

<b>Institution: Cardiff University</b>
<b>Unit of Assessment 9: Physics</b>
<p><b>1. Unit context and structure, research and impact strategy</b></p> <p><b><u>1.1 Context and structure</u></b></p> <p>Cardiff University's (CU) School of Physics and Astronomy, one of the seven Schools in the College of Physical Sciences and Engineering, is a leading research department focused on creating new fundamental understanding and impact on a wide spectrum of physical processes governing nature, from the small-scale physics of quantum devices all the way to the largest cosmological scales. Following REF2014, the School was identified by CU as a priority for investment, building on an explicit 'School Strategic Plan'. This included expansion in astronomy and compound semiconductors, high prioritisation of Equality, Diversity and Inclusion (EDI) and later supplemented by expansion into experimental gravitational wave physics.</p> <p>Four School research groups comprise the CU UOA9 REF2021 submission (academics listed as Professor (P), Reader (R), Senior Lecturer (SL), Lecturer (L) or Senior Research Fellow (RF)):</p> <ul style="list-style-type: none"> <li>• <b>Astronomy Group (AG):</b> (P) <b>Eales (Head)</b>, Gomez, Greaves, Whitworth (50%); (R) Clark, Peretto; (SL) Davis, Matsuura, Negrello; (L) Ragan, van de Voort; (RF) Bowey, Duarte-Cabral. Current PDRAs: 11 (with Dunne (80%), Maddox (80%) and Smith being returned); PhD students: 18.</li> <li>• <b>Astronomy Instrumentation Group (AIG) PIs:</b> (P) <b>Griffin (Head; 50%)</b>, Ade (50%), Calabrese (joint with AG), Hargrave, Tucker; (R) Doyle, Pisano; (RF) Sudiwala. Current PDRAs: 7; PhDs: 6.</li> <li>• <b>Condensed Matter and Photonics (CMP):</b> (P) <b>Langbein (Head)</b>, Giblin, Huffaker, Macdonald, Smowton, Williams; (R) Buckle, Lynch, Muljarov; (SL) Ladak, Read; (L) Abadia, Beggs, Deng, Hou, Kesaria, Klemencic (joint with AIG), Li, Oh, Pereiro-Viterbo. Current PDRAs: 21 (with Mandal being returned); PhDs: 49.</li> <li>• <b>Gravitational Exploration Institute (GEI):</b> (P) <b>Fairhurst (Head; 80%)</b>, Grote, Hannam, Sathyaprakash (25%), Schutz (50%), Sutton; (R) Dooley (95%); (SL) Raymond; (L) Antonini, Inserra (joint with AG); (RF) MacLeod. Current PDRAs: 8; PhDs: 15.</li> </ul> <p>The School also hosts the nascent Brain Imaging Group (BIG) (Murphy, Beltrachini, Tax) which drives interdisciplinary research involving physics, aligned to the University's flagship Cardiff University Brain Research and Imaging Centre (CUBRIC, see REF5a). The BIG both contributes to and benefits from the environment of the School; researchers from this group were submitted to UOA4. Consequently, all data subsequently reported for UOA9 excludes BIG.</p> <p>UOA9 has grown considerably since REF2014, from 34 to 53.1 academic FTE (both including T&amp;S), with 52.2 FTE REF Category A staff, and improved diversity (Juno Champion award in 2020; Section 2.8). The Unit has considerably grown its research income (to £114M in REF2021 compared to £46M in REF2014 and £36M in RAE2008). As a result, our cohort of postdoctoral researchers (PDRAs) and postgraduate (PGR) students has increased to its highest ever level (Sections 2.3 and 2.7). There has been multi-million-pound investments into refurbished laboratory space, as well as new space as part of Cardiff's new £131M 'Translational Research Hub', to be completed in 2022 (Section 3), which brings a state-of-the-art semiconductor fabrication facility and a further 1000 m<sup>2</sup> of high-quality physics laboratories. We have produced over 1800 publications and delivered a range of economic impacts, as well as leading on national and international research initiatives and engaging with communities through organising conferences and extensive public engagement (Section 4).</p> <p><b><u>1.2 Research strategy</u></b></p> <p>Our strategic vision is to advance basic understanding and application of physics and astronomy, including through international collaborations, both academic and commercial, allowing new discoveries that address significant research and societal challenges, while contributing to national economic growth. This is achieved through our research group structure which aligns with our strengths and future research aspirations. Since REF2014, considerable strategic development</p>

includes: the foundation of the Institute for Compound Semiconductors (ICS), jointly with Cardiff School of Engineering; the establishment of the Sêr Cymru Advanced Materials and Devices Research Group; the expansion of gravitational wave research with the addition of an experimental group and new positions in transient astronomy; growth of the AG through hosting Royal Society and STFC-funded research fellows achieving permanent academic positions. Aligned to this, substantial improvements in core facilities and research space have provided greater research capacity, enabling a strategic increase in PGR numbers and junior researchers. We have also made significant advances in EDI, a major element of our 2014 strategic plan (see Section 2).

Specifics of the approach in each area follow.

The **AG** focuses on how planetary systems, stars, galaxies and the whole Universe were formed and evolved. The group addresses these questions using observational programmes at major optical to millimetre wavelength observatories, and numerical simulations, and by focussing on the life cycle of interstellar dust, star formation and galaxy evolution, transient astronomy, the Cosmic Microwave Background (CMB) and exoplanets. Highlights include: leadership of a consortium of 16 UK universities collaborating with the East Asian Observatory on the continued operation of the James Clerk Maxwell Telescope (JCMT); leadership of an international astronomical survey (ePESSTO+); significant roles in the UK consortium for the Vera Rubin Observatory; thousands of hours awarded for observing time on multiple telescopes (Section 3.4).

The **AIG** leads, and is involved in, major international astronomy projects through building and exploiting far-infrared-millimetre instrumentation for astronomical observatories, for CMB studies, and for Earth observations. Key research is in superconducting detectors, metamaterial-based quasioptical components, ultra-low-temperature cryogenics and data processing. Highlights include: leading roles in recent high-profile missions and instruments including the *Herschel*-SPIRE and *Planck*-HFI satellite instruments, and the SCUBA-2 ground-based submillimetre camera; involvement in several current world-class projects including the Ariel exoplanet characterisation satellite (ESA's M4 mission), the Japanese-led LiteBIRD CMB satellite, the Simons Observatory (SO) ground-based CMB project; and provision of flight hardware for the microwave sounder (MWS) instruments to fly on EUMETSAT's next-generation of weather satellites (see impact case). AIG researchers work closely with the AG on mutually supportive strategic objectives, fostering in-house scientific exploitation of AIG projects, and guiding technical R&D. Examples include a strategy to build capacity in exoplanet science, and leadership by Cardiff astronomers of observing programmes which use AIG instruments.

The **CMP** group addresses understanding the optical, electrical and magnetic properties of materials, growth mechanisms of diamond and compound semiconductors, application to devices, and novel instrumentation for materials and device characterisation, including characterisation of biological materials. The group is strongly multidisciplinary with strong links to Chemistry (e.g., virus filtration, Welsh Government funded), Biosciences (e.g., Raman active proteins, EPSRC funded) and Engineering (e.g., integration of diamond with GaN, EPSRC funded), as well as the ICS and CUBRIC. Highlights include: the development of long-lived semiconductor lasers grown epitaxially on silicon, demonstrating coherent control in solid state emitters; developing understanding of magnetic monopoles; integration of diamond with GaN, filtration of viruses from the water supply and the establishment of a compound semiconductor (CS) research and manufacturing cluster in South Wales (see impact case).

The **GEI** is unique in developing all aspects of gravitational wave (GW) physics and astronomy, such as new instrumental techniques to improve detector sensitivity, identification of gravitational wave sources in the detector data, and modelling the physics and astrophysics of black holes and neutron stars. It is the fourth largest group in the international Laser Interferometer Gravitational Wave Observatory (LIGO) collaboration. It is a strong component of the University interdisciplinary Data Innovation Research Institute (DIRI) and includes joint appointments with AG. Highlights include: leadership roles in LIGO (Section 4.1), several multi-million-pound research awards (Section 3.1), and prominent involvement in the discovery of gravitational waves and their electromagnetic counterparts (see outreach impact case) followed by awards and recognitions (Section 4.5), e.g., Schutz's Eddington Medal and Nobel Prize opening lecture in 2017.

Our Research Strategy is formulated by synthesising documented strategic plans from each Research Group (RG), led by the RG heads, and refined and prioritised by the Head of School (HoS), supported by the School Board (SB). Since REF2014, the Research Committee (RC), chaired by the Director of Research (DoR), has been expanded so that Safety, Research Ethics and EDI are standing agenda items and are fully embedded in our research culture. The work of the DoR (Williams) is supported and shared by two deputies (Calabrese and Inserra), with all three coming from separate RGs. Further research leadership is provided by the RG Heads (all *ex officio* members of the SB and RC), who are responsible for the day-to-day organising and prioritising of activities in their areas, and for overseeing the periodic update of each group's strategic plan (covering research and appointment priorities, funding plans, publications, impact, and resource needs). The RG strategic plans feed into the research-related elements of the School strategic plan. The RC oversees policies and issues that affect all groups, such as space allocations, technical support, and infrastructure development. Research is a central agenda item at senior management meetings, including the SB. Systematic research support is also provided by the Director of Postgraduate Research Studies (DPGS), the Director of Innovation and Engagement (DI&E), the School Manager, the School's Technical Services Manager, and the Safety, Health and Wellbeing Coordinator.

### **1.3 Progress against REF2014 research strategy**

As described in Section 1.1, our strategy following REF2014 has focussed on critical mass, research quality, investment in facilities and research culture, including EDI, and incorporated and delivered all key elements from the 2014 environment template (text in bold).

1. Recruitment of high-quality academic staff to expand critical mass and **consolidate research strengths in all research groups** including **exoplanet research** (Sections 1.1 and 2, linked to delivery of goals 2, 4 and 5 below).
2. Establishing BIG to enhance interdisciplinary research, aligned to Cardiff's £44M investment in the multidisciplinary brain imaging centre, CUBRIC, which includes scanning facilities unique in the UK. BIG's research applies physical principles to neuroimaging for more accurate measurements of processes in the brain, is fully interdisciplinary and enables multidisciplinary networks within the School (e.g., with AIG, Section 3.1), and with researchers from Computer Science and Informatics, Engineering, Psychology, Medicine and Biosciences.
3. Foundation of the ICS, with Engineering (led by Smowton), as a major investment in infrastructure and expertise, with over £50M from external sources (e.g., UK Research Partnership Infrastructure Fund and EPSRC), and including a purpose-built 1350-m<sup>2</sup> fabrication cleanroom in the Translational Research Hub (TRH). The 10-year ICS development plan supplements existing CS academic expertise within CMP with eight new hires (three to date). ICS **enhances innovation activity and links with industry** as a core member of the Compound Semiconductor Cluster, which includes the Compound Semiconductor Applications Catapult and CSC Ltd., a company jointly owned by the University and semiconductor company IQE.
4. Establishment of the Sêr Cymru Advanced Material and Devices Research Group, targeting integrated and functional device platforms **to boost activity in semiconductor physics and technology** (and 3 above), merging optoelectronics with nanostructures, metamaterials and plasmonics. Applications include remote sensing and quantum technology with local, international and industrial collaborations (e.g., UCLA and Huawei, £270k). This has been enabled by **taking advantage of Welsh government investment** (Sêr Cymru programme to attract scientific talent – Huffaker – to Wales, £4.1M from the Welsh Government and £5.9M CU match).
5. Expansion of the Gravitational Physics Group (now GEI) enhancing a strong theoretical and computational team and, with £1.2M invested by the University, initiating an experimental programme with new academic positions and laboratories (Section 3.2). The GEI enables a comprehensive approach to problems in GW and offers a bridge to quantum and optical physicists in CMP, AIG and astronomy, **moving from preparation for gravitational wave detection to exploitation**.
6. Pivotal role (Fairhurst as initial Director and Schutz as founder) in the establishment of DIRI, approved in 2014 with a budget of £500K/year and designed to strengthen interdisciplinary

research in data science via sharing of expertise across Schools of Physics and Astronomy, Computer Science and Informatics, Mathematics and Engineering.

7. Formation of the Physics Education Research Group (PERG) to coordinate and systematise the School's substantial pedagogical expertise, thereby stimulating advances in physics teaching, and ensuring that innovations in teaching and engagement match our excellence in other areas of research.

8. **Diversification in funding**, with less dependence on STFC and more EU income (Section 3.1).

#### **1.4 Research impact**

Impact is a high-priority area and all research group strategic plans include impact. The DI&E (Hargrave) leads impact reporting to the RC and SB. The DI&E sits on the wider College Impact Forum, providing an effective support mechanism to introduce best practice into the Unit. Impact is central to individual academic staff Performance Development Reviews (PDR) and promotion, and researchers are empowered to exploit the impact of their research with time allocation, professional support and University training for impact, including IP protection and Market Awareness. We also use University Research Institutes such as DIRI to facilitate impact by bringing together diverse researchers with key stakeholders for research falling within their remit.

The School has supported specific initiatives since REF2014 to promote impact. The ICS was set up with a strategic focus on translation of fundamental research into applications, and to instigate consideration of manufacturing impact from the very inception of new research ideas. Co-location of research and manufacturing scale equipment, as well as industry and University staff, facilitates this approach. The ICS also acts as a conduit for Continuing Professional Development activities with local Compound Semiconductor Cluster companies (Beggs, Lynch; Section 4.3) creating a talent pool that supports industry (e.g., six PDRAs joined cluster companies since REF2014; Section 2.3). The School has part-supported an Ogden Science Lecturer and Director of Public Engagement (North, within AG and GEI), facilitating outreach activities across the School (Section 4.3). Accommodation is provided to three spin-out companies: the award-winning international science communications company, *Science Made Simple*; the long-established *QMC Instruments Ltd.*, specialising in cryogenics, filters, detectors and systems; and the newly-created *Sequestim Ltd.*, formed to develop and market novel video-rate THz security systems, based on detectors and data processing technologies invented for astronomy instruments (Section 3.1).

During the REF period, the DI&E worked with RG Heads and academics to identify and develop a breadth of potential impact cases. Of our five REF2021 impact cases, two cases are outreach and education based, detailing major international educational and teacher-training initiatives developed from AG and GEI research. A THz technology case study describes the impact arising from commercialisation of AIG technologies through QMCI and other AIG industrial partners. The other case study arising from the AIG is based on the development of unique quasioptical systems for the next-generation of European weather satellites. Finally, the ICS case study details the impact arising from CMP research, leading to major strategic investment in South Wales to create a CS research and manufacturing ecosystem. Two of the five cases are led by female academics (Gomez and Tucker).

#### **1.5 Interdisciplinary research**

Research collaborations exist with other Cardiff University Schools (e.g., Biosciences, Pharmacy and Pharmaceutical Sciences, Engineering, Chemistry, Psychology, Computer Science and Informatics, and Maths), and with external institutes and companies. Cross-disciplinary collaborations foster innovation in physics and astronomy research and impact for UOA9 in a wide range of sectors. Highlight projects include: Raman spectroscopy of proteins, and novel cell imaging supported by joint grants between Physics and Astronomy and Biosciences; the application of AIG research to other topics e.g., submillimetre hyper-spectral sensing of the Earth's atmosphere, provision of flight hardware for meteorological satellites, joint development with BIG of data curation systems for brain imaging facilities using practices developed for space astronomy missions; and multiple activities on diamond nanoparticles, such as controlling their surface chemistry to adsorb viruses and emit light at imaging relevant wavelengths for biomarking (Physics and Astronomy, Biosciences, Chemistry and Engineering) with multiple joint grants from BBSRC,



Leverhulme, DSTL, Wellcome and the Welsh Government, as well as a patent filing on virus filtration. See also Sections 3.1 and 4.1.

As a measure of both our interdisciplinary research and evidence of the success of our strategy, we are host and partner in several Centres for Doctoral Training (CDT; Section 2.7). These programmes allow us to train the next generation of physicists and astronomers, and to enhance transfer of knowledge between academia and industry. For example, our CDT in Compound Semiconductor Manufacturing ensures that every student has an industrial as well as two academic supervisors from different universities and disciplines.

### **1.6 Open Research**

The School is enthusiastically compliant with all funder requirements and the Concordat on Open Research Data, ensuring full online access to scientific information free of charge. Open data is managed through our institutional research information management system, with mandated datasets assigned a unique DOI. The Open Access (OA) Coordinator (Morgan), assisted by the University OA Team, manages OA for the School, overseeing staff training, recording and ensuring output compliance, and that all post-print files and bibliographic details for publications are held in Cardiff's digital publications repository, along with digital copies of all theses from the School. Following Research England's recommendations, 100% of Category A staff have ORCID registration. CU is a signatory to the San Francisco Declaration on Research Assessment (see REF5a). Assessment of research for funding, appointment, and promotion considerations is exclusively made based on intrinsic merits of the work, rather than journal-based metrics.

As part of a broader commitment to open research, many data products and outputs are made available to other researchers. For example, the design of one of our diamond growth systems has been made open source and published on wikiversity, and the OA data from relevant papers has been used by the Universities of Cadiz and Wurzburg and eVince Technology to build similar systems.

### **1.7 Research ethics and integrity**

Research Integrity training is mandatory for all academic staff and PGR students within the University. We comply with all University ethics protocols and the School Ethics Officer (EO, Beltrachini) is responsible for managing ethical issues in research and chairing the School Research Ethics Committee (SREC). The EO monitors the procedures, reviews issues, and ensures that all appropriate researchers receive the correct documentation. The EO reports to the RC and Head of School and yearly to the University, and conducts three-yearly reviews of the School's ethical procedures, relaying the outcome to the University Open Research Integrity and Ethics Committee. When relevant the SREC oversees that research involving human participants follows appropriate protocols and that all research proposals are checked against ethical concerns.

### **1.8 Future plans**

The Unit will maintain and build on its strategy of having the critical mass to tackle grand scientific and societal challenges while ensuring cross-fertilisation of ideas and activities between research groups, across the University and via international networks supporting advancement of the broader discipline. Future aims include:

- Continue to grow strength in gravitational physics, exploiting scientific opportunities facilitated by the now frequent detections, and to further cement links with the AG through activities in transient astronomy.
- Combine AIG and AG creating a Cardiff Institute for Astrophysics Research (working title) to strengthen the ability to address open questions in astronomy, contributing to and exploiting major international experiments, and maximising in-house guidance and exploitation of instrumentation projects. Appropriate recruitment will be necessary to maintain capability and support ambitious goals.

- Expand the ICS with recruitment of five high-quality academics to take advantage of the new TRH facilities, providing expertise in theory, modelling, materials growth, and device fabrication and characterisation, with translational activities to exploit outcomes.
- Expand BIG, increasing and driving opportunities for multidisciplinary collaborations and the University's broader research agenda.

Each RG has identified grand challenges for the coming period to ensure continued discipline excellence, while also strengthening collaboration networks inside and outside the Unit:

- The Institute for Astrophysics Research will address two out of the three Astronomy Science Challenges identified by STFC: 'How did the Universe begin and how is it evolving?' and 'How do stars and planetary systems develop and how do they support the existence of life?'. We will use new facilities which have already received large UK financial investment (e.g., the Rubin Observatory, the Square Kilometre Array, the ESA Euclid space mission) and next-generation CMB experiments, to study galaxy evolution and cosmology, and continue diversification into transient astronomy and into exoplanet science and astrobiology, building on our hardware and data-processing contributions to ESA's ARIEL mission. Staff are strategically positioned to have key leadership roles in these projects (e.g., Calabrese Science Chair of SO and Section 4.1). We will further develop detectors, metamaterial-based quasi-optics, and cryogenic technologies to enable new instrument concepts and capabilities for astronomy and Earth observation, and work with our QMCI and Sequestim spin-out companies to identify and realise commercial applications.
- CMP will focus on impact and interdisciplinary research, such as coherent Raman scattering, quantum biology with Biosciences, virus filtration with Pharmacy and Pharmaceutical Sciences, and build on strong industrial collaborations (e.g., with Huawei, 4K-MEMS, IQE and eVince Technology). The group will address both discipline and major societal challenges, further strengthening EPSRC's stated priority areas such as Photonic Materials, Materials for Energy Applications and Quantum Technologies. Facilities such as the Cardiff Diamond Foundry will be set up as TRAC facilities to complement the TRAC device fabrication of ICS and the MOCVD laboratory with links to the CS Cluster. By these means, CMP will demonstrate fundamental physics research connected to impact, such as manufacturing at scale.
- Having initiated a research programme that encompasses all major aspects of the field, GEI will establish the field of gravitational astronomy, using gravitational waves as a new tool to observe the Universe, and play a leading role in the development of the science and technical case for third-generation gravitational-wave detectors (such as the Einstein Telescope, a proposed European GW observatory). Through DIRI, GEI proactively seeks out collaboration with other CU departments in areas where sophisticated signal analysis is critical to progress, e.g., biologists or social scientists with large data sets requiring identification of useful patterns and separation from noise artefacts. "Big Data" techniques have enormous impact across many areas of science and society.

Building critical mass is about infrastructure, facilities, and support staff, as well as academic numbers. We will continue to invest to make sure that our academic teams have access to the best working environment, including multidisciplinary support (as in CUBRIC and the ICS). We will continue to provide support for all staff and early career researchers (ECRs) in particular on research and career development, and build on our Juno Champion award to guarantee that work is carried out in an environment that strongly supports diversity and inclusion.

We will ensure that the discipline is sustainable with a pipeline of trained people by adding to undergraduate, postgraduate taught, and doctoral training centres associated with each of our research groups, and by augmenting our technical support staff with apprentices. Planned initiatives include: a new MPhys programme with a focus on brain imaging; strengthening postgraduate taught programmes in semiconductor physics and astronomy; expanding doctoral training in gravitational physics.

**2. People****2.1 Staff development strategy**

Staff are strongly supported to achieve their full potential. Advice, guidance, and mechanisms for raising concerns are provided at the RG level, as part of the PDR process, and by promoting a strong cultural emphasis on equality and diversity. The School supports and encourages staff to take advantage of a wide range of training covering professional and personal development. Many of these courses are mandatory for all staff (see REF5a), including: EDI, Unconscious Bias, and Information Security; Line Management training is mandatory for all staff whose roles involve formal line management; Academic Practice is mandatory for ECRs; and Leadership and Management programmes are available for Senior staff. A specific mandatory training programme, which includes EDI as a key element, must be completed before being allowed to chair a recruitment panel.

All staff are appraised yearly through the PDR process – with 100% completion rate in four out of five years, and greater than 95% in the fifth year, pre-COVID. Career development of postdoctoral staff is a standing item in both the postdoctoral staff PDRs and in the PDRs for line managers of those staff (Section 2.3). There are clear routes of progression for academics on both Teaching & Research and Teaching & Scholarship career pathways. Academic promotion is by self-application and is encouraged in PDR. It is administered by the University, with a strong emphasis on external assessment. 27 academics in the Unit were promoted during the REF period; on average more than 80% of applications have been successful. Rapid career progression via promotion is strongly supported in significant cases, e.g., Calabrese was promoted from Lecturer to Professor.

The Unit has two University “Darlithwyr Disglair” (Brilliant Lecturers), a previous research-only postdoc (Klemencic) and an external hire (Deng). This scheme supports early career academics wishing to pursue lecturer roles by giving them the opportunity to experience life as a full-time University lecturer for two years along with specific leadership training. During this scheme Klemencic secured an EPSRC New Horizon grant and a permanent School post.

Other development programmes include Cardiff Futures, led by the Vice-Chancellor and designed to support early career academics to develop their career and explore how they might contribute to shaping the future of our University, promoting collaborative working across disciplines. Nine UOA9 staff attended the programme over the REF period; mentoring via this programme led Tucker to take on new positions on committees and boards, including Deputy Head of School. Four UOA9 staff participated in Welsh Crucible, a programme encouraging interdisciplinary working for the future research leaders of Wales (2013 Times Higher Education Award for outstanding contribution to leadership development). School public engagement experts (Griffin and North) have also participated in the programme with an annual presentation on media engagement. A Professorial Leadership Program, led by the Deputy Vice-Chancellor, helps newly promoted or appointed professorial staff refine and develop their understanding and skills relevant to their academic leadership roles. The majority of newly appointed Physics professoriate have taken advantage of this scheme; this led Sutton and then Fairhurst to become Head of GEI. UOA9 staff also received several nominations and awards in the University’s Celebrating Excellence Awards, recognizing the importance of UOA9 and its research to the University. The Vice-Chancellor Award for Outstanding Contribution to the University was awarded to the Gravitational Physics Group in 2016.

**2.2 Staffing and recruitment strategy**

UOA9 has expanded considerably since REF2014, by strategically recruiting new staff across all career stages to bolster capacity in our priority areas (Section 1.3), ensuring a healthy age profile, robust succession and progression planning as well as facilitating flexible approaches to retirement and part-time working (Section 2.4). The School requires that all interview panels include at least one female member of staff regardless of the post type or the gender of interviewees. Further, aligned to our commitment to improve our gender balance, the School introduced a gender decoder to check language in job adverts, and provides both a male and female contact in all adverts. The gender balance of staff recruited has increased significantly

since 2014 (Section 2.8); UOA9 hosts 57 full- or part-time academic staff, of which 23% are female (compared to 35 staff members and 11% in REF2014).

### **2.3 Early career researchers**

To help newly appointed academics establish themselves in their role, the policy is to give them priority access to PhD students as well as low-level teaching in their first year, followed by a half load the following year. As well as the support that they get through being embedded in their RG, junior appointees are mentored and advised by established academics, generally from different disciplines within the School or College, and have access to the School's library of grant applications (e.g., leading to Negrello (AG) and Pereiro-Viterbo (CMP) securing Marie Skłodowska-Curie fellowships). We encourage senior PDRAs interested in academic careers to give guest lectures and, in some cases, they also act as Module Organisers or Deputy Module Organisers, with active monitoring and guidance from an experienced academic in every case. The School and CU strongly support and involve ECRs in leadership, as well as developing the University's research strategy (see REF5a and below).

Fellowship applications are a strategic target for the Unit as a step towards independent academic positions, with an in-house discipline-specific mentoring scheme organised by the RGs in addition to the University's training, peer review of applications and practice interviews. 22 externally funded research fellowships were secured during the REF cycle (21% success rate). The majority have been Marie Skłodowska-Curie Fellowships (seven), followed by Sêr Cymru (six), STFC (six), and Royal Society URF (two); with 38% female and 21% BAME. In particular, in 2019 all STFC ERF candidates internally selected were female, and they all succeeded in securing fellowship awards from STFC and Royal Society. Six permanent staff members appointed in the REF period started as fellows (Antonini, Calabrese, Davis, Matsuura, Oh, van de Voort).

Start-up funds of ~£10k are provided for new academic appointees for travel/computing; in some cases a School-funded PhD student or postdoc is part of the start-up package; substantial funding for equipment is given (e.g., GEI experimentalists); and for most of the REF period a return of a fraction of grant overheads to grant PIs, providing an incentive to win grant funding and flexibility to manage their programmes and staffing, and to develop new initiatives. To encourage and support funded research, PhD studentships have been funded by the School for grants over £750K (over and above the EPSRC/STFC Doctoral Training Accounts). This is particularly helpful for ECRs starting to build a research team.

The Unit has a large contingent of PDRAs (headcount averaging over 50 throughout the REF period). The junior academic representative on the SB is specifically tasked with interacting with PDRAs personally and via the PDRA Forum which was set up for postdocs to share experiences, opportunities and issues. The RC has a postdoc representative to ensure good communication with, and representation of, postdoctoral staff; two positions for PDRAs are in place on the School's EDI Committee to ensure that the development of research culture is aligned to the needs of PDRAs. A School-customised PDR form (developed in consultation with the PDRA Forum) is used for all PDRAs, with guidance notes sent to reviewers including and emphasising career development. PDRAs are supported by the line managers, mentors, and during PDRs to establish their next career goal either in academia or in other sectors. For example, several of our PDRAs have progressed at Cardiff (e.g., Duarte-Cabral, now Royal Society Fellow), left for permanent academic roles (e.g., Pannarale, University of Rome; Nuttall, University of Portsmouth), joined industry (e.g., Boulbar, Newport Wafer Fab; Kastein, IQE; Royle, SPTS), or are partners of our spin-out companies (e.g., Rowe and Papageorgiou, Sequestim). A page on our intranet has been created to further help PDRAs source funding and develop career opportunities.

### **2.4 Research leave and flexible working**

The University's Research Leave scheme provides funding for teaching cover during periods of 6-12 months, focusing on generating high-quality publications and/or impact, and is available to all staff. During the REF period, ten UOA9 staff members took research leave (three female, seven male), leading to an ERC Consolidator grant (Gomez), Spitzer ALMA & NOEMA telescope time (Eales), and a two-year secondment to UCSB (Read). Staff returning from periods of long-term leave are offered additional support and flexibility to minimise the impact of extended leave on the



delivery of their duties. This allows them to refresh their skills, knowledge and confidence thus enabling continued career development.

We are supportive of flexible working, with reduced teaching and administration loads for staff with caring responsibility or coming back from parental leave, and of part-time working for staff approaching retirement, without any impact on their career progression (e.g., Gomez and Dooley have restarted research careers using flexible working following parental leave).

### **2.5 Technician Commitment**

In May 2017 the University became one of the founding signatories for the national Technician Commitment, led by the Science Council to ensure visibility, recognition, career development and sustainability for technicians working in higher education and research (see REF5a). The School supports the career development of its technical team and recognises and promotes the status of technical staff (Section 3.2). This included hosting the national Technical Managers at Universities (TMU) conference in June 2018, organised by technicians, for technicians. The School's current Technical Service Manager was a co-organiser of the 2018 TMU conference and is a member of the CU Technical Commitment working group. He is also technical contact for the GW4 Alliance (see REF5a). The School is also a member of HEaTED (Higher Education and Technicians Educational Development) and has signed up to the Employer Champion initiative which encourages staff to move towards professional registration. There are 19 volunteers engaged in this process and we achieved **Employer Champion Status** in 2018.

### **2.6 Staff wellbeing**

The University's Staff Wellbeing Group was formed in January 2018 to support and promote a wellbeing strategy across the University. It has in place an Employee Assistance Programme, a programme of wellbeing events, and provides bespoke events for teams and Schools. For example, the Mental Health First Aid training is mandatory for our Dignity at Work contacts (see below) who are now qualified Dignity at Work and Wellbeing advisors. Aligned to the University's approach, the School has implemented a range of initiatives to support staff and enhance wellbeing. We aim to hold meetings within core working hours (10am-4pm) and, where possible, limit them to 50 minutes and with breaks of 10 minutes between meetings. The School holds monthly informal all-staff meetings which are well attended and cover briefings on topical issues and developments, also providing a forum for staff to ask questions and raise concerns. These meetings are held at times accommodating staff with childminding or other home responsibilities (e.g., late morning or early afternoon). Since the COVID crisis, lunchtime and Friday meetings have been suspended. Eight wellbeing days, free of meetings and tasks, were introduced by the University during the lockdown, giving staff the opportunity to work on whatever they desired or take time off. For staff members with caring responsibilities, where it may be harder to deliver work at the normal level, close consultation on priorities and additional support was provided. A survey of staff home working conditions was carried out by the School's EDI committee with particular attention to PhD students, who are likely to work in less ideal conditions. Provision was made for staff and PhD students to pick up items (courier if required) for help with working from home as well as a budget of £100 automatically authorized, and higher amounts on a case-by-case basis. The School also initiated an independent survey by *Science Made Simple* to assess working conditions and concerns of all staff and PhD students (75% completion rate), and to make targeted adjustments to home working conditions.

Staff workload is agreed during PDR with an overall balancing overseen by the HoS and based on the University academic workload modelling scheme (see REF5a). To ensure an equitable and appropriate working environment where all staff can flourish, this workload modelling scheme has been carefully designed. This included undertaking an Equality Impact Assessment on the scheme and establishing specialist task groups to provide staff input to a thorough revision. Three School staff supported this process – the Juno lead (Sadler) advised on how to define what used to be classified as the 'other' activities beyond teaching and research, while Inserra (Deputy DoR) and Langbein (CMP head) advised on research matters.

Specific initiatives have responded to suggestions made/discussions held at the annual School awayday and at the monthly informal staff meetings. Examples include: establishment of well-advertised and proactive Dignity at Work contacts available to discuss and help resolve issues

before they become sufficiently advanced for more formal processes (84% of staff in the School agreed they were treated with respect by colleagues in our 2019 survey); in 2015 forming a Social Events Committee including members from academics, professional services, postdocs and PhD students, to promote integration of all staff and PhD students with a variety of family-friendly events (e.g., the annual departmental quiz night in December, the summer barbecue family outing, and boardgame evenings), with costs met by the School. A Facebook page (180 members) organised by the Social Events Committee regularly encourages all to join planned and ad hoc social events. There have also been improvements to the working/social environment with a refurbished coffee area, coffee machines and water fountains, ergonomic desks and chairs.

### **2.7 PGR recruitment, monitoring, and support**

During the REF period, 117 (36% female) PhD students have been recruited from 947 (28%) applicants. Studentships are clearly advertised on the CU website and on FindAPhD. Diversity of applications is encouraged, most recently using a language decoder to improve the attractiveness of adverts to females, and offering a wide portfolio of projects proposed by a diverse cohort of prospective supervisors (see Section 2.8 for improvement in gender balance).

Student monitoring is overseen by the DPGS (Lewis). All students have at least two supervisors and one independent mentor, with progression review panels populated with two independent academic staff. Students are interviewed at 9, 21 and 33 months, with intervening self-assessment and reported supervisor meetings. This rigorous and supportive process resulted in a 79% submission rate and led to 85 students completing their PhDs during the REF period.

PGR feedback is facilitated by the PG committee which includes the DPGS and EDI Committee chair. Monthly lunch consultations are held by the DPGS with the PGR students, and PGR reps can raise any issues brought to them by their cohort to a specific Postgraduate Staff-Student Panel or, in some cases, are invited to report directly at the SB (e.g., Eknath on gender). The School also provides a PG Disability Contact to aid with the implementation of reasonable adjustments requested by the Disabilities and Dyslexia Service. All students are invited to attend informal all-staff meetings, awaydays and regular seminars/colloquia/'Physics Chats'. In an initiative based in large part on active discussion with PGR students through these channels, a new PGR Support Module has been created on Learning Central (the University's online teaching and learning platform) with information and guidance on progress reviews, thesis submission, extenuating circumstances, health and safety, wellbeing, and teaching assistant duties. Feedback from students indicates that the new module is easier to navigate, more aligned with student requirements, and more effective in providing support.

PGRs are also supported by the University's Doctoral Academy, providing research and personal skills development, as well as a range of interdisciplinary community events and funding opportunities. The University's Careers & Employability service has supported the career development of PGR students and postdocs with over 70 sessions during the REF period, the majority being face-to-face careers appointments. The DPGS also arranges a School-based training programme for PGR students. For example, students who are involved with teaching and demonstrating are provided bespoke support and mentoring for their roles. This led to a PhD student (Askey) obtaining Associate Fellow of the Higher Education Academy (HEA) recognition and is currently in the process of applying for a full Fellowship of the HEA following further School-supported development. Students are supported with an organised Postgraduate Lecture Series which covers transferable skills and technical topics and ensures that students can achieve a top-level understanding of the research carried out in the Unit.

The Unit is heavily involved in four CDTs providing students with links with other Universities and industrial partners: the STFC Data Intensive CDT (3 Universities, >10 partners); UKRI Centre for Artificial Intelligence, Machine Learning & Advanced Computing (5 Universities, >20 partners); EPSRC Centre for Diamond Science and Technology (9 Universities, >20 partners) and Compound Semiconductor Manufacturing (4 Universities, >25 partners). The Unit is part of EU International Training Networks, including the Quantimomy consortium (Kesaria) and multidisciplinary imaging MUSIQ (Langbein/Borri, with Biosciences). These programmes provide excellent platforms to train the next generation of physicists and astronomers working across academia and industry.

**2.8 Equality, Diversity and Inclusion**

Equality, diversity and inclusion are core values and aspirations within the School, which promotes a culture of dignity and respect amongst all staff and research students. We believe this starts with strong role models, at both University and School level. For example in 2018, Holford, Deputy Vice-Chancellor, received a CBE for services to engineering and the advancement of women. Sadler (PERG) was awarded an MBE in 2017 for her work in communicating science, including to underrepresented groups, and Gomez (AG) was awarded an MBE in 2018 for inspiring the next generation of physicists and astronomers by communicating her research to a wide audience. Gomez, Huffaker and Sadler have been members of the Welsh Government Women in STEM committee.

As noted in REF5a, CU was awarded Global Stonewall Diversity Champion in 2019, the top UK University for the fourth consecutive year and 10th in the top 100 employers. It has held the Athena SWAN Institutional Bronze award since 2009 and created a Dean for EDI in 2019, alongside a Dean for Research Environment and Culture. The University has well-established networks for LGBT+ staff and postgraduates (Enfys), BAME staff, carers and working families, disabled staff, Welsh language speakers, and an international staff network. Led by the School, and also including the Schools of Engineering and Computer Science and Informatics, we have a dedicated Women in STEM networking group (TWiSTEM) bringing together those identifying as female across the Queen's Buildings campus with bespoke events (e.g., lunch, seminars, and diversity in physics workshop).

In 2020, the School was awarded **Juno Champion status** by the Institute of Physics (IOP), recognising further progress in EDI following its achievement of Juno Practitioner status in 2015. Since 2012 the School has made it its mission to improve equality and ensure diversity within its staff. As a result of our efforts and recruitments, the representation of females on academic pathways has increased dramatically over the REF period, from three (no professorial) in July 2014 to 13 (five professorial) in July 2020. The overall proportion of female academic staff is 22% (above the national average of 18% given in the Juno benchmark data), and the proportion of female of our staff returned in the current REF is 24%.

The School EDI Committee has continued to gain momentum since its establishment in 2012, and now includes staff, postgraduate and undergraduate representation. The committee meets three times a year, collects data on students and staff every August, and reports regularly on key issues at the informal staff meetings. The Committee chair produces an annual report of all key statistics and interventions which is presented to the School Board each September. University HR data are also being made available to the Committee chair for their annual report, helping identify any trends or areas of concern which need an amendment of our Juno action plan. An EDI Committee member sits on all major School committees.

At the REF census date there are a total of 160 staff, with 31% of those identifying as female. Within those employed on a research only pathway (academic staff and PDRAs) our female proportion is at 28%, which has more than doubled from the level of 11% in 2014. Our administration team has also become more gender-balanced with around 36% male (18% in 2019, 25% in 2018) compared to none at all in 2015. Our technical team is around 19% female compared to 16% in 2015. We have a total of 113 male staff, 12% of whom work part-time, and 52 female staff with 33% part-time. Since 2013, the average proportion of female PhD students has been 36% (with one year at more than 50%), well above the national average of 25%. Our taught postgraduate MSc programmes have attracted an average of 26% females. Combining all categories of staff, there has been a significant increase in both applications and recruitment of female staff over the REF period.

**3. Income, infrastructure and facilities****3.1 Research Income**

Our overall strategy and specific priorities and objectives depend upon healthy and sustainable grant income and, to this end, the Unit has significantly increased research awards over the REF period, with a grant and contract portfolio of over £114M (147% increase over REF2014). Most funding comes from research councils, major UK and European agencies, and industrial contracts,

achieving our REF2014 objective to have a more diverse range of funders. We have targeted longer-term awards as baseline support and continuity for our research groups, e.g., STFC Consolidated grants (£11M) support AG, AIG and GEI research, large EPSRC awards (£23M, including a Manufacturing Hub (Smowton)) support CMP, £10M ERC awards (Consolidator (Gomez, Hannam, Williams) and Starting (Calabrese) grants) across all RGs. These are supplemented with shorter duration grants from the UK Space Agency (£1M) and ESA (£2.4M) for our space astronomy instrumentation development programmes, other project-specific support obtained from the Leverhulme Trust, the Royal Astronomical Society, the Global Challenges Research Funding, Innovate UK, Welsh Crucible, Sêr Cymru, Cancer Research UK, Higher Education Funding Council for Wales, European Regional Development Fund, Biotechnology and BBSRC, alongside independent industrial support from Huawei, IQE and Airbus.

We have achieved our objective of increasing staff numbers (Section 2) through significant research income with STFC Rutherford, Royal Society, EU Marie Skłodowska-Curie, and Sêr Cymru Fellowships (Section 2.3). This has been particularly successful for the AG, being the main route to a doubling of staff numbers since REF2014 and facilitating coverage of the full spectrum of astronomy research and strong connections to other groups in the School with joint appointments. AG Fellows have contributed to significant breakthroughs in astronomy (e.g., the first image of a black hole) and releases of new state-of-the-art simulations, enhancing the School's visibility with a strong presence in the science news (Section 4.3).

Continuous support from a diverse range of funders is crucial to maintain and upgrade the infrastructure and expertise which underpins excellent science. For example, this strategy has provided the continuity necessary for AIG's participation in world-class astrophysics and cosmology projects, such as Ariel, SO, and LiteBIRD, and usage of the AIG's unique technologies in virtually all ground-based and spaceborne instruments at far infrared to millimetre wavelengths leading to front-rank scientific and technical publications. It has also fostered enhanced impact from the MWS meteorological satellite and the new Sequestim spin-out company, which develops and markets novel video-rate THz security systems, based on unique AIG detectors, filters, cryogenics, optics and data processing technologies invented for astronomy instruments.

To facilitate our strategy to develop a compound semiconductor research and manufacturing cluster we have invested in infrastructure, equipment and expertise through support from sources including the Welsh European Funding Office (£37M) and EPSRC (£2M). The former provides advanced equipment for semiconductor fabrication, long-term support for expert engineers and technicians, and for business development staff. The benefits are seen in high-impact, cross-disciplinary publications on electronic devices, biomarkers, photonics and a number of patents and translation. This is exemplified by the announcement (June 2020) of the £42M Strength in Places project (Smowton PI) to develop a compound semiconductor powerhouse in South Wales. This builds further infrastructure, expertise and interaction with, and translation of research results to, industry. It will consolidate the lobbying for high-value science and for outreach to schools and educational bodies such as Technquest, funded by ICS and the EPSRC Manufacturing Hub.

A 2017 University investment creating the GEI, and large and long-term awards (ERC, STFC and Leverhulme) have facilitated our strategy to expand staff numbers to incorporate all areas of gravitational wave research: experiment, data analysis, numerical modelling, astrophysics and multi-messenger astronomy. The group played a significant role in the first observations of gravitational waves and in the continuing exciting developments. With the 2020 award of a STFC/EPSRC £4M Quantum Technology grant led by GEI experimentalists and involving a UK-wide consortium, the GEI is now also at the forefront of future technological applications of GW interferometry in quantum and optical physics.

UOA9 has won over £63M contributing to research across multiple departments, demonstrating that Physics is driving multi- and interdisciplinary research. Examples include understanding the interface between diamond and aluminium nitride to facilitate diamond heatsinks for nitride-based RF electronics (Physics and Astronomy and Engineering, EPSRC program grant) and developing non-linear optics for microscopy of cells (Physics and Astronomy and Biosciences, EPSRC and BBSRC). The BIG exemplifies the interdisciplinary research culture embedded in the School,



including development of data curation systems for brain imaging facilities using practices developed for space astronomy missions (joint with AIG).

Academic staff, and in particular ECRs, are strongly supported in grant applications by the School and the research groups via announcement of upcoming grant calls in the Research Bulletin; active planning with line managers, including in PDRs; sharing of successful applications; review of ideas and proposals at the RG level as well as by the DoR; and by expert administrative support during the preparation and running of grants.

### **3.2 Operational and scholarly infrastructure and facilities**

The investment in the ICS (Sections 1 and 3.1), comprising a semiconductor fabrication facility for up to (currently) 150-mm wafers, is operated as a TRAC facility with open access (e.g., supporting AIG, CMP and industrial partners such as IQE) and with nine permanent support staff. Similarly, some of the Sêr Cymru investment (Section 1) in epitaxial growth (a serviced MOCVD reactor, based in IQE, and associated characterisation capability) is operated as TRAC, with supervised open access. Further related equipment such as twin chamber MBE (Sêr Cymru) and the Cardiff Diamond Foundry (four CVD growth reactors) are operated by academic experts in a collaborative fashion. It is School policy that facilities and equipment are shared, to improve efficiency and collaboration between groups and other Schools; all new equipment is listed within a centralised University database with contact points and access costing. For example, the University invested £300k in a dilution refrigerator, which has been operated as a shared resource by AIG and CMP and which has facilitated an ERC grant (Williams), three EPSRC grants (Giblin x2, Klemencic), an InnovateUK grant (Giblin and Klemencic), and industrial users such as SeeQC UK to observe a several Qubit system.

The Unit has benefited from the University Research Infrastructure Fund (RIF), allocated on a competitive and strategic basis, targeted towards facilities with potential to enhance research excellence, and supporting interdisciplinary research across the University (see REF5a). Since REF2014, RIF awards of £2.3M supported a new experimental gravitational wave laboratory, a diamond chemical vapour deposition system, a two-photon laser lithography installation (to create structures to observe magnetic monopoles), and infrastructure for the Compound Semiconductor Manufacturing CDT (complete training cleanroom fit-out). Other RIF-funded facilities supporting research in the Unit during this REF period include a Raman/photoluminescence system based in the School of Chemistry and an advanced electron microscopy suite, based in the School of Earth and Environmental Sciences, which serve our joint quantum technologies, advanced materials and biological sensing efforts. These RIF-supported investments have already led to significant new funding, including large EPSRC grants such as the GEI-led STFC/EPSRC Quantum technology grant, and industrial contracts.

The AIG has expanded the filters and metamaterials facilities for development and production of its unique optical components via a £1M contract with the Simons Observatory (SO). These new facilities support the increased demand from SO and provide crucial improved infrastructure for delivering devices to many other current and future CMB collaborations (such as CCAT-prime and CMB-S4). The School has supported this strategic participation by covering the Cardiff SO institutional membership (£94k).

Research is supported by a dedicated and highly skilled technical team, including three full-time machinists in our mechanical workshop, and two highly experienced mechanical design and manufacturing engineers in a dedicated AIG workshop. Both workshops are equipped with multiple CAD/CAM systems and jobs are moved between shops based on need and to expedite turnaround. A separate electronics workshop is staffed by two highly skilled and experienced electronics technicians, complemented by two newly recruited apprentices, and we have multiple vacuum and clean room specialists and process engineers working with ICS and AIG. The School's Technical Services Manager liaises with commercial suppliers and the University Estates division to support equipment installations and maintenance. Technical staff help drive the work of the RGs. For example, AIG engineers are critical to the group's involvement in major international projects, liaise directly with external collaborators, and have been recognised by the University through Outstanding Contribution awards.

The Unit has several computationally-intense research areas such as simulations of star formation, cosmology and gravitational wave physics which benefit greatly from access to the University's Advanced Research Computing at Cardiff (ARCCA) and Supercomputing Wales (SW) (see REF5a). ARCCA provides high performance computing and support for University researchers who need additional computing power and, during the REF period, has been extensively used by GEI, AG and AIG members. For example, GEI's contribution to gravitational wave results has been enabled by STFC-funded computing (over £1M) operated at ARCCA and a dedicated research software engineer funded by SW.

The University Library provides access to over 1.1m items with an annual budget of £6.4M, and electronic journal access from work or home, based on University subscriptions, is available to all staff. A University librarian liaises with a School-designated academic as library point of contact to ensure rapid response to changing requirements such as purchases of support materials and books.

During this REF period, renovations to infrastructure were undertaken, aligned to promotion of our EDI ambitions. Male-only toilets were converted in several areas of the building to easy access and unisex facilities, as requested by disabled and female staff, a lift was upgraded to accommodate a powered wheelchair and occupant, and hi-vis stair nosings were fitted at the main entrance to improve contrast for partially-sighted building users.

### **3.3 Professional services, contracts and impact support**

Academic staff are supported in the preparation and costing of grant proposals and contractual arrangements locally by the School Manager and two Finance staff, and at University level by Research and Innovation Services, including a dedicated European Office. In particular, the specialised and locally knowledgeable School financial and administrative staff ensure that the relevant aspects of grants are well-supported at the proposal stage and, when awarded, with accurate and up-to-date information about expenditure and commitments provided regularly to PIs. Group- and activity-specific grant-funded Programme Managers (three full time) and Programme Administrators (one full, two part time) organise and manage portfolios of grants. For the AIG's programme manager this includes national and international consortium-level management roles (otherwise national). Local administrators also provide expert HR support for recruitment and staff contract management supplementing University support.

IT facilities and computational research are supported by the University IT service, and project-specific IT support is requested on research grants when appropriate. The School has a policy of bringing in and training young apprentices in electronics, IT and other support areas (e.g., mechanical and electronics workshops) with two current apprenticeships. This resulted in follow-on internal positions for the two staff within the REF period.

The University Commercial Development and Contracts Teams provide support for all aspects of research-related contracts and spin-out companies, including consortium agreements, sub-contracts, confidentiality agreements, intellectual property, and work closely with our local research administrators and grant PIs. Further University support is provided by the Business Incubation team. The Unit has received almost £400K in University-administered STFC and EPSRC Impact Acceleration funds during the REF period used to support brain imaging data curation (STFC IA award to foster the deployment of astronomical observatory-style data archiving for brain imaging facilities) and THz video camera development (facilitating the spin-out of the Sequestim company).

### **3.4 Major benefits in-kind**

UOA9 researchers have been awarded significant access to facilities, equating to more than £2.7M, during the REF period. These are crucial to deliver our research goals and include: more than 1400 hours of observing time on highly-competitive telescope programmes such as JVL, IRAM, GBT, NOEMA, CARMA, VLA, NASA Swift; synchrotron beamtime at several facilities, including 35 days at the Advanced Light Source (Berkeley) and PSI; and computer time allocation at NERSC (Berkeley) and Della (Princeton).

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

##### **4.1 Research collaborations, networks and partnerships**

During the REF period, the Unit has strengthened and established new leadership or major roles in many large international consortia. Examples of strategic astronomy leadership include: a consortium of UK universities led by Cardiff (Eales PI) that has bought a share of the observing time on the JCMT; a large astronomical survey aiming at discovering the transient Universe (ePESSTO+, Inserra PI). Notable examples of the AIG leadership in worldwide projects and space missions such as *Herschel*-SPIRE Post-Operations 2014-16 (from Cardiff's leadership of the SPIRE instrument, Griffin PI); *Planck* HFI (Calabrese Core Team member of final cosmology release); the ARIEL exoplanet characterisation satellite (Griffin UK Co-PI); LiteBIRD (Calabrese and Pisano UK coordinators and Calabrese also European Deputy Spokesperson); the SO CMB experiment (Calabrese Science Chair); and the MUSCAT camera for the Large Millimetre Telescopes (Doyle PI). The GEI has influential management positions in world-leading collaborations (e.g., Fairhurst Executive Committee member and Program Committee Chair of LIGO, Dooley LIGO Academic Advisory Committee Co-Chair), and significant involvement in planning for future observatories (LISA space mission, Einstein Telescope). In CMP, Huffaker's appointment was a crucial component in the development of the ICS, Smowton leads research and training consortia across the Universities of Manchester, Sheffield and UCL, and 27 partner organisations, including IQE, National Physical Laboratory and CSC Ltd., where he is a Director.

In addition to multidisciplinary research described in Sections 1.5 and 3.1, collaborations with other CU Schools are fostered by topical research networks. Examples include: a cross-department multidisciplinary network on materials science, the Cardiff Materials Network (13 UOA9 academics participate); and participation in DIRI with Calabrese and Inserra (DIRI Ambassadors from the Unit) leading a Special Interest Group on unveiling and predicting data patterns.

##### **4.2 Relationships with key research users, beneficiaries and audience**

Recognising the importance of disseminating research activities and outputs to the scientific community, UOA9 members are very prominent at international conferences. During the REF period, UOA9 academics from all career stages organised/chaired 42 major conferences (e.g., the European Week of Astronomy and Space Science in 2015 and 2019 (Clark, Inserra), International Semiconductor Laser 2014 and Laser Electro Optics 2015-18 (Smowton), the American Physical Society meeting 2014 (Giblin), the European Material Research Society and MRS conferences 2019/2020 (Williams)), and have delivered 83 keynote/invited lectures at international conferences, including plenaries at the 25<sup>th</sup> Semiconductor Laser Conference 2016 (Smowton), Cosmo19 2019 (Calabrese), 66<sup>th</sup> Diamond Conference 2016 and Diamond D Day 2019 (Williams), ECR keynote talk at the Euclid Consortium Meeting 2017 (on invitation, Inserra).

The many international collaborations we are part of involve regular meetings. Active participation in these is of strategic importance to advance research collaborations and Cardiff visibility within them. To promote this, UOA9 academics have organised annual meetings of LIGO/VIRGO and SO, and hosted LiteBIRD and LSST:UK meetings in Cardiff. UOA9 researchers have also stimulated collaboration and knowledge exchange by organising several conferences and symposia in Cardiff (with 40 to 100 participants), including the annual "Semiconductor and Integrated Opto-Electronics (SIOE) Conference", the biennial bio-nano-photonics conference in collaboration with Biosciences; cooling electrons below 1 mK for novel physics (Institute of Physics); SPACEKIDS (AIG-led EU FP-7 project to develop kinetic inductance detectors for space applications) and Galactic Formation workshops. School funding has covered staff attendance and organisation of some of these meetings.

The research groups run dedicated seminar series (including online seminars during Covid-19) with external speakers from the UK and abroad, and also hold regular internal group meetings and journal clubs. There are cross-School, cross-College seminars and series with Bremen and Xiamen Universities.

##### **4.3 Examples of wider contributions to Economy and Society**

Public engagement is of key importance for the Unit. UOA9 academics, together with other School members, under the coordination of the School's Head of Public Engagement, North (Section 1),

have run successful and substantial programmes. The Cardiff-led *Universe in the Classroom* project (see impact case) targeted schools less likely to engage with science education, specifically those in rural areas, with more students in poverty, and lower educational attainment. It involved training of undergraduates and postgraduates as Stellar Role Models (STARS) able to attend Welsh primary schools and communities with our 0.4-m robotic telescope, sparking curiosity about the Universe in young children. STARS also count towards the Cardiff Award Scheme, which recognises extra-curricular activities and focuses on students' professional development. A number of large-scale outreach activities (e.g., *Physics Mentoring Project*, *UniverseLab*, and *Our Space Our Future*) have attracted over £1.5M in funding since 2016, from Welsh, UKRI, and EU funding sources, and involve staff and students from Cardiff and other universities, reaching out to the general public and school students across the UK (~43 million people with TV and radio interviews, and 16,000 school children during the REF period). Other public engagement activities include: physics and astronomy presentations to school groups and a Christmas Lecture pitched at GCSE students; participation in scientific fairs and festivals, including *Big Bang UK*, *Big Bang Cymru*, *Cheltenham Science Festival*, *the Eisteddfod*, *the Cardiff Science Festival*, and *the Diamond: more than a gemstone Royal Society 2016 Summer Science Exhibition*; taking science directly to the community with our *Science Busking* programme and *Pint of Science* (total public talk audience 20,000). We have also run a series of inspiring outreach seminars given to the public by prestigious scientists collaborating with UOA9 members, including 2017 Physics Nobel laureate Kip Thorne (live: 450 people, including 90 school children, YouTube views: 263,000). Our staff have made many appearances in high-profile mainstream media outlets including *The New York Times*, *The Financial Times*, *The Guardian*, *BBC News*, *BBC Wales News*, and *Sky News* on gravitational waves, astronomy (e.g., the potential discovery of phosphine on Venus), cosmology and diamond research. Research results produced by School members have also been highlighted on *BBC News*, *El Pais* and many other international web/paper journals, which covered 38 School research results during the REF period (total media: 60 million).

Impact on economics and wider society has been achieved via industrial applications of our research and partnerships, built on the strategy defined in Section 1.4. The interaction with semiconductor companies such as IQE, Newport Wafer Fab and CSC demonstrates the value of the School of Physics and Astronomy to the manufacturing economy - e.g., with IQE via an Innovate UK Knowledge Transfer Partnership on the rapid fabrication and characterisation techniques for novel CS products. Lynch is seconded for two days a week to the CS strand of a £1.3M HEFCW-funded project supporting industry in the region to address skills gaps and leading to School to PhD level provision in CS relevant skills across FE and HE. Beggs is also seconded to teach a continuing professional development course to 80 staff at Newport Wafer Fab helping to reposition the company in the CS field. Connections with industrial partners are also enhanced with over 20% of the UOA9 academics acting as consultants to industry. For example, Williams collaborated with 4K-MEMS on ultra-high temperature materials (also funded by EPSRC New Horizons) and Photonis on negative electron affinity surfaces for enhancing night vision, and our design of a low-cost diamond growth reactor (Williams, Mandal, Thomas) developed under EU FP7 "WASPS" which is now in use by eVince Technology as "one of the key in-house tools we use for several steps in the manufacturing process". This project led to the employment of 10 people, over £2.1M in financial angel funding and over £1M in grants/project income (Eurostars, ESA, Innovate UK). Surface acoustic wave devices demonstrated by the Cardiff Diamond Foundry are being developed by Huawei for 5G base stations. The ERC "SUPERNEMS" project led to a patent on virus filtration and a high frequency AC susceptometer which is currently being sold by the company RI.SE. AIG members (Ade, Doyle, Hargrave, Tucker) lead key applications of the group technology for spin-out companies (see impact cases).

#### **4.4 Contribution to the sustainability of the discipline**

To maintain the vitality and the high standard in research and teaching of the discipline, 32% of UOA9 academics have been external examiners (e.g., Tucker for the University of Maynooth Experimental Physics, Griffin for QMUL Astrophysics MSc, Smowton for St Andrews and Heriot Watt Optoelectronics MSc, Williams for UCL Nanotechnology MSc). UOA9 academics are also prominent on national and international advisory boards/committees, policy-making and research management bodies, and panels across the physics and astronomy disciplines. Examples include: EPSRC National Centre for III-V Technologies steering committee (Smowton); the UKSA Athena



PMB, Euclid Science Review Team, and ESA Euclid Independent Science Review Panel (Griffin, chair); and STFC Projects Peer Review Panel (Hargrave, Pisano); major leadership in collaborations proposing and developing new projects and facilities (Section 4.1), and helping research councils to establish future research priorities (e.g., LiteBIRD:UK and SO:UK for the 2018 STFC priority project call, Calabrese). UOA9 academics contribute to funding peer review, with many (e.g., Buckle, Calabrese, Fairhurst, Gomez, Griffin, Inserra, Matsuura, Sathyaprakash, Schutz, Smowton) serving on national (EPSRC, STFC, UKSA, Royal Astronomical Society, and REF2021) and international (e.g., Chinese Academy of Sciences, NASA, ESA, the European Commission, the University College Cork, LISA, LIGO, VIRGO) research programmes, review and funding panels.

Our researchers have contributed to current knowledge of the discipline and shaping future research panorama with textbooks and white papers. Books include: *Nanodiamond* (Williams), *Equations in Relativistic Gravity* (Schutz), *Inventing a Space Mission: The Story of the Herschel Space Observatory* (Griffin co-author) and *Gravitational Waves: A History of Discovery* (Grote). Book chapters include *Novel Aspects of Diamond* (Williams, Mandal), *Handbook of Supernovae* (Matsuura) as well as special issues in the IEEE Access (*Neural Engineering Informatics*, Beltrachini) and the IET Optoelectronics (Smowton, Beggs, Oh, Li). White papers include: *Astronomy 2030* (Matsuura lead author, Gomez and Inserra), ngVLA white paper (Davis), four Astro2020 Decadal Survey papers (Calabrese), and Origins Space Telescope ESA Voyage-2050 white paper (Griffin).

All academics contribute to the fundamental process of peer review for scientific journals. During the REF period, School members have also held senior editorial board positions: Griffin is editorial board member of the *Journal of Astronomical Instrumentation*, Fairhurst of the *International Journal of Modern Physics D* and *Classical and Quantum Gravity*, Smowton of *Semiconductor Science and Technology* and *IET-Optoelectronics*, Ladak of *Scientific Reports*; Williams is an associate editor of Elsevier's *Diamond and Related Materials*; Schutz is the founder and editor-in-chief of *Living Reviews in Relativity*; and Dunne is an Associate Editor of *Royal Society Open Science*.

#### **4.5 Indicators of wider influence**

More than 20 academics (e.g., Huffaker, Schutz) are members/fellows of international or learned societies, including the Institute of Physics, the US National Academy of Sciences, the International Society on General Relativity and Gravitation, the American Physical Society, and the Learned Society of Wales.

UOA9 researchers have received high-profile awards both as individuals and as members of consortia. International awards include: Special Breakthrough Prize 2016, Gruber Foundation Prize in Cosmology 2016, Princess of Asturias Award for Technical and Scientific Research 2017, Einstein Medal 2017, and Bruno Rossi 2017 (Schutz, Raymond, Sutton, Fairhurst/LIGO & Virgo Collaborations); MBE (Gomez, 2018); Gruber Foundation Prize in Cosmology 2018, Marcel Grossmann Award 2018, and European Physical Society Giuseppe and Vanna Cocconi Prize 2019 (Ade, Calabrese, Sudiwala/Planck team); Honorary Doctorate, Aix-Marseille University (Griffin, 2018); Richard Isaacson Medal of the American Physical Society (Schutz, 2020); Buchalter Prize in Cosmology (Sathyaprakash, 2020). UK awards include: RAS Group Achievement Awards (Griffin/SPIRE Team, 2014, and Ade, Calabrese, Sudiwala/ Planck Team, 2018); RAS Fowler Prize (Gomez, 2015); RAS Herschel Medal (Eales, 2015); RAS Winton Capital Award (Inserra, 2017); IOP Fred Hoyle Silver Medal (Greaves, 2017); Philip Leverhulme Prize (Dooley, 2018); RAS Eddington Medal (Schutz, 2019). This long list of awards includes several UOA9 members new since REF2014 and at different career stages (e.g., the Fowler prize for Gomez in 2015 recognized her early career achievements), highlighting the Unit's upwards trajectory of generating impact and success in the fields of physics and astronomy.