Institution: University of Warwick

Unit of Assessment: B9 Physics

1. Unit context and structure, research and impact strategy

1.1 Structure of Research

We aim to make discoveries across fundamental and applied physics and to apply that knowledge for the benefit of society. Over the last two REF cycles, we have expanded our collaborative and interdisciplinary activities within the University and beyond, and this has led to important impacts, particularly in the industrial and health sectors. Our strategy in core physics has been to build research power in astrophysics and particle physics, complementing our existing strengths in condensed matter, plasmas and theory. We now have critical mass in all our main areas of activity, with each working at the forefront of knowledge.

This REF period has seen continued growth in research volume – paper output (800 p.a.) and research awards (£21M in 19/20) have both doubled – and quality (average citation rate increased from 13 to 23 per article, total citations >40,000 p.a, 12 staff in the top 2% of global scientists per Stanford list), together with increased interaction with other disciplines and impact. Physics has a ten-year growth strategy, that includes expansion into new thematic and interdisciplinary areas, and will benefit from considerable investment in new science infrastructure. Much of the growth in this period has been achieved by appointing excellent early career researchers, who by 2030 will represent the core of the department.

Research in Physics is structured around five Research Clusters. Table 1.1 shows growth in every cluster since 2014, with the number of independent researchers submitted to REF2021 increasing by 38%. A corresponding increase in supported research is reflected in more PDRAs and PhDs. Boundaries within and between clusters are deliberately loose to encourage interaction between staff and with other departments/outside organisations. The clusters set their own priorities, guided by the departmental strategic framework developed after external review in 2012 (*20:20 Vision*) and renewed in 2019 (*2030 Insight*). In this, we have set priorities for future investment and expansion for the periods before and after moving into a new Physics building (University's STEM Grand Challenge, REF5a-4.2), which is a major part of the institutional strategy *Excellence with Purpose* (REF5a-2.1) planning 40% STEM growth at Warwick by 2030.

Research Cluster	Independent researchers		Postdocs		PhDs	
	2013	2020	2013	2020	2013	2020
Astronomy & Astrophysics	8	16	5	17	10	23
CFSA	8	9	7	9	26	22
Condensed Matter Physics	23 (+6[#])	28 (+3[#])	31	35	64	87
Elementary Particle Physics	9	18	11	13	17	22
Theoretical Physics	7	10	10	10	22	22
Total	61	84	64	77	139	176

Table 1.1: Distribution of research active staff and PhD students (heads), showing change between REF2014 and REF2021 census dates. [#]Submitted in UOA12.

1.2 Research Objectives

The following highlights illustrate alignment to the objectives set out in REF2014 and future direction for each research cluster:

a) **Astronomy & Astrophysics** (A&A) focuses on time-resolved observational astrophysics, encompassing white dwarfs [**Gänsicke**, **Marsh**, **Tremblay**], high energy transient events such as gamma-ray bursts (GRB) or mergers of stellar remnants that generate gravitational waves (GW) [**Levan**, **Lyman**, **Stanway**, **Steeghs**], and the discovery/study of exoplanets [**Pollacco, West, Wheatley**]. A&A staff make extensive use of ground- and space-based telescopes, and we operate our own facilities at premier observing sites in Chile and La Palma.

A&A is world-leading in the theoretical and observational analysis of white dwarfs. By exploiting data from the European Space Agency (ESA) Gaia mission we have enlarged the sample of known white dwarfs by an order of magnitude, and are leading the spectroscopic follow-up within the WEAVE, DESI, SDSS-V and 4MOST surveys [**Gänsicke**, **Tremblay**]; uniquely, A&A leads activity in all four experiments, as well as making high-time resolution observations of these systems with instruments we have developed **[Marsh]**.

Multi-messenger astrophysics is a rapidly growing area with enormous potential, especially driven by advances in LIGO's sensitivity and the ESA LISA mission due to launch in the 2030's. A&A is leading UK efforts to identify optical counterparts to GW events with our purpose-built Gravitational-wave Optical Transient Observer (GOTO, §3.2d) [**Lyman, Steeghs**]; two additional academics will be recruited in 2021 to expand this activity as a core of our forward strategy.

Exoplanetary science is a frontier research field in astrophysics. A&A has capitalised on the colocation of experts from the Wide Angle Search for Planets (WASP/SuperWASP) consortium and recruited a further 7 academic posts and 3 permanent research officers in this area to position Warwick as a leading global centre for exoplanet science (§2.1a). We aim to cover the full life-cycle of planets from their formation in the dusty proto-planetary discs around stars [**Kennedy, Meru**], through a potentially habitable phase [**Bayliss, Brogi, Cegla**], to debris on stellar remnants [**Gänsicke, Tremblay, Veras]**. Although principally an observational group, recent hires have provided significant modelling expertise [**Tremblay, Veras**] and developed machine learning techniques to find planets in massive survey data sets [**Armstrong**]. Building on the SuperWASP legacy, A&A has led development of the Next Generation Transit Survey (NGTS, §3.2b), which is now routinely discovering exoplanets of Neptune or smaller size [**Bayliss, Wheatley**]. Furthermore, **Pollacco** has driven the PLATO (PLAnetary Transits and Oscillations of stars, §3.2a) space telescope mission to adoption by ESA for launch in 2026 to search for Earth-like planets around bright stars.

A&A have developed an astrodynamics activity applied to debris in the near-Earth environment. Initially based on SuperWASP data, this has expanded to include other facilities, dynamical modelling, and partnership with DSTL, to commercialise tracking of bodies in low-Earth and geosynchronous orbits.

b) The **Centre for Fusion Space & Astrophysics** (CFSA) is an interdisciplinary centre embracing plasma physics applied to the grand challenges of magnetic and inertial confined fusion power (MCF, ICF), space plasma physics, solar physics, and astrophysics. The research spans fundamental theory, observation, and the analysis of experimental data, combined with high performance computing (HPC).

CFSA is engaged with key plasma research centres in our region, including Culham Centre for Fusion Energy (CCFE), Rutherford Appleton Laboratory (RAL) and AWE, as well as large, multi-£B international facilities for fusion (JET, MPI, KSTAR, ITER) [**Chapman, Dendy, Hnat, McMillan**], extreme plasmas (LLNL) [**Gericke**] and solar/space missions (NASA-Parker Solar Probe, NASA-SDO, GONG, ESA-Solar Orbiter, Cluster) [**Broomhall, Nakariakov, Verwichte**]. Recognising the importance of host star dynamics to planetary evolution has enabled us to exploit synergies between CFSA and A&A research in solar flares, astroseismology and transient astronomy.

CFSA is the leading centre for plasma HPC codes (e.g. EPOCH [Impact Case Study, ICS-1], Odin) applied in fusion physics, space weather prediction, and fundamental plasma physics of the solar corona, shocks and turbulence. CFSA works with international MCF experiments, combining simulation with experimental data to unravel kinetic physics underlying stability, current generation, and remote diagnostics for burning plasmas, all of which are on the critical path to fusion as a commercial power source. In this cycle, **Arber's** activity has expanded into ICF.

With space weather now on the UK National Risk Register, CFSA investigates the full chain of fundamental solar-terrestrial plasma physics and its implications. **Nakariakov** leads international radio astronomy projects based on his nonlinear MHD modelling and analysis of solar coronal observations. **Arber** is engaged in developing European space weather forecasting capability. **Chapman**, supported by a Fulbright scholarship, has built collaborations in space weather with leading institutes, most notably JHU/APL and NASA-JPL, and applied her analysis to climate change and its economic consequences in collaboration with Georgetown University, LSE, and the NORKLIMA network on climate.

c) **Condensed Matter Physics** (CMP) combines in-house experimental materials growth and characterisation research with research at, and management of, international facilities. CMP, previously structured as individual (REF2008) or combined (REF2014) research groups, is now returned as a single cluster to reflect the many interactions and collaborations between staff.

Activity in magnetic materials, 2D layered materials and ferroics has increased, through new appointments and facilities for thin-film devices [**Alexe**, **Broome**, **Wilson**]. Prior work in semiconductors and surface science [**Bell, Leadley**] has been applied to new research fields, such as Van der Waals epitaxy.

High resolution electron microscopy and X-ray diffraction underpin our nanoscale materials research [**Beanland**, **Sanchez, Sloan, Thomas**]. We make extensive use of and contribute to development of international neutron and synchrotron facilities (ISIS, ILL, ESRF, SPring8, Elettra etc.) [**Bikondoa, Duffy, Hase**]; together with Liverpool, we have run the XMaS beamline at the ESRF as a UK National Facility for over 20 years (§3.3b).

The Warwick Centre for Ultrafast Spectroscopy (WCUS, §3.3g) was co-created in 2016 by **Lloyd-Hughes** as a multi-user, femtosecond laser facility. Our terahertz activities have expanded with the appointment of **Milot** and **MacPherson**, whose THz studies of skin increases our medical physics activity, with impact in healthcare.

Single crystals of materials exhibiting high-Tc superconductivity, frustrated magnetism, 2D skyrmions, and topological insulators grown in Warwick are much sought-after and supplied to over 50 different research groups worldwide, as well as fuelling our extensive research program [**Balakrishnan**, **Goddard**, **Lees**, Paul, **Petrenko**, §3.3d].

Warwick's NMR strategy is to be at the leading edge of technique development and central to UK provision, running the UK National Facility for High Field Solid State NMR since 2010 [**Brown**, **Hanna**, **Iuga**, **Dupree,** §3.3a]. Our ssNMR research is highly applicable to a range of industries, spanning pharmaceuticals, materials for catalysis, biomaterials for tissue engineering, energy materials, supramolecular hydrogels, and cellulous in plant cells. Work with research partners, such as Astra Zeneca, BP, Infineum, Johnson Matthey, has led to significant impact [ICS-4].

Diamond research [**Newton, Green, Morley**, §3.3d] benefits from a long-standing relationship with De Beers and Element Six; commercial application led to ICS-3 & ICS-5. Warwick leads the UK Diamond Science and Technology (DST) CDT and have participated in three of the four UK Quantum Technology Hubs. Our research into diamond NV centres has led to expansion into theory and practical quantum measurement [**Green, Newton, Morley, Datta, Broome**].

Ultrasonics research [**Dixon, Edwards**], concentrating on industrially relevant research challenges, has led to three spin-outs in addition to generating impact with industry [ICS-2] through Warwick's Centre for Industrial Ultrasonics (CIU) [ICS-6] and the UK Research Centre for Non-destructive Evaluation (RCNDE).

d) **Elementary Particle Physics** (EPP) activity encompasses energy frontier studies with ATLAS, flavour physics with LHCb, and neutrino studies with T2K and now DUNE & Hyper-K. Research focuses on detector development, trigger hardware/software; event simulation/reconstruction; and physics analysis. EPP research capability has been significantly strengthened by strategic appointments in key areas: ATLAS trigger/real-time analysis [**Becker**, **Facini**], LHCb analysis [**Kenzie, Vesterinen**], neutrino interaction reconstruction [**Marshall**] and neutrino water Cherenkov detector readout and analysis [**Richards**]. EPP have a strong leadership record in major international collaborations: **Gershon**, **Murray**, **Ramachers**, **Harrison** have been Physics Coordinators for LHCb, ATLAS, SuperNEMO and BaBar, respectively; **Barker, Farrington** & **Gershon** have coordinated UK partners; all researchers are encouraged to take convener roles of important working groups (§4.1d).

EPP are contributing significantly to LHC upgrade projects and future neutrino experiments. For ATLAS, we deliver production and quality control of Inner Tracker modules [**Mitra**]. For LHCb [**Back, Kreps, Latham, Morgan**], **Gershon** is UK leader for Upgrade 2, we are part of TORCH, and have a key trigger upgrade role. In neutrino physics, **Barker** is PI of DUNE-UK; **Marshall** leads development of LAr reconstruction software; **Boyd** has a lead role in implementing optical calibration for Hyper-K and

Watchman, and **Richards** provides the data acquisition for many water Cherenkov projects, including Hyper-K. **Ramachers'** interest in high precision, ultra-low background experiments has opened new opportunities in quantum sensor technology for neutrino mass measurement (QTNM), dark matter (Darkside) and neutrinoless double-beta decay (LEGEND).

e) **Theoretical Physics, Soft Matter & Biophysics** (TP) works on problems in non-equilibrium biophysics, the dynamics of complex fluids, molecular and materials modelling, quantum transport and quantum information science. TP's longstanding leadership of scientific research computing across the University, **Quigley's** direction of the Scientific Computing Research Technology Platform, and appointments of **Hine** and **Bartok-Partay** (joint with the School of Engineering, SoE) place TP at the heart of the University's strong, interdisciplinary computational materials modelling capability (§1.3d, §3.4)**.** TP members collaborate extensively with experimental groups working on both hard condensed matter and bio-/soft matter, e.g. 2D heterogeneous materials, nanocrystallisation, permanent magnets [**d'Ambrumenil, Hine, Quigley, Römer Staunton**]. **Datta's** expertise in quantum information theory complements quantum technology developments by experimental CMP colleagues. Theoretical physics ideas [**Ball, Römer, Turner, Alexander**] are applied to mathematics of complex systems and the biosciences in interdisciplinary activities relating to antimicrobial resistance and physics of life [**Polin, Kantsler**]. As a result, an integrated theory/experimental project on DNA transcription combined optical measurements with theoretical modelling.

1.3 Interdisciplinary research

a) Interdisciplinarity is a key theme that enhances the vitality and sustainability of Warwick's research environment. The compact campus, open approach, and thematic Global Research Priorities (GRP, REF5a-2.9.1) present opportunities for physicists to have an impact on some of the world's most challenging issues through research in health, manufacturing, energy, food etc. Physics academics regularly work across disciplinary boundaries, collaborating on projects in chemistry, biophysics, medical physics, plant science and engineering. Physics initiated the Materials GRP (co-led by **Leadley** until 2019) and created a cross-faculty Centre for Habitability, co-led by **Armstrong**, that has become a University-wide GRP with members' interests spanning astrophysics and life sciences, to philosophy and film studies. In 2020, **Ball** initiated the interdisciplinary Warwick Centre for Soft & Active Matter to create a critical mass of 30+ academics from six departments, with interests spanning biological physics, polymers, nanocomposites and properties of cells.

b) Two staff have 50% joint appointments with SoE – in the Centre for Industrial Ultrasonics (CIU) and in computational materials modelling; two soft matter physicists have 30% appointments in Warwick Medical School (WMS). Three staff whose research is in applied physics/engineering are submitted in UOA 12 (Dixon, Edwards & Myronov).

c) Joint activity with Chemistry in the Millburn House Magnetic Resonance Centre extends to shared CDTs on analytical science and diamond. We operate joint facilities with Chemistry for X-ray photoemission spectroscopy (XPS) and ultrafast spectroscopy (WCUS, §3.3g). Research Technology Platforms (RTP, §3.3c, REF5a-4.3) for X-ray diffraction, electron microscopy, spectroscopy and scientific computing, directed by

Walton, **Beanland**, **Newton** and **Quigley**, respectively, provide facility access and data analysis for researchers across the institution and external users.

d) TP have a close relationship with Mathematics, esp. via Complexity, and co-supervise PhD students from interdisciplinary CDTs in mathematical, physical and life sciences. With the Centre for Predictive Modelling, **Staunton** and **Hine** created the EPSRC CDT in Modelling of Heterogeneous Systems (HetSys), which spans six departments. CDT activity unites researchers through jointly supervised PhD projects, retreats, workshops and interdisciplinary seminar series.

e) Our widespread collaboration in projects and international facilities (§4.1) provides further opportunities for interdisciplinary activity.

1.4 Impact

a) Our research and expertise are relevant in application areas across energy, materials, electronics, pharmaceuticals, as well as satisfying curiosity to understand the Universe. Our impact strategy is to ensure all researchers recognise the potential for impact inherent in their work and are provided with the time, skills and support to develop it.

b) Physics has built a strategy to actively manage the development of impact from our research and embed this within the culture. An academic Impact Director (REF5a-2.6), supported by an Impact Manager help researchers recognise exploitable aspects of their research, identify support mechanisms, build relationships with partners, and track progress from early stage ideas to IP licenses and/or establishment of fully-formed spin-out companies. The Physics Impact Director represents all of STEM on the University's Research Impact Advisory Group (REF5a-2.6). External users can access our expertise and facilities for short term, responsive projects that have been key to developing our impact, as illustrated in our ICSs. We have provided incubation space for three spin outs over the period: Sonemat, Advanced-Epi, Cytoswim.

c) Close contact with support staff in R&IS (REF5a-1.7), Warwick Innovations (WI, REF5a-2.8) & Warwick Scientific Services (WSS, REF5a-4.3.1) enables rapid signposting of opportunities and linking potential beneficiaries to the researchers. The impact support teams agree flexible IP positions and impact pathways with industrial collaborators at the start of research and translational projects, which also enables us to gather information on end-users of the technology.

d) For astronomy and particle physics, where direct pathways to impact are less obvious, an STFC Innovation Partnership Fellow (IPF) has been employed to seek exploitation opportunities which form an important part of our future impact pipeline (§4.2b).

e) Co-funded PhDs are very effective for external engagement. As well as EPSRC CASE studentships, Warwick Collaborative Postgraduate Research Studentships (WCPRS) share costs 50:50 between University and industrial partner. Currently, 27 PhD students have support from companies including Johnson Matthey, AWE, Huawei, De Beers, Rolls Royce, EDF, GSK and AstraZeneca, with their projects featuring in our ICSs. HetSys-CDT runs 3-day Industry Study Groups where staff and PhDs collaborate on genuine commercial problems.

f) Staff are encouraged and supported to develop Impact from their research via:

   i. *Funding* for staff time, consumables, equipment, prototype construction, secondments into and out of Physics for staff devoted to exploitation projects. Over £1M has been distributed from EPSRC/STFC IAAs & HEIF, via the

Warwick Impact Fund (REF5a-2.7), with a further £1M via ERC Proof of Concept and Innovate UK.

ii. *Time* for impact activities, made available within our workload model and the University Impact Leave scheme (REF5a-2.6), e.g. **Brown** spent 20% of his time for two years at AstraZeneca developing their ssNMR capability [ICS-4].

iii. *Embedding* themselves in company activities, supported via Royal Society Industry Fellowships (**Dixon** at Rolls Royce, ICS-6) or the company (**Newton** at Element Six ICS-3).

iv. Employing *Knowledge Transfer Partnership* fellows in companies (**Brown** - 3 KTPs with AstraZeneca; **Hanna** - KTPs with Infineum, Cryogenic).

v. Welcoming company staff (e.g. from Arcinova, Element Six) to use our facilities as *Visiting Professors/Researchers*.

vi. IAA funds have been used to employ *consultants* e.g. to advise on creating Sonic Driver Ltd. from Dixon's ultrasonics research and setting up its manufacturing capability [ICS-2].

vii. *Protecting IP*, with support from R&IS/WI to create initial NDAs, negotiate contracts for partnership activities, registering 43 new patent applications, and creating 10 new license agreements.

viii. *Training* researchers in entrepreneurship and identifying a market, through courses for staff, within doctoral training, and especially the ICURe scheme for ECRs (REF5a-2.8) experienced by three staff resulting in *spinouts* EddySense, Advanced Epi. and Cytoswim.

ix. Academic *promotion criteria* have been revised to explicitly reward engagement with external stakeholders and generation of impact – impact featured in eight successful promotions, including four to Professor.

g) Engagement activities are supported financially and logistically, ranging from bottom-up networking events for academics and industry on specific topics, branded as "Physics Days", to international meetings utilising Warwick Conferences' excellent facilities. Internal "Impact Days" highlight the range of potential impactful activities to PhDs, PDRAs, academic staff and support teams, create networking opportunities and inspire others to engage, thereby ensuring vitality and sustainability. Physics originated external facing "Industry Days" on specific themes to promote collaborative research (§4.2a). These now extend across STEM and have directly led to staff secondments and new projects. **Newton** (Conference Chair) organises The Annual Diamond Conference in partnership with De Beers (held at Warwick since 2009), attracting over 150 academics, equipment manufactures and end users of diamond products. Networking from this event underpins the DST-CDT, external funded use of the Spectroscopy RTP, and ICS-3/5. Annual CIU meetings and focus groups, attended by industrial partners and local MPs since 2011, have led to more than 20 industry collaborative projects [ICS-6].

h) Societal impact is generated from enhancing public knowledge of our exciting science. Research-based and educational outreach is delivered enthusiastically to schools, the general public, and industry across all our main research themes (§4.3).

1.5 Open research environment

a) Research papers are made available Open Access either before or immediately after publication on preprint servers, arXiv, INSPIRE, ADS and/or our institutional repository WRAP (REF5a-2.10). Gold OA is enabled where funding is provided by the research sponsor.

b) We follow the Concordat on Open Research Data (2016). **Thomas** chaired the Open Research Data Task Force, making recommendations to Government to benefit from open research data more rapidly. Examples of our engagement with open data:

- Researchers deposit publication data in WRAP as a permanent archive with persistent DOI.
- The large consortia (e.g. ATLAS) and international facilities we use all have data sharing agreements.
- SuperWASP data acquired since 2004 is available via the NASA Exoplanet Archive; 18 million lightcurves can be interrogated; papers on WASP planets have appeared at a rate of 34 p.a. throughout this REF cycle.
- The SDSS-V Science Archive is seen as its main product; previous SDSS data releases led to >10,000 papers.
- GOTO will survey the whole sky regularly, and publicly share discoveries in near real-time to maximise opportunities for studying the relatively short-lived events it discovers. Its survey dataset will offer a legacy archive for a broad range of time-domain astrophysics.
- NGTS releases reduced data products through the European Southern Observatory (ESO, our host) archive.
- XMaS follows the generic ESRF data sharing policy; raw data is backed-up on tape after 6-months with associated metadata, and made publicly available after three years. Commercial users pay an access fee for data rights; no copies are retained to protect the data.
- The National Facility for High Field ssNMR retains raw and processed data at the spectrometer, with daily backup. Users access their data remotely from protected directories, with confidential data invisible to others. After a period, non-proprietary data becomes public.
- For data intensive activities, only the code and parameters are stored, as rerunning a simulation is more economical than storing TBs of output data.
- Software is developed as Open Source (§3.4b) and made publicly available for non-commercial use [ICS-1].

1.6 Support for a culture of research integrity

The University Research Integrity and Ethics Committee (REF5a-2.4/2.5/2.11), which **Leadley** chairs as DPVC for Research, ensures the Concordat to Support Research Integrity is followed and provides ethical approval for research projects; esp. in medical and biological physics. All researchers (and PhDs) are required to complete Epigeum's Research Integrity training alongside modules on ED&I and Unconscious Bias. Guidelines have been developed to enable international collaboration within the Trusted Research framework.
Warwick supports the Technician Commitment (§2.1k) and the principle of fair attribution.

2. People

2.1 Staffing Strategy and Development

a) Our staffing strategy has been to expand while ensuring long-term sustainability. This has been achieved by (i) primarily recruiting at Assistant Professor level and developing staff internally; (ii) confirming indefinite positions for Senior Research Fellows who have either attained independence or remain vital to delivering our research; (iii) attracting holders of prestigious fellowships, and retaining them with indefinite positions – nine joined in the period. In total, 44 substantial fellowships have been held:

UKRI	Future Leaders Fellow Stephen Hawking Fellow	Cegla*, Lyman*, Richards* Nealon*
EPSRC	Career Acceleration Fellow Established Career Fellow Leadership Fellow Daphne Jackson Fellow	Datta, Goddard, Lloyd-Hughes, Quigley Dixon*, Sloan* Turner Spiga*
STFC	Ernest Rutherford Fellow	Armstrong*, Kenzie*, Veras*, Vesterinen*
Royal Society	Dorothy Hodgkin Fellow Industrial Fellow University Research Fellow	Meru* Dixon* Blake*, Morley*, Kennedy*
RAEng	Industry Fellow Research Fellow	Dixon Green*
Leverhulme	Research Fellow	Gänsicke*, Kapourniotis, Marsh*, Meru, Oates, Turner*
1851	Research Fellow	Knee
ERC	Advanced Grant Consolidator Grant Starter Grant	Gänsicke, Nakariakov Farrington*, Goddard*, Levan*, Vesterinen* Edwards, Gershon, Tremblay*
Fulbright-Lloyds of London Scholar		Chapman
Humboldt	Research Award	Alexe*
Wolfson	Research Merit Award	Alexe, Pollacco, MacPherson*

*Table 2.1 Fellowships held. *current awards*

The 28 indefinite appointments since REF2014 are designed to:

- Strengthen TP – **Datta** (2015, quantum measurement), **Hine** (2015, materials modelling), **Bartok-Partay** (2019, materials modelling, 50:50 with SoE)
- Enhance CMP, refocussing and linking existing staff – **MacPherson** (2017, THz/medical), **Broome** (2018, 2D materials/quantum), **Milot** (2018, THz/photovoltaics).
- Develop EPP, opening opportunities for new projects – **Mitra** (2016, hardware), **Marshall** (2018, neutrinos), **Vesterinen** (2018, LHCb), **Facini**, **Becker** (2019, ATLAS), **Kenzie** (2019, LHCb), **Richards** (2019, neutrinos).
- Grow astrophysics, especially exoplanets – **Tremblay** (2015), **Armstrong**, **Bayliss**, **Brogi**, **Kennedy**, **Veras** (2017), **Meru** (2018), **Cegla**, **Lyman** (2020).

- ❖ Confirm independence/secure indefinite positions for prominent research fellows – **Blake** (EPP), **Broomhall** (CFSA), **Bikondoa**, **Green**, **Iuga** (CMP).
- ❖ Create indefinite positions for critical facility support staff – **Goffrey**, **Bennett** (CFSA), **Ciomaga-Hatnean**, **Li**, **Walker** (CMP).

Six of these are women (21%), increasing the fraction of female staff submitted to REF2021 to 16%, in line with our long-term EDI strategy to promote women's careers in Physics.

b) Our 2019 Strategic Renewal set a staffing strategy to 2030, with posts identified to recruit at three Gateways along with new areas of expansion once additional space and facilities become available via Warwick's STEM Grand Challenge (REF5a-4.2). The immediate next priority is to expand time-domain astronomy, emphasising GW follow-up, and CMP in 2D materials, quantum science and NMR, with appointments in 2021/22 (after a Covid-induced delay).

c) Staff are highly satisfied working in Warwick Physics (80% positive, Pulse Survey 2019), with very few leavers (5) in the period, demonstrating the attractiveness of the research environment and collegiality of the department. Four professors left, two for family reasons – **Levan** taking a position in Nijmegen and **Farrington** in Edinburgh; McConville moved to Australia as a PVC; Paul sadly died in 2019.

d) Our flexible workload model accounts for funded research time in distributing administrative and teaching duties, including allowances for staff with caring responsibilities, running facilities, or management roles. Staff can take short periods away, to perform experiments at international facilities/telescopes, coordinate major projects, deliver external courses, or contribute to impact.

e) Academic Leave has benefitted 22 staff, most taking a full year to enable research collaboration with an overseas institute, take up an award (e.g. Leverhulme Fellowship, Fullbright Scholarship), build institutional links, or focus on particular research responsibilities (e.g. ATLAS Higgs coordinator). The 18% taken by female staff fully-reflects the population. Exchanges with industry are also facilitated via Impact Leave, KTP Associates, EPSRC and Royal Society Industry Fellowships. Industry personnel are able to use University facilities by appointment as Visiting Researchers (§4.1a).

f) Rotation of staff through key departmental committees improves representation, builds resilience and provides development opportunities to ensure sustainability. Active succession planning has enabled Marsh and Harrison, who founded the A&A and EPP groups in 2003/4, to transfer leadership of these expanding groups to **Steeghs** and **Barker**, respectively; **Leadley** was Deputy HoD for 5-years prior to becoming HoD in 2015 and will hand over to **Newton** in 2021.

g) Assistant Professors have up to six years of reduced teaching/administration, with mentoring and training, to establish their research activity; promotion to Associate Professor follows once probation criteria are satisfied. New appointees receive a start-up package, including a funded PhD studentship to grow their research group.

h) Development for researchers is encouraged at every career stage. Warwick follows the Concordat to Support the Career Development of Researchers (REF5a-3.3). Contract research staff and PhD students are specifically represented at the Physics Staff Meeting, Research Committee, and Welfare & Communications Group (WCG). Physics postdocs hold monthly seminars, in addition to thematic seminars in research groups. Warwick's Institute for Advanced Studies (IAS, REF5a-2.9.2) provides Early Career

Fellowships to support PhDs transition to independent postdoctoral research careers, and Associate Fellowships for PDRAs to join a diverse, respectful and mutually-supportive interdisciplinary community. ECRs are supported in fellowship applications, with successes shown in Table 2.1. More senior staff can develop management skills through the Warwick Leadership Programme. All staff (including PDRAs) have an annual Personal Development Review that includes setting research goals, identifying training needs and long-term career mentoring.

i) 58 academic staff have been promoted (98% success, REF5a-3.3), including 27 of the 35 non-professorial staff submitted to REF2014 (including all the women). Eight have been promoted twice, and one three times (becoming the department's fifth female professor). Five more-recent appointees have already been promoted, two twice. Twelve senior postdocs became Senior Research Fellows, recognising their growing independence. Further along the Research-focussed track, four became Principal Research Fellows and 3 full Professors. 32% of promotions on this track were female.

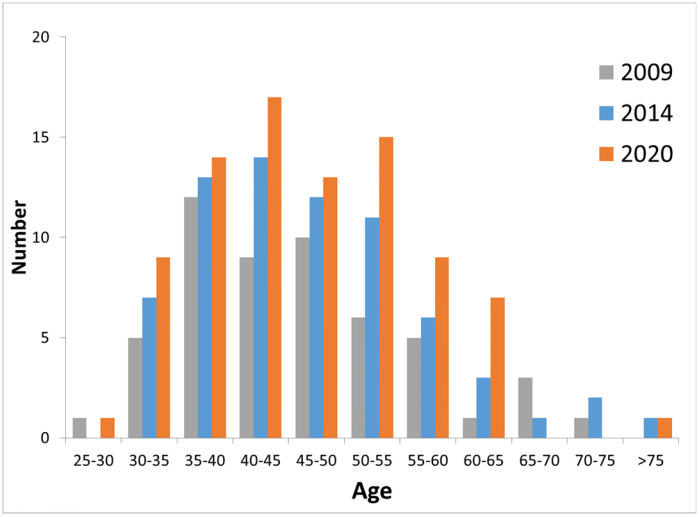

Figure 2.1: Age profile of independent researchers.

j) By predominantly recruiting ECRs, the demographic profile of independent researchers (Fig. 2.1) retains a median age of 46. On average, women and men establish a permanent academic appointment at age 31.6 and 33.9, respectively. This two-year difference persists through promotions; 33% of both male and female academic staff are Professors, with women reaching that grade at 42.6 and men at 45.0.

k) Warwick upholds the Technician Commitment to ensure visibility, recognition, career development and sustainability for technicians in HE. We co-lead the TALENT programme (REF5a-4.3.2) for the eight Midlands Innovation (MI) universities, with £3M of Research England funding, to enhance career opportunities and recognition for technicians. In 2015, MI founded the UK Higher Education Technicians Summit, attracting over 700 delegates in 2019, and recognises technicians through Papin Prizes which have been won by our Building Services Manager and two electron microscopy technicians. We have a rolling programme of appointing trainee and apprentice technicians, who rotate through workshops and research groups.

l) Staff are rewarded for their achievements in research and impact through external prizes (§4.4b), annual Merit Pay and institutional awards, e.g. Astrophysical Transients won Team of the Year 2018, Pollacco for Research Excellence 2016.
Physics instigated an annual prize for the best PDRA paper, which has now been replicated across the whole science faculty.

2.2 Research students

a) 253 research students were recruited in the period. Studentships are openly advertised, with applications encouraged from under-represented groups: the diverse postgraduate population is now 30% female, 25% BAME and 34% international. The current population of 167 PhDs exceeds a PhD:staff ratio of 2:1, is an increase of 30% over the REF period, and includes a student for all new staff. A further 19 PhDs registered in other departments are co-supervised by 10 Physics staff, representing 7% of the UOA supervisory load. Each year, about six complete an MSc by Research, with several subsequently enrolling for a PhD.

b) Studentship funding comes from a multitude of external and internal sources: EPSRC DTP/CDTs and STFC quota awards support the majority; Royal Society URFs secured 5 additional studentships; 4 came from ERC grants, and 27 were industry funded. Warwick has invested £4.1M for PhD scholarships in physics: 14 international students won University Chancellors Scholarships or partnership funding with Monash and EUTOPIA; 25 from department's own funds; WCPRS enabled 11 studentships to be 50% funded with companies and central facilities (ILL, Diamond Light Source, ISIS, Cockcroft), including 3 AWE employees studying part-time.

c) Physics staff lead three interdisciplinary CDTs (§1.3). Students in each CDT are separately recruited and have dedicated programmes of taught courses and cohort activities.

i. HetSys-CDT (Director: **Staunton**) spans all STEM areas, has 15 industrial partners and connections to 14 international research centres. HetSys exposes students to real world scientific computing challenges, including immersive challenges on actual problems that benefit the industrial partners, and ensures they gain the necessary theoretical/computational skills to contribute in a wide range of areas/careers.

ii. DST-CDT (Director: **Newton**) involves 10 UK universities and over 30 companies exploiting diamond. Initial cohort teaching at Warwick, followed by regular group activities and the annual Diamond Conference maintains student cohesion across multiple sites. DST-CDT follows the successful Integrated Magnetic Resonance CDT model (active to 2016). Graduate destinations include De Beers, NPL, E6, III-V Catapult, M2 lasers, and PDRA positions.

iii. AS-CDT (Director: **Brown**) exploits Warwick's world-leading analytical science facilities and expertise, together with external facilities at partners (e.g. Diamond, ILL, ISIS) to train PhD students in STEM, life and medical sciences, in close partnership with industry (e.g. AstraZeneca, Lubrizol, Syngenta).

Both DST- and AS-CDTs were created in 2013 with EPSRC funding, and are now self-supporting through strong industrial engagement and commitment from Warwick.

Ball, **Turner** and **Alexander** contribute to delivery and management of EPSRC Mathematics for Real-World Systems CDT, which involves Computer Science, Maths, Statistics and 25 external partners.
Polin and **Kantsler** contribute to the MRC Interdisciplinary Biomedical Research DTP, with WMS, SLS Computer Science and Statistics.
Warwick is one of six partners in the EPSRC CDT in Future Innovation in Non-Destructive Testing (FIND-CDT), led by Bristol which continues the RCNDE CDT, that also includes

49 international companies such as EON, EDF, Airbus.
Sanchez is on the advisory board for the EPSRC CDT in Compound Semiconductor Manufacturing.
The Centre for Postgraduate Training in Plasma Physics and High Energy Density Physics has provided training for CFSA PhDs, alongside those at Oxford and Imperial, in collaboration with RAL, AWE and CCFE, since 2014.

d) All postgraduates are assigned a primary and second supervisor. Each also has a "feedback supervisor", from outside their research area, who monitors progress. Students on industrial projects, or working away from Warwick (e.g. at ILL, ESRF, CERN), also have external supervisors. Additional support and guidance is provided by the Director of Graduate Studies (DGS), Postgraduate Coordinator, and through the University's Doctoral College (REF5a-3.10).

e) Students are trained in graduate-level physics via our Physics Graduate School (PGS) and develop transferable skills via Doctoral Skills (DS) courses, or equivalents within a CDT. The PGS provides a broad knowledge relevant to their research and expands their horizons beyond the immediate field, with modules from the Midland Physics Alliance Graduate School, Warwick-specific graduate-level modules, and external national/ international courses (e.g. STFC Summer Schools, ILL courses). Widely transferrable skills develop via DS activities include scientific writing, research ethics & integrity, project management, teaching, and team-working. The University developed SkillsForge for students to build their skills portfolio, perform development needs analysis, and discover additional training opportunities. DS activities contribute to the PG Certificate in Transferable Skills in Science, which is accredited by institutions including the IOP and maps onto CPhys requirements. Progression is monitored via interviews, cohort activities (posters & seminars), and tracking students' training portfolios.

f) Research students are fully integrated into the department's research culture. Every student has their own office space, with postdocs and other members of their research group. Each group has a seminar programme, including opportunities for student presentations. A postgraduate-only seminar series encourages informal interdisciplinary collaboration. An annual research symposium showcases their research. The Postgraduate Student Staff Liaison Committee meets twice termly to highlight and solve issues, e.g. students wanted additional mental health support and consequentially established a weekly well-being café.

g) We prioritized postgraduates in planning Covid-safe laboratory research and provided funded extensions for all those whose progress had been affected.

h) PhD students can contribute to undergraduate teaching and demonstrating. Initial training for teaching contributes to DS activities; extending this training with self-reflection leads to HEA Associate Fellowship. Revised employment contracts as Graduate Teaching Assistants now fix hours at the start of a year and provide greater security. Warwick Awards for Teaching Excellence have regularly been won by physics postgraduates.

i) Following introduction in Physics, a Faculty prize is awarded annually for the best thesis in each discipline. In addition, we nominate a Springer prize-winner and an astrophysicist for a Winton Capital prize.

j) 252 doctoral degrees have been awarded (REF4a: 222.29 FTE). After completion, 38% take up postdoc positions in prestigious universities around the world e.g. EPFL, Harvard, Oxford, NTU, Princeton, or are employed in a diverse range of occupations outside of

academia: scientific research (22%), computing, finance, consulting, teaching, patents etc. Advice is available from physics specific careers counsellors on academic and non-academic pathways. As well as University employment events, we run an annual PhD Careers Fair with representatives from employers, including Warwick alumni.

k) Several PhD students have founded their own companies e.g. Overleaf, a LaTex development environment; Luxembourg Ion Optical Nanosystems, helium ion microscopes (HIM SIMS).

2.3 Equality, Diversity and Inclusion

a) As detailed above, EDI is embedded in everything we do and recognised by Athena Swan Silver and IOP Juno Champion awards held and renewed in the REF period. Furthermore, Physics staff contributed strongly to promoting EDI across the University and the AS institutional Silver award (REF5a-3.4, **Thomas** lead author, **Leadley** on SAT, **Bell** on Gender Taskforce). EDI is a central agenda item for WCG, chaired by the HoD, but is also considered at all levels of decision making and represented in the make-up of departmental committees. We have now moved the EDI discussion beyond the male/female dichotomy to be fully-inclusive of all diversity and benefitting the entire staff, as seen in the highly positive staff survey results.

b) Advertisements for recruitment are written in inclusive language, with the option of part-time offered for all posts. All staff involved in short-listing and interviewing complete training in EDI and Unconscious Bias. Single gender shortlists require express HoD permission. Recruitment, progression, rewards, invited speakers are monitored for inclusivity and reported annually to all staff against our Juno/Athena Action Plan.

c) Health and Safety of staff and students is led from the HoD through a departmental H&S Committee with representation from academics, technicians and postgraduates. Protocols for risk management developed within Physics have been adopted across the University and the department has gained OHSAS 18001 certification.
We signpost to Wellbeing support (REF5a-3.4) for staff and students, including a 24/7 Employee Assistance Programme.

d) Staff with caring responsibilities, or returning from illness, are offered additional support (REF5a-3.4). Maternity leave (12 instances) of up to a year, including paid Keeping-In-Touch days, can be followed by an equal period of Warwick Returner's Fellowship to re-establish active research, with options of part-time working. Two staff have been supported in returning to scientific research with flexible Daphne Jackson and Dorothy Hodgkin Fellowships. In the last five years, 16 researchers have taken paternity leave and four have shared parental leave; three male staff have taken career breaks. Funds are provided for childcare to enable conference attendance for both staff and PhDs.

e) In preparing this REF submission, we followed the University COP (REF5a-3.5) to assess independence of researchers. A mixed gender panel selected on average 3.00 (2.34) Outputs from each female (male) submitted; BAME staff each contributed 2.75 Outputs.

3. Income, infrastructure and facilities

3.1 Research Funding

a) Research Income has grown steadily: **£67.3M** of income was received during the census period, with an average annual income 20% greater than REF2014. UKRI provides 76% of our funding: £30M from EPSRC; STFC funding doubled to £17.5M, in line with our targeted expansion and included £12.5M of Consolidated Grants for A&A, CFSA and EPP. £8.7M of EU funding was received and £4.4M came from industry/Innovate UK.

b) Income in-kind is vital to our research, contributing the equivalent of **£113.3M** for competitively reviewed international facility time (123% greater p.a. than in REF2014). In addition to £60.1M recorded in REF4c, we used £53.2M of non-UKRI sponsored facilities:

Facility	Name	Usage		Value £
		million AUs	months	
HPC	ARCHER/HECToR	500	+ 18	3,238,246
	Marconi fusion	420,000 node-hours		381,818
	HPC Mid+	20		357,015
	Cirrus	5		184,500
	BlueJoule, Hartree Centre		6	20,000
	DiRAC	value		10,320
	Isambard	"		6,776
		Days		
Synchrotrons	ELETTRA, Trieste	153		767,000
	SPring8	105		616,440
	NSLS-II, Brookhaven	69		225,000
	ANTARES, Soleil	30		152,000
	APS, Argonne	12		183,846
	Heinz Maier-Leibnitz (FRM II)	18		65,000
	Helmholtz Zentrum (XPP)	7		35,000
	Swiss Light Source	5		25,000
Solar Observatory	Big Bear	23		176,923
	Swedish Solar Telescope	20		65,455
		Nights	Orbits	
Telescopes	HST (full value)		307	23,615,385
	ESO, 3.6m	72		666,667
	CAHA	2		20,000
	TNG (via Italian GAPS)	144		900,000
	Observatoire Haute Provence	9		45,000
		Shifts	Days	
X-ray & free electron lasers	FELIX	7		15,000
	LCLS, SLAC	24		5,538,462
	NIF, LLNL		7	8,076,923
	European XFEL	15		6,136,364
	OMEGA, USA		3	230,769
	PHELIX, GSI Germany		20	490,909
	FLASH, DESY Germany		6	272,727
		Weeks	Hours	
Magnetic Fields	NHMFL, Florida	8		131,700
	HMFL, Nijmegen		80	203,636
	LANL, pulsed fields	20		308,000

We make significant use of:

- High performance computing (HPC) allocations worth **£3.82M** – Tier-1 HECToR/ARCHER; Tier-2 Dirac, Cirrus, Isambard, Mid+.
- CMP facilities – X-ray synchrotrons (ESRF, Diamond, Elettra, SLS, ANTARES, APS, NSLS, SPring8); neutron sources (ILL, ISIS, PSI); high magnetic field labs (Grenoble, Nijmegen, Los Alamos Tallahassee); NMR and free electron laser (FELIX). **£17.0M**.
- Solar observatories (Big Bear, Swedish SO & Goode solar telescopes), space probes (SDO, STEREO, Hinode, Parker Solar Probe, Solar Orbiter) and radioheliographs (SRH, eOVSA). The solar community generally shares data freely so these are not directly costed.
- A wide range of telescopes, both ground (VLT, NTT, ALMA, ING, LT, GTC, VLA) and space based (Chandra, XMM, HST). Warwick received one of largest allocations outside USA of 307 Hubble Space Telescope orbits. NASA assumes $100k/orbit, rather than the UK Space Agency contribution of £4.3k/orbit used in REF4c, valuing our HST use at £23.6M. **£35.0M.**
- X-ray lasers for plasma physics, with shots valued at **£20.8M**.
- Particle physics at CERN (ATLAS and LHCb) valued at **£35.1M**.
  Our extensive participation in neutrino experiments, T2K, MICE, ProtoDUNE, is not directly costed.

c) Research Awards continue to increase, averaging £12.8M p.a. (£5.7M p.a. for REF2014). 32% of T&R staff time, and 79% for research-focussed academics, is now recovered from external grants. £21M of awards in 2019/20 secures our future Research Income.

d) Investigators are directed to relevant funding opportunities, with R&IS (REF5a-1.7) support throughout the application. Warwick's flexible approach enables us to access opportunities at short notice. An especially successful aspect of our funding strategy has been to guide internal and external fellowship candidates, which netted **£18.5M** (including £6.4M of ERC grants).

e) ECRs have been mentored to obtain independent resources, e.g. **Brogi** received an STFC New Applicants grant in 2018; **Milot** won an EPSRC New Investigator Award in 2020. A £2M EPSRC award purchased underpinning multi-user equipment for ECRs. Postdocs have been helped to establish independence, e.g. 1851 Fellowship for Knee; Leverhulme ECFs for Oates, Kapourniotis; Daphne Jackson Fellowship for Spiga.

f) Over **£20M** has been invested in postgraduate research training, from a wide range of sources (§2.2b). £4.1M of Warwick's own funds has ensured all new staff recruit a student within their first two years. Industrial funding of £1.8M, particularly in NMR, diamond, ultrasonics and plasma physics, has contributed to postgraduate research reflected in our ICSs.

3.2 Strategic Investments in Astronomy

a) Growth of exoplanet science has been a strategic focus. **Pollacco** has been the driving force behind ESA's adoption of PLATO as the third medium-class mission in their Cosmic Visions programme. PLATO's main goal is detection/characterisation of terrestrial planets within the habitable zone of Solar-like stars. It will also characterise thousands of rocky, icy, and gaseous planets, investigate planetary system architectures,

and perform asteroseismology of thousands of stars, requiring ultrahigh precision, uninterrupted, photometric observations for periods up to several years. PLATO includes over 500 researchers from 14 ESA Member States. To coordinate scientific activities, Pollacco established the PLATO Science Management project office in Warwick, with two permanent scientific administration posts. New exoplanet researchers have been recruited (§2.1a) to establish significant research activity now, in preparation to reap maximum benefit from PLATO observations after 2026. Warwick has received £2.2M of PLATO income to date.

b) **Wheatley** leads the wide-field, ground-based Next-Generation Transit Survey (NGTS) at the Chilean Paranal Observatory. NGTS is a consortium with QUB, Leicester, Geneva, DRL and three Chilean universities. An array of 12 small fully-robotic telescopes operate at 520-890nm, maximising sensitivity to bright but relatively cool/small host stars. The unprecedented photometric precision (150 ppm) has enabled the discovery of exoplanets as small as 3 Earth radii. Combined with long-period observing capability, NGTS will enable detailed follow-up of candidate planets from survey instruments such as TESS. Warwick invested £370k to initiate NGTS and has subsequently received £2M from STFC for construction and operation.

c) The original SuperWASP instrument on La Palma has been repurposed primarily to study the near-Earth environment. As more satellites are launched, it is increasingly crucial to map and understand the nature of space debris, and minimize the impact on satellite operations. Over £2.5M has been invested in partnership with UKRI, DSTL and several SME's.

d) Building on our heritage of developing small, highly capable observatories, the Gravitational-wave Optical Transient Observer (GOTO) is a wide-field robotic telescope designed to rapidly search large areas of sky for transient optical sources. It is optimized, and synchronised, to respond to GW events detected by LIGO/VIRGO. GOTO's first phase, consisting of 4x40cm telescopes on a single mount to provide a 20 square degree field-of-view, has been deployed on La Palma, with £300k of Warwick funding and £1M contributions from 9 partners (§4.1b). 46 GW triggers were followed-up during LIGO/VIRGO Science Run 3 in one of the most comprehensive searches, typically spanning ~1000 square degrees. A further £3M of STFC funding now allows us to both double the La Palma instrument and build a Southern Hemisphere counterpart in Australia to complete the 32 telescope, 2-node configuration. The GOTO consortium is led by **Steeghs** and was pivotal to **Lyman's** FLF.

e) HiPERCAM has been developed, from UltraCAM by **Marsh** and Dhillon (Sheffield), as a portable, fast-transient camera with five spectral channels for mounting on large telescopes. HiPERCAM was deployed as a visitor instrument on the 4.2m WHT and 10.6m GTC telescopes in 2018. Over 200 papers have been published using UltraCAM data, with 2500 citations to date. These unique instruments observe black holes, white dwarfs, neutron stars, brown dwarfs, extrasolar planets/asteroids, AGN, FRBs, GRBs, SNe, ultra-diffuse galaxies and even planetary occulations. The related ULTRASPEC instrument now has a permanent home on the 2.4m Thai National Telescope (TNT), providing Sheffield and Warwick with 30 nights/year on the TNT in return for access to ULTRASPEC for the Thai astronomical community.

f) We have invested over £1M during this REF cycle for staff to join consortia, placing **Gänsicke** as a founding member of SDSS-V, and most recently **Cegla** joining HARPS3 and TerraHunter.

3.3 Strategic Investments in Condensed Matter

a) Millburn House Magnetic Resonance Centre contains 12 magnets for solid-state NMR and DNP from 2.3T (100MHz) to 23.5T (1GHz), with a large array of probes for magic angle spinning (up to 111kHz), static NMR and DOR. **Brown** directs the UK National Research Facility (NRF) for High Field Solid State NMR, with an 850MHz system serving the physical and life science communities since 2010. The NRF provides high-quality intellectual and scientific support via the Facility Manager, **Iuga**, who has his own scientific activity. It runs 24/7 with 85% of instrument time allocated to its 50-75 regular users; it also trains ~20 PhD students p.a. The NRF has enabled 115 publications and over 500 conference presentation. Considerable impact [ICS-4] flows via insight from ssNMR of technological importance to industries such as pharmaceutical (AstraZeneca, GlaxoSmithKline), oil/fuel (Infineum, Sasol), and catalysis/materials (BP, Johnson Matthey). These companies access the NRF either via paid-for contract research or industry-supported PhD students. In 2020, the NRF was enhanced by the UK's first 1GHz (23.5T) ssNMR spectrometer, funded by £8M of a £20M EPSRC investment in NMR equipment that **Brown** coordinated across UK institutions. Warwick has invested a further £1M to build the supporting infrastructure.

b) XMaS: The UK Materials Science National Facility at the ESRF, co-directed by **Hase** (with Lucas, Liverpool), has provided free-at-the-point-of-use access to synchrotron radiation since 1997. XMaS provides over 3400 hours of beamtime p.a. to 110 UK and international users, with 40% being new users and 50% ECRs. Diverse scattering/ spectroscopic experiments can be performed in a wide range of sample environments; an offline X-ray -source also enables use of these when the ESRF beam is unavailable. In 2019, the ESRF Enhanced Brilliance Source upgrade necessitated significant engineering changes and a complete overhaul of XMaS (after 20 years' continuous operation) with a capital injection of £2M. XMaS reopens in 2021 with enhanced operational capabilities, new detectors, and a refurbished diffractometer to exploit the extended X-ray energies (2-40keV), 75x increased brightness, and 10x smaller beamsize.

c) Extensive local facilities for analytical science developed within Physics, in electron microscopy, X-ray diffraction, and spectroscopy, have been transformed into Research Technology Platforms (RTP) available across the University and externally (REF5a-4.3). Over £10M of capital investment since 2014 has upgraded equipment in the physics-based RTPs. Each RTP has an academic Director and a dedicated technical Facility Manager to ensure smooth running of the equipment, high-quality service and training for users, development of new techniques, and promotion of interdisciplinary research. Physics researchers have free-at-the-point-of-use access to the RTPs, to maximise equipment usage, with actual usage logged and charged to grants where possible or otherwise underwritten by the department; this is especially important to enable access for PhDs and ECRs without their own funds. External RTP use is enabled through simplified WSS contracts, with 34 different universities and 84 companies using £813k worth of facility time since 2014. A joint Physics-Chemistry facility for X-ray photoelectron spectroscopy (XPS) and ARPES operates in a similar manner.

d) The Warwick Single Crystal Growth facility produces high-quality crystals of magnetic, superconducting and related material that provides samples to over 50 groups worldwide. Sustainability of the facility has been secured by over £1M of EPSRC investment, and by Warwick providing an indefinite post for Ciomaga-Hatnean. This has enabled major projects on Skyrmionics and Topological Insulators, amongst others, receiving £2.5M of external funding, leading to 124 publications, and over 4,000 citations since 2014.

e) We have invested £1.5M in multi-user facilities to set-up new appointees including: a laser lithography system for rapid device prototyping and material characterisation, creating for example ferroic devices (**Alexe**) and 2D lateral heterojunctions (**Wilson**, **Broome**); a flexible low temperature, tuneable laser facility for quantum state manipulation in 2D materials (**Broome**) and diamond NV centres (**Green**); microfluidics and optical microscopes to study cell motility for physics of life, biofilms and antimicrobial resistance programmes (**Kantsler**, **Polin**).

f) **Alexe** established a unique scanning probe microscope with a vector magnetic field, pulsed laser illumination, and variable temperature, via a 2015 EPSRC Strategic Equipment grant. Together with start-up funds for pulsed laser deposition, this has leveraged £3.2M of funded research on ferroic materials and devices, producing 46 papers cited over 1,000 times.

g) The Warwick Centre for Ultrafast Spectroscopy (WCUS) is a joint Physics/Chemistry femtosecond laser facility established in 2016, with an EPSRC Strategic Equipment grant (£620k) and matched investment (£510k). The 40fs laser is split into four beamlines to study molecules and materials across a broad spectrum (UV to THz) and in a variety of environments. Directors **Lloyd-Hughes** and Stavros (Chemistry) are supported by a dedicated facility manager to make this resource widely available. In 2019, 30 research groups used 3,400 facility hours, included 357 hours by external academics and 830 hours by industrial partners (e.g. Lubrizol, Newport, Syngenta, DeBeers). We further invested in THz spectroscopy by appointing **MacPherson** and **Milot**, with additional spectroscopy equipment in their start-up packages. £1.25M of external grants have already been won for THz studies, including **Milot's** New Investigator Award on metal halide perovskite devices, **MacPherson's** investigation on cancer prevention/treatment with a THz skinometer, and **Lloyd-Hughes** investigating multiferroics. Recent science highlights include work on efficient THz modulators and real-time THz imaging, and the first studies of the ultrafast dynamics of 1D van der Waals heterostructures.

h) Warwick is a leading UK centre for diamond research, exploiting diamond's unique properties for industrial applications, quantum technology and, of course, jewellery. The DST-CDT brought together >20 partners from across universities and industry. Diamond research, investments in spectroscopy, and collaboration with companies, such as Element Six, GIA, De Beers, Hach and DSTL has led to impact in diamond sensors, on lab-grown jewellery [ICS-3], and automated gemstone verification [ICS-5]. Experiments on NV centres took us into quantum technology, theory of quantum measurement, and development of highly sensitive magnetometer. This area of has received £4.2M of research funding, plus £4.5M for the CDT.

3.4 Strategic Computing Infrastructure

a) HPC is used extensively for simulation and modelling across all our research areas – from materials, through fusion plasmas, to particle collisions and solar system formation. The Scientific Computing RTP, directed by **Quigley**, provides shared Tier-3 HPC across the University, including 11,000 cores for parallel processing, 10PB storage, and a Linux-based desktop/server infrastructure for research computing. The principal machine is refreshed/replaced on a two-year cycle, with annual investment of over £1M, which in 2019 included a further £1.8M for a new energy-efficient machine room. Warwick is a leading partner of the HPC Midlands+ consortium that installed national Tier-2 HPC in Loughborough in 2016 and won a further £3M for the next machine, Sulis, installed in Warwick's new machine room in 2020. To benefit from this hardware, two Research

Software Engineers have been established in the SC-RTP to aid users professionalise their approach to research computing.

b) We lead development and support for a number of widely used codes, investing significant staff time: ONETEP (**Hine**) is a DFT code for electronic structure calculations; EPOCH (**Arber**) is widely used in plasma physics and has wide-reaching impact [ICS-1], a permanent position and promotion for its main author Bennett ensures sustainability. EPP staff (**Marshall**, **Morgan**, **Richards** and 3.5 PDRAs) develop: EvtGEN (b-physics generator), LAURA++ (Dalitz plot package), ToolDAQ (data acquisition/analysis for neutrino water-Cherenkov experiments), GEANT4 (particle interaction tracking through materials), and PANDORA (**Marshall**)which is becoming the code of choice for reconstructing particle tracks in neutrino detectors, esp. DUNE.

c) The wide interdisciplinary computing expertise in Warwick led to HetSys-CDT that trains students from across physical sciences to model complex real-world systems across multiple scales, motivated by the industrial partners, e.g. nanoscale devices, new catalysts, superalloys, smart fluids, laser-plasma interactions.

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

4.1 Collaborations and partnerships

a) In addition to the large EPP and astronomy consortia, we have over 600 active collaborations with academic institutes in all parts of the world and our researchers partner with more than 150 external companies/organisations. Collaborations have been built by individual contact, through joint projects and from institutional initiatives.

Physics staff have 34 Visiting/Adjunct Professorships at prestigious institutions worldwide, associated with research collaborations, many of which have deepened through Study Leave visits, have led to joint publications and delivery of innovative teaching.

We welcome incoming researchers, as short and long-term visitors. British Council schemes and Newton International Fellowships have enabled researchers from e.g. India, Brazil, Russia, Korea to visit. We regularly appoint, and review, Honorary/Visiting Professor/Researchers from academic and industrial collaborators (currently 84; 160 total since 2014), who contribute to our research, impact and teaching.

b) Physics has benefitted from the strategic institutional Monash-Warwick Alliance (REF5a-2.12.1): creating the Southern Hemisphere node for GOTO, with £3M of UK STFC funds, and separately leveraging Australian Research Council funding for OzGrav. The complementarity between Warwick's experimental EPP group and Monash theoreticians has enabled Monash to join the LHCb experiment, assisting Australia's progress towards becoming a CERN member state. Our theoreticians are active within the EUTOPIA strategic alliance: **Alexander** combines with Ljubljana experimentalists on liquid crystals topological defects and **Römer** collaborates with Cergy-Paris on disordered systems.

c) A&A use international observational facilities (§3.1) and lead consortia to develop new community facilities (§3.2b-e) and surveys (§3.2f). Their relationship with observatory staff at premier sites is key: working closely with the Instituto de Astrofísica de Canarias (IAC) we built SuperWASP, the Warwick 1m and GOTO (§3.2d) telescopes on La Palma; **Gänsicke** is on the Board of the Isaac Newton Group of Telescopes and **Steeghs** the International Scientific Committee for Canary Island Observatories. At Paranal, Warwick work with ESO to lead the NGTS consortium of six partners from the UK, Geneva and Berlin (§3.2b). **Steeghs** is on the Governing Council and **Levan** the Executive

Committee of ENGRAVE, a collaboration of over 250 astronomers using ESO facilities to research GW events. GOTO itself has nine partner institutions from the UK, Finland, Australia, and Thailand; close collaboration with LIGO/VIRGO allows us to receive real-time triggers and rapidly point GOTO at candidate GW events. **Pollacco** is Head of Science Management and Exoplanet Science Lead for PLATO (§3.2a), in which most Warwick exoplanet researchers are involved. **Brogi** is a member of the Italian GAPS consortium and associate of the Observatory of Turin. Multi-object spectroscopic experiments enable vast data sets to be recorded for eventual public release; **Gänsicke** is leading surveys in DESI, WEAVE, and SDSS-V, and **Tremblay** is part of 4MOST. As a founding member, **Gänsicke** directs the white dwarf science in SDSS-V.

d) CFSA has a longstanding collaboration with the fusion plasma theory group at CCFE, where **Dendy** (CCFE/Warwick) coordinates fusion research activities for UK universities with national and European projects. Dendy also leads activities with the Japanese National Institute for Fusion Science, Korean National Fusion Research Institute, and the MPI for Plasma Physics. CFSA's extensive participation in experimental fusion programmes includes JET/MAST at Culham, Euroatom and ITER.

Radio astronomers from China, Russia and India have benefitted from networks led by **Nakariakov**: "Radiophysics of the Sun", "Superflares on stars and the Sun". British Council funding initiated institutional links with the Space Research Institute of the Russian Academy of Sciences, and the School of Space Research, Kyung Hee University, Korea. He is also a member of the International Consortium for the Continued Operation of the Nobeyama Radio Heliograph, an associate investigator of NASA-SDO/AIA, co-founder of the heliospheric working group in the Square Kilometre Array project, and Co-I of Proba-3/ASPIICS.

Chapman is an associate investigator on ESA-Solar Orbiter/SWA. **Armstrong**, **Broomhall**, **Chapman**, **Nakariakov** and **Verwichte** participate in teams at the International Space Science institute in Bern. **Verwichte** also coordinates data-analysis for the UK consortium at the DKIST Solar Telescope, Hawaii. **Hnat** chaired the interdisciplinary EPSRC Network on "Emergence and Physics Far from Equilibrium". **Broomhall** is in the TESS and Kepler Astroseismic Consortia.

e) External collaborations in CMP are built around our unique materials analysis, modelling and synthesis capabilities. Extensive collaboration ensues from running the UK National Facilities for High Field ssNMR and XMaS, and local RTP facilities (§3.3). CMP staff perform measurements at 15 international facilities for synchrotron radiation, neutrons, muons, and high magnetic fields. The sample environment built for magnetic scattering by **Duffy** is available for all SPring8 users. **Wilson** contributed to creating Elettra's nanoARPES capability and subsequently to establish a UK facility at Diamond. **Hanna** established a joint doctoral programme in materials physics with NTU, Singapore.

Datta, **Green**, **Newton** and **Morley** have engaged with three of the four UK Quantum Technology Hubs, contributing on quantum measurements and diamond-based quantum technologies. Experimentalist and theoreticians combine their expertise on multi-institutional programmes, e.g. EPSRC Programme Grants on Crystallisation (Leeds led), Skyrmionics (Durham led) and Complex Nanostructures (Southampton led). CMP network through 7 EU COST actions, with **Balakrishnan** as vice-chair of three. **Leadley** was instrumental in setting up the SiNANO Institute (a Director until 2018) that united 18 European institutes in microelectronics research.

f) EPP are highly visible from their leadership roles in existing and future experiments. **Barker** is PI for DUNE UK (budget $1.5B, UK £45M, Warwick £1M) and chairs the DUNE UK Institute Board; **Marshall** is WP lead for event reconstruction software.

In LHCb, **Gershon** was Physics Coordinator and UK Spokesperson (2016-2020); group convenors include **Kreps** (Simulation), **Blake** (Rare Decays), **Latham** (Charmless B-Hadron Decays), **Kenzie** (Beauty to Open Charm), and **Vesterinen** (Semileptonic Physics & High-Level Trigger project leader). **Gershon** co-led the Heavy Flavour Averaging Group 2010-17.

Murray was ATLAS Physics Coordinator and now convenes the Higgs & DiBoson searches group; **Farrington** was UK Physics Coordinator 2016-18 and co-convener of HSG4 2013-15, where she oversaw publication of Higgs decay to tau leptons; **Facini** convened ATLAS Exotics 2016-18 (600 members), Exotics Jet & Dark Matter (200 members), founded the Cluster & Tracking in Dense Environments group and was Tile Calorimeter Coordinator; **Becker** has been Semiconductor Tracker Coordinator and convened working groups on several Higgs decay paths, now HSG4; Martin is Trigger Operation Coordinator.

Ramachers was SuperNEMO Physics Coordinator until 2018. **Boyd** was Operations Manager for MICE. **Richards** is Convener of Software & DAQ working groups at ANNIE.

g) In computing, **Arber** chairs the UK national Computational Collaborative Project (CCP) in Plasma Physics, the EPSRC High-End Consortium in plasma physics, co-directs the AWE-Warwick Centre for Computational Plasma Physics, and is on the DiRAC Management Board. **Quigley** chairs the HPC Midlands+ Strategic User Board and contributes to CCP5. **Staunton** chairs CCPmag for computational magnetism. **Brown** and **Bartok** support the multidisciplinary CCP-NC for NMR crystallography software. **Hine** is in CCP9, leads the ONETEP developers group for linear scaling DFT and the Car-Parrinello High-End Consortium for *ab initio* atomistic simulation.

4.2 Impact

a) Section 1.4 outlines our approach to developing impact. "Industry Days" showcase our expertise, highlight how we work with industry, and encourage industrial attendees to share their R&D challenges. Up to 700 have attended, 30% from industry, on topics such as Sensors, Sustainability, and Analytical Science. Their interdisciplinary nature has exposed companies working with a specific academic to other expertise within Warwick, e.g. Lubrizol expanded their engagement across the sciences and became headline sponsor for the 2019 British Science Festival. Cross-department industrial collaboration on conducting diamond based sensors for water quality monitoring resulted in a 2017 Royal Society Innovation Award to **Newton** and Macpherson (Chemistry). Providing easy and flexible access to our infrastructure and expertise, through various channels designed around industrial need, has directly led to the impact in four ICSs.

b) Opportunities for exploitation identified in the STFC area include a way to magnify vibrations in images, based on **Nakariakov's** solar plasma research, a predictive electoral voting programme arising from Harrison's Monte Carlo simulations, and UV-sensors developed jointly between EPP & CMP leading to the spin-out UVDyne. STFC-IAA funds seeded repurposing the wide-area WASP telescopes for tracking space debris (**Pollacco** & **Steeghs**), which now has considerable commercial interest from DSTL and other satellite operators. Furthermore, this led to the STFC Global Network

on Sustainability in Space (GNOSIS), coordinated by **Pollacco**, that brings scientists and industry together for discussion and seeding joint actions.

c) Collaboration with equipment manufacturers enrich our research environment. Our experts can access the latest equipment and showcase its ultimate performance through high impact science. Examples include long-standing relationships with JOEL and Bruker, for electron microscopes, NMR and EPR; Newport Spectra Physics helped design and setup WCUS's fast laser facility. **Beanland's** electron microscopy technique development has further benefitted JOEL by expanding their instruments' capabilities.

d) Warwick contributes to the development of major external science facilities, in the UK and overseas, to generate impact beyond the original field of research (§3.3). E.g. XMaS enriches research possibilities for industrial beamline users, and also holds nine commercial licenses to supply project-designed X-ray optics/instruments to synchrotrons worldwide.

e) Collaboration on real world problems with commercial partners further enhances the research environment by inspiring researchers. Industry inspired projects support 27 of our current PhD students and have been crucial to sustaining our CDTs. These partnerships also provide a route for employment e.g. recent PhD/PDRAs joining Astra Zeneca, De Beers, Infineum, Element Six, Rolls Royce and a range of SMEs; six have taken advantage of the KTP scheme to work across companies and university.

f) Our spin-outs (4), patent applications (43), and IP licensing agreements (10) all point to a healthy future impact pipeline. A flavour of these and examples of potential impact still at the pre-commercial stage follow:

- **Wilson** discovered graphene oxide makes an excellent support grid for TEM imaging. In 2019 alone, over 10,000 grids were made in Warwick and sold to an SME for distribution to end-users. Impact comes from employment of two people in the distributer, the improved measurements these end-users can make, the academic and commercial R&D it enables, and products that follow in fields from cancer research to environmental analysis.
- **Morley** developed quantum technology based on the spin of nitrogen vacancies in diamond to produce a highly sensitive magnetometer for medical and surveying applications.
- **Hanna's** ssNMR has contributed significantly to Johnson Matthey's battery materials and nanoparticle catalysis technologies, implemented in automotive/ marine engine emissions abatement and Fischer-Tropsch processes.
- **Kantsler's** microfluidics research on sperm cell motility has potential applications in livestock breeding. Through ICURe (REF5a-2.8) commercialisation opportunities were explored; this led to creation of CytoSwim, which now employs three people and is starting clinical trials in an incubator unit, with Innovate support.
- **Chapman's** expertise in analysing time-series, developed for space plasmas, has been applied to risk evaluation for extreme events, heat waves and climate change. **Arber's** plasma code is being developed for a European space weather forecast service. Aspects of plasma software (**Arber**, **Gericke**) are of particular interest to UK and US military.
- Expertise in XRD and corrosion science, together with XMaS and XRD-RTP facilities, contributed to cultural heritage investigation of artefacts from Henry VIII's Mary Rose warship, giving insight into Tudor brass production.

- Physics-based RTPs enabled 84 companies, from Aston Martin to Xerion Healthcare and including many SMEs, to increase their competitive advantage. For instance, access to skills and technology in the EM-RTP enabled Prima Dental, now the world's largest carbide bur manufacturer, to expand into design and manufacture of dental milling tools.
- The CIU has directly supported over 20 companies, with significant impacts in 15 [ICS-6].
- Through her THz imaging, **MacPherson** is collaborating with a suncream manufacturer to improve skin protection and developing new portable instrumentation for diagnosing and treating skin cancer with UHCW NHS Trust.

4.3 Public Engagement

Our extensive outreach and public engagement programme involves all groups of staff/students and aims to:

- ❖ improve scientific awareness amongst the public, in time impacting on society/policy;
- ❖ widely disseminate an appreciation of our research;
- ❖ excite young people by science, especially under-represented groups; encourage further study at school/university;
- ❖ support teachers to deliver engaging science lessons.

Physics has a full-time outreach post, originally established with The Ogden Trust. Our regular activities include: school visits with demonstration lectures, inviting schools on to campus (4,000 pupils); annual events – Primary Science Fair; School Physicist of the Year; Science Gala (800 guests, 2019); participation in national events like Big Bang and science festivals; residential workshops for under-privileged students, with Sutton and Smallpeice Trusts. While interaction with pupils is important, longer term impact comes from supporting, training and enthusing teachers. Our activities focus especially in local WP primary and secondary schools, often without physics-trained staff, by e.g. training 20 local science co-ordinators, raising enthusiasm at a struggling primary school, providing a framework for primary science projects.

Highlight activities:

- XMaS Scientist Experience – annually since 2015, 20 sixth-form girls visit ESRF for 4 days. Impact is made wider than the competitively selected group by pre-trip activities in school, post-trip presentations, involvement of participants in other events, and cohort follow-up. The model has been replicated by Lund University.
- Warwick Christmas Lectures – a Physics initiative, now an annual event across disciplines; 1,500 seat venue sold out twice in 2017; Christmas Lectures in 2020 were recorded as accessible videos (>2,400 views on YouTube).
- Live Q&A on space recorded in Leicester Prison for broadcast on National Prison Radio.
- Inception and delivery of Brownie/Guide Physicist Badge – local & national roll-out.
- British Science Festival 2019 hosted by Warwick – 17,000 visitors, prominent public talks from Physics staff, live Science of Music event in Coventry city centre, live appearance on BBC Sky at Night.
- Local pub-based Pint of Science – regular contributions particularly from ECRs/PhDs.
- International Masterclasses for Particle Physics – in the framework of CERN's International Particle Physics Outreach Group, connecting pupils across 60 countries every March.

- Online Atlas of Astronomy Groups, >12,000 views.
- Mobile planetarium – reaching >3,000 people in two years, Space Camp programme shortlisted for a Times Education Award in 2017.
- A&A led workshops – introducing A-level students to supernova and GWs, through problem solving and programming.
- Physics journal club – set up during Covid-19 lockdown to support A-level and GCSE students with activities, used by local (and even international) schools to enhance their online lessons.
- Physics researchers exhibited at the Royal Society Summer exhibition (2016: *Antimatter matters*; *Diamond: more than just a gemstone*) and London Science Museum (2015: *Diamonds are for Sensing*).
- **Edwards** is Deputy Director of Warwick's recently established Institute for Engagement (REF5a-4.3.4).

4.4 Indicators of wider influence and recognition

a) 39 staff have held 44 distinguished fellowships since 2104 (Table 2.1).

b) Prizes won include: (*PDRA)

Alexander	British Liquid Crystal Society, Young Scientist 2014
T2K (Barker, Boyd)	Breakthrough Prize for Fundamental Physics 2016
Blake	IOP HEPP Group prize 2015
Chapman	RAS James Dungey Lectureship 2014; AGU Ed Lorenz Lectureship 2020
Dixon	Roy Sharpe Prize, British Institute of NDT 2017
Facini, Martin*, Pianori*	ATLAS Outstanding Achievement Awards 2015
Levan	Blavatnik Young Scientist Awards Finalist for Physical Sciences 2018
Lupton*	LHCb Early Career Scientist Award 2020
Marsh	RAS Herschel Medal 2018
Morley	IOP/RSC magnetic resonance group prize 2014
Nakariakov	IOP Payne Gaposchkin Silver Award 2015
Newton	Royal Society Innovation Award 2017
Wilson	Royal Microscopy Society, Mid-Career Scientific Achievement 2020
Woodruff	IUVSTA Science Prize, 2019

IOPP has awarded the "PPCF Dendy Europe-Asia Pacific Award for Outstanding Research Collaboration in Plasma Physics" in honour of Richard Dendy since 2018.

c) 15 staff act as journal editors, 4 as Editors-in-Chief. All staff contribute to peer review, many for over ten journals. **d'Ambrumenil** and **Staunton** are APS Outstanding Referees. **Veras** moderates all 2,500 p.a. exoplanet manuscripts submitted to arXiv.

d) 19 staff are members of EPSRC's Peer Review College, **Pollacco** on EPSRC Engineering SAT; 18 review for STFC; 10 for The Royal Society, Woodruff deputy chair of URF panel; and 8 for ERC. Reviews have been performed for BBSRC, MRC, Leverhulme and Nuffield foundations, for national research agencies of 18 countries and Horizon 2020, where **Staunton** chaired ERC Panel PE3 and **Steeghs** is vice-chair of the MCSF Physics Panel. **Sloan** contributed to a German roadmap on Large-scale Research Infrastructure Projects. **Chapman** reviewed Norwegian Centres of Excellence.
27 staff partake in time allocation panels for international telescopes (HST, WHT, K2) beamlines (ISIS, ESRF, Diamond) and computing facilities (ARCHER).

11 staff are members of UKRI advisory committees: STFC – **Pollacco** (Science Board), **Ramachers**, **Steeghs**, **Thomas** (Council); **Pollacco** chaired STFC reviews of Nuclear Physics and of Astrophysics, **Barker** for Particle Physics; **Barker**, **Marsh**, **Ramachers**, **Steeghs** are on STFC oversight committees for Neutron EDM, MOONS spectrograph (chair), ISOL-SRS, A-LIGO+, respectively. **Barker** is also on the STFC Education, Training and Careers Committee. **Quigley** served on EPSRC's working group for future capital investments in Tier-1&2 HPC, and **Arber** on EPSRCs' Review of Nuclear Fusion.

Dendy serves the REF2021 Physics Panel, as in REF2014. He also chairs the EPS-APS Landau-Spitzer Prize selection.

e) Membership of, and active participation in, learned societies is encouraged. **Dendy** is Chair of EPS Plasma Physics Division; **Wilson** a member of the Royal Microscopy Society Council; **Broomhall** the RAS UK Solar Physics Council; **Stanway** the IOP Awards Committee; **Chapman** the EGU Alfven Medal Committee; **Veras** elected to the International Astronomical Union Steering Committee. 9 staff serve on IOP subject group committees. **Nakariakov** – Scientific Committee on Solar Terrestrial Physics, an interdisciplinary body of the International Council for Science.

f) Many staff serve on international facility User Groups, e.g. **Hase** was Chair of the Diamond Light Source User Committee (2014-17), he now chairs the Science Advisory Committee and sits on the Board of Governors.

International advisors include: **Alexe** – Centre for Innovation, Martin Luther University (Halle); **Arber** – Rosseland Centre for Solar Physics (Oslo); **Barker** – ATLAS Phase 2 Upgrade Scrutiny Group; **Brown** – French High Field NMR network; **Hase** – UAE Synchrotron; **Morley** – Hitachi, Cambridge; **Murray**, CepC (Beijing); **Staunton** – Hero-m, KTH (Stockholm); **Turner** – HKBU, Computational Research Centre (Beijing).

Morley coordinated a written submission to the House of Commons Science & Technology Select Committee Quantum Technologies Inquiry on behalf of the UK Diamond Quantum Technology community and advised the Government Office for Science on the same topic. **Pollacco** is a member of the UK Space Agency Science Policy Advisory Committee. **Dendy** was a government appointed member of the MOD Nuclear Research Advisory Council (to 2015) and the Marshall Aid Commemoration Commission (to 2016).

g) Over 800 invited talks, keynotes and plenaries have been given by staff, with a further 2,800 presentations contributed by PDRAs and PhDs. 66 events have been hosted in Warwick's award-winning conference facilities. Staff have chaired 35 conferences or symposia at major external meetings, e.g. EMRS, APS March Meeting, and been on the scientific organising committee of another 33.

h) Postgraduate training encompasses traditional (lectures, seminars) and applied (experimental, computational) activities. Staff regularly lecture and help organise international graduate summer schools, e.g. the annual *Warwick Week* benefits UK particle physics PhDs. From 2014 to 2018, Warwick led the national HPC Short Courses consortium of 12 universities to provide advanced computing training.

i) Our training provided through the nine CDTs described in §2.2c has benefited students in 16 UK universities, 17 international institutes and over 100 industrial partners.