Institution: Swansea University
Unit of Assessment: 09 Physics

Section 1: Unit Context and Structure

1.1 OVERVIEW OF DEPARTMENT STRUCTURE

The Department of Physics at Swansea University is a rich, integrated, and connected research ecosystem encompassing the core activities of the modern discipline with considerable interdisciplinarity across science, engineering, and medicine. The research portfolio encompasses a balance of experiment and theory, ranging from fundamental studies such as elucidating the properties of matter and antimatter and the origins of the universe, to applying knowledge to solve societal problems, including developing materials for clean energy or spectroscopic biomarkers for cancer and dementia. Our research fuels and benefits from close connectivity with regional, national, and international partners from industry, government, the third sector, academia and our local community including NHS Wales. The *Swansea Physics 2020 Research Environment* has evolved with deliberate strategic intent from REF2014 and delivers a modern vision of the discipline, supporting undergraduate and graduate training, delivering high quality research with impact across physics and beyond, addressing societal challenges and serving the community.

The Department has 26 (25.2 FTEs) category-A academic staff. There has been an increase of over 30 research and academic staff 2014-2020. The research portfolio (**Figure 1**) is arranged into three groups with distinct but complementary activities.

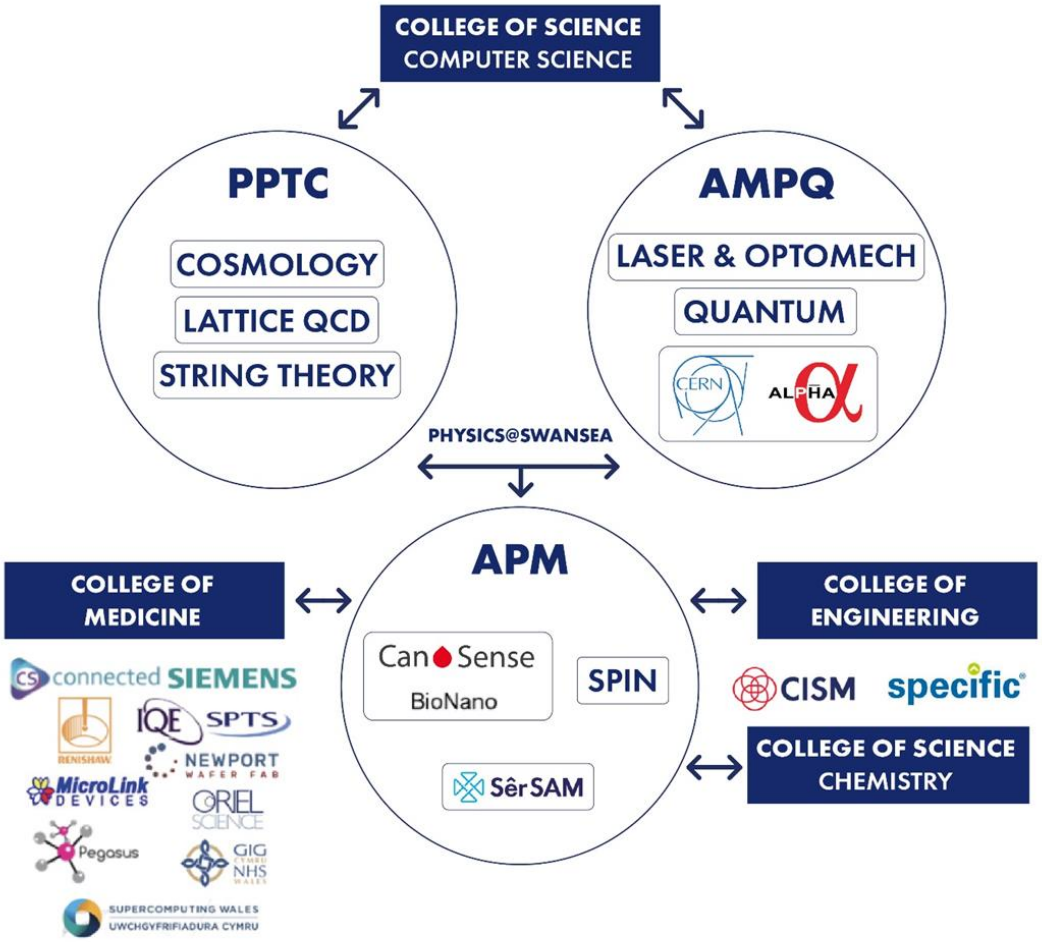

Figure 1. *The Department comprises three interconnected groups with strong links to cognate disciplines across the University, as well as CERN, NHS Wales, SuperComputing Wales and regional, national, and multi-national companies. Community engagement and communication are facilitated by Oriel Science, and impact through start-up and commercialisation outputs.*

Particle Physics and Cosmology Theory (**PPCT**): an established group with activities in quantum field theory, lattice quantum chromodynamics, and theoretical cosmology with the aim to uncover fundamental descriptions of matter and forces at the smallest length scales, and exploiting developments in high-performance computing, data science, and machine learning.

Atomic, Molecular and Quantum Physics (**AMQP**): a core group focusing on antimatter physics, including a major presence at CERN in the ALPHA collaboration, and specialist local facilities such as the slow positron beamline, which has recently expanded activities into laser physics, optomechanics and quantum control.

Applied Physics and Materials (**APM**): an expanding group with activities encompassing Sustainable Advanced Materials (Sêr SAM), semiconductor physics and medical spectroscopy. There is considerable overlap between these activities driving intra- and inter-department collaboration across the University (e.g., SPECIFIC in Engineering, CanSense in Medicine), and a large external partner base including regional and national industry.

Physics is one of six departments in the College of Science and benefits from pooled resources for finance, administration, technical and research support. Further operational support is provided by considerable programmatic funding (see **1.2**). Departmental research governance is managed though representation on the College Research Committee. Likewise, postgraduate research training and progression is overseen by the College Post-Graduate Research (PGR) Committee with a Physics PGR Director (see **2.2**).

1.2 EVIDENCE OF ACHIEVEMENT OF STRATEGIC OBJECTIVES OF REF2014

In accordance with the vision set out in REF2014, the Department has implemented a co-ordinated strategic plan with the following objectives:

OBJ1: Increase the quality and scale of research in existing core areas (PPCT and antimatter).
OBJ2: Diversify research with a focus on applied physics (APM).
OBJ3: Drive multidisciplinary research and closer engagement with industry.

Table 1 provides a 'snapshot' of the *Research Environment 2014* versus *2020* highlighting progress in achieving these objectives.

OBJ1 PPCT's activities have expanded dramatically through new staff appointments and fellowships (See sections **2** and **4)**. New research areas including high-performance computing and AI have enhanced and diversified grant capture (e.g. Science and Technologies Facilities Research Council [STFC] Consolidated Grant, Laser Interferometer Space Antenna [LISA] Consortium). The award of two Centres for Doctoral Training (CDT) has doubled postgraduate studentships: the STFC CDT in Data-Intensive Science currently funds 20 PhD students in particle physics, astronomy and cosmology at Bristol, Cardiff, and Swansea; and the Swansea-led UK Research and Innovation (UKRI) CDT in Artificial Intelligence, Machine Learning & Advanced Computing (AIMLAC) will train 55+ PhD students at Swansea, Cardiff, Bristol, Aberystwyth and Bangor. Both CDTs are supported by multiple industrial partnerships (**OBJ3**).

Table 1: *Swansea Physics Environment 2020* vs *2014* shows progress on REF2014 objectives.

Metric	REF2014	REF2021	Increase
Cat-A Academic Staff (FTE)	21	25.2	20%
Research Staff (FTE)	15	27	80%
PhD's Awarded (REF4a)	31	50	61%
Cat-A/research/ PGR staff (New Areas)	0	6/9/22	N/A
Grants Awarded	£13.2M	£22.5M	70%
Research Income (REF4b)	£ 9.1M	£11.9M	30%

Research Income In Kind (REF4c)	£108K	£1.26M	Significant Increase
Publications (Nature Suite)	~520 (2)	>800 (18)	>55% (9x)
Industry Partners	5	>50	10x
Grant Funding Bodies	~5	20	4x

Antimatter research has flourished as the ALPHA experiment transitioned to its exciting delivery phase, supported by numerous Royal Society, Leverhulme and Visiting Fellowship Awards, and considerable Engineering and Physical Sciences Research Council (EPSRC) grant income (total ~£10.5M). This scaling of activity is reflected by research outputs of over 50 high quality journal papers including 10 *Nature Suite*. The group's international prominence is highlighted by it being featured in 'Pioneer 14', the EPSRC's 20-year celebration publication.

OBJ2. Three academic staff were appointed to AMQP in the expansion areas of laser physics, optomechanics and quantum control. A European Research Council (ERC) Starter Fellowship has enabled AMQP to consolidate existing EPSRC funding and tap into new sources including Intelligence Advanced Research Projects Activity (IARPA), ERC and national facilities such as the Diamond Light Source. This expansion activity has resulted in considerable grant income (>£1M) and publications in high quality international journals.

An important achievement has been the creation of the APM group, which has grown to six academic staff, eight research staff and 22 PGR students (10 completed, 12 current), fuelled by the award of a Sêr National Chair and Rising Star Fellowship within the ~£6M Sêr SAM Programme Grant (ERDF 2017). This funding has enabled the deployment of experimental facilities for electro-optical materials and devices, and had led to 47 journal publications (since 2017) including eight in *Nature* and *Science* suites and over £50M in grants awarded. Group members are investigators on grants from diverse sources (Industry Strategy Challenge Fund (ISCF), EU, EPSRC Programme and Strategic Equipment, Research England, industry) and fellowships (COFUND, 1851). Biomedical research in APM, focused on development of new methods to positively impact healthcare (**OBJ3**), has also expanded. These activities have benefited from the award of several fellowships (Royal Society, Institute of Physics [IOP] and have attracted funding from diverse sources (EPSRC Platform, EU Networks, Cancer Research Wales & UK, NHS). Impact from this research has been significant (**1.3**) with the 'cancer diagnosis using Raman spectroscopy' project receiving multiple awards (e.g. Research Excellence in the NHS Award) and the subject of commercialisation.

OBJ3 Multidisciplinarity. Growth and diversification have been accompanied by significant expansion of multidisciplinary activities in AI and high-performance computing; next generation semiconductors with applications from solar cells to bioelectronics; and biomedical research from bio-photonics to Raman spectroscopy to MRI. Evidence of maturing impact includes:

- Publications in physics, maths, chemistry, computer science, engineering, materials science, and biomedical journals.
- Large-scale patient trials of a blood test for colorectal cancer in 35 GP surgeries across Wales and Good Clinical Laboratory Practice Accreditation for the Centre for Nanohealth.
- Increased participation and grant capture in multi-institutional programmes such as EPSRC Program Grants, EU Networks, ISCF Strength In Places Fund (SIPF) and CDTs.

OBJ3 Industry Engagement. Increased multidisciplinarity has driven a natural expansion of industrial partnerships. Tangible examples include: 12 industrial co-investment partners in the Sêr SAM-led initiative Centre for Integrative Semiconductor Materials (CISM); six industry partners in the Cardiff University-led ISCF CS Connected SIPF project; 11 industry partners in the Swansea-led EPSRC Program Grant on Application Targeted Integrated Photovoltaics [ATIP] (Sêr SAM, SPECIFIC IKC); and partnerships with Renishaw and Siemens in the development of biomedical imaging and spectroscopy.

The aggregated impact of this progress and growth can be seen in key metrics. For example, during the census period the Department's research grant expenditure has increased by 71% (by

value) and the PGR cohort doubled. The Department's research output surged to >800 publications (18 *Nature* suite) with a field-weighted citation impact score of 1.8, i.e., 80% above the global average, 194 (24.2%) of which are in the top-10% of most-cited publications, and 437 (64.6%) in the top-10% of journals according to *CiteScore*. The enhanced research environment has been a catalyst for interdisciplinary, international, and industrial collaboration with 54.8% of outputs involving international collaboration (citation impact 114% above the global average) and 67 outputs involving industrial partners. In summary, clear objectives and a coherent strategic plan (**1.3**) flowing from REF2014 have driven substantial enhancement of the UoA9 research environment at Swansea, which has created a more sustainable Department and improved the quality and breadth of undergraduate training.

1.3 RESEARCH AND IMPACT STRATEGY

1.3.1 Overall Research Strategy (Figure 2).

Drawing a baseline to REF2014, the core strengths of UoA9 at Swansea were Particle Physics and Cosmology and theoretical and experimental efforts in Antimatter. Arguably, this was too narrow a focus for a modern physics discipline, limiting scope for industrial engagement and broader multi-disciplinary impact. The overall Research and Impact Strategy for the UoA was thus to protect and grow the core while sustainably diversifying. This vision is reflected in the objectives **OBJ1-3** (stated in **1.2**) and underpinned by specific goals with targets relating to research capacity, funding, outputs and impact, and broader engagement. As described in **1.2** and illustrated in **Table 1**, these goals have been achieved and largely exceeded.

1.3.2 Specific Research & Impact Strategies

A portfolio of strategies were implemented during the census period to drive delivery of these goals, support multidisciplinary and enhance impact and engagement:

I. Strengthening core groups with targeted academic appointments and a coherent Fellowship strategy, yielding expansion in new directions in PPCT (cosmology and gravitational wave astronomy) and AMQP (lasers, optomechanics and quantum control).
II. Creating the APM group through major external programmatic funding (Sêr Cymru) and joint and visiting appointments.
III. Pursuing multidisciplinary partnerships to diversify and increase the funding base and deliver impact outside the UoA (ISCF, SIPF).
IV. Enhancing industry engagement with regional and national stakeholders (e.g., the South Wales semiconductor industry) and collaborations with industry-facing programmes within Swansea such as SPECIFIC.
V. Promoting impact-focused commercialisation efforts through industrial fellowships, seed corn funding (e.g., SURGE, see **REF5a, Sec 2.5**) and innovation training (see **2.1**).
VI. Increasing graduate student numbers and quality (see **2.2**) via a focus on forthcoming CDT opportunities and regional industry studentships such as Knowledge Economy Skills Scholarship (KESS).
VII. Continuous monitoring of progress versus targets and transparent communication on matters such as REF preparations.
VIII. Building of Departmental cohesion, identity and focus by promoting inter-group collaborations, joint seminars, and journal clubs, undergraduate PhySoc, etc.

1.3.3 Contribution of and Rationale for Impact Case Studies.

The UoA9 Impact Case Studies reflect the progress made in diversification and increased engagement during the census period:

1. *Raman Spectroscopy diagnostic application to colorectal cancer (APM)*: A blood test to replace a significant number of colonoscopies as a first stage screening tool for colorectal cancer. Trials involving several thousand patients are already underway and a start-up company has been running since 2018 (CanSense).

2. *BSMbench (PPCT):* A software suite that measures the speed of high-performance computer equipment to enable both vendors and buyers to assess different machines and see which are best value for money.
3. *Oriel Science (Cross-departmental, including the 'Wales at CERN' programme from AMQP)*: Oriel Science showcases Swansea's research in the community to extend the educational horizons of the Future Generation. It has been involved with 100 events and engaged with over 150,000 people since 2016.

These Studies exemplify the broad scope of the Swansea Physics 2020 Research Environment including our close industry engagement and connectivity with the public and other stakeholders such as the NHS. All three research groups are represented in the Studies, a clear indicator that the UoA has achieved its vision of a balanced and diverse portfolio.

1.3.4 An Open Research Environment

In addition to delivering impact, engagement and interdisciplinarity, the above strategies were also designed to provide a framework for an open research environment built on transparency and flexibility, compliant with the EU plan-S open access agenda, specificially:

i) Ensuring access to the UoA's research for a wide range of stakeholders by implementation of open access publication requirements via institutional repositories (CRONFA) and pre-print archives [Strategies III-IV].

ii) Providing an adaptive environment able to respond to changing opportunities, with two-way communication between the UoA and internal and external stakeholders [Strategies III-VI];

iii) Promoting clear communication of progress and strategies and sharing of collective responsibilities and rewards [Strategies IV, VII and VIII].

Research staff have ORCID IDs, and are encouraged to have GoogleScholar profiles, post preprints to open-access repositories (arXiv, ResearchGate, Academia, etc.), and publish datasets and code via appropriate repositories from FigShare to github.

1.3.5 Reproducibility, Responsible Research & Innovation (RRI) and Ethics

As described in **REF5a** Swansea University has developed a *comprehensive Research Integrity Policy Framework* which outlines the institutional approach to research integrity and provides the underpinning policies on governance. The Department has adopted these institutional principles with a view to creating an open and informed environment. Additional elements of the UoA9 Research Environment that overlay these institutional responses include:

- Mandatory training for all research active staff and PGR students
- Implementation of Transparency and Openness Criteria by Centre for Open Science
- Maintaining data redundancy to protect against loss or corruption of data
- Inclusion of research materials in institutional repository of outputs alongside research articles to ensure authors receive proper credit for all intellectual contributions
- Completion of ethics forms for all projects and plagiarism analysis in written reporting such as journal papers and PGR theses.

A particular feature of UoA9 during the census period has been a widening of the research portfolio into areas with diverse ethical and RRI considerations – for example medical trials, large multi-disciplinary programmes, and projects with considerable industry content. This will continue to require the principles outlined above to be firmly embedded in the UoA9 Research and Impact Strategic Plan.

Figure 2: *Research and Impact Strategy showing the clear relationship between initial objectives and 2020 outcomes using Institutional, Departmental and Group-level strategies.*

1.4 FUTURE STRATEGIC AIMS AND GOALS FOR RESEARCH & IMPACT

The UoA's Research and Impact Strategy 2020–2025 builds upon the substantial achievements described in **1.1 - 1.3** with the overall aim of exploiting the maturing, diversified research activity to deliver enhanced impact. The specific objectives for the forward Strategic Plan are:

OBJ1N: Create new, internationally-significant research infrastructure in key areas.
OBJ2N: Deliver major new research programmes in all areas (EPSRC Programme Grants, STFC Consolidated, ALPHA, CDTs).
OBJ3N: Drive impact through commercial and industry-focused activities (CanSense, SIPF, ISCF Driving the Electric Revolution [DER]).

These objectives will be addressed by a major restructuring of the University into new Faculties. Being part of the new Faculty of Science and Engineering presents considerable opportunities for multidisciplinary collaboration. Each of the three research groups have specific scientific goals and strategies underpinning the delivery of these objectives:

PPCT

1. Renew STFC Consolidated Grant, leveraging links with the CDTs to expand research collaborations with other research organisations and companies.
2. Expand collaborations with quantum information activities, e.g., applying lattice quantum chromodynamics (QCD) methods to quantum simulation and developing new interpretations of information loss in black holes.
3. Make significant contribution to international LISA consortium, a long-term, internationally significant collaborative endeavour and flagship for Swansea PPCT, by leading projects, particularly involving investigations of how gravitational wave detectors can probe the properties of primordial gravitational waves from cosmic inflation.

AMQP

4. Grow antihydrogen research efforts in the world-leading ALPHA collaboration with a permanent presence at CERN complemented by an expansion of the local infrastructure and expertise at Swansea in low energy positrons and laser spectroscopy.
5. Exploit new opportunities and synergies with APM, e.g., in deep UV photodetectors.
6. Expand collaborations with engineering in areas such as positron annihilation spectroscopy (PALS) and Doppler broadening spectroscopy (DBS).

APM

7. Deliver new CISM facility (mid-2022) [**Figure 3**] and progress its inclusion in major national facilities propositions such as the Henry Royce Institute and EPSRC National Epitaxy Facility (discussion already advanced in both cases).
8. Successfully complete the Sêr SAM program (end-2022) and transition advanced materials research to the CISM facilities and activity portfolio.
9. Lead the delivery of cross-university programmes (detailed in **3.1**) including: EPSRC Programme Grant ATIP; ISCF, SIPF, CS Connected; ISCF DER; Aerospace Technology Institute *HiDASP* and provide underpinning UoA9 support for major new EU funded programmes such as ASSET and FLEXIS.
10. Grow APM funding base by targeted bids such as CDT in Semiconductor Technology; EPSRC Manufacturing Hub; ISCF DER and Advanced Propulsion Centre CRD.
11. Translate research successes in healthcare (e.g. development of AI-based spectroscopy tools for cancer diagnosis) via clinical trials in collaboration with the NHS, facilitated by CanSense.

The group-specific goals and strategies are supported at the Departmental-level by the recent creation of a permanent new city-centre *Oriel Science* facility for expanded public engagement, a re-branding of 'Physics at Swansea' to better reflect our 2020 dynamic research environment, and the development of an updated UoA-level Strategic Plan in the context of the new Faculty structure and changes to the funding landscape.

***Figure 3**: CISM, to be completed mid-2022, is integral to the expansion of UoA9's research capacity. The infrastructure and associated project portfolio are designed to support a growing regional semiconductors industry. Its centrepiece is a sector-leading industrial research fabrication clean room with manufacturing-relevant process tools, state-of-the-art characterization & the UK's only II-VI-wide-gap-oxide epitaxial growth facility. Capable of co-processing silicon, compound and organic semiconductors, it will accommodate industry and university researchers (100+) and incubation space.*

Section 2: Staffing

The UoA has 26 cat-A submitted, academic staff, six Lecturers/Senior Lecturers, four Associate Professors and 17 Professors, populating three complementary groups. All are on permanent contracts, 25 are full-time and six early career researchers (ECRs). 45% are non-UK nationals, 19% BAME and 12% have a disability. Cat-A staff are supported by 27 fixed-term postdoctoral researchers and 22 PGR students. Underpinning this rich research ecosystem is a team of seven project-specific technical and administrative staff and 40 staff across the College of Science supporting IT, finance, reporting and bid preparation.

2.1 STAFFING STRATEGY & STAFF DEVELOPMENT

The UoA staffing strategy during the census period was guided by the Department-specific vision described in section 1 and overall institutional aims, especially, University Strategic Aim 2, to build an inclusive, supportive, and intellectually stimulating environment. The strategies relevant to delivering these objectives were:

1. Enhancing research in existing UoA core activities (**OBJ1**): The PPCT group has expanded its research in cosmology and QFT/strings with the addition of two Senior Lecturers and one Lecturer. Antimatter research activities (AMQP) expanded via the award of numerous Royal Society, Leverhulme and Visiting Fellowships including to maintain the permanent presence at CERN within the ALPHA collaboration.
2. Diversifying research in applied physics (**OBJ2**): AMQP has expanded its research in experimental physics, especially laser physics, quantum optics and control, and quantum information with the appointments of two Lecturers and one Senior Lecturer. The signature achievement in diversifying the UoA's research portfolio, the creation of the APM group, was enabled by the appointment of a Professor and Chair in the Centre for Nanohealth as HoD in 2016, followed by initiation of the Sêr SAM programme with the appointment of a Professor and Sêr Cymru National Research Chair in 2017 followed by a Senior Lecturer and Sêr Cymru Rising Star, and a COFUND Fellow and Senior Research Scientist. To provide additional leadership and support for the rapidly expanding semiconductor activities in Sêr SAM and CISM, a Professor from Cambridge University's Cavendish Laboratory was appointed on a 20% FTE in 2018.
3. The appointments in response to **OBJ2** were underpinned by the drive towards greater multidisciplinarity and engagement with industry (**OBJ3**). The new Head of Department (HoD) has international experience in academia (previously Texas A&M) and industry (including start-ups). The new Sêr SAM Chair was previously Director of two major multidisciplinary and industry-focused initiatives at the University of Queensland (Centre for Organic Photonics & Electronics, UQ Solar) and brought a track record of industrial research, policy interventions, and significant commercial start-up experience including raising venture capital. The head of the Cavendish semiconductor research efforts was targeted both for his national leadership in the field and very close ties and long track record of working successfully with industry (Toshiba, Teraview, E2V). Dedicated support enabled existing staff to focus on biomedical research and commercialisation of a colorectal cancer blood-test in collaboration with the Medical School and NHS Wales.

Several important elements of the institutional objectives of University Strategic Aim 2 underpin the departmental strategies. These institutional elements are covered by the performance enabling professional development review (PDR) and relate to matters such as staff development, training, progression, mentoring, and ECR support. Features of the PDR are described in detail in REF5a. Notable highlights that have impacted staff development in UoA9 during the census period include:

- ECR leadership training via award-winning Welsh Crucible and Leadership Foundation Aurora programmes

- Staff participating in the all-Wales Women in Universities Mentoring Scheme
- ECR career development and support including probationary supervision, mentoring and establishment of training requirements via Development and Training Services
- Reduced teaching loads for staff on fellowships/chairs (RSURF, STFC ERF, Sêr Cymru)
- Eligibility for research leave (teaching relief for a semester) every five years
- Allocating 50% FTE for research, innovation, and engagement for category-A staff

Clear indicators of the combined success of these departmental and institutional-level strategies are provided by the Research Environment enhancements detailed in section 1. Our success in creating research time is reflected in the data collected via the Time Allocation Survey under the TRAC framework. For 2014–19, Physics staff reported an average of over 50% of dedicated research time. Further evidence of success is provided by our record in staff recruitment and progression – 10 academic staff across all academic ranks during the last REF period have been recruited, there have been numerous promotions rewarding excellence, including three Professorships, three Associate Professorships, five Senior Lectureships, and eight successful applications for Fellowships. Staff retention is high with only two staff members departing and two retiring. We have gained external recognition with appointments to various learned societies (Meissner, Charlton, Ritchie, Meredith – Institute of Physics, Academia Europaea, Learned Society of Wales), the 2020 IOP Joseph Thomson Medal (Charlton), and an OBE in the 2020 Queen's Birthday Honours list for services to materials research and innovation (Meredith).

2.2 RESEARCH STUDENTS (PGR) TRAINING & SUPERVISION

The UoA's PGR Student Strategy recognises that our PGRs are the engines of research and at the heart of the virtuous circle that delivers research excellence and impact. Our postgraduate community is a major asset to our Research Environment and has thrived over the census period. Postgraduates are also ambassadors for Swansea and contribute enormously to the collegiality of our research culture. This recognition underpins the Department's contribution to the University Strategic Aim 3, 'to create a connected community of learning that enables the recruitment of diverse postgraduate students. Once again, the UoA approach to PGR students is a mix of Departmental, College and University-level strategies:

Provision of competitive fully-and-part-funded PhD studentships and fee scholarships: Over the census period PhD studentships have been secured via EPSRC/STFC [institutional DTPs and involvement in CDTs in Data Driven Science (UoA9 lead), Industrial Function Coatings (UoA15 lead) and Machine Learning and Advanced Computing (UoA11 lead)], the European Social Fund (ESF) and KESS. Highly competitive University scholarships such as Swansea University Research Excellence Scholarships (SURES) augment external schemes, with priority given to interdisciplinary projects and joint PhD programmes with international partners such as the University of Grenoble and the Houston Methodist Research Institute. Our PhD topics and supervision teams increasingly reflect interdisciplinarity and cross-institution reach.

Recruitment: Two PGR Admission Officers manage the recruitment of potential PGR applicants for experiment and theory. A uniform and transparent assessment process ensures an effective triage and robust interview process by an Equality, Diversity and Inclusion (EDI) balanced panel. This ensures quality control, student, supervisor and project match, and mitigates bias.

Supervision, administration and training: PGR students are assigned two supervisors and a non-specialist mentor. Progression is monitored online via a dedicated Research Management System (RMS), cited by QAA as best practice. PGR students are provided with subject-specific and soft-skills training through the UoA and Doctoral Training Centres (DTC), including free access to masters-level courses, journal clubs, seminars and training in Integrity and Ethics, Academic Writing, Research Networking, Enterprise and Entrepreneurship, etc. Training is also provided to staff supervising research students and is mandatory for new staff as part of CPD. Funding is available for PGRs to present work at conferences. Clear and transparent processes for thesis preparation, submission and examination including examiner vetting and selection, are in place. PGR directors at UoA and College level ensure compliance.

A PGR community approach: Although the Department Research Environment is organised into distinct but complementary groups, the PGR cohort is physically mixed in shared large office spaces and there is considerable cross-fertilisation in the various department seminar series. Furthermore, the students come together for their soft-skills training and there is a vibrant social scene. The PGR community is augmented by numerous international visitors, both informally and through programmes such as the NSF-funded US-UK International Student Research in Robust Control of Quantum Networks (with the University of Southern California and Cardiff).

The UoA's comprehensive approach to PGR student supervision and training has yielded considerable success. **This is evidenced by a 116% increase in PhDs awarded during the census period**, a large fraction of joint publications with other disciplines and institutions (**1.2**), and the growing interdisciplinarity with supervisory teams spanning multiple departments. Our commitment to generating high-quality PhDs is evident from the progression of our students to prestigious Fellowships, post-doctoral positions and industry, recent examples including a Humboldt Fellowship, and positions MPI Munich, CUBRIC Brain Imaging Centre, the University of Texas, SuperComputing Wales and SPTS. Looking forward to 2025, the increasing diversity of the UoA's funding, multi-disciplinarity and industry engagement driven by initiatives such as CISM will require a flexible approach to PGR provisions – for example, the need to embed industrial students in the Research Environment. The new Faculty of Science and Engineering will also afford opportunities for leveraging resources (including training) and creating critical mass across disciplines for enhanced CDT and other programmes.

2.3 SUPPORTING AND PROMOTING EQUALITY AND DIVERSITY

The Department is home to staff and students from all over the world with a wide range of ethnic, cultural, socio-economic, and educational backgrounds, gender identities, sexual orientations, and other protected personal characteristics and aims to provide a welcoming environment and equal opportunities for everyone, regardless of background, and actively encourages different perspectives and opinions.

Our commitment to equality and diversity is framed by the University's Strategic Equality Plan, which underpins a culture of inclusivity and values diversity in all areas of activity, including Welsh-language compliance. The Department implements a range of institution-wide strategies to promote EDI (see also **REF5a**) such as mandatory EDI training for all staff, EDI champions, and Juno and Athena Swan committees.

In line with the University's Code of Practice and UoA's Statement of Intent, the team making the decisions on the final selection of outputs received mandatory unconscious bias training and targeted REF specific training on the fair and transparent selection of outputs for inclusion in the submission. The submission comprises one best-quality output from each CatA submitted staff member with the balance made up of the best-quality outputs from the available pool of eligible outputs, including outputs of former eligible colleagues.

In relation to specific considerations for UoA9, additional EDI strategies have been implemented at the Departmental level, notably:

- Mandatory unconscious bias and EDI training for all academic staff
- EDI training modules for PGR students provided by DTC
- Recognition of EDI challenges in STEM and focus on diversity in recruitment
- EDI-balanced interview panels in staff and PGR recruitment
- Openess to host visiting research staff/students from emerging countries
- EDI standing agenda item at Departmental meetings

EDI is promoted by policies such as flexible working and generous parental leave allowances, subject to regular review and adaptation to ensure all personal situations are accounted for, e.g., allowing non-female LGBT staff to take maternity leave for adoption.

While the composition of category-A staff has not changed significantly yet, these strategies and initiatives have led to steady progress toward a more diverse Department. Increased diversity is

clearly evident in our PGR and postdoc population, and stronger recruitment of non-white/non-male and socio-economically-disadvantaged persons. This year, the first student put forward by the Department has been shortlisted for a Bell-Burnell scholarship for a project in medical physics, joint with the medical school, highlighting the value of the UoA's increased focus on applied physics and multidisciplinarity. The success of the UoA's EDI efforts has been recognized by Institute of Physics Juno Champion certification in 2018, and an Athena SWAN Bronze Award in 2019, following the University's 2017 Athena SWAN Silver Award.

Section 3: Income, Infrastructure and Facilities

3.1 RESEARCH FUNDING

3.1.1 Strategic Considerations & Overall Income Summary:

Strategies for both increasing and diversifying research funding have been core to the UoA's Research and Impact Strategy in the census period and underpin the three objectives described in section **1.** The Department has created an environment where staff are encouraged to explore new research directions and grant sources, develop new collaborations and consortia, and have the confidence and capacity to lead major programmatic applications. From a structural perspective, functions such as horizon-scanning, bid preparation and pre- and post-award support are provided via the College of Science Research Hub, while scientific peer review is facilitated at the group-level. As described in section **2**, institutional-level strategies such as sabbatical leave and protected research time, research income return incentives and seed-corn funding via numerous programmes (e.g., SURGE and EPSRC Impact Acceleration Accounts) are also valuable elements of the overall environment. **Figure 4** provides a breakdown of research grant income (REF4b) during the census period with notable achievements:

i) During the census period research income has increased by 81% and grants awarded 71%.

ii) Significant diversification of funding with first awards from the US Army Research Office, IARPA and National Science Foundation; European Research Council, UK medical sector (Cancer Research UK, Cancer Research Wales); UKRI (ISCF and SIPF not yet reflected in HESA but awarded in census period), underpinned by EPSRC, STFC, European Regional Development Fund and new CDTs.

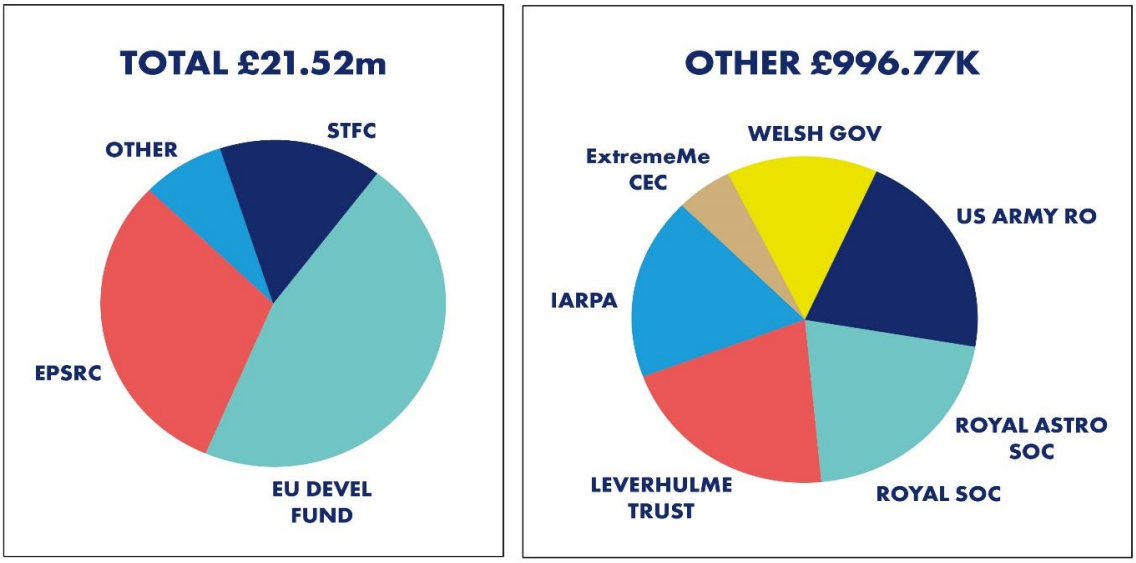

Figure 4: *Breakdown of research grant awards over the census period shows considerable diversification and income increases relative to REF2014.*

3.1.2 Major Awards by Research Group:

The aggregated achievements shown in **Figure 4** have been driven by successes across all three research groups and represents a substantial collective effort. This has been augmented by significant funding for public engagement through Oriel Science (£0.58M **Figure 5**). Group-specific grants awarded during the census period (not all of which reflected in the expenditure figures since they are ongoing and future) highlight the considerable expansion of the UoA's funding base.

PPCT: Core activities have been and continue to be funded by a series of three-year STFC Consolidated grants. During the census period, this funding amounted to £1,054k (14/17), £995k (17/20) and £1,257k (20/23). The latter increase was obtained in a highly competitive environment. PPCT activities are also supported by funding via individual fellowships including a RSURF (Thompson), three Wolfson Research Merit awards (Aarts, Lucini, Nunez), one Leverhulme Trust Senior Research Fellowship (Hands), two Leverhulme Research Fellowships (Aarts, Allton), two Newton Fellowships (Roychowdhury with Kumar, Zacarias with Nunez), and a Visiting Chinese Scholarship Council (Wu with Aarts). The lattice QCD area is a node in the EU Initial Training Network (ITN) Europlex, which provides a three-year ITN Fellow, co-supervised across Physics and Mathematics (Aarts, Lucini, 2019-2022). The lattice QCD area also benefits from the EU COST network THOR (2016-2020), which provides travel support.

AMQP: Antimatter research was significantly boosted by an EPSRC grant (£2M, 2017-21) and an EPSRC Strategic Equipment award (£1.5M) for frequency metrology. Quantum Information and Control research received a significant new investment via an EU Quantum Technology Flagship Grant for Advanced Quantum Computing with Trapped Ions (€0.5M, 2018-21), an ERC Starter Grant for Quantum Neural Networks (€1.5M, 2019-23) and an EC-FP7 Co-ordinated Action on Optimal Control Technologies in Quantum Information Processing (~€0.5M, 2013-2016). EPSRC funding for an Ultrafast Electron Microscope for Imaging Biochemical Interactions (£5M capital, £2M p/a ops) and a collaboration with the Rosalind Franklin Institute on femtosecond TEM (~£0.4M).

APM (Materials): Welsh Government and ERDF funding was instrumental in establishing the new APM group through a National Research Network in Advanced Engineering award in 2014, followed by a £6M Sêr Cymru II award for Sêr SAM in 2017. Materials research in the Department

and indeed across the University was further boosted by an RPIF award (£29.92M) for CISM, and associated additional equipment awards (2019 EPSRC Strategic Equipment [II-VI and Oxide MOCVD Reactor - £2.7M], 2020 ISCF DER Industrialisation Centres - £4.8M]), plus project and program funding (Sêr Cymru Capacity Builder [Optoelectronic Device Scaling - £0.54M], Wave 1 ISCF SIPF [CS Connected - £1.92M to Swansea with Cardiff as lead] and the Swansea-led EPSRC Programme Grant [Application Targeted Integrated Photovoltaics, £5.9M] with Imperial and Oxford as partners).

APM (**Bio-medical**): Funding from a wide range of sources allowed the further development of the bio-medical physics in APM. A Royal Society-Leverhulme Senior Fellowship (Shermer) and two NHS-funded research studentships on Novel Techniques for Quantification of Biomarkers (MRI/S) in 2014 were followed by an EPSRC Platform Grant on Engineering Blood Diagnostics in 2016 (£1,502,075), a COST Action Network Grant on Brillouin Light Scattering Micro-spectroscopy for Biological and Biomedical Research in 2017, funding from Cancer Research UK on Tumour Educated Platelets for Early Cancer Detection (£100,000; 2018-19), and an EPSRC Translational Alliance in Biophotonics for Cytometry (£201,932; 2016-19). Funding for blood-based cancer diagnostics totals over £1M since 2014 from various sources including the Welsh Government, Cancer Research Wales, Health and Care Research Wales, EPSRC, AgorIP and includes spin-out company activity, for example with Welsh Government SMART programmes and Innovate UK.

3.1.3 Funding Linked to Impact (see also **Section 4)**:

The impacts derived from research in the Department were highlighted in **1.3**, and the funding described above has underpinned excellent quality basic research which had led to a wide-range of impactful outcomes e.g., the development and commercialisation of cancer diagnostics (CanSense Ltd) and biomedical imaging (APM), pull through of advanced AI and of data driven science (PPCT), the development of realisable quantum technologies (AMQP), the creation of next generation, commercial solar PV technology (APM), and a whole raft of program and capital funding to support the UK semiconductor industry (APM-CISM).

3.2 OPERATIONAL INFRASTRUCTURE SUPPORTING RESEARCH AND IMPACT

3.2.1 Overall Infrastructure Context:

At REF2014 significant investments in Physics-related research infrastructure (around £20M) were foreshadowed at both the existing Department on the Singleton Campus and the new £500M industry-focused Bay Innovation Campus. This intent has been realized with refurbished office accommodation in the Vivian Tower providing a well-connected and pleasant environment for staff, PDRAs and PhD students, new labs for APM at the adjacent Centre for Nanohealth (CNH), and state-of-the-art microscopy, fabrication, and surface analytical facilities at the Bay campus. As current Departmental accommodation has little capacity for upgrade/expansion, the infrastructure will become increasingly distributed when the new CISM facility comes on-line in 2022. As described in section **2**, technical support is provided by pooled resources (technicians, dedicated mechanical workshop), augmented by group-specific grant-funded resources (e.g. two FTE technicians in Sêr SAM).

3.2.2 Group-specific Infrastructure:

APM and AMQP operate bespoke laboratories in the Vivian Tower and adjacent CNH.

AMQP facilities include: i) A slow-positron beamline – one of a handful of such systems worldwide – suitable for studying positron-atom/molecule interactions, material and positronium analysis; ii) A bespoke X-ray beamline including a high-energy spectrometer and metrology system for characterizing spatial properties of coherent x-ray beams plus visible beam adaptive optics systems using deformable mirrors and spatial light modulators; iii) Facilities for observing ultrafast electron emission from nanoscale metal tips with velocity map imaging, femtosecond electron diffraction and microscopy, and low-energy electron point-projection microscopy. This equipment enables the study of ultrafast structural dynamics and is augmented by femtosecond XUV-NIR and UV-NIR pump-probe spectroscopy. Strong-field few-cycle laser pulse generation and

metrology enables the study of ultrafast vibrational wave-packet dynamics in gas-phase molecules; and iv) New facilities for trapping cold atoms and levitated optomechanics serve as a versatile platform for exploring fundamental and applied quantum measurement and control.

APM: Comprehensive facilities for advanced materials research (see **Section 1**), housed in the CNH laboratories, include: I) extensive micro-and-nano-fabrication tools for next-generation semiconductor materials and devices (inert glove-box cluster-tool for organic and perovskite semiconductors); ii) an advanced electro-optical characterisation laboratory (electrical spectroscopy and ultra-fast photo-physics for materials and device analysis at cryogenic temperatures). The suite of biomedical related equipment has recently been expanded with advanced Raman spectroscopy supporting the cancer diagnostics programme, and time-resolved laser-based spectroscopy systems allowing bio-photonic studies of biologically derived functional materials.

3.3 CROSS-HEI SHARED & MAJOR UK / INTERNATIONAL RESEARCH FACILITIES

3.3.1 Cross-HEI Facilities:

Physics researchers have access to significant cross-university infrastructure representing 10s of £M of investment:

The Centre for Nanohealth (CNH) provides an integrated environment for nanotechnology and biomedical research and innovation. It includes a fully equipped nanofabrication class 1000/100 cleanroom; a class 1000 bio-cleanroom for tissue engineering and device functionalization as well as NMR, rheology, biomolecule printing, and various forms of microscopy. CNH also includes a category two biomedical laboratory suite offering cell and molecular biology capabilities including confocal microscopy, high-throughput analytical systems, microbiology, regenerative medicine and tissue engineering, and nano-genotoxicology. CNH also provides incubation space such as private offices, a clinical research facility, access to a 'first into man' clinical trials unit, MRI/CT patient imaging and health informatics.

The Clinical Imaging Facility (CIF) is a joint venture between Swansea University and Abertawe Bro Morgannwg University Local Health Board. CIF's primary role is to facilitate clinical research, including pharmaceutical-based studies in oncology, applications of MRI, and the development of imaging-based pathways. The facility houses a 3T Siemens Magneton MRI Scanner with high density coils for neuro, body, and orthopaedic scanning, together with the TIM 4th generation system to support ultra-high-density coils. The MRI suite hardware includes an infusion pump for IV injections and fMRI screen and response boxes. A research agreement with Siemens enables CIF users to develop, implement and test new physics-based MR pulse sequences and bespoke scanning protocols and customize hardware.

Advanced Microscopy & Surface Analysis. The Bay Campus is home to a fully integrated suite of advanced electron microscopes, X-ray diffraction and optical imaging systems that allows millimetre-to-angstrom structural analysis as part of the Advanced Imaging of Materials (AIM) facility. This is augmented with state-of-the-art surface analysis by way of X-ray Photoelectron Spectroscopy – which in combination provide a comprehensive capability used by a range of internal and external stakeholders.

3.3.2 Major UK / International Facilities:

ALPHA at CERN: The AMQP group makes excellent use of the ALPHA experiment at CERN, which after two decades of development is the world-leading facility for antihydrogen research. ALPHA comprises two main anti-atom-trap systems designed for spectroscopy and gravitational measurements and is the only EPSRC-supported experiment active at CERN, adding complementarity to the UK portfolio. ALPHA uses beam-time at the antiproton facility that now comprises the AD and ELENA deceleration machines providing round-the-clock access to low energy antiprotons for experimentation. In addition, thanks to EPSRC and Carlsberg Foundation (DK) support, the Swansea ALPHA group are building a metrology facility to house a state-of-

the-art Caesium fountain clock that will provide an absolute frequency reference for the ALPHA group's spectroscopic studies of antihydrogen.

ISIS, STFC & EPSRC: Materials research was supported by an STFC award for >15 days of beamtime on the ISIS Pulsed Neutron and Muon Source for projects in the Sêr SAM portfolio. Ultrafast laser research was supported by 'Artemis' at the Rutherford Appleton Central Laser Facility (CLF) providing access to high-power laser systems and diagnostics. Artemis was used, with Imperial College, to generate intense few-cycle IR pulses, and the XUV imaging beamline was used to measure spectra in the water window (~200-500eV). Extensive use has also been made of the EPSRC Laser Loan Pool operated by the CLF. Research on novel ultrafast electron sources was facilitated by the Accelerator Science & Technology Centre (ASTeC) at STFC Daresbury Laboratory. (Total value of in-kind awards £179k.)

Super Computing: Computational research has been facilitated by several awards of both computing resource and research software engineer support via competitive bids to the STFC Distributed Research Utilizing Advanced Computing (DiRAC). The most recent award included 310M core hours on the Extreme Scaling facility in Edinburgh as well as allocations on the Data Intensive machines at Cambridge and Leicester. The work also uses resource allocations on the Blue Gene/Q and Marconi KNL systems at Cineca (Italy) via the Partnership for Advanced Computing in Europe (PRACE) and SuperComputing Wales. (Total value of in-kind awards on DiRAC £2.19M.)

***Figure 5**: Oriel Science, a public engagement and outreach project founded and run by members of the Dept, has recently established a new city centre science venue to enhance Future Generations' educational and career journeys, address under-representations, and public engagement with science. It packages Swansea University' research into exciting, interactive exhibits, and puts these in places people go. Launched as a Pop-Up Science venue in Swansea's city centre in 2017, it welcomed 17,000 visitors over 100 days. Since then, it has engaged with 150,000 people in over 100 events including: annual 'Super Science Swansea' festivals in the National Waterfront Museum with over 3,000 daily visitors, exhibitions in Swansea Museum and the Glynn Vivian Art Gallery, exhibits at careers fairs, talks in schools, community events, the London Science Museum, and local and national Science Festivals. It has been awarded funding worth £580k.*

Section 4: Collaboration and Contribution to the Research Base, Economy and Society

4.1 RESEARCH COLLABORATIONS, NETWORKS AND PARTNERSHIPS

The Research and Impact Strategy has delivered a significant expansion in collaborations, networks, and partnerships: intra-university, inter-organisational, locally, nationally, and globally. **Figure 1** illustrates the connectivity of the Department and our broad stakeholder base across academia, industry, government and third sector. The impact delivered by this comprehensive

engagement has been a collective contribution across the three research groups with additional cross-department endeavours in public engagement, STEM diversification and EDI promotion (see **4.2, 4.3**). Notable major collaborations and partnerships include:

- *SuperComputing Wales* (SCW), the national supercomputing research facility for Wales, involving four Welsh universities. Representing a £16M programme of investment (ERDF and Welsh Government), it provides access to upgraded supercomputer hubs in Cardiff and Swansea. Swansea's involvement is facilitated by the Swansea Academy of Advanced Computing (SA2C), established in 2017 with members of the **PPCT** group. SCW was also instrumental in capturing CDT funding (see below) and provides co-ordinated training support. It works closely with external partners, including large companies (ATOS, IBM, Microsoft, Nvidia, etc.), locally based SMEs (Amplyfi, Quant Foundry, WePredict), and government and Research Council partners (DiRAC, GCHQ, Welsh Water). A good example of impact from the SCW network is a collaboration with Pulsar Physics, a spin-out software company from University of Eindhoven developing state-of-the-art charged-particle-dynamics modelling software, which has led to beta testing of new features for femtosecond electron microscopy design.

- The *international ALPHA consortium,* based at CERN, the globe's leading research endeavour in antimatter physics. By making precise comparisons of hydrogen and antihydrogen, the experiment uncovers fundamental symmetries between matter and antimatter. Swansea **AMQP** plays a central role in ALPHA, and as described in **A**, the experiment is a multi-decade endeavour, which has moved into the exciting delivery phase in the census period producing seminal results and field leading publications (c.f. 10 *Nature / Nature Suite* papers with AMQP authors). The Swansea group spearheads the EPSRC's involvement in ALPHA and has permanent staff and students at CERN as described in section **2**.

- *Application Targeted Integrated Photovoltaics (ATIP),* a five-year (2020-2024) EPSRC Programme Grant consortium led by Swansea (**APM –** Materials, Sêr SAM, SPECIFIC IKC) with partners Imperial, Oxford and 11 companies. The UK's only Programme Grant in the area, it seeks to maintain a nationally leading position in developing next generation, low embodied energy solar photovoltaics (PV), an important element of decarbonisation. ATIP is nationally and internationally connected with cognate programmes such as SUPERGEN SuperSolar (UKRI), SPARCII (Welsh European Funding Office), National Renewable Energy Laboratory (USA), Fraunhofer Institute for Solar Energy (Germany) and the Australian Centre for Advanced Photovoltaics. Swansea now has the largest collective of solar PV researchers in the UK.

- *CanSense and Biomedical Imaging* [**AMP** – Biomedical] – Research on medical imaging, magnetic resonance spectroscopy and multi-parametric MRI is conducted in a joint Clinical Imaging Facility (CIF) managed by the School of Medicine and shared facilities provided by CNH in close collaboration with NHS staff, radiologists, medical researchers, and researchers from Cardiff University's Brain Imaging Centre (CUBRIC), supported by a Research Agreement with Siemens and a start-up company (ACUITAS). Another significant multidisciplinary initiative between Physics and Medicine using CNH facilities is bio-spectroscopy (see below and **Section 1**) which has led the spinout company CanSense to commercialising a test for colorectal cancer.

In addition to these group-led major programmes, our researchers have been involved in numerous project-level collaborations such as the development of spintronic and dilute magnetic semiconductor devices (National Research Network in Advanced Engineering and EPSRC Manufacturing Hub at Cardiff). Other such examples include the recently awarded NSF project to create a US-UK Advanced Study Institute on Robust Control of Quantum Systems (Engineering Department at the University of Southern California and the Computer Science Department at Cardiff), and the PPCT-consortium 'FASTSUM' involving Lattice Field Theorists in Swansea, Denmark, South Korea, Taiwan, Ireland, Italy, and the US. Finally, it is worth highlighting two major initiatives that will come on-line in 2021:

- CISM will harness and contribute to the critical mass of the South Wales CS Connected industrial cluster in semiconductor manufacturing (see below and **Figure 3**) with a £20M portfolio of TRL-spanning collaborative projects (2020-2025).
- LISA (ESA / NASA's Laser Interferometric Space Antenna) in which Swansea PPCT will provide underpinning cosmological theory support for experiments launching in the early 2030s, including work package leadership in GW detectors.

4.2 CONTRIBUTIONS TO RESEARCH BASE

4.2.1 SUSTAINABILITY & PRIORITY RESPONSIVENESS.

As described in sections **1** and **3**, our funding base has diversified in response to emerging opportunities such as the ISCF, the formation of UKRI, and winding-back of EU Structural Funding. The UoA9 research portfolio has expanded considerably because of this strategic approach and has a solid and sustainable foundation going forward without heavy reliance on a single source. A good example of this robustness is CISM's funding base with programmes in key national priority areas: Clean Energy Systems; Nanohealth; and Power and Low Loss Electronics. Close connectivity with principle regional stakeholders such as NHS Wales and CS Connected also provide a firm foundation for local relevance, and involvement in major national and international programmes such as ALPHA and LISA ensures global reach. The UoA is well equipped to deal with changes to ERC / Horizon-2020 arrangements and respond to new opportunities afforded by the Faculty re-structure. With the acquisition of CDTs, the Department is in a robust position with respect to PGR provision, but this remains an area of exposure in the new areas of activity (see **1.4**).

4.2.2 WIDER CONTRIBUTIONS:

Beyond contributing broadly to their specific fields, staff also provide local, national, and international leadership.

1. *Journal responsibilities*: UoA staff review for a wide variety of international journals including Science, Nature, the Physical Review and Advanced Materials suites, IEEE Transactions, etc. Staff also serve on editorial boards, for example Proceedings of the Royal Society B, European Journal of Physics, Advanced Materials, RRL Solar, EP Techniques and Instrumentation and routinely contribute chapters, book reviews and proposals and field-leading Perspectives and Reviews. In 2020, Hands was named by the American Physical Society as an Outstanding Reviewer for the Physical Review.
2. *Grant Review & Research Councils*: UoA staff review for many national and international granting bodies and serve on decision panels including – UKRI, EPSRC, STFC, DFG (Germany), ANR (France), KAUST, EU (COST, ITN, FET-Proactive, MSCA-IF), the Royal Society, British Council, Max Planck Society, Australian Research Council, the Academy of Finland, and the US NSF and Department of Energy. Staff have served on STFC panels including Review of Particle Physics Phenomenology (2015); Balance of Programme Review (2016); Review of the Consolidated Grant Scheme (2019) and STFC's Particle Physics Theory Grants Panel. Meredith has served on the technical advisory board of the Australian Renewable Energy Agency, is an H2020 Major Project Monitor and EPSRC National Nuclear User Facilities Advisory Committee member. Ritchie is a member of the EPSRC ICT SAT.
3. *Conference Organisation & Contributions*: Staff have served on organizing committees and advisory boards and presented scores of keynotes and plenaries for conferences and workshops all over the world in areas ranging from antimatter to advanced materials, from theoretical particle physics to systems & control engineering. Examples include the 2021 NanoGe Fall Meeting (Armin), SPIE Optics and Photonics and MRS (Meredith), the 2015 3rd International Workshop on Antimatter and Gravity (Madsen), the 2019 Mainz Institute of` Theoretical Physics meeting on Dualities and Generalised Geometry (Nunez), etc.

4. *Other Leadership and Recognition*: Senior UoA staff have also provided significant field leadership to their communities, e.g., Aarts chairs the Scientific Board of the European Centre for Theoretical Nuclear Physics (interim Director from 1/1/21) and serves on the Joint Scientific Council of the FAIR/GSI accelerator facility in Darmstadt. Hands is co-chair of the DiRAC's Project Board, organised DiRAC Science Day in Swansea in 2018, and coordinated writing of the Science Case for the DiRAC 3 facility, which has recently received £20M under UKRI 'World Class Labs' funding and will commence operation in September 2021. Charlton serves on the Council of the Learned Society of Wales.
5. *Collaborative PGR Training*: As described in detail in section 2, the UoA hosts a node or leads two CDTs (AIMLAC – directed by Aarts, and Data Intensive Science), provides projects and supervision for multi-disciplinary projects including industry, and is an institutional though leader in collaborative PGR training.

4.3 CONTRIBUTIONS TO THE ECONOMY & SOCIETY

Public Engagement & Diverse Communities: As described in the UoA Case Studies and summarised in **Figure 5** (Oriel Science), the Department has a comprehensive portfolio of engagement with our local community, and particularly with school-age students in promoting STEM and increasing diversity. An example of such a contribution by UoA researchers over and above our Case Studies is our support for the Seren Network, a Welsh Government initiative dedicated to helping Wales' brightest students achieve their full potential and support them to gain access to leading universities in the UK or overseas, through workshop events and short research assignments. The UoA also contributes to the CERN Outreach Programme, which has hosted over 90,000 international students at the antimatter experiment. Swansea staff have welcomed over 10% of this total, including special relationships with 15 schools. The UoA has a sizeable public engagement programme including exhibits at the 2016 Royal Society Summer Science Exhibition, the 2017 Big Bang Fair and the National Eisteddfod. The antihydrogen work was also selected to present at the EPSRC Showcasing Physical Sciences Impact Event in 2019. Via the biomedical research theme in APM, the UoA also contributes to the School of Medicine's engagement programme (as part of Reaching Wider) to bring students from disadvantaged areas to the University to showcase the latest in healthcare innovations, emphasizing the important part Physics plays. The UoA is also a registered provider for the Go-Wales programme to deliver mentorship for students from minority backgrounds.

Other Economic & Societal Outcomes: The CanSense Case Study is an excellent example of societal benefits flowing directly from our research. Another example in the healthcare space is the contribution of our biomedical imaging researchers who provide support for clinical studies, e.g., for a recent prostate cancer study of 400 patients referred to the CIF by the NHS (funded by a cancer charity), where we provided analysis of the patient data and improvements to the MRI protocols that resulted both in cost savings and benefits to patients.

Finally, our relatively recent efforts to support the creation of high-value regional jobs in the semiconductor industry are beginning to bear fruit. CISM will provide underpinning research and innovation services, especially to SMEs, including training, incubation, supply chain connections and bespoke technology development. The current portfolio of CS Connected projects in which our research plays a critical role will create 500–100 jobs to 2025 (for example in the SIPF project and attempts to build a power electronics component supply chain via Driving the Electric Revolution which Swansea leads). Our UoA9 Research Environment is also now providing industry relevant PGR training to fuel the continued growth of the industry.

In conclusion, the UoA has made great strides during the census period in expanding its research activities and their impact on academia, industry and wider society, both locally and internationally.