuclear Physics Graduate School.
- The Positron Emission Centre has, thanks to growing industrial understanding of its utility (**Section 3.2.1**), recently launched as a national centre.
- UoA9 hosts the Midlands STFC Science to Industry Hub, to open national facilities (e.g., Diamond and ISIS) to the SME community, in partnership with the Manufacturing Technology Centre (MTC). *Freer* led a £10m smart manufacturing programme, which realised £15m investment in a development centre in Liverpool and £20m of industrial investment, with partners including GE, Siemens, MTC and Innovate UK.

In addition to sustaining the vibrant programmes above, our goals for the period 2021 – 2026 are to build an income stream from the new national neutron facility, and to realize impact from other

recent investments including BILPA and the Centre for Topological Science and Engineering (**Section 3.1.2**).

3.4 Operational and Scholarly Infrastructure Supporting Research and Impact

26 UoA9 technical staff provide dedicated research support, comprising a Buildings/Facilities manager, a Technical Manager, 20 research technicians and 2 IT Research personnel.

In addition to theme-related infrastructure, the main Workshop in UoA9 provides support across the portfolio. **It has had £1.1M of funding since 2014 to create a state-of-the art advanced machining facility** equipped with a range of Computer Numerical Control machining centres. There are also computer-controlled waterjet cutting and laser cutting/engraving machines and a professional 3-D printer able to print eleven different plastics.

Main Workshop

Our researchers also make use of the UoB's high performance computing facilities (**Section 4.5**, **REF5a**).

Scholarly infrastructure **helps sustain a vibrant research environment**. Support is embedded within the annual Performance Development Review (PDR) process, and formal mentoring.

- UoB provides an extensive research support ecosystem (**Section 4.1, REF5a**). Research Support teams help prepare grant applications, linking seamlessly into frameworks within UoA9 at Group and Theme level (e.g. workshops to help new staff develop applications, and practice interviews). UoA9 calls on the expertise of a dedicated Research Support facilitation team, and on the College Research Development Manager and her team. For EU/ERC schemes, UoB's EU Research Office pairs researchers with a reviewer who advises on schemes and regulations, and comments on drafts from conception to submission.
- UoB has a well-coordinated media and communications team, providing dedicated support to maximize impact and reach, through broadcast, social and print media, e.g., our gravitational waves research generated over 1,000 pieces of coverage and an audience of 180 million.

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

4.1 Collaborations

UoA9 has extensive networks of international and national collaborators. These include large-scale consortia and projects, involving formal agreements and structures; smaller collaborations with one or a few researchers; and developing relationships with industry.

- The UoA9 environment **supports early-career researchers to grow into leadership positions** within collaborations, and flexibility around teaching and administration allows senior academics to take up major leadership and research roles when opportunities arise. Conspicuous examples involving women include early-career leadership of a LIGO working group on compact binaries (*Schmidt*), and at senior academic level leadership of the NA62 consortium at CERN (*Lazzeroni*).
- UoA9 funding supports travel to help kick-start new collaborations.
- Our impact and translational activities support **a growing network of collaborations with industry**, most notably through the engagement of the Quantum Hub (**Sections 3.3, 4.2**).

Large-scale collaborations are a notable feature in ***Astronomy and Experimental Gravity*** and ***Particle and Nuclear Physics***, and we hold more than 30 prominent leadership and steering positions within them. Headline examples include:

- At CERN: Spokesperson for ATLAS (*Charlton*, 2013 – 2017) and NA62 (*Lazzeroni*, 2019 – 2021); membership of the Large Hadron Collider Committee (*Newman*, 2014 – 2019), ALICE Management Board (*Evans*, 2006 –), Fermilab Long Baseline Neutrino Committee (*Charlton*)
- Membership of the Council of LIGO Scientific Collaboration (*Vecchio*, *Freise*, 2011 –),the Consortium Board of LISA (*Vecchio*, 2018 –), Einstein Telescope Steering Committee (*Freise*, 2018 –)
- Membership of TESS Asteroseismic Science Consortium Board (*Chaplin*, 2015 –), *Kepler* Science Council (*Chaplin*, 2012 – 2015)

Smaller-scale collaborations flourish with colleagues at top-100 Universities, including Cambridge, MIT, Harvard, Princeton, Yale, Sydney, Toronto and Ohio State.

Within the ***Quantum Matter*** theme, it is more natural for collaborations to involve smaller networks. Examples of close collaborators include scientists at Cambridge, Imperial, Exeter, Heriot-Watt, Heidelberg, Paderborn, Pennsylvania State, Princeton, Harvard, Weizmann Institute, National University of Singapore, Australian National University, Southern University of Science & Technology China, and Tianjin.

Collaboration in the Quantum Hub with academics at Glasgow, Nottingham, Southampton, Strathclyde and Sussex is building a series of quantum prototype devices, developing the market and links between academia and industry.

4.2 Wider Contributions not Captured by Impact Case Studies

Sections 3.1.2, 3.2.1 and **3.3** capture achievements and plans around generating impact from the Quantum Hub, the MC40 cyclotron and Positron Emission Centre, and new national neutron facility and BILPA facilities.

Further examples of impact include:

- **UoA9 developed a strategic partnership between the National Physical Laboratory (NPL) and UoB**, which has led to two joint appointments with NPL (*T. Price*, *Guarrera*). It also realized a project, funded through the European Regional Development Fund (ERDF), to help local SMEs engage with the Quantum Hub.
- **UoA9 hosts the Midlands STFC Science to Industry Hub**, which we will grow to open national facilities to the local SME community (**Section 3.3**).

- The UoA9-led BEI has driven the funding of large-scale translational research activities, e.g., a £180M bid (£60M Innovate-UK, £120M industry) **to establish the Energy Research Accelerator** (ERA, Director *Freer*) a consortium of eight Midlands universities and BGS, which includes a £10M UoB-led project to develop smart (Industry 4.0) manufacturing for 50 nationally based SMEs, with construction of two factories (Factories in a Box) for down-selected SMEs.
- **In support of the ERA and BEI, UoB invested £2.7M** into Tyseley Energy Park in Birmingham (**Section 2.1.7**, **REF5a**). In collaboration with Birmingham City Council, it will deliver new city solutions for energy, waste and transport. Associated with the development of the BEI and BCNER have been major awards from the national robotics call and Faraday Challenge, and development of a joint UoB-Fraunhofer research platform with awards of over £20M.

A strong public engagement ethos is embedded within UoA9, with an extensive programme running 150 events per year. There is comprehensive engagement with children in schools, which forms part of one Impact Case Study (**Section 1.4**): **half the schools are from deprived areas**, where students are more likely to suffer low science capital. We also have a new innovative strand with **home-schooled children** (supported by an STFC Spark Award).

Our bespoke events include:

- Astronomy in the City, a series of (free) public evenings comprising talks on recent research highlights, a question-and-answer session and observing with telescopes on campus and trips to UoA9's Observatory a few miles from campus.
- Physics Big Quiz for schoolchildren: the 2019 event had 103 teams of Y9 pupils from 36 regional schools.

Members of UoA9 give many talks to public audiences, societies and other bodies, including in partnership with the likes of Pint of Science (e.g., the 2019 Astronaut Tour). UoA9 also hosts and organises the IoP West Midlands lectures programme, which reached thousands of people.

4.3 Indicators of Wider Influence

4.3.1 Prizes and Honours

UoA9 is proactive in nominating its staff, in recognition of their achievements. Staff at early, mid and senior career levels received prizes, including six awards to women [*Elsworth* (2), *Lazzeroni*, *Blackburn*, *Wilkin*, *H. Price*]. Awards included:

- ***Astronomy and Experimental Gravity***: Fellow of the Royal Society in (*Elsworth*, 2015); 2020 Royal Astronomical Society (RAS) Gold Medal (*Elsworth*); Members of the LIGO team (*Vecchio* and *Freise*) shared in 2016 Special Breakthrough Prize in Fundamental Physics, 2016 Gruber Foundation Cosmology Prize, 2017 RAS Group Achievement Award, 2017 Bruno Rossi Prize and 2017 Princes of Asturias Award; 2020 RAS Fowler Award (*Triaud*) finalist, 2020 Blavatnik Awards (*Triaud*, for Physical Sciences in UK under age 43); 2020 International Union of Pure and Applied Physics General Relativity and Gravitation Young Scientist Prize (*Gerosa*); 2020 Research Prize of the Italian Culture Ministry and the Lincei National Academy (*Gerosa*); 2020 IoP Fred Hoyle Medal and Prize (*Chaplin*).
- ***Particle and Nuclear Physics***: Fellow of the Royal Society (*Charlton*, 2014); 2017 IoP Richard Glazebrook Medal and Prize (*Charlton*); 2019 IoP Lise Meitner Medal and Prize (*Lazzeroni*); 2019 Blavatnik Award (*Nikolopoulos*); 2014 JINR-Dubna First prize (*Goudovski*); 2020 Guido Alatrelli award for outstanding work in QCD (*Ilten*).
- ***Quantum Matter***: 2014 IoP Henry Moseley Medal and Prize (*Blackburn)*; Fellow of the Optical Society of America (2016; *Zhang*); Highly Cited Researcher by Clarivate Web of Science (2018, 2019; *Zhang*); 2017 IUPAP Young Scientist Prize in Low Temperature Physics (*Hicks*); 2018 IoP Phillips Award (*Wilkin*); 2019 IoP Dennis Gabor Medal and Prize

(*Bongs*); IoP James Clerk Maxwell Medal and Prize (*H. Price* in 2018, *von Keyserlingk* in 2020); 2020 Royal Society of Chemistry Spiers Memorial Award (*Canham*).

4.3.2 Prestigious Fellowships

- ***Astronomy and Experimental Gravity***: Royal Society Wolfson Fellowship (*Freise*, *Vecchio*); Royal Society URF (*Sesana*); ERC Consolidator (*Miglio*) and Starting grants (*Davies*, *Triaud*; also *Gerosa* and *Nicholl* just awarded for next period); STFC Ernest Rutherford Fellowship (*Miao*, *Veitch*); Dutch Research Council VENI Fellowship (*Schmidt*, *Toonen*).
- ***Particle and Nuclear Physics***: Royal Society URF (*Goudovski*); Royal Society Dorothy Hodgkin Fellowship (*M. Watson*); ERC Starting Grants (*Goudovski*, *Nikolopoulos*).
- ***Quantum Matter***: Royal Society Wolfson Research Merit Award (*Bongs*, *Zhang*); EPSRC Leadership Fellowship (*Bongs*); Royal Society URF (*Beri*, *Demetriadou*, *H. Price*); ERC starting (*Beri*) and Consolidator (*Zhang*) grants; EPSRC UKRI Innovation Fellowship (*Guarrera*); one FLF (*von Keyserlingk*) just awarded for next period.

4.3.3 Service on Panels and Committees

We exerted influence to help shape development of the field through leadership delivered by chairs and memberships of important committees, panels and bodies. There is strong representation across all themes, with early- and mid-career staff already taking up positions of influence. These roles are taken into account when allocating workloads.

We had representation on around 70 committees and panels, including:

- **Committees providing top-level strategic advice for large communities**, e.g., IoP Vice President for Science and Innovation (*Freer*); STFC Science Board, UK Space Agency Science Programme Advisory Committee (*Chaplin*); Quantum Community Network of the European Quantum Technology Flagship (UK representative), European Space Science Committee, UK Space Academic Network (*Bongs*); International Advisory Committee of the US Centre for Frontiers in Nuclear Science (*Newman*)
- **Work on government policy commissions and consultations**, e.g., *Freer* led Policy Commissions, chaired by Lord Teverson and Sir David King, on Doing Cold Smarter, developing West Midlands Combined Authority's Energy Strategy; *Bongs* is a member of the Future Position, Timing and Navigation Panel, which advises Cabinet Office; and was on the European Parliament Science and Technology Options Assessment on Quantum Technologies.
- **Oversight of projects and programmes, including strategic reviews**: Examples of chairing included the STFC Nuclear Physics (*Freer*) and Particle Physics (*Newman*) Advisory Panels, 2016 review of the STFC Particle Physics Department (*N. Watson*); the establishment of an STFC Centre of Doctoral Training programme in Data Intensive Science (*Vecchio*); UK Space Agency programmatic review (*Chaplin*) and management boards for space missions (*Vecchio*, *Chaplin*).
- **Service on grants, fellowship and awards panels** (many examples) included STFC and EPSRC schemes and fellowships, ERC grants, EU schemes, NASA fellowships, and Royal Society URFs (two staff are FRS).

Early-career examples included memberships of:

- European Space Agency (ESA) "Voyage 2050" Topical Team, reviewing long-term planning of the ESA Science Programme (*Gerosa*)
- STFC Astronomy Observation (*Triaud*) and Particle Physics (*Goudovski*) Grants Panels
- EPSRC College of Referees (*Demetriadou*, *Navarro-Cia*)

And:

- IoP Gravitational Physics Group Committee Secretary (*Schmidt*);

- Giving evidence to the Secretary of State for Defence, Defence Innovation Initiative (2016) on applications of Quantum Technology based gravity sensing (*Holynski*).

4.3.4 Journal Editorships

UoA9 staff held 22 editorial positions for refereed academic journals, **12 for open access journals**, including:

- Editor in Chief for EPJ Quantum Technology (Springer);
- Division Associate Editor for Physical Review Letters (APS);
- Editorial Board memberships for Scientific Reports (Nature), Classical and Quantum Gravity (IoP), and the Journal of Physics Communications (IoP).

4.3.5 Conferences: Organisation and Presentations

Our staff chaired or led the organisation of approximately 50 international conferences and workshops; and were members of scientific or programme committees of at least another 70 meetings. We gave hundreds of talks at conferences, workshops and meetings.

We hosted 19 conferences in Birmingham, including:

- 2016 International Conference on Kaon Physics;
- 2017 IoP Nuclear Physics Conference;
- 2017 International TESS/*Kepler* Asteroseismology Conference (TASC3/KASC10);
- 2018 ATLAS-UK Meeting;
- 25th International Workshop on Deep Inelastic Scattering and Related Topics (DIS '17);
- 2019 IoP Conference on Quantum, Atomic and Molecular Physics.

UoA9 also won the bid to host the 2017 IUPAP International Conference on Women in Physics, a triennial event addressing issues around the well-recognised shortage of women studying and working in physics. We hosted 250 participants (90% women) from 60 countries, with significant sponsorship raised to enable teams from developing countries to attend.

ICWIP 2017

4.4 Concluding Remarks

UoA9 promotes a stimulating, collegiate and equitable research environment, supporting and developing our staff to:

- perform world-class research at the frontiers of ***Astronomy and Experimental Gravity***, ***Particle and Nuclear Physics*** and ***Quantum Matter***;
- grasp new interdisciplinary opportunities, between different domains of Physics, and to other natural sciences, and engineering;
- deliver significant impact, in collaboration with industry and other academic disciplines; and
- provide leadership internationally, shaping the field for the 21st Century.