

Institution: University of Nottingham														
Unit of Assessment: 9 Physics														
<p>1. Unit context and structure, research and impact strategy</p> <p>Since REF2014 the School has expanded through the investment of £25.9M in new infrastructure and the appointment of 14 staff to new academic positions. Active research awards on the census date total £30.9M, with an overall research spend of £56.7M. Staff have disseminated our research through >700 invited talks at international conferences, >150 at UK conferences, and acted as chair and/or organiser for >80 conferences. Our research has been recognised by the award of 7 Institute of Physics (IOP) medals and prizes, 25 staff have held externally-funded personal fellowships, and <i>Morris</i> was appointed CBE in 2018 for services to magnetic resonance imaging.</p> <p>1.1 Research structure and strategy</p> <p>Research activity is structured across six groups:</p> <table border="0"> <thead> <tr> <th></th> <th style="text-align: right;">Category A Staff</th> </tr> </thead> <tbody> <tr> <td>Astronomy (Astro)</td> <td style="text-align: right;">11</td> </tr> <tr> <td>Cold Atoms and Quantum Optics (ColdAtoms)</td> <td style="text-align: right;">4</td> </tr> <tr> <td>Condensed Matter Theory (CMTh)</td> <td style="text-align: right;">13</td> </tr> <tr> <td>Experimental Condensed Matter and Nanoscience (ECMN)</td> <td style="text-align: right;">22</td> </tr> <tr> <td>Particle Cosmology (PartCos)</td> <td style="text-align: right;">7</td> </tr> <tr> <td>Sir Peter Mansfield Imaging Group (SPMIG)</td> <td style="text-align: right;">12</td> </tr> </tbody> </table> <p>giving a total of 69 Category A staff (63.9 FTE).</p> <p>Our research strategy is co-ordinated by the School Director of Research (DoR; <i>Patanè</i>) who chairs the Research Committee (RC) and the Research Operations Group (ROG). The former is a broad forum for discussing long-term research strategy, while the latter meets monthly to co-ordinate our response to funding opportunities and operational research matters. Both groups have representatives from each research area, as well as members with specific responsibilities for financial and managerial aspects of research, infrastructure, technical services, and research ethics. The DoR reports to the School Management Group chaired by the Head of School (HoS; <i>Fromhold</i>, who served as DoR from 2008-16) and is a member of the Faculty of Science Research Committee. The DoR also leads discussions on research matters at the Staff Committee, whose membership includes all academic staff and key technical and administrative staff. Deputy Head of School (DHoS; <i>Kent</i>) leads on the development of research facilities, infrastructure, space management and PhD student finance. There is cross-representation between the RC, ROG and the School Diversity and Inclusion (D&I) Committee, ensuring that equality issues are considered in our research strategies.</p> <p>1.1.1 Research strategy and direction since REF2014</p> <p>Our strategic aims in REF2014 were developed to balance original, investigator-led, research with a recognition that our research is becoming increasingly concentrated on large-scale projects, often involving multiple universities and crossing traditional discipline boundaries. Accordingly, we have prioritised the integration and expansion of our research strengths into major programmes, including those within the University, while continuing to foster new research directions, which will form areas of growth beyond the assessment period.</p> <p>Our stated aims in REF2014 were:</p> <ol style="list-style-type: none"> (i) the promotion of interdisciplinary research; (ii) the establishment of further links between research groups; (iii) the enhancement of our international profile; 		Category A Staff	Astronomy (Astro)	11	Cold Atoms and Quantum Optics (ColdAtoms)	4	Condensed Matter Theory (CMTh)	13	Experimental Condensed Matter and Nanoscience (ECMN)	22	Particle Cosmology (PartCos)	7	Sir Peter Mansfield Imaging Group (SPMIG)	12
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- (iv) the provision of a vibrant research environment to promote internationally-recognised research across all sub-disciplines;
- (v) the realisation of the societal benefits of research through collaborations with partners across a range of governmental, healthcare and industrial sectors.

Exemplars of the success of this strategic approach include:

- **Quantum technology, quantum optics and biomedical imaging**

The development of quantum science and technology in areas linking our *ColdAtoms*, *CMTh*, *ECMN* and *SPMIG* groups has been a cornerstone of the School's research strategy since 2006. Nottingham Physics is a key node in the Quantum Technologies (QT) Hub in Sensors and Timing and received £7.7M across the 2014 and 2019 funding rounds of the UK QT Programme to support new directions in atom-based quantum sensors. In collaboration with the *ColdAtoms* and *CMTh* groups, *SPMIG* researchers showed that optically pumped magnetometers (OPM) could detect neuromagnetic fields, leading to the development of a completely novel, wearable, magnetoencephalography (MEG) system. This work (in collaboration with the Wellcome Centre for Human Neuroimaging at UCL) represents a major advance in biomedical imaging and has led to the formation of a spin-out company, Cerca Magnetics Ltd, as described in Impact Case Study **ICS OPM-MEG**. *Jensen* (Copenhagen), an expert in ultra-sensitive magnetic field detection using atomic sensors, was appointed in 2018 to strengthen this activity. *ColdAtoms* was further strengthened through the appointment of *Verlot* (Lyon), holder of an ERC Starting Grant (2018), whose activity in optomechanics has already led (with *Owers-Bradley* and Nottingham's School of Mathematical Sciences (MathSci)) to £1.4M funding from the 2020 STFC initiative, 'QT for Fundamental Physics'. In addition, with the Centre for Additive Manufacturing (Faculty of Engineering), and supported by an EPSRC Programme Grant (£6M), we have developed 3D-printed QT components and vacuum systems (see [Sec. 1.2.2](#)).

- **University strategic initiatives: Beacons of Excellence**

In 2017, the University established 6 transdisciplinary Beacons of Excellence (£22.5M investment during census period), building on research strengths across the University and targeting goals with societal impact, Institutional Environment Statement Section 2.1a (IES2.1a). The School holds leadership positions in 3 of the Beacons and played a major role in shaping their themes. *Patanè* is a member of the Leadership Team of the Propulsion Futures Beacon, which focuses on innovative electrified propulsion systems for sustainable transport, with activity in Physics focused on new materials and devices. *Bowtell*, Director of the Sir Peter Mansfield Imaging Centre, is the Deputy Director of the Precision Imaging Beacon, in which Physics-based researchers develop new magnetic resonance imaging (MRI) and MEG methods to improve the diagnosis and treatment of diseases. *Francis* is a member of the Steering Group of the Future Foods Beacon, which addresses sustainable food and nutritional security; *SPMIG* contribute expertise in biophysics and imaging to this programme. The School has received funds totalling £2.7M from the Beacons.

- **Research exemplars**

We highlight examples of activities which have grown from breakthrough papers to acquire critical mass and a major international profile during the assessment period:

- **Ultrafast spintronics using antiferromagnetism**

Campion, *Edmonds*, *Jungwirth*, *Rushforth* and *Wadley* (*ECMN* and *CMTh*), with the Czech Academy of Sciences and the Hitachi Cambridge Laboratory, demonstrated the first electrical control and readout of an all-antiferromagnetic memory device. This work grew from earlier Nottingham investigations of CuMnAs and offers the prospect of an ultrafast spintronic memory, as demonstrated in subsequent Nottingham papers. The work has stimulated a rapid, world-wide, expansion of the field of antiferromagnetic spintronics, the addition of antiferromagnets to the 2017 Magnetism Roadmap (J. Phys. D **50** 363001 (2017)) and dedicated symposia. This success has been supported through the appointment of *Wadley* to a proleptic lectureship.

Theory of non-equilibrium systems

Our strengths in this area have led to developments at the interface of classical and quantum many-body dynamics, many with direct connection to experiments. These include the emergence of constrained dynamics in atomic systems (so-called Rydberg Soft Matter), classical and quantum large deviation methods, and the prediction of novel dynamical states in driven open quantum systems. The recent appointments of *Nunnenkamp* (Cambridge) and *Brandner* (Keio, Japan) to *CMTh* have expanded our portfolio to encompass optomechanics, hybrid systems and quantum engines. The breadth and interdisciplinary nature of our research in this area led to the establishment in 2016 with MathSci of the 'Centre for Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems'.

Novel searches for dark energy

Former Anne McLaren Fellow, now Professor, *Burrage* and *Copeland* (*PartCos*) proposed a new experiment to test dark energy forces using atom interferometry, which has been implemented by groups at Berkeley and Imperial, leading to tight constraints on previously favoured models. *Burrage* has also constructed a framework for testing dark energy with particle colliders, which has been adopted by the ATLAS collaboration. In 2016 *Burrage* received a £0.8M Leverhulme Trust Research Leadership Award (one of only 13 awarded triennially across all fields) to support the growth of this area, and, since 2016, she has acted as convenor of the 'Beyond the Standard Model' working group of the CERN Physics Beyond Colliders study to determine the future of CERN's scientific programme. The award of a Nottingham Research Fellowship to *Millington* (*PartCos*) expands activity in this area.

Renal MRI

By adapting methods developed for brain imaging, *Francis* (*SPMIG*) demonstrated that MRI provides a powerful tool for quantitative assessment of kidney structure and function. This research seeded the growth of a wide-ranging programme on new MRI approaches for assessing, monitoring and managing kidney disease. *Francis* now leads the UK Renal Imaging Network, which brings together major UK research centres to translate renal MRI into clinical use. Her work is underpinned by a £0.8M MRC Partnership Grant and a £2.0M award from the National Institute for Health Research (NIHR) and forms part of several imaging studies of the long-term effects of COVID-19, including the C-MORE study, part of the UKRI-funded Post-hospitalisation COVID-19 (PHOSP-COVID) programme (see **ICS QuantMRI**).

1.1.2 Future research strategy

We will continue to be guided by the strategic aims above, while building on recent infrastructure awards and our strengths in interdisciplinary areas, such as biomedical imaging and quantum technologies.

Specific initiatives include:

- **Two-dimensional (2D) materials and layered semiconductors**
ECMN members will establish a unique facility (EPI2SEM) for the EPItaxial growth of novel, metal chalcogenide 2D SEMiconductors, and their characterisation using electron spectroscopies and scanning probe microscopy. EPI2SEM is funded by a £2.9M EPSRC Strategic Equipment Award (*Beton, Novikov, O'Shea, Patanè*) and University support (£1M). In combination with a molecular beam epitaxy (MBE) system for the growth of graphene and boron nitride (installed in 2014), the ongoing collaboration of *Eaves* with Manchester on graphene heterostructures, THz acoustic investigations of van der Waals interfaces and devices, and the award of an Anne McLaren Fellowship to *Yan* for research on 2D ferroelectrics, EPI2SEM establishes Nottingham as a centre with critical mass for the growth and investigation of 2D semiconductors.
- **Ultra-high field MRI**
We have led the collaborative effort to establish a national facility for ultra-high field (11.7T) human scanning, an area highlighted in the recent UKRI report, 'The UK's

Research Innovation and Infrastructure: Opportunities to Grow our Capability'. The increased signal-to-noise-ratio (SNR) at 11.7T will translate into much richer information content in structural and functional imaging thus enabling the assessment of brain function with a spatial resolution approaching 100 μ m, bridging the gap between standard neuroimaging and invasive electrophysiology/microscopy techniques. Additionally, gains in SNR for MR studies involving X-nuclei (e.g. ^2H , ^{13}C , ^{23}Na and ^{31}P) will significantly enhance metabolic mapping capability, opening new opportunities for patient studies in cancer and other diseases.

- **Gravitational waves and measuring the fundamental forces of nature**

A new 'Centre of Gravity' brings together the School and MathSci, coordinating existing expertise in gravity and expanding into new areas. It encompasses fundamental physics, mathematics, cosmology, relativistic astrophysics, experimental data, and modelling. It will form a hub for research, PhD training, and outreach, and provide the critical mass needed to access additional funding streams e.g. the new STFC Gravitational Waves consolidated grants scheme.

- **Machine learning (ML)**

Since 2014 all research groups have developed significant activity in ML. *Astro* and *PartCos* have applied deep learning and recurrent neural networks to the analysis of galaxies, clusters, gravitational lensing and large-scale cosmological structure. *CMTh* have explored connections between non-equilibrium statistical physics and ML, quantum dissipative neural networks, and interdisciplinary applications, for example on materials for healthcare with the School of Pharmacy. *SPMIG* and *ECMN* have used ML methods to analyse and classify MRI and scanning probe microscopy (SPM) images. Our research portfolio of ML-related research is now over £4M. We will exploit the synergies between these activities by bringing together relevant researchers in the School and building on our innovative postgraduate course on ML. The University has provided funds for a new 5-year appointment as part of their 2017 £0.7M Flexible Investment Fund 'Science through AI' programme in support of our growth strategy.

- **Spin at the single atom limit**

EPSRC has awarded *Moriarty* a Strategic Equipment Grant (£1.1M) for an ultra-high vacuum (UHV) combined scanning tunnelling/atomic force microscope, which can be operated at temperatures down to 0.3K and magnetic fields up to 9T, a Senior Fellowship (£1.8M) and a Horizon grant (£200k) to study spin at the atomic scale. These awards and infrastructure will underpin collaborative activities linking antiferromagnetic spintronics, spin in adsorbed molecules, 2D materials, and the application of ML to SPM.

We also identify selected research opportunities at the group level:

Astro will build on its collaborative focus on the formation of galaxies and larger-scale structure in the Universe. It will blend established activities with newer large projects in which it is strongly invested, including major roles in exploiting SDSS-IV/MaNGA to dissect nearby galaxies and unveil their spatially-resolved properties and formation history. With its leading positions in WEAVE/LOFAR, *Astro* will study these systems in dense environments and the large-scale structure around them. Members are also strongly involved in the development of upcoming facilities such as the ELT, and in designing the next generation of surveys for instruments such as the Chinese Space Telescope, JWST, Euclid and the Rubin Observatory. This positions the group to lead in the exploitation of this wealth of data. Observations will be complemented by cutting-edge computational work on structure formation and on the evolution of the intergalactic medium. The group is also expanding its research on the applications of ML to large astronomical data sets in fields such as gravitational lensing and galaxy morphology.

ColdAtoms will focus on quantum sensors, ranging from fundamental studies of quantum measurement limits to sensitive inertial force and magnetic field measurements. Building on the group's work on atomic gyroscopes, their demonstration of CMOS-based atom chips (integrating

photodiodes, rf signals and sequence control) for controlling cold atoms, and the 3D printing of alloy UHV chambers (see Quantum Technologies in [Sec. 1.2.2](#)), they will develop new quantum measurement systems. Collaboration with *SPMIG* will enable the translation of our ultra-sensitive, optically pumped magnetometers to new medical applications, while fundamental studies of nanomechanical oscillators will explore the limits of quantum macroscopicity and quantum effects at room temperature.

CMTh will build on their combination of expertise in complex quantum systems, non-equilibrium classical and quantum dynamics, quantum transport and optical properties of 2D multilayer systems to identify and exploit opportunities in new and emerging areas including in-house theory-experiment links in opto-mechanics, 2D materials, quantum optics and magnetometry. The group will also maintain a leading role in the Nottingham Physics-led interdisciplinary initiative on Machine Learning in Science.

ECMN will investigate nanoparticles and their applications in agriculture, cell-targeting and in-vivo fluorescence imaging. Investigations of Raman methods for cancer screening will continue with new activity on biological imaging using tip-enhanced Raman microscopy. THz acoustics activity will focus on superoscillation and superlensing effects, aiming for nanoscale acoustic imaging of, e.g., the structure of biological cells, while also extending activity on magnetostrictive nanostructures and magnon-phonon interactions. Soft matter research will be focused on flow and rheology in complex heterogeneous fluids formed from colloids, droplets and bubbles, including laboratory-based microgravity experiments. The group will continue to access national and international facilities, in particular the European Magnetic Field Laboratory and the Diamond, Soleil, ELETTRA and Advanced Light Source synchrotrons.

PartCos will focus on understanding the nature of dark matter and dark energy, and the physics of the early Universe, underpinned by its membership of the Dark Energy Survey, Euclid and LISA. The group will pursue new tests to discriminate between modified gravity and general relativity, and continue to pioneer the design of table-top experiments as probes of screening fields. Within the new University of Nottingham (UoN) Centre of Gravity, the group will use data from LIGO and multi-messenger astronomy to probe cosmic strings, modified gravity, primordial black holes and electroweak phase transitions. It will also develop new ML techniques to extract signals of cosmological defects and dark energy in noisy data.

SPMIG will combine extensive expertise in biomedical imaging and the physics of human biology, with unique infrastructure (enhanced by a 2014 MRC Clinical Research Infrastructure Initiative award (£7.7M)), to develop new imaging techniques for the study of human physiology and pathology. Together with the NIHR-funded Nottingham Biomedical Research Centre (BRC) and the pharmaceutical industry, we will exploit these techniques to investigate mechanisms of action of treatments, including neuromodulation, and also to develop methods to predict responses to therapies. Further development and application of OPM-based biomagnetic approaches to measure physiological activity, particularly in the brain, fetus and gut, will also be a priority, supported by the second phase of the QT Hub in Sensors and Timing.

1.2 Impact

1.2.1 Impact strategy, management and monitoring

The DoR has overall responsibility for impact, assisted by the School Head of Operations and our Research Support Officer, both of whom sit on RC and ROG. Supported by the QT Hub, we have also appointed a Business Development Manager to develop industrial collaborations, assist with management of externally-funded projects, and provide guidance on intellectual property (IP). External evaluation of our policies, advice on new opportunities, and access to commercial approaches for the evaluation of technological exploitation is provided by our Strategic Advisory Board (SAB), formed in 2012. The SAB has an external membership drawn from industry (current representation: Teledyne UK, Experian, DAB-Pfizer and Rolls Royce) and government agencies (STFC).

The School has a range of mechanisms (PhD studentships, research leave, access to infrastructure and facilities) to support the translation of our research. Since REF2014, staff have been awarded impact-related and industrial funding totalling £2.9M, including £0.6M of University-administered Higher Education Innovation Fund and/or EPSRC funds, such as the EPSRC Impact Acceleration Account (16 awards; total £475k), Hermes fellowships (7 awards; total £83k) and a Knowledge Transfer Secondment (£45k). We have also been awarded 5 Innovate UK (IUK) projects with a total value of £3.9 M (Nottingham share £0.6M) held jointly with 10 UK-based companies, and 3 Defence Science and Technology Laboratory (Dstl) Defence and Security Accelerator (DASA) projects (total value £231k). In addition, we have received £1.4M directly from industrial sponsors and collaborators.

The School also provides advice on available funding streams, protection of IP, development of links with industrial collaborators and the formation of spin-out companies. Researchers are encouraged to consider the value of IP at an early stage by submitting promising ideas via a Disclosure Form to the University's IP Commercialisation team who evaluate IP, advise on commercialisation, and co-ordinate the preparation and submission of patents. During the assessment period members of the School have submitted 60 Disclosure Forms which have led to the filing of 12 patents.

In REF2014 we identified the importance of working with other disciplines, particularly medicine and engineering, for the translation of our research; this strategy is linked to our approach to interdisciplinary research ([Sec. 1.3](#)). Several of our successes in impact have resulted from our long-term support for cross-Faculty (with Medicine and Engineering) collaborations.

1.2.2 Impact activity

Impact has been realised through direct commercialisation, outreach, contributions to governmental and regulatory standards, long-term industrial partnerships, collaborations with medical practitioners, and links with national security agencies.

We highlight the following areas which all have the potential for further significant growth:

- **Quantum technologies**

Translation of our QT activity related to MEG, including the establishment of spin-out company, Cerca Magnetics Ltd, is described in **ICS OPM-MEG**. We are also developing new designs of OPM for applications in healthcare (e.g. fetal heart monitoring), security (mine/submarine detection) and industry (non-destructive testing) funded by IUK and the Dstl DASA scheme. Through our role in the QT Hub we have links to >50 companies and are engaged in collaborative technology transfer with governmental organisations (National Physical Laboratory (NPL), British Geological Survey) and 15 industrial partners in the areas of sensors, navigation and geophysical survey. For example, *Fromhold (CMTh)*, three companies (Microchip, Compound Semiconductor Technologies, Inex Microtechnology) and NPL were awarded £1.9M by IUK to develop chip scale OPMs for non-destructive testing applications. An IUK award (£450k total, £165k to Physics) to *Fromhold* and *Hackermüller (ColdAtoms)*, with the Centre for Additive Manufacturing (Nottingham Engineering) and an associated spin-out, Added Scientific Ltd, supported the manufacture of components developed through Nottingham QT Hub activity. These include working prototype magneto-optical traps with 3D-printed UHV chambers and battery-powered trapping coils (drawing on *SPMIG* expertise in MRI gradient coil design), for QT applications including magnetic screening and measurement, and, with *Makarovskiy (ECMN)*, will be extended to the integration of flakes of graphene and 2D materials into 3D-printed structures.

- **Biomedical imaging**

In collaborative research, *SPMIG* use MRI to provide unique insights through non-invasive studies of, for example, kidney and liver disease, the gastrointestinal tract, multiple sclerosis, schizophrenia, mild traumatic brain injury and Parkinson's disease, plus the application of novel biomedical imaging in neuroscience. Our MRI research forms the basis of two case studies: **ICS QuantMRI** is related to medical diagnostics and applications in the food and

pharmaceutical sectors, and **ICS EMReg** describes how our research has provided the basis for transnational regulatory frameworks for electromagnetic field exposure. In addition, *Notingher (ECMN)* has developed fast Raman methods for the imaging and analysis of human tissue samples during cancer surgery, with tests of a prototype commercial system underway.

- **Surfaces, semiconductors and spintronics**

A strategic alliance with Teledyne UK (>2000 employees, global sales £150M) who established a facility in the School in 2010 to manufacture and develop microwave and THz devices (also supported by a Knowledge Training Partnership (KTP) (£194k)) is described in **ICS Teledyne**. The demonstration of a new all-antiferromagnetic memory device (see [Sec. 1.1.1](#)) has led to the filing of 3 patents. In the areas of surfaces and soft matter: *O'Shea's* company Molecularspray Ltd. commercialise electrospray deposition equipment developed in the School; *Sharp* has applied, with support from the Home Office, Time of Flight Secondary Ion Mass Spectroscopy to image fingerprints on bullet casings, and developed, with Adidas, an optical dynamic contact imaging system to measure the pressure and frictional force distributions beneath sports shoes; *Smith* works with Schlumberger UK on the adhesion of yield stress fluids to surfaces, a fundamental problem in biofouling; *Campion*, funded by a KTP (£238k), collaborates with Photek, a global manufacturer of vacuum-based photon detectors, on a novel MBE manufacturing process.

- **Outreach**

For over a decade we have developed novel, social media-based, outreach activities. In **ICS Sixty Symbols** we highlight the delivery of content through the YouTube channel Sixty Symbols. Our outreach activities are discussed in detail in [Sec. 4.2](#).

1.3 Interdisciplinary research

The School promotes interdisciplinary research through the allocation of PhD students, resources for cross-Faculty research centres, and appointments. Members of the School have ongoing collaborations with all Schools in the University's Faculty of Science and with all other Faculties, in particular Engineering, and Medicine and Health Sciences, as well as extensive external interdisciplinary collaborations (see [Sec. 4.1](#)); 28% of our returned outputs have co-authors from another discipline.

The Sir Peter Mansfield Imaging Centre (SPMIC), formed in 2015, brings together researchers in *SPMIG*, Medicine, and Psychology to provide a focal point for collaborations with NHS clinicians, life scientists and industry in the area of biomedical imaging. In addition to *SPMIG's* leading roles in the University Beacons of Excellence in Precision Imaging and Future Foods, *Gowland* co-leads the University's Interdisciplinary Research Cluster (IRC) in Technological Innovations for Health and Wellbeing. *Notingher (ECMN)* works with the Schools of Pharmacy and Medicine on the Raman imaging of live cells and nano-scale investigations of pharmaceutical formulations.

The School is a major partner, with the Schools of Chemistry and Pharmacy, and the Faculty of Engineering, in the Nanoscale and Microscale Research Centre (nmRC), which houses extensive material characterisation facilities (see [Sec. 3.2](#)) and enhances the strong interdisciplinary links of the *ECMN* and *CMTh* groups. University-supported Doctoral Training Centres promote interdisciplinary research within nmRC, with 12 studentships awarded to Physics since 2015. We collaborate with chemists on 2D supramolecular assembly, biocompatible quantum dots, photovoltaic materials, photo-electron spectroscopy and hybrid biocompatible nanostructures.

Mao (CMTh) is the Director of the Laboratory of Urban Complexity and Sustainability, which fosters interdisciplinary research in Computing and Geography, on the social, economic and environmental sustainability of cities, funded by a £1.5M Leverhulme Research Programme Grant. *O'Shea (ECMN)* is Director of the University of Nottingham Energy Technologies Research Institute, which co-ordinates energy research across a range of disciplines and played

a key role in securing the Energy Research Accelerator (£60M IUK project), and 4 (2 current) Energy-themed EPSRC CDTs. *Hackermüller* (*ColdAtoms*) leads the University's Quantum IRC.

1.4 Open research (IES2.3)

Publications are available from the University's Repository@Nottingham and in many cases also from the arXiv. Our Research Support Officer monitors publications to ensure compliance with institutional and funders' open access policies. We follow the Research Data Management policies of the University and our funding agencies, and have held a training event for staff. To support reproducibility, raw and processed simulation data are stored in the Nottingham Research Data Management Repository where they are publicly accessible and linked to published papers. Astronomical data are normally archived by the telescope/facility, or, alternatively, stored on our local servers for a minimum of 10 years. Data catalogues are uploaded to data centres. Data products from numerical simulations are made publicly available from local servers, while raw data are available on request, due to the large (~100TB) size. Where appropriate, codes are made available via public sites, such as GitHub.

1.5 Research integrity (IES2.4)

Responsibility for research integrity lies with the RC and ROG, working closely with the D&I Committee. Research governance is a standing item on the agendas of these groups ensuring a constant review of the impact of new technologies and working practices. Our Research Ethics Officer (*Gowland*, who also chairs the University's Research Integrity and Research Ethics Committee) is responsible for ensuring that all human studies have the correct regulatory and ethical approvals; *SPMIG* staff involved in human experiments have Good Clinical Practice training and human data are archived on GDPR compliant, secure central servers. We have introduced processes to check that grant submissions and student projects have considered research governance, ethics and safety issues. Postgraduate students are trained on research practice, integrity, safety, and ethics by their supervisors and through centrally-organised courses.

2. People

2.1 Staffing strategy and staff development

Our strategy is to recruit and retain the best international talent. During the census period, 4 academic staff have retired or left the School, while 14 staff have been appointed to **new permanent academic positions**. We have been particularly successful in attracting leading early career researchers (ECR) who hold Research Council, Royal Society (RS), and/or Nottingham Research and Anne McLaren Fellowships (NRF/AMF) to proleptic permanent positions; 12 of our new positions have been filled through this route. Since 2014 there were 8 (3 female (F)) **promotions** to Professor and 13 (3F, one of whom was also subsequently promoted to Professor) to Associate Professor.

New appointees (in addition to *Brandner*, *Jensen*, *Nunnenkamp*, *Verlot* and *Wadley*, discussed in [Sec. 1.1.1](#)) have strengthened our research as follows: *Russell* (AMF, STFC Ernest Rutherford Fellow) extends the *Astro* group's expertise in galaxy clusters and X-ray observations; *Potapov* has brought unique expertise to *SPMIG* in dynamic nuclear polarisation with magic angle spinning and the application of this approach to biomolecules; *Saywell* (*ECMN*) has established a highly interdisciplinary programme to investigate the interaction of gases with adsorbed molecules using low temperature SPM. A further 6 staff with fellowships awarded prior to the assessment period transferred to newly-created permanent posts in *CMTh* (*Li*, *Olmos*), *PartCos* (*Avgoustidis*, *Moss*), *ECMN* (*Smith*) and *Astro* (*Dye*). We have also made several appointments since the REF census date: *Bertini*, a RS University Research Fellow (URF) joins *CMTh* in autumn 2021 as a proleptic lecturer; *Millington* (*PartCos*, NRF) and *Weir* (*ECMN*, Beacon-funded NRF) commenced personal fellowships in late 2020. New staff are invited to give a colloquium soon after arrival to introduce their research to the whole School.

The first phase of our future **recruitment plan** is to appoint two lecturers in: *ECMN*, with particular focus on spintronics; *CMTh* linking with *ECMN*, especially in 2D materials. We will also

recruit to a 5-year post in machine learning, funded by the University's Flexible Investment Fund, to foster multidisciplinary research. Future recruitment will prioritise research that builds on major capital investments (2D materials, 11.7T MRI scanner, OPM-MEG, low temperature SPM), long-term inter-University strategic investments such as Quantum Technologies, and the appointment of internationally-leading ECRs across all areas of our activity.

2.1.1 Staffing profile

The age and gender profiles of our 69 returned staff are tabulated below. The fraction of female staff, 20% overall, is close to female representation at Professorial level, 18%, up from 9% in 2014, but the ratio is lower at Associate Professor level. This may be a legacy effect; while 28% of staff are aged over 55, only 7% of female staff are in this age range, suggesting that a re-balancing will occur in the medium term as older staff retire. Of all returned staff, 10% are BAME. Of postdoctoral staff, roughly 30% are female and 25% BAME. The School operates a **Diversity in Recruitment** policy. People from underrepresented groups are actively encouraged to apply for advertised positions, and diversity characteristics are monitored throughout the hiring process. Any problems are discussed at the D&I committee, and reported to the Staff Committee. The Gender Decoder tool for analysing language is applied to all job adverts in order to avoid wording which may deter underrepresented groups, in particular women, from applying.

	Total	Professor	Associate Professor	Assistant Professor/ Senior Research Fellow
Number (%) female	14 (20)	5 (18)	2 (10)	7 (32)
Number (%) male	55 (80)	23 (82)	17 (90)	15 (68)

Age range	26-35	36-45	46-55	56-65	65+
	6%	44%	23%	23%	3%

Our age profile is considered annually by the HoS, DHoS and DoR in the context of succession planning to ensure the smooth transfer of responsibilities for research (for example the appointment of *Bowtell* as Director of SPMIC following the transfer of *Morris* to a part-time contract in 2016) and the mitigation of the loss of key expertise and technical support. Our success in attracting ECRs holding fellowships in targeted areas has also allowed us to manage our staff profile, balancing the sustainability of current activities with new directions and opportunities.

2.1.2 Career progression and development

Advice on **career development** is provided through the University's Appraisal and Development Conversation (ADC) process (IES3.1) which, in the spirit of the Concordat to Support the Career Development of Researchers, is applied uniformly to research and academic staff, as well as to technical and support staff. All staff have biannual meetings with their Appraiser to discuss progress and future priorities, tailored to career stage (the Appraiser and Line Manager roles are separated ensuring that staff are given impartial guidance). Appraisers provide a range of advice regarding postdoctoral opportunities (for research staff), fellowship applications, the challenges of the transition to an academic role, postgraduate supervision, training opportunities and the balance of research, impact and teaching duties.

The ADC process also provides a forum for discussion of **impact** (translational research, commercialisation, outreach) and access to associated support mechanisms (see [Sec. 1.2.1](#); staff are also contractually entitled to perform 50 days per year of external consultancy). In addition, discussions can include applications for **study leave** to support new research and impact initiatives including industrial secondments, extended research placements and international collaborations. In accordance with the University's policy (IES3.1) staff can apply for one semester of leave in every seven semesters. Applications are prioritised by the HoS and DoR against School research strategy; 21 academic staff have taken study leave since 2014.

The School's Research Staff Committee (RStC) provides a forum for discussion between **post-doctoral research staff** and senior academics. The Concordat highlights the benefits of involving research staff in strategy development and decision making; accordingly, research staff representatives, who report to RStC, have been appointed to the School's D&I, Research, Safety, Staff, and Teaching Committees. We encourage research staff to be named researchers on grant applications and to assist with undergraduate teaching, supported by comprehensive training. During the REF period, 46 of our research staff or PhD students have obtained permanent academic posts in 19 different countries.

We also operate a Support Staff meeting providing a forum for our technical and support staff to discuss with the School leadership (HoS, DHoS) training opportunities, and issues of concern, risk, and potential for improvements in the delivery of technical services.

Newly-appointed lecturers are assigned an experienced academic **mentor**, to provide advice on e.g. procedures, postgraduate supervision, and are supported through specific courses on teaching, research and PhD supervision, have a teaching workload that ramps linearly to a full load over four years, and have priority access to PhD studentships and pump-priming grants. Since the outbreak of COVID-19, induction and mentoring for newly-arrived staff has been performed online.

For all staff, balancing the demands of teaching, administration and research is a priority. The School has had a **workload model** for more than 15 years, which has recently been superseded by a University scheme including all internal and external activities. A shadow lecturer scheme provides cover for teaching duties, allowing staff to undertake international visits or to give invited talks at major international conferences. Major administrative roles are rotated within the school every ~5 years. Our Staff Development Committee promotes **training** opportunities offered by the University's Professional Development Service; it also organises biennial staff training sessions on e.g. PhD supervision, open access publication, impact and grant writing. Three staff have participated in the University's 'Research Leaders Programme'.

All staff are encouraged to seek **personal research fellowships** and are supported via feedback (including from external consultants) on applications and mock interviews. 30 Category A staff have held personal fellowships during the assessment period, including 22 new awards: 2 EPSRC Career Acceleration Fellowships (*Hill, Rushforth*), 1 EPSRC Established Career Fellowship (*Notingher*), 1 EPSRC Leadership Fellowship (*Moriarty*), 1 ERC Advanced Grant (*Conselice*), 2 ERC Starting Grants (*Lesanovsky, Verlot*), 2 Leverhulme Trust Early Career Fellowships (*Sanchez Panchuelo, Wadley*), 3 Leverhulme Trust Research Fellowships (*Beton, Copeland, Patanè*), 8 RS URFs (*Bolton, Burrage, Moss, Nunnenkamp, Padilla, Saywell, Smith, Wadley*), 5 STFC Ernest Rutherford Fellowships (*Bamford, Dye, Gray, Hatch, Russell*), 1 UKRI Future Leaders Fellowship (*Brandner*), 8 NRF/AMFs (IES3.2) won in open competition (*Avgoustidis, Brandner, Li, Marcuzzi, Mullinger, Russell, Saywell, Yan*).

Following discussions at RStC, training in the preparation of fellowship applications is included at our Away Day for research staff; since 2014, this has led to 20 successful fellowship applications by our research staff and PhD students (7 are held in Nottingham, enhancing both the career of the fellowship holders and our research portfolio). We have also hosted 18 additional postdoctoral researchers with competitively-awarded personal fellowships since 2014.

The UoN has an annual **promotion** round for research and academic staff, with guidance provided to all eligible candidates. Staff are offered opportunities to discuss career progression with the HoS, who also discusses promotion with any staff who have not been promoted in the last 5 years, to ensure all potential candidates are identified. Applicants submit their paperwork to the School Promotions Group, which is chaired by the HoS and composed of female and male staff with broad research and teaching expertise. This group advises the candidate on the likelihood of success and provides feedback on their case. The finalised applications are submitted to a Faculty Promotions Group and then to the University Promotions Committee. Separately, staff can be nominated for bonuses for exceptional performance in teaching,

research or impact-related activity under the Nottingham Rewards Scheme (15 awards to Physics in 19/20 totalling £24k).

2.2 Postgraduate research students (PGR)

PhD student **recruitment**, monitoring and support are overseen by the Postgraduate Committee which, along with the D&I Committee, has PhD student representation. We currently have 110 research students, and, since 2014, have awarded, on average, 29 PhDs per year.

Studentships are advertised widely to attract a diverse cohort of well-qualified candidates and we receive applications from, typically, 130 students per year. Applicants are interviewed by multiple staff, given a departmental tour and an opportunity to meet current PhD students; some research groups (*Astro*, *PartCos*) run specific interview days, while others (*ECMN*, *CMTh*, *ColdAtoms*, *SPMIG*) have a rolling programme of recruitment (visits and meetings for prospective PhD students have been replaced by an online process during the ongoing pandemic). We ensure that the diversity of interviewers and postgraduate helpers reflects our staff and postgraduate populations. The gender balance of applications and offers is monitored and changes have been made to research group websites and interview processes to make them more inclusive to underrepresented groups. Since 2014, 32% of our PhD intake has been female and 28% BAME.

Studentships are funded by a wide range of sources (see table below): EPSRC and STFC doctoral training accounts (DTAs), research grants, Centres for Doctoral Training (CDTs), including the EPSRC/MRC funded Oxford-Nottingham Biomedical Imaging CDT), the QT Hub, EU Initial Training Networks (ITNs) and other schemes. School/University-funded studentships are allocated strategically, to leverage funding, and to support ECRs, staff returning from leave, or new research programmes. Self-funded students are predominantly international students funded by scholarships or their governments. Our annual summer internship scheme provides ~15 research placements for top-class undergraduates; since 2014, 15 interneers have enrolled as PhD students in the School.

Total number of studentships 2013/14-2019/20 by main funding source

Funding source	School/University	EPSRC DTA	STFC DTA	Research grant	CDTs	QT Hub	EU ITNs	Self	Other
Number	52	33	28	27	21	15	7	43	19

All students are assigned at least two supervisors. Student **progress** is monitored by mandatory monthly meetings that are formally recorded. At the end of their 1st and 2nd years, students submit a short written report, followed by an interview with a member of staff other than their supervisor. The fraction completing within 5 years has improved from 70% in 2012/13 to a 5-year average of 88% (73% submit theses within 4 years). Individual extenuating circumstances (predominantly ill health) account for most late submissions.

Pastoral support is available from two Postgraduate Tutors (one with responsibility for international students), a Special Tutor for female students and (since 2016) a dedicated School Welfare Officer. Since 2017, a student-led School Postgraduate Peer Mentoring programme assigns mentors to incoming postgraduate students on request. The School supports multiple self-organised groups for postgrads (LGBT+, female students, and BAME). In 2020 our PhD students organised a national Postgraduate Women in Physics Conference.

The Midlands Physics Alliance Graduate School provides a platform for high-quality, wide-ranging, **postgraduate training**. Currently 26 modules are offered, covering a diverse range of topics in physics, astronomy, statistics, and scientific programming. All 67 students in the Oxford-Nottingham Biomedical Imaging CDT participated in specialist training at Nottingham. We also hold in-house workshops to train students in writing research proposals, and careers workshops, where former Nottingham PhD students discuss career paths (within and outside academia). The University's Researcher Academy (IES3.3) provides additional generic skills

training. Students are encouraged to contribute to impact activities; since 2014, 7 students have been named on patent applications and their contributions are fully recognised by priority allocation of associated IP income.

Each research group organises regular research seminars. Monthly colloquia by internationally-leading researchers ensure that students and staff learn about topics outside their field. PhD students present their work at regular group meetings and, often funded by the School, at international conferences. A School postgraduate poster competition, sponsored by the scientific software company Tessella, is held annually. We strongly encourage student-led activities, such as journal clubs, to develop transferable skills. Students also run our highly successful Inflativerse outreach project and provide demonstrations and talks to local schools, public events and widening participation activities.

To mitigate the disruption caused by COVID-19, we have provided computers and related support to ensure that all PhD students can work effectively from home, while the University has provided funded extensions to students nearing completion (IES COVID-19 annex). In addition, we have replaced our community-building events with online activities.

2.3 Equality, diversity and inclusion (EDI)

Within the University, the School has played a leading role in the integration of equality and diversity issues into policies and strategies at both the School and institutional level. Our D&I Committee was formed in 2007 to implement strategies and policies to ensure that staff and students are treated solely on the basis of their merits, abilities and potential, independent of protected characteristics. Its membership includes academic, technical, research and administrative staff, together with undergraduate and postgraduate students. We received an Athena Swan Silver award in 2010 (re-awarded in 2017), contributed extensively to the University's Institutional Silver awards in 2012 and 2018, and are also an IOP Project Juno Champion. The D&I Committee meets quarterly (and its sub-committee, the Athena Swan Self-Assessment Team more frequently) to discuss challenges and new initiatives related to underrepresented groups in physics. The School runs biennial equality and diversity training events for all staff. New staff also complete online diversity training during their induction.

A quarterly newsletter, produced by the D&I Committee, is circulated to all School members. The newsletter publicises upcoming events and promotes awareness of actions the School is taking to address diversity issues. D&I is a standing item on the agendas of the Academic Staff, Research Staff and Support Staff Committees. Feedback is obtained via anonymous surveys and focus groups for specific groups (e.g. Female PGR and LGBT+ PGR) and issues (COVID-19). Networks (for PGR and staff) for Women, LGBT+, BAME and Disabilities provide a framework for mentoring members of underrepresented groups. An online D&I comments box (advertised in the D&I newsletter) is available for any member of the School to anonymously report any issue of concern. Responses are posted on the intranet, and a senior member of staff also reports to the relevant committee. We have introduced best practice guidance to promote more diversity of colloquium and seminar speakers; the percentage of female colloquium speakers has increased from 20% to 60% since 2017/18. Each year, one of the monthly School colloquia is focused on an EDI topic. Past topics include outreach activities aimed at encouraging BAME students into physics, and the experience of LGBT+ researchers in the physics community.

We have been very successful in supporting applications to the University's AMF scheme targeted at outstanding female ECRs (IES3.2). Since 2014 the School has hosted 6 AMFs, of whom 4 subsequently won RS/STFC fellowships, and, currently, 3/1/1 are Assistant/Associate/Full Professor. Four of our five ICSs involve female members of staff.

The School is part of the UoN STEMM-CHANGE program (funded by an EPSRC Inclusion Matters grant, Co-I *Burrage*). Part of this project addresses how biases in the use of language can impact negatively on recruitment, promotion and career progression. This research has already led to improvements in our recruitment practices. The project also considers how

language use by the public, particularly online, can deter certain groups of scientists from participation in outreach activities, and negatively impact their career progression. STEMM-CHANGE has also supported a reverse mentoring scheme (5 Physics staff have been paired with mentors with protected characteristics or from underrepresented groups), which has led to School and University-level improvements in the process of making adjustments for colleagues with disabilities. The project also includes an innovative mentorship and upskilling programme specifically for technical staff, in support of career development opportunities for underrepresented groups (a Physics technician has participated).

In a 2017 School survey, 34% of academic staff reported that they had taken advantage of the University's policies to **work flexibly** at some point (13% of Cat. A staff are currently **part-time**). To encourage a culture that accepts part-time working as a norm, some senior staff include their part-time status in their email signatures and our D&I newsletter has featured interviews with staff who work part-time. A longstanding scheme operated by the School to support childcare costs during **conference attendance** has recently been superseded by University- and Faculty-led arrangements, which also cover research visits. Of the 21 staff who have taken **study leave** (see [Sec. 2.1.2](#)) during the REF period, 4 are female.

All of our staffing policies ([Sec. 2.1](#)) apply equally to those on **fixed-term** contracts with particular emphasis on fellowship applications, career opportunities outside academia, and how to develop an independent research programme. Fixed-term staff are offered an interview with the Head of Operations covering career planning and CV development three months before the end of their contract.

The School is strongly supportive of any staff member (including fixed-term and part-time staff) taking maternity/adoption/shared **parental leave**. Staff are encouraged to do an assessment, with Human Resources and the HoS, of the impact of leave on their career development and research. Staff can take advantage of 'Keeping-in-Touch Days' and other forms of contact to maintain research activity during leave. We strongly support University policies that offer a variety of routes back to work, including job-share, term-time or part-time working; staff are also encouraged to use accrued annual leave to phase their return to work. We have a policy that no teaching is required in the first semester after return to work. The School offers further tailored support, such as temporarily reduced/flexible hours and provision for breast feeding/pumping. In a new voluntary School scheme, staff returning to work are paired with a mentor with recent experience of this transition. The School offers paid maternity leave for Home/EU PGR.

We have various policies to support staff **well-being**. The School annually consults staff to ensure that the timetable accommodates caring responsibilities; in an anonymous survey 23% of staff had taken advantage of this mechanism with support from the School. Whole-School meetings, events and training are held in core hours. 'Gender-neutral' (in addition to female and male) toilets have been installed in the main Physics building. Through our workload allocation model (see [Sec. 2.1.2](#)) we check for imbalances between groups of staff with and without **protected characteristics**. Staff with **disabilities** have their workload reduced in line with University policy. Our shadowing system for teaching aims to minimise work-related stress on staff who must suddenly respond to family crises. To combat the long-hours culture in academia, all staff are encouraged to take their leave entitlement. An anonymous survey has been carried out to identify causes of stress. Consequently, information on how to request assistance with various processes has been clarified and better publicised. Support for research student well-being is described in [Sec. 2.2](#).

In response to **COVID-19** our buildings were closed in March 2020 with a partial opening of experimental facilities in July 2020. The rapid switch to online teaching placed extreme downstream pressure on our research activities. To mitigate these effects we have: streamlined teaching, assessment and administrative loads; appointed three temporary Teaching Assistants to release staff research time in 2021/22; identified where COVID-19 affected individual staff or research projects particularly badly, and prioritised resources (including, after discussions in the D&I Committee, PhD studentships) accordingly. The pandemic has also greatly accelerated our

implementation of **flexible working practices**, by taking advantage of online media to interact through meetings and research seminars, as well as teaching.

The **preparation of our REF submission** has been guided throughout by the University's REF Code of Practice (IES3.6). Those with specific REF responsibilities have undergone REF EDI training and the Code has also governed our identification of Independent Researchers. All staff were invited to identify papers for inclusion in our submission. Members of RC and ROG (including Assistant, Associate and full Professors) ranked papers in each research area with further benchmarking between groups by the School REF co-ordinator taking account of the Declaration on Research Assessment. In autumn 2020 a provisional selection of outputs was circulated to all staff to provide an opportunity for further comment and suggestions; the final selection was circulated in March 2021. The average number of REF outputs assigned to both female and male staff is 2.5.

3. Income, infrastructure and facilities

3.1 Income

In accordance with our research strategy (Sec. 1.1.1) we support projects with scales that vary from consortia-led programmes, often involving several universities and/or disciplines, to focused activities involving smaller groups of investigators. The DoR, aided by ROG and the RC, monitors external funding calls and highlights potential opportunities to relevant staff. Support for the preparation of proposals, for example with costings, estimates of technical support, safety and space allocation, is provided by our Research Support Officer. For larger-scale proposals, the University's Research and Innovation department assists with contractual and IP issues. The School offers further support, for example partial funding of equipment and PhD studentships, for grants of particular strategic significance and/or with potential for impact (Sec. 1.2). The DoR also negotiates University support for major applications, and monitors our research portfolio, including the gender balance of proposals led by the School; 26% have had a female PI since 2017, consistent with the staff population.

These mechanisms have leveraged the growth of external funding in each of our research sub-disciplines. The value of awards active on the census date is £30.9M, while the overall research spend (REF4b) is £56.7M (table shows the breakdown by research group). In the STFC area, our *Astro* and *PartCos* groups have held PPARC/STFC Consolidated Grants since their introduction; the value of both awards has approximately doubled since 2014, with

Group	Income	Income (per person)
Astro	£4.3M	£0.4M
ColdAtoms	£5.3M	£1.3M
CMTh	£8.2M	£0.7M
ECMN	£17.1M	£0.9M
PartCos	£3.1M	£0.4M
SPMIG	£18.6M	£1.7M

concomitant increases in postdoc support, and are currently £1.5M (*Astro*, PI *Gray*) and £0.9M (*PartCos*, PI *Copeland*). Funding from the QT Hub (£7.7M) has supported the provision of new infrastructure (£3.6M; see Sec. 3.2) and support for staff and consumables, enabling researchers in *SPMIG*, *ECMN*, *CMTh* and *ColdAtoms* to expand their activities in quantum sensing (see Sec. 1.1.1, **ICS OPM-MEG**). *ColdAtoms* have received further support from the US Defence Advanced Research Projects Agency (DARPA), ERC, EPSRC and other sources to extend activity on nanomechanical systems, gyroscopes and additive printing of quantum systems. Our condensed matter research is funded principally through the EPSRC, EU and ERC; research successes in this area (see Sec. 1.1.1) have been underpinned by major awards for equipment, responsive mode grants and personal fellowships. *SPMIG*, and biomedical imaging researchers in *ECMN*, have, with the School of Medicine, attracted extensive support from the EPSRC, MRC, NIHR and Wellcome for major interdisciplinary consortium-based projects involving clinicians, psychologists and healthcare professionals, as well as extensive industrial support (£2.0M). This funding has provided the platform for our biomedical research, development of new MRI techniques, functional imaging of the brain, and significant impact as described in **ICs QuantMRI** and **EMReg**. Research income linked to: collaborations and

networks is described in [Sec. 4.1](#); and impact in [Sec. 1.2](#).

Our strategy of aligning our EPSRC-related activities with EPSRC Physics grand challenges, themes and national initiatives has been successful, while our strategic aim of a diversification of research income streams has resulted in a 40% increase in the value of non-UKRI awards since REF2014.

3.2 Infrastructure and facilities

The School's infrastructure and facilities for research and impact (IES4.2) have been enhanced by an investment of £23.1M in equipment and £2.8M in refurbishment over the census period.

Our infrastructure is clustered thematically in three buildings in close proximity:

SPMIG is based in a dedicated 1500m² building, which accommodates the UK's first 7T human MRI scanner. The group led a successful £7.7M bid for new medical imaging equipment (including a multi-transmit upgrade on the 7T MRI scanner, new 3T MRI scanner, 0.5T upright MRI scanner, SpinLab dynamic nuclear polarisation system for human studies, real-time MEG upgrade, functional near infra-red spectroscopy system and auditory brain stem electroencephalogram system) from the UK's Clinical Research Infrastructure initiative (2014). This was enhanced by University funding (£1.3M) for laboratory refurbishment and improved facilities for participants in imaging studies. These awards underpinned the establishment of the Sir Peter Mansfield Imaging Centre, a two-site centre which brings together the human imaging facilities in Physics and Medicine. **SPMIG** also operate the UK's first Dynamic Nuclear Polarisation Magic Angle Spinning Nuclear Magnetic Resonance (NMR) Facility, which became operational in 2015. This national facility, operated jointly with the Schools of Chemistry and Life Sciences, and funded through the EPSRC Strategic Equipment Initiative (£2.7M; £1.2M to Physics), has been accessed by more than 20 research groups from 15 different institutions.

Astro and PartCos are co-located in the 650m² Centre for Astronomy and Particle Theory (CAPT), with 40m² of new office space created since 2014 to accommodate expansion of these groups. **CMTh, ColdAtoms and ECMN** are housed in the 6000m² Physics Building, which includes five state-of-the-art laboratories for *ColdAtoms*, with close temperature control and vibration-damped optical benches, plus separate control rooms allowing fully-automated computer control of four experiments (total 200m²). Following the arrival of *Verlot*, this facility has been extended by 65m² for the investigation of nanotube-based nanomechanical resonators.

Investment in capital infrastructure associated with the QT Hub totals £3.6M and includes: a £2.1M 90m² Rapid Prototyping clean room and cold atom laboratory, which integrates the fabrication and in situ testing of quantum sensors; £1M equipment for existing cold atoms laboratories; £0.5M for a state-of-the-art magnetically-shielded room and MEG brain imaging system.

The School is well-equipped with cryostats, magnets, ultra-fast lasers, spectrometers (microwave, optical and Raman), scanning probe microscopes and a state-of-the-art X-ray diffractometer. Our infrastructure includes: three low-temperature UHV Atomic Force Microscope/Scanning Tunneling Microscopes (AFM/STMs) and a variable-temperature UHV AFM/STM; ultra-low temperature NMR facilities; a large-bore cryogen-free 19T magnet for magnetoscience; a combined Raman spectrometer and AFM with associated cell biology facilities; confocal microscopes for imaging biological materials, nanoparticles and exfoliated layered compounds; a cryostat with vector magnetic field capability and a vibrating sample SQUID magnetometer used in spintronics research. A new state-of-the-art ultra-low temperature (base temperature 0.7K) scanning probe microscope (see [Sec. 1.1.2](#)) has recently been delivered. The School's helium liquefier and mechanical, vacuum, and electronics workshops (including facilities for UHV construction and fine-machining), are operated by specialist technicians in support of the *ColdAtoms*, *ECMN* and *SPMIG* groups.

A large cleanroom suite (ISO Class 7 (Class 10000), 300m²), accommodates microfabrication facilities and 3 MBE systems, which grow III-V heterostructures, spintronic and nitride semiconductors. A dual-chamber MBE system, funded by EPSRC (£1.3M) and installed in 2014, is used to grow graphene/boron nitride heterostructures. A new facility EPI2SEM (see [Sec. 1.2.2](#)) funded by EPSRC (£2.9M) and the University (£1M) is currently under construction. Microfabrication facilities also include UV lithography, plasma etching, ellipsometry and metallisation (sputtering, thermal and electron-beam evaporation, electroplating). A 6-source magnetron sputtering system enables sequential growth of metals, oxides and, via transfer to the MBE systems, semiconductors. An ISO Class 7 cleanroom area (90m²), leased to Teledyne UK to support our ongoing partnership (see [ICS Teledyne](#)), extends the range of in-house processing techniques and expertise.

We have access to scanning and transmission electron microscopy, focused ion beams, X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy through the University's nmRC, which has benefitted from £2.4M investment since 2014, including a 50m² ISO Class 6 cleanroom housing an EPSRC-funded (£1.5M) electron-beam lithography facility and an imaging ellipsometer funded by the University.

The School makes extensive use (20M CPU-hours since REF2014) of the University's high performance computing (HPC) facilities, which were upgraded in 2018 to 4,720 cores providing 31TB of RAM. *Pearce (Astro)* served on the University HPC Management Committee from 2005-2019, playing a leading role in developing and procuring the HPC facilities. These local facilities are supplemented via the MidPlus Centre of Excellence for Computational Science, Engineering and Mathematics.

In addition to our access to RCUK facilities (Diamond Light Source, DiRAC, European Magnetic Field Laboratory, European Southern Observatory, European Synchrotron Radiation Facility, Hubble Space Telescope, ISIS neutron and muon source, William Herschel Telescope, total £7.4M, REF4c), staff secured access to the following **non-RCUK facilities**: Synchrotron Soleil (129 days, £774k), NASA Spitzer telescope (119 hours), Abel cluster of Norwegian NOTUR network (2M CPU hours), PRACE HPC (35M CPU hours, £375k).

Our industrial collaborations have led to various **benefits-in-kind**. Bruker BioSpin have donated equipment (value £300k) and directly funded research in hyperpolarised liquids for magnetic resonance imaging and spectroscopy. Teledyne UK have donated a 100GHz Gunn diode microwave source and a Schottky diode and cover all costs for industrial student projects in their labs. Molecularspray Ltd have donated an electrospray deposition system (£75k). FBH Berlin have provided photonic test chips. GlaxoSmithKline and AstraZeneca sponsor PhD studentships, and Adidas have funded a study leave placement and two summer studentships.

Access to equipment and infrastructure is organised at the group and investigator level and all staff are expected to attract external support for their activities. Our resources are also deployed in support of industrial collaborations and translating our research into **impact-related activities**, and this has proved crucial for the success in biomedical imaging, semiconductors and quantum sensors (see [Sec. 1.2](#); which also details additional mechanisms within the University to support impact-related access to infrastructure).

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

4.1 Collaborations, networks and partnerships

During the census period, staff **collaborated** with >150 groups in >30 countries and were partners in 40 EU/ERC projects, with a total value of £7.6M to the School.

We have membership of major international astronomy and cosmology projects, including DES, Euclid, JWST, LSST, LISA, Planck, and SDSS. *Aragon-Salamanca* is the lead scientist of the UK Participation Group for SDSS, co-chair of Science Committee and member of the Executive Committee of the MaNGA survey, and member of the SDSS-IV Collaboration Council and

Advisory Council. *Almaini* leads the Ultra-Deep Survey and serves on the Executive Committee of the CANDELS consortium. *Dye* is a Herschel-ATLAS collaboration Executive Committee Member and Chair of the gravitational lensing working group and was project scientist of the UKIRT Hemisphere Survey. *Pearce* and *Gray* sit on the steering committee for the Three Hundred Collaboration. *Merrifield* is the UK leader of the Planetary Nebula Spectrograph project. *Bolton* leads the Sherwood simulation collaboration that has developed a set of large-scale, high-resolution hydrodynamical simulations of the intergalactic medium.

We are involved in multiple international collaborations focused on quantum sensing, including several EU consortia: Entangled Rydberg matter for quantum sensing and simulations (*Li*, €0.3M to School); Error-proof Bell-state analyser (*Lesanovsky*, *Hackermuller*, €0.5M to School); MatterWave (*Fernholz*, *Lesanovsky*, €0.7M to School); Quantum integrated light matter interface (*Hackermuller*, *Fernholz*, *Lesanovsky*, €0.5M to School). *Fernholz* is a member of the US DARPA-funded programme on Atomic-Photonic Integration and *Verlot* recently initiated the British Optomechanics Research Network.

Patanè is the academic lead for the UK Membership of the European Magnetic Field Laboratory (EMFL); a national facility of the EPSRC (2015-2022, £4.2M) awarded ESFRI Landmark status in 2016. Nottingham, with the EMFL and other collaborators, is a partner of the EU Horizon 2020 project ISABEL (2020-24, €4.9M) aiming to expand the EMFL's industrial and user community. *Patanè* also leads the Nottingham node of the EU Graphene Flagship (€0.5M School share), a consortium of >150 academic and industrial research groups in 23 EU countries. *Novikov*, *Campion* and *Henini* have provided material grown by MBE to >80 academic and industrial groups in Africa, Asia, Australia, Europe, and North and South America. *O'Shea* is the academic lead for the near-ambient pressure XPS instrument (£1M, funded by IUK) within the UK Energy Research Accelerator network, a Nottingham-based facility for the study of batteries, fuel cells, photovoltaics, and water-splitting solar cells under realistic operating conditions. *Edmonds*, *Rushforth*, *Campion*, *Wadley* and *Jungwirth* have an ongoing collaboration with the Czech Academy of Sciences on antiferromagnetic spintronics, which has led to £0.5M (School share) of EU funding and 17 publications since 2014. Nottingham has an institutional-level Memorandum of Understanding with the University of Tübingen; *Lesanovsky* and *Olmos* have joint Tübingen/Nottingham appointments.

SPMIG collaborate extensively with clinicians and biomedical scientists, contributing to the Birmingham-Nottingham MRC Arthritis Research UK Centre for Musculoskeletal Ageing Research, Nottingham's Versus Arthritis Pain Centre and the NIHR-funded Nottingham BRC (£23.6M award on which *Gowland*, *Francis*, *Morris* and *Bowtell* are named as key researchers). Imaging is a cross-cutting theme in the BRC, as well as being a key element of four of the other BRC themes (Hearing, Gastrointestinal and liver diseases, Respiratory disease, Musculoskeletal disease). *Morris* and *Brookes* were Co-Is on a £3.5M MRC Grant with Manchester and Cardiff and a £0.8M MRC Partnership Grant for building capacity in clinical MEG research across the 8 UK MEG centres. *Gowland* and *Bowtell* were Co-Is on a \$3.2M US National Institutes of Health (NIH) grant to investigate the structure and function of the placenta. *Francis* is PI on the £0.8M MRC Partnership Grant, which supports the UK Renal Imaging Network across 13 UK institutes. *Brookes* and *Bowtell* hold a £1.4M Wellcome Collaborative Award in Science with UCL for OPM-MEG development, and are Co-Is on a \$4.2M NIH grant on next generation magnetoencephalography for human social neuroscience, with Virginia Tech. *Bowtell* leads the UK7T Network, which brings together the UK's seven sites with 7T MRI scanners supported by a £1.1M MRC Partnership Grant (Co-Is *Francis*, *Glover*, *Gowland*, *Morris*). *Bowtell* and *Francis* have been sub-group leads for the EU Joint Programme-Neurodegenerative Disease-funded ultra-high-field imaging network for neurodegenerative diseases. *Gowland* is Nottingham lead for the IMAGEN consortium, the largest comprehensive longitudinal study of brain imaging and genetics in adolescents worldwide.

Gowland coordinated the High-field Magnetic Resonance EU ITN (€3.6M, €0.8M to School). *Fernholz* coordinated the Quantum Sensor Technologies and Applications ITN (€4.2M, €0.8M to School) and is Training School Coordinator of the European COST network AtomQT. *Moriarty*

coordinated the ACRITAS ITN, which involved interactions between Physics, Chemistry and Biosystems (€3.9M, €0.9M to School).

4.2 Contributions to society

Research user representation on the School's Strategic Advisory Board provides broad industrial input to inform and refresh our research and impact strategies. New collaborations since 2014 span a wide range of fields including: condensed matter physics (Asahi Kasei Coporation, Hitachi, Photek, Schlumberger); imaging (AstraZeneca, Brain Products GmbH, B. Braun, Fresenius Medical Care, GE Healthcare, GlaxoSmithKline, Magnetic Shields Limited, Motilent, Nestle, Perspectum, Philips, Quotient, QuSpin, RiverD, Sanofi, 3M, Unilever, Vertex, Zespri); numerical modelling (Rolls-Royce); quantum technologies (Added Scientific Ltd, Austria Micro Systems, Unitive Design and Analysis) and also Adidas, Durham & Cleveland Police, and Johnson-Matthey.

SPMIG are regularly involved in Patient and Public Involvement activities ensuring that stakeholders are directly involved in the design of research projects. *Mao* co-organised a workshop for Nottingham city council on urban planning. *Burrage*, *Conselice* and *Moriarty* have taken part in the Royal Society's MP pairing scheme.

We organise and participate in a wide range of **public engagement** activities such as community events (e.g. Science in the Park, Festival of Science and Curiosity), lectures in schools and colleges, public talks (e.g. Pint of Science, Café Scientifique, astronomical societies), popular science articles, A-level Masterclasses and Summer Schools. A highlight is our interactive Spring into Science event, which is attended annually by >350 year 8 students from inner city Nottingham schools with a large BAME cohort. We also run a work experience scheme, aimed at students from underrepresented groups. Of the students who attended Nottingham Potential or Sutton Trust Summer Schools, 26 subsequently enrolled on Nottingham Physics degrees.

We have initiated several major novel outreach projects. In the Sixty Symbols series of YouTube videos, a range of topics, including original fundamental, applied and interdisciplinary research, are presented by our staff (**ICS Sixty Symbols**). The channel has >350 uploaded videos, >800k subscribers and >88M video views. This innovative collaboration won the IOP's 2016 Kelvin Medal, the Digital Media award at the University's 2016 Knowledge Exchange and Impact Awards and was a finalist for the 2018 Times Higher Education Outreach award.

Our activity on MEG was exhibited as 'Quantum Sensing the Brain' at the 2018 Royal Society Summer Exhibition (~14k attendees), the New Scientist Live exhibition, and the 2018 National Quantum Technologies Showcase. Our industrial partners (QuSpin) have also used this exhibit at a technical exhibition. Former PhD student, now postdoc, *Boto* (*SPMIG*) won the 2019 UoN Vice Chancellor's Medal for this exhibit. *SPMIG* were involved with the Dementia Choir (featured on The One Show in 2018). *Bamford* (*Astro*) is the founding Science Director of the Zooniverse, an international project which engages millions of members of the public in the scientific process itself and was awarded the 2019 RAS Group Achievement Award. We also run Inflativerse, an inflatable planetarium, which we have exhibited at schools and community events across the East Midlands.

4.3 Indicators of wider influence

In this section, highlights are chosen to span all groups and to reflect all career stages.

Awards & Prizes: (in addition to fellowships, listed in [Sec. 2.1.2](#)) CBE (*Morris*, 2016), IOP Maxwell Medal and Prize (*Lesanovsky*, 2014; *Burrage*, 2015), IOP Kelvin Prize (*Merrifield & Moriarty*, 2016), IOP James Joule Medal and Prize (*Bowtell*, 2020), IOP Nevill Mott Medal and Prize (*Eaves*, 2020), IOP Peter Mansfield Medal and Prize (*Gowland*, 2020), Biomag Mid-career Award (*Brookes*, 2018), RS Wolfson Merit Award (*Lesanovsky*, 2017), Gruber Cosmology Prize (*Moss* as member of Planck collaboration, 2018), Buchalter Cosmology Prize 2nd (*Padilla*, 2015).

Visiting positions: Fellow at All Souls College, Oxford (*Garrahan*), honorary professorship Institute of Semiconductors, Chinese Academy of Sciences (Beijing) and Chinese Academy of Sciences President's International Fellowship (*Patanè*).

Journal editorships: served on 33 Editorial Boards including Astrophysical Journal (*Conselice*, lead editor for Galaxies and Cosmology), Proceedings of the National Academy of Sciences (*Garrahan*), Physics in Medicine and Biology (*Gowland*, deputy editor), Journal of Cosmology and Astroparticle Physics (*Green*), European Physical Journal Quantum Technology special issue on Quantum Magnetometers (*Jensen*).

Grants committees: participated in 35 grant committees for BBSRC, EPSRC, STFC, Leverhulme Trust, RS, ERC and funding bodies in Europe and North America, including ERC Advanced Grant Panel (*Campion*), RS Wolfson Merit Award Scheme (*Eaves*), UKRI Future Leaders Fellowship Panel (*Fromhold*), Wellcome Biomedical Resource and Multi-User Equipment Committee (*Gowland*), STFC Astronomy Grants Panel (*Gray*), STFC Particle Physics Grants Panel (*Green*).

Membership of Research Council committees: >50, including Chair of STFC DIRAC Resource Allocation Committee (*Bolton*), Non-core Member STFC Science Board (*Copeland*), Chair of European Extremely Large Telescope Steering Committee (*Merrifield*).

National and international advisory roles: highlights include IPPP Steering Committee (*Copeland*), STFC Astronomy Evaluations Panel (*Hatch*), Member of REF2014 Sub-Panel 9 (*Eaves*), International Member of Committee for Canadian Science Prizes (*Morris*), Member of REF2014 Sub-Panel 1 and of REF2021 Main Panel A, with responsibility for Interdisciplinary Research (*Morris*), Peer Review Committee 2-SOLEIL Synchrotron (*O'Shea*), Council Member of European Magnetic Field Laboratory (*Patanè*), Vice Chair Commission 8-International Union of Pure and Applied Physics (*Patanè*). Numerous international telescope time allocation committees, including ESO IPC (*Conselice*), ING (*Dye*).

Leadership in professional bodies: Chairs of IOP Quantum optics, Quantum information and Quantum control (QQQ) group (*Fromhold*), Conference Committee (*Moriarty*), BSRG Magnetic Resonance Group (*Owers-Bradley*). President of the European Society of Magnetic Resonance in Medicine and Biology (*Bowtell*), Member of IOP Science Board (*Moriarty*), Chair of UK Cosmology (*Padilla*).

Invited talks: >700 at international conferences and >150 at national conferences. Highlights include: Physics Beyond Colliders, CERN (*Burrage*, 2016), Mansfield Lecture 25th annual meeting of the International Society of Magnetic Resonance in Medicine, Hawaii, (*Gowland*, 2017), opening review talk at Evolving Galaxies in Evolving Environments (*Gray*, 2014), 23rd International Conference on High Magnetic Fields in Semiconductor Physics, Toulouse, France (*Makarovskiy*, 2018), 16th European Conference on the Spectroscopy of Biological Molecules (*Notingher*, 2015), keynote talk at APS meeting Boston (*Wadley*, 2019).

Conference organisation: organised >80 conferences. Highlights include: Probing the Dark Sector and General Relativity At All Scales 2017 CERN (*Burrage*), Photon2020, main international optics conference of the IOP (*Fernholz & Notingher*), chair Gordon Conference on In Vivo MR 2014 (*Gowland*), chair Phonons 2015: 15th International Conference on Phonon Scattering in Condensed Matter (*Kent*), chair 19th International Conference on Non-contact Atomic Force Microscopy 2016 (*Moriarty*), RS meeting on X-ray Astronomy and Fundamental Physics (*Russell*).

Refereeing: >150 journals, and >60 funding bodies in >25 different countries.

External PGR training: lectures at 15 schools, including tutorials on deep learning at National Meeting of Data-Intensive Science CDTs in Edinburgh (*Bamford*).